Indirect Searches for Dark Matter with Gamma rays and Other Messengers

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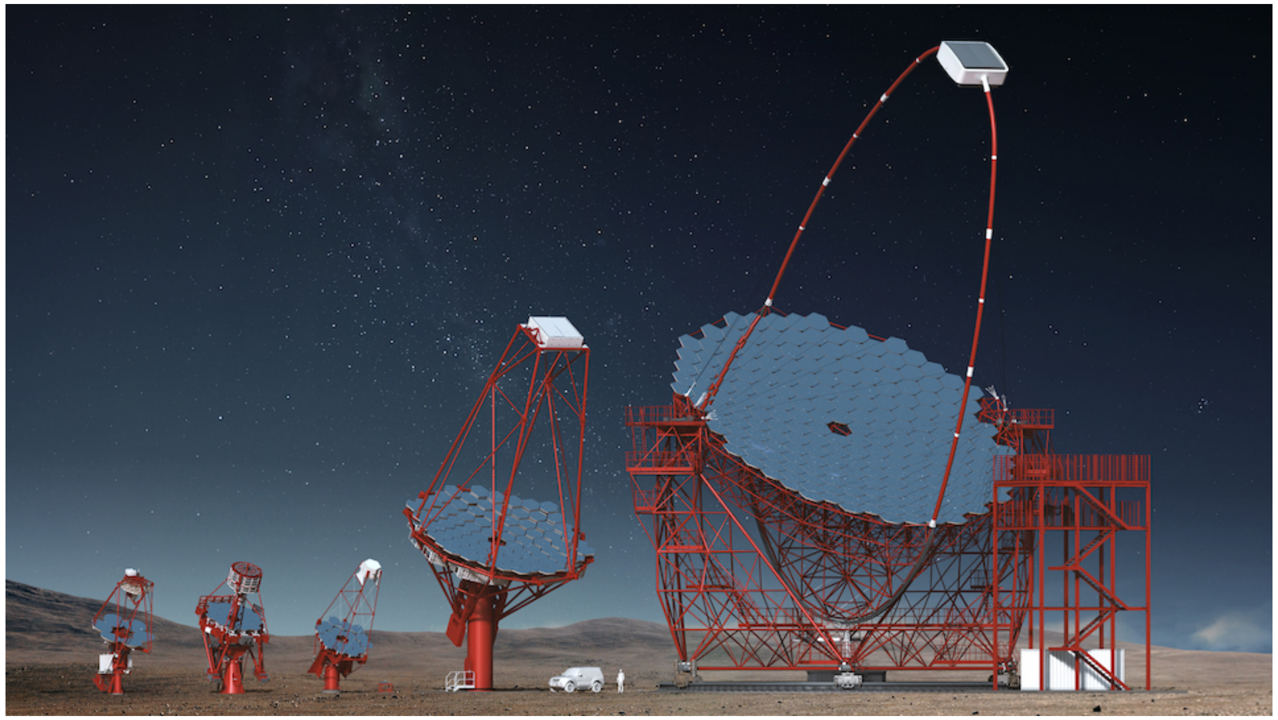


Fermi

Institute for
Space-Earth Environmental Research

February 28 – March 2, 2018
KMI School on “Dark Matter”
Nagoya University, Japan

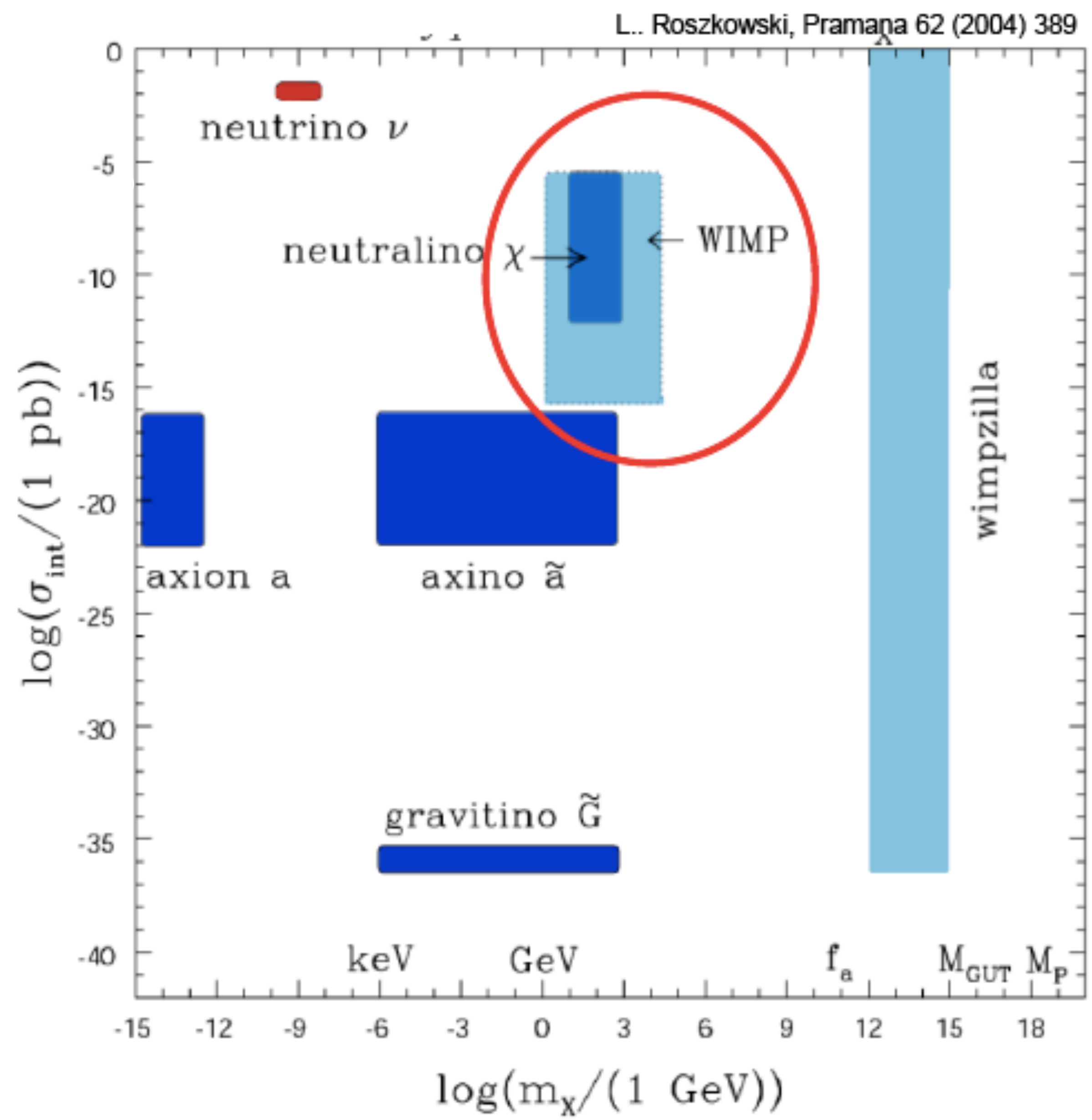
Outline

- Introduction
- Dark matter searches with charged cosmic rays
- Dark matter searches with GeV gamma rays
  - “Galactic Center Excess”
  - Dwarf Spheroidal
- Dark matter search with TeV gamma rays
- Future prospects

Dark Matter

- What we know
  - Dark matter exists
    - Orbital velocities of stars in galaxies, velocity dispersions of galaxies in clusters, temperature distribution of hot gas in clusters of galaxies and gravitational lensing
  - Non-relativistic ("cold dark matter")
  - ~6 x ordinary matter
- What we don't know
  - What is dark matter?
    - MACHO: constrained by micro-lensing
    - WIMP
      - Weak scale new particles happen to have suitable mass and cross-section

        WIMP miracle
    - Axion



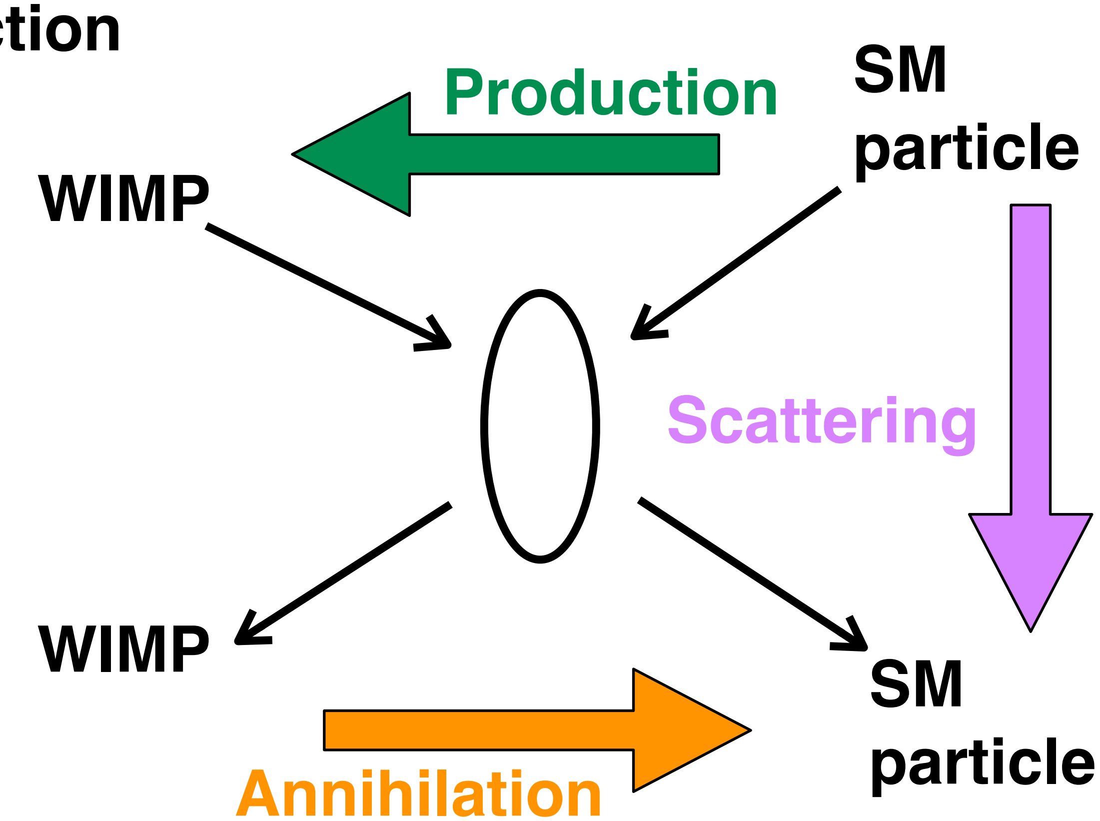
WIMP Search Approaches

- **Accelerator production**
  - **Exhaustive searches can be made for specific mode and mass range as far as WIMP has coupling to quarks**
  - **Mass reach is heavily model dependent**
- **Direct detection of WIMP scattering**
  - **Wide mass coverage**
  - **Sensitivity limit due to neutrino backgrounds**
- **Indirect detection of WIMP annihilation**
  - **"Direct" constraints on annihilation cross section**
  - **Sensitivity is less model dependent**
  - **Large systematics due to astrophysics**

particle physics

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\varphi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_{ann} v\rangle}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f \times \int_{\Delta\Omega\,(\varphi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\varphi'))\,dl(r,\varphi')$$

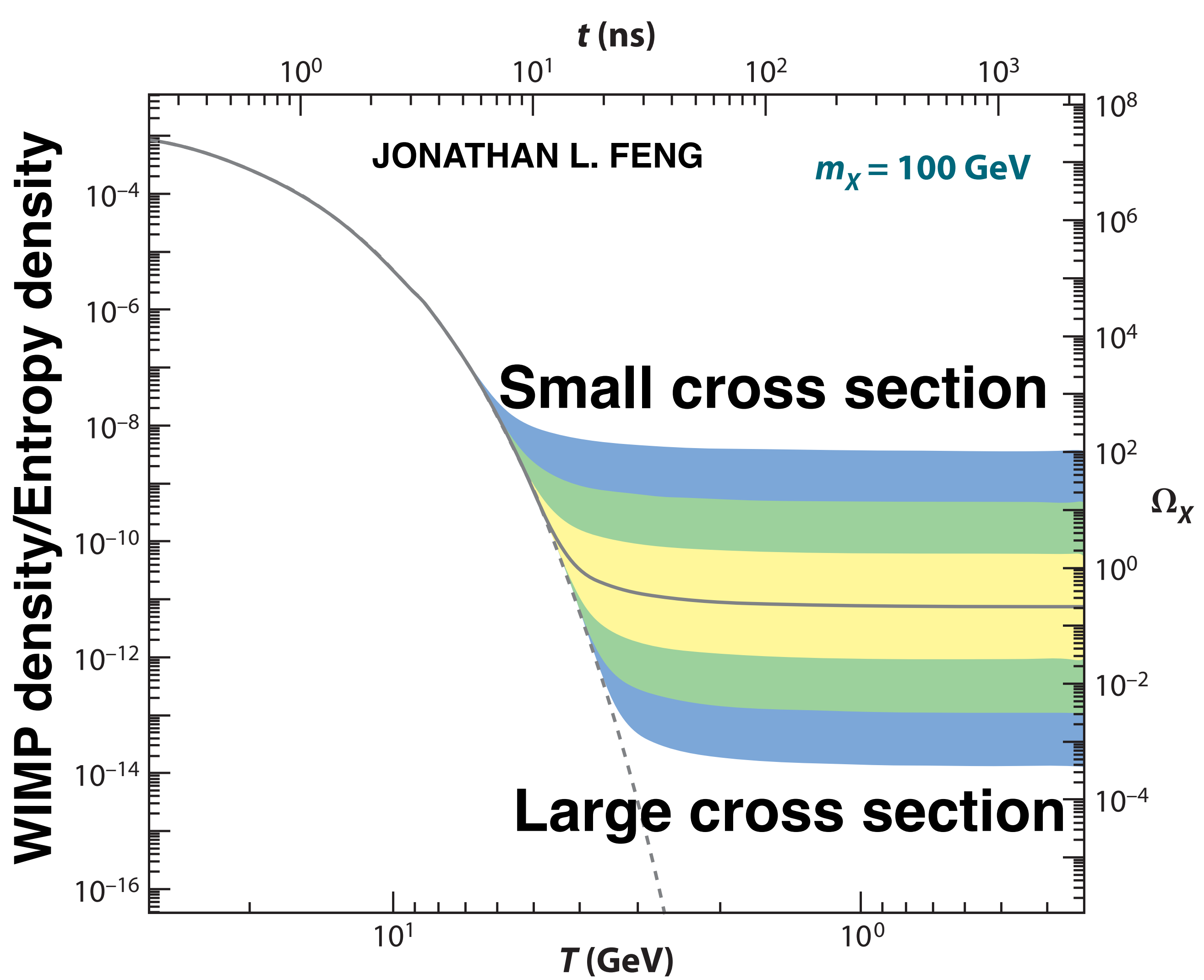
DM distribution



- **Those approaches are complimentary**
  - **Different model dependences and sensitivity phase space**

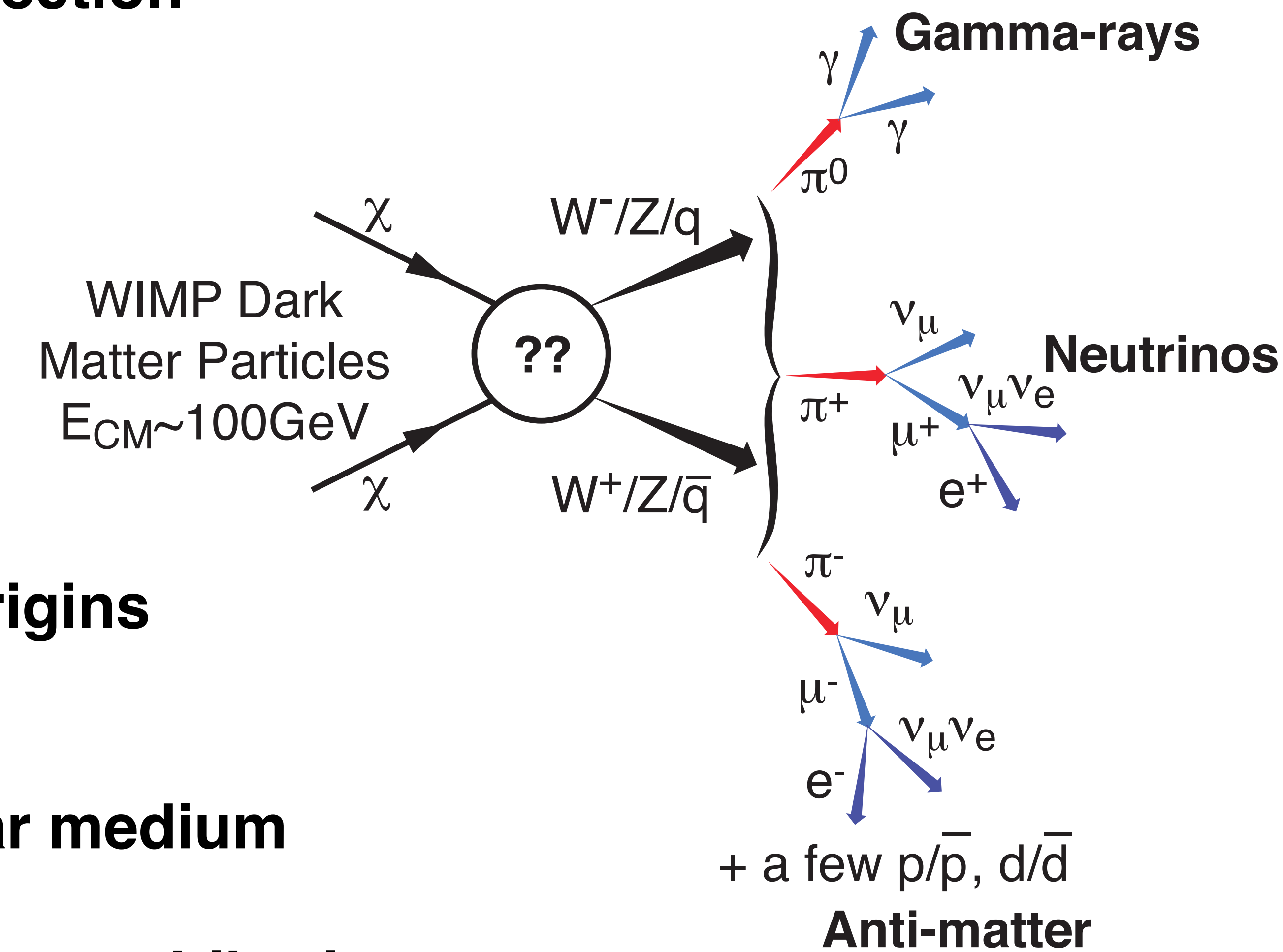
Thermal Relic Dark Matter (WIMP)

- WIMP is in equilibrium between pair creation and annihilation in early Universe
  - Pair creation stops when thermal energy is not sufficient
  - Annihilation continues and WIMP density become too low compared with annihilation cross section
    - WIMP density and annihilation cross section is anti-correlated
  - Current dark matter density (Ω_{DM}) constrains annihilation cross section to ~3×10^{-26} cm^2/s
- Indirect searches are sensitive to WIMP annihilation cross section



Indirect Searches for Dark Matter

- Dark Matter Searches with Charged Cosmic Rays
  - Anti-particles are in general secondary particles from interactions of cosmic rays with interstellar gas
  - Dark matter annihilations and decays can produce more or less equal amount of particles and anti-particles in energies close to DM mass
  - Anti-particle spectra from DM tend to have bump structures which tend to be different from spectra for secondary particles Cosmic ray
  - Weak constraints on annihilation cross section

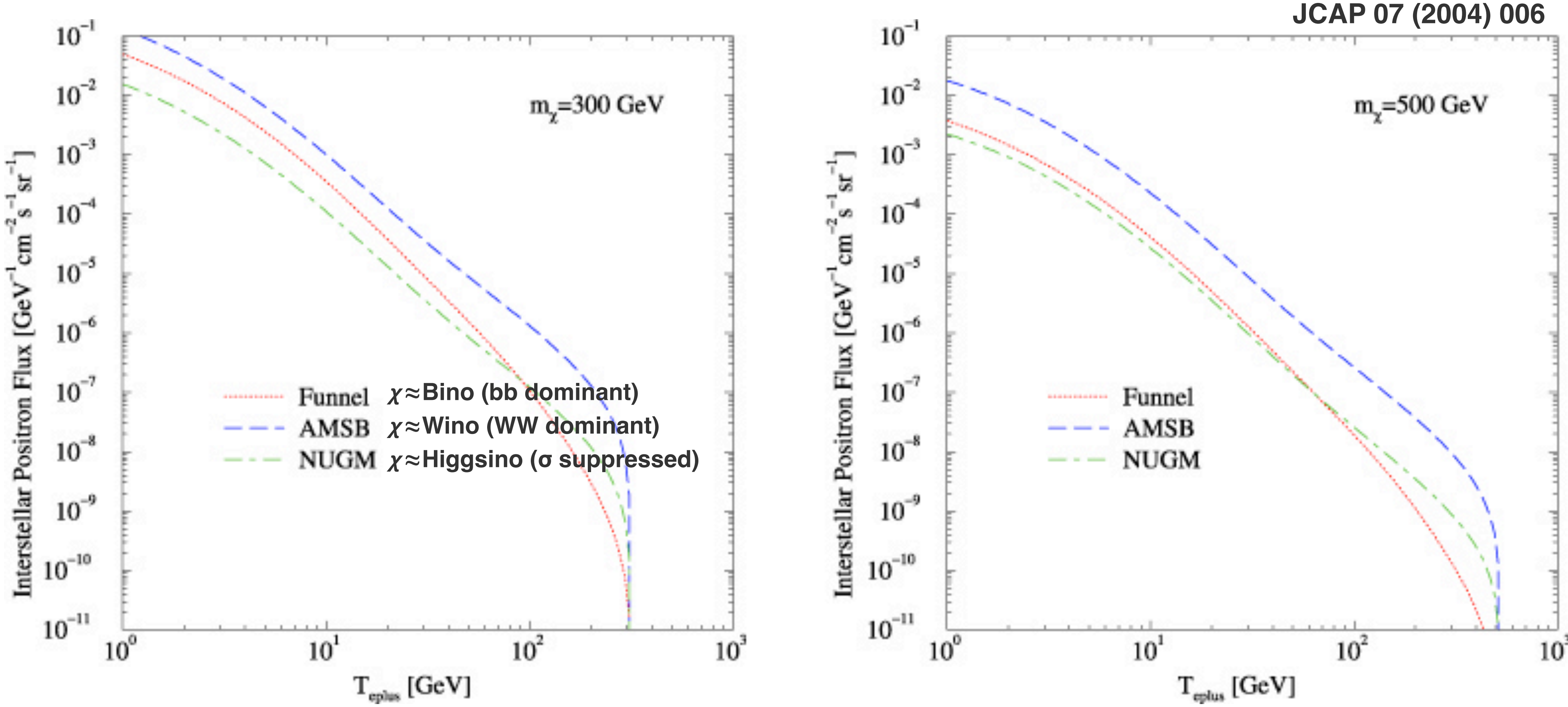


- Dark Matter Searches with Gamma rays
  - Gamma rays can be used to locate the origins and image their shapes
  - Backgrounds
    - Cosmic-ray interactions with interstellar medium
    - Gamma-ray astronomical objects
      - Supernova remnants, pulsars, gamma-ray bibaries,

DM Searches with Positrons

- Positrons can be produced directly by DM interactions (annihilations and/or decays)
  - Positrons can also be produced via π^+, τ^+ and μ^+ from DM interactions
  - Positron spectra depend on mass and properties of DM
- Pulsars can also produce positrons with bump spectra
  - Spectra depends on number of nearby (<500 pc) pulsars (in particular, at high energy end) and spectra at the origins
  - Dipole anisotropy is expected for nearby pulsars

JCAP 07 (2004) 006



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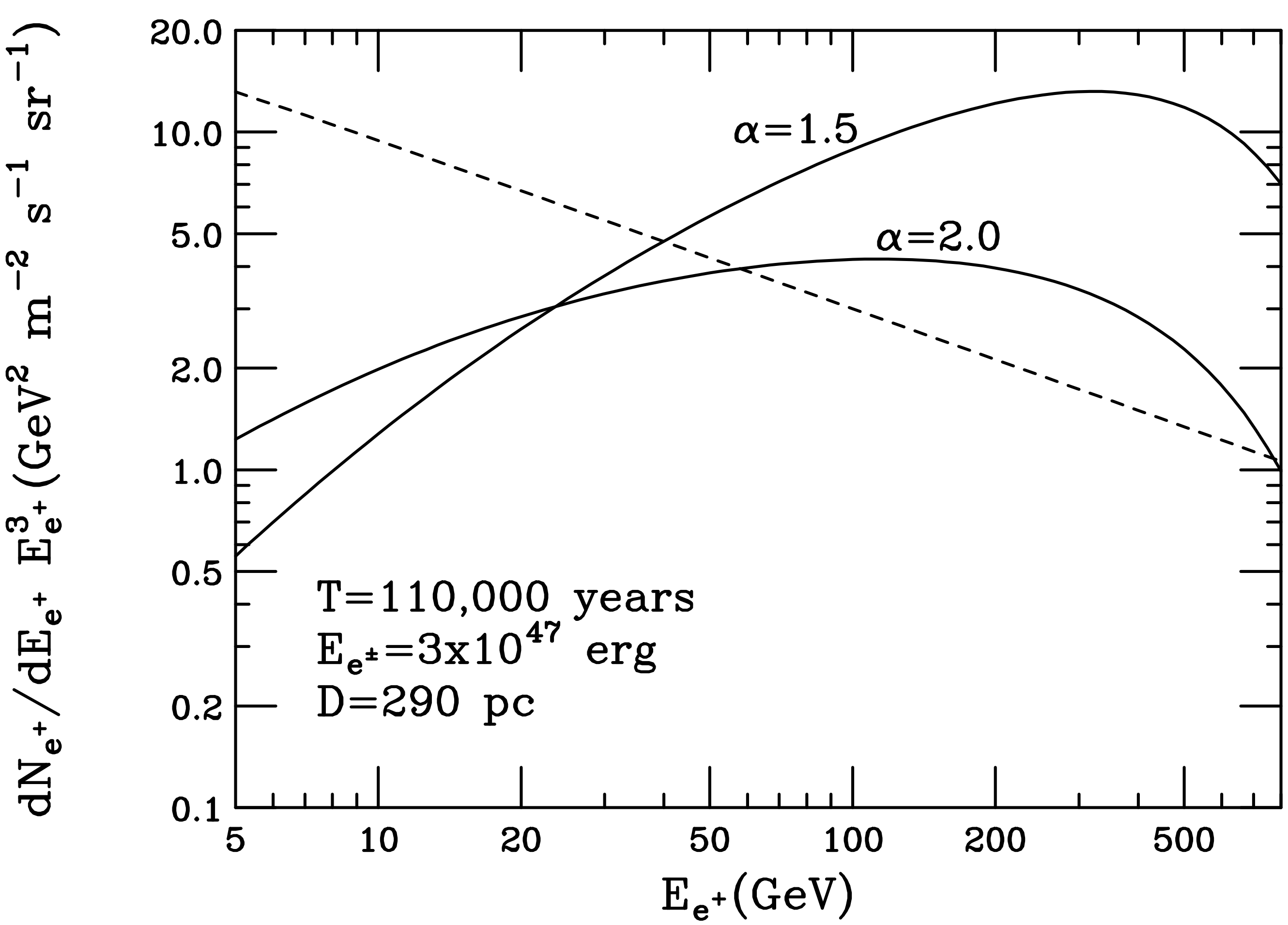
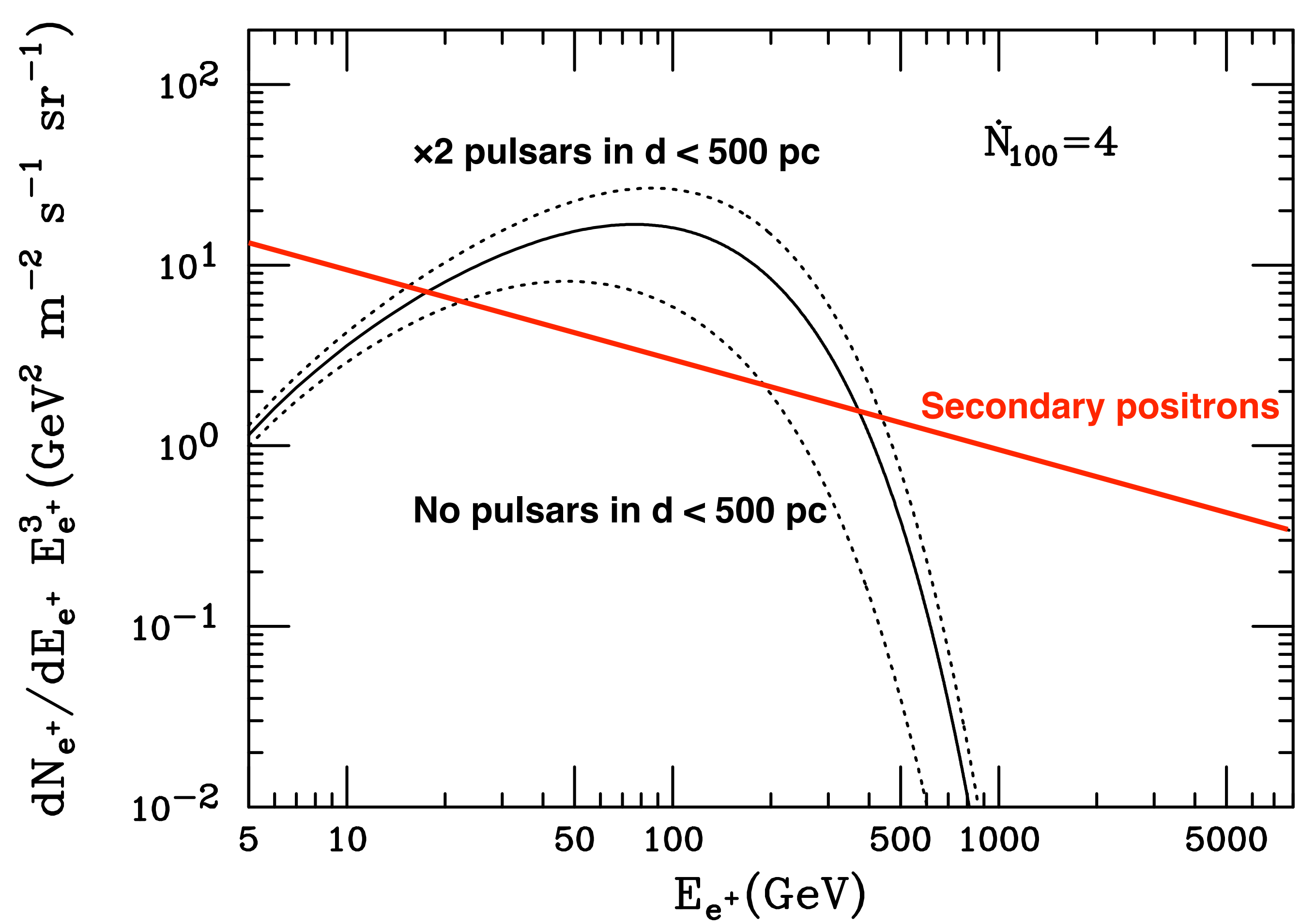
JCAP 0901:025,2009





