Where Next for Indirect Dark Matter Searches?

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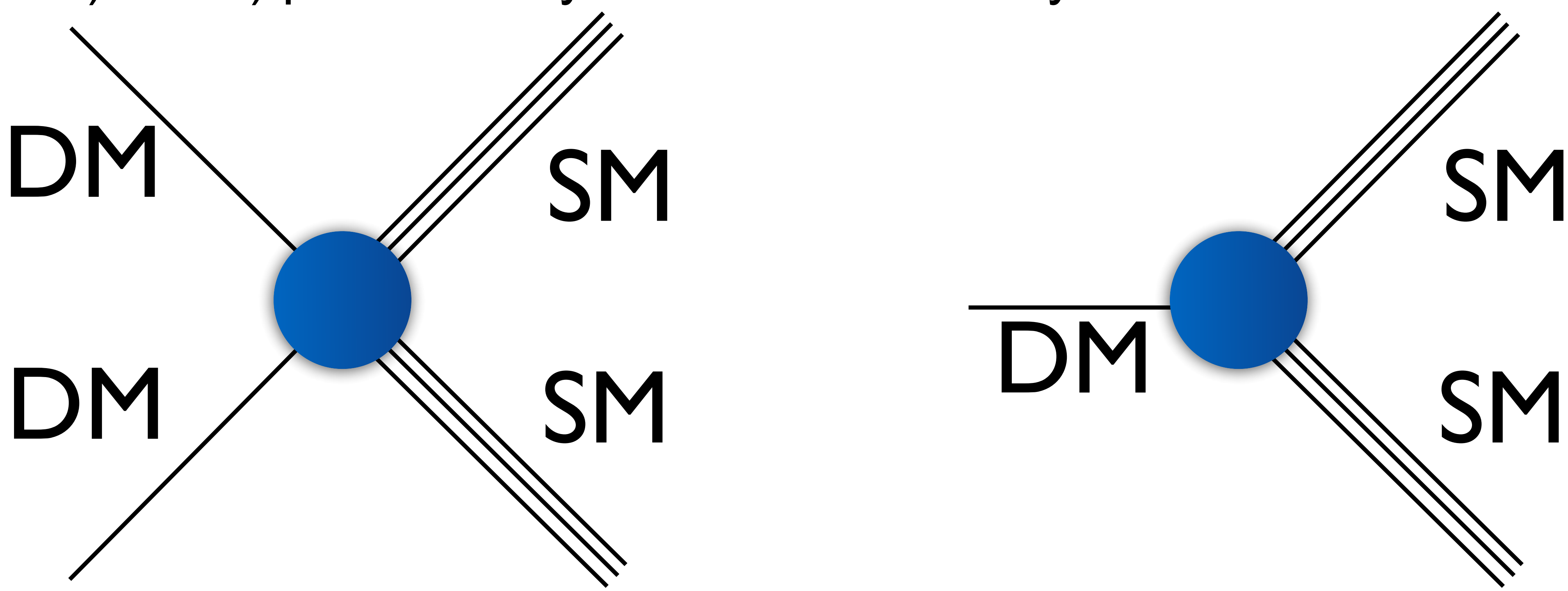
Indirect detection

- A tentative definition: search for signals of dark matter interactions
  (1) by measuring Standard Model particles,
  (2) where the relevant dark matter interactions occur <u>outside</u> the detector

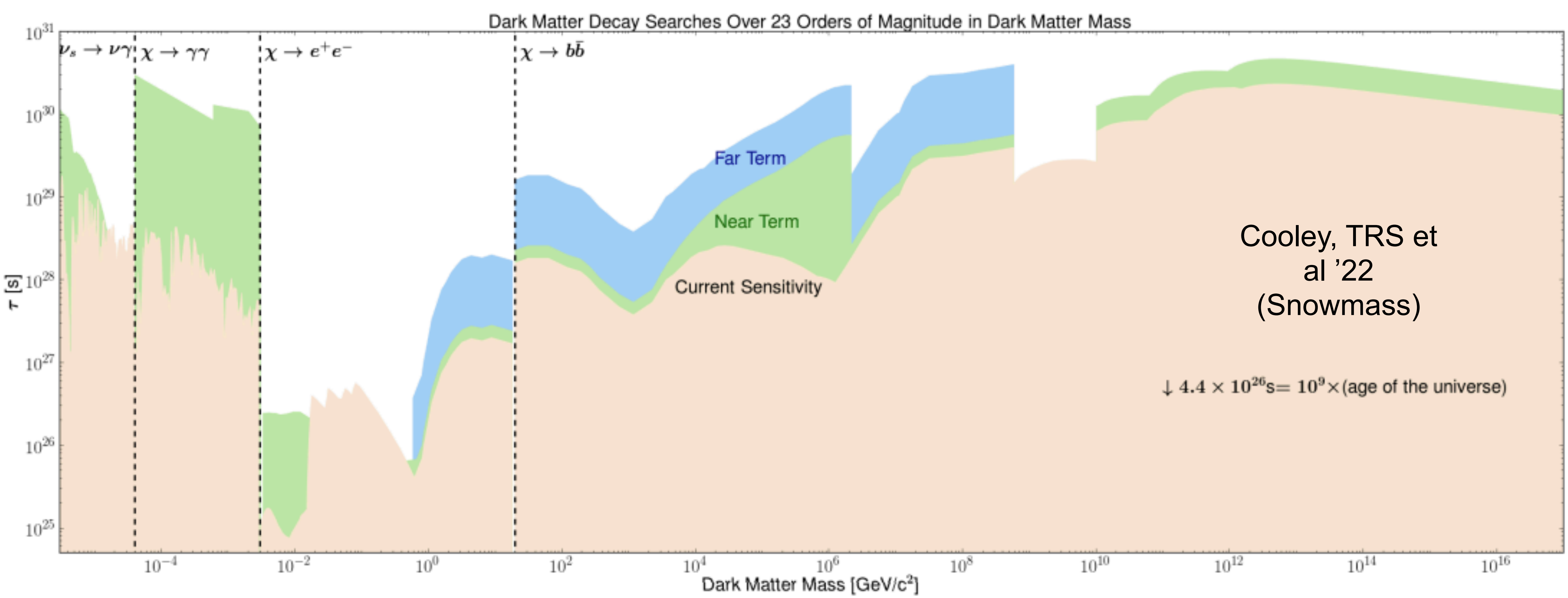
- Classic examples: search for long-lived particles (photons, neutrinos, (anti)nuclei) produced by annihilation / decay of dark matter



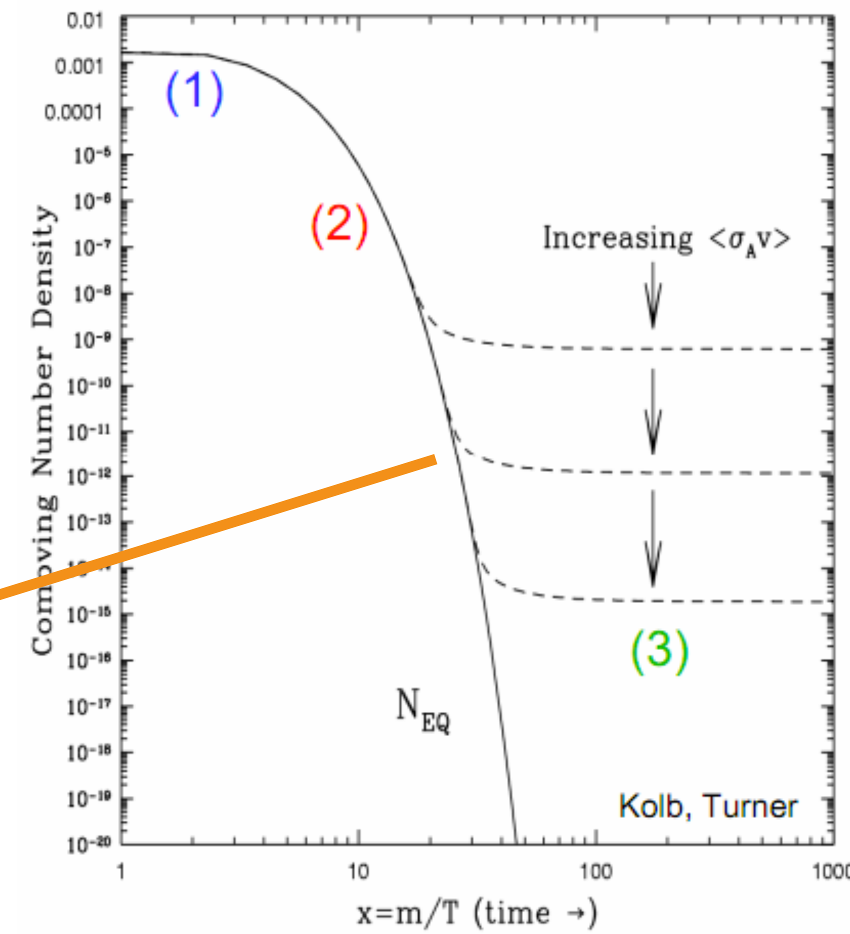
- Variations: search for other production mechanisms (e.g. axion-photon oscillation), search for downstream observable effects rather than the particles themselves (e.g. heating of gas clouds, ionization of early universe)

Why indirect detection?

