Dark Matter Theory

Tracy Slatyer

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
MIT CENTER FOR THEORETICAL PHYSICS – A LEINWEBER INSTITUTE

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The puzzle of dark matter

We know it:

- Comprises 84% of the matter in the cosmos by mass
- Is ~cold and ~collisionless, and forms the primordial scaffolding for the galaxies
- Has no detected non-gravitational interactions
- Consequently, cannot be explained solely via physics we understand

Credit: NASA/CXC/M.Weiss

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Open questions:

- WHAT IS IT?

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Open questions:

- What it's made from.
- Is it one particle, or more than one, or not a particle (e.g. primordial black holes)?
- How it interacts with other particles.
- Whether it's absolutely stable, or decays slowly over time.
- Why its abundance is what it is.
- If/how it's connected to other deep problems in particle physics.
- And more…

Credit: NASA/CXC/M.Weiss

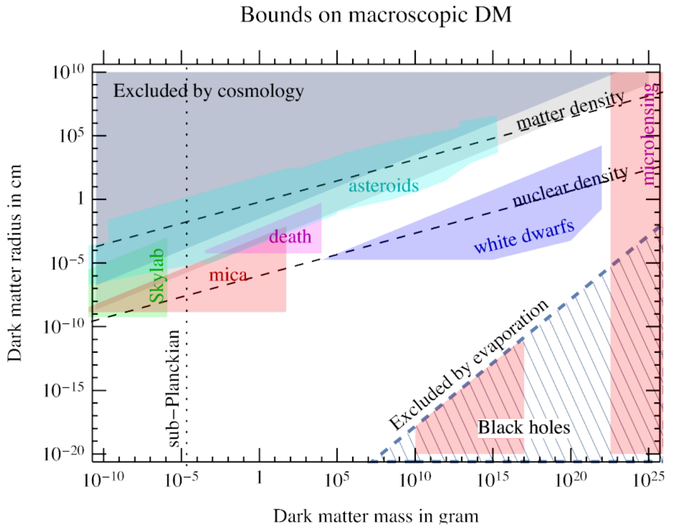
Quality of the “cold collisionless dust” approximation

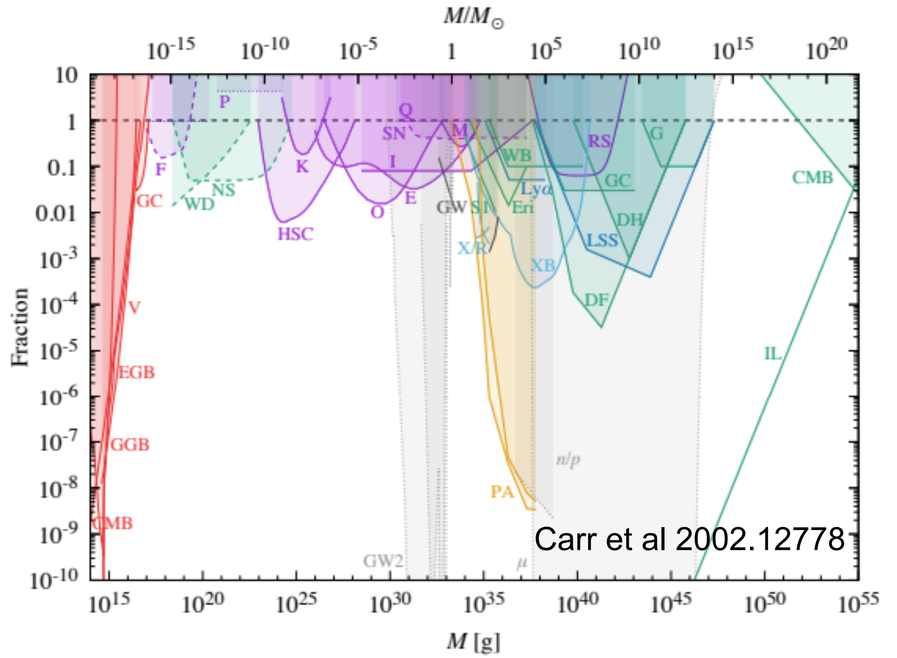
- Cosmic probes of dark matter continue to set new stringent constraints on its properties: see talk by Hendrik Hildebrandt
- Equation of state looks consistent with matter (+ only a few percent of DM can have decayed invisibly by the present day, e.g. Poulin et al 1606.02073, Simon et al 2203.07440); some interest in modified evolution motivated by DESI results [e.g. Khoury et al 2503.16415, Bedroya et al 2507.03090]. No clear evidence yet of new (microphysics-induced) scale in matter power spectrum.
- DM mass $\gtrsim 10^{-(18-19)}$eV based on gravitational perturbations of stars in dwarf galaxies from wave interference effects [e.g. May et al 2509.02781] (limit applies for 100% of DM; sub-percent fractions can be much lighter)
- Stronger mass bounds in specific cases: fermionic dark matter mass $\gtrsim 410$ eV [Boyarsky et al 0808.3902], “warm dark matter” mass $\gtrsim 7$ keV (e.g. Gilman et al 2606.05277, exact limit depends on phase-space distribution), thermal relic DM must have mass $\gtrsim 4$ MeV from nucleosynthesis (also stringent limits on sub-MeV new d.o.f. that thermalize with the Standard Model)
- DM self-interaction $\sigma/m_{\rm DM} \lesssim 0.1-0.4\,{\rm cm}^2/g$ at scale of Galaxy clusters ($v \sim 2000$ km/s), $\sigma/m_{\rm DM} \lesssim 1\,{\rm cm}^2/g$ at scale of galaxy groups ($v \sim 1000$ km/s), less constrained at lower velocities [Adhikari et al 2207.10638]
  [Note: in particle physicist units, $1{\rm cm}^2/g \approx 1/(60{\rm MeV})^3$: QCD-scale cross sections for QCD-scale DM mass]
- Infinite-range purely-dark-sector forces can be constrained at the level of <1% of gravity using LSS data [e.g. Bottaro et al 2407.18252, which also finds a 2 sigma preference for long-range interactions at the level of 0.4% of gravity]

How heavy could the DM be?

- Ultraheavy DM is a viable possibility and can range from heavy fundamental-particle DM to massively composite states to macroscopic objects; can be tested via direct detection, cosmology, gravitational lensing
- Classic example at the heaviest mass scale is primordial black holes: potentially formed during inflation or during an early-universe dark-sector phase transition (still substantial theory uncertainties, especially in tails of mass distribution)
- There is an open window for all DM to be PBHs for PBH masses $M \sim 10^{17}$-10^{23}g
- At the low end of this window, PBHs slowly evaporate via Hawking radiation; potential to gradually push up the limit with future space-based gamma-ray experiments [e.g. Ray et al 2102.06714, Caputo et al 2210.09310]
- The high end of the window is constrained by lensing; regions of this window are potentially testable with X-ray microlensing [e.g. Bai & Orlofsky 1812.01427, Tamta et al 2405.20365]

Searches for general macroscopic DM [Cirelli et al 2406.01705]

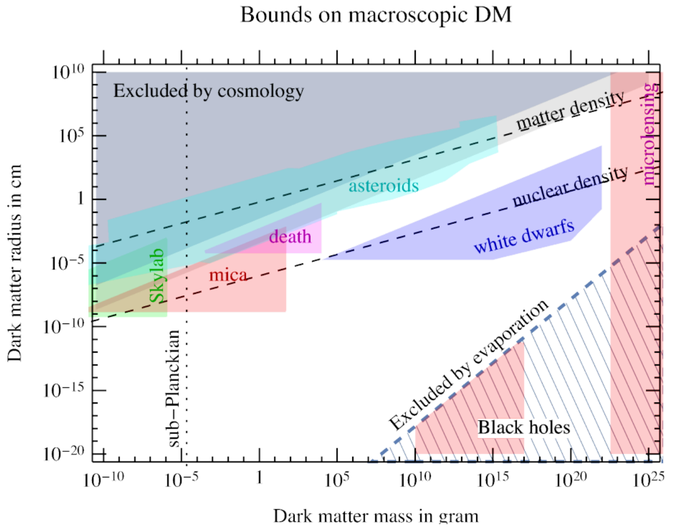


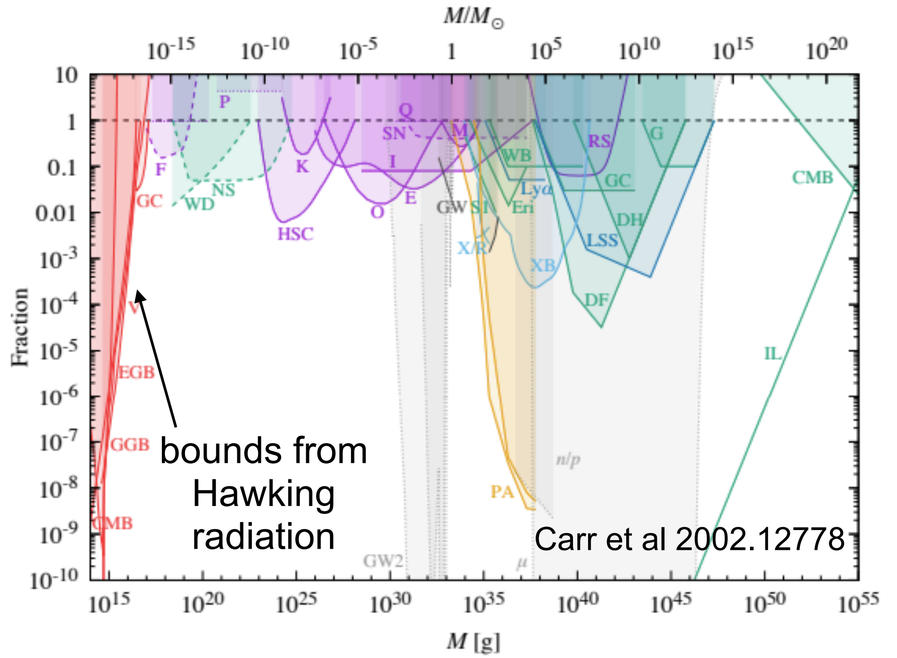


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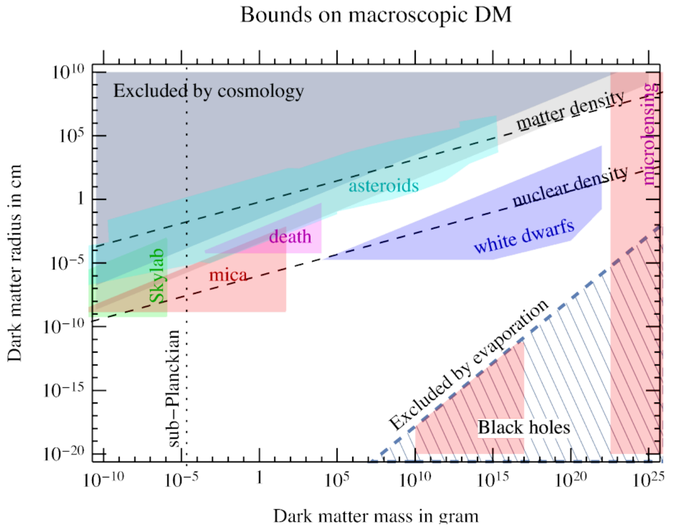


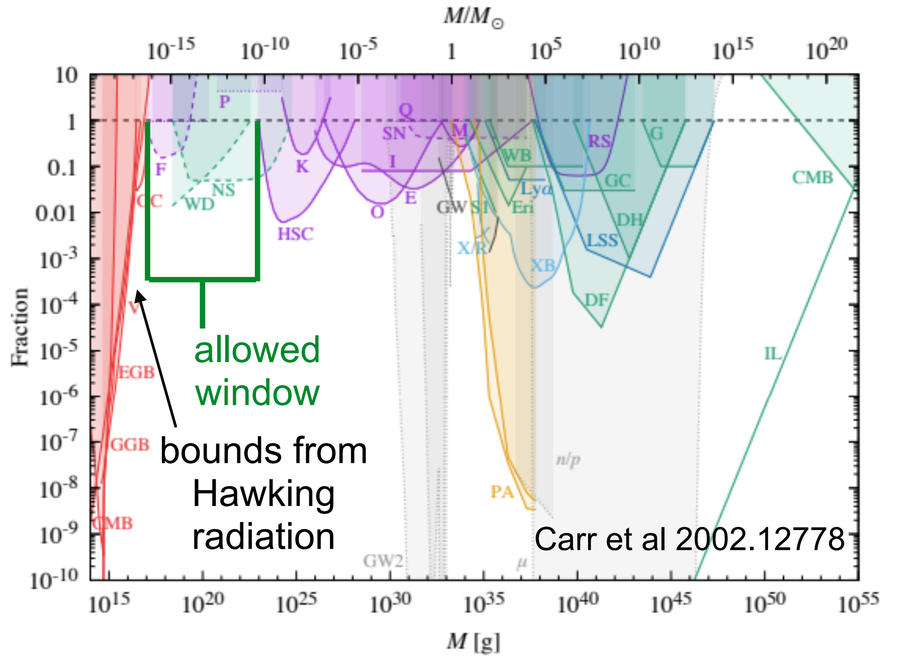


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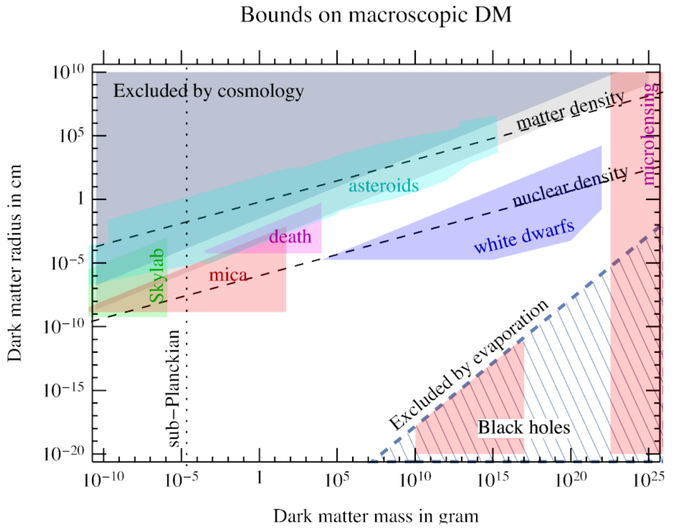


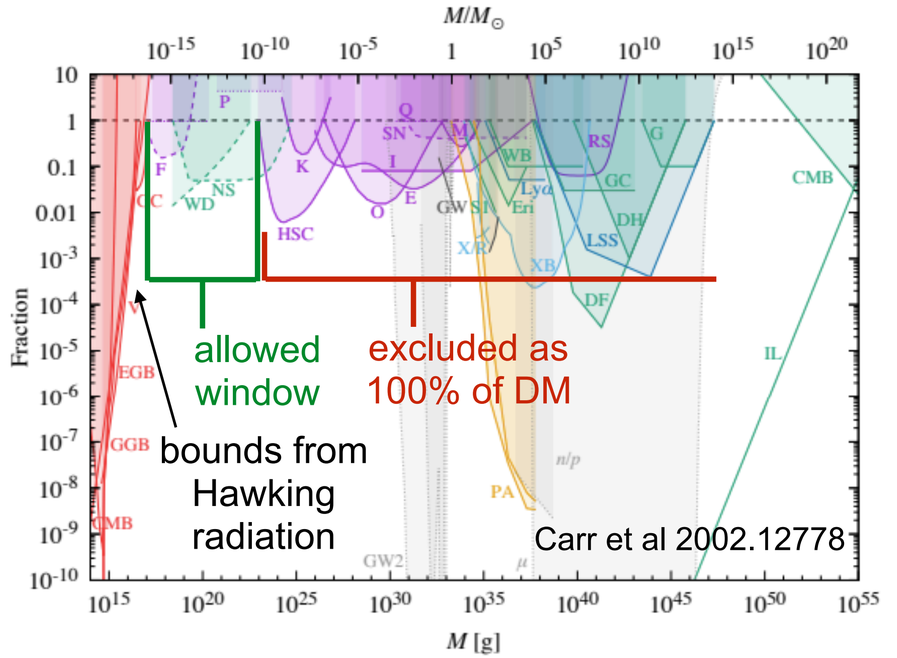


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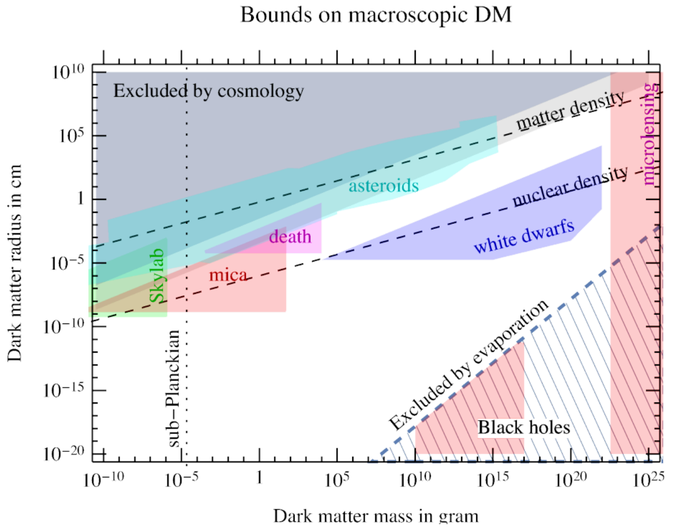


