Streams21: Running Notes

• Zoom • Wonder.me (pw: 162162) • Indico (pw: 162162) • Slack •
• Intro slides • Talk Abstracts •

Global Suggestions, Ideas, and Action Items

Use this area to collect ideas, suggestions, and action items that are generally-applicable:

- A set of globular cluster / dwarf galaxy streams evolved in a hydro simulation, especially for testing our modeling methods, understanding what the streams are sensitive to
- …
-
- Community Efforts and Ideas
    - From day2->Blind modelling challenges. Very useful in other fields. It is not necessarily a test of 'who is best'. Methods have different strengths. It takes time away from analysing data so needs to be a real community effort. -> similar to the efforts started in the Gaia Challenge Meeting series
    - From day2-> Tools for orbit integration in time dependent potentials (e.g. "easily" including LMC)
    - common framework to share potential model (within e.g. the gala framework)
    - Following day2 -> How do we combine the best of large-scale cosmology (well-developed model; many independent tracers; awesome funding sources) and near-field cosmology (thrill of data exploration; followed by plentiful discoveries and surprises; being able to make significant contributions with a small team; and easily assign credit, especially to junior members of the community)

Monday Feb 22: Milky Way Streams and Substructure

[Moderators's Summary Slides]

Moderators overview

- Discussion intro / overview of talks:
    - Many ways of splitting the population of streams we have:
        - Dwarf galaxy vs. globular cluster
        - Progenitor vs. progenitor-less
    - New methods for discovering streams, new data for better characterizing known streams
    - Unique tracers: proper motions to 100 kpc HSCxSDSS, Type II Cepheids, RR Lyrae (and velocities)

Structured breakout topic brainstorm

- Why would we need to push for discovering more streams (and work on completeness)? Why would we focus on better characterization of known streams?+ What data do we need from discovery to dark matter constraints?
- What are the most interesting objects (streams or progenitors) to focus on? What types of streams are the most interesting for your research goals? What observations are we missing for the 4 classical streams (Pal 5, GD-1, Orphan, Sag)?
- How do we design spectroscopic surveys of streams? Low-res vs. High-res? (or low-res *then* high-res?)
    - How many tracers in a stream are sufficient?
    - Spectroscopy of stars in and around gaps at sub-km/s precision
- Discover new streams vs. characterize existing streams: We are still in a phase where each new stream has brought interesting new discoveries and questions. When can we call a stream detection robust?
- How do we tell which streams are real and which ones are associated with each other?
- Need for HR velocities (especially for near the gaps)
- From simulation point of view, hard to make precise model of progenitor-less stream, so need observation of a lot of stars along different part of stream
- What theoretical effort do we need to better interpret the data? E.g. simulate more realistic streams +
- Detectability of streams and how to estimate completeness: important for accretion history
- Having progenitors, or full 6D information for progenitor-less streams, is important for doing first simulations of the streams
- What is a stream?
- How many data do we need on stellar streams? +
- Do we need to know whether a stream is from a dwarf galaxy or star cluster? +
- Does it matter if it’s streams, clouds, tidal tails, or other stellar substructures +

Breakout session themes:

- What set of questions do we want to answer in the next 5 years related to streams? To answer these questions, what sets of data do we need (theoretically, observationally) do we need?
  - Questions related to dynamics, dark matter
  - Questions related to MW assembly history, stream progenitor population

Returning to the full group after breakouts:
- In the stream discovery regime: how to find more streams with existing data or future data?
- What does the future surveys can help us on streams and how to utilize these data (e.g. LSST, DESI, 4MOST, WEAVE, etc)
  What is the target coverage of these surveys?

Random Breakout room notes

Room 3: Sukanya Chakrabarti, Alex Ji, Roelof de Jong, Zephyr Penoyre, Juan Miro, Alex Drlica-Wagner, Ana Bonaca, Pierre-Antoine Oria, Khyati Malhan, Anton Rudakovskyi
- Do we need a complete sample of streams, what do we learn from the census?
- Stream science (and halo science generally) is hard in the Galactic Plane!
- Do we have anyone from DECaPS around? Crowded field photometry will be important to use data close to the plane with Rubin Observatory
  - I don't think we have at the moment, but we could definitely ask!
  - We need to put out the Eddie Schlafly signal! Save us Eddie!
- What is happening with Antlia 2?
  - Looks like it just started disrupting in the last pericentric passage, at ~50kpc
  - A massive multiplex survey like 4MOST would be valuable for measuring metallicity / kinematics
- Do we need to search more streams?
  - Yes: especially more distant ones
  - Yes: so far every stream has told us something new
  - Yes: especially in regions of parameter space that are chaotic, say by LMC. Can we detect disrupting satellites around the LMC to help map the potential? Do we expect such systems to exist?
  - But: better characterizing a stream is more valuable than discovering 3 streams in the same region of the parameter space

Room 5: Guillaume Thomas, Carl Grillmair, Orlin Koop, Martín Mestre, Matt Buckley, Jeff Carlin, Paul Zivick,
- HR velocity
- Need precise distance because a lot of stars with proper motion are not used and RRL and BHB are sparse
- Need more streams at large distance (The colder the better)

Room 9: Adrian PW, Sophia Lilleengen, Raphael Errani, Raj Kumar Pradhan, Tian Qui, Tereza Jerabkova, Nil Banik, Kiyan Tavangar, Gustavo Medina, Nathaniel Starkman

- Sophia: Interested in the LMC influence on streams, so important to find more streams in the vicinity of the LMC or in the path of the LMC
    - For the streams that have been known to be perturbed by the LMC, what missing dimensions are important for improving constraints
    - Spectroscopic follow-up (radial velocities)
- When will we see the impact of the LMC on streams?
    - Already now, from the infall over the last few 100 Myr
    - Depends on the scale of the perturbation: on large scales, the reflex motion and shift of the inner halo, which effects the orbits of the streams
    - The fact that the Sun / inner MW is in a non-inertial frame and moving w.r.t. streams in outer halo, the orbits will be affected
- Simulating the LMC impact is a challenge!
    - How can we simulate a dwarf galaxy and a globular cluster with decent resolution for both
    - Large dynamic range simulations
    - Can be done but needs custom simulation tools (can't fire up Gadget-2!)
    - What we need from simulations is different from what NBODY6 *or* Gadget can do
    - PeTaR (new simulation code)
    - Another suggestion: AMUSE architecture (bridge between diverse N-body codes)

Room 2: Kathryn Johnston, Pau Ramos,

- Should we focus on finding new streams or characterising

existing streams

- Depends on what you want to do: if looking at history, find as many as possible; if you're measuring potentials then we probably have enough
- Need to get models up to scratch
- E.g running cosmological models and inserting globulars clusters

What are we asking of observers

- For potential measuring, we want connections to distant halo and streams out there. There are already objects out there within 10 kpoc that have very radial orbits
- Problem is distance - RR Lyrae
- Looking for shells in outer galaxy to connect to
- Like we said in our group, if the question is "do we need more streams or better data of the existing streams," the answer is "yes" :)
- Another mantra was "In the meantime, we do what we can with the data we have."

Room 8: Jaclyn Jensen, Alex Riley, Ting Li, Adam Smercina, Edgar Marrufo, Borja Anguiano, Kathy Vivas, Zdenek Prudil, Mark Fardal, Jen Marshall

- substructure not stream like (e.g. clouds) are not mentioned much but we should understand them better and their connection to the halo. E.g. Virgo overdensity, TriAnd. Also their connection to GES. +
- What are streams? What streams we are interested in? Eridanus-Pieces stream from open cluster (100 pc 100 Myr?), Nyx/Helmi? Progenitors?+

- Chemical tagging the halo stars and associate them with streams/systems. Come up a good science case for future spectroscopic survey like MSE
- Probing the proper motion beyond Gaia using ground based astrometry

Room 1: Rohan Naidu, Cecilia Mateu, Youjia Wu, Andreas Koch-Hansen, Camila Navarrete, Xiaolong Du, Tariq Hilmi, Xilong Liang, Benne Holwerda

- Can we say based on current observables whether a progenitor should be observable?
- What is a stream? Do we need radial velocities or chemical coherence to classify something as a stream?
- How much spectroscopic followup is need?
- How do we defined the "end" of a stream? RGB-tip methods could be useful
- Can narrow band photometry be used to provide more detailed chemical info?

Room 6 (Jason Sanders, Alis Deason, Diederik Kruijssen, Stella Reino, Tom Donlon, Aneesh Naik):

- For action-based approaches, higher quality data of known streams would be great!
- Is there really a discrepancy between observed numbers of GCs and dSphs? What are the constraints/expectations for this? GCs easier to find as higher contrast, also only disrupt more recently due to dynamical friction? Or is it due to other properties?
- What are action-based approaches telling us? Do they put strong constraints on regions of the potential far from the stream?+
- We need more chemistry on streams to distinguish globular cluster streams from dSph streams.

Room 10 (Eugene Vasiliev, Monica Valluri, Kohei Hattori, Eduardo Balbinot, Sarah Pearson, Elena Sacchi, Elise Darragh-Ford, Anna Wright)

- Better data for distant streams. Sub-km/s velocities for distant streams or for stream gaps (to probe different physical mechanisms on gap formation), dedicated targeting efforts in large-scale surveys (though both WEAVE and DESI are currently at 1-2 km/s precision level)
- Chemical properties of the streams revealing their origin: e.g. in-situ cluster disruption or clusters from external accreted galaxies would both be narrow/thin (but see Khyati's recent work) but differ in chemical/age properties. Need to relate to the chemical properties of (rather scant) glob clusters in Local group dSph.
- Morphological features (gaps, fanning, etc) in prograde/retrograde streams probe different physical mechanisms (bar, spiral interactions vs DM clumps).

Room 7:

We discussed if we can develop an algorithm similar to streamfinder that can find accreted dwarf galaxy debris instead of just cold stellar streams. Can Via Machinae do this?

Structured Breakout room notes

Room 1 (dynamics, dark matter)

What questions do we want to answer that are stream related in the next 5 yrs?

- Comparing CDM to SIDM and other dark matter models

What data (observational/theoretical) do we need to answer these questions?

- To match up streams and subpopulations: need many dimensions (element abundances, RVs, distances, ages??)
- For large-scale potential constraints: low-precision RVs and distances
- For substructure constraints: <1 km/s precision RVs and precise distance
    - Tracers like RR Lyrae / BHB stars

Notes:

- For potential modeling / orbit modeling, low-res spectroscopy and current data is pretty good! But to get substructure, we need <1 km/s RVs
- Specific surveys:
    - 4MOST down to G=17 for the entire survey region (Vlos+chemistry), G ~ 20 for Vlos only
    - Gaia RVs to G ~ 16 mag
    - DESI to G ~19 for Gaia targets [proper-motion cut to downselect nearby M-dwarfs relative to distant Mgiants], G ~ 21 mag in some cases (will need to confirm if the Vlos precision of 1-2 km/s can be reached)
    - WEAVE to G ~ 20 mag (Vlos, [fe/h], [alpha/fe])
    - But what about completeness in parts of the CMD?
    - Which of these surveys are whole sky ones as Gaia? [none! - ground based surveys from a single telescope won't see the whole sky]
- Different streams are good for different things -- Pal5, GD-1 good for dark matter substructure so focus higher resolution observations there and lower res on a broader sample.
- "Kill zone" radius - where the progenitor gets disrupted depends on its properties (eg. density profile) so is an indirect probe of the structure of DM haloes (statistically)
- SIDM changes large-scale structure of halo. For this we need a large number of probes in the outer halo, and also structure of the progenitors.
- MOND strong equivalence principle tested by cold globular cluster streams at Galactocentric radii 20-80 kpc (need more of those, yeah!)
- Occurrence of streams is a useful test of dark matter models: e.g. Ant2 produces a stream at larger pericentric radius in alternative models.
- If we had 100s of streams known at low signal to noise, what could we do differently from having 10s of streams with good characterization? Is there still a lack of simultaneously modelling of many streams? There are several recent studies (Reino+2020) that look at many [well, a few at a time] streams. Also theoretical efforts looking at information content in large samples of simulated streams [see Bonaca & Hogg 2018 for a theoretical framework, although AFAIK it hasn't yet seen

actual application]. Different streams test different regimes e.g. some more sensitive than others for probing LMC
    - But: each stream we look at so far seems to be interesting and unique in its own right! So focus has been on the details of individual stream formation
    - Simultaneous fits of many (100s) of streams become sensitive to the modelling assumptions/priors. Better use several independent methods to model one or a few streams than apply one method to tens of streams - if it is biased in some way, you won't know.
- The parameter space for multiple streams is large and difficult to explore.
- What summary statistics can be extracted from large samples of MW streams and compared to high resolution simulations? A very simple example would be the number of streams -- does this constrain the models at all? [or perhaps it's not quite accessible observationally - we don't have a good idea about completeness/detection efficiency]. Some statistics are sensitive to detection efficiency/completeness.
- A common framework for dynamical models (in particular MW halo potential model) would make comparisons easier. This was brought up ~5 years ago at Ringberg. What progress has been made since?
- Related but slightly different: What do we want to report from our measurements, or aim for? I think we have found enough complexity that "mass" or "mass profile" has lost its utility :) Do we need a "time-dependent mass profile" or something even beyond that?

Room 2 (assembly history, progenitor population)

What questions do we want to answer that are stream related in the next 5 yrs?
What data (observational/theoretical) do we need to answer these questions?
Stream discovery? Stream population? Stream progenitor? accretion history

The following questions likely will require different kinds of data:

- Where do all the streams come from? A unified halo model for each star to its origin (by object): this has happened for most intact systems but not yet for streams. (And then where do the stars in the stellar halo come from?)
  Or "Put the stars back in the box" (where do all the halo stars come from)
    - Might already be almost there: Sgr, LMC, GES
- Statistical: frequency of types of objects? E.g. percentages of each building block in the halo.
    - The lower percentage objects might be the most interesting
- What about just the major contributors to the galaxy? ^
- Streams/structures that don't seem to be represented in existing bound structures.
    - E.g., phoenix stream (GC below the current metallicity threshold, would only be able to observe at high redshift, but not at this level of detail)
- Chronology of the accretion events?
    - E.g. did a major merger produce the thick disk or not?
    - Comparing fully mixed dwarf galaxies, disrupting now (streams), and intact systems
    - Associations with the Magellanic Clouds and Sgr vs ancient accretion events

- Not all of the Milky Way accretion is probed with stars? -> certain aspects of the history can only be probed by streams (rather than major accretion events)
- Population of disrupting objects (e.g., need to add disrupted galaxies to measure the full luminosity function of satellites)
- Connect all of this in context to other systems (through cosmic time)
    - Also, what do different GC systems imply about the Milky Way
- Channel into studying what the milky way looked like in the past from its response to mergers (e.g., the formation of the in-situ halo)
- For assembly, we should focus on disrupted objects, rather than just streams.
- Is there a gap in the accretion history (are we missing an object at intermediate times, after GSE)?
    - Sgr in this category, so not clear if there is a gap -- might more be a monotonic decline of the merger mass ratio with time.
    - There are very few globular clusters younger than 10 Gyr old unassociated to a known dwarf galaxy progenitor, so this places an upper mass limit of ~5x10^7 Msun on any other progenitors in the merger history between lookback times of 0-10 Gyr yet to be discovered.
    - […] Discussion -> slack
    - ^Alex finds this discussion very helpful and would like if you had it on a thread somewhere!
    - JMDK: discussion added to the slack day1 channel

What data do we need?

