Current Indirect Detection Searches

Tracy Slatyer

MIT

Les Houches Summer School on Dark Matter
Lecture 5

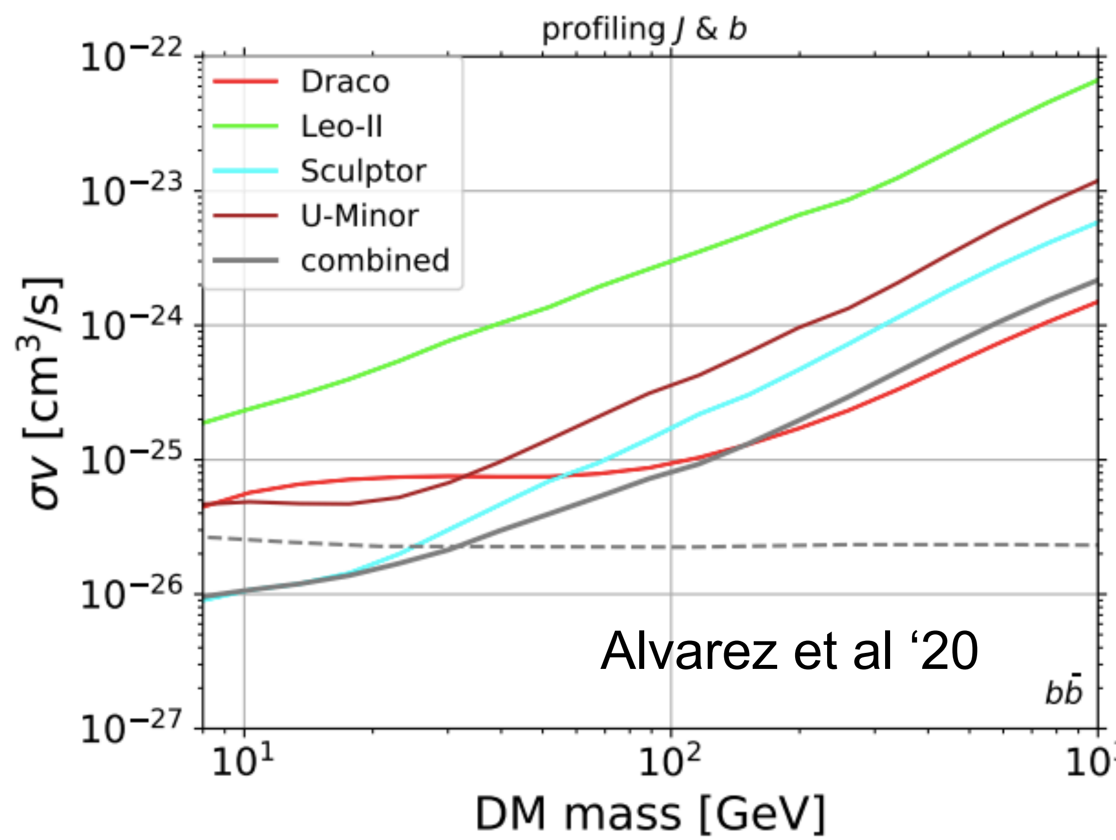
U.S. DEPARTMENT OF ENERGY | Office of Science

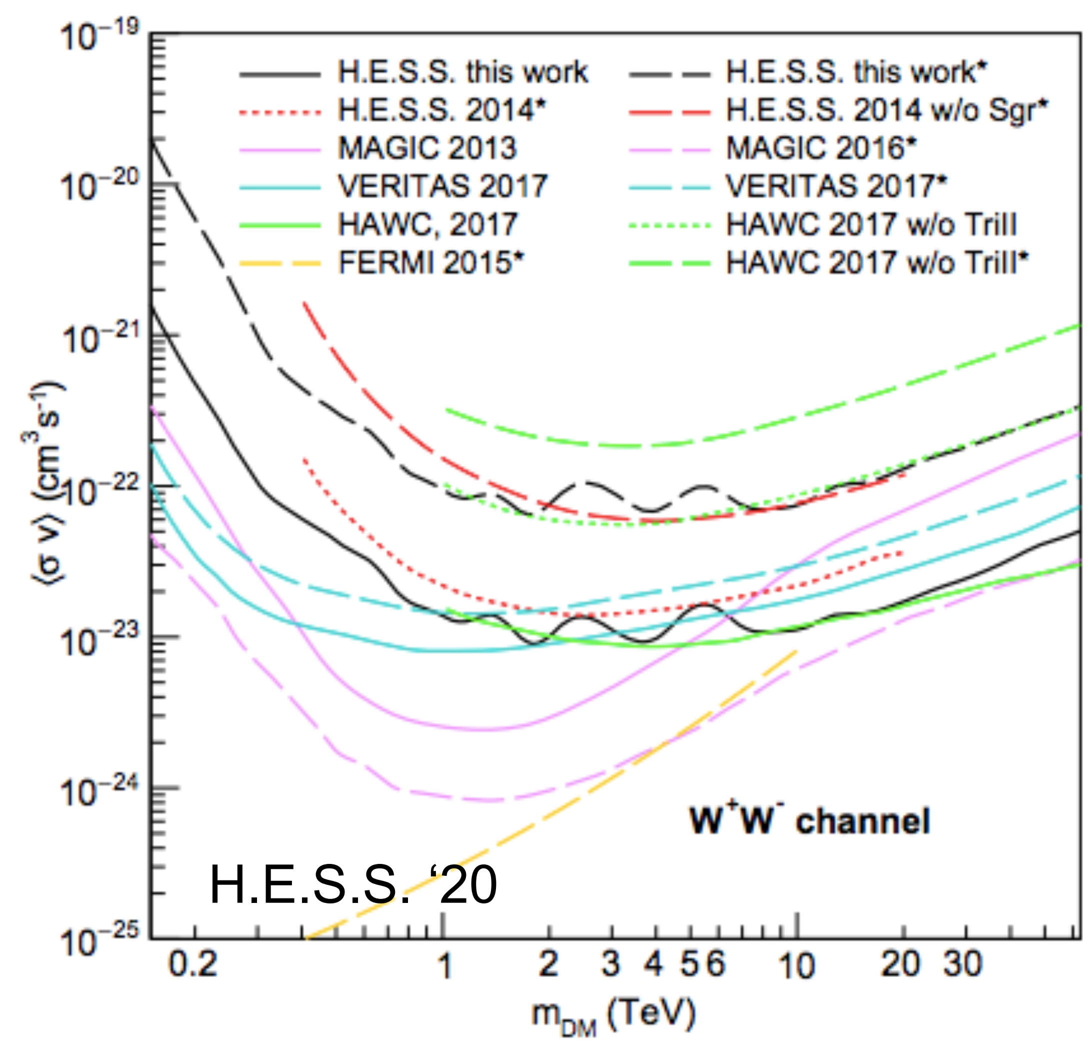
Goals for this section (recap)

- Summarize leading indirect-detection constraints for both annihilation and decay, across a broad range of DM masses and final states
- Understand the status of current anomalies/excesses

WIMP annihilation & gamma rays

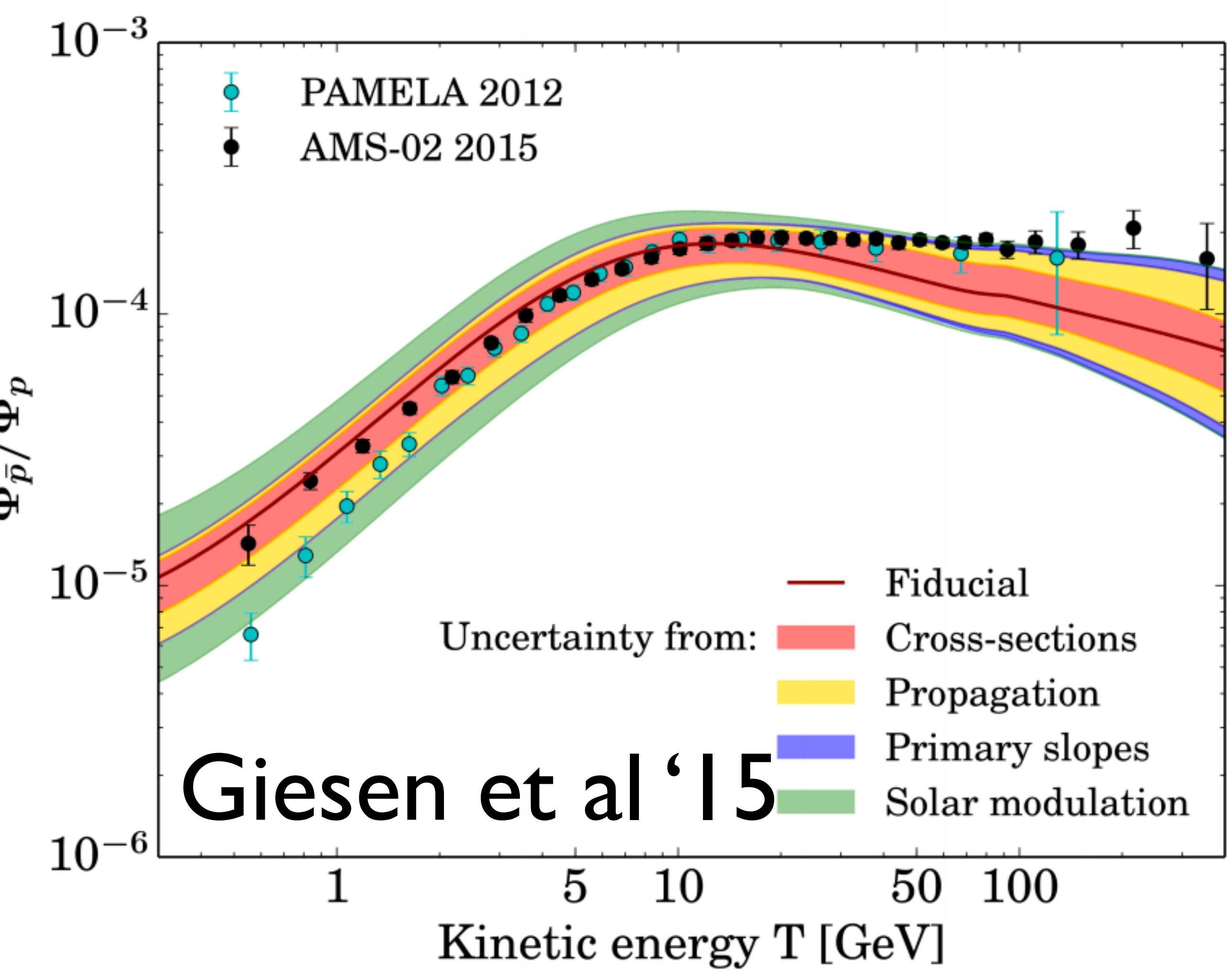
- Dwarf galaxies are low-background environments + relatively nearby (i.e. moderately large J-factors)
- Expected gamma-ray emission from baryonic physics in the dwarfs themselves is ~zero [e.g. Winter et al ‘16] (however, there are foregrounds from the Galactic line-of-sight emission)
- Uncertainties in J-factors are substantial - taking these uncertainties into account, dwarf observations constrain the thermal cross section for hadronic final states + DM masses up to a few 10s of GeV [e.g. Alvarez et al ’20]
- Limits of similar strength are obtained from studies of MW Galactic halo, galaxy groups [e.g. Chang et al ’18, Lisanti et al ’18], albeit with different systematic effects
- At higher masses, the ground-based telescopes have also set limits from dwarf galaxy observations (above the thermal relic cross section), taking over from Fermi around the TeV scale
- Nominally stronger limits can be obtained from observations of the GC, but with much greater systematic uncertainties

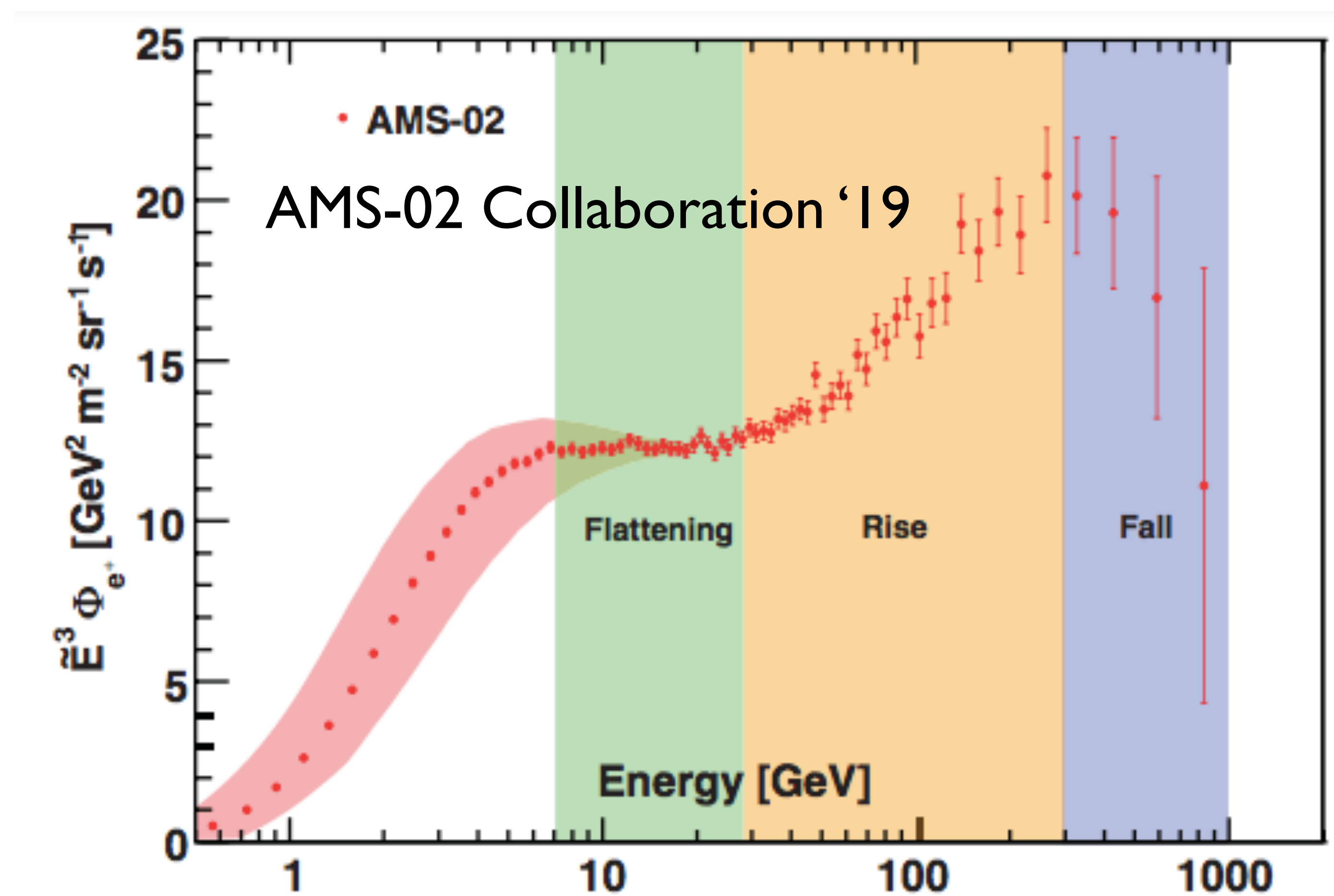




Cosmic-ray observations

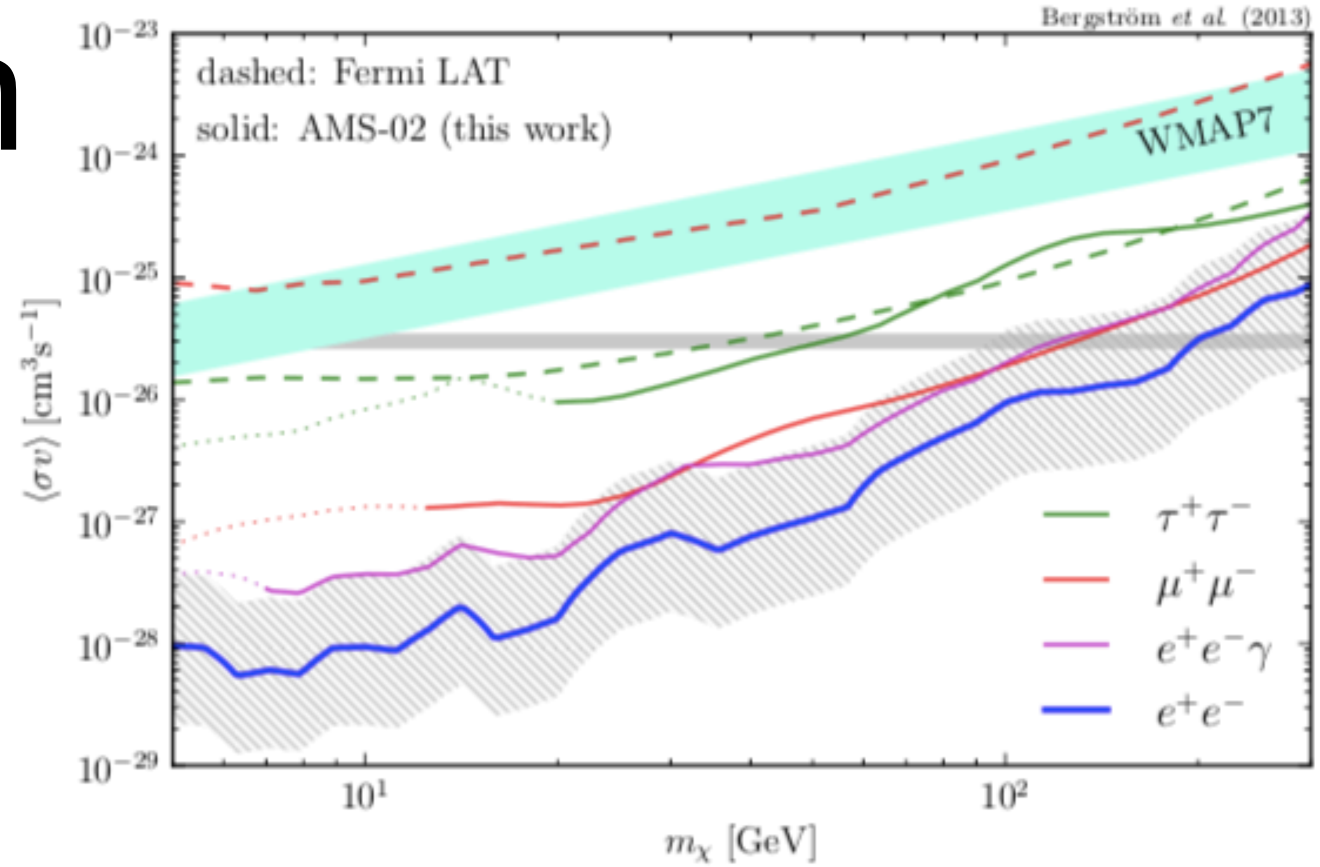
- Strong limits on thermal relic DM come from antiproton and positron measurements by AMS-02, for hadronic & leptonic final states respectively



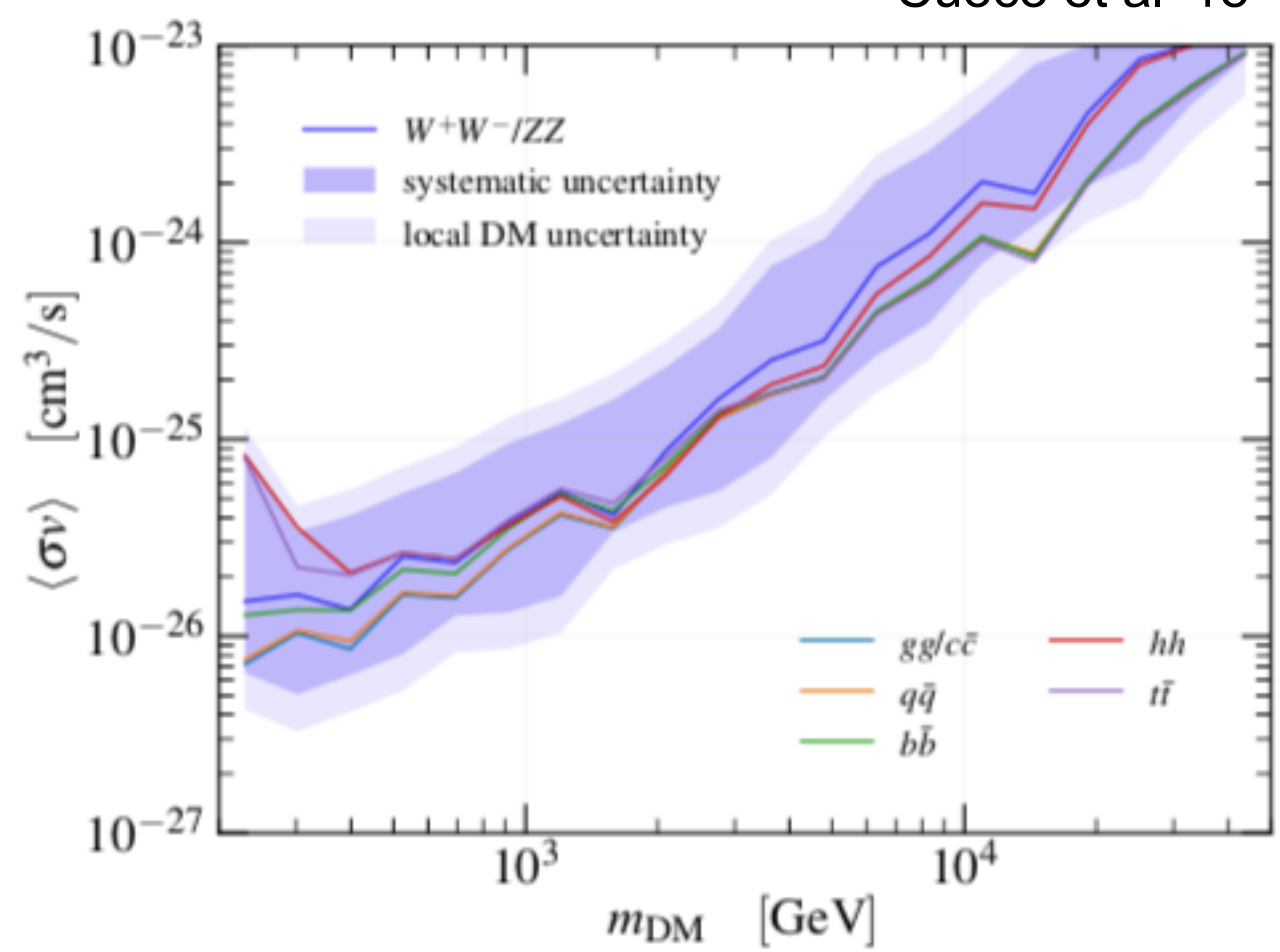


WIMP annihilation & cosmic rays

- Modeling cosmic-ray propagation leads to significant systematic uncertainties
- For production of antiprotons and heavier hadrons, production uncertainties can also be significant
- Nonetheless, CR bounds provide some of the strongest limits on DM annihilation
  - AMS-02 positron observations constrain leptonic final states + thermal relic cross sections up to O(100) GeV DM mass [see also John & Linden '21]
  - antiproton observations constrain hadronic final states + thermal relic cross sections for DM up to hundreds of GeV in mass
- Synchrotron from e+e- in the Galactic magnetic field can produce radio signals - also large systematics (in propagation + B-field), but potentially very strong limits [e.g. Chan et al '19, Regis et al '21]

