Millisecond pulsar interpretation of the Galactic center gamma-ray excess

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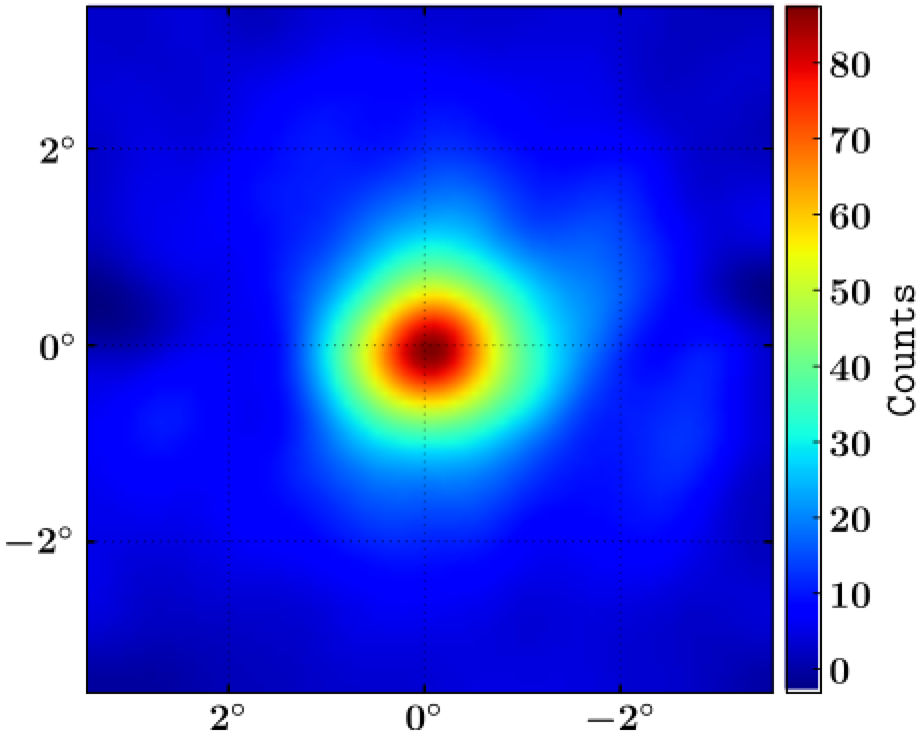
Outline

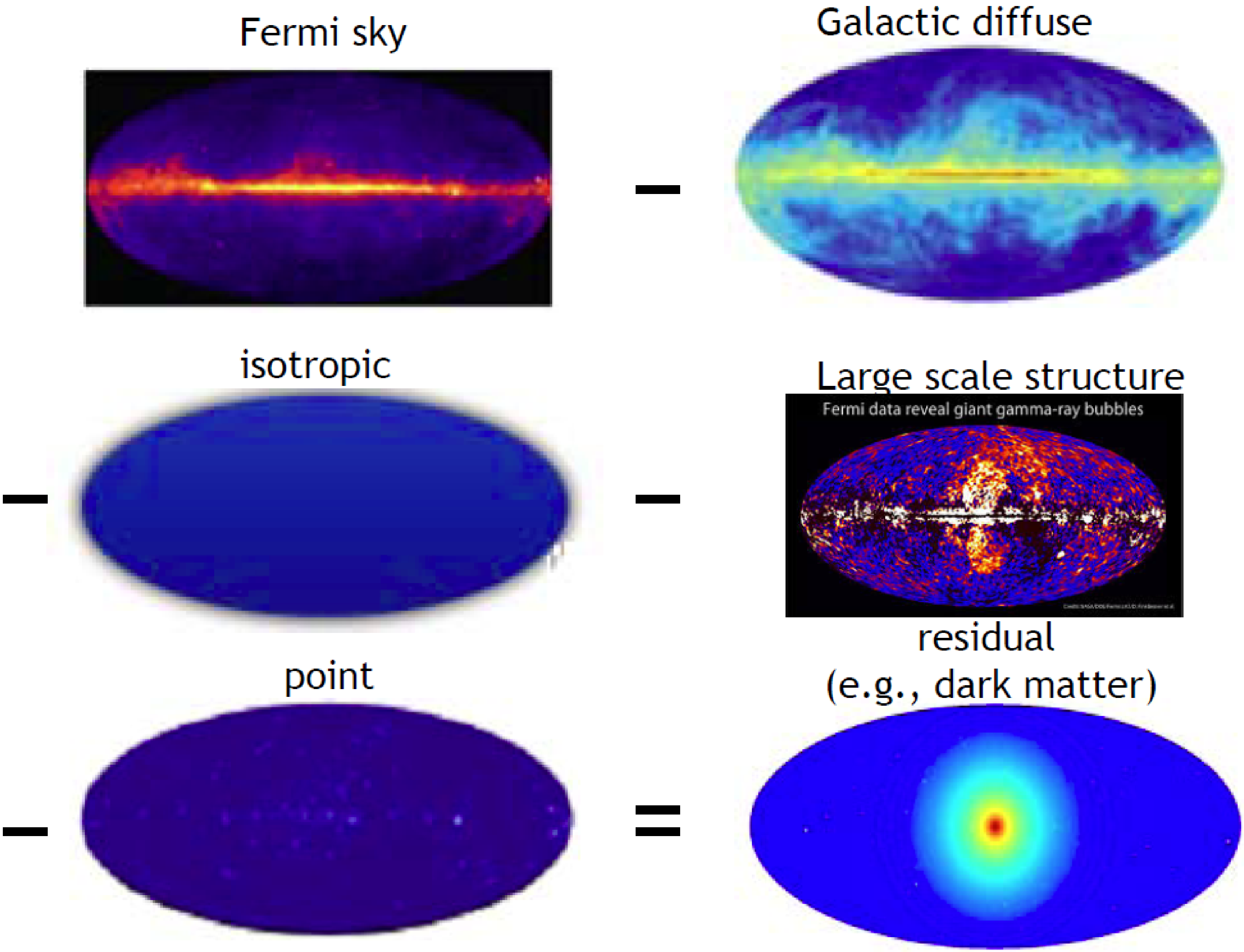
- Introduction to GeV gamma-ray excess
- Millisecond pulsar explanation
- Conclusion

Gamma-ray residual found in Fermi-LAT data in GC

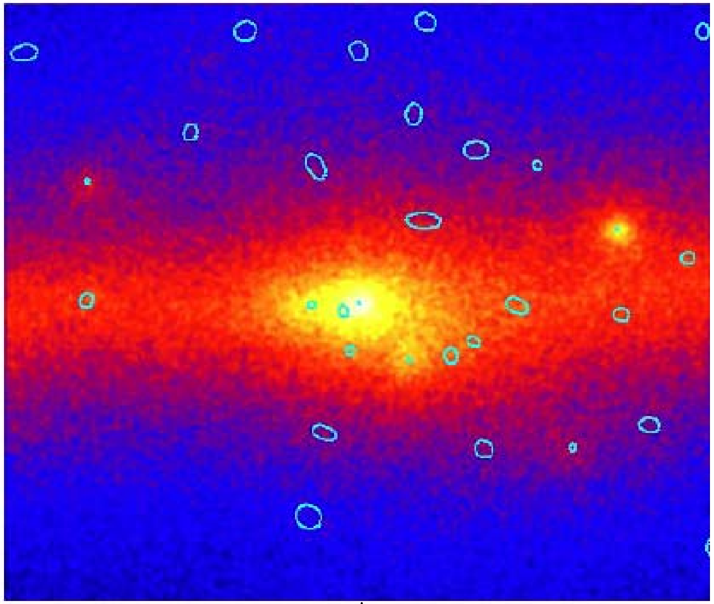
PHYSICAL REVIEW D **88,** 083521 (2013)



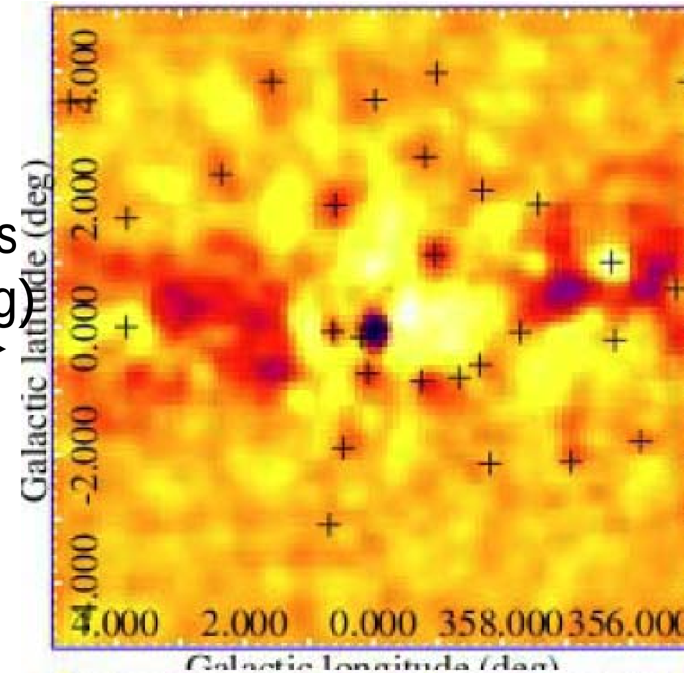
Goodenough & Hooper (2009)
Vitale & Morselli (2009)
Hooper & Goodenough (2011)
Boyarsky et al. (2011)
Hooper & Linden (2011)
Abazajian & Kaplinghat (2012)
Gordon & Macias (2013)
Huang et al. (2013)
Abazajian et al. (2014)
Daylan et al. (2014)
Zhou et al. (2014)


Fermi sky
Galactic diffuse
isotropic
Large scale structure
Fermi data reveal giant gamma-ray bubbles
point
residual
(e.g., dark matter)

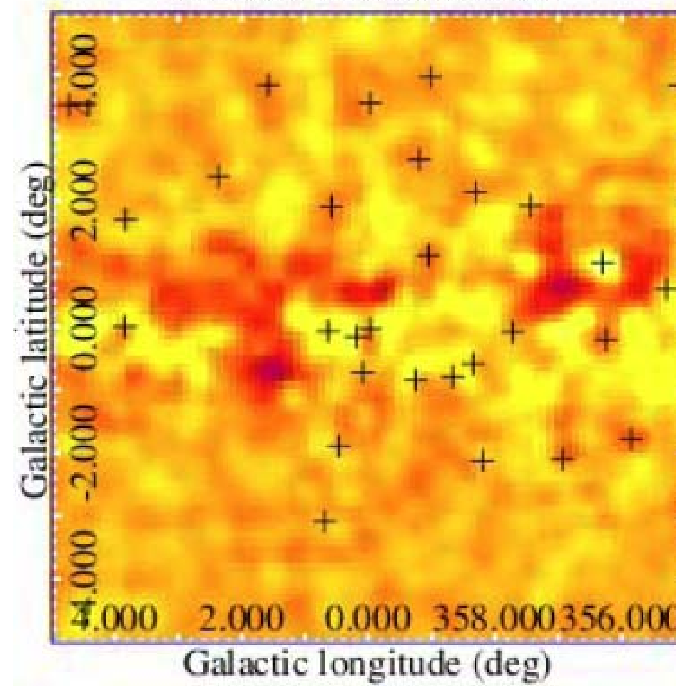
GC counts map



Data-model (known sources and diffuse bkg)

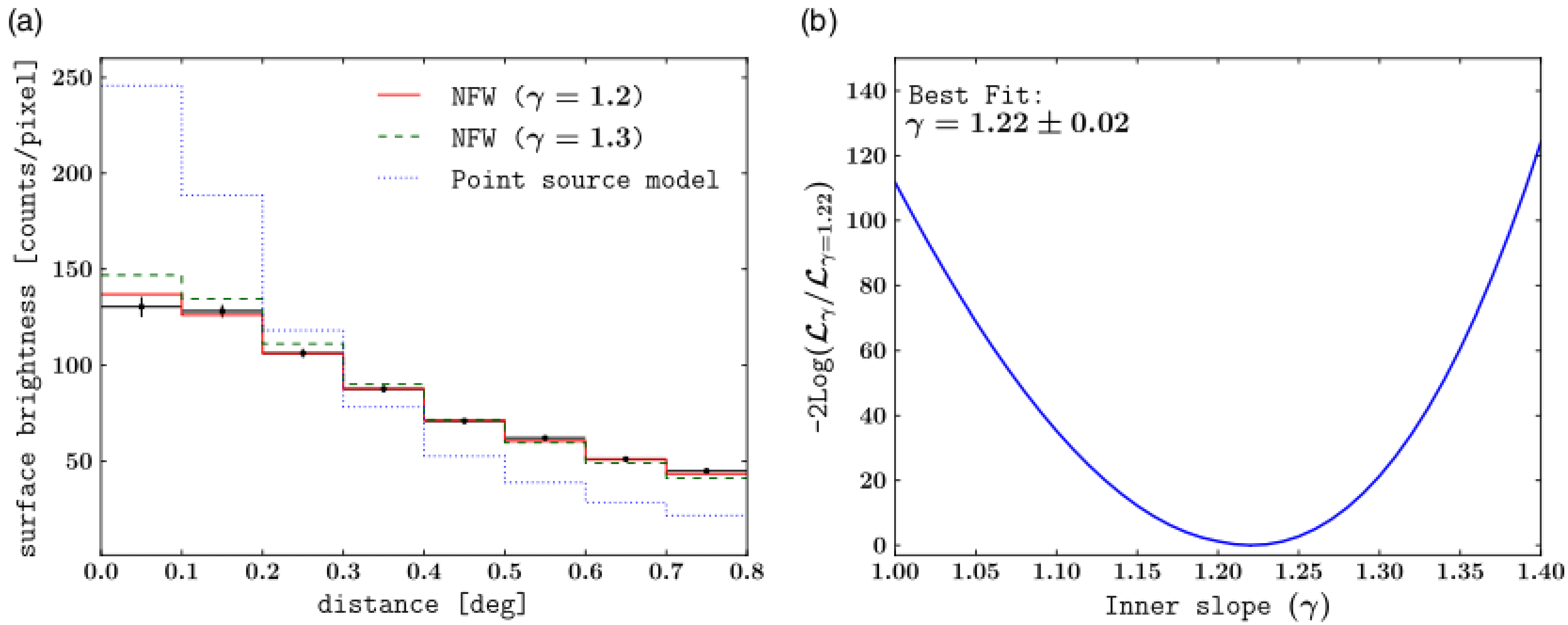


Data-model (with an additional extended component)



