Indirect Searches for WIMP Dark Matter

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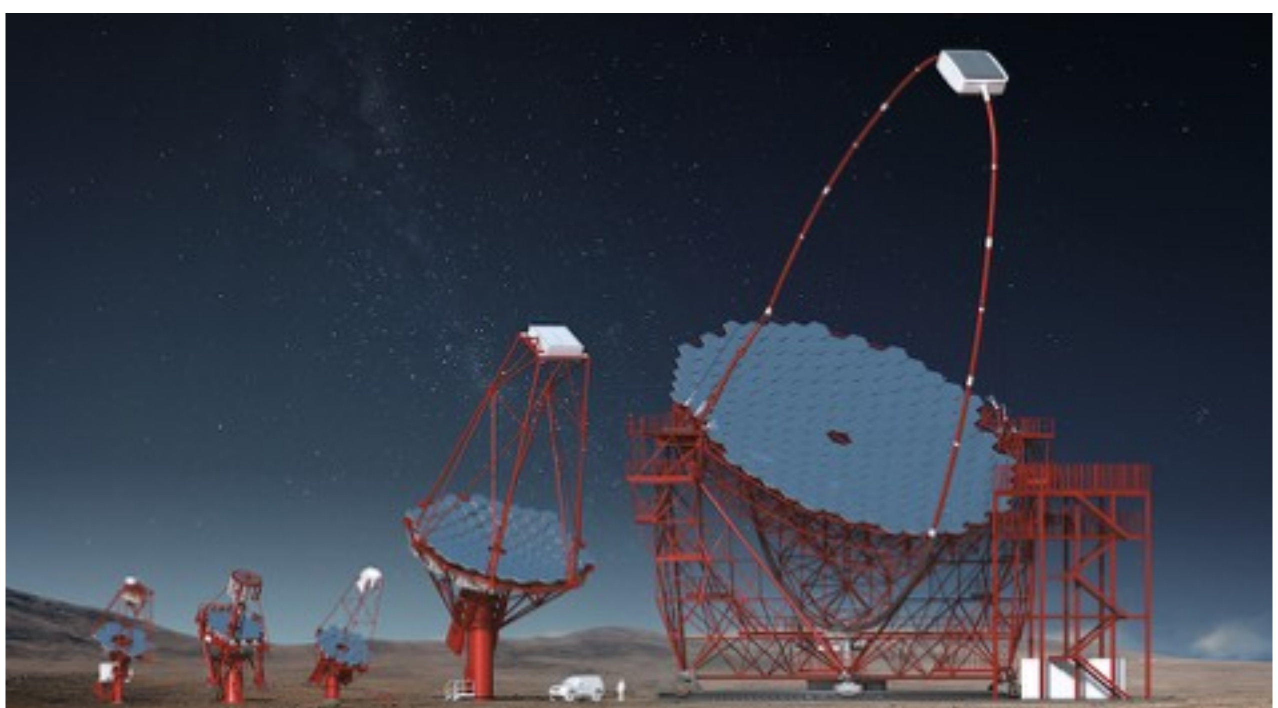

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Physics in LHC and the Early Universe
University of Tokyo, Japan

Outline

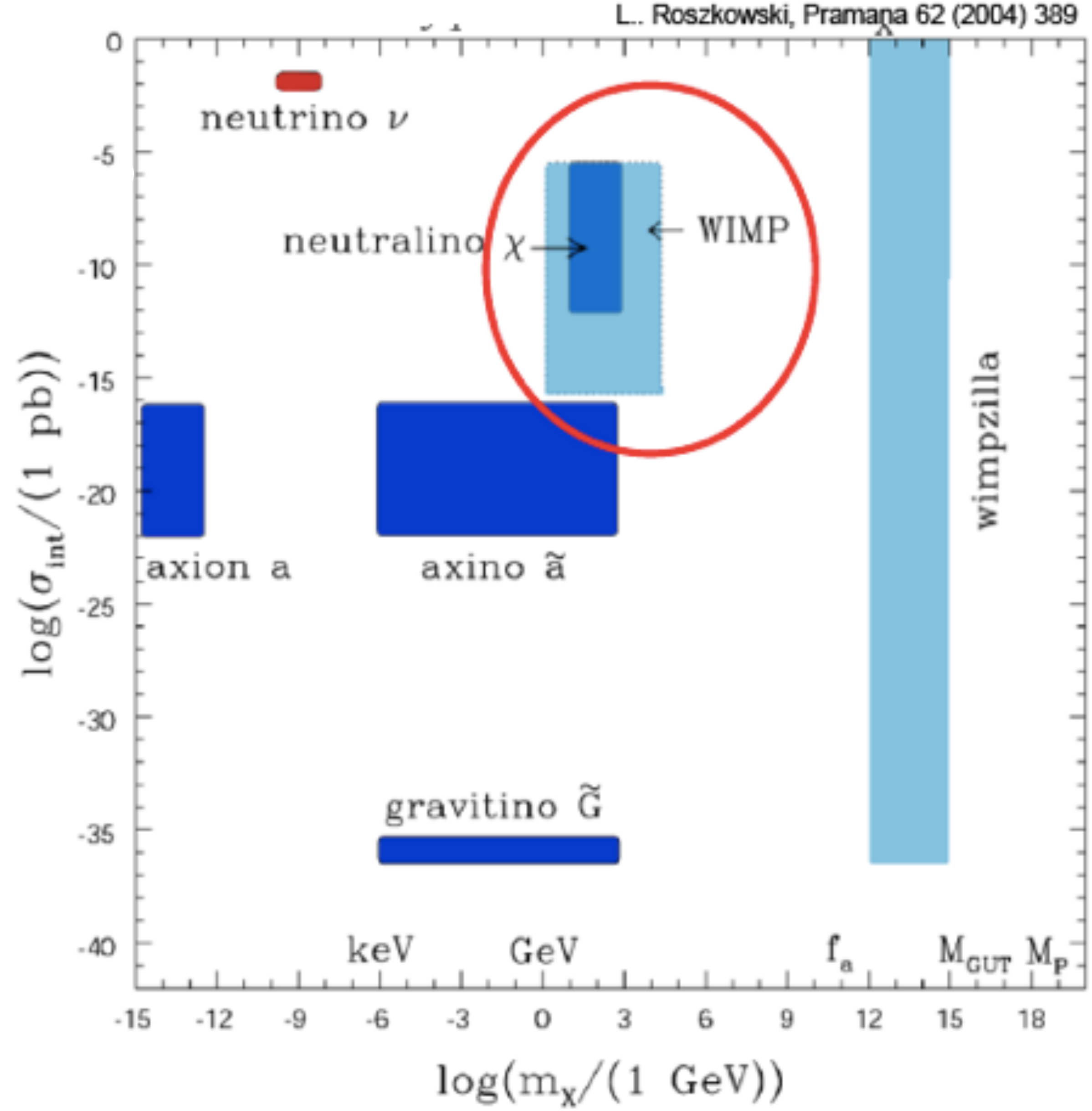
- Introduction
- WIMP searches with Fermi-LAT
  - “Galactic Center Excess”
  - Dwarf Spheroidal
- WIMP search in TeV gamma rays
- WIMP searches with cosmic rays
- Future prospects

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
    - Axion

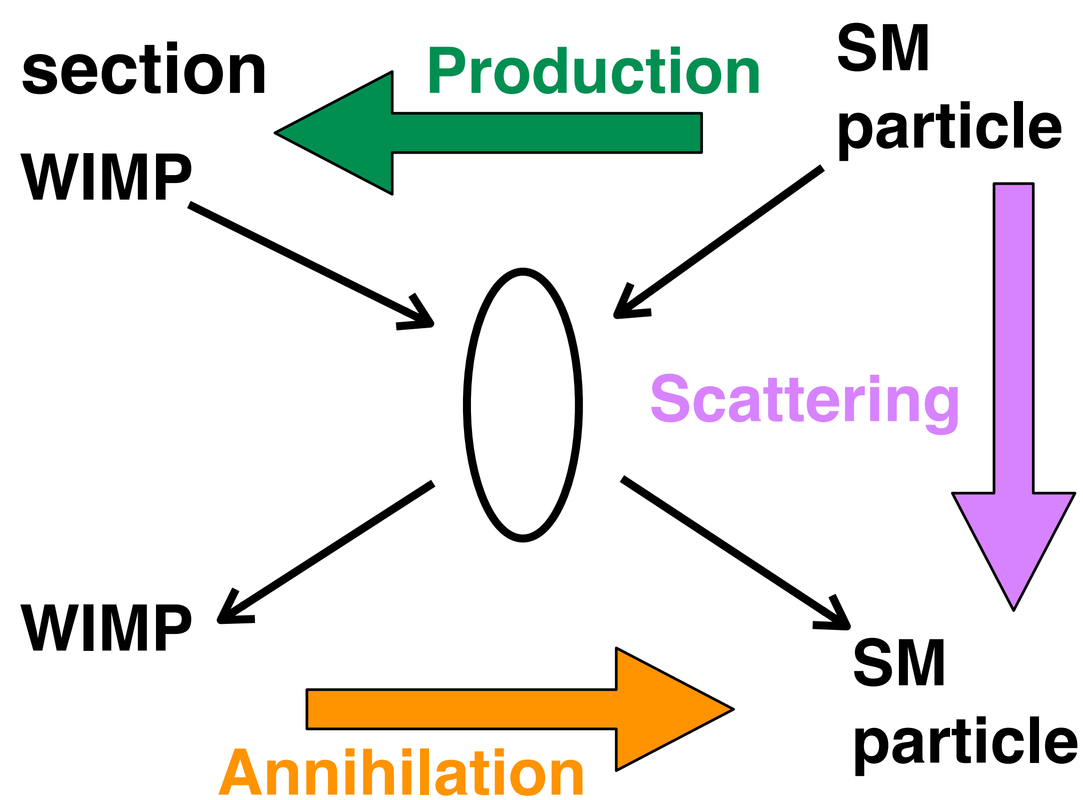
WIMP miracle

L.. Roszkowski, Pramana 62 (2004) 389



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

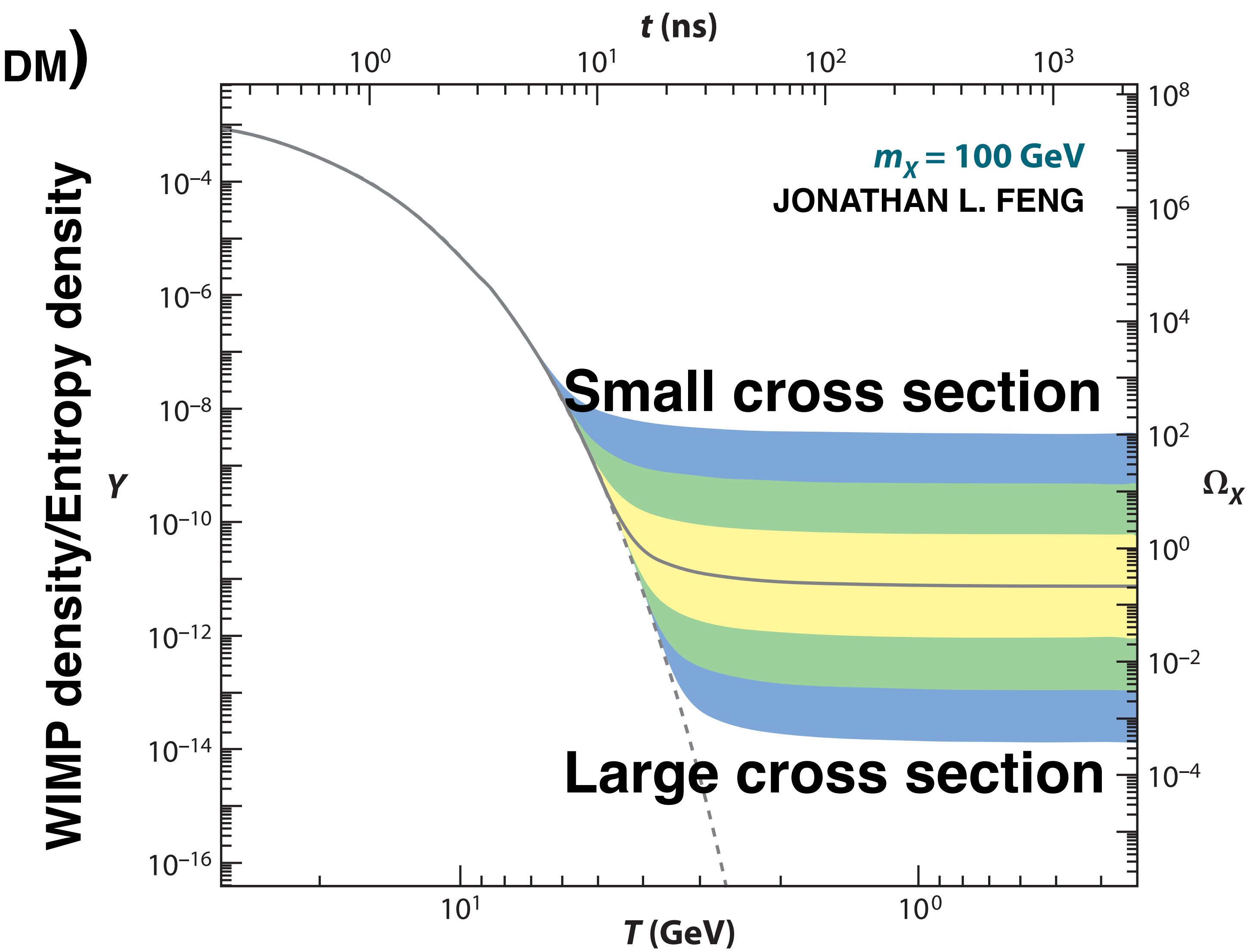
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \varphi, \theta) = \frac{1}{4\pi}\frac{\langle \sigma_{ann} v \rangle}{2m_{WIMP}^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma} B_f \times \int_{\Delta\Omega(\varphi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\varphi'))\, dl(r,\varphi')$$

DM distribution

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

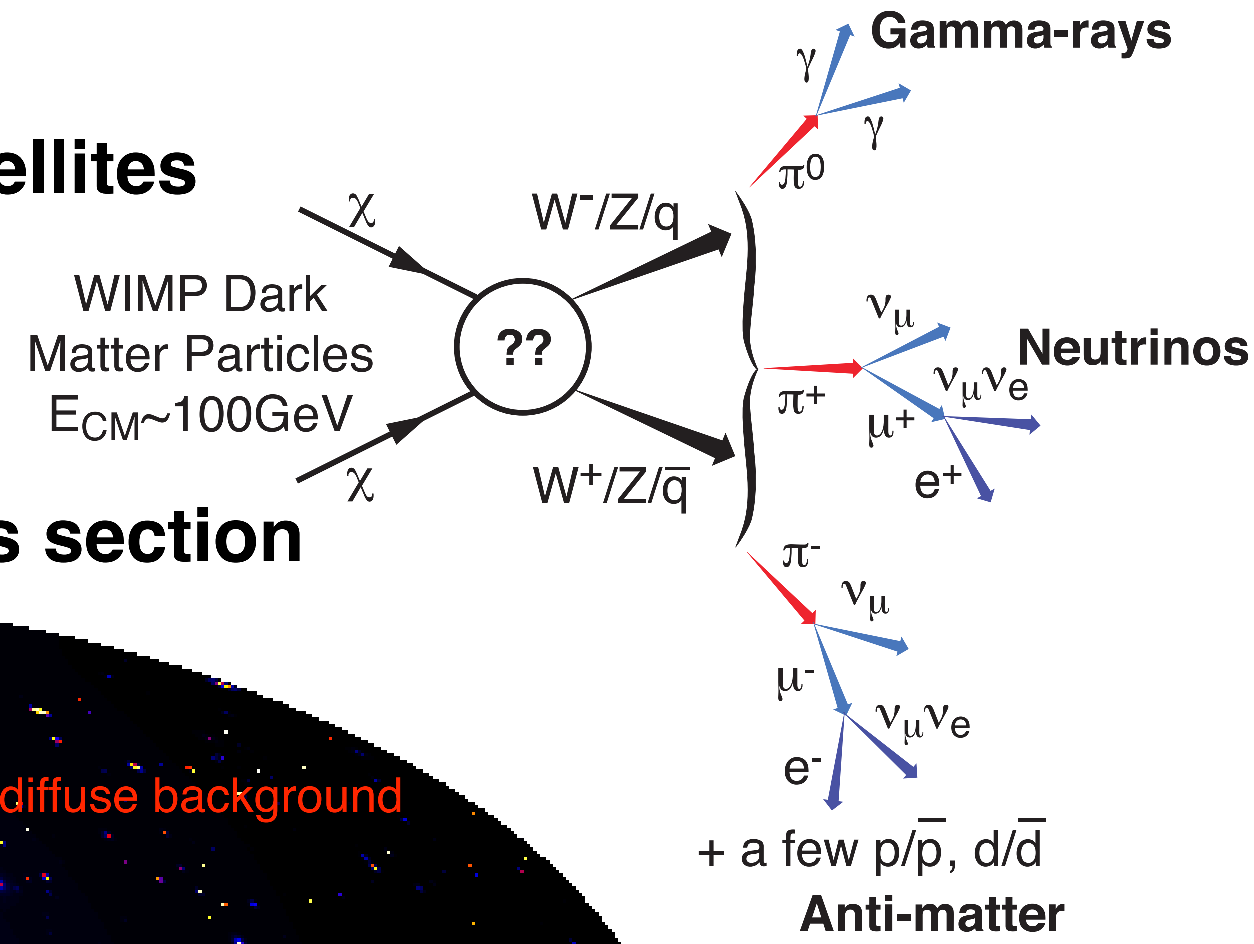
Thermal Relic Dark Matter (WIMP)

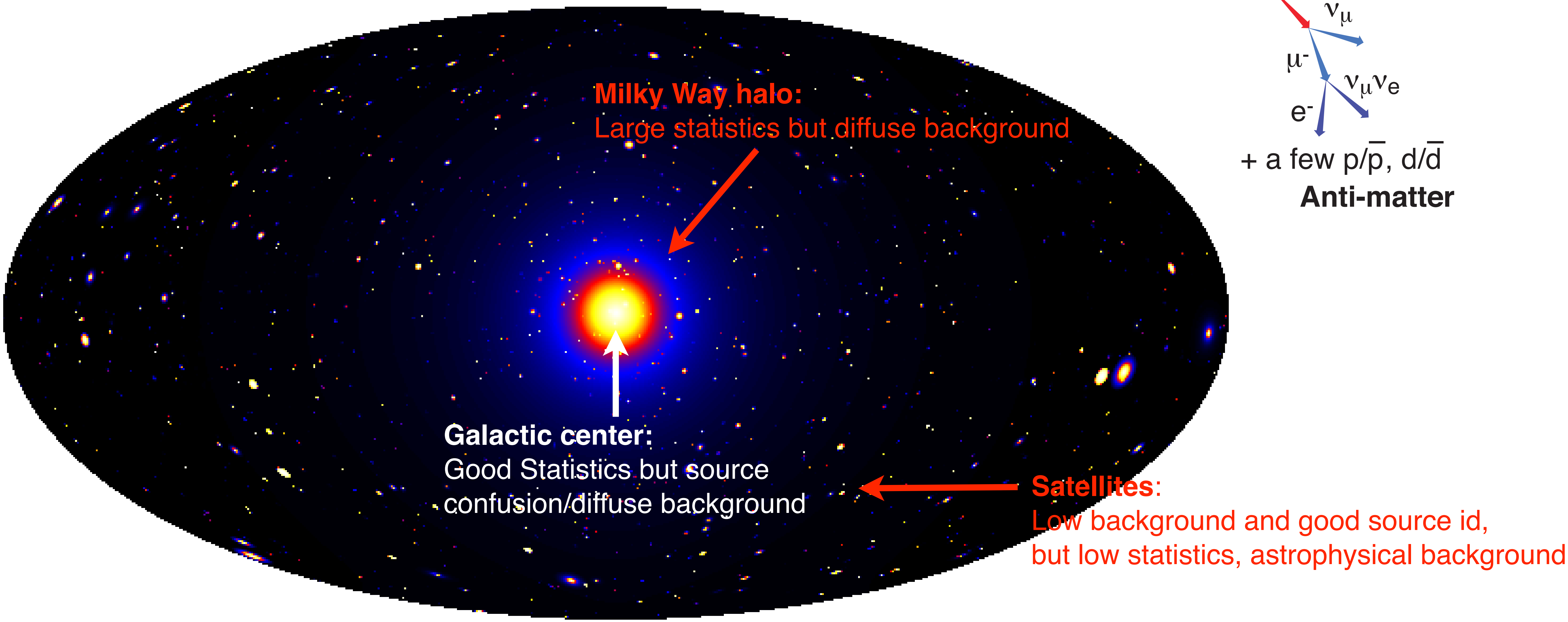
- WIMP is in equilibrium between pair creation and annihilation in early Universe
  - Pair creation stops when thermal energy is not sufficient
  - Annihilation continues and WIMP density become too low compared with annihilation cross section
    - WIMP density and annihilation cross section is anti-correlated
  - Current dark matter density (Ω_{DM}) constrains annihilation cross section to ~3x10^{-26} cm^2/s



Indirect Searches for WIMP

- Gamma ray
  - Galactic center, Milky-Way halo, satellites
  - Line emission, diffuse backgrounds
- Cosmic ray
  - Anti-particles
  - No constraints on annihilation cross section





