Millisecond pulsars and other compact objects at the Galactic center

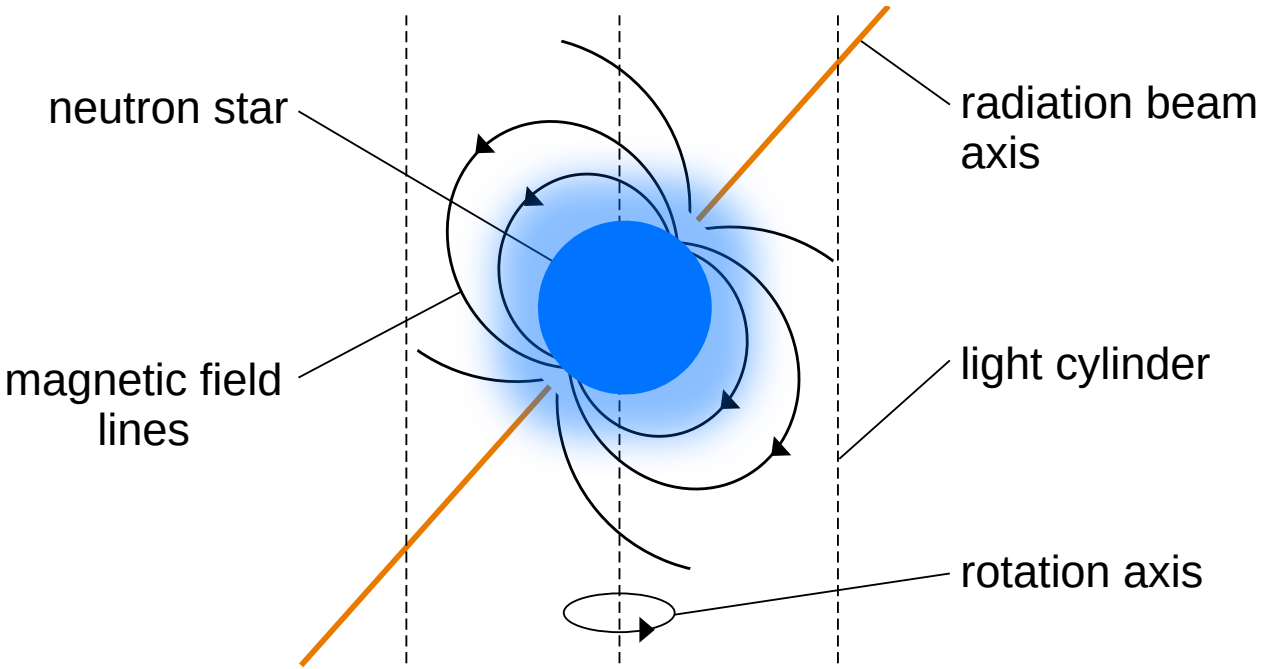
Based on Berteaud, Calore, Clavel, Marvil et al. (in prep.)

Joanna Berteaud

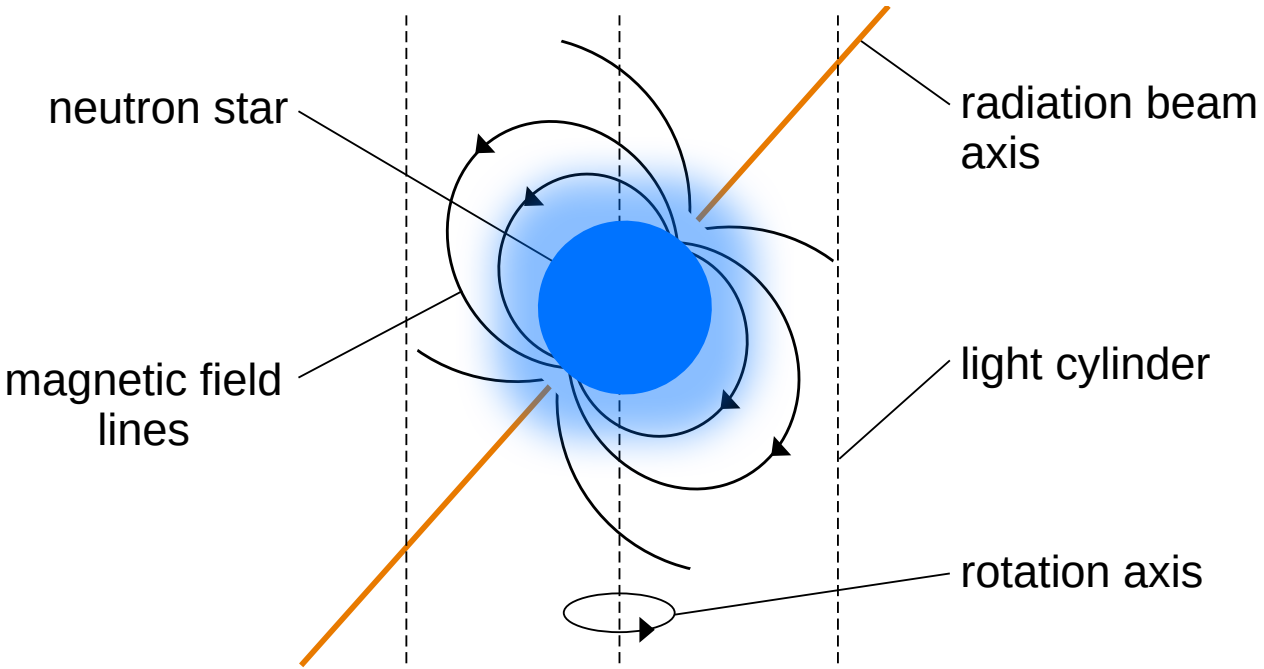
astrocosmolapth.wordpress.com

Journées PNHE, Paris, September 2023

Pulsars


neutron star
magnetic field lines
radiation beam axis
light cylinder
rotation axis

Pulsars



Millisecond pulsars (MSPs): P < 30 ms

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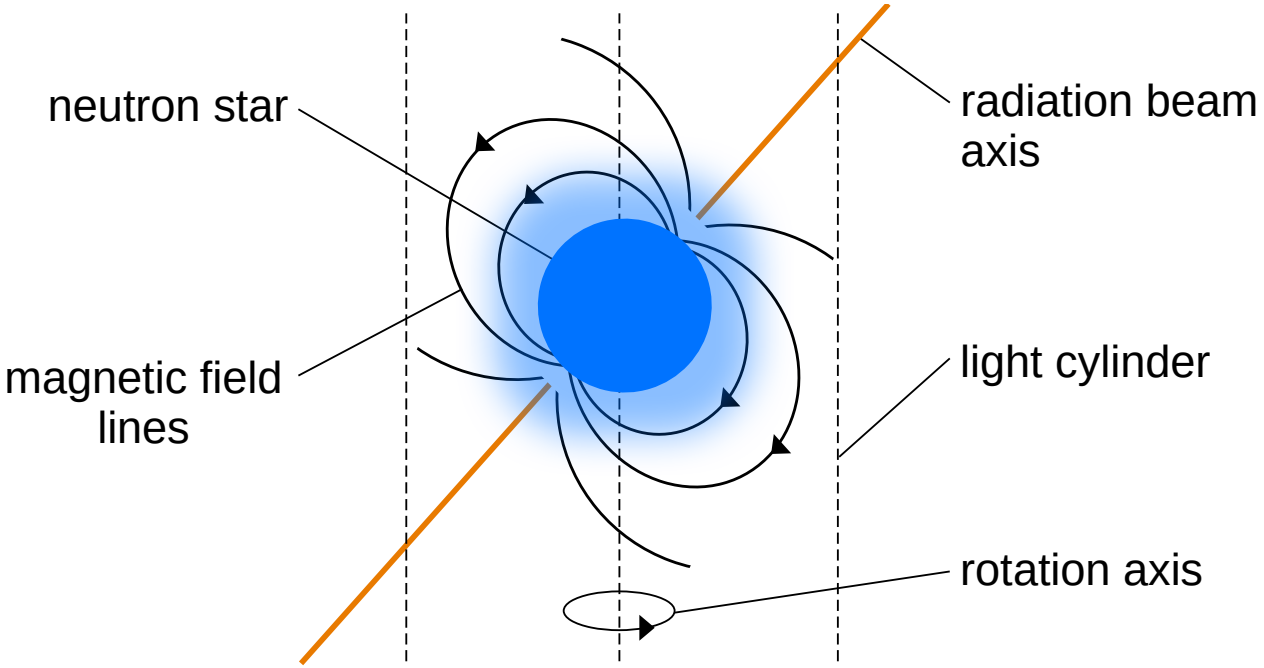

