New developments in indirect dark matter searches

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Bright ideas for a dark universe
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Outline

- Overview of a range of probes of new physics via indirect detection
- Recent developments and future prospects across a range of energies
- An update on the Galactic Center excess

Some mechanisms for indirect signals

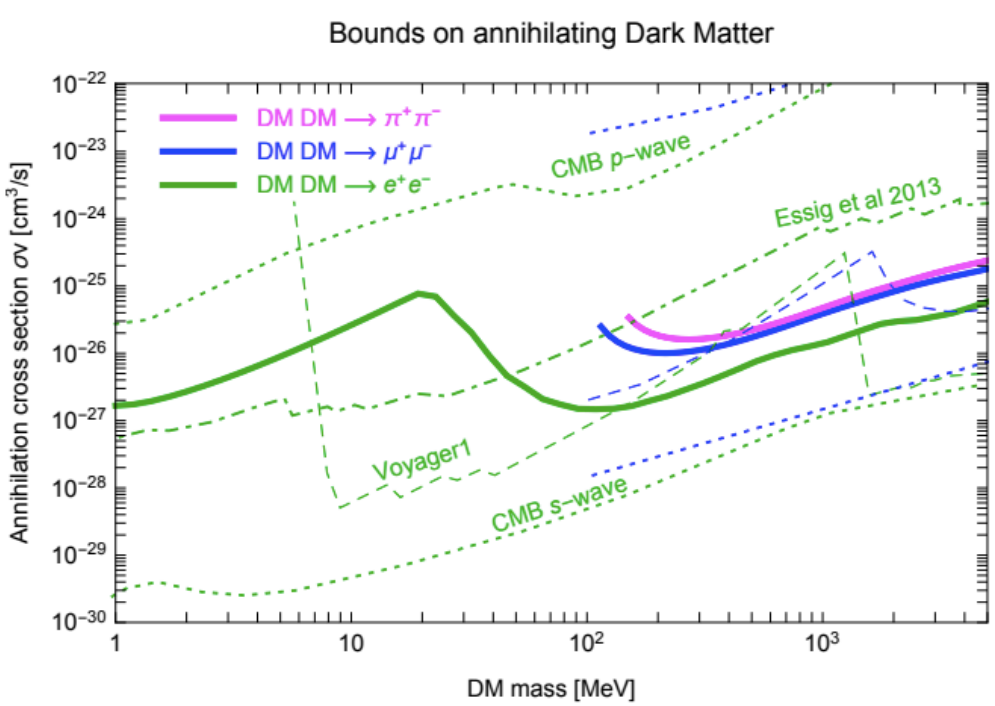
- Collisions that produce visible particles
    - Has natural benchmark cross section, if annihilation depletes early-universe DM abundance to its observed value:

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

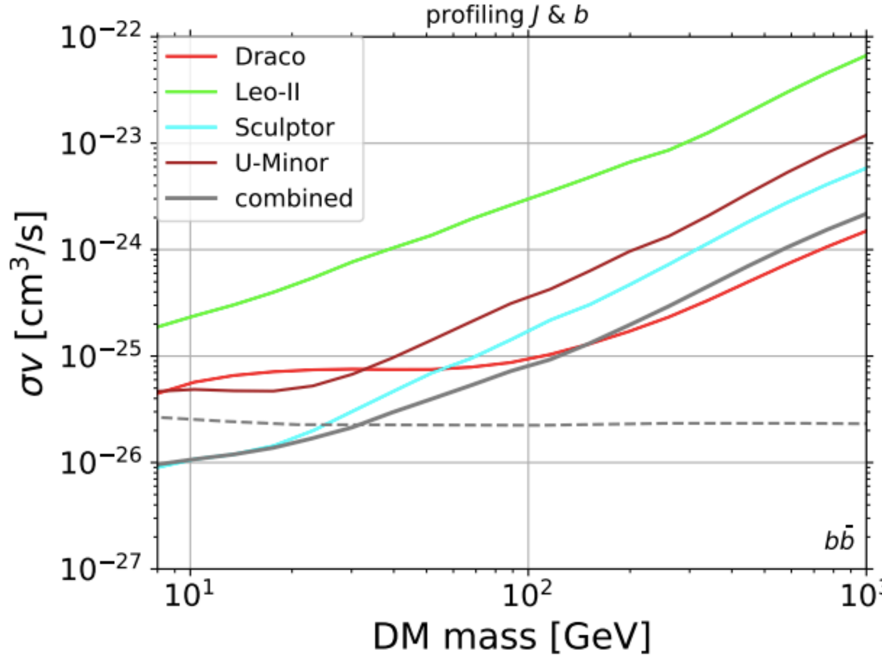
- Decay into visible particles, directly or through intermediate states - lifetime must be >> age of universe
- Scattering on visible particles leading to indirect signals
- Oscillation into visible particles, and vice versa

Constraints on annihilation

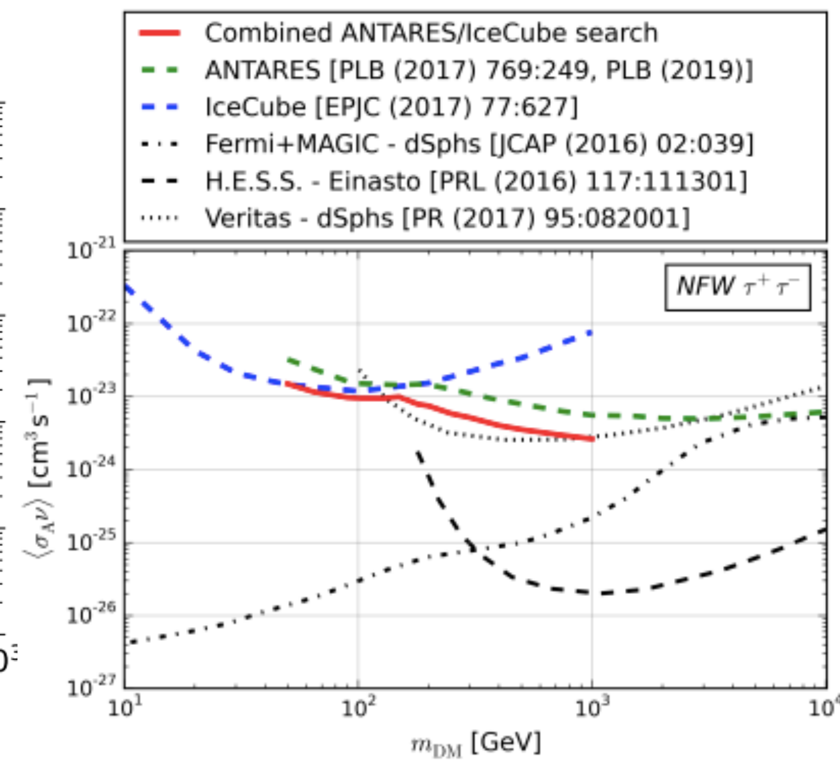
- Multiwavelength photon and cosmic-ray observations constrain thermal relic cross sections up to O(10s-100s) GeV, for all final states except neutrinos
- In this mass range, antiproton and gamma-ray measurements generally give the strongest bounds for hadronic final states [e.g. Alvarez et al ’20, Cuoco et al ’18, Reinert & Winkler ’18]
- 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