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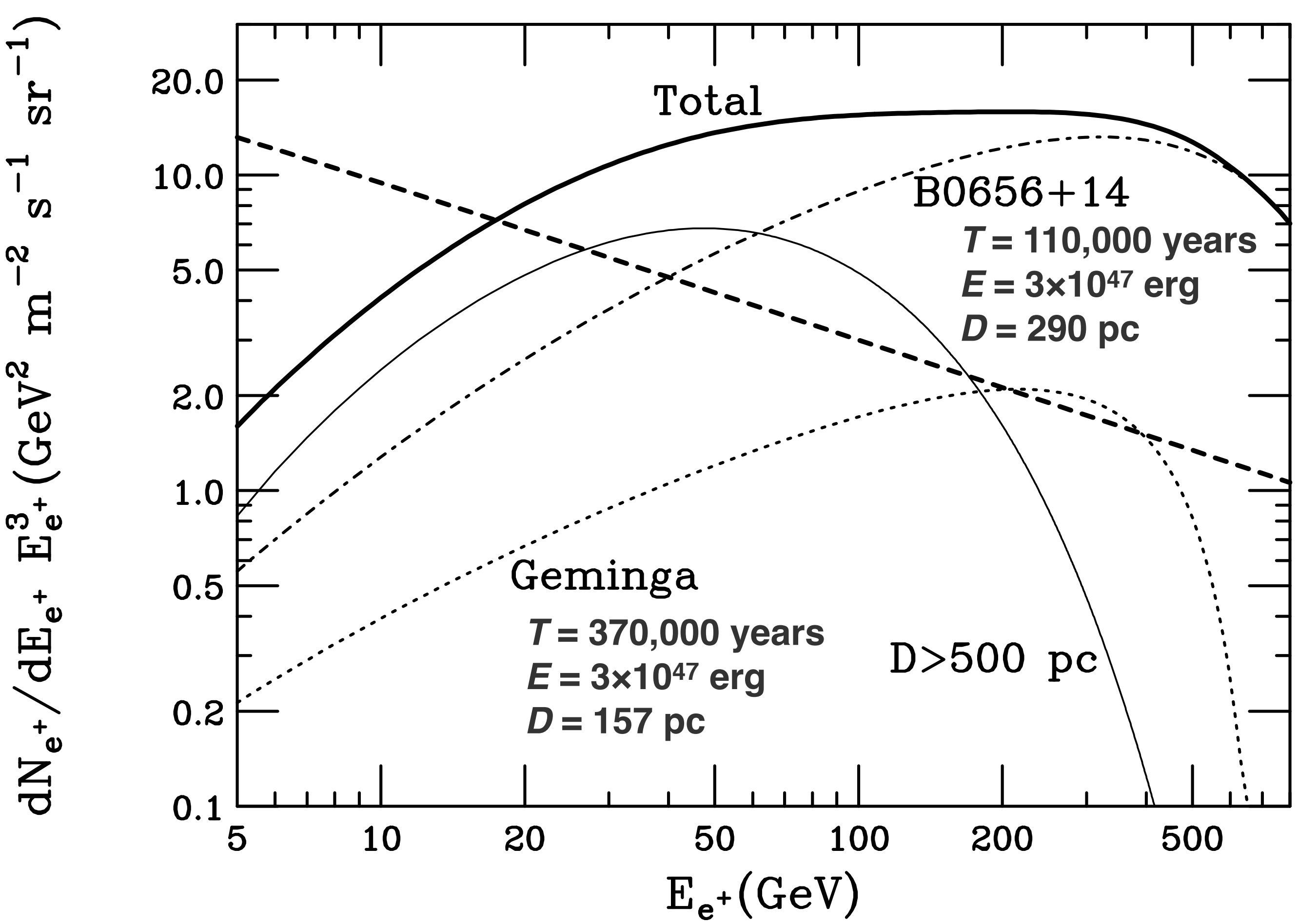
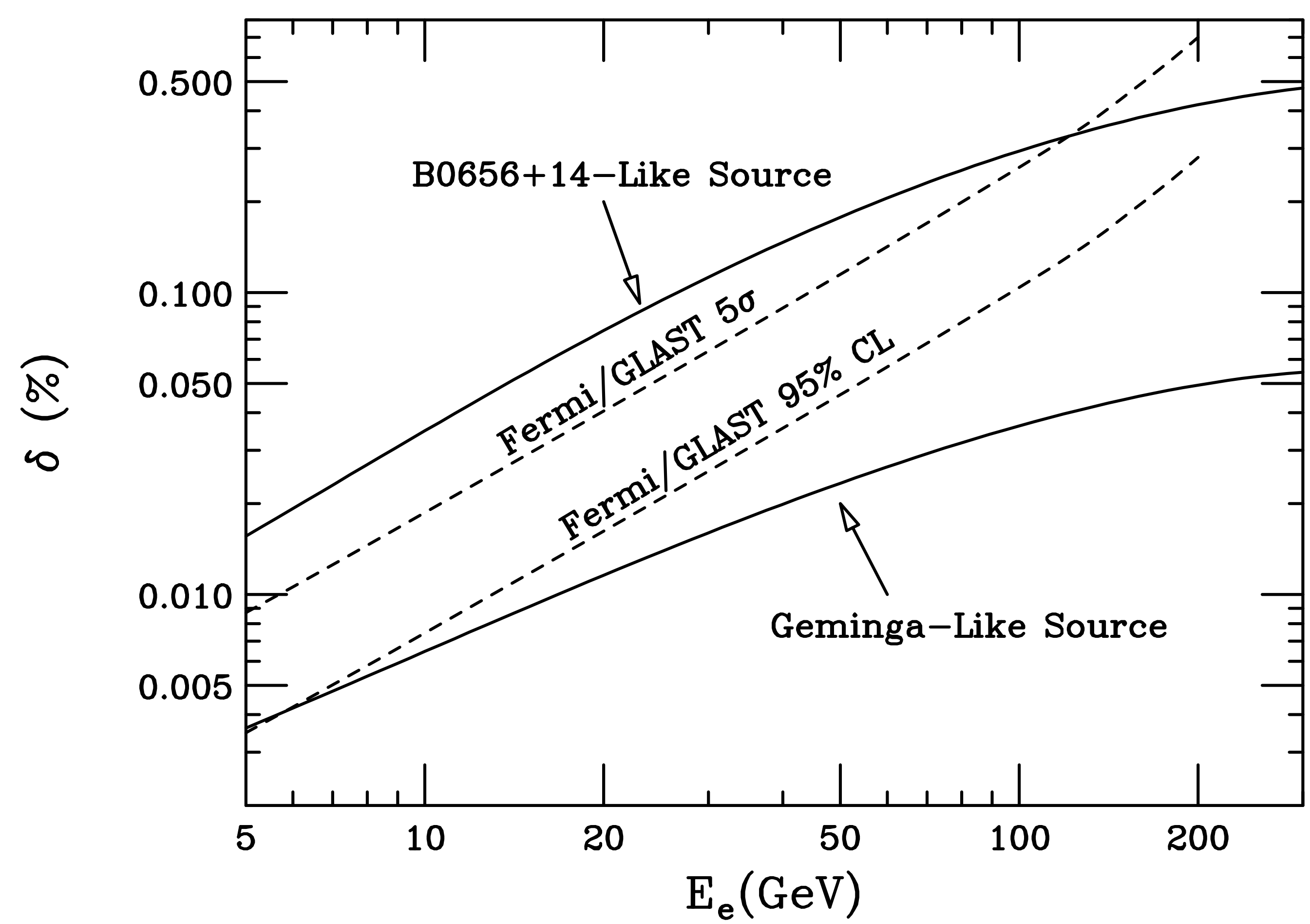
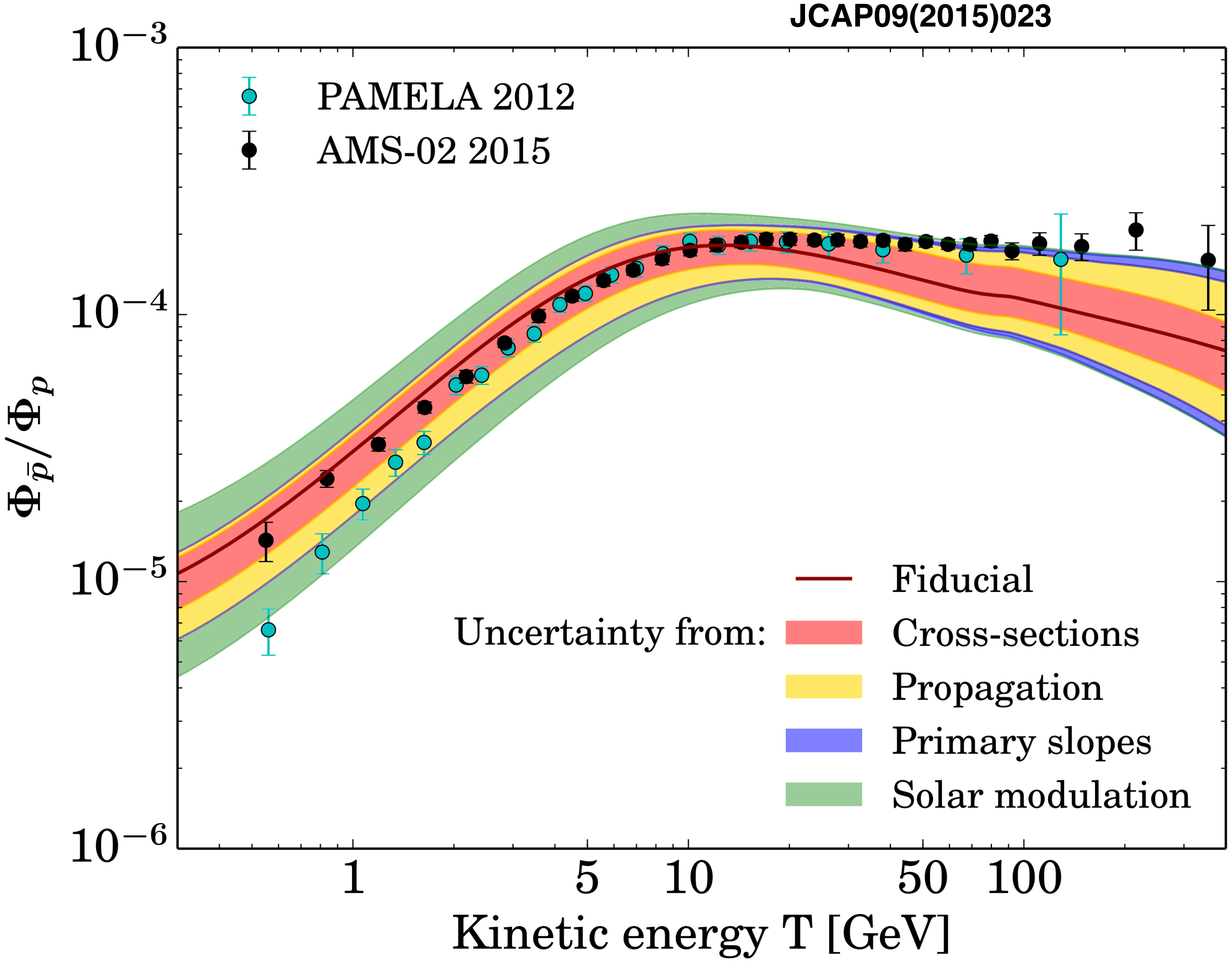




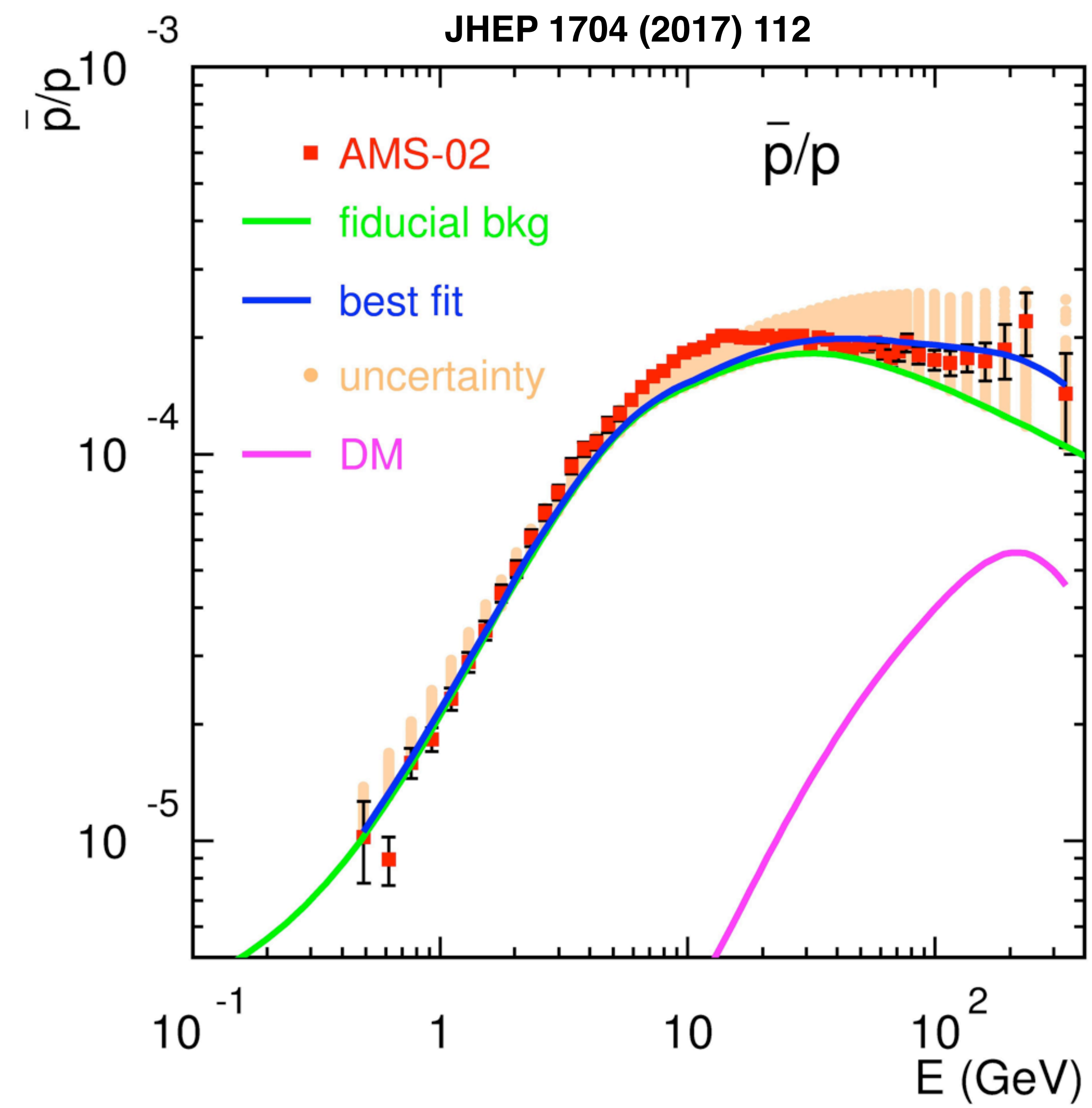
Anti-protons and Anti-deuterons from DM

- Dominant background is cosmic-ray interactions
  - No major background expected from astronomical sources
  - Anti-proton backgrounds are greater than DM signals in general
    - Uncertainties of anti-proton backgrounds can mask DM signals
  - Anti-deuteron signal can be clearly separated from secondary backgrounds

JCAP09(2015)023



JHEP 1704 (2017) 112



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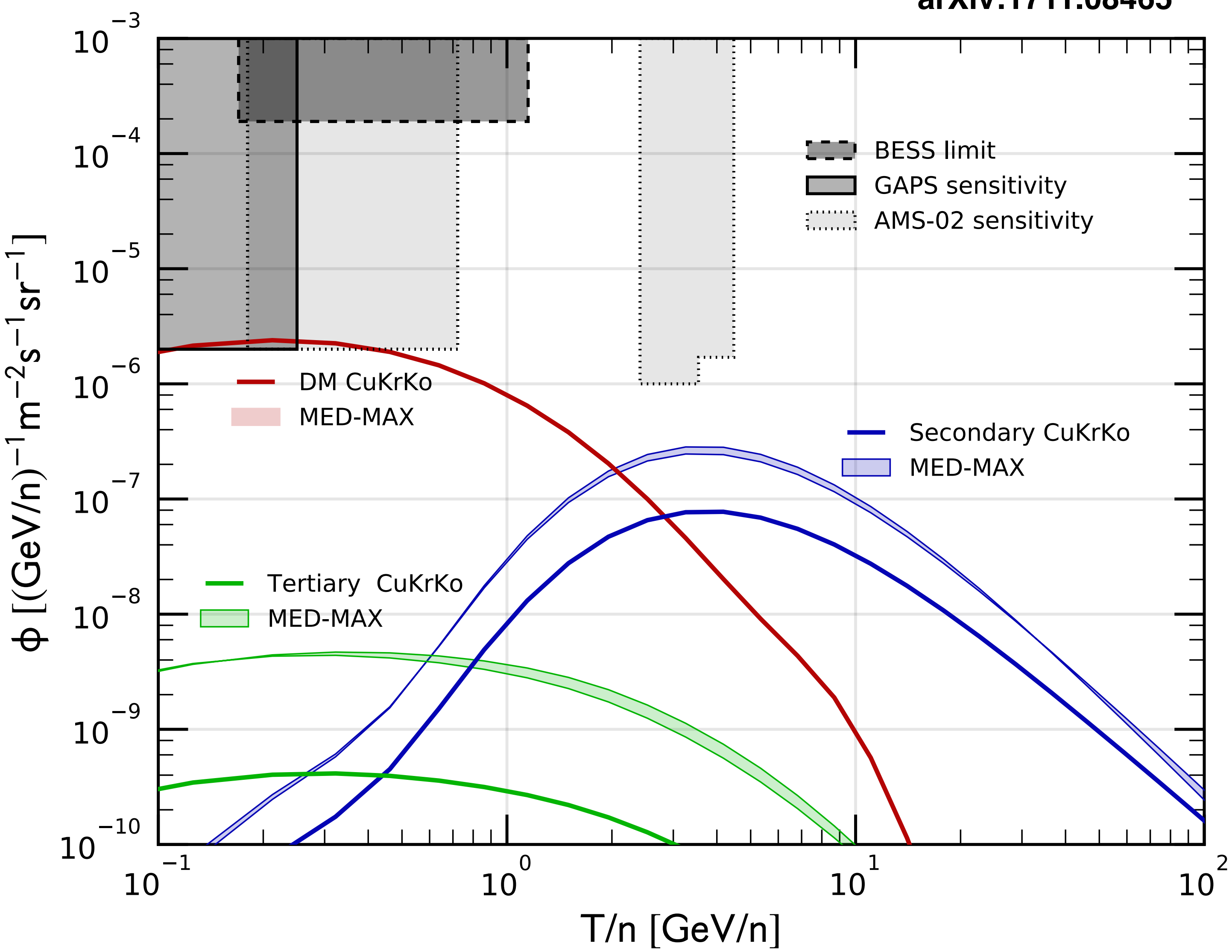
arXiv:1711.08465



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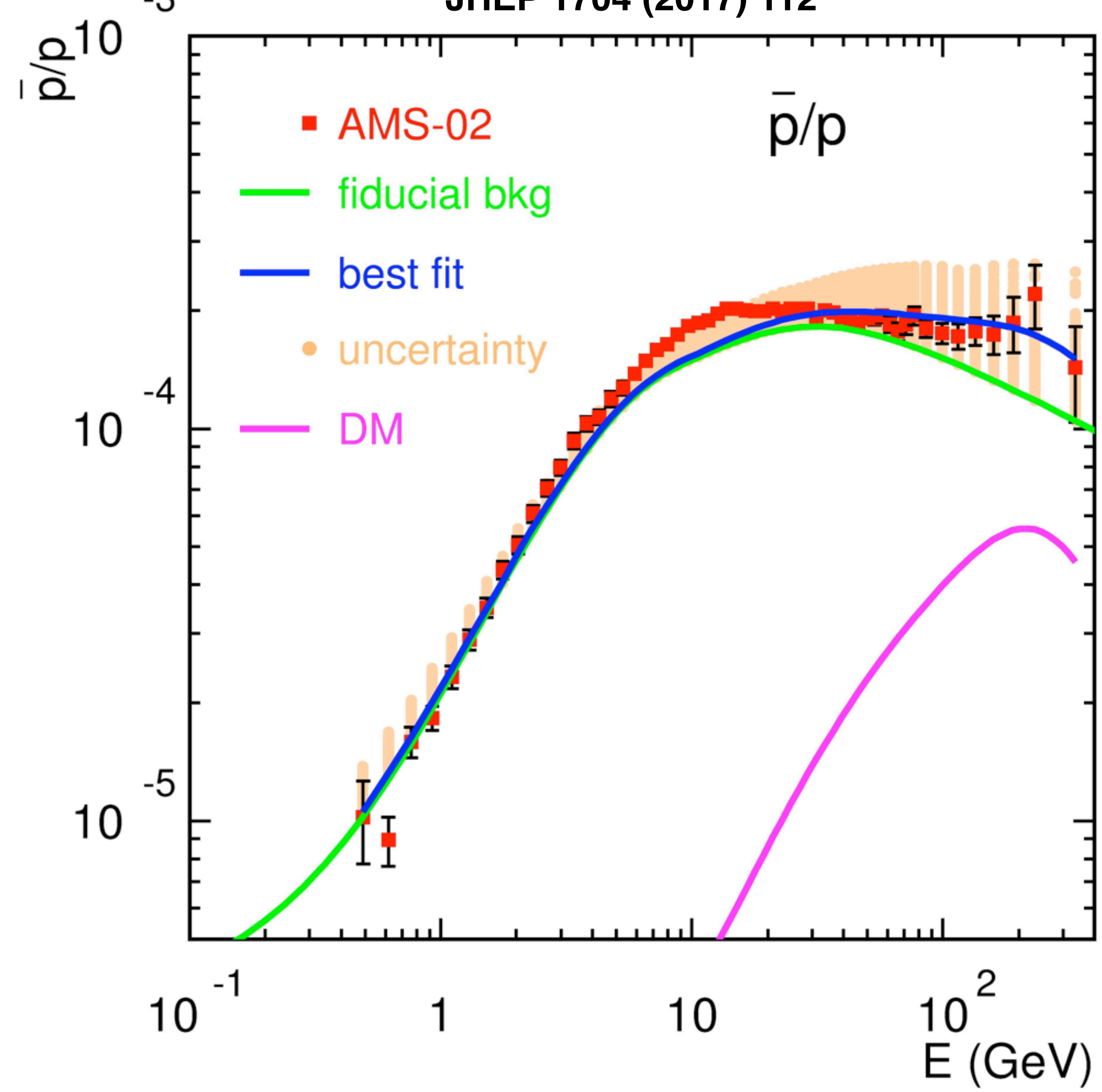
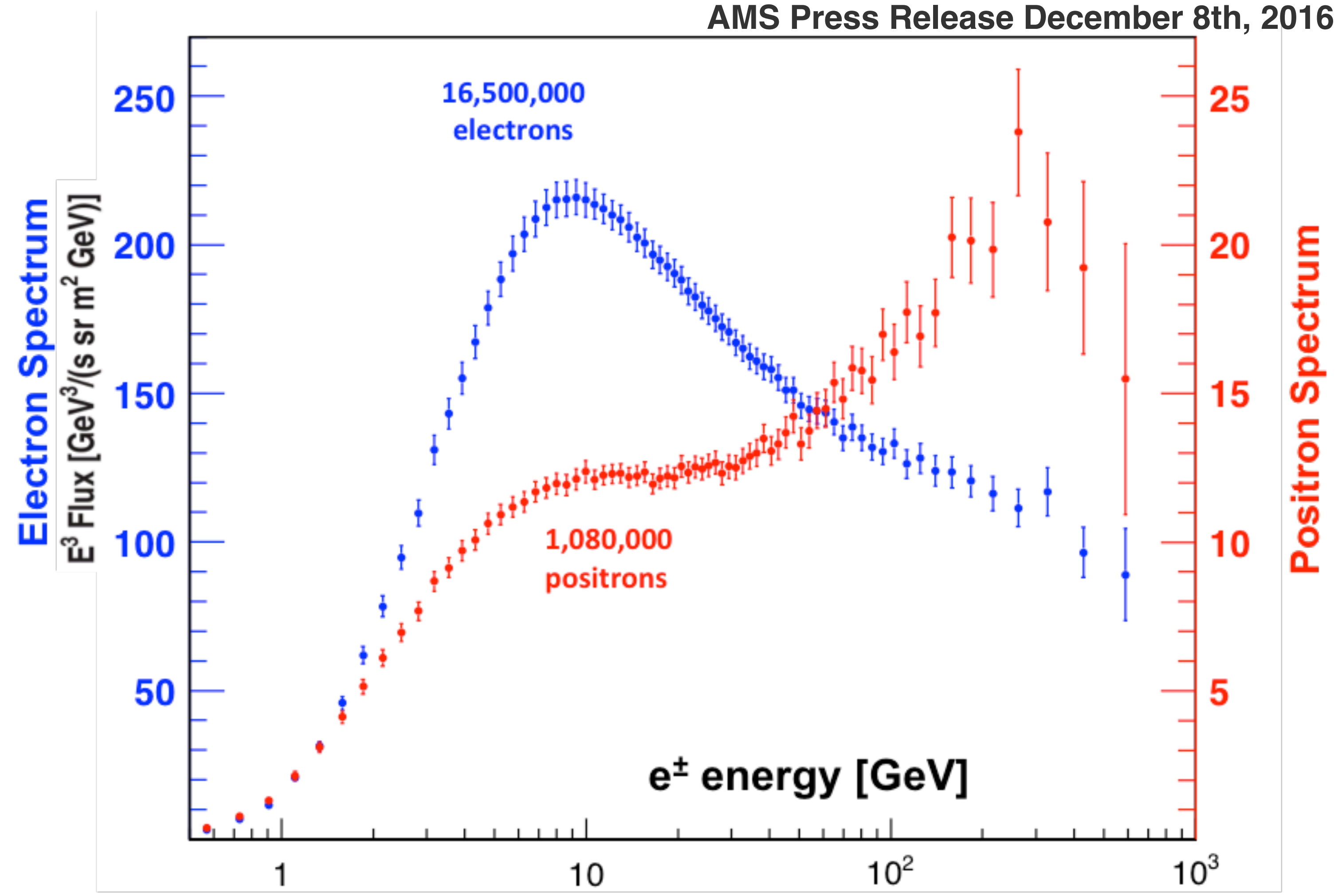


AMS-02 Results

- AMS-02 observed positron spectrum which may peak at several 100 GeV
  - AMS suggested WIMP hypothesis
- AMS-02 also observed anti-proton spectrum which is similar to proton and positron spectra, but different from electron spectrum

AMS Press Release December 8th, 2016



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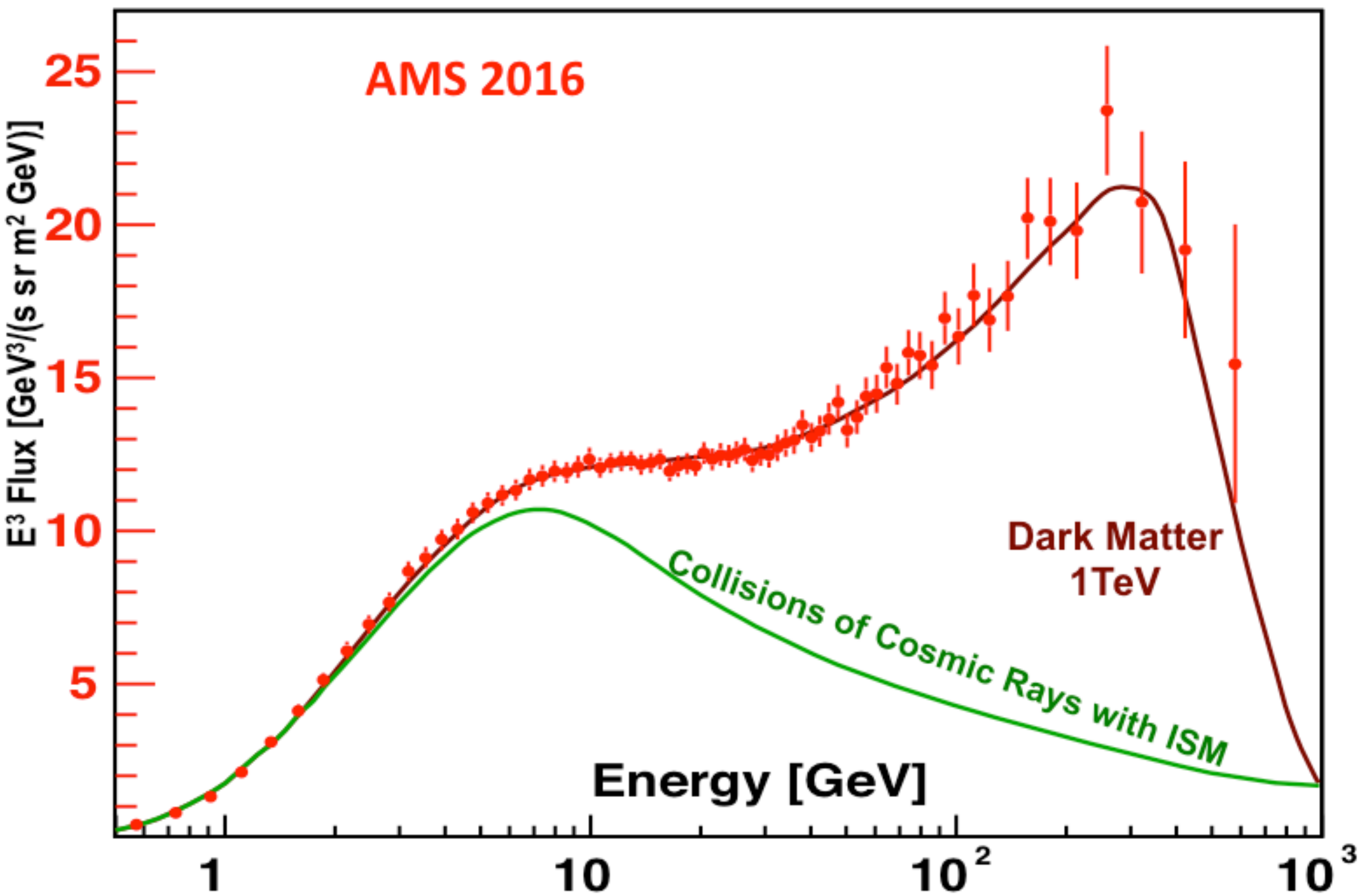

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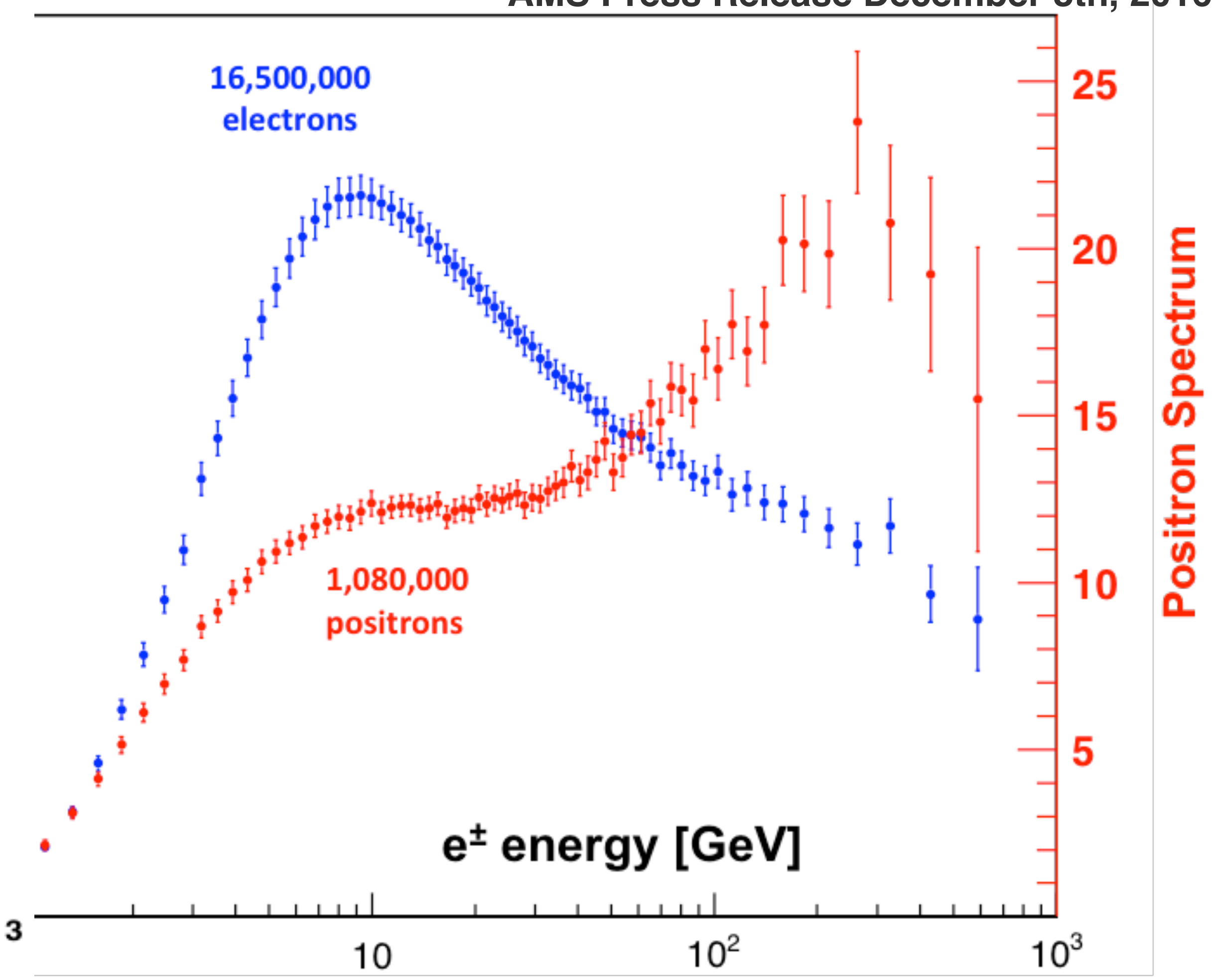

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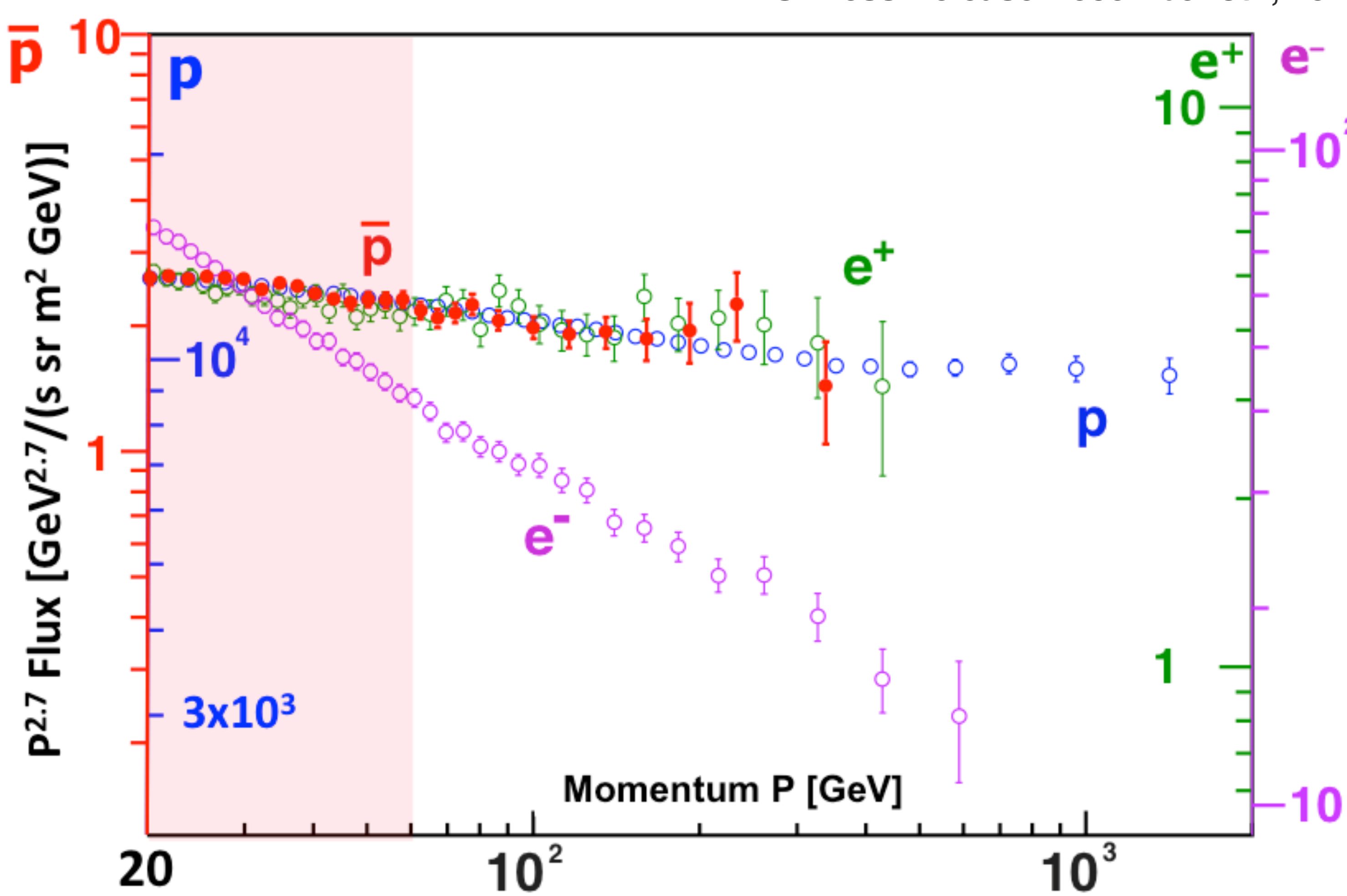
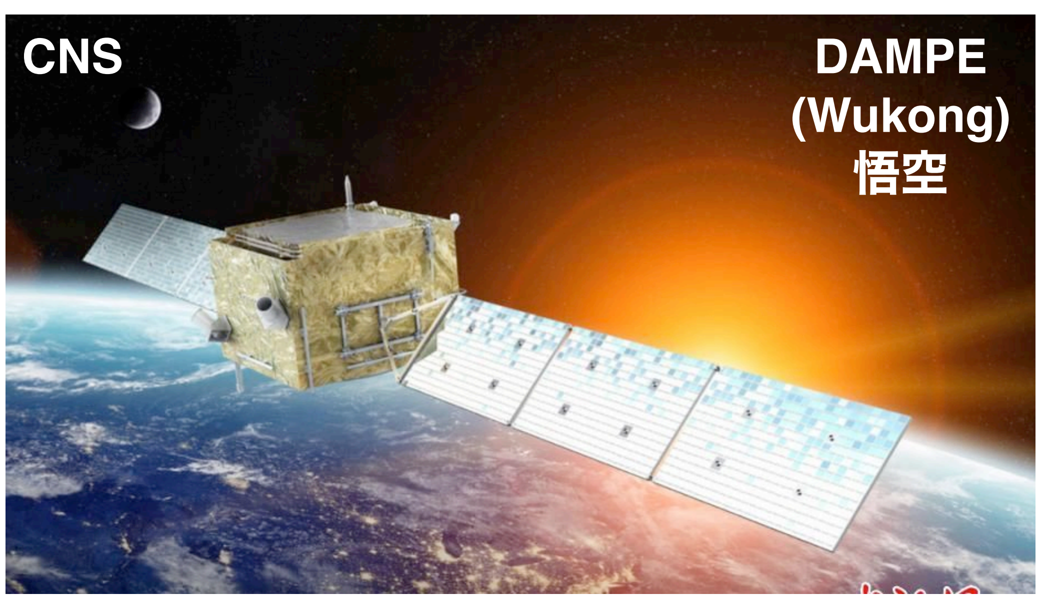
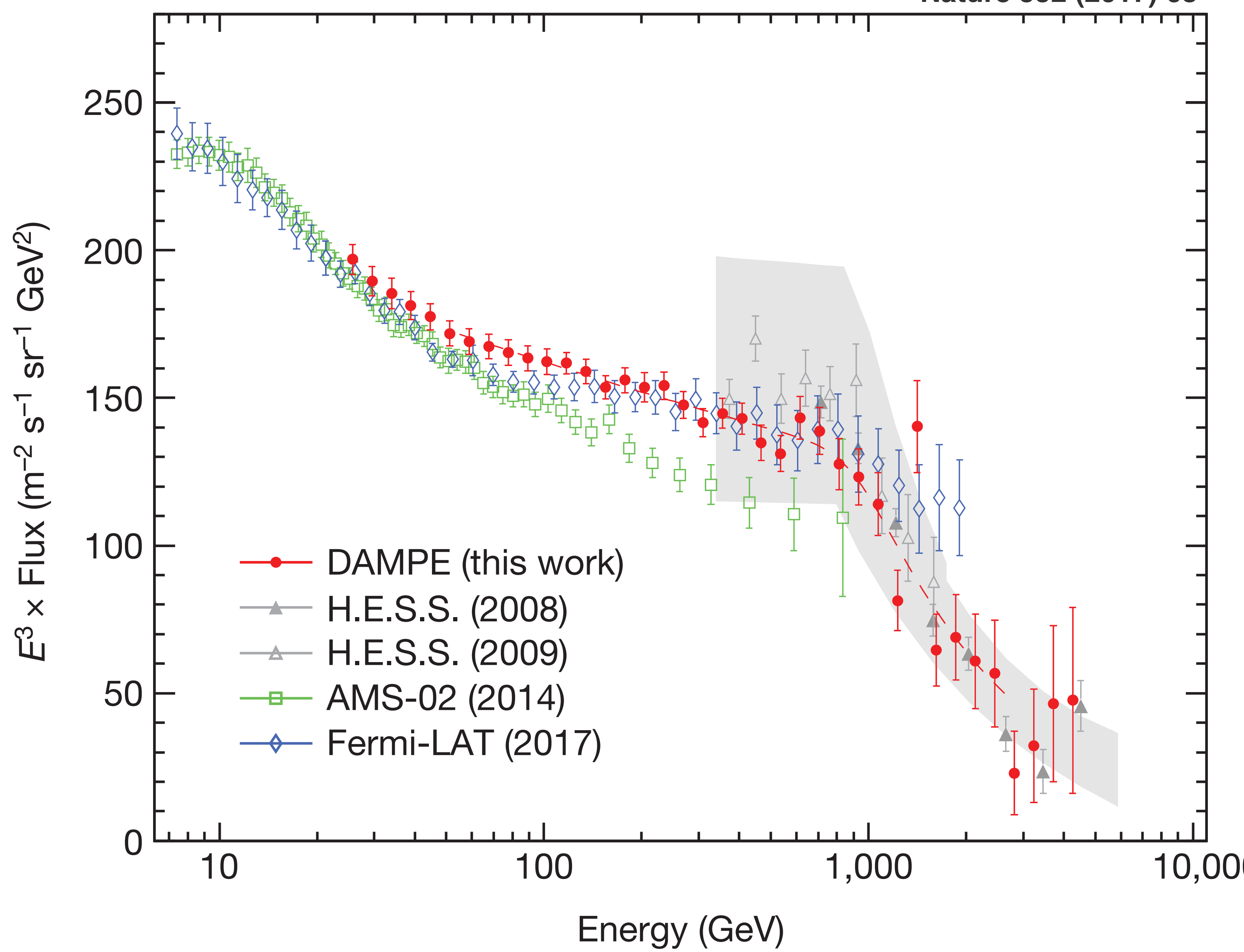


