Dark Matter Indirect Detection: Lecture 2

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The Almost Invisibles: Exploring the Weakly Coupled Universe
SLAC Summer Institute 2020
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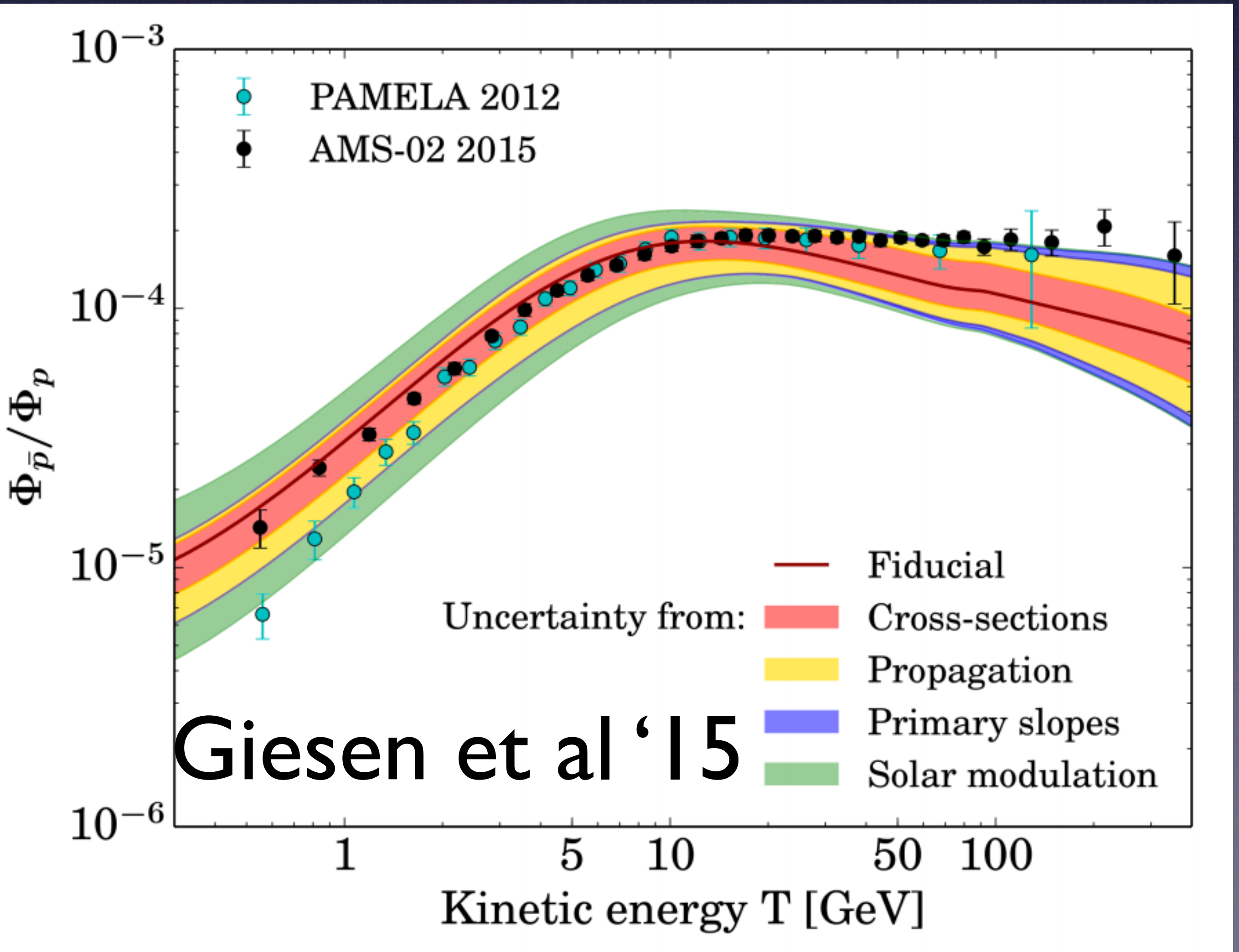
Goals: lecture 2

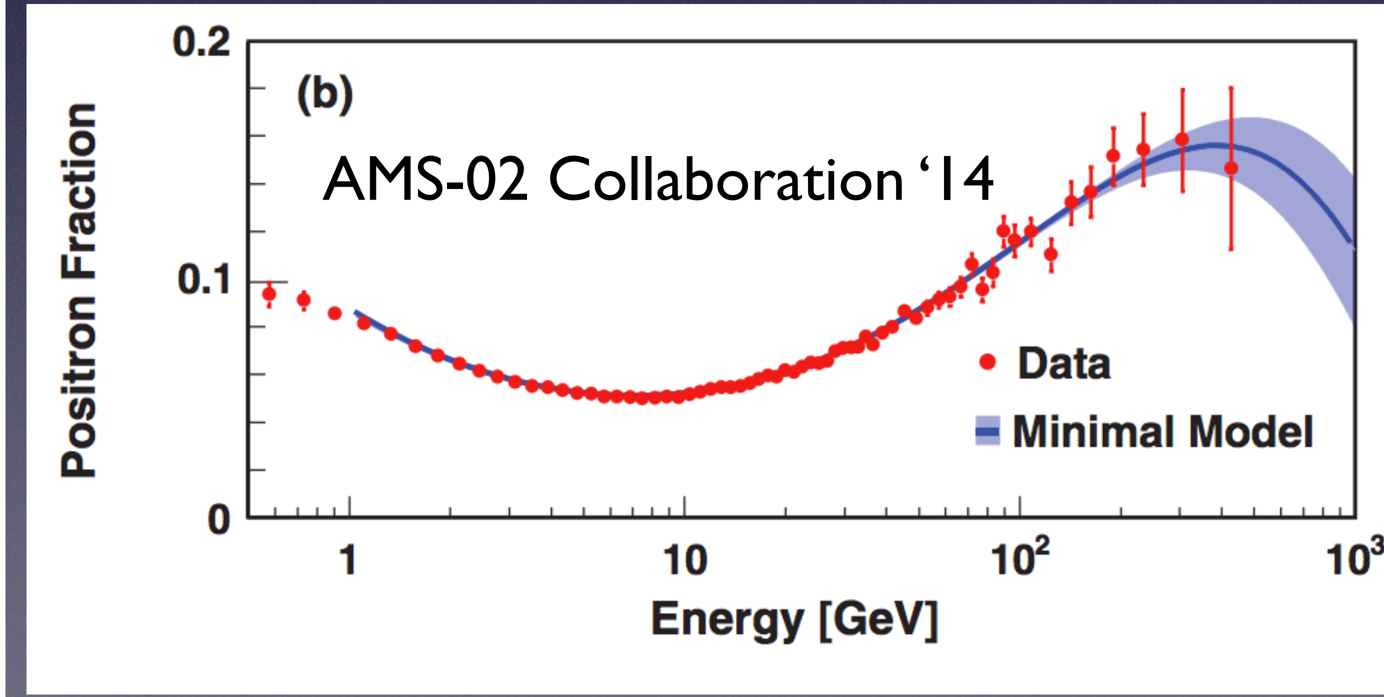
- Summarize limits from cosmic-ray searches
- Estimate the energy injection from DM in the early universe, and its potential effects on the visible matter and radiation
- Summarize current limits on DM annihilation/decay from observations of the early universe
- Outline current claims of possible signals in various indirect searches, and comment on the arguments for and against a dark matter origin

Cosmic-ray limits

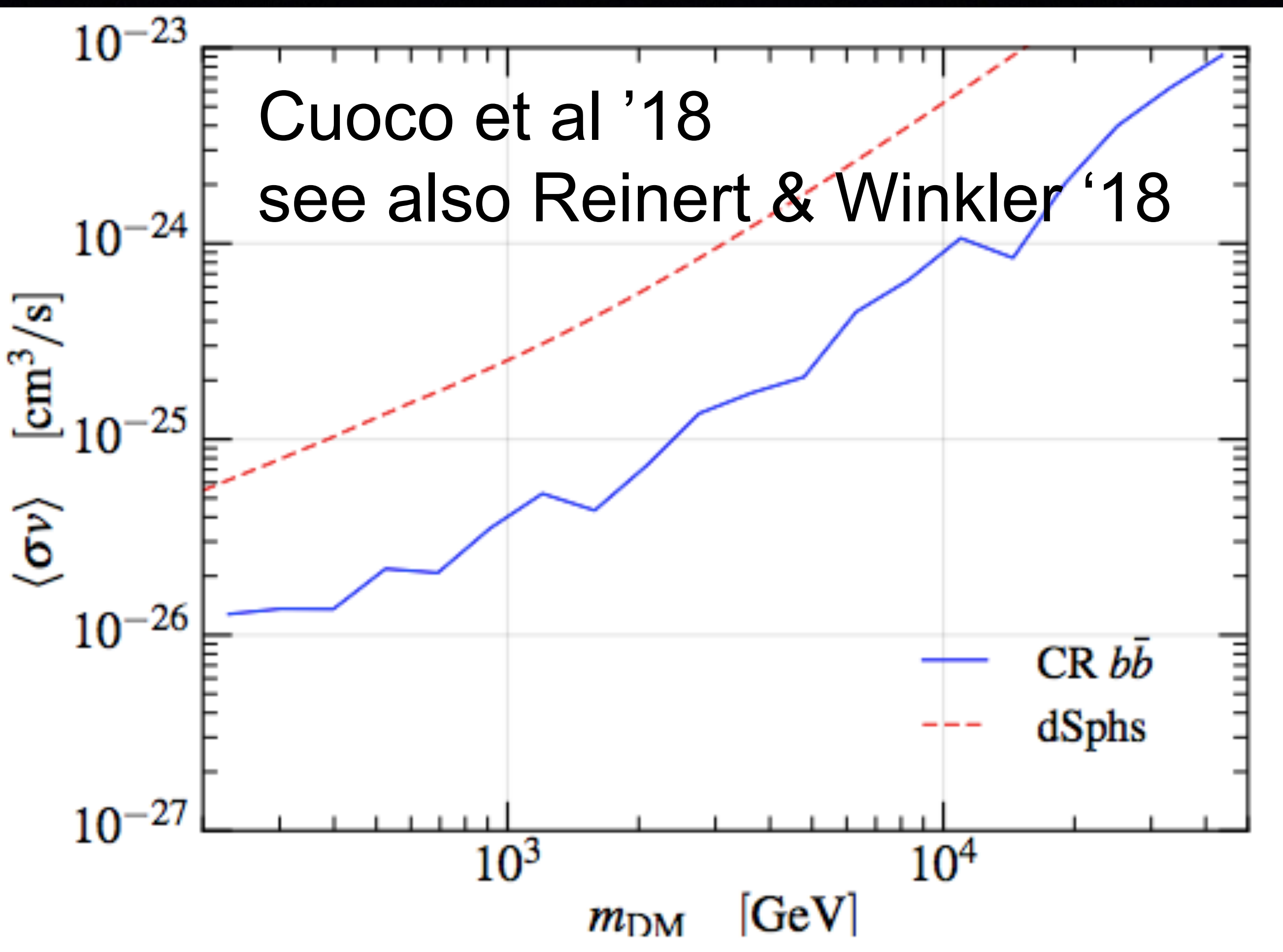
Antiprotons and positrons

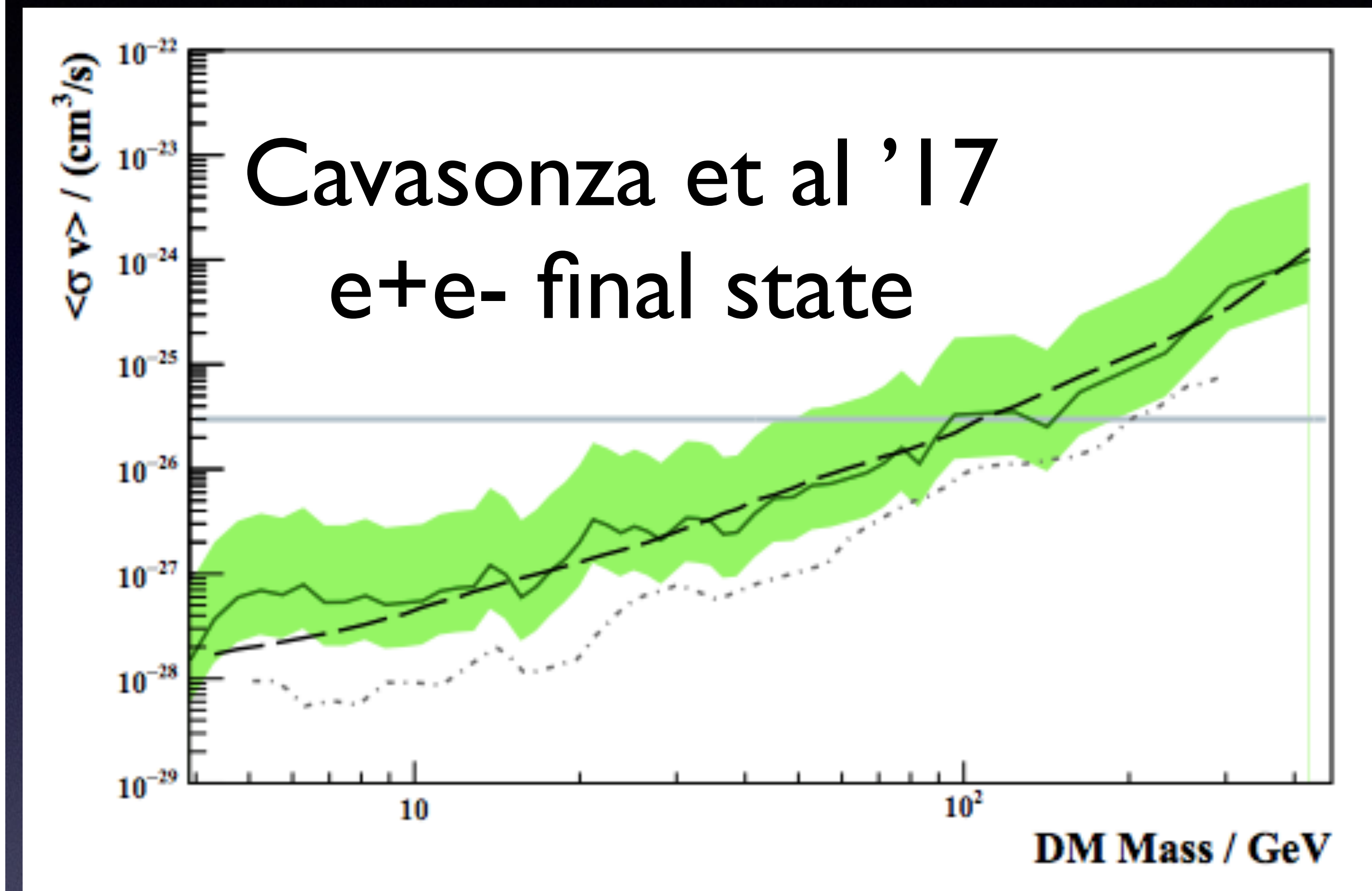
- AMS-02 has presented measurements of a range of cosmic ray species
- for DM searches the most relevant are positrons and antiprotons (although others help constrain propagation)





