New developments in indirect dark matter searches

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Dark Sectors of Astroparticle Physics:
Neutrinos, Black Holes and Gravitational Waves
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U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Overview of a range of probes of new physics via indirect detection
- Recent developments and future prospects across a range of energies
- A quick overview of (some) current anomalies

Some mechanisms for indirect signals

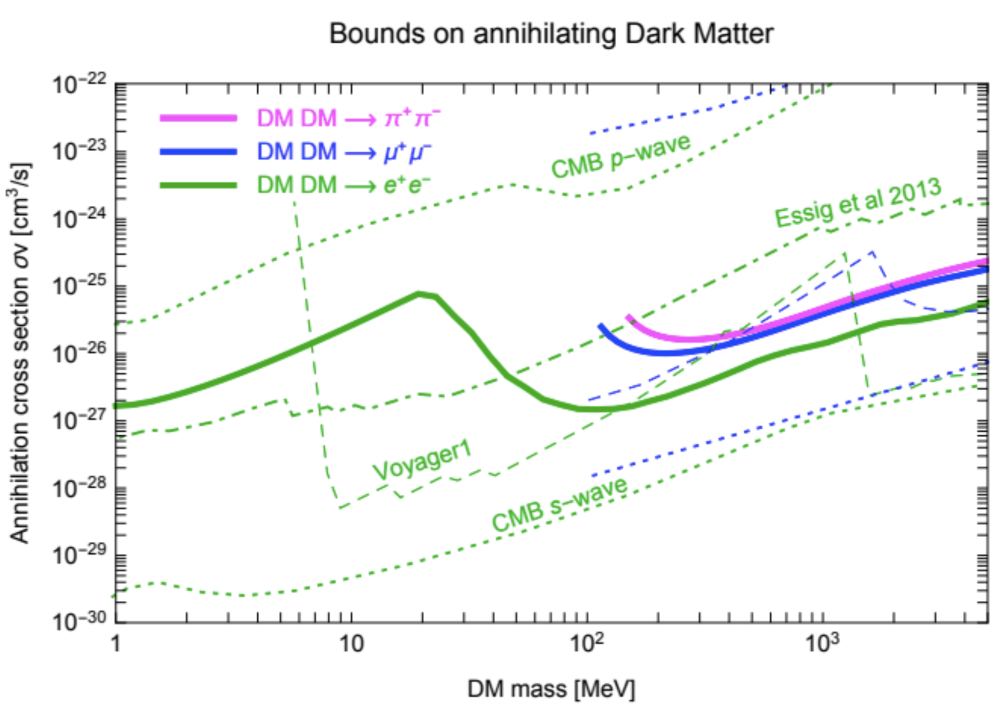
- Collisions that produce visible particles
  - Has natural benchmark cross section, if annihilation depletes early-universe DM abundance to its observed value:

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

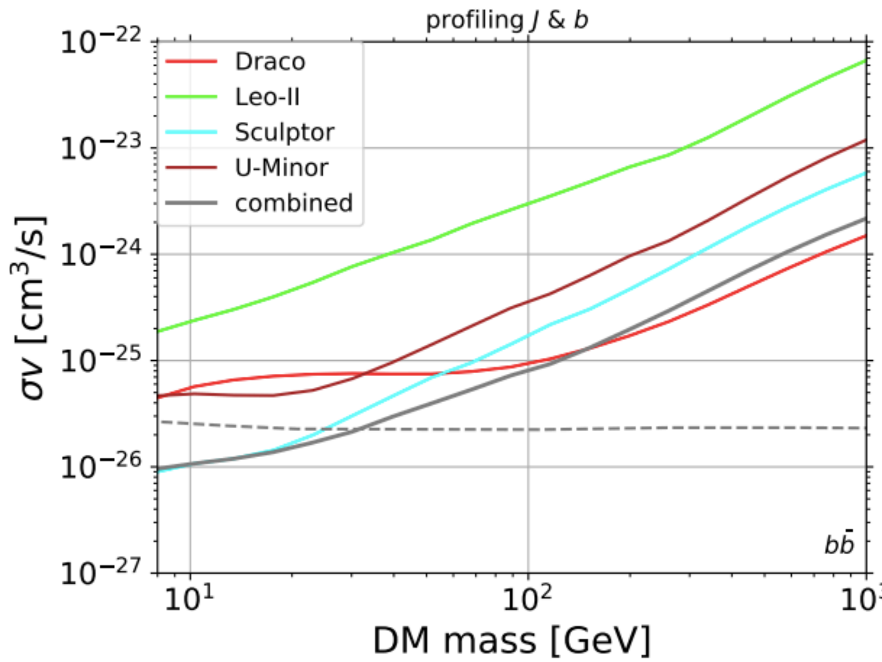
- Decay into visible particles, directly or through intermediate states - lifetime must be >> age of universe
- Scattering on visible particles leading to indirect signals
- Oscillation into visible particles, and vice versa

Constraints on annihilation

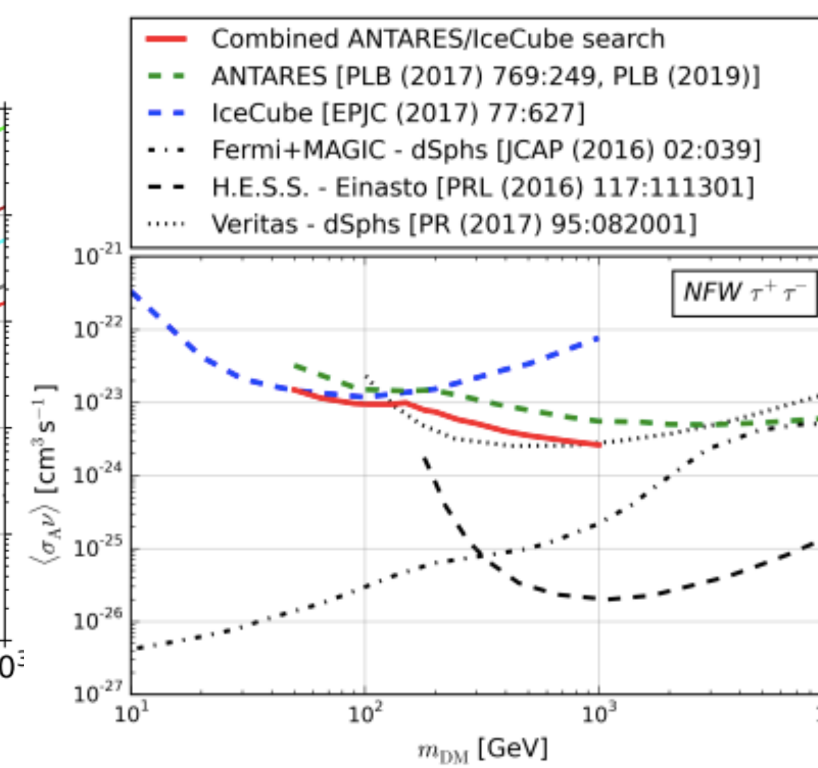
- Multiwavelength photon and cosmic-ray observations constrain thermal relic cross sections up to O(10s-100s) GeV, for all final states except neutrinos
- In this mass range, antiproton and gamma-ray measurements generally give the strongest bounds for hadronic final states [e.g. Alvarez et al ’20, Cuoco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