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Radio

Infrared (IR)

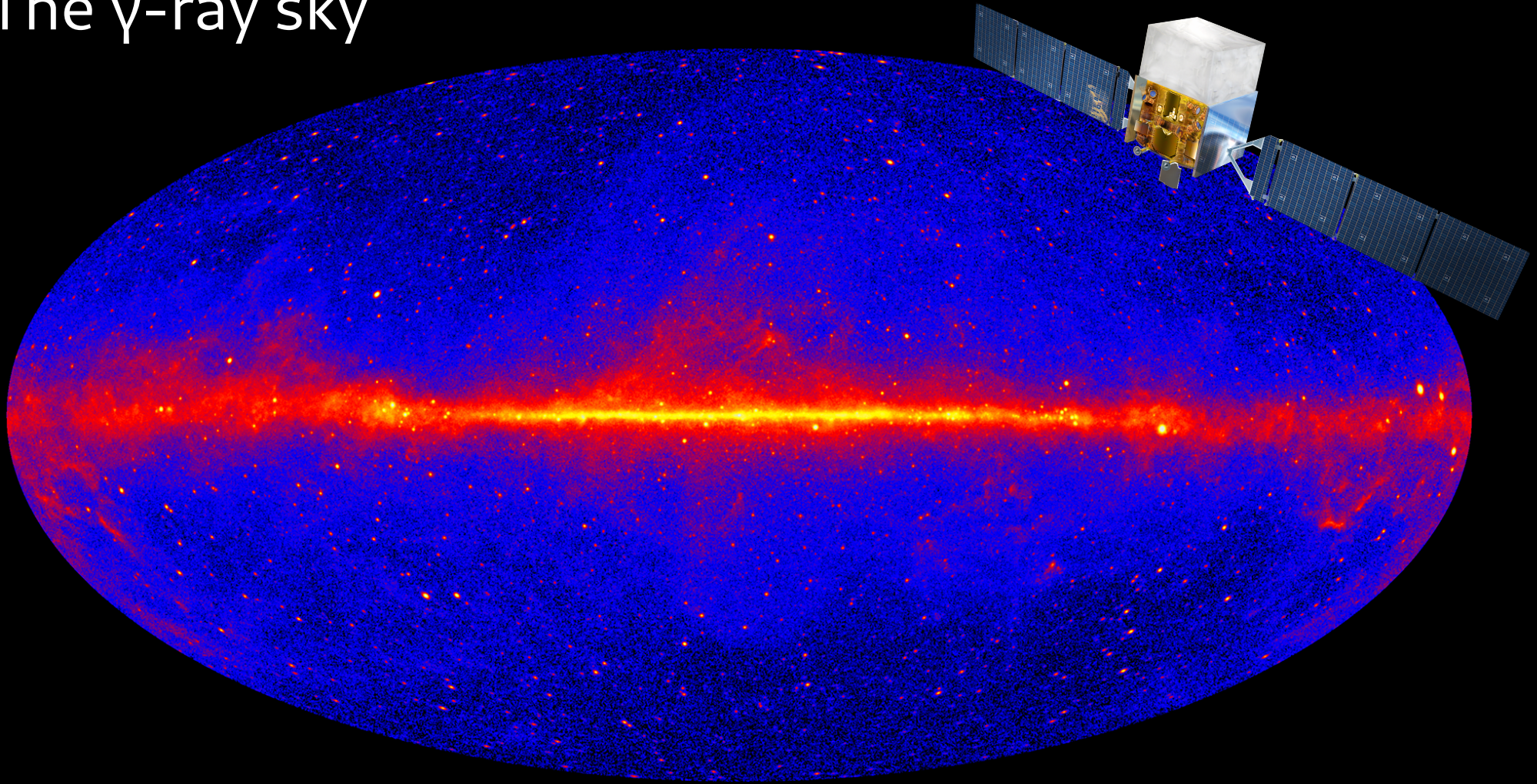
Optical

Ultraviolet (UV)

