Indirect searches for dark matter

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Outline

- Overview of physics tested by indirect detection
- Summary of current constraints
- Brief outline of several current excesses/anomalies
- A status update / case study on the Galactic Center excess

Some mechanisms for indirect detection

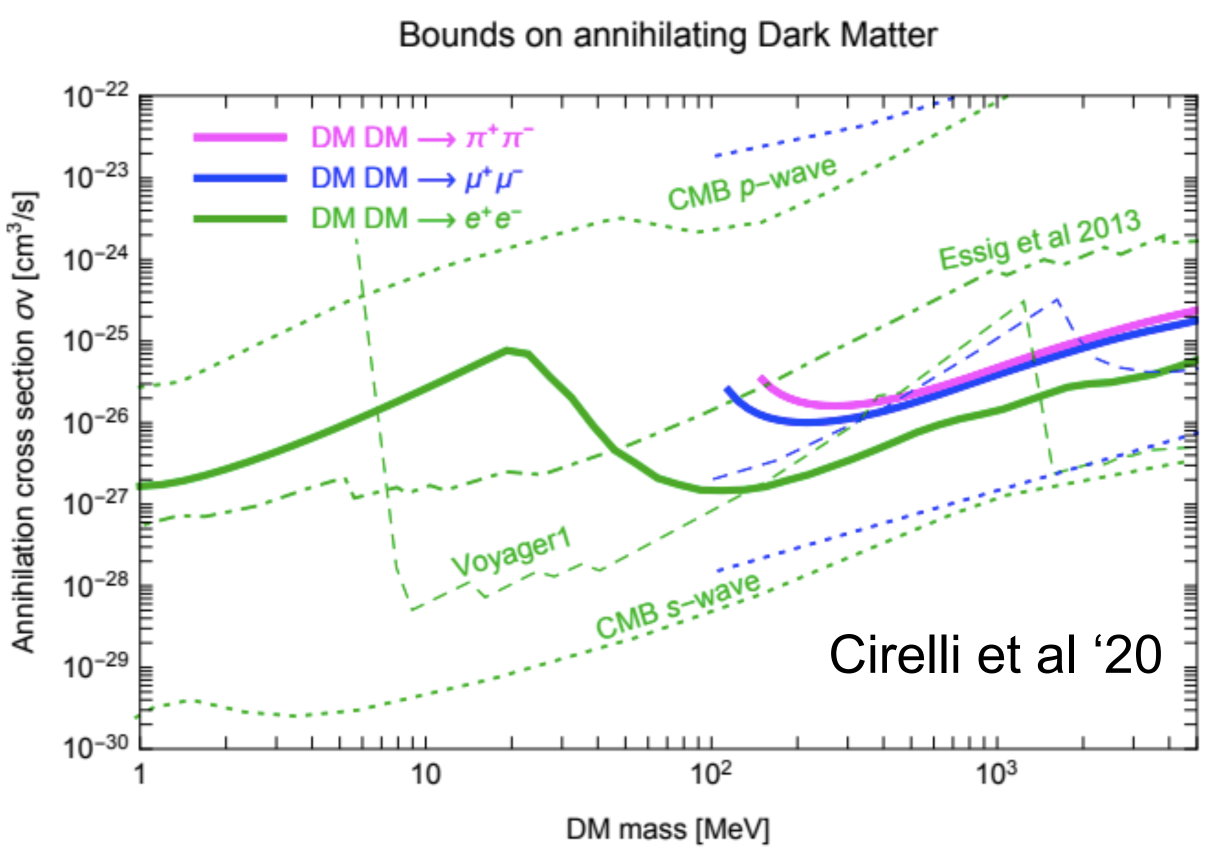
- Collisions that produce visible particles
  - Has natural benchmark cross section, if annihilation depletes early-universe DM abundance to its observed value:

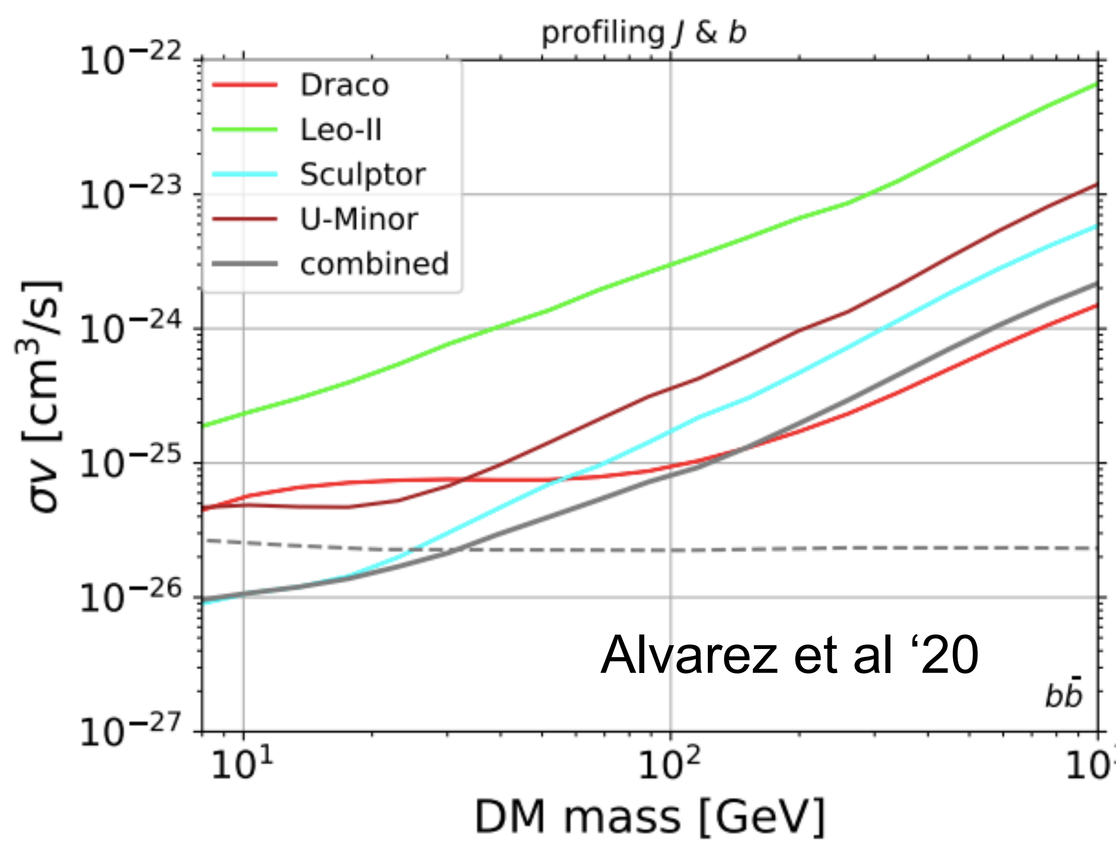
$$\langle \sigma v \rangle \sim \frac{1}{m_{\mathrm{Planck}} T_{\mathrm{eq}}} \sim \frac{1}{(100\mathrm{TeV})^2} \approx 2 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

- Decay into visible particles, directly or through intermediate states - lifetime must be >> age of universe
- Scattering on visible particles leading to indirect signals
- Oscillation into visible particles, and vice versa

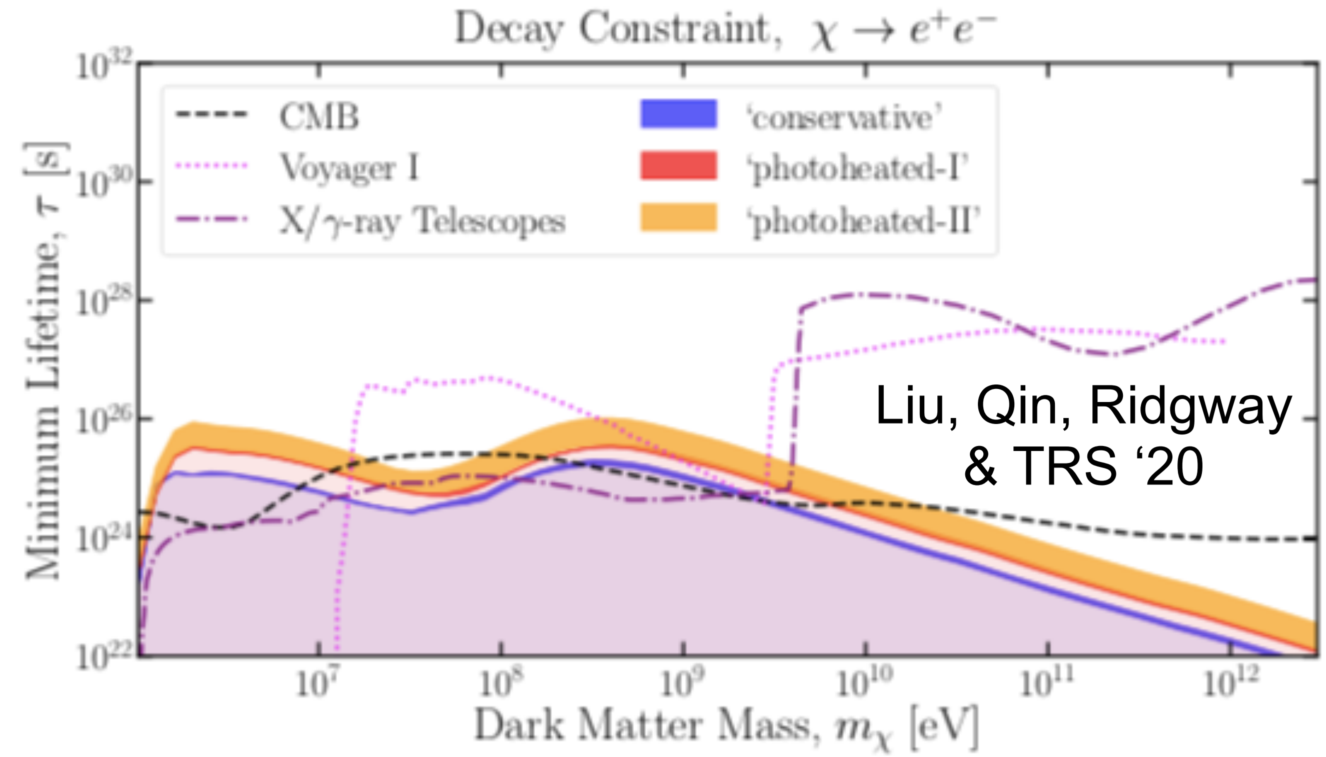
Constraints on annihilation

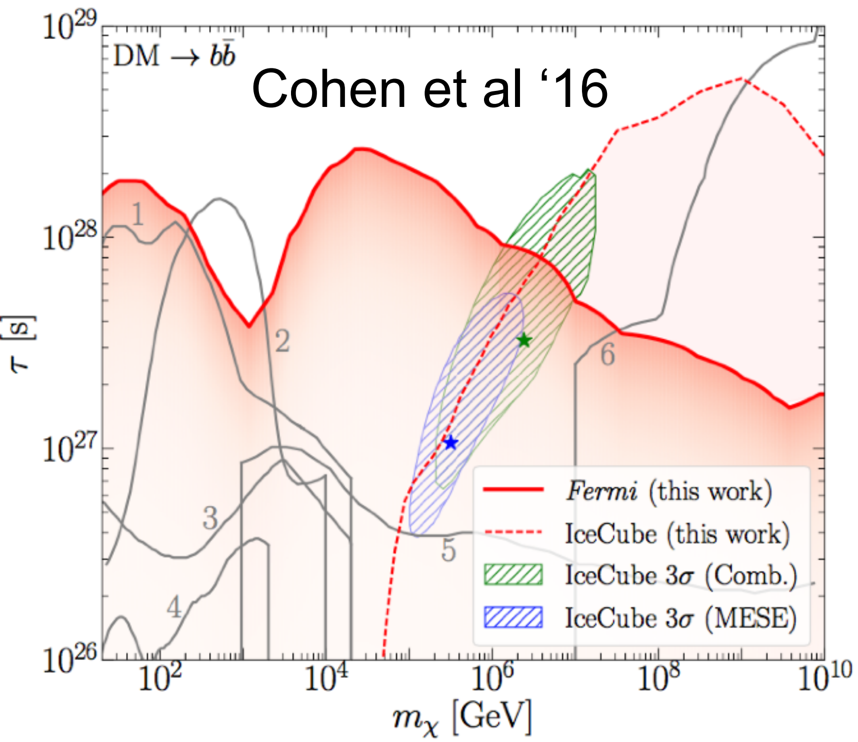
- Multiwavelength photon and cosmic-ray observations constrain thermal relic cross sections up to O(10s-100s) GeV, for all final states except neutrinos
- In this mass range, antiproton and gamma-ray measurements generally give the strongest bounds for hadronic final states [e.g. Alvarez et al '20, Cuoco et al '18, Reinert & Winkler '18]
- In the same mass range, AMS-02 positron measurements generally give the strongest bounds for electron/muon-rich final states [e.g. Leane, TRS et al '18]
- Much lower cross sections can be tested for lower masses, e.g. via observations of the cosmic microwave background (DM annihilation would cause extra ionization in the early universe which perturbs the CMB) [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.