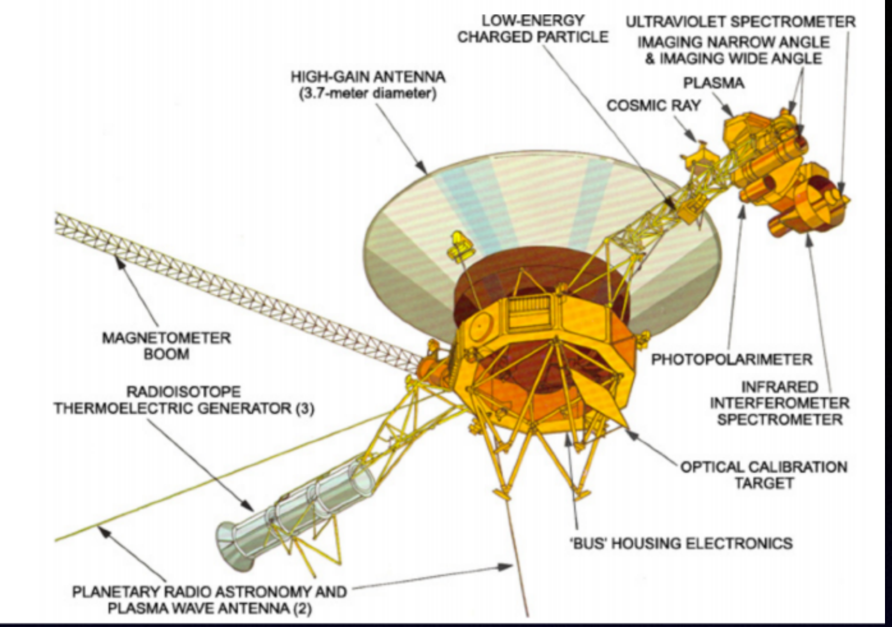
Cosmic ray limits





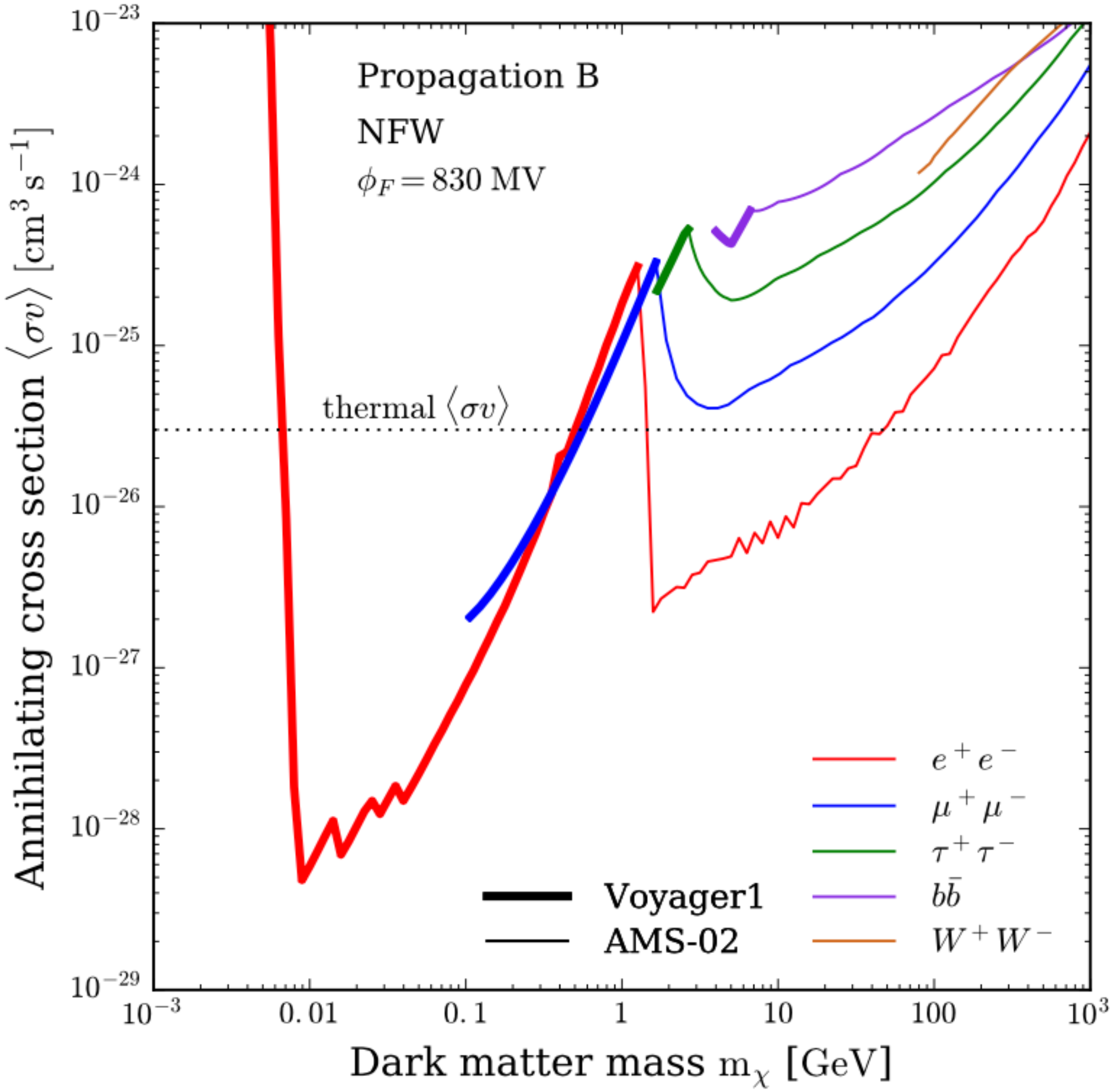
- AMS-02 measurements of positrons and antiprotons provide interesting probes of leptonic and hadronic annihilation channels respectively (and possible excesses).
- However, there are substantial uncertainties associated with cosmic-ray propagation/production, and instrumental effects.

Voyager (!) limits

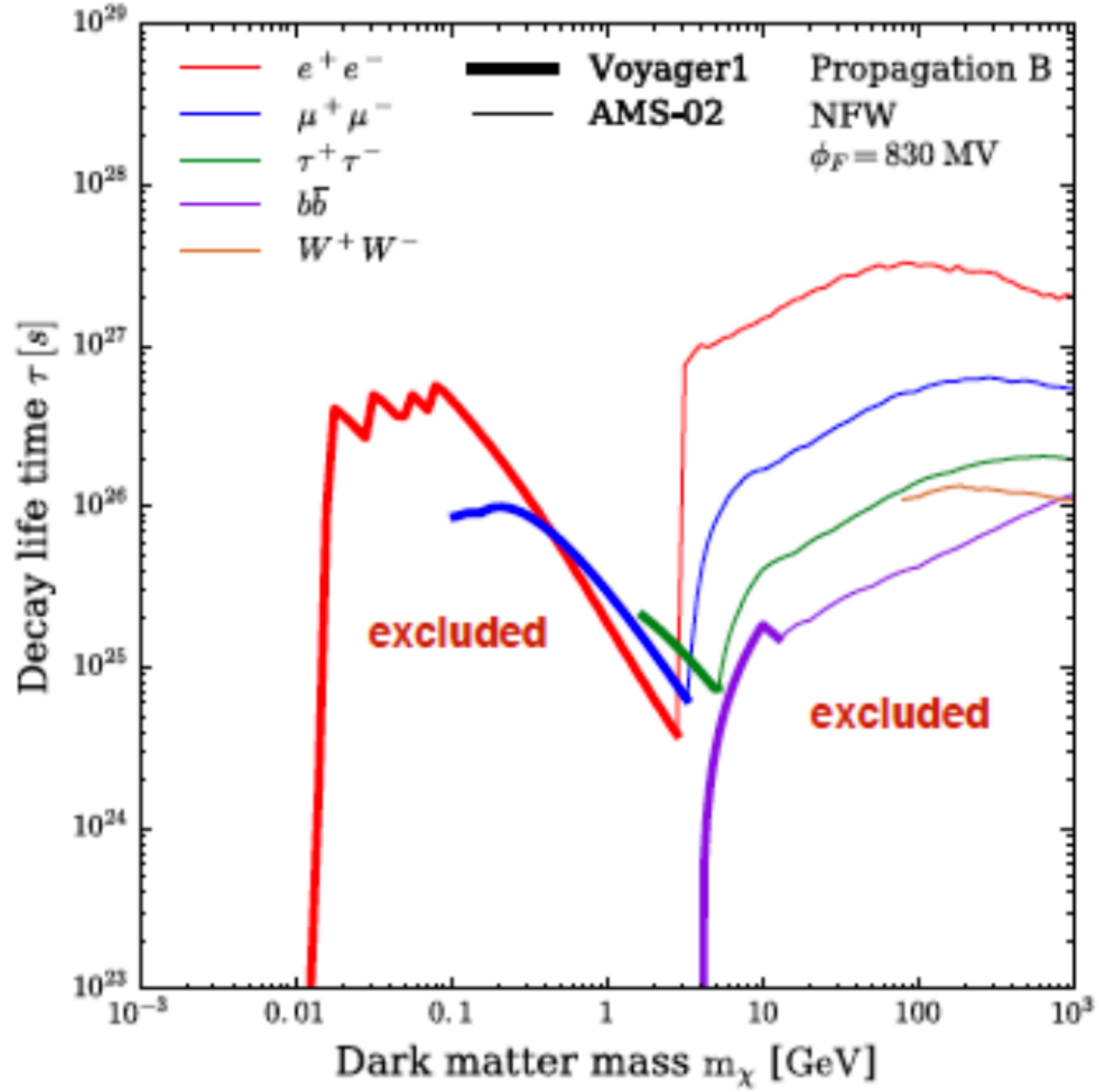


- Voyager 1 has a spectrometer capable of measuring low-energy cosmic rays
- Now beyond the heliopause - provides unique measurements of interstellar cosmic rays (unaffected by our Sun) and sub-GeV CRs (supppressed by solar wind inside solar system)
- Best limits on ~10 MeV - GeV DM decaying to electrons/positrons, or annihilating with velocity-suppressed annihilation.

Annihilating Dark Matter



Decaying Dark Matter



Boudaud et al '16

see also Boudaud et al '19 for p-wave annihilation

VERY INDIRECT DETECTION - EARLY UNIVERSE BOUNDS

Secondary effects of annihilation/decay products

- If DM annihilation and/or decay are present today, they have likely been occurring for the universe's whole history.
- Even if we cannot measure the products of annihilations at early times directly, they can affect aspects of the universe's history that we <u>can</u> measure.
- Examples: modifications to Big Bang nucleosynthesis, changes to the ionization and temperature history (affecting the CMB and 21cm radiation).
- Early-universe limits have the advantage that they do not depend on modeling Galactic astrophysics, or (if sufficiently early) details of how the DM is distributed at late times.

Limits from the cosmic dark ages

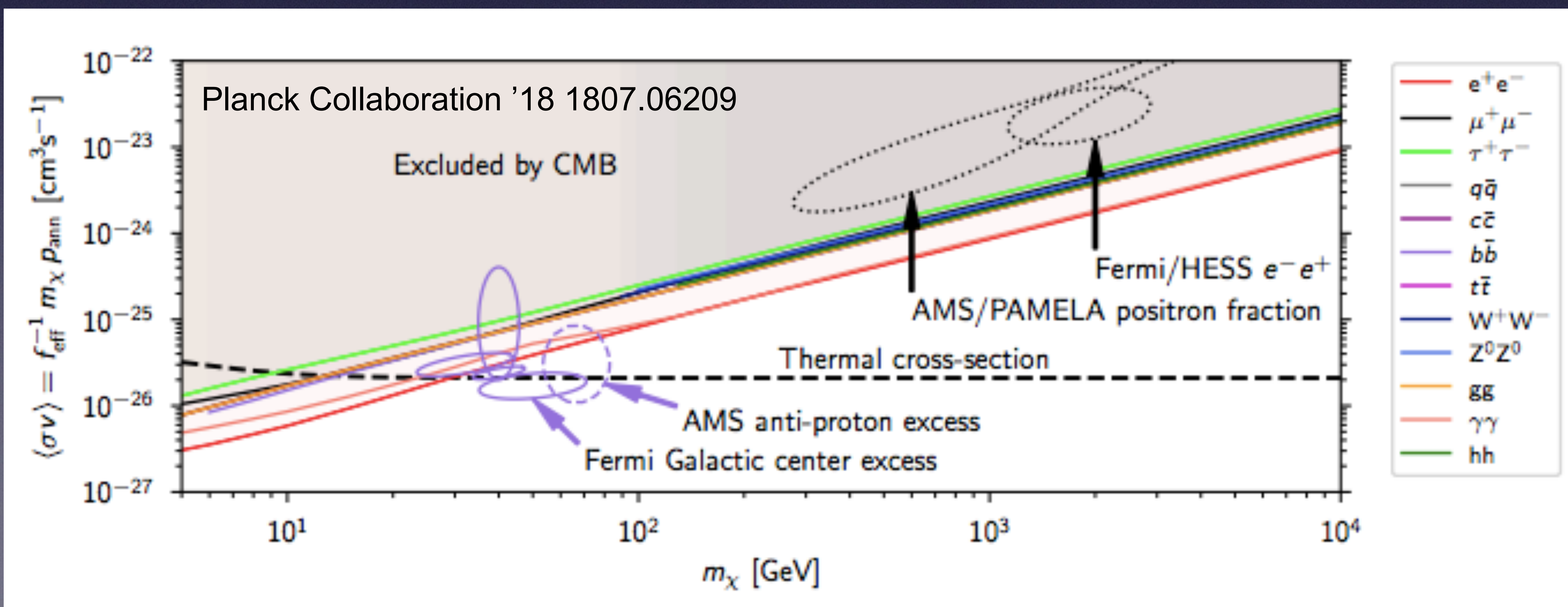
- Between redshifts z~10-1000, the universe was almost completely neutral - "cosmic dark ages"
- At the beginning of this epoch, the CMB radiation began free-streaming; any extra ionization acts as a screen for CMB photons
- Consider the power from DM annihilation - how many hydrogen ionizations?
  - 1 GeV / 13.6 eV ~ 10^8
  - If 10^{-8} of baryonic matter were converted to energy, would be sufficient to ionize entire universe. There is ~5x as much DM mass as baryonic mass.
  - If one in a billion DM particles annihilates (or decays), enough power to ionize half the hydrogen in the universe.

Estimating signals from thermal DM

- What do we expect from thermal freezeout?
  - During radiation domination and after freezeout, fraction of DM that annihilates per Hubble time is $\sim n\langle\sigma v\rangle/H \propto T^3/T^2 \sim T$ (if $\langle\sigma v\rangle$ is redshift-independent).
  - At freezeout, $n\langle\sigma v\rangle/H\sim 1$, so at late times this ratio is approximately T/T_f.
  - We expect a ratio of $O(10^{-9})$ at recombination ($T\sim 0.1$ eV) for thermal DM freezing out at $O(100$ MeV$)$ - later freezeout = larger signal.

Annihilation limits from Planck

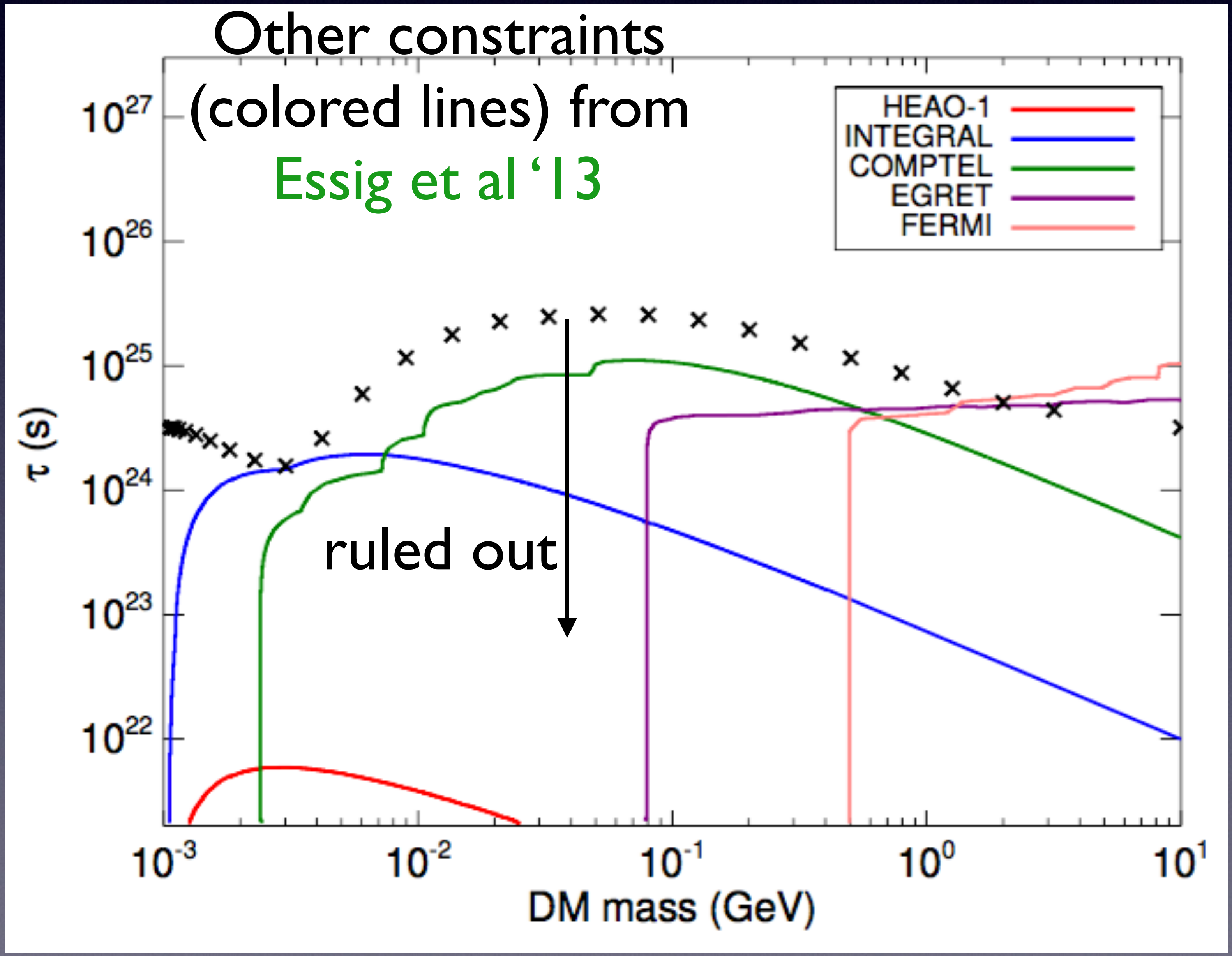
- Calculating the impact of DM annihilation on the CMB in detail [TRS ’16], we can obtain stringent and general constraints on light DM annihilating - rules out thermal relic benchmark for masses below ~10 GeV.
- Can likewise apply these bounds to decaying DM, primordial black holes and other sources of ionizing energy.



