Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

State of Cosmology

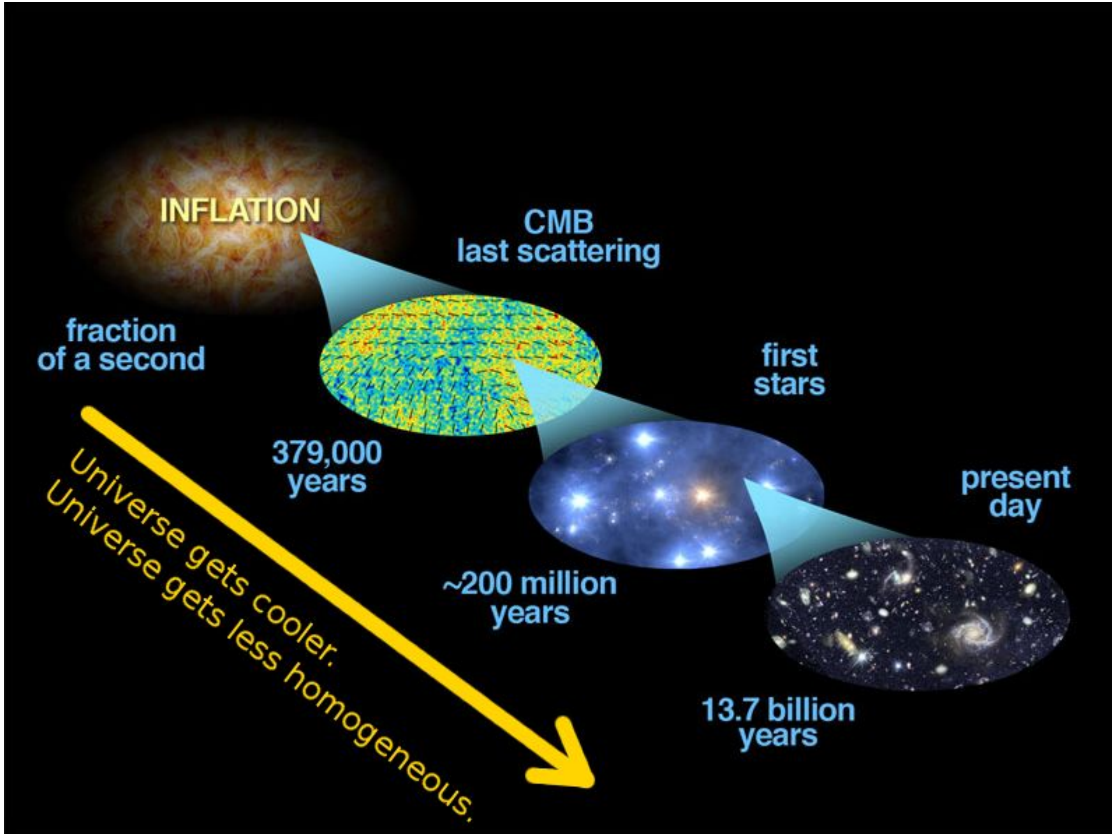
Anže Slosar, Brookhaven National Laboratory

Portorož, 13 April 2022

Overview

- What is cosmology is context dependent:
    - for a stellar astronomer, everything extragalactic is cosmology
    - for a string theorist, cosmology ends with inflationary reheating
    - for classically educated HEP physicist, any astronomical probe of fundamental physics is cosmology
    - …
- I’ll focus on traditional cosmology, but other constituencies are growing:
    - dark matter through non-canonical probes
    - gravity waves as a probe of fundamental physics
- This is a somewhat US centric talk…

Evolution of the Universe



- As Universe expands it becomes:
  - cooler
  - less homogeneous
  - more complex
- Universe becomes easier to observe and harder to explain as we move from high redshift to low redshift

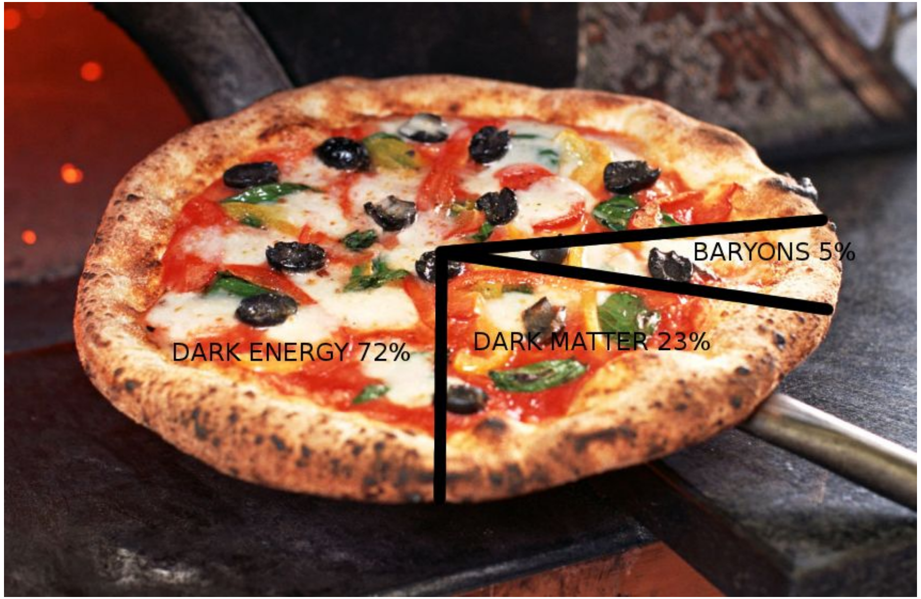
Cosmic Pizza

- 95% of the Universe made of stuff we don't know

- dark components well understood macroscopically, but their physics remains a mystery