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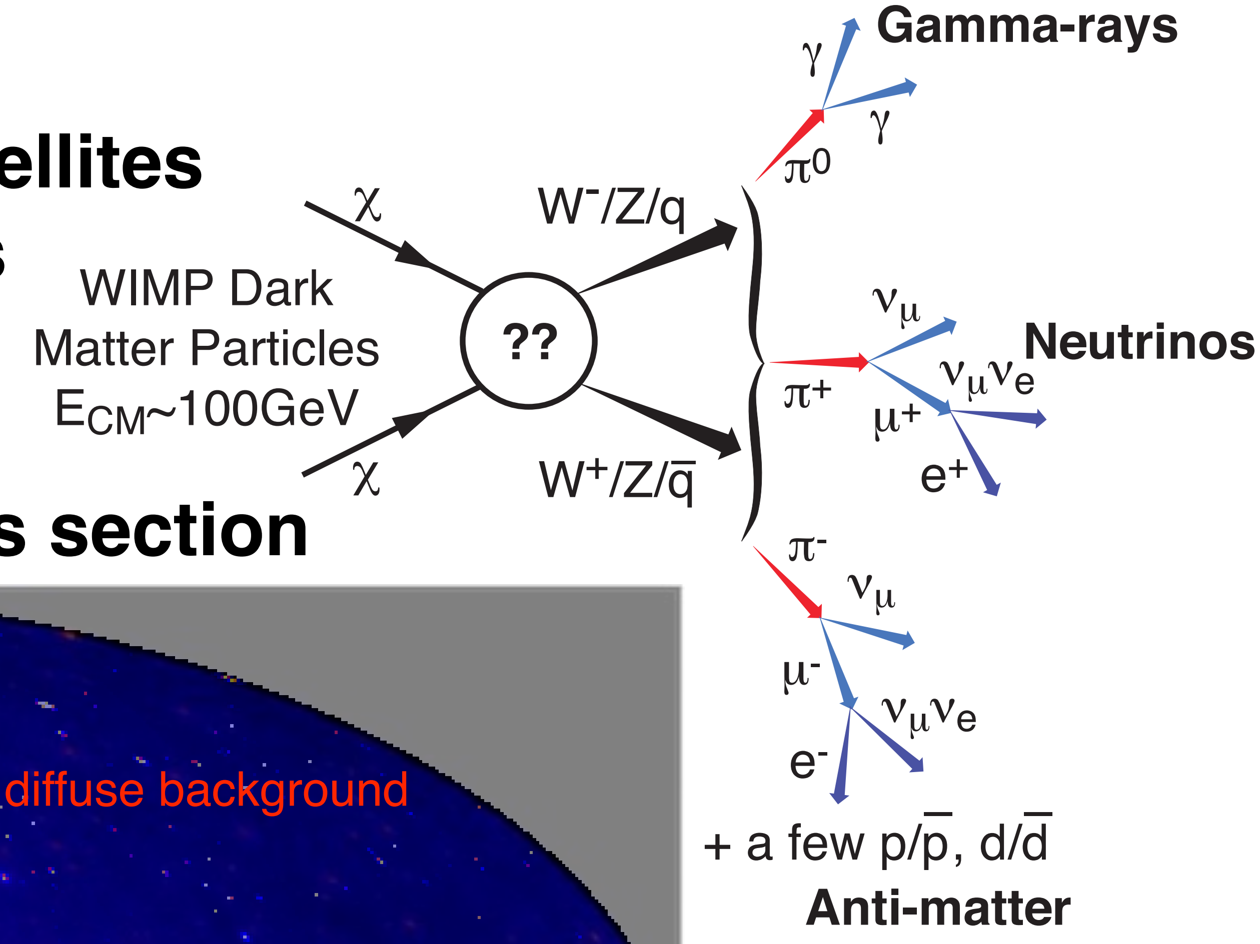
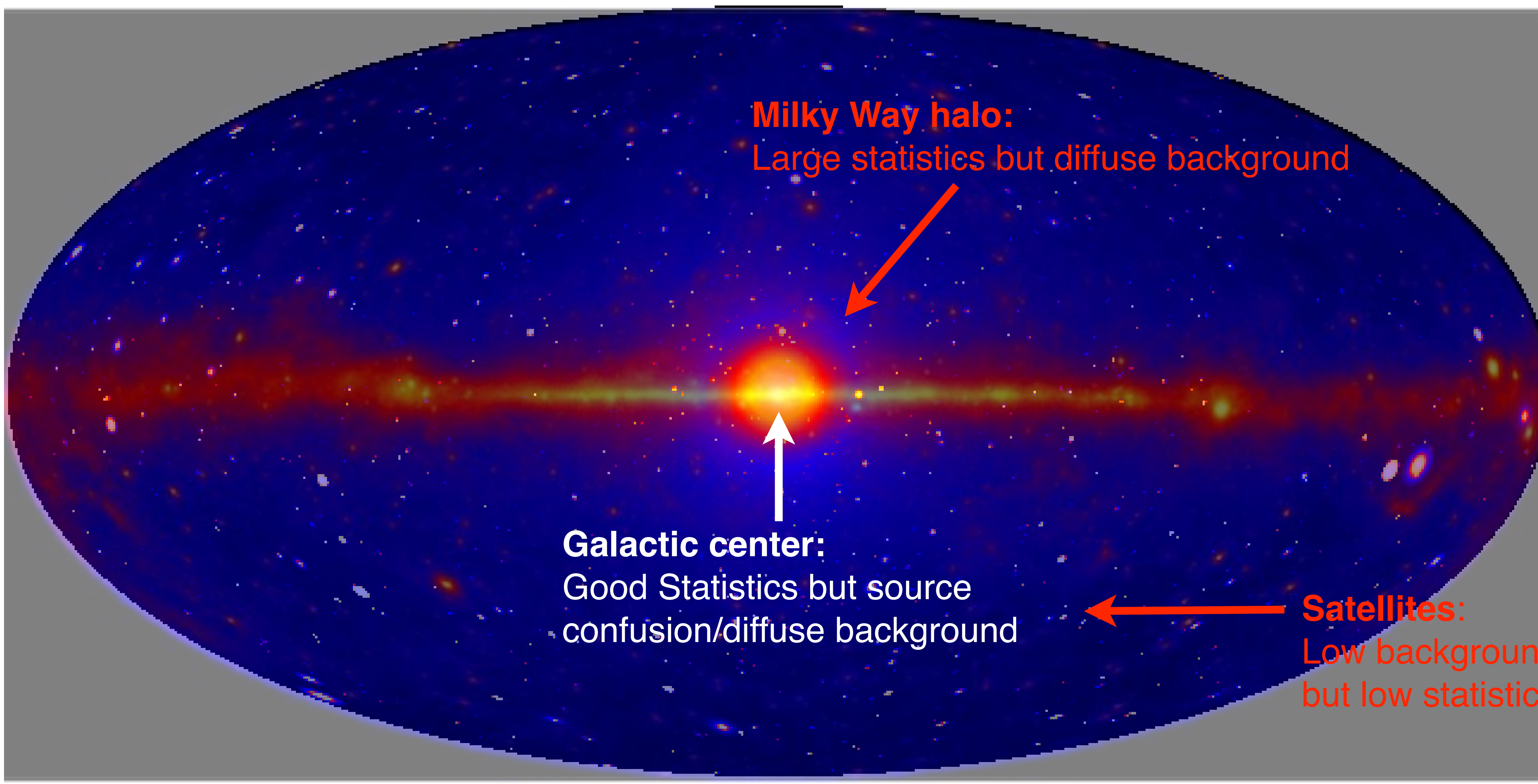
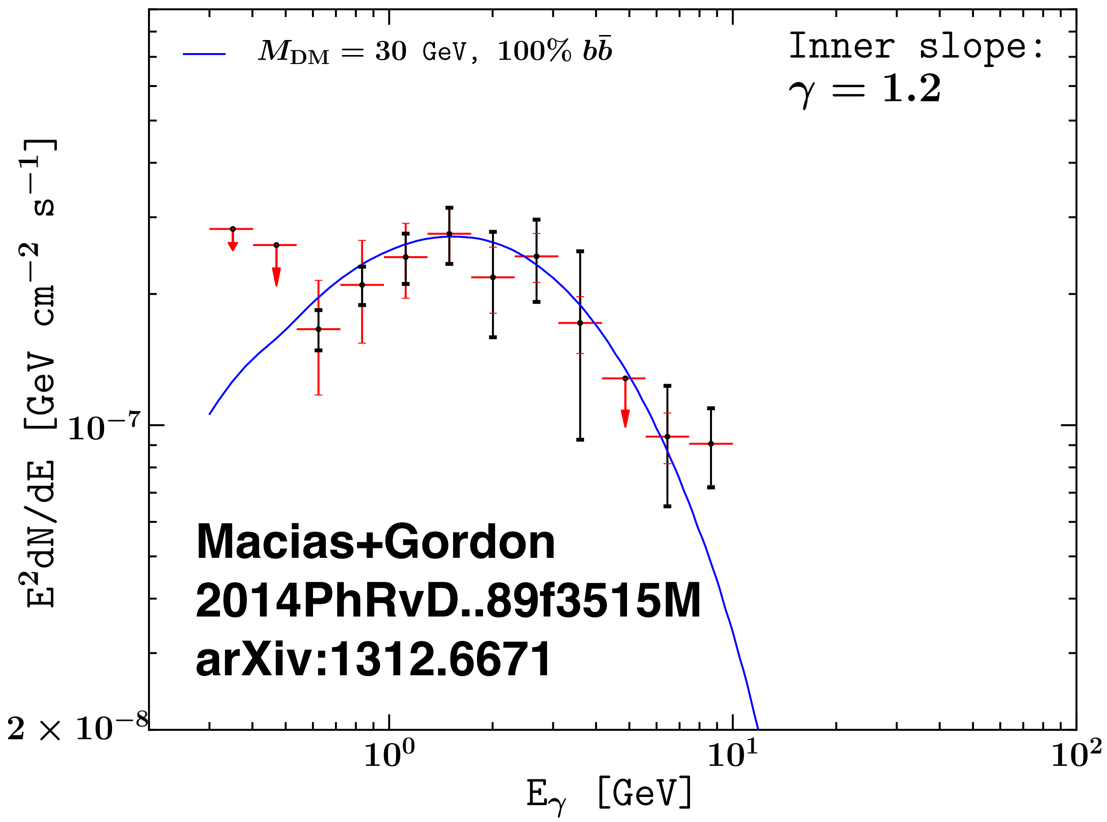
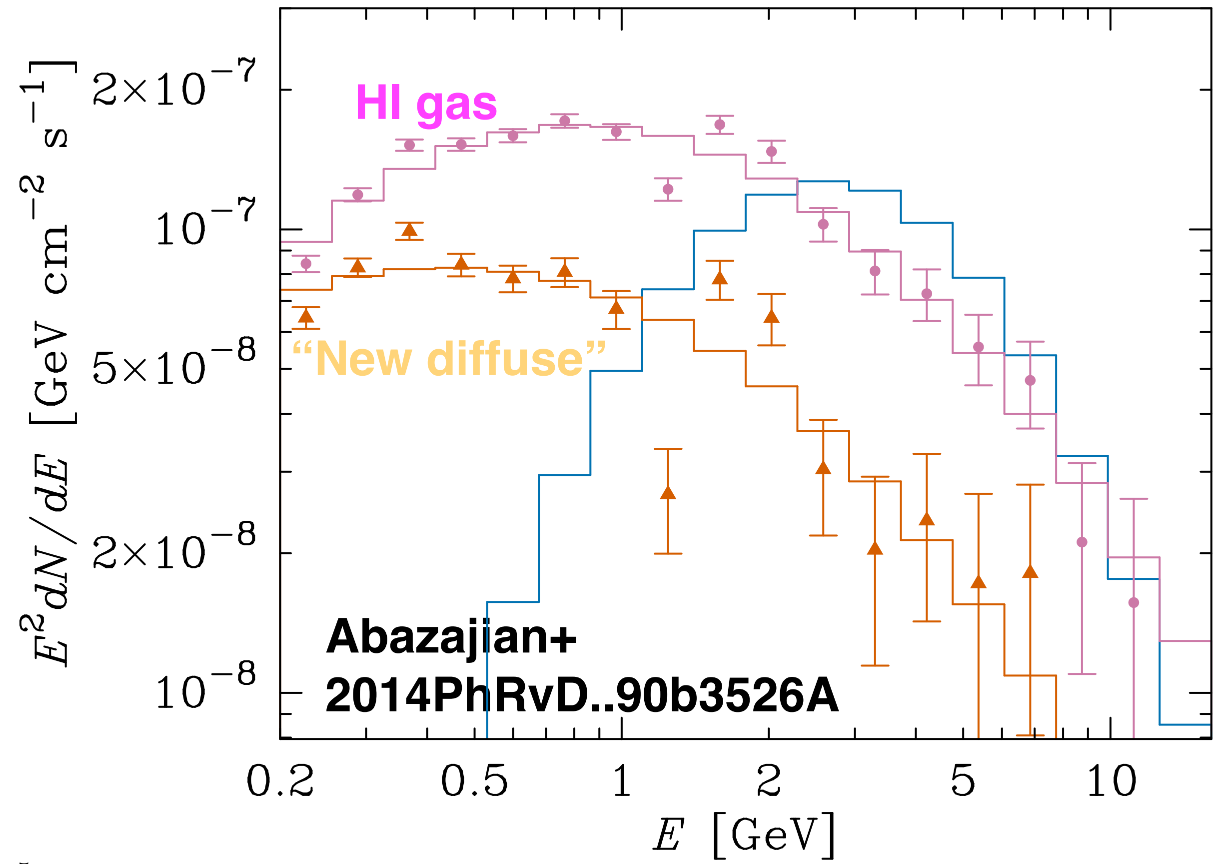
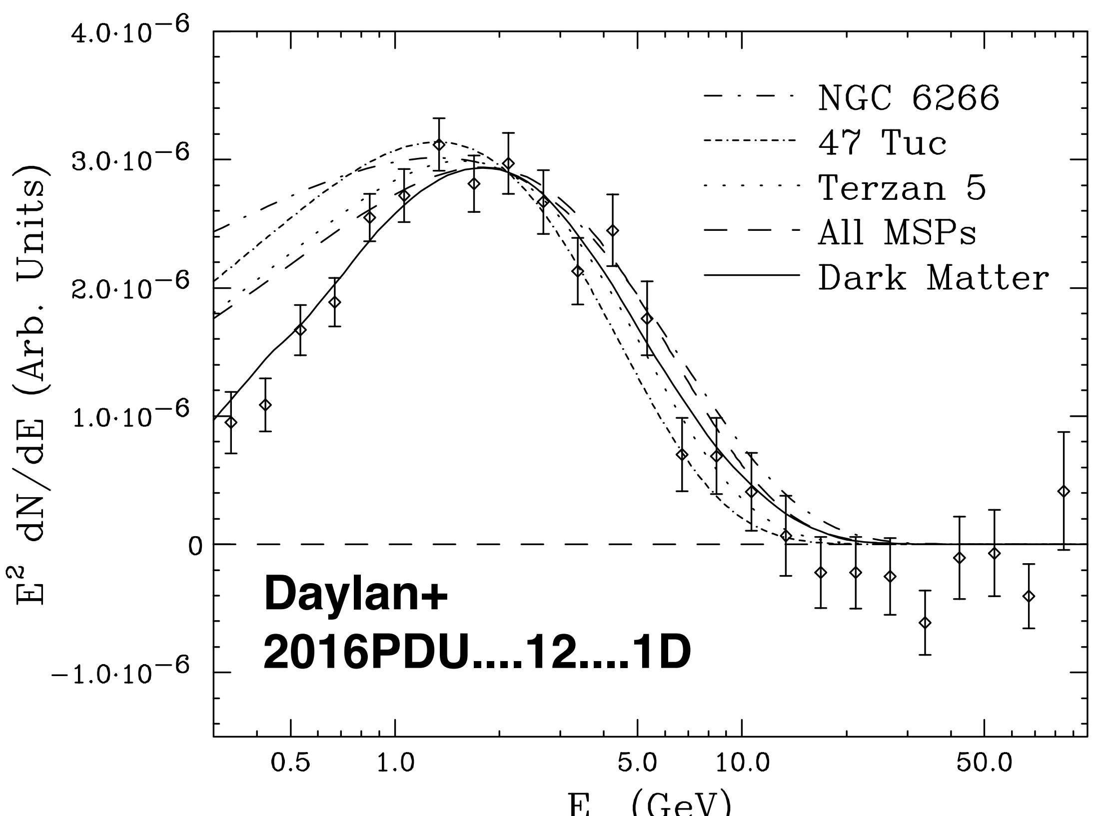


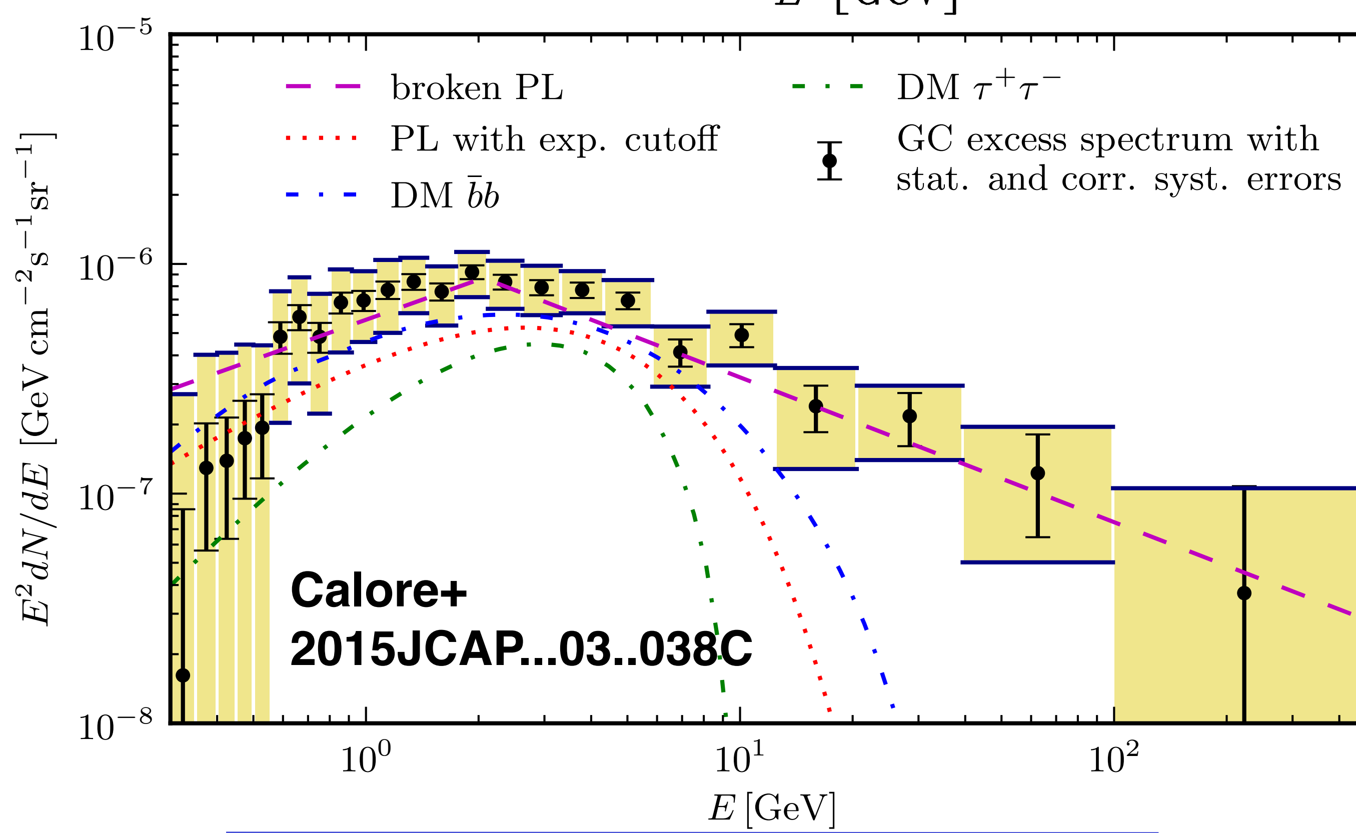


Fermi “Galactic Center Excess”









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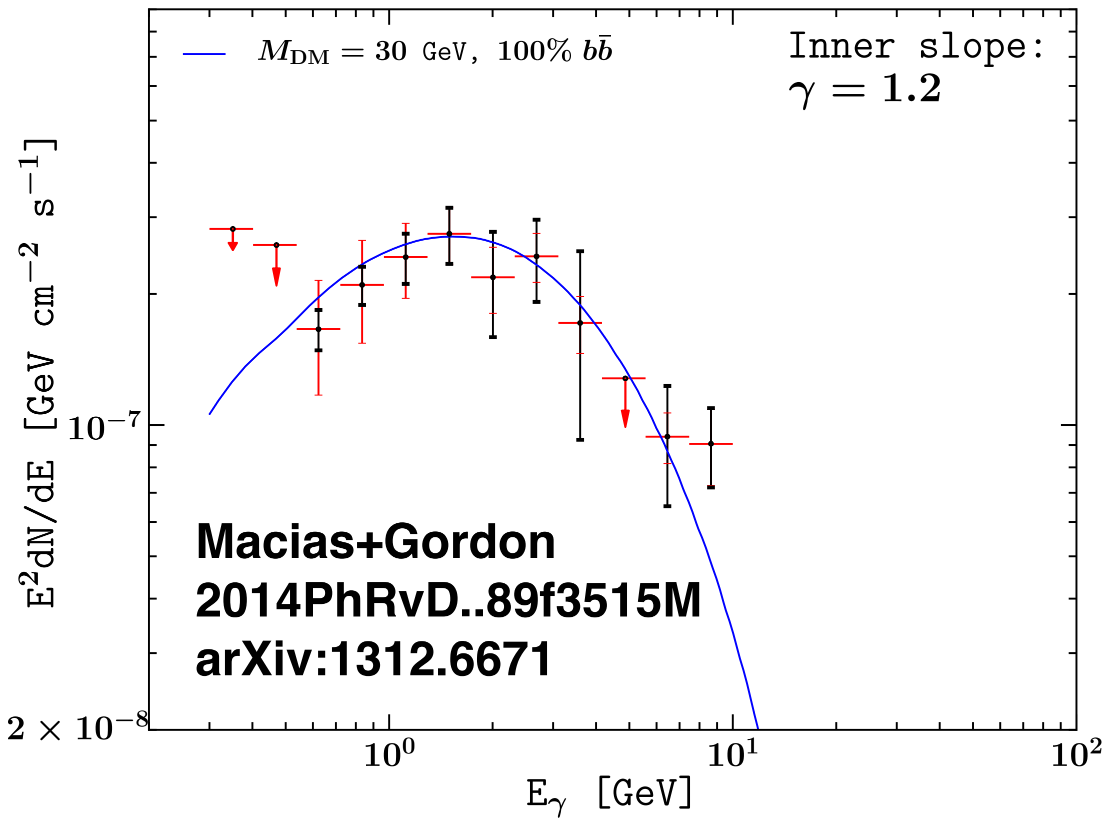