DAMPE Electron+Positron Spectrum

- **DAMPE measurement of electron+positron spectrum shows clear break around 1 TeV**
  - **Sharp peak at 1.4 TeV is 2σ level**
  - **Consistent with Fermi-LAT + H.E.S.S. spectra**



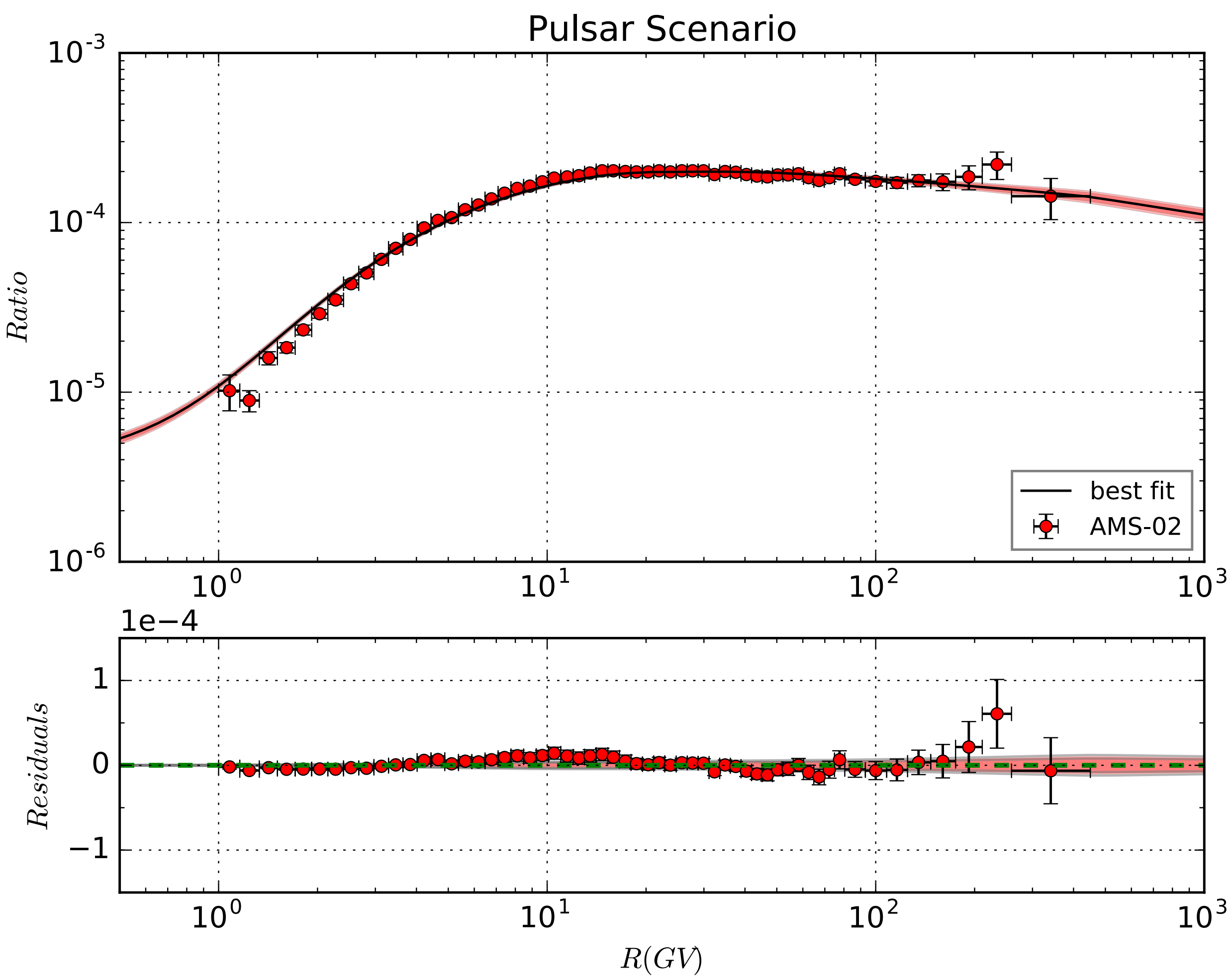
Nature 552 (2017) 63



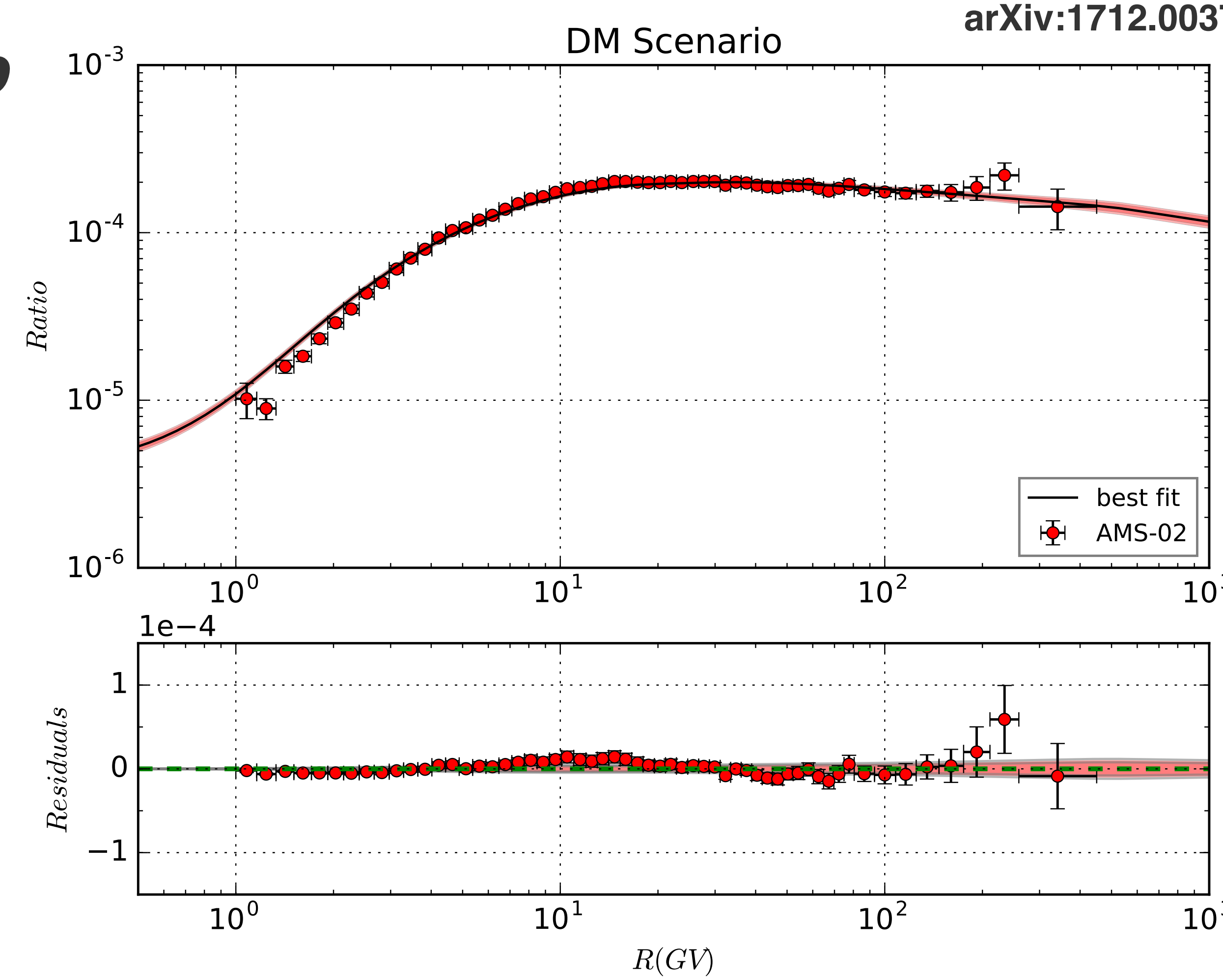
Interpretation of AMS/DAMPE Spectra

- $\overline{p}/p$, position, electron+positron spectra can be interpreted by pulsar and DM models
  - χ^2/d.o.f = 255/298 for pulsar model
  - χ^2/d.o.f = 277/296 for DM model

arXiv:1712.00372



$\overline{p}/p$



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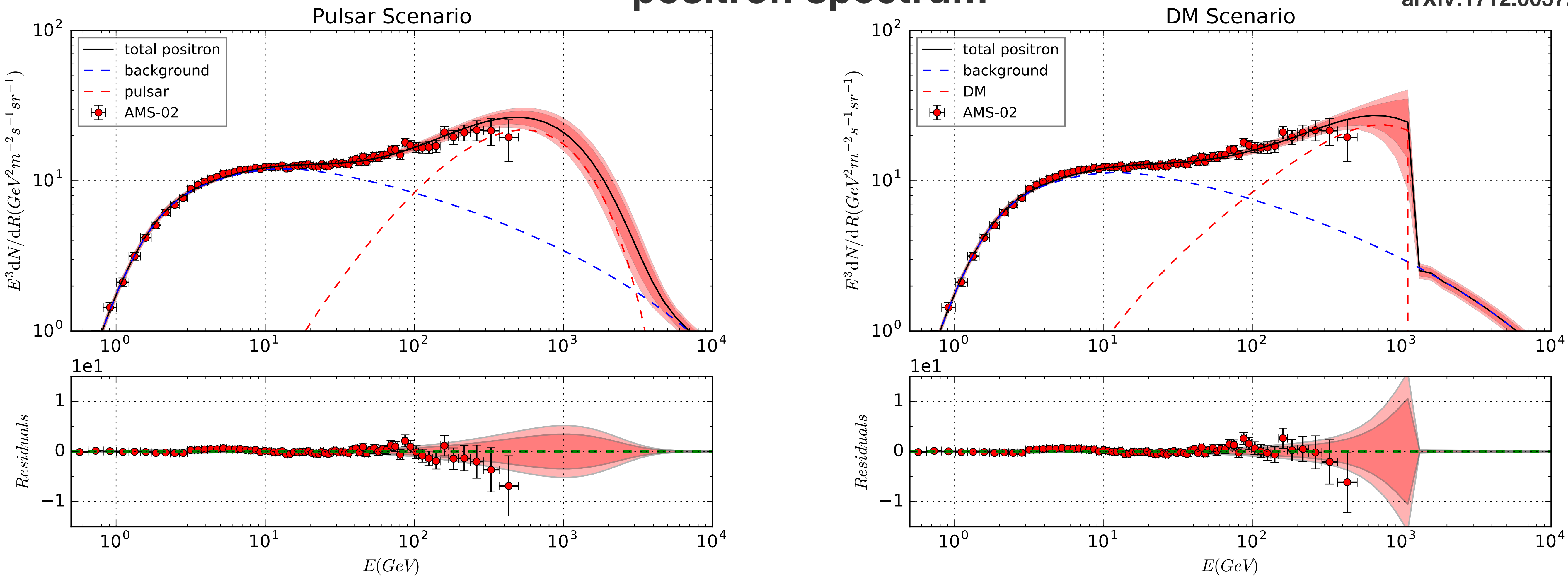

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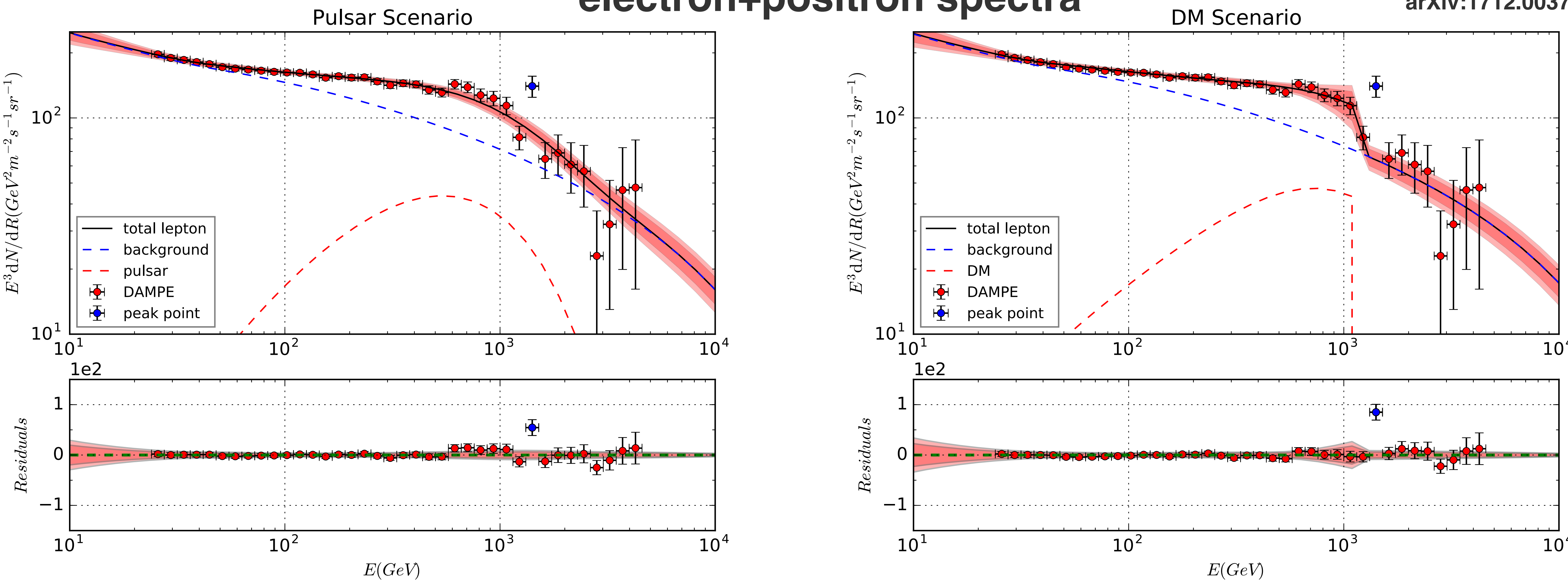
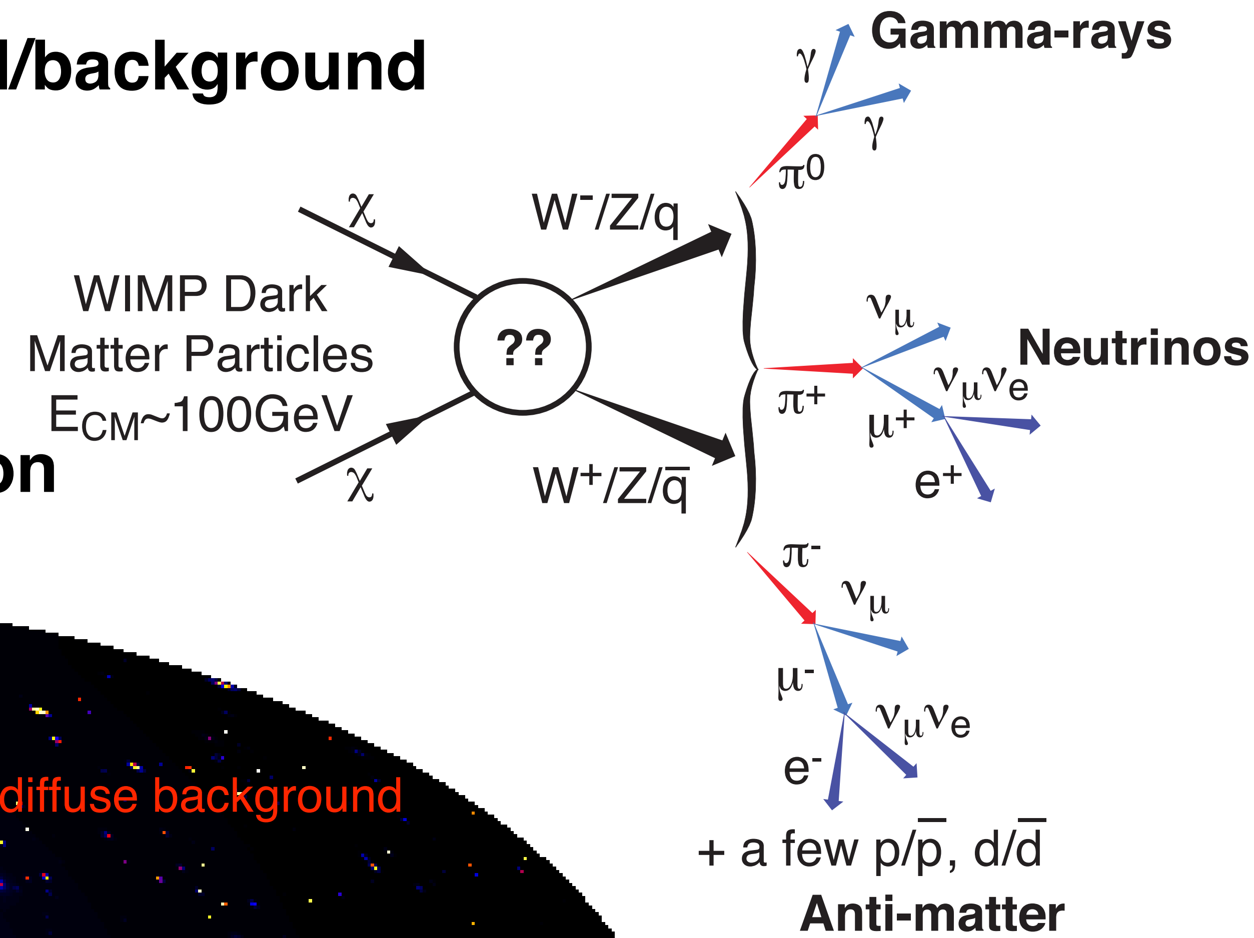
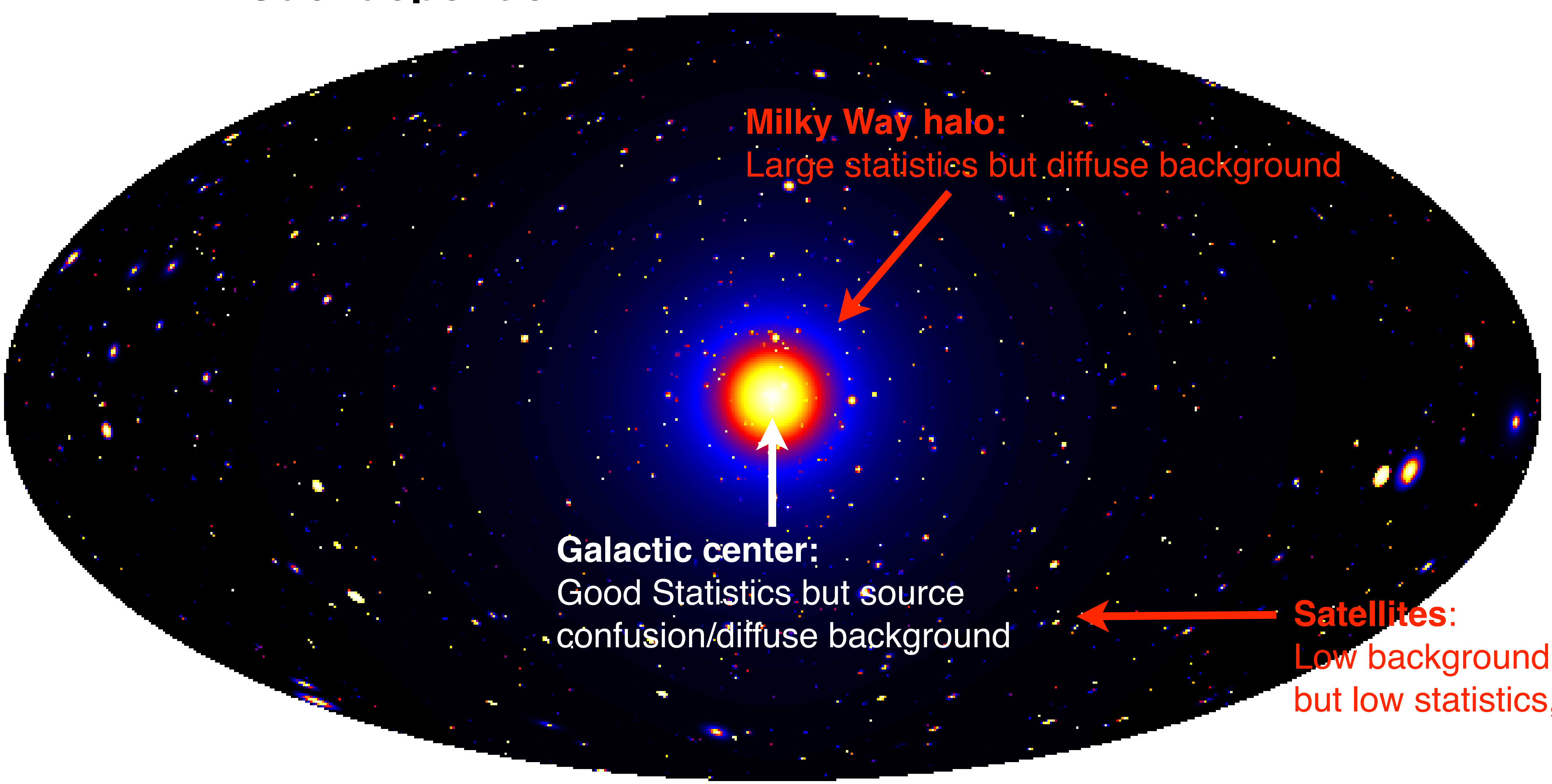


Dark Matter Searches with Gamma Rays

- Multiple approaches with different signal/background
  - Galactic center, Milky-Way halo, satellites
  - Line emission, diffuse backgrounds
- Gamma-ray spectrum depends on particles produced by DM annihilation
- Sensitive to DM annihilation cross section
  - DM model dependent





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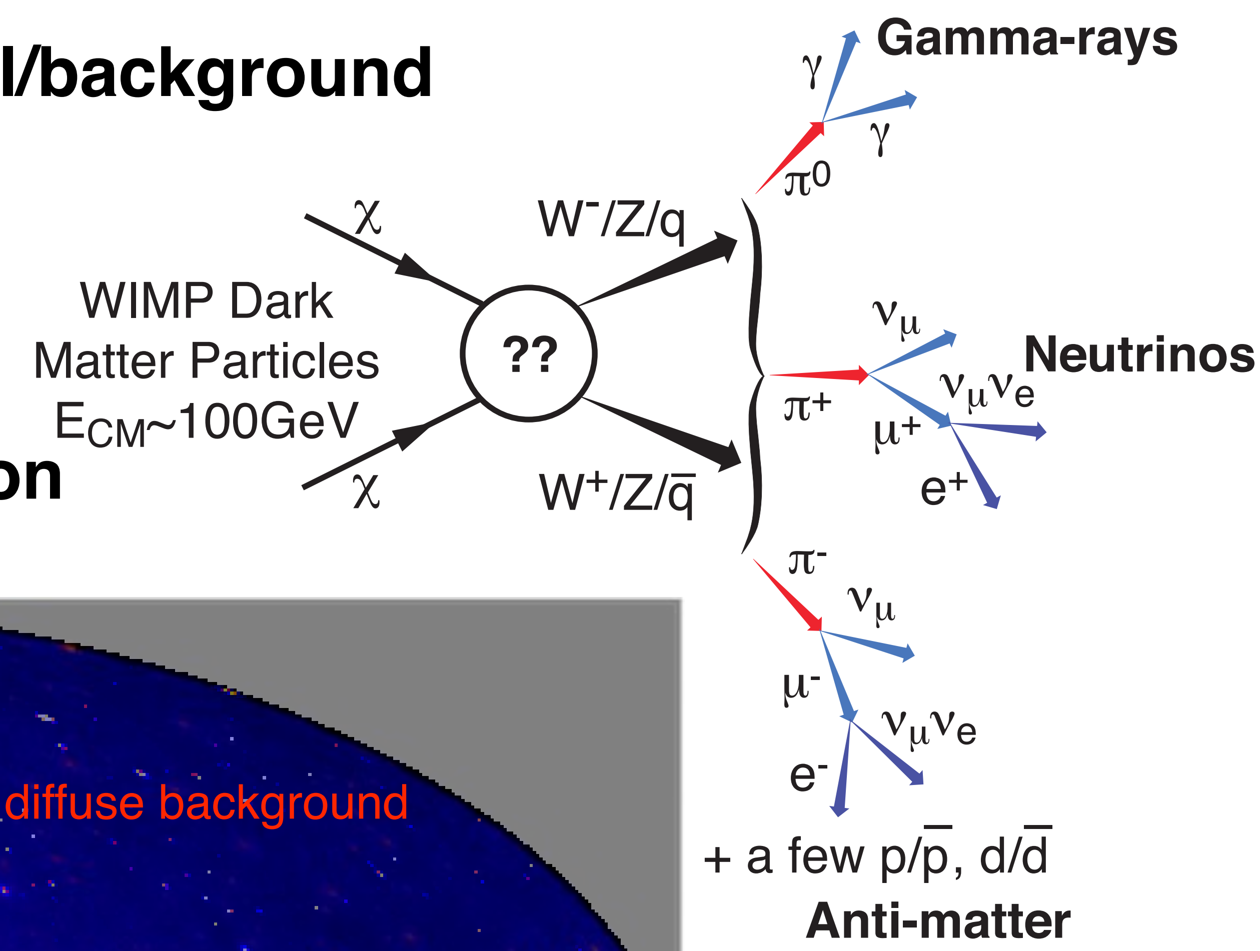

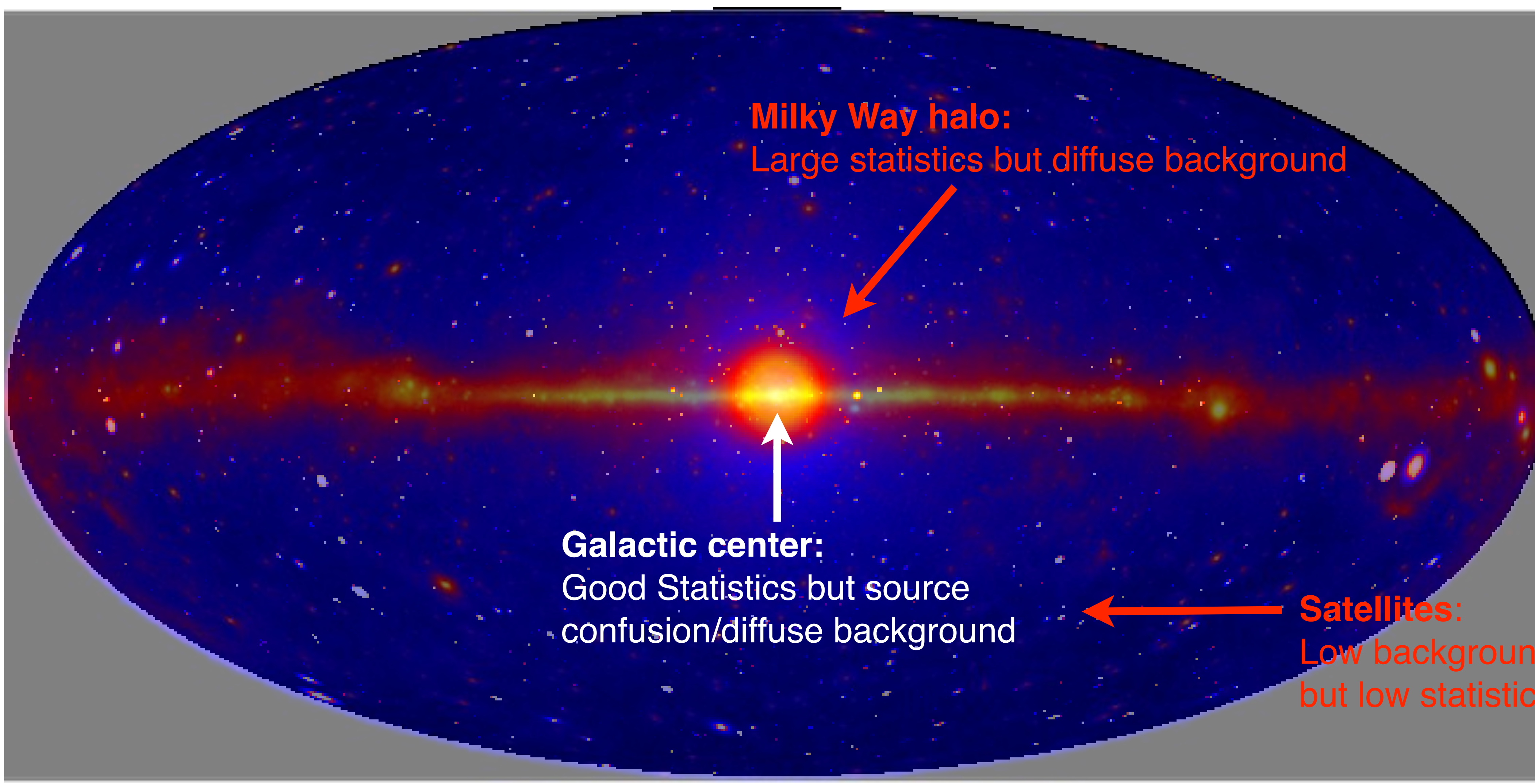

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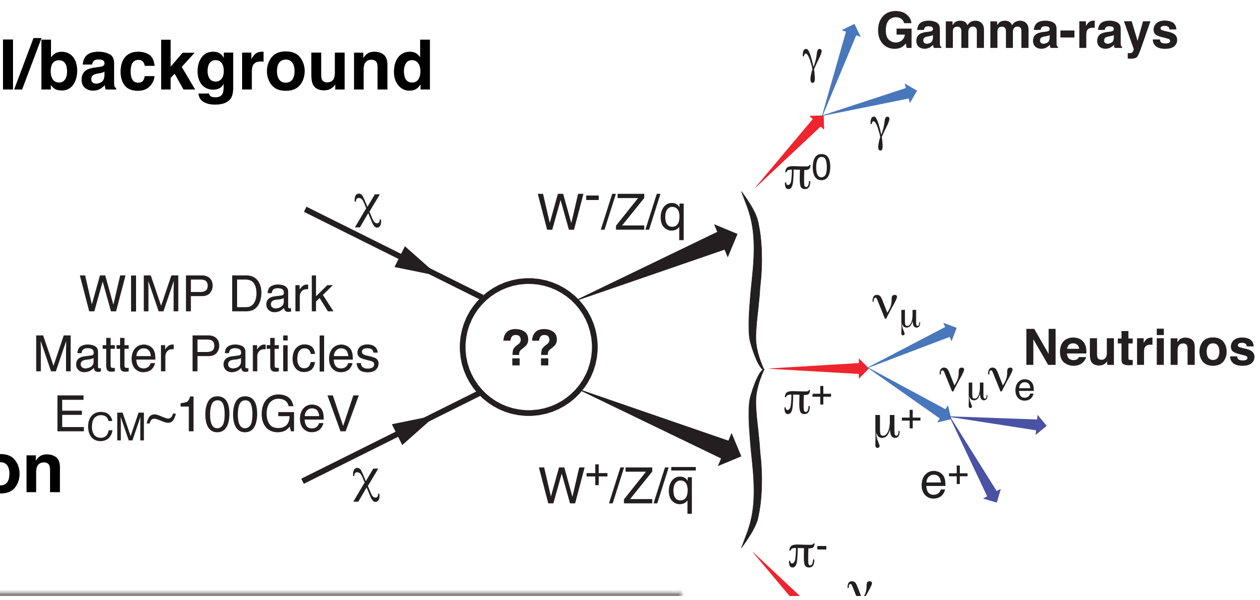

