Galactic Bulge Millisecond Pulsars

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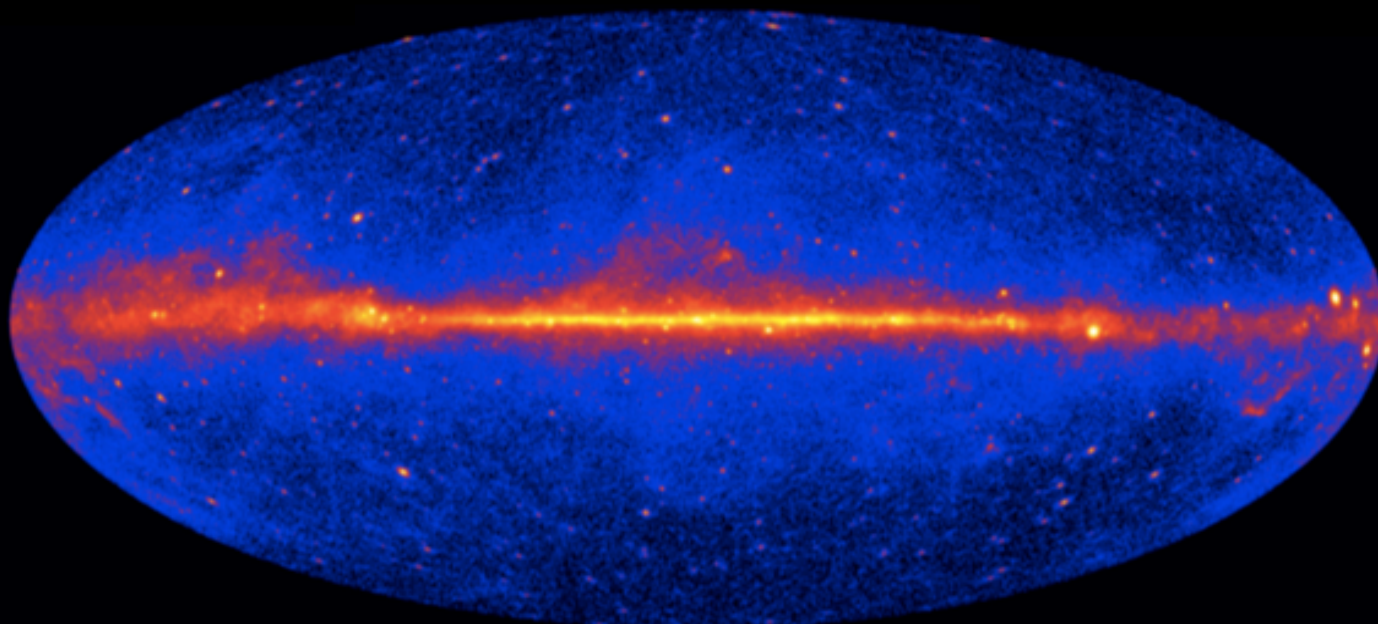


- Macias O., Gordon C., Crocker R., Coleman B., Paterson D., Horiuchi S. and Pohl M., Nature Astronomy.
- Ploeg H., Gordon C., Crocker R. and Macias O., Journal of Cosmology and Astroparticle Physics 2017.

Fermi Gamma-ray Space Telescope (2008 - present)

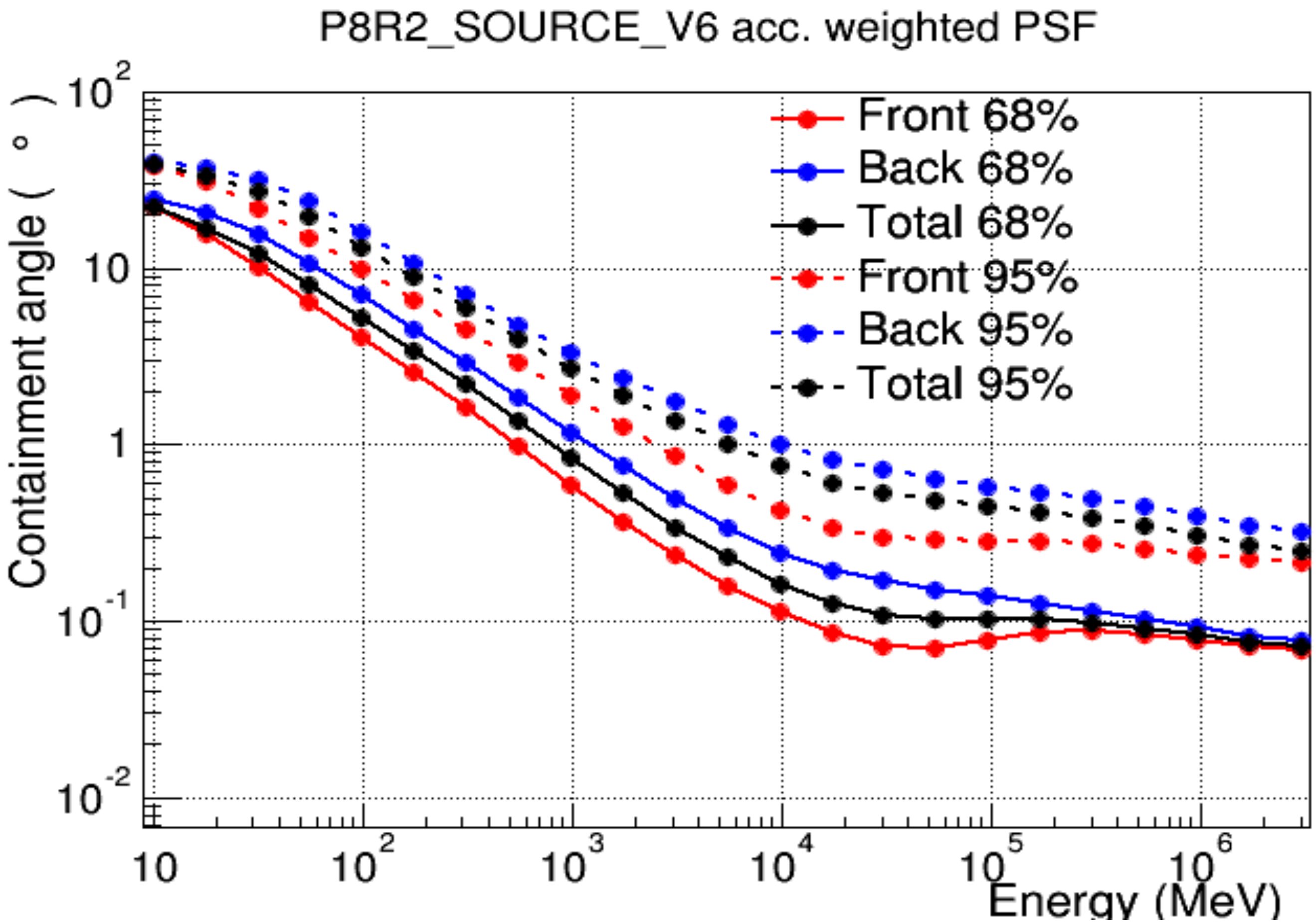


Image Credit: https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.html

Indirect Detection of Weakly Interacting Massive Particle (WIMP)Dark Matter

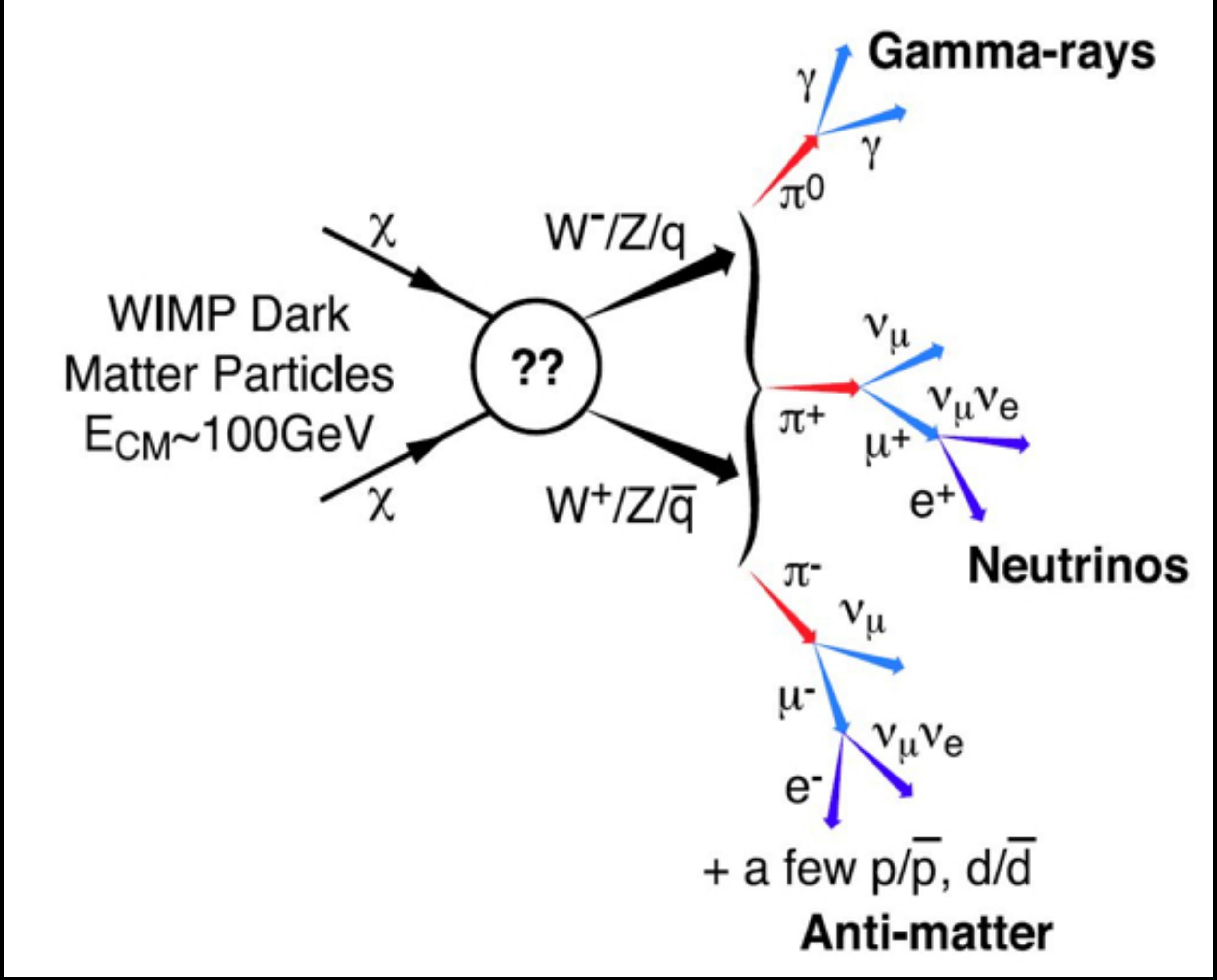
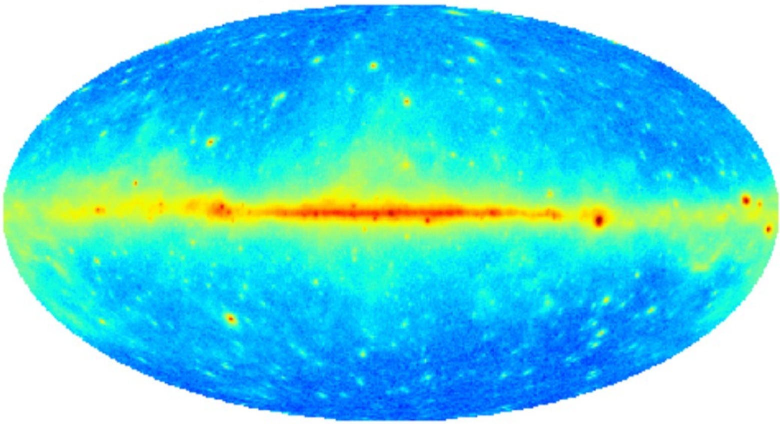