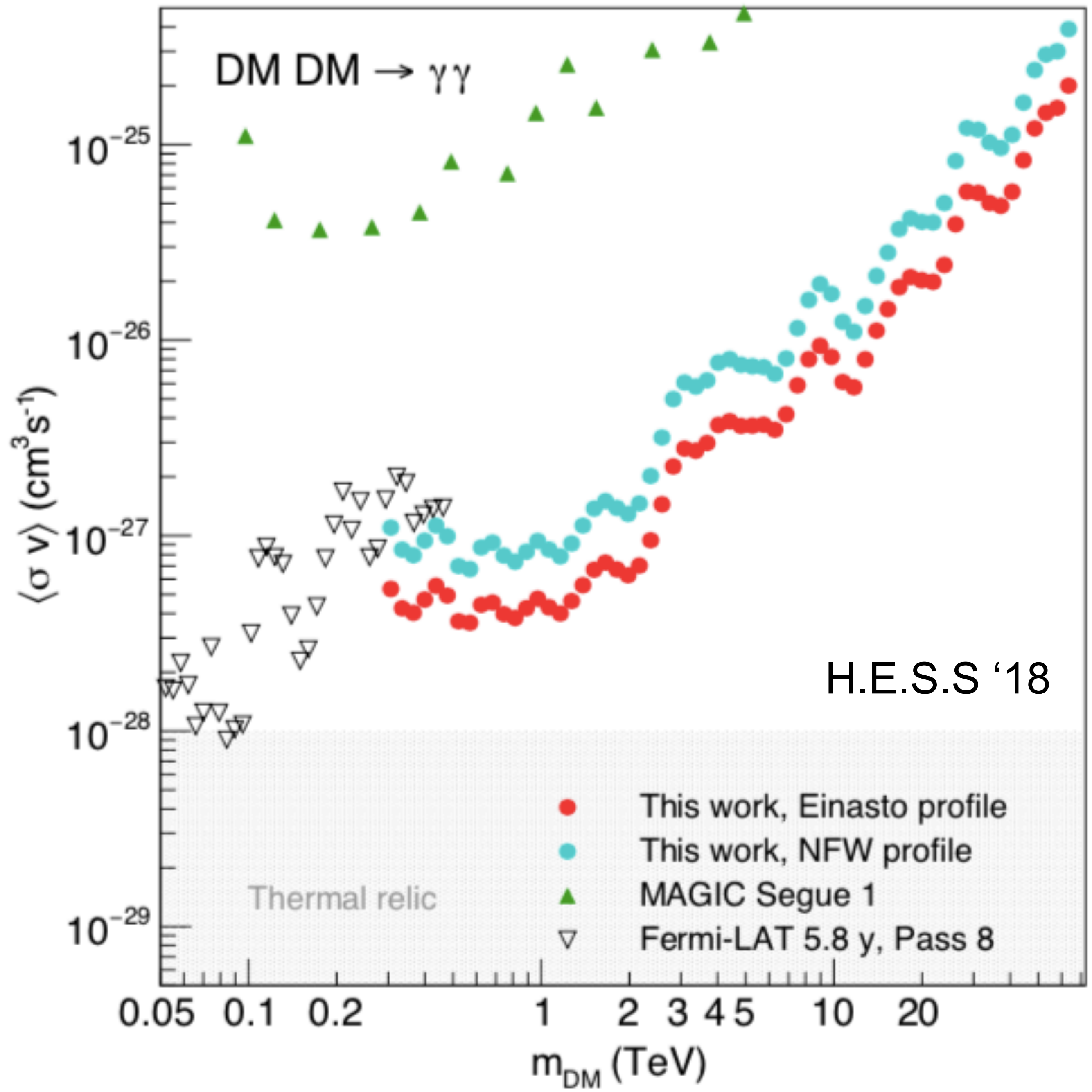


Cuoco et al '18



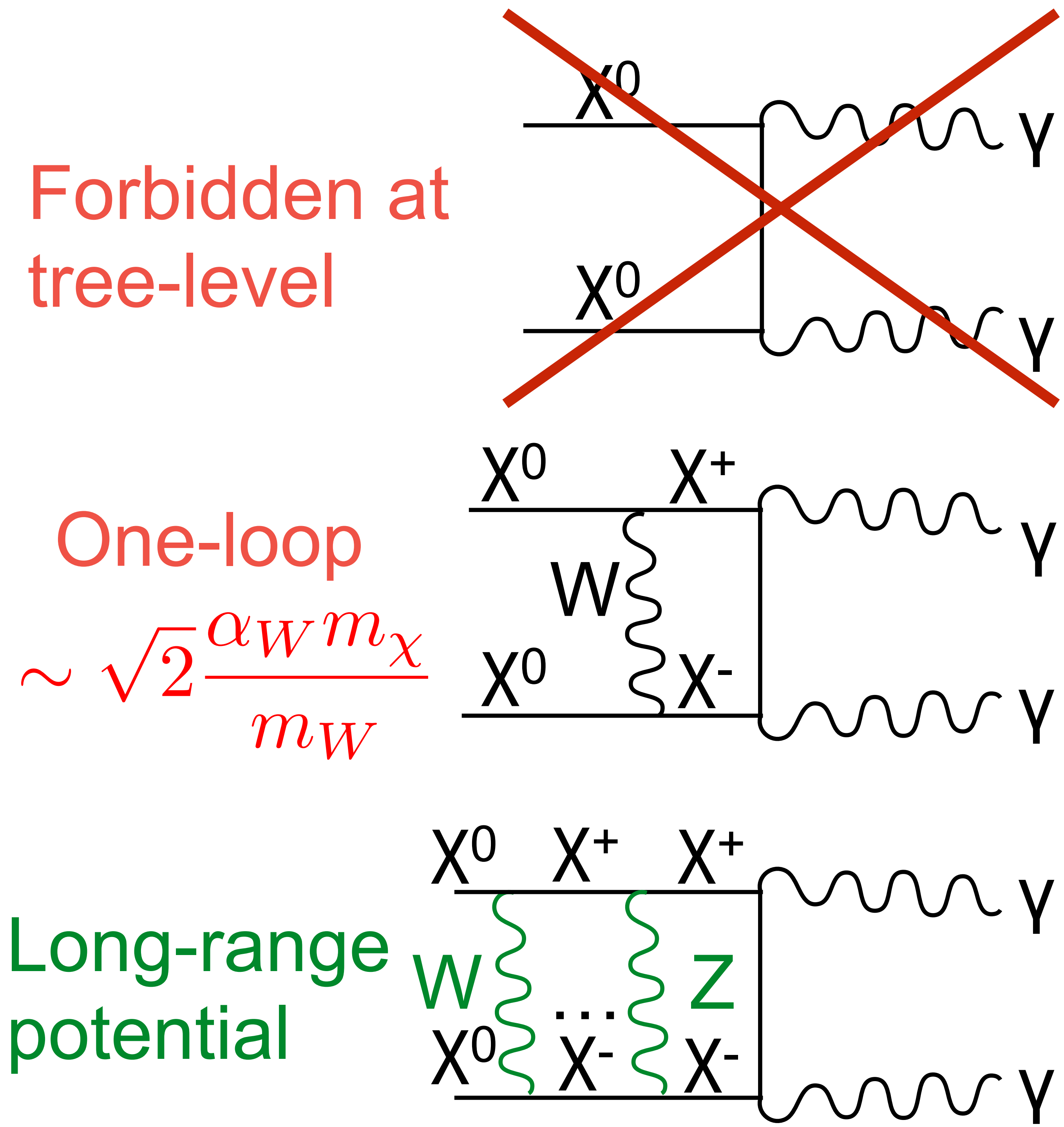
Gamma-ray line searches

- Gamma-ray spectral lines have essentially no astrophysical background
- Advantageous to look at regions of highest J-factor - i.e. the Galactic Center (GC)
- Main systematic uncertainties are in the J-factor (due to uncertainty in extrapolating DM density profile to the GC)
- Stringent limits from Fermi-LAT, H.E.S.S
- Cross sections well below thermal can be probed - but in general the expected branching ratio to line photons is small



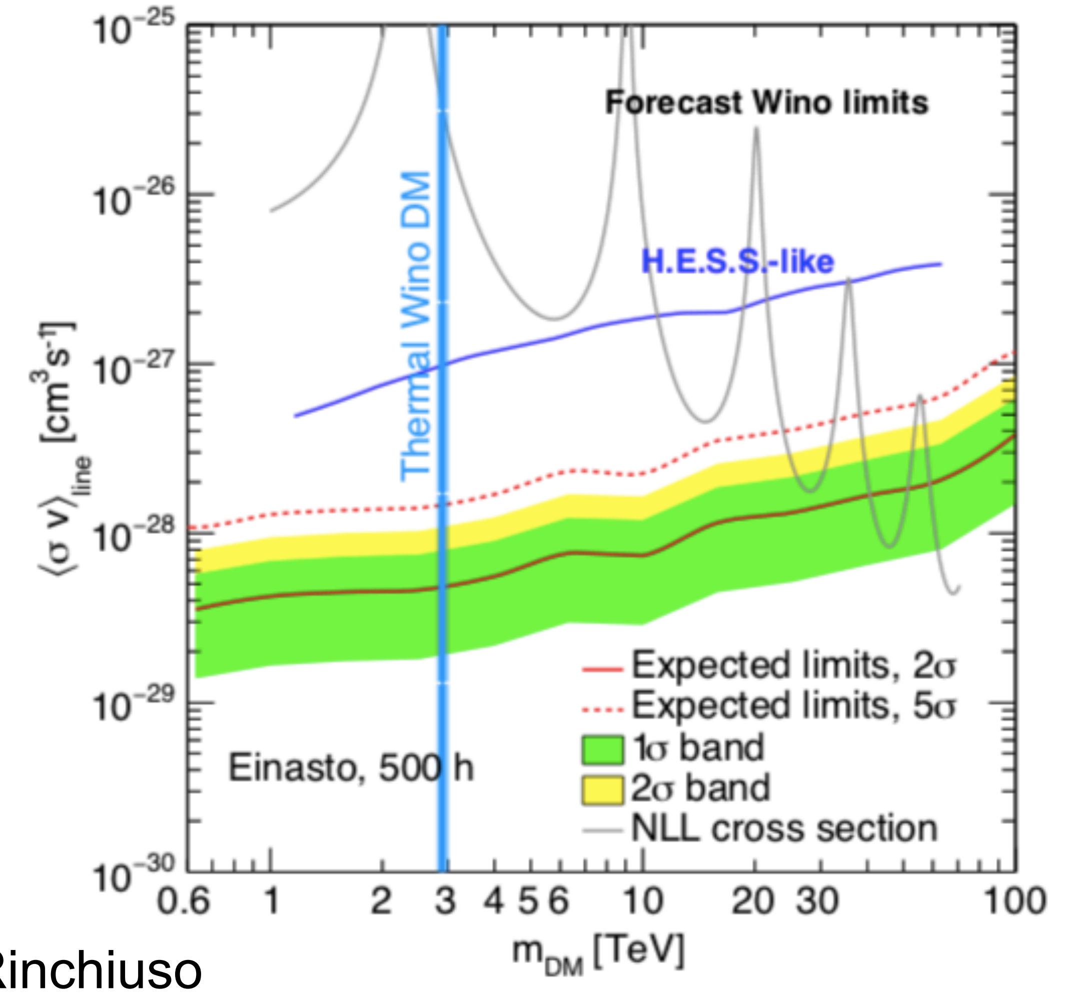
Example: wino DM

- Fermionic DM in the triplet representation of $SU(2)_L$ - interacts through weak gauge bosons
- Appears in SUSY models as the W superpartner
- Naive expectation that line signal is loop-suppressed breaks down for winos when DM mass $m_\chi > m_W/\alpha_W$.
- Long-range potential from W exchange allows virtual excitation from $\chi^0\chi^0$ to (nearly degenerate) $\chi^+\chi^-$ state. Can annihilate at tree-level to γγ, γZ, ZZ.
- General lesson: a long-range potential can affect <u>relative</u> detectability of different channels, e.g. enhancing line signals if particles in the ladder diagrams are charged.

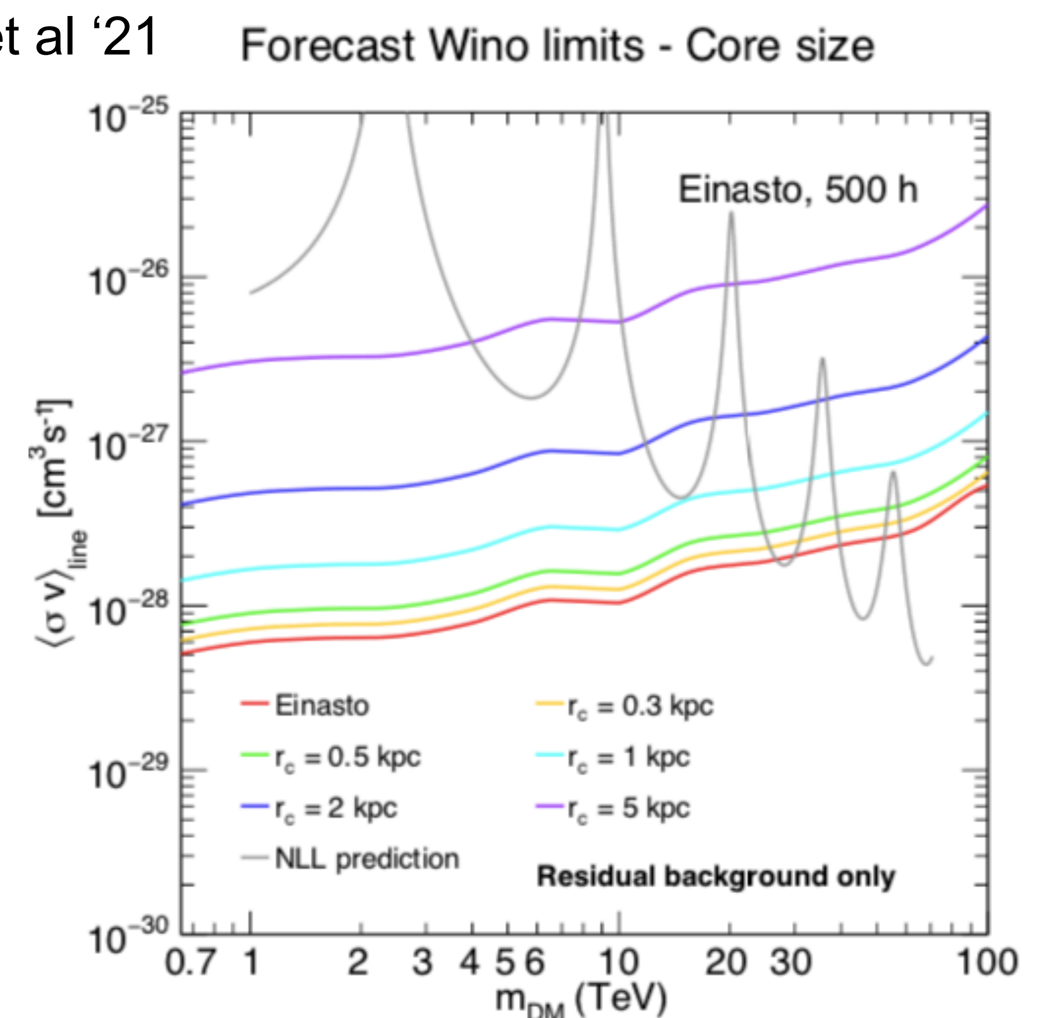


Constraints on wino DM

- As well as the enhancement from the long-range potential, precise predictions need to account for large Sudakov log corrections, full photon spectrum near the line energy [e.g. Baumgart, TRS et al ’19]
- When this is done, wino DM appears to be excluded from H.E.S.S GC observations unless the DM density is very flat toward the GC
- There are also stringent limits from antiproton searches - high DM mass, but cross-section >> thermal due to long-range potential

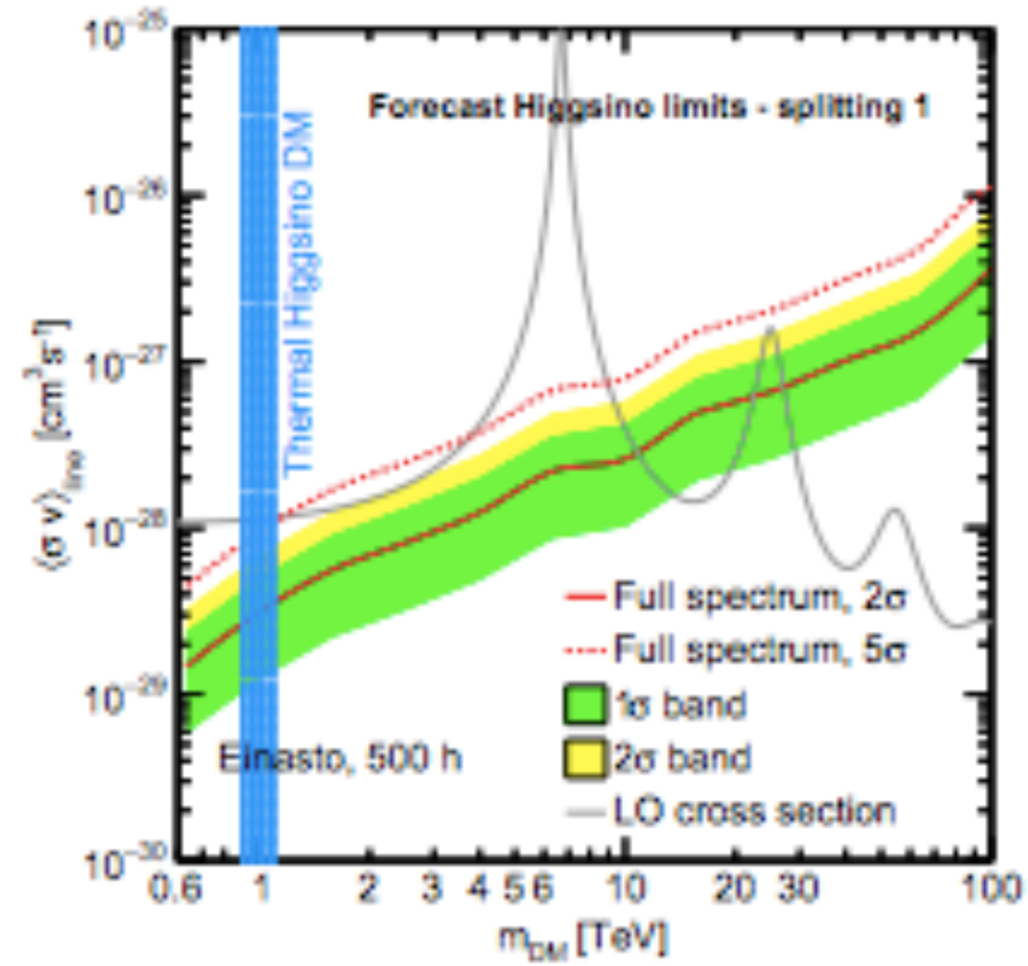


Rinchiuso et al ‘21

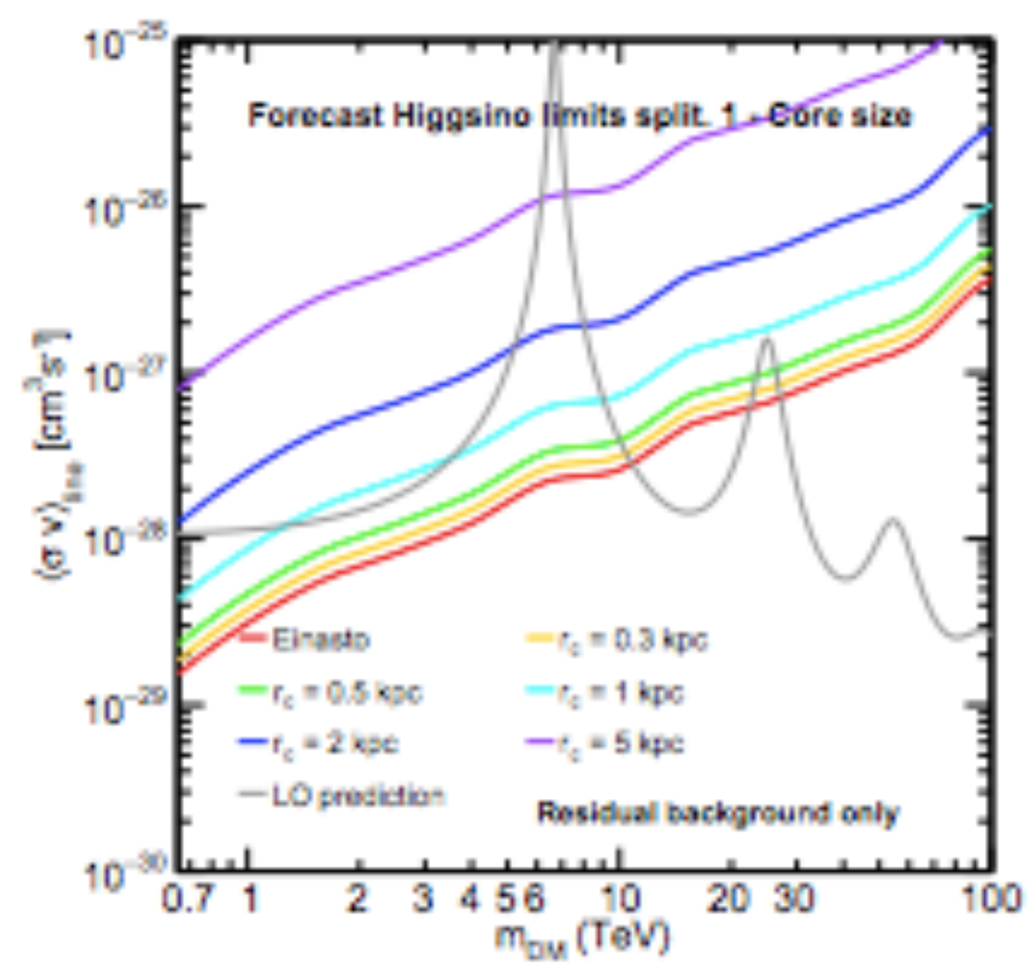


Higgsino DM

- Another example is the <u>higgsino</u> - fermionic DM transforming as a $SU(2)_W$ doublet, appears in supersymmetry as the Higgs superpartner
- Obtains the correct relic density for m_{DM} ~ 1 TeV
- Direct detection signal is below neutrino floor; undetectable with current colliders - very simple yet difficult-to-test model
- Precise theory predictions for heavy higgsinos require careful effective field theory analysis [e.g. 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]

