U.S. DEPARTMENT OF ENERGY
Office of Science

Indirect Searches for Dark Matter

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TeV Particle Astrophysics
Ohio State University, Columbus
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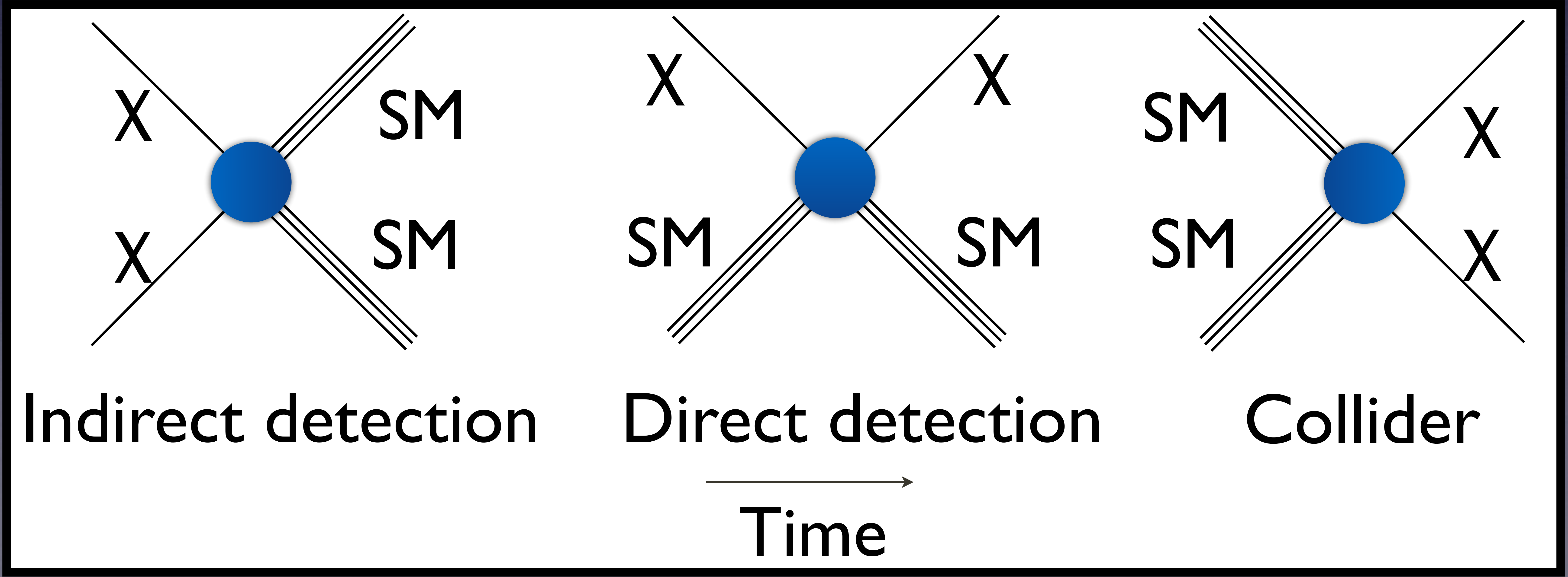
Dark matter searches

- Indirect detection: look for Standard Model particles - electrons/positrons, photons, neutrinos, protons/antiprotons - produced by DM interactions.
- Direct detection: look for Standard Model particles recoiling from collisions with invisible dark matter.
- Colliders: produce DM or dark-sector particles in collisions, look for missing energy / decay products.



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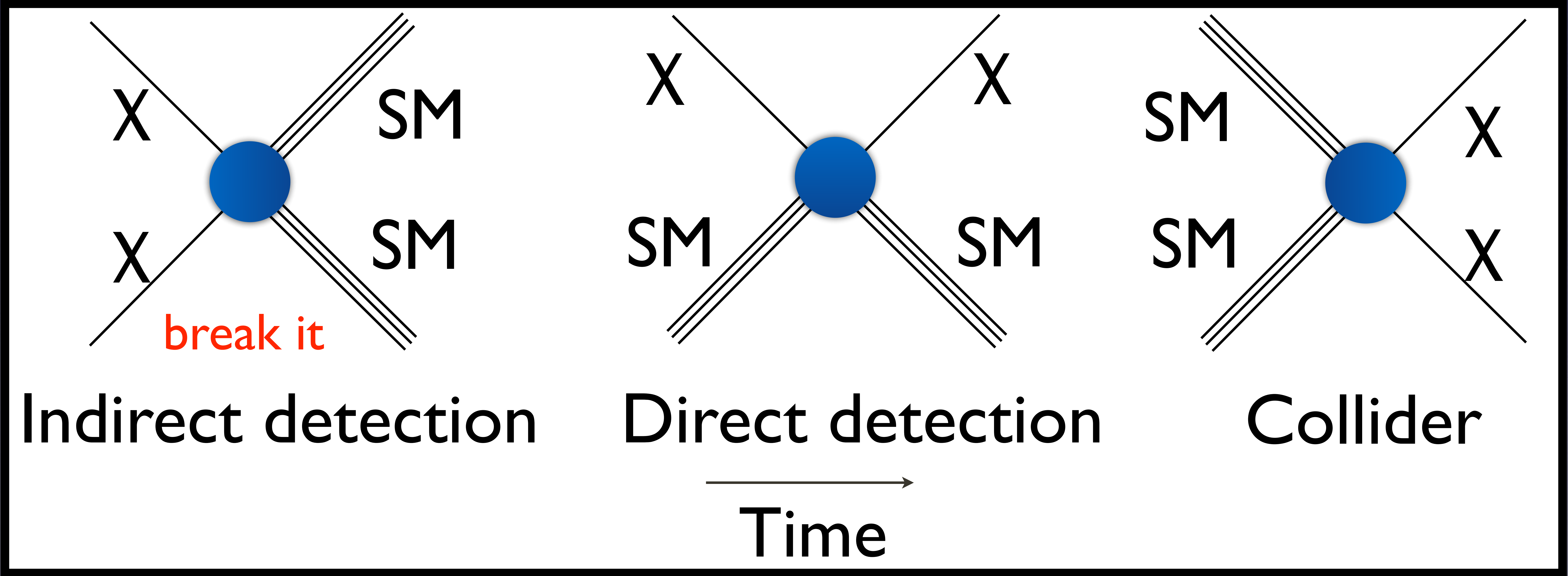

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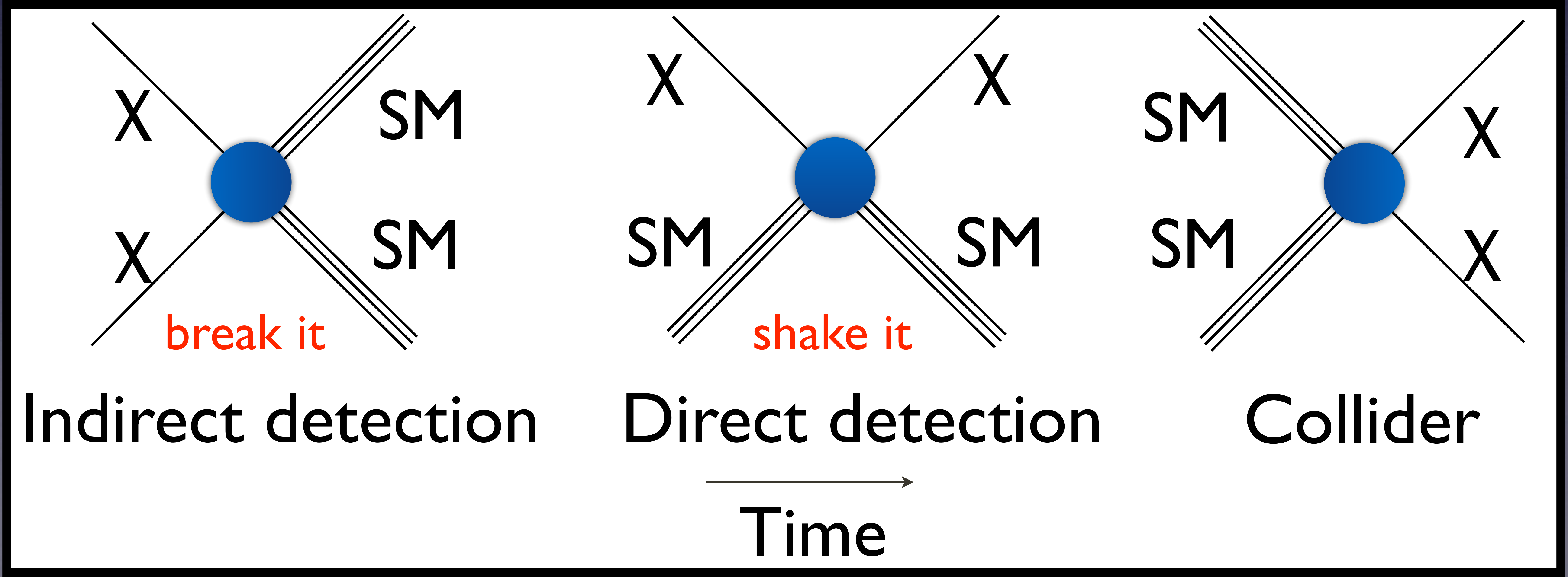

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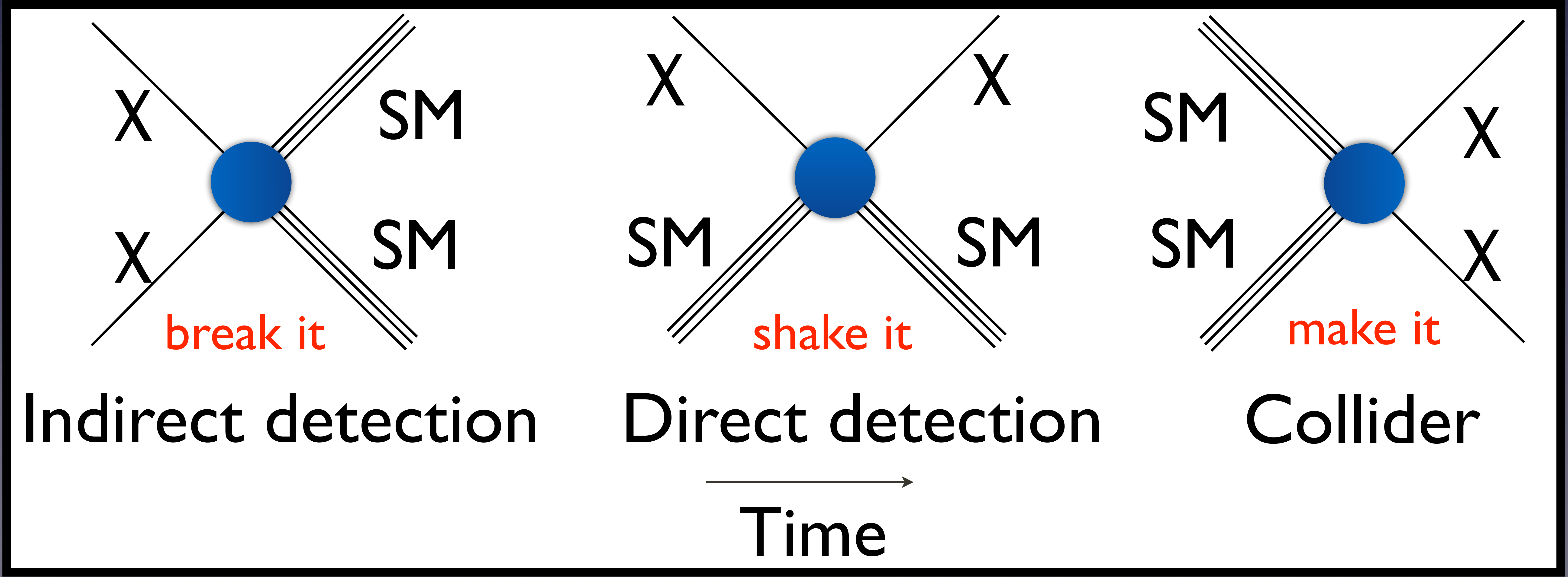

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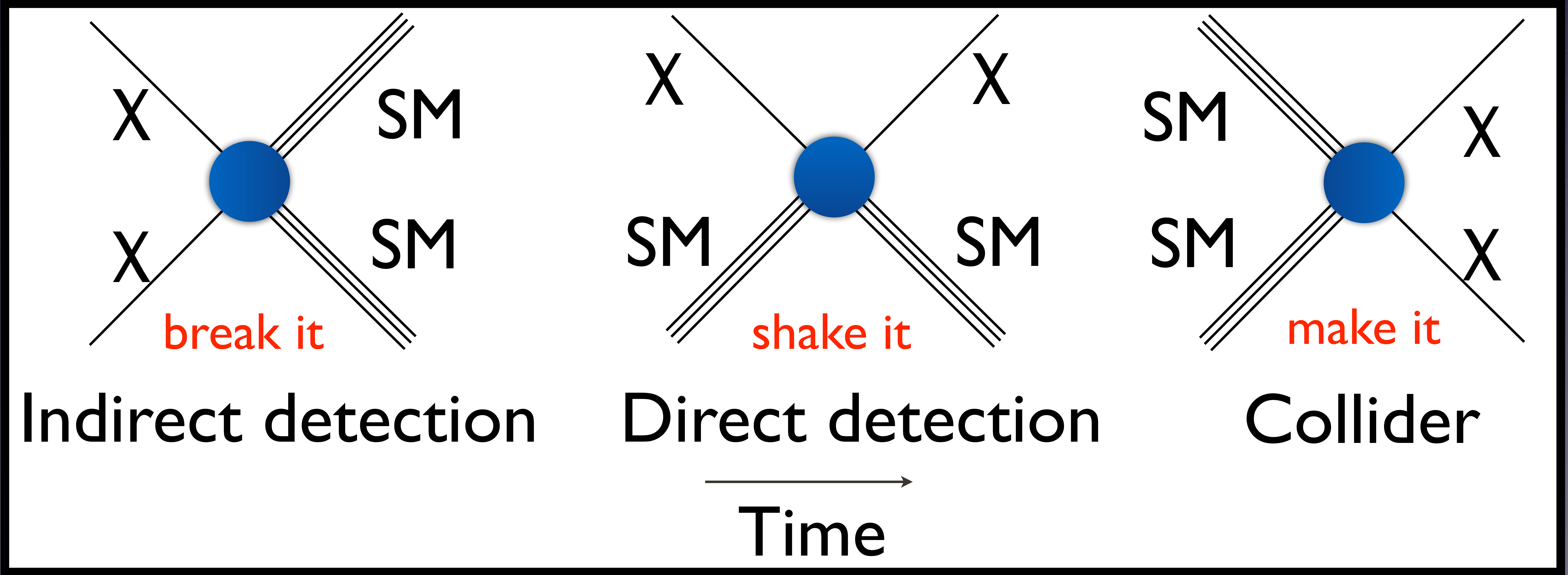

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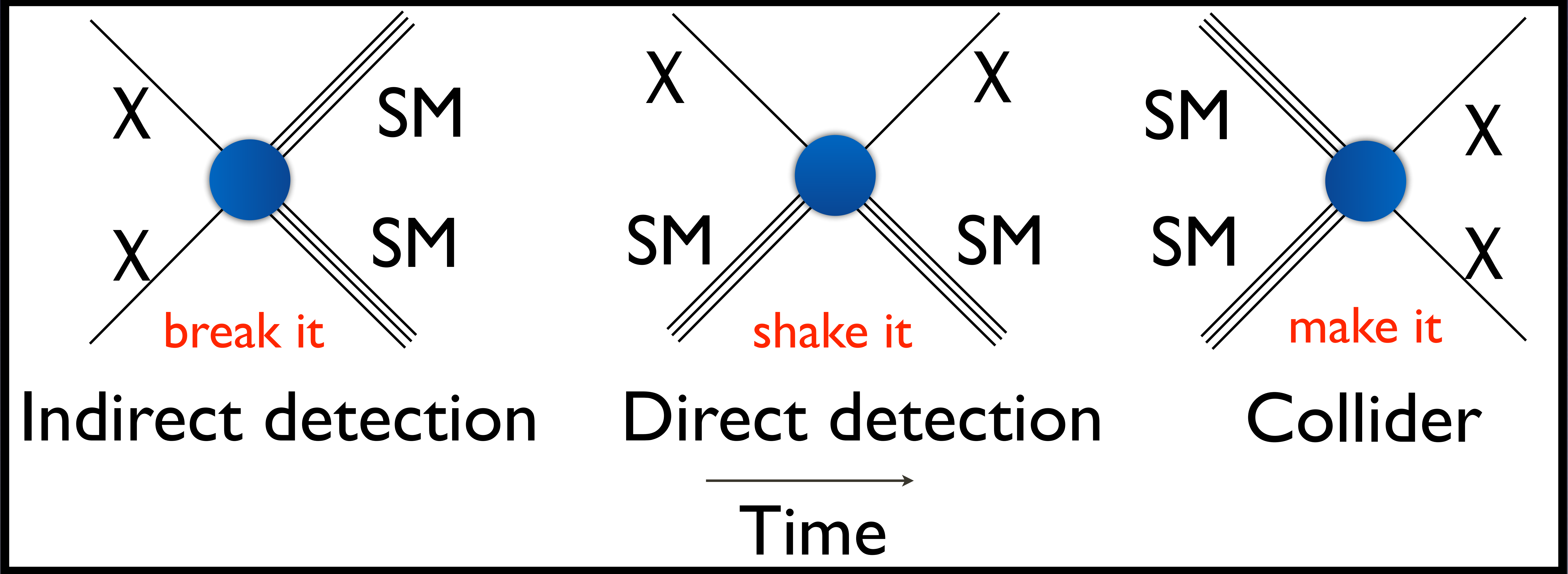
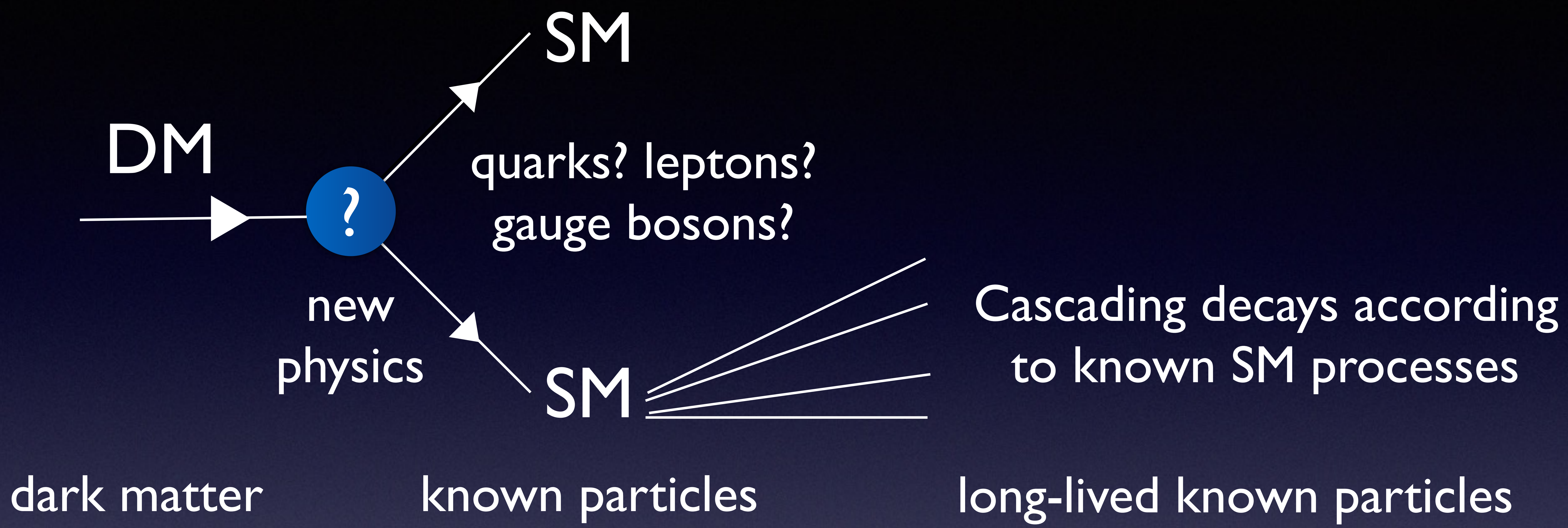
- Axion searches: DM behaves as coherent field, not particle. See talks by Safdi, Wester, Vogel, Shortino, Foster, Armendariz, Mohapatra.



Direct or indirect?

- Scattering (direct-detection mechanism) → indirect signatures (observed with telescopes)
  - Dark matter can capture in the Sun or Earth by scattering, then annihilate leading to neutrino signals.
  - Scattering can heat or even destroy astrophysical bodies [talk by Tsai] - potentially strong limits if very cold neutron stars are observed [Baryakhtar et al '17; talk by Raj].
  - Elastic scattering between DM and visible particles could modify cosmic-ray propagation [talk by Cappiello].
- Annihilation (indirect-detection mechanism) → direct signatures (scattering on terrestrial targets)
  - Boosted dark matter - detection of highly relativistic dark matter produced by annihilation [Agashe et al '14]
- ELDER models [Kuflik et al '16]: dark matter relic density set by scattering, not annihilation - prediction for present-day direct-detection signals, not present-day annihilation rate.

Decay



DM

?

SM

quarks? leptons?
gauge bosons?

new
physics

SM

Cascading decays according
to known SM processes

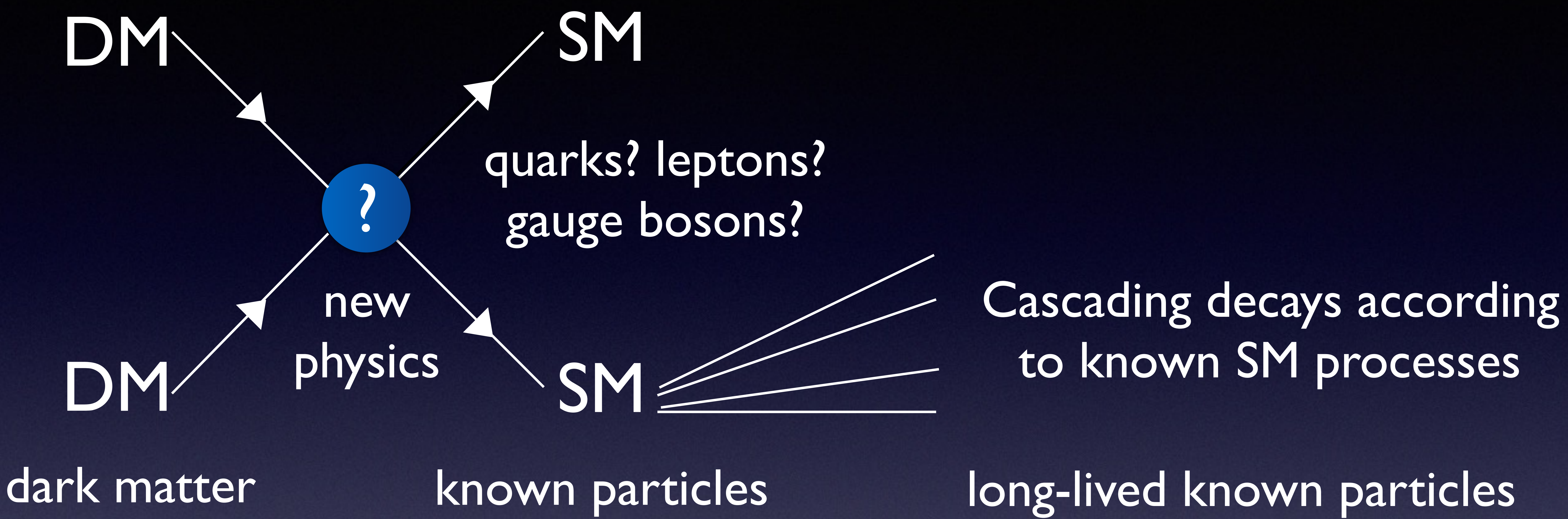
dark matter

known particles

long-lived known particles

- Observable signatures are controlled by DM mass (total available energy), preferred decay channels (controls spectrum of products), and decay lifetime (controls rate).
- Lifetime must be >> than age of universe, so decay rate is proportional to 1/lifetime.
- Rate is proportional to DM density; integrated rate from a region is proportional to total DM content of that region.

Annihilation



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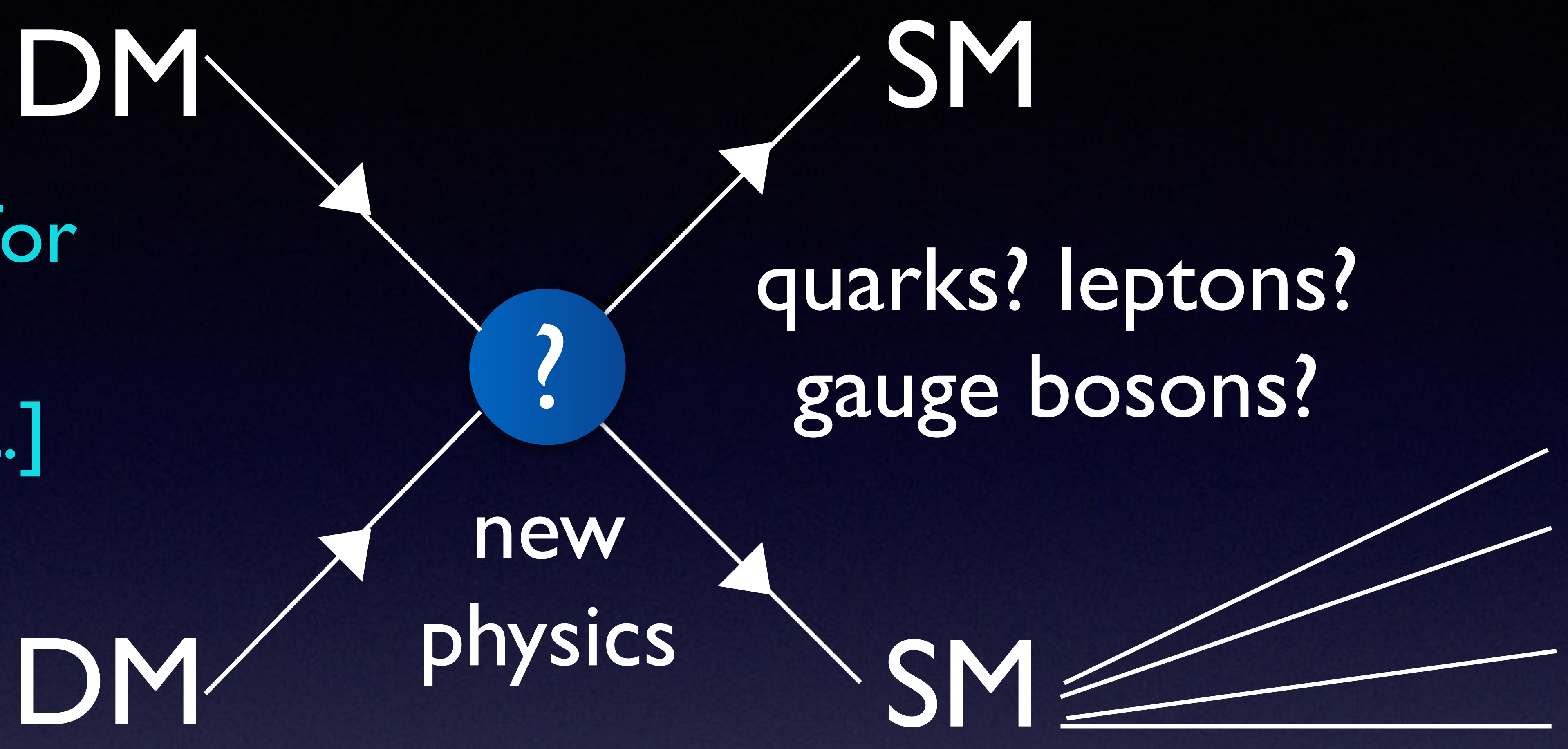
- Rate is proportional to DM density ρ squared; integrated rate from a region is proportional to $\langle \rho^2 \rangle$ for that region.
- Rate can also depend on other factors, e.g. DM velocity - simplest common case has velocity-independent rate, but either enhancement or suppression at low velocities is possible.