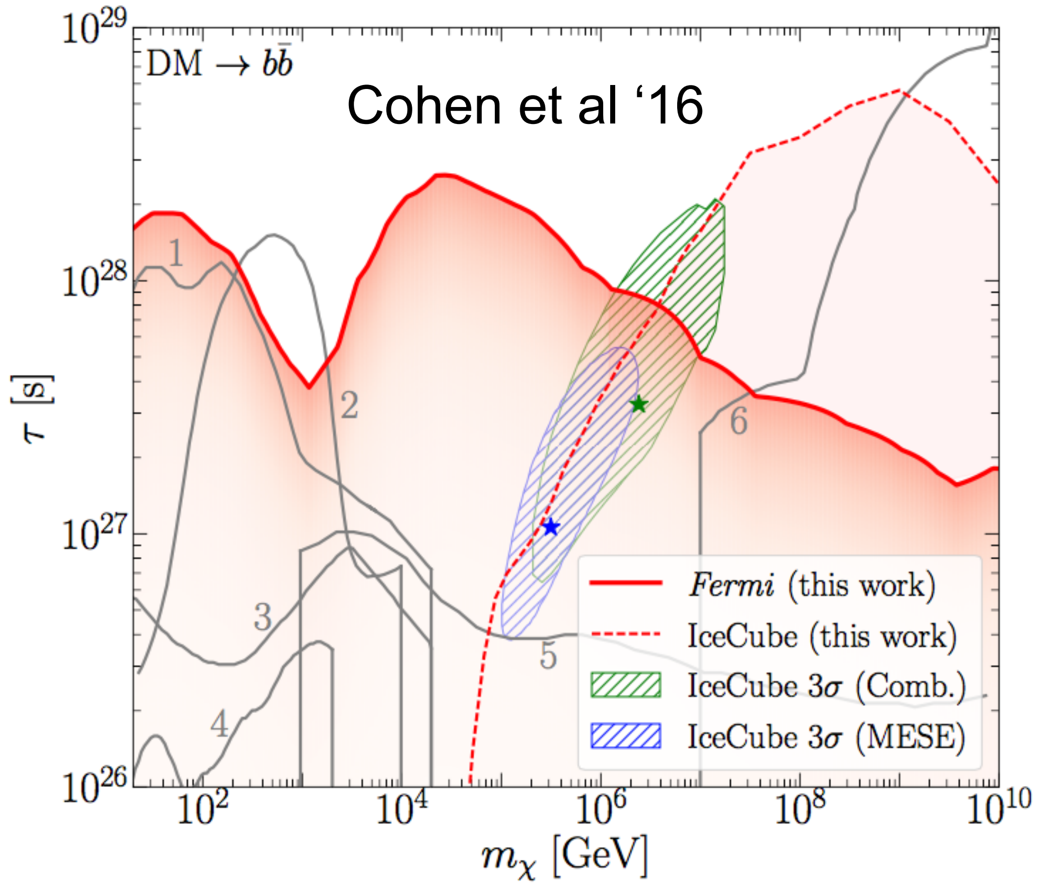


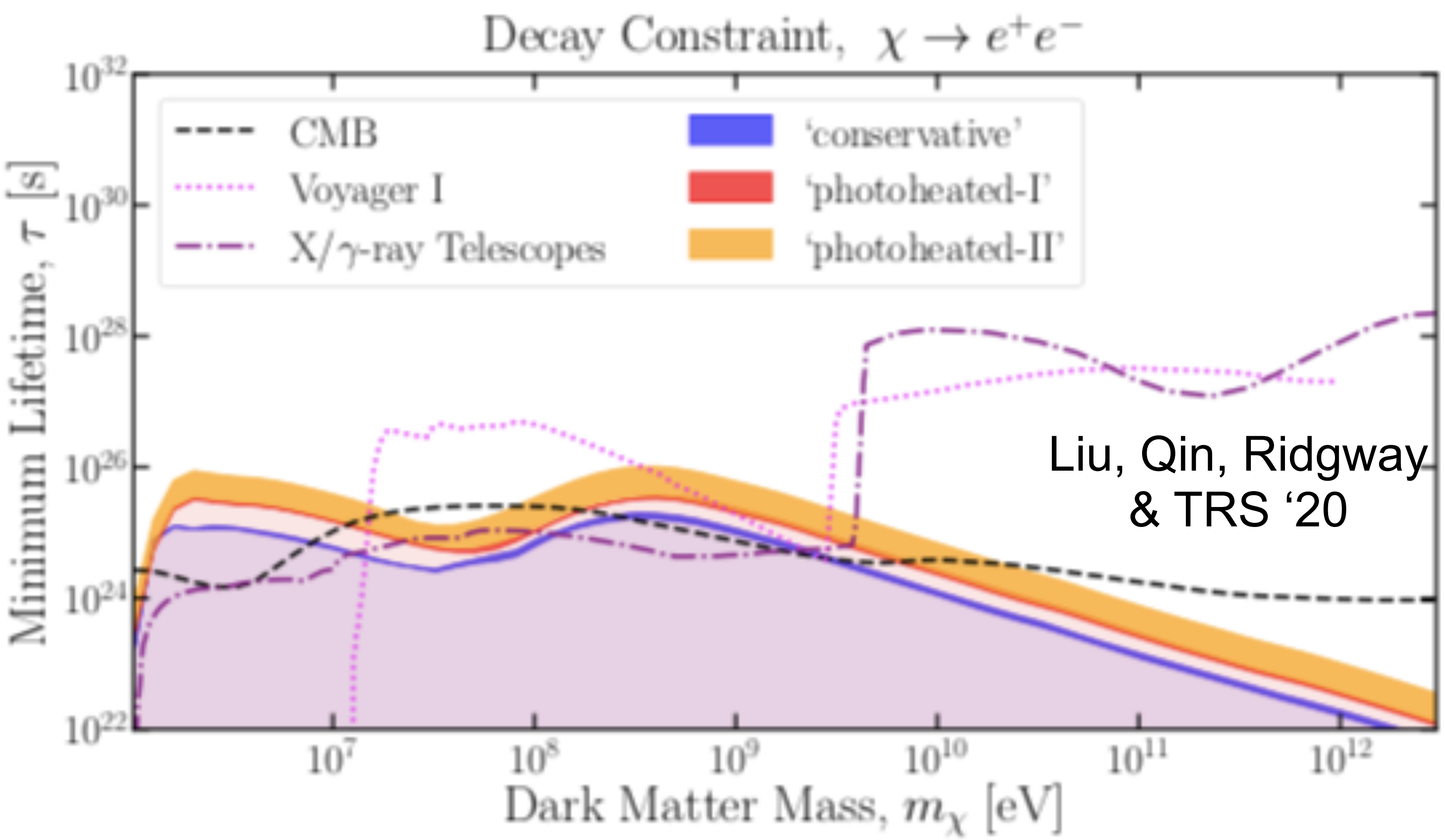
Alvarez et al ‘20



Albert et al ‘20

Constraints on decay



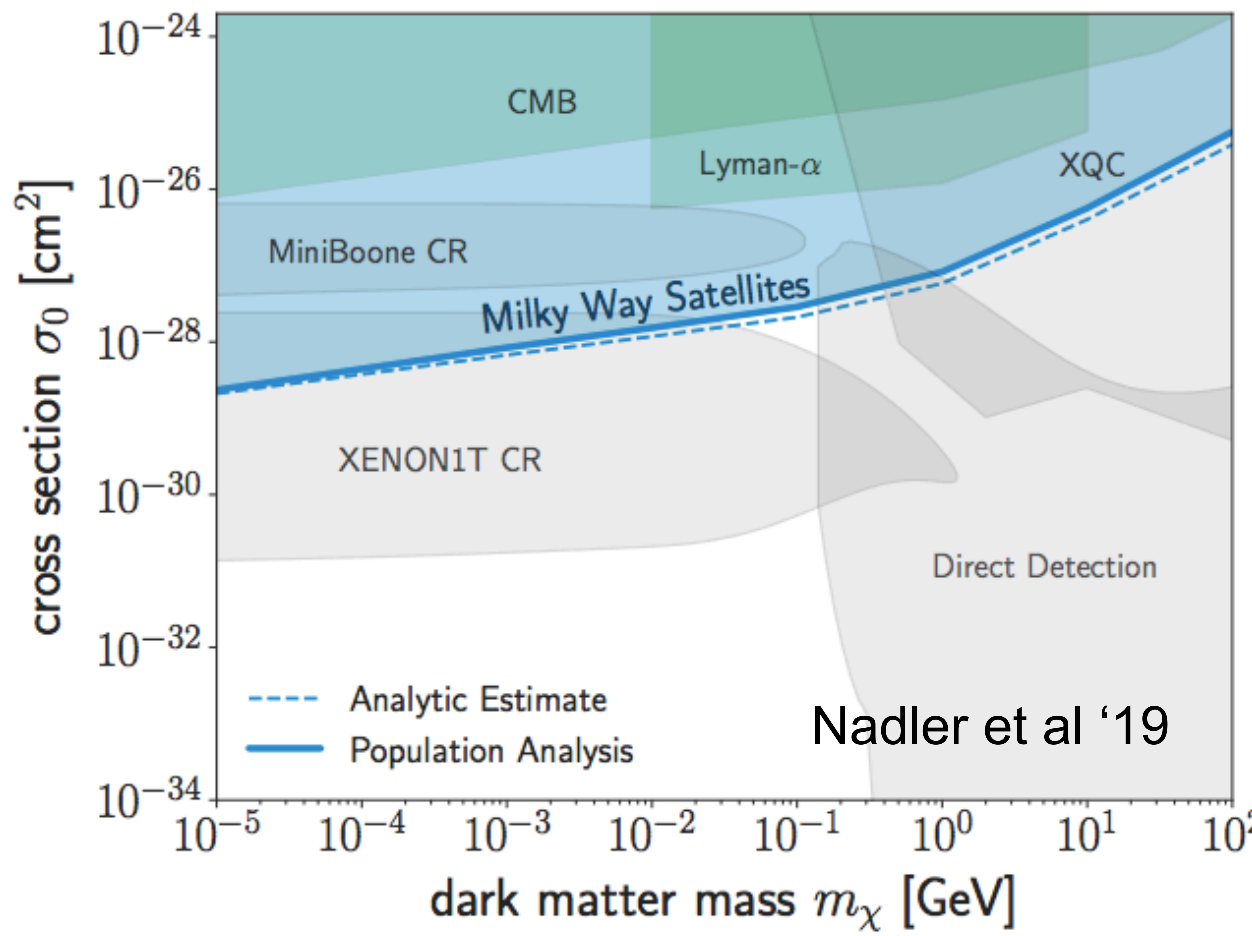


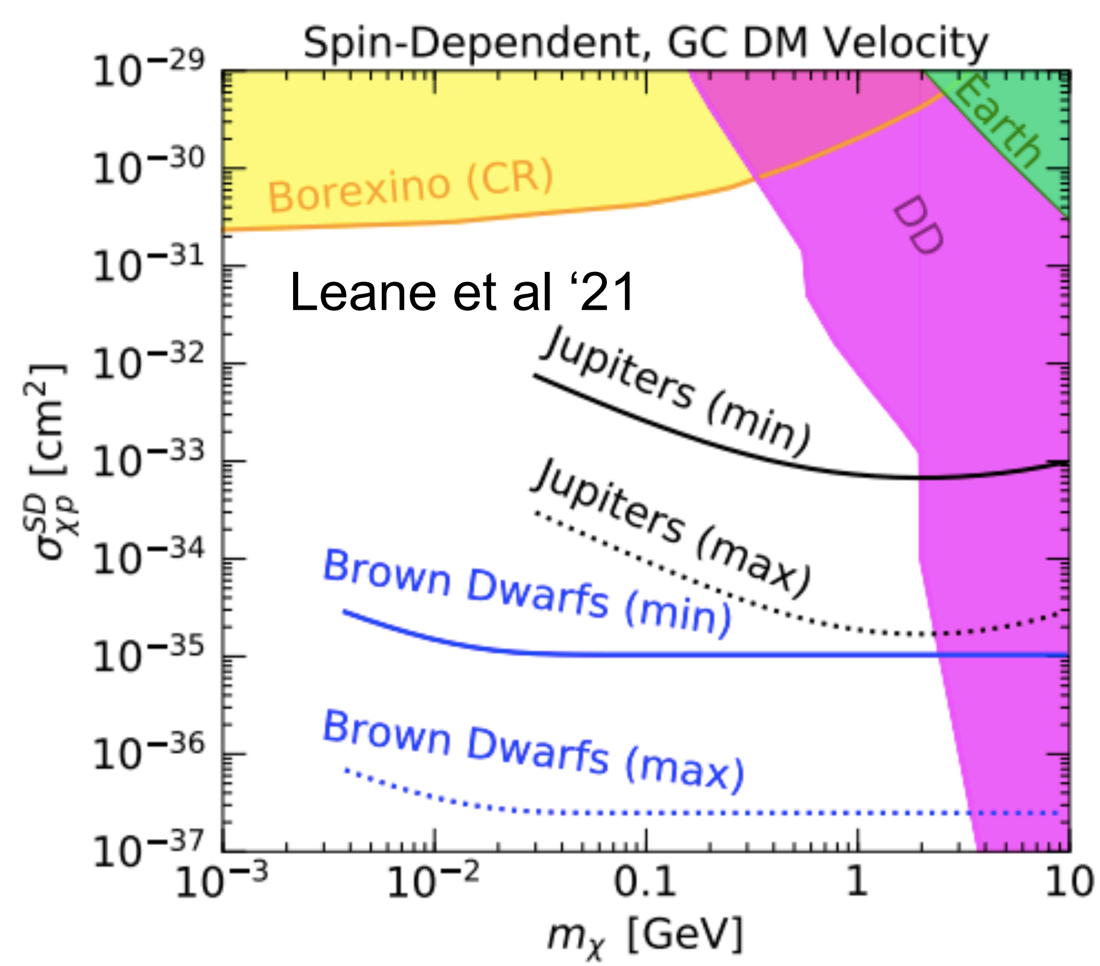
- Observations of gamma rays and (at high energies) neutrinos constrain DM decay to photons or hadronic final states to have lifetimes exceeding 10^{27-28} s, for the full range of masses from several keV to 10^{10} GeV.