- Take advantage of existing multiwavelength/multimessenger ensemble of observatories designed to study astrophysics → tests DM properties over enormous mass range
- Interactions can occur anywhere outside detector = can probe enormous time/length scales, unique sensitivity to properties like DM lifetime
- In thermal freezeout scenarios, directly probes annihilation process that sets DM abundance
- Example: for visible decays, DM lifetime must be 8+ orders of magnitude longer than the age of the universe over 20+ orders of magnitude in mass



Testing thermal freezeout



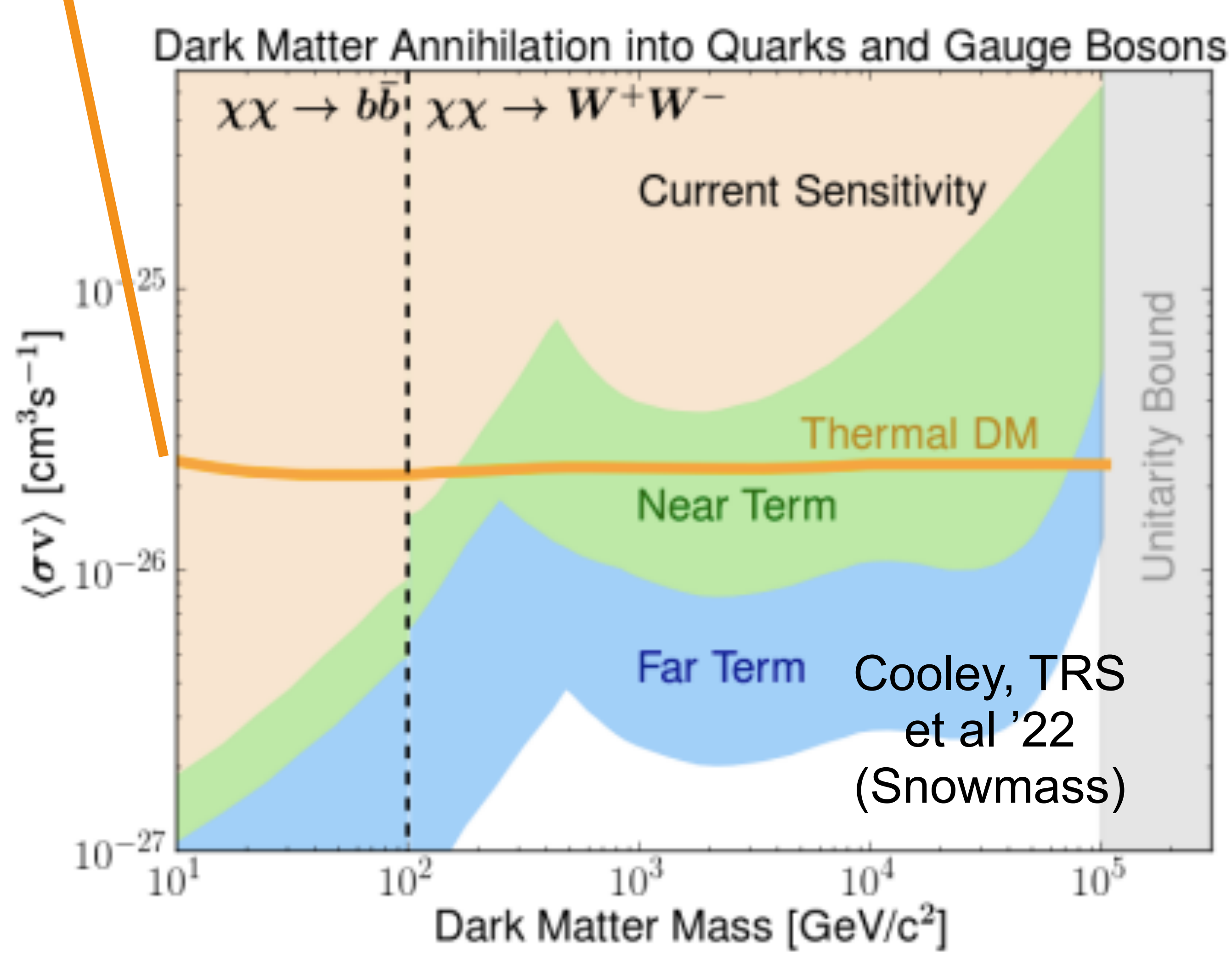
- Can we exclude DM that annihilates with the thermal relic cross section into SM particles? (or mediators that promptly decay to SM particles)

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

- Generally viable down to m_{DM} ~ 1-10 MeV; new mediators required for $m_{DM} \lesssim 2$ GeV. Unitarity + standard cosmology requires m_{DM} < 100 TeV - 1 PeV [Smirnov, Beacom '19]

- Currently, multiwavelength photon and cosmic-ray observations (especially *Fermi*, AMS-02) constrain thermal relic cross sections up to O(10s-100s) GeV, for all final states except neutrinos

- In the next 10 years: large southern hemisphere ground-based gamma-ray telescopes aim to test thermal relic cross-section up to 10s of TeV (expanding on existing program with HESS, VERITAS, MAGIC, HAWC, LHAASO)



The next generation of high-energy gamma-ray telescopes

- **LACT** at LHAASO: add air Cherenkov telescope array in LHAASO site (existing water Cherenkov telescope) [see plenary talk by Zhen Cao]. First light in the next year. Northern hemisphere => Galactic Center at high zenith angle [but see e.g. Abe et al 2212.10527 (MAGIC) for an example of competitive constraints with high-zenith-angle observations].

- **Cherenkov Telescope Array** (CTA): air Cherenkov telescopes, 20 GeV - 300 TeV. “Alpha Configuration” has funding in place for construction during 2022-2027 [see plenary talk by Manuel Meyer]. Southern hemisphere site in Chile.

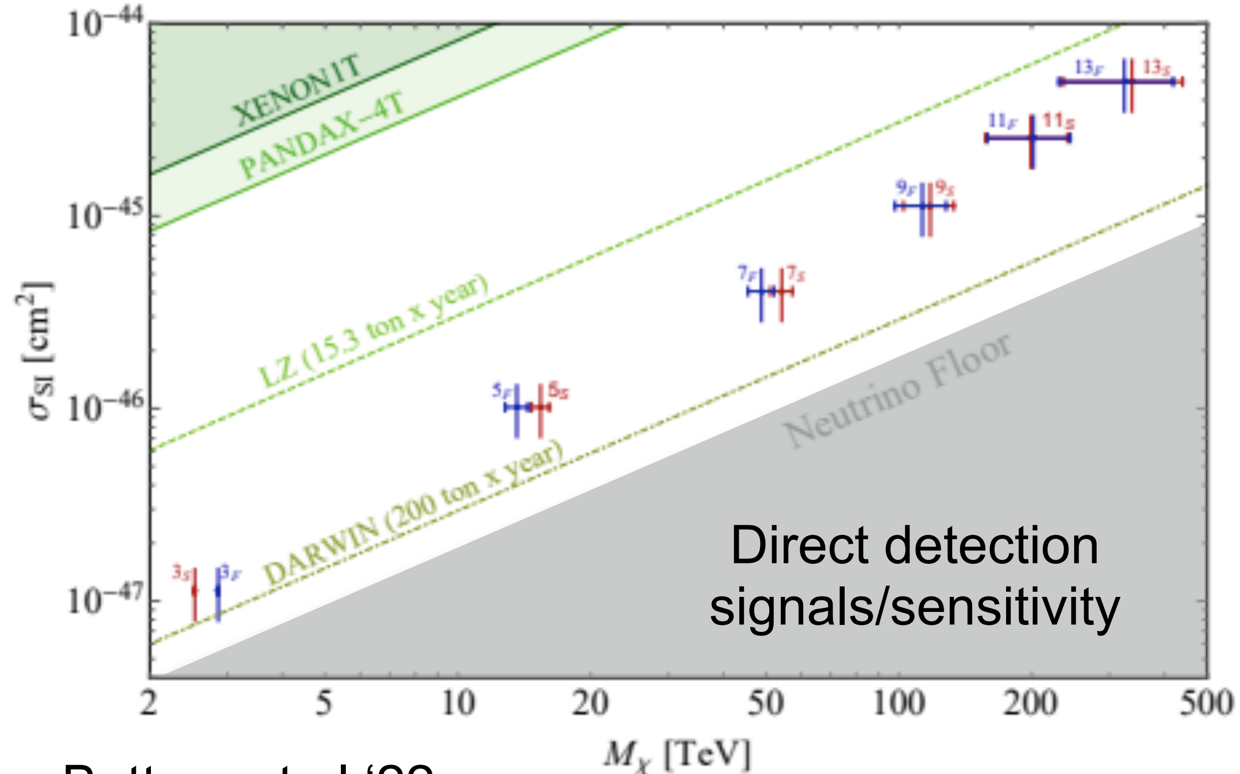
- **Southern Wide-Field Gamma-Ray Observatory** (SWGO): water Cherenkov telescopes, energies ~100 GeV - PeV, large field of view (45 degrees) = longer viewing of targets, better sensitivity to extended sources. Recent announcement on August 12 - site chosen at Atacama Astronomical Park in Chile. Construction start “as early as 2026”, “begin gamma-ray observations before the end of the decade” (source: https://www.swgo.org/SWGOWiki/doku.php?id=site_press_release). NSF has provided R&D funding to date.

- **Advanced Particle-Astrophysics Telescope** (APT): space-based, much smaller area, focused on lower energies (< TeV) - could significantly improve on *Fermi* limits in GeV-TeV range [e.g. Xu et al 2308.15538]. Demonstrator ADAPT scheduled for balloon flight in 2025.