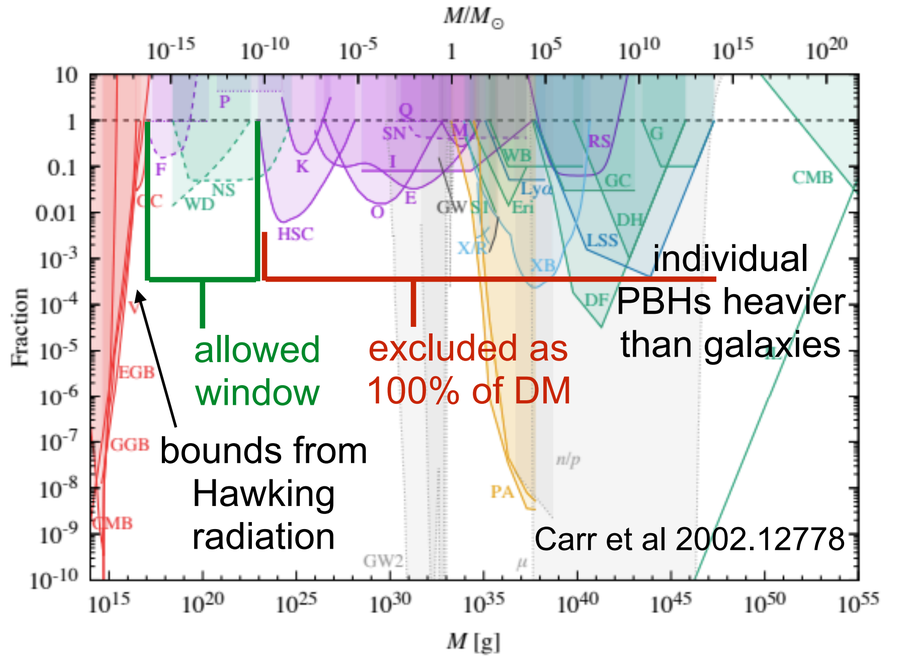


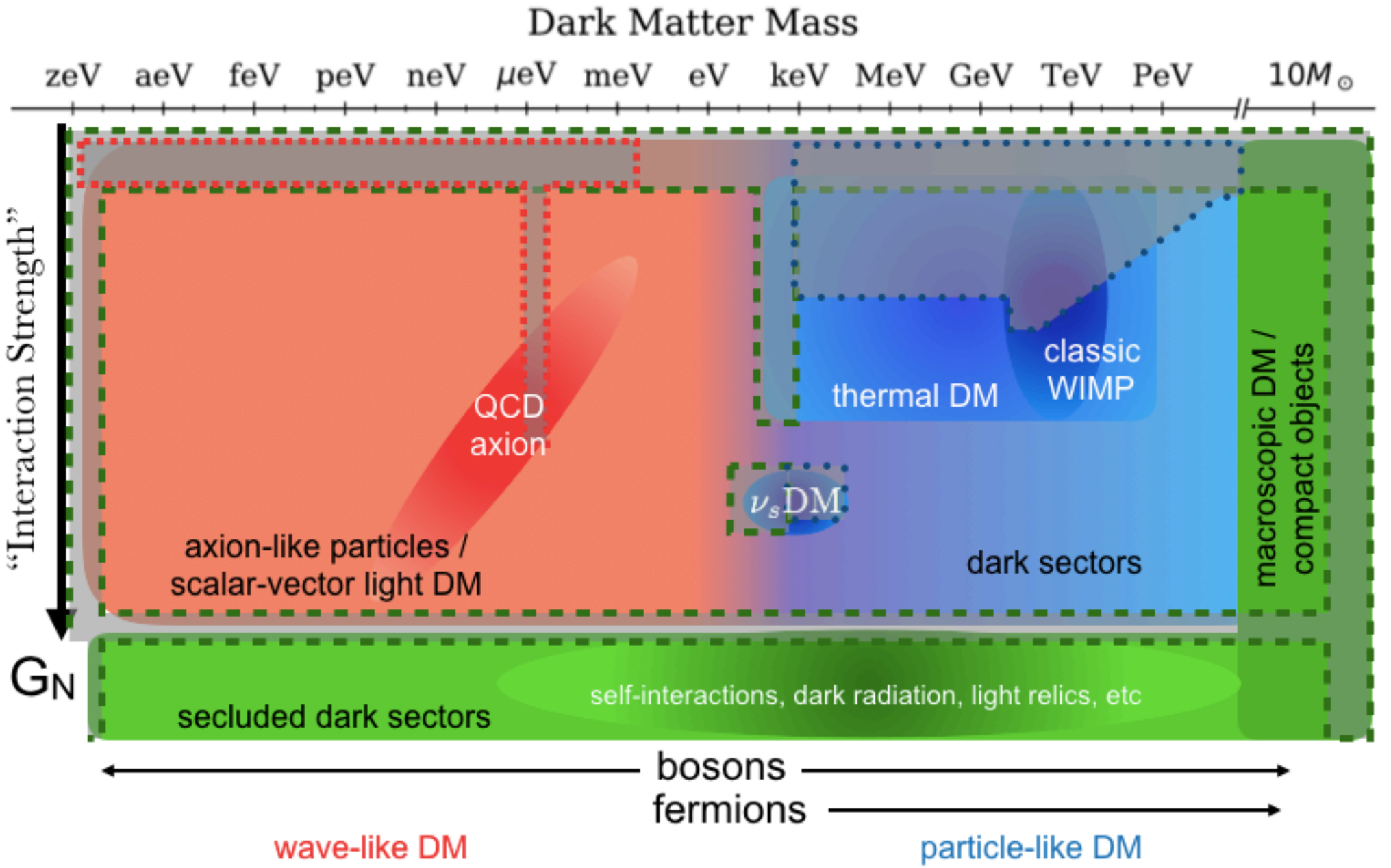
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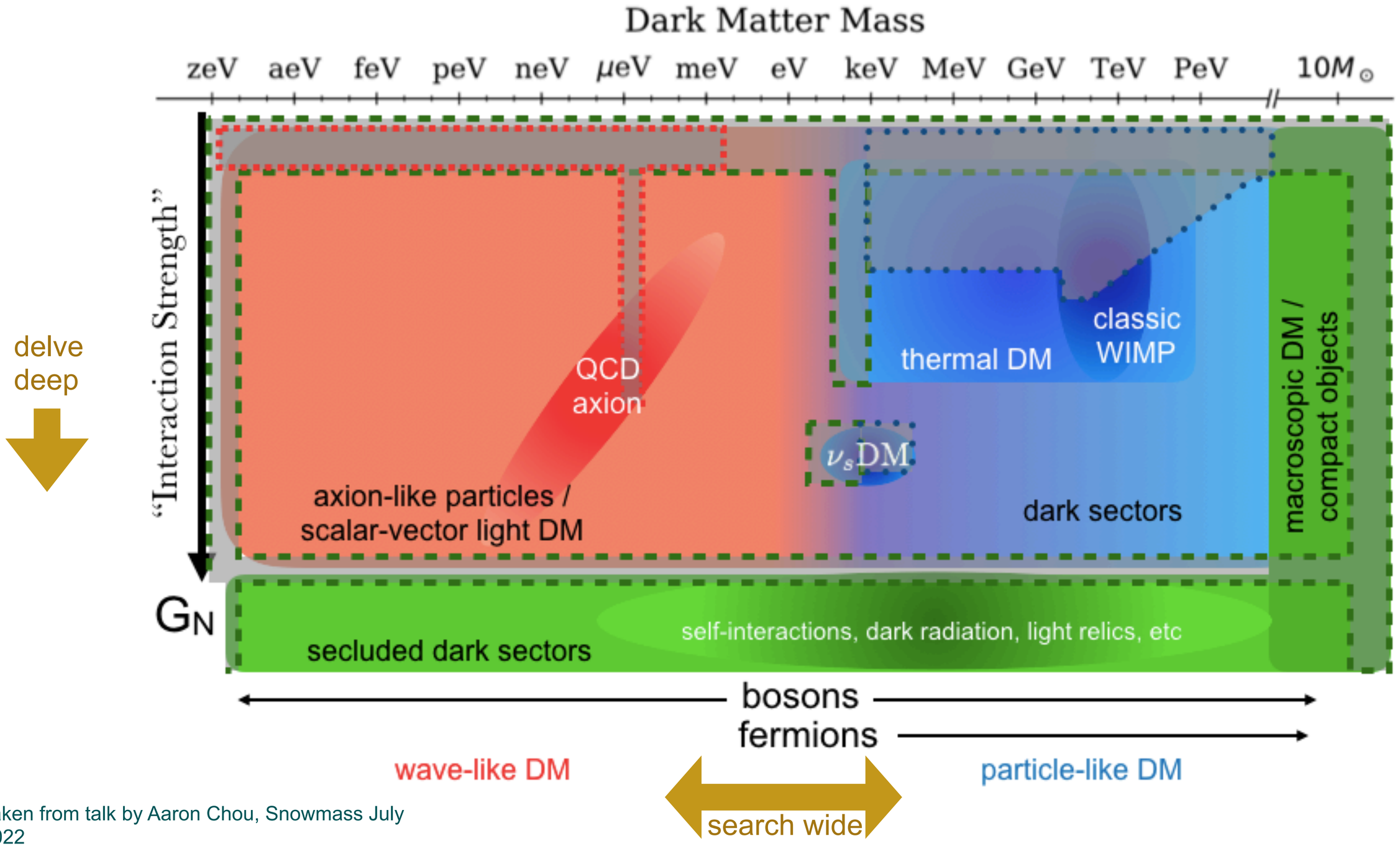
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Taken from talk by Aaron Chou, Snowmass July 2022

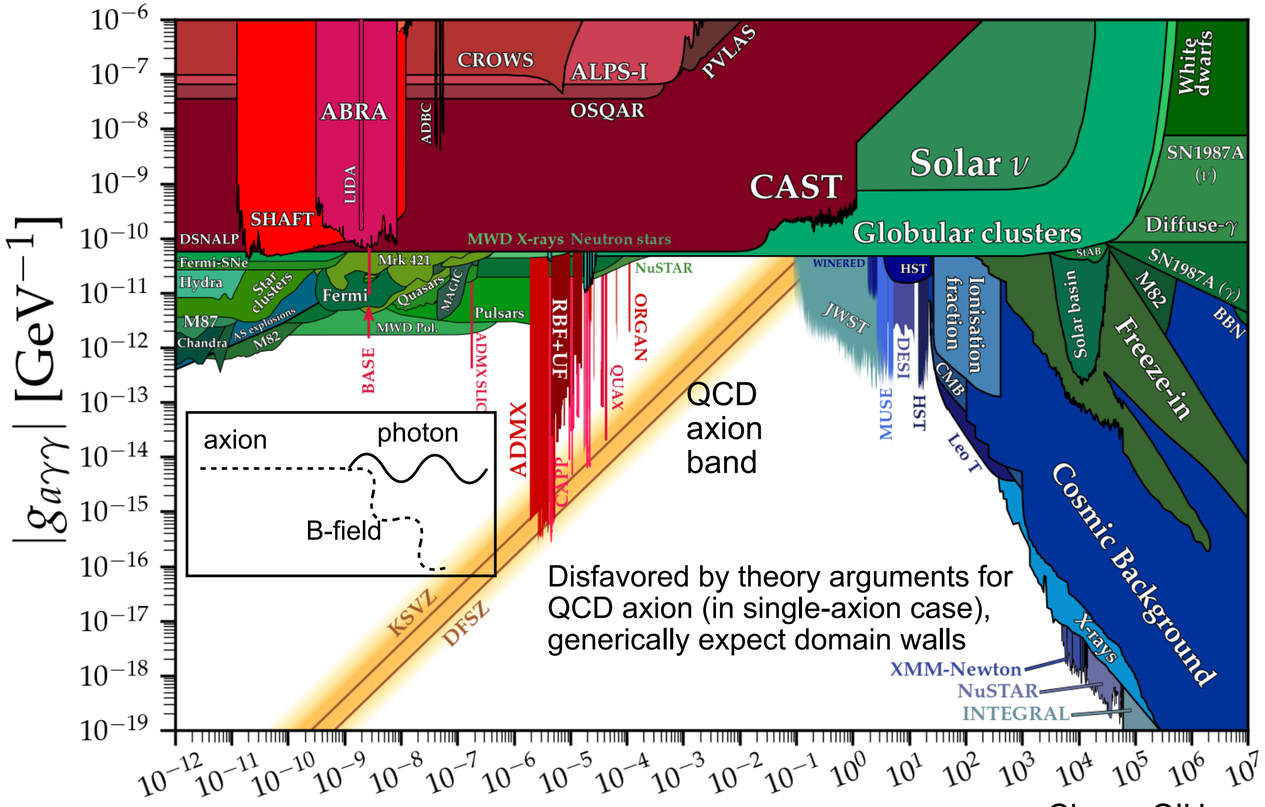


Taken from talk by Aaron Chou, Snowmass July 2022

Wave-like DM & the QCD axion

- For DM masses ~10^{-18} eV to ~1 keV, DM must be bosonic and avoid thermal contact with the Standard Model (=feeble interactions)
- Most classic benchmark is the QCD axion (motivated by the strong CP problem), also interest in axion-like particles (ALPs), light scalars, and dark photon dark matter (U(1) vector boson coupled through the kinetic term).
- Naively we expect O(1) CP violation in the strong interactions, associated with $\bar{\theta}$ angle: $\mathscr{L}_\theta = \frac{\bar{\theta}}{16\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu}$
- This should generate a neutron electric dipole moment at the level of [Liang et al 2301.04331] $d_n = 1.5 \times 10^{-16}\bar{\theta} e\text{cm}$ but experimentally, we know that $|d_n| \lesssim 1.8 \times 10^{-26} e\text{cm}$ [Abel et al 2001.11966]
- Axion solution: promote $\bar{\theta}$ to a dynamical field a/f_a, minimum of its potential is the CP-conserving point $a = 0$
- Implies couplings proportional to $1/f_a$, mass m_a fixed by $m_a f_a \sim m_\pi f_\pi \sim (0.1\text{GeV})^2$

- There is a broad range of constraints on the QCD axion parameter space from (somewhat model-dependent) coupling to photons, which also apply to ALPs that couple to the photon in the same way
- Theory constraints disfavor QCD axions below the “DFSZ” line [Choi et al 2309.03937]



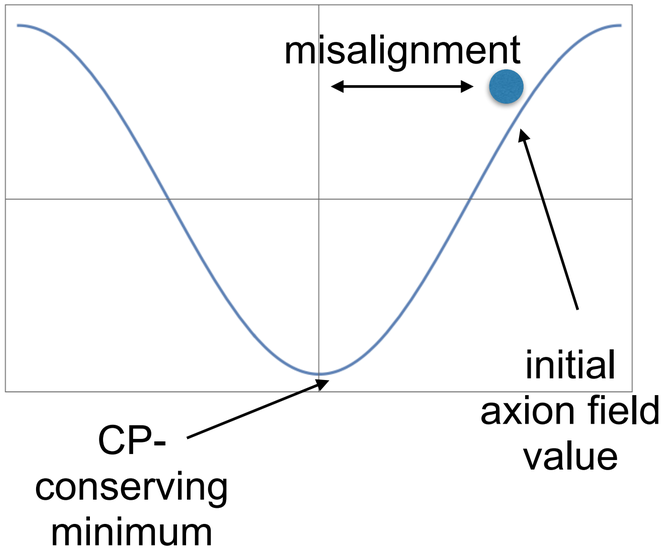
See talk by Igor Irastorza for axion experimental program!