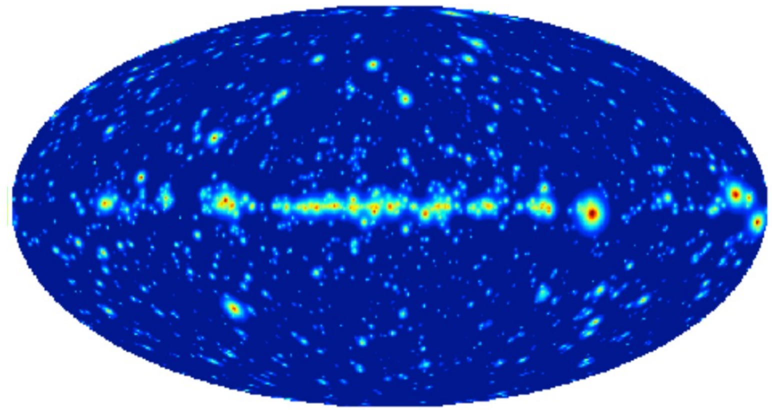
Image Credit: https://fermi.gsfc.nasa.gov/science/eteu/dm/

Gamma-ray Sky



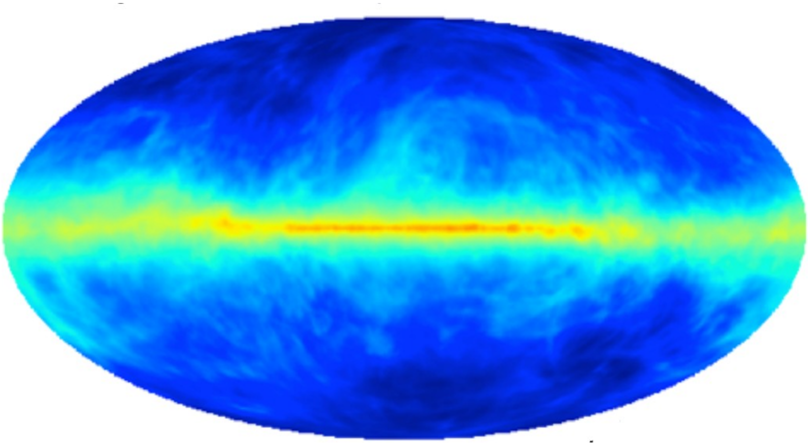
Data

=



Point sources

+



Galactic Diffuse

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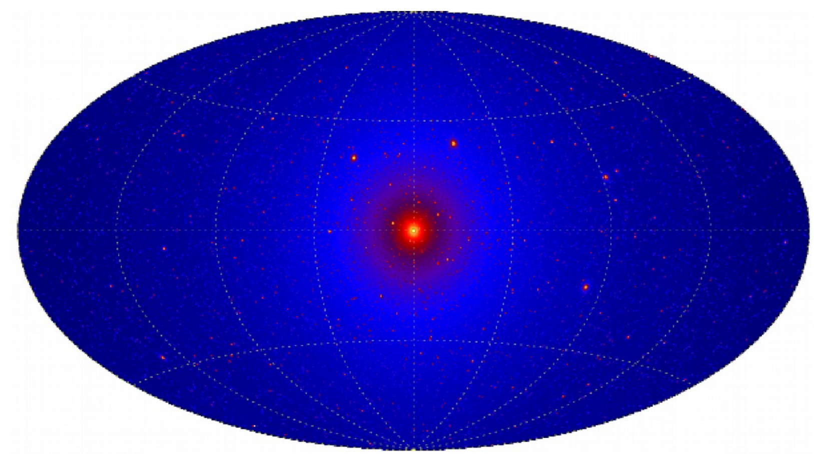
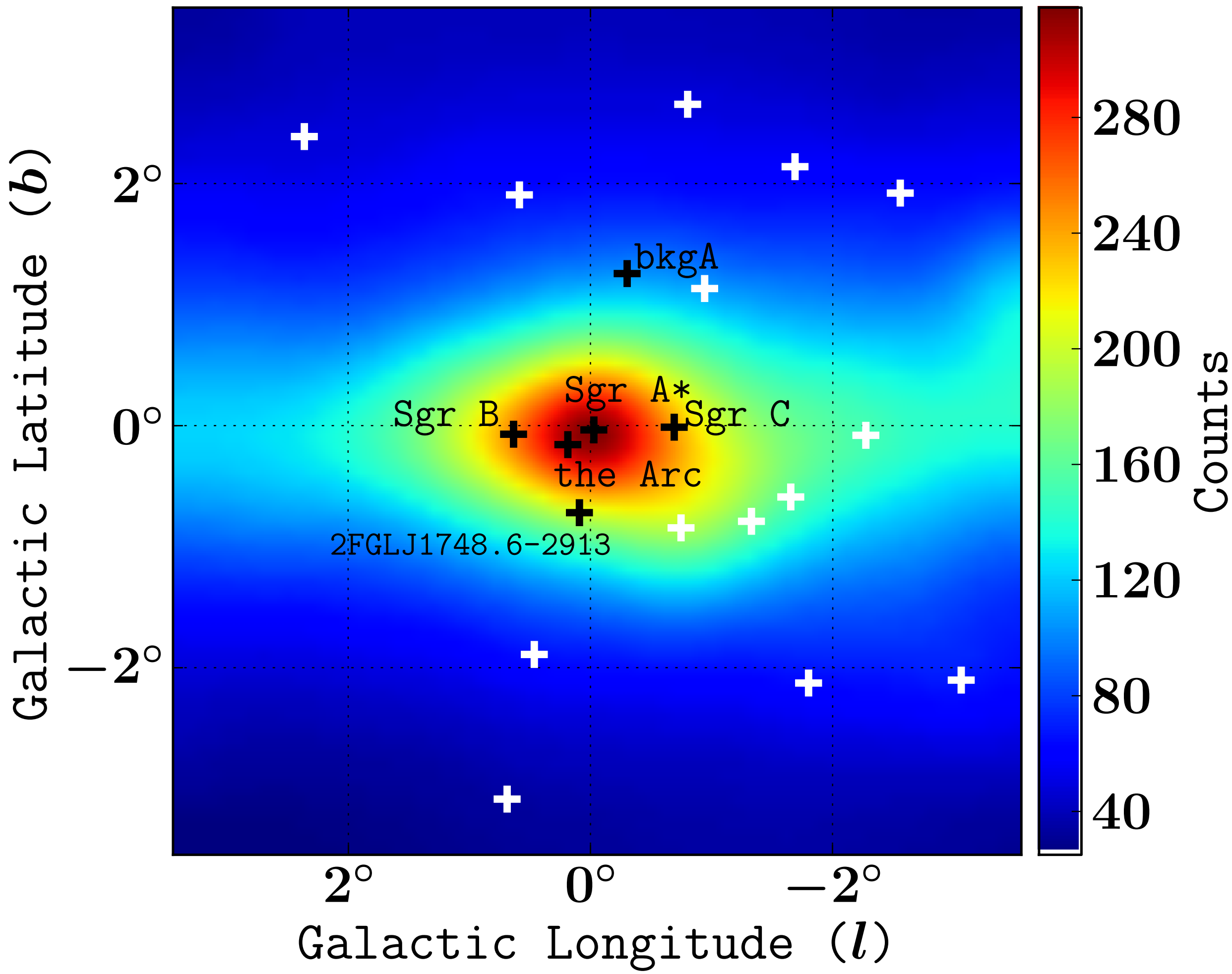


Dark Matter?

Excess Emission from Galactic Center

- Hooper and Goodenough (2009)
- Confirmed by several groups including CG&Macias (2013, 2014) and now by the Fermi team.



