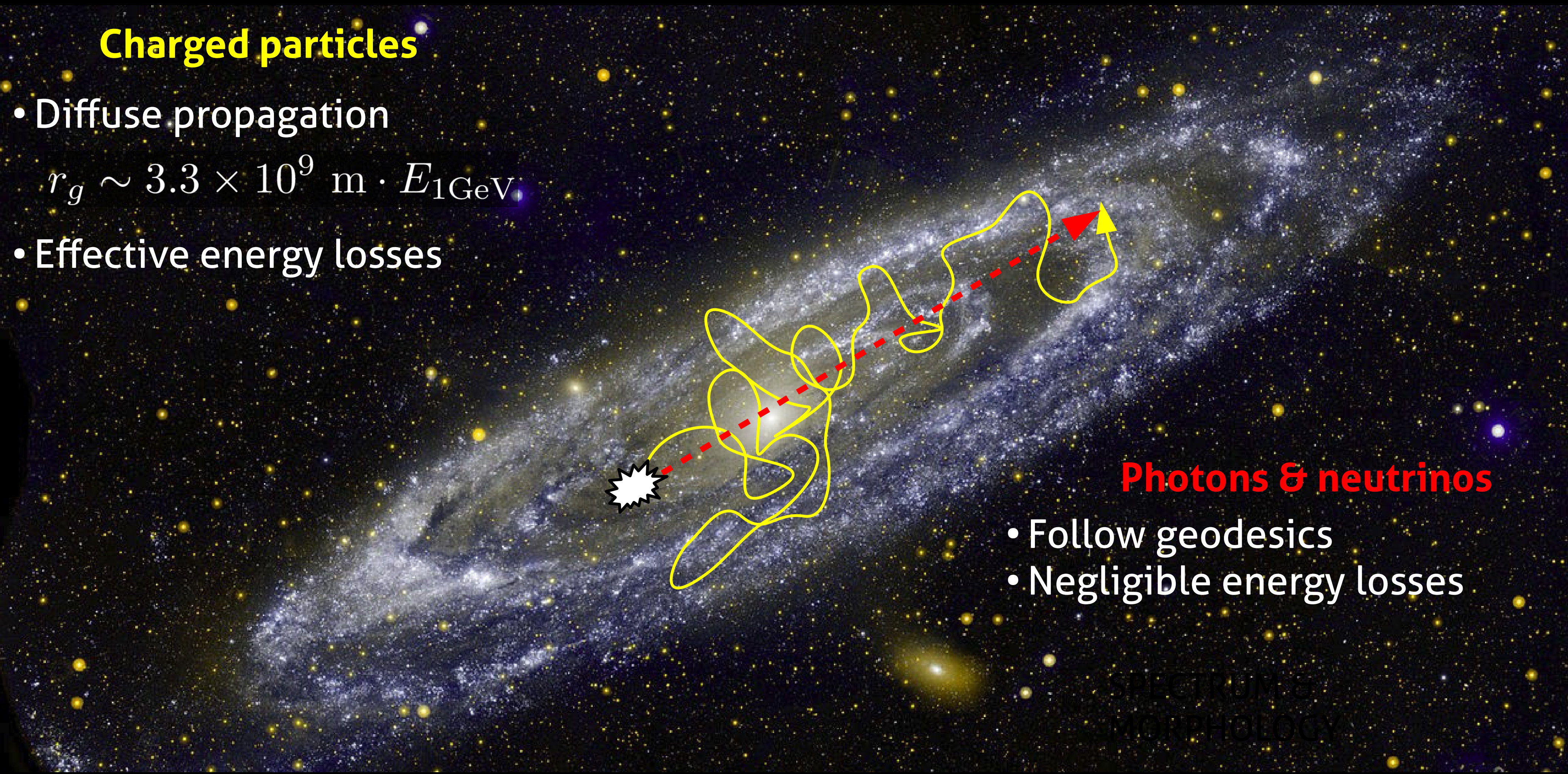
Propagation of messengers from DM

Differential emissivity of DM annihilation products

$$\frac{d^3 N_X}{dV\,dt\,dE} = \frac{\langle \sigma v \rangle \rho_{\rm DM}^2}{2 m_{\rm DM}^2} \frac{dN_X}{dE}$$



Charged particles

- Diffuse propagation

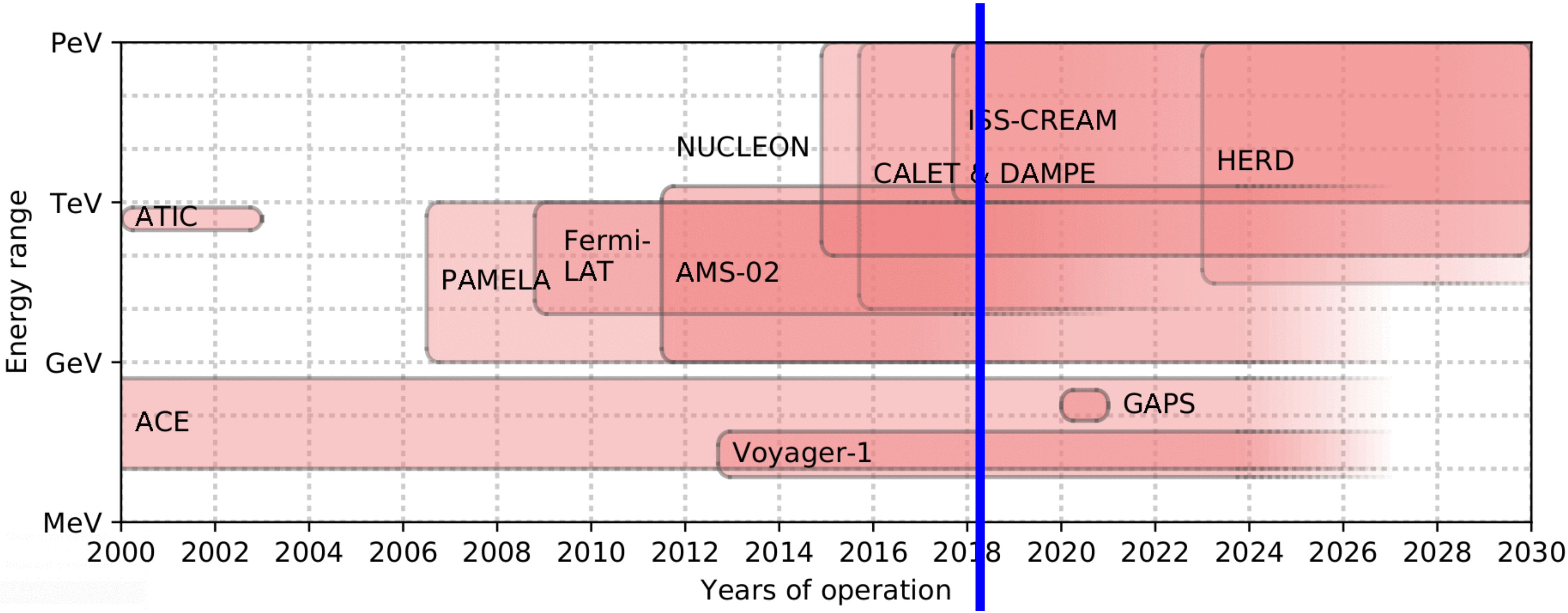
  $r_g \sim 3.3 \times 10^9\ \mathrm{m} \cdot E_{1\mathrm{GeV}}$

- Effective energy losses

Photons & neutrinos

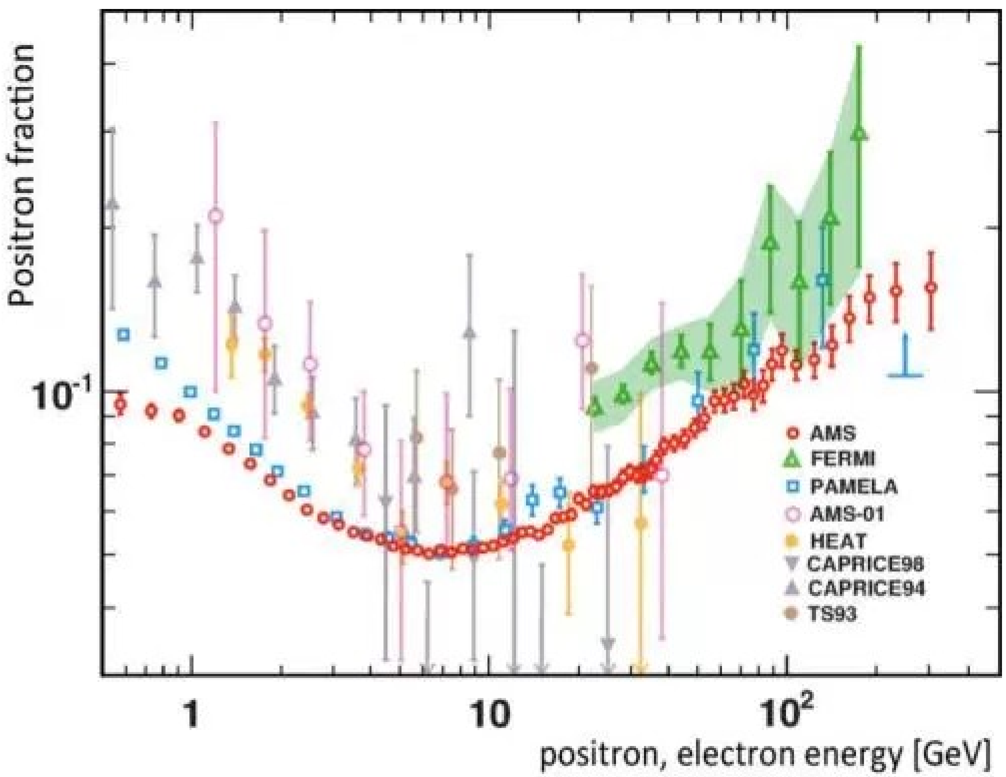
- Follow geodesics
- Negligible energy losses

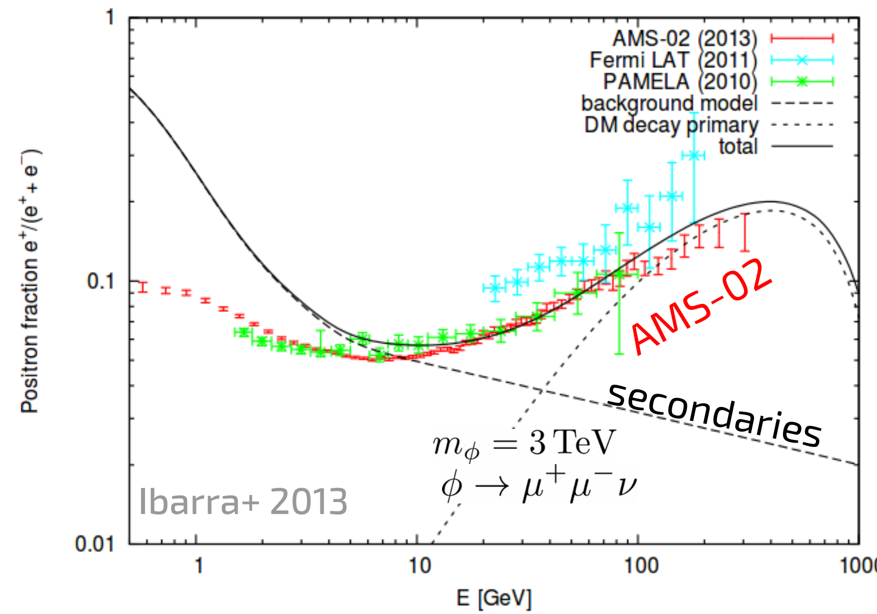
Instrumental panorama – Charged cosmic rays



- GeV – TeV: AMS-02 higher statistics, more analyses
- TeV – PeV: Various new satellite experiments will significantly improve statistics
- sub-GeV: GAPS

The CR “positron excess”

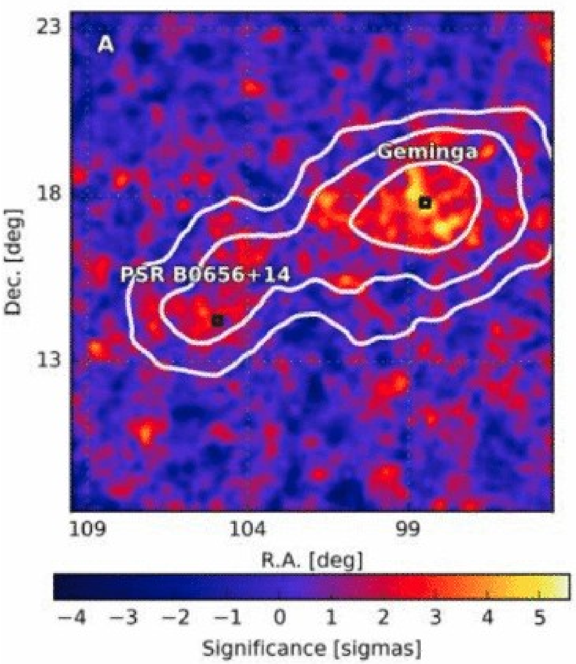


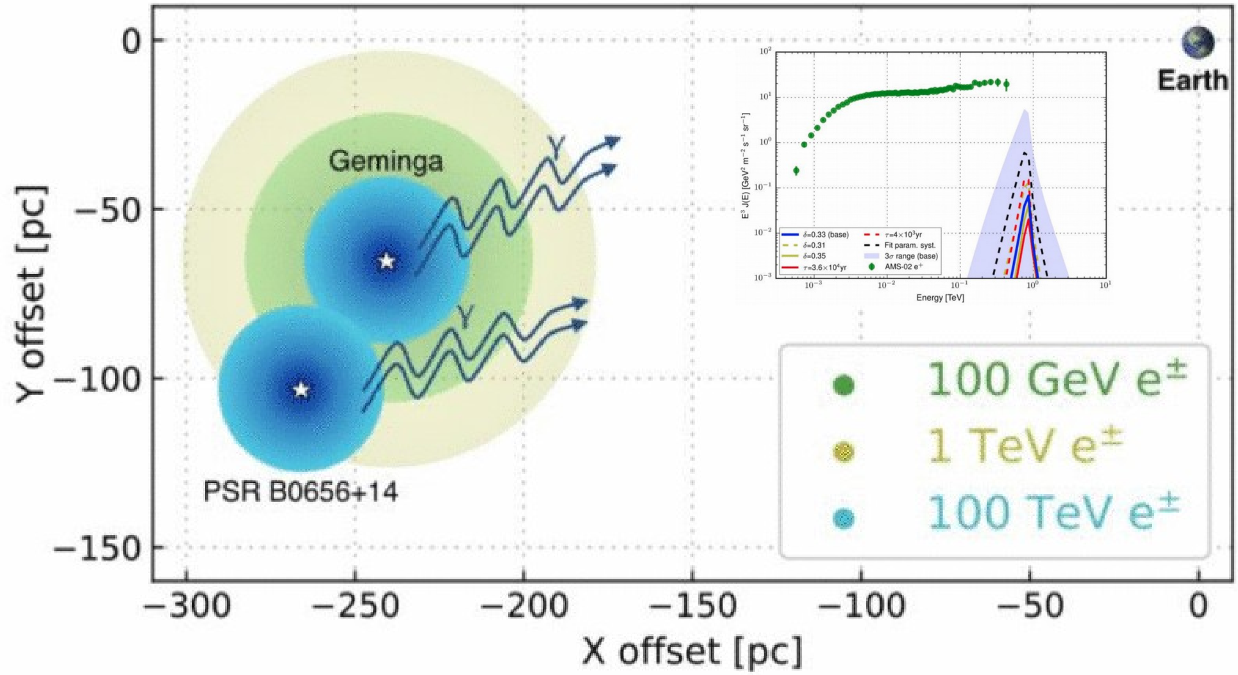


Status

- Excess above generic secondary expectations (e.g. Delahaye+ '10, Kappl & Reinert '16)
- Explaining 100% of the excess with DM is largely excluded (nothing in gamma, CMB, pbar etc) (e.g. Papucci & Strumia '10, Cirelli+ '10, Ibarra+ '13, Slatyer '15)
- Pulsar origin is possible, but also, e.g., microquasars, SNRs (secondary production in primary sources), dark matter, ...

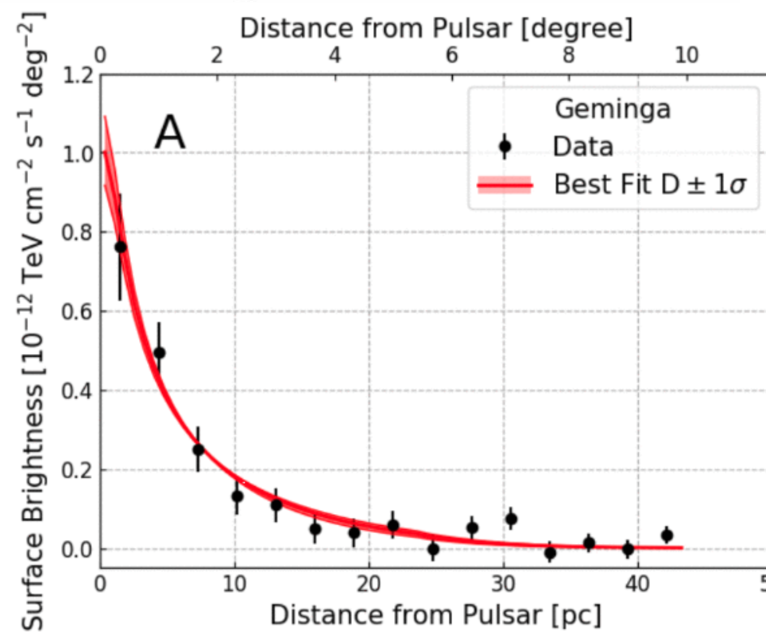
Do pulsars contribute to the positron excess?



