Indirect Dark Matter Detection

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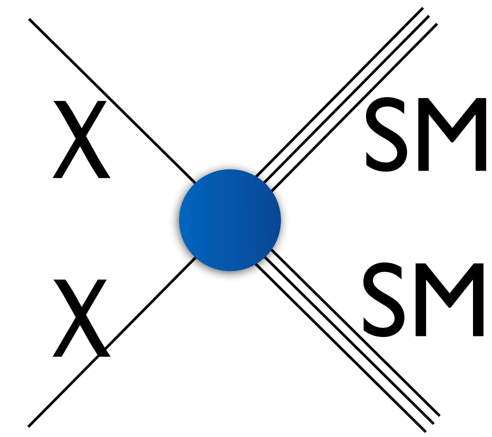
U.S. DEPARTMENT OF ENERGY | Office of Science

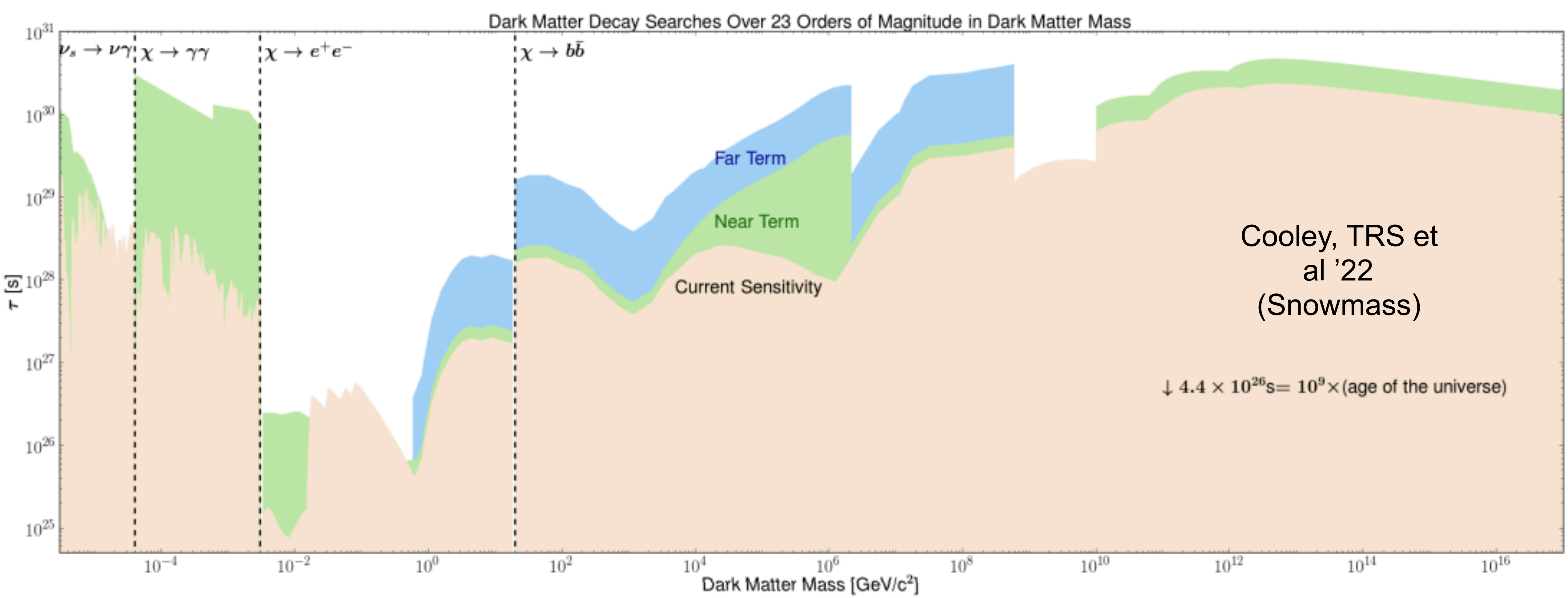
Indirect detection



- One of the classic search strategies for WIMP dark matter
- Search for dark matter interactions outside the detector via the "cosmic messengers" they produce (promptly or as secondaries)
- Messengers: traditionally photons, cosmic rays, neutrinos, now + gravitational waves
- Classic production mechanisms: annihilation, decay
    - can also get interesting signals from oscillation, scattering, etc
- Also very interesting: searches for DM in "natural laboratories", where astrophysical objects are affected by the presence and/or interactions of DM
- For neutral messengers, directional information allows selection of specific target regions: Galactic center/halo, other nearby galaxies, galaxy clusters/groups, extragalactic backgrounds, dwarf galaxies, dark subhalos, etc

Why indirect detection?

- Take advantage of existing multiwavelength/multimessenger ensemble of telescopes designed to study astrophysics → limits on DM spanning 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 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



Challenges for indirect detection

- Frequently large systematic uncertainties and backgrounds related to astrophysics and/or DM density distribution
- Complementary observations/analyses that help reduce and/or quantify these uncertainties can thus have large payoff
- A complementary strategy is to seek especially low-background signals (e.g. monochromatic lines, antinuclei) and/or focus on low-background regions (e.g. dwarf galaxies)
- There are currently a number of detected excesses above (our understanding of) backgrounds
- Unraveling the origin of these excesses will provide important insights into backgrounds - and could potentially reveal a DM signal

Status/future

- We attempted to summarize the current status and near-future prospects of indirect detection in the CF1: Particle-Like Dark Matter report for Snowmass [Cooley, TRS et al '22, arXiv:2209.07426].
  - That report focused on eV+ DM ("particle-like"), left natural laboratories and GWs mostly to CF3 ("Cosmic Probes"), and left neutrino searches mostly to the Neutrino Frontier (see talk by Francis Halzen) - I will ~follow this approach today
- Some shared science goals of the upcoming/proposed experimental program:
  - Test the classic thermal WIMP scenario up to the unitarity bound
  - Close the "MeV gap" in gamma-ray sensitivity
  - Improve X-ray sensitivity + achieve energy resolution sufficient to resolve linewidth from Galactic DM decay
  - Seek first confirmed detection of low-energy antimatter cosmic rays
  - Improve the characterization of key backgrounds and systematic uncertainties (both in general and with the goal of resolving current excesses, one way or another)

The classic thermal WIMP

- Once in thermal equilibrium with visible particles; annihilation depletes the original abundance to its present-day value:

$$\boxed{\langle\sigma v\rangle \sim \frac{1}{m_{\rm Planck} T_{\rm eq}} \sim \frac{1}{(100{\rm TeV})^2} \approx 2\times 10^{-26}{\rm cm}^3/{\rm s}}$$

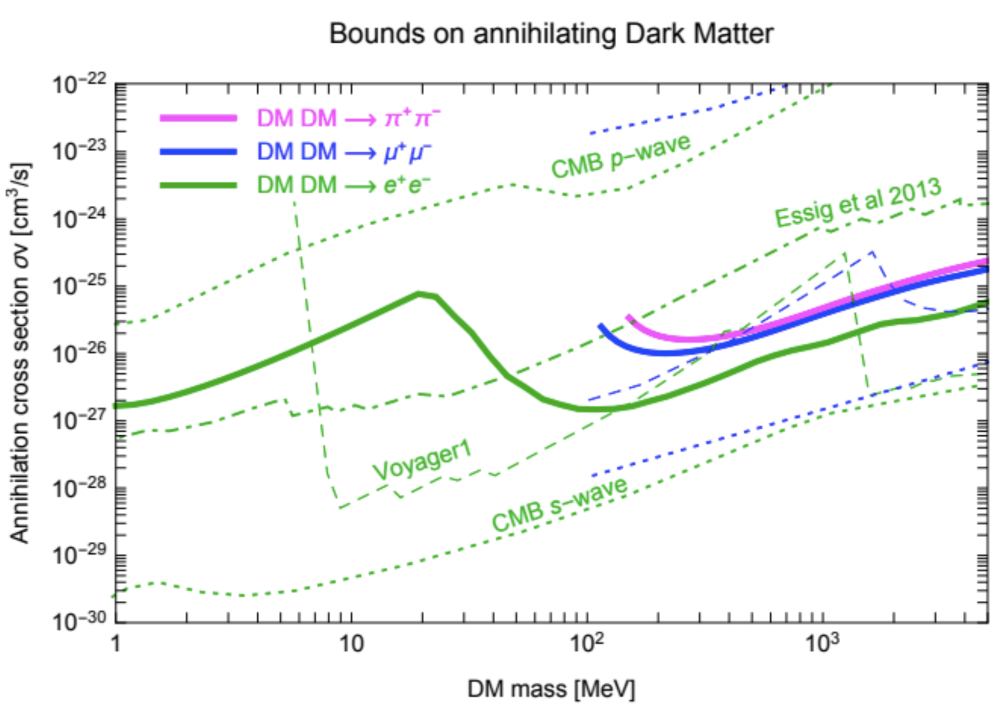
- This value relies on assumptions of a standard cosmological history

- In many simple models, $\langle\sigma v\rangle$ retains its early-universe value today - this is what I mean by “classic” (but more generally, it may be either enhanced or suppressed)

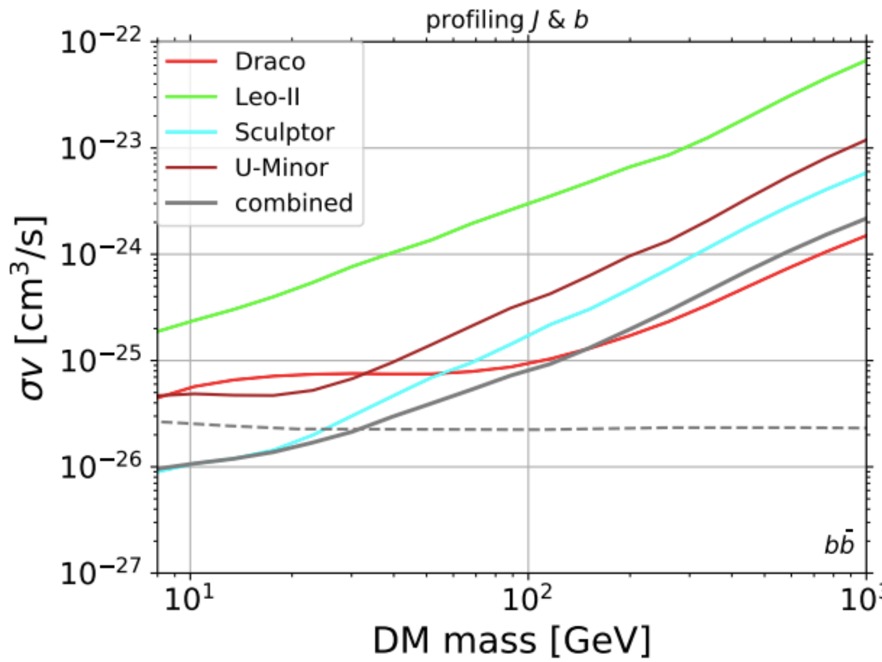
- General unitarity-based arguments require m_{DM} < 100-1000 TeV to achieve this cross section [Smirnov, Beacom ’19]

Constraints on annihilation

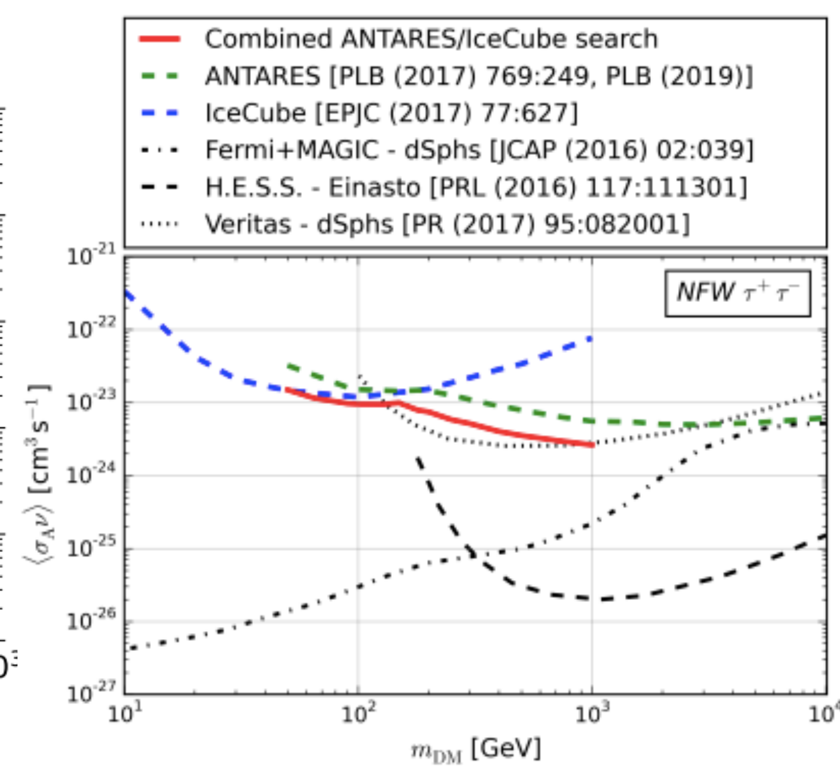
- Multiwavelength photon and cosmic-ray observations constrain thermal relic cross sections up to O(10s-100s) GeV, for all final states except neutrinos
- In this mass range, antiproton and gamma-ray measurements generally give the strongest bounds for hadronic final states [e.g. Alvarez et al ’20, Cuoco et al ’18, Reinert & Winkler ’18, Calore et al ’22]
- AMS-02 positron measurements constrain electron/muon-rich final states [e.g. John & Linden ’21]
- Much lower cross sections can be tested for lower masses, e.g. via observations of the cosmic microwave background [e.g. TRS ’16]
- Larger cross sections can be tested up to the 100 TeV - PeV scale by ground-based gamma-ray telescopes [e.g. Oakes et al ’20, Abdallah et al ’18, Archambault et al ’17, Abdallah et al ’16] and neutrino telescopes such as Antares and IceCube [e.g. Albert et al ’20].



Cirelli et al ‘20

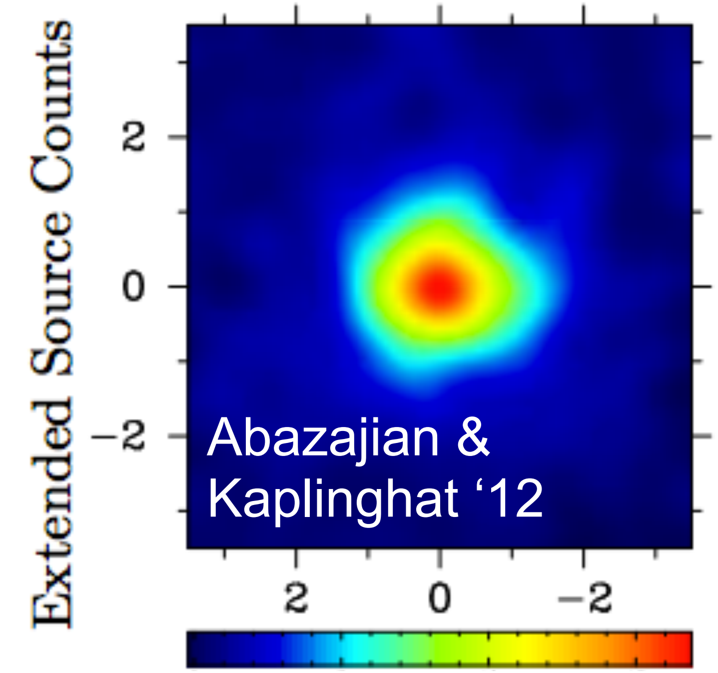


Alvarez et al ‘20



Albert et al ‘20

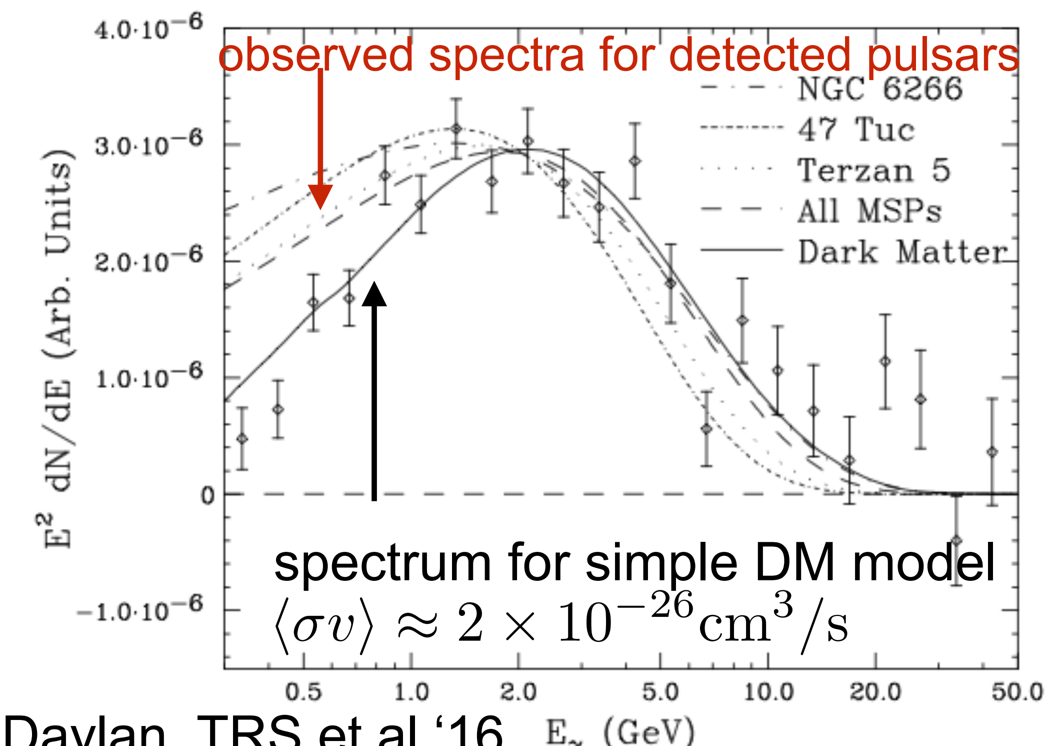
The Galactic Center excess (GCE)



