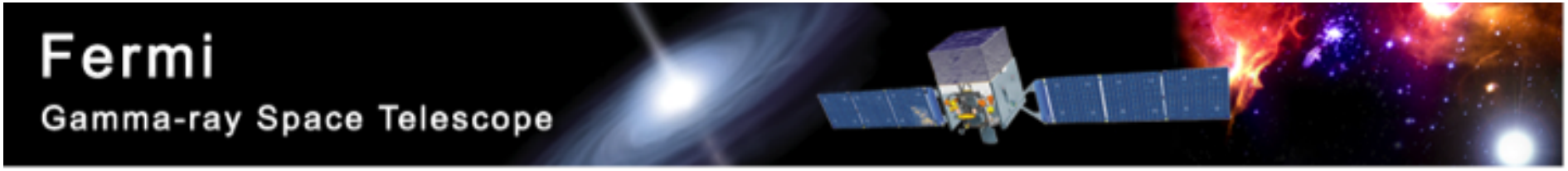


Millisecond Pulsars and the Galactic Center Excess

Peter L. Gonthier

Hope College

13th Rencontres du Vietnam
Exploring the Dark Universe
ICISE
Quy Nhom, Vietnam

1. Pulsar Zoo
2. Millisecond Pulsars
3. Population Synthesis
4. Globular Clusters
5. Galactic Center Excess

Collaborators

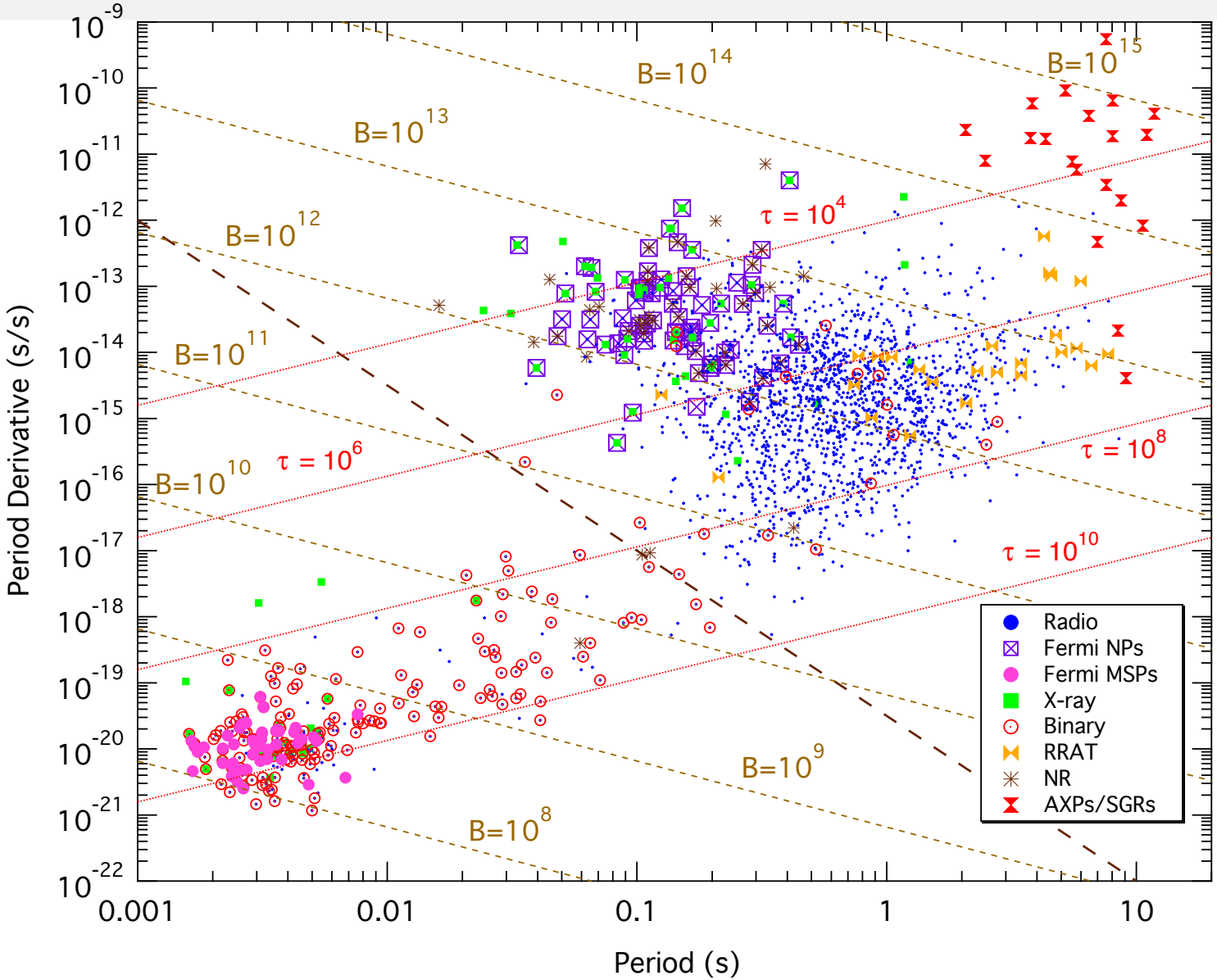
Population Synthesis of Millisecond Pulsars from the Galactic Disk and Bulge

- Alice Harding & Elizabeth Ferrara — NASA Goddard Space Flight Center
- Sara Frederick — University of Maryland
- Victoria Mohr — Washington and Jefferson College
- Yew-Meng Koh — Hope College

Fifty Years...July 1967— Jocelyn Bell and Anthony Hewish

http://www.nature.com/news/pulsars-still-dazzle-after-50-years-1.22243?sf95441793=1

Pulsar Zoo with over 2530 subjects



ATNF - `http://www.atnf.csiro.au/research/pulsar/psrcat`

Radiation Models

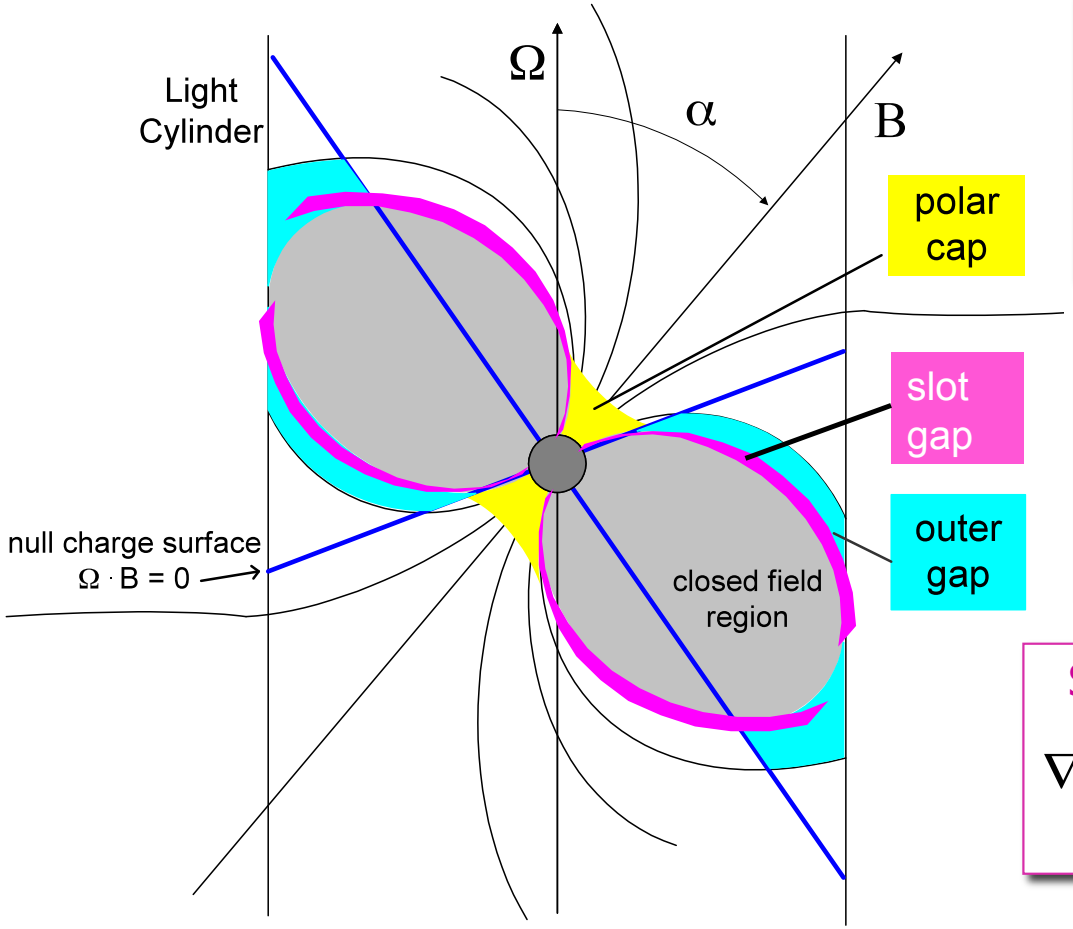
- Radio emission - core and cone beams
- γ-ray emission - Slot Gap Two Pole Caustic (TPC), Outer Gap (OG), and Pair Starved Polar Cap (PSPC)
- Phenomenological Luminosities