- 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

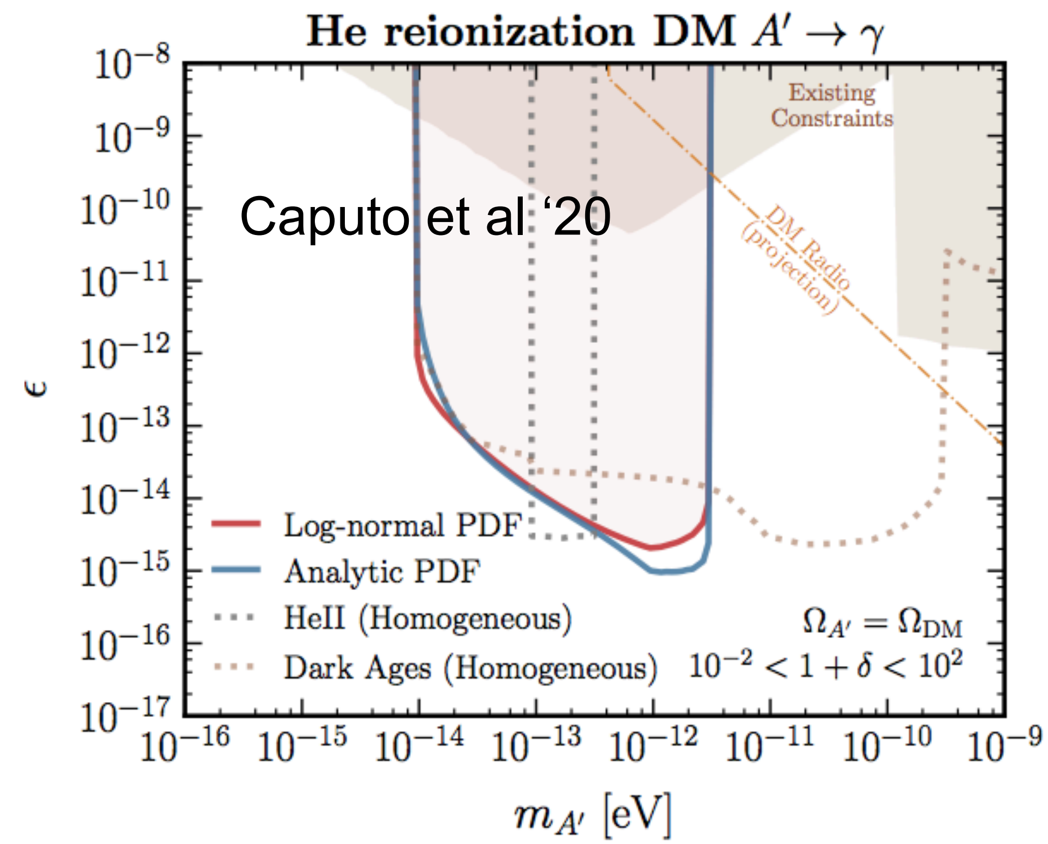
- Scattering is often considered the regime of direct detection, but can be tested in indirect searches as well
- Can exclude large cross-sections that might prevent DM from reaching terrestrial detectors
- Cosmology (CMB + large-scale structure) and astrophysics (Milky Way satellite population) sets 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)

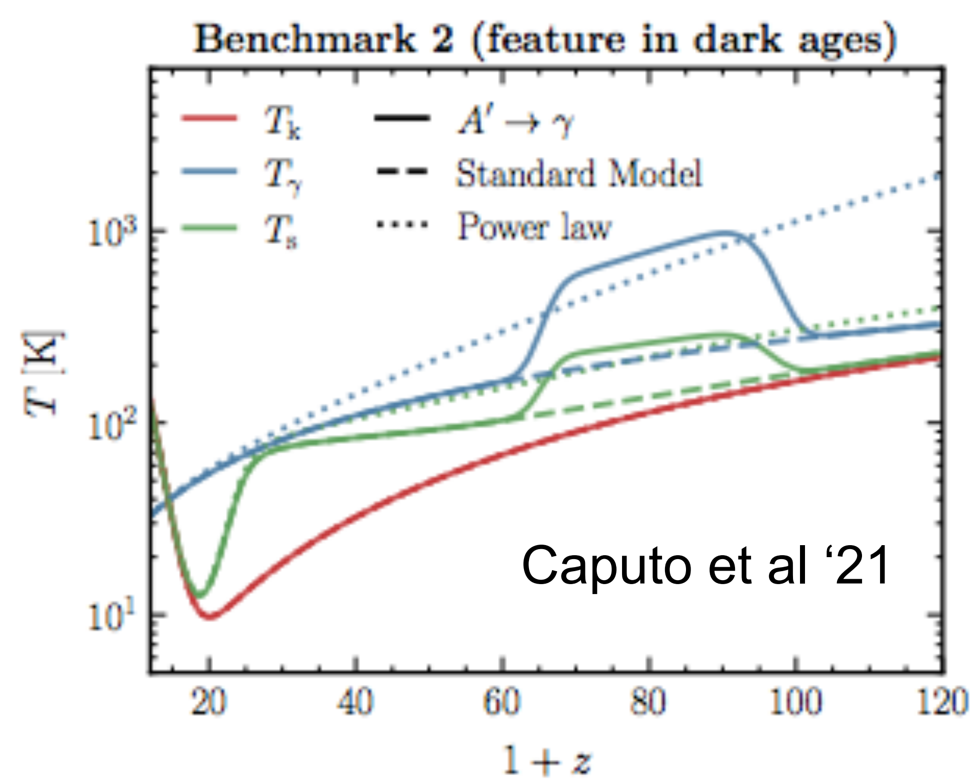




Constraints on oscillation

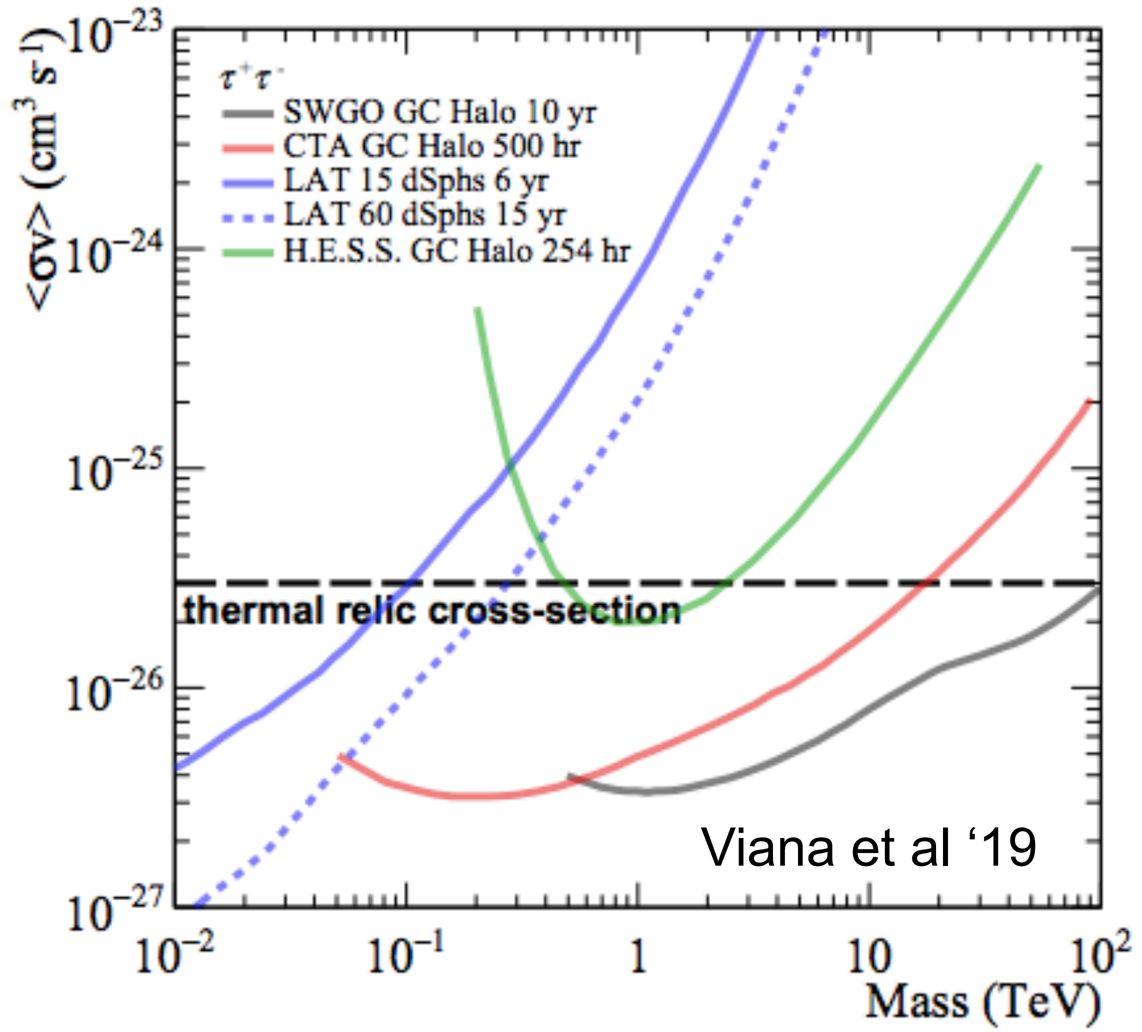
- If dark matter is an axion, it can oscillate into a photon in the presence of an external magnetic field
- Dark photons (may or may not be the DM) which mix with the SM photon could oscillate into SM photon, resonantly enhanced when dark photon mass = SM photon plasma mass
- Give rise to a wide range of astrophysical/cosmological signals [see talk by Ben Safdi later today on axions]
- A few examples (not close to exhaustive!):
    - 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]
    - dark photon - visible photon oscillations could leave spectral edges and endpoints in global 21cm signal [e.g. Caputo et al '21]

