Dark Matter Indirect Detection

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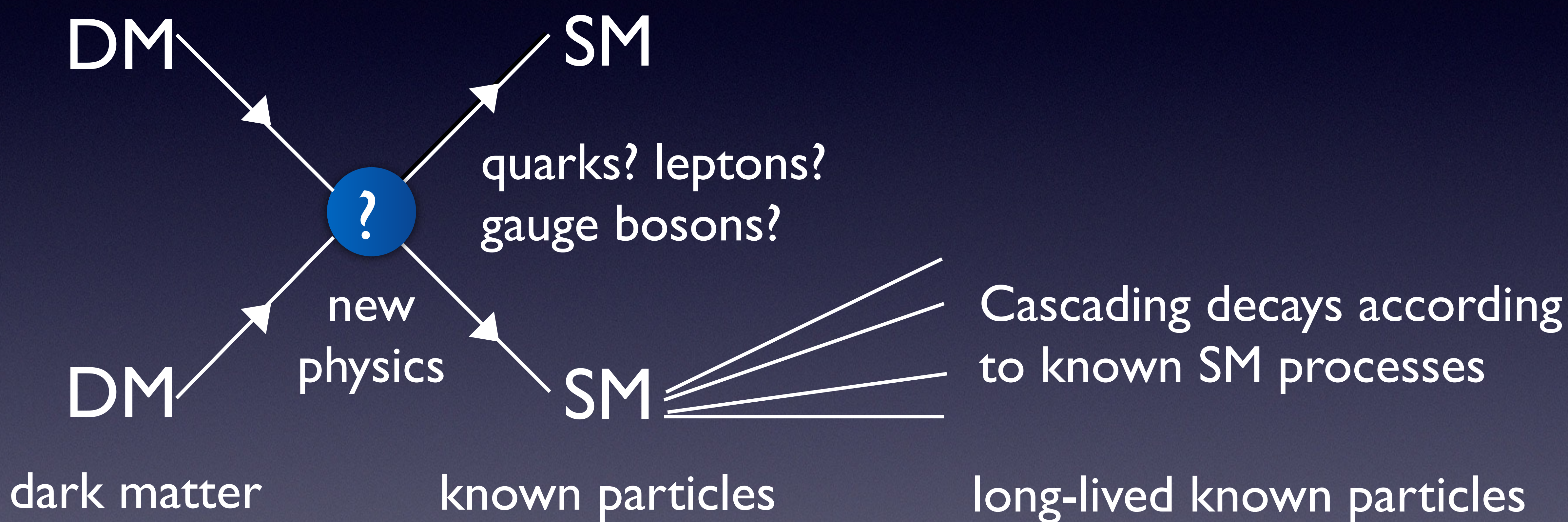
Indirect detection

- “Indirect detection” - search for Standard Model particles produced from dark matter, or their secondary effects.
- Allows probing DM stability/lifetime through search for decay products.
- In thermal relic models, indirect searches are the most direct probe of the origin of dark matter.
- In general, provides complementary sensitivity to other searches.

Annihilation



- Generically 2-body annihilation dominates
- Rate scales as the square of the DM density
- 3-body and higher annihilation is possible, but usually subdominant (but see e.g. literature on SIMPs)

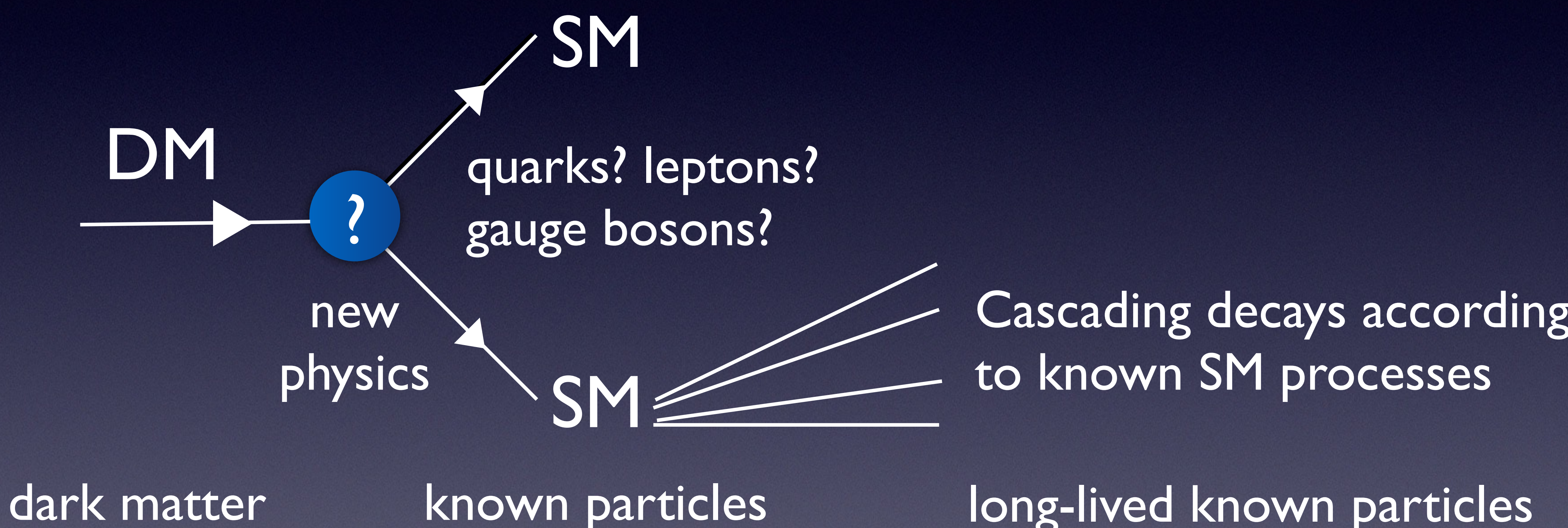
An annihilation benchmark

- We have already talked about the WIMP miracle / thermal relic scenario
- DM is in thermal equilibrium early on, then is depleted via annihilation (DM does not need to be weak-scale)
- Present-day abundance fixes cross section to be

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

- Coannihilation, velocity-dependent annihilation, dark matter asymmetry, etc, can change relationship between annihilation in early universe and today

Decay



- DM need not be perfectly stable, although lifetime must be >> age of universe
- Single-body process; rate of decays scales with 1 power of DM density

Decay benchmarks

- Decay lifetime is not connected to abundance in the same way as annihilation, but we can do some order-of-magnitude estimates for plausible rates
- Suppose DM annihilates through some higher-dimension operator + DM mass is ~weak scale (~TeV) + high mass scale is ~GUT scale (~10^{16} GeV):
  - dimension 5: $\tau \sim m_{\mathrm{GUT}}^2/m_{\mathrm{DM}}^3 \sim 0.1s$ very excluded
  - dimension 6: $\tau \sim m_{\mathrm{GUT}}^4/m_{\mathrm{DM}}^5 \sim 10^{25}s$ interesting!
  - dimension 7: $\tau \sim m_{\mathrm{GUT}}^6/m_{\mathrm{DM}}^7 \sim 10^{51}s$ totally unobservable

OBSERVATIONS OF NEUTRAL ANNIHILATION/ DECAY PRODUCTS

Photons and neutrinos

- Travel in straight lines (although may need to account for redshifting, absorption)
- Thus we can obtain 2D (occasionally 3D) information on source distribution - very valuable for separating signal from background
- Strength of signal from a given source determined by dark matter content - parameterized by "J-factor"

J-factors (I)

- Take volume element dV at a distance R from the observer, with DM density ρ.
- Rate of annihilations/volume/time (assuming identical DM particles):

$$\frac{1}{2} n_{\rm DM}^2 \langle \sigma v \rangle = \frac{1}{2} \frac{\rho^2}{m_{\rm DM}^2} \langle \sigma v \rangle$$

- If spectrum produced per annihilation is dN/dE, then spectrum produced/volume/time is:

$$\frac{1}{2} \frac{\rho^2}{m_{\rm DM}^2} \langle \sigma v \rangle \frac{dN}{dE}$$

- Particle spectrum per unit time incident on detector of area A (if no redshifting/absorption/deflection):

$$\frac{1}{2} \frac{\rho^2}{m_{\rm DM}^2} \langle \sigma v \rangle \frac{dN}{dE} dV \frac{A}{4\pi R^2}$$

J-factors (II)

- Integrating over all such volume elements dV, working in spherical polar coordinates (centered at observer), the total observed spectrum per unit (detector) area per unit time is:

$$\frac{dN_{\rm obs}}{dE\,dt\,dA} = \underbrace{\frac{1}{8\pi m_{\rm DM}^2}\langle\sigma v\rangle\frac{dN}{dE}}_{\text{particle physics}}\underbrace{\int\rho^2 dR d\Omega}_{\text{astrophysics}}$$

particle physics

astrophysics (measurable by gravity) "J-factor"

- For decaying DM, the same argument gives:

$$\frac{dN_{\rm obs}}{dE\,dt\,dA} = \frac{1}{4\pi m_{\rm DM}}\frac{1}{\tau}\frac{dN}{dE}\int\rho dR\,d\Omega$$

Estimates with J-factors

- Typical J-factors: dwarf satellite galaxies of Milky Way: 10^{17-20} GeV^2/cm^5, Galactic center region (within 1 degree) 10^{22} GeV^2/cm^5
- This assumes a "cuspy" Navarro-Frenk-White profile (from first lecture) - may not be a good assumption at small distances:

$$\rho \propto \frac{r^{-1}}{(1+r/r_s)^2}$$

- Example: thermal relic cross section, 100 GeV DM, ~1 photon produced per annihilation in energy bin of interest
- Rate of photons observed on Earth from GC region:

$$10^{22}\text{GeV}^2/\text{cm}^5 \times 3 \times 10^{-26}\text{cm}^3/s \times \frac{1}{8\pi}\frac{1}{(100\text{GeV})^2} \sim 10^{-9}/\text{cm}^2/s$$

- In this example, need O(1 year) with 100 cm^2 detector to see one photon.

J-factors + redshift

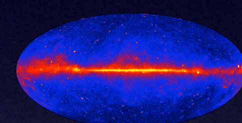
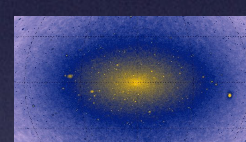
- What if photons come to us over cosmological distances, so redshifting cannot be ignored?
- Source spectrum needs to be evaluated at E' = E(1+z).
- Recast integral in terms of redshift z rather than distance.
- Easiest to work in comoving coordinates - must take into account that the physical volume dV corresponding to a given comoving volume is smaller at earlier redshift, by a factor $(1+z)^3$.

$$\frac{dN_{\mathrm{obs}}}{dE\,dt\,dA} = \int \frac{d\Omega}{4\pi} \int dz \left(\frac{dN}{dE'}\right)\bigg|_{E'=E(1+z)} \frac{1}{H(z)(1+z)^3}$$

$$\times \begin{cases} \frac{\langle \sigma v_{\mathrm{rel}} \rangle}{2 m_{\mathrm{DM}}^2} \rho(z,\theta,\phi)^2 & \text{annihilation} \\ \frac{1}{m_{\mathrm{DM}}\tau} \rho(z,\theta,\phi) & \text{decay} \end{cases}$$

- To include absorption etc, insert appropriate redshift- and position-dependent factors inside the integral.

Where to look?

- Dwarf galaxies 
- Galactic center 
- Galactic halo 
- Other galaxies and clusters 
- Dark matter subhalos 
- Extragalactic background radiation

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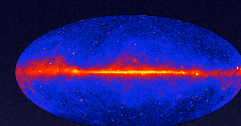
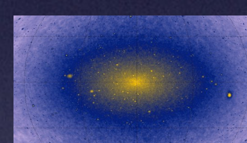
- Galactic center 
- Galactic halo 
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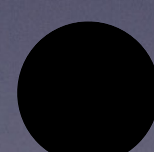
- Dark matter subhalos 
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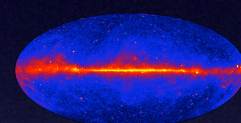
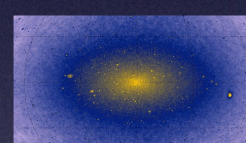
- Galactic center  high signal, high background, sensitive to presence of density cusp/core
- Galactic halo 
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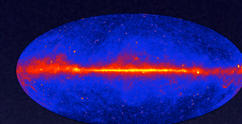
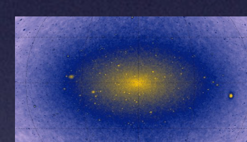
- Galactic center  high signal, high background, sensitive to presence of density cusp/core
- Galactic halo  large area, nearby, complex backgrounds
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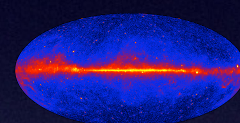
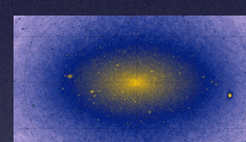
- Galactic center  high signal, high background, sensitive to presence of density cusp/core
- Galactic halo  large area, nearby, complex backgrounds
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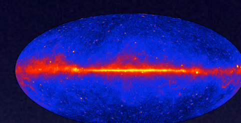
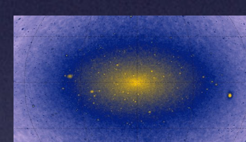
- Galactic center  high signal, high background, sensitive to presence of density cusp/core
- Galactic halo  large area, nearby, complex backgrounds
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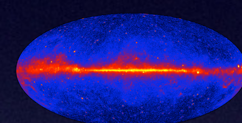
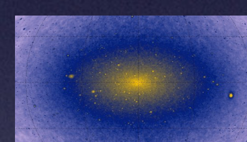
- Galactic center  high signal, high background, sensitive to presence of density cusp/core
- Galactic halo  large area, nearby, complex backgrounds
- Other galaxies and clusters  large dark matter content, (potentially) hold redshift information, sensitive to amount of substructure
- Dark matter subhalos  potentially numerous, probe small-scale structure
- Extragalactic background radiation — holds redshift information, probes halos at all scales

Gamma-ray limits

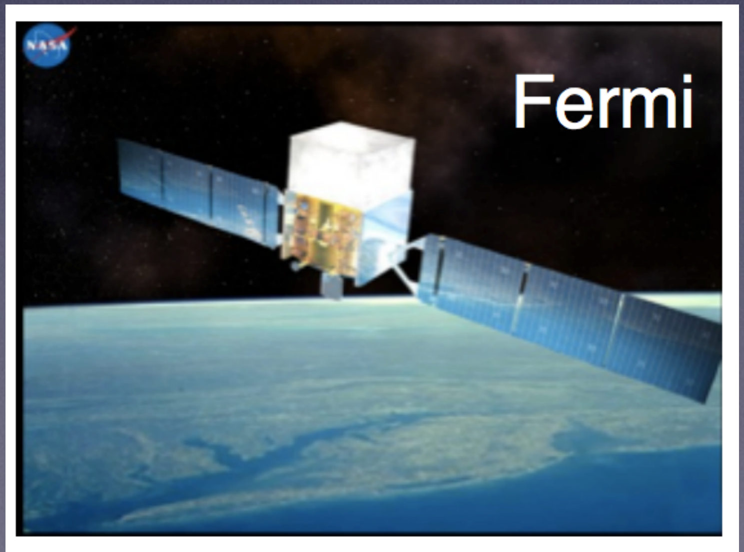
HAWC

few TeV - 100 TeV

100 GeV - 10s of TeV

also VERITAS, MAGIC

100 MeV - 1 TeV

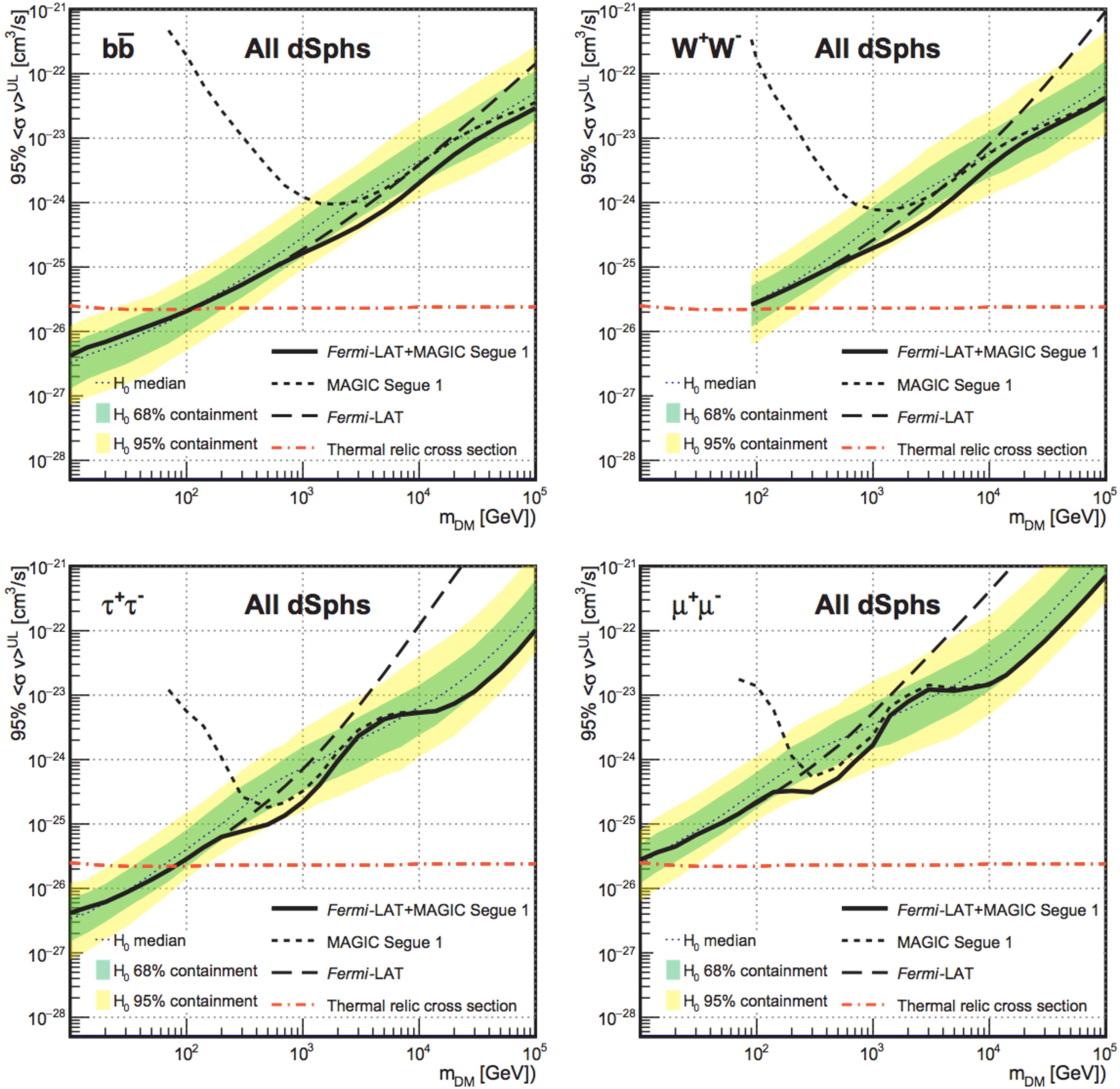


also DAMPE

Continuum limits from dwarfs

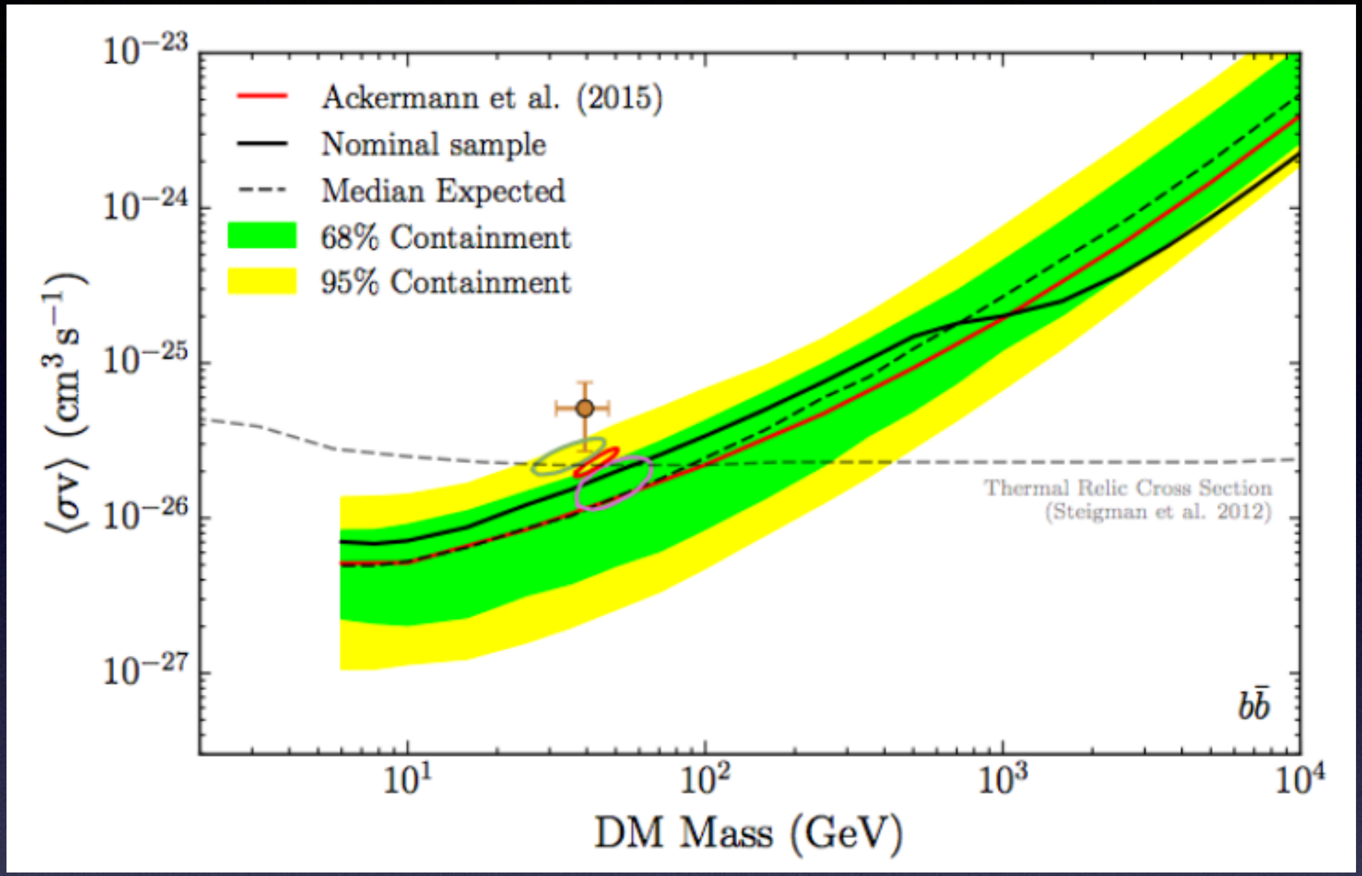
- Fit for localized gamma-ray emission over smooth background at location of dwarf galaxies, compare observed and predicted dwarf gamma-ray signal in likelihood analysis.
- The Fermi Gamma-Ray Space Telescope (~1 m^2 telescope, this year is 10-year anniversary of launch) has presented limits based on 45 dwarf galaxies and candidates (Albert et al '17). Strongest robust bounds on sub-TeV DM annihilating to photon-rich channels.
- Limits are publicly available as likelihood functions for fluxes in each energy bin (https://www-glast.stanford.edu/pub_data/) - can set constraints on arbitrary spectra.
- Examples shown for annihilation into b quarks and tau leptons.
- VERITAS and MAGIC also set constraints on these channels from a similar dwarf study (HESS bounds exist too, see Abramowski et al '14, but are slightly weaker) - but currently difficult to compete with Fermi.

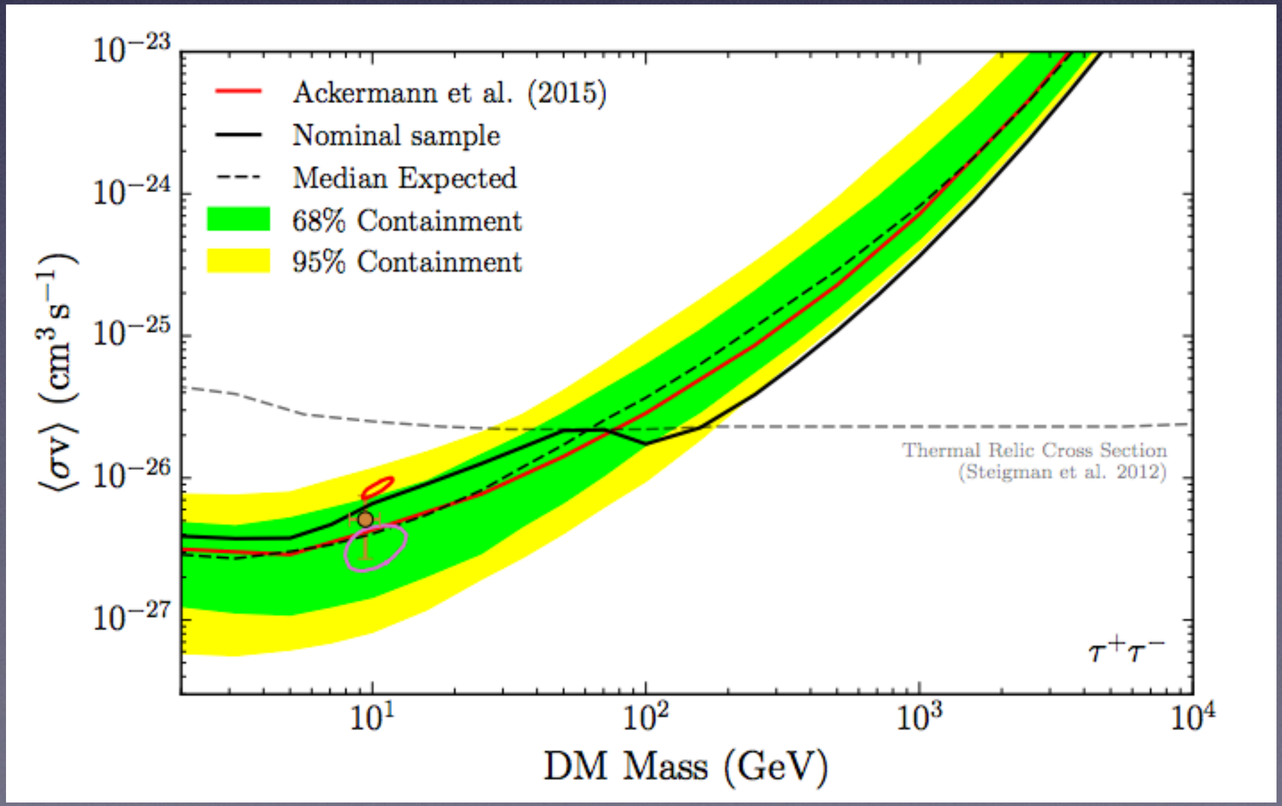
- Combined analysis of dwarf galaxies with Fermi and MAGIC



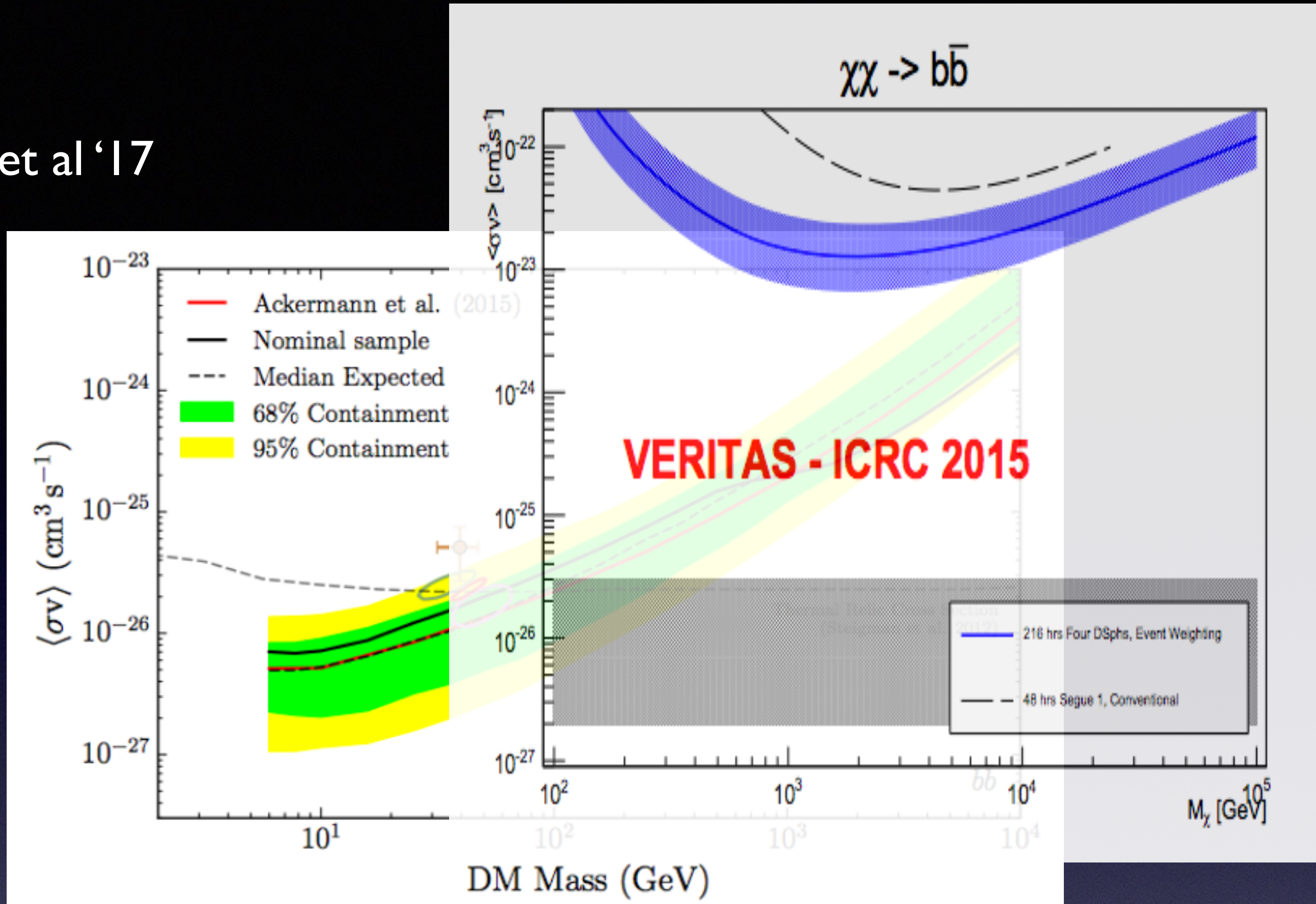
Ahnen et al '16

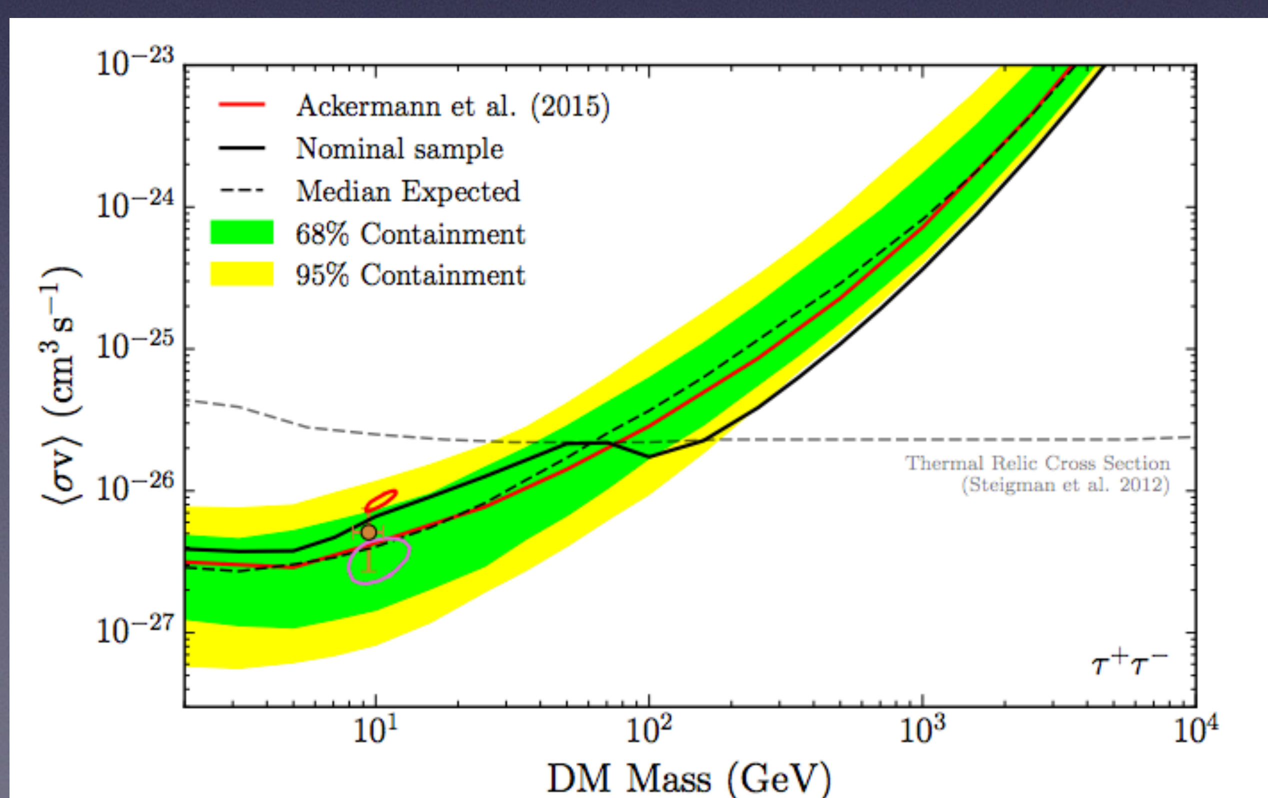
Albert et al '17





Albert et al ‘17





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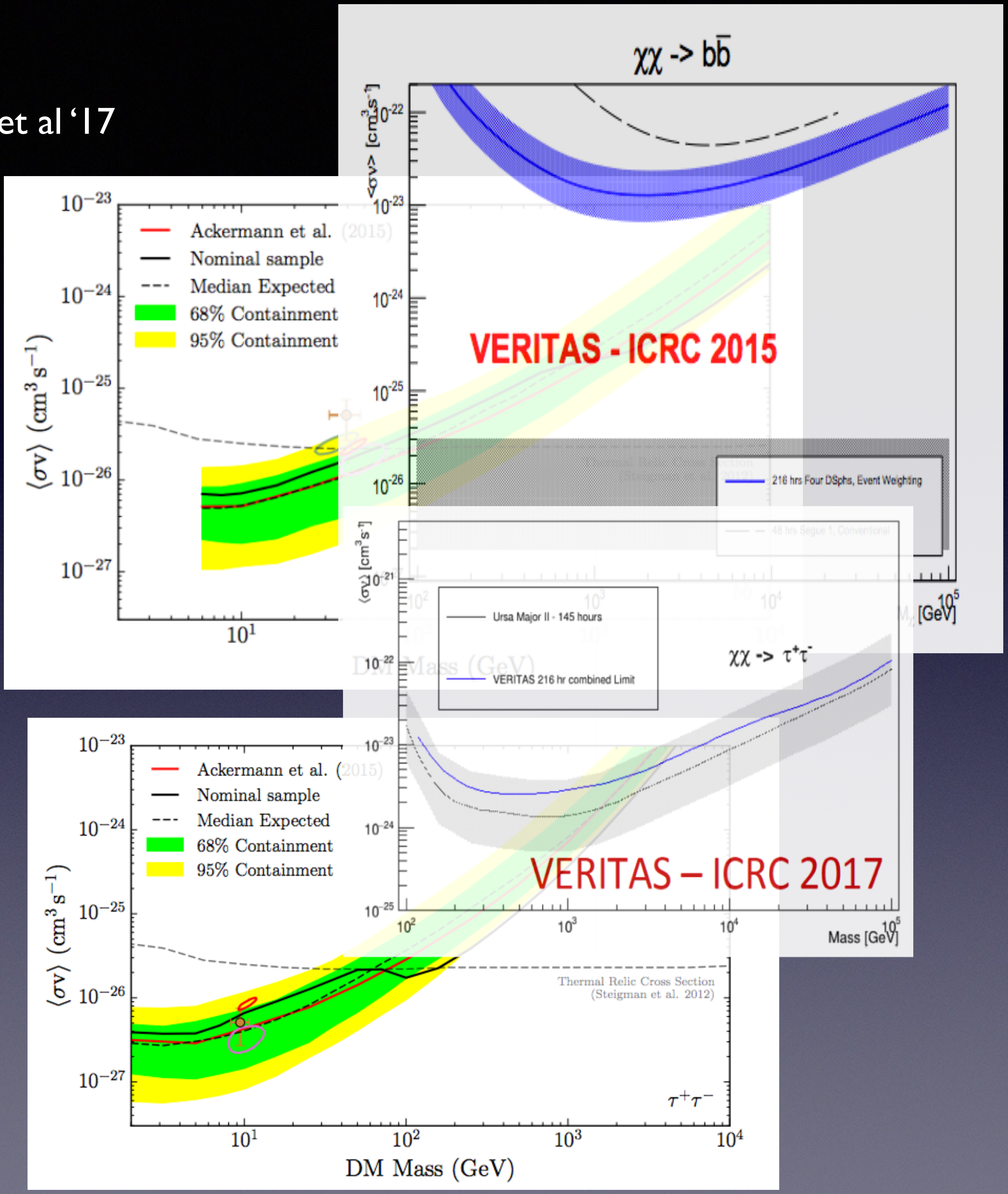

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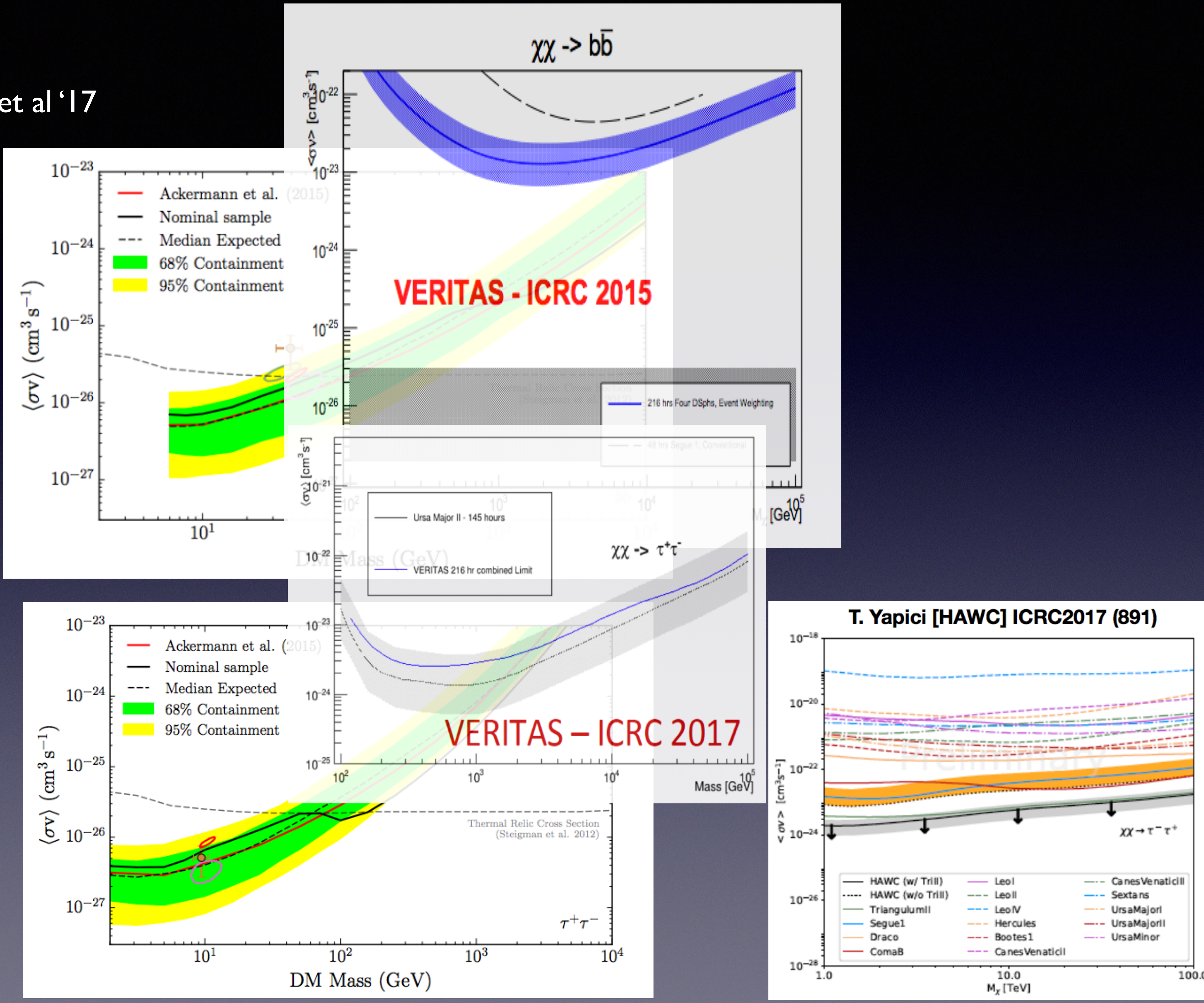


Heavy DM decay

- GeV+ decaying DM constrained by dwarf galaxies, galaxy clusters, extragalactic gamma-ray background, Milky Way halo.
- Lifetime lower limits ~$10^{27\text{-}28}$ s, for DM masses in the $10\text{-}10^{10}$ GeV range, for representative hadronic decay channels.

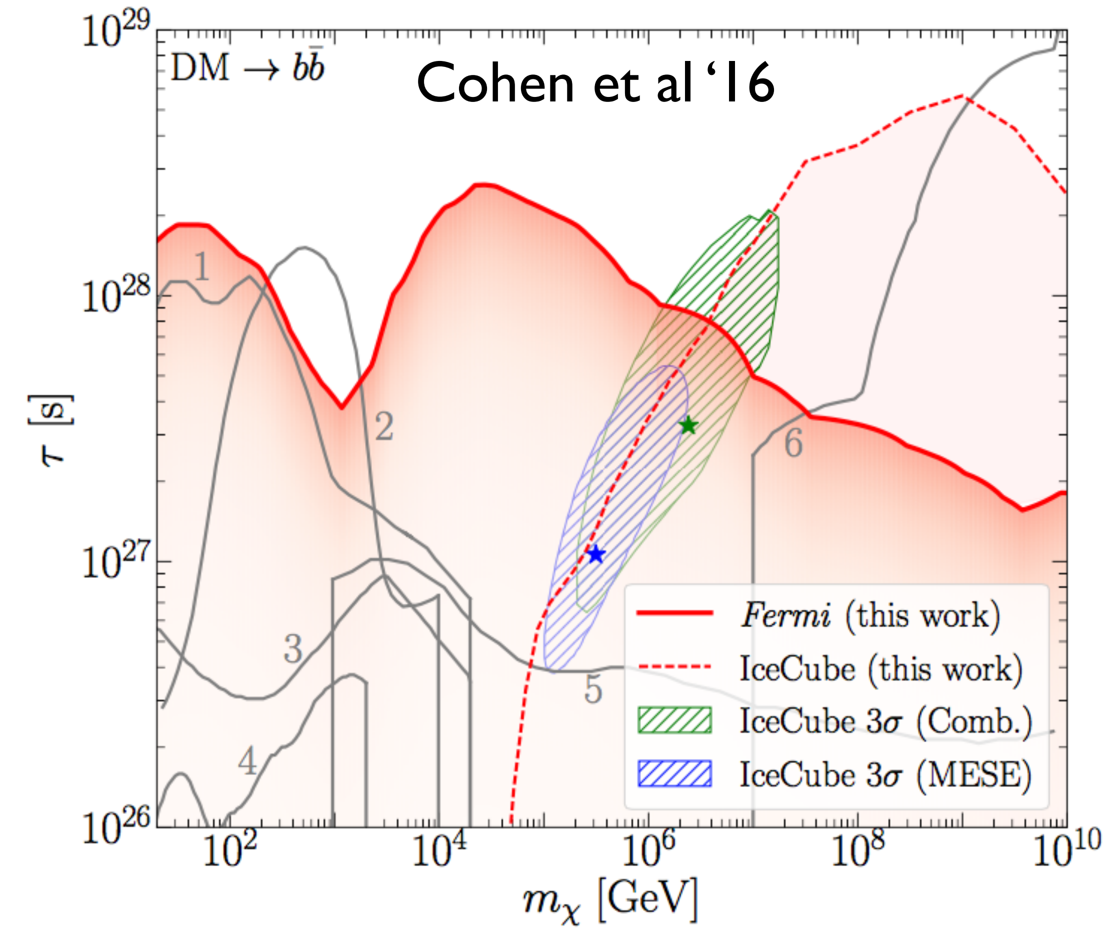


FIG. 1: Limits derived in this work on DM decays to $b\bar{b}$, as compared to previously computed limits using data from *Fermi* (2,3,5), AMS-02 (1,4), and PAO/KASCADE/CASA-MIA (6). The hashed green (blue) region suggests parameter space where DM decay may provide a $\sim 3\sigma$ improvement to the description of the combined maximum likelihood (MESE) IceCube neutrino flux. The best-fit points, marked as stars, are in strong tension with our gamma-ray results. The red dotted line provides a limit if we assume a combination of DM decay and astrophysical sources are responsible for the spectrum.

Light DM and the photon diffuse background

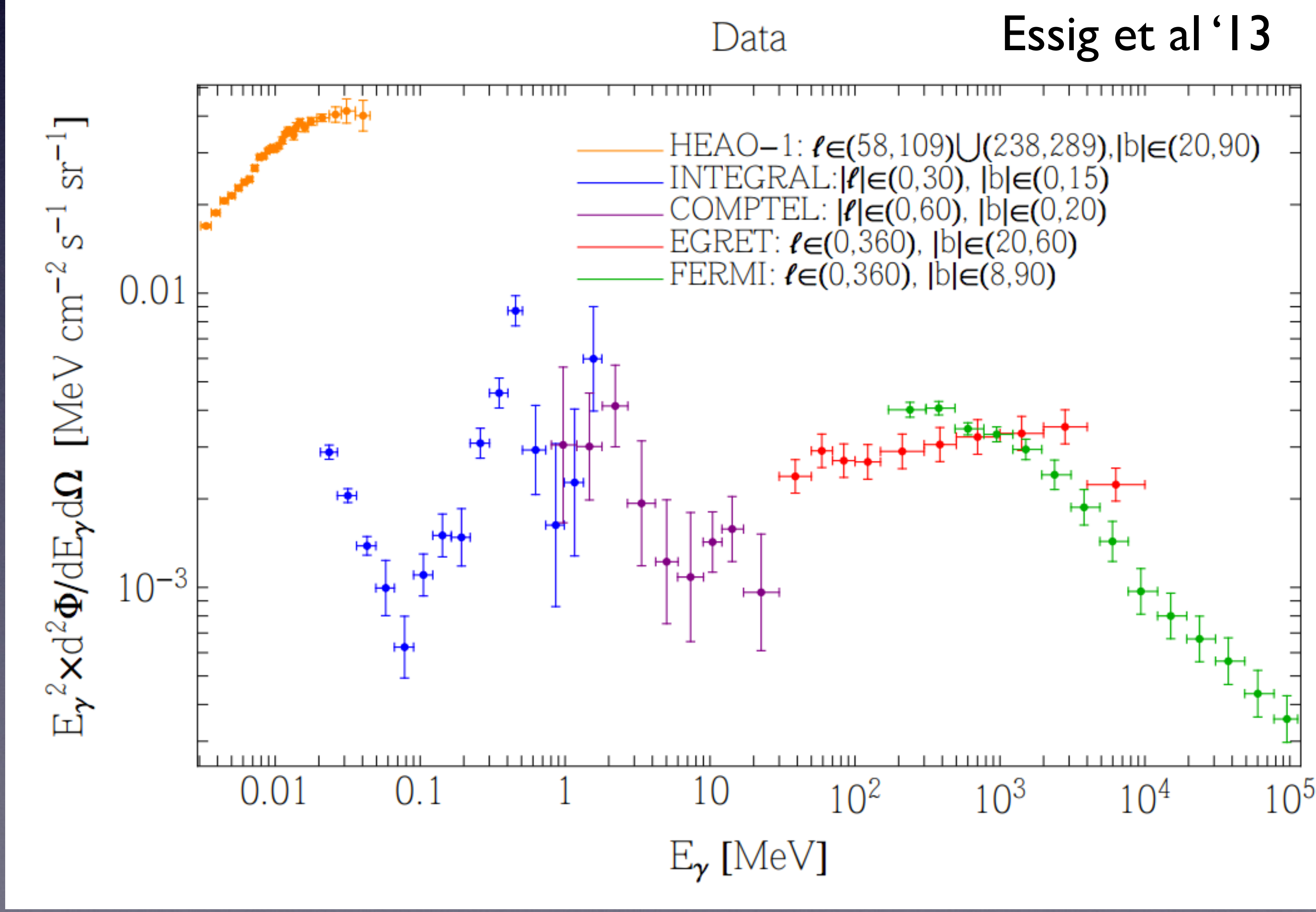
<<1 GeV: dominant annihilation to electrons/positrons, photons, neutrinos

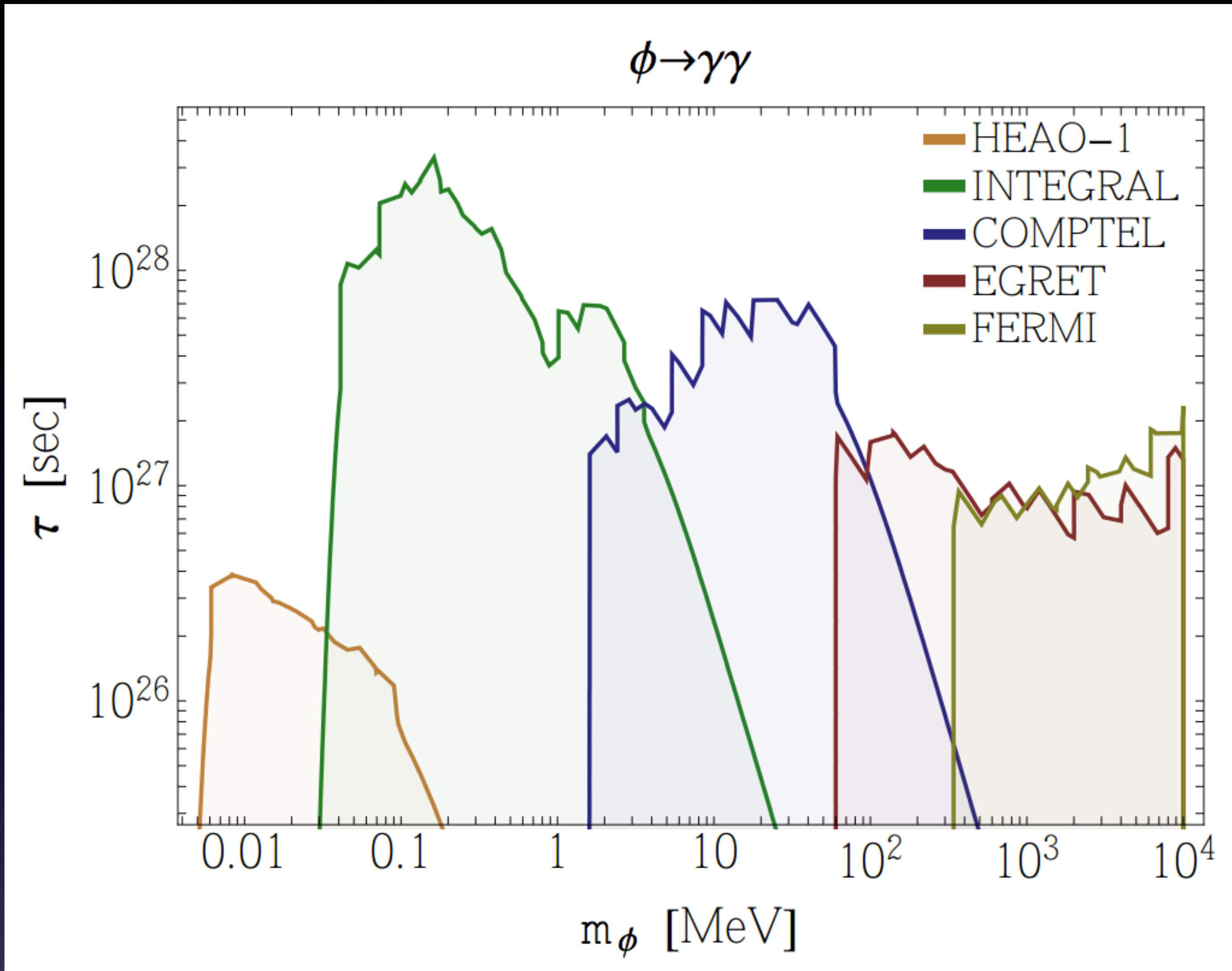
- Photon spectrum often predicted to be either line-like or have a hard spectrum

- For channels that produce copious photons, strongest limits on <u>decay</u> come from studying gamma-rays from the Milky Way halo.