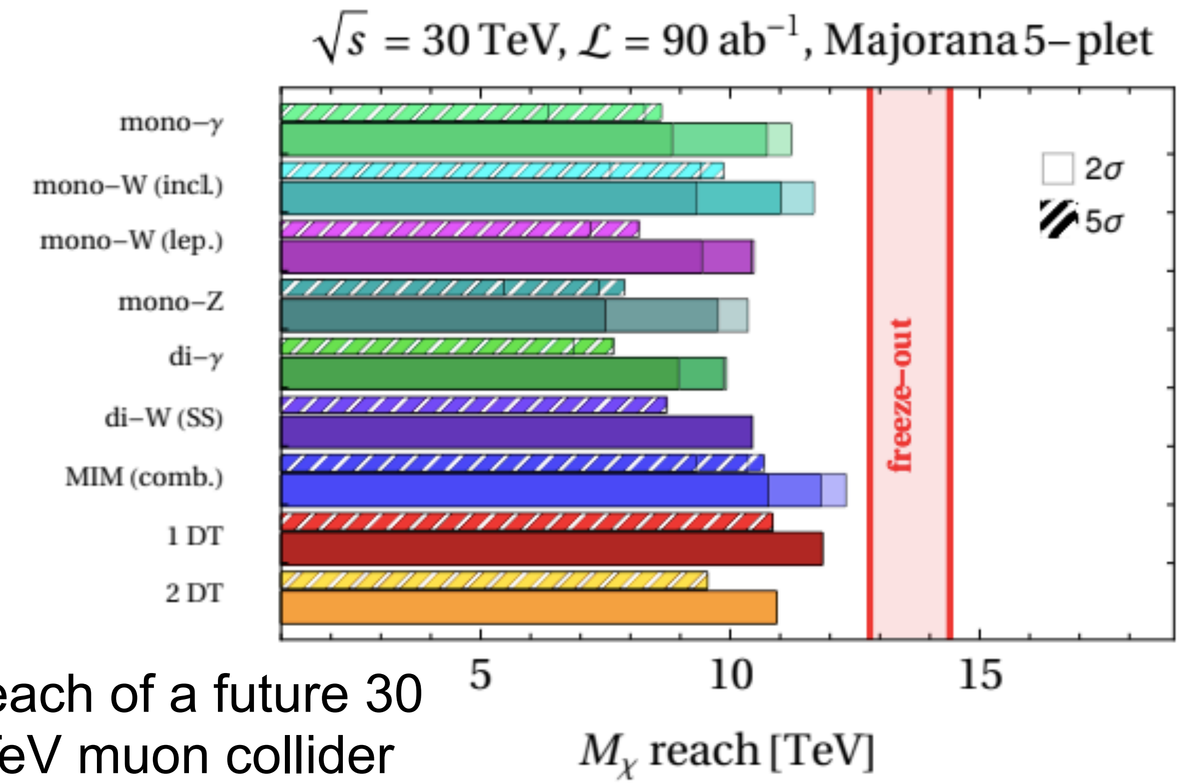
- Neutrino telescopes (**IceCube,** in future **P-ONE**) can also set competitive constraints in this heavy mass range [e.g. Abbasi et al (IceCube) 2303.13663, Desai et al 2302.10542]

Heavy SU(2) WIMPs

- In addition to the thermal relic cross-section as a generic benchmark, one can consider specific models that inhabit this space
- "Minimal dark matter" scenarios [Cirelli et al '05] provide some simple benchmarks that are generally not yet excluded
- Basic idea is just to add a new $SU(2)_L$ multiplet to the SM - abundance is obtained by thermal freezeout, which fixes the mass
- Preferred masses are at the TeV+ scale and are difficult to probe with future colliders; direct detection signals are near/below neutrino floor
- Potential for a clean/striking indirect detection signal from annihilation producing gamma rays



