# On millisecond pulsar: a closer look to a possible bulge population

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# The Fermi γ-ray galactic center excess

An excess at the galactic center (GC) at GeV energies is observed in Fermi-LAT data (Hooper&Goodenough 2009, Vitale&Morselli 2009, Hooper&Goodenough 2014, Hooper&Linedn 2011, Abazajian&Kaplinghat 2012, Gordon&Macias 2013, Macias&Gordon 2014, Abazajian et al. 2014, Dylan et al. 2014, Zhou at al. 2014, Calore et al. 2015, Fermi-LAT Coll. 2015)

The excess is likely to be caused by significant emission from the GC and galactic bulge, roughly spherical morphology and is resilient to background systematics (Calore, Cholis, Weniger 2015)

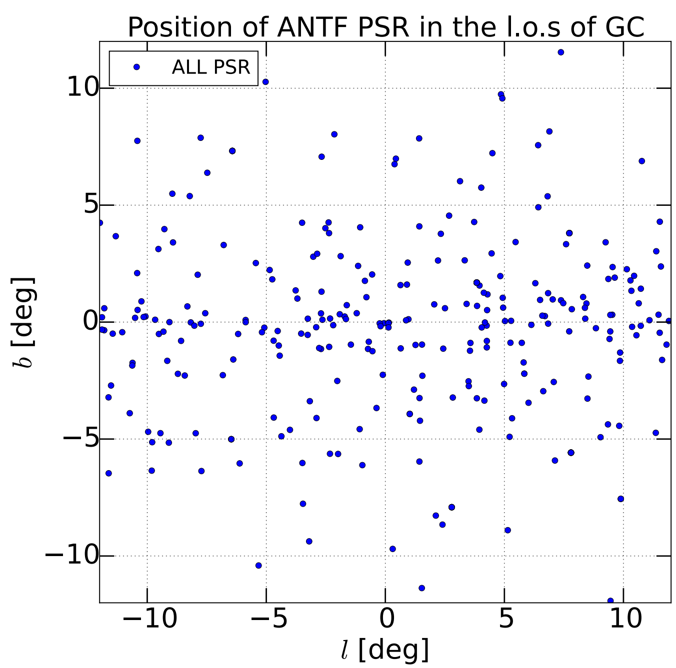
Among many possible explanations, there are **point sources** (Bartels, Krishnamurty & Weniger 2015; Lee, Lisanti, Safdi, Slatyer, Xue 2015) just below the Fermi-LAT threshold, and in particular **millisecond pulsars (MSP)** (Abazajian 2011, Abazajian et al. 2014, Gordon&Macias 2013, Yuan&Zhang 2014)

For all the details: many talks
(Hooper, Linden, Calore, Malishev, Murgia, Gaggero; O'Leary)

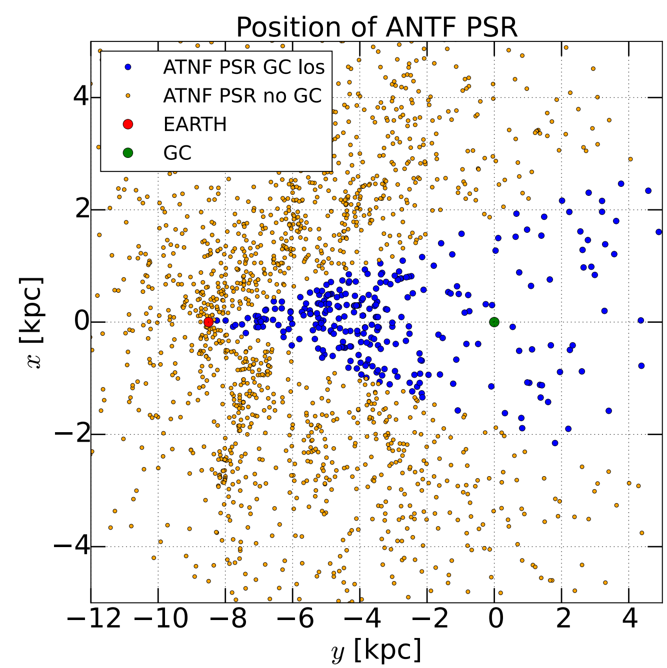
# The millisecond pulsar (MSP) interpretation of the GC excess

F. Calore, M. Di Mauro, F. Donato, J. Hessels, C. Weniger, very soon

## The inner Galaxy pulsars (PSR) in the ATNF catalog




View integrated along l.o.s.
**331 PSR** with |b|<12°, |l|<12°




Projection onto the galactic plane
Blue: 2°<|b|<12°, |l|<12° (left panel)
**38 PSR** are found in the inner 2 kpc

# MILLISECOND PULSARS: few generalities

Fast rotating neutron stars with small spinning period:
**$P_{MSP}$ < 10–30 ms** (while $P_{PSR}$~0.5s)