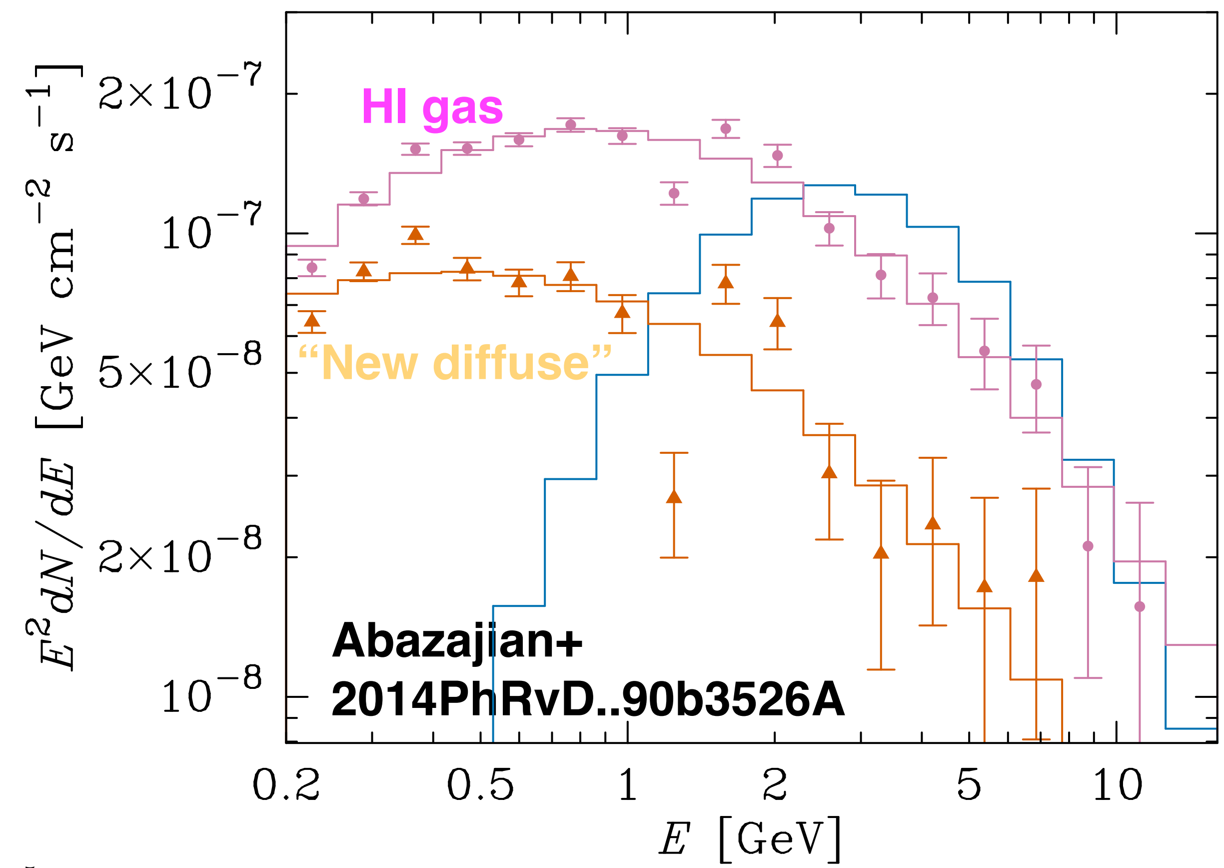

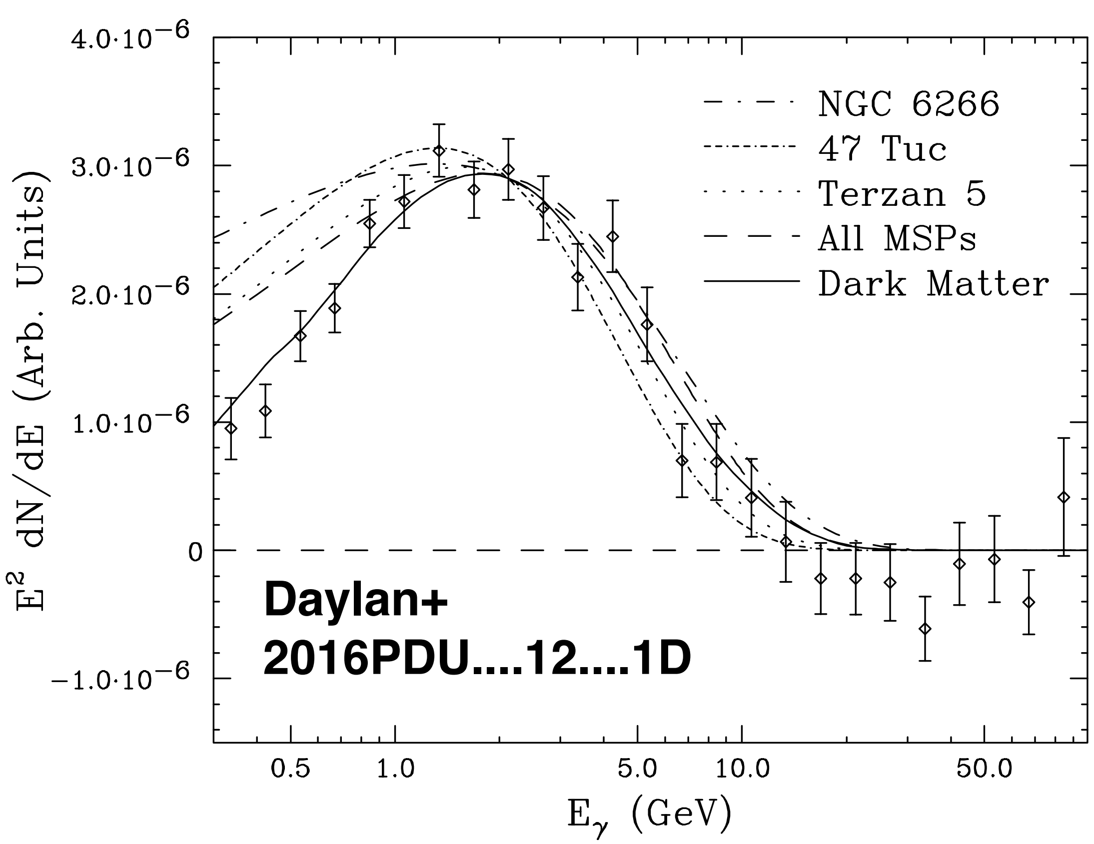

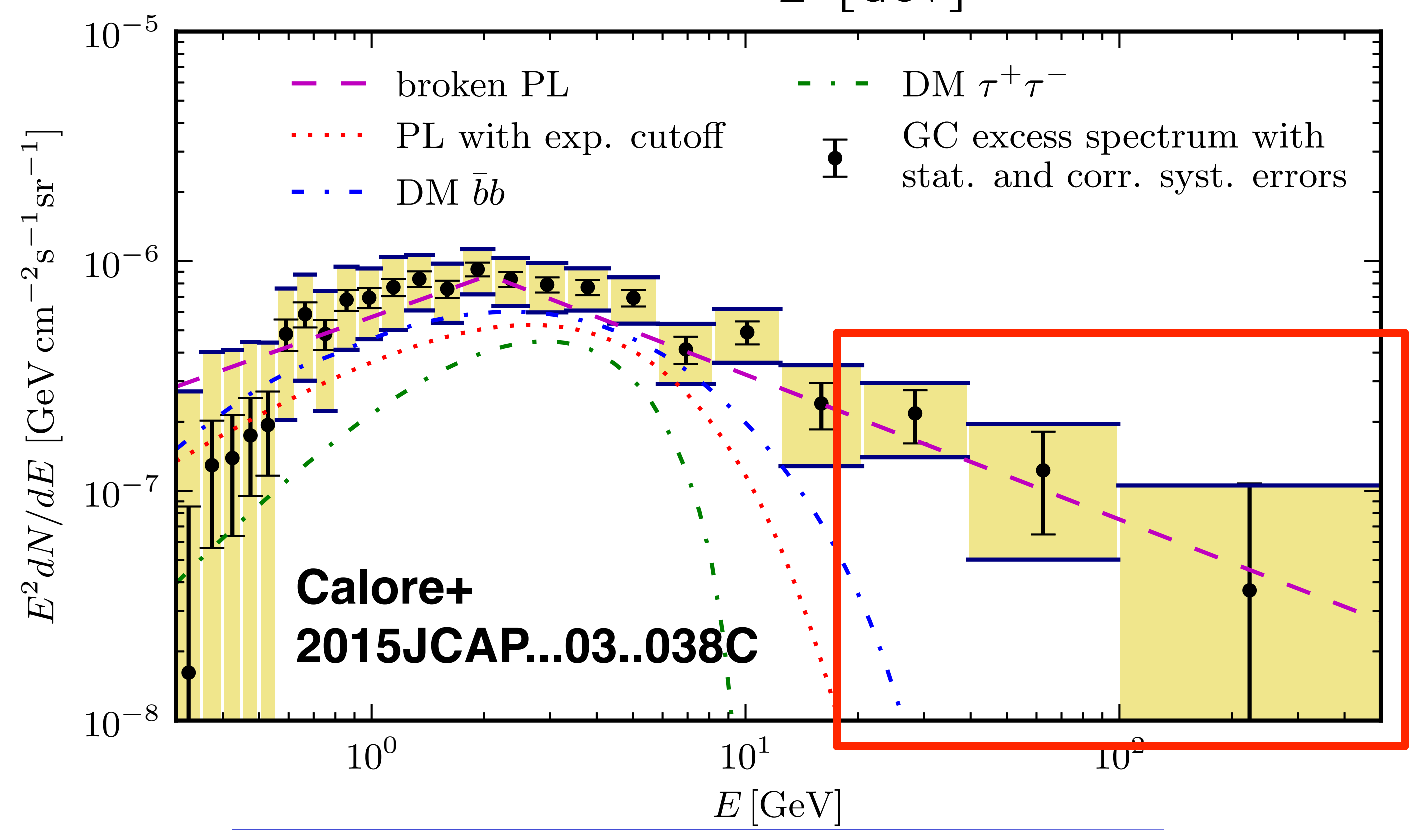

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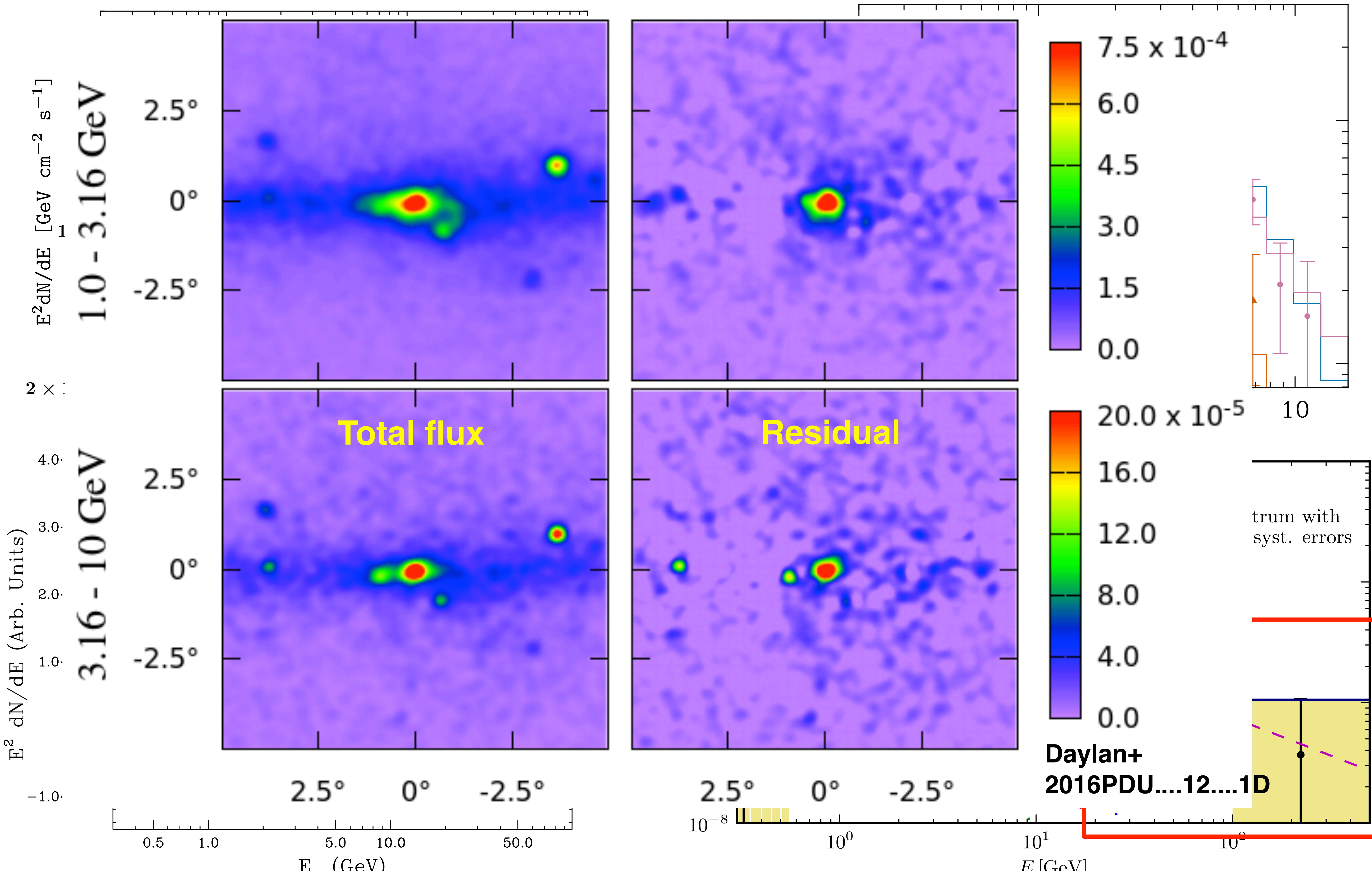

Daylan+
2016PDU....12....1D

"Galactic Center Excess" Summary

Publication	Data set	Galactic diffuse model	m_{DM} (GeV/c^2) (for bb pair)	$\langle\sigma v\rangle$ (10^{-26} cm^3/s) (for bb pair)
2014PhRvD..89f3515M	Pass 7, 45 months, $\lvert b\rvert<3.5°$, $\lvert\ell\rvert<3.5°$	Fermi/LAT p7v6 + HI gas (20 cm)	29±9	2.0±0.6
2014PhRvD..90b3526A	Pass 7, 57 months, $\lvert b\rvert<3.5°$, $\lvert\ell\rvert<3.5°$	HI gas (20 cm) + "new diffuse"	39.4±7.9	5.1±2.1
2016PDU....12....1D	Pass 7, 64 months, $1<\lvert b\rvert<20°$, $\lvert\ell\rvert<20°$	Fermi/LAT p6v11 + Fermi Bubbles	~35.5	~3.0
	Pass 7, 64 months, $\lvert b\rvert<5°$, $\lvert\ell\rvert<5°$	Fermi/LAT p7v6 + HI gas (20 cm)	35.5±4.5	3.0±0.5
2015JCAP...03..038C	Pass 7, 64 months, $2<\lvert b\rvert<20°$, $\lvert\ell\rvert<20°$	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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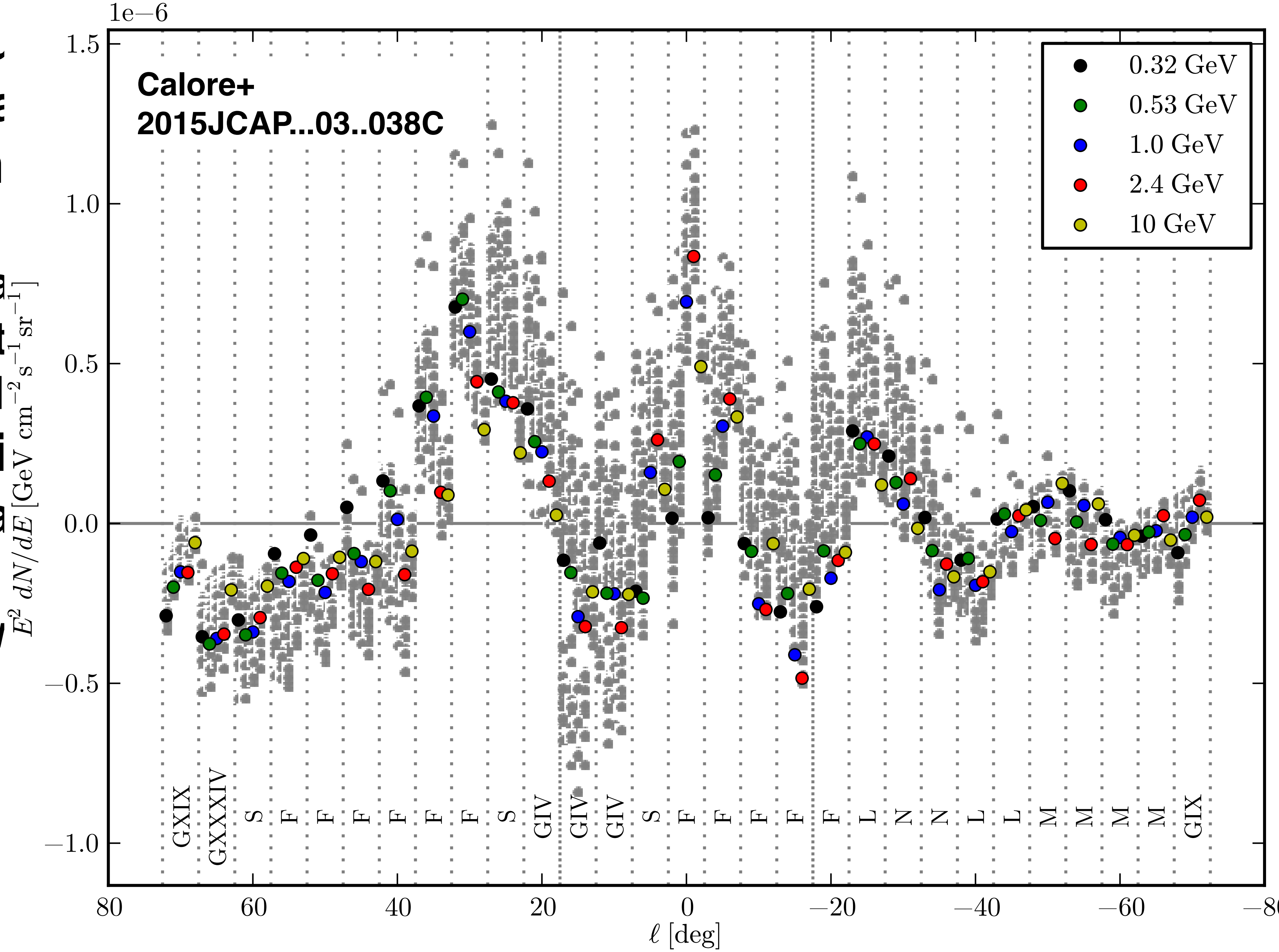


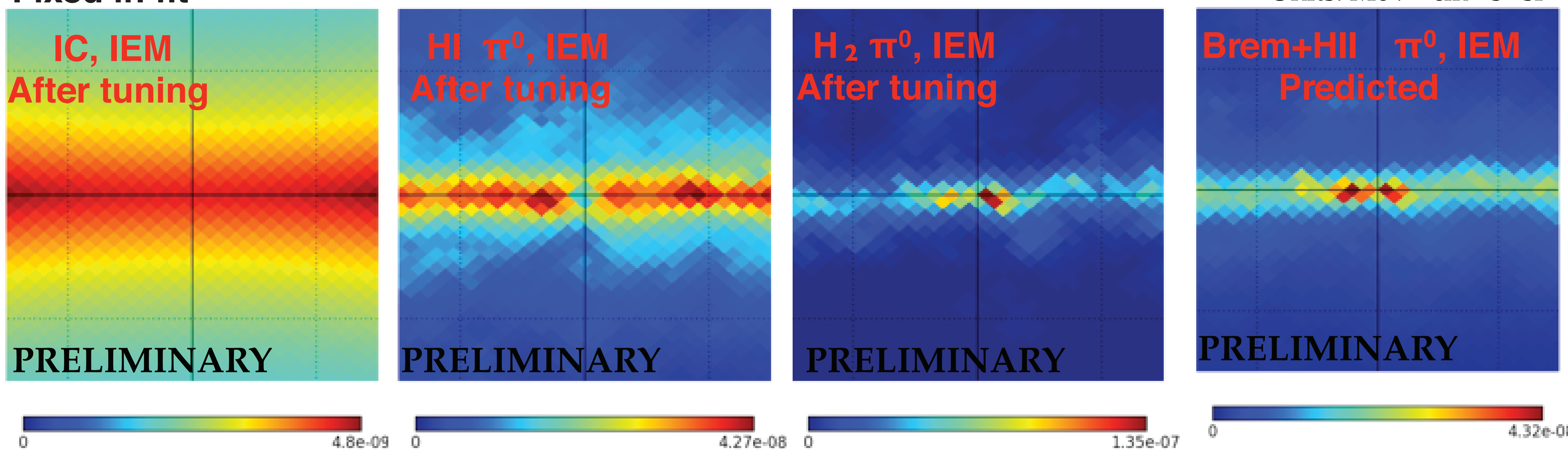
- Excess is not limited to Galactic Center

“GCE” Analysis by LAT Team

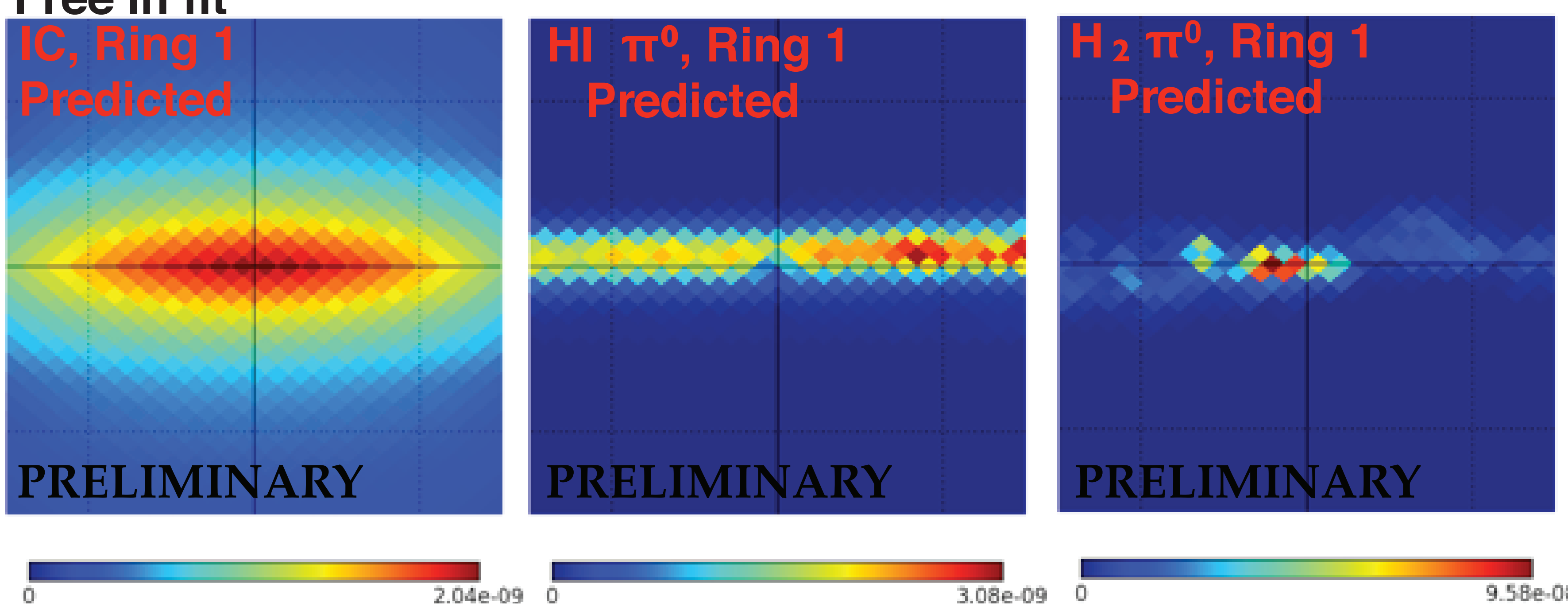
- Detailed modeling of Galactic diffuse emissions

Fixed in fit

Units: MeV^{-1} cm^{-2} s^{-1} sr^{-1}



Free in fit



IEM: Ring II+
(r>4 kpc)

15°x15° ROI
E>1 GeV

~0.23° pixels

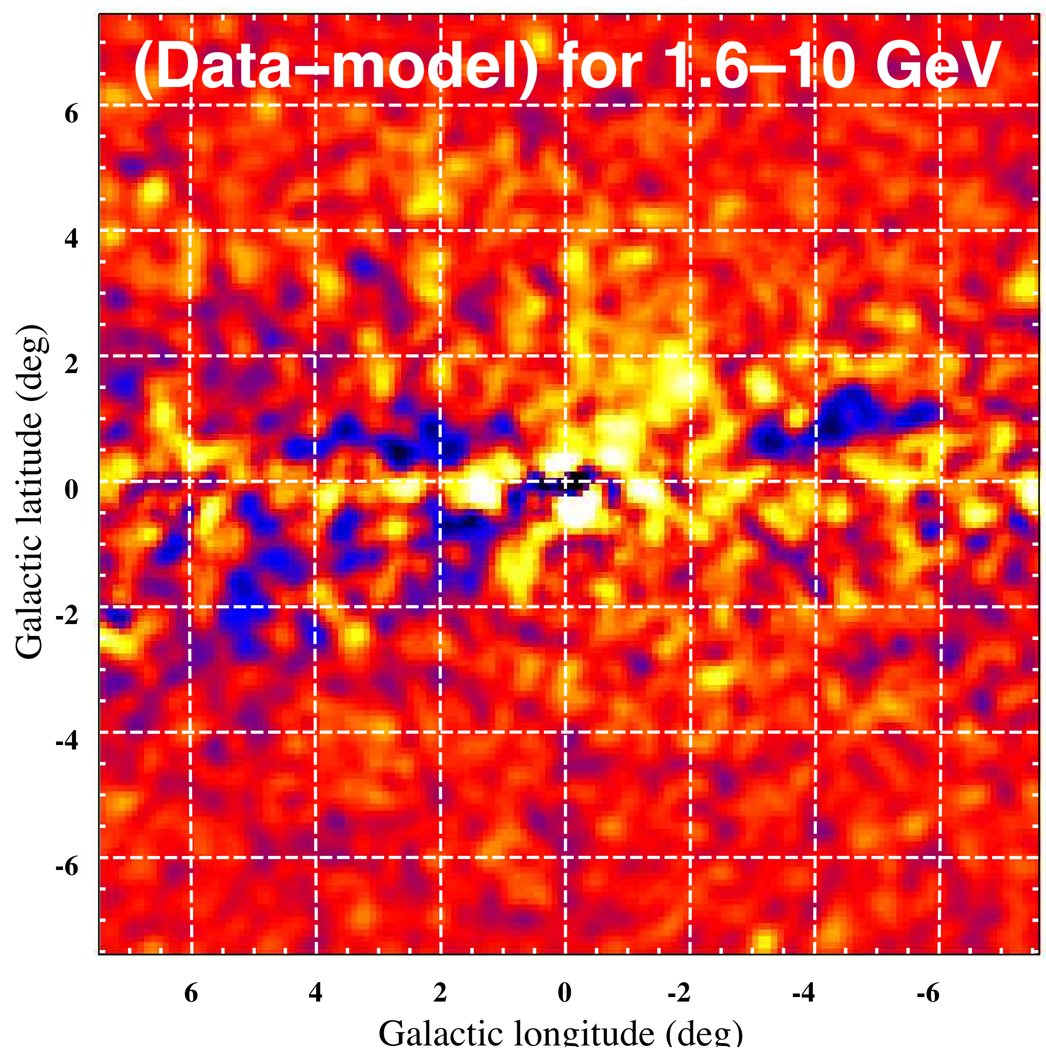
Presented by Simona Murgia at 5th Fermi Symposium in 2014

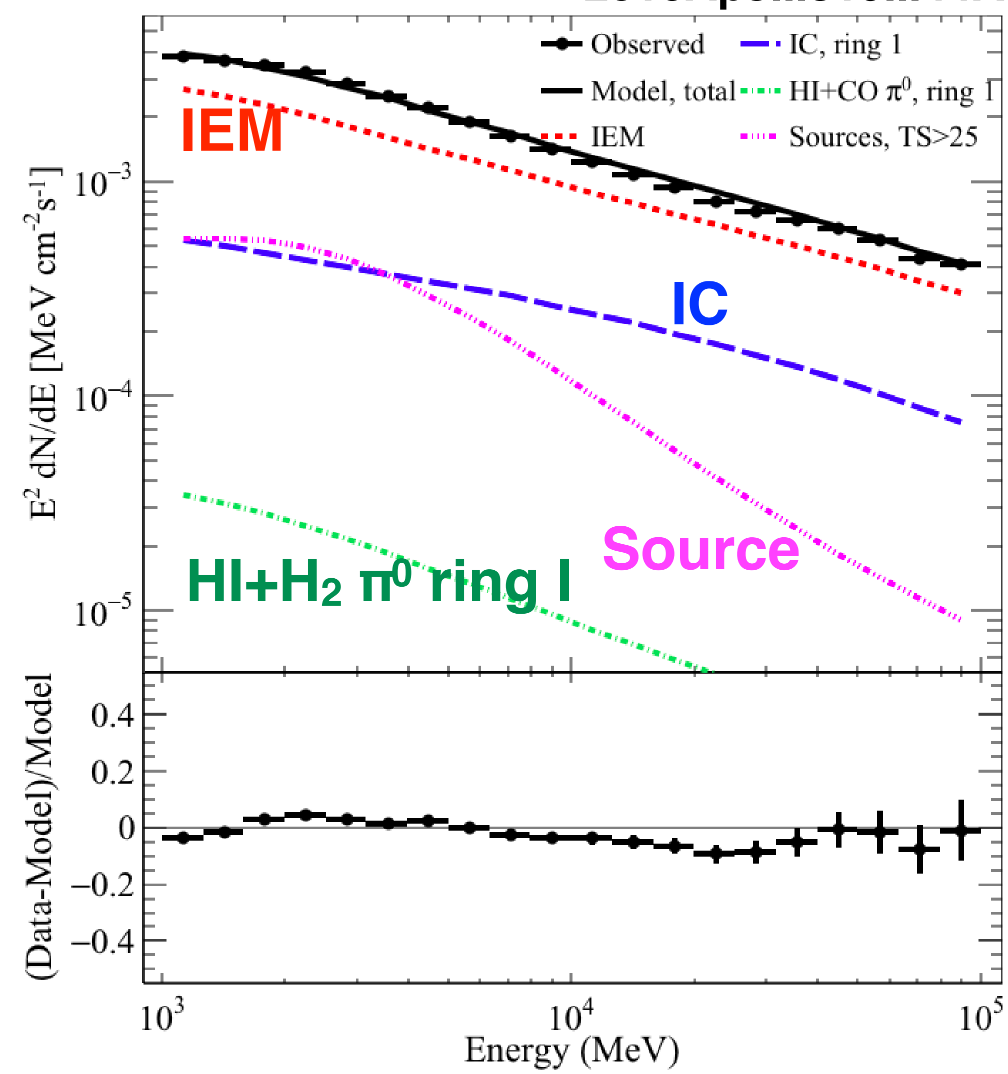
- Point sources are detected from scratch with new diffuse model

"GCE" Results by LAT Team

- IEM (contributions from r>4 kpc) is dominant
- IC emission for ring 1 is brighter than the gas emission and larger (6–30x) than predicted from Galprop model
  - Higher intensity of interstellar radiation field, higher cosmic-ray lepton intensities and/or undetected sources
- Adding WIMP component does not eliminate residual

2016ApJ...819...44A





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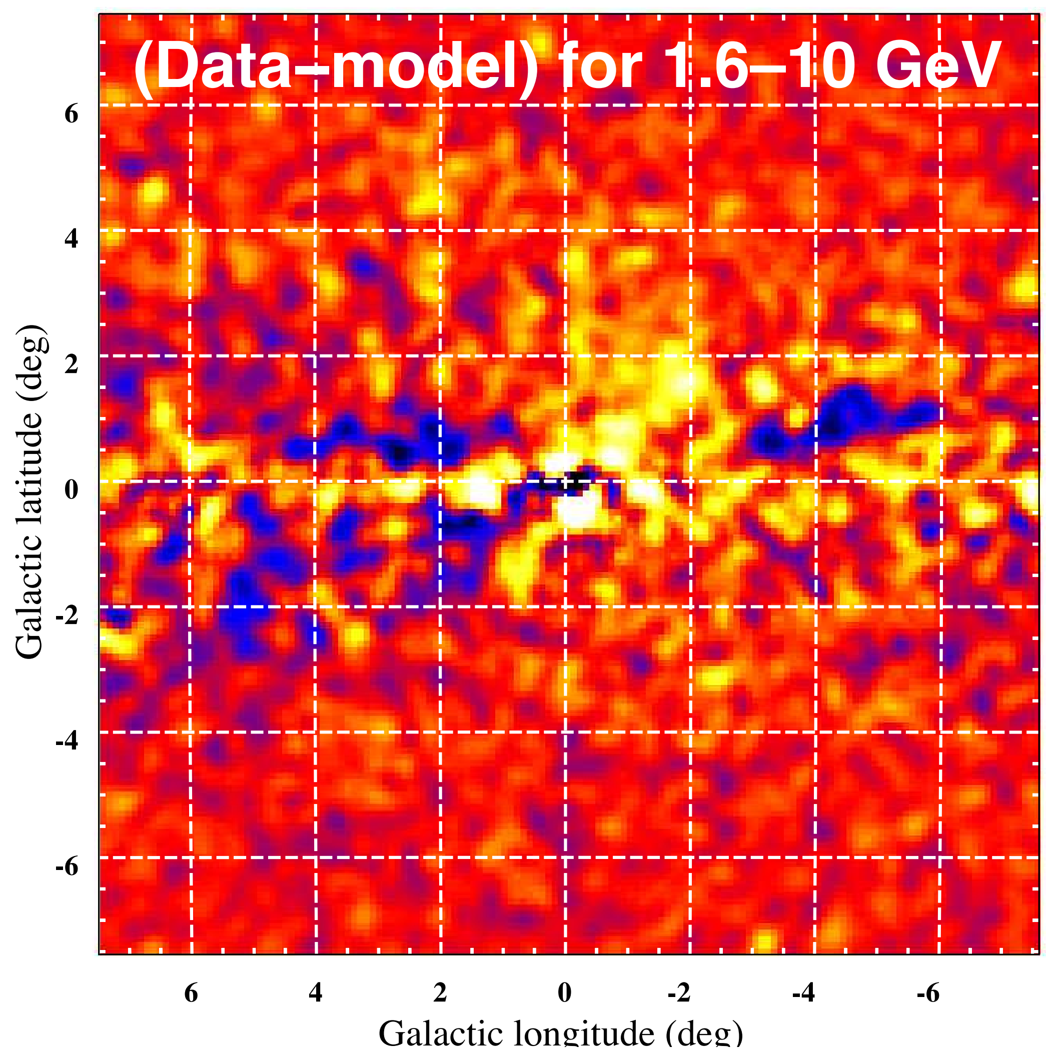