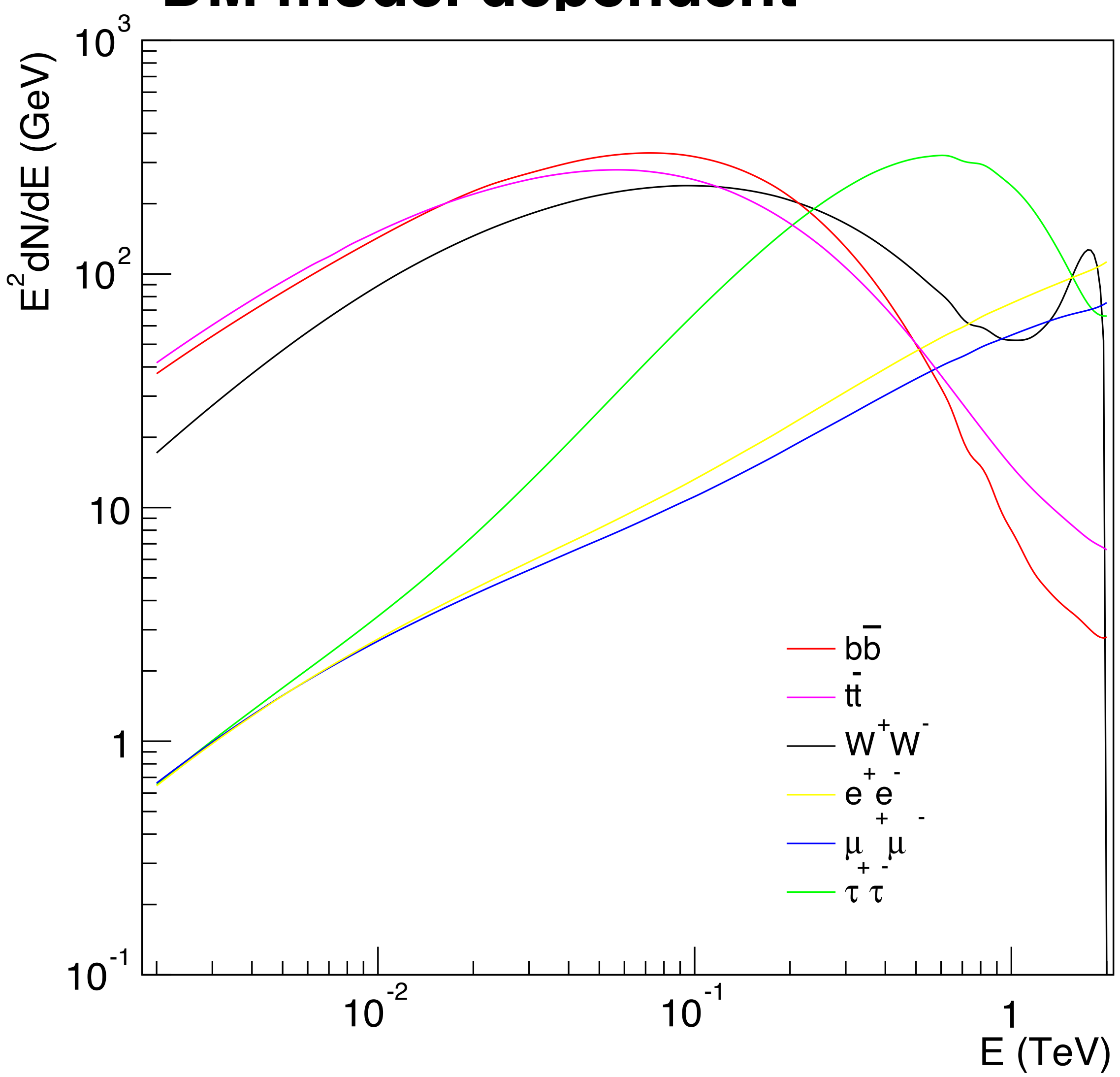

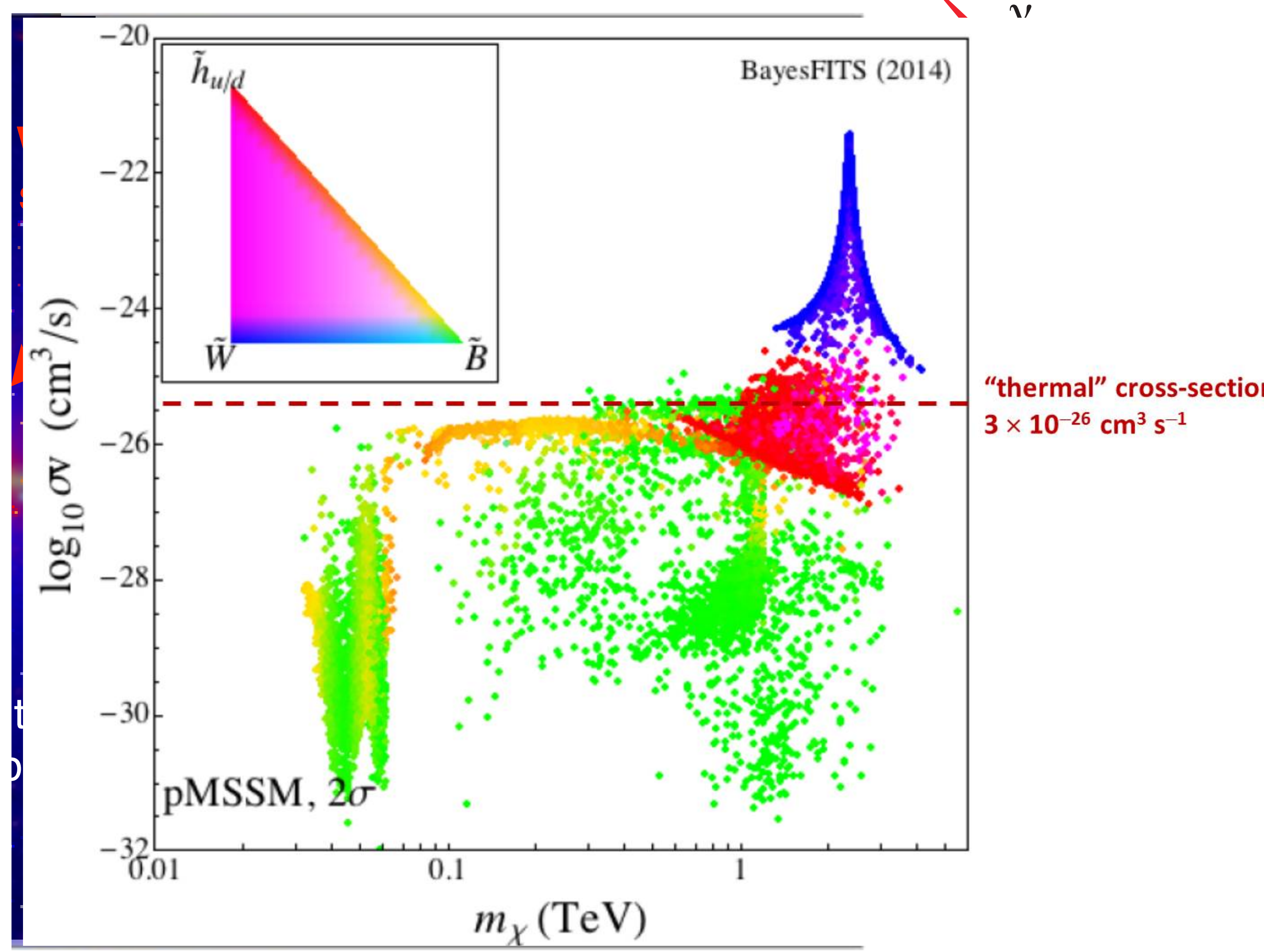

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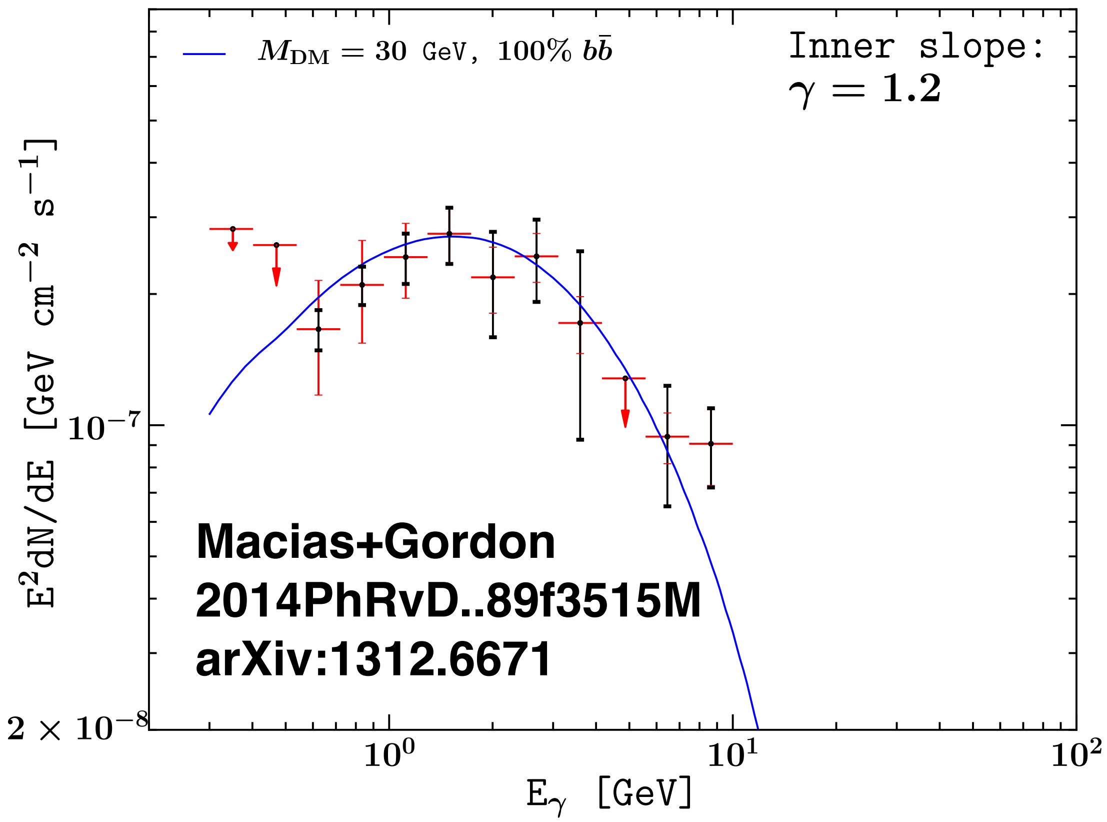
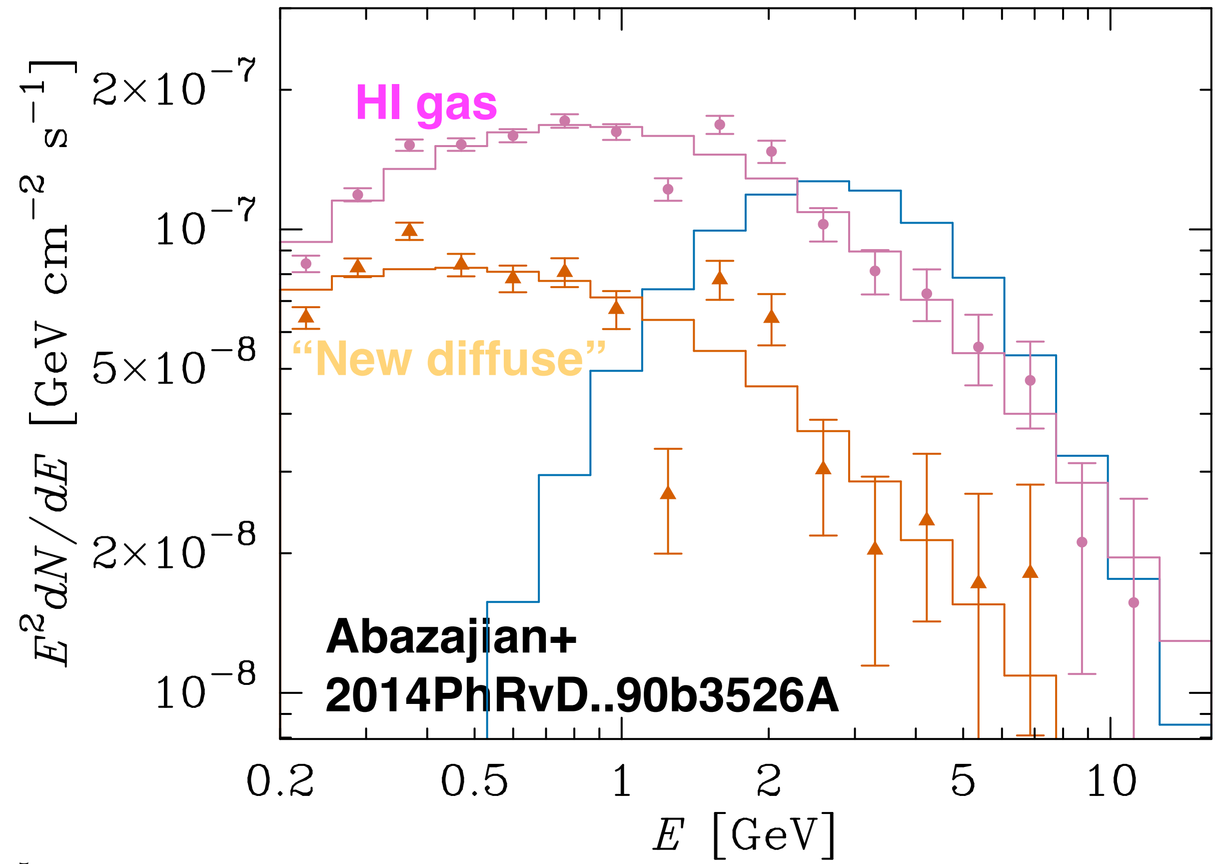
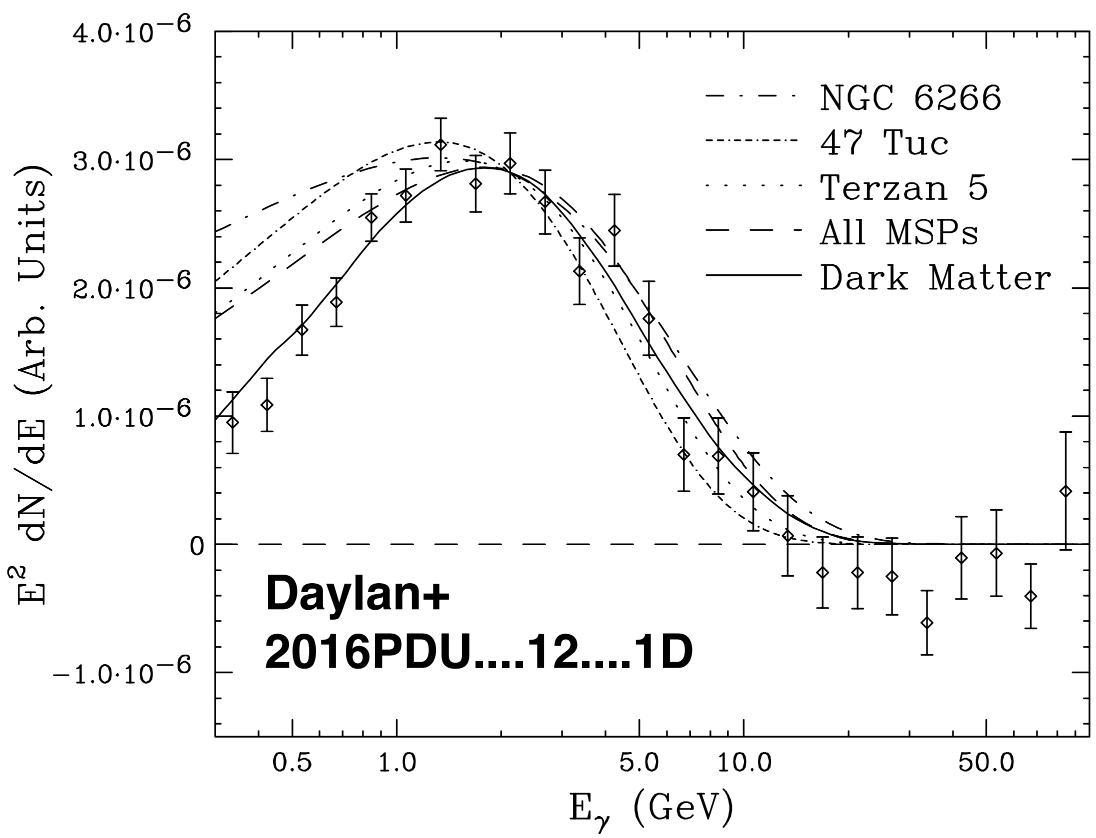
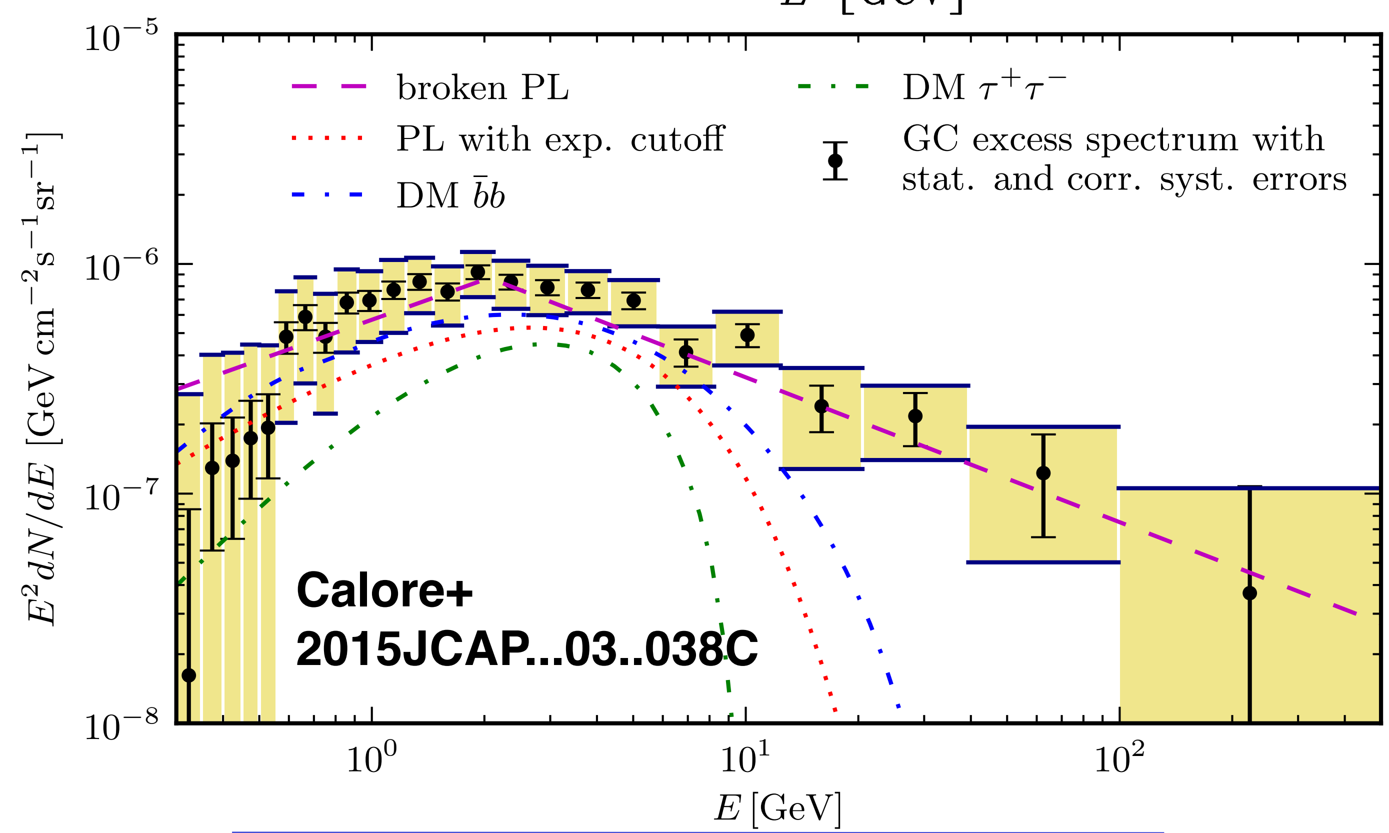
Fermi "Galactic Center Excess"









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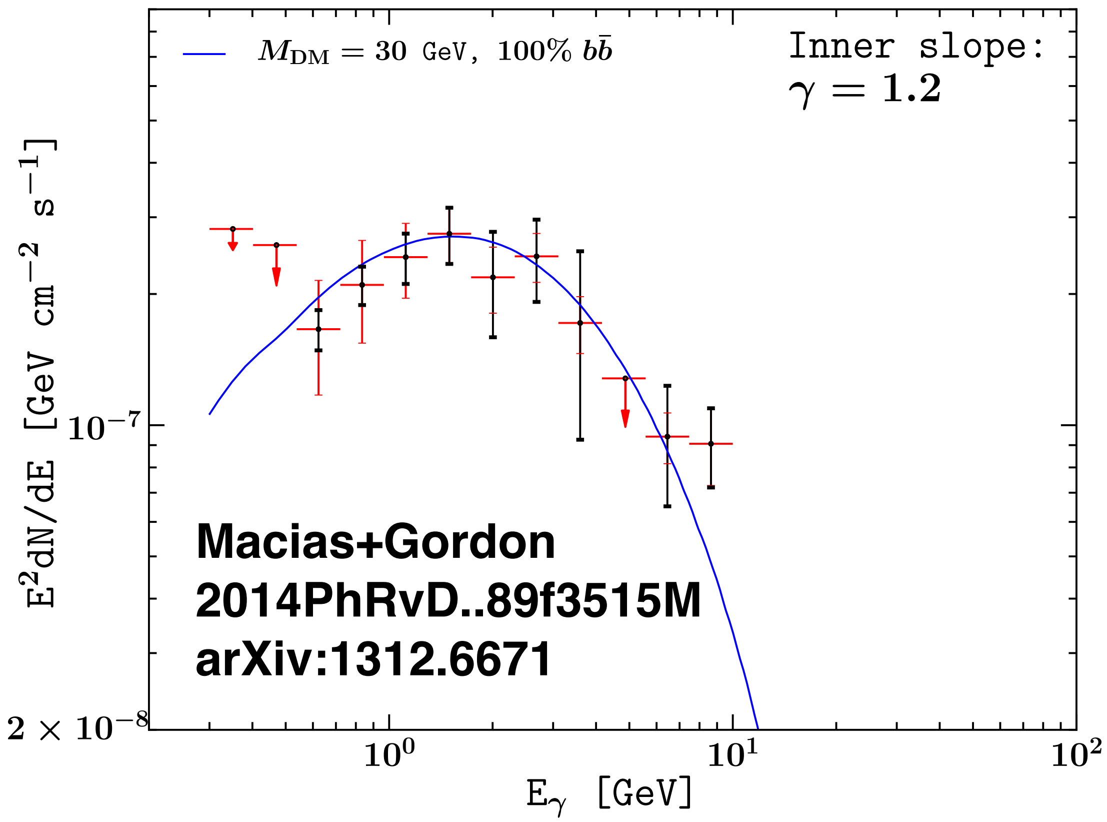

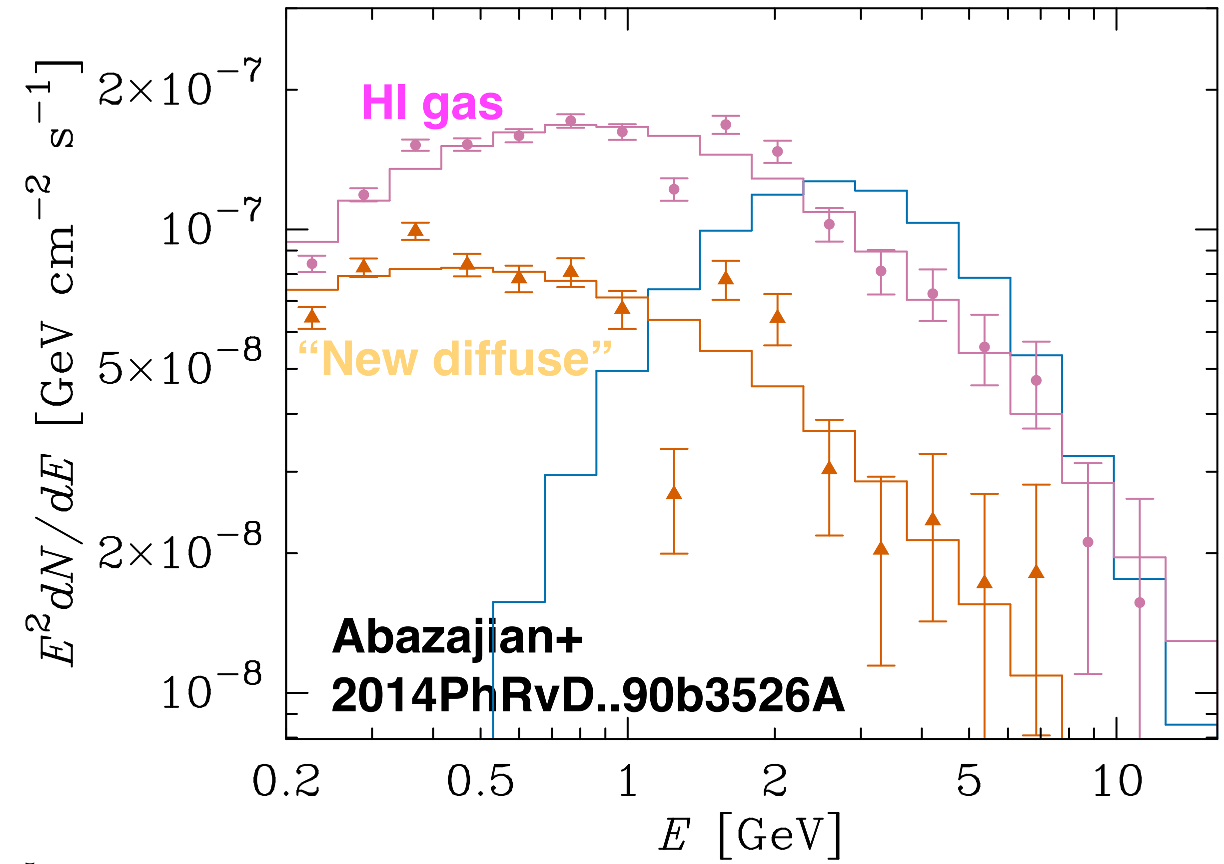

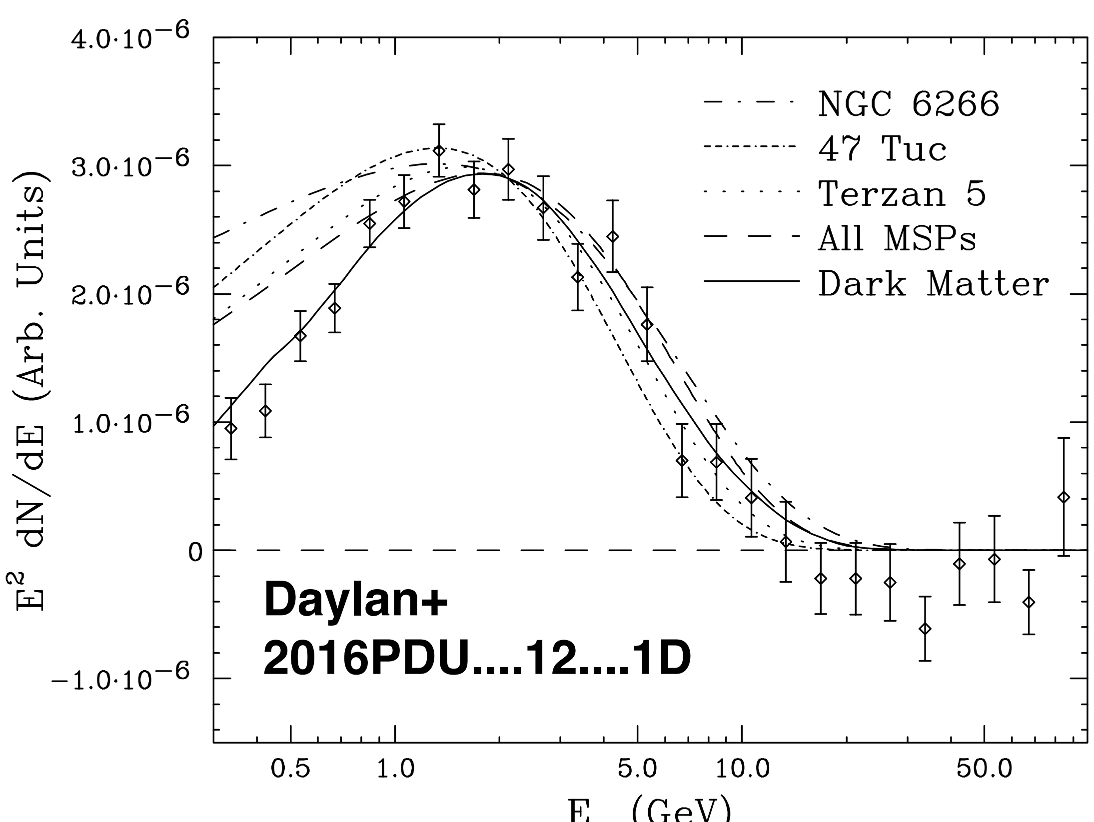

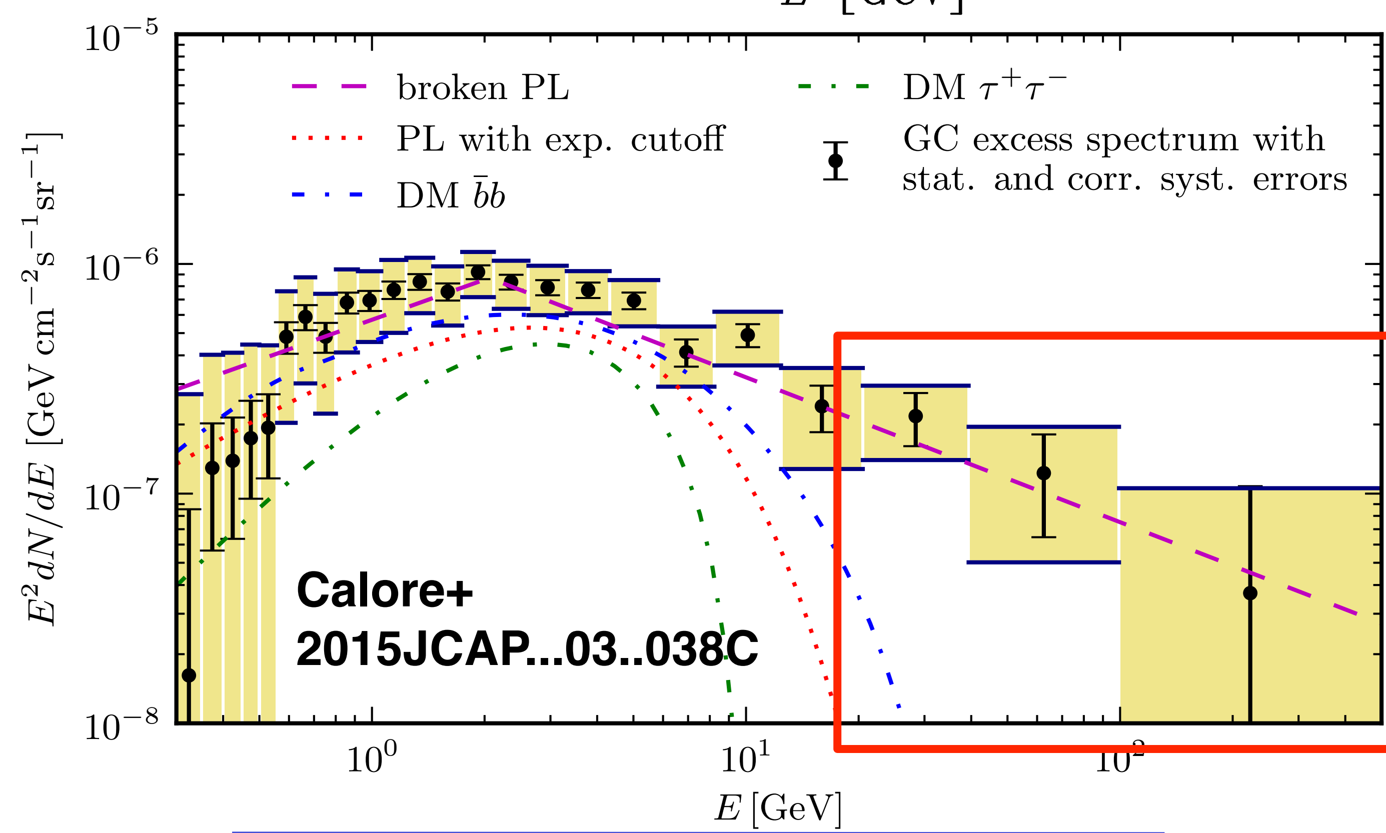

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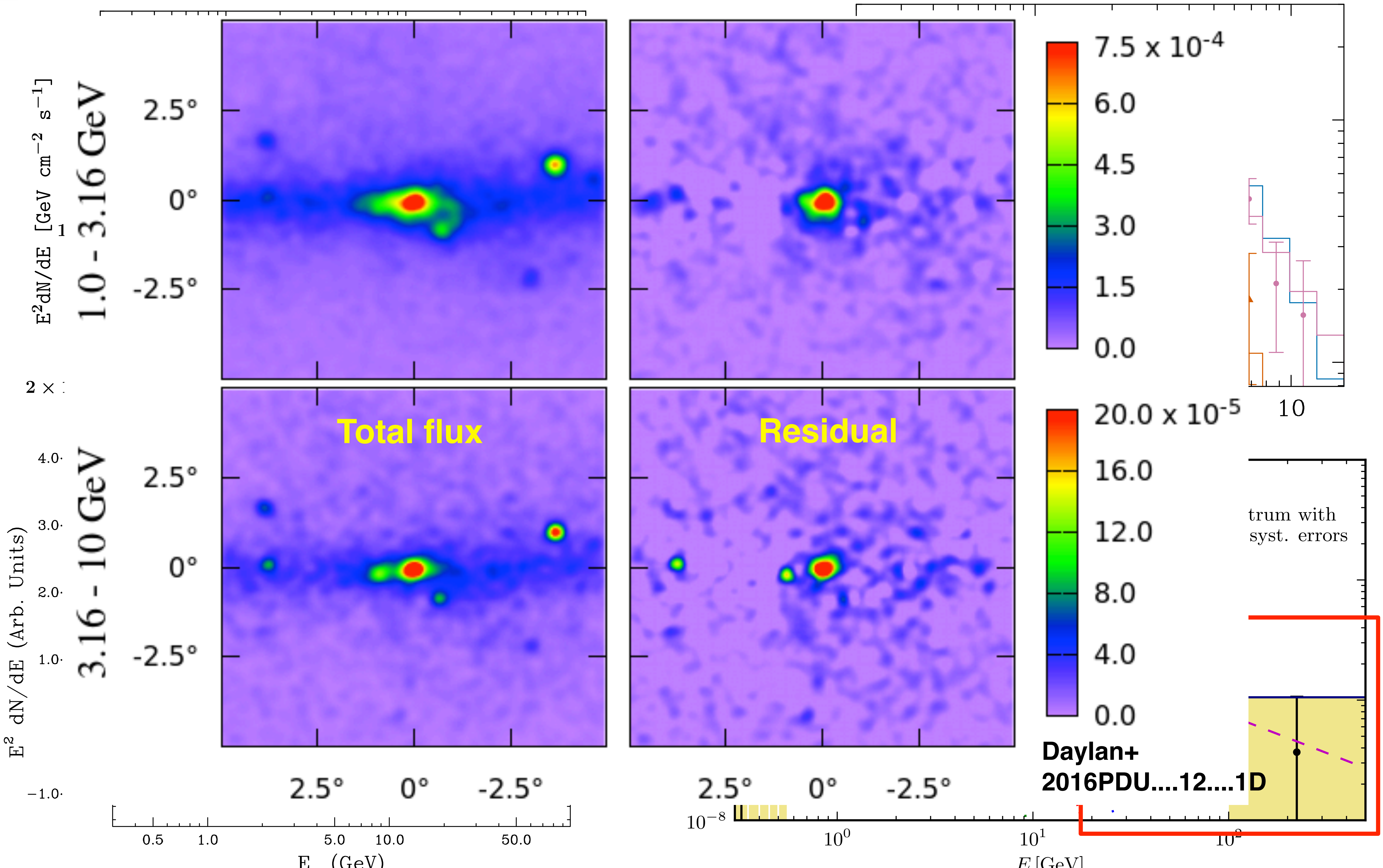

Daylan+
2016PDU....12....1D

"Galactic Center Excess" Summary

Publication	Data set	Galactic diffuse model	m_{DM} (GeV/c^2) (for bb pair)	<σv> (10^{-26} cm^3/s) (for bb pair)
2014PhRvD..89f3515M	Pass 7, 45 months, |b|<3.5°, |ℓ|<3.5°	Fermi/LAT p7v6 + HI gas (20 cm)	29±9	2.0±0.6
2014PhRvD..90b3526A	Pass 7, 57 months, |b|<3.5°, |ℓ|<3.5°	HI gas (20 cm) + "new diffuse"	39.4±7.9	5.1±2.1
2016PDU....12....1D	Pass 7, 64 months, 1<|b|<20°, |ℓ|<20°	Fermi/LAT p6v11 + Fermi Bubbles	~35.5	~3.0
	Pass 7, 64 months, |b|<5°, |ℓ|<5°	Fermi/LAT p7v6 + HI gas (20 cm)	35.5±4.5	3.0±0.5
2015JCAP...03..038C	Pass 7, 64 months, 2<|b|<20°, |ℓ|<20°	HI&H_2 gas + Inverse Compton	49±6	1.8±0.3

- Fermi/LAT diffuse model is **NOT** intended for diffuse analysis
  - "All the released diffuse models were derived for point sources and compact extended sources studies only, and are not suited for studies of extended sources and/or large-scale diffuse emissions. "
  - "Each diffuse model should be used with the corresponding Event Selection and IRF."