Decay limits from ionization + the CMB

- For decaying dark matter, can use same approach.
- Sets some of the strongest limits on relatively light (MeV-GeV) DM decaying to produce electrons and positrons.
- For short-lifetime decays, can rule out even 10^{-11} of the DM decaying! (for lifetimes $\sim 10^{14}$ s)

TRS & Wu, PRD '17



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  - One-in-a-billion fraction of mass energy liberated = distortion of energy spectrum of CMB at level of one in 10^6 or less. Much less sensitive than ionization for $z < 1000$.

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  - Down to z~200, CMB and ordinary matter are coupled in temperature - need to heat whole CMB, not just matter. Same estimate as for spectral distortion.
  - Baryon number density is ~9 orders of magnitude smaller than CMB number density - heating divided between a much smaller number of particles for $z < 200$. One-in-a-billion fraction of mass energy liberated => increase baryon temperature by ~5 eV per particle ~ 50,000 K - two orders of magnitude higher than baseline temperature at decoupling.

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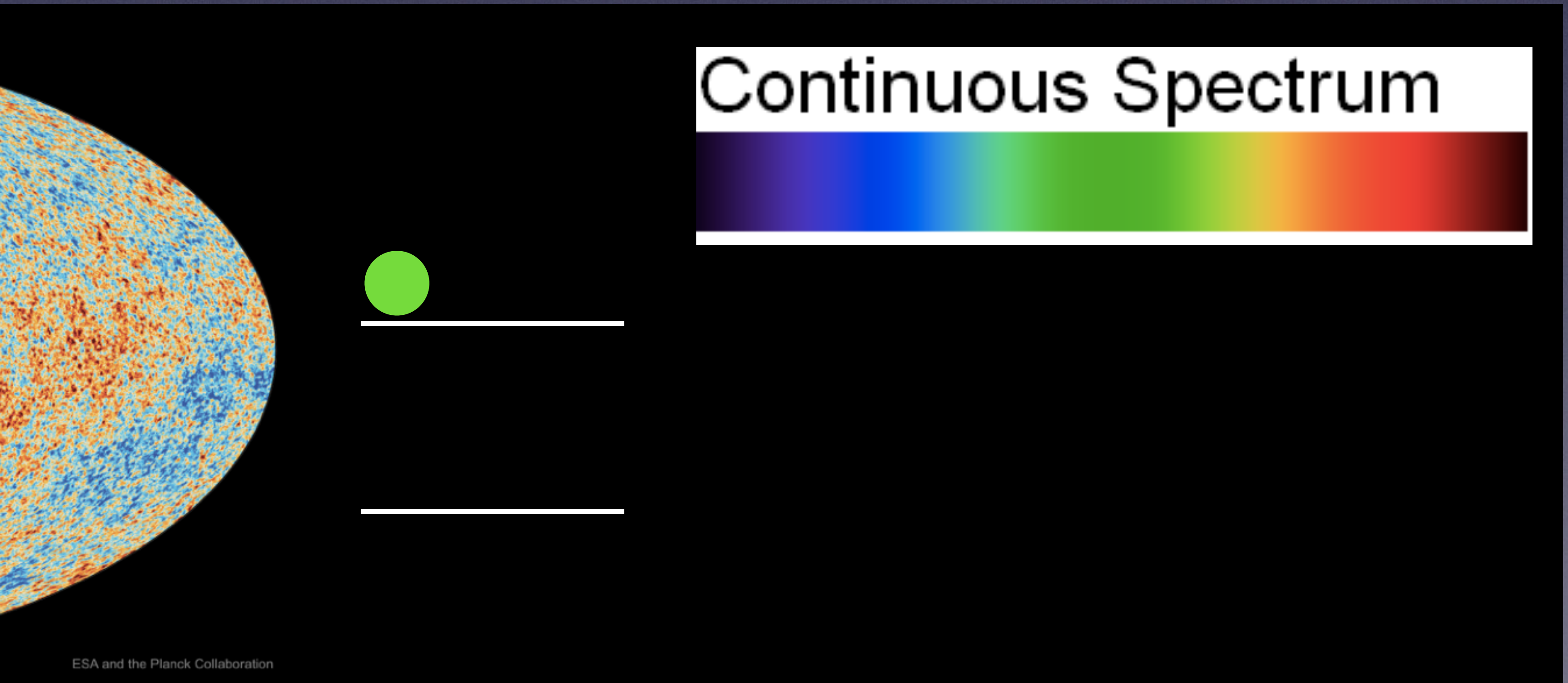
not probed by CMB, but potentially a large effect for z < 200 - can we see it in Ly-α or 21cm?

Taking the universe's temperature with 21cm

- To measure the gas temperature at late times, we can search for atomic transition lines - in particular, the 21cm spin-flip transition of neutral hydrogen.
- As the universe expands, the energy of these photons decreases - lines get smeared out into a broad structure.
- "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, 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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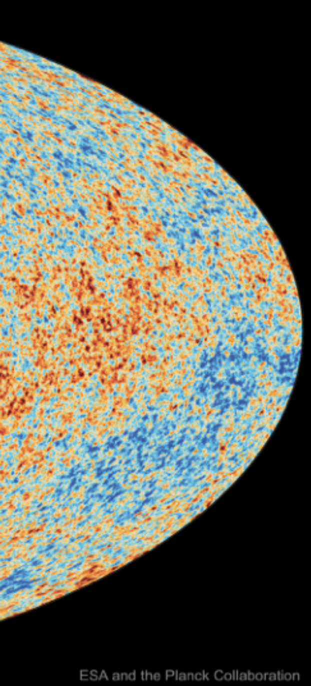

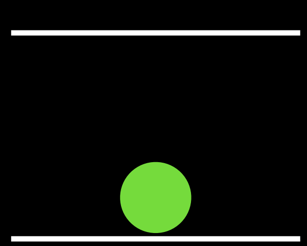

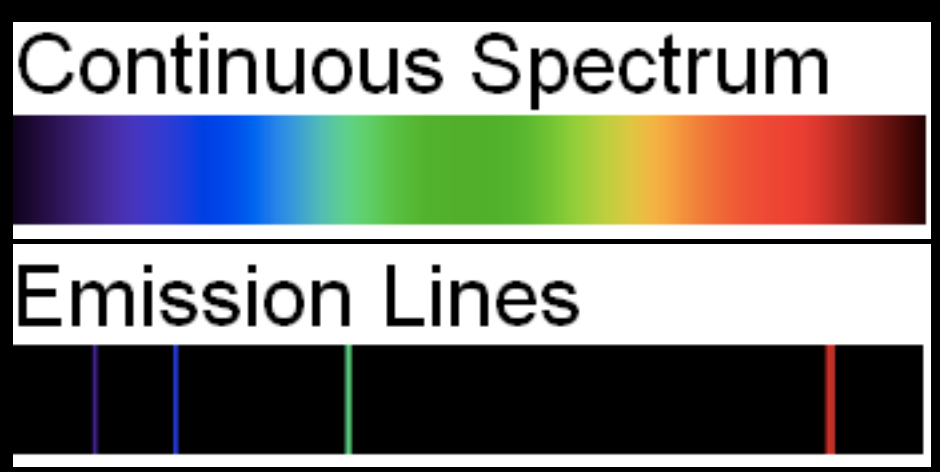

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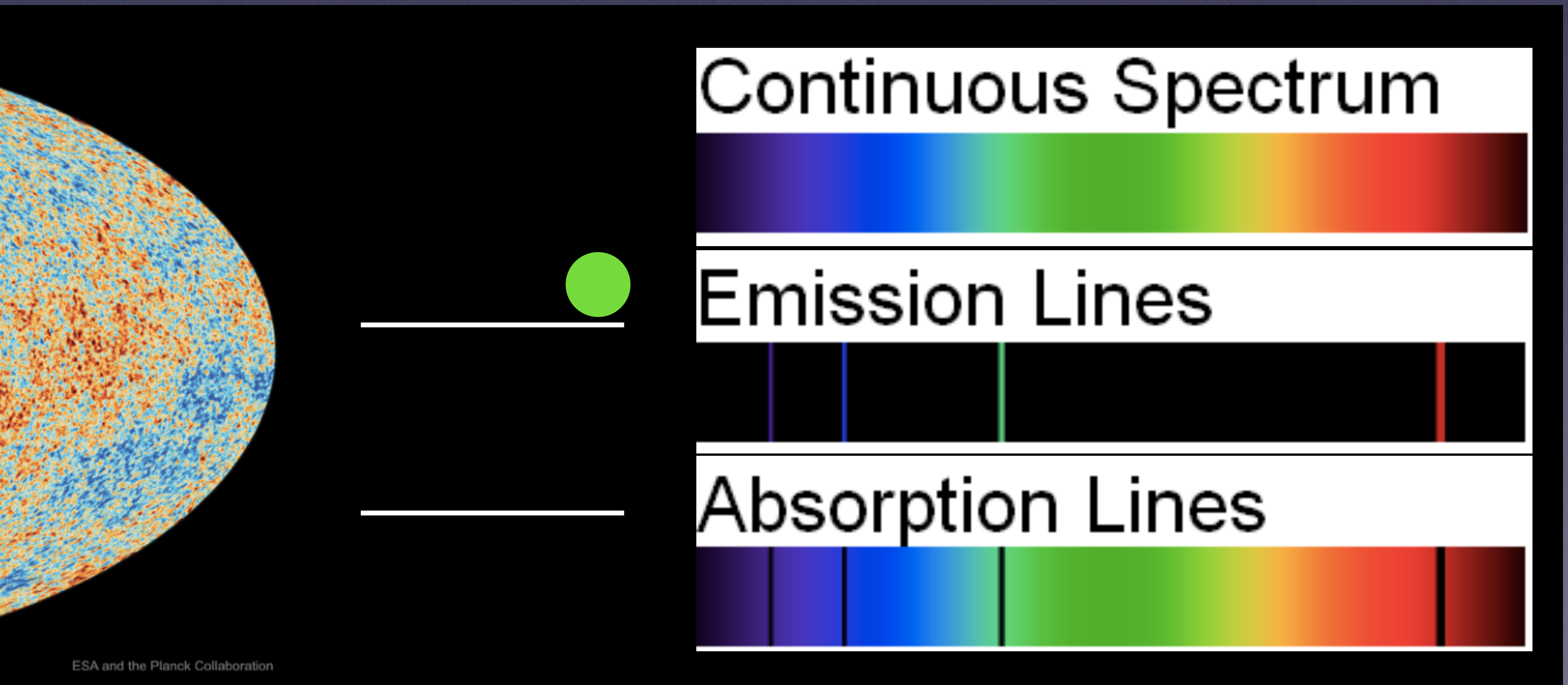

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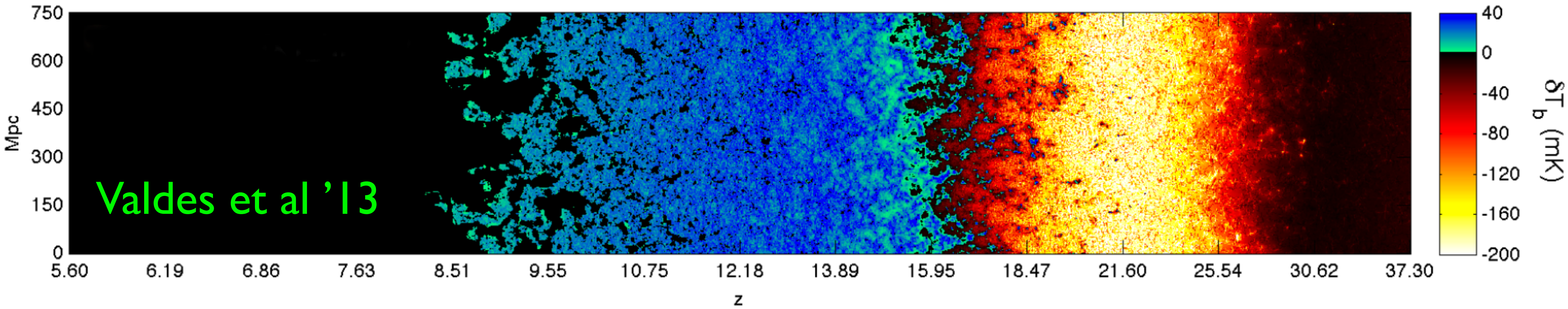
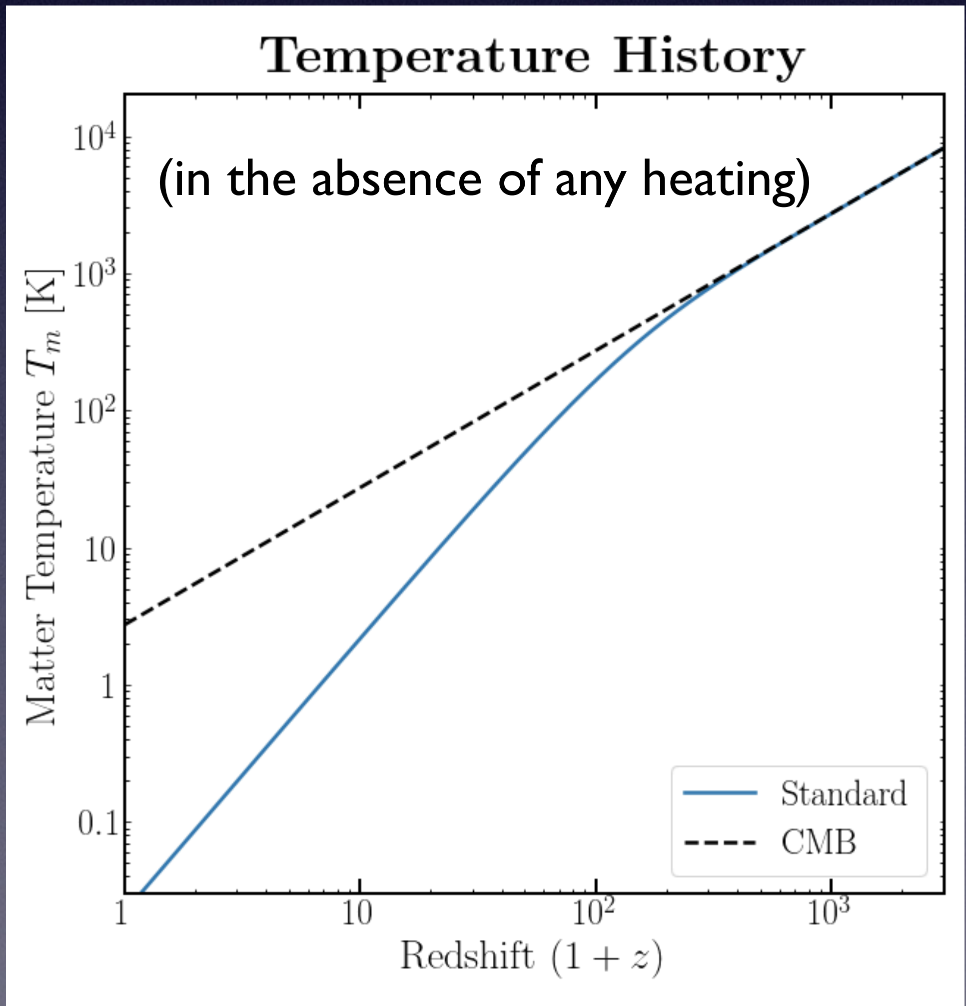
Expectations for a 21cm signal



- 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 - leading to absorption signature.
- Later, stars heat $T_{gas} > T_R$, expect an emission signal.
- Heating of the gas from DM decays could potentially lead to early emission at z~20-25 [e.g. Poulin et al '17].
- There are a number of current (e.g. EDGES, HERA, LOFAR, MWA, PAPER, SARAS, SCI-HI) and future (e.g. DARE, LEDA, PRIZM, SKA) telescopes designed to search for a 21cm signal, potentially probing the cosmic dark ages & epoch of reionization.