- We do have a lot of streams that we understand very well, but it's in a very small volume -> Gaia-sphere.
    - Still missing a lot of the volume, what we have is a small part of the overall picture
    - We need streams at large distances -> distant halo proper motions?
- Vast majority of streams are cold (likely an observational bias)
    - Maybe we need to find warmer streams
    - What is a typical halo stream? Is it GD-1 like or something much more diffuse?
    - How do we find them: better algorithms? Or deeper data? Or searching in the chemical space?
    - For fully reconstructing history, we also need streams of all shapes (and shells++)
- We have found many streams but it's still a small handful that are well-characterized.
    - A gold standard set of measurable properties
- Chemical tagging of streams?
- For reconstructing history, we need to also consider things that no longer appear coherent
- Outer halo special regime:
    - Formed later, fewer stars, not so informative on the formation history
    - Good for potential though
- Inner halo (10s of kpc):
    - Individual stars are good for reconstructing early accretion/low mass systems.

    - Oldest objects, oldest lower-mass objects, looking at the early universe, oldest objects
    - Most of the mw formed a long time ago (GSE, Sequoia), and are present in the inner halo
    - Taking apart the inner halo: maybe multiple smaller old mergers that are being mistaken for single large things
    - Bulge is also a part of the inner galaxy, has many globular clusters, are there bulge streams? What do they tell us?
- *distances* are really important. We can do this for a few tracers, but can we do better?
- High quality abundance work across a large number of streams to break up phase mixing: needs a large survey across all types of structures
    - But would be extremely valuable to discover older / lower mass objects

Summary session

- Common modelling framework
    - One tool is perhaps not good enough. We need to consider the time dependence of the potential
    - the data means we have gone beyond constraining the mass and flattening profile. We ideally would like to report the time dependence of a set of basis function coefficients. This is necessary to capture the MW + LMC interaction.
    - Need to run tests of how well we can measure the time dependence of the coefficients using cosmological simulations. Need to understand the limitations. Is it possible to do this without running expensive simulations?
    - Does it still make sense to discuss distribution functions and total masses in the presence of significant non-equilibrium effects? (answer: of course, but these may not be described in terms of integrals of motion..)
    - We should be measuring accelerations. Basis function coefficient constraints will be highly correlated. Even worse with time dependence!
    - Basis functions can satisfy the Poisson equation so have a dynamical relevance. Decomposing simulations in terms of BFE helps us to separate out and characterise the properties of different effects.
    - This sort of machinery is the way to go but it is hard work. Might take several years :) It is worth the effort!
    - Can measure accelerations directly from pulsar timing. Can this be integrated into wider constraints on the force field using streams.
    - BFE is perhaps the way to combine many stream constraints in a flexible way.
    - Can we probe the inner Galaxy with streams? Do we have the tools for this region?
- RR Lyraes in the outer halo with spare fibres
    - [dump from the zoom chat]
    - 11:50:24 From Alex Drlica-Wagner (he/him) : On the other hand, the number RRL candidates is increasing rapidly...
    - 11:50:37 From Adrian Price-Whelan (he/him) : If you do high-z quasars, we should ask for some favors from them!

- 11:50:46 From Adrian Price-Whelan (he/him) : (not the quasars...the people observing them)
- 11:52:20 From Alexander Ji : It sounds like a community database of all the highest priority tracers showing who has targeted what across the community would be useful. Can also share with people outside the community to make it easy for them to provide said favors
- 11:52:49 From Ana Bonaca : +1
- 11:52:56 From Ana Bonaca : that's a great idea Alex!
- 11:53:01 From Cecilia Mateu (she/her) : Yes! And alsto to keep track of the stars that have already been observed and avoid too many redundancies
- 11:53:06 From Adrian Price-Whelan (he/him) : Yes! +1 to this. I keep bringing up the exoplanet community, but tehy have frameworks in place for this kind of thing
- 11:53:13 From Jeff Carlin : It's really hard to get spectra/RVs of distant RRLs - part of the limitation is that you need a large aperture system because you can't expose for very long due to the short RRL pulsation cycle.
- 11:53:37 From Guillaume Thomas : Need a database of those tracers
- 11:53:54 From Ana Bonaca : and for RRL, it won't hurt to have multiepoch spectroscopy ;)
- 11:54:18 From Guillaume Thomas : (And of streams and streams candidates, people doing extra galactic stuff need to know where are the stream to avoid that regions that are contaminations for them)
- 11:54:20 From Alexander Ji : ^yes! And if you combine with multiepoch photometry + phases you can get an RV out of a longer integration I think
- 11:55:04 From Monica Valluri : Do halo field stars have a role to play in dynamical models using time-dependent basis function expansions.
- 11:55:35 From Cecilia Mateu (she/her) : @ JeffCarlin, yes, but there's also a case of how useful it would be to have a large sample of RRLs at lower res /higher errors, so, going for big numbers and a statistical approach in that case
- 11:56:07 From Kohei Hattori : It seems expressing MW+LMC density profile with time-dependent multipole expansion may require a large number of (high-order) coefficients. Is there a smart way of reducing the number of coefficients?
- 11:56:24 From Jeff Carlin : @Cecilia Totally agree. RVs with large errors are better than none at all!
- 11:56:25 From Guillaume Thomas : +1
- 11:57:02 From Ana Bonaca : great discussion on follow-up here, will copy to the running notes!
- 11:57:11 From Zdenek Prudil : If you have photometry for a given RR Lyr, you can get systemic velocity from a single spec. measurement. You can get even some info on metalicity.
- 11:57:23 From Jo Bovy : Flipside of the dynamical connectionL assumes Poisson's equation!
- 11:57:27 From Zdenek Prudil : Photometry I mean at least 10-20 points
- 11:59:02 From Nicolas Martin : About RRLyr and BHBs, large spectroscopic surveys like WEAVE, DESI, 4MOST will observe most of them in the next 5-7 years, no?

Will they? How the targets are gonna be selected one needs to apply for time/programme, right?

- 11:59:24 From Lemasle Bertrand : One can probe deeper using type II Cepheids since they are 1-5 mag brighter than RR Lyr, but they are extremely rare (See Hitesh's talk)
- 12:00:11 From Alex Drlica-Wagner (he/him) : Do we have some time to discuss future large facilities?

Tuesday Feb 23: Large-scale Constraints on Dark Matter

Today's format

- 1st session:
    - 15 minutes intro (+ 5 minutes flex)
    - 25 minutes for breakouts (+ 5 minutes flex)
    - 25 minutes for return
- Coffee break 30m
- 2nd Session
    - 40 min breakouts (+5 min flex)
    - 30 min for return

Summary of Random Breakout Rooms

- Can we measure the MW potential directly from the data, without making assumptions about the form of the potential model?
- Going beyond static / fixed potential models is hard - there are no standard tools
    - What would it look like to develop a set of tools to enable this?
    - User-friendly basis-function expansion analysis / resimulation code?
        - Agama / Gala / Galpy do support some of this
- Need for a community repository for sharing stream data
    - Will enable using multiple streams to make measurements
- What do we learn from studying the shape of the MW potential and comparing to cosmological simulations?
    - How serious are the agreements / disagreements?
    - Is 1st-order "shape" too simplistic?
- Get better constraints on the potential with multiple streams
    - Knowing one stream in extreme detail doesn't solve the full potential
    - Streams just at pericenter or apocenter not as good as streams that span a range of phases
- Are streams less sensitive to messiness of the potential? But as they are phase-coherent are they not more sensitive probes? They are insensitive to the assumption of equilibrium. More direct probes of the acceleration (as mentioned on Monday?).
- Some streams aren't sensitive to the LMC :) so the methods are still good.
- Streams have clear features which cannot be reproduced by time-independent potentials (proper motion - on-sky misalignment). Other halo tracers are also sensitive (e.g. net velocity) but streams perhaps more sensitive?
- Streams are not self-gravitating so they are test particles in the potential. There are fewer assumptions.
- Action computation depends on our assumptions regarding the potential. Can machine-learning approaches be used for more general potentials?
- Basis function expansions essential for understanding the detailed structure of the halo.

- Is there a radius within which we can assume equilibrium? Direct acceleration measurements can test this.
- Do we need to incorporate the merger history into our understanding of the evolution of the dark matter halo?
- (Ages of GCs in Sgr -- Minniti)
- How do you know you have expanded your potential correctly?
- Action-space clumping -- how do you know it is a unique progenitor?
  Time-dependence of action-angles in cosmological simulations.
- Chemistry & distances are important!
- Different streams are sensitive to different things. Do we need catered approaches for different streams (under a common MW potential umbrella)?
- We need to test methods using cosmological simulations. Do sims have all the necessary complexities? They are the best we have! Uncertainties are realistic (no systematics).
- LL: I think the point when using clustering in action space to constrain the potential (Stella and Niayesh's talks) can be complicated by this point that actions can't necessarily be treated the same way in every part of the galaxy. Some regions of the Galaxy are subject to large perturbations/large changes in the actions. But some parts respond adiabatically to the LMC perturbation so actions are still good! We would like a coherent framework for all parts of the MW.
- MF: If we are worrying about tidal distortion of the LMC halo in our potential models, do we need to worry about the SMC too? Maybe one day…
    - LMC and SMC fell in together, which affects both the total mass and the orbits
    - SMC is heavily disrupting now, so the current mass is ~low (looks like it affected Tuc4, streams not that much)
    - However SMC halo mass used to be ~10^10Msun, and it's orbiting the SMC, so likely included in the current modeling of the LMC
- ..

Moderator's Summary

[Moderator's Summary Slides]

- Big question = large-scale properties of Galactic potential (mass, shape etc.) and what constraints do they put on DM models?
- LMC seems to be the new "magnetic fields": you can't ignore it any longer
- What is the connection to small-scale problems?
- Action-angles are useful but what about time-dependence/non-equilibrium!
- Are we really measuring what we think we are measuring given everything is a mess!

Random Breakout Rooms

Breakout Room 1: Tomer Yavetz, Marius Cautun, Kiyan Tavangar, David Shih, Johanna Hartke, Carl Grillmair, Eduardo Balbinot, Ceclia Mateu, Tilly Evans, Ting Li

- Converse quantities under adiabatic potential in action space. Action and phase space has their own pros and cons. Should not prioritize one or the other.
- What kind of stream and how many streams do we need to disentangle this "messiness" / what kind of data do we need? Also, will we encounter more "messiness" when we get better data? Cosmological simulations might help on this. How precise we need to measure in terms of the potential?
    - Can we learn the MW potential with data itself, e.g. a data driven way with machine learning, without any modeling like throwing an LMC or a Sgr, etc. Where do we get the training sample? From simulations?
- Also on the data, what is more important, larger sample size vs high precision of the data. (this is mainly on distance and RV)
    - Measurement at different distances are important to measure enclosed mass
- Can we do this just with 4D (PM+RA/DEC) data alone?
- Limitation in action space is that one needs to make assumptions about the potential / distribution function, state of equilibrium
- Lack of accessible tools for simulating streams in time-dependent potential +
- What can we achieve using machine learning? Is it possible to infer the MW potential using Neural Networks? What would be the training set?

Breakout Room 2: Ana Bonaca, Zdenek Prudil, Bertrand Lamasle, Carton Zeng, Alex Drlica-Wagner, Elise Darragh-Ford, Tjitske Starkenburg, Benne Holwerda

- Introductions
    - What can machine learning do to help inform the shape of the stellar halo?
    - What can observers help contribute?
    - What/how can we combine other tracers with streams?
- Machine learning
    - What error bars should observers provide? For example, identifying where streams end is hard.
    - R ~ 30k spectrograph gives sub-km/s resolution.
    - Are the data uncertainties even the limiting systematic?
    - What model issues of halo shape and halo profile?
    - Don't know what model is the best to interpret the halo
    - Can we trust data, simulations, or neither?
    - How close is your simulated galaxy to the Milky Way?
    - How much do we distrust the simulations? Does this change our interpretation of stream membership? General halo shape is one question, but the unique history and environment of our Milky
    - How do we use machine learning *output* reliable uncertainties on physical parameters?
- Data in the MW becoming detailed enough that we are past making average statements on e.g., the shape of the halo, which makes it difficult to compare to the simulations
    - Solution: study streams in external galaxies to distinguish generalities of dm halo shapes and masses with what the mw is individually

    - Does this change the kinds of questions we ask about the milky way? Do we care what the exact shape of our own galaxy is? -> we still want both!
    - MW merger history may not be representative
- What is the next step in halo modeling?
    - Moving to a radial dependence in the asphericity?
    - Should we be thinking in basis function expansions? Flexible potentials?
    - Can we access *all* the data? Combining data sets is a challenge. Is anything setup to give to *everything*? Probably not… Cecilia's repo is great; Gaia is also great; but need more!
    -

Breakout room 3: Eugene Vasiliev, Niayesh Afshordi, Robyn Sanderson, Khyati Malhan, Monica Valluri, Emma Dodd, Hitesh Lala, Tom

- Streams near apo/peri are not useful (or rather, more prone to biases in recovered potential - see Stella Reino's paper 2007.00356, also some insights from Bonaca & Hogg 1804.06854). Best are streams that are spread over a range of radii and phase angles (unsurprisingly..)
- Having more streams (over a range of radii/energies) is more valuable than having more stars in a given stream (at least in the context of action-space clustering methods).
- Preponderance of the method to overfit the data can be tested by examining the distribution of orbital phases of stars in the best-fit potential: if these are concentrated around peri/apo, this raises suspicions.
- Disequilibrium models: seems that the inner 30 kpc or so are "somewhat" less affected by diseq., so actions could be more useful (also because the intrinsic timescales are shorter than the timescale of LMC perturbation, see e.g Denis's talk)

Breakout room 4: Nora Shipp, Adrian Price-Whelan, Ethan Nadler, Raj Kumar Pradhan, Anna Wright, Gustavo Medina, Pau Ramos, Roelof de Jong, Orlin Koop

- Discussion about perturbations to streams
    - What streams are perturbed by Sagittarius? Is that large-scale?
- How do we measure large-scale properties of the Milky Way that actually tell us about dark matter?
    - Global parameters and summary properties are important for comparing to models, but don't capture all of the dynamics or reality
    - For example: mass profile or enclosed mass is a poor representation of the dynamic nature of the Galaxy, but maybe they are good enough to compare to dark matter predictions?
    - Is there more power in the small-scale statistics?
- Using action-angle coordinates to describe the dynamics / kinematics
    - Obviously very useful for local studies (substructure)
    - Unclear how to use them for global studies (because they are always computed in the wrong background model)
    - <Adrian says crank things about foliations, foliage and plumage>
- More discussion about the topic of summary statistics and comparisons to simulations as a way of constraining models

- What data are missing to enable using more streams to measure the global MW mass model?

Breakout room 5: Jason Sanders, Juan Miro, Nathaniel Starkman, Adam Smercina, Mark Gieles, Bob Zinn, Jianling Wang, Francois Hammer, Megan Barry

- Action-angles! Are they any good? ;)
- Action-angles are useful in the axisymmetric case and can work in the triaxial case away from chaos/resonances but are the methods generally applicable?
- How does the LMC bias calculations? Mass measurements based on Jeans estimators biased upwards (?). Also the bulk motion of the MW centre with respect to the outer halo. There is a region within which we are safe to ignore?
- The HI gas stream observations there should be a constraint on the LMC mass. Is there tension with massive LMCs?
- Streams in the FIRE simulation -- subhalo depletion.
- Is there a review article on the best constraints on the mass profile of the MW? [Wang+2019]
- Unified modelling approaches and unified system for reporting the results.
- M31's halo -- similarly massive to MW. Do we understand M31 better or just don't know what we don't know?
- Should we be skeptical of all halo mass measurements?