$$
\begin{aligned}
L_\nu &= f_\nu \, P_{-3}^{\alpha_\nu} \, \dot{P}_{-20}^{\beta_\nu} \quad \mathrm{mJy} \cdot \mathrm{kpc}^2 \cdot \mathrm{MHz} \\
L_\gamma &= f_\gamma \, P_{-3}^{\alpha_\gamma} \, \dot{P}_{-20}^{\beta_\gamma} \quad \mathrm{eV} \cdot \mathrm{s}^{-1}
\end{aligned}
$$

- Explore model free parameter space with Markov Chain Monte Carlo (MCMC) techniques.

γ-ray Emission in the Pulsar Magnetosphere

Possible sites of particle acceleration



In most of magnetosphere

$$E \bullet B = 0$$

Deficient charge supply

$$E \bullet B \neq 0$$

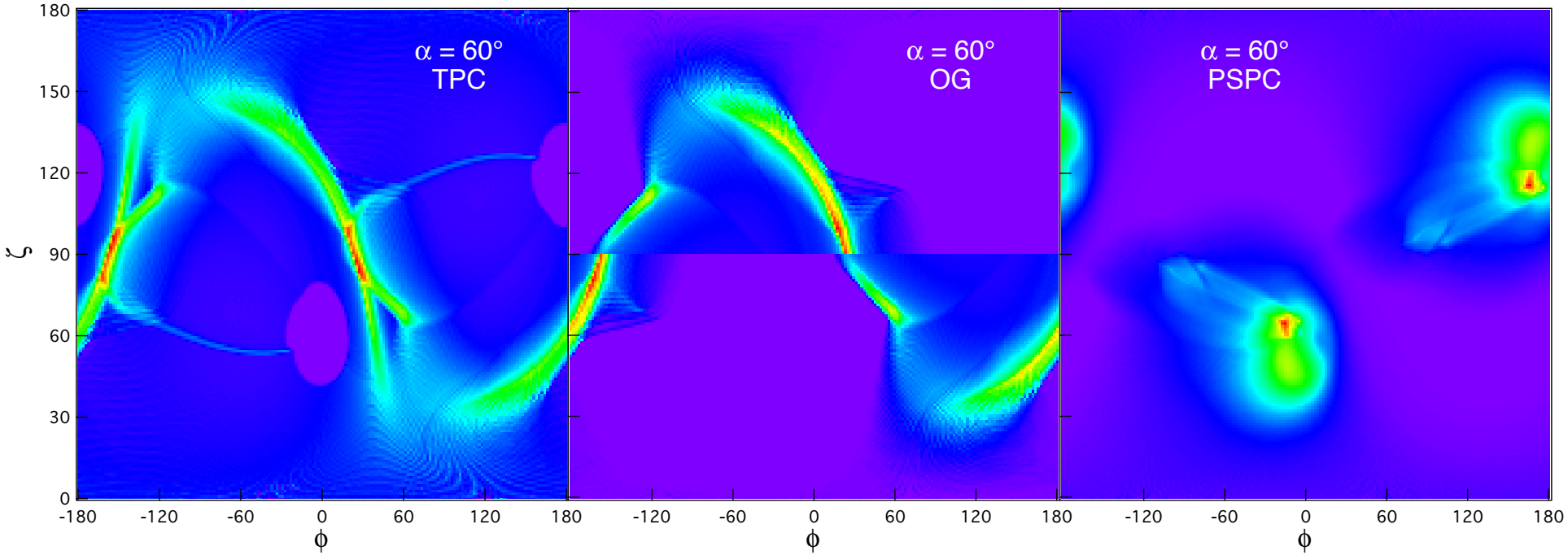
→ acceleration

Solve Poisson's Eqn

$$\nabla \bullet E_{\parallel} = 4\pi(\rho - \rho_{GJ})$$

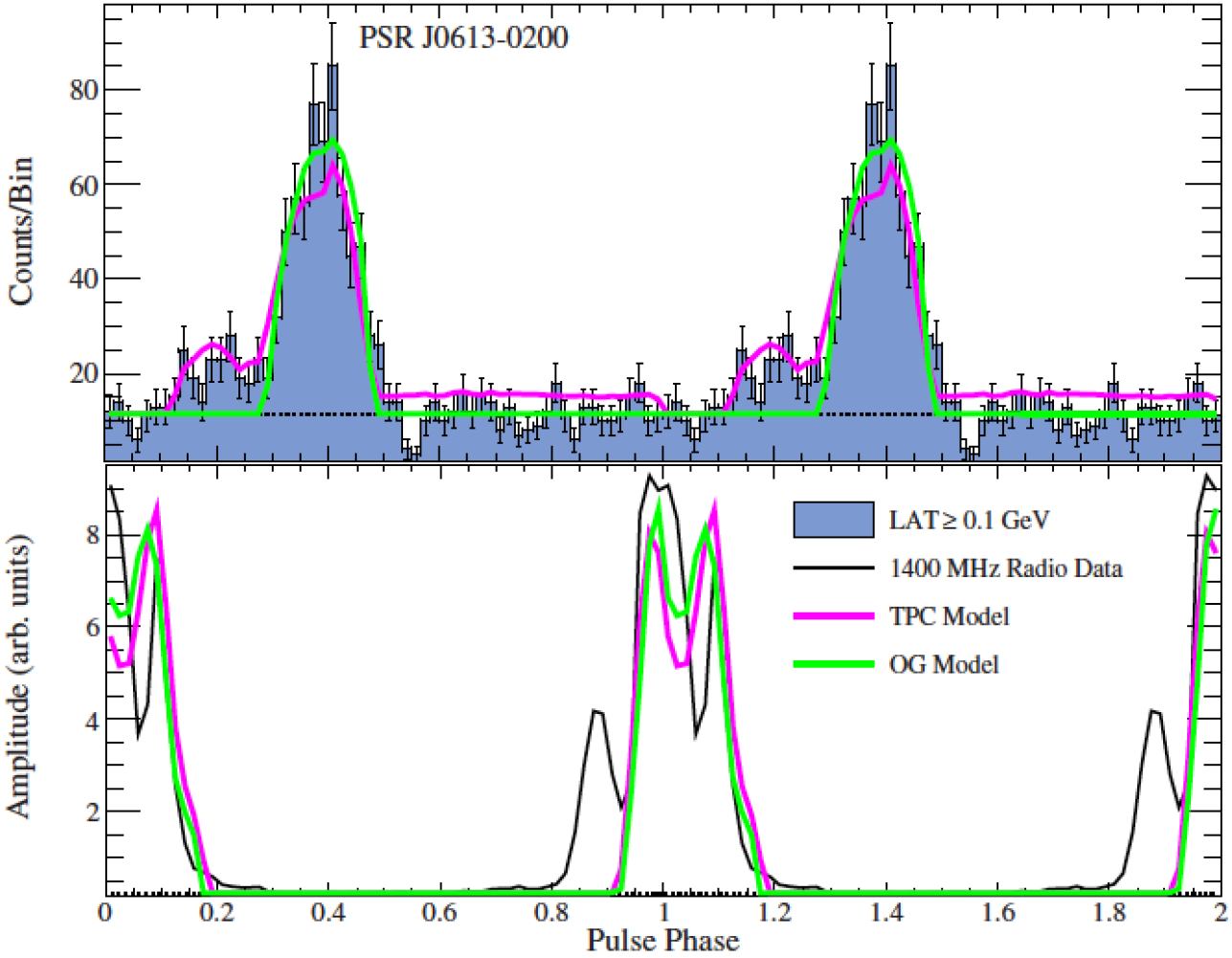
fermi.gsfc.nasa.gov/science/mtgs/summerschool/2011