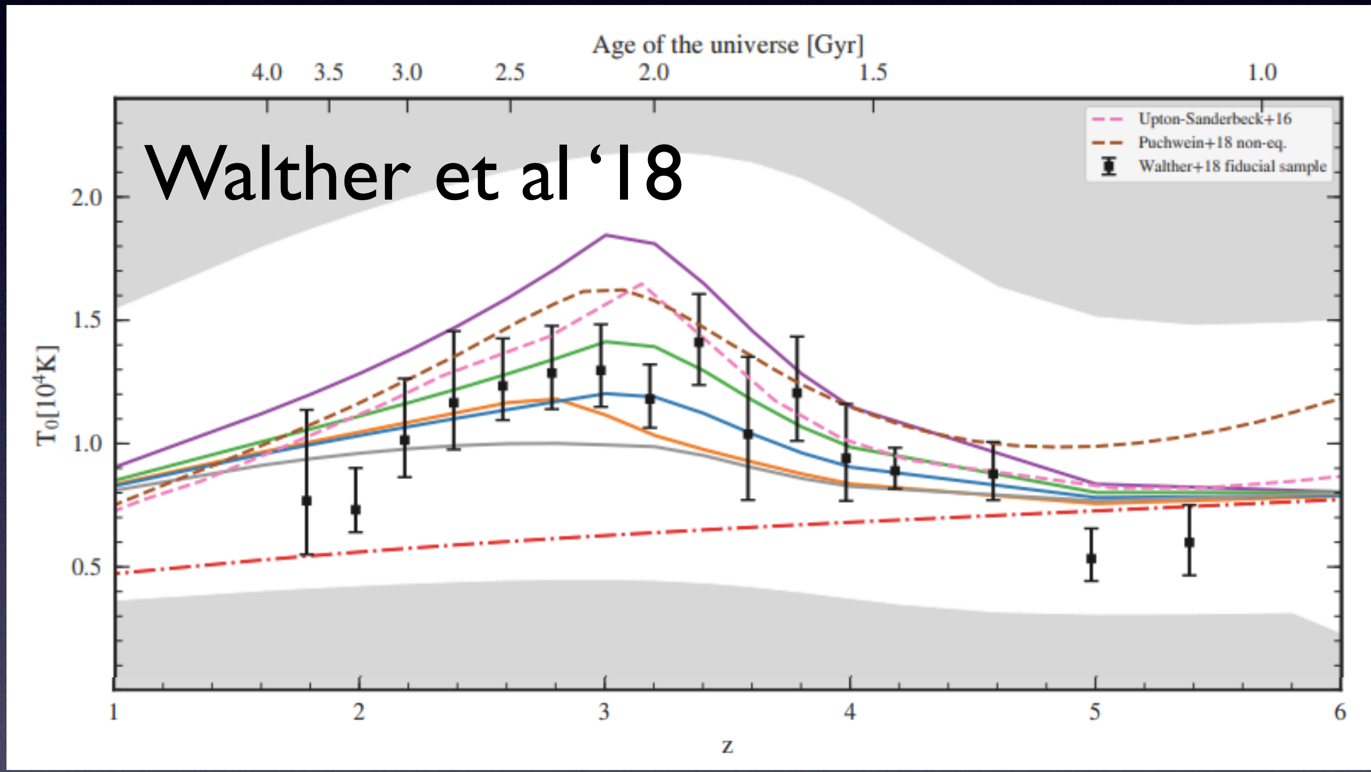


The Lyman-alpha forest

- The 21cm radiation signal + other atomic transitions require the presence of neutral hydrogen
- Before reionization, neutral hydrogen is abundant - radiation at frequencies corresponding to more rapid transitions gets 100% absorbed
- After reionization is mostly complete, there are still clouds of neutral hydrogen in the universe - light passing through these clouds produces absorption features in the spectrum
- As the universe expands, these features shift to lower frequency
- By studying the resulting spectrum we can learn about the distribution of the neutral hydrogen clouds as a function of redshift

Temperature with the Lyman-alpha forest

- The temperature of the hydrogen gas affects the width of the absorption features in the forest through Doppler broadening.
- The temperature history also affects the underlying distribution of the hydrogen gas, which is smoothed out by the gas pressure on small scales.
- Several recent studies [Walther et al '18, Gaikwad et al '20] have compared measurements of the Ly-α forest with simulations, to extract the gas temperature for z~2-6.

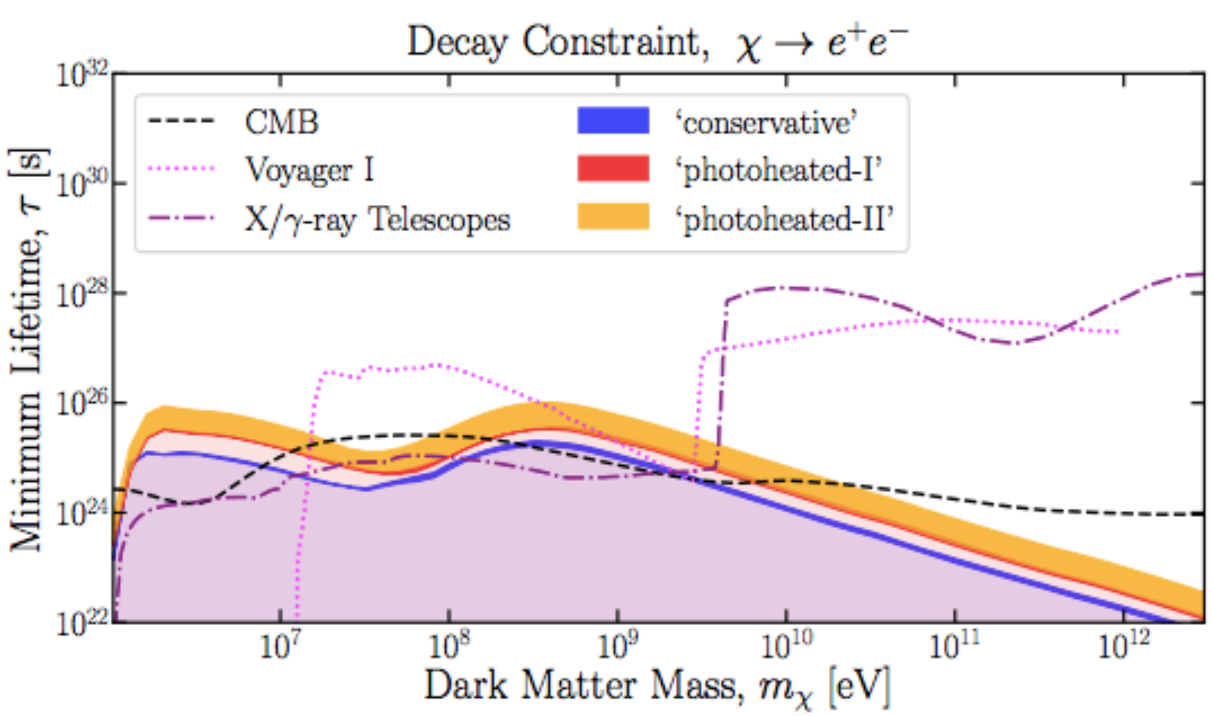


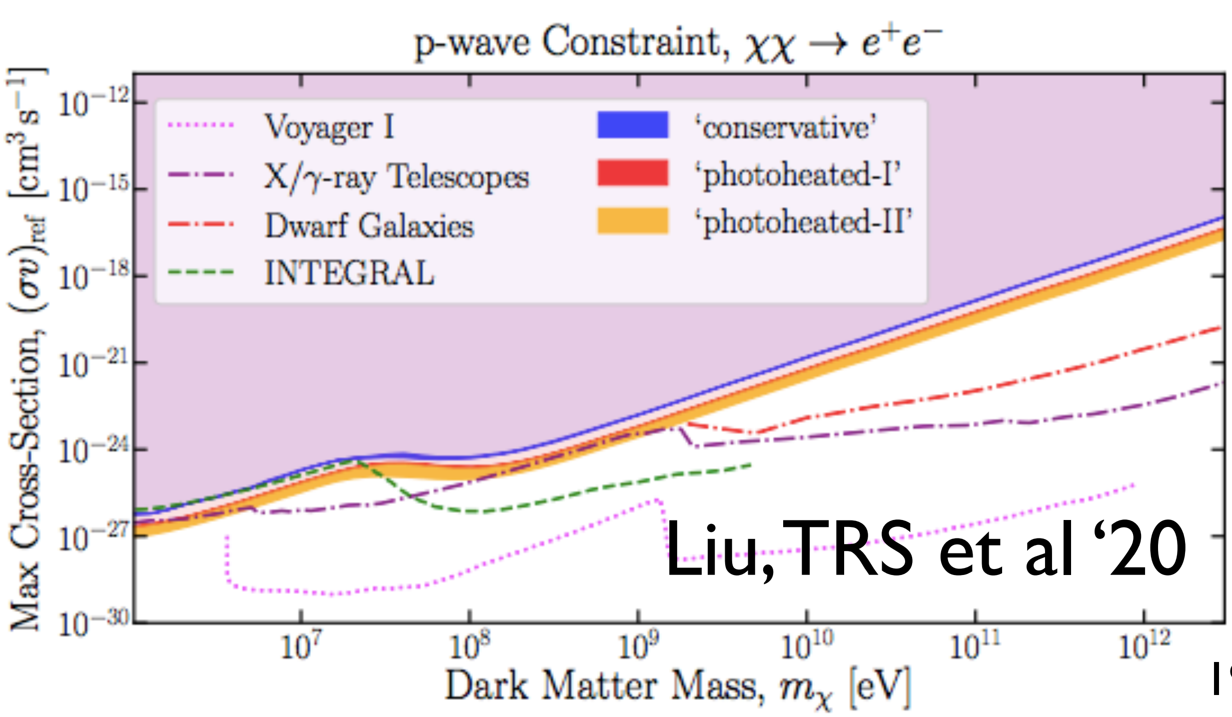
Gaikwad et al '20

Redshift	$T_0 \pm \delta T_0$
$5.3 < z < 5.5$	11000 ± 1600
$5.5 < z < 5.7$	10500 ± 2100
$5.7 < z < 5.9$	12000 ± 2200

Constraints on DM decay/ annihilation from Ly-α

- We used the code package DarkHistory to set limits on DM decaying or annihilating to electrons and positrons
- Width of bands denotes uncertainty in reionization history + photoheating model.
- Limits are broadly competitive with other constraints, and currently the strongest bounds for 1-10 MeV DM.

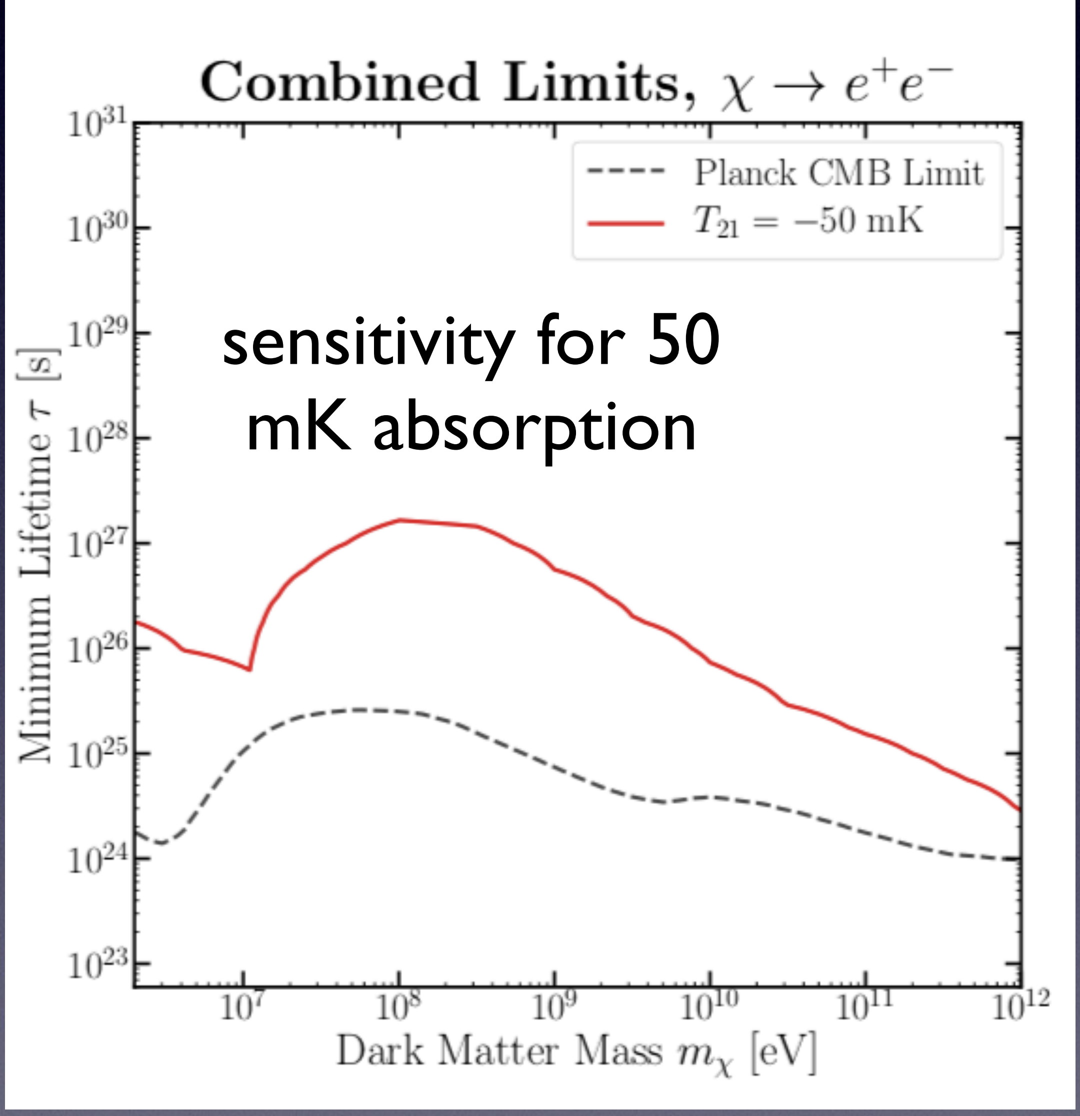




Liu, TRS et al '20

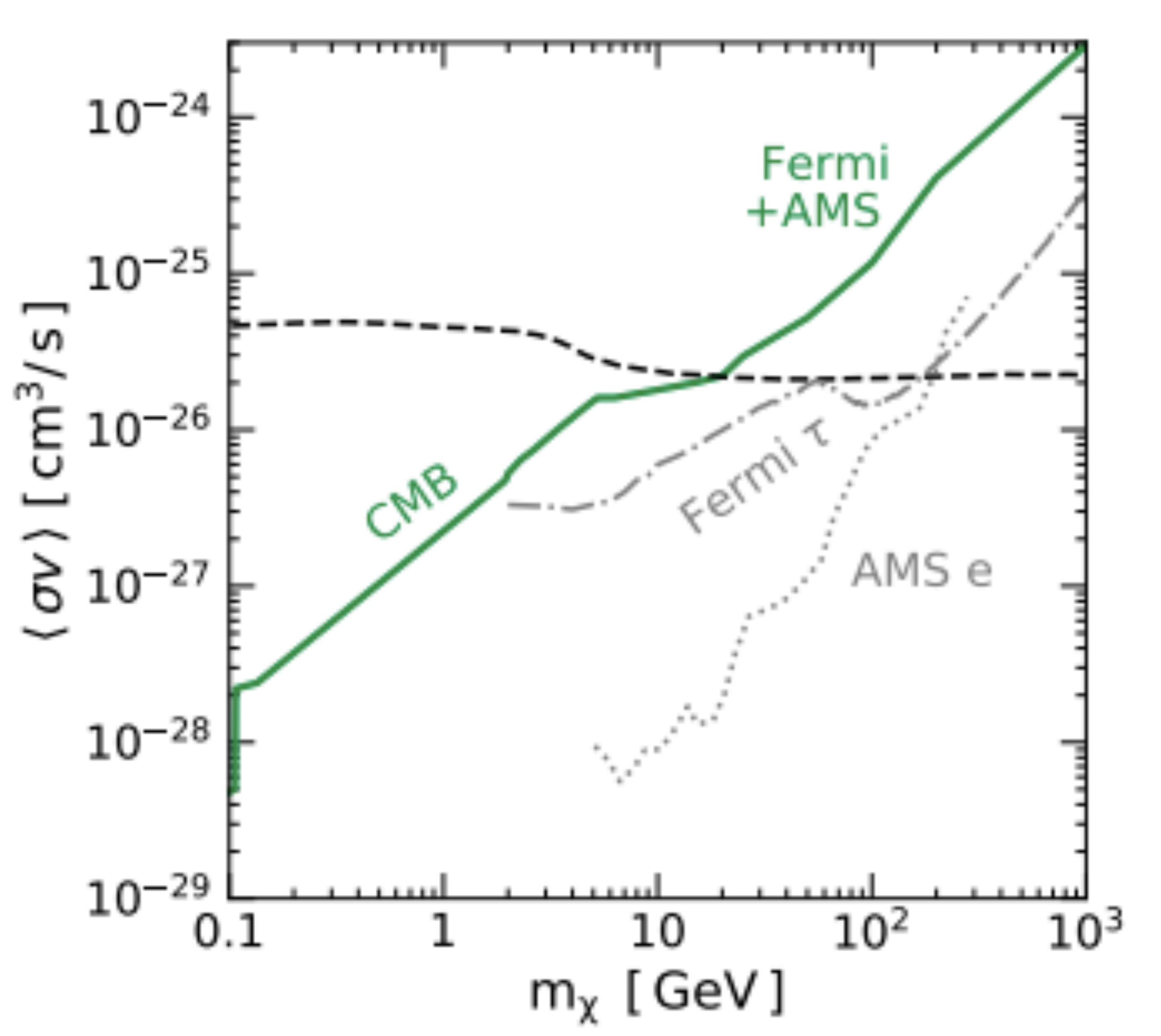
Decay sensitivity from heating + 21cm

- Consider a hypothetical 21cm measurement of T_{21} < -50 mK at z~17. If T_R=T_{CMB}, this corresponds to an upper limit on the gas temperature of T_m~20 K.
- With DarkHistory, it is easy to compute the resulting limits.
- Limits on light DM decaying leptonically (for example) could improve by two orders of magnitude - or optimistically, we could see a strong heating signal.



