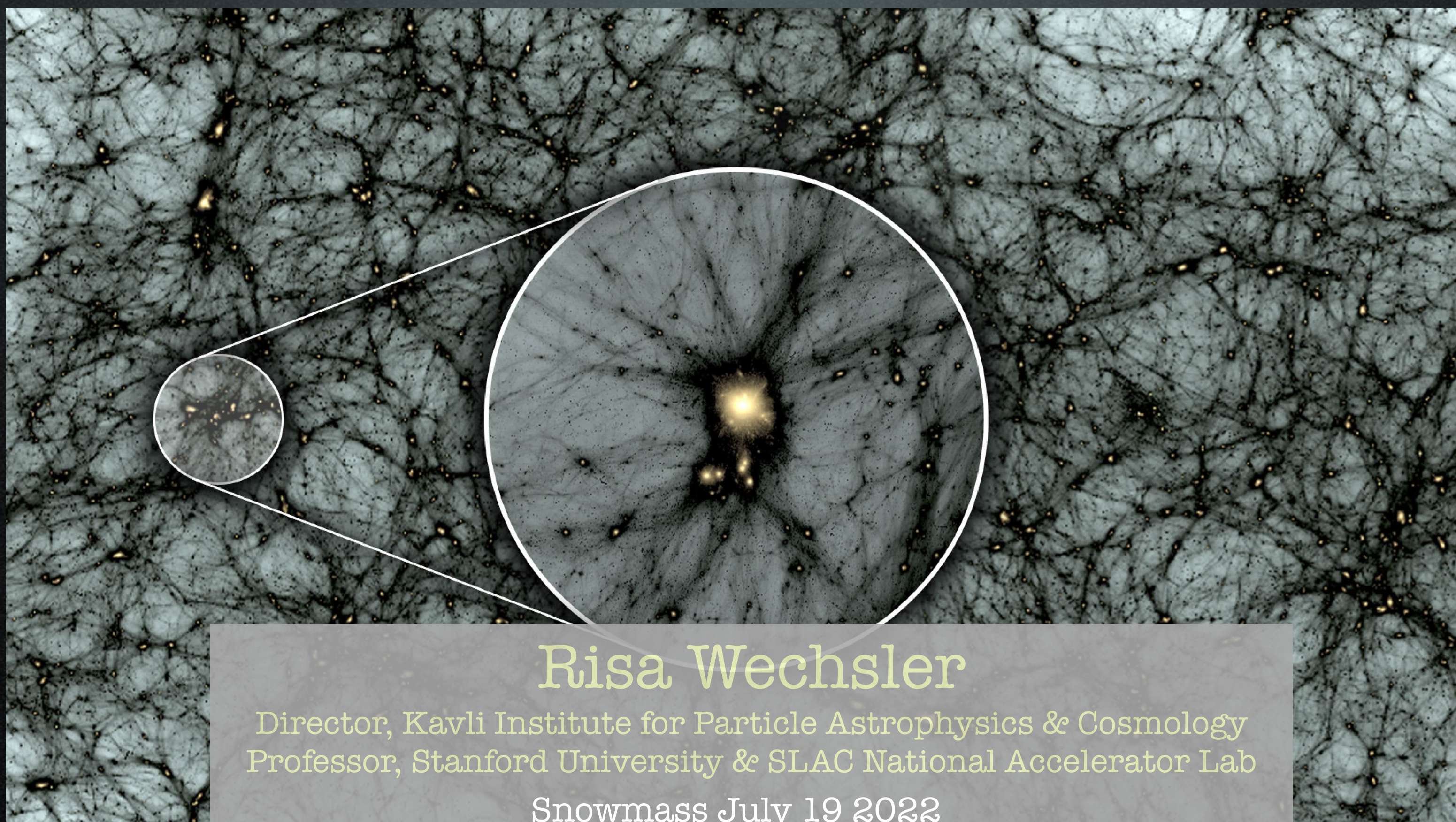
Pathways to Discovering DM with Cosmic Probes



Risa Wechsler
Director, Kavli Institute for Particle Astrophysics & Cosmology
Professor, Stanford University & SLAC National Accelerator Lab

Snowmass July 19 2022

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helpful discussion and inspiration*:

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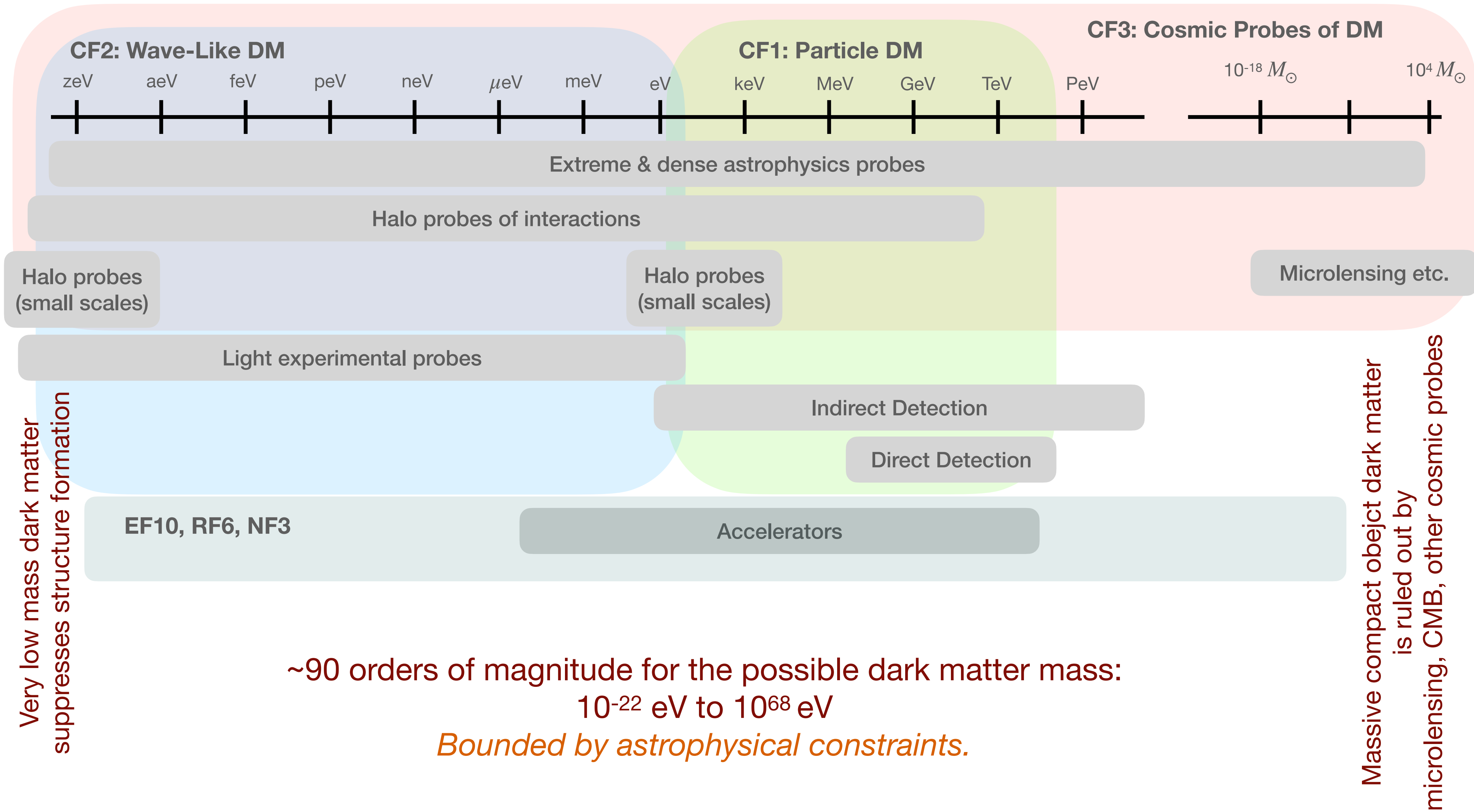
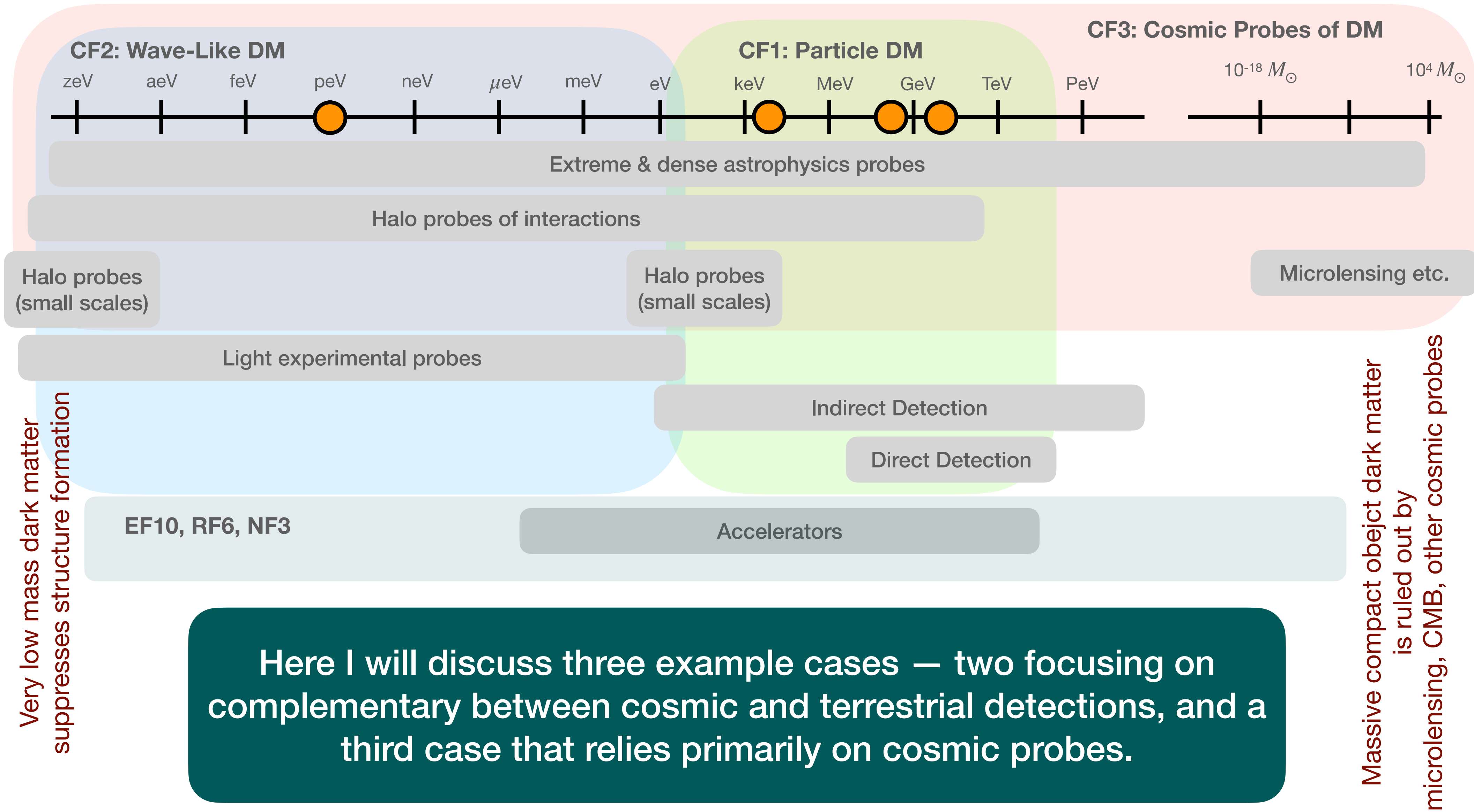
Tracy Slatyer, Tim Tait, Jed Thompson,
Natalia Toro, Lindley Winslow, Haibo Yu

*all inaccuracies and omissions mine!