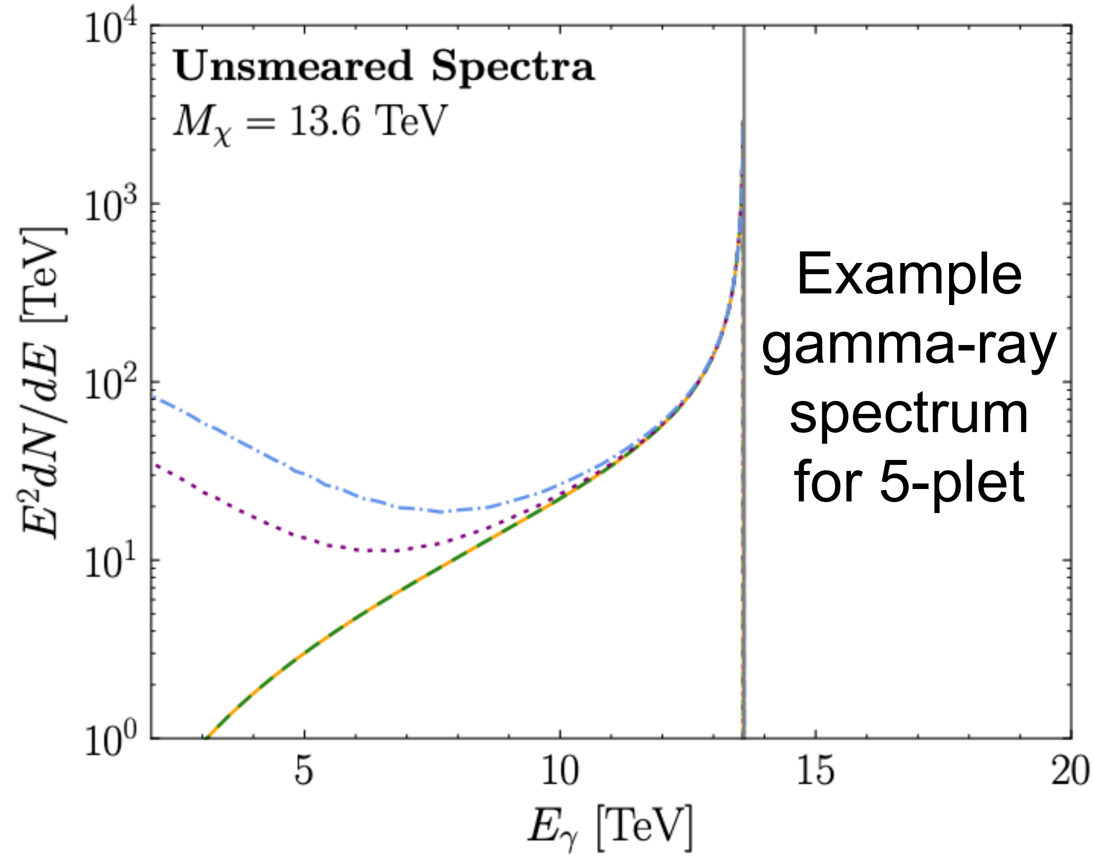
Bottaro et al '22

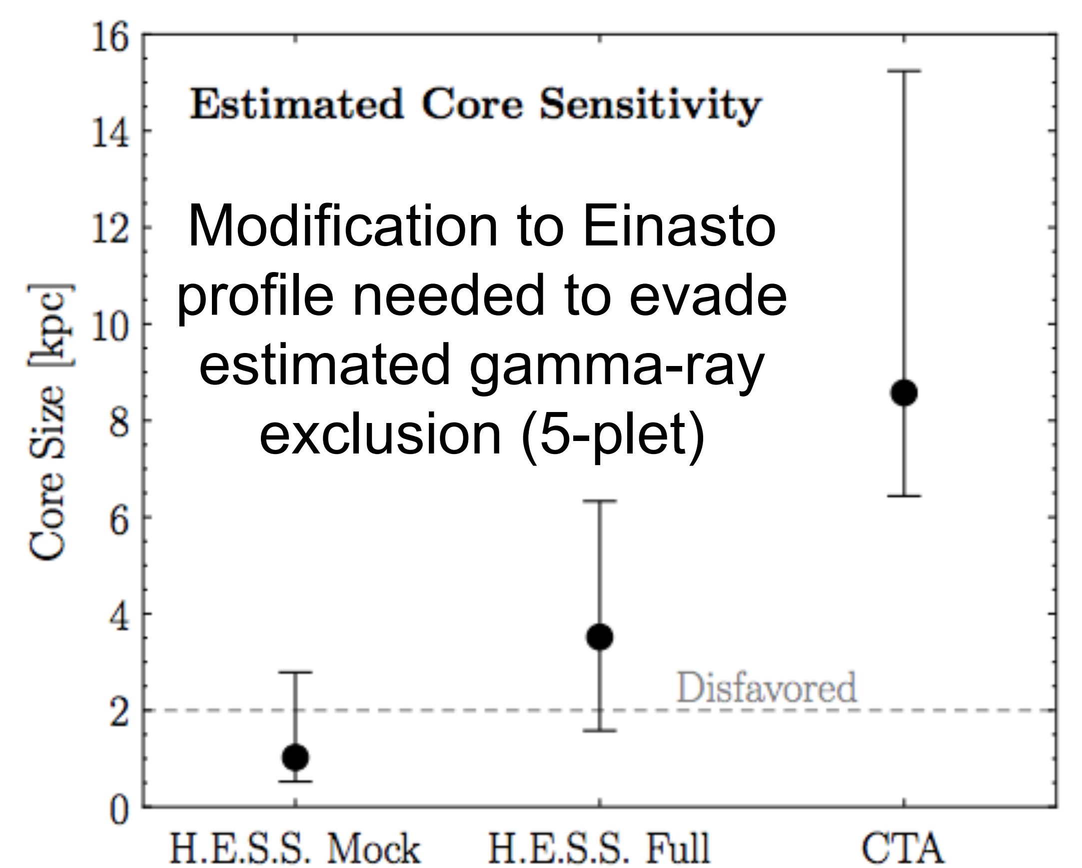


Reach of a future 30 TeV muon collider

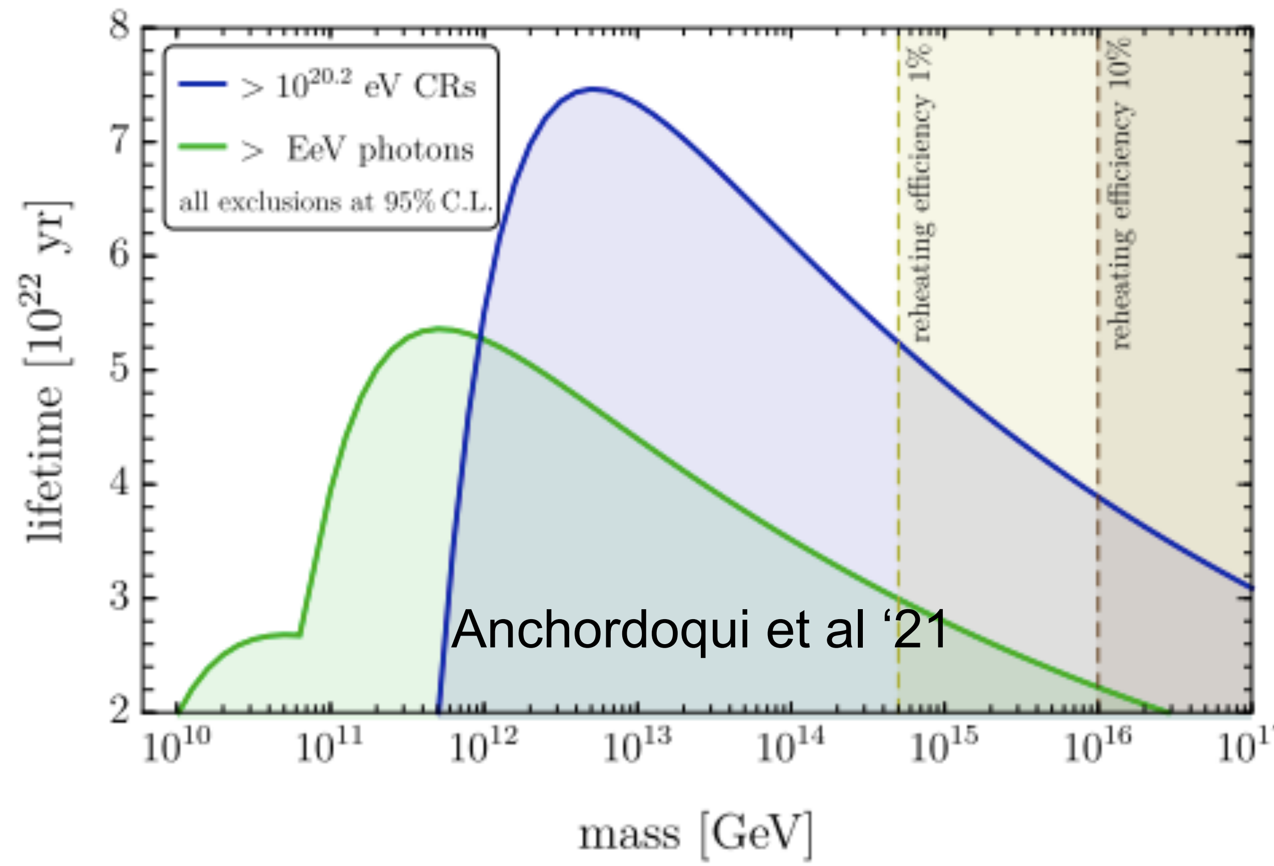
Minimal DM in indirect detection

- Precise theory predictions for heavy electroweakinos require careful effective field theory analysis [e.g. Hisano et al ’03, ’04; Baumgart, TRS et al ’19, ‘23; Beneke et al ’20, ’22]
  Lightness of W and Z relative to DM gives rise to large effects that need to be resummed.
- Detailed studies have been done for higgsino (doublet), wino (triplet), quintuplet (5-plet).
- Strongest limits use Galactic Center data; systematic uncertainty from DM density profile [see talk by Matt Baumgart for dwarf limits].
- Current HESS data are in tension with wino and marginally consistent with 5-plet (depending on density profile).
  Should both be robustly detected or excluded with future CTA gamma-ray observations.
  Higgsino should be testable with CTA; no conflict with current data even for peaked density profiles, mild excess at the right mass with *Fermi* [Dessert et al ‘22]
- Resummation calculation has been generalized to all odd representations [Baumgart, TRS et al ’23]; CTA sensitivity analysis for higher representations in progress





Above the thermal window: ultraheavy DM



- (Much) higher masses can be achievable even for thermal relic DM when standard assumptions break down, e.g. via modifications to cosmology such as a first-order phase transition in the dark sector [e.g. Asadi, TRS et al '21], or formation of many-particle bound states after freezeout [e.g. Coskuner et al '19, Bai et al '19] - can lead to macroscopic DM candidates

- Non-thermal production mechanisms (e.g. out-of-equilibrium decay of a heavier state) are also viable

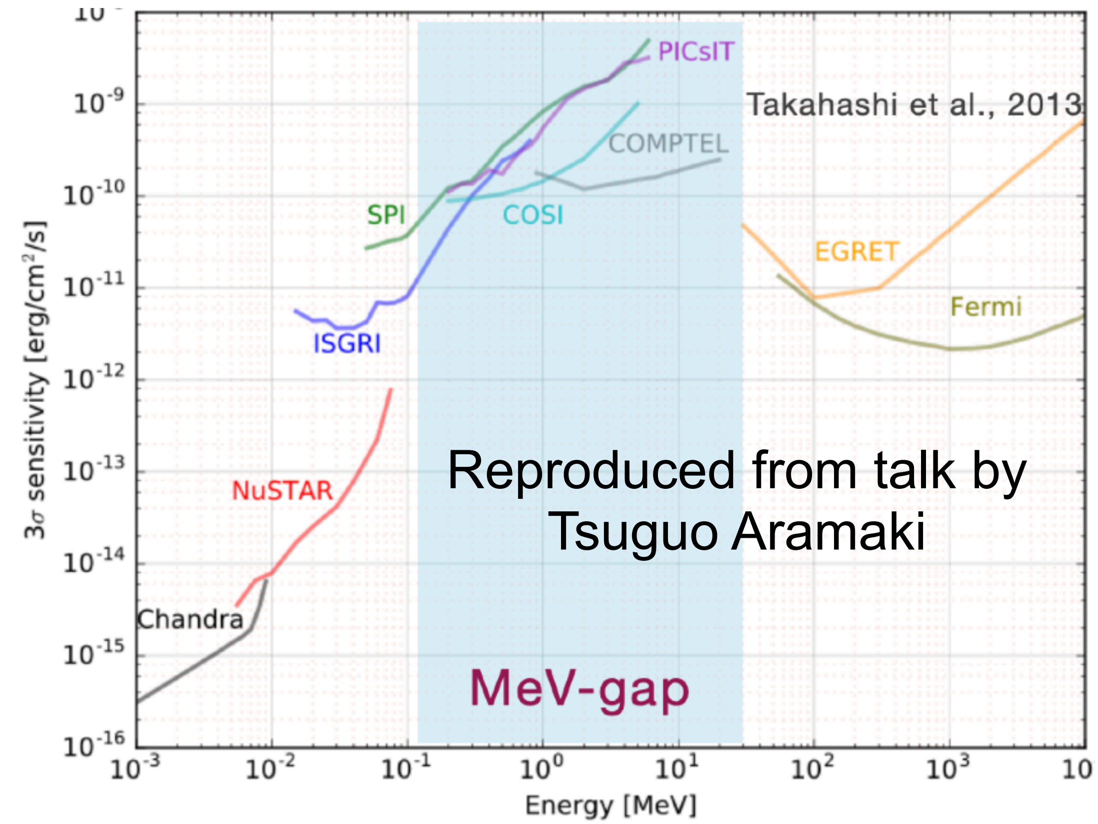
- Observations of ultra-high-energy CRs and photons could provide sensitivity to decays of ultraheavy DM candidates [e.g. Berezinsky et al '97, Romero-Wolf et al '20, Anchordoqui et al '21], as could observations of secondary particles from cascades, using lower-energy gamma-ray and neutrino telescopes

Future experiments				
CTA	Photons	20 GeV - 300 TeV	Targeted	Chile & Spain
SWGO	Photons	100 GeV - 1 PeV	Wide	South America
IceCube-Gen2	Neutrinos	10 TeV - 100 EeV	Wide	Antarctica
LHAASO (full)	Photons	100 GeV - 10 PeV	Wide	China
KM3NeT	Neutrinos	100 GeV - 10 PeV	Wide	Mediterranean Sea
AugerPrime	Photons & Neutrinos	1 EeV - 1 ZeV	Wide	Argentina
POEMMA	Neutrinos	20 PeV - 100 EeV	Wide	Space