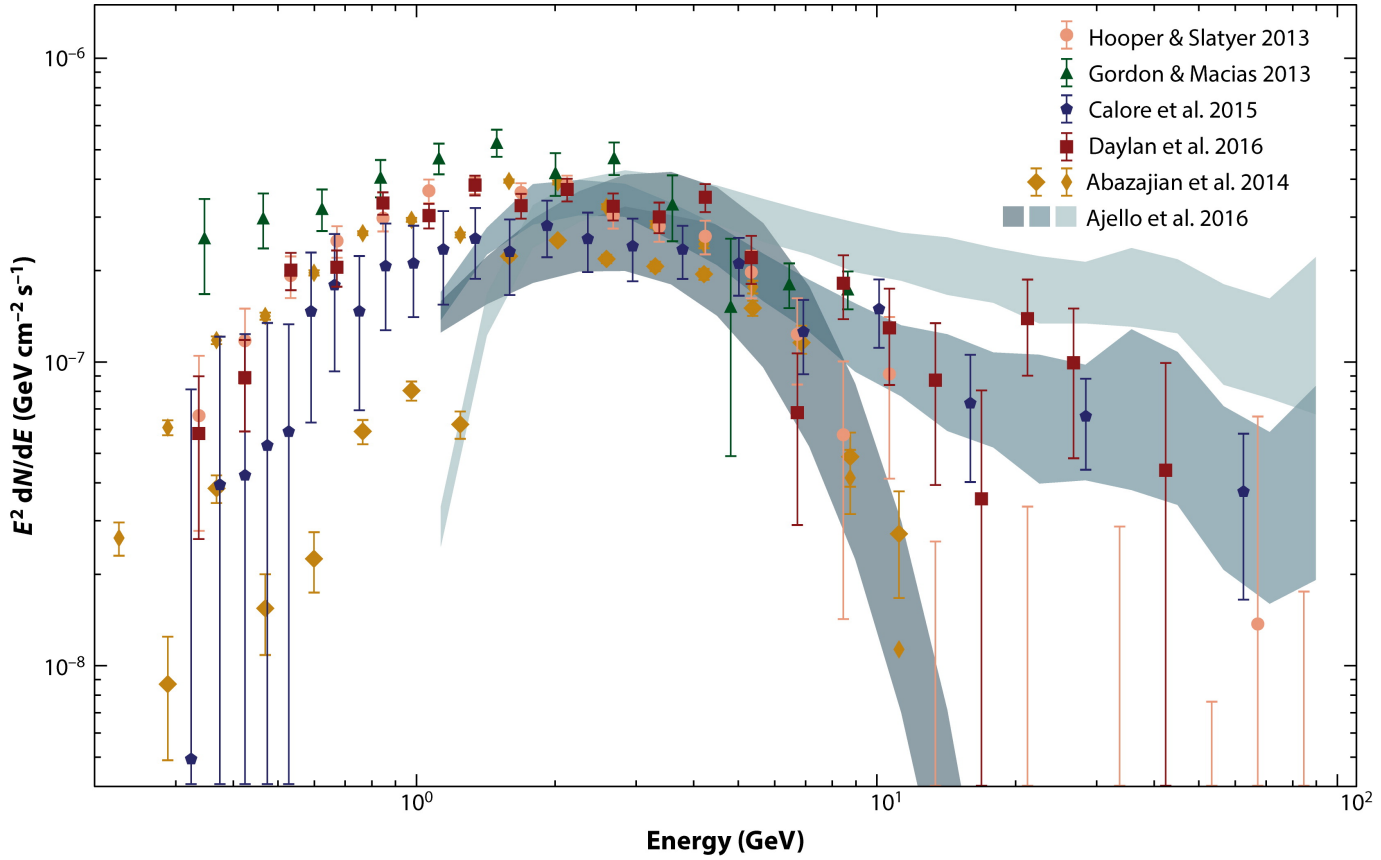
X rays

γ rays

The γ-ray sky

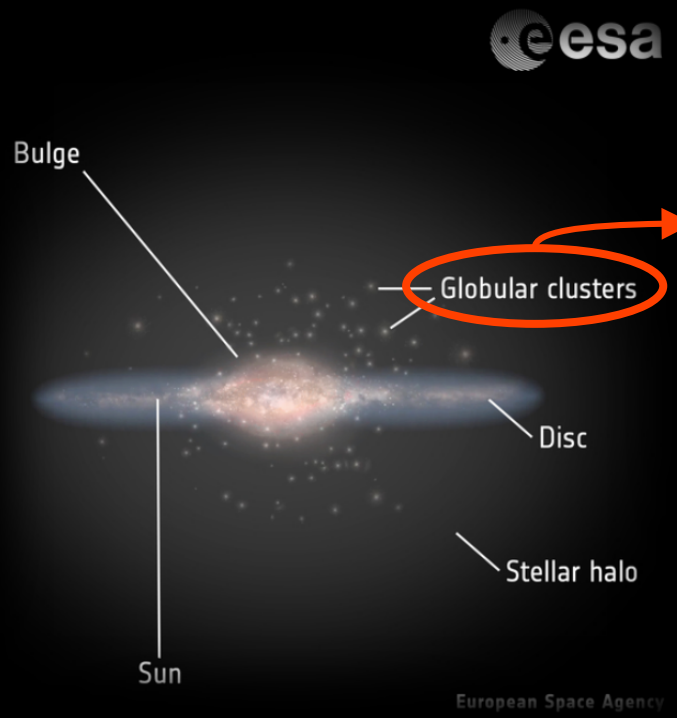


The *Fermi* GeV excess



Murgia S. 2020.
Annu. Rev. Nucl. Part. Sci. 70:455–83

The Galactic MSP population



- More than 250 MSP pulsations detected in radio
- Diffuse γ-ray emission seen by the *Fermi*-LAT

The Galactic MSP population

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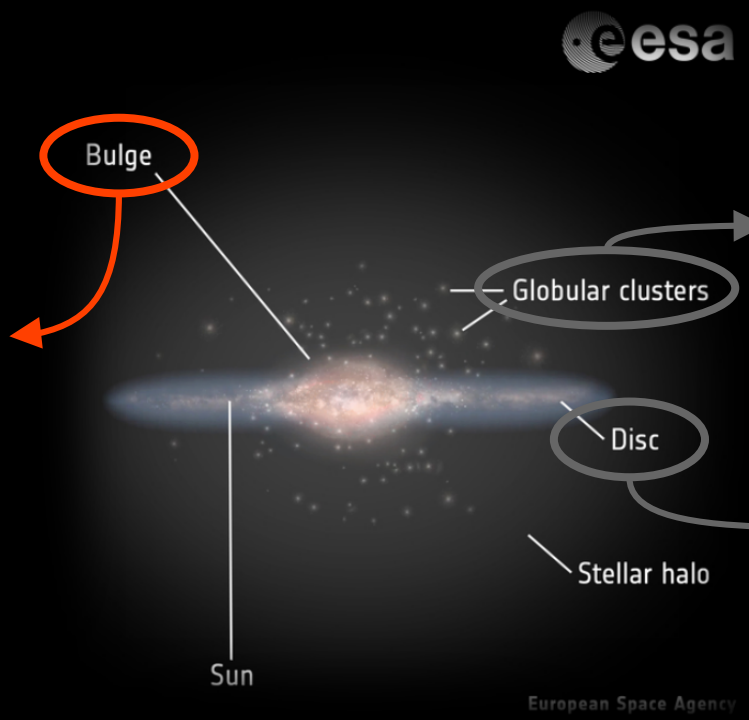
- The rest, more than 300

The Galactic MSP population

- No evidence from individual detections
- Putative origin of the *Fermi* GeV Excess



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MSPs at the Galactic center

Probes of:

- The Galactic Center Excess and its dark matter origin
- The free electron density
- The gravitational potential of the region
- Theories of gravity
- …

MSPs at the Galactic center

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The Galactic center shows:

- A large stellar density
- A profusion of massive stars

→ **ideal place to find compact objects**

MSPs at the Galactic center

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Unresolved, by definition ← **γ rays**

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Calore et al. (2015): current ← **Radio** surveys not sensitive enough

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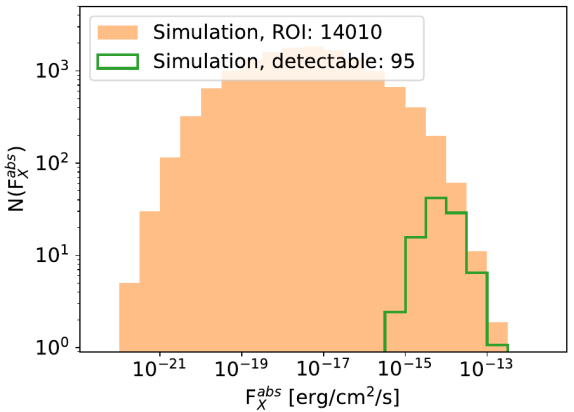
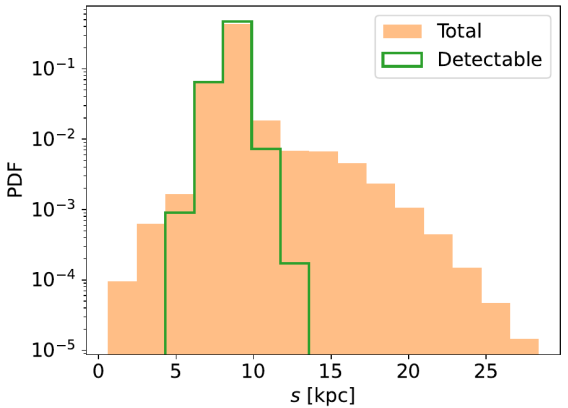
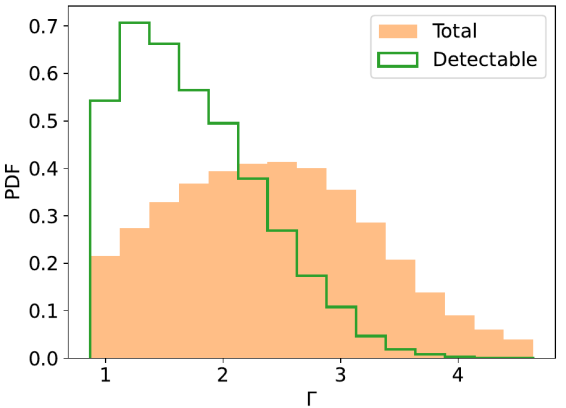
X-ray detectability of the Galactic MSP population

Berteaud et al. (2021)







- **ROI**: 6°×6° around the Galactic center
- **Detectable** simulated MSP: simulated flux > *Chandra* sensitivity

Monte Carlo simulation available on Zenodo!