Acero, F. et al. 2016, ApJS, 223, 26

Problems with "GCE" Analyses

- Most analyses use wrong Galactic diffuse models
  - Some authors are aware of caveat from the LAT team
- Uncertainties in cosmic-ray propagation in the Galprop model
  - Assumptions
    - Homogeneity and isotropy of cosmic-ray diffusion and re-acceleration
    - Radial symmetry of cosmic-ray source distribution: ignore spiral arms
    - Same spatial distribution of hadronic and leptonic cosmic-ray sources
- Unknown contributions from undetected gamma-ray sources
  - Spectrum of Calore+ is not necessarily compatible with dark matter spectrum
    - slow rise below the peak
    - no clear cutoff above 10 GeV
- Excess is not limited to Galactic Center

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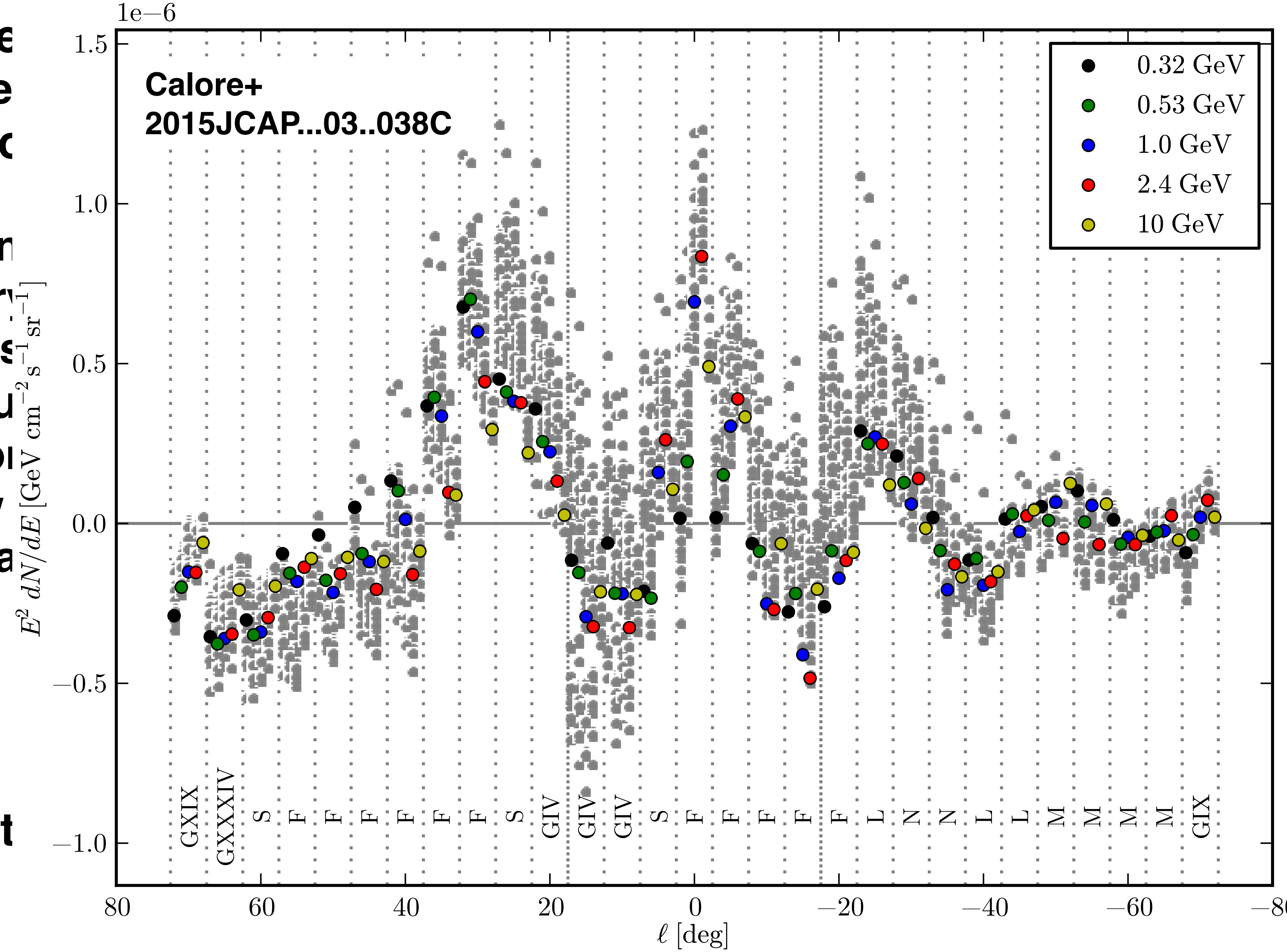
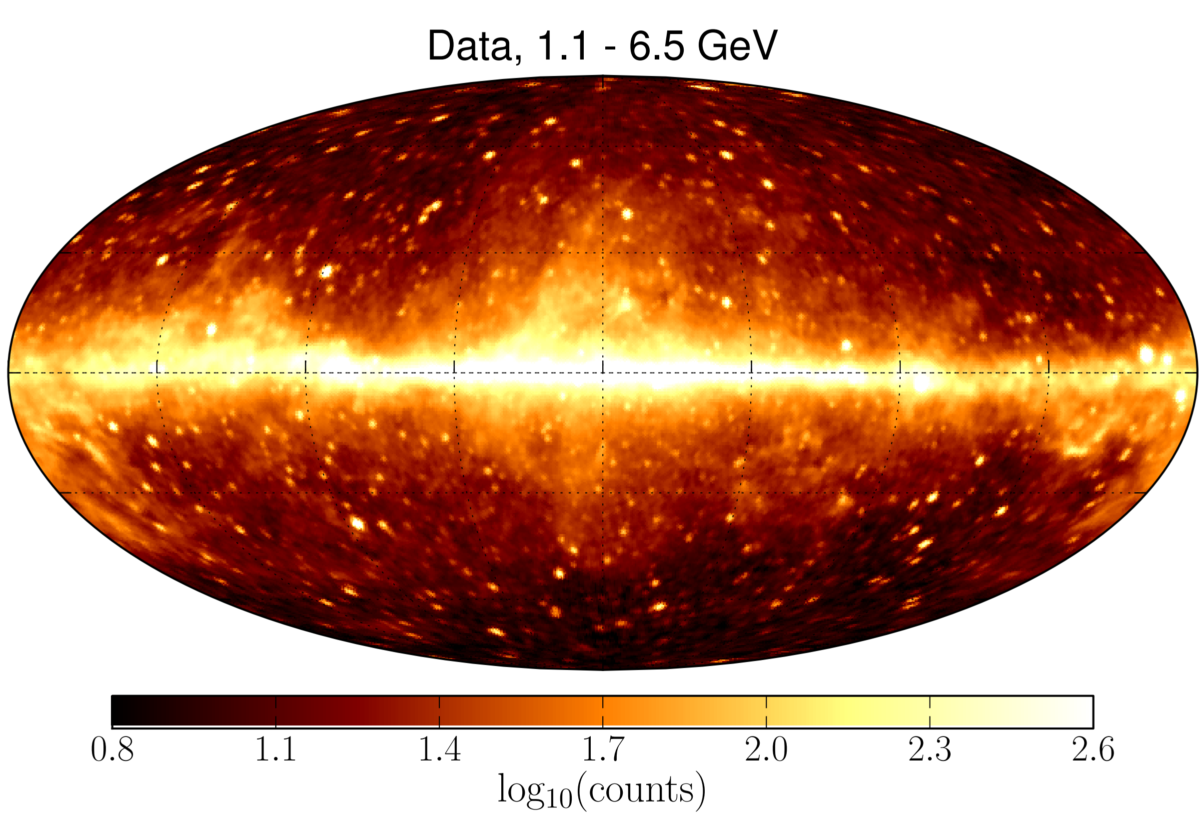
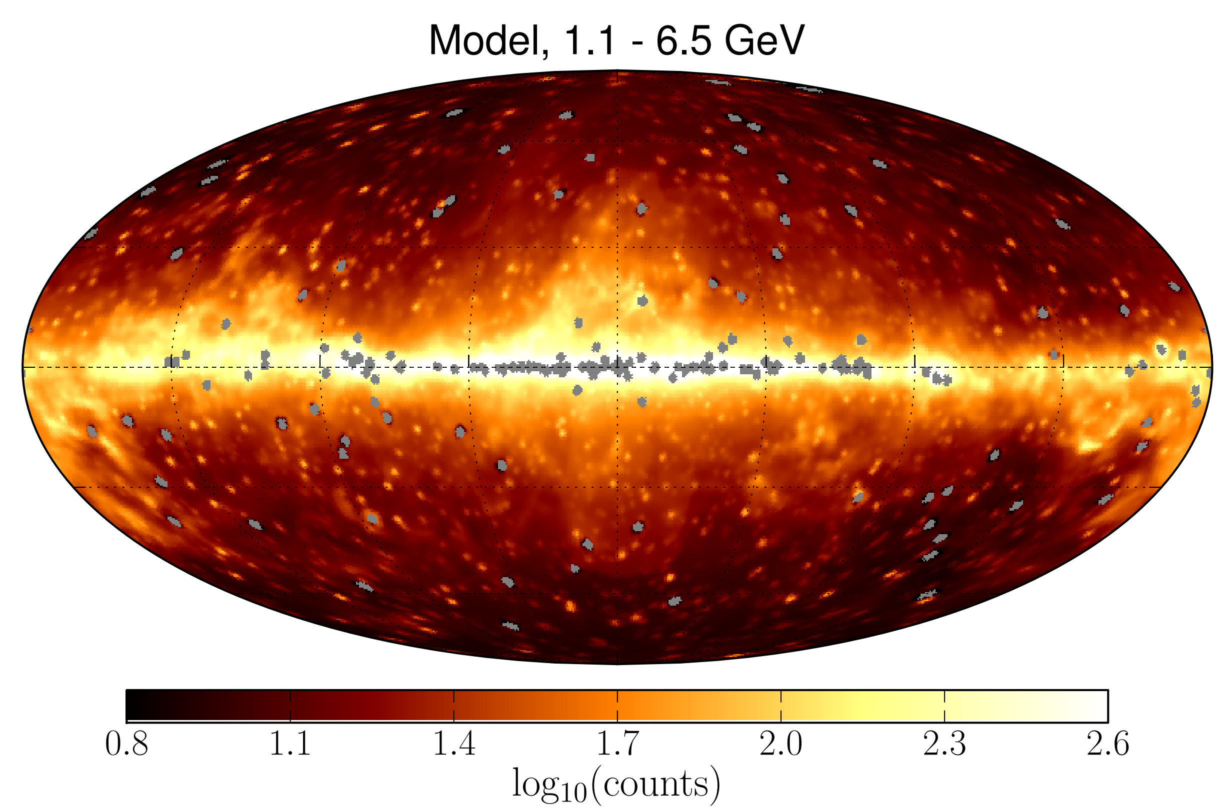


Recent "GCE" Analysis by LAT Team

- Detailed modeling of Galactic diffuse emissions
  - CR interactions with interstellar medium
  - CR electron interactions (bremsstrahlung, Compton up-scattering)
  - Fermi bubble at low galactic latitude
- GeV excess at Galactic center region is statistically significant
  - GCE spectrum vary by a factor of 3 at ~ a few GeV
  - Fermi bubble is major cause of uncertainties
  - GCE shape is not symmetric
  - Similar excess can be found outside of Galactic center region

ApJ, 840 (2017) 34





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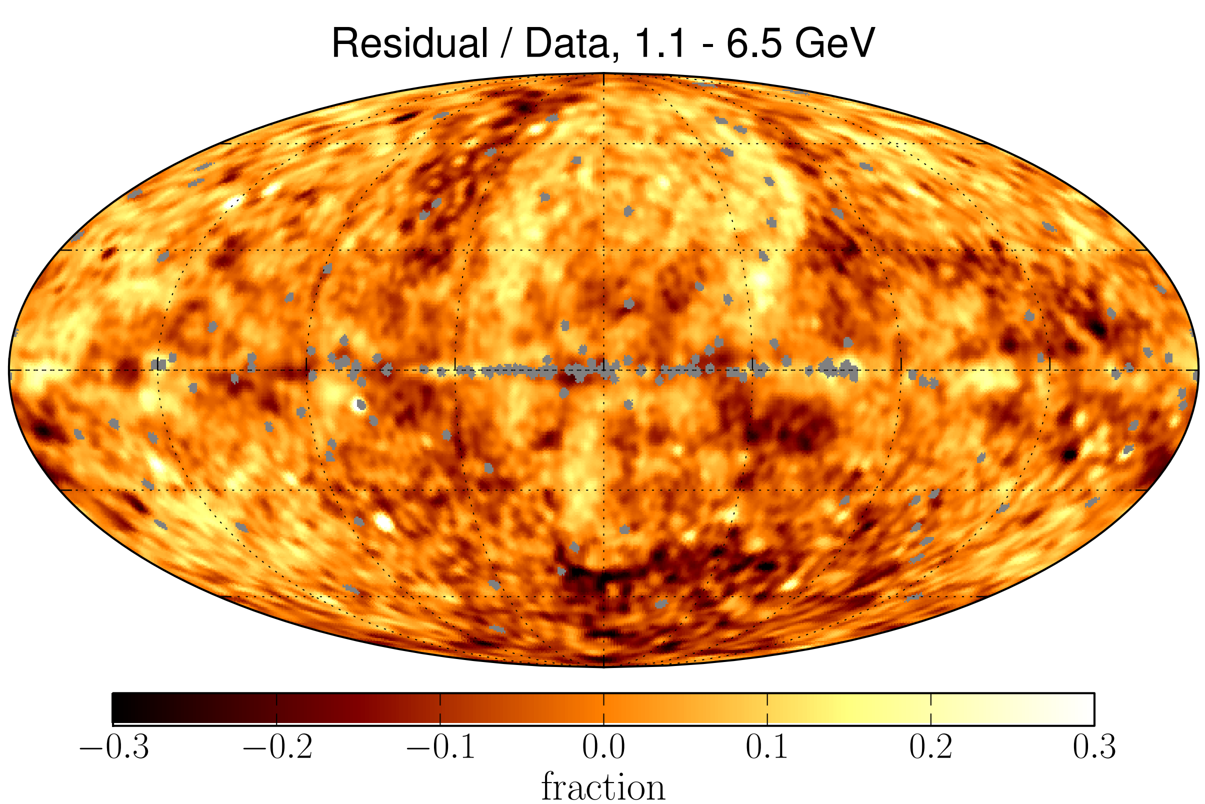

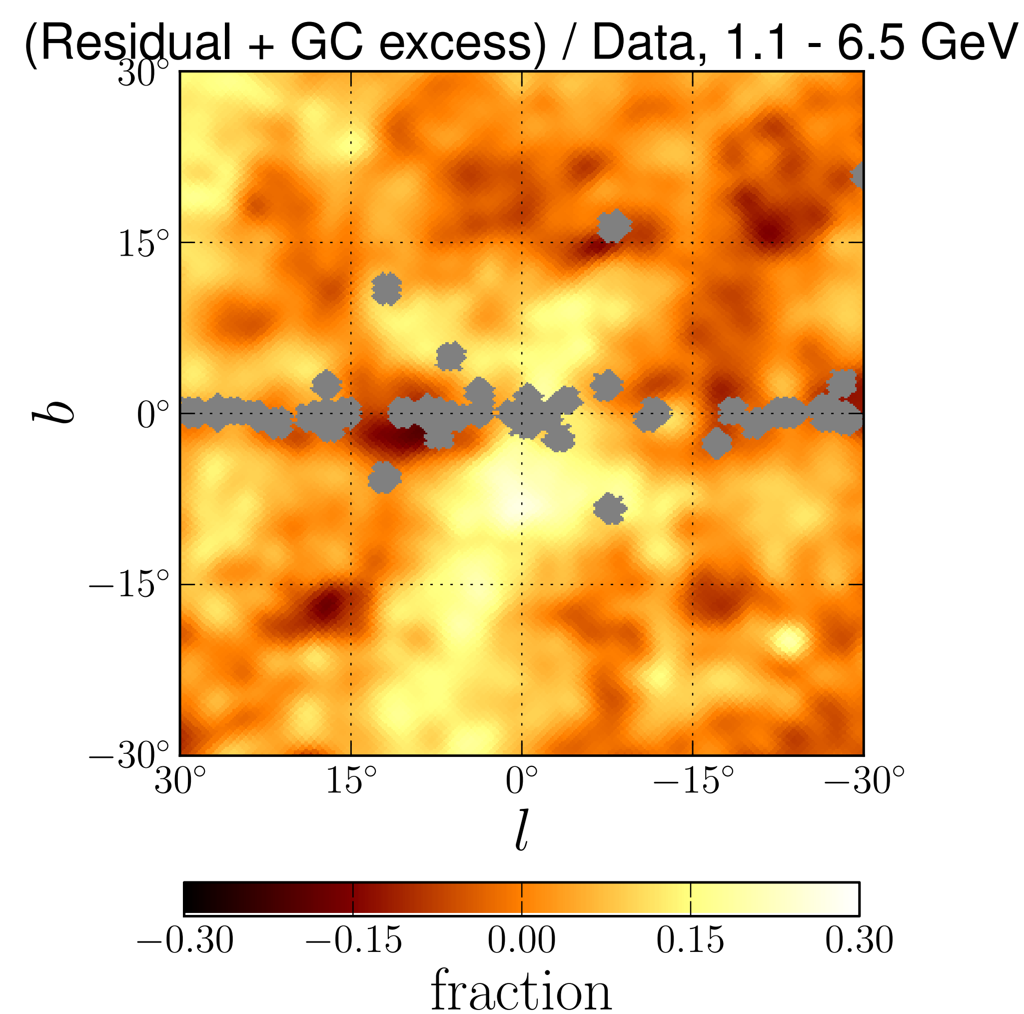

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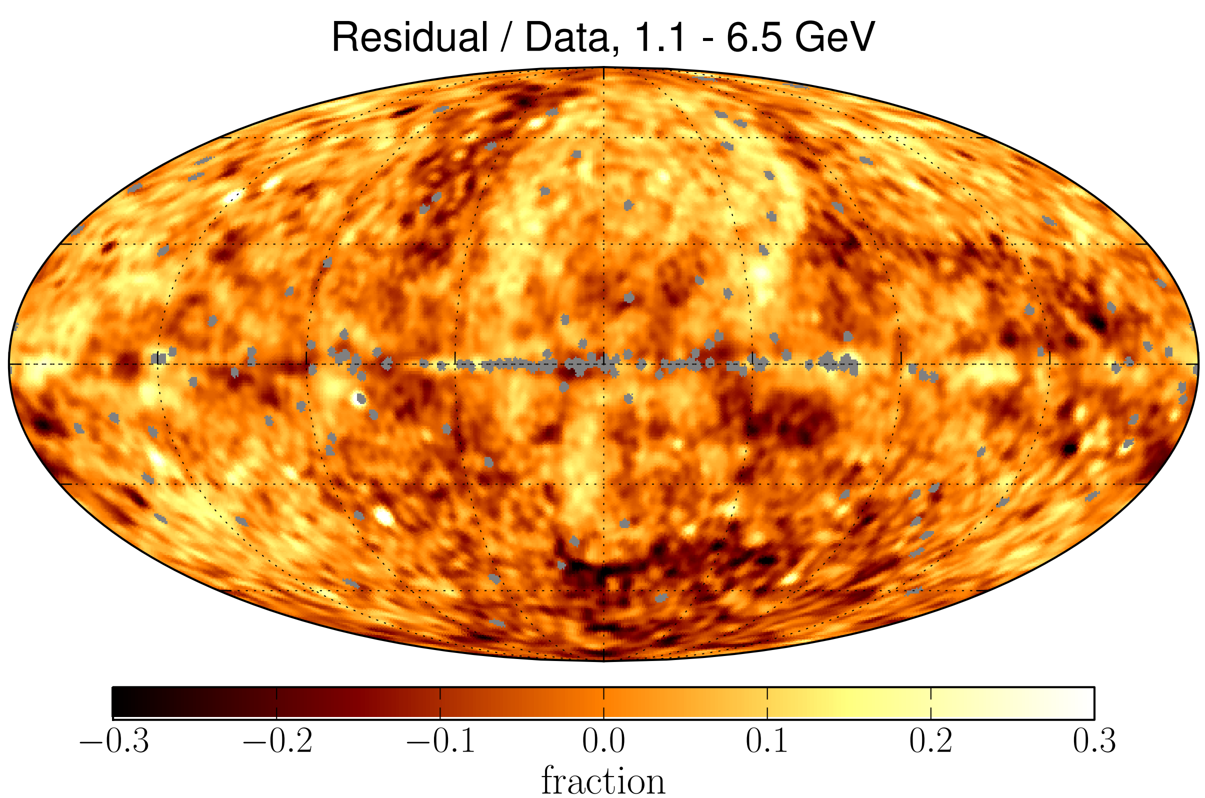

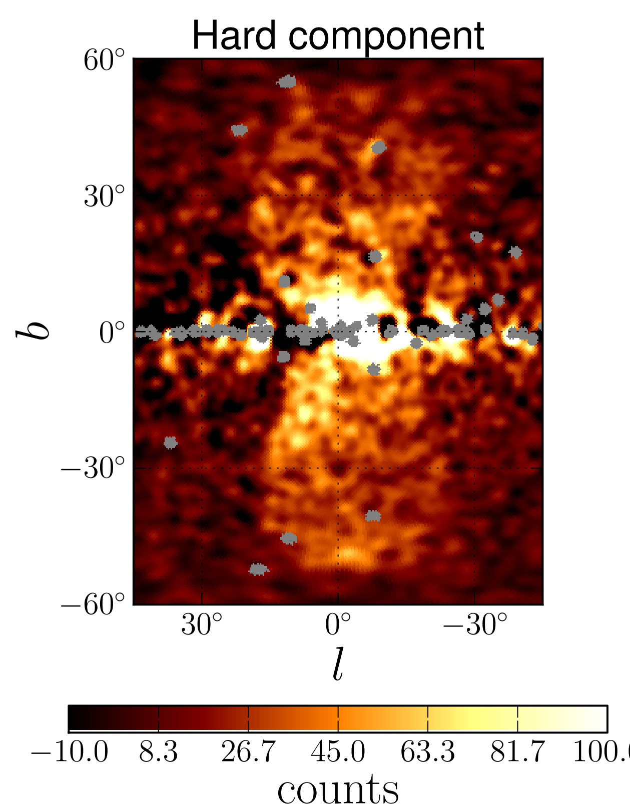

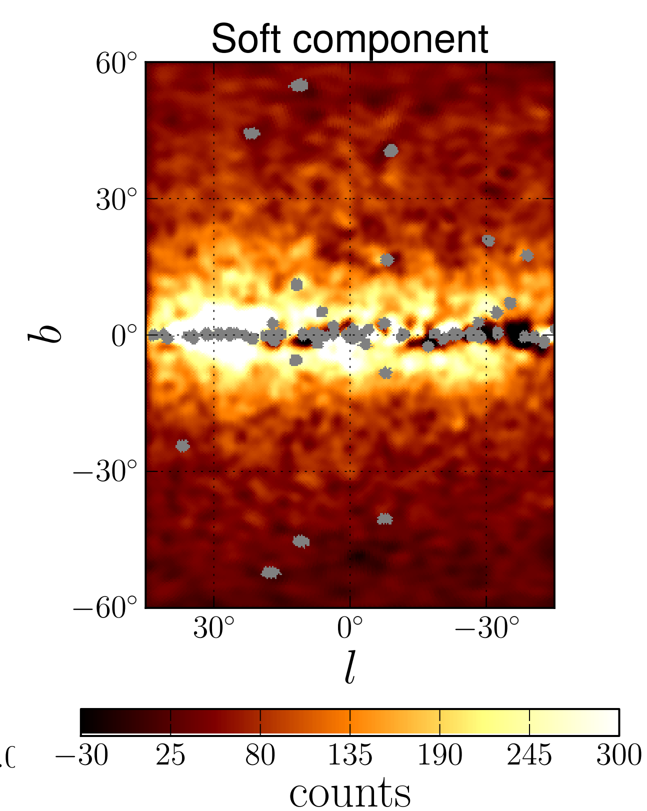

Recent “GCE” Analysis by LAT Team

- Detailed modeling of Galactic diffuse emissions
  - CR interactions with interstellar medium
  - CR electron interactions (bremsstrahlung, Compton up-scattering)
  - Fermi bubble at low galactic latitude
- GeV excess at Galactic center region is statistically significant
  - GCE spectrum vary by a factor of 3 at ~ a few GeV
  - Fermi bubble is major cause of uncertainties
  - GCE shape is not symmetric
  - Similar excess can be found outside of Galactic center region

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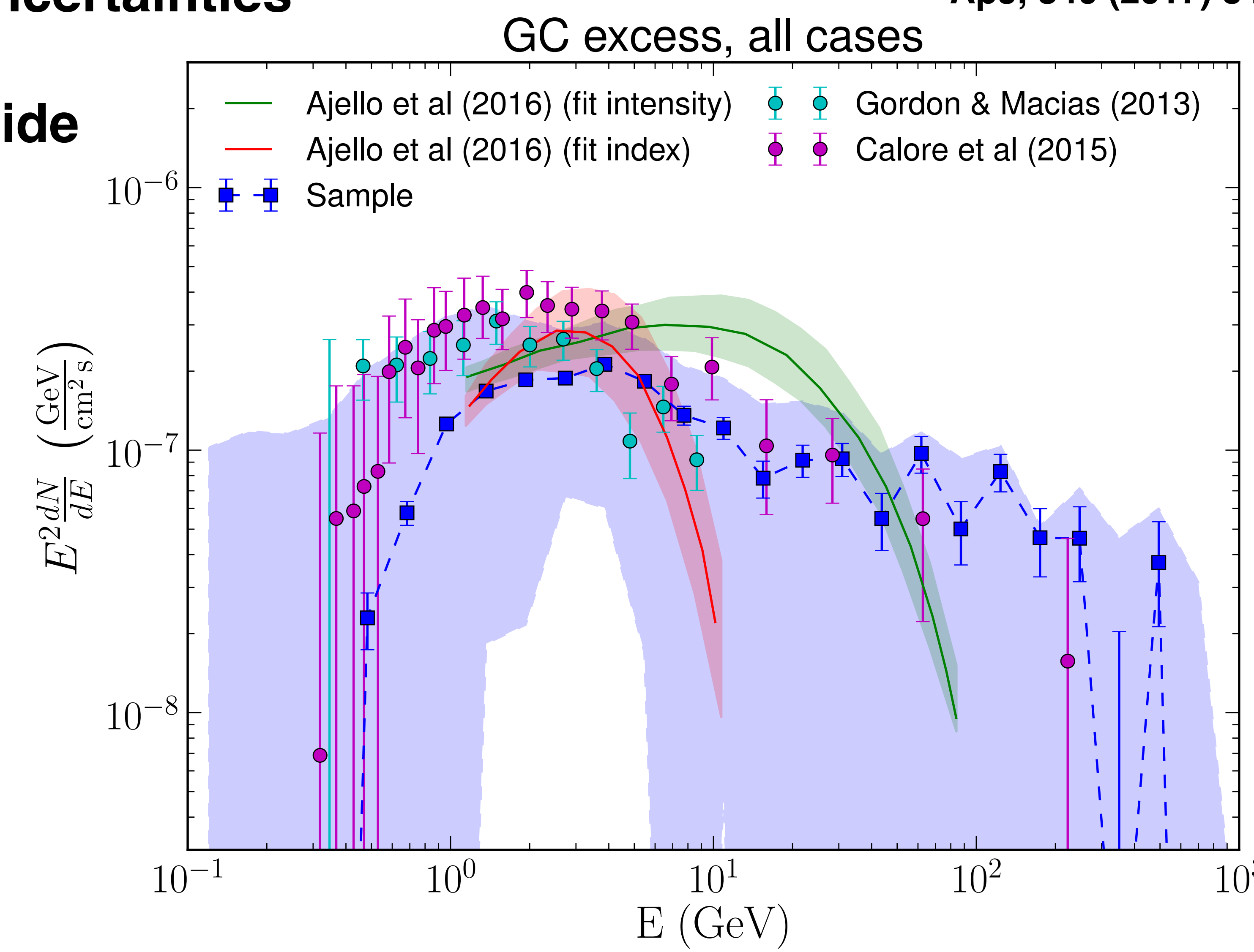

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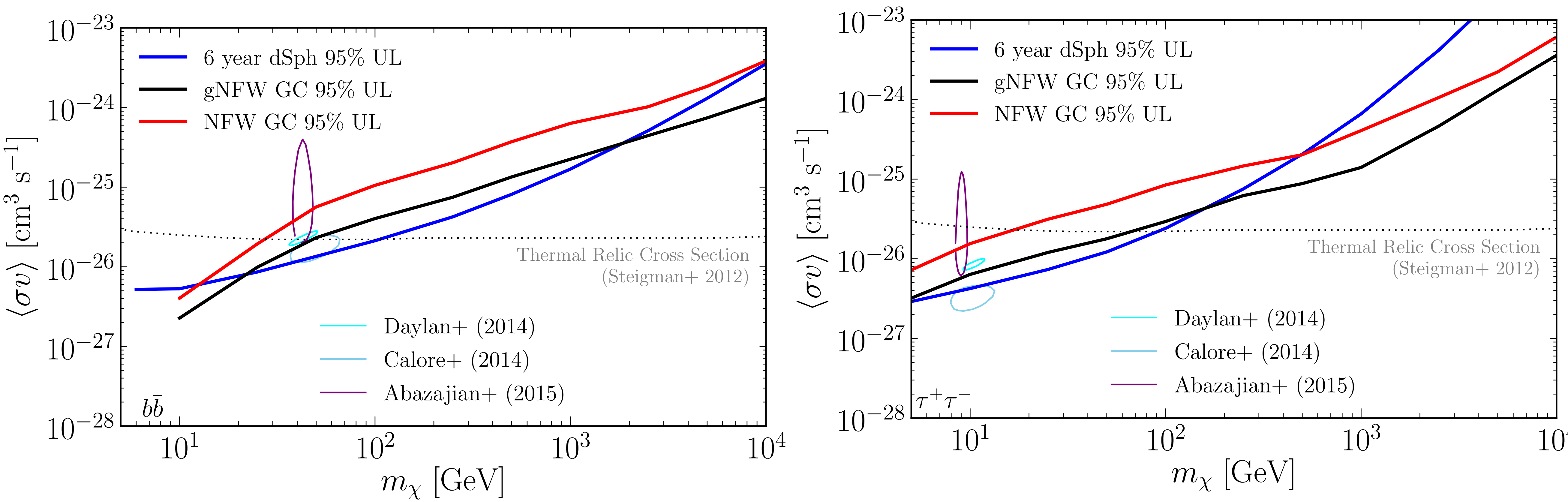
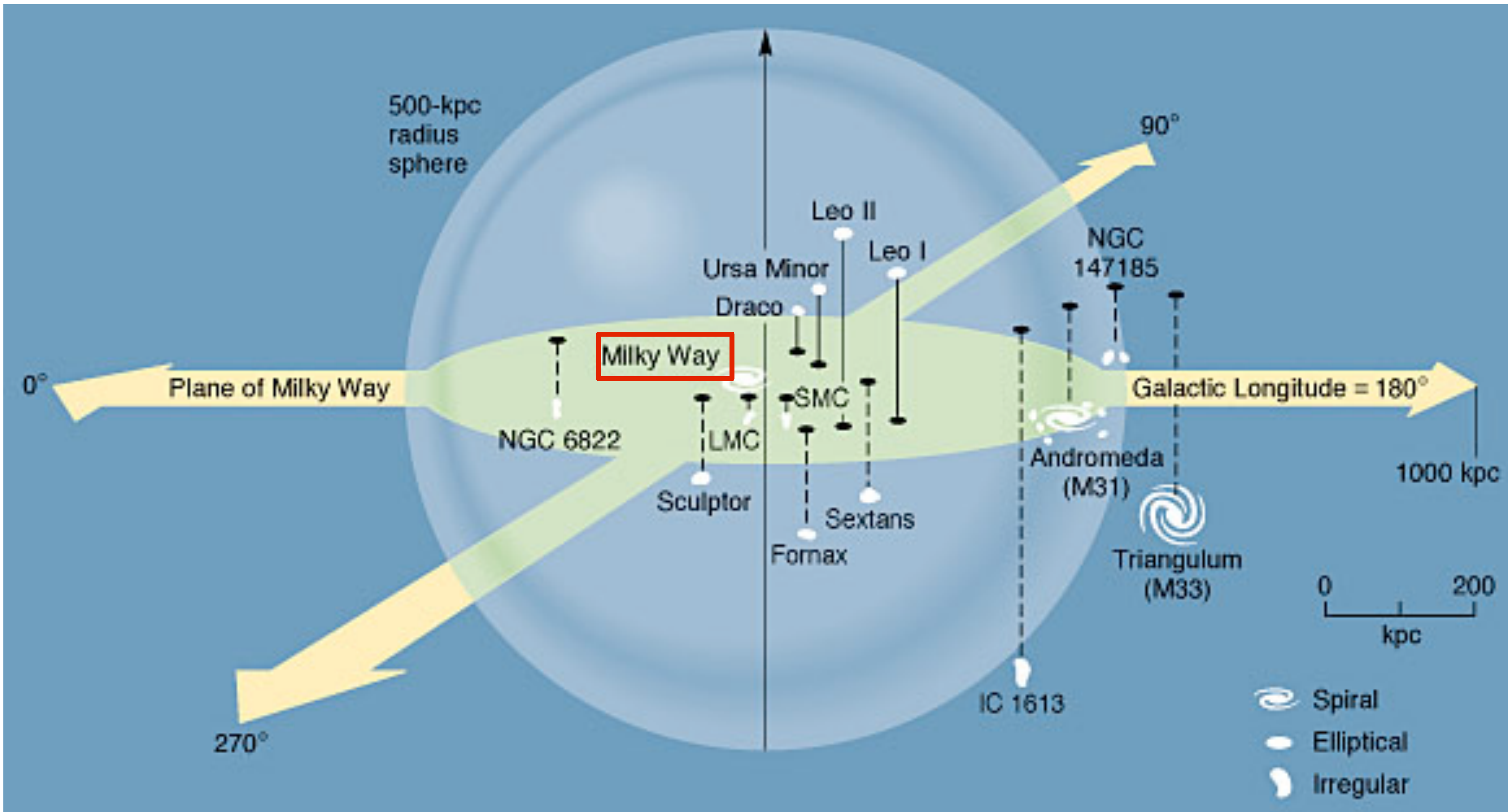