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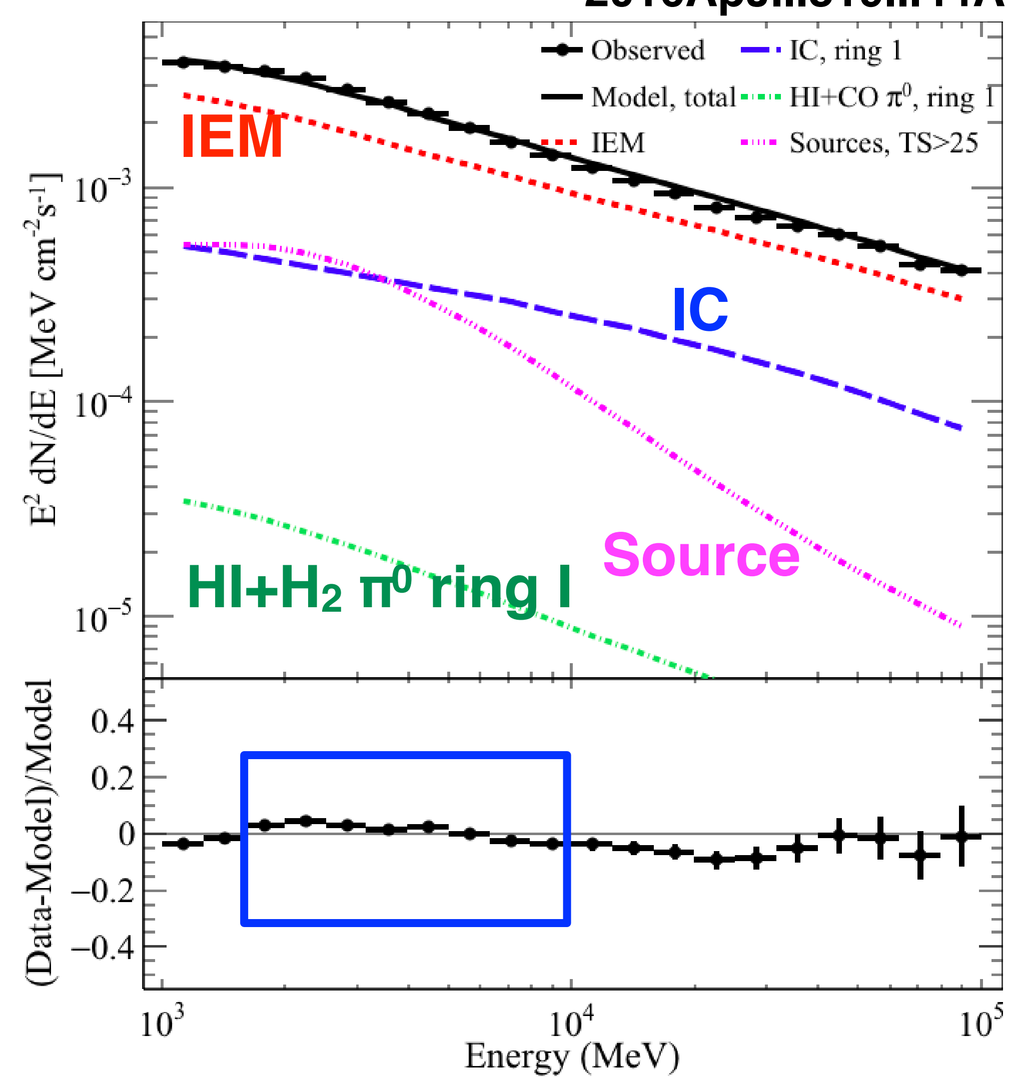

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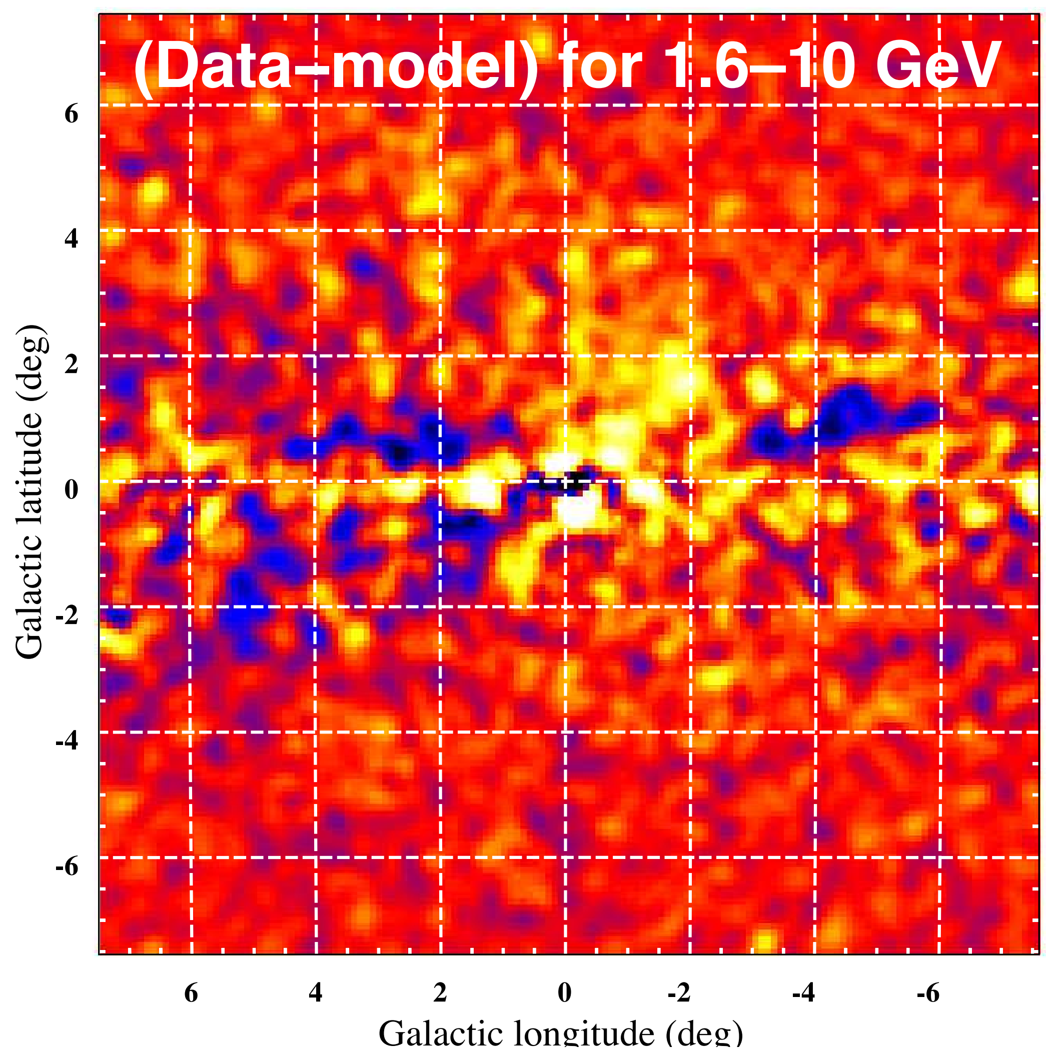

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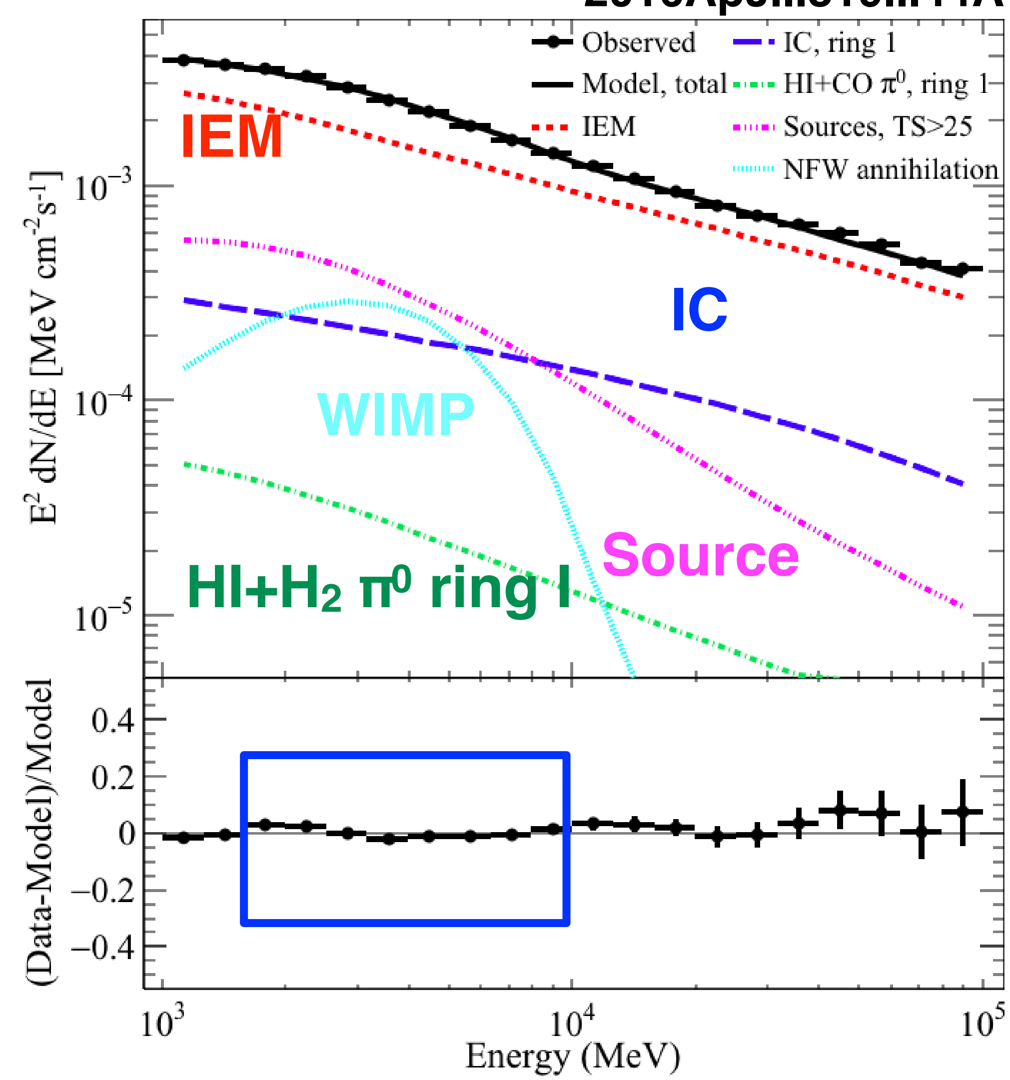
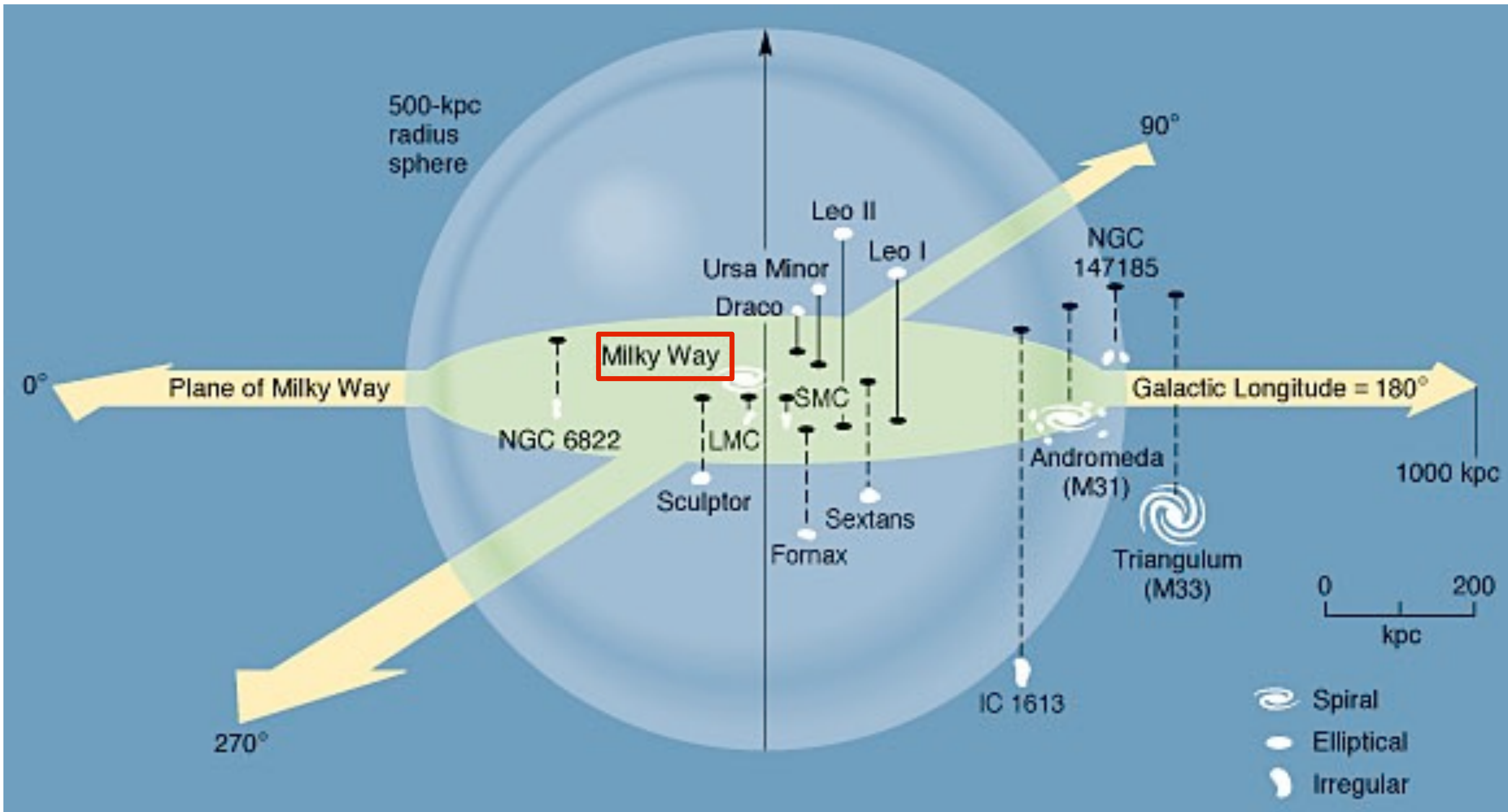


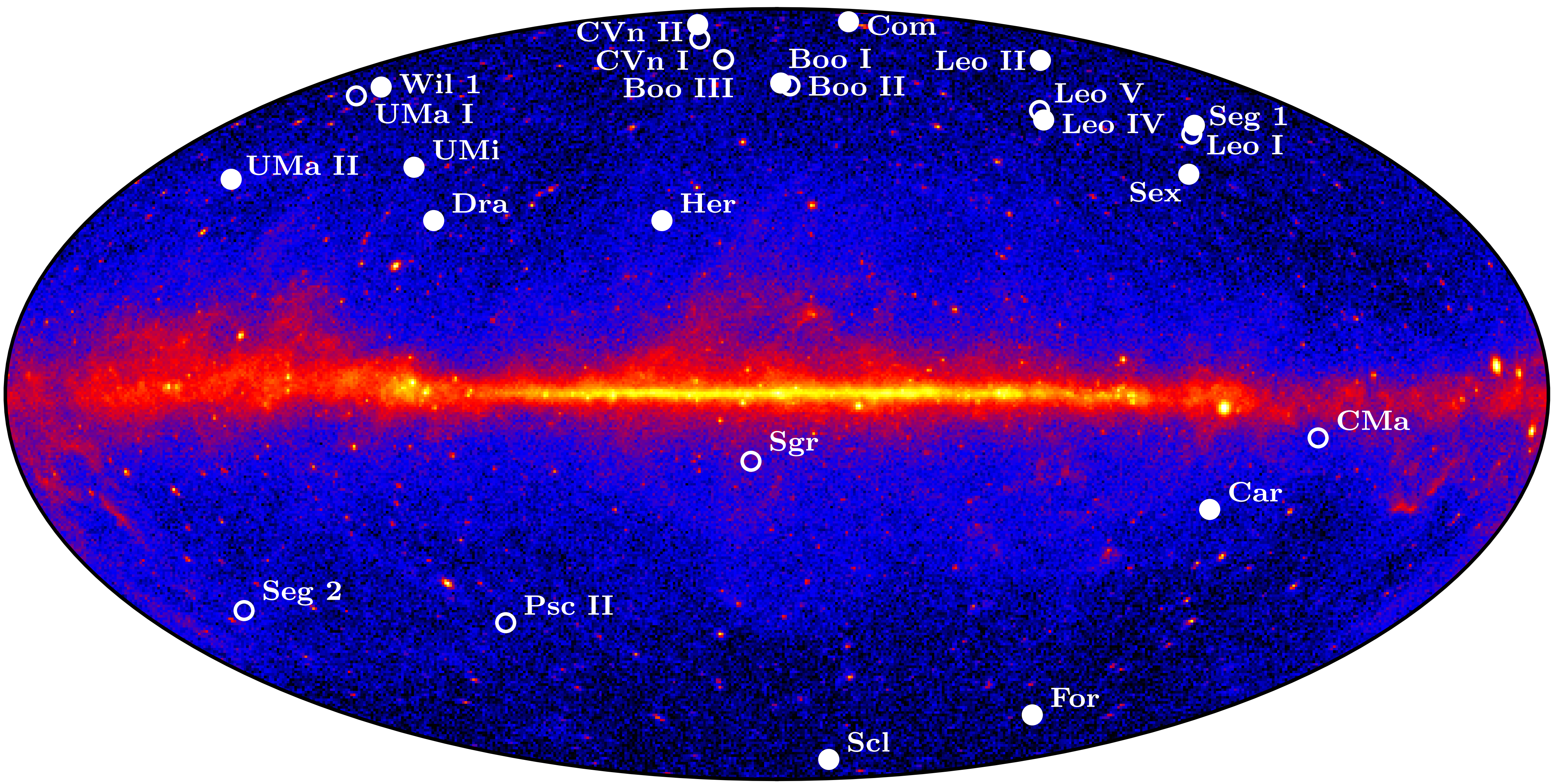
Dwarf Spheroidal Galaxies

- 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 WIMP 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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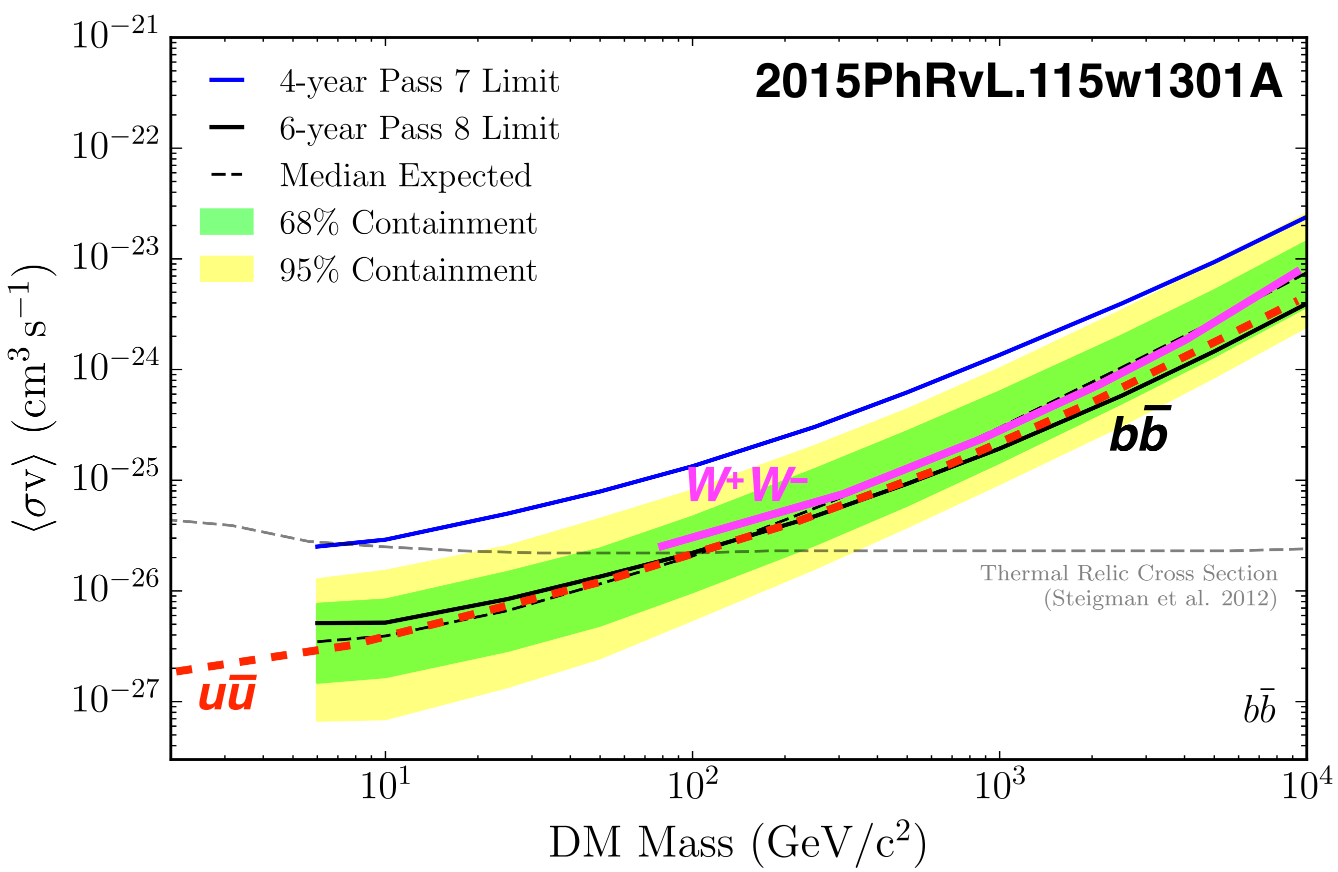
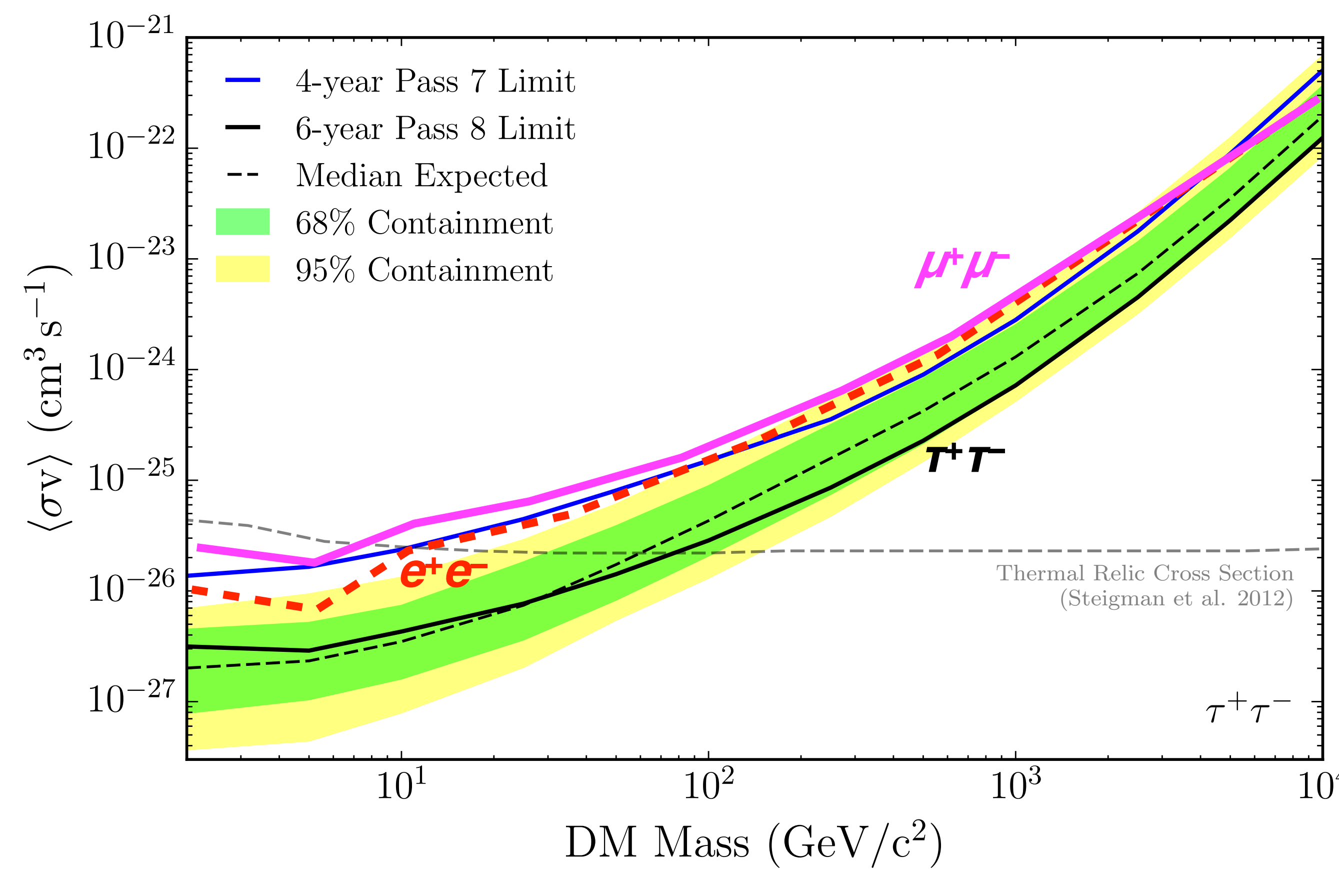
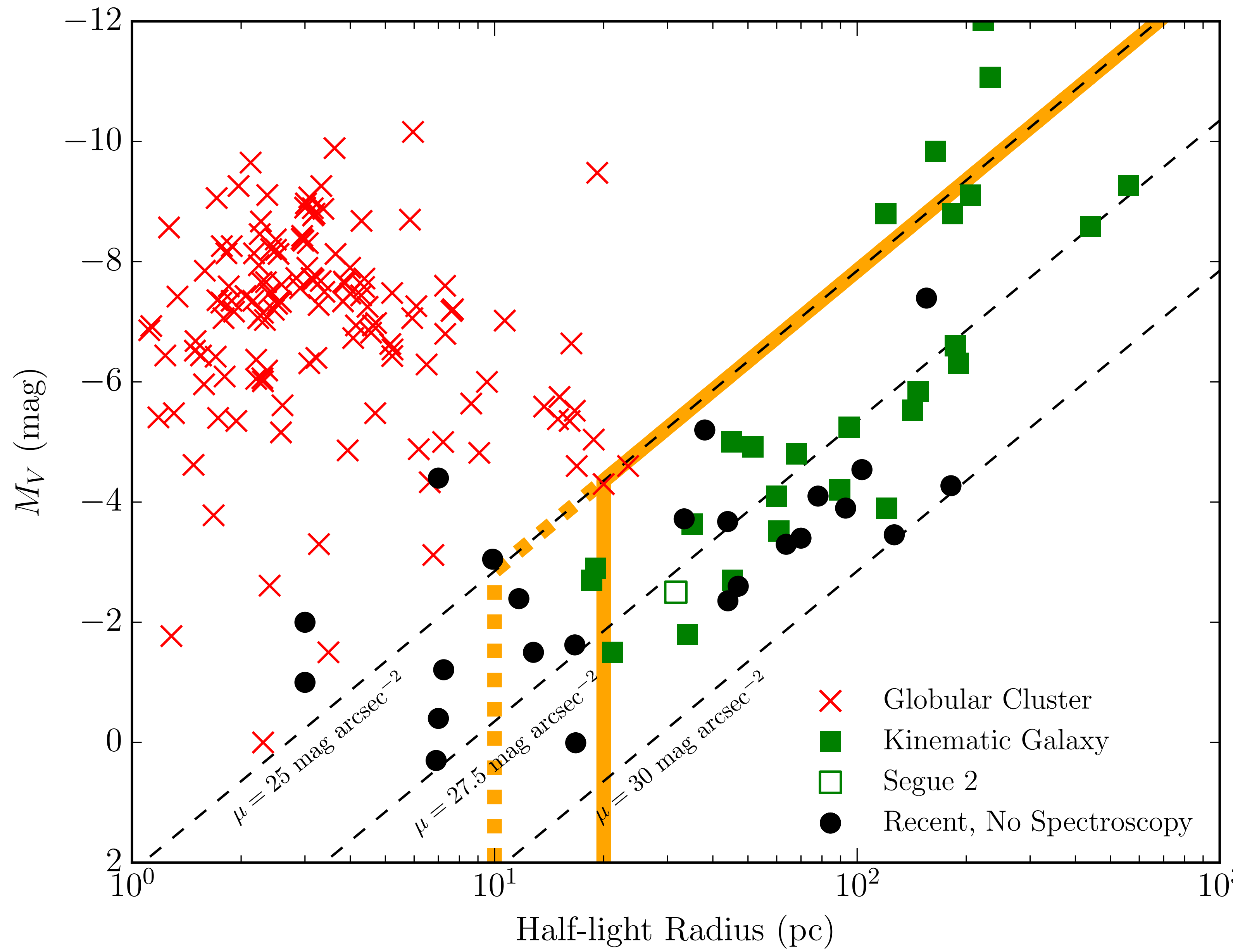




