# DM annihilation in the early universe

How does cosmological DM annihilation scale with time?

$n \propto a^{-3}$

Annihilations ~~per~~ in a comoving volume ~~per~~ in a Hubble time

$$= \cancel{\propto} \; \frac{n^2 \langle \sigma v \rangle}{2} \times V_{\text{comoving}} \times H^{-1}$$

$$\propto \; a^{-6} \langle \sigma v \rangle a^3 H^{-1}$$

During radiation domination, $H^2 \propto \rho \propto a^{-4} \Rightarrow H \propto a^{-2}$

$\propto a^{-1}$

During matter domination, $H^2 \propto \rho \propto a^{-3} \Rightarrow H \propto a^{-1.5}$

$\propto a^{-1.5}$

During DE domination, H = constant, anns/comoving V /Hubble time $\propto a^{-3}$.

At freezeout, by definition a DM particle annihilates on average ~once/Hubble time

i.e O(1) fraction of DM annihilates in a Hubble time

~~eg~~ Consider e.g BBN. T ~ 1 MeV, still in radiation-dominated epoch.

Suppose we have ~100 GeV thermal relic DM. Freezeout at ~5 GeV,

⇒ a scales by a factor of $\sim 5 \times 10^3$, so ~~one~~ ~1 in ~~$10^3$~~ $5 \times 10^3$ DM particles now annihilates in a Hubble time. $O(10^{-3})$ energy in baryons is liberated. Potential to affect subdominant nuclear abundances, e.g $^6\text{Li}/\text{H} \sim O(10^{-12})$

see Jedamzik & Pospelov 0906.2087

CMB: $T \sim 1$ eV, (shortly) after matter-radiation equality

Using same estimate, $O(10^{-10})$ of DM particles would annihilate in a Hubble time, for 100 GeV DM. But $10^{-10}$ of DM mass density $\approx 5 \times 10^{-10}$ baryon mass density.

Hydrogen ionization energy $= 10^{-8}$ hydrogen mass.

But 100 GeV DM $\Rightarrow O(20)$ baryons per DM particle $\Rightarrow$ enough energy to ionize ~ 5% of hydrogen?

Each annihilation liberates ~200 GeV energy $\sim 2 \times 10^{10} \times \underset{\sim H \text{ ionization energy}}{(10\,\text{eV})}$

$\Rightarrow$ ionize ~ 10% of H per Hubble time?

This would be very visible, after recombination – extra electrons screen CMB, CMB anisotropies sensitive to changes of just a few $\times 10^{-4}$ to ionization fraction.

(Better calculation: include temperature changes due to entropy dumps, changes in degrees of freedom. But still turns out to be an interesting effect!)

Today: $\sim \dfrac{\text{Rate}}{dV_{\text{comov}}\, dt_H}$ drops by ~9 o.o.m from freezeout to matter-radiation equality, ~6 o.o.m from MRE to now → ~15 o.o.m total. Only one in $10^{15}$ particles annihilates in smooth DM – but today we have galaxies etc, much higher density (e.g. at Earth ~[illegible]$\times 10^{5}$ critical density)

What fraction of DM near us has annihilated?

Chance of annihilating /time

$= n \langle \sigma v \rangle_{3 \times 10^{-26}\,\text{cm}^3/\text{s}}$

$= \left(\dfrac{0.4\,\text{GeV}}{m_\chi}\right) \dfrac{3 \times 10^{-26}\,\text{cm}^3/\text{s}}{\text{cm}^3}$

$\approx 10^{-26} \left(\dfrac{m_\chi}{\text{GeV}}\right)^{-1} /\text{s}$

Lifetime of universe $\sim \pi \times 10^{17}$ s

For 100 GeV DM

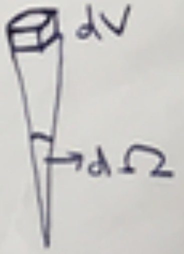
1 in $10^{[illegible]}$ annihilates

# J-factors

Photons & neutrinos travel to us in straight lines

In general we have only 2D ~~inform~~ view of the sky (some exceptions where we have redshift info, etc)

Photons/neutrinos ~~from solid angle $d\Omega$~~ arriving at telescope (area A) from DM annihilation/decay in volume $dV = r^2 dr\, d\Omega$, $r$ = distance between dV & telescope



$$\frac{dN_\gamma}{dV} = \frac{A}{4\pi r^2}(n_\gamma) \text{ per annihilation/decay} \times \# \text{ of annihilations/decays per unit volume}$$

↓ fraction of photons/neutrinos received

$$= \frac{A}{4\pi r^2}(N_\gamma)_{\text{per ann}} \times \frac{1}{2}\langle\sigma v\rangle n_{DM}^2\, dt$$

$$\frac{dN_\gamma}{dt\, d\Omega} = \frac{A}{4\pi r^2} r^2 dr \times \frac{1}{2}\langle\sigma v\rangle n_{DM}^2 (N_\gamma)_{\text{per ann}}$$

$$= \frac{A}{8\pi}\underbrace{\langle\sigma v\rangle (N_\gamma)_{\text{per ann}} \frac{1}{m_\chi^2}}_{\text{particle physics}} \underbrace{\int \rho_{DM}^2(\vec{r})\, dr}_{\text{astrophysics}}$$

~ separation assumes $\langle\sigma v\rangle$ is constant – else include in integral, & result depends on velocity distribution

Likewise for decay:

$$\frac{dN_\gamma}{dt\, d\Omega} = \frac{A}{4\pi r^2} \times r^2 dr \times (N_\gamma)_{\text{per dec}} \times \frac{n_{DM}}{\tau}$$

$$= \frac{A}{4\pi}\frac{(N_\gamma)_{\text{per dec}}}{m_\chi \tau}\int \rho_{DM}(\vec{r})\, dr$$

For localized objects (e.g dwarf galaxies, clusters), total photons/neutrinos are

$$\frac{dN_\gamma}{dt.A} = \frac{\langle\sigma v\rangle}{m_\chi^2}(N_\gamma)_{\text{per ann}} \times \underbrace{\frac{1}{8\pi}\iint_{\substack{\text{area}\\ \text{of object}\\ \text{on sky}}}\!\!\int_0^\infty \rho^2_{DM}(\vec{r})\, dr\, d\Omega}_{J_{ann} \;=\; \text{“J- factor”}}$$

e.g for spherically symmetric object,

let $d$ = distance from observer to center of object

$r$~~ℓ~~ = distance from observer to annihilation point

~~θ, φ angles describe angle between~~

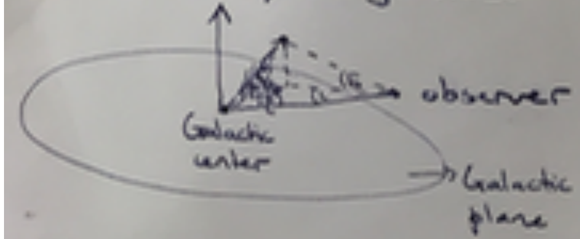
Use spherical polar coords centered on observer, z-axis points to center of object

Then $\rho_{DM}$ depends only on

distance from DM ~~to~~ annihilation point to center of object, ~~z~~

$$\ell = \sqrt{r^2+d^2-2dr\cos\theta}$$

Frequently used Galactic coordinate system



$$\cos\theta = \cos \ell \, \cos b$$

On sky:

$$\frac{dN_\gamma}{dt\,d\Omega\,dA} = \frac{\langle\sigma v\rangle}{m_\chi^2}(n_\gamma \text{ per annihilation}) \times \frac{1}{8\pi}\int \rho(\vec{r})^2 dr, \quad \frac{dN_\gamma}{dt\,dA} = \frac{\langle\sigma v\rangle}{m_\chi^2}(n_\gamma \text{ per ann}) \times \frac{1}{8\pi}\int d\Omega\, dr\, \rho(\vec{r})^2$$

Particle physics piece: replace $N_{\gamma,\nu}$ with $\frac{dN_{\gamma,\nu}}{dE}$ - we often can measure spectrum, not just counts

Ann. $\quad \frac{\langle\sigma v\rangle \frac{dN_{\gamma,\nu}}{dE}}{m_\chi^2}$

Dec $\quad \frac{\frac{dN_{\gamma,\nu}}{dE}}{m_\chi \tau}$

For ~~photo~~ neutrinos, & gamma-rays from our galaxy, spectrum propagates to us ~undistorted

From more distant targets, must consider redshifting, & possibly absorption

For example, consider contribution from smooth, isotropic DM background, accounting only for redshifting

$$\frac{dN_{\gamma,\nu}}{dE\,dV_0} = \int_0^\infty dz \underbrace{\left(\frac{dN}{dE}\right)_{\text{per ann.}} \frac{\langle\sigma v\rangle}{2} n_{DM}^2}_{\text{photons/energy/time/volume}} \times \underset{\substack{\downarrow \\ \text{convert to photons/} \\ \text{energy/dz/volume}}}{\frac{dt}{dz}} \times \frac{dV_z}{dV_0}$$

$dV_z \rightarrow$ physical volume of a given comoving volume at redshift $z$

$dV_0 \rightarrow$ physical volume of the same comoving volume today

Now $E_z = E_{\text{today}}(1+z)$

$$\frac{d}{dt}\ln(1+z) = -\frac{d}{dt}\ln a = -H(z) \Rightarrow \frac{1}{1+z}\frac{dz}{dt} = -H(z)$$

In matter + dark-energy-dominated cosmos,

$$H(z) \approx H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$

$$\Rightarrow \frac{dN}{dE_{\text{today}}}\frac{dt}{dz} \approx -\frac{1}{H(z)(1+z)}\frac{dN}{dE_{\text{today}}} = -\frac{1}{H(z)}\frac{dN}{dE_z}$$

$\frac{dN}{dE_z}$ } determined by particle physics, independent of $z$, except via dependence on $E_z$

$$\Rightarrow \quad \frac{dN_{\gamma,\nu}}{dE\,dV_0} = \int_0^\infty dz \left(\frac{dN}{dE_z}\right)_{\text{per ann}} \frac{\langle\sigma v\rangle}{2} \frac{(n_{DM,0})^2(1+z)^6}{H(z)} \times \frac{1}{(1+z)^3} \rightarrow \text{ratio of volumes}$$

$$= \int_0^\infty dz \underbrace{\left(\frac{dN}{dE_z}\right)_{\text{per ann}} \frac{\langle\sigma v\rangle}{2m_\chi^2}}_{\text{particle physics}} \frac{(\rho_{DM,z=0})^2(1+z)^3}{H_0\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}$$

For example, for line, $\frac{dN}{dE_z} = \delta(E_z - m_\chi)$, $E_z = E(1+z) \Rightarrow 1+z \rightarrow \frac{m_\chi}{E}$ in integral, for $E \leq m_\chi$

$$\left(\frac{dN_\chi}{dE\,dV_0}\right) = \frac{\langle\sigma v\rangle}{2m_\chi^2} \frac{(\rho_{DM,0})^2 (m_\chi/E)^3}{H_0\sqrt{[illegible]}}$$

For decay, replace $\frac{\langle\sigma v\rangle}{2m_\chi^2} \longrightarrow \frac{1}{m_\chi \tau}$, $(\rho_{DM,z=0})^2 \longrightarrow (\rho_{DM,z=0})$, & $(1+z)^3 \rightarrow (1+z)^0$

---

In general, include both non-uniformity & redshifting: $\frac{dN_{\gamma\nu}}{dE\,dA\,dt} = \int \frac{d\Omega}{4\pi} \times \int dz \frac{\langle\sigma v\rangle}{2m_\chi^2} \frac{\rho^2(z,\theta,\phi)}{H(z)(1+z)^3} \left(\frac{dN}{dE'}\right)_{E'=E(1+z)}$

To include absorption, add $e^{-\tau(E,z)}$ term.

What about $\frac{dN_{\gamma\nu}}{dE}$ - at source?

often parameterize by following logic:

- If 2-body final states allowed, they will (usually) dominate rate
- Consider all possible 2-particle SM final states
  e.g $e^+e^-$, $b\bar{b}$, $p\bar{p}$, etc, ~~work out data~~ test against observations
- In general, ~3 types of final state:
  - Photon-rich continuum – ~~[illegible]~~ involves $\tau$ leptons & all hadronic channels. Produces $\pi^0$'s in decay, also $\pi^+\pi^-$, $\pi^0 \rightarrow \gamma\gamma$ with 99% branching ratio, so copious photons & charged particles

- Leptonic final states - $e^+e^-$, $\mu^+\mu^-$ ~~con~~

  Photons produced only by 3-body ~~pa~~ final states

  ⇒ e.g FSR, suppressed + hard spectrum

  Copious charged leptons

Photon signals hard & peaked toward DM mass

Similar effects from degeneracies in spectrum, decaying force carriers, etc.

- Lines - $\nu\bar{\nu}$, $\gamma\gamma$

  Can perform "bump hunt", backgrounds much lower

  But for $\gamma\gamma$, signal also suppressed as DM uncharged, so must be 1-loop+.

- Presence of more complicated dark sectors (hadronization, cascades etc) can give spectra outside SM 2-body final states.
- Cosmic rays from DM (next section) can also give rise to <u>secondary</u> photons - for leptonic channels, often largest photon signal.

<u>Backgrounds</u>

- For sufficiently high-energy lines ~~pa~~/sharp peaks, almost nothing - just a matter of statistics
- For continuum gamma rays, cosmic rays interacting with gas + starlight → $\gamma$'s
- For X-rays, both continuum (hot gas) & atomic lines
- ~~etc~~ For radio, dust, CMB(!)

Parametrics:

$$E_{\gamma'} \sim \underbrace{\gamma^2}_{\text{electron boost factor}} \underbrace{E_0}_{\text{energy of original photon}}$$

Typical sizes of J-factors assuming Navarro-Frenk-White profile

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

Dwarf galaxies: $J \sim 10^{17-20}$ GeV$^2$cm$^{-5}$

Inner 1 degree around Galactic center: $J \sim 10^{22}$ GeV$^2$cm$^{-5}$

Dwarfs: low background, but (expected) lower signal

- Can be exception in case with Sommerfeld enhancement - velocities small in dwarfs

Galactic center: high background, but (expected) high signal

Beyond overall J, morphology may also provide clues to DM origin

$$\langle\rho^2\rangle \neq \langle\rho\rangle^2$$

Note: ~~$\int\rho^2 \neq (\int\rho)^2$~~

Small-scale <u>substructure</u> can greatly increase J

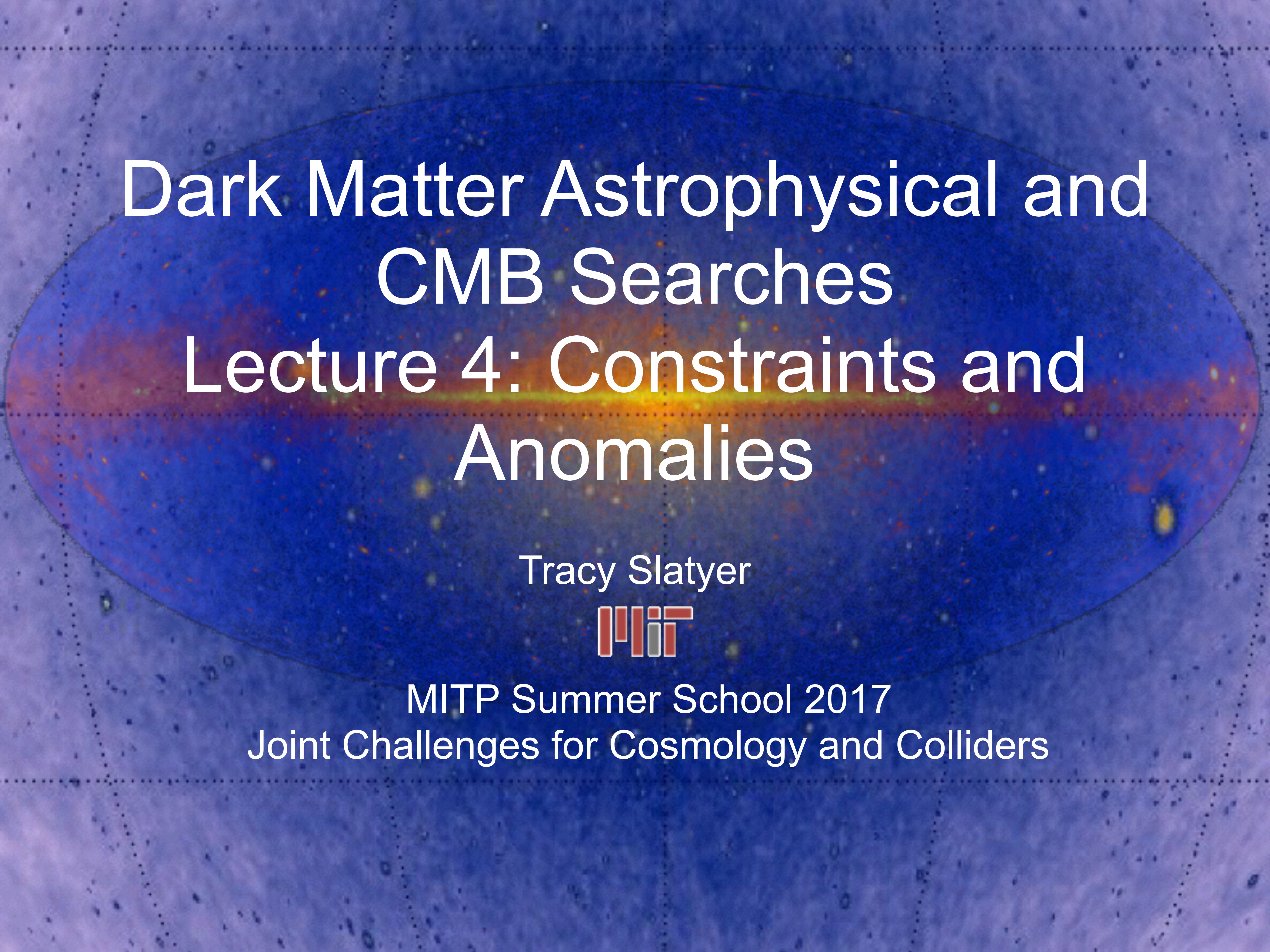
Bigger effect in larger structures

For clusters could potentially be $O(10^3)$ boost, although more modern estimates instead find $O(1-10)$ boosts

But not well understood from simulations, as they cannot resolve ~~too small~~ $\lesssim 10^{5-6}$ solar mass halos, most of boost comes from smaller halos.

Decay: substructure irrelevant, only $\int \rho \, dr \, d\Omega \approx \rho \, dV/4\pi r^2$ matters.

Larger effects wherever there is more total DM - clusters make good targets.



# Dark Matter Astrophysical and CMB Searches
# Lecture 4: Constraints and Anomalies

Tracy Slatyer

MITP Summer School 2017
Joint Challenges for Cosmology and Colliders

# Gamma-ray limits

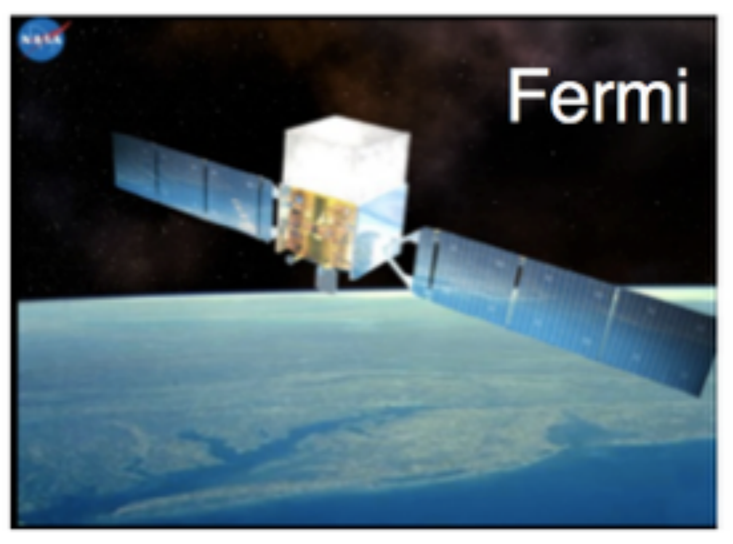
HAWC

few TeV - 100 TeV

100 GeV - 10s of TeV

also VERITAS, MAGIC

100 MeV - 1 TeV

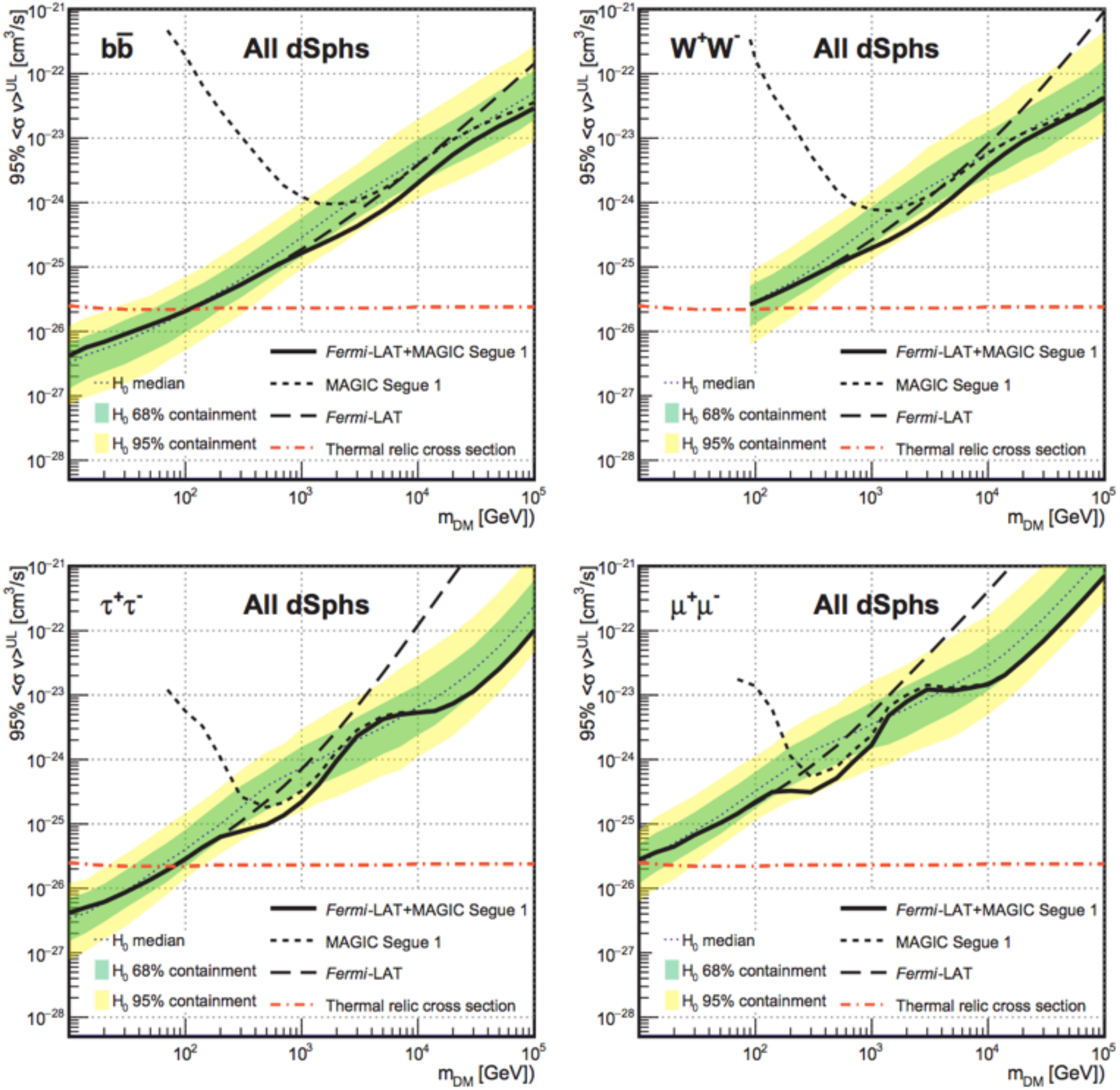


also DAMPE

# Continuum limits from dwarfs

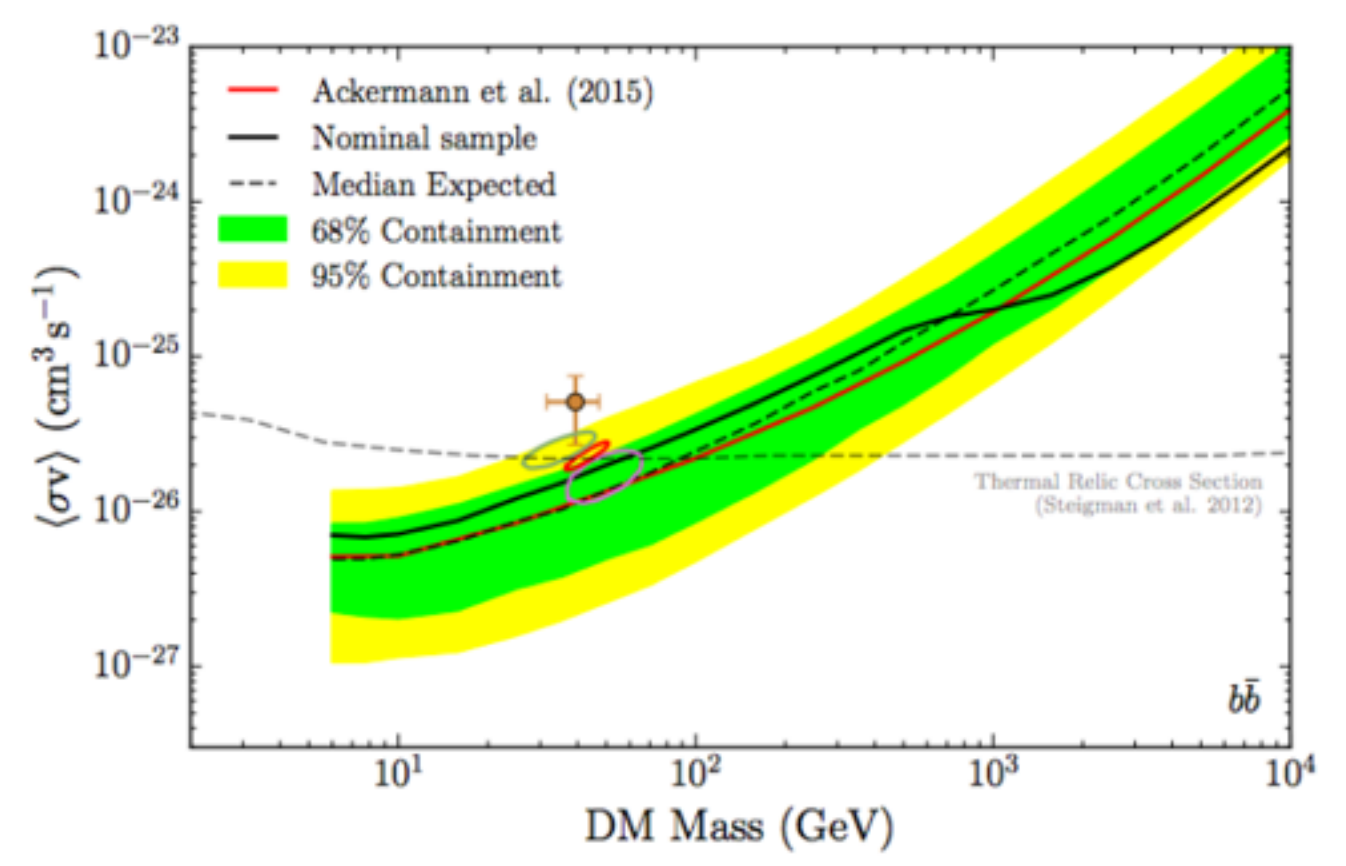
- Estimate dwarf J-factors from stellar kinematics, fit for localized gamma-ray emission over smooth background at dwarf location, compare observed and predicted dwarf gamma-ray signal in likelihood analysis.
- The Fermi Gamma-Ray Space Telescope presented updated limits based on 45 dwarf galaxies and candidates earlier this year (Albert et al '17). Strongest 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.

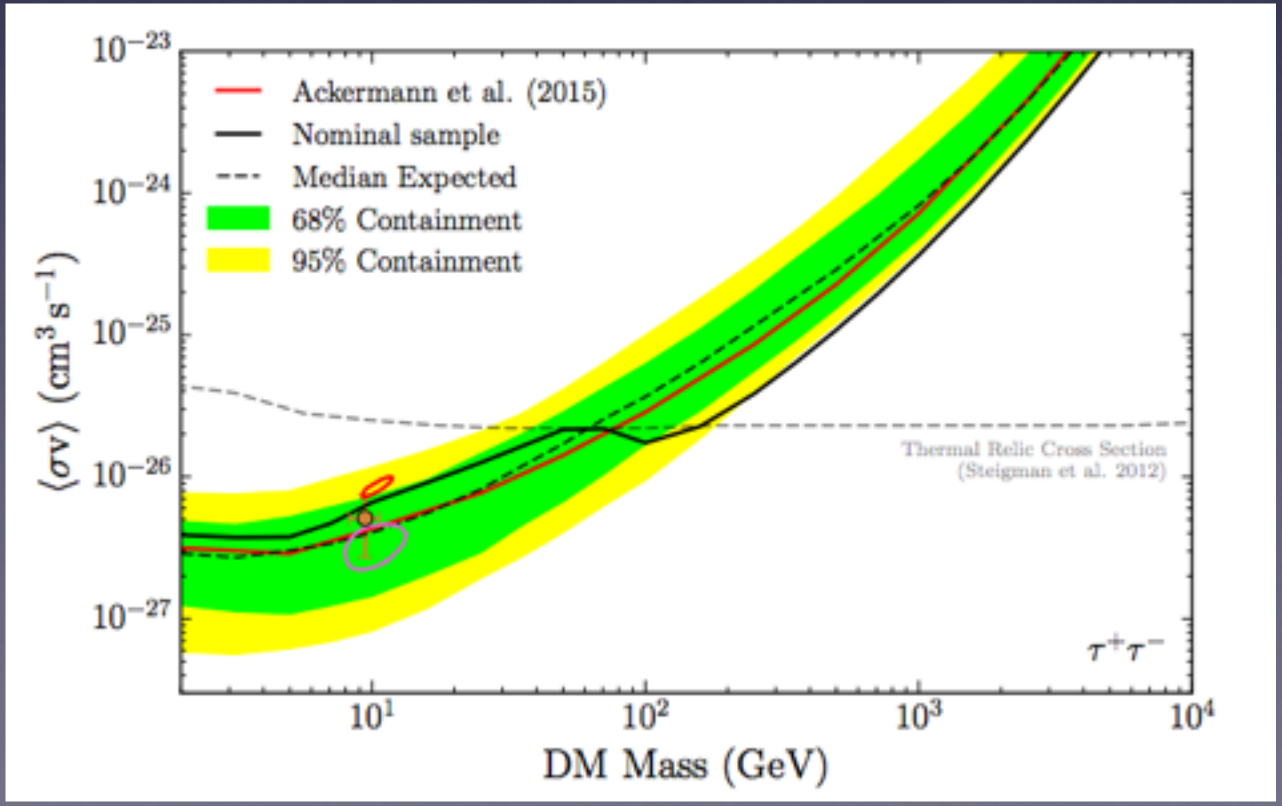
- Combined analysis of dwarf galaxies with Fermi and MAGIC