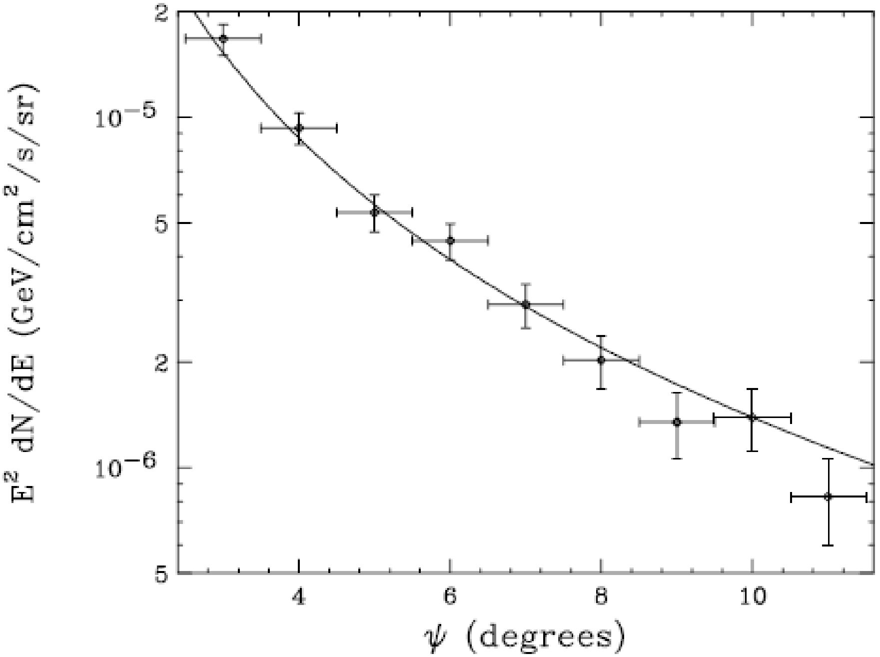
Spatial distribution: extended power-law (gNFW^2)

$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1+\left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}$$

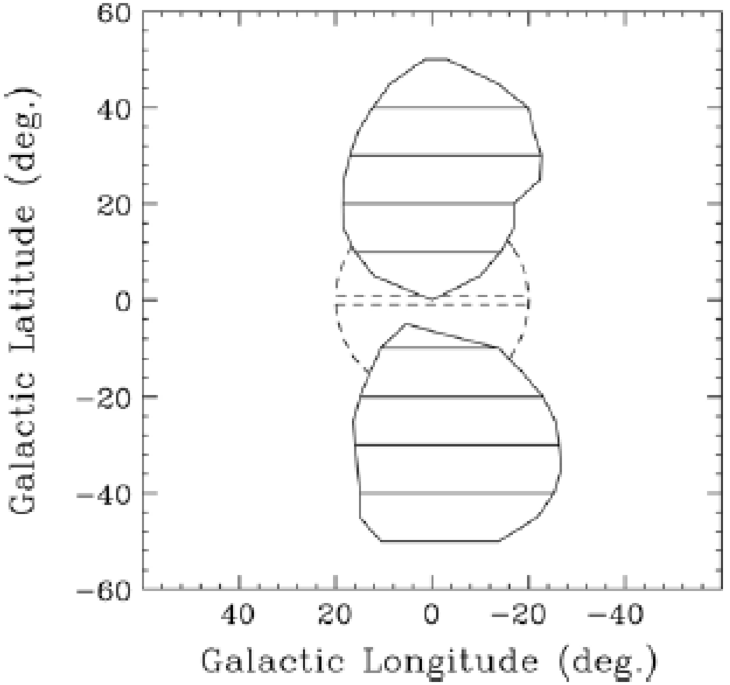


Gordon & Macias (2013)

Spatial distribution: extending to (very) large scale

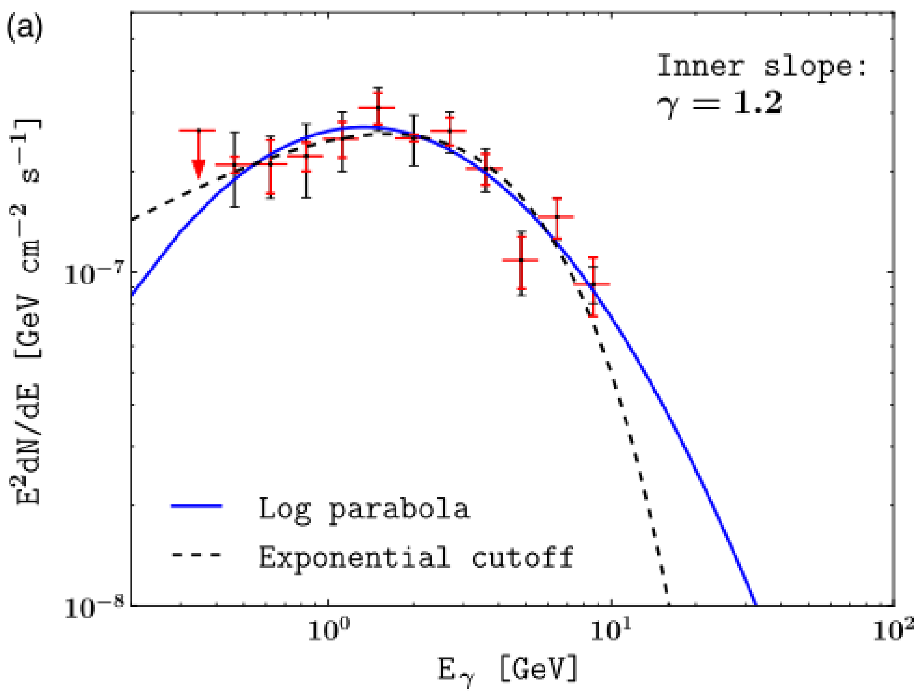


Daylan et al. (2013)

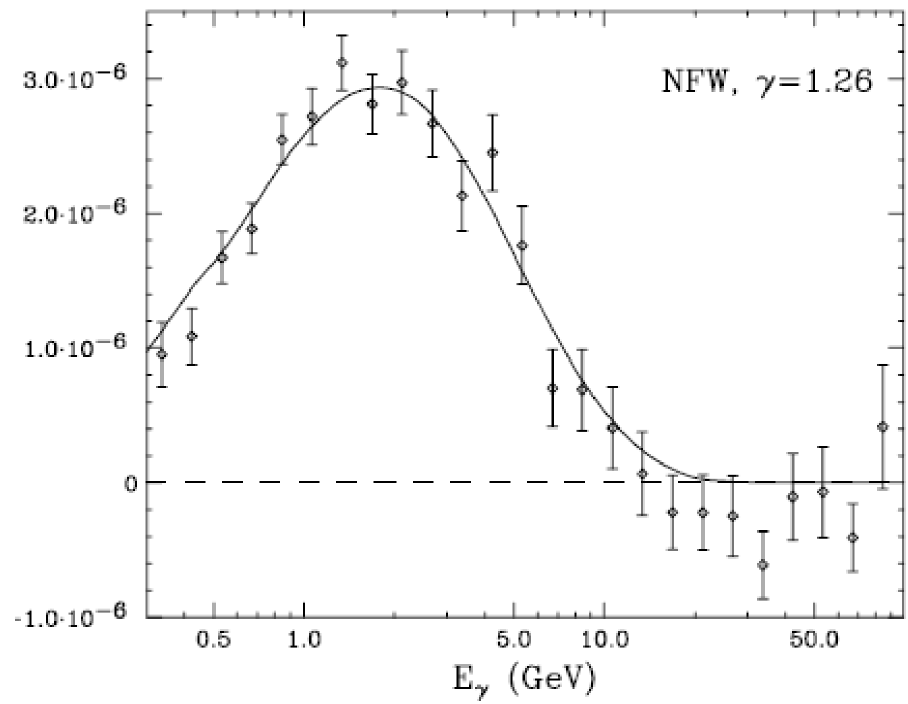


Hooper & Slatyer (2013)

Energy spectrum: peak at 1-3 GeV (power-law exponential cutoff; log-parabola)

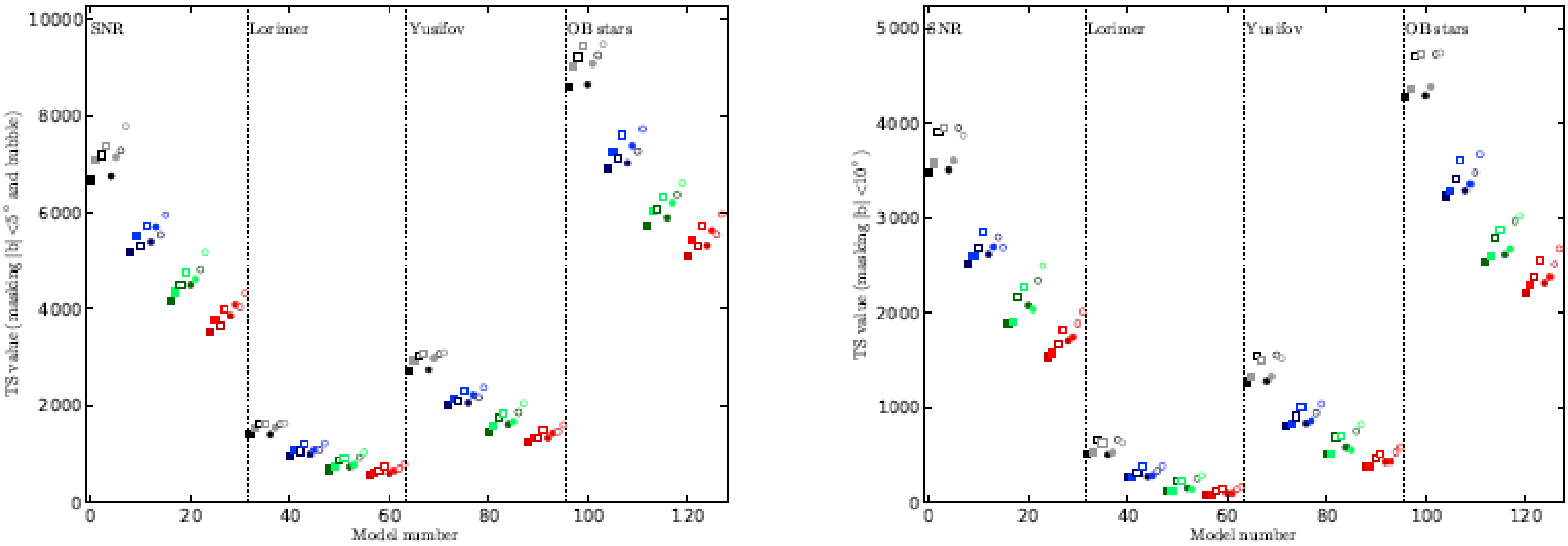


Galactic center
Gordon & Macias (2013)



Larger scale inner Galaxy
Daylan et al. (2013)

Systematics from diffuse backgrounds



the possible dark-matter-like GeV excess. The minimal TS value for the dark-matter-like excess component is ≈ 663 (568 excluding regions of Fermi Bubbles) in the region of $|b| > 5°$, and ≈ 82 in the region of $|b| > 10°$, suggesting that the excess is indeed statistically significant. The prospect of

Zhou et al. (2014)

Summary of the phenomena

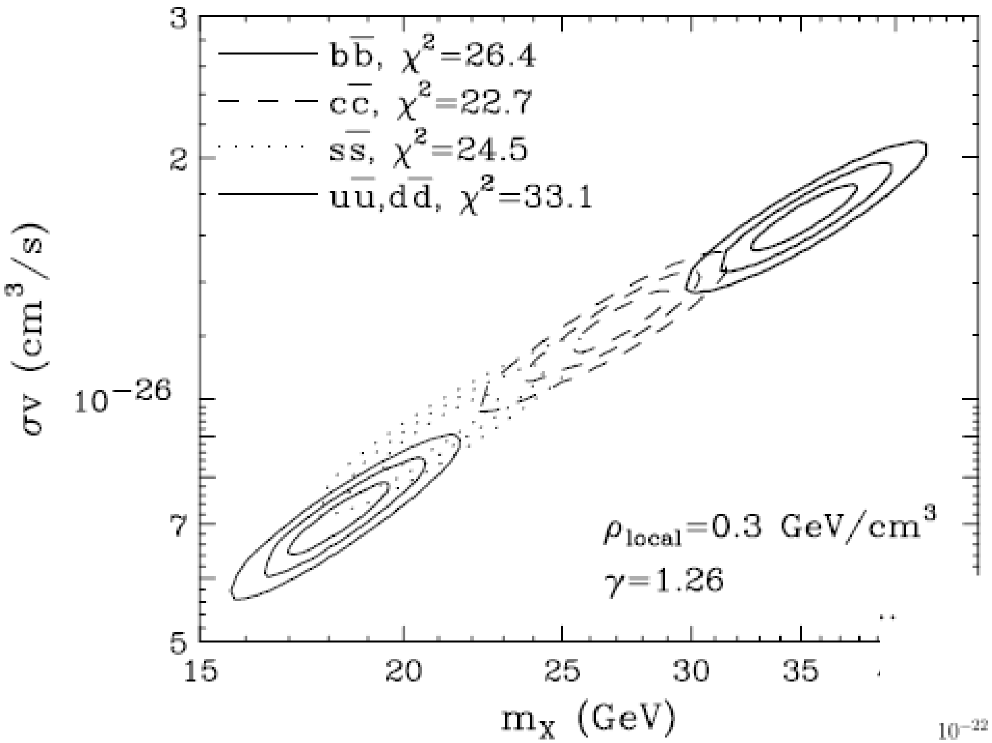
1. Circular gamma-ray excess at Galactic center with projected profile $r^{-1.4}$ (generalized NFW^2)

2. Spectrum peaks at 1-3 GeV, in good agreement with 30-40 GeV dark matter annihilation

3. Normalization to the signal corresponds to a dark matter annihilation cross section ~1e-26 cm^3/s

Amazing for DM annihilation signal!