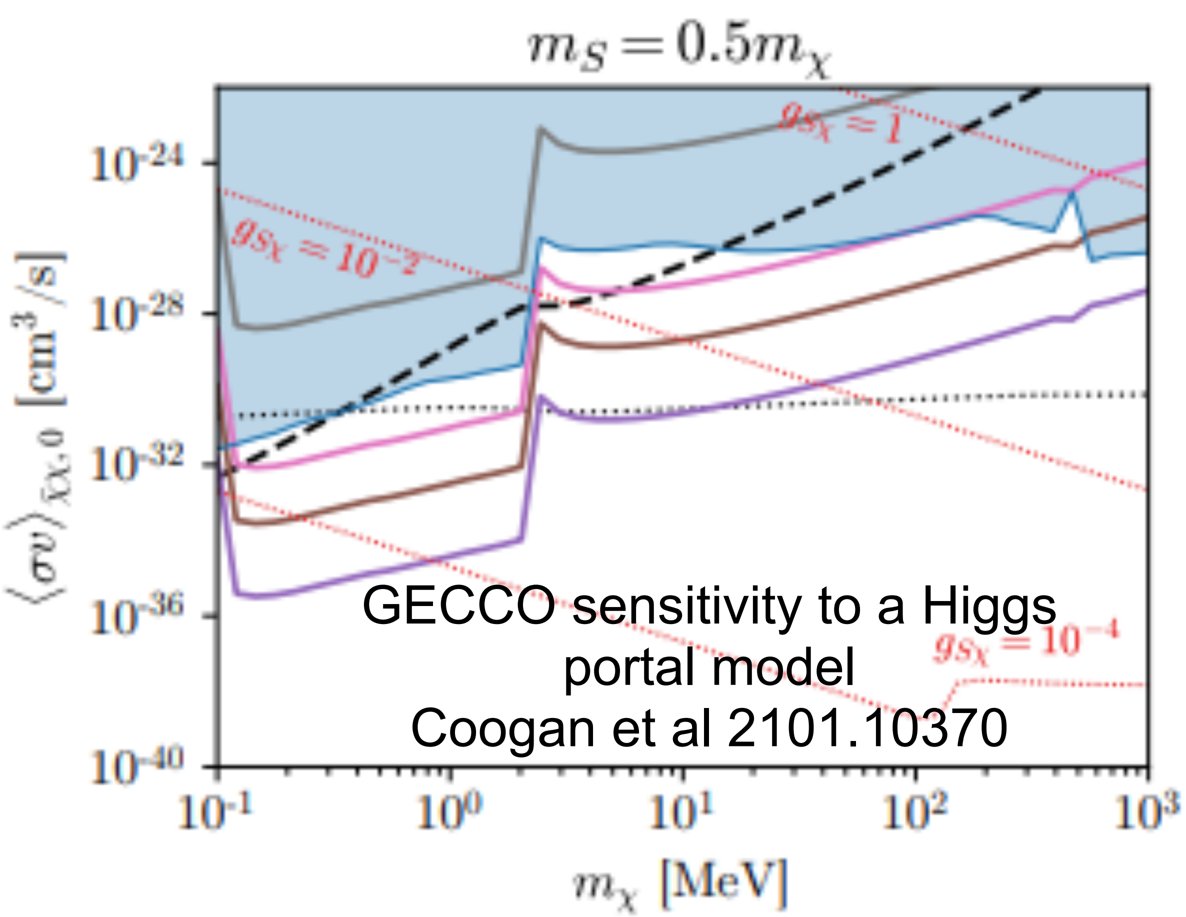
The MeV gap

- MeV-GeV band is currently the focus of a huge amount of effort in accelerator and direct searches.

- Indirect limits are already quite strong at these energies, so viable models are not produced by thermal freezeout or have suppressed annihilation today



- However, there is a gap in sensitivity for energies between *Fermi* and X-ray telescopes



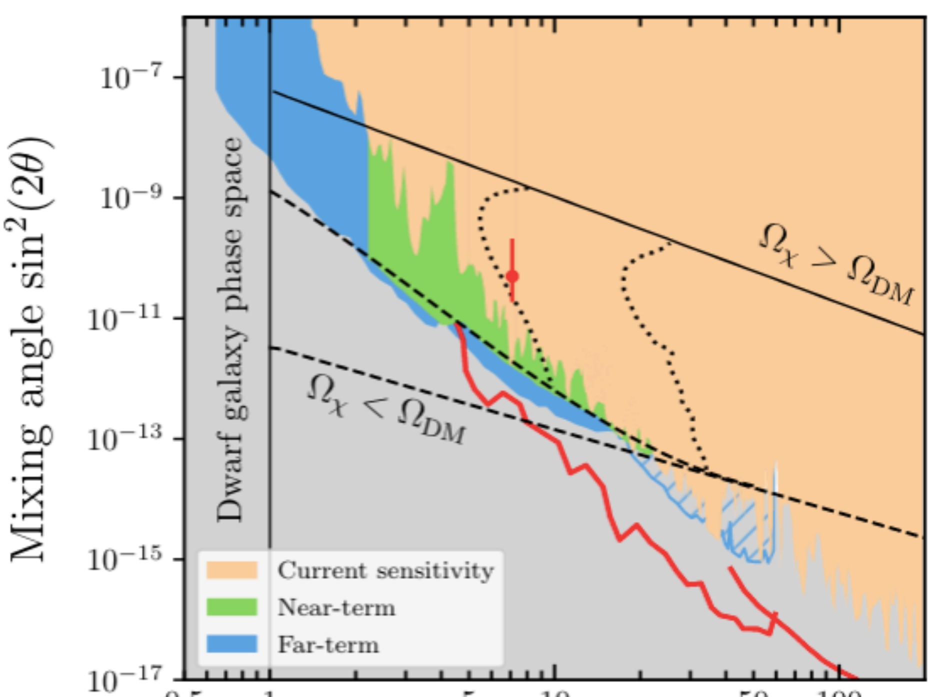
- Many recent ideas for experiments to close this gap, primarily balloon- and eventually space-based telescopes [e.g. SMILE, GECCO, GRAMS, GammaTPC, AMEGO-X, e-ASTROGAM; see talks by Regina Caputo and Tsuguo Aramaki]

- COSI is a new wide-field soft gamma-ray telescope (0.2-5 MeV), scheduled for launch August 2027.

- With future ideas, some prospect of reaching p-wave thermal relic cross section (suppressed by v^2) for sufficiently low mass DM [e.g. Coogan et al 2101.10370], plus will offer new sensitivity to primordial black holes [e.g. Ray et al 2102.06714]

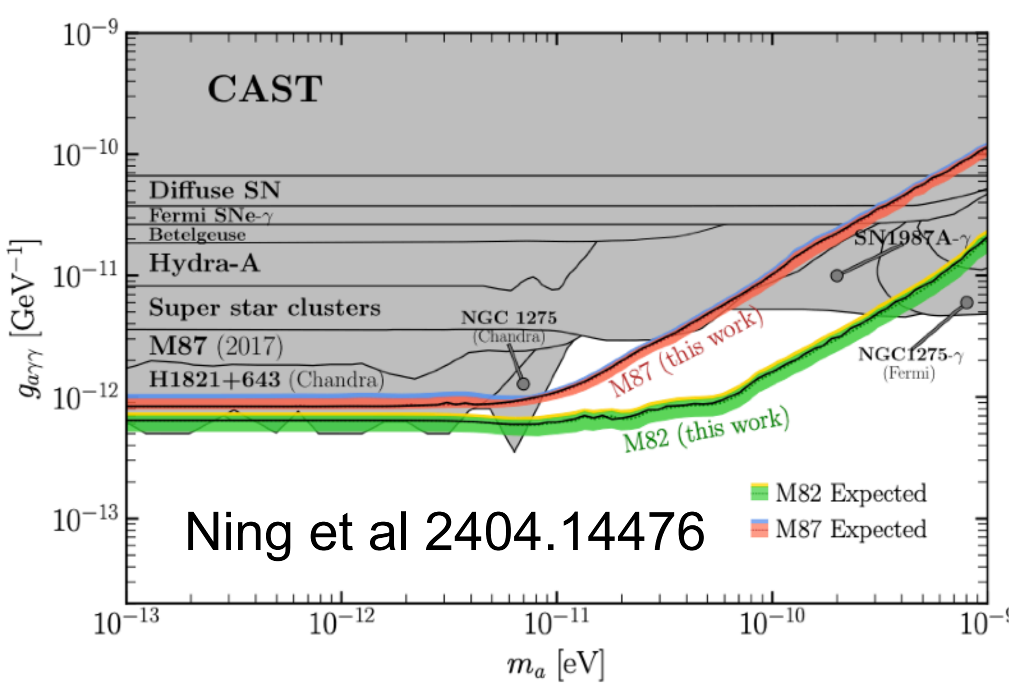
X-ray indirect searches

- Not many annihilation/decay channels open for DM lighter than the electron mass - models often predict monochromatic photon spectral lines.
- Several current/future experiments are targeting fine energy resolutions: e.g. 7 eV (XRISM, launched September 2023), 3 eV (Micro-X), 2.5 eV (Athena).
  10^{-3} energy resolution would be sufficient to measure Doppler linewidth for Galactic DM.
- X-ray observations can set stringent constraints on low-energy photons produced by higher-mass DM [e.g. Cirelli et al 2303.08854], and can also constrain other DM interactions, e.g. axion-photon oscillations.