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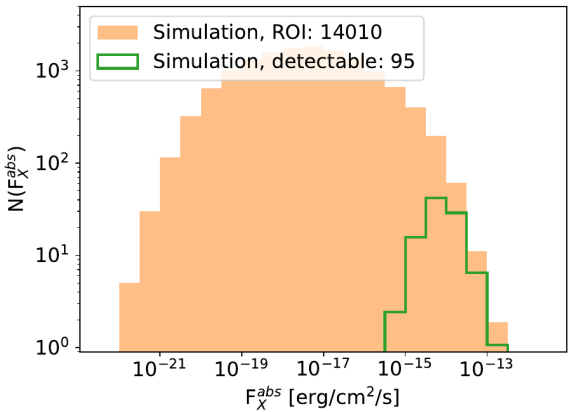

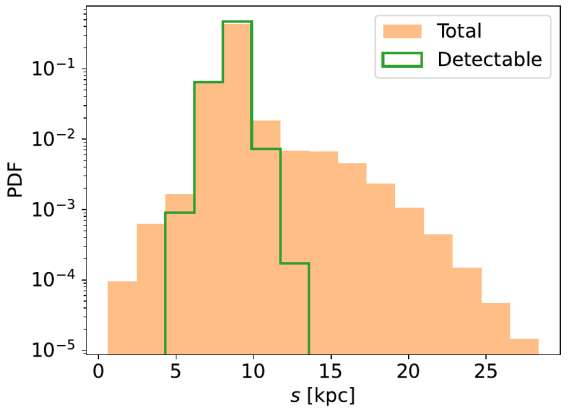

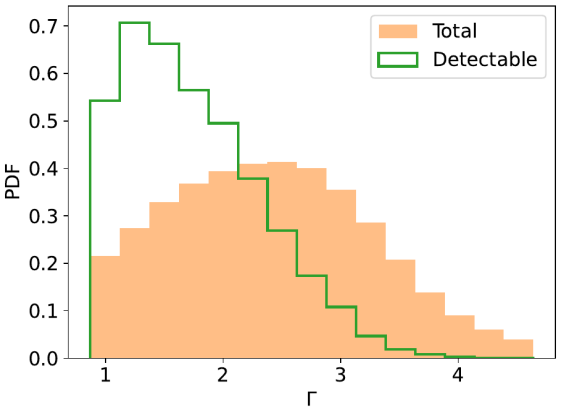

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➔ ~100, minor contribution from the disk
➔ Between 5.2 and 11.9 kpc, at 8.5 kpc on average
➔ Hard X-ray sources

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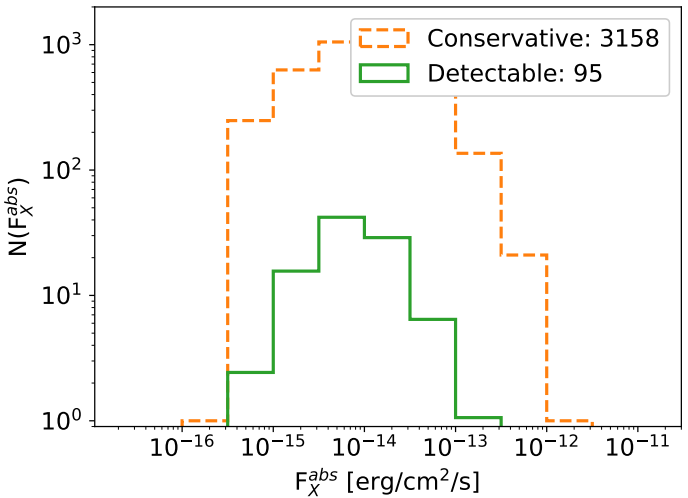
Selection of MSP candidates

Berteaud et al. (2021)



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     → **3158** candidates > **95** expected

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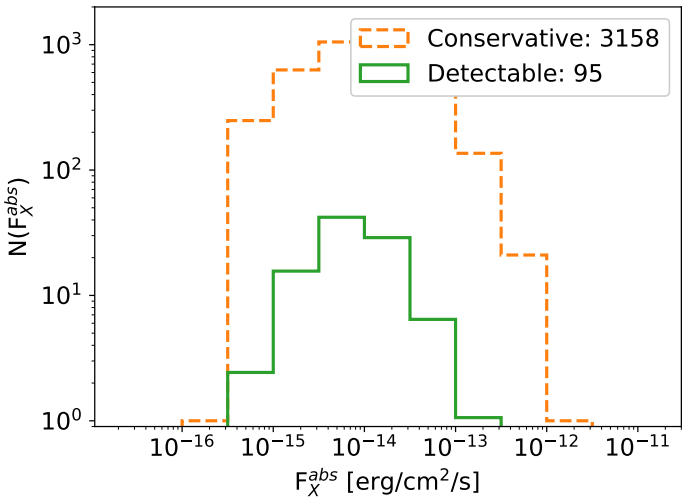

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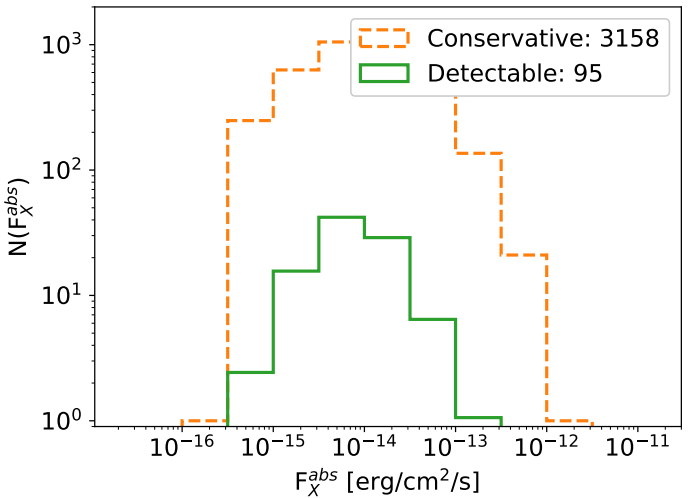

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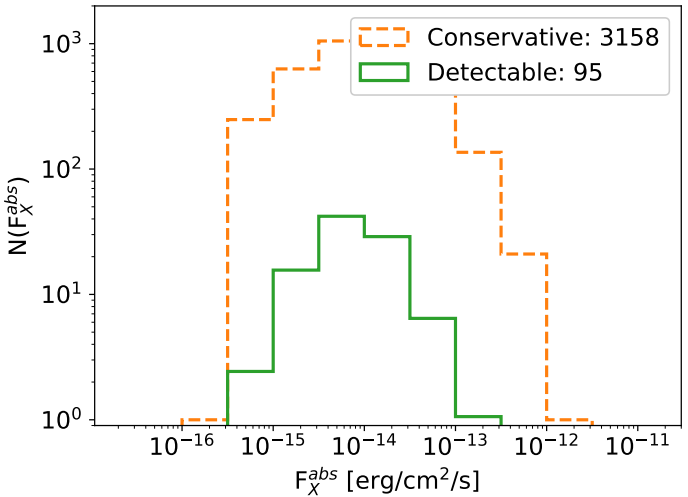

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4. IR constraints with 2MASS, VVV, etc:
   - no counterpart or
   - compact objects (CO, Lin et al. 2012):