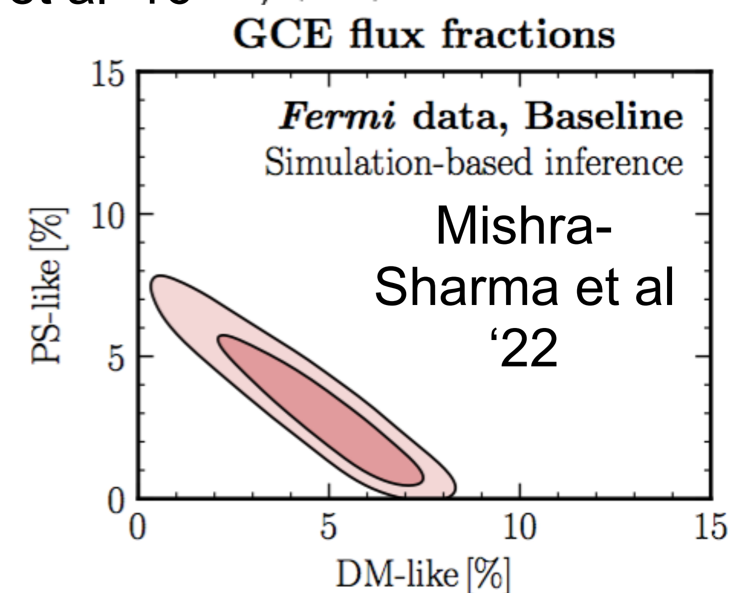
- Excess of gamma-ray photons, peak energy ~1-3 GeV, in the region within ~10 degrees of the Galactic Center; discovered by Goodenough & Hooper in 2009

- Can be fitted with DM annihilation. Also plausibly explained by a new population of millisecond pulsars, but (in my view) we have not definitively excluded the DM hypothesis:
  - Earlier apparent evidence that we had actually detected the pulsars in gamma rays was exaggerated by a systematic bias [Leane & TRS '19, '20; Buschmann et al '20] - updated analyses [e.g. List et al '20, '22; Mishra-Sharma et al '22] show only mild evidence for point sources in the excess
  - The excess morphology, which we would like to use to distinguish hypotheses, appears quite sensitive to uncertainties in the background modeling [e.g. Pohl et al '22, McDermott et al '22]

- Conclusively resolving these (and similar) excesses may require new analysis techniques and/or new datasets (e.g. SKA may find the GCE pulsars for us!) - whether or not they are telling us about DM, they are something we need to understand



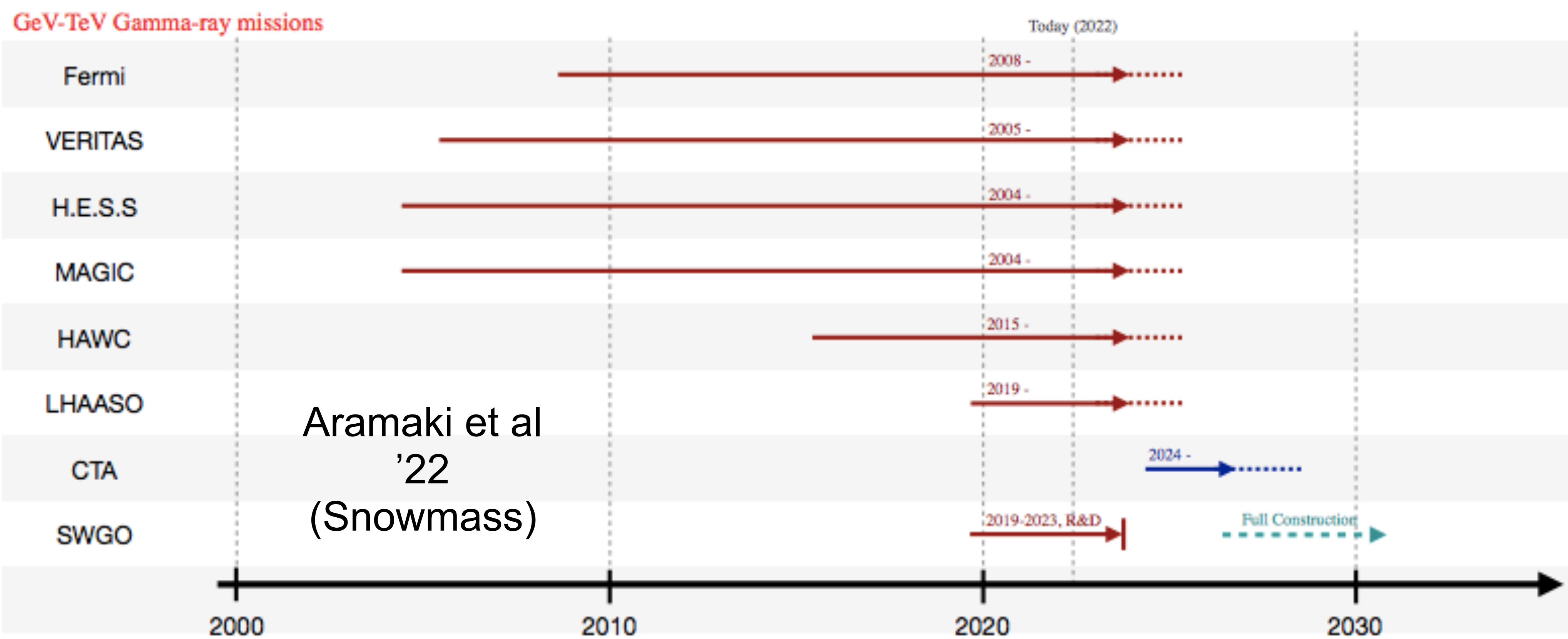
Daylan, TRS et al '16



Where next?

- 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) [see talk by Elisa Pueschel]

- Two key projects, both aiming to improve sensitivity relative to current counterparts by a factor of ~10:
  - Cherenkov Telescope Array (CTA): air Cherenkov telescopes, 20 GeV - 300 TeV. “Alpha Configuration” has funding in place for construction during 2022-2027. Commissioning of telescopes underway (e.g. arXiv:2210.00775 uses data from the prototype telescope LST-1).
  - Southern Wide-Field Gamma-Ray Observatory (SWGO): water Cherenkov telescopes, energies ~100 GeV - PeV, large field of view (45 degrees) enables longer viewing of targets, better sensitivity to extended sources. Currently has R&D funding from NSF.



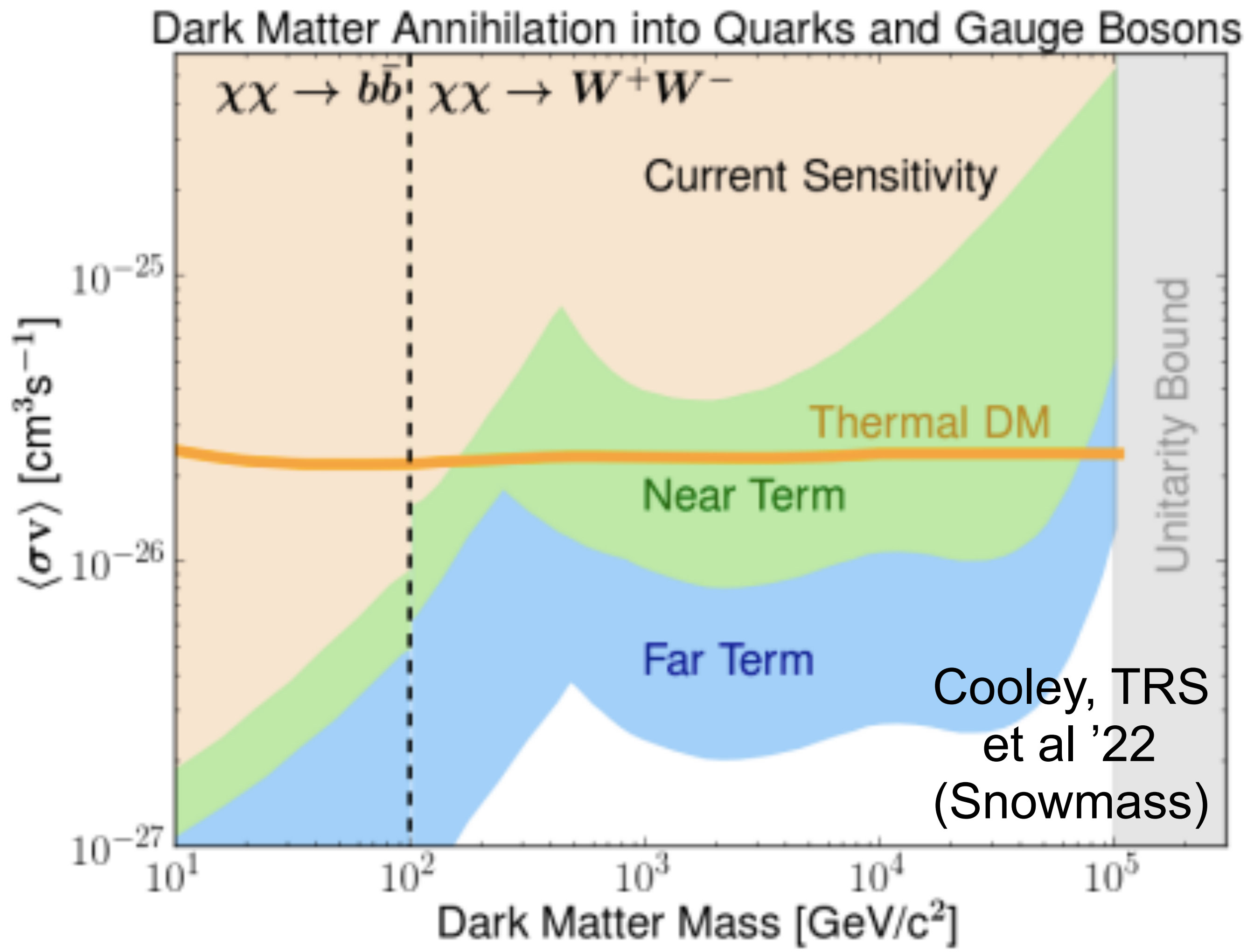
- Angular resolution for these instruments <0.2-0.3 degrees, energy resolution ~5-15% for CTA, estimated at <40% for SWGO.

Future sensitivity

- If CTA/SWGO are successful, could scale up by adding more telescopes (“far term" line assumes km^2 SWGO analogue)

- At lower energies, the Advanced Particle-astrophysics Telescope (APT) [Buckley et al '19, Astro2020] is a concept for a Fermi-LAT successor that would improve sensitivity by a factor of ~10 in the 100 MeV-TeV range.

- The ADAPT (Antarctic Demonstrator for APT) suborbital mission was recently funded by NASA and is planned for a 2025 Antarctic flight. Satellite version would be 2030+.



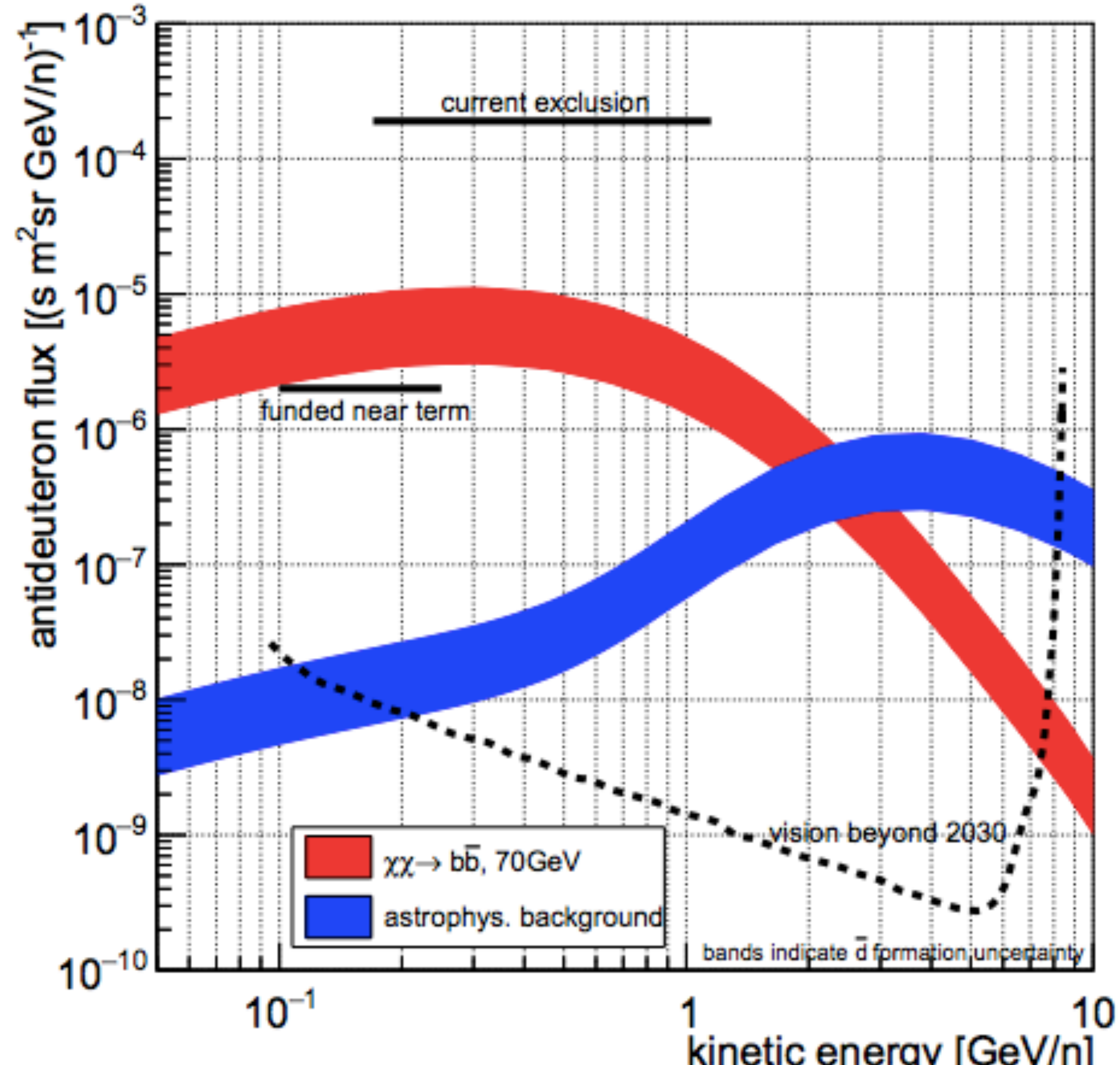
Cooley, TRS et al ’22 (Snowmass)

- If we exclude the thermal relic cross section, of course doesn't exclude DM in this mass range - could be non-thermal or have annihilation suppressed at late times, similar to current situation for sub-GeV thermal targets

- Quoted sensitivity at TeV+ depends on observing the Galactic Center - uncertainties associated with DM density profile, gamma-ray backgrounds will impact our ability to set robust constraints

New low-background channels

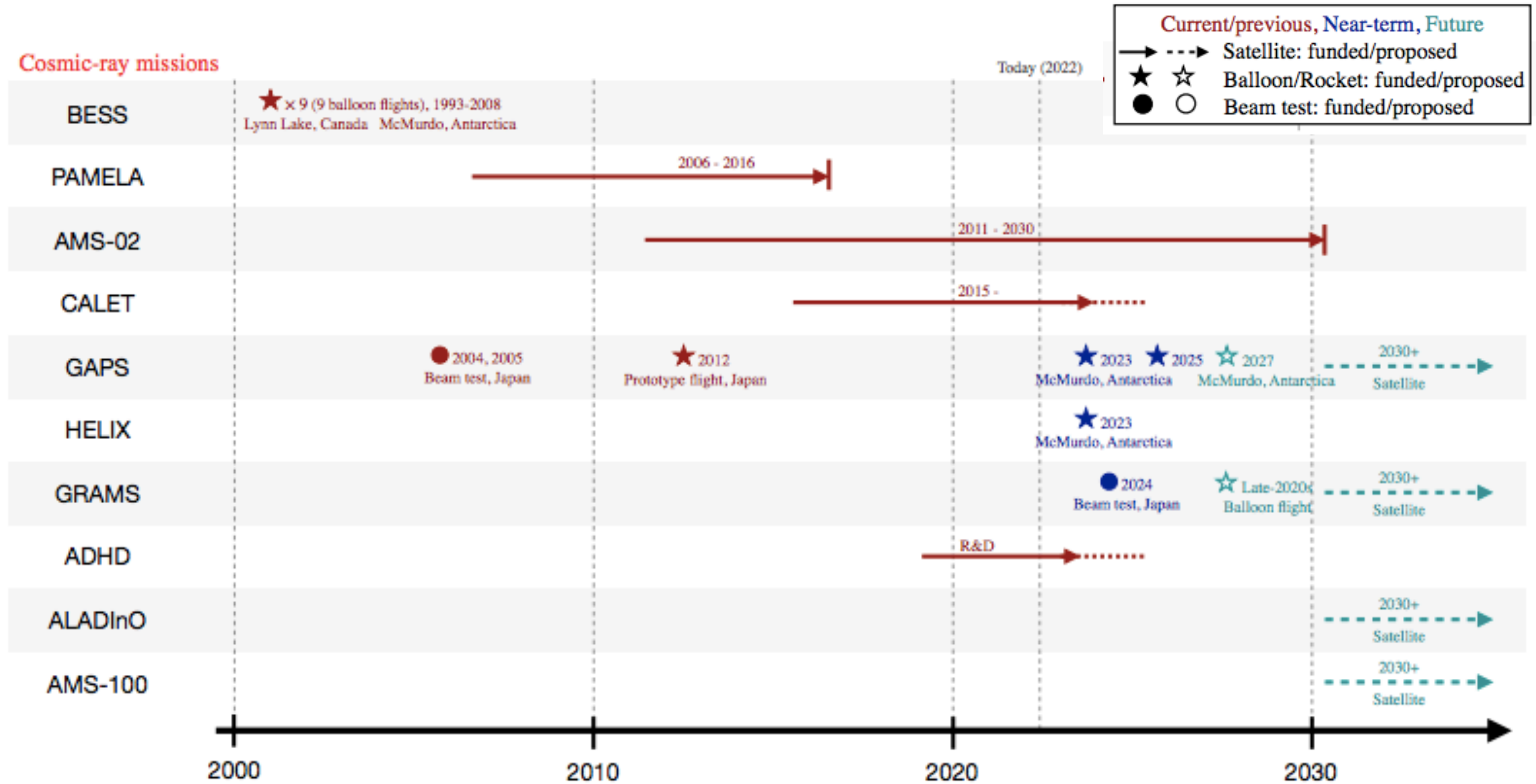
- The astrophysical backgrounds for low-energy antinuclei (in particular antideuterons, antihelium) are expected to be very small
- Discovery would be transformative
- Near-term: dedicated GAPS balloon experiment scheduled for this year, should have sensitivity to hadronically annihilating thermal relics around ~100 GeV mass (i.e. relevant to GCE)
- See talk by Philip von Doetinchem