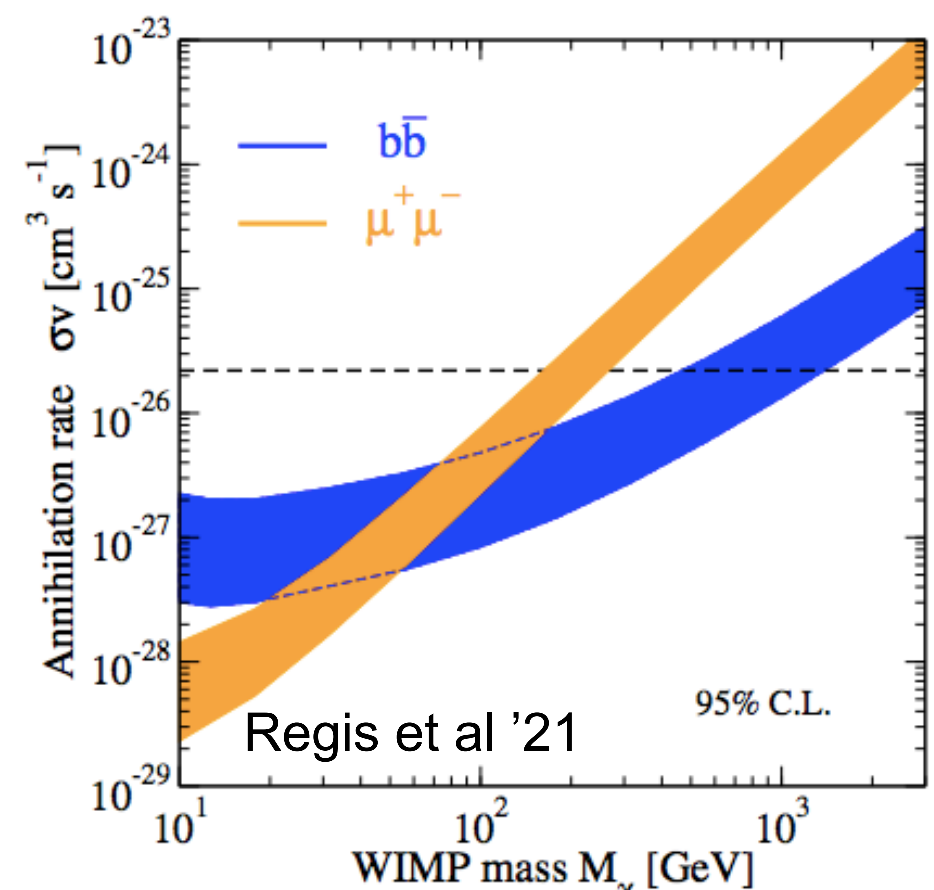




Annihilation beyond 100 GeV

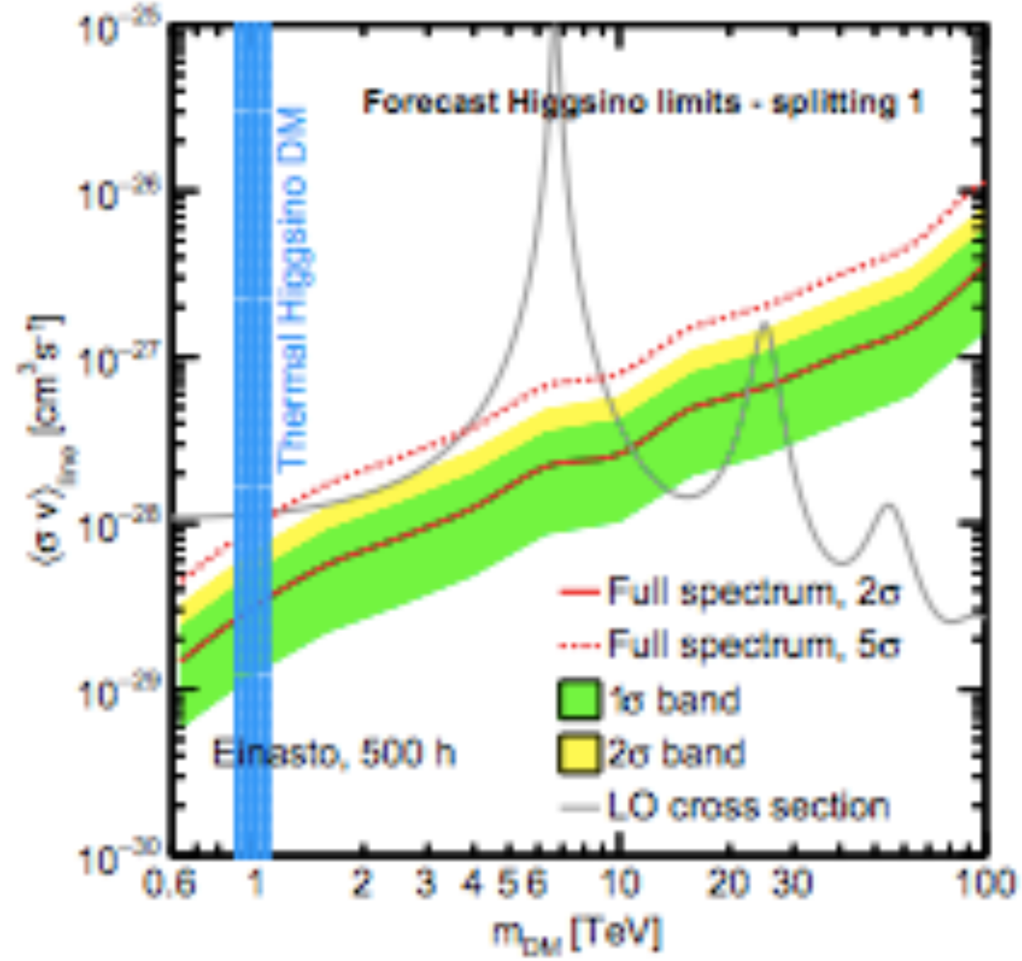
- Future ground-based gamma-ray telescopes have the possibility to probe thermal relic xsec up to O(100) TeV
- Some current searches have higher potential sensitivity, subject to systematic uncertainties
- HESS observations of the Galactic Center sensitive to O(TeV) thermal relics IF the inner Galaxy has a cuspy DM density profile
- Synchrotron from e^+e^- in the Galactic magnetic field can produce radio signals - systematics in propagation + B-field, but potentially very strong limits [e.g. Chan et al '19 from Andromeda, Regis et al '21 from the LMC]
- Potential for nearly background-free searches, e.g. low-energy antideuterons with GAPS experiment [e.g. von Doetinchem et al '20]