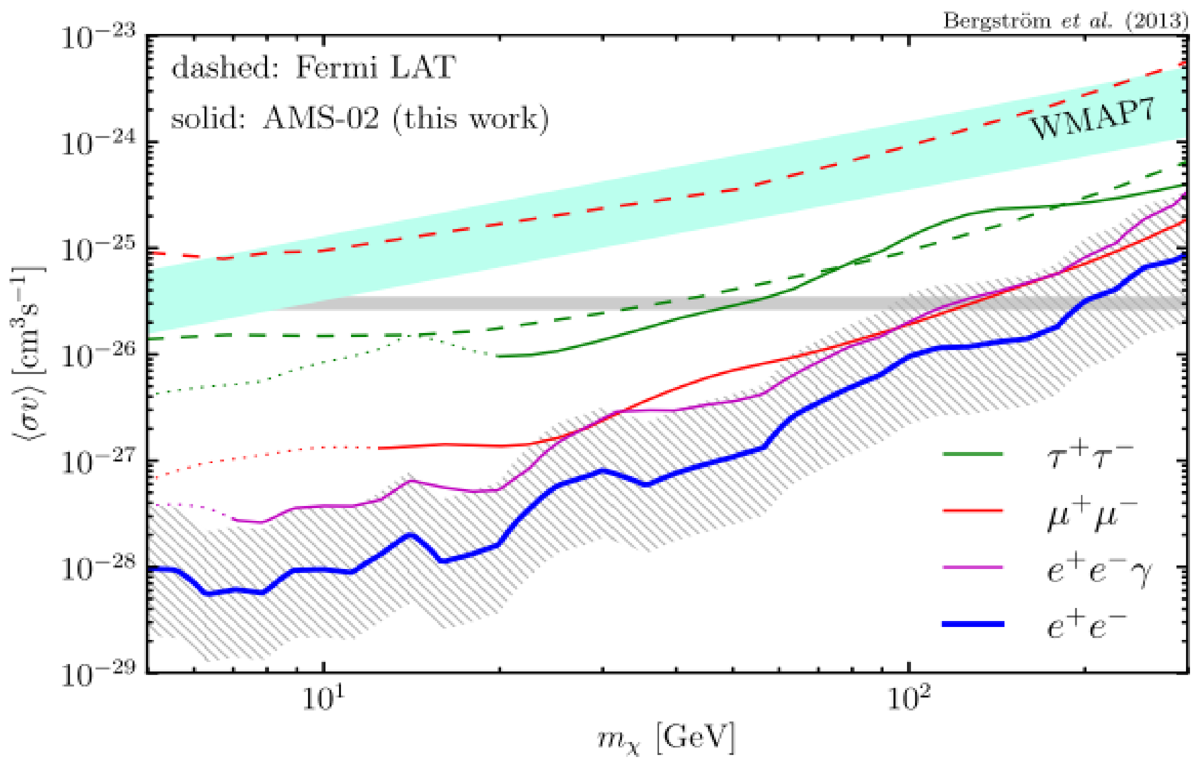


HAWC observations of Geminga and PSR B0656+14 (Monogem)

- Observations of compact TeV emission halo → extremely low diffusion coefficient (x100 times lower than from B/C) → Monogem/Geminga do not contribute to positron excess
- But: last step relies on adopting low diffusion coefficient for entire (local) ISM, which seems to be in conflict with general observation of ~10 TeV electrons (Hooper & Linden 17, see also Lopez-Coto & Giacinti 17)



No spectral features in positron flux

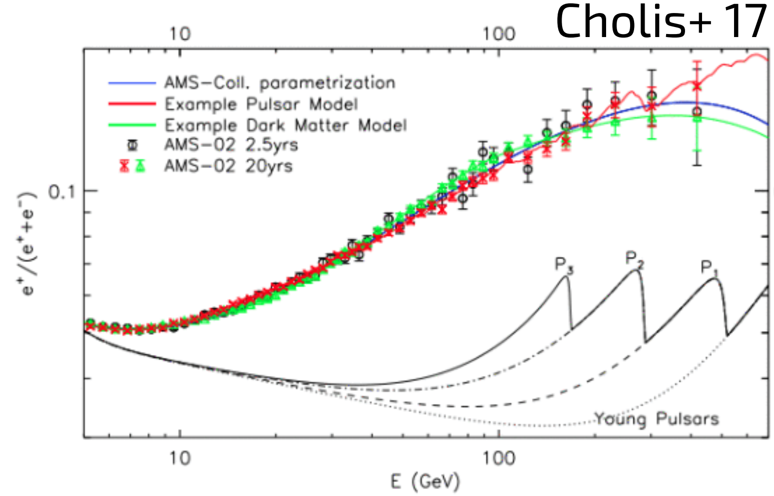


AMS-02 positron spectrum rather smooth

- strong upper limits on light DM annihilation from non-observation of spectral signatures in positron flux

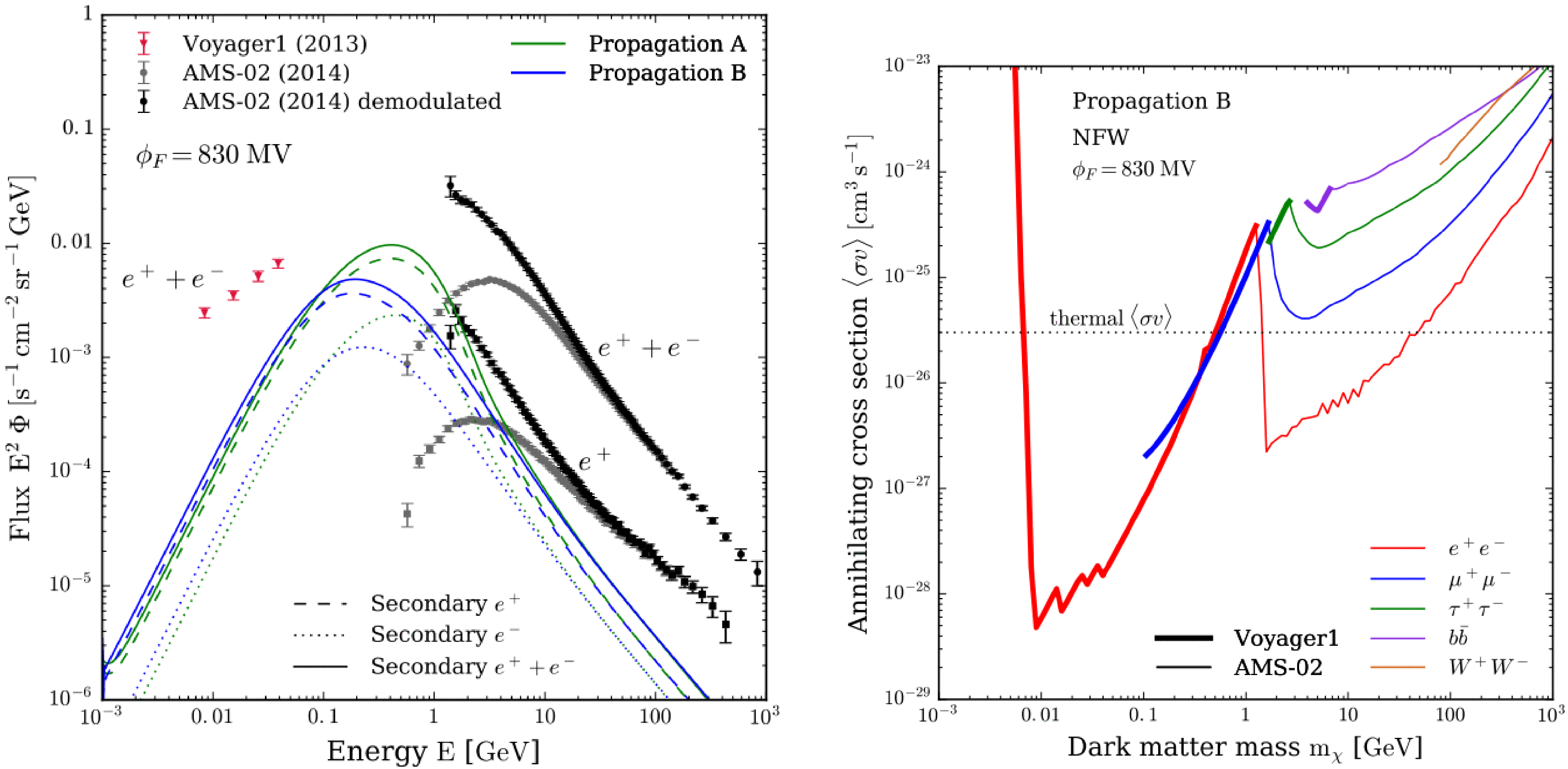
BBCHW 2013, Ibarra+ 2013

Cholis+ 17



Pulsar-related wiggles in positron spectrum can potentially be detected in AMS-02 (10 yrs) or DAMPE (3 yrs) data (Cholis+ 17).

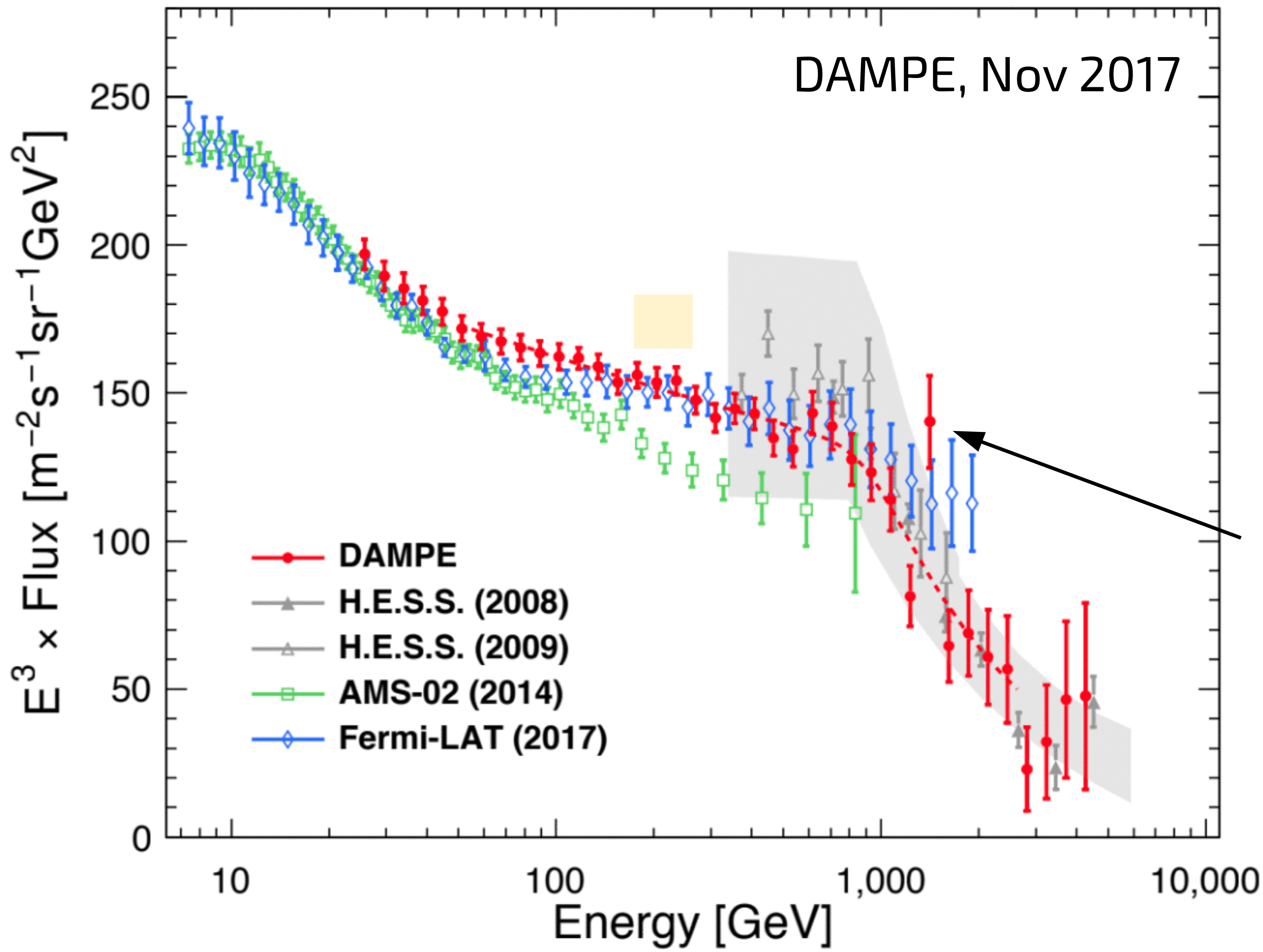
sub-GeV electrons from Voyager-1



- Voyager 1 crossed heliopause 2012
- Measured electron+positron spectrum unaffected by solar modulation
- → Limits on MeV DM annihilation (for p-wave annihilation stronger than CMB)

Boudau+ 17

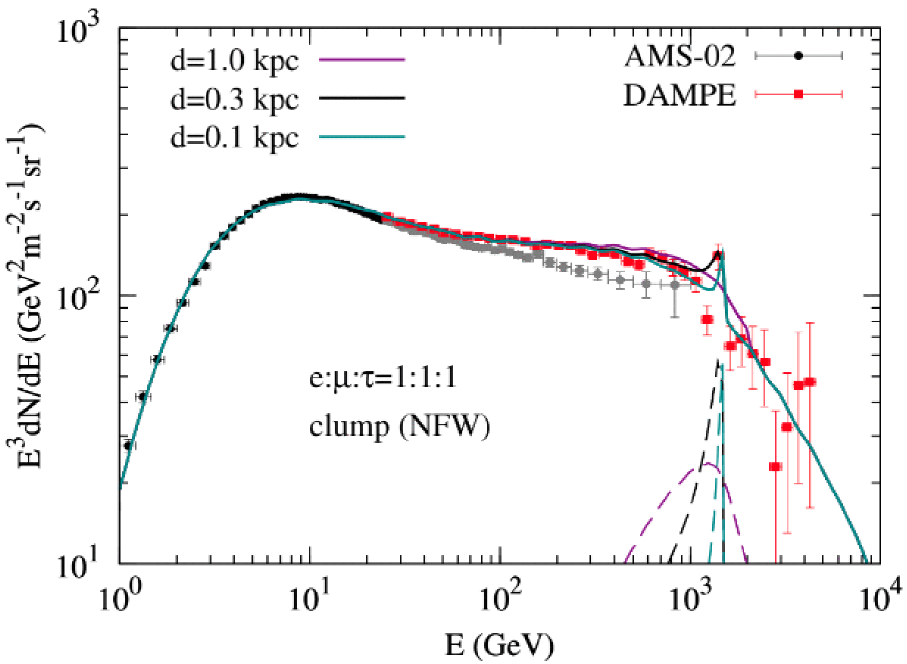
Positrons + electrons with DAMPE



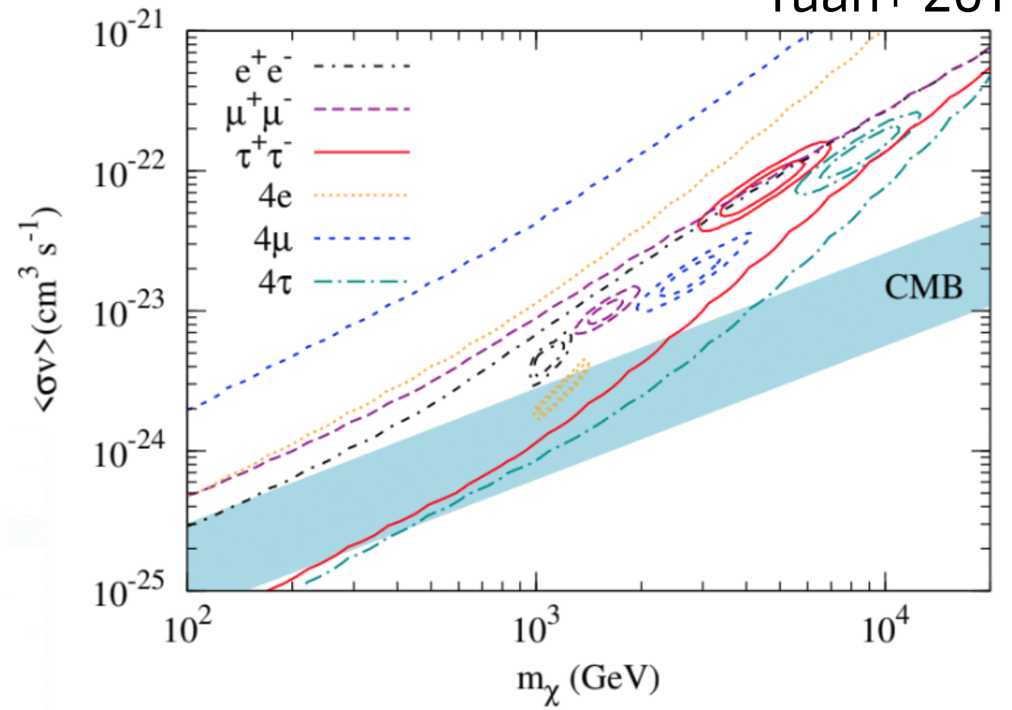
1.4 TeV line?
2.3 global significance
(Fowlie 2017)

- Spectral break measured by HESS clearly confirmed
- A suggestive peak at 1.4 TeV (~3 papers/week)
- Energy resolution is better than 1.2% @ > 100 GeV

Interpretations of DAMPE result



Yuan+ 2017



Interpretations of the 1.4 TeV feature

- Statistical fluctuation
- Cold, ultra-relativistic e+e- pulsar wind
- DM annihilation into monoenergetic e+e- pairs. This requires local (< 1 kpc) DM clump to switch off effects of cooling which would distort spectrum. Very small probability that such a clump is there (VL).