Dwarf Spheroidal Constraints

Gamma ray Flux:

$$\Phi(E_\gamma, b, l) = \Phi^{PP}(E_\gamma) \times J(b,l),$$

$$\Phi^{PP}(E_\gamma) = \frac{1}{2}\frac{\langle\sigma v\rangle}{4\pi M_{DM}^2}\sum_f \frac{dN_f}{dE_\gamma} B_f,$$

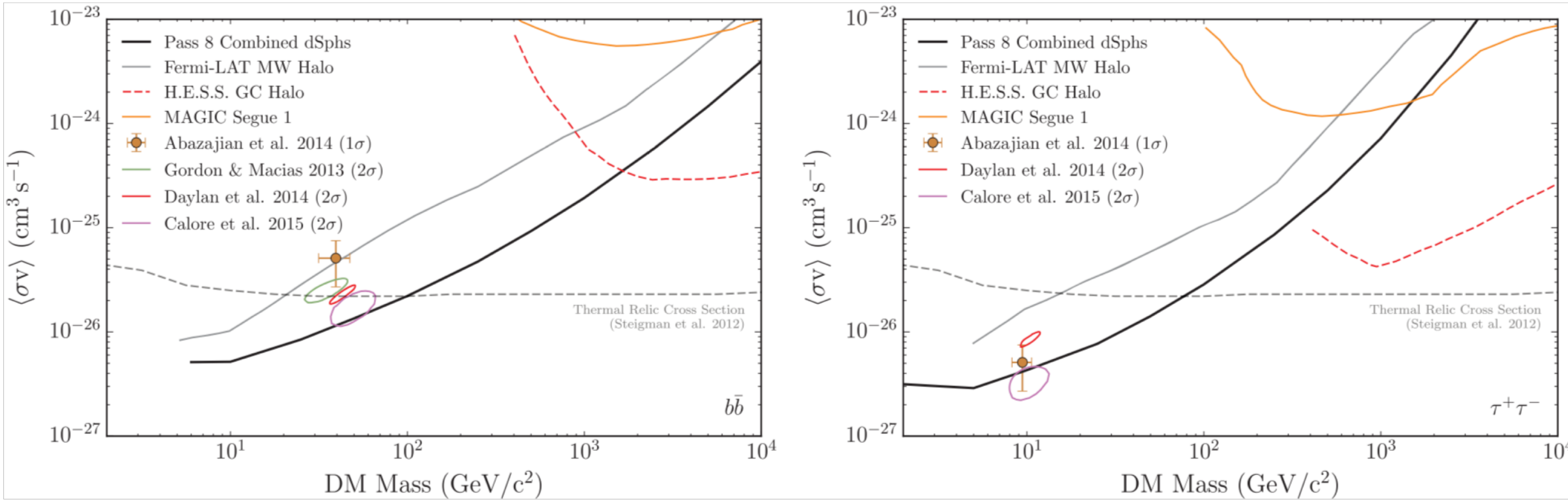
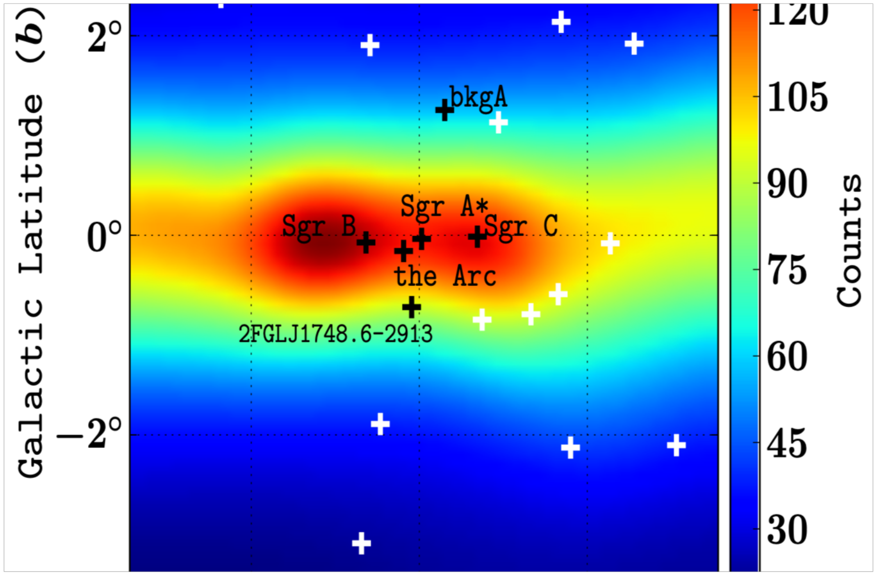
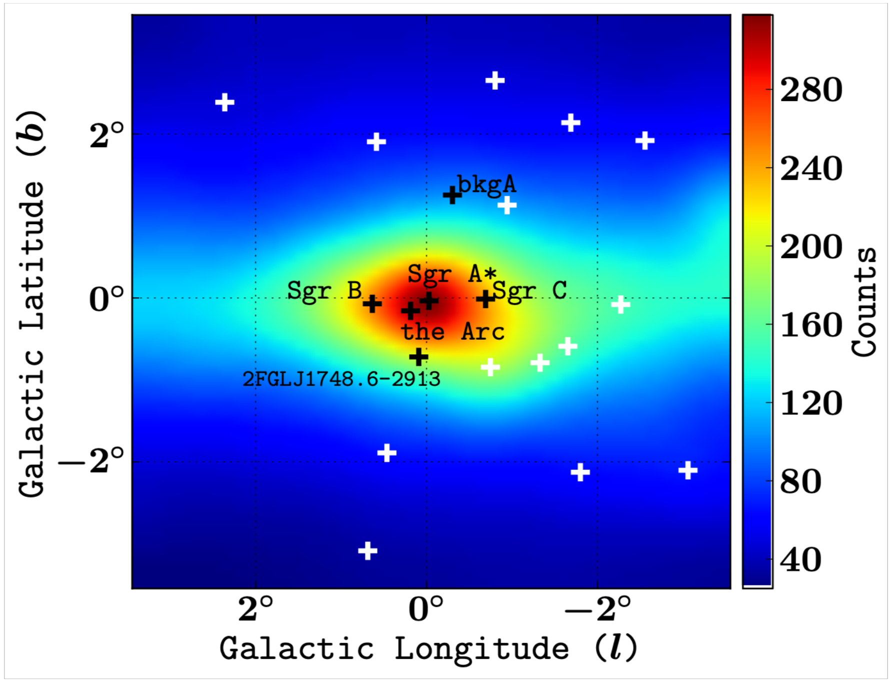


Image Credit: Fermi-LAT collaboration, PRL 115, 231301 (2015)

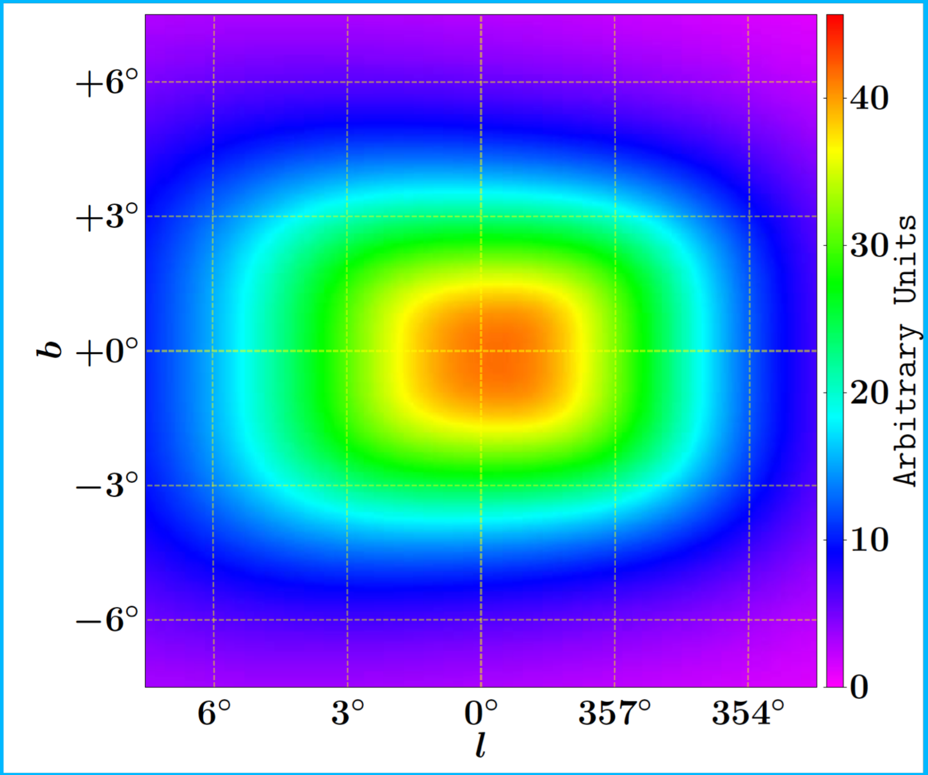


Diffuse Galactic Emission

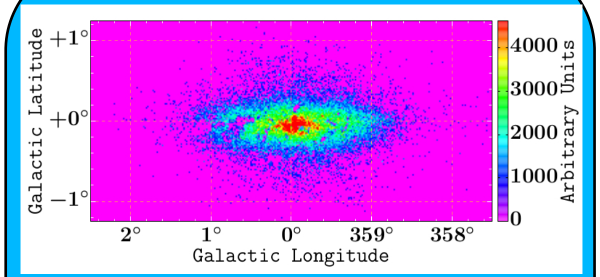


Fermi gamma-ray data

Best Fit Model



Galactic Bulge
(Freudenreich, 1998)



Nuclear Bulge
(Nishiyama et al., 2013)

Millisecond Pulsars (MSPs)