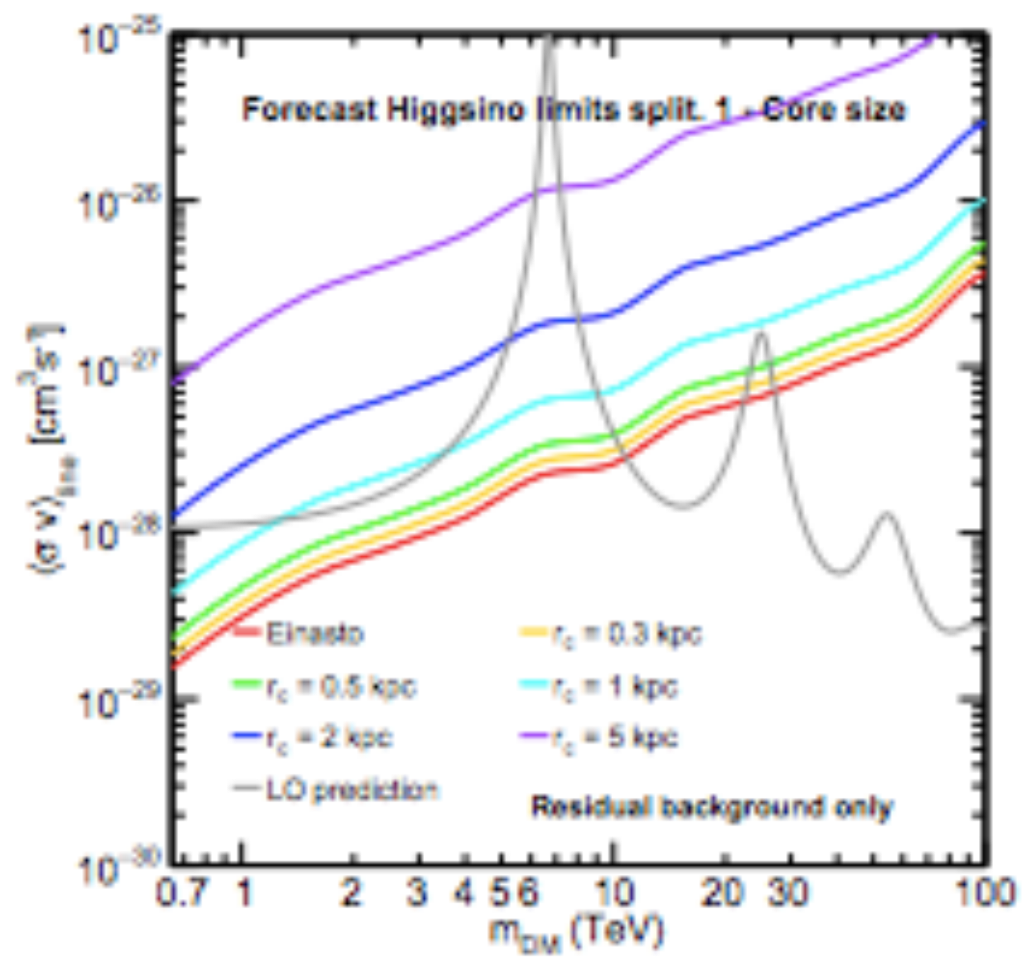


Electroweak DM

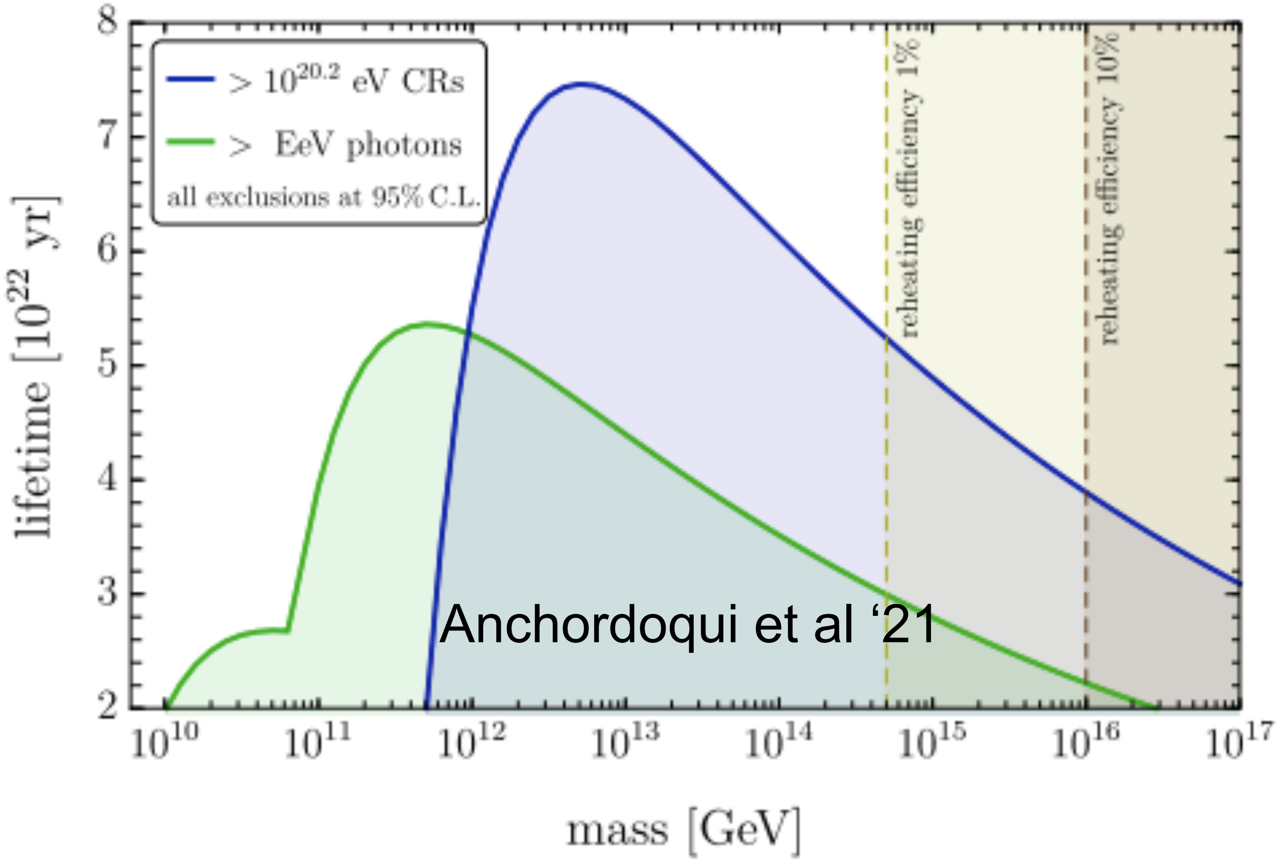
- Some of the simplest classic WIMP models remain unconstrained - DM could still interact through the W and Z bosons!
- One example is the higgsino - fermionic DM transforming as a $SU(2)_W$ doublet, appears in supersymmetry as the Higgs superpartner
- Obtains the correct relic density for $m_{DM} \sim 1$ TeV
- Direct detection signal is below neutrino floor; undetectable with current colliders
- Precise theory predictions for heavy electroweakinos require careful effective field theory analysis [e.g. Baumgart, TRS et al '19, Beneke et al '20]
- Potentially detectable in gamma rays with CTA, or with future colliders [e.g. Canepa et al '20, Capdevilla et al '21]