Aramaki et al ’22
(Snowmass)

Proposed CR experiments

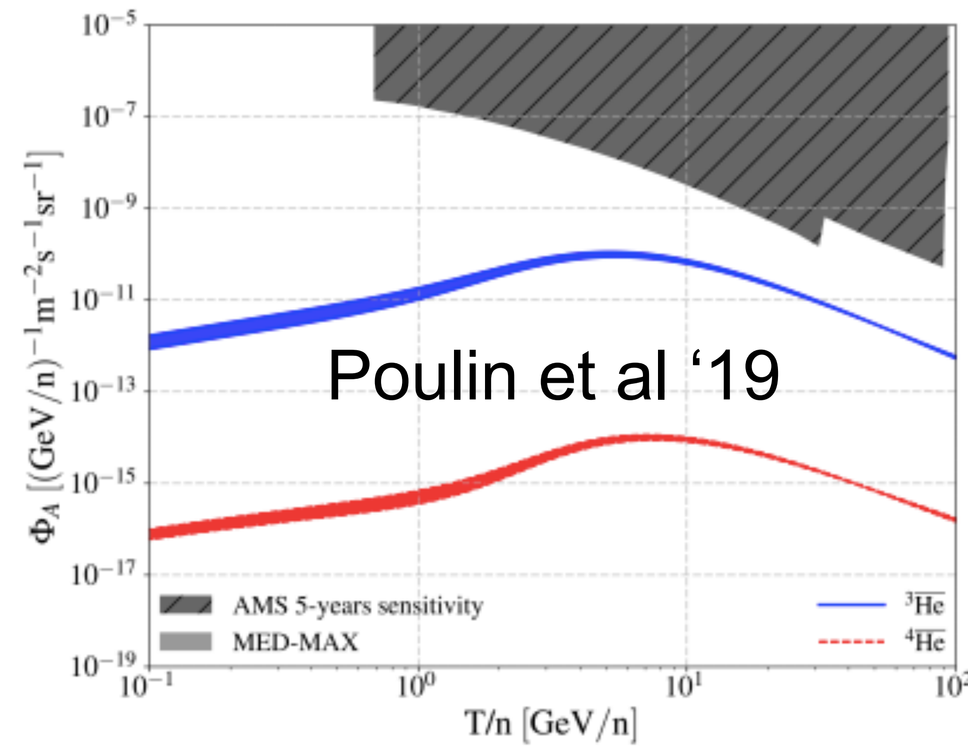
- HELIX = near-term balloon experiment, will constrain cosmic-ray propagation by measuring beryllium

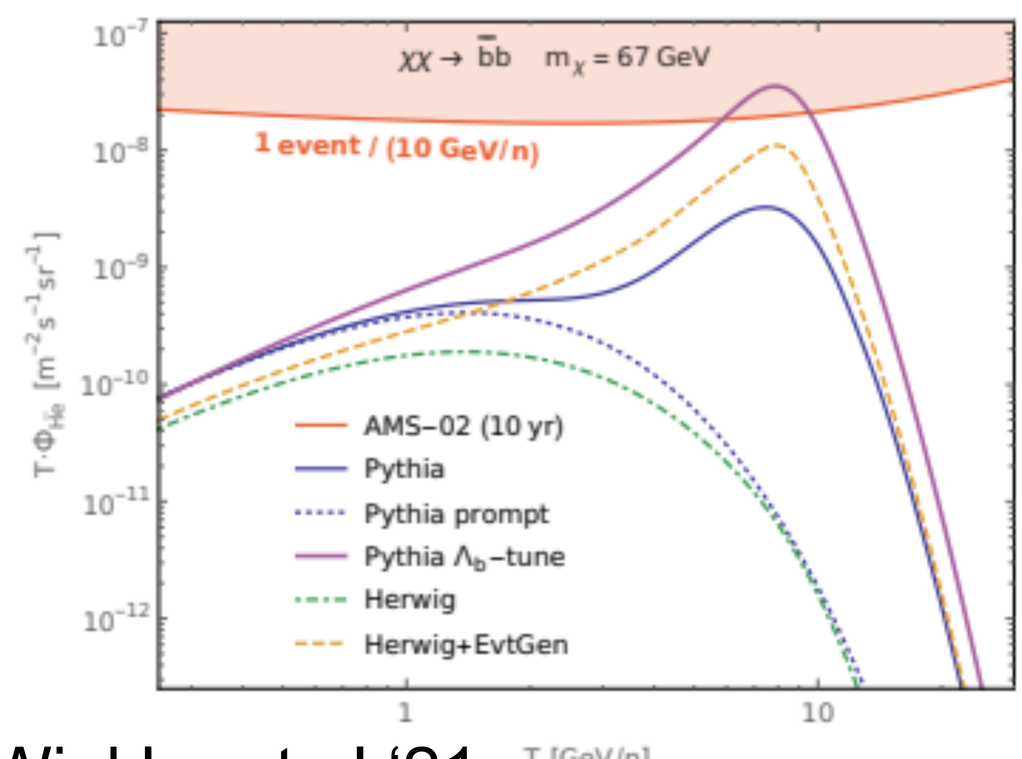


- GRAMs would aim to measure both antideuterons and MeV-band gamma rays
- Proposed AMS-02 successor experiments ALADInO, AMS-100 would have increased acceptance generally, but in particular would aim to measure low-energy antideuterons/antihelium. (ADHD = new approach for detecting antinuclei via annihilation in helium)

AMS-02 antihelium

- AMS-02 Collaboration announced tentative possible detection of six apparent anti-He-3 events and two apparent anti-He-4 events ["AMS Days at La Palma, La Palma, Canary Islands, Spain," (2018)]
- Expected astrophysical background is tiny - but so is expected DM signal!
- One proposal is that clouds of antimatter or anti-stars could generate these events [Poulin et al '19]
- Some theory work suggested DM signal calculations might have missed an important process [Winkler & Linden '21], production of $\bar{\Lambda}_b$-baryons which decay to antihelium could boost the signal



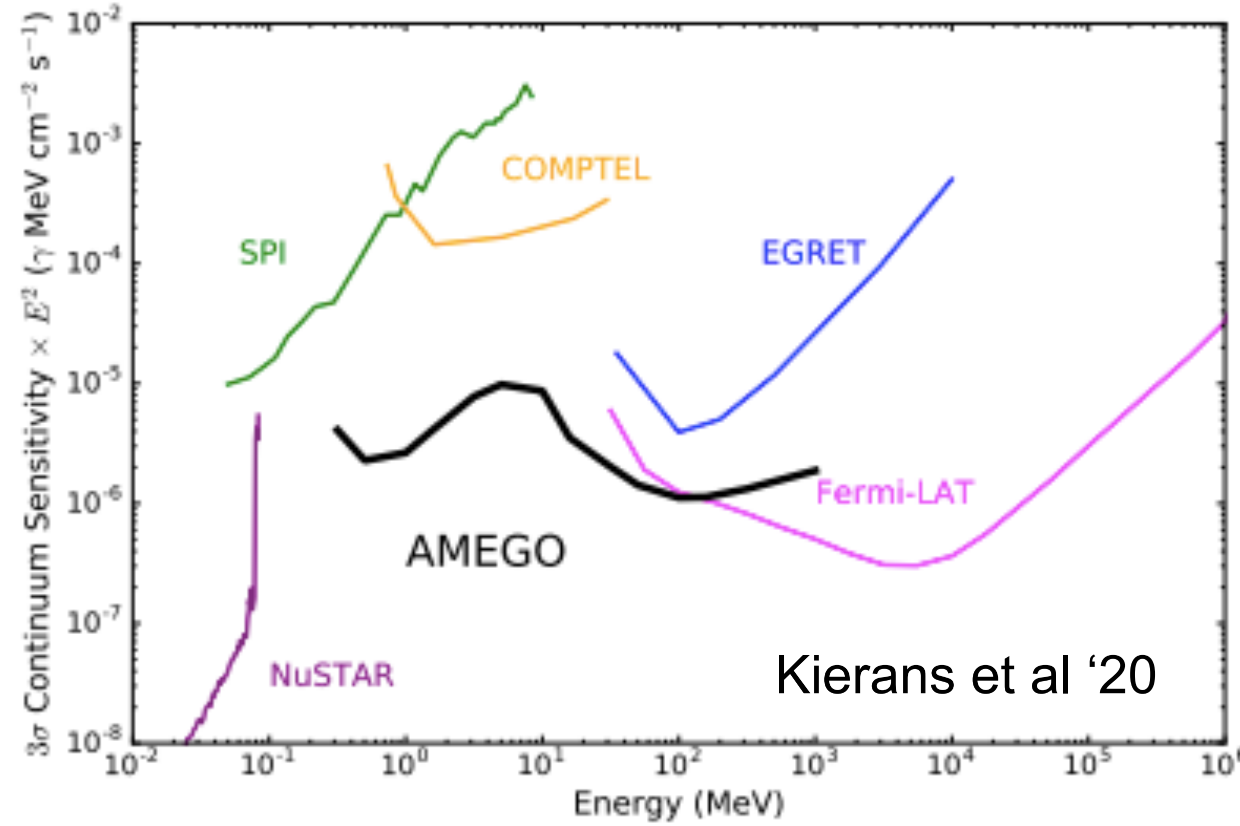


Winkler et al '21

The MeV gap

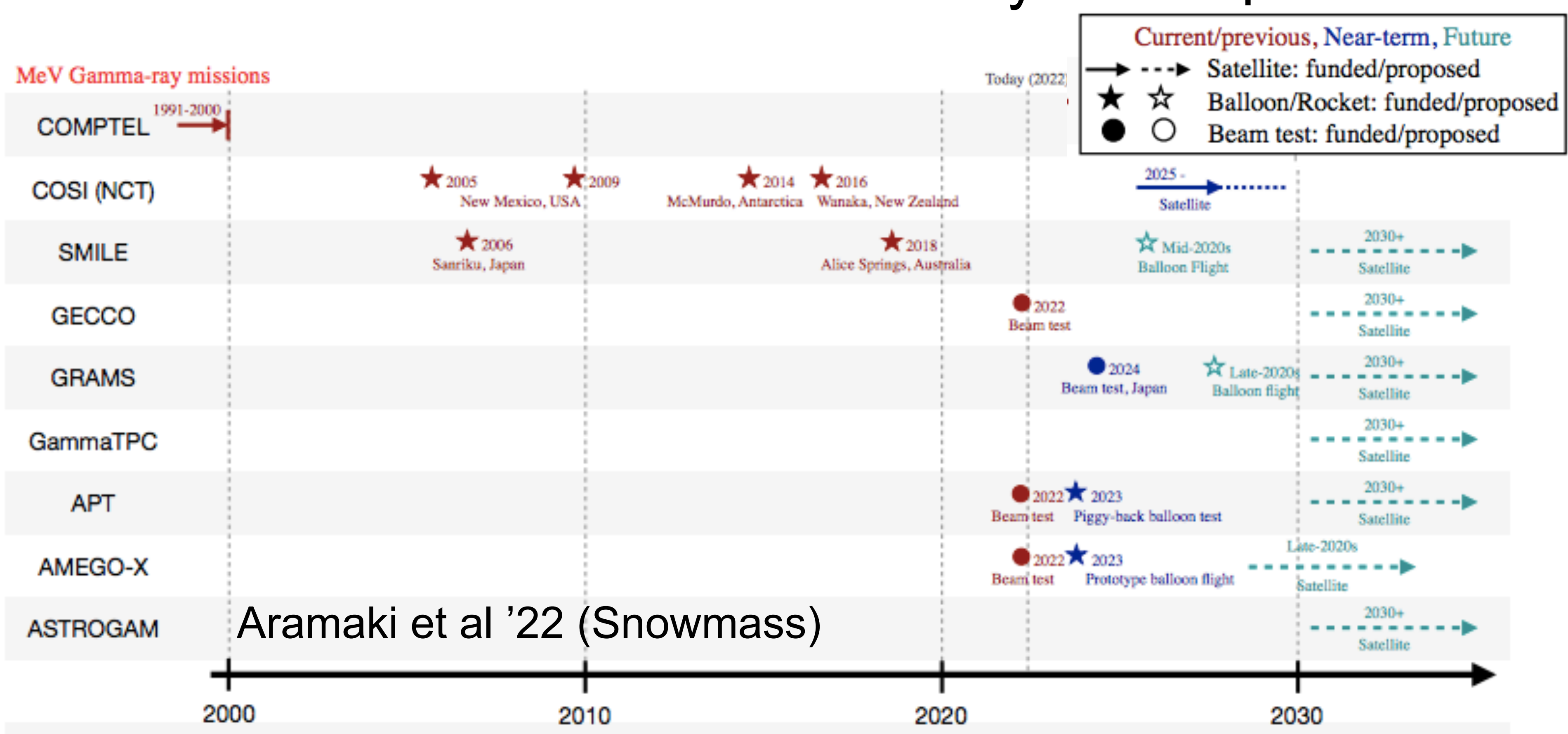
- MeV-GeV band is currently the focus of a huge amount of effort in accelerator and direct searches.

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



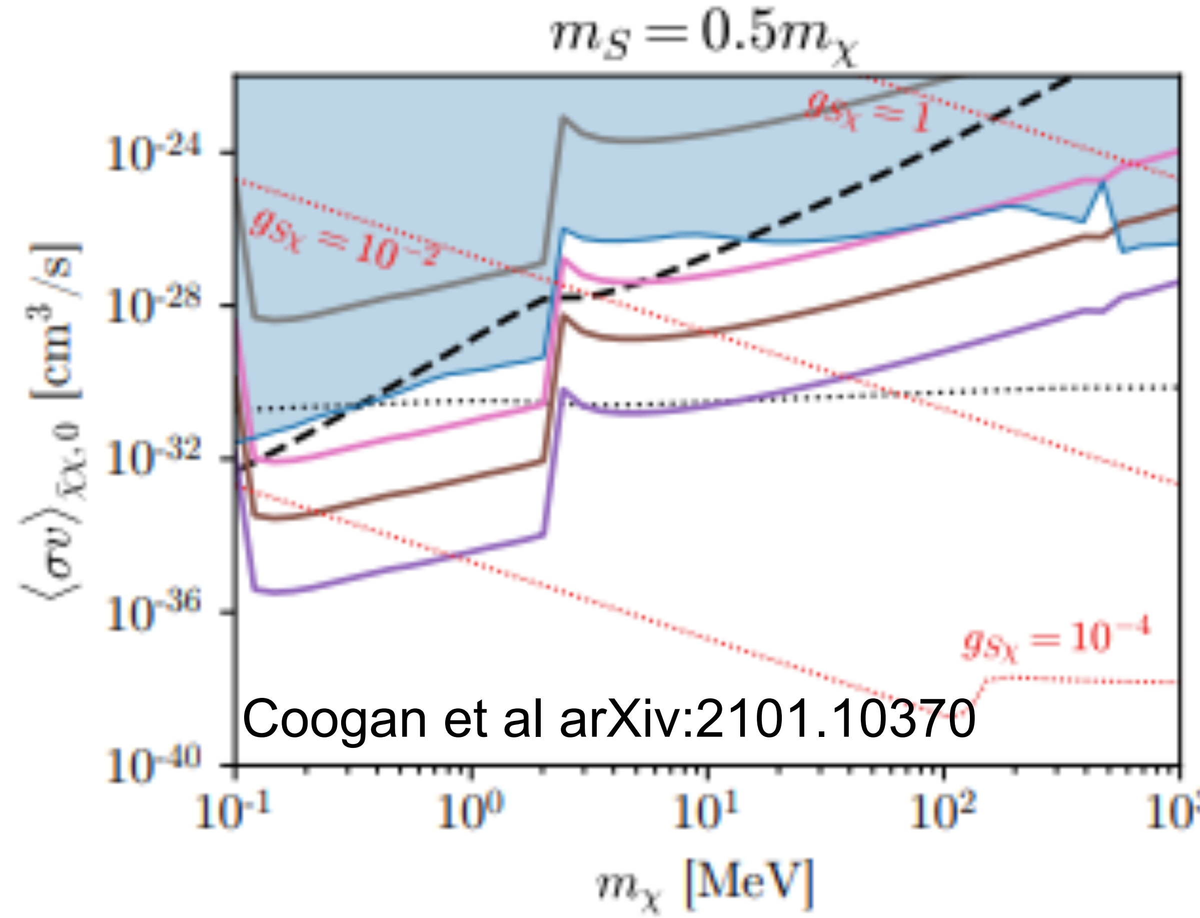
- However, there is a gap in sensitivity for energies between Fermi and X-ray telescopes