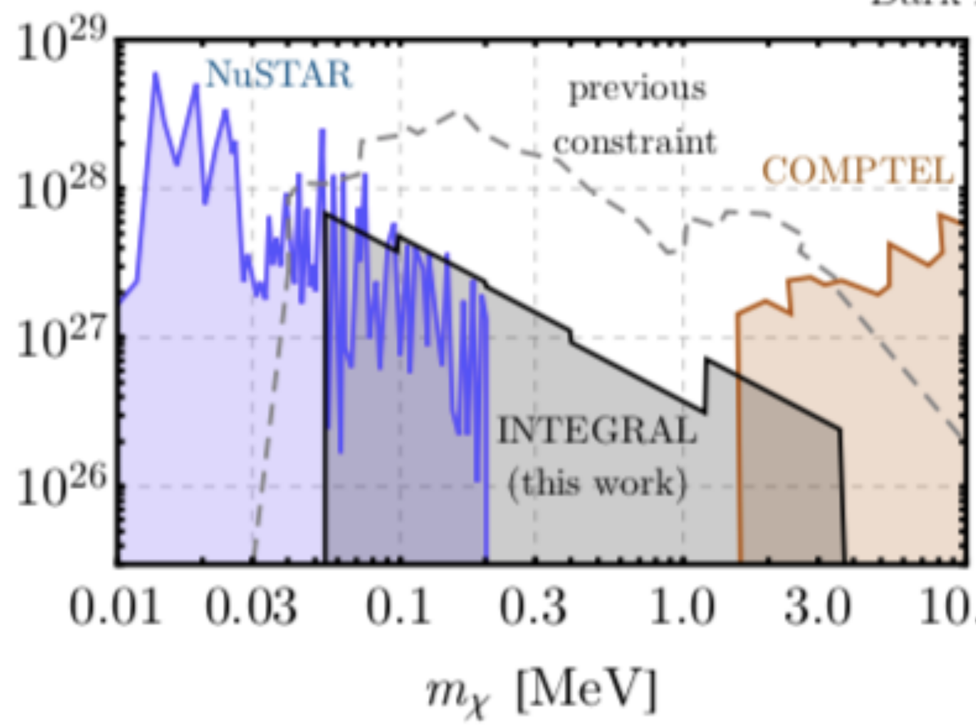


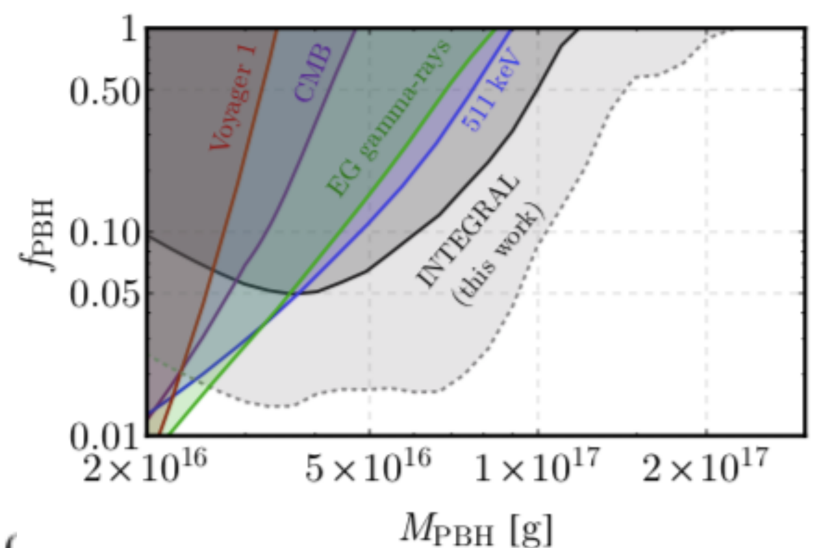


Constraints on decay









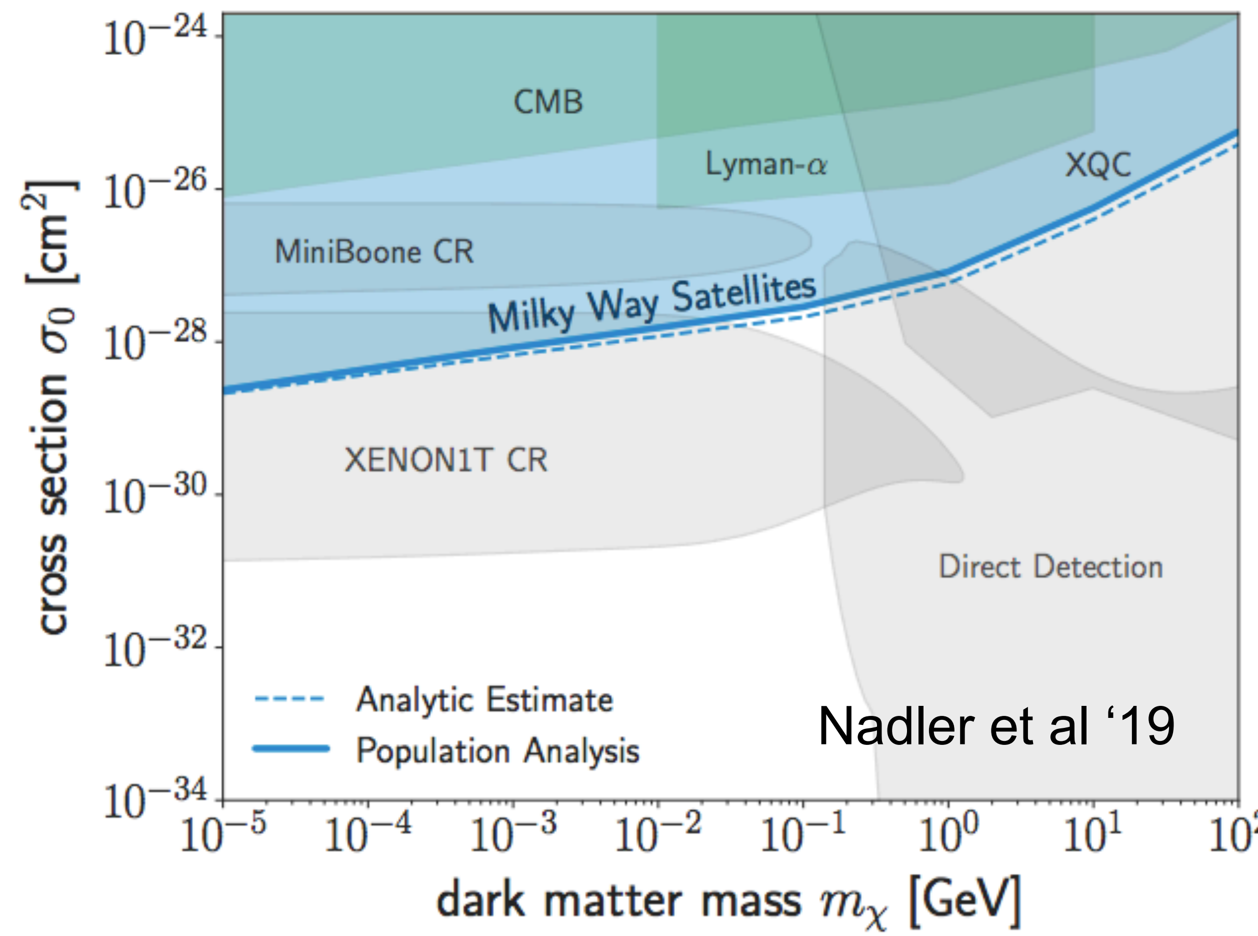
Laha, Munoz & TRS '20

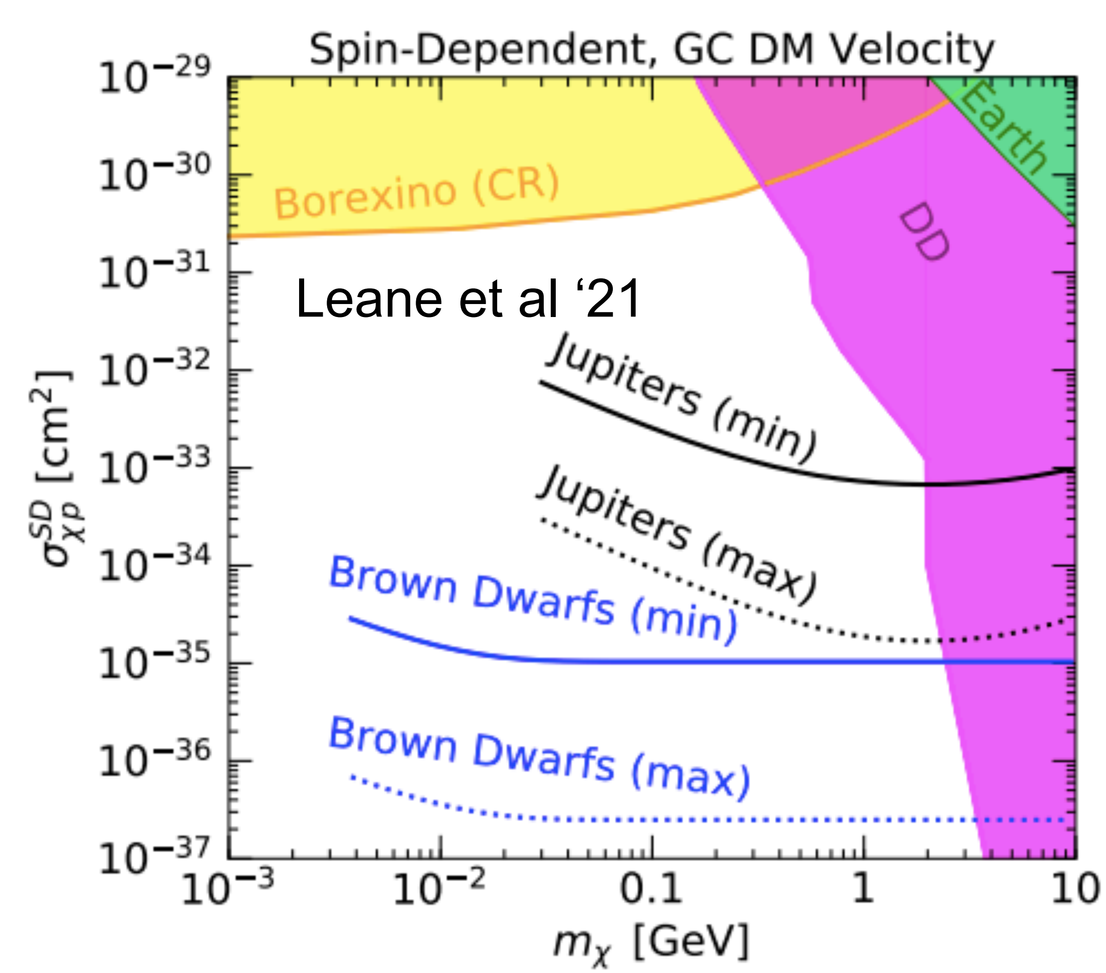
- Observations of gamma rays and (at high energies) neutrinos constrain DM decay to photons or hadronic final states to have lifetimes exceeding 10^{27-28} s, for the full range of masses from several keV to 10^{10} GeV. Also constrains primordial black holes as DM for masses up to 2 x 10^{17} g.

- DM decays to other channels can also be constrained by these observations; for MeV-GeV DM decaying leptonically, Voyager limits on low-energy cosmic rays [e.g. Boudaud et al '16] and bounds from early-universe cosmology [e.g. Wu & TRS '17; Liu, Qin, Ridgway & TRS '20] are somewhat stronger than photon-based limits.

Constraints on scattering

- Scattering is often considered the regime of direct detection, but can be tested in indirect searches as well
- Can exclude large cross-sections that might prevent DM from reaching terrestrial detectors
- Cosmology (CMB + large-scale structure) and astrophysics (Milky Way satellite population) sets limits on DM-SM scattering via its effects on perturbations + structure formation [e.g. Boddy & Gluscevic '18, Xu et al '18, Nadler et al '19]
- DM scattering/capture in compact objects could modify the cooling/evolution of those objects (e.g. neutron stars [Baryakhtar et al '17], exoplanets [Leane & Smirnov '21]), even with small cross sections (but see also Garani and Palomares-Ruiz '21)



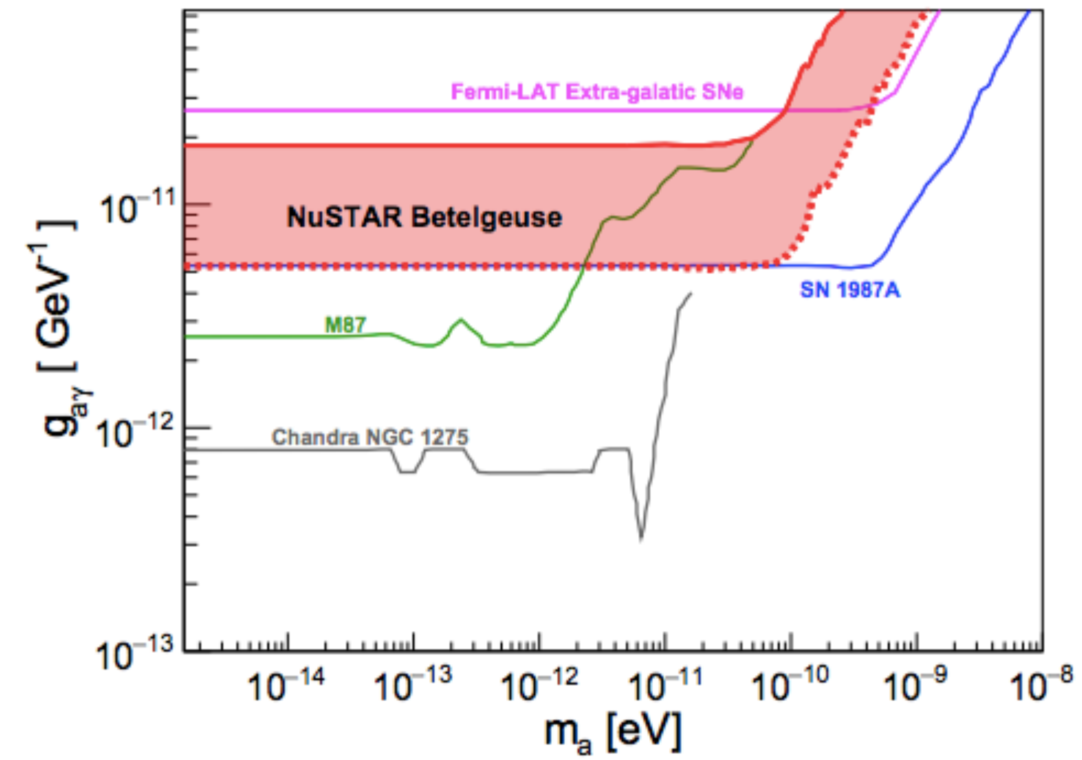


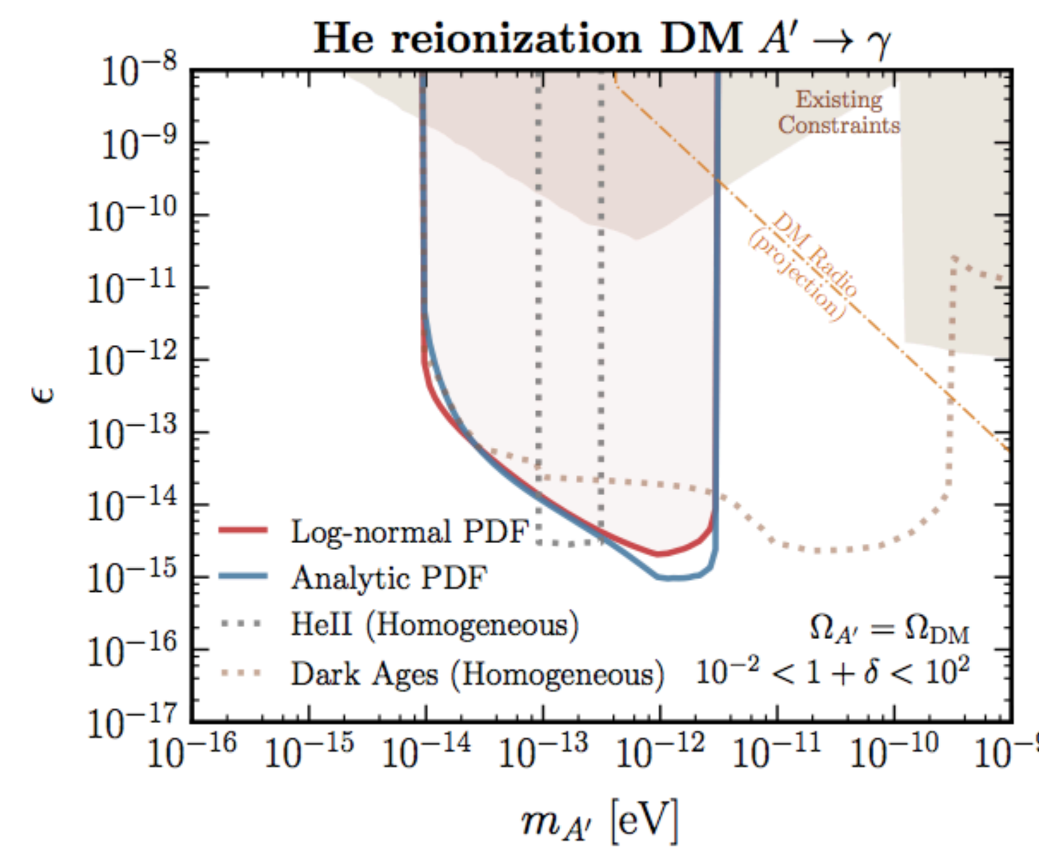
Constraints on oscillations

- If dark matter is an axion (ultralight pseudoscalar particle), it can oscillate into a photon in the presence of an external magnetic field
- Another much-studied possibility is that there exist dark photons (may or may not be the DM) which mix with the SM photon - can oscillate into SM photon, resonantly enhanced when dark photon mass = SM photon plasma mass
- Provides powerful probes of very low-mass dark matter
- Enormous range of constraints and searches (https://cajohare.github.io/AxionLimits/ is a helpful reference)

Oscillation limits: examples

- New feebly-interacting particles could be produced in the cores of stars, escape the star, convert back into visible particles in surrounding B-field
  - used to set constraints on axions via observations of Betelgeuse [Xiao et al '21], in addition to earlier SN1987A bounds.
  - motivates search for non-thermal emission from "Magnificent Seven" neutron stars [Dessert et al '20].
- CMB photons oscillating into dark photons could distort the CMB [e.g. Mirizzi et al '09]; dark photon dark matter oscillating into visible photons could heat the primordial plasma [e.g. Caputo et al '20].