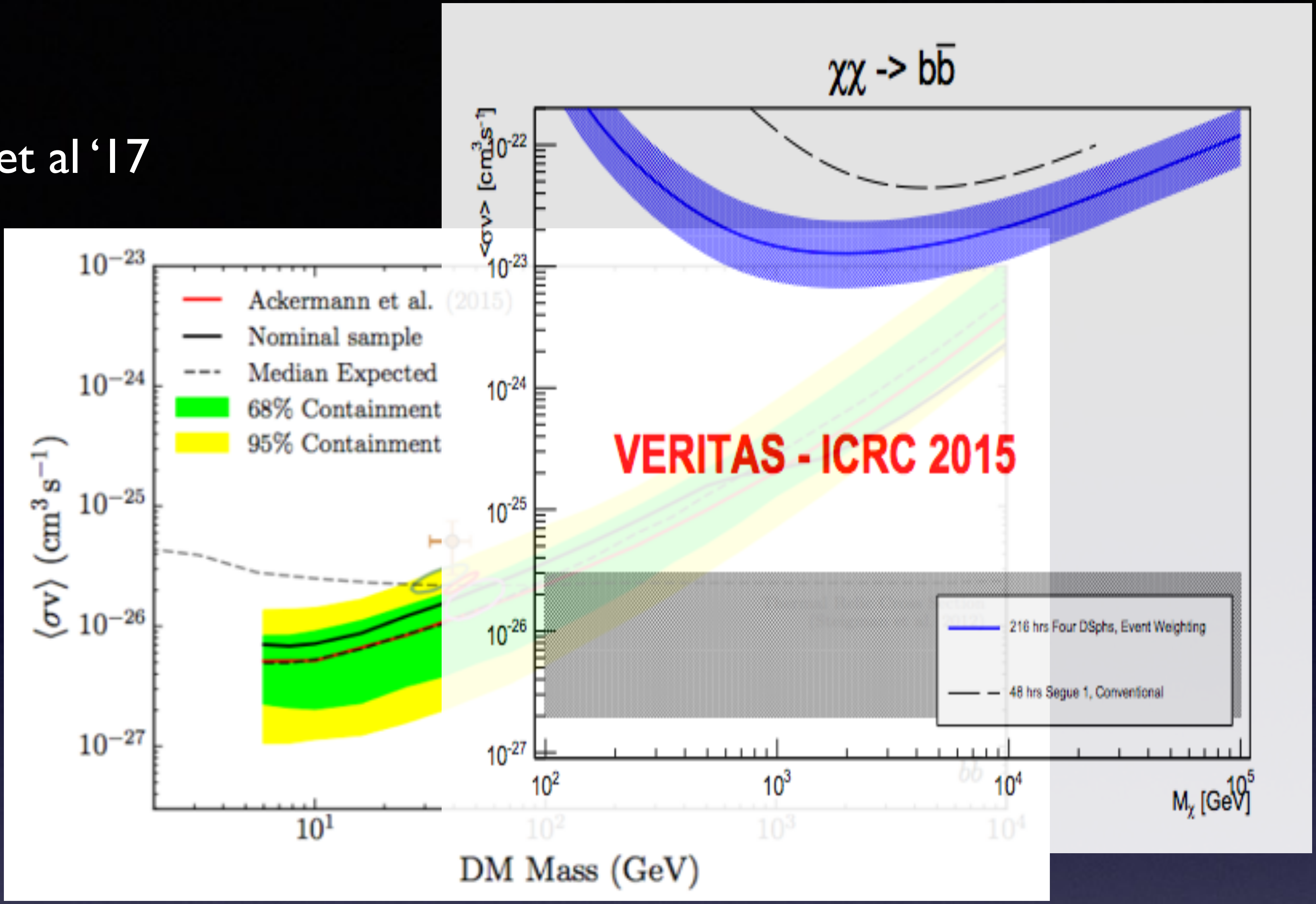
Ahnen et al '16

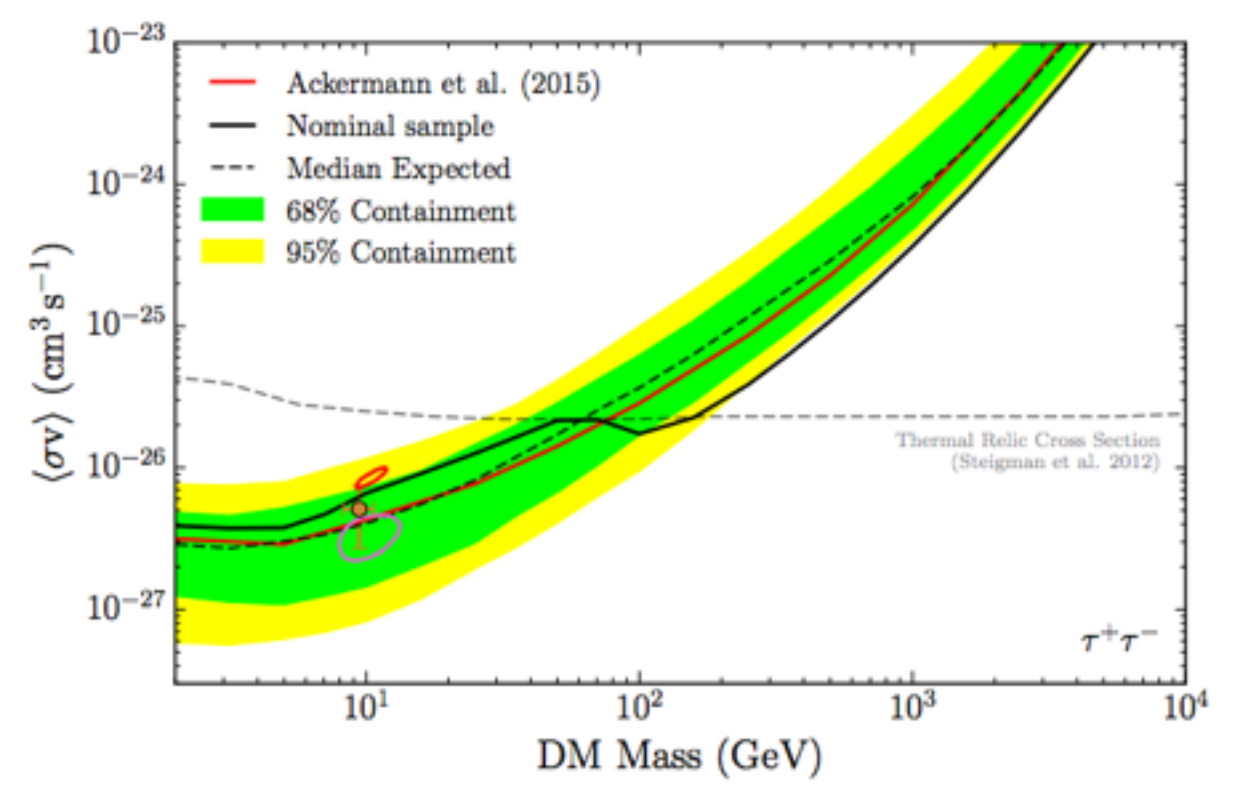
Albert et al ‘17



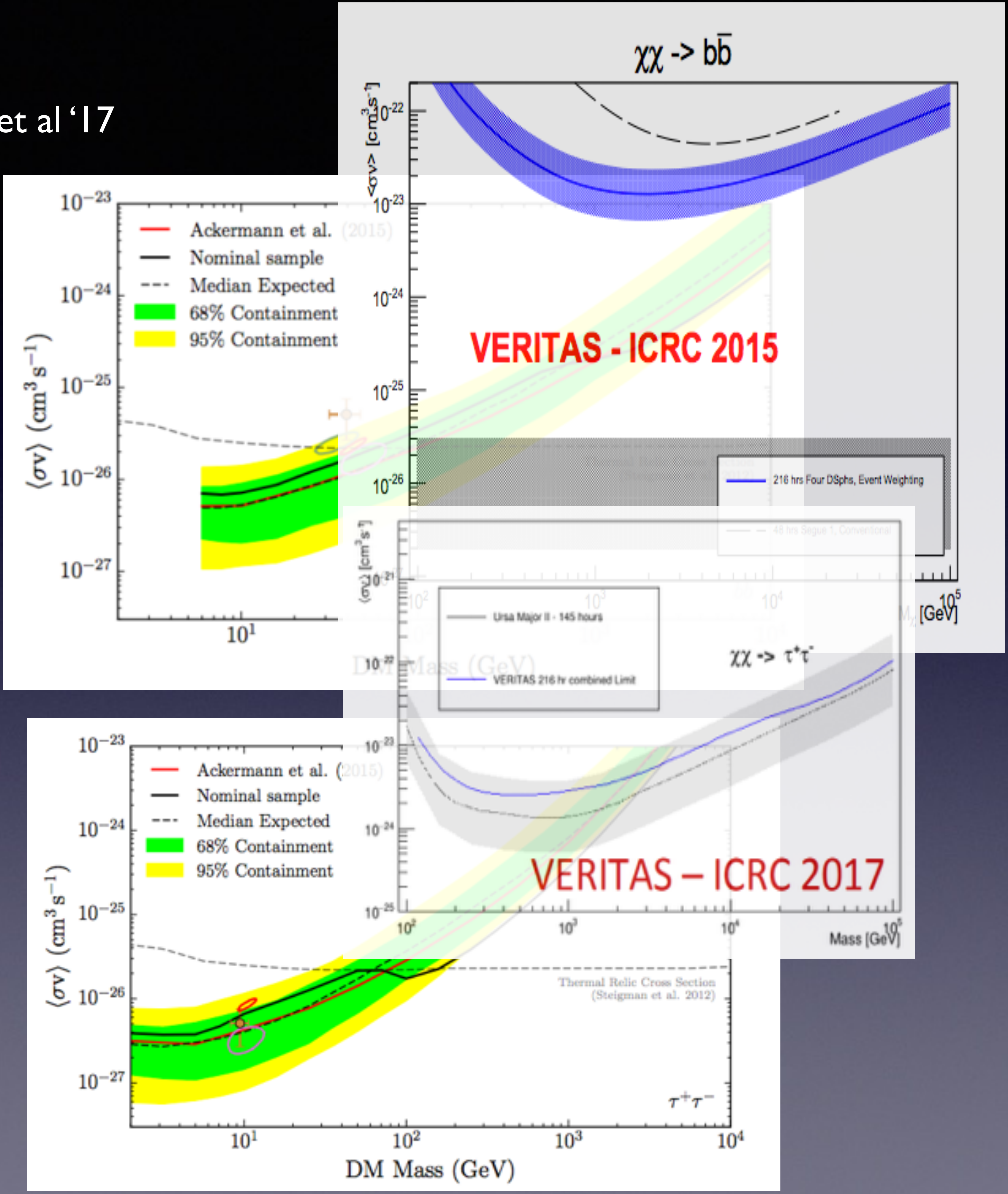


Albert et al '17

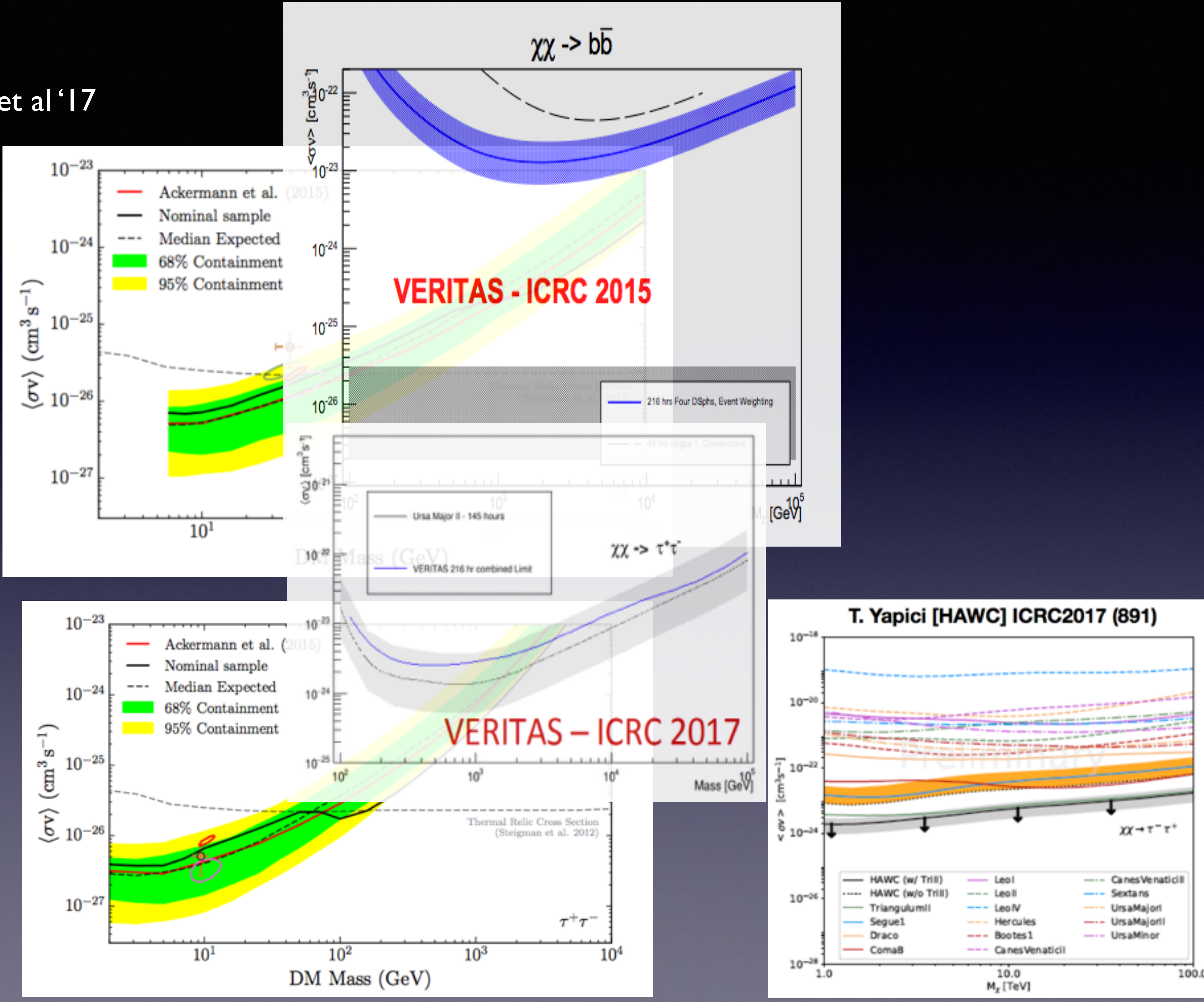




Albert et al ‘17



Albert et al ‘17



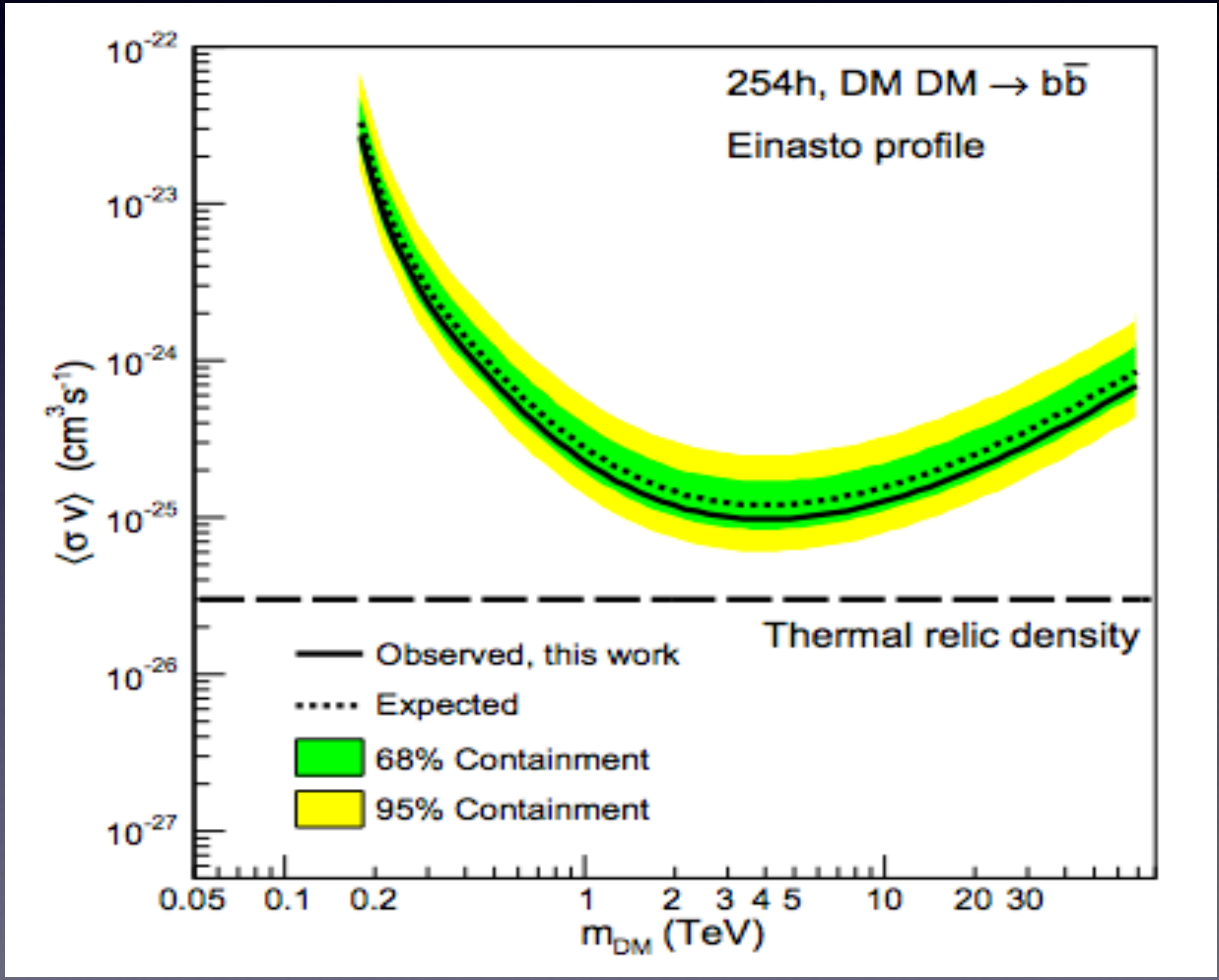
VERITAS - ICRC 2015

VERITAS – ICRC 2017

T. Yapici [HAWC] ICRC2017 (891)

# 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 Einasto profile, no density core.



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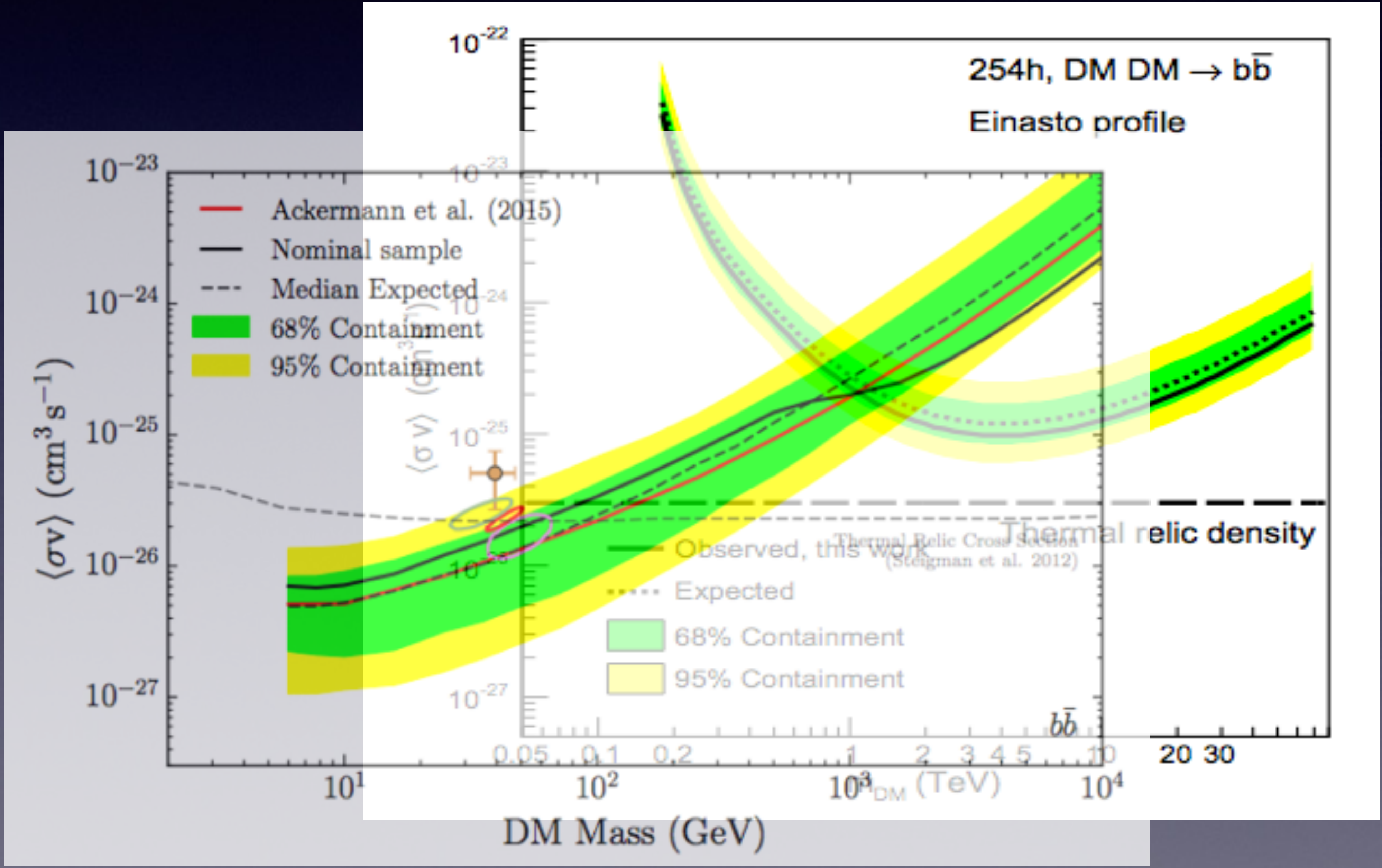
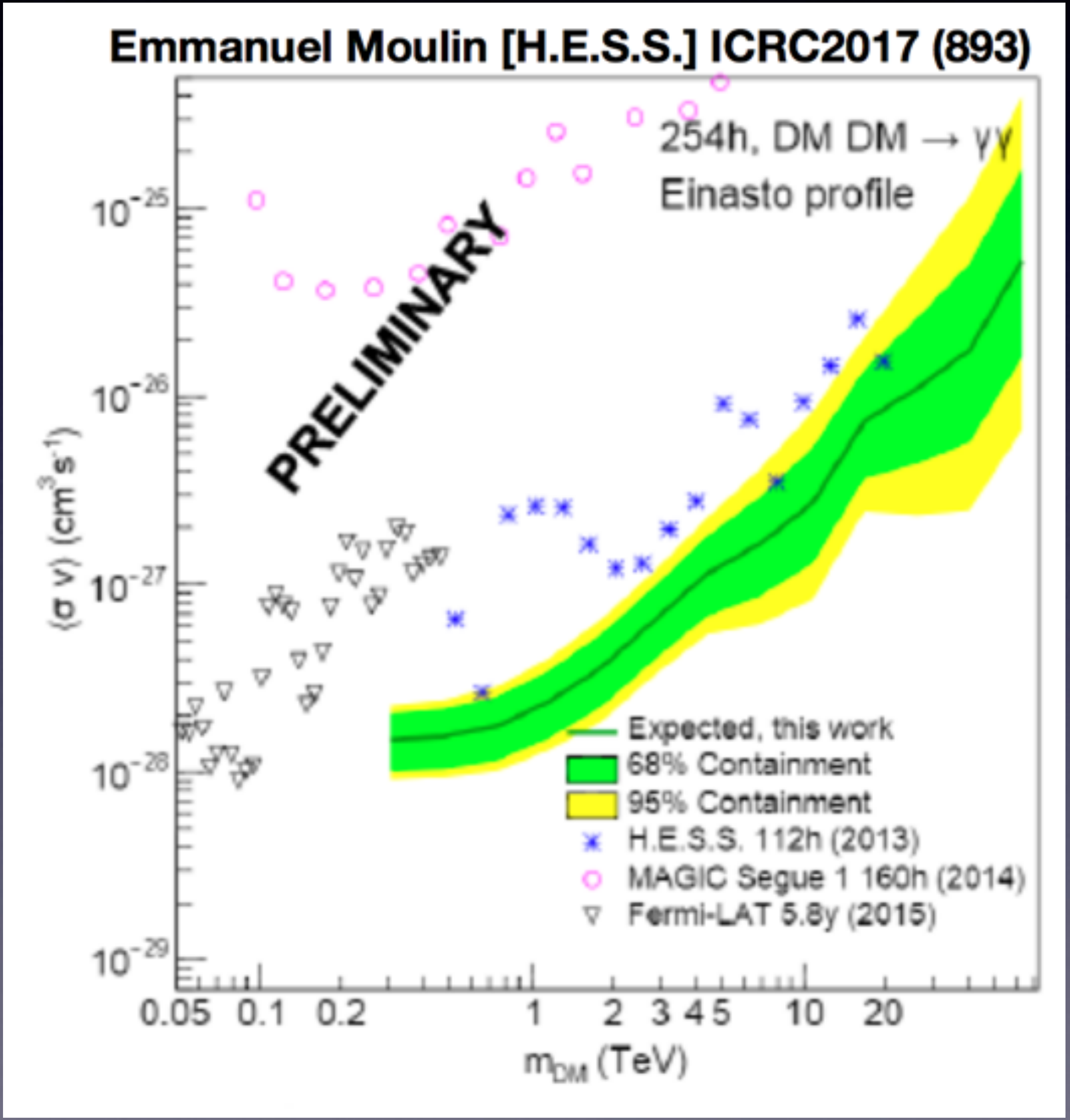


# Line limits from GC

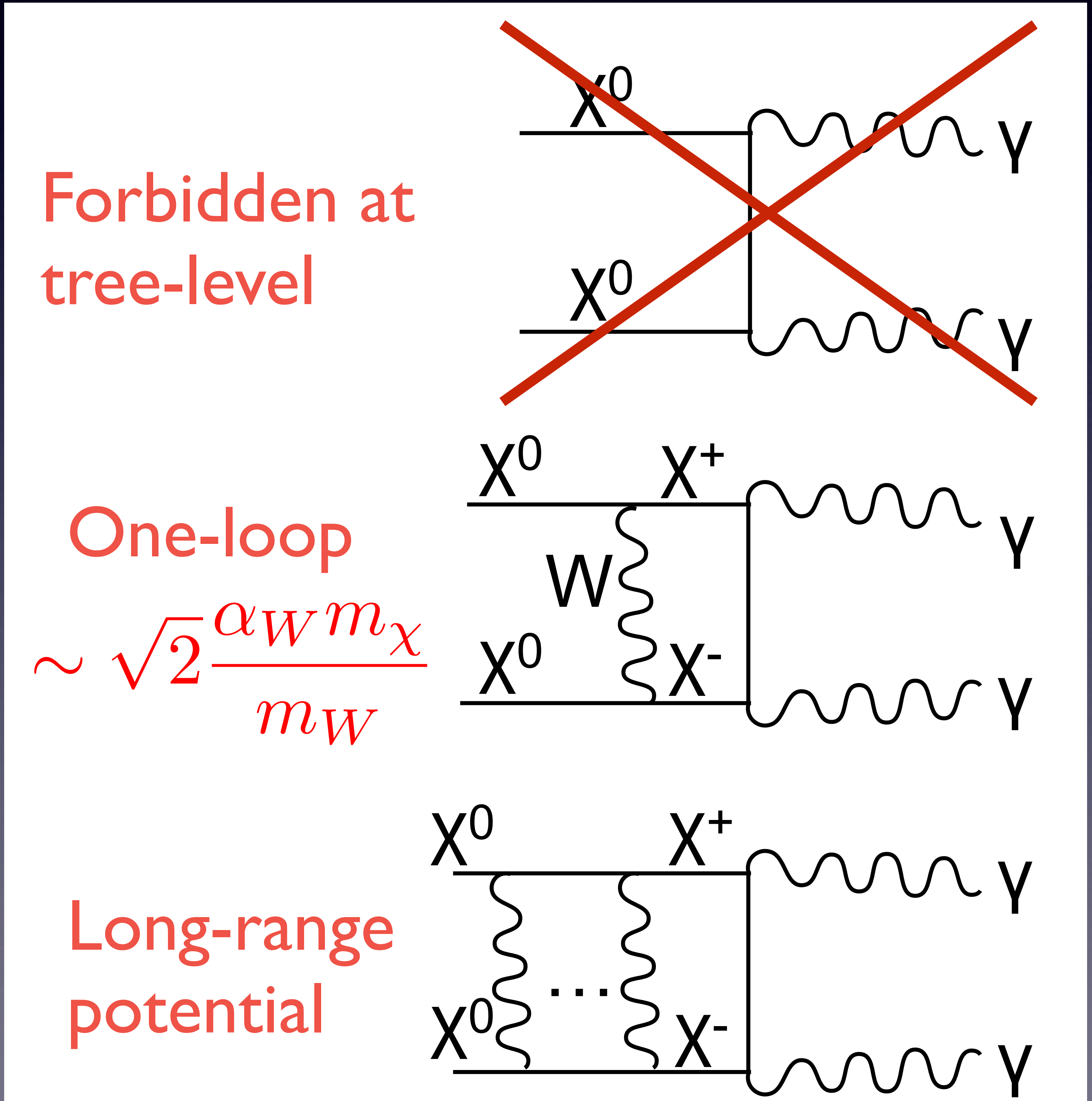
- For gamma-ray lines, astrophysical backgrounds are low
- Need to optimize statistics - motivates search toward inner Galaxy
- Line limits from dwarfs have also been derived (e.g. Liang et al '16 )



# 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

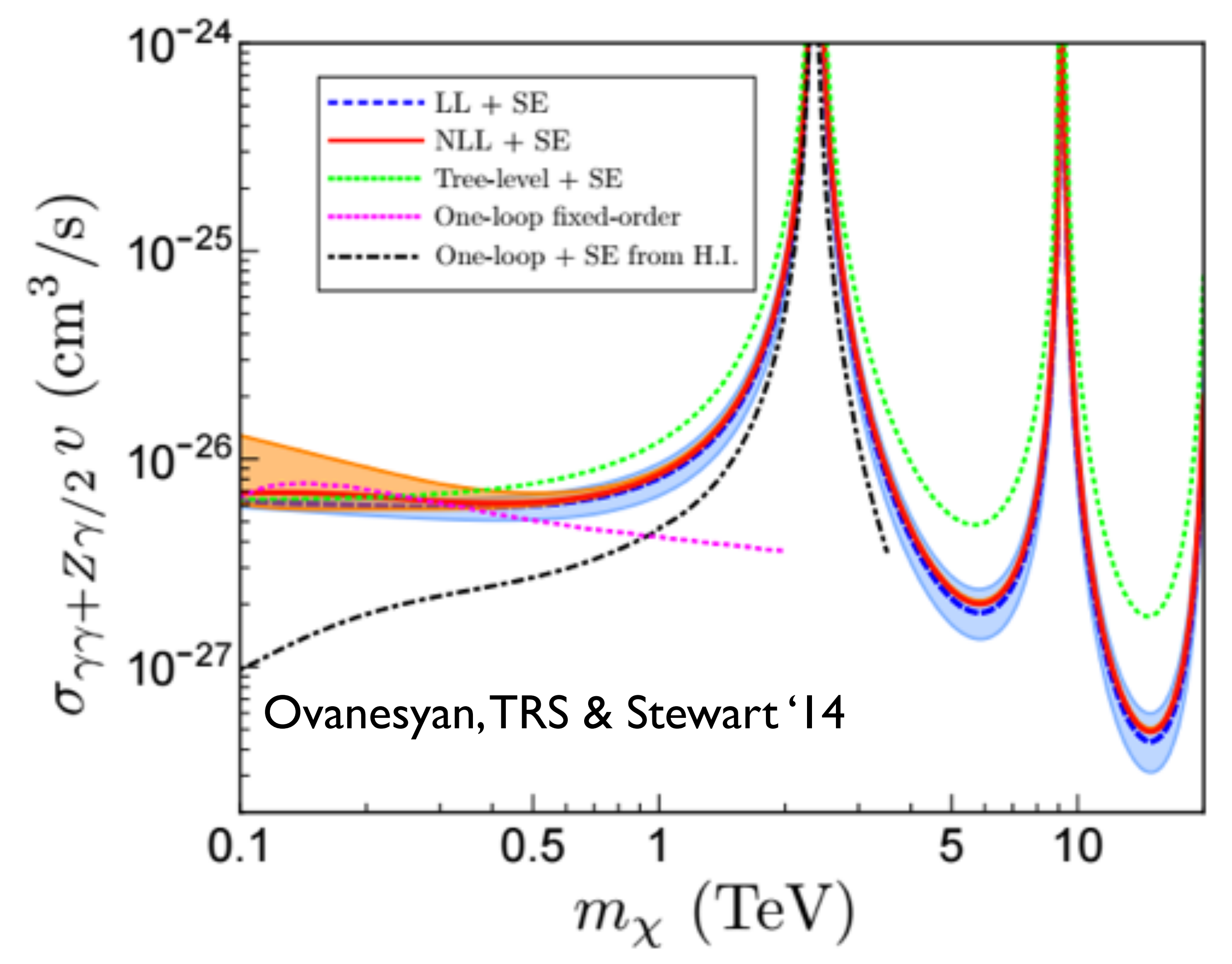

Forbidden at tree-level

One-loop

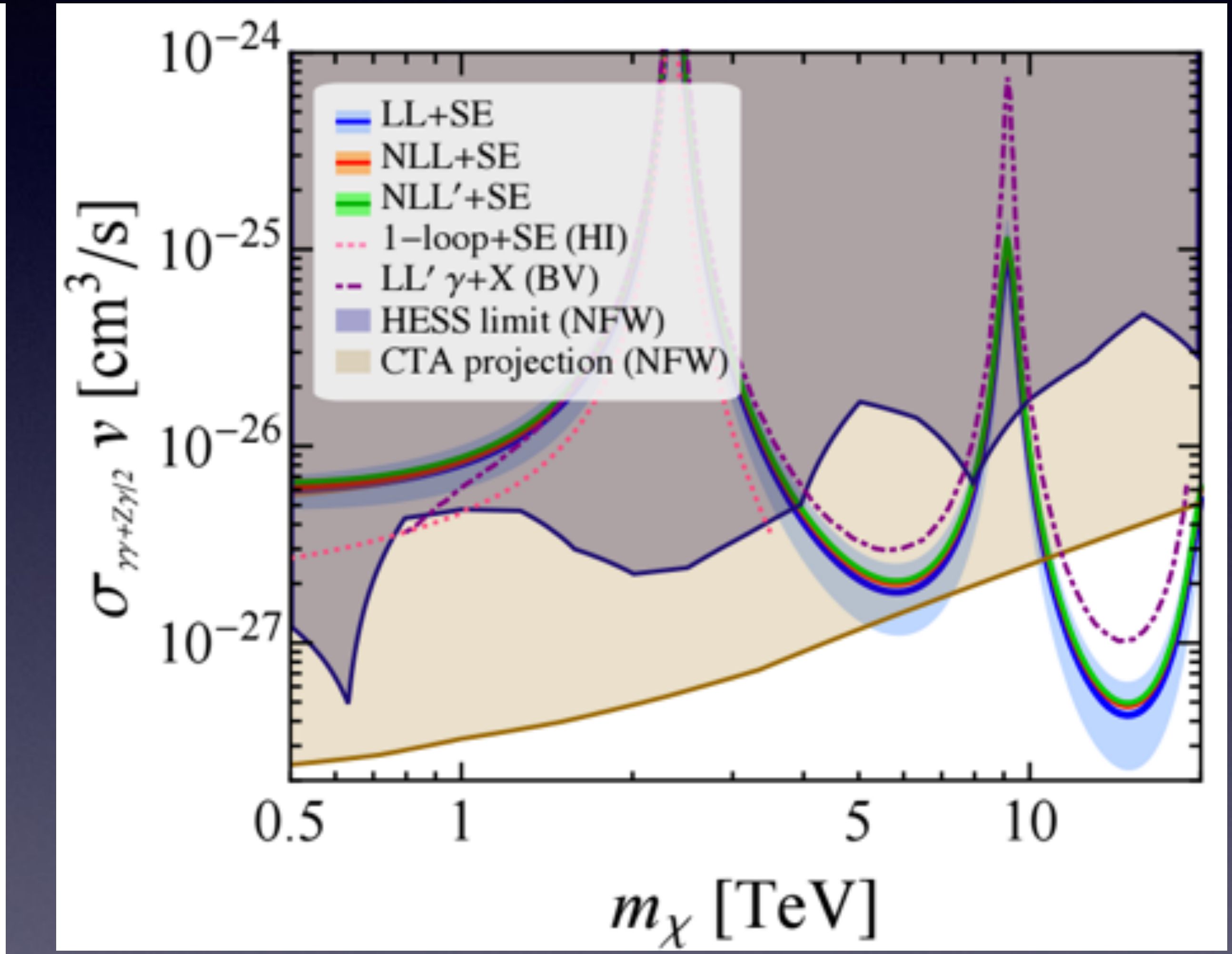
$$\sim \sqrt{2}\frac{\alpha_W m_\chi}{m_W}$$

Long-range potential

# Example of line constraints for wino DM



Ovanesyan, TRS & Stewart '14

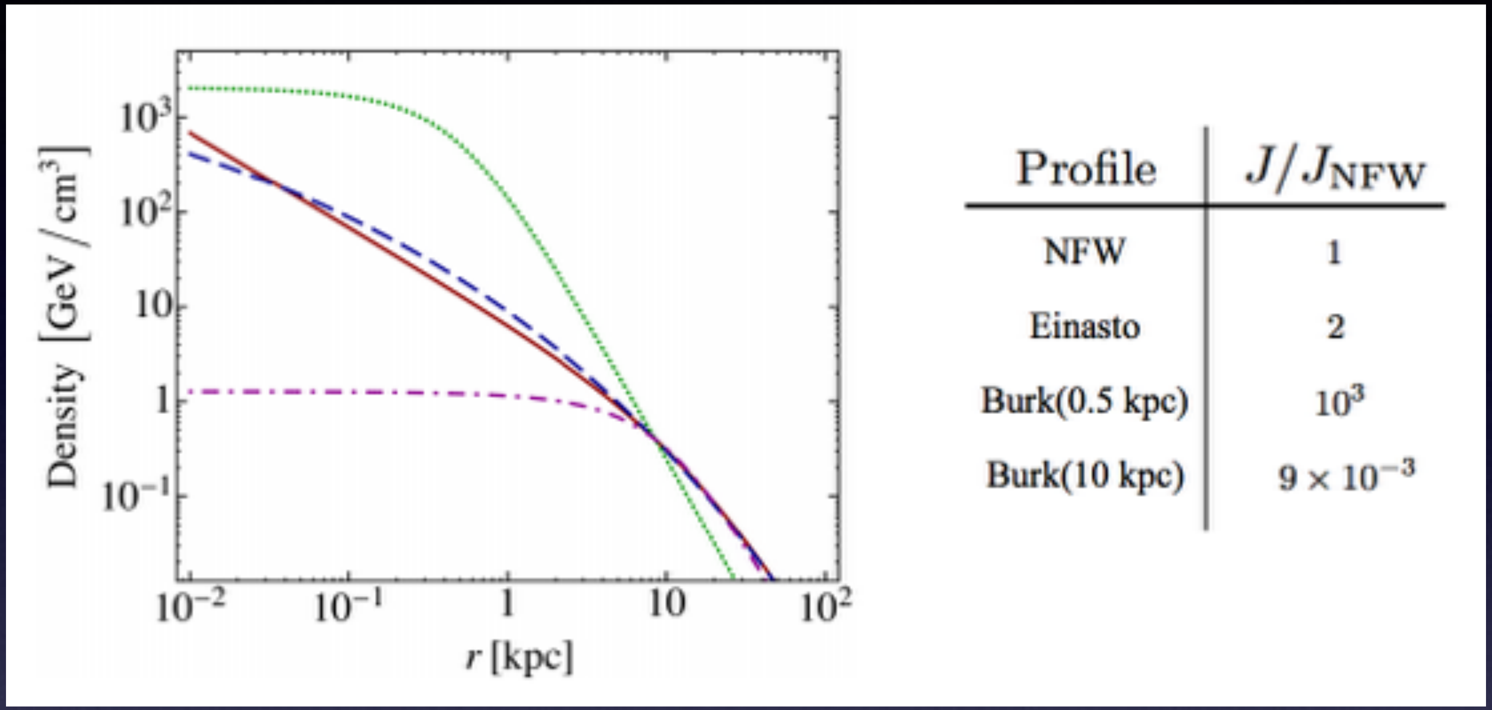


Ovanesyan, TRS, Rodd & Stewart '17

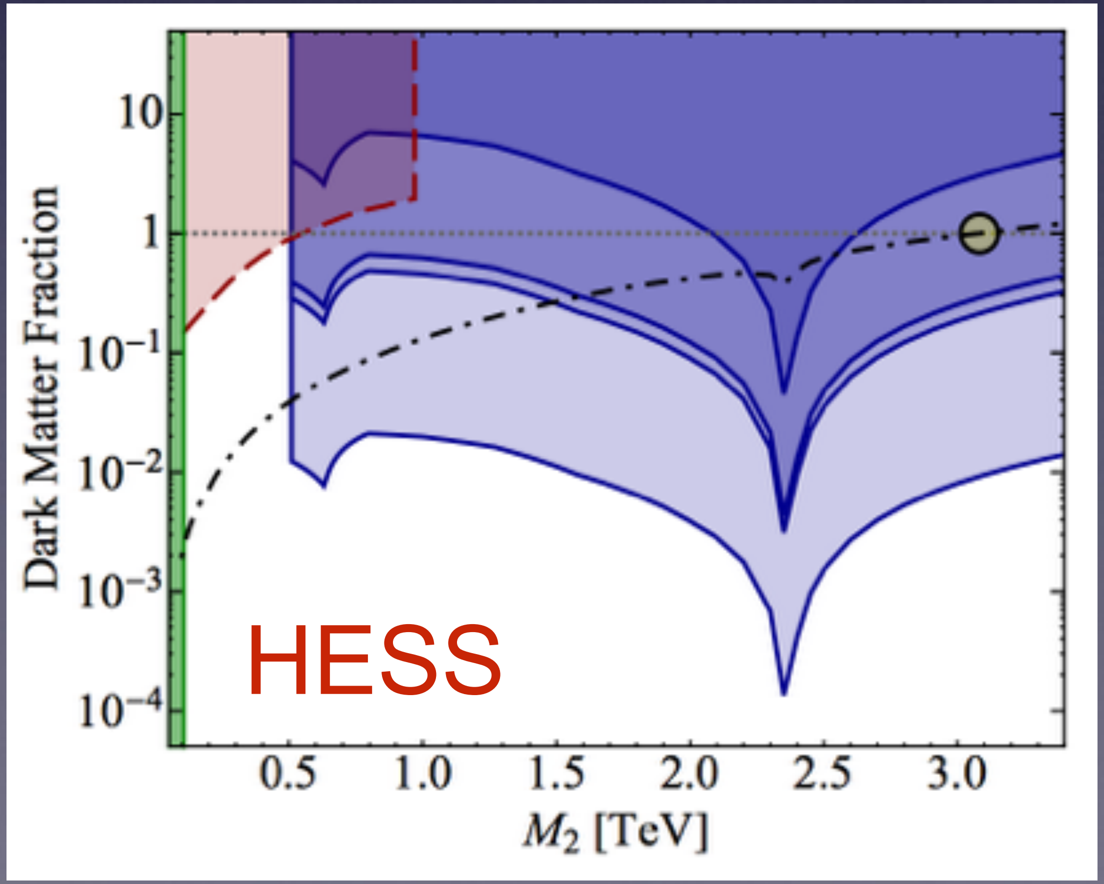
- Theoretical prediction is quite subtle - Sudakov logs + Sommerfeld enhancement (+ bound state effects, but these are small - Asadi et al '17, Braaten et al '17).
- Brown constraint region is projected limit from upcoming CTA experiment.

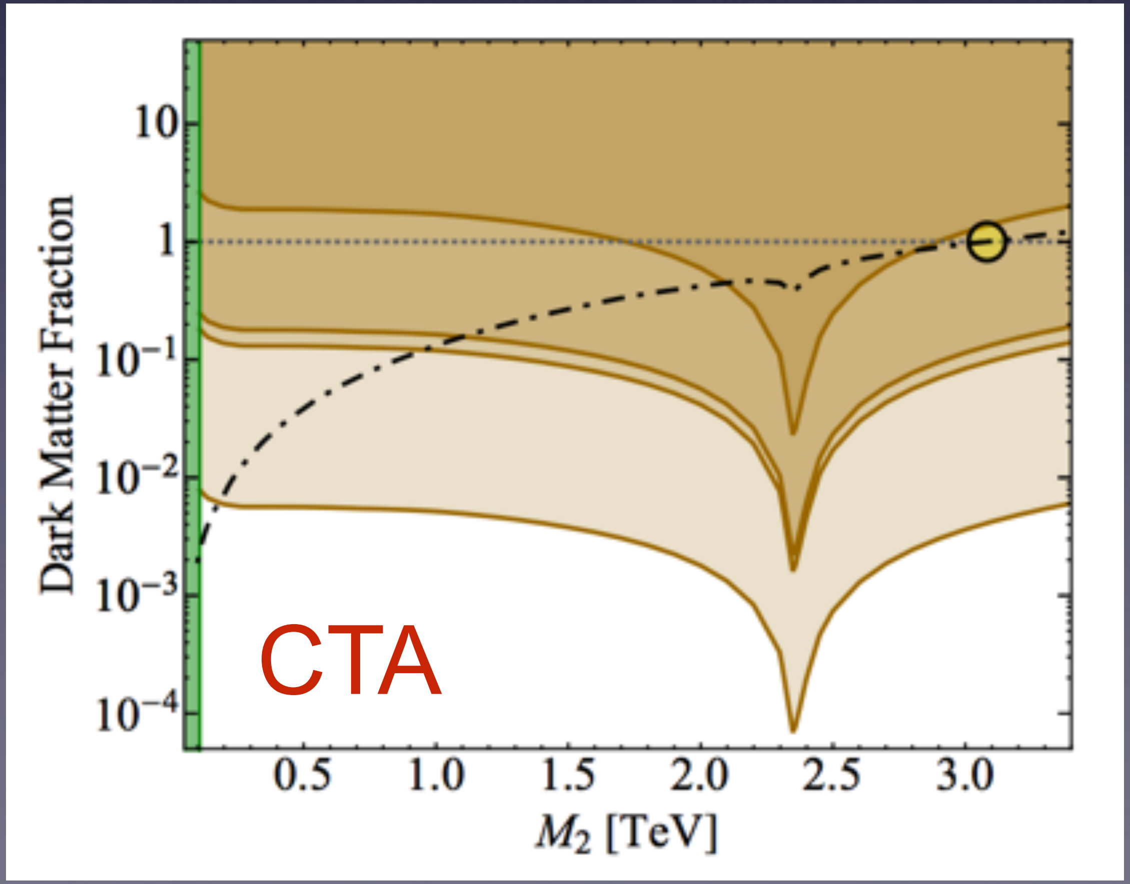
# Dependence on the profile

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



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





# 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-$10^{10}$ GeV range, for representative hadronic decay channels.

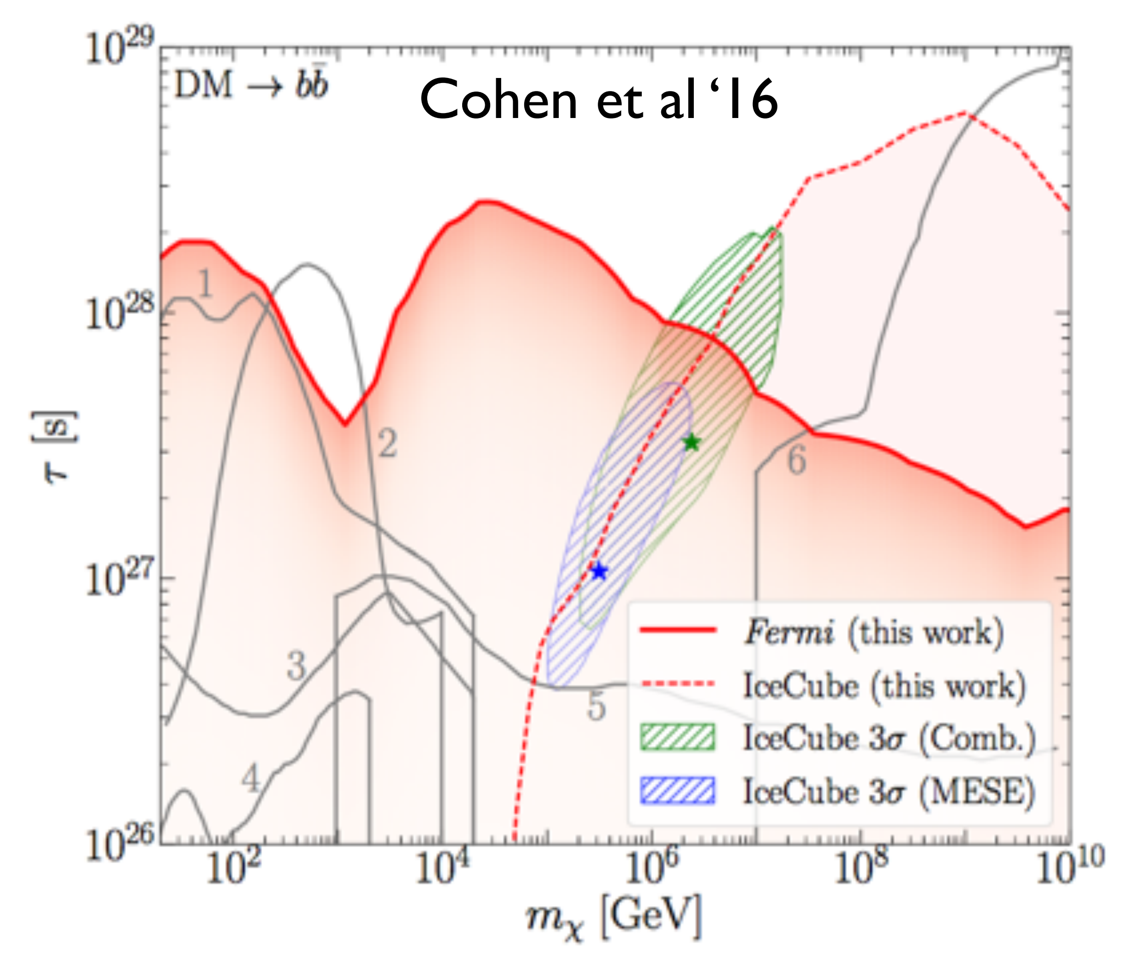
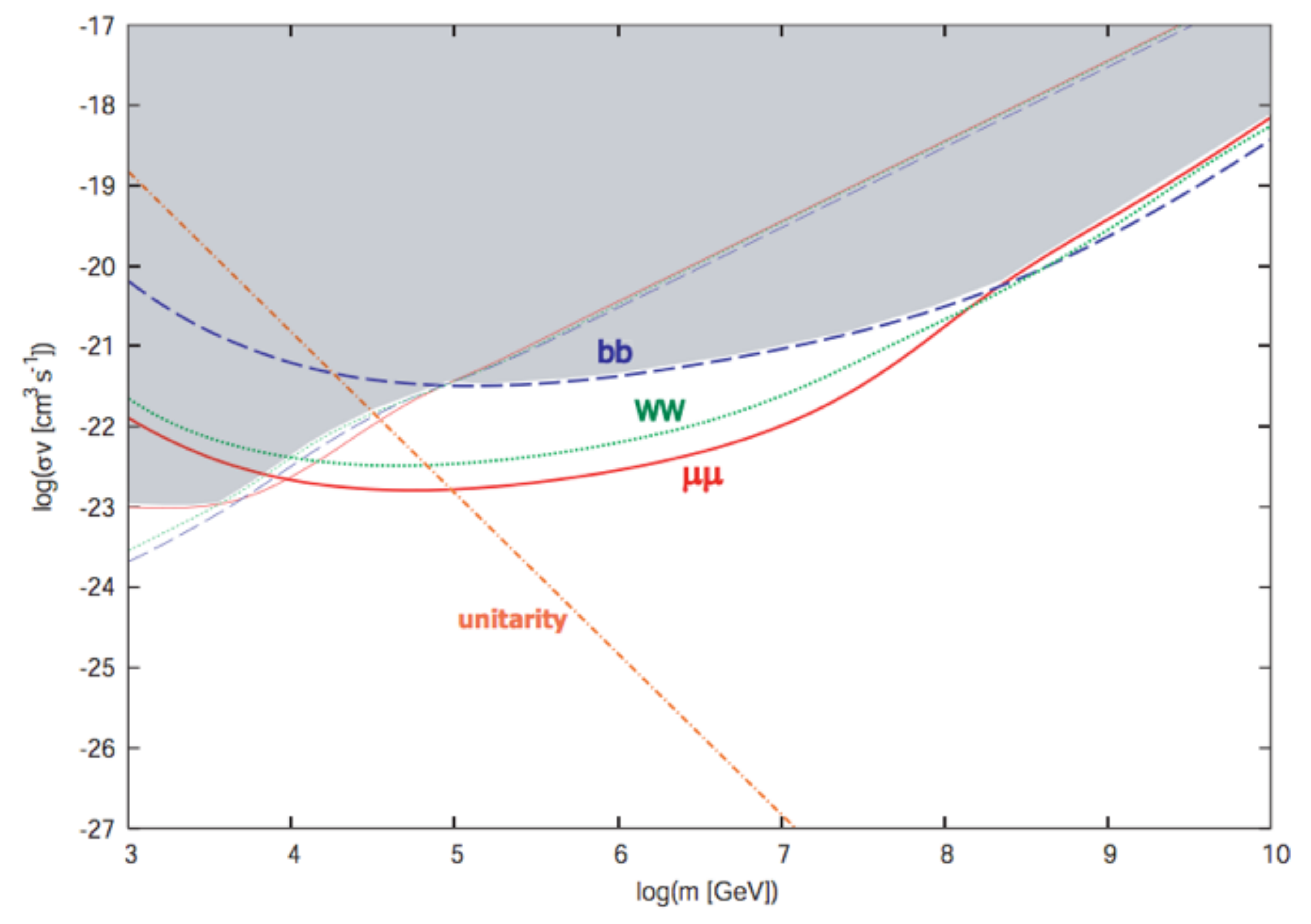


FIG. 1: Limits derived in this work on DM decays to $b\bar{b}$, as compared to previously computed limits using data from *Fermi* (2,3,5), AMS-02 (1,4), and PAO/KASCADE/CASA-MIA (6). The hashed green (blue) region suggests parameter space where DM decay may provide a $\sim 3\sigma$ improvement to the 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.