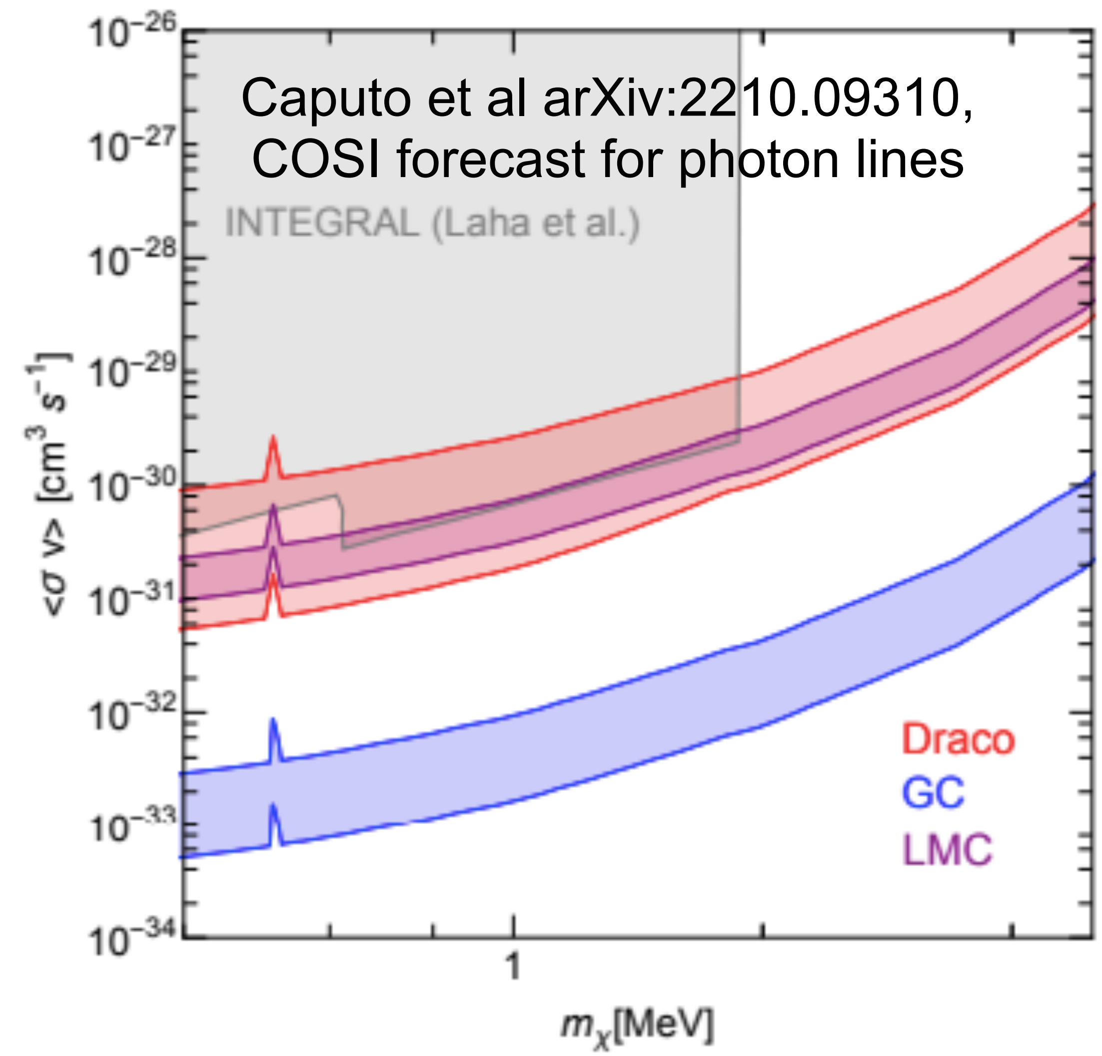
- Many new ideas for experiments to close this gap, primarily balloon- and eventually space-based telescopes (e.g. see talk by Tsuguo Aramaki)



Implications for particle DM

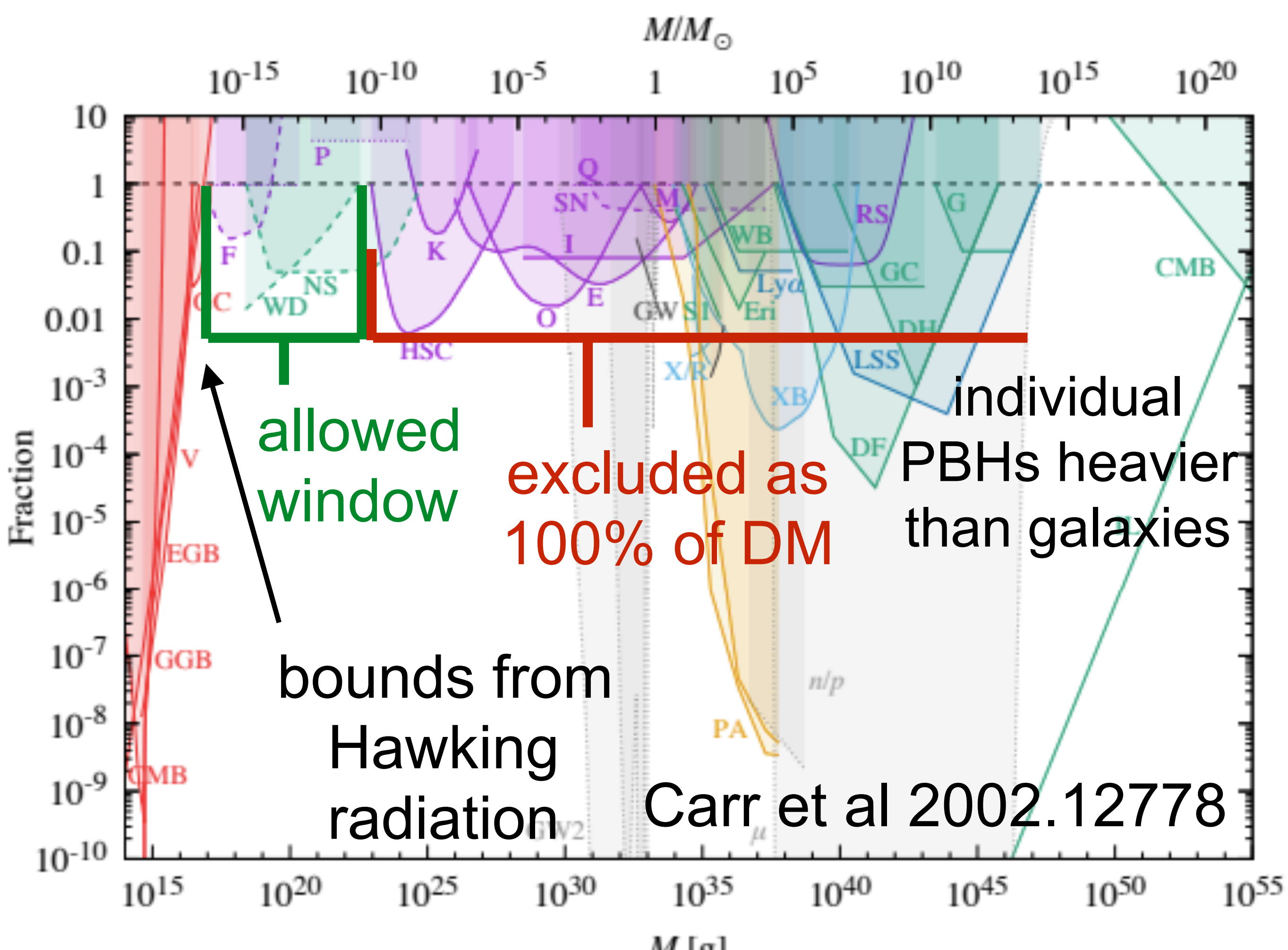
- Proposed experiments could potentially probe p-wave thermal relic cross sections (example on top right is for a Higgs portal model with GECCO proposed telescope)
- Various proposals would improve sensitivity via a combination of improved energy resolution, angular resolution, and effective area
- Would also open up sideband measurements for studying backgrounds at GeV+ scale and in X-rays

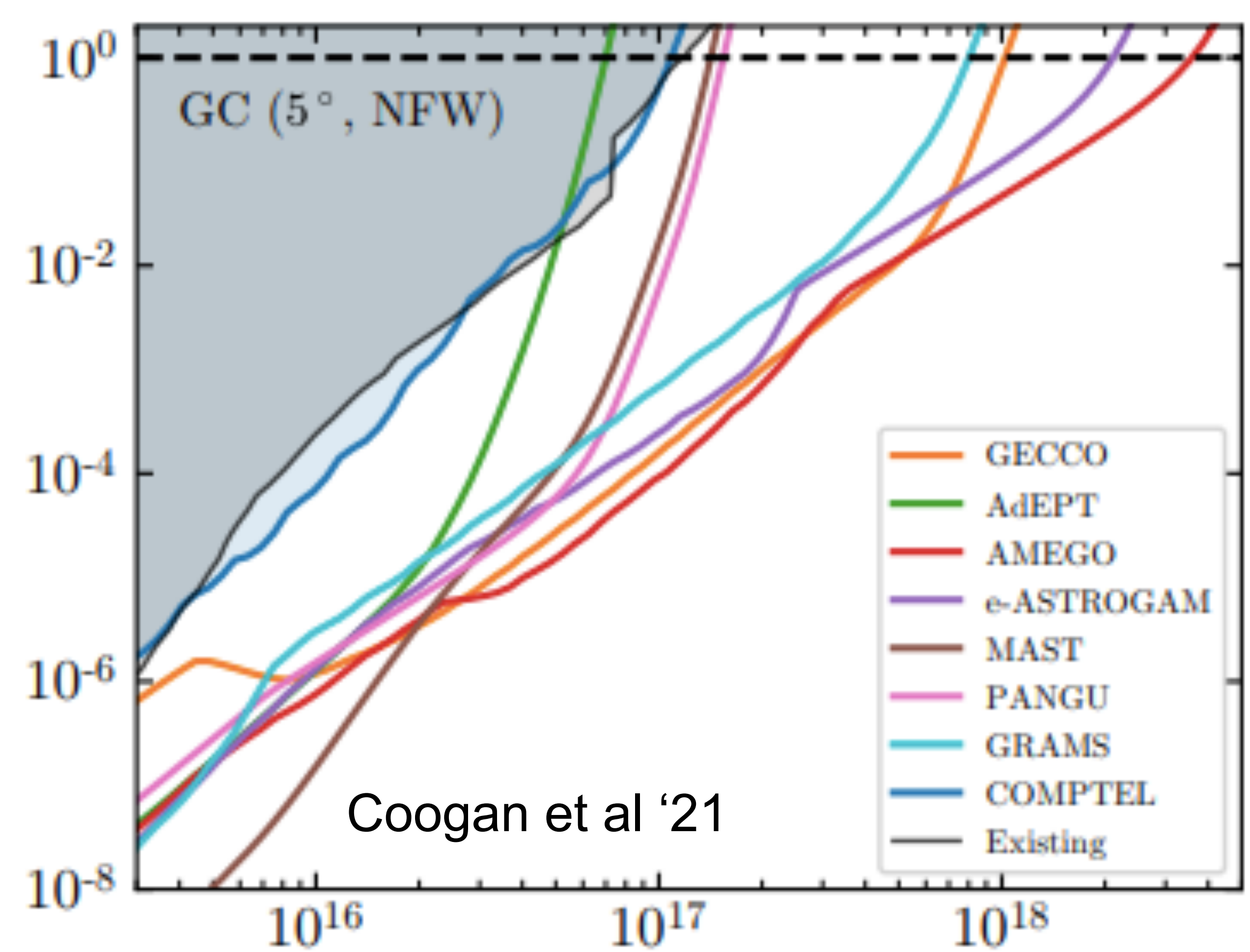




Primordial black holes

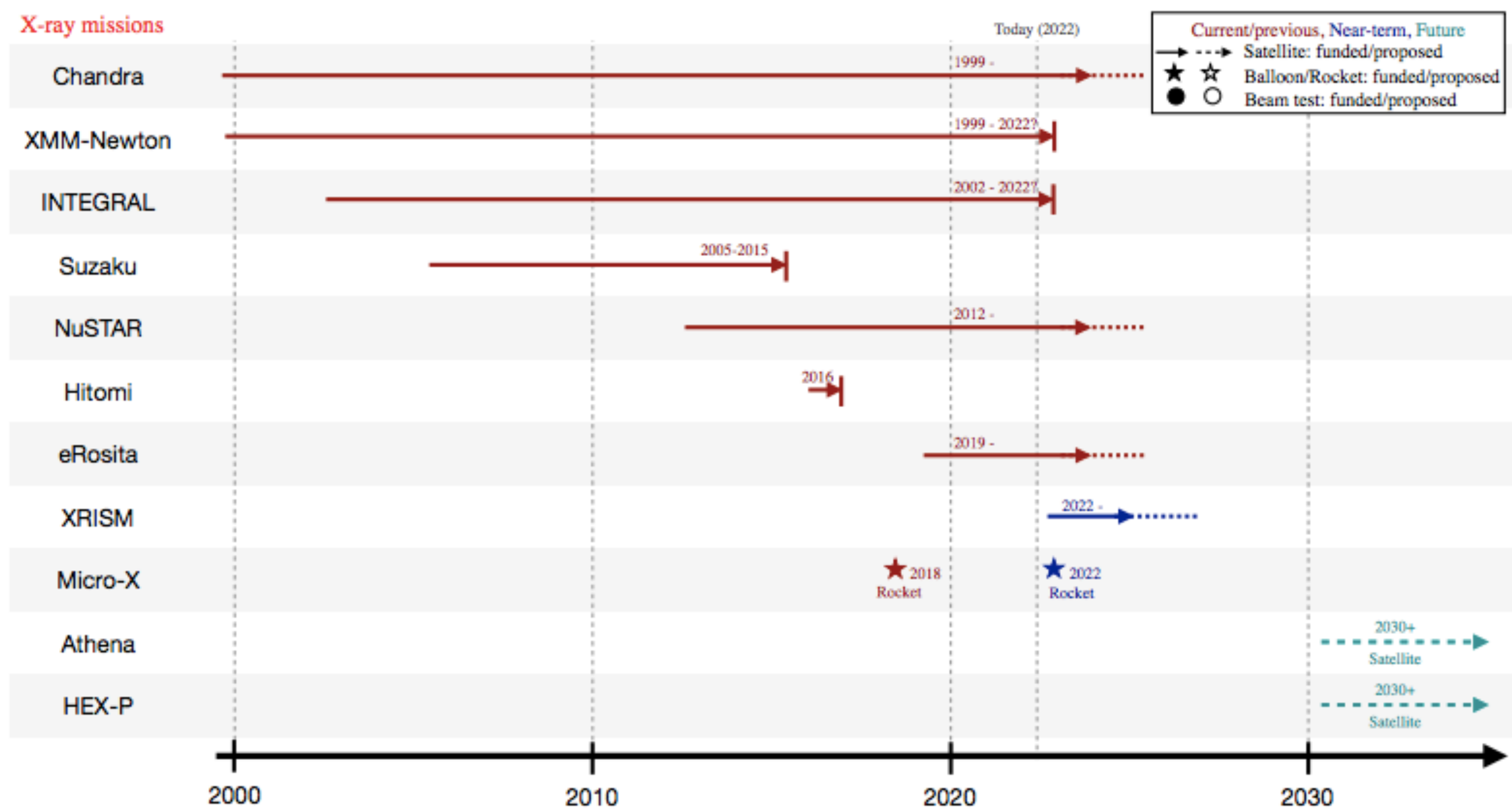
- Primordial black holes (PBHs) can serve as a DM candidate if they lie in the right mass range - $10^{17\text{-}23}$ g PBHs appear viable to constitute 100% of the DM (see talk by Volodymyr Takhistov).
- PBHs are decaying DM - they slowly decay through Hawking radiation (with temperatures far less than the BH mass), PBHs around 10^{17} g would produce X-ray and soft gamma-ray radiation.
- Current best limits are around 4 x 10^{17} g [Berteaud et al '22]. Future space-based gamma-ray experiments focused on the MeV-GeV band have the potential to extend the mass reach up to around 10^{18} g [Coogan et al '21, Ray et al '21].





Proposed X-ray experiments

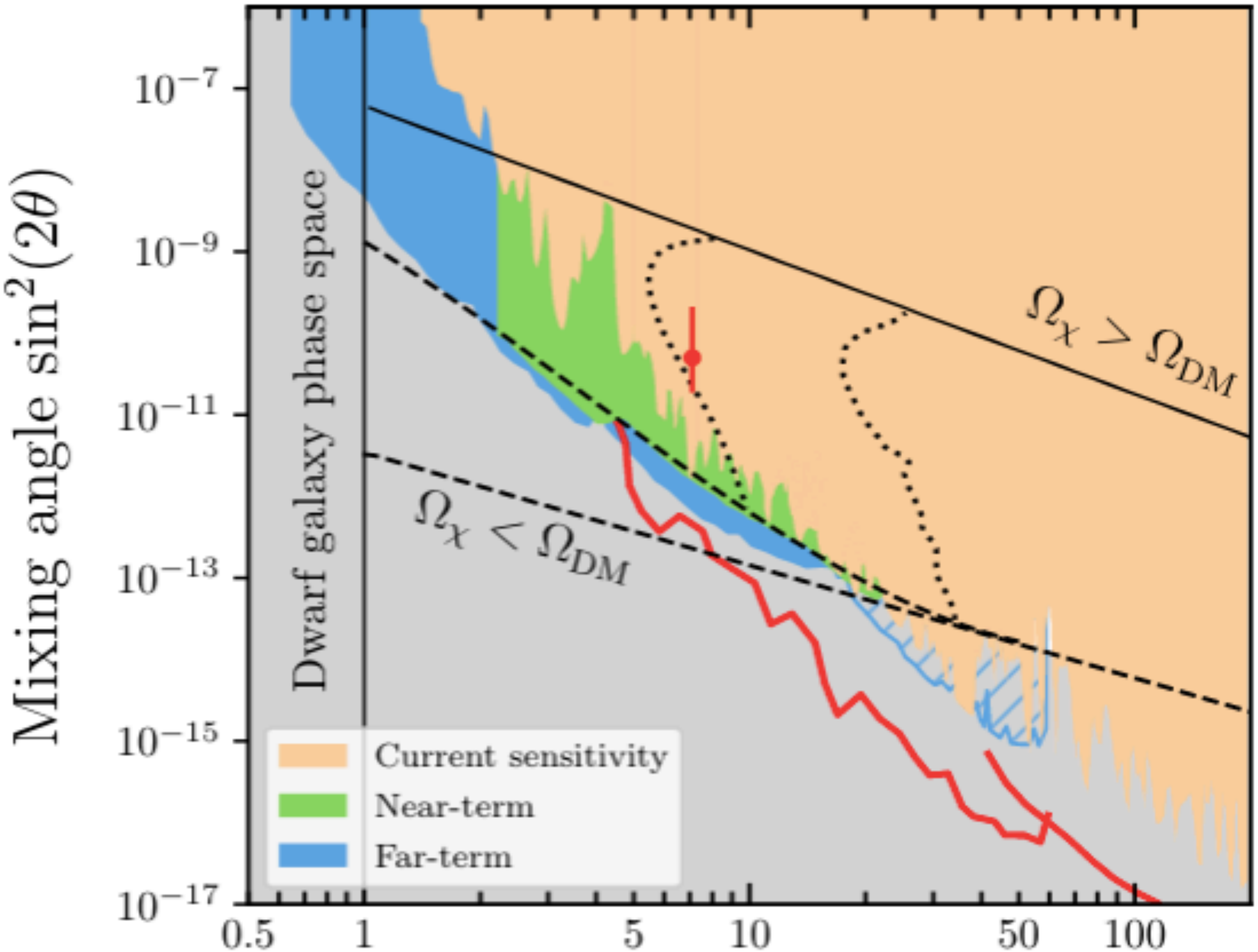
- DM annihilation/ decay searches are primarily for photon lines
- Several experiments are targeting fine energy resolutions: e.g. 7 eV (XRISM), 3 eV (Micro-X), 2.5 eV (Athena)
- 10^{-3} energy resolution would be sufficient to measure the Doppler linewidth for Galactic DM