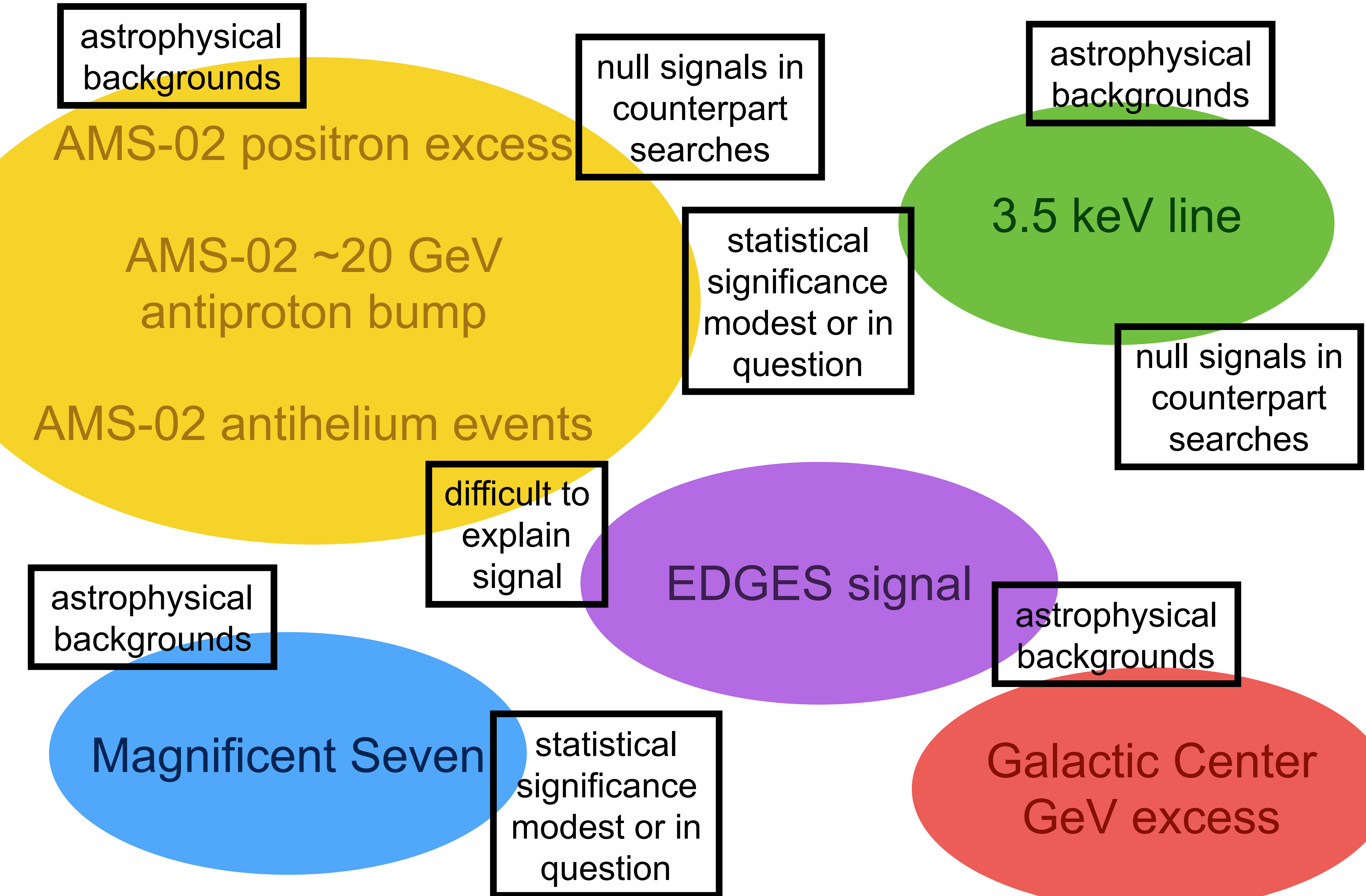




Some excesses/anomalies

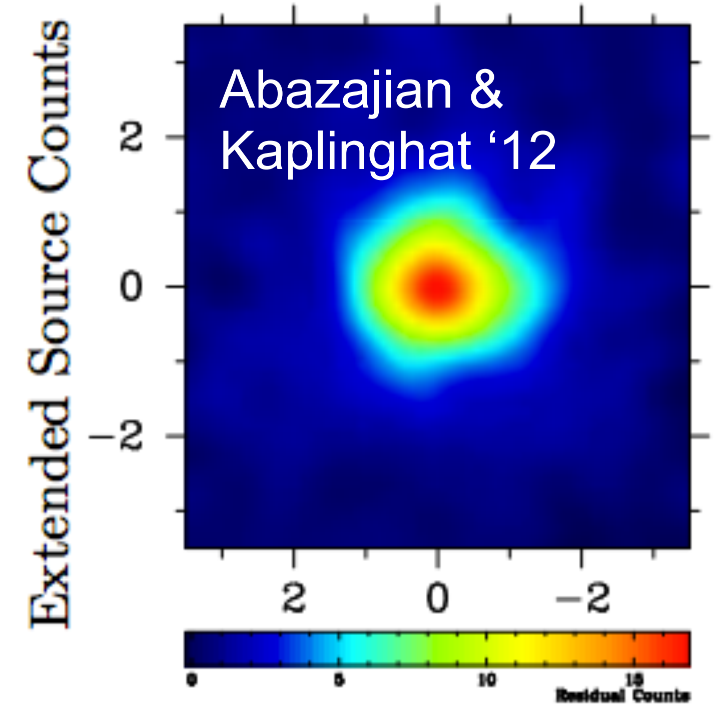
- Annihilation/decay?
  - PAMELA/AMS-02 positron excess (needs O(TeV) DM with large cross section / short lifetime) [Aguilar et al (AMS-02) ’13; see also Hooper et al ’17]
  - AMS-02 ~10-20 GeV antiproton bump (needs O(10-100) GeV DM with thermal relic cross section) [Cui et al ’17, Cuoco et al ’17; see also Boudaud et al ’19, Cuoco et al ’19]
  - AMS-02 antihelium events (?? maybe annihilation?) [AMS Days at La Palma, La Palma, Canary Islands, Spain ’18; see also Poulin et al ’19, Winkler & Linden ’21]
  - 3.5 keV X-ray line detected in a range of systems (needs 7 keV decaying DM, e.g. sterile neutrino) [Bulbul et al ’14, Boyarsky et al ’14; see also Abazajian et al ’17, Dessert et al ‘20]
  - Galactic Center excess (GCE) seen in Fermi gamma-rays (to be discussed further…)
- Scattering? EDGES claimed observation of primordial 21cm signal with deep absorption trough (could potentially be explained by colder-than-expected early universe) [Bowman et al ’18; see also Hills et al ’18, Bradley et al ’19].
- Oscillation? Hard non-thermal X-ray emission seen from 2/7 among nearby “Magnificent Seven” isolated neutron stars (could potentially be explained by light axions produced in stellar core which escape and convert to photons) [Buschmann et al ’20].

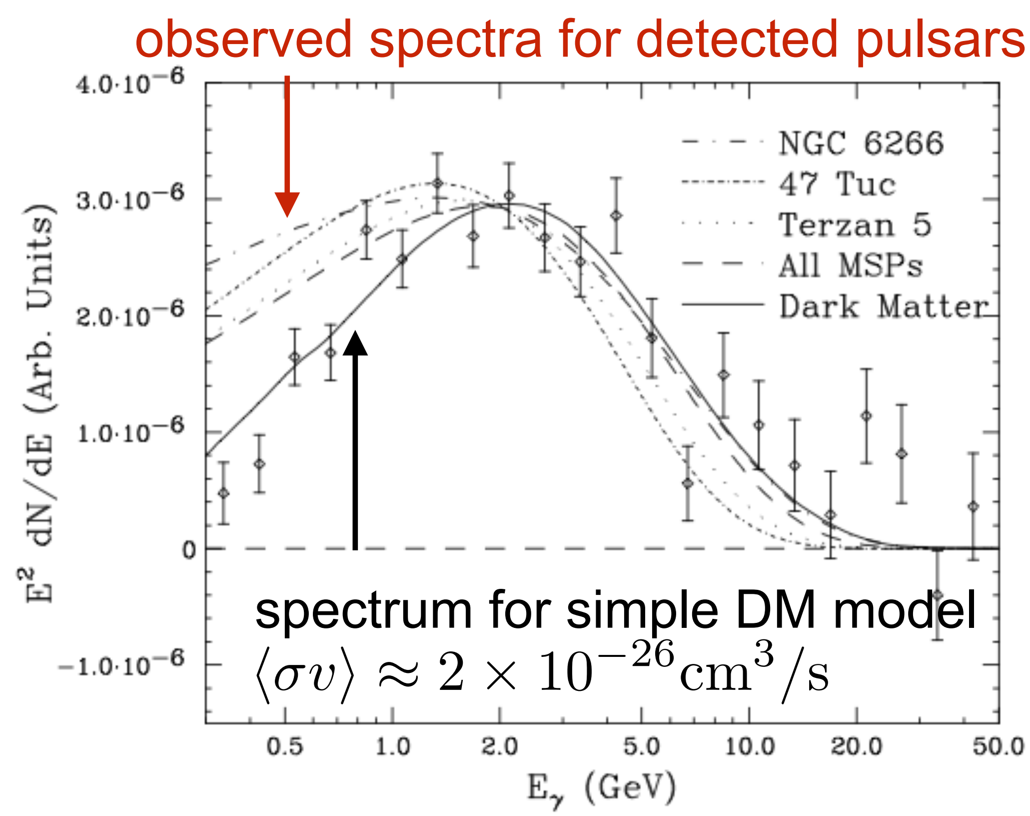
Some excesses/anomalies



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 ’09, confirmed by Fermi Collaboration in analysis of Ajello et al ’16 (and many other groups in interim).
- Simplest DM explanation: thermal relic annihilating DM at a mass scale of O(10-100) GeV
- Leading non-DM explanation: population of pulsars below Fermi’s point-source detection threshold





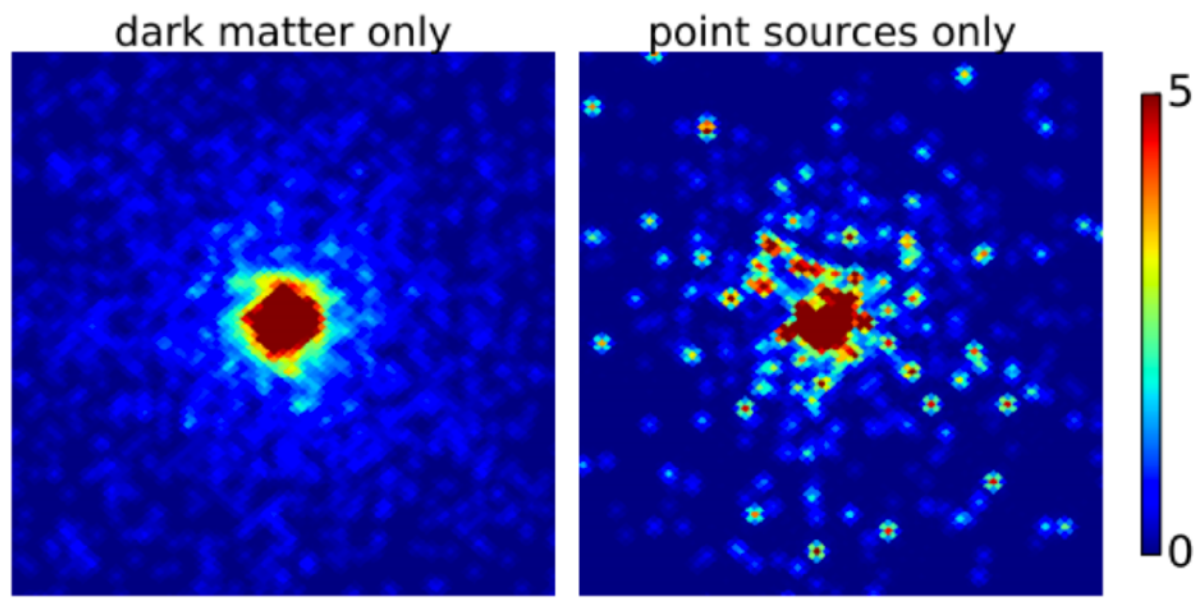
Daylan, TRS et al ‘16

Photon statistics

Lee, Lisanti, Safdi, TRS & Xue '16

DM origin hypothesis

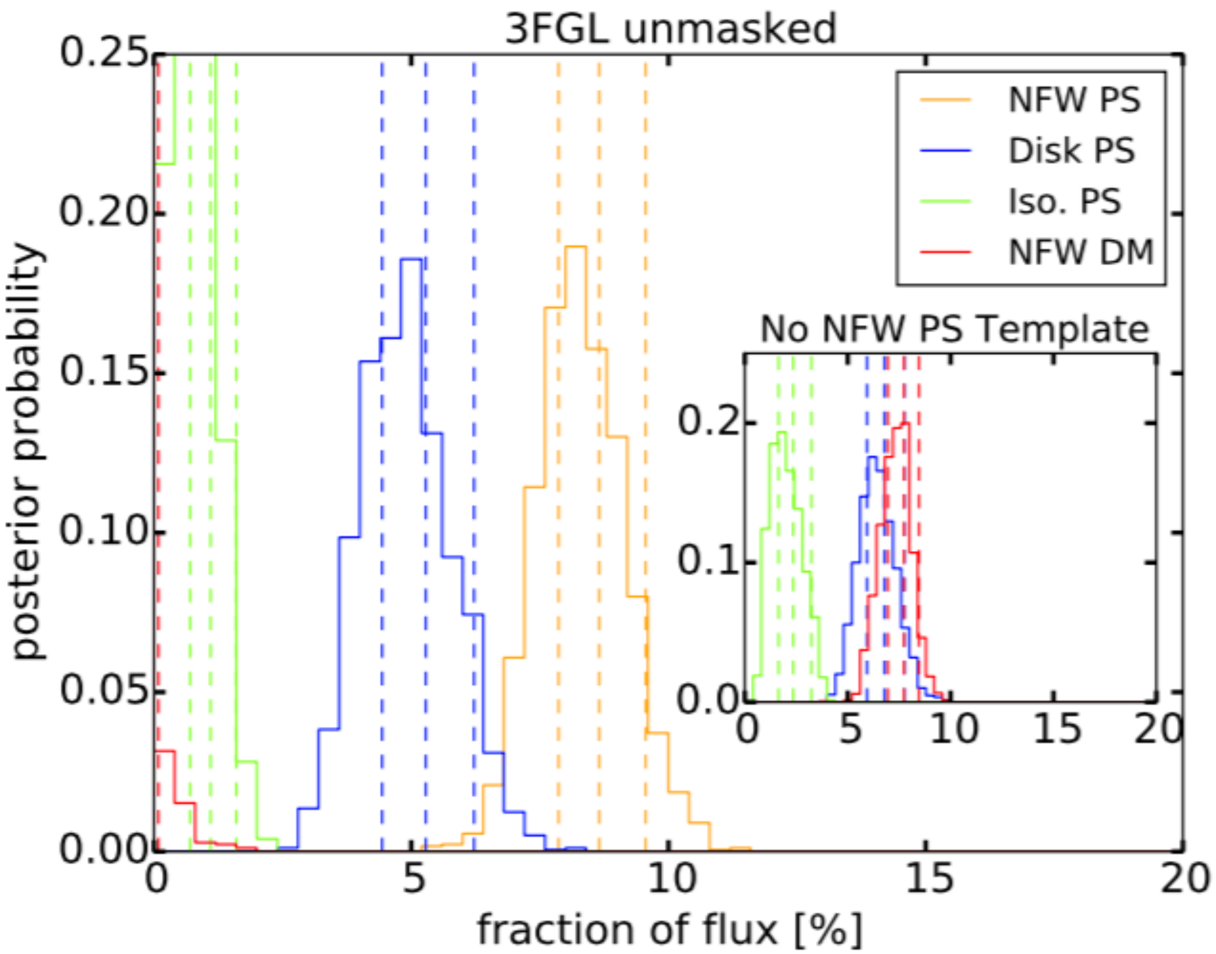
signal traces DM density squared, expected to be ~smooth near GC with subdominant small-scale structure