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

Annihilation

[See talks by Natale, Liu for examples where 3→2 annihilation is important.]



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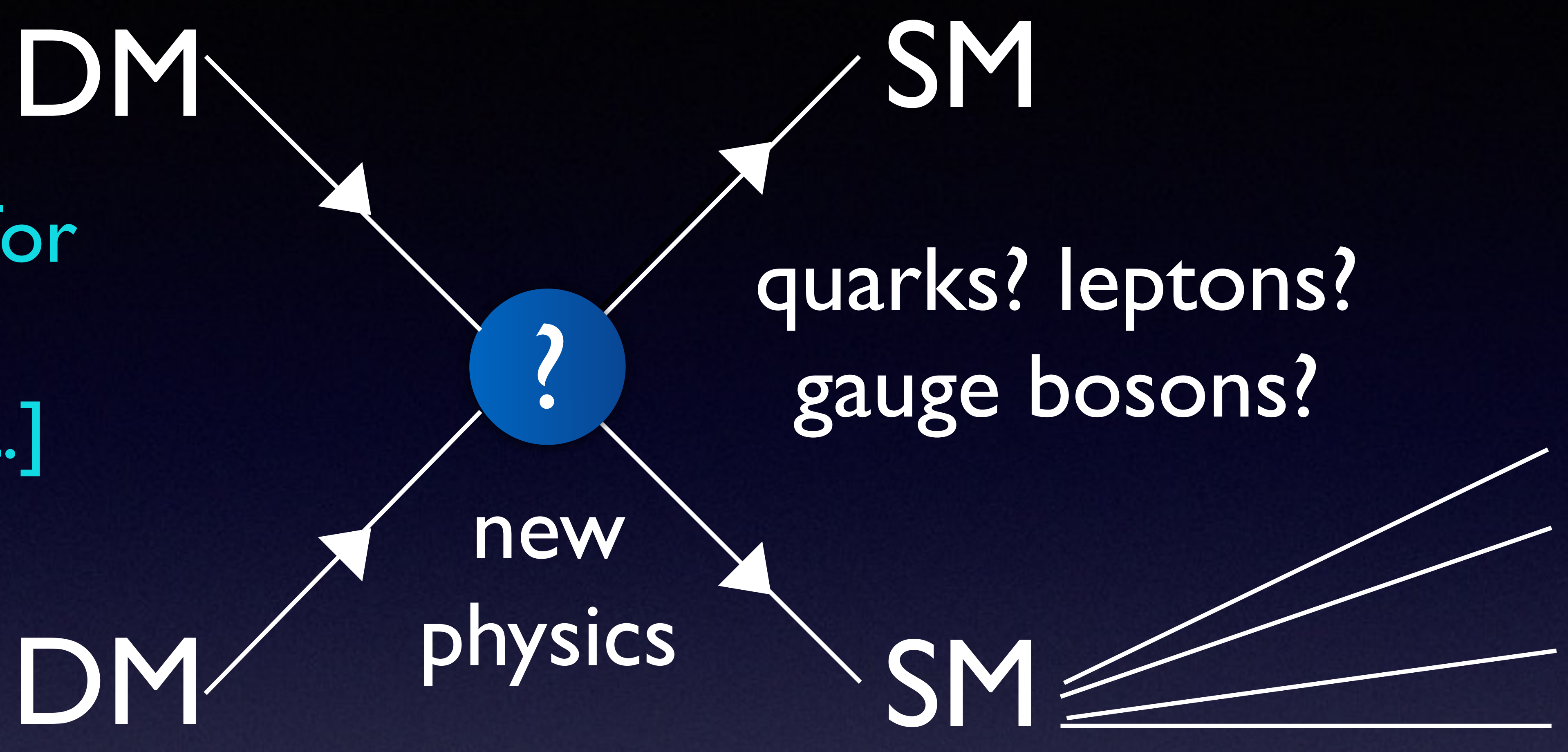

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[See talk by Berlin for a discussion of light thermal DM.]

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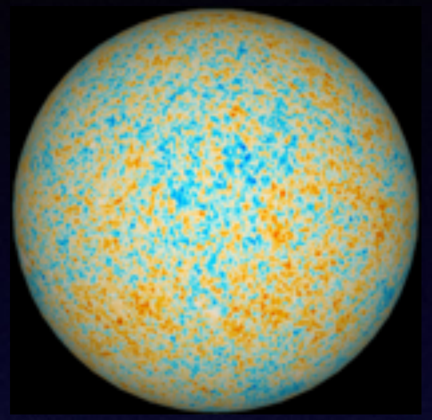

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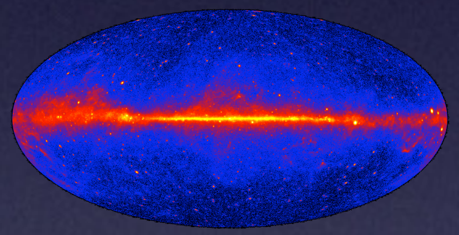

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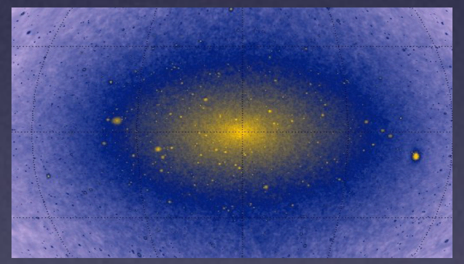

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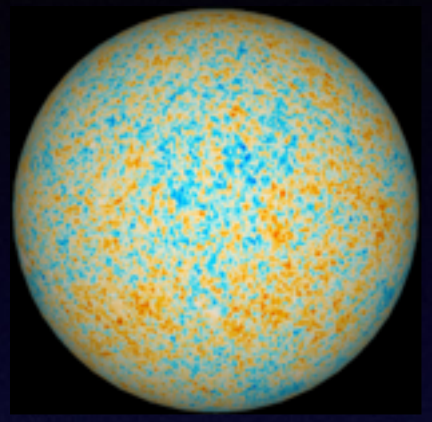

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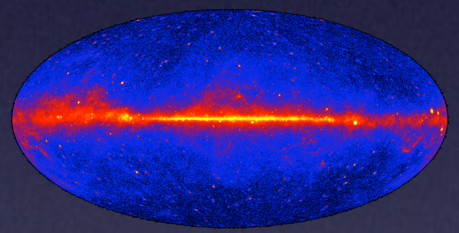

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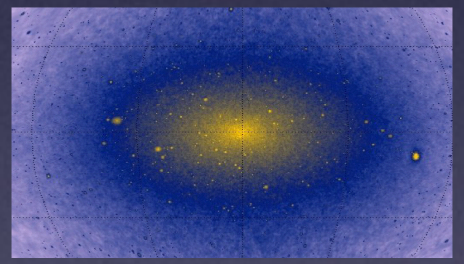

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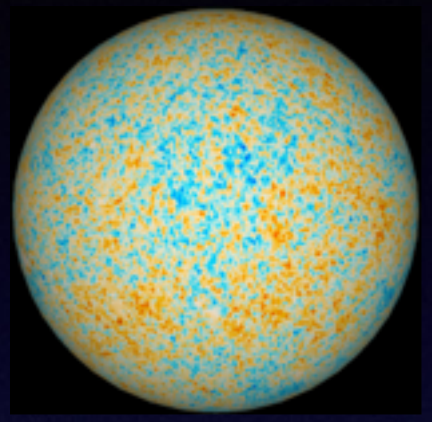

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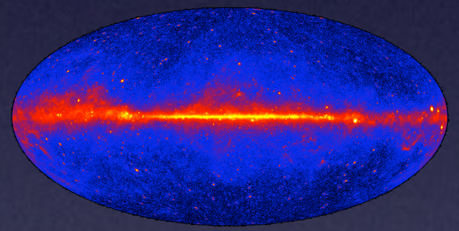

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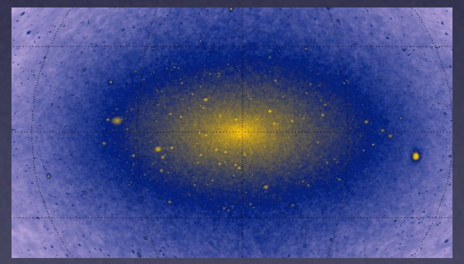

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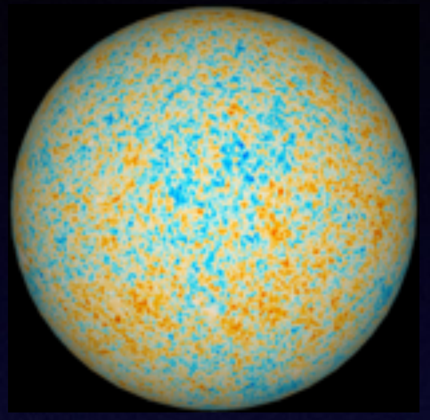

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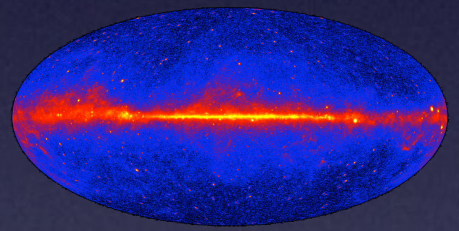

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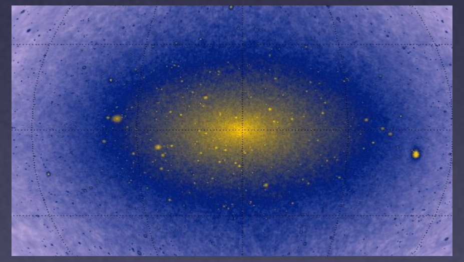

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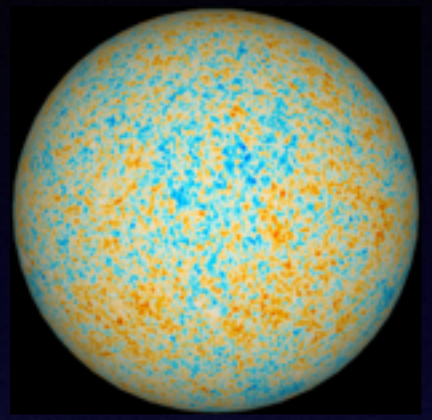

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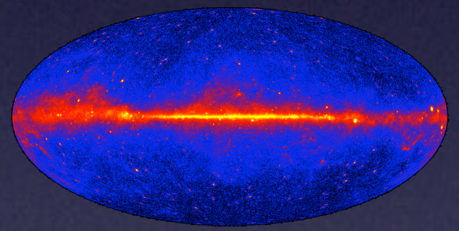

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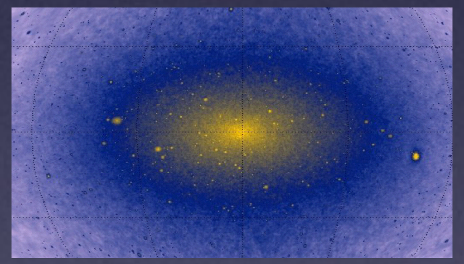

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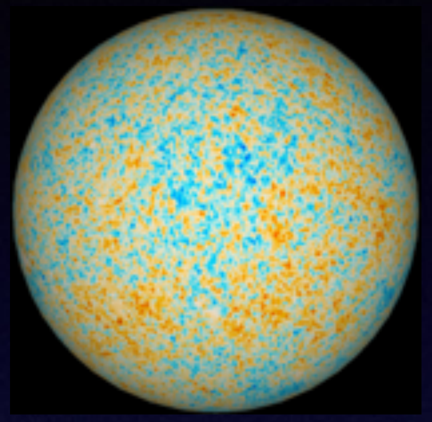

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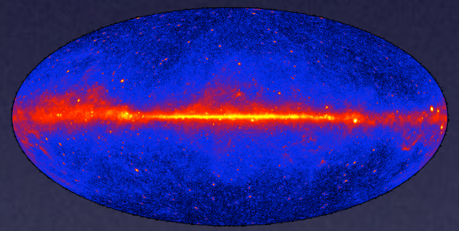

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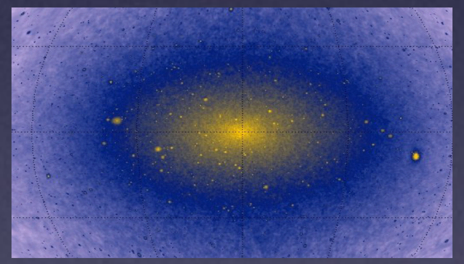

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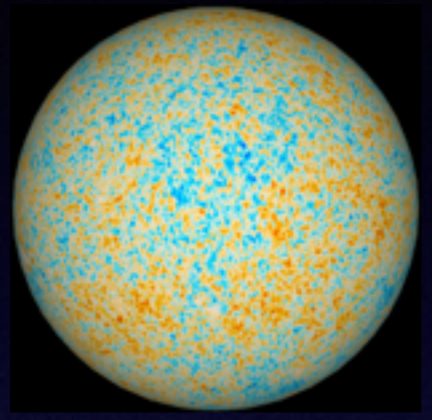

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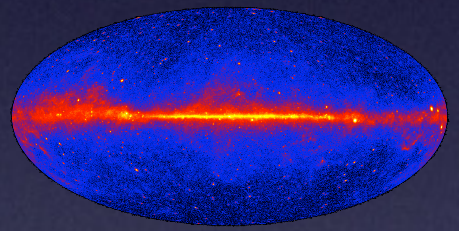

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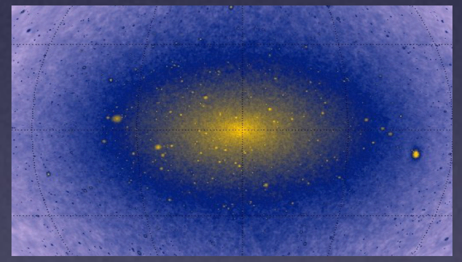

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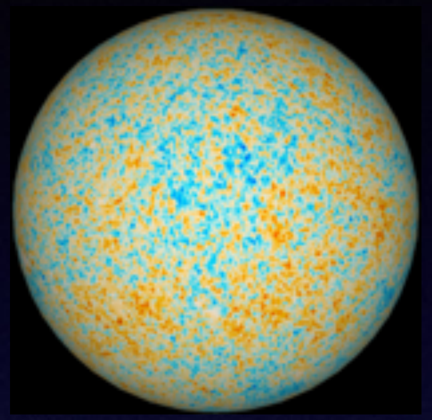

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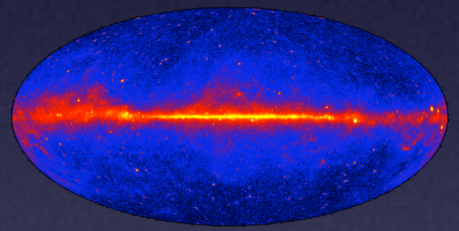

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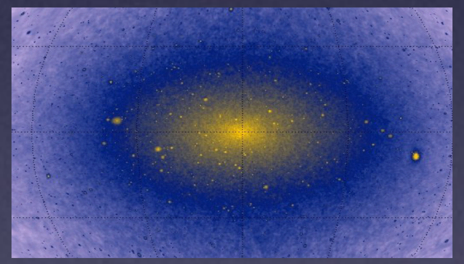

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holds redshift information, probes halos at all scales

Current limits

Short version:

Thermal annihilation cross-section benchmark ruled out / in tension for DM masses below 10-100 GeV, for non-neutrino final states.

Decay lifetimes below ~10^{27-28} s ruled out for most final states and keV-EeV DM masses; for few-MeV DM decaying to e^+e^-, lifetimes can be as short as 10^{24-25} s.

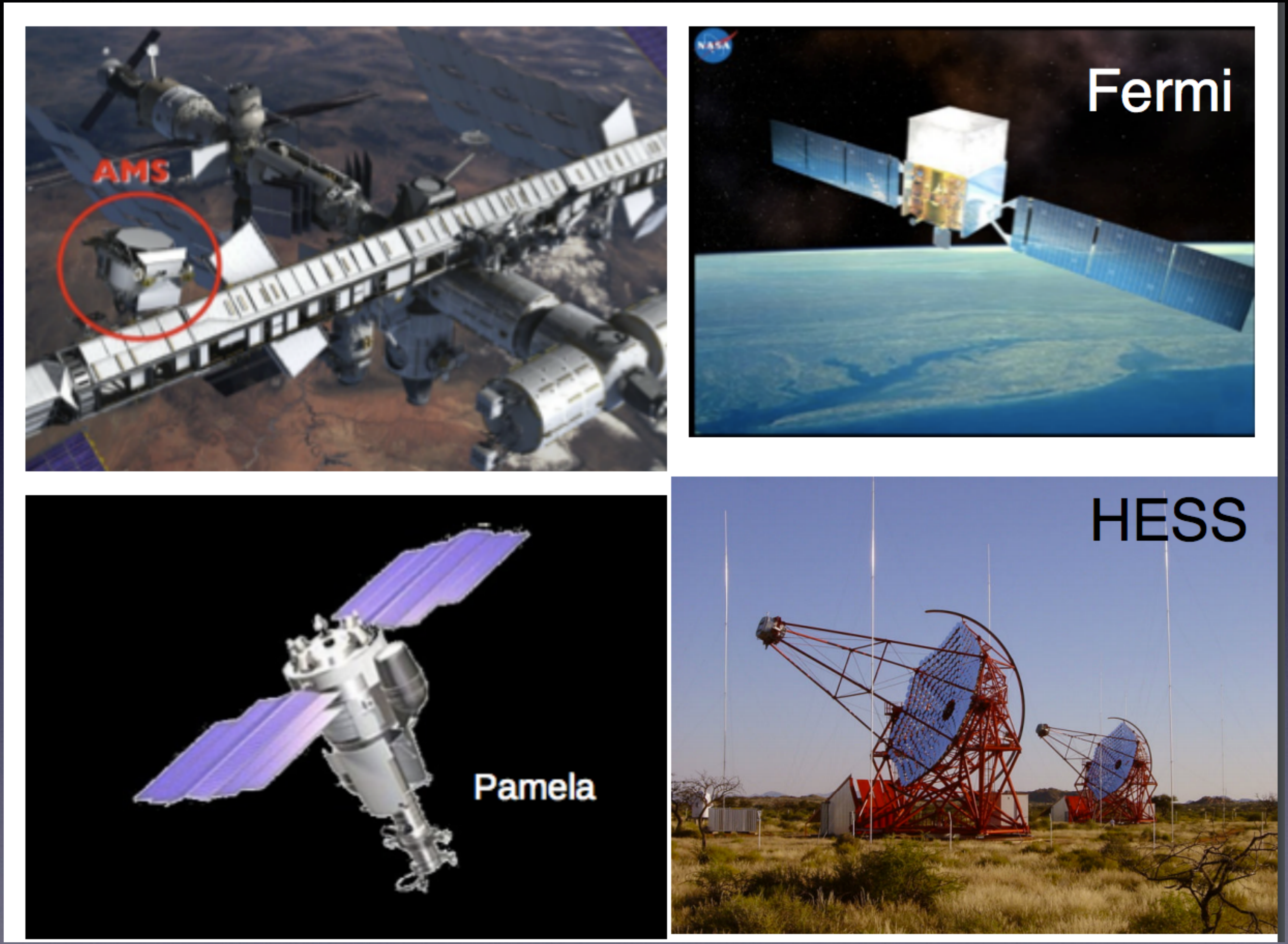
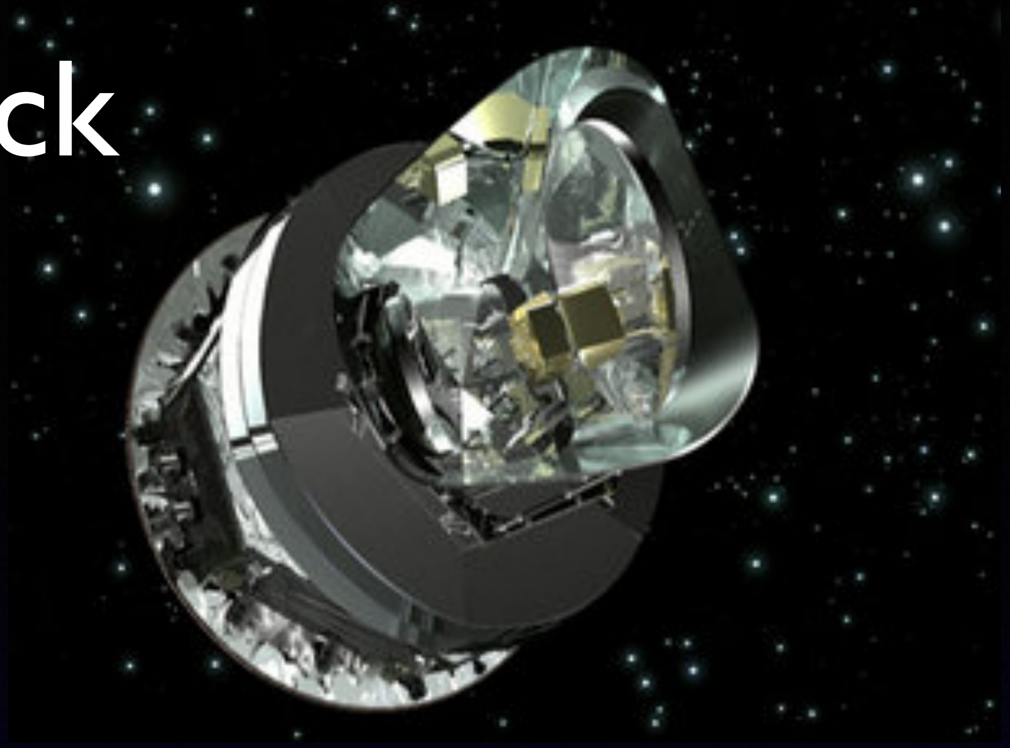


Image credit: Carsten Rott

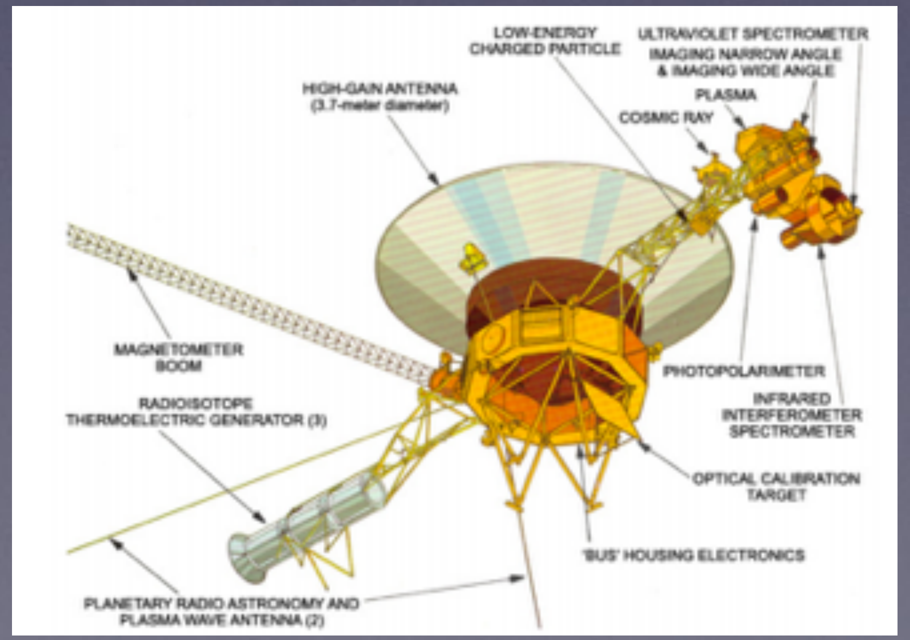
+VERITAS, MAGIC

Planck



HAWC

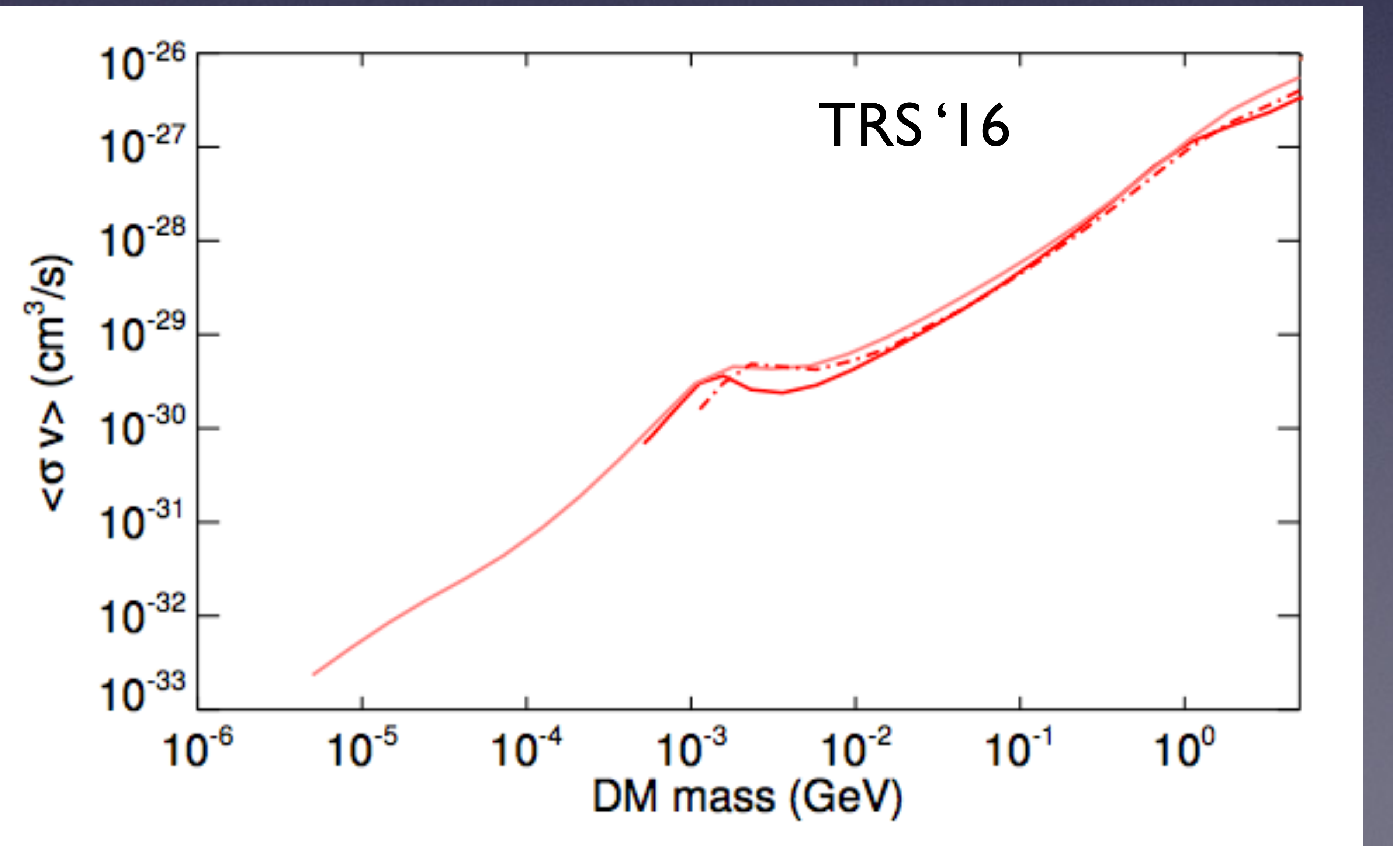
Voyager 1 (!)