- Most upcoming experiments will focus on <10 keV, but HEX-P would have sensitivity at 2-200 keV, relevant for secondary signals from MeV-band DM

Sterile neutrino limits

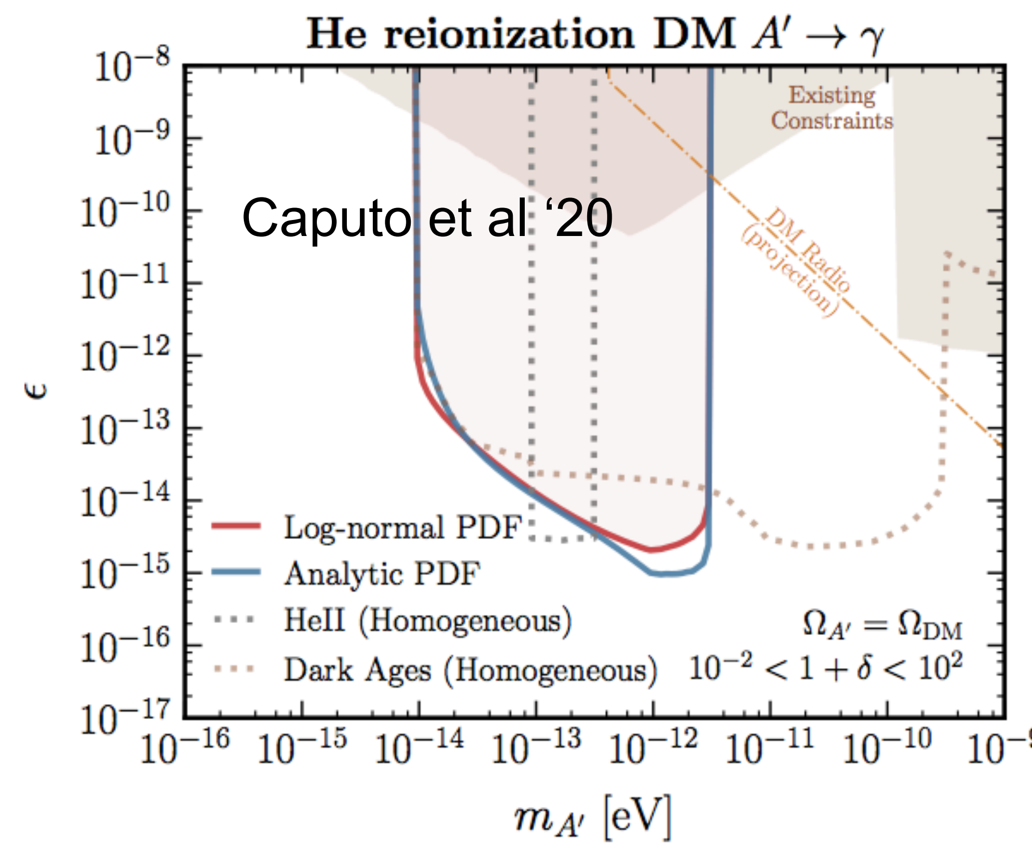
- Limits on nuMSM from X-ray experiments + warm DM bounds and production limits are already very stringent
- See talk by George Fuller for more on sterile neutrinos

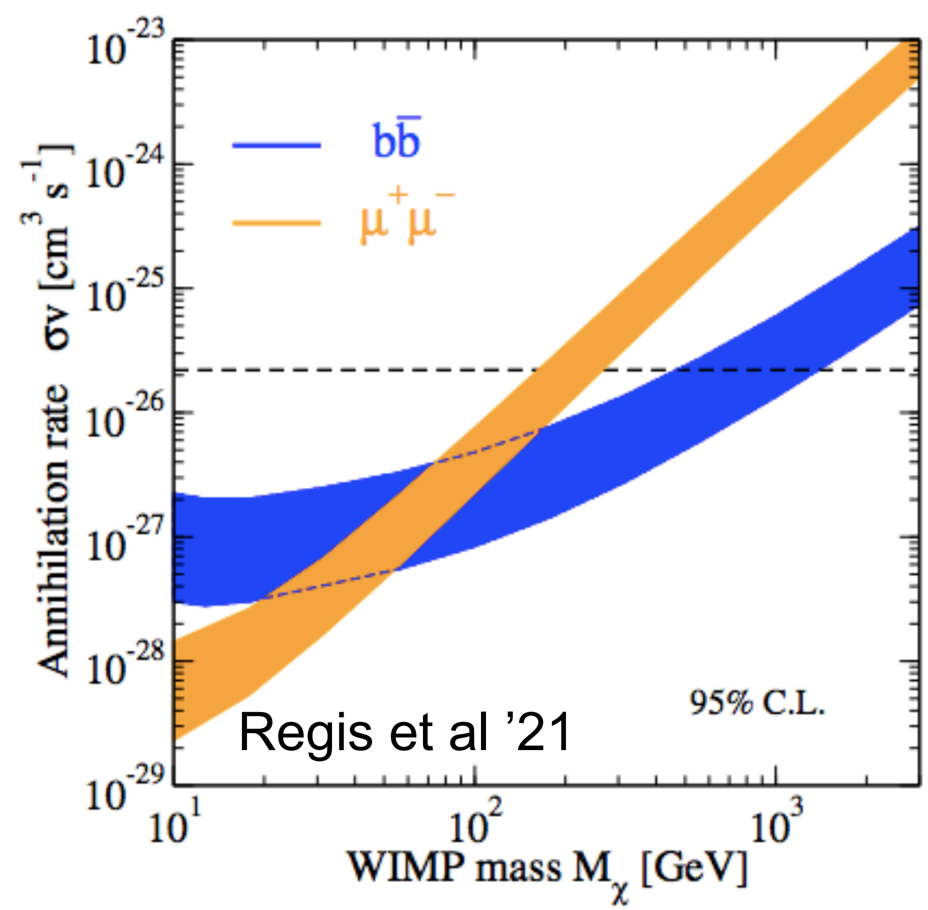


Credit: Brandon Roach

Lower energies

- Below the X-ray band, still many interesting observations for indirect detection
- Radio, microwave, optical etc are especially relevant for very light DM, but 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 propagation + B-field, but potentially very strong limits on heavy DM [e.g. Chan et al '19 from Andromeda, Regis et al '21 from the LMC]
- Many interesting cosmological bounds on DM (including from CMB and in future 21cm), see e.g. talk by Vera Gluscevic





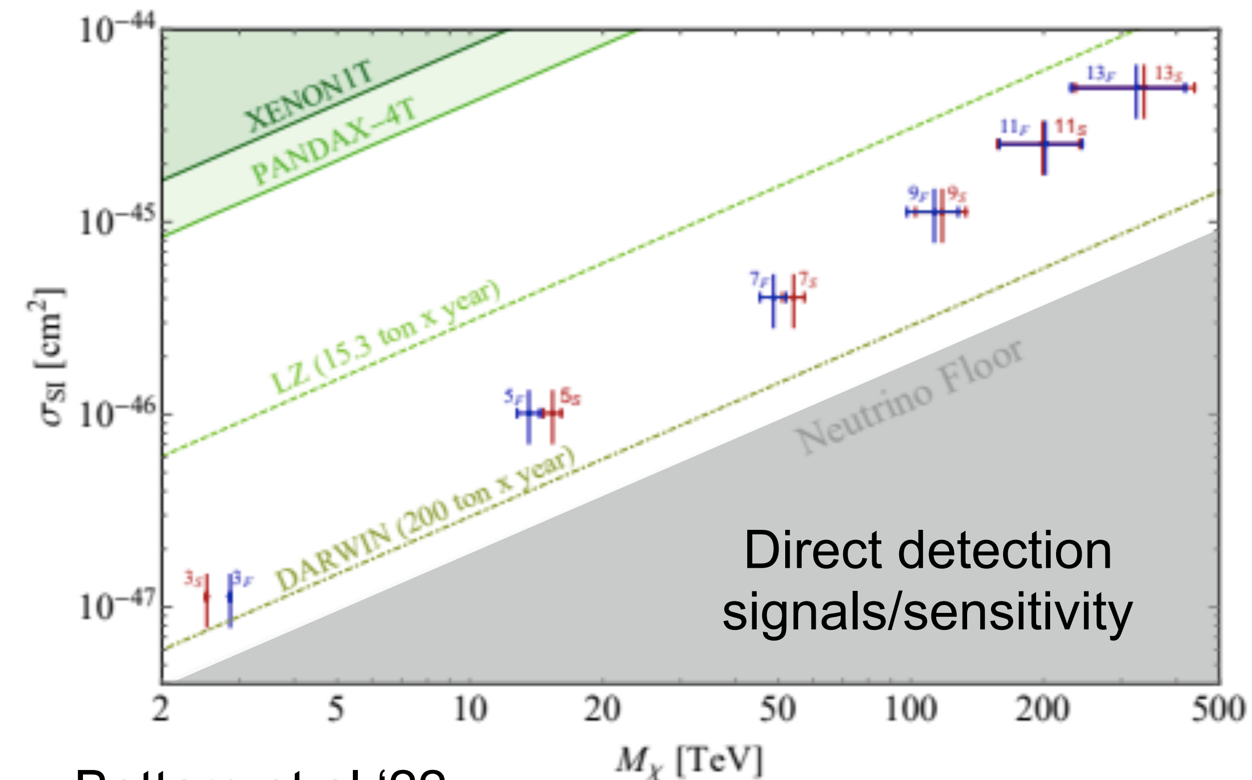
Summary

- Indirect searches for dark matter currently:
  - test thermal relic annihilation cross sections up to O(10s-100s) GeV DM
  - exclude decay lifetimes up to $10^{27\text{-}28}$ s over a very wide DM mass range,
  - serve as novel probes of other possible DM interactions with visible particles
- Future experiments offer many exciting prospects, including:
  - greater sensitivity to significantly higher-mass thermal DM, up to the O(100) TeV scale (and non-thermal models with lower cross-sections)
  - 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
- A number of possible anomalies exist in the data, but no consistent/confirmed detections yet - some may need additional data and/or new analysis strategies to resolve

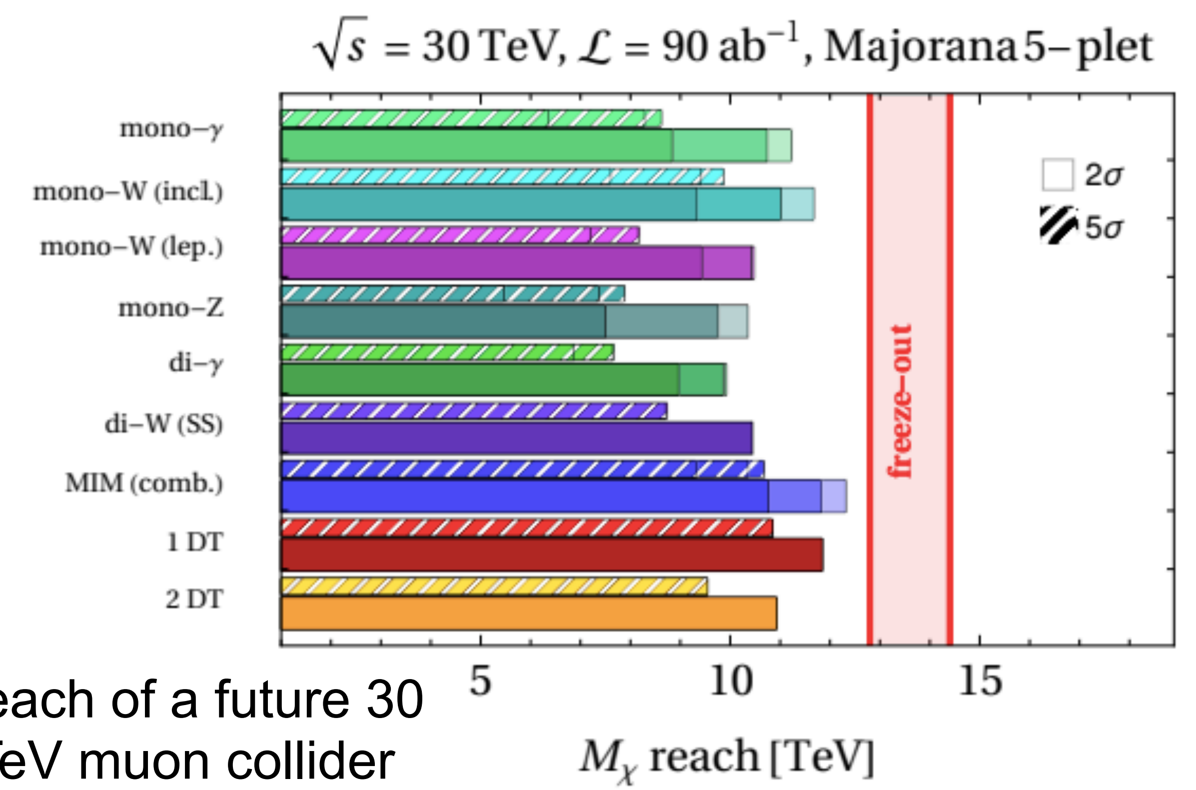
Bonus slides

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 (see talk by Ben Safdi yesterday on higgsino)
- 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 not yet excluded (although potentially testable with next generation)



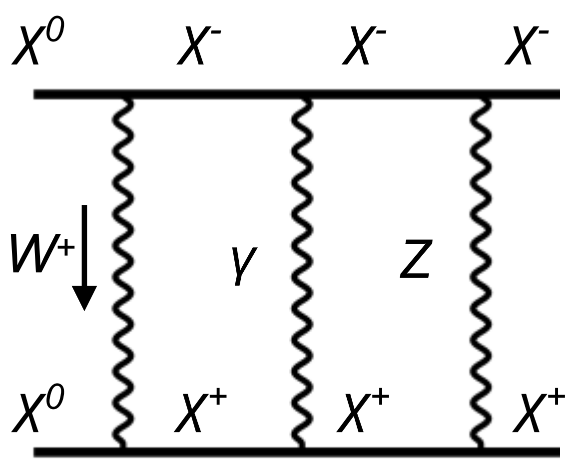
Bottaro et al ‘22

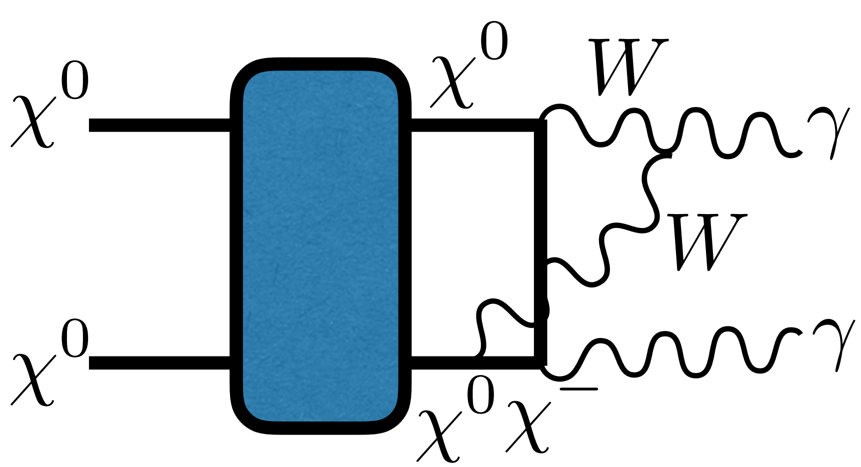


Reach of a future 30 TeV muon collider

Theoretical challenges in the indirect signal prediction

- Weakly-interacting DM with mass $\gtrsim m_W/\alpha_W \sim 2.4$ TeV feels an effective potential from W exchange that can support bound states
- Bound state formation and wavefunction deformation by the potential (Sommerfeld enhancement) boosts the annihilation rate [Hisano et al ‘03, ’04]
- Proximity of nearly-degenerate charged partners (in the multiplet) enhances the line signal
- 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]
- Similar physics can also appear in more general dark sectors





Example: wino annihilation

Baumgart, Cohen, Moult, Rodd, Solon, TRS, Stewart & Vaidya '18

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

$$\frac{d\sigma^{\rm LL}}{dz} = 4\,|s_{0\pm}|^2\,\sigma^{\rm tree}\; e^{-2\Gamma_0\,\tilde\alpha_W\,L_\chi^2}\;\delta(1-z)$$
$$+\;4\,\sigma^{\rm tree}\;e^{-2\Gamma_0\,\tilde\alpha_W\,L_\chi^2}\Big\{C_A\,\tilde\alpha_W\,F_1\Big(3\,\mathcal{L}_1^S(z)-2\,\mathcal{L}_1^J(z)\Big)\,e^{2\Gamma_0\,\tilde\alpha_W\,\left(\Theta_J L_J^2(z)-\frac{3}{4}\Theta_S L_S^2(z)\right)}$$
$$-\,2\,C_A\,\tilde\alpha_W\,F_0\,\mathcal{L}_1^J(z)\,e^{2\Gamma_0\,\tilde\alpha_W\,L_J^2(z)}\Big\}. \qquad (5.30)$$

$$\Gamma_0 = 4\,C_A \qquad \tilde\alpha_W = \frac{\alpha_W}{4\pi}$$

$$L_J(z) = \log\left(\frac{m_W}{2\,M_\chi\sqrt{1-z}}\right) \quad L_S(z) = \log\left(\frac{m_W}{2\,M_\chi(1-z)}\right) \quad L_\chi = \log\left(\frac{m_W}{2\,M_\chi}\right)$$

large logs

$$\Theta_J = \Theta\left(1-\frac{m_W^2}{4\,M_\chi^2}-z\right)$$
$$\Theta_S = \Theta\left(1-\frac{m_W}{2\,M_\chi}-z\right)$$

$$\sigma^{\rm tree} = \frac{\pi\,\alpha_W^2\,\sin^2\theta_W}{2\,M_\chi^2\,v}$$

tree-level cross section

$$\mathcal{L}_1^J(z) = \frac{L_J}{1-z}\Theta_J\,, \quad \mathcal{L}_1^S(z) = \frac{L_S}{1-z}\Theta_S$$

power divergences in (1-z)

$$F_0 = \frac{4}{3}\left|s_{00}\right|^2 + 2\left|s_{0\pm}\right|^2 + \frac{2\sqrt{2}}{3}\left(s_{00}\,s_{0\pm}^* + s_{00}^*\,s_{0\pm}\right),$$
$$F_1 = -\frac{4}{3}\left|s_{00}\right|^2 + 2\left|s_{0\pm}\right|^2 - \frac{2\sqrt{2}}{3}\left(s_{00}\,s_{0\pm}^* + s_{00}^*\,s_{0\pm}\right),$$

Sommerfeld factors

At NLL, the power-law terms are dressed with additional logs.

