CF1 Meeting: DD Experiments at low mass Part 2 - Oct 2, noon - 1:30 CDT

56 participants at 12:34 CDT

Talk 1: Kathryn Zurek - New Ideas in Dark Matter Detection
(Overview of Superconductors, SemiConductors and Deflection Techniques)

Asked to give a summary of new ideas in light dark matter direct detection - new ideas are now a very long list, will focus on specific techniques asked about
Focus on meV-1 GeV window
Many hidden-sector ideas populating this theory space
We've had an enormous push to detect DM interacting via the weak force or the Higgs boson; these experiments have been very tuned on the WIMP, the question is what ideas we need to go to lower mass
Looking for hidden-sector DM in direct detection is just as motivated as looking for the WIMP, based on the abundance
WIMP idea: both abundance and interactions related to annihilation, sets a natural mass scale around the TeV scale
Same reasoning applies when you go below the weak scale; you can lower the mass scale and the coupling constant and equally well have the abundance set by interactions with the Standard Model
Gives clear targets for direct detection experiments, not a shot in the dark, helpful when designing these experiments
Showed theoretical target plots for two well-motivated models, asymmetric DM and freeze-in, which can be probed by proposed experiments
There's a broad range of proposals, can't cover all of them
Going to highlight the ideas that broadly cover this space

-Electron excitation in semiconductors - most mature technology that's moving forward in R&D, currently some results
-At lower masses, can look for phonons - collective excitations of ions or atoms - very generic, first proposed in the context of superfluid helium but we'll talk about them in the context of other materials. When you create these phonon excitations there are multiple ways to detect them - superconducting detectors, nanowires, microwave kinetic inductance devices.
-Materials with small gap electrons - superconductors, graphene
-Different and complementary to previous studies, which look for dark-matter-induced excitations - "direct deflection"

Looking at electron excitations lets you go down to 1 MeV, below the MeV scale need to look at collective excitations down to keV, then can buy another 6 orders of magnitude looking at absorption rather than scattering

Nuclear recoil worked well when the DM mass was kinematically well-matched to the nuclei
Can improve energy reach by looking at lighter targets
Semiconductors have smaller energy gaps, allow reduction of energy threshold again

Silicon semiconductors work for direct detection down to MeV, works by excitation from the valence band to the conduction band
SENSEI is a funded experiment, moving forward, it can reach significant parts of well-motivated theory space
SuperCDMS is also doing quite a lot of work in this area with single electron excitations and a bias voltage of 100V. Proto SENSEI is also moving forward.
All of this is going to depend not just on building up mass, but also on reducing dark counts in the experiments
In order to be able to punch down in the mass space and get to other dark candidates, will need to reduce dark counts, that is the focus of the experimental push in addition to increasing mass

Once you drop below MeV the wavelength associated with the momentum transfer becomes longer than the interparticle spacing, can excite phonons
This is a general idea, can be applied to many materials
First examined in the context of superfluid helium, superconductors/semiconductors, then polar materials
Polar materials have oscillating dipoles that give large coupling to photons
Optical modes are gapped
Generic semiconductors don't have optical modes but have acoustic photons, would be good to reach DM that has coupling to nucleons
Broad statement - details depend on the collective modes and the DM couplings
If you pull out a typical material, e.g. sapphire - polar material, has electrons with eV-type gaps, semiconductor - the phonon modes in this material start to open up around 100 meV, lots of modes, 10 ions in a unit cell => 30 collective modes. These modes can oscillate in phase or out of phase -> gapped modes, particularly good for dark matter couplings. Speed of sound in materials is well below DM velocity - for good coupling of acoustic modes want a material with high speed of sound, or alternatively optical modes / gapped modes. Dark photons can couple to oscillating dipoles.
You want to know what material should be used - we studied a large number of them, including some already being used (see slides for list).
We can compare the reach of these different materials for light dark matter - it does matter what kind of polar material you have, with a single target you can pick up both the electron excitation and the collective excitation
Silicon oxide is a particularly good one because of very strong oscillating dipoles
Sapphire is another example, strongly directional
Looking now at nucleon couplings, diamond has an excellent threshold - if you are interested in very light dark matter, very hard minerals have an advantage due to high sound speed
At higher masses, speed of sound drops out, universality between these materials
Common R&D path - sensor can be coupled to multiple different targets

In the interests of time, skipping small gap electron materials, but will highlight graphene
Graphene due to its structure has very small-gap electrons
Downside: 2d material, hard to get a large amount of it
Recently: proposal to use graphene Josephson junctions, don't need to eject electron and can look for much smaller energy deposition, very low threshold
No shielding in this material, similar to polar materials, can get excellent reach with modest amounts of target material