Complementarity between annihilation searches

- We can ask which DM masses are currently allowed for the simplest thermal relic scenario, scanning over SM final states (other than neutrinos - neutrinos are always the least constrained).
- Hadronic decays produce neutral pions which in turn yield photons → photon searches are efficient at constraining most SM final states.
- The exceptions, electrons(+positrons) and muons(+anti-muons) are tested by AMS-02.
- CMB fills in the low-mass region.
- The least constrained channel overall (not counting neutrinos) is muons - can have thermal relic cross section down to masses ~20 GeV.



Leane et al '18

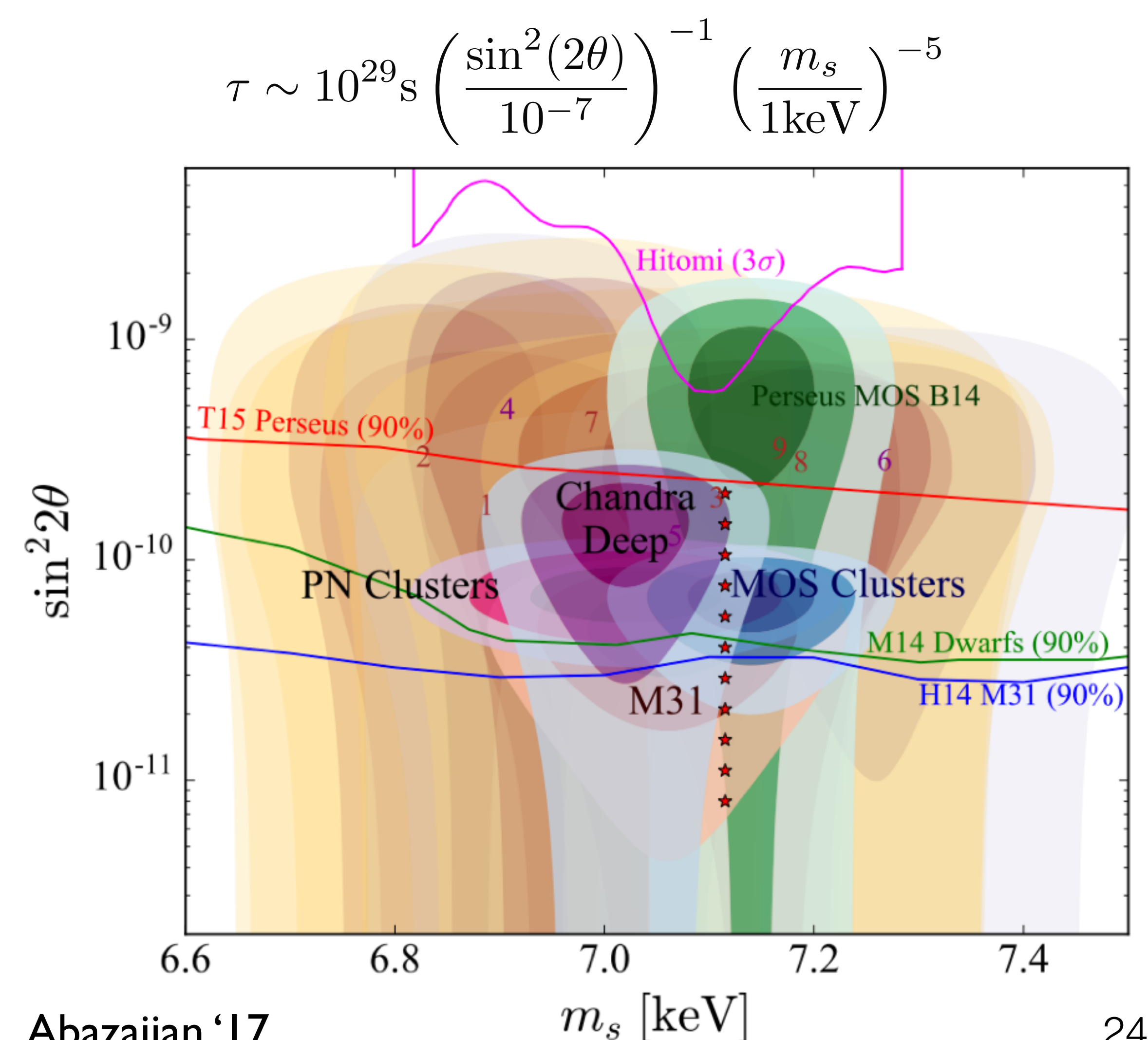
Summary of constraints

- We can search for the visible products of dark matter annihilation and decay in a broad range of experiments and target regions
- For most final states (neutrinos excepted), we can:
  - place stringent limits on the thermal relic cross section up to O(10-100) GeV DM masses (limits on annihilation to neutrinos are typically a few orders of magnitude weaker)
  - constrain decay lifetimes $\sim 10^{25-28}$ seconds for DM masses from O(keV) to O(10^{10} GeV)

Beyond constraints: hints of signals?

The 3.5 keV line

- 3.5 keV X-ray spectral line: initial discovery in XMM-Newton data claimed by Bulbul e '14 and Boyarsky et al '14, at ~4σ significance.
- Possible non-DM contributions: atomic lines (from K, Cl, Ar, possibly others), charge-exchange reactions between heavy nuclei and neutral gas.
- Simplest dark matter explanation: decay of ~7 keV sterile neutrino (summarized in figure)
  - In some tension with observations of dwarfs [Malyshev et al '14], stacked galaxies [Anderson et al '14], M31 observed by Chandra [Horiuchi et al '14], and blank-sky observations with XMM-Newton [Dessert et al '20].
  - Possible to relax constraints by looking at DM processes other than decay.



Abazajian '17

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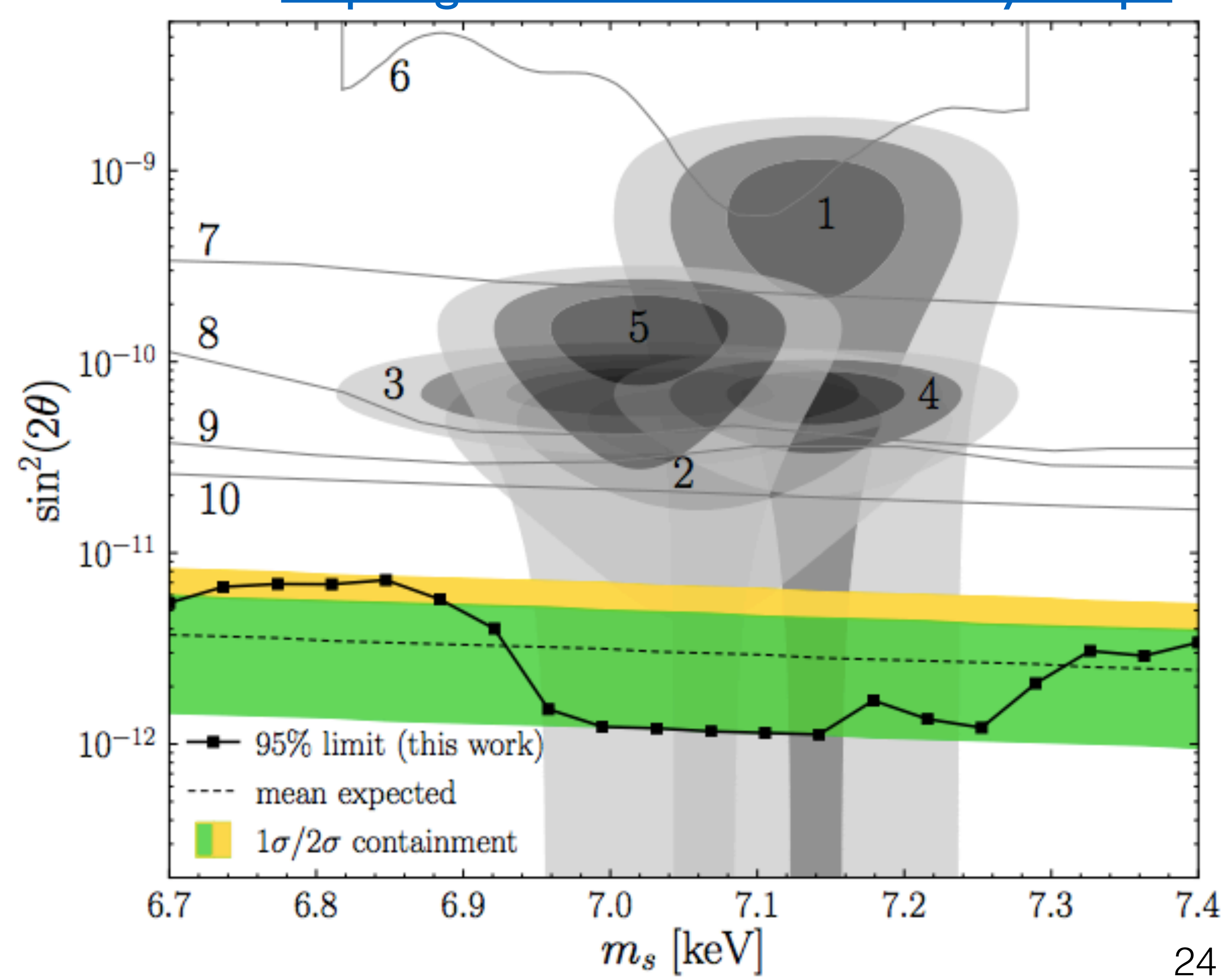
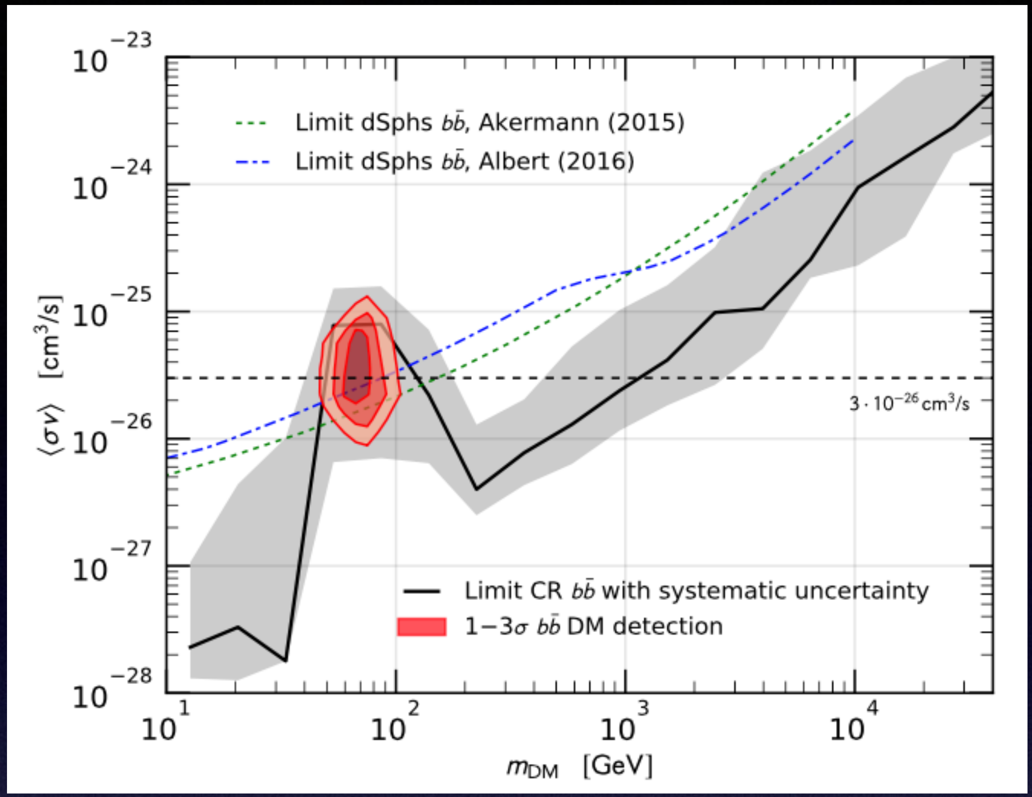
Dessert et al '20

See https://github.com/bsafdi/BlankSkyfor3p5

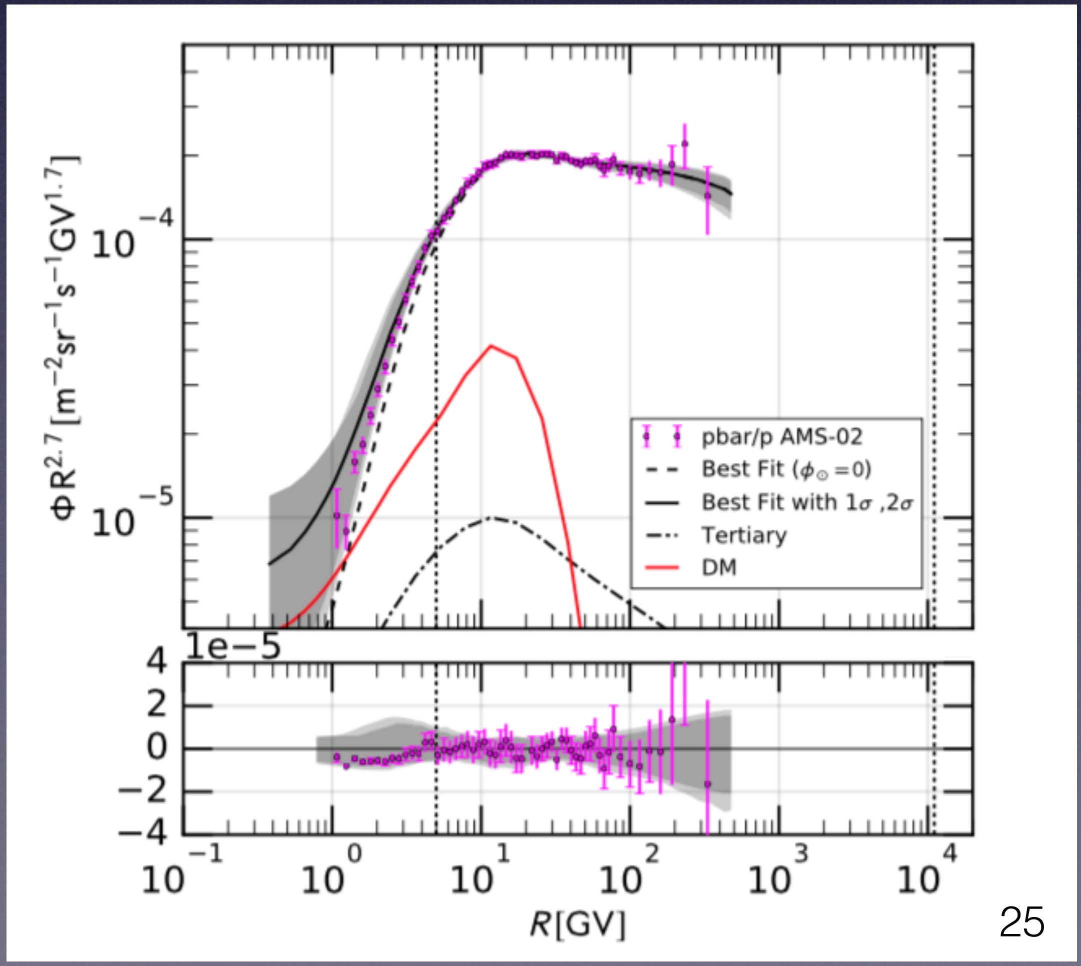


AMS-02 antiprotons

- Cui et al ’17 and Cuoco et al ‘17 use AMS-02 antiproton data to set limits on DM annihilation to hadronic channels.
- Both papers claim detection of a possible excess with significance 4.5σ [Cuoco et al] / Bayes factor 2 ln K = 11-54 [Cui et al ’17].
- Similar fits for other annihilation channels with ~thermal cross sections, 40-130 GeV mass [Cuoco et al ’17].
- Challenges: modeling of antiproton production cross section, cosmic-ray propagation, solar modulation, instrumental effects.
- Significance level is 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.