New WIMP Search in Dwarf Galaxies

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

arXiv: 1611.03184v1



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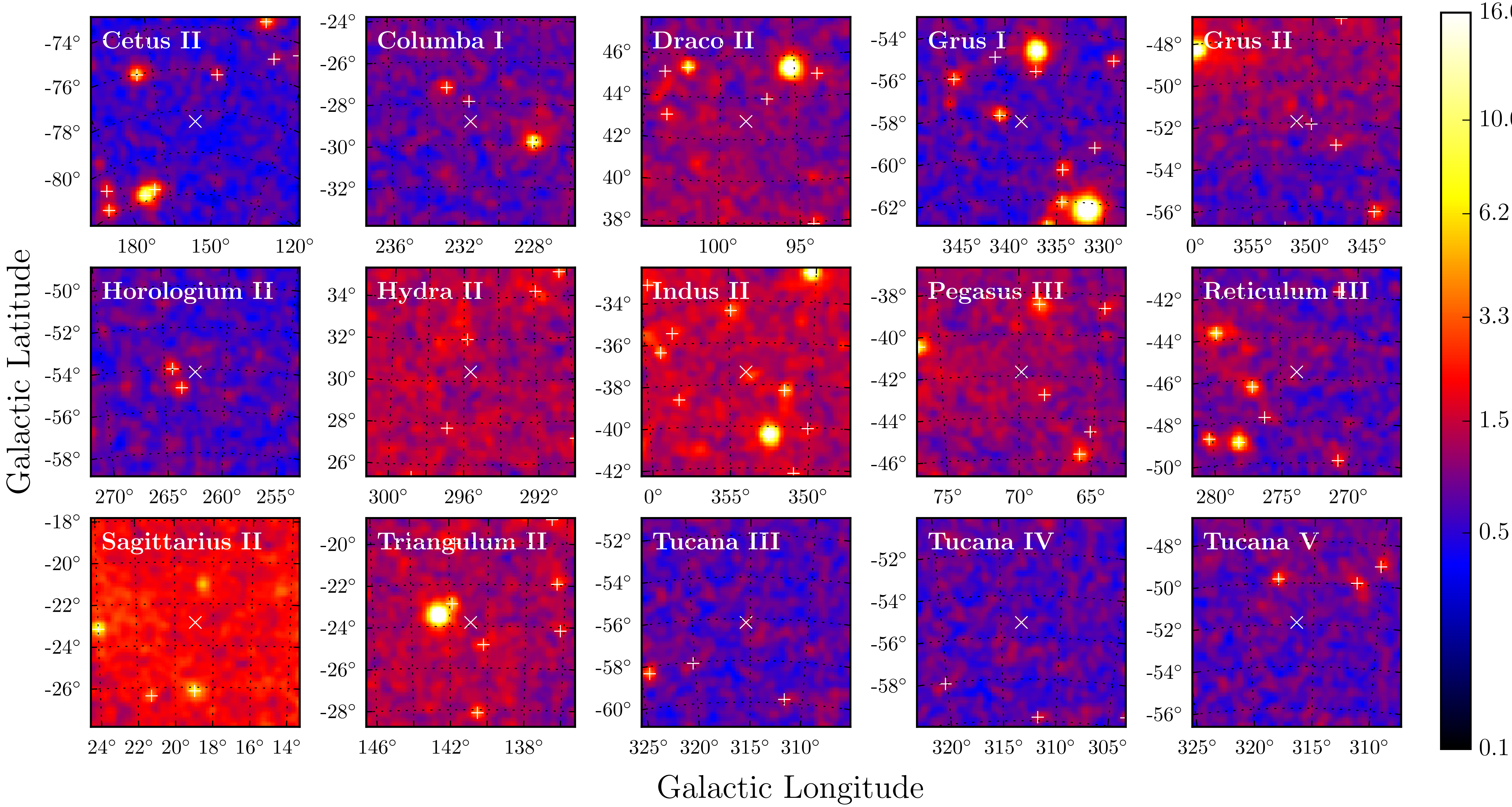

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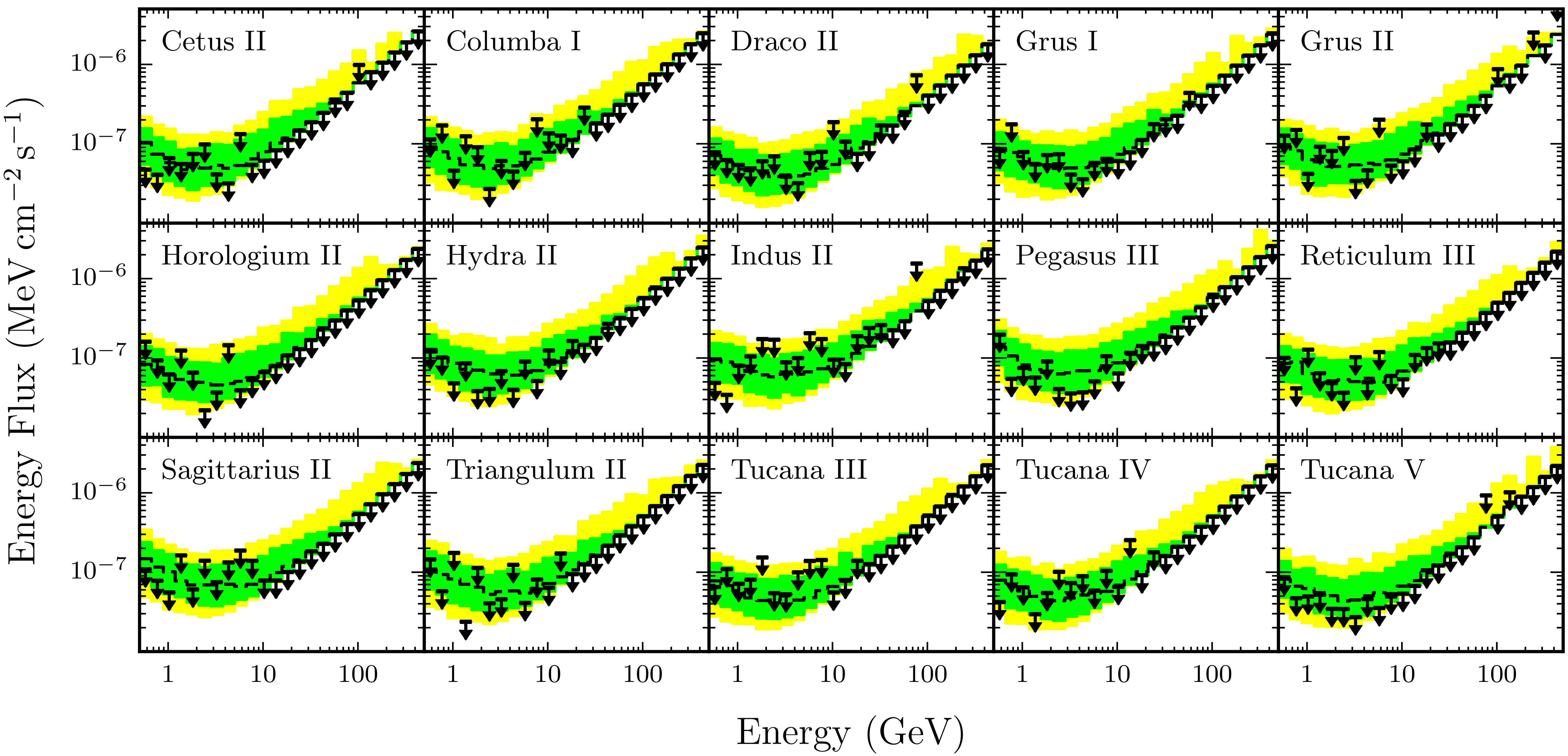

Constraints on WIMP Mass

- Test statistic (TS=−2[ln$L$−lnL_0]) for each dSph as a function of WIMP mass show no coherent peak at a certain WIMP 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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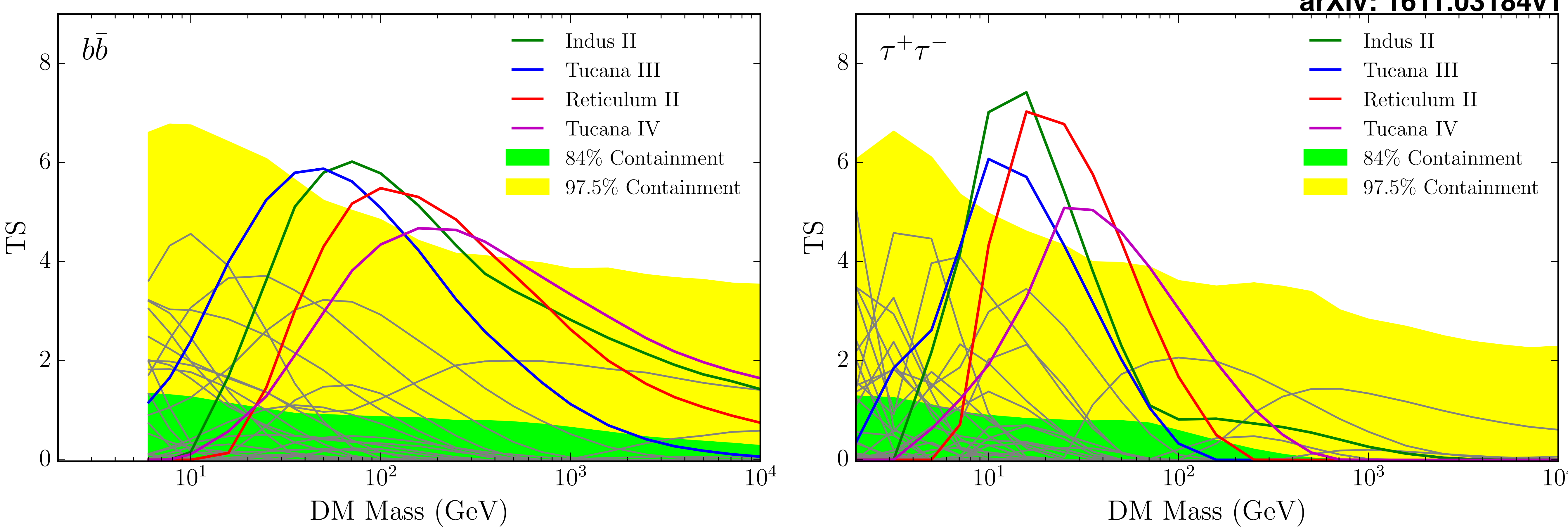

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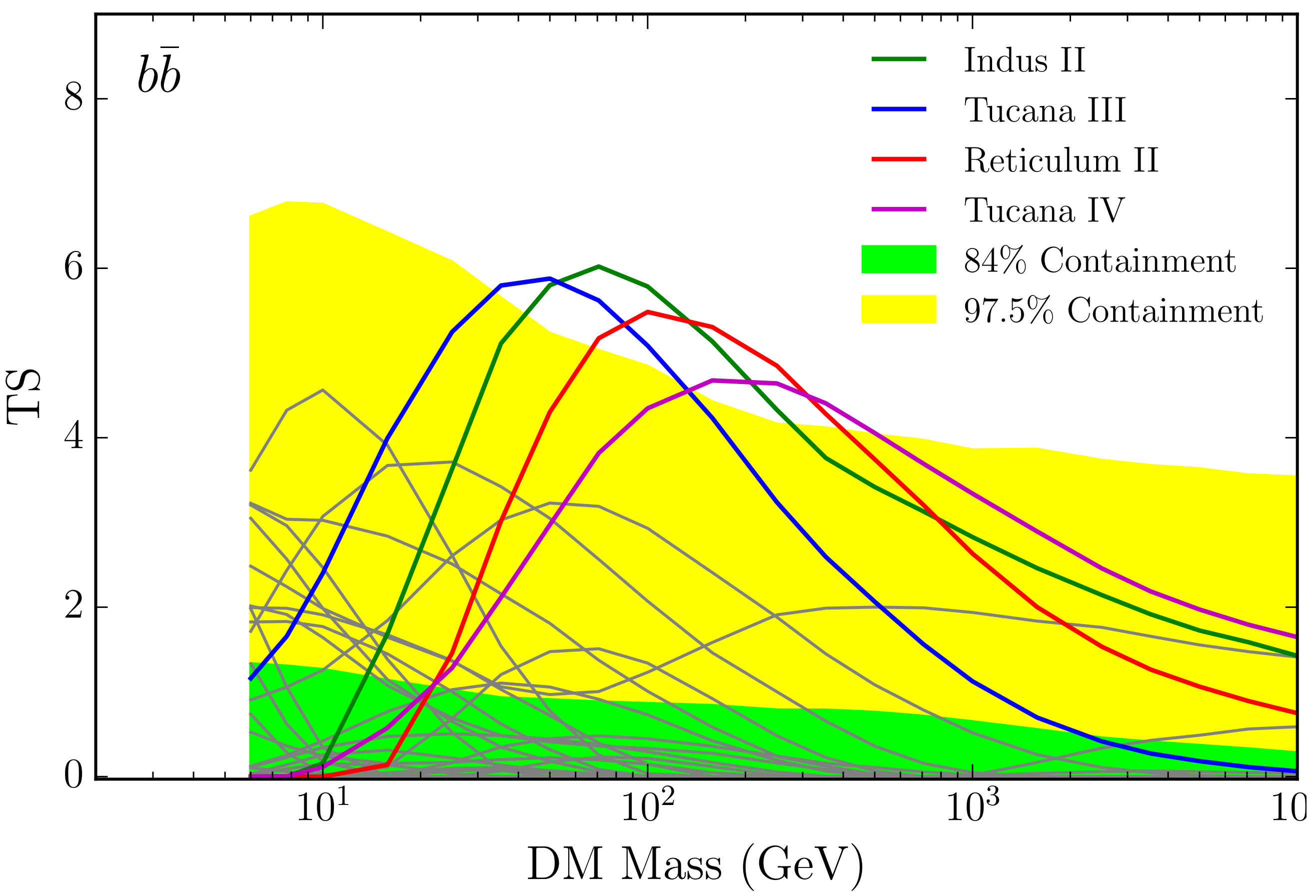

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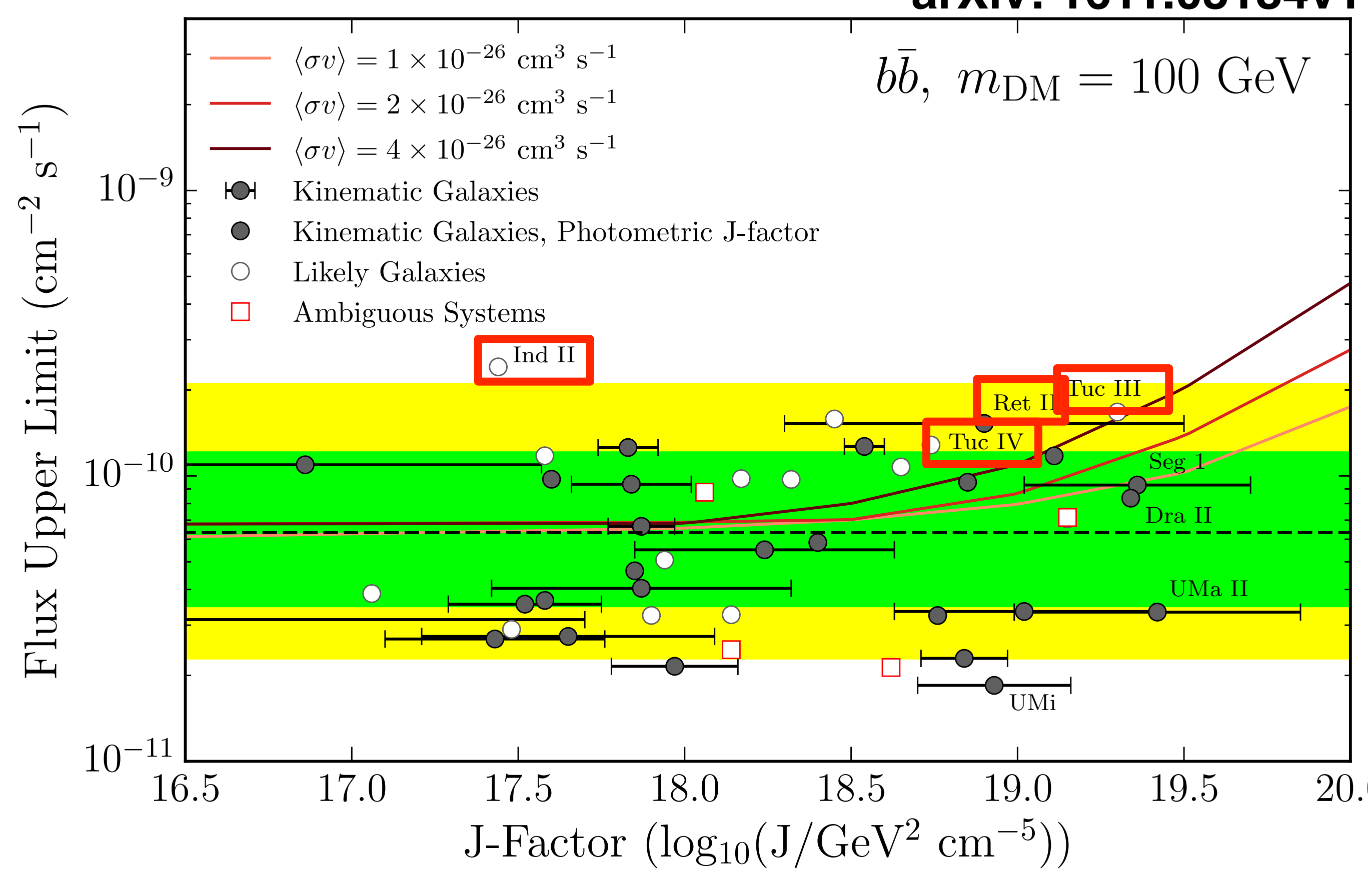

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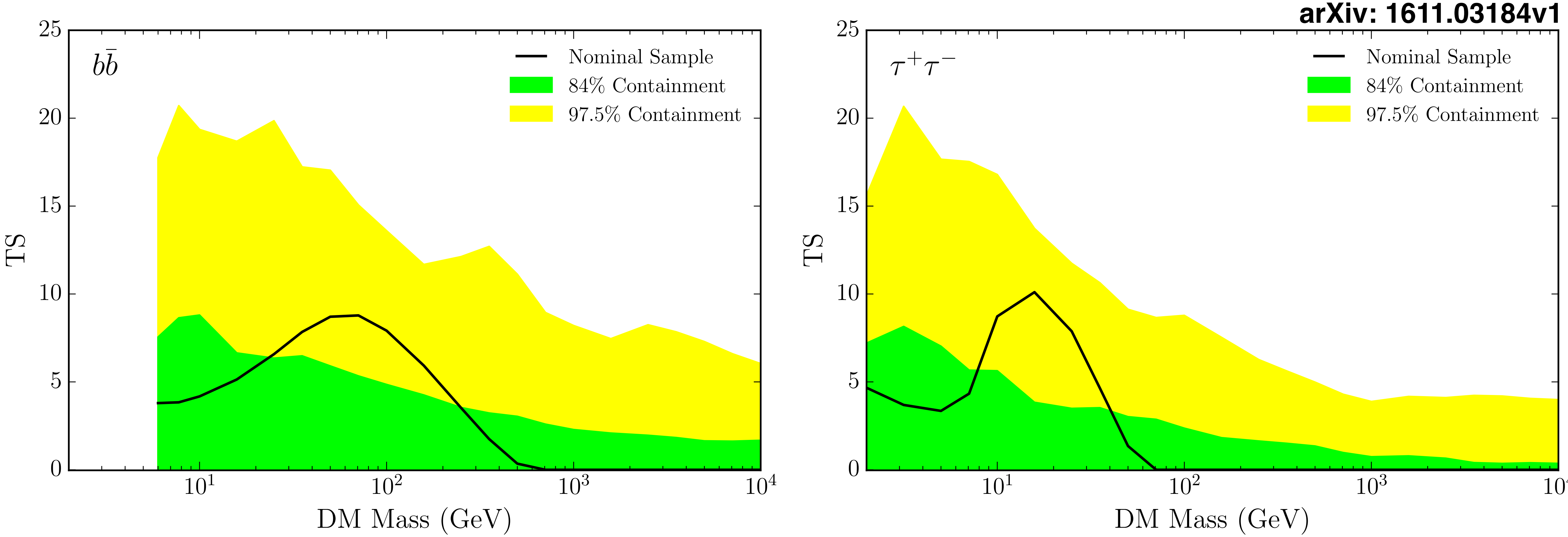