Credit: Brandon Roach

- X-ray line limits (combined with warm DM bounds) place stringent limits on sterile neutrino DM

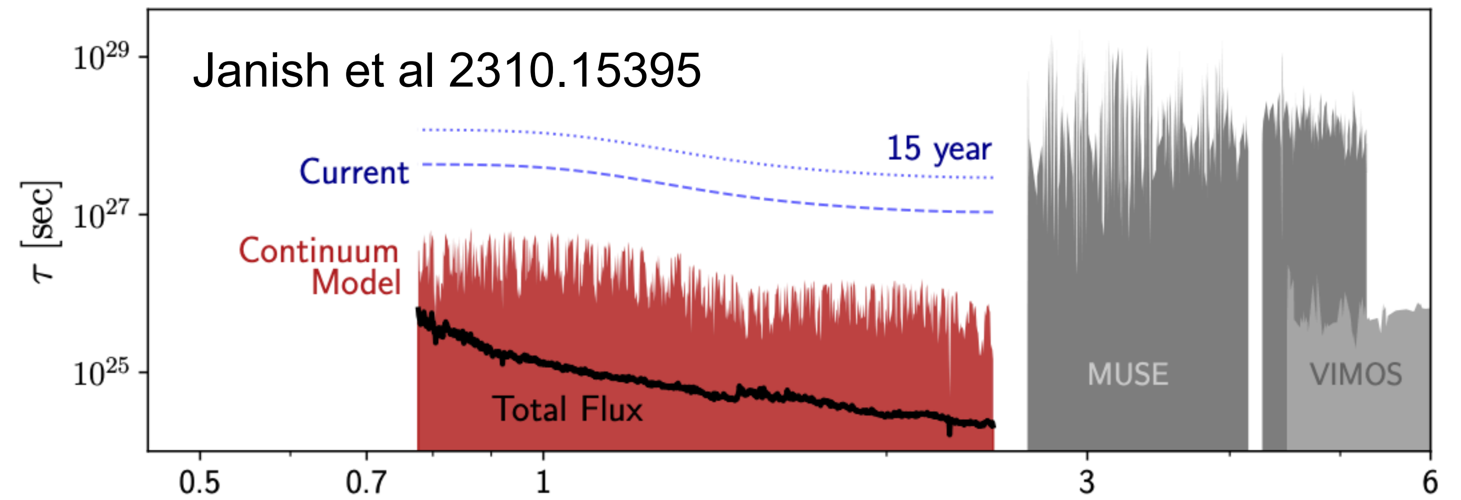


- Axion-like particles produced in stars can convert into keV-scale photons in B-fields; background keV-scale photons can convert into axion-like particles, modulating their spectrum

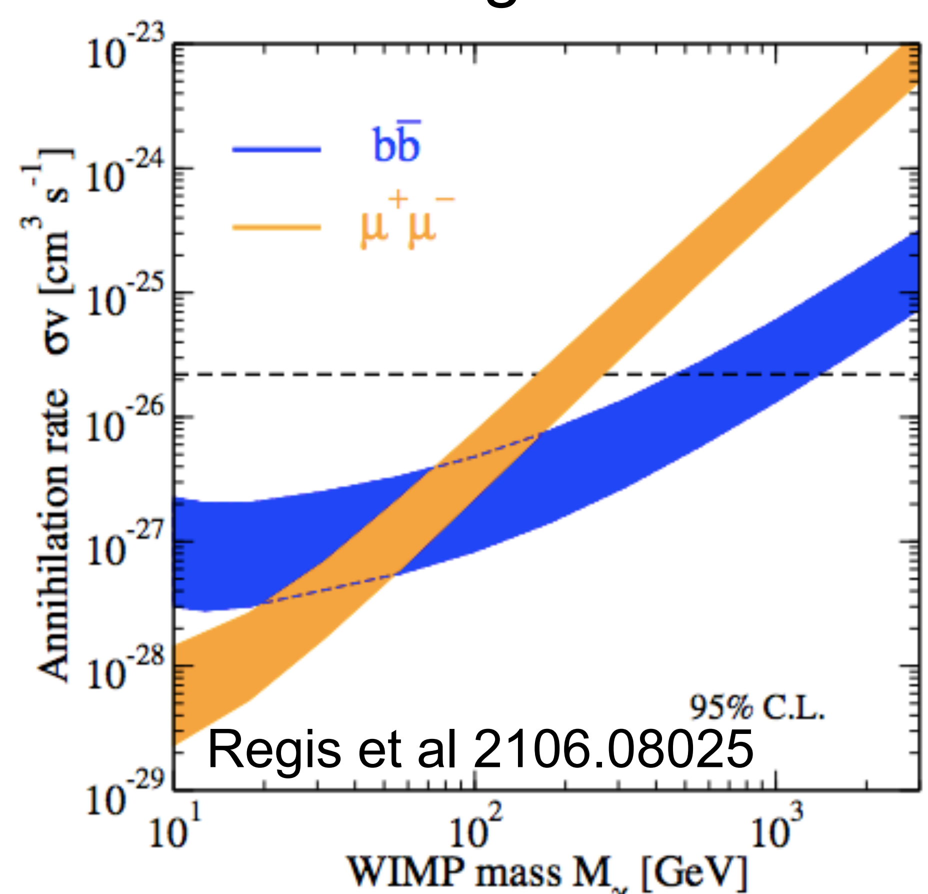
Lower-energy photons

- Below the X-ray band, still many interesting observations for indirect detection
- Radio, microwave, infrared, optical, UV etc are especially relevant for very light DM
- Can also be populated by secondary emission from higher-energy DM
- e.g. synchrotron from e^+e^- in the Galactic magnetic field can produce radio signals
- systematics in cosmic-ray propagation + B-field modeling, but potentially very strong limits on heavy DM [e.g. Chan et al '19 from Andromeda, Regis et al '21 from the LMC, Kadota et al '24 from compact objects]