There is 3D graphene - Dirac materials - where it could be possible to build up more target material, but some questions remain

Before I close, want to put up slide on idea of direct deflection
Different from all other ideas discussed
Not detecting single DM particles
Take the fact that if DM is effectively millicharged, interacts with SM via very light dark photon (wavelength > whatever's doing the deflecting), then you can put it through an oscillating electric field that deflects + and - charged DM in different directions, have a detector with a LC circuit similar to DM radio
Complementary - not reading out single excitations but using wave properties
Strong reach at low masses, complementary to electron excitation and phonon excitation

Haven't been exhaustive given limited time
Theoretical ideas are pretty well-established and quite simple
From my perspective, on experimental side we need multi-pronged approach, explore which approaches based on these broad principles are viable

Talk 2: Matt Pyle
Shared Athermal Phonon Detector Challenges

Examining common challenges that athermal phonon detectors will face - going to highlight shared problems, not those specific to any technology
Matches arrangement of LOIs in IF frontier (IF1 specifically)

Many detectors have been proposed that use athermal phonon detection tech
Original CDMS, CDMS-HVeV
Gallium arsenide
Optical haloscopes
...
Set of experiments looking for coherent neutrino scattering use similar technology

Set of experiments looking at different mass ranges and different couplings
What do they have in common?
Focus on two shown in orange
SPICE - sensitive to nuclear recoils at the high end, recoil energy scale goes as mass^2 of DM, drops rapidly at low masses
Automatically see why phonon sensors become very powerful, at mass scales ~100 MeV, stop producing charge
Charge and photon detectors won't be able to see these interactions, need to go to phonon excitations
Go to even lower masses, get into coherent modes, need to look for coherent vibrational excitations - need a phonon detector

Vibrational and nuclear recoil interactions are well motivated

Less clear - more competition - when looking for electronic recoils or photons. Why would one want to use a phonon detector in these cases? SuperCDMS HVeV is pushing this.
Amazing competition here - silicon CCDs by SENSEI and DAMIC are much more sensitive than HVeV right now, so why should we go down that path? One argument - scales better
Second argument: timing rejection, difficult to get in a CCD-like setup
Third argument: for inelastic electron recoils, SuperCDMS HVeV puts voltage across crystal, electron-hole pair is drifted, convert energy into photons. Measure electrostatic potential energy.
Look at backgrounds: you can see 1e, 2e, 3e peaks, you can distinguish between electron and nuclear recoil via quantization shown
Also works for things that occur on side wall - surfaces are the problem, naturally get rid of these surfaces as leakage off the side wall is not in signal area
Consider tritium background - unclear what is initial and final state of He3 atom that's left in the lattice, if it's neutral or if it's charged. If the state varies then this contribution will also not be quantized.
We can go a step further - with improved phonon sensitivity, can separate even the charge leakage (currently limiting sensitivity of HVeV) from inelastic electron recoils

See slide for summary of energy sensitivities that one needs for various experiments
SPICE is most difficult to achieve
What will we need to do this?
For single-phonon excitations, need a dilution fridge
Use some kind of superconducting technology - will not distinguish between MKIDS, transition edge sensors, etc
Athermal phonon is produced, bounces around, is eventually absorbed and breaks a Cooper pair, then is absorbed by the [qubit or TS??]
If you keep bouncing the phonon for longer then you can increase sensitivity, sensitivity of TS scales as sqrt(volume)*Tc^3
Big problem is shared by all these experiments is thermalization on the surface
In the 1980s they did a bunch of studies, changed surface properties of silicon, e.g. put neon down - there is an inelastic scattering probability on that surface
Good enough for next gen but for SPICE and single-phonon sensitivity need a factor of 4 below what has been shown
Another thing all these systems share is environmental vibration noise
Will be shared no matter what the readout
We need to be able to get rid of vibrational sensitivity
Another shared problem is residual stress in the detectors which every once in a while could release a little micro-earthquake of phonon vibrations

Best performance we've achieved is in this big coherent phonon detector experiment
3-inch diameter silicon wafer 1mm thick
Achieved 4 eV resolution
Next generation of devices aiming for 100 meV energy resolution range
To go beyond that we have to lower Tc for TSs, or switch to a different technology (MKIDS, phonon-sensitive qubits)

Conclusion: athermal phonon detectors have wide applicability, to electronic interactions as well as single-vibration interactions. Significant progress over the last few years. Suggests we can get to the ultimate phonon sensor reach so long as we can keep environmental noise under control. Every experiment, even qubit-based, requires research into athermal phonon down-conversion at surfaces, EMI mitigation.