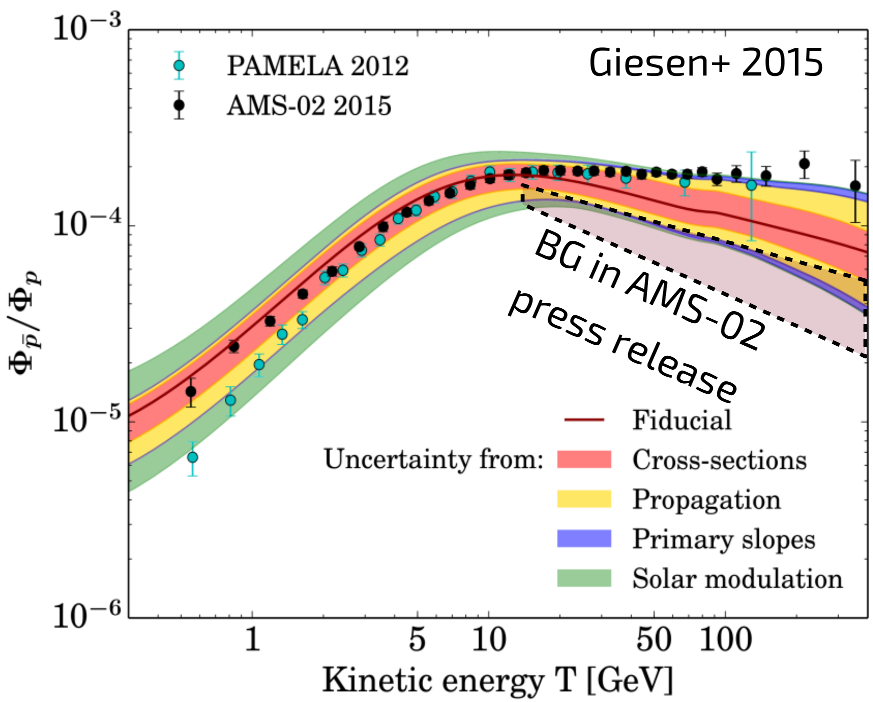
Interpretations spectral cutoff

- Dark matter annihilation (TeV masses, the usual very large cross-sections)
- Maximum acceleration limits of sources

See also: Athron+ 17, Duan+ 17, Fan+ 17, Gu 17 (also 3.5 keV line!), Yang+ 17, many others

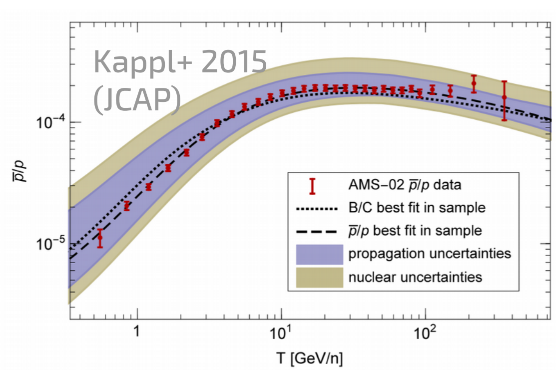
AMS-02 anti protons – ~100 GeV

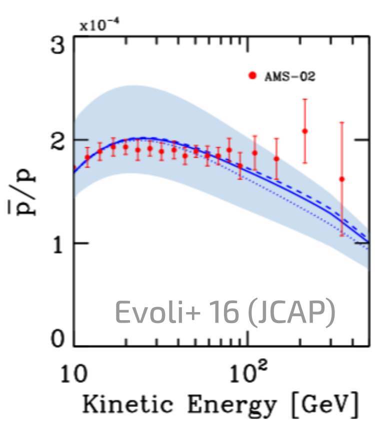
Hadronic annihilation/decay channels contribute to cosmic-ray anti protons. No clear excess is observed above backgrounds



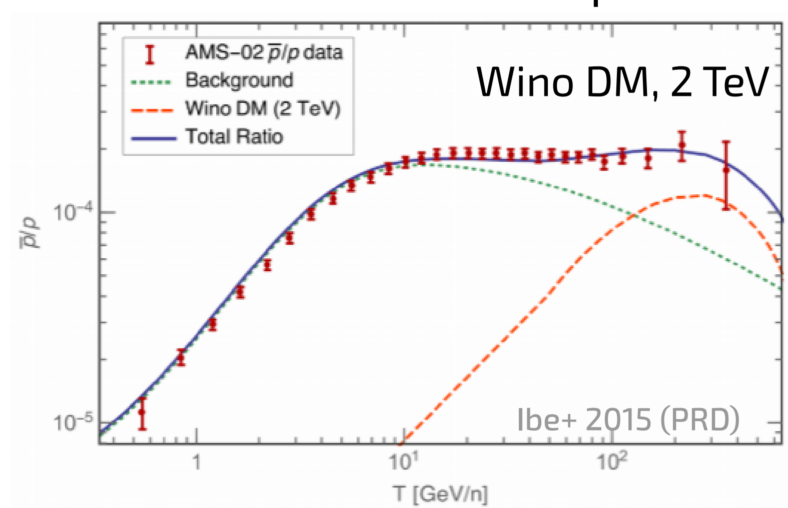
Situation

- Background of secondary anti-protons can be predicted within factor of a few
- Measurements marginally consistent with secondary background (Giesen+ 15; Evoli+ 15)
- Hard to exclude astro explanation for excesses above secondaries (e.g. nearby SNR; e.g. Kachelriess+ '15, non-universal diffusion, etc)

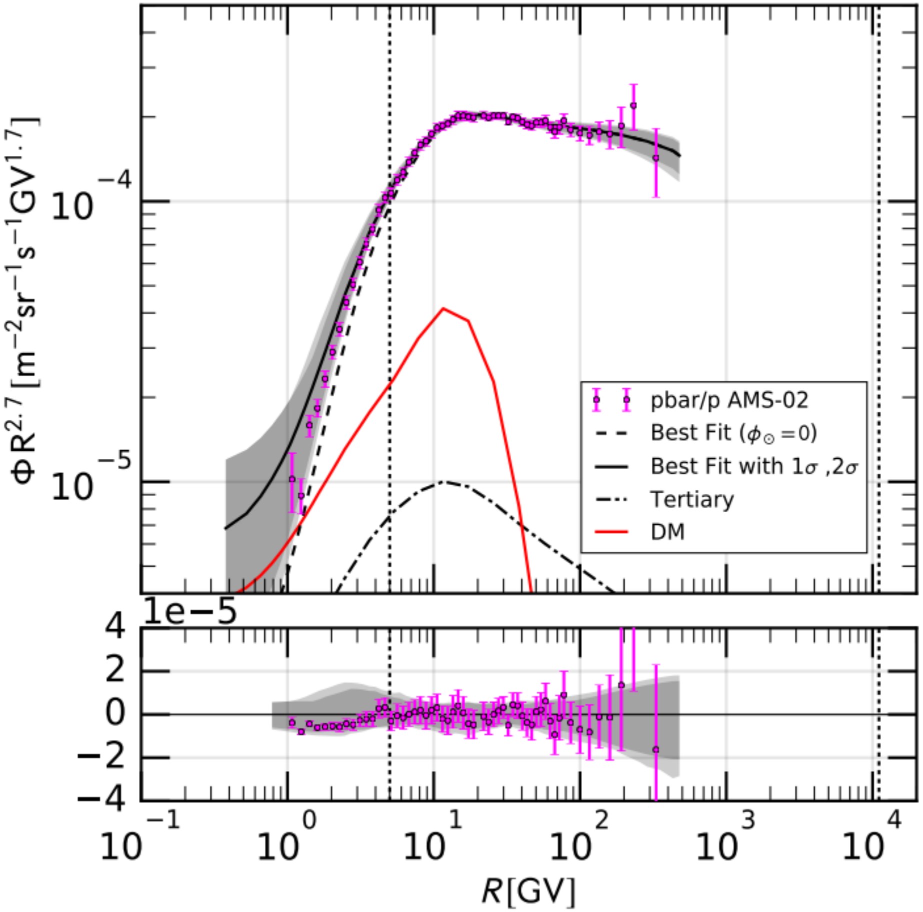


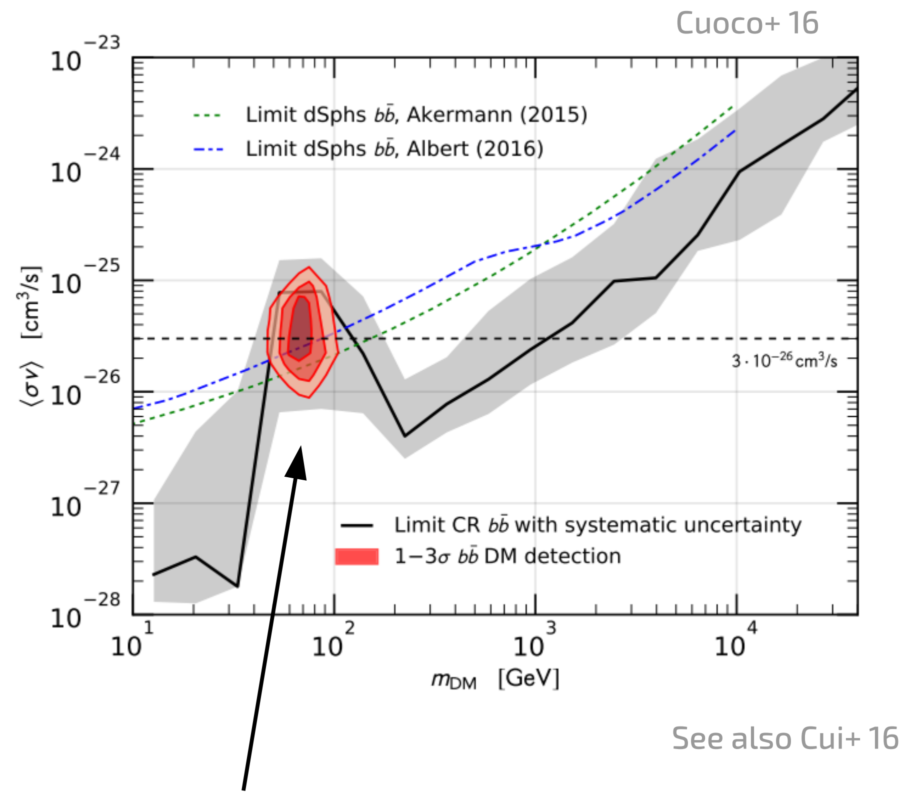


But: DM fit is possible



AMS-02 anti-protons - ~ 10 GeV





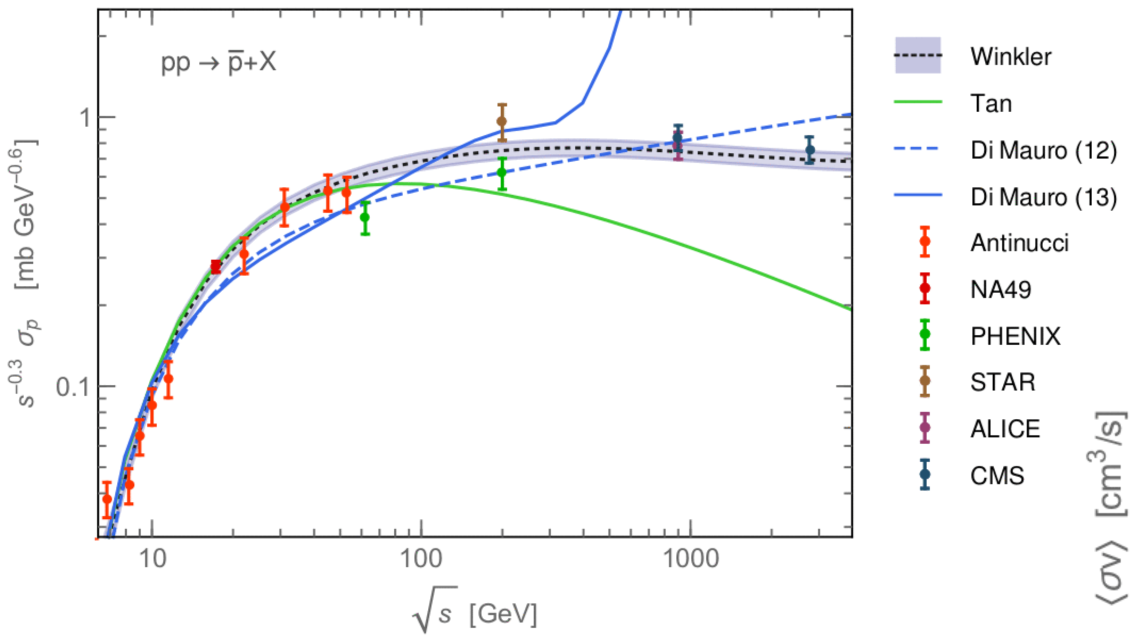
Agrees with Fermi GeV excess…

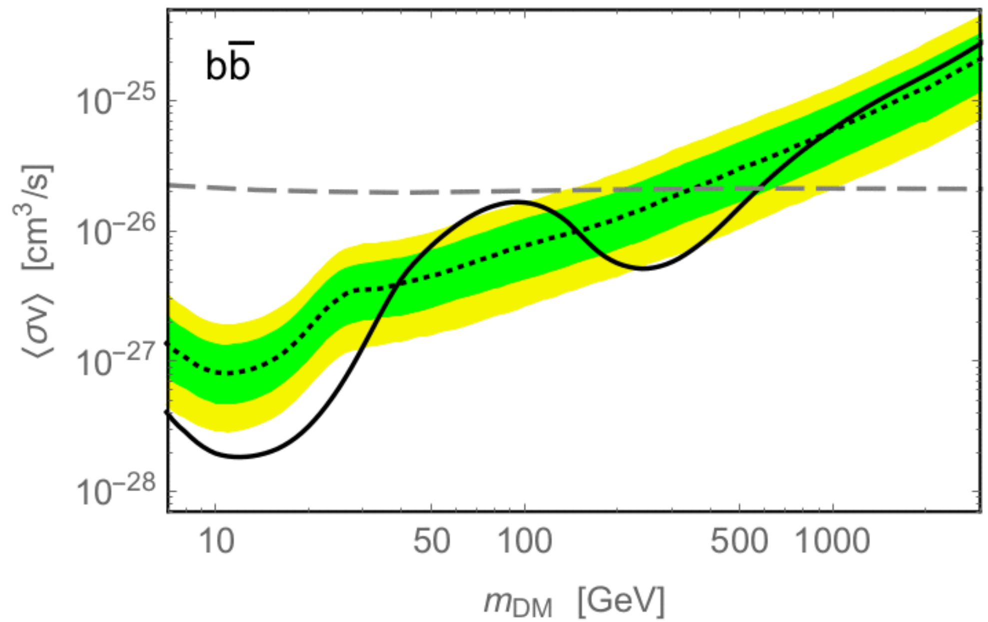
Indications for an excess around 10 GeV (Cuoco+16, see also Cui+ 16)

- Formally ~5 sigma preference for DM contribution, mass & flux compatible with GCE
- But: Simple propagation scenarios are insufficient to explain *all* CR data (and DM does not help) → Extraction of reliable limits or signal becomes a huge challenge

See also: Winkler+ 17; Carlson+14; Cirelli+14; Jin+15; Ibe+15; Hamaguchi+15; Lin+15; Kohri+15; Balazs&Li15; Doetinchem+15; Fornengo+13

Effect of various systematic uncertainties





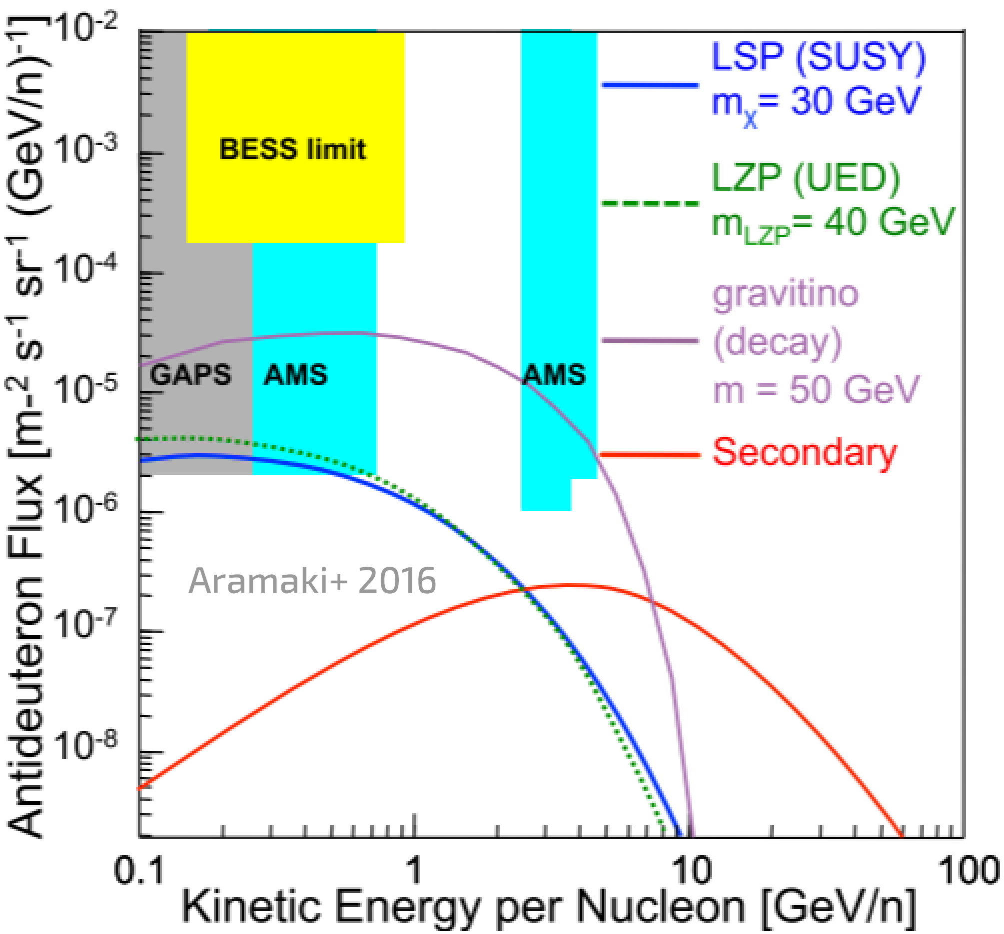
Accounting for covariances of various systematics (Reinart & Winkler 2017)

- Refitting nuclear spallation data for Boron production from Carbon, Oxygen, Nitrogen, etc
- Charge-dependent solar modulation
- Refitting primary cosmic ray measurements
- → Reasonable fit to B/C and pbar data with universal diffusion-reacceleration model
  → Significance for ~80 GeV DM contribution drops to below 2 sigma
  → Very strong limits on DM annihilation at low and higher DM masses

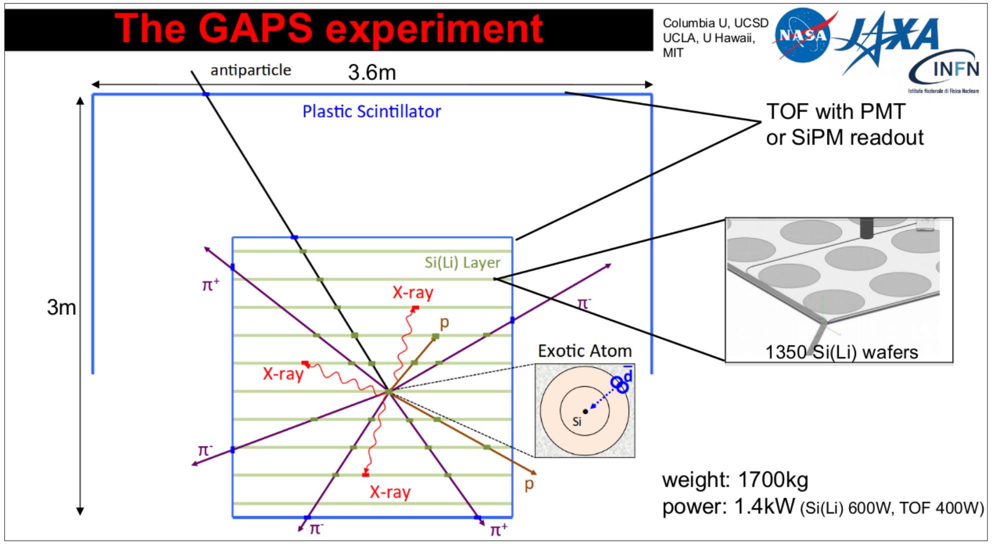
General AntiParticle Spectrometer (GAPS)

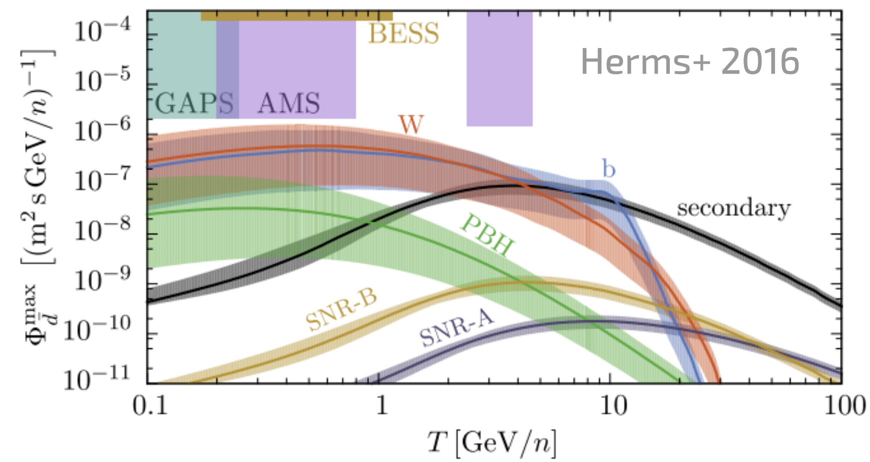
Searches for **anti-deuterons** with exotic atom formation

Funded by NASA & JAXA. First flight planned for ~2020.