# 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



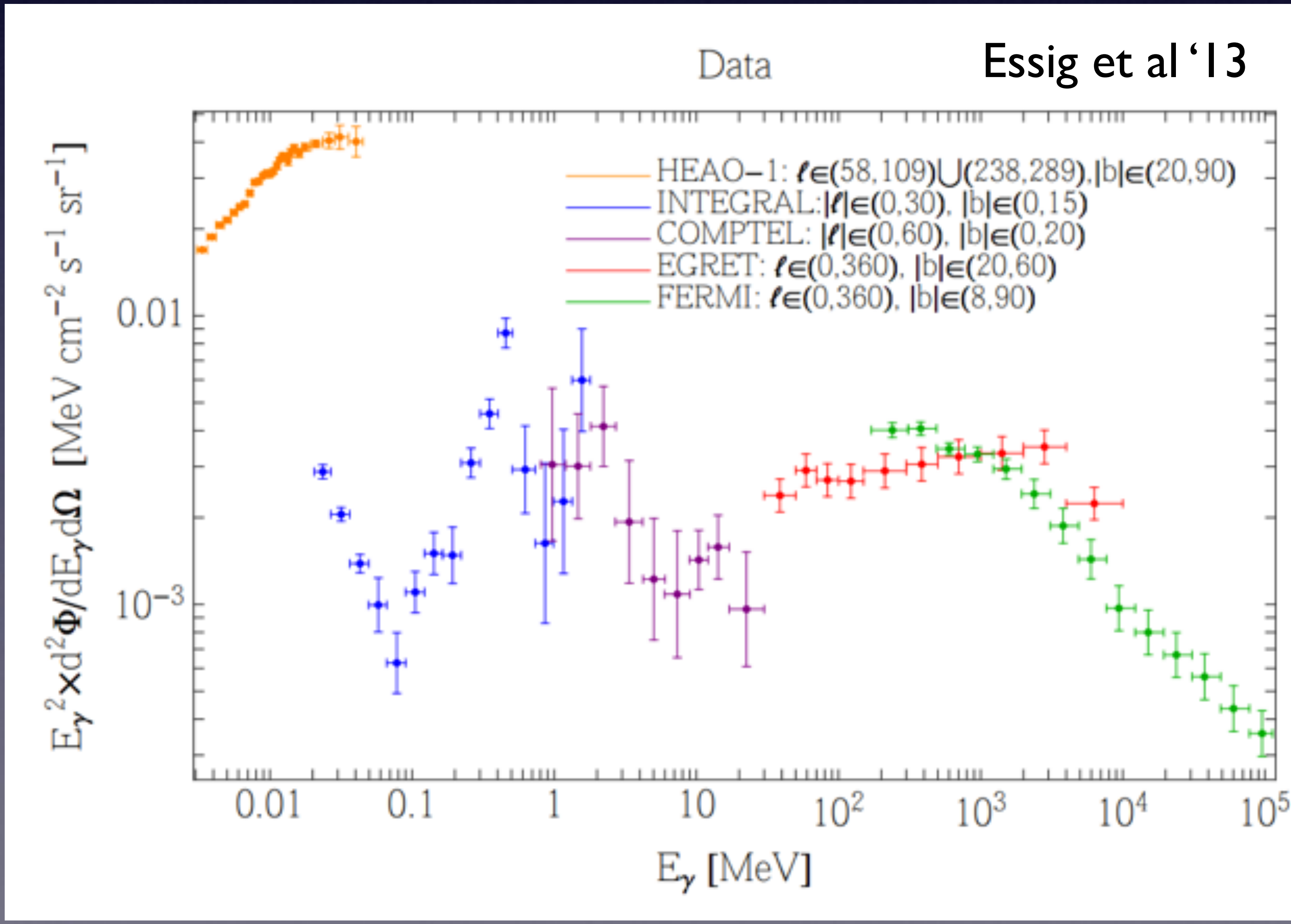
Murase & Beacom '12

# Light DM and the photon diffuse background

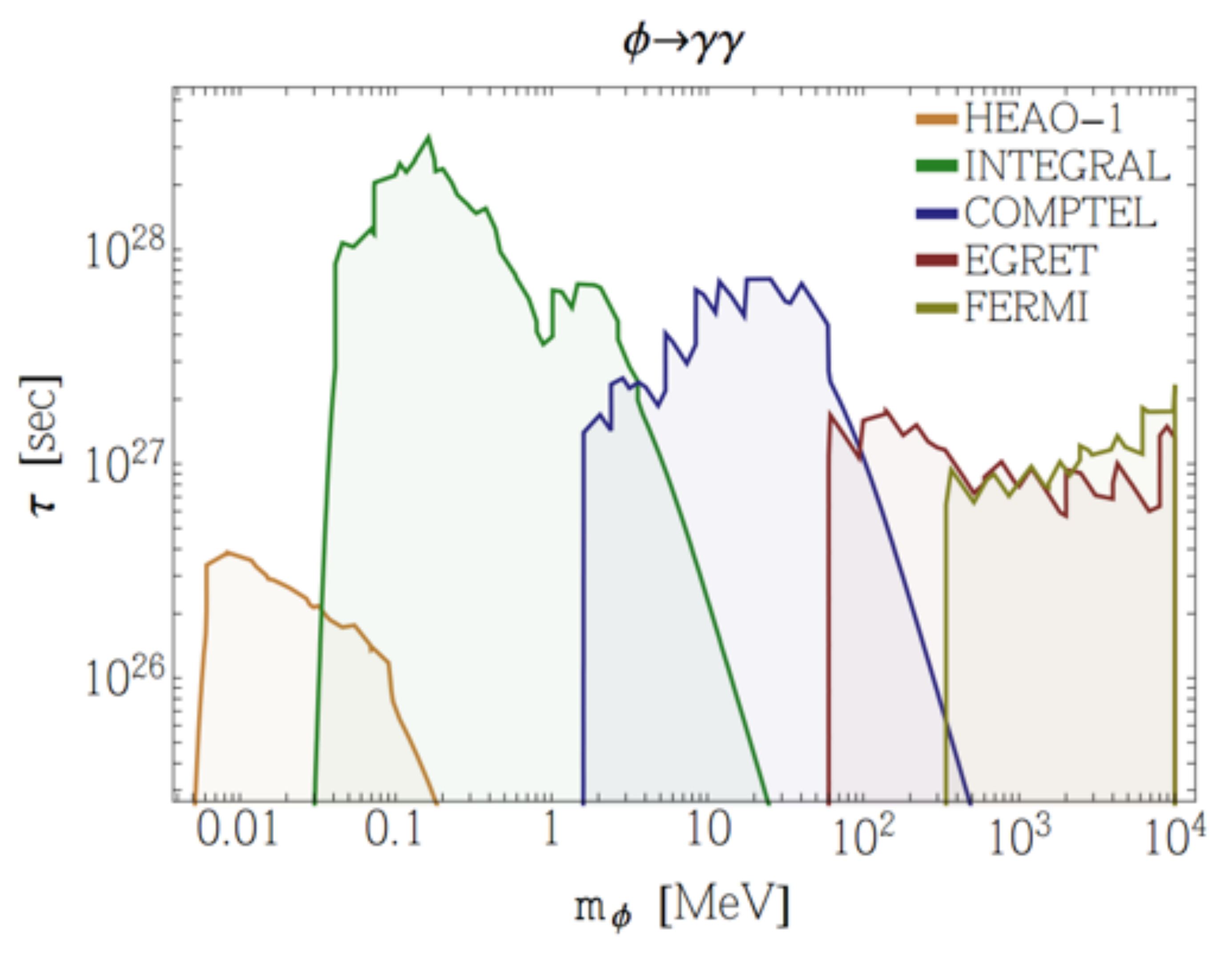
<<1 GeV: dominant annihilation to electrons/positrons, photons, neutrinos

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

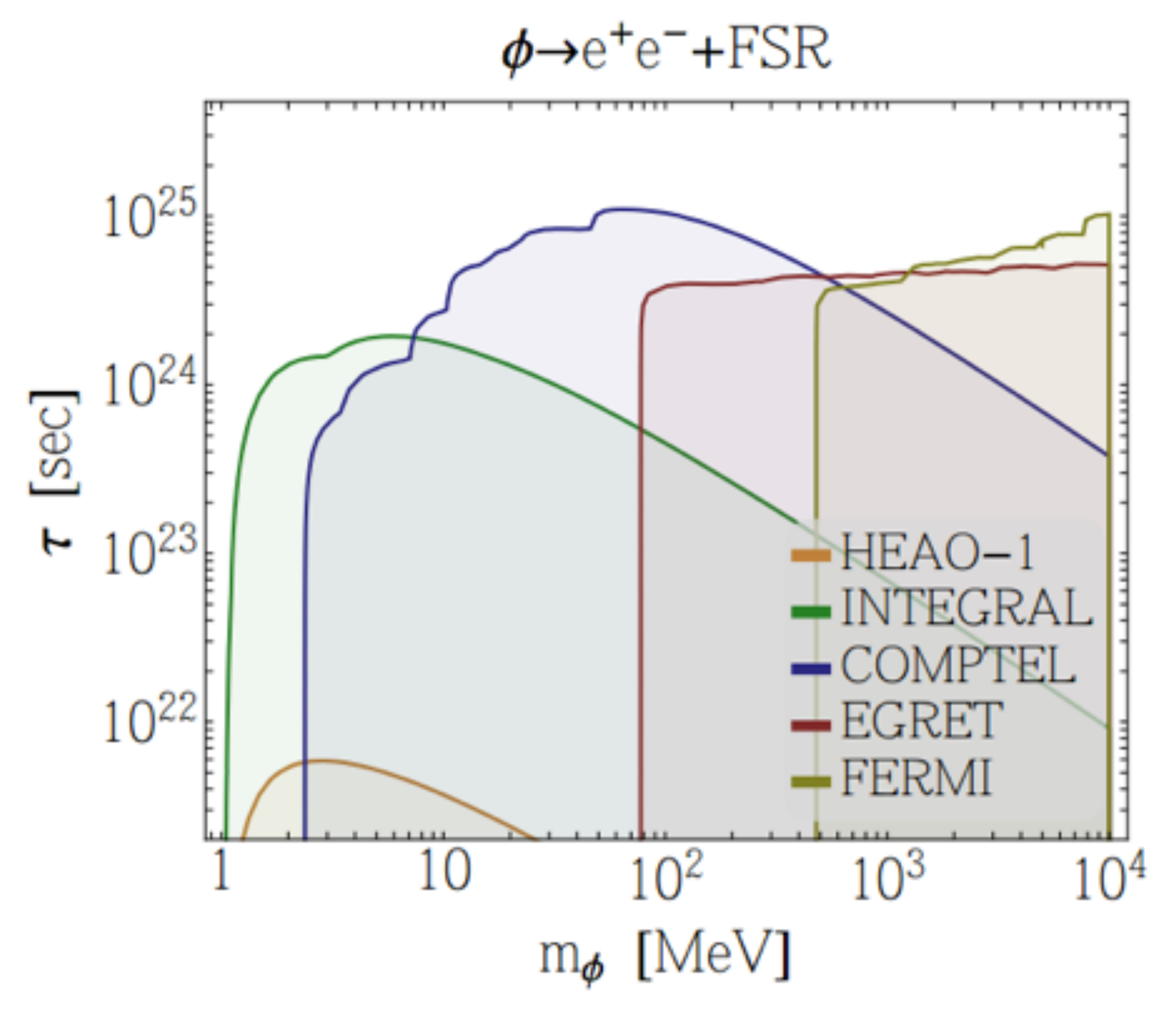
- We will discuss CMB and cosmic-ray constraints later.
- For channels that produce copious photons, strongest limits on <u>decay</u> come from studying gamma-rays from the Milky Way halo.
- Constraints are competitive for decay and p-wave annihilation to electrons (but not s-wave annihilation).



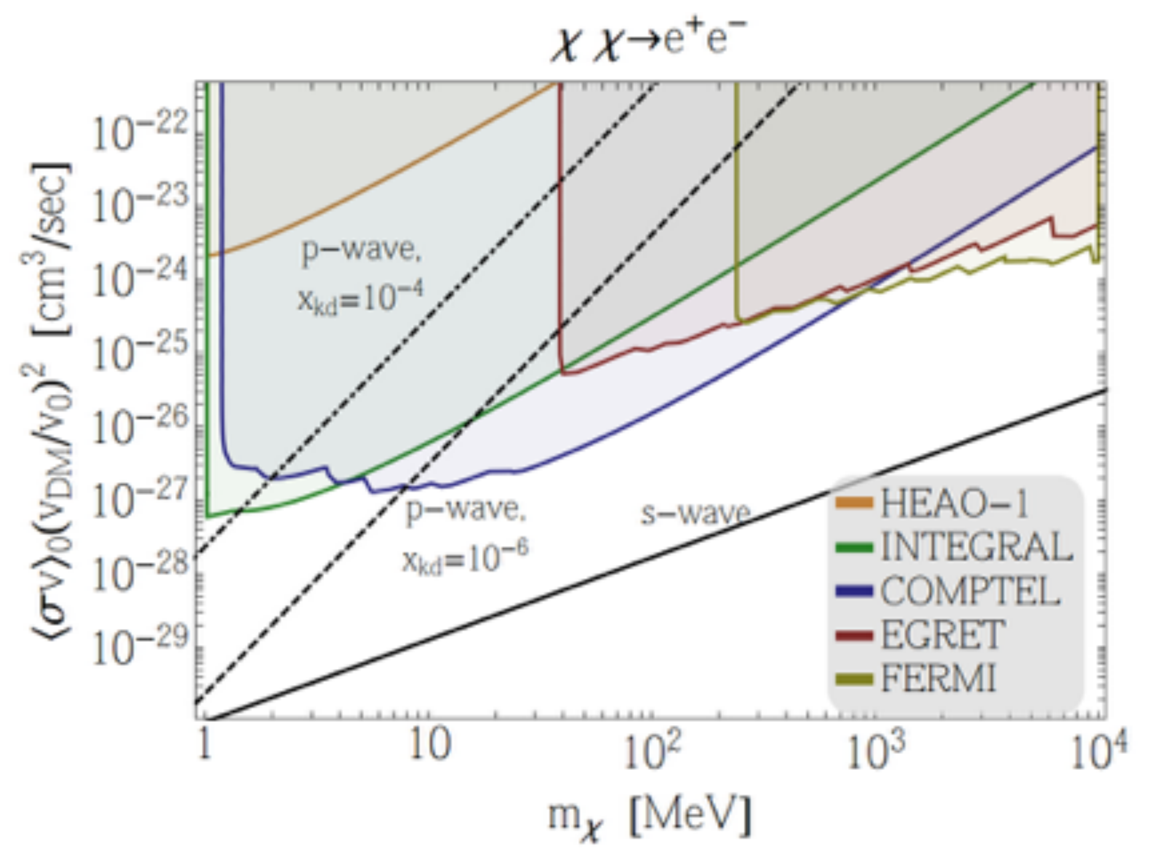
Essig et al '13



$\phi \to \gamma\gamma$



$\phi \to e^+e^- + \mathrm{FSR}$



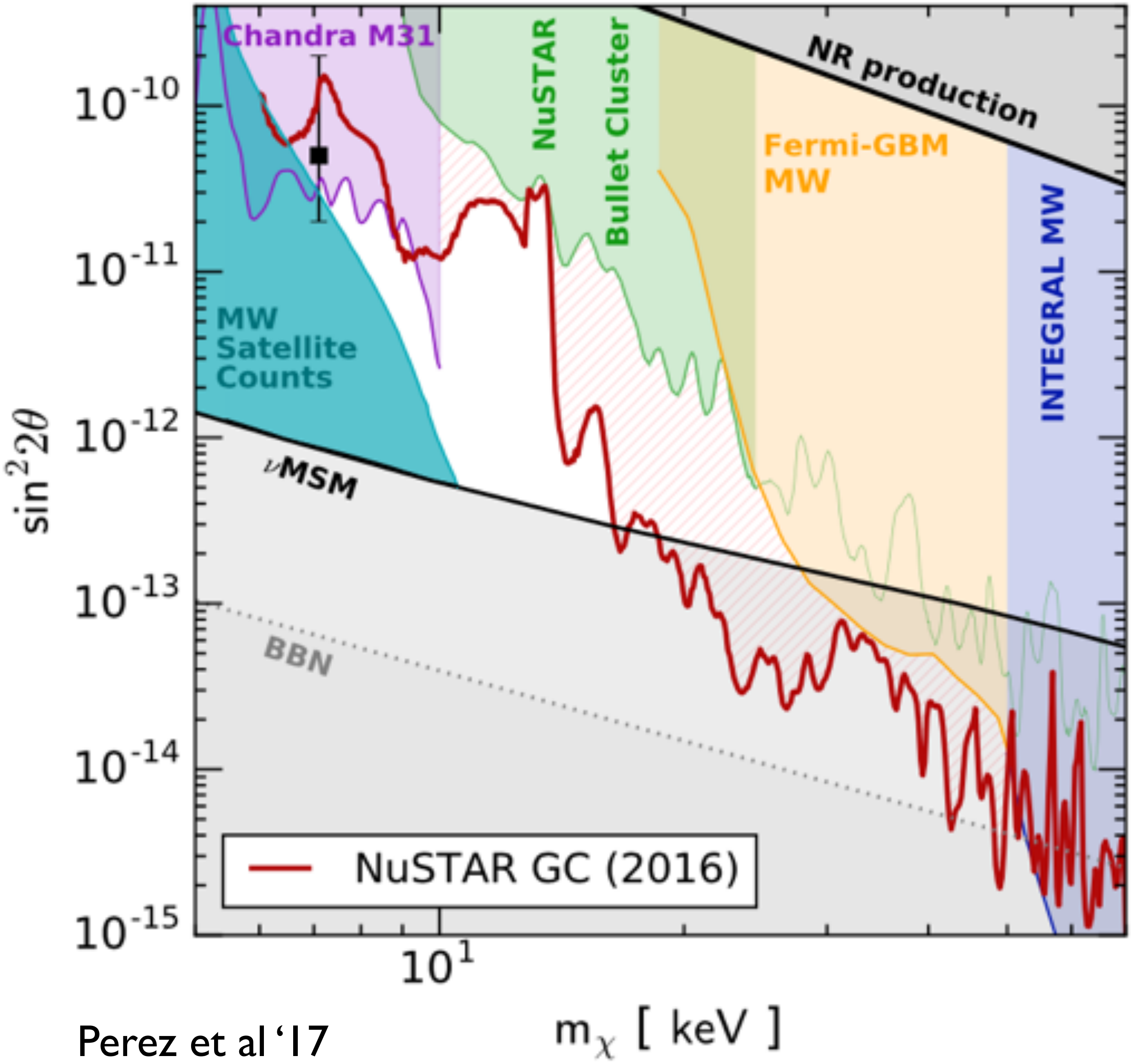
$\chi\chi \to e^+e^-$

# Even lighter DM - X-ray limits

- As discussed on Monday, sterile neutrinos can decay to produce photons with a long lifetime.

- X-ray telescopes can probe this signal - plot on right shows constraints from several telescopes.

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

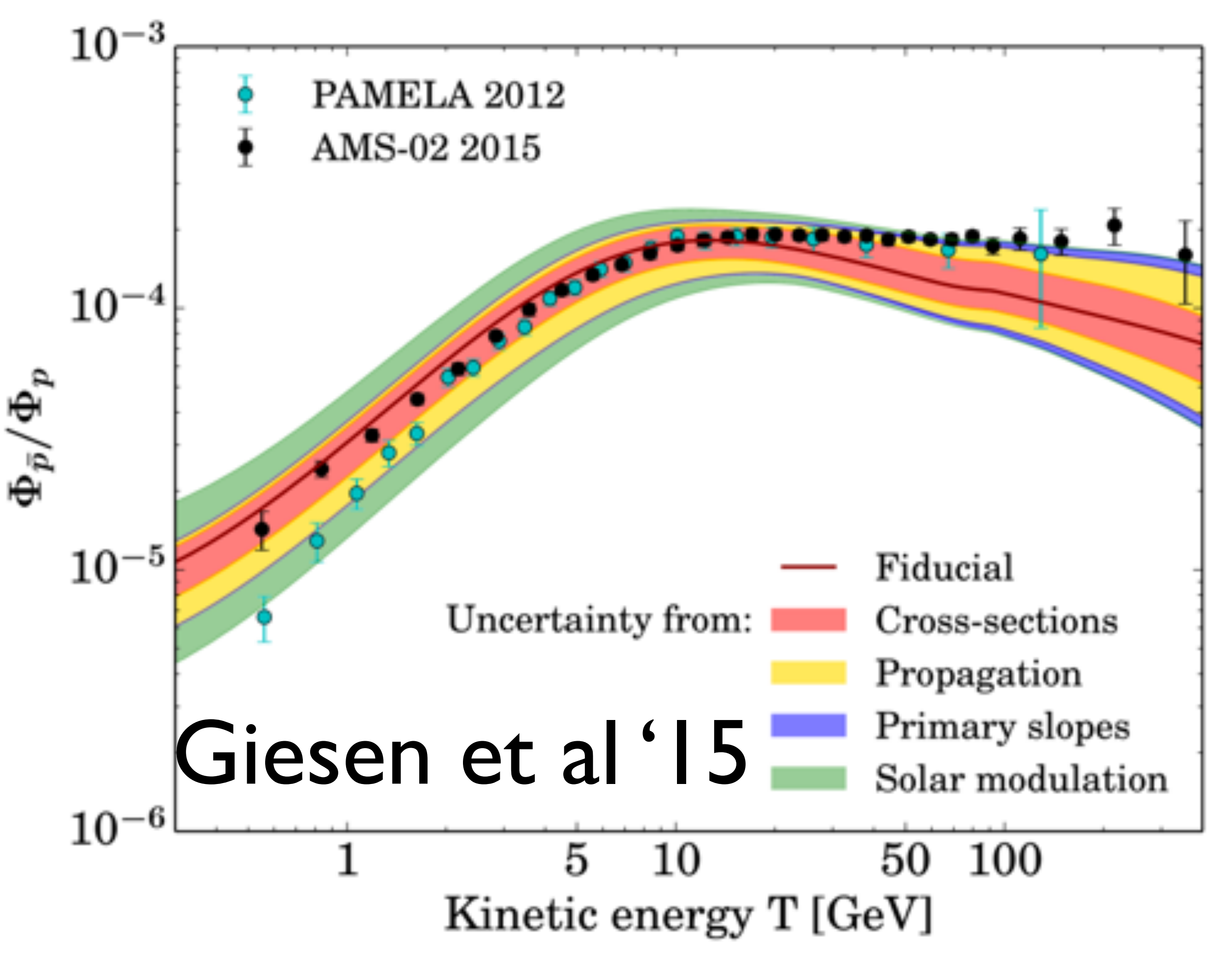


Perez et al '17

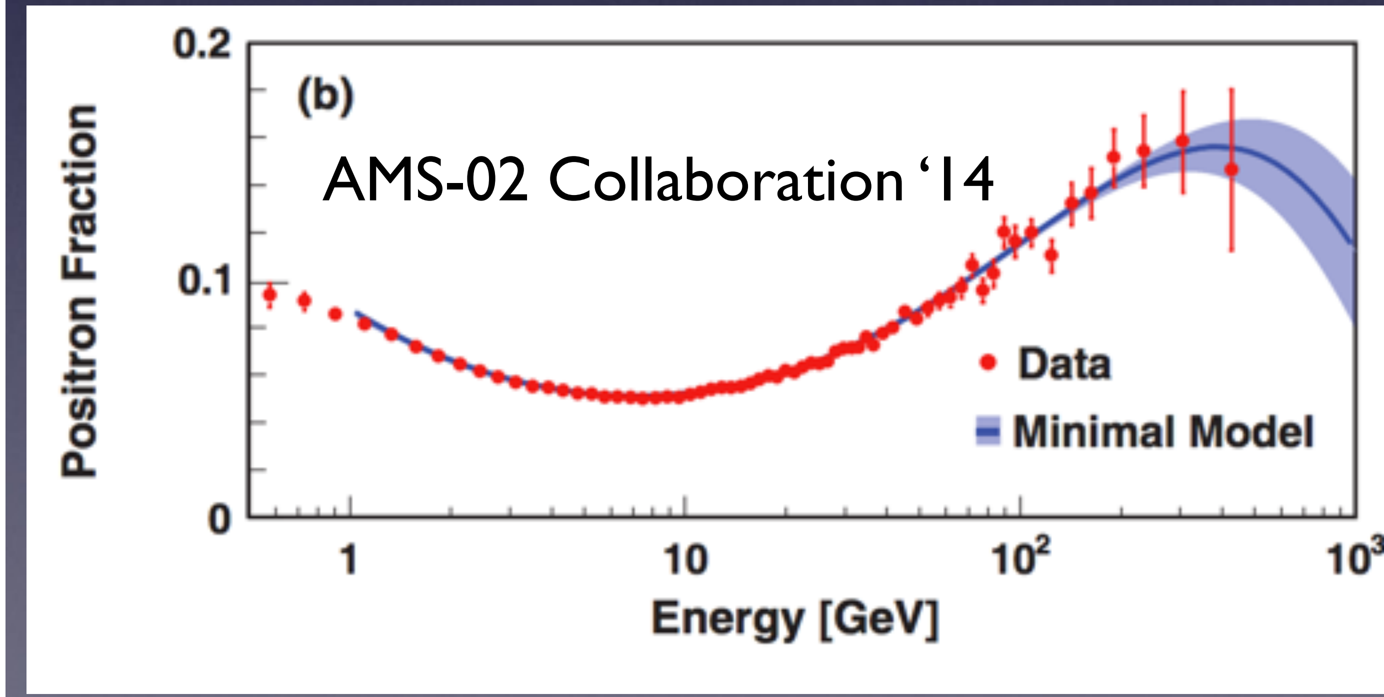
# Cosmic-ray limits

# 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)

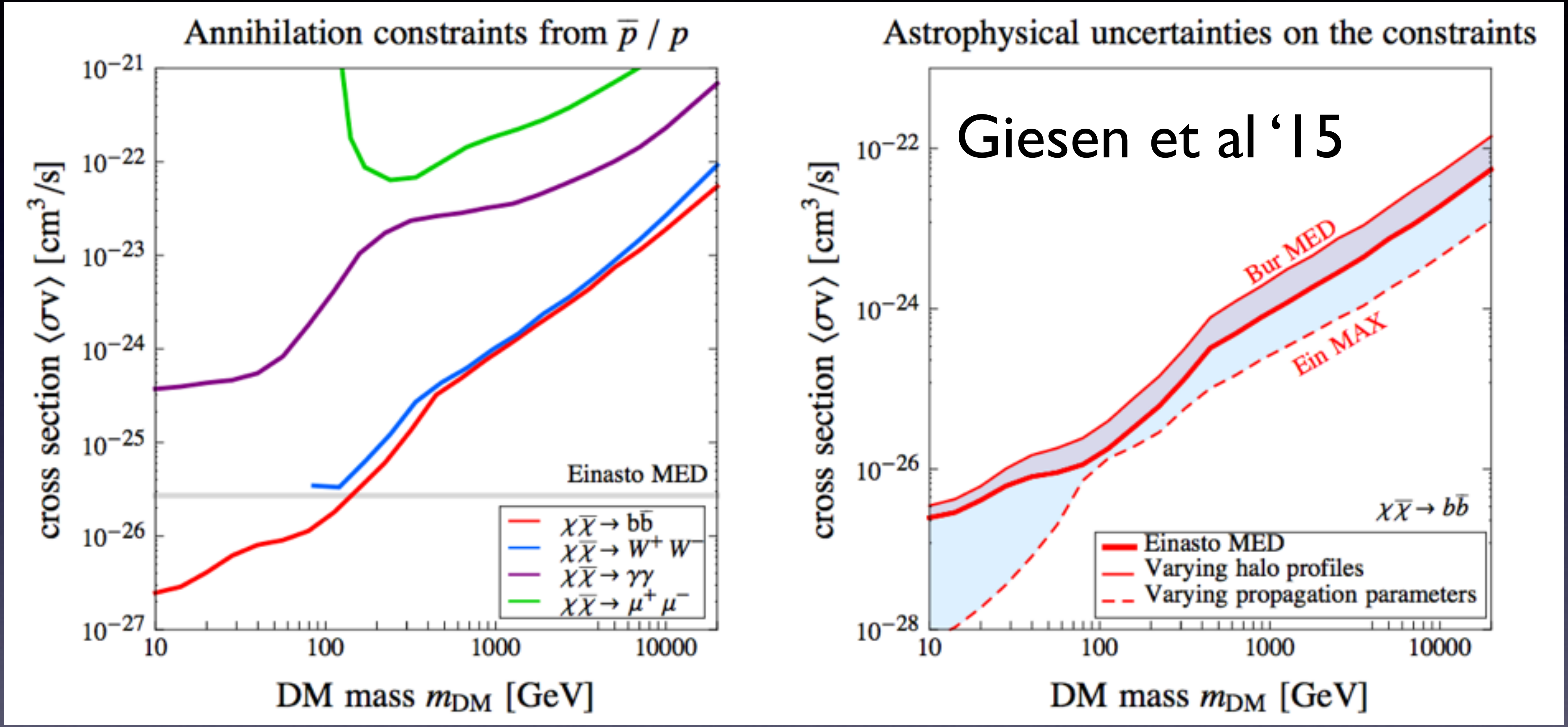


Giesen et al ‘15



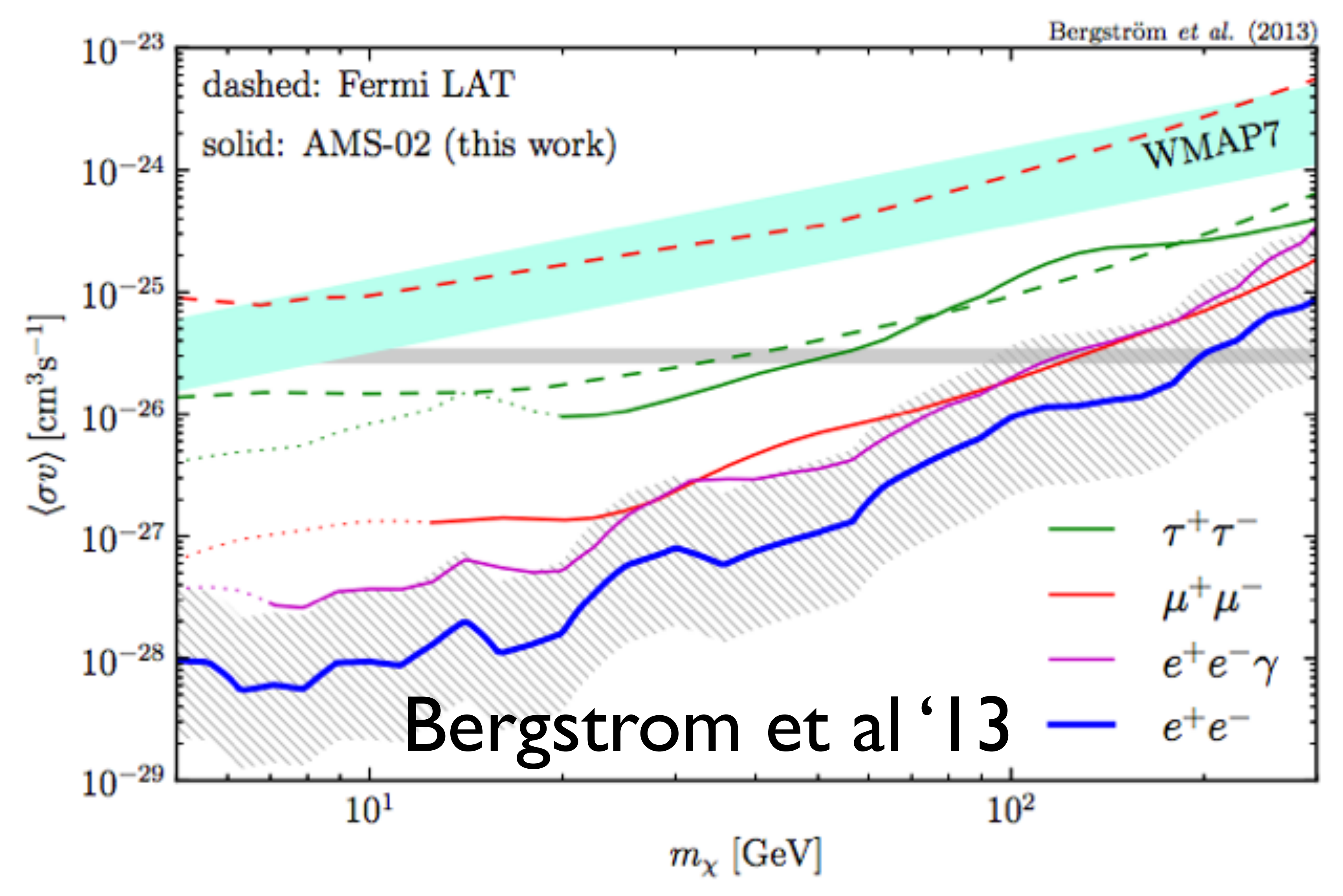
AMS-02 Collaboration ‘14

# 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.

# Cosmic ray limits



Bergstrom et al '13

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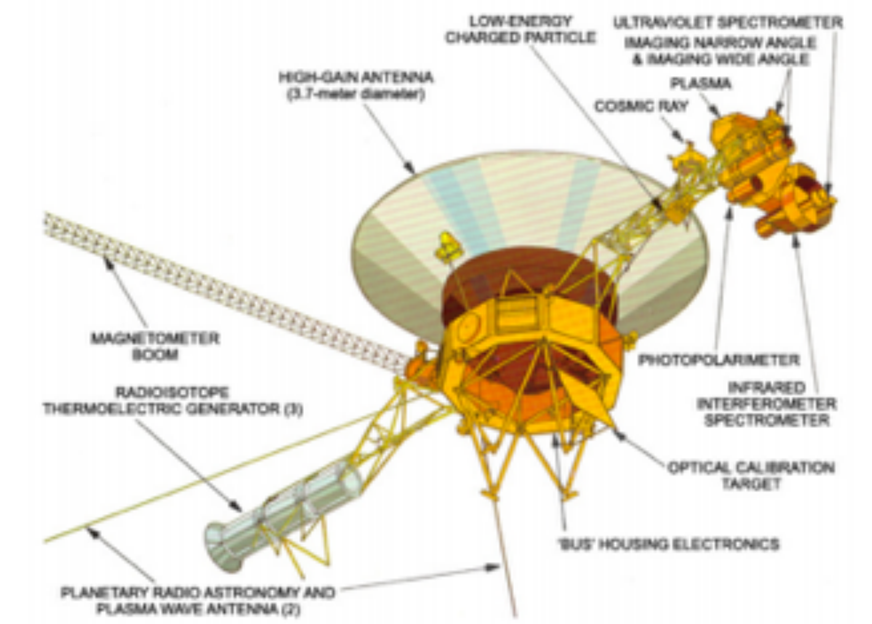
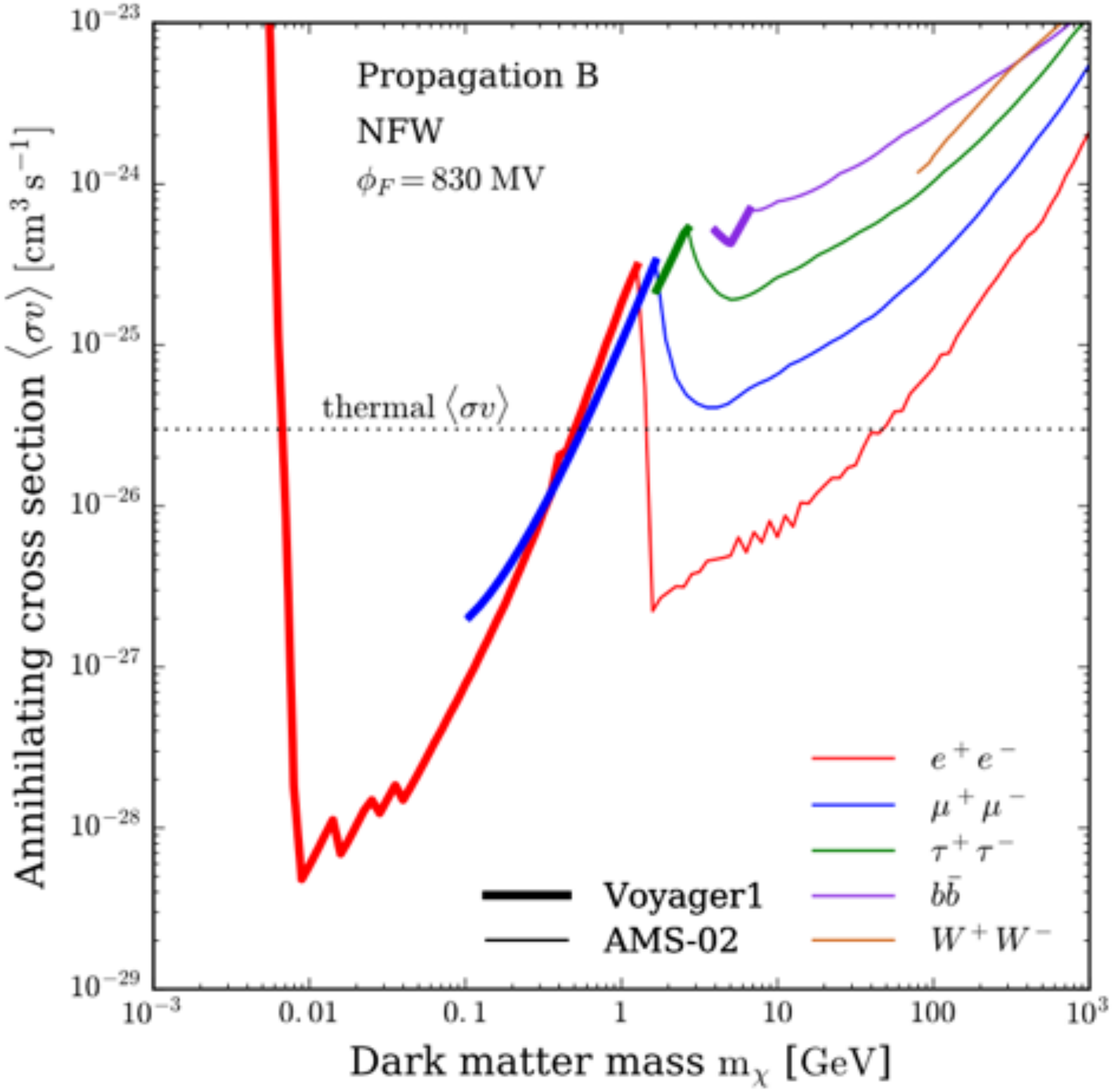
- However, large uncertainties, associated with cosmic-ray propagation/production.