γ-ray Sky Maps — Magnetic Inclination of 60°



- TPC – Two Pole Caustic Model (Slot Gap) — geometric model — narrow emission along the last open field surface
- OG – Outer Gap Model — emission high in the magnetosphere with one pole contributing for a given ζ
- PSPC – Pair Starved Polar Cap Model — emission from the entire open volume region above the polar cap

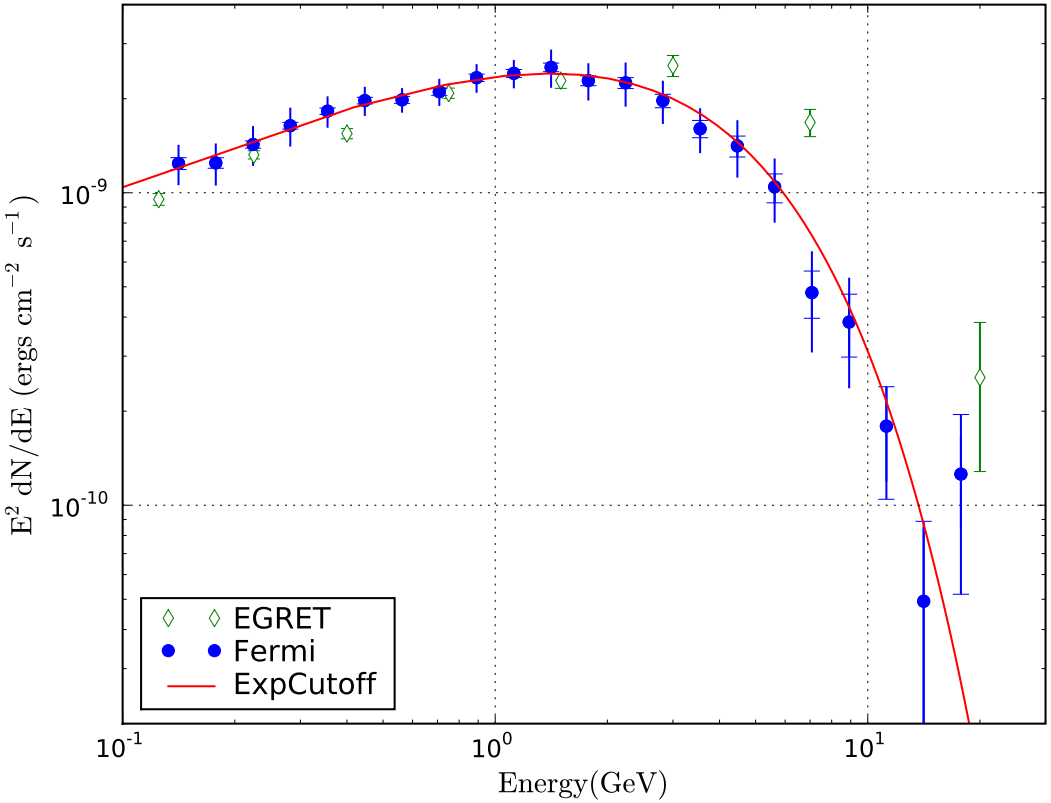
Fitting radio and γ-ray light curves of MSPs



Johnson et al. 2014, *Constraints on the Emission Geometries and Spin Evolution of Gamma-Ray Millisecond Pulsars*, ApJS, 213, 6

High Altitude γ-ray Emission - Spectral Power of the Vela Pulsar

- $\frac{\mathrm{d}N}{\mathrm{d}E}$ — Photon Spectrum
- $\frac{\mathrm{d}N}{\mathrm{d}E} = E^{\Gamma} e^{-E/E_c}$
- $\Gamma = -1.51 \pm 0.01$
- $E_c = 2.89 \pm 0.09$ GeV
- Super-exponential cutoffs
- $\frac{\mathrm{d}N}{\mathrm{d}E} \propto e^{-(E/E_c)^b}$ with $b = 2$ excluded to $16\,\sigma$
- γ-ray emission occurs at high altitudes near the light cylinder in most cases of young pulsars



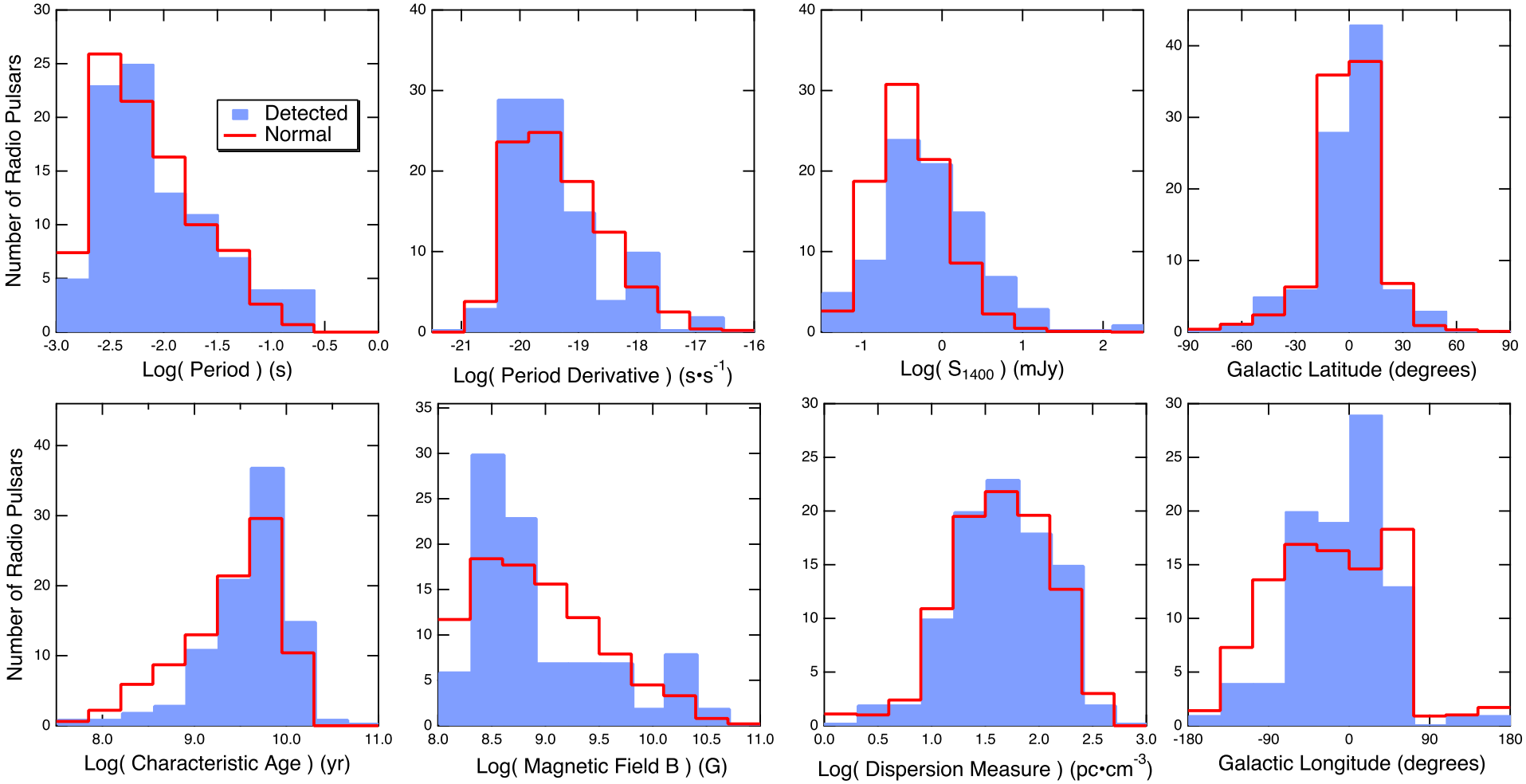
Abdo et al. *Fermi LAT Observations of the Vela Pulsar*, 2009, The Astrophysical Journal, Volume 696, Issue 2, pp. 1084-1093