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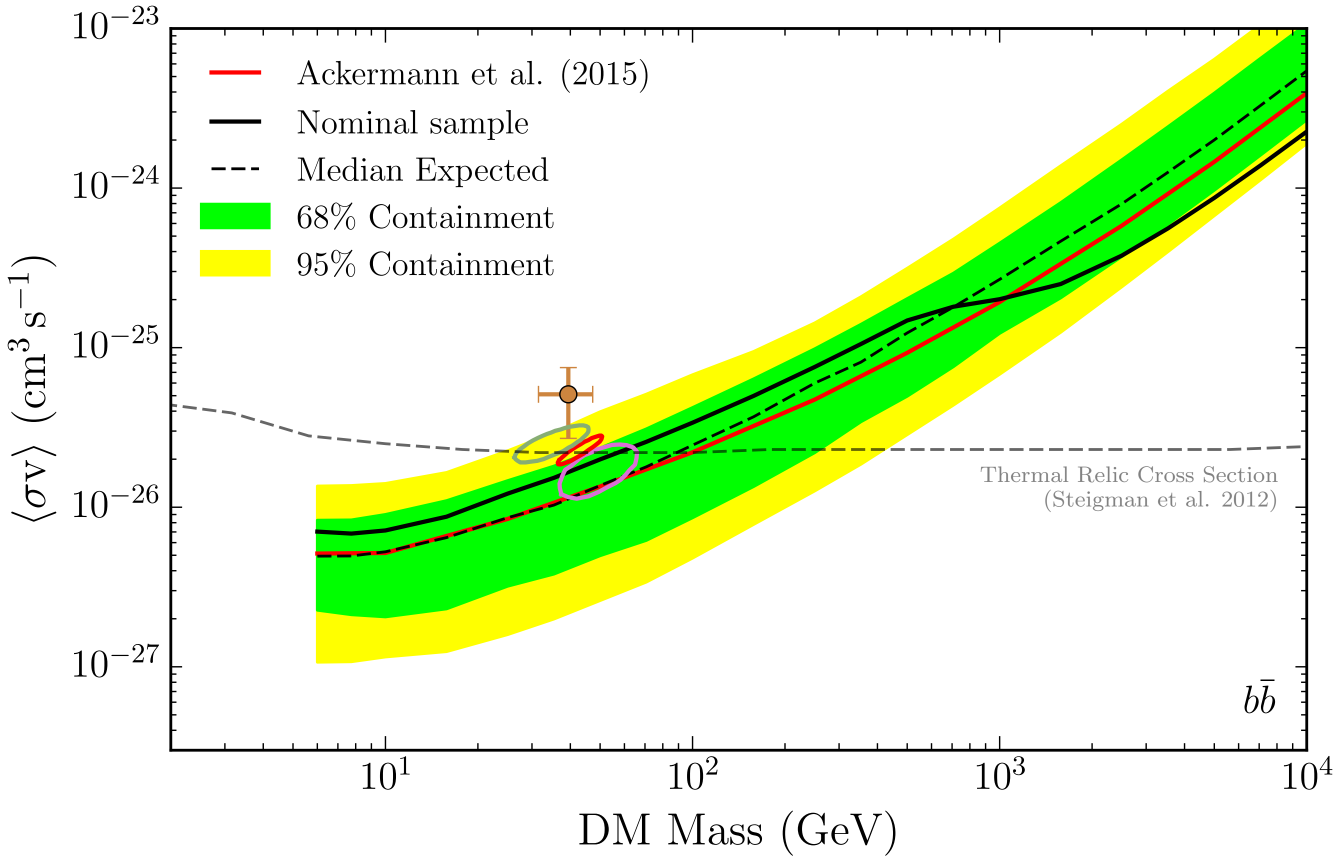
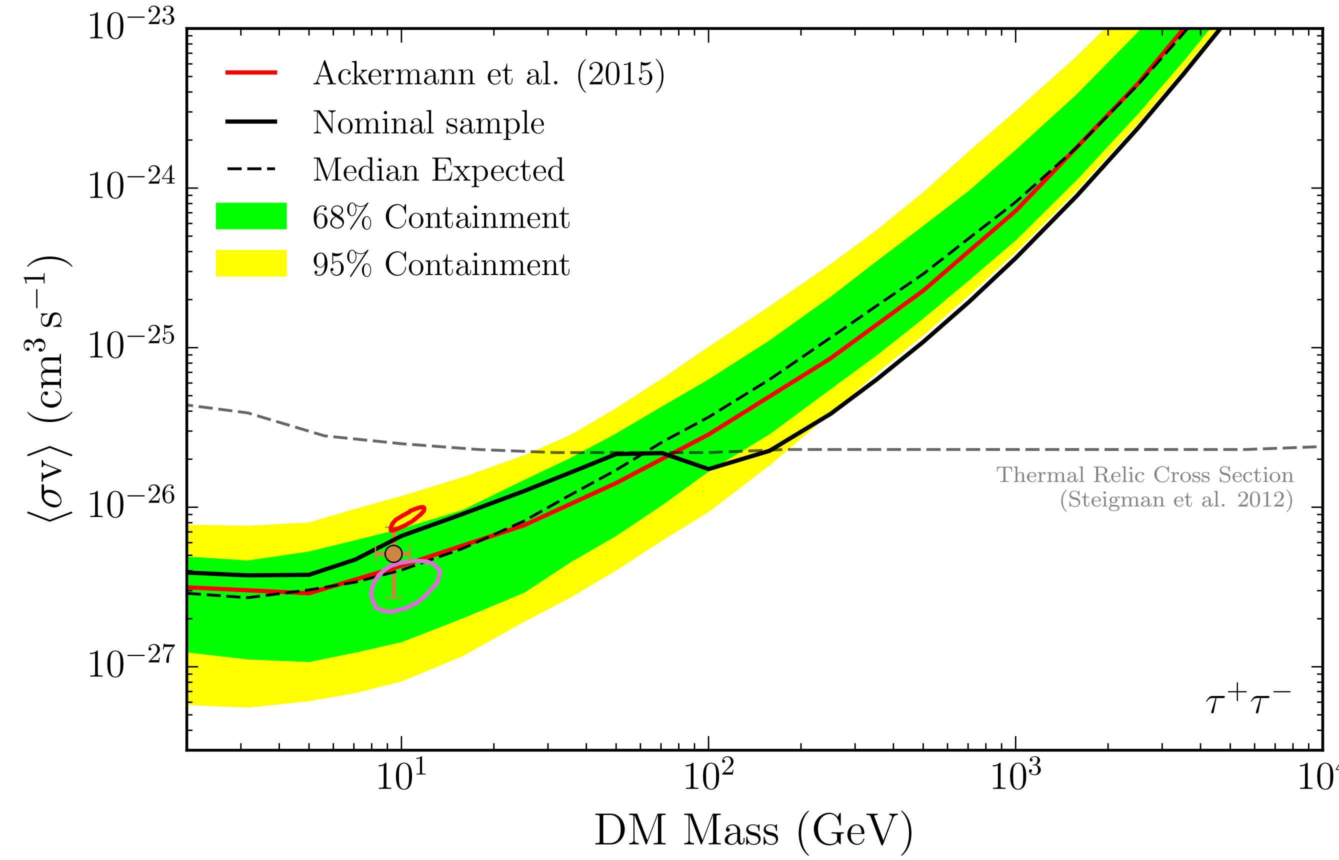
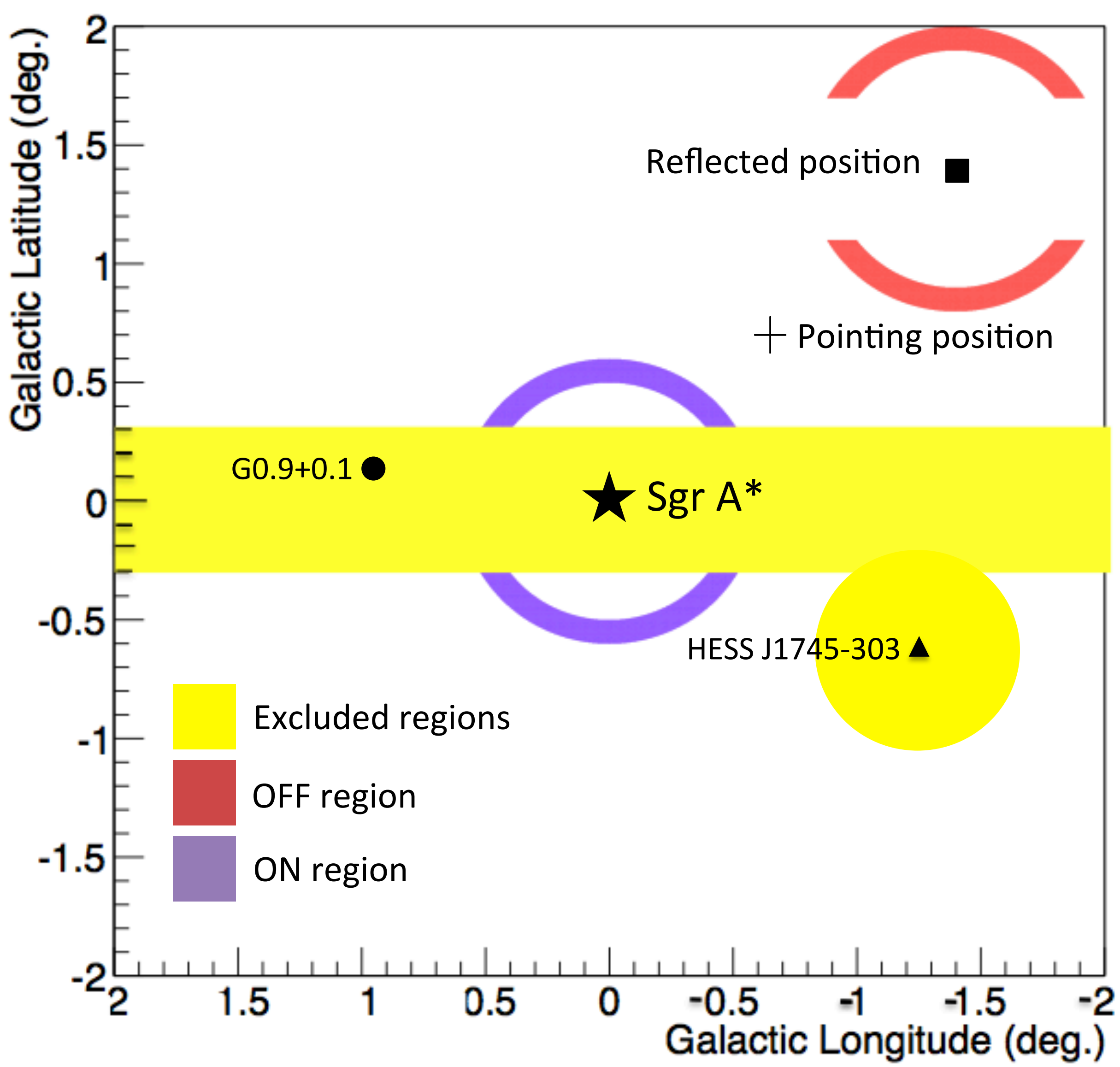
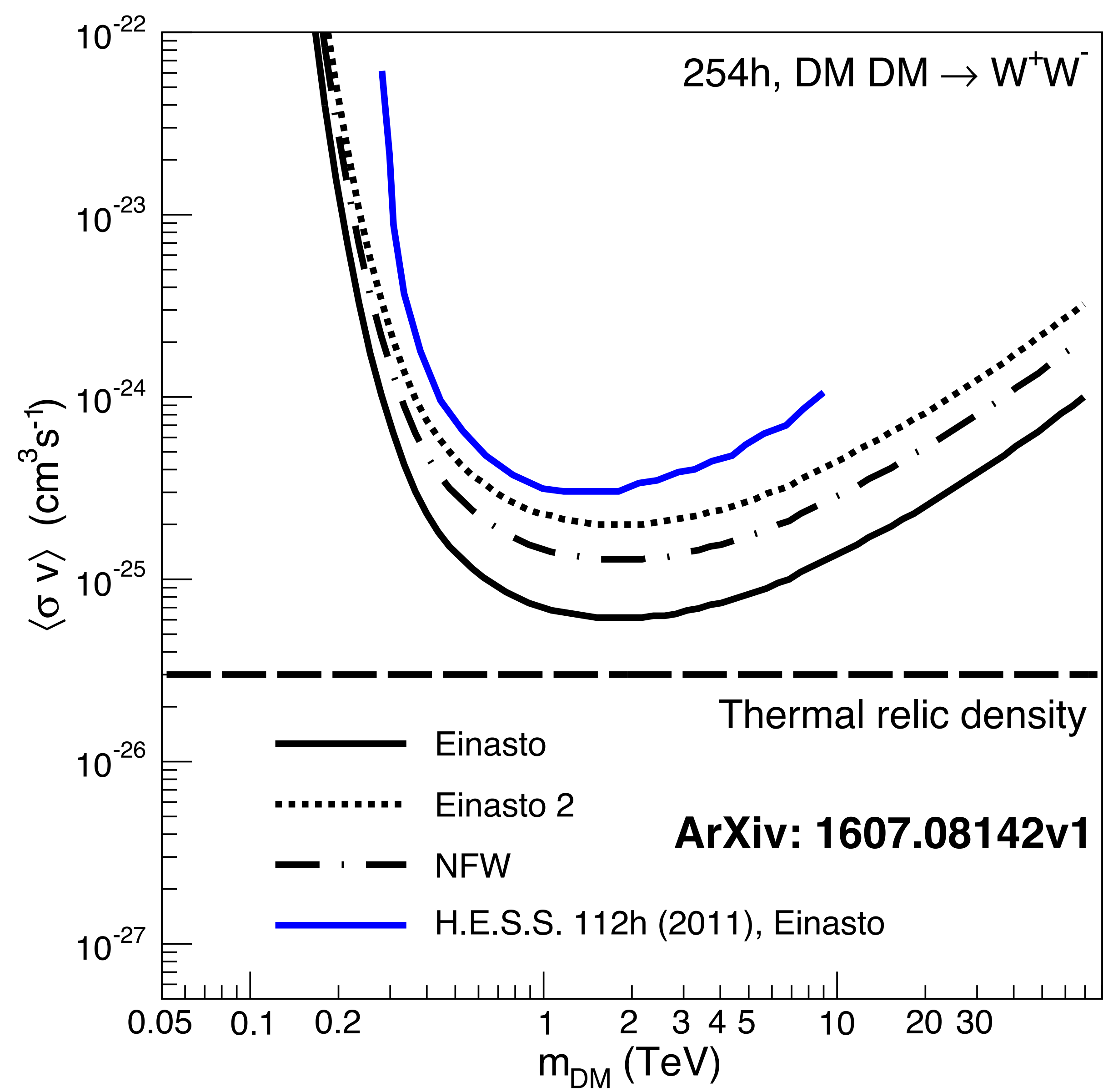




TeV WIMP Search in Galactic Center

- 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 WIMP density profile give large uncertainties





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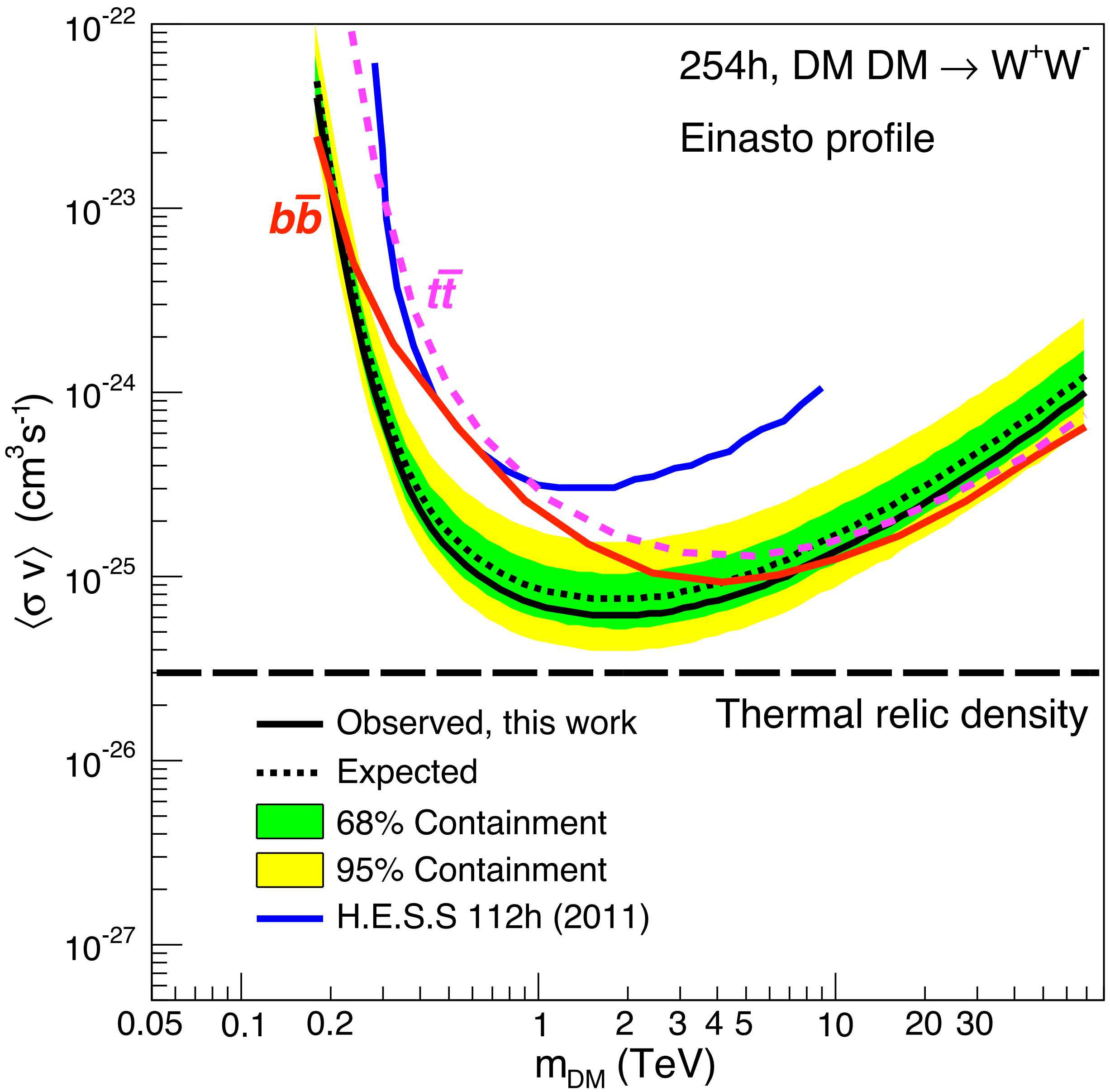
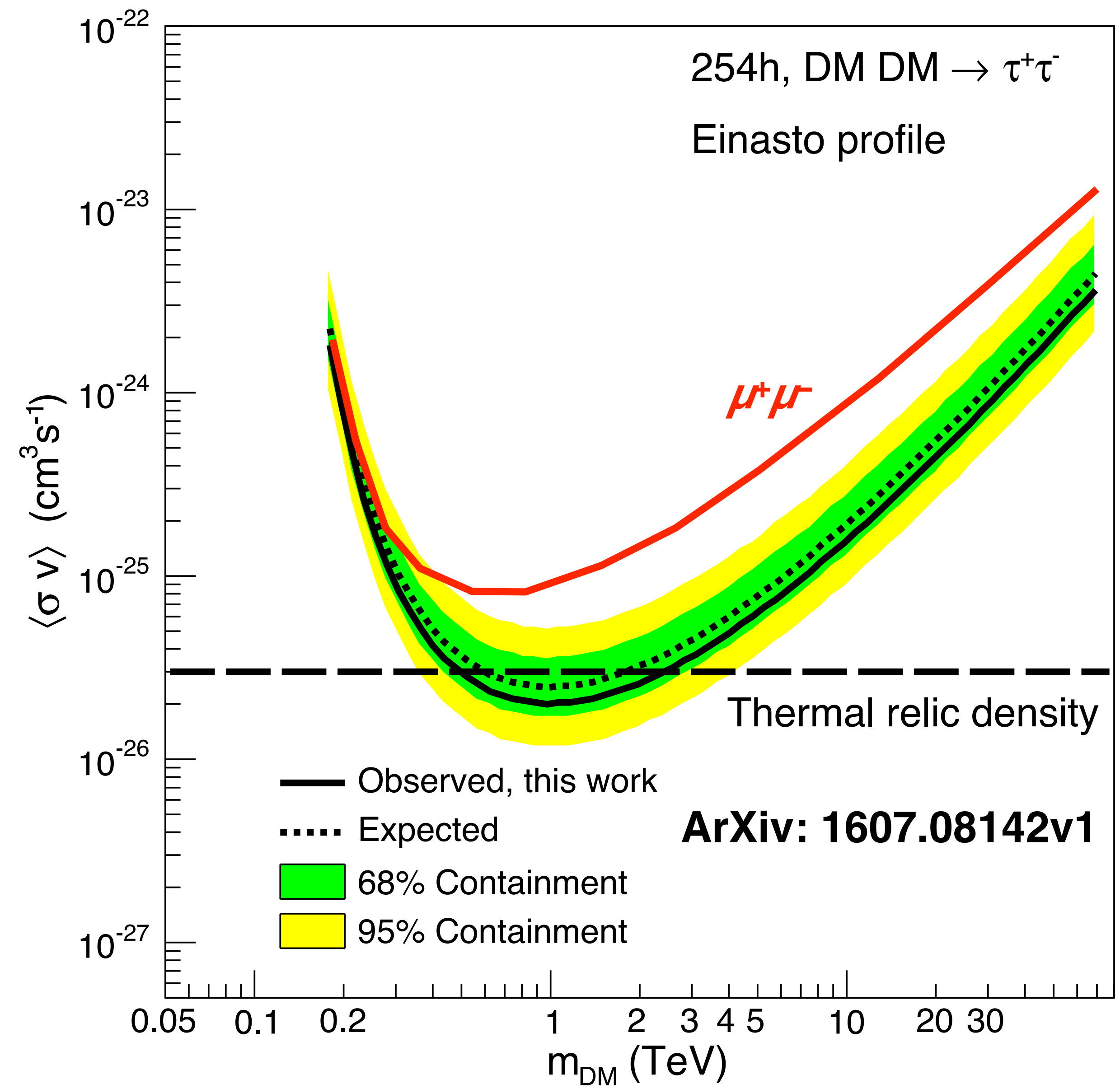
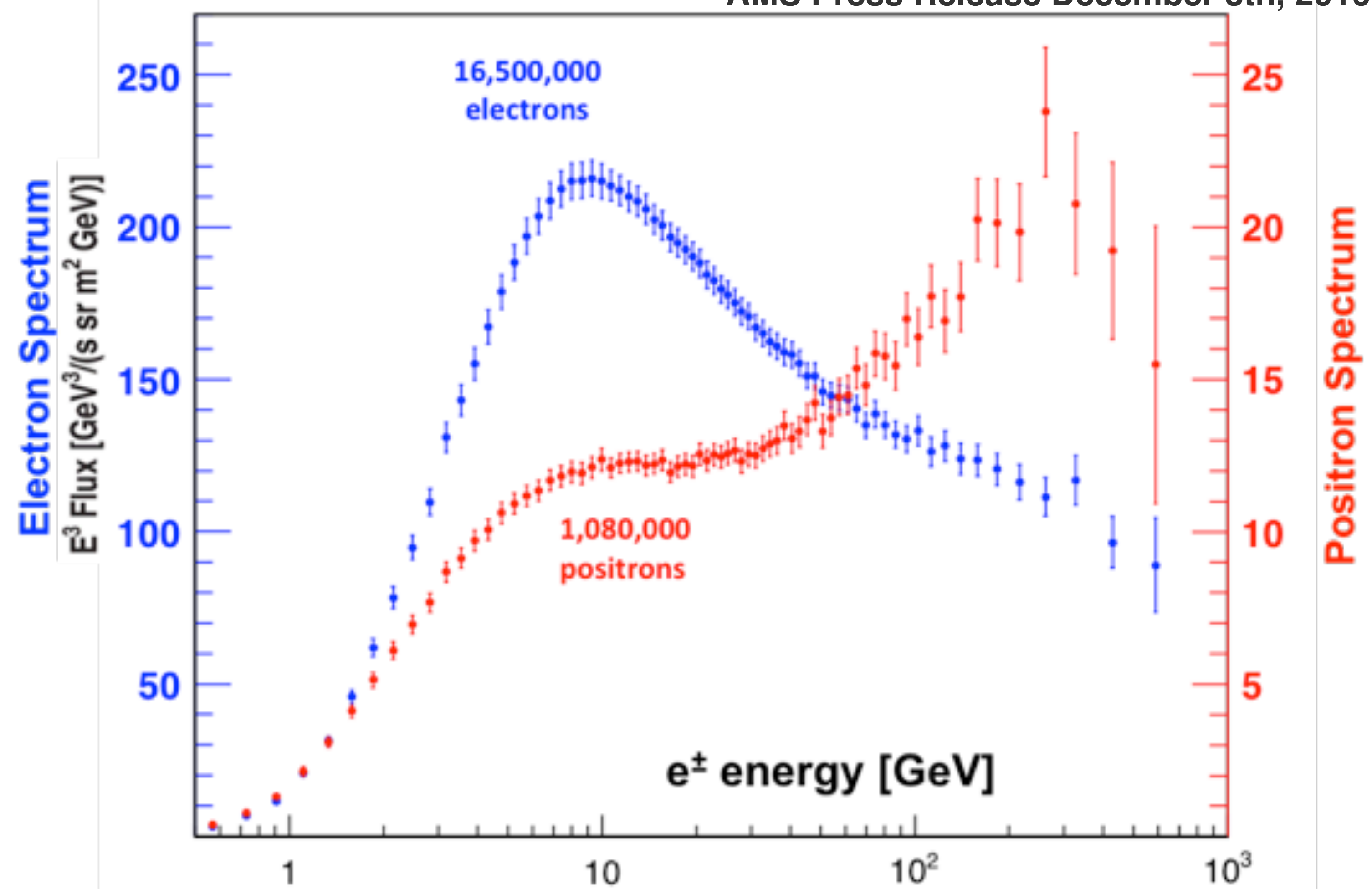




Updates on AMS-02 Results

- AMS-02 observed positron spectrum which may peak at several 100 GeV
  - These high energy electrons are expected to be produced locally since ~TeV electrons lose energies very quickly
  - AMS suggested WIMP hypothesis
  - Other astrophysical sources such as pulsars can also explain this spectrum
- 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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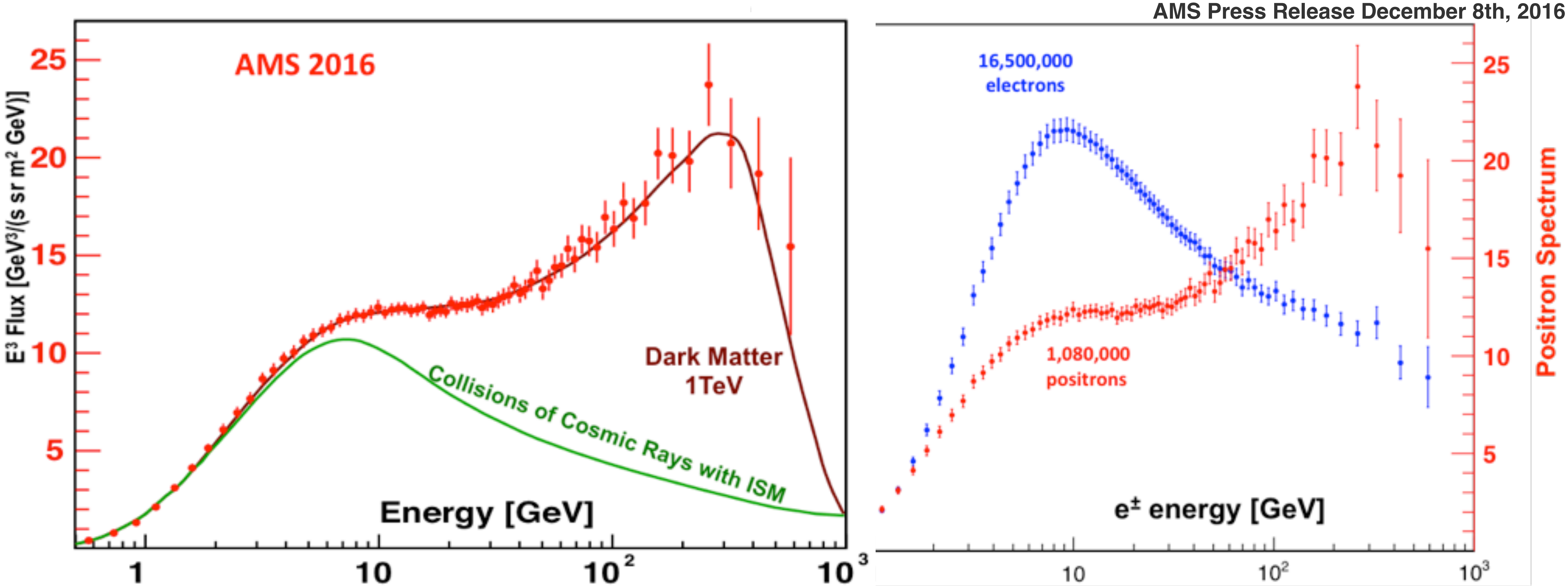