Limits on light decaying DM from JWST in IR

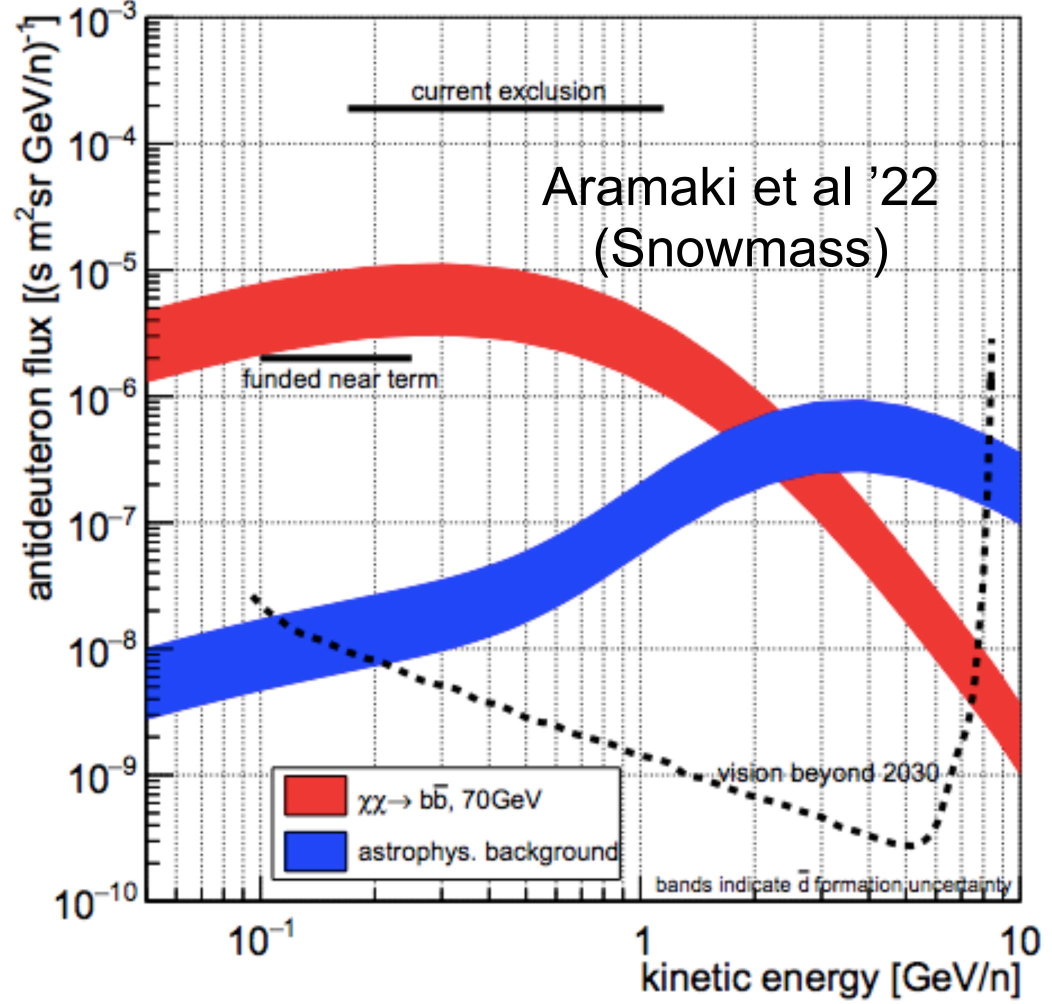


Limits on heavy annihilating DM from radio



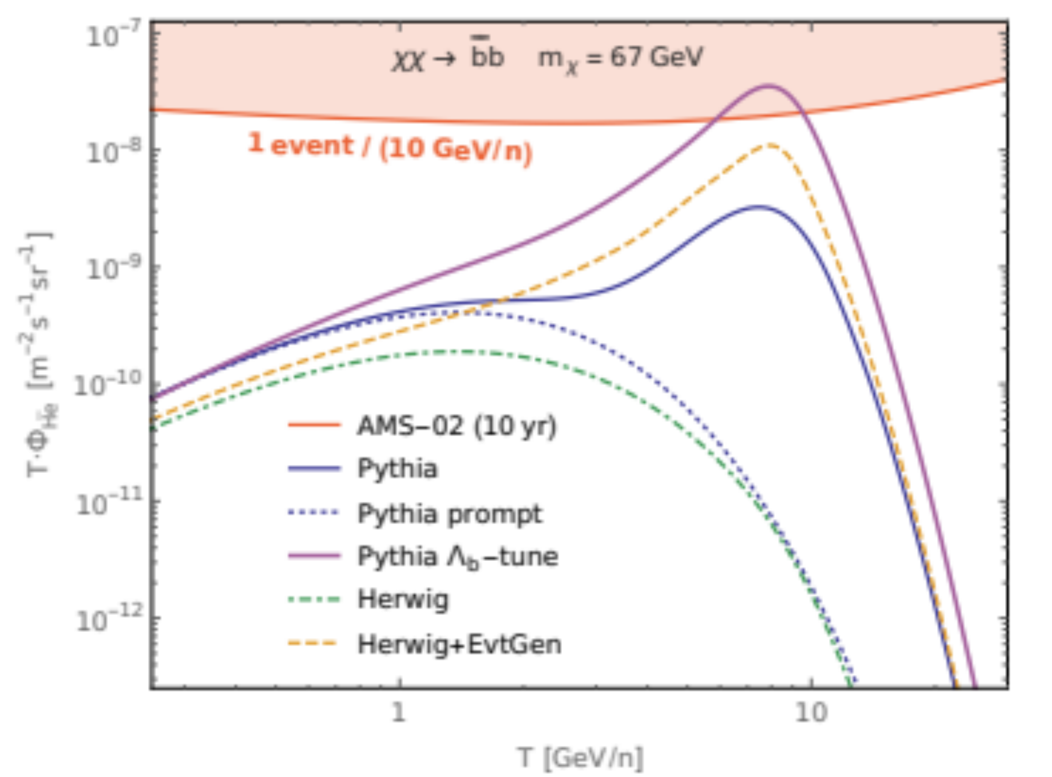
Cosmic ray antimatter

- The astrophysical backgrounds for low-energy antinuclei (in particular antideuterons, antihelium) are expected to be tiny
- Near-term: GAPS balloon flight scheduled for 2024-25 austral summer, dedicated search for low-energy antiprotons + antideuterons (see also talk by Tsuguo Aramaki)
- 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.
- Also non-trivial to achieve with DM annihilation, although production of $\bar{\Lambda}_b$-baryons which decay to antihelium could boost the signal [Winkler & Linden '21]
- There are large theory uncertainties in all the possible production channels - potential to clarify at accelerators (ALICE).
- De La Torre Luque et al '24 argues anti-He-4 events cannot be produced with simple DM models (or known astrophysics).



Aramaki et al '22 (Snowmass)

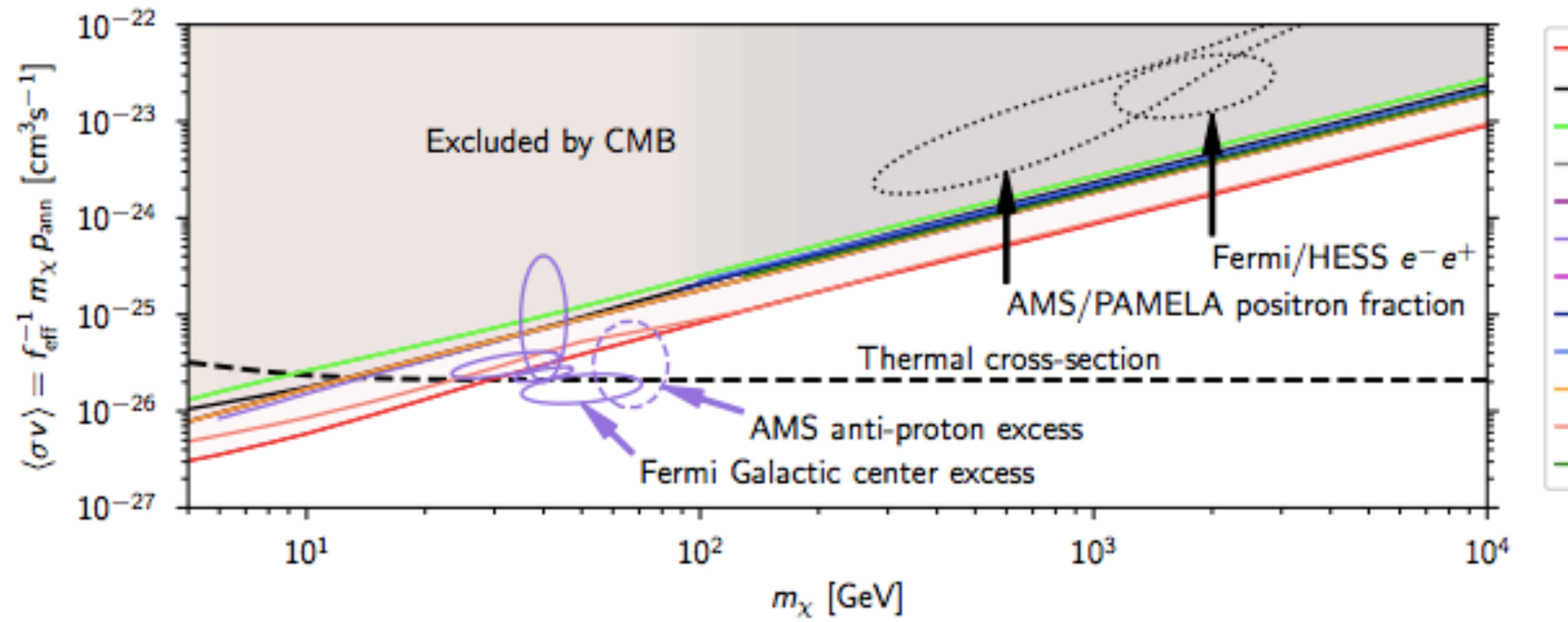
Winkler et al '21



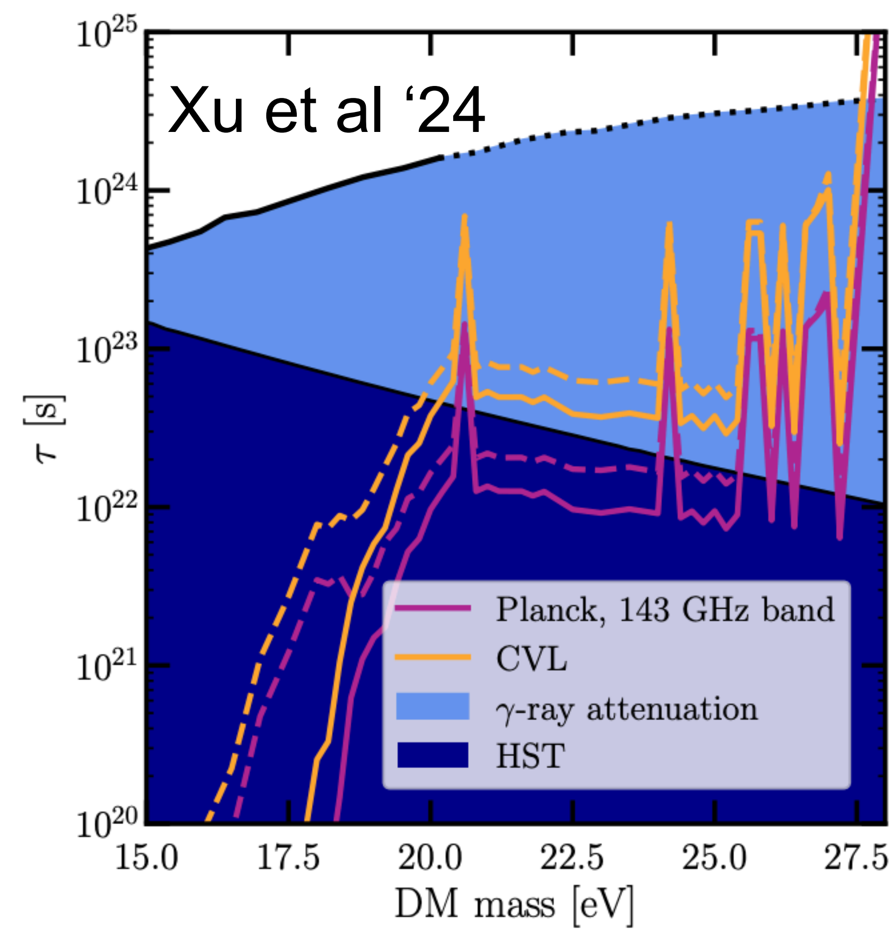
The cosmos as calorimeter

- DM annihilation/decay would affect the evolution of the cosmos throughout its history
- Annihilation limits take advantage of higher density at early times - increased ionization modifies the CMB, giving stringent+robust constraints especially on light DM