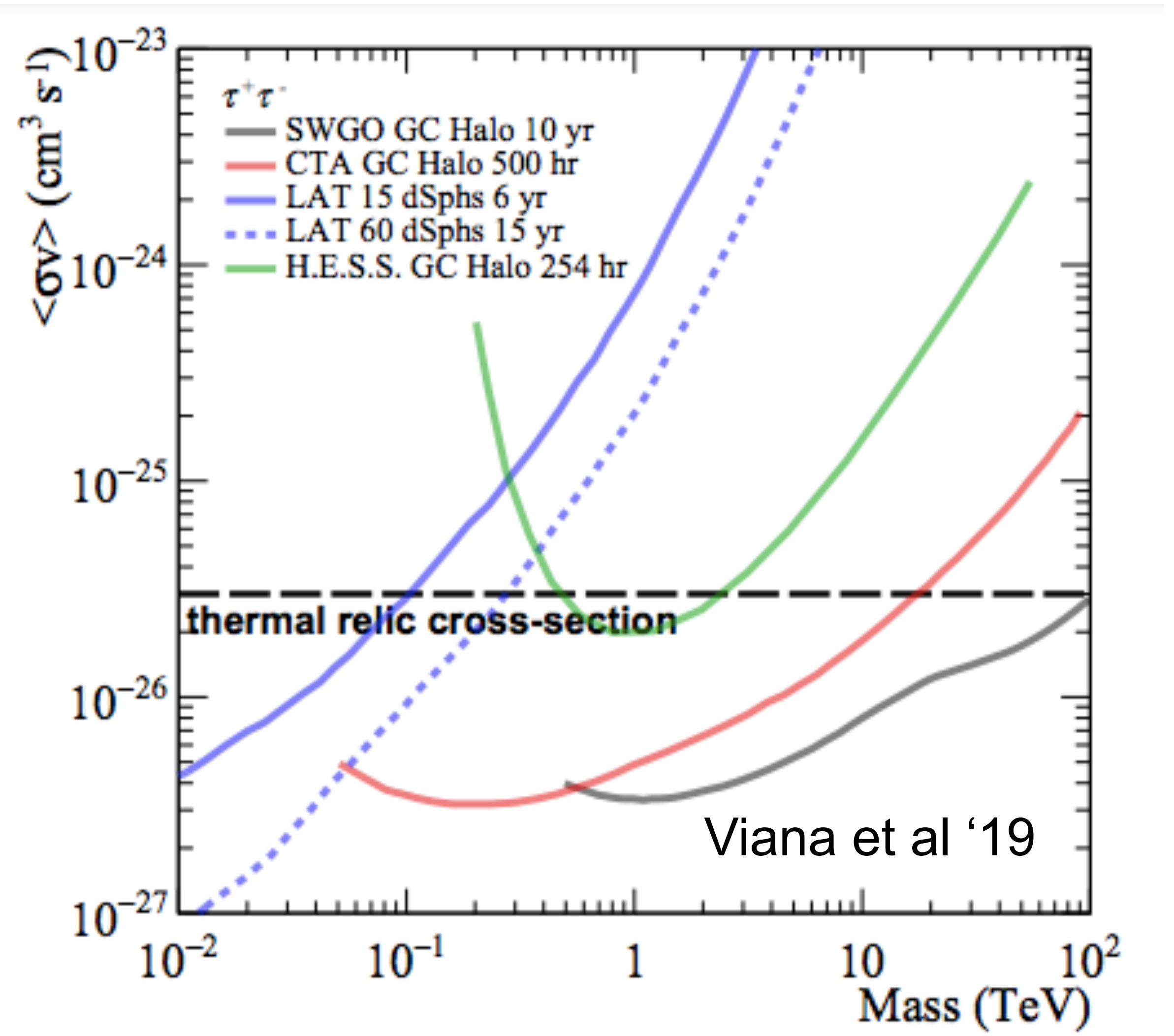


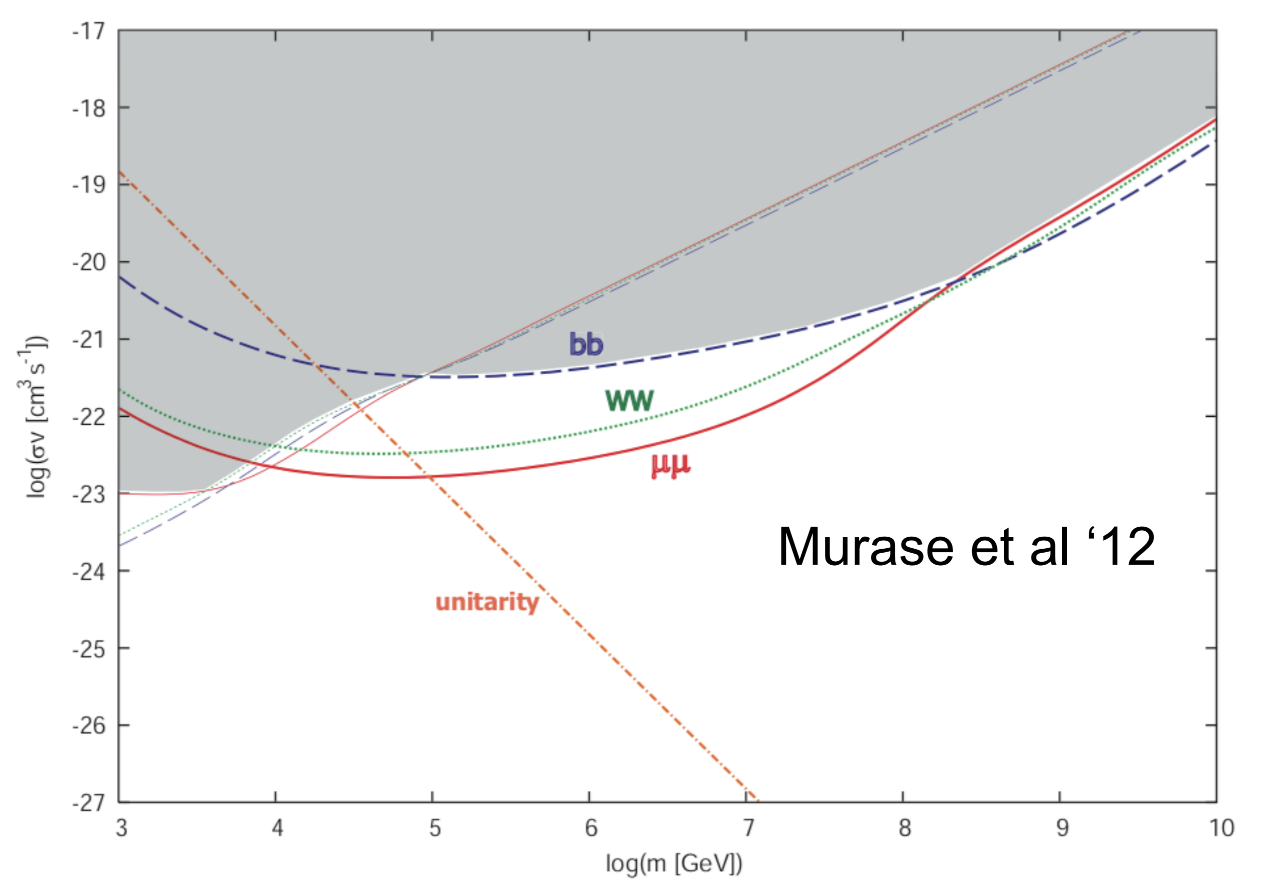
Rinchiuso, TRS et al '21



Annihilation bounds for heavier DM

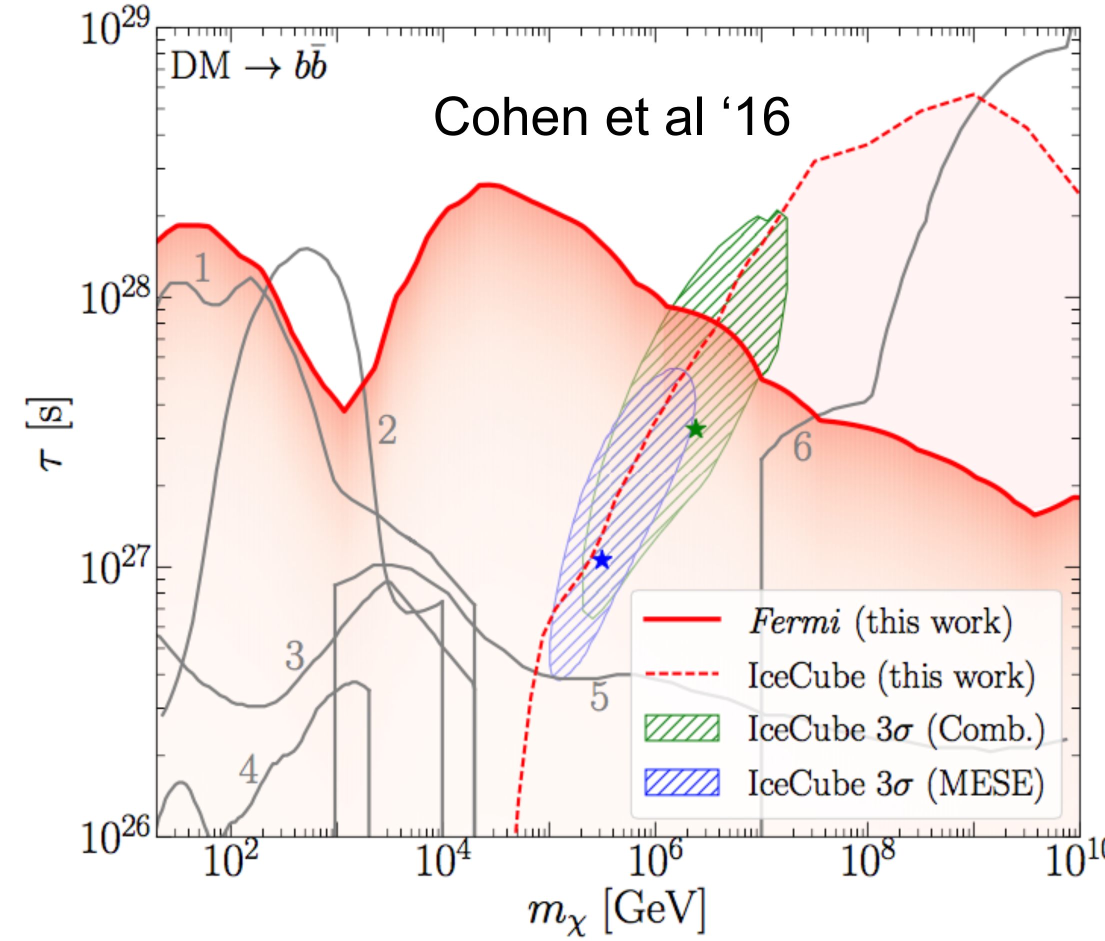
- H.E.S.S. observations of the inner Galaxy test thermal relic xsec up to ~1 TeV mass IF there is no flat-density core
- Future experiments (CTA, SWGO) have the possibility to test thermal relic xsec up to 10-100 TeV
- Limits continue to much higher masses (10^{10} GeV) - important to account for secondary cascades from particles interacting as they travel through the cosmos

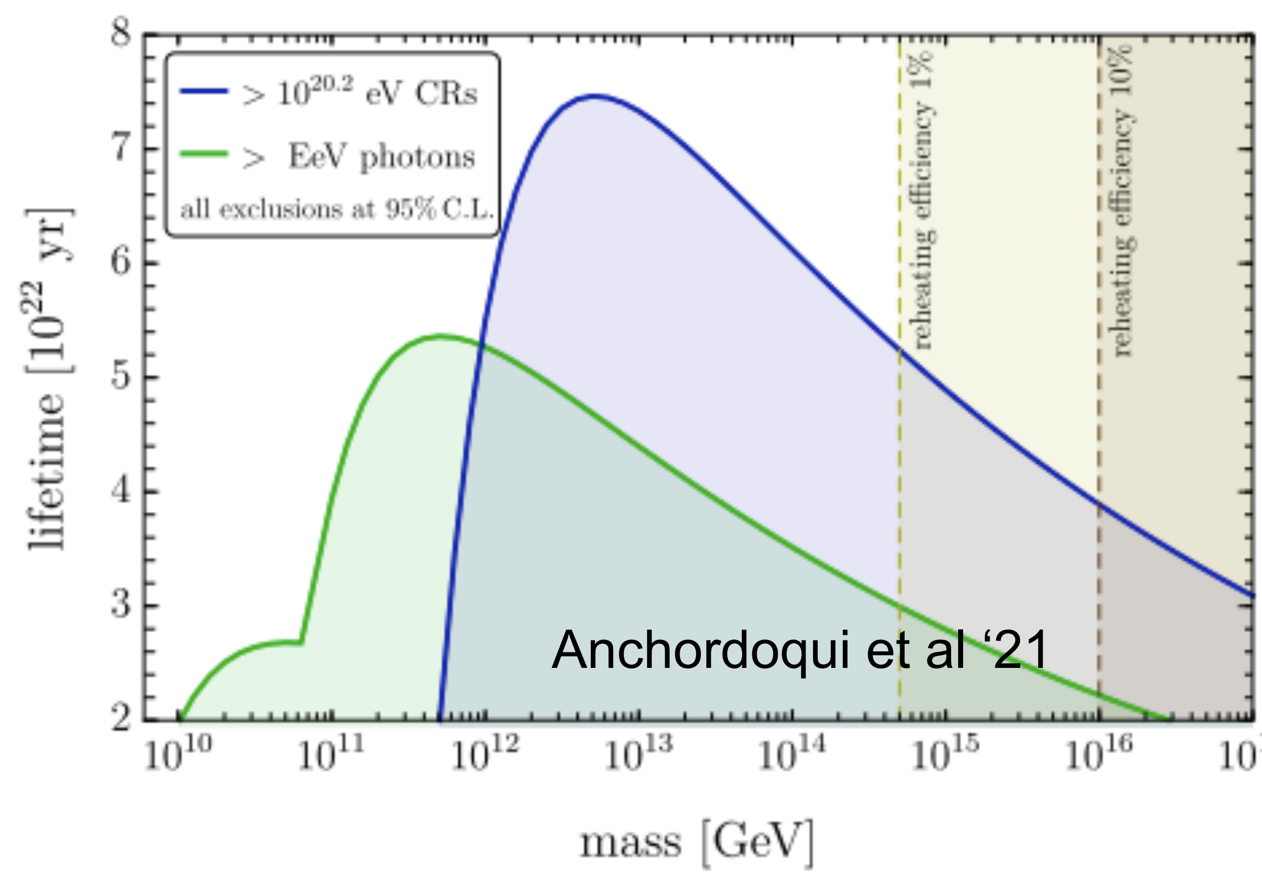




Decaying DM at WIMP+ masses

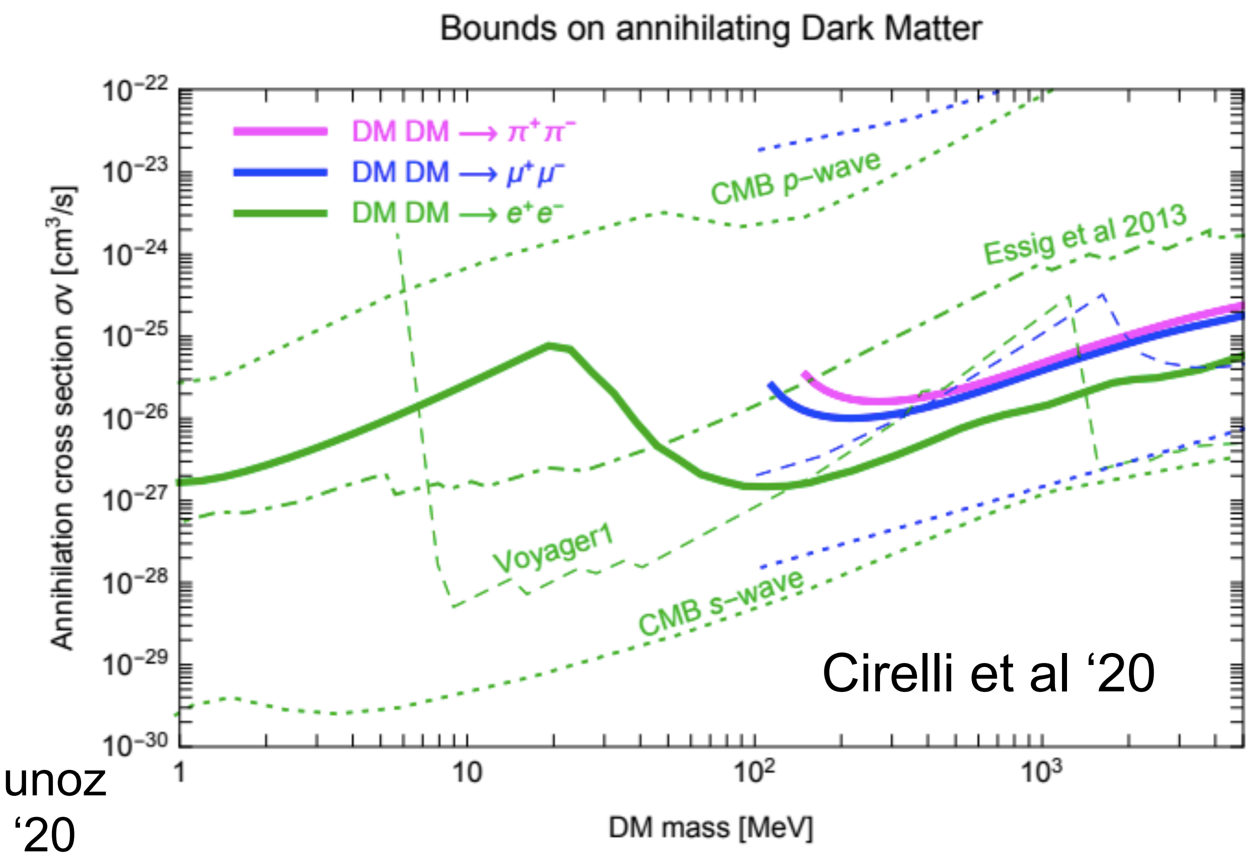
- Observations of gamma rays and (at high energies) neutrinos constrain DM decay to photons or hadronic final states to have lifetimes exceeding $10^{27\text{-}28}$ s, for masses up to 10^{10} GeV.
- Telescopes observing relatively low energies (such as Fermi) can constrain much heavier DM as they can look for the secondary particle cascade
- Observations of ultra-high-energy CRs and photons could also provide sensitivity to these heavy DM candidates [e.g. Berezinsky et al '97, Romero-Wolf et al '20, Anchordoqui et al '21]