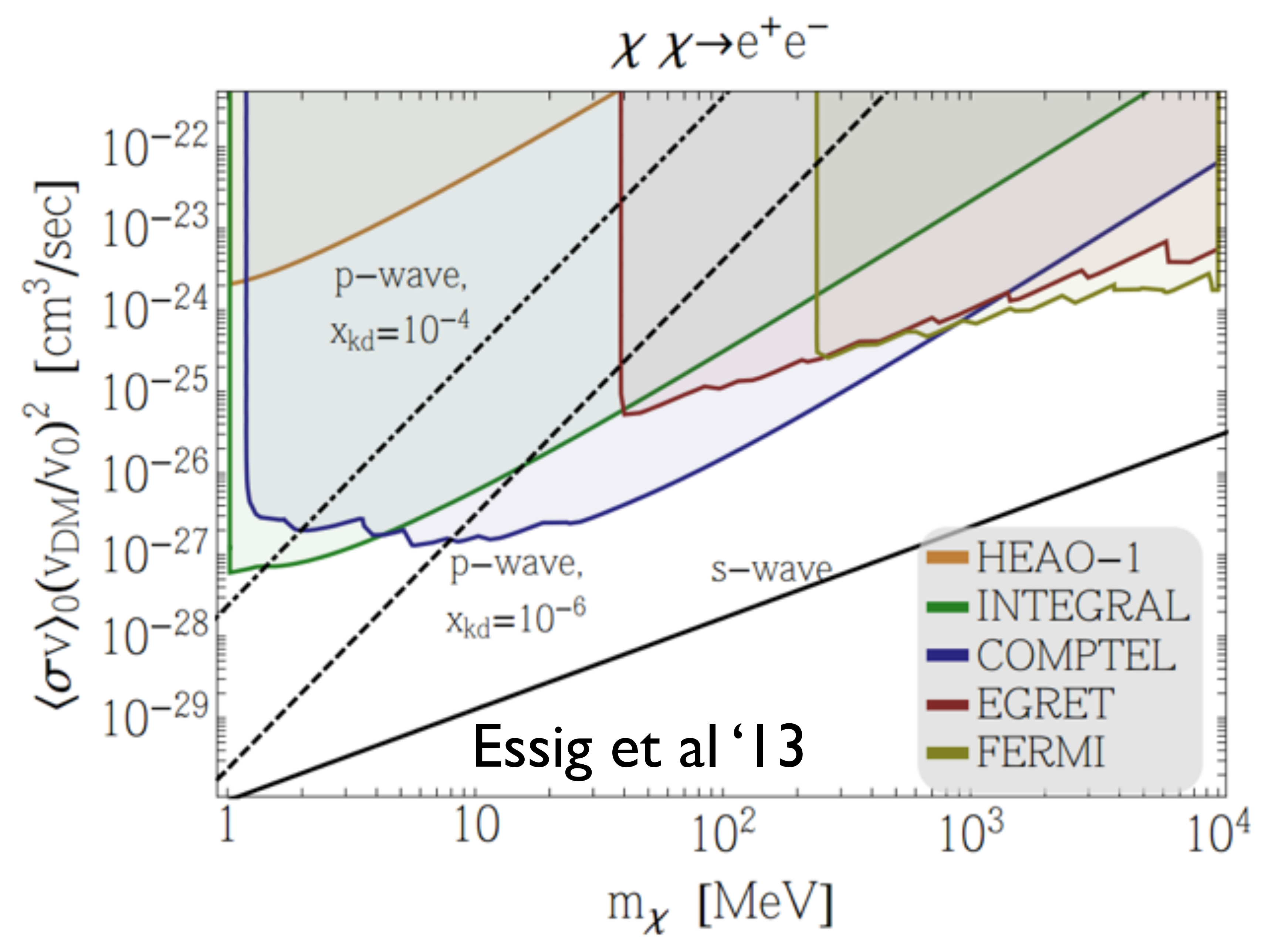


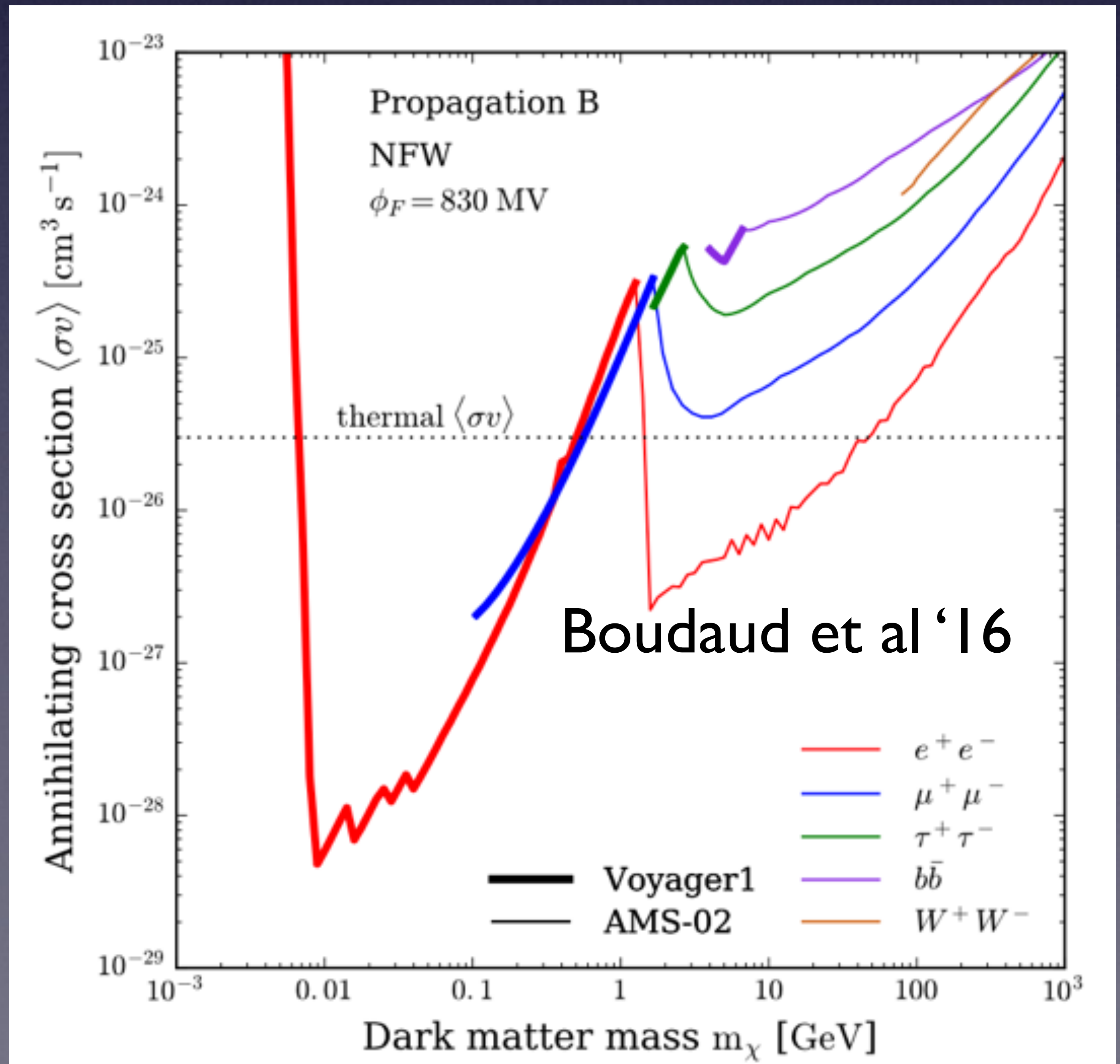
Light DM annihilation

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

- DM annihilation to electromagnetically interacting particles can induce additional ionization in early universe, distort CMB anisotropy spectrum - places stringent limits on e+e- and photon channels.
- For velocity-suppressed annihilation, CMB constraints are weak; stronger limits come from measurements of the photon Galactic diffuse background, and measurements of cosmic rays by AMS-02 and Voyager.


TRS '16

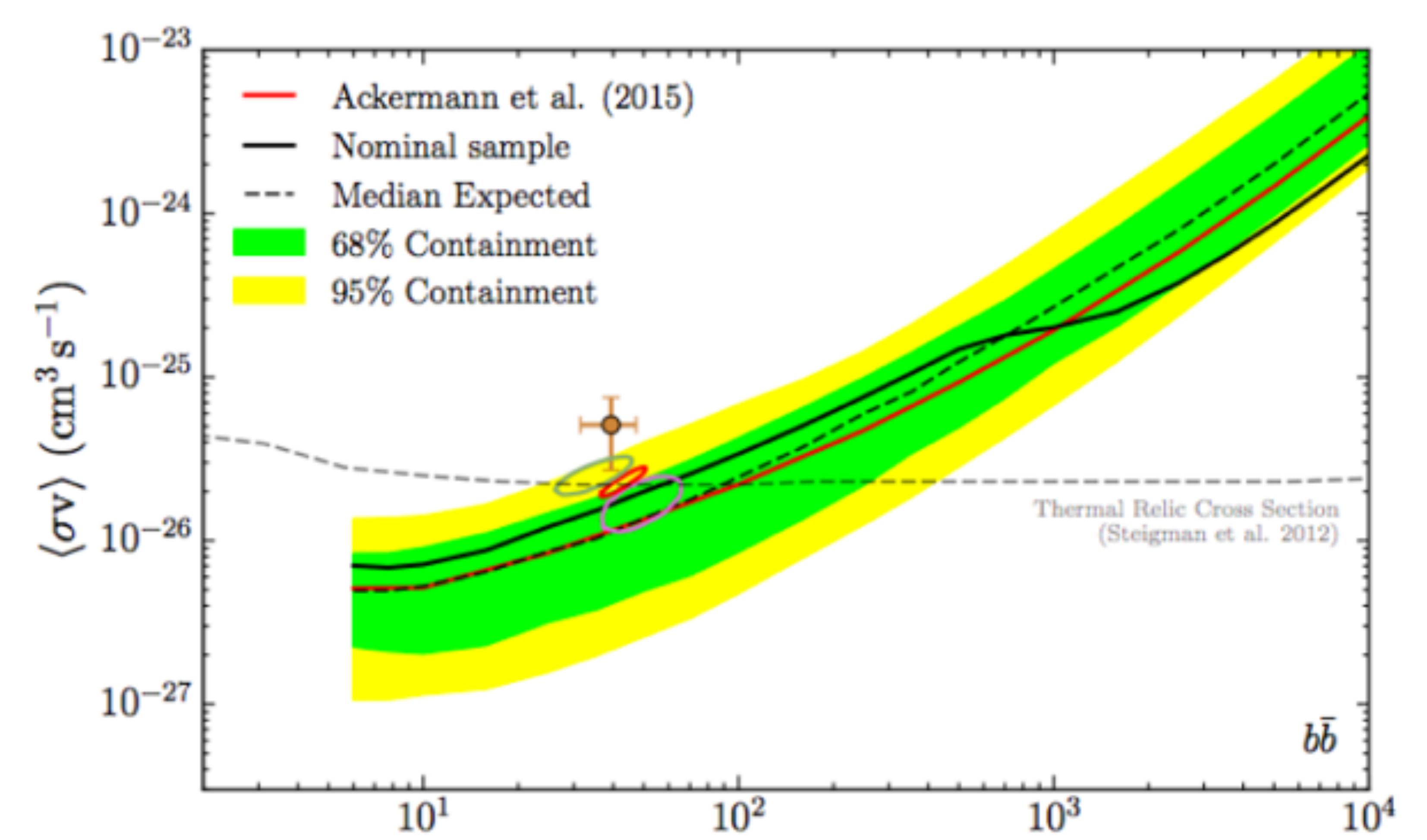

Essig et al '13


Boudaud et al '16

WIMP-scale DM annihilation

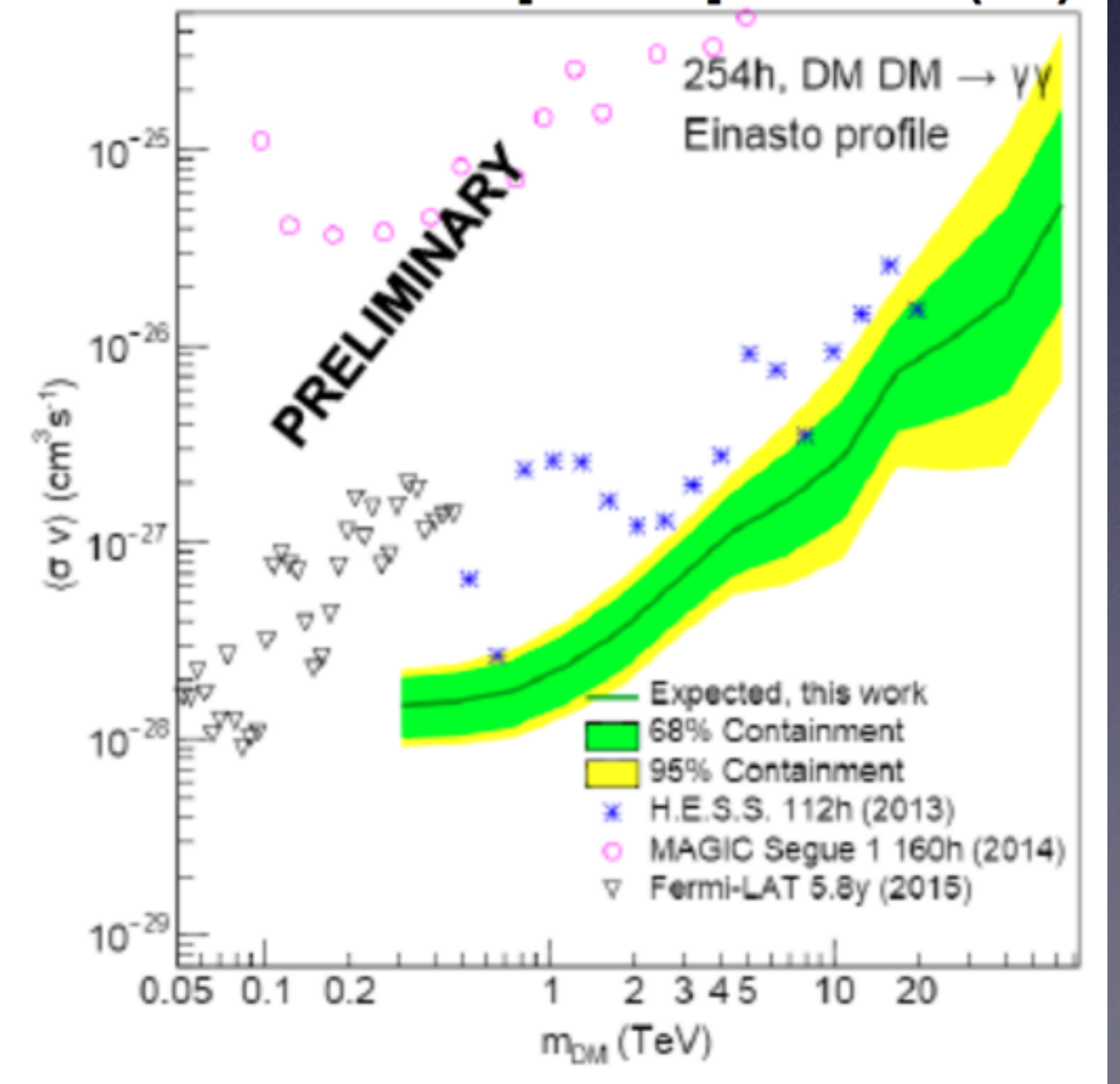
~GeV-100 TeV DM masses: rich array of possible annihilation products

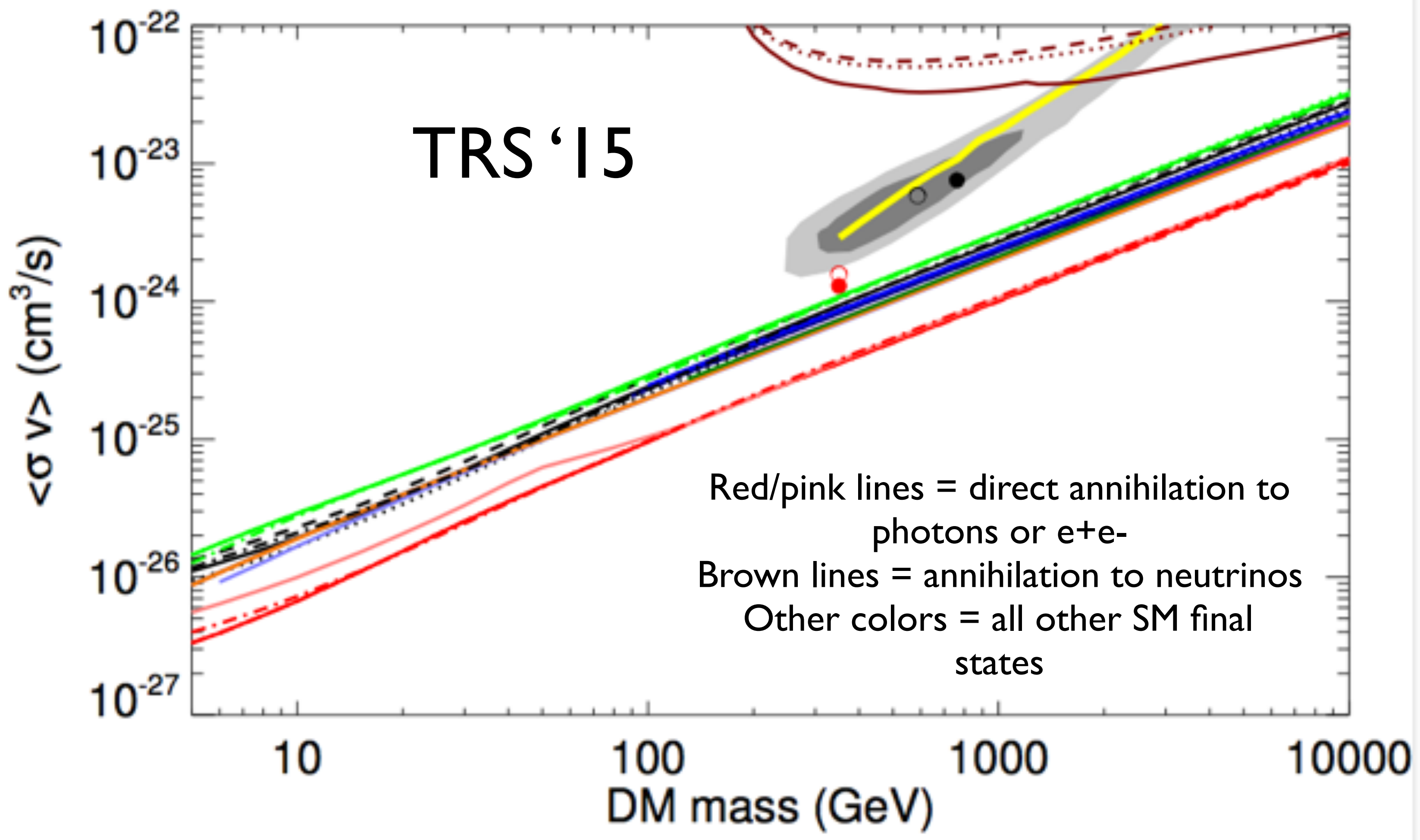
- CMB rules out thermal relic cross section for s-wave annihilation for masses below ~10 GeV (unless annihilation is dominantly to neutrinos).
- For photon-rich channels, stronger limits from dwarf galaxies (modulo J-factor uncertainties) - rule out thermal relic cross section below several tens of GeV. At masses above 1 TeV, strong limits from H.E.S.S observations of the inner Galaxy (Abdallah et al '16).
- AMS-02 antiproton bounds are also competitive for hadronic channels, and for annihilation to e+e-, there are strong limits from AMS-02 positron measurements.
- For gamma-ray lines, strong limits from Galactic center gamma-ray observations.



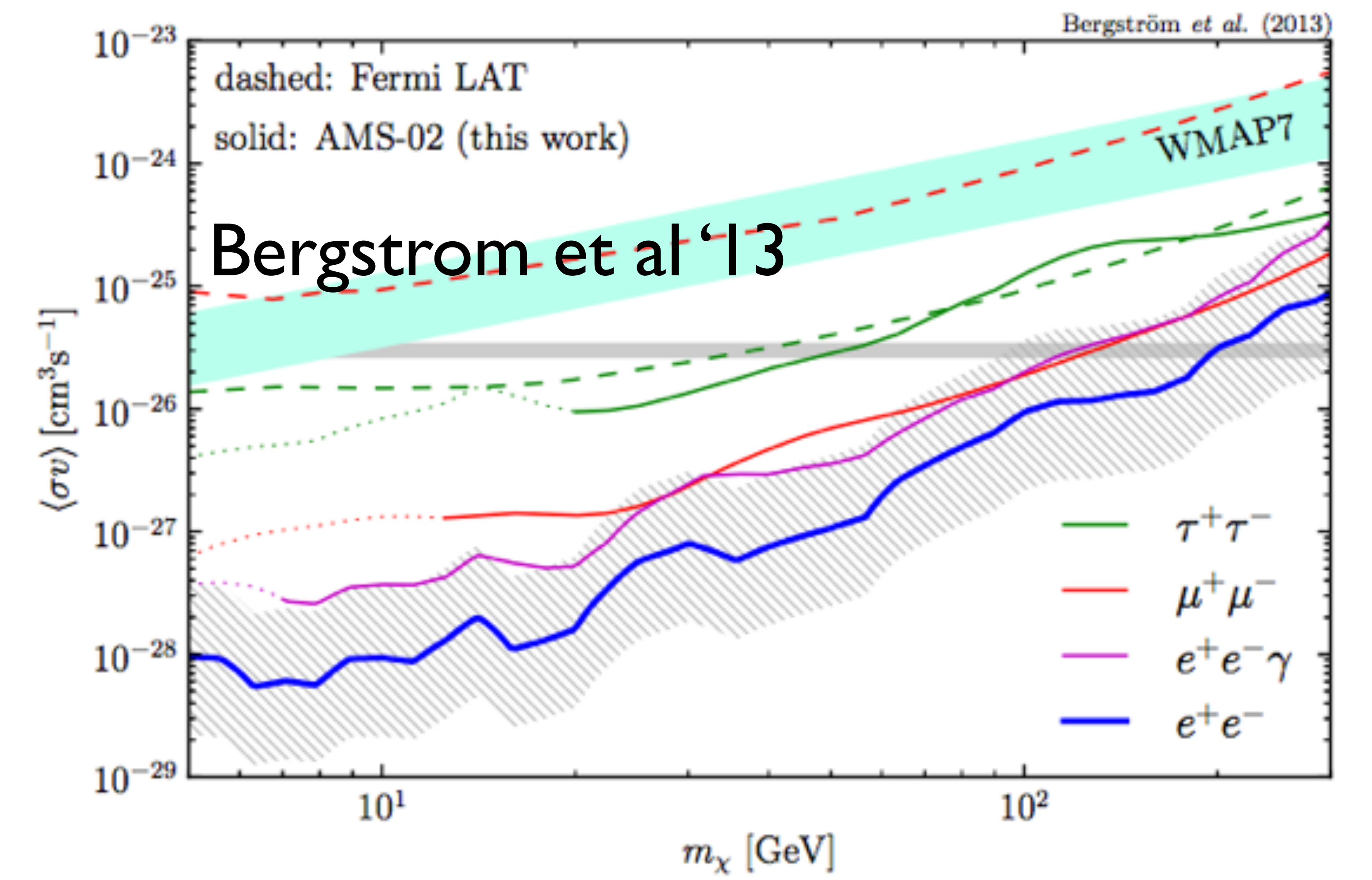
Albert et al '17

Emmanuel Moulin [H.E.S.S.] ICRC2017 (893)





Red/pink lines = direct annihilation to photons or e+e-
Brown lines = annihilation to neutrinos
Other colors = all other SM final states