Scenario 1: dark matter annihilation

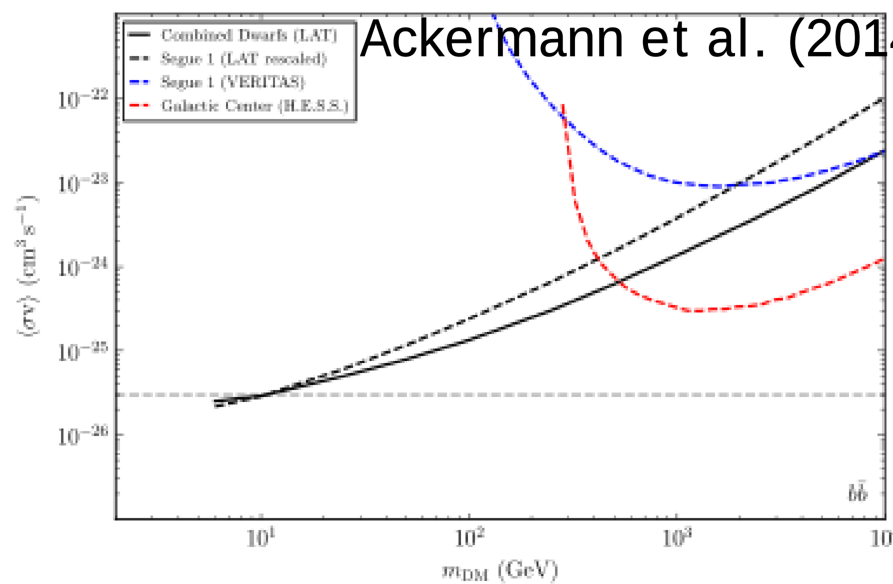


Daylan et al. (2014)

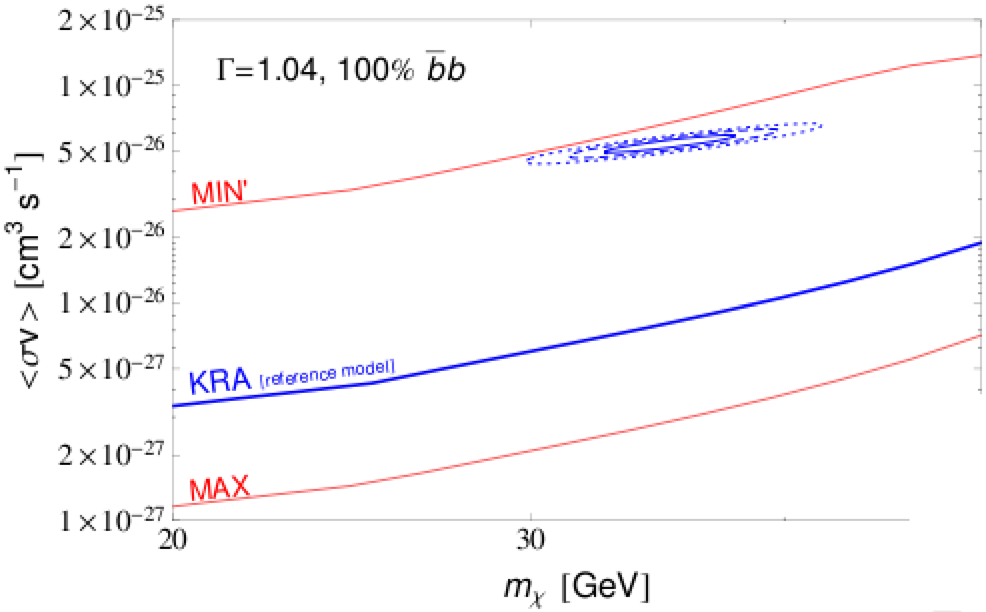
Prasad+13; Hagiwara+14;
Agrawal+14; Cerdene+14;
Abdullah+14; Ghosh+14;
Basak+14; Boehm+14;
Han+14;Berlin+14; ...

PHYSICAL REVIEW D **89,** 042001 (2014)

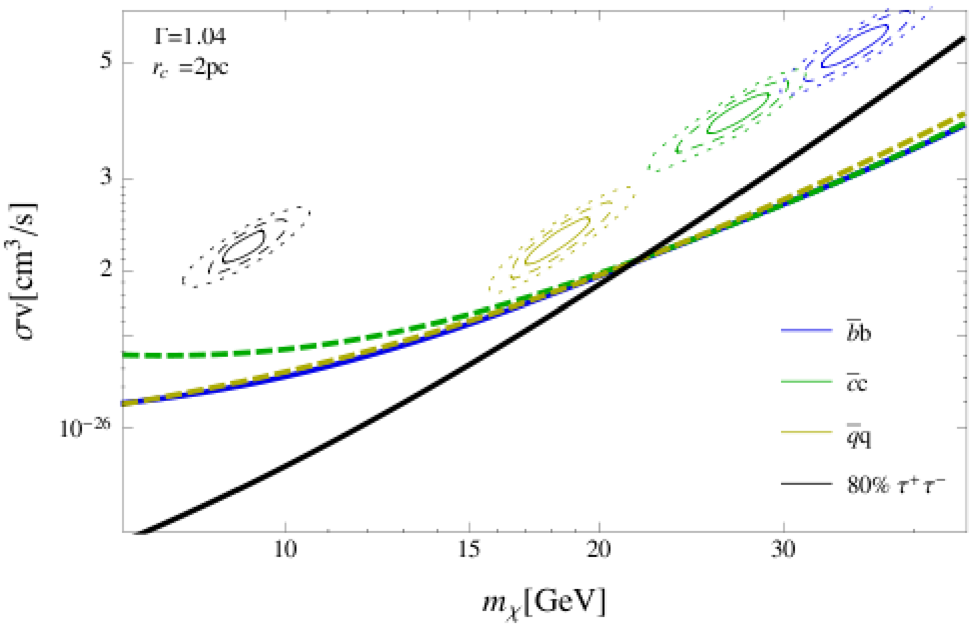
Ackermann et al. (2014)



Updated constraints on dark matter annihilation with cosmic ray and radio data

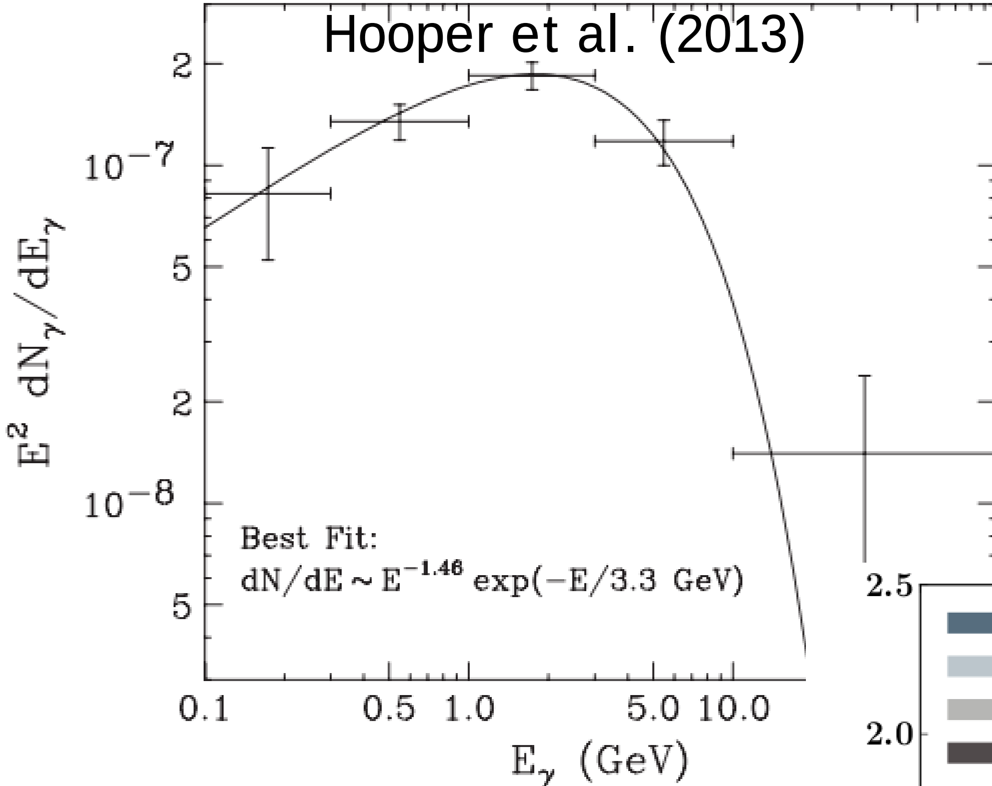


Bringmann et al. (2014)
Cirelli et al. (2014)



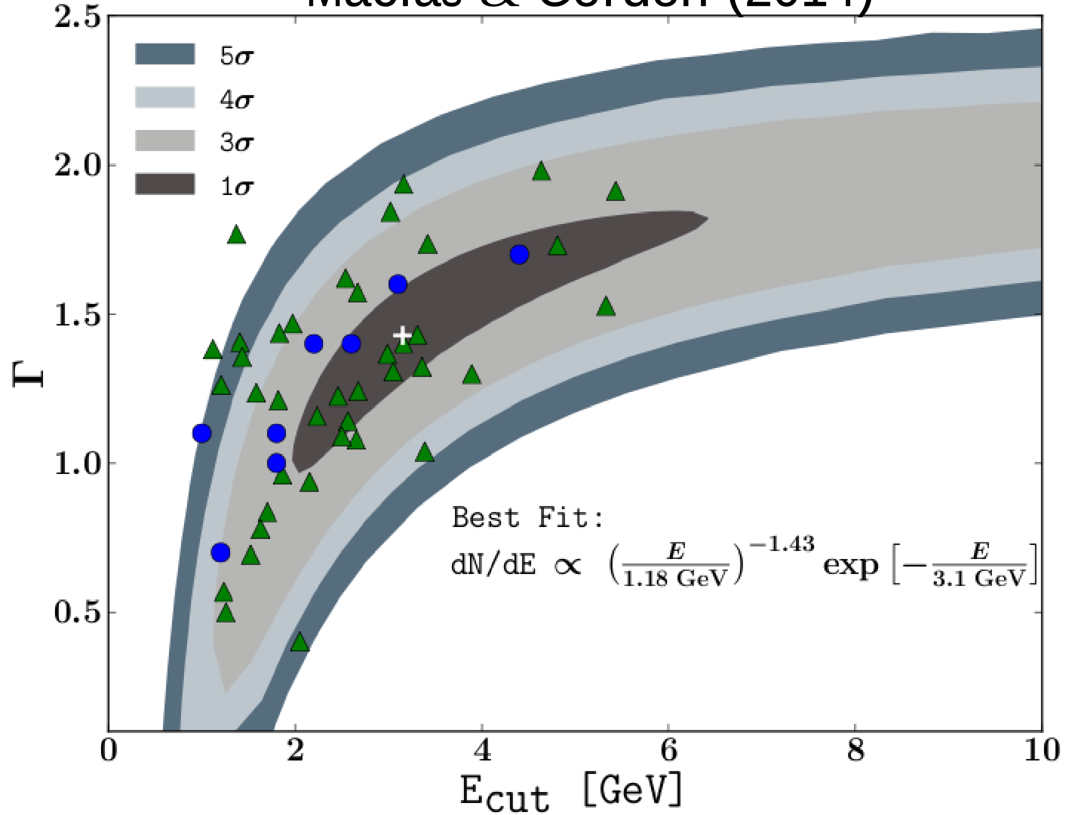
Uncertainties:
- propagation model
- DM density profile

Hooper et al. (2013)



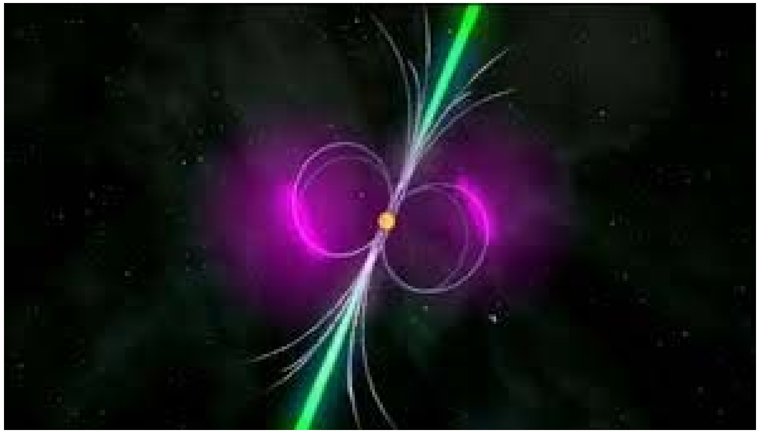
Scenario 2: millisecond pulsars (MSPs) in the bulge

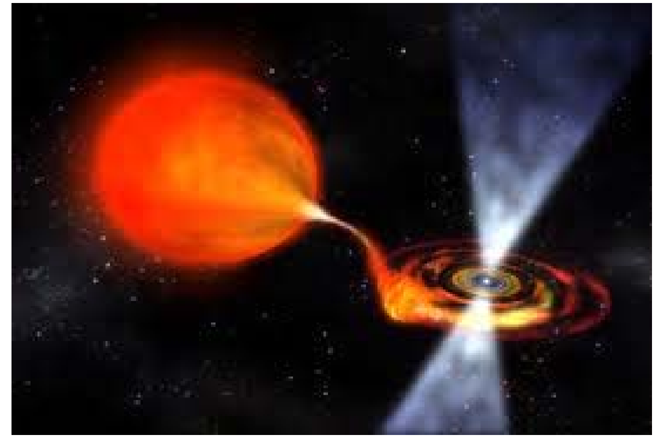
Macias & Gordon (2014)



Number of MSPs: ~1000
Fermi average MSPs

Why Millisecond pulsars?