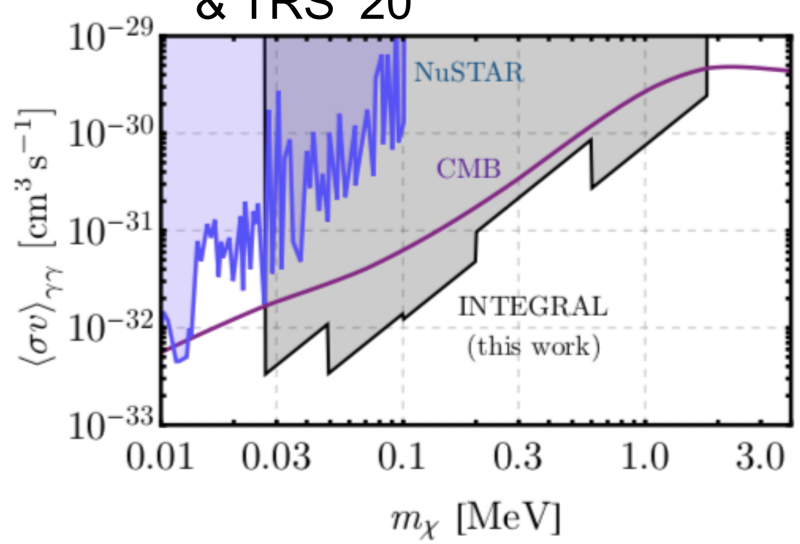


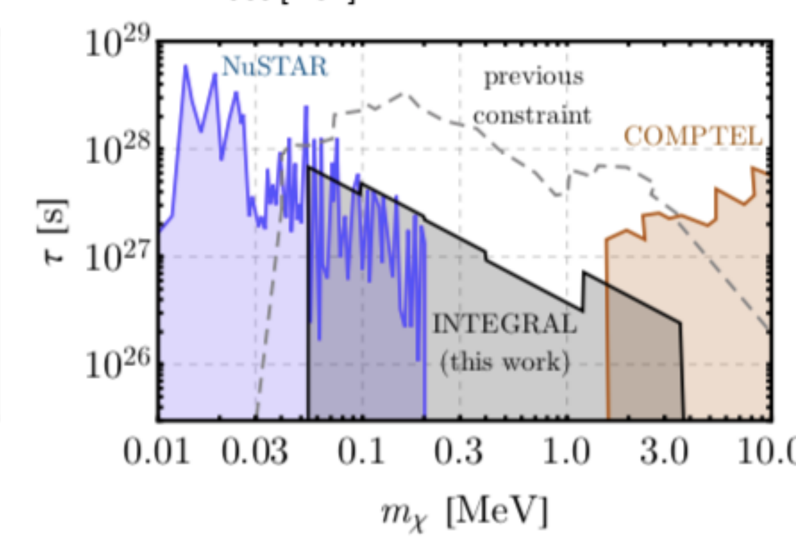
Sub-GeV DM

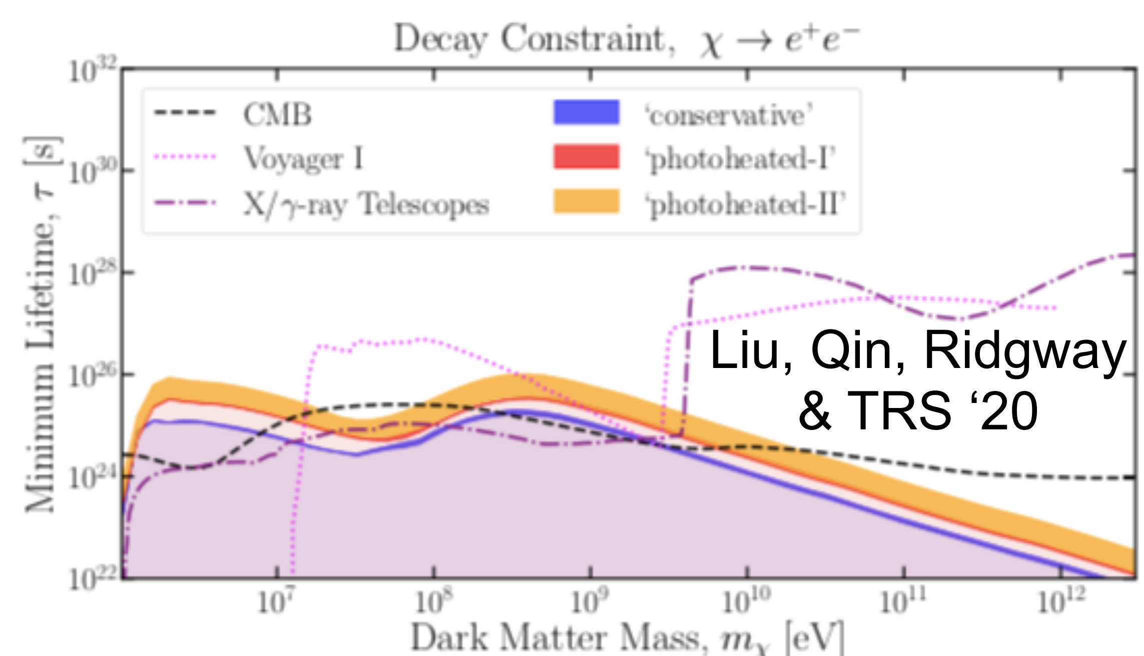
- For sub-GeV DM, often the cosmological constraints discussed earlier are the strongest bounds
- However, there are complementary limits from X-ray/gamma-ray observations, and the cosmic-ray spectrometer on Voyager 1
- Decay lifetime limits for photon-rich channels are again O($10^{27\text{-}29}$) s down to O(keV) DM
- For leptonic channels, limits can be slightly weaker, down to O(10^{25}) s, for <10 MeV DM
- s-wave thermal relic cross section ruled out across this regime unless annihilation is mostly to invisible/neutrino final states - limits on models with suppressed annihilation



Laha, Munoz & TRS '20

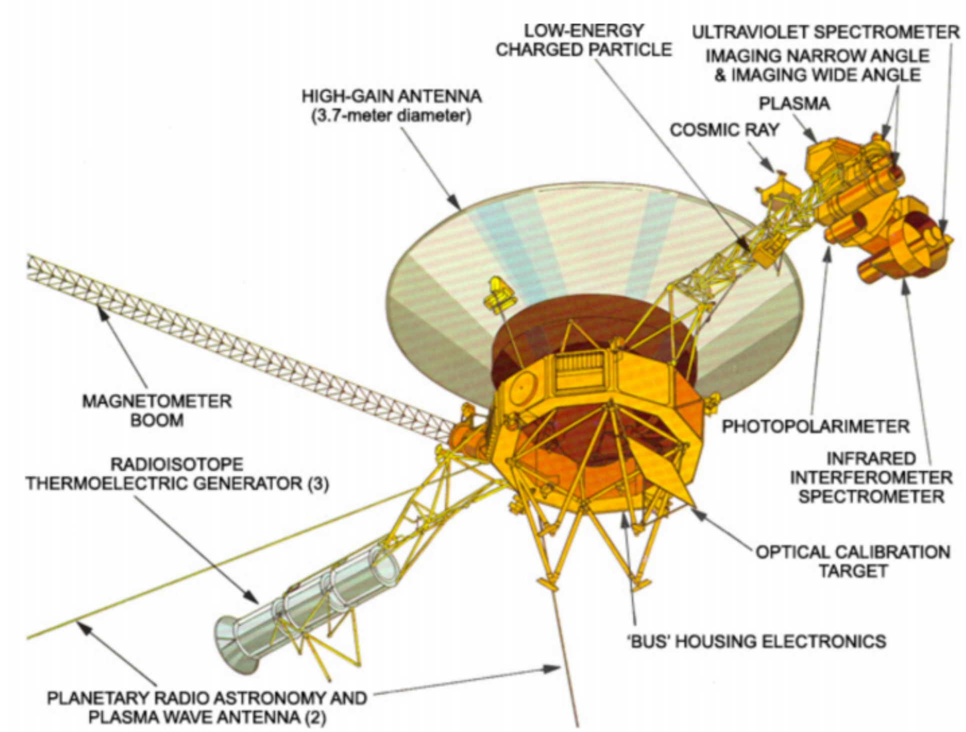


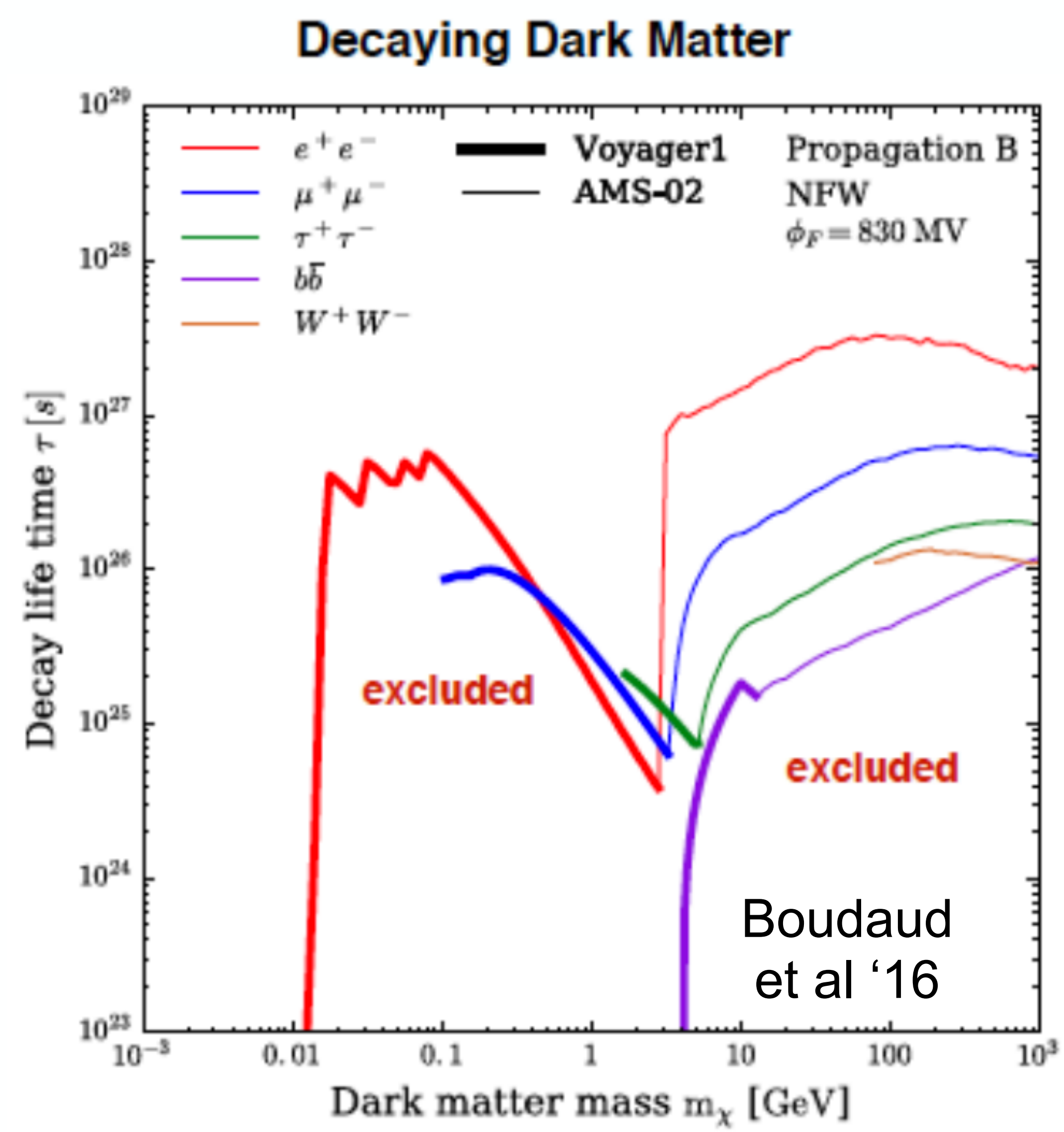




An aside: why Voyager?

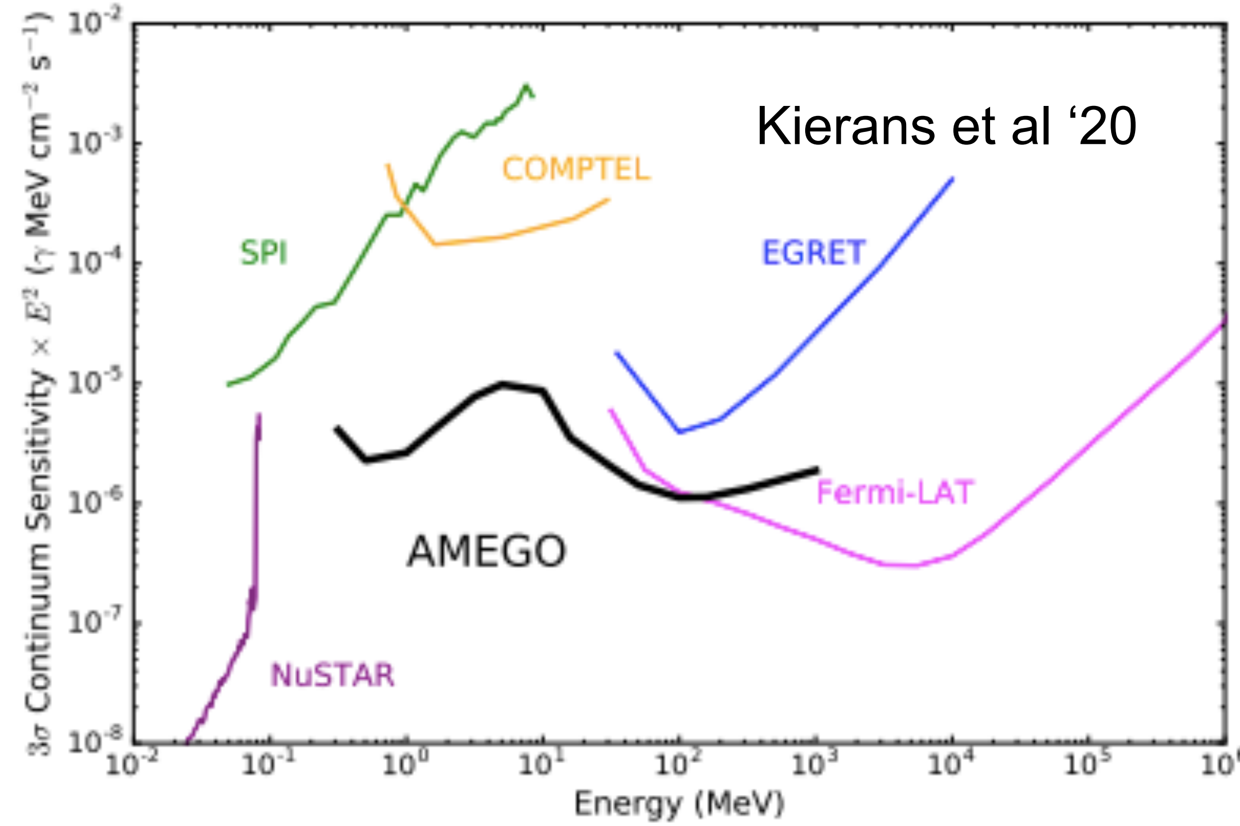
- Voyager I has a spectrometer capable of measuring low-energy cosmic rays
- Now beyond the heliopause - provides unique measurements of interstellar cosmic rays (unaffected by our Sun) and sub-GeV CRs (supppressed by solar wind inside solar system)
- Best limits on ~10 MeV - GeV DM decaying to electrons/positrons, or annihilating with velocity-suppressed annihilation.

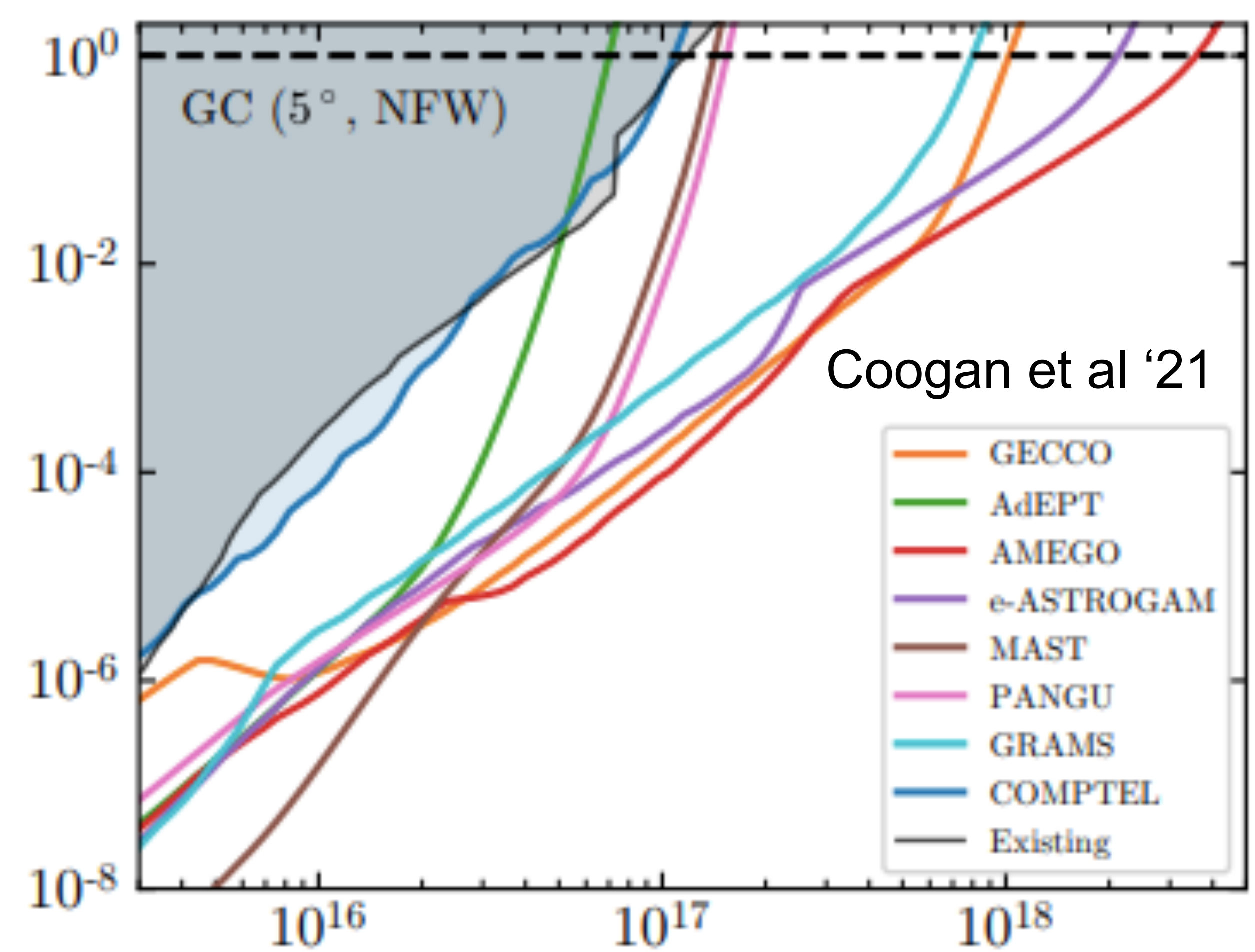




Future experiments for sub-GeV DM

- MeV-GeV band is currently the focus of a huge amount of effort. Generally requires new mediators to the Standard Model - "dark sectors".
- Classic direct detection experiments lose sensitivity for DM masses below 1-10 GeV, and accelerator-based searches often need to be redesigned
- Many new direct-detection, accelerator-based searches being proposed [e.g. Cosmic Visions report, Battaglieri et al '17].
- Indirect limits remain strong, but can be evaded if annihilation is suppressed (e.g. asymmetric DM, p-wave annihilation suppressed at low velocities, etc)
- In indirect detection, proposed missions such as AMEGO, GRAMS, GECCO, can cover the "MeV gap" in gamma-ray sensitivity - would also set relevant limits on primordial black holes as DM





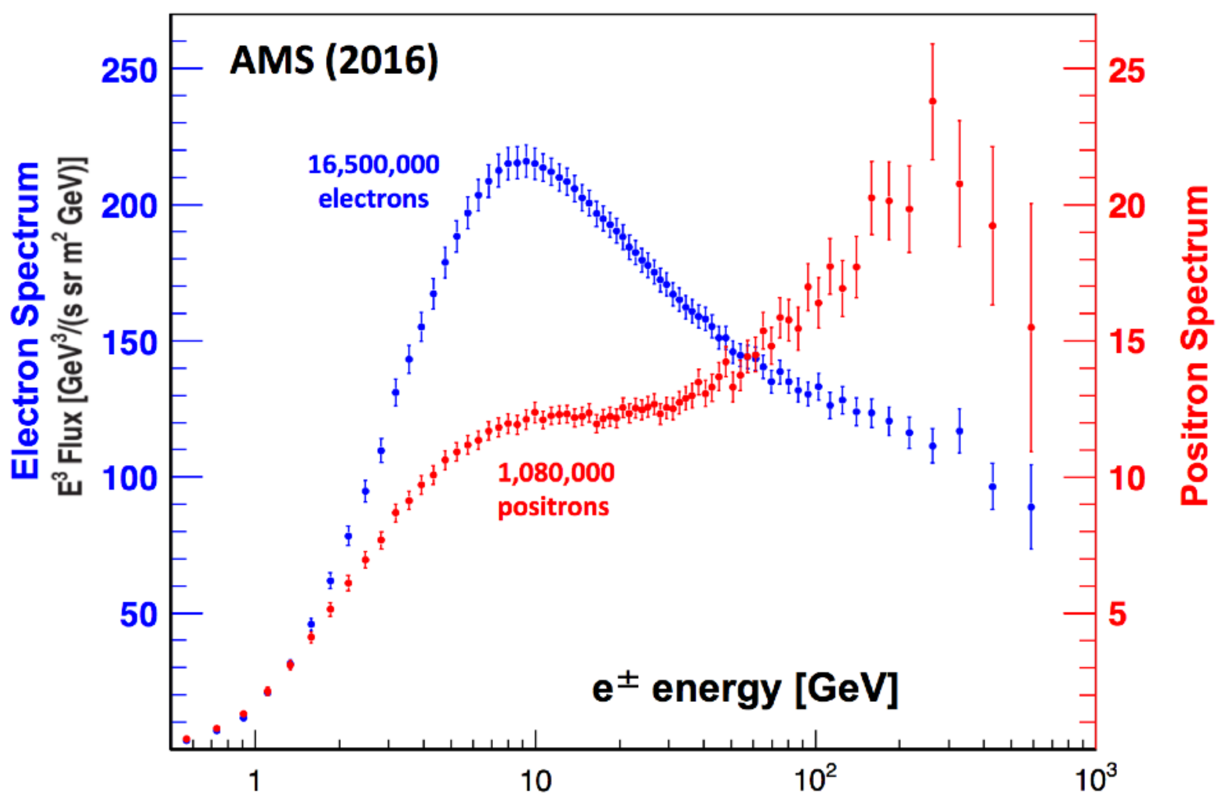
ANOMALIES

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 [Goodenough & Hooper '09, other references to be discussed later]
- 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].