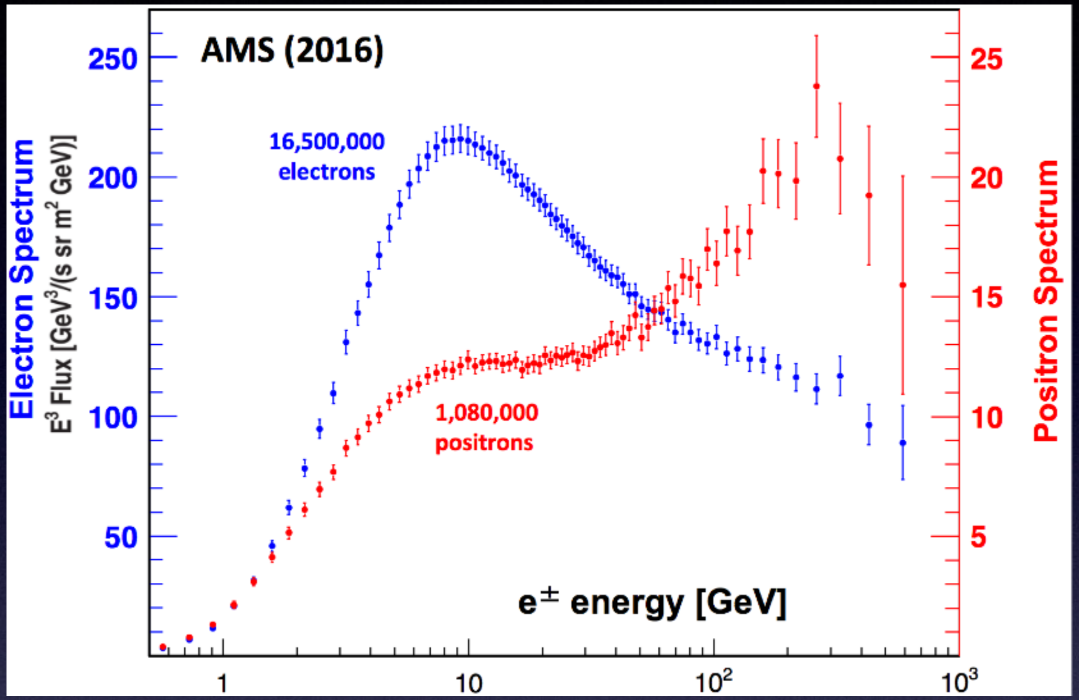
Cuoco et al ‘17

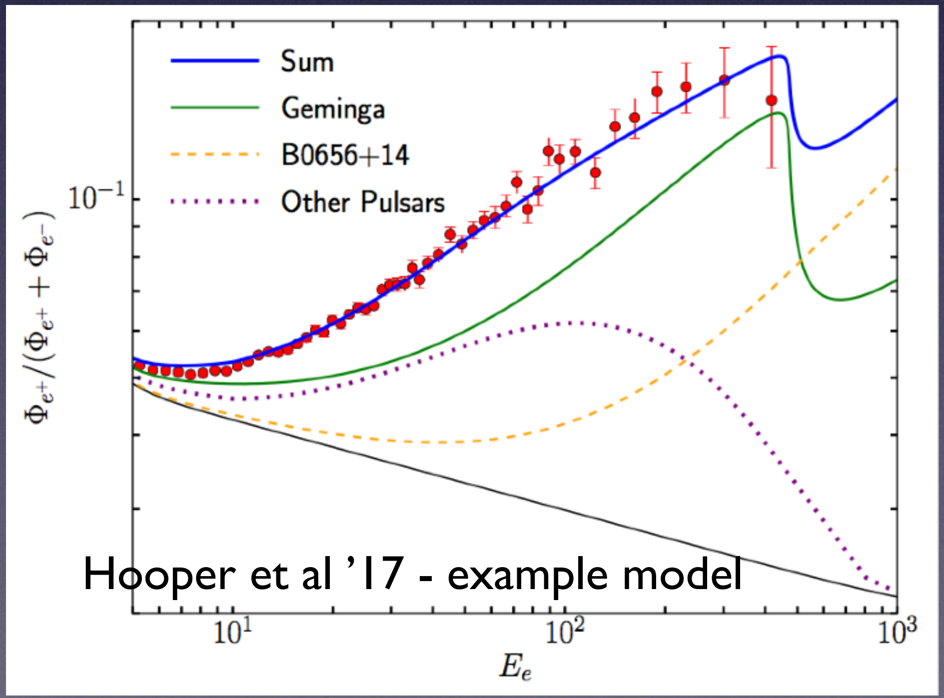


AMS-02 positrons

- AMS-02 sees a large excess of positrons above ~10 GeV, compared to expectations for secondary positrons from proton collisions with the interstellar medium.
- Extensively discussed as a possible signature of DM annihilation or decay, albeit in tension with other measurements.
- HAWC has detected extended gamma-ray emission around two nearby pulsars, Geminga and B0656+14 [Abeysekara et al '17, 2HWC catalog].
- If interpreted as a halo of inverse-Compton-scattered light, these results constrain e+e- production by these pulsars.
- Hooper et al '17, Profumo et al '18 argue these measurements suggest pulsars provide a dominant contribution to the AMS-02 positrons. (Note: this does require inhomogeneous diffusion for e+e-.)

Sam Ting, 8 December 2016, CERN colloquium

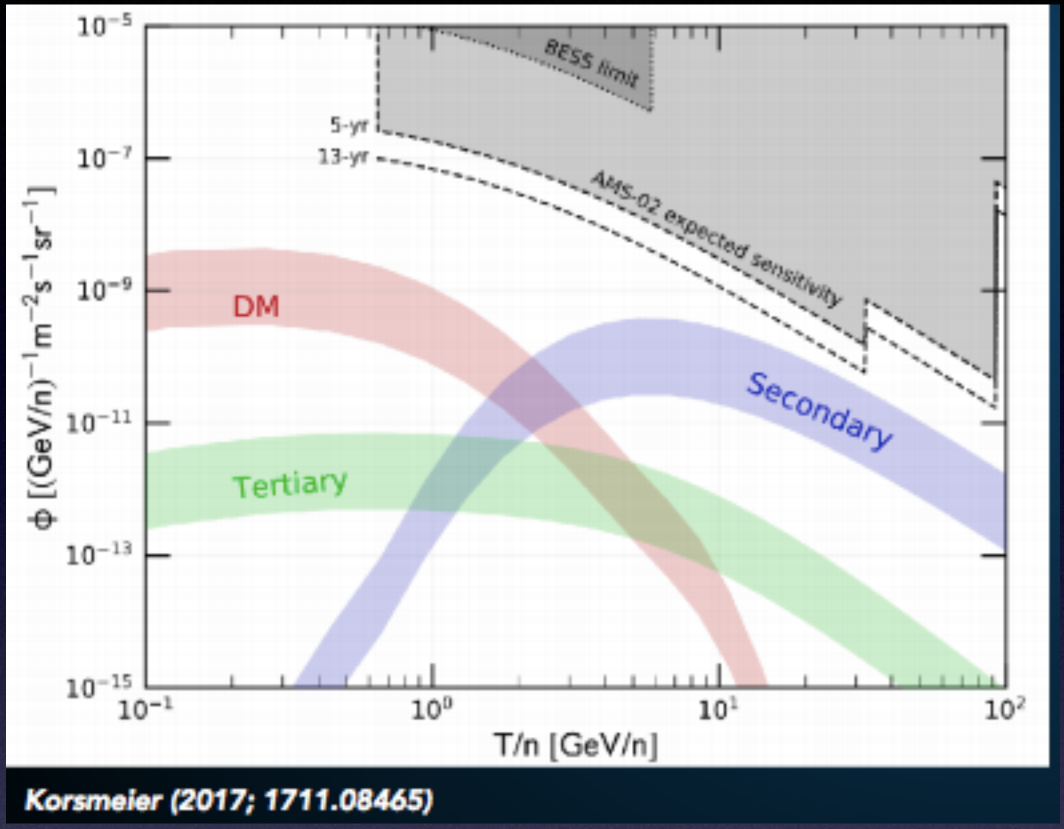




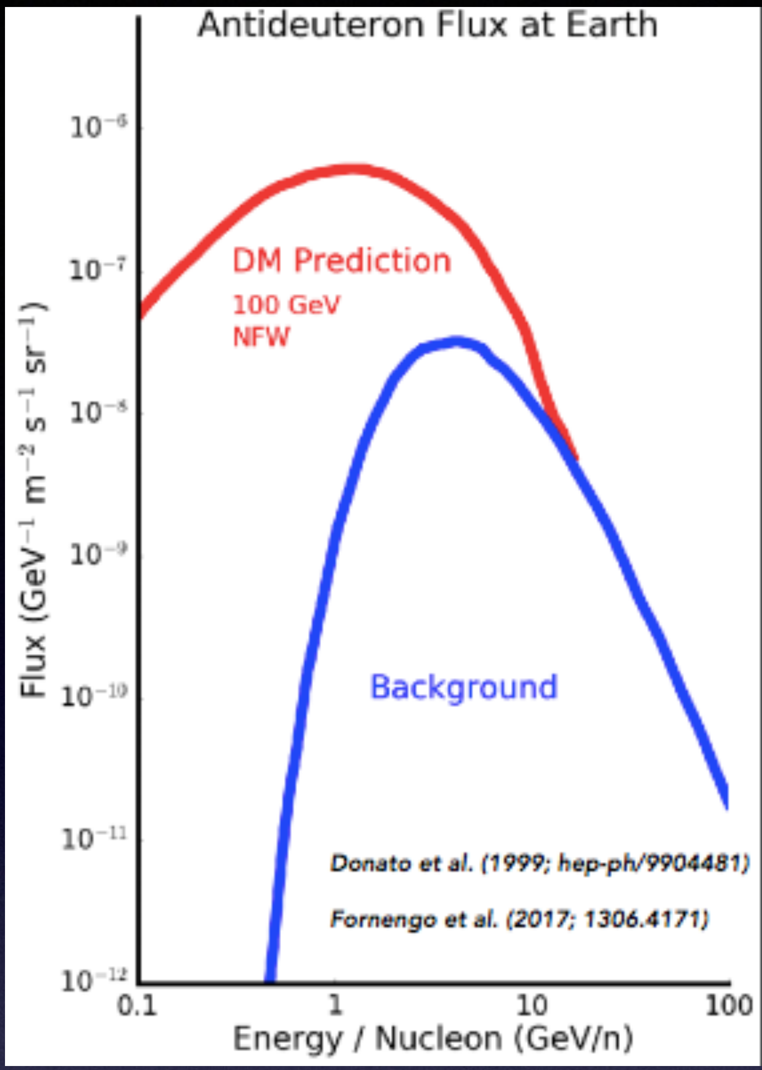
Hooper et al '17 - example model

AMS-02 antihelium

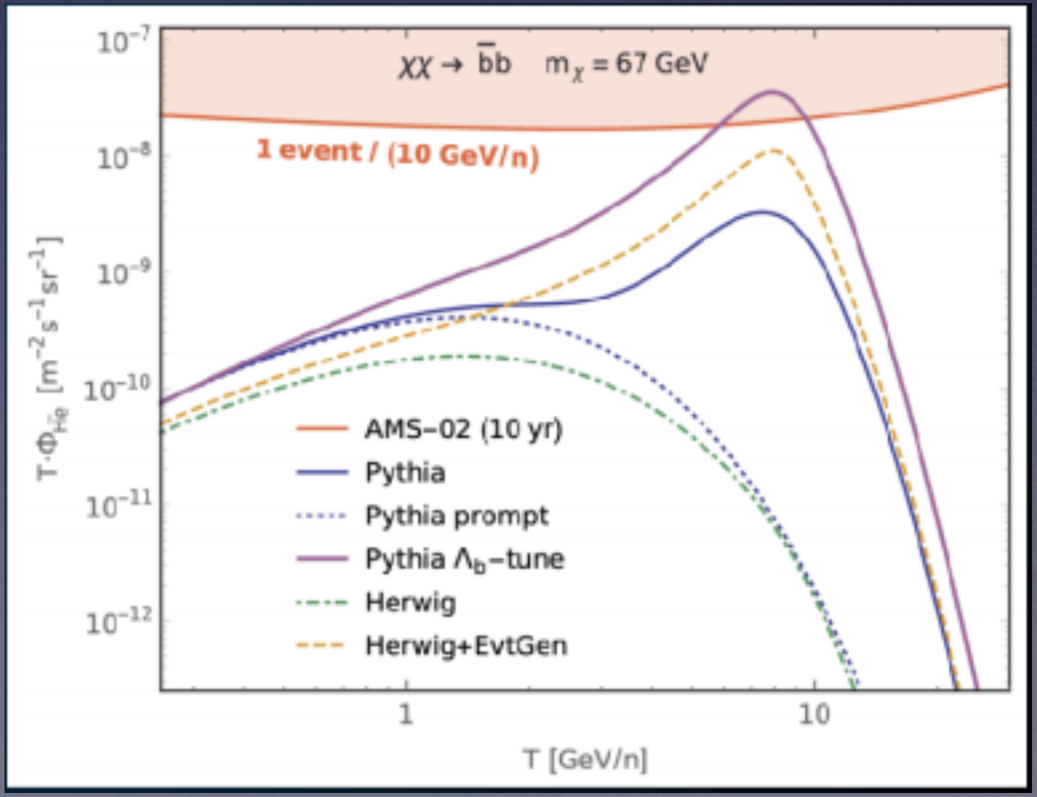
- Astrophysical backgrounds are expected to be extremely small for low-energy antinuclei - clean search channel
- Upcoming GAPS experiment will search for antideuterons
- But AMS-02 already preliminarily claims to have observed 8 events consistent with anti-helium [Sam Ting, La Palma Conference 2018].