Planck Collaboration '18



- Below the ionization threshold, soft photons can still efficiently heat the gas [e.g. Acharya et al 2303.17311, Cyr et al 2404.11743]; higher-energy photons can modify radiation backgrounds and excite hydrogen [e.g. Xu, Qin & TRS 2408.13305]
- Heating, ionization and extra background radiation can change the evolution of the first stars [see talk by Wenzer Qin]
- Other interactions - e.g. DM-baryon scattering [see plenary by Vera Gluscevic], axion-photon oscillations can also leave distinctive imprints in cosmological data

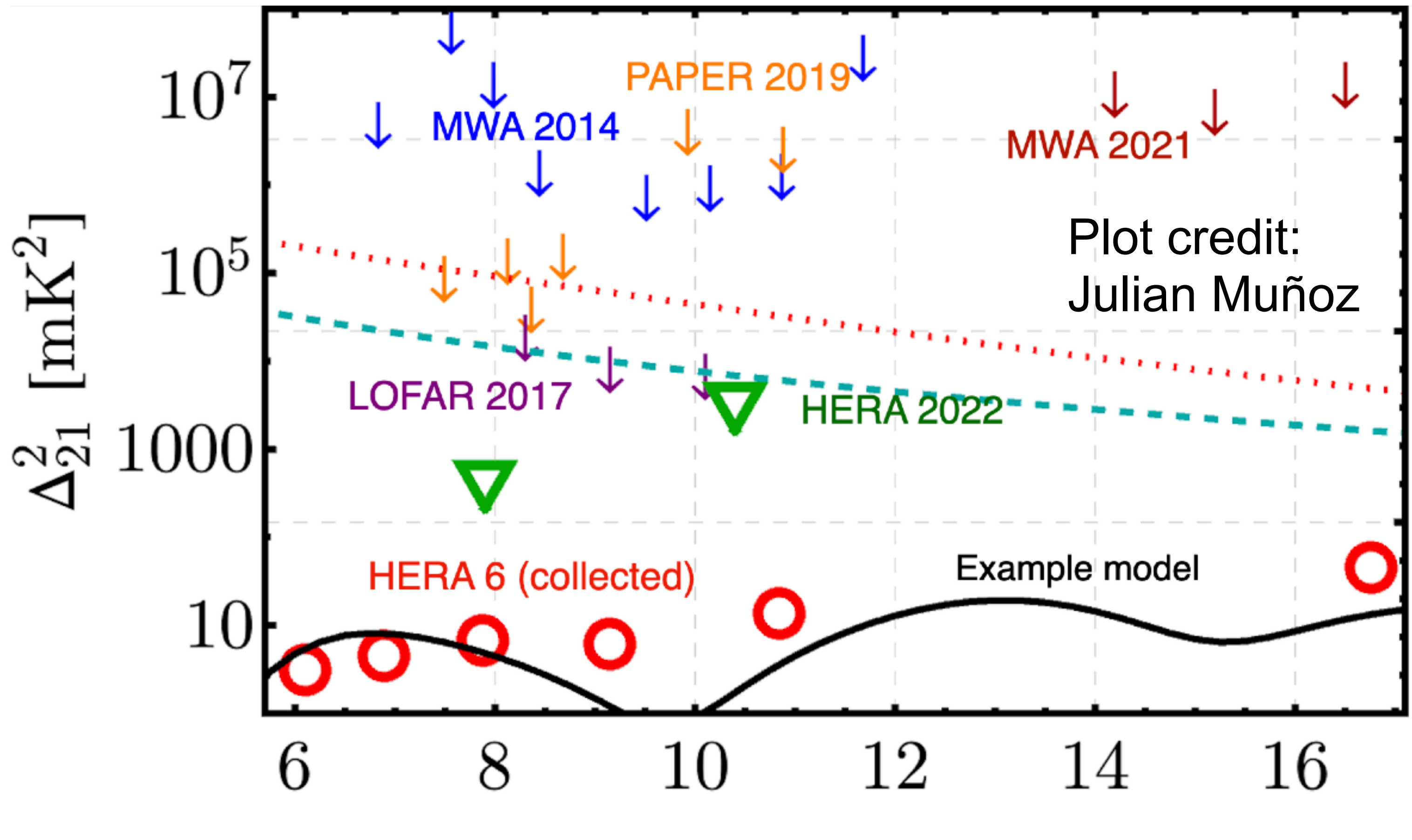


21cm as a probe of decaying dark matter

- A cosmological 21cm signal would provide a new window on cosmic dawn and the end of the cosmic dark ages [see also plenaries by Julian Muñoz and Phil Bull]

- HERA has "Season 6" data in hand, plausible astrophysical models would predict a detectable signal in this dataset [Breitman et al 2309.05697]

- 21cm can be used to probe properties of first stars/galaxies, which in turn depend on DM halos



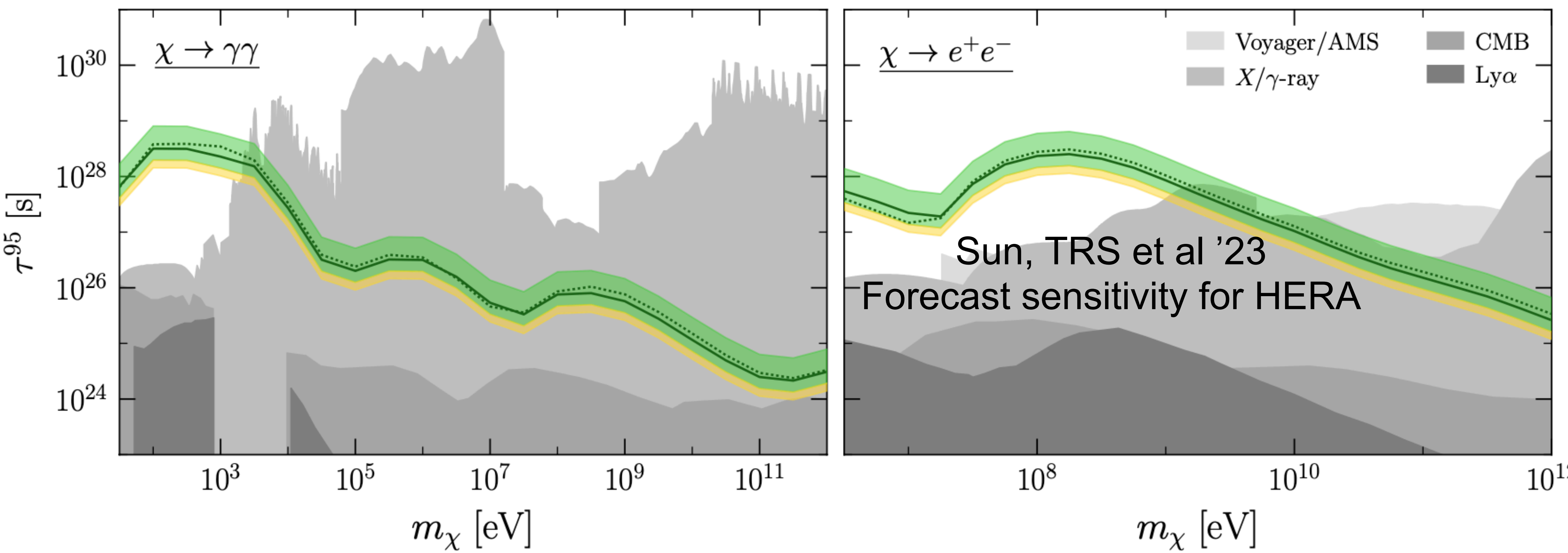
HERA coll. 2022

- Can also be used as a "cosmic thermometer" - probes early heating/ionization

- A detection could thus be used to constrain DM decay/annihilation

DM21cm

- We recently presented a new public code (https://github.com/yitiansun/DM21cm) built to work with existing public 21cmFAST package [Sun, TRS et al 2312.11608]
- Models effects on 21cm light-cone from DM decay into arbitrary final states, for the first time taking into account the inhomogeneity of the decay signal
- More generally, enables modeling general injection of photons/electrons/positrons (arbitrary spatial dependence, redshift dependence, energy spectrum) in 21cmFAST



Complementary measurements

- Definitely a case where there are both challenges and opportunities
- Indirect searches would greatly benefit from a better understanding of:
    - Cosmic ray production, composition, and propagation (input from fixed-target experiments, cosmic-ray measurements, better modeling)
    - Galactic diffuse photon emission (input from multiwavelength studies of the Galaxy, new tracers of interstellar gas, better modeling)
    - Improved understanding of the DM density distribution, e.g. in dwarfs / toward the Galactic Center, and for the smallest clumps of DM
    - and more…
- Novel analysis methods (including but not limited to techniques involving ML/AI) can yield new insights as well

Summary

- Indirect searches for dark matter currently:
  - test thermal relic annihilation cross sections up to O(10s-100s) GeV DM
  - exclude decay lifetimes up to 10^{27-30} s over a very wide DM mass range,
  - serve as sensitive probes of other possible DM interactions with visible particles
- Future experiments offer many exciting prospects, including:
  - sensitivity to significantly higher-mass thermal DM, up to the O(100) TeV scale (+ lower cross-sections at lower masses)
  - improved sensitivity to MeV-GeV photons, closing the “MeV gap” in sensitivity - relevant both for light particle DM and primordial black holes
  - probing new low-background detection channels, such as anti-deuterons / anti-helium
  - new limits/signal channels from an improved understanding of the early universe