Bergstrom et al '13

WIMP-scale DM annihilation

~GeV-100 TeV DM masses: rich array of possible annihilation products

- CMB rules out thermal relic cross section for s-wave annihilation for masses below ~10 GeV (unless annihilation is dominantly to neutrinos).
- For photon-rich channels, stronger limits from dwarf galaxies (modulo J-factor uncertainties) - rule out thermal relic cross section below several tens of GeV. At masses above 1 TeV, strong limits from H.E.S.S observations of the inner Galaxy (Abdallah et al '16).
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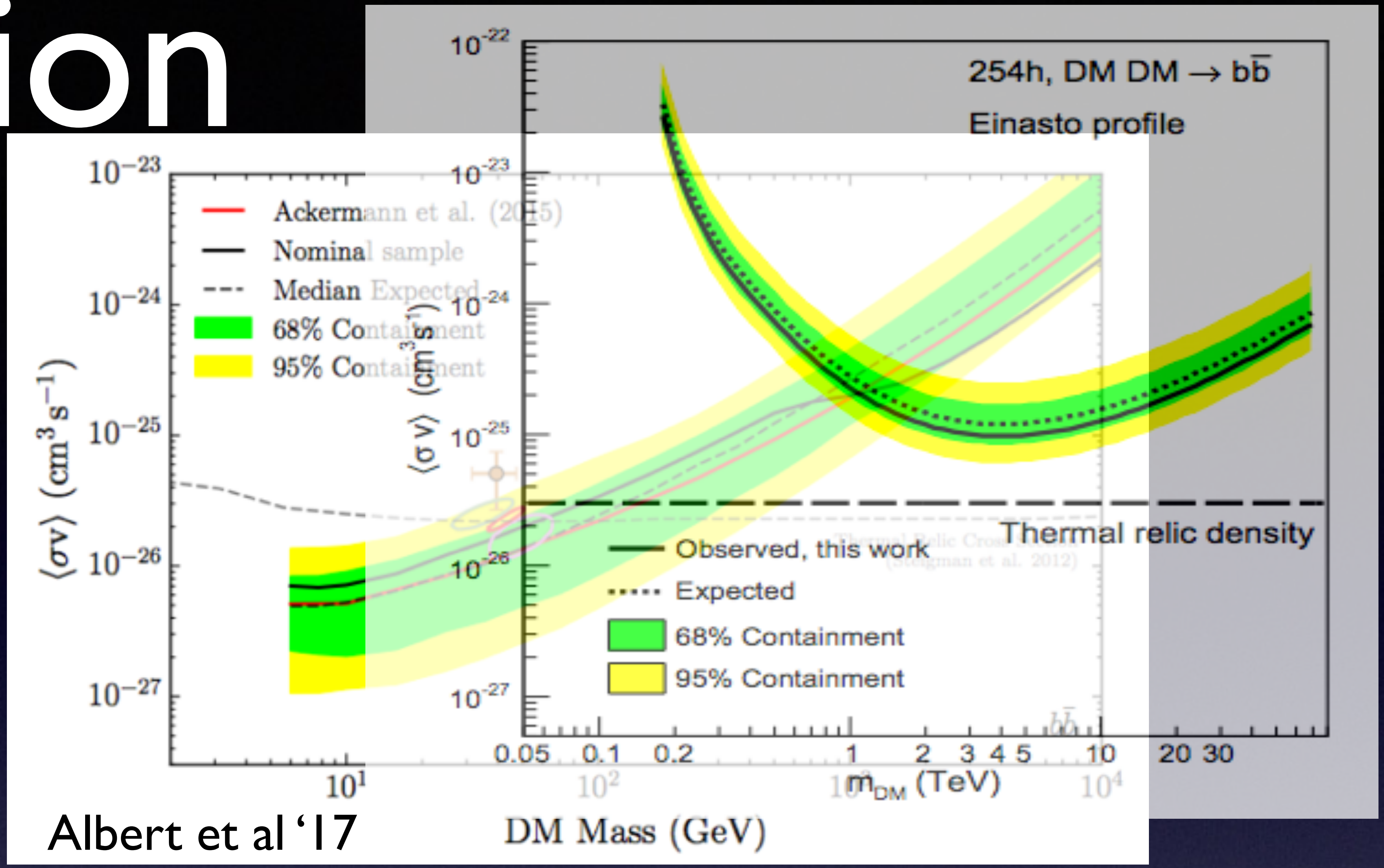
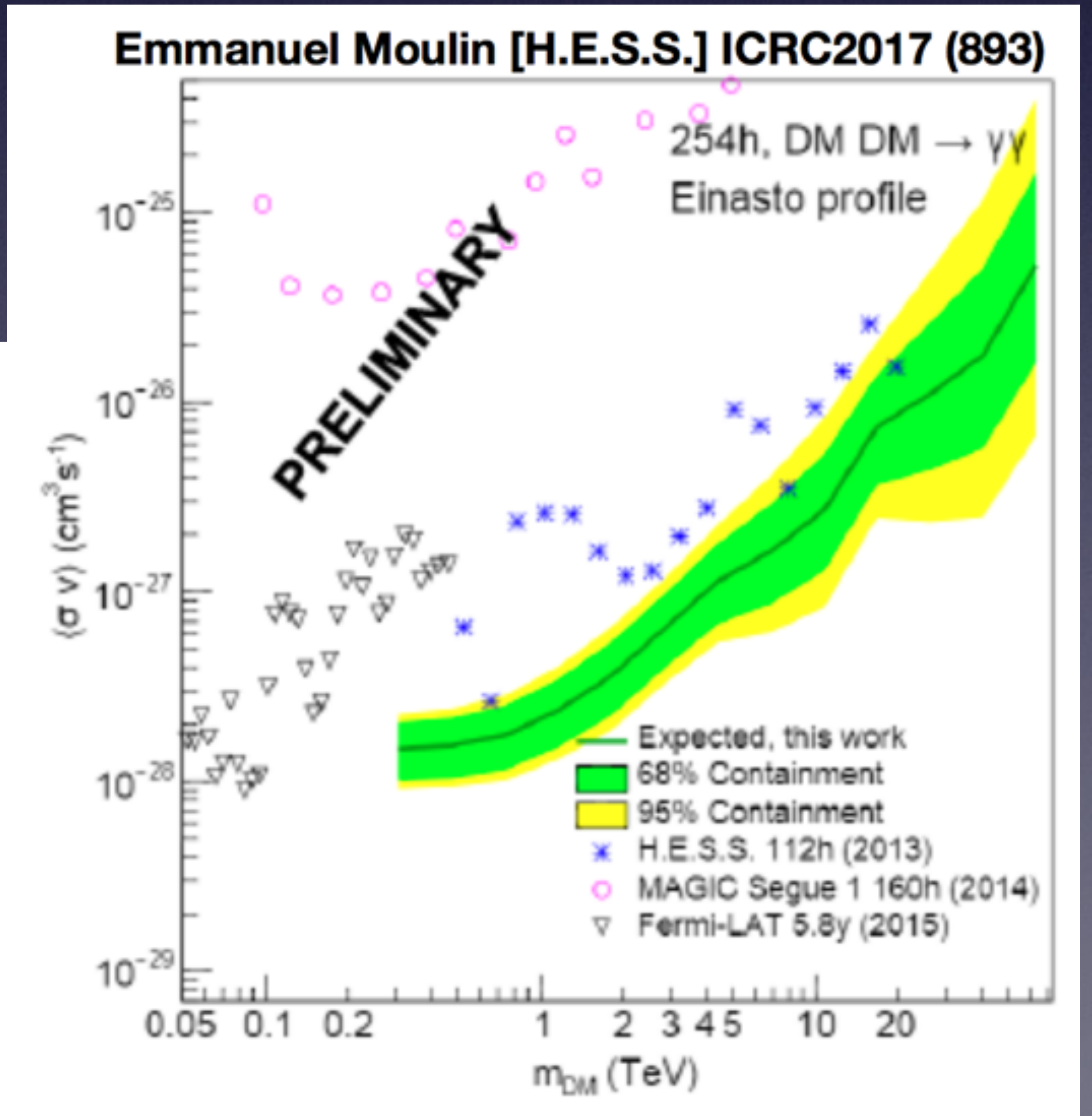
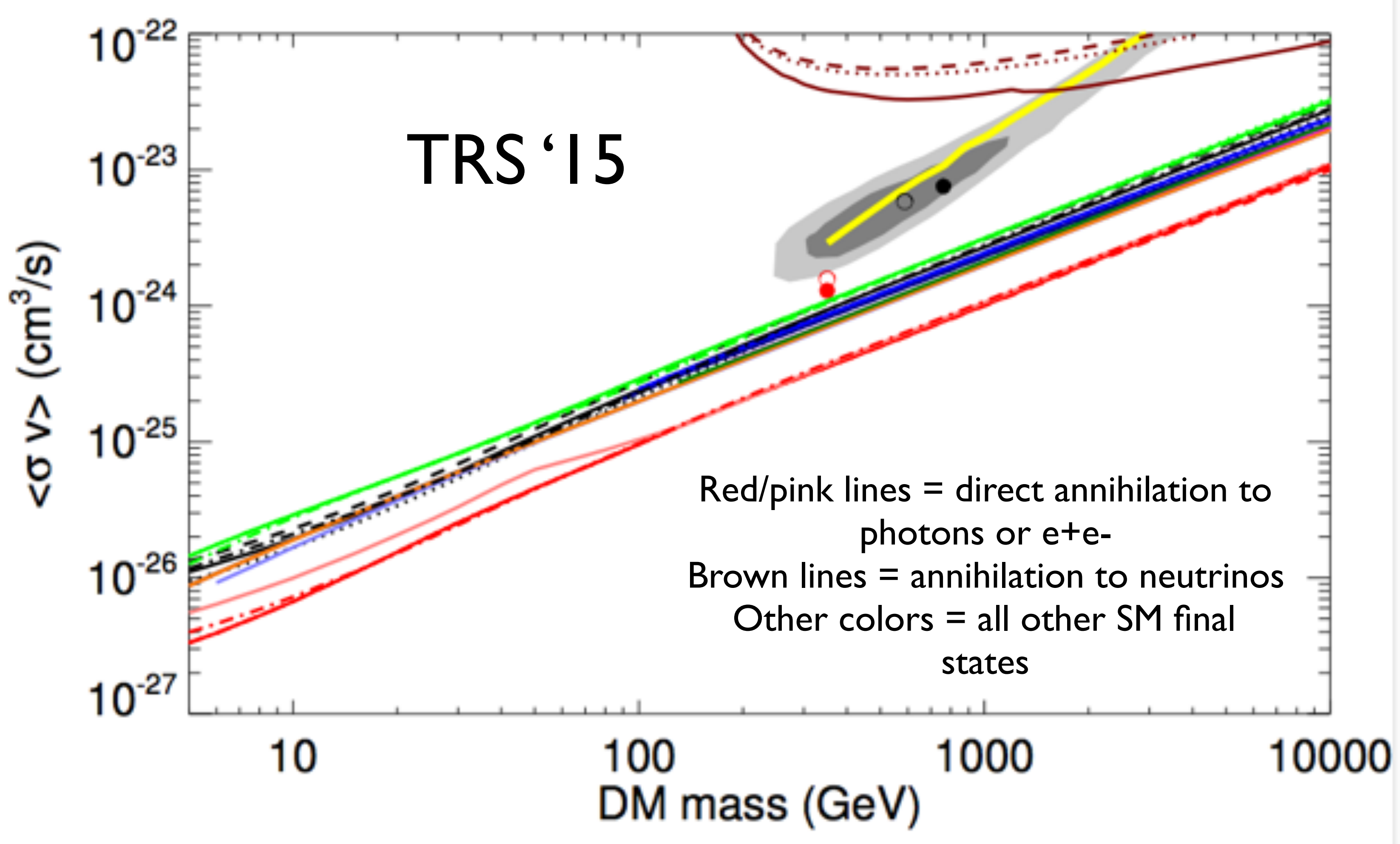


Albert et al '17



Emmanuel Moulin [H.E.S.S.] ICRC2017 (893)



TRS '15

Red/pink lines = direct annihilation to photons or e+e-
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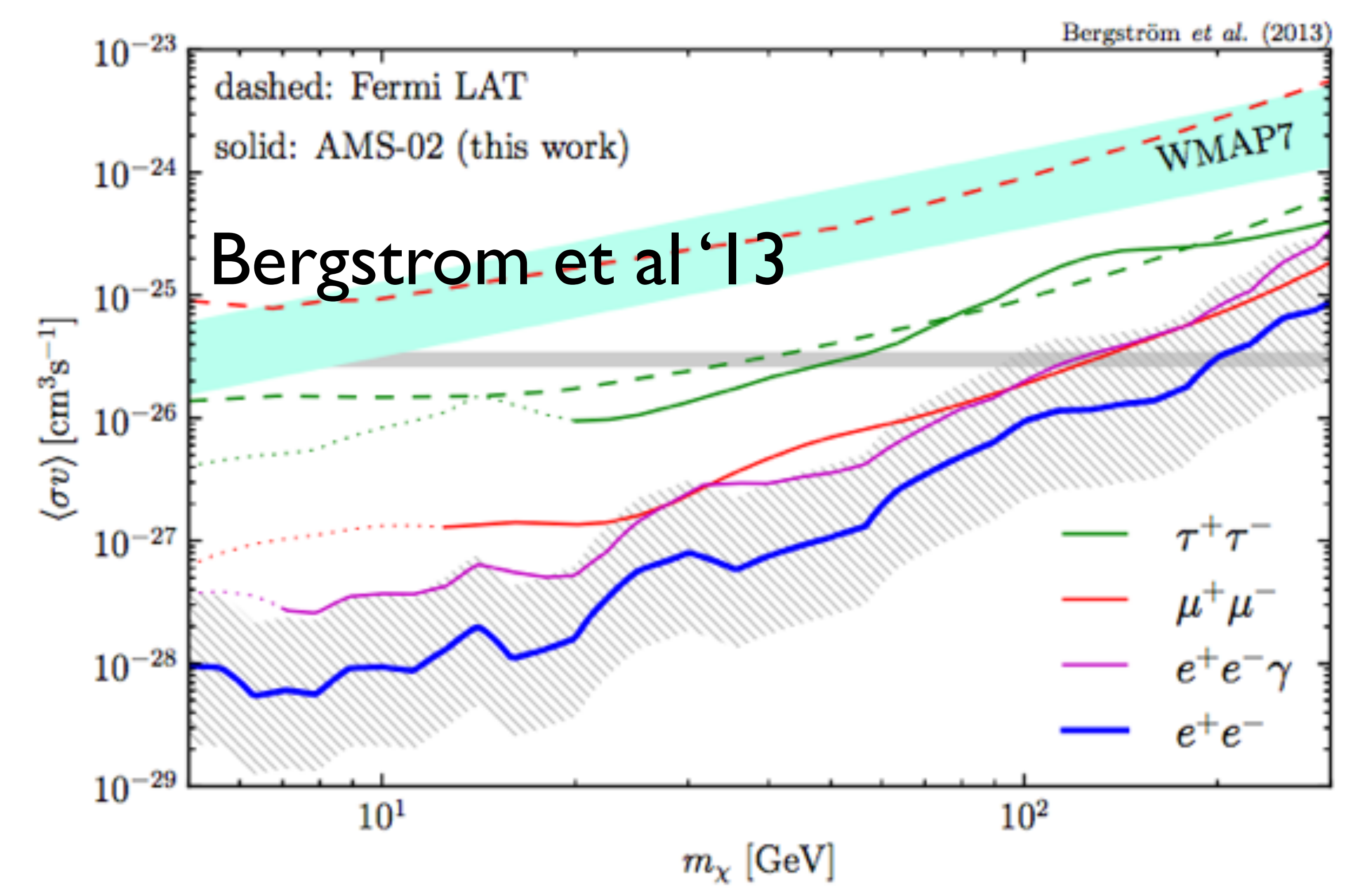

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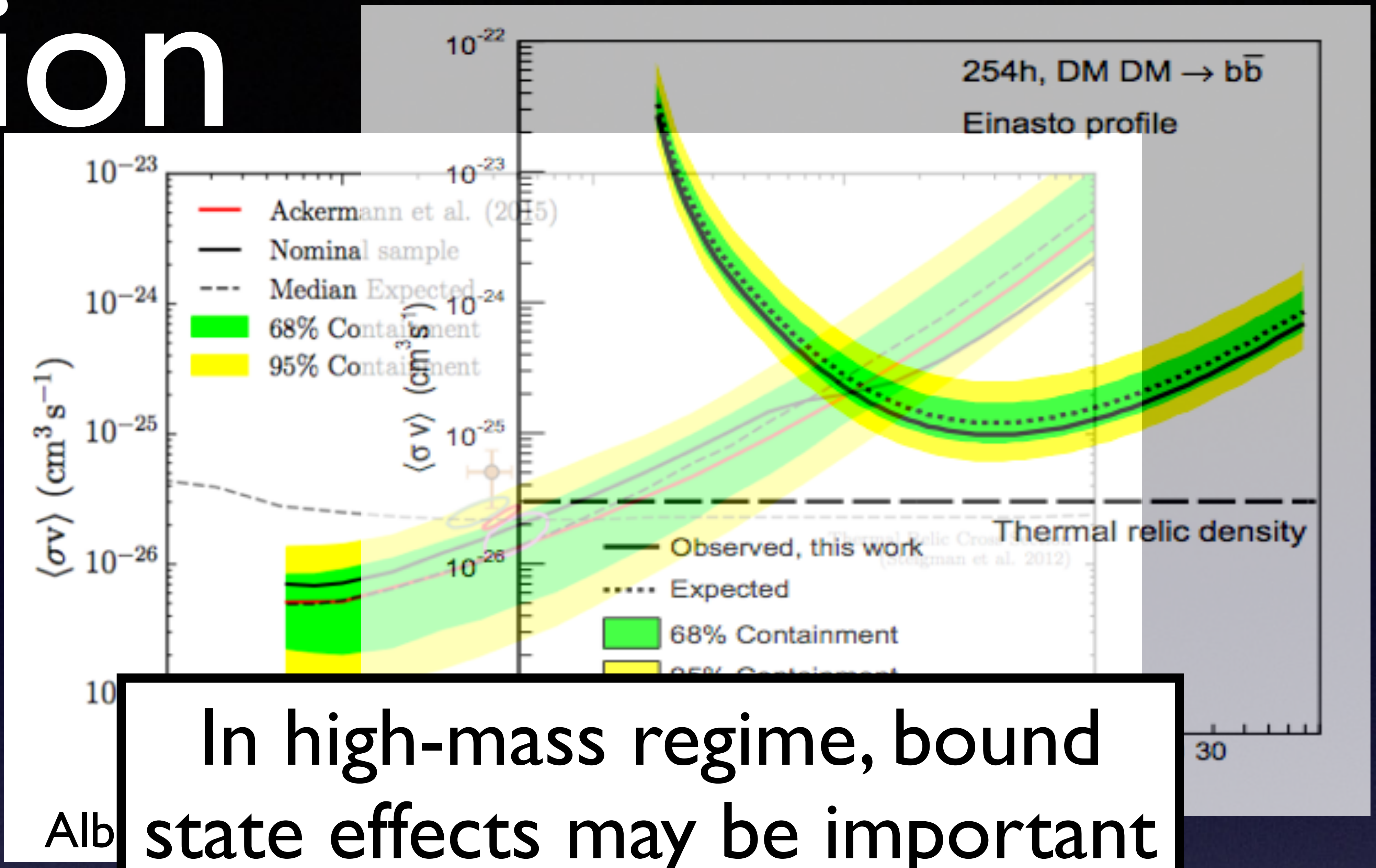
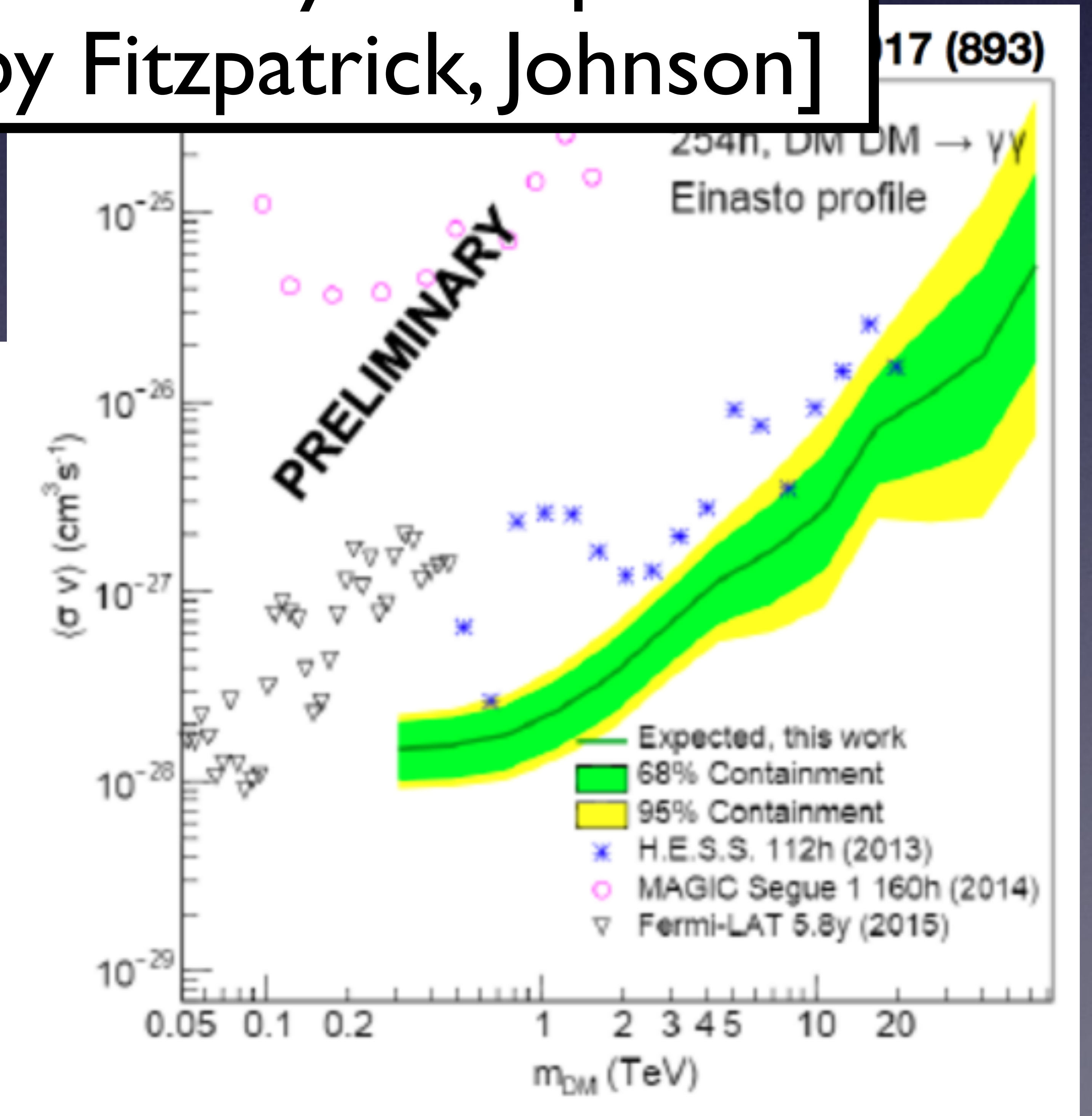
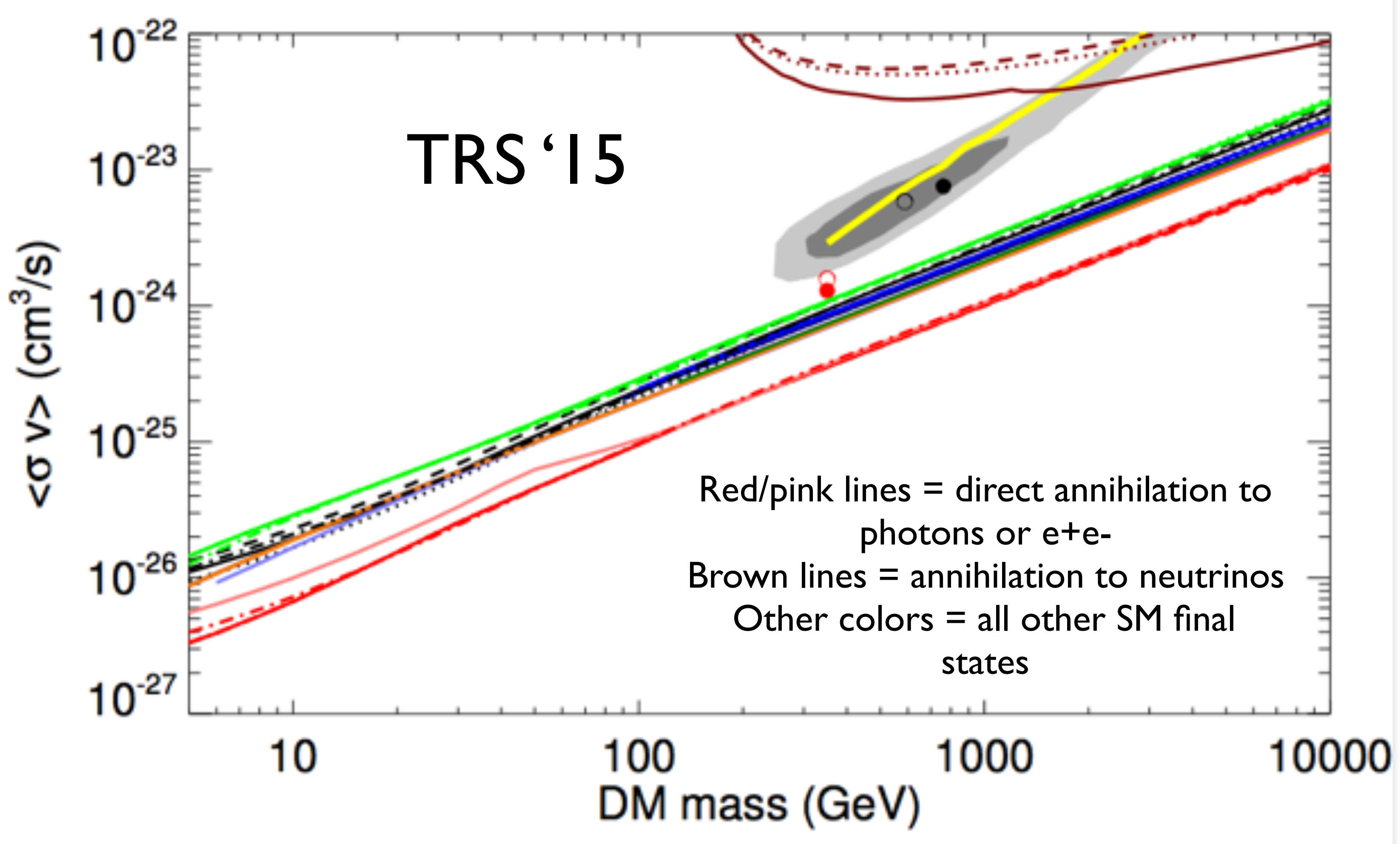


In high-mass regime, bound state effects may be important [talks by Fitzpatrick, Johnson]