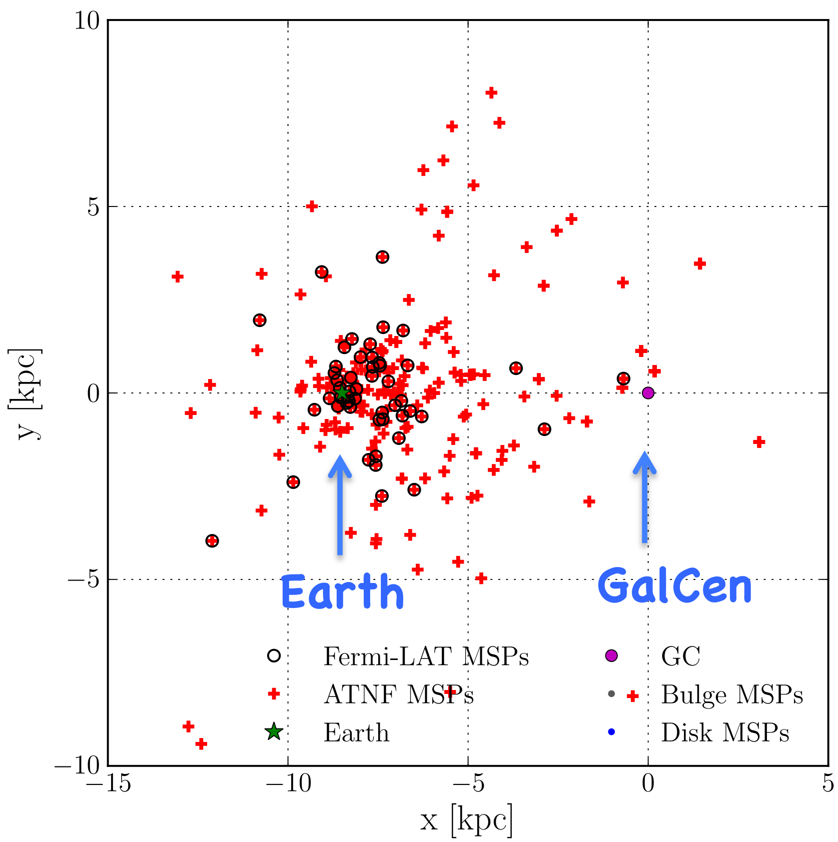
Mostly in binary systems. The companion star transfers mass to the PSR, decreasing its magnetic field ($<10^9$ G) and increasing its angular momentum. Period is slowing down at **$dP_{MSP}/dt \sim 10^{-19}$ s** (wrt $dP_{PSR}/dt \sim 10^{-15}$ s)

Can survives even up to **$10^{10}$ years**, so they can be found at higher latitudes than ordinary PSR

Mostly found in **globular clusters**

They can be **numerous** at the galactic center, due to both enhanced stellar densities (easier to end up into binary systems) and disruption of globular clusters – talk by Brandt (Thursday)

# The MSP in the ATNF radio catalog



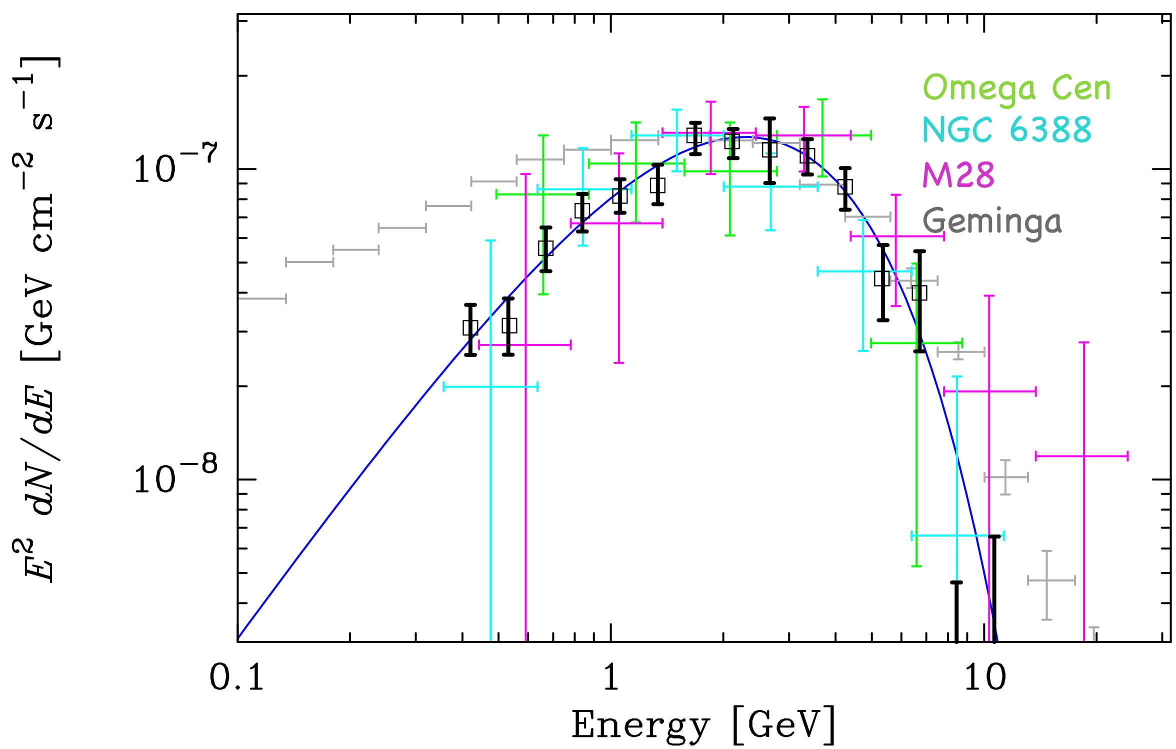

- ✓ 362 MSP are detected at radio wavelengths
- ✓ 233 are field MSPs in the Galactic disk
- ✓ 129 are associated to 28 GLOBULAR CLUSTERS
- ✓ Clustering on 3-4 kpc around the Earth
- ✓ Only few sources in the inner 2 kpc

About 70 MSP were discovered in radio follow-ups pointing at Fermi-LAT unassociated sources