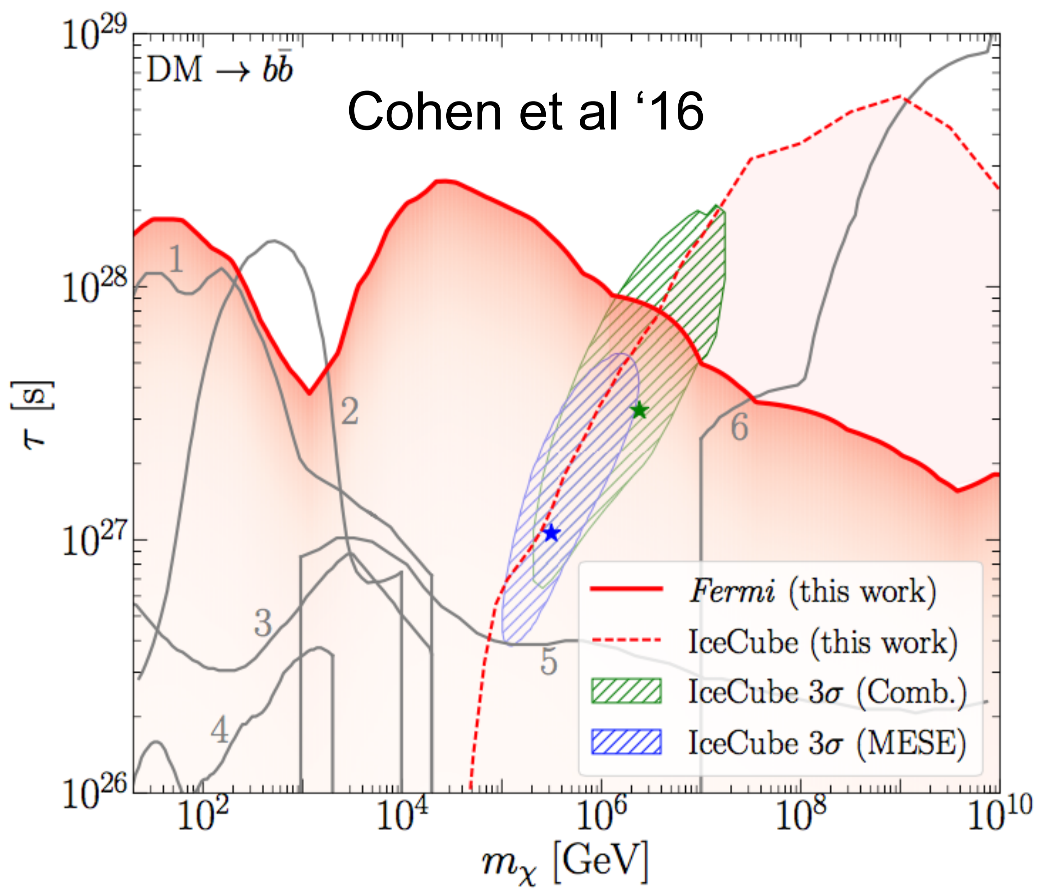


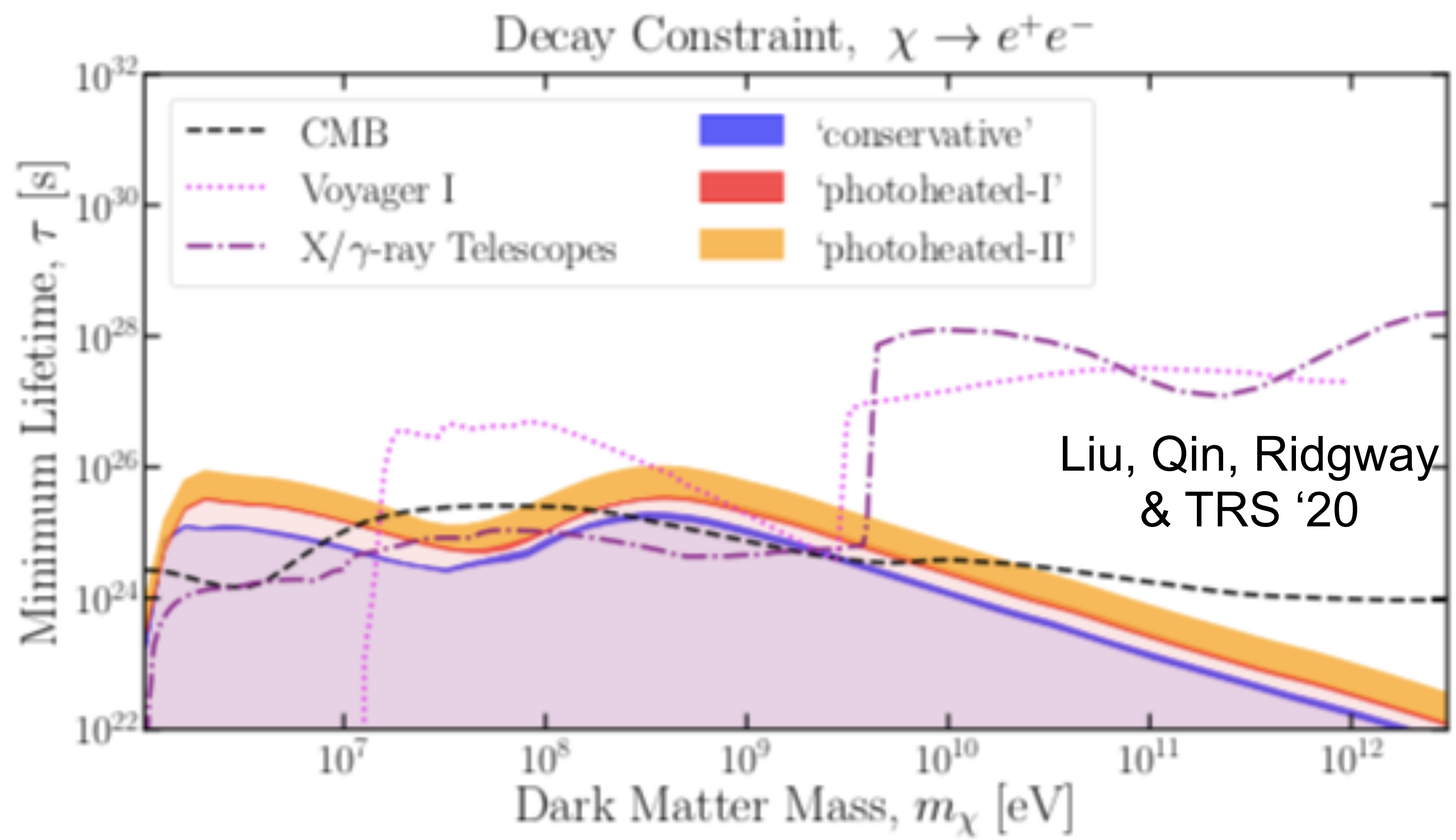
Alvarez et al ‘20



Albert et al ‘20

Constraints on decay



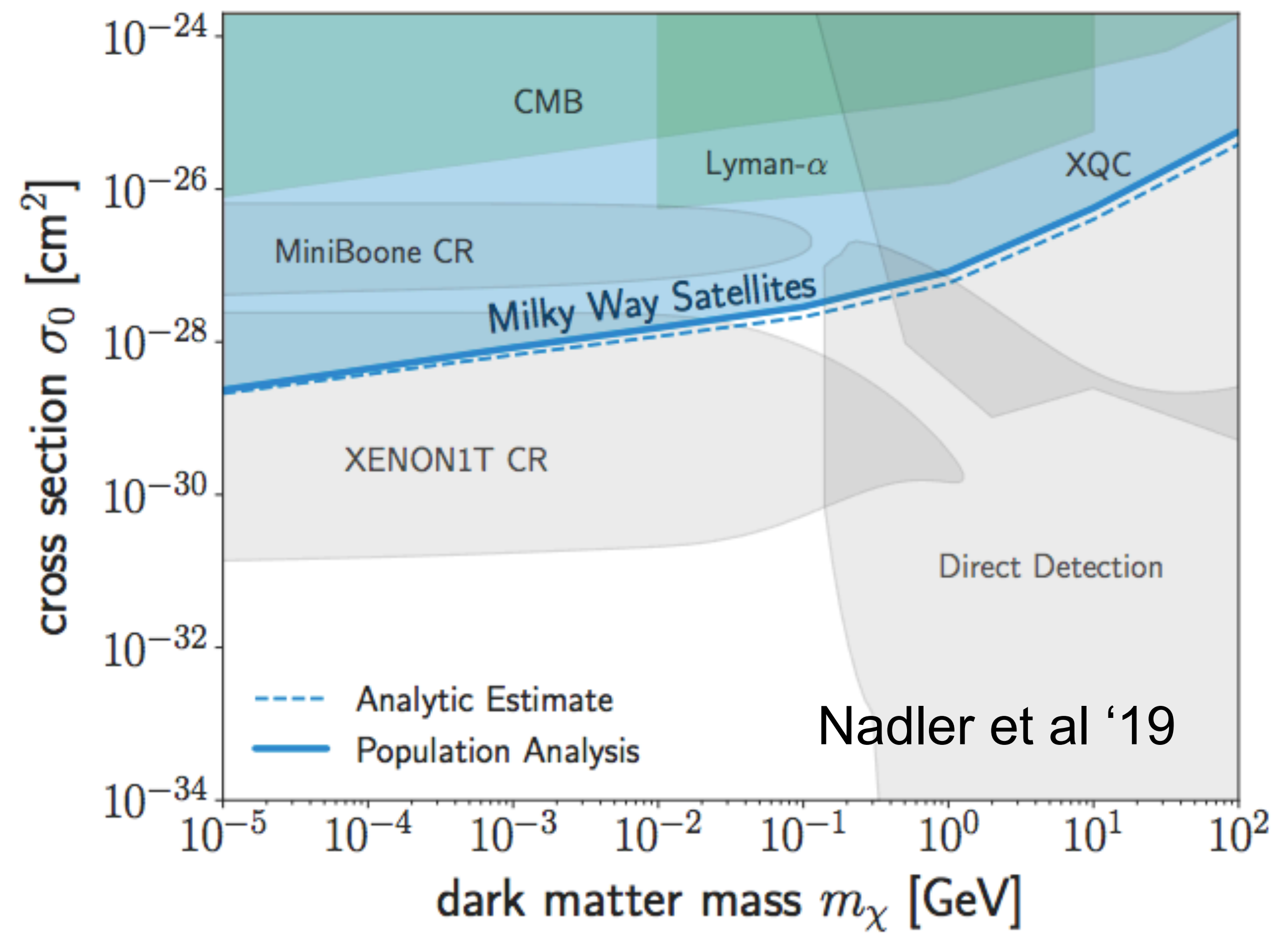


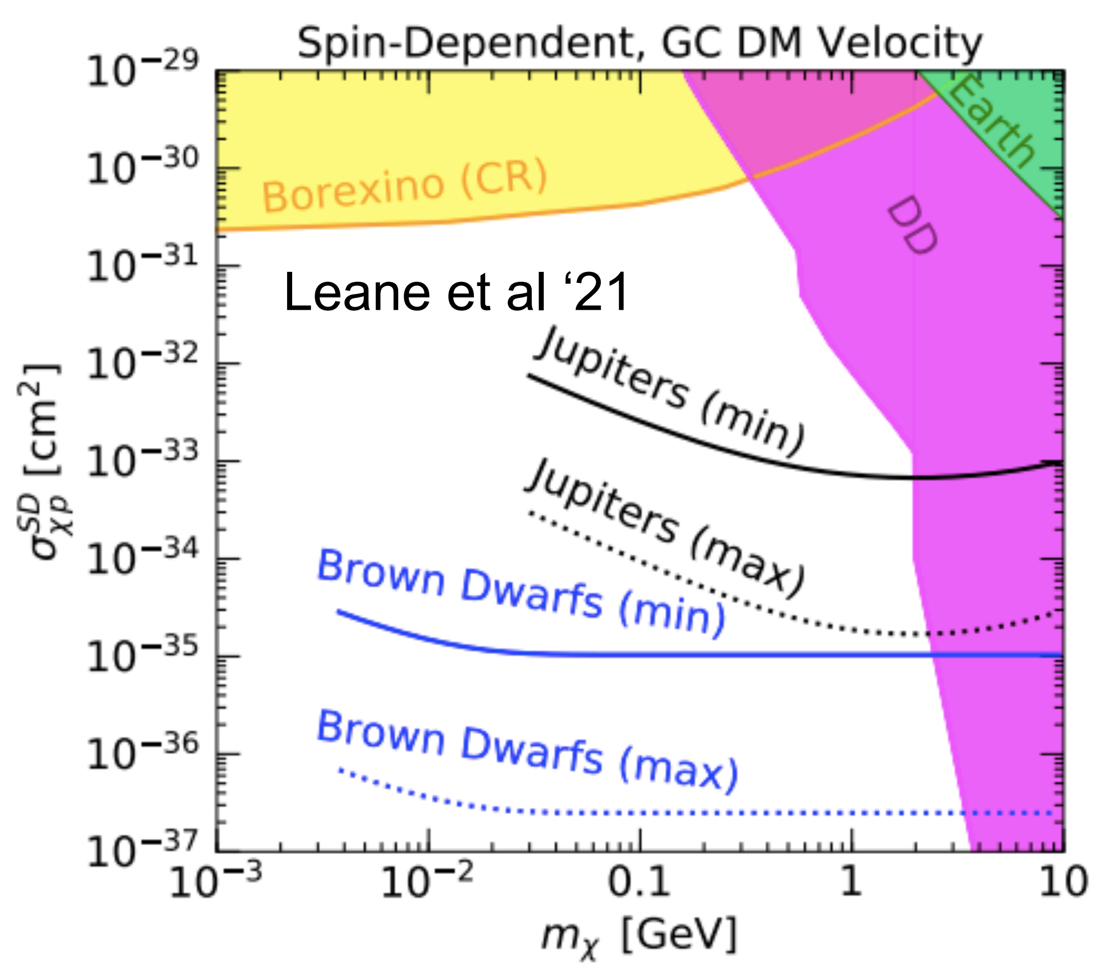
- Observations of gamma rays and (at high energies) neutrinos constrain DM decay to photons or hadronic final states to have lifetimes exceeding $10^{27\text{-}28}$ s, for the full range of masses from several keV to 10^{10} GeV.

- 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

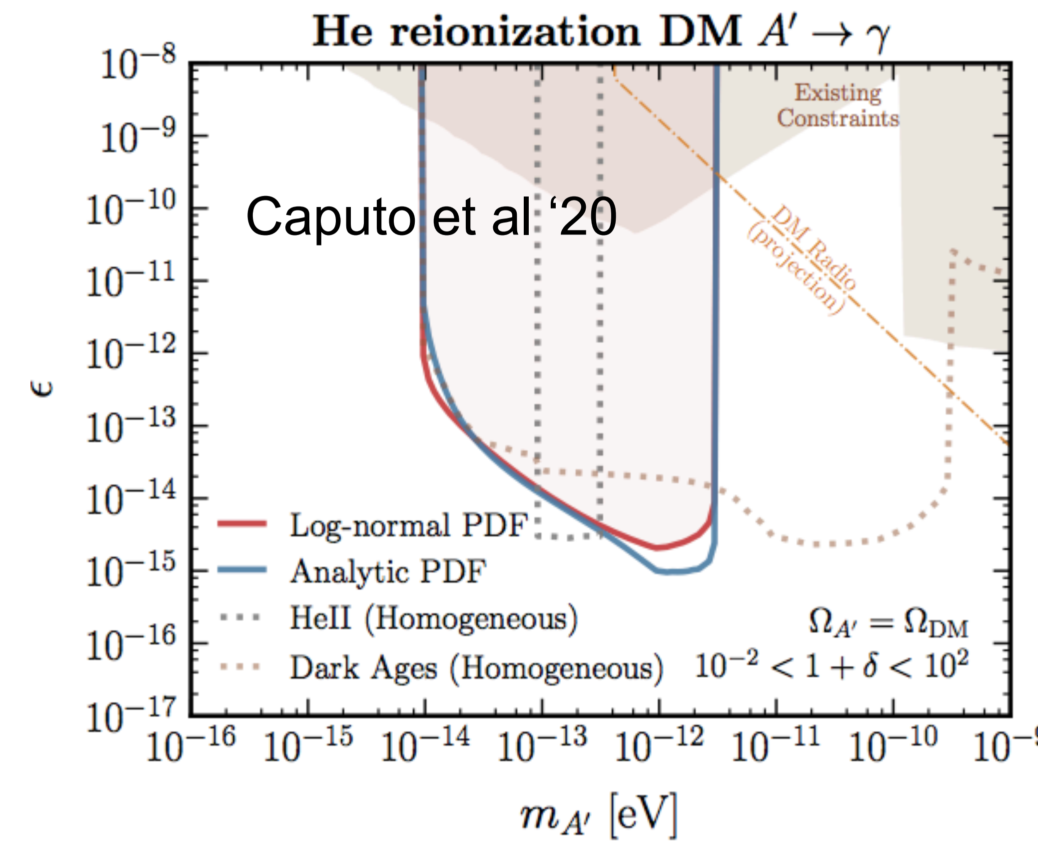
- Scattering is often considered the regime of direct detection, but can be tested in indirect searches as well
- Can exclude large cross-sections that might prevent DM from reaching terrestrial detectors
- Cosmology (CMB + large-scale structure) and astrophysics (Milky Way satellite population) sets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