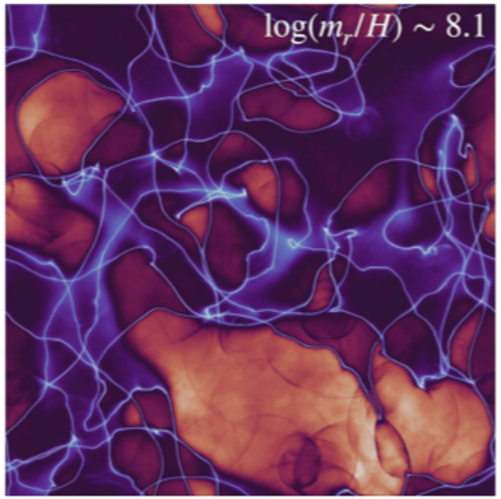
Is there a preferred mass for the QCD axion?

- The initial misalignment angle of the axion field can be fixed either pre-inflation (same angle across observable universe) or post-inflation

- If the misalignment angle is set post-inflation, we expect a network of axion strings to form and decay - what is the contribution to the DM density and the modification to the preferred QCD axion mass? Varying predictions, from ~20-500 μeV; recent estimates include 40-300 μeV [Benabou et al 2412.08699], 17-40 μeV [Correia et al 2609.20801]; friction with the thermal bath may also be important [Hook et al 2603.00237]

- If the misalignment angle is set pre-inflation, it is usually treated as a free parameter; some suggestions that string theory + grand unification may favor a low-mass window, at [10^{-11}, 10^{-8}] eV [Benabou et al 2505.15884], or [0.5, 0.8] neV for heterotic string theory [Benabou et al 2605.04142]





Some other active theory questions for wave DM

- How much of an issue is the axion quality problem, i.e. are there good mechanisms to ensure that corrections to the potential do not move the minimum from the CP-conserving point?
  - Higher-dimensional axions can evade the problem [e.g. Craig et al 2408.10295]; there have been arguments that there may be general tensions between solving the quality problem and an acceptable cosmological history [e.g. Lu et al 2312.07650], but also recent examples of models that aim to resolve this tension [e.g. Di Luzio 2609.16110]
- What kinds of models produce the right amount of dark photon dark matter, noting that in the presence of a dark Higgs, vortices can drain energy out of the DM field? [East & Huang 2206.12432] How robust are the cosmological bounds on dark photon dark matter, once plasma effects are taken into account? [Hook et al 2510.13956]
- What is the right way to treat the quantum nature of wave DM (i.e. not approximating it as a classical wave), and capture the wave→particle transition at higher mass? [Cheong et al 2408.04696] Some recent work on this problem implies it is very difficult to measure intrinsically quantum properties of ultralight DM (or gravitational waves!) [e.g. Bao et al 2510.05198, 2607.27313]

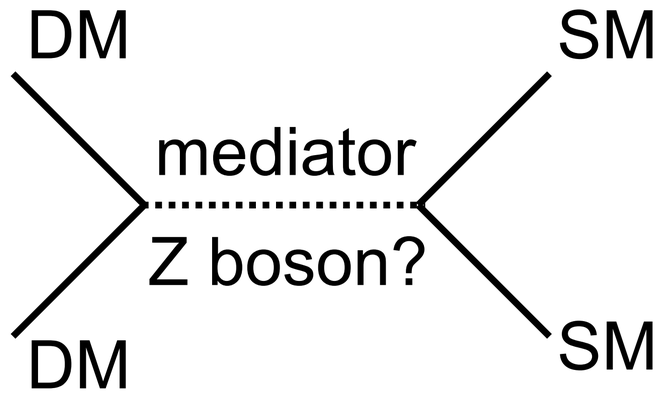
Particle-like DM & the thermal window

- For MeV+ DM, the DM could potentially be thermally coupled to the Standard Model
- One key question for all DM scenarios is "where did the DM abundance come from?”
- Classic ‘WIMP’ hypothesis is that DM was in thermal equilibrium with SM in early universe + density was depleted through annihilations, DM DM → SM SM; DM is a “thermal relic”
- Observed present-day density → annihilation rate:

$$\langle \sigma v \rangle \approx 2 \times 10^{-26} \mathrm{cm}^3/s \approx \frac{1}{(25\mathrm{TeV})^2} \sim \frac{1}{m_{\mathrm{Pl}} T_{\mathrm{eq}}}$$

- Correct cross section for weakly-interacting particles with weak-scale masses - Weakly Interacting Massive Particle (WIMP) “miracle”
- Mechanism works for DM masses up to ~100 TeV - for heavier DM the required annihilation rate becomes impossible to attain (in standard cosmology), exceeding generic upper bound from unitarity
- This mechanism implies significant DM-SM interactions, including a target annihilation cross section, and complementarity with direct and collider searches.
- There are also many variations on this mechanism - considerable theoretical work to study such variations, including scenarios where the DM (and possibly other dark-sector particles) do not fully thermalize

Low-mass thermal DM vs classic WIMPs



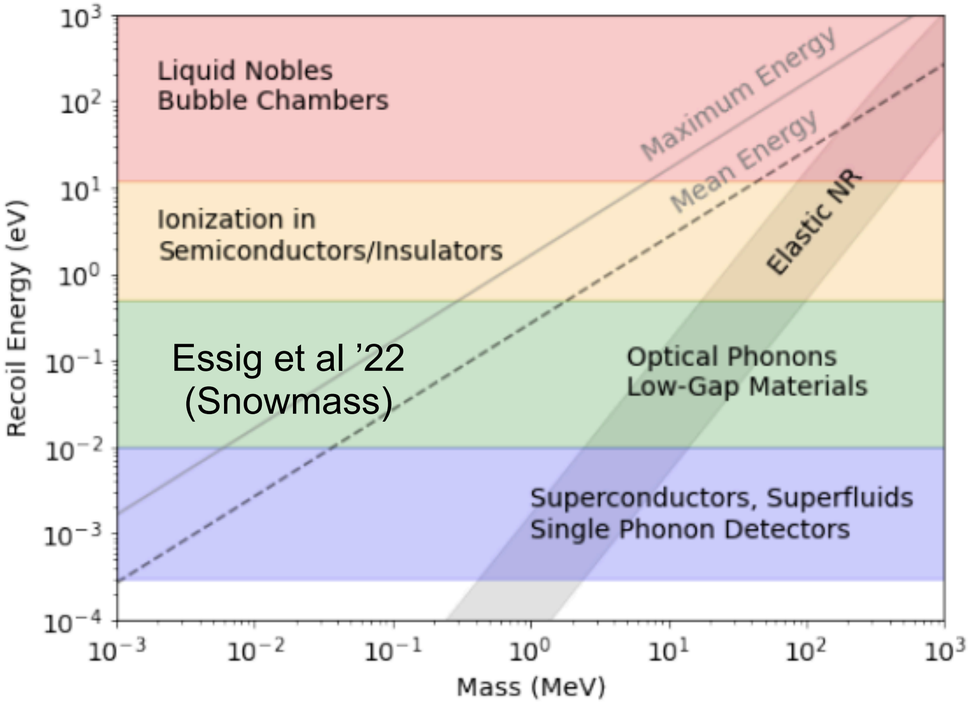
- Lee-Weinberg bound: if we assume DM annihilates through the Z boson (or a weakly-interacting mediator of similar mass, like the W or Higgs), we expect the cross section to satisfy $\sigma v \lesssim \alpha_W m_{\rm DM}^2 / m_Z^4$
- This implies, for thermal relics, $m_{\rm DM} \gtrsim (90{\rm GeV})^2/(25{\rm TeV})/\sqrt{\alpha_W} \approx 2{\rm GeV}$, otherwise cross section is too small and the universe is overclosed
- This is the Lee-Weinberg bound - helped motivate historical focus on GeV+ dark matter with weak-scale interactions.
- However, this relies on the assumption that the mediator is weak-scale. New lighter mediators remove this bound - naturally leads to "dark sectors" where the DM interacts with one or more new particles, allowing thermal relic DM in the MeV-GeV band. [See Tamara Vazquez Schroder's beautiful talk on Tuesday.]

Portal	Interactions
Dark Photon, A'_μ	$-\epsilon F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Heavy Neutral Lepton, N	$y_N L H N$

- We often classify these models based on the "portal" to the Standard Model - only renormalizable options (for SM-singlet mediators) are vector portal, scalar portal, neutrino portal

Direct detection with low energy thresholds

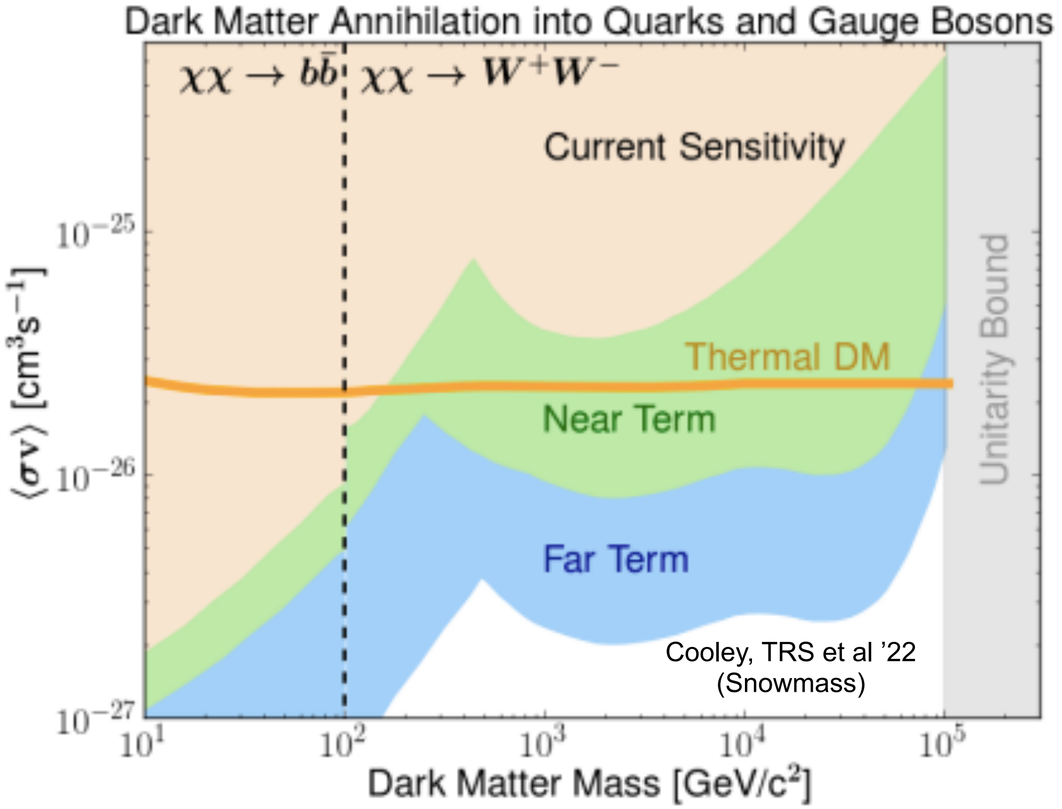
- Light mediators are good for direct detection (and no requirement to restrict to thermal relics)
- Classic direct detection experiments (see talk by Shingo Kazama) search for nuclear scattering. Great for high-mass DM, but the recoil energy is strongly suppressed for DM mass << nucleus mass due to kinematic mismatch
  - although the Migdal effect, where electrons are produced in conjunction with nucleus-DM scattering, can allow sensitivity - direct observation for neutron scattering in Jan 2026 by Yi et al (Nature)
  - scattering of DM in the Sun can also boost light DM particles to the point where they can be detected [An et al 1708.03642]



- One option is to switch to electron scattering, moves the relevant mass scale from O(10-100 GeV) to O(MeV) - being already implemented in experiments such as SENSEI and DAMIC-M, setting stringent constraints on light dark sectors [Aggarwal et al 2503.14617]
- Can also look for special materials that are sensitive to very tiny energy deposits (e.g. semiconductors with tiny band gaps, molecular crystals, superconductors) and/or allow for other signatures, such as daily modulation - groups now working to do this search systematically [e.g. Cook et al 2501.00091, Griffin et al 2506.19905]
- Collective/in-medium effects are often critically important.

Testing the thermal annihilation cross section

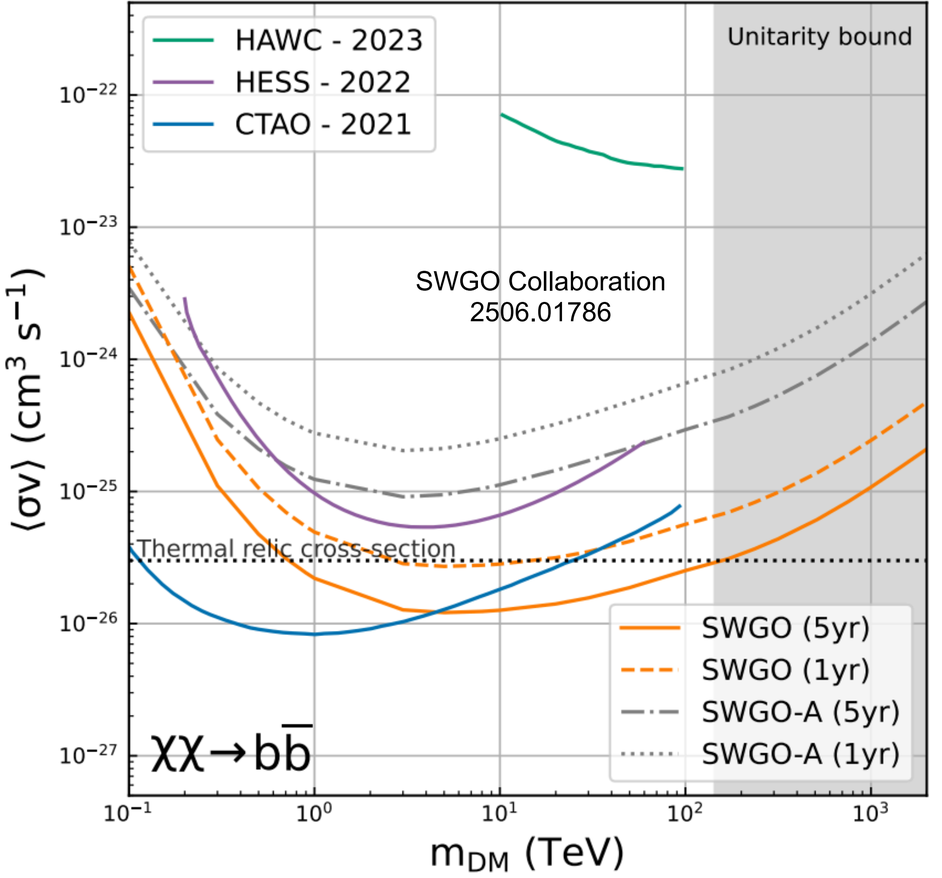
- Limits from the CMB, gamma-ray and cosmic-ray experiments probe the thermal relic cross section up to DM masses of 10s-100s GeV, for all SM final states except neutrinos.
- Future experiments have the possibility of reaching this cross section for 10-100 TeV DM.
  - Large ground-based gamma-ray telescopes (CTAO, SWGO, LACT) are needed to reach the thermal relic benchmark cross-section at these masses
  - Southern hemisphere locations are valuable to observe the Galactic Center where DM density is expected to peak
- For light dark sectors, we are already restricted by indirect detection to models which have suppressed annihilation signals. We rely primarily on direct + accelerator/collider searches for these models, although future MeV telescopes can also have an impact
- Cosmological probes using the CMB and future 21cm observations can also put stringent constraints on DM decay/annihilation (primarily at lower masses) [e.g. Facchinetti et al 2308.16656, Sun, TRS et al 2312.11608]