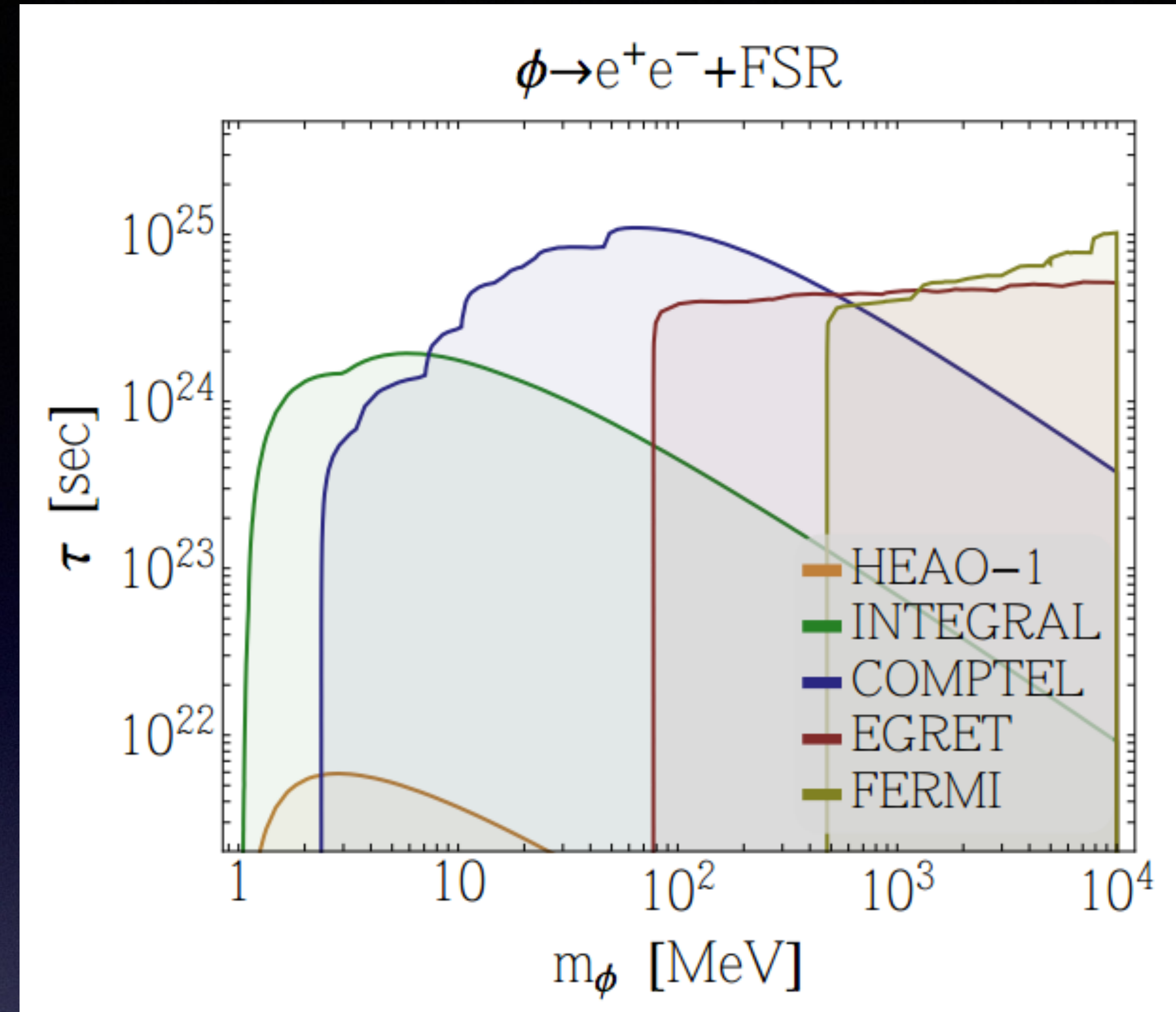
- Constraints are competitive for decay and p-wave (velocity-suppressed) annihilation to electrons (but not s-wave annihilation).

Essig et al '13

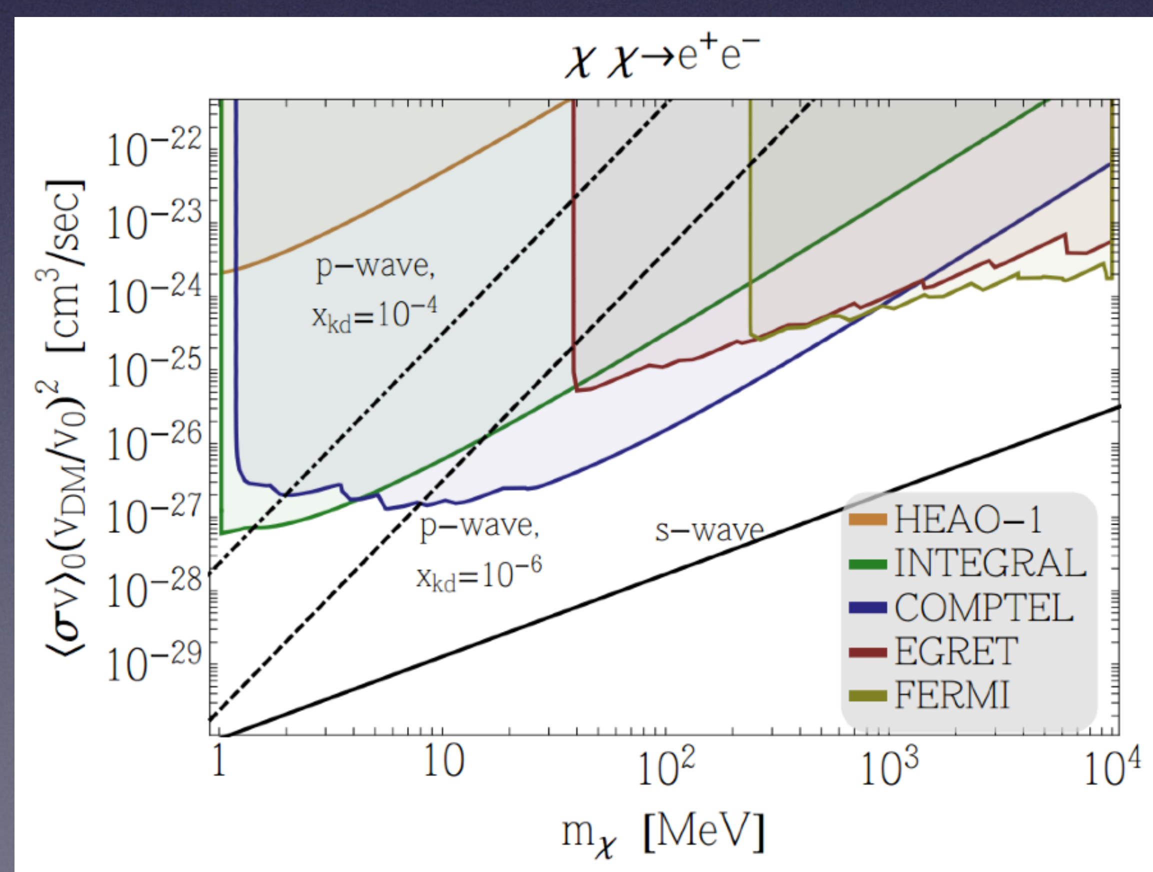




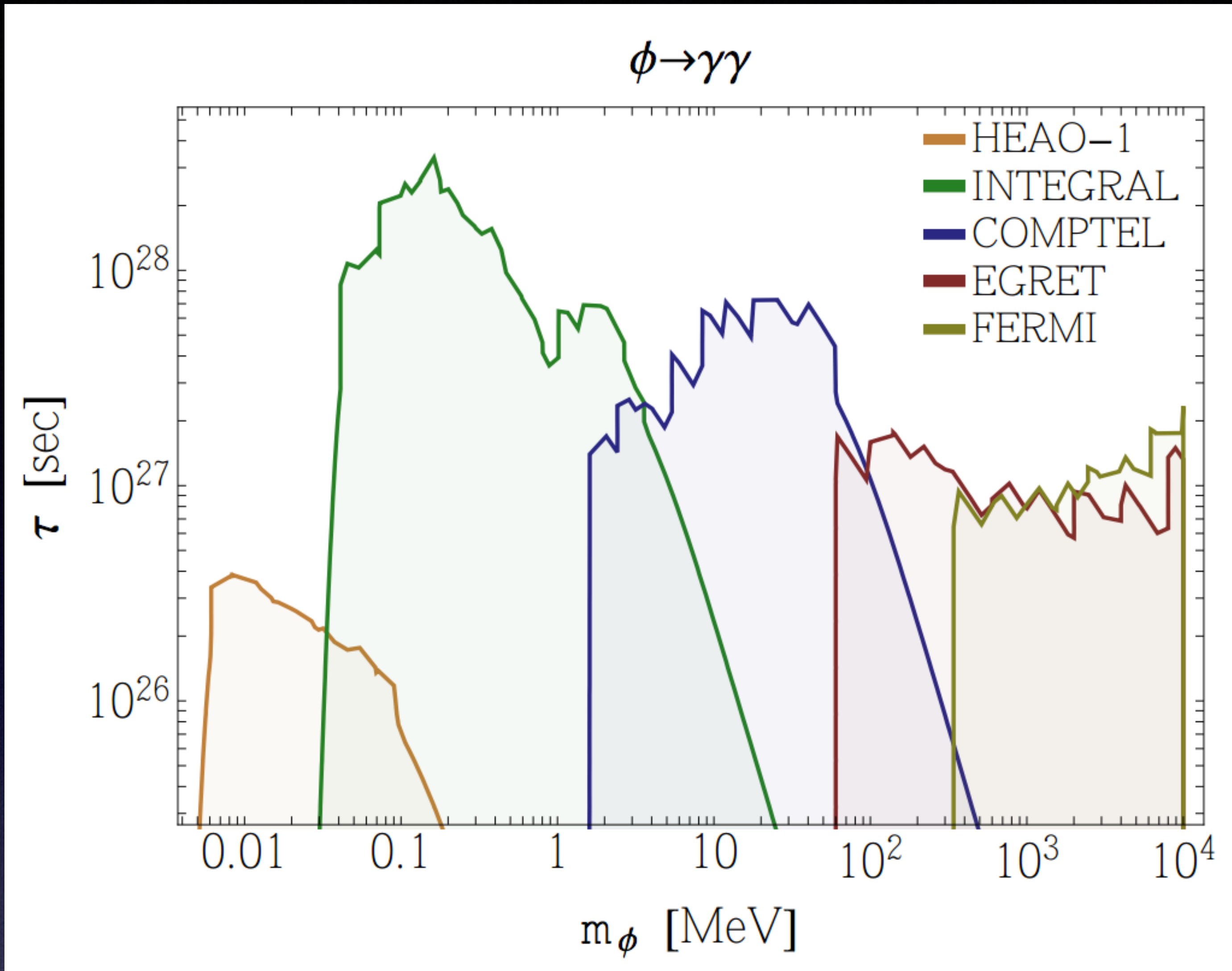
$\phi \to \gamma\gamma$
HEAO−1
INTEGRAL
COMPTEL
EGRET
FERMI
τ [sec]
10^{28}
10^{27}
10^{26}
0.01
0.1
1
10
10^2
10^3
10^4
m_ϕ [MeV]



$\phi \to e^+e^- + \mathrm{FSR}$
10^{25}
10^{24}
10^{23}
10^{22}
τ [sec]
HEAO−1
INTEGRAL
COMPTEL
EGRET
FERMI
1
10
10^2
10^3
10^4
m_ϕ [MeV]



$\chi\chi \to e^+e^-$
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
$\langle \sigma v \rangle_0 (v_{DM}/v_0)^2$ [cm^3/sec]
p−wave,
$x_{kd}=10^{-4}$
p−wave,
$x_{kd}=10^{-6}$
s−wave
HEAO−1
INTEGRAL
COMPTEL
EGRET
FERMI
1
10
10^2
10^3
10^4
m_χ [MeV]



$\phi \to \gamma\gamma$
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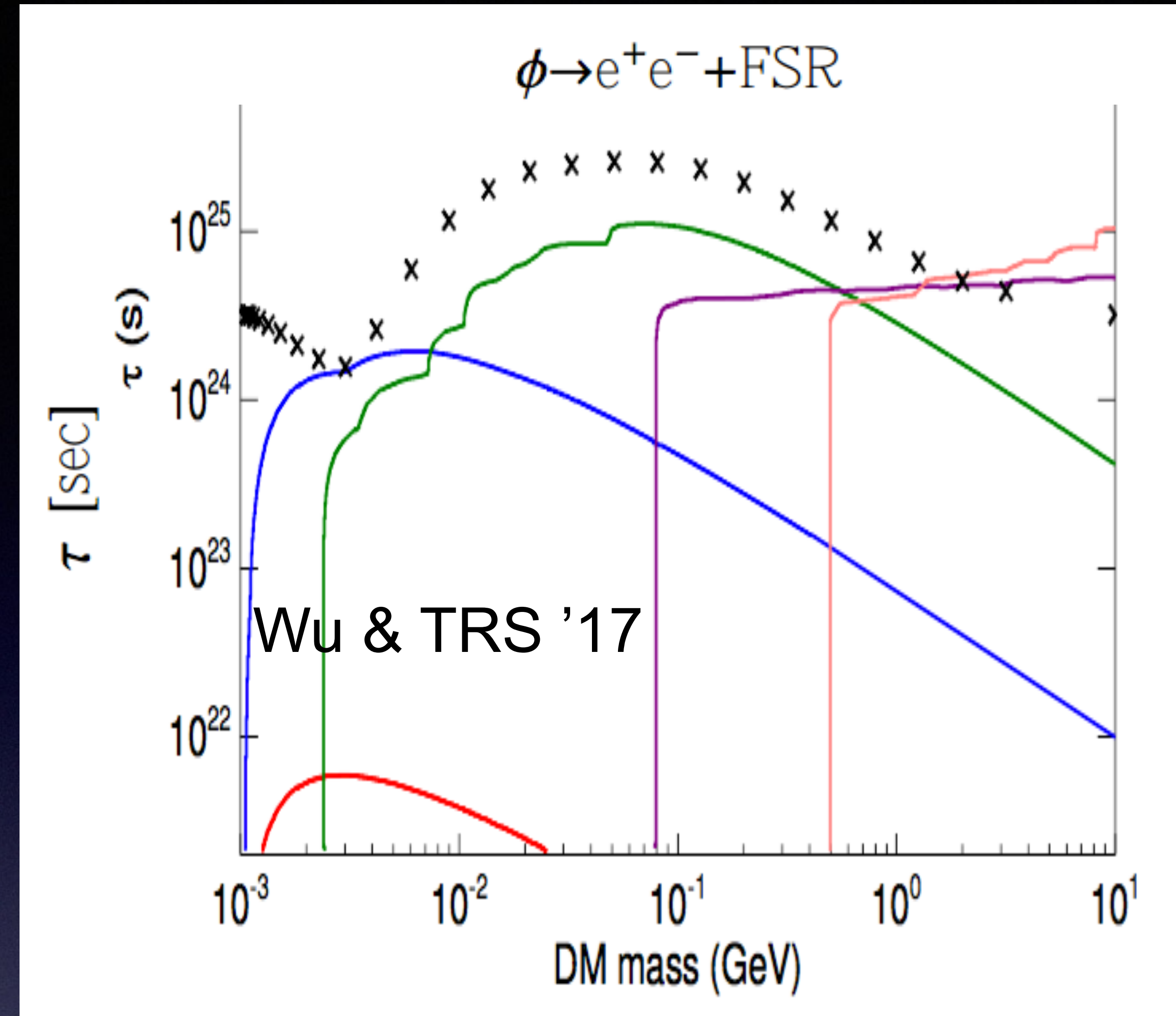
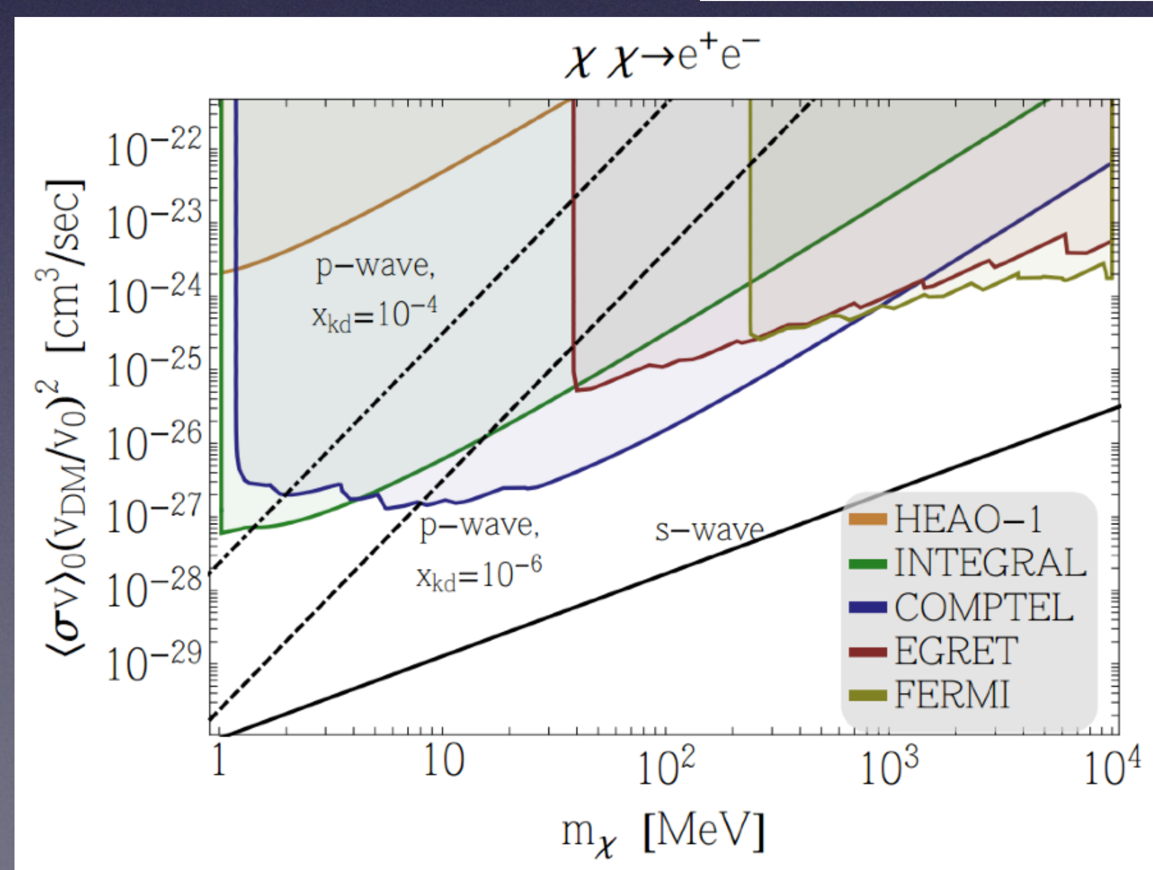
τ [sec]
m_ϕ [MeV]



$\phi \to e^+e^- + FSR$
Wu & TRS '17
τ [sec]
τ (s)
DM mass (GeV)

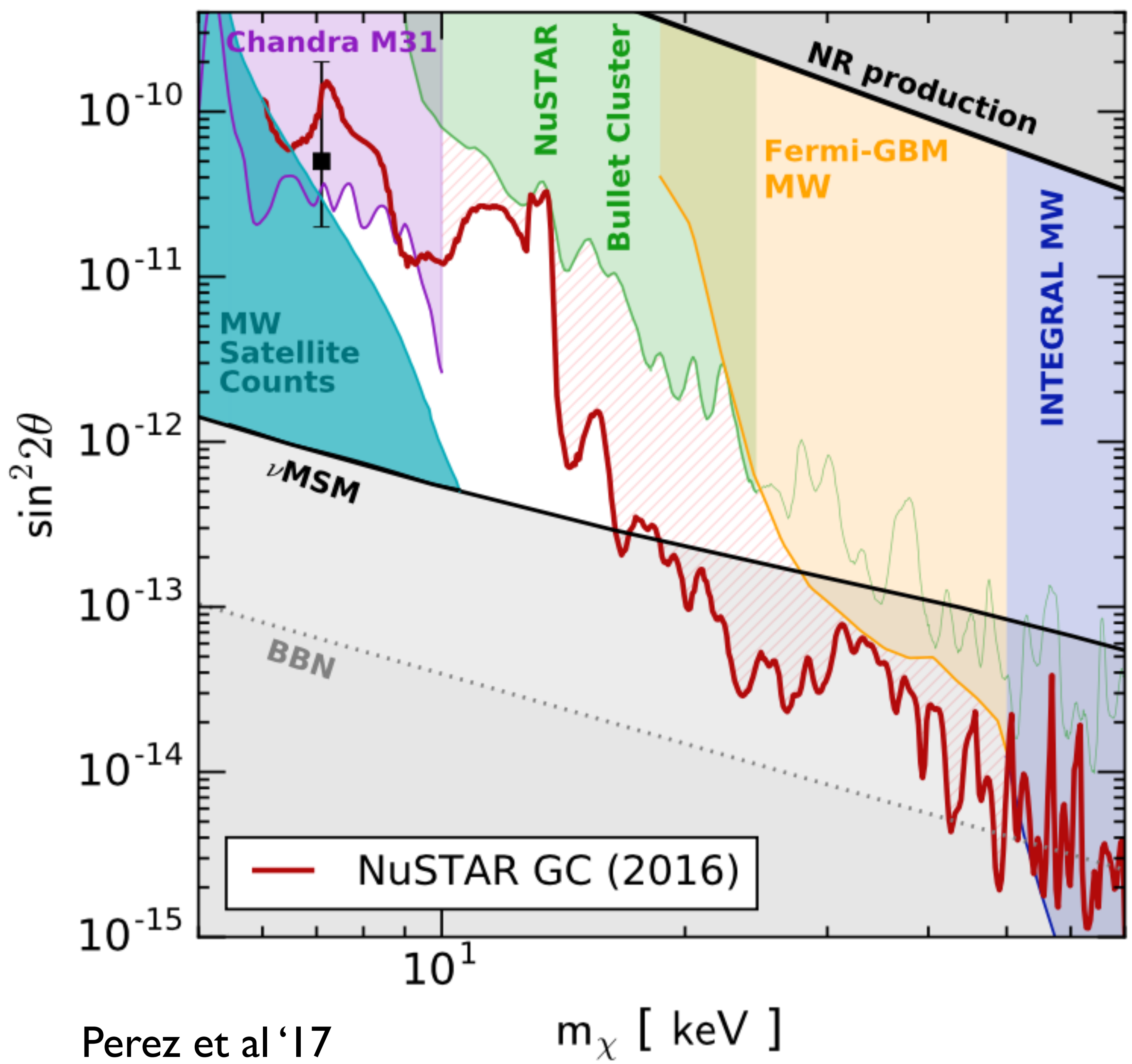


$\chi\chi \to e^+e^-$
p−wave, $x_{kd}=10^{-4}$
p−wave, $x_{kd}=10^{-6}$
s−wave
HEAO−1
INTEGRAL
COMPTEL
EGRET
FERMI
$\langle\sigma v\rangle_0 (v_{DM}/v_0)^2$ [cm^3/sec]
m_χ [MeV]

Even lighter DM - X-ray limits

$$\tau \sim 10^{29}\mathrm{s} \left(\frac{\sin^2(2\theta)}{10^{-7}}\right)^{-1} \left(\frac{m_s}{1\mathrm{keV}}\right)^{-5}$$

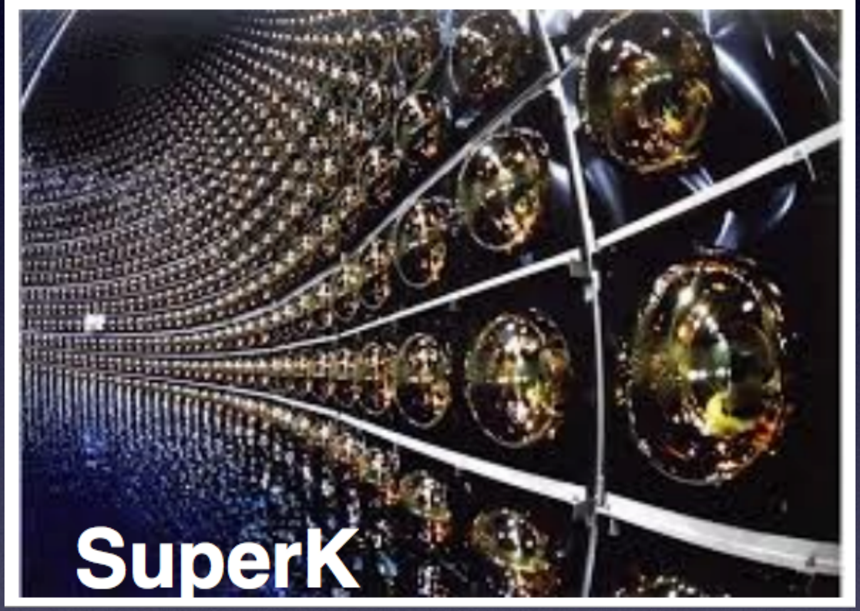
- Sterile neutrinos are a classic example of DM that could decay to produce photons, with a long lifetime.
- X-ray telescopes can probe this signal - plot on right shows constraints from several telescopes.



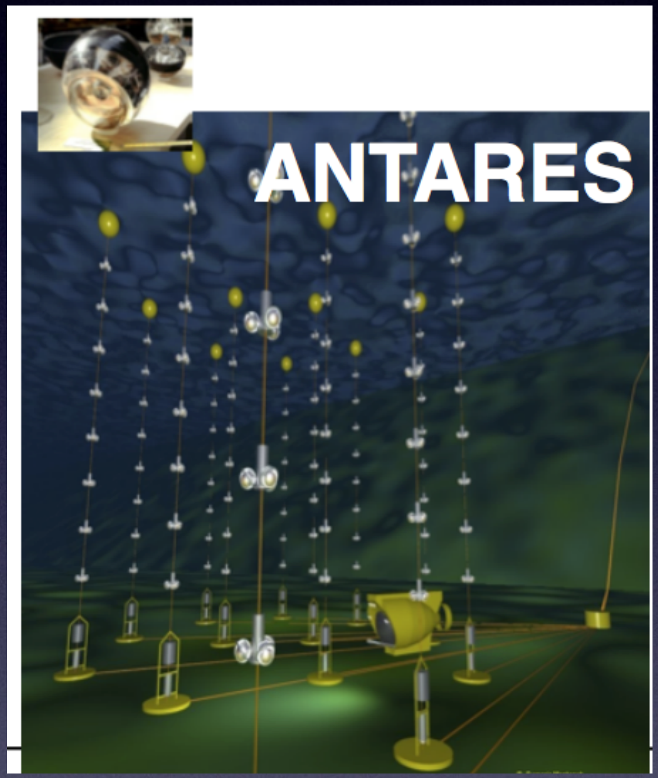
Perez et al '17

Neutrinos from dark matter

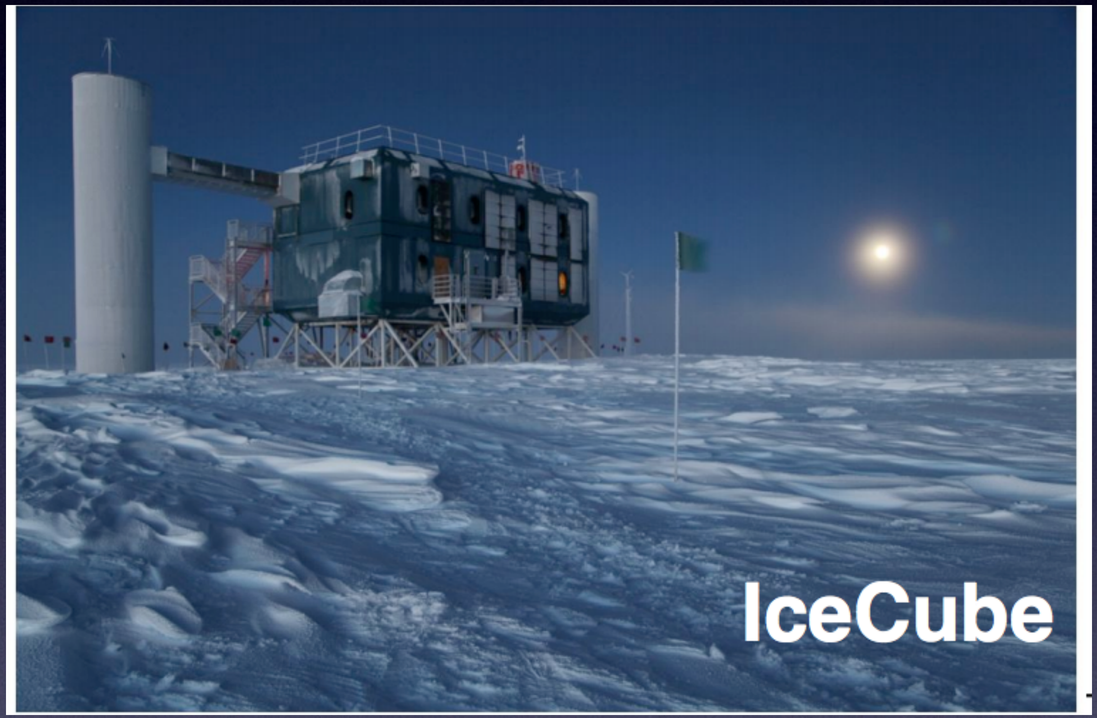
few MeV - TeV



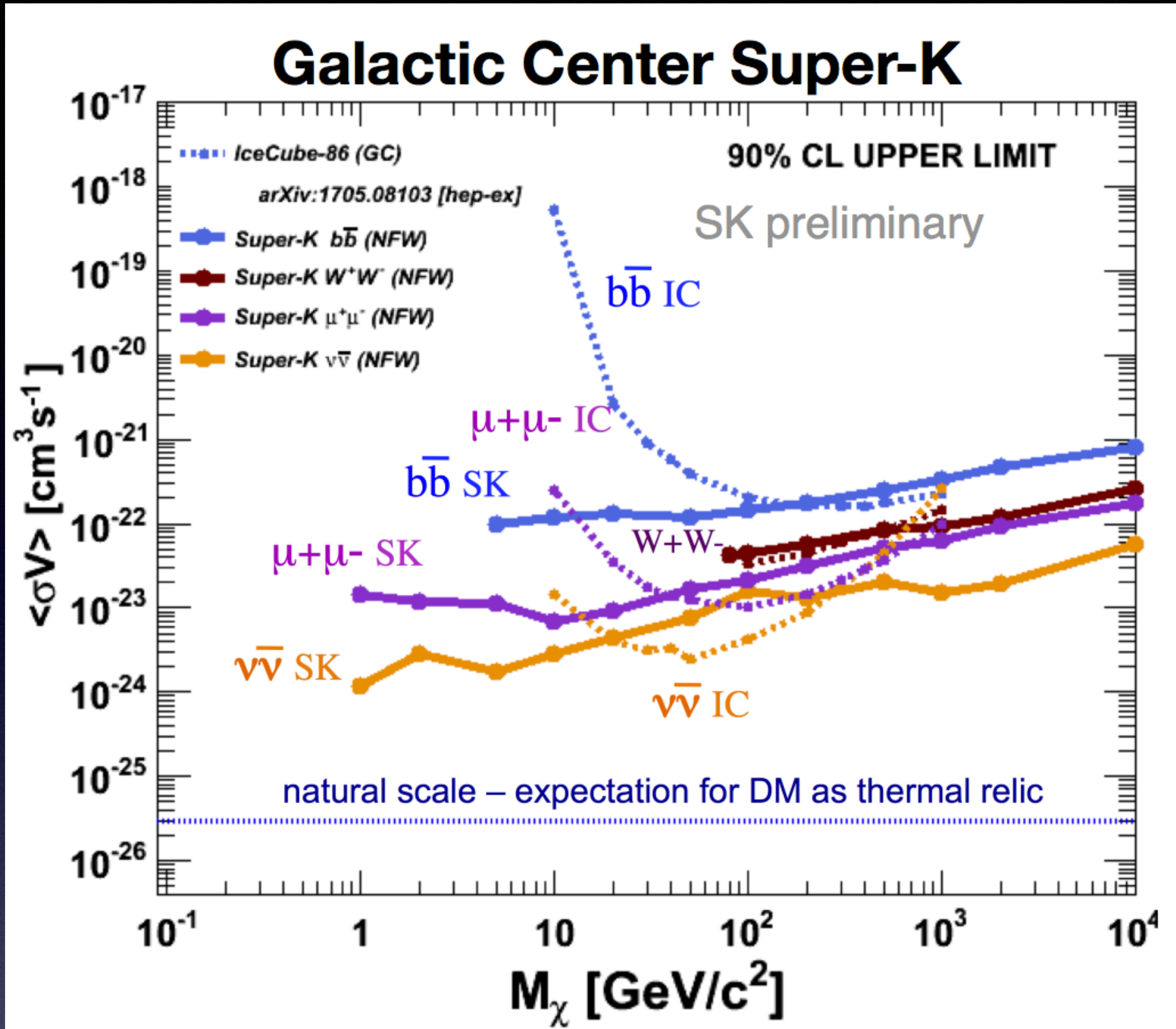
100 GeV - 100 TeV

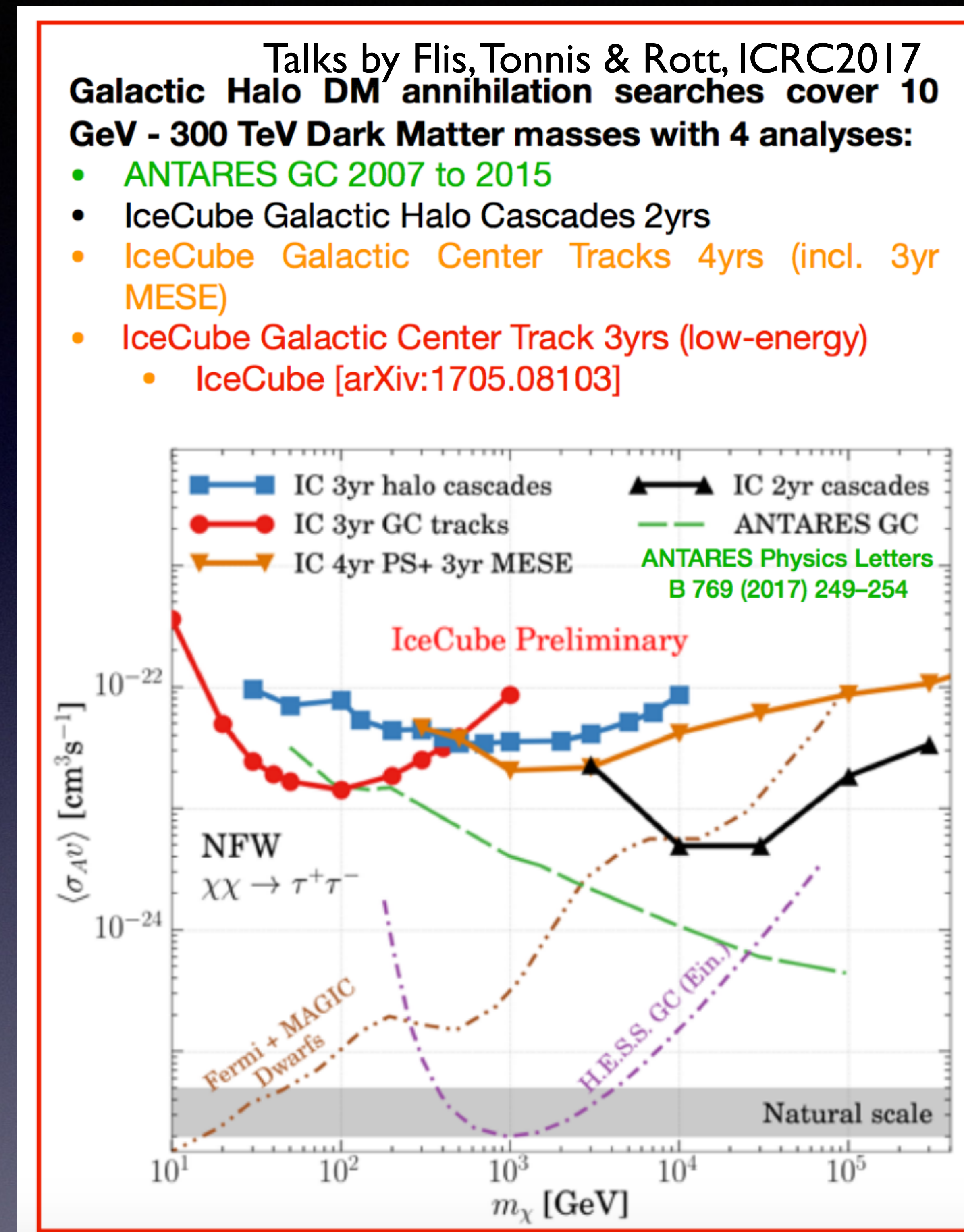


100 GeV - 10^9 GeV



- Neutrino experiments can constrain and cross-check DM annihilation/decay to any SM particle that decays producing neutrinos.
- Unique sensitivity if neutrinos are main annihilation/decay product.





- SuperK and IceCube set stringent limits on GeV+ DM annihilating to neutrinos. Even for non-neutrino channels, can set competitive limits at high mass scales.

OBSERVATIONS OF CHARGED ANNIHILATION/ DECAY PRODUCTS

Indirect searches with cosmic rays

- Charged particles are affected by Galactic magnetic fields - trajectories do not point back toward sources
- Makes signal/background separation more difficult, unless expected background is very small (true for anti-deuteron searches)
- Main observable is the energy spectrum of particles measured in neighborhood of Earth
- Modeling expected signal is significantly more complicated than for photons/neutrinos
- Propagation uncertainties affect both signal and backgrounds

Diffusive propagation

- Basic picture: our Galaxy is a sea of cosmic rays diffusing through the Galactic magnetic field, losing energy as they propagate
- Strategy: solve diffusion equation for cosmic ray propagation

$$\frac{\partial \psi}{\partial t} = D(E)\nabla^2 \psi + \frac{\partial}{\partial E}(b(E)\psi) + Q(\vec{x}, E, t)$$

$$\frac{dn_{\mathrm{CRs}}}{dE} = \psi(\vec{x}, E, t)$$

- In practice, use numerical solvers - e.g. GALPROP, DRAGON - or pregenerated results (e.g. PPPC4DMID)

The diffusion equation

$$\frac{\partial \psi}{\partial t} = D(E)\nabla^2\psi + \frac{\partial}{\partial E}(b(E)\psi) + Q(\vec{x}, E, t)$$

- Simple approach: model Galaxy as cylindrical slab
- Impose free-escape conditions at boundaries of slab
- Assume isotropic+homogeneous diffusion, model diffusion coefficient as a power-law function of energy
- Can modify any/all of these assumptions, and/or add more terms - e.g. for convection, fragmentation, reacceleration

The diffusion equation

$$\frac{\partial \psi}{\partial t} = D(E) \nabla^2 \psi + \frac{\partial}{\partial E}(b(E)\psi) + Q(\vec{x}, E, t)$$

diffusion coefficient

energy loss rate

source term

- Simple approach: model Galaxy as cylindrical slab
- Impose free-escape conditions at boundaries of slab
- Assume isotropic+homogeneous diffusion, model diffusion coefficient as a power-law function of energy
- Can modify any/all of these assumptions, and/or add more terms - e.g. for convection, fragmentation, reacceleration

Steady-state solutions

- DM annihilation/decay expected to be a steady source, not transient - want to look at steady-state spectrum of cosmic rays.
- Set ψ time-independent, assume ψ to have a power-law-like energy dependence (so $\partial/\partial E \sim 1/E$), write $\nabla^2\psi \sim \psi/R^2$ where R is the length-scale of the problem (set by boundary conditions).
- Then the diffusion equation becomes:

$$Q \sim \psi \left(\frac{D(E)}{R^2} + \frac{b(E)}{E} \right)$$

- Straightforward solution: $\psi \sim Q \min(\tau_{\rm diff}, \tau_{\rm loss})$

$$\tau_{\rm diff} \sim R^2/D(E) \qquad \tau_{\rm loss} \sim E/b(E)$$

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$\tau_{\rm diff} \sim R^2/D(E)$ $\tau_{\rm loss} \sim E/b(E)$

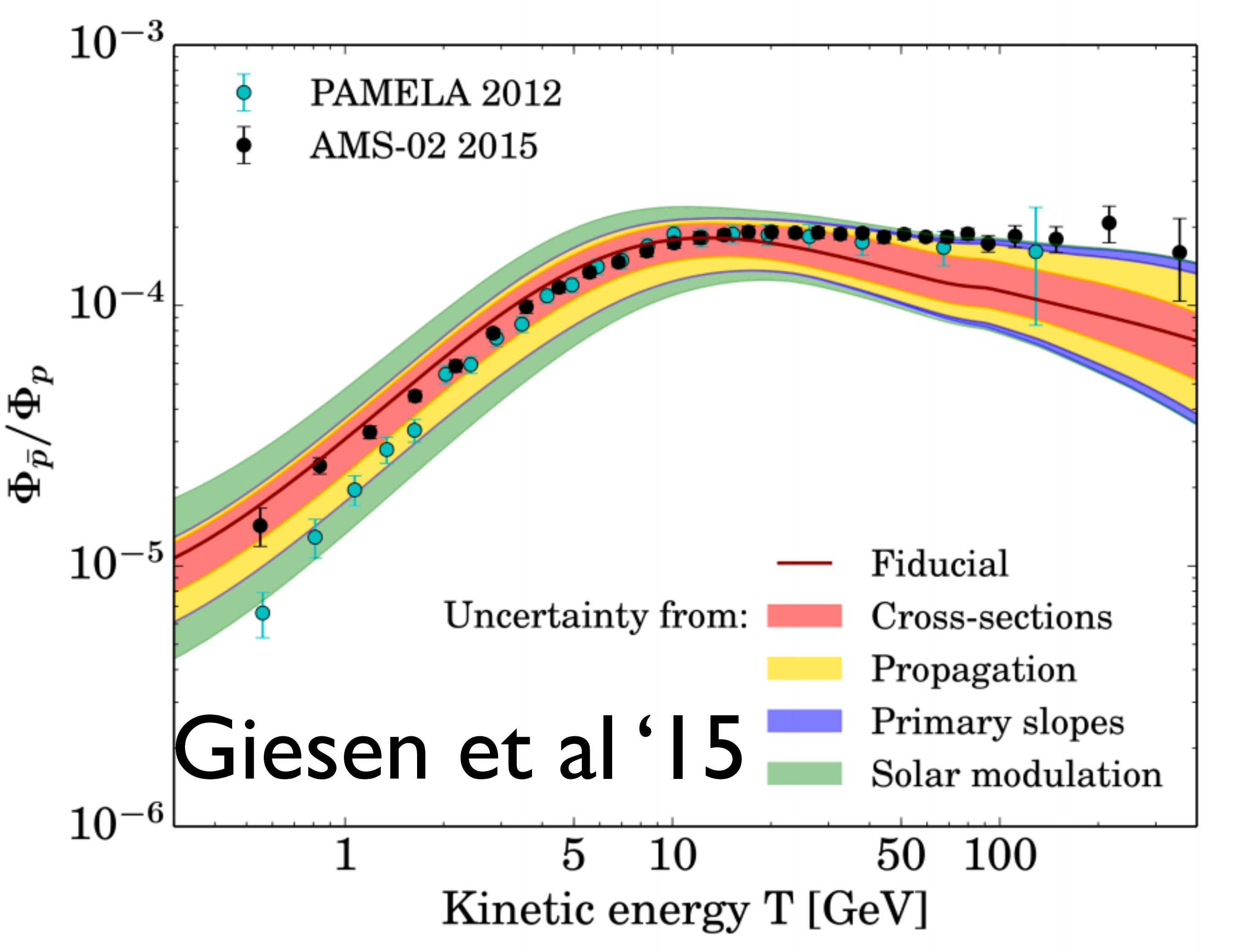
Effects of diffusion/ energy loss

- We expect the diffusion coefficient D(E) to increase modestly with energy, $D(E) \sim D_0 (E/E_0)^\delta$, $\delta \sim 0.3$-0.7.
- Diffusion-dominated regime ($\tau_{diff} << \tau_{loss}$): steady-state spectra look like source spectra multiplied by $E^{-\delta}$ - expectation for protons/antiprotons.
- Loss-dominated regime - expected to hold for high-energy positrons/ electrons: dominant cooling mechanisms have $b(E) \sim E^2$. Steady-state spectra look like source spectra x 1/E.
- Sometimes diffusion dominates at some energies and losses at others - leads to features in the spectrum.
- Diffusion/losses make spectra softer (or features broader - try a delta-function injection!) Secondary particles (source = steady-state spectrum of another species) should have softer spectra than their progenitors.