Breakout Room 6: Amina Helmi, Alex Riley, Marcel Pawlowski, Raphael Errani, Shany Danieli, Youjia Wu, Zhaozhou Li, Mark Fardal, Nico Garavito

- Introductions
- Jeans equations, equilibrium are great, but we probably need to move past them (LMC, time-dependence). But how?
  - Nico: two main effects. LMC is moving the Milky Way (outer halo moving faster than inner halo) + dark matter wake (aspherical perturbation on the mass distribution of the halo)
  - Do other satellites also matter? Sagittarius might depending on what you care about (we see its effect on the cold disk)
  - Constraining the effect of the LMC: not really a matter of lack of data at this point, mainly just tools (e.g. running orbits), though those seem to be coming
  - Is the LMC perturbing fast enough to violate conservation of actions? Don't quite know
  - Mark: actions can be useful for coordinate concepts, but direct orbit integrations seem more practical in halo when only there's only time for a few orbits and there are multiple perturbers
- Should all satellites/GCs produce streams?
  - Raphael: you can get tidal remnants well after streams have formed (and dissipate)
  - What sets timescale? Dynamical times of the satellite vs. where it is in the halo

Breakout room 7: Alis Deason, Rodrigo Ibata, Anton Rudakovskyi, Heidi Newberg, Kathy Vivas, Kohei Hattori, Sarah Pearson, Tariq Hilmi

- Introduction
- Clustering in action space etc.
    - moving groups
    - Similar Lz, different energy = shells
- Does chemistry help discriminate between different substructures? Can chemistry be useful to include in the methods that measure the potential with streams?
- Is action clustering useful if the system is huge? How about for phase-mixed streams?
- Pre-selection of sample in angular momentum or energy might be dangerous (or circular argument) for clustering.
- Actions as a function of time in cosmological simulations
- Actions are not the only ones. Should we also incorporate frequencies/angles?
- Distance uncertainty is a problem when finding substructure that is completely destroyed.

Breakout room 8: Kathryn Johnston, Sophia Lilleengen, Denis Erkal, Lachlan Lancaster, Tom Donlon, Jonathan Freundlich, Nicolas Martin, Jeremy Webb, Nilanjan Banik

- SL: Actions don't seem constant in hydro sims, so how useful are they?
- KVJ: How exactly are they not constant? (perhaps there is still information there?)
- DE: There are a variety of small and large changes in actions due to various perturbations. In certain parts of the Milky Way actions could be more useful
- JW: had a project looking at GC movement in action space by just a few perturbations from dwarf galaxies and they move around quite a bit.
- KVJ: With actions being changed by a lot, maybe you can actually constrain all of that, right? There's a lot of potential information there?
- DE: Our approach has been to do the full N-body. But it's complicated to think about how this can be done within the action angle formalism.
- NM: Actions are probably okay for finding streams, even with inaccuracies in potential models. Looking at the chance in action as a function of potential is more challenging. What is a good enough measurement of the MW (when do we stop caring)?
- KJ: power of using ACTIONFINDER without needing a potential, can we use this better to understand changes and jumps in actions along streams?
- TD: potential approx to what MW looks like. Ideally N-body of every star in MW and not needing potential then; for MW history and structure, also for determining DM nature
- JF: nature of DM for feedback in simulations; shape of DM for LCDM or SIDM or fuzzy DM; Fuzzy DM (very light DM particles) and streams: should dynamically heat streams so could constrain mass of fuzzy DM
- KJ: no limit in determining halo so we can be able to measure wakes, twisting, figure rotation, …
- NB: better understanding of potential, using GC disruption and infall within DG and if there is an effect from DG on GC streams; constraining DM with that?; If potential very well measured: splashback radius of DG measurable

- DE: many precise things doable if we know halo well: deformation of halos -> see DM being tidally stripped in data, distinguishing modified gravity and DM models; SIDM cosmo sims more spherical; fit streams with rigid models already quite well, allowing to deform leads to larger changes than error; signatures to tell difference between rigid and live? MW often aligned with orbital plane of LMC (Sgr and Orphan fit) -> does MW account for disruption of LMC
- KJ: MW halo to be extorted from LMC: DM stripped and global wake (all across galaxy); wake could be traced with all streams?
- NM: Center of MW big mess, finding structures and find potential from that (but stay away to fit anything about MW because also too many baryons); get away from using axisymmetric potentials, wanting a potential that changes shape as function of radius in non-parametric way, but how? -> BFEs (KJ, DE, SL, TD)!!
- DE: Sag fits (Vasiliev) are twisted in shape and switched from axisymmetric to triaxial, describe with low-order multipole expansion
- KJ: Joy of BFEs: tools of noise in expansions could be seen for numerical simulations and data

Breakout room 9: Charlie Conroy, Rohan Naidu, Sukanya Chakrabarti, Madison Walder, Vasily Belokurov, Martin Mestre, Xilong Liang, Dante Minniti

-- Charlie's question to Mike Petersen -- how do you know you've expanded the potential correctly?

-- direct accelerations : pulsar timing + EDR3 measurement of solar acceleration

-- Charlie -- what do we want to know in 5-10 years? Rohan: we can now reconstruct the merger history and we have a sketch of the timeline for how the mergers went. From simulations -- MW was at half its present day mass at z ~ 2. Incorporate information from this succession of mergers into how we think about shape of dark matter halo. Charlie -- we didn't have a convergence on mass of LMC and Sgr, we should have a better idea of this in the 5-10 years. Pulsar timing + RVs in the next 5-10 years -- sub-structure + slope of rotation curve.

-- Rohan -- interested in knowing ages of GCs in Sgr of the ones discovered by Dante

-- Martin -- is there knowledge of an equilibrium radius? Within which we can more or less assume equilibrium. Many different views on this! This equilibrium radius could be much smaller than we expect (~ kpc) from pulsar timing direct acceleration measurements. It's clear that Sgr influenced the disk. Effect of LMC on outer halo, collective motions.

Breakout room 10: Chervin Laporte, Alex Ji, Guillame Thomas, Borja Anguiano, Paul Zivick, Tereza Jerabkova, Xiaolong Du, Hector Manuel Velazquez

- Does equilibrium mean anything? How do we quantify disequilibrium?
    - Basis function expansions seem cool but don't know what level of detail to go
    - Can still learn something from equilibrium model (in the 30 inner kpc at least)
    - Depends on where you care about in the halo, e.g. LMC: within ~30 kpc it doesn't really matter? Larger than that you do?
    - The shape of the halo is still rather difficult; a *lot* of dimensionality
    - What does the shape of the halo mean in a dynamic halo? Worry about distance distribution of existing streams and e.g. influence of baryons,
    - When are there fictitious forces that matter? v

- The misalignment effects are really big
    - Though any stream at apocenter will be misaligned
    - Informs you of regions where you have to be careful!
    - Would be good to have some sort of map for what where when
- A big perturbation of the LMC: potential before or now? What can we learn from the pre-LMC perturbation, and where should we look for it?
- Question: where are we in N-body simulations right now?
    - 10s-100s of millions of particles are needed to resolve structures, which is like 10^4-5 Msun particle mass (this is now good enough
    - Streams themselves are being treated as tracer particles, though BFEs allow getting this better in the future. -> a lot of potential for interesting stuff here
- Advantages and disadvantages of BFEs? (esp for star clusters)
    - Currently just putting in things like the bar by hand, but they are actually dynamical e.g. evolving with the halo that can be approximated with BFEs.
    - Machine learning for the potential vs known functions? We haven't fully explored the known functions

Session (b) breakout topics (vote by adding a "+" next to a topic):

- Conceptual aspects of Milky Way modelling -- What do we want to measure? What is "shape"? Are the models of the LMC-SMC-MW-Sgr interaction complex enough? Are we missing important stuff?
- Methods and tools for Milky Way modelling -- What methods can handle equilibrium vs. disequilibrium? What tools exist / are missing to enable this?

Room 1: Conceptual Aspects of Milky Way modelling

- How the shape changes in distance and in time?
- How to compare our galaxy with other galaxies in cosmological simulations?..
- Putting streams (and other tracers) in the cosmological simulation and see how it actually works..
    - What are the most important aspects of the simulations for assessing?
    - Is it more important to have realistic galaxy formation (hydrodynamics, etc.), or more important to capture the present-day details (like location and orbit of the LMC), accretion history (GES, Sag?)
    - Largest effect in hydro sims is contraction and overall redistribution of mass in the halos, making the inner halo more spherical. Also important is that galactic disks change/flip wrt larger/halo scale
- Shape is well-defined in simulations at a snapshot, but it's not clear what we are actually measuring in the Milky Way with streams
    - Complex shapes naturally implies time-dependence, so the shape and structure will change over time
    - Do we measure some averaged shape over time?

    - This could be a theoretical question that can be answered without having to inject streams into big simulations: start with dark matter only and figure out what shape / property streams are most sensitive to
- What would it take to inject globular cluster streams into more realistic simulations like hydro simulations? Re-simulation is hard with hydro?
    - But all that matters is force-playback, so we just need to know that
- Fitting multiple streams
    - Issue: can get inconsistent constraints on the shape etc if model not flexible enough
    - But seems like this is mitigated at least to some extent by having streams with the range of apo/pericenters
- Do the statistical properties of the streams (length, width, etc.) correlate with cosmological properties or dark matter / galaxy formation parameters?
    - Very important to understand this for external galaxies
    - Hendel & Johnston work on stream morphology and connection to progenitor orbital infall distributions (which connects to cosmology)
- How do we propagate the accretion origin of globular cluster streams into stream modeling?
    - For many accretion events, we have the accretion redshift, so in principle, detailed modeling that takes this into account should be possible
    - Now that we know that we have to deal with the LMC perturbation, we can't really just sweep the other accretion events under the rug
- ..
- ..

Room 2: Methods & tools for Milky Way modelling

What methods can handle equilibrium vs. disequilibrium? What tools exist / are missing to enable this?

- **Common framework for reporting results**
    - Do Monte Carlo chains for constraints on the Milky Way mass profile need to be made available for people to use. To combine different constraints (i.e. use priors from one method/dataset to constrain the behaviour of the potential in the range not probed by the other method). This is made complex by the different choices of parametrization _and_ different biases inherent to each method... We don't yet have a common potential model for the Galaxy.
    - It would be good to have a common framework where people could share their potential model (within e.g. the gala framework). For example, EV has reported the BFE coefficients for his joint MW-LMC model fit.
    - -> day 5 community efforts: would be nice to have fiducial models e.g. of the MW+LMC interaction in a form that can be used in other contexts (e.g. integrating a stream orbit in an evolving potential)? As part of Agama, Galpy, Gala (should have a more unified interface perhaps?)

- Galpy has been a great service to the community. Somewhat homogenised approaches to orbit modelling. E.g. MWPotential14 as a fiducial model. It seems important to provide more complex fiducial models now to incorporate LMC effects etc, while still keeping them as simple as possible.
- Known issues already: Masses measured best at different radii, flattening in density vs potential

- **Basis function expansions**
  - How many basis function terms do we need? How many to resolve the simulation correctly? How many terms do we need to report when comparing results?
  - how computationally expensive are the new basis function expansions if we want to resolve also small substructures, say 1e6 Msol perturbers? (I guess this means high order of expansion needed ?) -- can we use BFEs then to develop an intuition of the systems by trying all sorts of parameters, or is it a more of a one-simulation one-shot situation? In theory we could use a very high order BFE but overfitting. Probably this is a mis-use of the formalism: the idea is to get the _global_ potential right (with some degree of sophistication and detail), not to resolve individual clumps - these could be superimposed on top of the smooth global profile.
  - 'Next-gen' sims should be time-evolving BFE expansion + NBODY6. TD: *We are actually working on this in the MilkyWay@home Nbody code! We are able to run simulations with a live MW and live dwarves with 10^6 Msun resolution. See Heidi's Friday talk.*
  - BFE is useful for resimulation of streams in 'realistic' cosmological potentials. Namely, represent the time-dependent potential of the original simulation with a sequence of BFE parametrizations, then compute the evolution of your favourite stream/cluster/satellite in this smooth potential without rerunning the whole thing. (See Lowing+14, Sanders+20)
  - How can you be sure you have reproduced all parts of the simulation if you rerun simulations with BFE. Collective effects?
  - Regarding LMC-induced time-dependent potential, I think it is useful if the community have a series of time-dependent models [basis-function-expansion coefficients as a function of time] with different mass of LMC. (For example, a user can interpolate between these models to fit stream models in a MCMC for example.)
- **Suite of tests for methods**
  - We would like many complementary methods to test systematics. This is the current status.
  - One way of measuring departure from equilibrium is by comparing the results of procedures that assume equilibrium against procedures that do not assume equilibrium. How different are the two types of methods? E.g. direct measurements of acceleration vs. measured potentials and stream data.
  - All methods involve assumptions. There is then a danger when one compares results/constraints of producing biases.
  - The MW configuration (presently) is rare. So we need very carefully designed simulations for testing. It is not good enough for the methods to work on some 'mean' MW-like simulation. See Ethan Nadler's talk (Day 5).
  - Biases in Jeans models when including a Sgr in a simulation (ref?)

    - Blind modelling challenges (blind meaning that the community analyzing the mock data did not know the details of the input simulation aspects and target parameters when providing their results). Very useful in other fields. It is not necessarily a test of 'who is best'. Methods have different strengths. It takes time away from analysing data so needs to be a real community effort. EV: *we had this kind of effort in the community - "Gaia Challenge" series of meetings, intended to test a bunch of modelling methods on the same mock datasets. it came up with some preliminary conclusions, and then people fanned off to apply their favourite tools to actual observations :)* [Gaia Challenge] - perhaps need to continue these efforts (and do a real blind test after all!)
    - Testing is good but we don't have a ground truth. Can we design a useful test case which everyone can agree on?
    - Controlled N-body sims are great but starting from equilibrium is unrealistic and maybe introduces biases? But cosmological simulations have limited resolution. Maybe Andrew Pontzen's approach (genetic modelling) which combines advantages of both controlled & cosmological.
    - Does the uncertainty in the sun's velocity introduce large systematic uncertainties in the fitted models?
- **Modelling streams with/without progenitors**
    - How can we efficiently model streams without progenitors? How do we find ICs of the progenitor? Is this significantly more complicated than a system with a progenitor? You marginalize. But with the progenitor you know dSph vs. GC or other properties of the disruption. Do we understand the progenitors of streams well enough? Progenitor vs progenitor-less answer different questions.

Summary wrap-up reconvening

- What are the questions we are trying to answer? We need to design simulations to answer these questions. What do we still need to know about galaxy assembly, dark matter and star clusters? How does adding complexity to the models (cosmological, controlled or otherwise) help?
- There are not necessarily a well-defined set of numbers (a *standard model*) which we are trying to compute (for example, cosmology experiments are often planned to measure well-defined quantities). AB: *Sort of like gaia is to planck as biology to physics?* RS: *Gaia is not [just] a particle collider*
- The MW/streams field is currently maybe more driven by discovery in the data, rather than having set experiments to answer specific questions. Should there be more of a community effort to define sets of questions we wish to answer, so we can propose programs and experiments?
- Should the next workshop focus on designing an appropriate test suite? This can be done on Day 5. Should there be another Gaia Challenge (when was the last one? Paris 2019?)
- Speaking of methods/models/testing: we should talk about blinding and unblinding of mock/real data in this context more broadly (see Room 2 discussion).