- **Dark Matter** is cold, non-interacting "stuff" collapsing under its own gravity

- **Dark Energy** drives an accelerate expansion of the Universe - on of the most unexpected turns of late 20th century

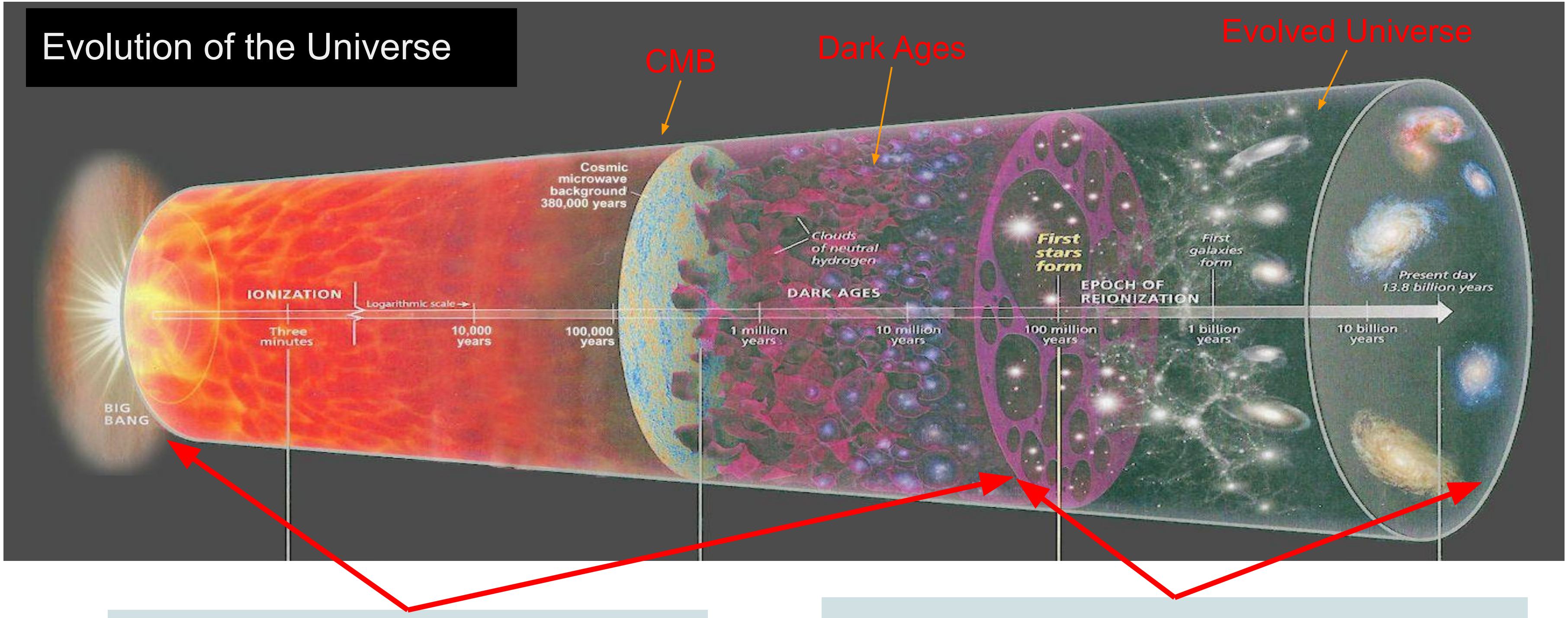


- Dark components are discovered and studied through their macroscopic properties
- We do yet know how they fit into the Standard Model

Foundational Questions

- What are the microscopic properties of Dark Matter and Dark energy:
  - currently no evidence for new physics
  - O(1) effects in dark energy and dark matter equations of state excluded
  - how long do we search before we give up?
- Is Gravity explained by Einstein relativity on all scales and at all times?
- What sets the initial conditions for the hot big bang:
  - can we learn more about inflation?
  - Two promising avenues:
    - measure non-Gaussianity of initial conditions telling us about field couplings in the early universe
    - measure residual features in the primordial power spectrum
- Total particle content of the universe:
  - measure light degrees of freedom