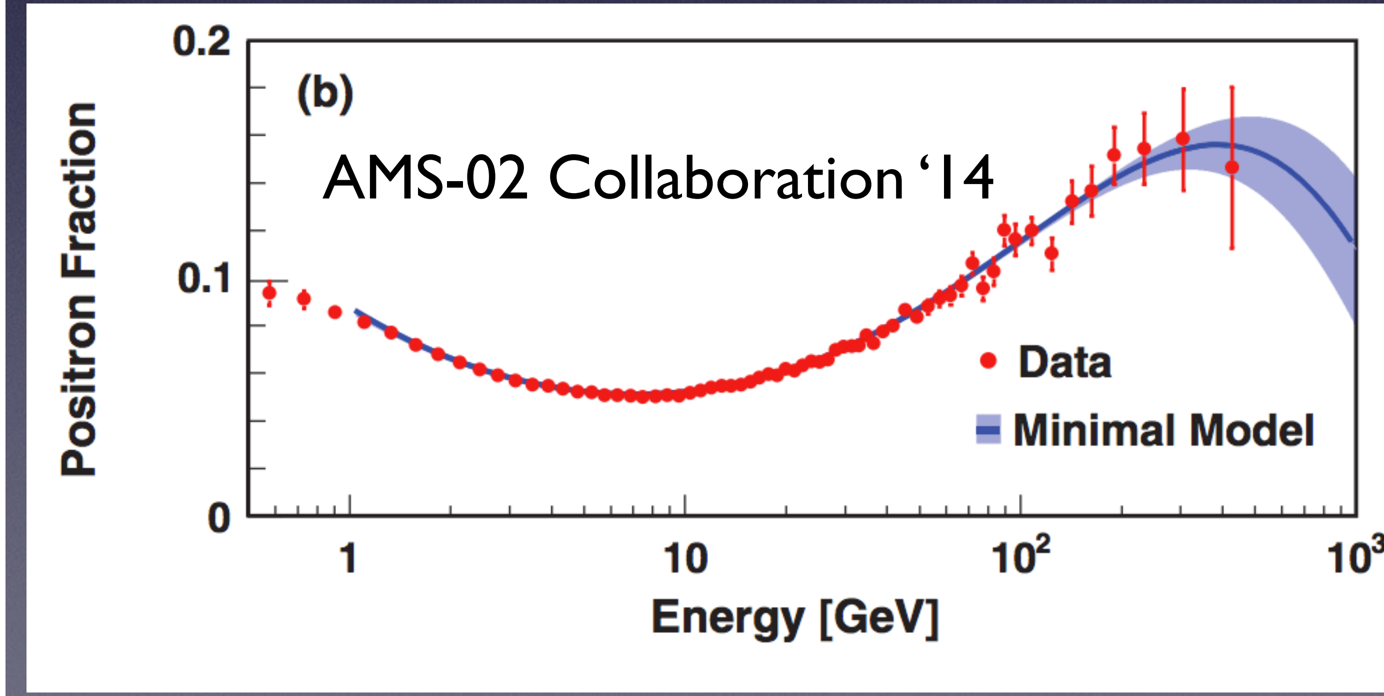
Cosmic-ray limits

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)

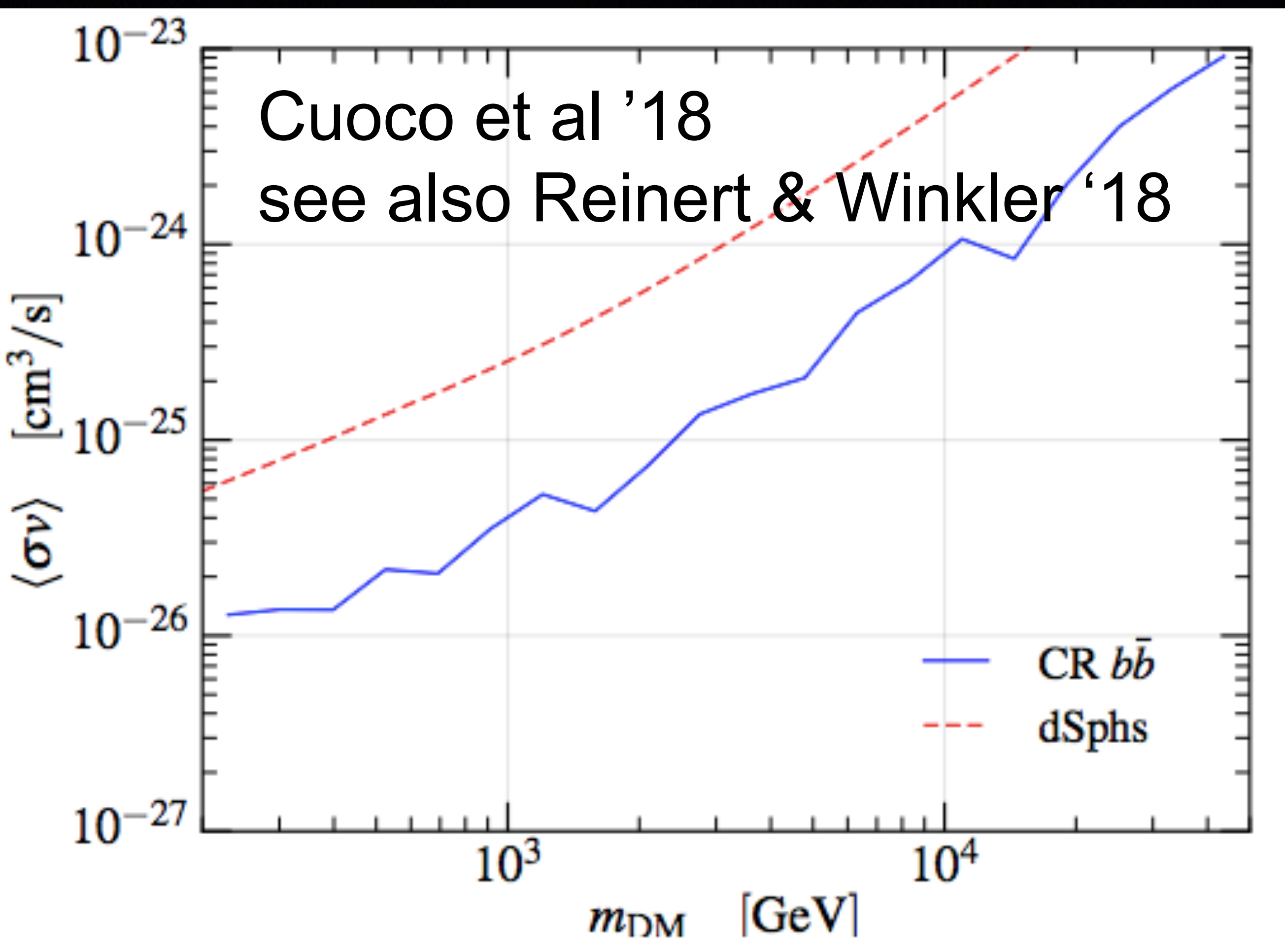


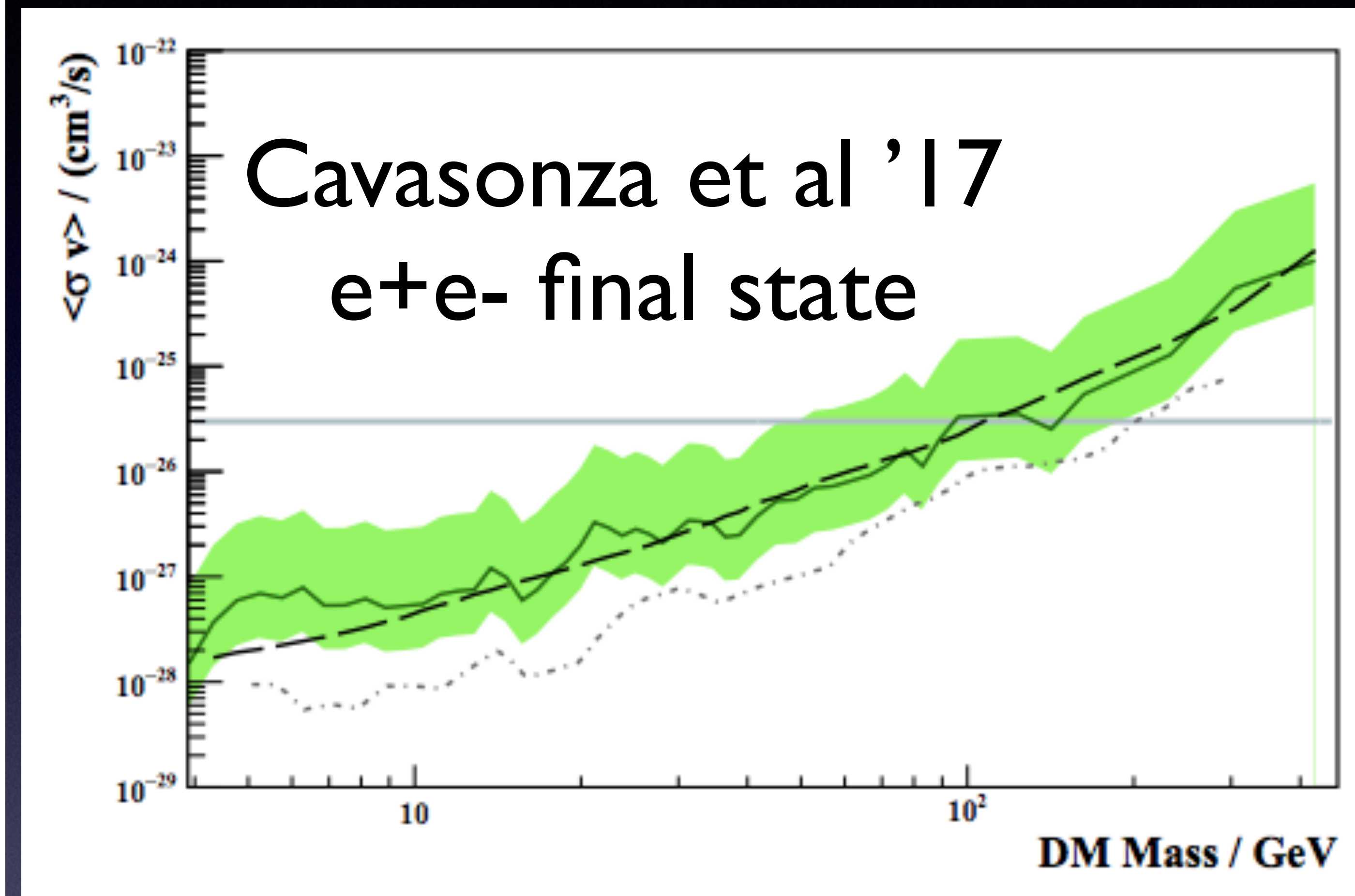
Giesen et al '15



AMS-02 Collaboration '14

Cosmic ray limits

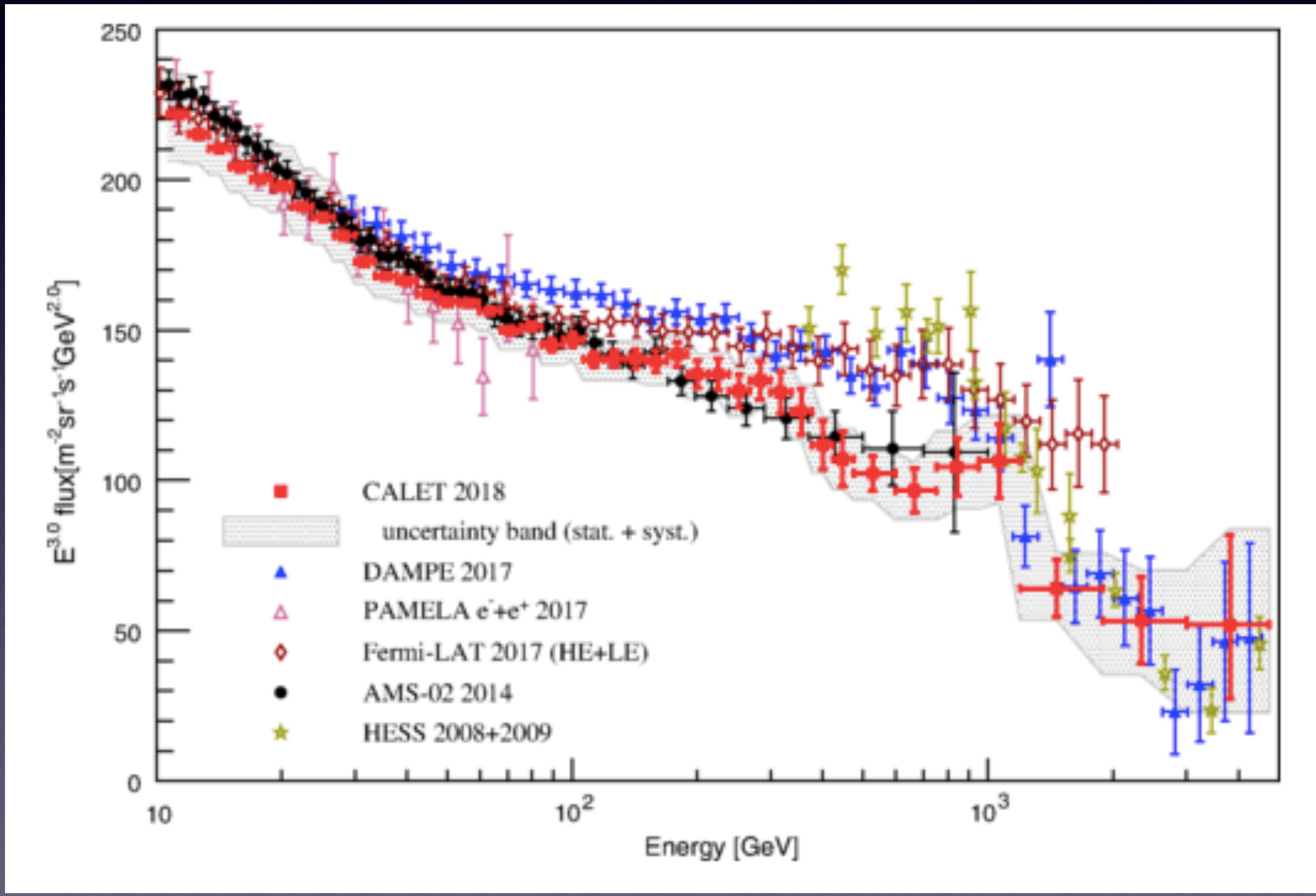




- AMS-02 measurements of positrons and antiprotons provide interesting probes of leptonic and hadronic annihilation channels respectively (and possible excesses).
- However, large uncertainties, associated with cosmic-ray propagation/ production.

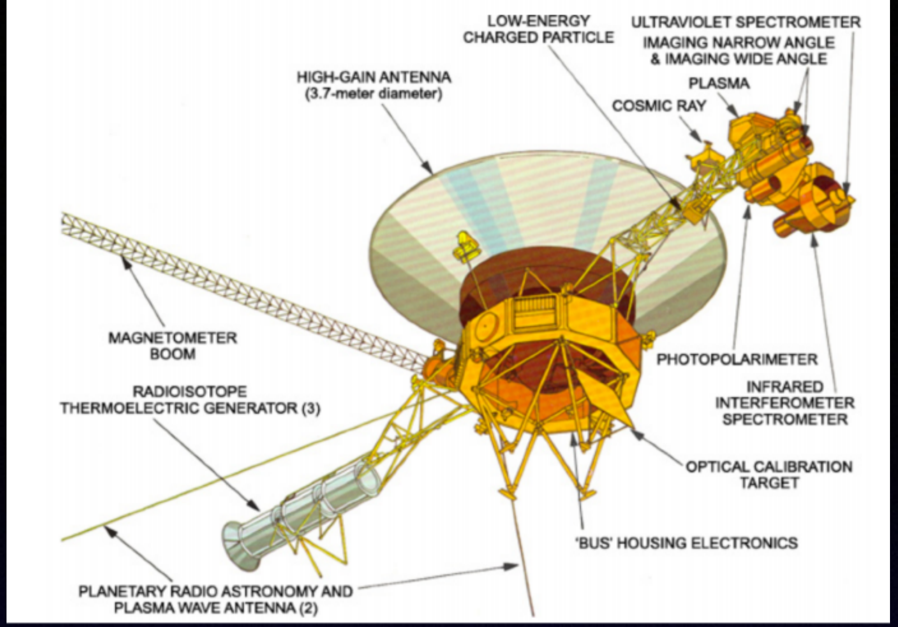
Measurements from DAMPE & CALET

- Last year saw updates on the electron+positron spectrum from DAMPE and CALET - both measure a break in the spectrum at ~1 TeV, although slope of spectrum below break differs.
- Also claim of a "line-like excess" in DAMPE, but significance is not very high.



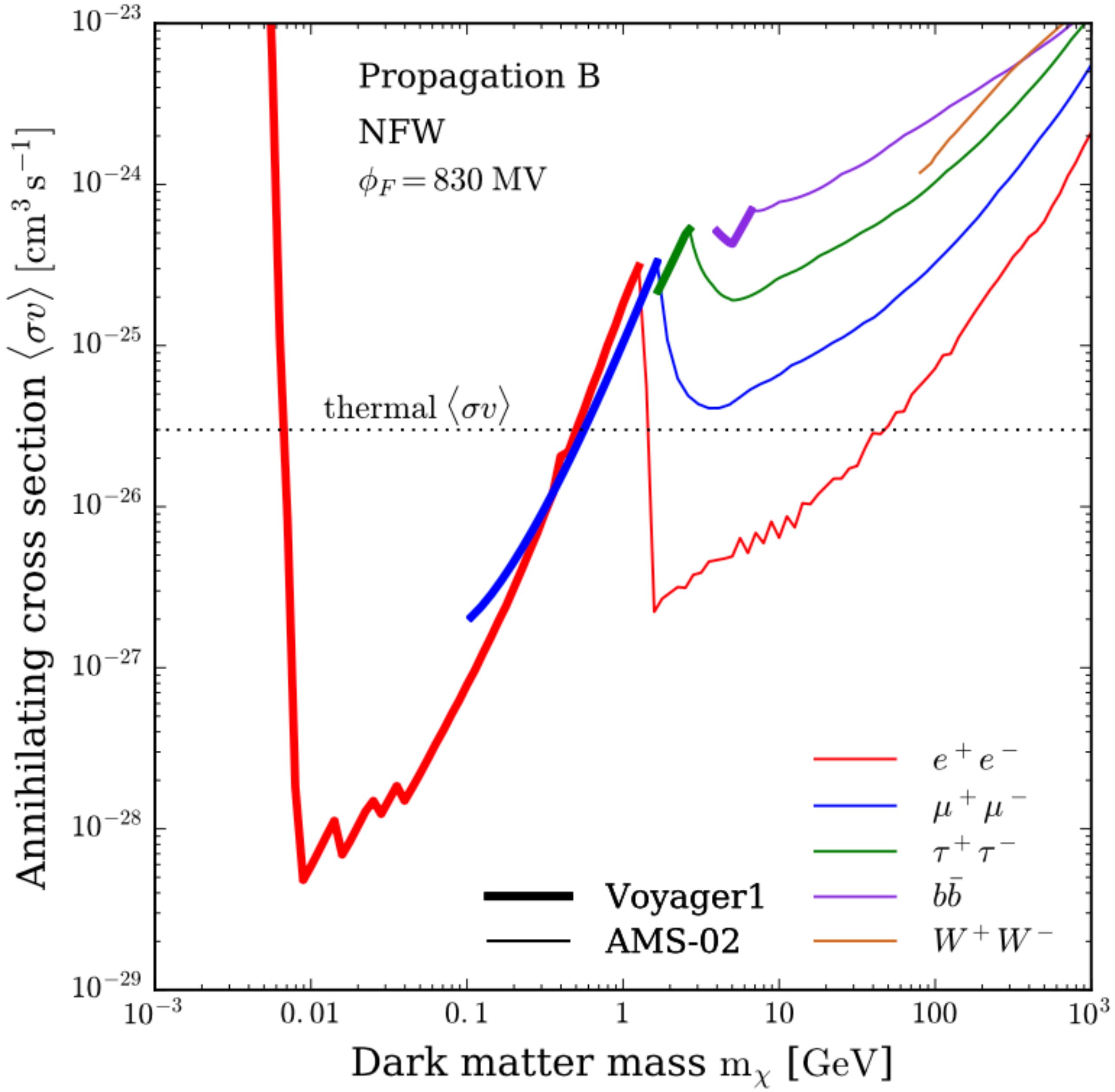
CALET Collaboration '18

Voyager (!) limits

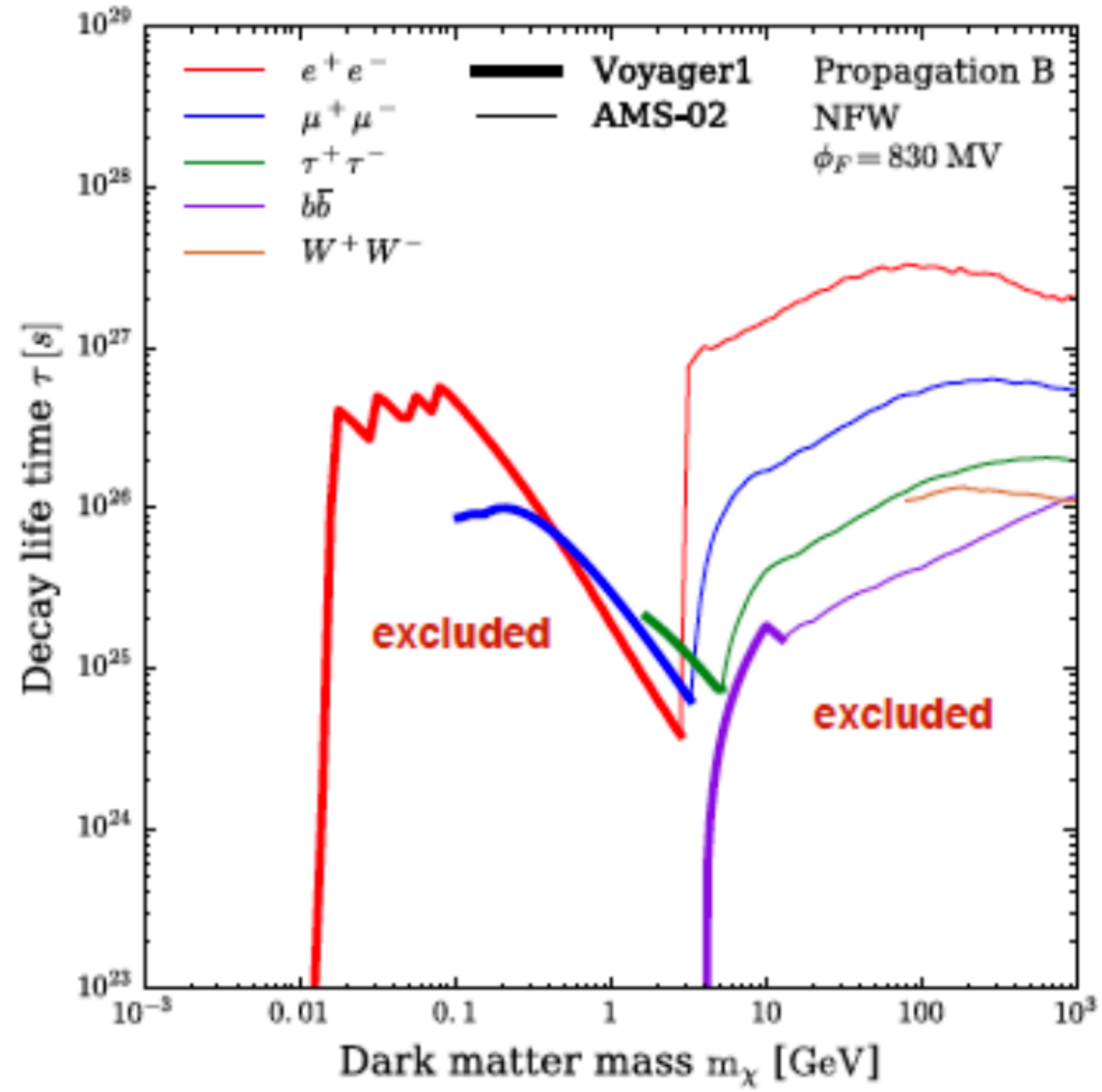


- Voyager 1 has a spectrometer capable of measuring low-energy cosmic rays
- Now beyond the heliopause - provides unique measurements of interstellar cosmic rays (unaffected by our Sun) and sub-GeV CRs (supppressed by solar wind inside solar system)
- Best limits on ~10 MeV - GeV DM decaying to electrons/positrons,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

Annihilating Dark Matter



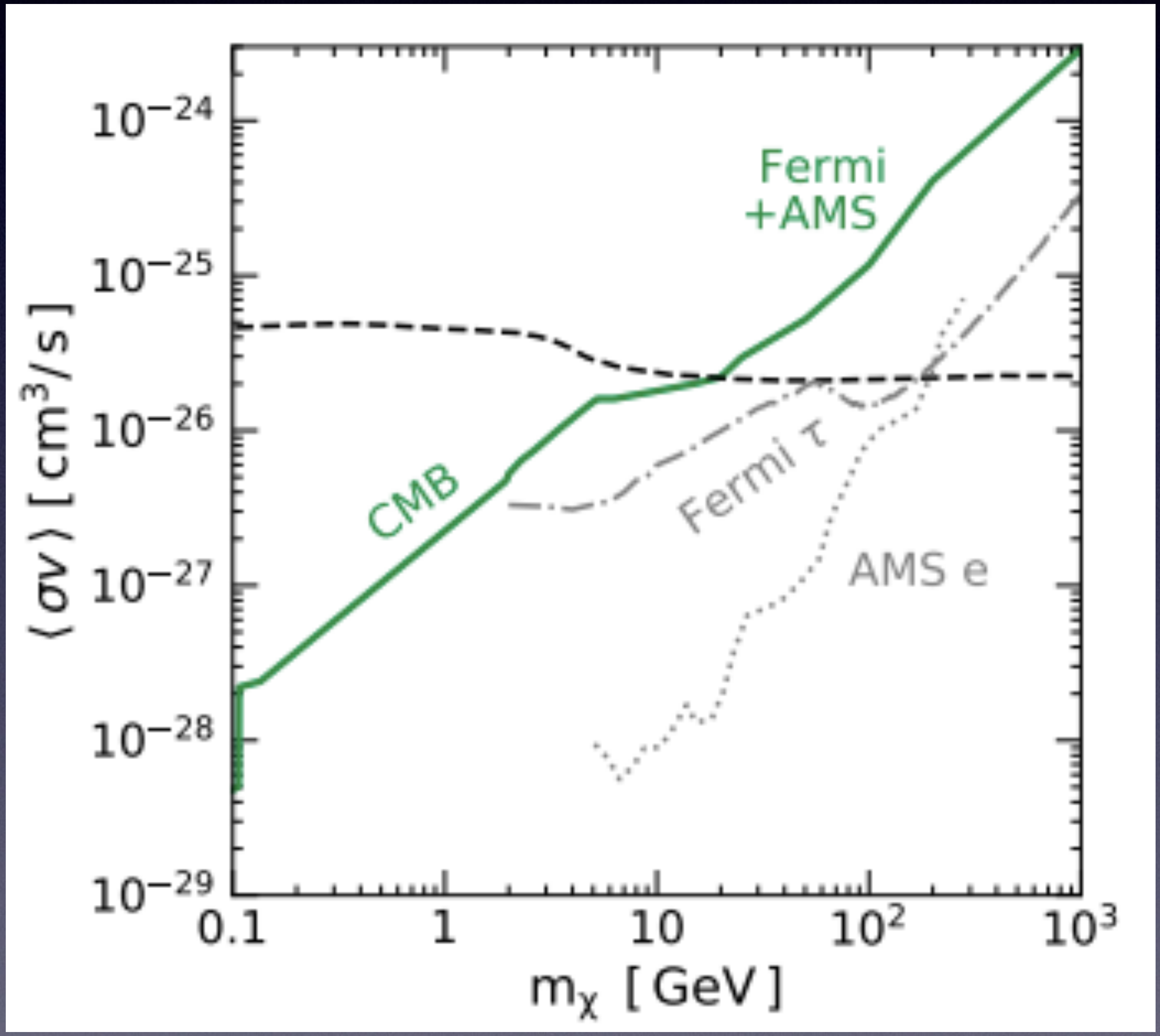
Decaying Dark Matter



Boudaud et al '16

Complementarity between indirect searches

- 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 cosmic-ray experiments.
- 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

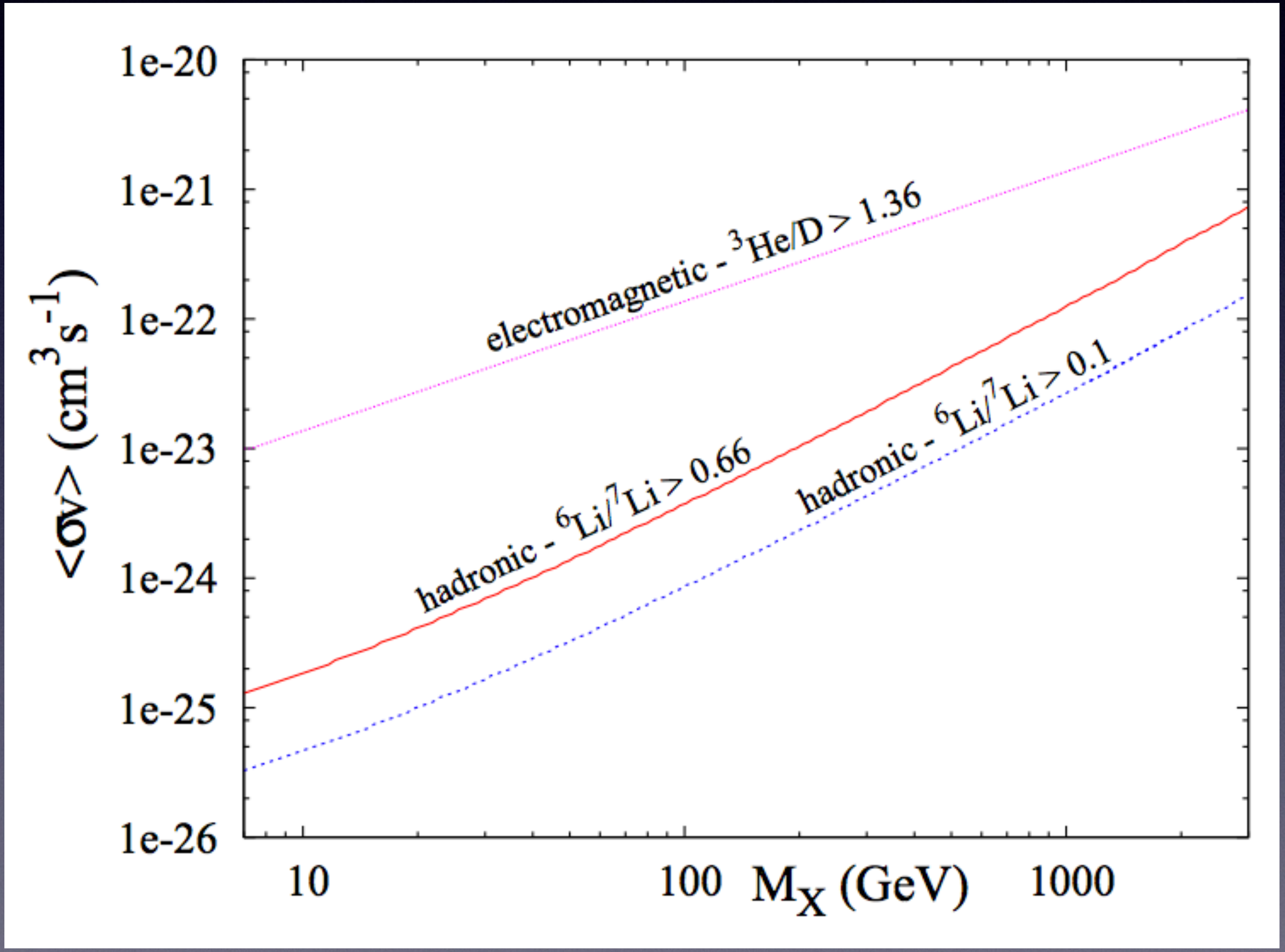
VERY INDIRECT DETECTION - EARLY UNIVERSE BOUNDS

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 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 details of how the DM is distributed at late times.

Bounds from BBN

- Jedamzik & Pospelov have a useful 2010 review on BBN constraints.
- See also Poulin & Serpico '15.
- As well as annihilation, constrains small fraction of DM decaying with a short lifetime (0.01-10^{12} seconds).

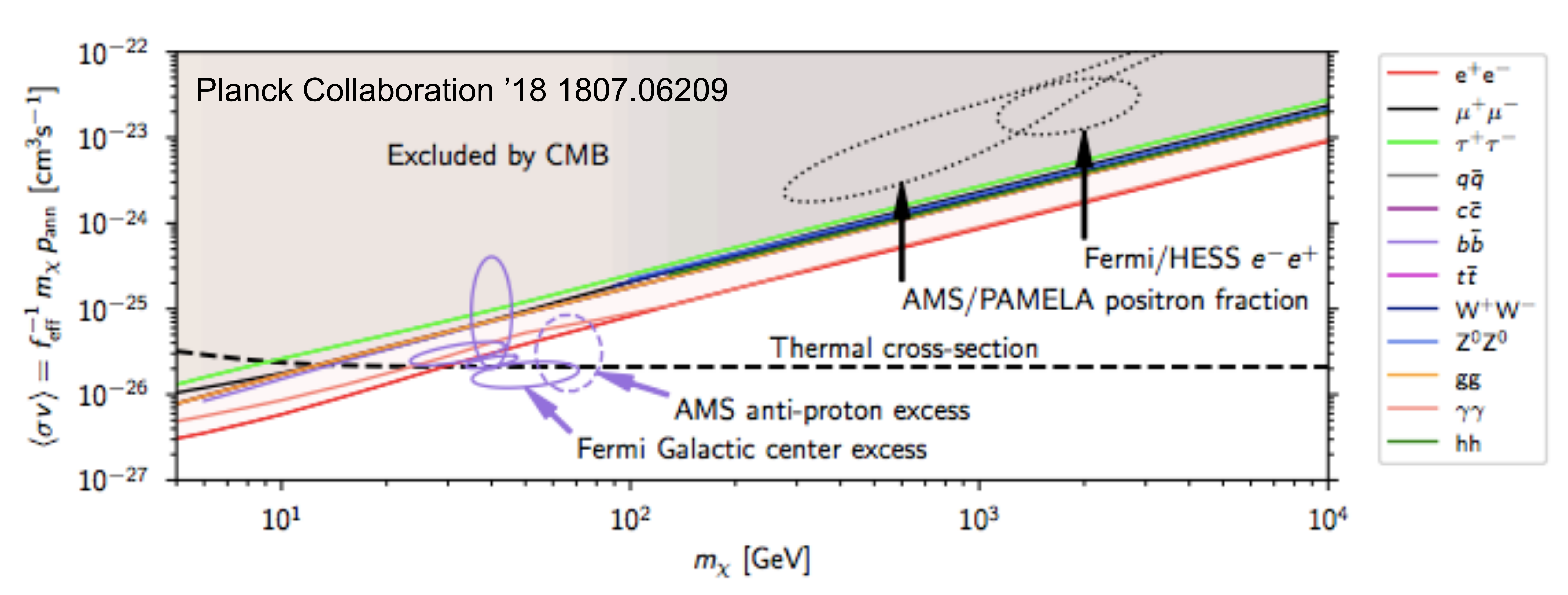


Limits from the cosmic dark ages

- 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.

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.



Future probes

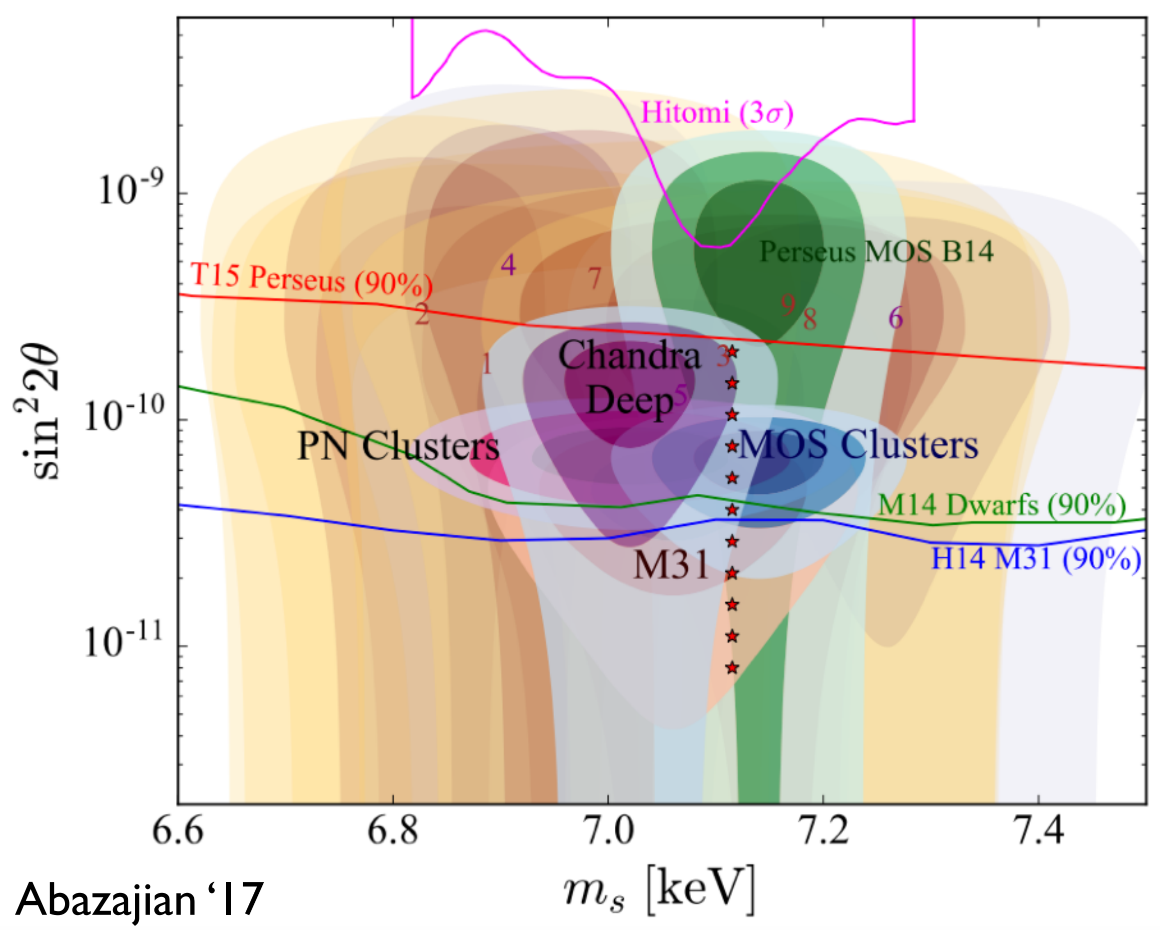
- 21cm measurements - probe the temperature and ionization history of the end of the cosmic dark ages and epoch of reionization
  - Potentially very sensitive, especially for light decaying dark matter (e.g. Lopez-Honorez et al ‘16, Poulin et al ’17).
  - Could also provide new probes of DM-baryon scattering (e.g. Dvorkin et al ’13, Munoz et al ’15), extra low-energy radiation (Feng & Holder ’18, Pospelov et al ’18).
  - First claimed observation from February (Bowman et al ’18), by EDGES experiment.
- Spectral distortion of the CMB blackbody - signal predictions are 4-5 orders of magnitude below current limits, but next-gen experiments could improve limits by several orders of magnitude.

Beyond constraints: hints of signals?

The 3.5 keV line: signals and constraints

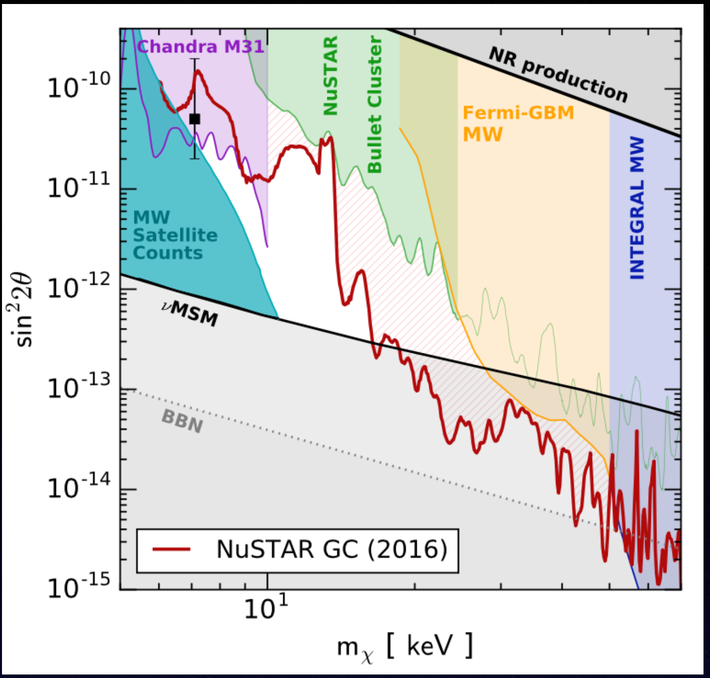
- 3.5 keV X-ray spectral line: initial discovery in XMM-Newton data claimed by Bulbul et al '14 and Boyarsky et al '14, at ~4σ significance.
- Possible non-DM contributions: atomic lines (from K, Cl, Ar, possibly others), charge-exchange reactions between heavy nuclei and neutral gas.
- Simplest dark 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 '19).
  - Possible to relax constraints by looking at DM processes other than decay.

$$\tau \sim 10^{29}\text{s}\left(\frac{\sin^2(2\theta)}{10^{-7}}\right)^{-1}\left(\frac{m_s}{1\text{keV}}\right)^{-5}$$



Abazajian '17

Testing the 3.5 keV line

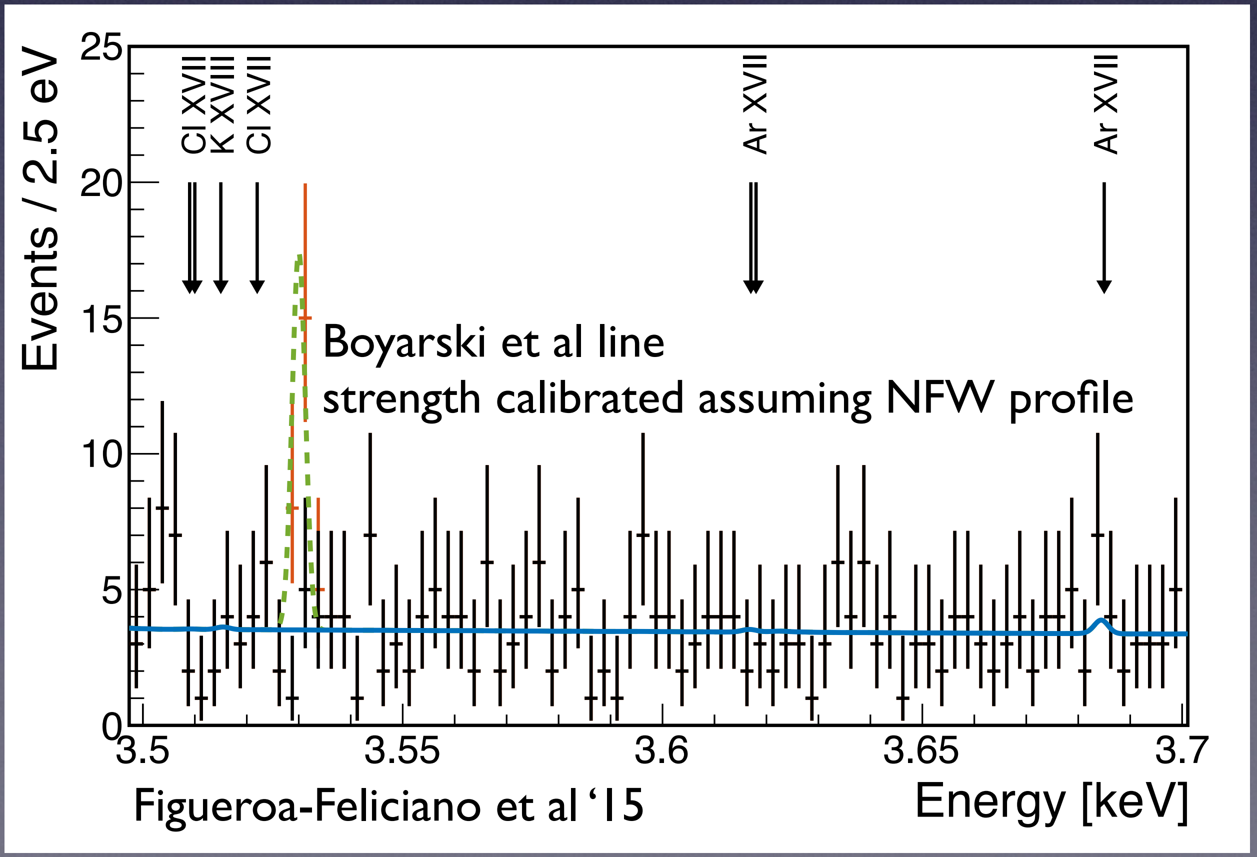


- There are already stringent constraints on DM decay to X-ray photons from X-ray telescopes, most recently NuSTAR.

- Difficult to separate DM-associated line signal from possible astrophysical backgrounds.

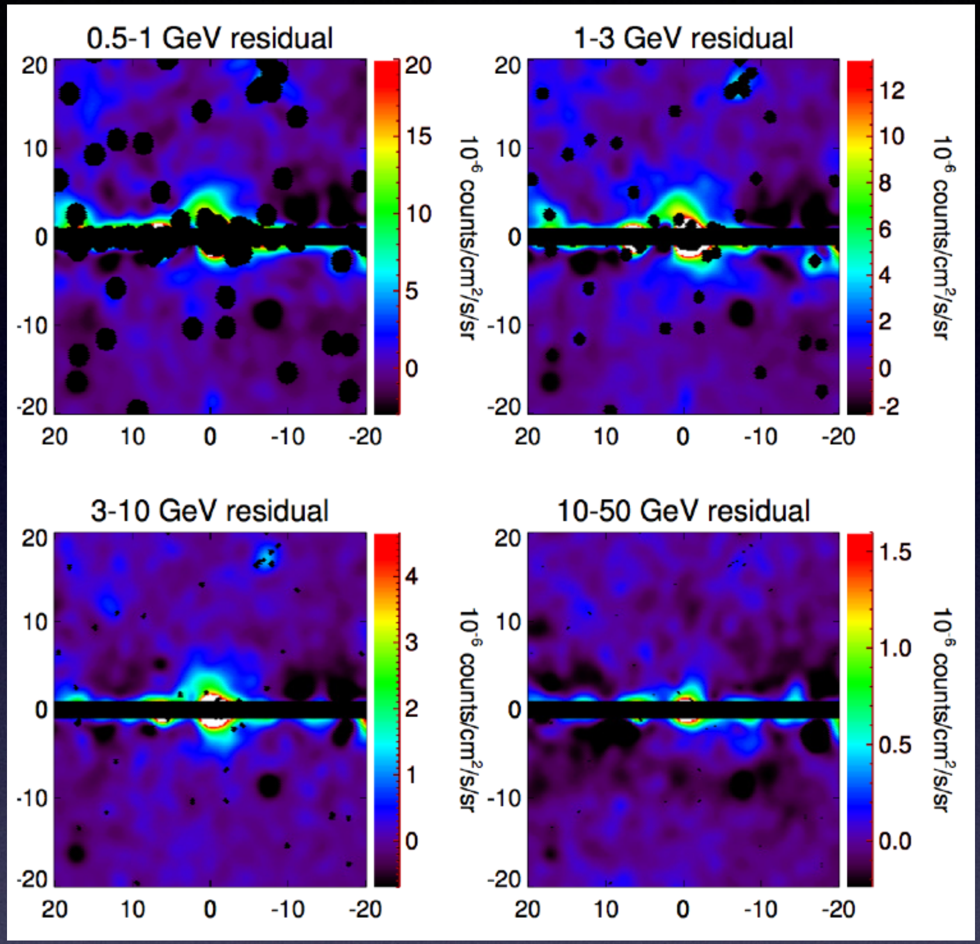
- One strategy: seek energy resolution sufficient to probe velocity distribution of DM in Galactic halo, via Doppler shift causing line broadening (Speckhard et al '16, Powell et al '17).

- One possible instrument: Micro-X sounding rocket, DM search flight scheduled for 2021.
  - Short exposure (5 minutes per flight)
  - No pointing information
  - Large field of view (20 degree radius)
  - Excellent energy resolution (3 eV)



The GeV excess

- Apparent new gamma-ray component, discovered in 2009 by Goodenough & Hooper using public Fermi data.
- Spectral energy distribution peaks around 1-3 GeV.
- Centered ~on Galactic Center (GC), steeply peaked power-law-like radial profile, ~spherical.
- If interpreted as DM annihilation, suggests O(10-100) GeV mass scale, near-thermal cross section. Details depend on modeling of backgrounds (see e.g. Karwin et al '17).