Population Synthesis of MSPs — Comparison Group

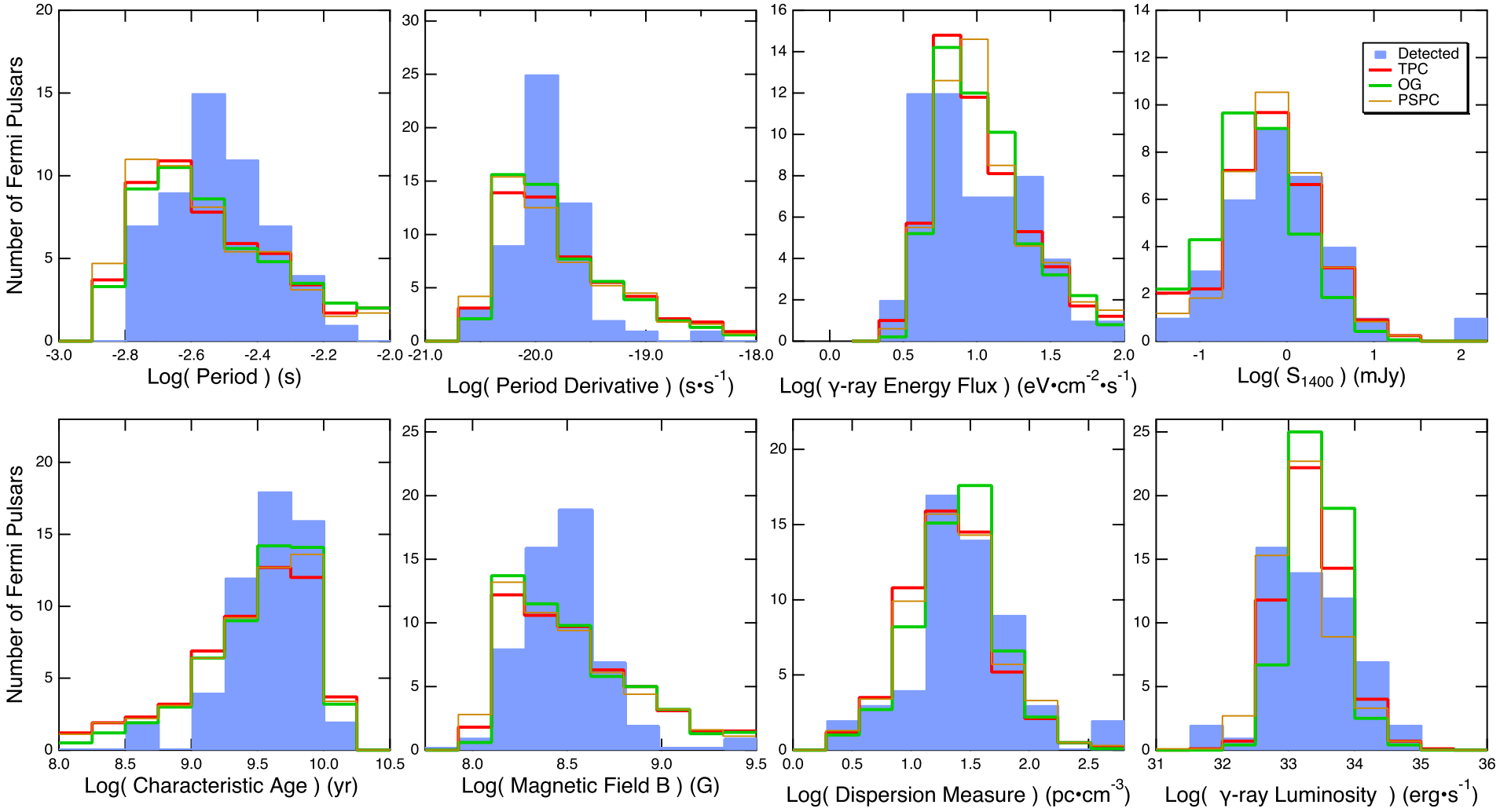
To tune unknown radio and γ-ray luminosity model parameters:

- *Fermi* First Point Source Catalog (Abdo et al. 2010) (1FGL) - 11 month viewing - 54 *Fermi* MSPs detected as point sources
- 13 radio surveys are included in the simulation - 92 radio MSPs
- Target birth rate of 4.5×10^{-4} MSPs per century (Story, Gonthier, & Harding 2007, ApJ, 671, 713.) — 4.5 per Myr
- Normalization of the simulation - to simulate 92 radio MSPs and predict *Fermi* radio-loud MSPs for other viewing periods.

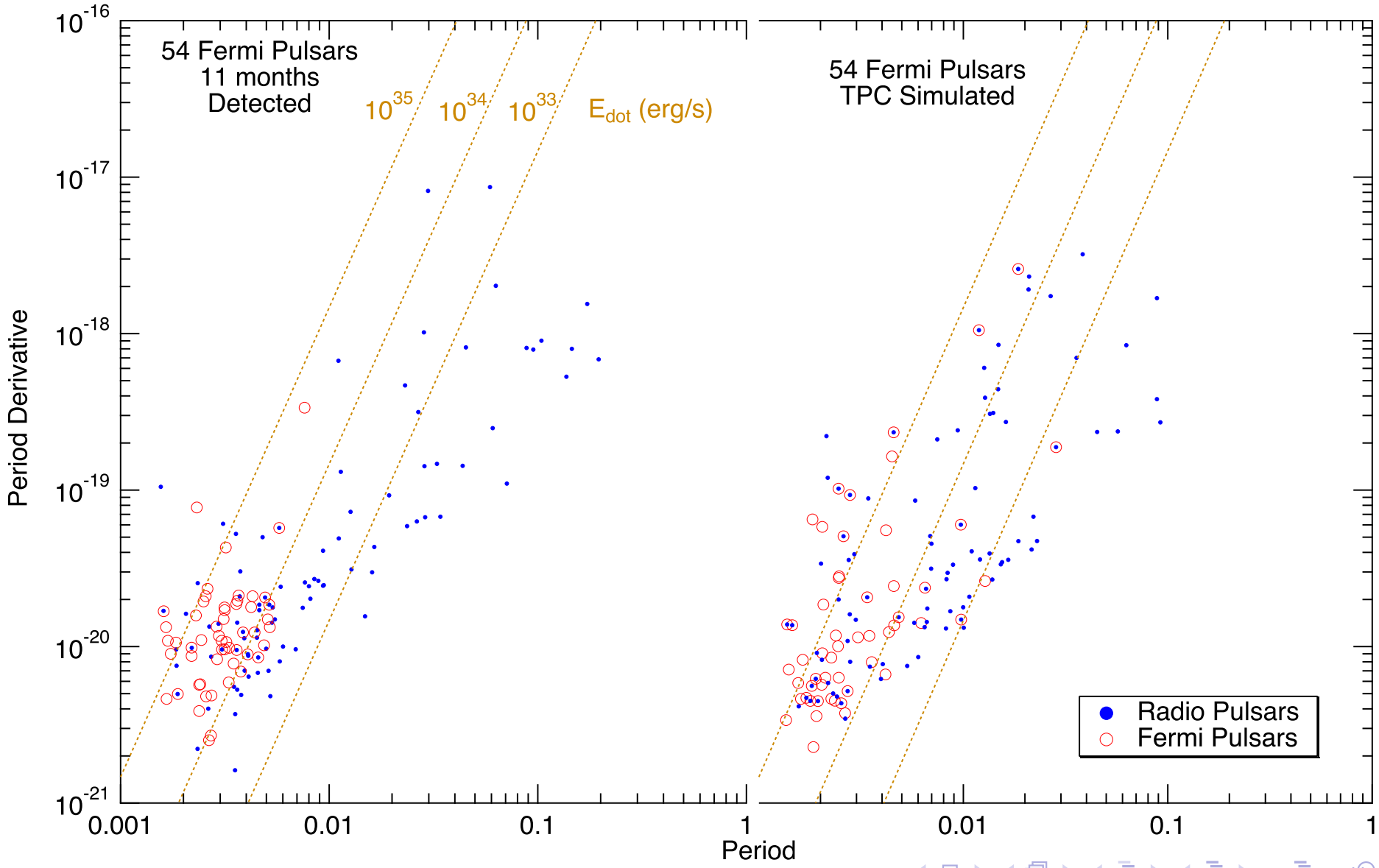
MC Results - Histograms of Radio Pulsars