TRS '15

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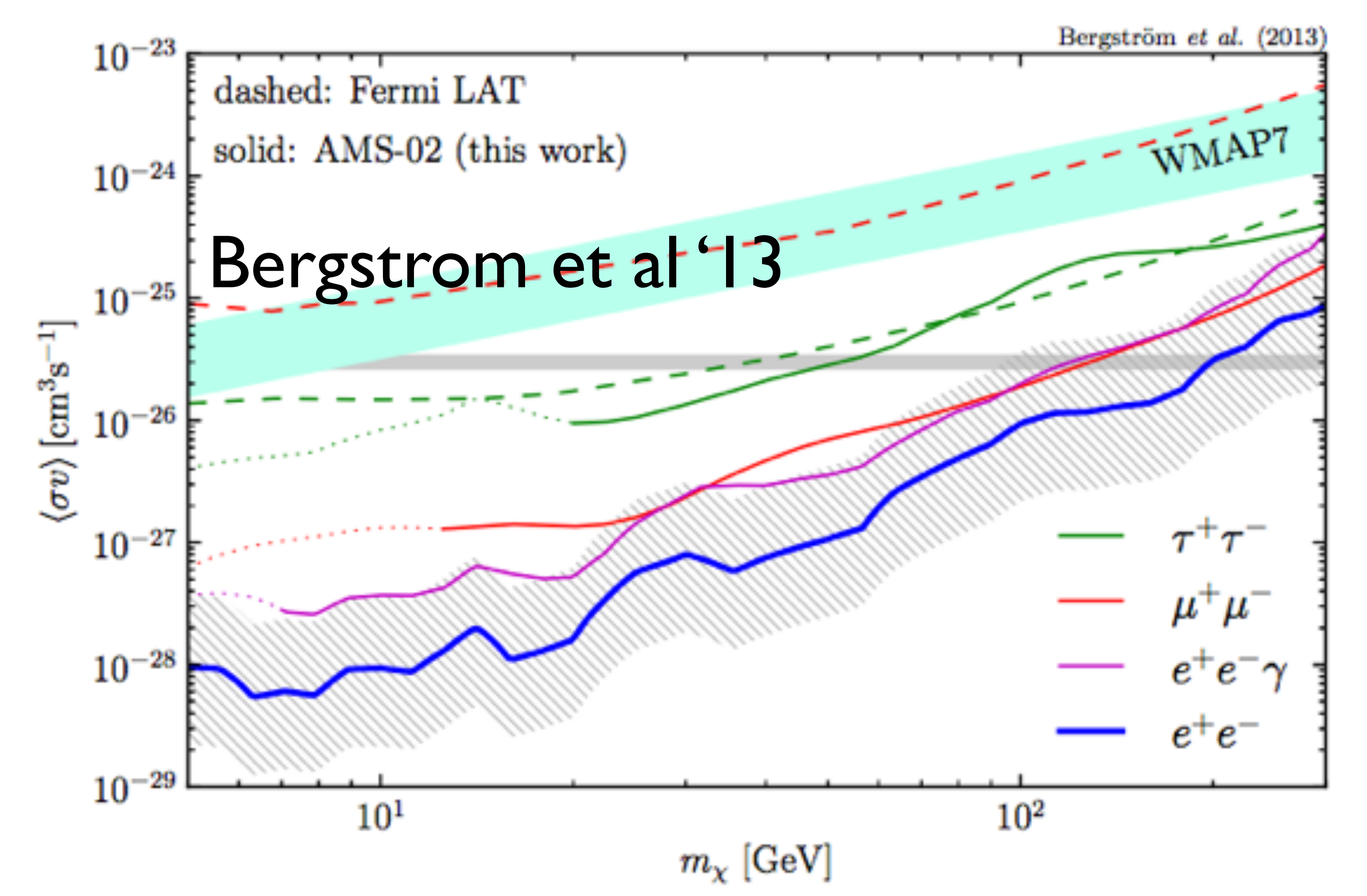
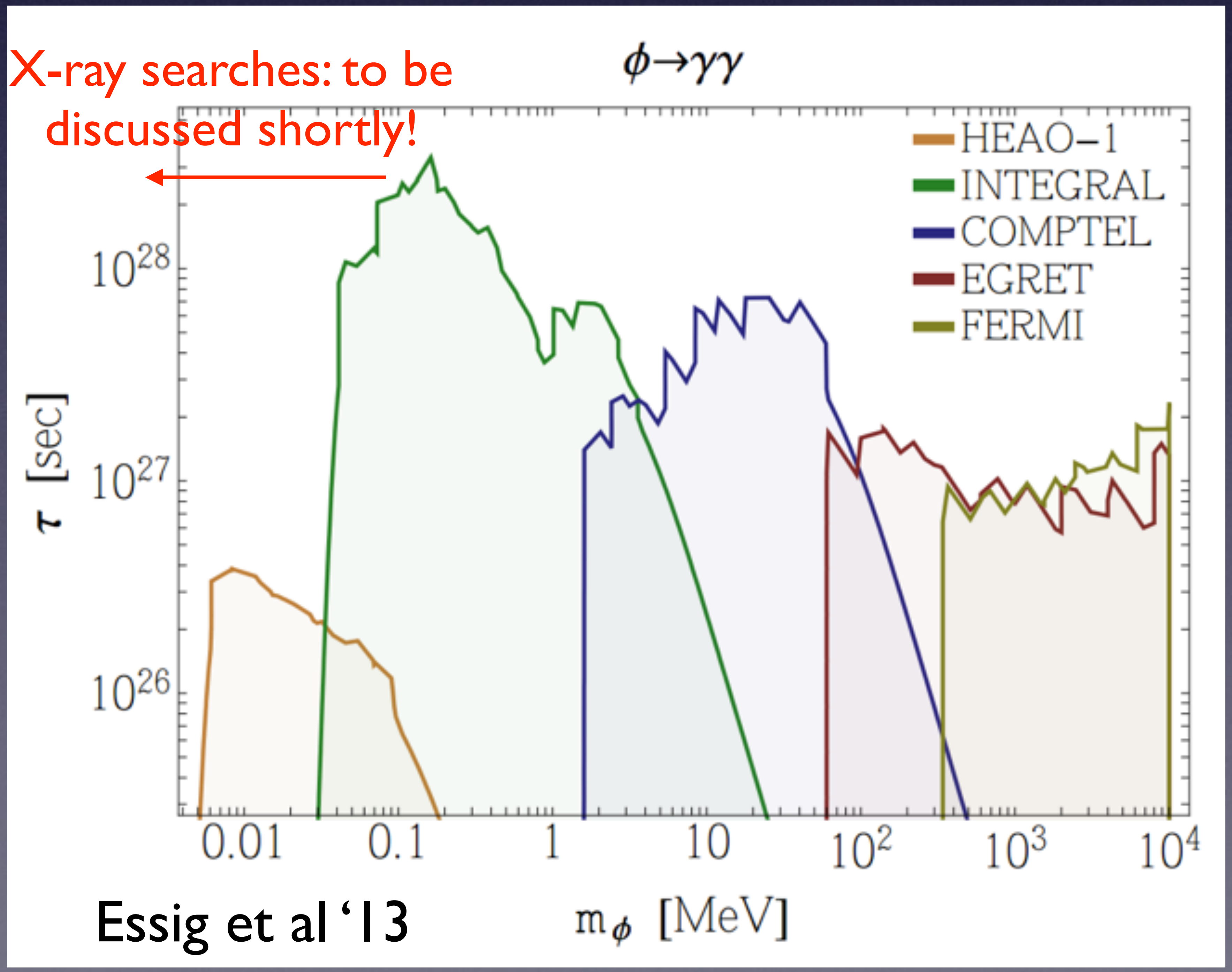


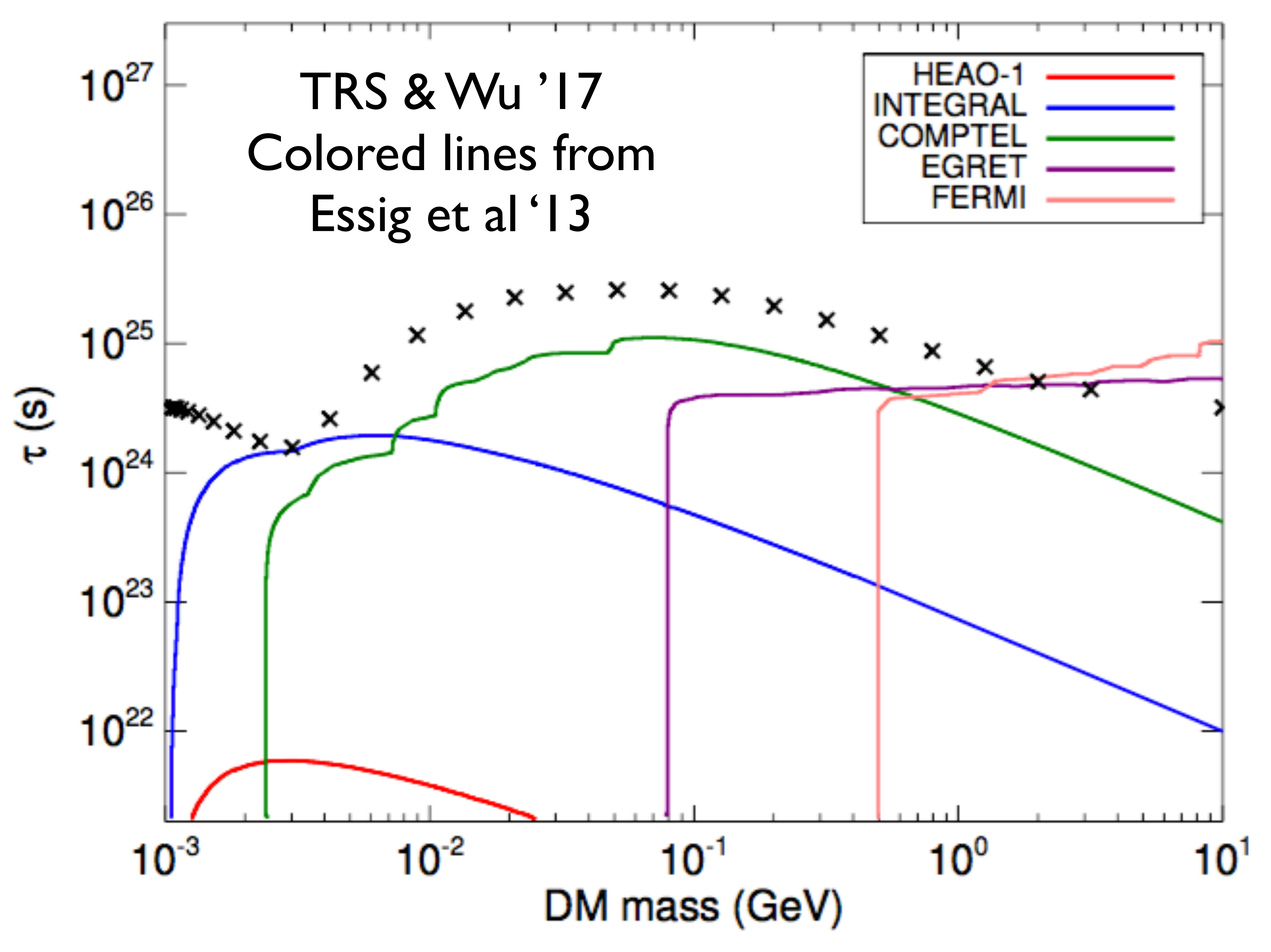
Bergstrom et al '13

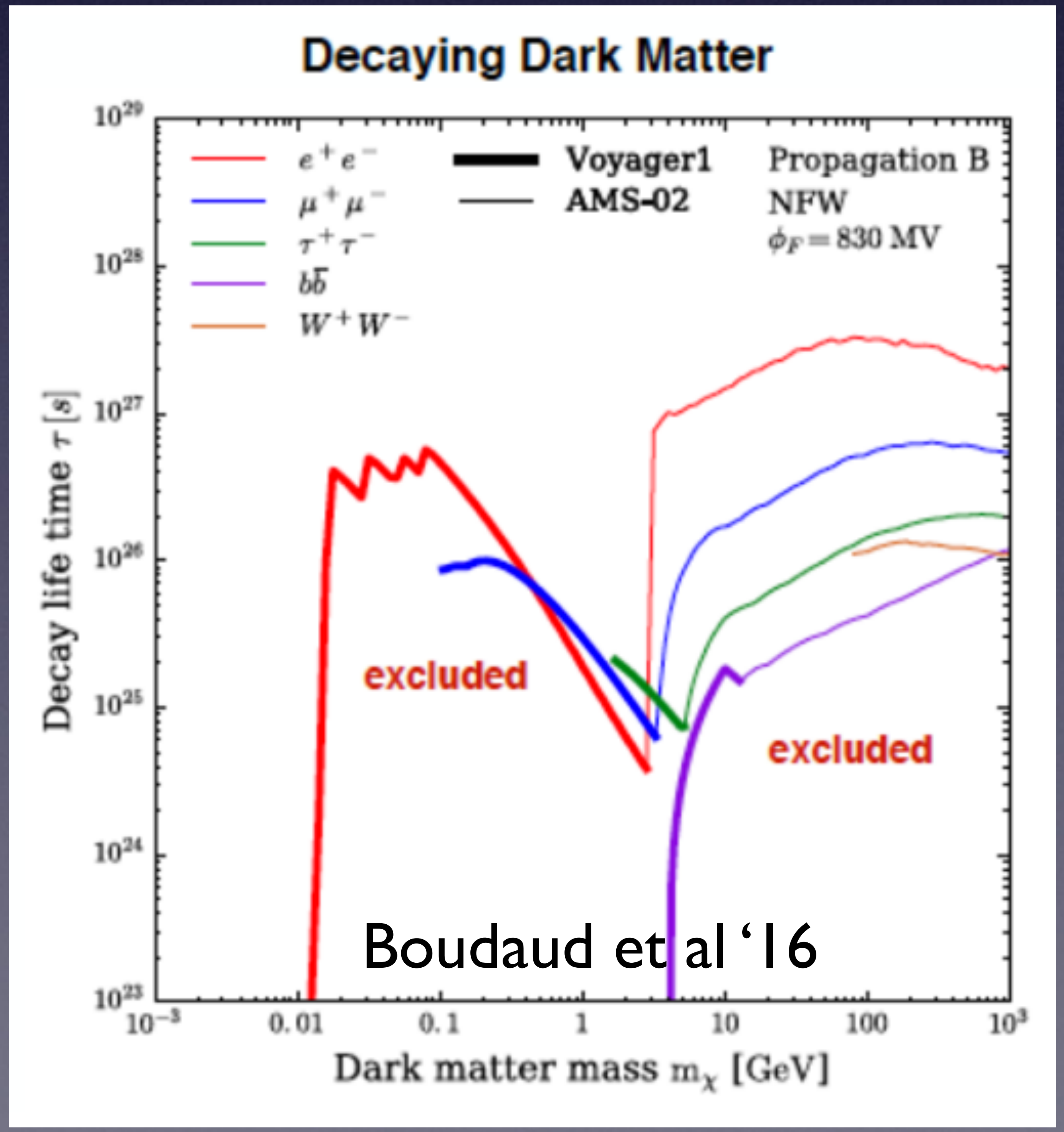
Light DM decay

- Light decaying DM can be constrained by photon diffuse background.
- Comparable constraints on e+e- channel from the early universe [talk by Wu] - e.g. heating of the gas, CMB limits on extra ionization (see e.g. Diamanti et al '13, Liu, TRS & Zavala '16, TRS & Wu '17).
- Very powerful constraints on 10 MeV-GeV DM decaying to electrons from Voyager.


X-ray searches: to be discussed shortly!

Essig et al '13


TRS & Wu '17
Colored lines from
Essig et al '13


Boudaud et al '16

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.

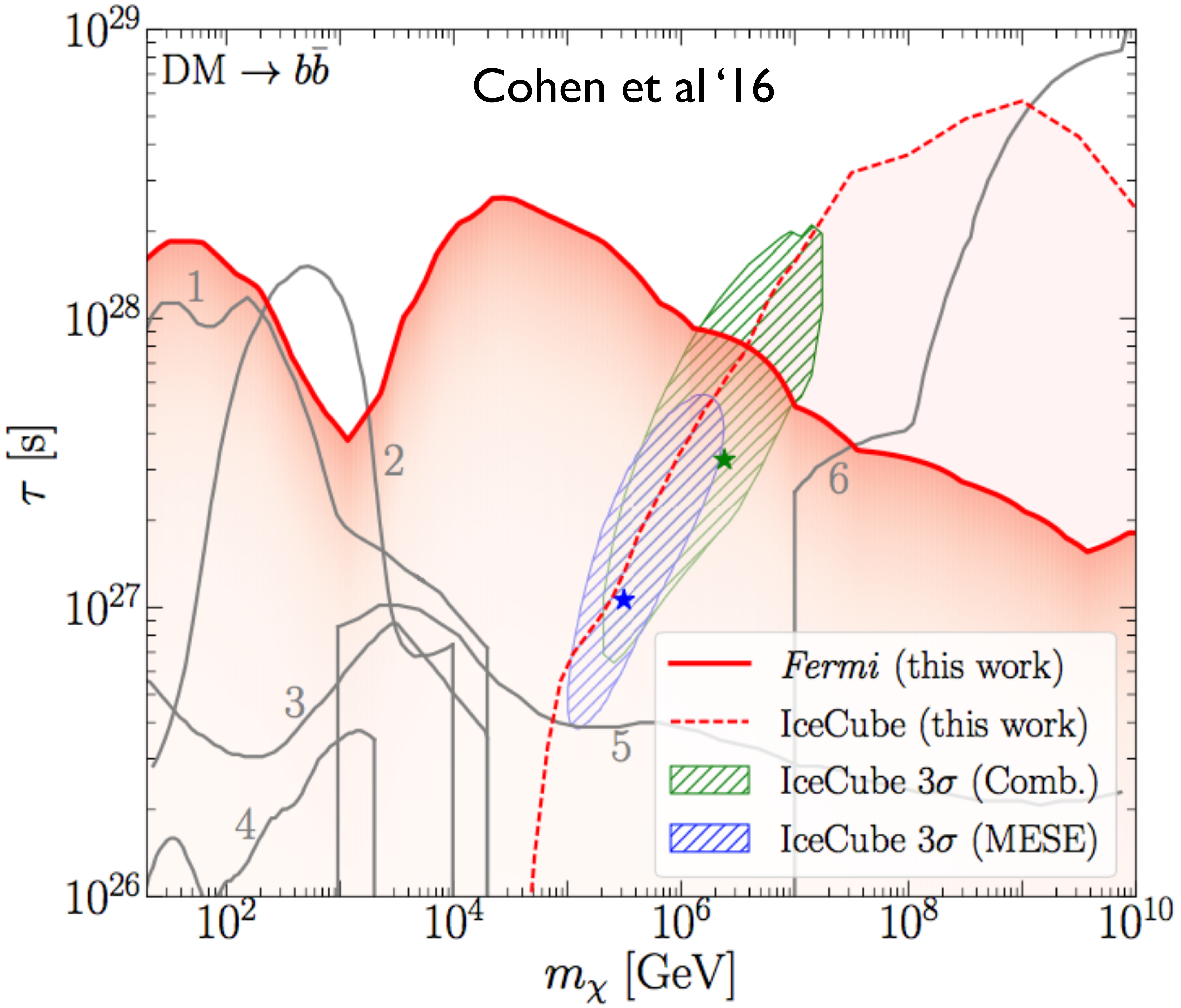
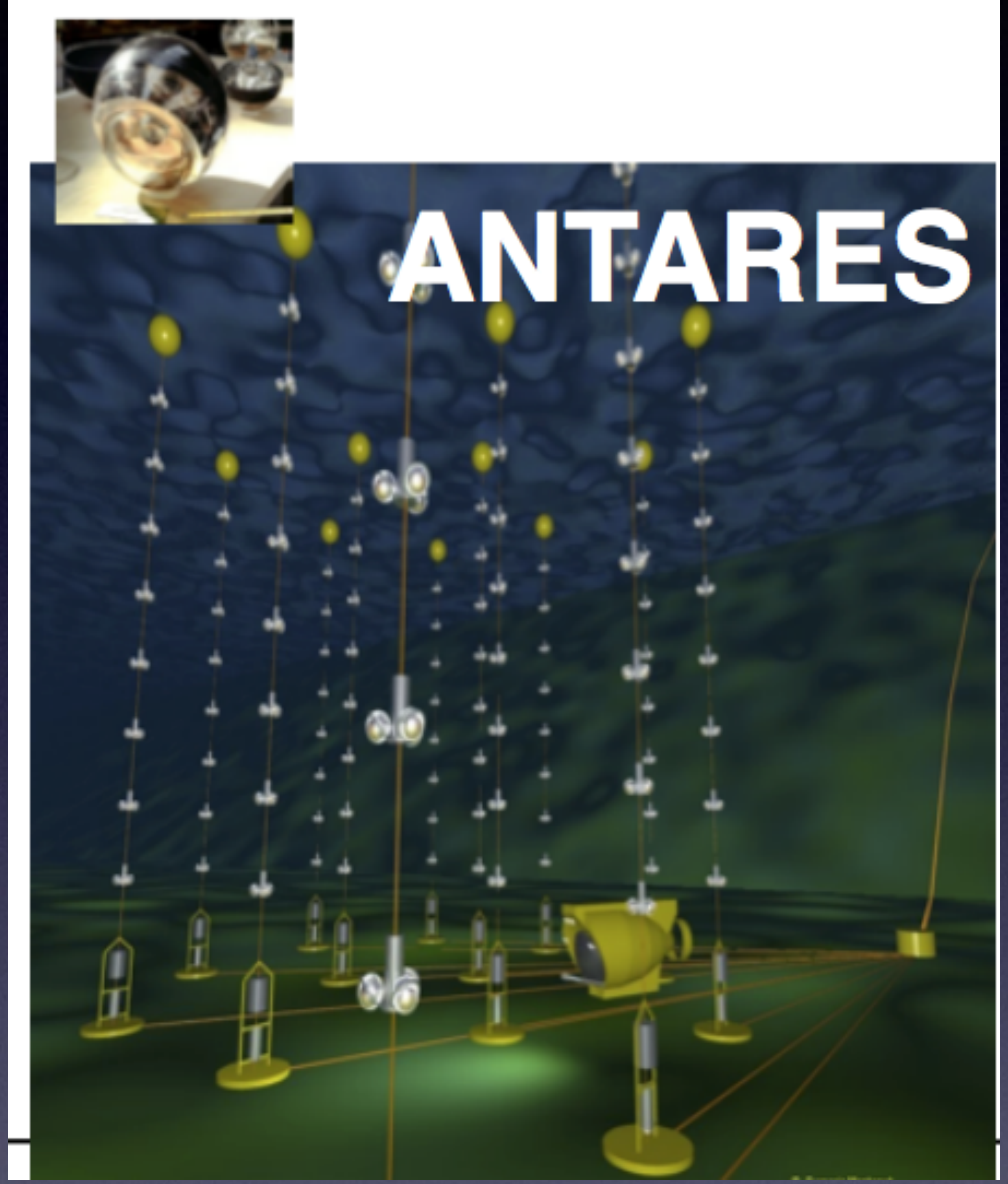
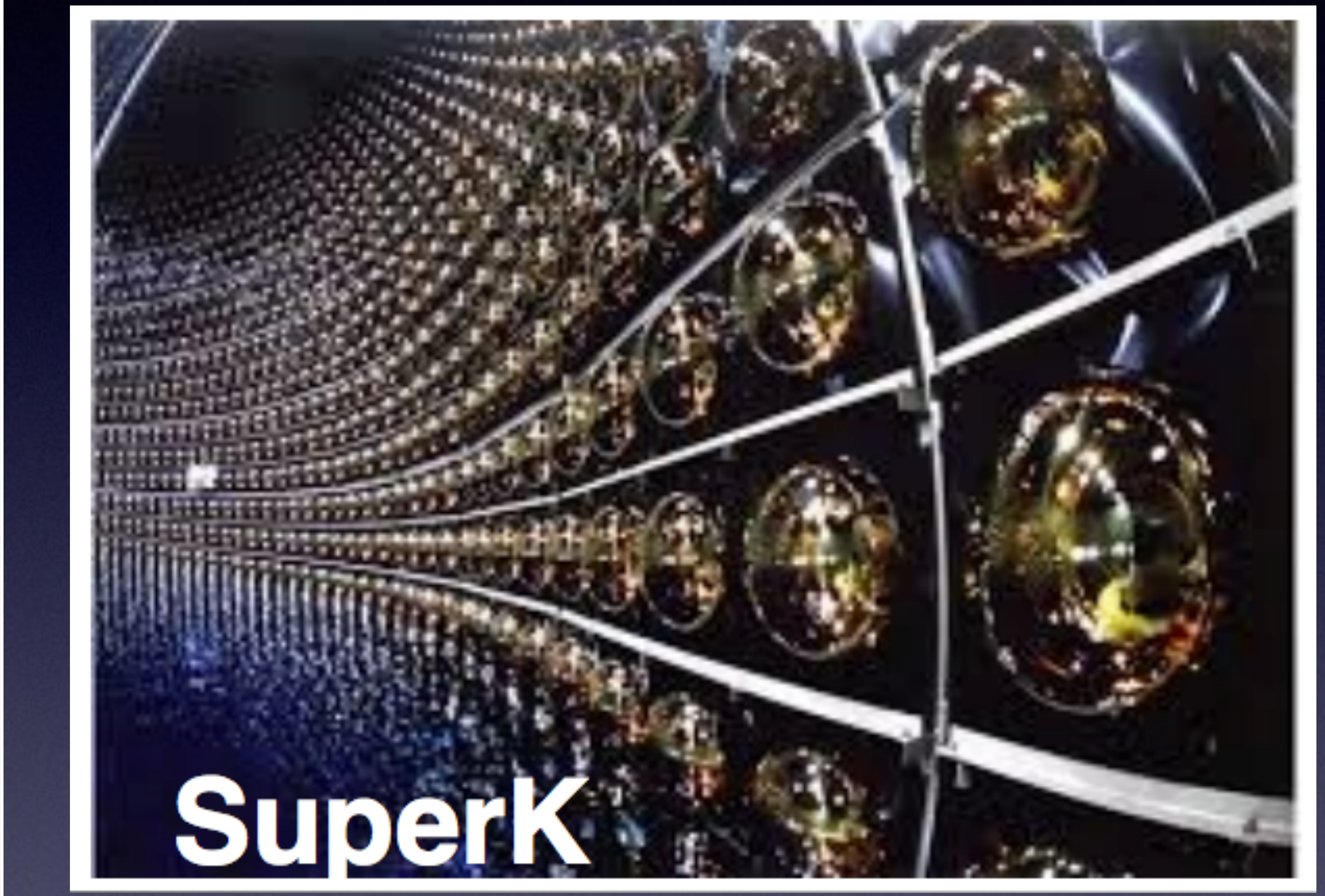


FIG. 1: Limits derived in this work on DM decays to $b\bar{b}$, as compared to previously computed limits using data from *Fermi* (2,3,5), AMS-02 (1,4), and PAO/KASCADE/CASA-MIA (6). The hashed green (blue) region suggests parameter space where DM decay may provide a ∼3σ improvement to the description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

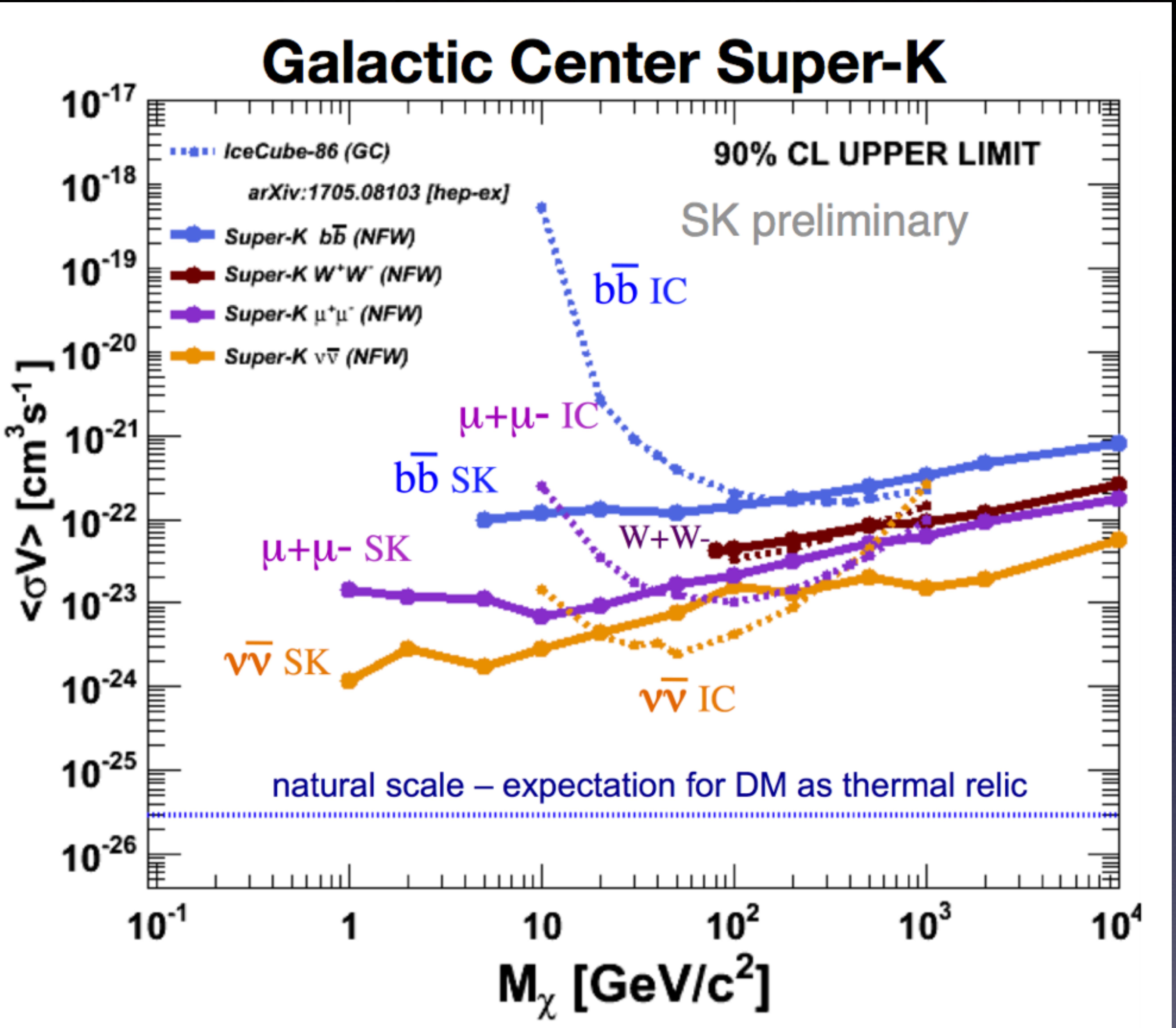
Neutrinos from dark matter





- Neutrino experiments can constrain and cross-check DM annihilation/decay to any SM particle that decays producing neutrinos.