# Voyager (!) limits

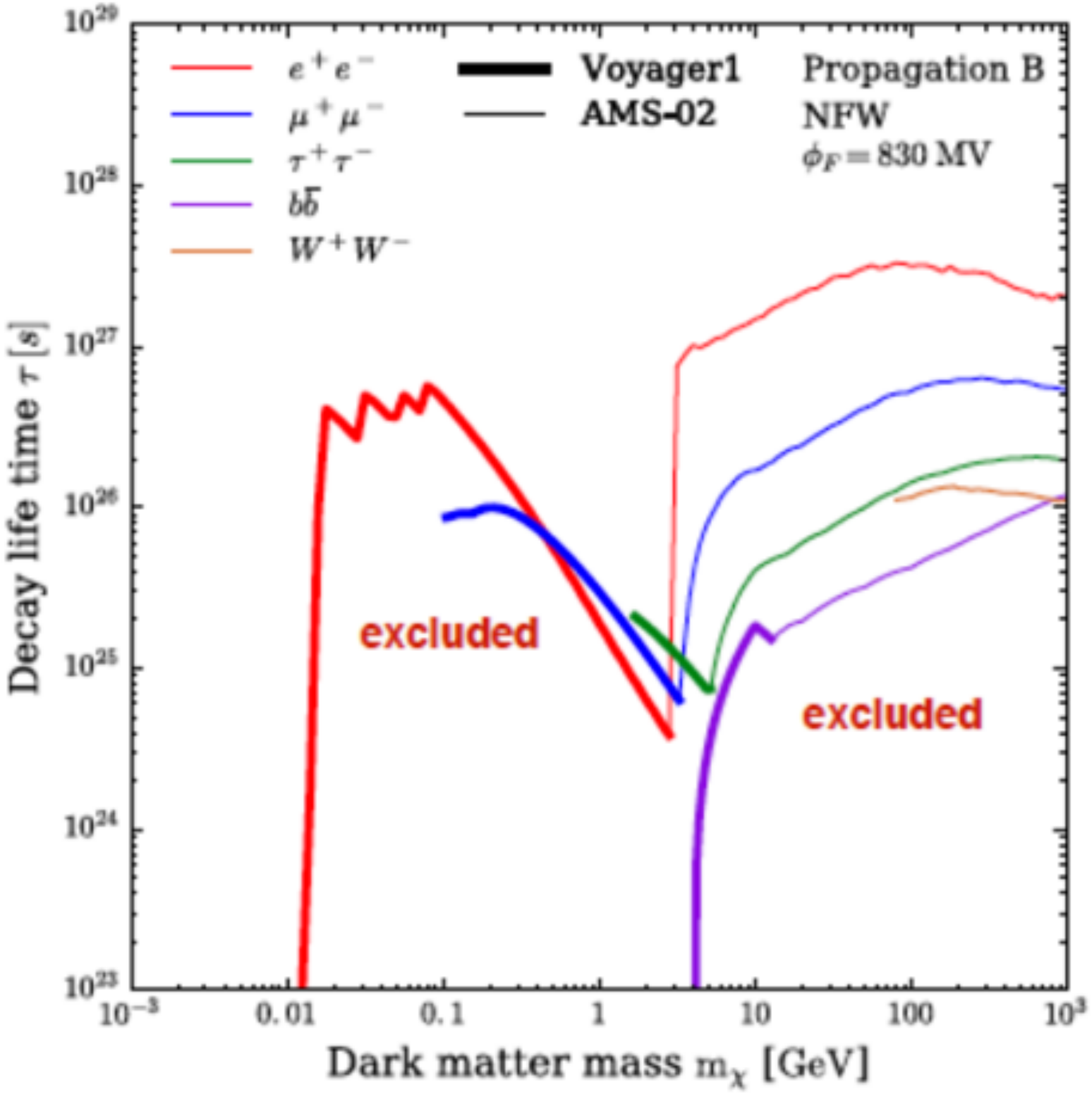


- Voyager I has a spectrometer capable of measuring low-energy cosmic rays
- Now beyond the heliopause - provides unique measurements of interstellar cosmic rays (unaffected by our Sun) and sub-GeV CRs (supppressed by solar wind inside solar system)
- Best limits on ~10 MeV - GeV DM decaying to electrons/positrons,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

Annihilating Dark Matter



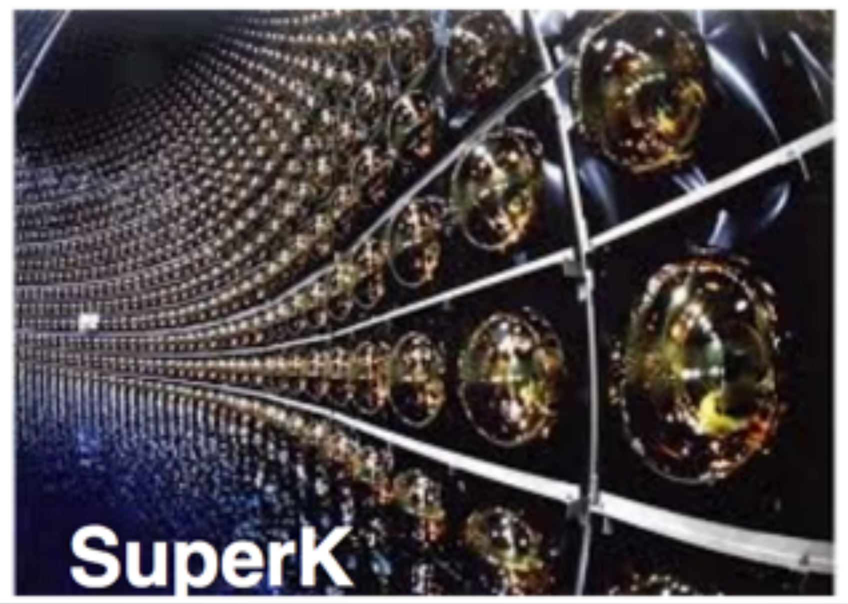
Decaying Dark Matter



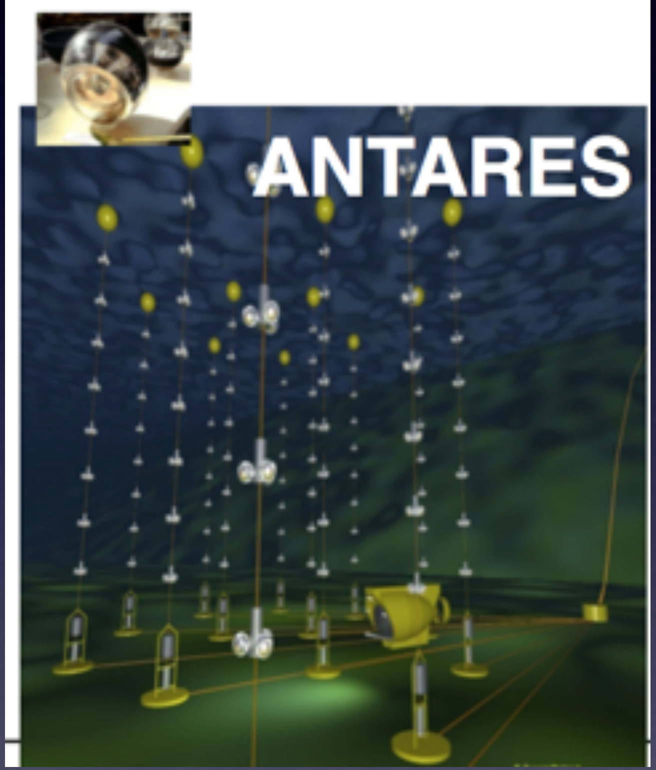
Boudaud et al '16

# Neutrinos from dark matter

few MeV - TeV



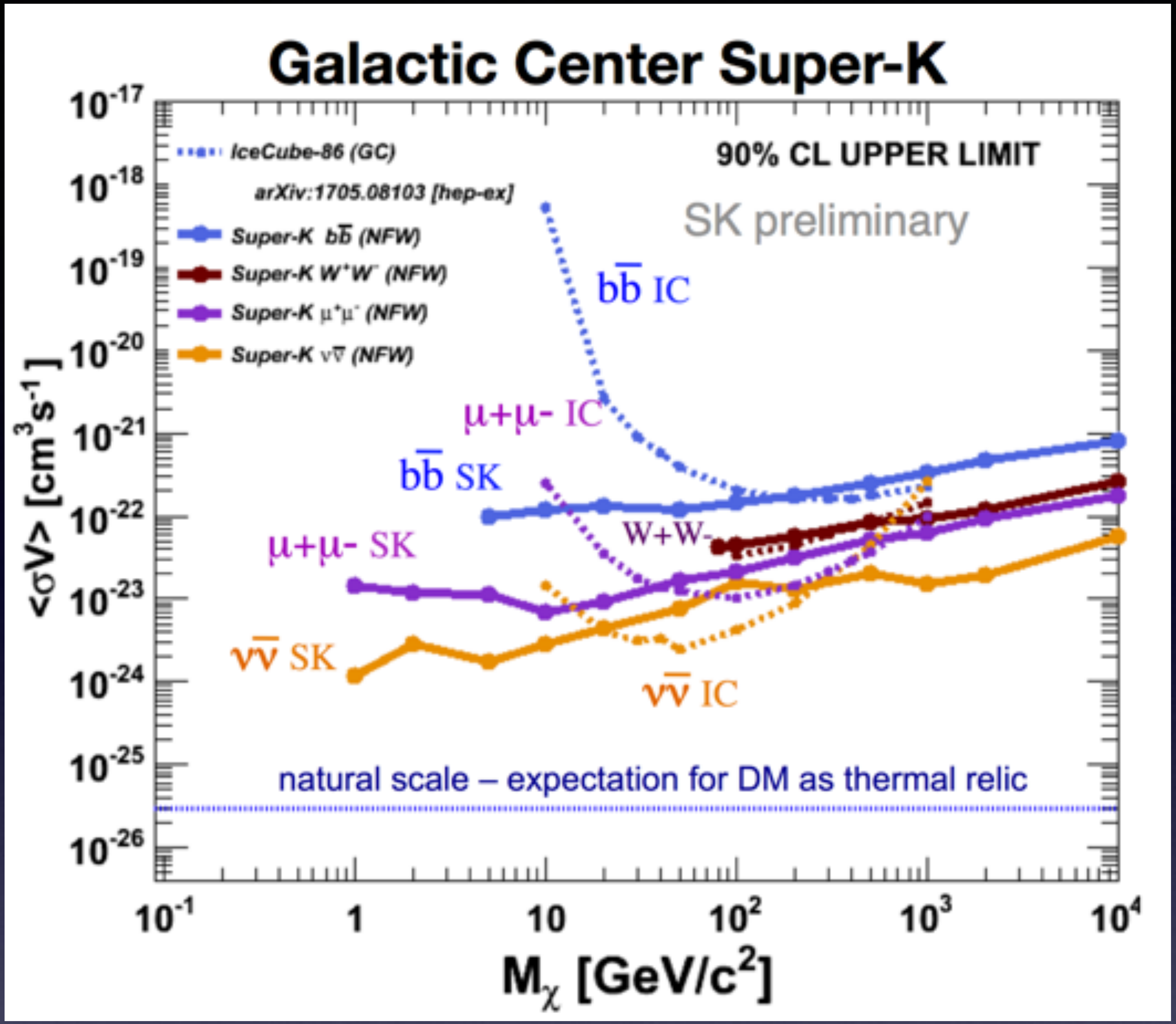
100 GeV - 100 TeV

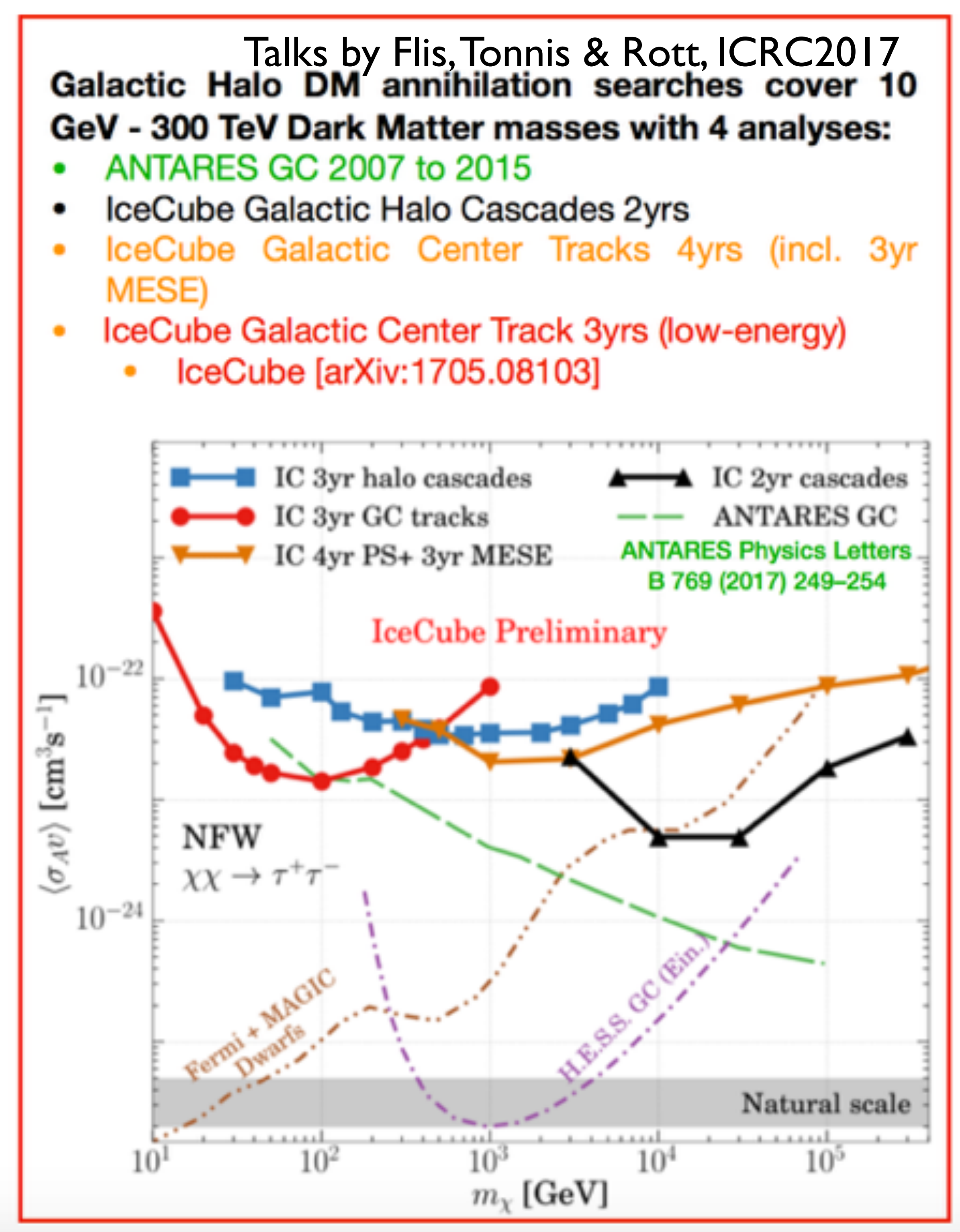


100 GeV - $10^9$ GeV

- 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.





Talks by Flis, Tonnis & Rott, ICRC2017

**Galactic Halo DM annihilation searches cover 10 GeV - 300 TeV Dark Matter masses with 4 analyses:**

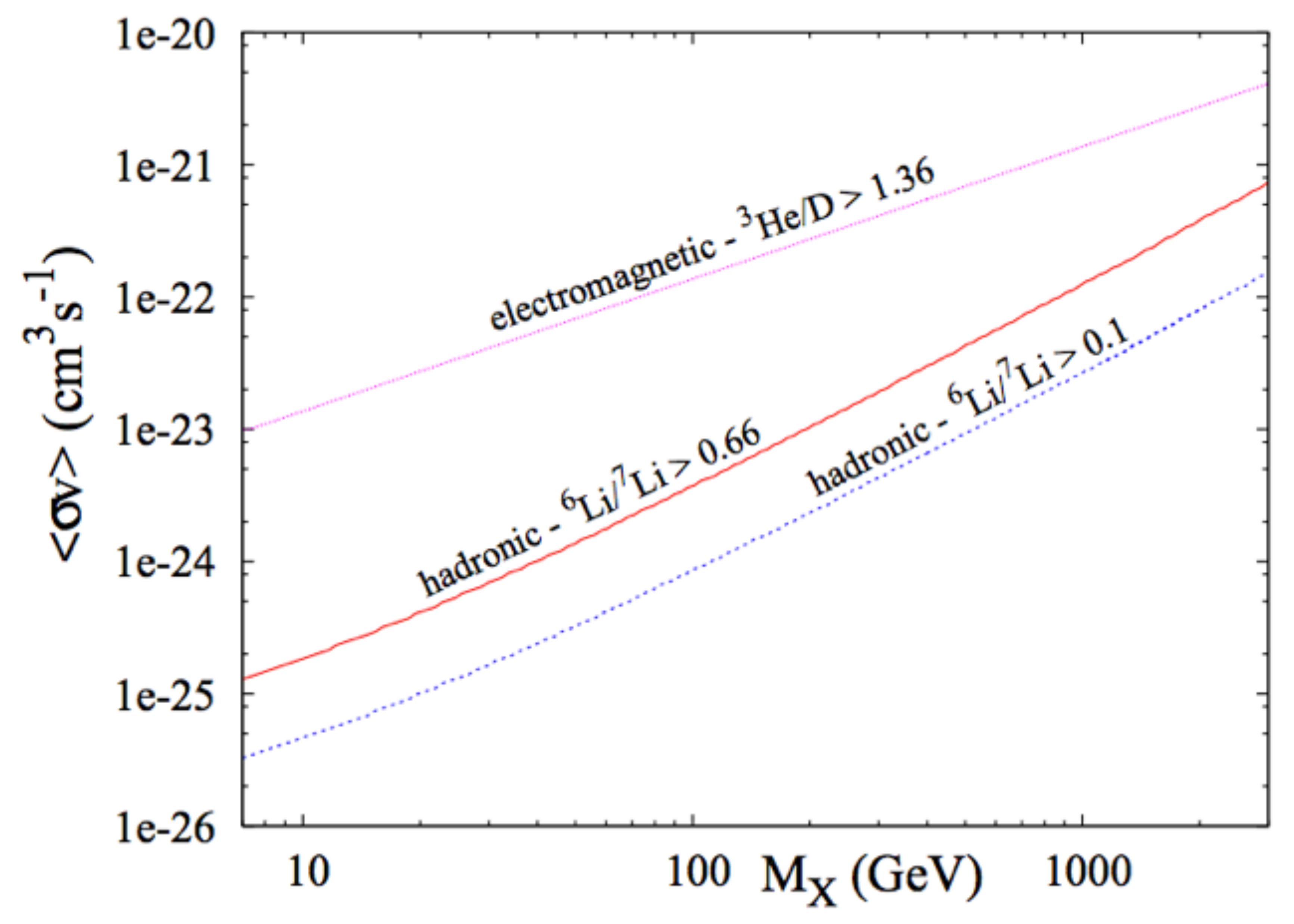
- ANTARES GC 2007 to 2015
- IceCube Galactic Halo Cascades 2yrs
- IceCube Galactic Center Tracks 4yrs (incl. 3yr MESE)
- IceCube Galactic Center Track 3yrs (low-energy)
  - IceCube [arXiv:1705.08103]

- 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.

# Early universe bounds

# 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).



# 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

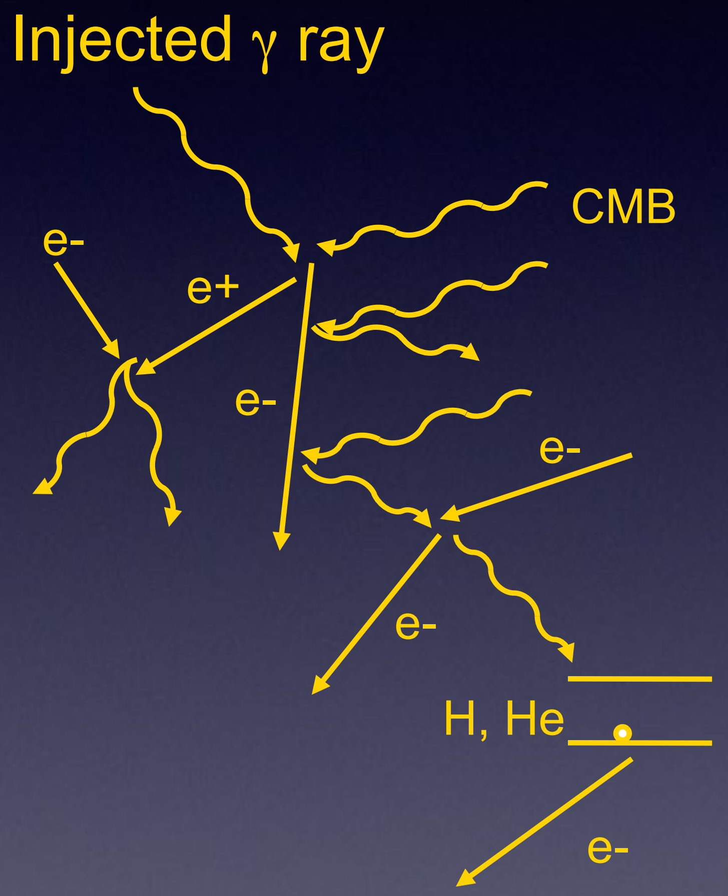
Perturbations to CMB anisotropies

# 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.

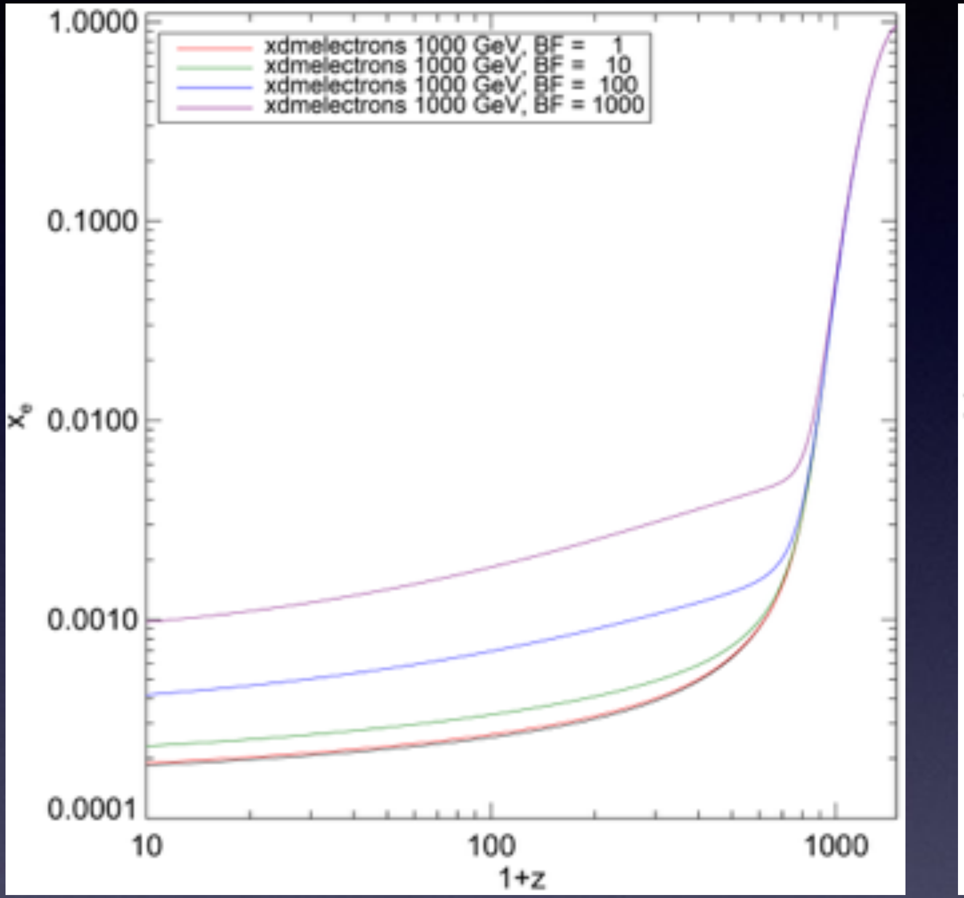


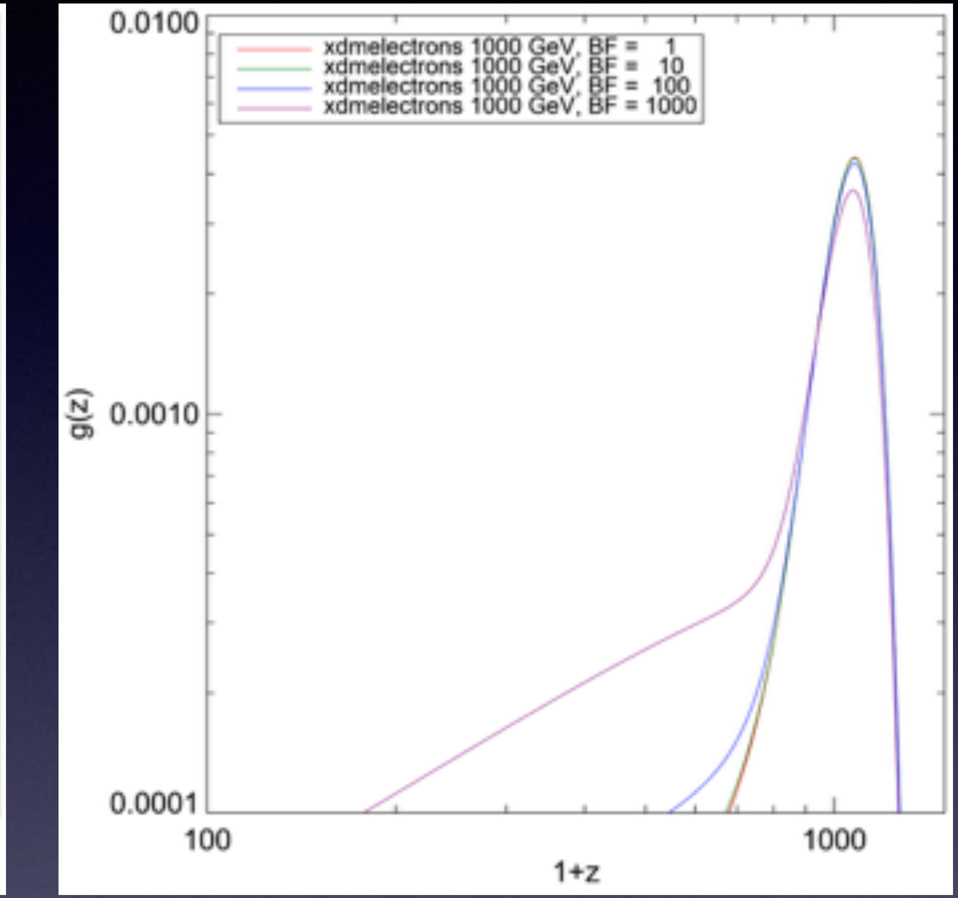
Schematic of a typical cascade:
initial $\gamma$-ray
-> pair production
-> ICS producing a new $\gamma$
-> inelastic Compton scattering
-> photoionization

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

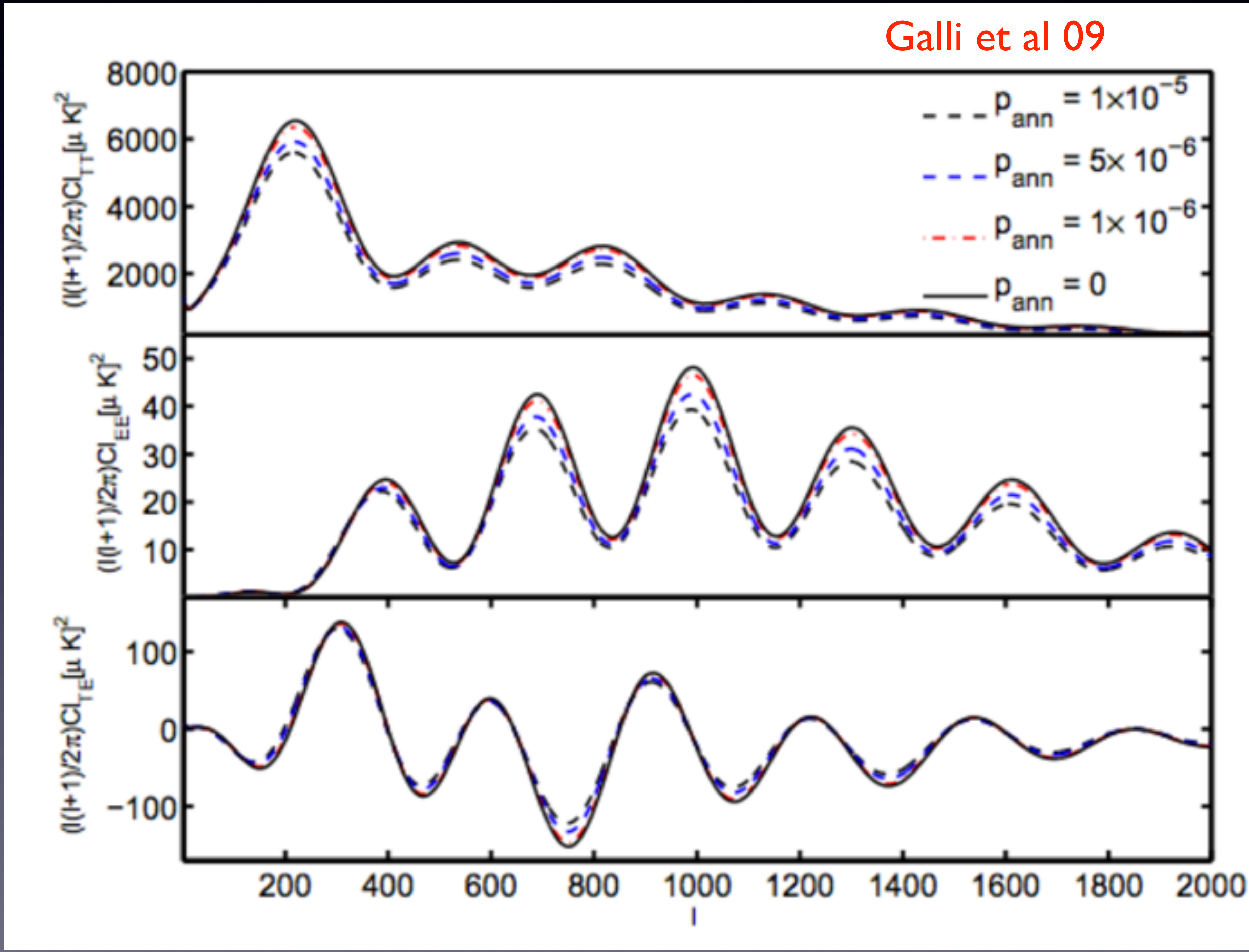




- Example DM model, 1 TeV DM annihilating to electrons.
- Use public codes RECFAST (Seager, Sasselov & Scott 1999) / CosmoRec (Chluba & Thomas 2010) / HyRec (Ali-Haimoud & Hirata 2010) to solve for ionization history.
- At redshifts before recombination, many free electrons => the extra energy injection 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).

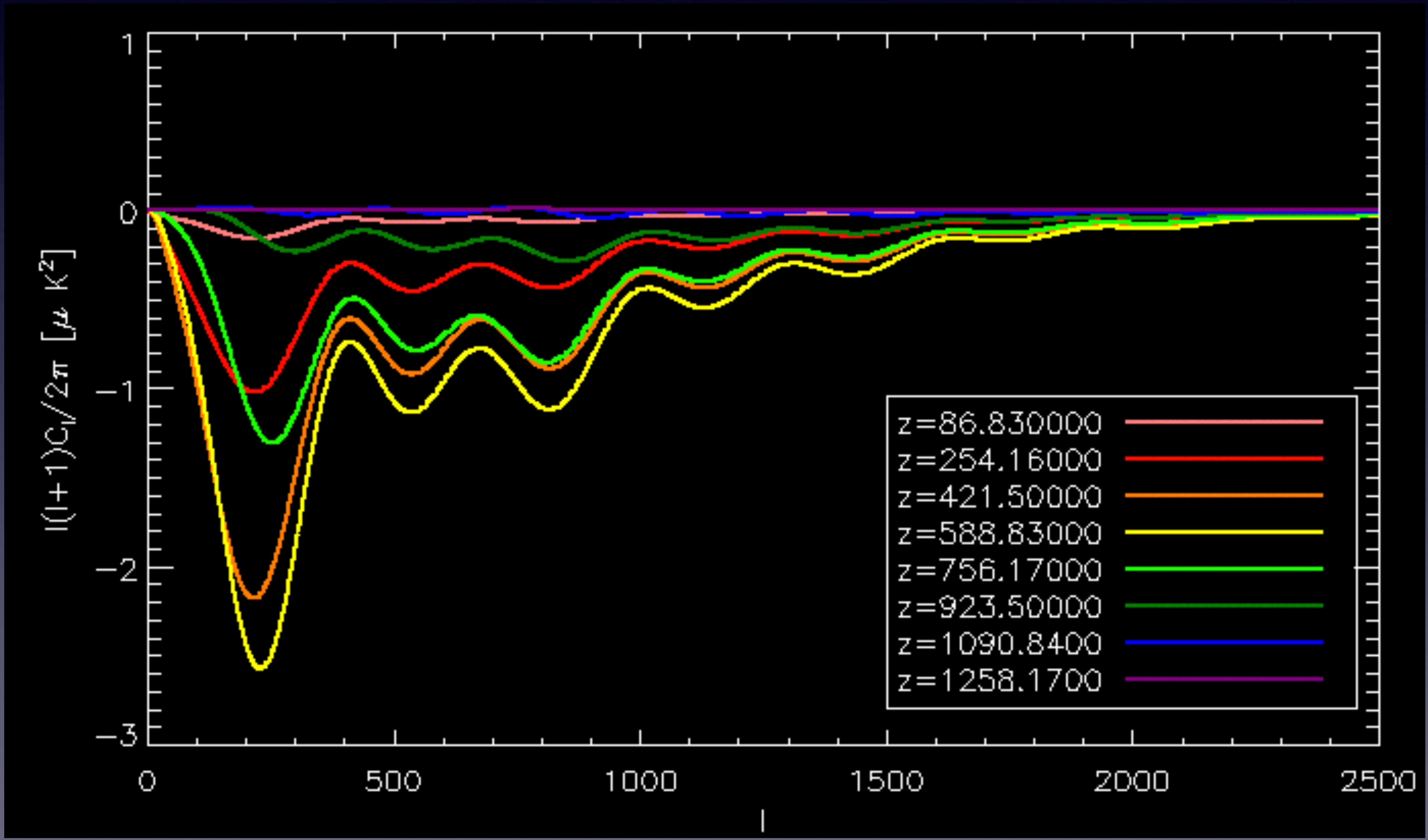


Galli et al 09

# The range of CMB signals

- 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.

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



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.

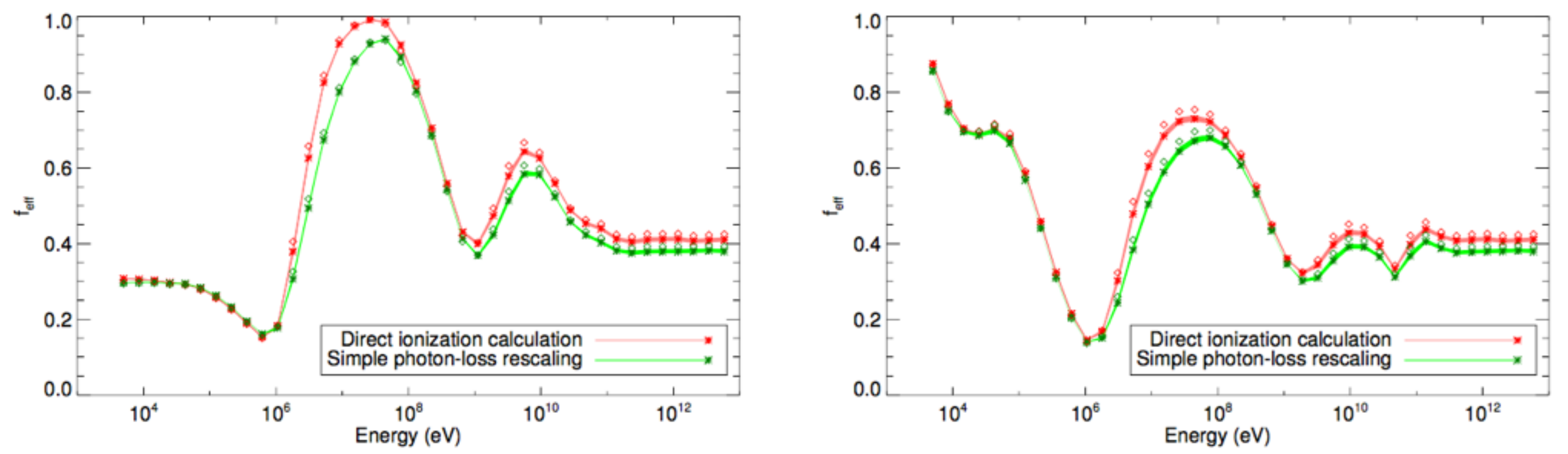
# Principal component analysis

- 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

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

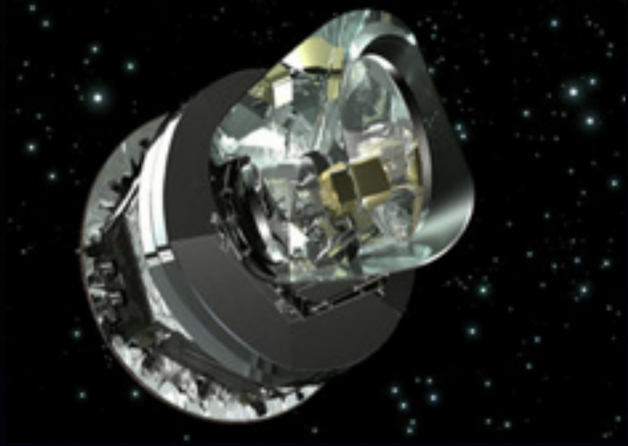
$$(F_e)_{ij} = \sum_\ell \left(\frac{\partial C_\ell}{\partial \alpha_i}\right)^T \cdot \Sigma_\ell^{-1} \cdot \frac{\partial C_\ell}{\partial \alpha_j}.$$

# Energy-dependent efficiency factor

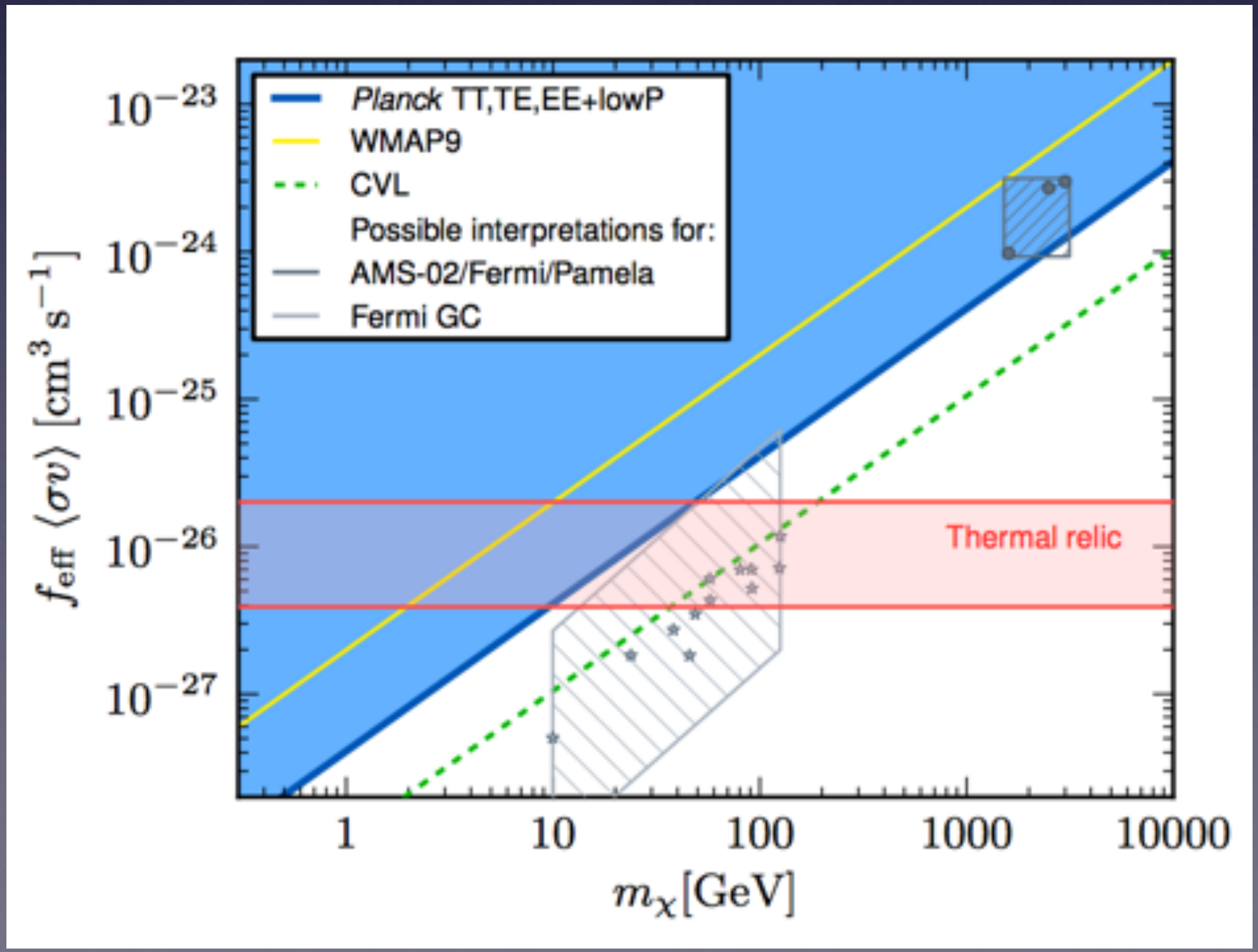


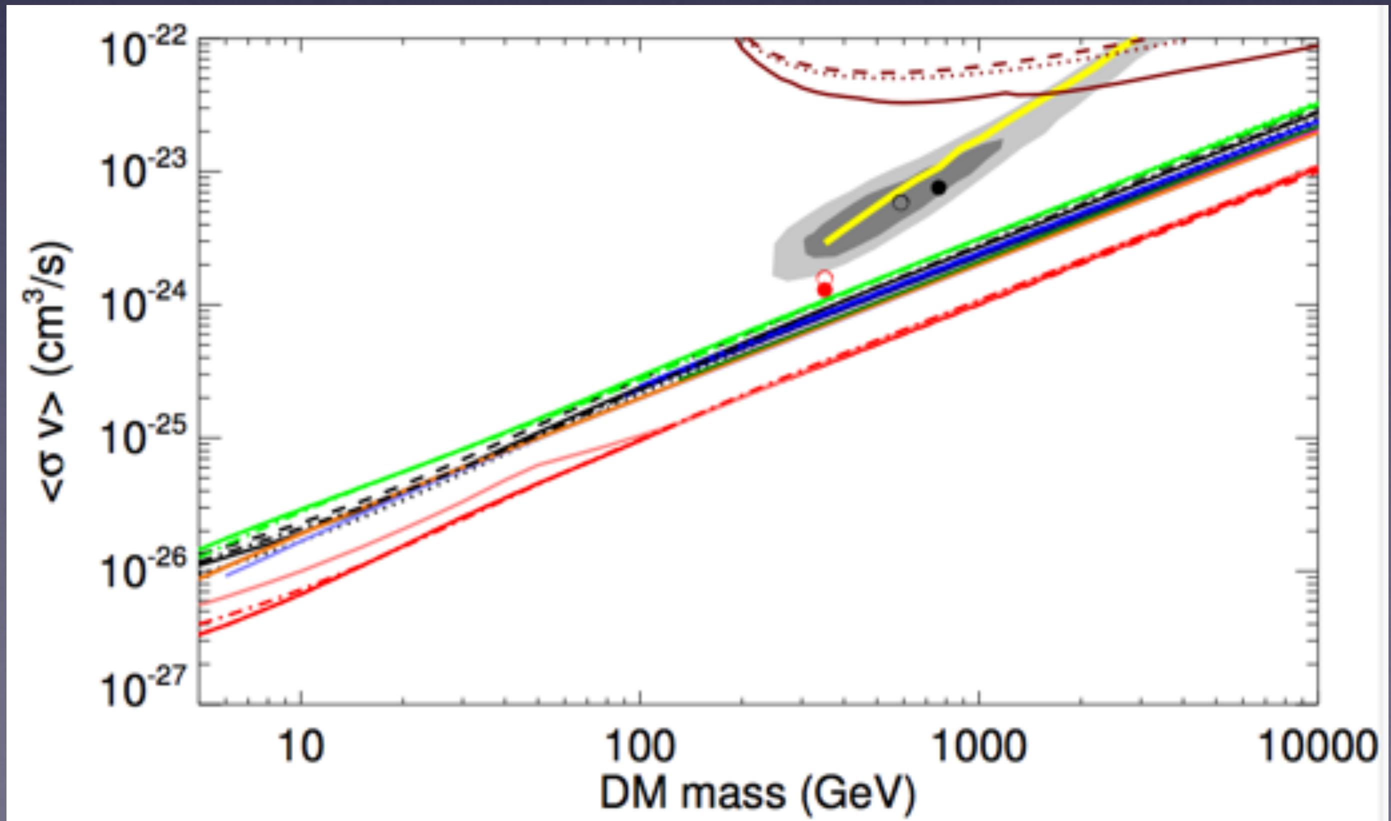
- Accordingly, every DM annihilation model has same imprint on the CMB, up to a normalization factor - each model is characterized by one number (determined roughly by absorption efficiency at z~600; principal component analysis can give precise weighting function). Available at http://nebel.rc.fas.harvard.edu/epsilon/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

# Limits from Planck

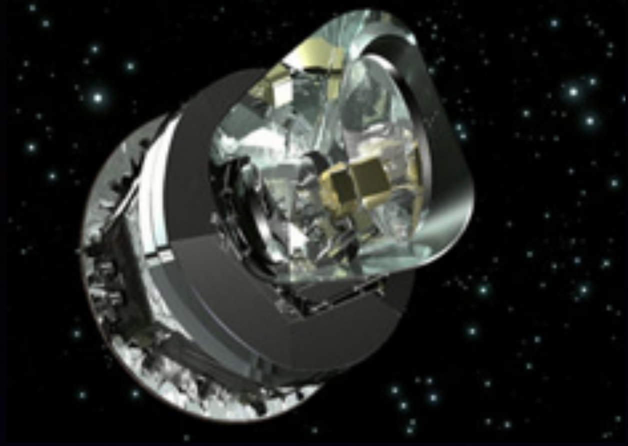


- Planck '15 presented bounds on DM annihilation; consistent with sensitivity predictions from TRS et al, Galli et al 2009.
- Left plot shows Planck bound, right plot shows resulting cross-section limits for a range of channels from TRS '15.
- These limits appear to rule out the DM annihilation interpretation of the excess positrons observed by PAMELA, Fermi and AMS-02.