CF2: Wave-Like DM
CF1: Particle DM
CF3: Cosmic Probes of DM
zeV
aeV
feV
peV
neV
μeV
meV
eV
keV
MeV
GeV
TeV
PeV
10-18 M⊙
104 M⊙
Extreme & dense astrophysics probes
Halo probes of interactions
Halo probes (small scales)
Halo probes (small scales)
Microlensing etc.
Light experimental probes
Indirect Detection
Direct Detection
EF10, RF6, NF3
Accelerators
Very low mass dark matter suppresses structure formation
Massive compact obejct dark matter is ruled out by microlensing, CMB, other cosmic probes
~90 orders of magnitude for the possible dark matter mass:
10-22 eV to 1068 eV
Bounded by astrophysical constraints.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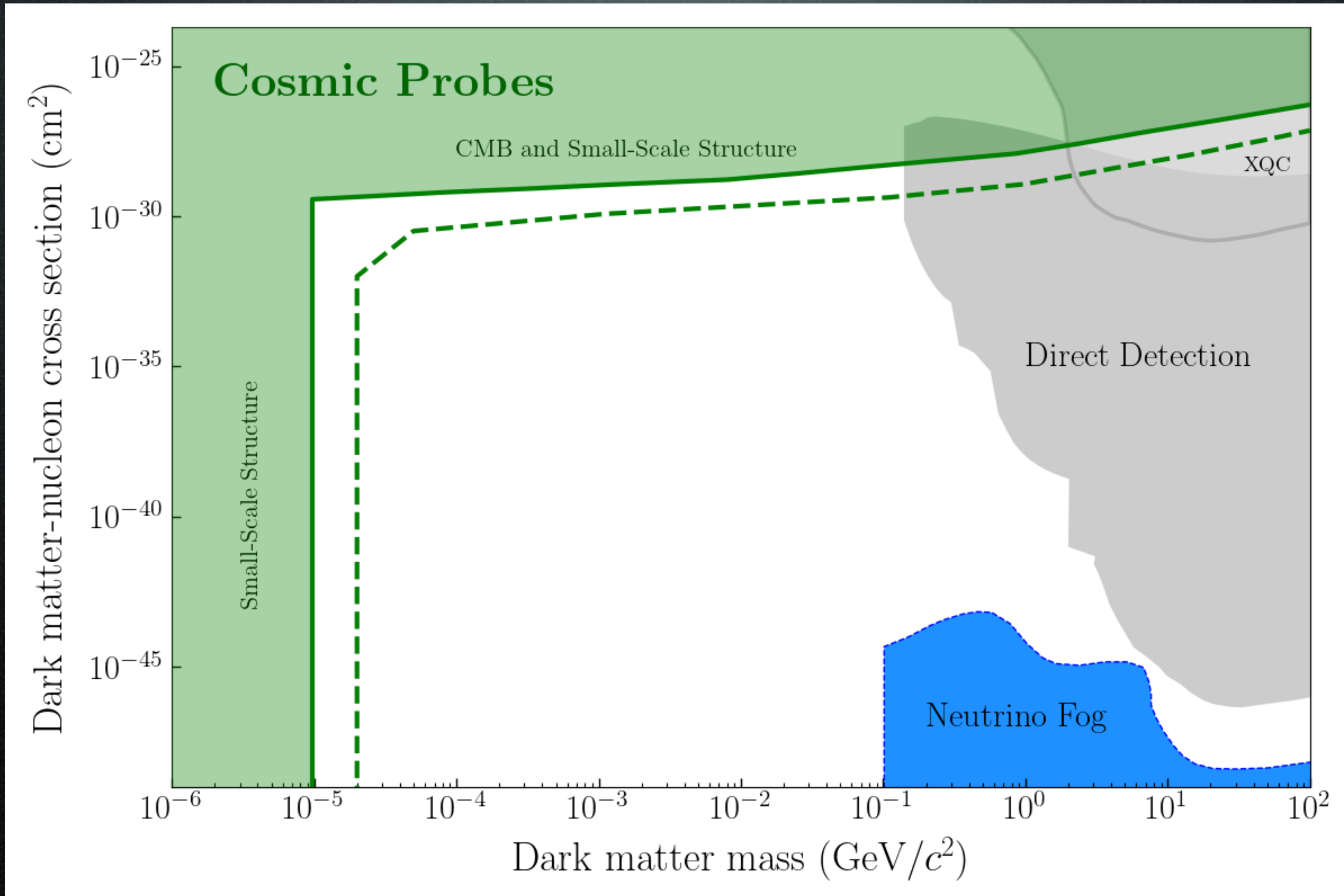
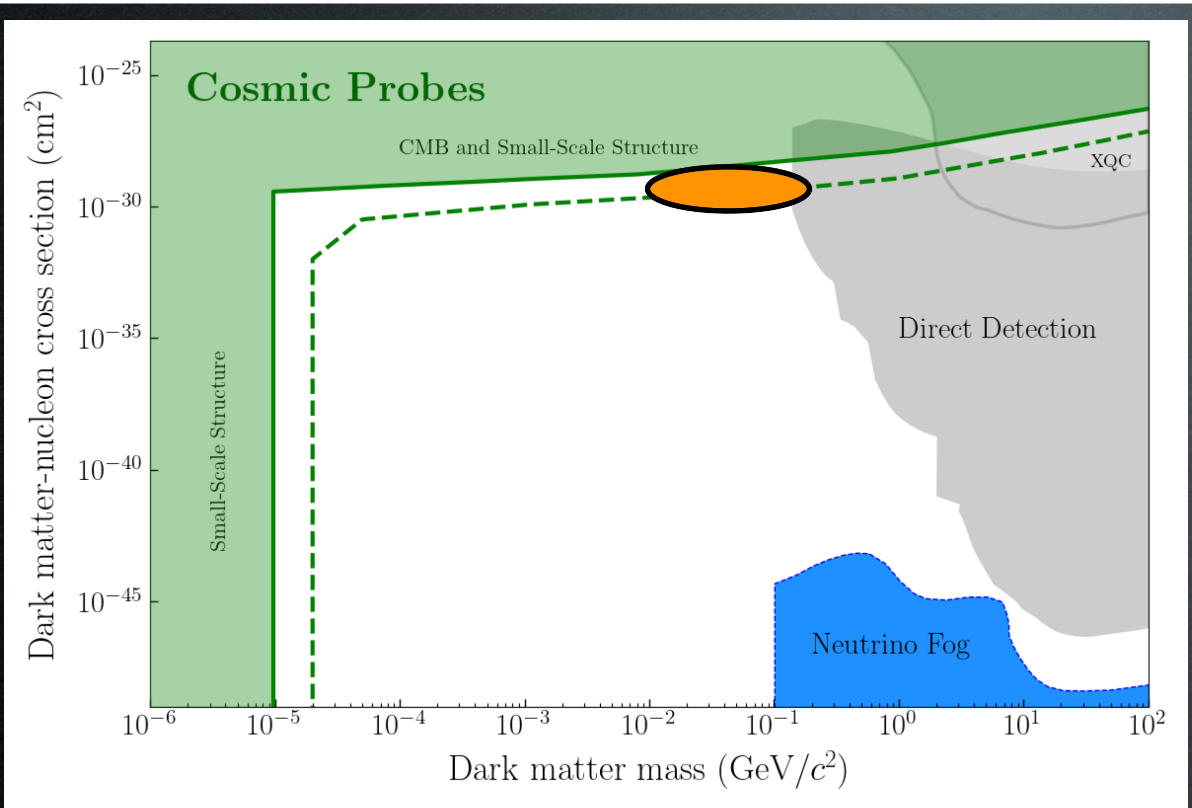
Here I will discuss three example cases — two focusing on complementary between cosmic and terrestrial detections, and a third case that relies primarily on cosmic probes.

Example 1:
Light thermal DM with DM-nucleon interactions



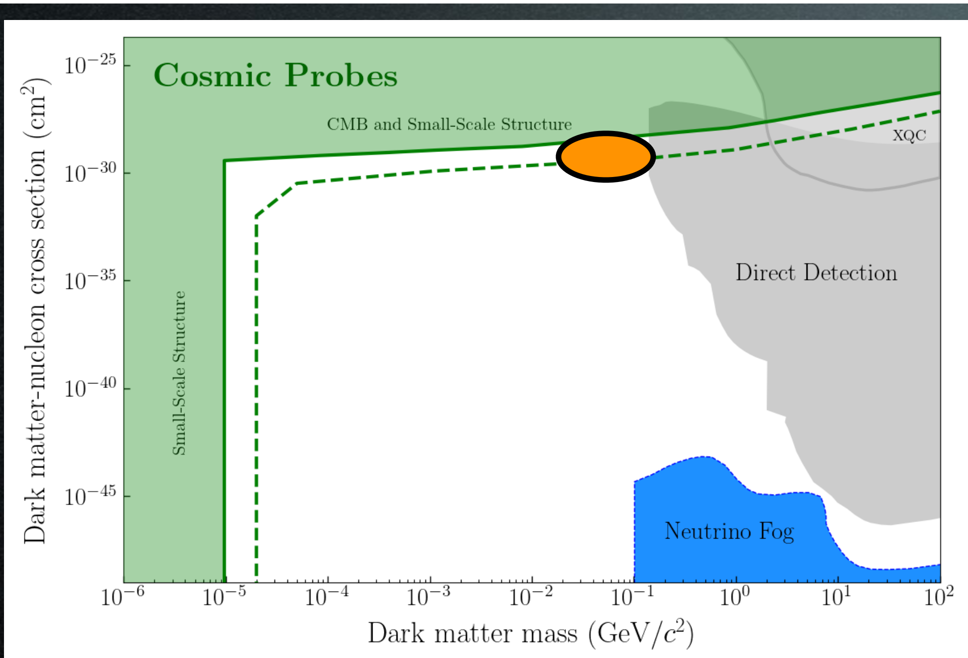
Snowmass2021 CF3 White Paper



Current interesting excess in low-threshold detectors below a few hundred eV.