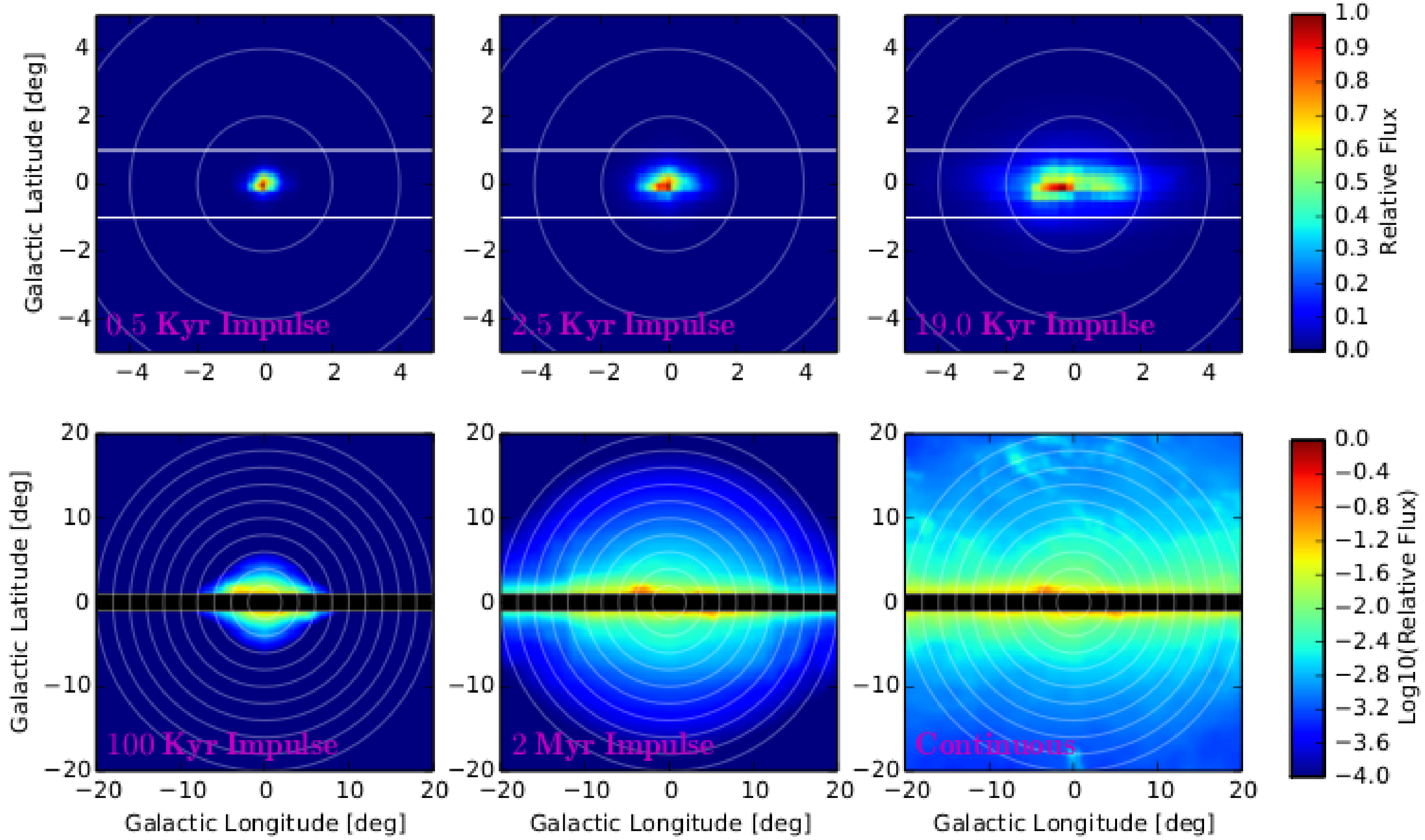
1. MSPs (mostly in binary system) have much smaller kick velocity, could be concentrated in the bulge

2. Some of MSPs are formed by stellar encounter, they can be even more concentrated in the very center

3. MSPs are long-aged (billion yrs), they can extend to large scales although the kick velocity is small

Scenario 3: cosmic ray interactions

Calson & Profumo (2014)
Petrovic et al. (2014)



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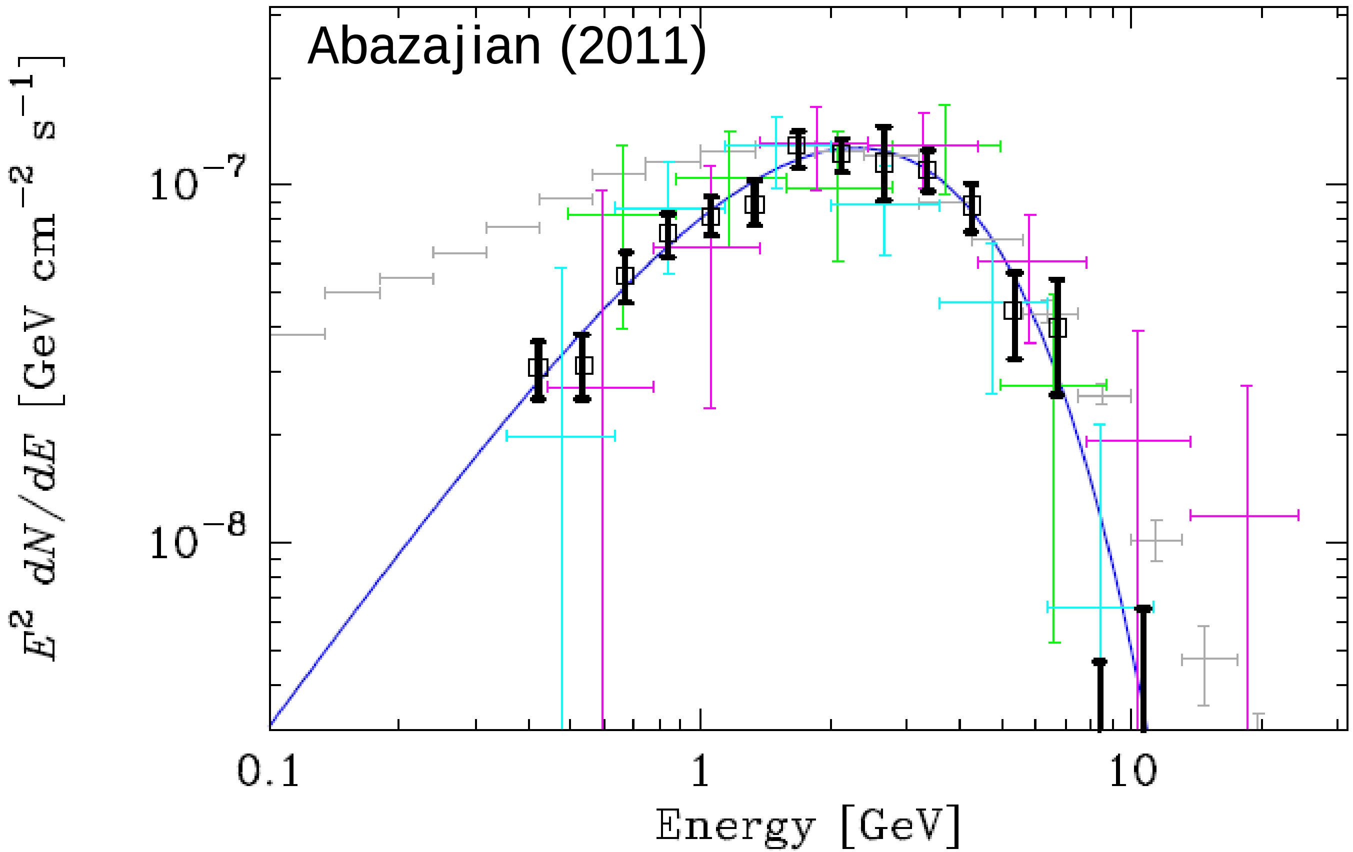
First look of MSP scenario

Hooper & Linden (2011)
Abazajian (2011)
Mirabal (2013)
Gordon & Macias (2013)



NO, MSP cannot!

PHYSICAL REVIEW D **88**, 083009 (2013)

Millisecond pulsars cannot account for the inner Galaxy's GeV excess

Dan Hooper,[1,2] Ilias Cholis,[1] Tim Linden,[3] Jennifer M. Siegal-Gaskins,[4] and Tracy R. Slatyer[5]

NO, NO, MSP can!

Millisecond pulsar interpretation of the Galactic center gamma-ray excess

Qiang Yuan[a,b], Bing Zhang[b]

NO, NO, NO, MSP cannot!

Challenges in Explaining the Galactic Center Gamma-Ray Excess with Millisecond Pulsars

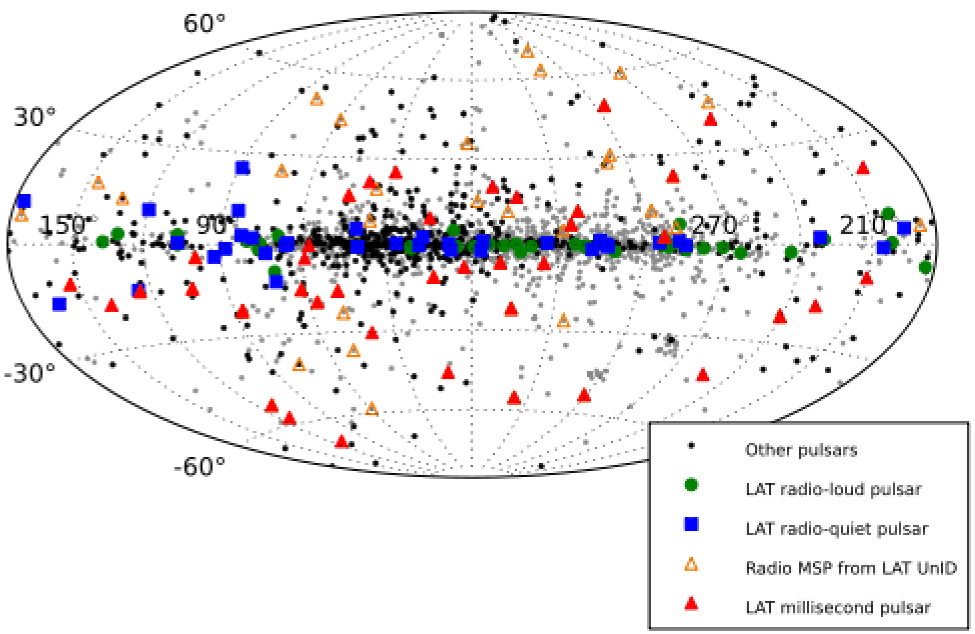
Ilias Cholis,[1] Dan Hooper,[1,2] and Tim Linden[3]

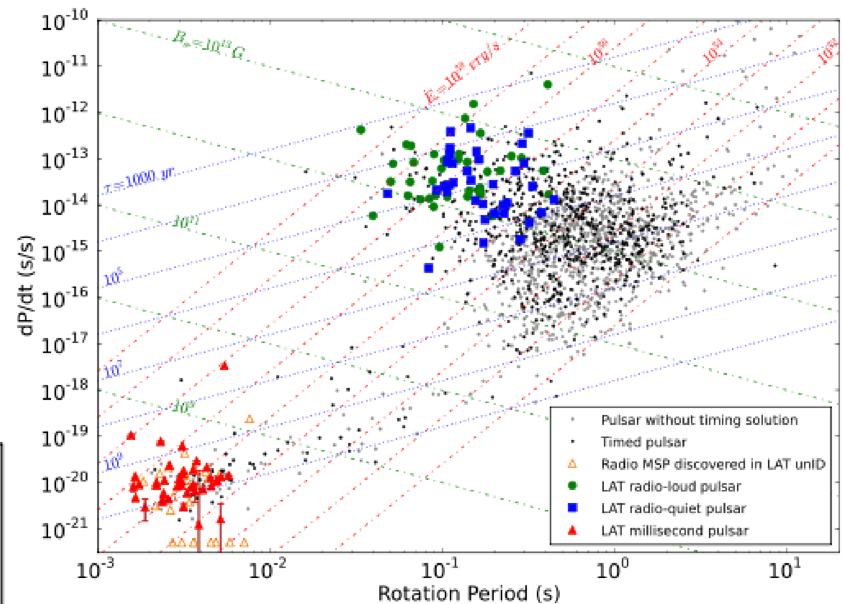
……?

The Astrophysical Journal Supplement Series, 208:17 (59pp), 2013 October doi:10.1088/0067-0049/208/2/17

THE SECOND *FERMI* LARGE AREA TELESCOPE CATALOG OF GAMMA-RAY PULSARS

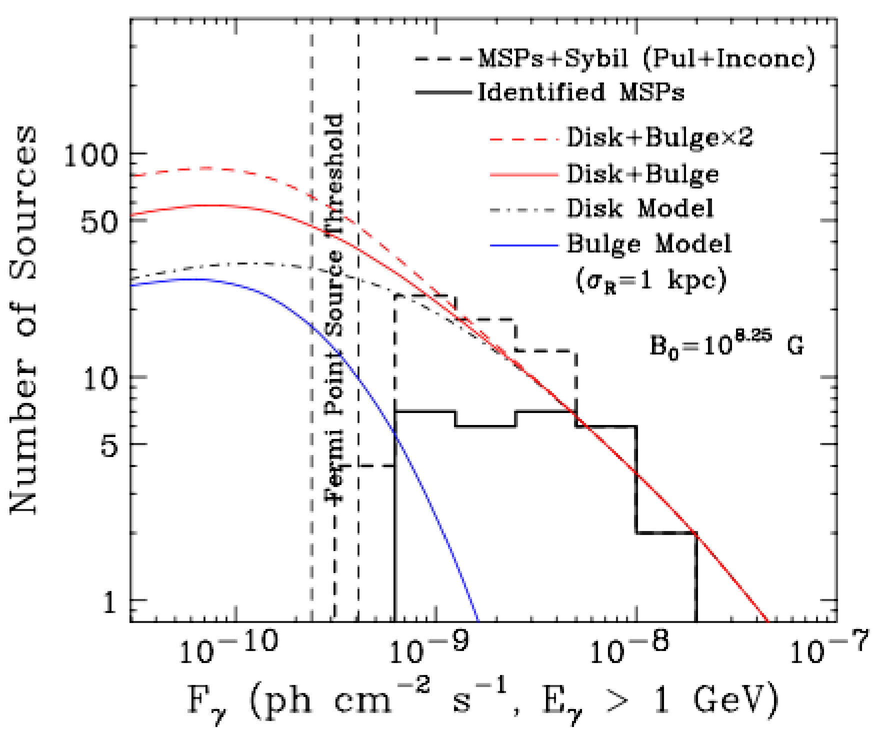
A. A. Abdo[1,88], M. Ajello[2], A. Allafort[3], L. Baldini[4], J. Ballet[5], G. Barbiellini[6,7], M. G. Baring[8], D. Bastieri[9,10], A. Belfiore[11,12,13], R. Bellazzini[14], B. Bhattacharyya[15], E. Bissaldi[16], E. D. Bloom[3], E. Bonamente[17,18], E. Bottacini[3],