- Significant theory work in the past year+ to improve yield predictions for antinuclei, calibrating against collider data [e.g. di Mauro et al 2603.19352, Stefanuto et al 2605.08338]
- GAPS balloon experiment had successful science flight December 16, 2025 - January 10, 2026 Dedicated search for low-energy antiprotons + antideuterons

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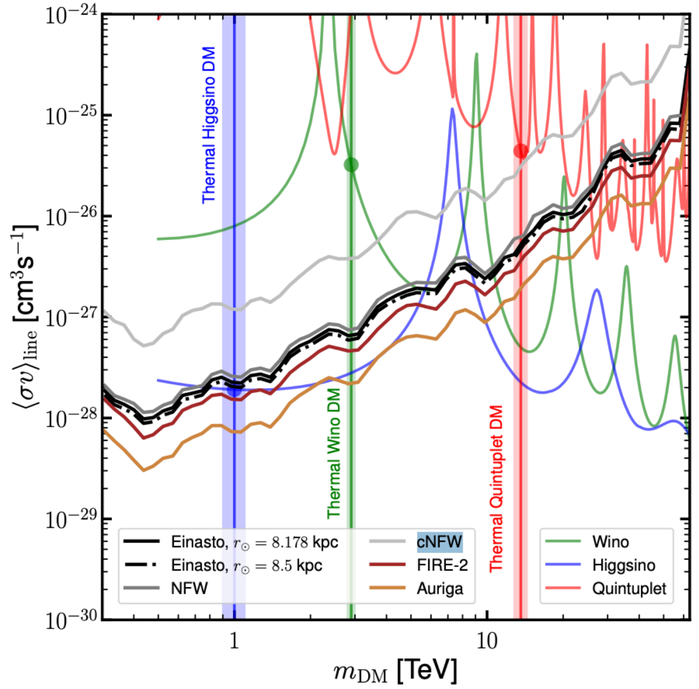


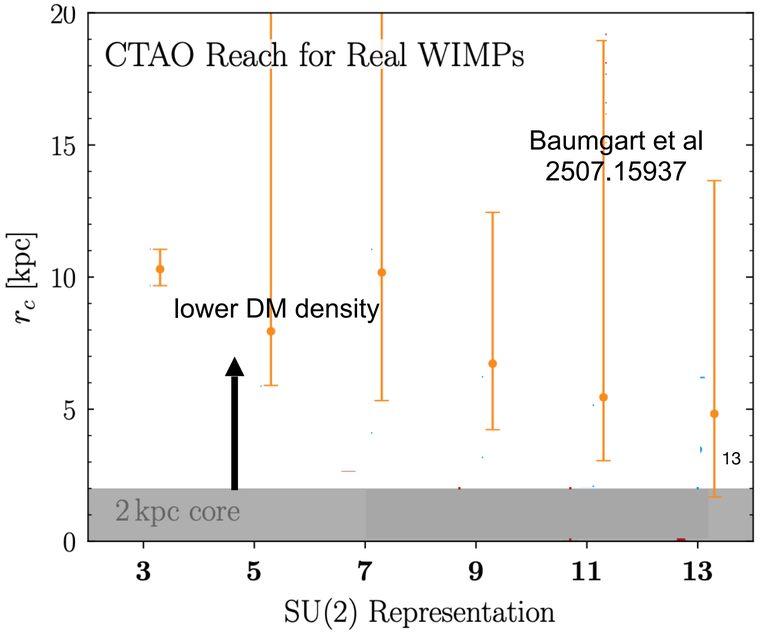
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Classic WIMPs: minimal dark matter benchmarks

- Classify models by $SU(2)_W$ representation (doublet, triplet, etc) and fermion vs scalar - interactions are then fully determined.
- Obtaining correct relic abundance fixes DM mass (~1.1 TeV for 2-plet, 3 TeV for 3-plet, 14 TeV for 5-plet, etc). Even-numbered multiplets may be relevant for LZ, which will be discussed in Shingo Kazama's talk.
- Calculation of indirect detection signals requires non-trivial theoretical technology to resum effects from electroweak potential (similar physics to toponium!), large logs from $m_{\rm DM}/m_W$ ratio - used SCET techniques pioneered for collider physics
- Wino (3-plet) already appears strongly excluded by *Fermi* and HESS data; 5-plet and 7-plet have some tension [Safdi et al 2507.15934, Aghaie et al 2507.17607, Aharonian et al 2608.07234]
- Full CTAO observations of Galactic Center should test ~all odd-numbered multiplets even for very conservative DM density profiles [Baumgart, TRS et al 2507.15937]
- Higgsino (2-plet) is potentially testable by 2030 with high-zenith-angle observations at CTAO-North only [Abe et al 2506.08084], although the scenarios giving the largest signals may now be excluded by HESS 2026 line search

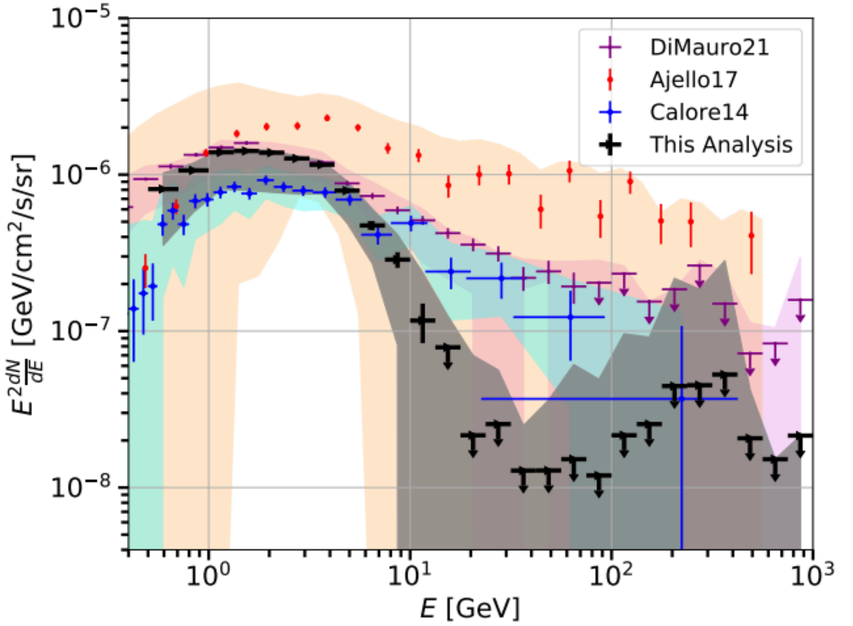
Aharonian et al 2608.07234



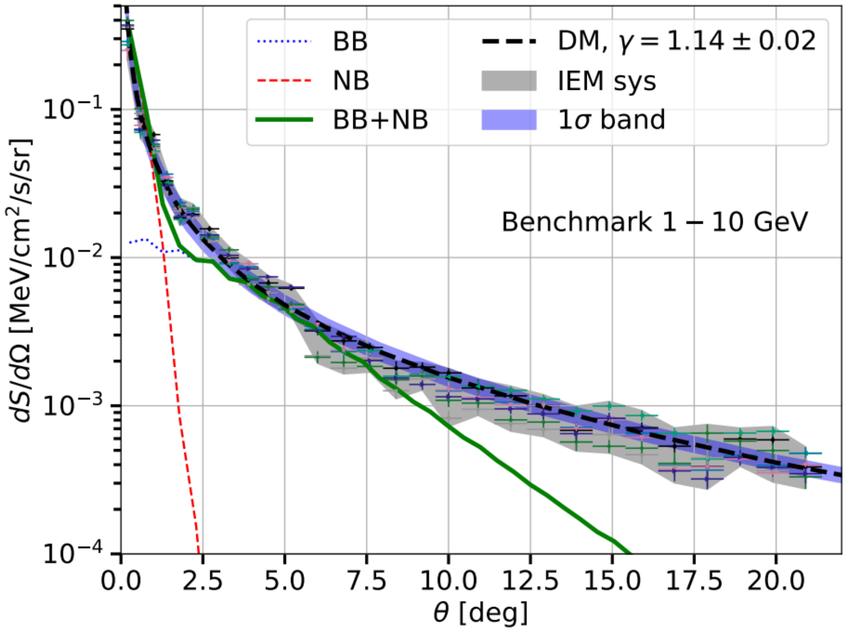


Status of the Galactic Center excess

- In the Galactic Center region (radius $\gtrsim 10°$) there is a long-standing excess of O(GeV) gamma rays, first identified by Hooper et al 0910.2998 (now also seen in DAMPE data [Alemanno et al 2512.23458])
- Highly significant, and (in my view) still consistent with a DM annihilation signal - but there is a competing SM explanation via a large population of millisecond pulsars (requires >35,000 according to analysis by List et al 2507.17804)
- Difficult to distinguish hypotheses given uncertainties in background modeling, pulsar number/distribution, and DM distribution [e.g. Muru et al 2508.06314]
- Generic DM models are in tension with non-detection in terrestrial experiments but not too hard to find model classes that work for ~50-100 GeV DM [e.g. Hu, TRS et al 2509.08043]
- Also a more recent claim of a “halo-like excess” at ~20 GeV energy and higher latitude [Totani 2507.07209] - a follow-up analysis suggested this does not have the expected morphology for a DM signal and is likely associated with the Fermi Bubbles [Cholis et al 2610.10695]



Recent morphology/spectrum analysis by di Mauro 2605.22913



Summary

- The nature of DM is one of the central puzzles of fundamental physics.
- Knowns: cosmological abundance (precisely), phase space distribution (in part), upper limits on interactions, lower limit on lifetime, upper + lower bounds on mass (very widely separated!)
- Unknowns: values of mass, lifetime, non-gravitational interactions (if any); origin of abundance; one or multiple species; and many more…
- Because the range of options is so broad, we need to both “search wide” and “delve deep” - make sure we explore the broad space of possibilities for dark matter, but at the same time push forward an ambitious program to explore well-motivated directions
- Lots of exciting theoretical work going on to understand and test the broad space of possibilities for DM (far beyond this talk - only time for a handful of examples here)
- Theoretical advances have identified boundaries on the available dark matter parameter space, allowed the use of existing data to test novel scenarios, sharpened predictions for the signals we hope to see at current/upcoming experiments, established the complementarity of different probes, drawn connections with other areas of physics, and initiated ideas for novel analyses and experiments.

BACKUP SLIDES

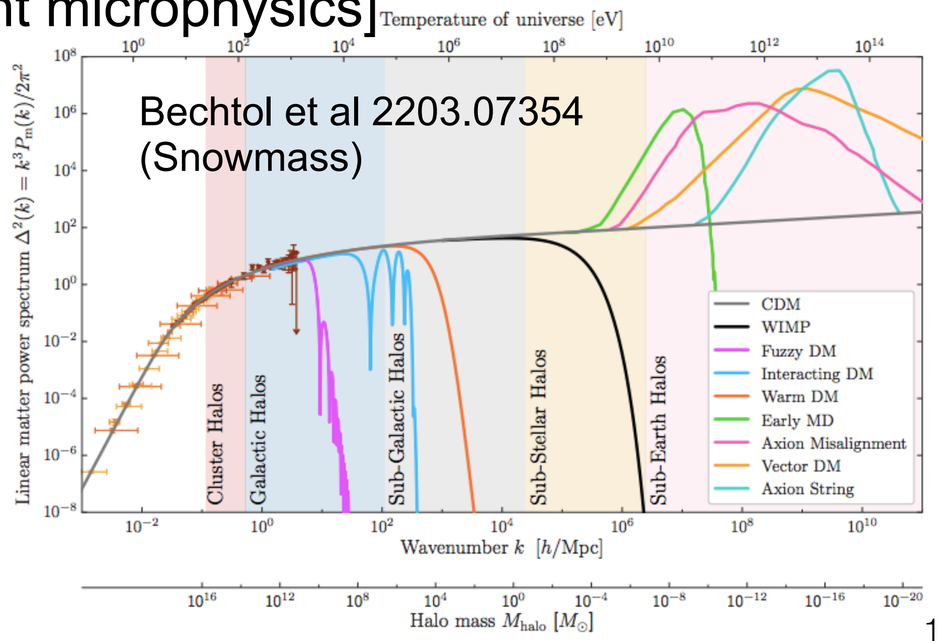
What more can we learn from purely gravitational probes of DM?

- Key idea: map how DM is distributed through the cosmos (in both space and time), via gravitational effects on stars/galaxies/gas clouds/etc, gravitational lensing, effects on radiation backgrounds, etc

- Many variations on DM physics would lead to suppression or modification of DM halos at some characteristic scale, e.g. DM-DM interactions, DM-SM interactions, a large primordial velocity or a tiny mass [*many* references, but e.g. Bechtol et al '22 (Snowmass), Adhikari et al 2207.10638 and Antypas et al 2203.14915 are useful reviews; Rose et al 2405.00766 describes the DREAMS project, a large-scale effort to simulate a wide range of relevant microphysics]

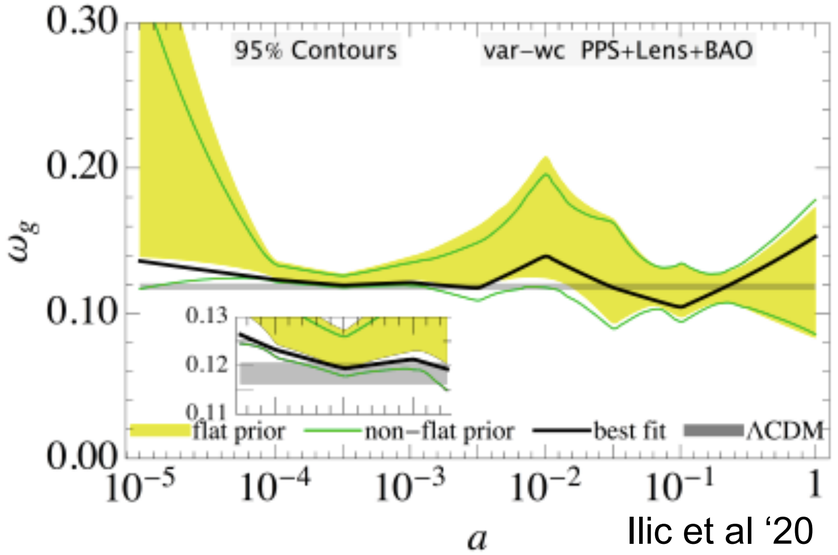
- Smallest scales are probed by stellar streams, Lyman-alpha forest, strong lensing, Milky Way satellites

- Most precise measurements are at large scales via CMB & increasingly large scale structure (LSS) - significant theory work in recent years to improve perturbative calculations via effective field theory treatment [e.g. public tools are described in Chudaykin et al 2004.10607, Reeves et al 2507.20990]