Talk by Eatough

# The gamma-ray energy spectrum of MSP and the GC excess

Abazajian 2011

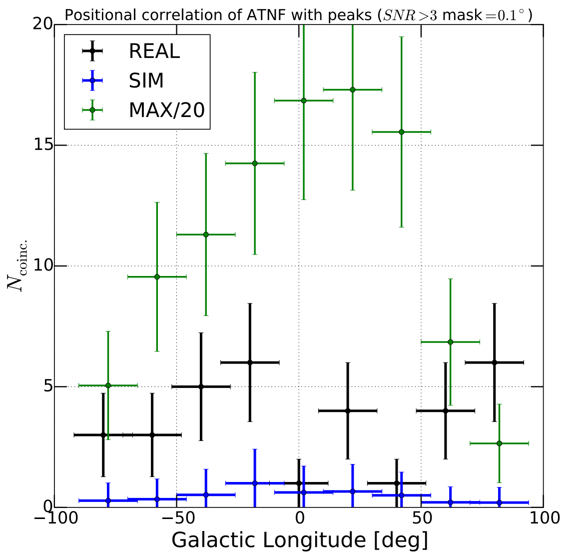


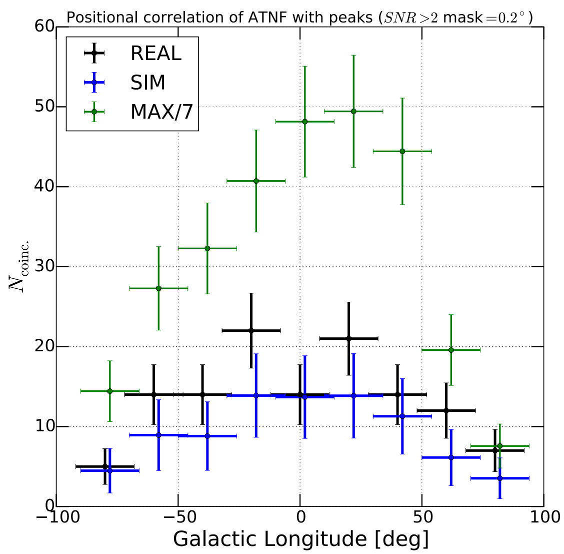

The galactic center excess spectrum (Hooper&Goodenough PLB 2011)
is consistent with emission from Globular Clusters

(see also Cholis, Hooper, Linden PRD 2014)

# Spatial correlation between wavelet analysis (Bartels, Krishnamurty & Weniger 2015) and ATNF sources

## See Bartels Talk today




REAL = number of coincidences between the peaks found with the wavelet analysis and the ATNF PSRs

SIM = number of coincidences between a simulated Isotropic distribution of sources and the ATNF PSRs

MAX = number of maximal correlations: 100% of the Wavelet peaks are correlated with ATNF PSRs

SNR is ~ peak statistical significance, and the correlation is found in angles of 0.1° or 0.2°.

**Lack of a significant spatial correlation between wavelet peaks and ATNF PSRs ➔ the gamma-ray seeds interpretation as sources in the GC is not invalidated**

# Bulge MSP population: radio detection

## We estimate the number of radio MSPs of the bulge population required to explain the GC excess

- Number density of the MSP bulge population follows the GC excess as in Calore, Cholis, Weniger 2015:

$$\propto r^{-\Gamma} e^{-r/R_{\rm cut}} \qquad \Gamma = 2.5 \qquad R_{\rm cut} = 3\,{\rm kpc}$$

- Energy spectrum (McCann 2015):

$$dN/dE \propto e^{-E/E_{\rm cut}} E^{-\gamma} \qquad E_{\rm cut} = \; 3.60 \pm 0.21\,{\rm GeV} \text{ and } \gamma = 1.46 \pm 0.05$$

- Total gamma luminosity: $L_\gamma^{\rm bulge} \simeq (2.7 \pm 0.5) \times 10^{37}\,{\rm erg\,s^{-1}}$

- HYP 1: The MSPs in the bulge and in **globular clusters** have the same gamma ray and radio emission properties

- HYP 2: All the gamma-ray emission from **globular clusters** comes from MSPs

# Number of radio MSPs in the galactic bulge

1. The number of radio MSPs in **globular clusters** is estimated from radio luminosity function (Bagchi, Lorimer, Chennamangalam 2011)

2. Total gamma-ray luminosity in globular clusters from Fermi-LAT observations (Acero+ 2015)

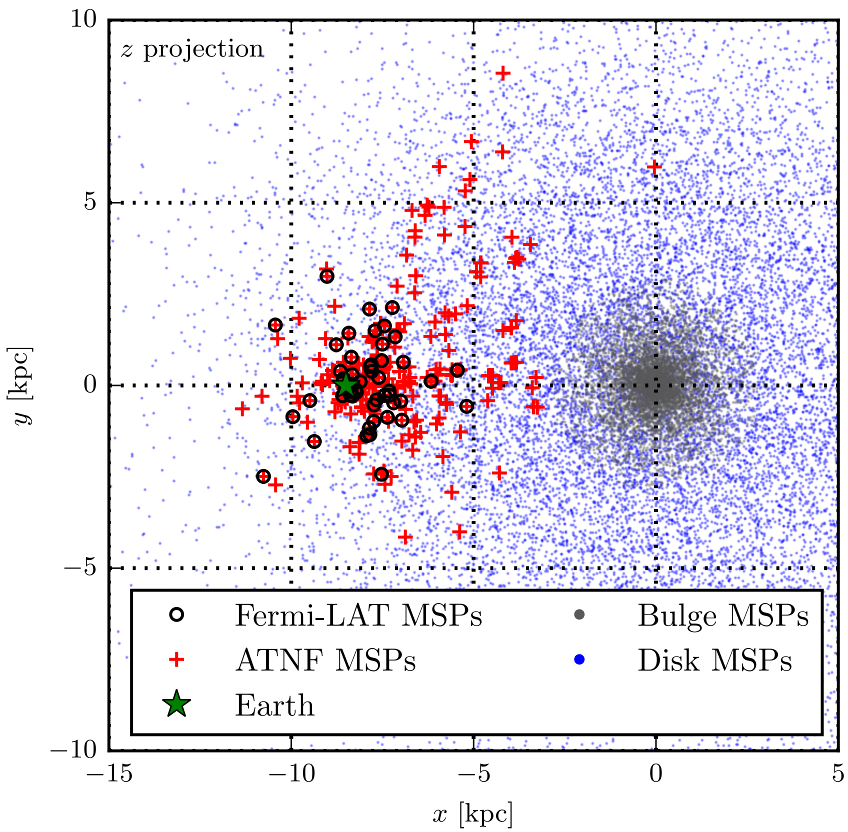
→ We derive the gamma-ray luminosity per source.