Pulsar origin hypothesis

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

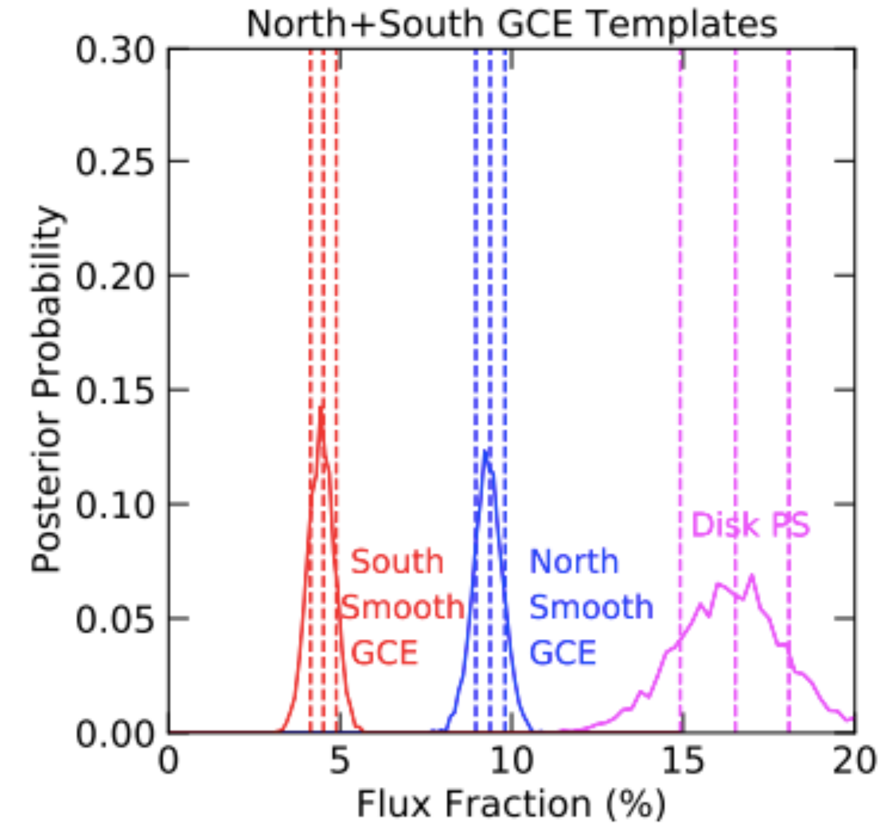


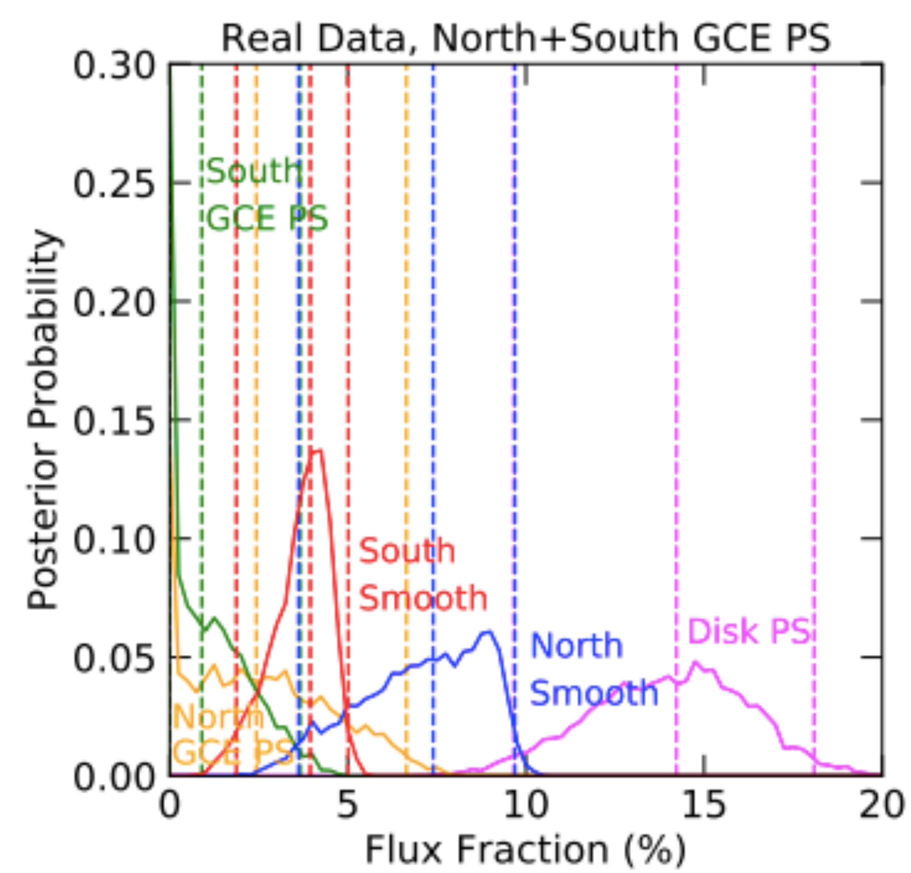
- Lee et al ‘16: fit shows a strong preference to assign all GCE flux to new PS population (Bayes factor in favor of model with PSs ~10^9, roughly analogous to 6σ)
- Suggests signal is composed of a relatively small number of just-below-threshold sources

- 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)

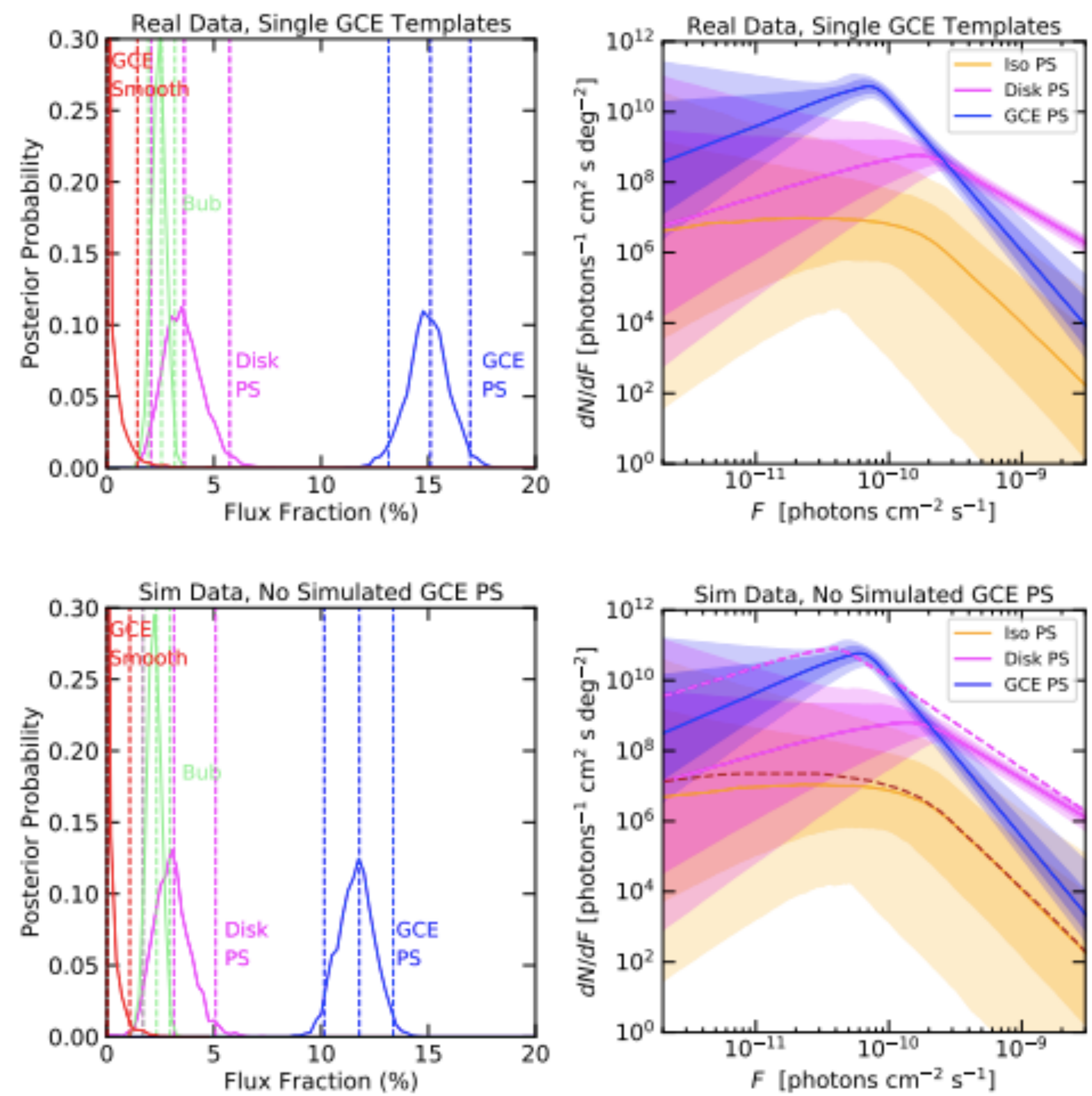
- We found this by accident - trying to test the spatial morphology of the GCE in more detail
- In the region of interest we used, when we split the GCE into 2+ spatial components, all evidence for GCE PSs went away (BF > $10^{15} \rightarrow$ BF < 10 with one added d.o.f)
- Apparent preference for PSs 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

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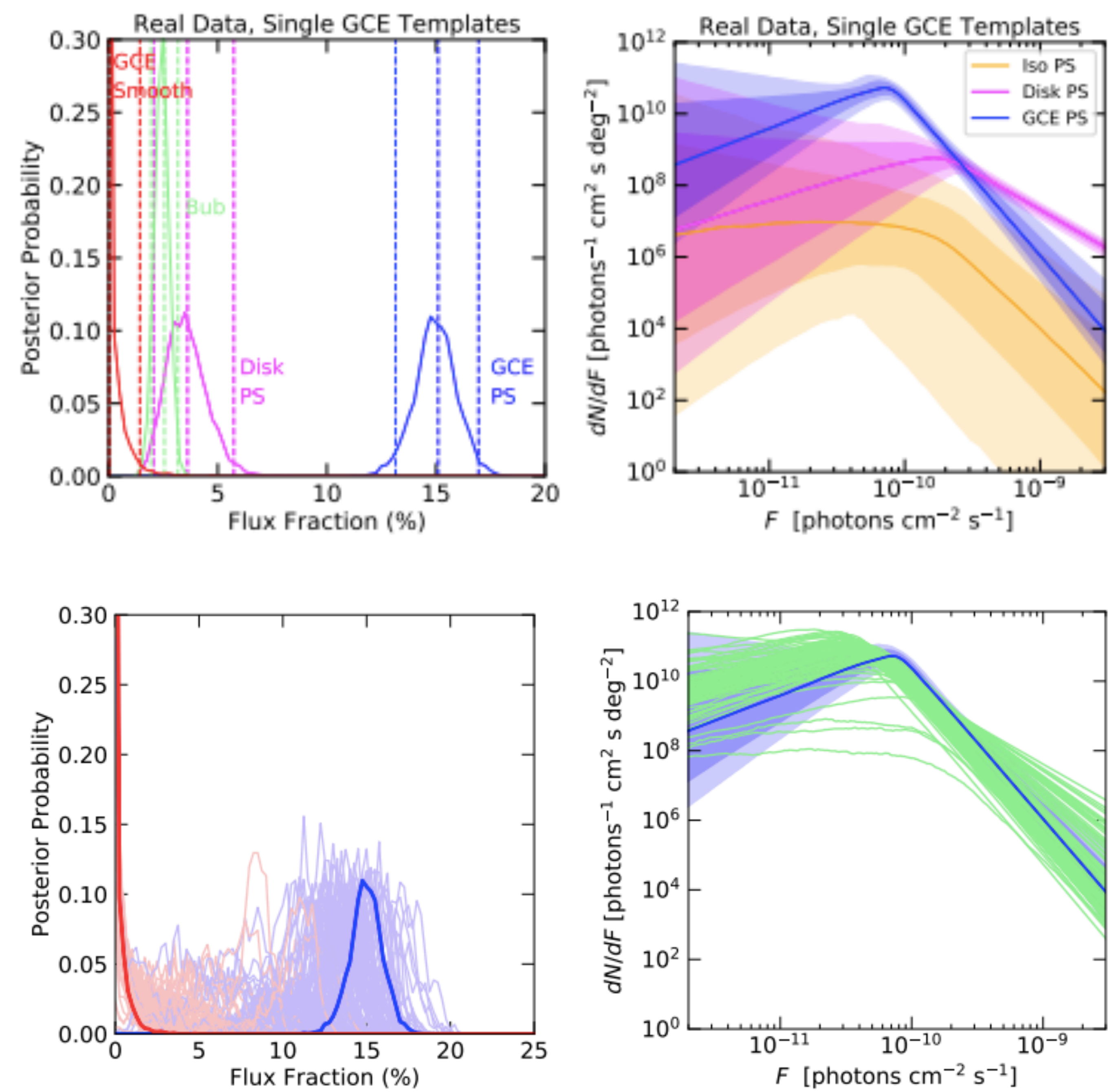


100 realizations

Where next in indirect detection?
(an incomplete sample)

- In high-energy gamma rays, next-gen telescope CTA will dramatically improve sensitivity [e.g. Acharyya et al ‘20]
- Several proposals for experiments to close the MeV-GeV sensitivity gap in gamma rays: e.g. AMEGO/ComPair [e.g. Kierans et al ’21], GRAMS [Aramaki et al ’19]
- GAPS experiment will search for antideuterons, improve measurements of low-energy antiprotons [e.g. von Doetinchem et al ’20]
- Current and upcoming radio telescopes [e.g. EDGES, HERA, LOFAR, MeerKAT, MWA, PAPER, SARAS, SCI-HI, DARE, LEDA, PRIZM, SKA] offer prospects for a possible confirmed detection of primordial 21cm emission, much stronger constraints on DM signals from cosmology (especially for light DM), and a better understanding of backgrounds in our galaxy, in particular pulsars (relevant for the GCE)
- Lots of exciting work going on in multimessenger searches (neutrinos, cosmic rays, gravitational waves) and in photon searches at all frequencies

Summary

- Indirect searches for dark matter:
  - 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 powerful probes of other possible DM interactions with visible particles, including scattering and oscillation
- There are a number of excesses/anomalies worth keeping an eye on, but none yet that (in my view) provide a clear-cut detection of new physics
- Previous claims that the GCE <u>must</u> consist of near-detection-threshold point sources were likely too strong due to systematic biases in the analysis - both pulsars and dark matter still appear to be viable possibilities

Bonus slides

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.