Korsmeier (2017; 1711.08465)



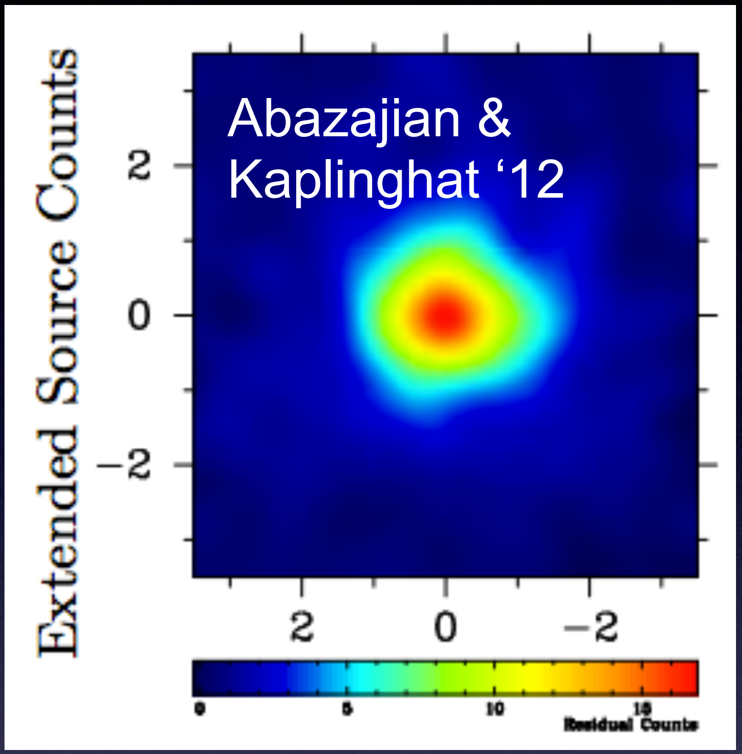
Winkler & Linden '20

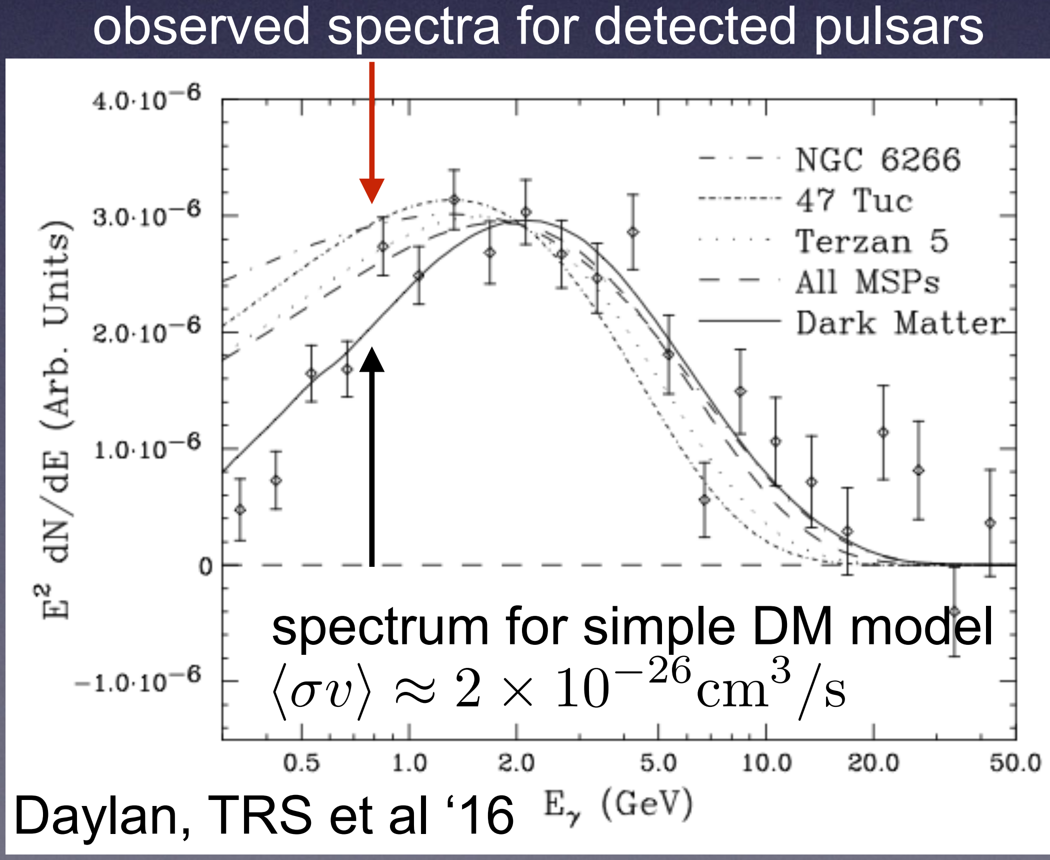


This is naively very difficult to explain as DM prediction is also tiny - but recent work suggests production of $\overline{\Lambda}_b$-baryons which decay to antihelium could give a visible signal

The Galactic Center GeV excess

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





Status of the GCE - a renewed controversy?

- Arguments against the DM explanation:
  - Spatial morphology of excess was originally characterized as spherical, but in newer analyses, is better described as boxy-bulge-like extended emission + central nuclear bulge component [Macias et al '18, Bartels et al '18, Macias et al '19, Abazajian et al '20]. If the extended emission is robustly Bulge-like, suggests a stellar origin - although result can be sensitive to background modeling and choice of region-of-interest [Bartels et al '18].
  - Constraints from other searches - limits from dwarf galaxies can appear to be in tension with DM explanation [e.g. Keeley et al '18], but depends on Milky Way density determination + dwarf J-factors + astrophysical background for dwarf analyses [e.g. Alvarez et al '20, 2002.01229].
  - Photon statistics.

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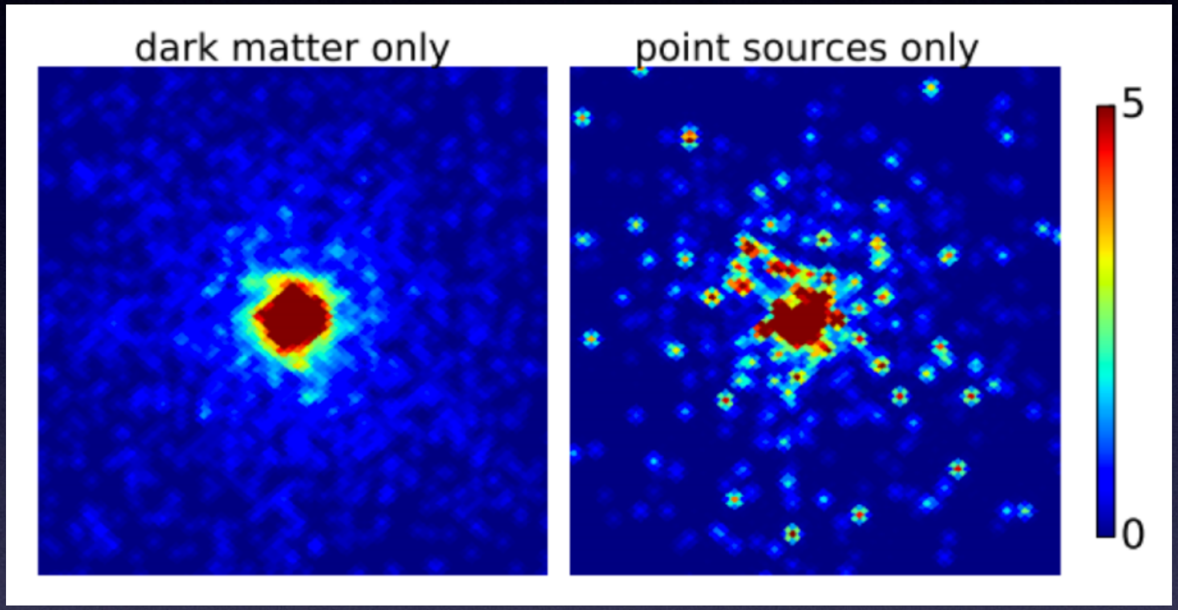
Deciphering the GCE with photon statistics

<u>DM origin hypothesis</u>

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



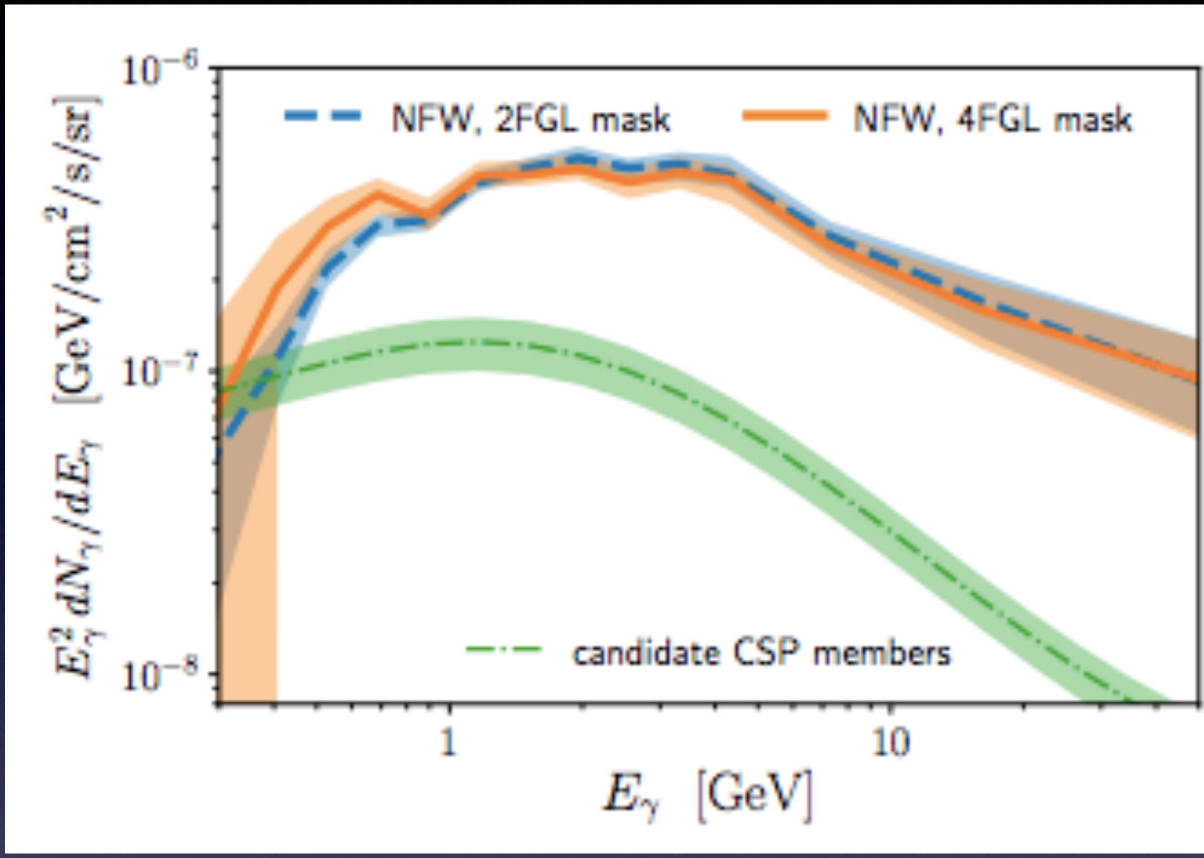
<u>Pulsar origin hypothesis</u>

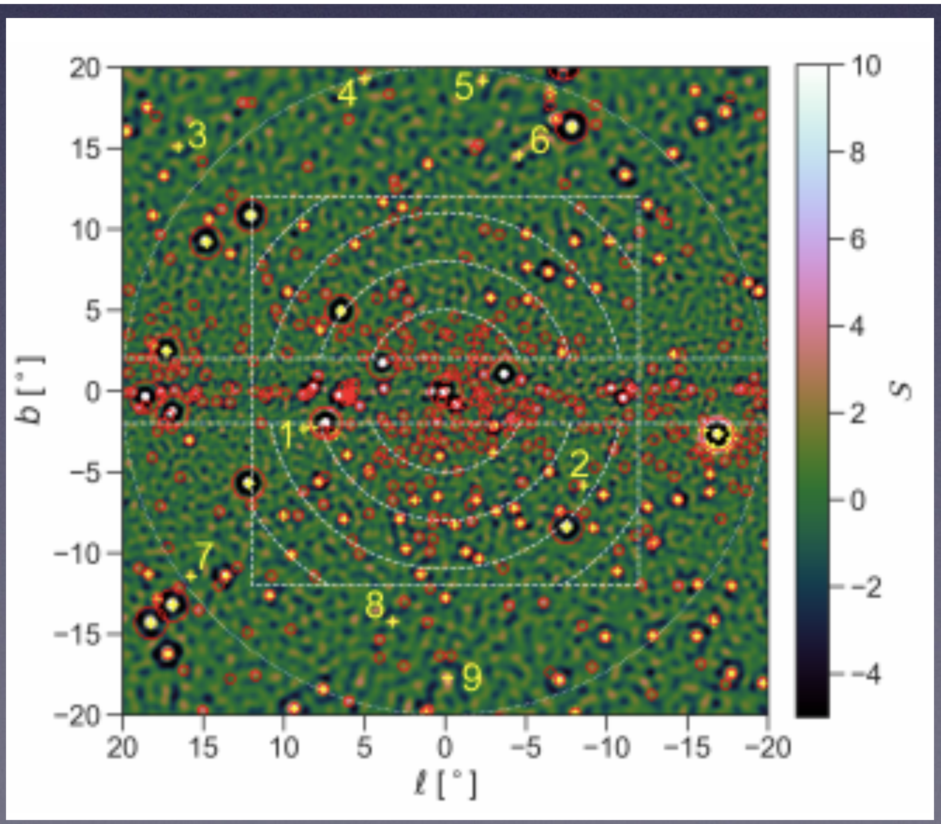
signal originates from a collection of compact objects, each one a faint gamma-ray point source

- Hope to distinguish between hypotheses by looking at granularity of the photon signal - presence or absence of "hot spots".
- Two main analyses in 2016, both claimed evidence for point source populations:
  - Exploiting non-Poissonian statistics of fluctuations from an unknown point source distribution [Malyshev & Hogg '11; Lee, Lisanti & Safdi '15; Lee, Lisanti, Safdi, TRS & Xue '16].
  - Using wavelet-based method to look for small-scale power above expectations from diffuse backgrounds [Bartels et al '16].

2020 update: from wavelets to 4FGL

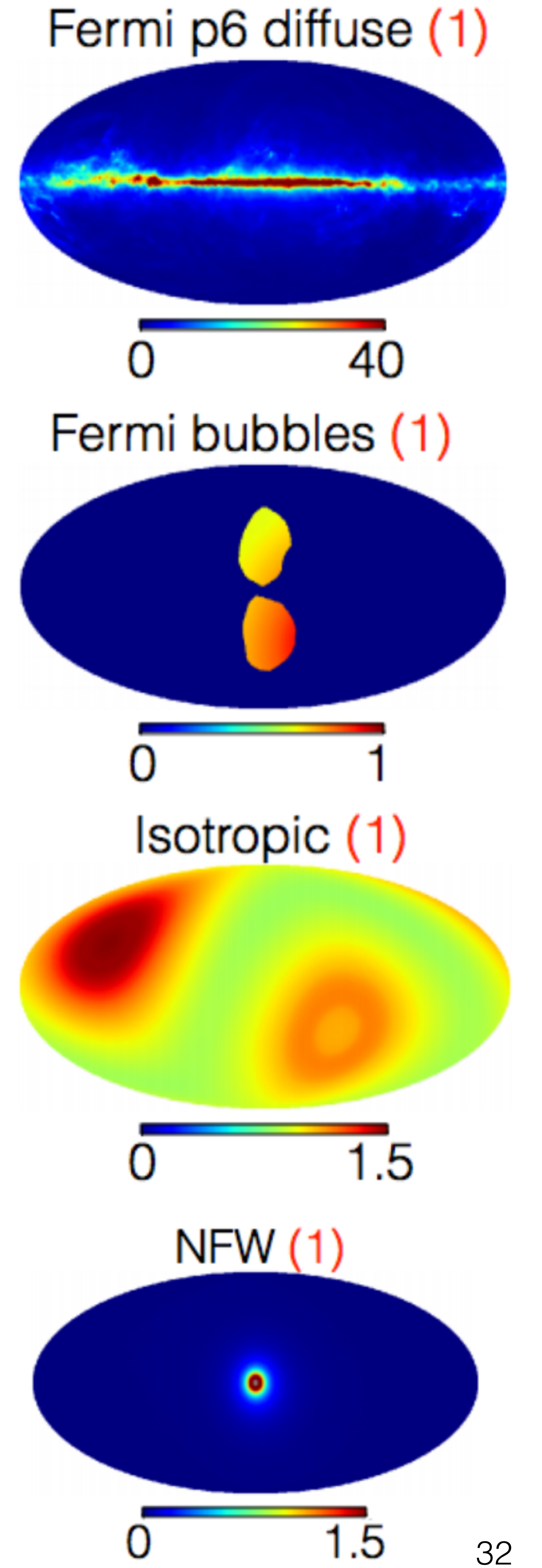
- Recent analysis repeats wavelet analysis of Bartels et al '16, but now compares identified high-significance peaks to latest gamma-ray source catalog (4FGL) [Zhong et al 1911.12369].
- Of 115 peaks, 107 are near a source; 40 of these are potential members of a central GCE population (identified as Galactic pulsars, or unidentified/unassociated).
- Wavelet analysis essentially gives 4FGL subset.
- Masking 4FGL sources does not reduce GCE.
- Total emission from candidate central-pop sources is a factor ~4-5 below GCE.
- Implies bulk of emission should be diffuse or originating from faint sources.