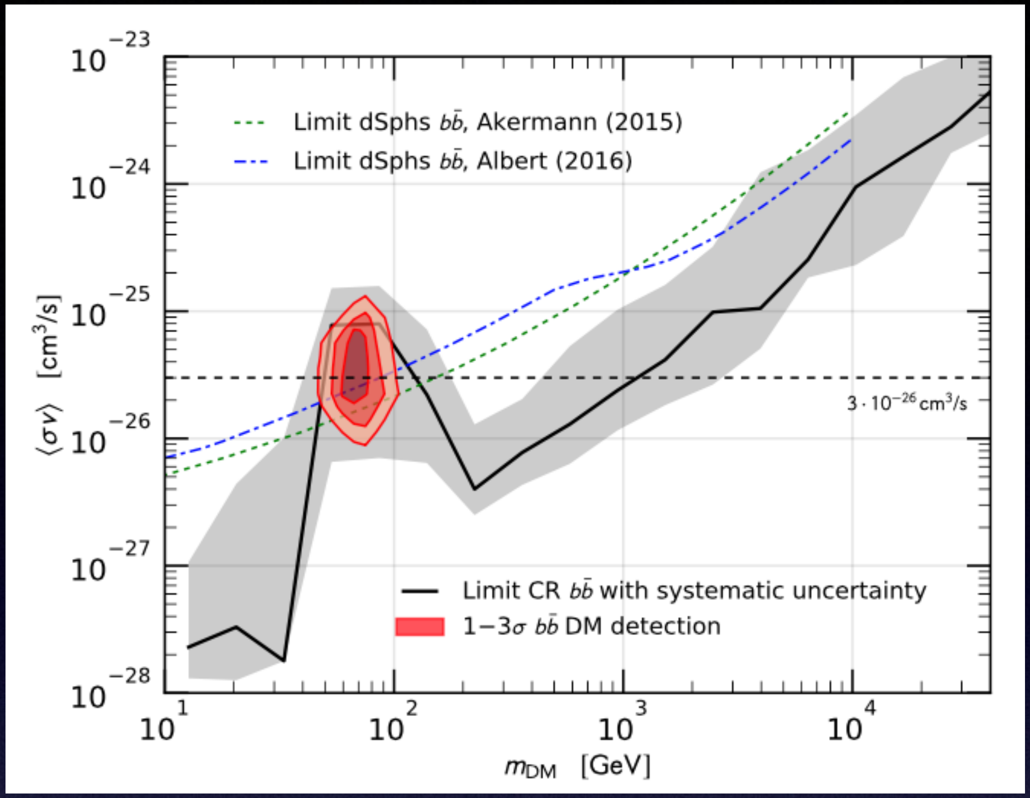


Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd & TRS '16

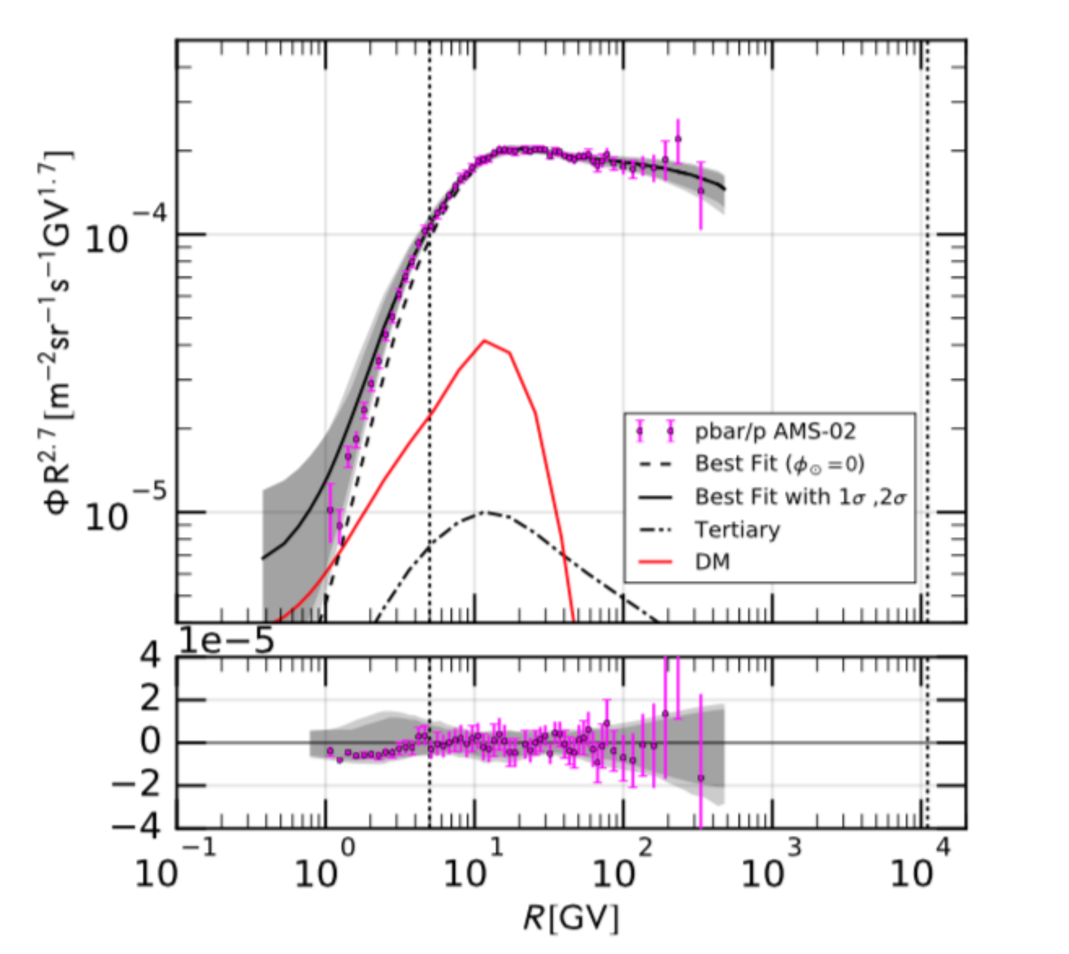
- Faint hints (<3σ) of possible corresponding signals from two dwarf galaxies (Reticulum II and Tucana III), but whether these are consistent with GCE + null results depends strongly on (not well constrained) dwarf J-factors.
- Several studies find evidence for a non-DM origin (Lee, Lisanti, Safdi, TRS & Xue '16, Bartels et al '16, Bartels et al '17, Macias et al '18) - most frequent hypothesis is a new pulsar population. Possibly testable with radio telescopes (Calore et al '16).

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) et al '17). Cholis et al '19 argue excess is robust, Boudaud et al '19 say it is not.
- Similar fits for other annihilation channels with ~thermal cross sections, 40-130 GeV mass (Cuoco et al '17).
- Broadly consistent with GCE dark matter interpretation.
- Challenges: modeling of antiproton production cross section, cosmic-ray propagation, solar modulation.



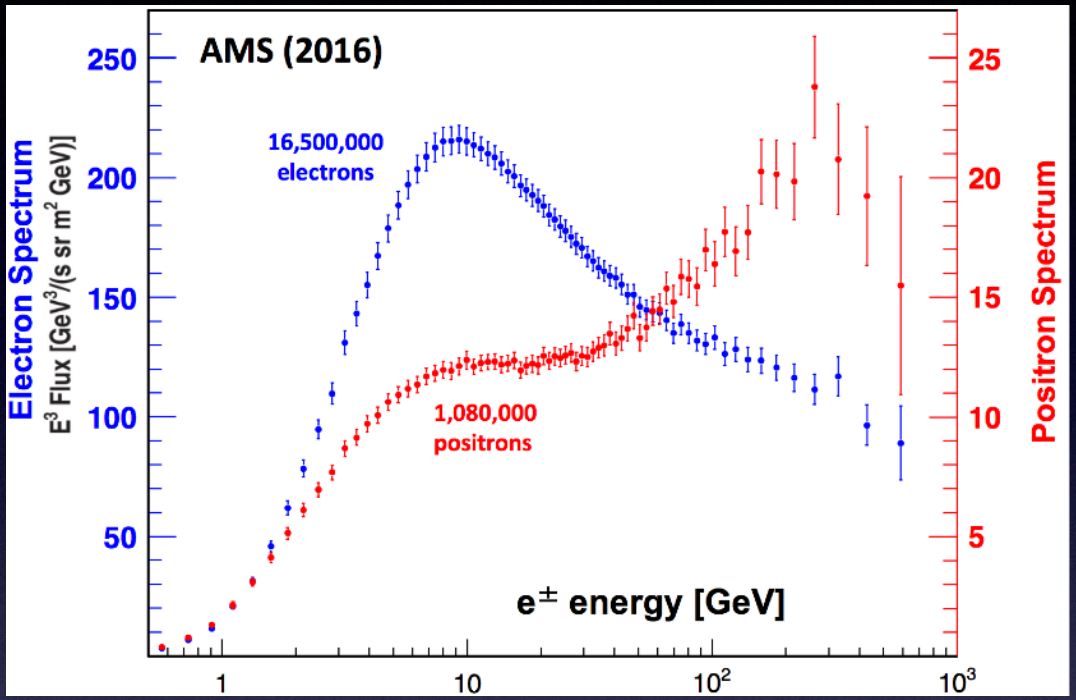
Cuoco et al '17

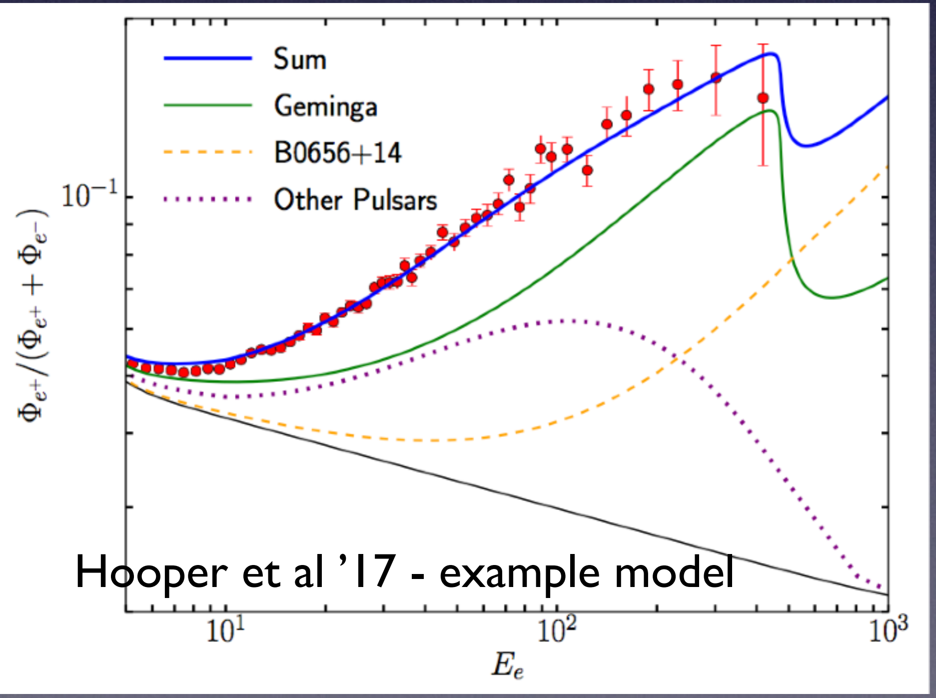


AMS-02 positrons

- 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





(an incomplete sample of) Future directions

- Modeling signal: better understanding of dark matter distribution - substructure, populations and properties of dwarf galaxies, presence/absence of dark disks, etc.

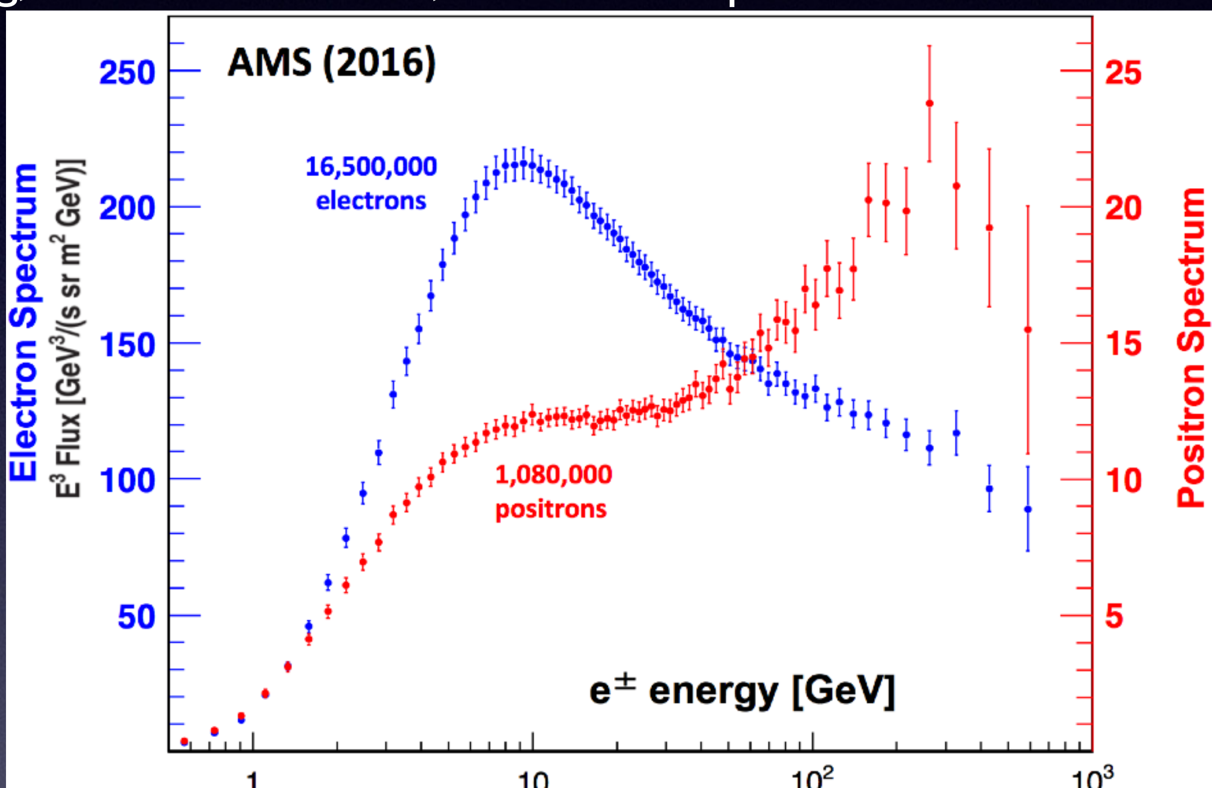
- Modeling background: improved methods for modeling the gamma-ray foregrounds/backgrounds, new probes for pulsars with upcoming radio telescopes MeerKAT/SKA.

- 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.

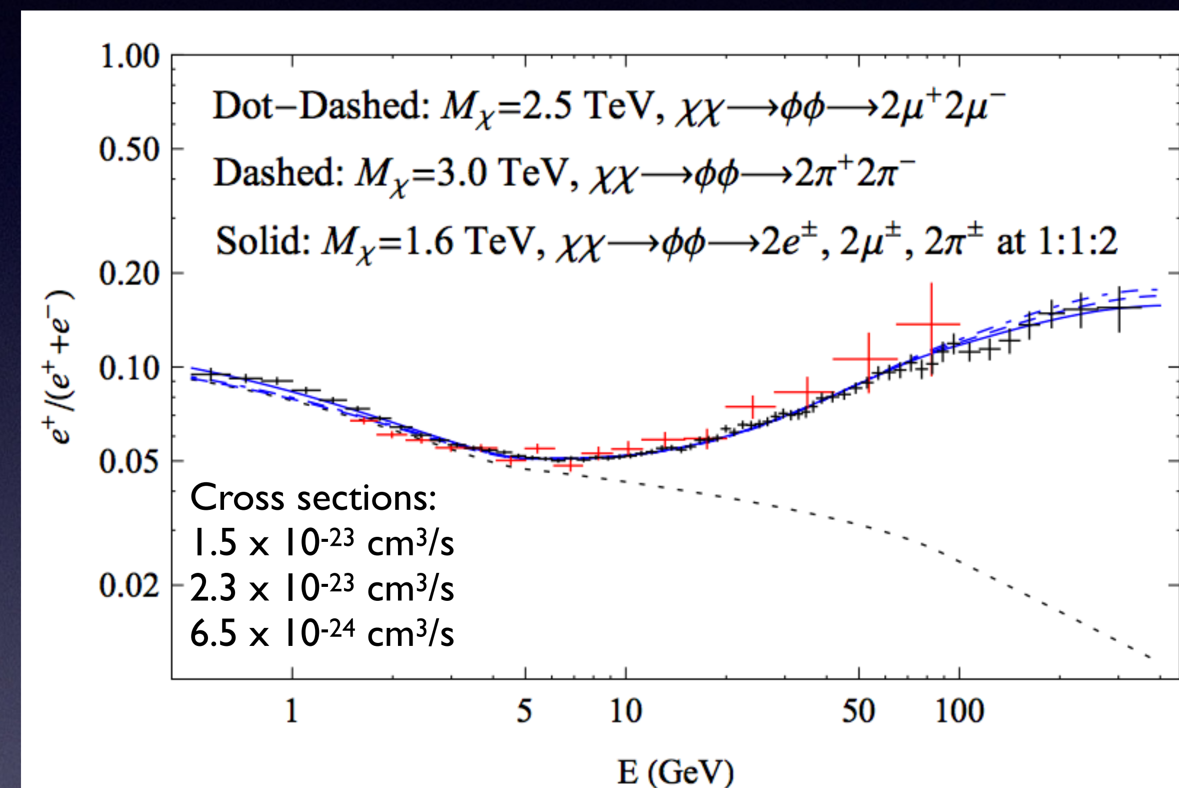
Bonus slides

The PAMELA/Fermi/AMS-02 positron excess

Sam Ting, 8 December 2016, CERN colloquium



Cholis & Hooper '13

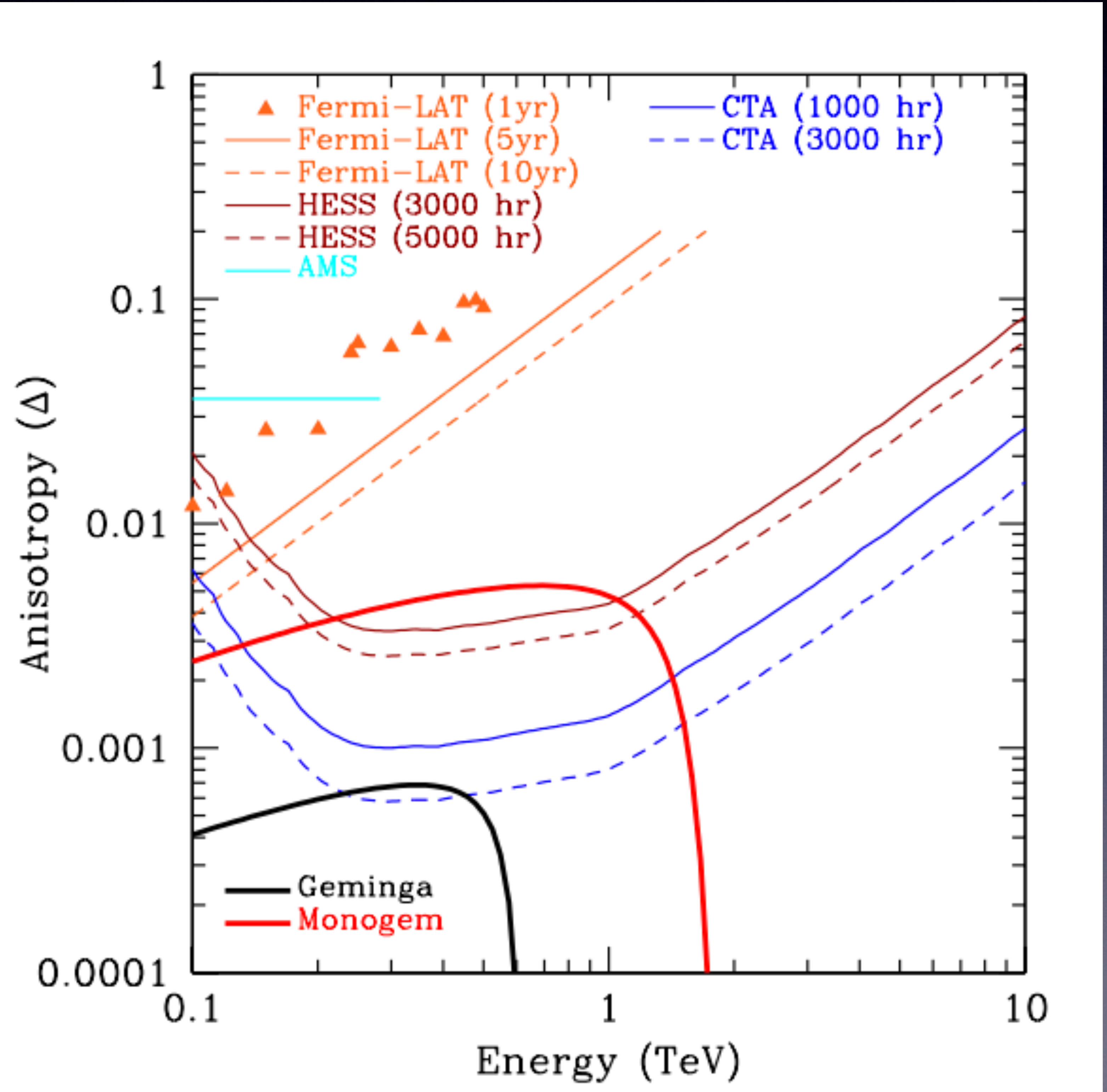


- Rise in positron fraction above 10 GeV observed by PAMELA experiment in 2008, later confirmed by Fermi, now confirmed to extend up to at least 500 GeV by AMS-02.
- Possible signal of DM annihilation, producing additional primary positrons. (Other possibilities: pulsars, supernova remnants, modified cosmic-ray production and/or propagation.)
- DM models generally require large masses, annihilation/decay to mostly leptonic channels, and (if annihilation) large cross sections.
- Required parameters are in tension or apparently excluded by several other searches.

Possible tests of astrophysical interpretations

Linden & Profumo '13

- Anisotropy in cosmic-ray arrival directions could potentially probe source distribution
- But Galactic B-fields scramble arrival directions - expected anisotropy is small
- Could potentially be tested using observations of cosmic rays by atmospheric Cherenkov telescopes (high-energy gamma-ray telescopes)



Pulsar halos?

- Recent development: 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.
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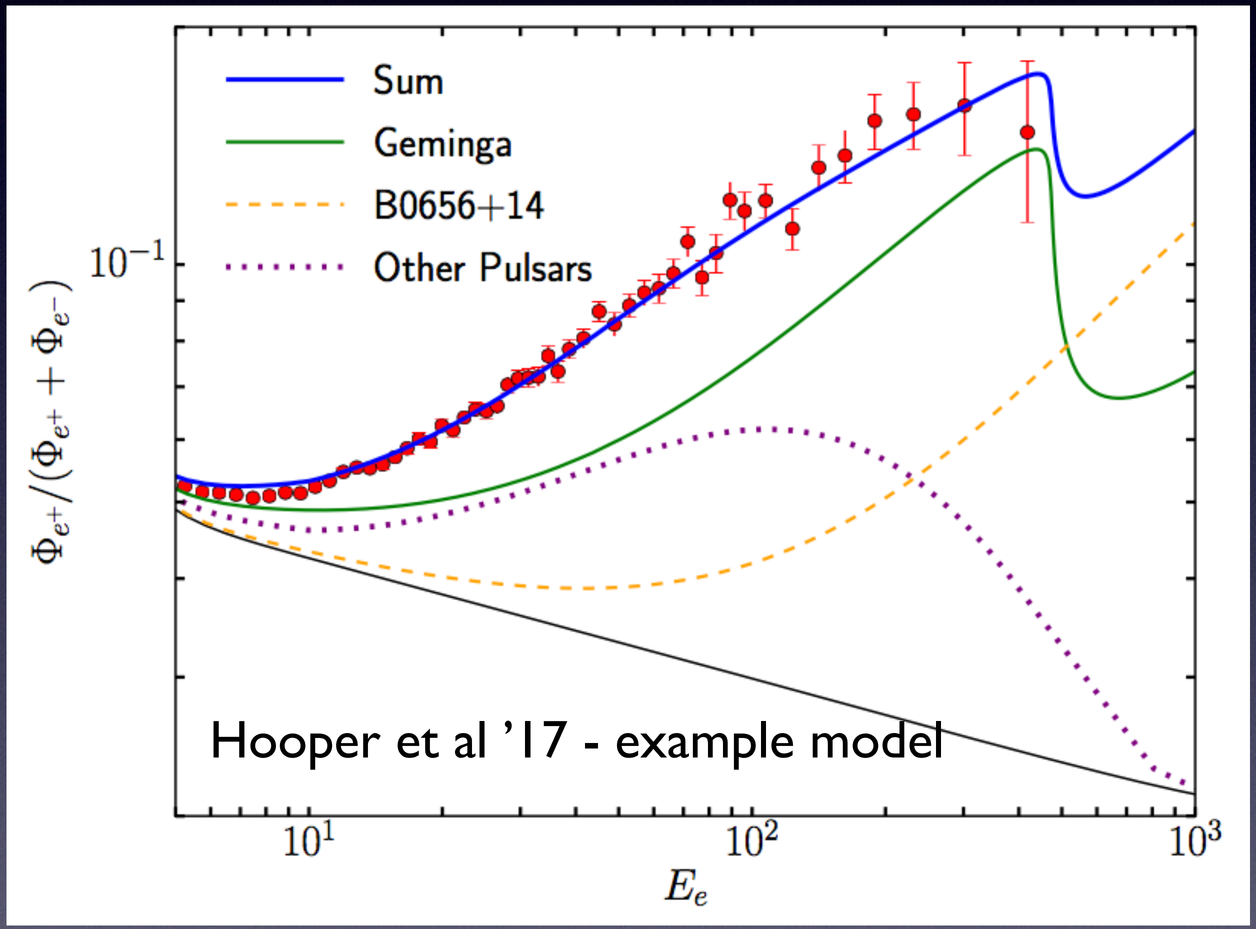

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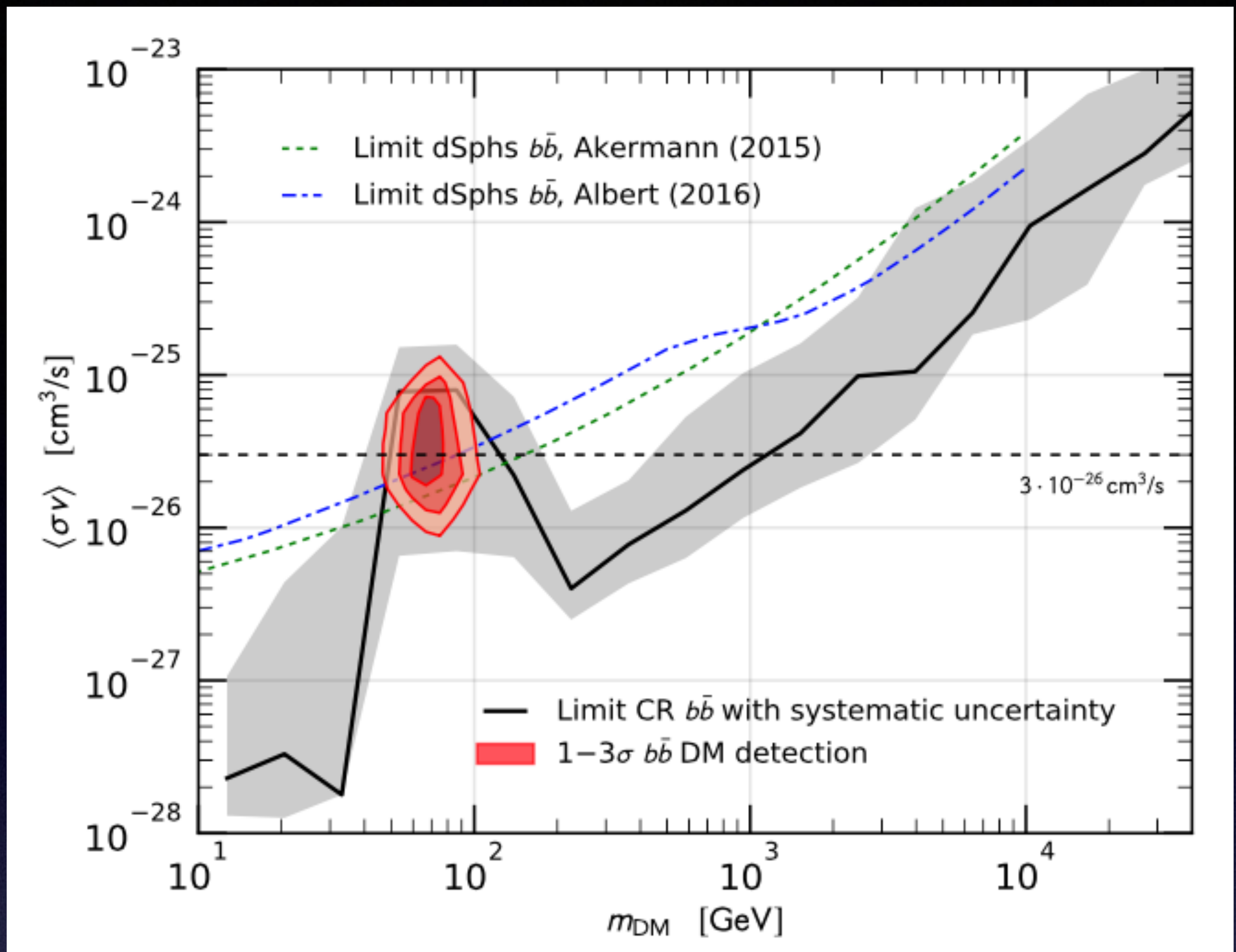

Cuoco et al '17

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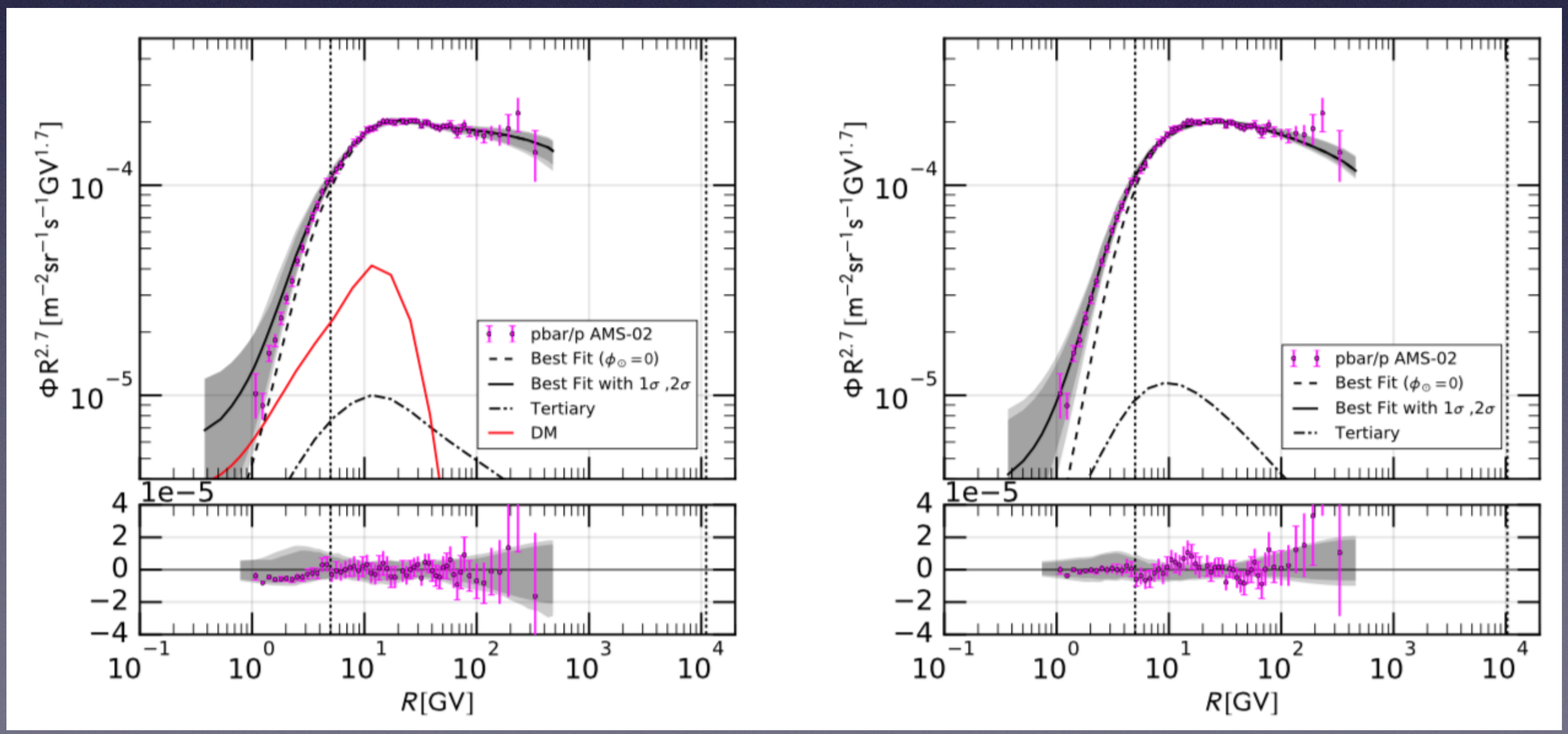
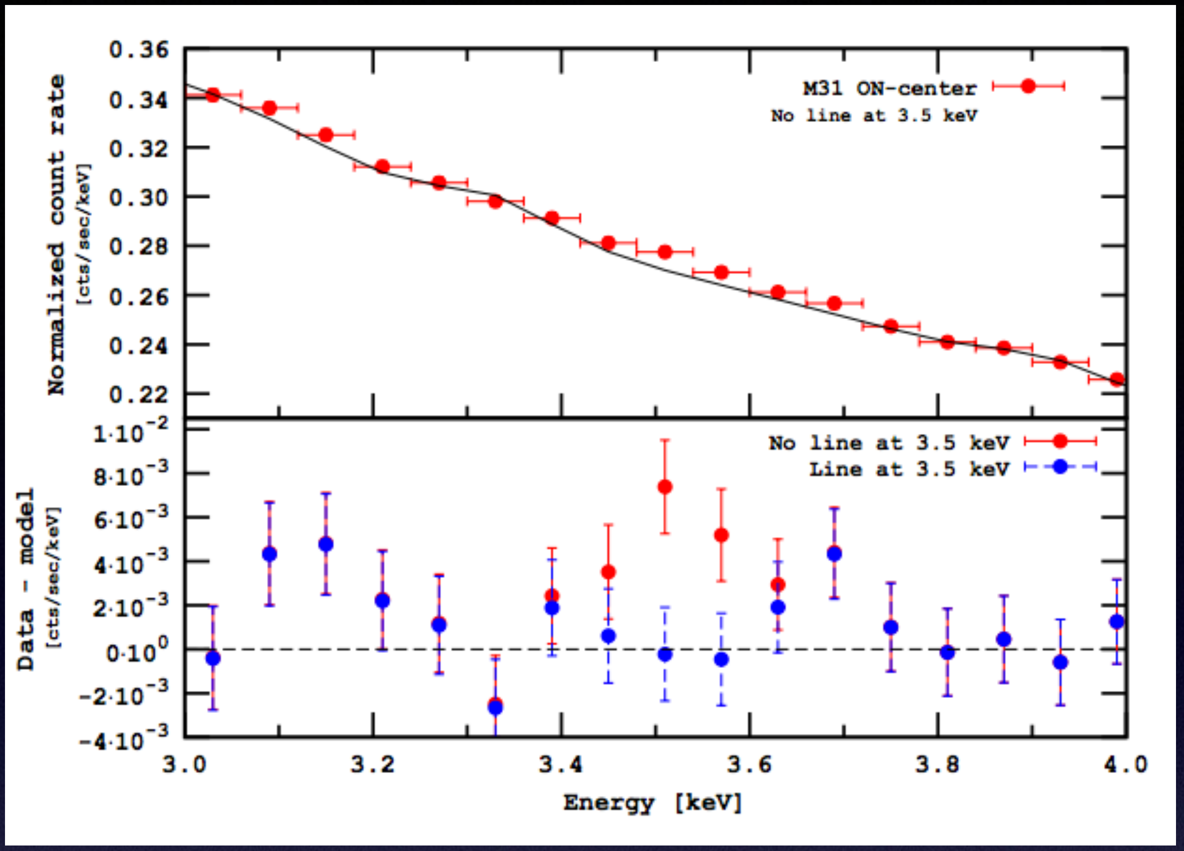


The 3.5 keV line

- 3.5 keV X-ray spectral line: initial discovery in XMM-Newton data by Bulbul et al (1402.2301) and Boyarsky et al (1402.4119), at ~4σ significance.

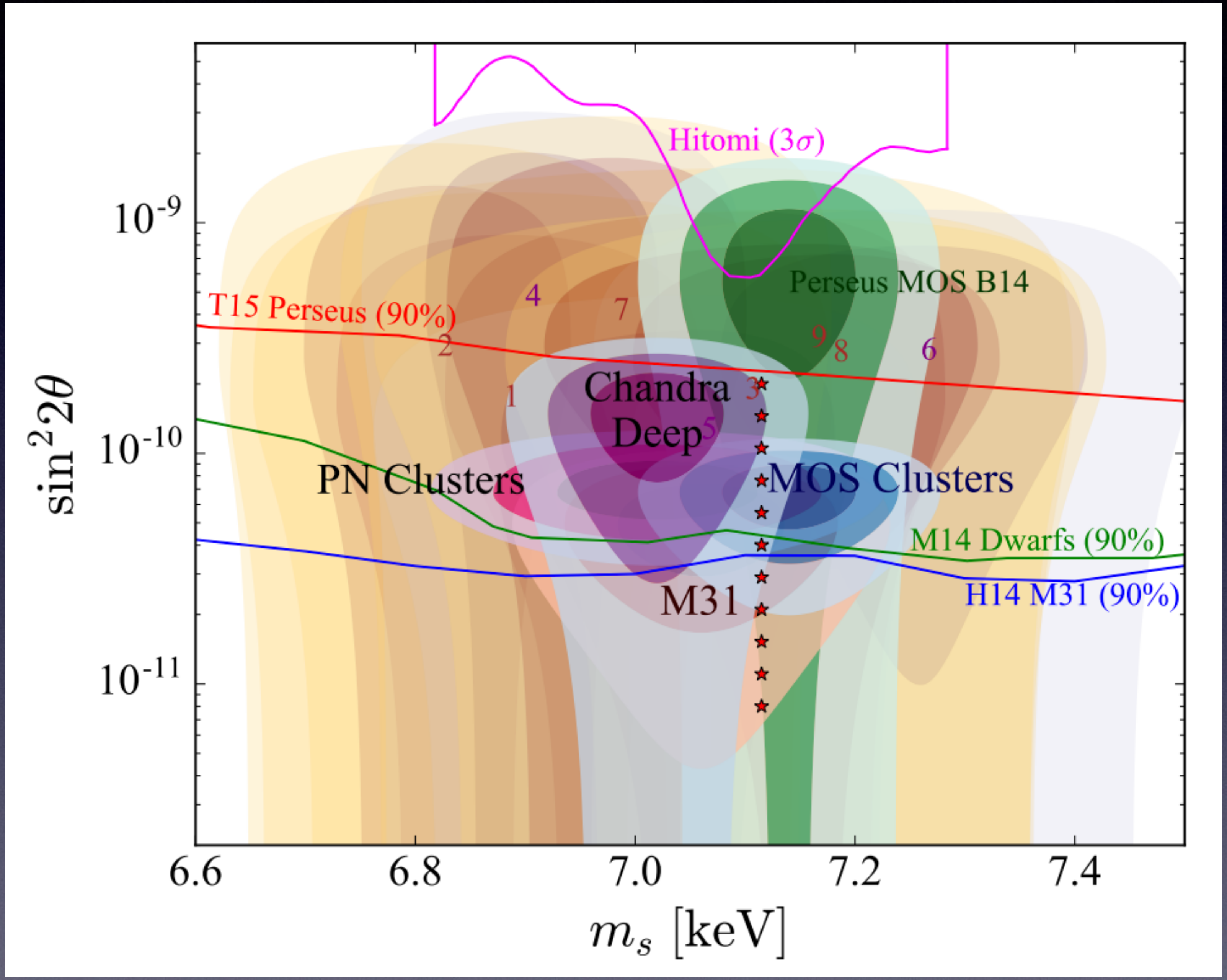


- Follow-up observational studies by:

Riemer-Sorenson (1405.7943, MW with Chandra data)
Jeltema & Profumo (1408.1699, MW)
Boyarsky et al (1408.2503, MW center
Malyshev et al (1408.3531, dwarf spheroidal galaxies)
Iakubovskyi et al (1508.05186, other clusters
Anderson et al (1408.4115, stacked galaxies with Chandra and XMM-Newton)
Urban et al (1411.0050, Suzaku)
Tamura et al (1412.1869, Suzaku)
Jeltema & Profumo (1512.01239, Draco)
Ruchayskiy et al (1512.07217, Draco)

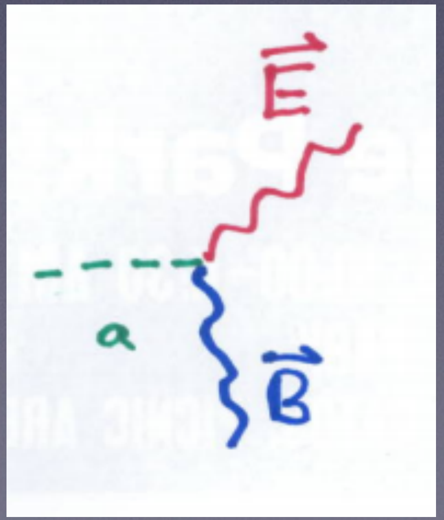
	XMM-Newton	Chandra	Suzaku
Stacked Clusters	+		
Perseus Cluster	+	+	±
Coma, Virgo, Ophiucus	+	-	-
Other Clusters	+		
Andromeda Galaxy	±		
Milky Way Galactic Center	+	-	
Stacked Galaxies	-	-	
Milky Way Dwarfs	-		
Draco	±		

Abazajian '17



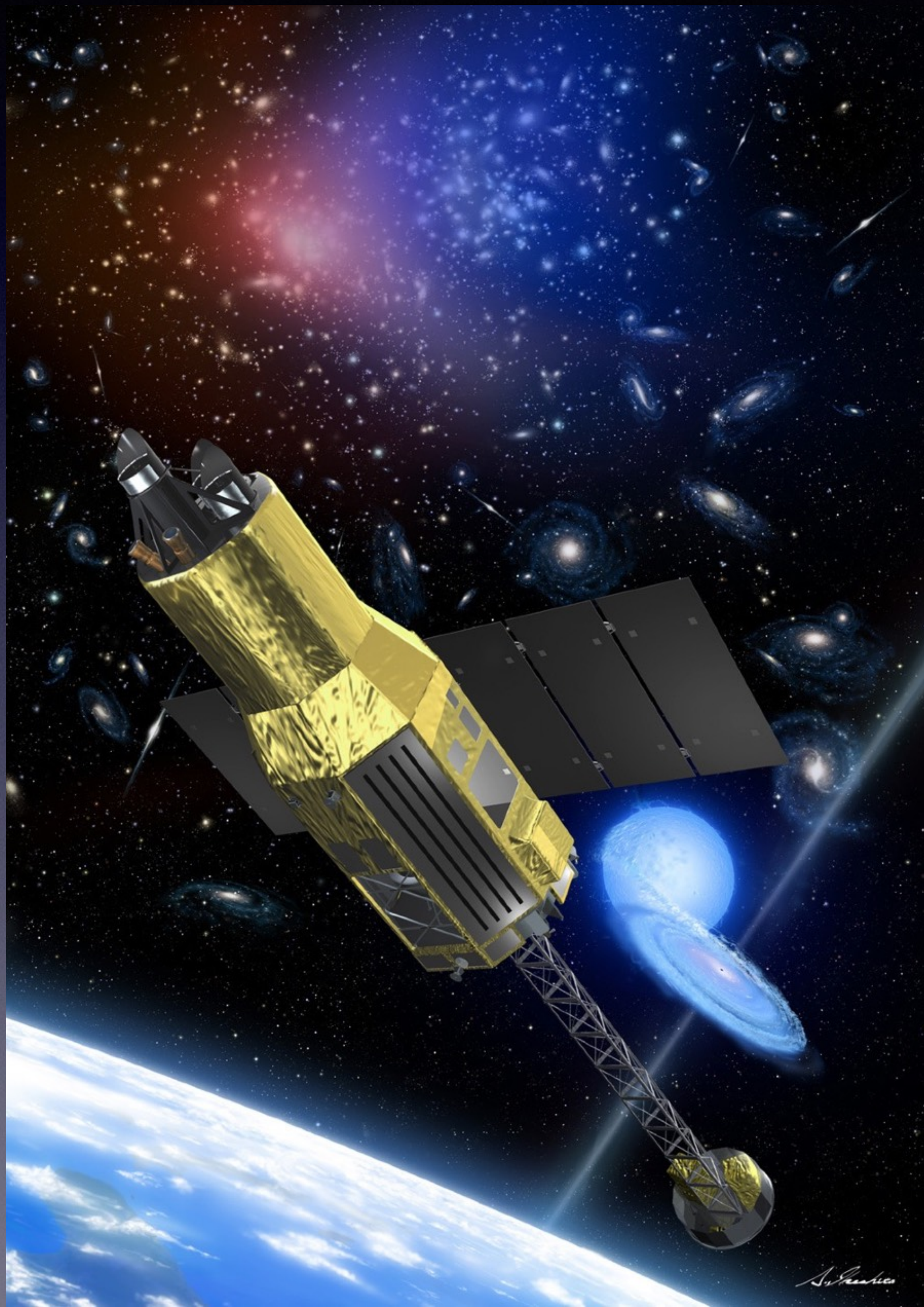
DM interpretations

- Simplest DM explanation is decaying sterile neutrino at a mass around 7 keV - long-standing DM candidate.
- However, simple DM decay models appear ruled out (at 12σ) by non-detection in dwarfs and stacked galaxies (1411.1758 also claims Perseus and Galactic Center morphologies are incompatible with DM decay).
- DM alternatives include exciting dark matter (Finkbeiner & Weiner 1402.6671, Cline & Frey 1410.7766)
  - 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. 1404.7741) - can lead to widely varying signals from different systems (e.g. 1410.1867).



Possible backgrounds

- Ongoing controversy over possible contamination from potassium and chlorine plasma lines, or charge-exchange reactions between sulfur nuclei and neutral hydrogen.
- Hope was that Hitomi experiment would resolve this issue - but it broke up in orbit, and data on Perseus was not conclusive.
- Micro-X sounding rocket may be able to provide a test (Figueroa-Feliciano et al '15).