Talk 3: Rick Gaitskell and Scott Hertel
Calibration

Rick:
Our job is to present a reality check
With these DM and neutrino experiments we are trying to convince people we really can see the signals we're setting out to see
In this piece we'll focus on the NR element of signal deposition
We can talk convincingly about recoils all the way down from 100s of keV into eV regime - quite some significant progress
Solar neutrinos may become a calibration source, but first need to see it unambiguously

Going to cover the old workhorse - proton-lithium accelerator dedicated source
Can go over to portable DD/DT sources, reflection of neutron sources
Time-of-flight techniques become highly relevant as we go to the low-mass regime, relevant to effects Kathryn talked about
Will also mention using high-energy gammas to scatter off nuclei

[description of figure on slide]

Now able to cover this regime all the way from 100+ keV down into the eV scale (x-axis is an indication of the COM angle for a particular target, have used scattering angles as a very effective way of demonstrating that you understand how much energy should've been deposited on an event-by-event basis)

Proton-lithium accelerator is 2.2 MeV, have to go to it (not portable)
Continues to be a successful way of calibrating detectors, can't really go below about 0.5 MeV in terms of neutrons there
There are very successful portable DT (deuterium-lithium) and DD (deuterium-deuterium?) neutron generators
Unambiguously answer what is signal efficiency in entire regime, can go down to sub-MeV regime
Bouncing DD neutrons off deuterium-loaded target, can take away 8/9 of the energy, leave 1/9
Have a 350 keV portable source, tagged
Working on bouncing off hydrogen targets to create neutrons in a range 1-100 keV, each individual neutron is tagged so can do time-of-flight
Can use photo-neutron effect - gamma scattering from beryllium nucleus, can eject a neutron with energy fixed by gamma energy. Has already been demonstrated, very portable, but there's a lot of gamma activity coming out of it - have to figure out successful strategies for eliminating those gammas, works well for detectors that are insensitive to gammas, else you need heavy shielding.

Scott:
Neutron filters made up of nucleus where nucleus has a notch in scattering xsec, acts like a filter, only neutrons with a long mean free path escape the material via notch in xsec
Typically sources use a high neutron flux for starting source, e.g. nuclear reactor
R&D focus: how can we use these filtering techniques on smaller scales, lower initial neutron flux
One possibility: use a DD or DT generator. Another is to use a photo-neutron source. Some pros and cons here - the generator can be pulsed and turned on/off which is nice. Photo-neutron source = no higher-energy neutrons. Special case where photo-neutron source matches a notch, lets out neutrons in a monoenergetic way as the initial condition.

That's our lowest-energy monoenergetic neutron source. Below keV, very hard to have monoenergetic neutron source. Spallation neutron sources can be used here - time-of-flight techniques eliminate need for monoenergetic source.

Really low-energy neutron sources: need to detect neutron scattering angle using capture rather than scattering, we're entering a transition in calibration techniques now, from scattering-based to capture-based detectors. R&D task in and of itself - need large areas instrumented with high efficiency

Last technique: use gammas, coherent gamma-ray nuclear scattering, can be useful at lowest energies
Two regimes to separate the needed scatters from dominant background: lack of ER response, precisely tagged gamma scattering angle

Snowmass LOI on this topic
Broad array of existing methods we tried to advertise here
Need to keep the technology up to pace as we push thresholds lower and lower - unfortunate if we have meV threshold but nothing to calibrate it with
Long term need to better define requirements for each of these detectors, how can they deal with higher-energy neutron backgrounds and gamma backgrounds, how pure do their sources need to be, etc.