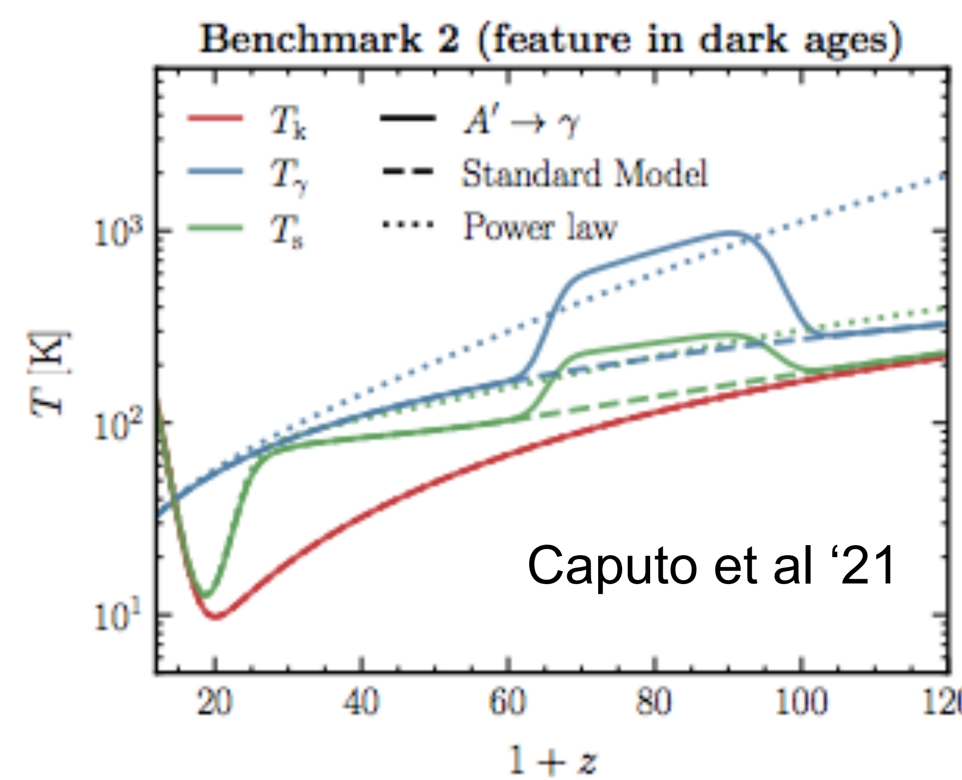




Constraints on oscillation

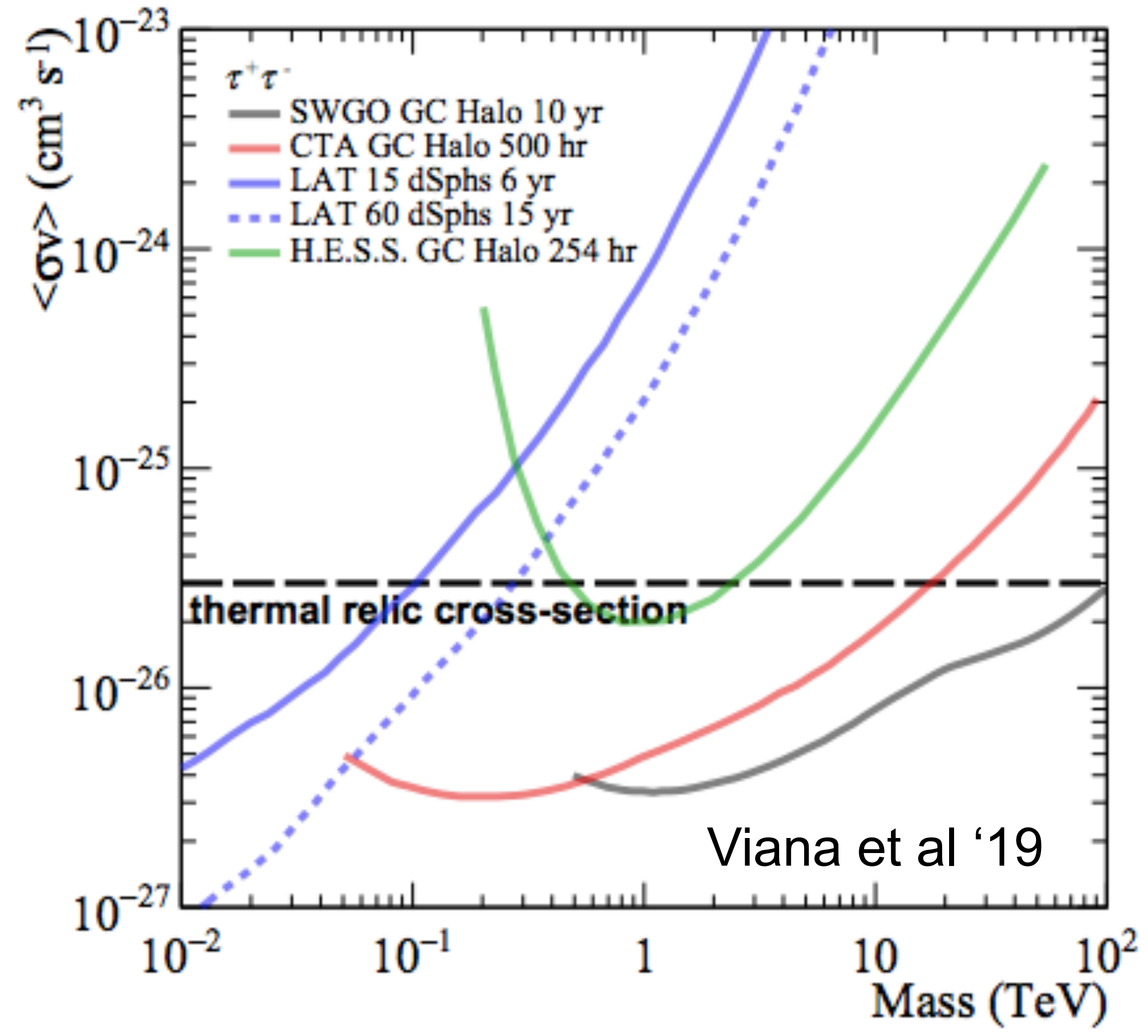
- If dark matter is an axion, it can oscillate into a photon in the presence of an external magnetic field
- Dark photons (may or may not be the DM) which mix with the SM photon could oscillate into SM photon, resonantly enhanced when dark photon mass = SM photon plasma mass
- Give rise to a wide range of astrophysical/cosmological signals [see talk by Ben Safdi tomorrow on axions]
- A few examples from cosmology (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]

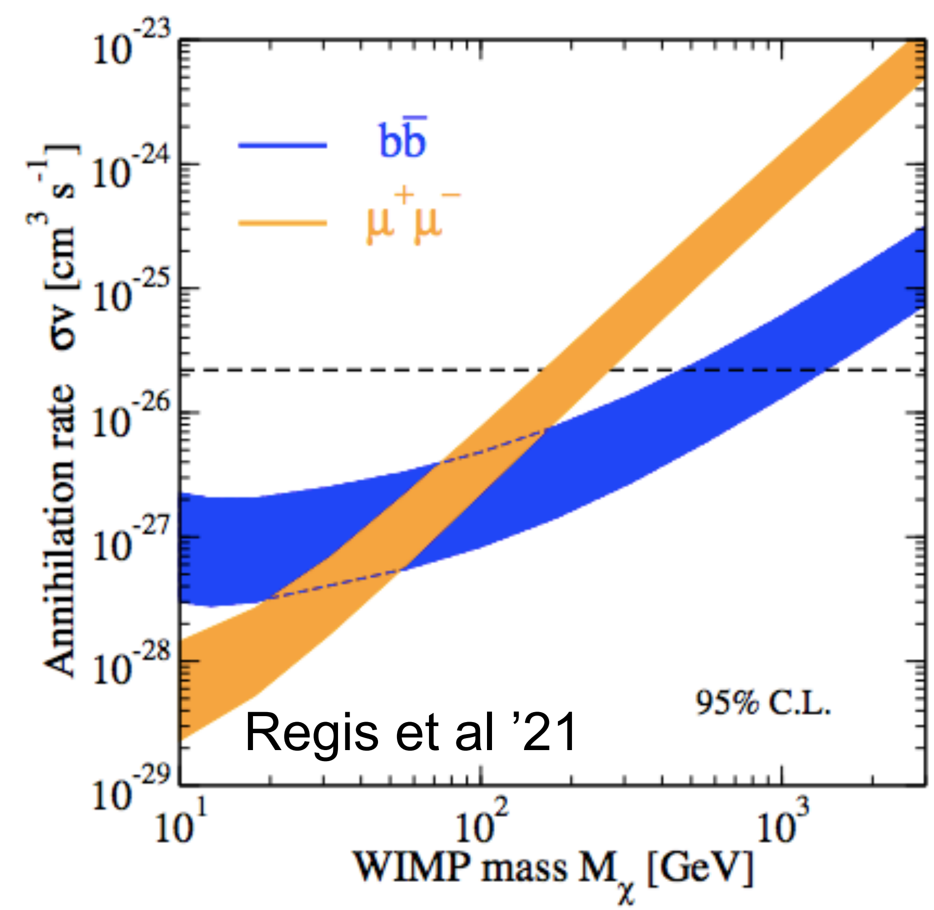




Annihilation beyond 100 GeV

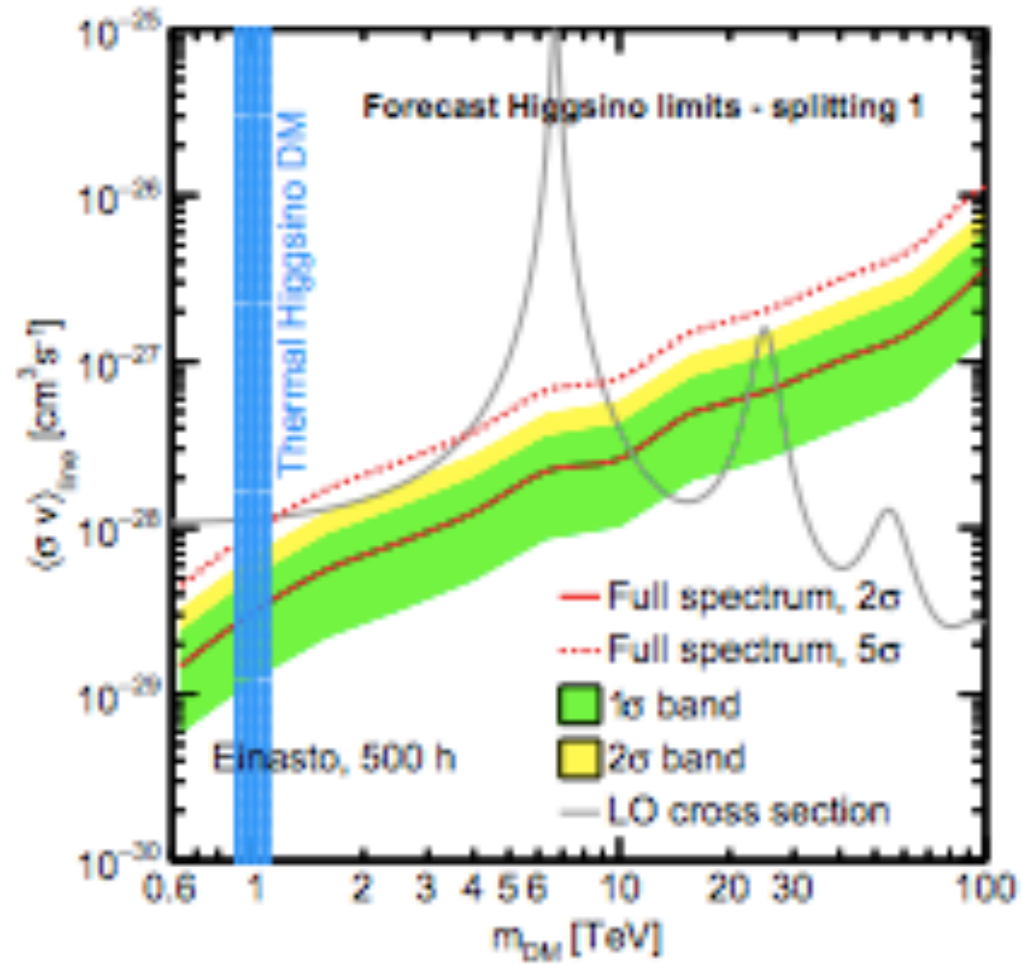
- Future ground-based gamma-ray telescopes have the possibility to probe thermal relic xsec up to O(100) TeV
- Some current searches have higher potential sensitivity, subject to systematic uncertainties
- HESS observations of the Galactic Center sensitive to O(TeV) thermal relics IF the inner Galaxy 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]