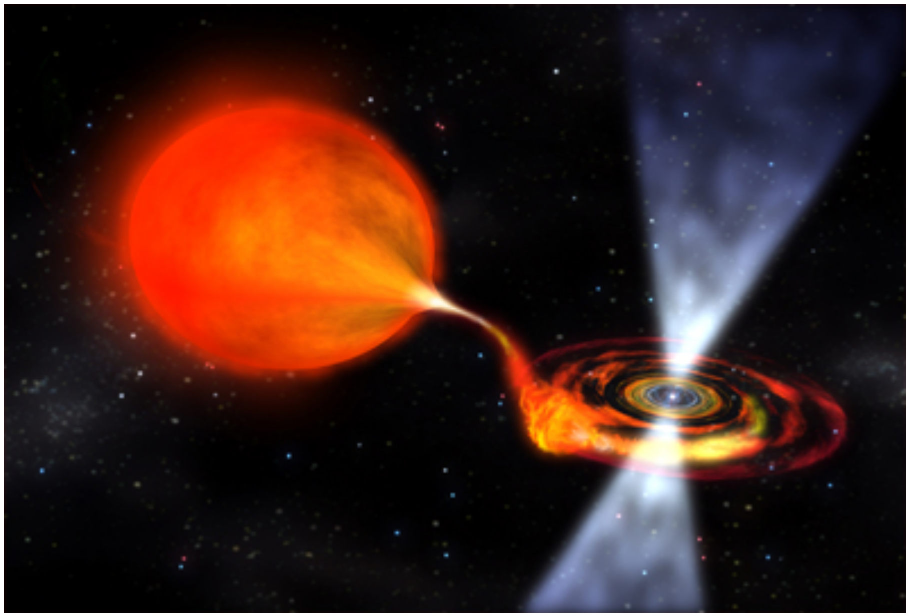
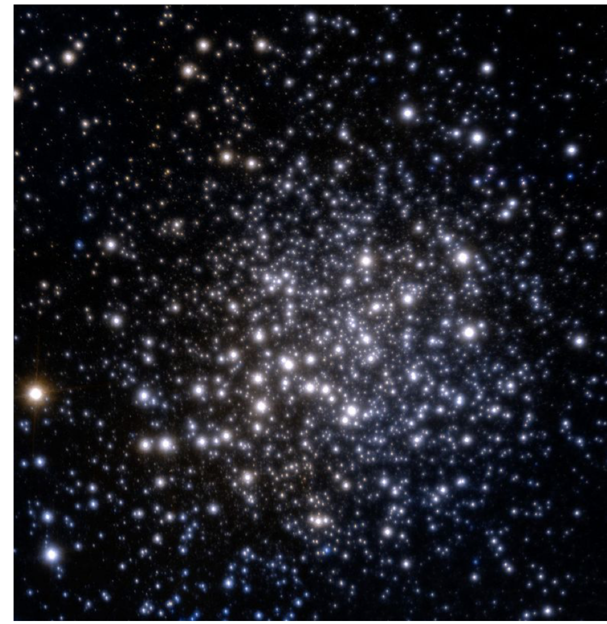


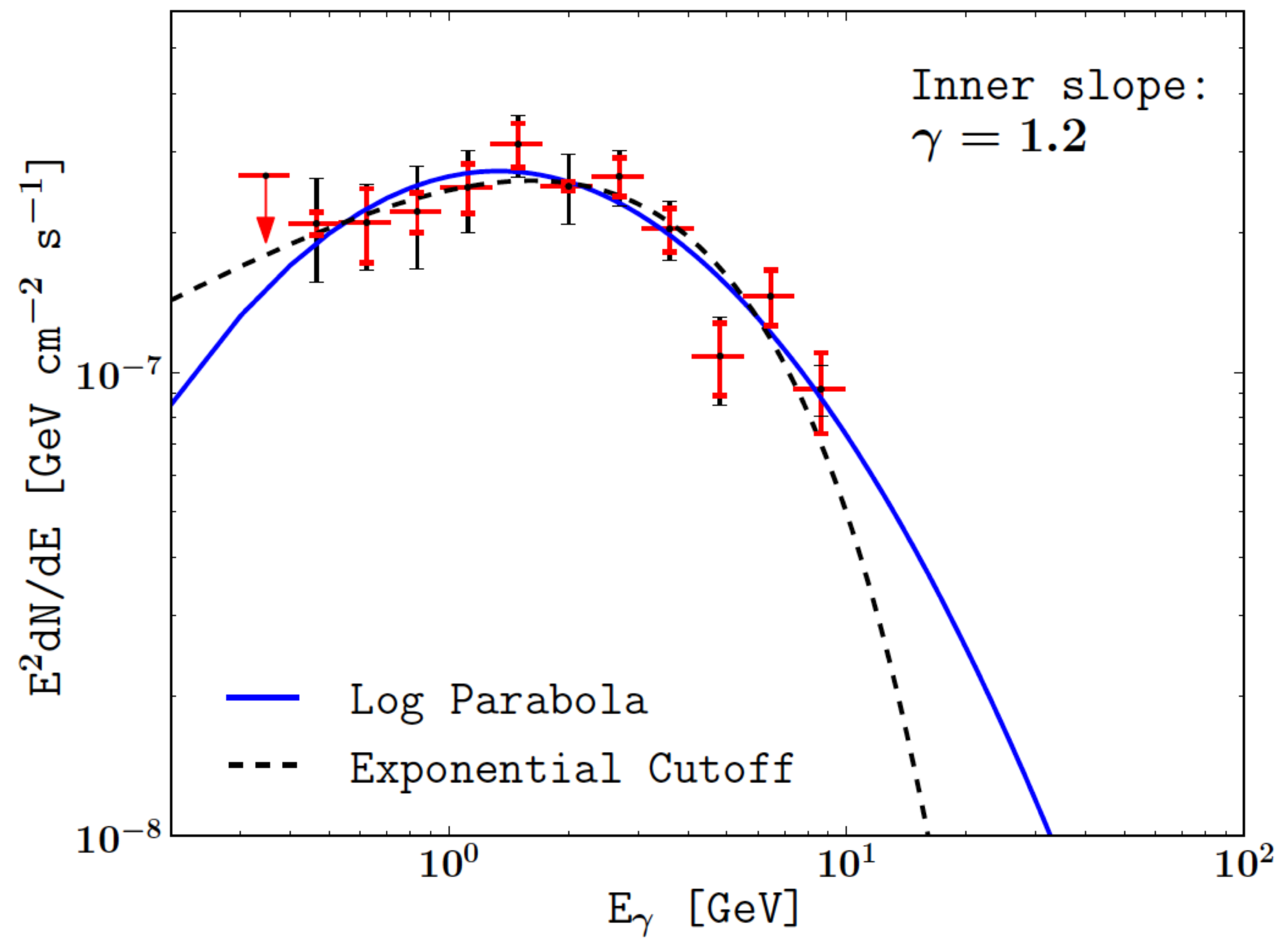
Image: NASA/Dana Berry.



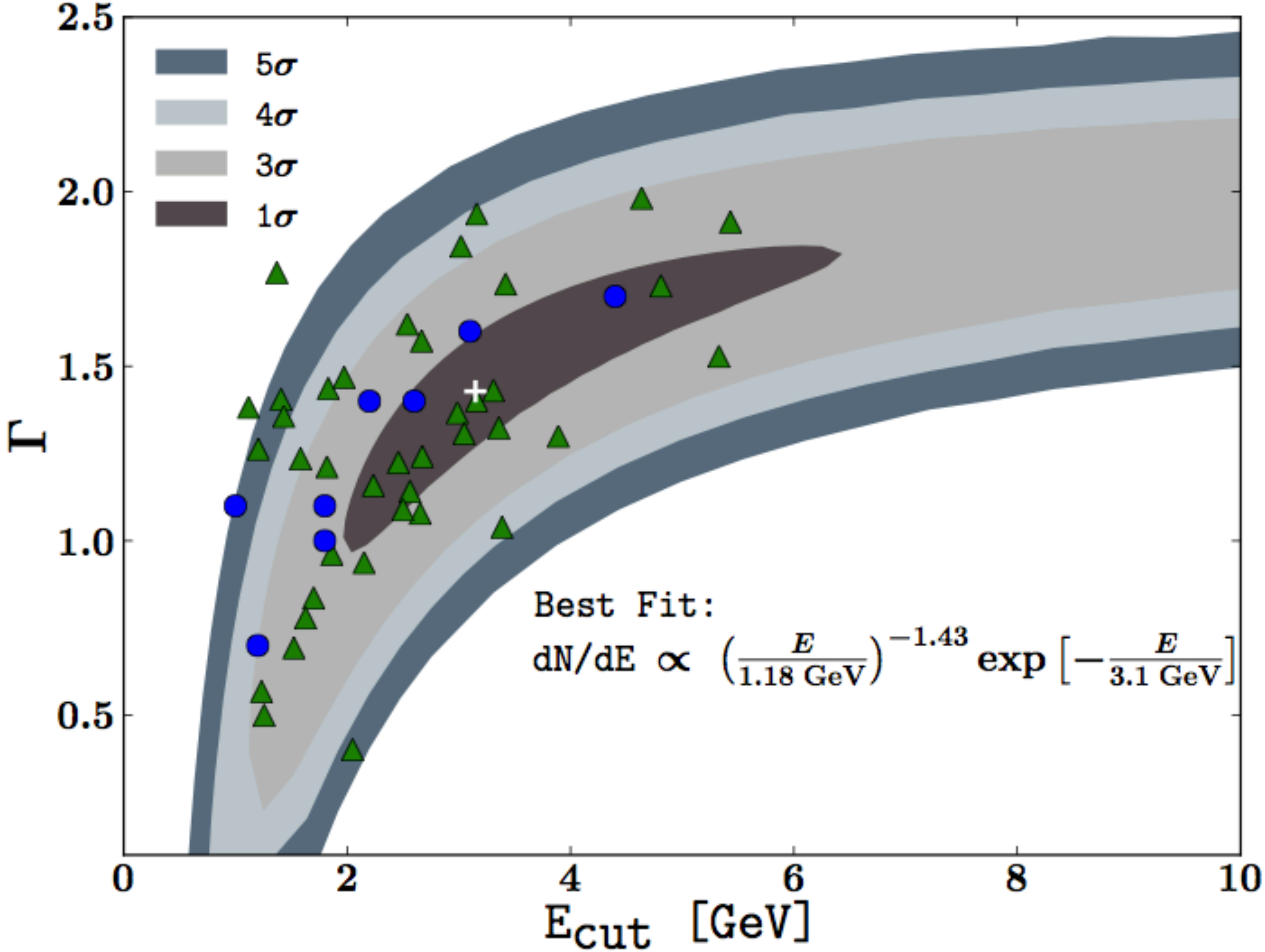
ESO image of Globular cluster Terzan 5 which hosts about 100 MSPs.