Could it be dark matter? How would we confirm it?

https://arxiv.org/abs/2202.05097 EXCESS workshop



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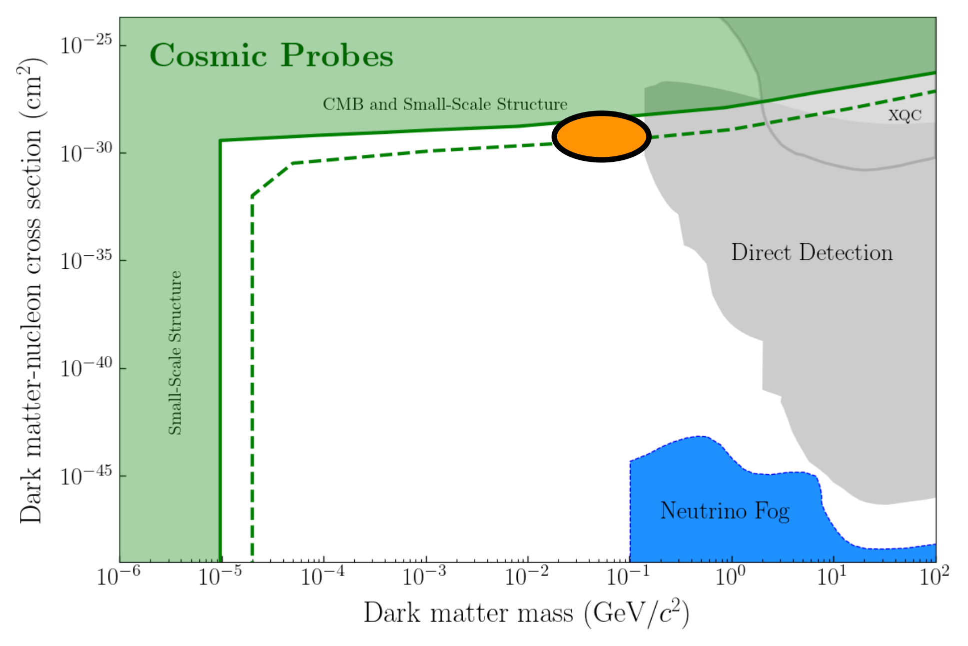
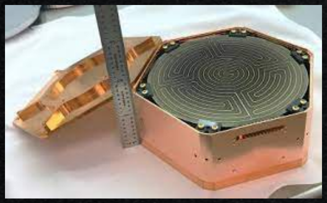


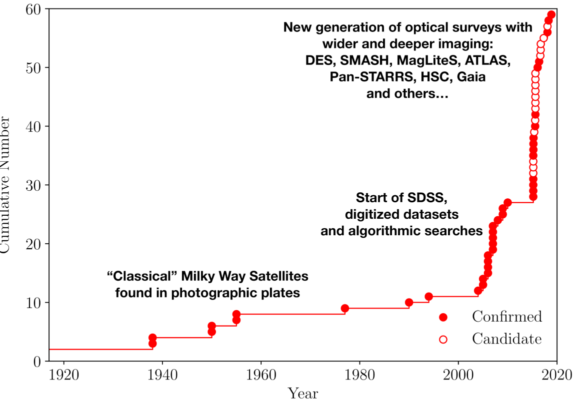
- Interesting excess in low-threshold detectors at ~ 50 MeV.

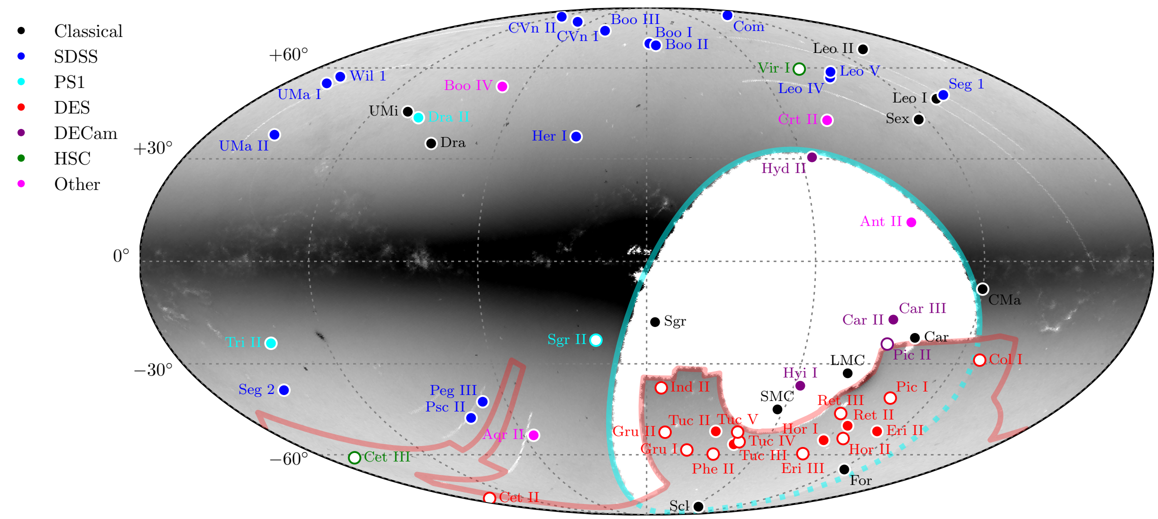


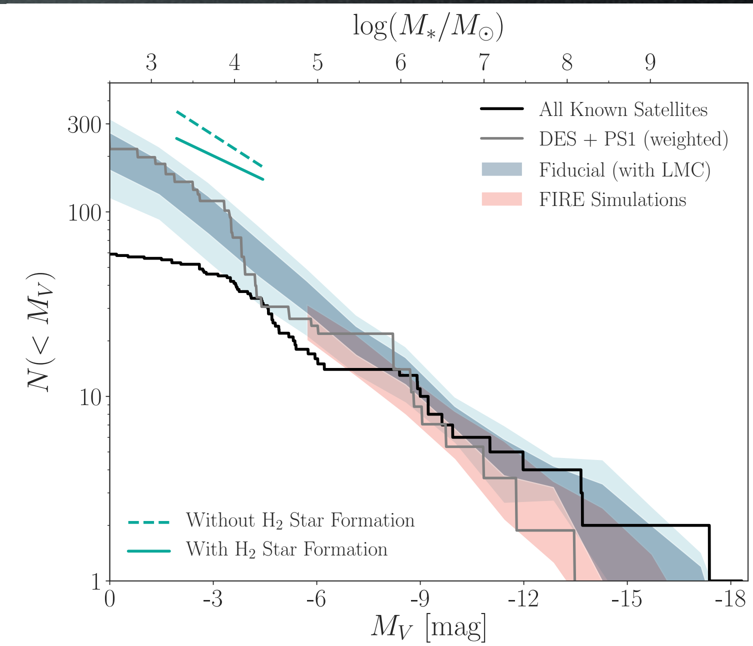
SuperCDMS turns on low threshold detectors in 2024, continues to see some events here.