- Do we have any system (stream?) that is well enough modelled? We should continue pushing for very detailed well-fitting models to test our fundamental understanding of gravity.
- Bulk motion of the inner Galaxy well known.
- How unique is the MW? What does it tell you about galaxies in general?
-

Wednesday Feb 24: Small-scale Constraints on Dark Matter

Running notes here

[Link to intro slides]

Today's format

- 1st session:
    - 15 minutes intro (+ 5 minutes flex)
    - 25 minutes for breakouts (+ 5 minutes flex)
    - 25 minutes for return
- Coffee break 30m
- 2nd Session
    - 40 min breakouts (+5 min flex)
    - 30 min for return

Questions for discussion

- <add your anonymous questions here!>
- <add your anonymous questions here!>

Moderator Slides [here]

Summary of Random Breakout Rooms

- More effects but more streams!
- Finding a perfectly smooth stream would be interesting…
- Do we want more detail (precise kinematics) or statistics on density of many streams (e.g. around other galaxies)? Gap occurrence vs. radius.
- Running more detailed progenitor disruption models (e.g. Gieles)
- What can be done with 1st year LSST + DECAM data for PMs?

Session (a) random breakout rooms

Breakout room 1: Robyn Sanderson, David Shih, Megan Barry, Kiyan Tavangar, Anna Wright, Khyati Malhan, Tom Donlon

- Are streams too messy to actually constrain DM?
- Are there other effects that can cause the same effects as DM on streams?
- Clumpy halos/bar resonance/other effects need to be removed to measure DM, and we don't have a complete grasp on those yet
- Just because you *can* model a perturbation with a s/h intxn doesn't mean that's what did it
- GC work has been historically the most useful, but introduces a bias into the analysis

- Need to look into outer halo for muted baryonic effects - still lots of orbital resonance?
- Information from other galaxies!
- MW is slightly abnormal b/c of LMC - we need a larger sample to get around it
- What do we need to further the field?
- GC-Dwarf interaction can cause stream perturbations
- Stream pre-processing
- Higher time resolution in cosmological sims needed for better understanding of dwarf galaxy streams
- M110 around M31 (and M32?) may potentially be good analogues for LMC interaction with M31 [Q: should that read "interaction with MW"?]

Breakout room 2: Peter Ferguson, Tomer Yavetz, Kohei Hattori, Zephyr Penoyre, Elise Darragh-Ford, Andrew Benson, Veronica Arias, Paul Zivick, Adrian Price-Whelan

-
- Introductions
- Kohei: dynamics in general
- Tomer : Fuzzy DM
- Andrew: model subhalo population
- Elise : understanding DM population
- Peter : characterizing stellar stream in MW
- Zephyr : Analytic work
- Veronica : Dynamics ; streams ; halo;
- Paul : internal dynamics of dwarf galaxies
- Adrian: dynamics; perturber
-
- Are streams too messy to be a *powerful* constraint on dark matter?
    - On the one hand, more and more things can mask signatures of subhalo interactions
    - But: we are finding more and more streams -- power in the population
- Have we reached the limit of what modeling individual streams can tell us? Will we learn more from statistical approaches that can utilize the whole population?
    - Still power to individual streams: we don't know all of the dynamical pieces (and their couplings) that can affect streams
- "Messy" == unexpected as compared to toy simulations
    - As we improve our models, will we not call the observed streams "messy" because they encode a lot of useful and important information
    - To improve models on individual streams, will it help to use other constraints on the overall Milky Way potential?
    - A lot of the mess may not be in the structure *now*, but the time evolution of the mass distribution can introduce chaotic
- With future surveys, we will hopefully extend the population of streams to include a diverse set of orbital characteristics
    - Streams with larger pericenters = maybe easier to interpret?
- A lot of work trying to explain a single feature in a stream with one effect
- At what point will we use machine learning methods trained on dynamical effects to help model the streams?

    - Somewhat less satisfying because we want to learn some mathematical representation of the dynamics ourselves :)
- "Sibling" Streams: streams on very similar orbits
    - Differential studies: what is similar, what is different?
    - Or pairwise comparisons (similar eccentricities but different pericenters)
- What would it take to say that we have detected non-LCDM physics from streams?
    - Finding that streams are all perturbed is in some sense the least interesting outcome of finding all of these streams :)
    - But: GD-1 spur requires a very dense perturber. Denser than CDM produces at those mass scales. Maybe if we find that more streams require dense subhalos, this could be important?
    - Difference in dynamical friction in different DM models
-

Breakout room 3: Kathryn Johnston, Mark Fardal, Alex Drlica-Wagner, Jorge Penarrubia, Nora Shipp, Raj Pradhan, Marcel Pawlowski, Jo Bovy, Tjitske Starkenburg

- Introductions
- Starting with talks in the session
- Jorge: If we want to detect small structures, want to study weakly bound systems, so try wide binaries. Millions of wide binaries detected by Gaia, but how can they survive? Tightly coupled in phase space -> stellar streams. Probability proportional to phase space density. Now have an idea how long the wide binaries have been around (and where). Main issue for binaries in the field.
- Maximum orbital period? Few hundred megayears for 1 pc separation
- Adrian has been talking about "streams of two"; Willman & Strader galaxy definition allows "galaxies of two"!
- How well do you need to know the survey selection function (and background) for stellar streams?
- GD-1 has an unusually regular pattern… but Pal 5 doesn't. If they all did that would be strange. Power spectrum does not give you correlation along the stream.
- Supergalactic scale civilizations firing dark matter halos at us… Proven by Andrew Wetzel's LMC talk. Half the subhalos are alien!
- Do we need to drop our assumption of isotropy of subhalos? Do we need to think about the concentration of subhalos? And which streams would be more susceptible? Would this be different for other DM models?
- Epicycles?
- Jorge: I don't think LCDM subhalos can be (totally) disrupted. We think about forces, which will be dominated by most massive subhalos. On the other hand tidal forces are dominated by the closest subhalos (which tend to be the least massive). Wide binaries care about the derivative of the force (tidal forces). Kathryn: This means something for stream heating vs gap/disruption. Jo: Spent time trying to understand whether the low-mass halo tidal heating is reflected in simulations. Jorge: Divergence of orbits in phase space dominated by small subhalos, but only observable in the most sensitive systems (binaries in streams).

- Kathryn: LMC adding subhalos. Can we think of the LMC as a relaxing GCs? Most massive subhalos in the center? Jo: LMC 10^11 Msun, but very little DF for 10^8 Msun subhalos. Would subhalos change impact of the LMC on deformation of the MW halo?
- FDM also creates coherent fluctuations. The deeper we dig, the more complex the model predictions become. Do we need to dig this deeply into other alternative DM models? Is it worth the resources/time?
- Modified gravity also makes things really complicated. Wouldn't expect subhalos, but other effects.

Breakout room 4: Amina Helmi, Azi Fattahi, Tariq Hilmi, Charlie Conroy, Elena Sacchi, G Thomas, Jeremy Webb

- Which streams are more sensitive to baryonic effects?
- Far streams could be impacted by LMC and Sagittarius
- We need a homogenous approach to model all components
- A background potential would be useful to study small scale perturbations (also indirect ones) but that is complicated to model (e.g. changing with time)
- What can produce multiple stellar populations that end up mixed in e.g. GD-1
- Is there an atlas of all the observational signatures of sub-haloes?

Breakout room 5: Roelof de Jong, Alex Riley, Tom Callingham, Sarah Pearson, Tilly Evans, Rohan Naidu, Cecilia Mateu

- Introductions
- At what point can we convince others that we've actually constrained dark matter? (instead of progenitor properties, baryonic structures)
- Lots of uncertainty because we don't know what GD-1'' progenitor was like
    - Even having a progenitor isn't everything, e.g. Pal 5
- GD-1 is the only good candidate so far, need more streams? (!)
    - Maybe external galaxies, but no kinematics
- But we only have these complicated observations because we have more high-quality data (proper motions)
- Will we be able to get high-quality proper motions for more distant streams that are less likely to be perturbed (likely yes, with Rubin)
- Is there an observational bias in that most of the streams we're finding are near their pericenters? (or is it apocenters?)
- Quantifying (any) bias is important -- cosmological sim, realistic mocks, fold in observational bias (both STREAMFINDER-esque and matched-filter + eyes)
- Gaia isn't done! DR3 proper, future releases will continue to improve proper motion errors
- Roman telescope could act as 2nd epoch combined with Gaia to improve Gaia pm uncertainties of faint stars
- For gaps, you don't need to see the full stream (just around the gap)
- Also important to fold in the accretion history of the Milky Way (Khyati's talk, Bonaca + Naidu work in the past year)

Breakout room 6: *Matt Buckley, Eugene Vasiliev, Marius Cautun, Rapha Errani, Tereza Jerabkova, Ting Li, Carl Grillmair, Mike Petersen*

- Key points:
    - *Are there easy tools to predict how streams would react to fluctuations from DM backgrounds*?
    - *What are the masses of the subhaloes we are looking for? 10^4 -10^6? What is the range we are looking to constrain?*
    - *Do we need to understand GCs from birth to study the structure of streams? Can we distinguish this observationally to some necessary level? The consensus is that we should look at GC streams to distinguish between different DM models? Can we rule out that features we see come from internal dynamics? Relative impact of external vs internal.*
- Rapha: *Are there easy tools to predict how streams would react to fluctuations from DM backgrounds*? E.g. something from a small cluster. Need mass-size relationship, velocities
- From a given DM model, do we have a consistent or robust way to model the fluctuations from a given scale. If you have the potential, you can model it!
- Can we do Monte Carlo with arbitrarily large numbers of subhaloes floating around? If the mass scale goes as m^{-2}, what can we do to simulate this?
- Use AMUSE to add a simple mass spectrum to model a galactic potential with some subhaloes or perturbed (like GMCs, as in Tereza's case).
- *What are the masses of the subhaloes we are looking for? 10^4 -10^6? What is the range we are looking to constrain?* Should we focus on subhaloes just below the star formation threshold to distinguish between WDM/CDM models?
- Seems to boil down to the mass-size relation for the subhaloes that do exist? Changes as a function of galactic tidal field.
- Try to model the tails of streams down to arbitrarily low masses
- We need developments both on the observational and theoretical side
- Preheating of GCs inside a parent dwarf: how do we even start to understand this problem? Are the signals in cold streams coming from pre-heating? cf. Malhan's talk. *Do we need to understand GCs from birth to study the structure of streams?*
- For GC stripping, there are different mechanisms for making streams: tidal stripping (where the tidal radius eats away at the outskirts of the cluster) vs internal collisional processes driving the creation of tidal streams. *Can we distinguish this observationally to some necessary level?*
- Many of the newly-discovered streams (cf. Rodrigo Ibata's talk) are more spread out, so perhaps these are indicative of different stream creation mechanisms.
- Are streams too messy for DM constraints? Internal processes, even in an analytical potential. For example, epicyclic processes causing overdensities (cf. Pal 5?). Is there a catalog of stream morphologies, one that we could use to as an ensemble for studying stream structure?
- *The consensus is that we should look at GC streams to distinguish between different DM models?* Do any such GC clusters exist (Pal 5)? *Can we rule out that features we see come from internal dynamics? Relative impact of external vs internal.*

Breakout room 7: Vasily Belokurov, Monica Valluri, Rodrigo Ibata, Mark Gieles, Megan Gialluca, Emma Dodd, Denis Erkal, Xinyu Li

- Introductions
- Emma: Lots of discussion of how can you rule out baryonic effects (e.g., the bar) -- what if you add them all simultaneously? Denis: This is done to a certain extent, but in many cases you can simply neglect certain effects because they won't really matter (e.g., the bar, disk don't matter for GD-1 because it's on a retrograde orbit).
- Xinyu: effect of FDM is more pronounced on power spectrum -- how well can we measure this with streams?
- Rodrigo: Do we need 10-yr LSST PMs to be able to get good stream kinematics at the faint end, or can we do it earlier? Jeff: To pick up where Gaia leaves off, the assumptions are 10-year LSST depths, but by using (e.g.,) DES/DELVE as a first epoch, early LSST data could extend PM limits early in the survey.
- Monica: most sims of GC streams don't take into consideration 2-body interactions within streams. Are we missing some important physics? Mark: tried with N-body6, but can't really insert enough stars to create GD-1. Answer should come from actual N-body model. Initial density and BH population have large effects.
    - Denis's models initially had to start with a really large size to get mass-loss started, so adding density via BHs helps this.
    - Rodrigo: with full gravity sims, didn't see the epicyclic peaks. Denis: differences prob due to different mass-loss rates. The only way to get epicycles in models is to have it "explode" really quickly at each pericenter.
- Haven't really looked at binaries in streams (a la Jorge's talk today). Mark sees capturing of "stars" (particles) in streams to form binaries in his models.
- Denis: re: Khyati's talk - how much of the evolution/processing of GCs happened in their dwarf hosts rather than MW halo? His sims are fully N-body (both the halo and GC).
- Which streams are more useful? A: those further out. But they're hard to find. Maybe we'll "get lucky" and find one that was on a very radial orbit and will go far out into the halo… We know one stream (Gaia 1?) that is now at ~20 kpc but will go out to 200 kpc.