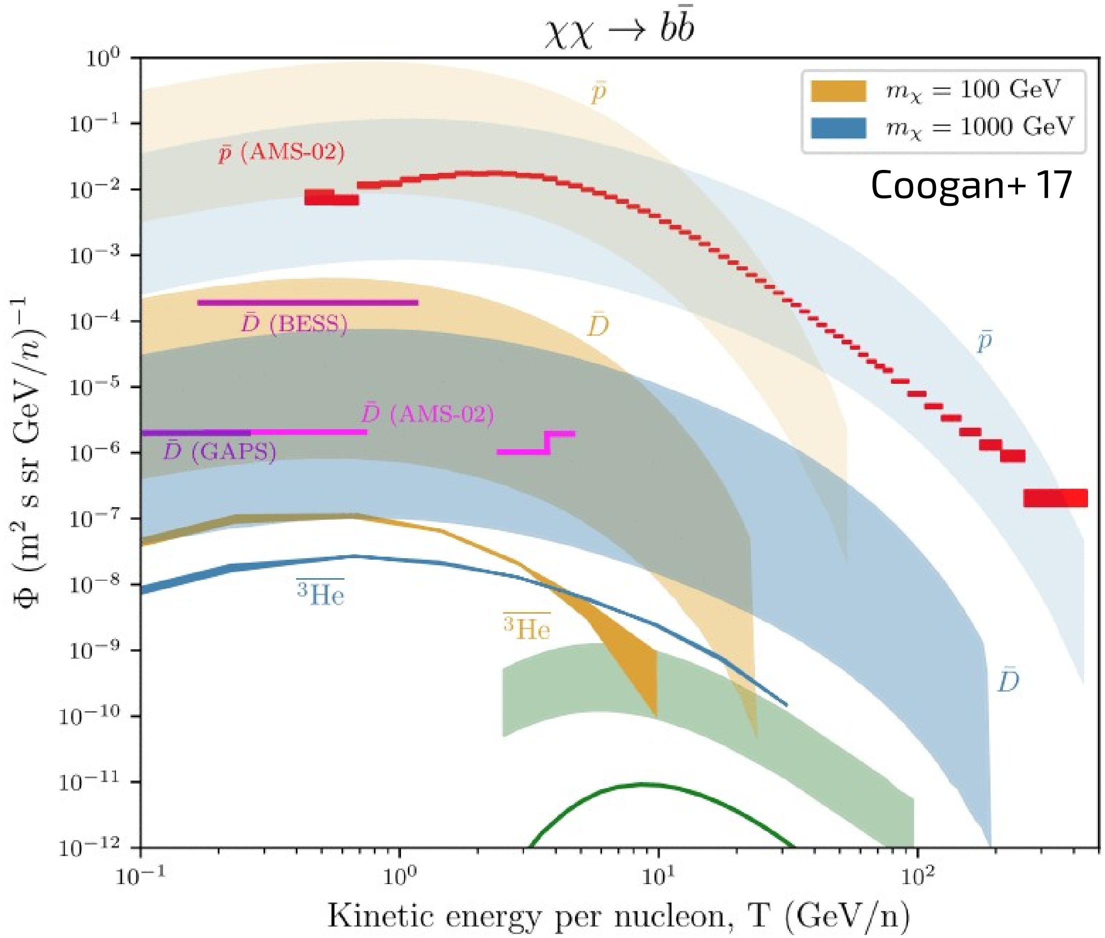
Credit: P. von Doetinchem

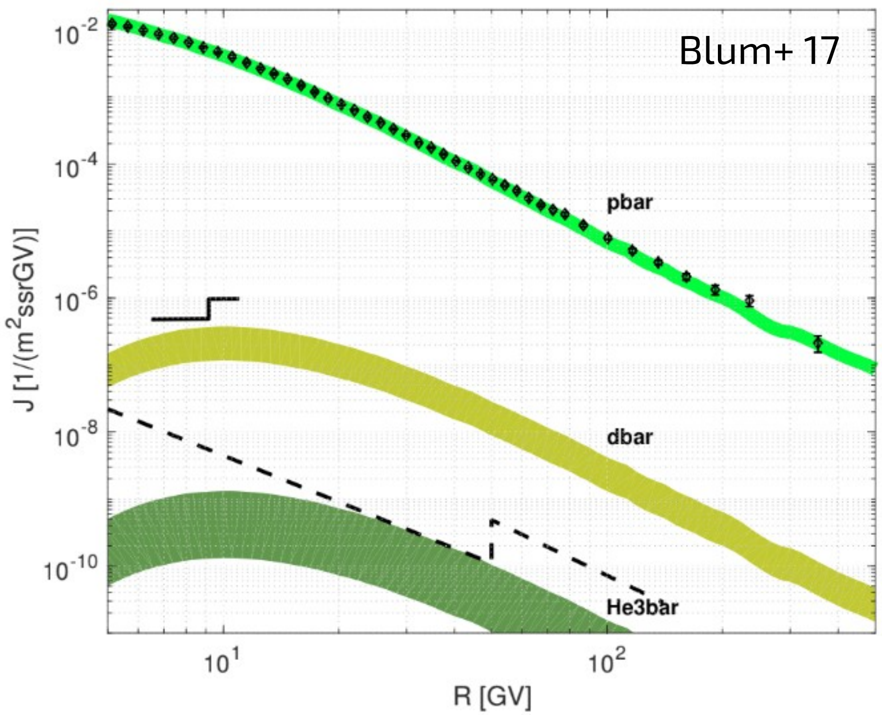




Sever constraints on the range of detectable models comes from AMS-02 anti-protons.

Dark matter searches with anti-^{3}He



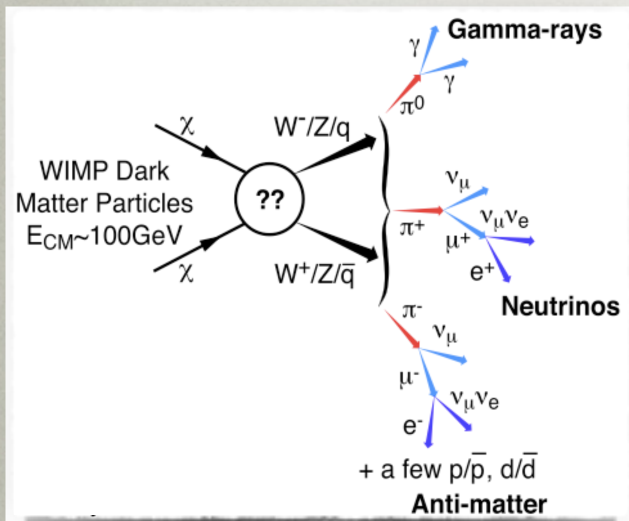


Ong+ 17; Blum+ 2017; Coogan+ 2017

Searches for anti-^{3}He

- Recently considered by Carlson+ 14, Cirelli+ 14
- Smaller rates than anti-deuteron signal, but thought to be even cleaner than anti-deuteron
- However, new estimates indicate secondary anti-^{3}He background might be larger and in reach of AMS-02 (Blum+ 2017)
- Ting (Dec 2016 CERN): Few ^{3}He candidates in AMS-02 data, will take years to confirm → Secondary? Dark matter?

Indirect Searches
Gamma Rays



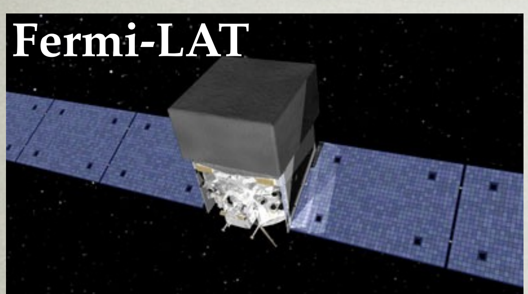
particle physics

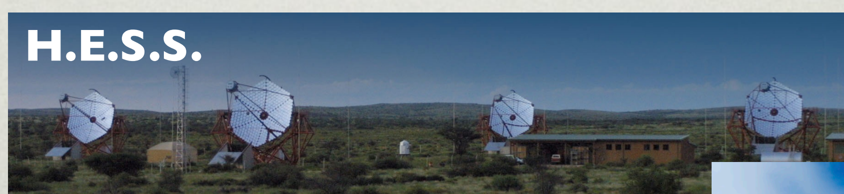
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) \;=\; \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f$$

$$\times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

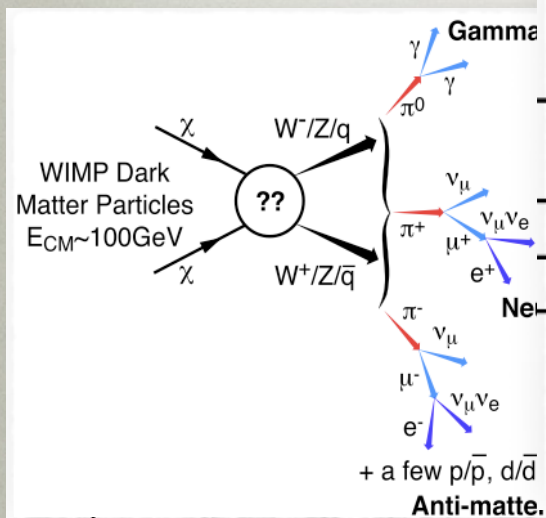
DM distribution

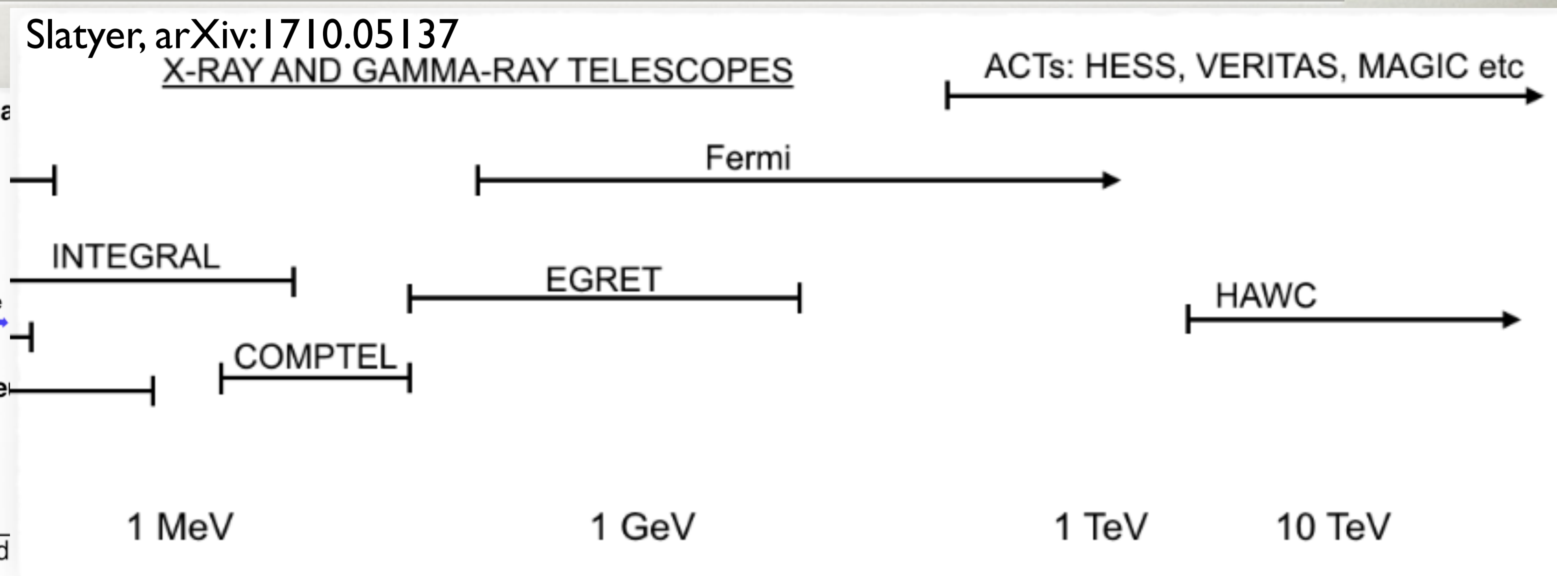
J - factor

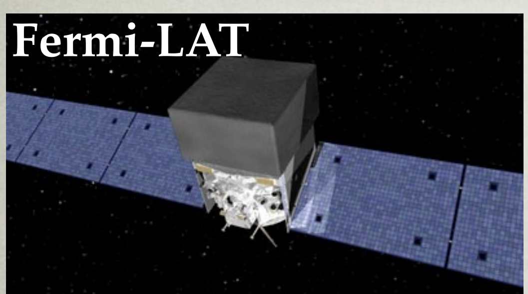


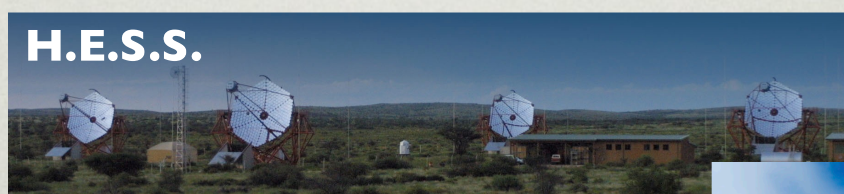


Indirect Searches
Gamma Rays



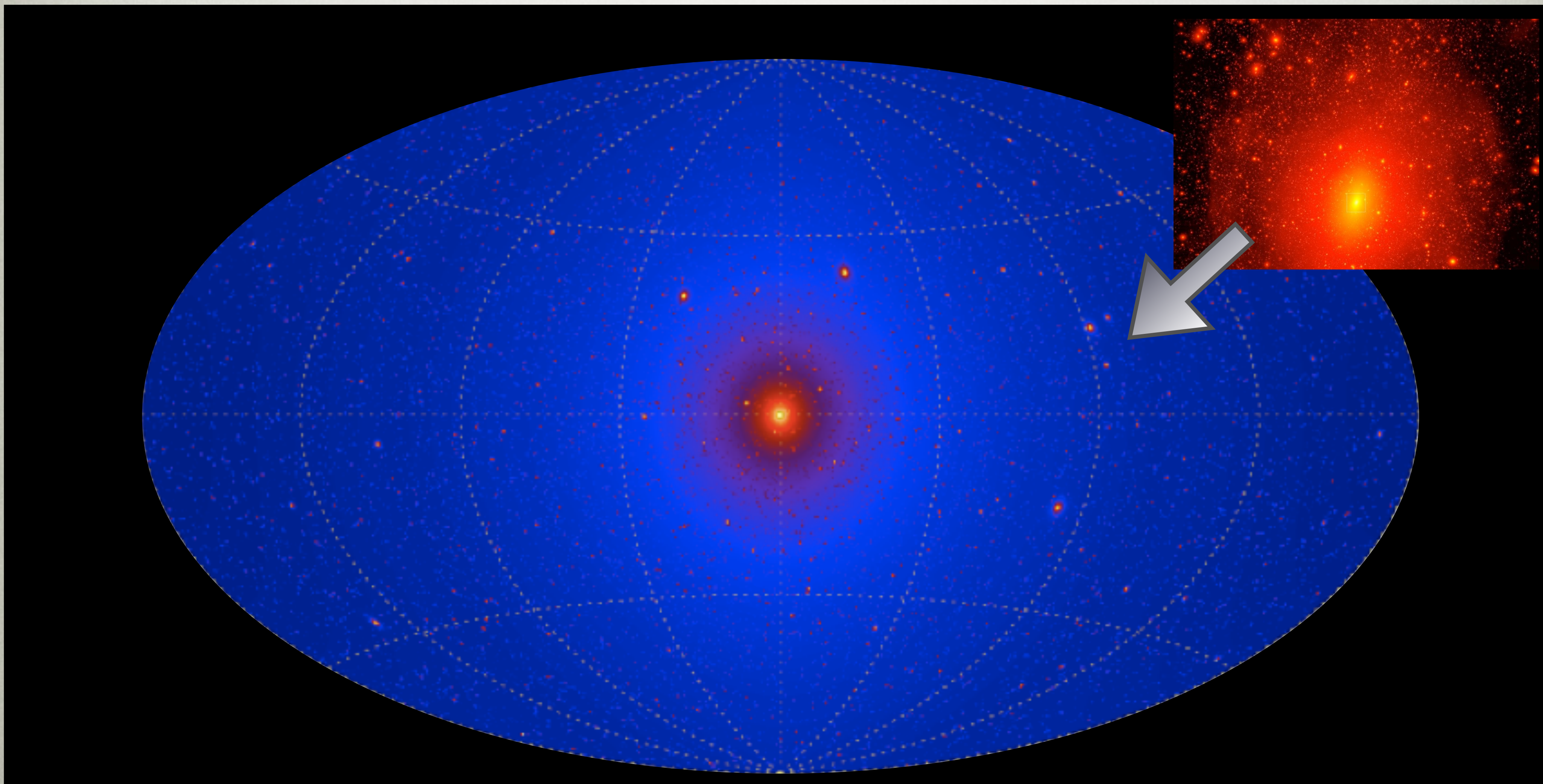






Gamma rays from Dark Matter Annihilation:

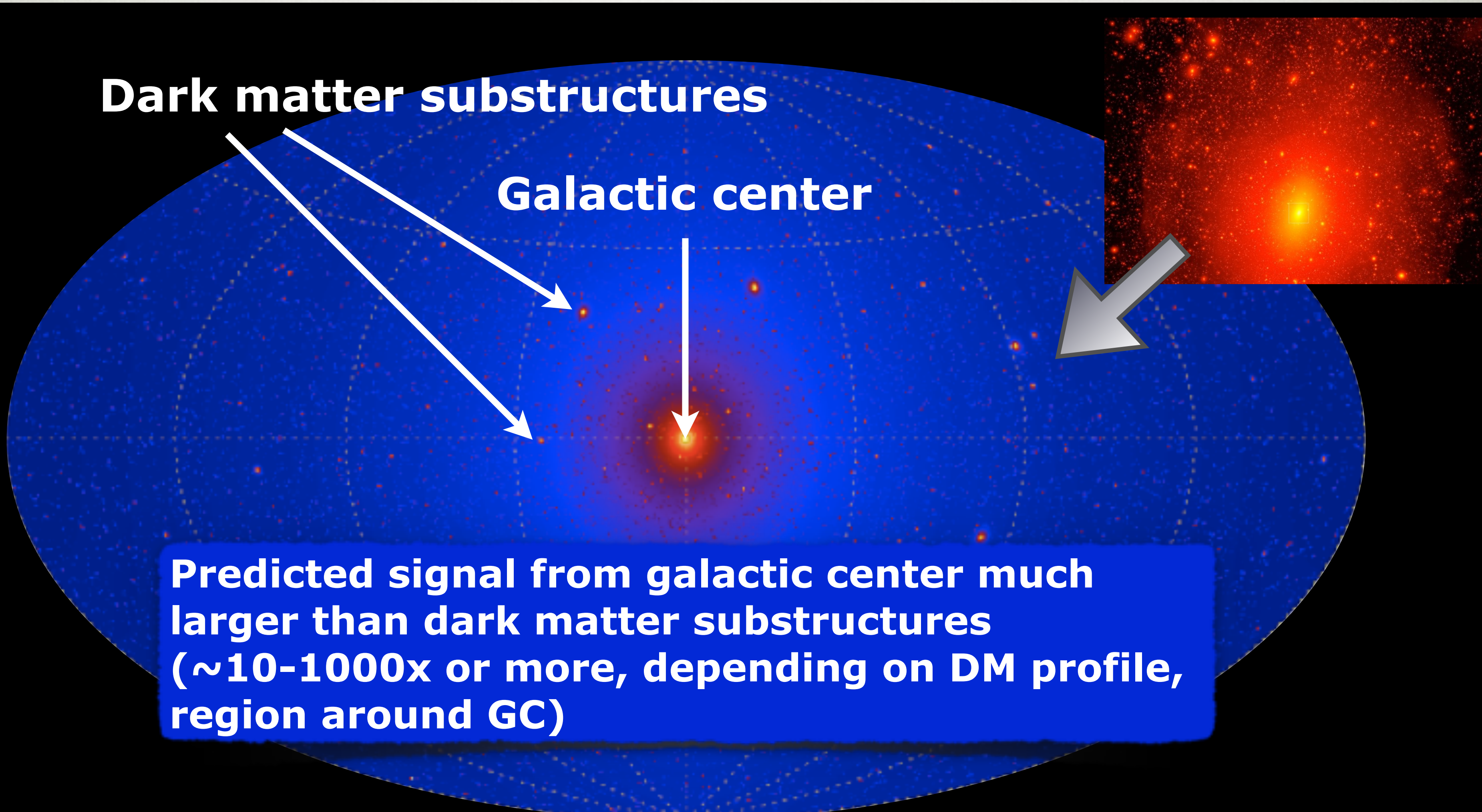
The Milky Way & its satellites



Pieri et al, arXiv:0908.0195

Gamma rays from Dark Matter Annihilation:

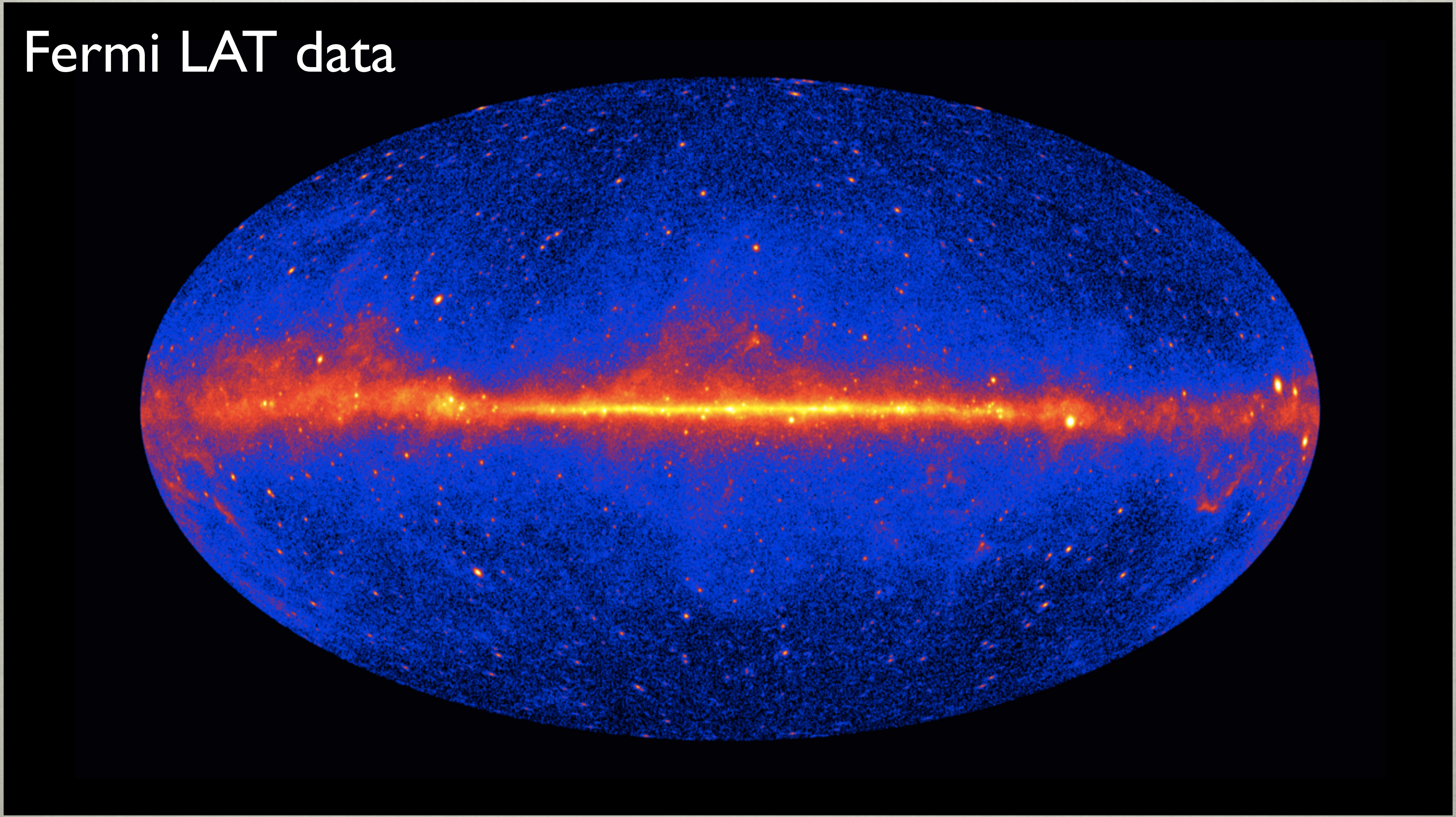
The Milky Way & its satellites



Predicted signal from galactic center much larger than dark matter substructures (~10-1000x or more, depending on DM profile, region around GC)

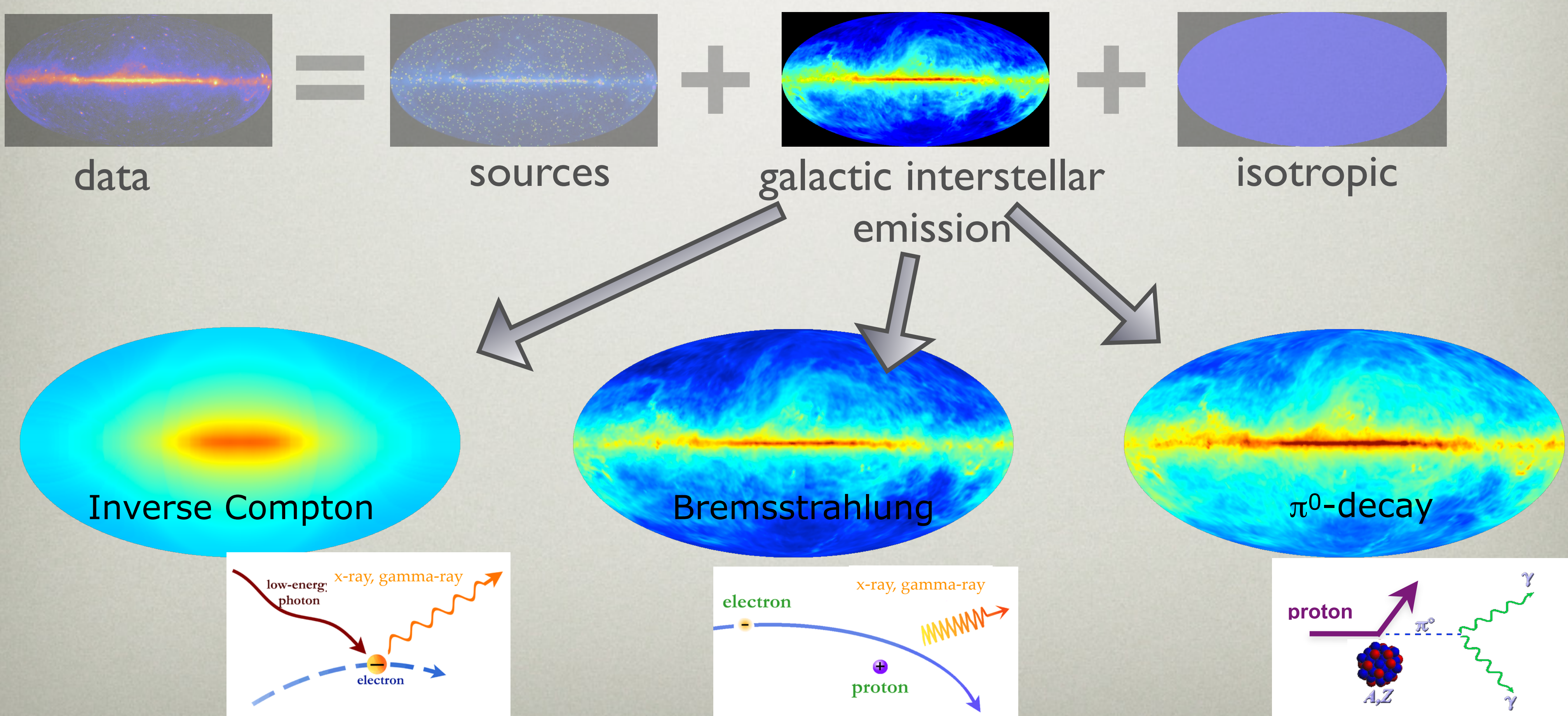
Pieri et al, arXiv:0908.0195

The Fermi Sky



Galactic Gamma-Ray Interstellar Emission

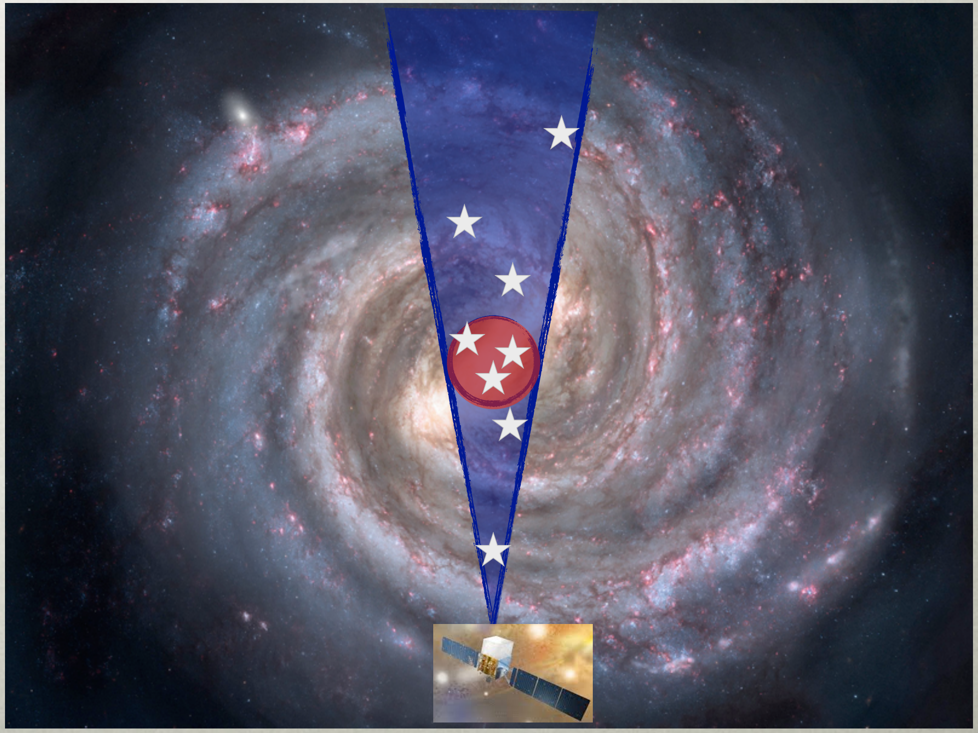
- The interstellar gamma-ray emission in the Milky Way is produced by cosmic rays interacting with the interstellar gas and radiation field



Galactic Gamma-Ray Interstellar Emission

- The interstellar gamma-ray emission in the Milky Way is produced by cosmic rays interacting with the interstellar gas and radiation field

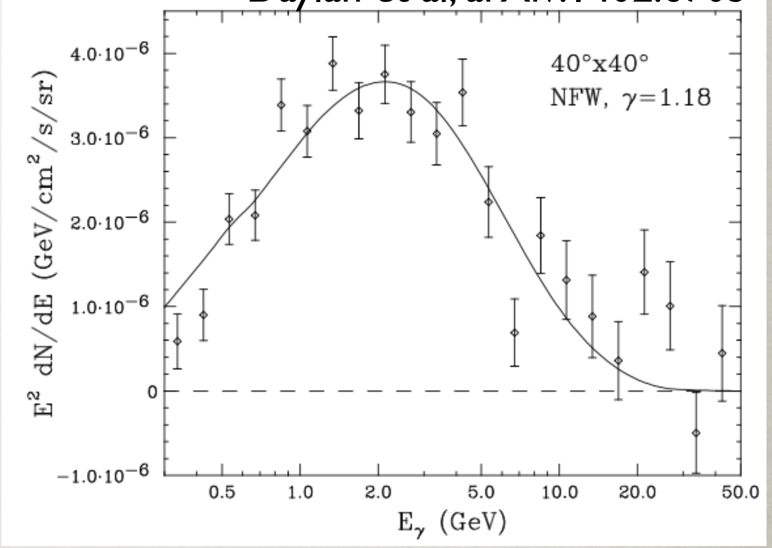
➡ Galactic center region: a dark matter signal is predicted to be largest here, where modeling of the interstellar emission (and sources) is problematic!
CR intensities, density of radiation fields and gas are highest and most uncertain, long integration path over the entire Galactic disc, large density of sources



Galactic Center Excess

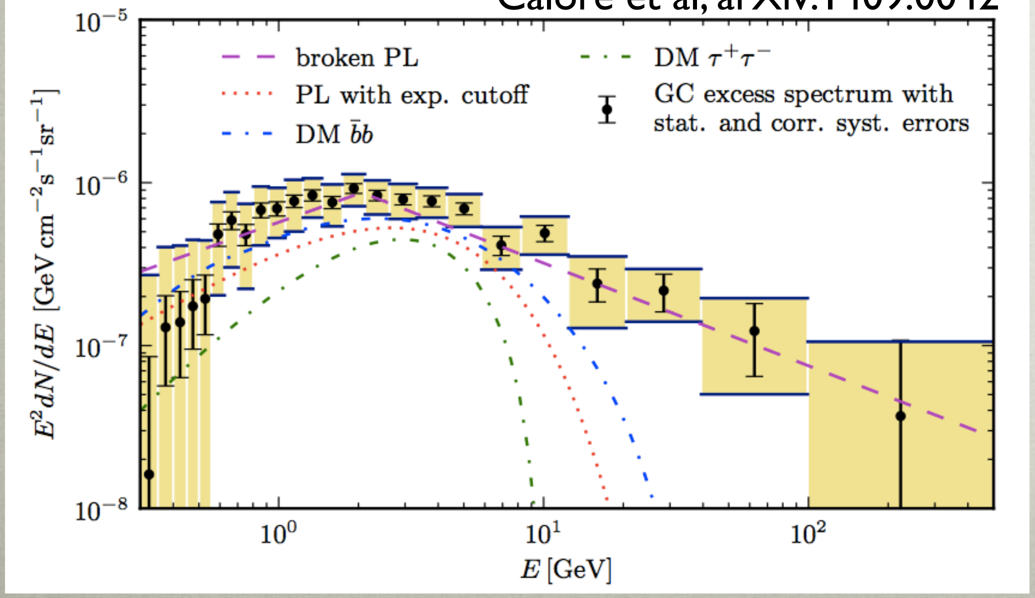
- An excess in the Fermi LAT GC data consistent with dark matter annihilation was first claimed by Goodenough and Hooper in 2009 (arXiv: 0910.2998.) Several analyses since then confirm the excess
- Different approaches in modeling the interstellar emission model:
the characterization of the signal depends on this!