Cosmological constraints on DM properties

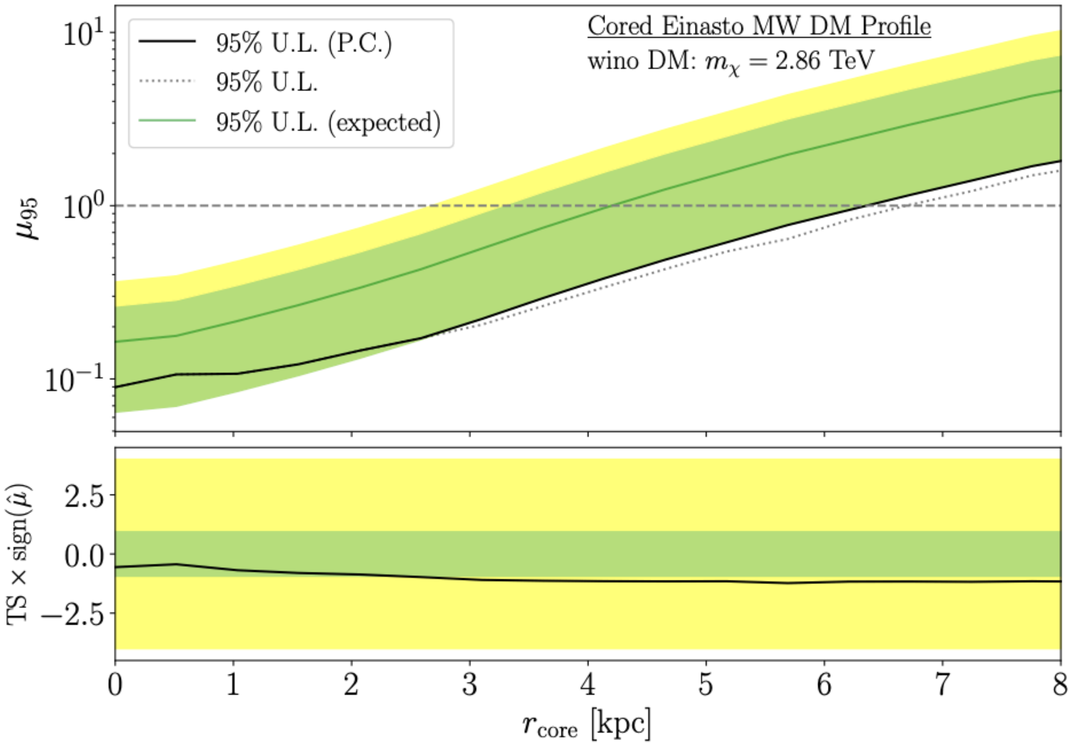
- Measurements of the abundances of light nuclei constrain the radiation content (N_{eff}) at the time of nucleosynthesis - set limits on light DM and possible associated dark sectors [e.g. Sabti et al 1910.01649, Giovanetti et al 2109.03246, An et al 2202.03515]
  - new codes to do this calculation include LINX [Giovanetti et al 2408.14538], PRyMordial [Burns et al 2307.07061], PRIMAT [Pitrou et al 1801.08023]
- Cosmology gives limits on how the DM content of the universe has changed over time, using observations of the CMB and large-scale structure [e.g. Poulin et al 1606.02073, Ilic et al 2004.09572, Simon et al 2203.07440]
- In wake of DESI results, there has been interest in models where the DM mass/abundance evolves at late times, e.g. to avoid phantom dark energy [e.g. Khoury et al 2503.16415, Bedroya et al 2507.03090]

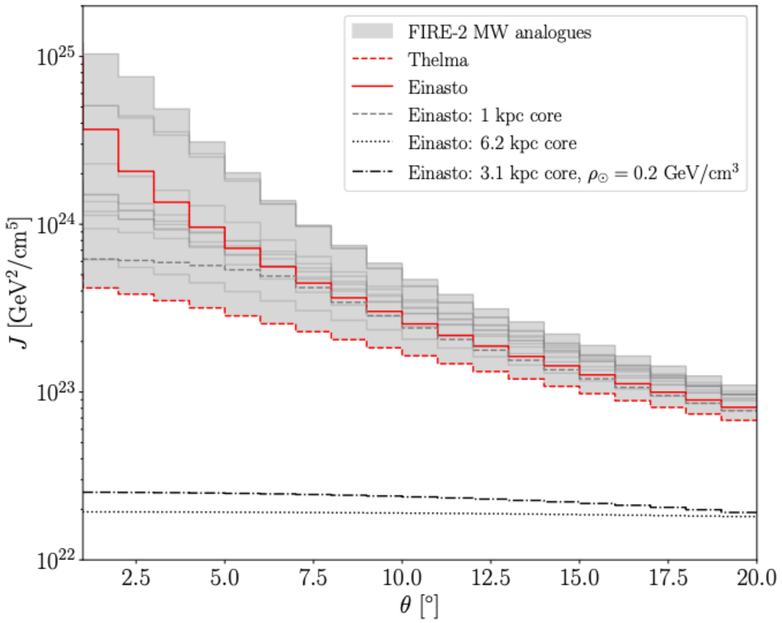


Ilic et al '20

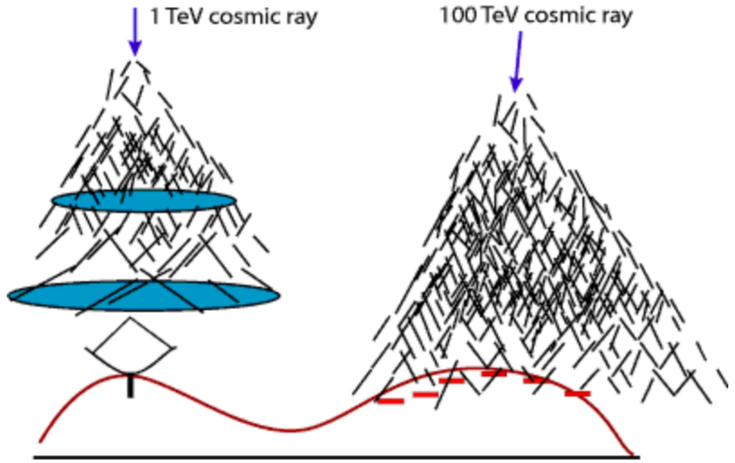
Limits on the wino

- Safdi & Xu ’25: thermal wino + standard cosmology is ruled out from Fermi data for core sizes less than ~6 kpc, also for ~3kpc core with local DM density 0.2 GeV/cm^3
- Thermal winos that do not make up all the DM are OK below 1.8 TeV (signal suppressed by DM density^2)
- Loopholes for heavier winos (above 3.5 TeV or so) making up 100% of DM if they are diluted to avoid overclosure
- Thermal higgsino is hard to test with indirect detection but potentially detectable with CTA/SWGO [e.g. Rodd et al 2405.13104]
- Other recent papers study experimental viability of relatively light neutralinos as DM in the phenomenological MSSM (pMSSM) and find there is still allowed parameter space [Barman et al 2402.07991, Constantin et al 2505.11251]





Next-generation high-energy gamma-ray telescopes

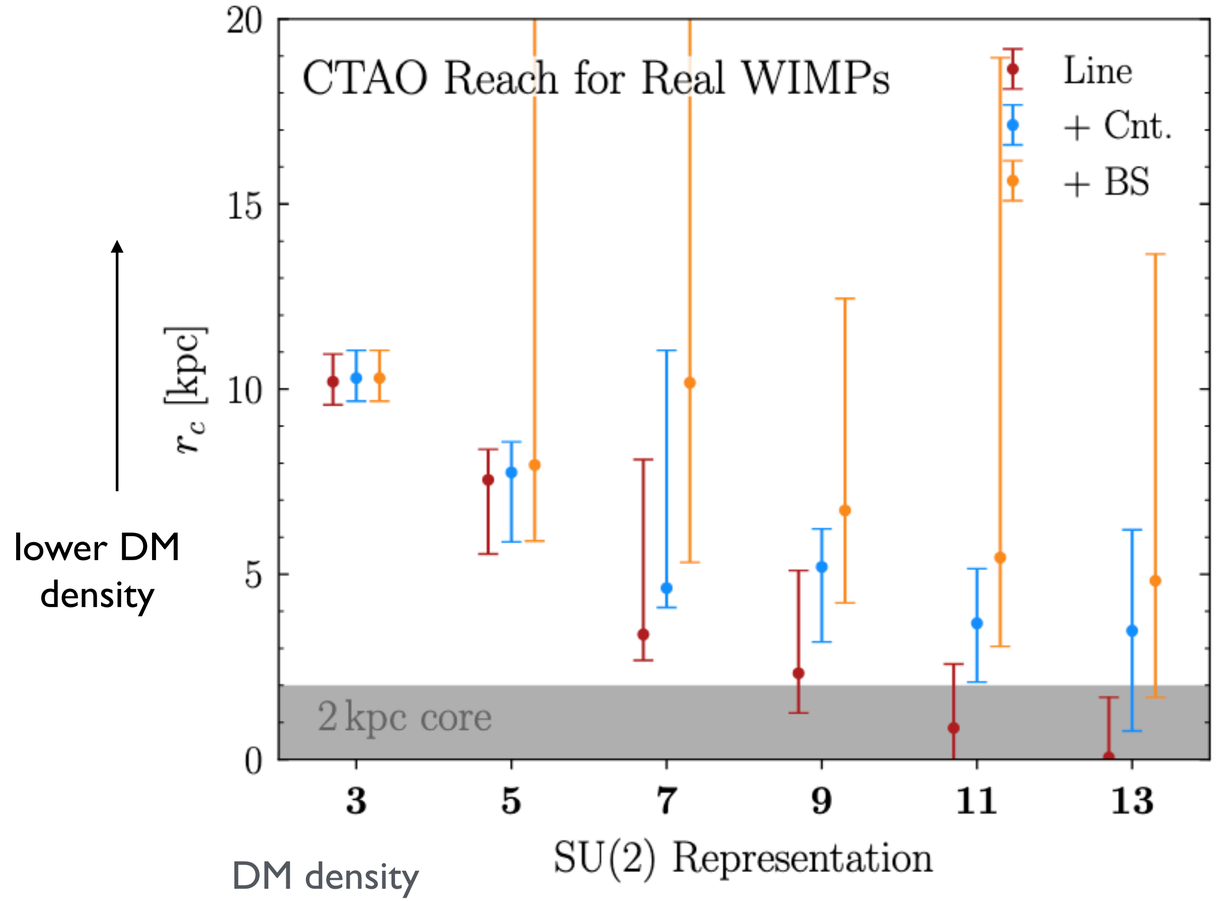


The observation of an extensive air shower particle cascade using by collecting Cherenkov radiation (left) and observing the shower particles at ground level (right). From the Milagro collaboration (copyright © 2002, University of California).

- **Cherenkov Telescope Array Observatory** (CTAO): air Cherenkov telescopes, 20 GeV - 300 TeV. “Alpha Configuration” has funding in place for construction during 2022-2027. Southern hemisphere site in Chile.
- **Southern Wide-Field Gamma-Ray Observatory** (SWGO): water Cherenkov telescopes, energies ~100 GeV - PeV, large field of view (45 degrees) = longer viewing of targets, better sensitivity to extended sources. Planned for Chile, construction start as early as 2026.
- **LACT** at LHAASO: add air Cherenkov telescope array in LHAASO site (existing water Cherenkov telescope) in China. In talks last year (e.g at TeVPA 2024), said could take data as early as this year.
- Also **Advanced Particle-Astrophysics Telescope** (APT): *Fermi* successor, space-based, much smaller area, focused on lower energies (< TeV); neutrino telescopes (**IceCube,** in future **P-ONE**)

Forecast constraints for heavy multiplets

- Use likelihood ratio method, test both binned and unbinned approaches
- Test effect of including only line signal, line + lower-energy photons from decays of annihilation products, + also bound states
- Express in terms of the ‘core radius’ needed to evade the constraints
- We find that CTAO should be able to test all these scenarios

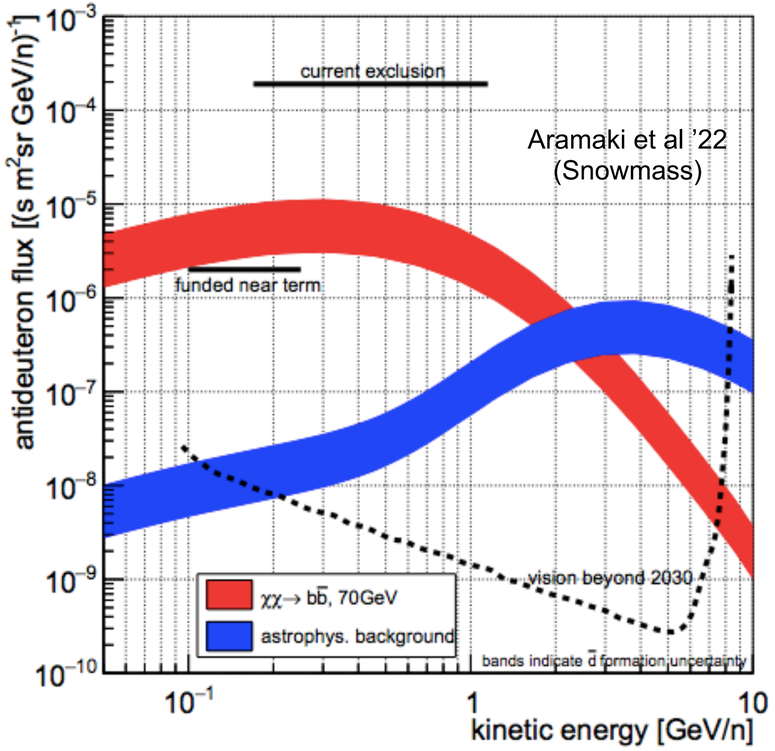


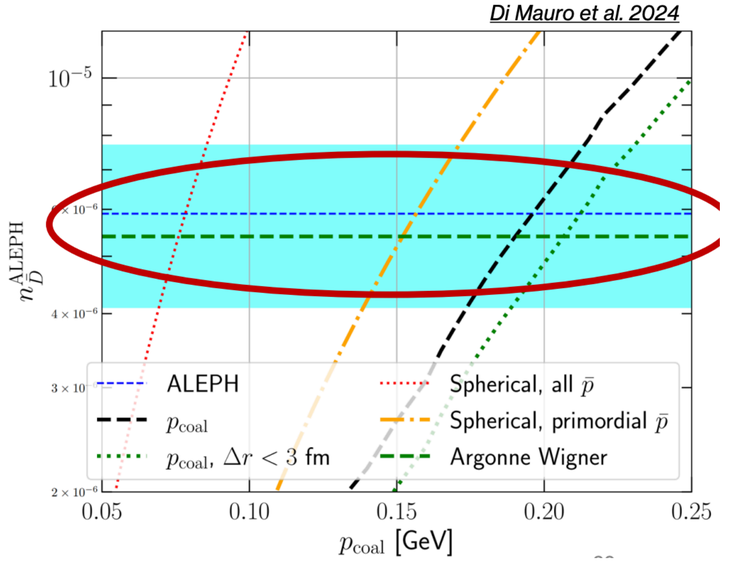
lower DM density

DM density consistent with observations/ simulations

Antinuclei as a smoking gun?