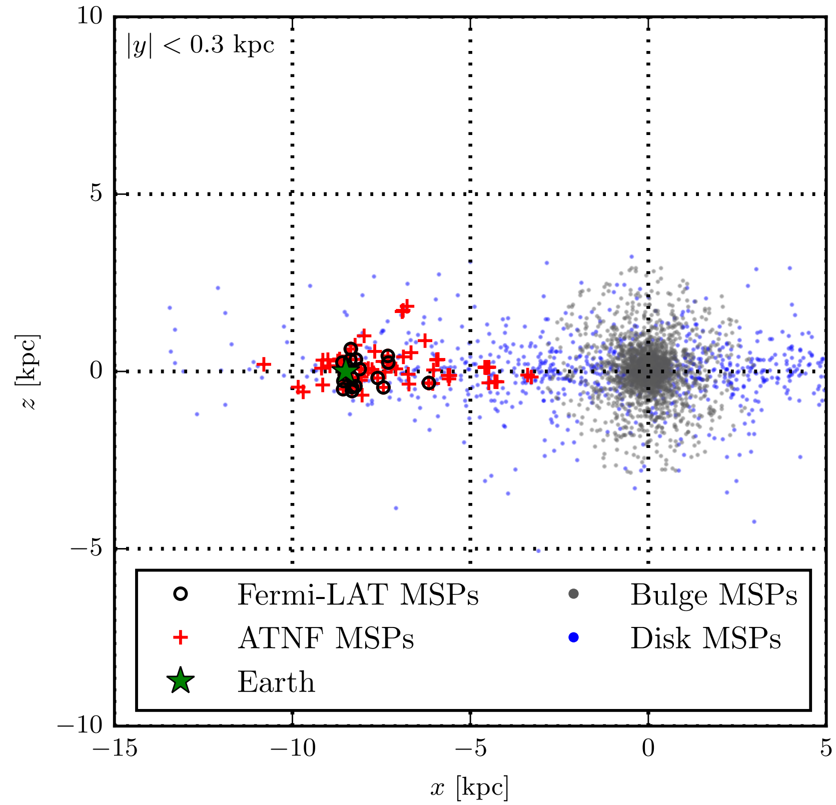
3. From total Galactic center gamma-ray luminosity, assuming all is due to the putative bulge MSP population:

$$N_{\rm rad}^{\rm bulge} = (8.9 \pm 0.3 \times 10^3)$$

(~$2.7 \times 10^3$ are radio bright, > 10 μJy)

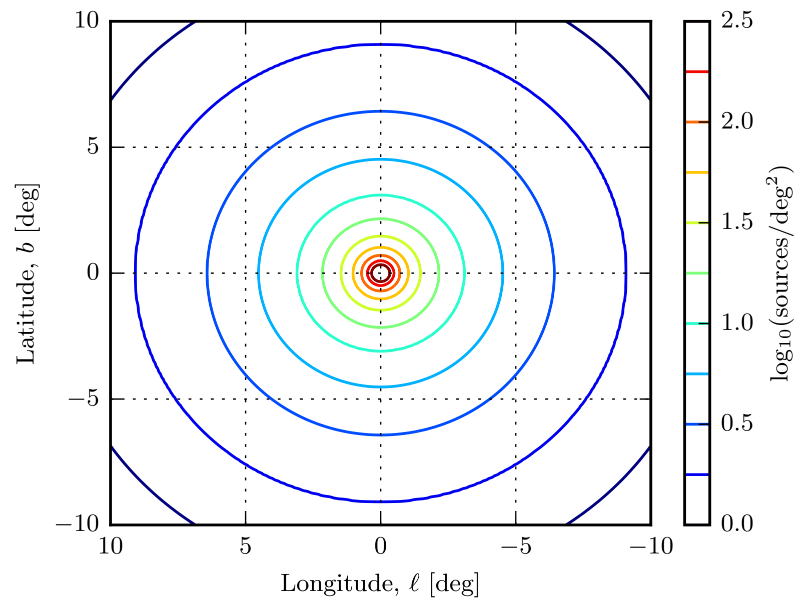
# The bulge population




Also plotted the thick disk population (about 20000 sources are predicted).
Observed MSPs are ruled by selection effects.