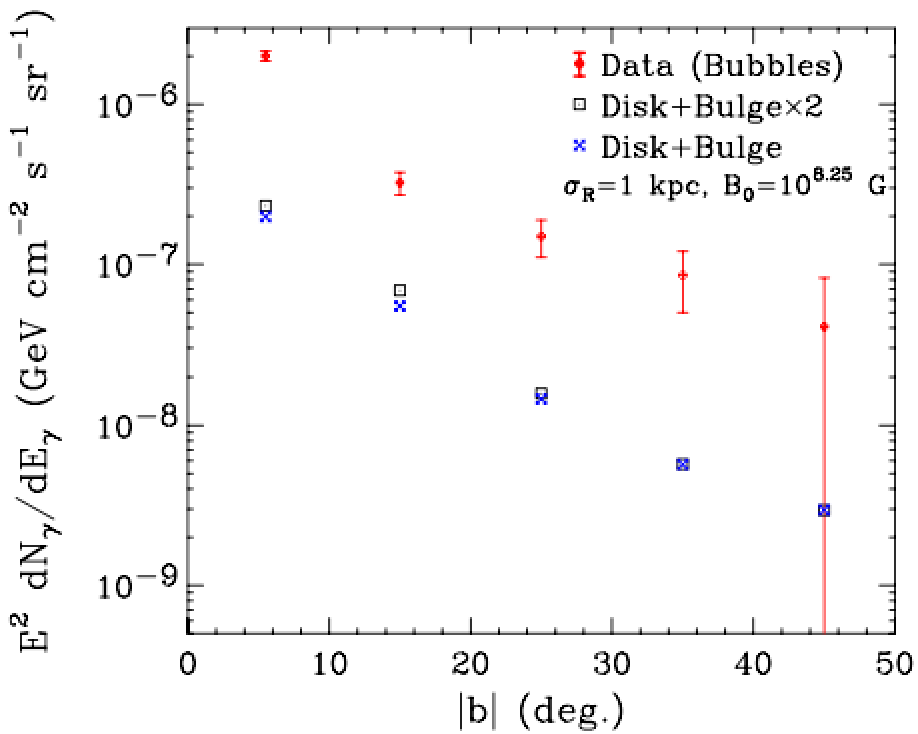




Fermi sample will constrain MSP properties!

Unresolved population is constrained by the detected flux distribution. MSPs can contribute less than ~10% without violating Fermi flux distribution.

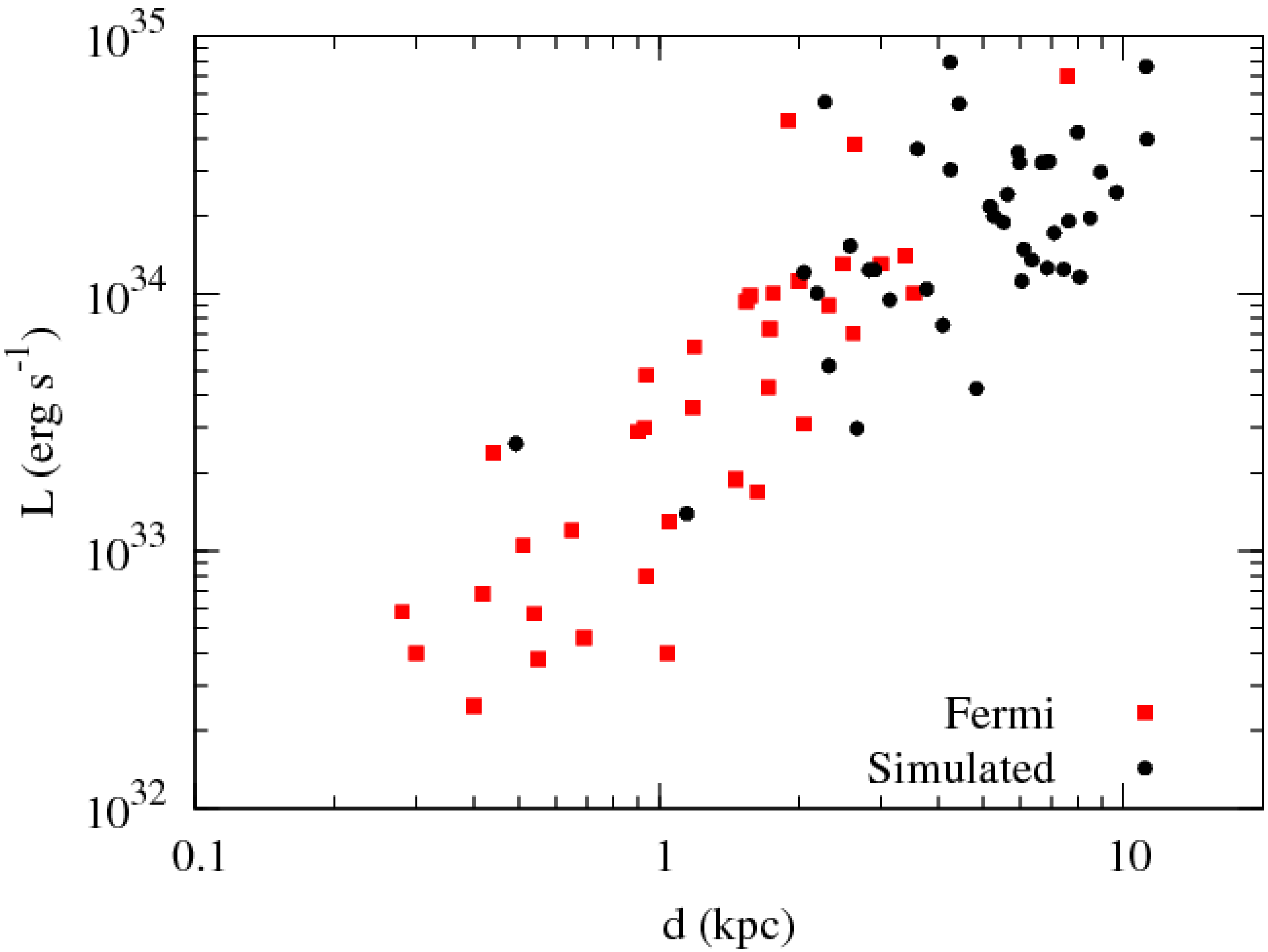




Hooper et al. (2013)