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.
  - Positron background expected to fall faster than electron background - suggests some new primary source of positrons



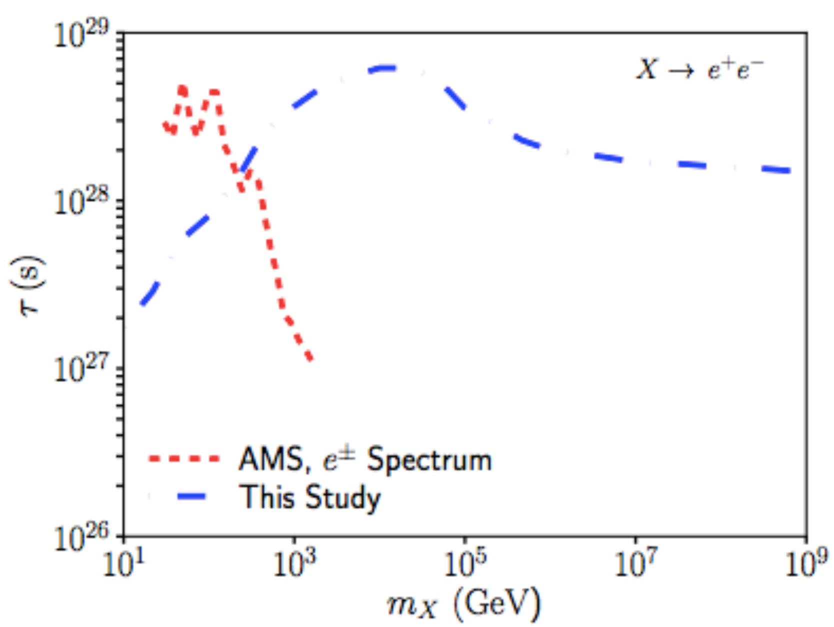
Sam Ting, 8 December 2016, CERN colloquium

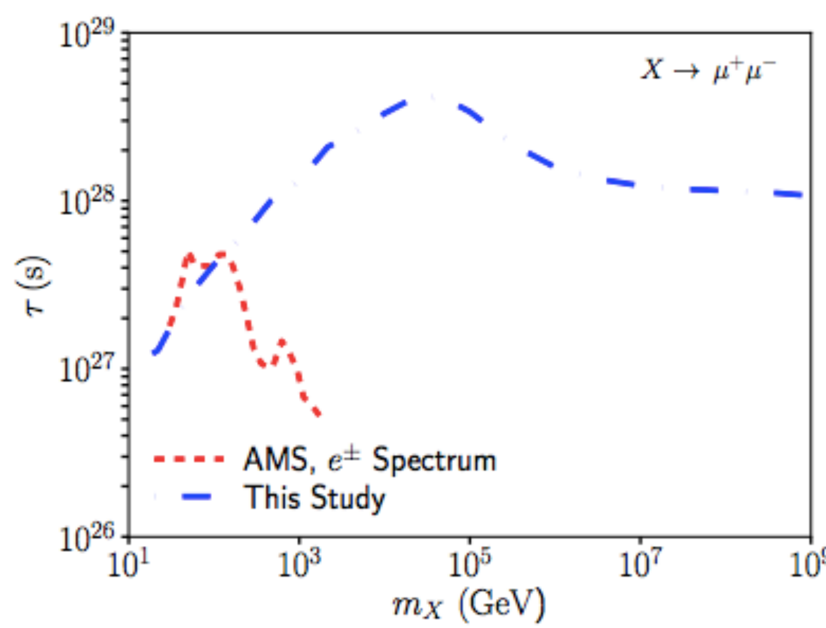
- DM explanation: TeV-scale DM annihilating or decaying dominantly into leptons
  - if annihilation, requires rate several orders of magnitude above thermal - can be natural due to e.g. Sommerfeld enhancement
  - need to suppress annihilation to quarks to avoid overproducing antiprotons - can be natural if DM is leptophilic or annihilates into sub-GeV mediators that then decay

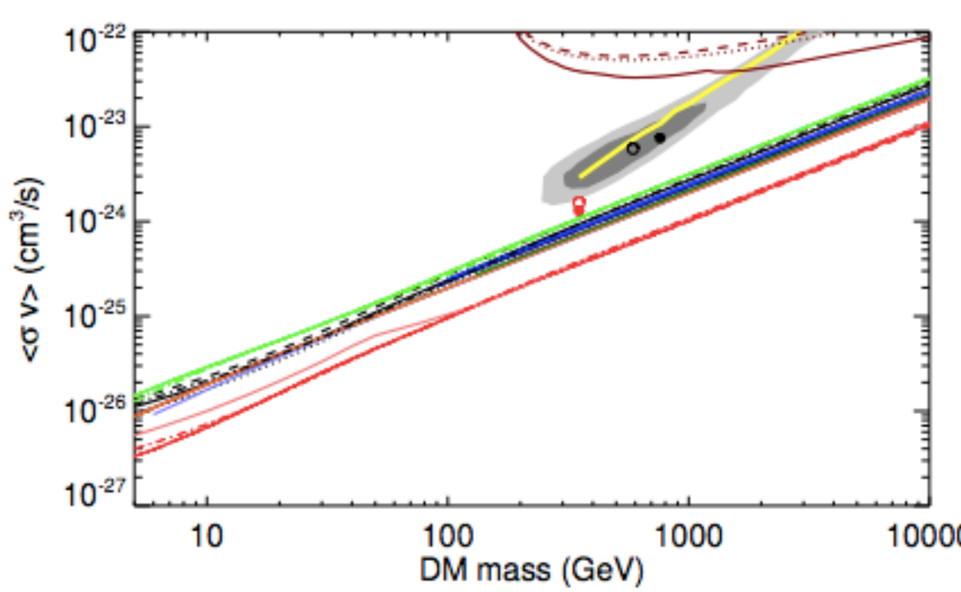
Challenges for the DM interpretation

- DM annihilation interpretation is challenging due to null results in CMB searches + gamma-ray searches - needs extra ingredients (e.g. large DM overdensity, either nearby or combined with annihilation to a long-lived particle, Kim et al 1702.02944 has an example)

- DM decay interpretation may be easier to reconcile, but tight constraints from galaxy clusters, extragalactic gamma-ray background [e.g. Blanco & Hooper '19]

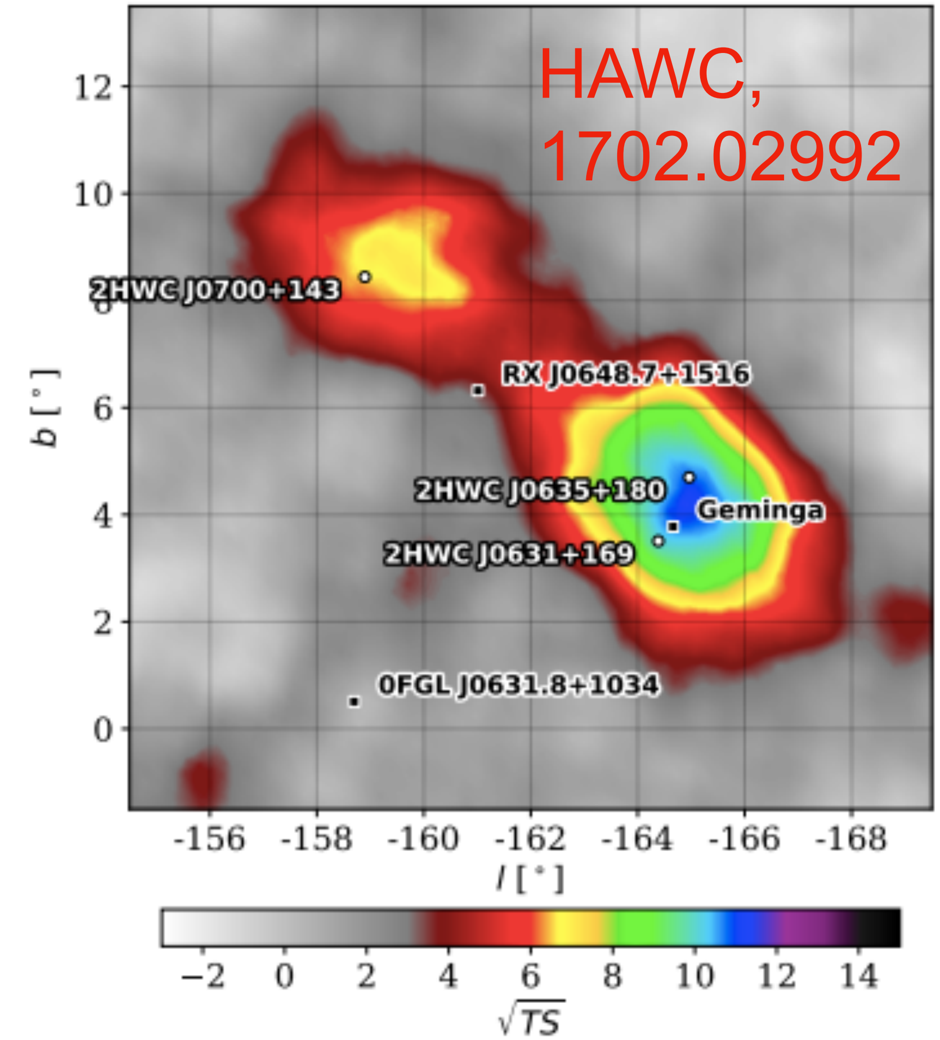


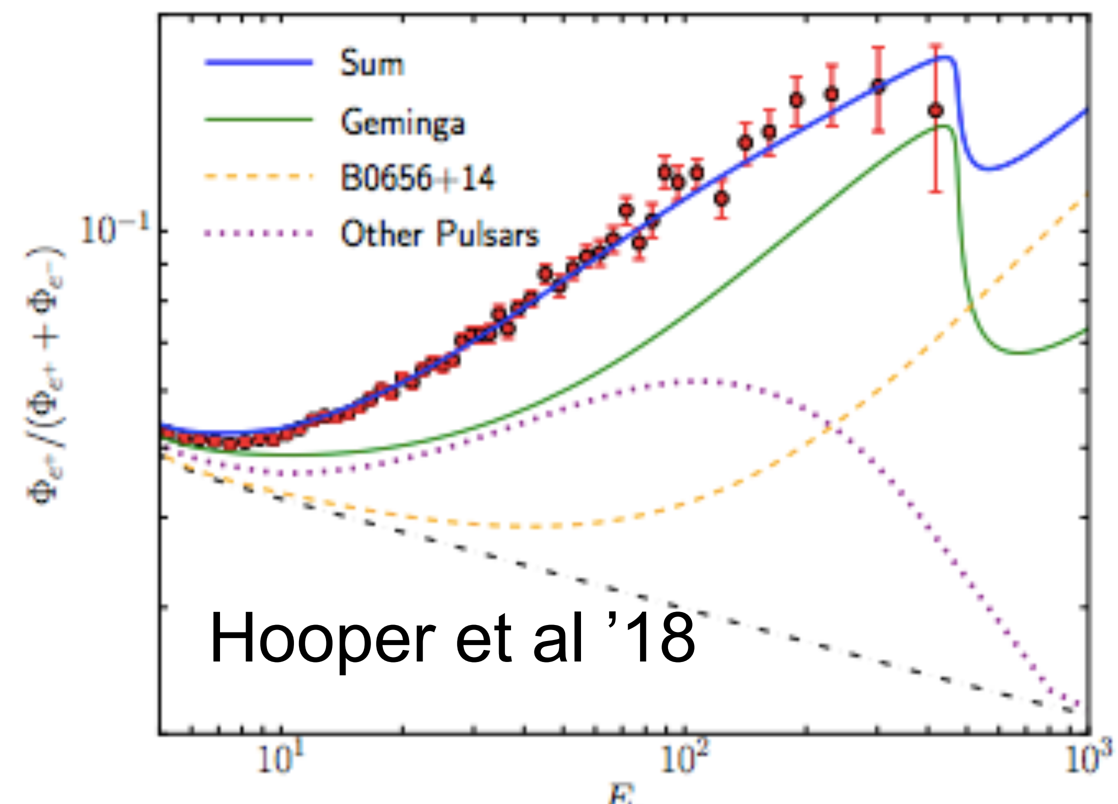




TeV pulsar halos

- Quite surprisingly, in 2017 the HAWC gamma-ray telescope discovered “TeV halos” of gamma-rays around nearby pulsars (Geminga, Monogem) - since IDed around other pulsars
- Surprising because the expectation is e^+e^- from the pulsars would spread out too far for HAWC to detect the emission
- Hypothesis is now that pulsars are producing TeV+ e^+e^- but diffusion around the pulsars is impeded [see e.g. Evoli et al ’18 for a model]
- Implies large fraction of spin-down power goes into e^+e^-, and no problem producing TeV+ e^+e^-

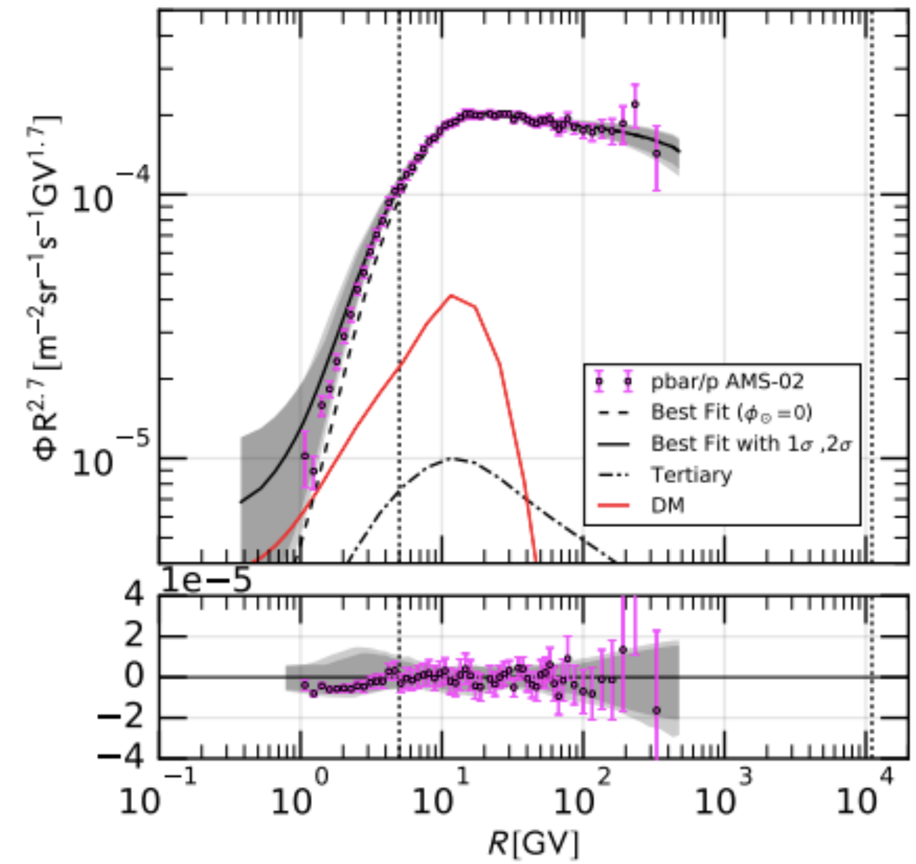


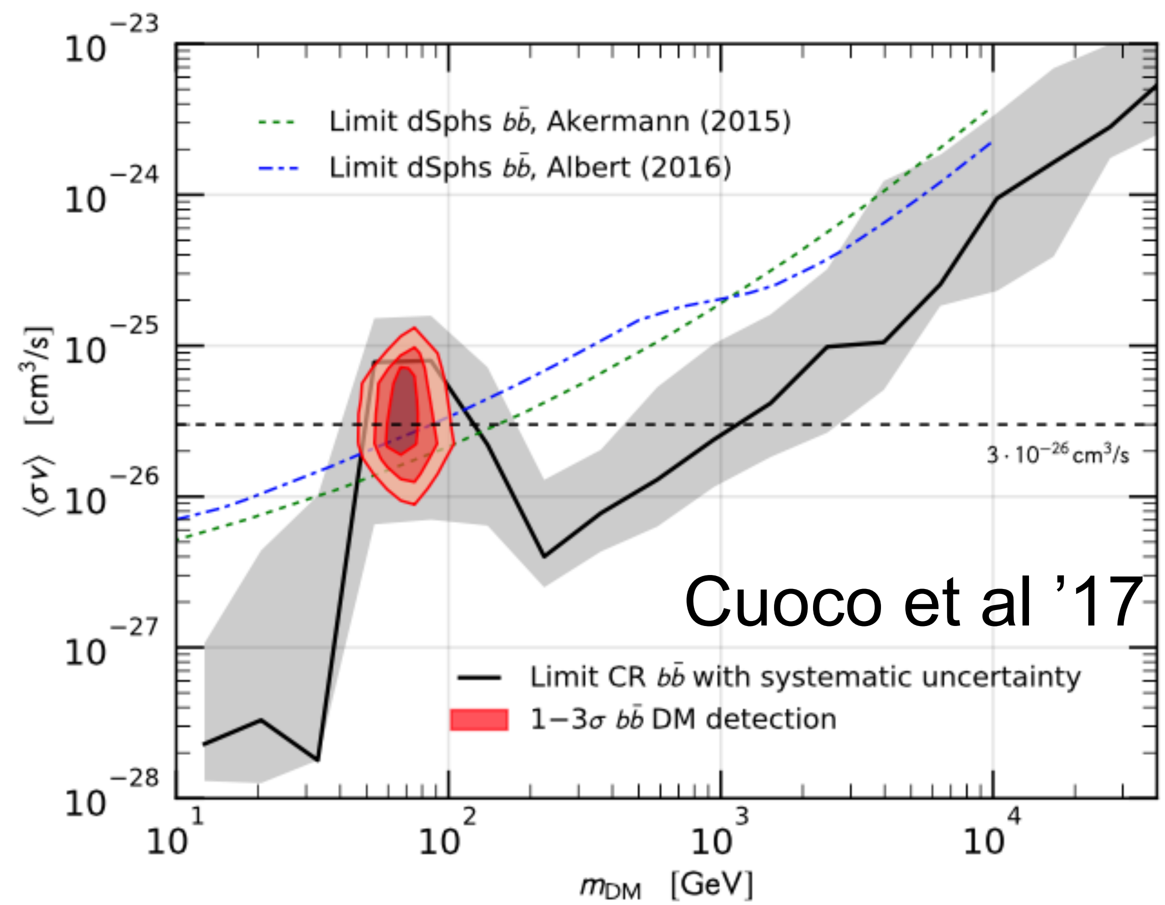


Note: this is a plausible model, not an a priori prediction

AMS-02 low-energy antiproton bump?

- Two independent groups claimed in 2017 that AMS-02 data reveal a modestly significant “bump” in ~10-20 GeV antiprotons [Cui et al ’17, Cuoco et al ’17]
- Corresponds to a ~thermal cross section and ~40-130 GeV DM mass.
- Not visually obvious and highly significant like positron signal - could be just a statistical fluctuation
- But interesting parameter space - would align well with Galactic Center Excess



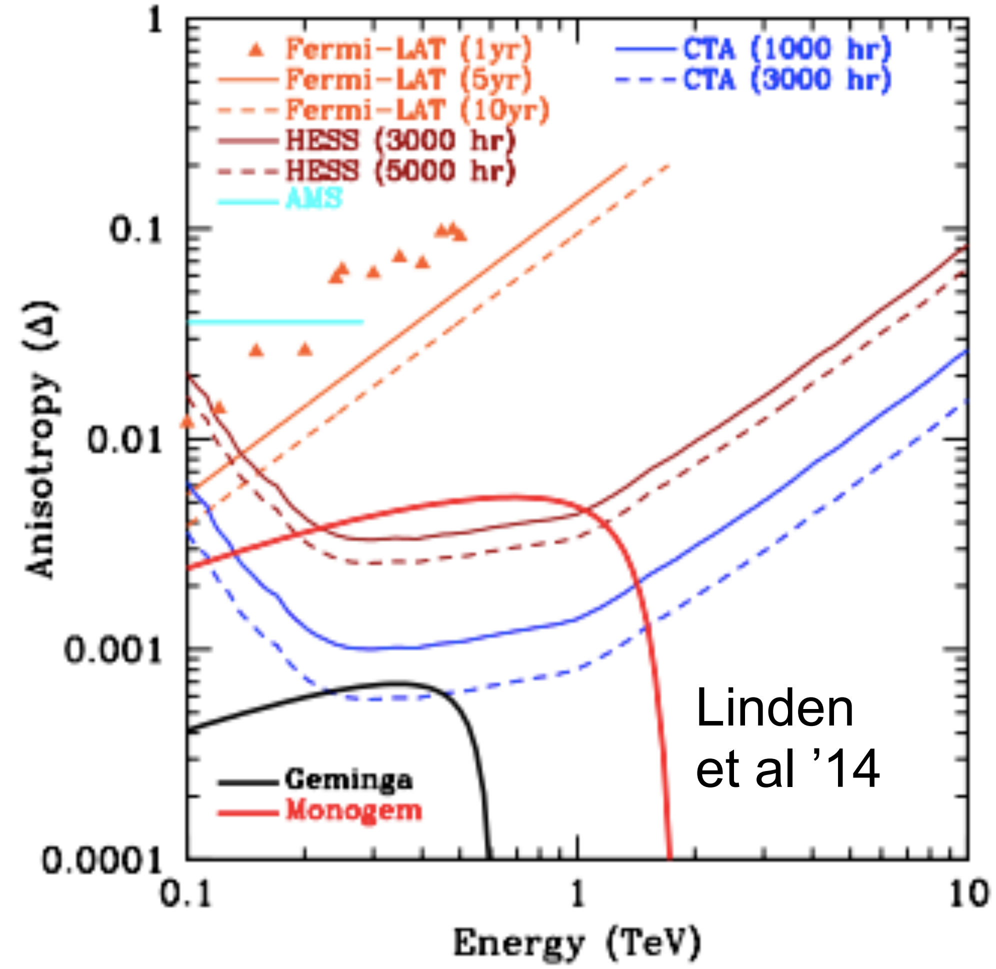


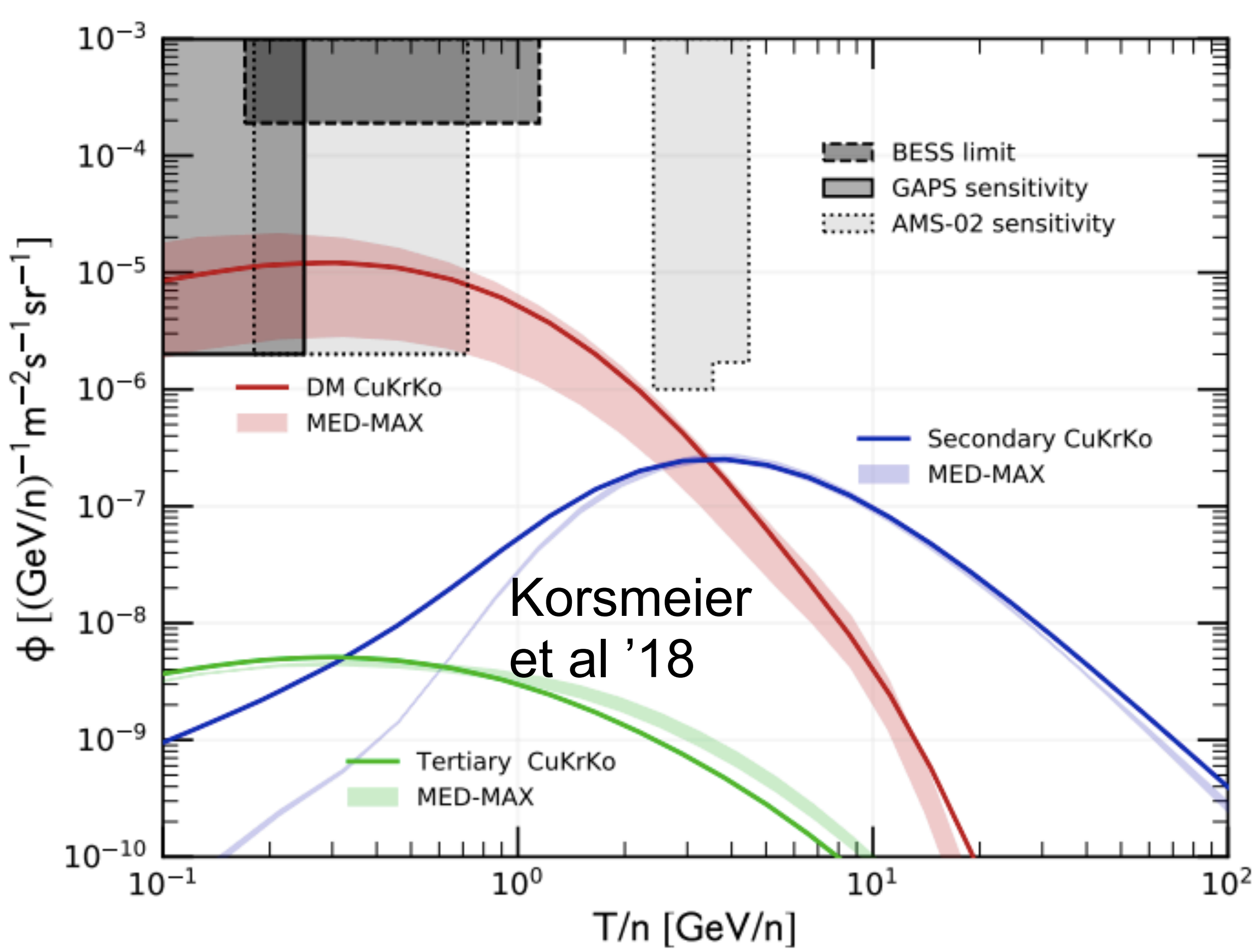
Trouble with correlations

- Boudaud et al ’19 “AMS-02 antiprotons’ consistency with a secondary astrophysical origin”, claims full consistency with astrophysical origin when including an estimated covariance matrix for the data
- Similar results from Heisig et al ’20, focus on systematic uncertainties in absorption cross-section of CRs within detector material
- Cuoco et al ’19 “Scrutinizing the evidence for dark matter in cosmic-ray antiprotons” - claims over 5 sigma evidence when systematic error correlations are included using a data-driven method
- These papers attempt to model correlations between systematic errors at different energies, using AMS-02 data; they obtain widely varying results for the significance of the signal

Where next for positrons and antiprotons?