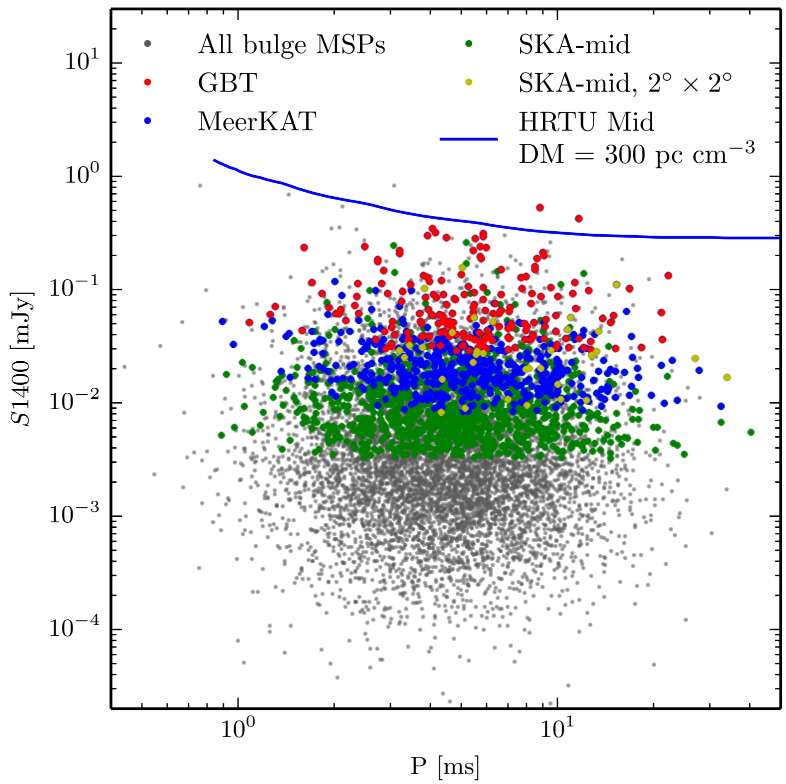
# MSP bulge surface density




The surface density of the putative bulge population (number of sources/deg$^2$)

At the very Galactic center the number of sources is ~ $10^3$,
while it drops remarkably out of a 5 deg ring

# Radio MSP bulge population detectability: flux density vs period

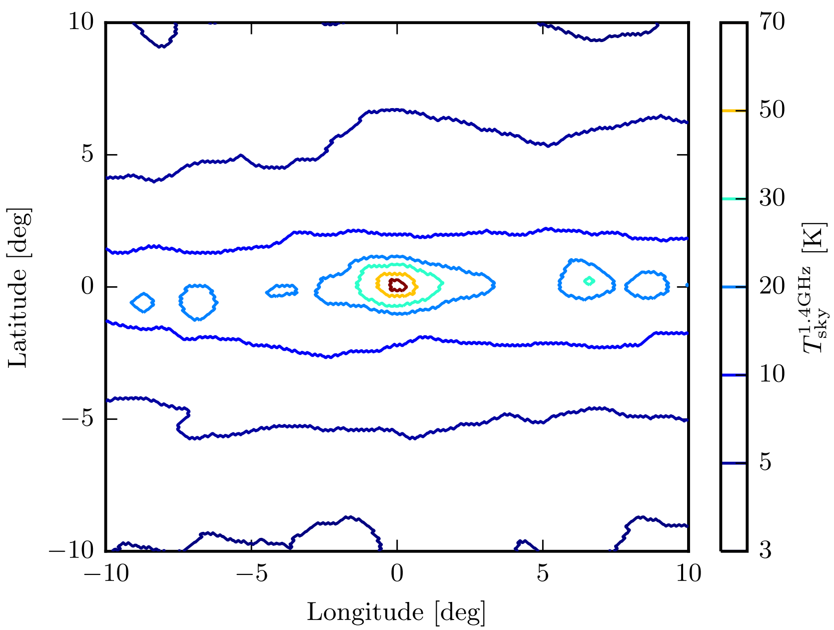



- ✓ Flux density is for 1400 MHz
- ✓ Current Parkes HTRU survey cannot probe the bulge population
- ✓ Reference observation time per pointing is 60 – 120 – 60 min for GBT – MeerKAT – SKA
- ✓ **Green Bank Telescope and upcoming telescopes could detect hundreds of sources**

# Uncertainty in the flux detection

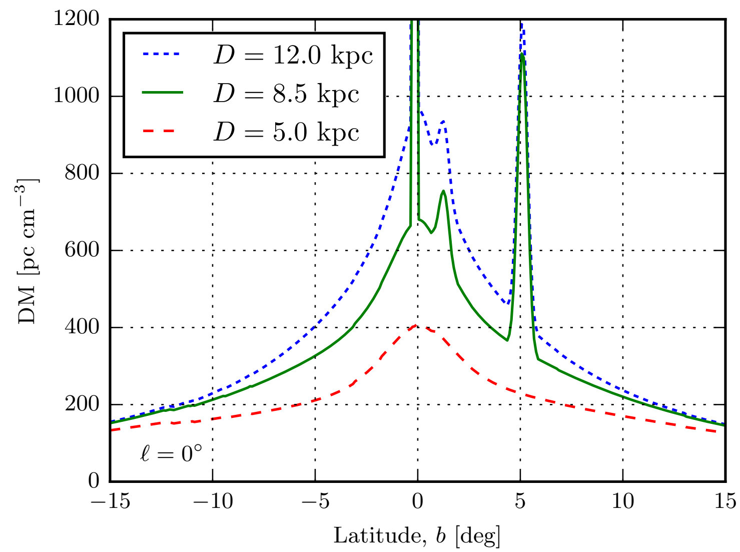
RMS uncertainty of the flux density:

$$S_{\nu,\mathrm{rms}} = \frac{T_{\mathrm{sys}}}{G\sqrt{t_{\mathrm{obs}}\,\Delta\nu\,n_p}}\left(\frac{W_{\mathrm{obs}}}{P - W_{\mathrm{obs}}}\right)^{1/2}$$