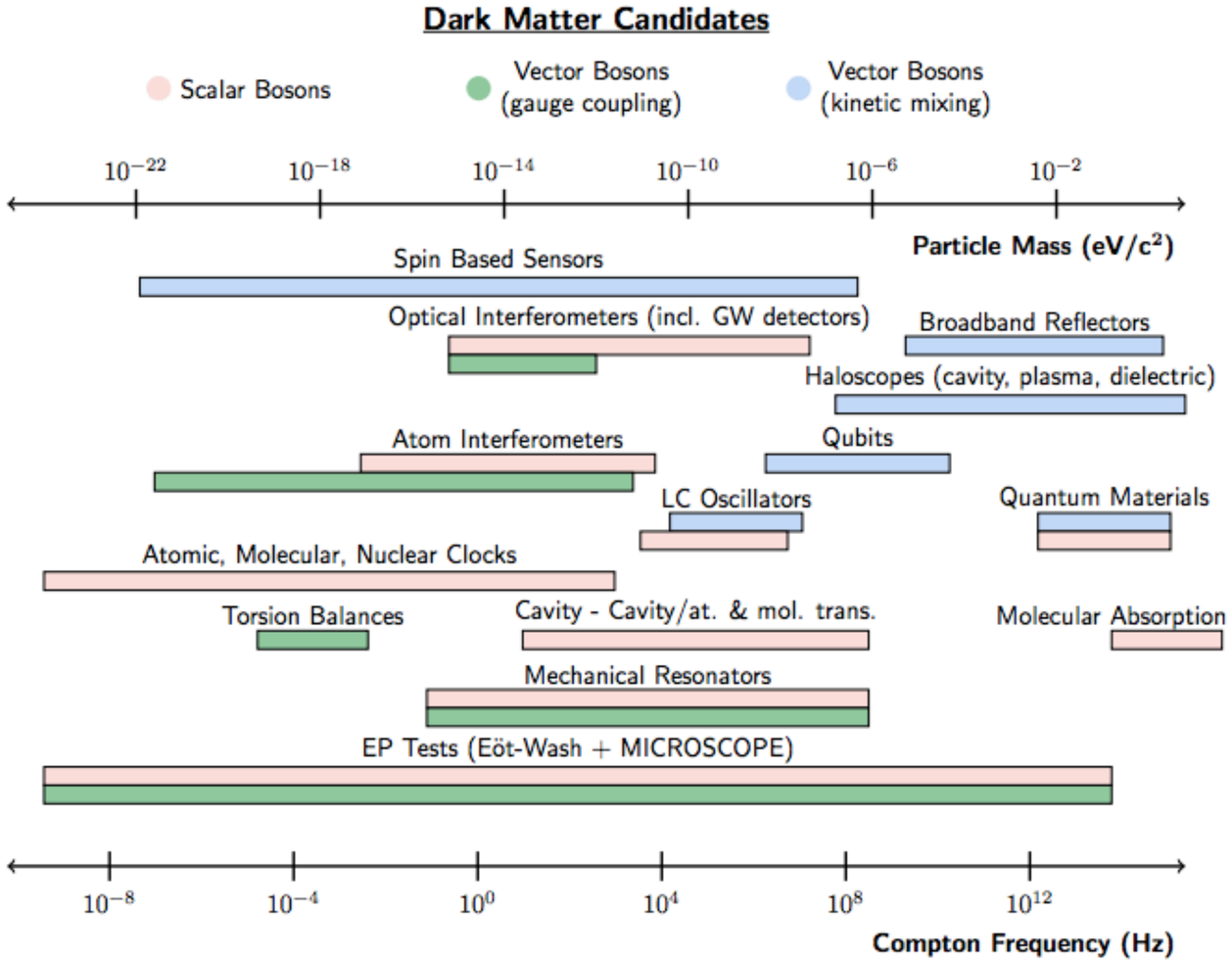
- Low-energy antinuclei (e.g. antideuterons, antihelium) are expected to have tiny astrophysical backgrounds
- Near-term: GAPS balloon flight scheduled for 2025-26 austral summer (rescheduled from 2024-2025), dedicated search for low-energy antiprotons + antideuterons
- AMS-02 has tentatively observed (at higher energies) O(10) anti-He events, including a claim of 2 anti-He-4 events ["AMS Days at La Palma, La Palma, Canary Islands, Spain," (2018)]
- This would be extremely unexpected - naively expect astrophysical flux to drop by O(10^{-4}) for each antinucleon added. However, large theory uncertainties, for both DM annihilation + astrophysical backgrounds - challenge for theorists.
- Winkler & Linden '21: production of $\bar{\Lambda}_b$-baryons which decay to antihelium could boost antihelium signal from DM annihilation, potentially to detectable levels; however, Pythia tune to capture this process may be in tension with preliminary LHCb data (LHCb-CONF-2024-005 + talk by Marta Razza, DarkTools 2025)
- Mahlein et al 2302.12696, di Mauro et al 2411.04815: new quantum-mechanical calculation to describe probability distribution to form an antideuteron, using Argonne v_{18} wavefunction:
  - no ad hoc parameters after tuning from nucleon-scattering datasets
  - validated on ALEPH data for $e^+e^- \rightarrow$ hadrons, matches multiplicity reasonably well
- Future prospects for further validation (e.g. for hadronic initial states) with ALICE data on antinuclei (e.g. ALICE 2407.10527)





Ultralight/wave-like DM

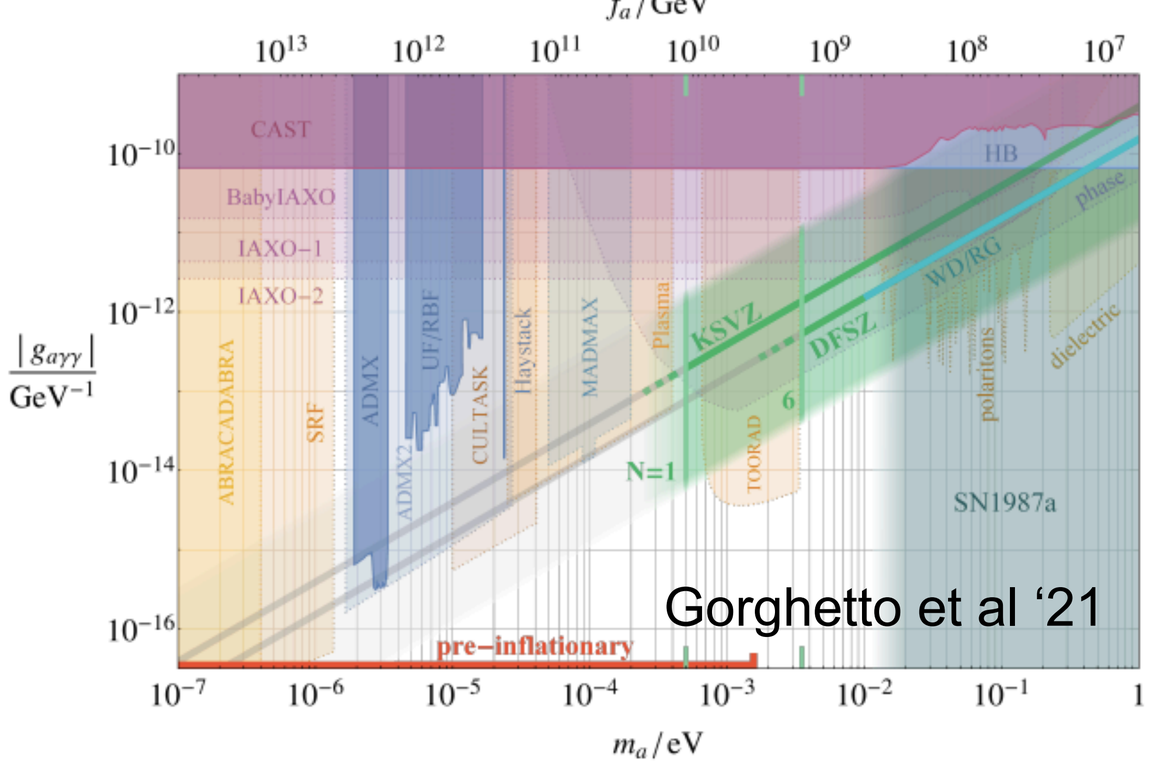
- For DM masses between 10^{-18} eV and ~1 keV, DM must be bosonic and avoid thermal contact with the Standard Model (= very weak interactions)
- At meV scales and below, wavelength is often macroscopic compared to terrestrial experiments
- Canonical example of DM in this range: QCD axion
- But DM could also be a new ultralight scalar/vector more generally - many ideas for tests for such particles

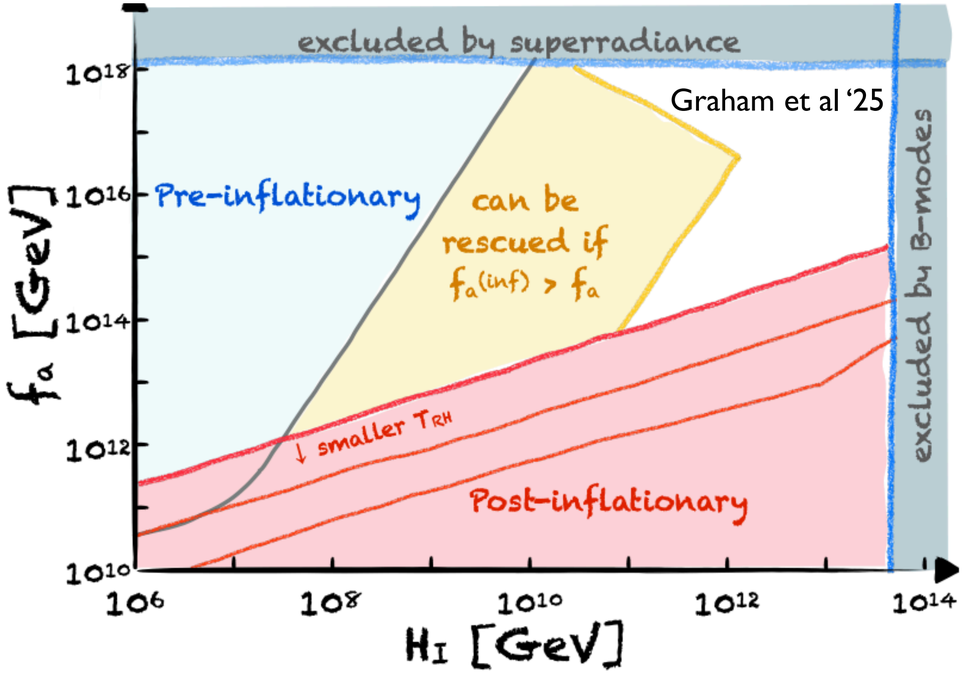


See Jaeckel et al '22 (Snowmass) and references therein

Some theory challenges for the QCD axion

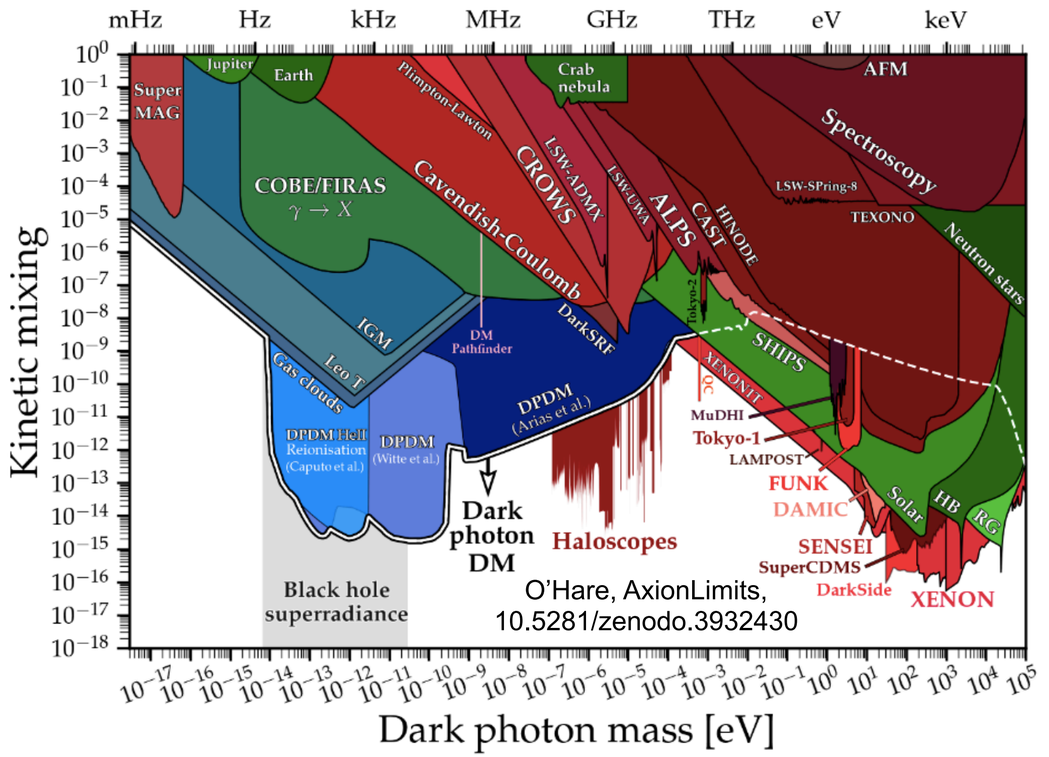
- Abundance: can obtain correct abundance from “misalignment mechanism”, however:
  - for "pre-inflation axion”, abundance fixed by initial condition, low axion masses require very small initial misalignment angle
  - for "post-inflation axion”, abundance calculation is challenging due to impact of axion string network; current latest estimate is correct abundance obtained for 40-300 μeV axions [Benabou et al 2412.08699]
- For pre-inflation axion models, stringent limits from (lack of) isocurvature modes in the CMB, although these limits can be avoidable in specific models [e.g. Graham et al 2506.03348, Chakraborty et al 2507.12519]
- “Axion quality problem” - need to avoid corrections to the axion potential that move the minimum away from the CP-conserving point. Generalized symmetries [see talk by Shao yesterday] can help [Craig et al 2408.10295]
- For post-inflation axion models, some generic tension between cosmology + solving the quality problem [Lu et al 2312.07650]

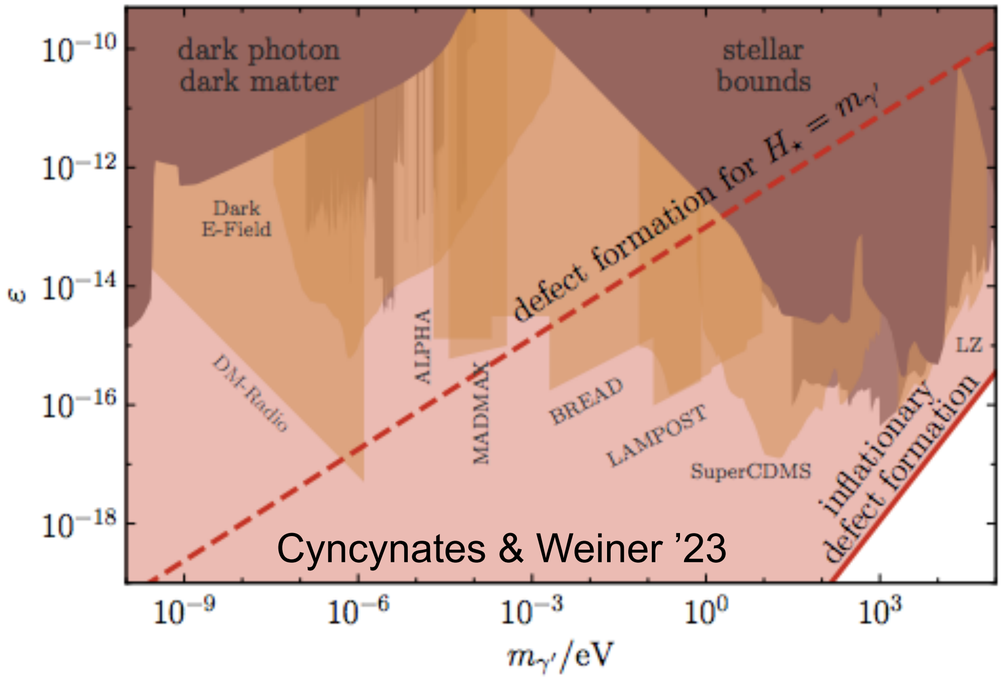




Some theory challenges for dark photons

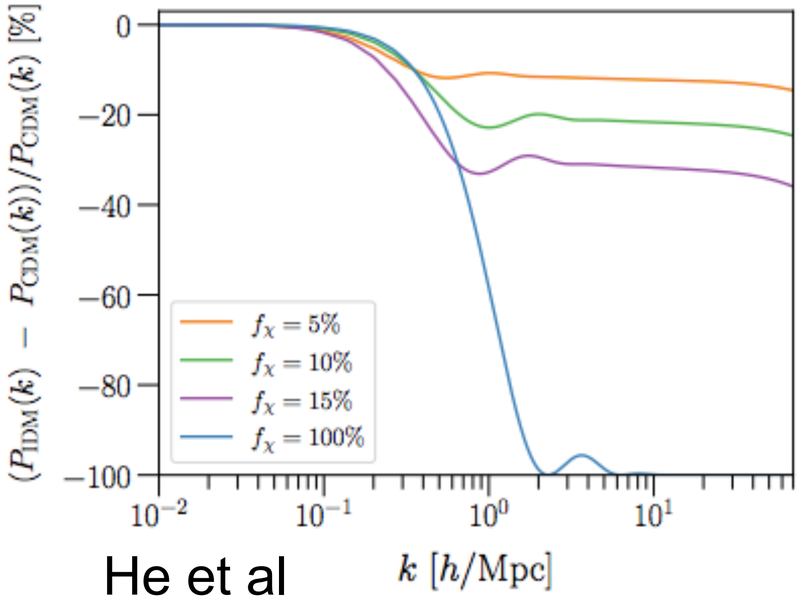
- Dark photon dark matter (i.e. U(1) vector boson) is a frequent benchmark for light vector DM, but some theoretical challenges:
  - Production is non-trivial; misalignment works for scalar fields, not vectors (but can convert energy stored in other fields, e.g. Agrawal et al 1810.07188 uses oscillation from an axion field; Graham et al 1504.02102 have an inflationary production mechanism)
  - East & Huang 2206.12432 pointed out that many production scenarios lead to vortices that drain energy out of the DM field (in the presence of a dark Abelian Higgs)
  - Parameter space may also be constrained from a top-down perspective by weak gravity conjecture [Reece 1808.09966, Craig & Garcia-Garcia 1810.05647]
  - These latter points depend on the origin of the dark photon mass, e.g. from a dark Higgs field or a Stueckelberg mass term