Rinchiuso, TRS et al '21



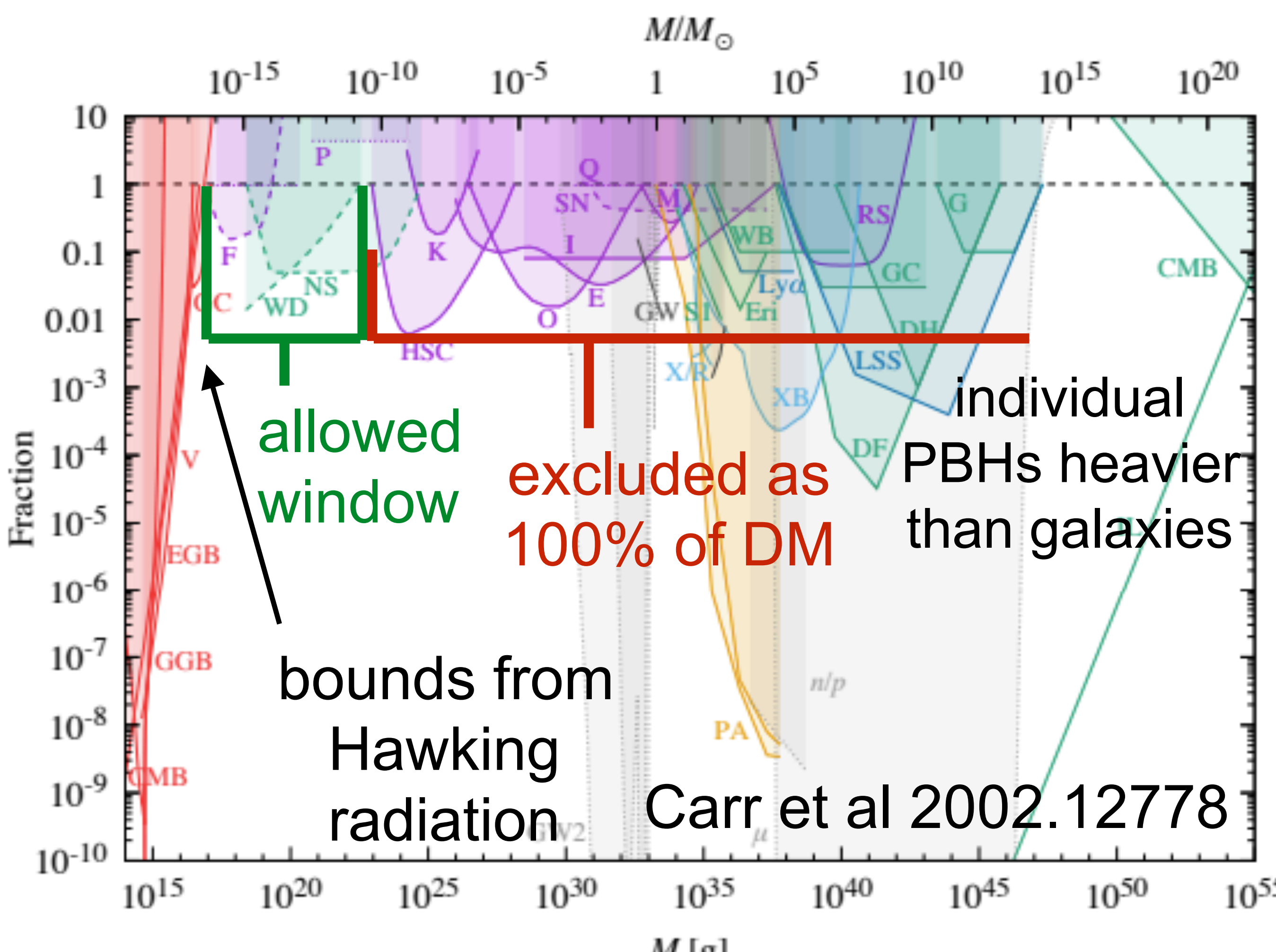
Above the thermal window: ultraheavy DM

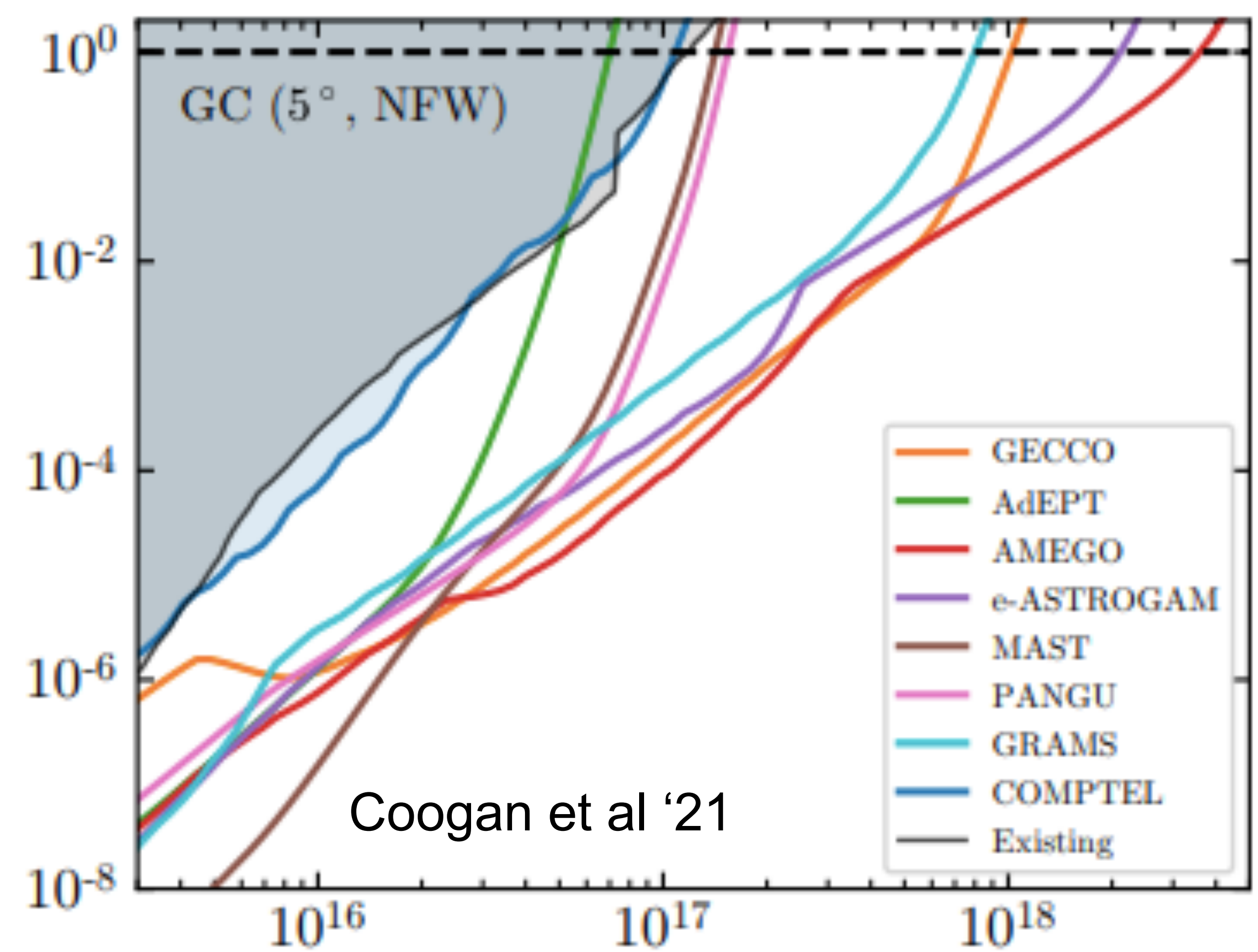


- In the presence of a long-range force, contributions from bound state formation, high partial waves can saturate and extend the unitarity bound for thermal relic DM, up to ~PeV [e.g. von Harling & Petraki '14, Smirnov & Beacom '19]
- (Much) higher masses can be achievable for thermal relic DM when 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 possible
- 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]

Primordial black holes

- Primordial black holes (PBHs) can also serve as a DM candidate if they lie in the right mass range - 10^{17-23} g PBHs appear viable to constitute 100% of the DM.
- 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.
- The non-observation of this radiation sets the strongest current bounds on such PBHs - possible to improve the limit with future MeV-band observations, where a number of new telescopes have been proposed.





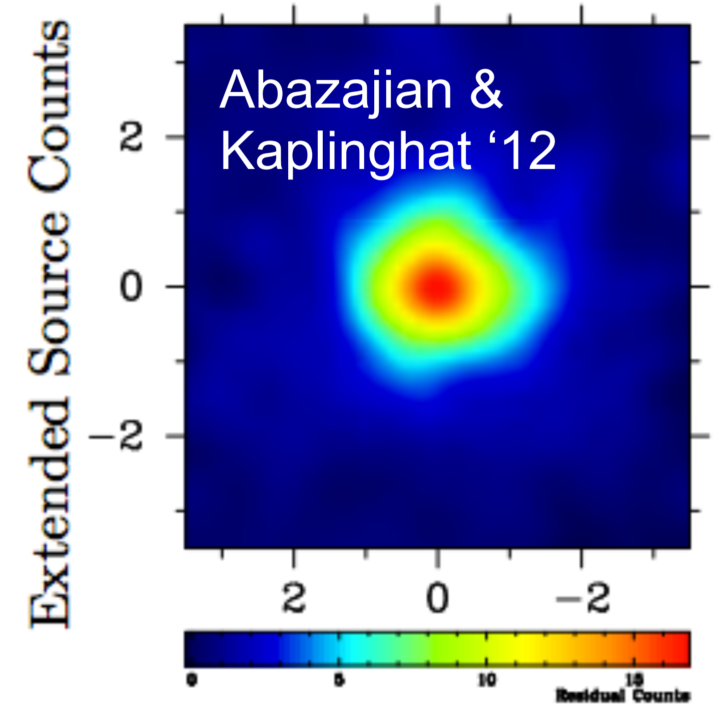
The Galactic Center excess (GCE)

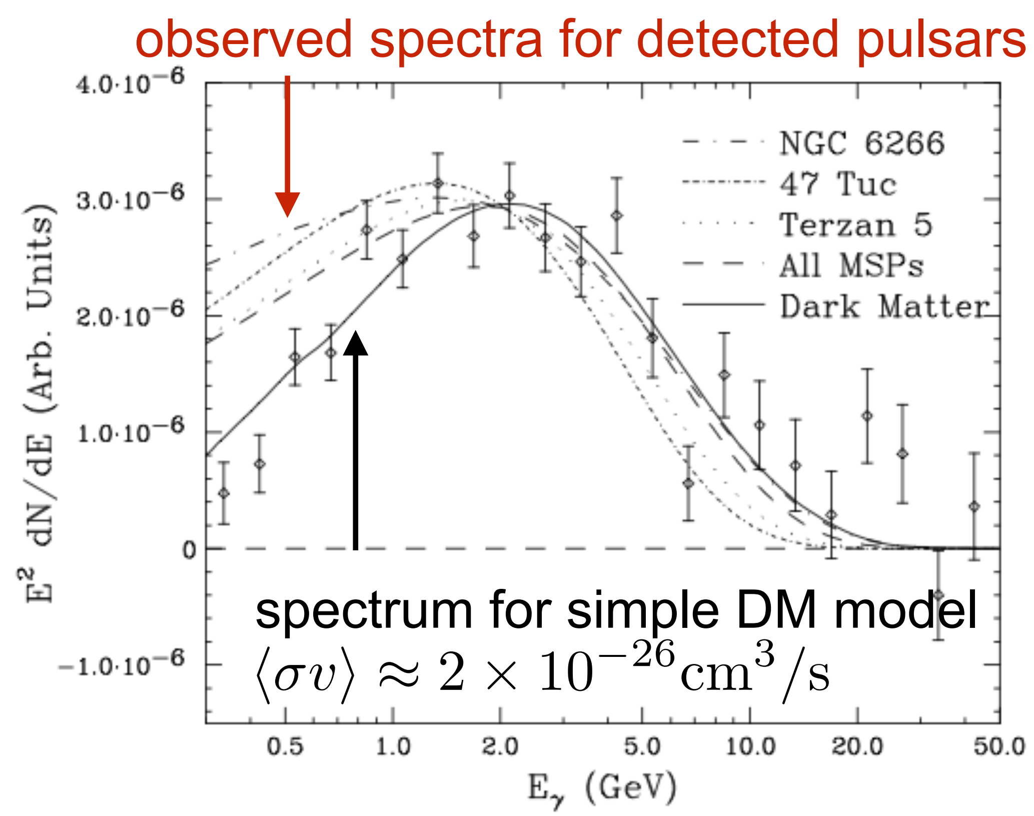
- Excess of gamma-ray photons, peak energy ~1-3 GeV, in the region within ~10 degrees of the Galactic Center.

- 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

Status of the GCE - a renewed controversy?

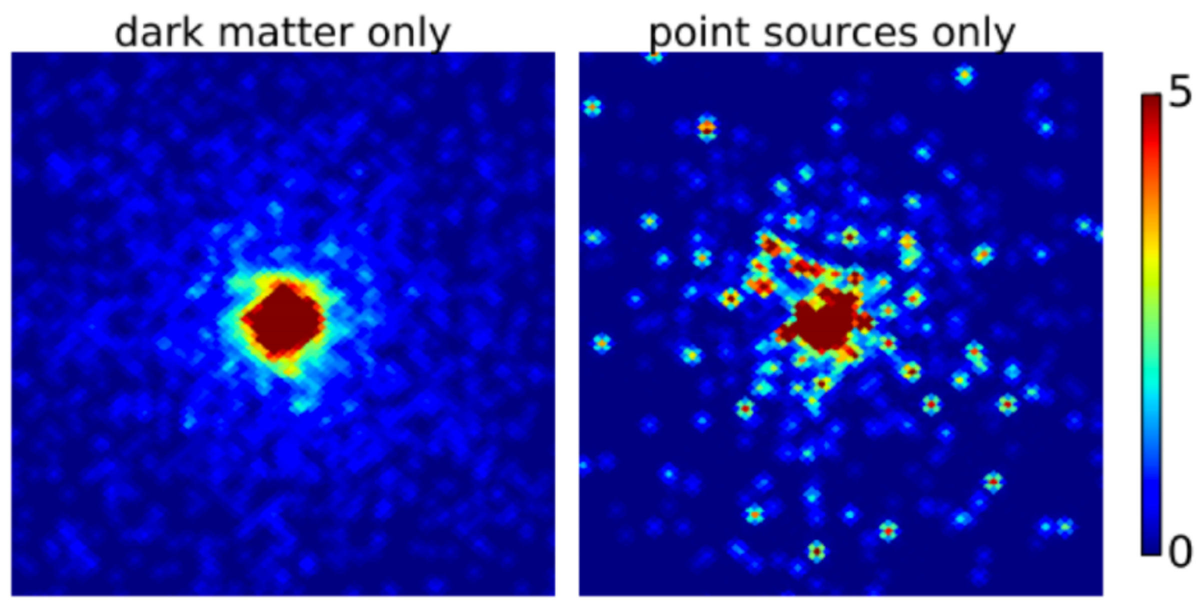
- Key argument in favor of pulsars: energy spectrum
- Current/past arguments against the DM explanation:
  - Spatial morphology of excess was originally characterized as spherical, but can also be described as boxy-bulge-like extended emission + central nuclear bulge component [Macias et al ’18, Bartels 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>