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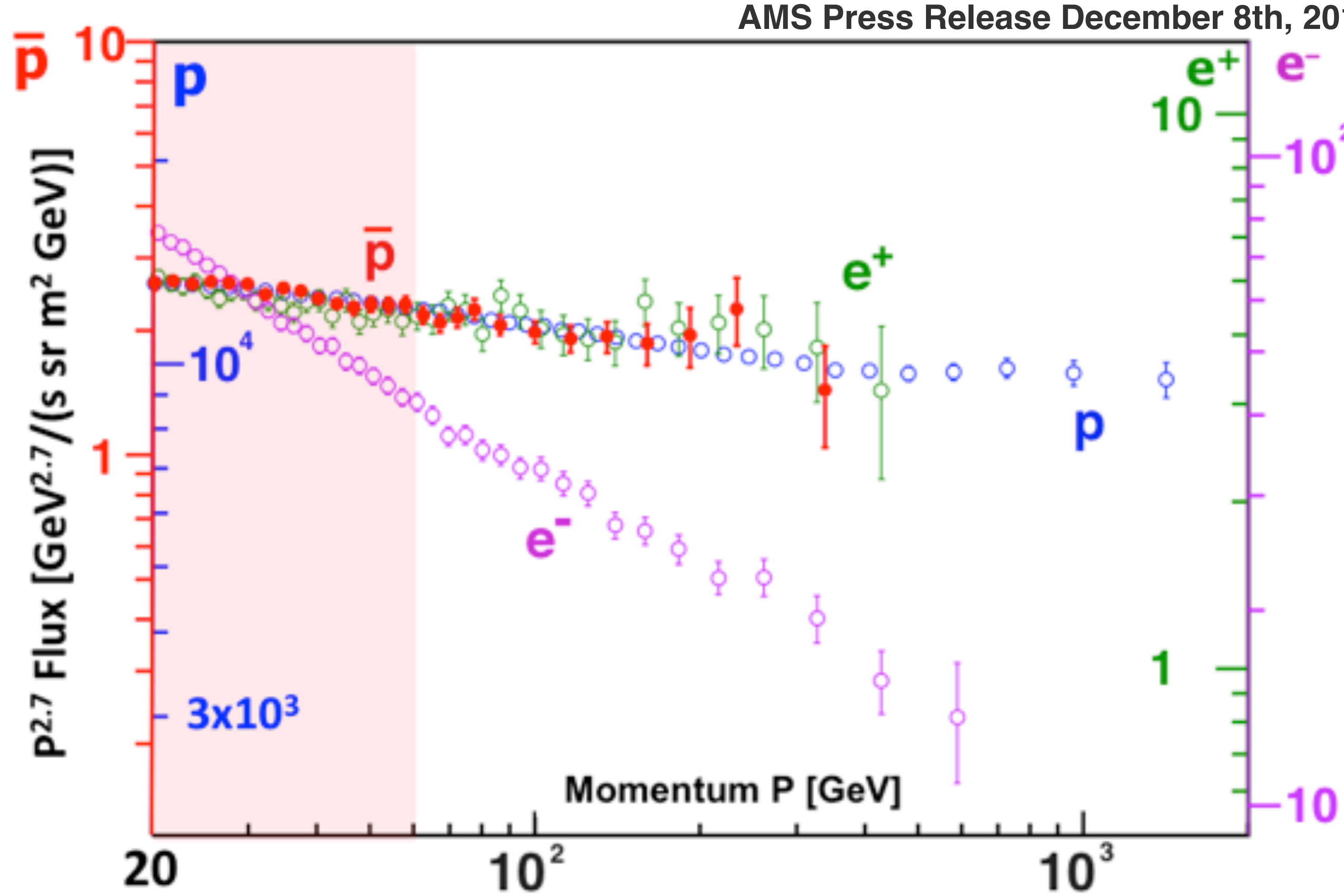
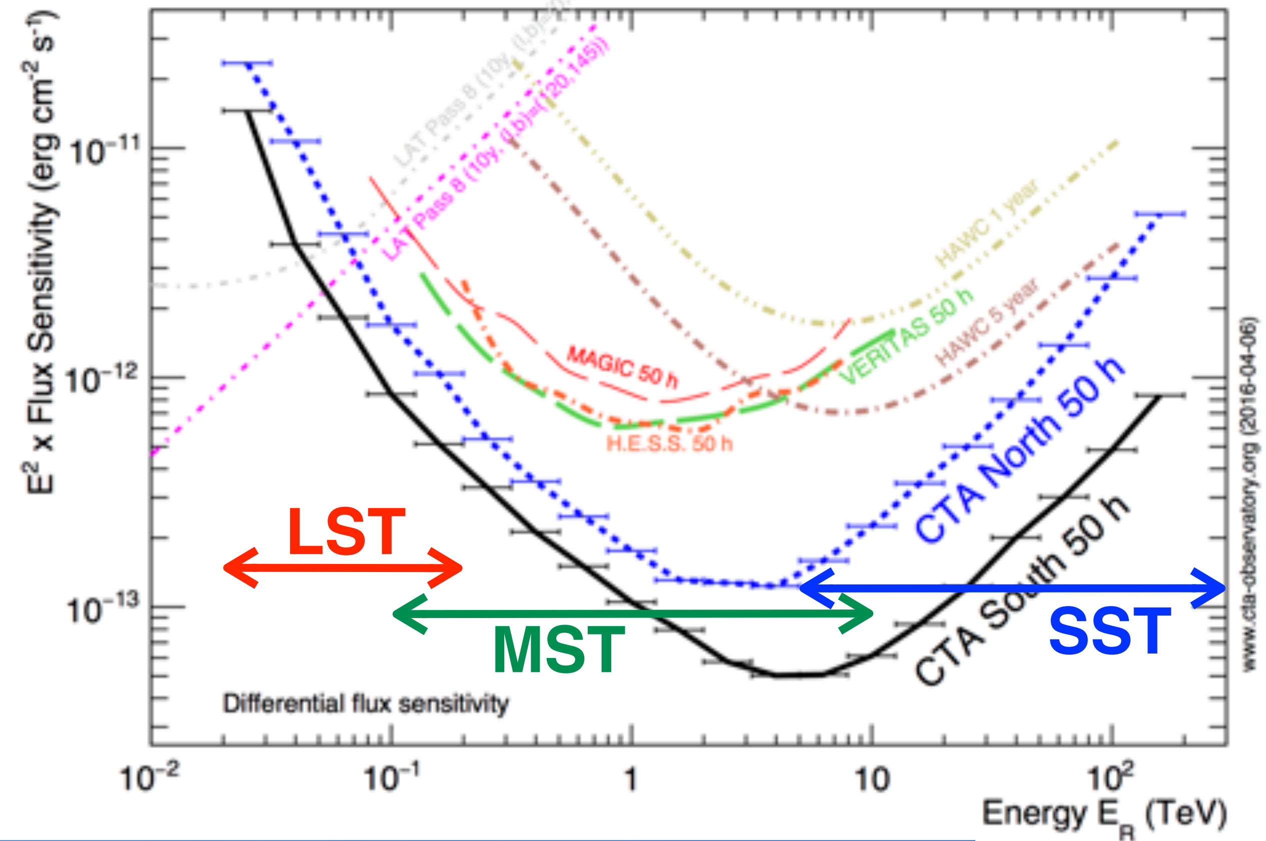
- AMS-02 also observed anti-proton spectrum which is similar to proton and positron spectra, but different from electron spectrum

AMS Press Release December 8th, 2016

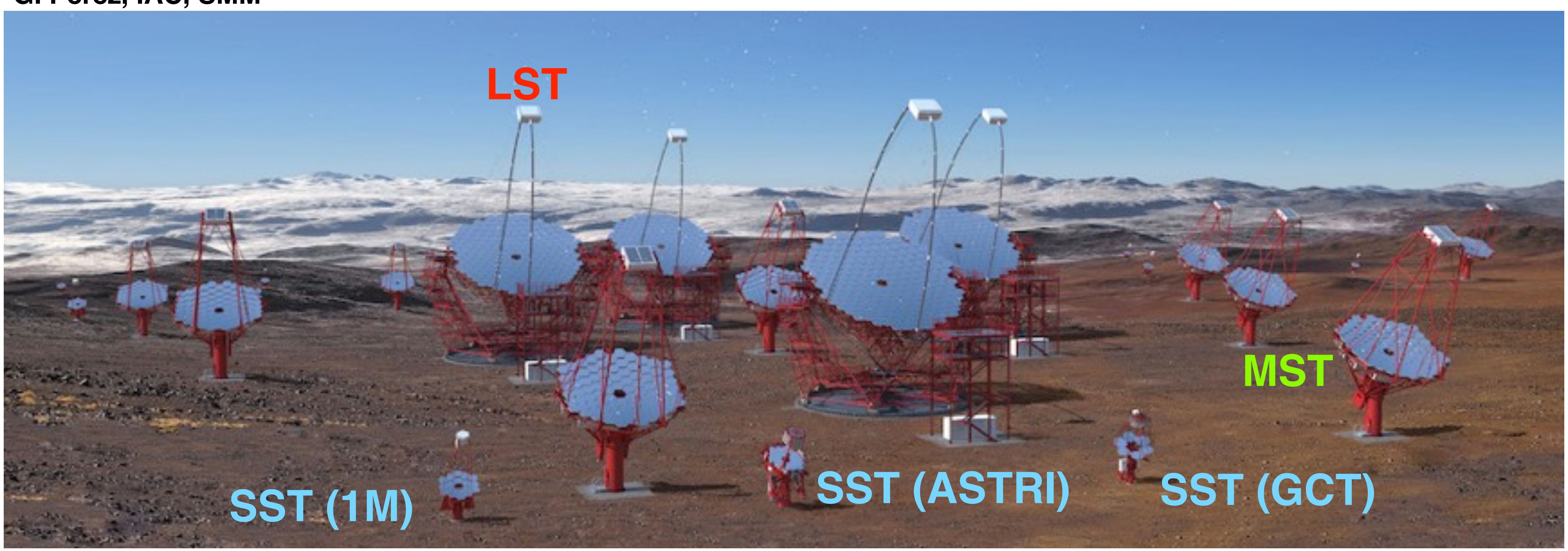


Future Gamma-ray Observatory

- 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

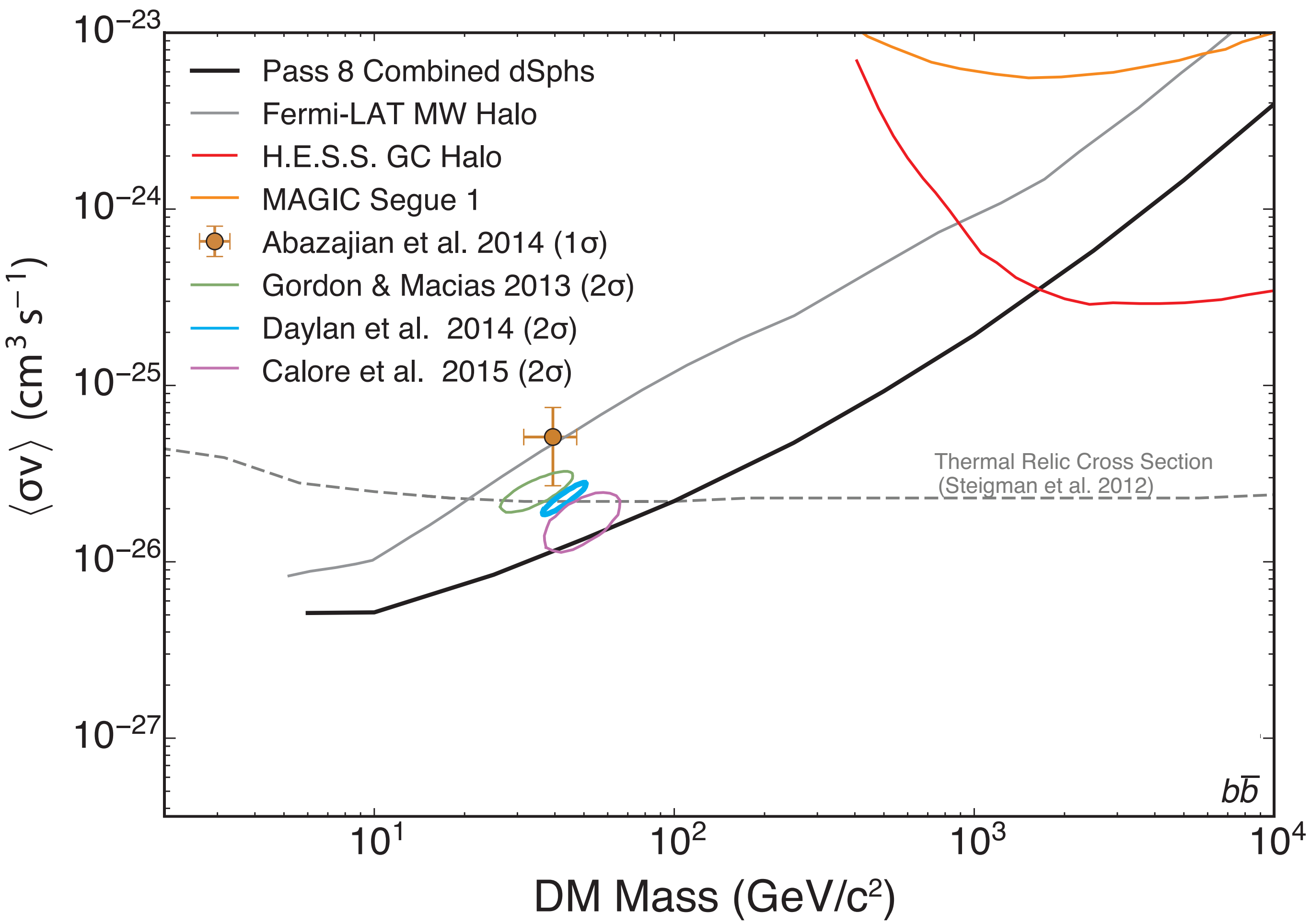


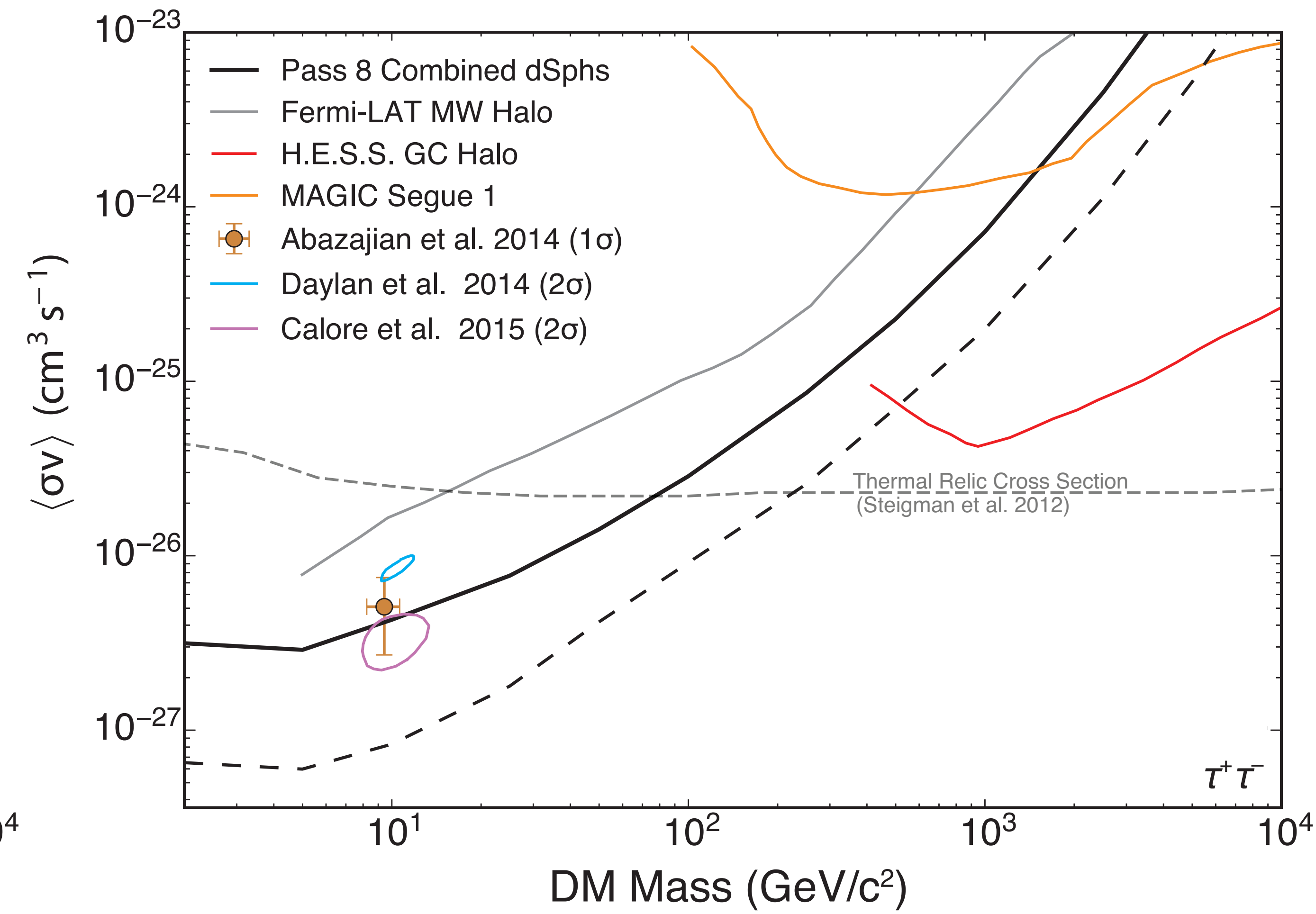
G. Pérez, IAC, SMM



Future Prospects for 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
  - Cherenkov telescope: better sensitivities with CTA





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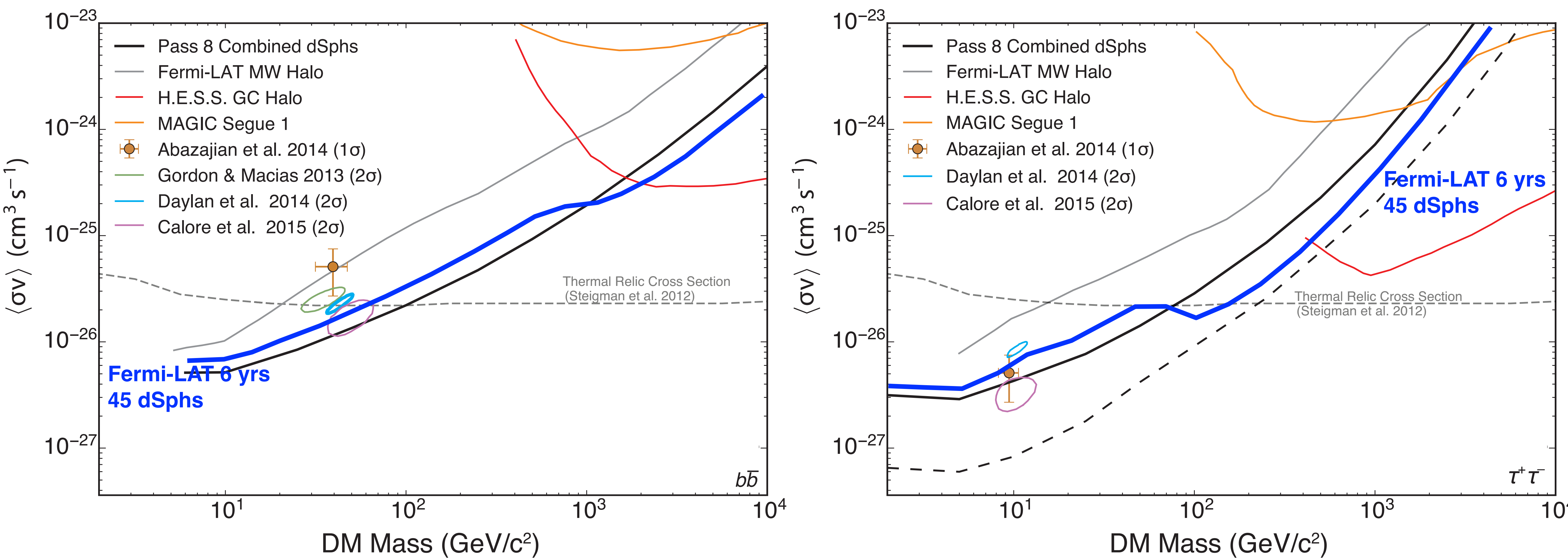

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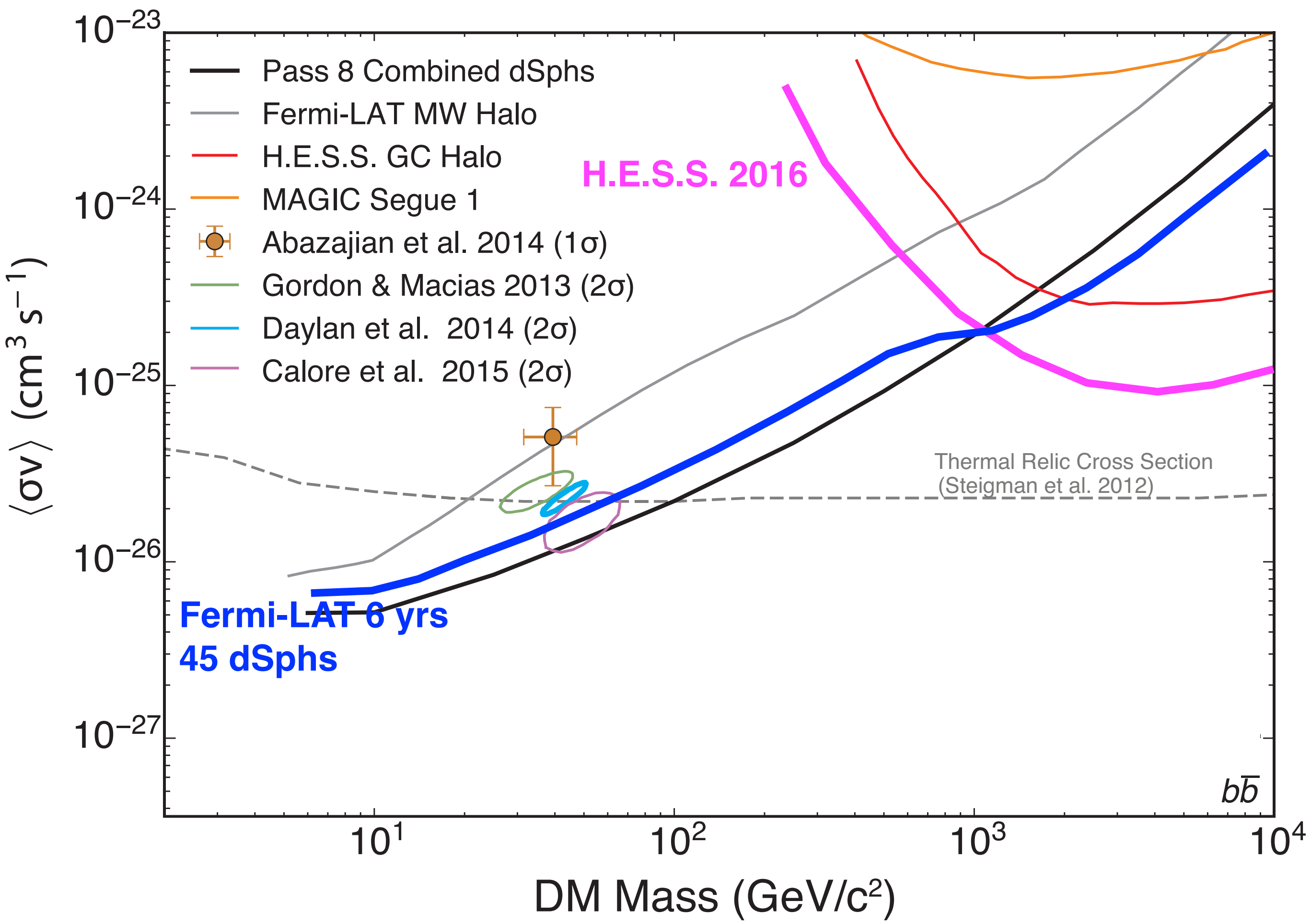