Spectral Fit

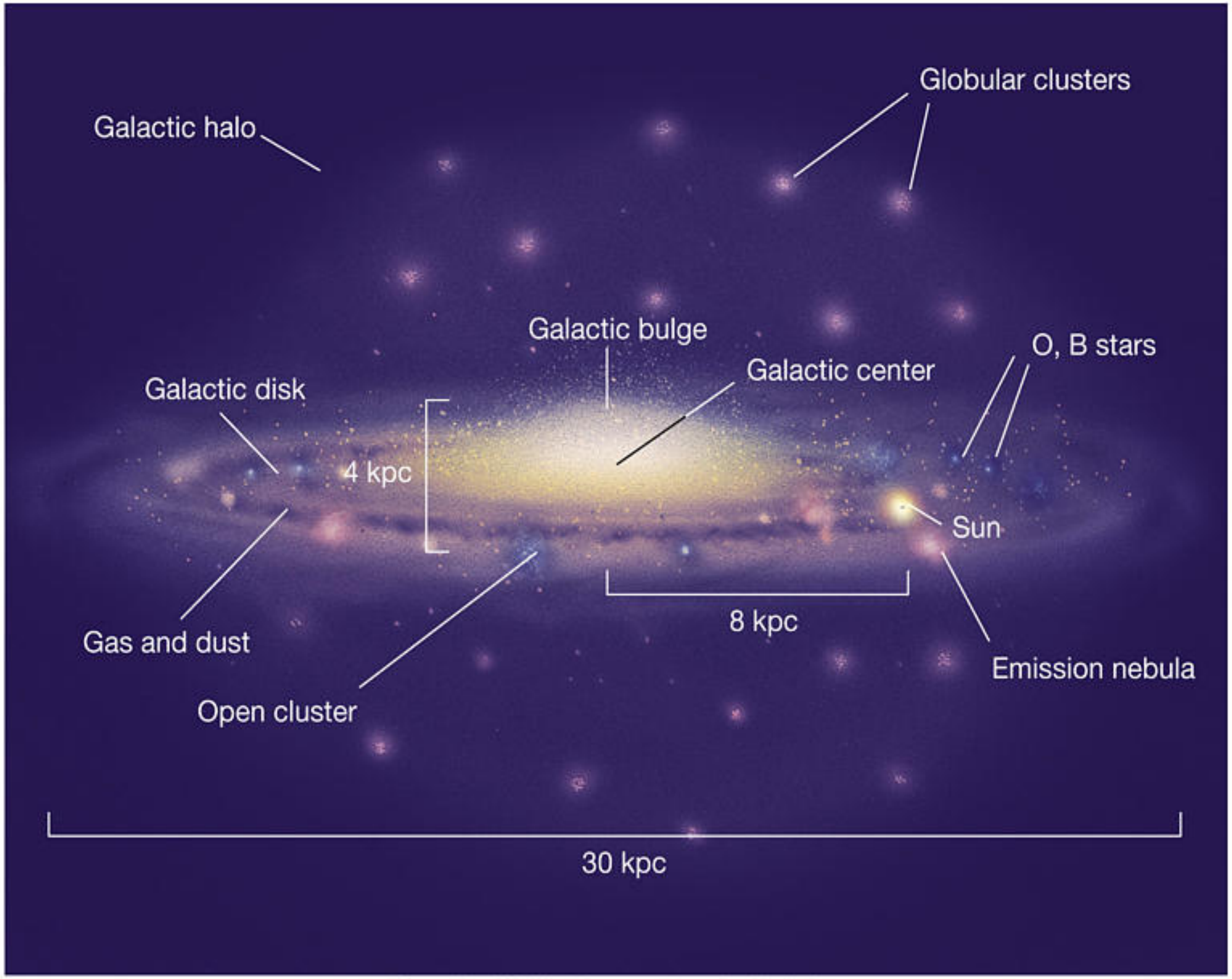
$$dN/dE \propto E^{-\Gamma} \exp(-E/E_c).$$

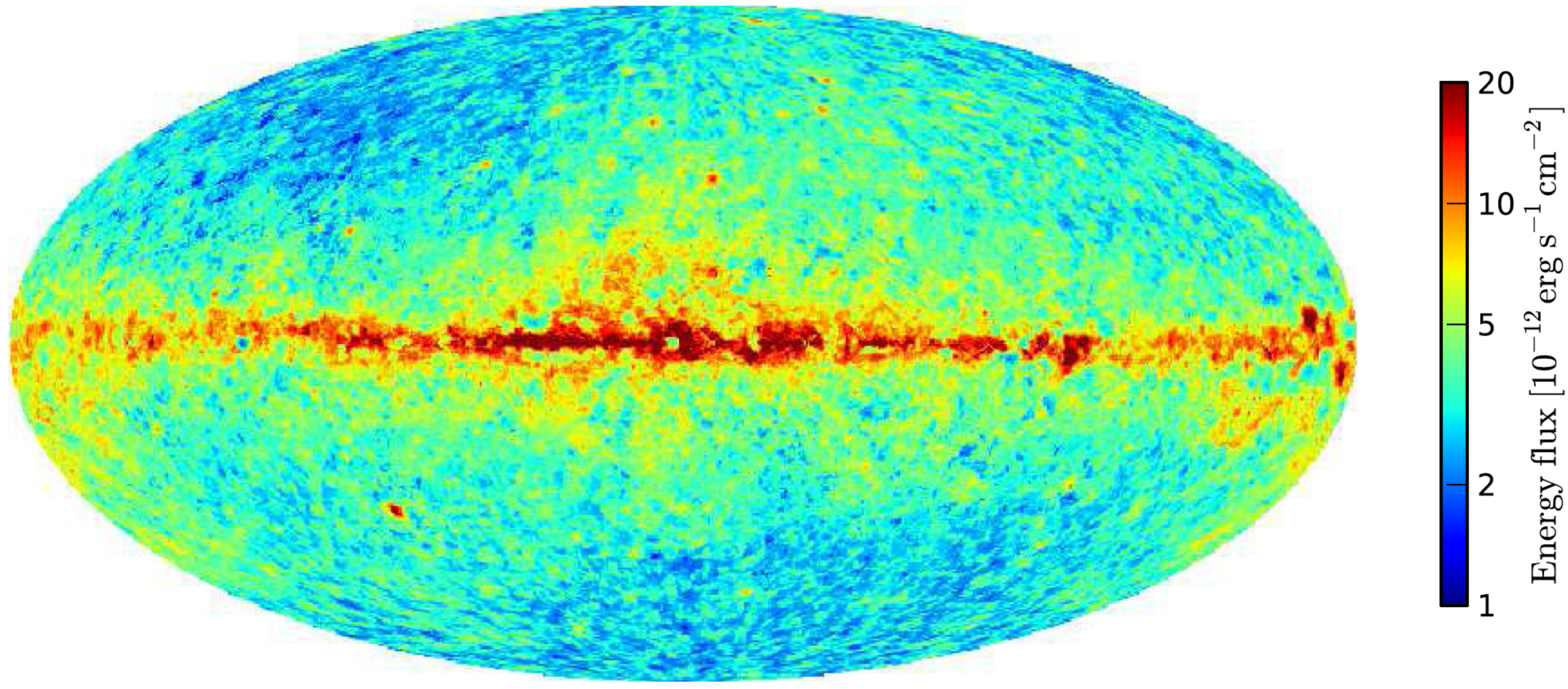


Spectral Fit



Edge-on view of the Milky Way





Hammer–Aitoff projection of the LAT three-year sky-survey **energy flux sensitivity** above 100 MeV, assuming a pulsar-like exponentially cutoff power law energy spectrum. Image credit: Abdo et al., ApJ 208:17, 2013.

Geometrical Model

Cylindrical coordinates

Number of disk MSPs

$$\rho_{\rm disk}(r_{\rm cyl}, z, N_{\rm disk}) = \frac{N_{\rm disk}}{4\pi\sigma_r^2\sigma_z}\exp(-r_{\rm cyl}^2/2\sigma_r^2)\exp(-|z|/\sigma_z)$$

Density of MSPs

Number of bulge MSPs

$$\rho_{\rm bulge}(r, N_{\rm bulge}) = \frac{3N_{\rm bulge}}{20\pi r_{\rm bulge}^{0.6}}r^{-2.4}, \quad 0 \le r < r_{\rm bulge}$$

Distance to Galactic Center

Fixed at 3 kpc

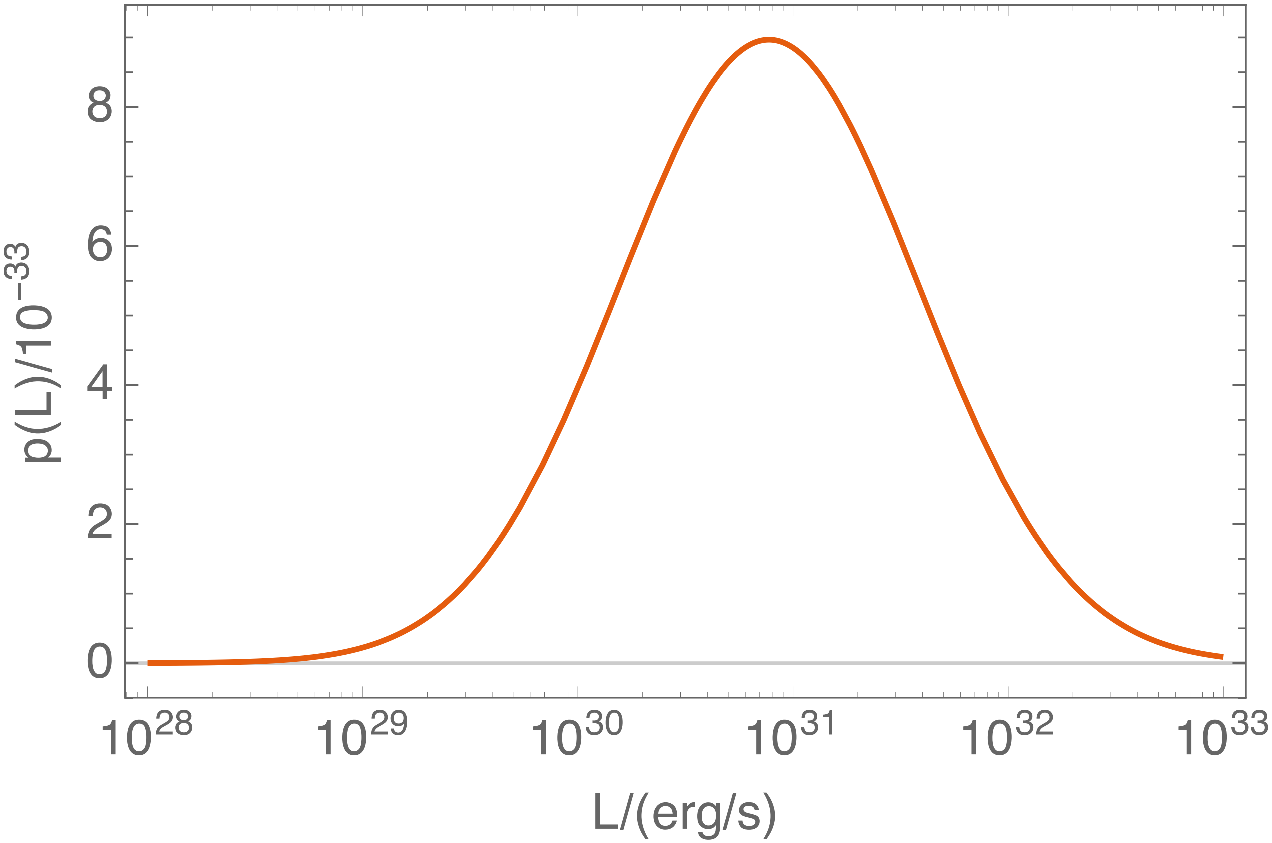
MSP Luminosity Function

$$p(L) = \frac{1}{\sigma_L L \sqrt{2\pi}} \exp\left[\frac{-(\ln(L) - \ln(L_{\mathrm{med}}))^2}{2\sigma_L^2}\right]$$