Luminosity function (from dN/dP) $\mathrm{d}N/\mathrm{d}L \propto L^{-3/4}$

$\longrightarrow$ Underestimate low-luminosity and nearby sources

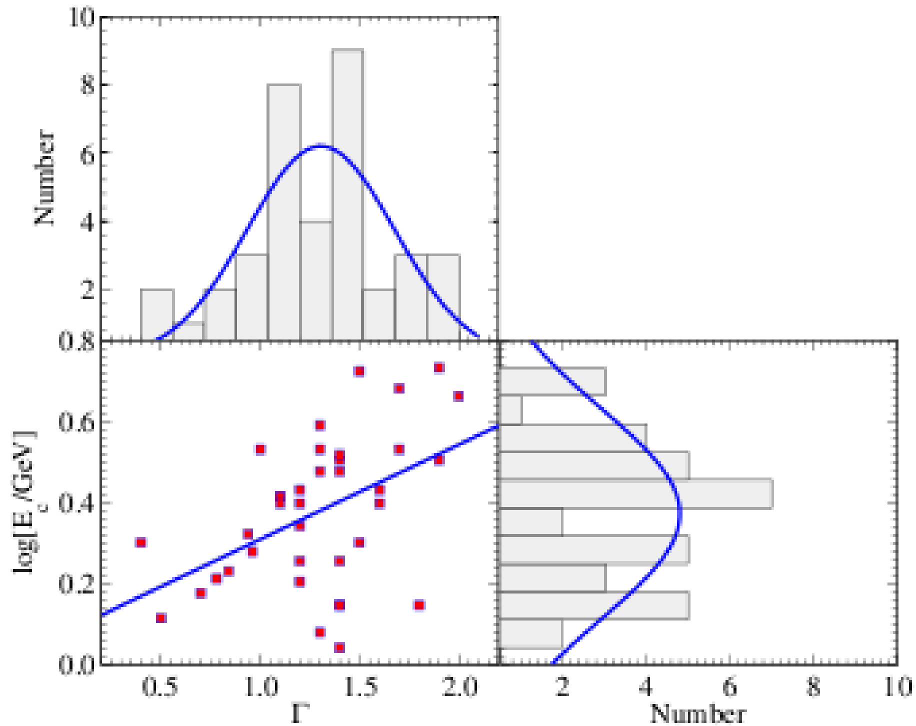


Re-modeling of the disk MSPs

Spatial distribution

$$n(r, z) \propto \exp(-r^2/2\sigma_r^2)\exp(-|z|/\sigma_z),$$

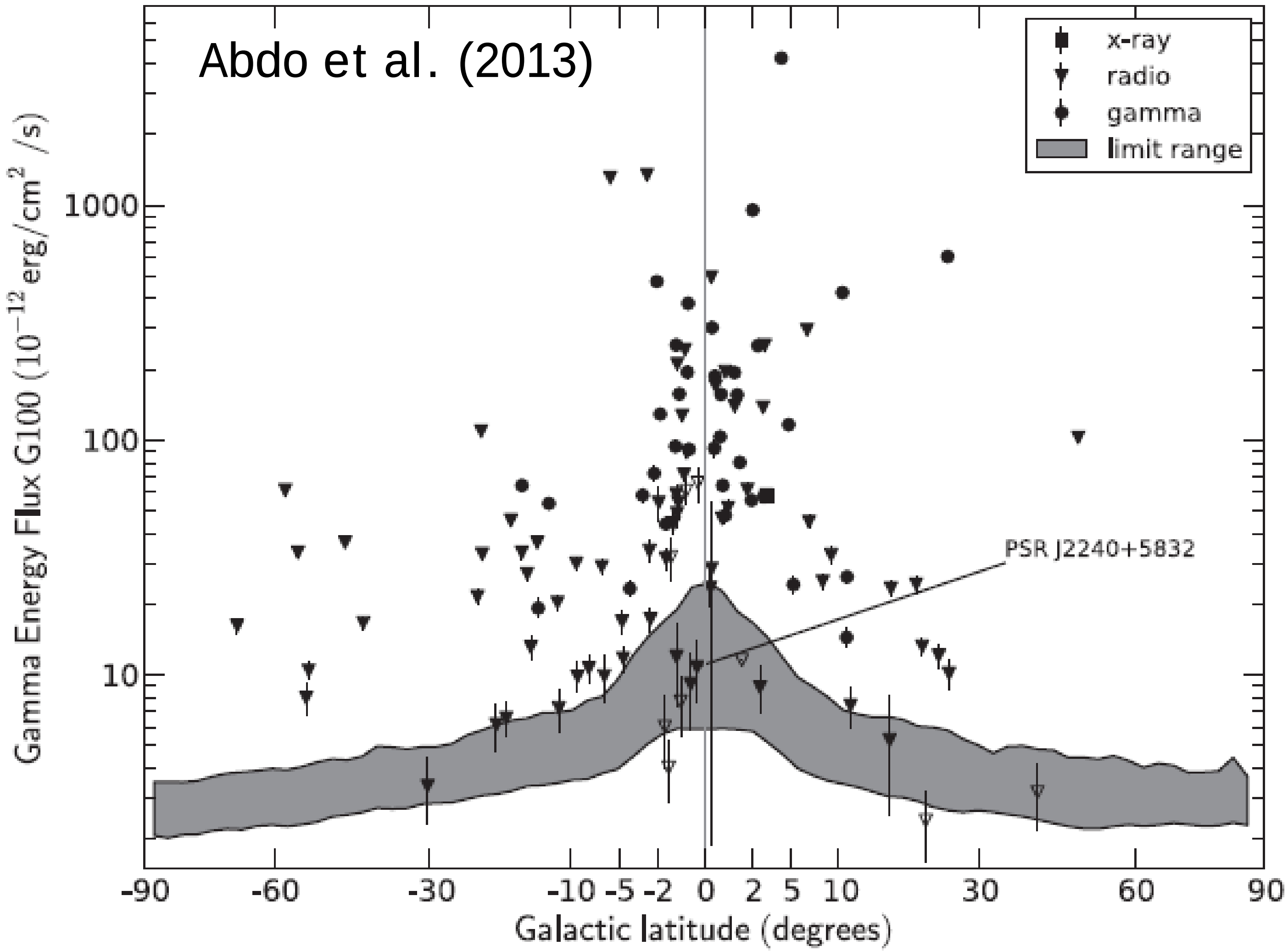
Spectral distribution



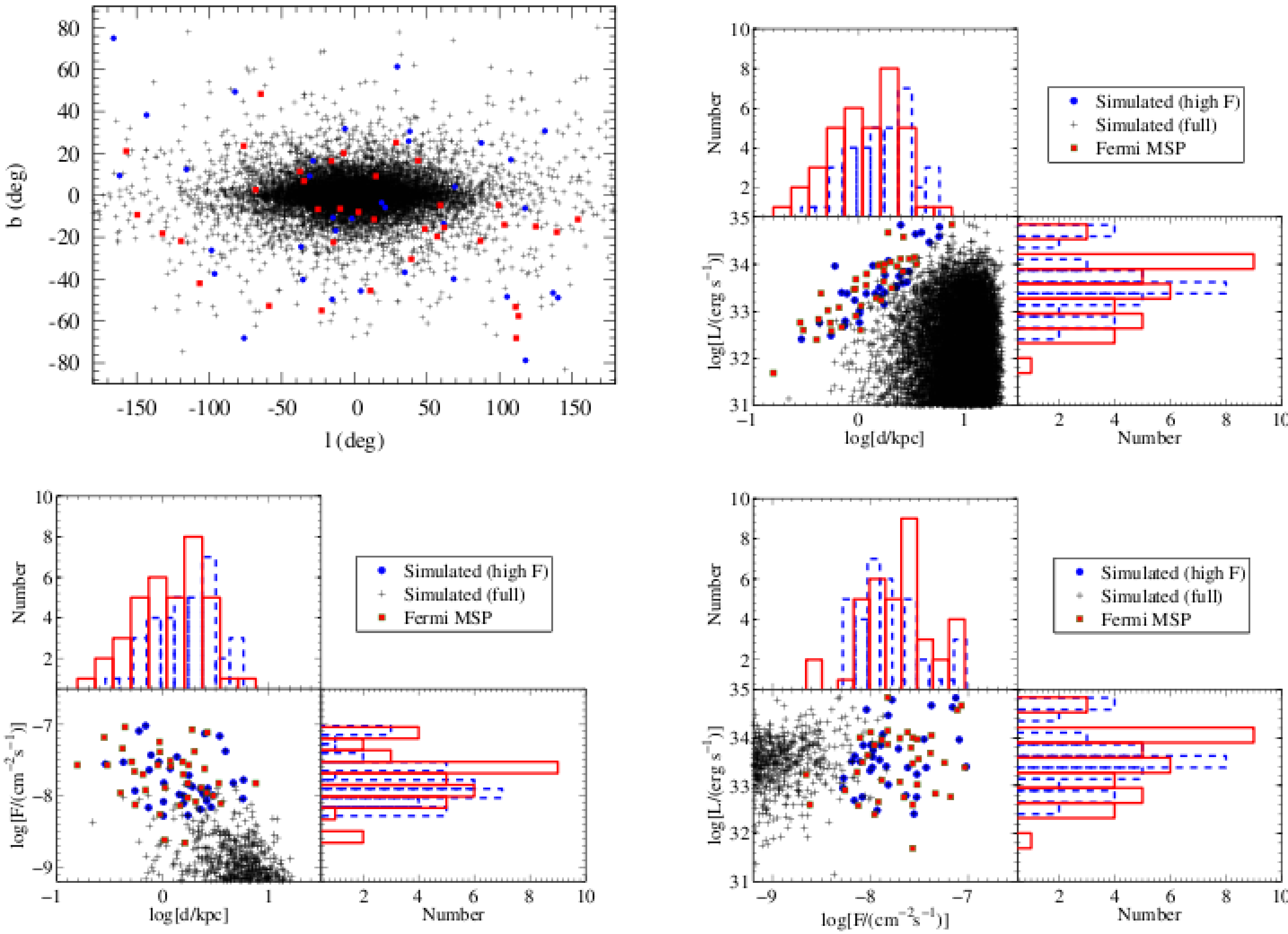
Luminosity function

$$\mathrm{d}N/\mathrm{d}L \propto L^{-\alpha_1}\left[1 + (L/L_{\mathrm{br}})^2\right]^{(\alpha_1-\alpha_2)/2}$$

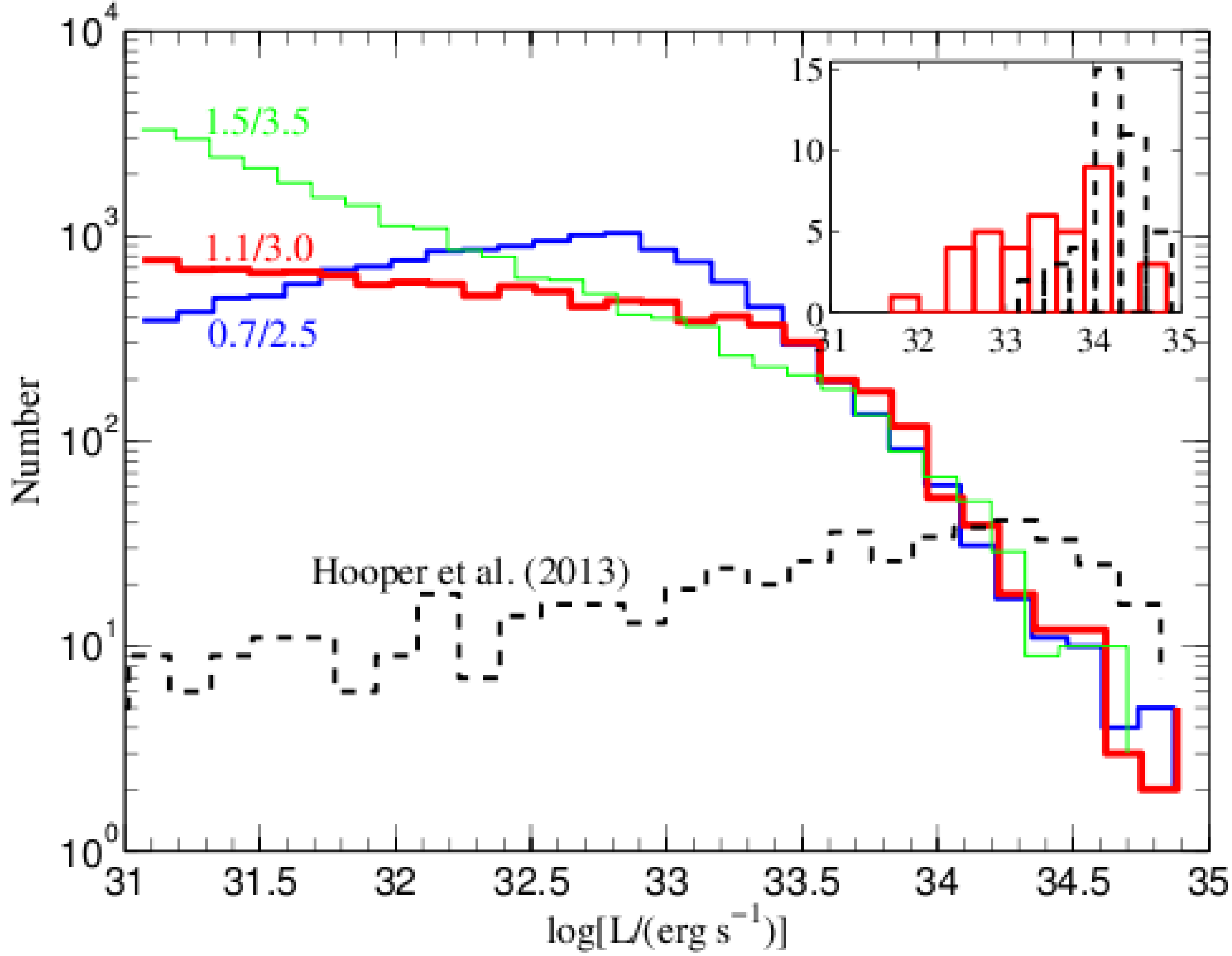
Detection threshold



Reproducing observational properties of MSPs



Luminosity function

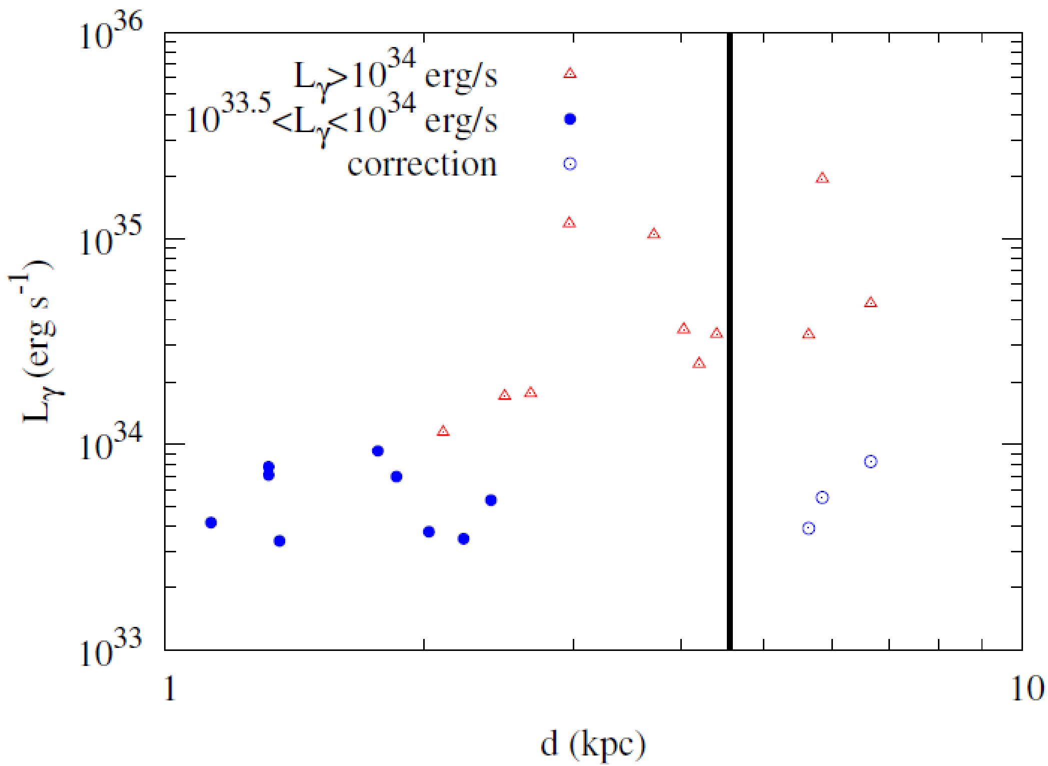


arXiv:1407.5583

A New Determination of the Spectra and Luminosity Function of Gamma-Ray Millisecond Pulsars

Ilias Cholis,[1] Dan Hooper,[1,2] and Tim Linden[3]

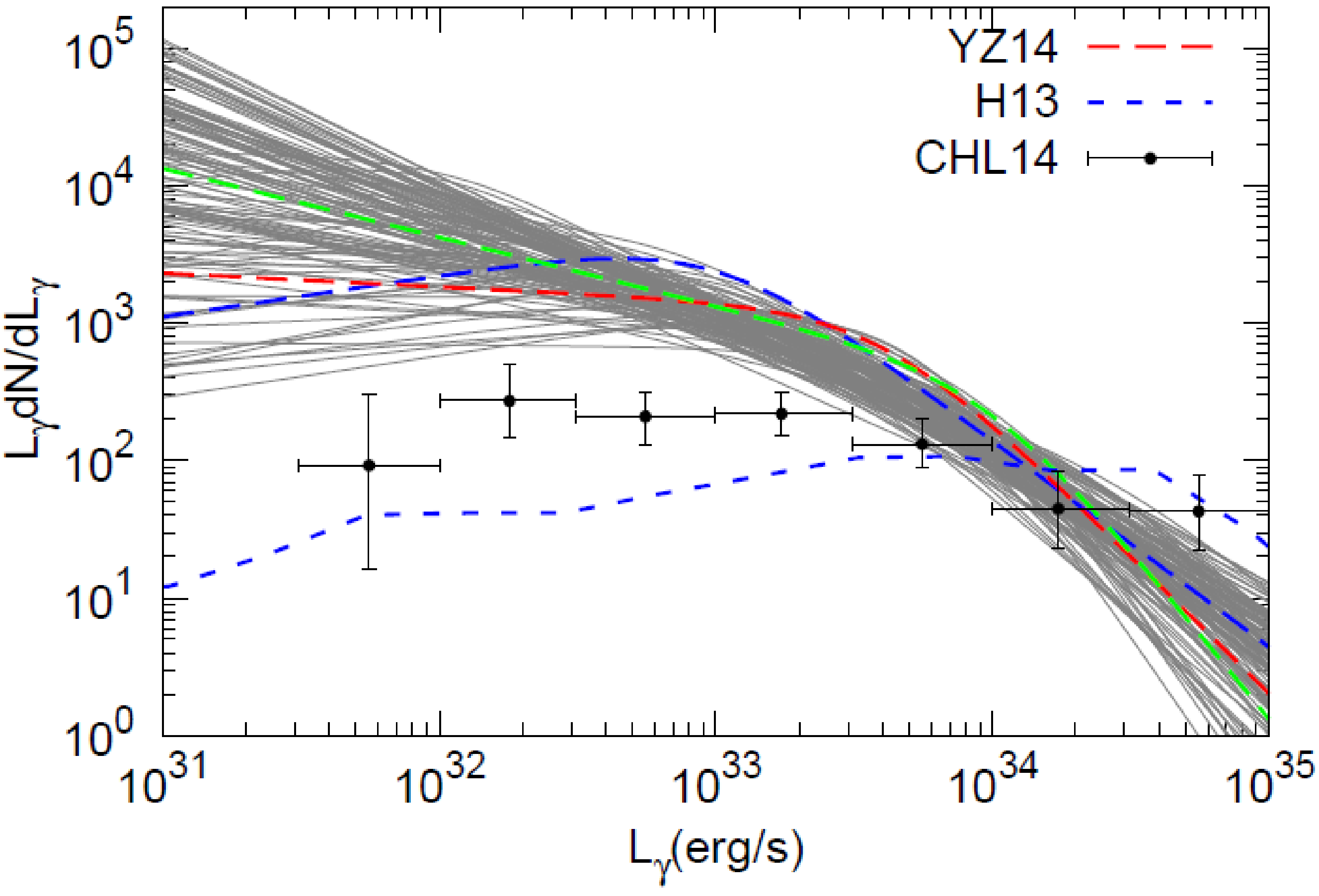
- Assumption: high L (~1e35 erg/s) sample is complete
- Define a horizon r(L) as a function of L for low L MSPs
- Correct number of low L MSPs with fraction: N(tot,>L)/N(<r,>L)