Generalizing to larger representations

Baumgart, Rodd, TRS & Vaidya, in progress

- Bound state capture rates and Sommerfeld enhancement need to be re-computed separately for larger representations (at least in the current analysis)

- However, (preliminarily) for the SCET calculation it turns out to be possible to separate out the representation information; most of the calculation is unaffected

$$\mathcal{L}^{(0)}_{\text{hard}} = C\left(\chi_v^T i\sigma_2 \left\{t_\chi^a, t_\chi^b\right\}\chi_v\right)\left(Y^{abcd}\mathcal{B}^{ic}_{\perp n}\mathcal{B}^{jd}_{\perp \bar{n}}\right) i\epsilon^{ijk}(n-\bar{n})^k\,,$$
$$C = -\pi\frac{\alpha_W(\mu)}{2M_\chi}\,,$$
$$Y^{abcd} = \left(Y_v^{ae}Y_n^{ce}\right)\left(Y_v^{bf}Y_{\bar{n}}^{df}\right)\,.$$

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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 adjoint rep (gauge bosons)

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controlled solely by physics of adjoint rep (gauge bosons)

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

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

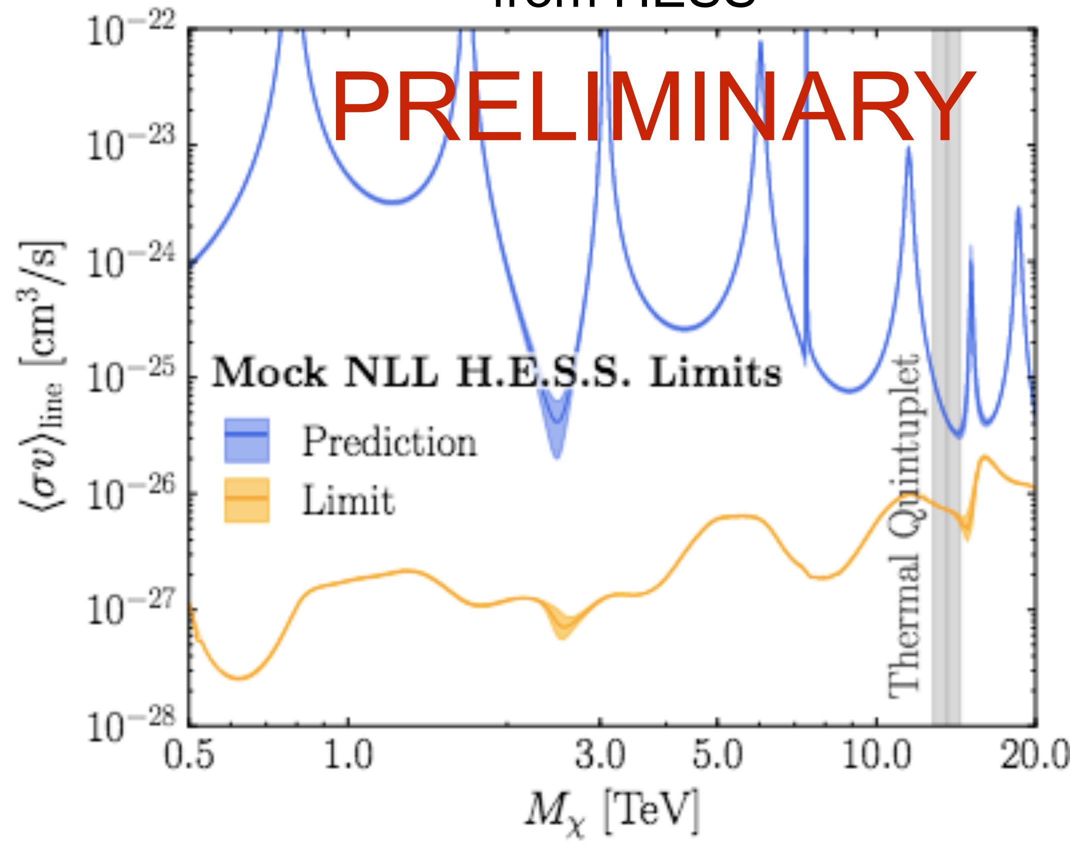
$$F^{a'b'ab} = \langle (\chi^0 \chi^0)_S | \left(\chi_v^T i\sigma_2 \left\{ t_\chi^{a'}, t_\chi^{b'} \right\} \chi_v \right)^\dagger |0\rangle\langle 0| \left(\chi_v^T i\sigma_2 \left\{ t_\chi^a, t_\chi^b \right\} \chi_v \right) |(\chi^0 \chi^0)_S\rangle$$

incorporates Sommerfeld factors & representation dependence from initial state

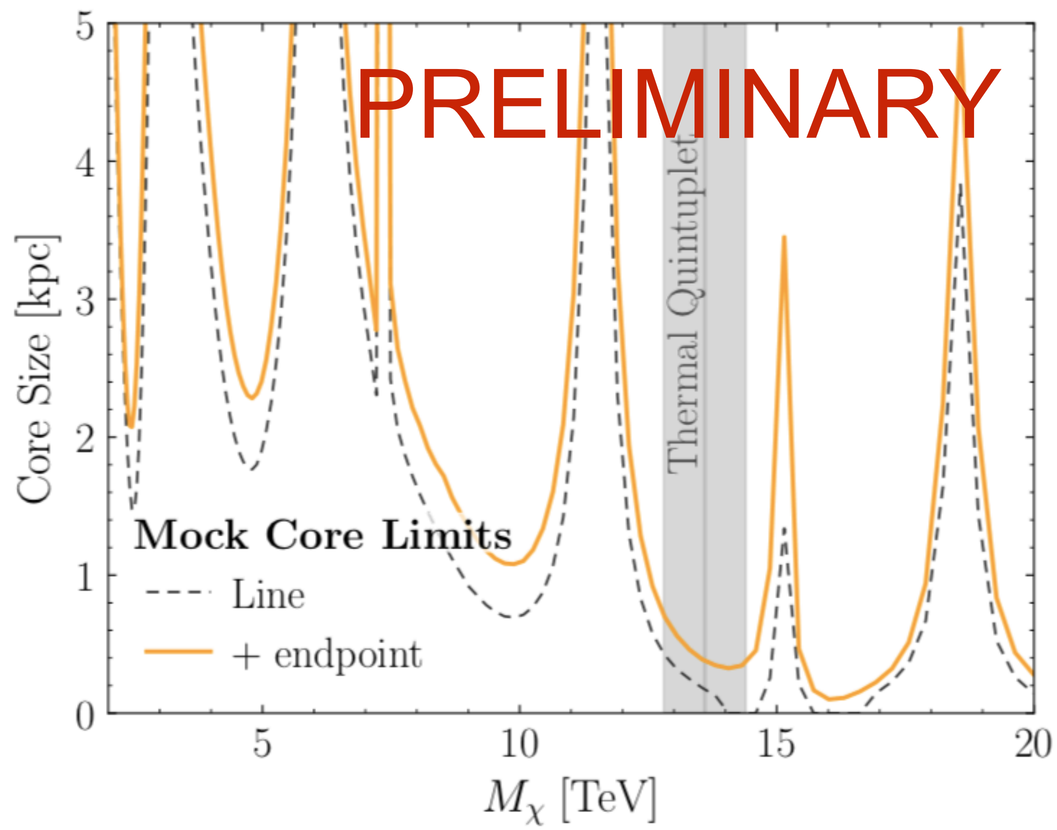
Quintuplet: preliminary results

- In work in progress, we applied this to the $SU(2)_L$ fermionic quintuplet
- We can make a rough estimate of the sensitivity based on older H.E.S.S measurements of the inner Galaxy gamma-ray spectrum
- Consider DM density profiles that are Einasto outside a core radius, with a flat density profile within that radius
- (PRELIMINARY) In this analysis, for the quintuplet, even a small flattened core (<0.5 kpc) would evade detection
- Montanari et al '22 uses our signal prediction with a more sophisticated background model and confirms that in the non-cored case the quintuplet should be detectable by H.E.S.S

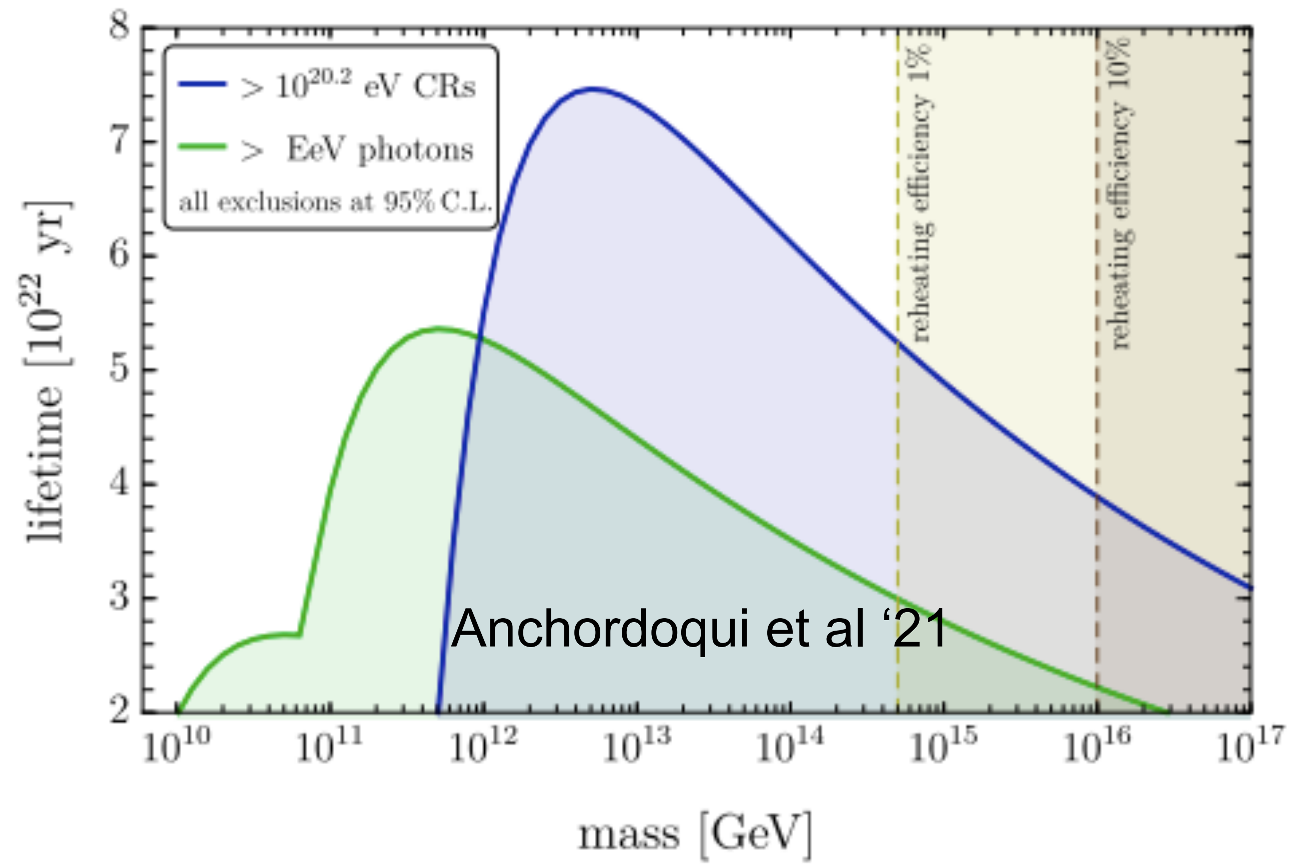
Estimated quintuplet sensitivity from HESS



Core size needed to evade estimated exclusion



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

Complementary measurements

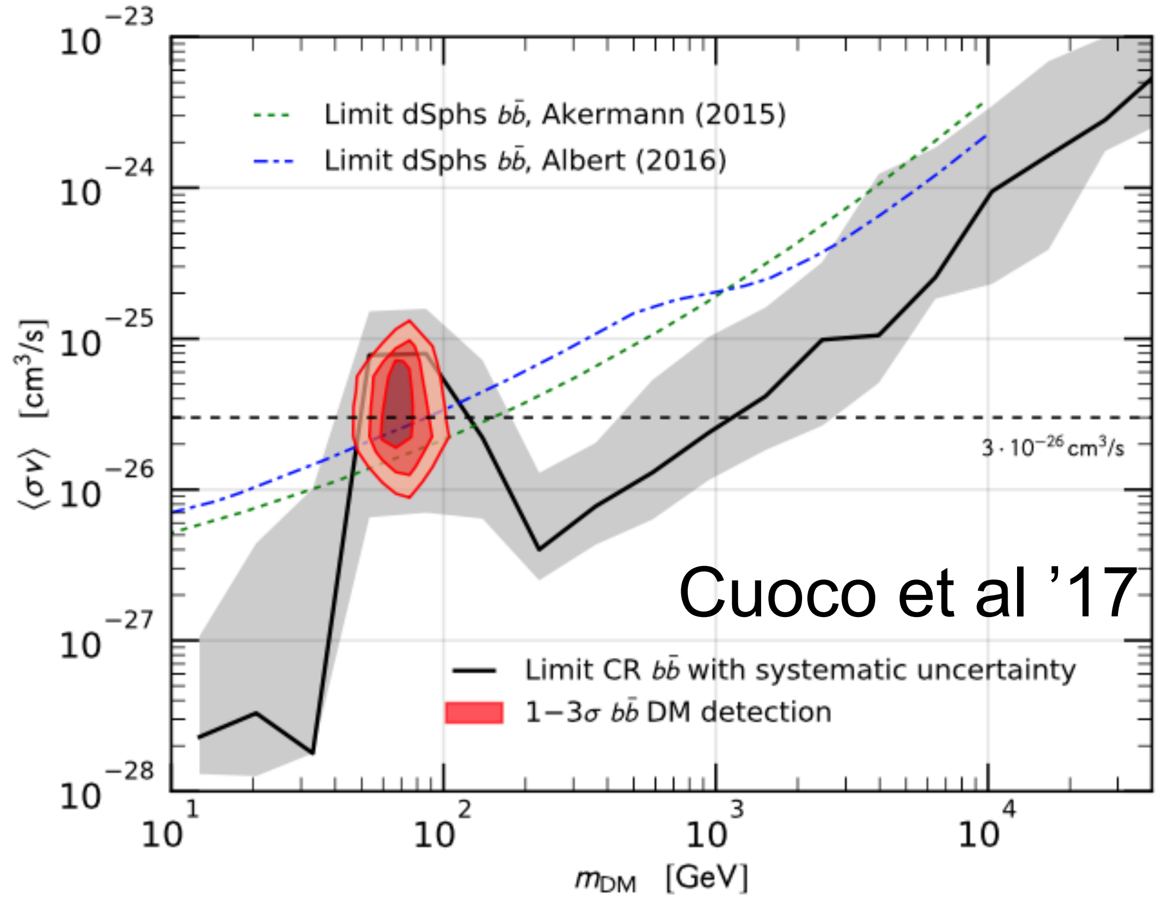
- Lengthy discussion in Cooley et al, but indirect searches would very much benefit from a better understanding of:
  - Cosmic ray production, composition, and propagation (input from fixed-target experiments, cosmic-ray measurements, better modeling)
  - Galactic diffuse photon emission (input from multiwavelength studies of the Galaxy, new tracers of interstellar gas, better modeling)
  - Improved understanding of the DM density distribution, especially in dwarfs / toward the Galactic Center
  - and more…