Dwarf satellites

Nadler, RW+ 2020

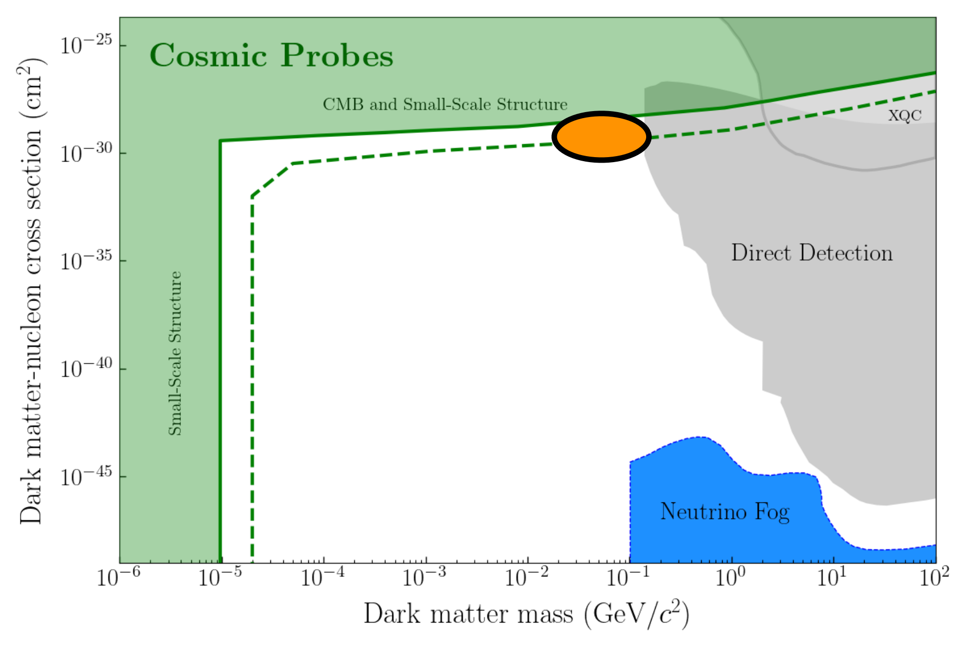






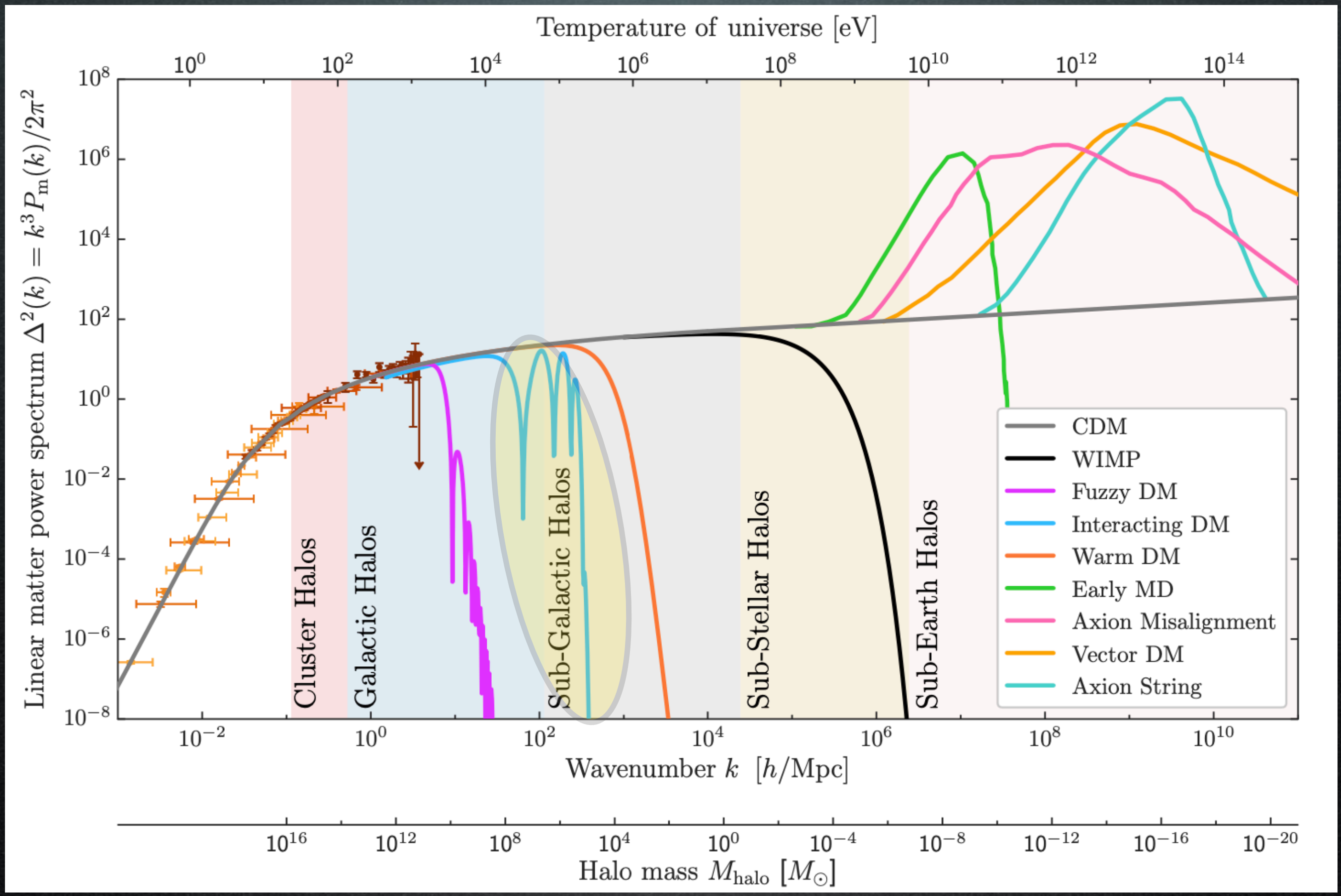
Currently ~60 known MW satellites, predict ~220 total MW satellites over full sky

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 ~ 50 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

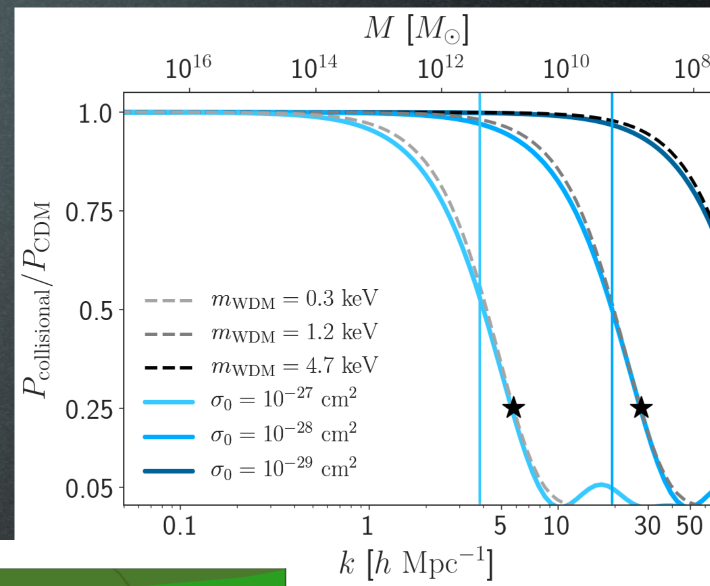
- Collisional damping due to DM–baryon scattering at early times suppresses power on small scales
- Mass of the smallest halo allowed to form corresponds to the size of the horizon when

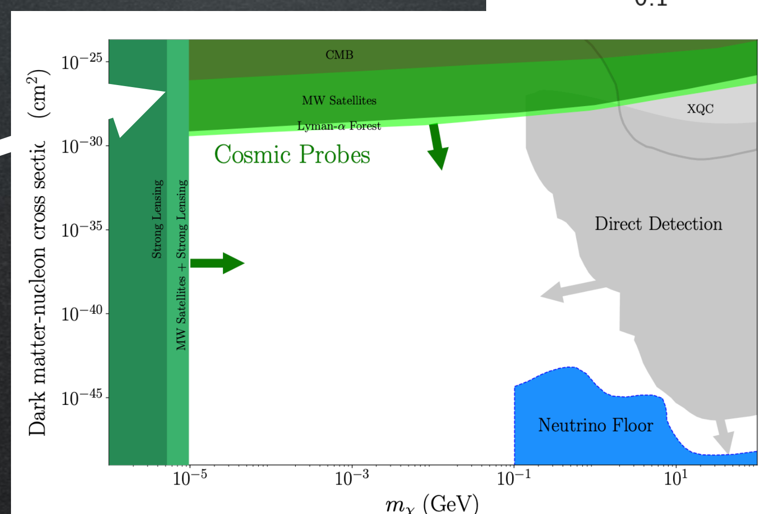
$$R_\chi \sim aH$$

Momentum transfer rate

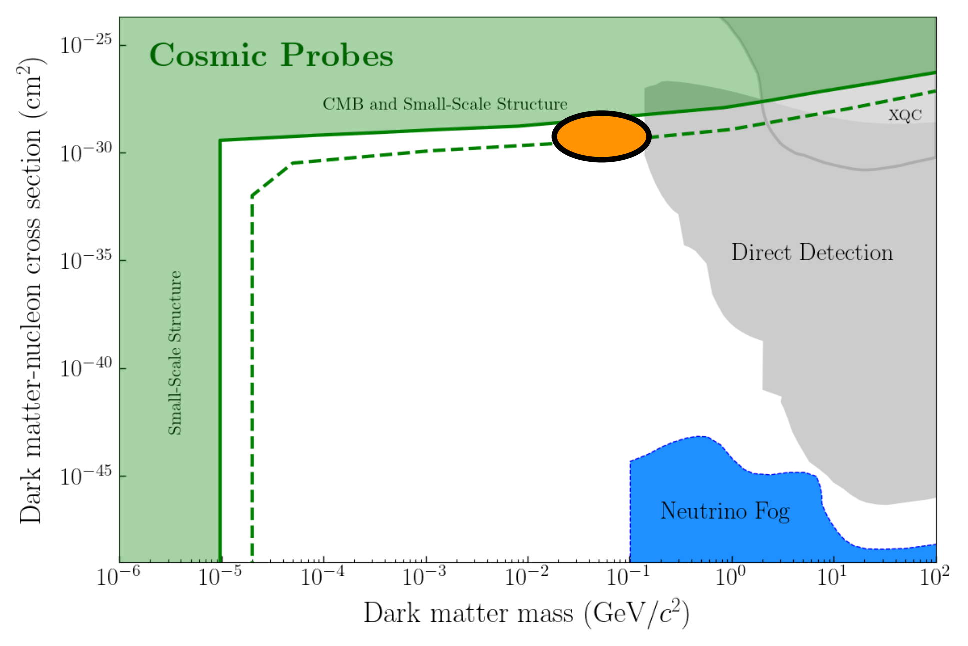
Hubble rate

Suppression of power maps to WDM:
Nadler, Gluscevic, Boddy, RW, 2019





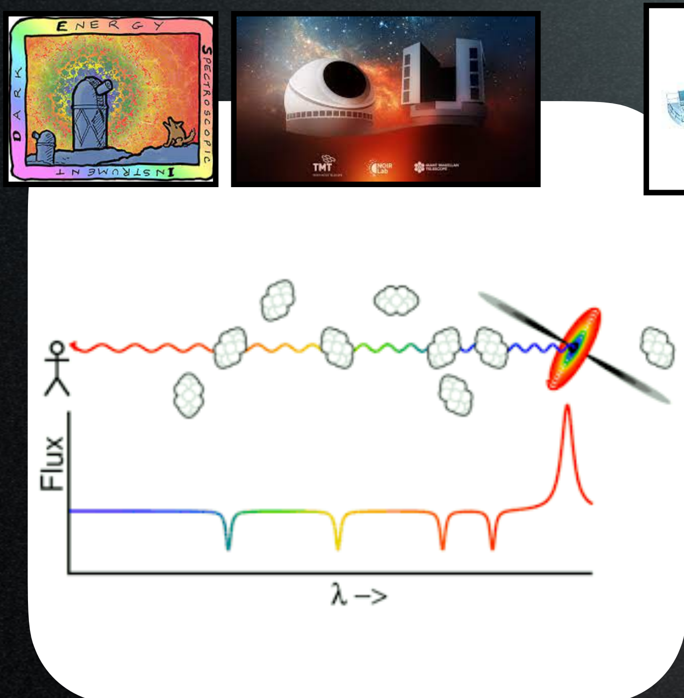
Constraints from Dwarf Galaxies
(Nadler+DES Collaboration 2021)
Lyman-alpha forest (Rogers, Dvorkin & Peiris 2022)



- Interesting excess in low-threshold detectors at ~ 50 MeV.
- As SuperCDMS turns on lower threshold detectors, they continue to see events in this regime.