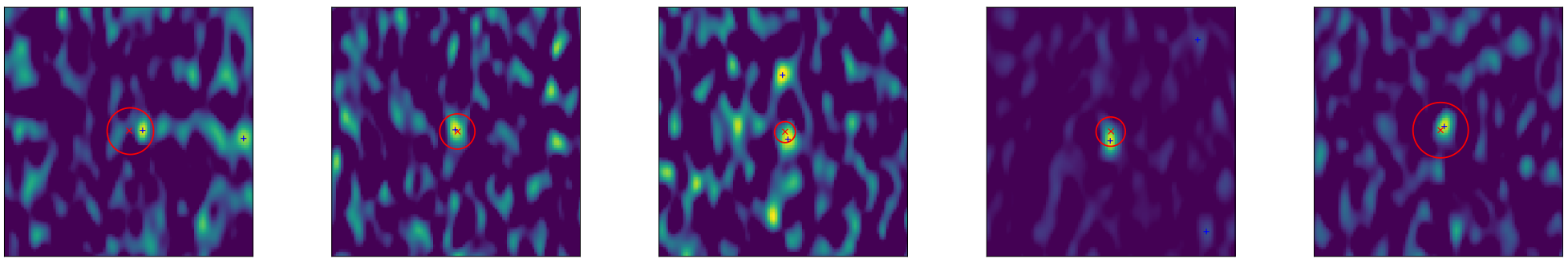
$$\log_{10}(F_X/F_K) > 0.5$$

→ **1422, 57 CO candidates**

Radio counterparts

NRAO VLA Sky Survey (NVSS):
→ shallow, sources above 2.5 mJy

Unpublished VLA 1.4 GHz imaging data (PI: M. Kerr):
→ 13 positive cross-matches, **5 interesting MSP candidates**



Candidate positions

1422 MSP candidates, including:

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- 5 promising radio sources
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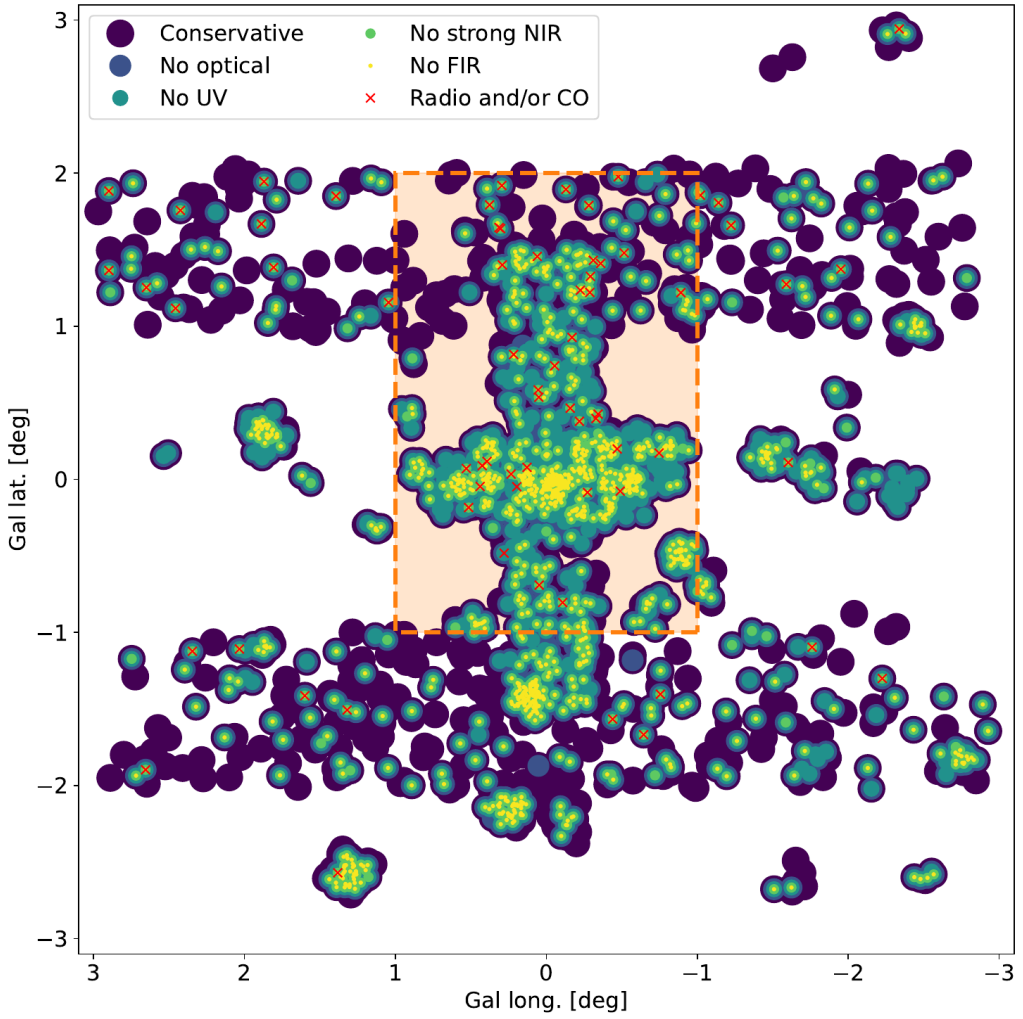

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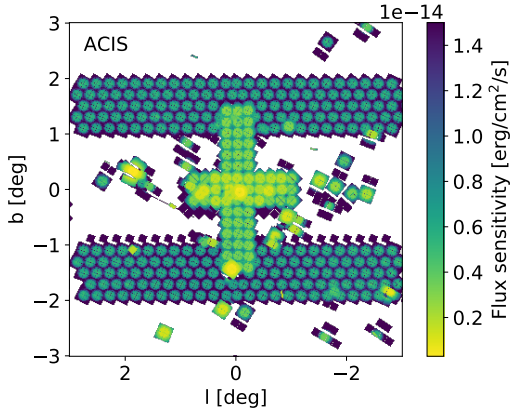