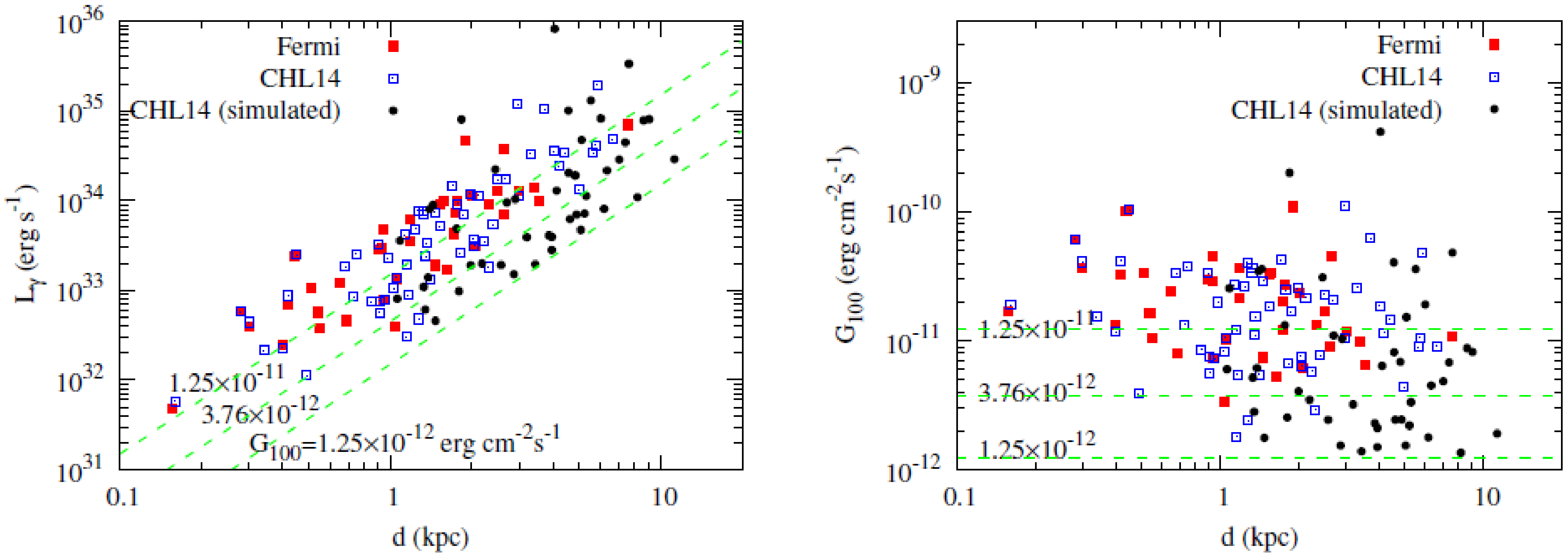
N(blue, true)=N(blue, obs) × N(red, tot)/N(red, left)=12.4

- High L sample is complete(?)
- The correction is absolutely biased!
- Corrected distributions of all L should be the same but obviously not (horizon is not proper)

Comparison of luminosity function



Can a hard luminosity function work?

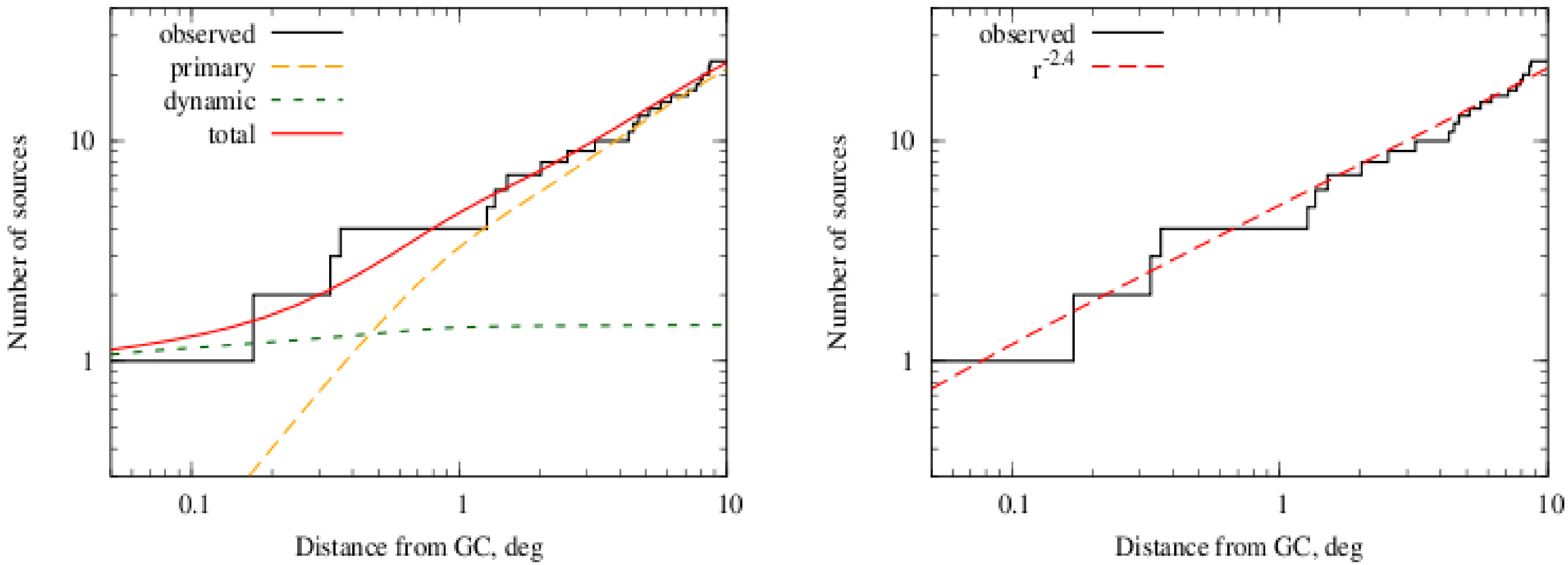


Still under estimate nearby and low luminosity sources: need a softer luminosity function!

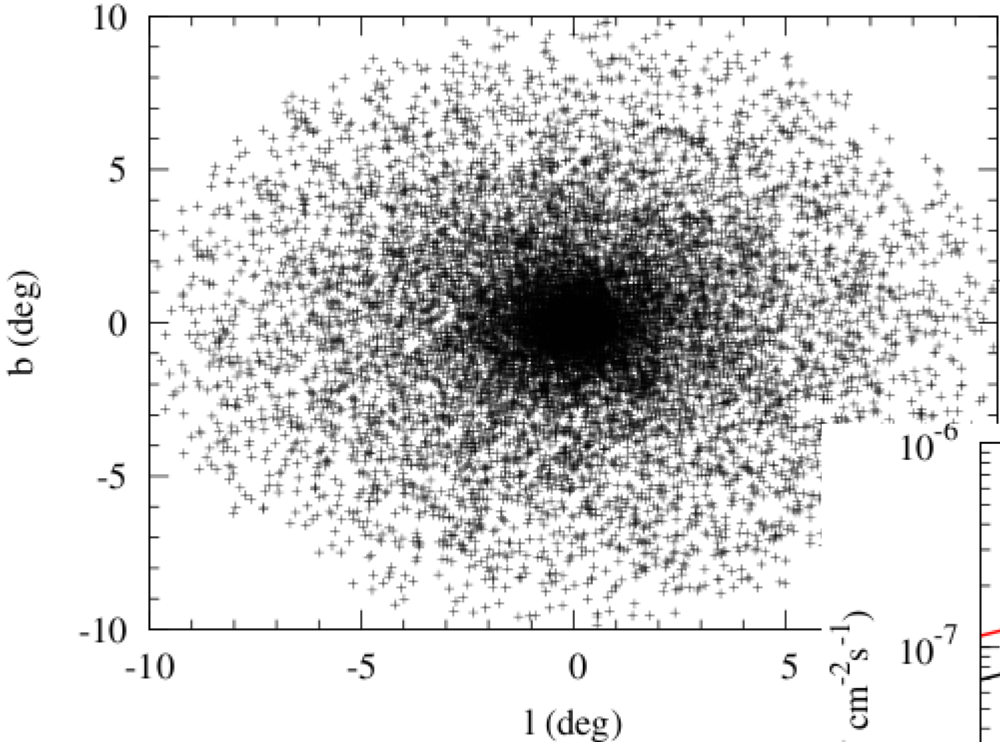
Bulge component of MSPs

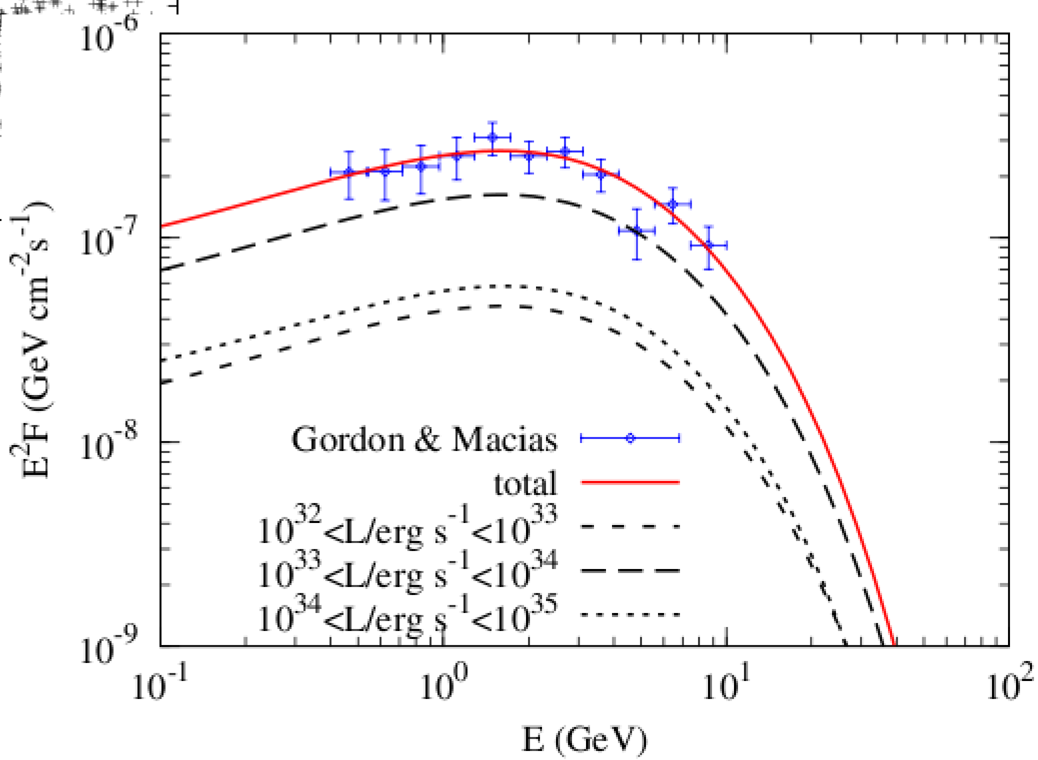
Spectra and luminosity function: same as disk component