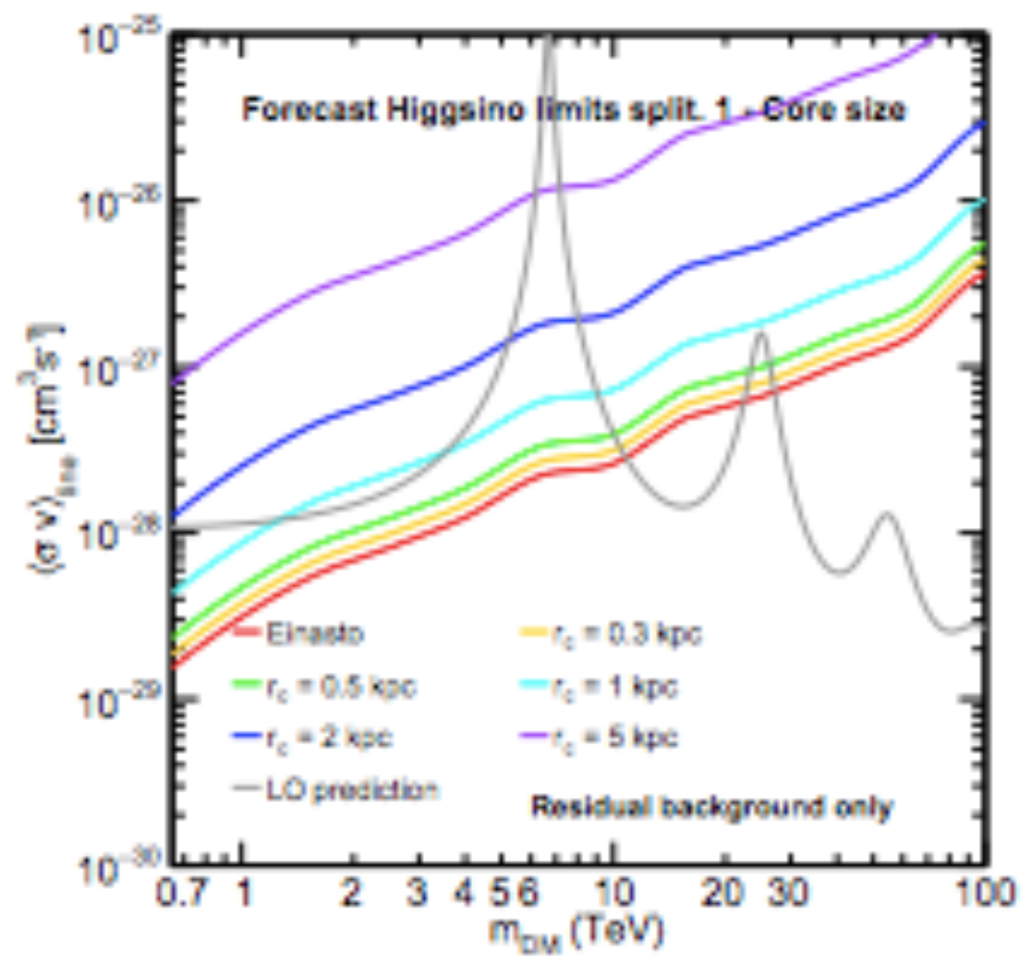


Electroweak DM

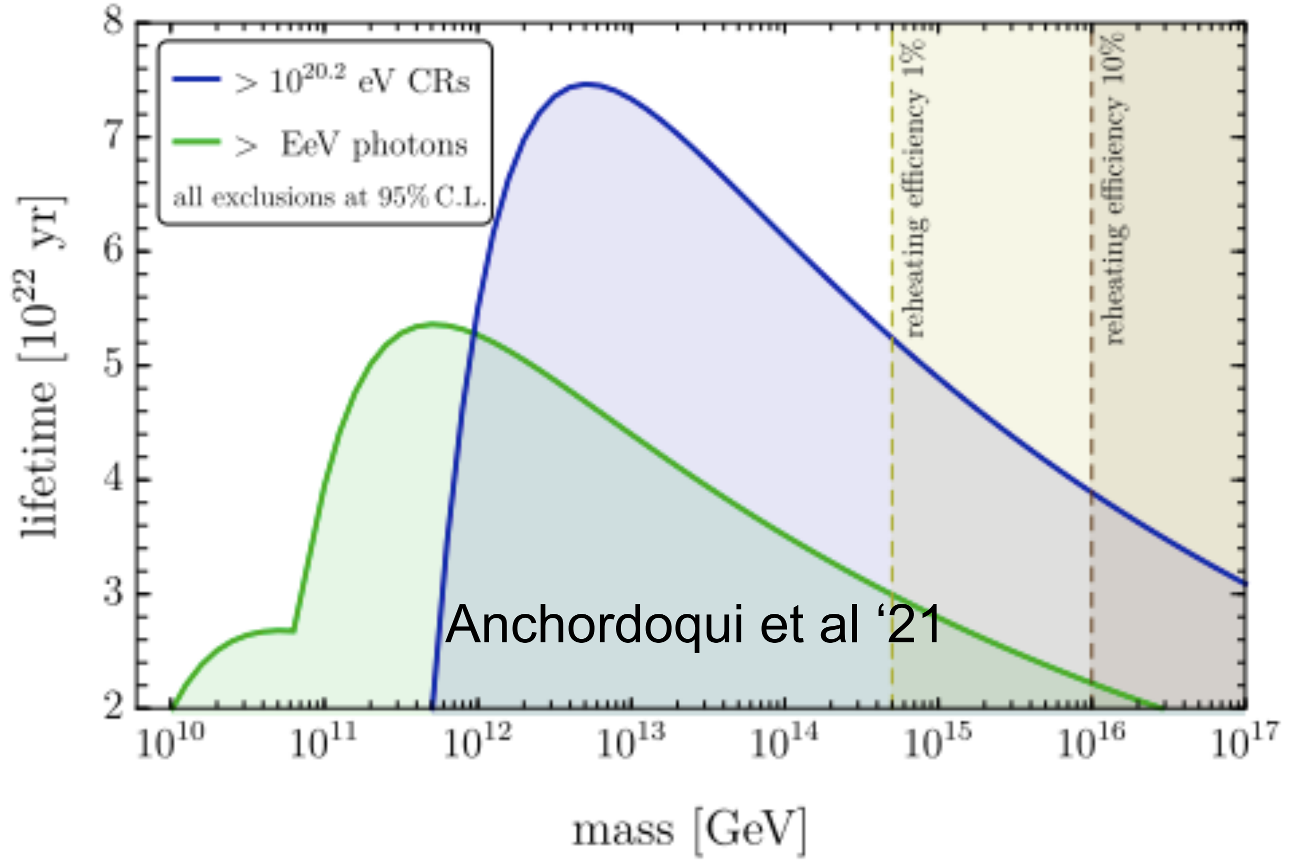
- Some of the simplest classic WIMP models remain unconstrained - DM could still interact through the W and Z bosons!
- One example is the <u>higgsino</u> - fermionic DM transforming as a $SU(2)_W$ doublet, appears in supersymmetry as the Higgs superpartner
- Obtains the correct relic density for $m_{DM} \sim 1$ 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



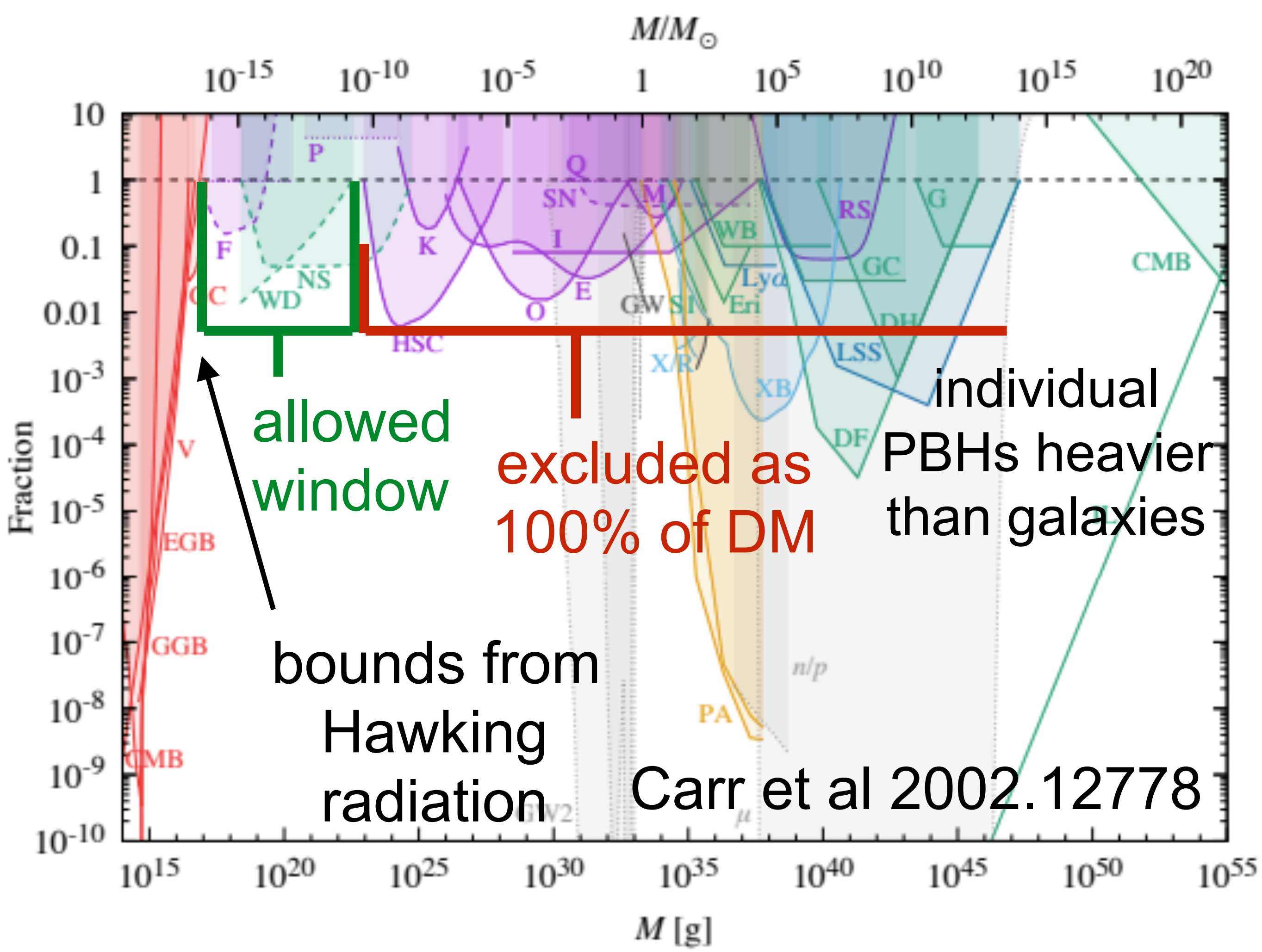
Above the thermal window: ultraheavy DM

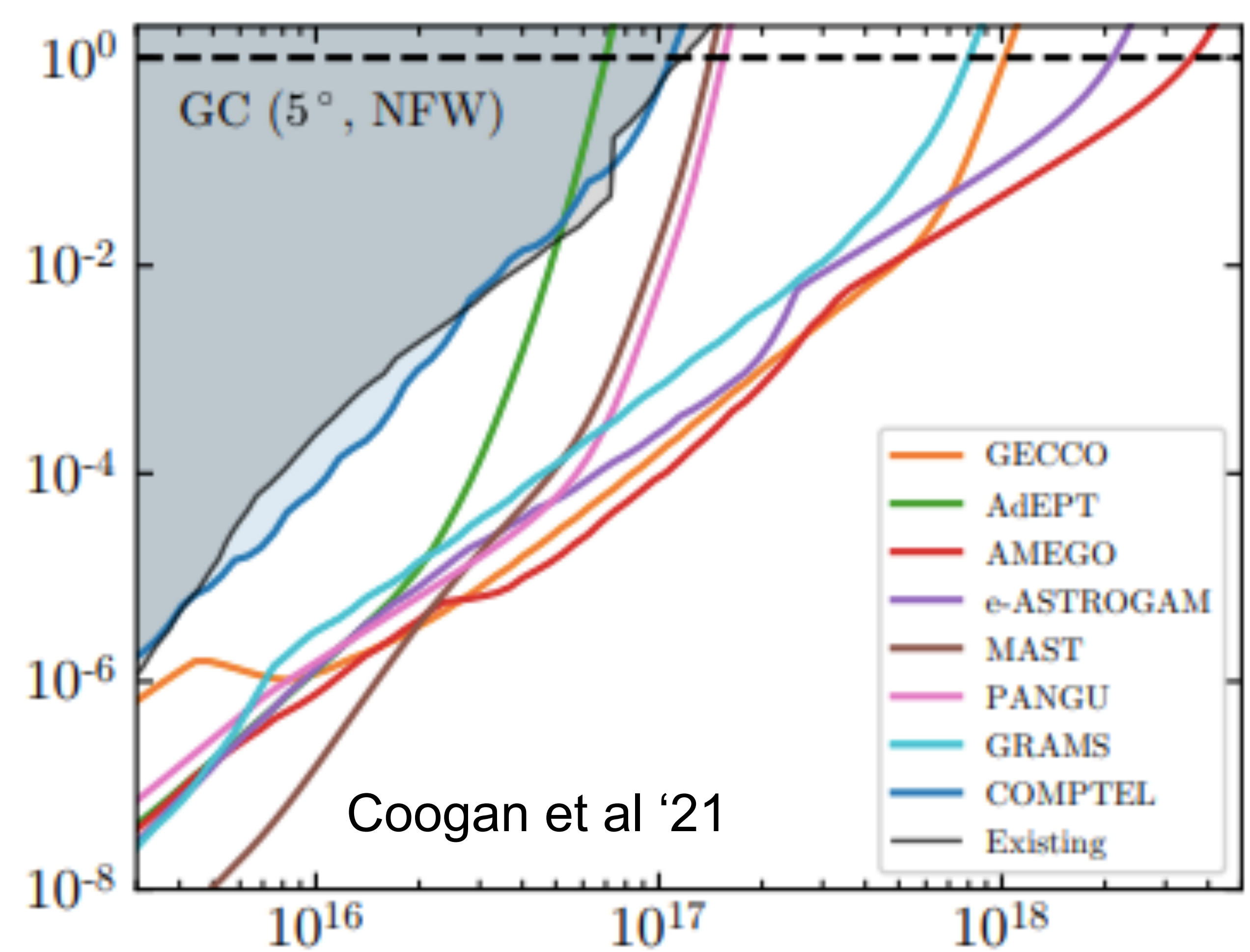


- In the presence of a long-range force, contributions from bound state formation, high partial waves can saturate and extend the unitarity bound for thermal relic DM, up to ~PeV [e.g. von Harling & Petraki '14, Smirnov & Beacom '19]
- (Much) higher masses can be achievable for thermal relic DM when 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 - $10^{17\text{-}23}$ 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.





