Pathways to Discovering DM with Cosmic Probes

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*all inaccuracies and omissions mine!
Very low mass dark matter suppresses structure formation.

~90 orders of magnitude for the possible dark matter mass:

$10^{-22}$ eV to $10^{68}$ eV

Bounded by astrophysical constraints.
Here I will discuss three example cases — two focusing on complementary between cosmic and terrestrial detections, and a third case that relies primarily on cosmic probes.
Example 1:
Light thermal DM
with DM-nucleon interactions
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Interesting excess in low-threshold detectors at ~ 50 MeV.

SuperCDMS turns on low threshold detectors in 2024, continues to see some events here.
Currently ~60 known MW satellites, predict ~220 total MW satellites over full sky
Expect ~100 from Rubin LSST if DM is consistent with CDM on these scales [and if we are not yet at the galaxy formation cutoff]
• Interesting excess in low-threshold detectors at \( \sim 50 \text{ MeV} \).
• As SuperCDMS turns on lower threshold detectors, they continue to see events in this regime.

In 2026, the first analysis of Rubin LSST data detects only 5 new MW satellites.
Snowmass2021: Dark Matter Physics from Halo Measurements Fig 1. arXiv:2203.07354
Interacting Dark Matter

- Collisional damping due to DM–baryon scattering at early times suppresses power on small scales
- Mass of the smallest halo allowed to form corresponds to the size of the horizon when $$R_X \sim aH$$

Constraints from Dwarf Galaxies (Nadler+DES Collaboration 2021)
Lyman-alpha forest (Rogers, Dvorkin & Peiris 2022)
• Interesting excess in low-threshold detectors at ~ 50 MeV.
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In 2026, the first analysis of Rubin LSST data detects only 5 new MW satellites. → indication of either suppressed small-scale power or detection of the limit of galaxy formation

How do we tell the difference?
Small-scale structure probes

Lyman-alpha forest power spectrum

Strong gravitational lensing

Stellar streams

Stage V Spectrograph
Lyman-alpha forest, strong lensing, and stellar streams all find less substructure than CDM predicts, below the threshold of galaxy formation.

• Interesting excess in low-threshold detectors at ~ 50 MeV.
• As SuperCDMS turns on lower threshold detectors, they continue to see events in this regime.
• The first published analysis of Rubin LSST satellites only detects 5 satellites.
An analysis of neutron stars and exoplanets by JWST shows both are hotter than expected.
Neff is sensitive to DM-baryon interactions

CMB measurements can put a lower limit on the DM mass due to its impact on Neff.

By this point, several low threshold experiments have continued to see events at 50 MeV.

Design an experiment to see the peak in the velocity distribution function rather than just the tails.

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- CMB indicates a DM particle with M > 10MeV.
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• CMB indicates a DM particle with $M > 10\text{MeV}$
• Clear detection of a 50 MeV signal in SuperCDMS

Detection or absence in accelerator-based experiments (e.g. LDMX) would disentangle mass-scale from coupling of new DM-SM interaction.
Example 2:
Axion-like particles with axion-photon interactions
Gravitational wave hints of an axion-like particle

Advanced LIGO observes a continuous wave signal with a frequency 300 Hz - 15 kHz. Indicates an axion mass of $10^{-13} - 10^{-11}$ eV due to BH super radiance — a "boson cloud" around the spinning black holes.

Provides a clear indication of where to look in future cavity, NMR, and lumped element experiments.

Experimental probes of wave-like DM
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Detection made! Enables a map of the DM density and velocity in the DM halo.
Towards mapping the DM halo with an ALP

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Targeted NMR search for a $10^{-13} - 10^{-11}$ eV ALP with NMR experiments and make a detection!

Expand experiments that can target this mass range, including NMR, SRF cavity, and lumped element experiments.

Use these to map the DM halo and its annual modulation —> future synergies with astrophysical measurements and predictions of the local DM density and velocity in the Solar circle.
Example 3:

DM with self-interactions and suppressed small-scale power
DM halo profiles in SIDM

- Measurements of cluster profiles with cores provide indication of self-interactions
- Measurements of dwarf galaxy profiles also show cores

Snowmass2021: Dark Matter Physics from Halo Measurements Fig 4. arXiv:2203.07354
Suppressed small-scale power

- LSST detects 5 satellites, significantly fewer than expected.
- Strong lensing and streams see impact of dark substructures at $5 \times 10^8$ Msun.
- Missing power is observed below the scale of galaxy formation (e.g. $10^7$ Msun) by strong lensing (Rubin + JWST, ALMA), streams (Rubin+Gaia+DESI+ELTs), and Lyman-alpha forest (DESI+ELTs)
Consistent with WDM+SIDM

- Could be 10 keV DM with self-interactions

CF3 Draft Report (with Nadler, Yan et al)
Consistent with WDM+SIDM

- Could be 10 keV DM with self-interactions
- Also consistent with 10 GeV DM that is coupled to a light mediator + dark radiation, which suppressed small-scale power in a similar way.
- If profiles are measured at different mass scales, this can pin down the DM mass.
- In the latter case, there will be a signal in $N_{\text{eff}}$ as measured by the CMB (e.g. CMB-S4)
Wide range of astronomical observatories will be relevant to the next generation of DM searches!
Three examples of many possibilities!

Discussed 3 examples:

• **Thermal DM particle at \( \sim 50 \text{ MeV} \).** Signals of suppressed small-scale structure, extra heating in dense objects, and detection possible in low-threshold direct detection experiments.
  
  Cosmic probes help distinguish DM from background events, inform the mass and interaction strength, and motivate expanded direct detection and accelerator experiments.

• **Axion-like particle at \( \sim 10^{-12} \text{ eV} \).** Signal of BH super-radiance detectable in GW; detection possible in NMR and cavity experiments.
  
  Cosmic probes provide a target for the search region of terrestrial experiments; which then enable mapping the DM halo.

• **Self-interacting DM combined with suppression of small-scale power.**
  
  Cosmic probes are the primary window.

★ Extensive complementarity across CF and across frontiers. Wide range of experiments and astronomical observations are relevant to pinning down each of these cases! Very exciting discovery potential this decade.