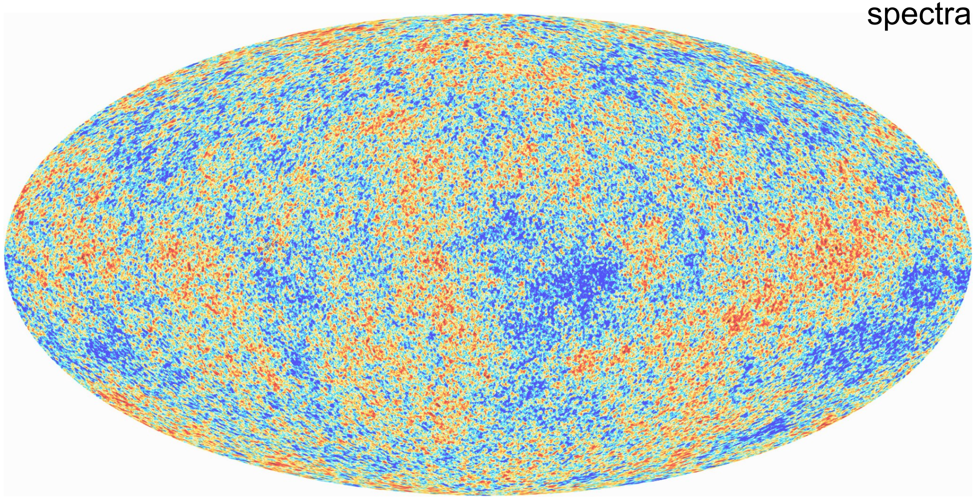
Evolution of the Universe



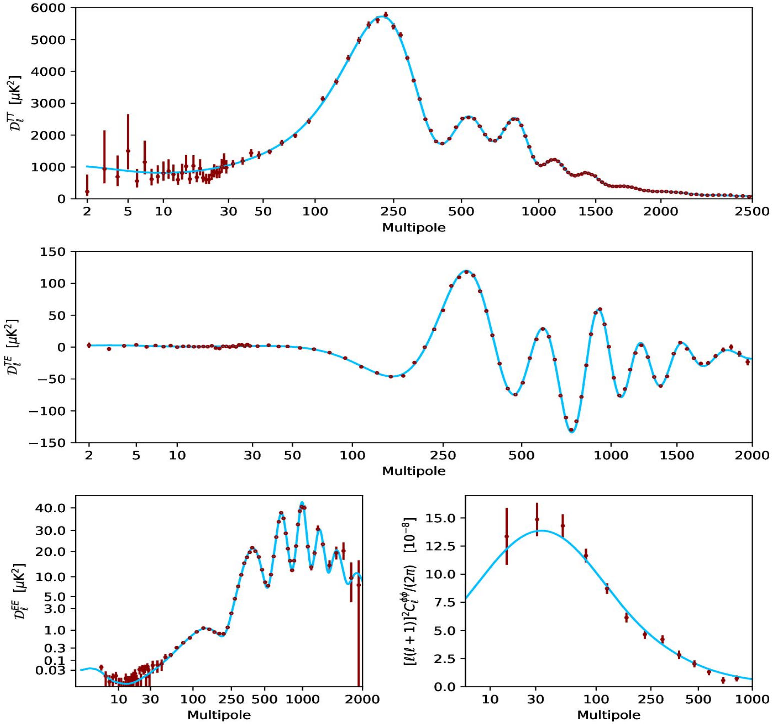
Easy
Before first stars form, linearized GR, thermodynamics and atomics physics predict **everything** using controlled perturbation theory.

Hard
After the first stars form, the universe is not modelable from the first principles.
Density perturbations reach non-linear levels where they are only modelable approximately using N-body techniques.

Planck



Planck Power spectra



- Planck is the cornerstone of modern cosmology
- The errorbars are incredibly small and a five-parameter model fits everything very well
- Fundamental degeneracies in the data: model becomes very degenerate as soon as we move away from flat LCDM.
- This is where I send MOND crackpots
- Planck is cosmic variance limited for power spectrum

Galaxy Surveys

- At low redshift we use galaxies to trace structure in the Universe
- This can be made theoretically robust using locality arguments
  - Our lack of knowledge of how galaxies form is absorbed into bias parameters
- Two approaches:

Spectroscopic Surveys:

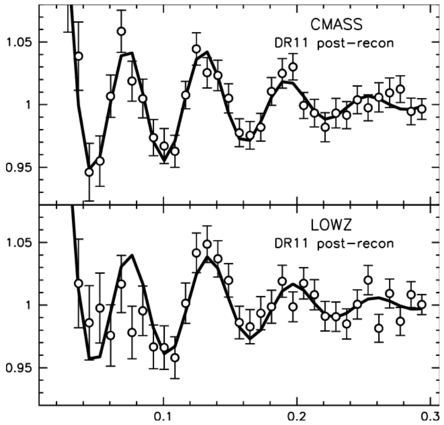
- Take spectra of objects
- With redshifts you can make 3D map of the sky
- Have access to redshift-space distortions
- Very robust
- Number of objects over a million in current generation.

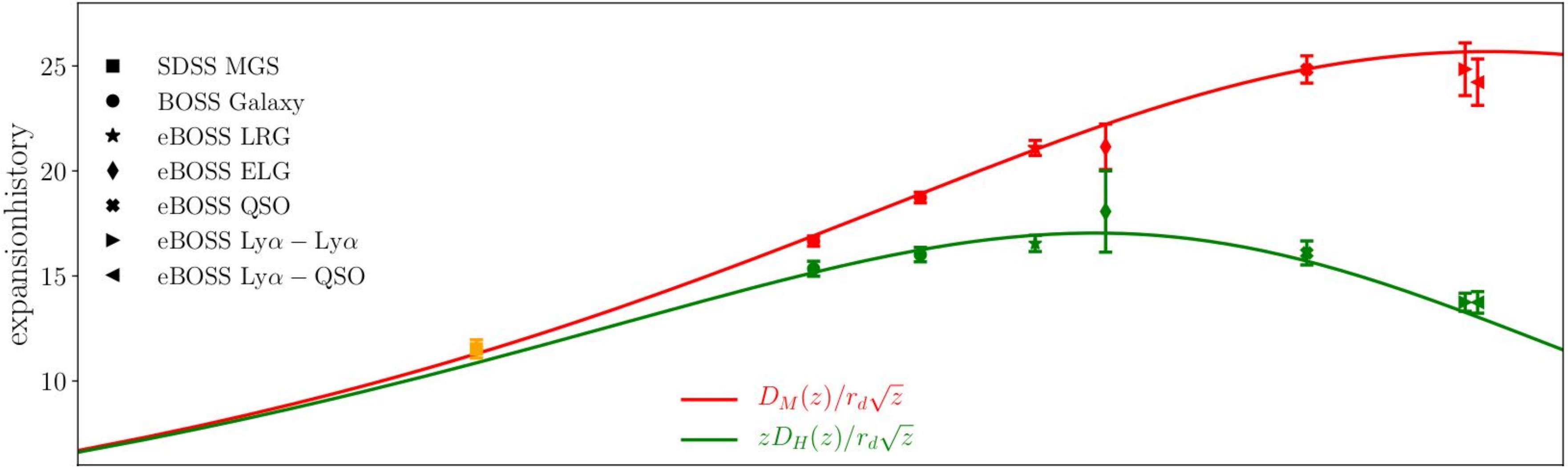
Photometric Surveys:

- Take images of the sky
- See many more galaxies, measure weak lensing distortions
- Guess approximate redshifts from colors to make 2.5D maps
- Number of objects over hundred million in current generation.

Baryonic Acoustic Oscillations

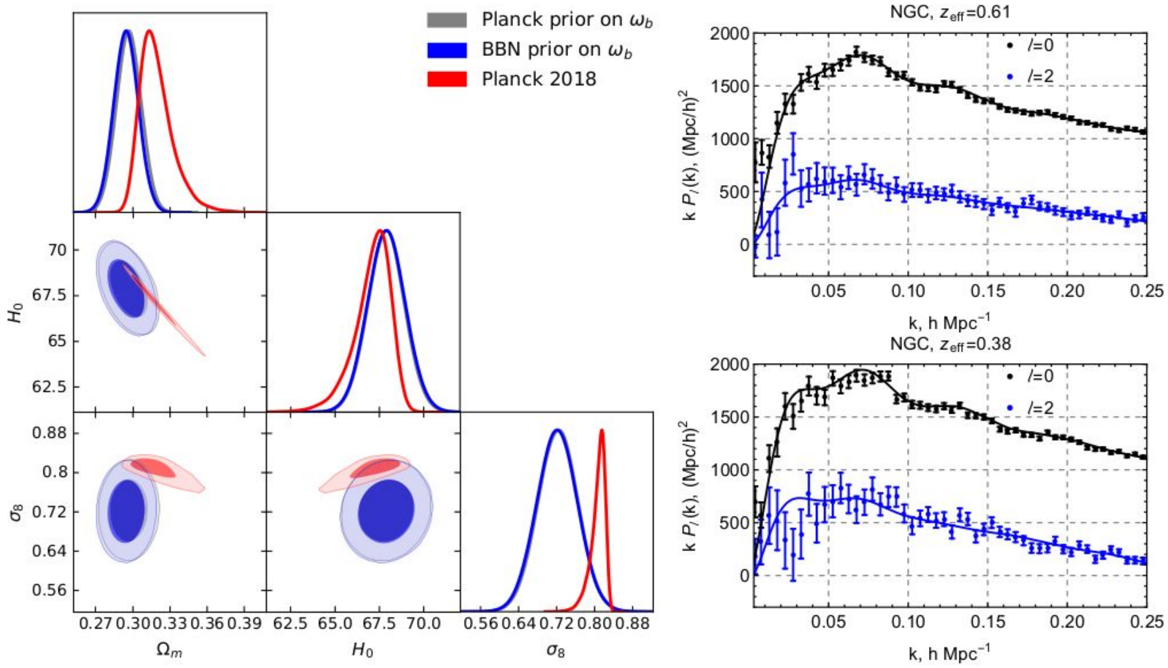
- The same oscillations that we see in the CMB, can also be seen in distribution of galaxies
- This requires 3D maps of the universe
- This allows use to measure distances as a function of redshift.
- These are percent-level measurements coming from over one million spectra in the eBOSS Data Release 16





Spectroscopic Power spectrum using EFT

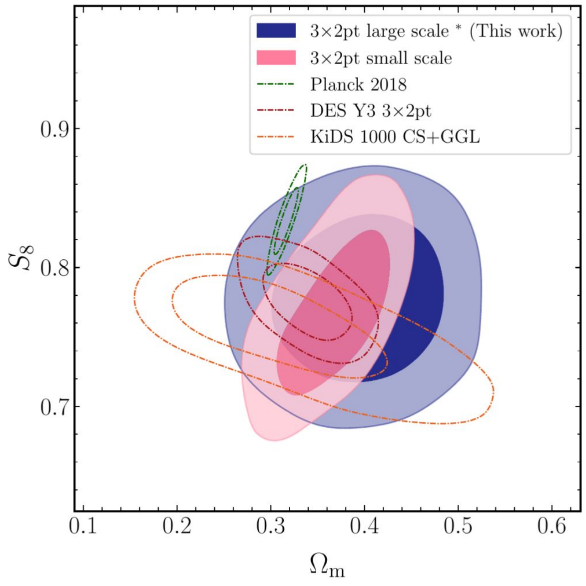
- Entire industry of theorists modeling power spectrum using Effective Field Theory approaches
- Can get information beyond distances robustly



from Ivanov et al 2020

Weak lensing and photometric galaxy clustering

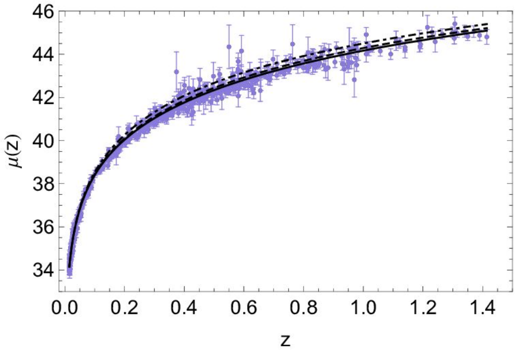
- Photometric experiments are finally starting to deliver (after decade of promises)
- Errorbars are still at the 10%
- The probe dark matter directly
- (but with hard to understand systematics)
- 3x2pt refers to 3 measurements of correlation (2-point) functions:
    - shear x shear
    - shear x galaxy clustering
    - galaxy clustering x galaxy clustering