Breakout room 8: Ana Bonaca, Nico Garavito-Camargo, Juan Miro, Anton Rudakovskyi, Alexander Ji, Orlin Koop, Shahram Talei

- Introductions
- Q: Is there any meaning to find more constraints on (W)DM?
    - What are the current constraints on WDM? (e.g., Nadler et al. m_WDM>6.5keV)
    - Concern about the functional form of the shape of the WDM SHMF -> much more subhalos with newer fits at higher resolution simulations [costs a lot]
    - Results are dependent on statistics, bayesian approach, i.e. assumed prior.
    - Solution1: More simulations with >6keV WDM, which needs higher resolution
    - Solution2: Robust statistics. (Nadler et al. lower bound is more like 7keV, not 10)
    - What would be an upper limit for mass to stop WDM as a possibility

        - From particle physics there is none, since they look for lower bounds. From cosmology: possibility of resolving smallest halos (10^5Msun) dictates this. <- though smaller halos can maybe affect dynamics
    - Q: Is there a range of mass directly detectable in CERN, is that interesting?
        - Depends on the DM candidate discussed (e.g., thermal relic, sterile neutrino).
    - This probe (small scale stream perturbations) breaks the degeneracy for baryonic physics.
- Can DM wakes (specifically that trailing the LMC due to dynamical friction) be used to break degeneracies for (SI)DM models?
    - Alternative gravity can also be studied, and the expected wake will look differently depending on the model in question.
- What modeling frameworks are needed to constrain dark matter with streams?
    - How long will this take to model? What are the next steps needed?
    - 'Wind-tunnel'-like LMC simulation into a DM halo of different types of particles.
        - What kind of resolution is needed? E.g., Nil Banik's work indicates 1Msun resolution needed to accurately capture subhalos -> maybe analytic work would be helpful in this regime
        - Still WIP for the wake simulations.
        - ^a thought here: I think the 1Msun is for the statistical things, but maybe not needed for large features explainable by single impacts?
    - For a detection of a dark-matter subhalo, we'd need to locate it in the sky; statistical constraints seem to be very degenerate with baryonic physics

Breakout room 9: Zili Shen, Shany Danieli, Simon Birrer, Eduardo Balbinot, Quynh Lan Nguyen, Johanna Hartke, Kiyan Tavangar

- Introductions
- Signatures of perturbations: what has been observed beyond changes in the morphology? Accelerations?
    - We seem to be still at the stage that we don't have the velocity precision on the average velocity of the stream, but we cannot really detect kinematic signatures, as they are extremely small
- Main uncertainty is the origin of the gab, it could still be baryonic
- Is there an expectation on this for a given DM model?
- There is still some uncertainty about the mass and distribution of giant molecular clouds that can also introduce gaps
- What about abundances along the stream?
    - Streams originating from globular clusters will have very homogenous
- Does it matter whether the stream comes from a globular cluster or from a dwarf galaxy?
    - GC streams are much thinner (Pearson), while it's harder to make out gaps in thicker streams with dwarf galaxy progenitors
    - Minimum mass limit for impact that can be detected based on progenitor origin
- Gravitational lensing: globular clusters versus DM minihalos

- Upcoming facilities:
  - VLBI: issue: not so many radio-bright sources
  - ALMA for dusty sources
  - Unresolved flux sources: need to quantify the source population
  - Below 10^6 Msol its going to be challenging
- What about alternatives to CDM? Fuzzy DM, …
  - In fuzzy DM halos density fluctuations in the halo can disrupt stellar streams
  - Can fuzzy DM be tested with lensing? Lack of predictions from theory makes it challenging
- Testing modified gravity with streams

Breakout room 10: Jason Sanders, Pau Ramos, Jonathan Freundlich, Ethan Nadler, Madison Walder, Stella Reino, Dante Minniti, Chervin Laporte

- **Fuzzy DM**
  - Fuzzy DM -- deBroglie wavelength ~1kpc. Solitonic core + NFW halo. Discontinuity in derivative of density.
  - How do we run simulations using fuzzy DM? See Banik for an effective method. Or can use method for approximate kicks due to fuzzy DM.
  - Fuzzy DM sims scaling is horrible! You need to resolve on a range of scales. Ethan Nadler running controlled FDM sims.
  - What is the differentiating signature of FDM and CDM on streams?
  - We need to educate ourselves more on different DM models :)
  - What does tidal disruption look like for different dark matter models? What are the differences?
- **Mass of Sgr**
  - Dynamical friction measurements. E.g. Ibata+ 2020 Sgr.
  - Do we have a complete catalogue of all non-DM perturbing mechanisms?
  - Do we understand the substructure within the Sgr stream? Not due to DM but important to understand.
  - How do globular clusters evolve within their host dwarf galaxy? How many survive and stay with the dwarf? How many are immediately disrupted? Currently at the limits of Gaia. Does Sgr have more clusters than before? What does this mean for the dark matter mass of Sgr?
  - Jiang & Binney (2000) advocating higher Sgr mass? Perhaps supported by GC count. Can this be reconciled with present day measurements (Vasiliev) -yeah, it lost perhaps 99% of initial mass by today (or about 90% of its mass since 3 Gyr ago)

Session (b) breakout topics:

1. What evidence would convince you that some particular effect in a stream was NOT baryons (for the baryon room) or dark matter substructure (for the DM room)?
2. What observational and/or theoretical advances do we need to

produce that evidence?

Room 1: Baryonic effects

What baryonic effects can perturb streams and how do we account for them all?

- **MW disc substructure**
  - Prograde streams (e.g. Pal-5) are more affected by baryonic effects. Retrograde (e.g. GD-1) are more reliable.
  - Anything associated with the disc can be separated out as the geometry is different.
  - The interaction time of the baryonic potential is the important quantity.
  - In the impulse approx. relative velocity is important but so too is interaction distance. Can we always rule out giant molecular clouds (GMCs)? GMCs have different central density. Amorisco (2016) looked at this. Banik+ marginalize over present-day GMC population. Models for GMCs are perhaps overly simplistic? What if they were modelled as a clump of clumps?
  - The timing of the gap is important. If we know the disc-crossing time/pericentric passage time then the gap formation must coincide. With what precision can we date the perturbations? ~10Myr uncertainty on a 500Myr old interaction from density + track on sky + radial velocities of simulated streams (Erkal & Belokurov 2015). But the posterior is highly multi-modal. These degeneracies can be broken by measuring velocity differences between main stream and off-track features (e.g. spur).
  - Work to be done fully modelling GMCs within simulations. Maybe we need to extract better toy, time-evolving models of mass in GMCs to test in stream simulations? Time-dependent basis function expansions everywhere!
- **Knowledge of orbits & potential**
  - Resonances due to LMC or Sgr -- are there models of the impact of transient resonances on streams? Typically streams models include LMC + Sgr now, fully time-dependent MW+LMC interacting potential.
  - Subhaloes/haloes with clumps or significant tails. Do these change the models?
  - How well do we need to know the orbits of stream progenitors? Perhaps for understanding the effect of the bar it is important. But many streams not sensitive to specifics of the bar.
  - How much can we trust the back integrations of GC orbits to figure out whether a stream interaction has occurred in the past? Maybe backwards integration in the complex potential of MW+LMC is very sensitive so difficult? We need to know both the orbits *and* the potential (of LMC,Sgr). LMC is only important recently. Sometimes LMC is not on first passage!
- **Complex disruption (heating)**
  - How can we separate out complex disruption scenarios? We perhaps need chemistry to demonstrate there was a dSph host. But will there be any background/host/field stars? Maybe the GC (or multiple GCs?) formed in a fully dark subhalo? dSph disrupted earlier so could be quite dissociated from the GC.

- What about baryonic effects within the stream itself? Binaries, triples, compact objects? Likely that the stars in the stream don't care about each other but only the MW/host potential.
    - For stripping of GC in host subhalo, do we have a clear observational signature? From cosmological sim? What is our way in here? How do we model this? Maybe kinematics are completely different?
- Do we need better cosmological simulations? Are they good enough for a set of initial conditions at infall?
- **Streams far out in MW or in other galaxies**
    - Maybe we need to go to thin streams in other galaxies (they still need to be discovered…). Are the baryonic effects (spirals, bars) less important?
    - Is there a list of distant GCs which may be tidally disrupting and not sensitive to the fine-scale baryonic potential? NGC5466 with Gaia. But with VRO further out. Typically these streams will be on radial orbits so not very streamy. And if we detect such a stream, it will likely be pointing toward us, so distances are the most important information that we will need to find a gaps, and even with a 2-3% precision as given by RRlyrae, you will not be at a level of 1 kpc of precision. With LSST we'll (hopefully) find boatloads of streams, but it's going to be difficult to get high-res RVs of those faint stars to characterize dynamics. Perhaps we should be (as Sarah said) considering statistical approaches (both in and beyond the MW)? For how many galaxies will MSTO stars contribute enough signal to the surface brightness that we will be able to robustly detect density variations? The RVs are probably hopeless, but perhaps with photometry alone and by having a statistical sample you could still learn sth and more easily compare to expectations from cosmological accretion of subhalos in galaxy outskirts (MW or external). More discussion in chat… probably on slack??

Room 2: Dark matter effects

What can convince you that a signal isn't due to dark matter?

- Individual interactions: if you can trace it back to a particular baryonic effect
- Is there evidence about GMCs affecting streams? Need a good understanding of mass-size relation for this (we have decent models for CDM/WDM halos)
    - Josh S: Larson relations for GMCs
    - Mark F: but they're not "spherical cows" - they're "fractal cows" (like subhalos!)
- We need to constrain density profiles of dark perturbers better to understand unique signatures relative to baryonic sources
    - Detailed modeling of gap -> profile of the perturber
    - Geometry of impact is also important - perhaps will contain information about perturber origin
- Can we "stack" the signals to make an average? Like for power spectrum?
    - Can we do this for perturbations we think are caused by baryonic structures? Group by interloper and develop templates, do statistical consistency test on subgroups if we could get enough

    - For ones that don't match, look to dark matter
    - For GMCs particularly, open cluster tails might be a rich source of statistics
- Statistical constraint might not be so convincing - do we need to point to a specific intxn?
- Priors for subhalo orbits from cosmological simulations could be used to try to rule out individual DM models
- Mass loss, orbit structure depends on which models you're trying to rule out. WDM just removes subhalos below a certain mass scale, but SIDM changes internal structure + orbits
- Distribution of subhalos in the Milky Way
    - LMC brings in a fair amount of subhalos: ~10-25% of the Milky Way's total subhalo population. At fixed MW halo mass, systems with LMCs host more subhalos overall, not just directly due to the LMC contribution! (e.g. Andrew Wetzel's talk).
    - Radial + Azimuthal dependence of subhalo distribution
    - Also LMC subhalos have experienced less tidal stripping, so mass function would be different
    - How long are Sgr subhalos important as perturbed?
        - Def need more theoretical work (subhalos of subhalos are a dynamical range challenge)
    - Contribution of the dwarf depends on the exact mass (number of subhalos linearly proportional to the mass, so even a factor of 2 uncertainty is significant)
        - Hard to disentangle the mw dm from the lmc bc the mw halo shape is elongated in the direction of the lmc (expected from cosmo sims, but)
- Needed from theory: properties of subhalos in the Milky Way for different models of dark matter for all mass scales
    - Accounting for effects of LMC, sgr, etc: we need to know better masses for these to understand their contribution to the dark subhalo population. To what precision? # of subhalos is linear in mass
- We need more progenitors of streams! Esp to know what to expect for velocity dispersion and fold this in as a measure of DM perturbation with gaps and PS
    - Streams get hotter w time in general, but bc phase-space density is conserved, as the stream gets longer, the velocity dispersion gets colder (both orbit and phase dependent -> need to know them well)
    - Timing of accretion can be used to date streams (for streams whose progenitors were accreted with a dwarf galaxy), although this provides just an upper limit on the age of the stream

Summary

- We don't yet have a 'perfect' model of Pal-5.
- Streams could be the most sensitive probe of baryonic effects.
- In thin streams in other galaxies, GCs still can cause gaps. What can we learn from large samples of streams around other galaxies through comparison to cosmological sims?
- What do theorists want from observers? In an ideal world, 6D kinematics + chemistry.

More practically, perhaps complete samples of RRL (PS1+DES+ZTF already has provided a lot here). Are these sources dense enough for the kind of measurements we need to make? We need high quality multi-dimensional data in the ‘interesting’ regions (e.g. GD-1 spur, c.f. S5 strategy) and lower quality more complete coverage across the entire streams (maybe RRL here). Do we need ‘reference fields’ in the ‘non-interesting regions’?

- Do we need better proper motions beyond what Gaia provides? E.g. HST or Rubin. We want <1km/s precision.
- Ages are also important (10% for MSTO photometry+spectroscopy). They are not informative on disruption time (from cosmo sims) but star formation histories?
- Can we measure the mass function in streams?
- MegaMapper -- currently in the hands of decadal survey. Wait and see. June 2021.

Thursday Feb 25: Connecting the Milky Way to Cosmology

Running notes here

Moderator Slides [here]

Today's format

- 1st session:
    - 15 minutes intro (+ 5 minutes flex) **(end at :20)**
    - 25 minutes for breakouts (+ 5 minutes flex) **(end at :50)**
    - 25 minutes for return **(end at :15)**
- Coffee break 30m **(back at :45)**
- 2nd Session
    - 40 min breakouts (+5 min flex) **(end at :25)**
    - 30 min for return

Questions for discussion

- <add your anonymous questions here!>
- <add your anonymous questions here!>

Summary of Random Breakout Rooms

...

Session (a) random breakout rooms

Breakout room 1: Marcel Pawlowski, Elena Sacchi, Edgar Marrufo, Jonathan Freundlich, Mark Fardal, Denis Erkal

- Lots of different interest in external galaxies ranging from gas properties, dark matter potential, gaps, different galaxy types
- Correlating streams with star formation history, e.g., Ruiz-Lara et al. 2020
- Fitting the potential
    - Need more than just projected information to fit a stream
    - Hopefully we can get some kinematic information but may be limited to only a handful per stream
    - M31 is a good stepping stone for this where we have additional information (i.e. distances)

    - Maybe there's something in the morphology of streams (e.g. precession of orbital planes, evolution of stream width) which can tell us about the shape of the halo from a statistical sample of streams
    - Just like in the Milky Way, we can use other information (e.g. rotation curve, dwarf kinematics) to combine with streams to measure the potential
- Gaps in external streams
    - Maybe this is more promising because we don't need to know the precise potential
    - However, we may need to marginalize over the unknown orbit of the stream?
    - Good that we will probe different types of galaxies with different baryonic component (e.g. dwarfs, ellipticals)
- Connection to cosmology
    - What can we learn about dark matter/cosmological models?
    - Are there any falsifiable predictions we can hope to test? (Maybe stream gaps?)
- How do we get ready for streams in external galaxies?
    - What kinds of mocks do we need to compare with?
    - Do we need to test observational techniques on realistic mocks?

Breakout room 2: Adam Smercina, Adrian Price-Whelan, Tom Donlon, Anna Wright, Youjia Wu, Juan Miro, Stellar Reino, Veronica Arias, Tilly Evans

- Diverse set of interests related to streams around external galaxies
- Question: what can we learn about dark matter / dynamics from streams in projection when we have little other kinematic information?
    - Get projected stream track
    - Also get projected stream width
    - Need new modeling methods to handle fitting these things
- Other debris structures are possibly more informative about the potential
    - Shell galaxies are potentially very constraining about the potential
    - In the Milky Way, maybe streams are more informative because we can get 6D kinematics, streams span more orbital phase
    - But in projected position only, maybe shells are better?
    - Shells are easier to see in external galaxies: caustics, so very sharp density enhancement
- For Milky Way accretion history, when clustering in actions or actions+chemistry, how important is it to include the LMC in the potential?
- For action-based clustering methods: Using streams and globular clusters in the Milky Way as tracers to do clustering. Any new associations?
    - Clustering in orbital poles vs. actions
- Globular cluster within a dwarf galaxy, accreted into another galaxy: what

does the cluster stream look like? Does it retain memory of its dwarf?
    - What is up with the 300 km/s stream?
- Something we could maybe do with projected streams only: look for cocoons around thin streams??
- Globular clusters associated with different merger events, like the GES clusters
    - Associations in E–Lz space
    - How much can we really learn about associations between structures from dynamical invariants alone?
    - Do we need elemental information? But then clusters have their own abundance patterns…
- Is it surprising that so many GES globular clusters have survived evolving in the Milky Way? Many have large eccentricities / small pericenters. How do they compare to Kraken GCs?

Breakout room 3: Ethan Nadler, Alex Riley, Raphael Errani, Nora Shipp, Shahram Talei, Kathy Vivas, Kathryn Johnston, Zili Shen

- Introductions
- Zili: Mireia's talk on DF4 concludes that lack of DM comes from tidal disruption. Distances (supposed disruptor vs DF4) might not be right for this picture. Using Dragonfly to look for tidal debris
- Where does (large-ish) uncertainty in distances come from? Zili using TRGB (w/ Hubble data). Mostly a matter of (total) exposure time
- Prospects for looking at WFIRST
- Dynamical modeling for external galaxies. You can basically increase (model) velocities as long as you increase the mass, so very hard to learn anything from stream tracks (line-of-sight velocities may help?)
- Can we get good enough data to get dark matter constraints? With enough numbers, you can get statistical properties (both large-scale and small-scale effects)
- Very different regimes: down to Sagittarius in external galaxies. But actually, with e.g. WFIRST, you could probably get globular clusters
- Without line-of-sight velocities, how can you distinguish dark matter perturbations from epicyclic overdensities? Statistics, good modeling (including baryonic effects) can maybe get you there. We're also really far from that
- Do we need modelers to look at this, at least in a very basic way? Number of streams as a function of host halo mass, radial distributions
    - We don't know a lot of things (disk potential, what subhalos look like in the center)
    - A lot of work to do
- <inspirational message from Kathryn about how the field has evolved and how the young'uns right now are asking the right questions> "just please don't think lesser of us olds" (paraphrase)
- Looking in chemical space is also really useful! Nora Shipp + S5, Danny Horta + APOGEE in the inner galaxy, Rohan Naidu + H3 have all done really good stuff with the Milky Way. Can we do similar stuff in other galaxies?