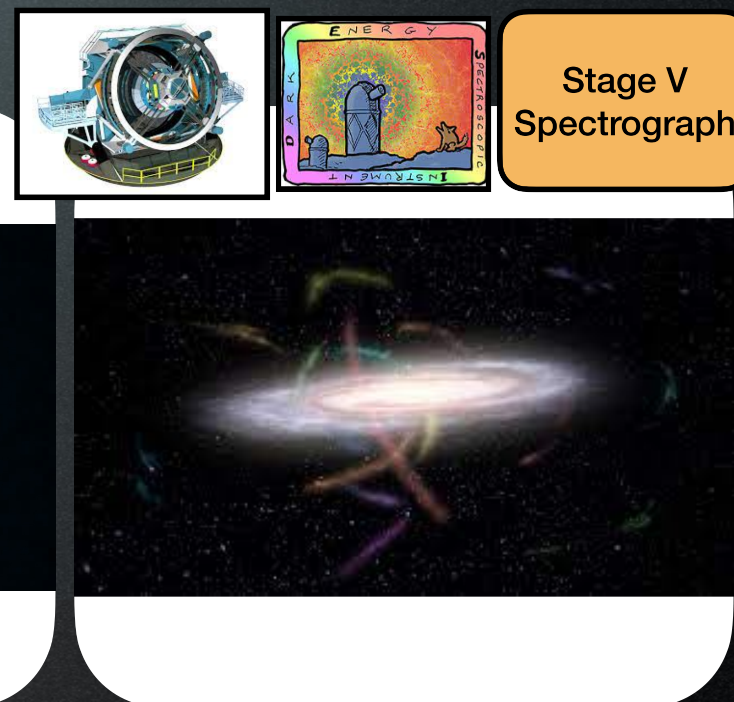
In 2026, the first analysis of Rubin LSST data detects only 5 new MW satellites.
—> indication of either suppressed small-scale power
or detection of the limit of galaxy formation
How do we tell the difference?

Small-scale structure probes

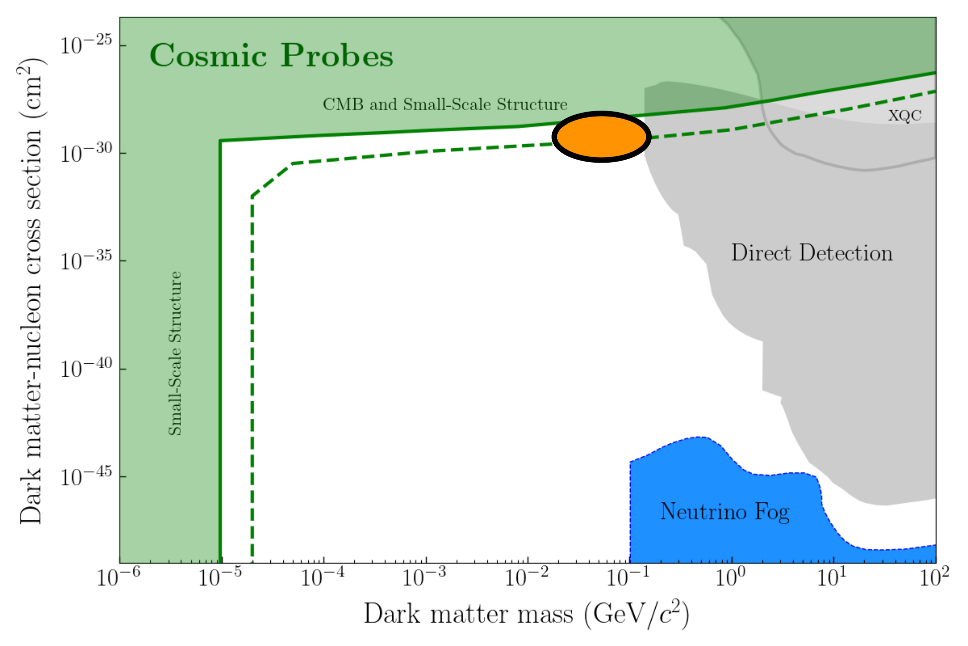


Lyman-alpha forest power spectrum

Strong gravitational lensing



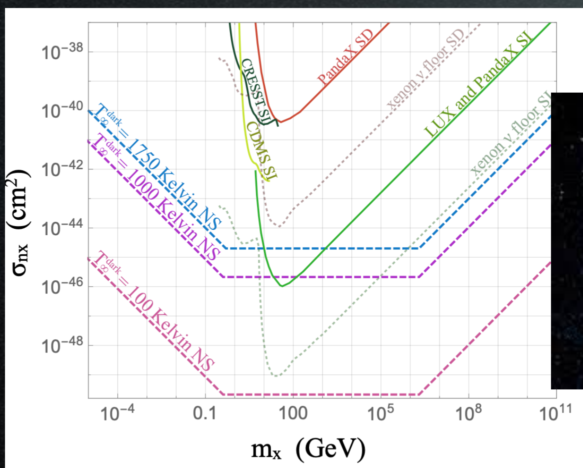
Stellar streams



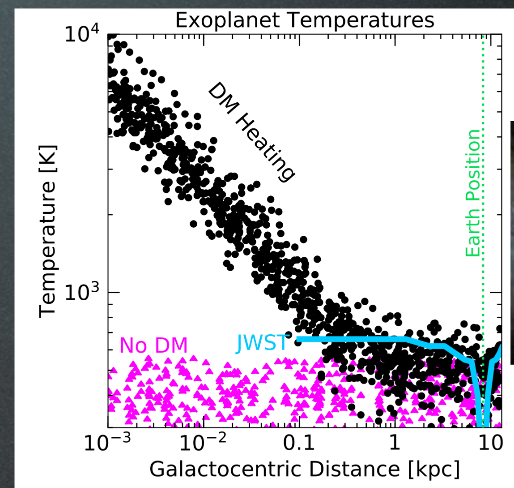
- Interesting excess in low-threshold detectors at ~ 50 MeV.
- As SuperCDMS turns on lower threshold detectors, they continue to see events in this regime.
- The first published analysis of Rubin LSST satellites only detects 5 satellites.

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

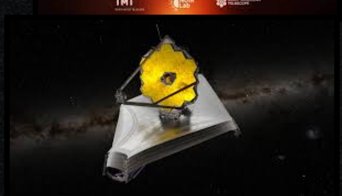
DM heating



https://arxiv.org/abs/1704.01577

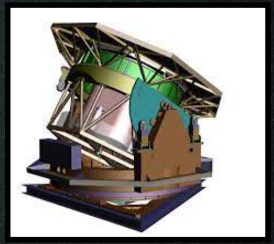


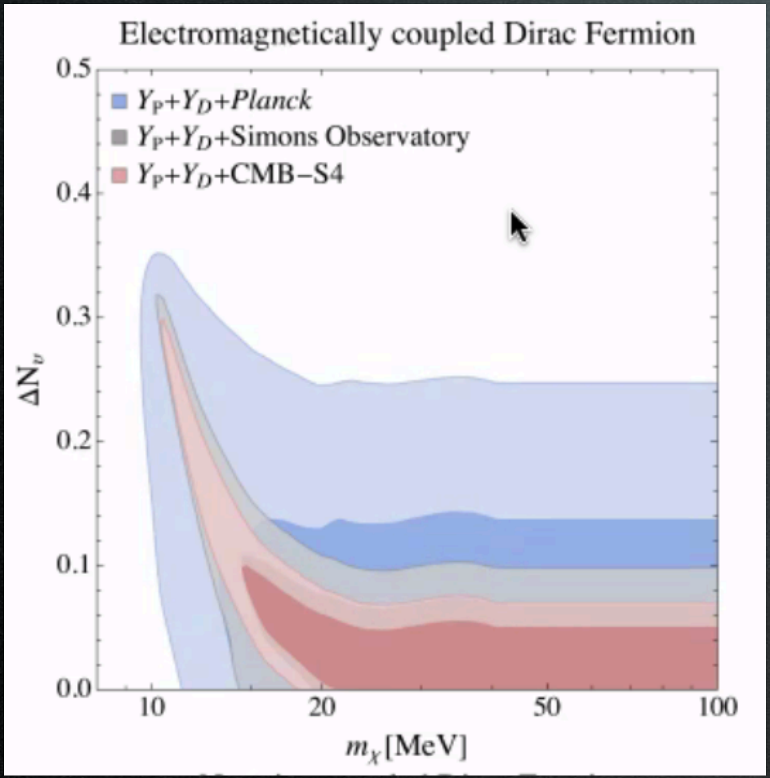
https://arxiv.org/abs/2010.00015



An analysis of neutron stars and exoplanets by JWST shows both are hotter than expected.

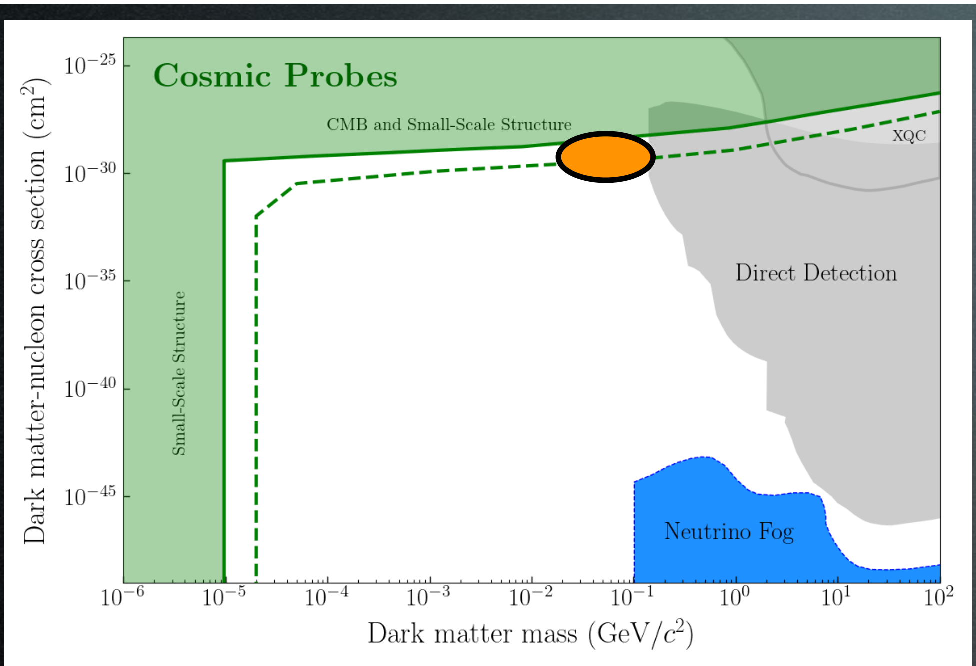
Neff is sensitive to DM-baryon interactions