- Very active effort to find more TeV halos around pulsars & determine how common they are in the Galaxy
- Anisotropy in arrival direction is a possible probe, but scrambling of arrival directions by B-field makes detection challenging - may be testable using air Cherenkov telescopes [Linden et al '14]
- For antiprotons, there may still be work to do on the theory/analysis side, trying to nail down uncertainties in production cross-sections + error correlations
- GAPS is a balloon experiment expected to fly in the next few years (delayed due to covid)
- Could potentially test similar parameter space in anti-deuterons [e.g. von Doetinchem et al '20].





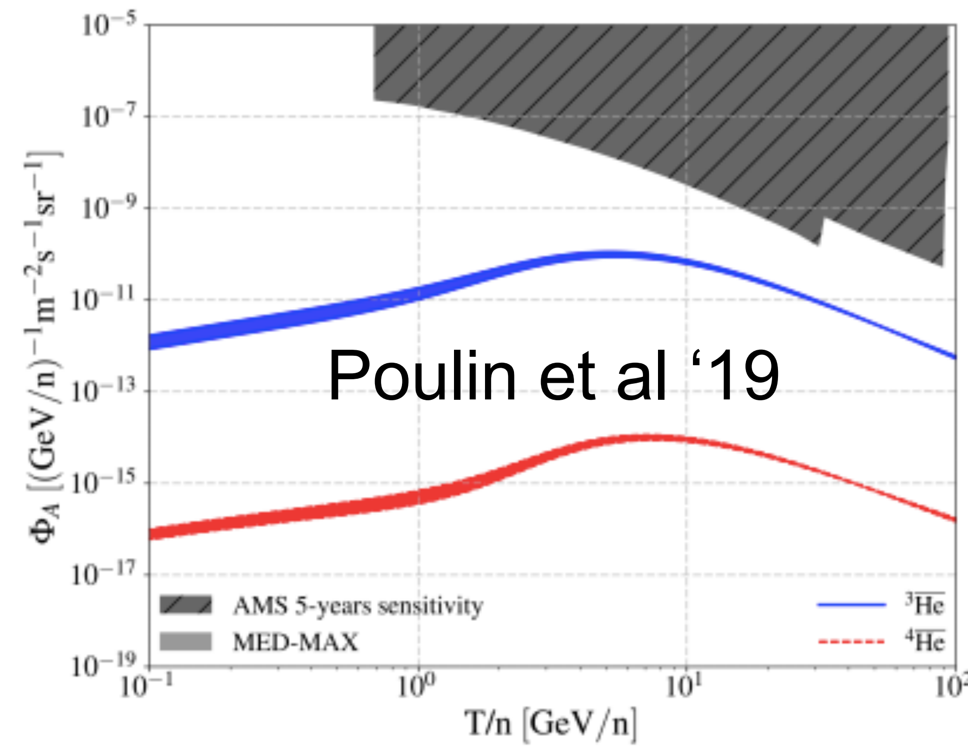
AMS-02 antihelium events

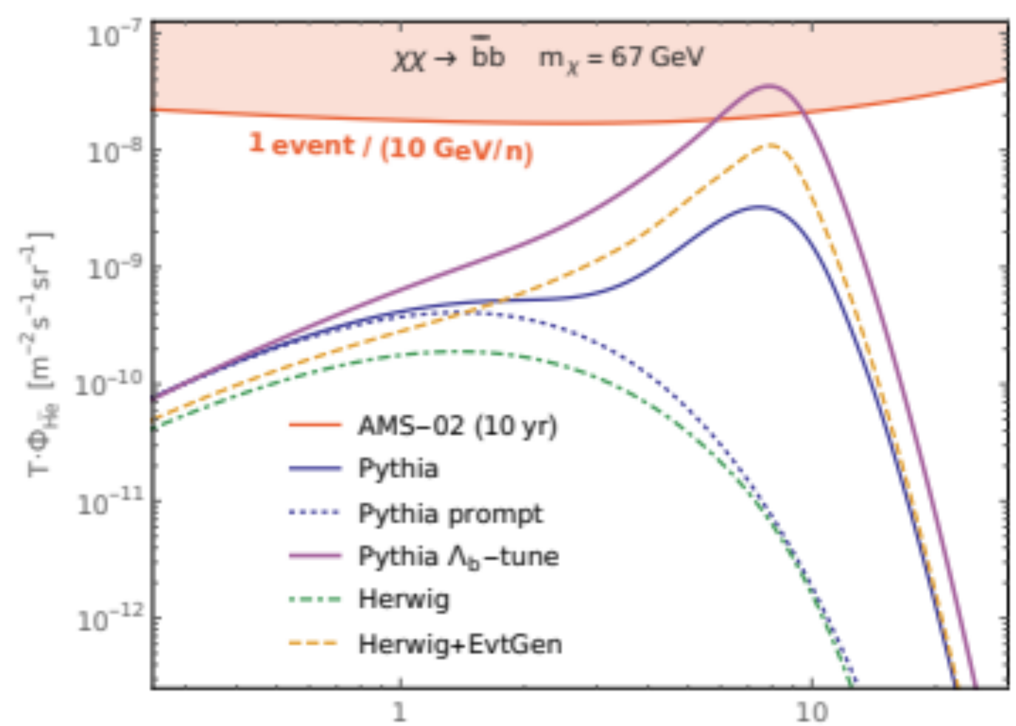
- AMS-02 Collaboration announced tentative possible detection of six apparent anti-He-3 events and two apparent anti-He-4 events ["AMS Days at La Palma, La Palma, Canary Islands, Spain," (2018)]

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

- One proposal is 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

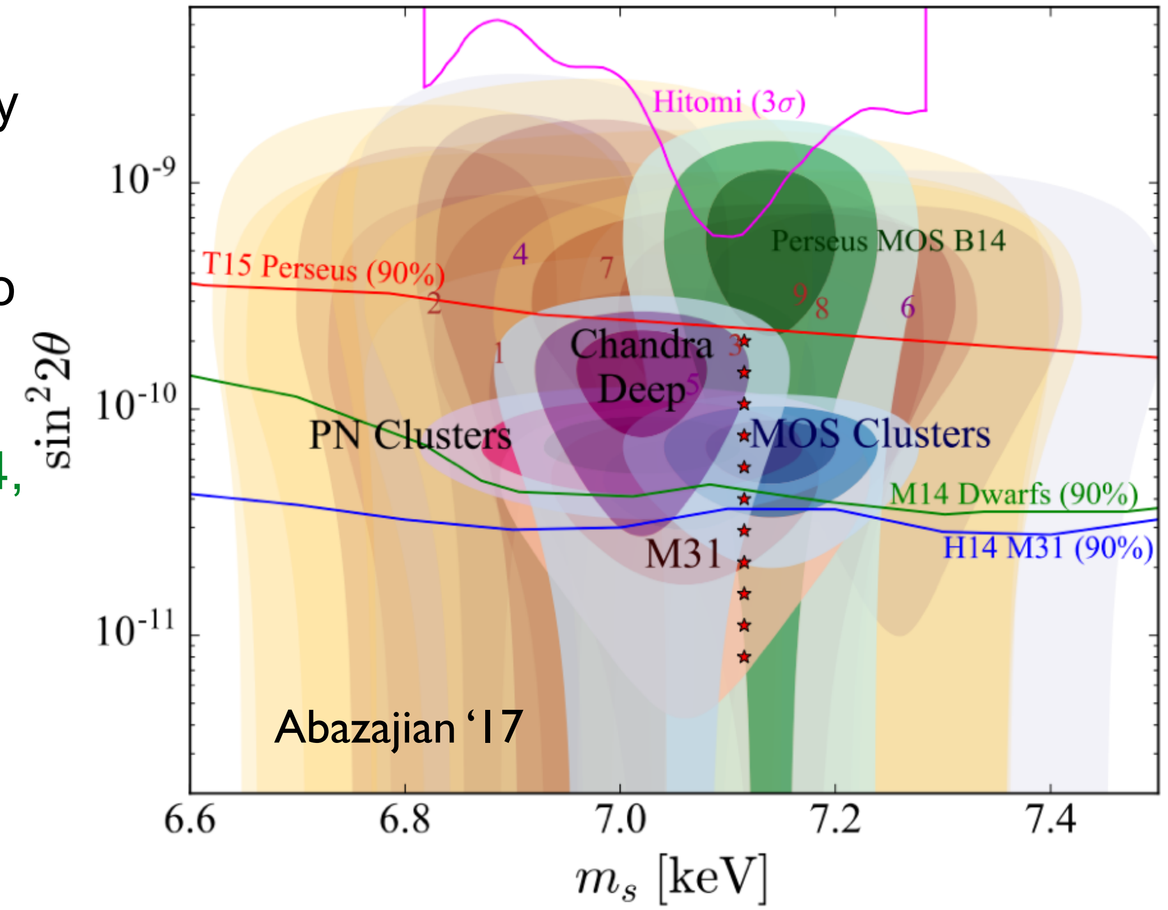


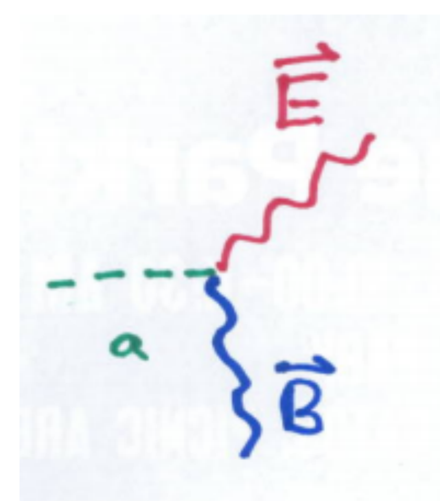


Winkler et al '21

The 3.5 keV line

- Apparent X-ray spectral 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.
- DM alternatives include exciting dark matter [Cline & Frey '14, Finkbeiner & Weiner '16]
  - DM has a metastable excited state 3.5 keV above the ground state.
  - This state is excited by DM-DM collisions, and subsequently decays producing a photon.
  - Rate of excitation scales as density^2 x velocity dependence - much less constrained than just DM density, seems to allow compatibility with data.





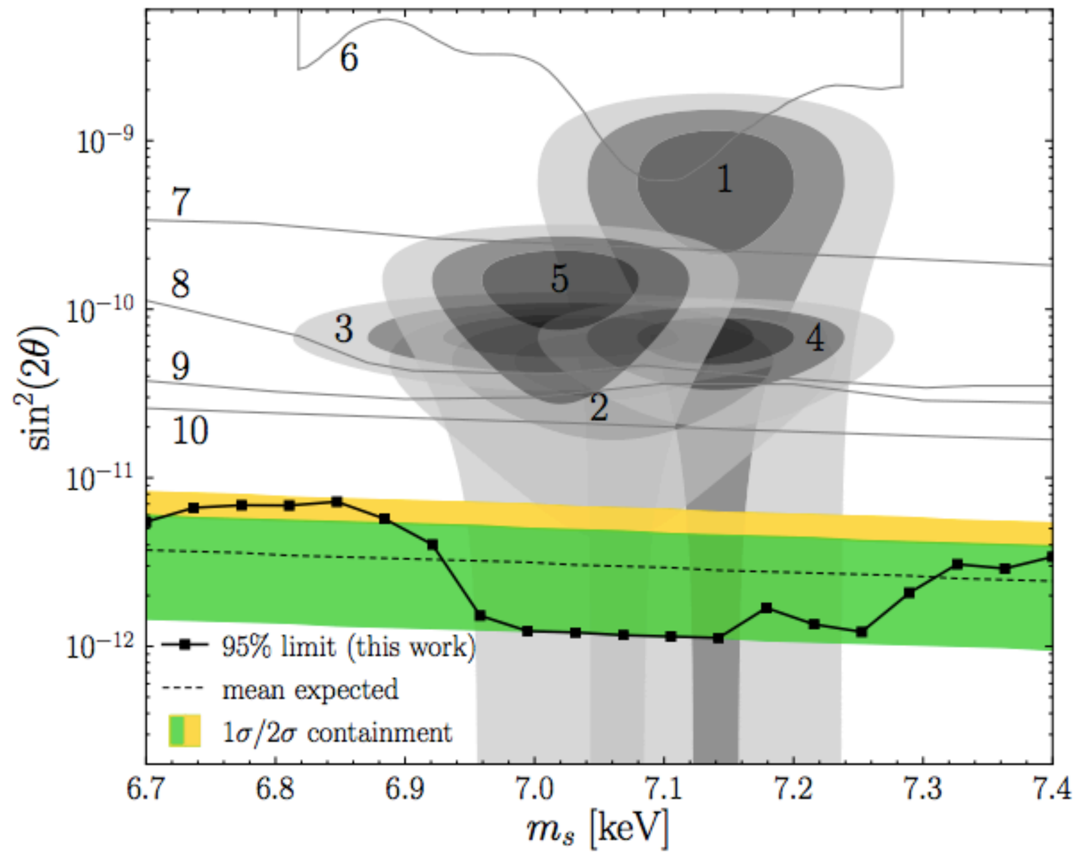
- Another possibility is conversion of an axion-like particle to an X-ray photon in the presence of magnetic fields [e.g. Conlon & Day '14] - can lead to widely varying signals from different systems [e.g. Alvarez et al '15].
- Possible non-DM contributions: atomic lines (from K, Cl, Ar, possibly others), charge-exchange reactions between heavy nuclei and neutral gas [e.g. Shah et al '16].

Challenges to the DM interpretation

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

- 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.

- Future X-ray experiments (eXTP, XRISM, Micro-X, possibly eROSITA) should have the sensitivity to see the signal, in some cases with improved energy resolution.

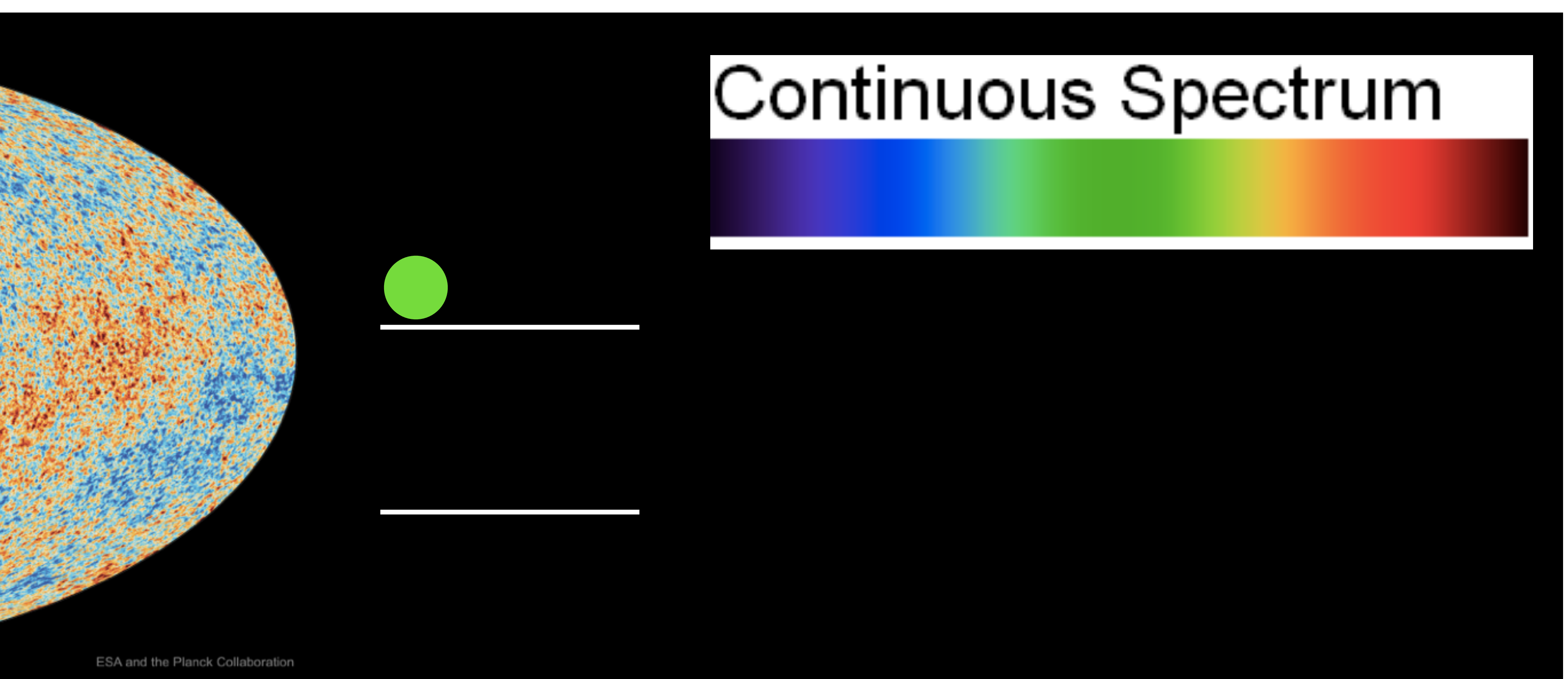


Dessert et al ’20

- One strategy: seek energy resolution sufficient to probe velocity distribution of DM in Galactic halo, via Doppler shift causing line broadening [Speckhard et al ’16, Powell et al ’17].

21cm radiation as a probe of temperature and ionization

- Look for photons from the (redshifted) 21cm spin-flip transition of neutral hydrogen
- "Spin temperature" T_S characterizes relative abundance of ground (electron/proton spins antiparallel) and excited (electron/proton spins parallel) states - T_S gives the temperature at which the equilibrium abundances would match the observed ratio.
- If T_S exceeds the ambient radiation temperature T_R (i.e. the temperature describing the photon density at the line frequency), there is net emission; otherwise, net absorption.



$$T_{21}(z) \approx x_{\rm HI}(z) \left(\frac{0.15}{\Omega_m}\right)^{1/2} \left(\frac{\Omega_b h}{0.02}\right) \times \left(\frac{1+z}{10}\right)^{1/2} \left[1 - \frac{T_R(z)}{T_S(z)}\right] 23\,\mathrm{mK},$$

21cm radiation as a probe of temperature and ionization

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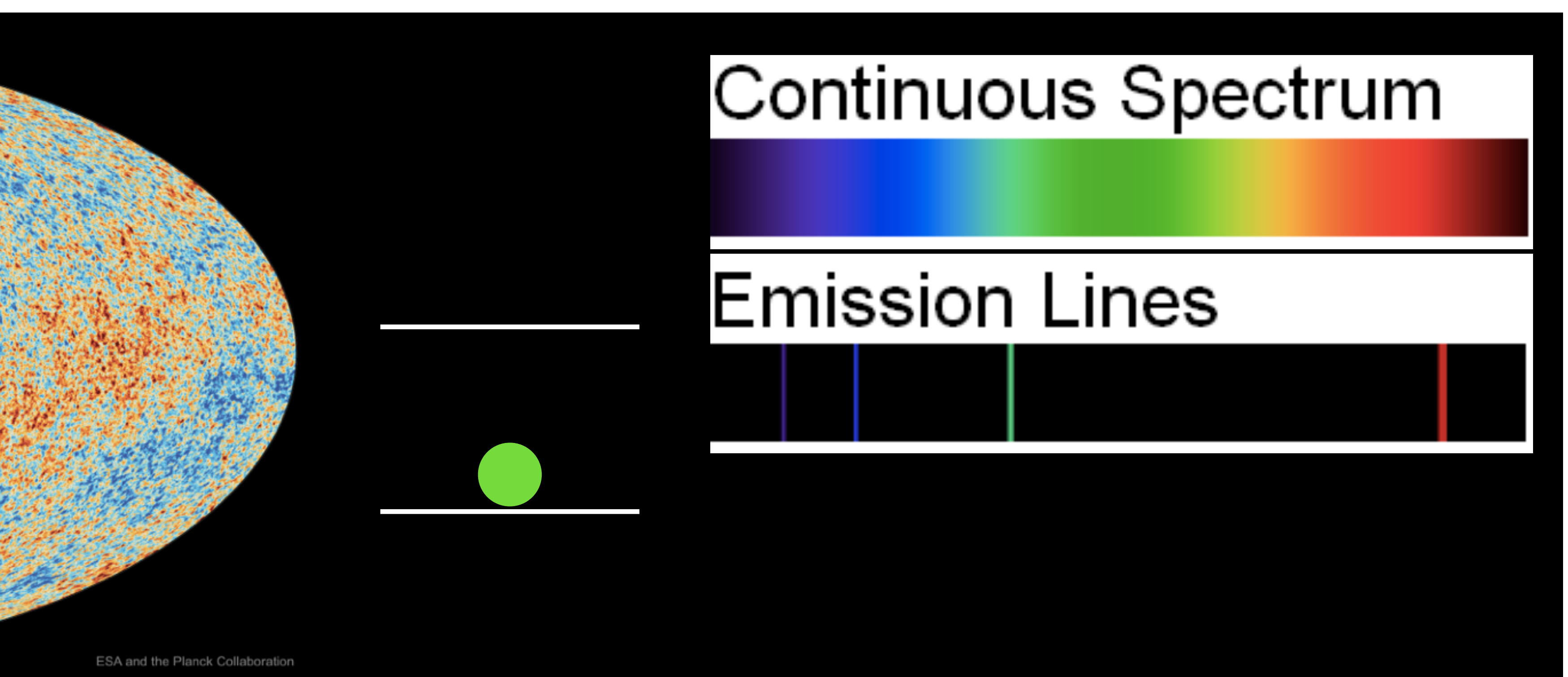
- "Spin temperature" T_S characterizes relative abundance of ground (electron/proton spins antiparallel) and excited (electron/proton spins parallel) states - T_S gives the temperature at which the equilibrium abundances would match the observed ratio.
- If T_S exceeds the ambient radiation temperature T_R (i.e. the temperature describing the photon density at the line frequency), there is net emission; otherwise, net absorption.