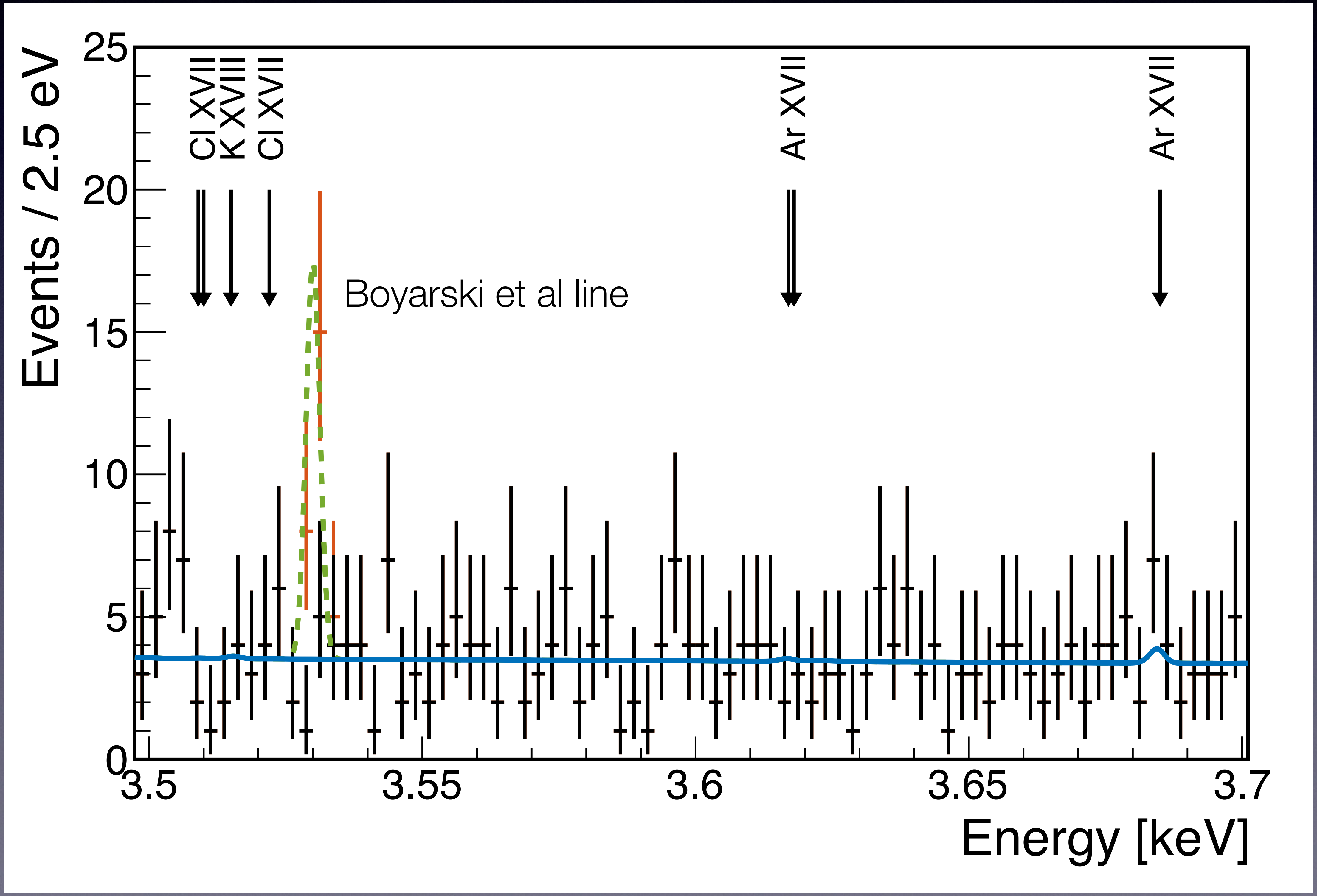


Micro-X

- Short exposure (5 minutes)
- Large field of view (20 degree radius)
- No pointing information
- Excellent energy resolution (3 eV)
- Strategy: search for DM decay signal from local Galactic halo, not from specific targets
- Energy resolution close to good enough to probe velocity distribution of DM in Galactic halo (via Doppler shift causing line broadening)

Micro-X mock observation

thanks to Tali Figueroa-Feliciano for the slide

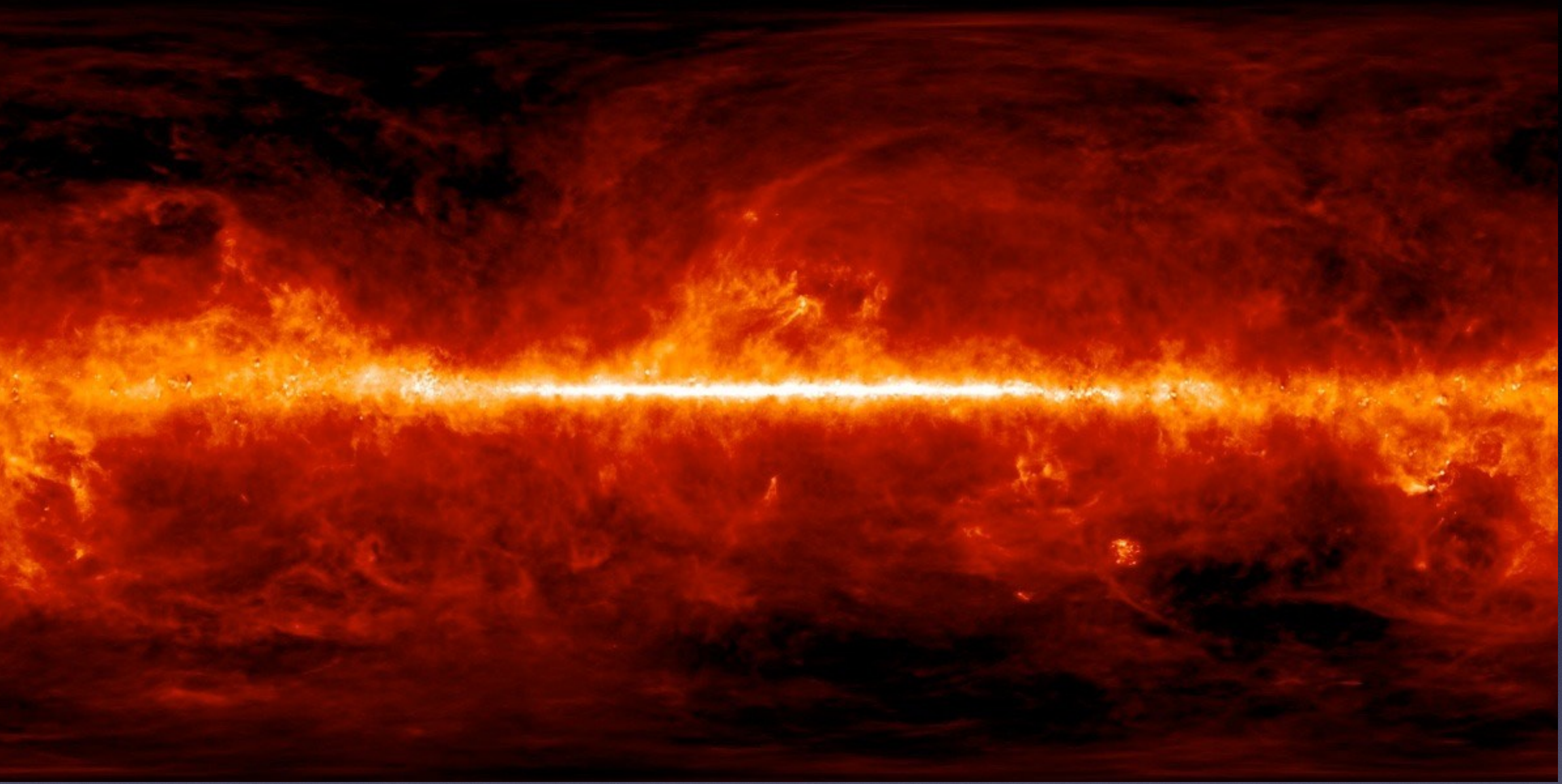


J-factors (III)

- What if photons come to us over cosmological distances, so redshifting cannot be ignored?
- Source spectrum needs to be evaluated at $E' = E(1+z)$
- Integral needs to be recast into integral over z, not R:
  - work with comoving coordinate r (corresponding to physical distance R as measured today)
  - fraction of particles observed is $A/(4\pi r^2)$, as previously
  - note physical volume element at time of annihilation, corresponding to comoving coordinate separation dr, is $dV = d\Omega\, dr\, r^2 / (1+z)^3$.
  - thus annihilation per dz $d\Omega$

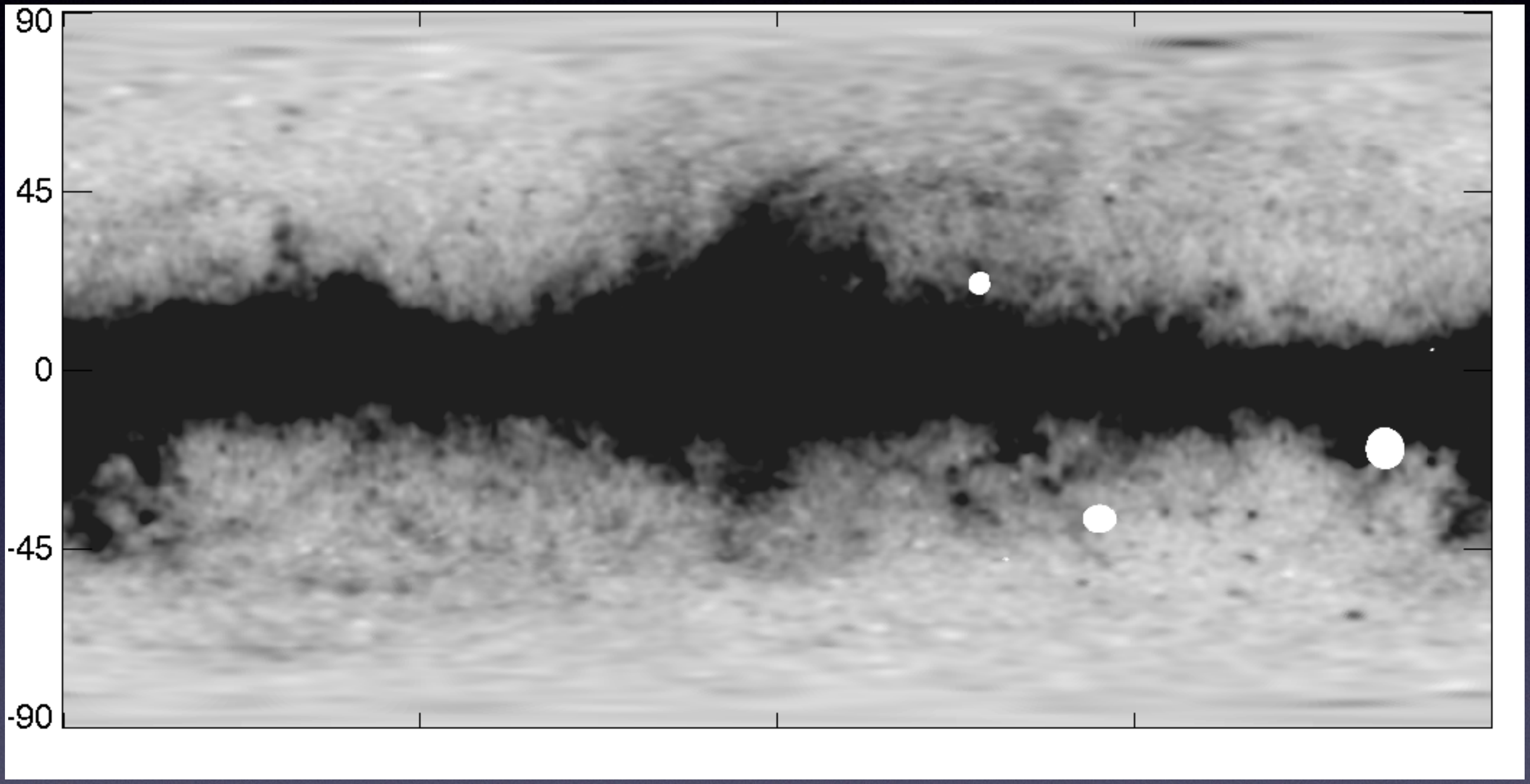
Continuum gamma-rays in the Galactic Center

- In absence of line signal, need a way to estimate or parameterize backgrounds in the Galactic Center.
- At weak-scale energies, dominant backgrounds come from:
  - Cosmic ray protons striking the gas, producing neutral pions which decay to gammas.
  - Cosmic ray electrons upscattering starlight photons to gamma-ray energies.
  - Compact sources producing gamma-rays - pulsars, supernova remnants, etc.
- Backgrounds should roughly trace gas, starlight, star formation, supernovae, etc - all more common in the disk of the Milky Way.
- Physical processes are fairly well understood, but 3D distribution of gas/starlight/etc is not well measured.



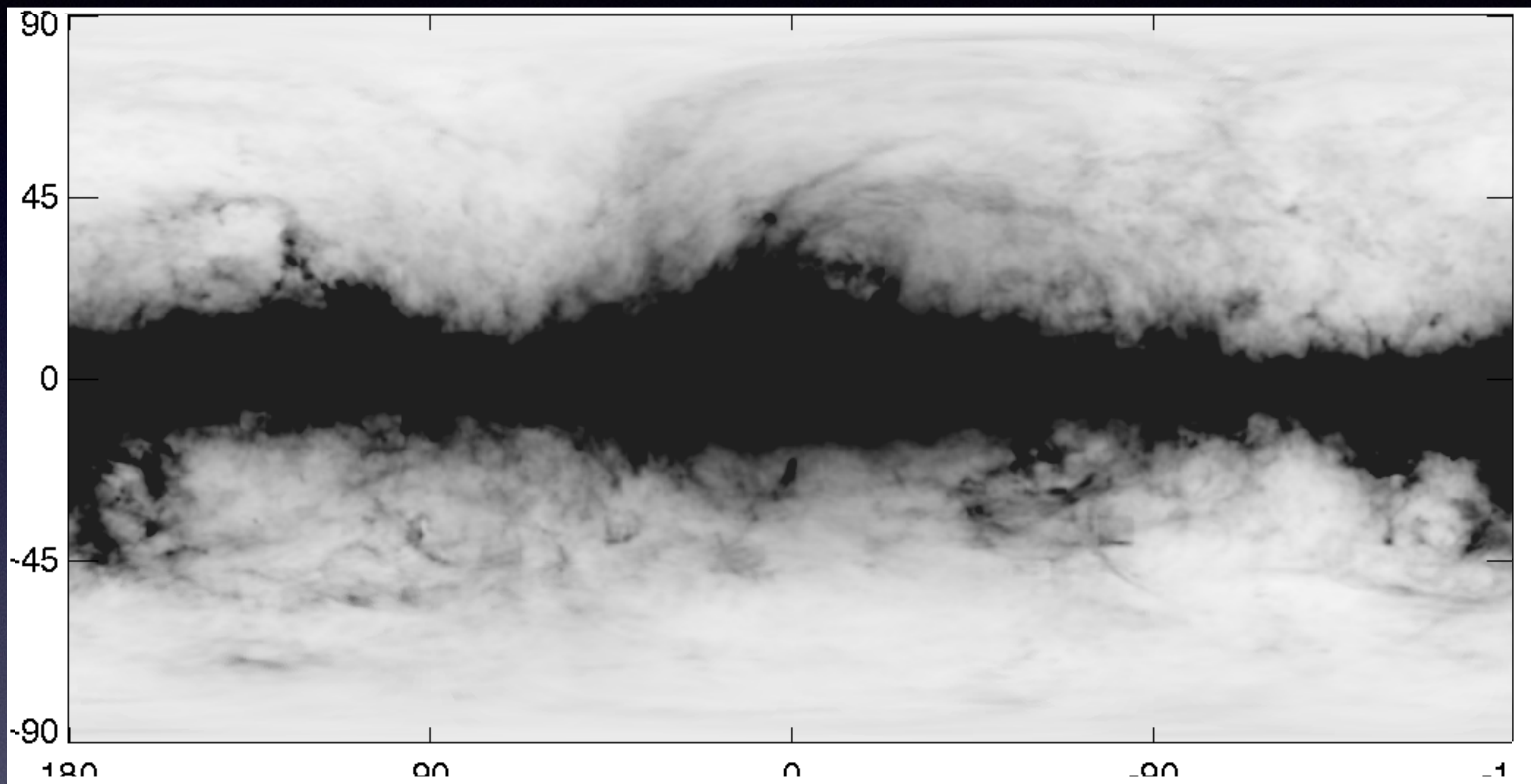
- Dominant background emission roughly traces the distribution of gas in the galaxy, other components depend on starlight distribution, sources of cosmic rays, etc.
- Very “disk-like” - brightest along the plane of the Galaxy.

Modeling the background



- Can build a model for the background incorporating maps of the gas + models for the cosmic-ray and radiation distributions, the latter e.g. based on the public GALPROP code.
- Some public models made available by the Fermi Collaboration; later models include ad hoc spatial templates to absorb large-scale discrepancies between data and model.
- Not restricted to gamma-rays; similar template methods have been used in the microwave sky to extract the CMB and probe possible DM signals.

Modeling the background



- Can build a model for the background incorporating maps of the gas + models for the cosmic-ray and radiation distributions, the latter e.g. based on the public GALPROP code.
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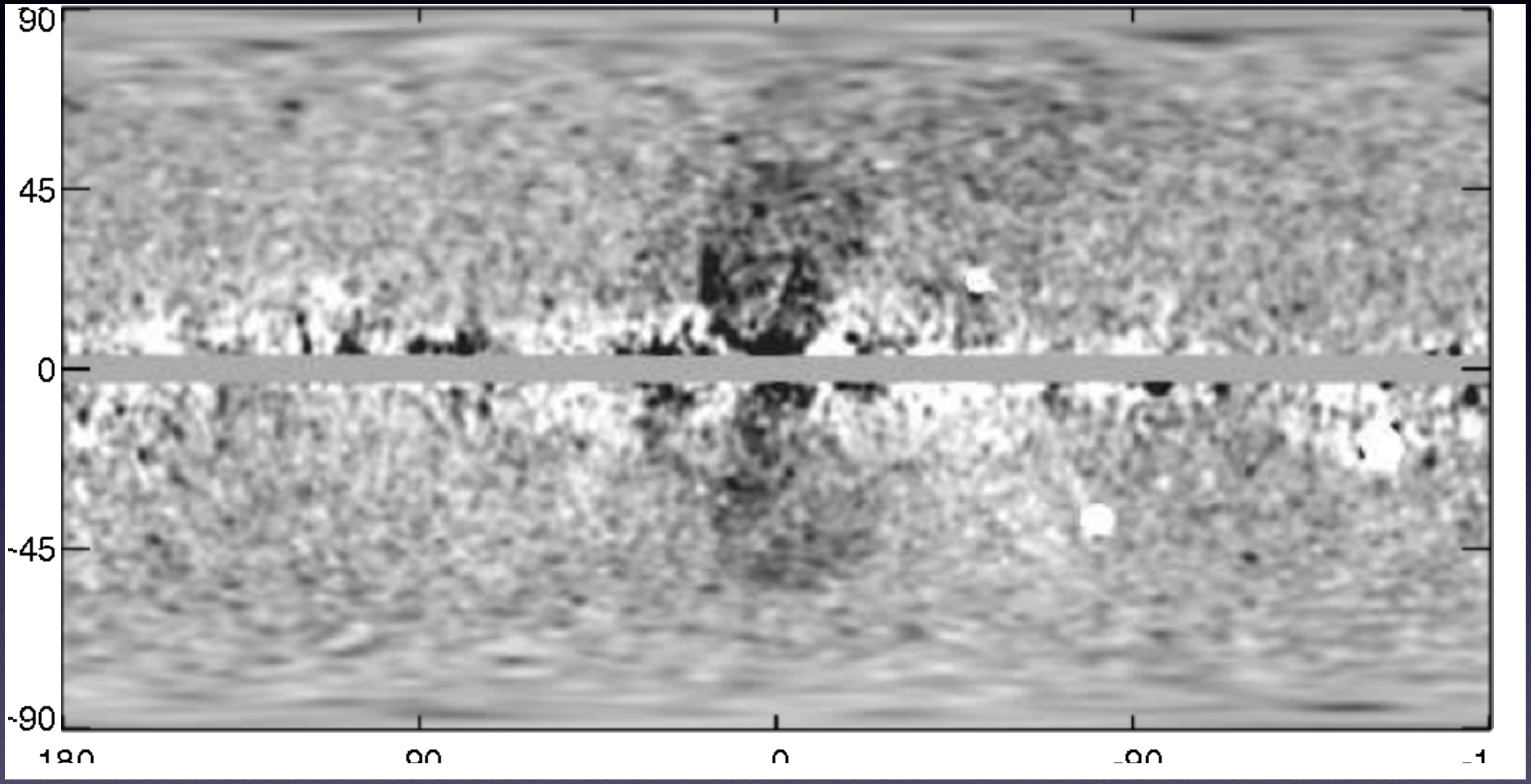

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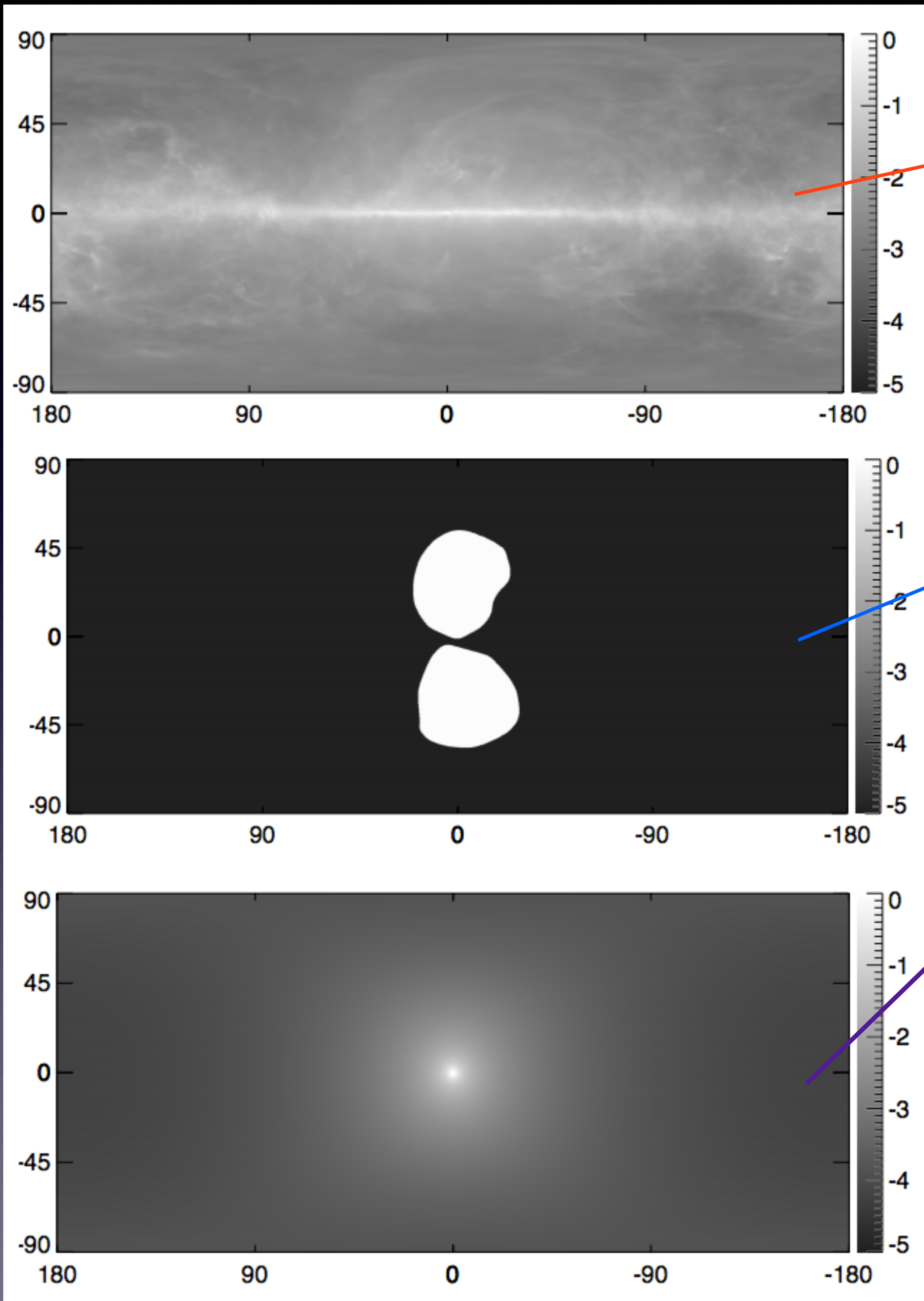
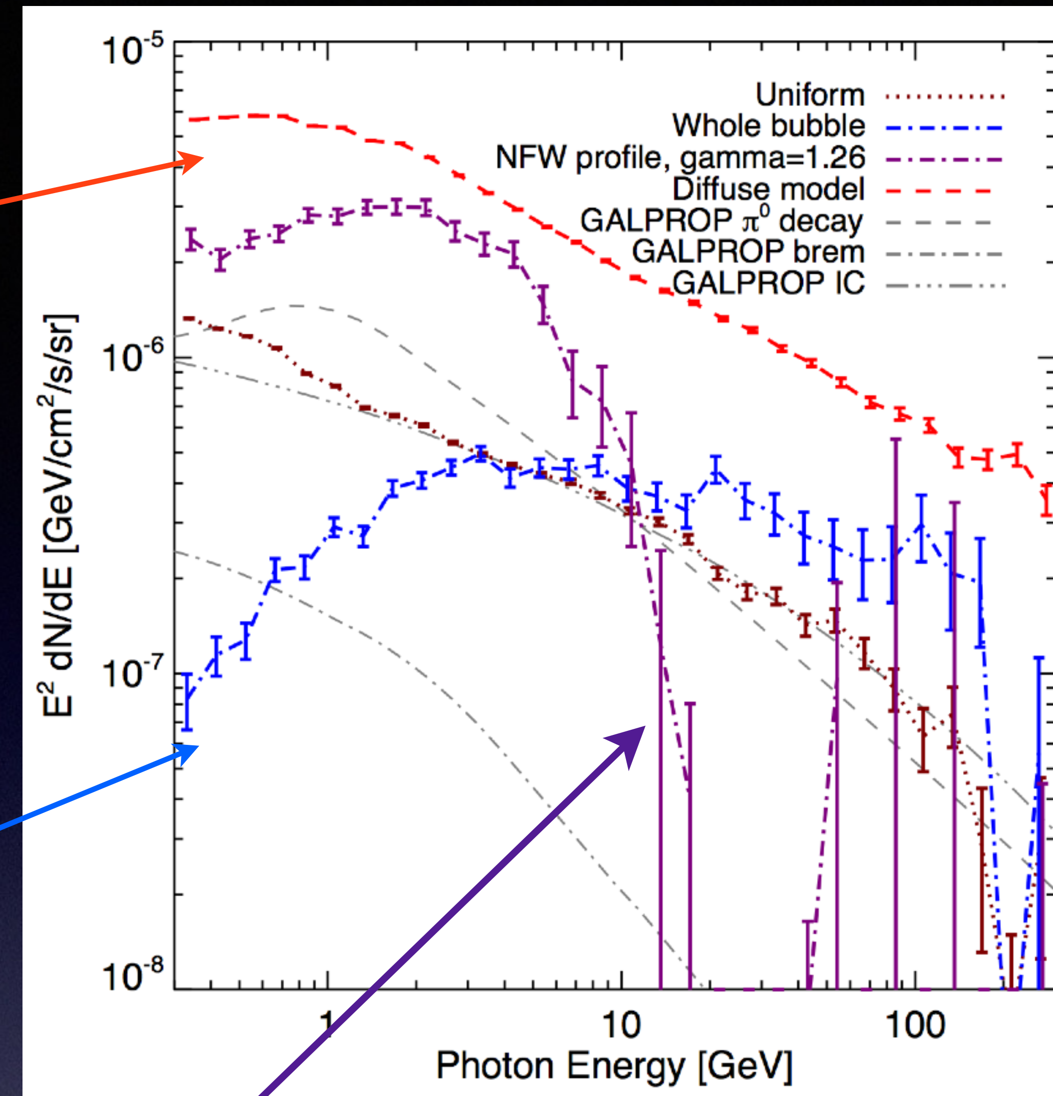
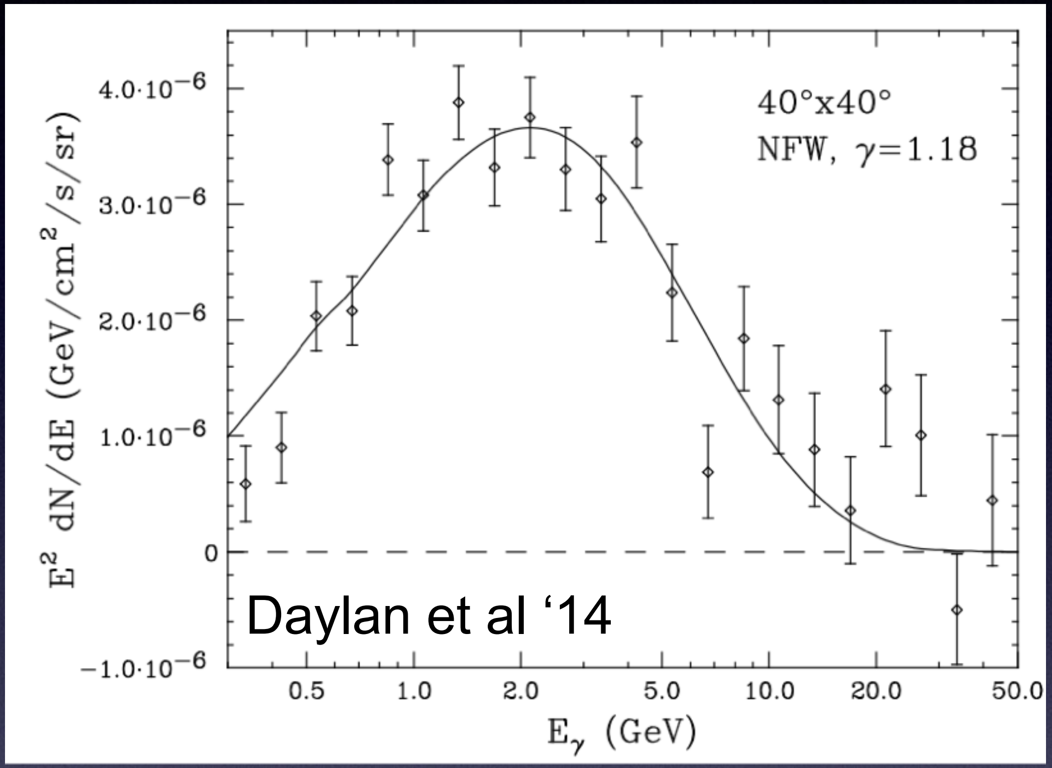


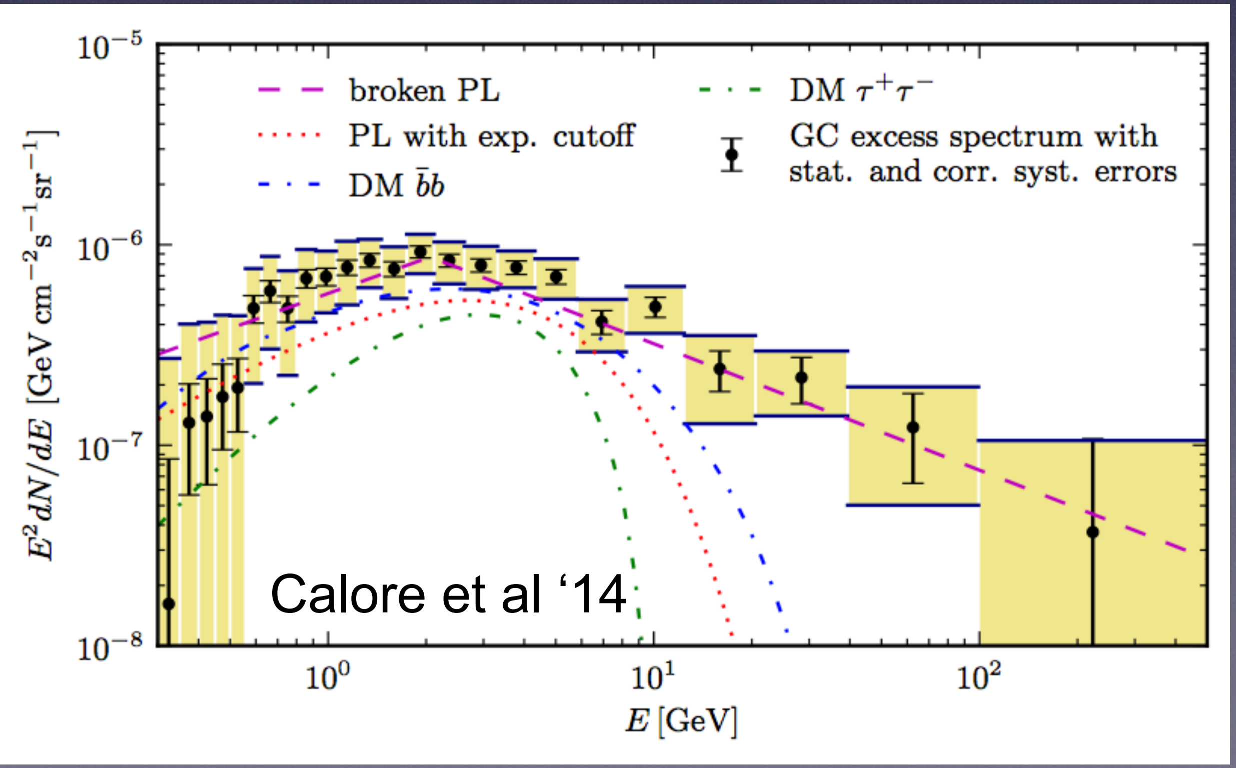


- Can add a model for a DM signal motivated by N-body simulations (or your favorite cored model) - generalized NFW profile, squared and projected along the line of sight.
- Fit the data as a linear combination of background(s) + signal, extract best-fit coefficient and error bars for each - “template fitting”.
- Repeat at each energy to find a spectrum for each component.

The GeV excess

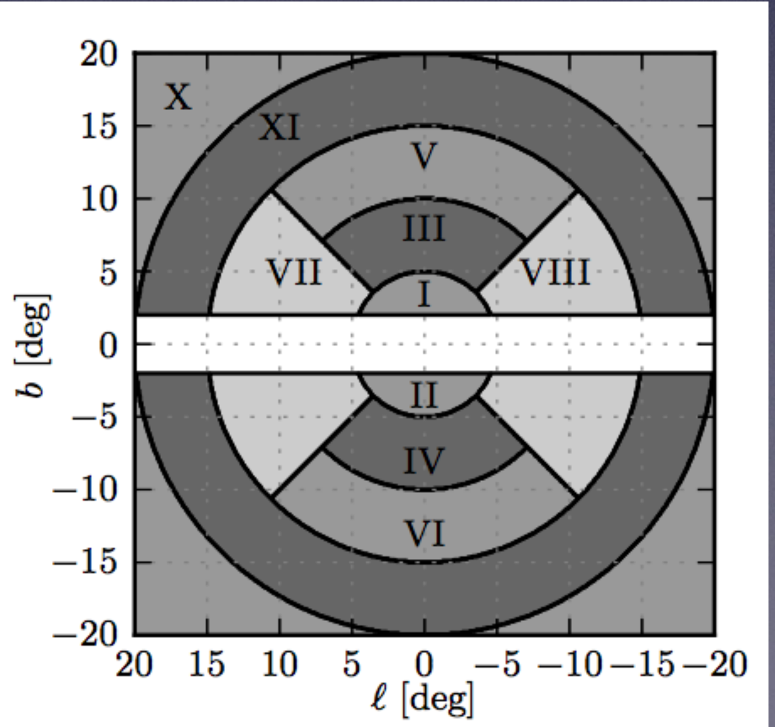
- There appears to be evidence for a new component in the Galactic Center (Goodenough & Hooper '09) and inner Galaxy (Hooper & TRS '13).
- Spectrum peaked at ~1-3 GeV.
- Rate consistent with simple thermal relic scenario, for ~50 GeV DM annihilating to quarks.
- Spatially, resembles a slightly steepened NFW profile (no core).



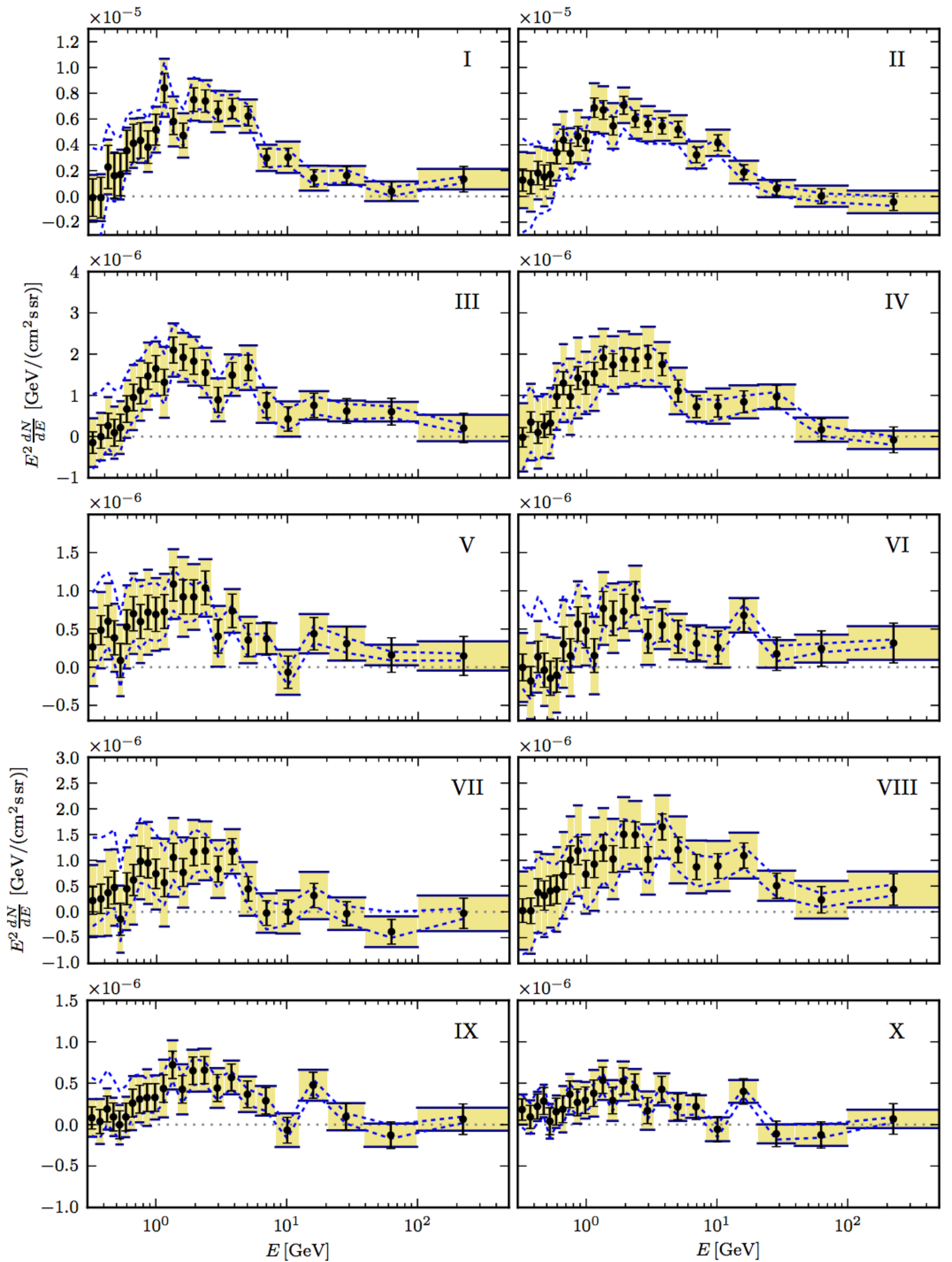


Morphology

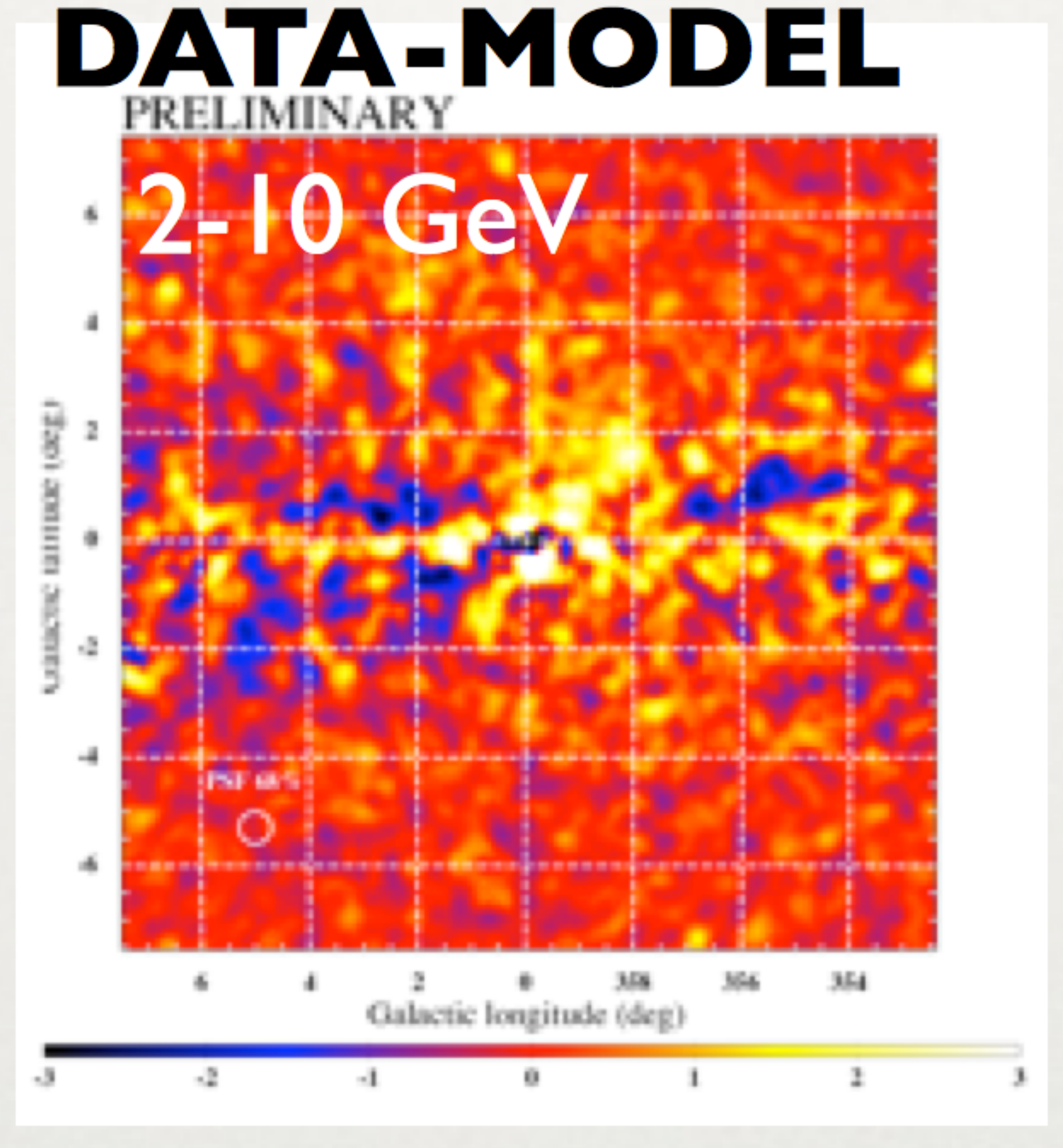
- Highly spatially symmetric about the GC, not elongated along plane (showed in Daylan et al '14, studied further by Calore et al).
- Also appears centered on GC (Daylan et al '14).



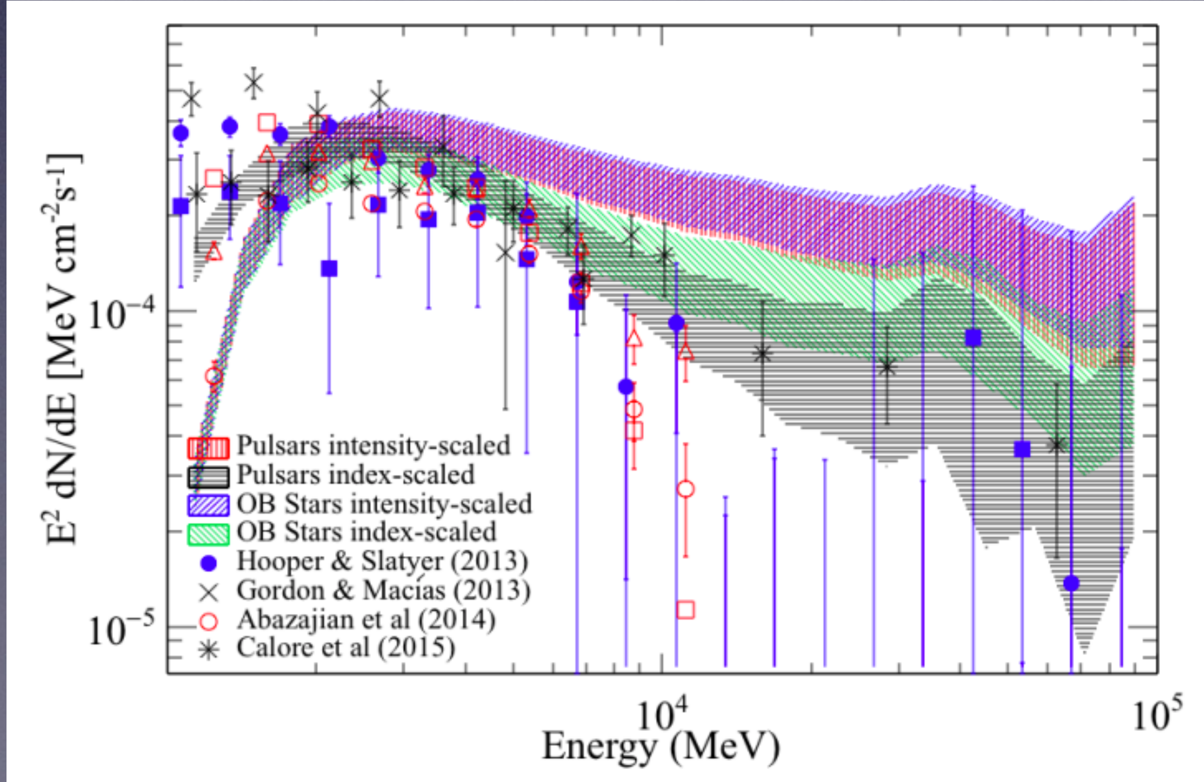
Plots taken from Calore, Cholis & Weniger '14



Fermi Collaboration analysis

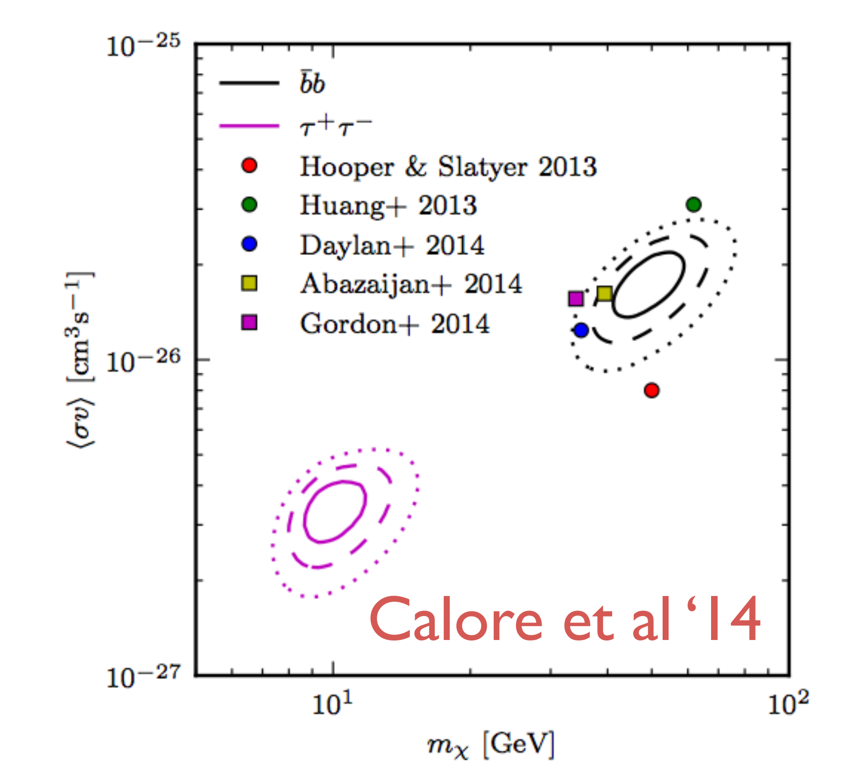


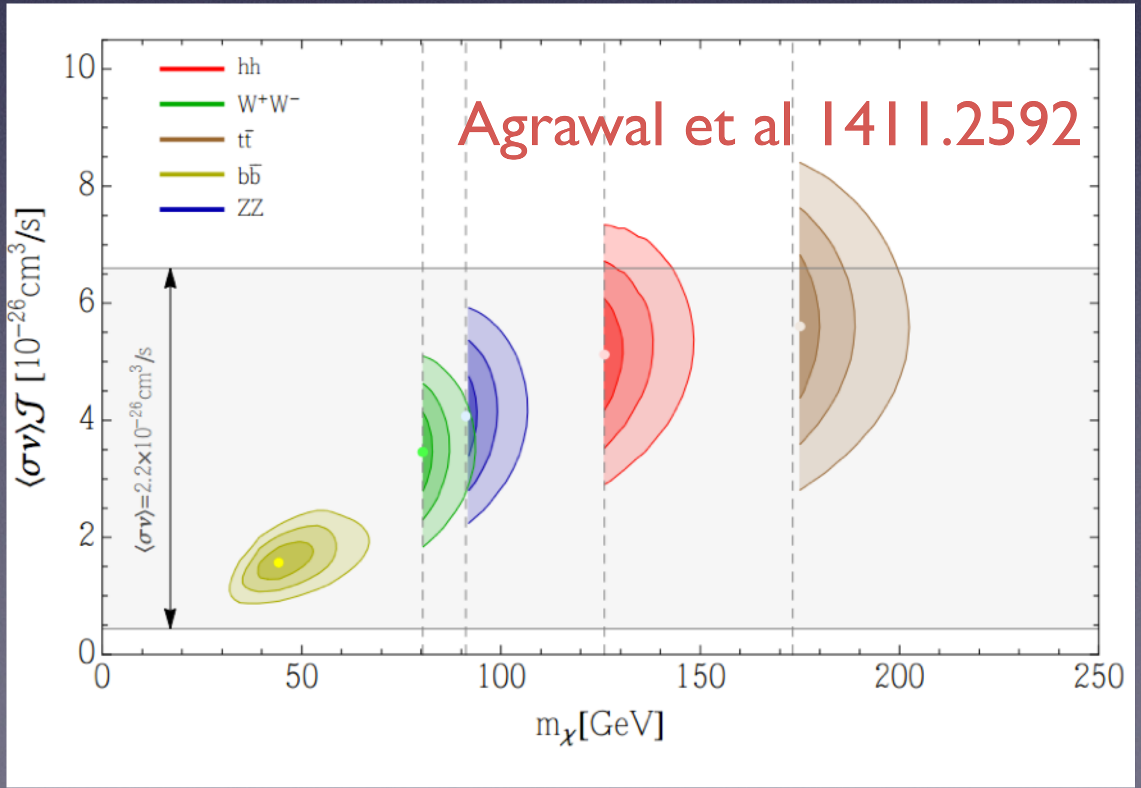
- Work by the Fermi LAT Collaboration (Nov ’15) seems to identify the same excess.
  - Careful alternate approach to background/foreground modeling
  - Spectrum depends on diffuse model, but peak around a few GeV seems consistent
  - Greatest improvements in the fit provided by spatial models peaked steeply toward the GC



If it is dark matter…

- Best fits are for DM masses around 10-50 GeV depending on channel, ~35-45 GeV for b's. Cross section is ~thermal, i.e. ~weak-scale.
- Heavier DM annihilating to hh can also provide a good fit to CCW results (1411.2592; Calore et al 1411.4647). Preferred DM mass is right at the threshold.
- Annihilation to W's, Z's and tops provides a worse fit.