# Limits from Planck



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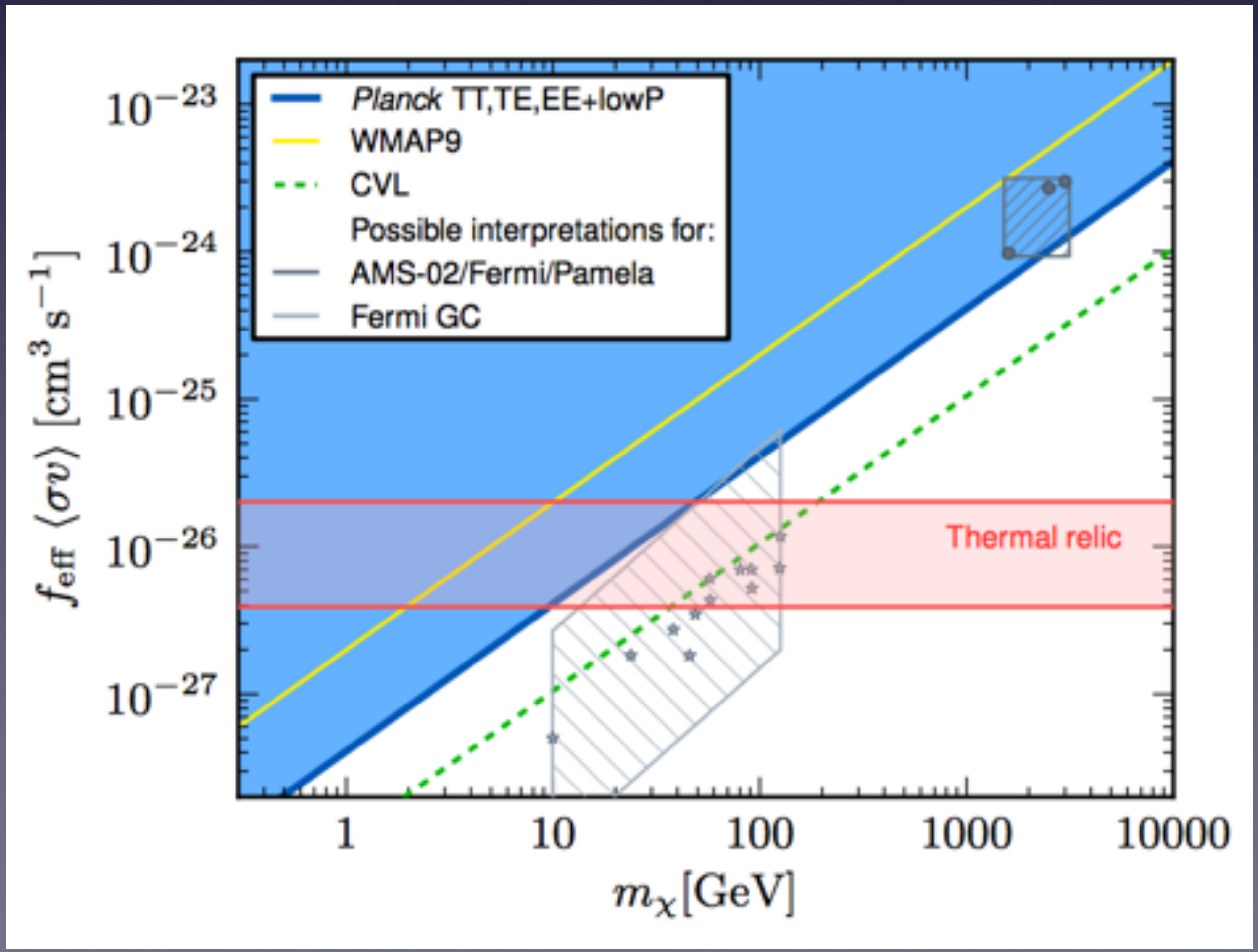
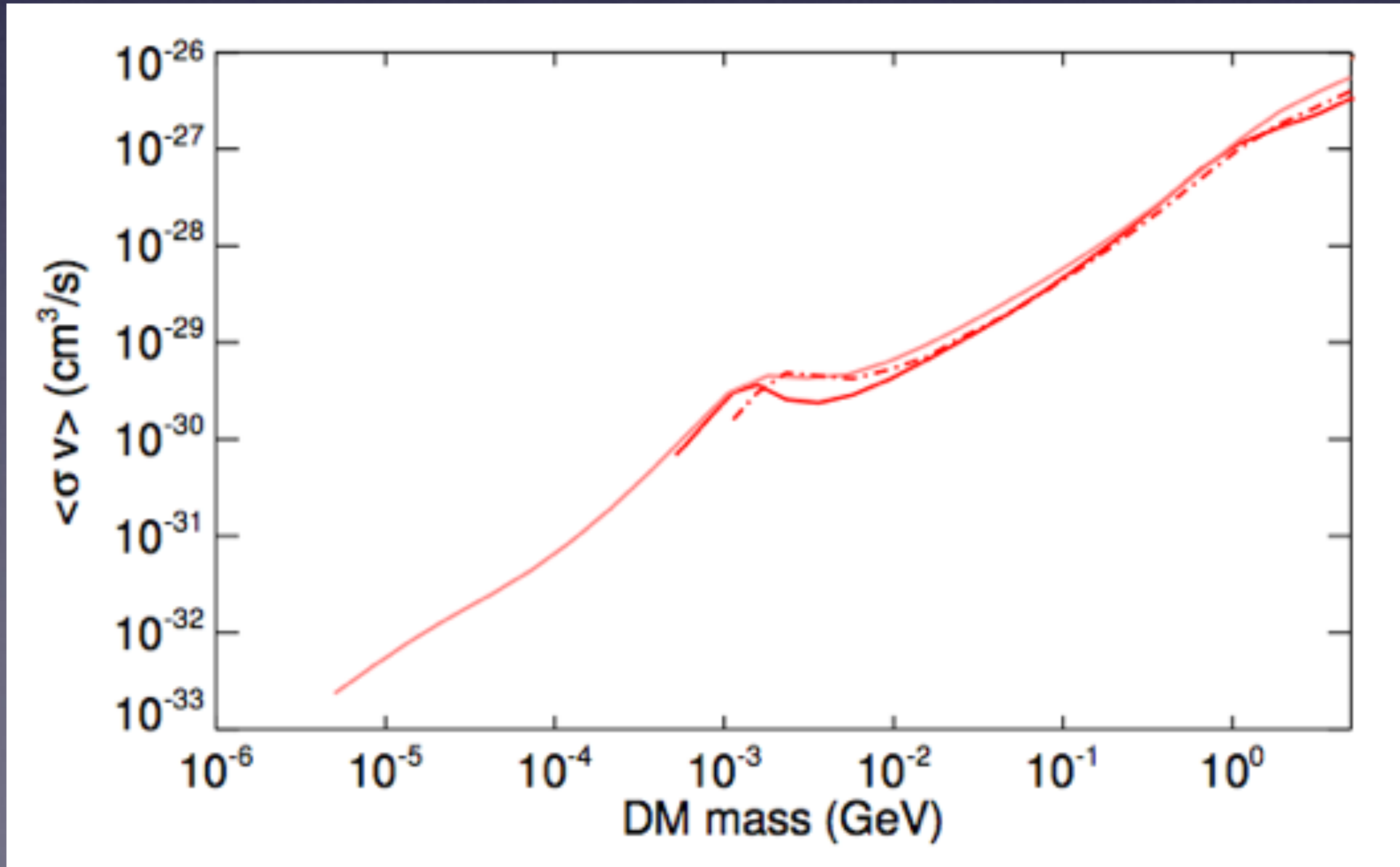
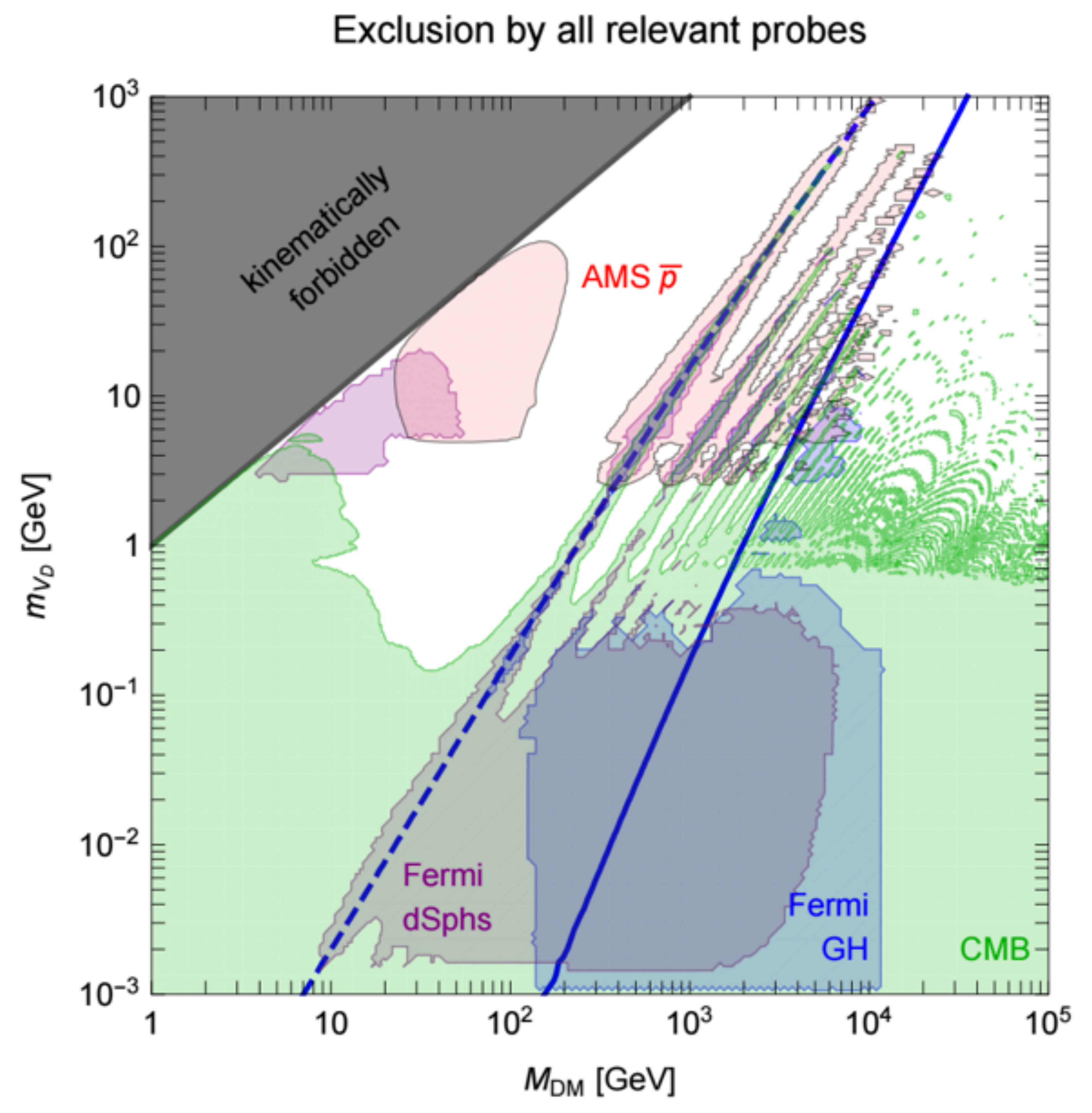




# CMB constraints on dark photons

Cirelli et al ‘17

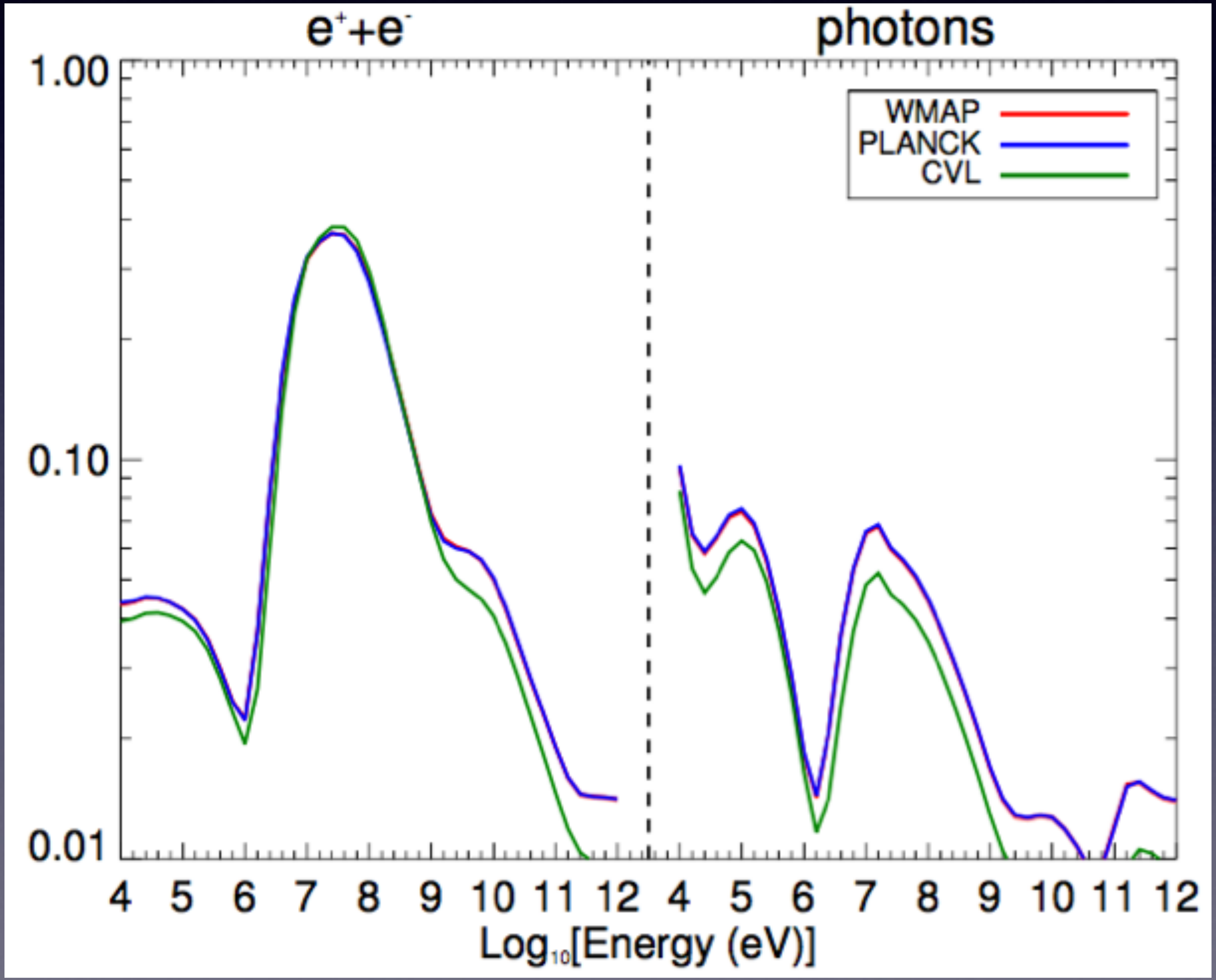


- Model of dark matter coupled to new “dark photons”, mediating dark matter self-interaction.
- Green region ruled out by CMB, assuming DM is a thermal relic and main annihilation channel is to dark photons (sets DM-dark photon coupling).

# Efficiency factors (decay)

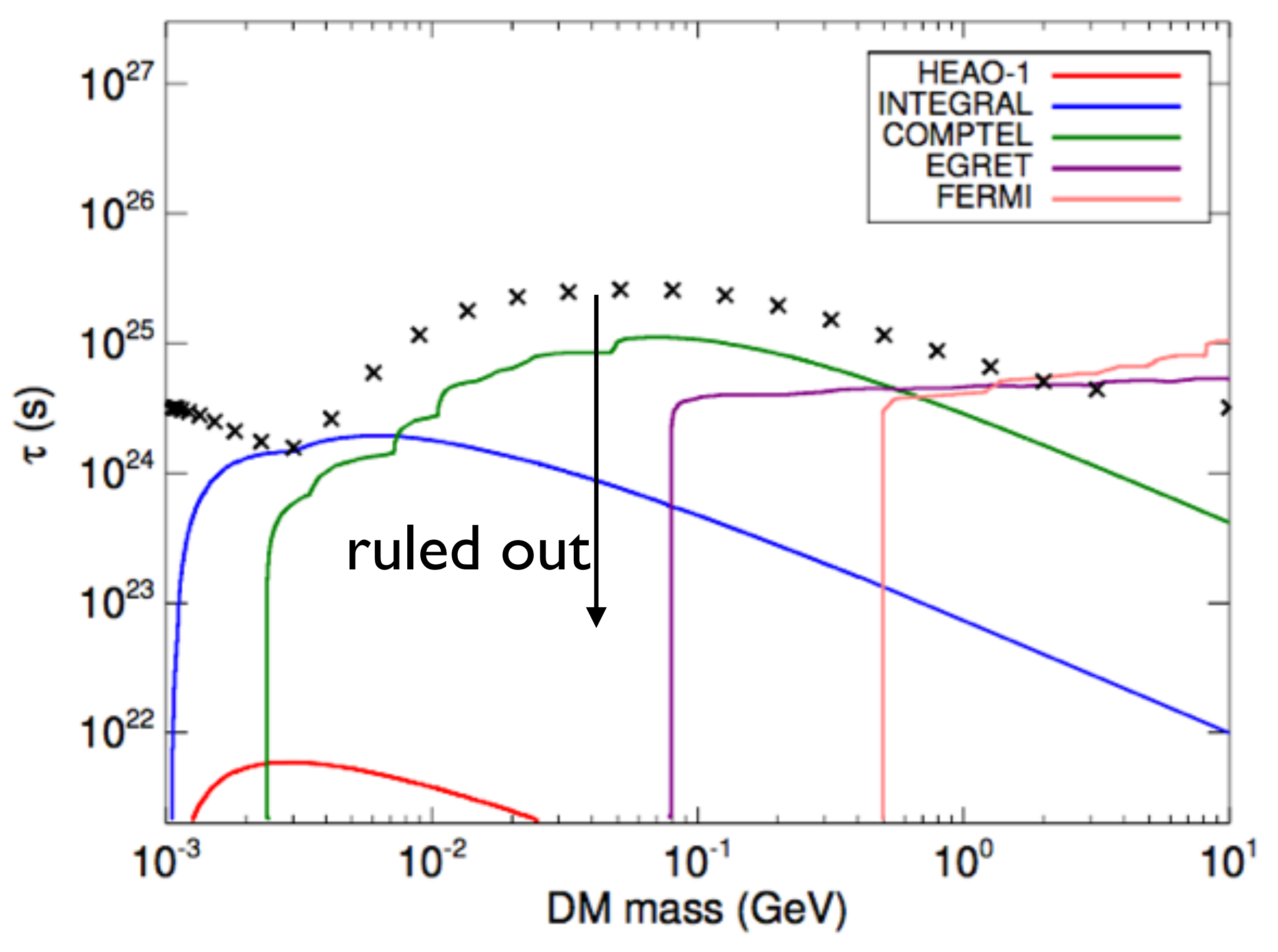
TRS and Wu, PRD95, 023010 (2017)

- 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

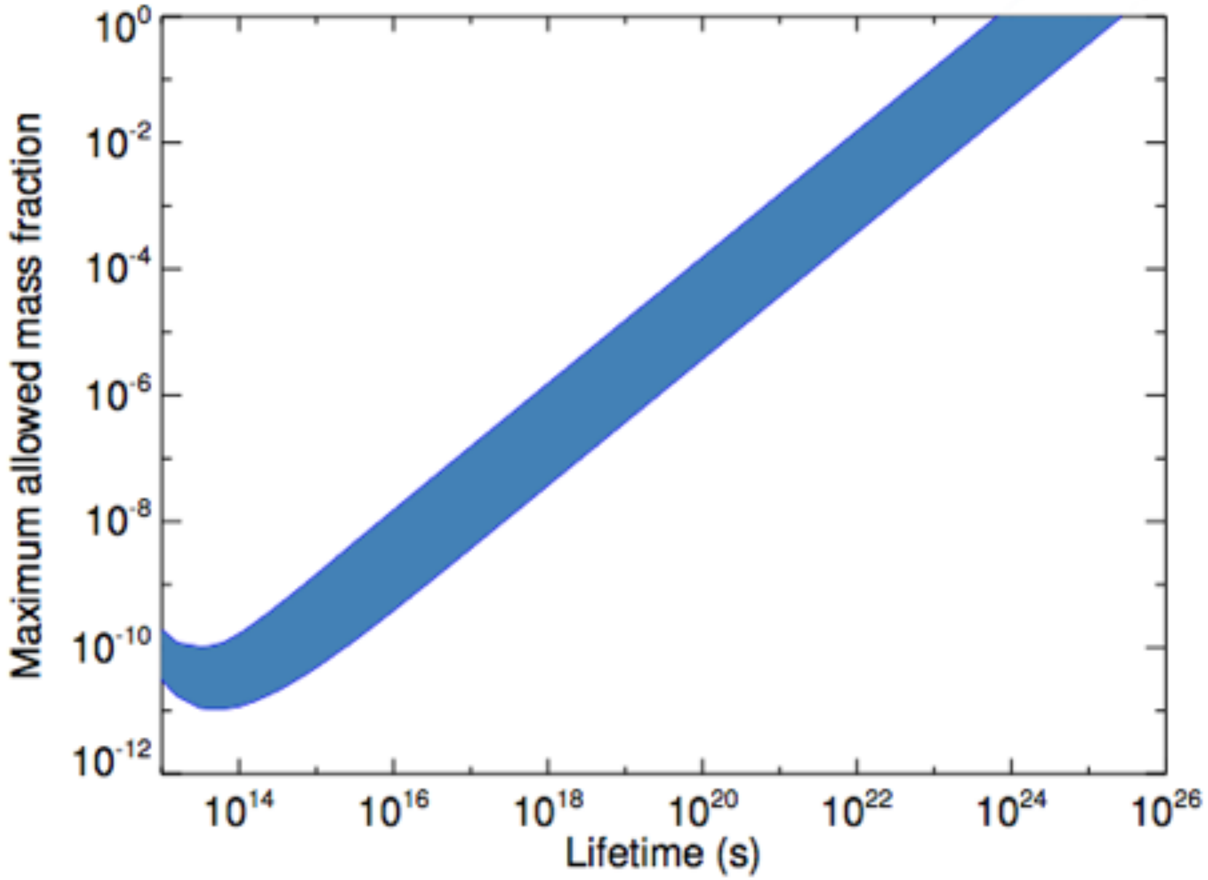
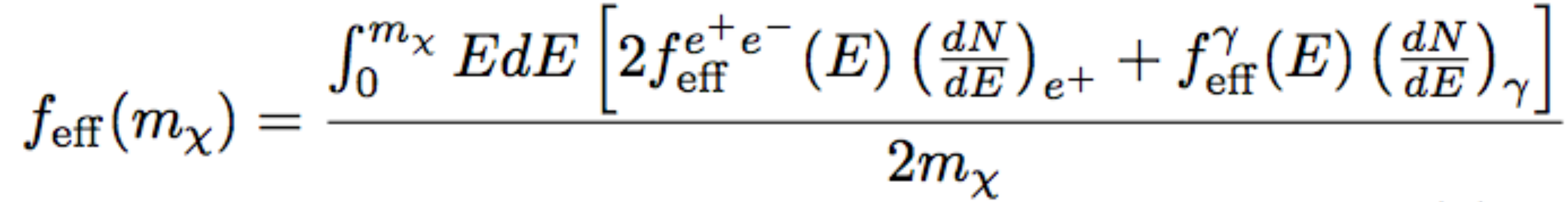


FIG. 11: Range of upper bounds on the mass fraction of DM that can decay with a lifetime $\tau$, for injections of 10 keV – 10 TeV photons and $e^+e^-$ pairs; the width of the band represents a scan over injection species and energy. The constraint is based on the PCA (first PC only) calibrated to the 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 $f_{\text{eff}}$ by average over photon and electron spectra:



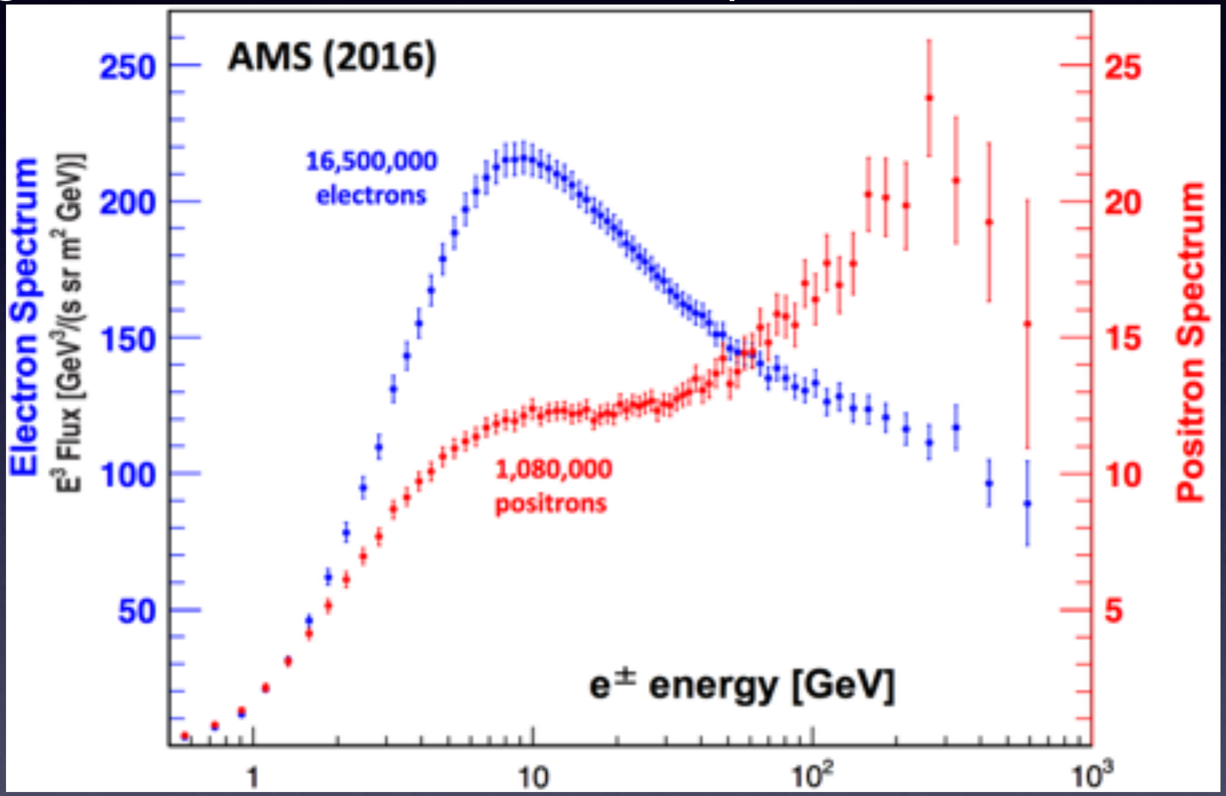
$$f_{\text{eff}}(m_\chi) = \frac{\int_0^{m_\chi} E dE \left[2 f_{\text{eff}}^{e^+e^-}(E) \left(\frac{dN}{dE}\right)_{e+} + f_{\text{eff}}^{\gamma}(E) \left(\frac{dN}{dE}\right)_\gamma\right]}{2 m_\chi}$$

- For annihilation, impose constraint on annihilation parameter: $f_{\text{eff}} \frac{\langle \sigma v \rangle}{m_\chi} < 4.1 \times 10^{-28} \text{cm}^3/\text{s}/\text{GeV}$
- For decay, write $g_{\text{eff}} = f_{\text{eff}} / f_{\text{eff}}$(30 MeV $e^+e^-$), apply constraint on lifetime: $\tau / g_{\text{eff}} \gtrsim 2.6 \times 10^{25} s$

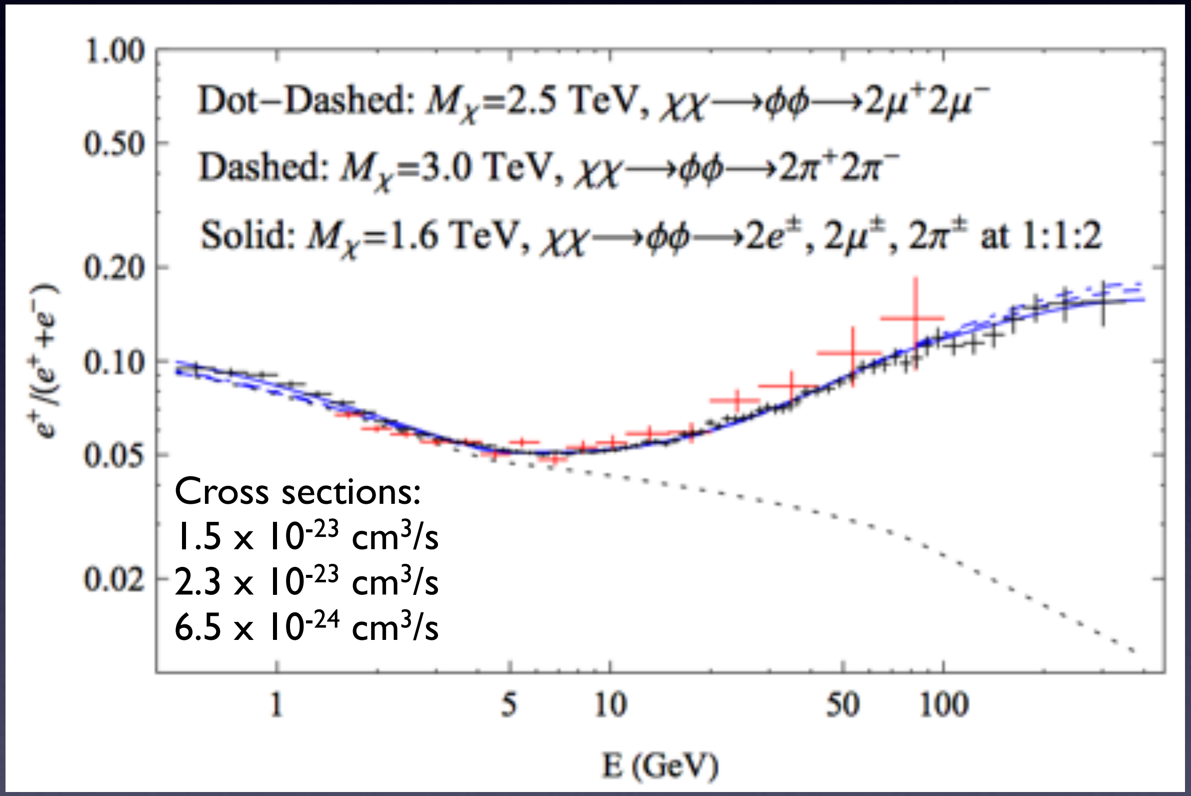
# Beyond constraints: hints of signals?

# The PAMELA/Fermi/AMS-02 positron excess

Sam Ting, 8 December 2016, CERN colloquium



Cholis & Hooper '13



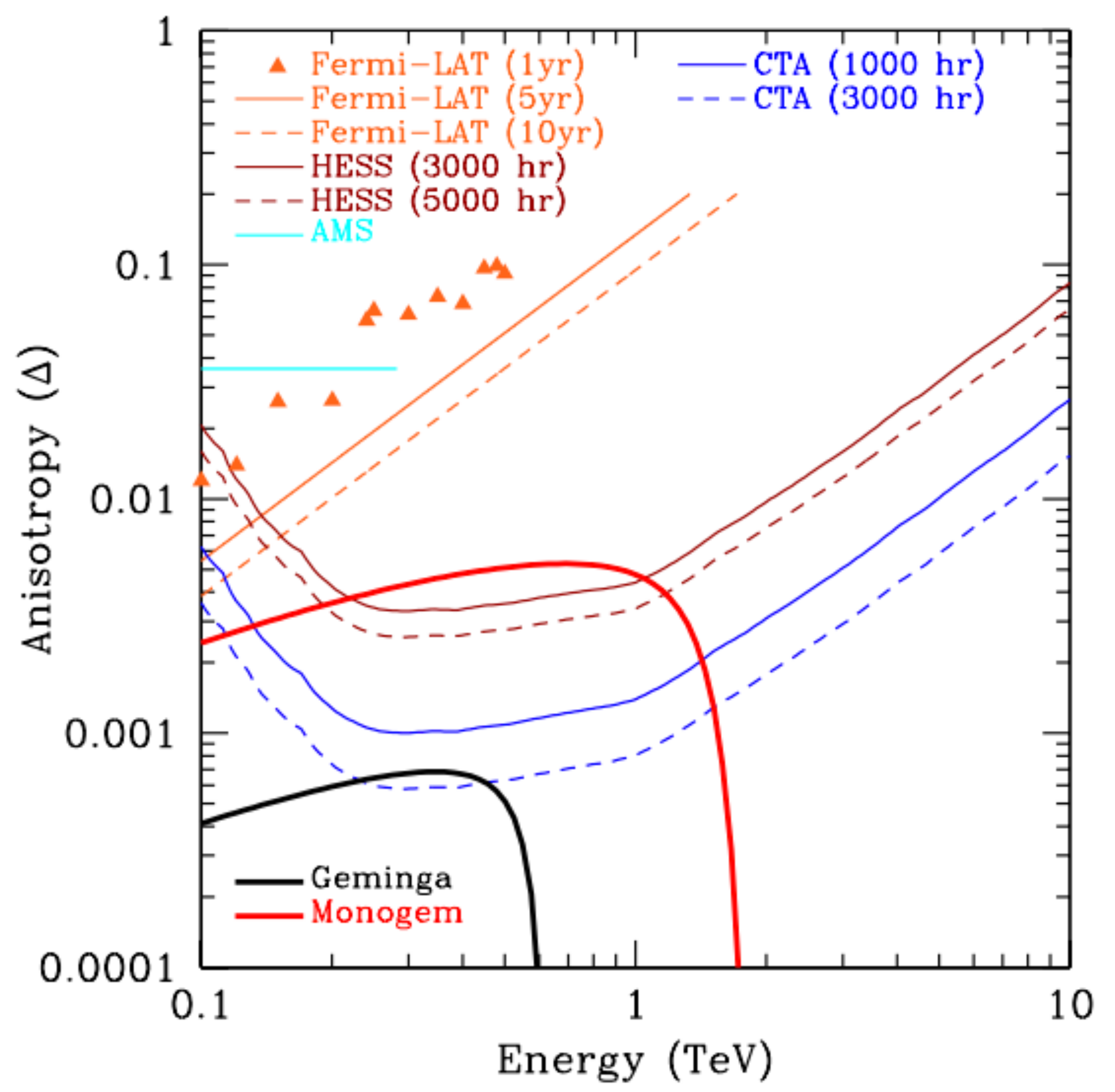
Cross sections:
$1.5 \times 10^{-23}$ cm$^3$/s
$2.3 \times 10^{-23}$ cm$^3$/s
$6.5 \times 10^{-24}$ cm$^3$/s

- 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

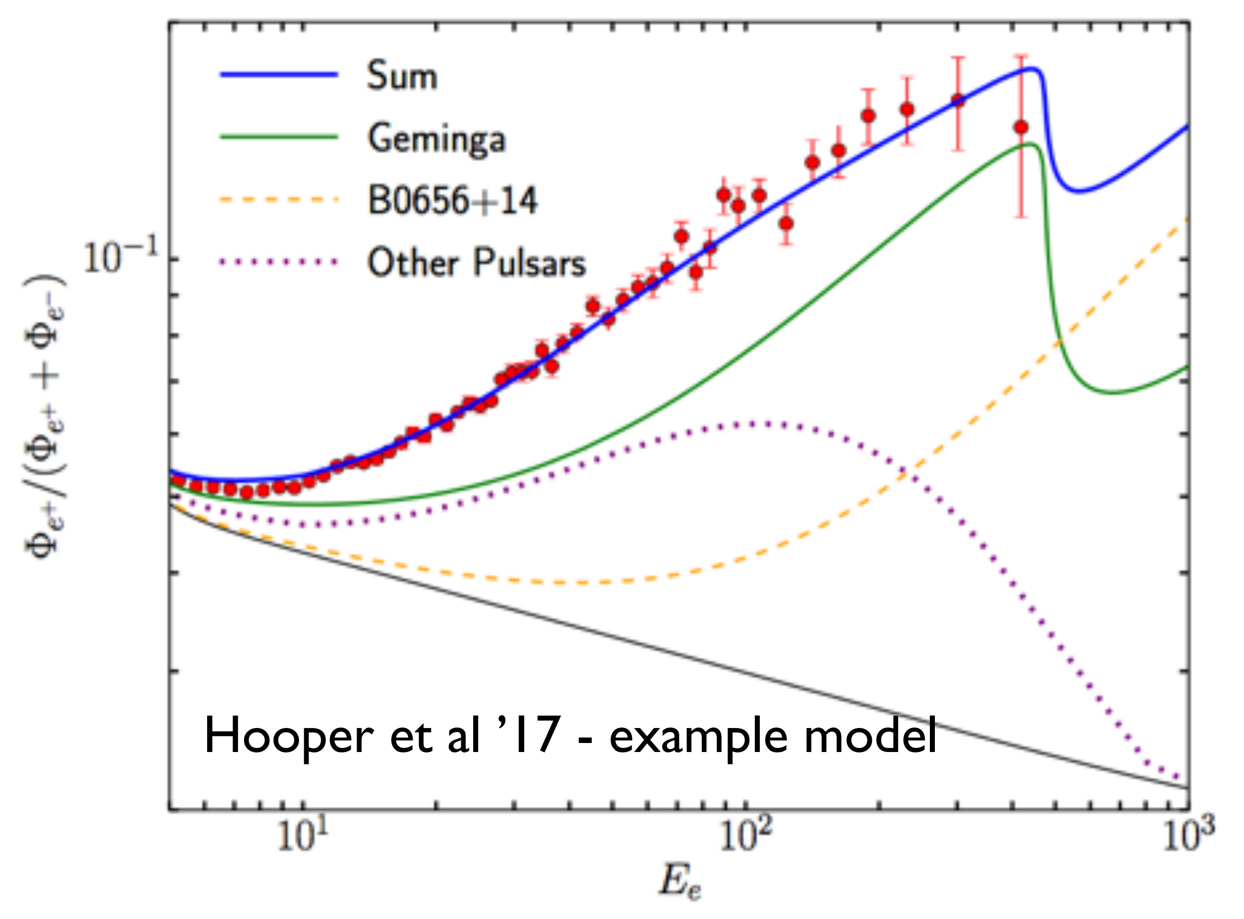
Linden & Profumo '13

- 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?

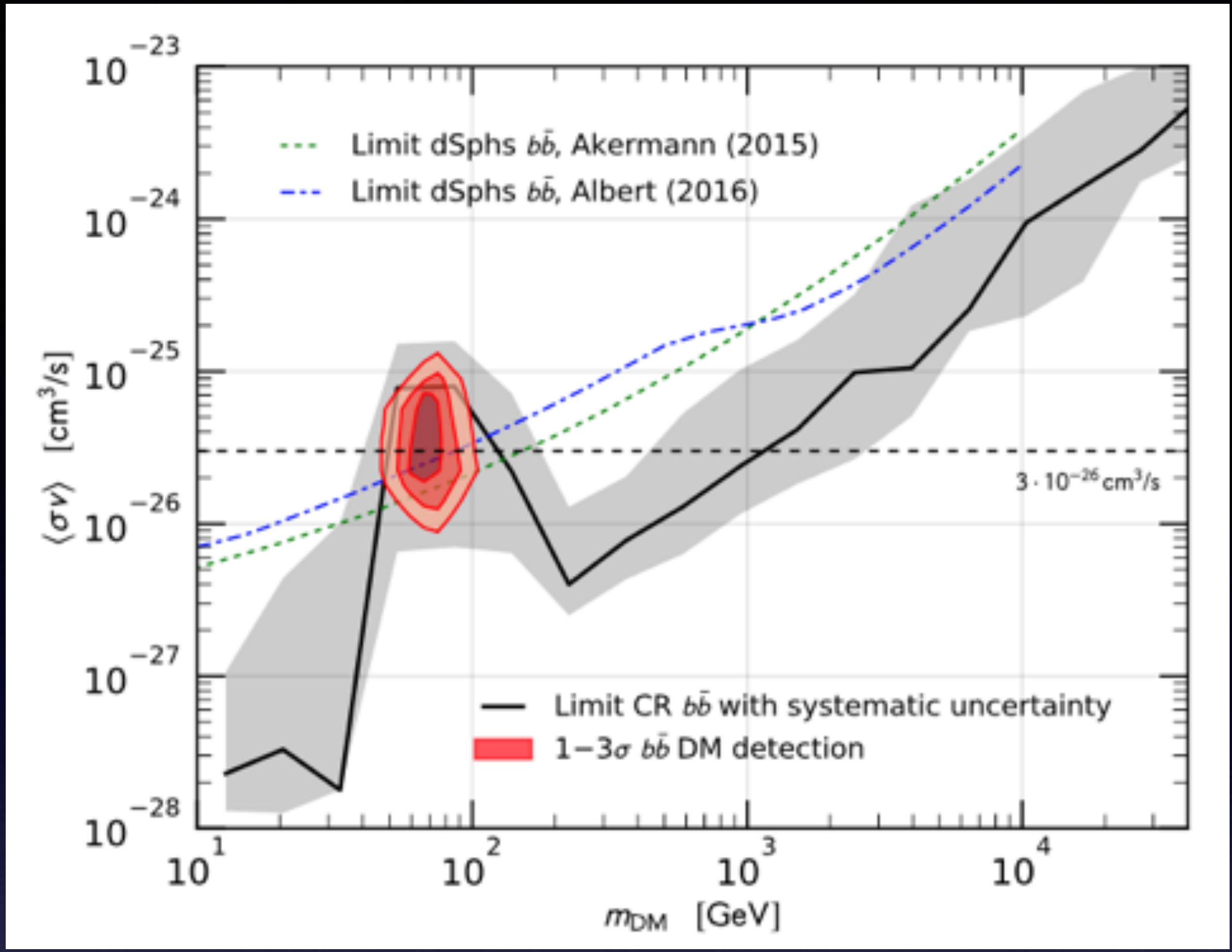
- Recent development: HAWC has detected extended gamma-ray emission around two nearby pulsars, Geminga and B0656+14 (Abeysekara et al ’17, 2HWC catalog)
- If interpreted as a halo of inverse-Compton-scattered light, these results constrain e+e- production by these pulsars.
- Hooper et al ’17 argue these measurements suggest pulsars provide a dominant contribution to the AMS-02 positrons.