Some excesses/anomalies

- Annihilation/decay?
  - Galactic Center excess (GCE) seen in Fermi gamma-rays [Goodenough & Hooper '09]
  - 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]
- Scattering/oscillation? 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 Galactic Center excess (GCE)

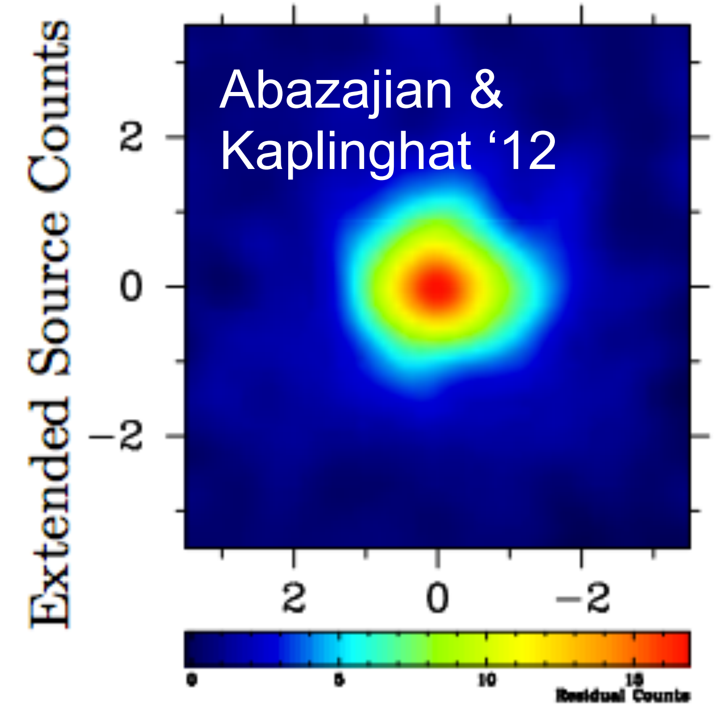
- Excess of gamma-ray photons, peak energy ~1-3 GeV, in the region within ~10 degrees of the Galactic Center.

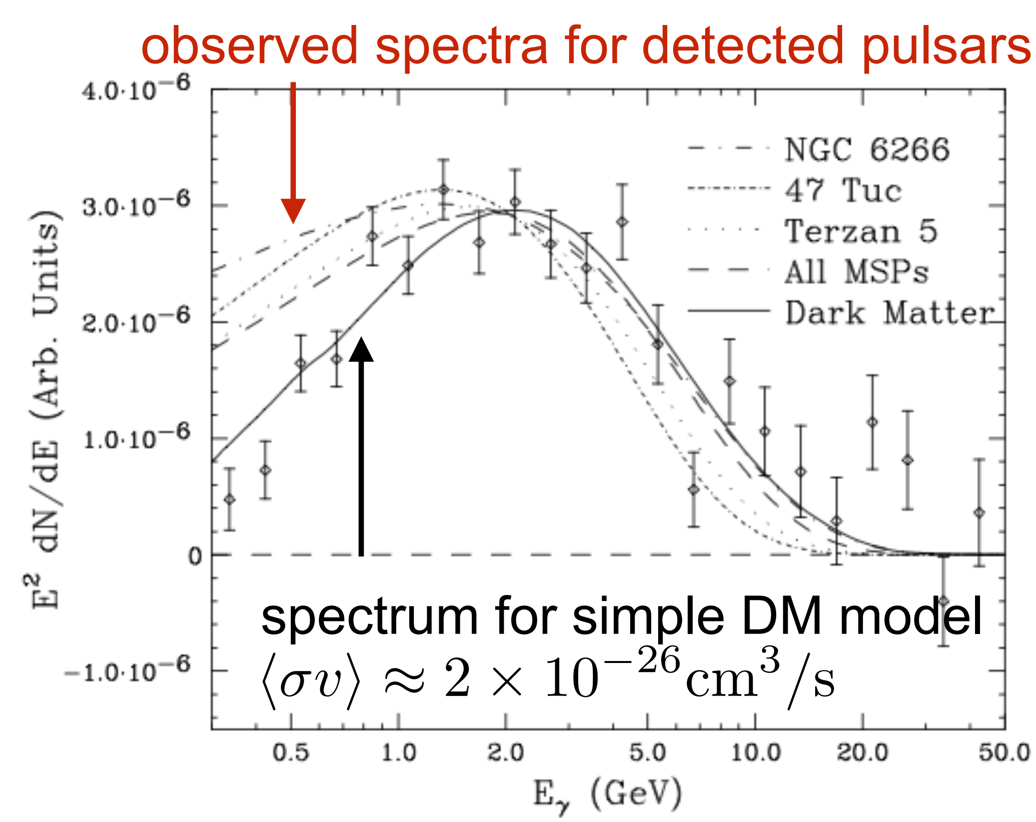
- Discovered by Goodenough & Hooper ’09, confirmed by Fermi Collaboration in analysis of Ajello et al ’16 (and many other groups in interim).

- 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

- See talk by Dan Hooper later today

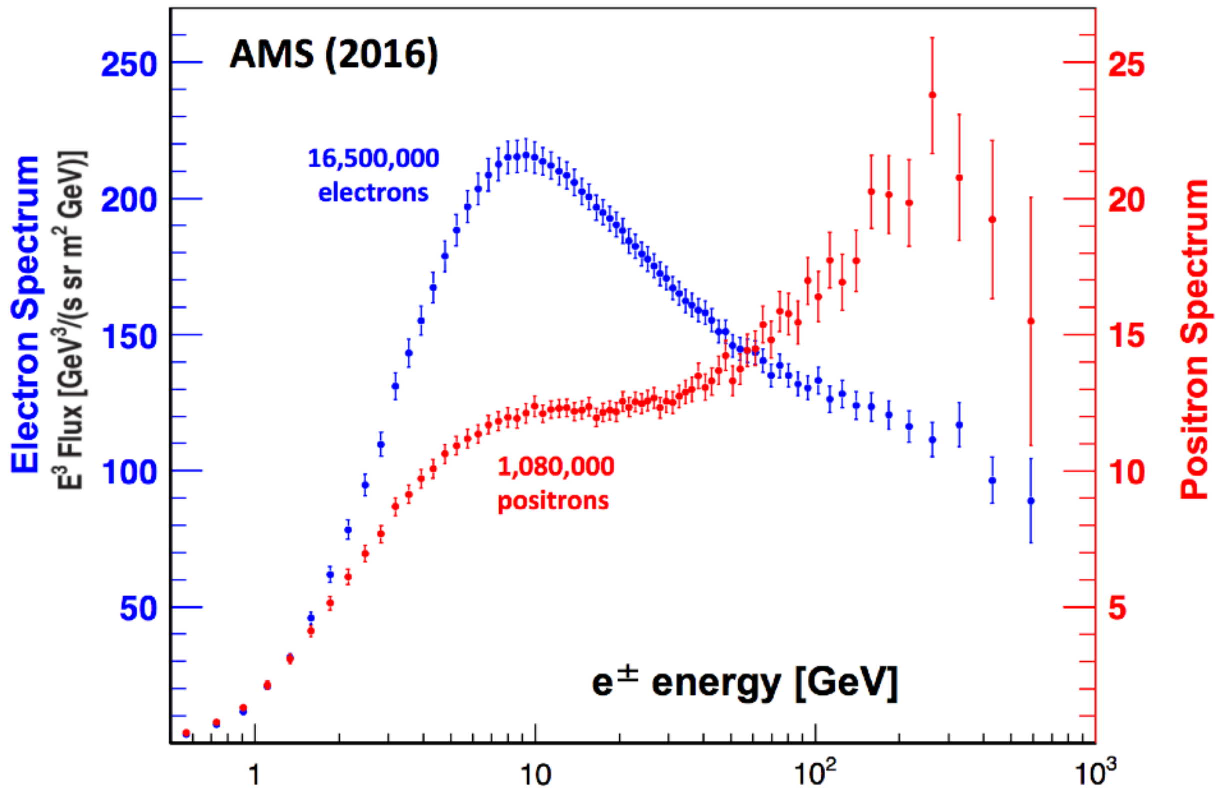




Daylan, TRS et al ‘16

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



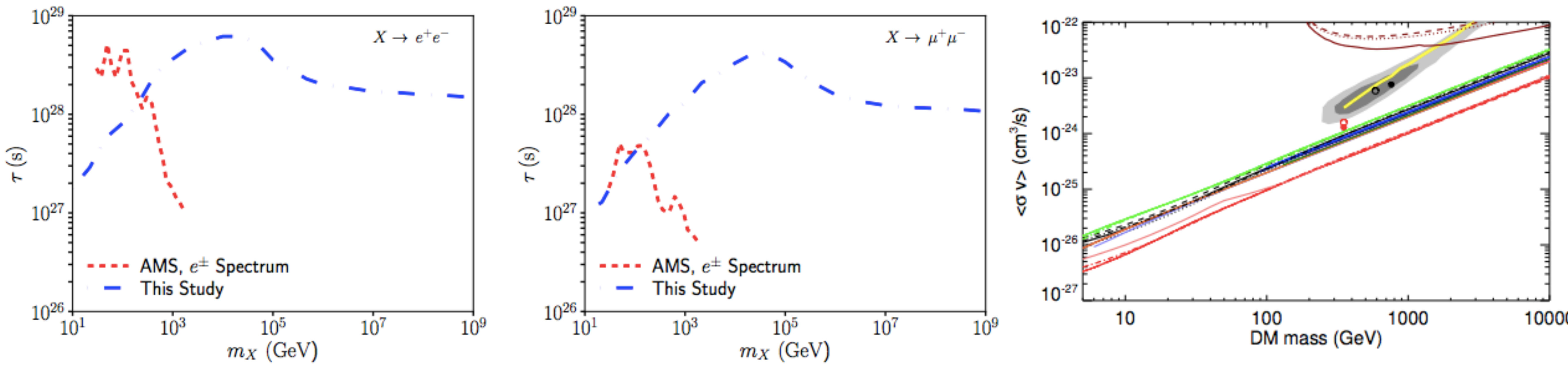
Sam Ting, 8 December 2016, CERN colloquium

- 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

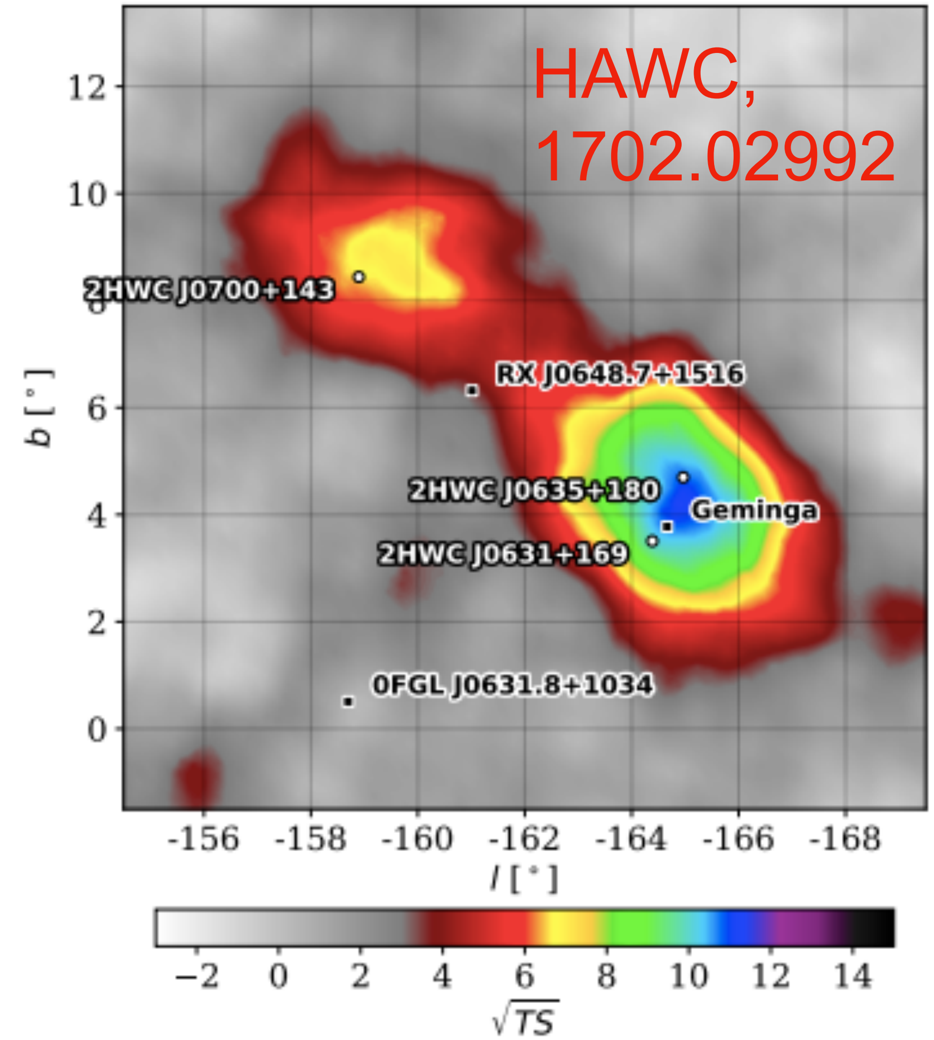
- DM annihilation interpretation is challenging due to null results in CMB searches + gamma-ray searches - needs extra ingredients (e.g. large DM overdensity, either nearby or combined with annihilation to a long-lived particle, Kim et al 1702.02944 has an example)