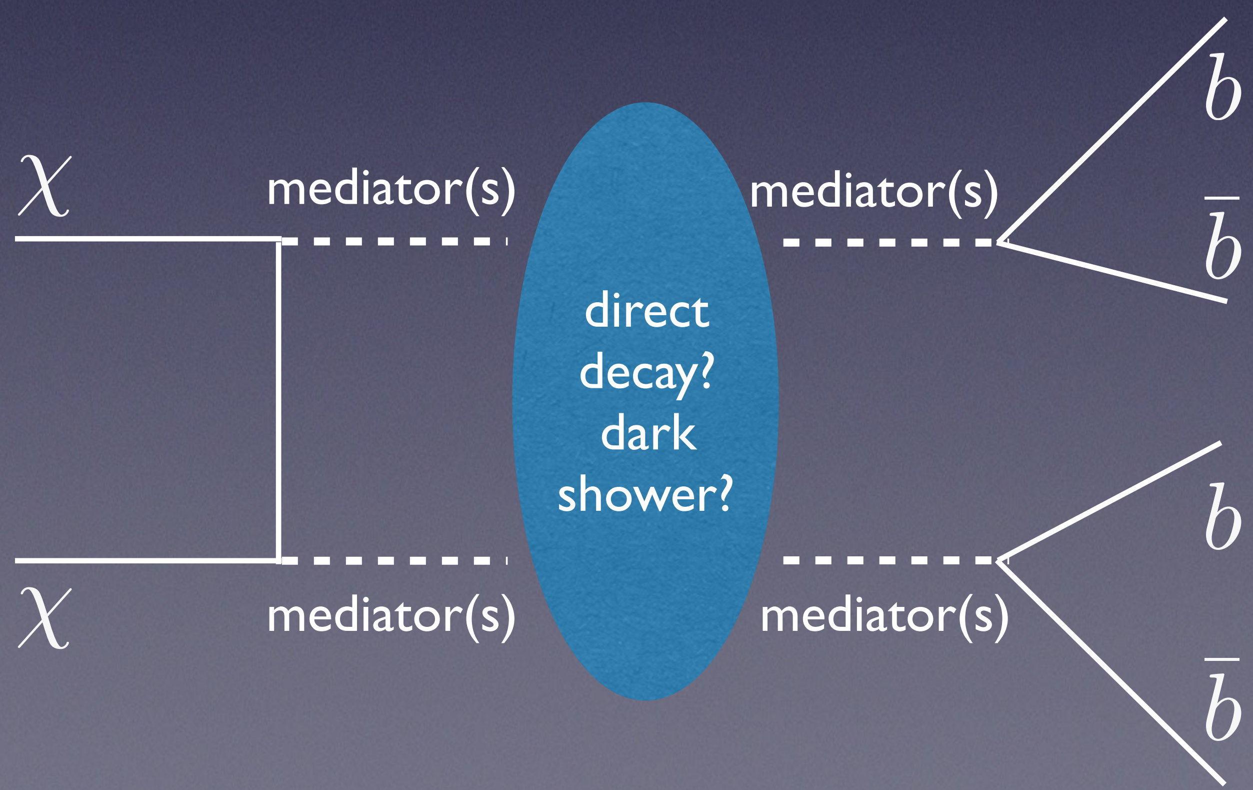


Model-building challenges

- Direct detection is very sensitive in this mass range, why haven't we seen it?
  - Annihilation may be resonant
  - Direct detection may be dominantly spin-dependent or otherwise suppressed (although in many models, upcoming direct detection experiments have sensitivity anyway)
  - Annihilation may be $2 \to 4$ and the intermediate particles may have small couplings to the SM
- What about bounds from colliders?
  - Sensitivity is reduced in the presence of light mediators, which may be needed to raise the cross section to thermal relic values
  - Nonetheless, substantial classes of simplified models can be ruled out.
- There are existence proofs of UV-complete models that satisfy all constraints.

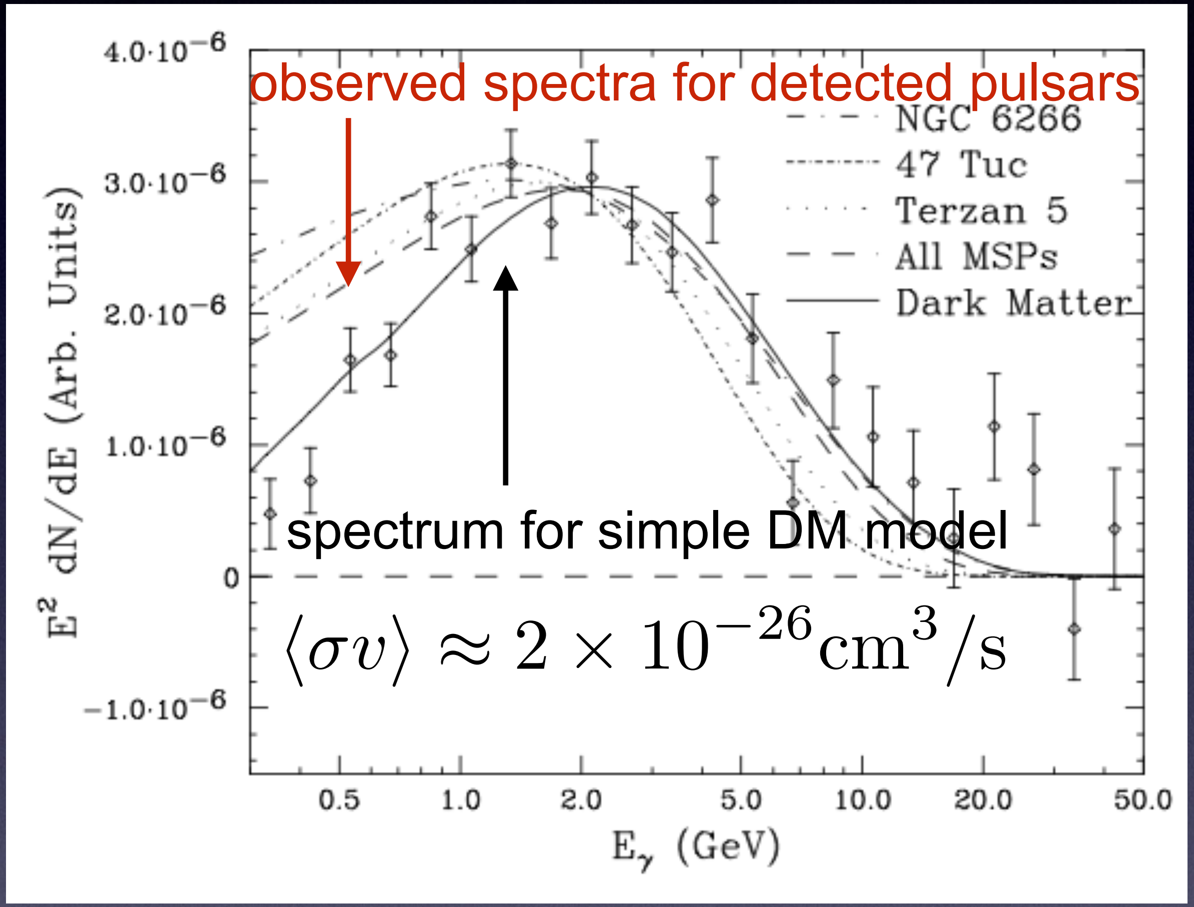
Examples

- Annihilation through a pseudoscalar to b's (e.g. "coy DM" of 1401.6458)
    - Renormalizable model presented in 1404.3716, pseudoscalar mixes with CP-odd component of 2HDM
    - Z_3 NMSSM implementation in 1406.6372, bino/higgsino DM annihilates through light MSSM-like pseudoscalar. General NMSSM study in 1409.1573.
- 2→4 models - DM annihilates to an on-shell mediator, subsequently decays to SM particles (e.g. 1404.5257, 1404.6528, 1405.0272, dark photon and NMSSM implementations in 1405.5204, dark-sector showering in 1410.3818).



But is it dark matter?

- Pulsars (spinning neutron stars) are known to emit gamma rays with a similar spectrum
  - No reason to expect this spatial distribution
  - That doesn't mean it's impossible
- Outflows of high-energy cosmic rays from the Galactic Center could also produce gamma rays
  - Protons striking gas - although signal doesn't look gas-correlated
  - Electrons upscattering photons - although not easy to accommodate constant spectrum



Daylan et al '14

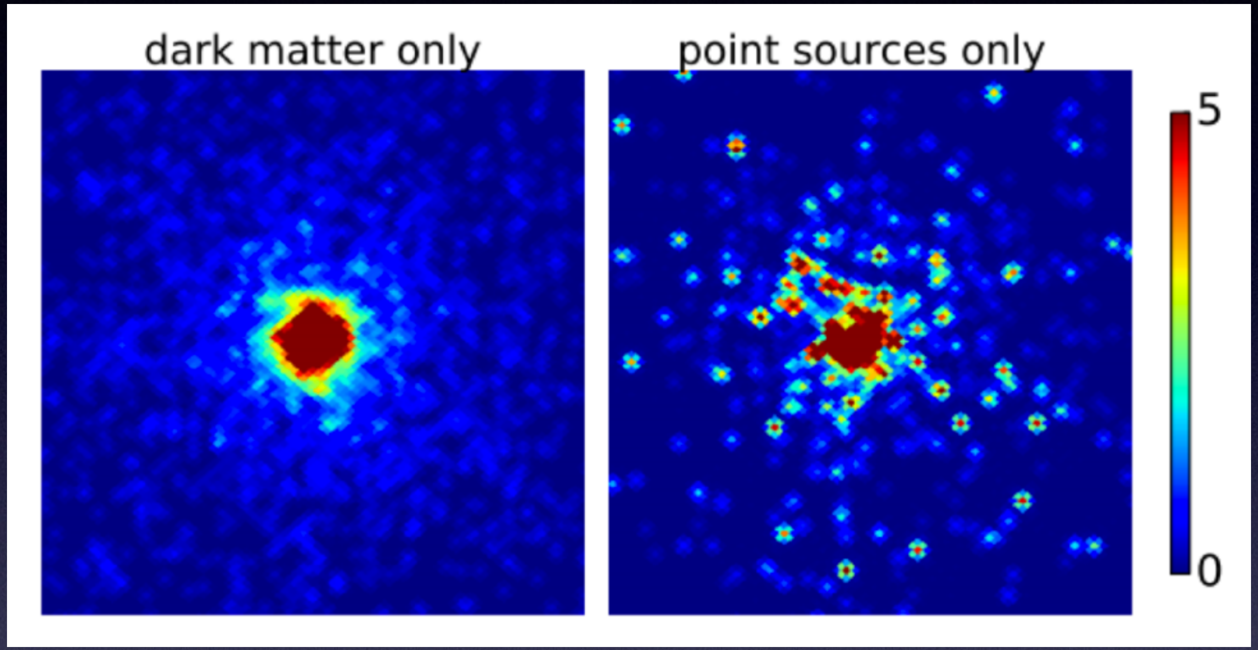
A brief and not exhaustive list of references:
1405.7685, 1405.7928, 1506.05119, 1507.06129

Photon statistics

Lee, Lisanti, Safdi, Xue & TRS '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.
- If we are looking at dark matter or an outflow, we expect a fairly smooth distribution.
- In the pulsar case, we might instead see many "hot spots" scattered over a fainter background.
- Can be made quantitative by considering the differing photon statistics in these two cases - variance larger for same mean when point sources are present, modifies likelihood.
- Related analysis by Bartels et al '16, using wavelet approach - finds consistent results.

An example

I expect 10 photons per pixel, in some region of the sky. What is my probability of finding 0 photons? 12 photons? 100 photons?

Case 1: diffuse emission, Poissonian statistics

$P(12 \text{ photons}) = 10^{12} e^{-10}/12! \sim 0.1$

Likewise $P(0 \text{ photons}) \sim 5 \times 10^{-5}$, $P(100 \text{ photons}) \sim 5 \times 10^{-63}$

Case 2: population of rare sources.

Expect 100 photons/source, 0.1 sources/pixel - same expected mean # of photons

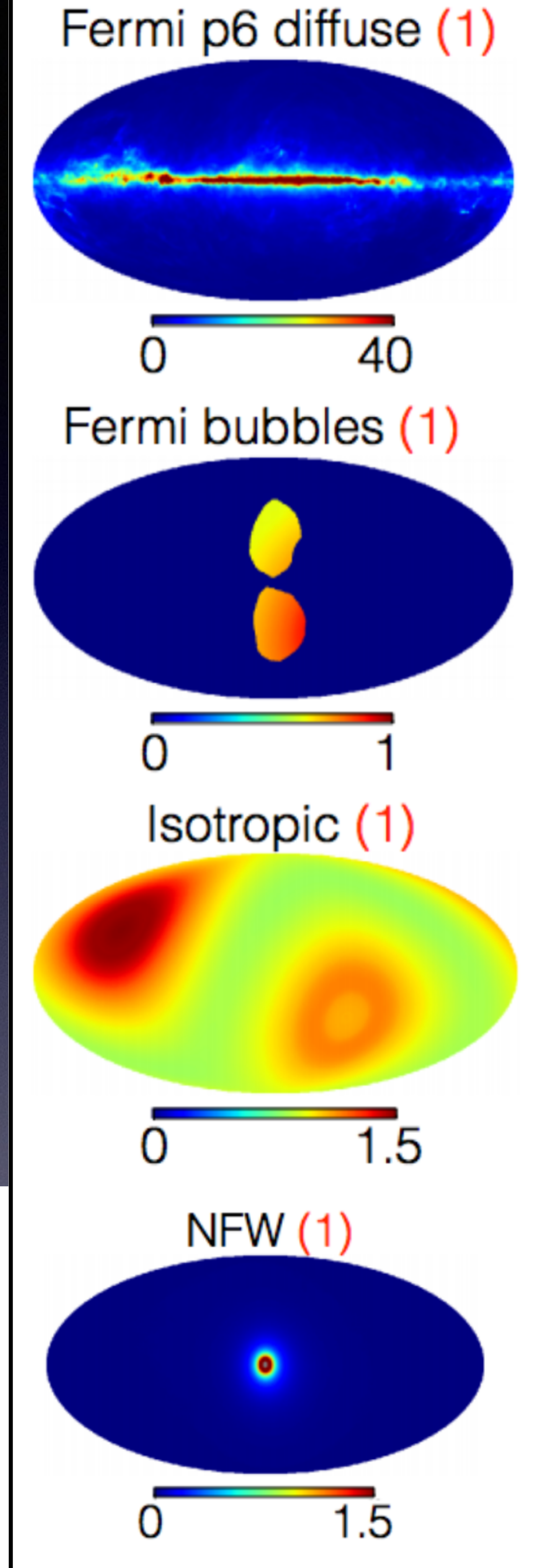
$P(0 \text{ photons}) \sim 0.9$, $P(12 \text{ photons}) \sim 0.1 \times 100^{12} e^{-100}/12! \sim 10^{-29}$,

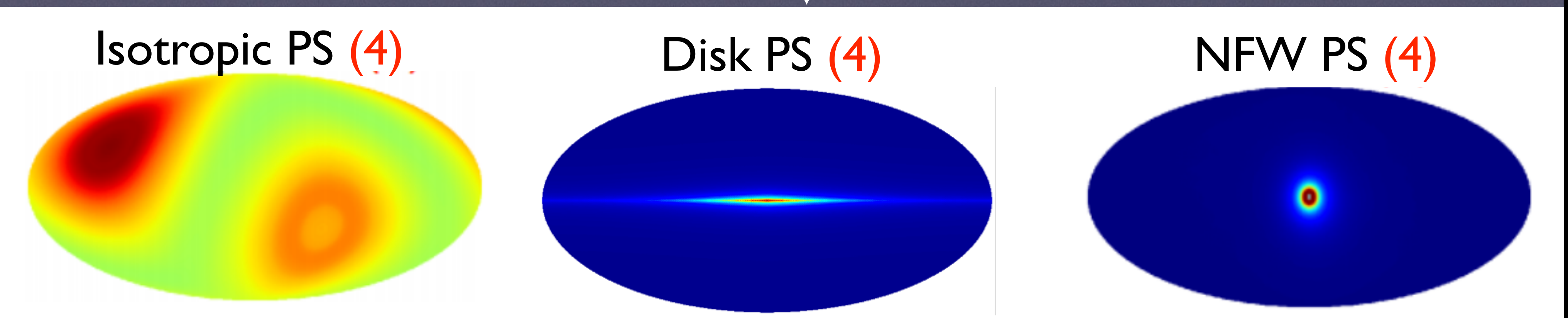
$P(100 \text{ photons}) \sim 4 \times 10^{-3}$

(plus terms from multiple sources/pixel, which I am not including in this quick illustration)

Template fitting II

- Model sky (within some energy bin) as linear combination of spatial templates
- Templates may either have
  - Poissonian statistics
  - Point-source-like statistics - extra degrees of freedom describing number of sources as a function of brightness

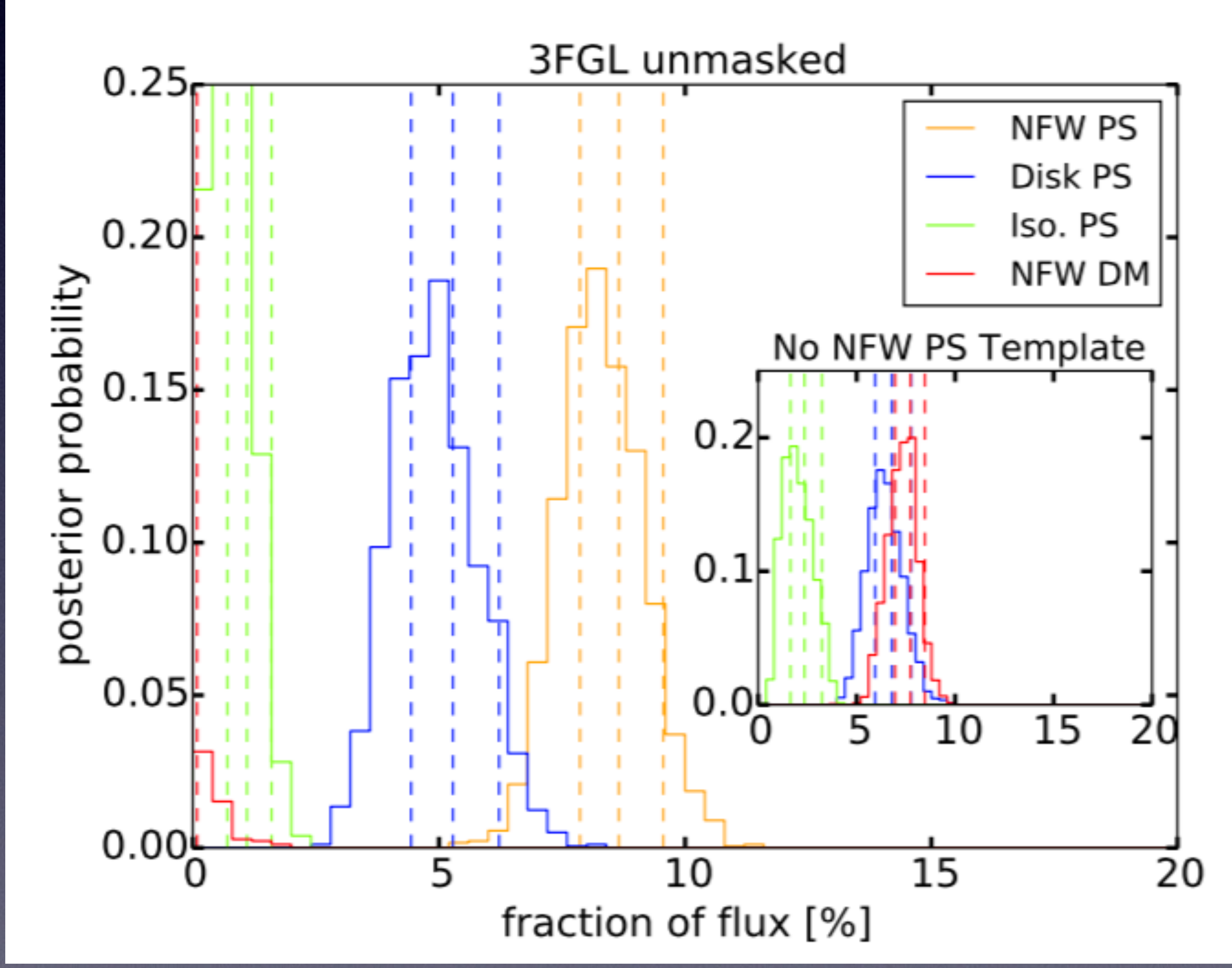




Point source templates

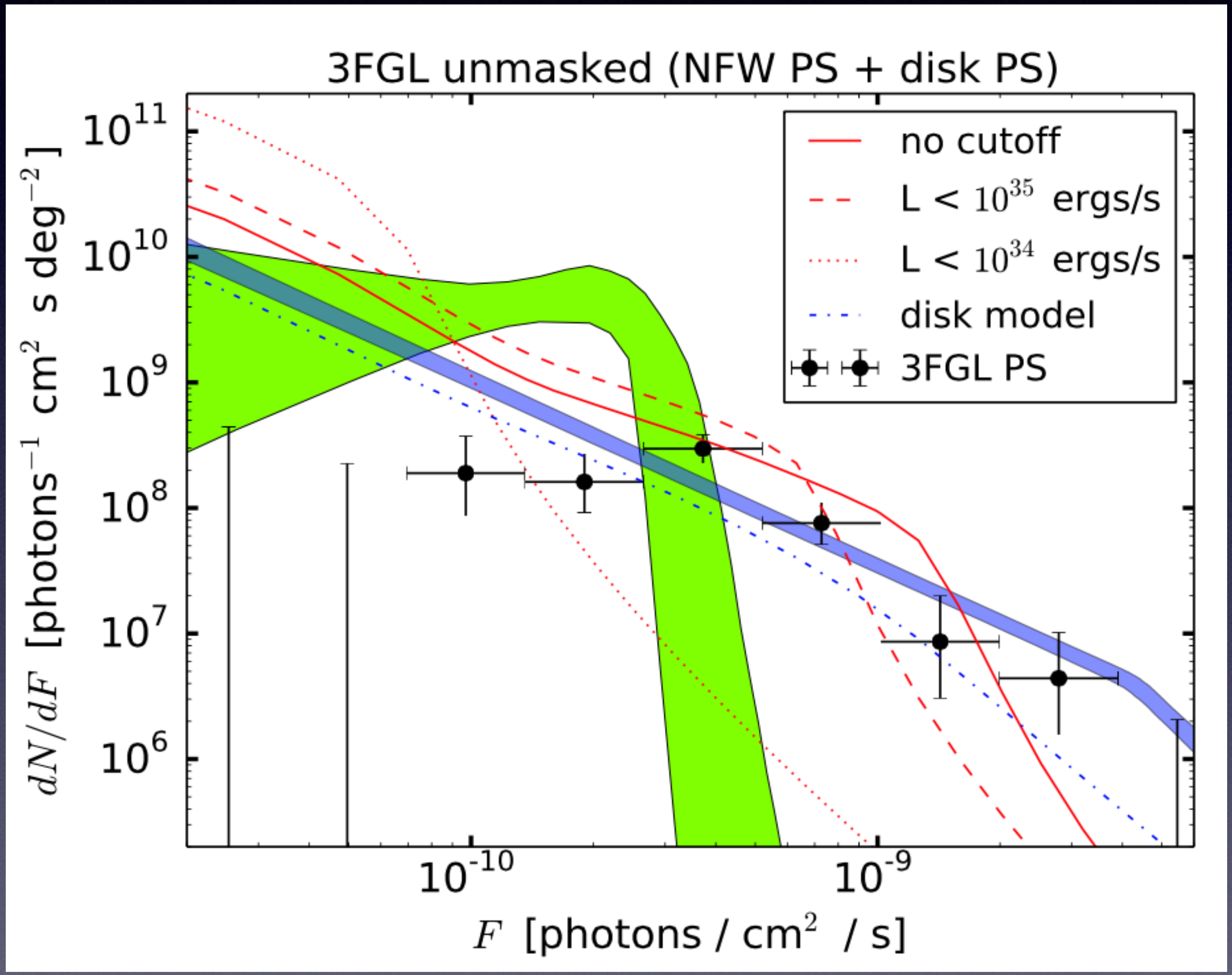
A preference for point sources

- Compare fit with and without point-source template peaked toward GC, "NFW PS".
- In both cases there is a smooth "DM" template peaked toward GC, "NFW DM".
- If "NFW PS" is absent, "NFW DM" template absorbs excess. If "NFW PS" is present, "NFW PS" absorbs full excess, drives "NFW DM" to zero.



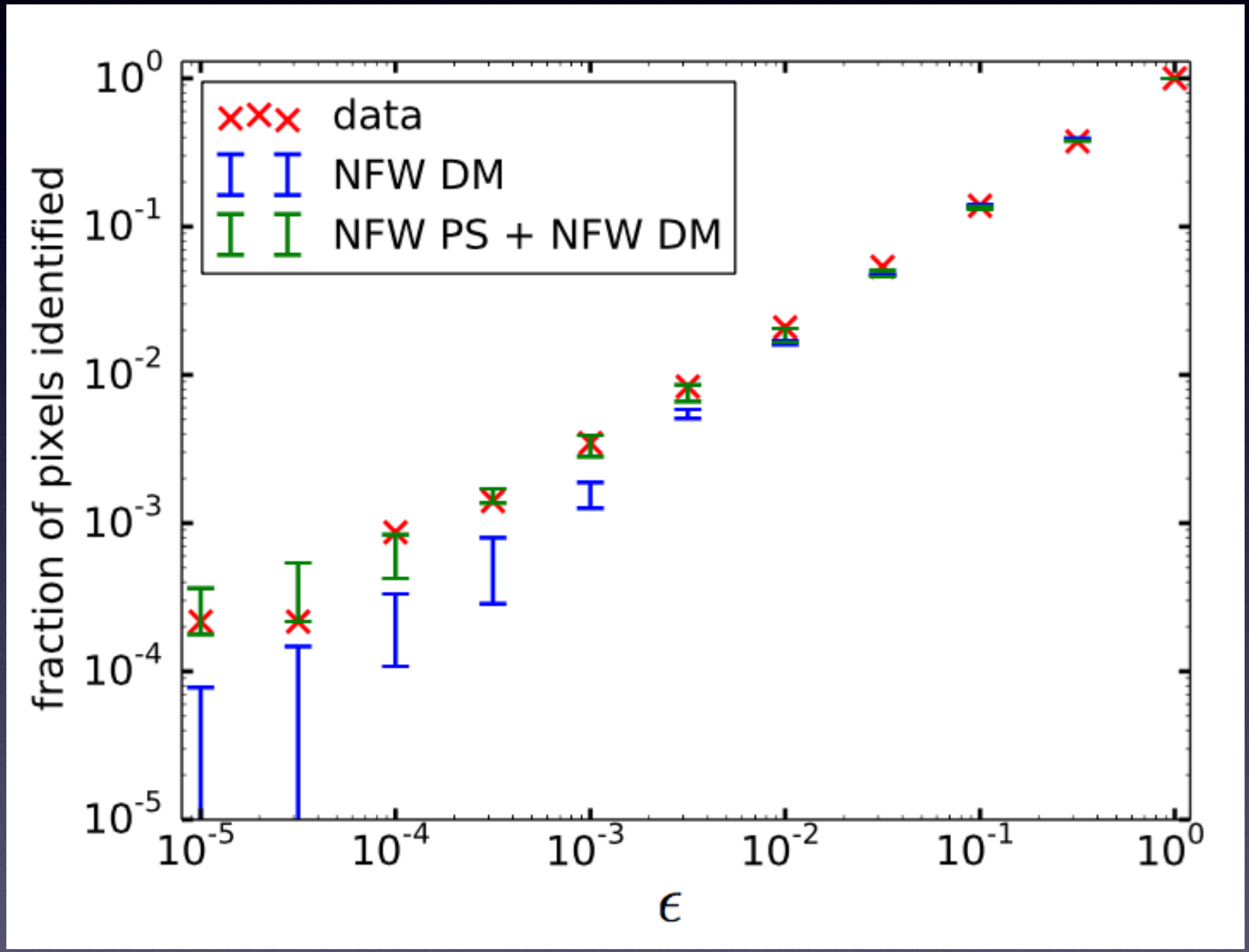
The luminosity function

- Disk distribution largely absorbs known sources.
- NFW PS template appears to prefer a novel population peaked just below current detection threshold.



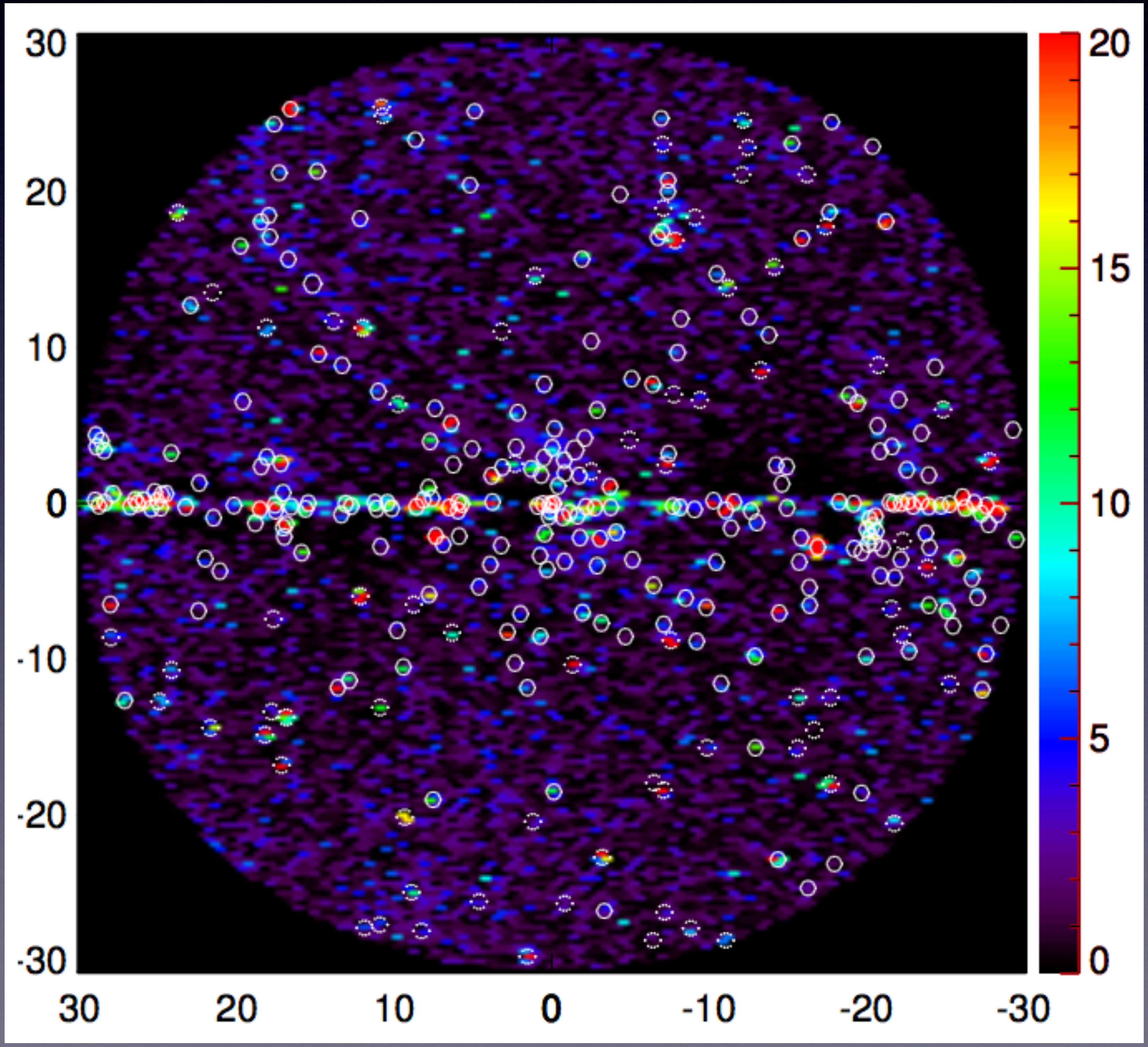
What drives the point-source preference?

- Preference for non-Poissonian statistics driven by presence of more bright/faint pixels than expected.
- Can show this explicitly by computing # of outlier ("hot" or "cold") pixels, comparing to Poisson expectations.
- n_p = actual observed number of photons in a given pixel, define ε_p = P(# photons > np) under model with only Poissonian statistics (including DM template).
- Small εp corresponds to "hot pixels" - unusually bright relative to purely diffuse model.
- Fraction of pixels with small ε_p is a diagnostic for PS contribution - are there more than are expected from Poisson statistics?



Results shown for mock data with no NFW PSs and best-fit DM model ("NFW DM"), mock data including NFW PSs ("NFW PS + NFW DM"), and real data. In all cases template fit includes NFW DM but not NFW PS, with 3FGL mask.

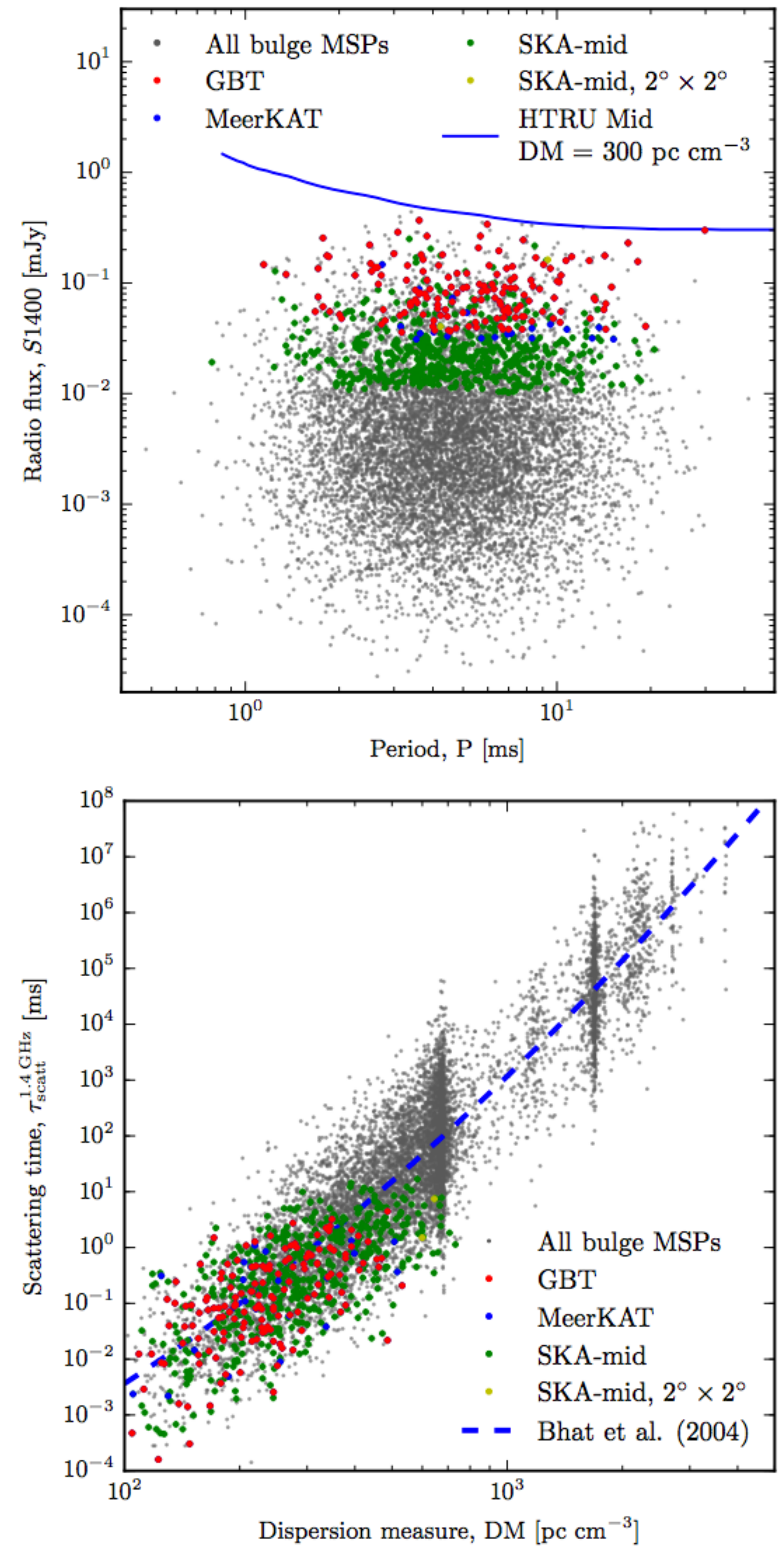
Hot pixels and known sources



- Plot shows degree to which pixels are outliers with respect to Poissonian-only background model (-logεp).
- Such "hot pixels" are potential point source candidates.
- Including unmasked data, we recover many known sources.
- Circles = known (3FGL) sources, dotted circles are believed to be extragalactic.

Can we find them?

- Pulsars = leading candidate for the point sources, due to spectral similarity
- Could potentially be probed by radio or X-ray telescopes - see e.g. Calorie et al '16.

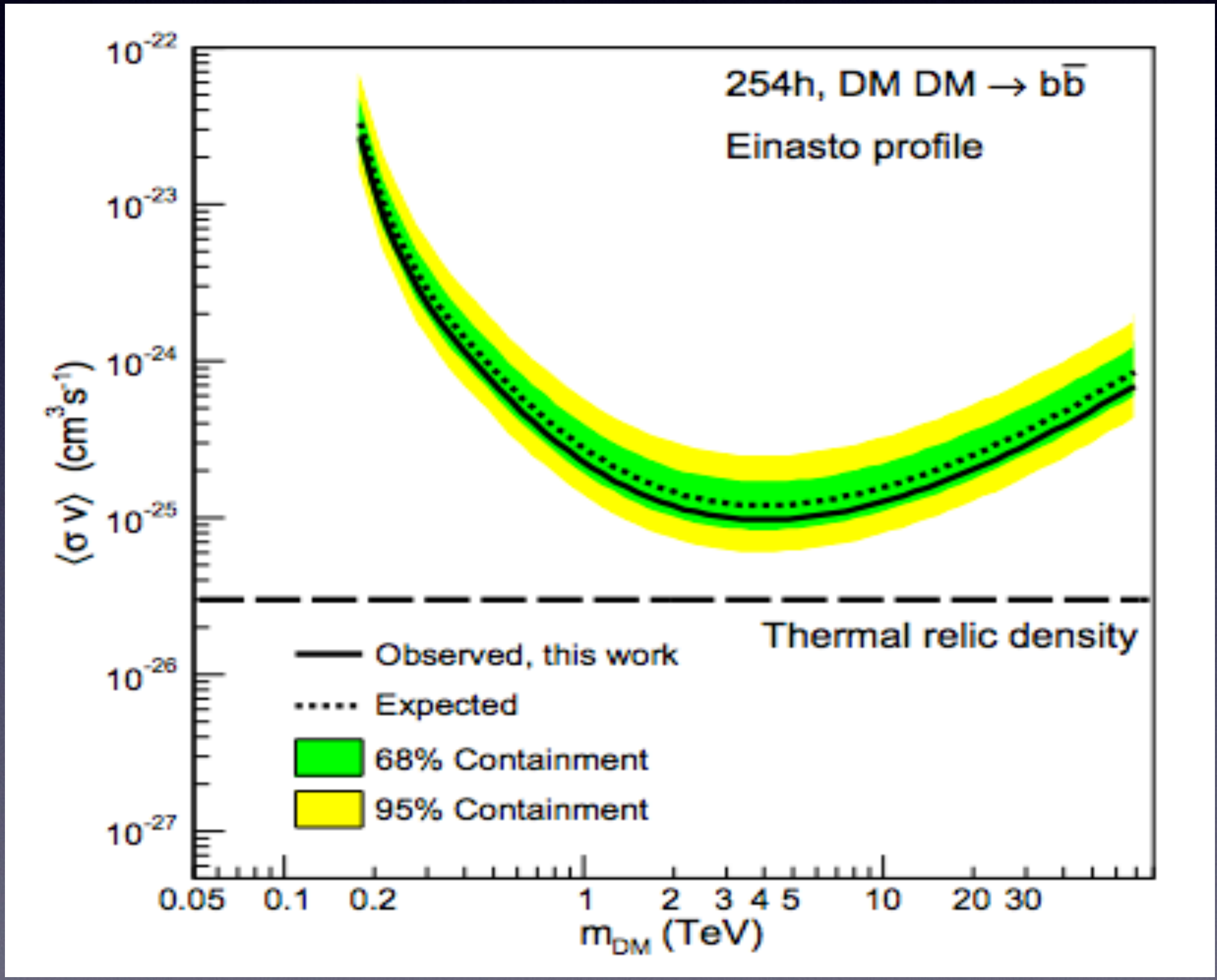


Non-Poissonian template fitting

- Now available as a fully public code package at https://github.com/bsafdi/NPTFit
- Documented in Mishra-Sharma et al 1612.03173

Continuum limits from the Galactic Center

- Nominally strongest limits above 1 TeV come from HESS observations of a small region of the inner Milky Way (Abdallah et al '16).
- However, this constraint assumes a cuspy density profile.



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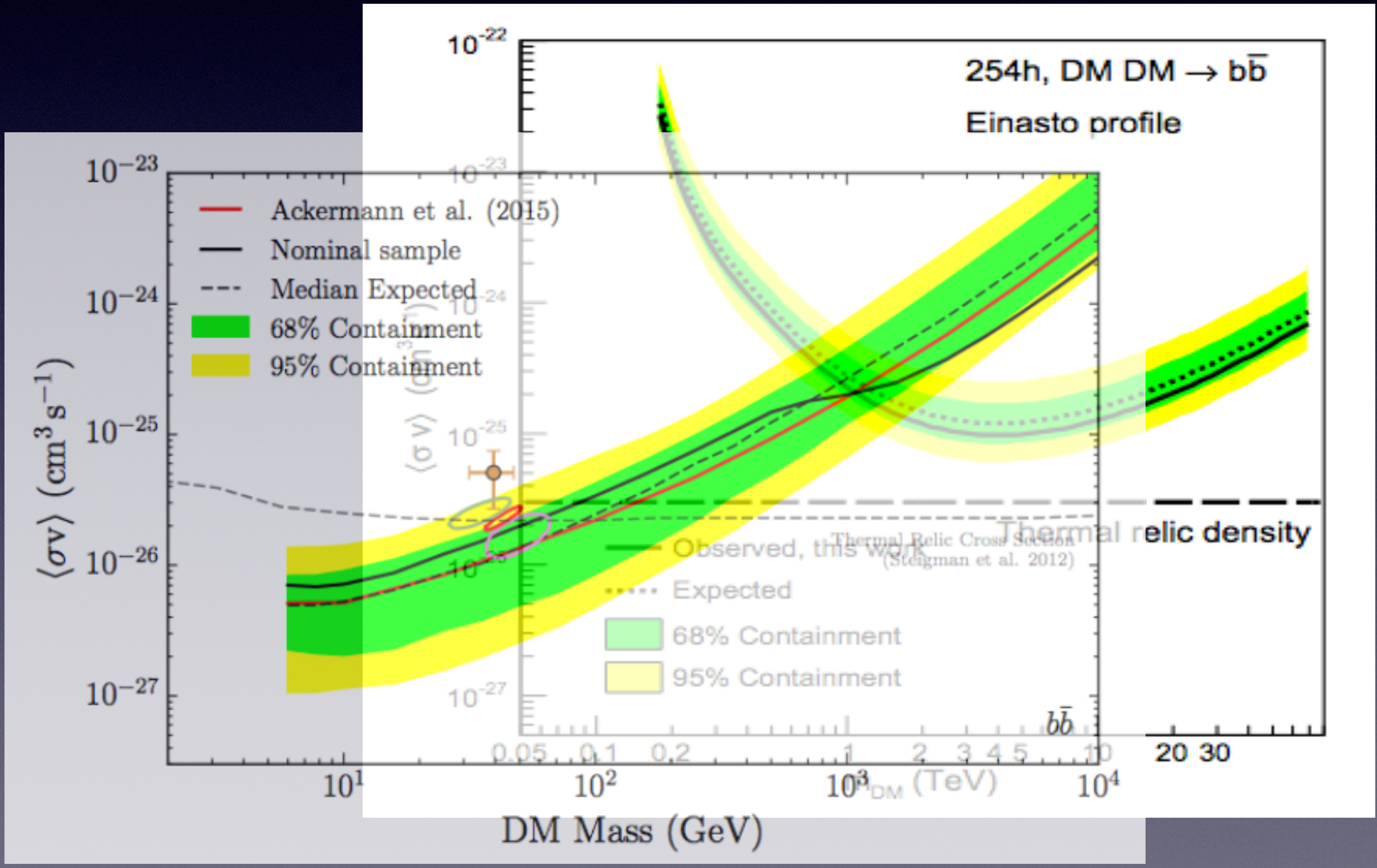
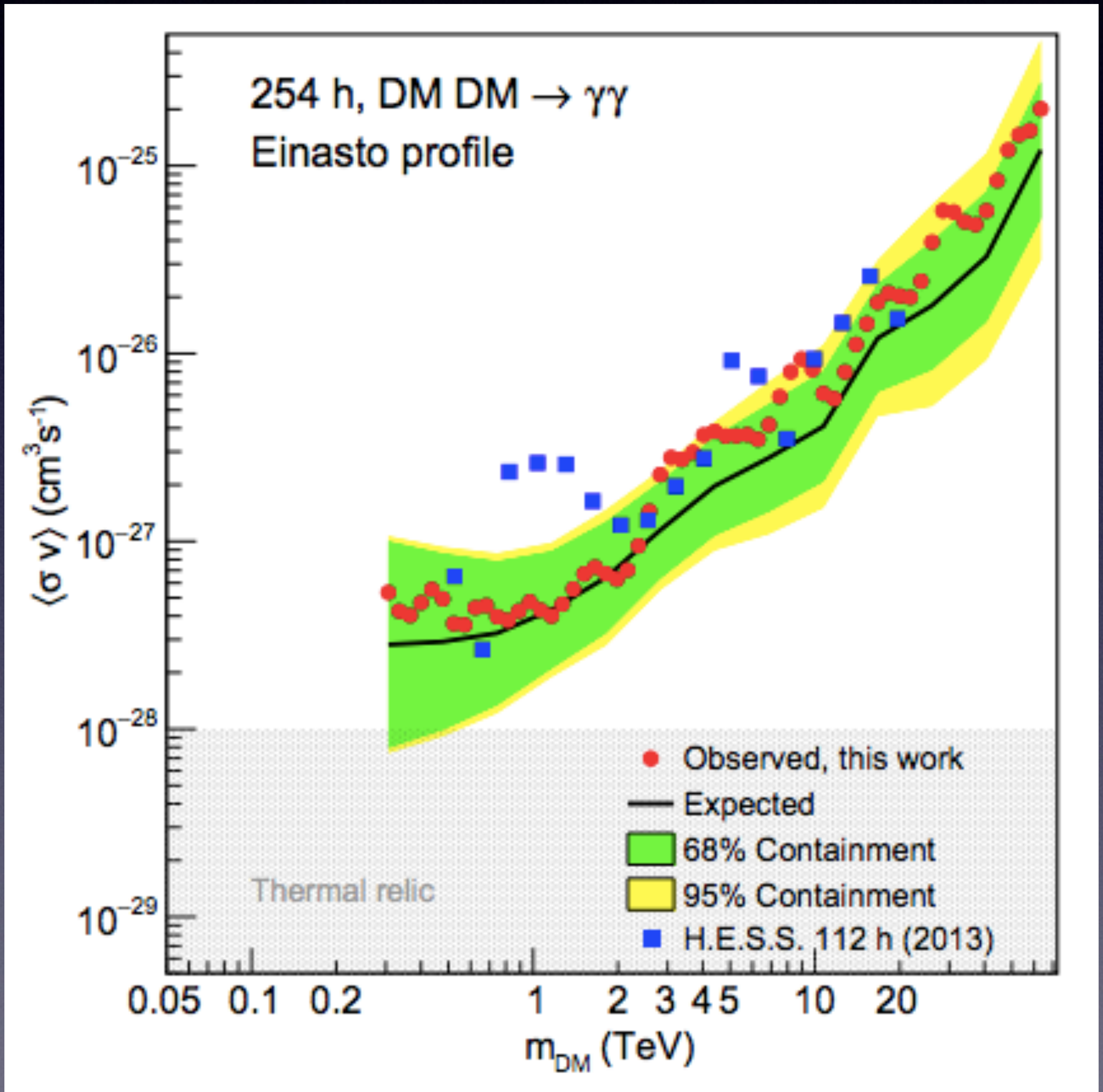


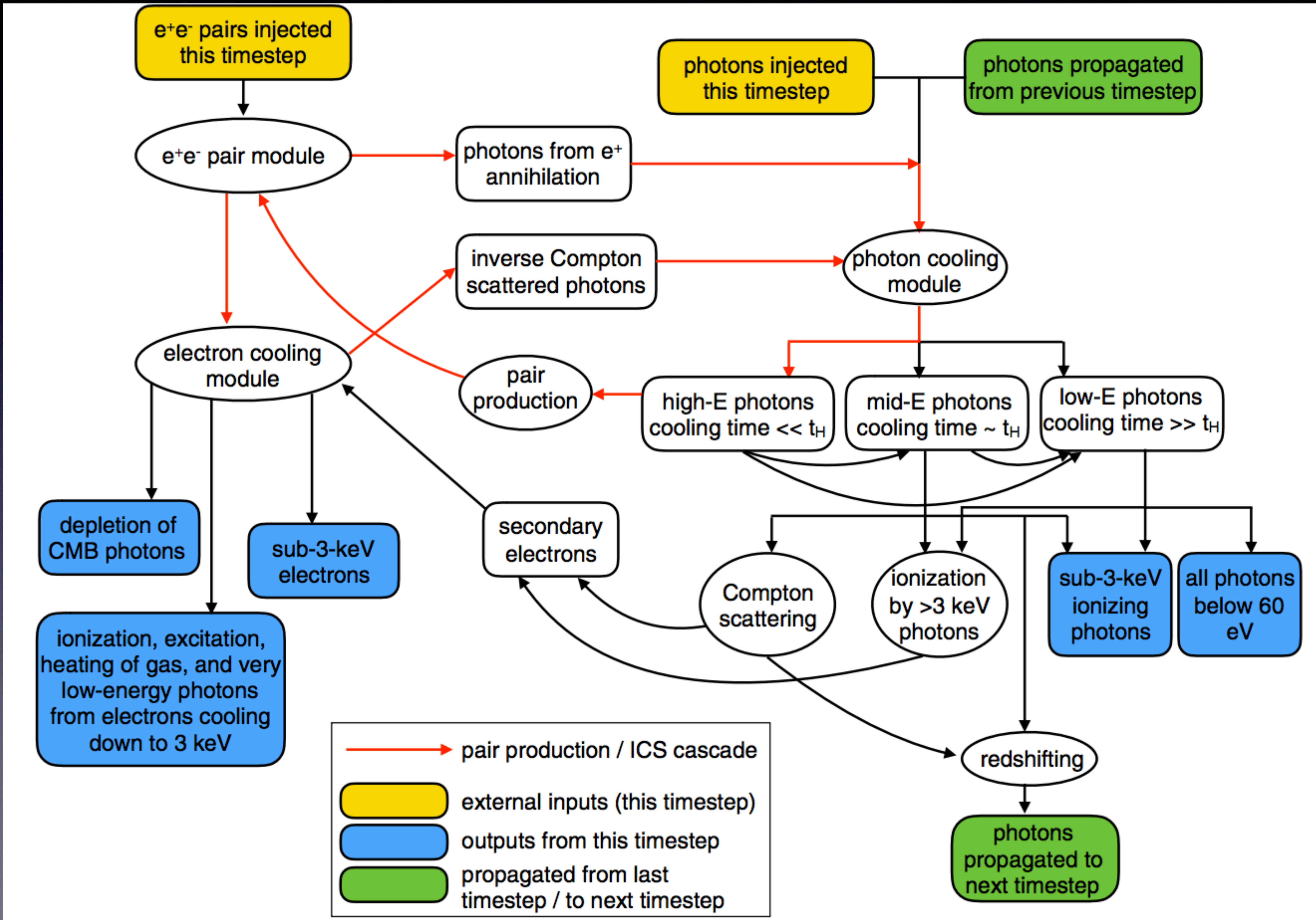
Line limits from GC

- For gamma-ray lines, astrophysical backgrounds are low
- Need to optimize statistics - motivates search toward inner Galaxy
- Line limits from dwarfs have also been derived (e.g. Liang et al '16)