Sky temperature contours at 1.4 GHz
as derived by the Haslam (408 MHz) maps.
The strong emission at the Galactic center
and along the Galactic disk increases
the background noise noise

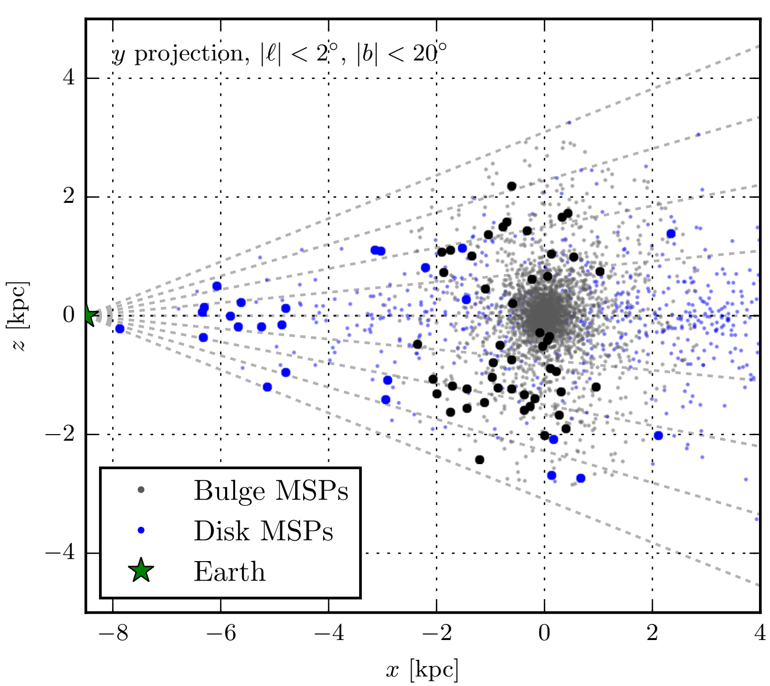
Dispersion measure at l=0

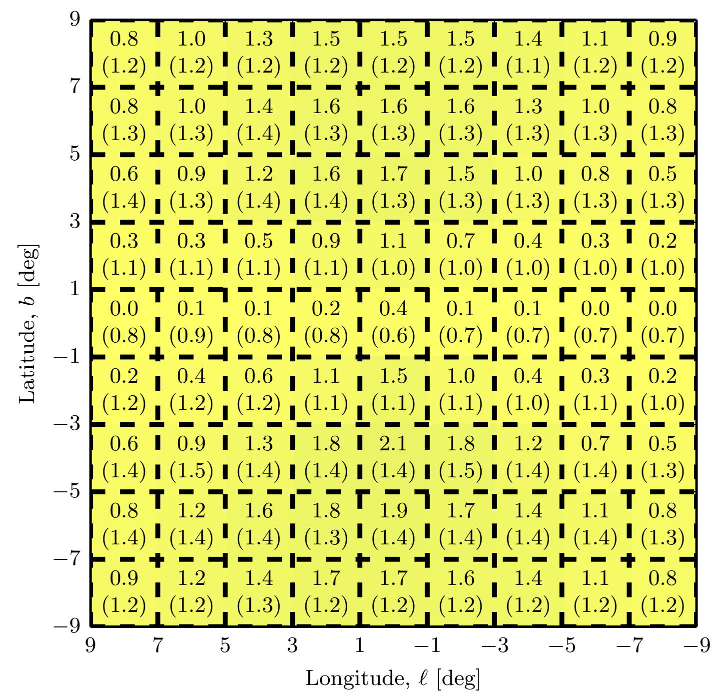



From Cordes & Lazio models 2002

# Radio detection perspectives: GBT

Spatial distribution of the bulge and simulated disk MSP population



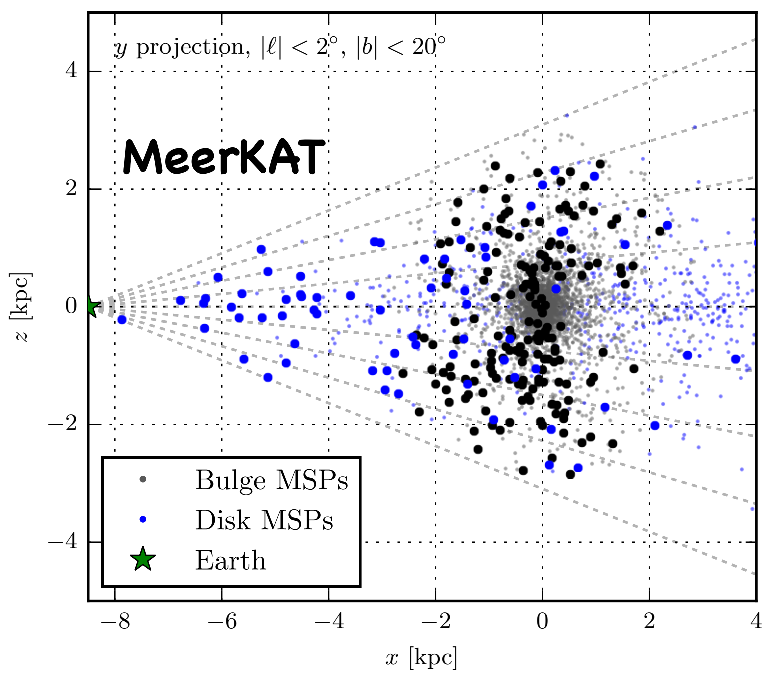



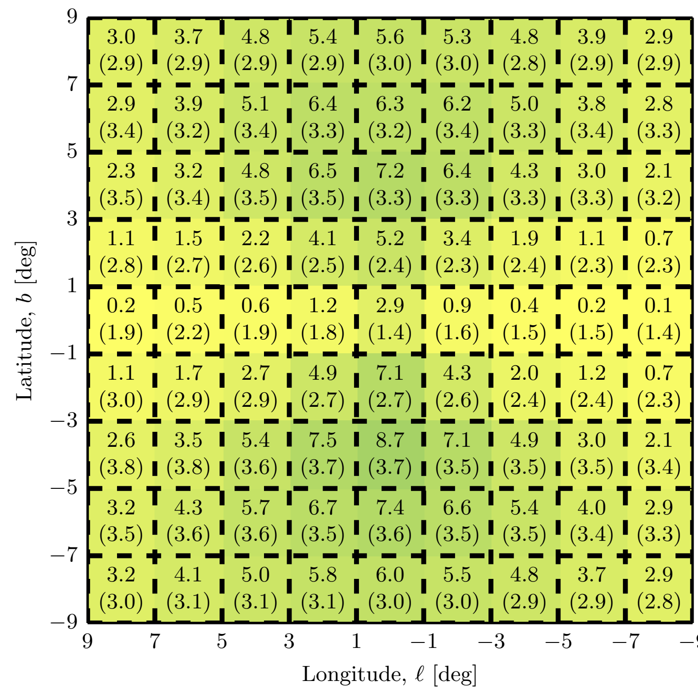