    - At 20 Mpc, you can't get spectra of individual stars. Just the whole globular cluster. Maybe closer works?
- What are the observables on accretion history for other galaxies? Some work has been done on this to get info from density profiles, colors (Alis Deason, Eric Bell)
    - CMD matching to stellar populations, or spectra (population synthesis), get you star formation history. Closest we can probably get to accretion history
- What role do cosmological simulations play? There's a HUGE dynamic range problem. Trade-off between dynamic range and realism
    - Big improvement over old particle tagging is tracking stellar evolution as the simulation gets run
    - Semi-analytic models are much faster
    - Raphael: trying to get tidal evolution completely parametrized. Don't need any N-body to figure out where final things end -- as long as you don't care about the tidal debris
- <Kathryn pushes all the young'uns to promote themselves, especially if they're entering the job market>

Breakout room 4: Martin Mestre, Kohei Hattori, Shany Danieli, Ana Bonaca, Diederik Kruijssen, Hector Velazques, Andrew Benson

- The M31 results by Sarah are very interesting! We can learn so much by exploring other galaxies.
- Question: if we find two streams that are close to each other in E-L plane, how can we know that they are the same stream.
- Q: how did the Milky Way form and assemble, especially in the context of different tracers (stars, globular clusters)? Do we have a complete record of its merger tree already? -> getting close
- **Kraken / Heracles** (discovered first in GCs, then confirmed with metal-poor stars)
    - How do we best combine this data to build a holistic picture of the Galaxy?
    - Different methods have different blindspots: H3 gets the small things, but mainly in the outer halo (can go to low masses with stars), but H3 doesn't go into the inner galaxy
    - GCs are good for tracing the inner galaxy, but that puts a limit on the mass of the detectable galaxy (how can you identify a galaxy that only brought in a single globular cluster?)
        - However, might look for globular clusters surrounded by stellar streams
        - Hard because with streams you don't know what kind of galaxy it came with, but in a sense GC provides a chronometer
- **How do we confidently identify streams with the same progenitor galaxy**
    - Perhaps just clustering in the phase space is not enough
    - Some sort of dynamical estimate of the cluster (~mass)

        - Chemistry spread in GCs gives the mass (also distinguishes between streams from a globular cluster vs dwarf galaxy)
            - Need more spectra!
- **What can we learn from extragalactic streams?**
    - There are many detected by now, so, how do we model them?
    - Fewer observables (2D spatial, 1 velocity) for a large population (some chemistry from IFU, but basically need Keck/KCWI, so it will always be for few targets)
    - Use machine learning on GCs in simulations to find what these data is telling about the underlying physics
        - In the future we could do that on streams
    - Even with one extragalactic stream, it should be possible to measure the shape of the dark matter halo (we learn a lot from Sgr in the MW)
        - But we need to test exactly how well this will be done
    - Contribution to the stellar halo from completely disrupted GCs:
        - How can we be confident if a given field halo star is coming from a GC?
        - Chemistry ? (Anti-correlation between Al-Mg?)
        - But it may be a challenge because the disruption should have happened at an early time.
    - Are there any gc streams beyond the MW?
        - Not in diffuse light, really hard
        - Maybe in resolved stars w the Hough
        - Need to follow up (HSC has the field-of-view, otherwise hard)
        - Is there a distance where HST can still resolve stars and cover a large enough area to detect gc streams? -> perhaps at the edge of the Local Group

Breakout room 5: Sarah Pearson, Rohan Naidu, Borja Anguiano, Eduardo Balbinot, Rodrigo Ibata, Zephyr Penoyre, Mike Petersen

- Introductions
- Possible questions:
    - *Can we say that the LMC doesn't have any thin streams around it? What is the role of the SMC in the LMC process for streams?*
    - *Can we look at the ultrathin disc galaxies (that are supposed to not have any interaction history), how many GCs are there?*
    - M*odelling external streams: what information is there in a single stream around an external galaxy? Trying to learn something about the structure of the halo.*
    - *With Roman, how well will we do detecting gap statistics in M31?*
    - *Is there a strong correlation between the mass and the number of streams in a galaxy? (We still don't understand GC formation)*
- MW accretion history

    - How many more GD-1s exist within the MW? Are we close to a full census of streams in the halo that are going to be good for relatively complex modeling (proper motion limited to get accurate orbits).
    - Finding many new coherent objects in the bulge, what will we learn from this?
    - *Can we say that the LMC doesn't have any thin streams around it?* There is a large GC population around the LMC, are there more streams? *What is the role of the SMC in the LMC process for streams?* Can we make any predictions for where material might be piled up in the LMC-SMC halo system?
    - In the MW stellar halo, the inner halo seems to be dominated by GSE material, which we connect ~30 GCs to the merger. Did the MW have GCs before this?
    - The geometry of the GSE merger is important. The initial conditions of GCs are also very important (cf. Mark Gieles' Pal 5 talk that has a fluffy cluster to start)
    - *Can we look at the ultrathin disc galaxies (that are supposed to not have any interaction history), how many GCs are there?* What would the MW have looked like without any interactions? There is a specific frequency GC increase for galaxies with a thick disc?
    - If you had knowledge of streams associated with a specific event: how can we incorporate that knowledge?
- Going beyond the the Milky Way
    - What do we learn from the presence of streams around external galaxies? Trace back when mass was accreted.
    - M*odelling streams: what information is there in a single stream around an external galaxy? Trying to learn something about the structure of the halo.*
    - *With Roman, how well will we do detecting gap statistics in M31?* The goal is to have enough streams to see which have gaps and locate those in their parent halos. Will one be able to get down to the horizontal branch to get RR Lyrae in streams? <- depends how long you are willing to expose? It's still not well constrained about how deep one would need to go to be confident in gaps.
    - In the local volume, how many dwarf streams will be detected?
    - Are we more sensitive to external Sgrs or external thin streams? We need resolved stars for the thin streams.
    - *Is there a strong correlation between the mass and the number of streams in a galaxy?* (In the case of M31, there are 3x more GCs as compared to the MW, what does this mean?)
    - *(We still don't understand GC formation)*

Breakout room 6: Matt Buckley, Robyn Sanderson, Mireia Montes, Madison Walder, Roelof de Jong, Charlie Conroy, Xiaolong Du

- How much progress have we actually made detecting streams in other galaxies? We need stats as well as deep observations, + a sense of the selection function, in order to understand stream counts
- What counts as a stream for resolved stars & integrated light? How do we avoid double counting?
- What can we learn? About DM models for example?
- Degeneracy between stream age, DM model, accretion history, mass. Can be partially resolved with metallicity measurements. SFH is sensitive to DM model via potential depth, for example, and streams give different epoch of SF than existing sats
- RVs - integrated light or individual stars? Depends on distance - at nearby systems MUSE doesn't pick up too many stars in one image…very challenging. ELTs can push deeper but with tiny FOV, and you will only pick up RGBs which are sparse. Not easy to get enough time. How to avoid interlopers when picking stars? - density + metallicity help reduce contam.
- Power for DM models is from faintest structures (re. substructure)
- But e.g. if dynamical friction works differently, need the high-mass things to rule out those models (on galactic scale), and a single galaxy will only have a handful of those so you need many
- What are **lessons learned from GHOSTS**?
    - FOV matters - Roman will make a difference here
    - Biggest difference (from integrated light) is you have info about indiv stars (metallicity etc)
    - Reaching HB (e.g with JWST) would constrain ages
    - Theory - **need statistics of streams** (fn of radius, relative to disk, etc)
    - For large enough samples, we need to **calibrate tagging DM-only sims - which baryonic effects are important and which can we ignore**?

Breakout room 7: Tjiske Starkenburg, Khyati Malhan, Elise Darragh-Ford, Robert Zinn, Gustavo Medina, Tariq Hilmi, Sophia Lilleengen, Benne Holwerda

Substructure in the MW

- How well do we understand the GES? Was it definitely one merger event?
- How well do we know that we are measuring what we think are measuring in terms of disrupted substructure? What do we need to do to make this more robust? More metallicities? Better sims? Can we get estimates of background contamination from current simulations?
- What is the effect of the evolution of the MWs potential on our ability to reconstruct substructure?

Streams Outside of the MW:

- How can we improve resolution to compare observations to cosmological sims? Do current observations agree with simulations?

- New/upcoming data is very exciting!
- Can start to test our modeling predictions
- How disrupted is the SMC? Would it count as a stellar stream around an "LMC-like" object in the MW
- What do we want to do with external streams? -- Potential to constrain shape of external galaxies potential, bar, disk, etc. Or find very smooth galaxies to constrain dark matter models
- How hard to get RVs for external streams? Can we start to constrain halo shapes?
- Just use HI for kinematics to constrain DM halo? Then constrain bar potential?
- Can we start to understand link between inner and outer components of galaxy? I.e. can we link bar rotation to angular momentum of the dark matter halo
- AS always, what more can we learn about streams from leveraging synergistic datasets!
- Planes of satellites? Can we learn more? Do they exist?
- How do we move beyond understanding individual objects to understanding galaxies statistically?
-

Breakout room 8: Eugene Vasiliev, Tomer Yavetz, Emma Dodd, Jeff Carlin, Megan Barry, Carl Grillmair, Raj Kumar Pradhan, Cecilia Mateu

- How do we take what we know from the Milky Way to extragalactic streams?
- Is it easy to study streams in other galaxies? Have to go quite deep. So few stars at the tip of the RGB. We will be able to go to low surface brightness with LSST. 2-3 mag deeper than MSTO means ~26 mag (at which distance?)
- Resolved populations: MW foreground is nonexistent at these magnitudes, but background galaxies become the nuisance. However, the colour of the stellar RGB branch seems to be reasonably well separated from that of the background galaxies. Surveys typically use two or three bands. With two colours you can get better star galaxy separation but with only two bands you can get a larger area or go deeper.
- Surveys mainly limited to photometry, but can hope to get some kinematic measurements from rather complicated analysis of spectroscopic datacubes (namely: put fibers at any overdensity bright enough to be measurable, then use a higher-res (HST-class) photometry to understand what exactly you just measured - a background galaxy or a star of interest. [NB: a similar technique is used by S.Kamann with MUSE observations of crowded fields such as globular cluster centres - deconvolve multiple stars' spectra falling into the same spaxel with the help of hi-res photometry]

- What about a long slit along the stream? Then a control field elsewhere in the galaxy, subtract the spectrum of the control field to get the signal from the stream.
- Very difficult to get radial velocity and metallicities. How far can we go with just photometry? Not sure if we can identify gaps due to low statistics. Even how to make sure we observe a structure not a fluke?
- In other galaxies we might have a better chance of finding more massive / more luminous progenitors that we don't have in the Milky Way.
- Streams by track on the sky. Select on RGB box at the distance of the galaxy.
- Integrated light vs resolved stars. Star counts go deeper than integrated light.
- Any gaps that we would be able to see would need to be huge gaps, not small dark matter subhalos. At a few Mpc away, a gap from a 1e6 Msun subhalo wouldn't be observable.
- First things we would want to count the number of streams, there are constraints on the potential from the curvature of the stream on the sky.
- Very hard to see shells in our own galaxy, in outside galaxies we can see these better. Constraints on the potential from the number and radial spacing of shells. Degeneracies between the accretion time, mass distribution of the host galaxy, so geometry without kinematic information may not be the most useful. Although the distance between shells may be useful for constraining the potential. Will we pick up these shells when we search for streams like e.g. in Sarah Pearsons methods?
- Wavelets to find curved features in their data.
- Comparing the thinness of streams in different galaxies. Can we use this to quantify how thin a stream is? Depending on the type of potential e.g. triaxial vs spherical. But how do we know if the thinness or thickness is from the progenitor or the environment. But with a big sample maybe we can do this.
- GD1 is very narrow, Milky Way potential has to be regular to allow GD1 to exist as it is. Stream should have thickened over time if the potential isn't regular. Why is GD1 so smooth and narrow? To do with resonances?
- Some constraints on the accretion history just from how many streams.
- Couldn't see the inner galaxies from photometry and the outer lower SB streams. So how far can we go in determining how typical the MW accretion history was? But maybe did these inner galaxy (like hercules) mergers create these shells, can we maybe infer them from this?

Breakout room 9: Jason Sanders, Johanna Hartke, Peter Ferguson, Alex Drlica-Wagner, Jorge Penarrubia, Jaclyn Jensen

- How do you dynamically model tidal streams from just projected position data? What can we gain from radial velocities? 3d positions (distances) > radial velocities? Is this generic? Basic knowledge of whether a stream wrap is in front or behind the system.

- Perhaps we start with thin streams as can be modelled quickly. Shells and hotter streams harder.
- Reminiscent of the strong lensing community -- suddenly a very large number of systems which require detailed modelling. Currently carefully modelling system by system. Need an efficient automatic approach. Do we need a general modelling framework? Is this possible?
- How do we separate out individual streams in a system? E.g. M31. Chemistry can help. Machine learning image recognition to identify the number of streams in simulated images.
- Is there a preferred sample of nearby galaxies we can view as MW analogues? Edge-on would be useful as we can cleanly separate streams from the galaxy. Does this introduce biases?
- Small-scale density variations in external streams. Do we have the tools to extract information from the density variations? Perhaps some collaborative efforts are necessary here -- the technology is there.
- Resolved vs. unresolved. How do we measure radial velocities? Field of view for 30m small. Can we use 8m. This is ambitious.
- What would the MW look like from afar? (c.f. Pearson)
- What would we learn from Sgr-like stream around another galaxy? GC streams more sensitive to small-scale dark matter. Could investigate number of GCs per accretion event -- need to know ages and metallicities. GCs useful for kinematic follow-up. GC streams will “never” have kinematics. It is very difficult to associate GCs with dwarf disruption -- projection effects! It sucks to work in 2d.
- Every step in the distance scale we have different tracers/different probes.
- But with larger distances, larger samples!
- Calibrating the dark matter - # of GCs relation, Looking at small galaxies with IFUs.
- Can we look at halo triaxiality from a statistical sample of streams? From Jorge’s experience, even constraining flattening is hard. Can we stack/average? What if we had lensing+streams example? What would we know? Small-scale lensing hard. If we could trust simulations then we can test. Even if wrong, they are useful.
- Hot streams as probes of Dynamical friction. M33 and M31

Breakout room 10: Ting Li, Nico Garavito, Alan McConnachie, Ivanna Escala, Nathaniel Starkman, Monica Valluri, Alex Ji

- Q: prospects for streams beyond the MW, what’s the sweet spot?
    - Spectroscopy is maybe not able to provide what people are interested in? Radial velocities is the only thing you can hope to get.
        - Integrated light: you might get an integrated velocity but it’s not clear what you learn at all.