Recent/future GCE inputs

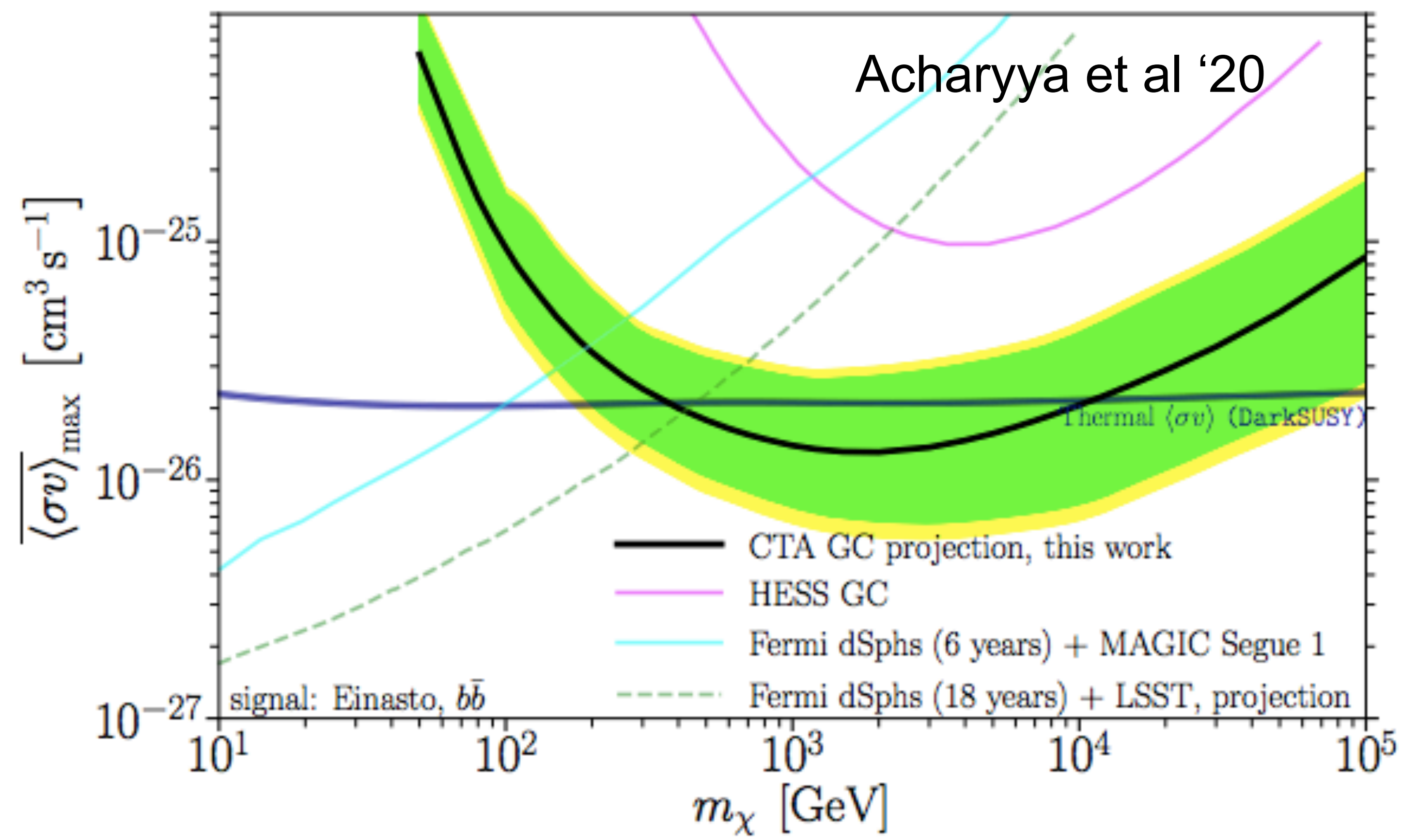
- Neural network trained to discriminate PSs from smooth emission → prefers smooth emission (but tests show some bias in this direction, + sufficiently-faint PSs = smooth) [List et al ’20]

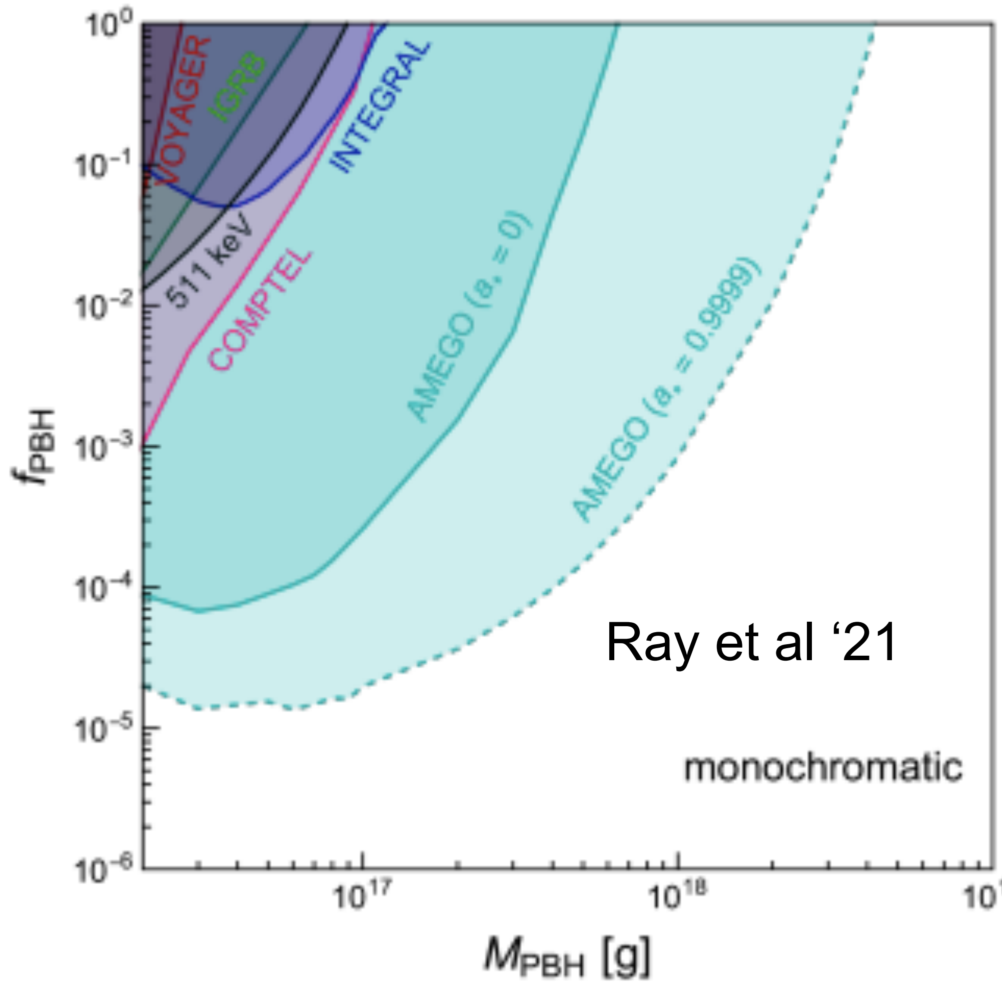
- Photon-count analysis using adaptive background models finds evidence for both unresolved PSs and significant smooth emission in GCE region (but unresolved PSs may be due to known populations, which are not separated out) [Calore et al ’21]

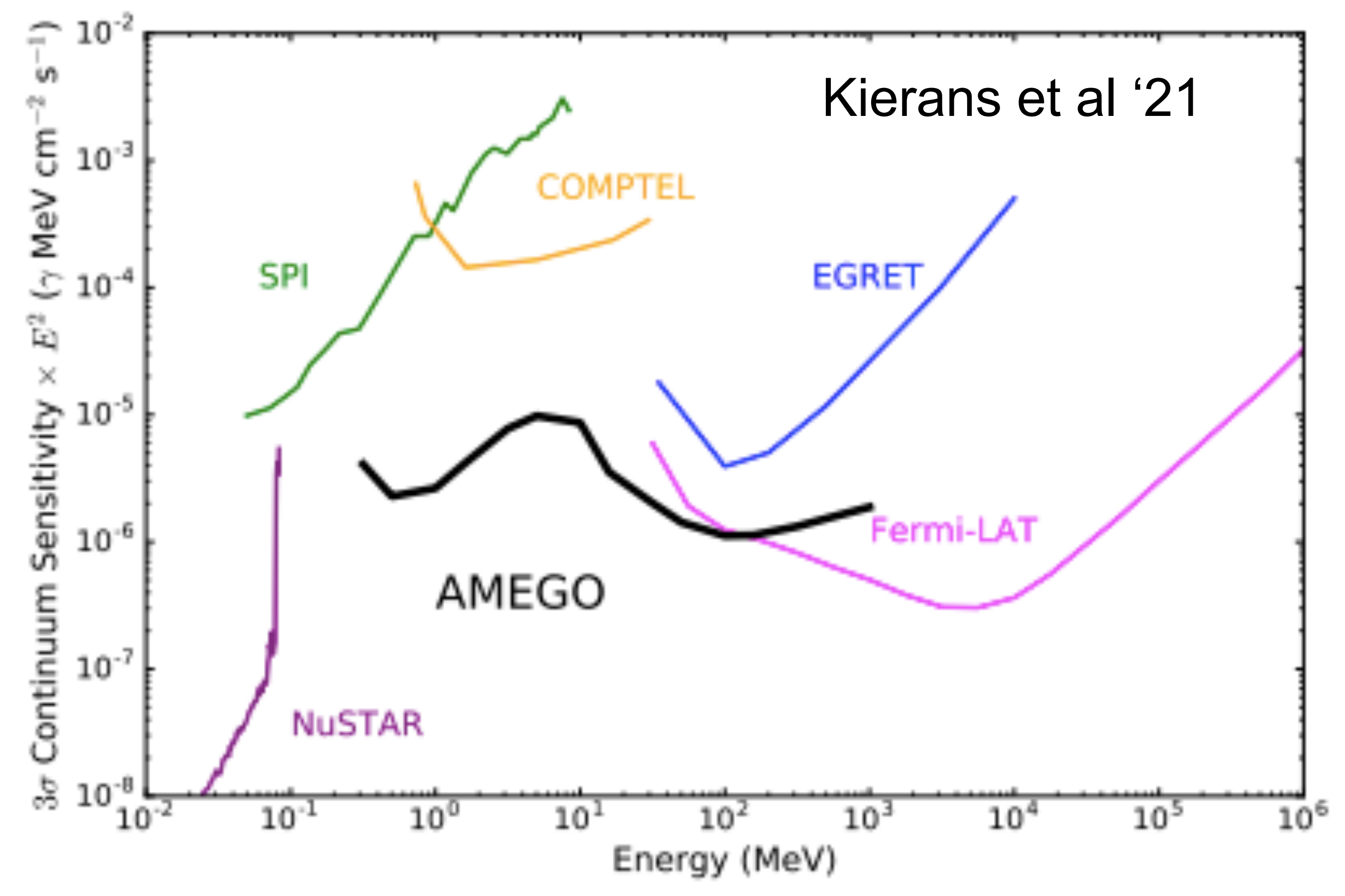
- Modeling of the luminosity function indicates that plausible pulsar luminosity functions can likely explain the GCE without obviously contradicting the observed number of bright sources [Ploeg et al ’20]

- 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]

Sensitivity for upcoming experiments

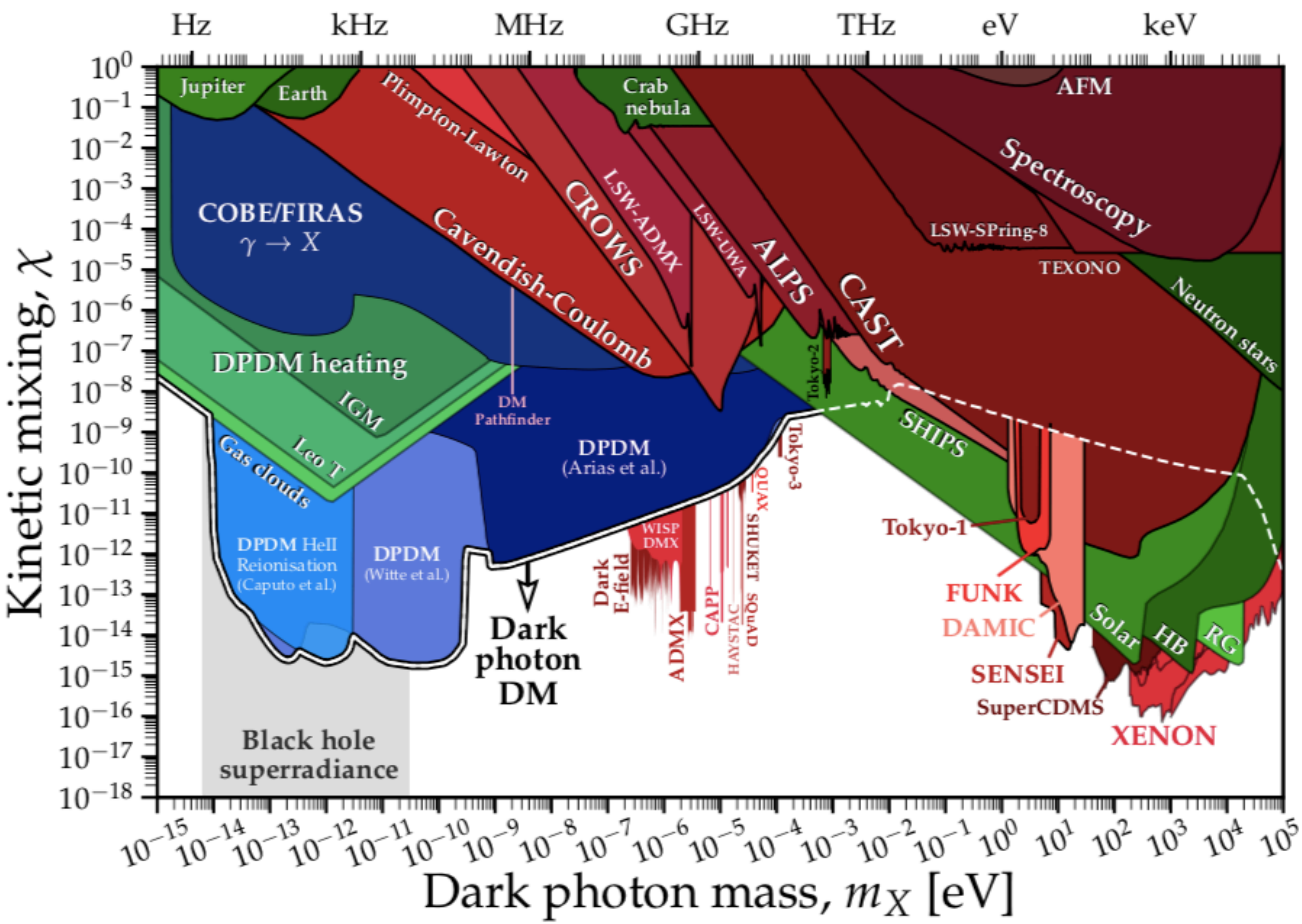






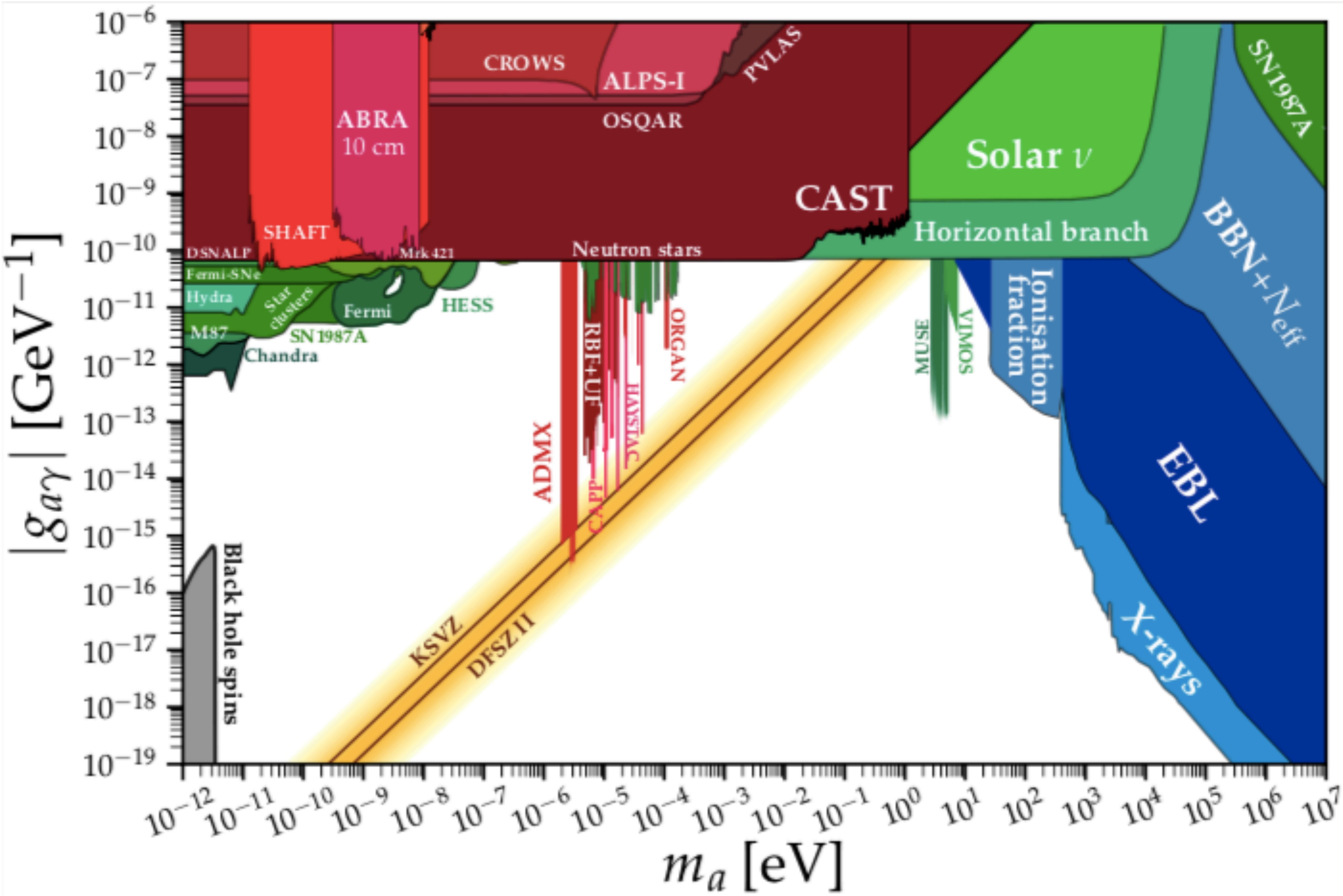
Dark photon limits

(credit https://cajohare.github.io/AxionLimits/)