Luminosity

Probability distribution function

Parameters to be fit

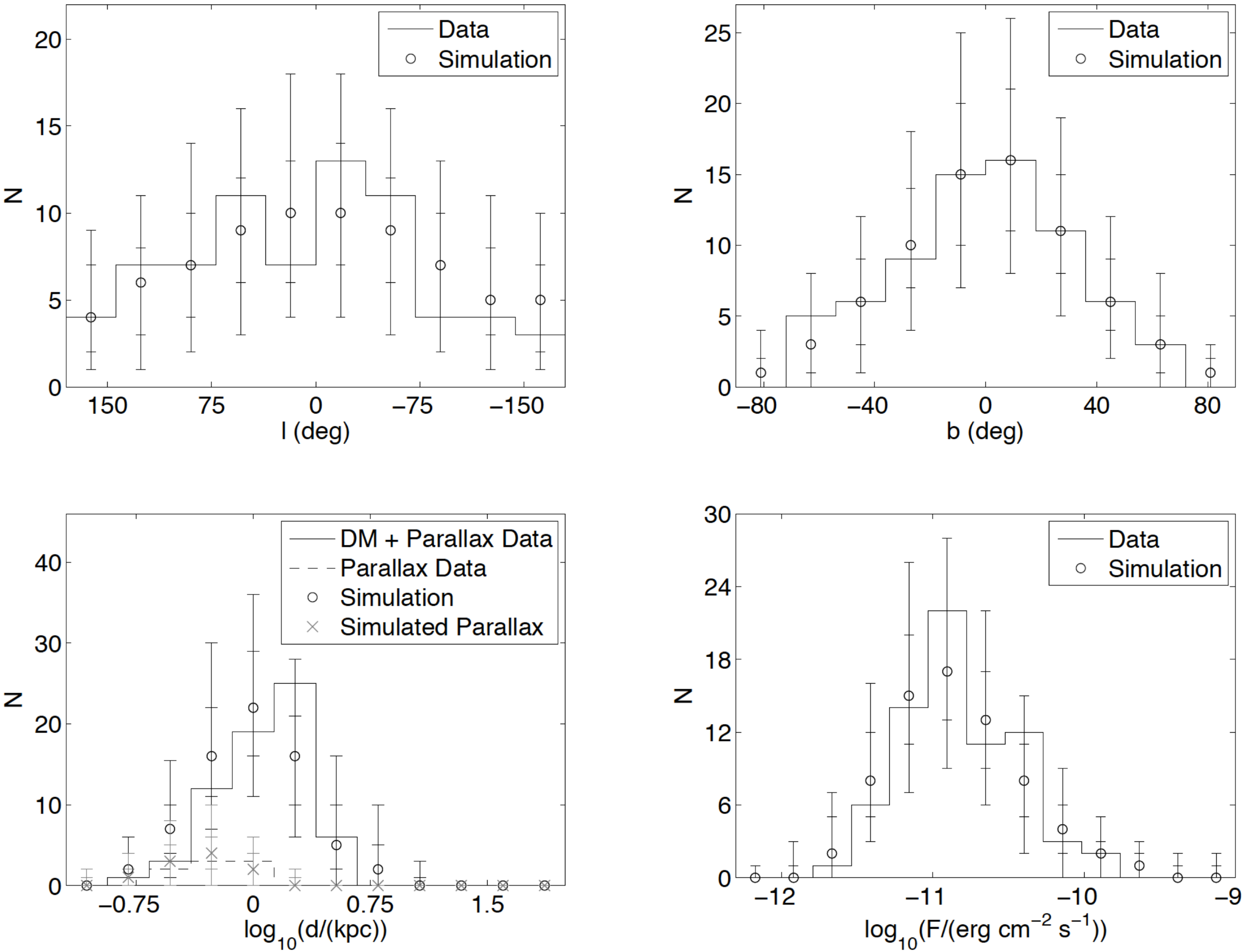


Parameter Estimation

$$p(\theta|\mathrm{data}) = \mathcal{L}_{\mathrm{res}} \times \mathcal{L}_{\mathrm{GCE}} \times \mathcal{L}_{\mathrm{parallax}} \times p(\theta)$$

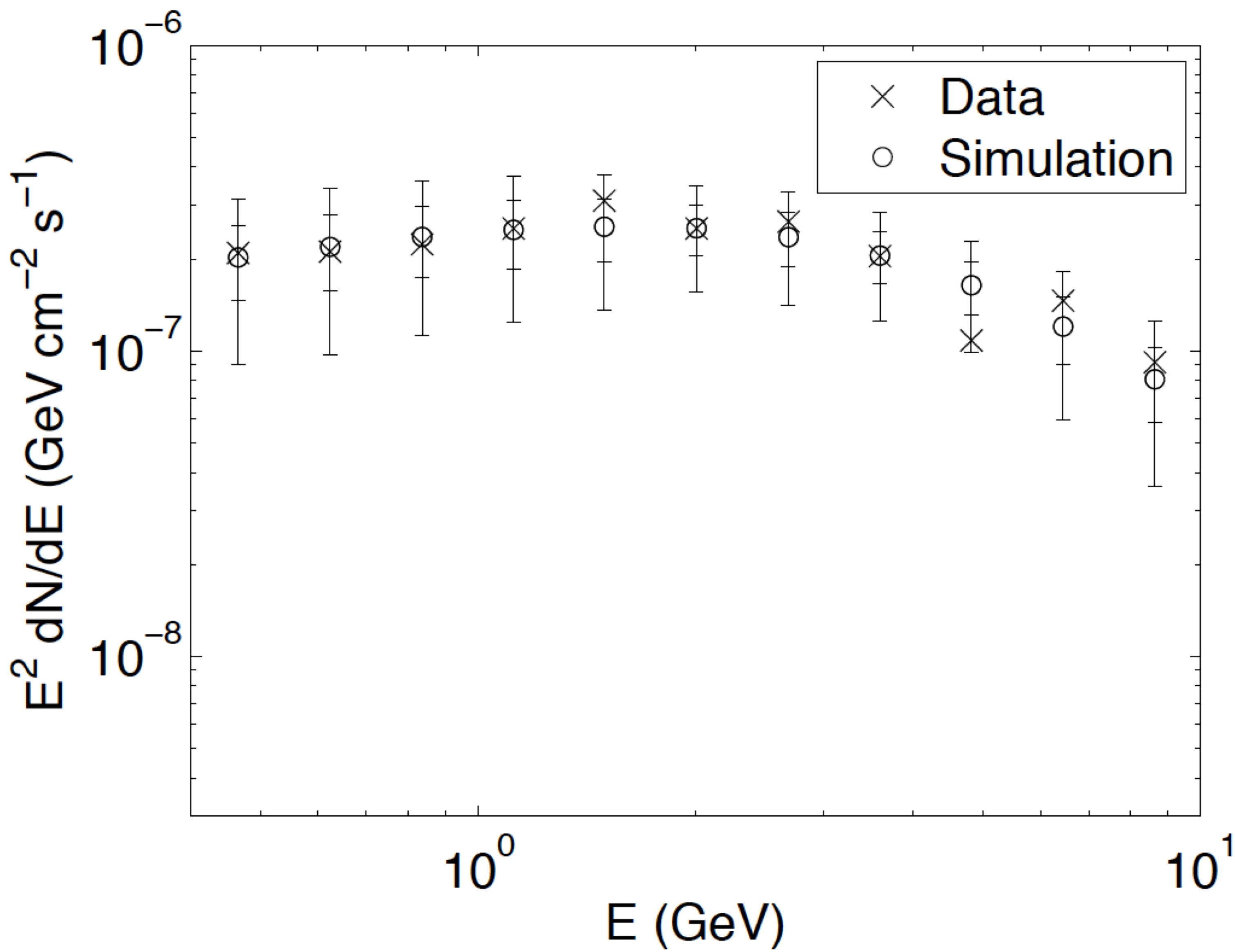
$$\mathcal{L}_{\mathrm{res}} \propto \exp(-\lambda_{\mathrm{res}}) \prod_{i=1}^{N} \rho(l_i, b_i, d_i, F_i)$$

$$\mathcal{L}_{\mathrm{GCE}} \propto \prod_{i=1}^{N} \exp\left[- \left(\left(\frac{dN}{dE}\right)_{\mathrm{sim},i} - \left(\frac{dN}{dE}\right)_{\mathrm{data},i} \right)^2 / (2\sigma^2_{\mathrm{data},i}) \right]$$