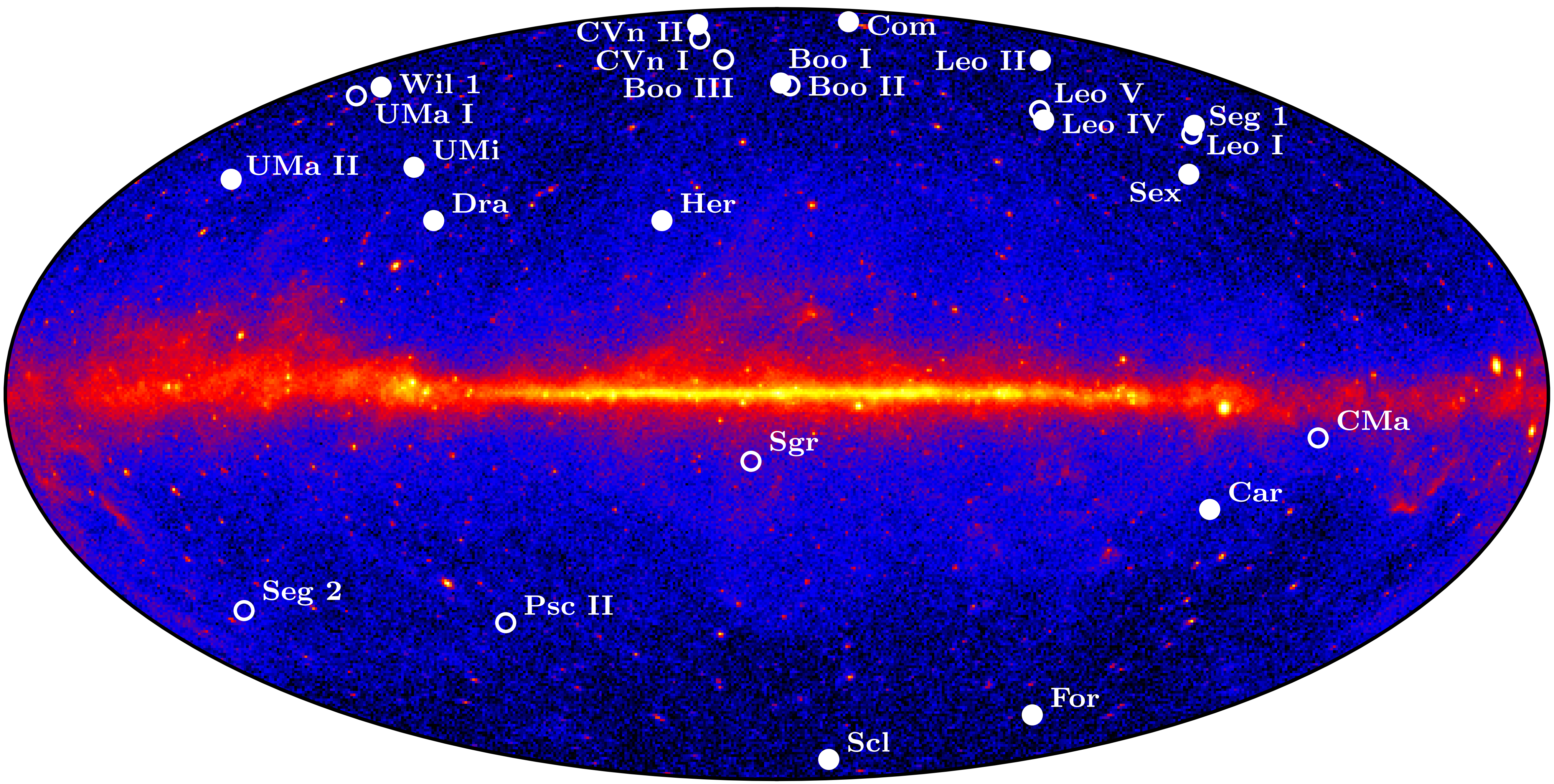
Dwarf Spheroidal Galaxies

- Many dwarf spheroidal galaxies (dSph) around our Galaxy
  - dSphs are known to have large dark matter fraction (~100%)
  - Negligible gamma-ray backgrounds from ordinary matter (few stars)



Fermi DM Search in Dwarf Galaxies

- 15 dwarf spheroidals (dSphs) with 6 years of Fermi-LAT data
  - Selected based on distance, matter/light (M/L) ratio
- New "pass 8" data set: >20% more acceptance, ~10% more FOV
- Exclude up to ~80 GeV/c^2 in $\tau^+\tau^-$, ~100 GeV/c^2 in *bb* (and *uu*)



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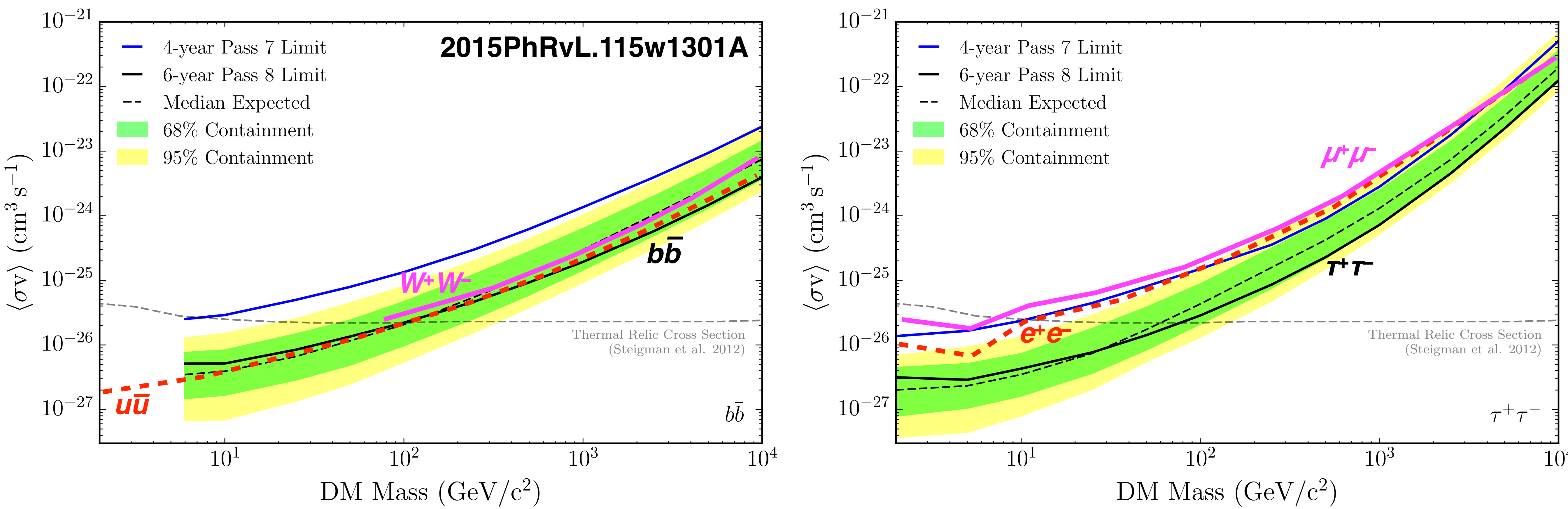
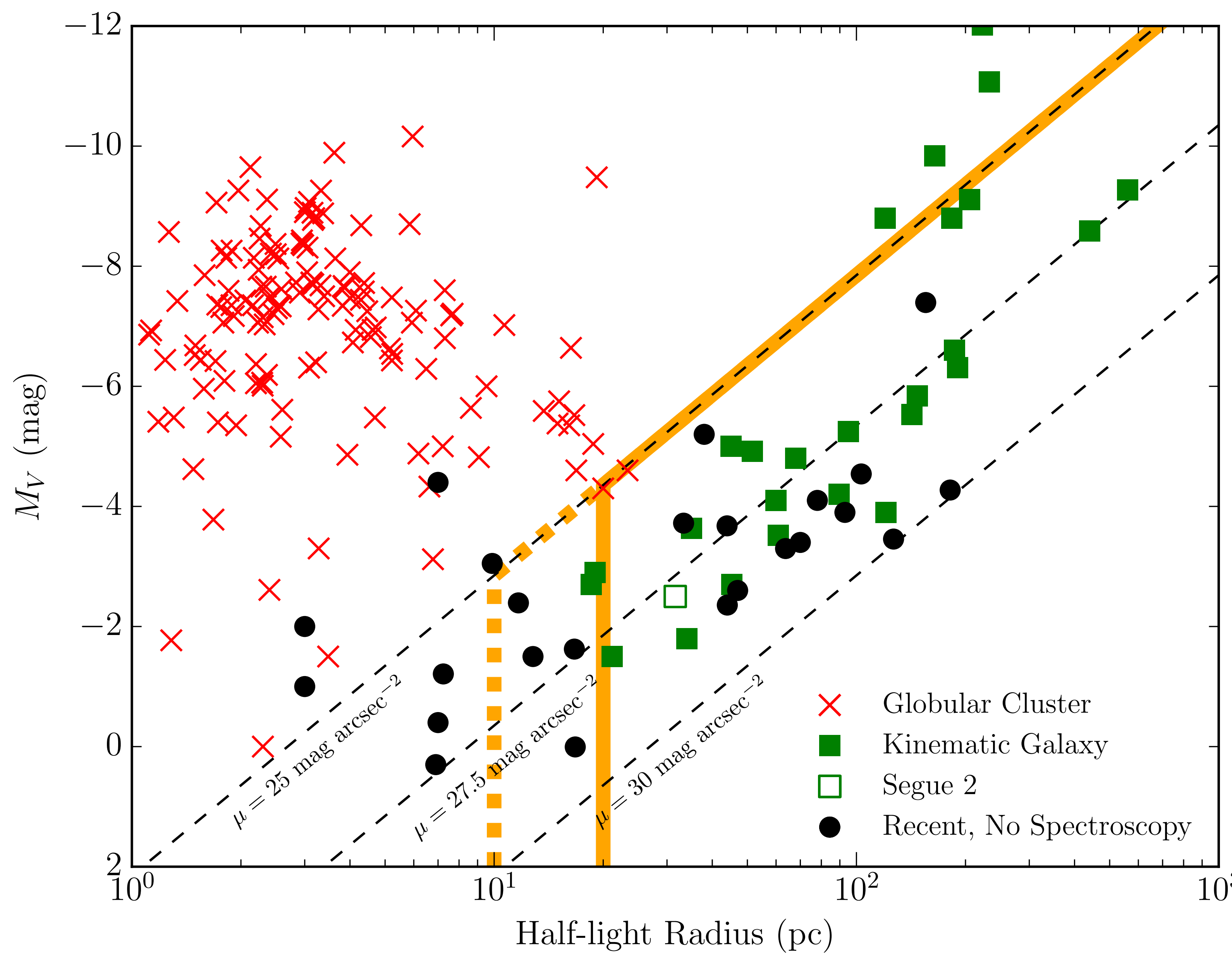


New DM Search in Dwarf Galaxies

- 45 dSphs with 6 years of Fermi-LAT data
  - 28 kinematically confirmed and 17 recently discovered dSphs
- No significant WIMP signal observed

ApJ 834 (2017) 110



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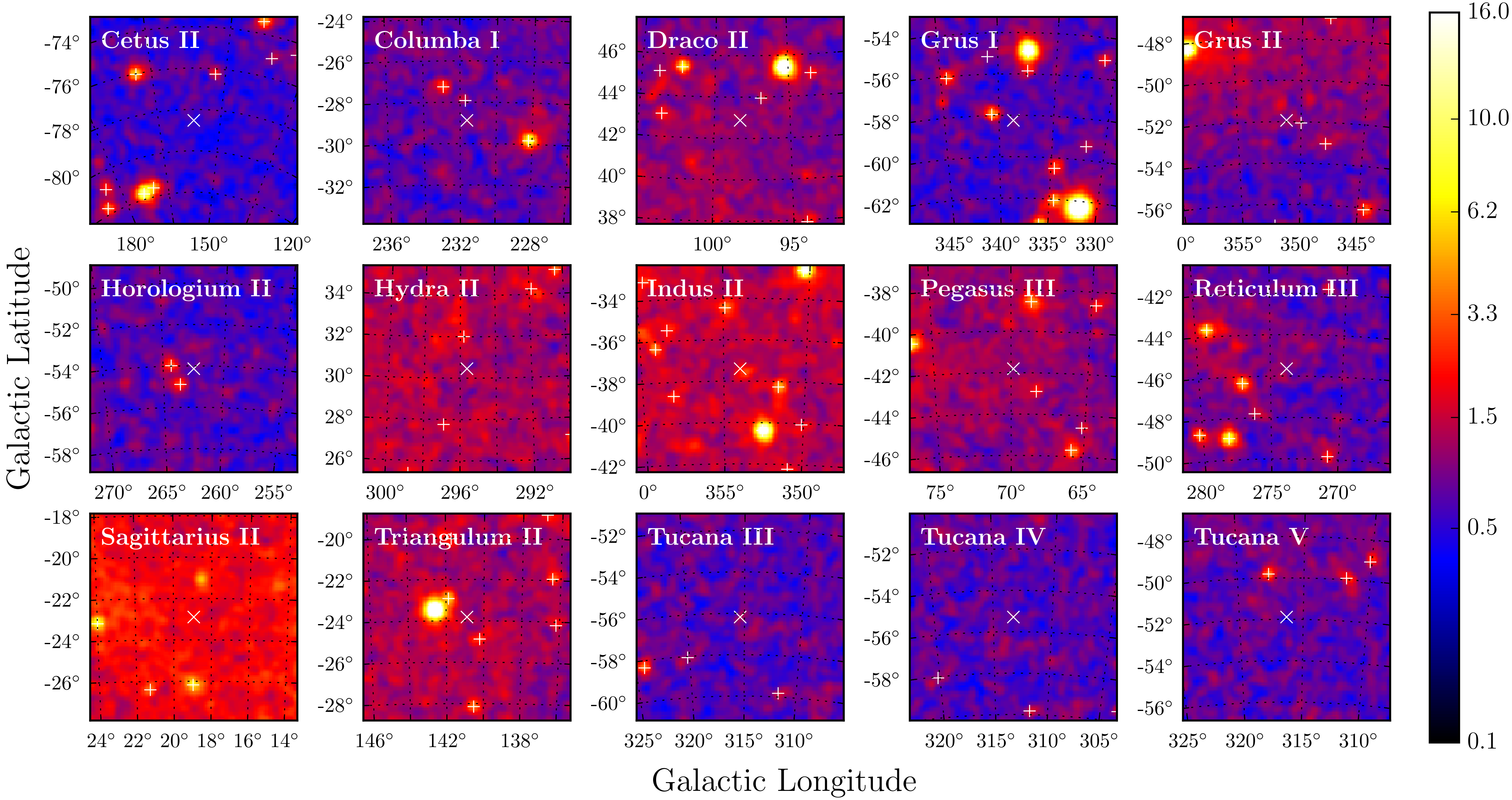

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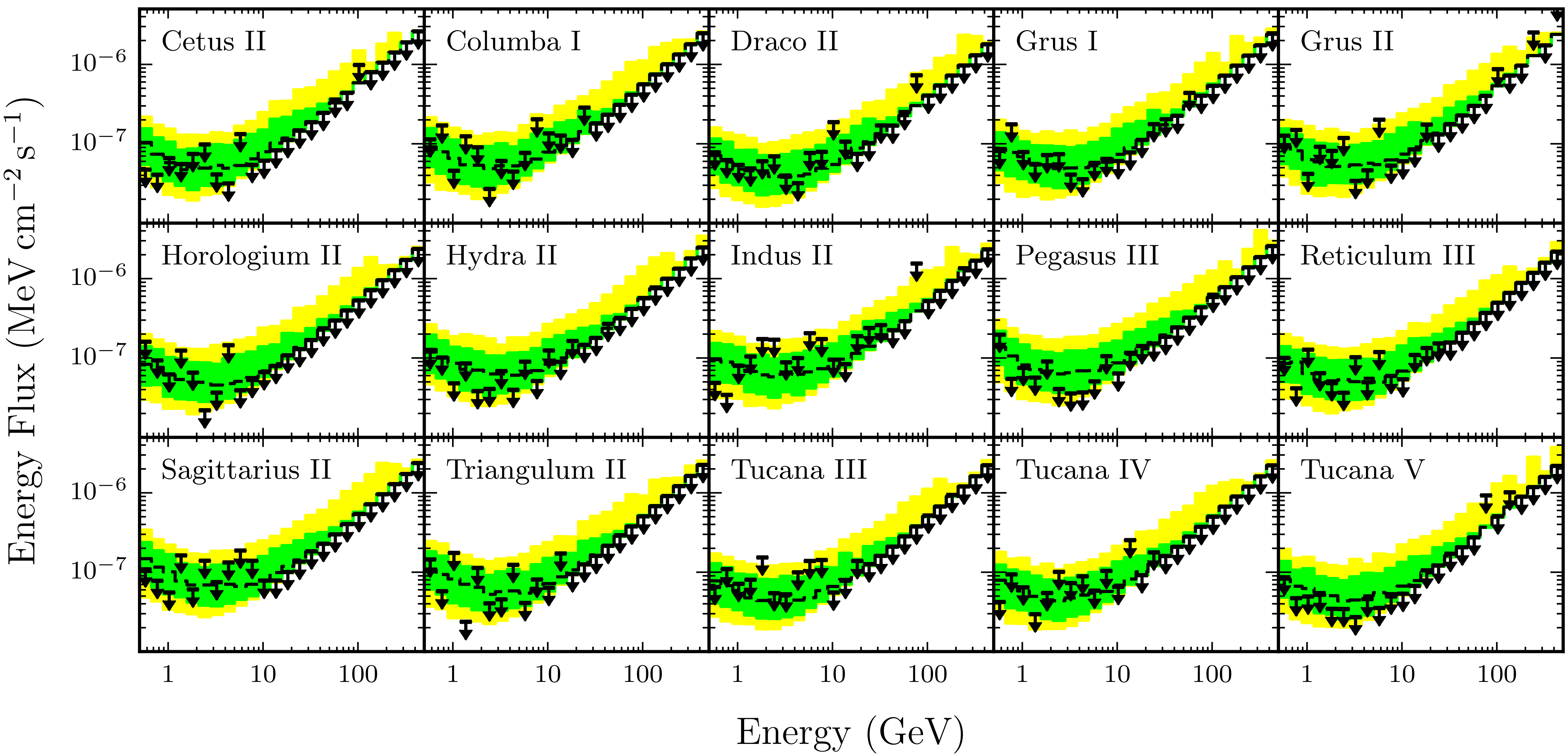

Constraints on DM Mass

- Test statistic (TS=−2[ln*L*−ln*L*$_0$]) for each dSph as a function of DM mass show no coherent peak at a certain DM mass
  - 4 dSphs are inconsistent with null at 97.5% C.L.
- Combined TS with proper weighting by J-factors still has a peak (J-factor ∝ expected # of annihilation)
  - This structure is reflected into the U.L. on the annihilation cross section

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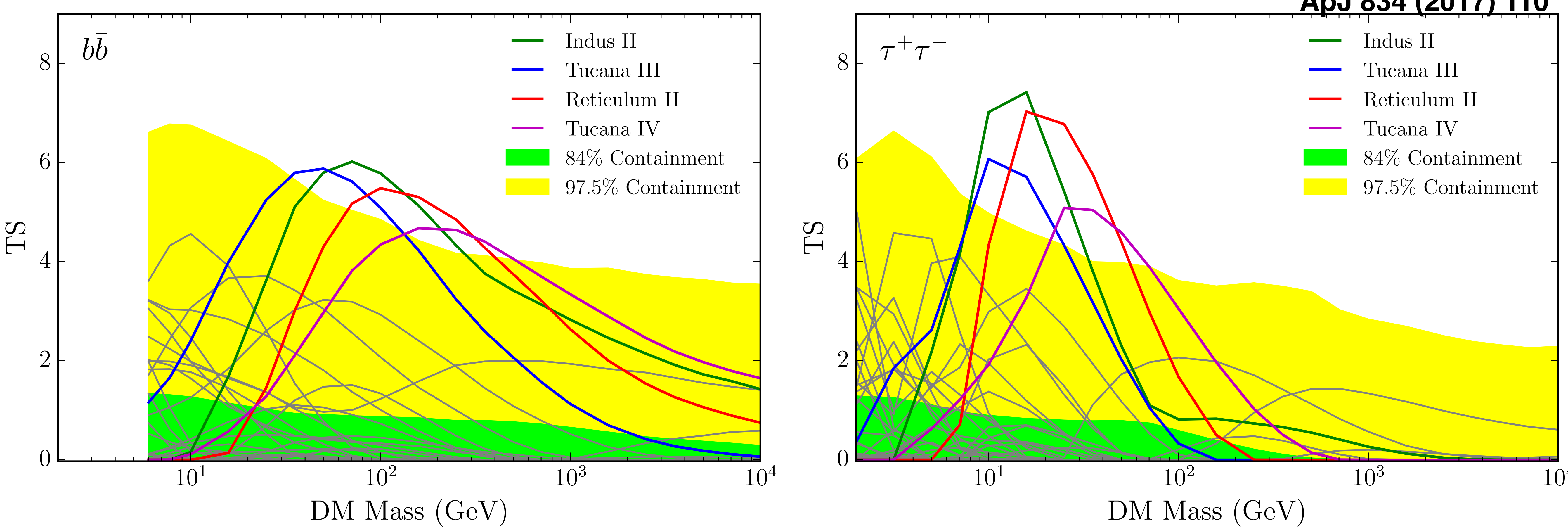

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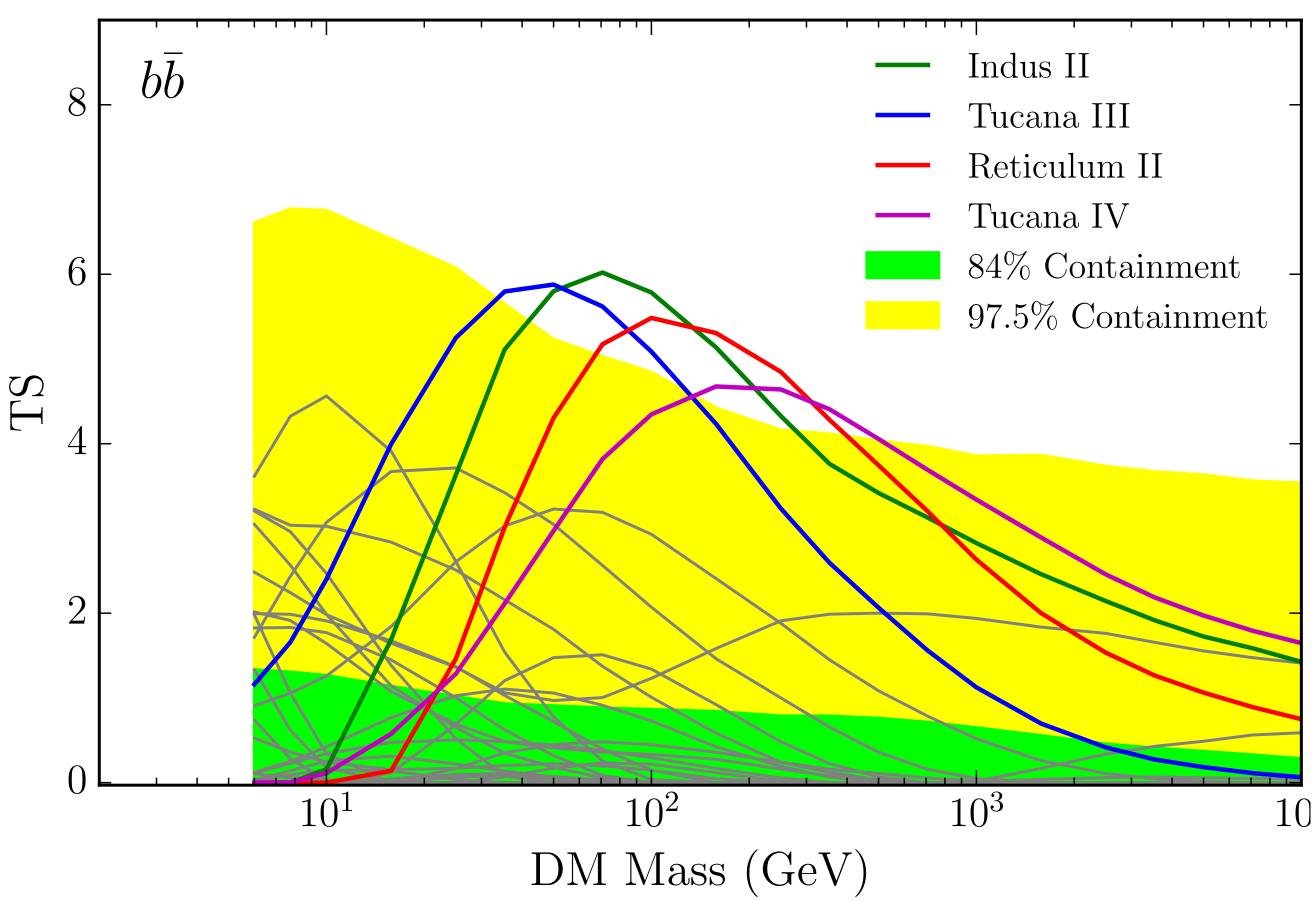

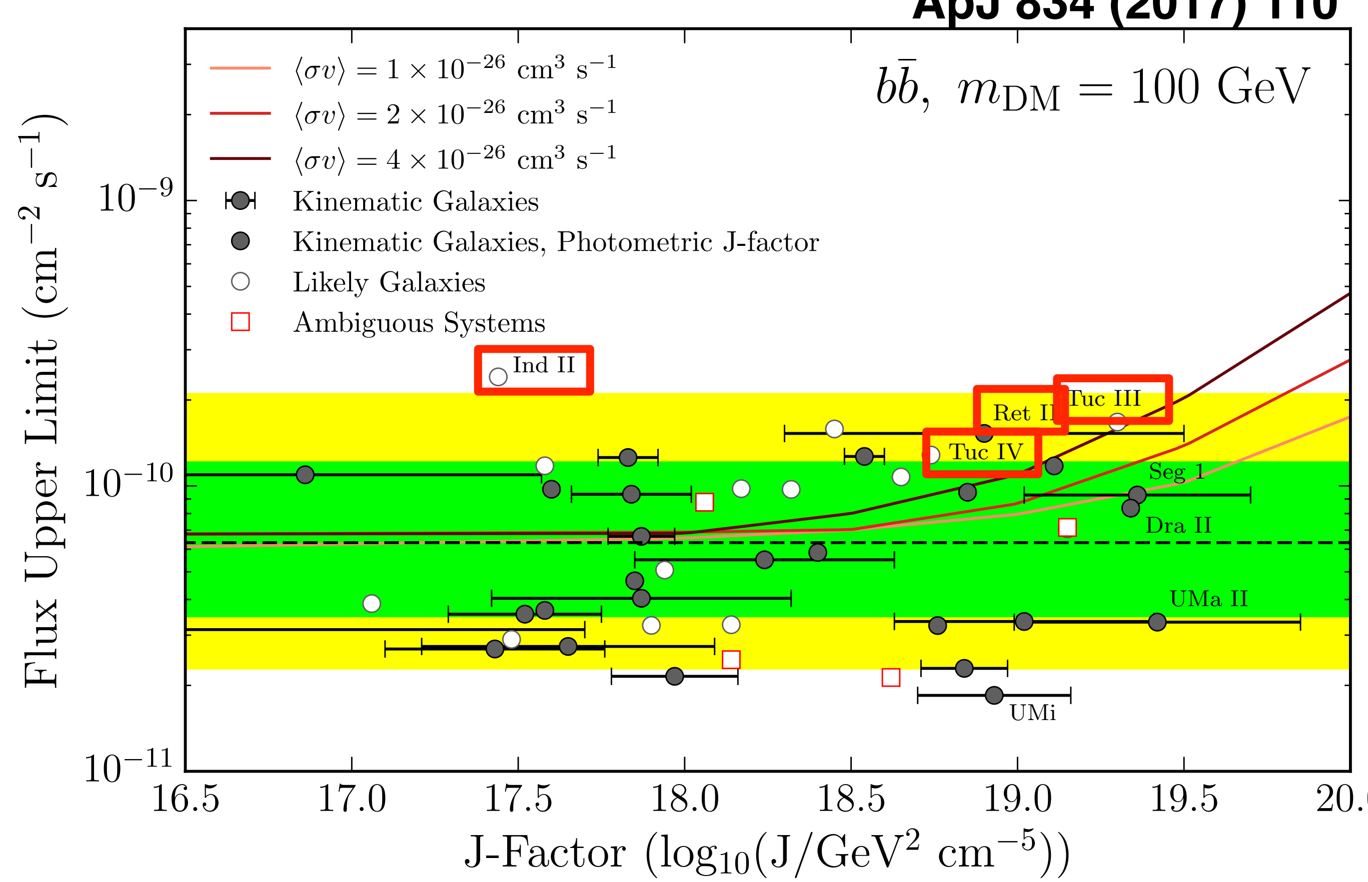

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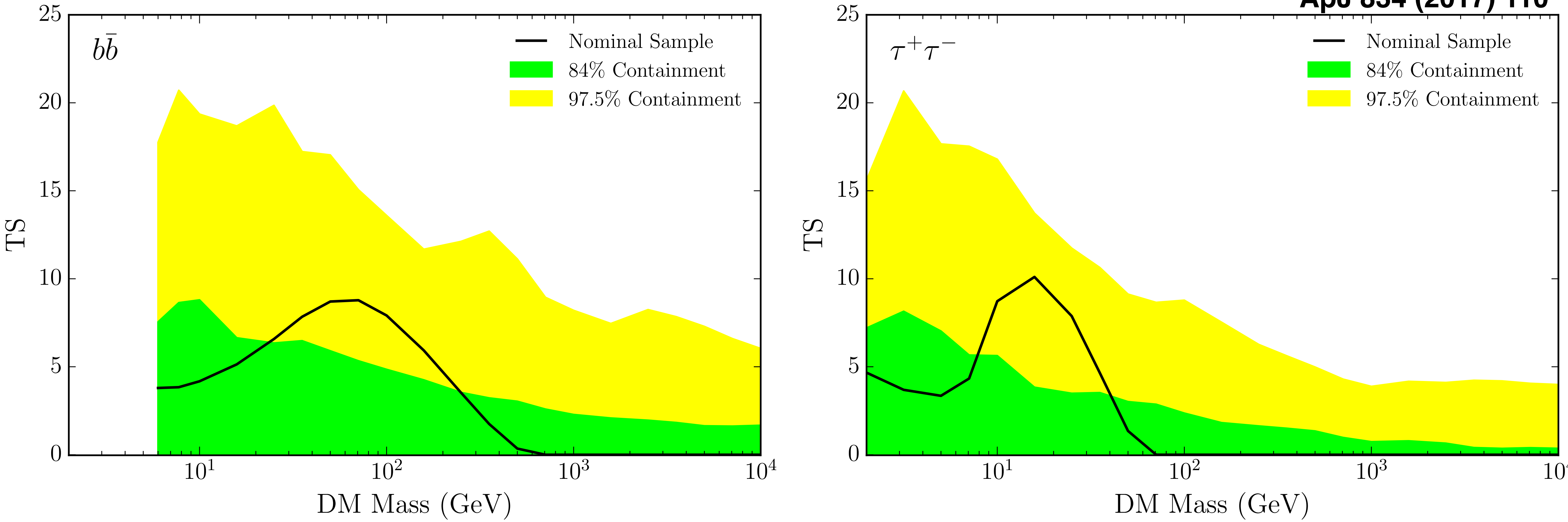

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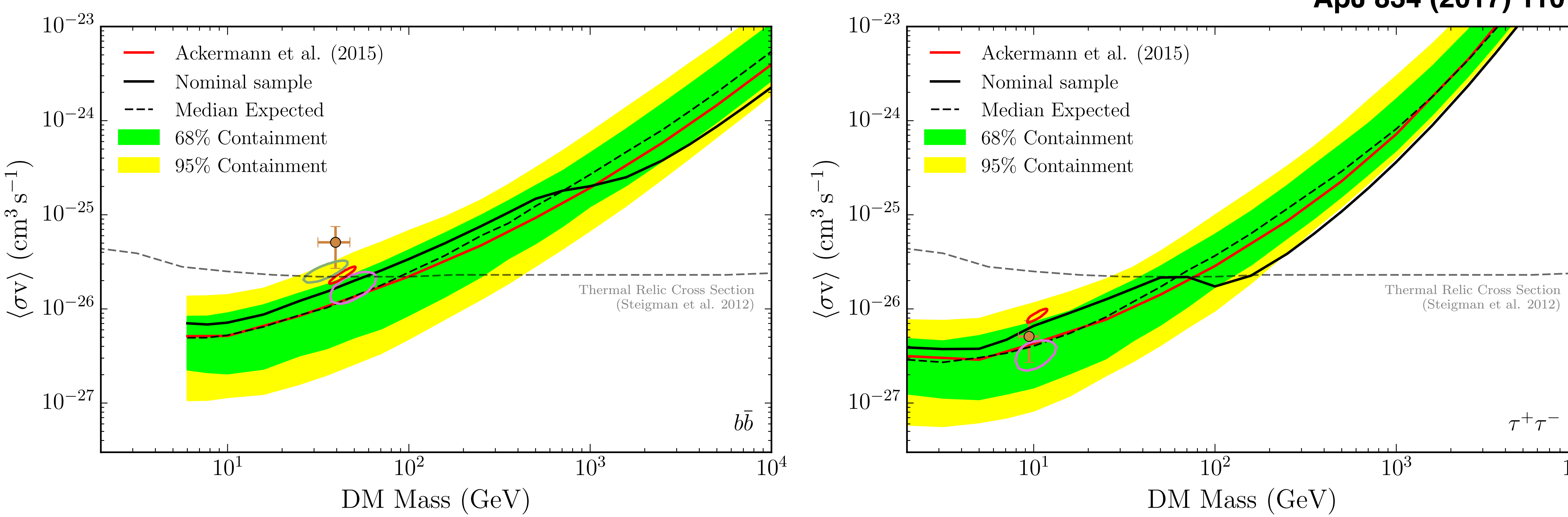
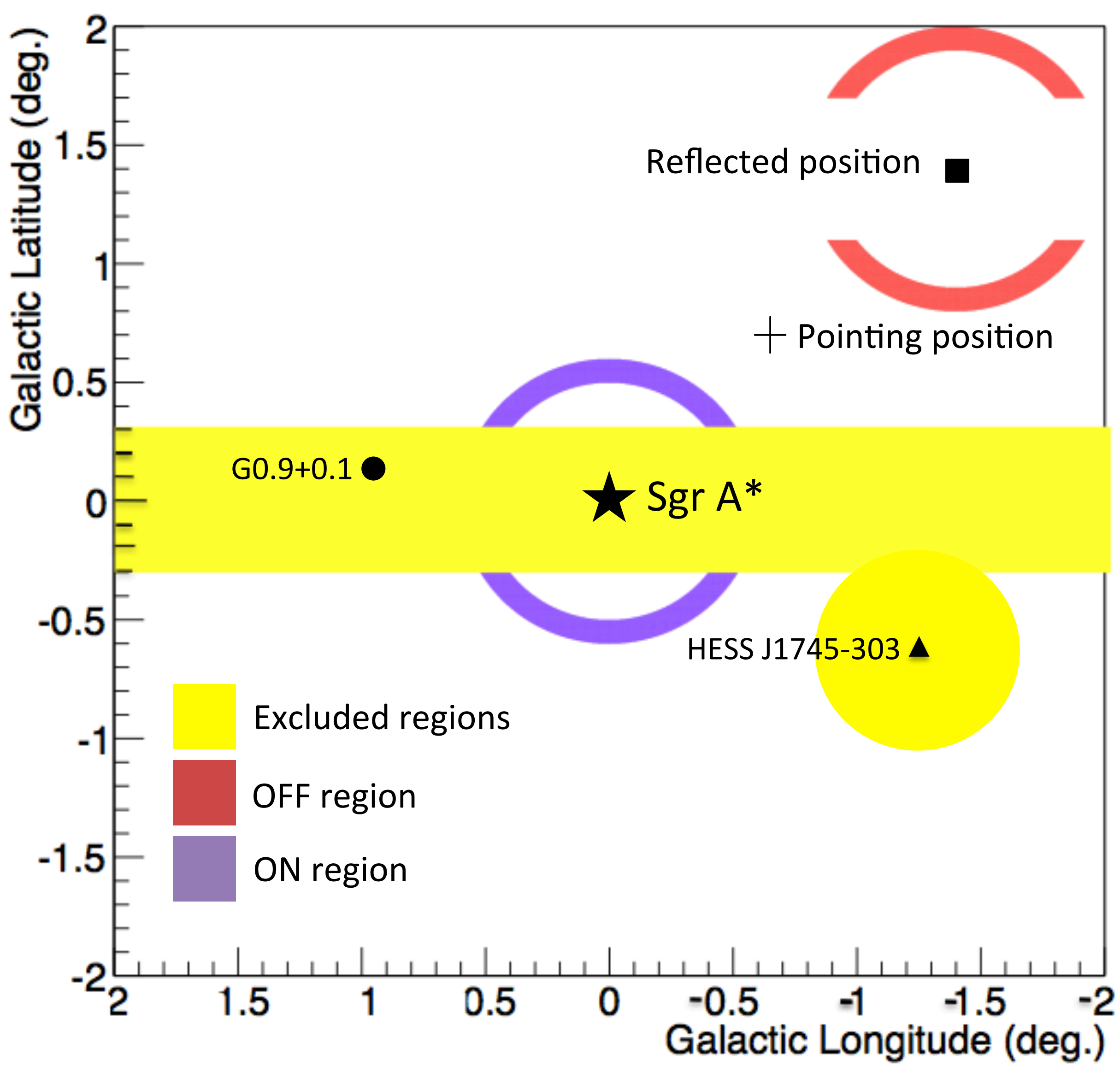
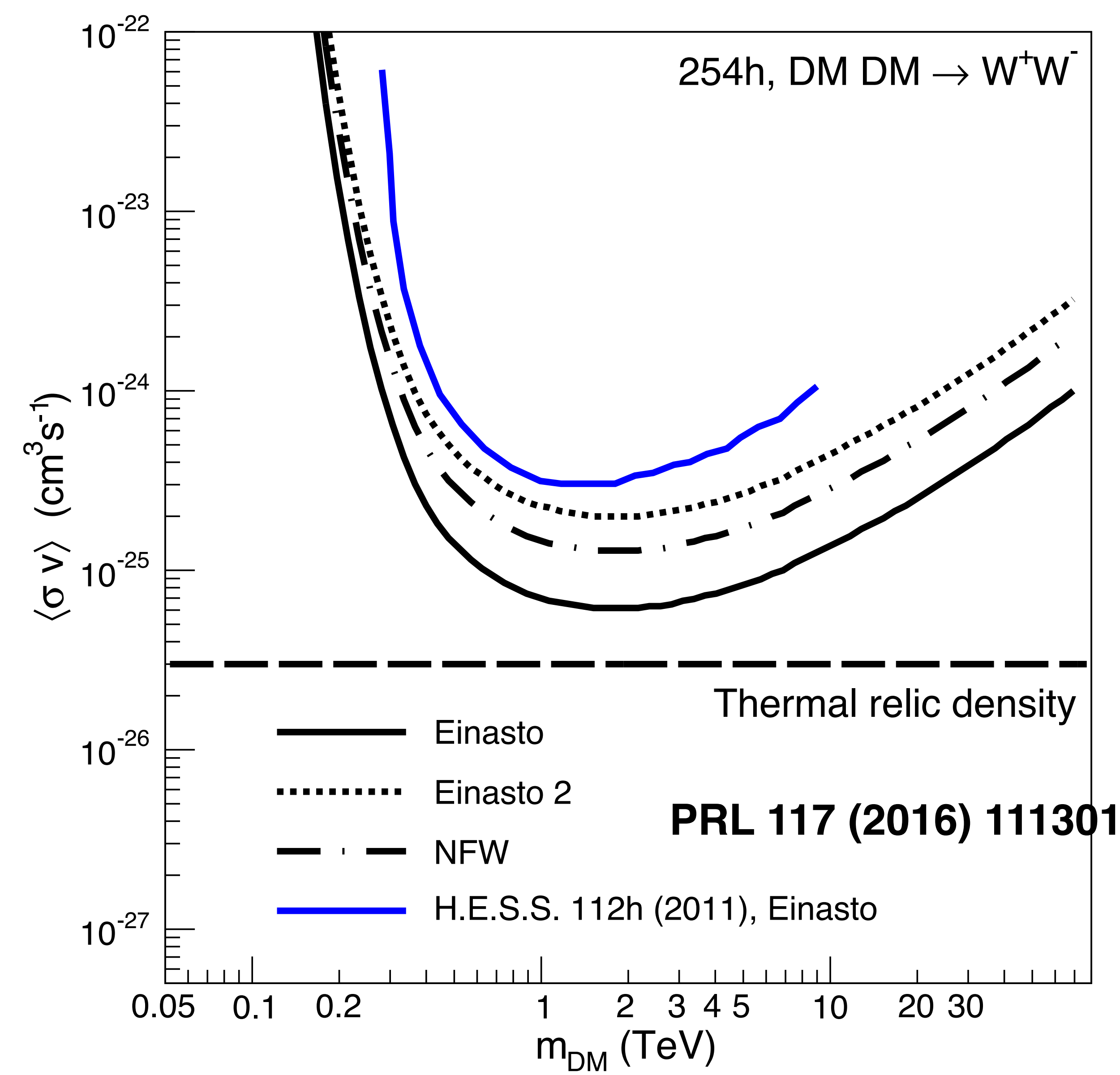