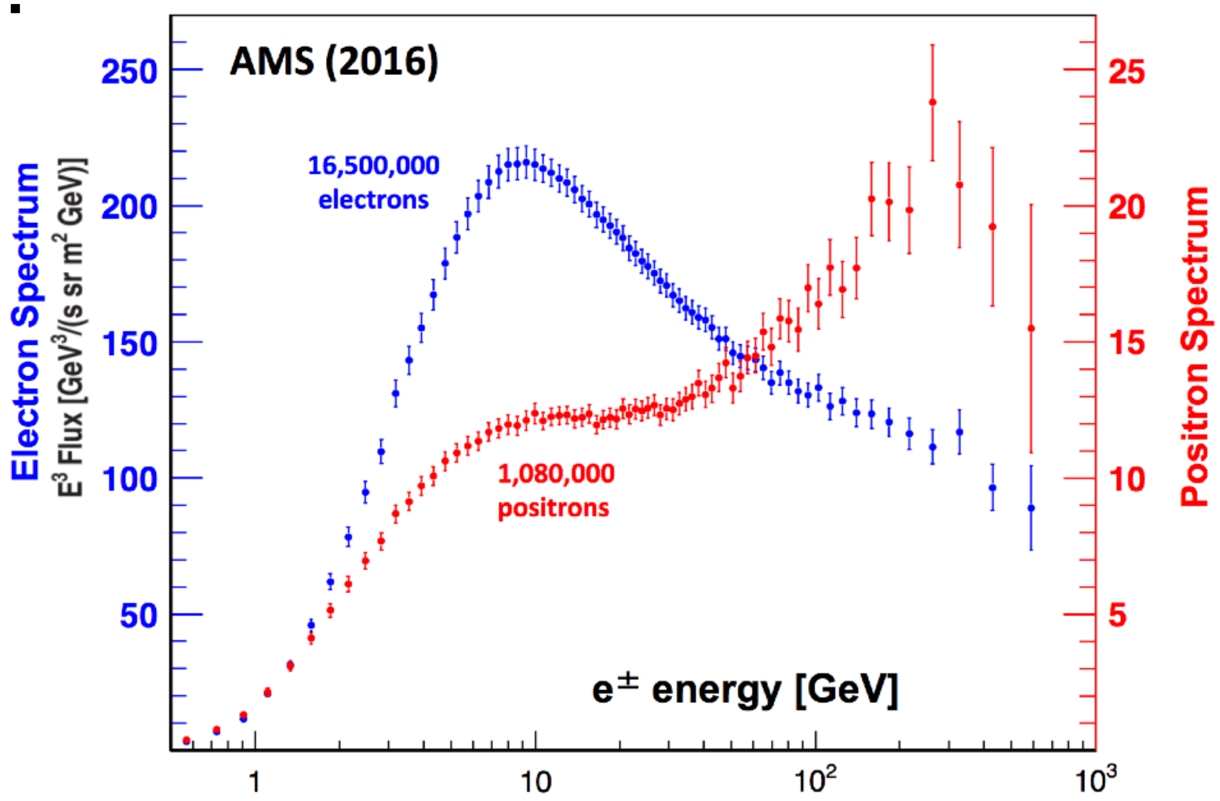
Axion limits

(credit https://cajohare.github.io/AxionLimits/)



The positron excess

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

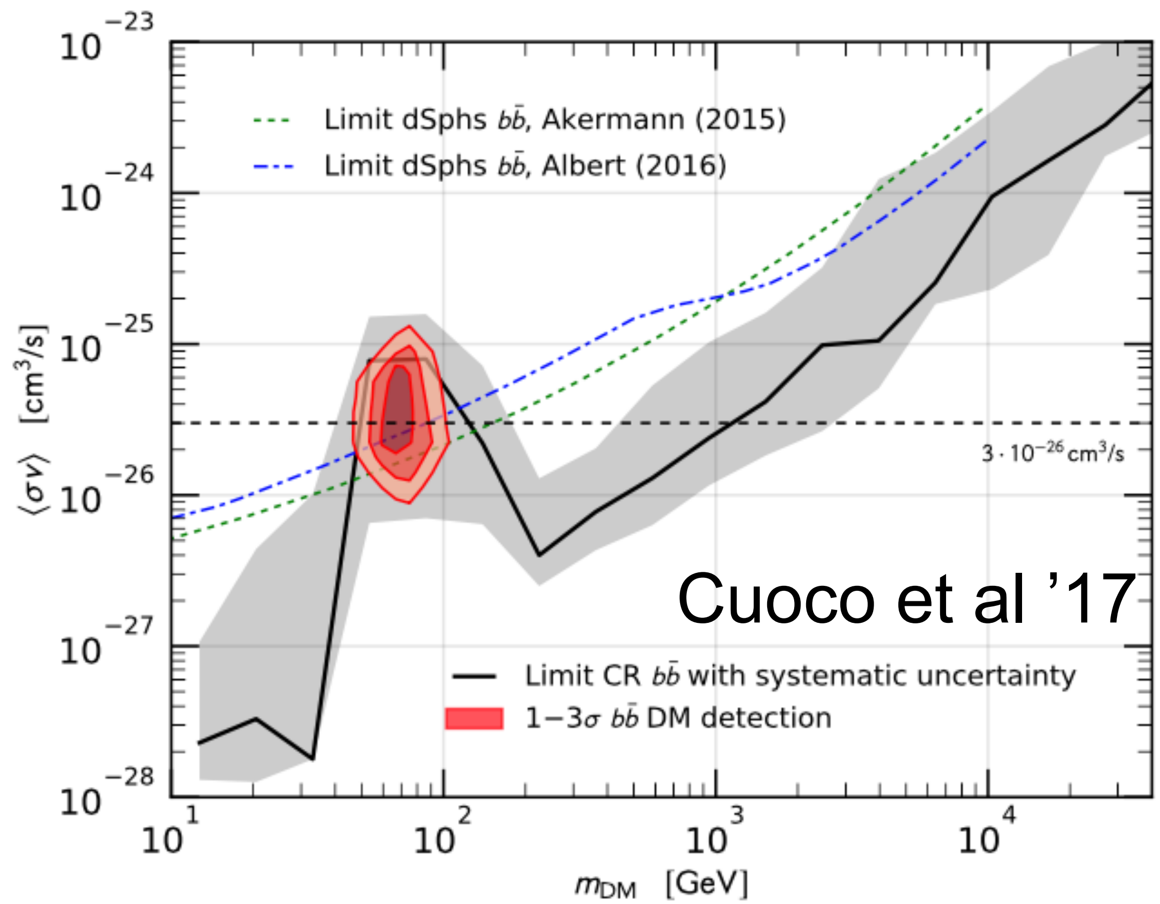


Sam Ting, 8 December 2016, CERN colloquium

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

The antiproton excess

- 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 is still highly debated [see 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.



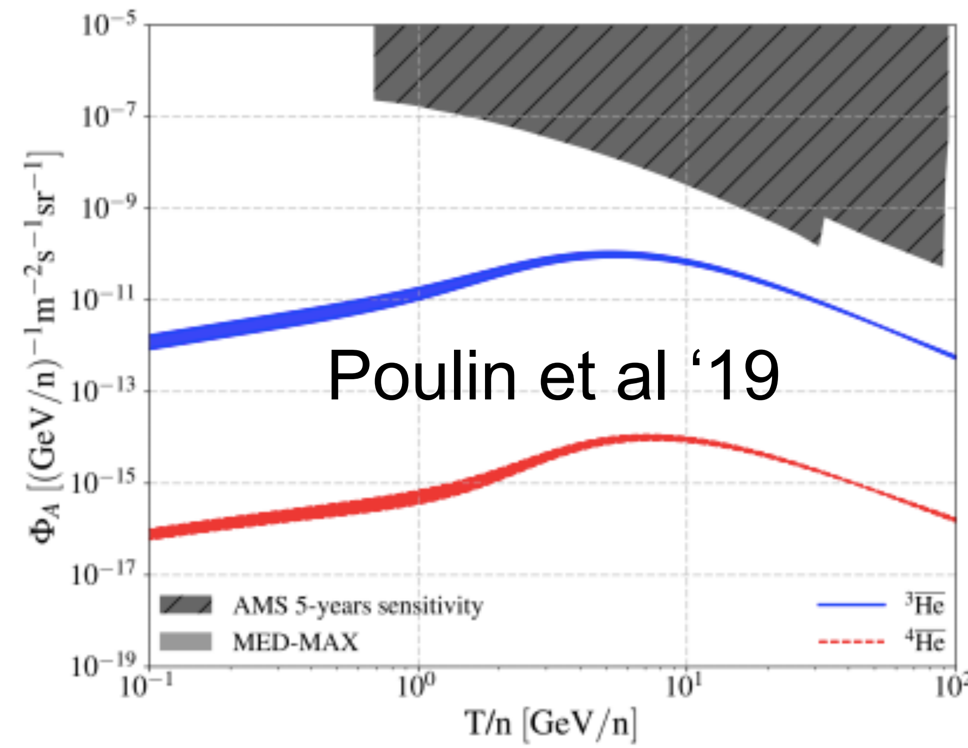
AMS-02 antihelium events

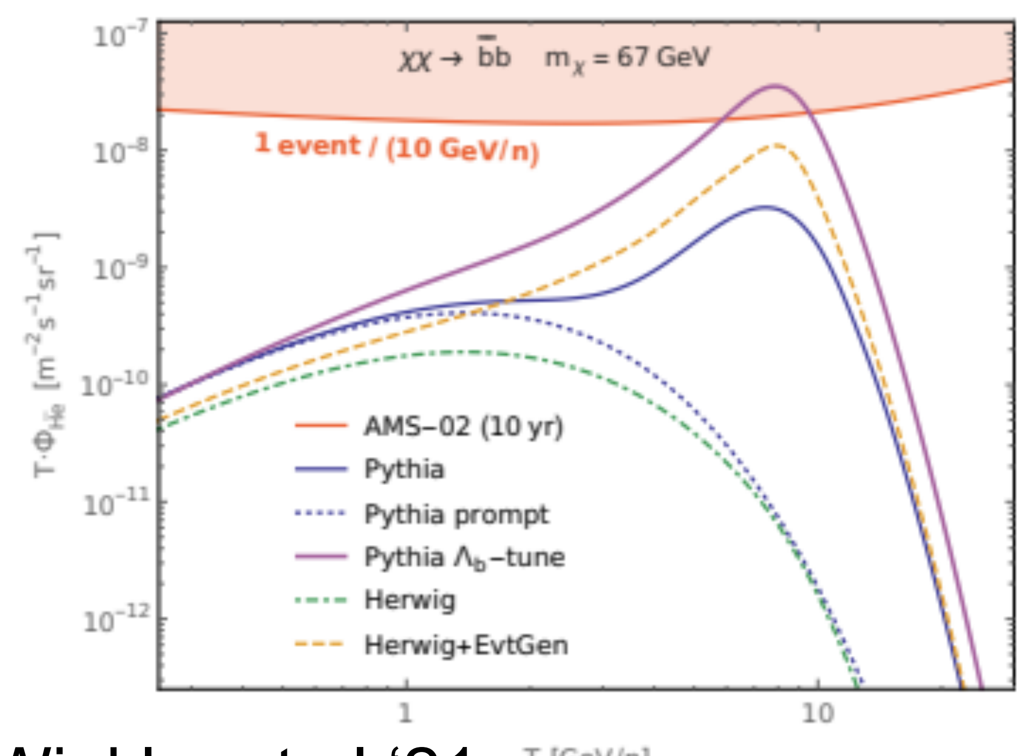
- AMS-02 Collaboration announced tentative possible detection of six apparent anti-He-3 events and two apparent anti-He-4 events [“AMS Days at La Palma, La Palma, Canary Islands, Spain,” (2018)]

- Expected astrophysical background is tiny - but so is expected DM signal!

- It was proposed that clouds of antimatter or anti-stars could generate these events [Poulin et al ’19]

- Alternatively, recent theoretical work suggested that the DM signal calculations might have missed an important process [Winkler & Linden ’21], and production of $\bar{\Lambda}_b$-baryons which decay to antihelium could boost the signal