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

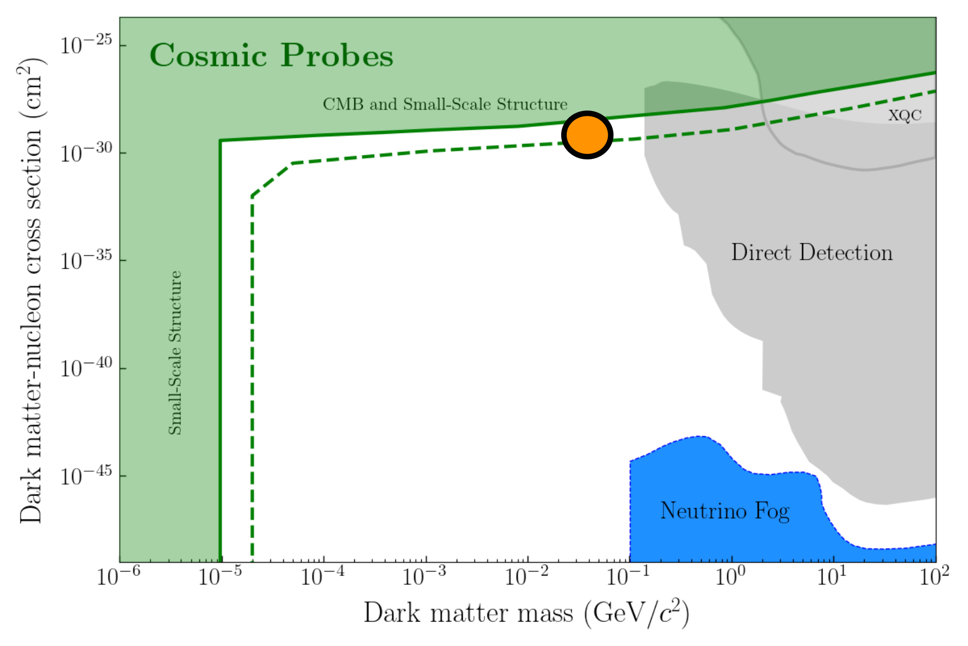
https://arxiv.org/abs/2202.03515



- 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.
- Lyman-alpha forest, strong lensing, and stellar streams all find less substructure than CDM predicts
- Neutron stars and exo-Jupiters are hotter than expected.
- CMB indicates a DM particle with M > 10Mev

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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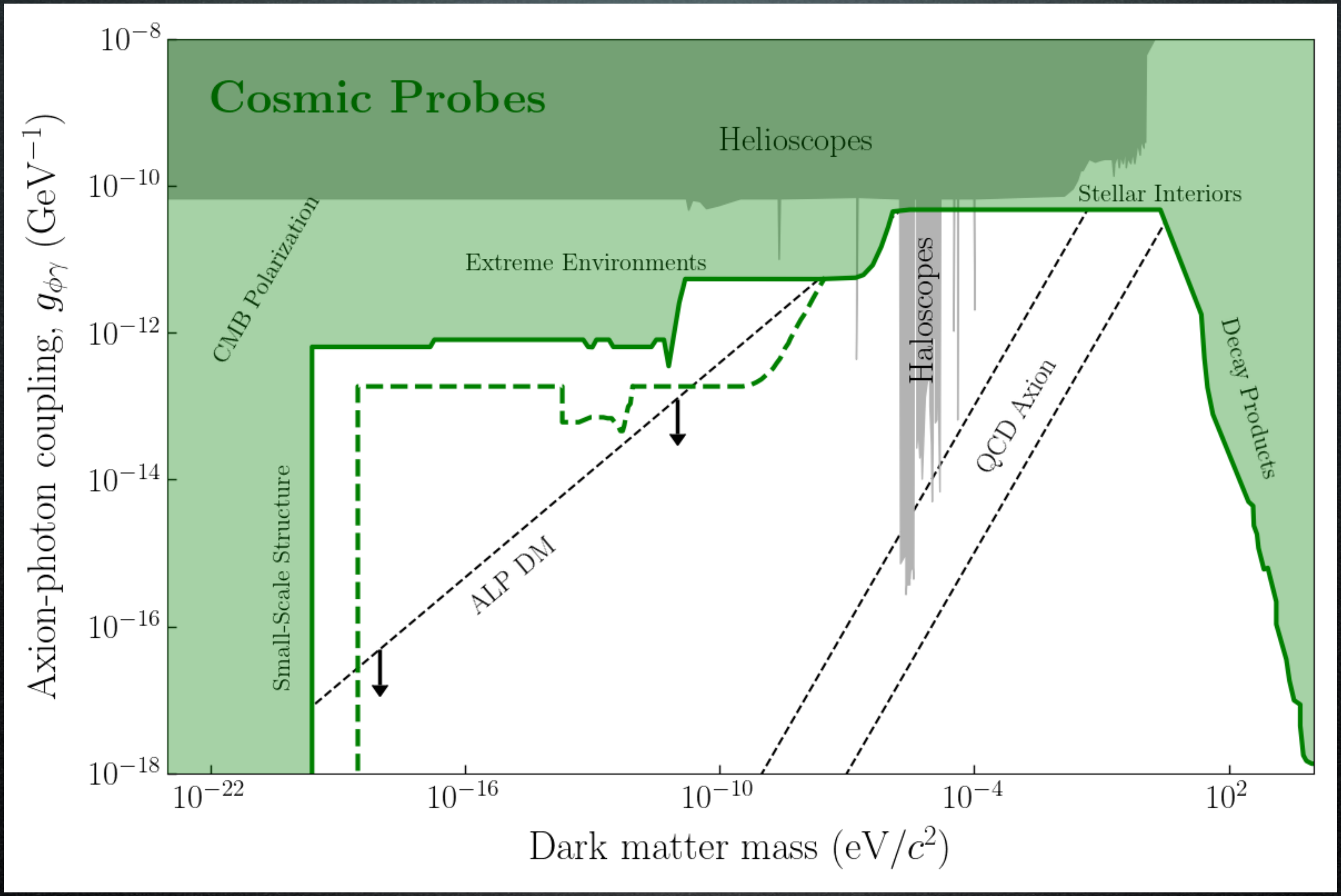
- Neutron stars and exo-Jupiters are hotter than expected.
- CMB indicates a DM particle with M > 10Mev
- Clear detection of a 50 MeV signal in SuperCDMS

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



Snowmass2021 CF3 White Paper

Gravitational wave hints of an axion-like particle

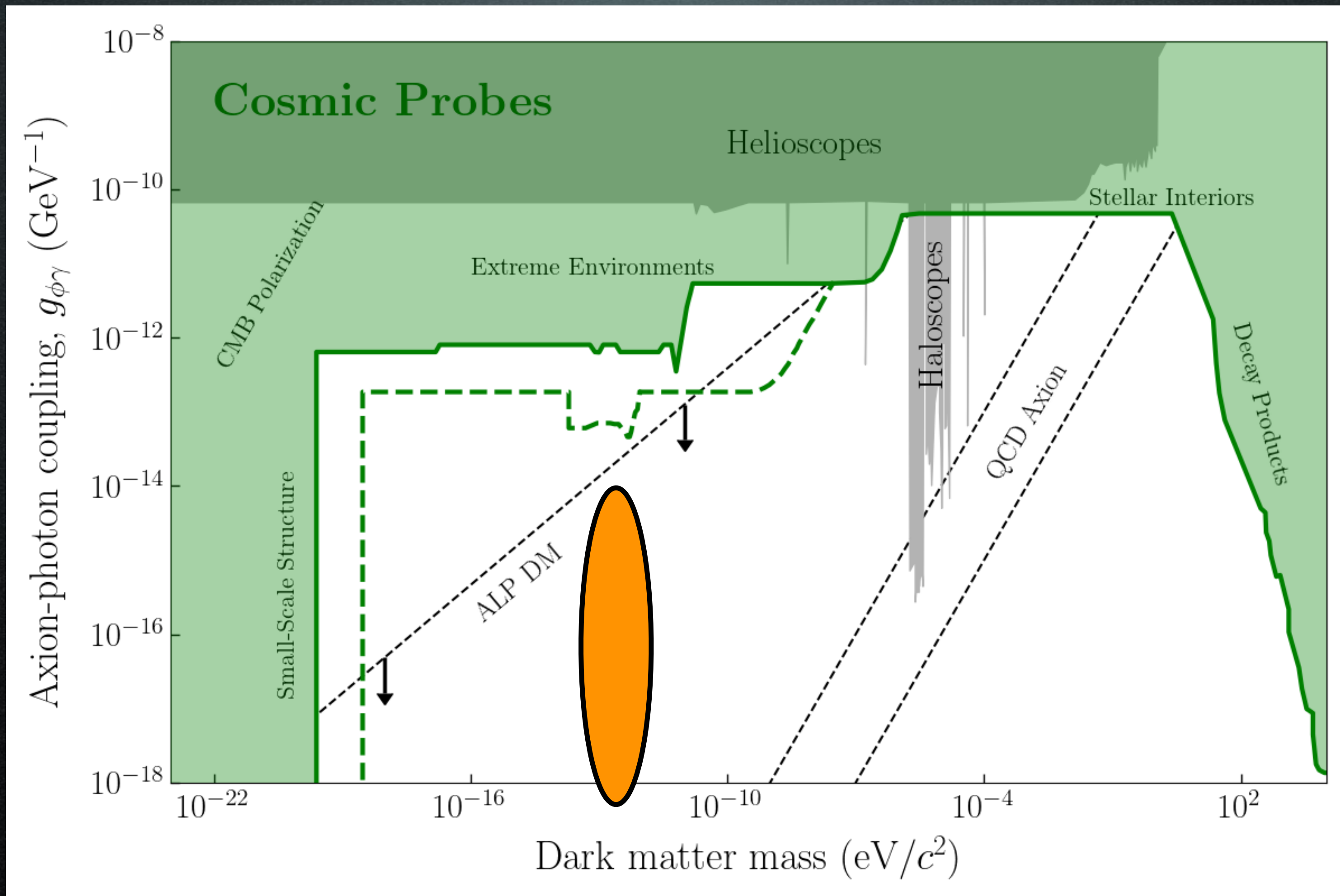
Advanced LIGO observes a continuous wave signal with a frequency 300 Hz - 15 kHz.

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.