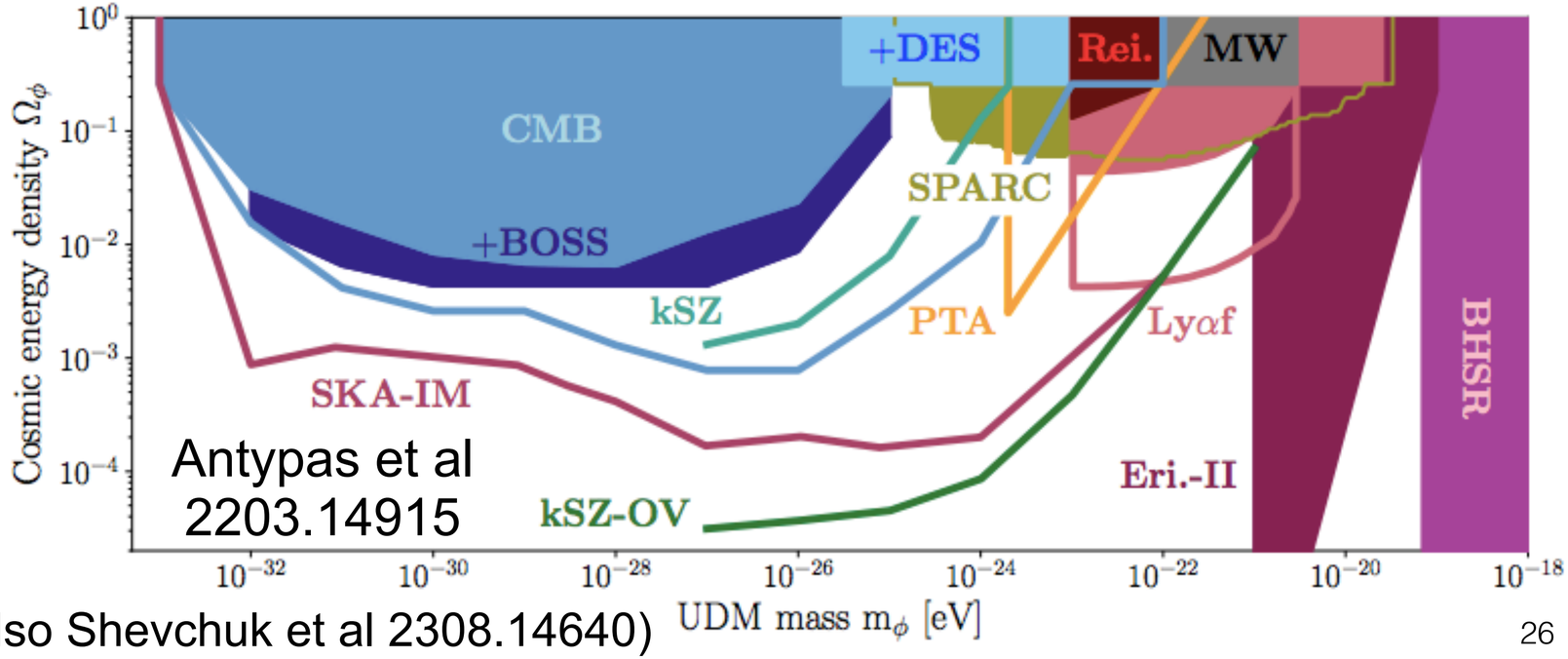


Tests of light dark matter

- Dark matter that is ultralight (large de Broglie wavelength), fast-moving, or has significant interactions with the SM, will have structure damped on small scales - cutoff in power spectrum of matter fluctuations
- If only a small fraction of the DM has such properties, suppression of power leads to plateau in power spectrum (can help with mild tension in measurements of S_8 parameter, describing matter fluctuations at 8 h^{-1} Mpc scale)
- Probe these features with precision cosmological probes + searches for the smallest dark matter halos + effects on evolution of astrophysical systems



He et al
2301.08260

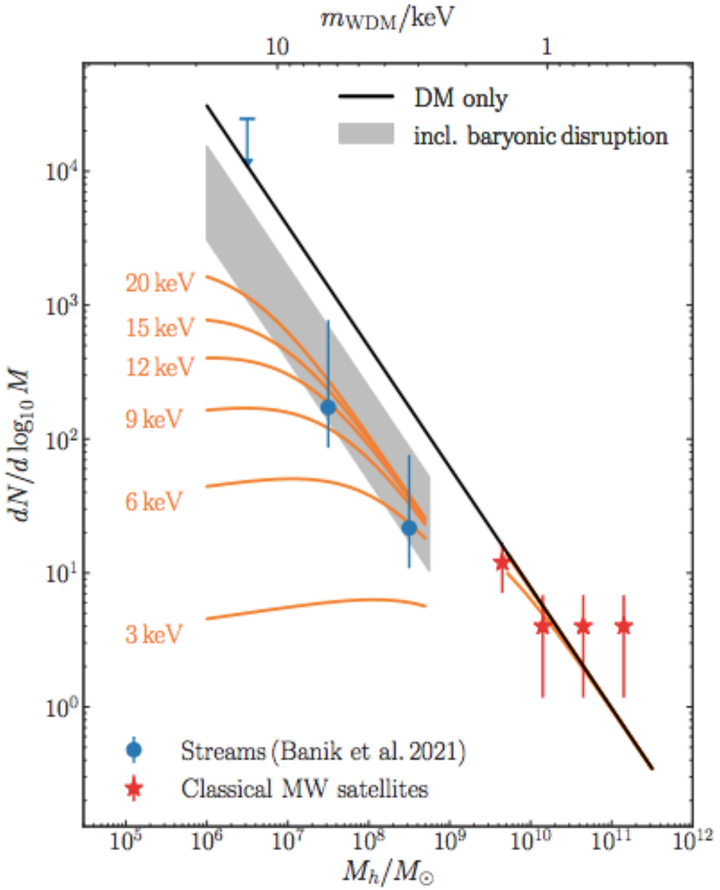


Antypas et al
2203.14915

(see also Shevchuk et al 2308.14640)

The smallest DM halos

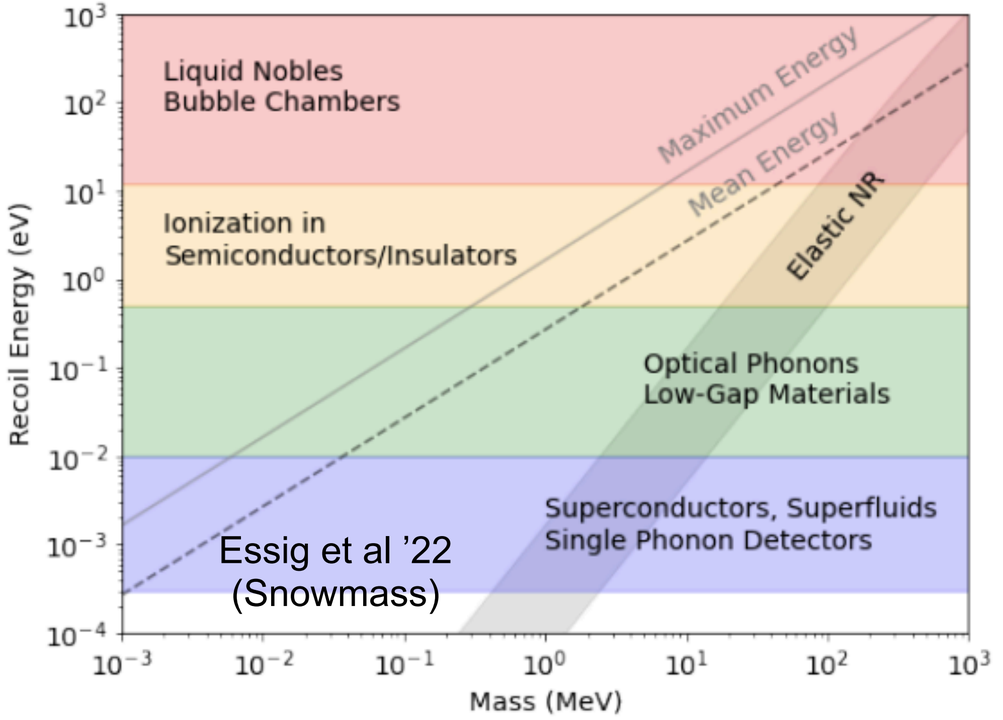
- One open question: what are the smallest bound DM structures in the universe, and what is their internal structure? Probes many types of physics:
  - Sufficiently light DM would have macroscopic de Broglie wavelengths - “fuzzy DM”
  - Free streaming of fast-moving DM in the early universe would erase small halos; if DM was once efficiently heated by interactions with SM, too-light DM would be fast-moving (like neutrinos)
  - DM interaction strengths (with itself and baryons) at low velocities [e.g. Nadler et al ’19, Bondarenko et al ’21, Andrade et al ’21]
- Multiple approaches to mapping the smallest currently-observable halos (~$10^{7\text{-}8}$ solar masses):
  - Lyman-α forest (probes matter clumpiness at redshift~2-6) [e.g. Armengaud et al ’17, Irsic et al ’17, Nori et al ’19]
  - Fluctuations in the density of stellar streams (perturbed by DM subhalos) [e.g. Banik et al ’21]
  - Strong gravitational lensing of quasars [e.g. Hsueh et al ’19, Gilman et al ’19, Nadler et al ‘21]
  - Observations of faint Milky Way satellite galaxies [e.g. Nadler et al ’19, ’21]



Low-mass direct detection

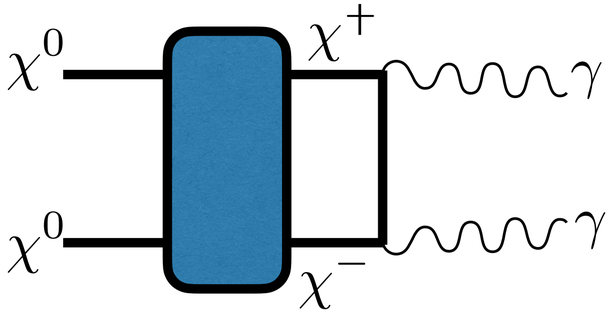
- There is a great deal of current interest in the MeV-GeV mass band
  - Simple dynamical explanations for DM abundance (thermal freezeout, freeze-in, and many variations)
  - Generally requires new mediators connecting DM and the Standard Model - "dark sectors", new "dark forces".
  - Constrained by indirect detection - picks out classes of models with small/absent annihilation signals

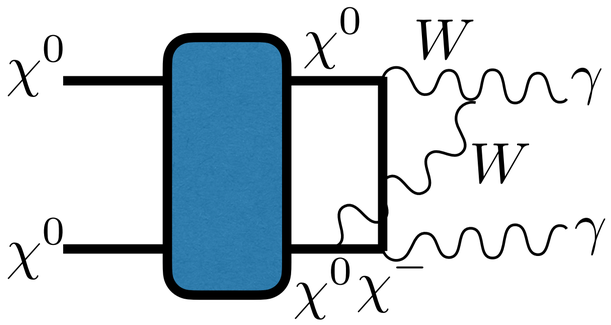
- Classic direct detection experiments lose sensitivity for DM masses below 1-10 GeV - kinematic mismatch between DM and atomic nuclei leads to tiny energy recoils
  - However, secondary photons/electrons produced in conjunction with nucleus-DM scattering, via bremsstrahlung or the "Migdal effect", can be detectable [e.g. Kouvaris et al '17, Ibe et al '18, Bell et al '20]
- Can gain by looking at electron recoils (better kinematics for MeV-scale DM)
- Very active research program underway to work out possibly observable signatures of tiny energy depositions, often using special features of carefully-chosen target materials, e.g. tiny bandgaps (see Essig et al '22 (Snowmass) for a review)



Precise signal predictions for MDM

- Sommerfeld enhancement = enhancement to annihilation from attractive long-range potential
- Same potential can support bound states
- Presence of similar-mass charged partners (in the multiplet) enhances direct annihilation to photons - clean signal, no astrophysical background (at gamma-ray energies)
- m_W/m_{DM} hierarchy leads to large Sudakov logs that need to be resummed [e.g. Baumgart, TRS et al '19, Beneke et al '20], using methods of Soft Collinear Effective Theory (SCET)





SCET for MDM

Baumgart, Rodd, TRS & Vaidya 2309.11562

- LONG and complicated calculation (done in great detail for the 3-plet in a series of papers by multiple groups starting in 2014)