        - -> Globular clusters and planetary nebulae is a tracer that can be done further (but maybe not .
    - Abundances there is not much hope. PFS/MSE is probably what is needed for dynamical M31 map/to really do anything.
    - Outside of M31, we have no chance of distances or radial velocities for 3D
        - 10-year LSST promises to 23rd magnitude proper motions, but it's not useful for M31…
    - Key issue is star-galaxy separation. **Roman and Euclid** is going to be needed.
    - Quantifying photometric statistics (as a function of distance) is the only thing we'll really get.
        - M31 is a key stepping stone for developing our use of external galaxies stream morphology + limited spectroscopy/proper motions to see what we can do.
- Collective wakes in the halo: detectability in other galaxies?
    - Can you do this in M31? There *is* a massive merging event, need to separate from halo/see in projection.
    - With just photometry, **can see if there's an offset in the outer vs inner halo**. Asymmetric halo, disk is asymmetric to the outer parts. That indicates minor mergers that move things.
    - Big benefit of other galaxies-> it comes back to statistics. E.g. "On average, blue stuff is closer than red stuff". ~6 galaxies to do in resolved stars, a vast number of integrated light systems to get the most massive few accretions.
- What are the prospects for resolved spectroscopy GSS in M31? (e.g. Stream from M32 or disk?)
    - There's a fair amount of spectroscopy now by PANDAS/SPLASH, now has some abundances too. (FoV is ~3kpc so pencil beam; spatial variations is hard). PFS is what to wait for.
    - Q is where progenitor of GSS distance. HSTPROMO on M32 will help a lot. Spectroscopy in M32 is difficult b'c of density.
- We'll find a lot of dwarf galaxy Sgr-like streams beyond M31: what kind of science do we get from this?
    - [Contrasting with Sarah's talk on cold streams, those will be detectable but maybe not characterizable: confirming streams are streams is hard, but maybe not needed if looking at other galaxies because of statistics/distance. Depends on if you're 10% or 95% false positives. This needs to be tested in M31.]
    - Merging ratios?
    - Stream tracks on sky?
    - Statistics of the accretion history of Local Group galaxies
        - Recent paper trying to automatically classify all the structures around galaxies: narrow stream, shell, etc. (Alan will fill in)

        - How many mergers occur? Shell vs stream-like orbit fractions?
        - As a function of host mass. As a function of thing being destroyed.
        - Where does the Milky Way fit into the spectrum of histories?
        - Halo masses, dwarf galaxy masses (getting moderate spectroscopy for many systems is the way to think of it rather than a few small things)
        - HSC subaru strategic program (Erin Kado-Fong) features. https://ui.adsabs.harvard.edu/abs/2018ApJ...866..103K/abstract
- Finding filaments/cosmic web structure
    - Compton Y maps giving large scale structures -> preferred orientations
- Stuff we've talked about so far today in detail:
    - For the dynamics/precision constraints you are stuck with the Milky Way.
    - For merger histories, massive photometry-only datasets do give you a lot of insight. Imagine if you have 100 PANDAS-like images. What does that give you?
    - A lot of effort has gone into finding external galaxy satellite counts. This is the direction to go with stream features.
    - Possible things to put in distributions: Mass of stellar halo, degree of stellar substructure.
    - GHOSTS ~6 galaxies has already provided some very interesting things on color gradients, accreted halo mass, mean stellar metallicity, etc.
- Dwarf galaxy halos/where they have them? Yes we can do it. M33, LMC-esque galaxies. It's already puzzling in the local group.
    - E.g. M33 has no satellites (maybe something halo-like?), LMC has a gazillion.
    - Tidal features around any of these at all. Rarer/harder to find but statistics of that is interesting too.

Session (b) suggested breakout topics:

- The Milky Way in context: Stellar halos and galactic assembly
- The Context: Tidal debris beyond the Milky Way

Breakout Room 1: The Milky Way in context: Stellar halos and galactic assembly

- **How do we take information about the accretion history of the Galaxy and use it to inform our modeling about stellar streams?**
- Globular cluster locations, density profiles, number densities in the accreted dwarfs (GSE/Sgr/etc) might be able to be backed out with Bayesian statistics as our census grows more and more complete.
- Does the GC luminosity function make sense given what we're seeing in the Milky Way (almost all streams arise from accreted GCs)? Yes! (Kruijssen+19, 20...) Also shows why Kraken == Heracles (can't have another major merger in the inner halo without upsetting our understanding of the GCLFs and the relation between N_GC and galaxy mass).
- JWST + evolution of low mass globular cluster luminosity function (stream GC progenitors are probably less luminous than surviving GCs?)
- Can a single globular cluster be assigned with a high degree of confidence to a particular accretion event? Can use contextual information (are there other surrounding fossil streams? is it a cluster of GCs that are similar in IoMs/chem.?) to make progress.
- GC progenitors of observed streams are less luminous than surviving GCs (=> if surviving GC scaling relations are applied they'll be biased; Bonaca+ submitted)
- Metallicities of progenitor-less GC streams are metal poor feh~<-2, in contrast to Sgr from Sgr, LMC which cover a range of metallicities
    - Are there any streams at higher metallicities?
      (^a question not for the discussion, but did we miss anything due to our search strategies?)
- **Can we detect group infall long ago: e.g., could GSE have been an LMC/SMC-like pair?**
    - In integrals of motion space hard to disentangle, but chemistry should be different in the two cases
    - For GES: chemistry looks like a single galaxy
    - For retrograde shards: different metallicities in similar region of phase-space, so likely different merger events
    - Although, afeh plots are nontrivial to interpret (Sequoia track looks similar to other tracks, is it really distinct?)
        - Do we need a larger sample of stars? -> we'll be getting them
        - Do we need other elements (Ba, r-process)?
        - Well sampled MDFs do separate in unimodal, multimodal when available (e.g., with H3, and in the future with 4MOST, etc)
    - Are z=0 phase-space positions by themselves able to distinguish group infall?
        - Depends on orbit, time since infall (both better mixed, and also had more similar chemistry originally), how tightly bound the galaxies were originally

        - Simulations exist to test this on higher-mass end, but not in large boxes
    - If pair mass ratio is not 1:1, it gets really hard to distinguish from single progenitor. And even for 1:1, this assumes we have factor of 2 precision. Do we?
    - Sims with chemistry might help! (EMP-MOSAICS incoming)
    - Afeh track following sf efficiency, which is very similar in the early universe, so not the best way to distinguish different galaxies
- How well are the GC kinematics known? Can we create a distribution function of globular clusters in a galaxy, e.g., in a dwarf galaxy?
    - In principle, information exists in sims like E-MOSAICS to test this in detail (as a function of accretion history, mass distribution of mergers etc) and there are efforts to start looking into this.
    - If you're interested in helping out with this, please contact E-MOSAICS folks.
- Observational things we should be looking for:
    - Is there anything we've seen in other galaxies that is hard to detect in the mw, e.g., shells?
        - Yes, shells! Hard to find in the MW, but Tom Donlon is looking
    - Relationship between tidal streams and bar/MW features?
    - The LMC moves the MW disk to move, if this was happening in an external galaxy, would see lopsidedness in the disk isophotes
        - Observed in many galaxies externally
        - Need to look into simulations if an LMC-like interaction (torquing) is a plausible origin
        - Note that even in the MW we were only able to see it very recently!
            - But I think the idea is it's easier to see lopsideness in external galaxies?
- Completeness of globular clusters around the Milky Way?
    - This is a really hard problem that we should work on.
-

Breakout Room 2: The Context: Tidal debris beyond the Milky Way

- **Technological advances**
    - We are not yet in a position to analyse and extract information (accretion history) from large samples of streams around other galaxies. What are the science questions? Community effort needed. See Hendel work (https://arxiv.org/pdf/1811.10613.pdf).
    - Star-galaxy separation.

    - What will we do with 100,000s unresolved tidal feature candidates? Classification, processing to generate a statistical sample. Citizen science project (generate crude N-body to reproduce features). StreamZoo (Slack, day 5?) -- interface is there, need to decide questions. HSC SSP is a good pilot dataset.
    - Probing information content of 2d projections of streams. Without velocities, don't know mass. What do velocities add?
    - We need methods to extract stream tracks for external galaxies.
- **What data?**
    - HSC SSP wide field data (release soon). There don't appear to be any interesting local galaxies for finding resolved features. Unresolved, yes. Covers SAGA data.
    - What is the 'sweet spot' for follow-up observations of promising streams/features? IFU observations? Resolved star spectroscopy not feasible beyond LG until nextgen telescopes, then <2-3 Mpc. <10Mpc combination of ground-based + space-based resolved (photometry)
- **DM constraints**
    - In an NFW all orbits are ~trefoil. Pins down orientation of stream and indicates that a dark matter halo is needed (test of alternative models of gravity). With only baryons, too Keplerian. How unique are the solutions which we find?
    - Crude distance information is vital for breaking degeneracies. Without distance gradients it is hard to know the direction the stream is moving in.
    - What does MW look like from the outside? What would we learn? See perhaps Martin work.Can use GCs or PNes as stream tracers. HST UV for population separation.
- The questions for external streams are possibly different to questions on MW streams.
- Gas streams. M81 has gas and stellar streams -- lots of information (dynamics and hydrodynamics)! There may be more examples.
- GHOSTS - there are some isolated cases with detected sub-structure. The main results are the ability to characterize the stellar component

Summary

- GalaxyZoo has a merger question/flag. StreamZoo would involve more questions/richer classification. Very low resolution N-body simulation currently possible within the framework. User assesses which is most like data. Integrate with reCAPTCHA.
- Finding streams around dwarf galaxies (<7Mpc). Theoretical work on GC disruption in dwarfs is perhaps lacking. All GC halo streams were formed in dwarf.

- DFs of GCs within dwarfs are not well understood.
- A globular cluster in a dSph is subjected to some tidal field, and when this dSph gets accreted/disrupted by the MW (or even when the cluster is stripped from it), the strength of the tidal field in the MW remains roughly the same.

Friday Feb 26: Community Efforts and Resources

Running notes here

- Future large facilities. Extra slides here (also on Day 5 Indico page):
  - 4MOST - Roelof de Jong
  - WEAVE - Giuseppina Battaglia
  - MegaMapper - Josh Simon
  - Mauna Kea Spectroscopic Explorer (MSE) - Ting Li
  - Rubin/LSST -

Moderator slides:
https://docs.google.com/presentation/d/1fMxRb8Z6zgou7a7K27zLpl8SMEUlKxOvJ-11YXU3fNM/edit?usp=sharing

Session (b) breakout topics (vote by adding a "+" next to a topic):

- <list topics here>

Breakout Room 1: Ting Li, Tjitske Starkenburg, Khyati Malhan, Kiyan Tavangar, Roelof de Jong, Alex Drlica-Wagner, Diederik Kruijssen, Emma Dodd, Johanna Hartke

- What is mostly need from data/sim/model?
  - The modeler from each group is limited and need more people doing modeling to connect to the data
- What is the collaboration structure for future surveys
  - 4MOST is 70% from consortium and 30% from community; data first be available within the science team and become public after 2 year (expected to be mid-2025 for first public DR1)
- Spec surveys are mostly focusing on instrumentation and data collection, but people on simulations are also very important and could be brought in via external collaborators.
  - 4MOST will have something similar; each WG can bring in 15 external collaborators.
- Do we have theory people's voice in these major spectroscopic surveys?
  - In photometric surveys, there are simulators.
- We should allow for random observations for discoveries in new parameter space
- GC streams formation study requires more observations or modeling/simulations?
  - (E-)MOSAICS-type modelling is being extended to other simulation suites (EMP-MOSAICS, COLIBRE), but requires long development timescale.

    - Need a comprehensive chemistry inventory (beyond obvious elements) on GCs (starting from MW, extending to other galaxies)
    - Also improving the census of tidal tails coming out of surviving GCs would help greatly.

Breakout Room 2: Tomer Yavetz, Heidi Newberg, Megan Barry, Mark Fardal, Edgar Marrufo, Jaclyn Jensen, Denis Erkal, Orlin Koop, Rodrigo Ibata

- Introductions
- What happened with previous GAIA challenge efforts for shared databases? (refer to chat in initial session)
    - We did not appreciate the 'mess' yet, but now we see 'weird' features in almost all streams.
    - Challenges were done for testing fitting methods in increasingly detailed, and different models of stream formation, so we should look into this with some coding experts.
- What do we want and what will we be able to measure from mocks?
    - It will be useful, but will need lots of warnings too since sims will only be as good as our current techniques.
        - So if fitting with these mocks does not work, we have systematic uncertainties.
    - So we need to know the limitations of our simulations.
        - Compare to how cosmologists do this.
        - Are baryons important? Is the potential more flat or spherical depending on matter component etc.
    - We maybe can find a cosmo-code to inject a particle-spray into (not make it ourselves, since that would be too much work and should be done by experts)
- How should we go about implementing some effects we see today like LMC wake and SMC recoil.
    - Or easy ways of time-dependent potentials, with like one or two perturbers coming in to affect that.
        - Maybe an easier way to get time-dependent BFE-codes for this.
            - Taking time-dependent coefficients from a simulation and use that to inject a stream.
    - MW@H has now time-dependent analytical potentials to try and fit data, and we would like the simulated objects to end up at our current epoch, but this seems to be hard.
        - Taking current position of a stream as a single particle and integrating backwards in this, and then forwards again as N-body makes it difficult to get it to line up due to the 'chaotic' process this is.
- How to combine inference from different projects?
    - We need to converge around standard models.
    - I.e., use equal potentials, physical models etc.
        - To do this we need flexible enough potentials to allow for some flattening etc so everyone will be able to use it.
        - Or make and provide a neural network to produce an acceleration field.

    - Do we want to faithfully reproduce the acceleration field or do we want something that can teach us something (i.e. maybe Bovy's model is already too complicated)
- Useable survey footprint database combined with galstreams?
    - Yes that would be nice. +1

Breakout Room 3: Alex Riley, Guillaume Thomas, Sarah Pearson, Elise Darragh-Ford, Hitesh Lala, Zephyr Penoyre, Robyn Sanderson
- Introductions!
- Having a catalog of stellar streams is super important (for both people discovering and people who are doing followup)
    - What observations are needed to move from candidate -> confirmed? Probably spectroscopy!
    - Other observers (extragalactic) want to avoid streams
    - Institutional support is very important
    - Galstreams is a good example
    - Separate footprints from data
    - Exoplanet archive is a good example of this (you can also directly import to astropy) -- but NASA funds this!
    - LSST might be a good place to go for this. Gaia might be better for access in some countries (e.g. China)
    - Databases that are able to accommodate different data access situations, so collaborations can give up what they can
    - Putting candidates in the database are important
    - You can also link two different "databases" (footprints vs. stream members)
- Some functionality is already offered by Vizier / SIMBAD / CDS - what we need is a flag for streams or repository linking to those data
- How do we decide candidate vs confirmed stream?
- Adrian's visualization
- Doing science via JavaScript - lets you directly get data from the Internet
- Stream naming
    - No rules can lead to more diversity
    - Pushing back on this a bit -- you can have rules that are very culturally inclusive (e.g. names of rivers in different cultures/regions for STREAMFINDER and DES streams)
    - Not all stream names should need to be English. And many of the new ones aren't
    - We don't have to standardize that away - many astronomical objects have multiple names, and databases handle it just fine
- Scientific efforts that people are doing
    - Robyn: making the engines for generating mock data public
    - Sarah: tools to model/fit external galaxy streams

Breakout Room 4: Vasily Belokurov, Ana Bonaca, Alejandro Borlaff, Marius Cautun, Quyn Lan Nguyen, Stella Reino, Adam Smercina, Monica Valluri
- What can we learn from data management in large surveys like Euclid?
    - Archive will provide data products, room available for specific science topics
    - There will be calls for PI proposals in Euclid past year 1

    - Dealing with star-galaxy separation at Euclid depth: will there be data products trying to separate this
- Modeling
    - LMC can't be ignored, but need to treat it properly (time-dependent potential w the MW response)
        - Harder to do on personal computers, are there ways to speed up the computations?
        - One approach: run simulation, calculate BFEs (saved in fine time steps); but limited by the number of simulations you can run
        - More basic approach (add LMC as a Plummer sphere/parametric potential): not capturing mw's distortion, realistic dynamical friction, just the global response to the LMC
        - Need to figure out how important high order effects are
        - Could produce an emulator (interpolate between a grid of sims w different LMC masses, orbits, mw masses)
            - For cosmological sims w 10 params -> 100 simulations
            - Not sure how it scales to the MW
        - Would genetic modifications help (Andrew Pontzen's work): give power to dial down params, but preserving the realism of fluctuations being sampled
            - Maybe this can be used to always have LMC at the present-day location, just sampling from a random field would take forever
            - Needs testing: galform is a very nonlinear process
            - Genetic modifications start from cosmological IC, whereas currently best LMC models (Nico's) are more idealized galaxy collisions simulations
            - People to ask for further: Andrew Pontzen, Justin Read
    - Particle sprays
        - Because they are discrete models of streams, they introduce numerical noise into likelihood surface
            - Is interpolation of the track the way to go?
        - Also, can we reduce the number of particles to have even more efficient inference?
    - We need stream simulations in non-CDM!