Daylan et al, arXiv:1402.6703

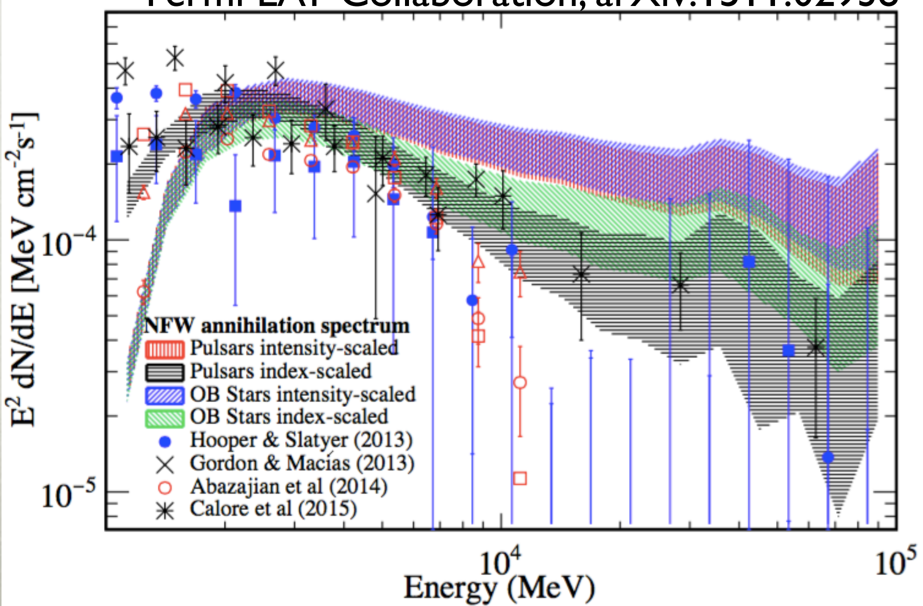


SPECTRUM

Calore et al, arXiv:1409.0042



Fermi LAT Collaboration, arXiv:1511.02938

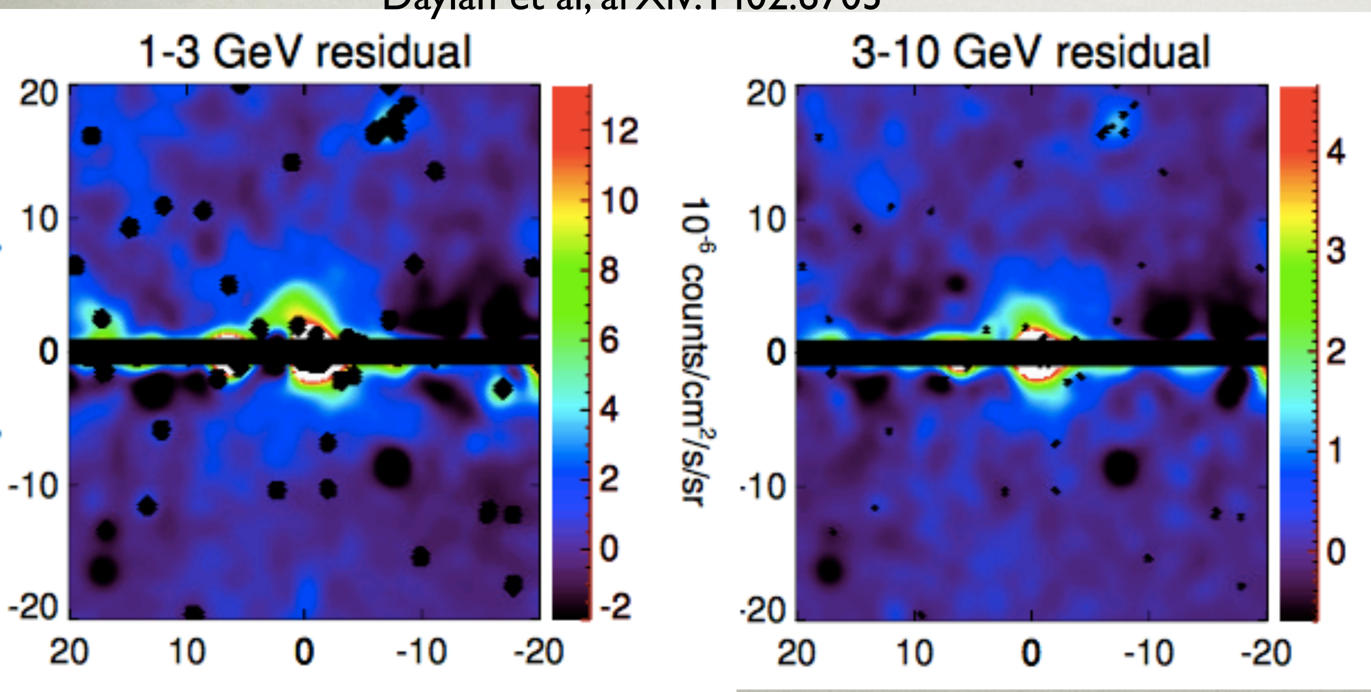


Galactic Center Excess

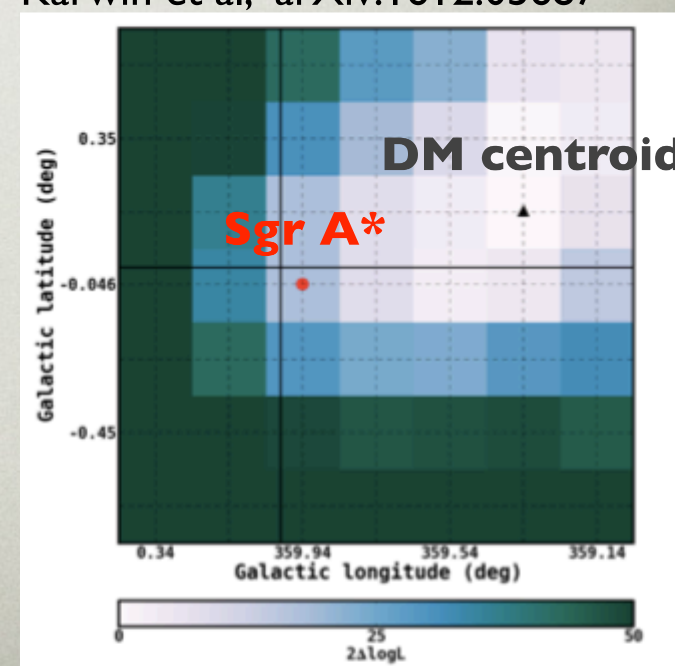
- Excess extends out to 10° from GC, approximately spherically symmetric NFW profile with slope γ=1-1.3 (but see also Linden et al arXiv:1604.01026, Horiuchi et al arXiv:1604.01402, Macias et al arXiv:1611.06644, Bartels et al arXiv: 1711.04778)
- Possibly offset from GC (Calore et al arXiv:1409.0042, Linden et al arXiv: 1604.01026, Karwin et al arXiv:1612.05687)

MORPHOLOGY

Daylan et al, arXiv:1402.6703



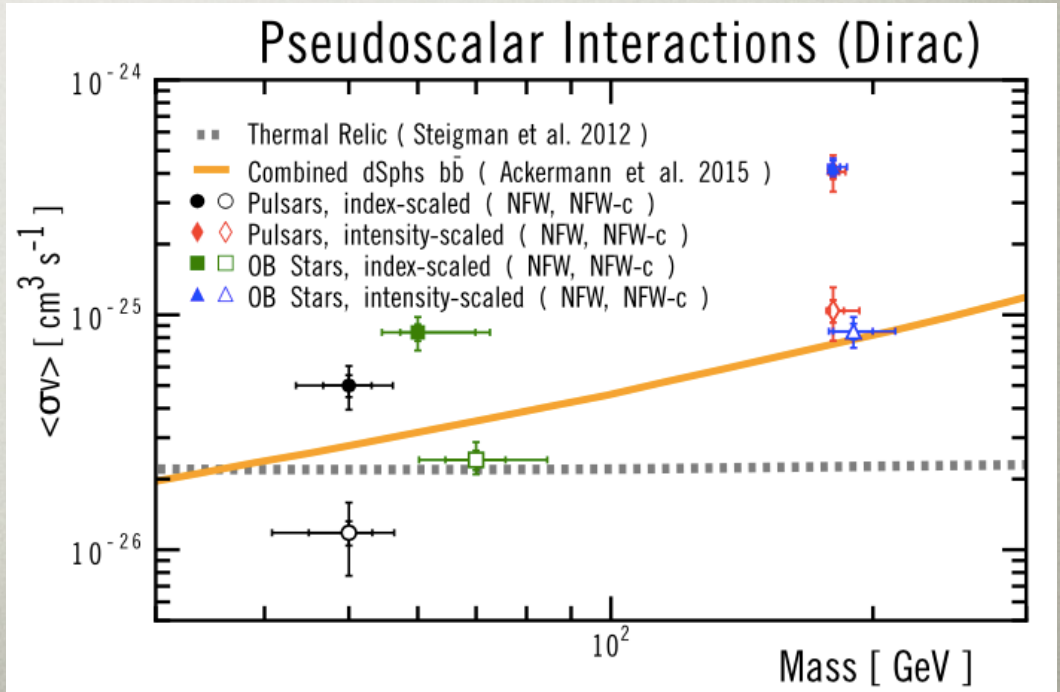
Karwin et al, arXiv:1612.05687



Implications for Dark Matter Models

- The data favor a DM particle with mass in the range ~50 (200) GeV, annihilating mainly into bottom (top) quarks with an annihilation cross section consistent with predictions for a thermal relic, ~ 10^{-26} cm^3/s (see e.g. EFT interpretation by Karwin et al arXiv:1612.05687)
- *In the framework of the MSSM, a neutralino annihilating into a pair of top quarks with DM masses above 250 GeV is favored (A. Butter et al arXiv:1612.07115). Direct detection rules out much of the lower mass range (see also Achterberg et al arXiv: 1502.05703, Bertone et al arXiv:1507.07008)*

Karwin et al, arXiv:1612.05687

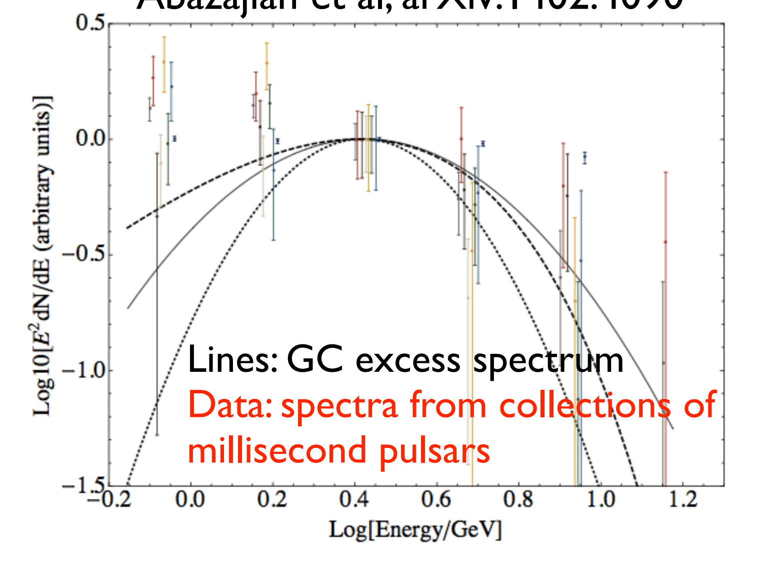


Pulsars

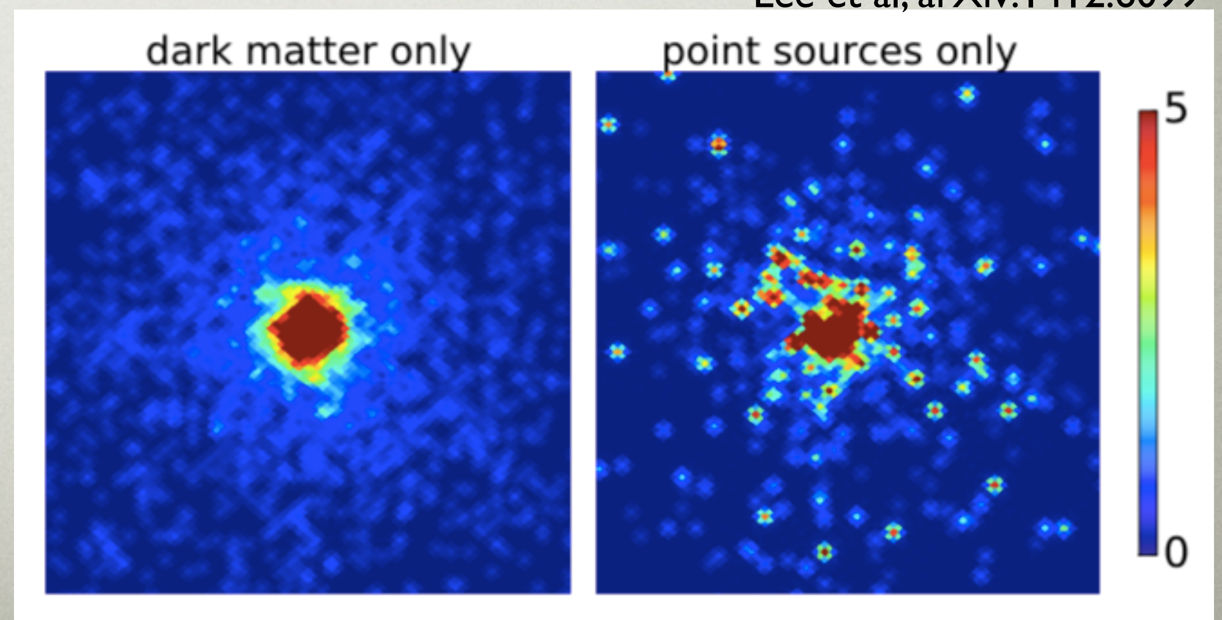
- An unresolved population of millisecond pulsars can explain the excess
  - Claimed excess is found consistent with *O(1000) millisecond pulsars* within ~1 kpc of GC (Abazajian et al arXiv:1402.4090, but see also Hooper et al arXiv:1606.09250.) Very young pulsars might also contribute to the excess (O'Leary et al arXiv:1504.02477)
  - *Spherical symmetry? Cuspy distribution? Extend out to 10^o? Possibly* (e.g. Abazajian et al arXiv: 1402.4090, Brandt et al arXiv:1507.05616)

➡Analyses based on non-poissonian photon statistics templates and wavelet decomposition (Lee et al arXiv:1412.6099, 1506.05124; Bartels et al arXiv:1506.05104) find that the **excess is consistent with a collection of discrete gamma-ray emitters**

Abazajian et al, arXiv:1402.4090

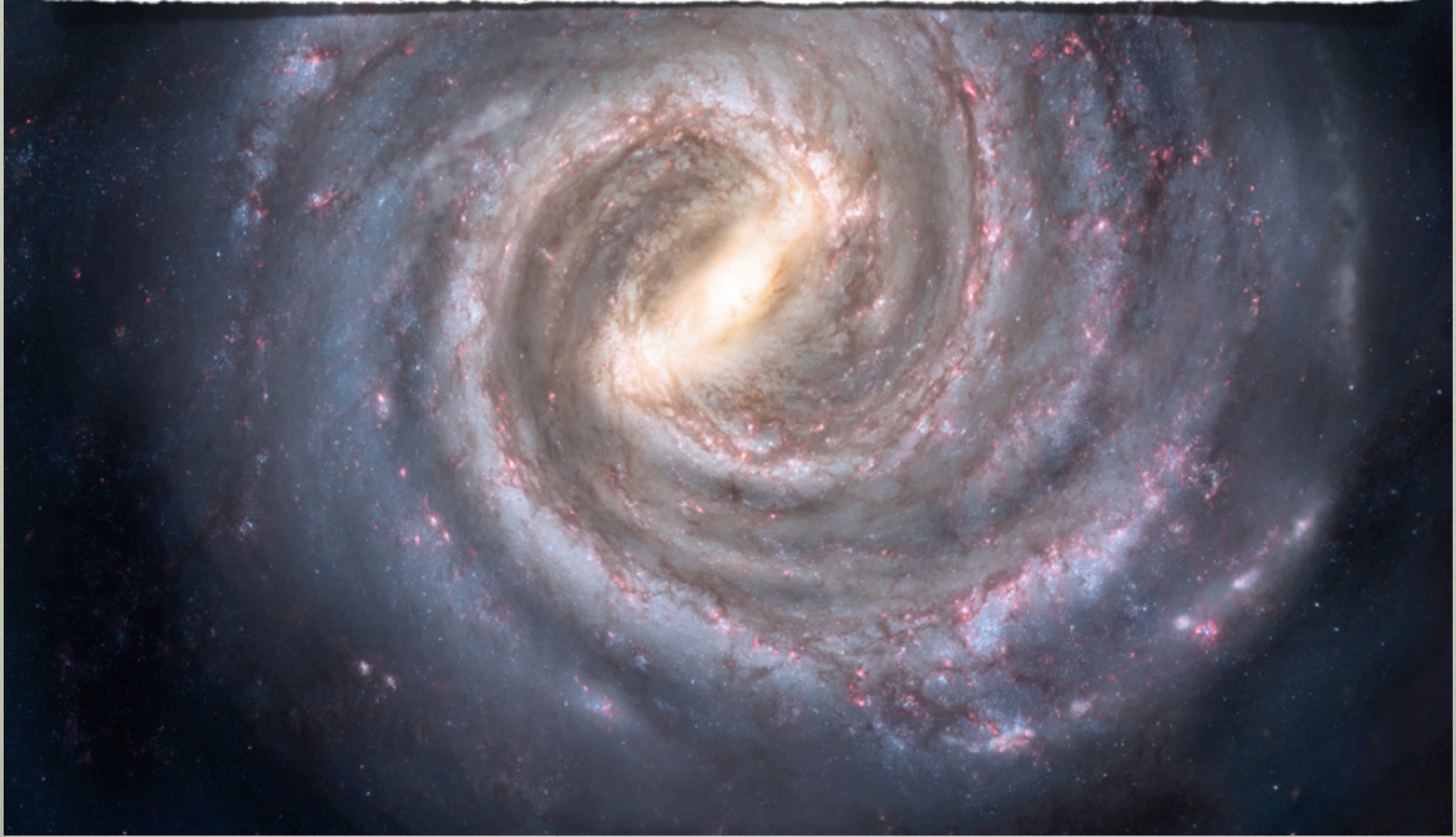


Lee et al, arXiv:1412.6099



- ✦ There are limitations in all interstellar emission models employed so far (e.g., cylindrical symmetry, the gas distribution, as well as interplay between the interstellar emission and point sources)