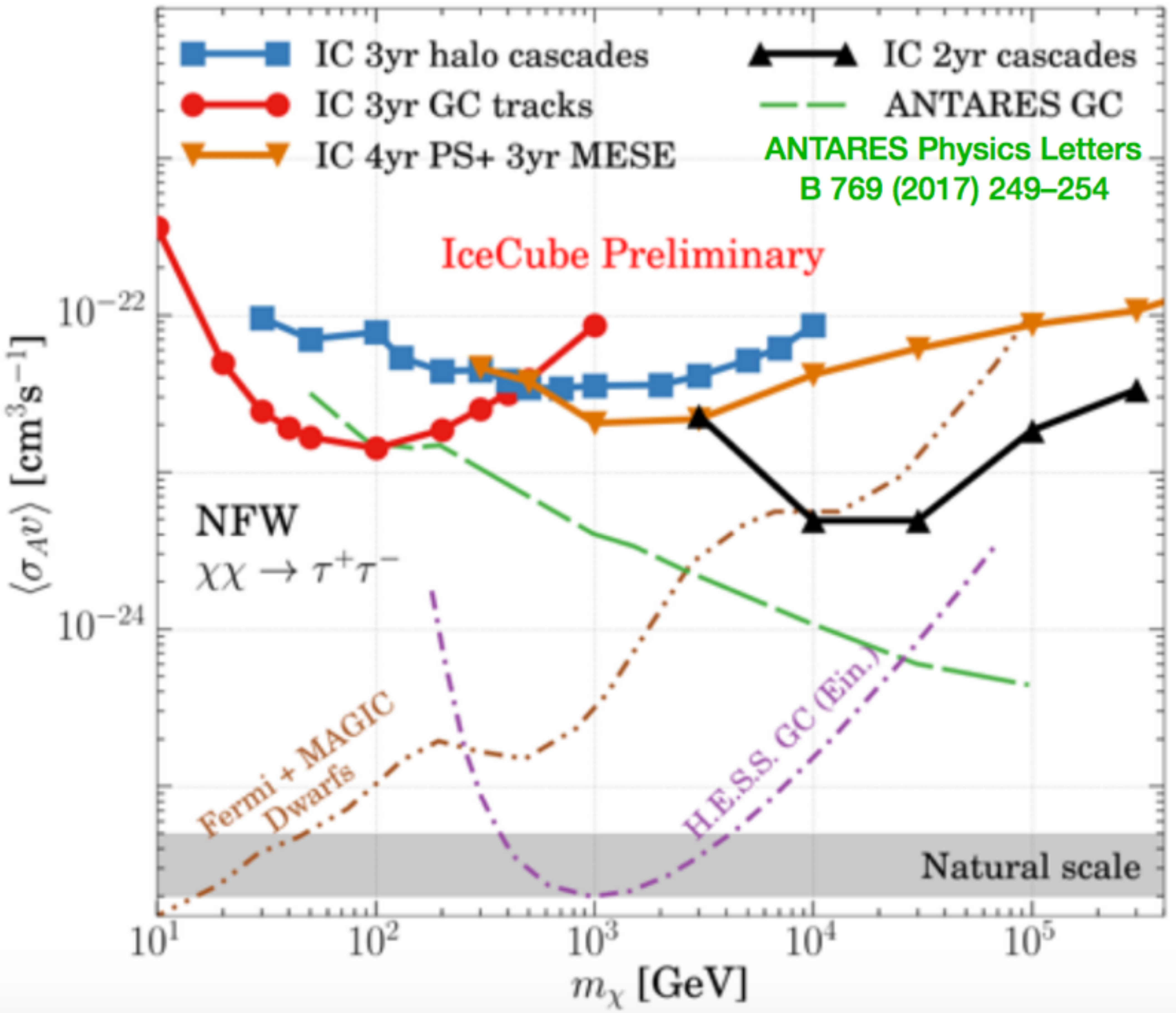
- Unique sensitivity if neutrinos are main annihilation/decay product.



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.

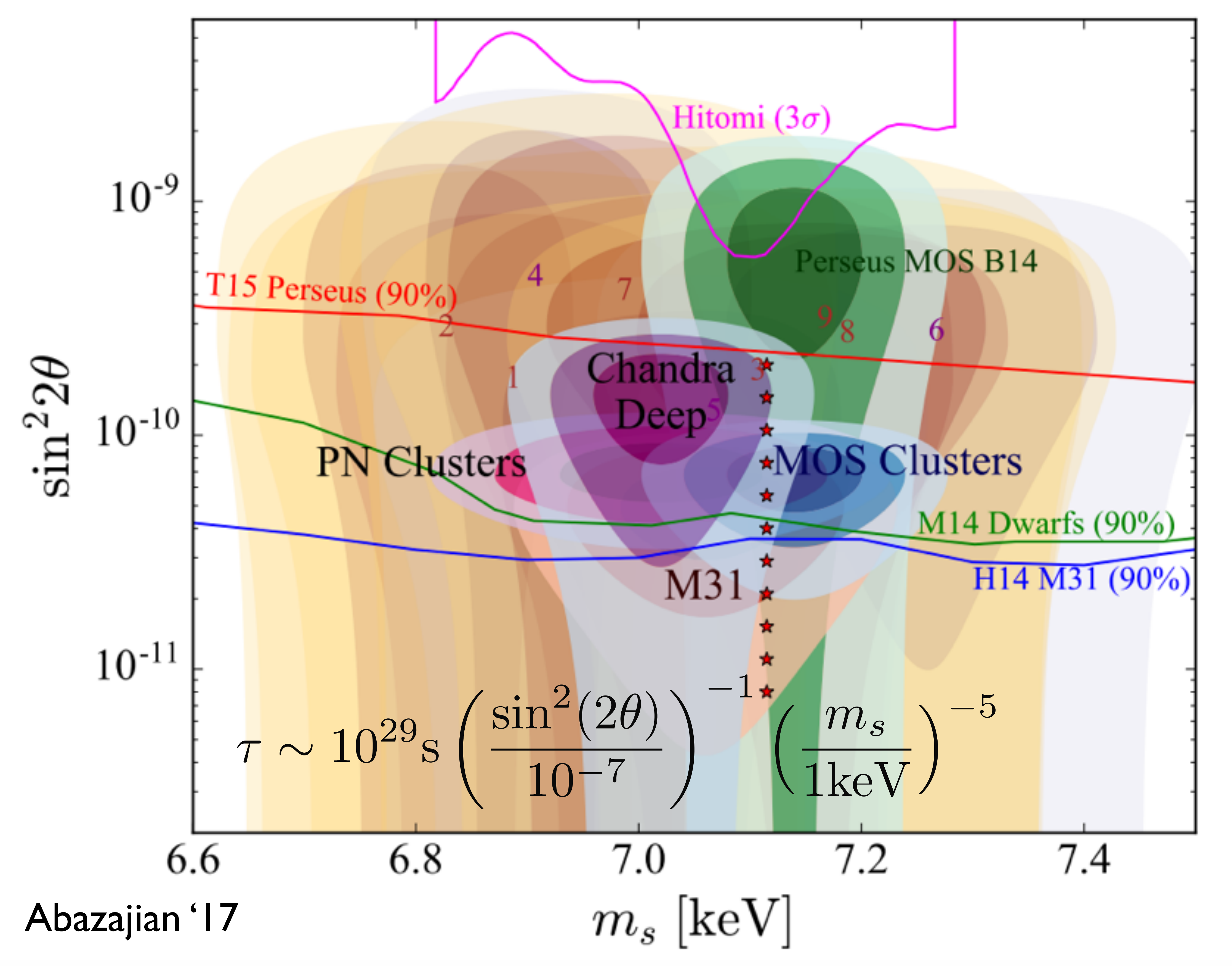
Beyond constraints: are there hints of signals?

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. [See plenary by Bulbul.]

- Possible non-DM contributions: atomic lines (from K, Cl, Ar, possibly others), charge-exchange reactions between heavy nuclei and neutral gas.

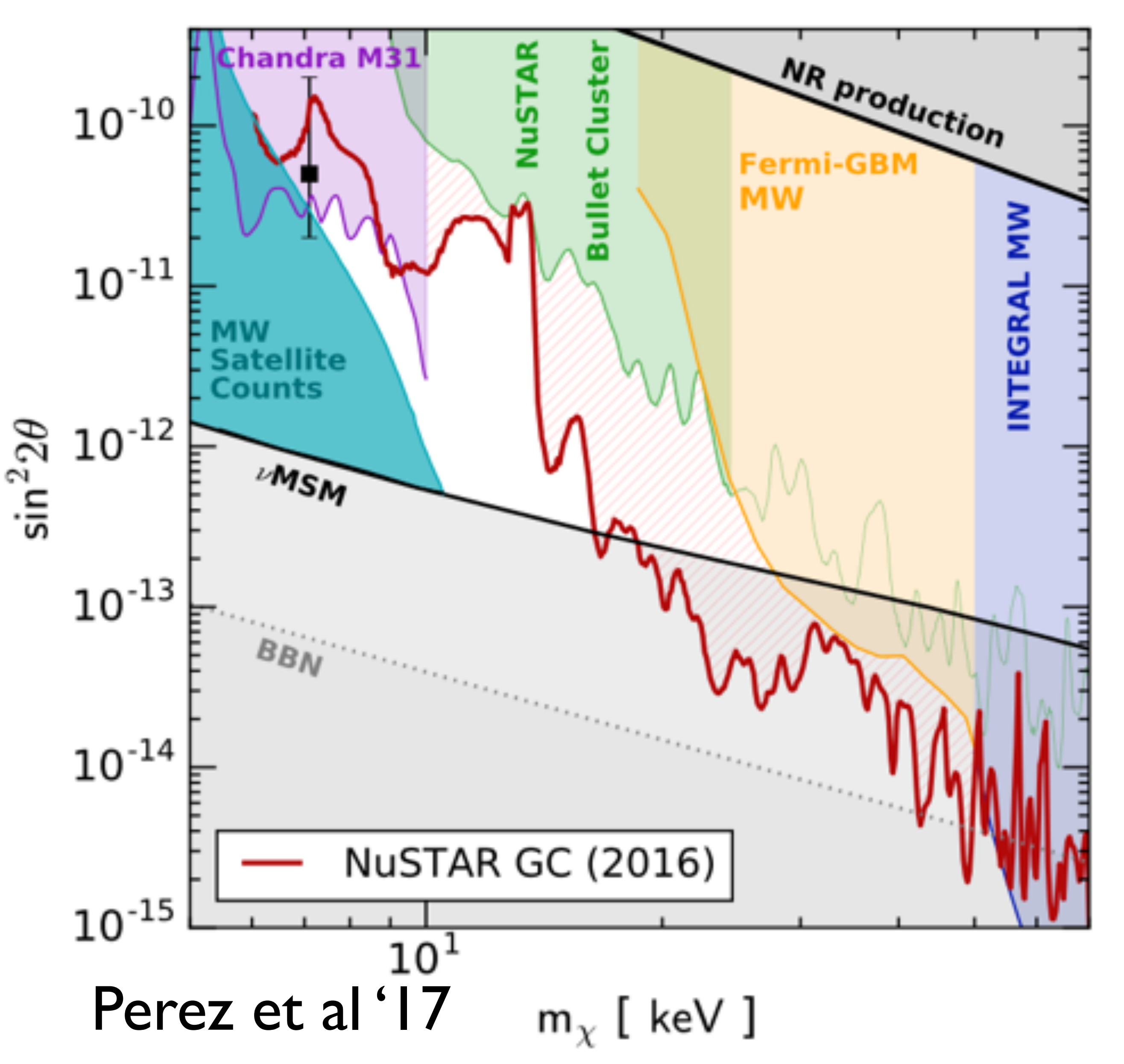
- Simplest dark matter explanation: decay of ~7 keV sterile neutrino (summarized in figure)
    - In some tension with observations of dwarfs (Malyshev et al '14), stacked galaxies (Anderson et al '14), and M31 observed by Chandra (Horiuchi et al '14).
    - Other DM-related explanations: annihilation, de-excitation, decay to axion-like particles which convert to photons in magnetic fields.



Abazajian '17

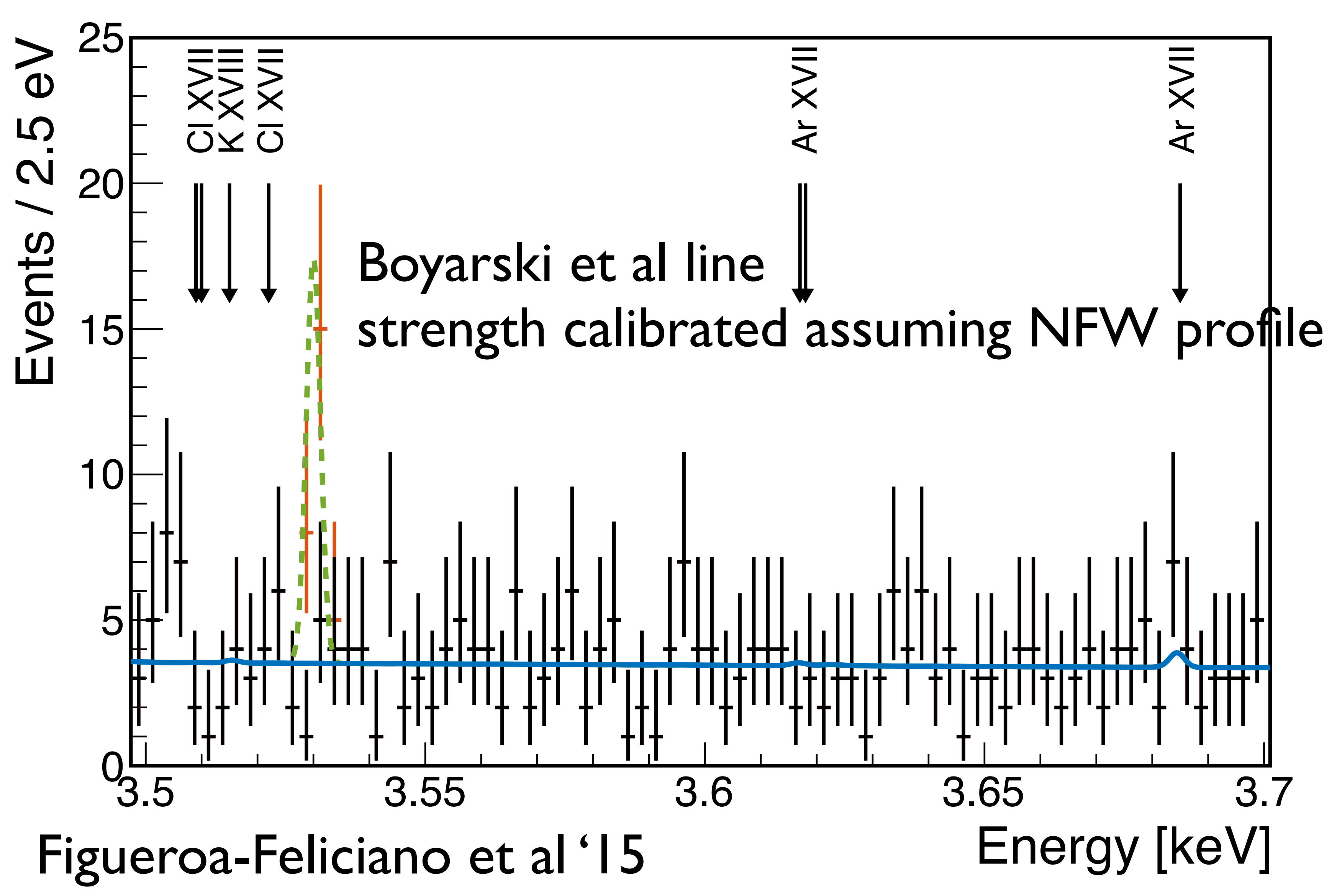
Testing the 3.5 keV line

- 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.



Perez et al '17

- One strategy: seek energy resolution sufficient to probe velocity distribution of DM in Galactic halo, via Doppler shift causing line broadening [talk by Laha; Speckhard et al '16, Powell et al '17].
- One possible instrument: Micro-X sounding rocket, DM search flight scheduled for 2019.
  - Short exposure (5 minutes per flight)
  - No pointing information
  - Large field of view (20 degree radius)
  - Excellent energy resolution (3 eV)



Boyarski et al line strength calibrated assuming NFW profile

Figueroa-Feliciano et al '15

The GeV excess

- Apparent new gamma-ray component, discovered in 2009 by Goodenough & Hooper using public Fermi data. [Plenaries by Lisanti, Gaggero; parallel session talks by Escudero, Keeley, di Mauro, Bartels, Macias.]

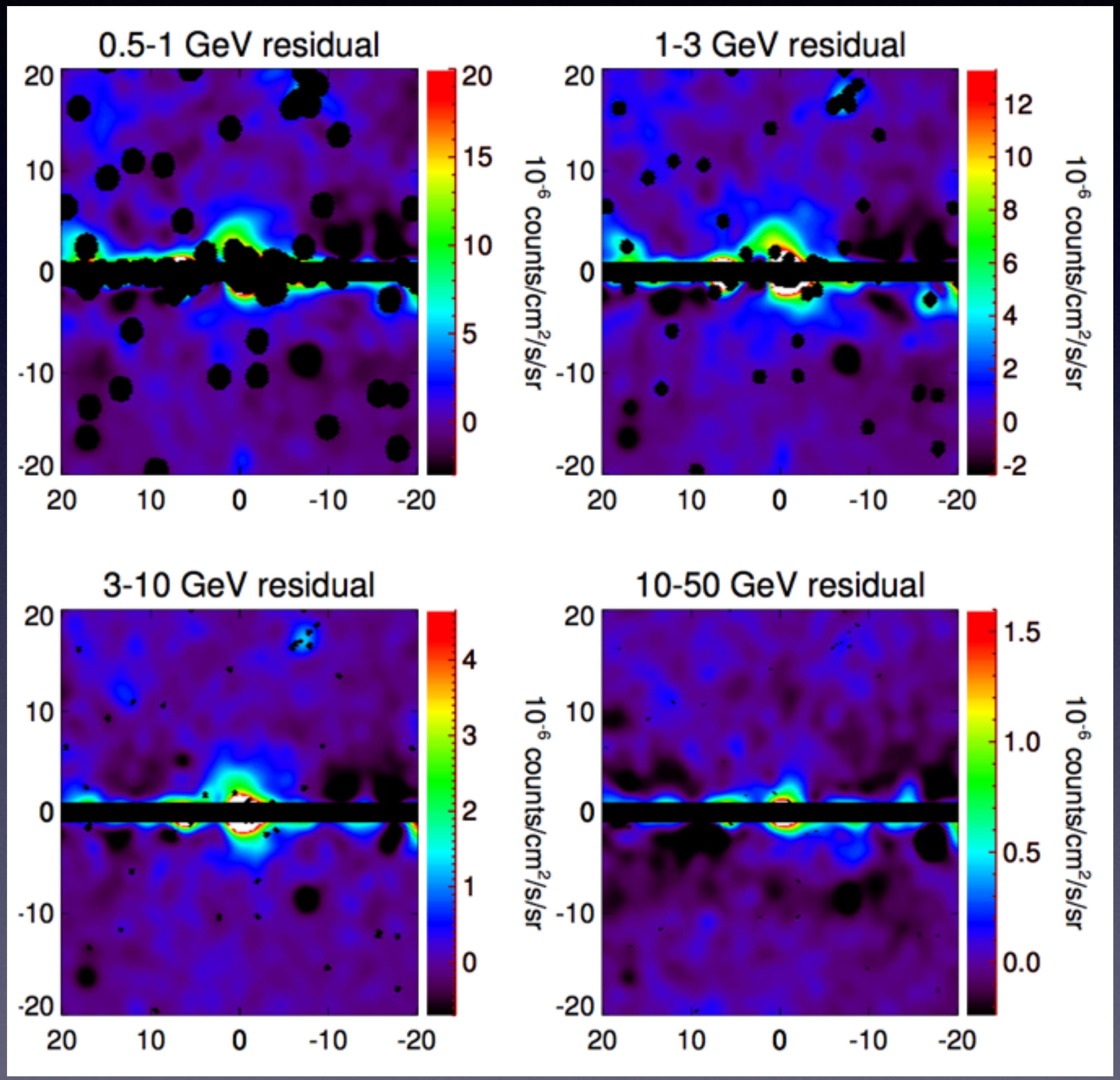
- Spectral energy distribution peaks around 1-3 GeV.

- 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).

- 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.

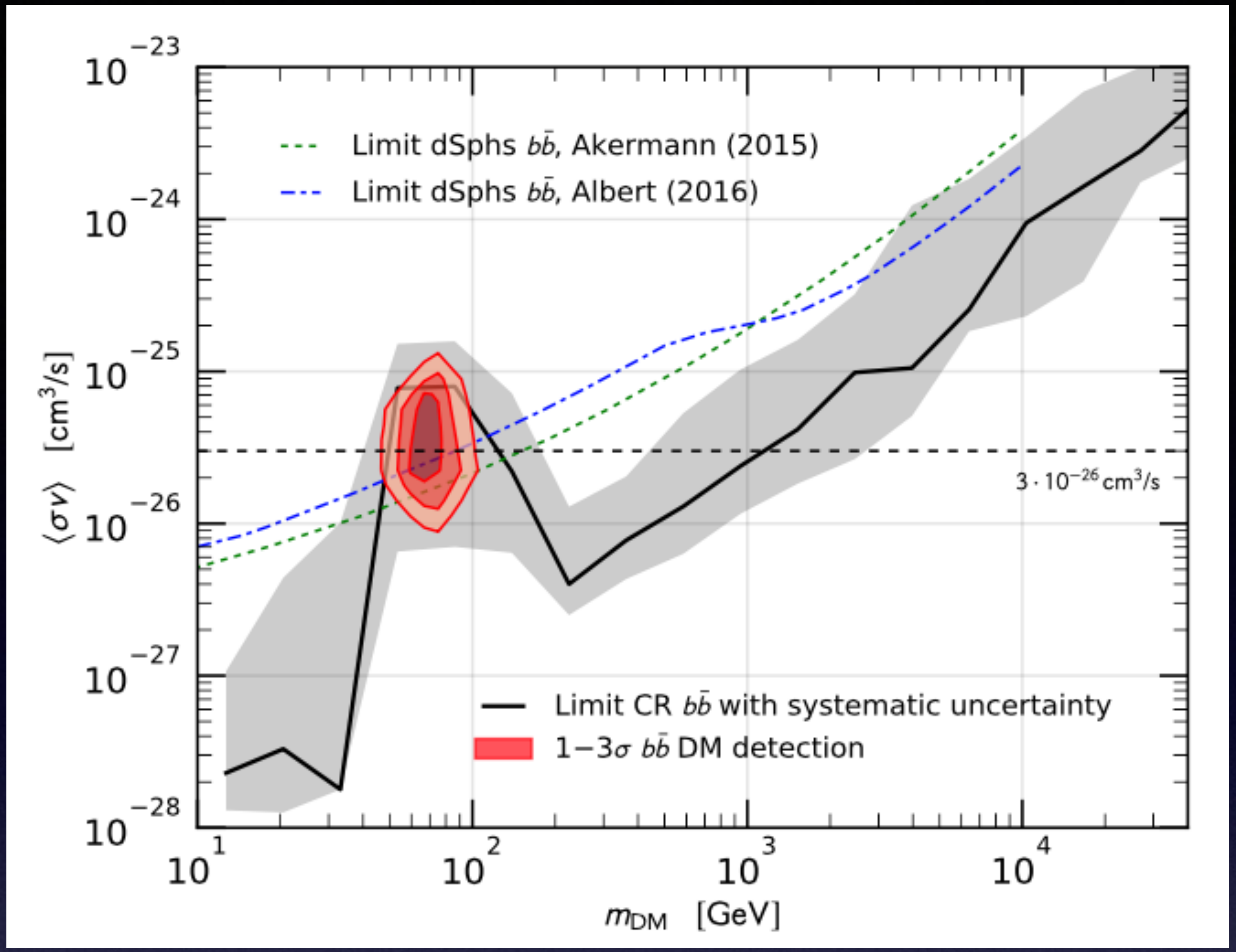
- Several studies suggest evidence for a non-DM origin (Lee, Lisanti, Safdi, TRS & Xue '16, Bartels et al '16, Fermi-LAT Collaboration '17) - most frequent hypothesis is a new pulsar population. Possibly testable with radio telescopes (Calore et al '16).