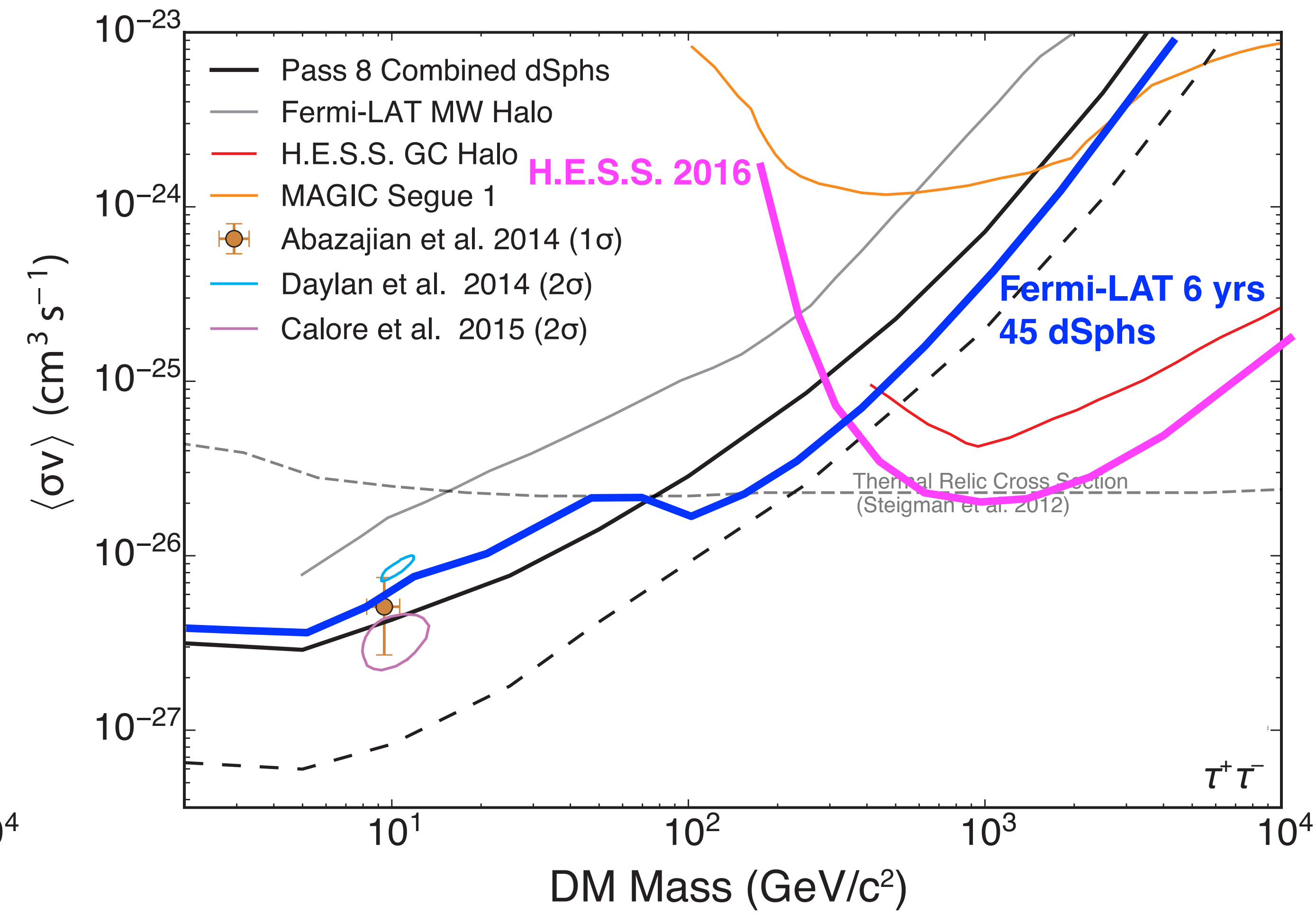

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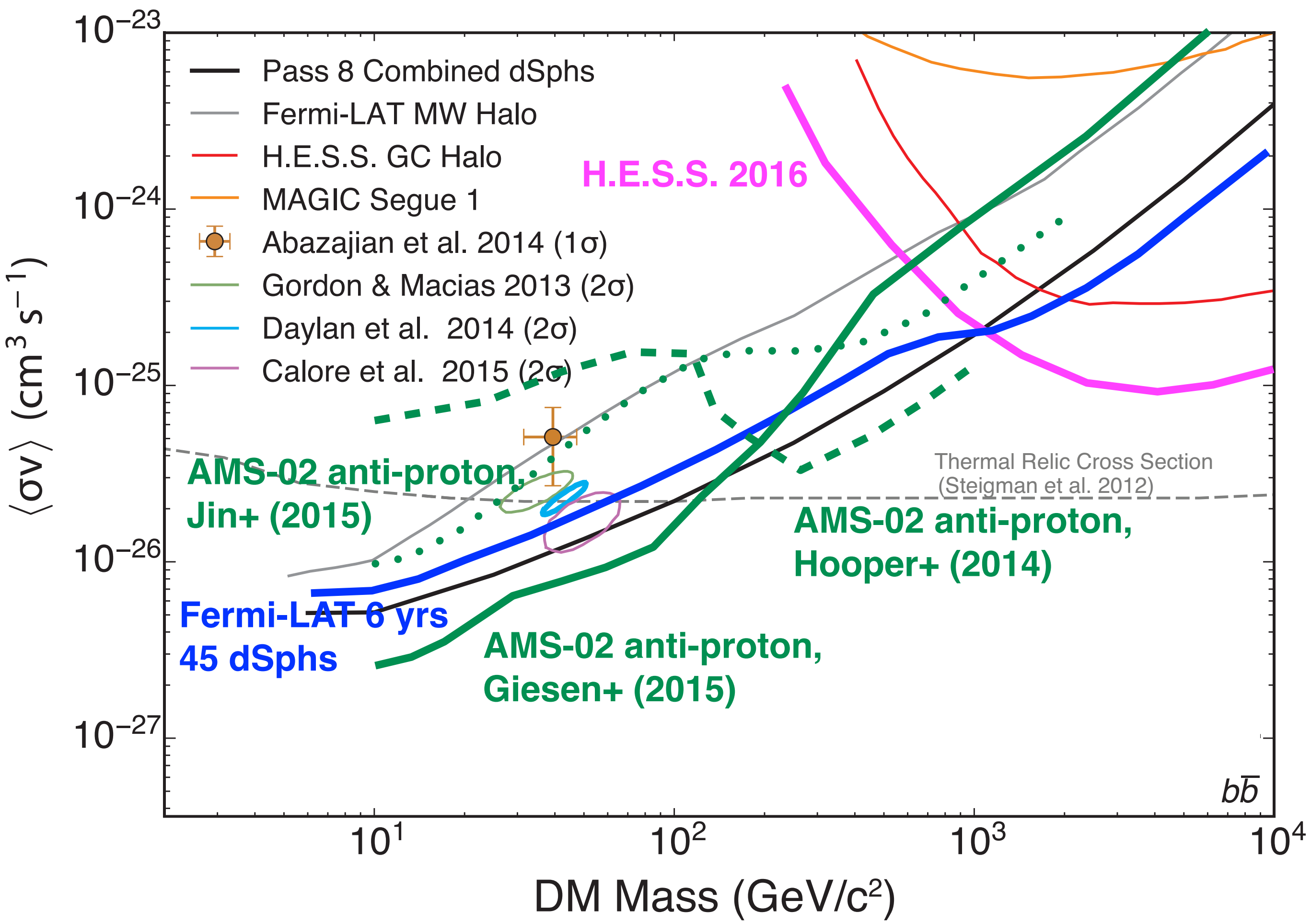

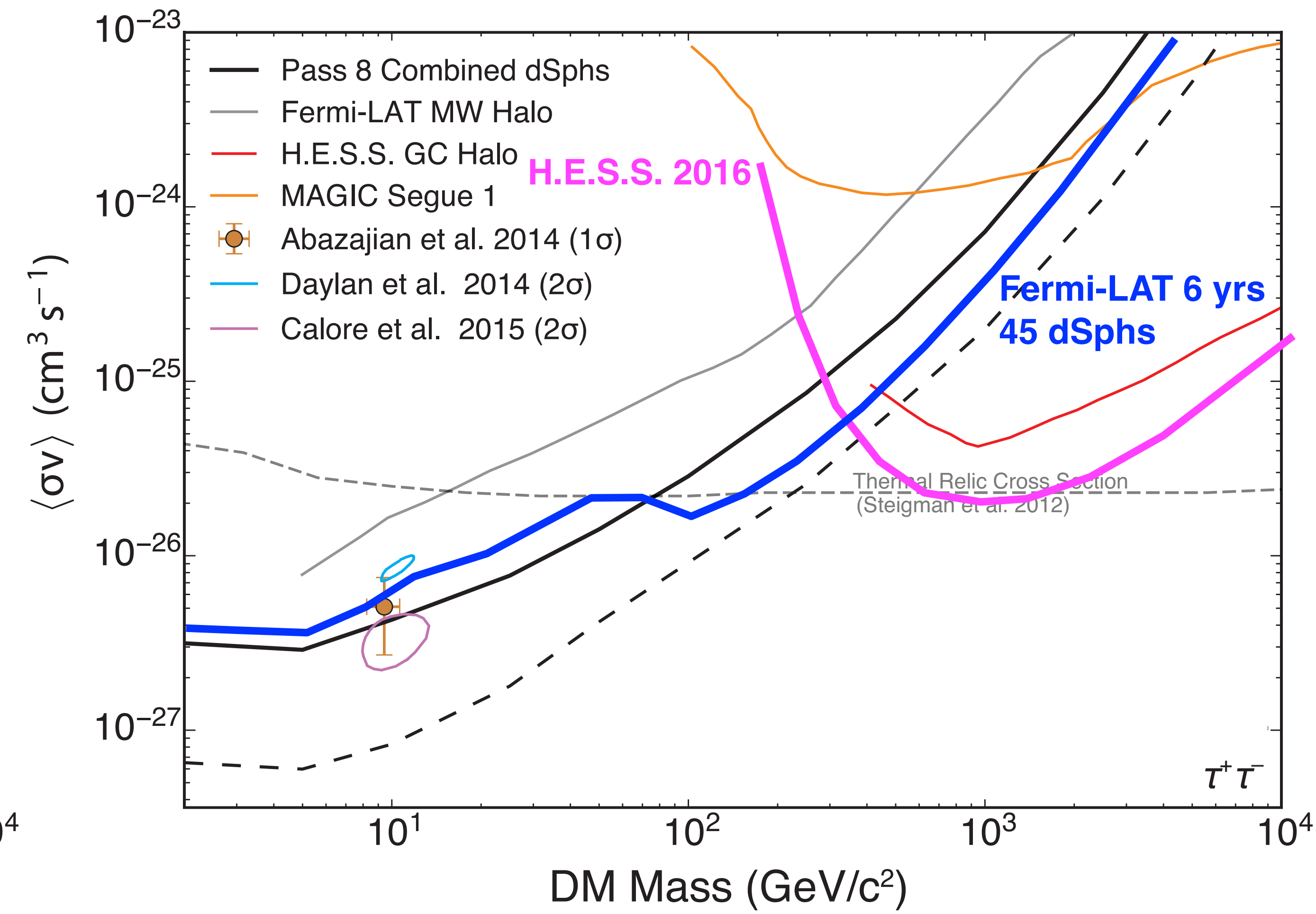

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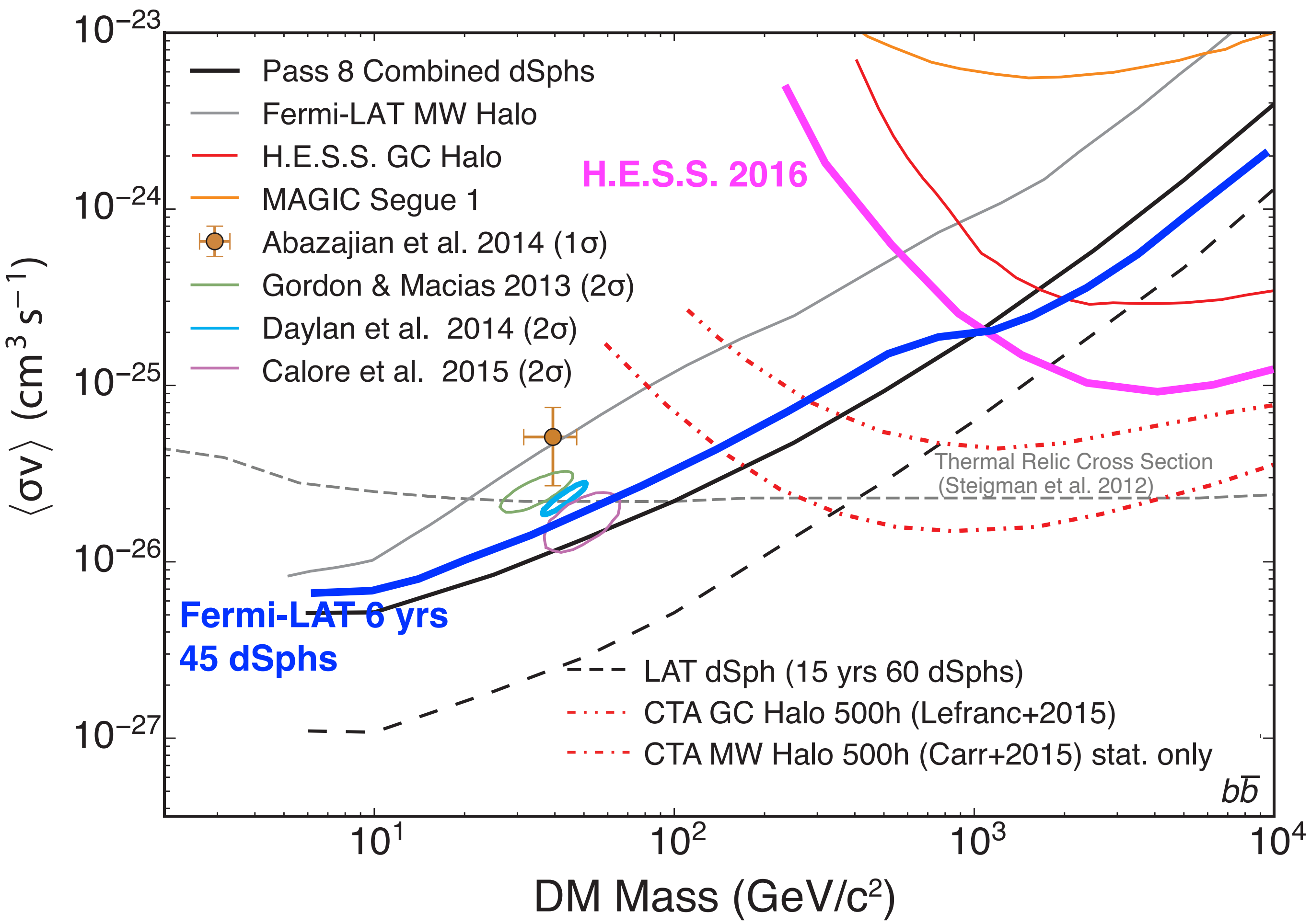
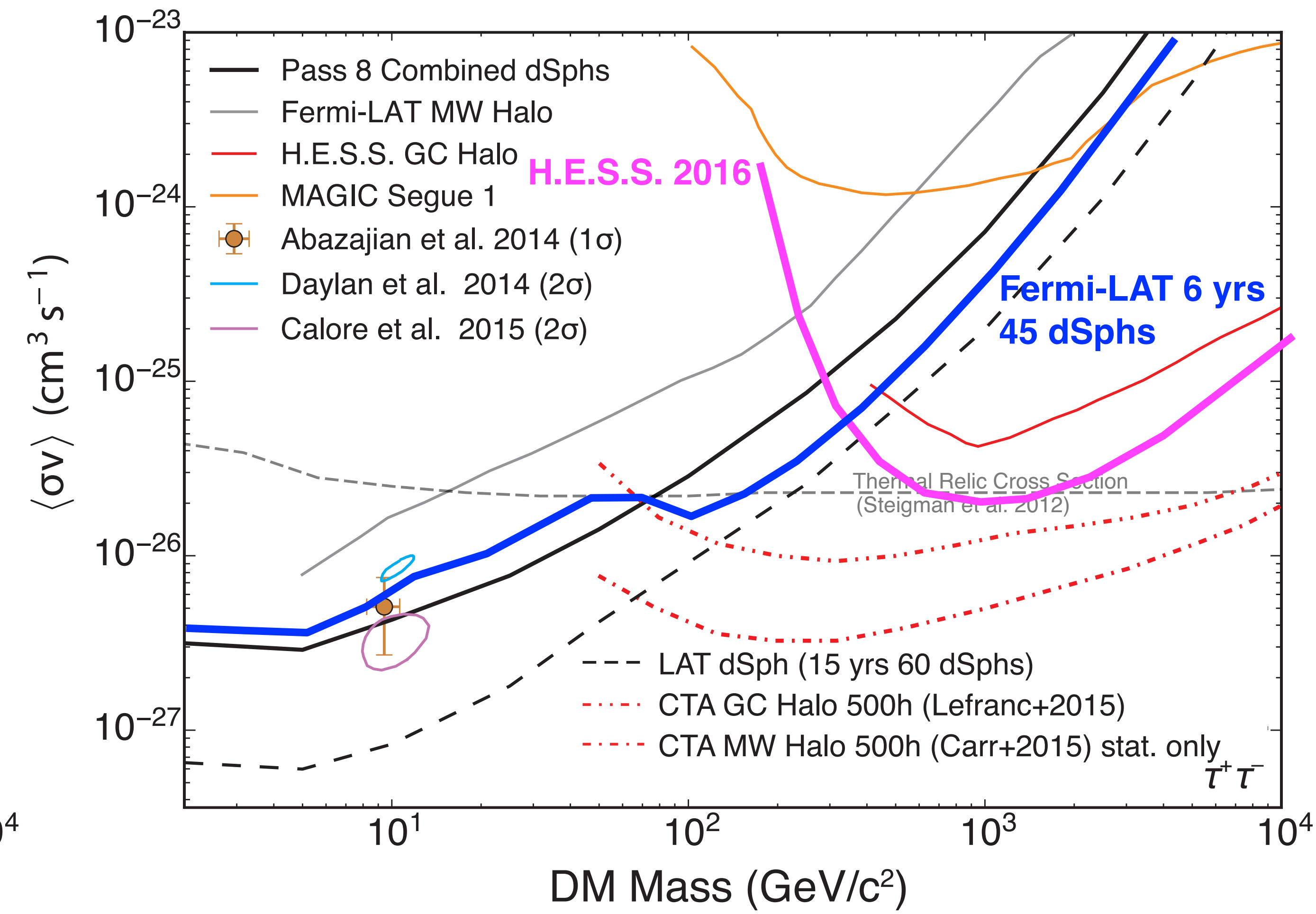


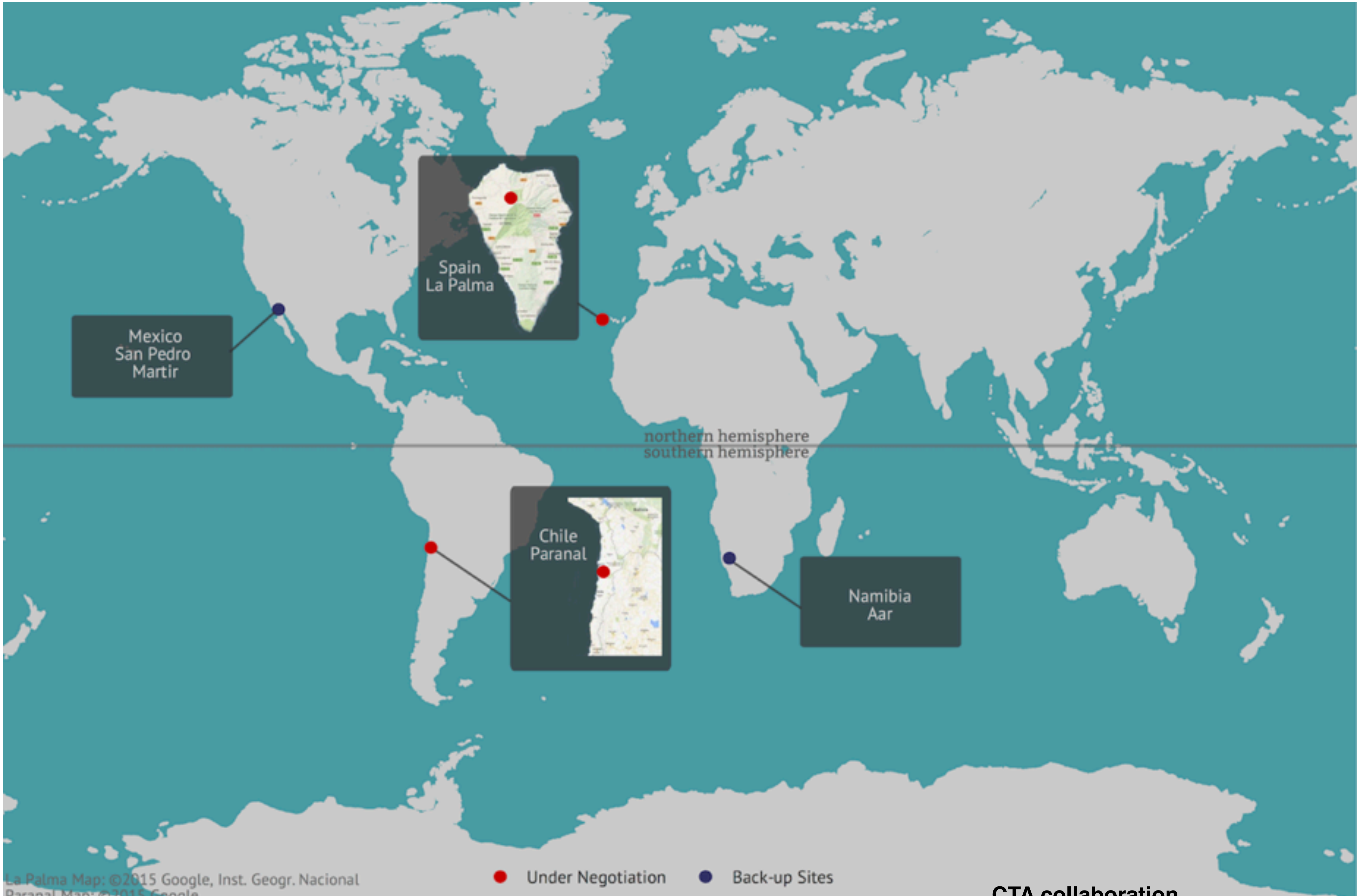


Summary and Future Prospects

- Indirect search is one of complimentary approaches in WIMP dark matter studies
- Fermi-LAT "Galactic Center Excess" is intriguing, but premature to draw any conclusions
- Fermi-LAT exludes thermal relic WIMP 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 WIMP in TeV energy band
  - Excluded mass range would extend to ~10 TeV/c^2
    - Interesting mass range for some SUSY models
  - CTA can access WIMP phase space where collider and direct searches cannot access

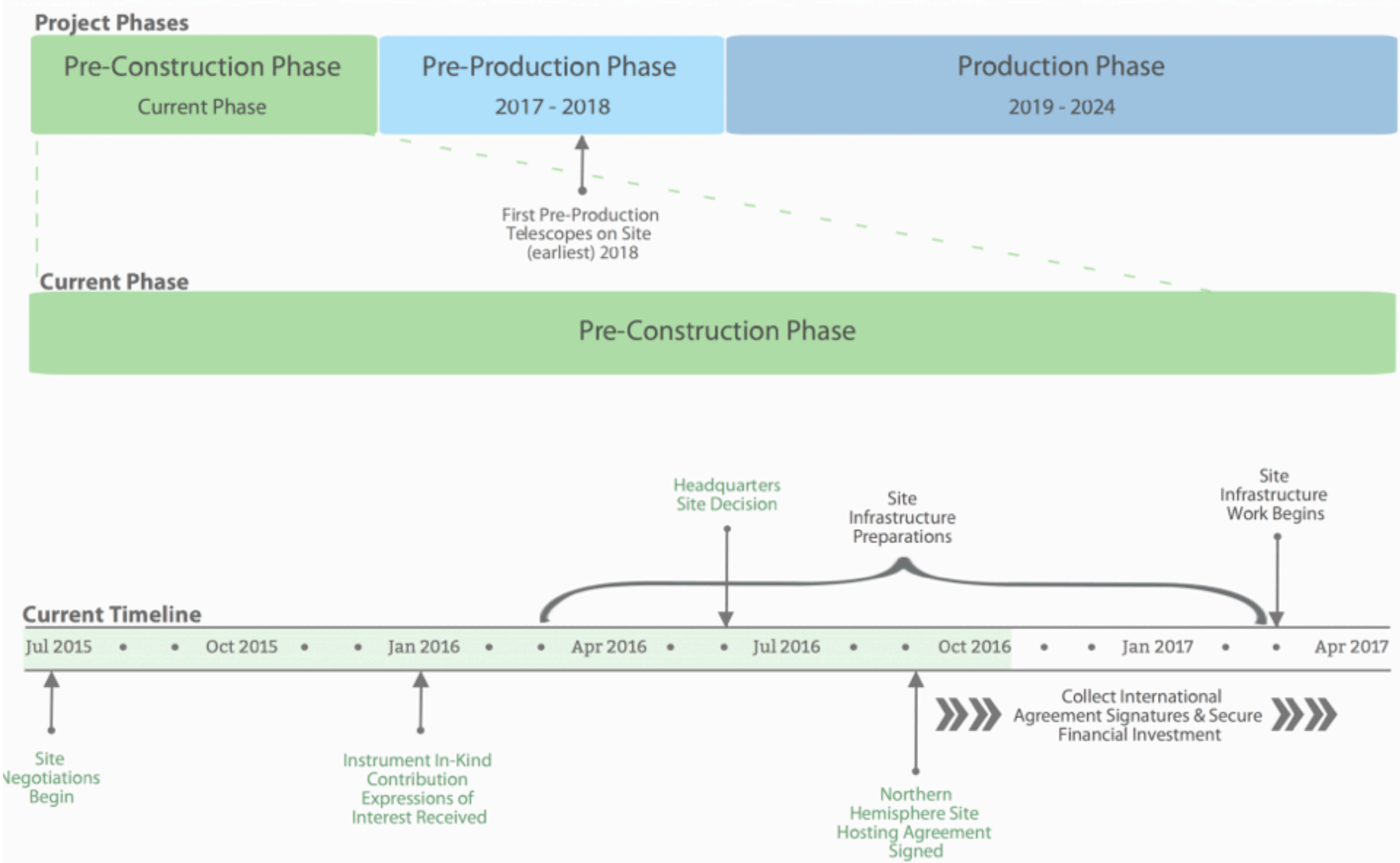
backup

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