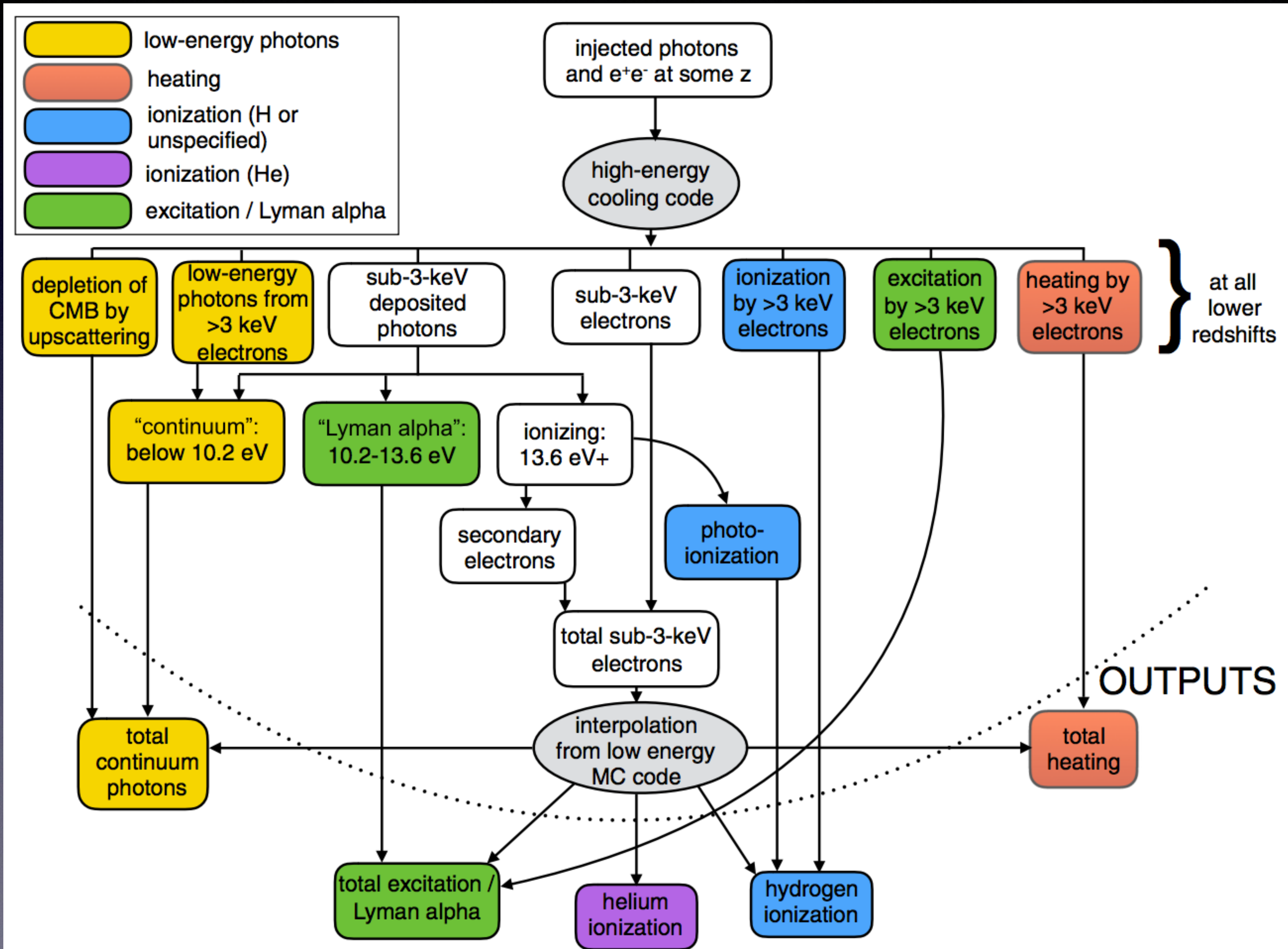


H.E.S.S. Collaboration '18 (1805.05741)

Modeling energy loss (high)



Modeling energy loss (low)



Bounds from the CMB

DM model

public codes
HyREC, CosmoRec, CLASS, CAMB, CosmoMC, MontePython

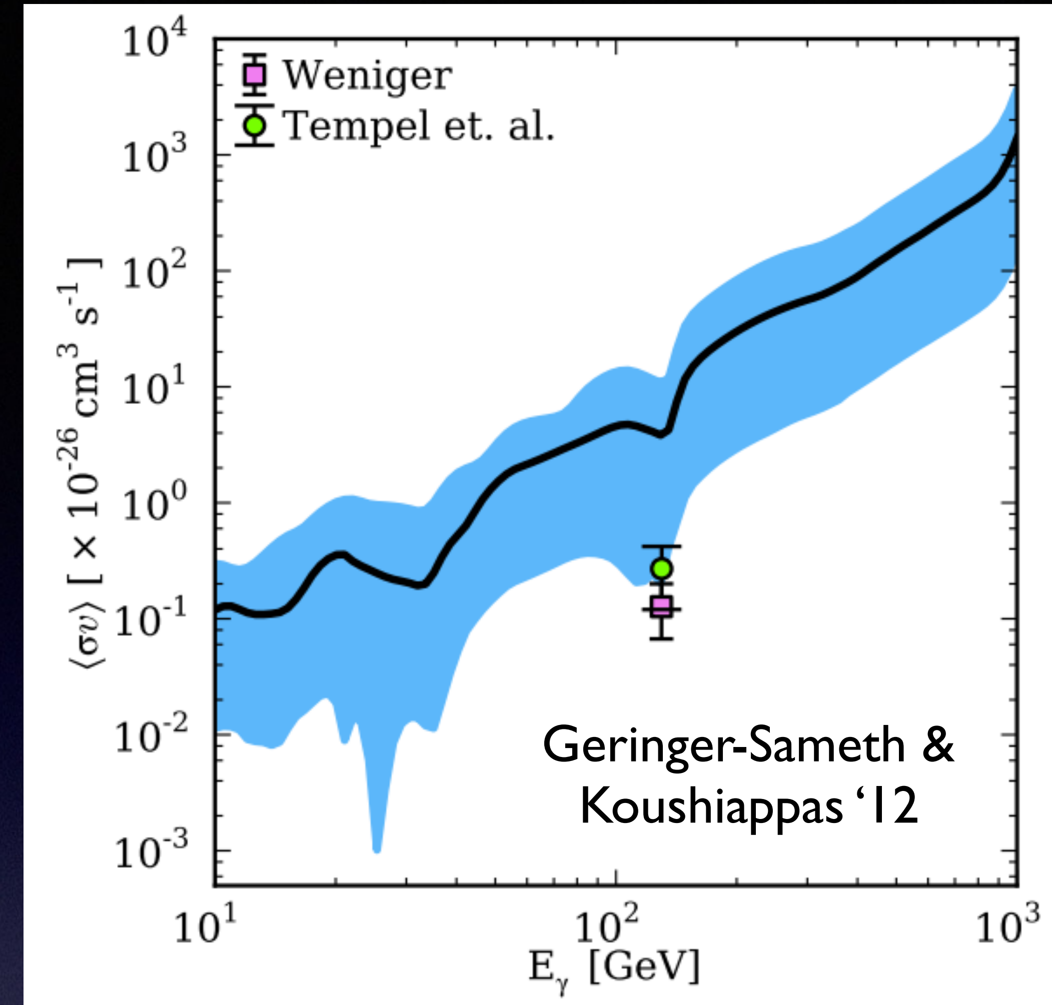
DM annihilation → photons, electrons, positrons → ionization → scale-dependent perturbation to CMB anisotropies

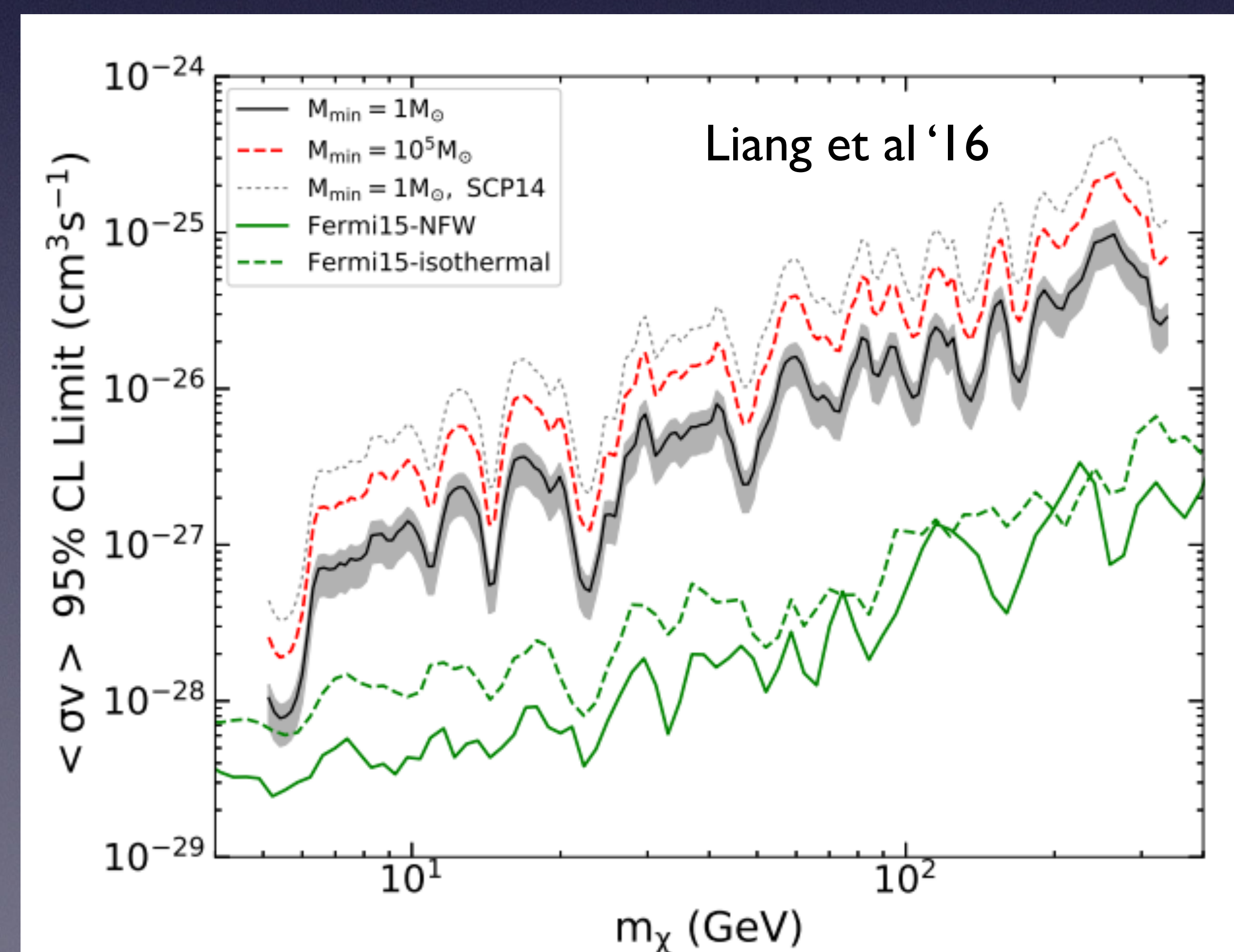
must understand efficiency of this process

Adams, Sarkar & Sciama 1998; Chen & Kamionkowski 2003; Finkbeiner & Padmanabhan 2005

- There is a limit on (s-wave) annihilating DM from the CMB - turns out to depend on essentially one number: excess ionization at z~600 (Galli, Lin, TRS & Finkbeiner '11, Slatyer '15).
- Parameterized by efficiency parameter f_{eff}: first computed in TRS, Padmanabhan & Finkbeiner '09, significant updates to calculation described in Galli, TRS, Valdes & Iocco '13.
- f_{eff}, and hence the constraint on a given (s-wave annihilating) DM model, depends on:
  - PRIMARILY, how much power goes into photons/electrons/positrons vs neutrinos and other channels.
  - SECONDARILY, the spectrum of photons/electrons/positrons produced (but most variation is for particles below the GeV scale).

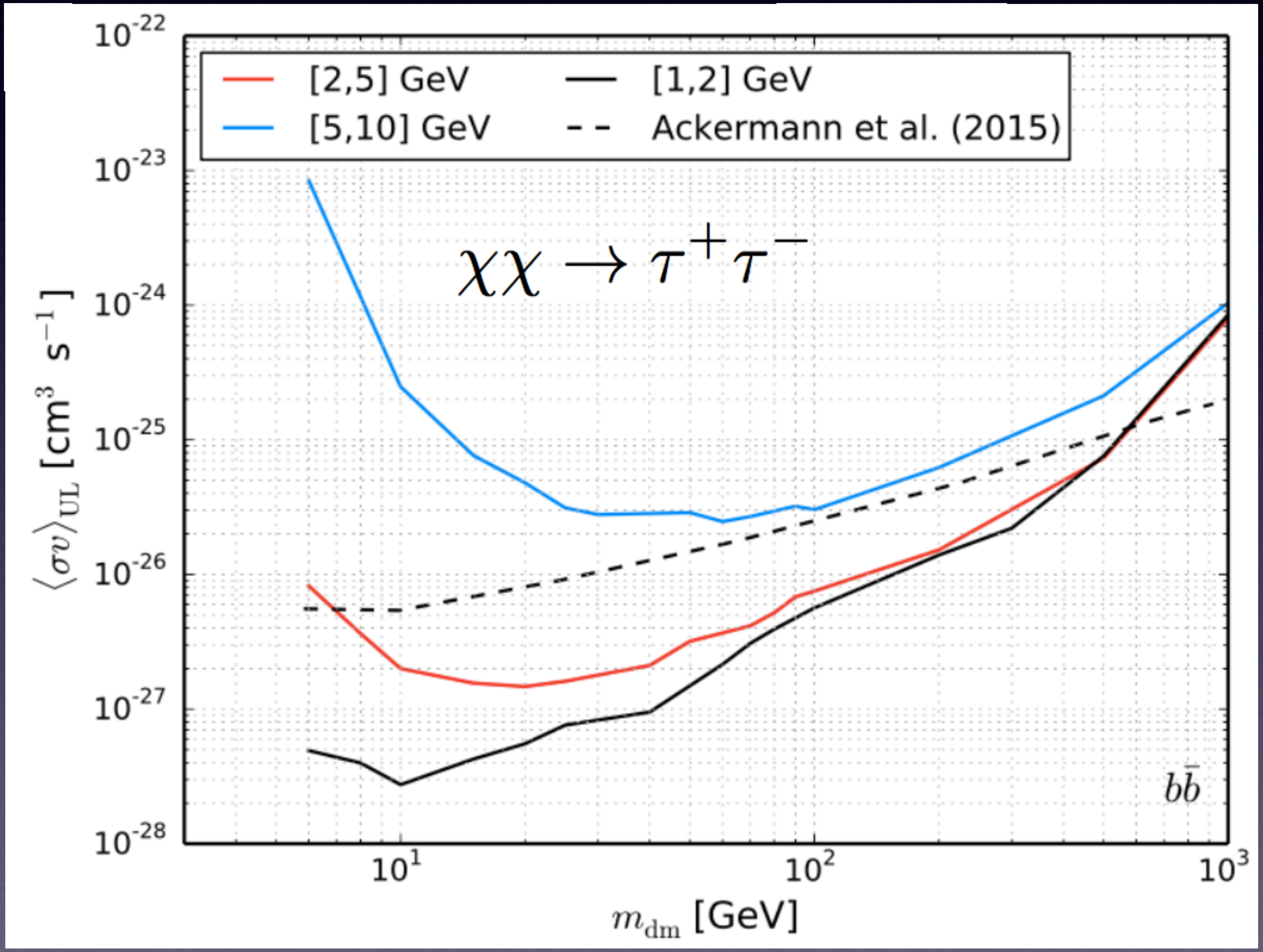
Line limits from dwarf galaxies





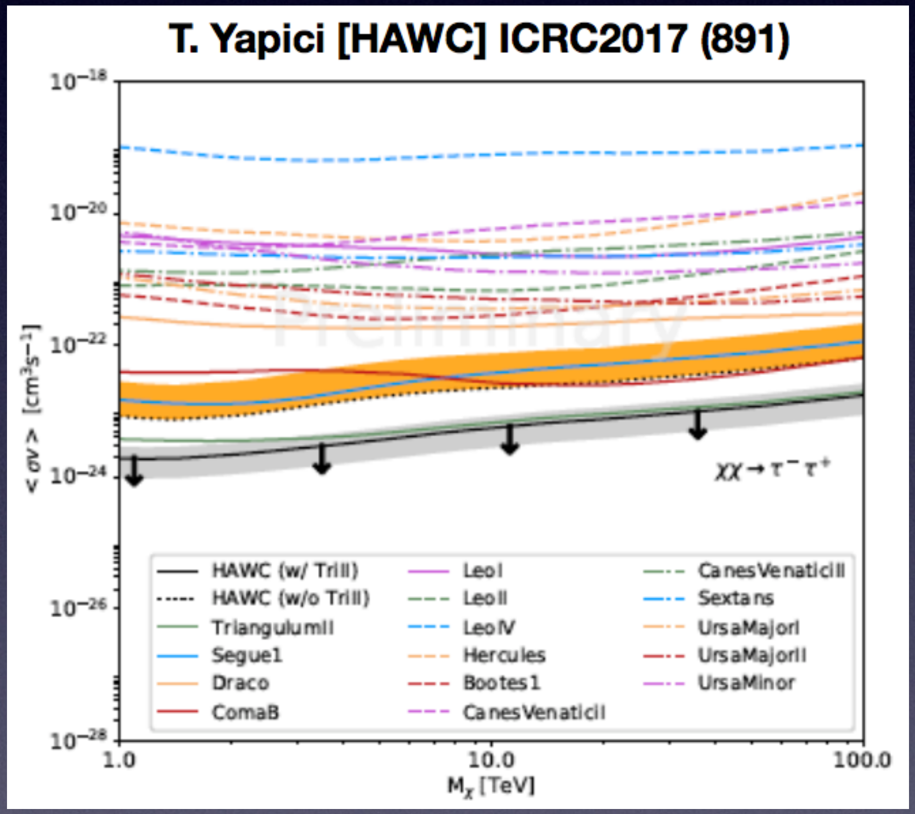
- Geringer-Sameth & Koushiappas 2012, based on seven dwarf galaxies
- See also Profumo et al '16, Liang et al '16

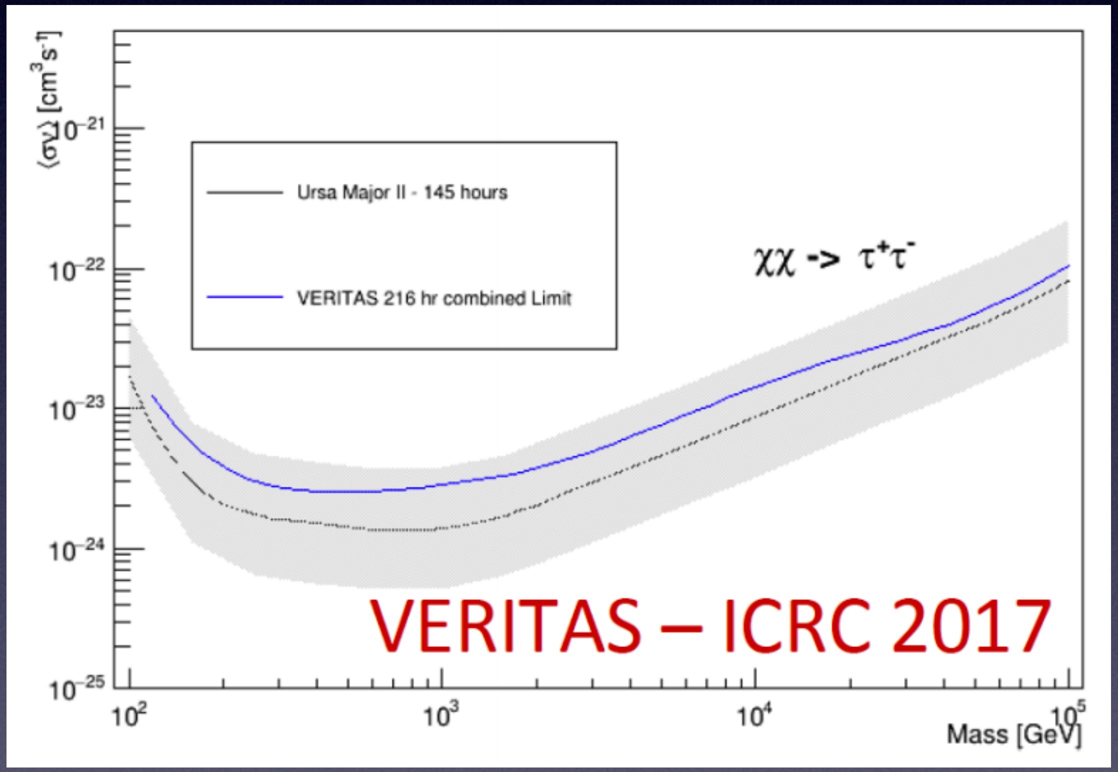
The extragalactic gamma-ray background



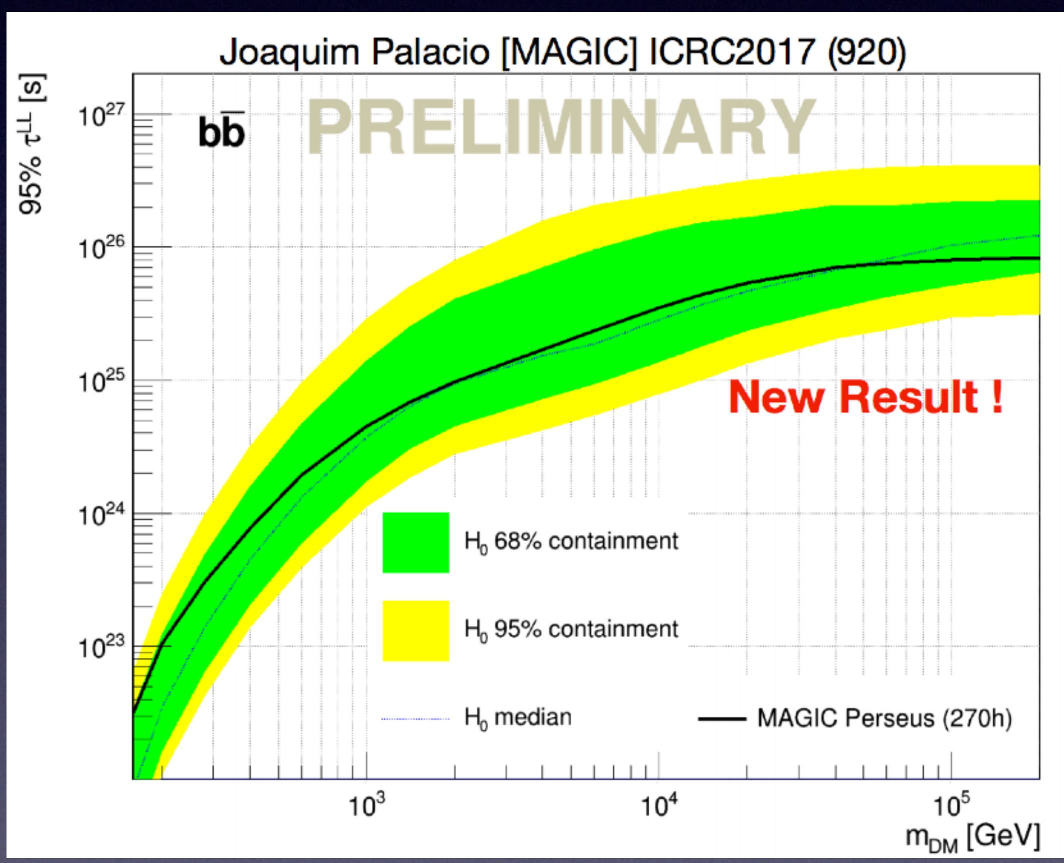
Hannes-S. Zechlin ICRC2017 (922)

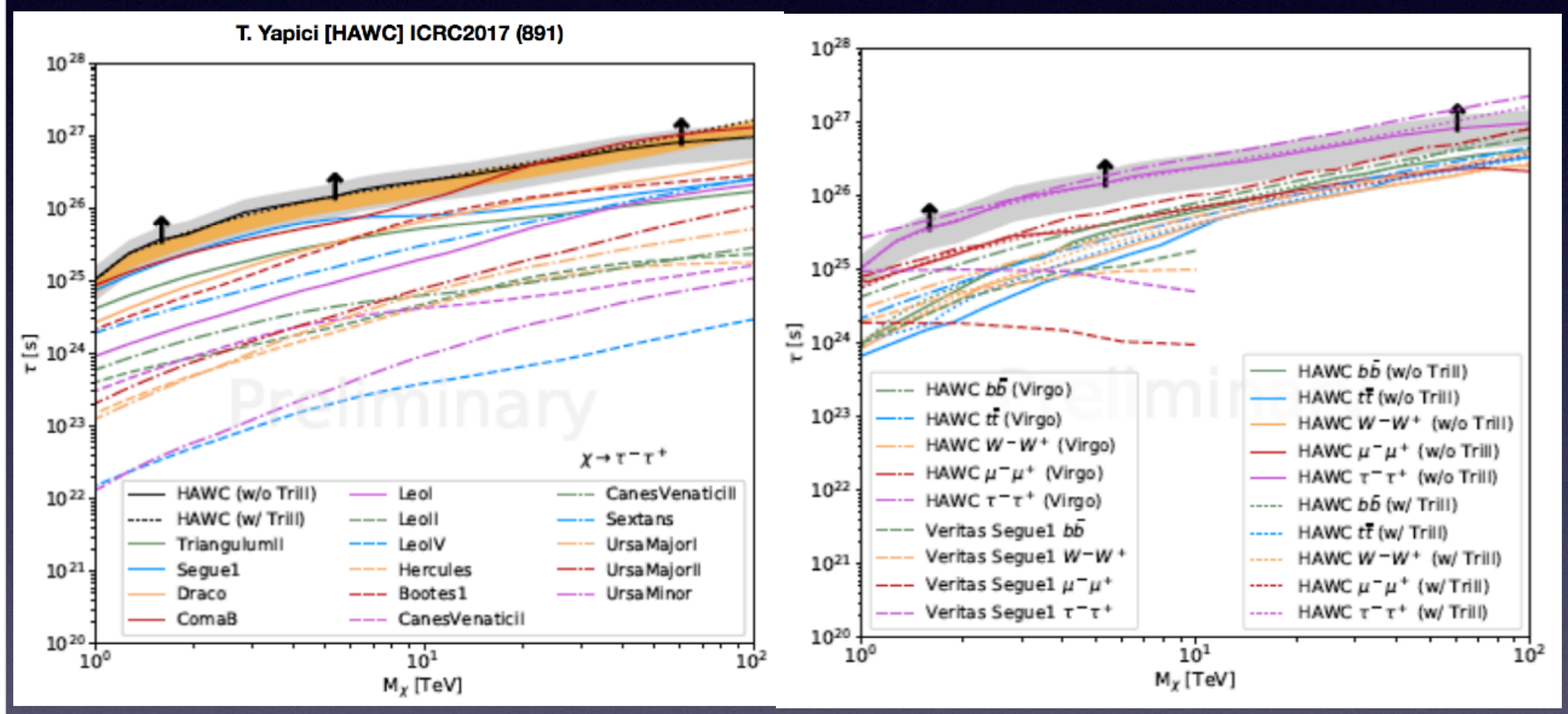
Other dwarf galaxy limits





Additional decay limits





Annihilation and abundance

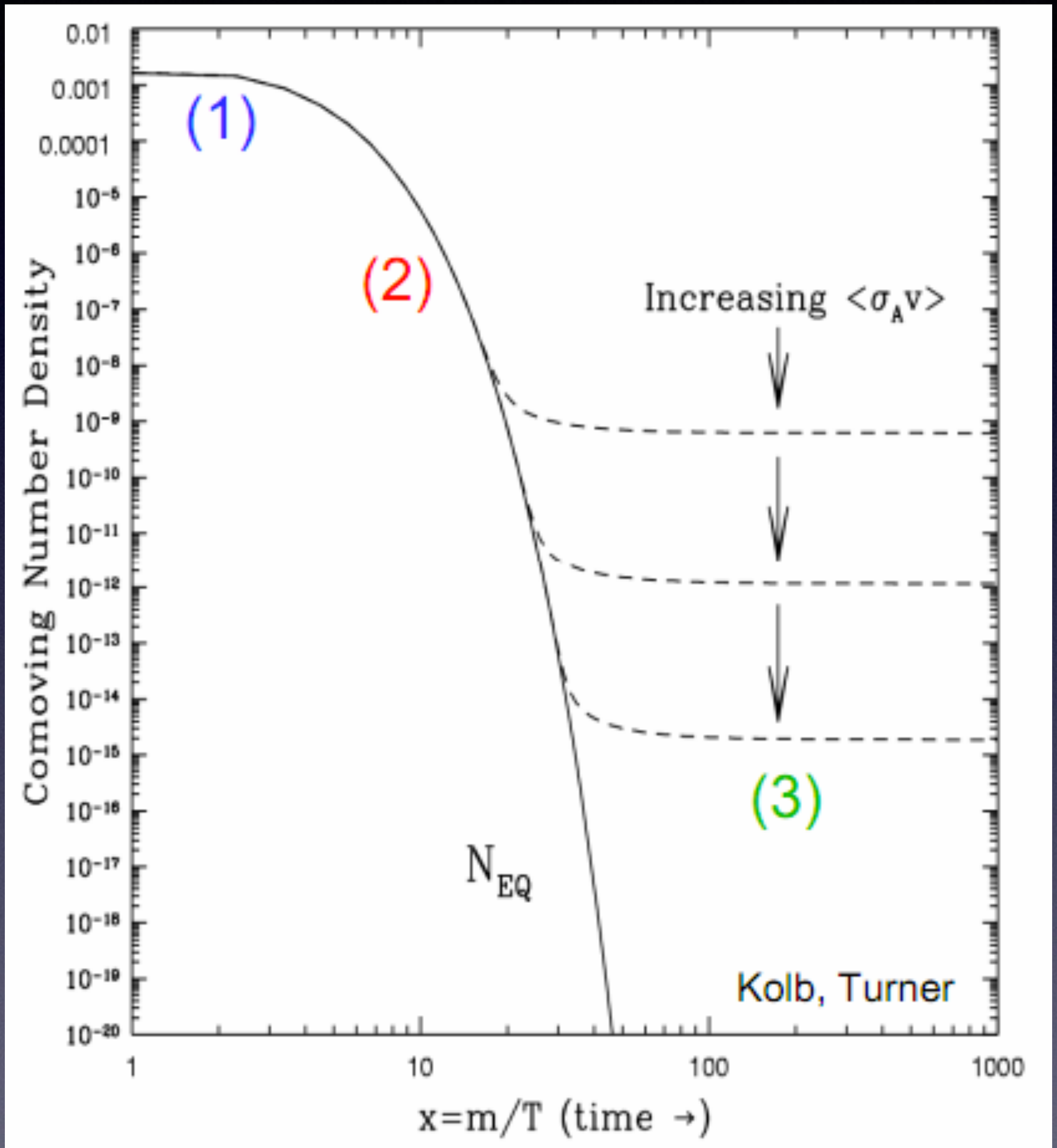
- In the early universe, suppose DM & visible matter (SM) in thermal equlibrium.
- DM can annihilate to SM particles, or SM particles can collide and produce it.

$$\chi\chi \leftrightarrow \mathrm{SM}\,\mathrm{SM} \quad (1)$$

- Temperature(universe) < particle mass => can still annihilate, but can't be produced.

$$\chi\chi \rightarrow \mathrm{SM}\,\mathrm{SM}$$
$$\chi\chi \not\leftarrow \mathrm{SM}\,\mathrm{SM} \quad (2)$$

- Abundance falls exponentially, cut off when timescale for annihilation ~ Hubble time. The *comoving* dark matter density then freezes out.



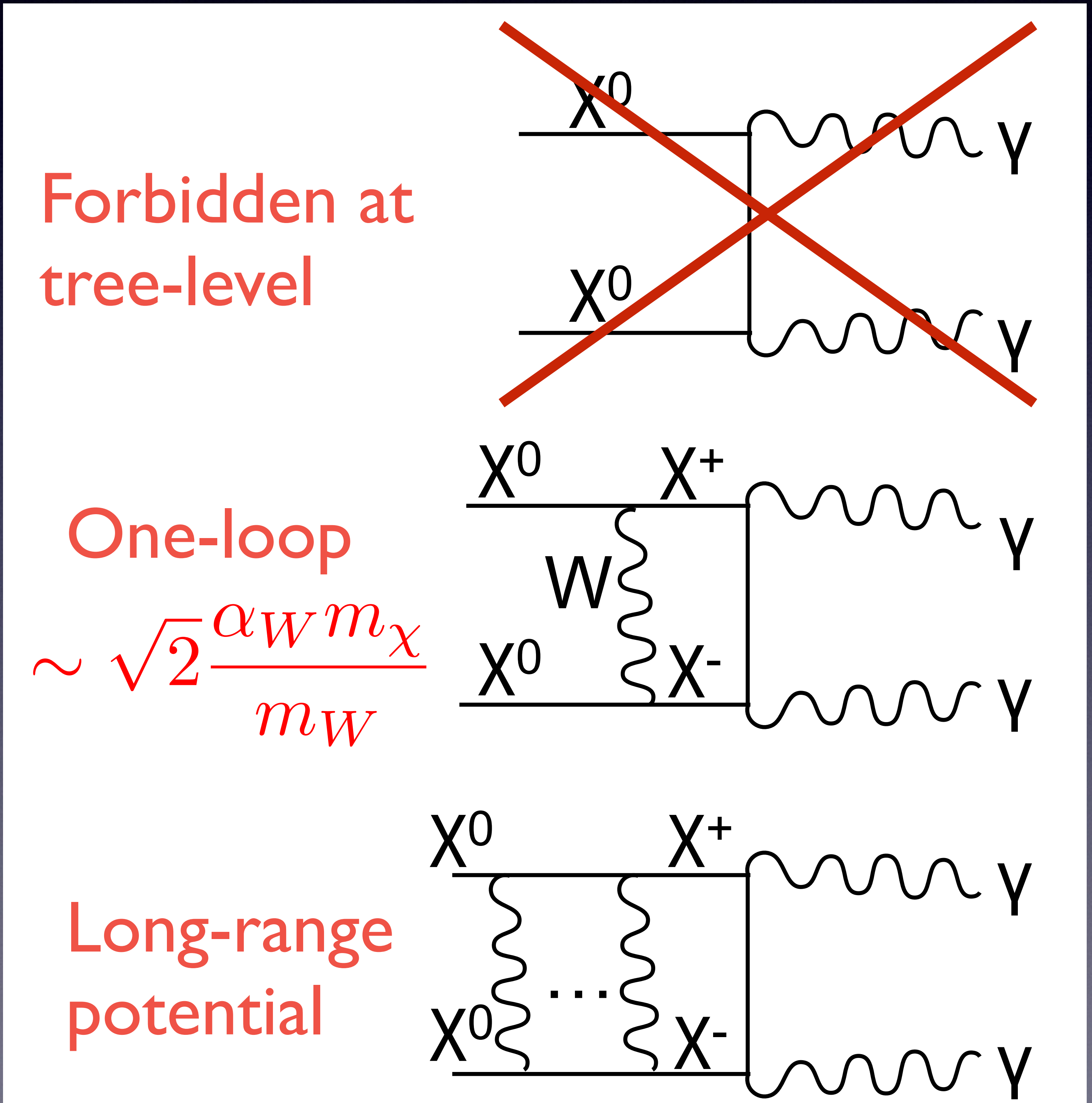
So (known) late-time density is set by annihilation rate.

$$\langle\sigma v\rangle \sim 3\times 10^{-26}\mathrm{cm}^3/\mathrm{s} \sim \pi\alpha^2/(100\,\mathrm{GeV})^2 \quad (3)$$

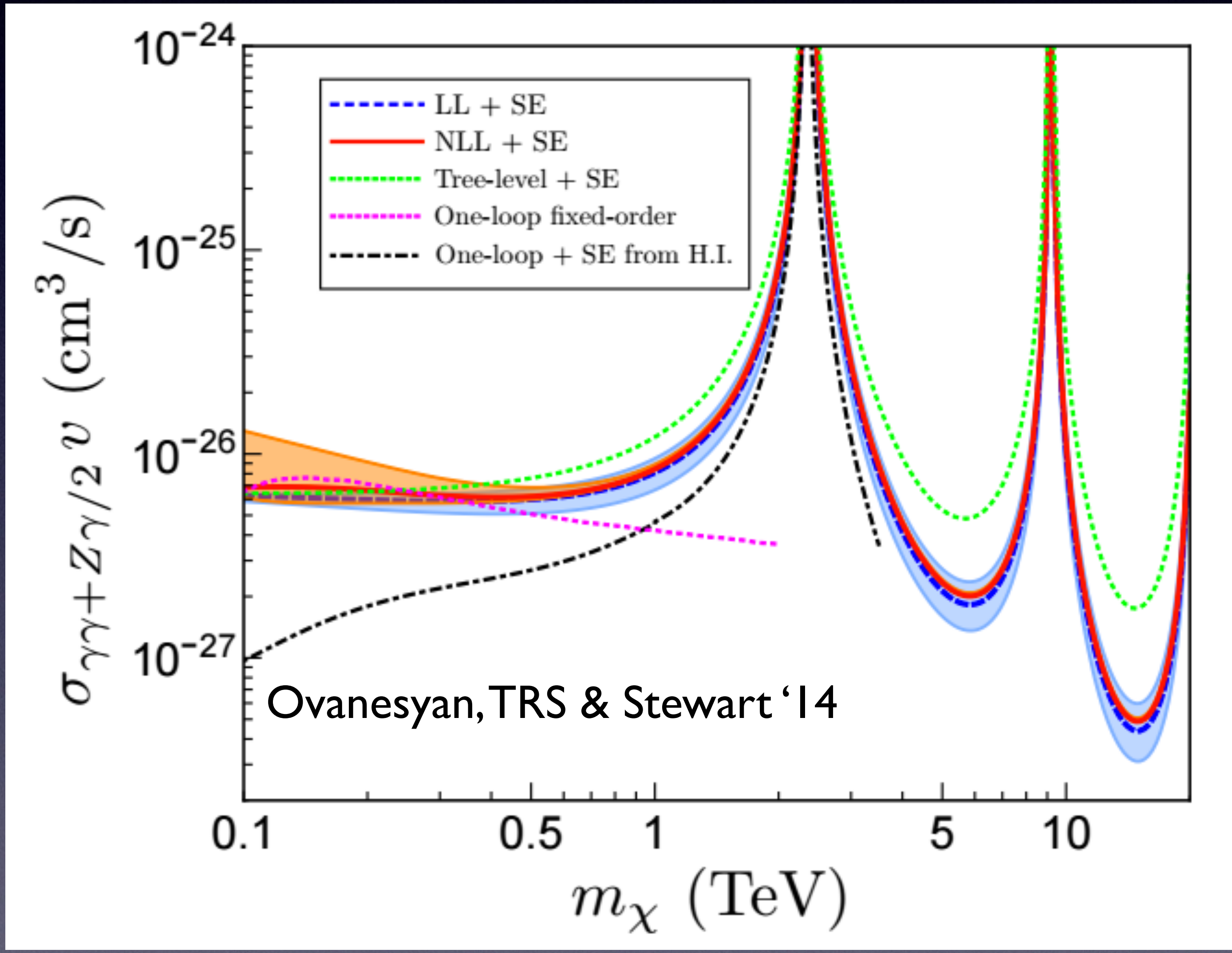
Heavy DM and Sommerfeld enhancement

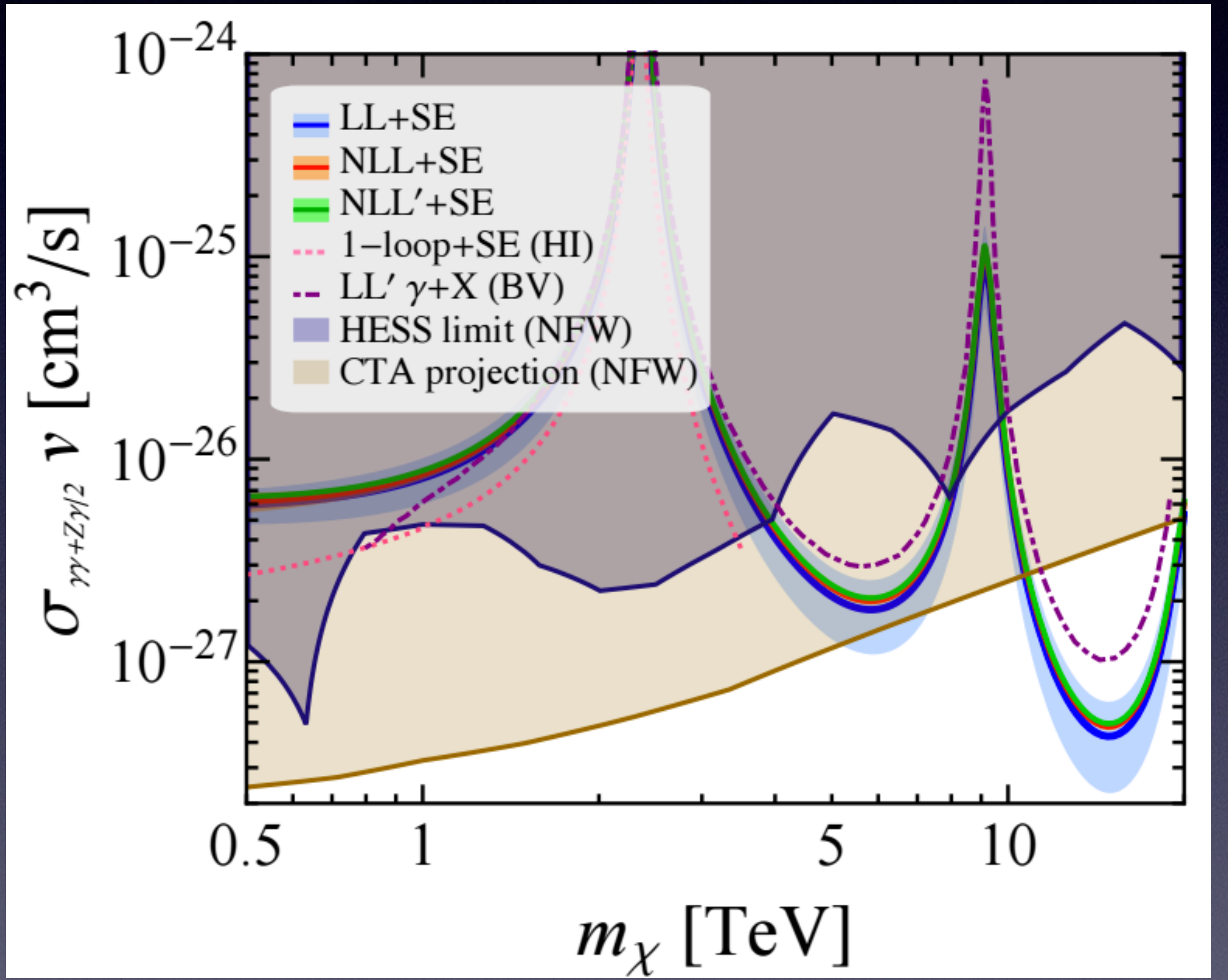
- Heavy dark matter (mass $>m_W/\alpha_W$) coupled to weak gauge bosons generically benefits from "Sommerfeld enhancement" of annihilation signal.
- Coupling to a lighter particle can mediate a long-range attractive force, enhancing annihilation.
- Enhancement can be 1-2 orders of magnitude, or more for line signals (as potential allows leading-order contribution from charged particles annihilating to photons).

Example: wino-like dark matter



Example of line constraints for wino DM



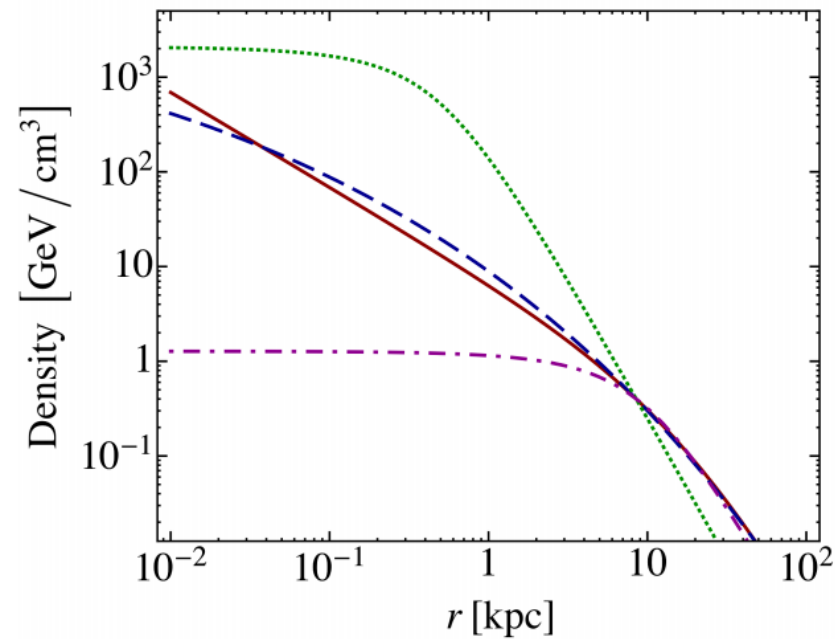


Ovanesyan, TRS, Rodd & Stewart '17

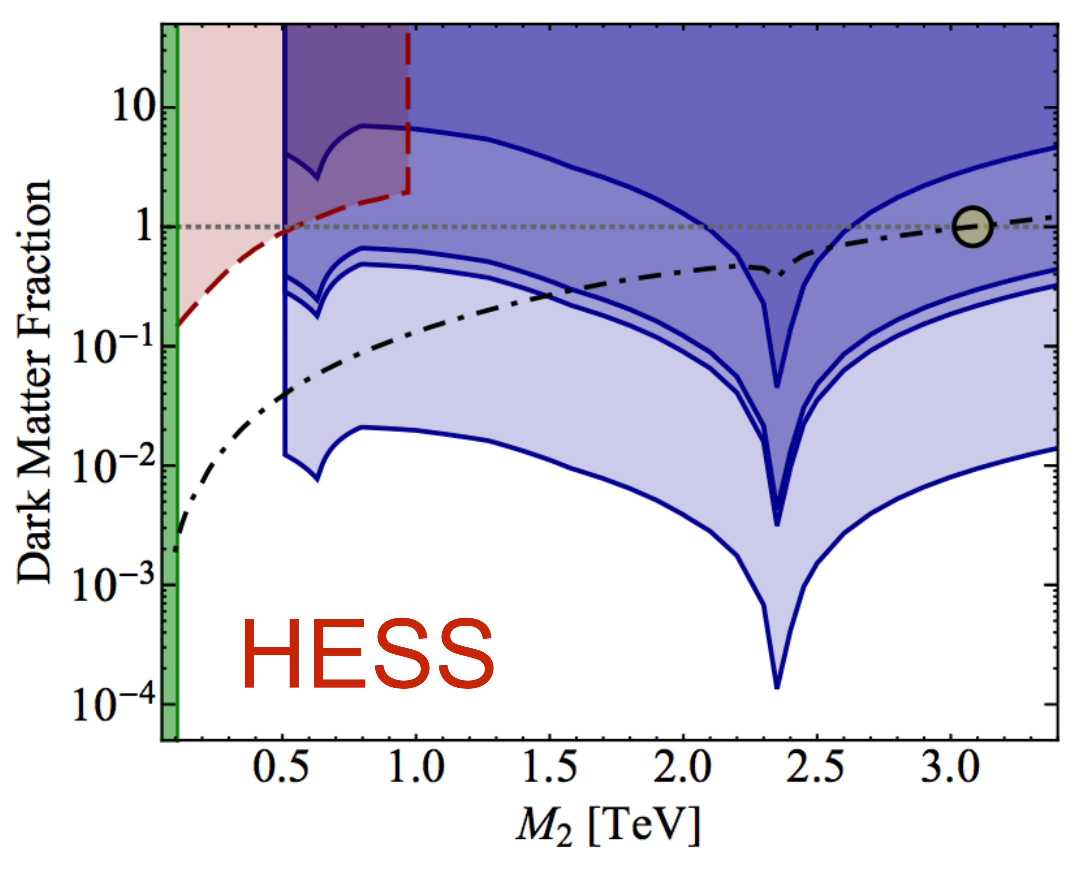
- Theoretical prediction is quite subtle - Sudakov logs + Sommerfeld enhancement (+ bound state effects, but these are small - Asadi et al '17, Braaten et al '17).
- Brown constraint region is projected limit from upcoming CTA experiment.