MC Results - Histograms of *Fermi* Pulsars



MC Results - $\dot{P} - P$ diagram



Predicted *Fermi* -LAT future detections

Catalog	Observing Period	Detected	Simulated — radio-loud & (radio-weak)		
			TPC	OG	PSPC
BSL	3 months	13	27 (25)	27(37)	27 (8)
1FGL	11 months	54	54 (50)	54 (74)	54 (21)
2FGL	2 years	68	80 (77)	79 (114)	84 (31)
3FGL	4 years	82	114 (117)	108 (160)	118 (47)
	5 years		126 (132)	120 (179)	132 (51)
	10 years		171 (180)	166 (256)	182 (77)

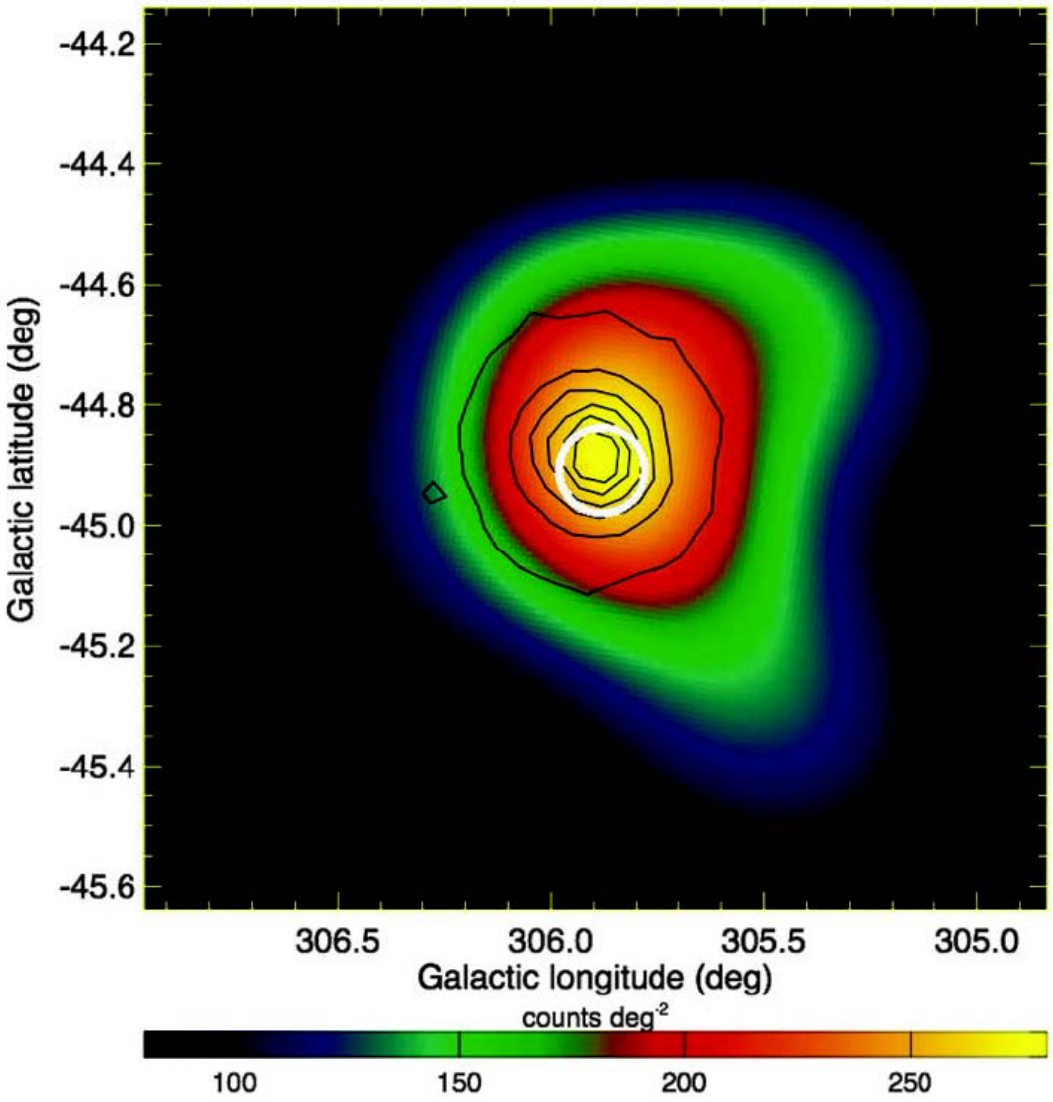
Point Source Catalogs are still incomplete!

Catalog	Detected	Possible Additional MSPs
1FGL	54	10
2FGL	68	16
3FGL	82	16

(private communication, Elizabeth C. Ferrara)

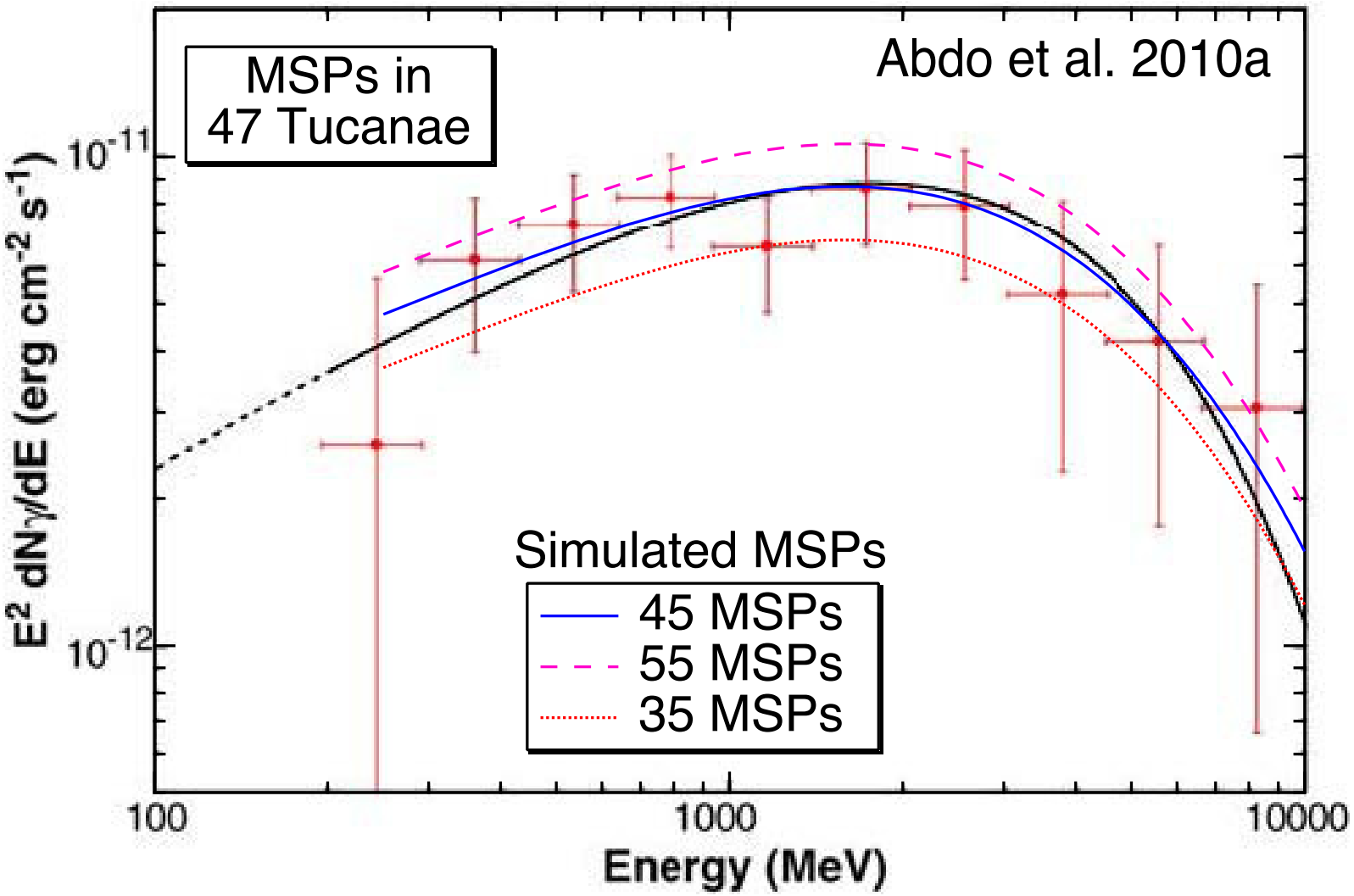
47 Tuc seen in γ rays for the first time by *Fermi*