- However, it turns out to be possible to separate out the representation; most of the calculation is unaffected by going to larger multiplets

$$\mathcal{L}^{(0)}_{\rm hard} = C\left(\chi_v^T i\sigma_2 \left\{t_\chi^a, t_\chi^b\right\}\chi_v\right)\left(Y^{abcd}\mathcal{B}^{ic}_{\perp n}\mathcal{B}^{jd}_{\perp\bar{n}}\right) i\epsilon^{ijk}(n-\bar{n})^k\,,$$

$$C = -\pi\frac{\alpha_W(\mu)}{2M_\chi}\,,$$

$$Y^{abcd} = (Y_v^{ae}Y_n^{ce})\left(Y_v^{bf}Y_{\bar{n}}^{df}\right)\,.$$

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Depends explicitly on representation of DM particles via generators, contributes to same terms as Sommerfeld factors

controlled solely by physics of gauge bosons

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Depends explicitly on representation of DM particles via generators, contributes to same terms as Sommerfeld factors

controlled solely by physics of gauge bosons

$$\sigma = F^{a'b'ab} \hat{\sigma}^{a'b'ab}(z_{\rm cut})$$

can read this off (or trivially re-compute) from SCET wino calculation

$$F^{a'b'ab} = \langle (\chi^0\chi^0)_S | \left(\chi_v^T i\sigma_2 \left\{t_\chi^{a'}, t_\chi^{b'}\right\} \chi_v\right)^\dagger |0\rangle\langle 0| \left(\chi_v^T i\sigma_2 \left\{t_\chi^a, t_\chi^b\right\} \chi_v\right) |(\chi^0\chi^0)_S\rangle$$

incorporates Sommerfeld factors & representation dependence from initial state

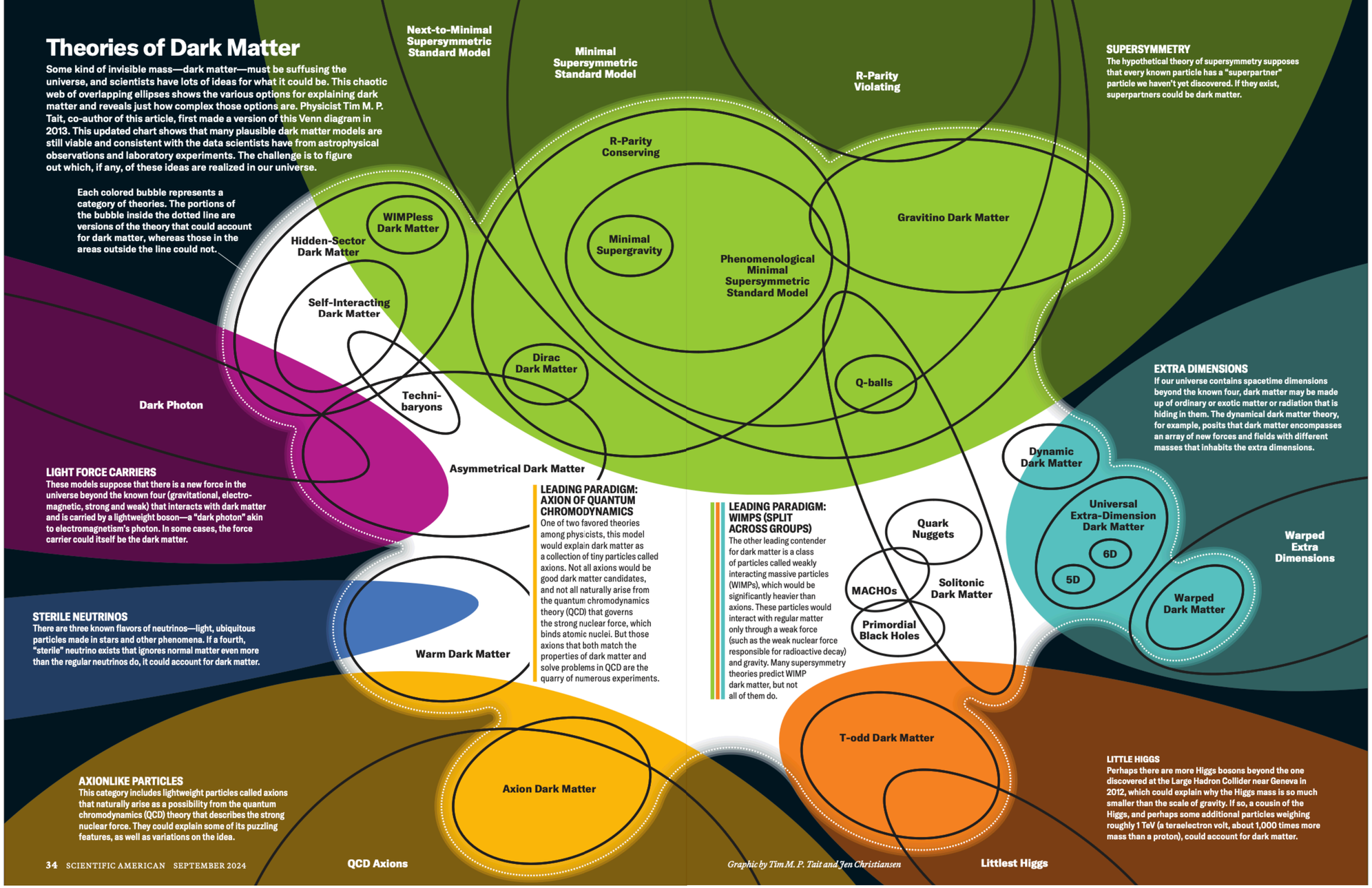
Recipe for MDM indirect signals

- Solve the Schrodinger equation to determine:
  — the distortion of the wavefunction of the colliding particles (Sommerfeld enhancement)
  — the spectrum of bound states in the theory
  Note: may also need to account for higher-order corrections to the potential, e.g. Beneke, Szafron & Urban ‘19

- Use perturbation theory in non-relativistic quantum mechanics to compute the capture rate into bound states and transition rate between bound states

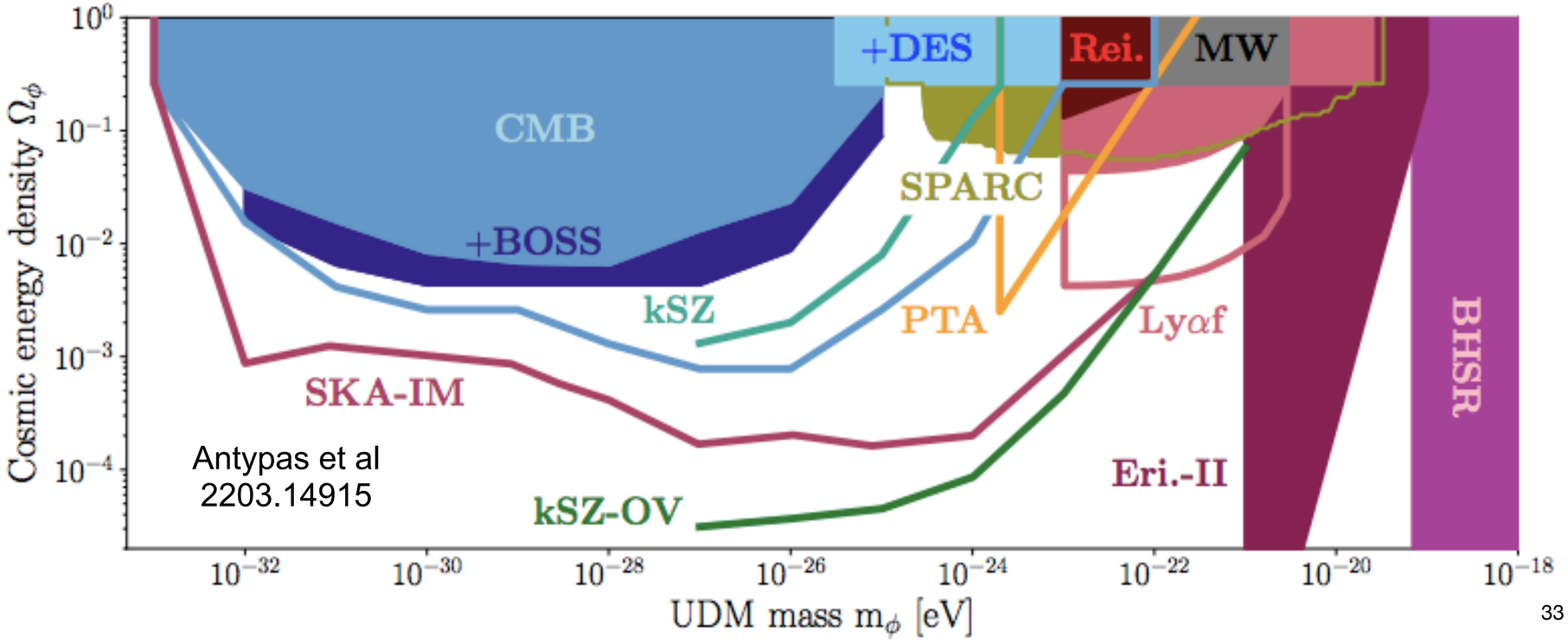
- Use Soft Collinear Effective Theory (SCET) techniques to compute the annihilation rate of both unbound DM and all the (meta)stable bound states, and the spectrum of gamma rays produced

- The techniques developed here should also be applicable to more general DM scenarios, whenever there is a large mass hierarchy between the DM and particles it interacts with


Theories of Dark Matter
Some kind of invisible mass—dark matter—must be suffusing the universe, and scientists have lots of ideas for what it could be. This chaotic web of overlapping ellipses shows the various options for explaining dark matter and reveals just how complex those options are. Physicist Tim M. P. Tait, co-author of this article, first made a version of this Venn diagram in 2013. This updated chart shows that many plausible dark matter models are still viable and consistent with the data scientists have from astrophysical observations and laboratory experiments. The challenge is to figure out which, if any, of these ideas are realized in our universe.
Each colored bubble represents a category of theories. The portions of the bubble inside the dotted line are versions of the theory that could account for dark matter, whereas those in the areas outside the line could not.
Next-to-Minimal Supersymmetric Standard Model
Minimal Supersymmetric Standard Model
R-Parity Violating
SUPERSYMMETRY
The hypothetical theory of supersymmetry supposes that every known particle has a "superpartner" particle we haven't yet discovered. If they exist, superpartners could be dark matter.
R-Parity Conserving
WIMPless Dark Matter
Hidden-Sector Dark Matter
Minimal Supergravity
Gravitino Dark Matter
Phenomenological Minimal Supersymmetric Standard Model
Self-Interacting Dark Matter
Dirac Dark Matter
Q-balls
Techni-baryons
Dark Photon
EXTRA DIMENSIONS
If our universe contains spacetime dimensions beyond the known four, dark matter may be made up of ordinary or exotic matter or radiation that is hiding in them. The dynamical dark matter theory, for example, posits that dark matter encompasses an array of new forces and fields with different masses that inhabits the extra dimensions.
Dynamic Dark Matter
Universal Extra-Dimension Dark Matter
6D
5D
Warped Extra Dimensions
Warped Dark Matter
LIGHT FORCE CARRIERS
These models suppose that there is a new force in the universe beyond the known four (gravitational, electromagnetic, strong and weak) that interacts with dark matter and is carried by a lightweight boson—a "dark photon" akin to electromagnetism's photon. In some cases, the force carrier could itself be the dark matter.
Asymmetrical Dark Matter
LEADING PARADIGM: AXION OF QUANTUM CHROMODYNAMICS
One of two favored theories among physicists, this model would explain dark matter as a collection of tiny particles called axions. Not all axions would be good dark matter candidates, and not all naturally arise from the quantum chromodynamics theory (QCD) that governs the strong nuclear force, which binds atomic nuclei. But those axions that both match the properties of dark matter and solve problems in QCD are the quarry of numerous experiments.
LEADING PARADIGM: WIMPS (SPLIT ACROSS GROUPS)
The other leading contender for dark matter is a class of particles called weakly interacting massive particles (WIMPs), which would be significantly heavier than axions. These particles would interact with regular matter only through a weak force (such as the weak nuclear force responsible for radioactive decay) and gravity. Many supersymmetry theories predict WIMP dark matter, but not all of them do.
Quark Nuggets
MACHOs
Solitonic Dark Matter
Primordial Black Holes
STERILE NEUTRINOS
There are three known flavors of neutrinos—light, ubiquitous particles made in stars and other phenomena. If a fourth, "sterile" neutrino exists that ignores normal matter even more than the regular neutrinos do, it could account for dark matter.
Warm Dark Matter
T-odd Dark Matter
AXIONLIKE PARTICLES
This category includes lightweight particles called axions that naturally arise as a possibility from the quantum chromodynamics (QCD) theory that describes the strong nuclear force. They could explain some of its puzzling features, as well as variations on the idea.
Axion Dark Matter
LITTLE HIGGS
Perhaps there are more Higgs bosons beyond the one discovered at the Large Hadron Collider near Geneva in 2012, which could explain why the Higgs mass is so much smaller than the scale of gravity. If so, a cousin of the Higgs, and perhaps some additional particles weighing roughly 1 TeV (a teraelectron volt, about 1,000 times more mass than a proton), could account for dark matter.
QCD Axions
Littlest Higgs
Graphic by Tim M. P. Tait and Jen Christiansen
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The lower mass limit

- If the DM wavelength is astrophysical in size, can modify the DM distribution and visible astrophysical tracers in observable ways
- For 100% of DM, DM mass $\gtrsim 3 \times 10^{-19}$eV (sub-percent fractions can be much lighter); at this mass range, limits come from constraining heating of stars in ultra-faint dwarf galaxies due to wave interference effects in the DM density, e.g. May et al 2509.02781
- Other DM physics that can modify the smallest DM halos: large primordial velocity (warm DM), DM-SM interactions, DM-DM interactions

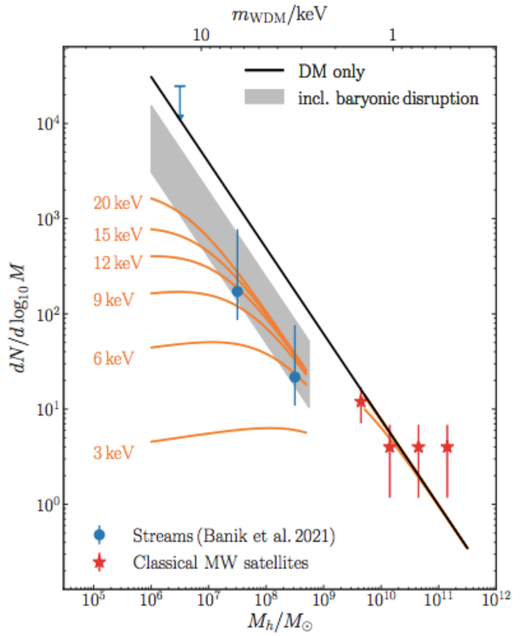


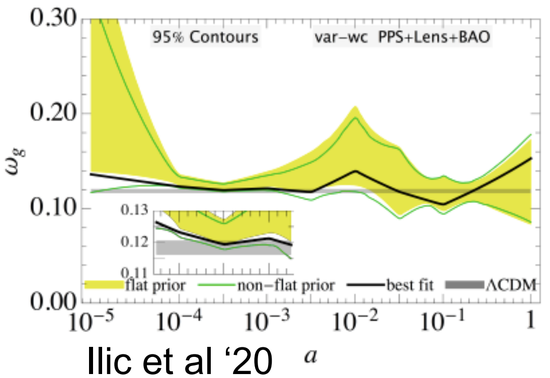
Mass bounds and spin-statistics

- The Tremaine-Gunn bound: Pauli exclusion means identical fermions cannot be packed arbitrarily tightly
- Thus if the observed DM number density exceeds a certain threshold, it implies the DM must be bosonic (or consist of many fermionic species)
- The best limits come from dwarf galaxy observations; different methods find lower limits on the fermionic dark matter mass around a few hundred eV (410 eV in Boyarsky et al 0808.3902, 190 eV in Savchenko et al 1903.01862)
- Thus DM in the broad range $3 \times 10^{-19} \lesssim m_{\rm DM}/{\rm eV} \lesssim 400$ must be bosonic
- DM must also be cold/slow-moving (no large free-streaming length) when the SM temperature was O(keV), to avoid erasing modes that later contribute to structure formation
- Sets stringent bounds on the DM interaction with SM, especially models where DM is produced from or thermalized with the SM (e.g. freeze-in, freeze-out)
- For classic “warm dark matter” scenario, limits from strong lensing require $m_{\rm DM} \gtrsim 7$ keV for fermionic DM [Gilman et al 2606.05277], with comparable limits from the Lyman-alpha forest, stellar streams, and dwarf galaxy observations
- Thus roughly sub-keV DM must be bosonic, cold, feebly interacting with SM

What more can we learn about DM from its gravitational footprint?

- Potential to improve these limits (or detect breakdown of ‘collisionless cold dark matter’ framework) with ongoing push to probe the smallest detectable DM structures
- Ongoing theoretical work to better model signatures of modified DM physics and determine optimal observables, e.g. the DREAMS project [https://www.dreams-project.org/]
- Work on simulations + analysis of stellar data is also sharpening understanding of DM density/velocity distribution in the Milky Way (relevant to direct+indirect detection) [e.g. Hussein et al 2501.14868, Folsom et al 2505.07924, Zhang et al 2610.28731]
- Cosmology gives stringent limits on how the DM content of the universe has changed over time, using observations of the CMB and large-scale structure [e.g. Poulin et al 1606.02073, Ilic et al 2004.09572, Simon et al 2203.07440]
- In wake of DESI results, there has been interest in models where the DM mass/abundance evolves at late times, e.g. to avoid phantom dark energy [e.g. Khoury et al 2503.16415, Bedroya et al 2507.03090]





Ilic et al ‘20