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

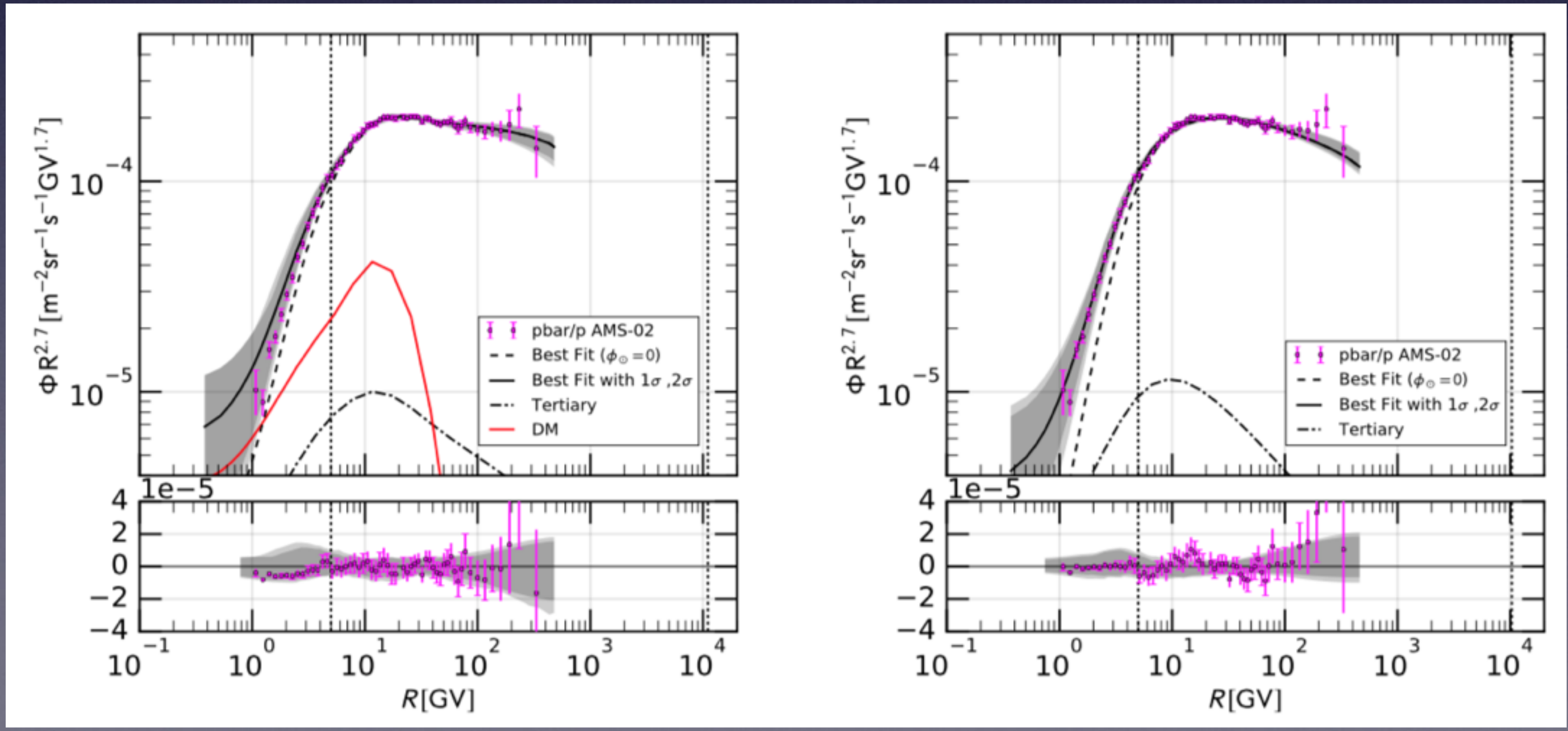
AMS-02 antiprotons

- See also plenary by Gaggero, talk by Bachlechner.
- 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).



Cuoco et al '17

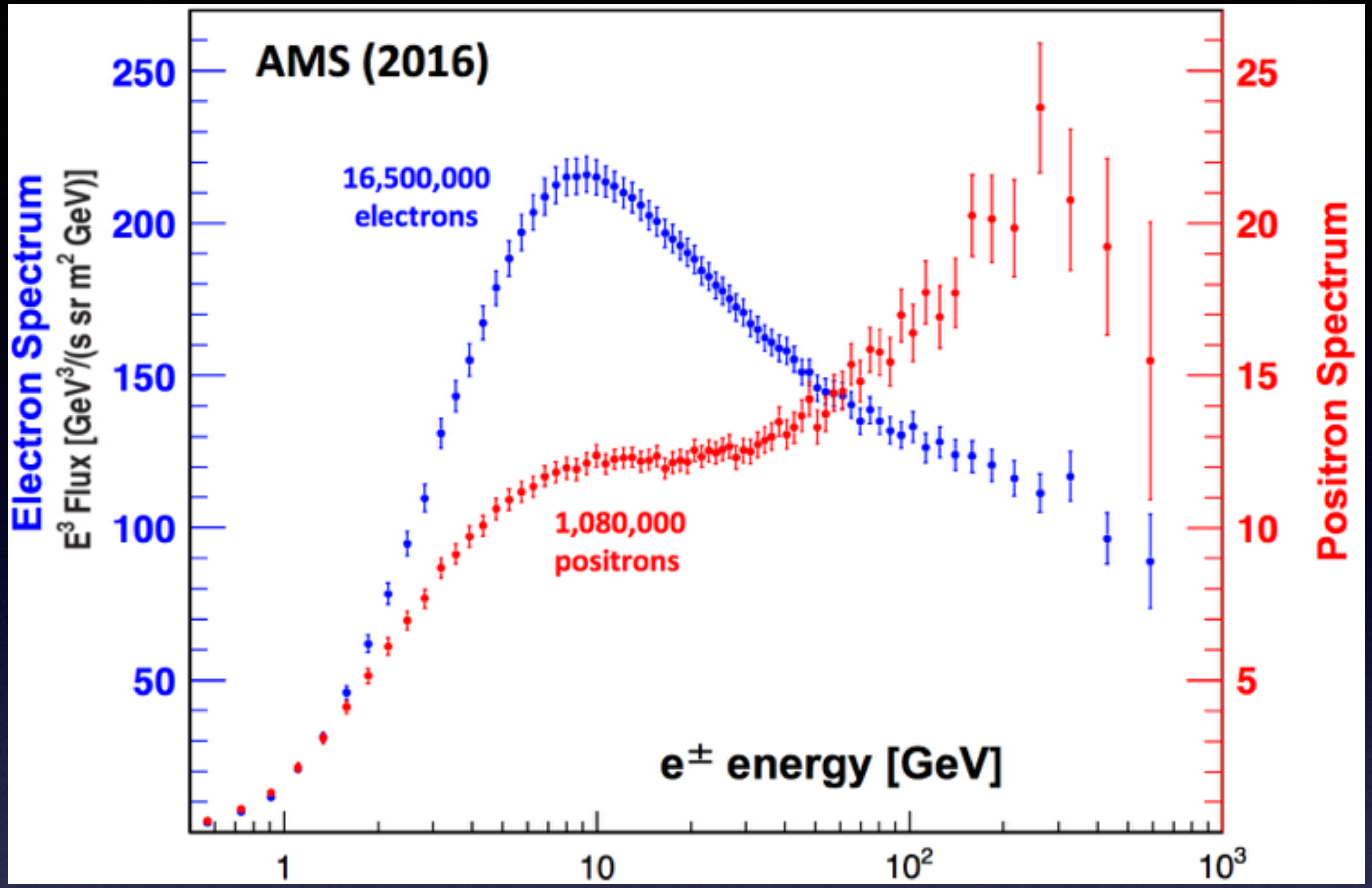
- Similar fits for other annihilation channels with ~thermal cross sections, 40-130 GeV mass (Cuoco et al '17).
- Broadly consistent with GCE dark matter interpretation.
- Challenges: modeling of antiproton production cross section, cosmic-ray propagation, solar modulation.

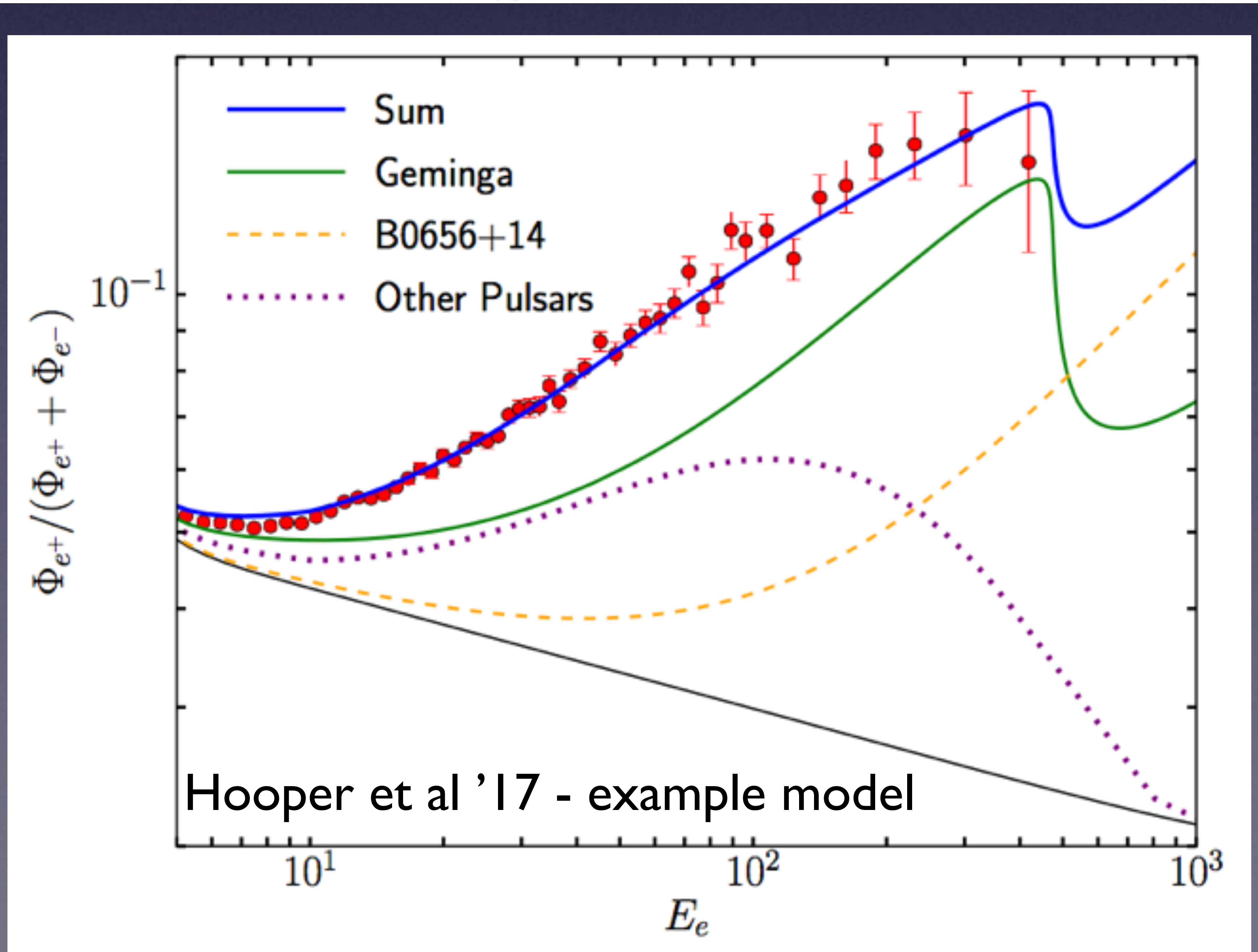


AMS-02 positrons

- 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 [talk by Buch].
- Recent development: HAWC has detected extended gamma-ray emission around two nearby pulsars, Geminga and B0656+14 (Abeysekara et al ’17, 2HWC catalog); talk by Linnemann.
- 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 [talks by Linden, Hooper].

Sam Ting, 8 December 2016, CERN colloquium





Hooper et al ’17 - example model

(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 [talks by Nierenberg, Schutz, Bechtol].

- Modeling background: improved methods for modeling the gamma-ray foregrounds/backgrounds [talks by Porter, Calore], new probes for pulsars with MeerKAT/SKA.

- First results now emerging from DAMPE [plenary by Zimmer], CALET [talk by Asaoka].

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

Summary

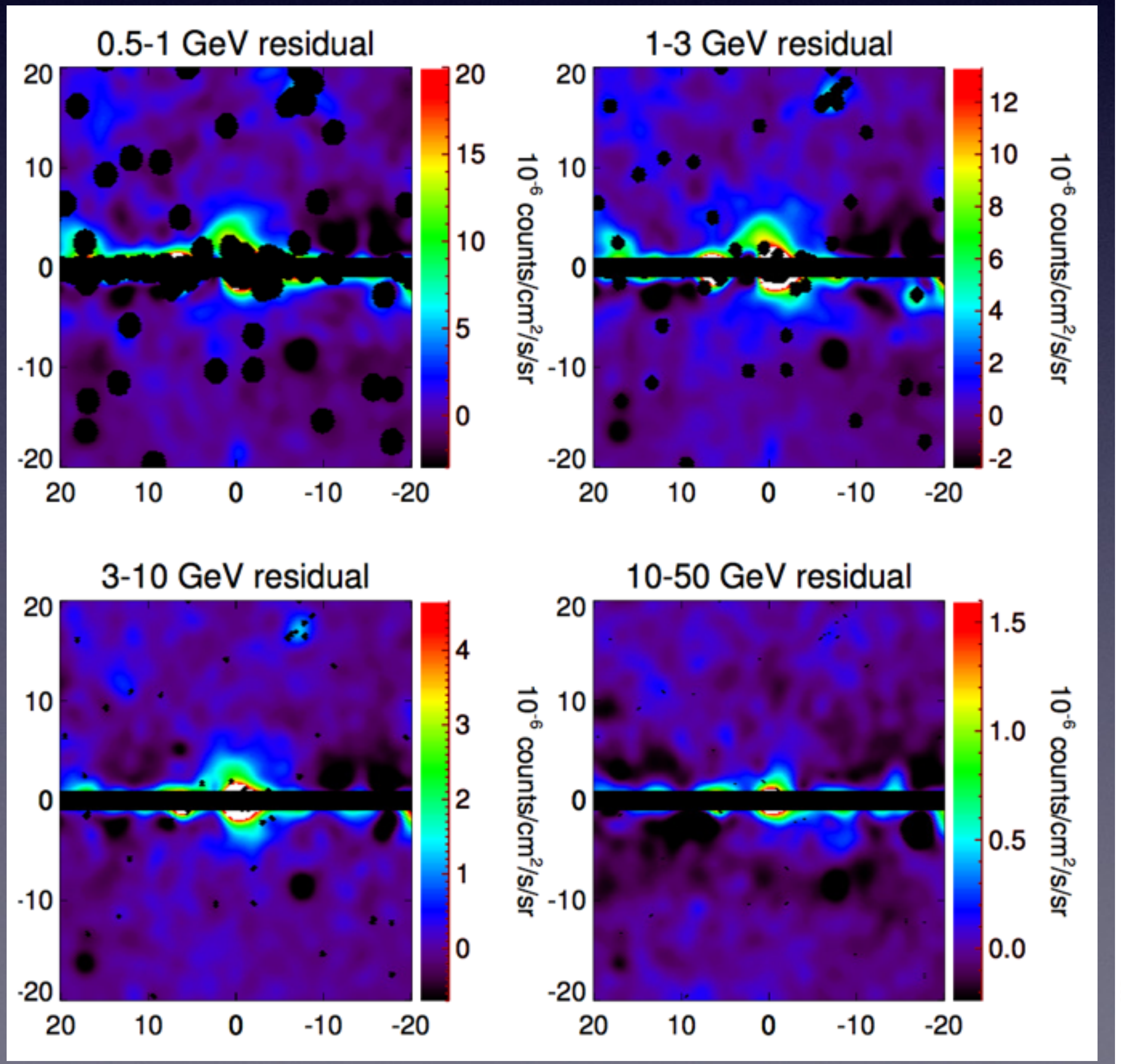
- Current indirect constraints: cover a wide range of masses and cross sections/lifetimes.
  - Decay lifetimes (for 100% of the DM) shorter than $10^{25\text{-}28}$ s can be excluded across the keV-EeV mass range.
  - We can rule out s-wave annihilating DM with a thermal relic cross section for masses below 10-100 GeV depending on channel - except if annihilation is to neutrinos, where the limit is a few orders of magnitude above the thermal value across a large mass range.
- There are several tentative signals that might originate from DM physics, but could also come from astrophysical sources:
  - 3.5 keV line observed in clusters, Galactic Center and the Chandra Deep Field. [See Bulbul's talk!] Future high-energy-resolution instruments could potentially detect the Doppler shift due to the motion of the dark matter, establishing or refuting a DM origin.
  - Few-GeV gamma-ray emission observed from the Galactic Center, and possibly (low significance) from dwarfs [Lisanti's talk!]
  - A possible excess in cosmic-ray antiprotons peaking at ~10-20 GeV, consistent with 40-130 GeV DM annihilating with a thermal relic cross section (but with potentially large systematic uncertainties).
  - The well-established large flux of high energy positrons (~10-600 GeV); HAWC measurements of gamma-ray halos around nearby pulsars may shed light on the pulsar contribution to the positron flux.

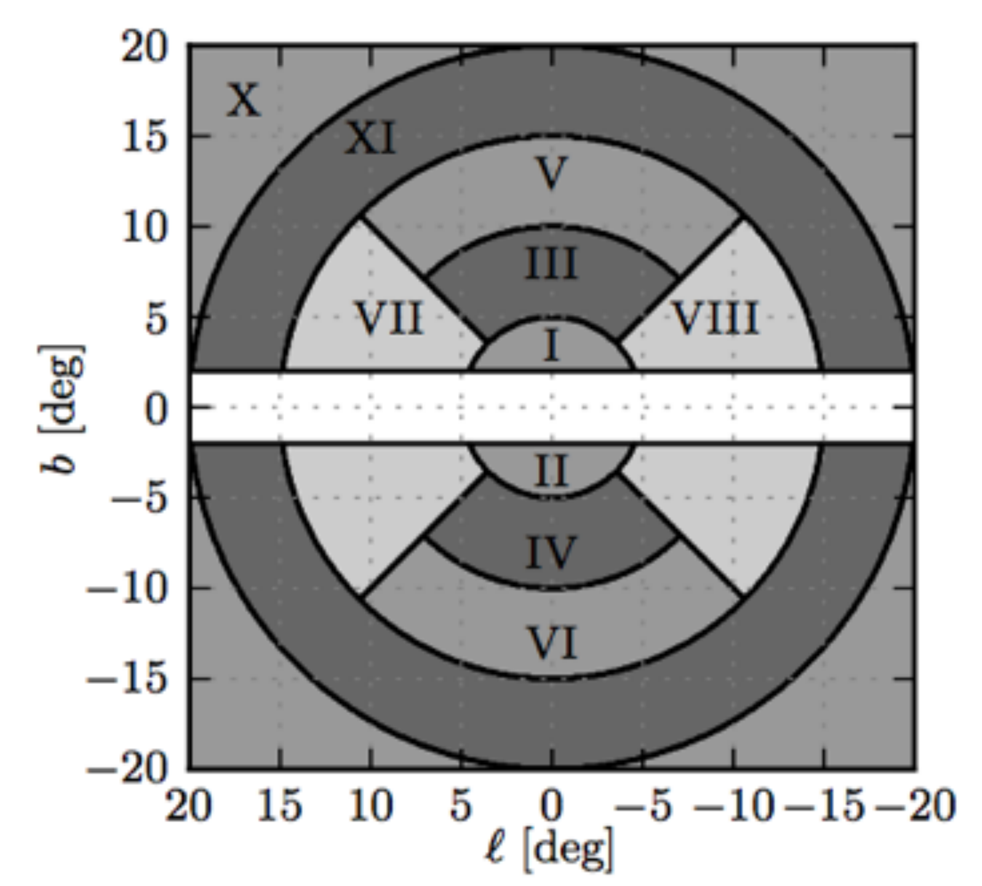
BONUS SLIDES

The GeV excess

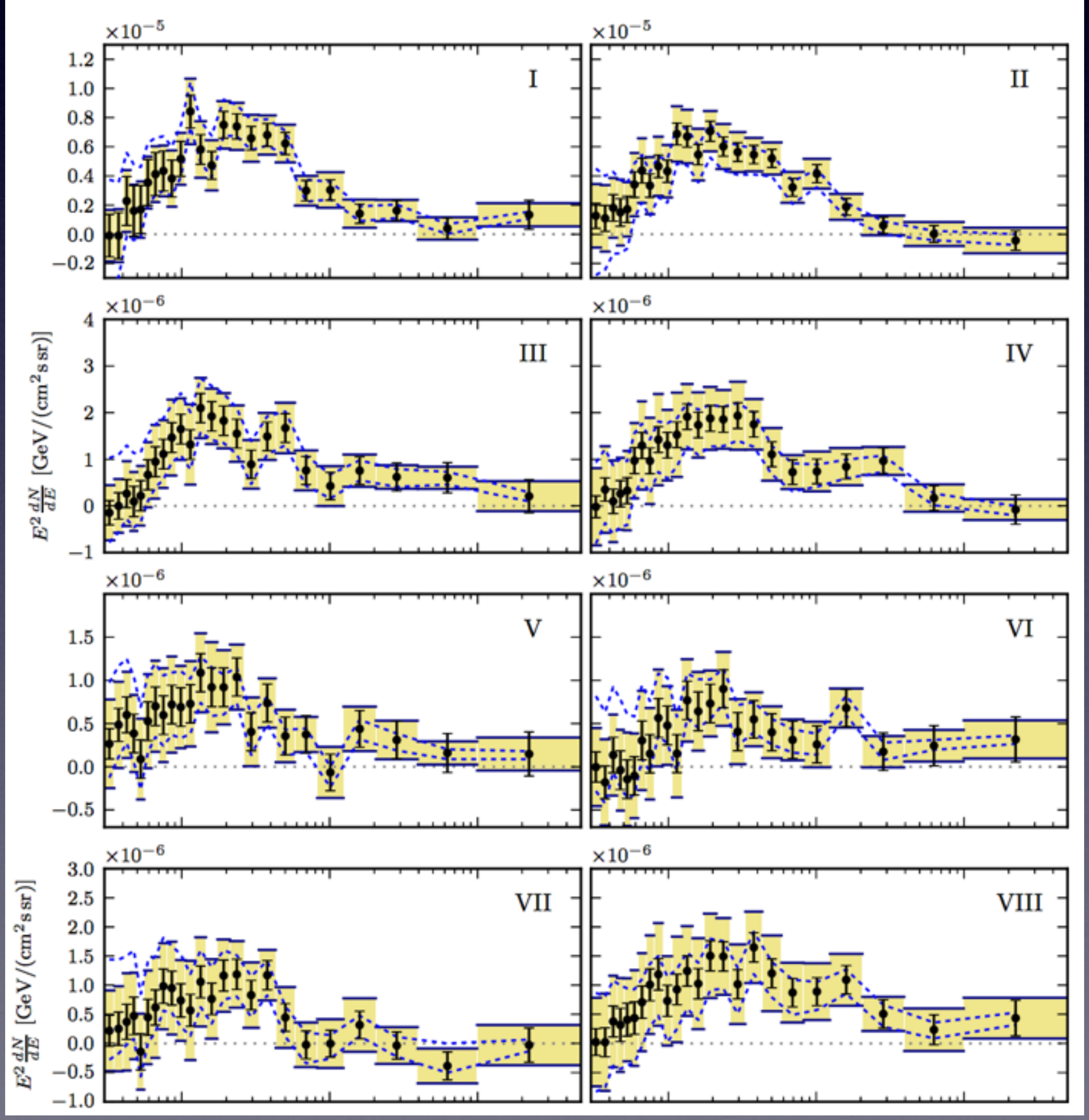
- See plenaries by Lisanti, Gaggero; parallel session talks by Escudero, Keeley, di Mauro, Bartels, Macias.
- Apparent new gamma-ray component.
- Based on Fermi Gamma-Ray Space Telescope data initial discovery 2009 by Goodenough & Hooper.
- Spectral energy distribution peaks around 1-3 GeV
- Centered on Galactic Center (GC), steeply peaked (flux/volume ~ $r^{-2.5}$), appears ~symmetric under rotation about the GC.