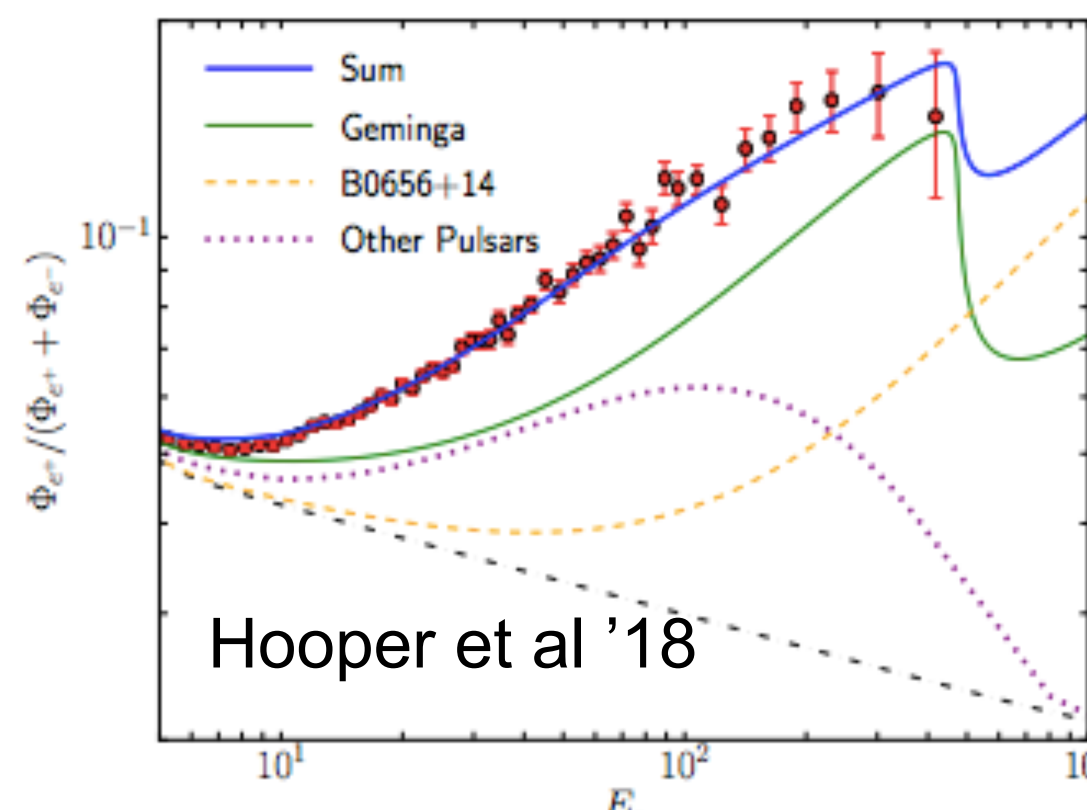
- DM decay interpretation may be easier to reconcile, but tight constraints from galaxy clusters, extragalactic gamma-ray background [e.g. Blanco & Hooper '19]