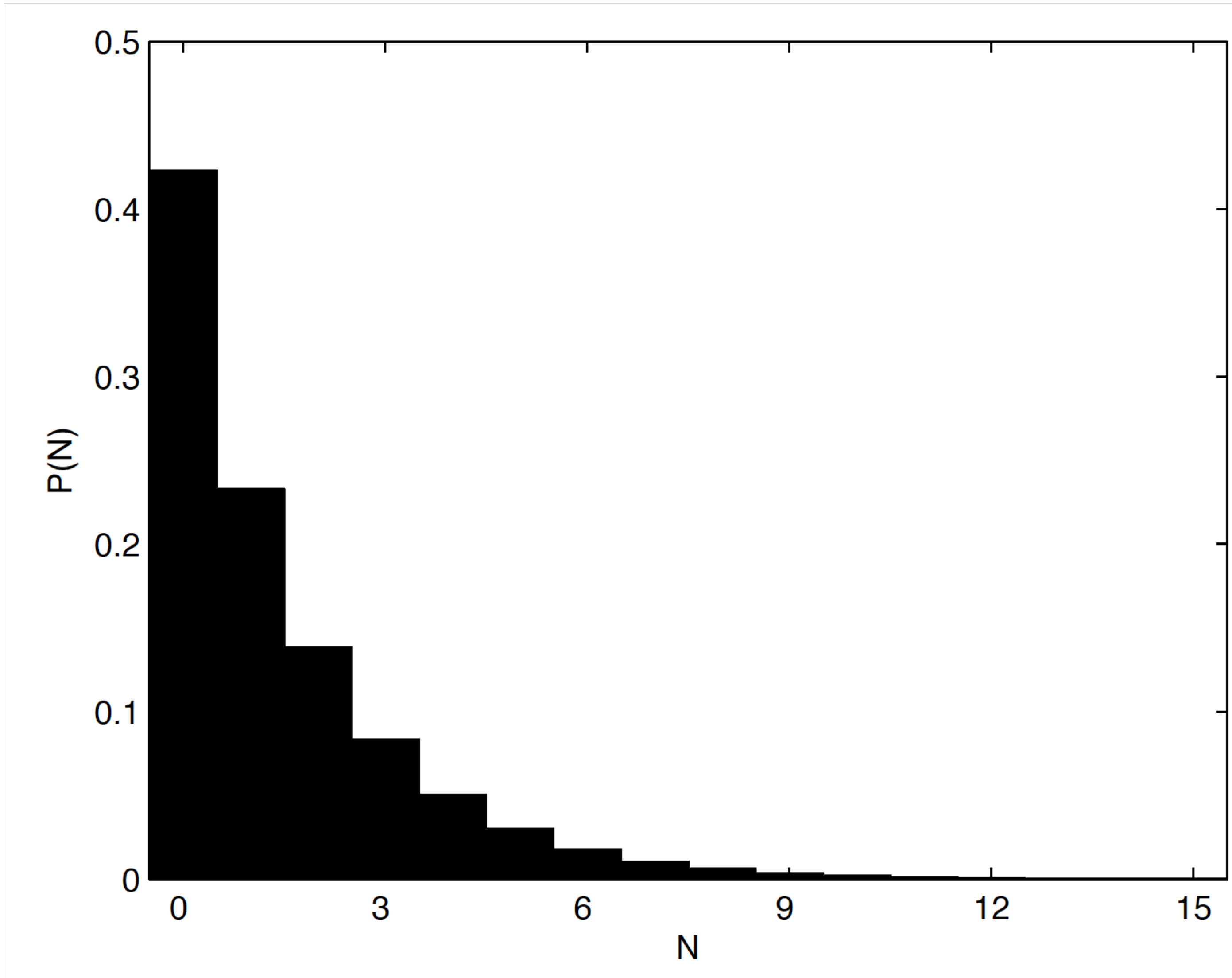


Data
Simulation
N
l (deg)
150
75
0
−75
−150
0
5
10
15
20
b (deg)
−80
−40
0
40
80
25
DM + Parallax Data
Parallax Data
Simulated Parallax
log10(d/(kpc))
−0.75
0.75
1.5
30
40
log10(F/(erg cm−2 s−1))
−12
−11
−10
−9
6
12
18
24

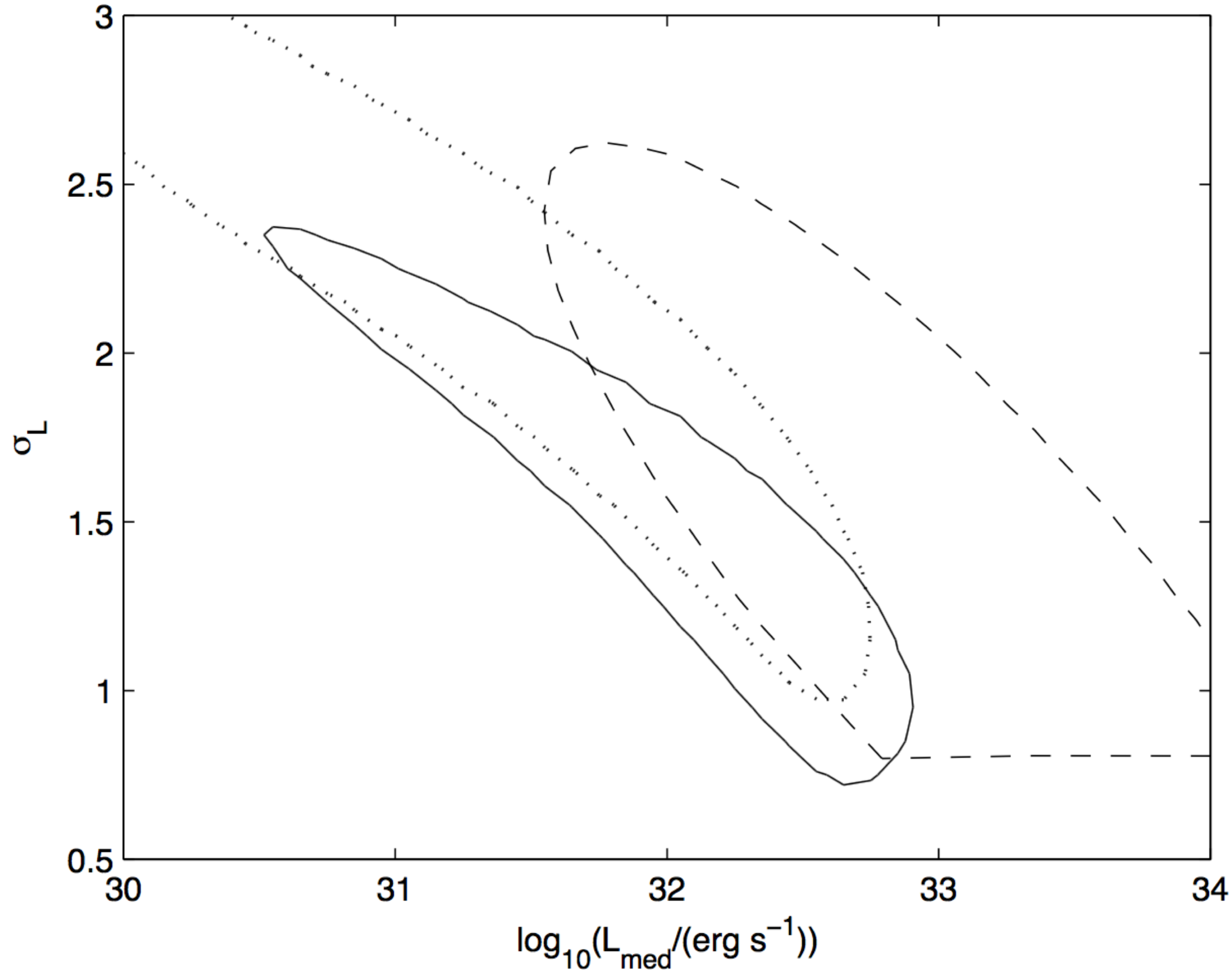
Galactic Center Excess



Predicted Number of Resolved Bulge Pulsars



Comparison to Hooper and Mohlabenga (2016)



Millisecond Pulsars

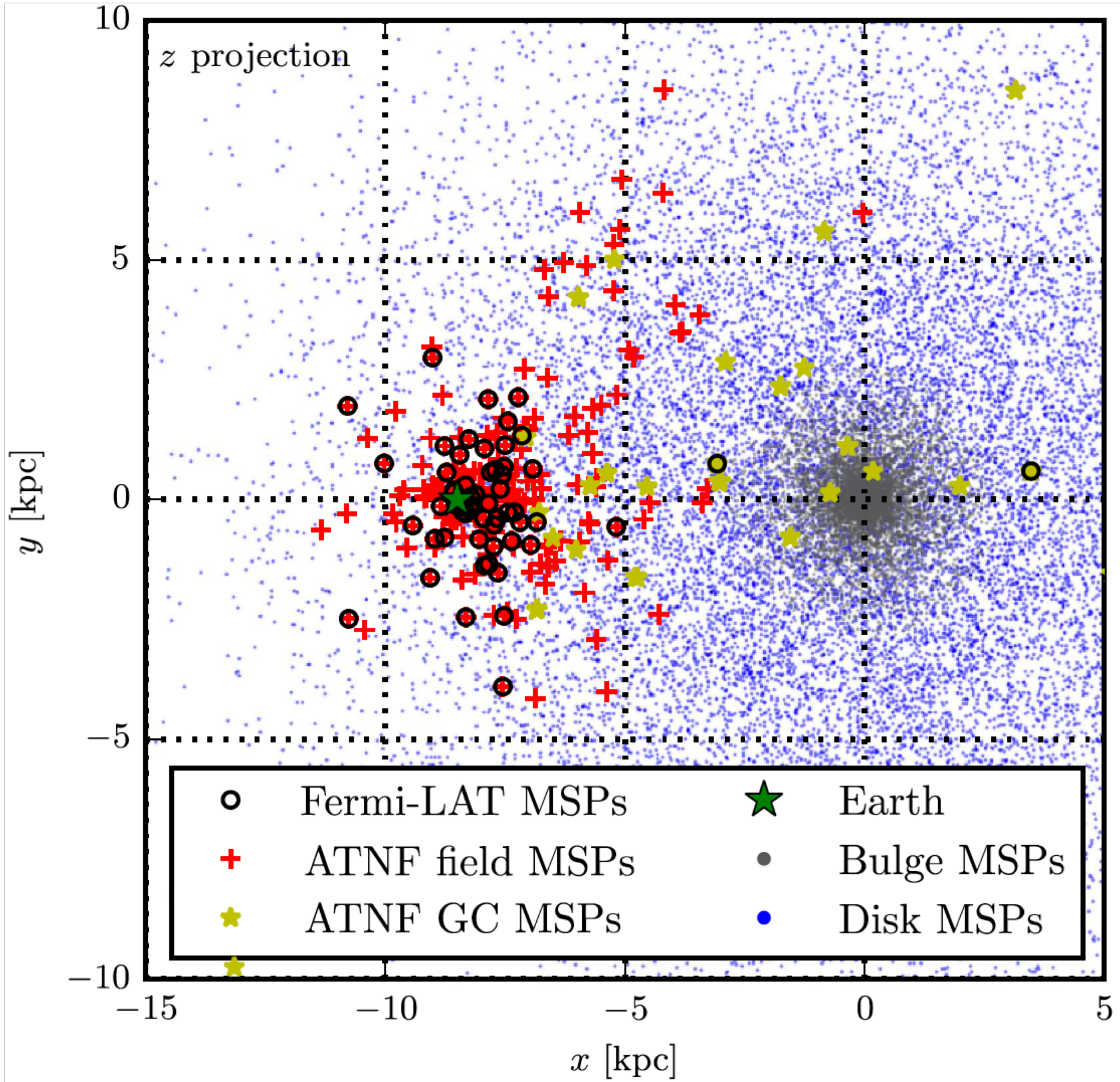
Macquart and Kanekar (2015) estimate the optimal search frequency for an MSP population for two present and two future telescopes, the VLA, the GBT, the SKA1-Mid and the full SKA, assuming that the GC pulsar population has a luminosity distribution similar to that of field pulsars.