Spatial distribution: traced by low-mass X-ray binaries



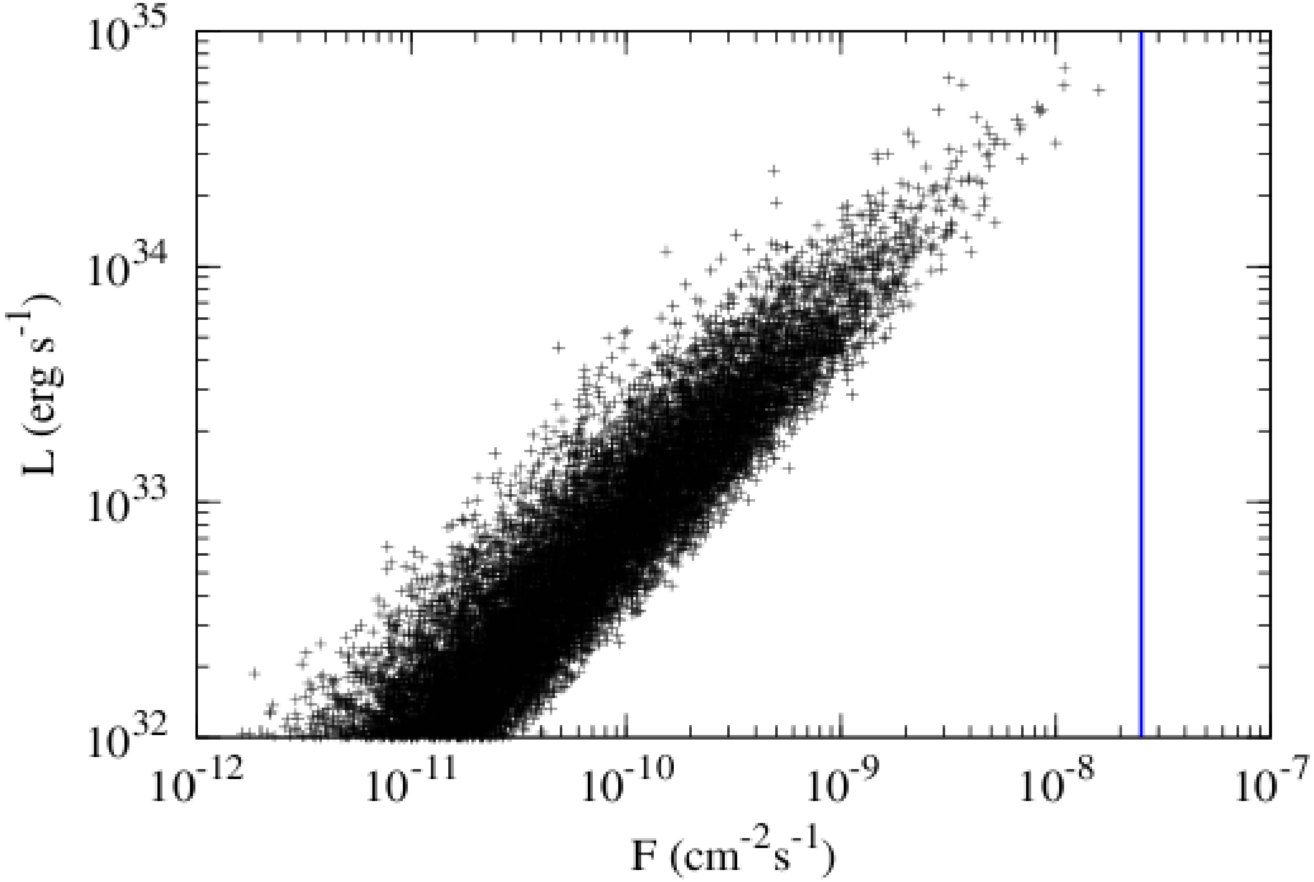
Unresolved contribution of bulge MSPs



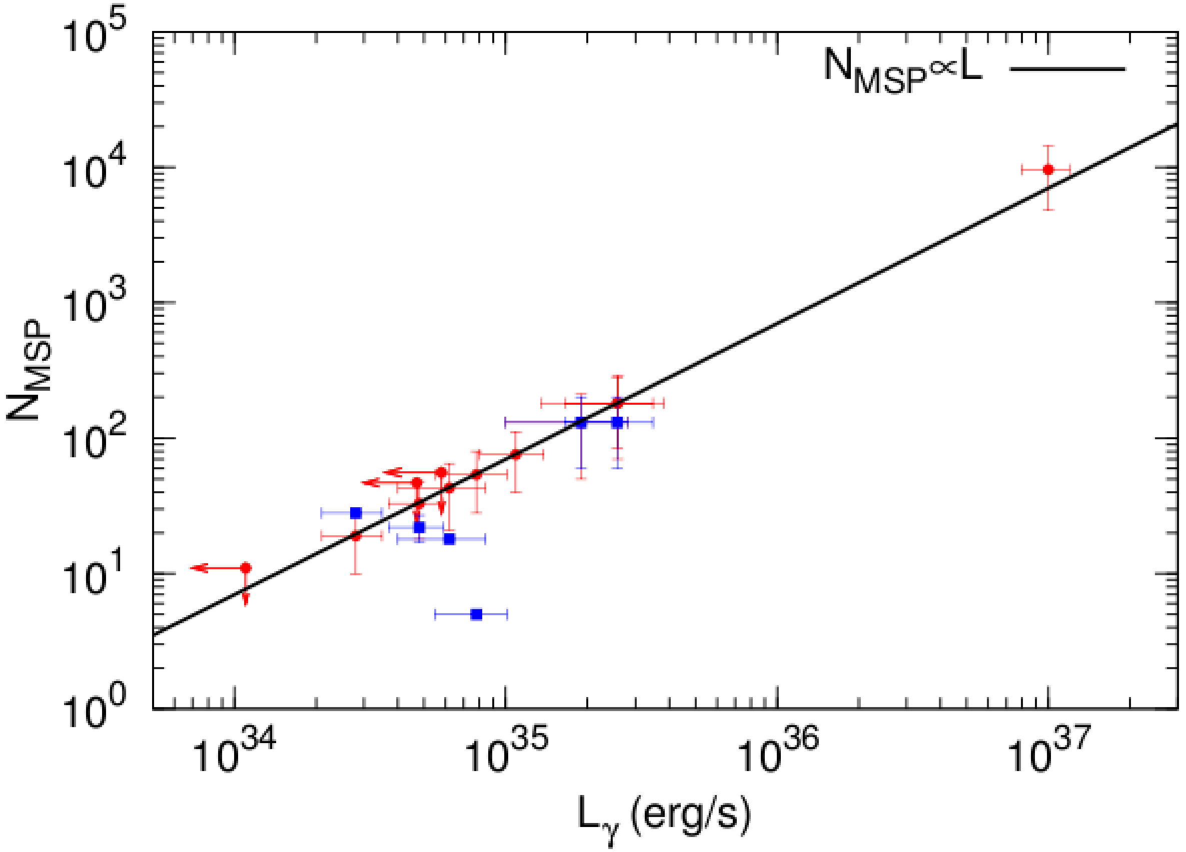


Normalize to gamma-ray excess needs ~10000 MSPs for L>1e32 erg/s

None of the bulge MSPs could be detected as individual sources by Fermi. MSPs can naturally explain the data.



Comparison between globular clusters (GC) and Galactic center (GC)



Conclusion & Discussion

- A population of bulge MSPs can explain the gamma-ray excess, both the morphology and spectrum, without violating Fermi detectable source distribution

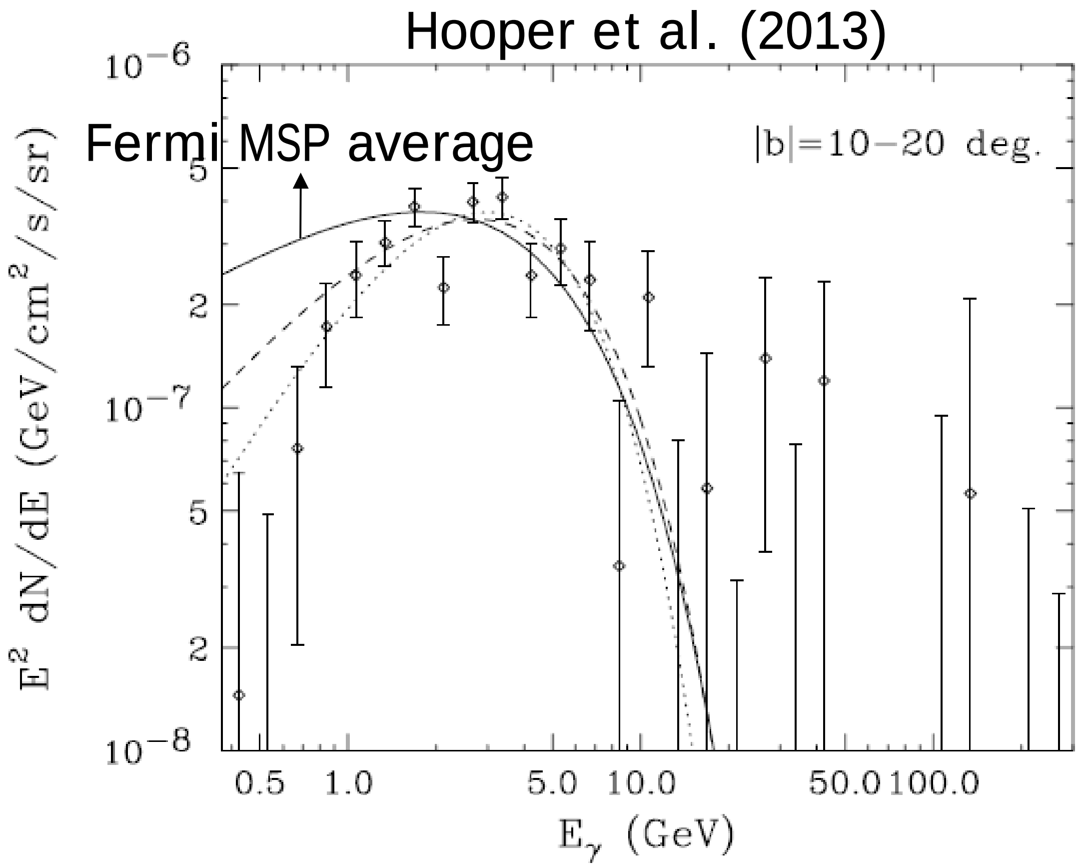
- The MSP component seems definitely existing, its contribution to gamma-rays is guaranteed (stellar evolution to determine the normalization?)

- How to discriminate different scenarios? (multi-wavelength data; energy dependence of morphology; ...)

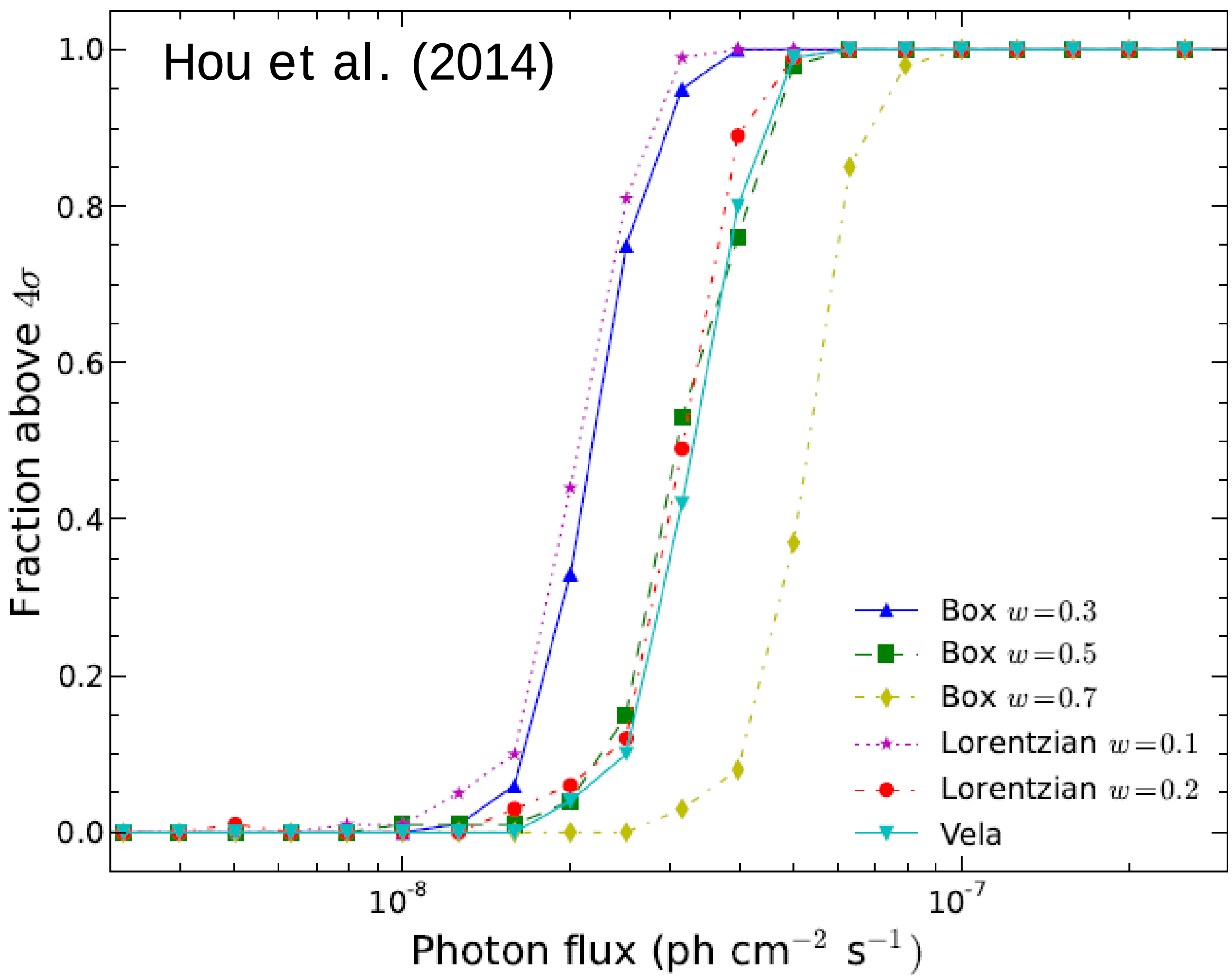
ありがとう

谢谢

Harder spectrum at large scales

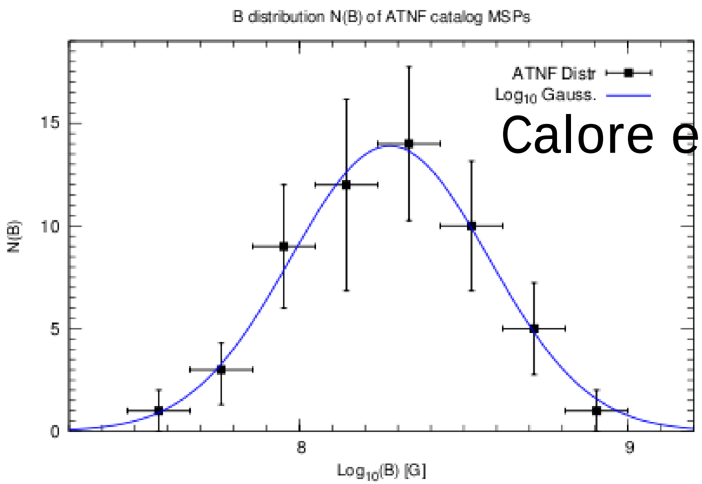


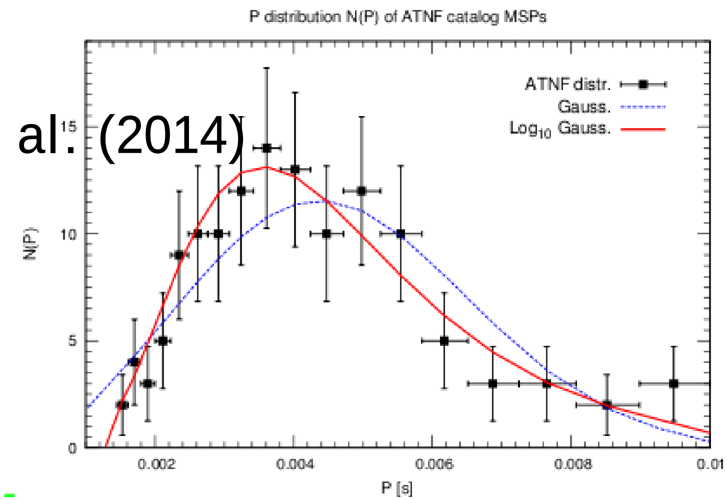
More precise detection threshold of pulsars

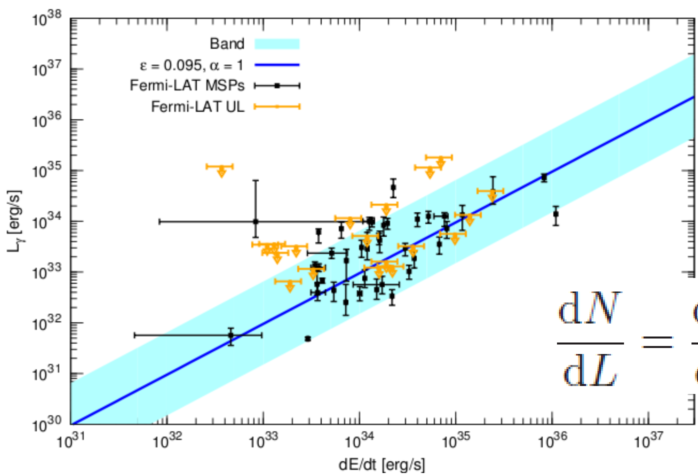


Understanding the luminosity function

Calore et al. (2014)







$$\frac{\mathrm{d}N}{\mathrm{d}L} = \frac{\mathrm{d}N}{\mathrm{d}P} \cdot \frac{\mathrm{d}P}{\mathrm{d}\dot{E}} \cdot \frac{\mathrm{d}\dot{E}}{\mathrm{d}L}$$