Thick dots: sources detected by GBT in |l|<2° and |b|<20°, assuming that Pixels of 2 × 2 are covered by 100 h observation

Contamination of disk sources – Difficulty in survey the true GC sources

# Radio perspectives: MeerKAT-like

Spatial distribution of the bulge MSPs and of simulated MSP disk population



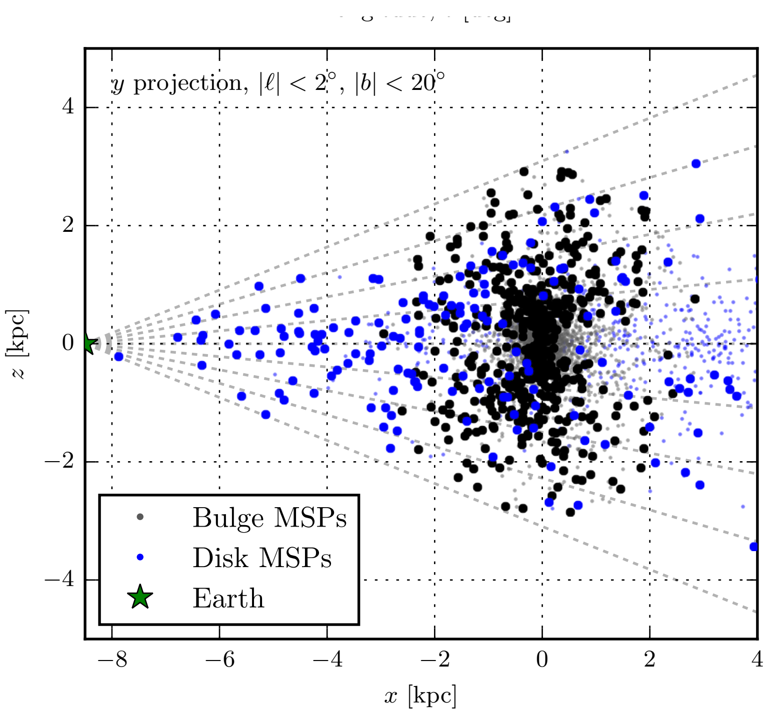



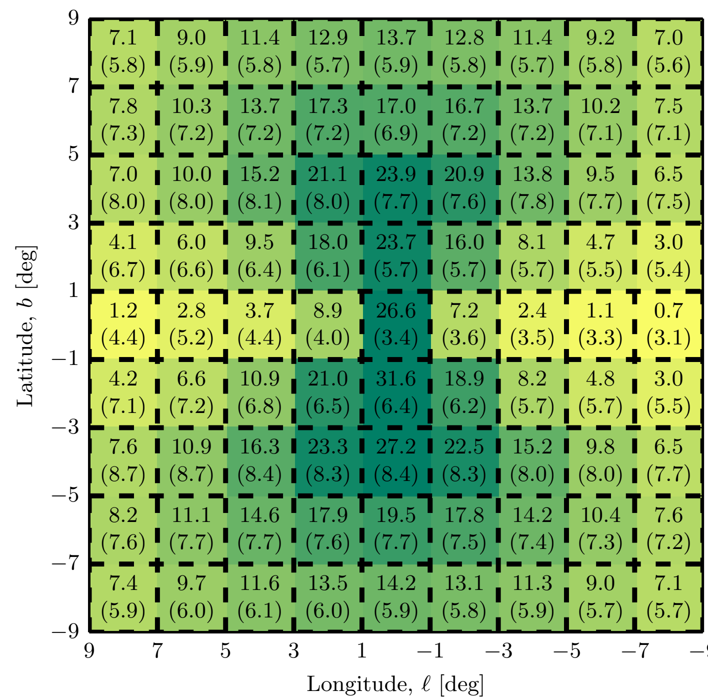

Thick dots: sources detected by MeerKAT-like telescope in |l|<2° and |b|<20°, assuming that pixels of 2 × 2 are covered by 100 h observation