Hooper et al ’17 - example model

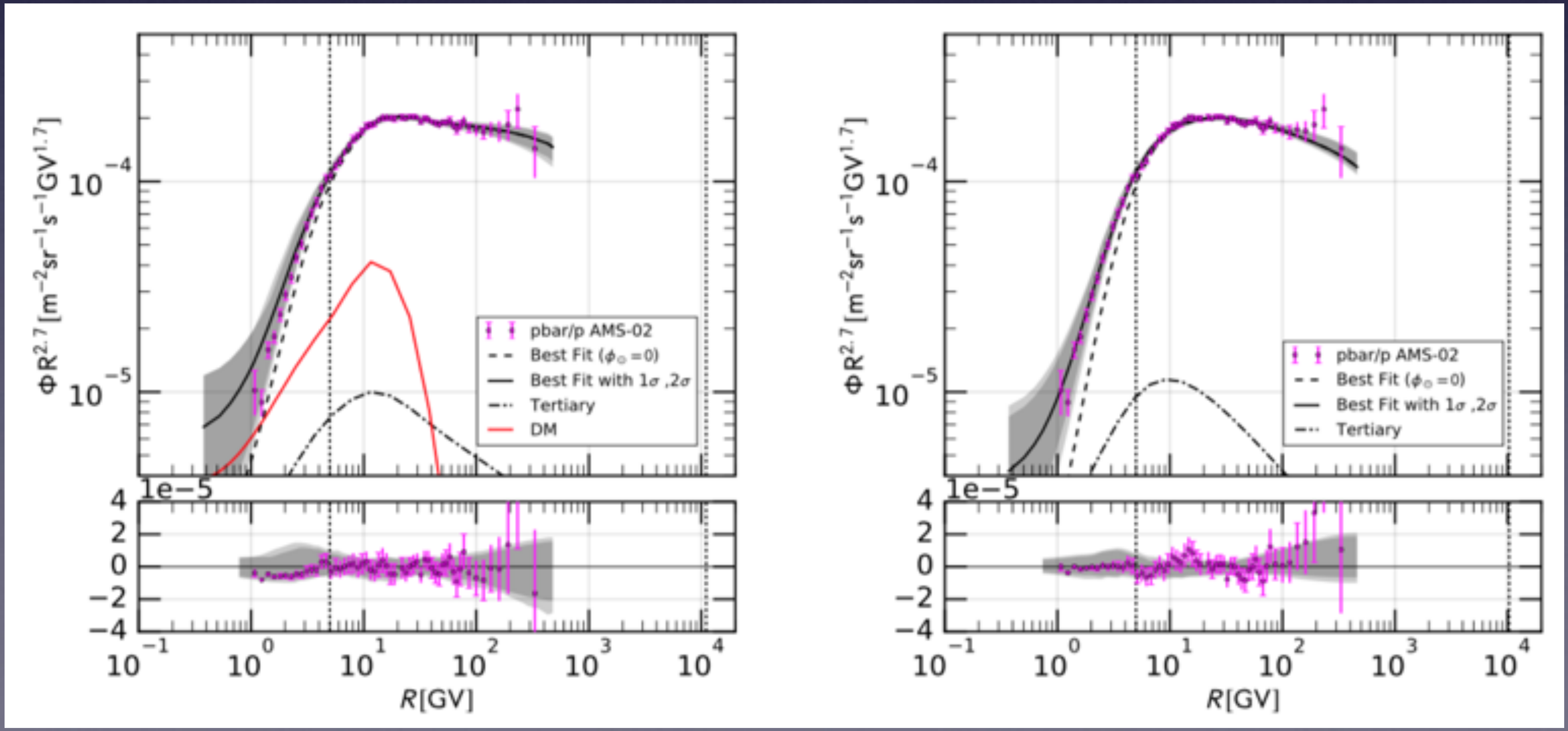
# AMS-02 antiprotons

- 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 $4.5\sigma$ (Cuoco et al) / Bayes factor 2 ln K = 11-54 (Cui et al).

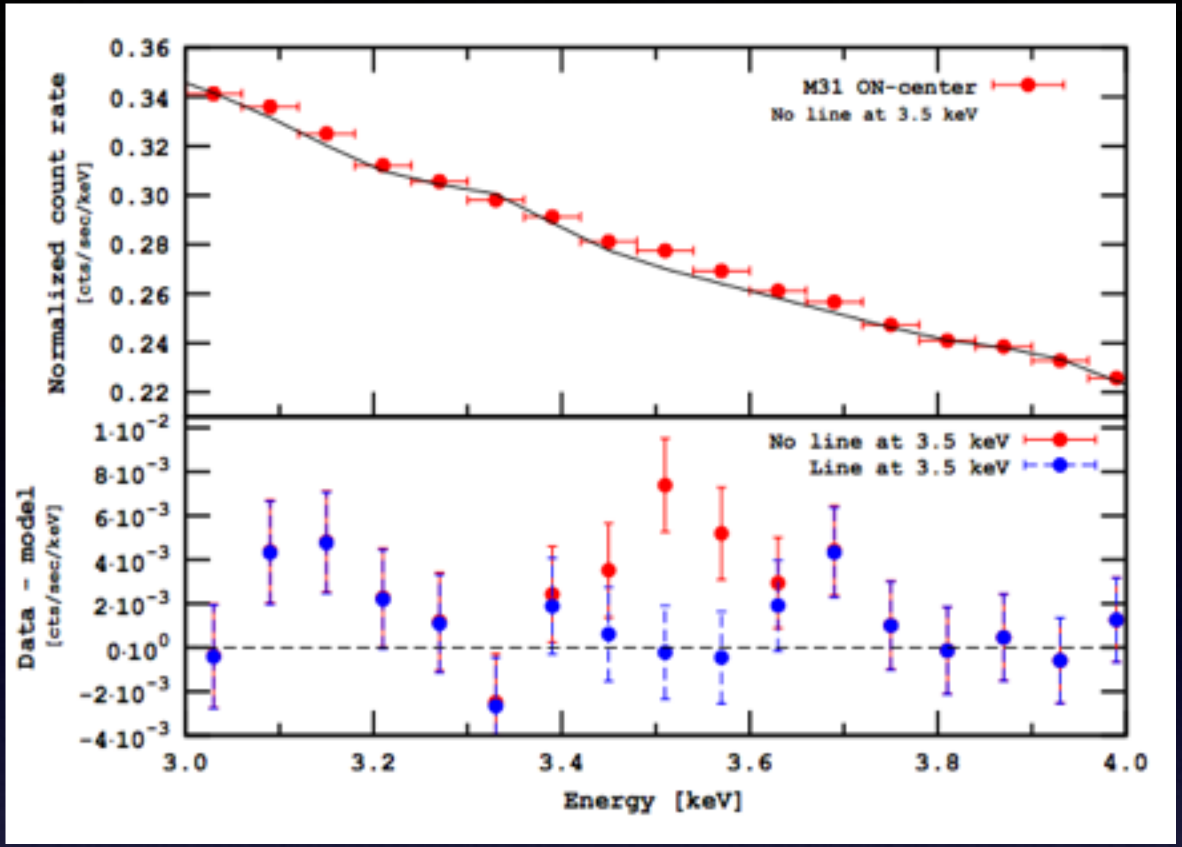


Cuoco et al '17

- 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.

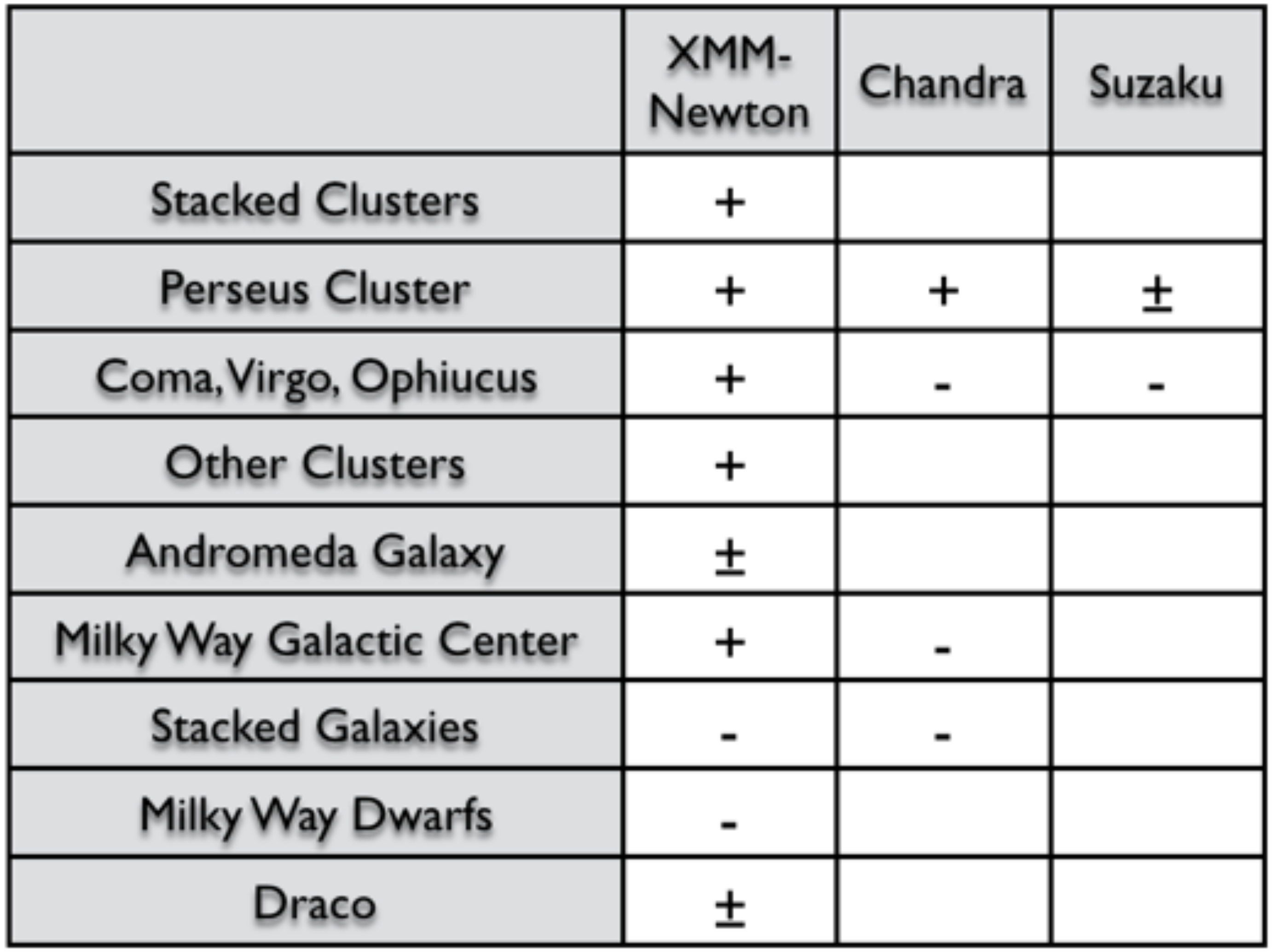


# The 3.5 keV line



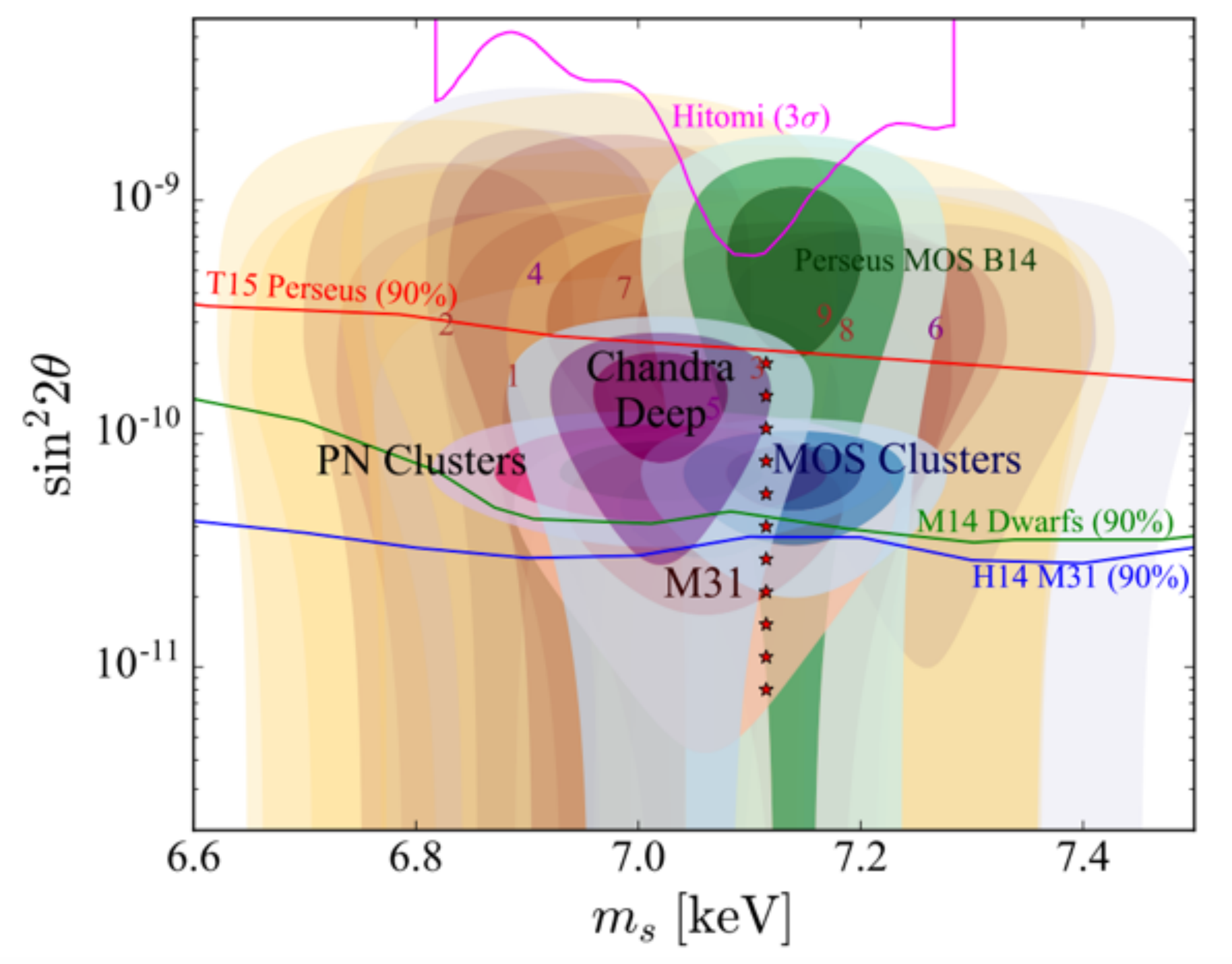
- 3.5 keV X-ray spectral line: initial discovery in XMM-Newton data by Bulbul et al (1402.2301) and Boyarsky et al (1402.4119), at ~4σ significance.
- Follow-up observational studies by:

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)



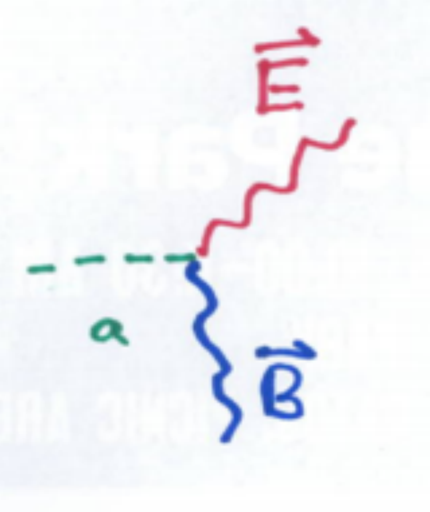
| | XMM-Newton | Chandra | Suzaku |
|---|---|---|---|
| Stacked Clusters | + | | |
| Perseus Cluster | + | + | ± |
| Coma, Virgo, Ophiucus | + | - | - |
| Other Clusters | + | | |
| Andromeda Galaxy | ± | | |
| Milky Way Galactic Center | + | - | |
| Stacked Galaxies | - | - | |
| Milky Way Dwarfs |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

Abazajian ‘17



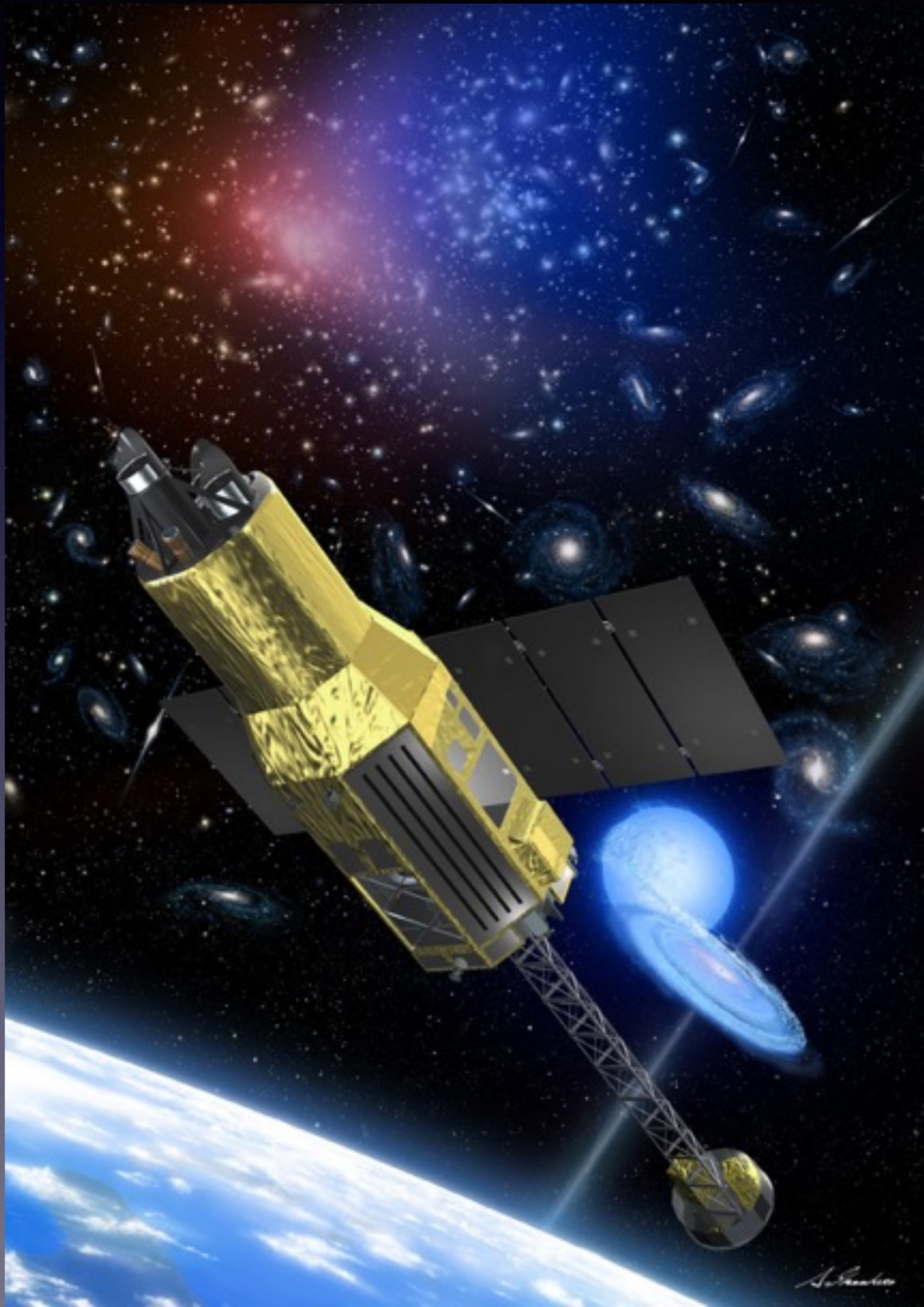
# DM interpretations

- 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 $12\sigma$) 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).

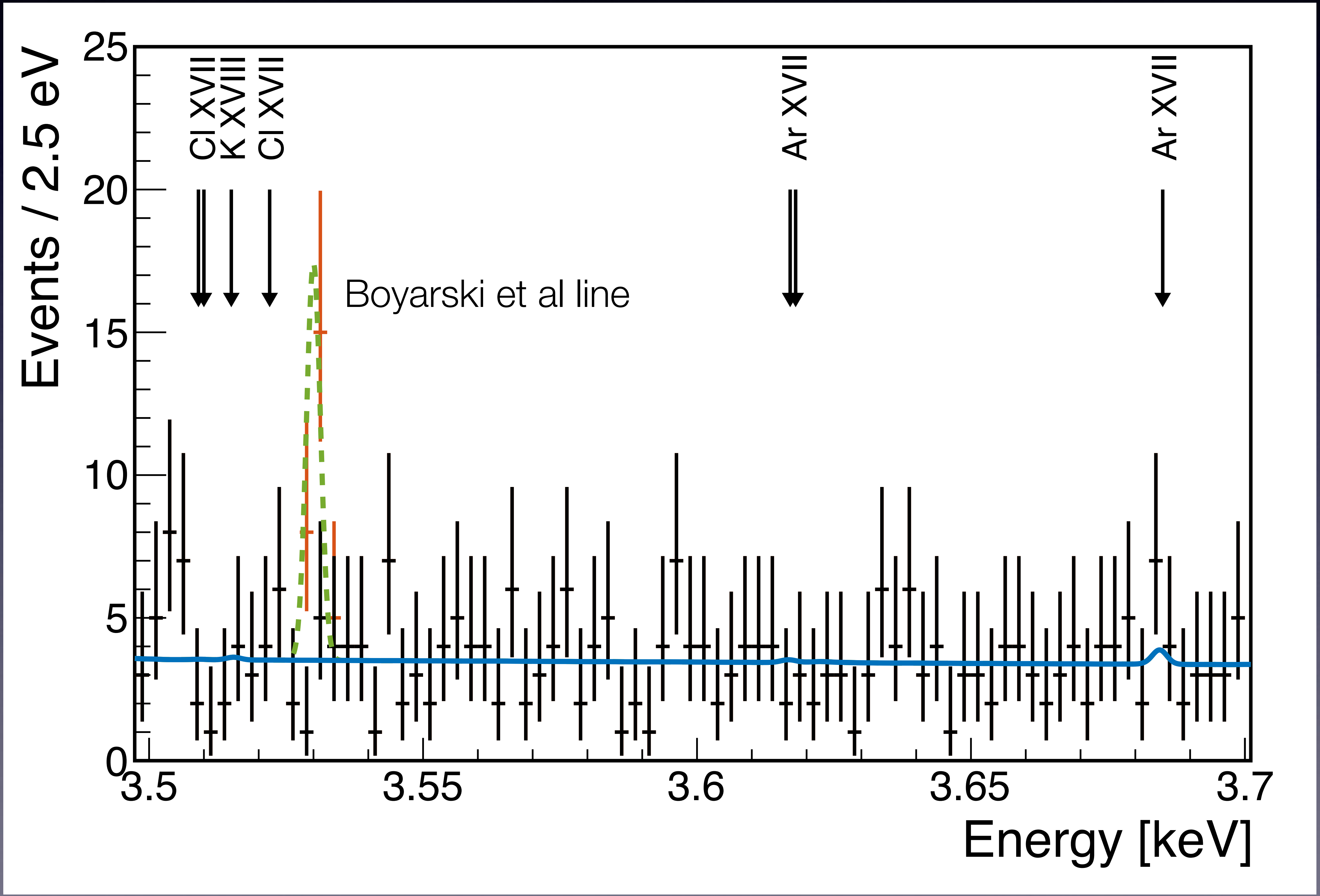


# Micro-X

- 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)

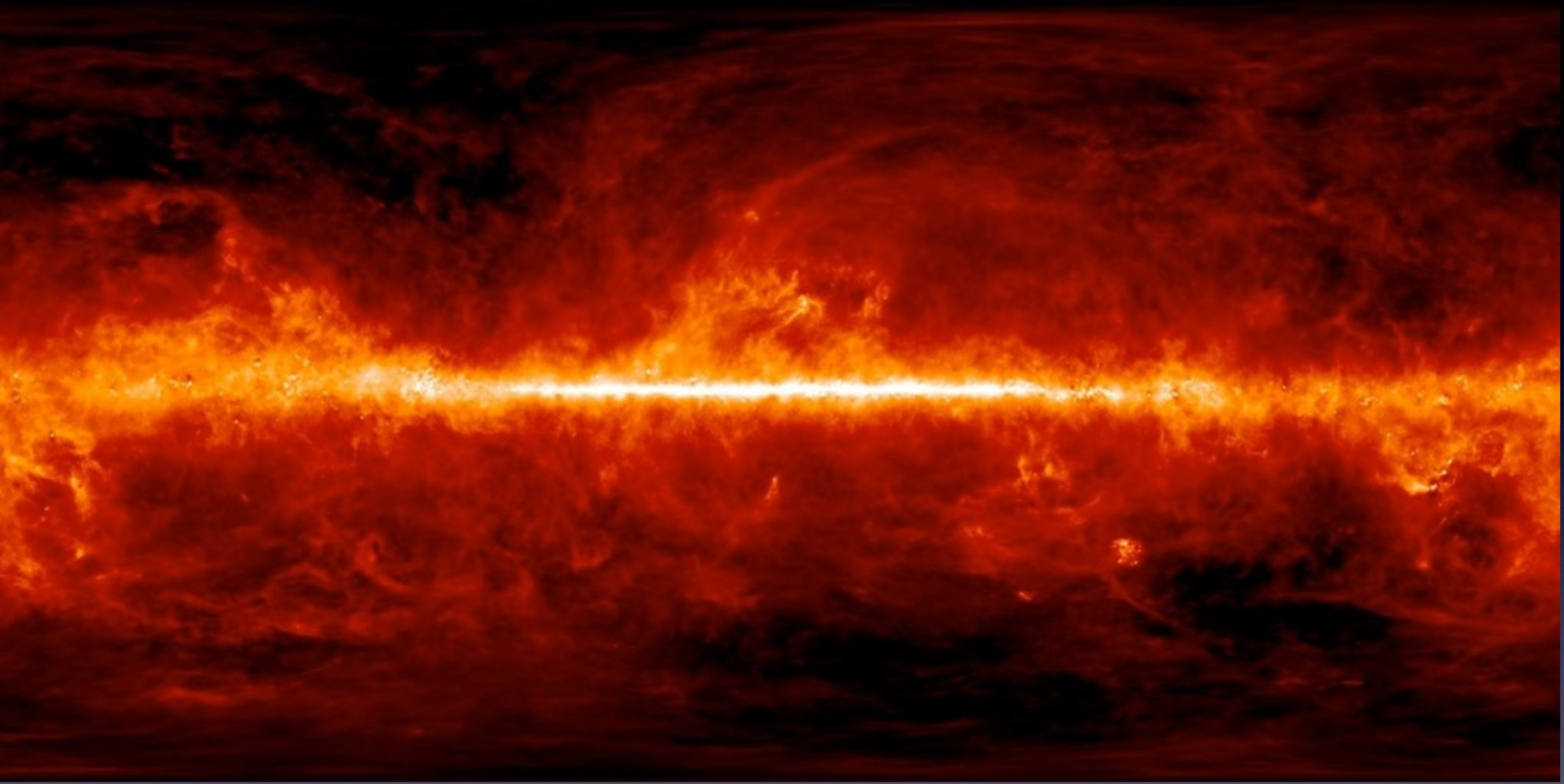
# Micro-X mock observation

thanks to Tali Figueroa-Feliciano for the slide



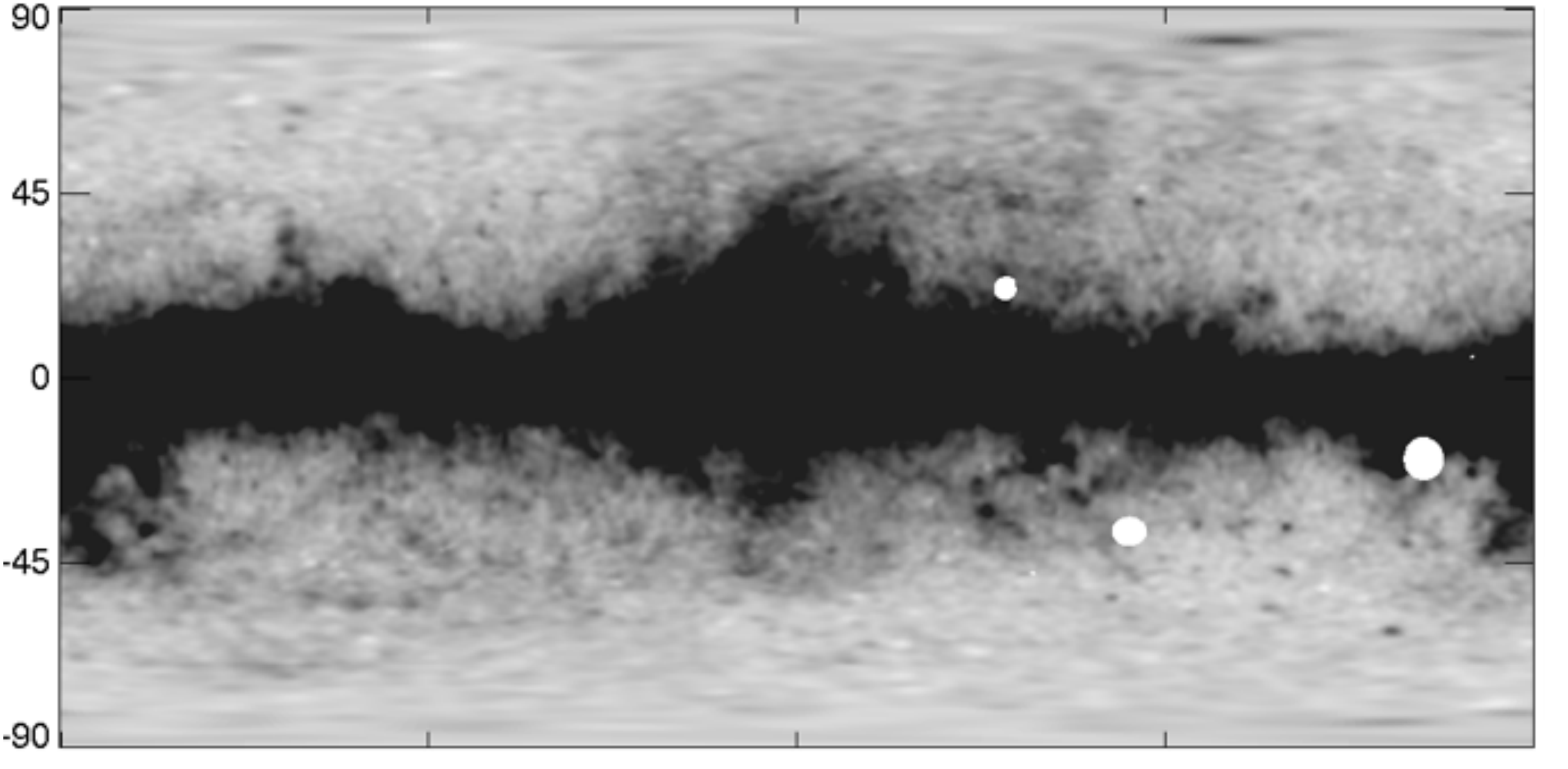
# Continuum gamma-rays in the Galactic Center

- 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.

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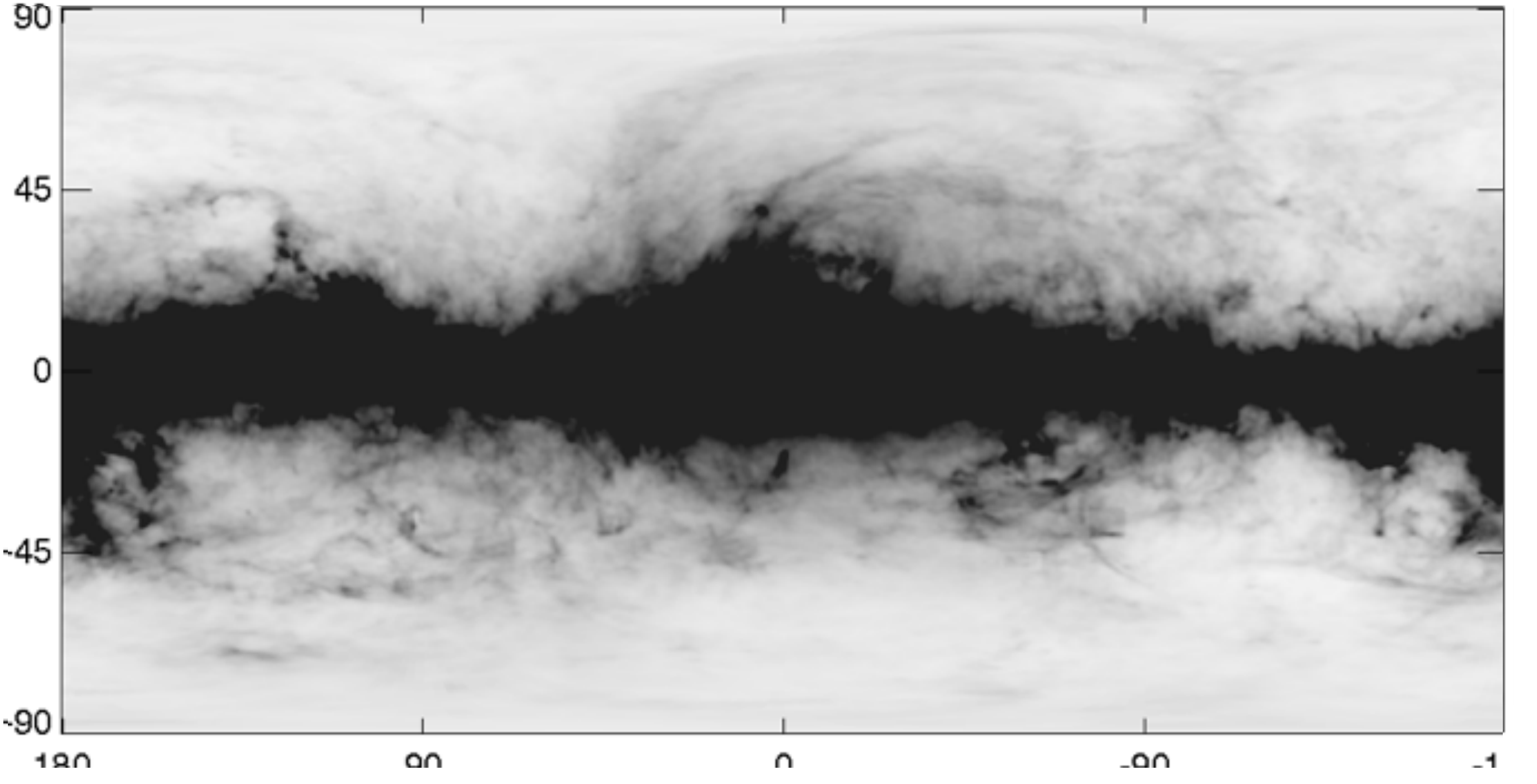

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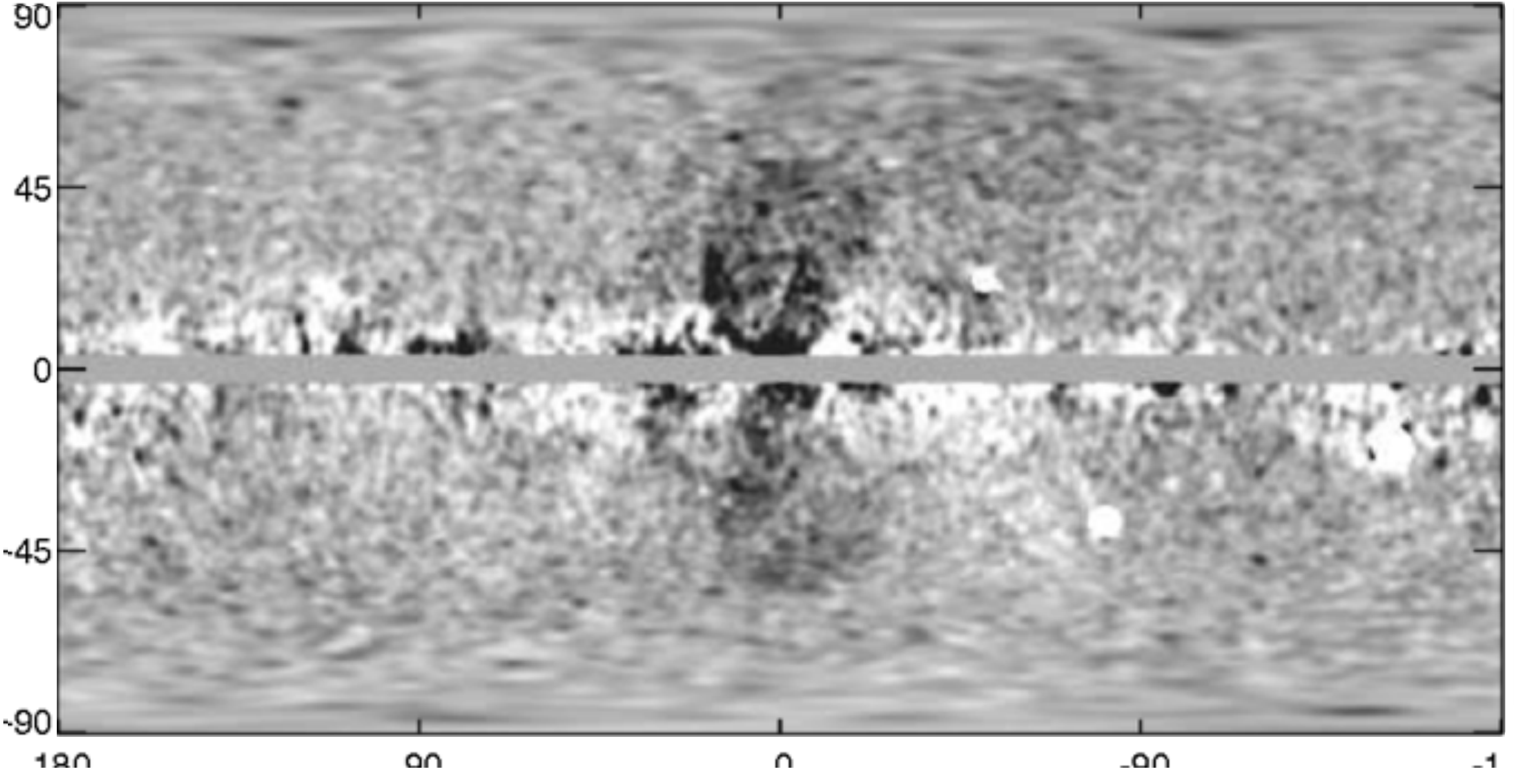