Sugiyama et al, 2023

Summary so far

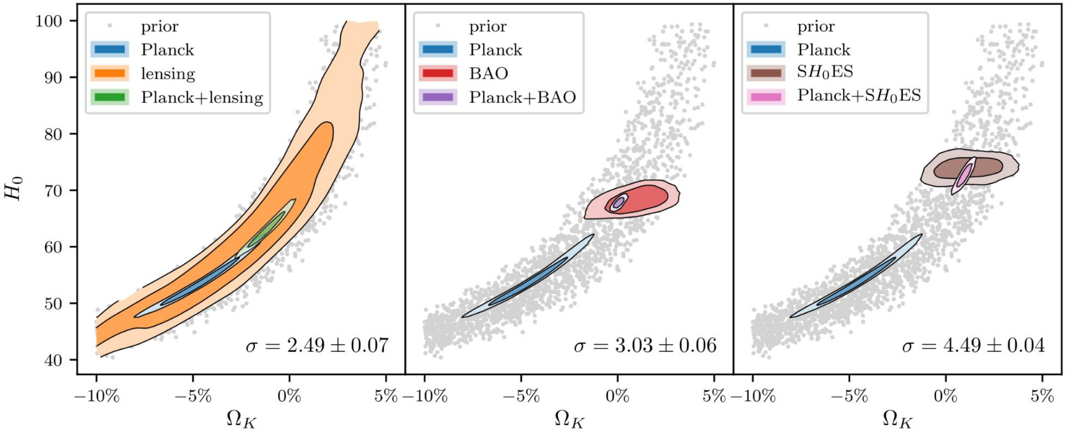
- Today's cosmological model rests on Planck + BAO:
  - they contain 90% of information content for LCDM
- Plethora of supporting data:
  - full spectrum modelling
  - weak gravitational lensing
  - Supernovae-Ia
  - strong gravitational lensing
  - Lyman-alpha forest
  - cluster cosmology
  - ...
- Supporting data incredibly important since they impart robustness



Pantheon SN Ia expansion history

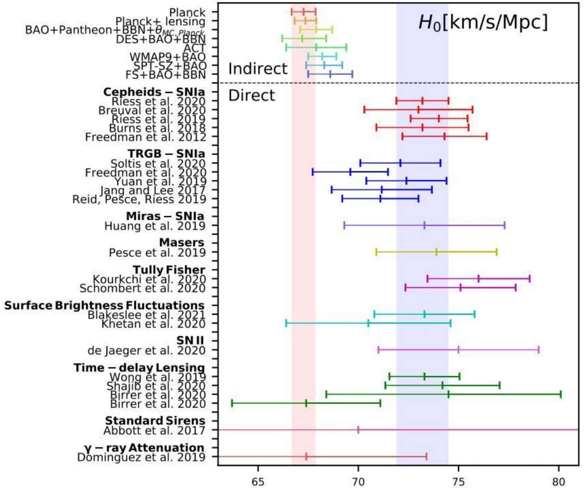
Tension #1: Internal Planck tensions

- Planck data does seem to have internal tensions:
  - If you relax curvature in Planck alone, chi2 improves by 11 units
  - A very similar effect is if you one the A_L parameter
  - Planck wiggles are “too smooth”
  - All parameter slide down their degeneracy values into a total insane cosmology
- Sociologically interesting:
  - Mentioned and explained without much fanfare in Planck 2015 and 2018 papers
  - Re-discovered by di Valentino et al. , 2019 and Handley 2019



Tension #2: Hubble parameter tension

- Hubble parameter measures expansion rate today
- Perhaps the most interesting tension
- Distance ladder: **high H0**
- Anything else:
  - Planck in LCDM
  - Planck + extended LCDM + something else
  - BAO + something else
  - … gives **low H0**
- Sociologically interesting:
  - Riess is a Nobel prize winner
  - Theorists still don’t give a shit



Dataset	Cosmological model	H_0 (km s^{-1}Mpc^{-1})	Comments
CMB T&P+BAO+SN	ow_0w_aCDM	67.87 ± 0.86	Inverse distance ladder
BBN+BAO	ΛCDM	67.35 ± 0.97	No CMB anisotropies
CMB T&P	ΛCDM	67.28 ± 0.61	*Planck* 2018 (a)
CMB T&P	oΛCDM	$54.5^{+3.3}_{-3.9}$	*Planck* 2018 (a)
Lensing time delays	ΛCDM	73.3 ± 1.8	H0LiCOW (b)
Distance ladder	-	74.0 ± 1.4	SH0ES (c)
GW sirens	-	70 ± 10	LIGO (d)
TRGB	-	69.6 ± 1.9	LMC anchor (e)
TFR	-	76.2 ± 4.3	Cosmicflows (f)