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^-

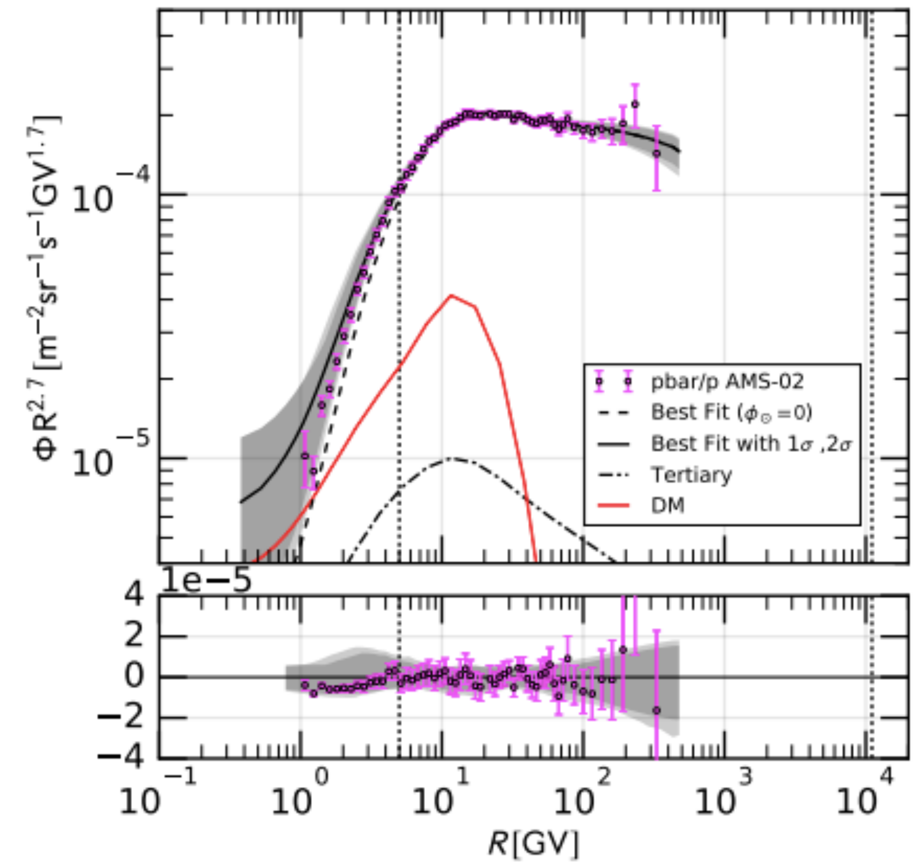


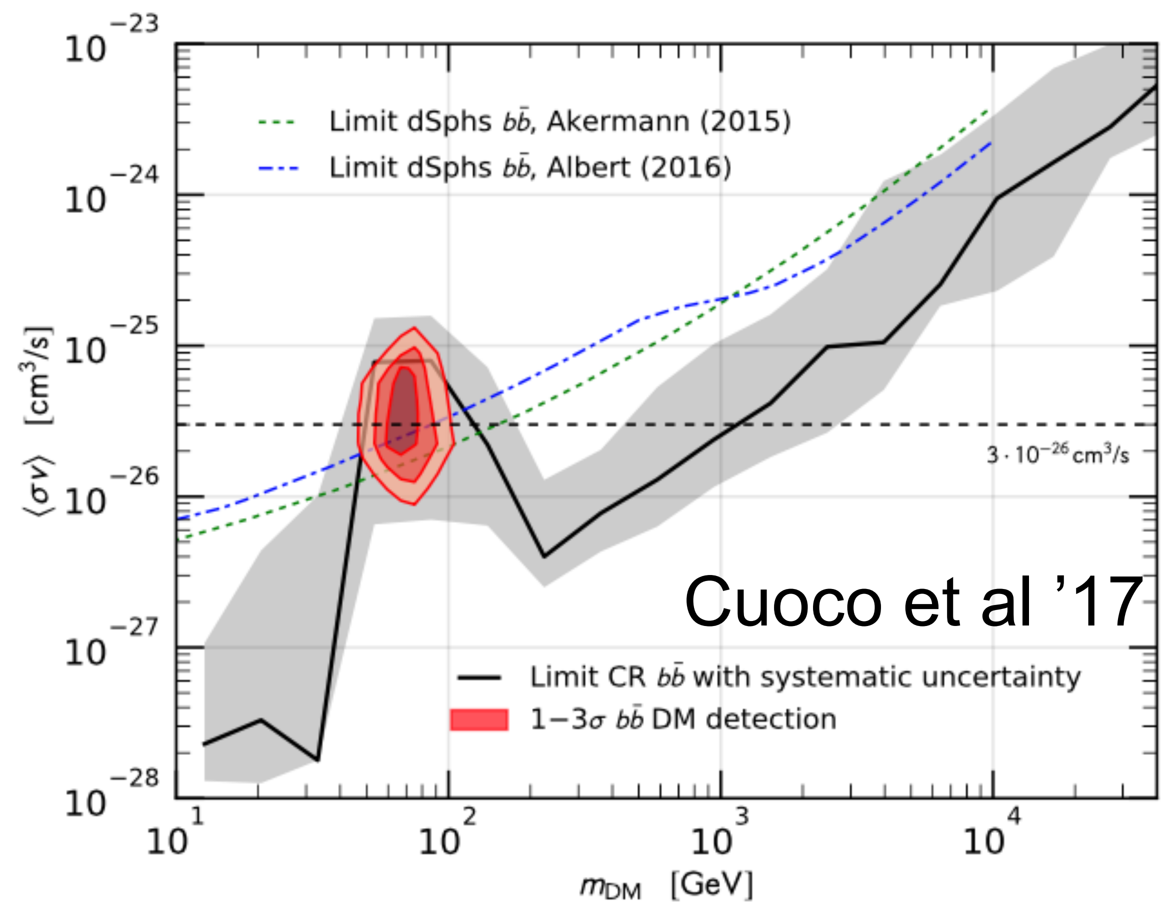


Note: this is a plausible model, not an a priori prediction

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



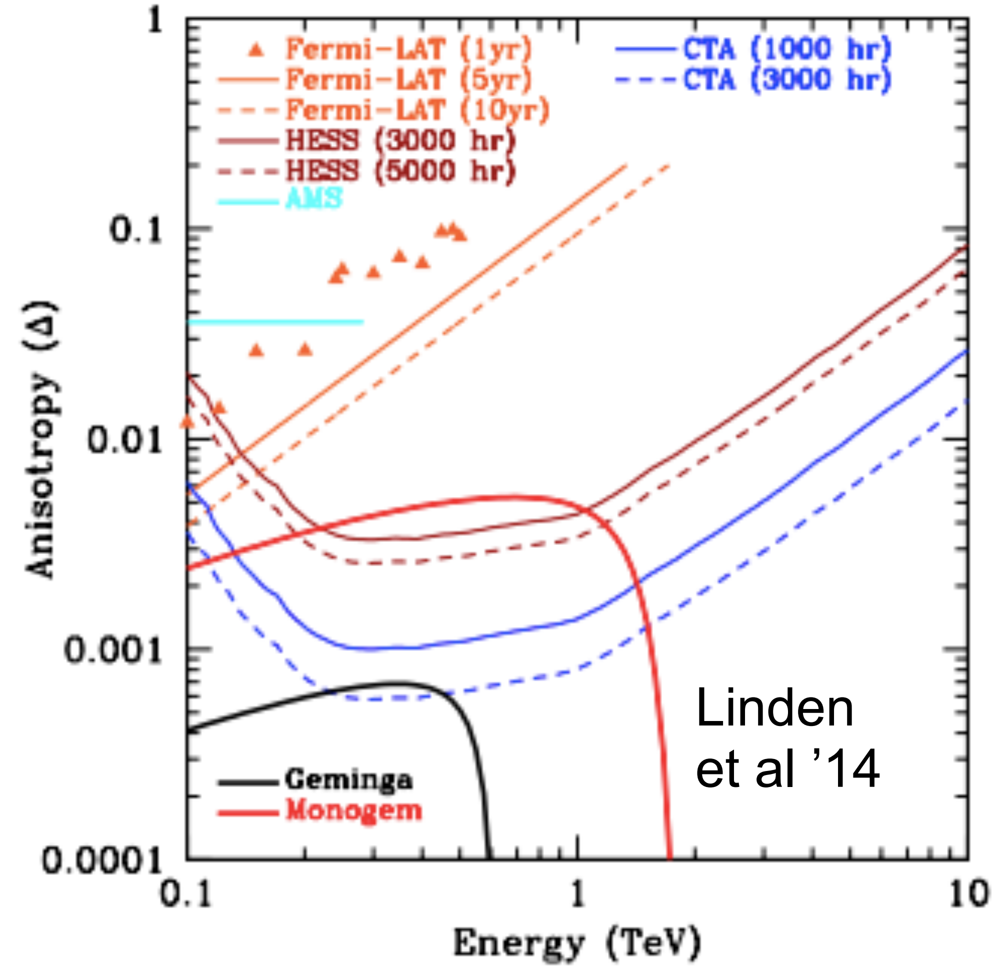


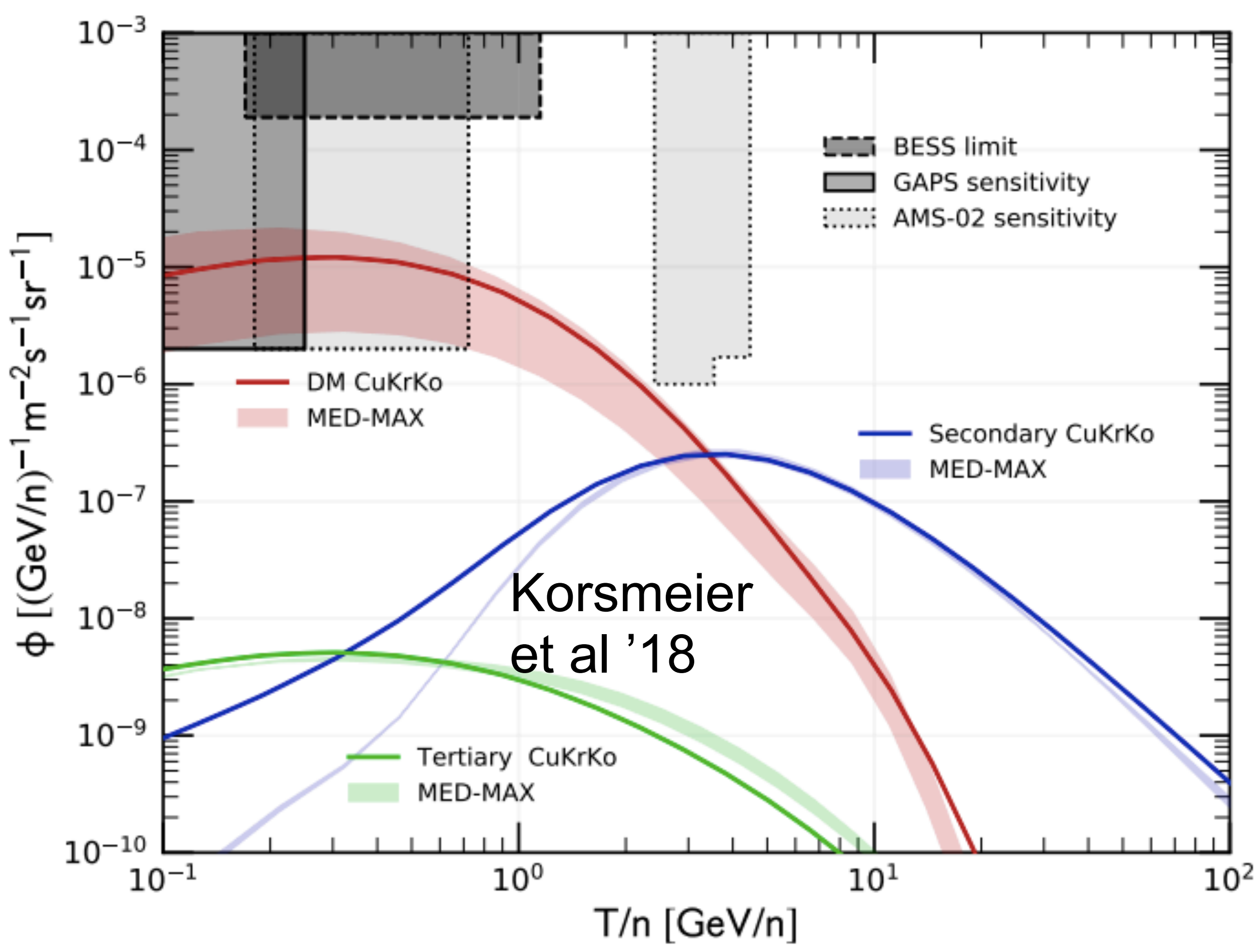
Trouble with correlations

- 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?

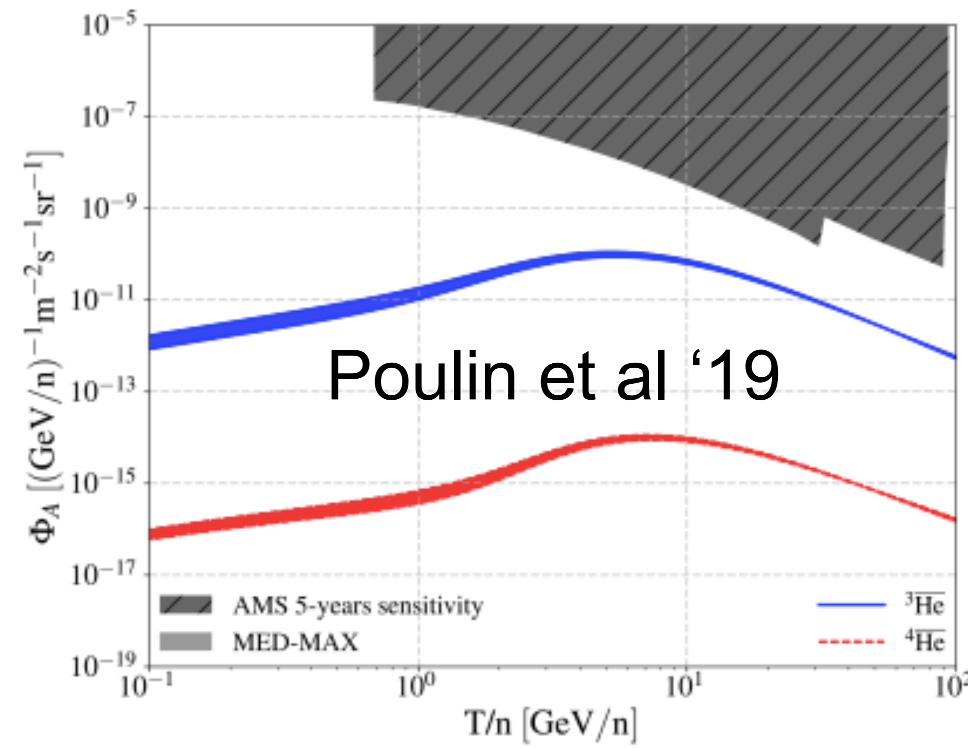
- Very active effort to find more TeV halos around pulsars & determine how common they are in the Galaxy
- Anisotropy in arrival direction is a possible probe, but scrambling of arrival directions by B-field makes detection challenging - may be testable using air Cherenkov telescopes [Linden et al '14]
- 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].

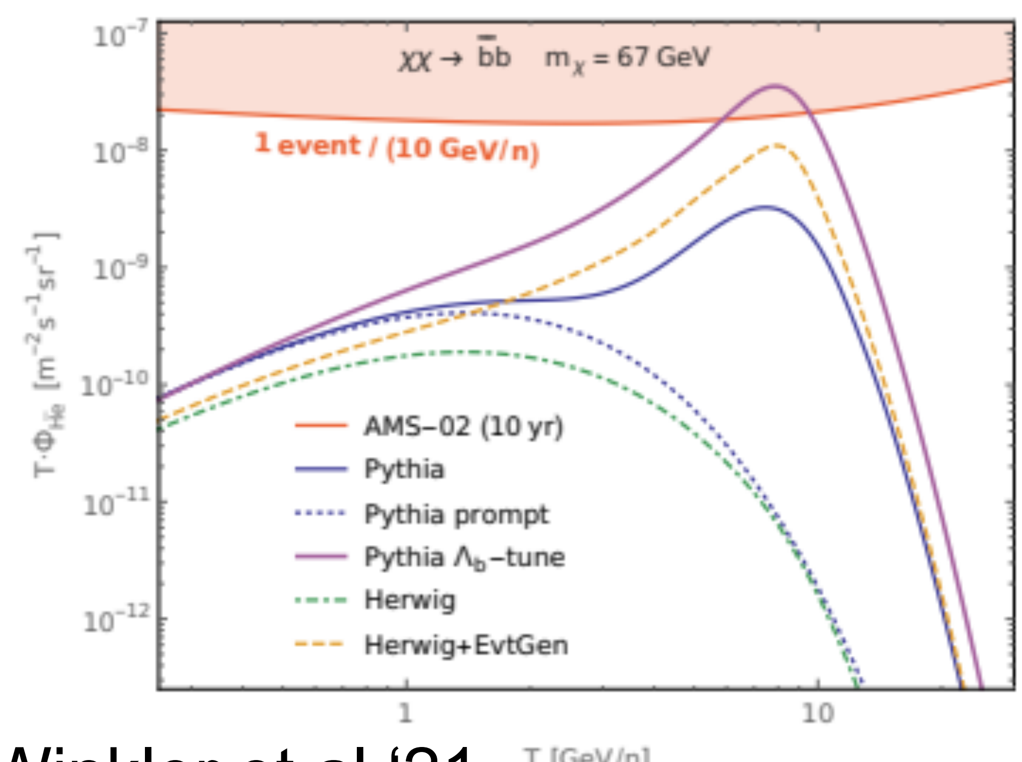




AMS-02 antihelium events

- 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

- Observed originally in stacked galaxy clusters [Bulbul et al ’14, Boyarsky et al ’14], subsequently in other regions.

- Individual signals are modestly significant (~4σ).

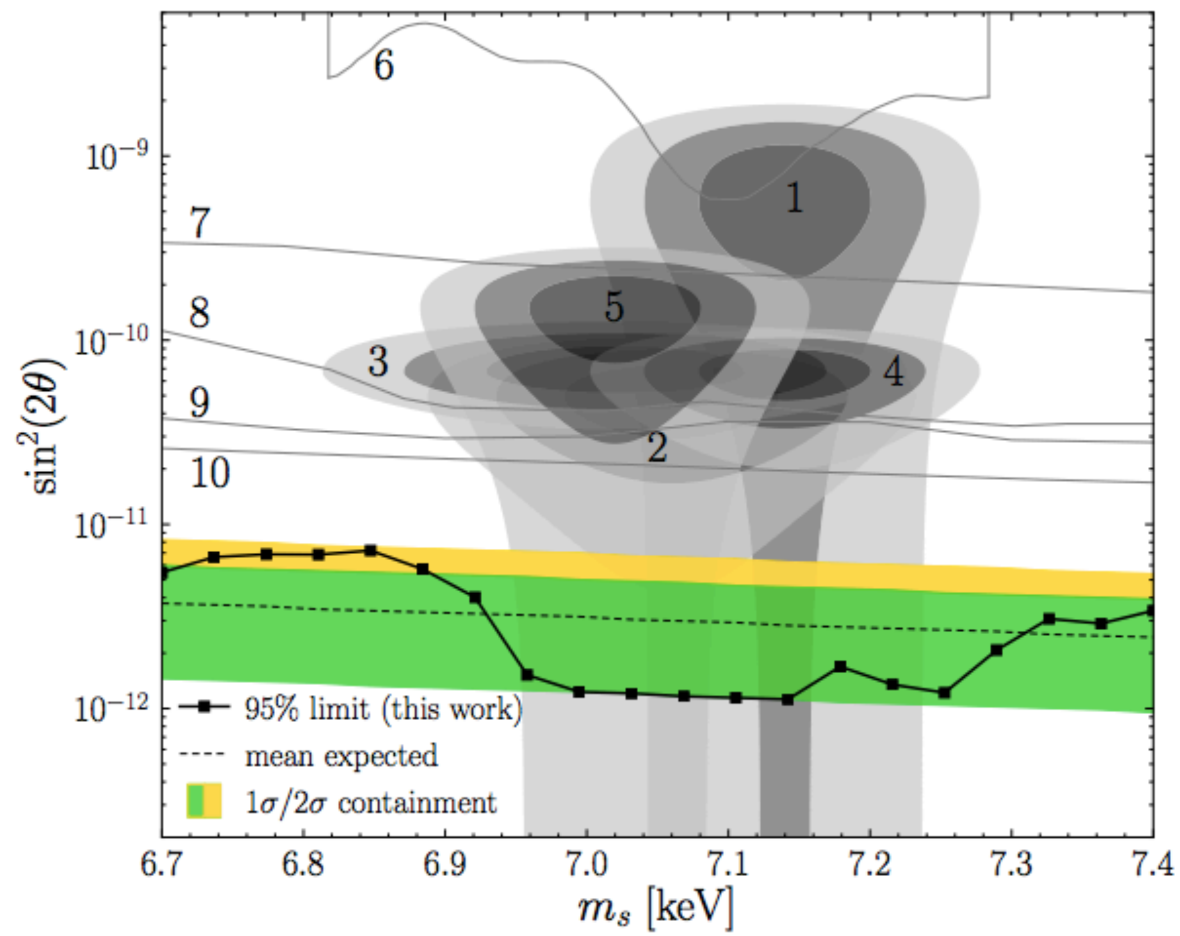
- Simplest DM explanation: 7 keV sterile neutrino decaying into neutrino+photon. (Other explanations involving annihilation, oscillations etc are possible.)

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

- Simple decay explanation seems inconsistent with null results in other searches, e.g. 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.