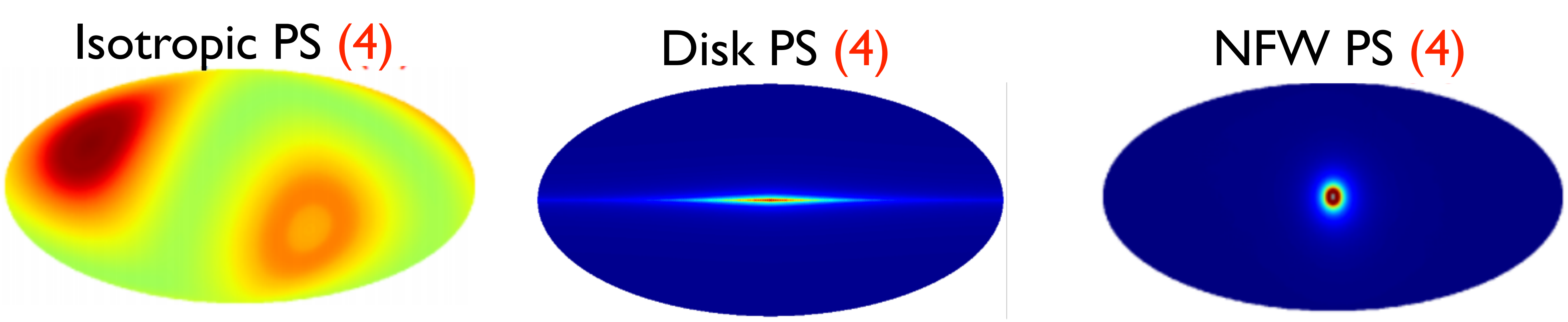




Non-Poissonian template fitting (NPTF)

- Model sky (within some energy bin) as linear combination of spatial templates
- Evaluate P(data|model) as a function of template coefficients + other parameters - maximize P (frequentist), or use it to derive posterior probability distributions for the parameters (Bayesian).
- Templates may either have
  - Poissonian statistics
  - Point-source-like statistics - extra degrees of freedom describing number of sources as a function of brightness





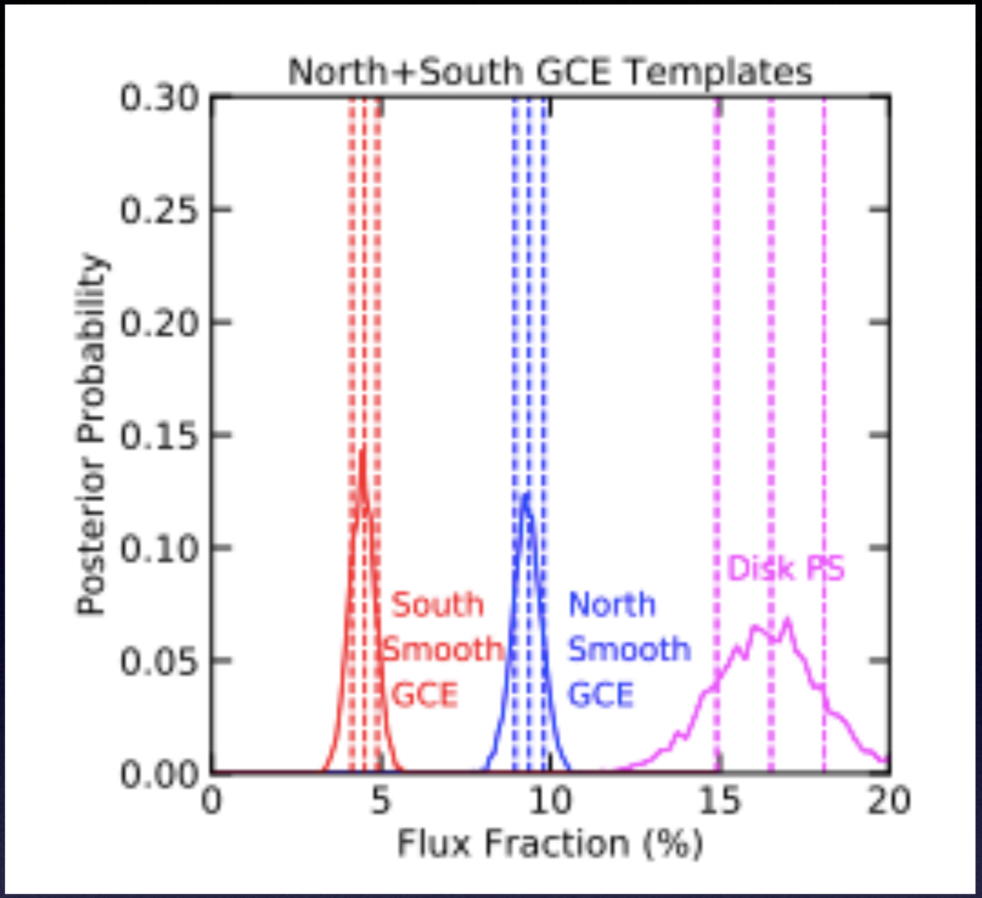
Point source templates

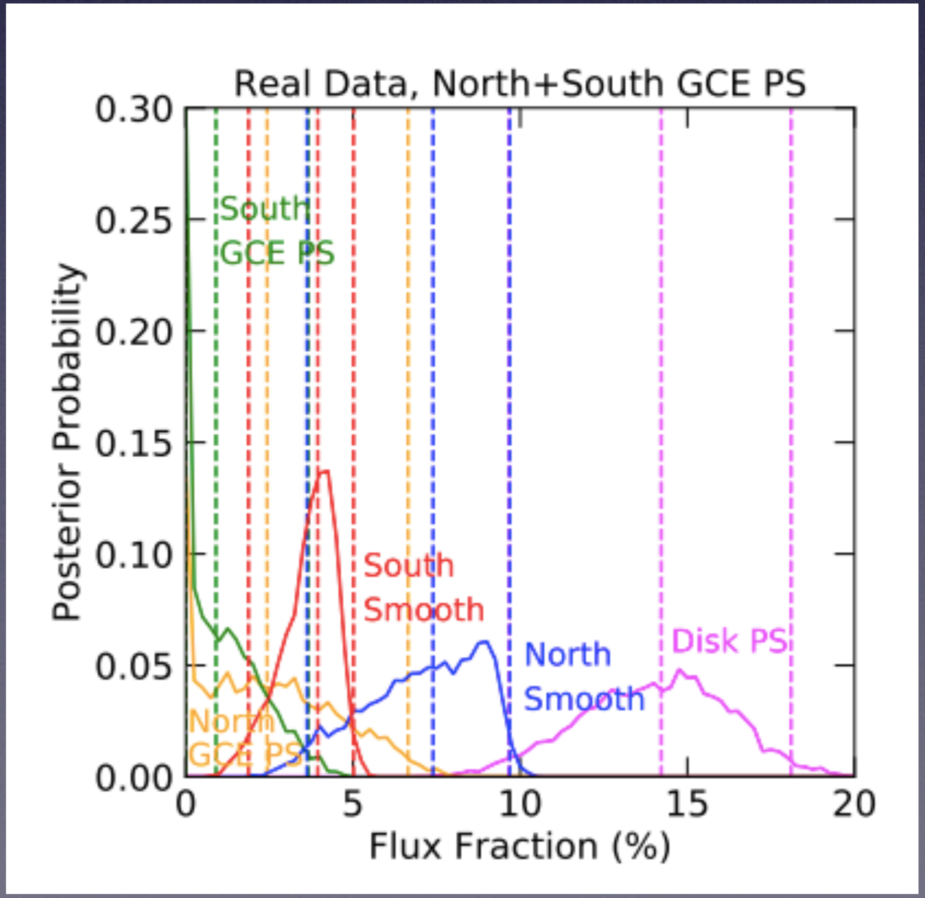
2020 update: NPTF

- Lee et al '16: fit shows a strong preference to assign all GCE flux to new PS population (Bayes factor ~10^9, roughly analogous to 6σ)
- Leane & TRS '19: same analysis actually prefers to assign strongly negative flux to smooth/DM template. Indication of a systematic bias, likely due to "mismodeling" - imperfect templates. Need to understand this behavior to establish whether apparent PS evidence is real.
- Chang et al '19, Buschmann et al '20:
  - can quantitatively explain the observed preference for a negative flux by imperfections in the Galactic diffuse emission model
  - can construct newer models which do not prefer a (unphysical) negative coefficient for the smooth/DM component
  - with these models, there is still a preference for a PS population, albeit at lower significance (Bayes factor $10^{3\text{-}4}$, analogous to $3\text{-}4\sigma$)
- Leane & TRS '20a, b: preference for a PS population can be an artifact of a different systematic (not considered in Buschmann et al '20): an overly-rigid signal model

Spurious point sources in the data

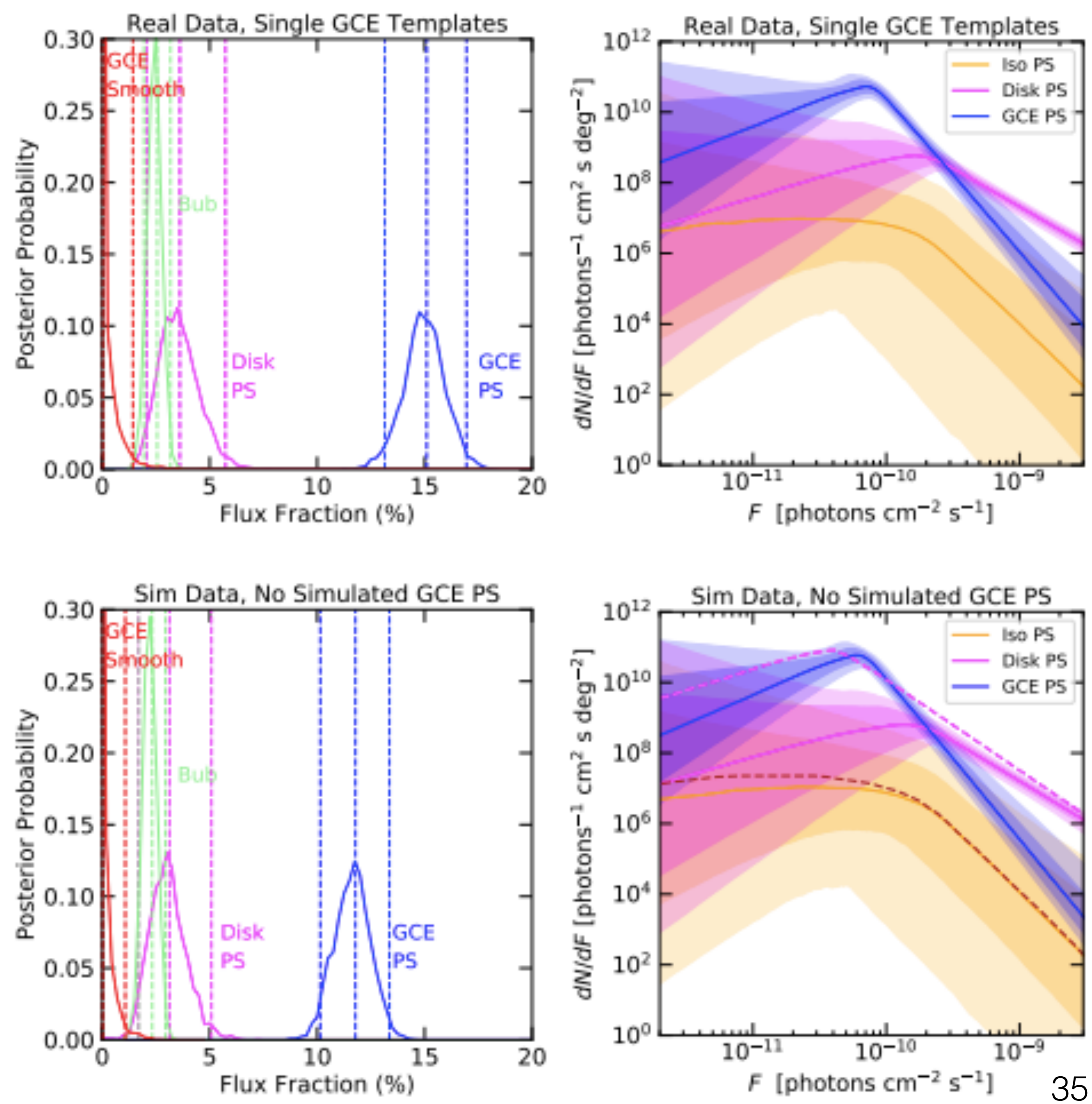
- We focused on a 10° radius region surrounding the GC as a testbed
- In this region we can explicitly identify a mismatch between the standard template and the fit's preference - data prefers a substantial north/south asymmetry (up to 2:1 depending on analysis choices)
- Point sources are initially strongly preferred (Bayes factor > 10^{15} with default background model), using symmetric signal templates.
- Once signal template is allowed to be asymmetric, preference for PSs drops to insignificance (BF~7).





Comparison of data and simulations

- We can see (and quantitatively explain) this effect in 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 we know in the simulations the preference for a PS population is **spurious**
- This casts doubt on the apparent NPTF detection of GCE PSs.



One example realization

Comparison of data and simulations

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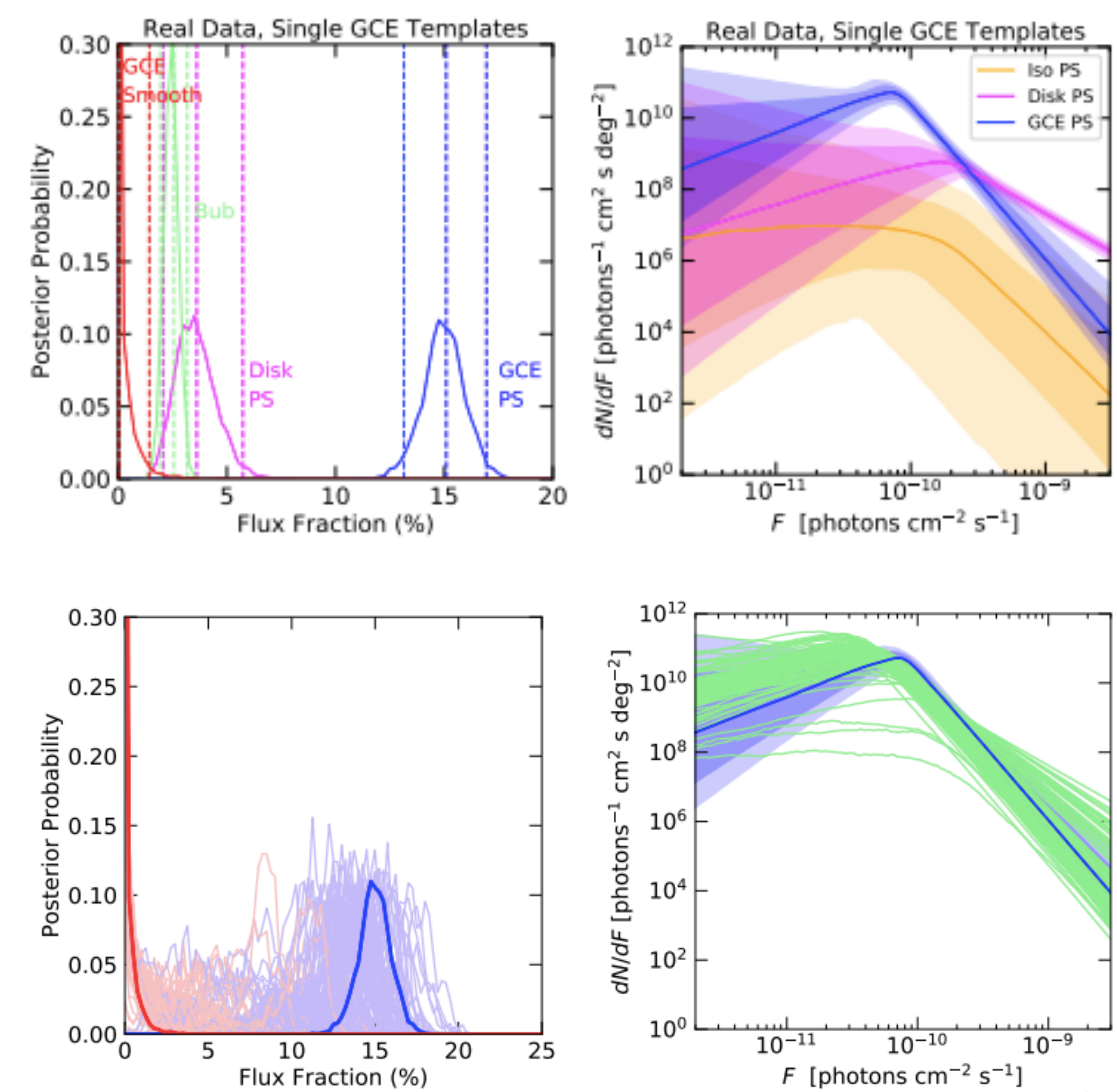

100 realizations

(an incomplete sample of) Future directions

- Modeling signal: better understanding of dark matter distribution - substructure, populations and properties of dwarf galaxies, presence and properties of non-equilibrium structures in the Milky Way, etc.

- Modeling background: improved methods for modeling the gamma-ray foregrounds/backgrounds, understanding inhomogeneous diffusion for cosmic rays, new probes for pulsars with upcoming radio telescopes MeerKAT/SKA.

- Future missions: many, but include CTA for high-energy gamma rays, AMEGO in the MeV-GeV gamma-ray band, GAPS to probe cosmic-ray antideuterons, new windows on the early universe with CMB Stage 4 & 21cm experiments.