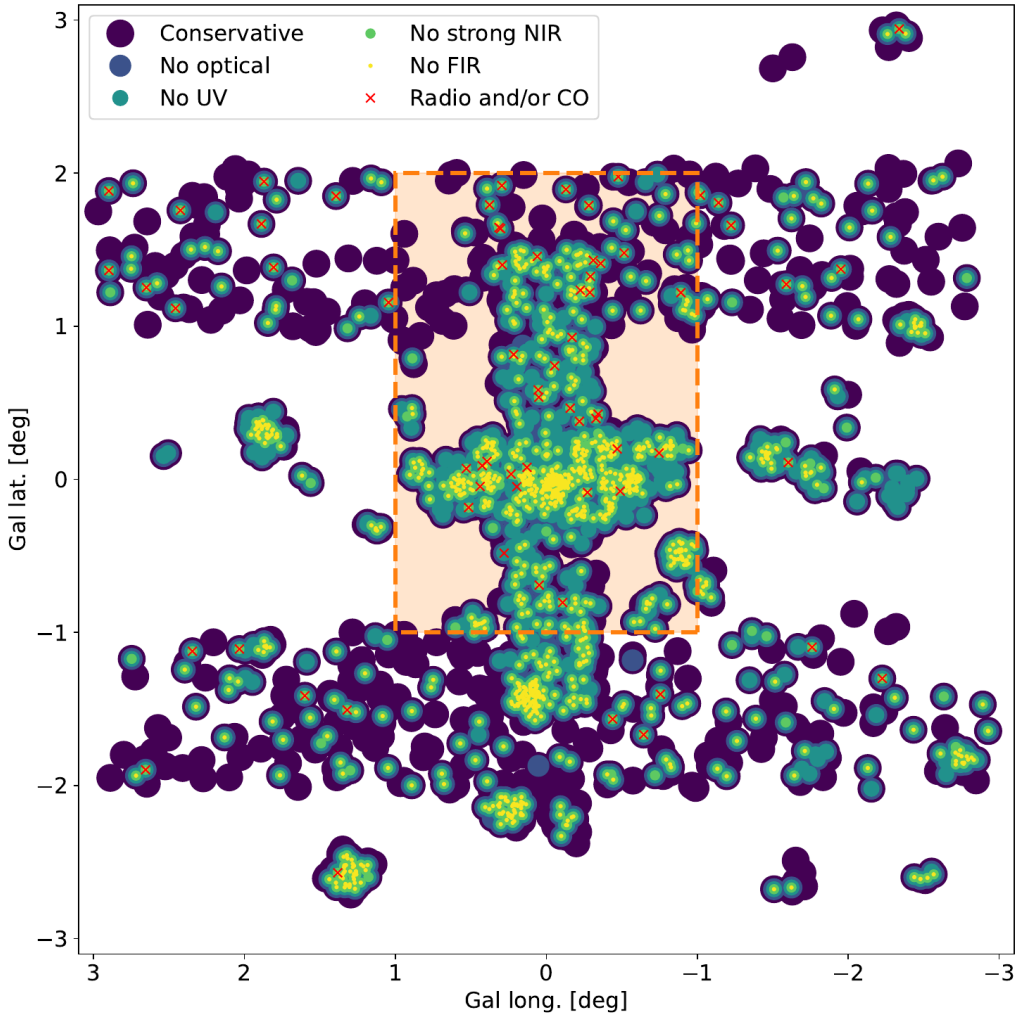

Take-home messages

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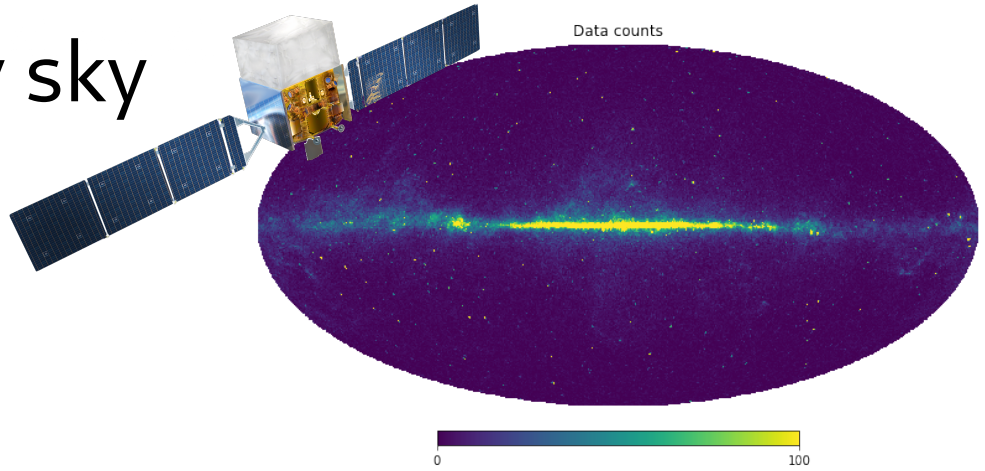
Thank you for your attention!

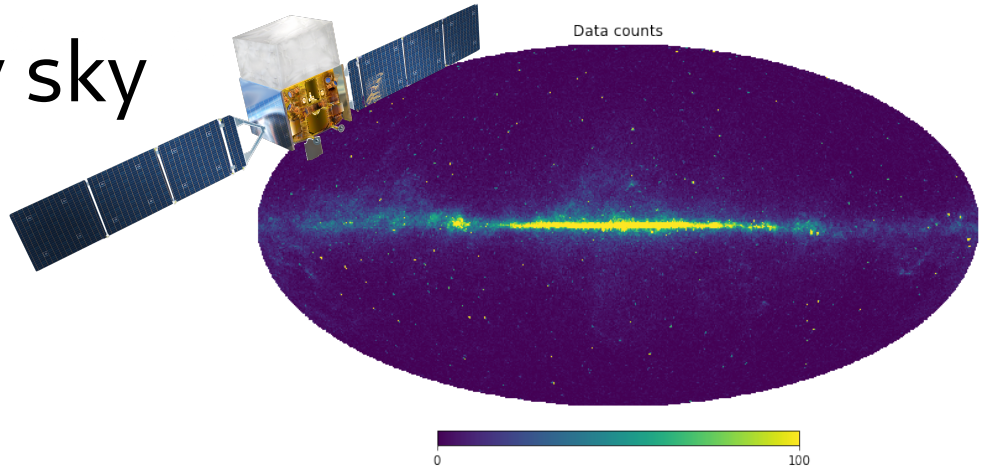
Back up

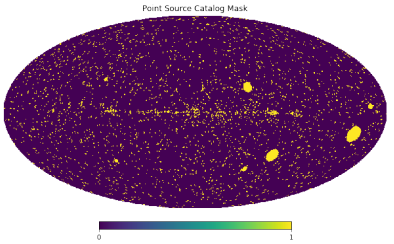
The γ-ray sky



https://nptfit.readthedocs.io

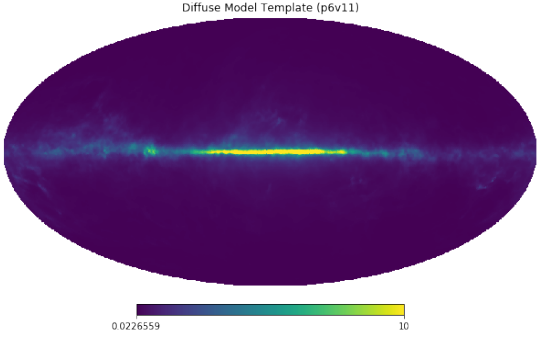
The γ-ray sky

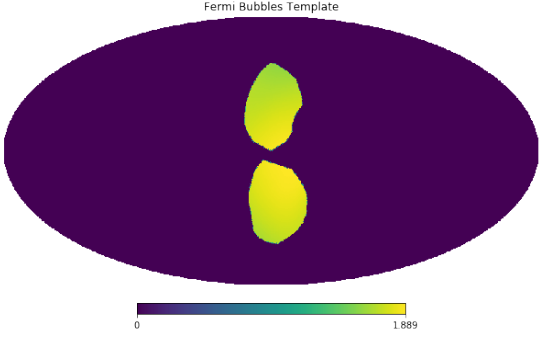


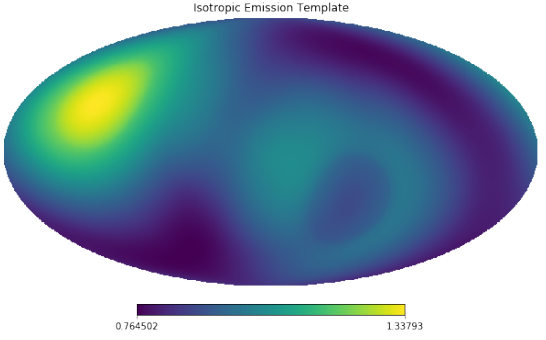


data with point sources masked =

diffuse emission (ICS, Bremsstrahlung, π^0) + Fermi Bubbles + isotropic emission







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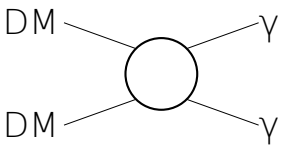
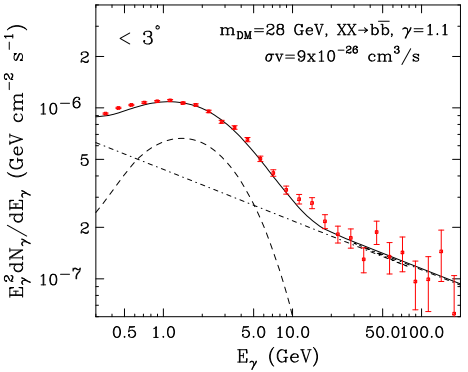
(Non-exhaustive) Timeline of the Fermi GeV excess