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



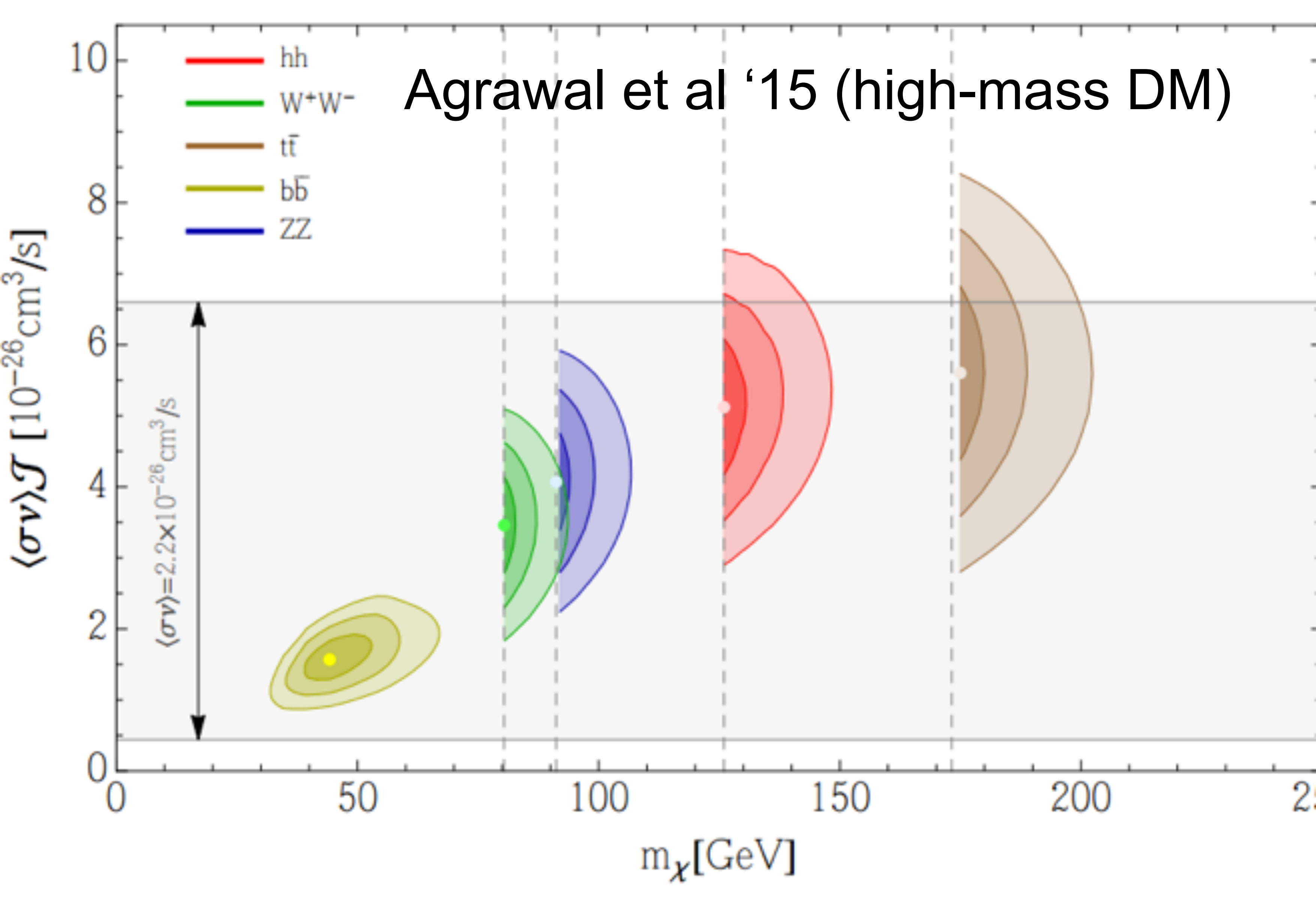


Calore, Cholis & Weniger'15

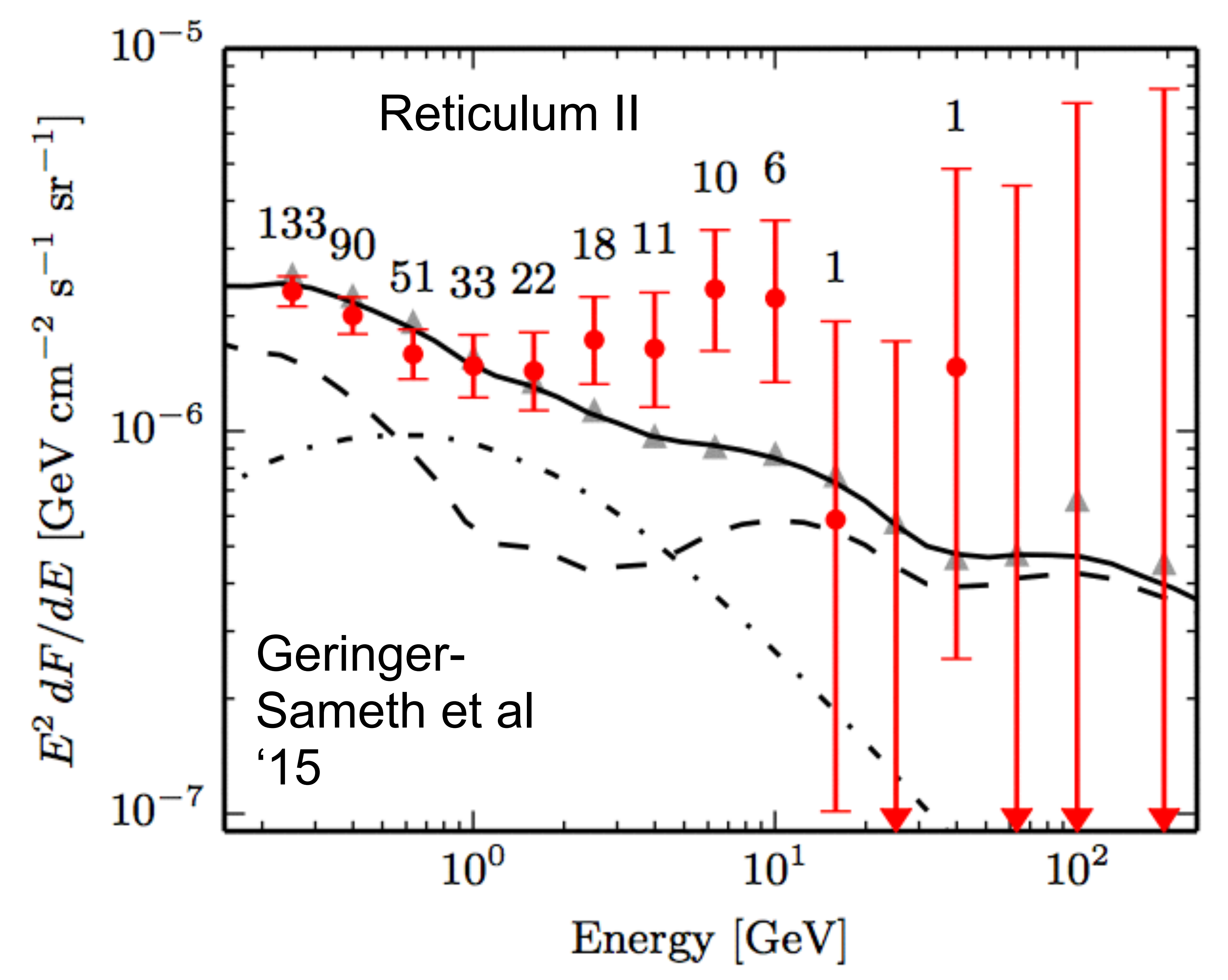


Dark matter interpretations

- Many studies have been performed of possible DM interpretations; most suggest a O(10-100) GeV mass scale for the DM, and a near-thermal cross section. Details depend on modeling of backgrounds (see e.g. Karwin et al '17).
- Some tension with non-detection in dwarf galaxies.
- But also faint hints (<3σ) of possible corresponding signals from two dwarf galaxies (Reticulum II and Tucana III).
- However, (a) consistency with Galactic Center excess, and with non-detection in other dwarfs, depends strongly on uncertainties in DM content/distribution, (b) significance depends strongly on prescription for trials factor.



Agrawal et al '15 (high-mass DM)



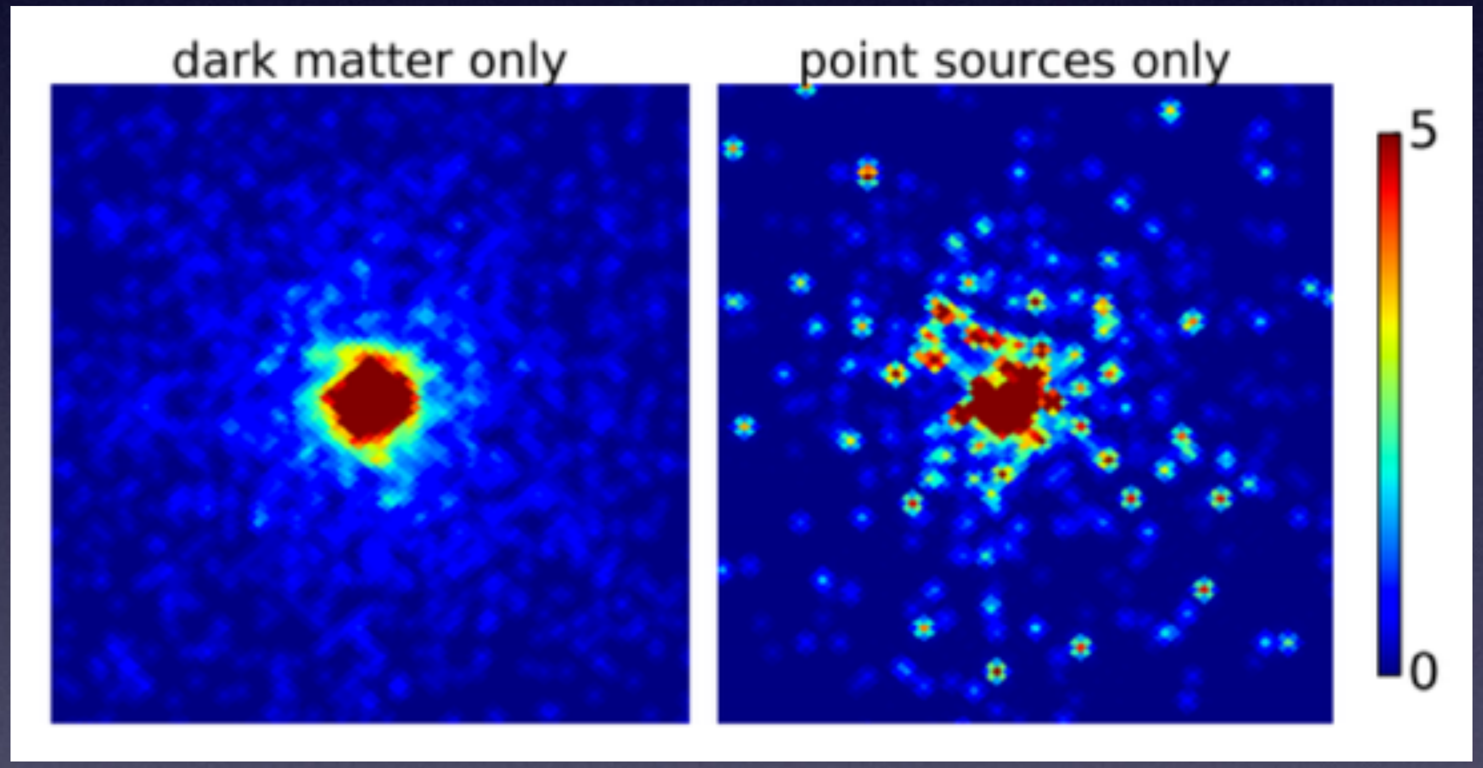
Geringer-Sameth et al '15

Evidence for pulsars

- Overall spatial morphology suggestive of dark matter origin (NFW-like profile, appears roughly symmetric, doesn't trace Galactic disk).
- But studies of photon fluctuations find evidence (Bayes factor ~10^6, ~6σ) for point-source-like structure. Spectrum consistent with either light dark matter or gamma-ray pulsars.

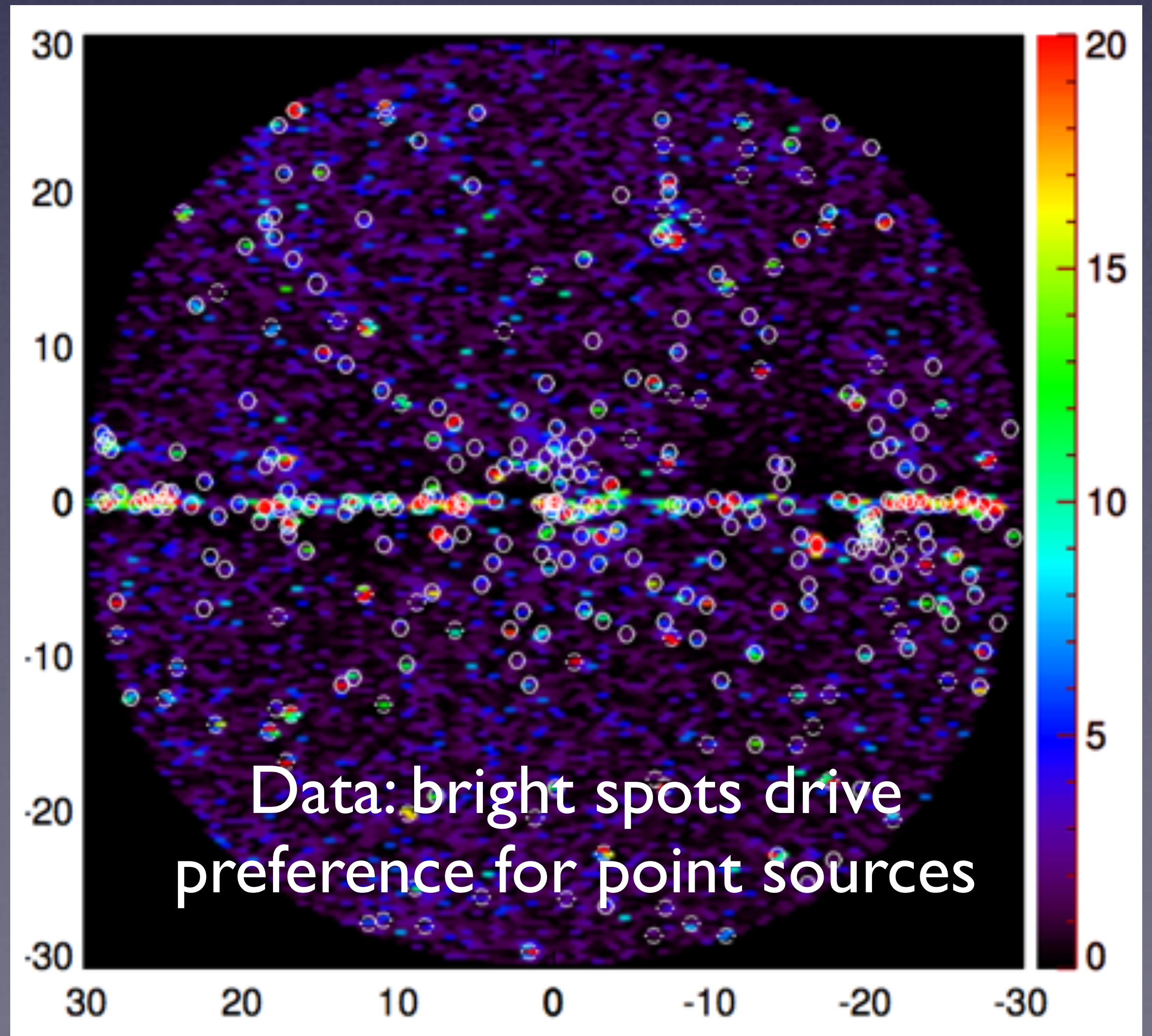
DM origin hypothesis

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



Pulsar origin hypothesis

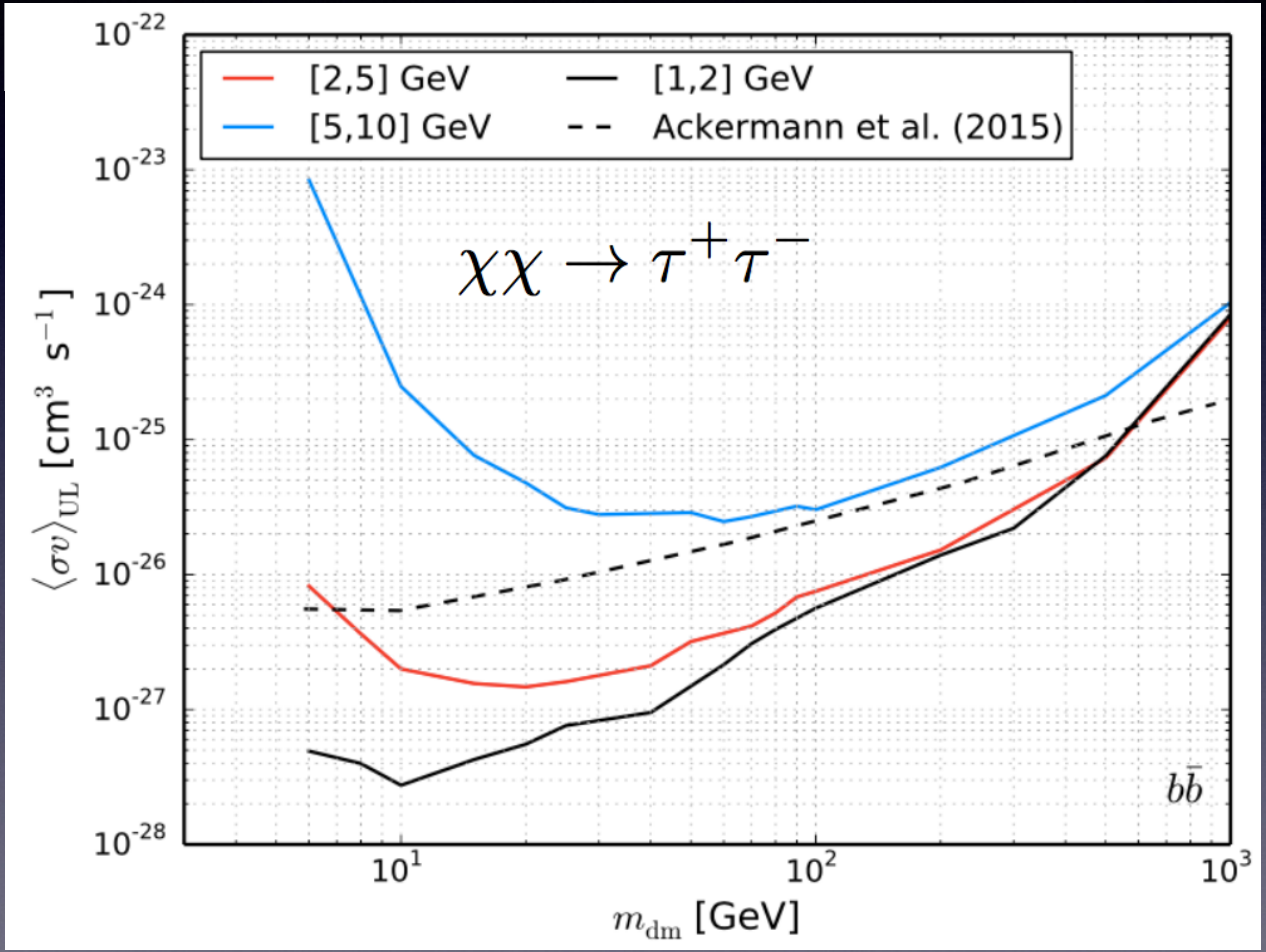
signal originates from a collection of compact objects, each one a faint gamma-ray point source



Data: bright spots drive preference for point sources

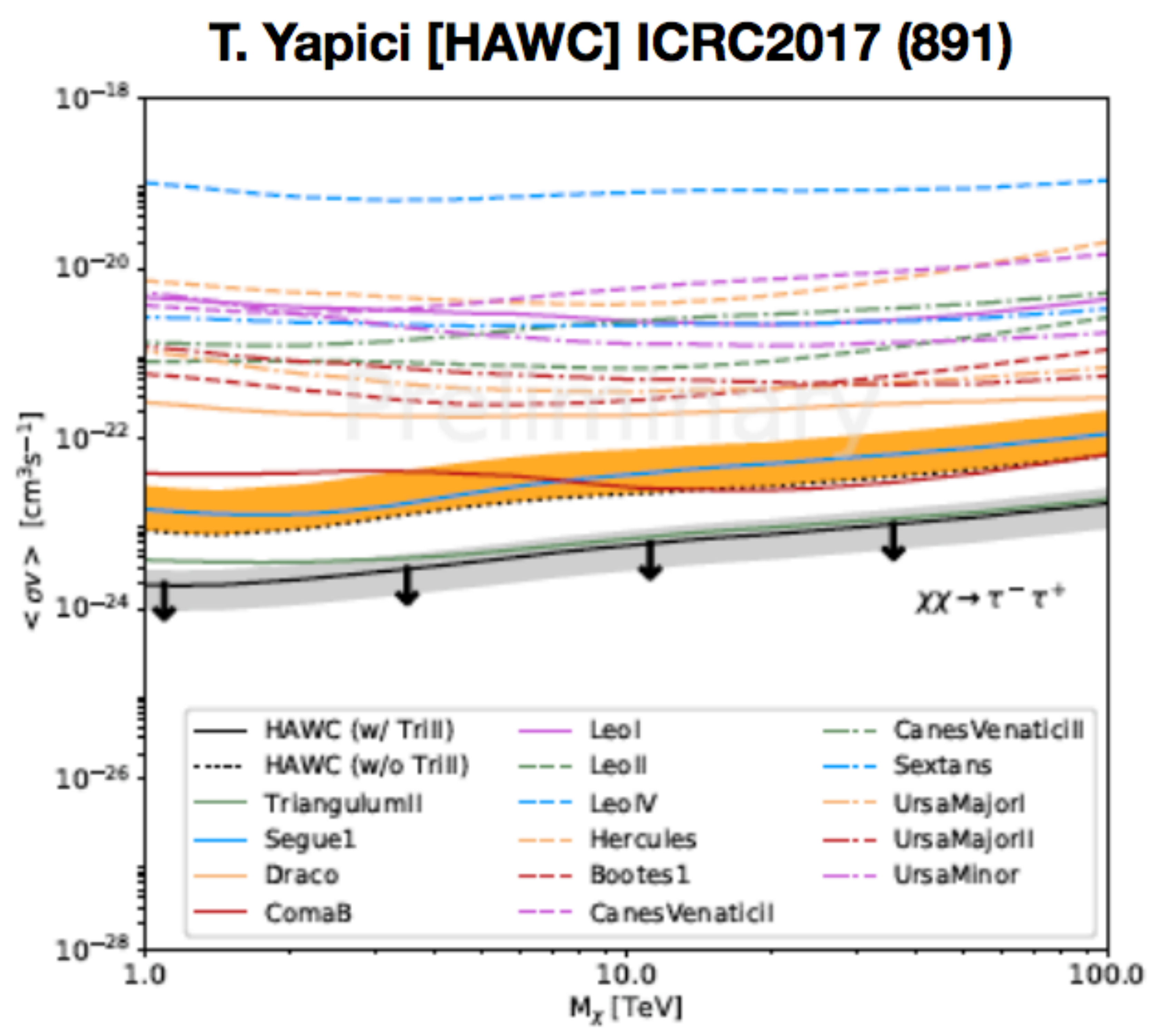
- Lee, Lisanti, Safdi, TRS & Xue '16: non-Poissonian template fitting (see also Mishra-Sharma et al '17 for public code package).
- Bartels, Krishnamurthy & Weniger '16: wavelet analysis.
- Most recently, Fermi-LAT Collaboration '17: studied point sources in this region with pulsar-like spectra, found evidence for a point source population centered on the Galactic Center, compared to the fit with a disk population alone.

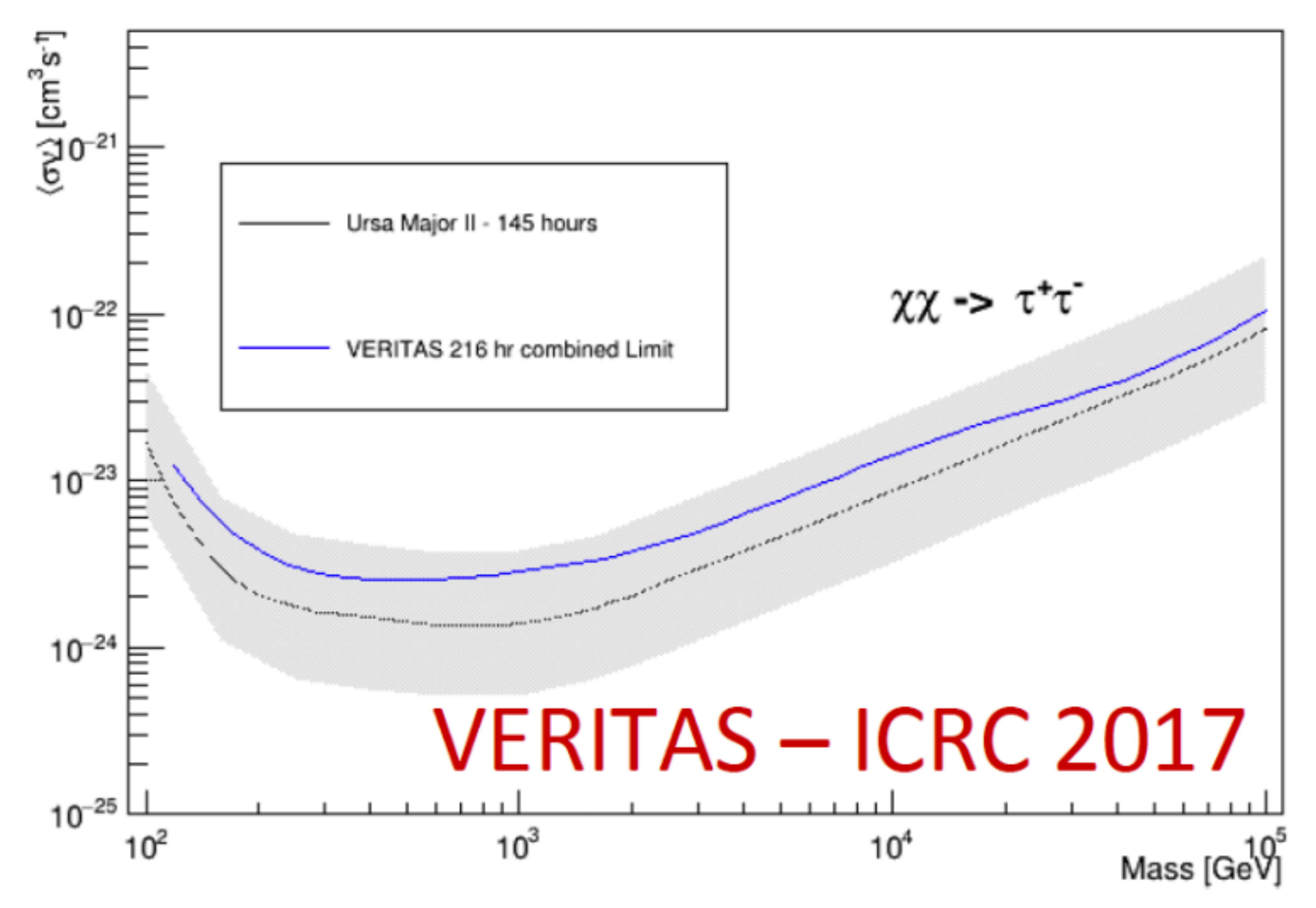
The extragalactic gamma-ray background



Hannes-S. Zechlin ICRC2017 (922)

Other dwarf galaxy limits





Additional decay limits