- 47 Tuc is a steady γ-ray source - non-variable
- There are 23 known radio MSPs in 47 Tuc.
- *Fermi* does not see individual pulsations from MSP - too far - 4 kpc
- Using the ephemerides from 21 radio MSPs, *Fermi* saw no pulsations
- γ-ray flux is not due to a single MSP



Abdo et al. 2009, Science, 325, 845

Fermi Spectrum of 47 Tuc



Expected Number of MSPs from Abdo et al. 2010

Name	$L_\gamma \left(10^{34}\ \mathrm{erg}\cdot\mathrm{s}^{-1}\right)$	N_{MSPs}	Simulated N_{MSPs}
47 Tucanae	$4.8^{+1.1}_{-1.1}$	33^{+15}_{-15}	45 ± 10
Omega Cen	$2.8^{+0.7}_{-0.7}$	19^{+9}_{-9}	20 ± 5
M 62	$10.9^{+3.5}_{-2.3}$	76^{+38}_{-34}	85 ± 20
NGC 6388	$25.8^{+14.0}_{-10.6}$	180^{+120}_{-100}	220^{+80}_{-70}
Terzan 5	$25.7^{+9.4}_{-8.8}$	180^{+100}_{-90}	200^{+20}_{-40}
NGC 6440	$19.0^{+13.1}_{-5.0}$	130^{+100}_{-60}	150 ± 50
M 28	$6.2^{+2.6}_{-1.8}$	43^{+24}_{-21}	50 ± 10
NGC 6652	$7.8^{+2.5}_{-2.1}$	54^{+27}_{-25}	70 ± 30
Average	$0.14^{+0.04}_{-0.03}$ per MSP	89^{+24}_{-19}	105 ± 13

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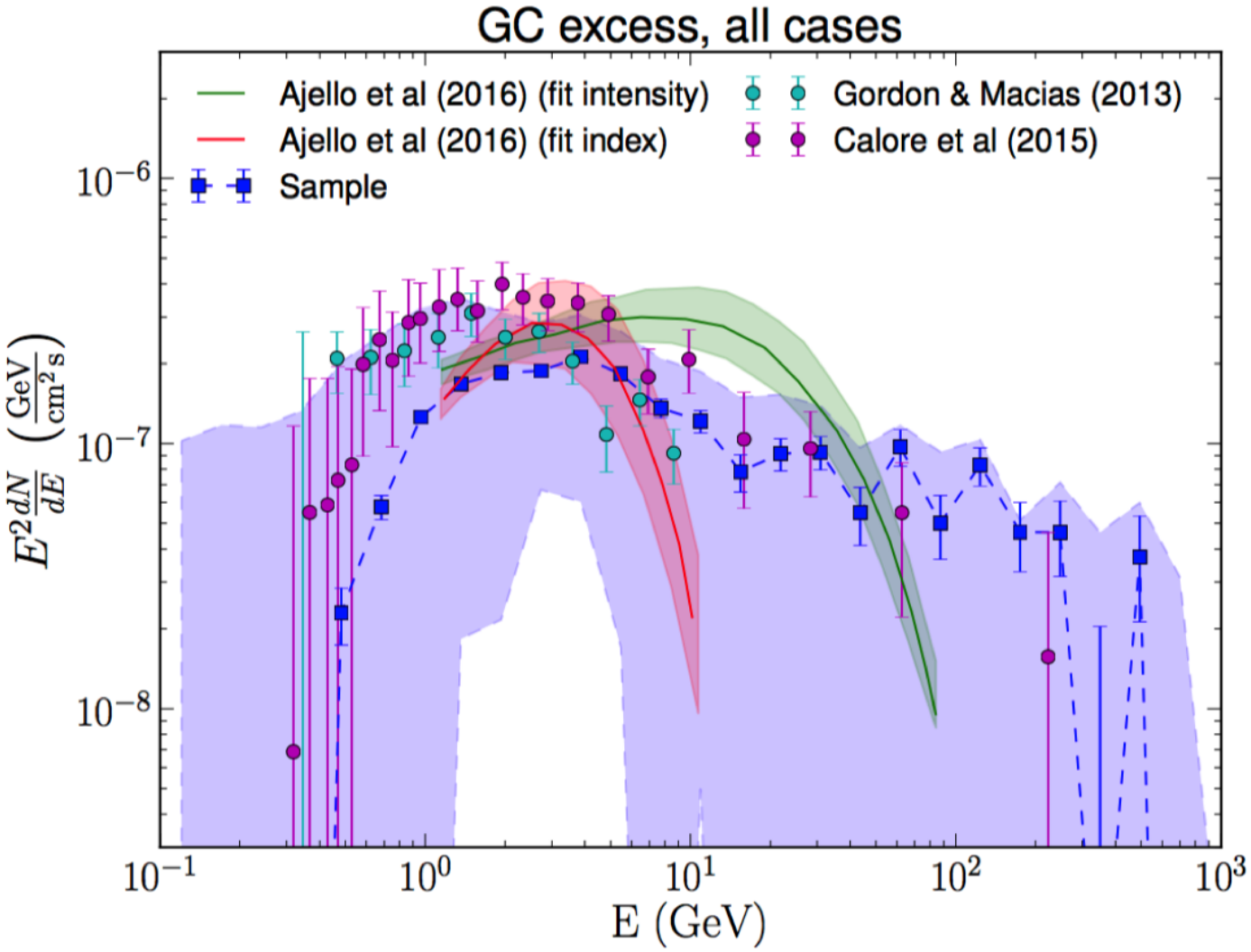
Key Point

expect ~ 100 MSPs per cluster

Galactic Center Excess



Ackermann et al. 2017

Galactic Center Excess - Gordon & Macias 2013

- Dark Matter (DM) WIMP with mass $M_{\rm DM}$ (20 – 60 GeV) annihilate via channels: $\tau^+\tau^-$ and b^+b^- as suggested by this study.
- γ-ray flux from WIMP is factorable into "particle physics" and "astrophysical" factors

$$\Phi\left(E_\gamma, b, \ell\right) \;=\; \Phi^{PP}\, E_\gamma \;\times\; J\left(b, \ell\right) \tag{2}$$

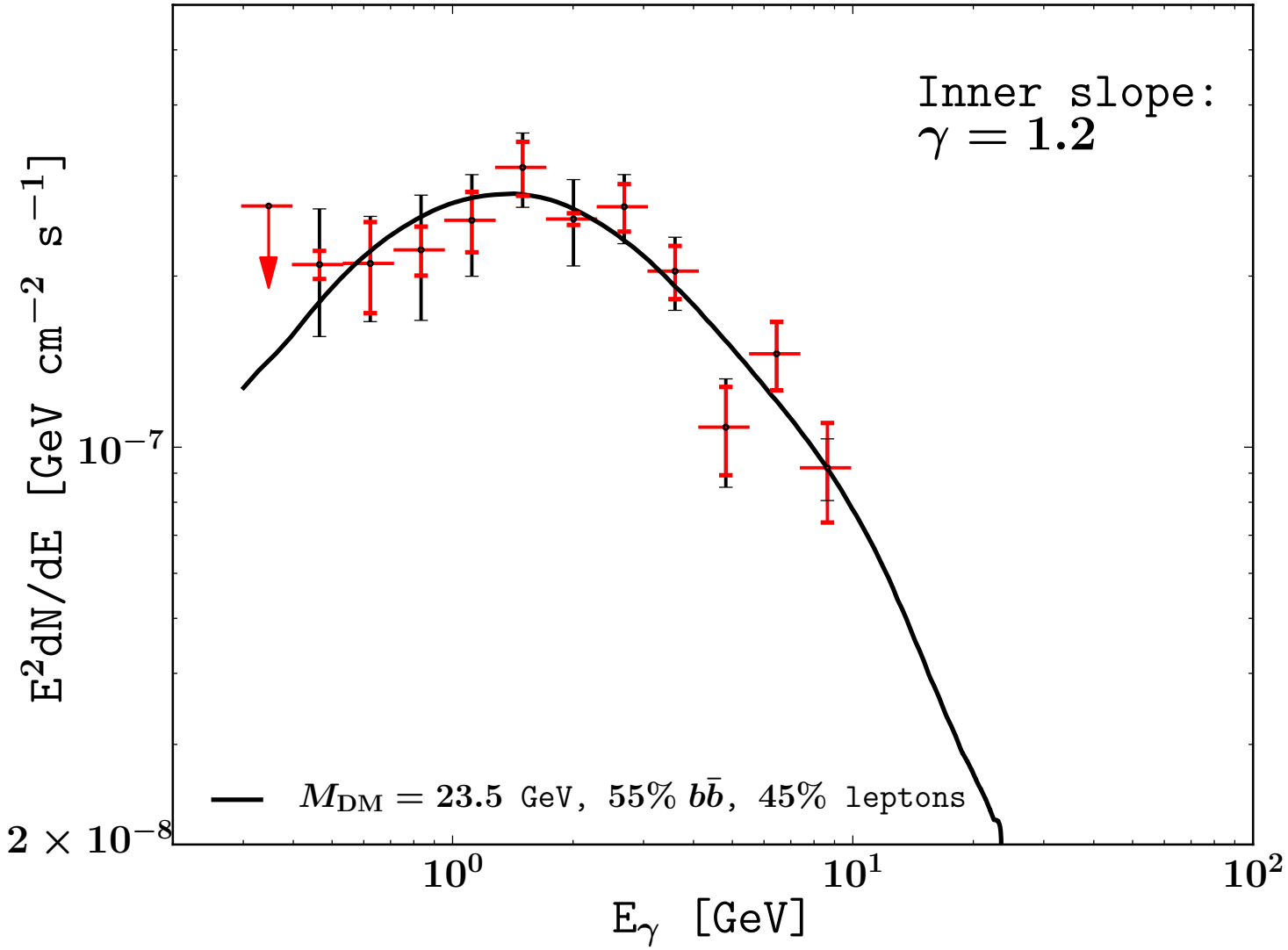
$$\Phi^{PP}\left(E_\gamma\right) \;=\; \frac{1}{2}\left(\frac{\langle\sigma v\rangle}{4\pi\, M_{\rm DM}^2}\right)\sum_f \frac{dN_f}{dE_\gamma} B_f \tag{3}$$