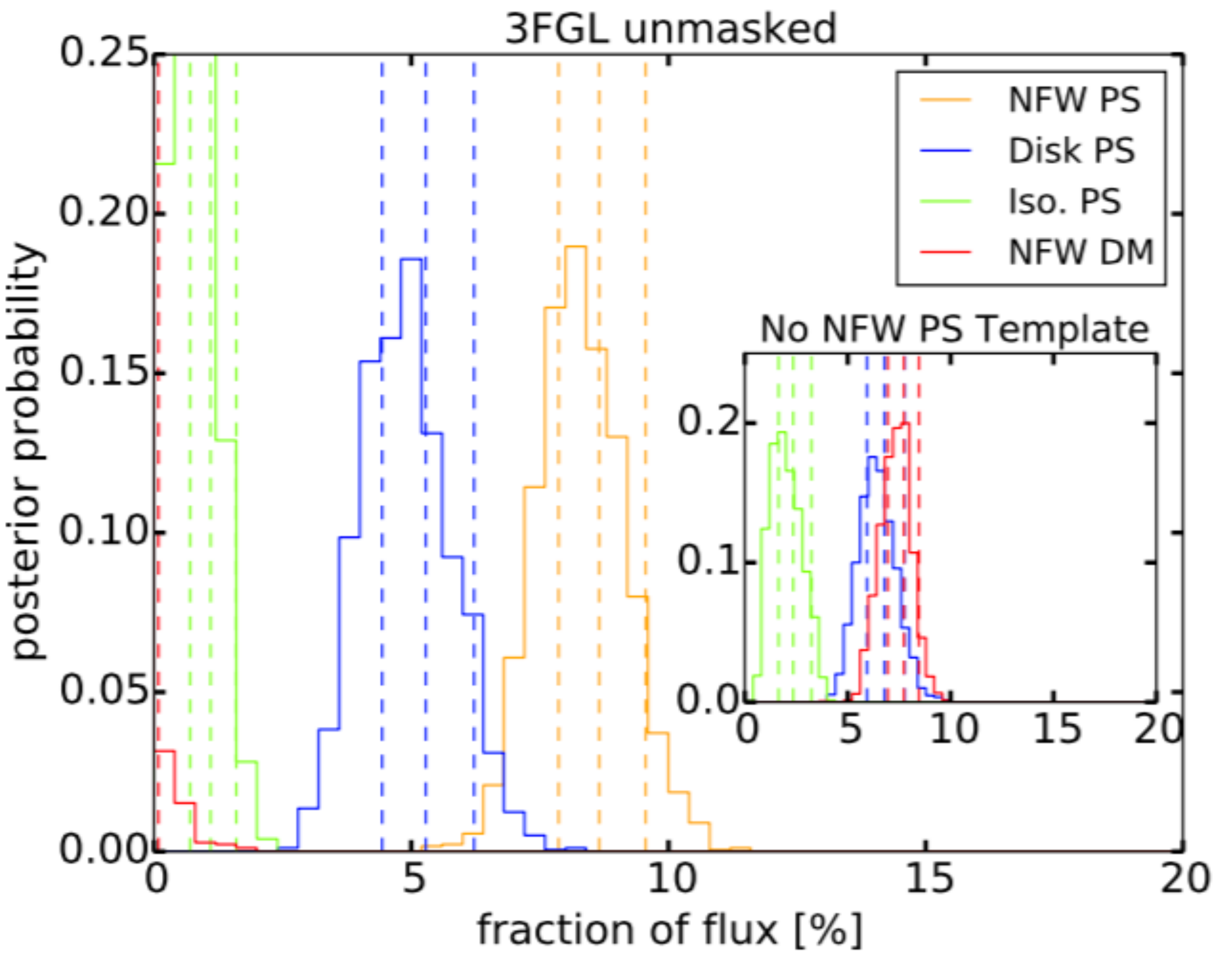
signal traces DM density squared, expected to be ~smooth near GC with subdominant small-scale structure



<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

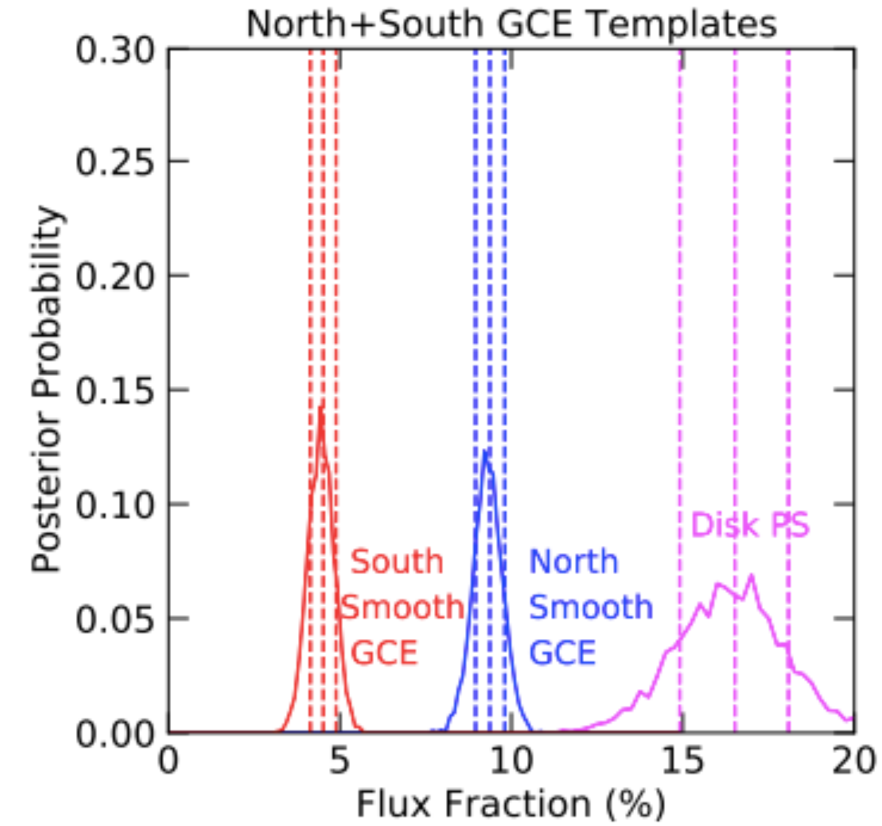
Spurious point sources (data)

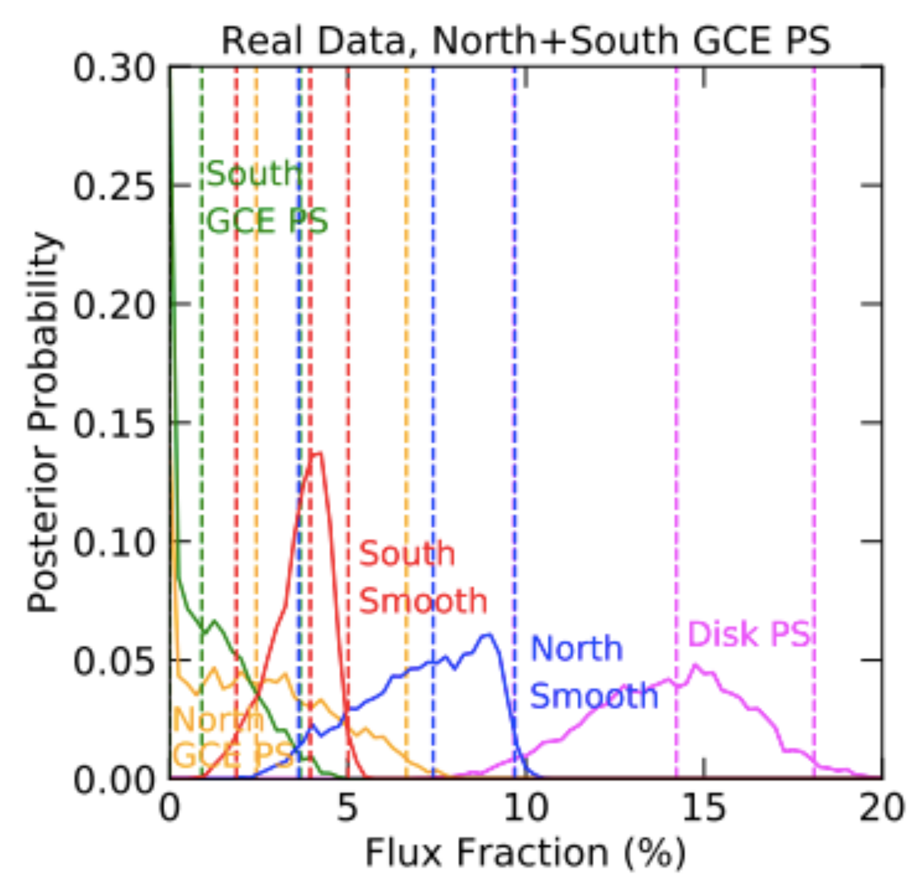
- We found this by accident - trying to test the spatial morphology of the GCE in more detail