$$H_0 = 73.04 \pm 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1},$$

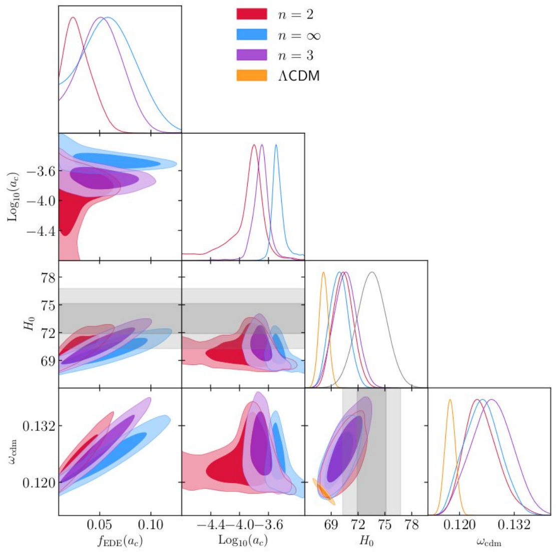
Riess latest

Hubble tension: explanations

- Seems to be impenetrable to sensible explanations
- The inverse distance ladder argument (CMB->BAO->z=0) requires a change in pre-recombination physics
  - change in pre-recombination physics without side-effects impossible (or fine-tuned)
- The closest is early dark energy, but even that is now discouraged
- Either: Riess is wrong or there is some fundamental shift in our understanding
- NB: H_0 is one of the very few parameters with units

Early Dark Energy Can Resolve The Hubble Tension

Vivian Poulin[1], Tristan L. Smith[2], Tanvi Karwal[1], and Marc Kamionkowski[1]
[1]*Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, United States and*
[2]*Department of Physics and Astronomy, Swarthmore College, 500 College Ave., Swarthmore, PA 19081, United States*
(Dated: June 12, 2019)



Early Dark Energy Does Not Restore Cosmological Concordance

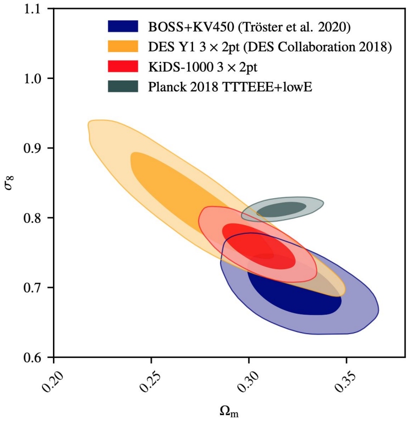
J. Colin Hill,[1,2] Evan McDonough,[3,4] Michael W. Toomey,[3] and Stephon Alexander[3]
[1]*Department of Physics, Columbia University, New York, NY, USA 10027*
[2]*Center for Computational Astrophysics, Flatiron Institute, New York, NY, USA 10010*
[3]*Brown Theoretical Physics Center and Department of Physics, Brown University, Providence, RI, USA 02912*
[4]*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

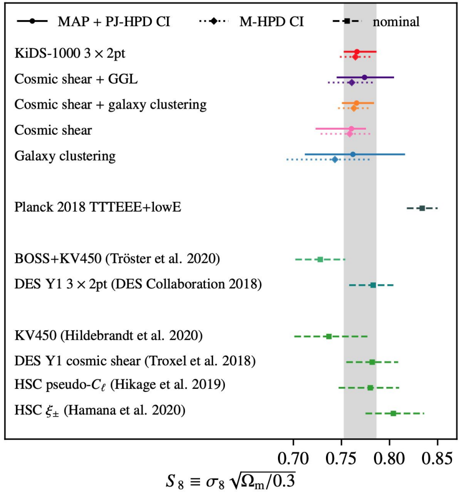
(2020)

Tension #3: the S_8 tension

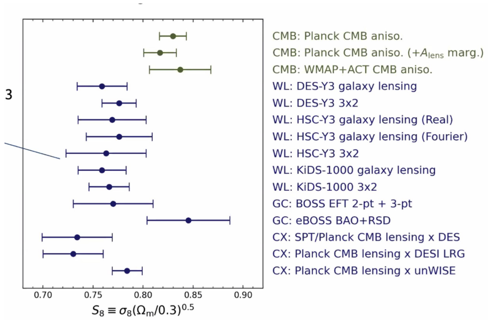
$$S_8 = \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{1/2}$$

- S_8 is a weak lensing parameter
- It is consistently low in weak lensing surveys
- Not statistically very significant, around 3 sigma
- Not present in CMB lensing alone, but in some CMB-lensing x galaxy clustering
- Socially Interesting:
  - weak lensing people don't really have precision,
  - ... at least they have a tension....





Heymanns et al 2020



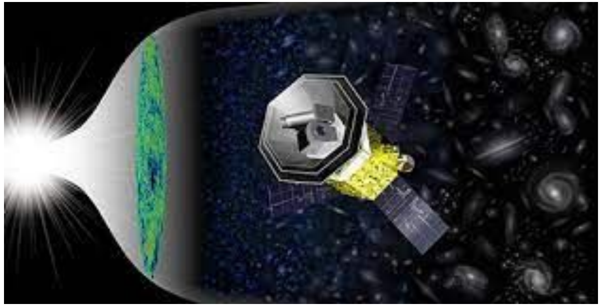
Form recent ACT results

What next?

- US is going through its decadal planning exercise:
    - For cosmology, there are two relevant planning exercises:
        - NASA/NSF/DOE Decadal Survey
        - Snowmass/P5 process, approximately equivalent to European Strategy for Particle Physics
- There is no similar planning exercise for cosmology alone in Europe
- This process has been dragged out due to pandemic
- What are the results?