$$J\left(b, \ell\right) \;=\; \int_0^\infty \rho(r)^2\, ds \tag{4}$$

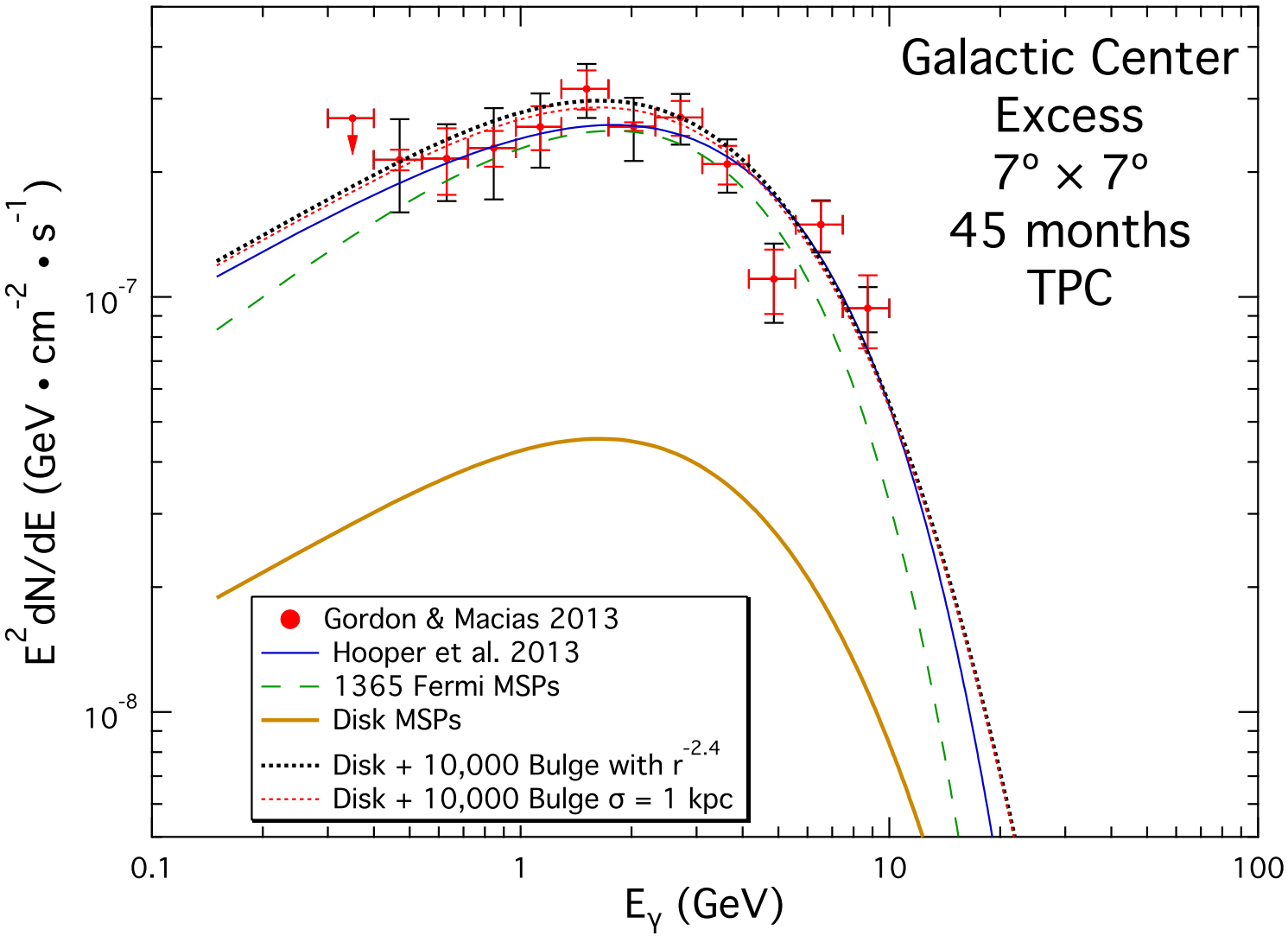
$$\text{Navarro} - \text{Frenk} - \text{White} \qquad \rho(r) \;=\; \frac{\rho_s}{\left(\frac{r}{r_s}\right)^\gamma \left[1 + \left(\frac{r}{r_s}\right)\right]^{3-\gamma}} \tag{6}$$

Galactic Center Excess - Gordon & Macias 2013 - Fig. 7b

$\langle \sigma v \rangle \sim 3 \times 10^{-26}\ \mathrm{cm}^3 \cdot \mathrm{s}^{-1}$ Thermal annihilation cross section

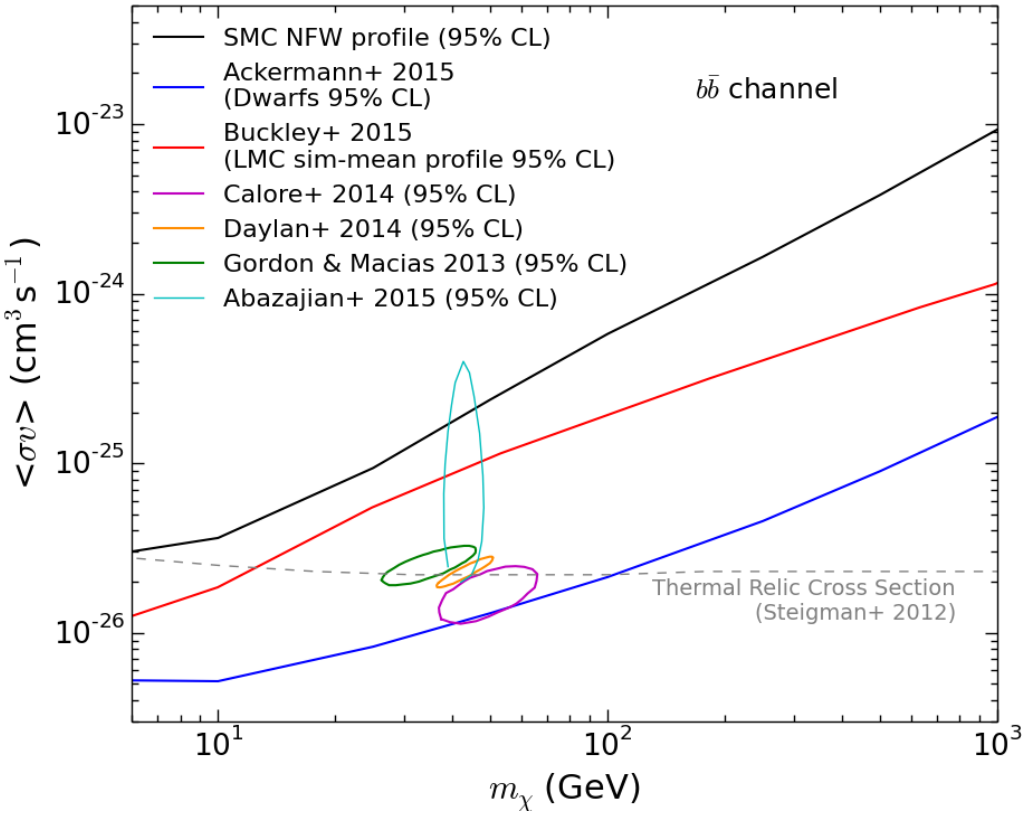


Galactic Center Excess - Gordon & Macias 2013



Dark Matter WIMP Constraints

Caputo et al. 2016, Phys. Rev. D 93, 062004.