Contamination of disk sources – Difficulty in survey the true GC sources

# Radio detection perspectives: SKA

Spatial distribution of the bulge MSPs and of simulated MSP disk population



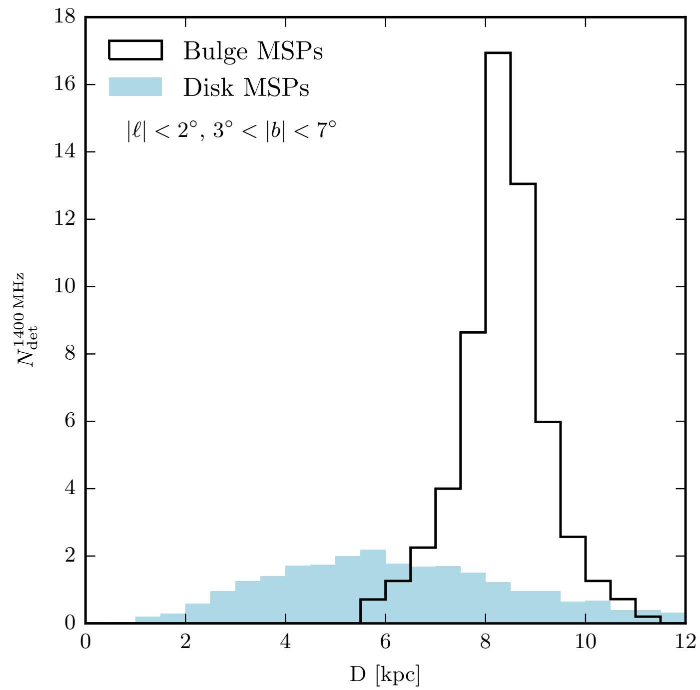




Thick dots: sources detected by SKA in |l|<2° and |b|<20°, 100 h/pixel

**The most efficient survey would be ~ 5° about the galactic center**

**Role of the scattering of the radio signal**

# Discrimination between disk and bulge MSP populations

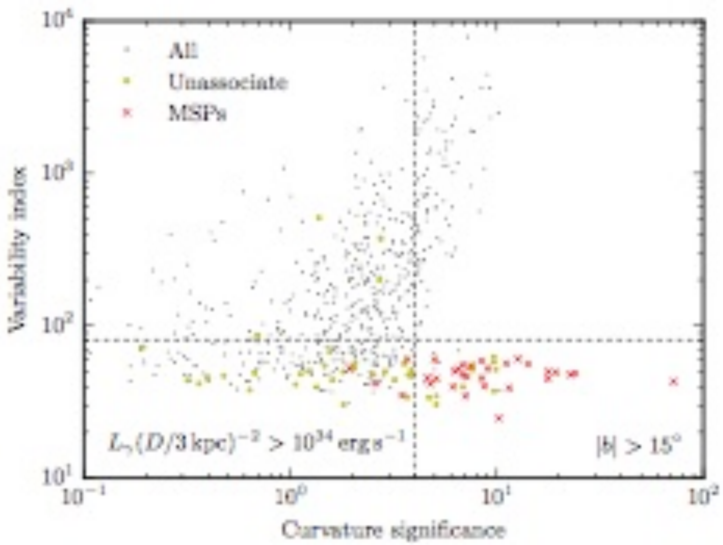



Histogram of distances of detected disk (blue) and bugle MSPs, assuming a MeerKAT reference survey.

**The two populations can be clearly separated**

We estimate that a few MSP detected in the bulge (provided Their distance is measured) can discriminate this population Agaist the disk foreground MSP

# Radio targeted searches




| Instrument | $t_{obs}$ total | Detection of MSP candidates Probability | Number (20 total) |
|---|---|---|---|
| GBT | 20 h | 21.4% | 4.3 |
| MeerKAT | 40 h | 44.0% | 8.8 |
| SKA-mid | 20 h | 60.0% | 12.0 |

Many unassociated Fermi sources have MSP characteristics and could Be detected as MSP in the bulge already by GBT after a deep search campaign.

On short timescale, radio observations of the first bulge MSP candidates with GBT could find the first bulge MSP

# Conclusions

- We investigate the possibility the all the gamma-ray galactic center excess might be due to **a bulge population of field millisecond pulsars**
- We estimate the **number** of these MSPs in the **radio** band, passing through the gamma and radio properties of globular clusters
- This putative radio MSP bulge population could be investigated by ongoing and future **radio surveys**
- The best region to look for bulge MSPs is few degrees around the galactic center, where tens of sources could be detected by SKA
- Our predictions, as well as their intrinsic interest, could help to reduce the **ambiguity between the MSP and the dark matter** interpretation of the GC excess.
- **Followups** with GBT on unassociated sources look promising

# Detector performances

| Parameters | HTRU | GBT | MeerKAT | SKA-mid |
|---|---|---|---|---|
| $\nu$ [GHz] | 1.0 | 1.4 | 1.4 | 1.67 |
| $\Delta\nu$ [MHz] | 340 | 600 | 1000 | 770 |
| $T_{\rm rx}$ [K] | 23 | 23 | 25 | 25 |
| $G$ [K/Jy] | 0.74 | 2.0 | 2.9 | 15 |
| $\theta_{\rm FWHM}$ [arcmin] | | 8.56 | – | – |
| FoV [deg$^2$] | | 0.016 | 0.86 | 0.49 |
| $T_{\rm point}$ [min] | | 60 | 120 | 60 |
| $T_{4\,{\rm deg}^2}$ [h] | | 250 | 9.3 | 8.2 |