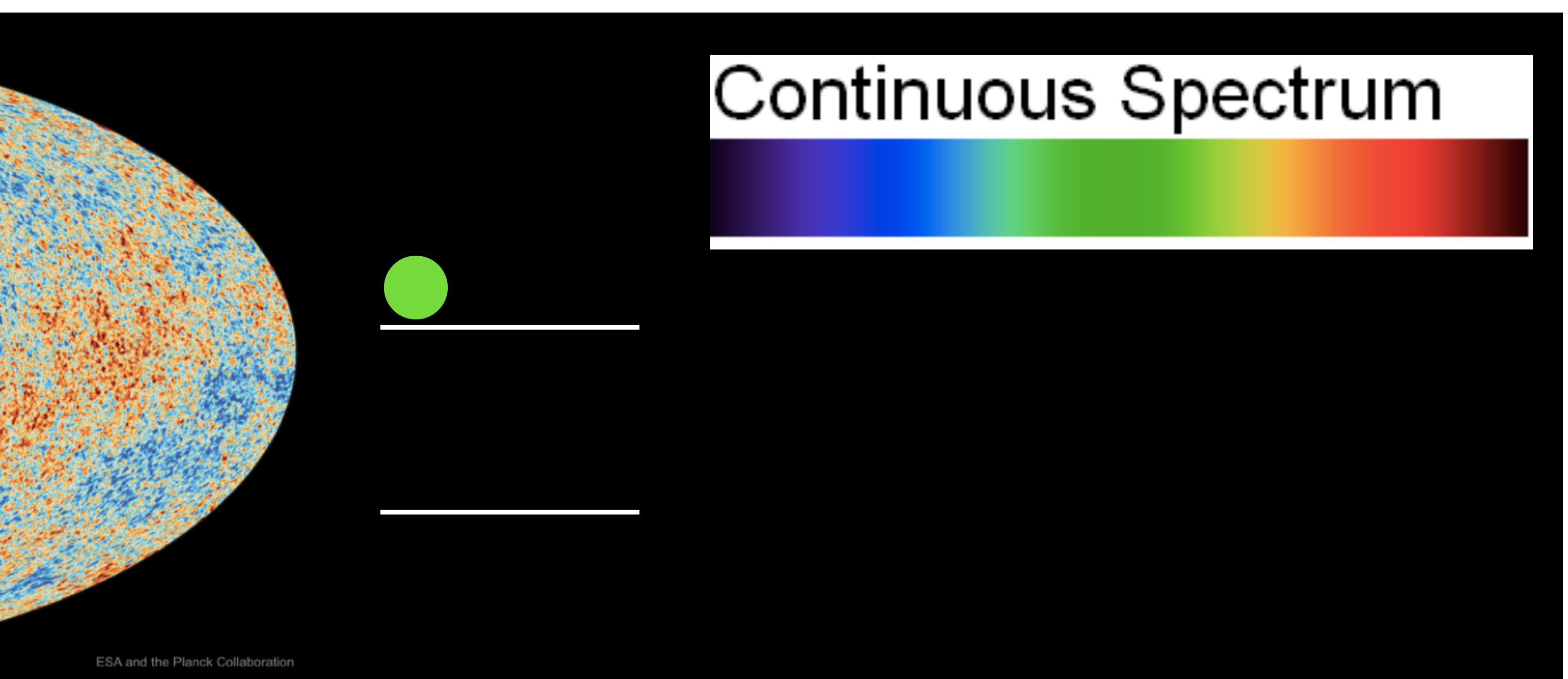
- Future X-ray experiments (eXTP, XRISM, Micro-X, possibly eROSITA) should have the sensitivity to see the signal, in some cases with improved energy resolution.



Dessert et al ’20

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.
- T_S expected to be coupled to T_{gas} by Lyman-alpha photons from first stars
- 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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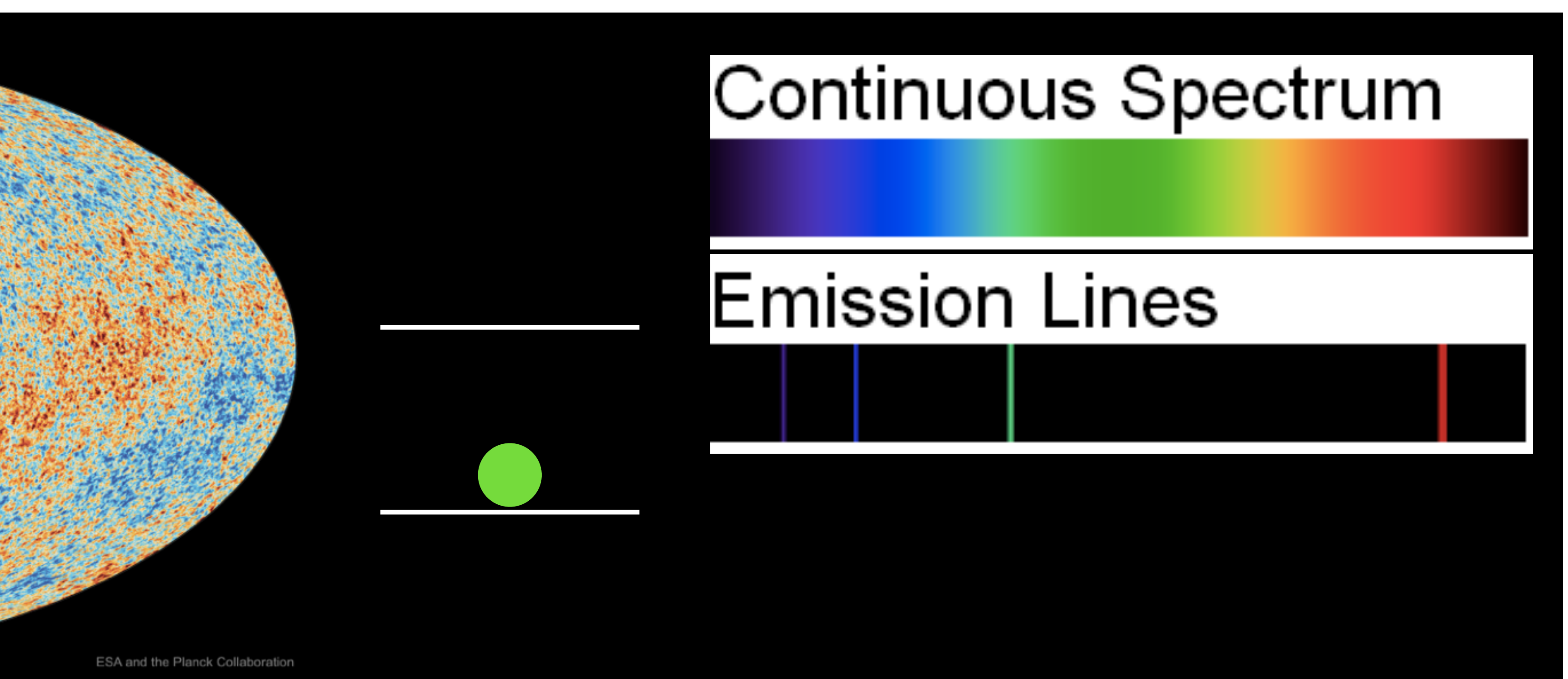

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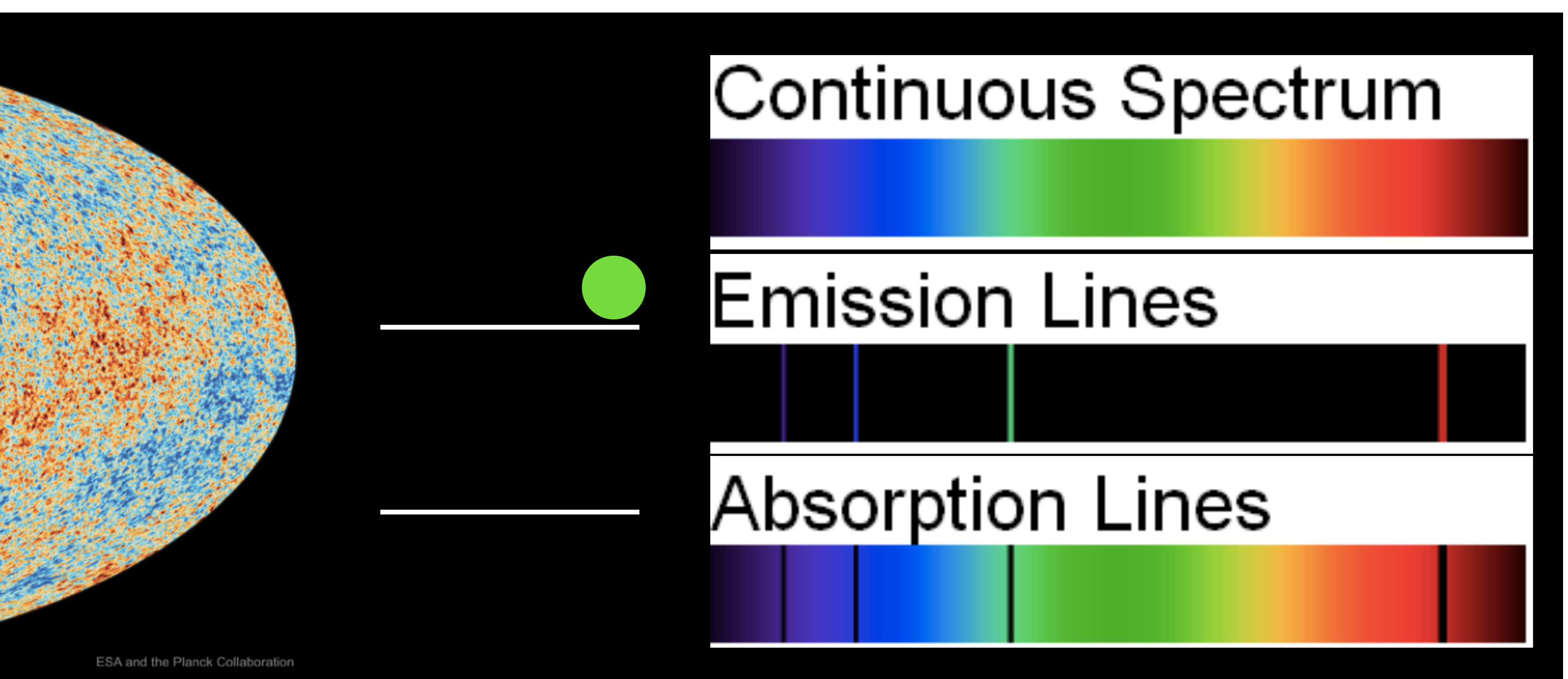

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The EDGES absorption trough

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

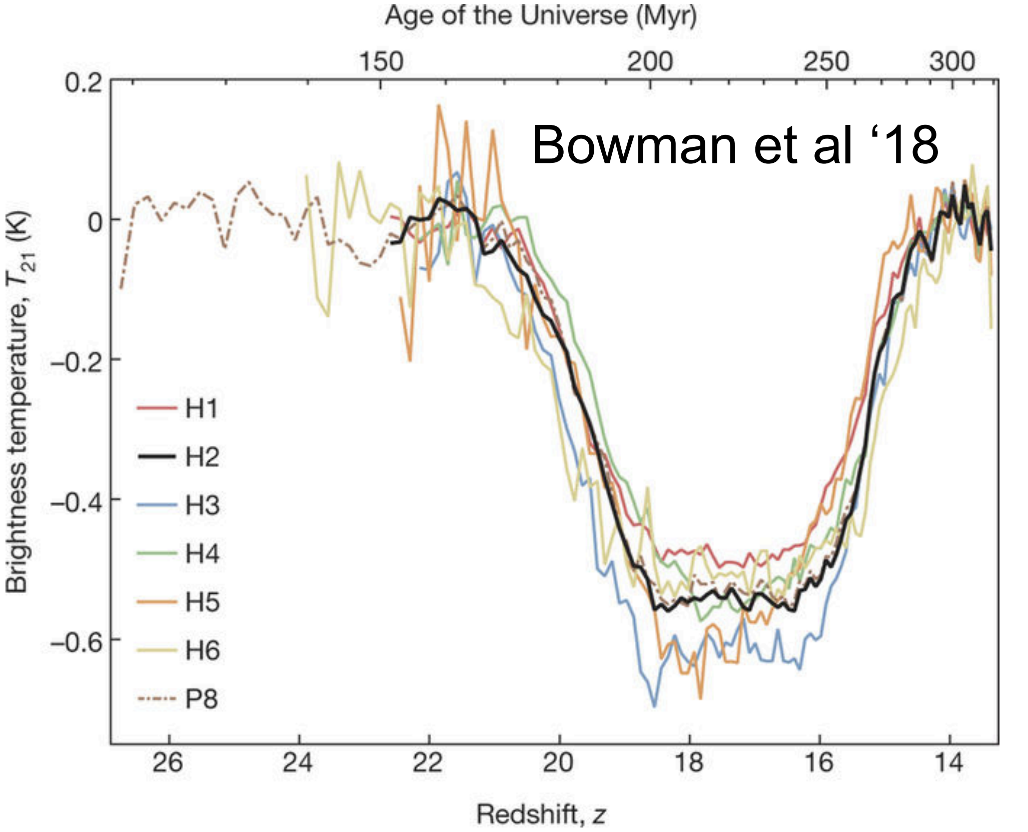
- The Experiment to Detect the Global Epoch-of-reionization Signature (EDGES) has claimed a detection of the first 21cm signal from the cosmic dark ages [Bowman et al, Nature, March '18]

- 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].

- Many other experiments seeking to measure primordial 21cm radiation, could potentially provide cross-checks (e.g. EDGES, LOFAR, MWA, PAPER, SARAS, SCI-HI, HERA)



What new physics could cause this?

- Three broad options:
  - reduce T_{gas} - need some kind of heat sink, or earlier decoupling [e.g. Munoz et al ’18, Berlin et al ’18, Barkana et al ’18]
  - 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)
  - requires light DM (for large number density) with large DM-SM scattering cross section
  - some parameter space open for millicharged DM making up a sub-fraction of DM [e.g. Boddy et al ’18, Kovetz et al ’18, Liu et al ‘19]
- In the second category, can (for example) exploit resonant oscillation of dark photons into visible photons; may need a dark decaying species to generate dark photon bath

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