$$T_{21}(z) \approx x_{\rm HI}(z) \left(\frac{0.15}{\Omega_m}\right)^{1/2} \left(\frac{\Omega_b h}{0.02}\right) \times \left(\frac{1+z}{10}\right)^{1/2} \left[1 - \frac{T_R(z)}{T_S(z)}\right] 23\,\mathrm{mK},$$

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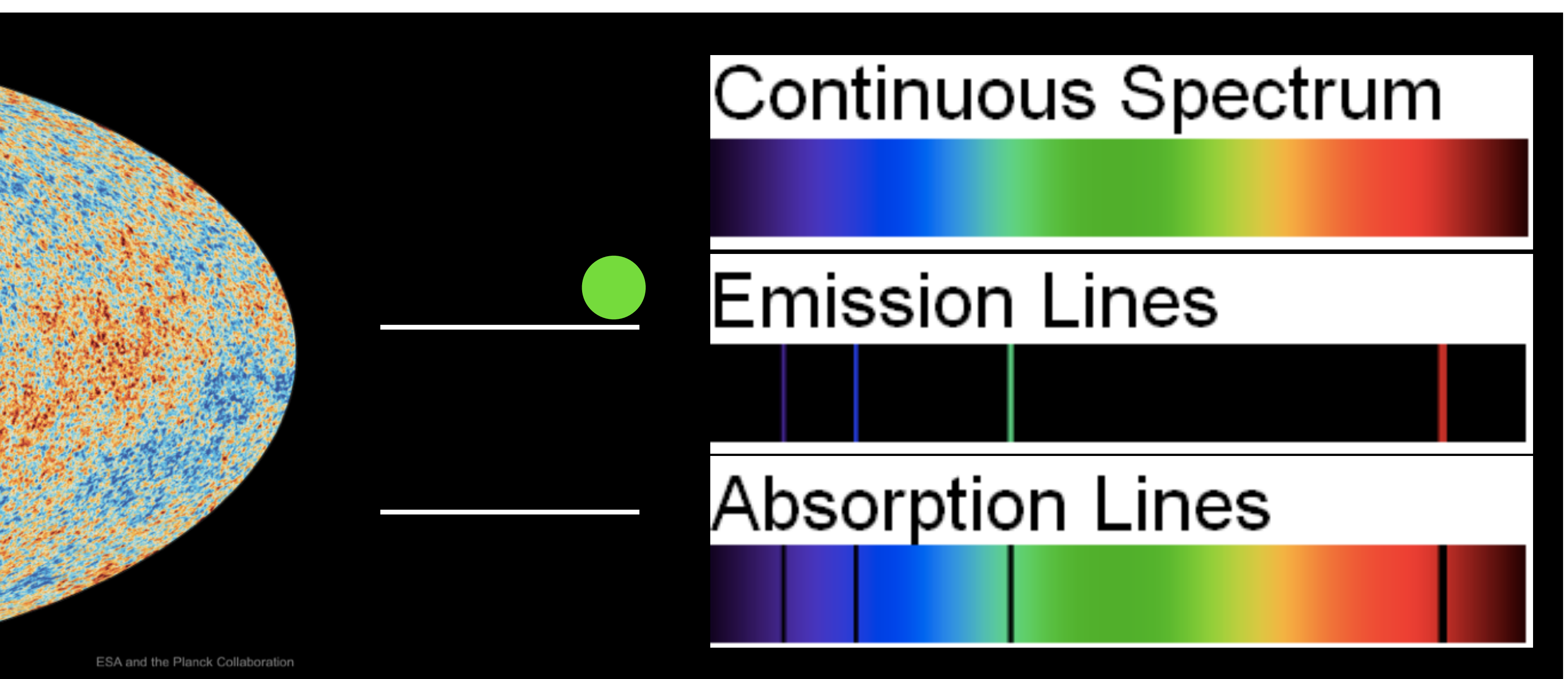

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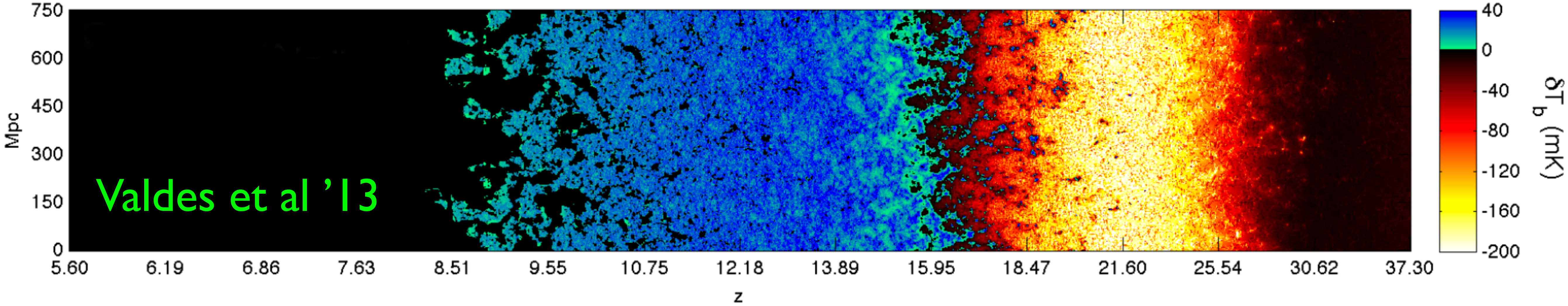
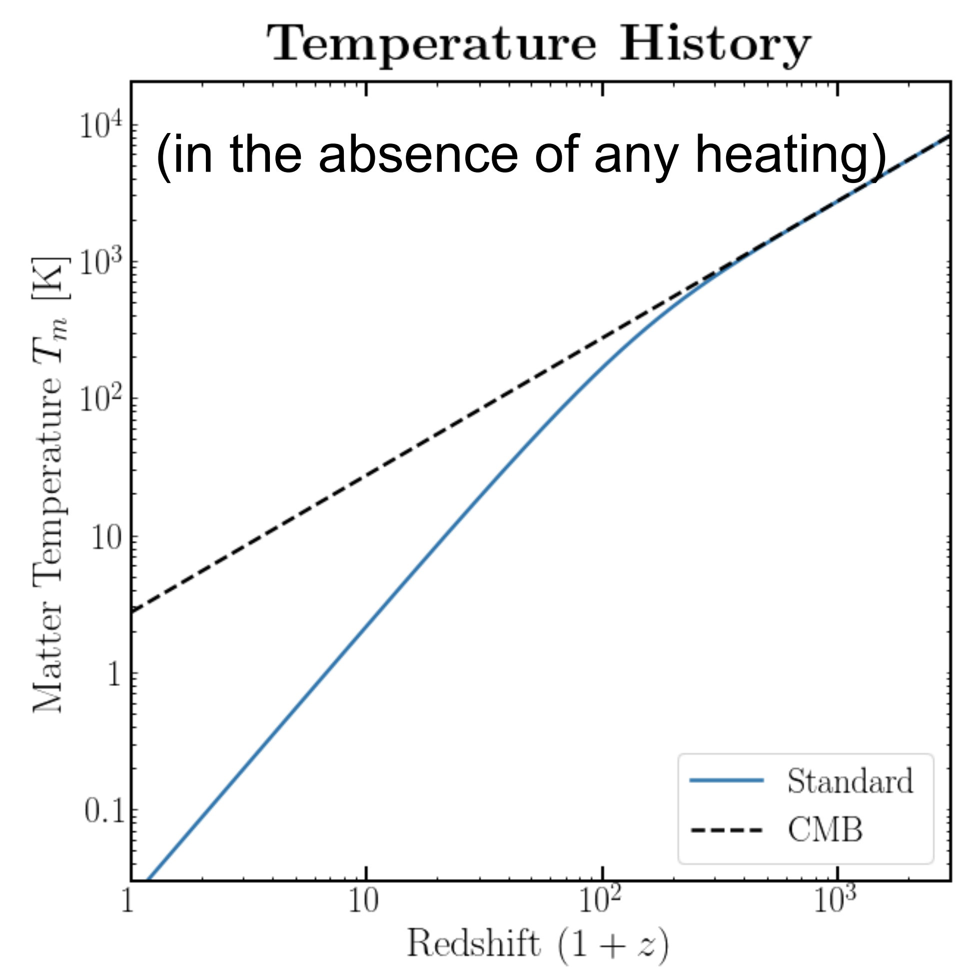
Expectations for a 21cm signal



- First stars turn on = flux of Lyman-alpha photons - couples T_S to the hydrogen gas temperature T_{gas}.
- We expect $T_{gas} < T_R$ initially - gas cools faster than the CMB after they decouple around z~150 - leading to absorption signature.
- Exotic heating from annihilation/decay could lead to an early emission signal [e.g. Poulin et al '17].
- Later, stars heat $T_{gas} > T_R$, expect an emission signal.
- There are a number of current (e.g. EDGES, LOFAR, MWA, PAPER, SARAS, SCI-HI) and future (e.g. DARE, HERA, LEDA, PRIZM, SKA) telescopes designed to search for a 21cm signal, potentially probing the cosmic dark ages & epoch of reionization.
- Any measurement of global T_{21} will set a bound on T_{gas}. In the absence of any stellar heating, we expect T_{gas} ~ 7 K at z=17.



The EDGES absorption trough

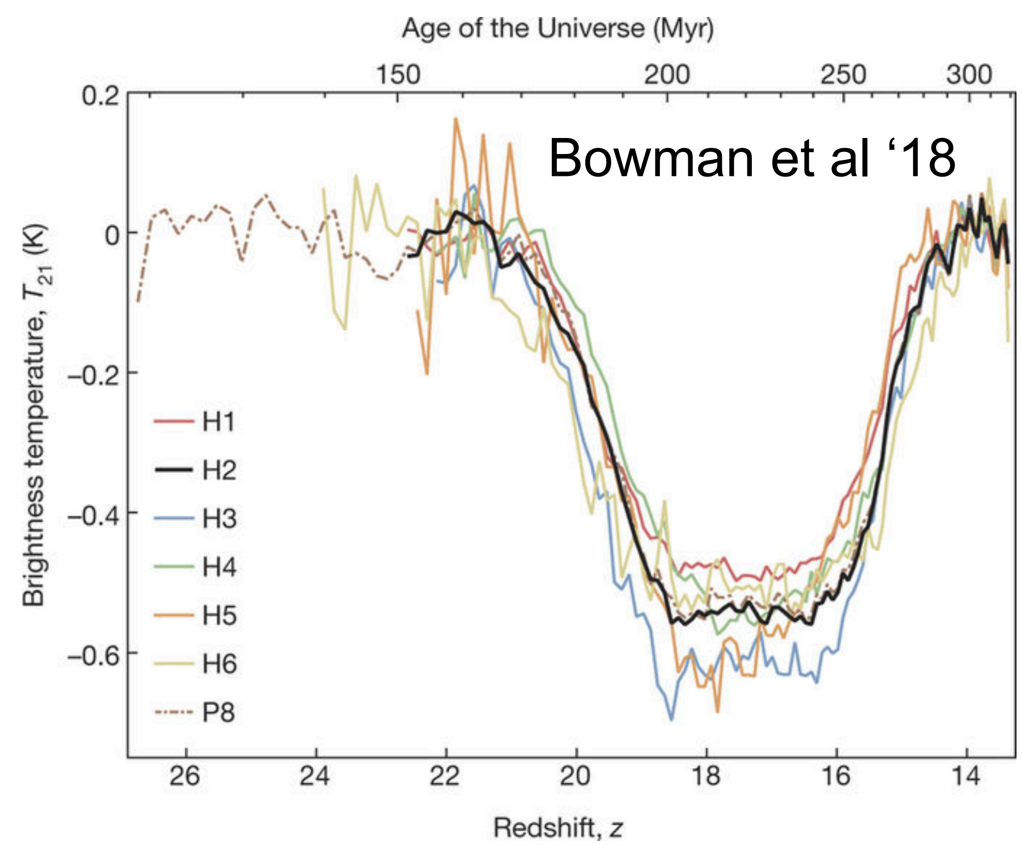
- The Experiment to Detect the Global Epoch-of-reionization Signature (EDGES) has claimed a detection of the first 21cm signal from the cosmic dark ages [Bowman et al, Nature, March ’18]

- 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].

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



What new physics could cause this?

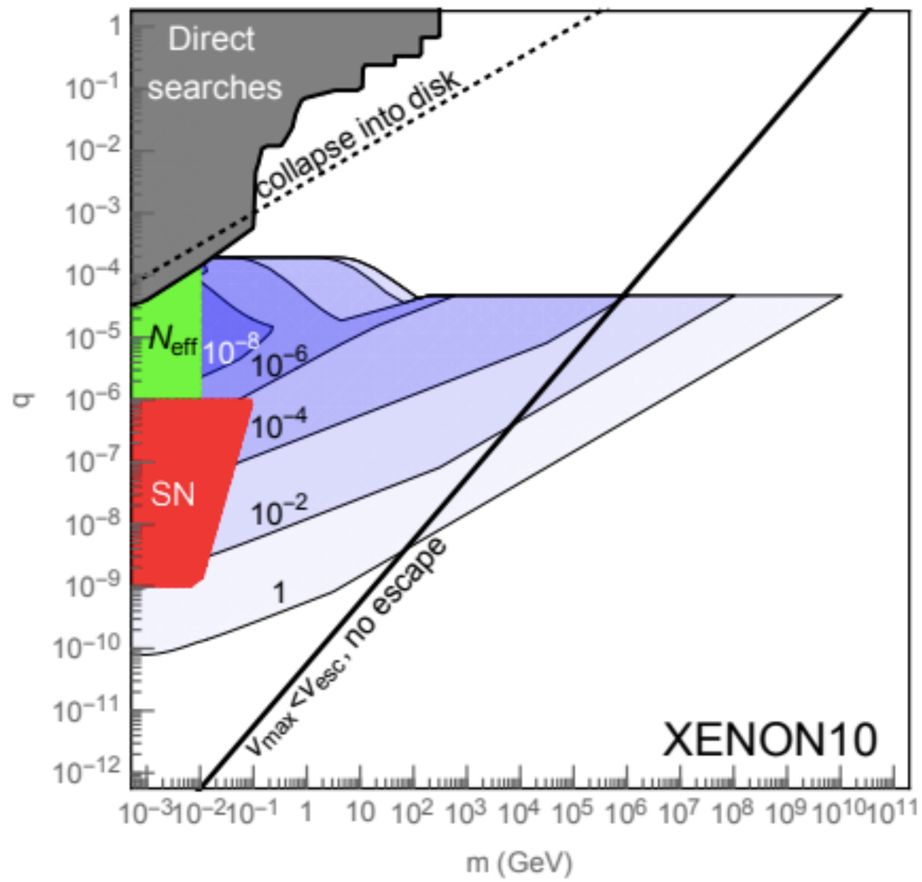
- Three broad options:
  - reduce T_{gas} - need some kind of heat sink, or earlier decoupling
  - increase T_R - need some new source of 21cm radiation in early universe [e.g. Ewall-Wice et al ’18, Fraser et al '18, Pospelov et al ’18.]
  - modify cosmology in some non-trivial way
- In the first category, one possibility is to try to use the DM as a heat sink - expected to be much colder than visible matter (as it has been decoupled from photons for longer)
- O(1) change in SM particle temperature requires DM number density at least comparable to baryon density => DM must be lighter than a few GeV
- Also need an appreciable DM-SM scattering cross section for efficient heat transfer

Cooling from DM-baryon scattering?

- DM-baryon scattering can cool down the ordinary matter [e.g. Munoz et al ’15], leading to stronger 21cm absorption - opposite effect from decay/annihilation, which induces heating.
- But strong DM-baryon interactions would also modify both the CMB anisotropies and CMB blackbody spectrum [Dvorkin et al ’13, Gluscevic et al ’17, Boddy et al ’18, Xu et al ’18].
- There are also limits on DM-baryon interactions from powerful direct-detection experiments on Earth - tend to be much stronger than cosmological bounds at DM masses >> 1 GeV.
- Best-case scenario for a strong 21cm signal comes from models of low-mass DM where scattering is enhanced at low velocities - consider models where cross section scales as strongly as v^{-4} (Rutherford scattering).

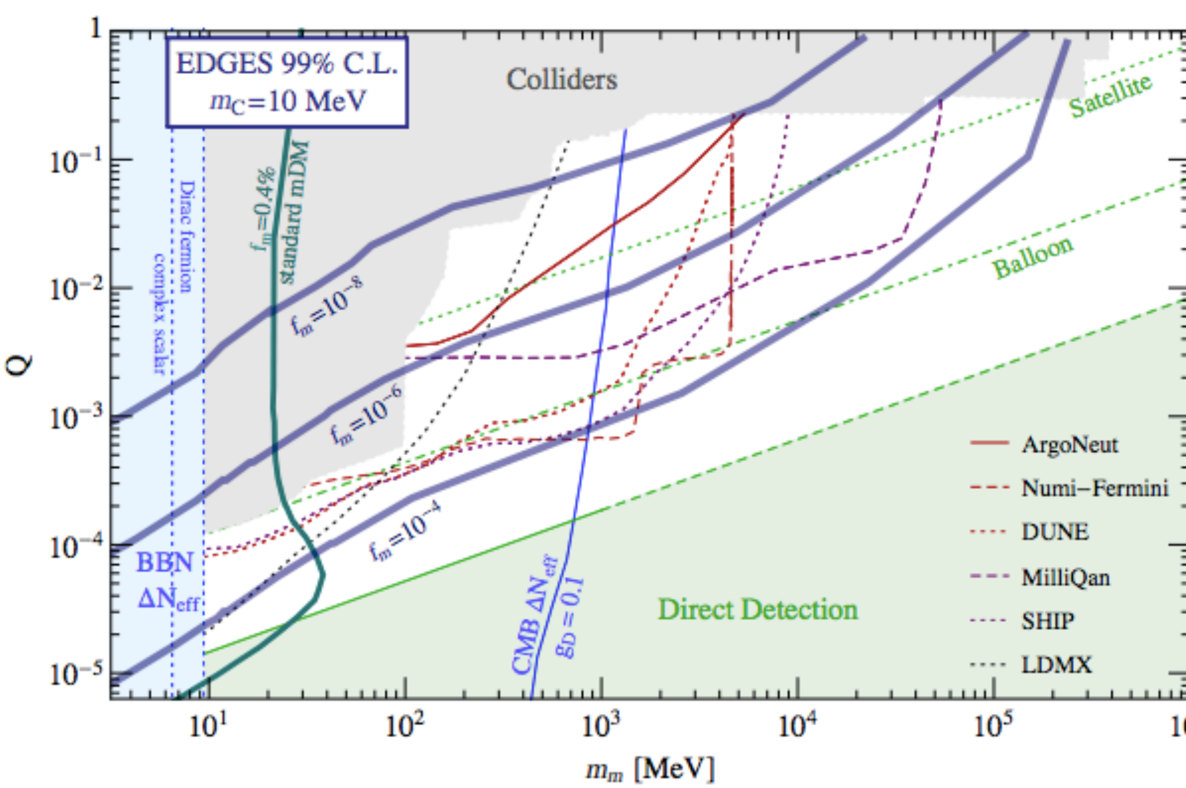
Millicharged DM?

- This motivates models of millicharged DM [e.g. Munoz et al '18, Berlin et al '18, Barkana et al '18].
- To further evade the CMB constraints, can posit that only a small fraction of DM has these interactions, with the rest being inert.
- If this component doesn't interact with the rest of the DM, require millicharged fraction to be 0.01-0.4% of DM, DM in mass range 0.5-35 MeV [Boddy et al '18, Kovetz et al '18].
- Strength of direct-detection constraints is debated - depends on whether millicharged DM is efficiently ejected from Milky Way [Dunsky et al '19 argue there should be a large abundance in the MW].
- If millicharged component interacts with inert component, fraction can be much smaller [Liu et al '19].