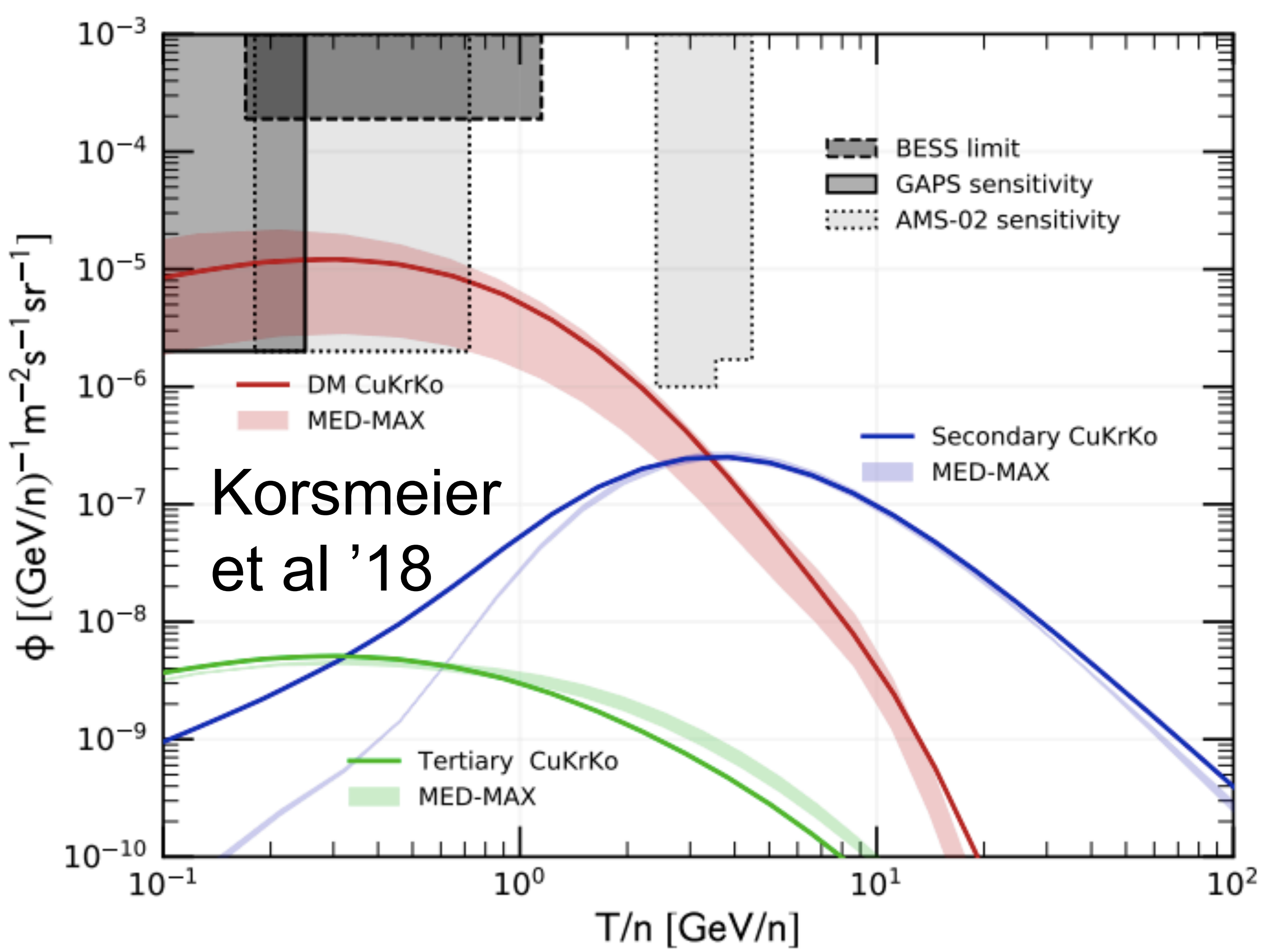
Some anomalies/excesses

[see Leane et al 2203.06859 (Snowmass) for a more in-depth review]

AMS-02 antiprotons

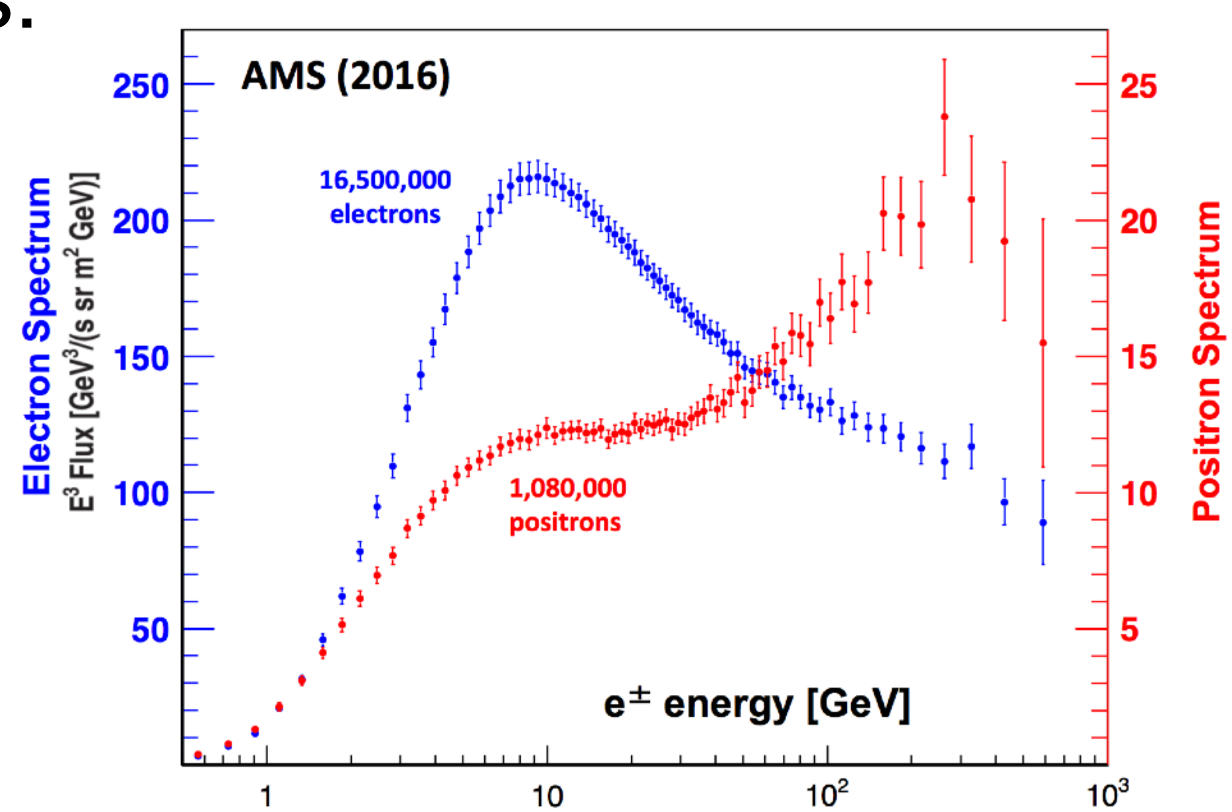
- AMS-02 observes a hint of an excess in ~10-20 GeV antiprotons, relative to background models
- Corresponds to a ~thermal cross section and ~40-130 GeV DM mass.
- Significance level has been highly debated [see Heisig et al '20, Boudaud et al '19, Cuoco et al '19, Cholis et al '19, Reinert & Winkler '18, Cui et al '17, Cuoco et al '17] - depends sensitively on model for correlations between bins, latest studies find it is not significant (<1 sigma).
- GAPS could potentially test similar parameter space in anti-deuterons [e.g. von Doetinchem et al '20].





AMS-02 positrons

- PAMELA/AMS-02 positron excess:
  - Cosmic-ray positron flux is enhanced relative to electron flux between ~10 and several hundred GeV.
  - Highly statistically significant.



Sam Ting, 8 December 2016, CERN colloquium

- DM explanation: TeV-scale DM annihilating or decaying dominantly into leptons (if annihilation, requires rate >> thermal).
- Observations of nearby pulsars suggest they produce abundant TeV-scale positrons that likely explain the excess [e.g. Hooper et al ’17].

The 3.5 keV line

- Claimed originally in stacked galaxy clusters [Bulbul et al ’14, Boyarsky et al ’14], subsequently in other regions. Individual signals are modestly significant (~4σ).

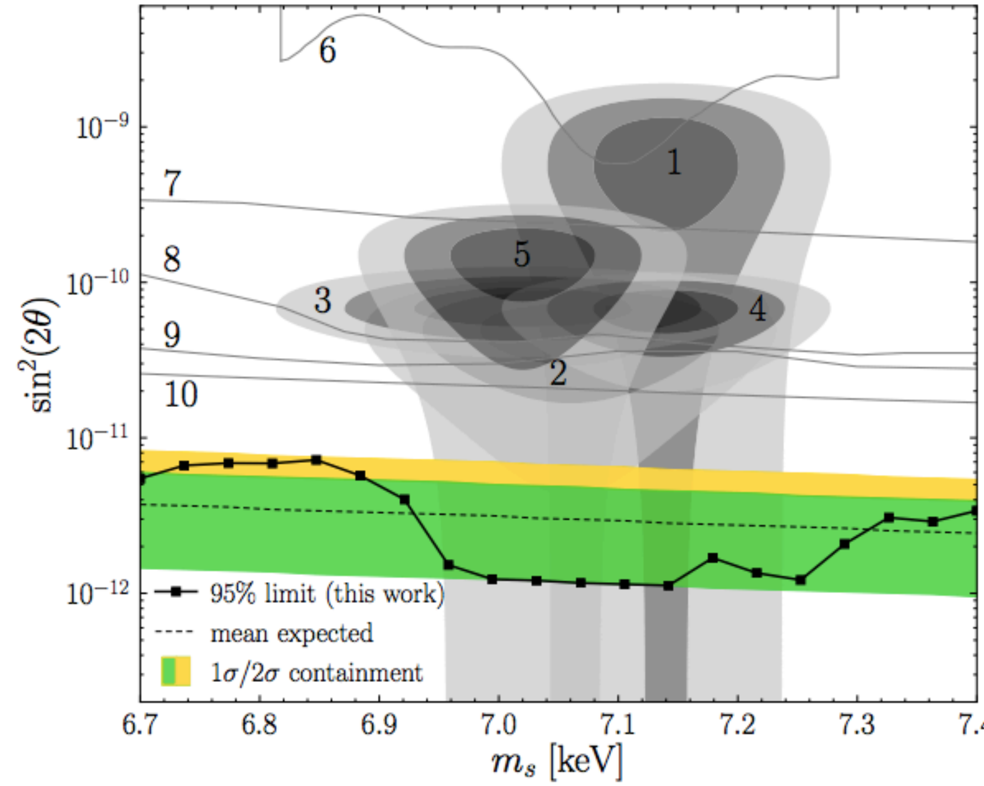
- Simplest DM explanation: 7 keV sterile neutrino decaying into neutrino+photon. (Other explanations involving annihilation, oscillations etc are possible.)

- Possible non-DM contributions: atomic lines (from K, Cl, Ar, possibly others), charge-exchange reactions between heavy nuclei and neutral gas [e.g. Shah et al ’16].

- Simple decay explanation seems inconsistent with null results in other searches, in particular work by Dessert et al ’20, https://github.com/bsafdi/BlankSkyfor3p5

- Some debate over validity of upper limits [Abazajian 2004.06170, Boyarsky et al 2004.06601] - key points are flexibility of background model, energy range considered.

- Future X-ray experiments (e.g. XRISM, Micro-X, possibly eROSITA) should have the sensitivity to see the signal, in some cases with sufficient energy resolution to resolve its width / identify substructure.



Dessert et al ’20

Status of the GCE - a renewed controversy?

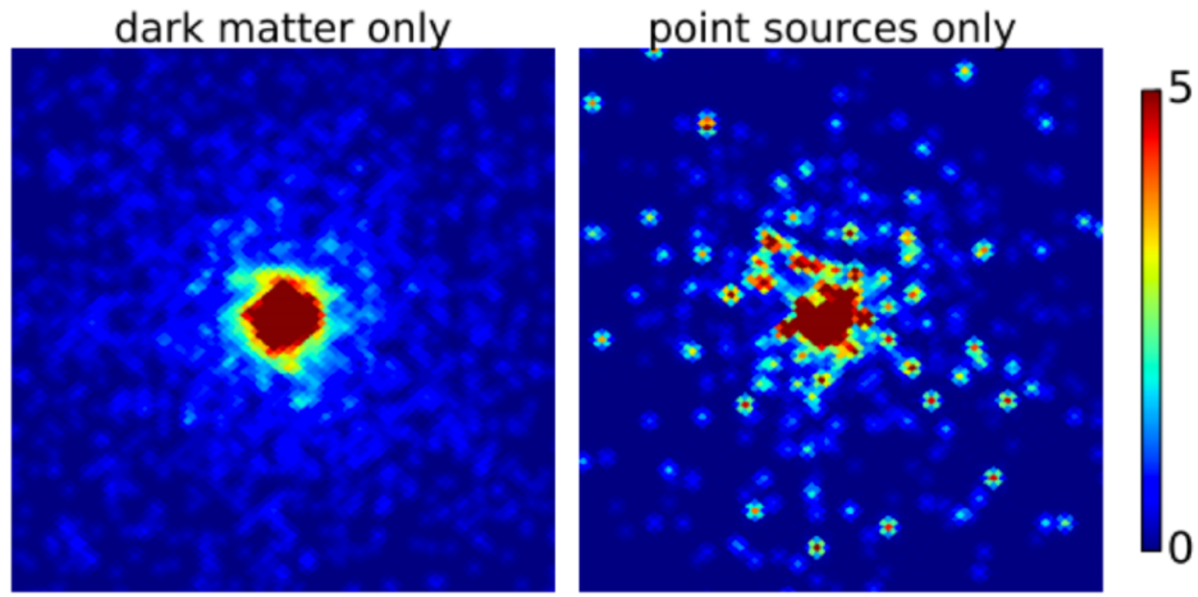
- Key argument in favor of pulsars: energy spectrum
- Current/past arguments against the DM explanation:
  - Spatial morphology of excess was originally characterized as spherical, but can also be described as boxy-bulge-like extended emission + central nuclear bulge component [Macias et al ’18, Bartels et al ’18, Macias et al ’19]. If the extended emission is robustly Bulge-like, suggests a stellar origin, but sensitive to background modeling [e.g. di Mauro ’21].
  - Constraints from other searches - limits from dwarf galaxies are in some tension with DM explanation [e.g. Keeley et al ’18], but depends on Milky Way density determination.
  - Photon statistics.

Photon statistics

Lee, Lisanti, Safdi, TRS & Xue ’16

<u>DM origin hypothesis</u>

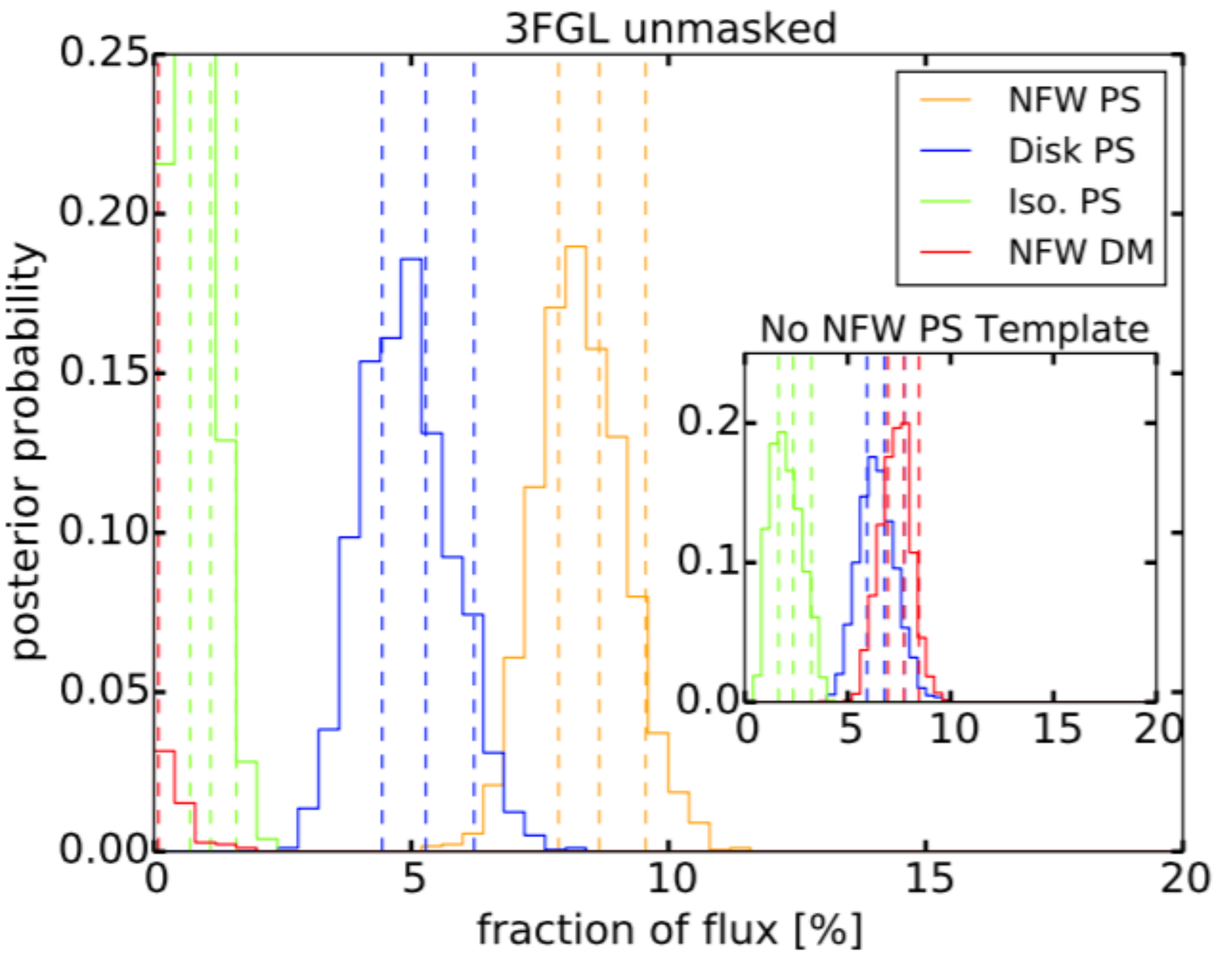
signal traces DM density squared, expected to be ~smooth near GC with subdominant small-scale structure



<u>Pulsar origin hypothesis</u>

signal originates from a collection of compact objects, each one a faint gamma-ray point source

- We may be able to distinguish between hypotheses by looking at clumpiness of the photons [e.g. Malyshev & Hogg ’11; Lee, Lisanti & Safdi ’15].
- If we are looking at dark matter (or another diffuse source, like an outflow), we expect a fairly smooth distribution - fluctuations described by Poisson statistics.
- In the pulsar case, we might instead see many “hot spots” scattered over a fainter background - non-Poissonian fluctuations, higher variance.
- Related analysis by Bartels et al ’16, using wavelet approach



- Lee et al ‘16: fit shows a strong preference to assign all GCE flux to new PS population (Bayes factor in favor of model with PSs ~10^9, roughly analogous to 6σ)
- Suggests signal is composed of a relatively small number of just-below-threshold sources

- Leane & TRS ’19, Chang et al ’19, Buschmann et al ’20:
    - background models used in original analysis lead to significant bias against DM signal, reconstruct injected smooth signals as ensembles of point sources;
    - newer models can be created that do not have the same clear bias, evidence for PSs drops to Bayes factor $10^{3.4}$, analogous to 3-4σ
- Leane & TRS ’20a, b: even with perfect background models, an overly-rigid signal model can lead to a spurious preference for a PS population