- Is the GCE a result of an unknown DM particle?
- Or a result of known astrophysical sources, MSPs, but have not been observed?

The GCE and Point Sources

Two independent studies conclude that point sources are responsible for the GCE.

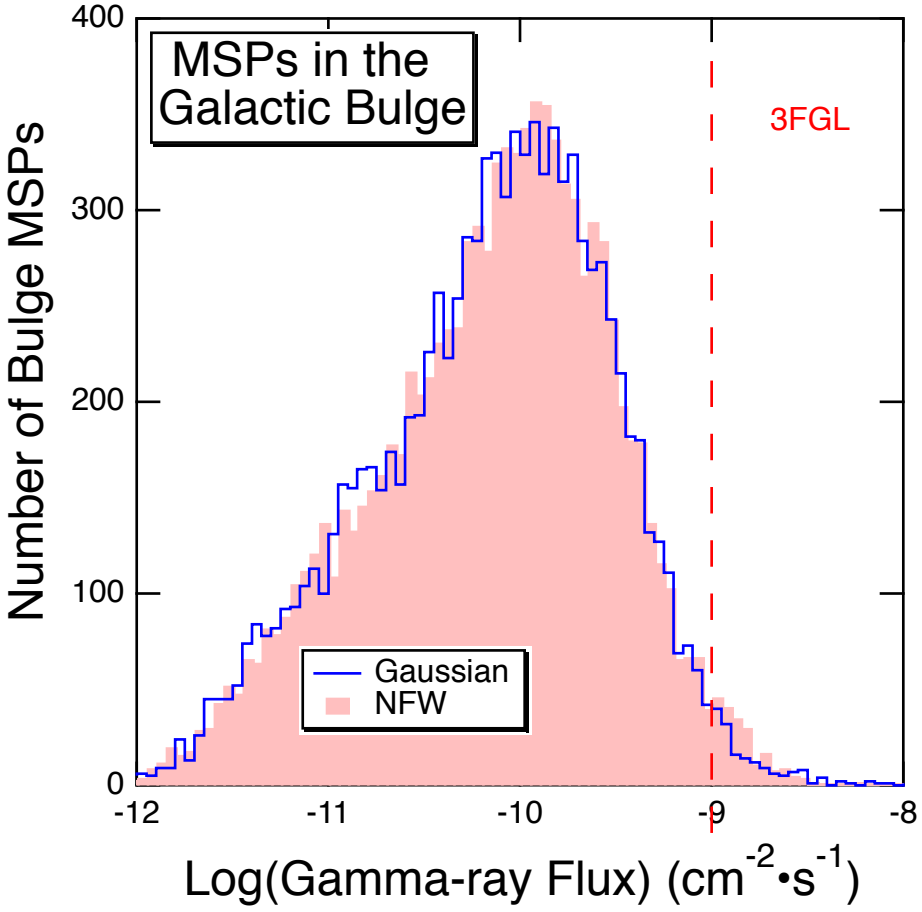
- Lee, S. K., Lisanti, M., Safdi, B. R., Slatyer, T. R., & Xue, W., *Evidence for Unresolved γ-Ray Point Sources in the Inner Galaxy*, 2016, Phys. Rev. Lett., 116, 051103. — non-Poissonian template fit. (Princeton, Broad Institute, and MIT)
- Bartels, R., Krishnamurthy, S. & Weniger, C., *Strong Support for the Millisecond Pulsar Origin of the Galactic Center GeV Excess*, 2016, Phys. Rev. Lett., 116, 051102. — wavelet decomposition of the γ-ray sky. (*GRAPPA* Institute and University of Amsterdam)

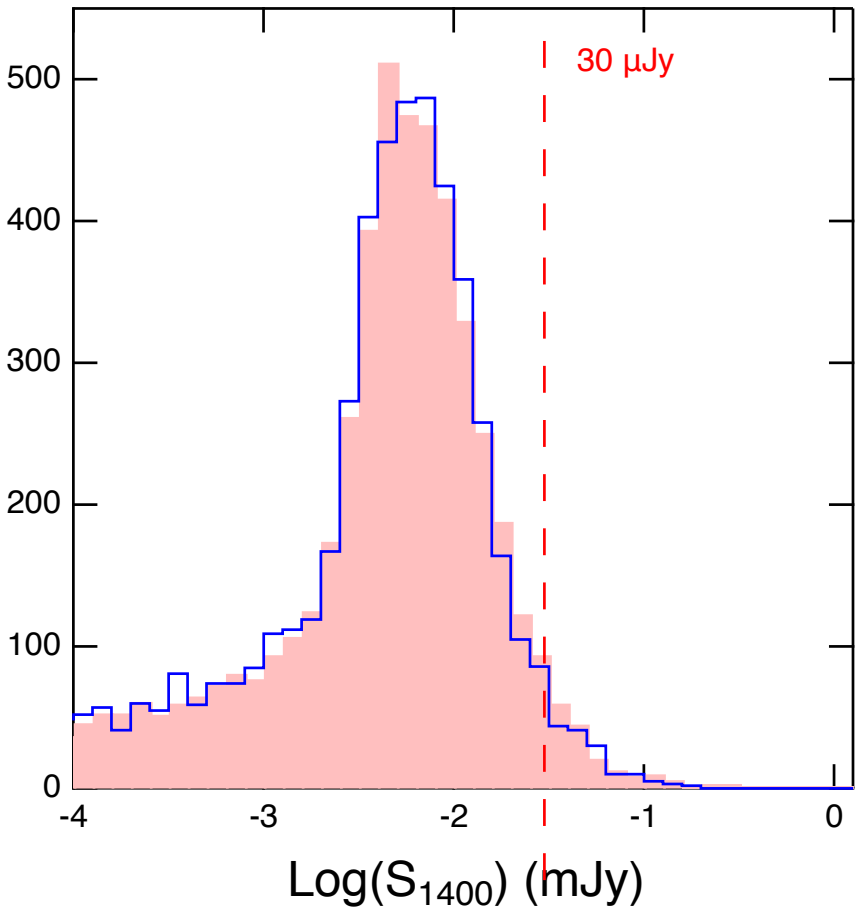
The Source of MSPs in the Galactic Center

The dynamical inspiraling of globular clusters in a dynamical friction model.

- Gnedin et al. (2014) estimate that 2 to 6 $\times 10^7\ M_\odot$ in globular clusters where dragged into a region of 3 to 5 pc (1.2' to 2.0') from the GC.
- Gnedin & Ostriker (1997) list the masses of 119 globular clusters giving an average mass of $3.8 \times 10^5\ M_\odot$ per cluster.
- These studies would suggest that 50 to 160 globular clusters might have been captured by the GC.
- We estimated previously that there are about 100 MSPs per cluster.
- 100 captured globular clusters could provide 10,000 MSPs needed to account for the spectrum of the GCE.
- This is in agreement with our prediction.

The Future will tell!





10,000 MSPs simulated in the GC

Acknowledgments

We also are grateful for the generous support of:

- The Michigan Space Grant Consortium
- The National Science Foundation under grant Nos. REU: PHY/DMR-1004811, and RUI: AST-1009731
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- The NASA Astrophysics Theory and Fundamental Physics Program under the grant No. NNX13AO12G