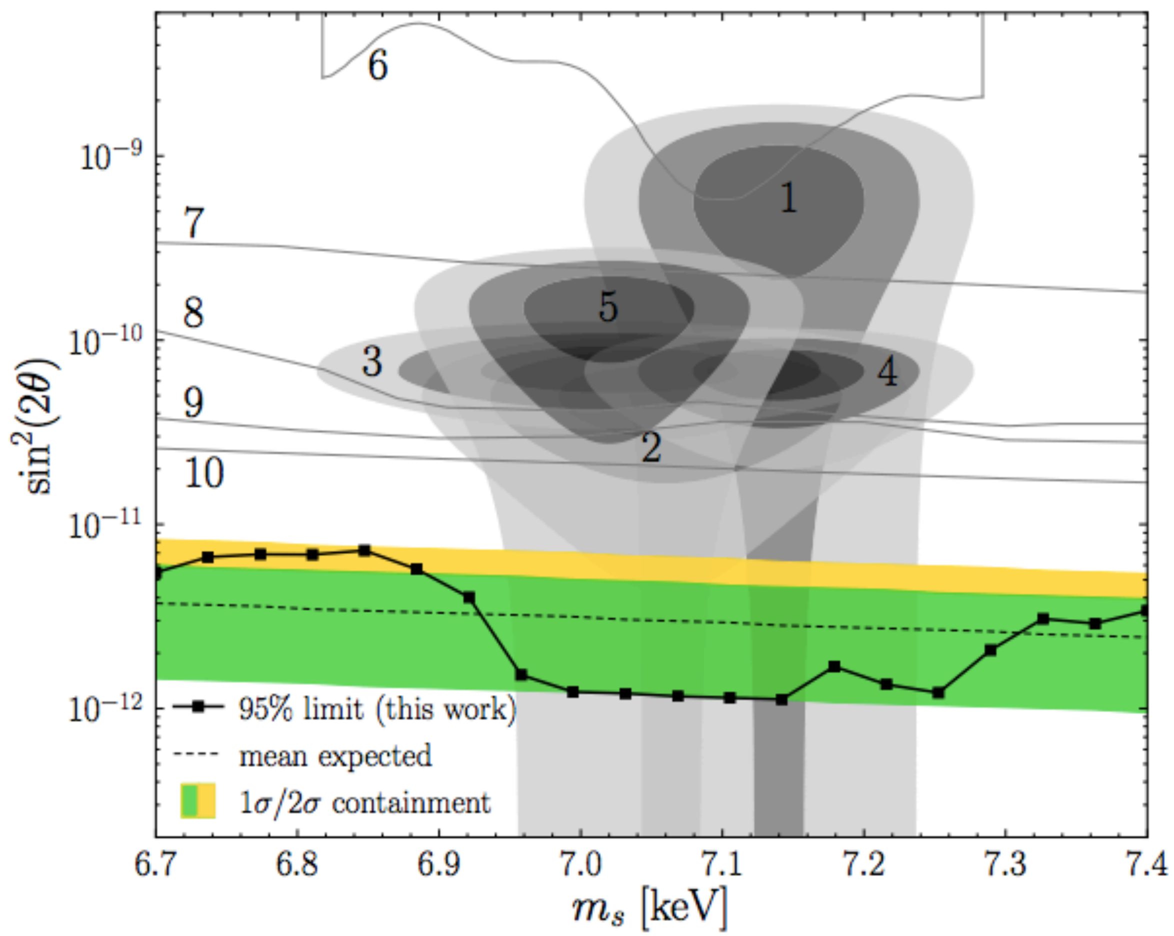




Winkler et al ‘21

The 3.5 keV line

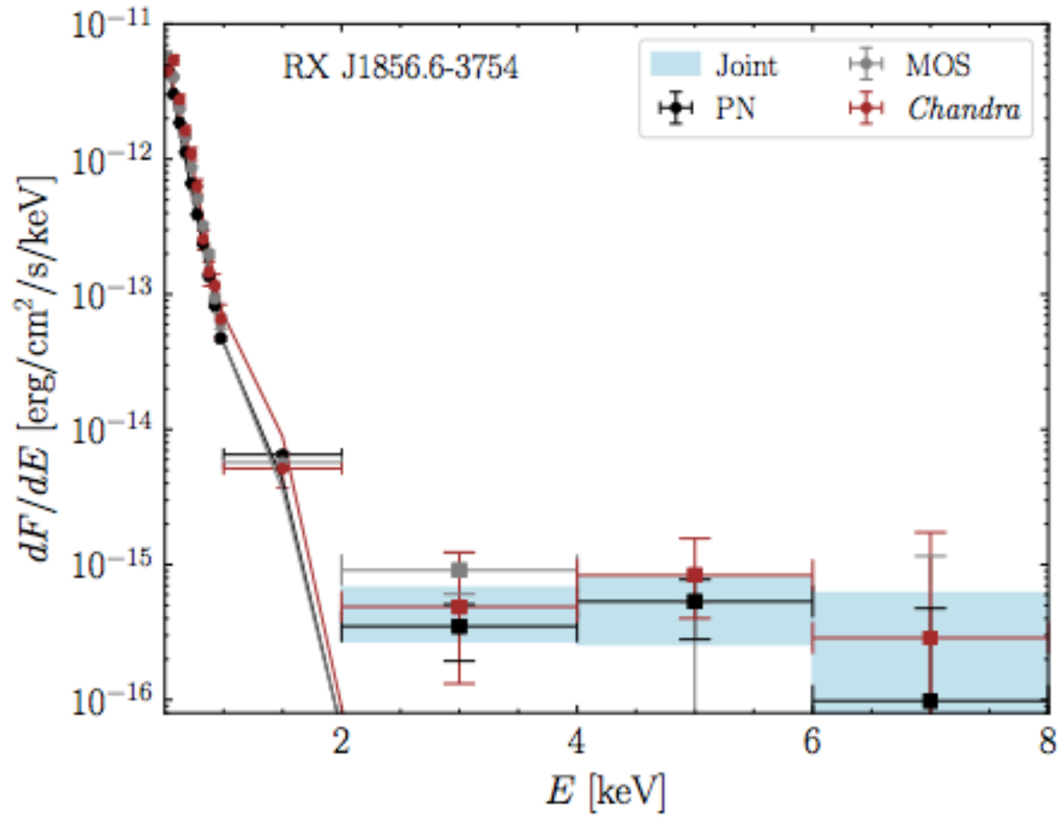
- Observed originally in stacked galaxy clusters [Bulbul et al '14, Boyarsky et al '14], subsequently in other regions.
- Individual signals are modestly significant (~4σ).
- Simplest DM explanation: 7 keV sterile neutrino decaying into neutrino+photon. (Other explanations involving annihilation, oscillations etc are possible.)
- Possible non-DM contributions: atomic lines (from K, Cl, Ar, possibly others), charge-exchange reactions between heavy nuclei and neutral gas.
- Simple decay explanation seems inconsistent with null results in other searches, in particular recent work by Dessert et al (Science, March 2020).
- Active controversy over validity of upper limits [Abazajian 2004.06170, Boyarsky et al 2004.06601] - key points are flexibility of background model, energy range considered.
- Simplified version of Dessert et al analysis is publicly available for cross-checking: https://github.com/bsafdi/BlankSkyfor3p5

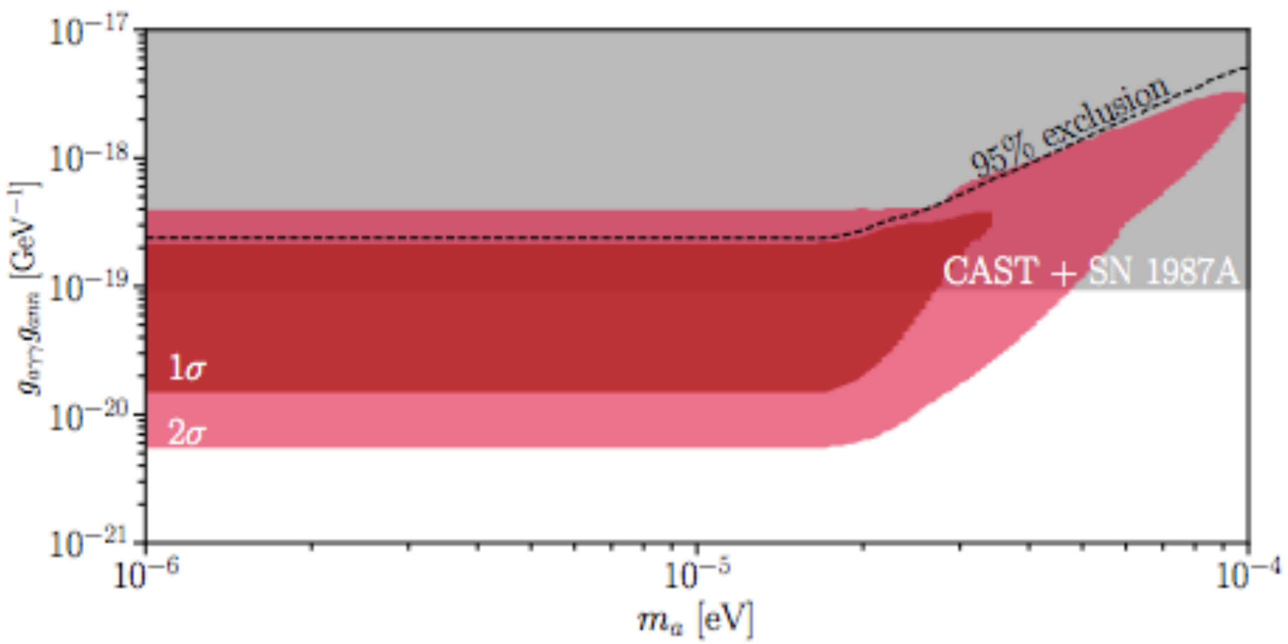


Dessert et al '20 (arXiv: 1812.06976)

The Magnificent Seven

- Two (of seven) nearby isolated neutron stars display hard non-thermal X-ray (2-8 keV) spectra of modest significance [Dessert et al ’20]
- One possible explanation: thermal axions are produced by oscillations in the hot core of the star → escape → oscillate to X-ray photons in the surrounding magnetic field [Buschmann et al ’20]

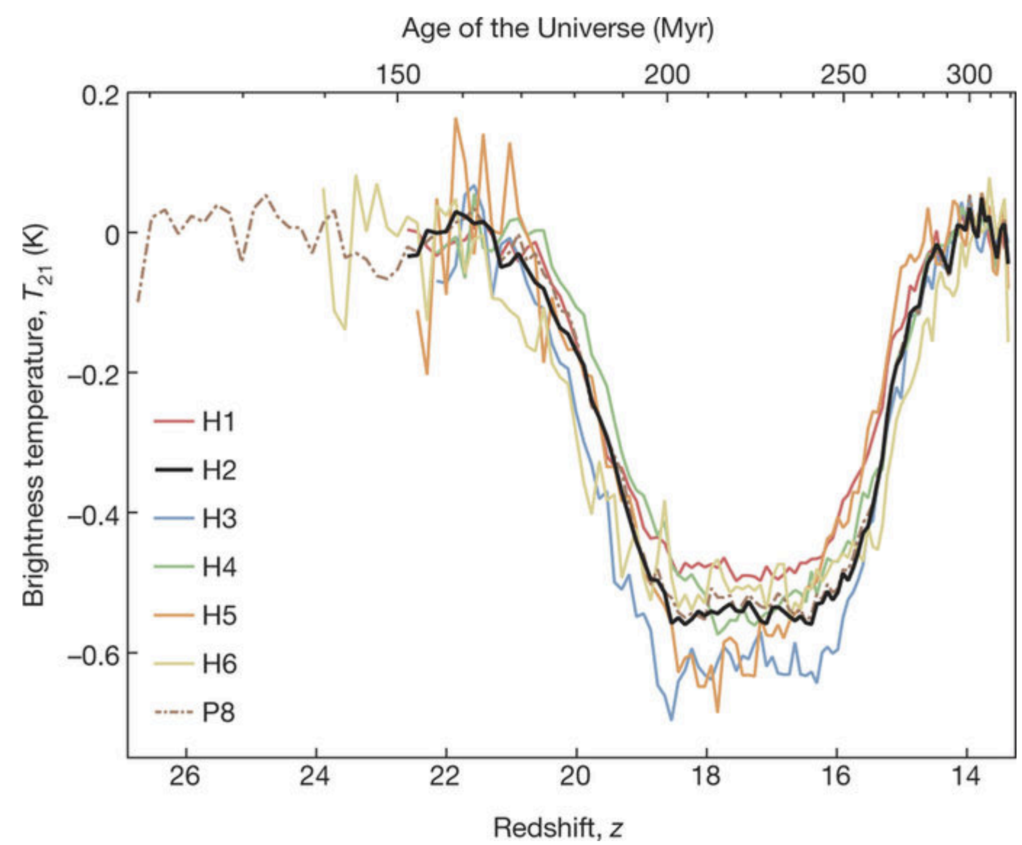




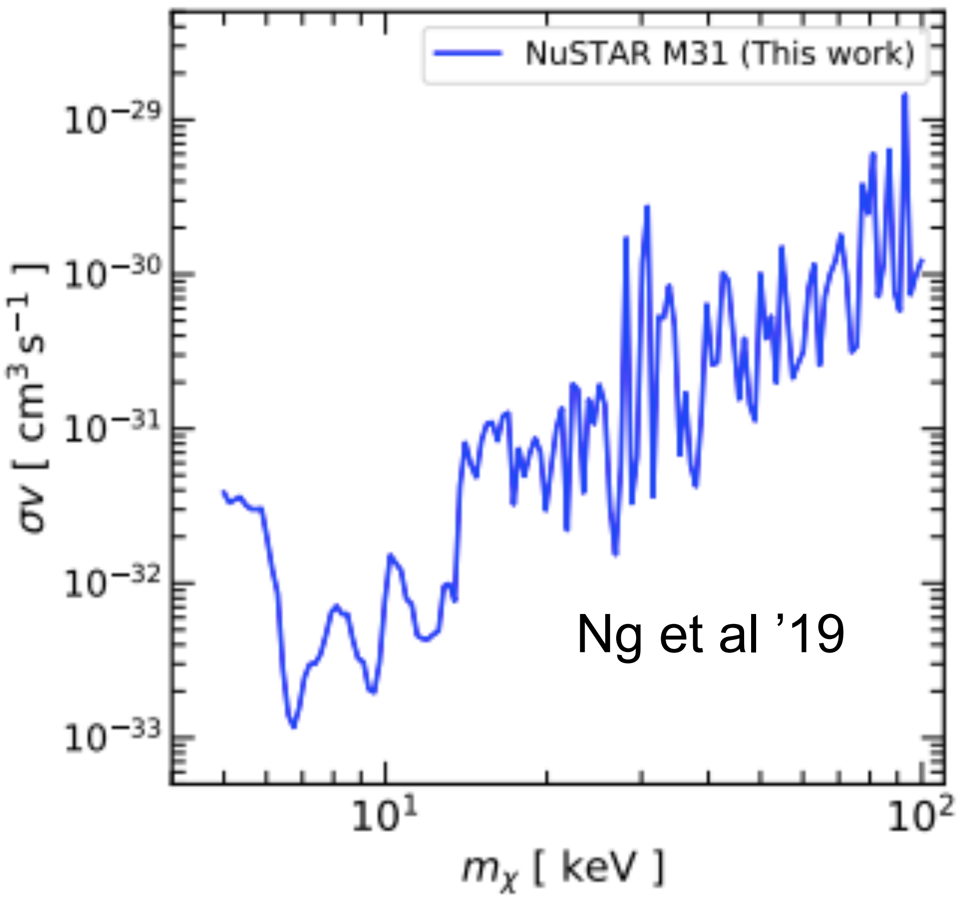
The EDGES absorption trough

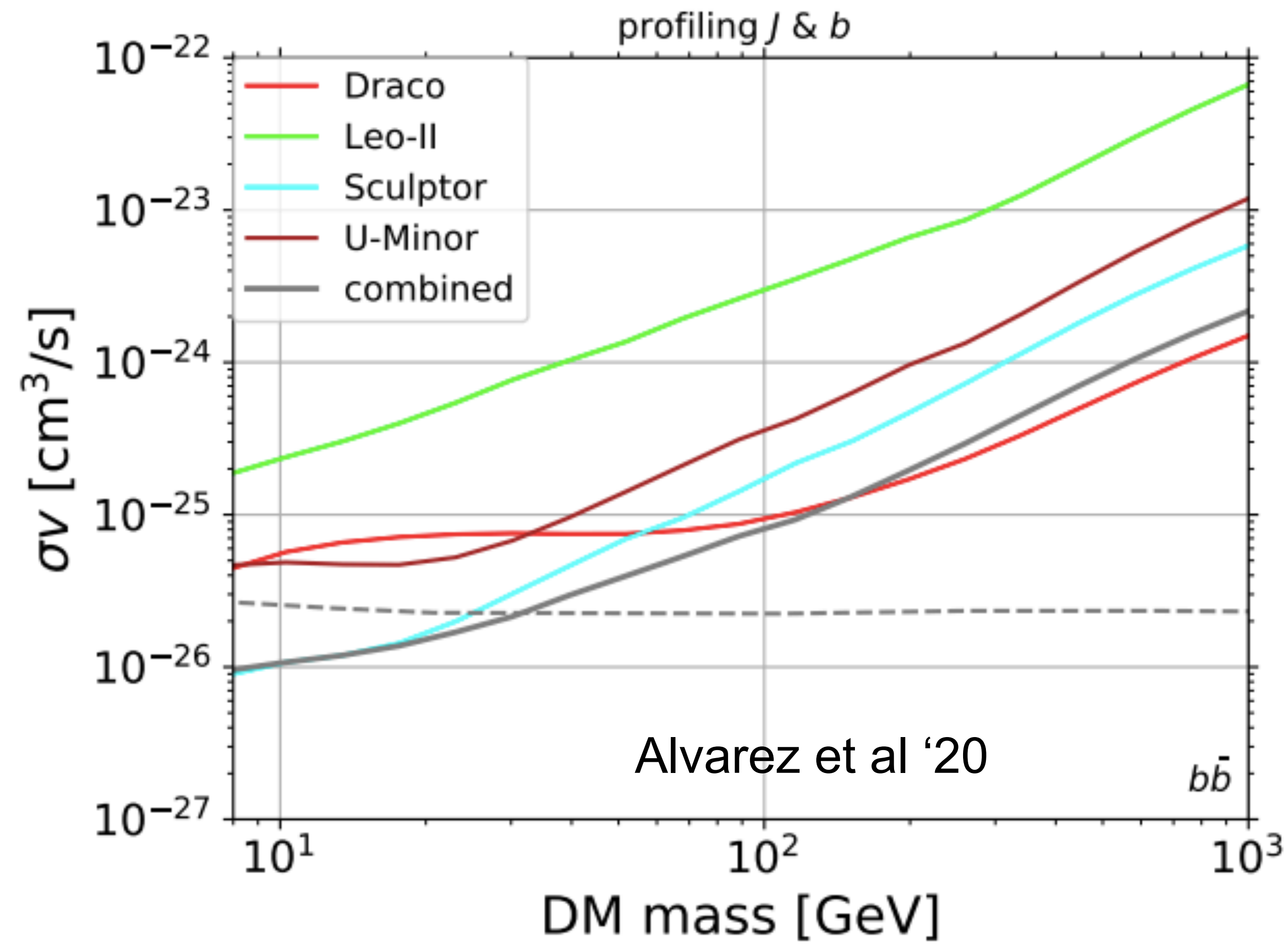

EDGES antenna in western Australia (photo credit: Judd Bowman/ASU)