➡ Work is underway to improve these models

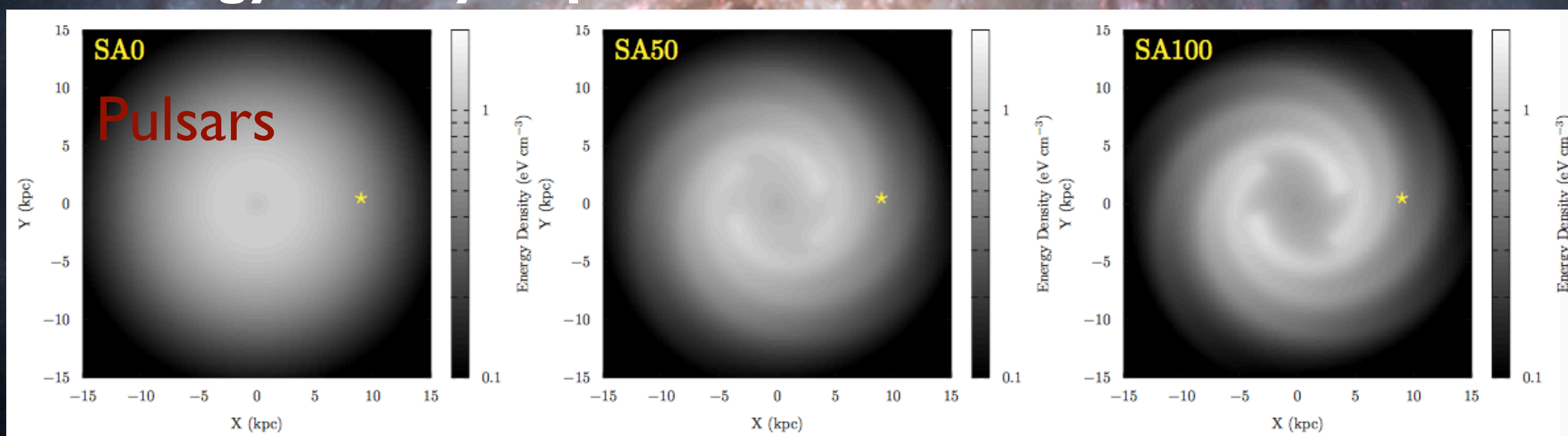


✦ There are limitations in all interstellar emission models employed so far (e.g., cylindrical symmetry, the gas distribution, as well as interplay between the interstellar emission and point sources)

➡ Work is underway to improve these models

CR energy density at plane

Porter et al, arXiv:1708.00816

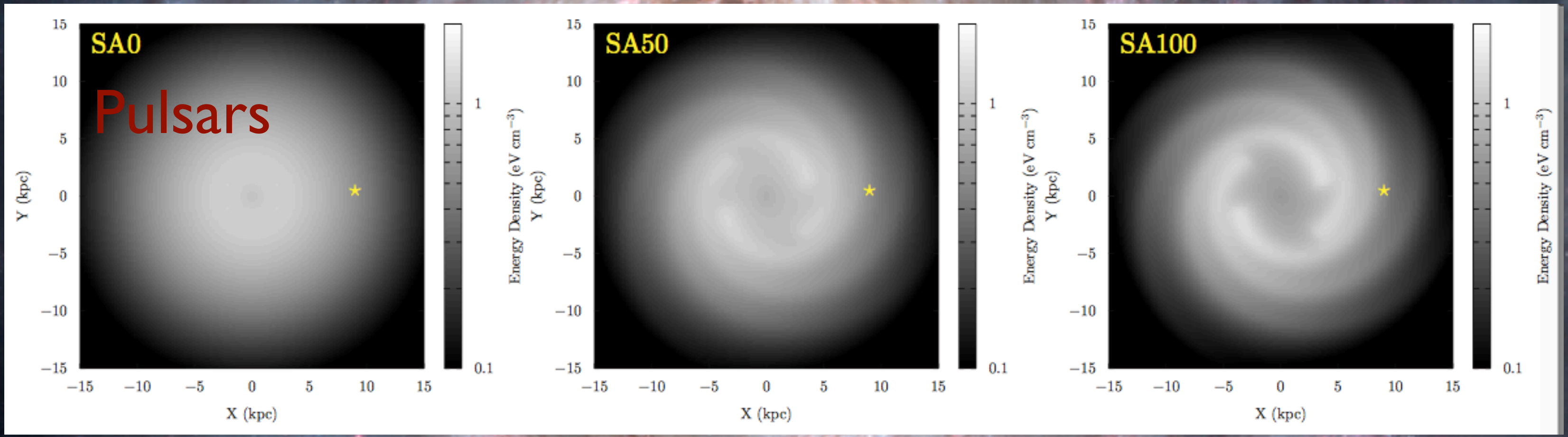


✦ There are limitations in all interstellar emission models employed so far (e.g., cylindrical symmetry, the gas distribution, as well as interplay between the interstellar emission and point sources)

➡ Work is underway to improve these models

CR energy density at plane

Porter et al, arXiv:1708.00816



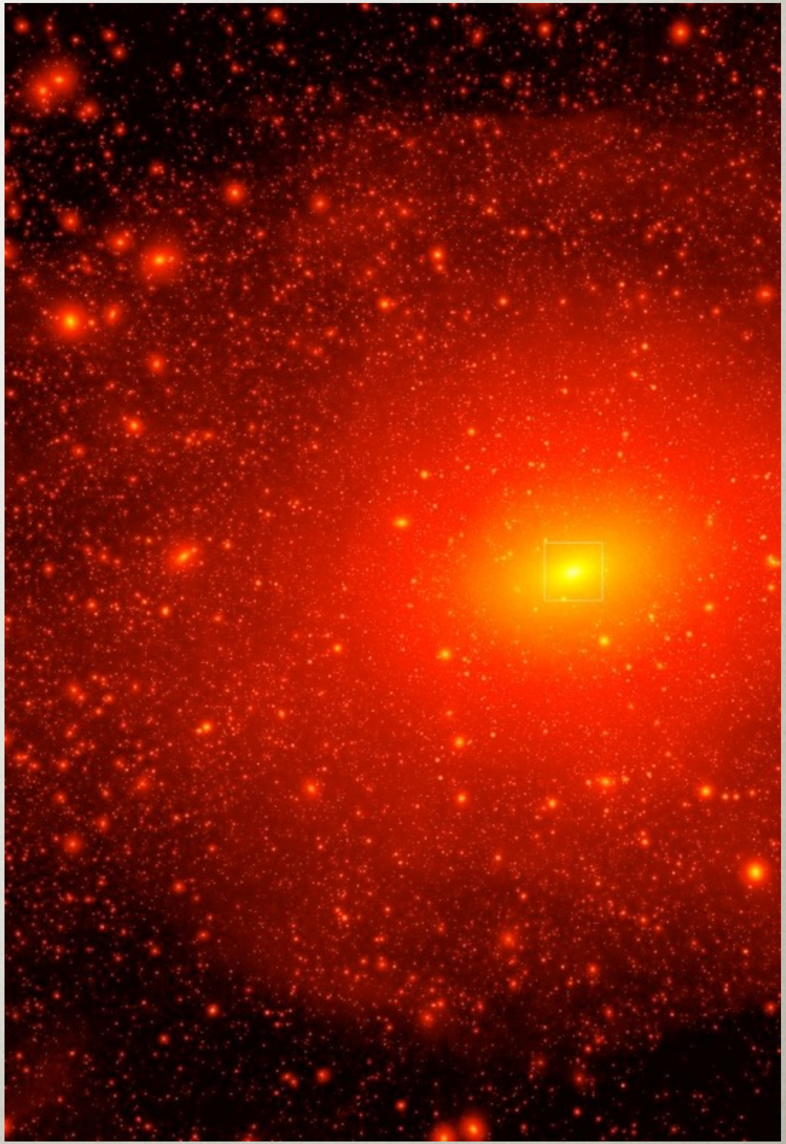
✦ The GC excess is a small fraction of the total observed emission (e.g. ~5-10% in a 15°x15° region)

➡ Improvements in modeling the interstellar emission are crucial to determine/confirm the properties of the excess!

Dwarf Spheroidal Galaxies

- Optically observed dwarf spheroidal galaxies: largest clumps predicted by N-body simulations

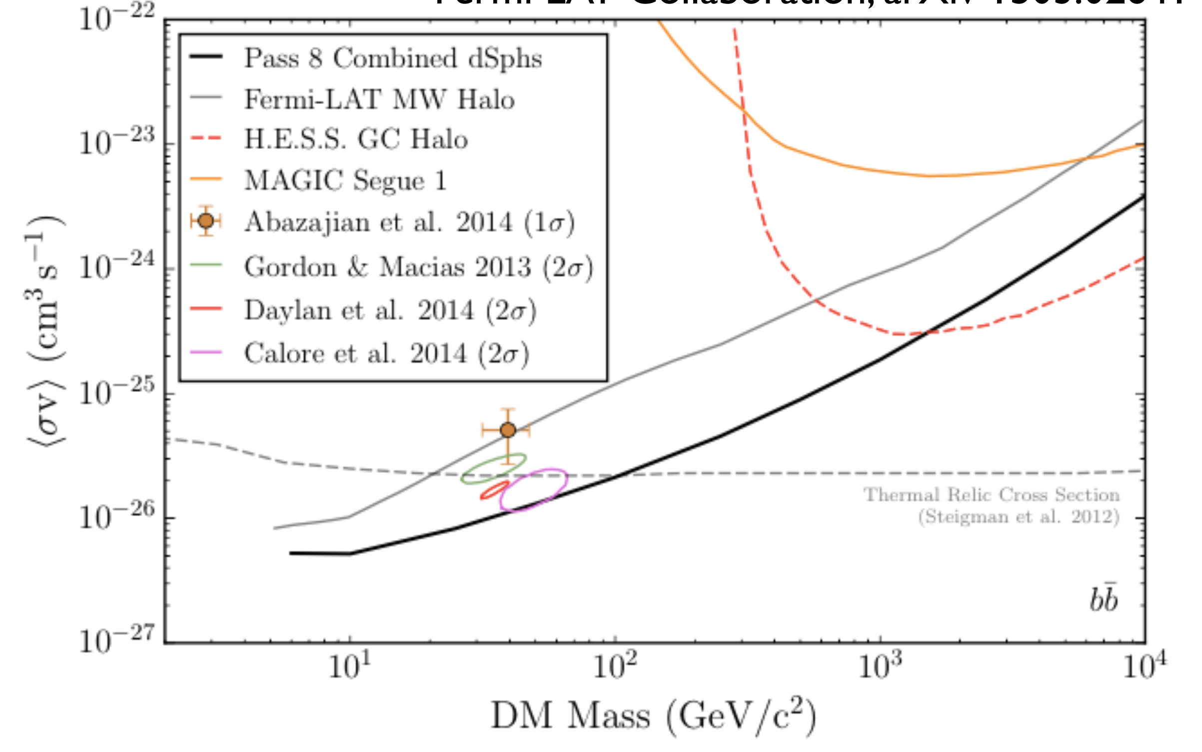
- Excellent targets for gamma-ray DM searches
  - Very large M/L ratio: 10 to ~> 1000 (M/L ~10 for Milky Way)
  - DM density inferred from the stellar data!
  - Expected to be free from other gamma ray sources and have low dust/gas content, very few stars



Dwarf Spheroidal Galaxies

- No significant emission in stacked analysis of dwarf spheroidal galaxies with Fermi LAT 6 yrs of data (Fermi LAT Collaboration arXiv 1503.02641, Albert et al arXiv:1611.03184)
- Limits probe DM explanation of the GC excess

Fermi LAT Collaboration, arXiv 1503.02641



Dwarf Spheroidal Galaxies

- No significant emission in stacked analysis of dwarf spheroidal galaxies with Fermi LAT 6 yrs of data (Fermi LAT Collaboration arXiv 1503.02641, Albert et al arXiv:1611.03184)
- Limits probe DM explanation of the GC excess

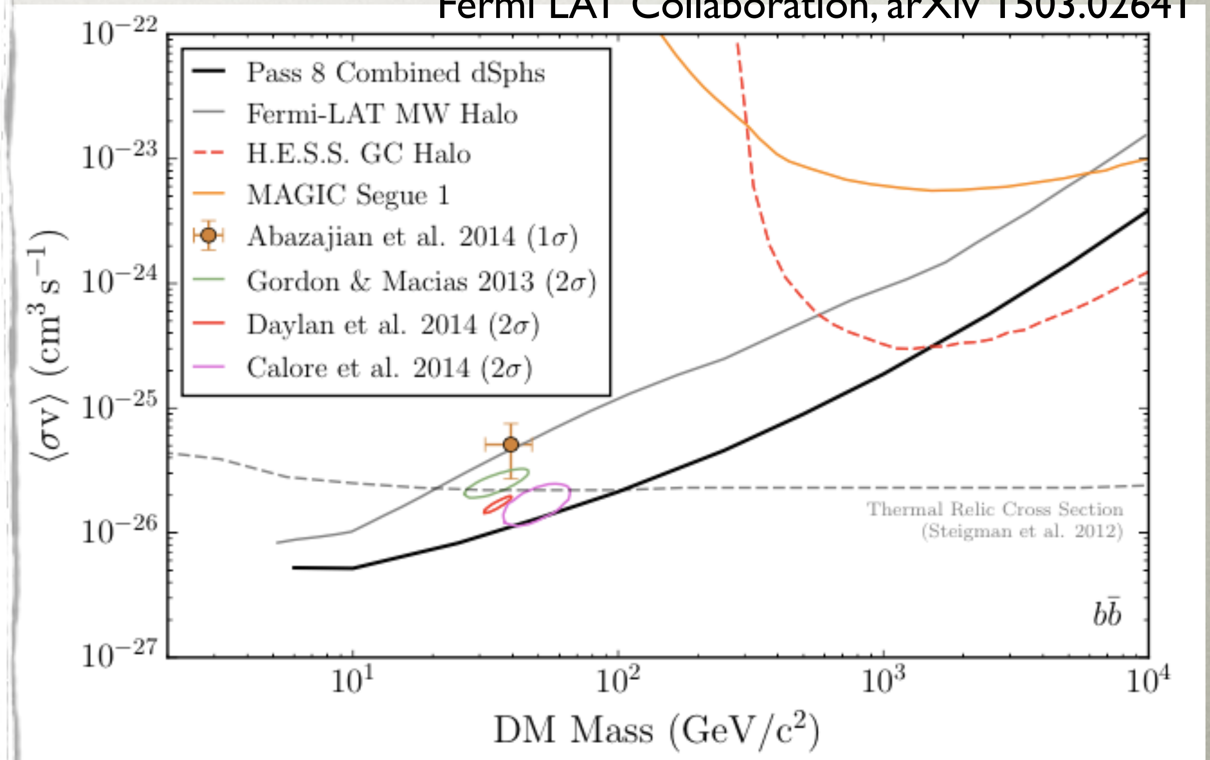
N.B.:

Uncertainties in the astrophysical background model also allow for a broader range of DM masses and annihilation channels (see e.g. Agrawal et al, arXiv:1411.2592, Karwin et al arXiv:1612.05687)

Non-spherical DM halos weaken dSph limits by ~2x (see e.g. Hayashi et al, arXiv:1603.08046, Klop et al, arXiv:1609.03509).

GC excess contours do not fully reflect uncertainties in the DM distribution (also see Abazajian et al, arXiv:1510.06424, Benito et al arXiv:1612.02010)

Fermi LAT Collaboration, arXiv 1503.02641



Dwarf Spheroidal Galaxies

- No significant emission in stacked analysis of dwarf spheroidal galaxies with Fermi LAT 6 yrs of data (Fermi LAT Collaboration arXiv 1503.02641, Albert et al arXiv:1611.03184)
- Limits probe DM explanation of the GC excess

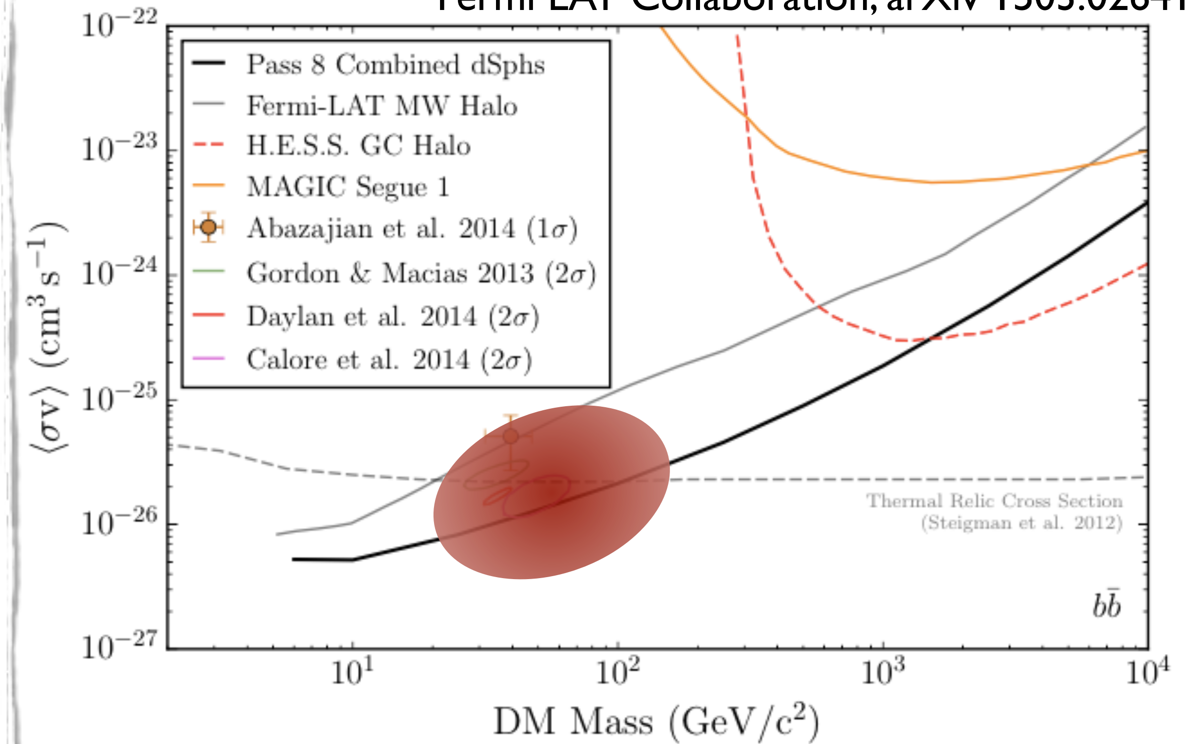
N.B.:

Uncertainties in the astrophysical background model also allow for a broader range of DM masses and annihilation channels (see e.g. Agrawal et al, arXiv:1411.2592, Karwin et al arXiv:1612.05687)

Non-spherical DM halos weaken dSph limits by ~2x (see e.g. Hayashi et al, arXiv:1603.08046, Klop et al, arXiv:1609.03509).