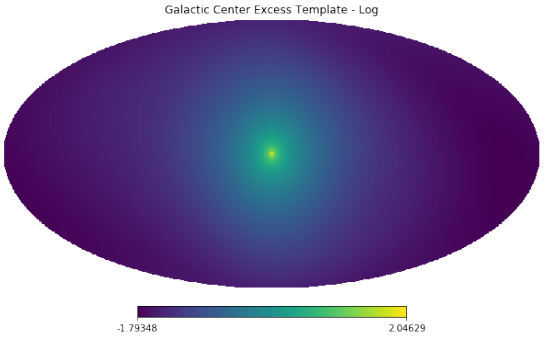


First claim

Goodenough & Hooper

2009





2008 Launch of the Fermi-LAT

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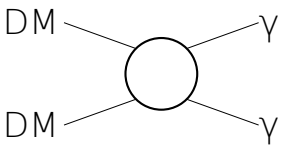

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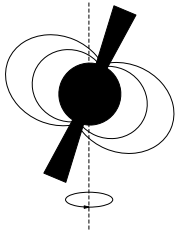

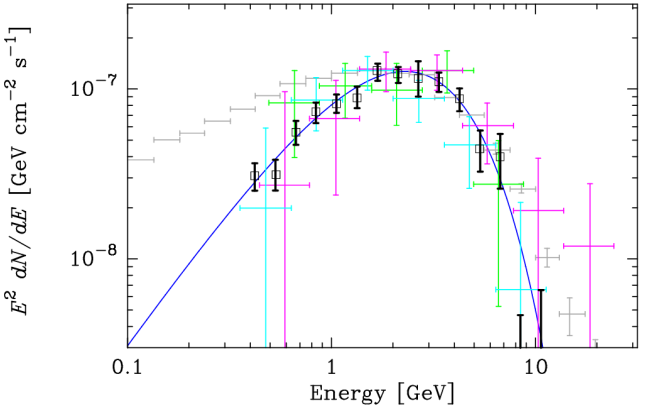

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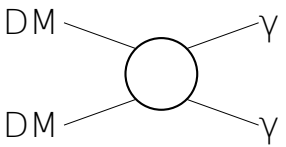

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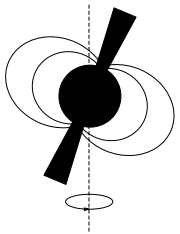

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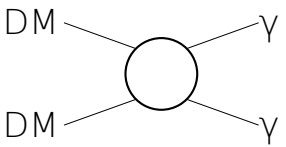

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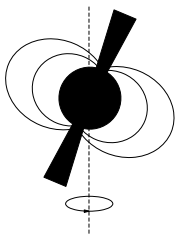

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Macias et al.
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Emission from
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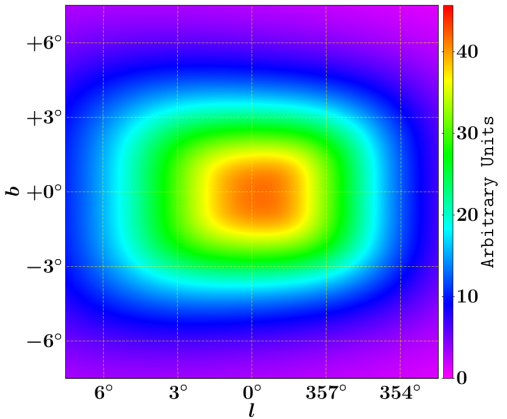

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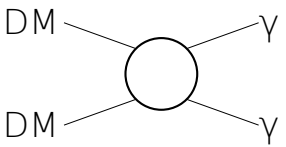

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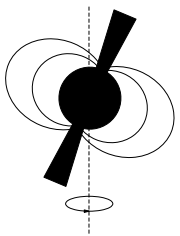

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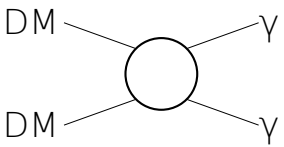

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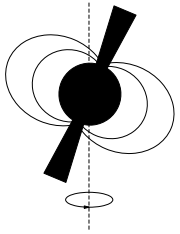

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2022
No evidence for
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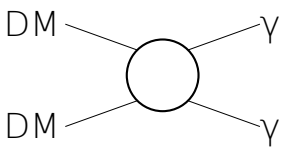
Dark Matter (DM) versus Millisecond Pulsars (MSP)

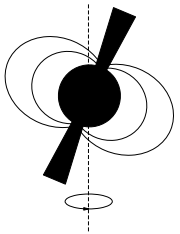


Spherically symmetric morphology

DM annihilation spectrum

Not enough LMXBs

...



Bulge-like morphology

Globular cluster spectrum

Accretion-induced collapse

Photon-count statistics

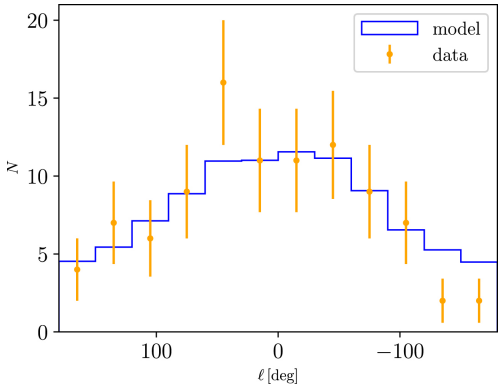
...

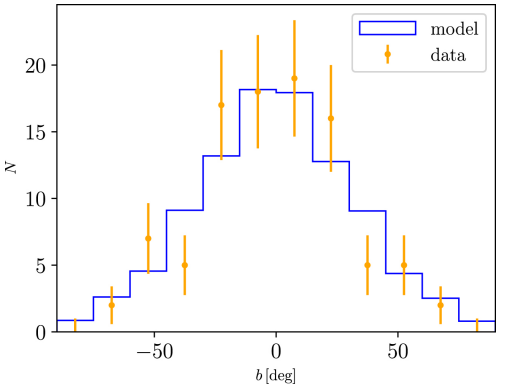
Almost 15 years of debate!
Resolve the MSP population would finally settle the case.

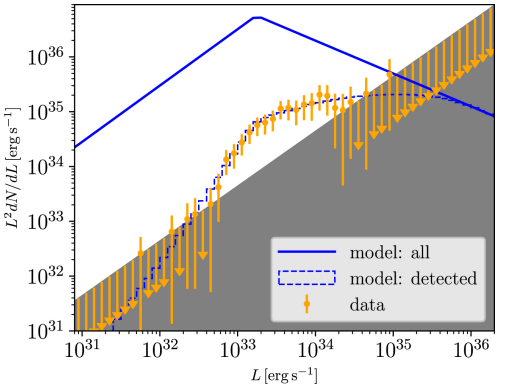
Simulation of the Galactic MSP population

Monte Carlo simulation available on Zenodo!

	Disk	Bulge
Number density	~100 γ-ray detected MSPs Bartels et al. 2018b	
γ-ray luminosity function	Broken power-law Bartels et al. 2018b	
X-ray emission model		







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I. Simulation and X-ray detectability of the Galactic bulge MSP population

Berteaud et al. (2021)

Simulation of the Galactic MSP population

Monte Carlo simulation available on Zenodo!