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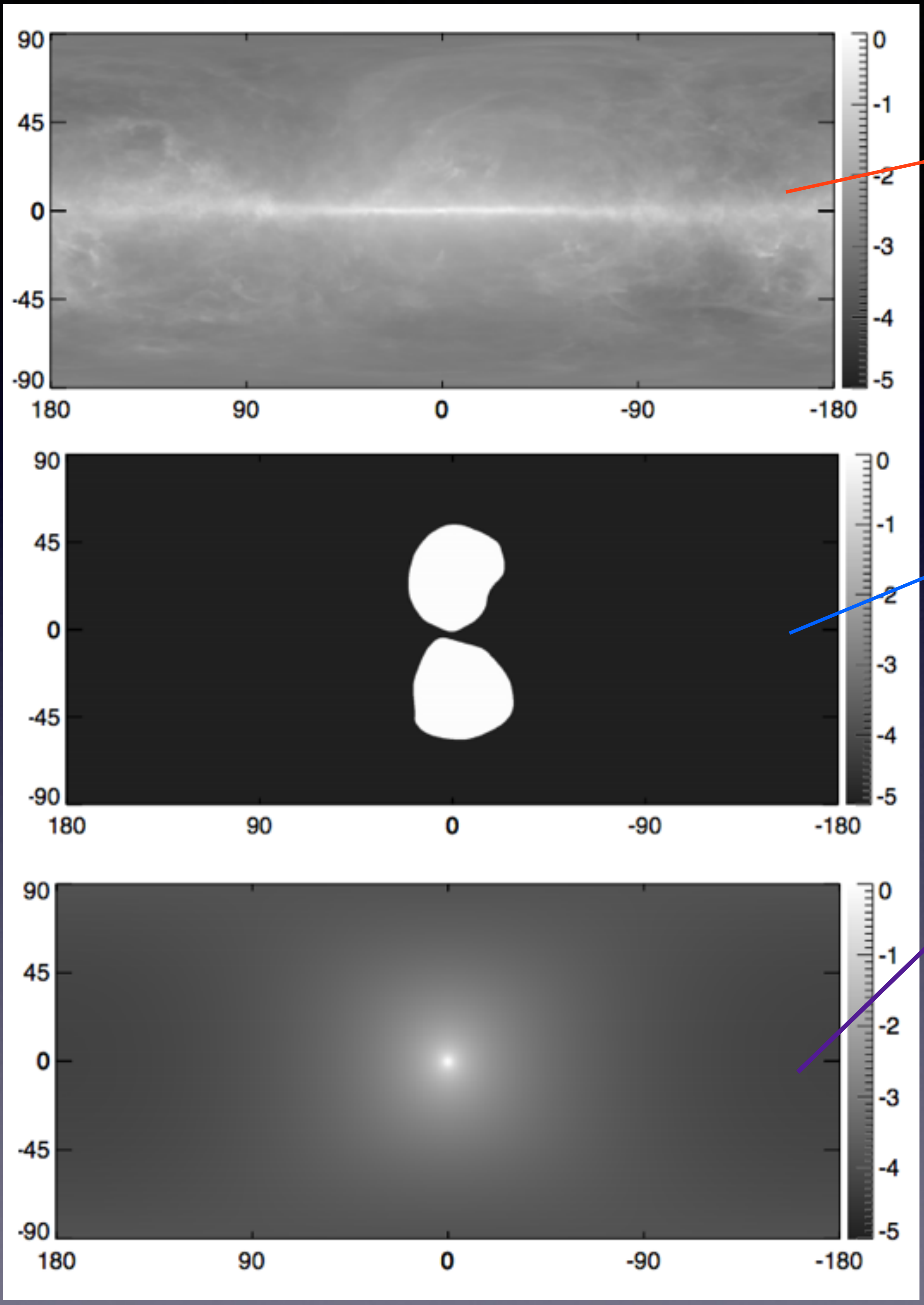
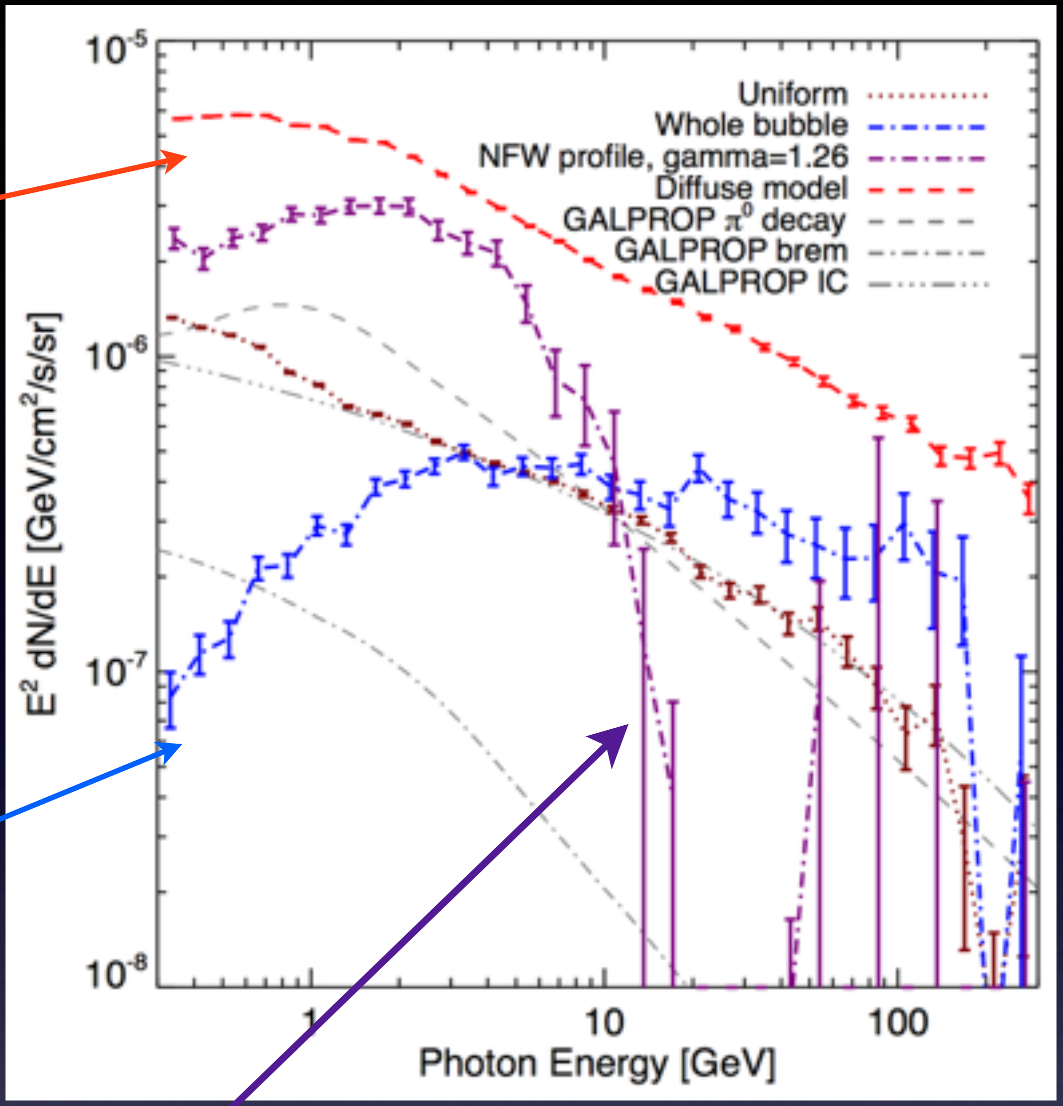
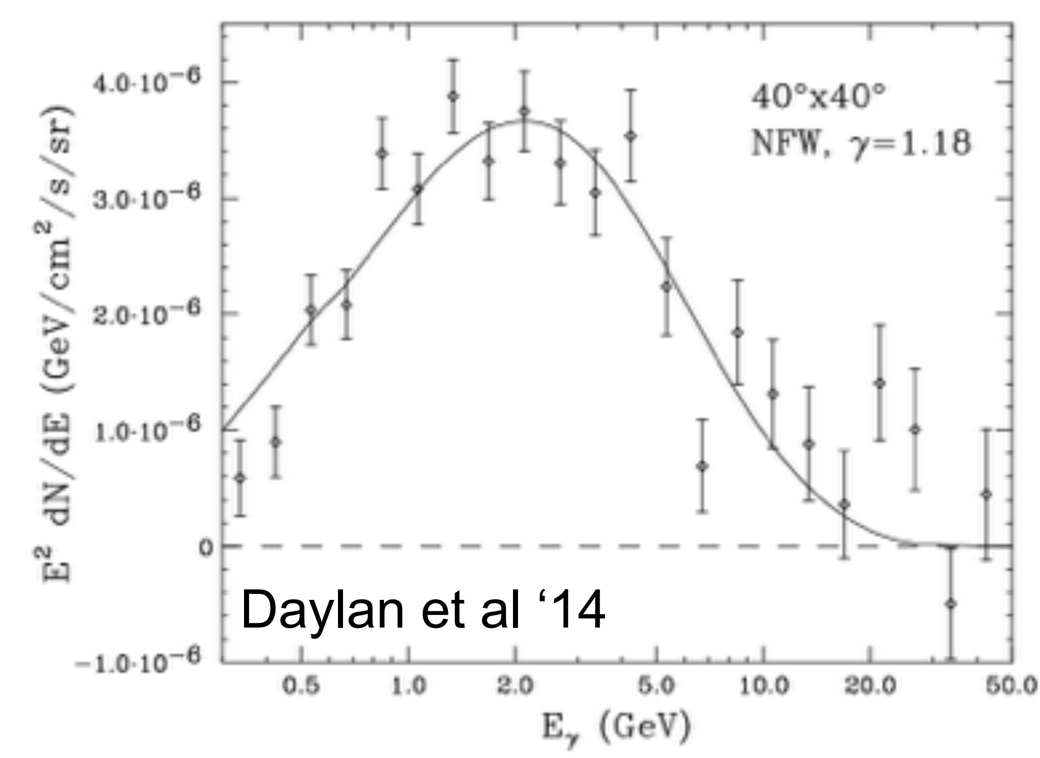




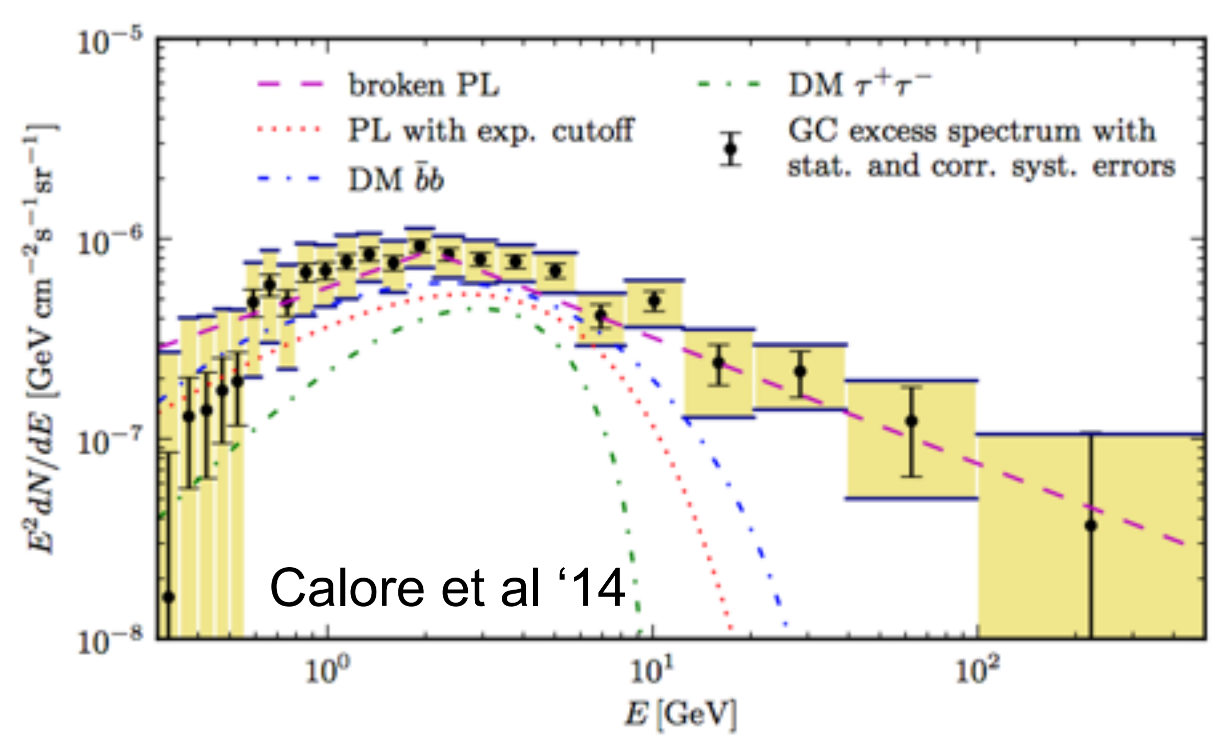
- Can add a model for a DM signal motivated by N-body simulations (or your favorite cored model) - generalized NFW profile, squared and projected along the line of sight.
- Fit the data as a linear combination of background(s) + signal, extract best-fit coefficient and error bars for each - “template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



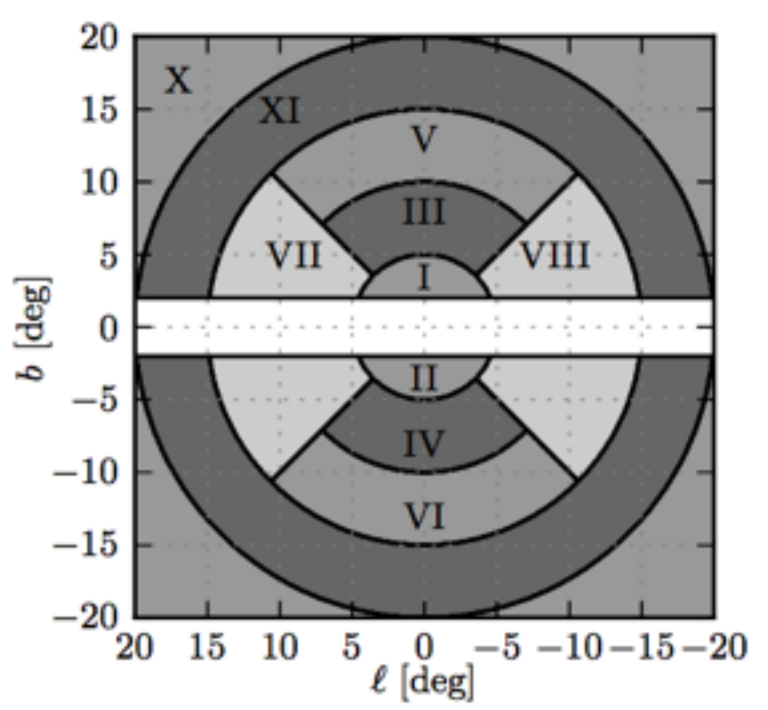
Daylan et al '14



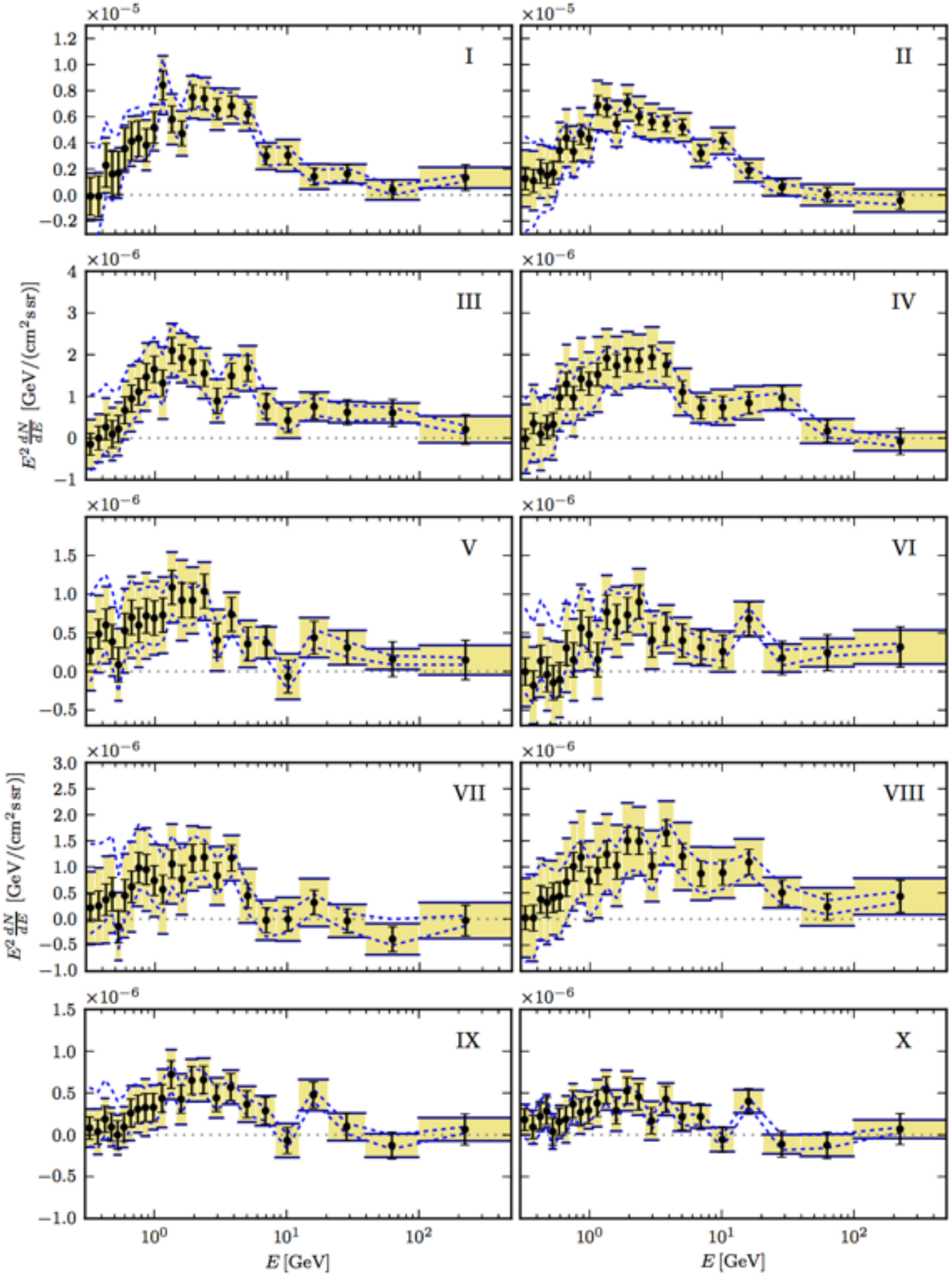
Calore et al '14

# 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).

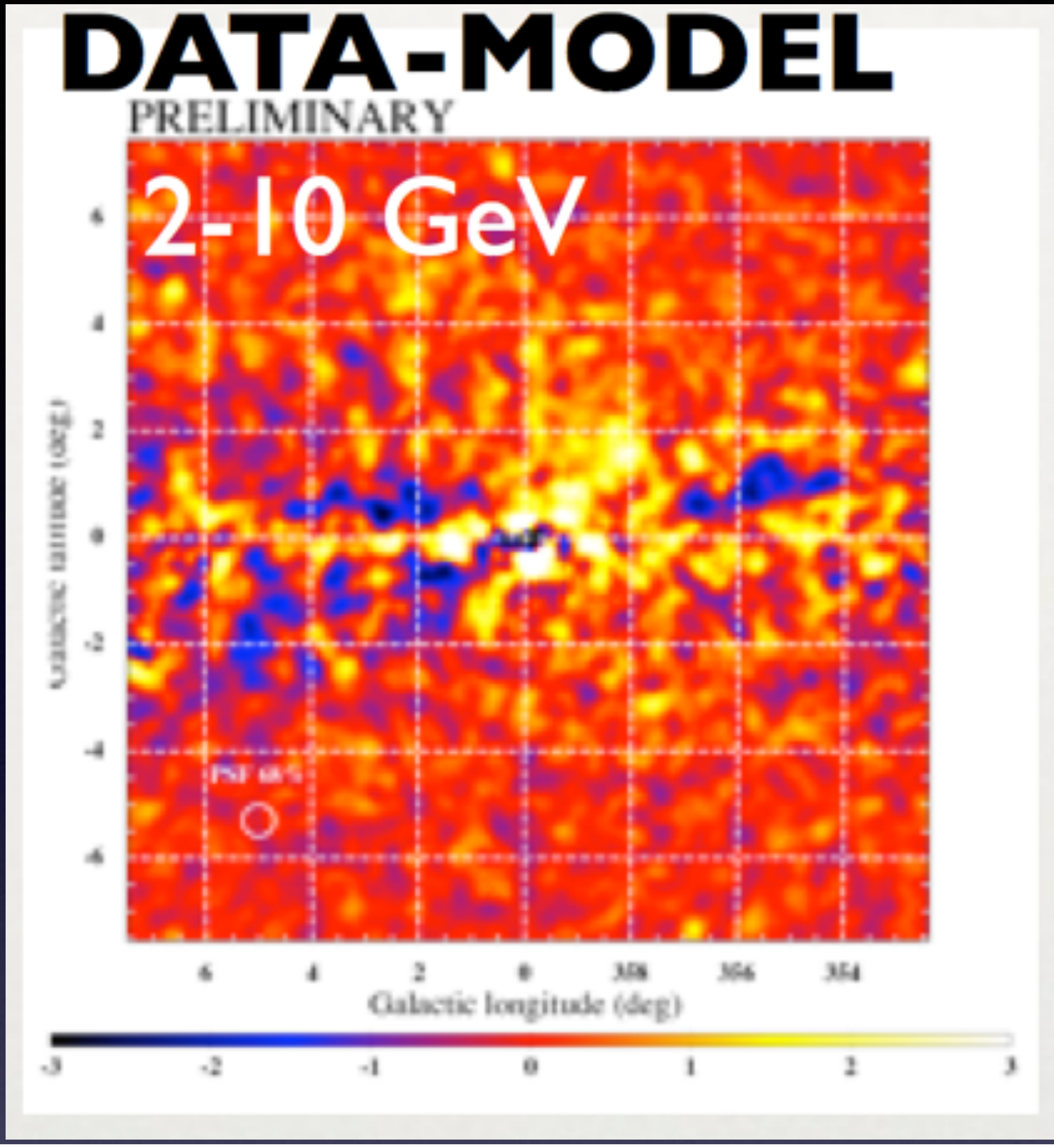


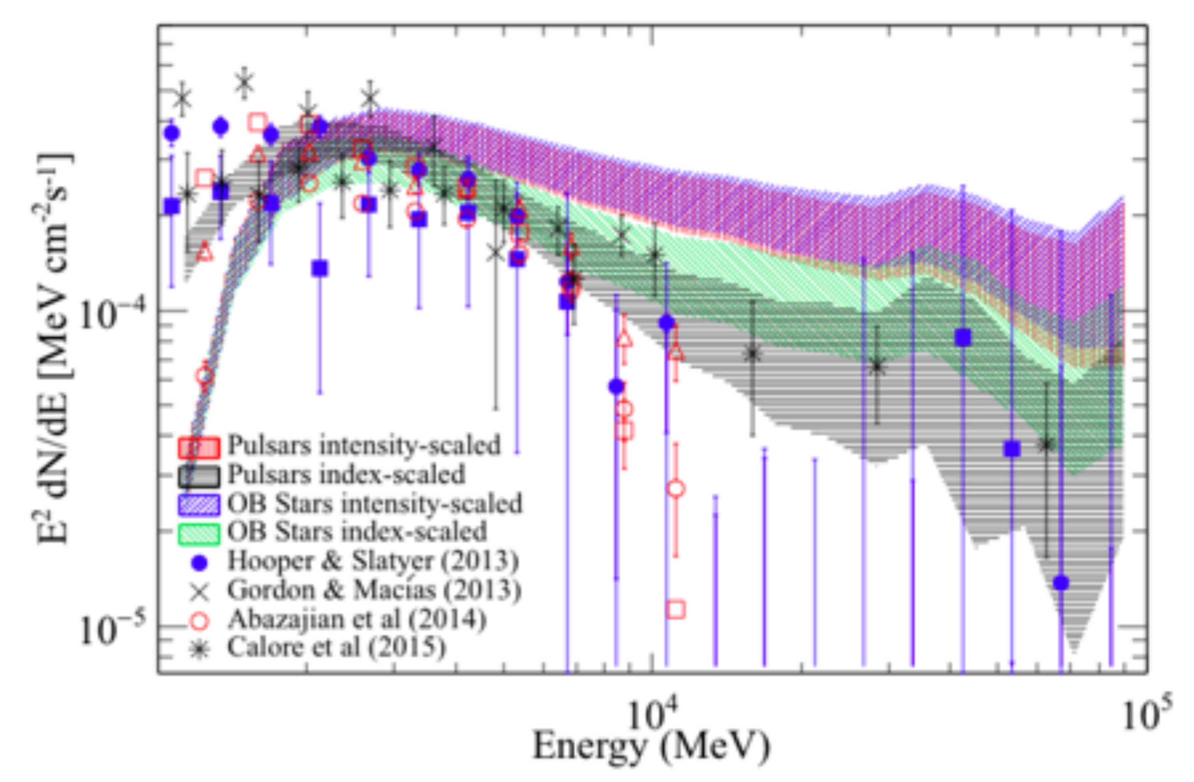
Plots taken from Calore, Cholis & Weniger '14



# Fermi Collaboration analysis

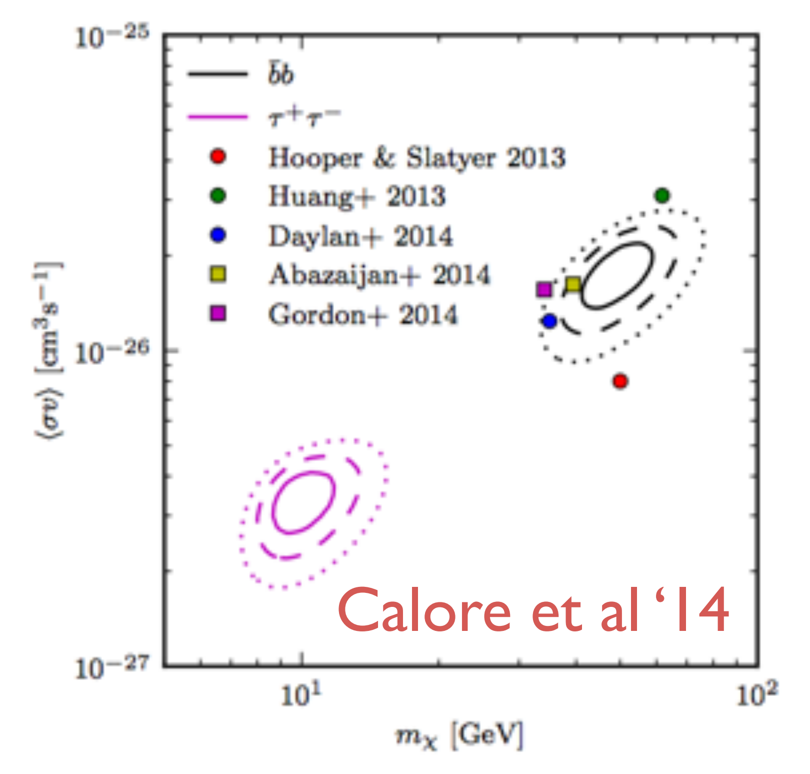
- Work by the Fermi LAT Collaboration (Nov ’15) seems to identify the same excess.
    - Careful alternate approach to background/foreground modeling
    - Spectrum depends on diffuse model, but peak around a few GeV seems consistent
    - Greatest improvements in the fit provided by spatial models peaked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



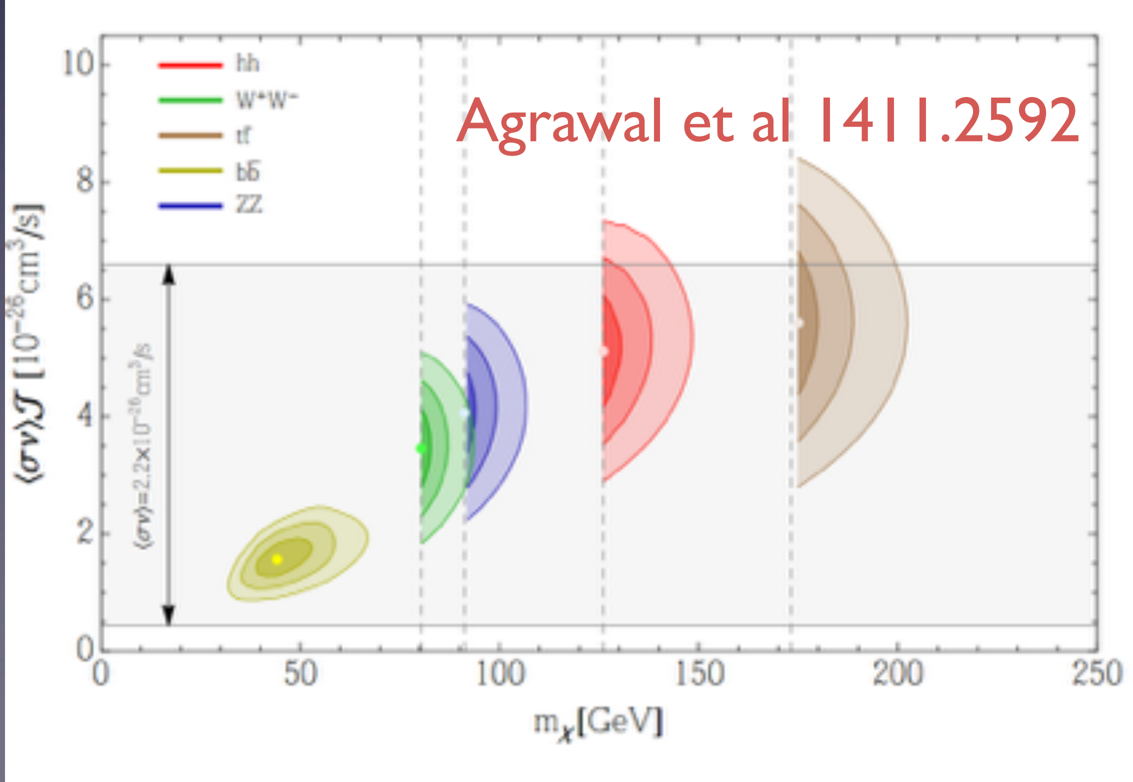


# If it is dark matter…

- 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.



Calore et al '14



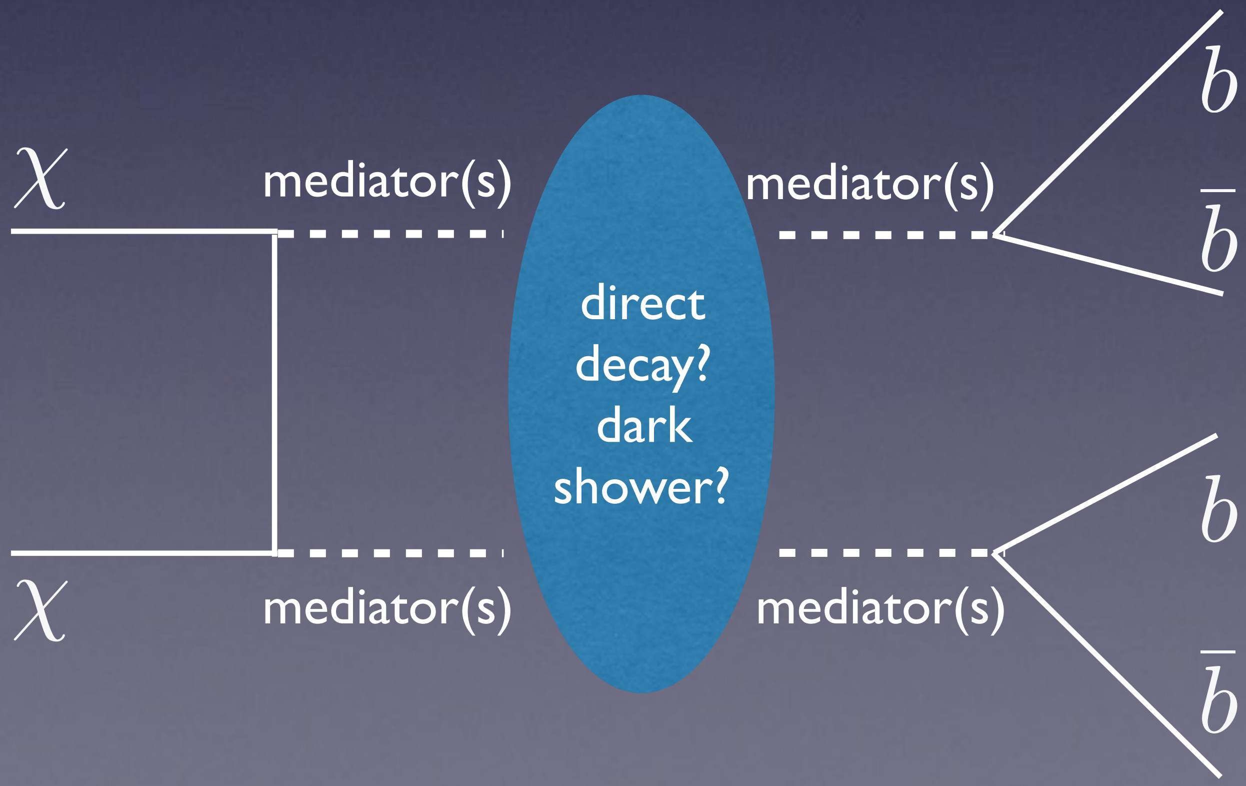
Agrawal et al 1411.2592

# 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→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.

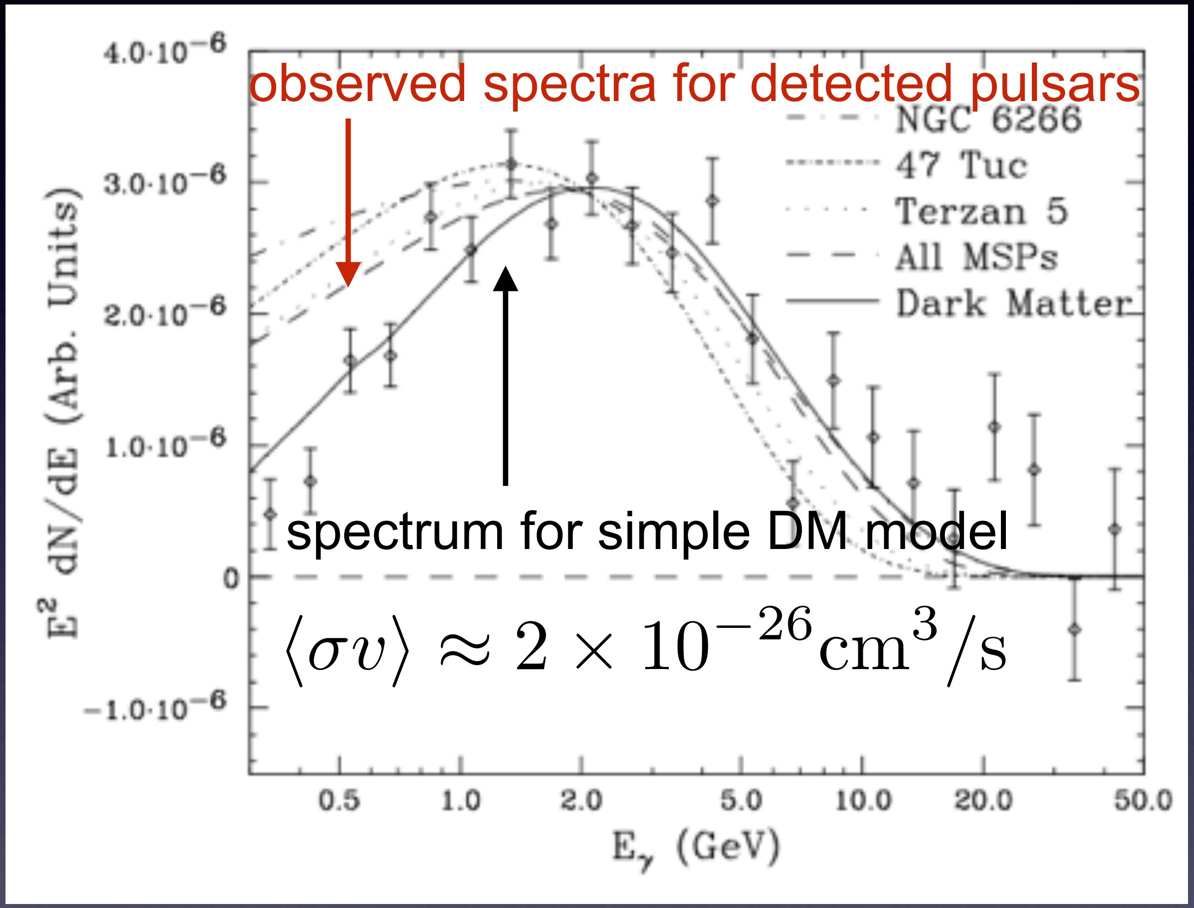
# Examples

- 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

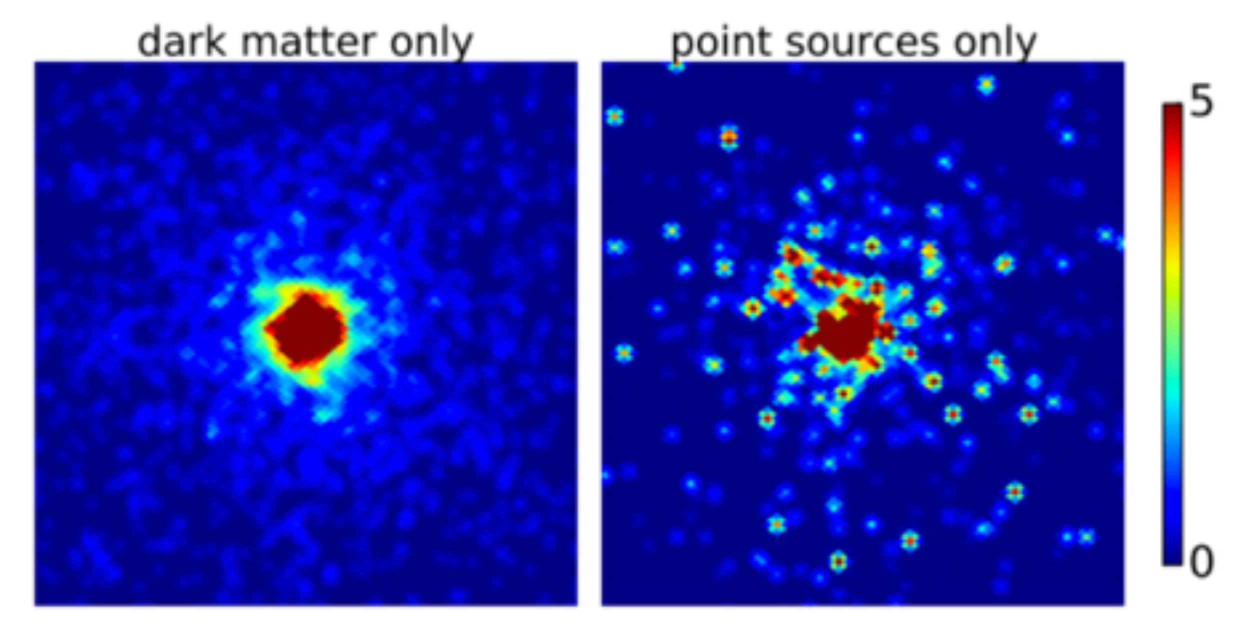
A brief and not exhaustive list of references:
1405.7685, 1405.7928, 1506.05119, 1507.06129

# 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 photons) = $10^{12}\ e^{-10}/12! \sim 0.1$
Likewise P(0 photons) ~ $5 \times 10^{-5}$, P(100 photons) ~ $5 \times 10^{-63}$

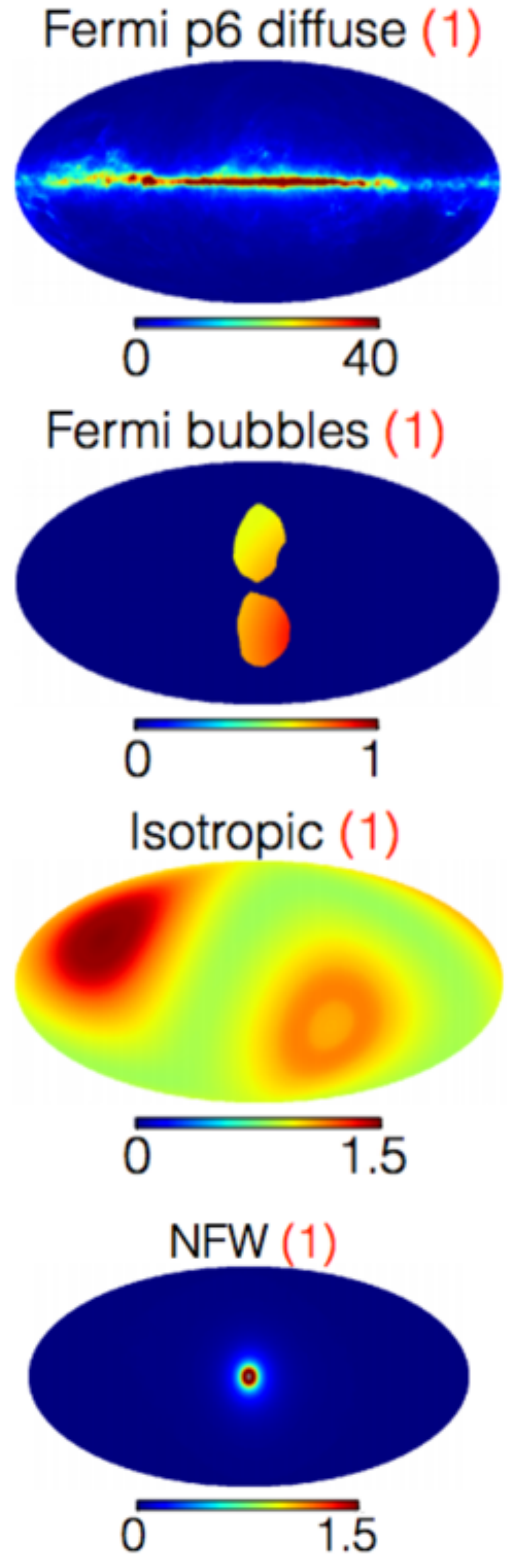
Case 2: population of rare sources.
Expect 100 photons/source, 0.1 sources/pixel - same expected mean # of photons

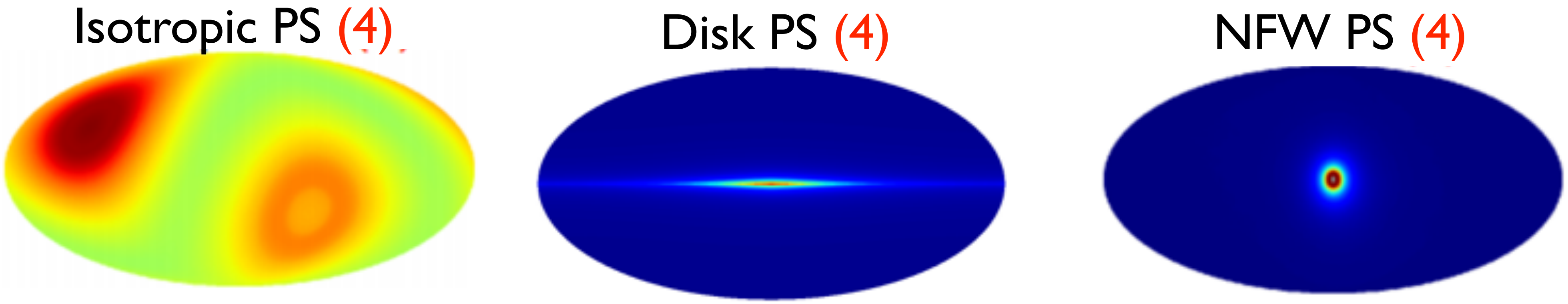
P(0 photons) ~ 0.9, P(12 photons) ~ $0.1 \times 100^{12}\ e^{-100}/12! \sim 10^{-29}$ ,
P(100 photons) ~ $4 \times 10^{-3}$

(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

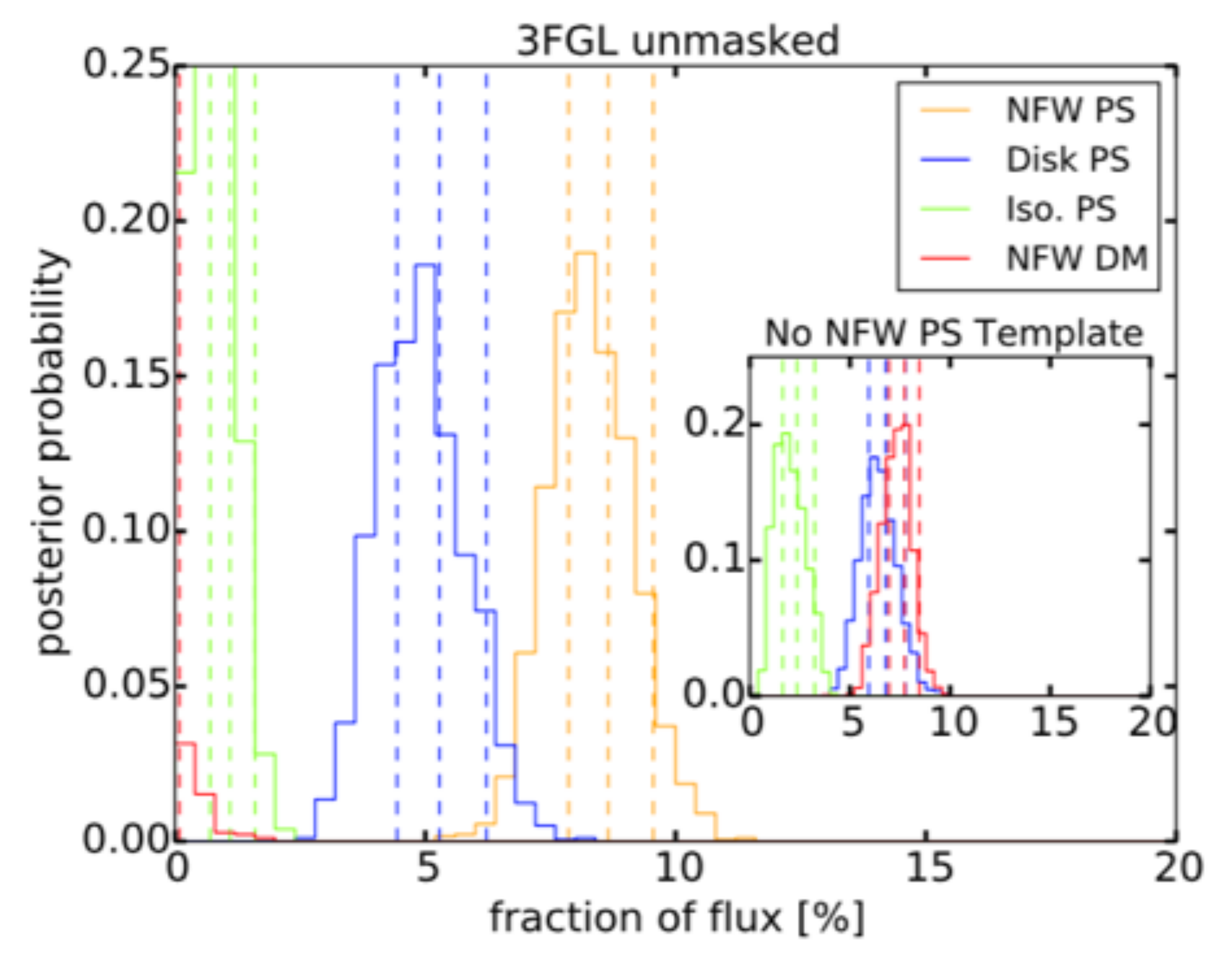




Point source templates

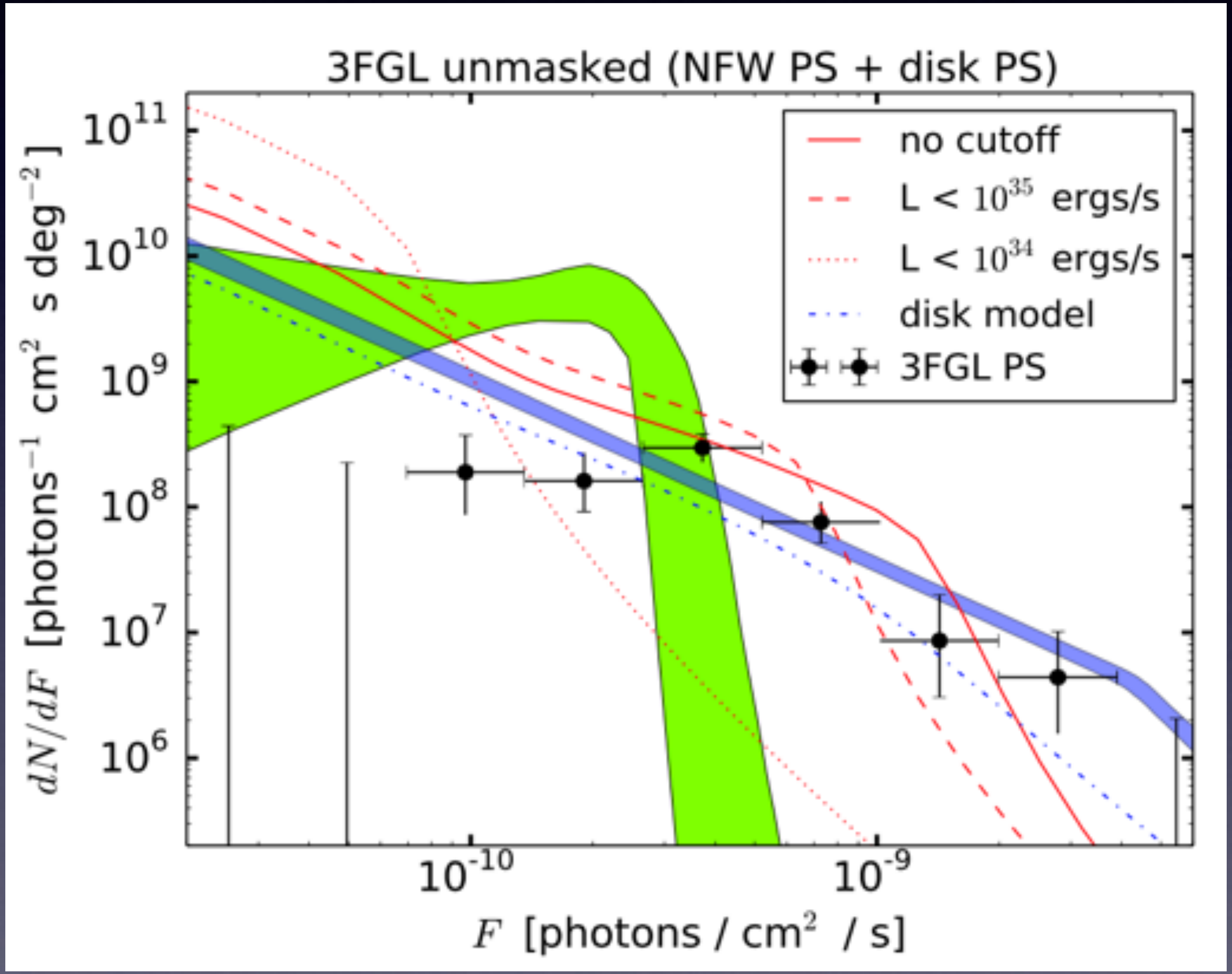
# A preference for point sources

- 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.