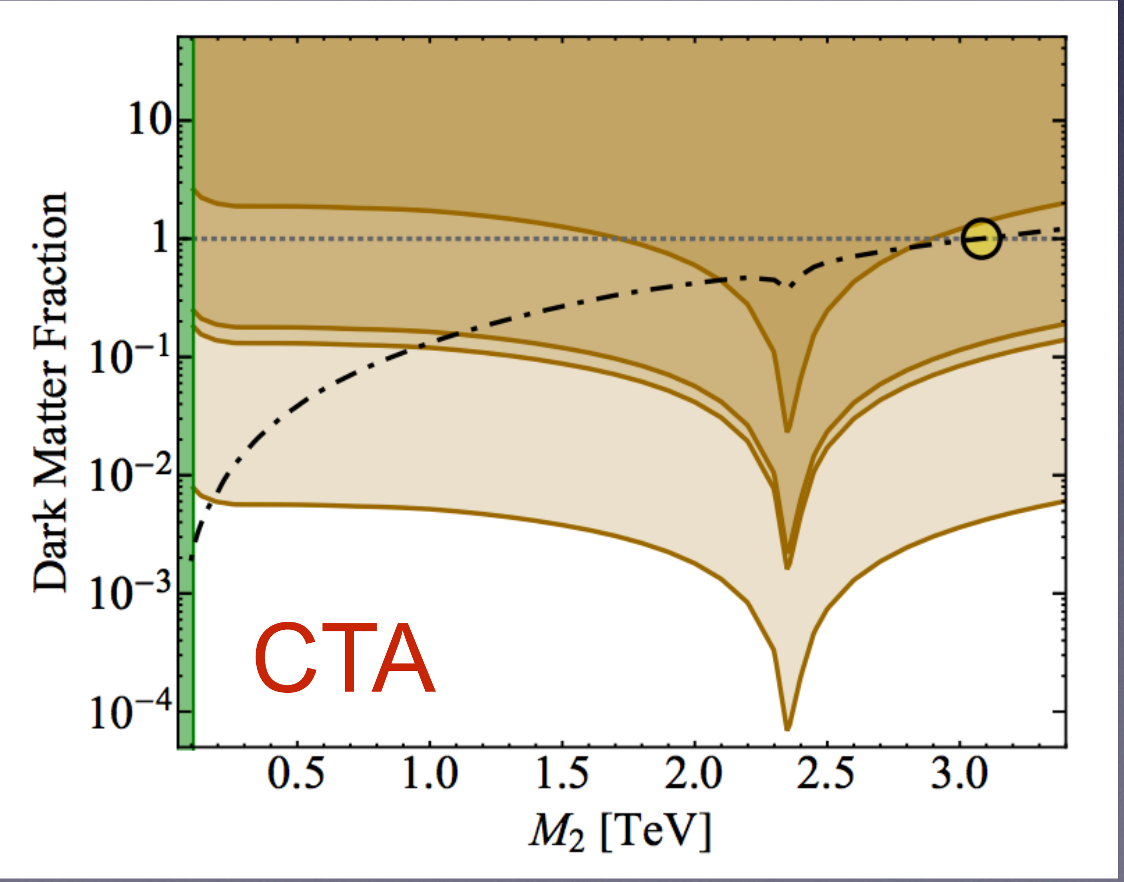
Dependence on the profile

- Large cores in the Milky Way density profile could still allow thermal wino DM.
- Results taken from Cohen, Lisanti, Pierce & TRS '13.



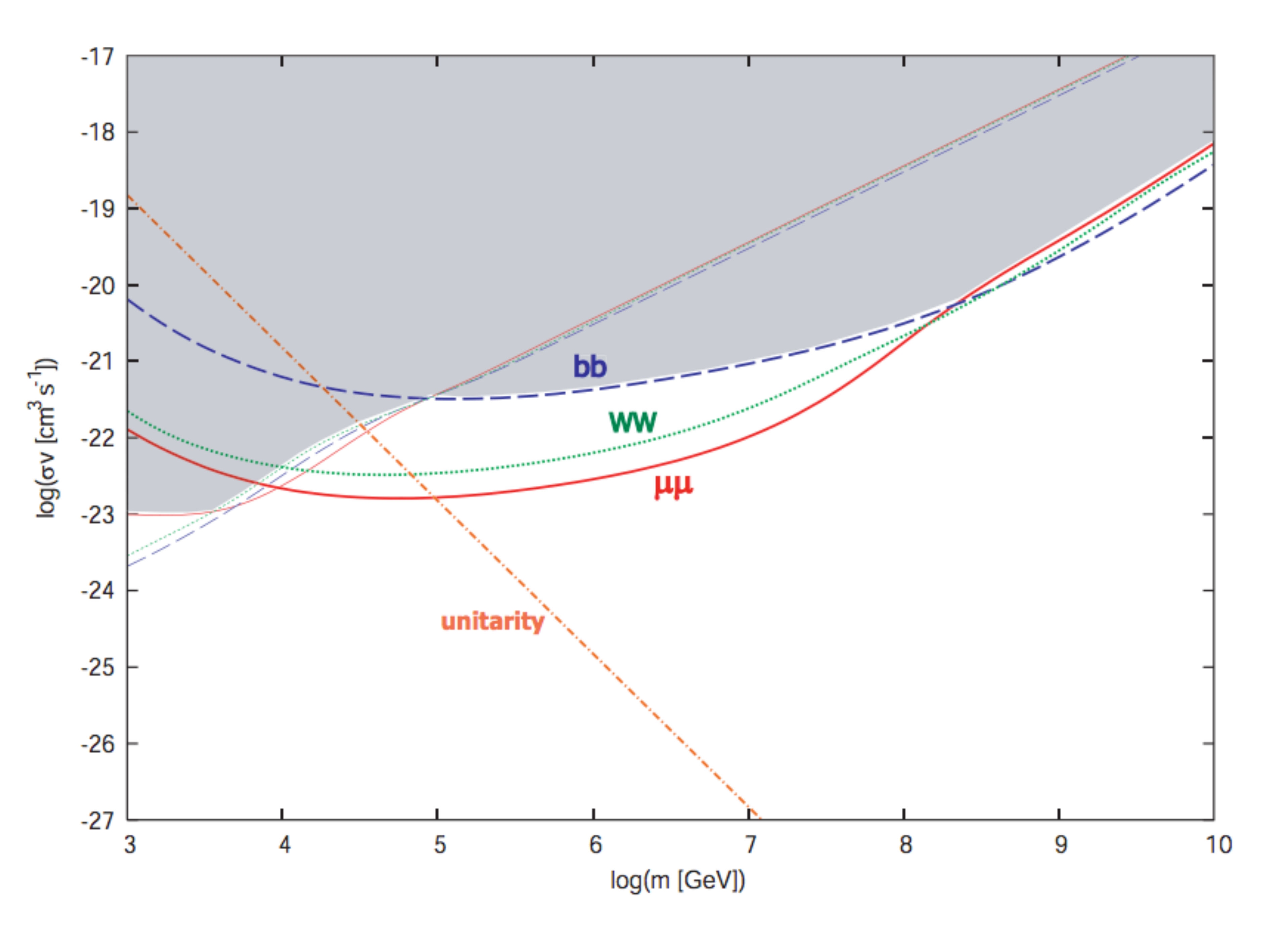
Profile	$J/J_{\rm NFW}$
NFW	1
Einasto	2
Burk(0.5 kpc)	10^3
Burk(10 kpc)	9×10^{-3}





VERY heavy DM annihilation

- Combined neutrino (IceCube) and gamma-ray (Fermi) constraints
- Includes model of DM substructure for extragalactic signal
- Includes modeling of energy losses for gamma rays

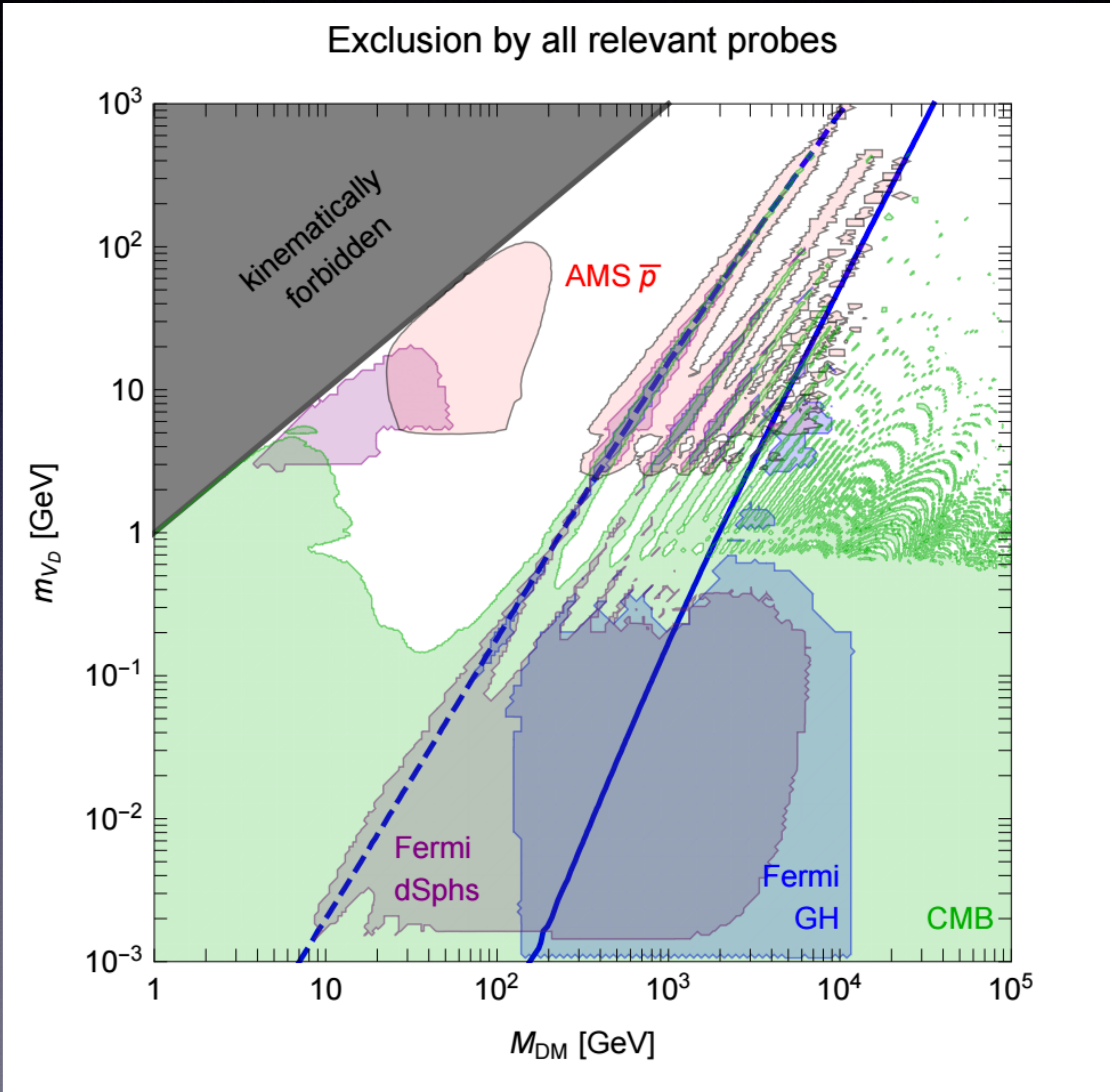


Murase & Beacom '12

CMB constraints on dark photons

Cirelli et al '17

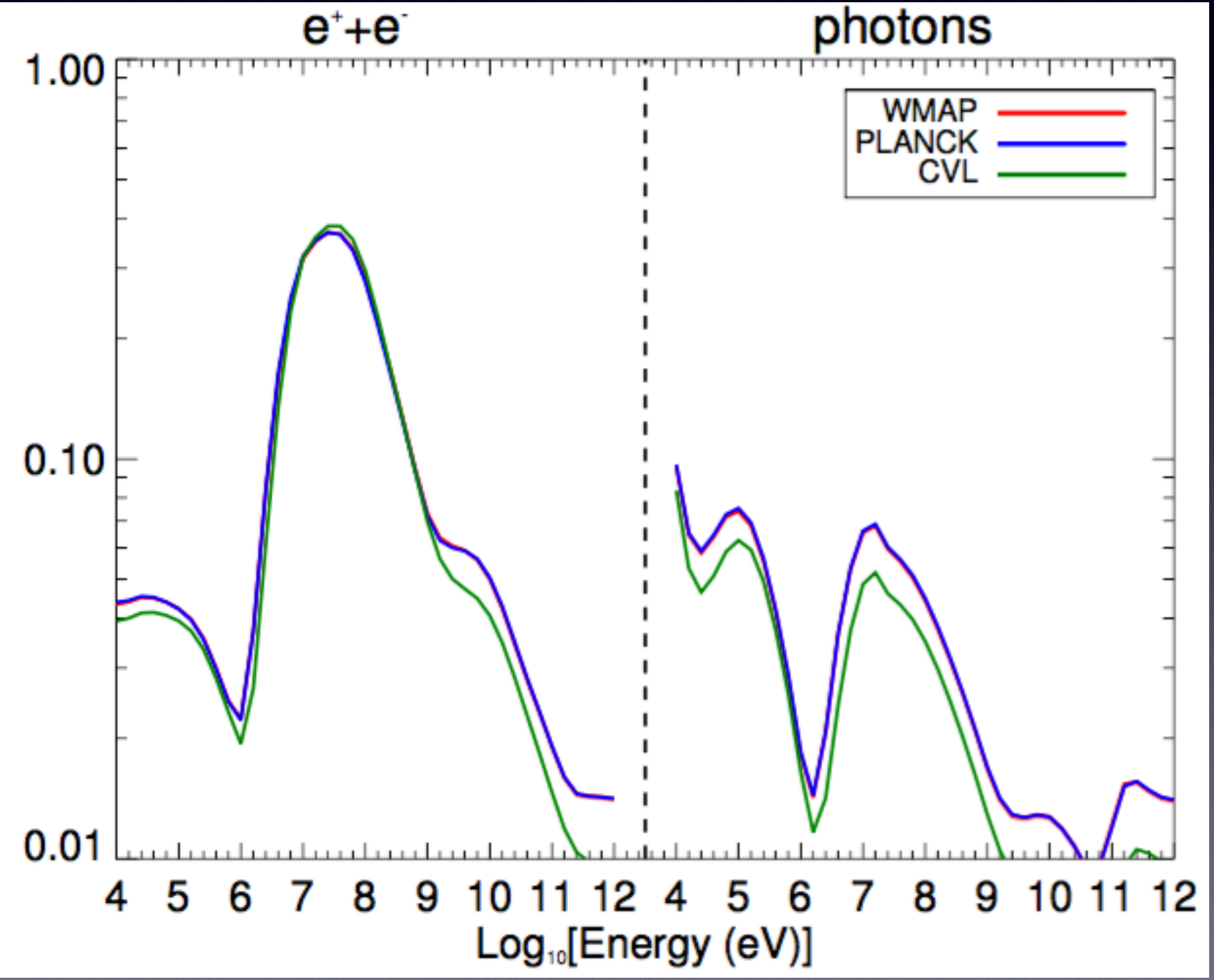
- Model of dark matter coupled to new "dark photons", mediating dark matter self-interaction.
- Green region ruled out by CMB, assuming DM is a thermal relic and main annihilation channel is to dark photons (sets DM-dark photon coupling).



Efficiency factors (decay)

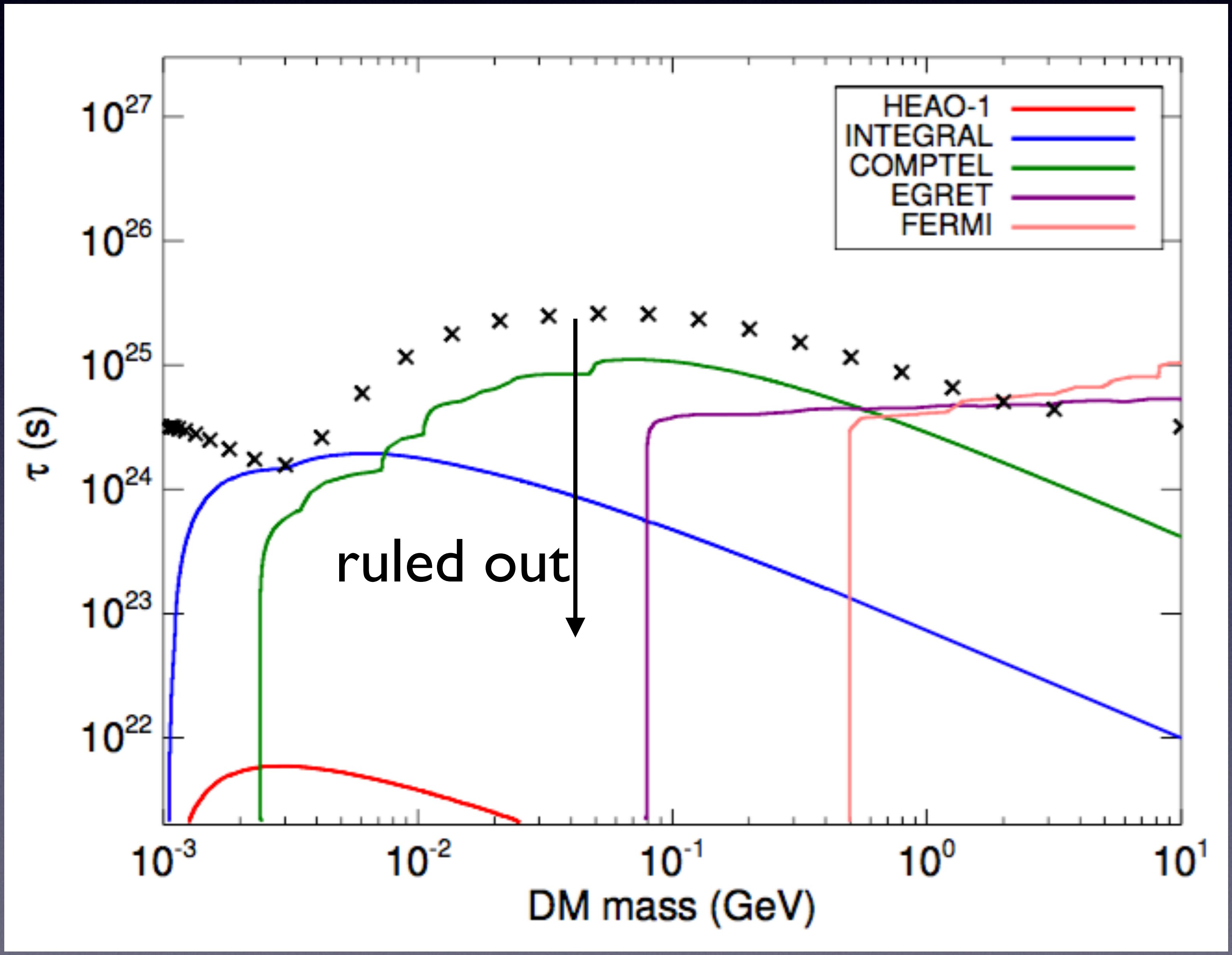
TRS and Wu, PRD95, 023010 (2017)

- Can perform a similar analysis for decaying DM - again find a universal imprint on the CMB
- Can set constraints on DM decaying with a long lifetime, or other species decaying during the cosmic dark ages



Constraints on decay from Planck

- For long-lifetime decays, this method sets competitive limits on relatively light (MeV-GeV) DM decaying to produce electrons and positrons.
- Voyager limits appear to be stronger in the 10 MeV - GeV range, but less robust.



Other constraints from Essig et al JHEP11(2013)193

CMB constraints on short-lifetime decays

- Long-lived particles could decay completely during cosmic dark ages
- Alternatively, decays from a metastable state to the final DM state could liberate some fraction of the DM mass energy
- CMB constrains the amount of power converted to SM particles in this way; width of band reflects variation with energy of SM products

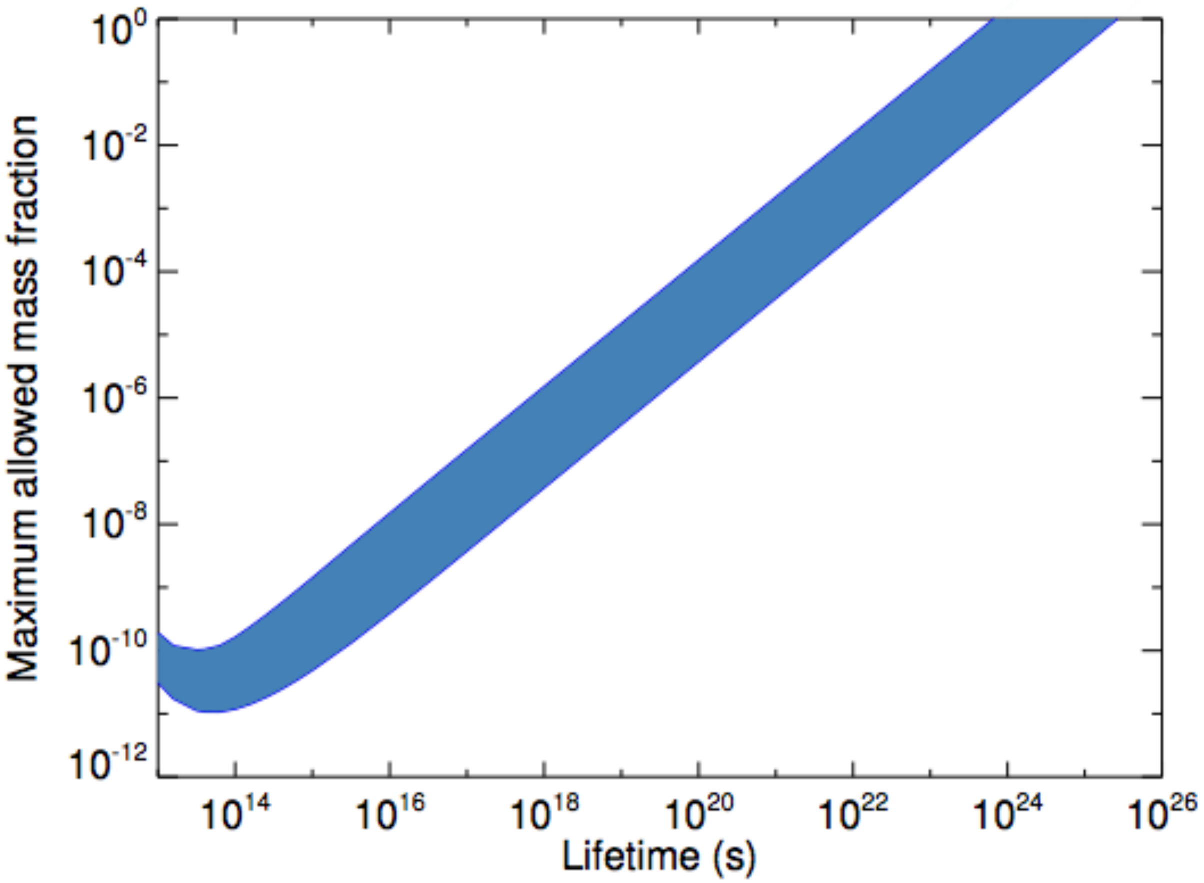


FIG. 11: Range of upper bounds on the mass fraction of DM that can decay with a lifetime τ, for injections of 10 keV – 10 TeV photons and e^+e^- pairs; the width of the band represents a scan over injection species and energy. The constraint is based on the PCA (first PC only) calibrated to the MCMC bound for our reference model.

Recipe for generic DM model

(with decay or s-wave annihilation)

- Given DM mass and couplings, determine spectra of e+e- pairs and photons produced per annihilation:
  $\left(\frac{dN}{dE}\right)_\gamma, \left(\frac{dN}{dE}\right)_{e^+}$
- Determine $f_{\rm eff}$ by average over photon and electron spectra:
  $$f_{\rm eff}(m_\chi) = \frac{\int_0^{m_\chi} E dE \left[2 f_{\rm eff}^{e^+e^-}(E) \left(\frac{dN}{dE}\right)_{e^+} + f_{\rm eff}^{\gamma}(E) \left(\frac{dN}{dE}\right)_\gamma\right]}{2 m_\chi}$$
- For annihilation, impose constraint on annihilation parameter: $f_{\rm eff} \frac{\langle \sigma v \rangle}{m_\chi} < 4.1 \times 10^{-28} \mathrm{cm}^3/\mathrm{s}/\mathrm{GeV}$
- For decay, write $g_{\rm eff} = f_{\rm eff} / f_{\rm eff}(30\ \mathrm{MeV}\ e^+e^-)$, apply constraint on lifetime: $\tau / g_{\rm eff} \gtrsim 2.6 \times 10^{25} s$

CMB constraints

Annihilation/decay injects high-energy particles

↓ Decay with Pythia or similar program

High-energy photons + e^+e^- (others largely escape)

↓ Cooling processes (based on TRS et al 09, interpolation tables now public)

Absorbed energy (ionization+excitation+heating)

↓ Modify public recombination calculator (RECFAST, CosmoRec, HyRec)

Cosmic ionization history

↓ Public CAMB or CLASS code

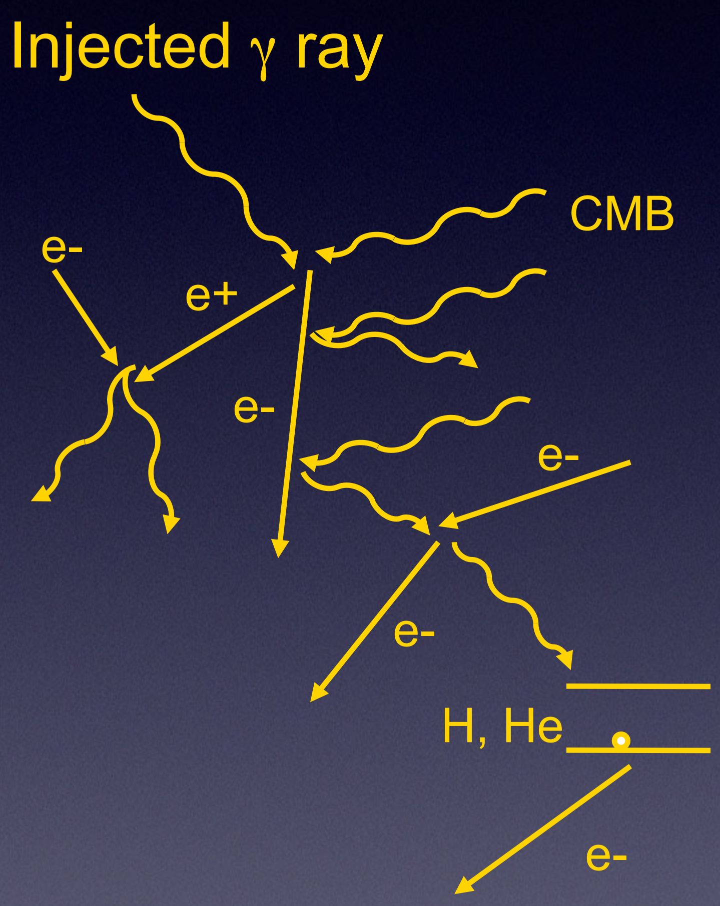
Perturbations to CMB anisotropies

The photon-electron cascade

TRS, Padmanabhan & Finkbeiner, PRD80, 043526 (2009)

ELECTRONS

- Inverse Compton scattering on the CMB.
- Excitation, ionization, heating of electron/H/He gas.
- Positronium capture and annihilation.
- All processes fast relative to Hubble time: bulk of energy goes into photons via ICS.

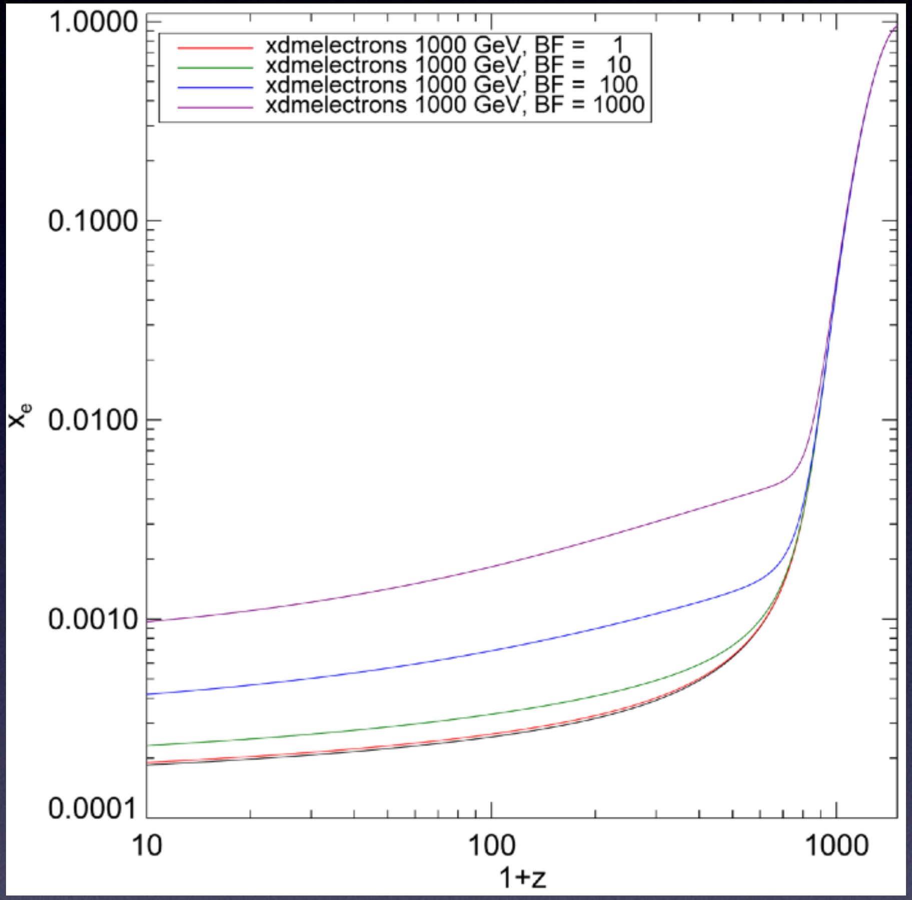


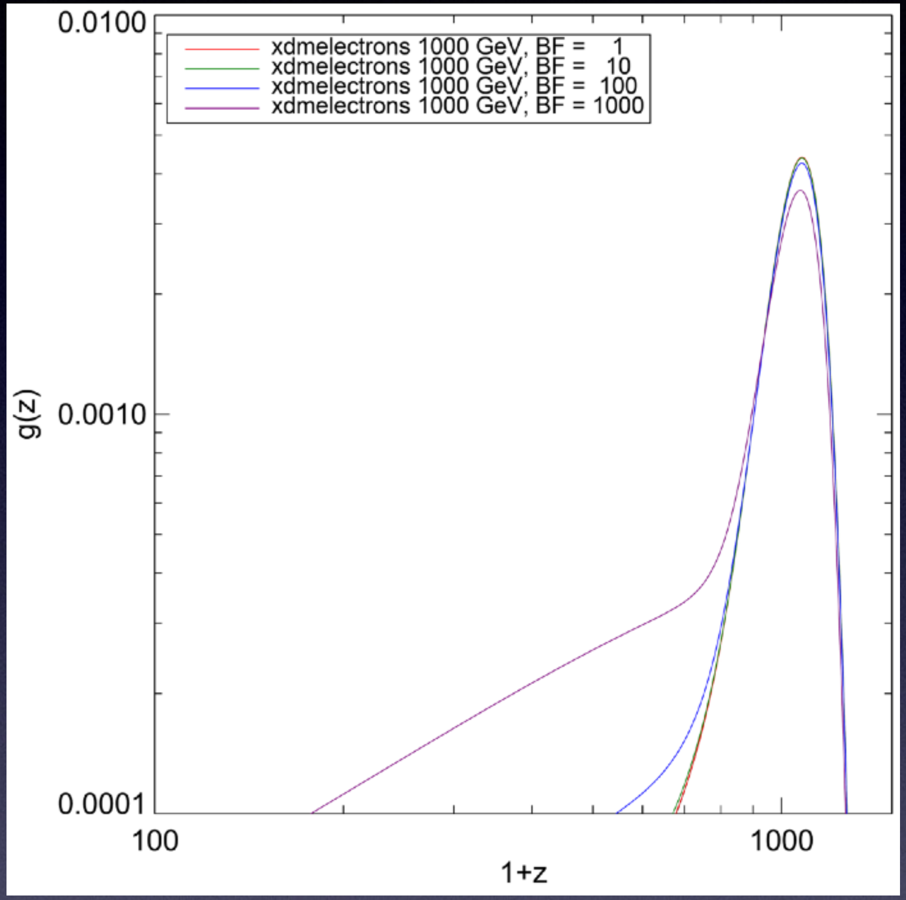
Schematic of a typical cascade:
initial γ-ray
-> pair production
-> ICS producing a new γ
-> inelastic Compton scattering
-> photoionization

PHOTONS

- Pair production on the CMB.
- Photon-photon scattering.
- Pair production on the H/He gas.
- Compton scattering.
- Photoionization.
- Redshifting is important, energy can be deposited long after it was injected.

Example ionization history

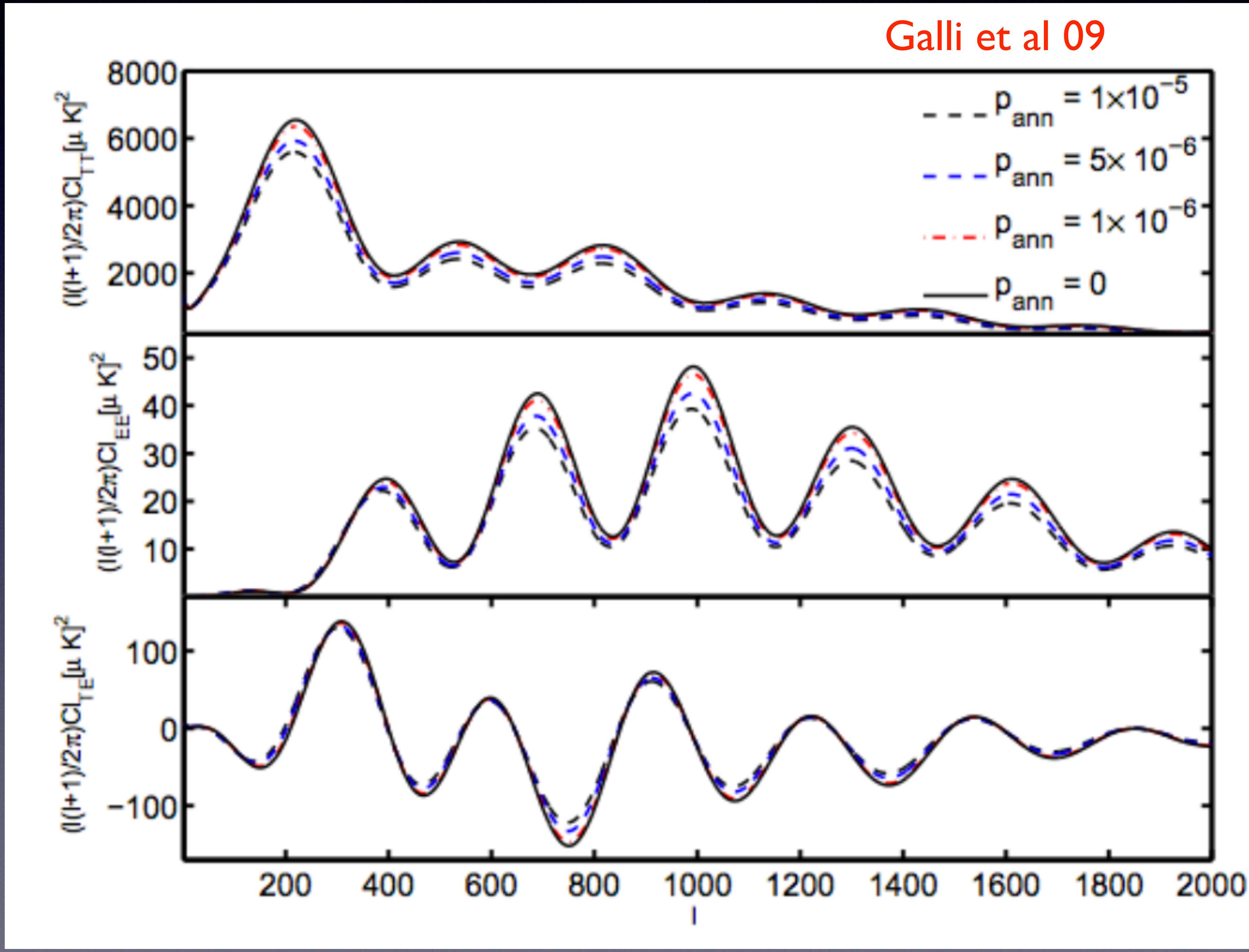




- Example DM model, 1 TeV DM annihilating to electrons.
- Use public codes RECFAST (Seager, Sasselov & Scott 1999) / CosmoRec (Chluba & Thomas 2010) / HyRec (Ali-Haimoud & Hirata 2010) to solve for ionization history.
- At redshifts before recombination, many free electrons => the extra energy injection has little effect.
- After recombination, secondary ionization induced by DM annihilation products => higher-than-usual residual free electron fraction.
- Surface of last scattering develops a tail extending to lower redshift.

DM annihilation & the CMB

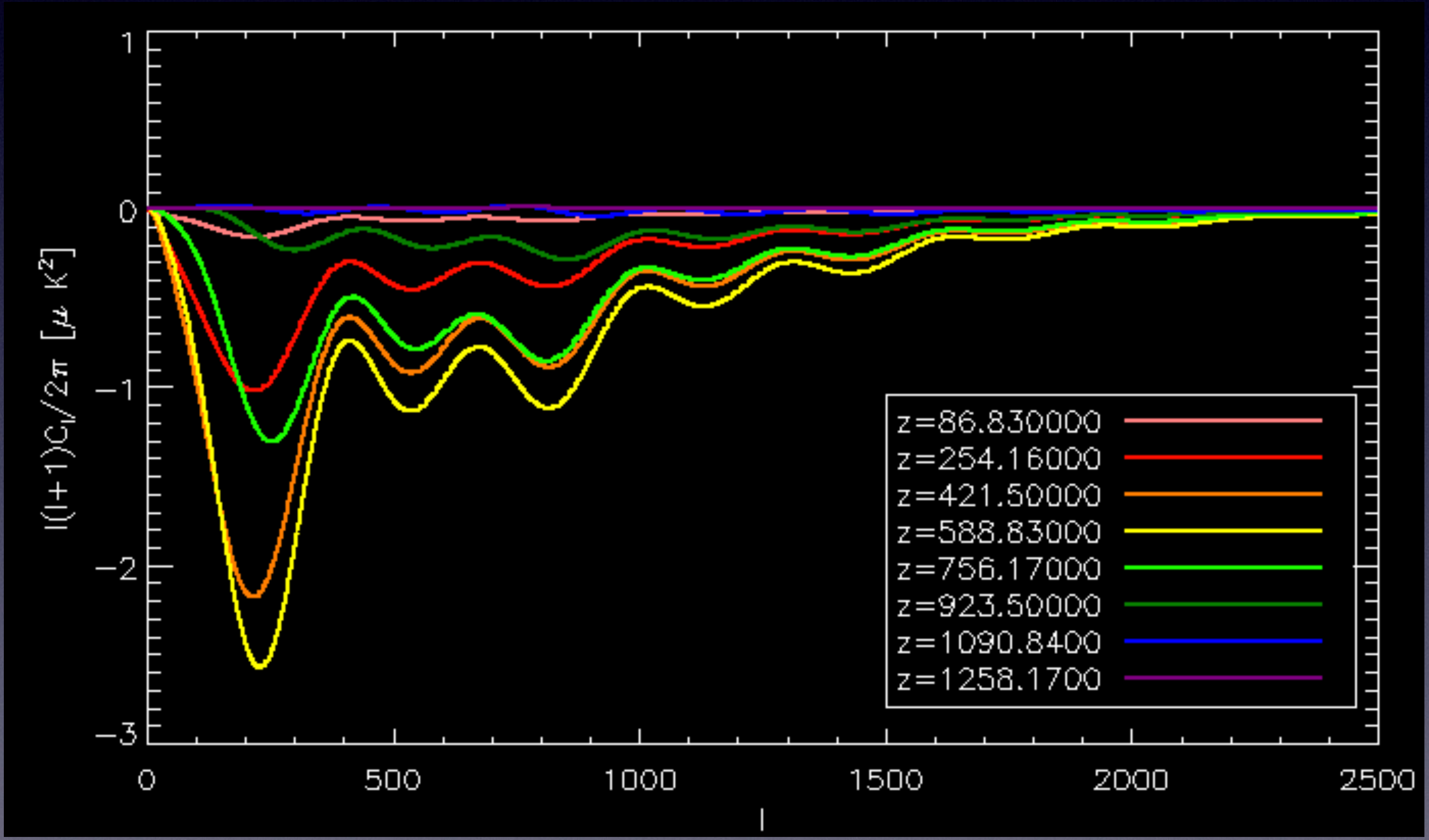
- Extra ionization from DM annihilation would suppress & distort temperature and polarization anisotropies in the CMB
- Consider large range of different DM annihilation products. Demonstrated in TRS '15 that effect on CMB is <u>universal</u> (for keV-TeV-energy annihilation products).



The range of CMB signals

Finkbeiner, Galli, Lin & TRS, PRD85, 043522 (2012)

- Consider energy absorption sharply peaked around a particular redshift, study its imprint in the CMB.
- Can be used to construct any arbitrary energy deposition history.



Note: results shown here assume a simple partition into excitation/ionization/heating. Since the signal is driven almost entirely by ionization, errors in the ionization prescription can be absorbed as differences in the energy absorption history.

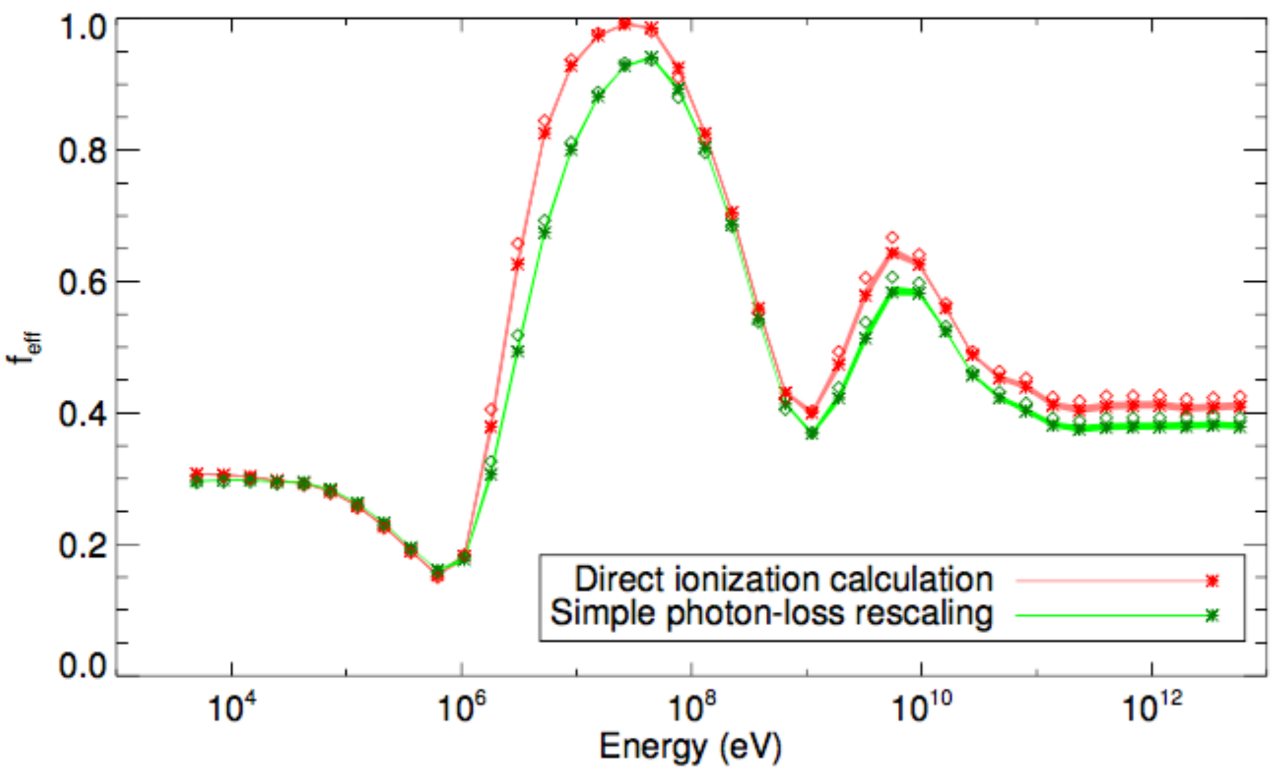
Principal component analysis

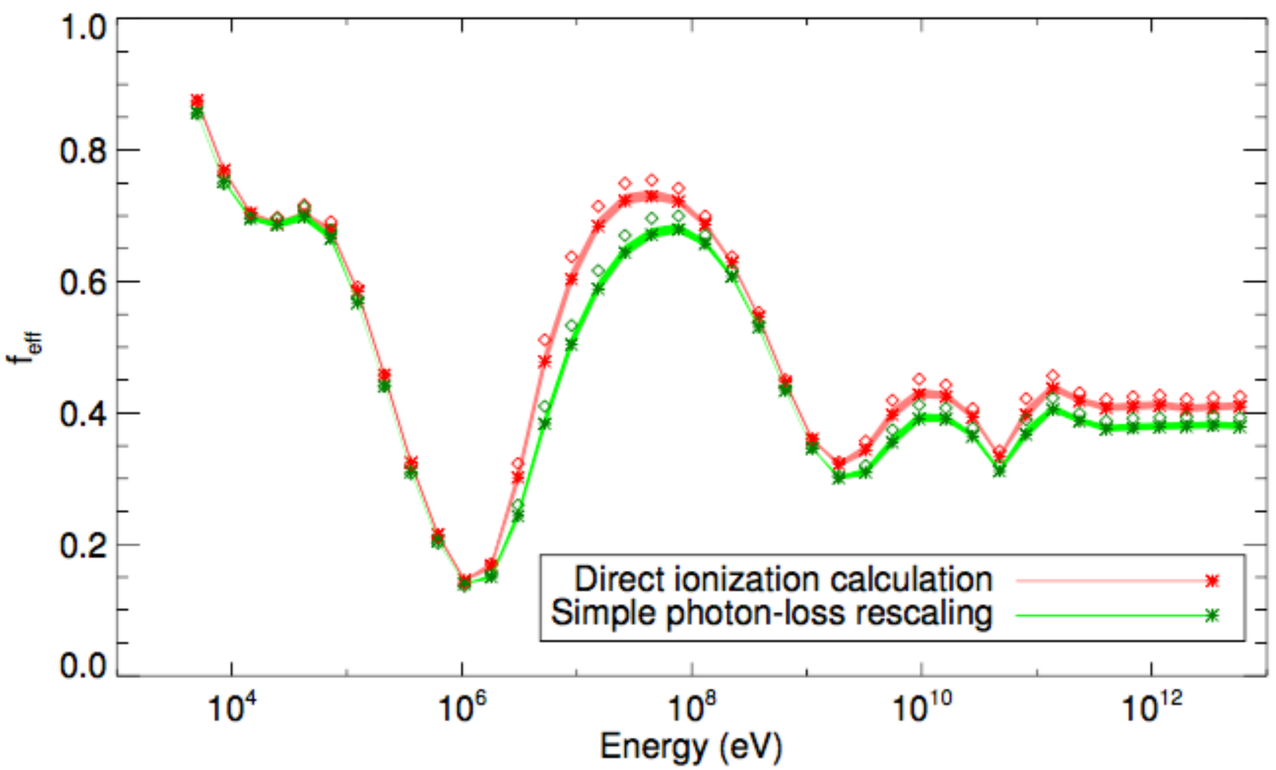
- Consider space of CMB signals produced by annihilation-like or decay-like injections of particles at a given energy
- Estimate detectability, covariances using Fisher matrix method - approximates likelihood as Gaussian
- Diagonalize Fisher matrix (describing detectability) to obtain eigenvectors: orthogonal basis of perturbations to the CMB, ranked by eigenvalue/detectability
- For DM annihilation, first eigenvector explains more than 99% of variance: space of CMB perturbations is ~1-dimensional

$$\Sigma_\ell = \frac{2}{2\ell+1} \times \begin{pmatrix} \left(C_\ell^{TT}\right)^2 & \left(C_\ell^{TE}\right)^2 & C_\ell^{TT} C_\ell^{TE} \\ \left(C_\ell^{TE}\right)^2 & \left(C_\ell^{EE}\right)^2 & C_\ell^{EE} C_\ell^{TE} \\ C_\ell^{TT} C_\ell^{TE} & C_\ell^{EE} C_\ell^{TE} & \left[\left(C_\ell^{TE}\right)^2 + C_\ell^{TT} C_\ell^{EE}\right] \end{pmatrix}$$

$$(F_e)_{ij} = \sum_\ell \left(\frac{\partial C_\ell}{\partial \alpha_i}\right)^T \cdot \Sigma_\ell^{-1} \cdot \frac{\partial C_\ell}{\partial \alpha_j}.$$

Energy-dependent efficiency factor





- Accordingly, every DM annihilation model has same imprint on the CMB, up to a normalization factor - each model is characterized by one number (determined roughly by absorption efficiency at z~600; principal component analysis can give precise weighting function). Available at http://nebel.rc.fas.harvard.edu/epsilon/
- Results for arbitrary spectra can be determined by taking linear combinations of these results.