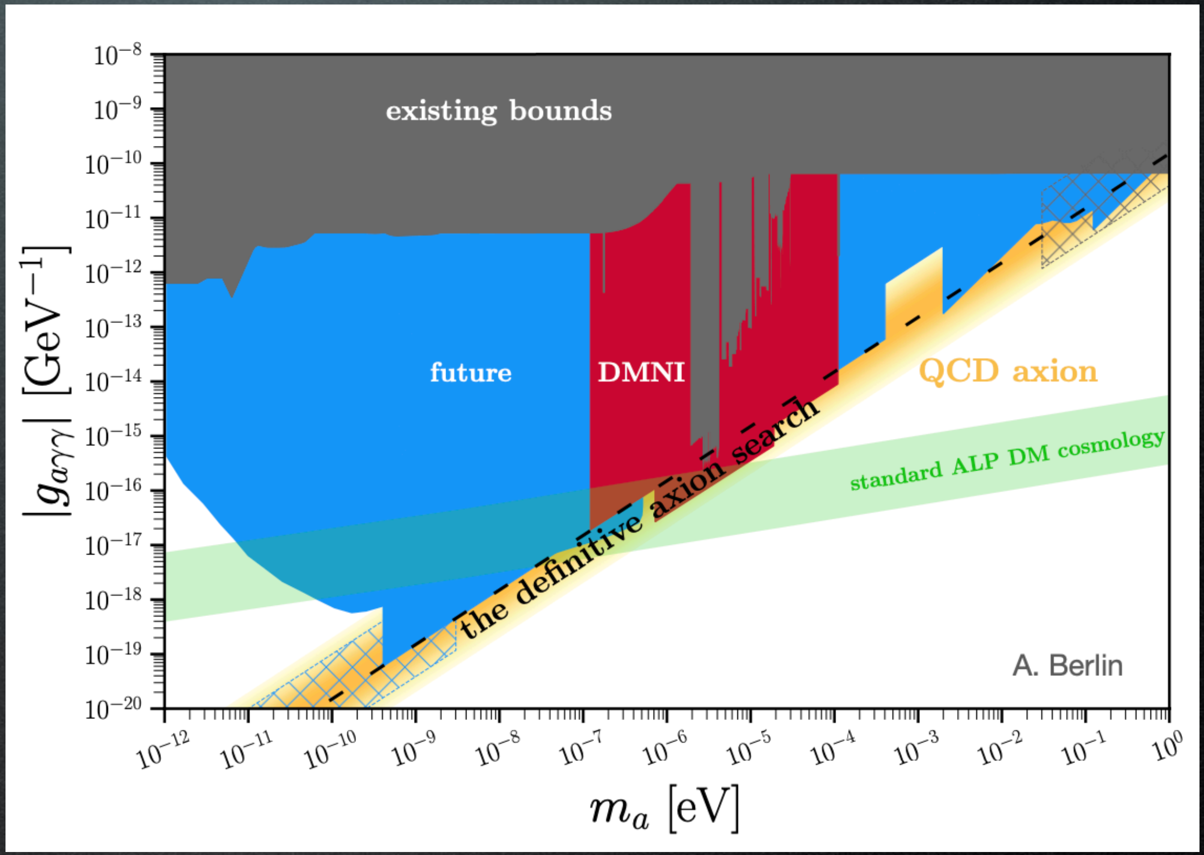
First search outlined in R. Abbott *et al.* (LIGO, Virgo, KAGRA) Phys. Rev. D **105**, 102001
based on ideas outlined in Zhu et al 2020 ; See also https://arxiv.org/abs/2203.07984

10^{-12} eV ALP DM detection example



Snowmass2021 CF3 White Paper

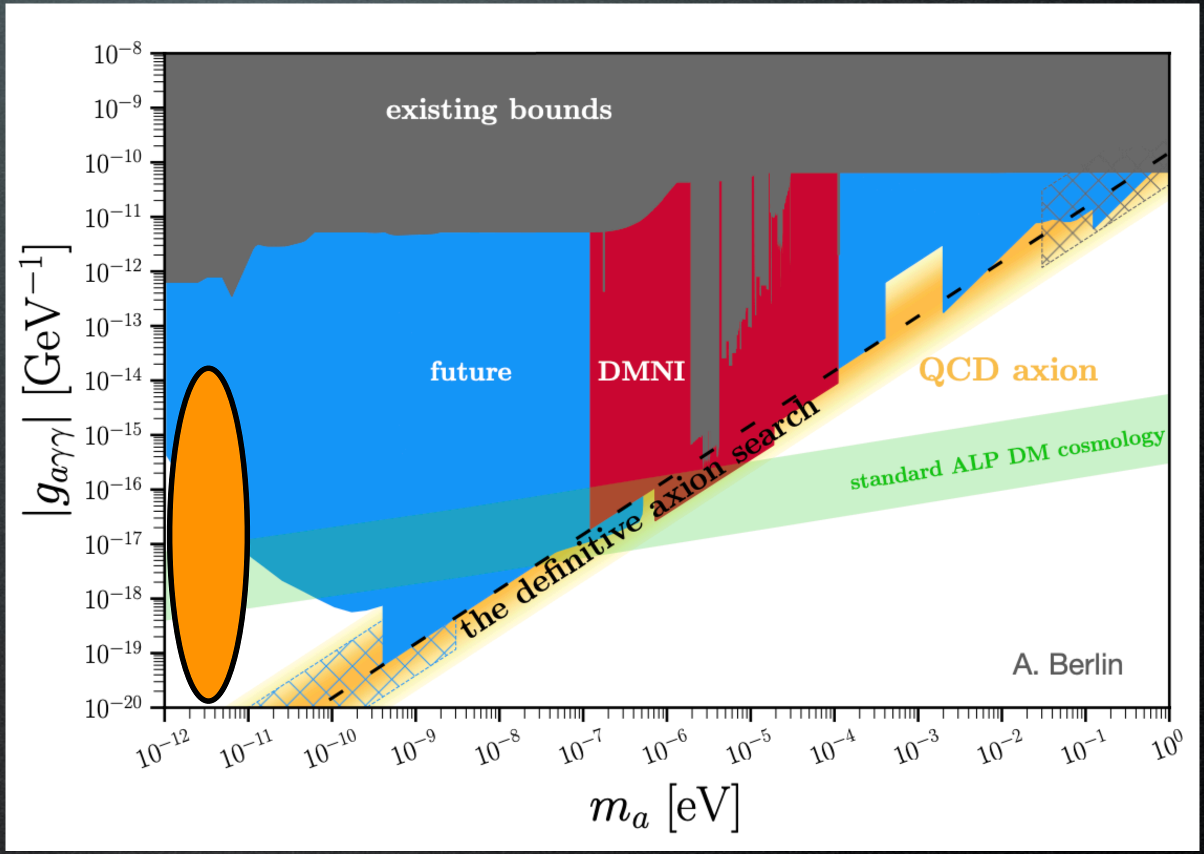
Experimental probes of wave-like DM



Snowmass2021 CF2 White Paper

Experimental probes of wave-like DM

Do a targeted search in NMR or cavity experiments at 10^{-13} — 10^{-11} eV.

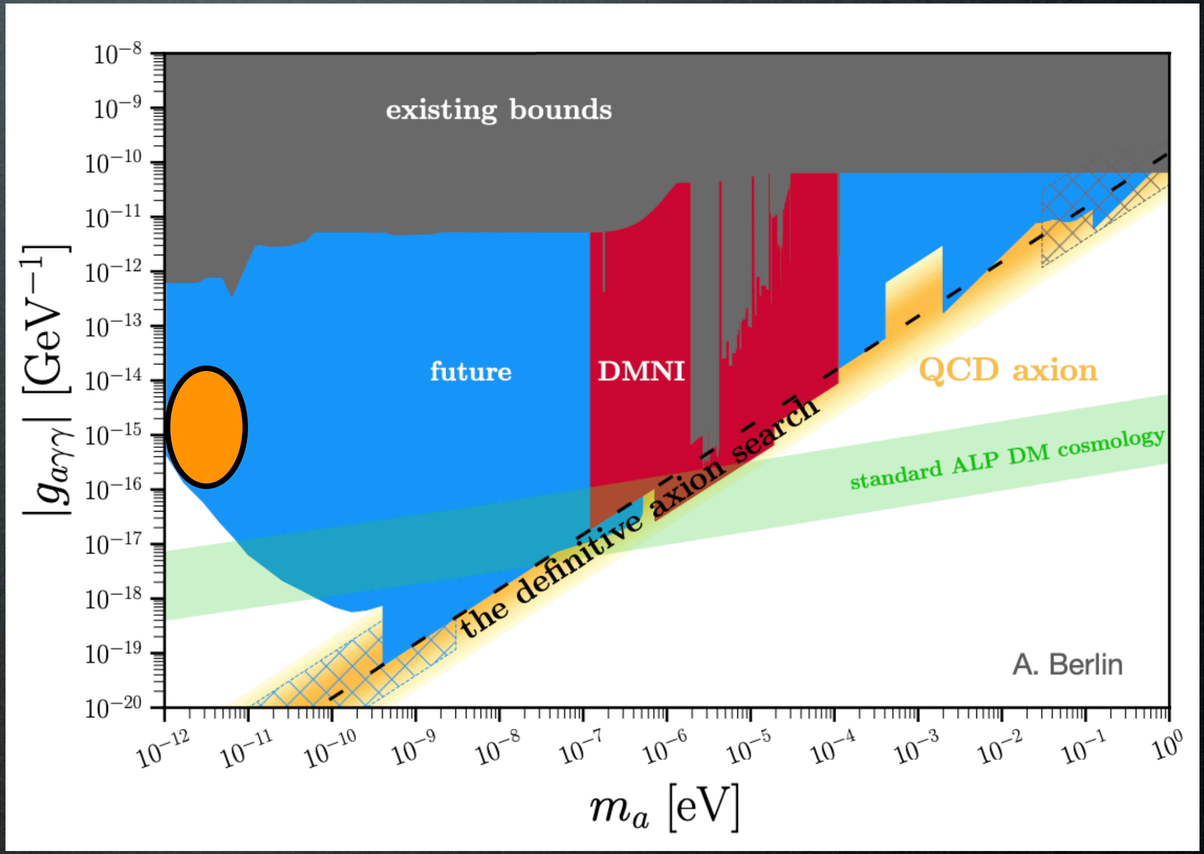


Snowmass2021 CF2 White Paper

Experimental probes of wave-like DM

Do a targeted search in NMR or cavity experiments at 10^{-13} — 10^{-11} eV.

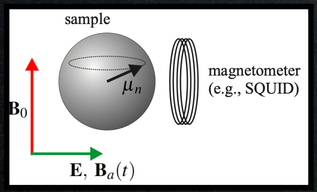
Detection made! Enables a map of the DM density and velocity in the DM halo.



Snowmass2021 CF2 White Paper

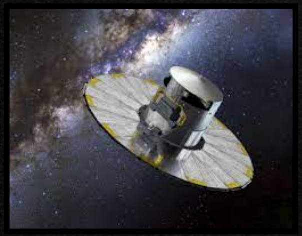
Towards mapping the DM halo with an ALP

Advanced LIGO observes a continuous wave signal with a frequency 300 Hz - 15 kHz. Indicates an axion mass of 10^{-13} — 10^{-11} eV.