Matt Holister & Tali Figueroa
Common Facilities: NEXUS and the National mK Facility¶

Tali: talk about NEXUS and then hand it off to Matt
NEXUS is a facility at Fermilab, Northwestern Experimental Underground Site
107m underground, in NUMI tunnel
Inside clean room, have vibration-isolated dilution refrigerator
No hadronic showers from muons because underground
Putting up a lead shield around the system
Equipping the facility with optical fibers and various calibration sources

Ticks all of the points Matt was talking about when it comes to prototyping, testing, running searches for light-mass-DM detectors
We want to do prototyping and calibration so we have a DD generator set up with a backing array we will install in the future; DD generator delivered and tested this year
See slide for setup
Experimental space: 500mm tall, 300mm in diameter
8 DC SQUID channels, expanding to 12
10 RF channels being installed by end of year
Installing a new mounting plate for MKID and qubit studies
Magnetic shield to be installed by end of year
In terms of lead shield, we are in the process of building this shield right now, doing first tests this month
Facility is open to different collaborations; currently doing a lot of SuperCDMS HVeV work; doing QIS work as part of the Quantum Science Center; with Caltech doing MKID dark matter detector development; doing development for RICOCHET detectors

Matt:
Building off what Tali was describing there, want to discuss idea he has been talking about with various groups over the past few years
National mK User Facility
Idea: try to establish a facility with emphasis on mK testing facilities for various fields, focal point for mK engineering and workforce development
Goal: try to democratize R&D process in cryogenics
Relatively high bar for entry into R&D in general, especially in cryogenics / mK regime
Equipment is very expensive, hard for small research groups or PIs
Technically quite challenging - behavior of materials and engineered structures can be quite curious
Issue of doing proof-of-principle tests - fine to have a nice idea and write a proposal, but much stronger if you could demonstrate the idea works on a small scale
Obviously would require funding - fee-based model might be the most viable approach
Cost of access to the facility would be on a sliding scale depending on who the customer is, possibly get industry customers to subsidize academic users
Quantum Economic Development Consortium, set up to drive "quantum ecosystem", identified a similar facility as a priority, especially from perspective of workforce development - engineering and training in this field is extremely limited

Broke this down into three thrusts:
Thrust 1: test facilities
Originally conceived as a way to provide test facilities for superconducting detectors and electronics, but could extend this
Could add underground facilities, like NEXUS

Thrust 2: engineering
Lots of engineering in low-temperature regime is quite challenging, very specialized
Such a center could serve as a locus for engineering knowledge and information

Probably have all made use of NIST materials database, but hasn't been actively maintained in 2 decades - very out of date
Lots of new materials we could be using
Currently experiments are often restricted to using a very limited set of materials
Such a center could provide a venue to approach engineering and materials at low T in a much more systematic way

Thrust 3: workforce development
Training new generation of cryogenics specialists is very challenging - needs hands-on experience on rare and expensive equipment
Facility could help fill this gap, provide access for students to run experiments or be mentored by experts in these areas
As part of National Quantum Center Development , smaller-scale program being planned for Northwestern itself - at least one dilution fridge would be available to train undergrad and postgrad students

Jodi: there was a comment in the chat asking about recoil from gamma emission following thermal capture. Any comments on that?

Kim Palladino: fascinating talks. Lots to discuss on technical side. Crux of complications in CF1 right now: what is this subfield going to look like in 10 years? How many collaborations with different targets, how many people in those collaborations? Are we setting ourselves up for consolidation and downselect like happened in the higher-mass WIMP area, or are we trying to do something different?

Yoni Kahn: you need smaller detector masses to be useful in this mass range, ton of physics mileage from quite small detectors, hopefully not as much pressure to downselect as if experiments are all multi-ton.

Hugh: true now, but maybe not true in 10 years once first round of experiments has run.

Yoni: question of where your theory targets are - well-covered by kg-year exposures. Not true at high masses. Although of course theory targets can move.

Tali: it's a good point that you can do a lot with a small experiment, in the short term. But later on then we will need facilities like the one Matt discussed, if we don't see DM and we need to dig deeper down into the cross section, will need more attention to background reduction, multiple targets, etc.

Andrew Sonnenschein: About workforce development. With multiple BNs of dollars dumped into low temperature physics for quantum centers, it's going to be impossible to hire cryogenic engineers. All our students and postdocs are accepting jobs with quantum companies. One positive aspect of QC program is attention to workforce development. What are prospects for developing formal University programs in cryo engineering to increase supply to build and operate experiments. I don't know if you can get a degree in this in the US.

Matt: Can't explicitly. There are some places that allow you to focus to an extent on aspects, but you're getting a general engineering degree To speak to your first point, lots of people are getting recruited into industry as soon as they graduate, definitely is an issue - try to address e.g. with Northwestern facility, the concern I have is that it's just going to act as a pipeline into industry and won't come back to fundamental science
There are plans completely independent of this that we've been working on at Fermilab to have a masters-level course in low-temperature cryogenics covering both accelerators and mK technologies, in collaboration with Stonybrook; we wrote some course syllabi for it but nothing much has happened yet. Talk of doing something similar at Northwestern.