Breakout Room 5: Madison Walder, Nico Garavito, Ethan Nadler, Cecilia Mateu, Carl Grillmair, Hector Velazquez, Anna Wright,

- Introductions :-)
- Would be great to have an easily accessible/unified streams database. Does Galstreams have everything we "want"?
- Right now there is only spatial (sky coordinate) information. Will have detailed stream tracks, distance gradients, RVs where possible soon! Metallicity too, hopefully. Other "metadata" e.g. stream poles (heliocentric poles? A bit weird but can be useful)
- Might be helpful to "Python"-ize Galstreams. Flexibility/documentation for e.g. other projections might be useful.
- What do observers want from simulations: mock catalogs. Easy way to identify where the streams are (not only star particles).

- Ethan's sims are DMO. Particles of disrupted MW progenitors can be tagged in post-processing to identify remnants, "streams," etc.
- A unified simulation database (or at least metadatabase) showing {name of simulation, class of simulation, data products, etc.} would be very useful. Something like a wiki page where a point person for each simulation can maintain things.
- What can we learn from exoplanet and cosmology communities re: data storage, maintenance, distribution? Maybe we just need money. Funding proposals, white papers.
- How to keep the conversation open after the meeting? Slack channel can/should stay open. Talks, notes will all be kept publicly available. Many +1s for keeping this Slack workspace active. Someone will have to pay once > 10k messages are reached ...

Breakout Room 6: Jason Sanders, Tom Callingham, Alex Ji, Kohei Hattori, Tariq Hilmi, Chervin Laporte

- Which package to use? Agama, gala, galpy
    - Jason uses agama, especially custom potentials; quick tutorials use galpy because bigger userbase/installation; gala for arbitrary coordinate systems
    - Dream combination?
        - Adrian PW's comment from zoom chat: What I want in "agalapy": Gala frontend and tie-in to astropy coordinates and units, Agama backend / potentials and C++ framework, w/ Galpy action solver implementations and DF stuff :)
    - Concerns about making things too easy, that people stop understanding stuff. Algorithms are often approximate and only work so well, the limitations are not appreciated! E.g. AGAMA action-computation machinery doesn't work on *prolate* potentials
    - Analogy to MCMC: "It's so 'simple' to use you might as well write the basic algorithm once"
- Agreed standards about e.g. a "MW2021" potential does seem good
- Some idea about what to do with black boxes for actions and having multiple methods. Everyone just kind of uses whatever is fastest (might become the ActionFinder).
- Data sharing and open astronomy catalogs
    - Code to turn fits files into data?
    - Automated spectral fitting -- needs care as can easily lead to biases (in metallicities and radial velocities). Very easy to misuse.
- Simulations
    - Standardisation of computing e.g. potentials.
    - Now people will often share particle data by request, but things become obsolete/reinvent the wheel a lot. Using basis functions to describe the simulations seems much better as a way to report. **A repository of basis functions.**
        - This is fine for e.g. dark matter halos, but stops working for very thin disks or substructure.

- For static potentials, sharing is relatively easy; but for evolving potentials it becomes very complicated, or marginalizing over uncertainties etc
    - Making code available on git is important for this

Breakout Room 7: Mike Petersen, Andy Everall, Martin Mestre, Peter Ferguson, Jonathan Freundlich, Youjia Wu, Rapha Errani

- Data accessibility:
    - RE: Is there a unified catalog of local kinematics, with uniform treatment of error bars?
        - *Can we make something like a database to upload error distributions?*
        - A unified database is obviously worthwhile, given that multiple people are just using McConnachie's compilation
    - *Can we get a list of published stream members star by star with something like Gaia IDs?*
        - One con: makes very strong priors for membership in cluster
- Model accessibility:
    - People are shopping around for various tools to do modelings (NEMO, agama, etc). Tools are somewhat easier to use than expected! *Primary goal is simplicity, but would like a piece of software that can be edited without much difficulty. <- Is this a framework?*
    - *What are we going to do for time-varying potentials*? <--simple applications in galpy
    - Keys: easy to use on the surface, but lots of possibilities for flexibility. Options to go much deeper. *Triaxial potentials.*
    - Cons: accessibility can lead to misuse cases. If people build their own tools, then we are all checking each other's work and deepening our own understanding. Are we getting into a rut with outdated models? *We should have deep understandings of what we are putting into our models.* Idealised models versus real systems as the division between simplicity and complexity? *'The educational aspect'*
    -

Breakout Room 8: Eduardo Balbinot, Bertrand Lemasie, Nathaniel Starkman, Nora Shipp, Rohan Naidu, Marcel Pawlowski, Jeremy Webb, Adrian Price-Whelan, Sophia Lilleengen

<u>Renaming streams:</u>

- Not finding a convention but identifying streams which should be renamed (Orphan [also sausage++++])
- Who should have a say in this? The original namer if something is renamed, or survival of the fittest (eg Kraken vs Herakles)?
- Streams are more coherent to identify and name (rather than a region in action space)
- **How do we propose un-/renaming streams?**
- Will people accept renaming of streams which have been around for long?
- Do something similar like the NGC catalogue… Order them and count then

<u>Modelling / Software:</u>

- APW: One place for all dynamics software or easier interaction between Agama / gala / galpy
- NS: has wrappers for framework for the 3 packages with potentials using astropy coordinates
- SL: combination of the best of each package in sensible units would be nice
- RN: for simple things, frontend should stay the same for each package people are using; but uniting them would be nice
- APW: Autodiff available on everything would be an improvement
- EB: MW2014 + LMC with pre-made ICs published would be a something useful to have for eg different LMC masses; JW: has something like this potential in galpy
- APW: time-dependence in those packages? Just reflex motion? Or even using BFE coefficients (will be implemented in Gala based in Nico Garavito-Camargo's models)
- NS: updatable parameters (as in astropy) from updated potential measurements would be nice in other packages

<u>Data sharing / open frameworks for follow-ups:</u>

- APW: Would that be useful for us?
- EB: Tried an open catalogue for GC (an update from Harris) and engage community for this but saw very little engagement; if done, by one person or group and not very community-depending
- MP: People adding to common database does not seem to work so far; also people have different preferences and needs for which measurements they need; important discussion to have though and something which would be super helpful to have
- APW: Exoplanet community had some initial seeds who implemented these databases and then community started to use and update them
- RN: people do not want "to give their work away" - APW: we need to be better at engaging the community
- NS: issues with consistency; what is the best way to do this? S5 are happy with sharing data and have lot of stream spectroscopy
- MP: the more we do data sharing, the more people will do this

Breakout room 9: (David Shih, Thomas Donlon, Jeff Carlin, Eugene Vasiliev, Juan Miro, Kathy Vivas..)

- Data: keep track of bibliography - perhaps can use SIMBAD infrastructure but need to make sure they consistently use and collect stream names;
- Data: encourage people to publish lists of candidate members for streams discovered or discussed in each paper (looking at you, Rodrigo!)
- Would be ideal to have a list of all [candidate] stars in all streams as part of galstreams (with 6d phase space, Fe/H, age, number of habitable planets…)
- Models: easy to use infrastructure for sharing galactic potentials (BFE coefs?)
- Realistic mocks of MW with all the mess around, plus realistically injected streams (cold, with gaps, faint.. not as prominent as GD1)

Discussion Room 1 - Open Data and Follow-Up

- Updates for galstreams https://github.com/cmateu/galstreams:
    - Will publish stream coordinates, stream polygons, reference frames, references, etc. [Help, Cecilia! The note-takers were both distracted when this convo started.] "It's all going to be self-consistent."

- What about streams found a while back, and/or those that didn't publish coordinates for individual stars? How do we manage follow-up - sometimes we have to digitize points from plots, etc. But most have now been recreated (esp. since many have been "re-discovered"), so this isn't so much a problem now...
- Q: if 4MOST makes a catalogue available of 300M halo stars, what kind of use cases would you need? Download whole catalog, search for individual streams, polygon search, row of circles, rv range, etc?
    - Star/galaxy classification, coordinates,
    - **Gaia IDs**
    - Gaia-like ADQL
    - Healpix based
    - Portals for working next to the data rather than pulling it first.
        - Can cross match in the portal
- Q: Can we create repositories of (e.g.,) spectroscopically confirmed members (and things people would _like_ followed up!), RR Lyrae, etc. A centralized location to access stream stars and candidates.
    - Especially for the things that are expensive: faint or time domain
    - A query you could run once a day across several datasets?
    - 4MOST is going to want to do everything regardless, but it may not go back
        - Though some deep fields will have multiple observations (as much as 60)
    - DESI has high priority category (~"all" BHBs, RRLs between 16-19th mag will be observed)
    - Catalog of nearby bright stars for RV standards (this was particularly in the context of RRLs -- Cecilia said the same standard is always used, 'cause there are no others) -- Hitesh noted that LAMOST medium res survey has some bright RRLs with >30 observations
- There's an online catalog software (astrocats) for curated datasets. Alex Ji has found it very useful. [Note: data policies may make things a bit tricky…]

Discussion Room 2 - Modelling framework & software tools

- What's the difference between "modeling" and "simulation"?
    - Difference between running full (slow?) simulations (cosmological or N-body), and fast things that can be embedded into a statistical model to compare to data / compute in a likelihood function
- Some discussion about standardizing MW dynamics tools (agama/gala/galpy)
    - Is it useful to think about standardizing the "tool"-level aspects (integrators, potential models, etc.), then building models on top of a shared framework / infrastructure
- Standard MW models (like MWPotential2014) clearly very useful
    - Having short path from ICs to simulation is great! (mock streams, orbits in MW, etc.)
- Is it too early to have a standard MW + LMC model?
    - Premature to "fix" a standard model because so much still unknown, so could end up hurting us?
    - OTOH having a range of models is still useful, and need a starting place

    - Use the goal of having a standard MW+LMC to develop the infrastructure behind enabling this. [?]Equivalent to changing the halo mass in MW model, can change infall of LMC or whatever and easily generate
- Other DM models or alternative theories like MOND not explored well because no standard tools
    - Need equivalent models in other DM models or theories
    - But: nonlinearity of Poisson equation is a barrier!
- Even having a bad MW+LMC model probably still has utility!
    - It's probably better than just using a static / standard MW model, which many are doing
    - Or at least it gives a point of comparison to those models
- Having MCMC samples for potential parameters is a good practice, but only represents the precision of the model fits
    - But the variance / systematics of the model won't be captured by the samples
    - That's why it is valuable _not_ to standardize the entire workflow - but rather to cross-check the results against alternative toolchains..
- Isn't it a goal to have samplings and proper quantification of uncertainties in our constraints on these models?
    - Yes! Just important to communicate / be honest about the limitations
- Hierarchy of models:
    - Standard disk/halo/bulge through time-dependent deformations of the halo!
    - People are using these potentials to compute millions of actions or very different contexts
    - Argues for Tools not fixed / rigid things!
- Standard way of representing mass models
    - BFEs / multipole expansions
- Standardized bar-MW model?
    - With a few representative bar pattern speeds? - ATM there is not a single publicly available / easy-to-access barred MW potential model, should ping the groups who have explored it in some detail (e.g. Ortwin's).

Discussion Room 3 - Simulations and mock catalogs

- What kind of simulation information is being provided? Snapshots vs full merger trees
    - Releasing initial conditions (Ethan's suite). Often these are "public" already (in that they're taken from MUSIC)
    - Would be nice to make an interface that makes it easy to run same DMO sim w/ e.g. embedded potentials
- Mock catalogs of streams for external galaxies would also be interesting (see Robyn in Slack if interested)
- Comparing substructure can be difficult to determine which past mergers actually created features (merger trees are hard to navigate if you don't do simulations). Tagging substructures to specific accretion events
    - Part of the reason that this doesn't get released is to protect student projects within simulation collaborations

        - Ana: is it plausible to have an agreement to release merger trees widely as long as there's an agreement to protect students?
        - Robyn: licensing covers some of it but not all. Really want to protect grad students (most vulnerable in our community)
    - Fairly complicated: details of how you assign particles (or mock stars) to a particular structure is not always objective (and work intensive)
    - Different definitions/scientific interests: when were structures quenched? When was it accreted (what does "accreted" mean)?
    - A little easier to do something like this with E-MOSAICS, where the clusters are simulated and easier to track/tag than actual star particles
- Generating mocks for different surveys is hard (parameters of surveys always change). Simulators excited about it, ask if you want a particular effort
    - Some of the tools are fairly standardized (Snapdragons) and public
    - There often are tutorials, but simulators need to take initiative to add those examples to public databases
    - However, onboarding takes awhile (how complicated that is scales with how complicated the simulation is)
    - One reason simulators want to collaborate (as opposed to releasing everything) is they often know the drawbacks and how best to connect to observations. Also, there's no way they'll ever do all projects that the simulations are useful for
    - Also an intimidating aspect of it, in terms of data volume and richness. Having a collaborating simulator can walk you through that
- Open data with simulations? Lots of progress from observations (SDSS, Gaia), large-scale simulations (EAGLE, Illustris), but a little less for zooms
    - Organizationally there's a lot of overhead. Easier for large collaborations to provide support, overhead
- How realistic do mocks need to be? Fold in Gaia selection, error functions?
    - Really depends on your science. This is a recurring problem for generating any mocks

Key Takeaways / Questions

Add your ideas below! Try to group like topics under themes.

- Mass assembly history of the Milky Way:
    - How much mass was accreted to what radius at what time?
- Global properties of the Milky Way mass distribution (because people still like to quote or know the mass profile of the galaxy for other fields!)
- Small-scale aspects of the dark matter distribution in the Galaxy:
    - Mass function of dark matter subhalos below 10^8 Msun
- Can we rule out (or confirm?) MOND (completely?) with streams and stellar halos? With the LMC wake?
- We need to keep the momentum of this meeting! Working groups and follow-up discussions on:
    - Open streams catalogs (astrocats?)
    - RR Lyrae follow-up
    -
    - <add here!>
- ..
- ..