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

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

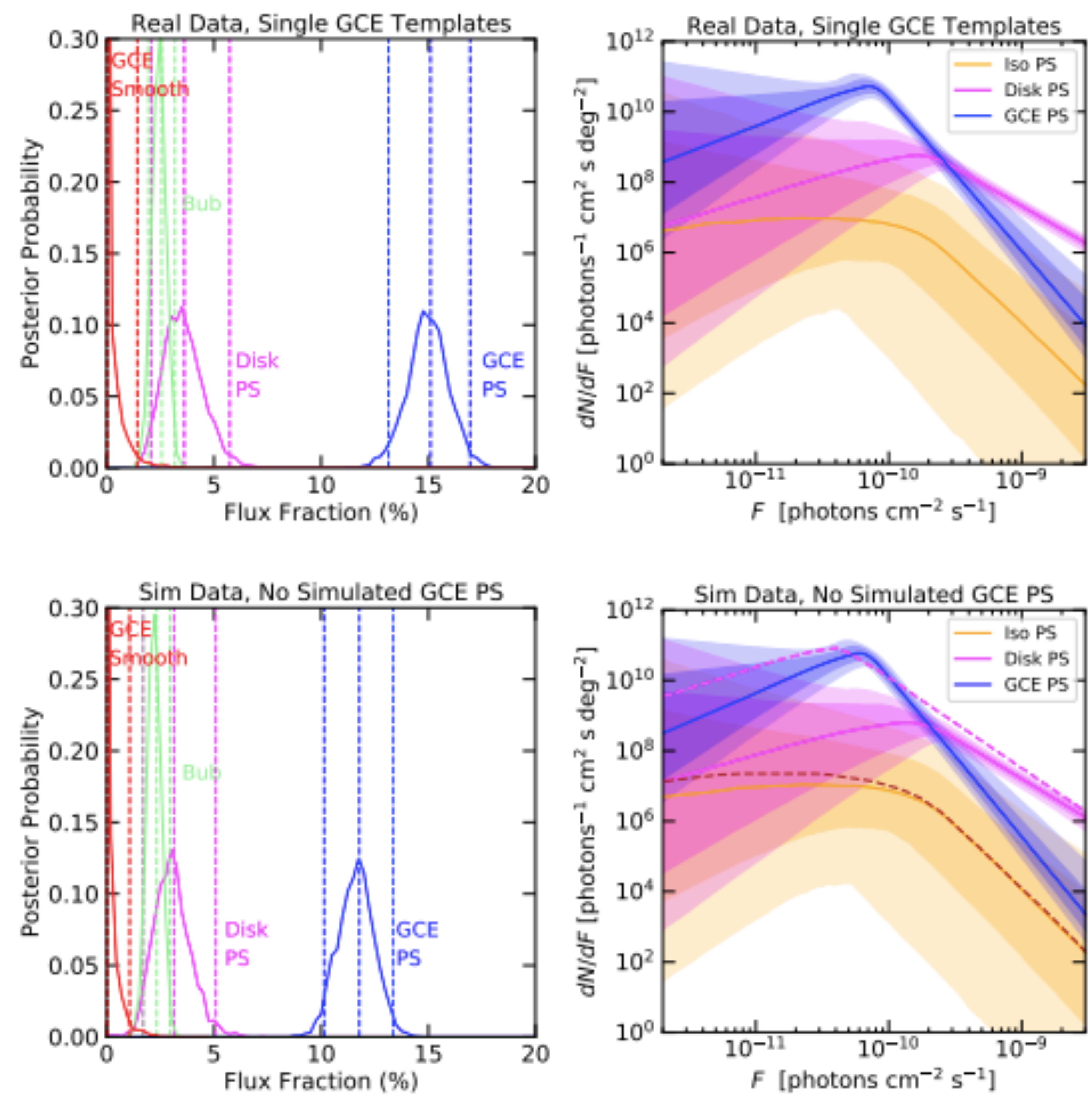
- Occurs because bright PS populations inherently have a higher error bar on flux - easier to explain a “bad" signal template





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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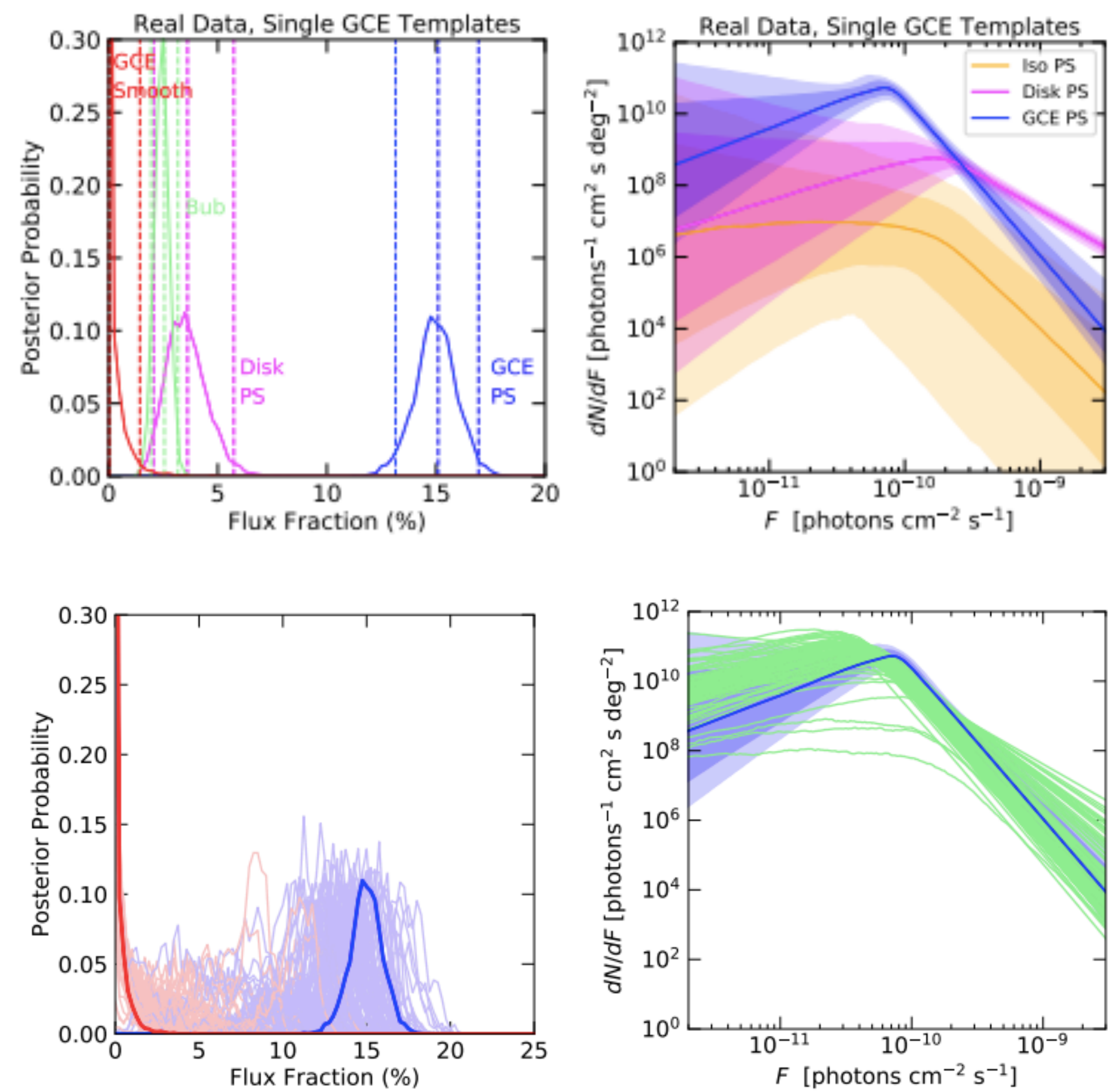
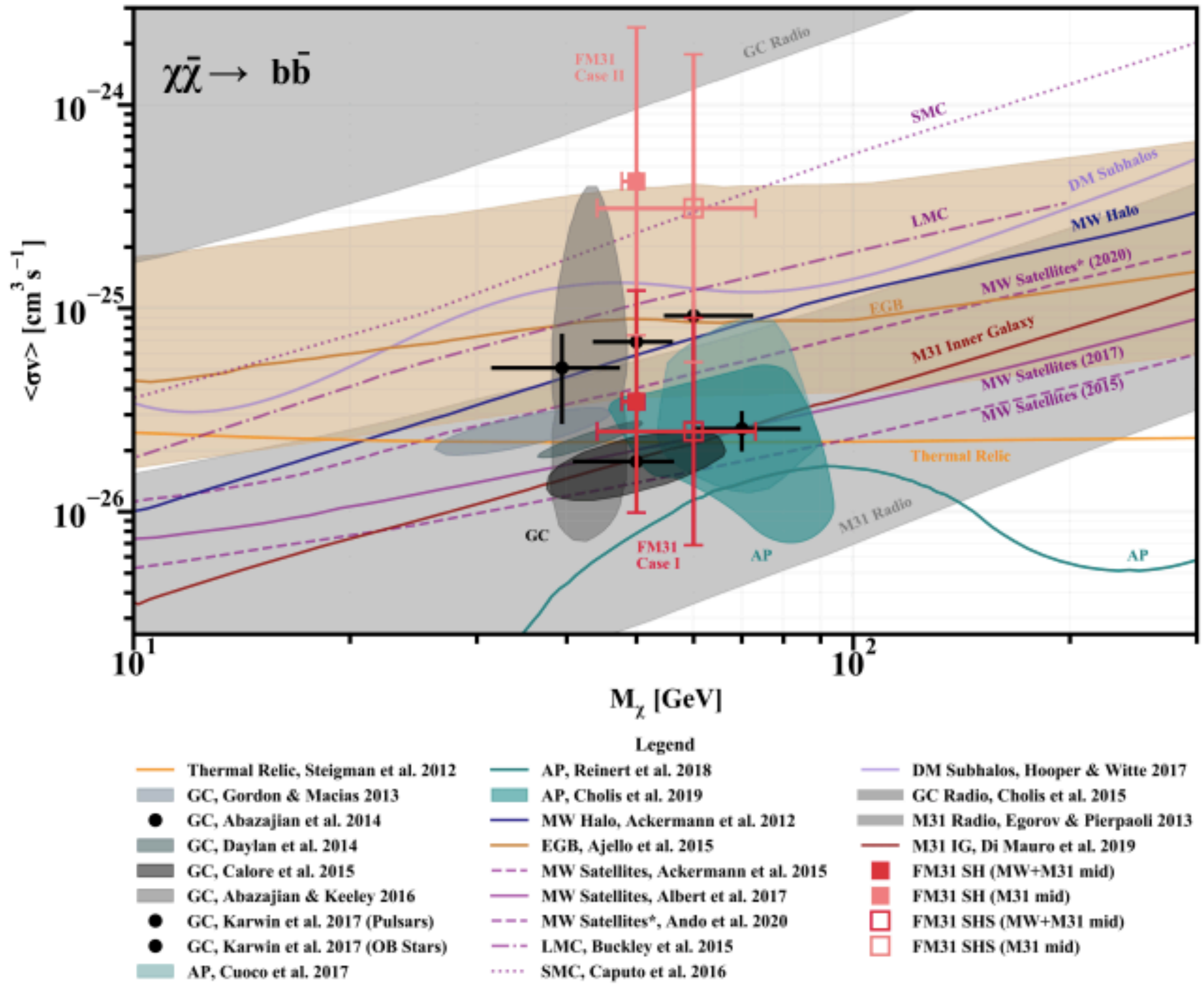


100 realizations

Possible GCE counterparts?

- Long-standing claim of consistent antiproton excess in AMS-02 data [Cui et al ’17, Cuoco et al ’17]
- But statistical significance is unclear once systematic uncertainties + correlations are taken into account [e.g. Boudaud et al ’19, Heisig et al ’20]
- 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]

- 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]

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^{27-28} 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
- 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 sources for the bulk of the GCE from the perspective of photon statistics