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.

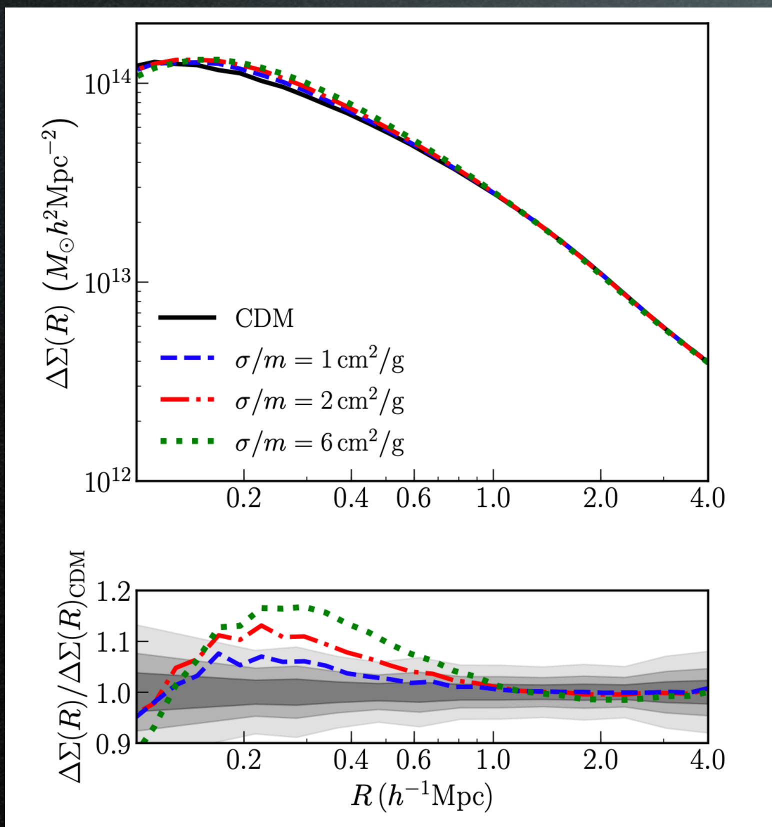


Use these to map the DM halo and its annual modulation —> future synergies with astrophysical measurements and predictions of the local DM density and velocity in the Solar circle.

Example 3:

DM with self-interactions and suppressed small-scale power

DM halo profiles in SIDM



Snowmass2021: Dark Matter Physics
from Halo Measurements Fig 4. arXiv:2203.07354

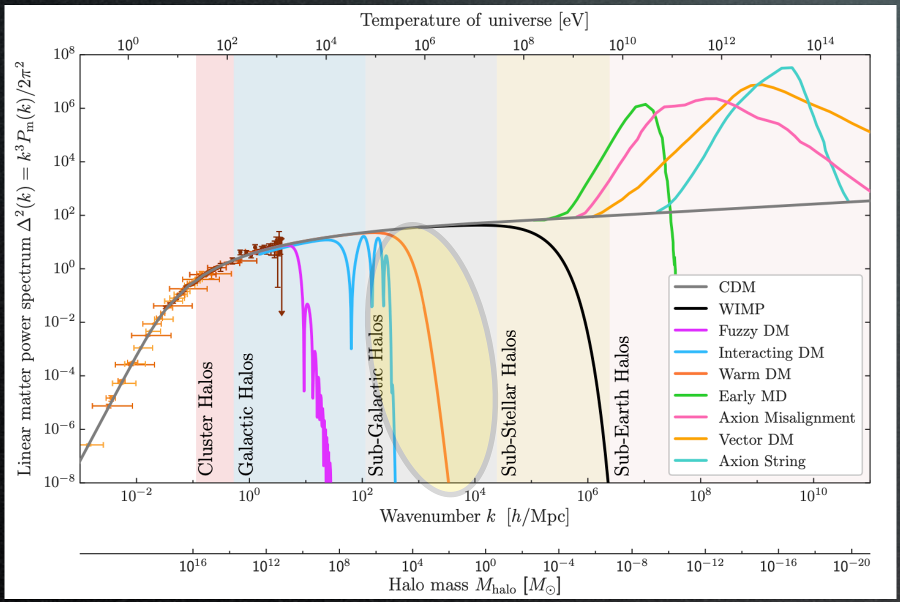
- Measurements of cluster profiles with cores provide indication of self-interactions



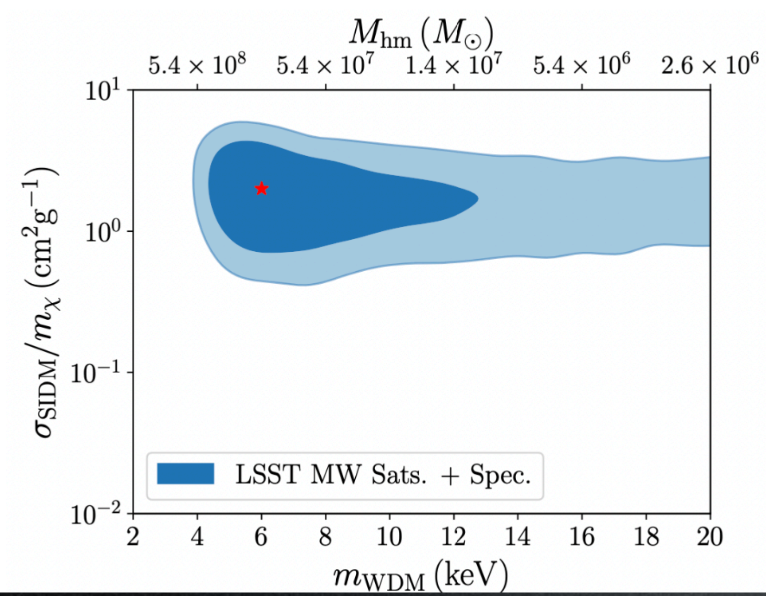
- Measurements of dwarf galaxy profiles also show cores

Stage V Spectrograph

Suppressed small-scale power



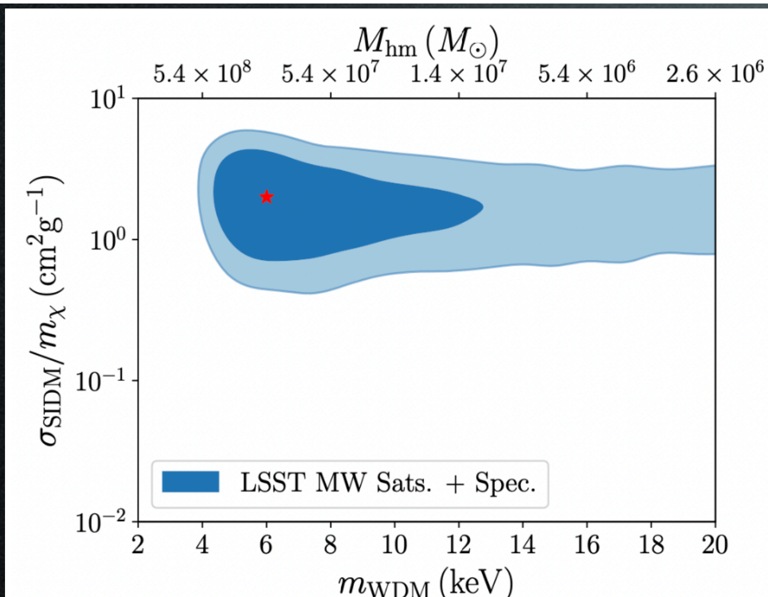
- LSST detects 5 satellites, significantly fewer than expected.
- Strong lensing and streams see impact of dark substructures at 5×10^8 Msun.
- Missing power is observed below the scale of galaxy formation (e.g. 10^7 Msun) by strong lensing (Rubin + JWST, ALMA), streams (Rubin+Gaia+DESI+ELTs), and Lyman-alpha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

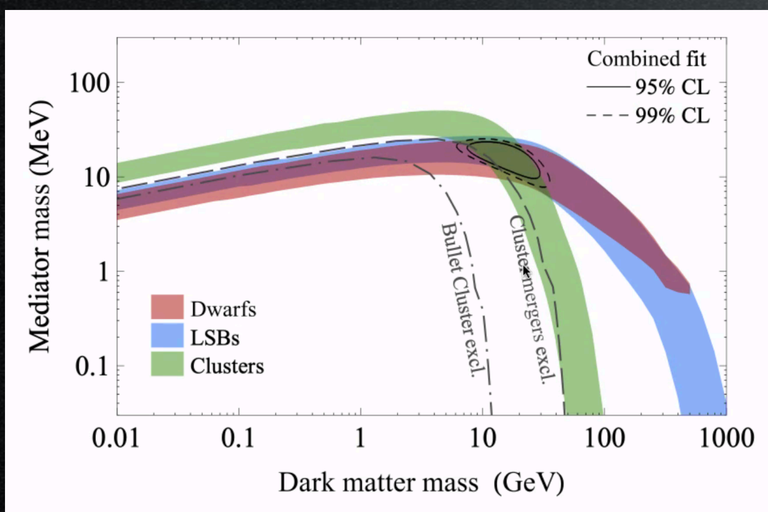


CF3 Draft Report (with Nadler, Yan et al)

Consistent with WDM+SIDM

- Could be 10 keV DM with self-interactions





Tulin & Yu 2018

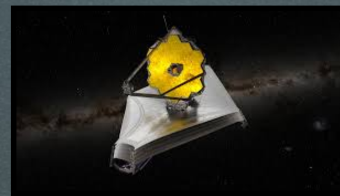
Consistent with WDM+SIDM

- 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 Neff as measured by the CMB (e.g. CMB-S4)

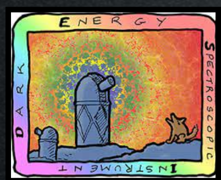
Wide range of astronomical observatories will be relevant to the next generation of DM searches!

Imaging

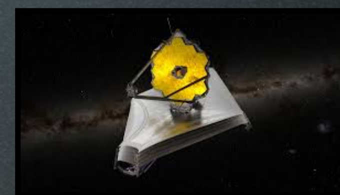




Spectroscopy



Stage V Spectrograph

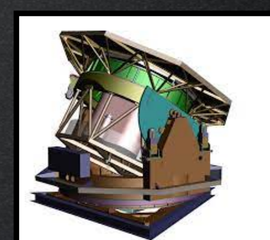

X-ray



Astrometry

GW


CMB



Three examples of many possibilities!

Discussed 3 examples:

- Thermal DM particle at ~50 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 ~10^{-12} 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.