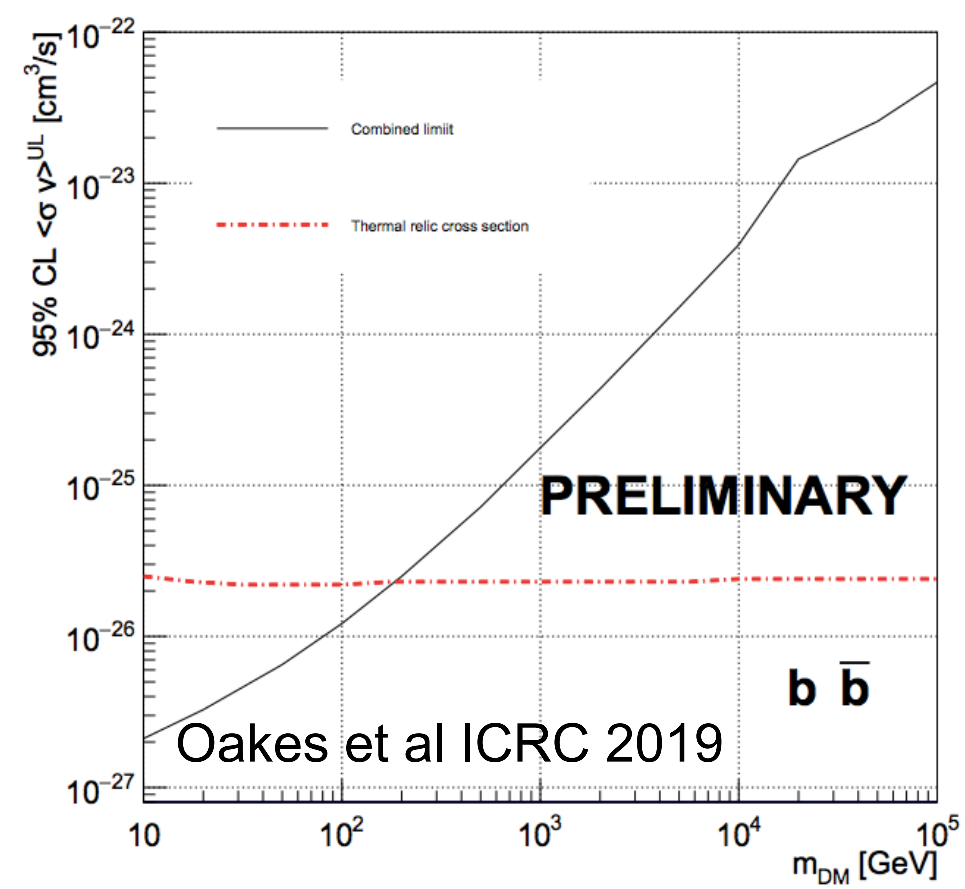
- The Experiment to Detect the Global Epoch-of-reionization Signature (EDGES) has claimed a detection of the first 21cm signal from the cosmic dark ages [Bowman et al, Nature, March '18]
- Claim is a very deep absorption trough corresponding to z~15-20 - implies gas temperature < CMB temperature, $T_{gas}/T_R(z=17.2) < 0.105$ (99% confidence).
- Very surprising result - trough is much deeper than expected.
- Suggests either new physics of some form, or a systematic error [e.g. Hills et al '18, Bradley et al '19].



Constraints on annihilation I

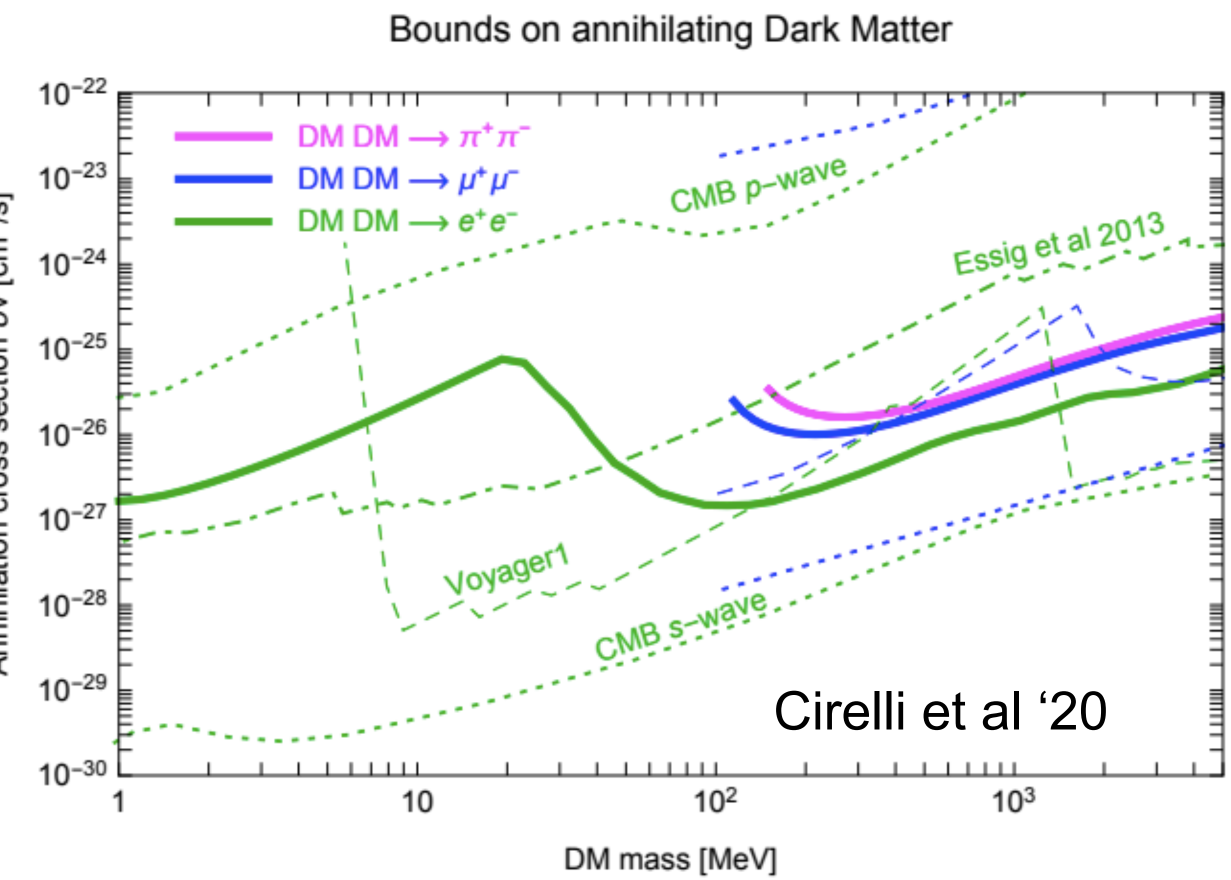


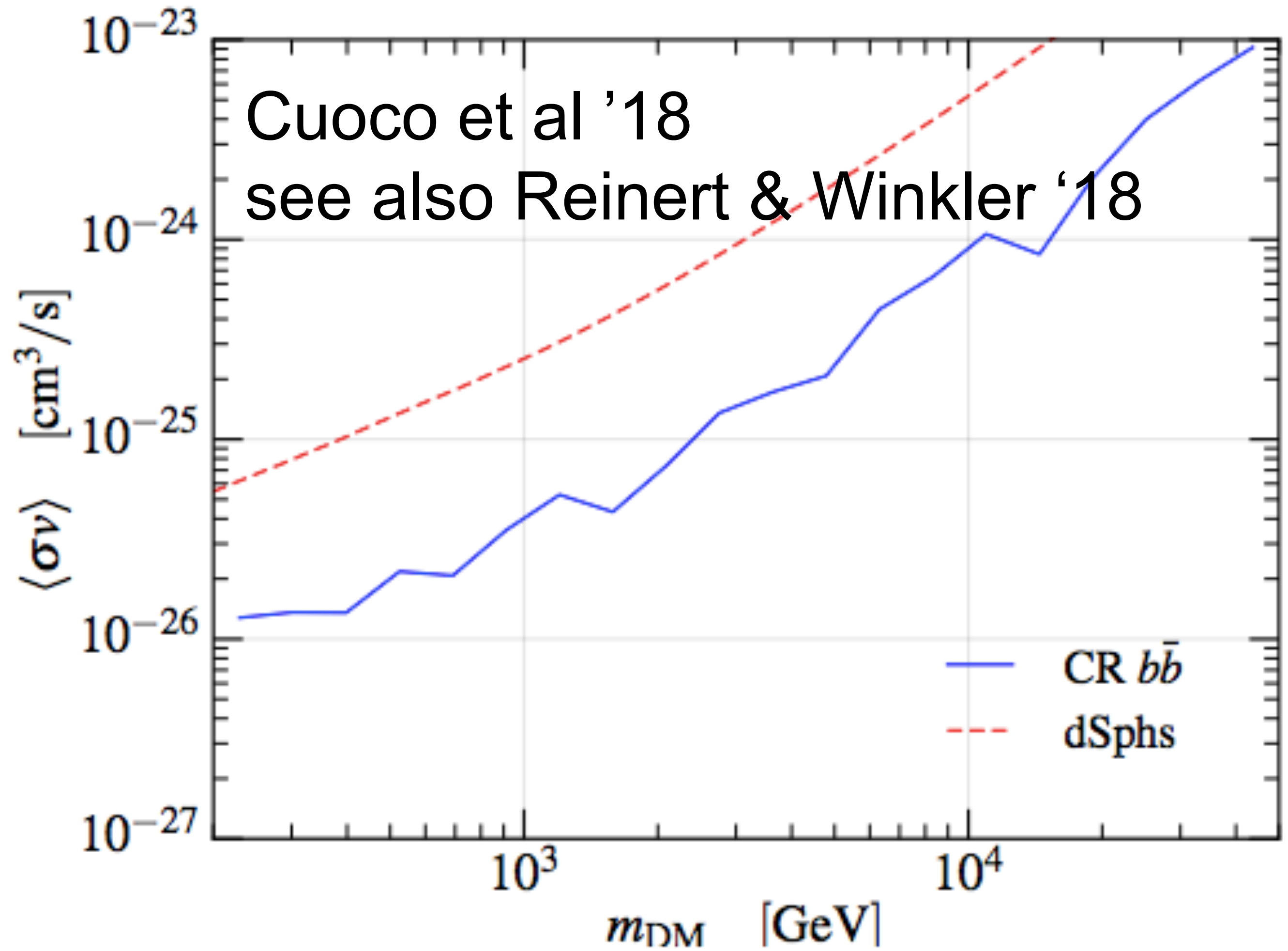


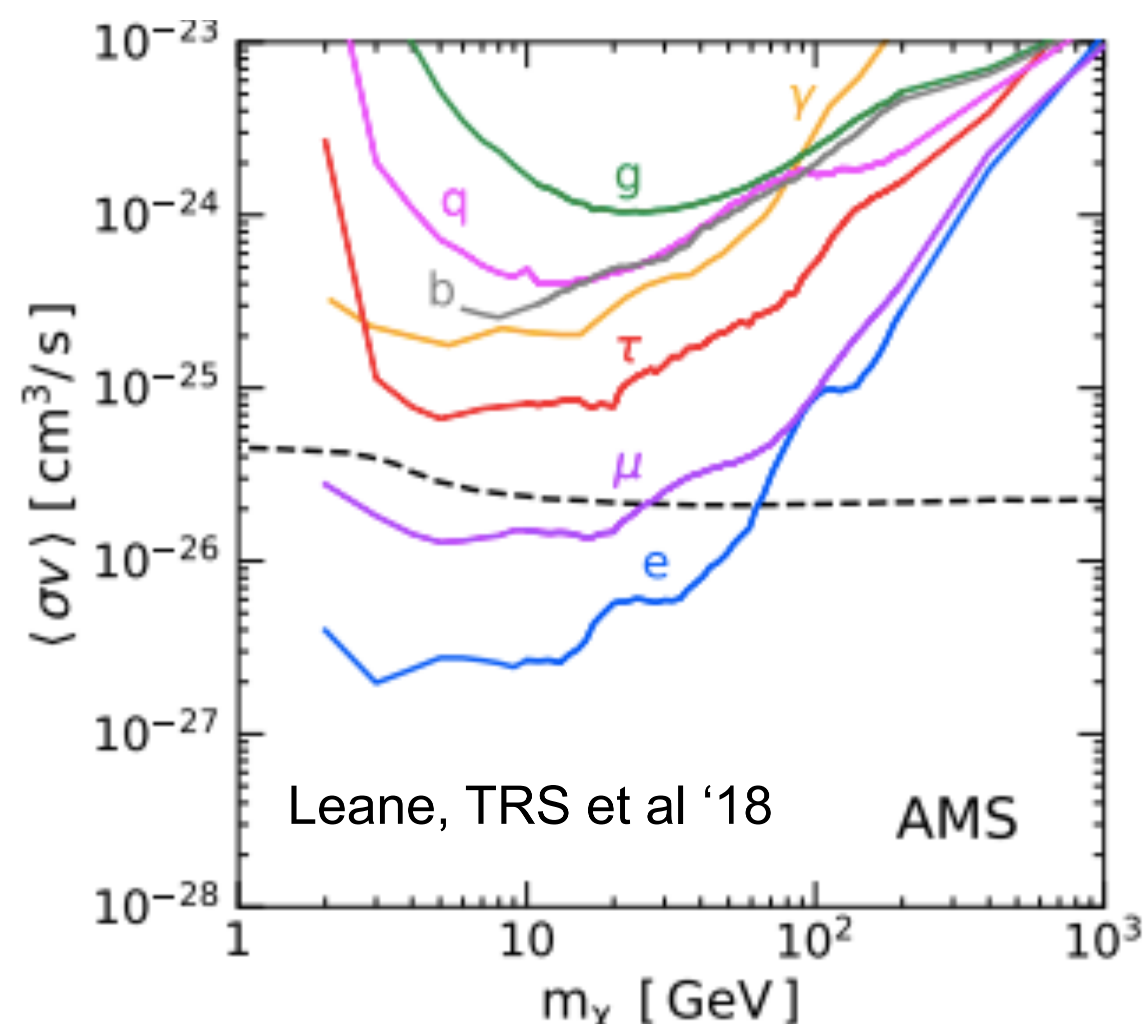


- Observations of X-rays with NuSTAR constrain annihilation of non-thermal keV-MeV-scale DM [e.g. Ng et al '19] to rates several orders of magnitude below the thermal relic cross section
- Observations of gamma-rays with Fermi (dwarf galaxies [e.g. Alvarez et al '20], galactic halo [e.g. Chang et al '18], other galaxies [e.g. Lisanti et al '18]) probe thermal relic cross sections up to O(10s-100s) GeV
- Ground-based gamma-ray telescopes such as H.E.S.S, VERITAS, MAGIC, HAWC, set limits on large annihilation cross sections up to the 100 TeV mass scale [e.g. Oakes et al '20, Abdallah et al '18, Archambault et al '17, Abdallah et al '16]

Constraints on annihilation II







- Observations of the cosmic microwave background constrain injection of ionizing particles in the early universe - strongest current constraints for all channels for velocity-independent annihilation and DM masses from keV-200 MeV [e.g. TRS '16, Planck Collaboration '18].
- Antiproton and positron observations by AMS-02 [Aguilar et al (AMS-02) '13, '16] set strong constraints on annihilation to hadronic and leptonic channels respectively, again probing thermal cross sections for DM masses of O(10-100) GeV.