DM Search with TeV Gamma Rays

- H.E.S.S. Observations of Galactic center for 254 hours
  - Galactic diffuse BG in TeV band is relatively low compared with GeV band due to steep spectrum
  - Local cosmic-ray electrons producing EM showers are dominant BG
  - Uncertainties of DM density profile give large uncertainties





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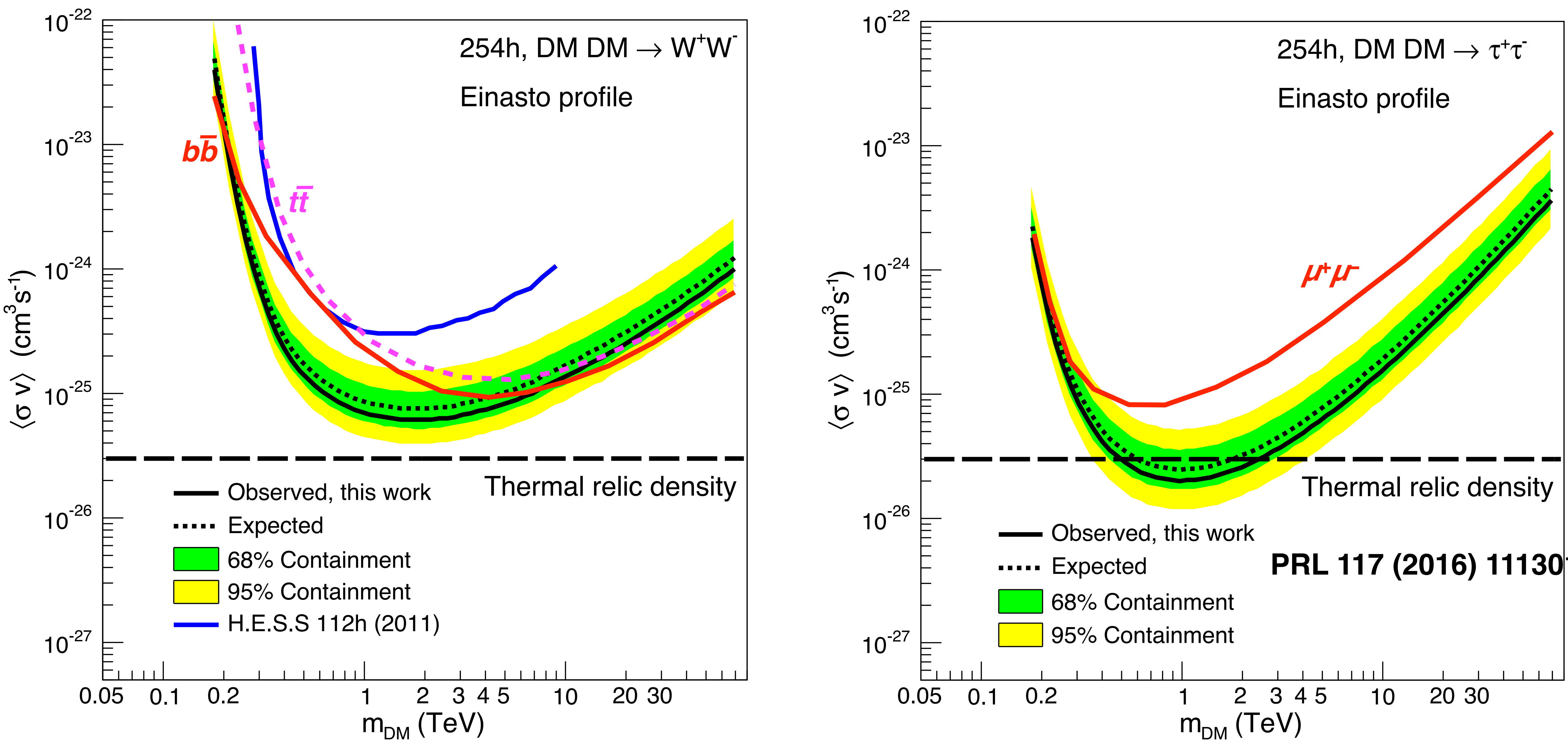
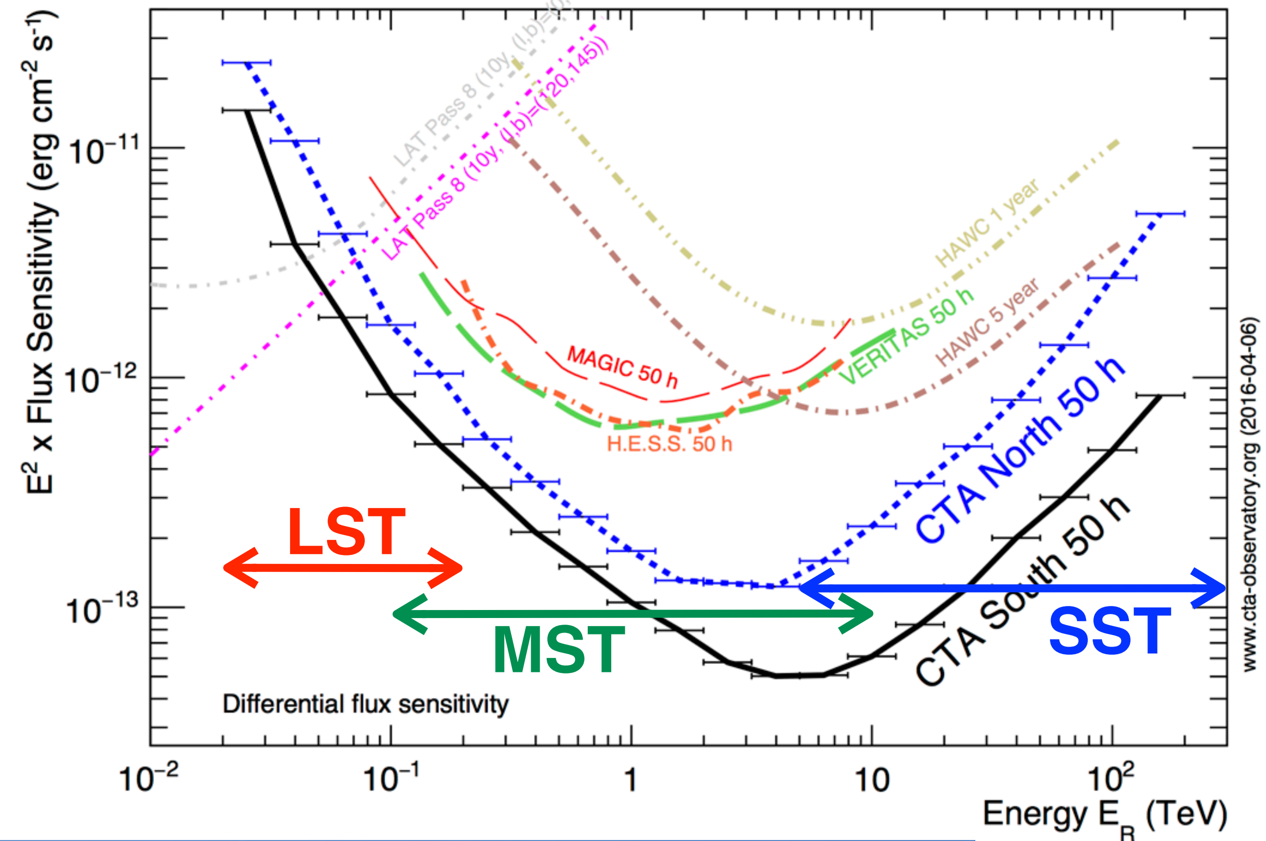


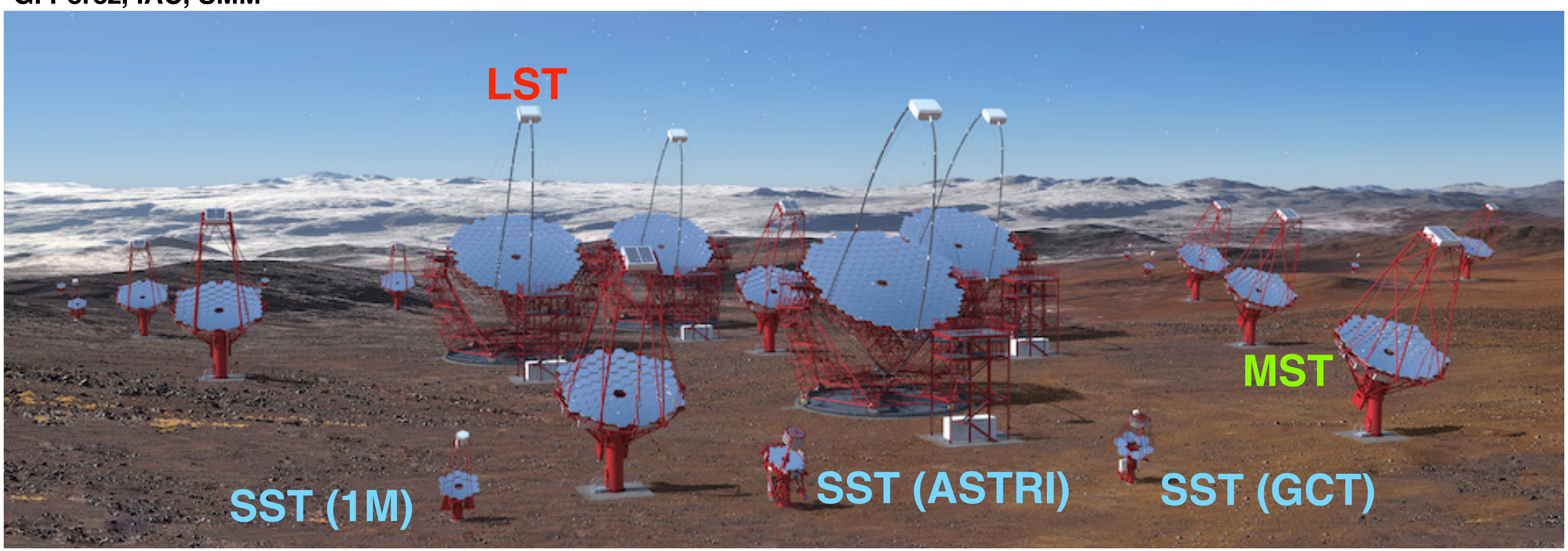
PRL 117 (2016) 111301

Future Gamma-ray Observatory

- Cherenkov Telescope Array (CTA)
  - Large number of telescopes
    - Large collection area (×~30)
    - Better angular resolution (0.03°)
  - Optimized telescope configuration
    - LST: ~23 m ϕ × 4, ~20 GeV – 200 GeV
    - MST: ~12 m ϕ × 20, ~100 GeV – 10 TeV
    - SST: ~4 m ϕ × 70, ~5 TeV – 300 TeV
  - ~1000 of TeV gamma-ray sources

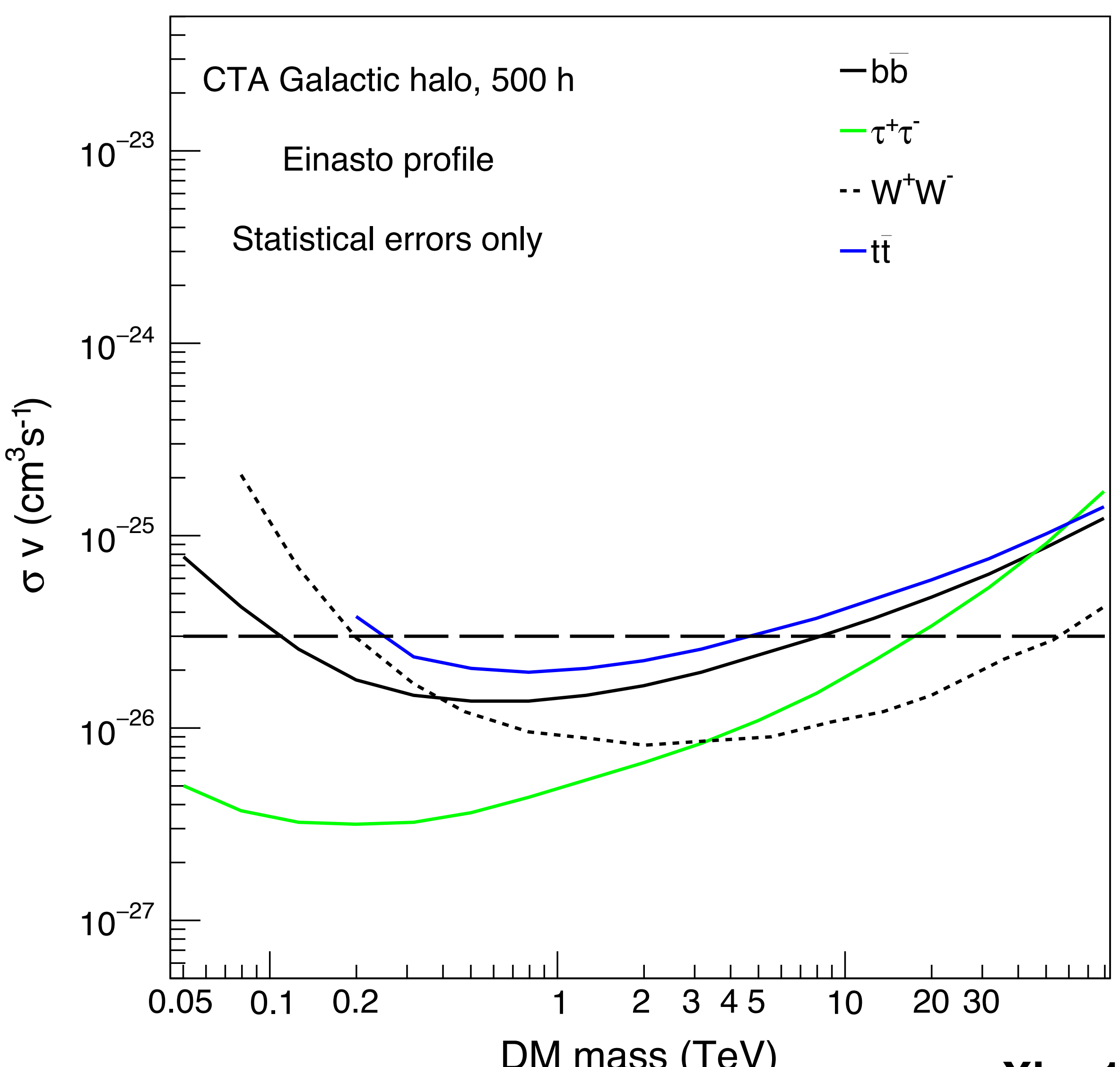


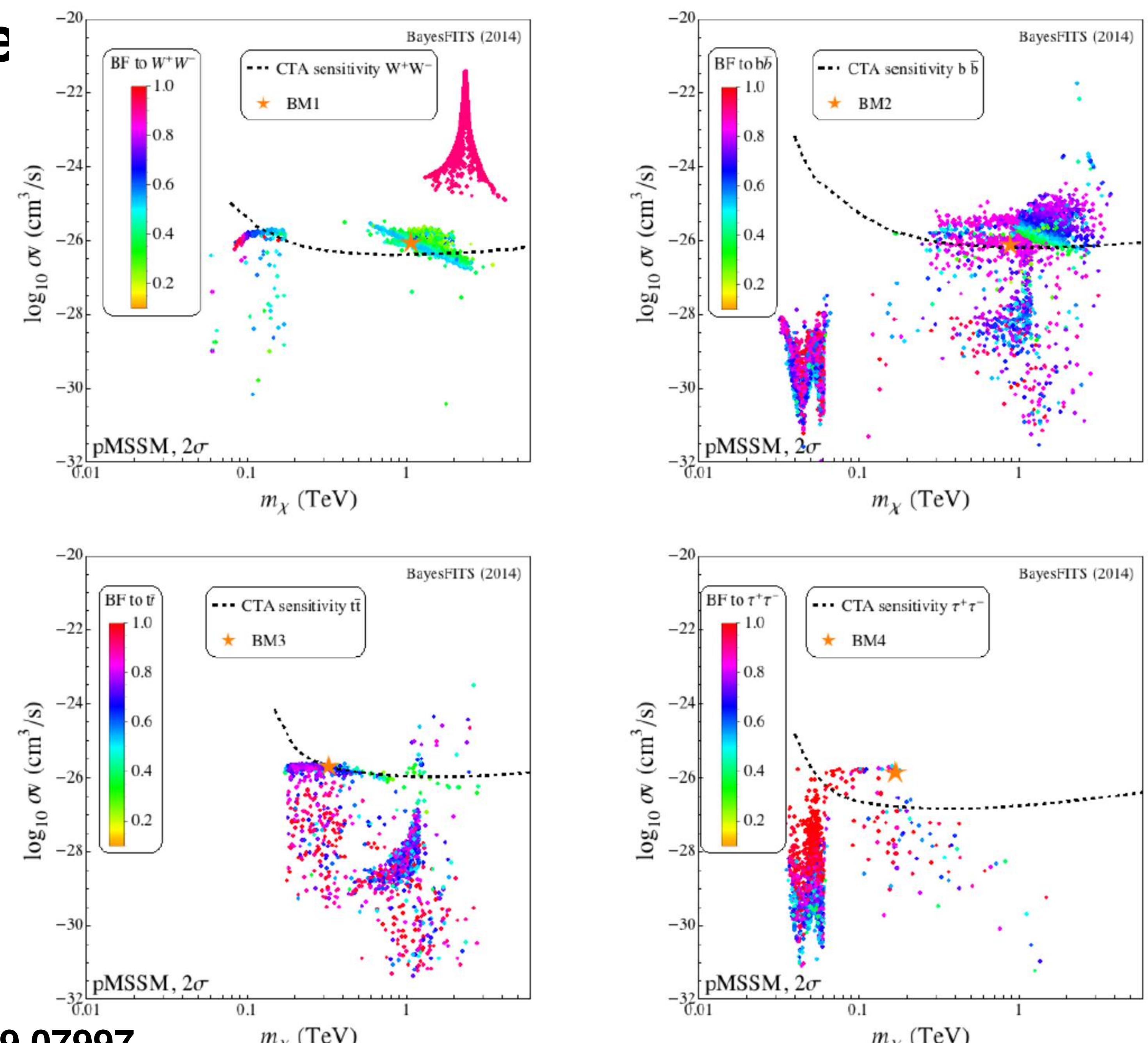
G. Pérez, IAC, SMM



CTA Sensitivities on Dark Matter

- Sensitivity depends on particle produced by DM annihilation and DM annihilation cross section
  - Those are dependent on DM particle model
- Systematic errors due to CR e





arXiv: 1709.07997

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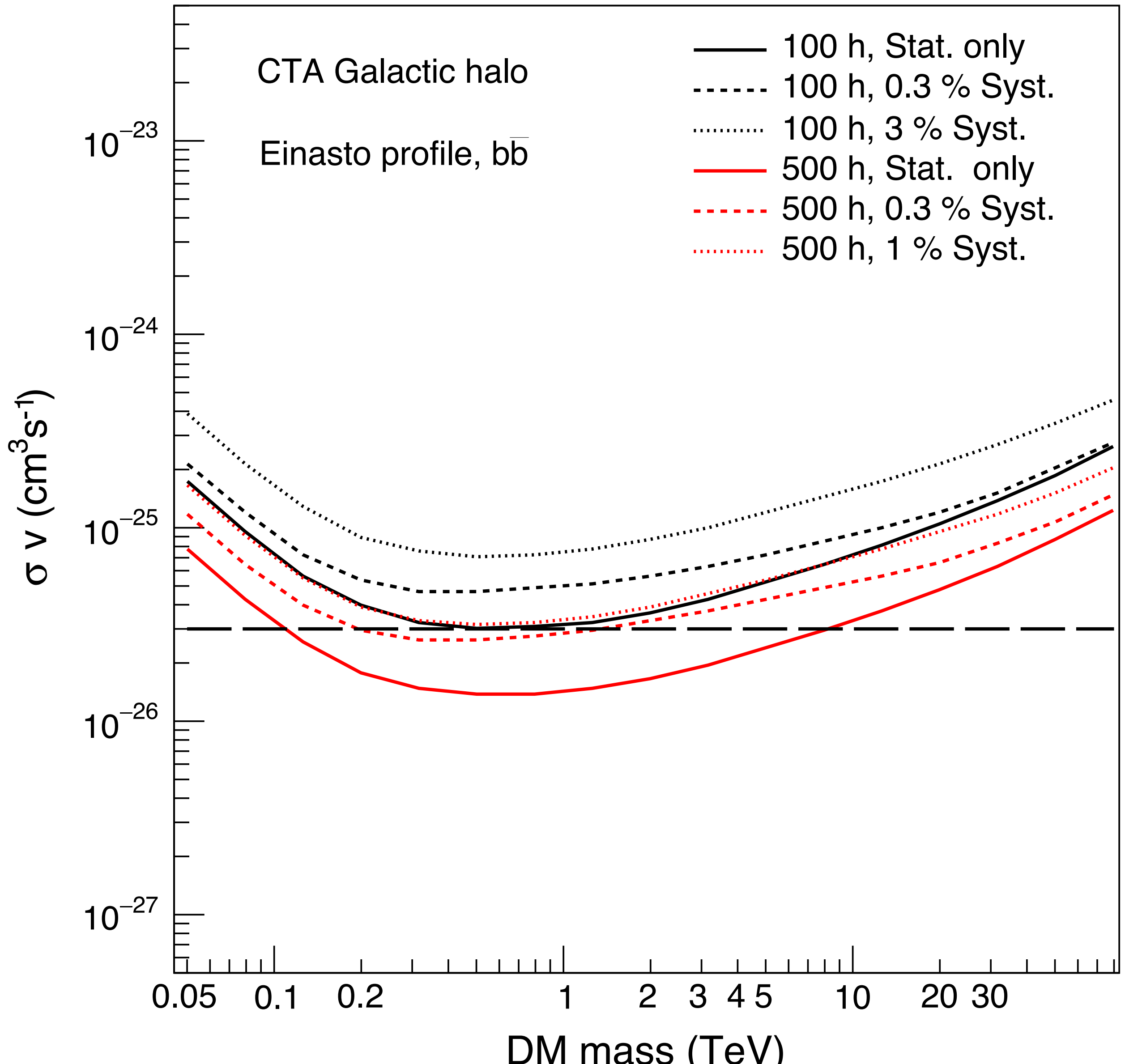

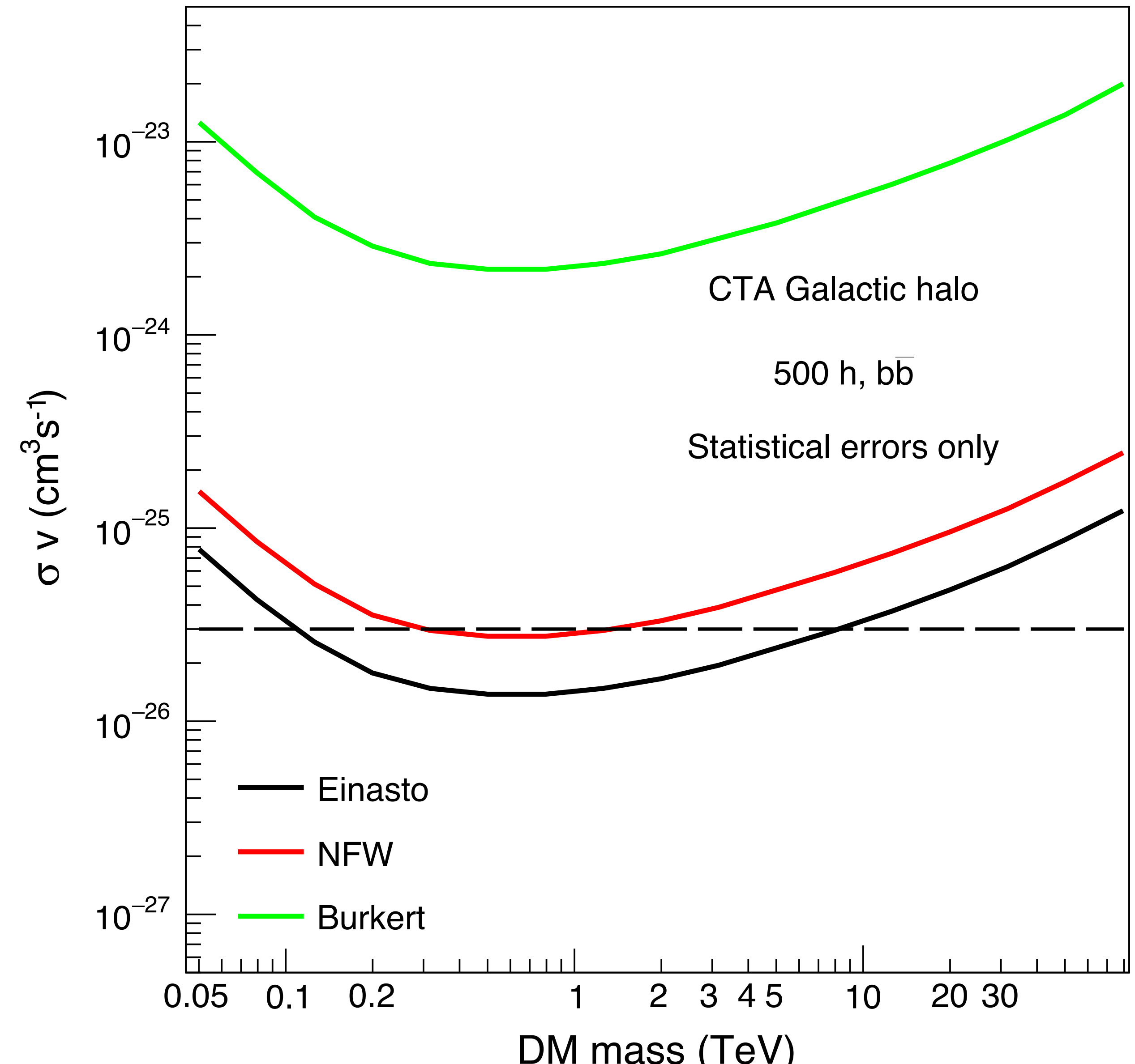

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Summary of Indirect Searches

- ~ an order of magnitude improvements expected up to 10 TeV/c^2
  - Fermi-LAT: increased statistics and more dwarf spheroids
    - New dwarf spheroids have been discovered due to improved detection techniques
    - Improved Galactic center analysis
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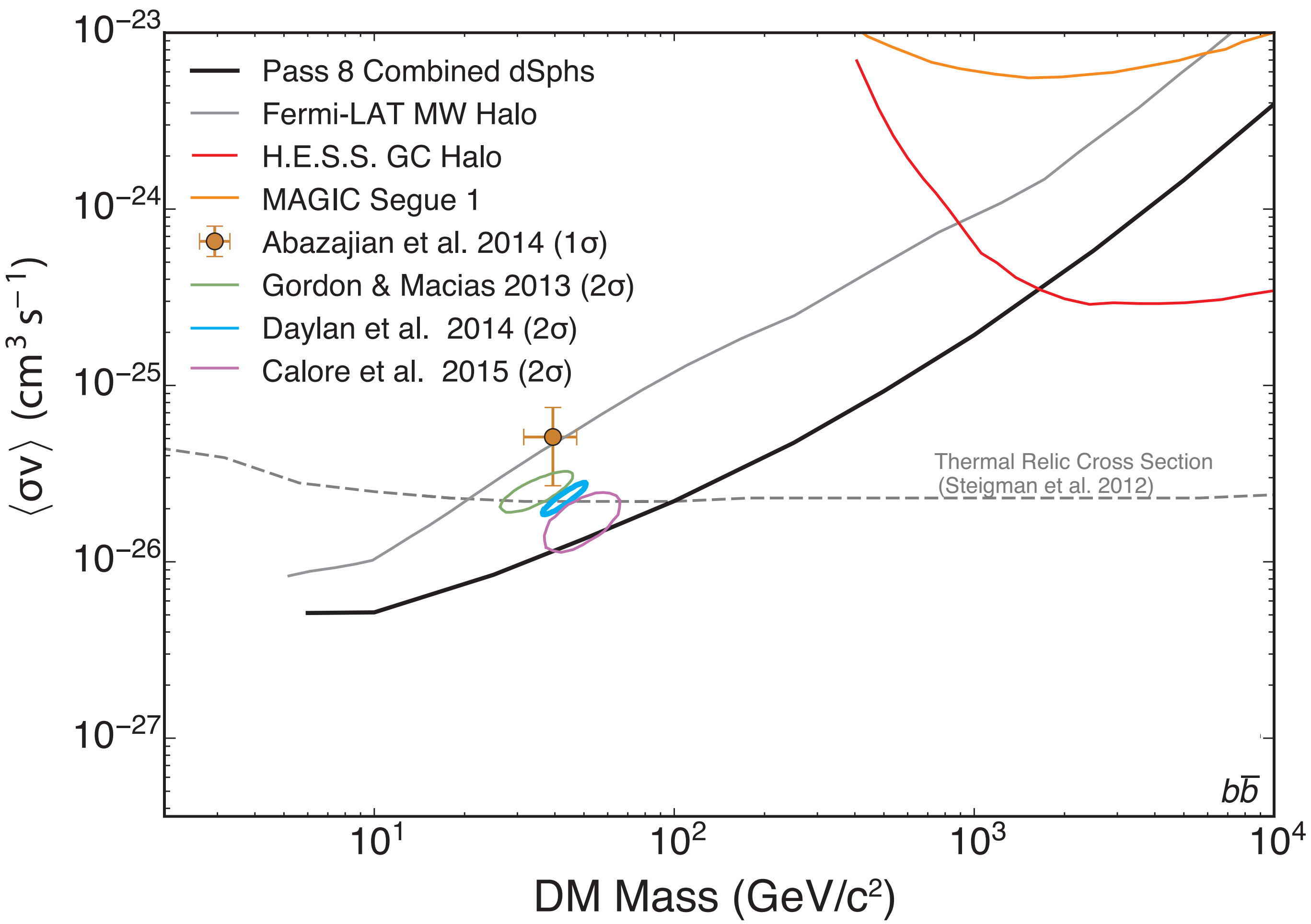