Hugh: do you know if any of that is happening in Snowmass community development sections?

Matt: not to my knowledge.

Hugh: calibration talk was excellent, very useful, focused on nuclear recoil stuff. Lots of low-mass detectors are focusing on other kinds of recoils/processes - what are the calibration needs for those? How different are they in scale/scope?

Scott: we spoke to our expertise - can anyone working on these other experiments speak to this question? In general - if you're looking for a quantum as your signature, you have to produce that quantum for calibration, can be easier than nuclear recoils for e.g. single electrons

Yoni: not sure that's 100% true - consider Migdal effect, different matrix element depending on what you're scattering on [I missed a lot of this], can calibrate Migdal effect pretty well based on photon-nucleon interactions [??] but not necessarily single-electron recoils

Priscilla: Kim's question still stands and we need to be considering it as we write our final reports - keep it in mind
A couple of things come to mind - last time we discussed complementarity, but that didn't end up preventing the downselect
If we concentrate more on some initiatives that have been started for collaborative research, e.g. NEXUS, user facility for neutron calibrations, we might become a more cohesive field , wrest those decisions away from the agencies, have them done more as a group

Jodi: I'll take that as an opportunity to show where we are sort of as conveners. Where we see CF1 going forward in near future. We're very hopeful that out of this process we get a statement that DM is top priority of field. This is a message we want to get out of process. It shows up in all the frontiers right now. We want to update our understanding of the complementarity that includes the developments since last snowmass, both in CF1 and across frontiers. THere's a session 150 that is a start for that. Each of the breakout sessions will report back to that session to summarize what they are talking about, what their concerns about, and what is the next step. Aimed at bigger complementarity picture.

Later in 2021, bigger workshop, may have some pre-workshop workshops. At CPM, starting to converge on number and format of summary white papers to convey the physics of particle dark matter. WE got 147 LOIs. Encourage people to work together to get down to a dozen summary white papers. We as conveners would write a report for the entire community using those as references and supporting documentation. These are 8 sessions that CF1 is involved in - so our approximation of it. Example: should we redefine what a WIMP is? What are dark sectors? We might benefit from having a common vocabulary.
The schedule is hard to read, so we've been trying to send out emails what we are involved in to make sure our communities are represented. Because there are so many, some run in parallel. Here's a table with days and time slots.

Dan McKinsey: Thoughts on what intermediate white papers might be. ~10 - do you know what titles might be.

Tracy: We would like to know your ideas.

Jodi: it's been a lot in a short period of time. We're trying to throw out a goal.

Tracy: Some of the guidance we've been getting is variable, especially over the last week. So some of what we're saying could change in the future. But structure of whatever contributed papers you want, but then there will be topical group summaries with white papers as references. Probably worth it to make sure you're represented in those summary white papers. This is just my opinion. We're getting changing guidance, but hopefully this should converge.

Tracy and Jodi - more detail about how process has changed, things are still in flux, this is our best guess.

Jodi: I suspect as the next month progresses it will be come clearer how these might end up working out.

Tracy: aNd this will be a topic at CPM. [Lots of good advice about it]

Kim: Feels like there's another dimension too. Everyone in CF and CF1 in particular are excited about the number of LOIs and hte number of people working on it. Is there a way to preserve some of that competitiveness with other frontiers while also not weakening us by having so many papers that no one can decide what to do.

Jodi: number of authors is also an indication of interest

Kim: but this isn't clear whether it's a small number of big collaborations or genuinely a very large array of ideas

Dan M: Focus on the science as usual. Exciting science, organzie via what models can be tested. If it just looks like a laundry list, you get in trouble.

Jodi: Agreed. We've been trying to group this by science in some way, we went with candidates and mass ranges, and map them that way. I agree Dan that the physics is what we want to go after to show we have a good portfolio of options to go after those goals and that we don't want just one technique. There is use in having more than one experiment going after a result.

Andrew: The physics is the most important thing. But the sheer number of new techniques in this field really dwarfs what's going on in NF or EF. Could make a quantitative statement, and that should be a talking point for people in this field. New technologies from condensed matter or quantum that's driving interest. And we really do have a quantitative advantage in that sense

Jodi: I agree.

Jodi: Ok, we're at the hour. We will probably take a break on Friday meetings after CPM to decompress, but we'll be in touch with slack and email.

Hugh: Thanks to all speakers. We have recordings and detailed notes of every session, so hopefully that can be a reference of what was discussed.

Tracy: Thanks also.

Jodi: Speakers for today, please post your slides.