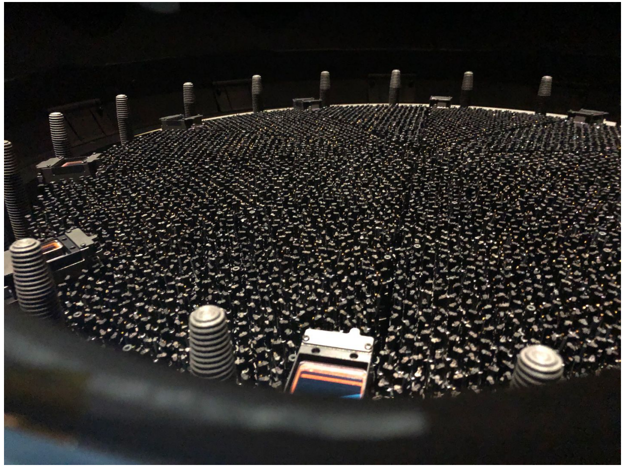
CMB

- Planck stopped observing in 2013, last papers in 2018 data release
- CMB-S4 is the next big thing
- Endorsed in 2012 at cost of ~$150mil total
    - Now the cost is $600mil + operations
    - Starting observations around 2033
    - Need to wait for DUNE to get through the pipeline
    - NSF hands are also full
- Flagship science:
    - tensor modes as probed by B-mode polarization
    - N_{eff} to search for light relics
- Still most likely going forward
- Other piece of the landscape is Japane lead LiteBird:
    - also after tensor modes



Litebird concept

Optical experiments: current situation



Rubin Observatory / LSST:

- US flagship photometric experiment
- To start observations in summer 24
- A 8m telescope with largest etendue ever served by 3.2Gpix camera
- Will do all kinds of astronomy, in cosmology it will transform gravitational lensing and time-domain astronomy

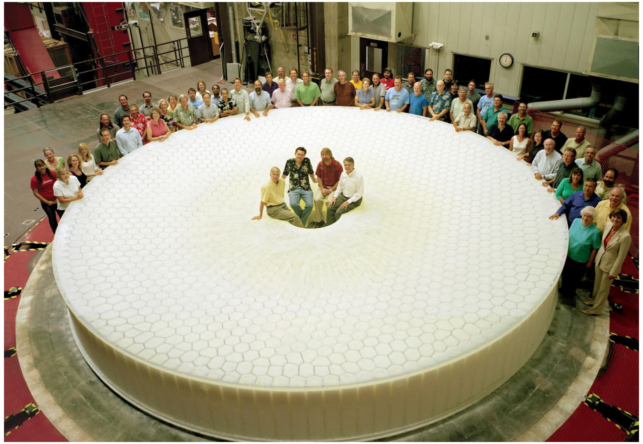
DESI:

- US flagship spectroscopic experiment
- 5000 fiber robot on a refurbished 4m Mayall telescope
- Taking data for a few years
- Have ~10 million of spectra already (more than SDSS combined in 20 years)

LSST / DESI timelines

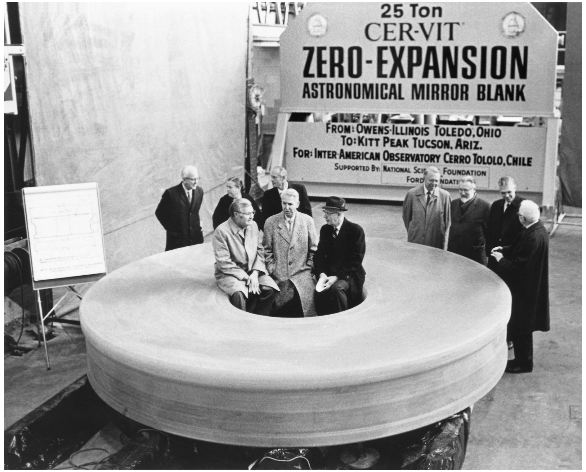
LSST:

- First proposed in 1996 as a Dark Matter telescope
- From idea to realization: 28 years (!)
- To build a new dedicated telescope facility it takes a lot of time and money



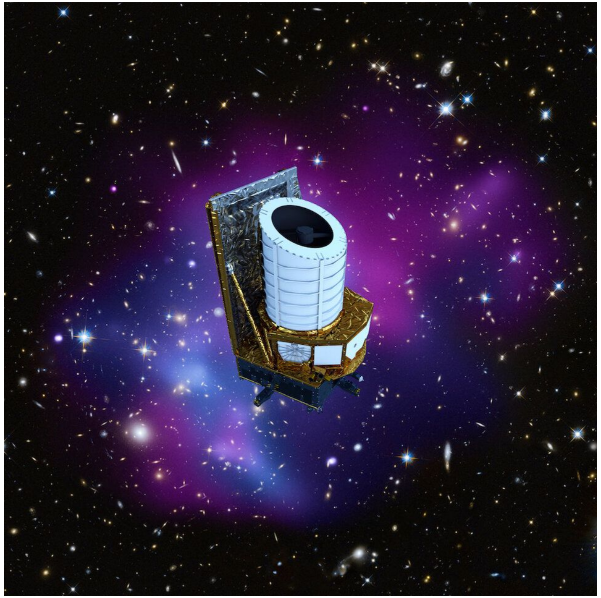
DESI:

- First proposed in 2011 as a BigBOSS
- Uses refurbished Mayal telescope
- We ran out of old telescopes to refurbish



What is EU doing?