They consider two scattering cases, weak scattering, where the scattering screen is roughly midway between us and the GC, and strong scattering, where the screen is ≈ 130 pc from the GC. They find that the optimal MSP search frequencies are ≈ 8 and ≈ 25 GHz in the weak-scattering and strong-scattering cases, respectively.

Deep (10– 30 hr) integrations with the VLA or the GBT should allow a detection of MSPs at the GC at 10σ significance if the weak-scattering case is indeed applicable, as suggested by the recent detection of a magnetar close to the GC.

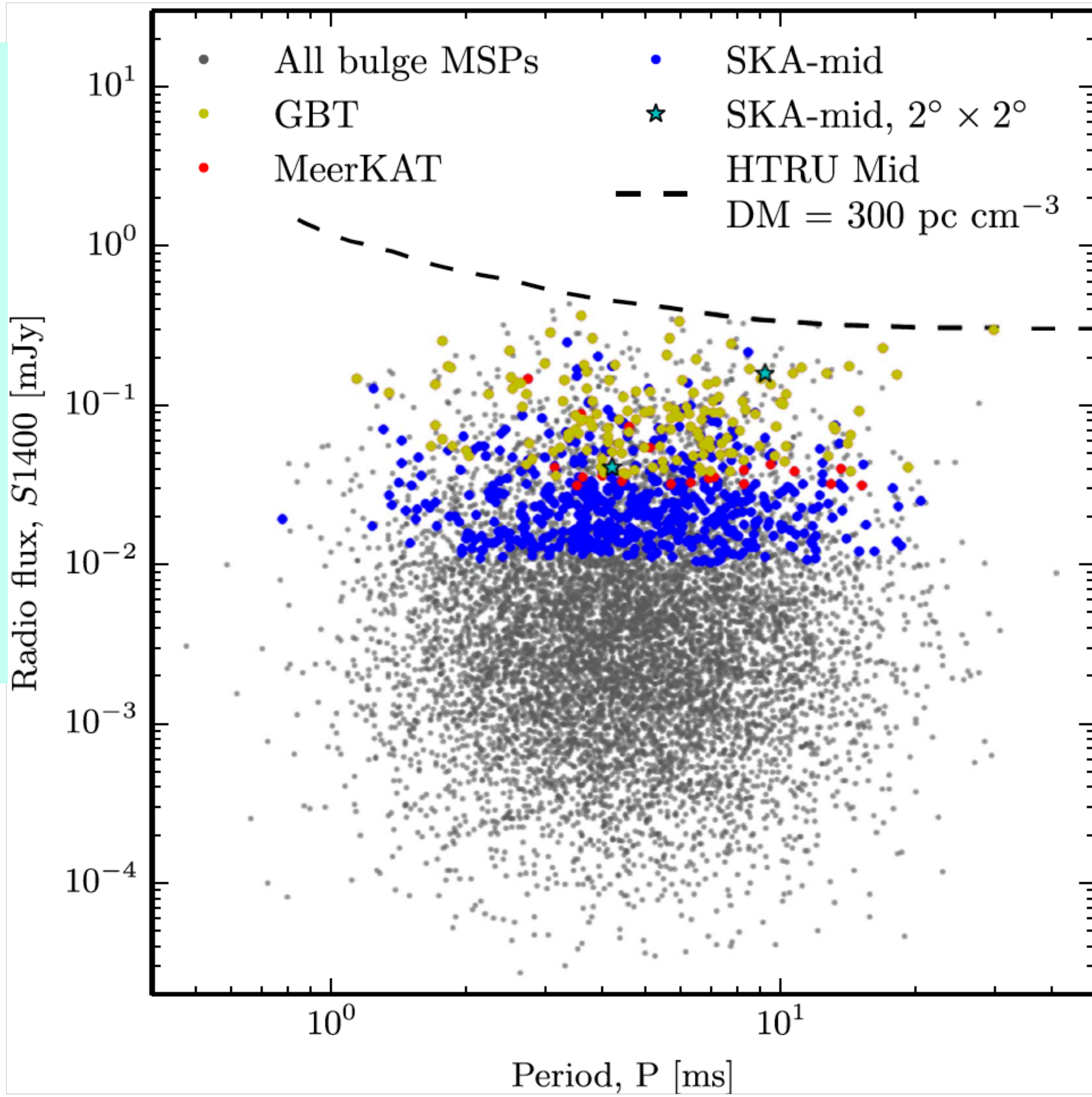
However, the strong-scattering scenario would require the full SKA to detect and time MSPs at the distance of the GC.

Predicted spatial distribution of MSPs in the bulge (gray dots) and the disk (blue dots). Also shown are, Australia Telescope National Facility (ATNF) catalog, both sources in the field (red crosses) and MSPs in globular clusters (yellow stars). We also show gamma-ray detected field MSPs (black circles). Image credit: Calore et al. (2016).



Forecasts for MSP Radio Surveys

- Image credit: Calore et al. APJ 827:143(2016).
- Sensitivities for the future MeerKAT and SKA-mid are based on the SKA Phase 1 System Baseline Design report.



Dependence on Stellar Mass

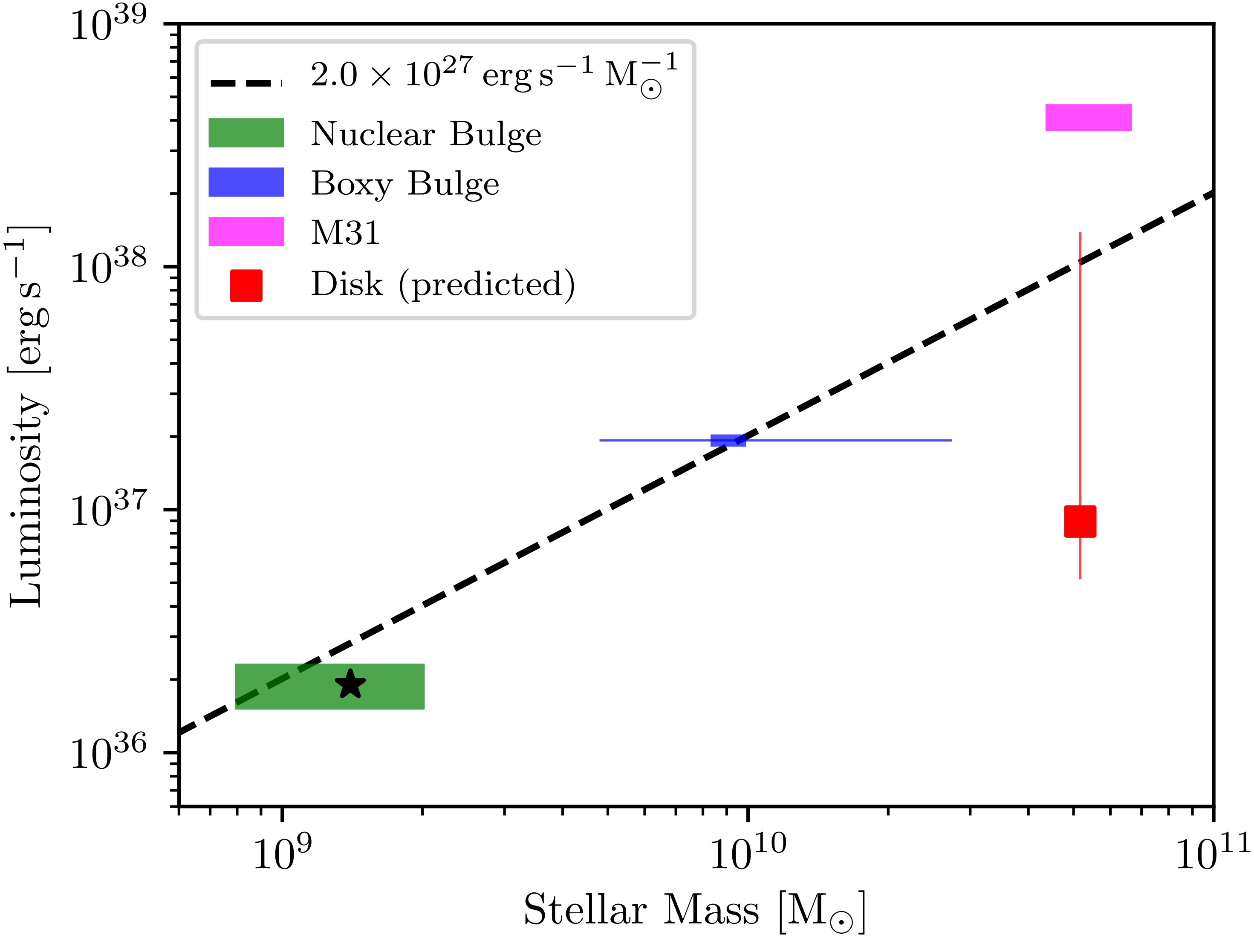


Image Credit: Bartels et al. (2018).

Conclusions

- Galactic Center Excess (GCE) traces Galactic Bulge stars thus favoring the majority of the signal being due to MSPs rather than self-annihilating dark matter.
- Found a similar number of bulge MSPs to disk MSPs could provide a good fit and it's consistent for non bulger MSPs to have been resolved yet.
- SKA-mid observations may be needed to eventuate exactly how much of the GCE is due to MSPs. If there is some excess remaining there may still be the possibility of a dark matter self-annihlatin contribution.