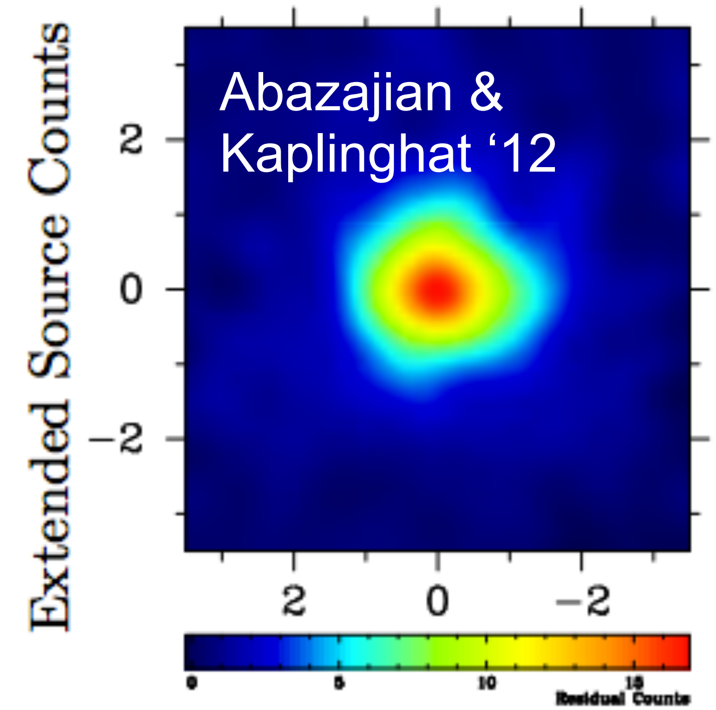
Dunsky et al '19

Liu et al '19

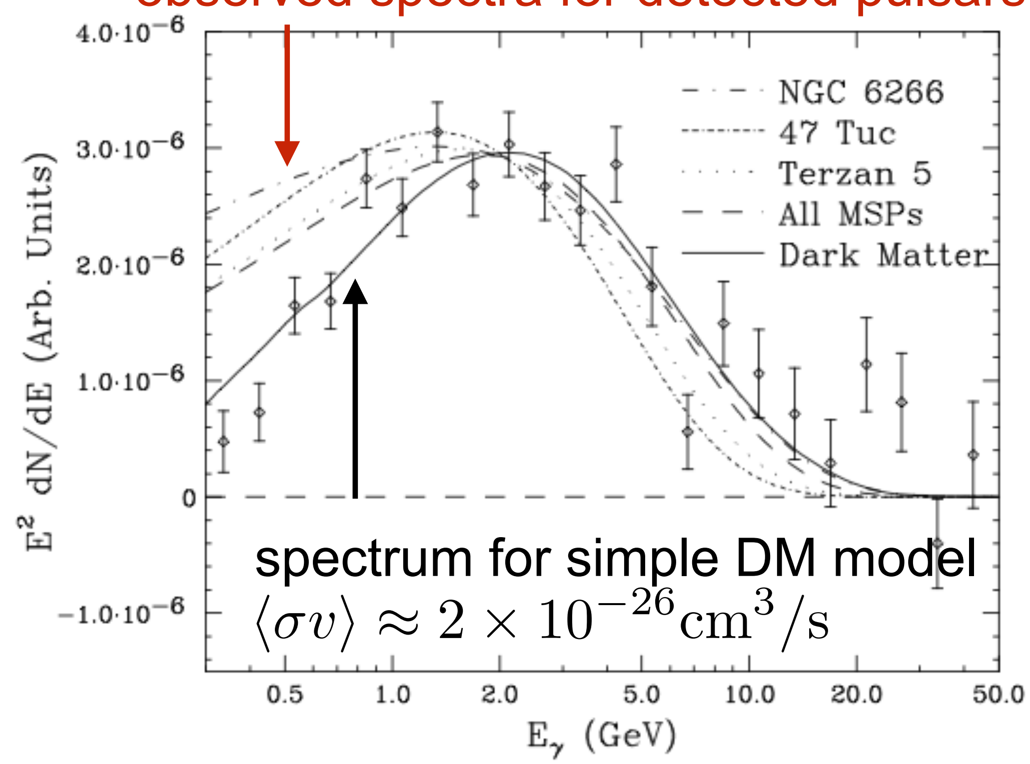


The Galactic Center excess (GCE)

- 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



observed spectra for detected pulsars



Daylan, TRS et al '16

Status of the GCE - a renewed controversy?

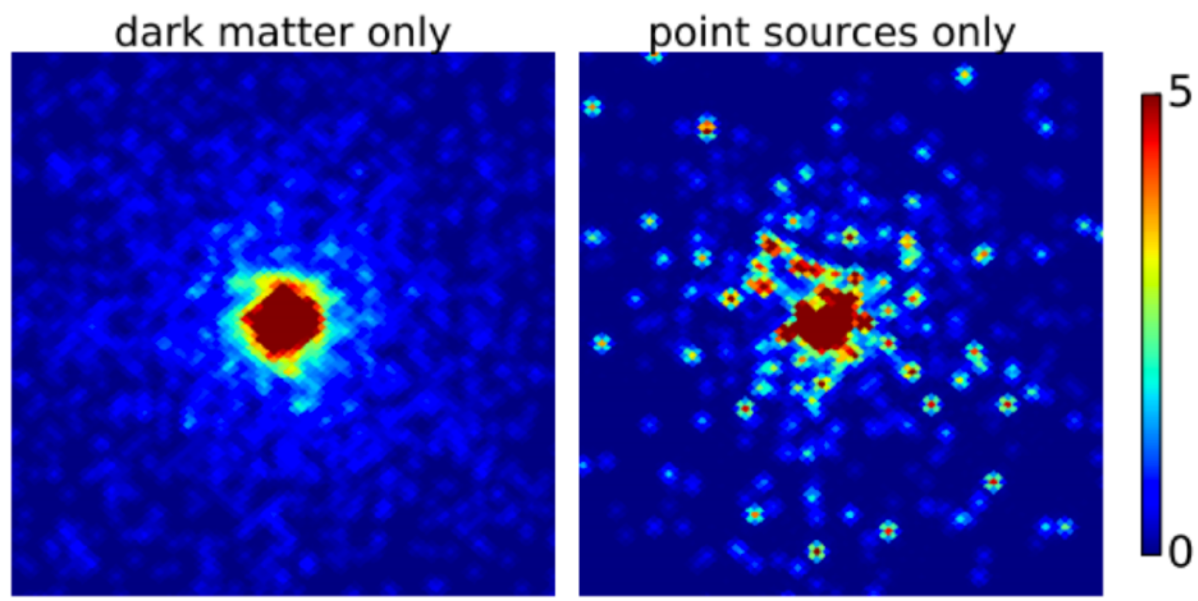
- Key argument in favor of pulsars: energy spectrum
- Current/past arguments against the DM explanation:
  - Spatial morphology of excess was originally characterized as spherical, but can also be described as boxy-bulge-like extended emission + central nuclear bulge component [Macias et al ’18, Bartels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

DM origin hypothesis

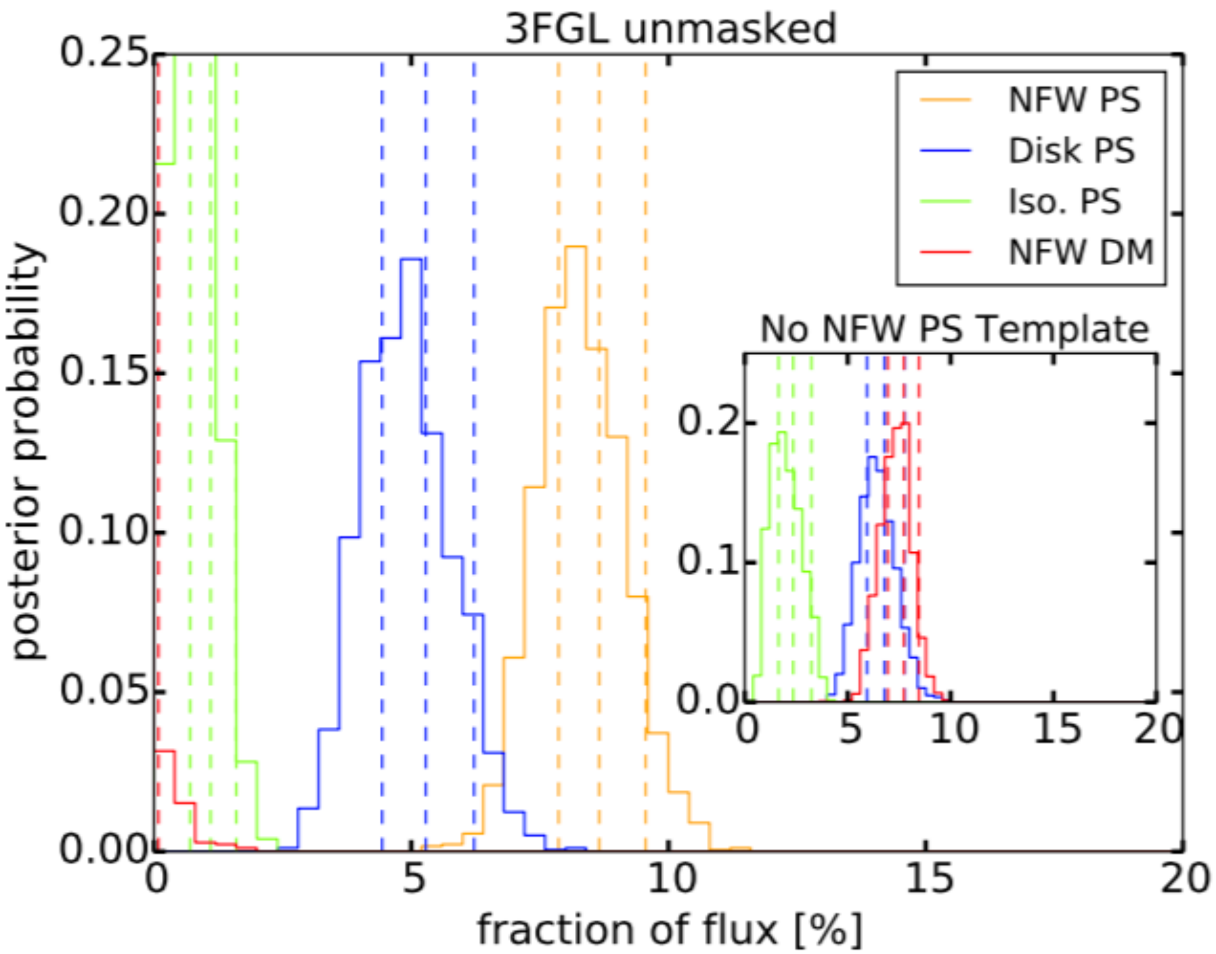
signal traces DM density squared, expected to be ~smooth near GC with subdominant small-scale structure



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 (updated analysis by Zhong et al '20 - comparison with the 4FGL catalog indicates most sources found by wavelet method are not potential contributors to the GCE)

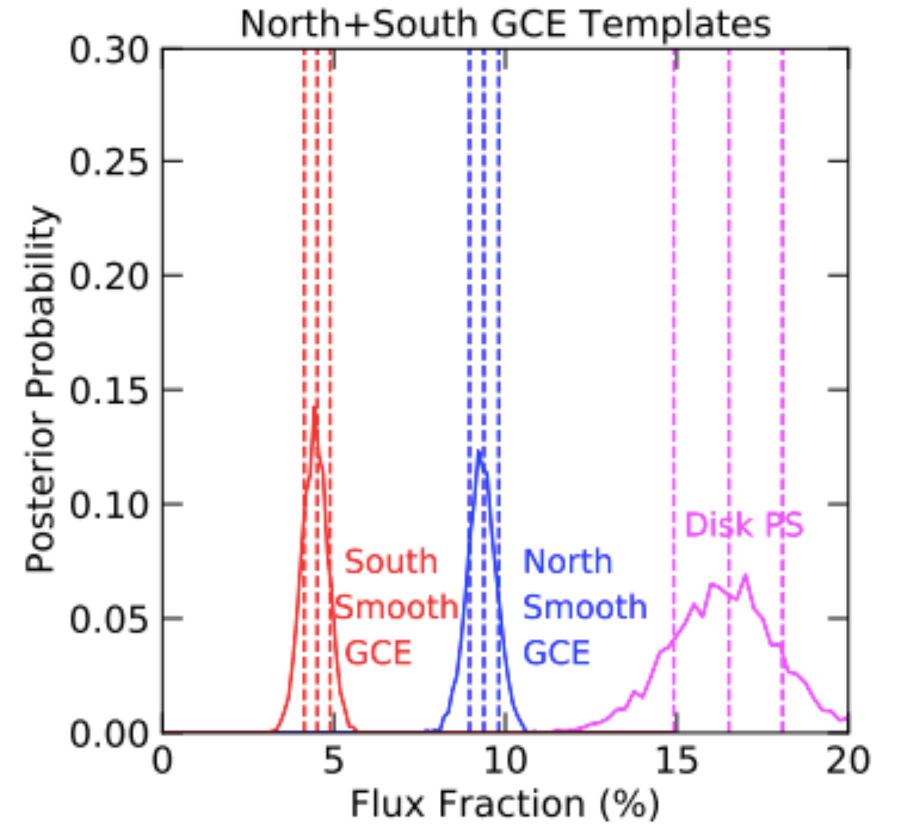


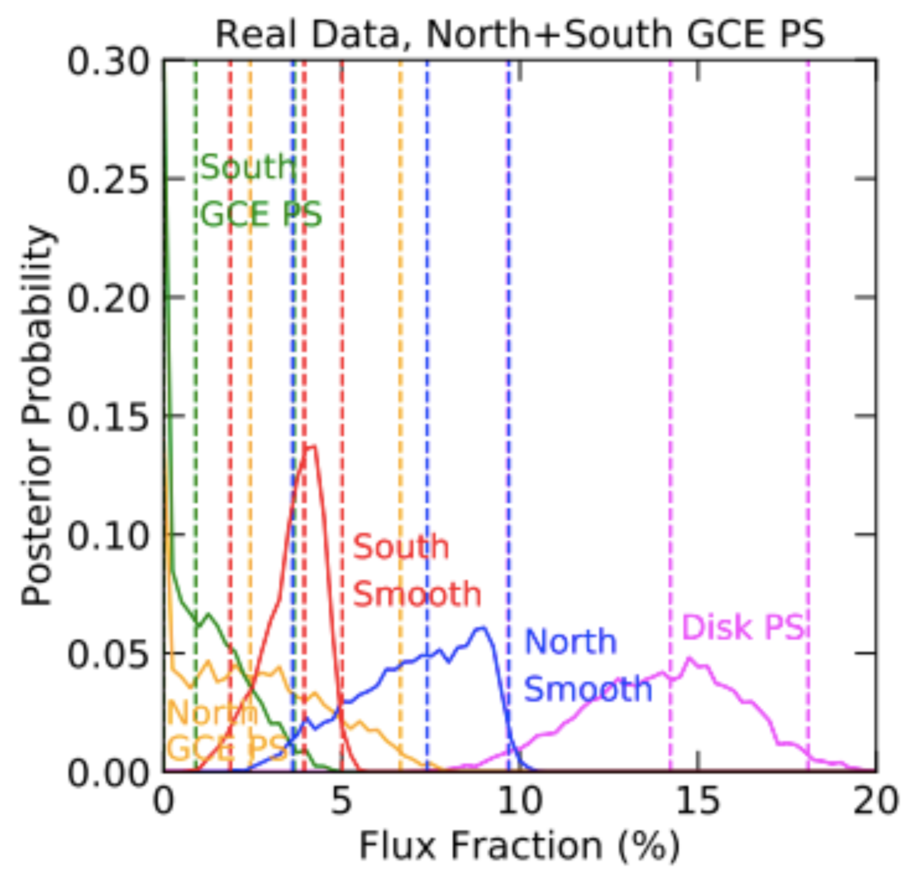
- Lee et al ‘16: fit shows a strong preference to assign all GCE flux to new PS population (Bayes factor in favor of model with PSs ~10^9, roughly analogous to 6σ)
- Suggests signal is composed of a relatively small number of just-below-threshold sources

- 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)

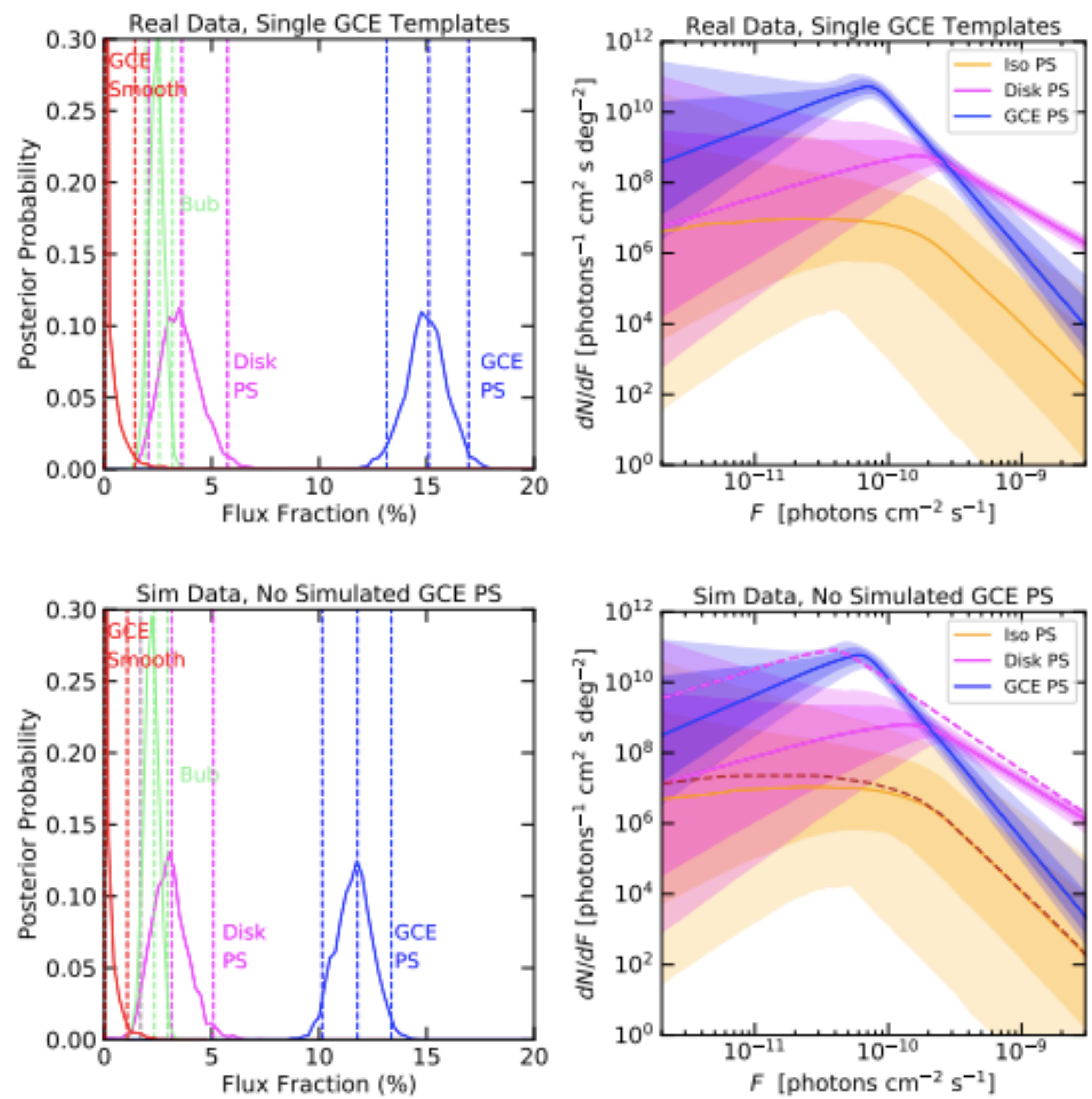
- We found this by accident - trying to test the spatial morphology of the GCE in more detail
- In the region of interest we used, when we split the GCE into 2+ spatial components, all evidence for GCE PSs went away (BF $> 10^{15} \rightarrow$ BF < 10 with one added d.o.f)
- Apparent preference for PSs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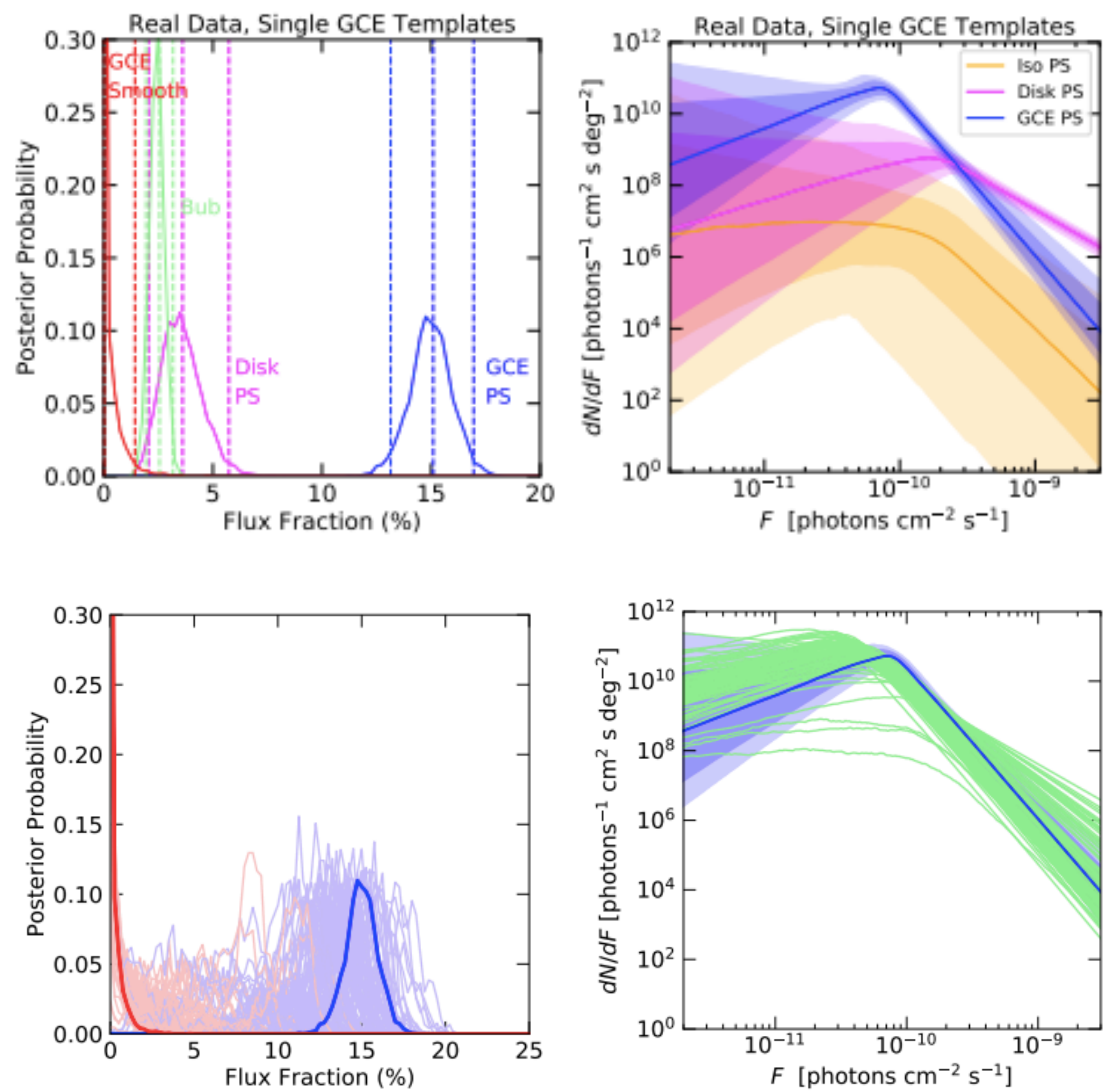

100 realizations

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]

- 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]