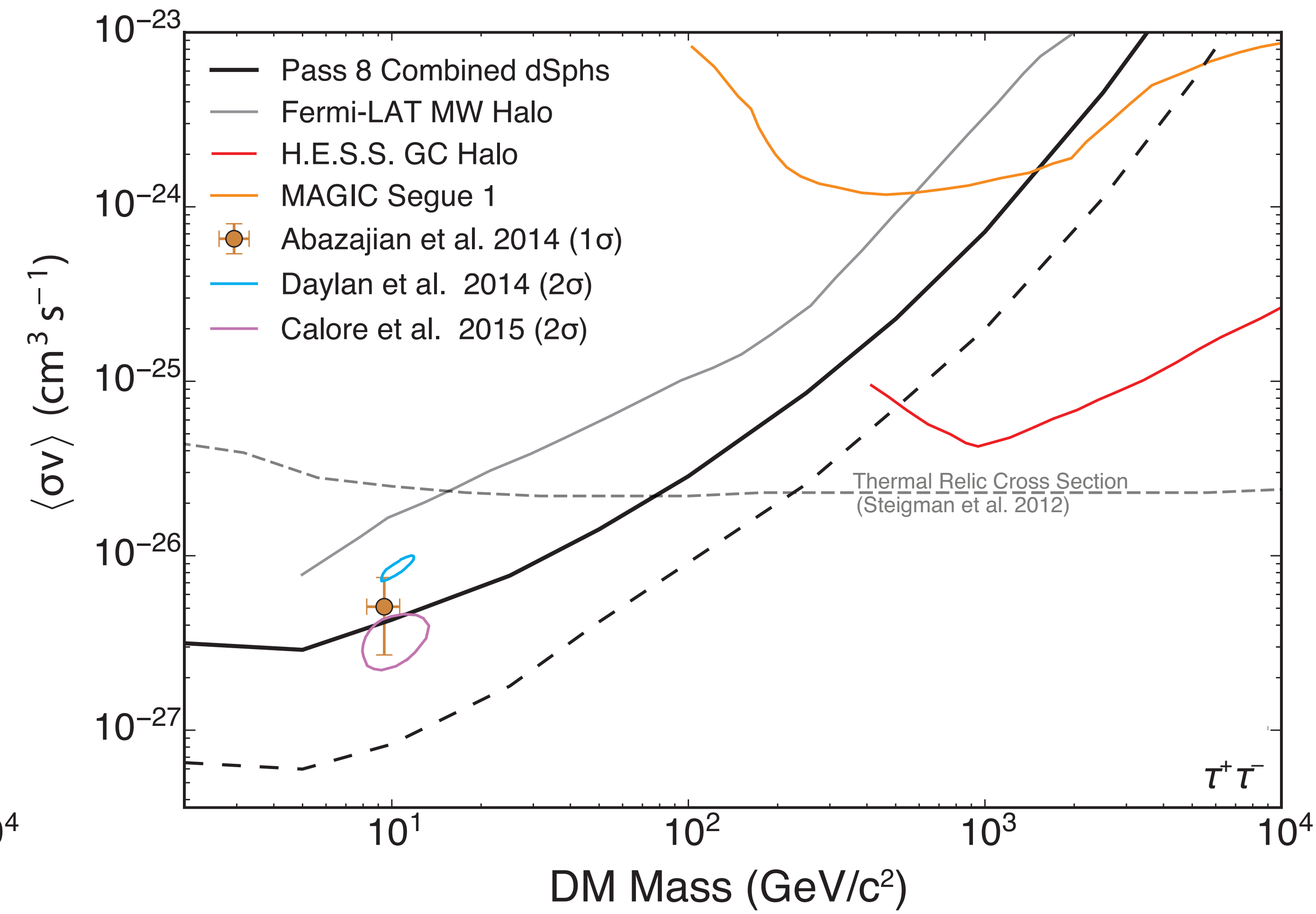

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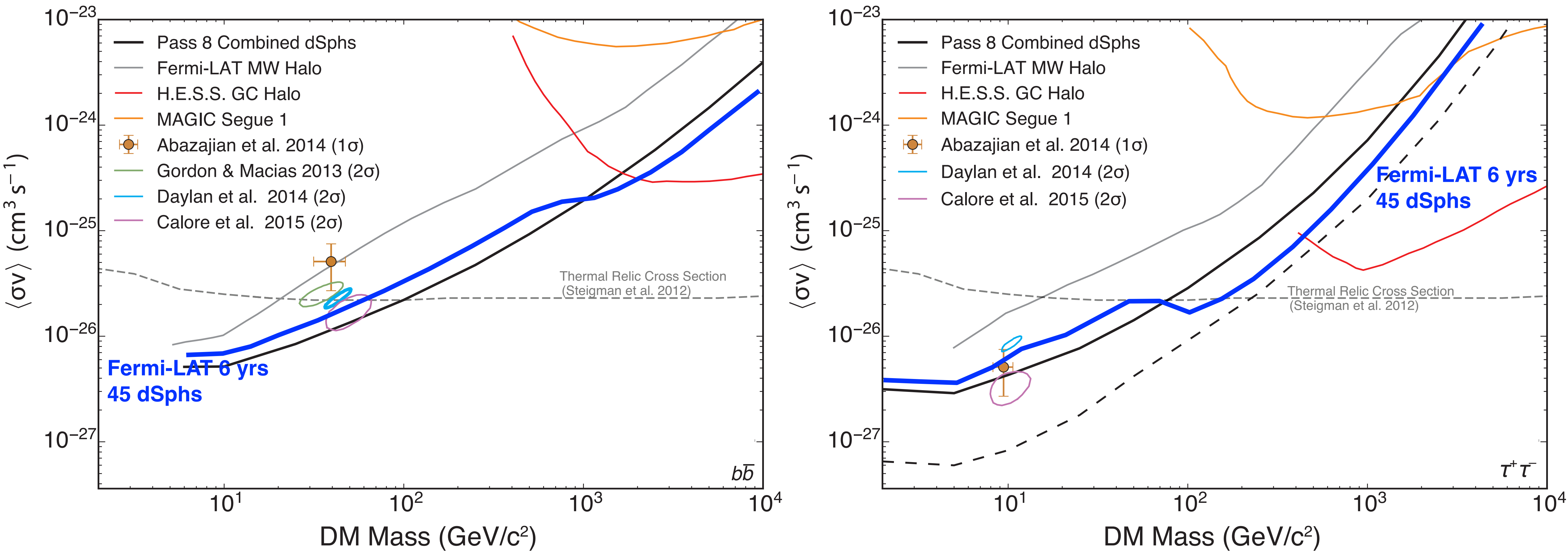

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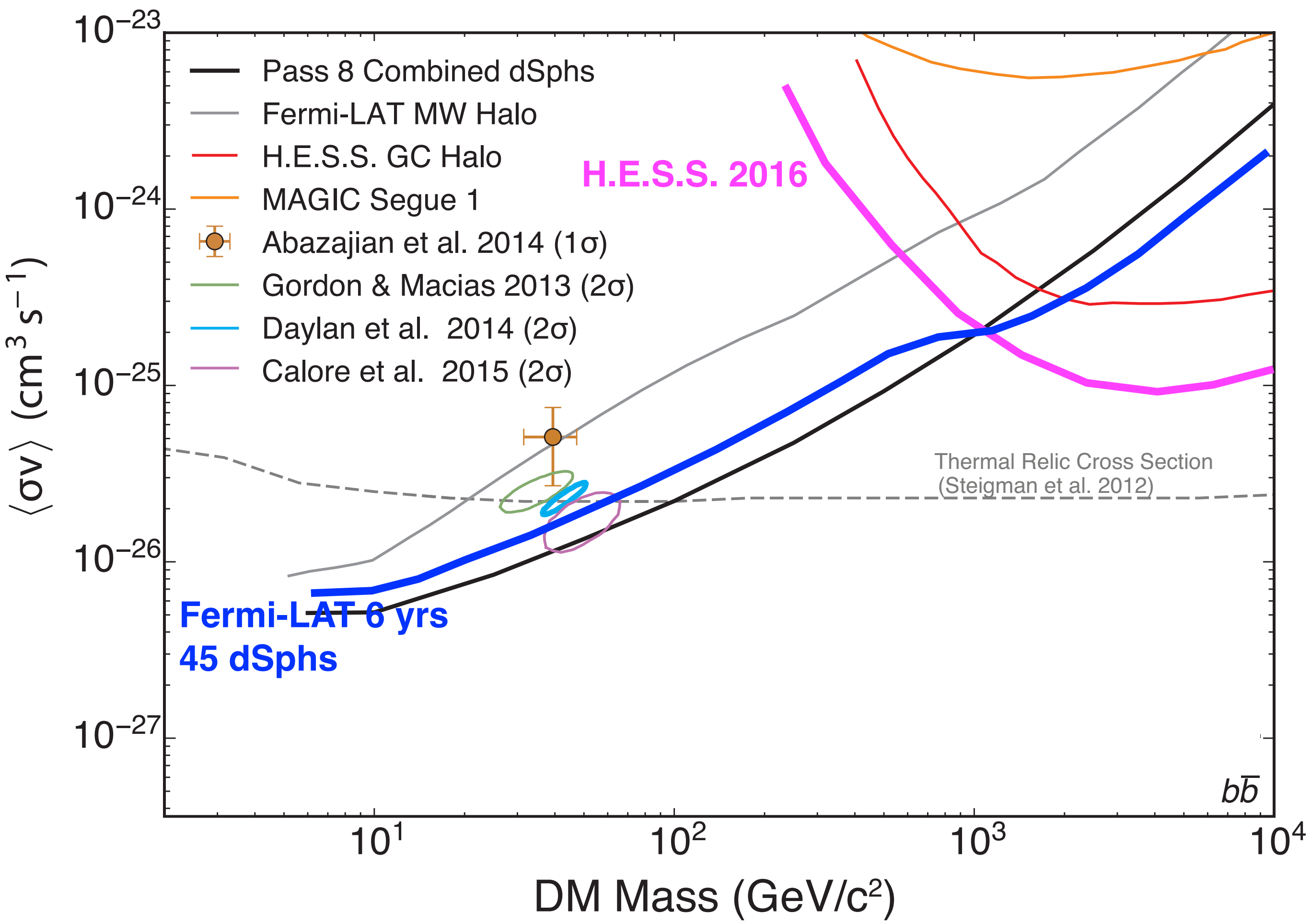

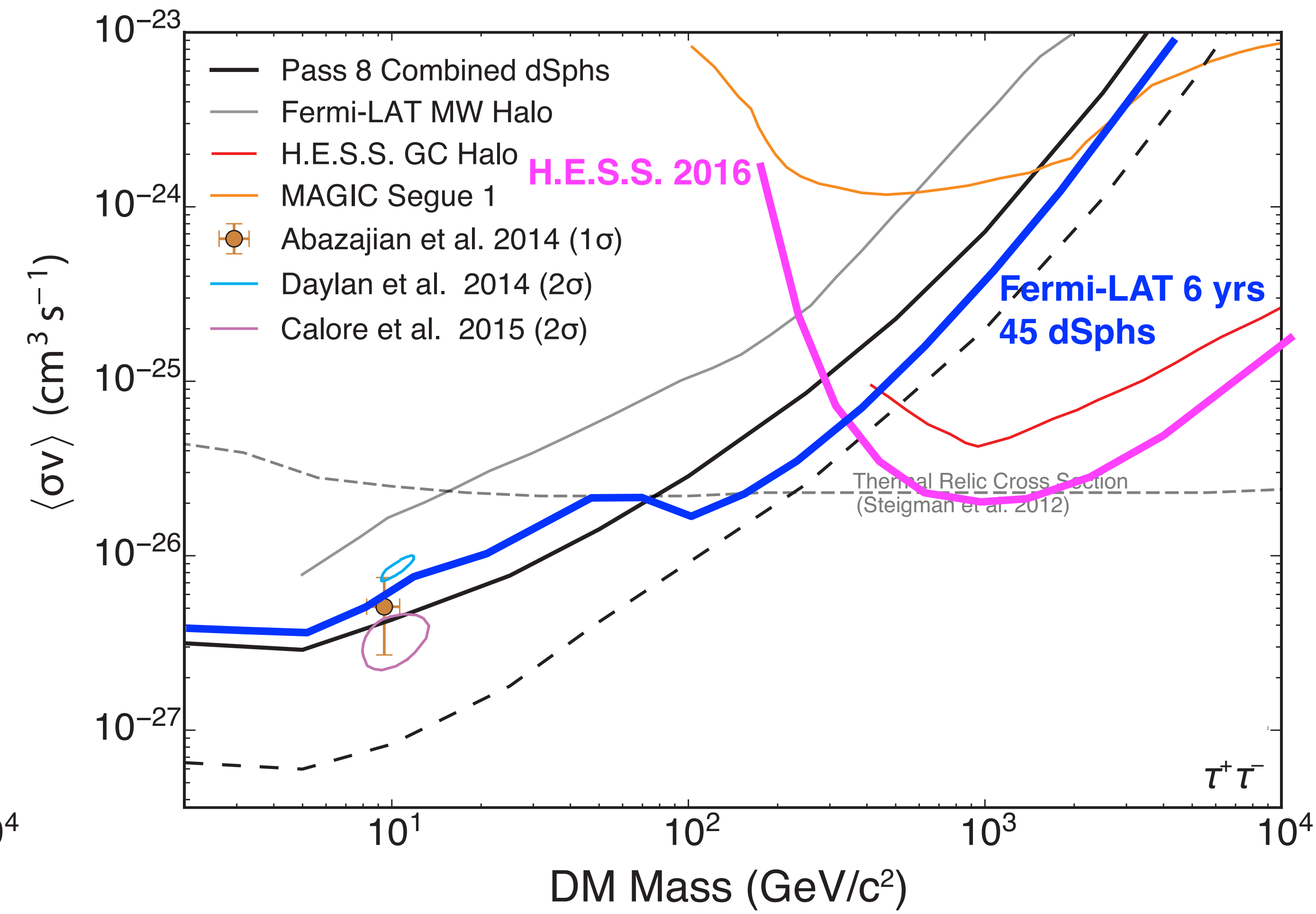

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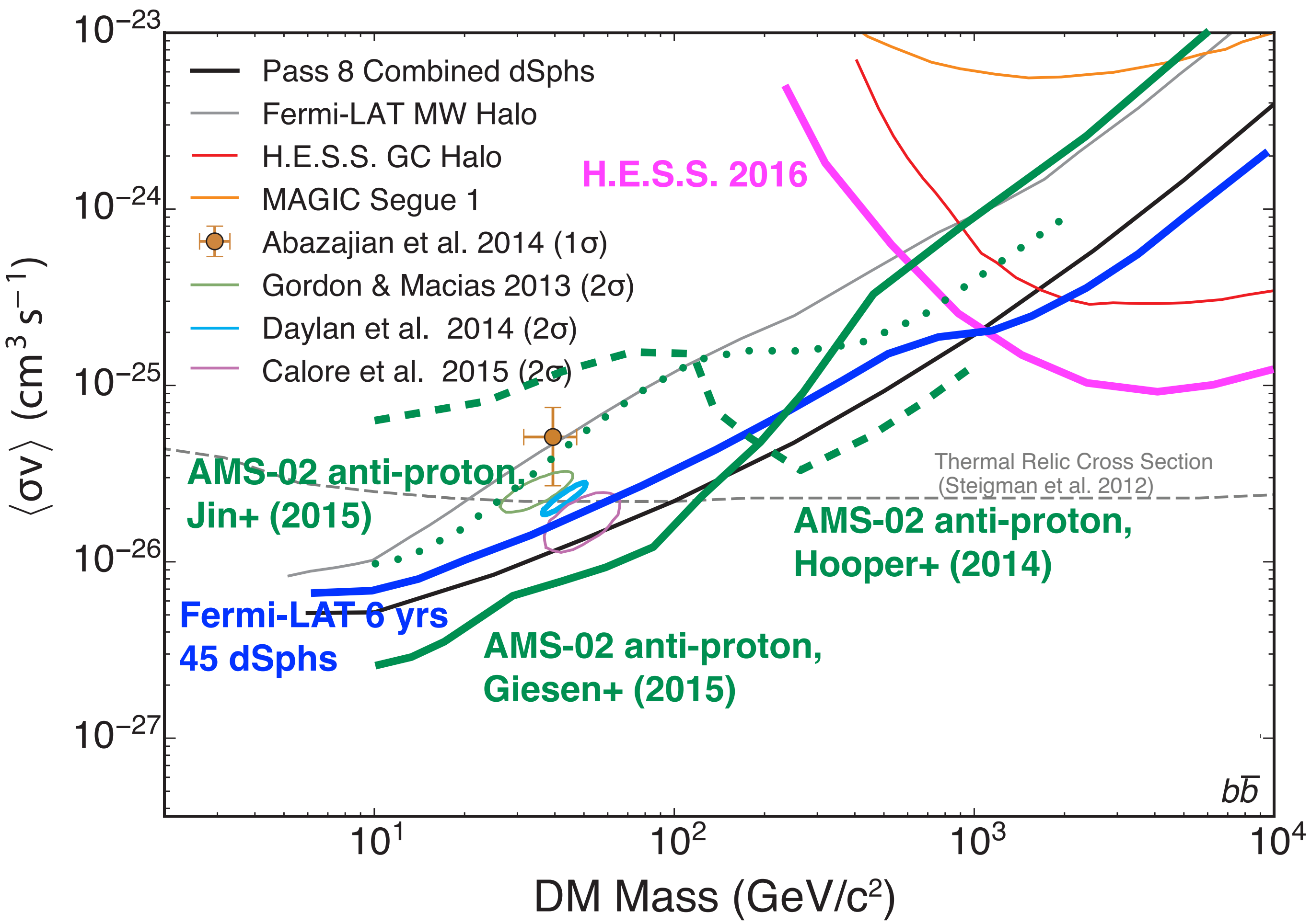

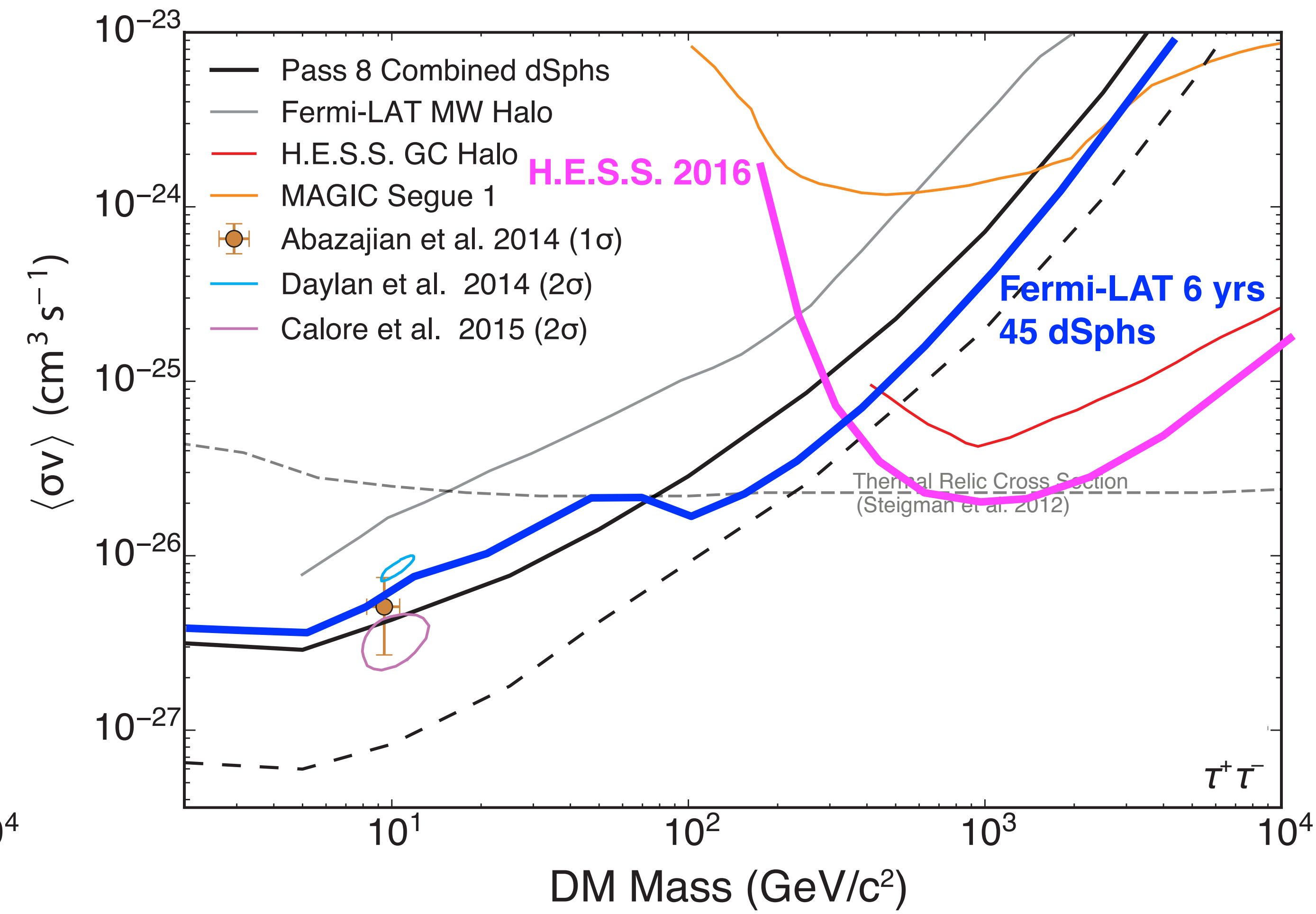

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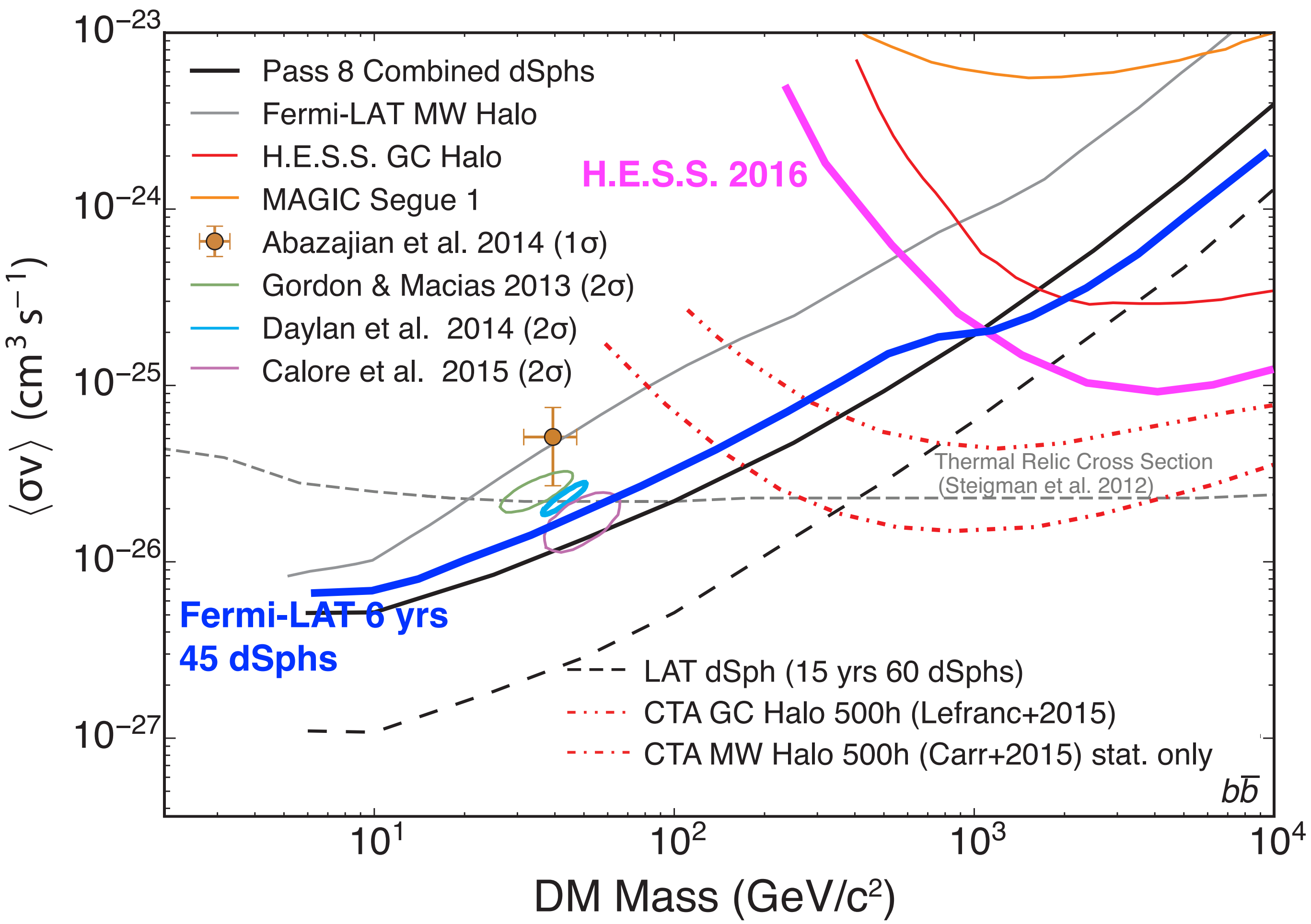
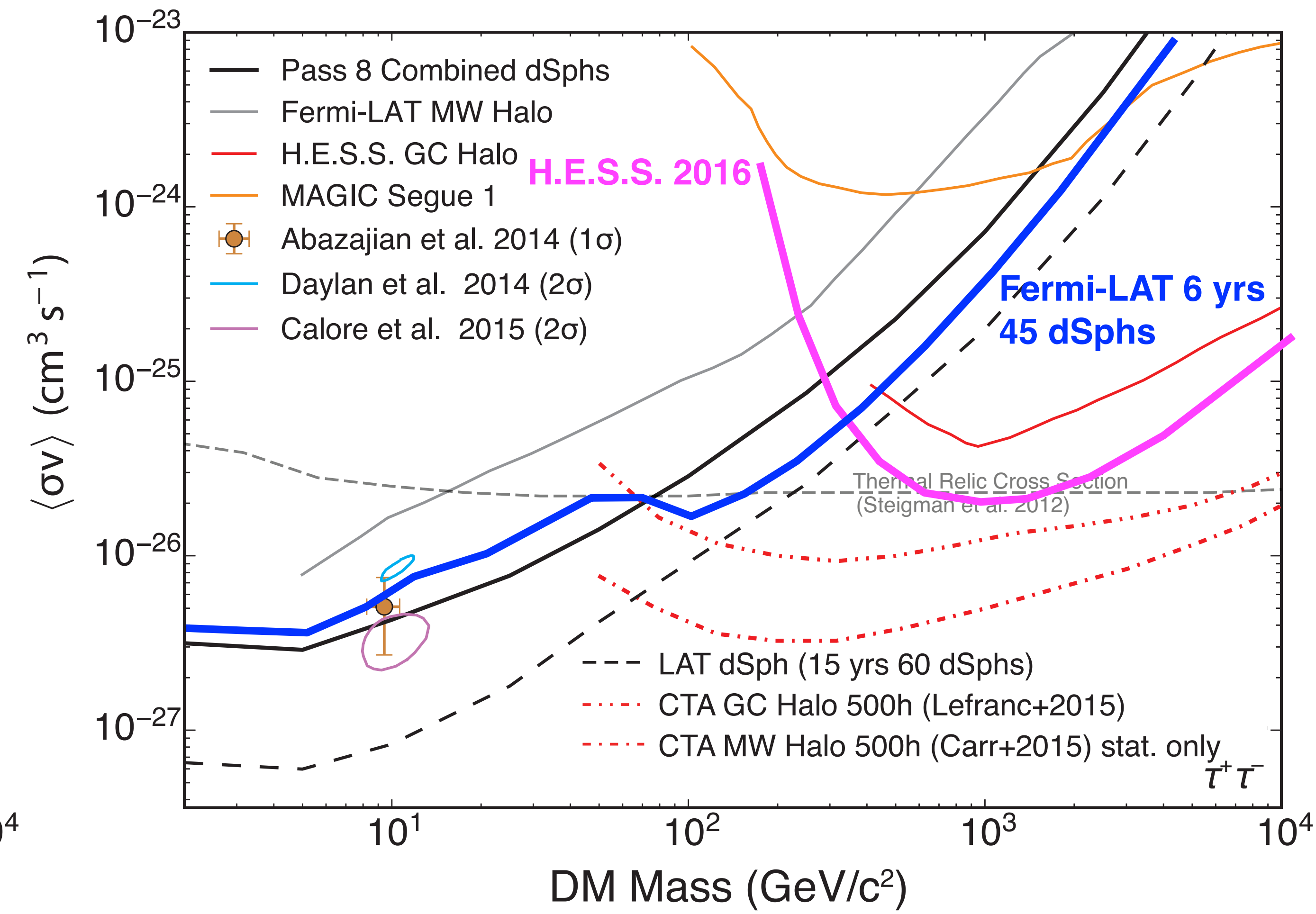


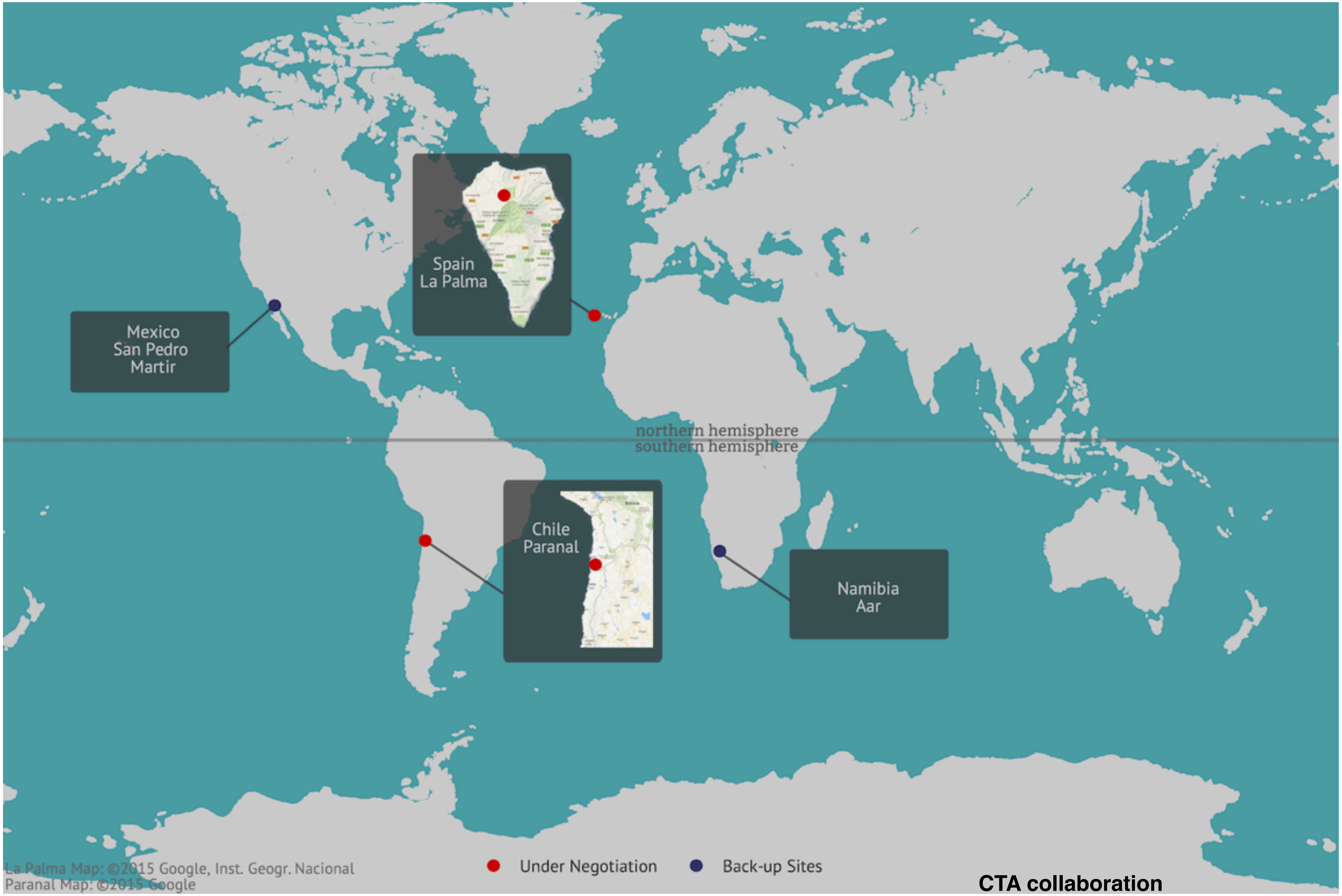


Summary and Future Prospects

- Indirect search is one of complimentary approaches in dark matter studies
- Cosmic anti-particle spectra may provide information for existence of dark matter
  - Current measurements by AMS-02 and DAMPE are not sufficient to claim dark matter signature
- Fermi-LAT "Galactic Center Excess" is intriguing, but further studies are required to draw any conclusions
- Fermi-LAT excludes thermal relic DM for the mass below 80–100 GeV/c^2
  - Excluded mass range would extend to multi-100 GeV/c^2 in the future with longer observations with more targets
- CTA is a promising project to search for DM in TeV energy band
  - Excluded mass range would extend to ~10 TeV/c^2
    - Interesting mass range for prominent SUSY models
  - CTA can access DM phase space where collider and direct searches cannot access

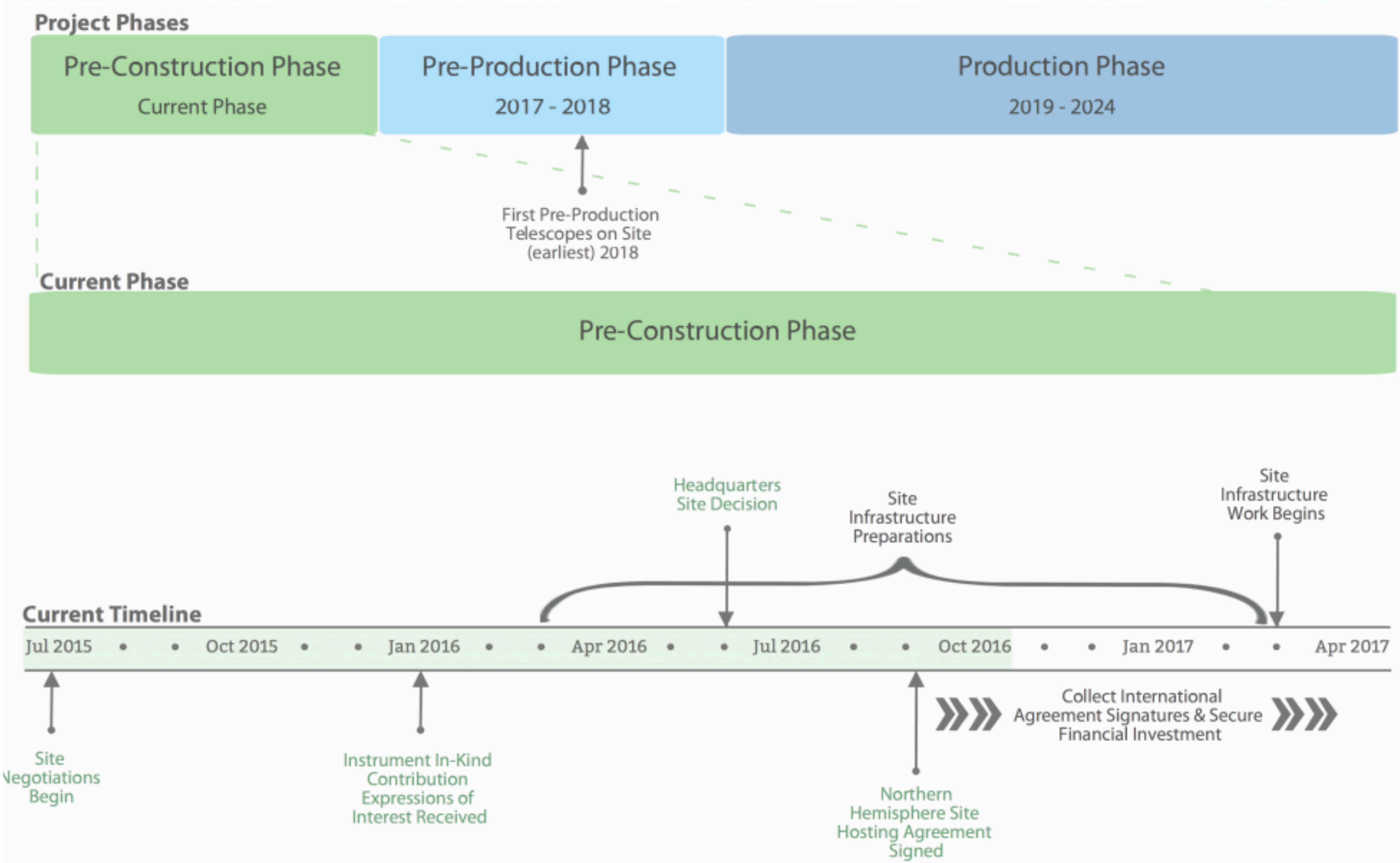
backup

CTA Sites



CTA collaboration

CTA Project Timeline



CTA collaboration (as of Oct, 2016)

J-Factor Determination for dSphs

- J-Factor is well correlated with the distance
  - Comparison of three different method to estimate J-factors