GC excess contours do not fully reflect uncertainties in the DM distribution (also see Abazajian et al, arXiv:1510.06424, Benito et al arXiv:1612.02010)

Fermi LAT Collaboration, arXiv 1503.02641



Dwarf Spheroidal Galaxies

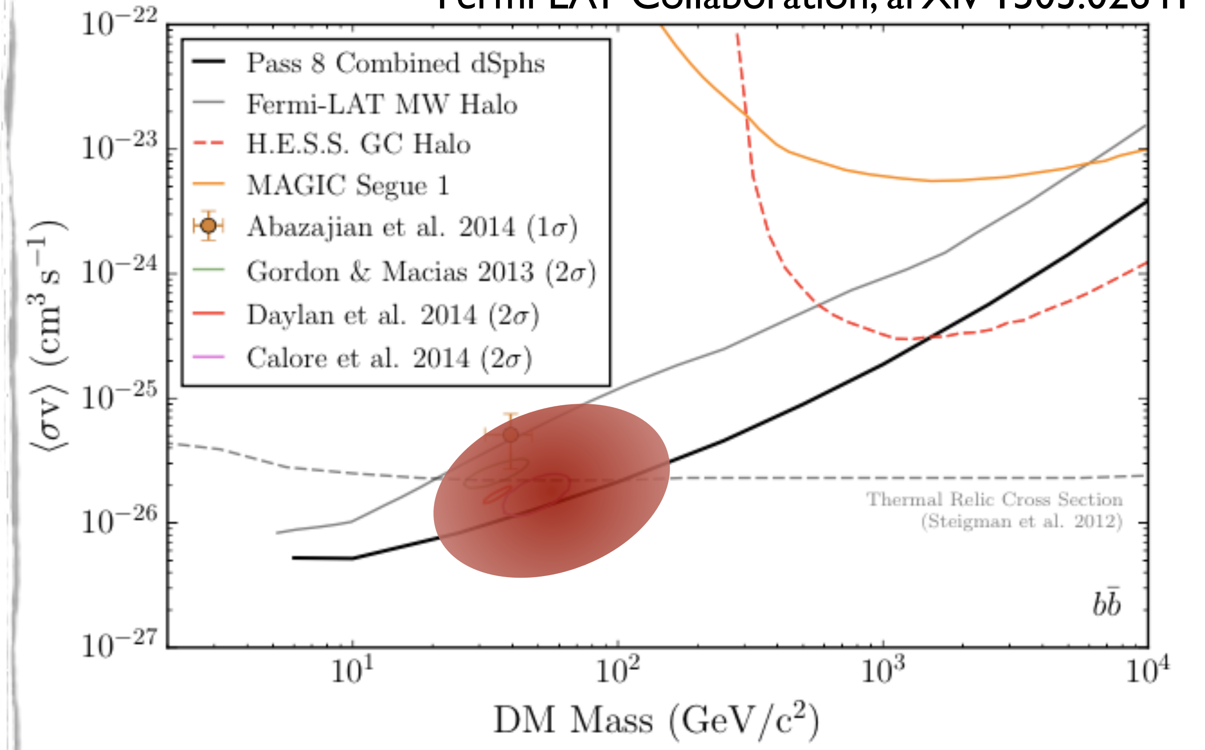
- No significant emission in stacked analysis of dwarf spheroidal galaxies with Fermi LAT 6 yrs of data (Fermi LAT Collaboration arXiv 1503.02641, Albert et al arXiv:1611.03184)
- Limits probe DM explanation of the GC excess
- (<3σ excesses in Reticulum II and Tucana III, spectrum and <σv> compatible with GC excess, Geringer-Sameth et al arXiv:1503.02320, Albert et al arXiv:1611.03184)

N.B.:
Uncertainties in the astrophysical background model also allow for a broader range of DM masses and annihilation channels (see e.g. Agrawal et al, arXiv:1411.2592, Karwin et al arXiv:1612.05687)

Non-spherical DM halos weaken dSph limits by ~2x (see e.g. Hayashi et al, arXiv:1603.08046, Klop et al, arXiv:1609.03509).

GC excess contours do not fully reflect uncertainties in the DM distribution (also see Abazajian et al, arXiv:1510.06424, Benito et al arXiv:1612.02010)

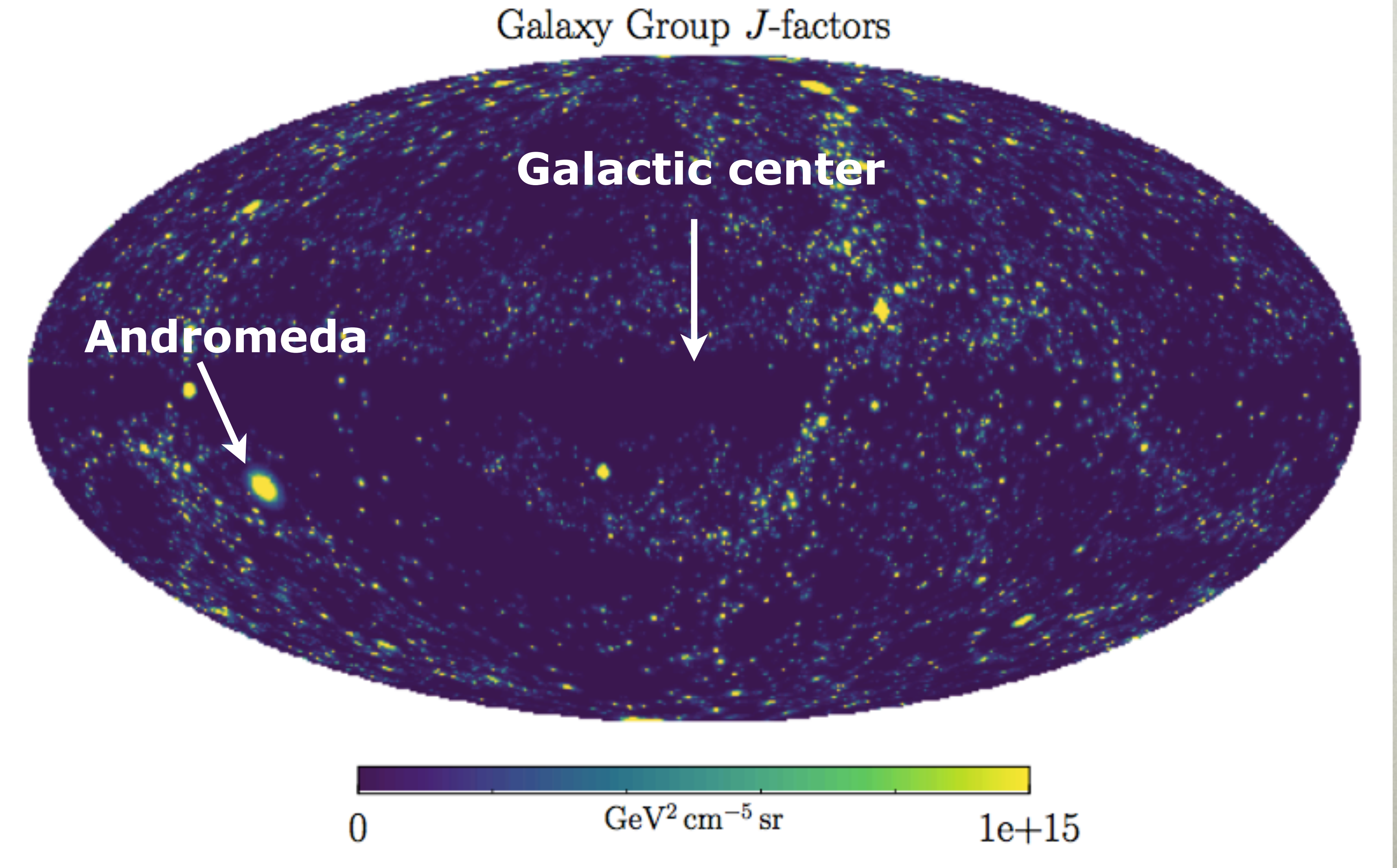
Fermi LAT Collaboration, arXiv 1503.02641



Gamma rays from Dark Matter Annihilation:

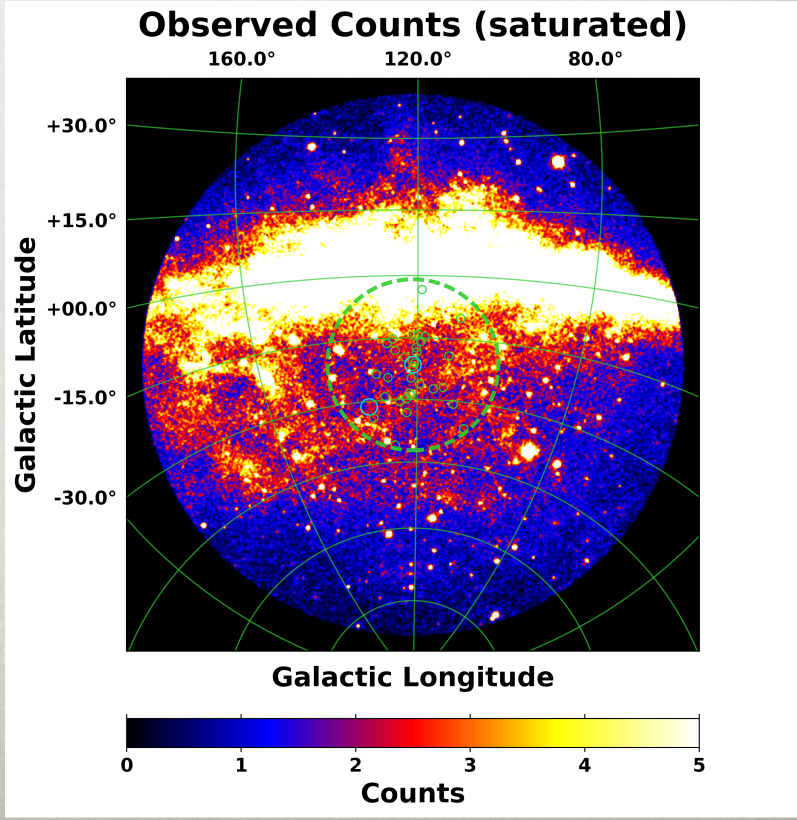
Beyond the Milky Way

Lisanti et al, arXiv1708.09385



Andromeda (M31)

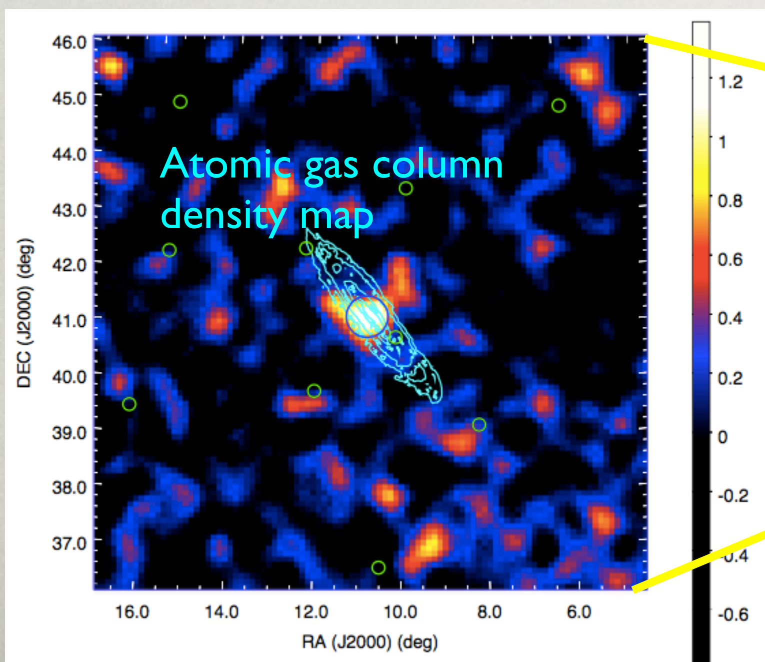
- DM halo extends several degrees across the sky, with a gradient strongly dependent on DM distribution, substructures and profile.
- Disentangling a DM contribution from M31 is complicated by conventional astrophysics, including the foreground from the Milky Way.



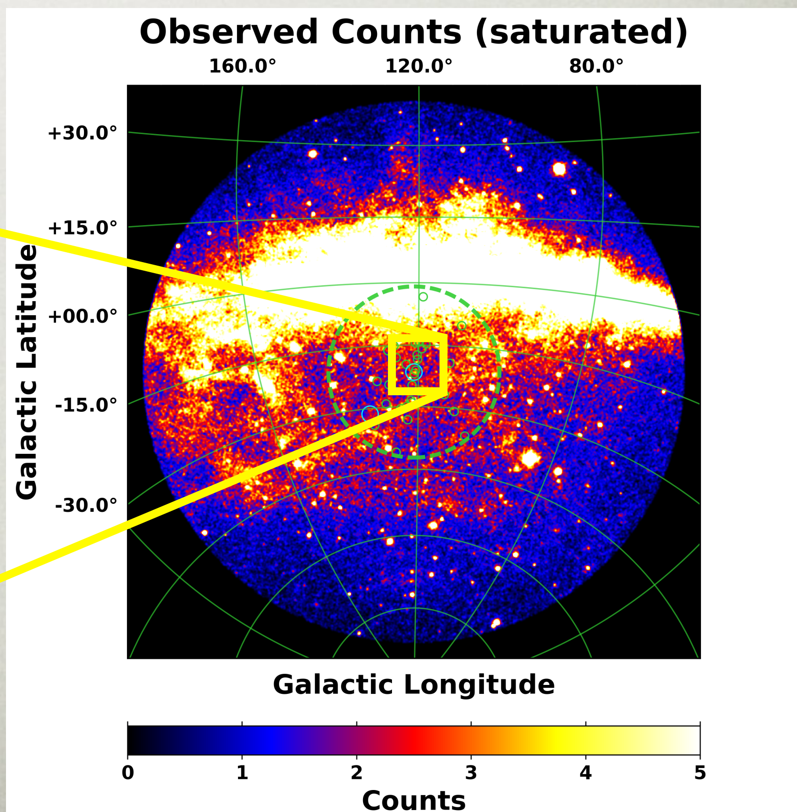
Karwin et al, in prep

Andromeda (M31)

- DM halo extends several degrees across the sky, with a gradient strongly dependent on DM distribution, substructures and profile.
- Disentangling a DM contribution from M31 is complicated by conventional astrophysics, including the foreground from the Milky Way.
- Evidence of a spherical γ-ray halo around M31, ~1° across (Pshirkov et al PoS ICRC2015 867, Fermi LAT Collaboration arXiv:1702.08602) not correlated with regions rich in gas or star formation activity



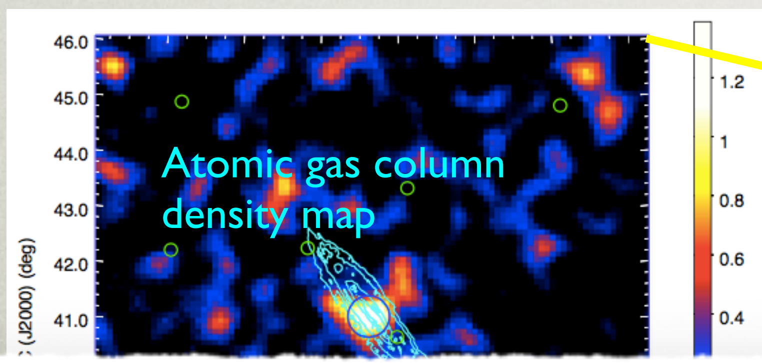
Fermi LAT arXiv:1702.08602



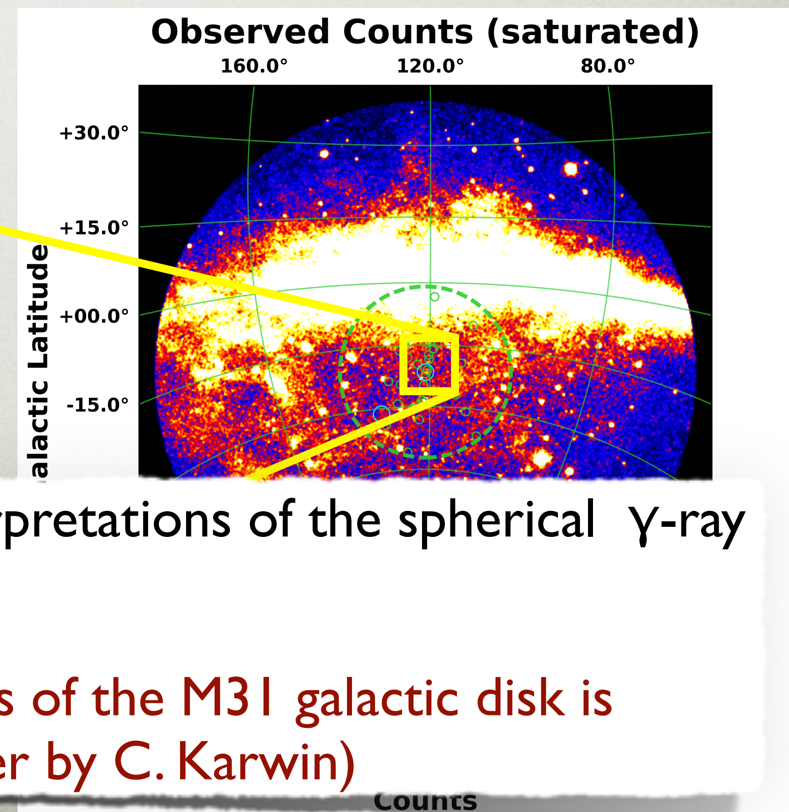
Karwin et al, in prep

Andromeda (M31)

- DM halo extends several degrees across the sky, with a gradient strongly dependent on DM distribution, substructures and profile.
- Disentangling a DM contribution from M31 is complicated by conventional astrophysics, including the foreground from the Milky Way.
- Evidence of a spherical γ-ray halo around M31, ~1° across (Pshirkov et al PoS ICRC2015 867, Fermi LAT Collaboration arXiv:1702.08602) not correlated with regions rich in gas or star formation activity



Fermi LAT arX



Karwin et al, in prep

DM and/or millisecond pulsars are possible interpretations of the spherical γ-ray halo, also compatible with GC excess

Search for γ-ray emission beyond the boundaries of the M31 galactic disk is complicated by Milky Way foreground (see poster by C. Karwin)

Beyond the Local Group

- A stacked analysis of ~500 galaxy groups ($z< 0.03$, $M \gtrsim 10^{12}\ M_{\odot}$) from recent catalogs shows no evidence for a DM signal and set constraints comparable to the dwarf spheroidals
- J-factors inferred by luminosity-based mass estimates and mass-to-concentration relations

Lisanti et al, arXiv1708.09385