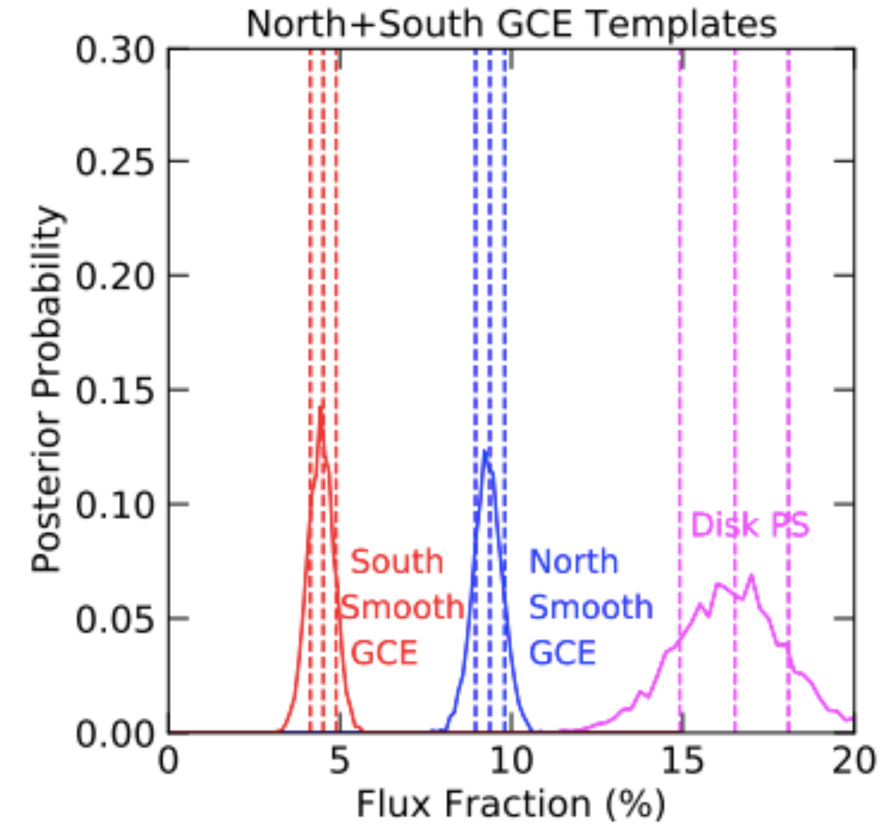
Spurious point sources (data)

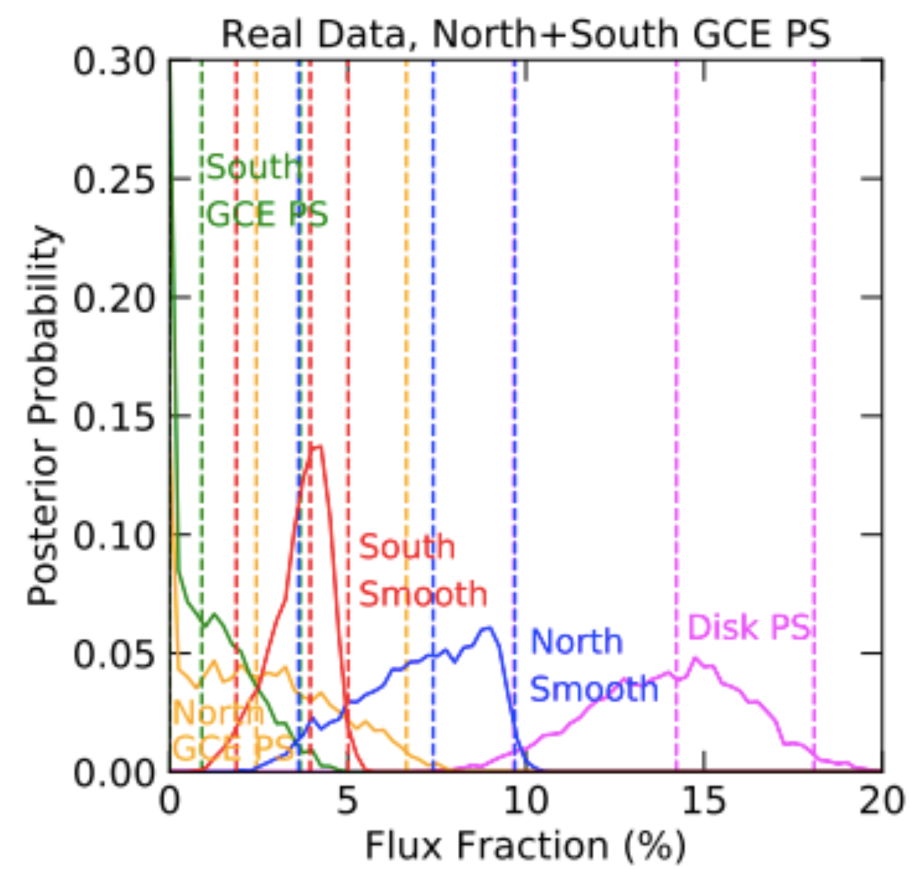
- We found this by accident - trying to test the spatial morphology of the GCE in more detail

- In the region of interest we used, when we split the GCE into 2+ spatial components, all evidence for GCE PSs went away (BF > 10^{15} → BF < 10 with one added d.o.f)

- Apparent preference for PSs is really just a preference for N/S asymmetry

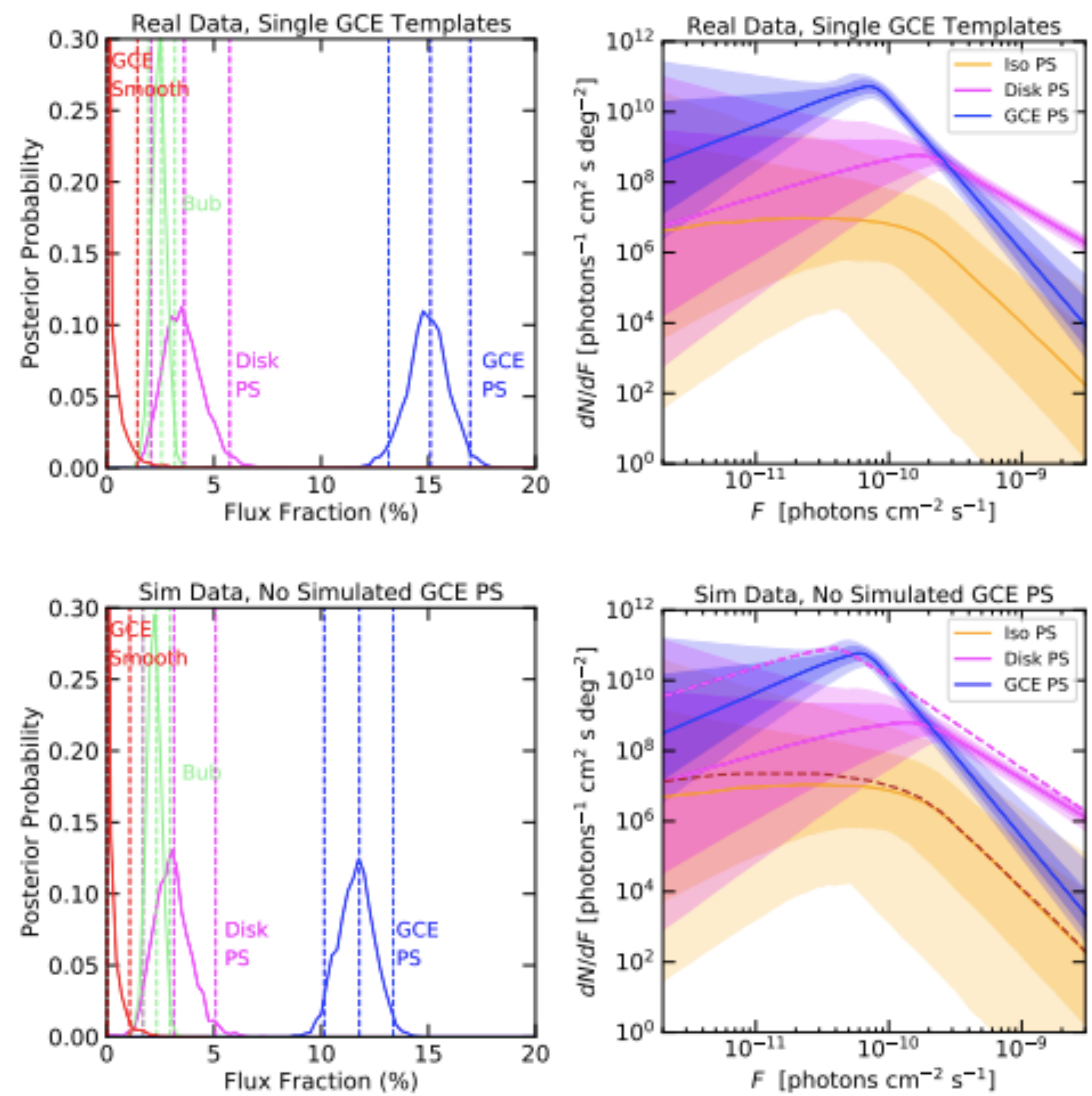
- Occurs because bright PS populations inherently have a higher error bar on flux - easier to explain a “bad" signal template





Spurious point sources (simulations)

- Simulate smooth GCE with asymmetry, fit as linear combination of symmetric smooth template + symmetric PS template
- The observed behavior matches what we see (for the same fit) in the real data very closely, although in the simulations we know the PS population isn't real
- So perhaps the apparent PSs in the real data are spurious?



One example realization

Spurious point sources (simulations)

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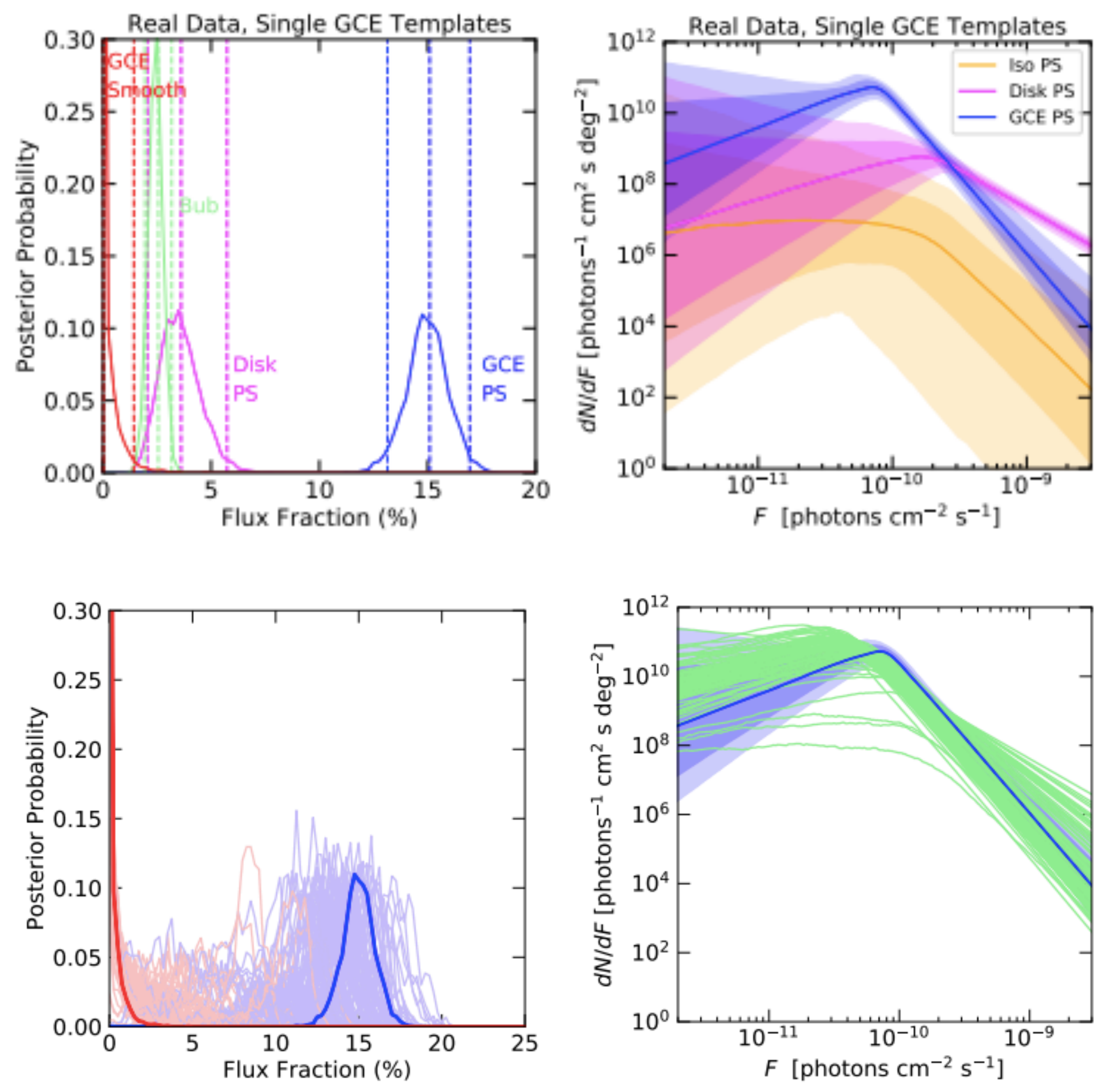


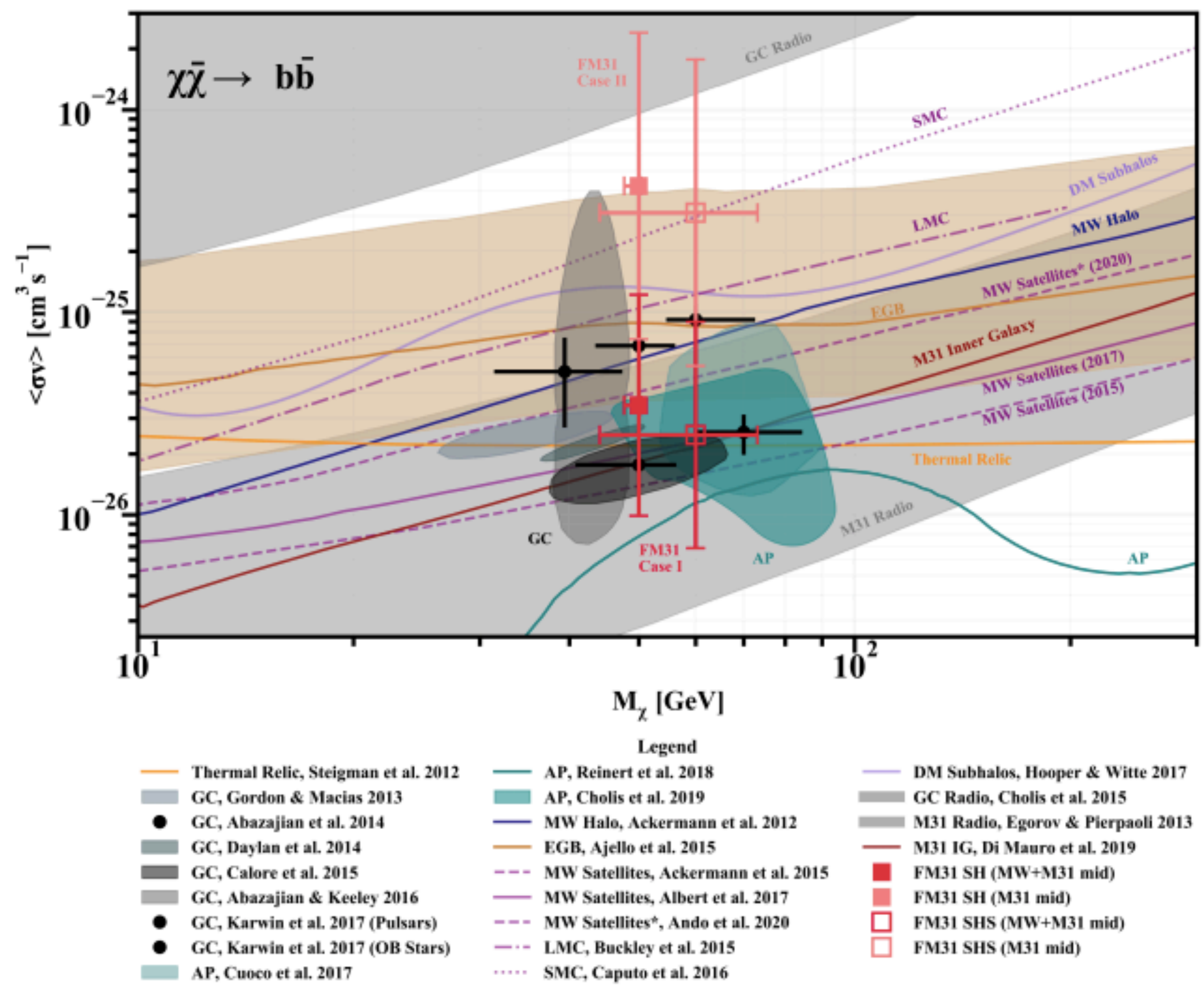
100 realizations

Possible GCE counterparts?

- Antiproton “excess” is consistent but (as discussed earlier) statistical significance is unclear

- Recent claims of possible Andromeda counterparts in gamma-rays [Karwin et al ’19, ’21, Burns et al ’21] and radio [Chan et al ’21]

Karwin et al ‘21



Other recent/future GCE inputs

- Neural network trained to discriminate PSs from smooth emission → prefers smooth emission (but tests show some bias in this direction, + sufficiently-faint PSs = smooth) [List et al ’20]; more recent work finds 2 sigma preference for at least some PSs [List et al ’21, Mishra-Sharma et al ’21]
- Photon-count analysis using adaptive background models finds evidence for both unresolved PSs and significant smooth emission in GCE region (but unresolved PSs may be due to known populations, which are not separated out) [Calore et al ’21]
- Modeling of the luminosity function indicates that plausible pulsar luminosity functions can likely explain the GCE without obviously contradicting the observed number of bright sources [Ploeg et al ’20, Gautam et al ’21]
- Best hope for a quick resolution may be to detect GCE pulsars in radio [Calore et al ’16] or X-ray [Berteaud et al ’20]