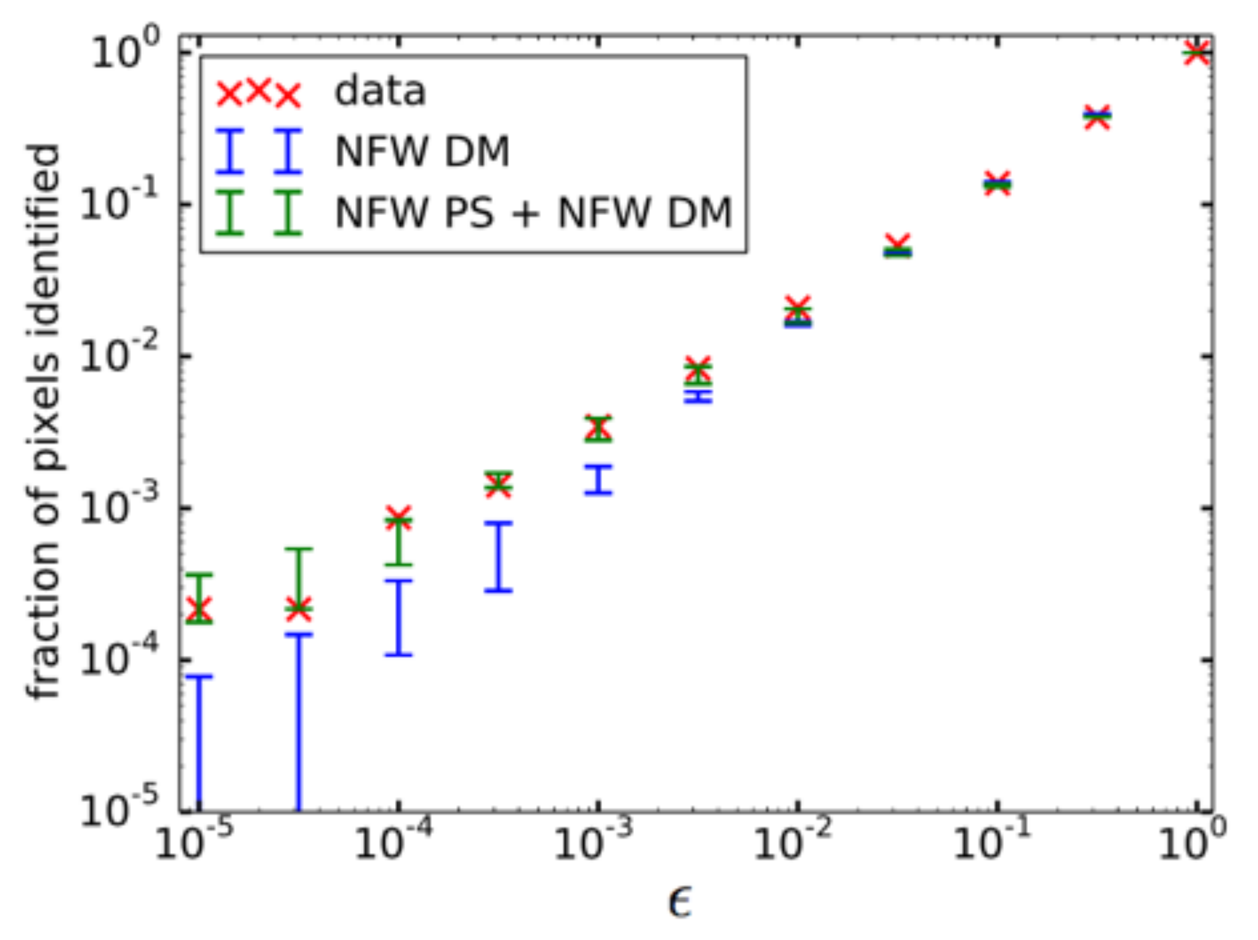
# The luminosity function

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



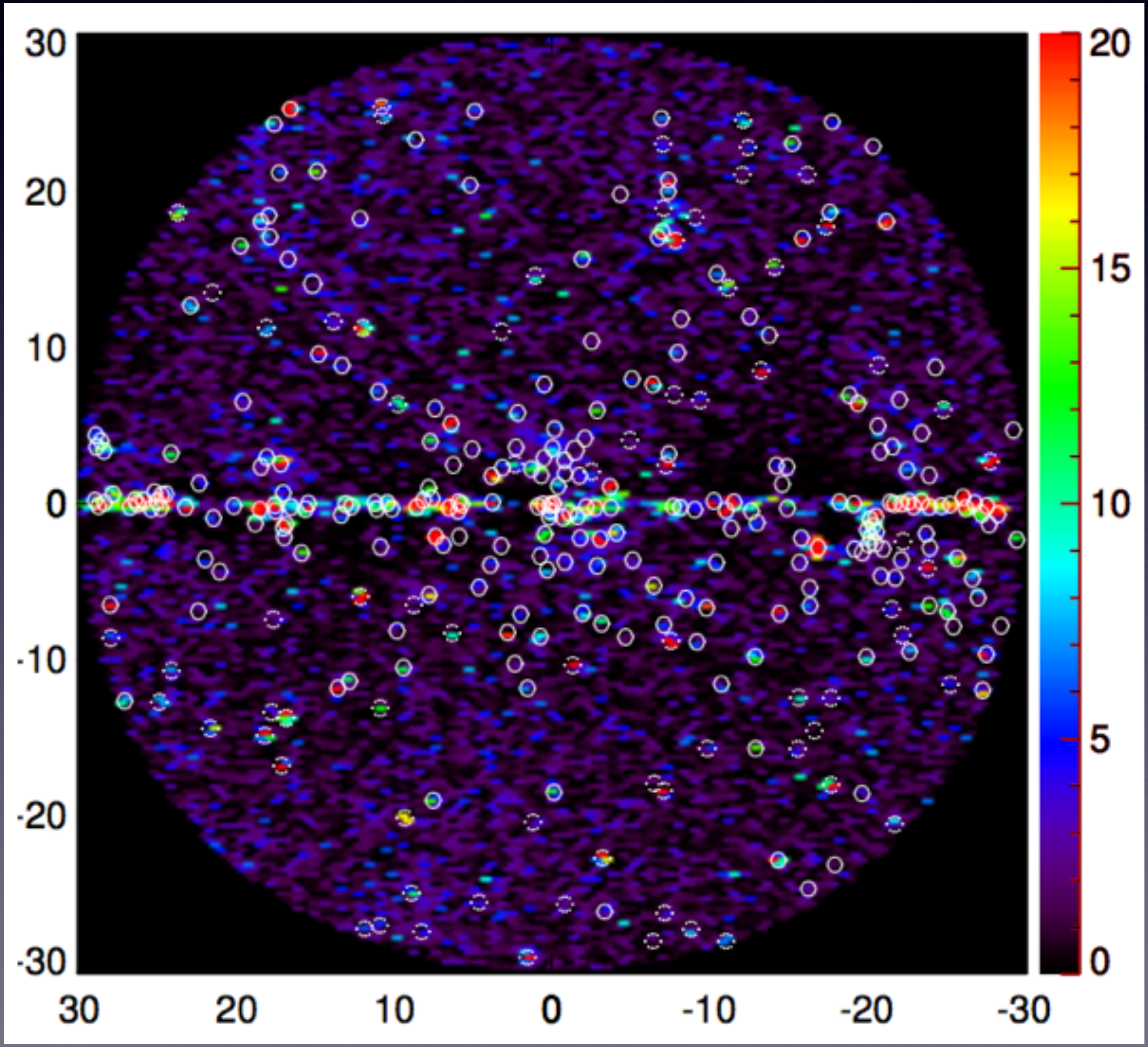
# What drives the point-source preference?

- 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 $\varepsilon_p$ = 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 $\varepsilon_p$ 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.

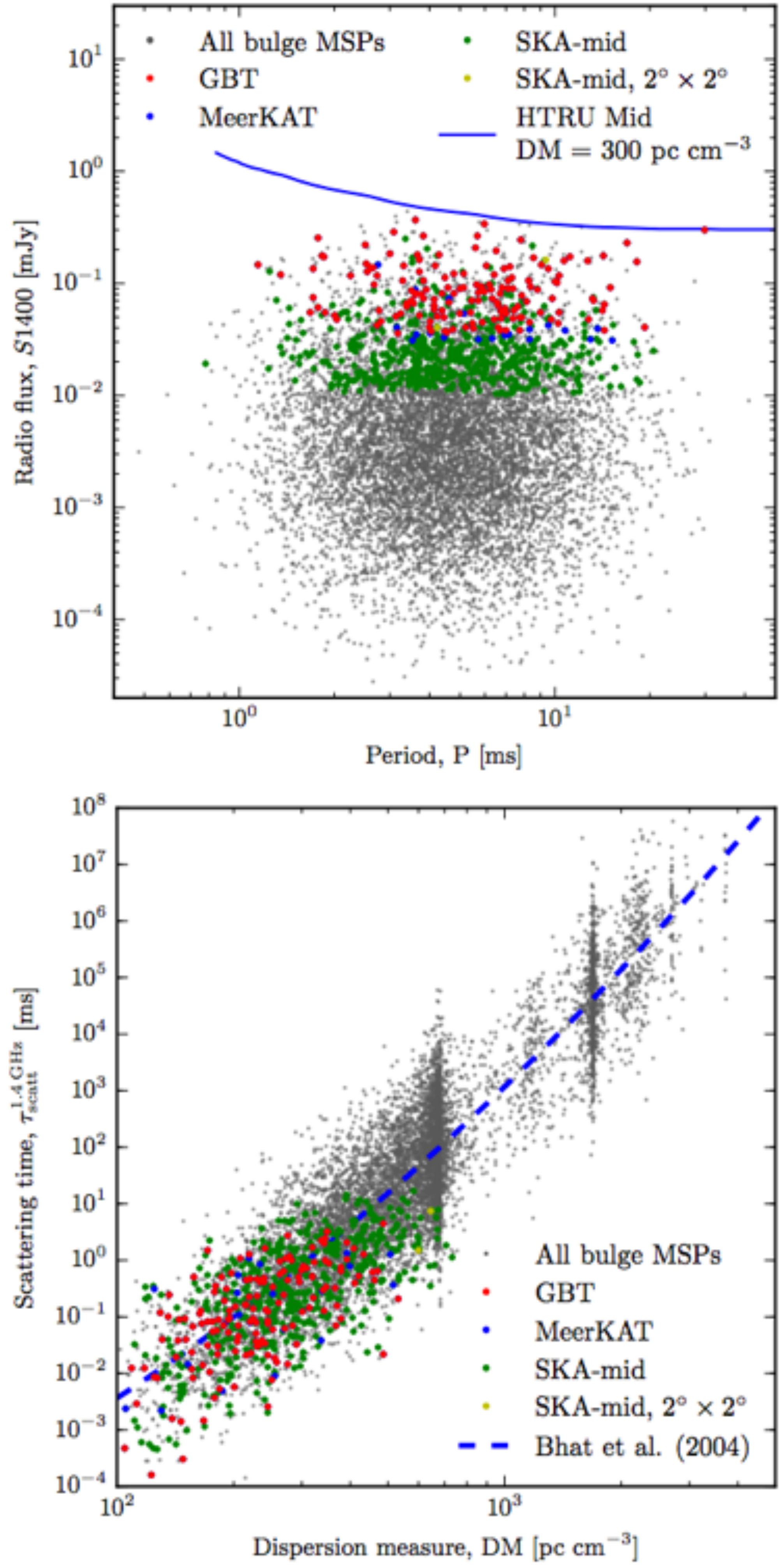
# Hot pixels and known sources



- 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.

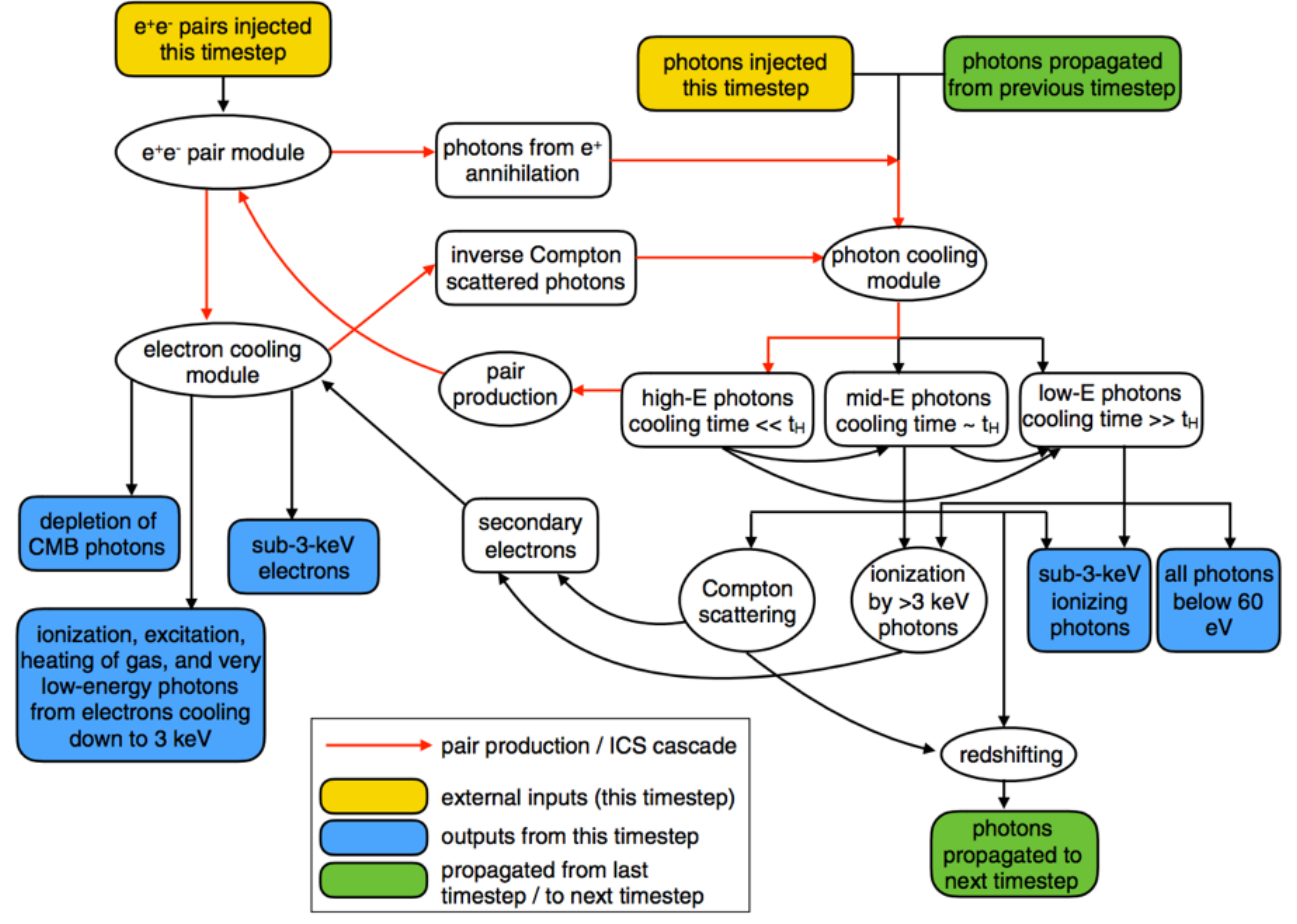


# Non-Poissonian template fitting

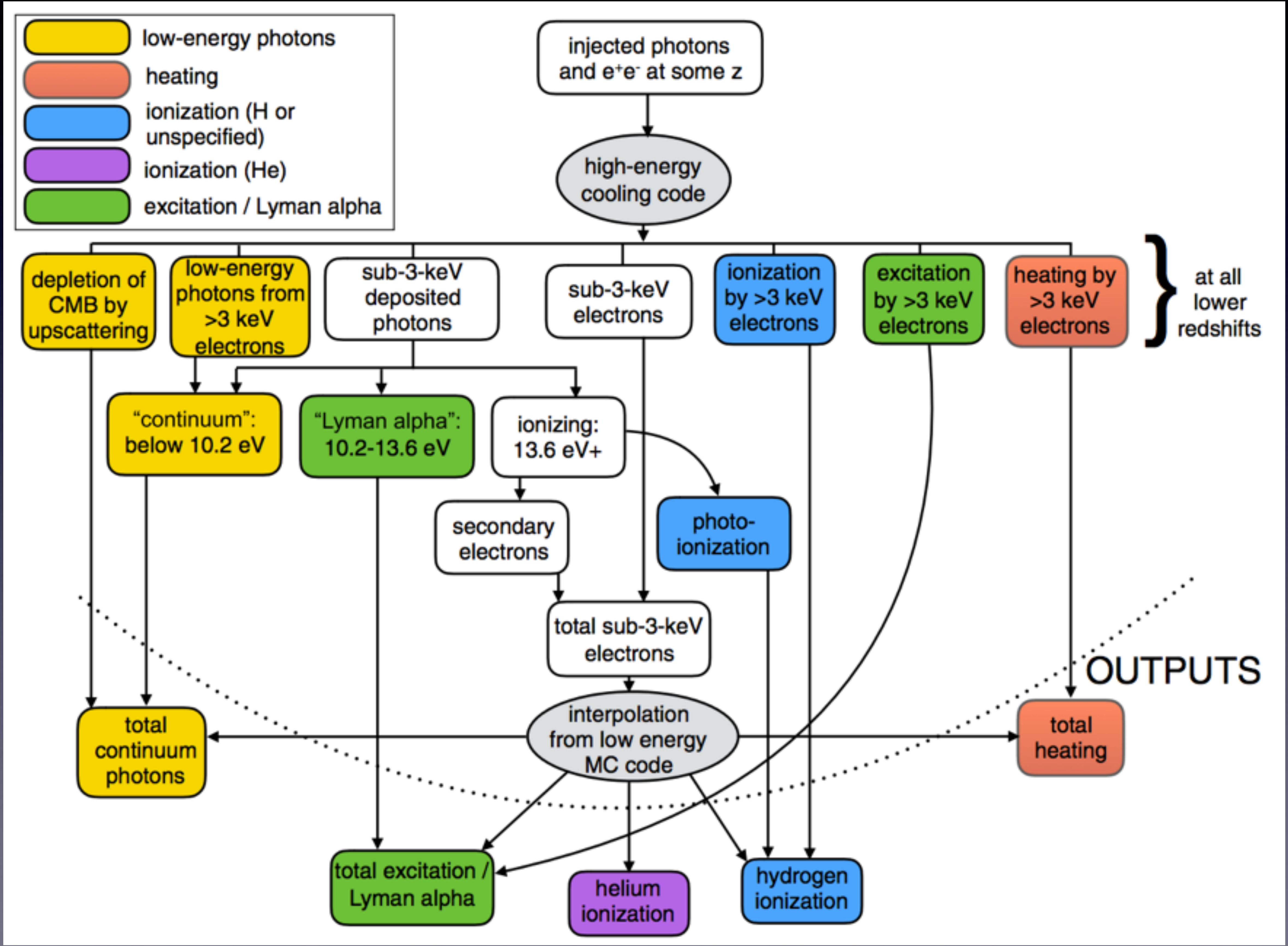
- Now available as a fully public code package at https://github.com/bsafdi/NPTFit
- Documented in Mishra-Sharma et al 1612.03173

# Bonus slides

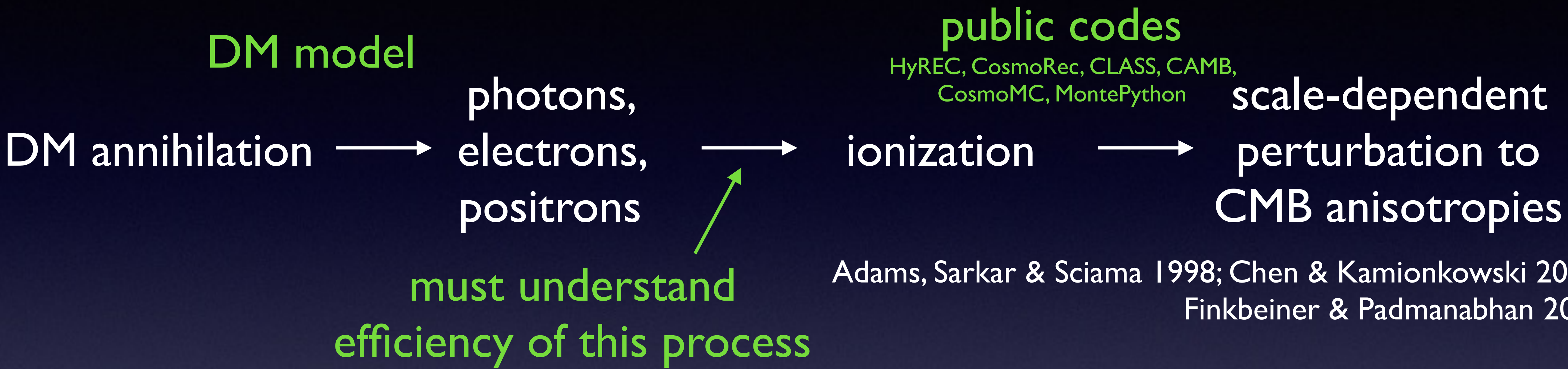
# Modeling energy loss (high)



# Modeling energy loss (low)



# Bounds from the CMB



DM model

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

public codes

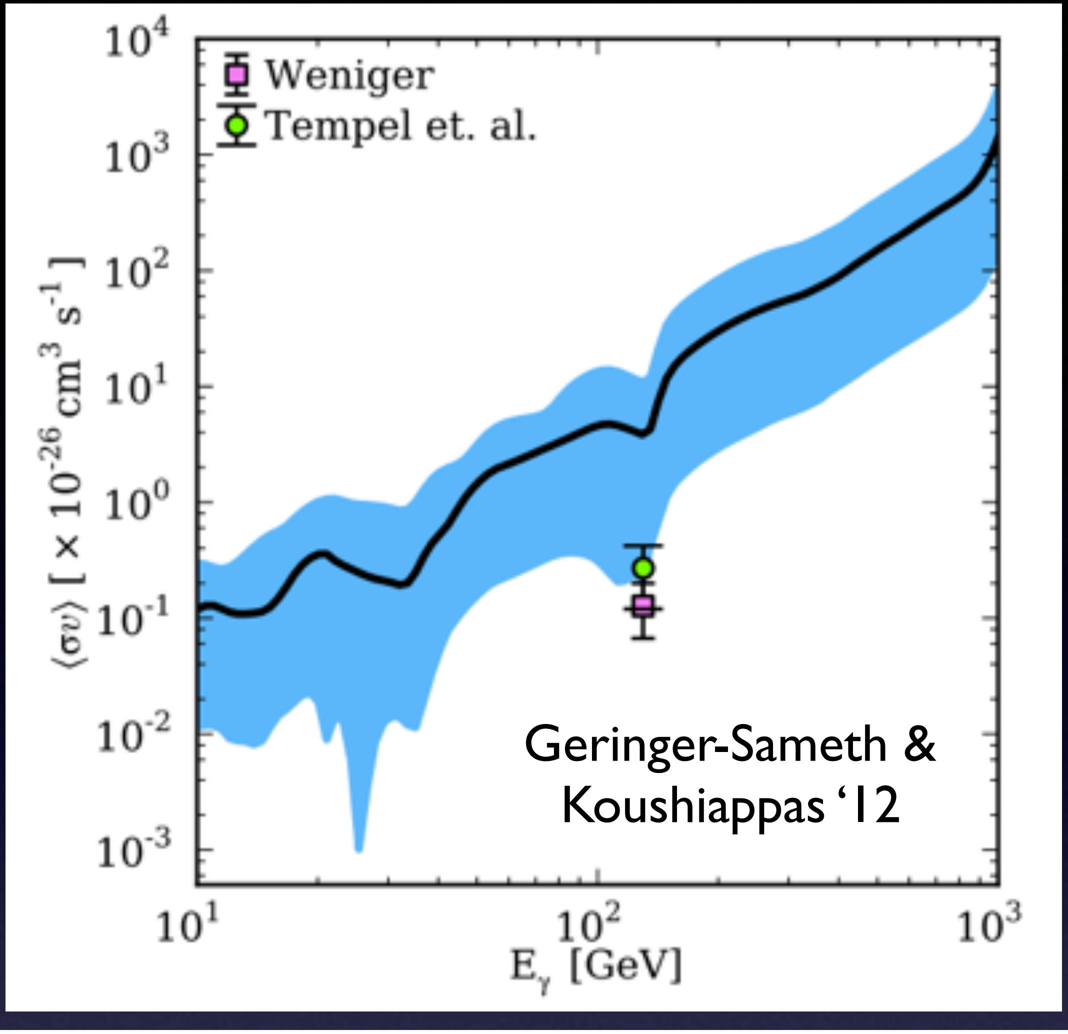
HyREC, CosmoRec, CLASS, CAMB, CosmoMC, MontePython

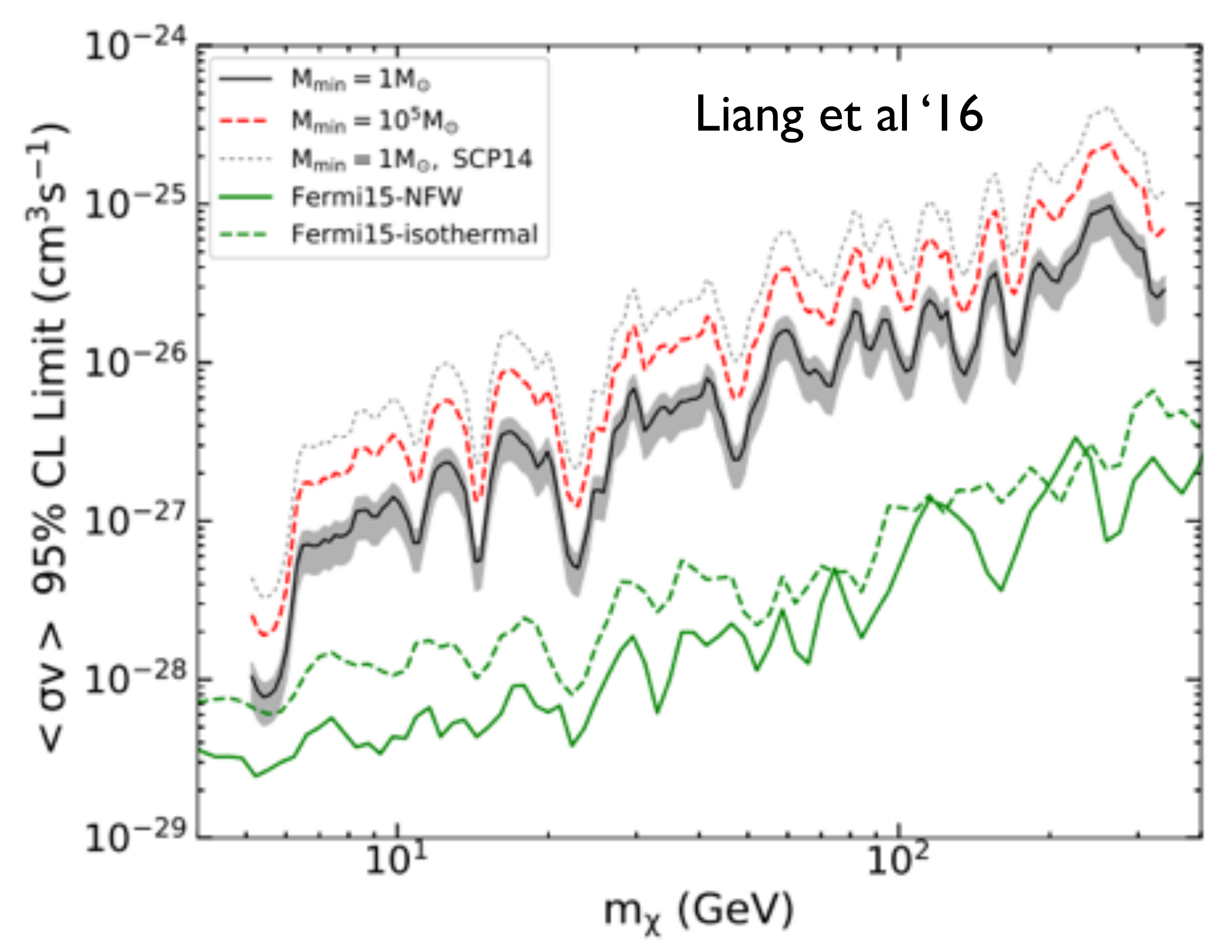
must understand efficiency of this process

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).

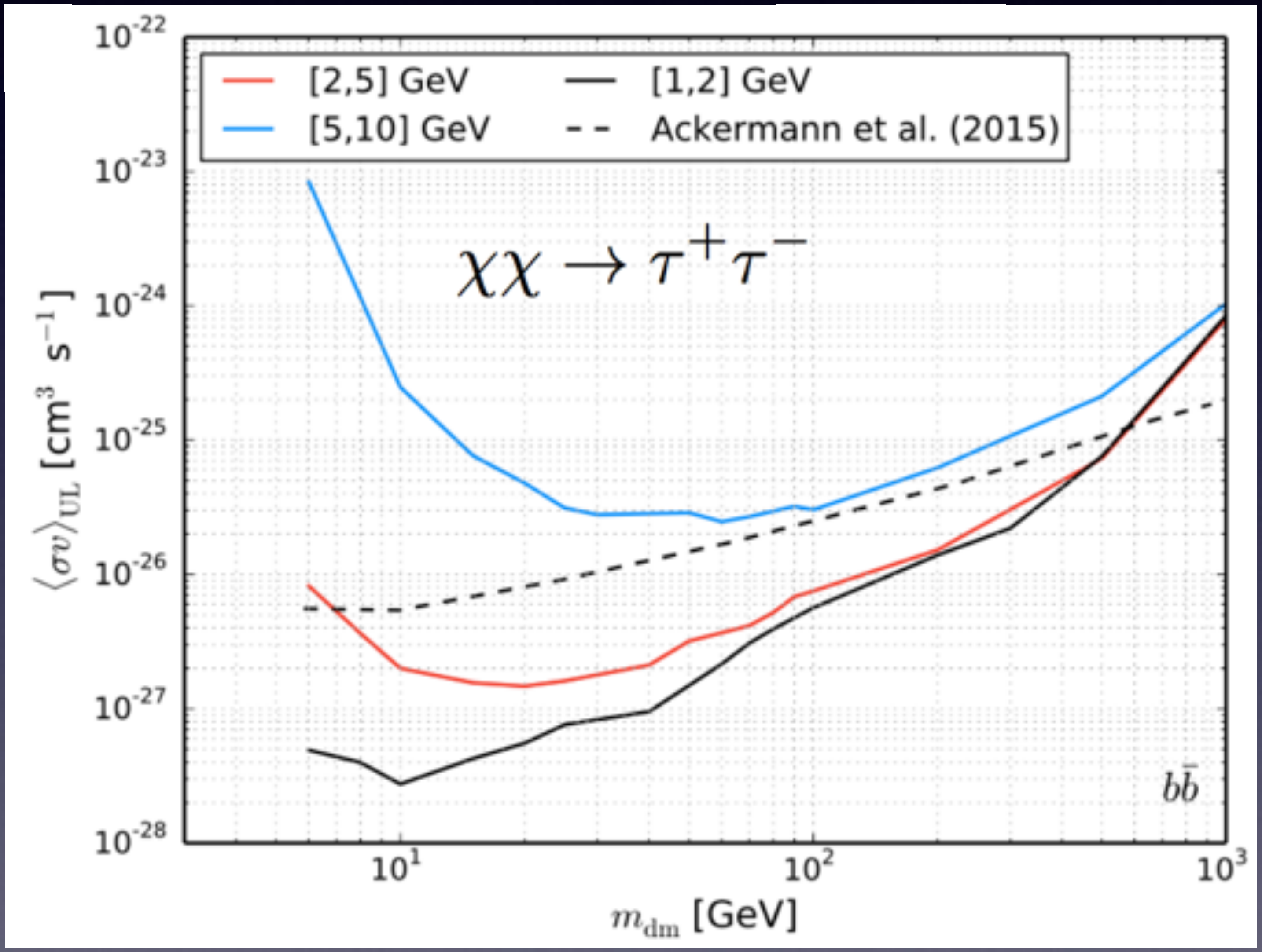
# Line limits from dwarf galaxies





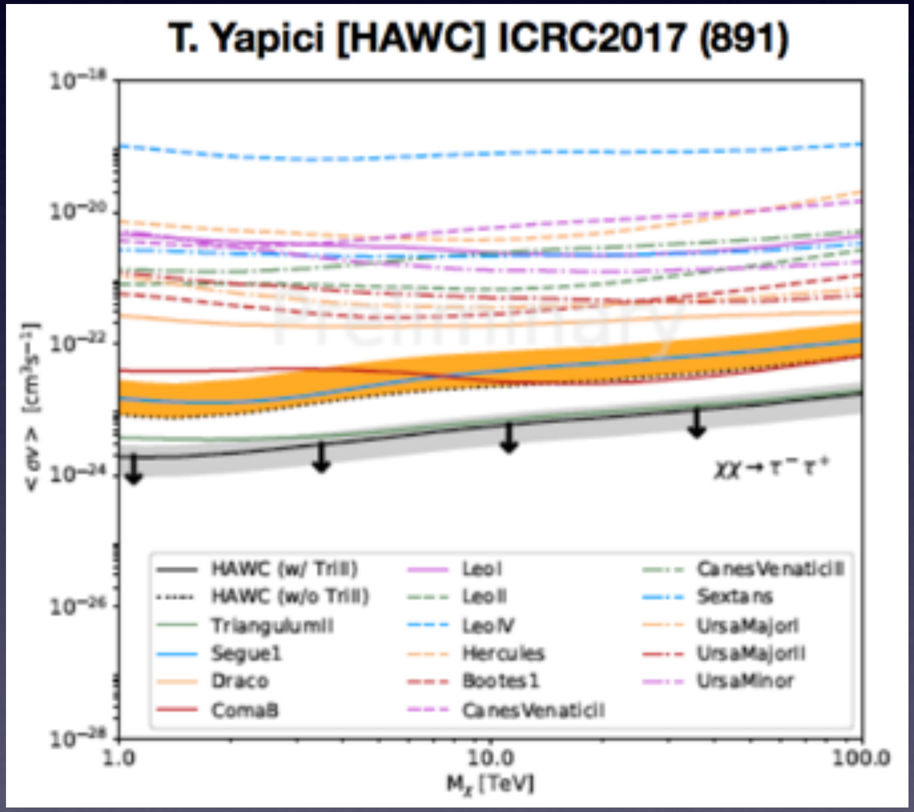
- Geringer-Sameth & Koushiappas 2012, based on seven dwarf galaxies
- See also Profumo et al '16, Liang et al '16

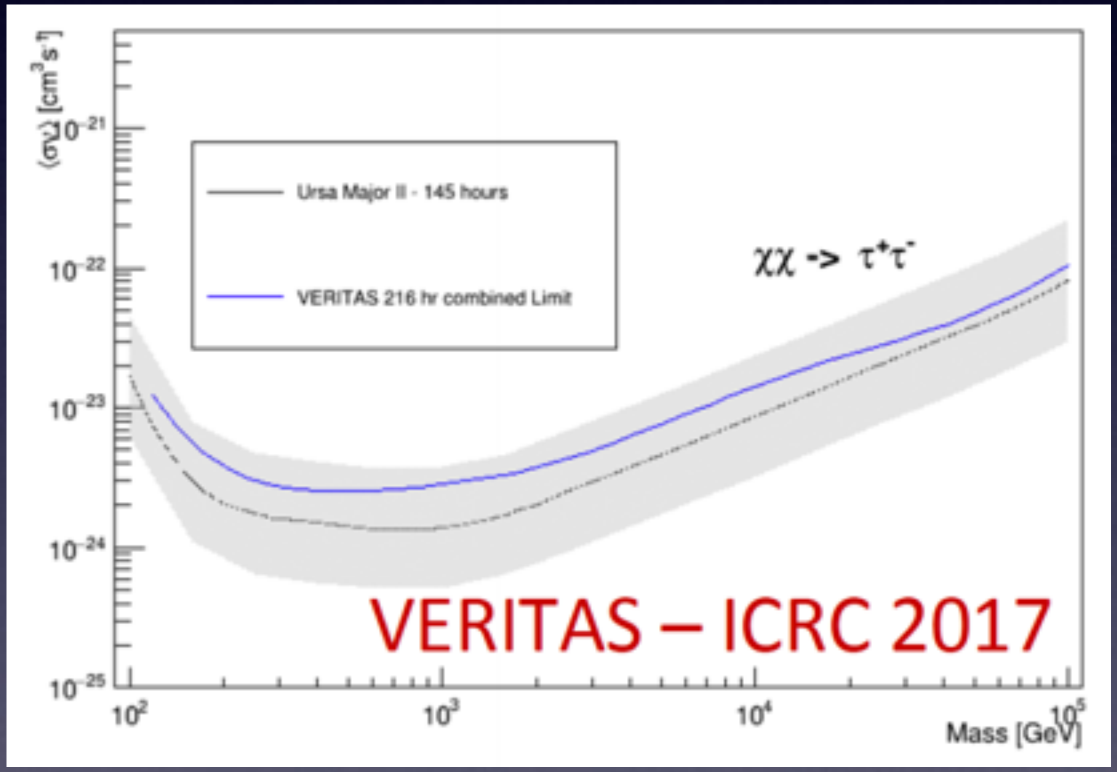
# The extragalactic gamma-ray background



Hannes-S. Zechlin ICRC2017 (922)

# Other dwarf galaxy limits





# Additional decay limits