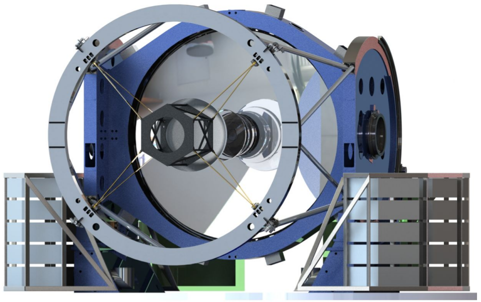
- The main big thing in Europe right now is Euclid
  - Scheduled to launch by Falcon 9 in July 23
  - An optical imaging / spectroscopic experiment
- Also big participation in Vera Rubin / LSST:
  - LSST@Europe 5 in Poreč in Sep this year



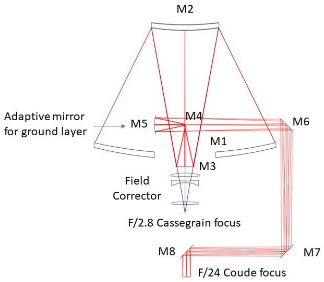
Euclid in space with mysterious pink shit around it

Spec S5

- It is clear that then next big thing will be a new generation spectroscopic instrument:
- Fibers: 5000 -> 20k-50k
- Mirror-size: 4m -> 6-12m
- Community real has not converged on a single concept:
  - Go aggressive and risk LSST-like first light in 2050?
  - Go realistic and end up with a boring incremental experiment?
  - Sounds familiar?
- European are developing a similar concept called WST which is also in very early stages
- Nobody knows.



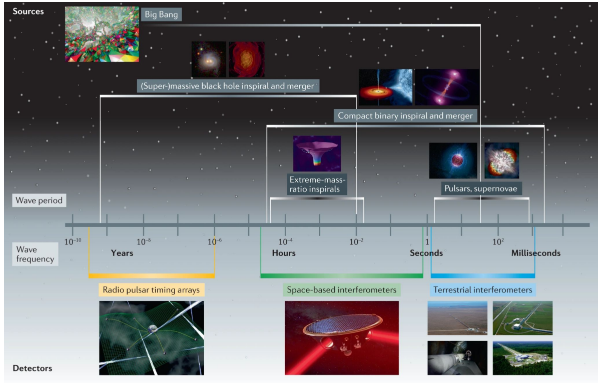
MegaMapper: an Spec-5 concept



SpecTel: another Spec-5 concept

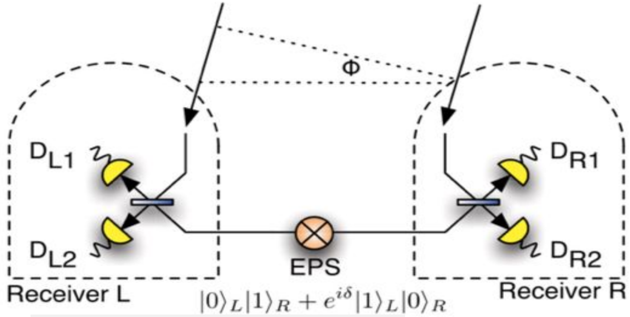
Gravitational Waves

- First detected in 2015 after decades of attempts
- Amazing technical feat
- GW170817 shows that $c_{GW} = c_{light}$:
  - total bloodshed in theory of modified gravity
- Lot of new experiments coming online:
  - some push for particle physics to embrace this
- To me, there was scope for some ground-breaking discovery, but now it turns into astronomy



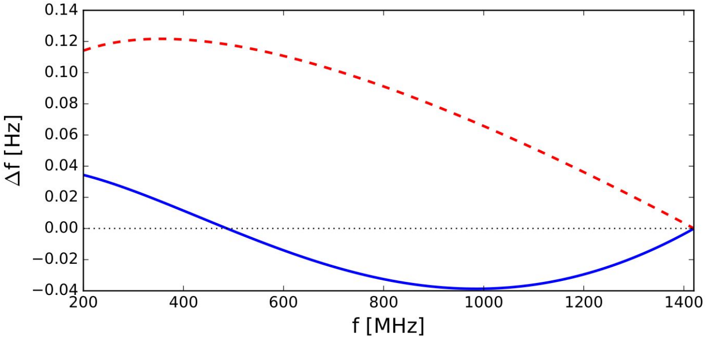
High Precision Frontier

- Extreme precision in both spectroscopy and astrometry
- These measurements could open fundamentally new windows into the expansion of the universe:
  - measure the expansion of the universe directly
  - measure existence of gravitational waves
  - See dark matter streams moving
- Most of these efforts is R&D and there is a general consensus that they should be developed further



D.Gottesman et al, PRL 109, 070503 (2012)

quantum assisted interferometry



redshift drift over 5 years: LCDM (blue) vs EdS (red dashed)

CLPS - Commercial Lunar Payload Services

- renewed push from above that NASA/DOE should collaborate
- advent of SpaceX taught NASA that a lot of money can be saved with commercial providers
- a similar program is developed to support Artemis program
- actively looking for payloads
- this is a cheap way to put HEP experiments on the Moon if you can use that:
    - low frequency radio astronomy
    - 0.1-7Hz gravitational waves
    - dark matter search

LuSEE-Night is scheduled to land on the far side of the moon in January 2026 by the Firefly aerospace

Conclusions

- Cosmology is moving in the same directions as experiments HEP:
  - experiments are more expensive, take longer to happen and increasingly incremental
- Standard cosmological model works at percent level:
  - there are tensions, but none really promising
- A new generation of experiments is upcoming to further test the model
- focus is moving from Dark Energy further into Inflationary theory