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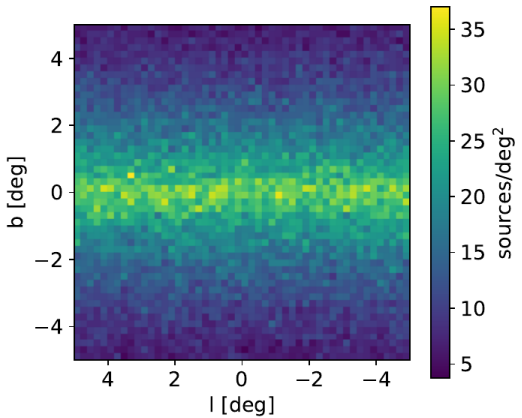
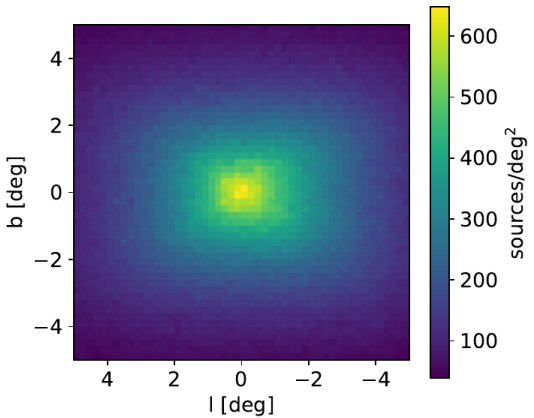
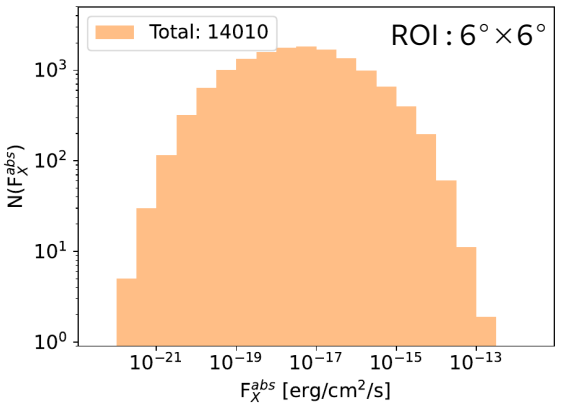
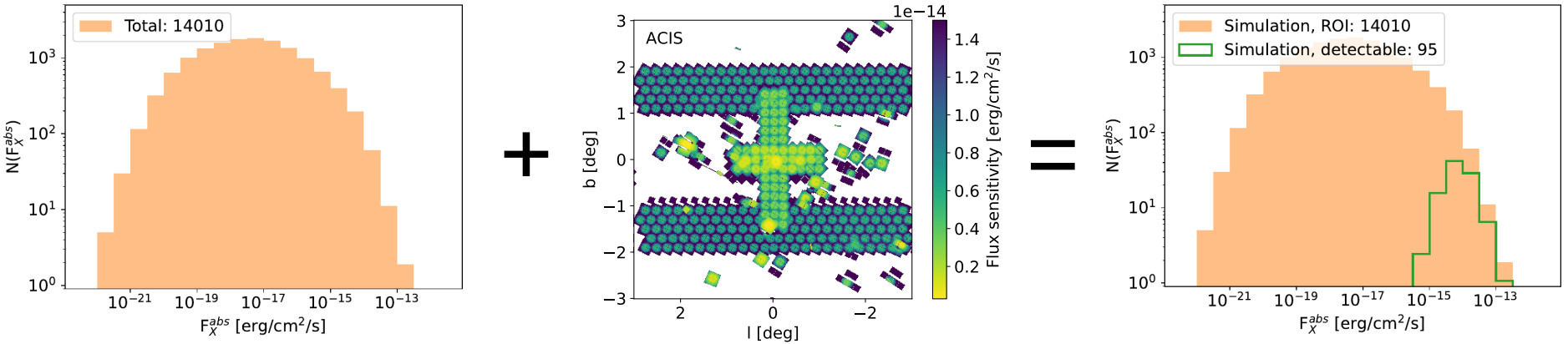




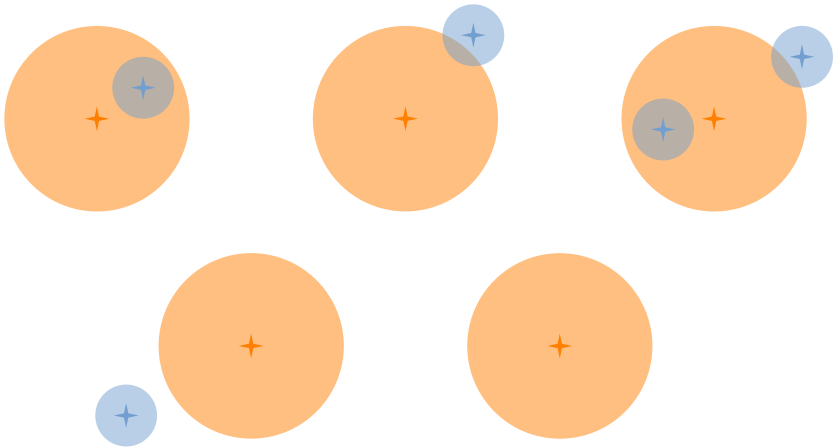


X-ray detectability of the Galactic MSP population



- Detectable simulated MSP: MSP simulated flux > Chandra sensitivity
- **About 100**, minor contribution from the disk (Berteaud et al. 2021)

Selection of MSP candidates



1. From the Chandra catalog:
   - Non-variable
   - Non-extended
   - Hard sources

2. Optical constraints with Gaia:
   - at bulge distance
     → **3158** candidates > **95** expected
   - no counterpart → **2358**

3. UV constraints with XMM-OM:
   - no counterpart → **2298**

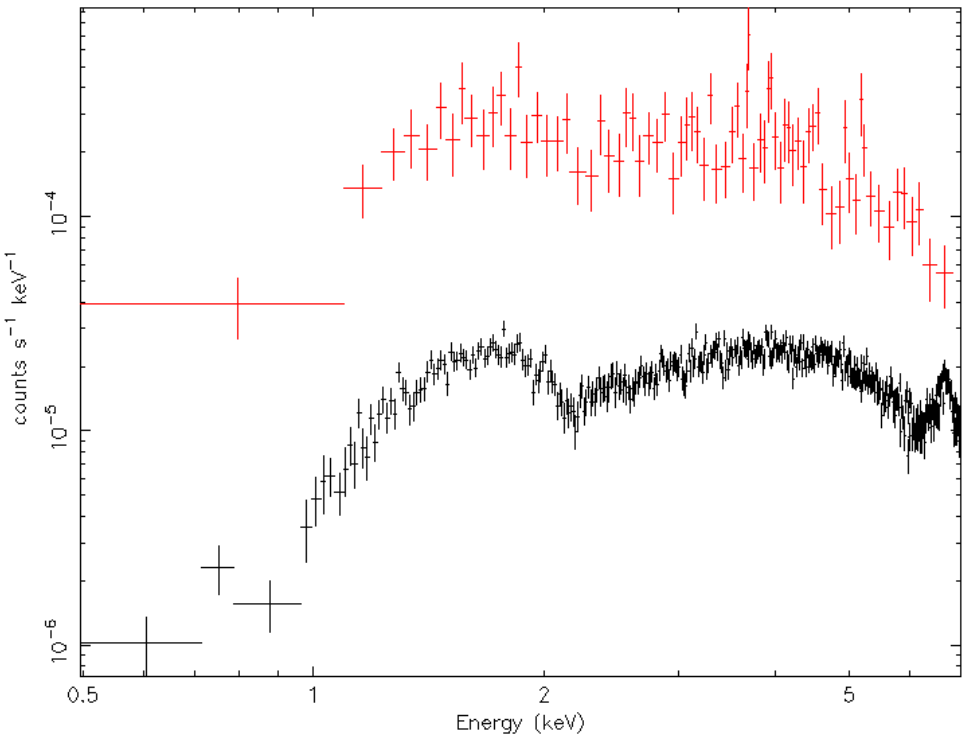
4. IR constraints with 2MASS, VVV, etc:
   - no counterpart or
   - compact objects (CO, Lin et al. 2012):

$$\log_{10}(F_X/F_K) > 0.5$$

→ **1422, 57 CO candidates**

Cumulative X-ray emission of MSP candidates

~60 CO candidates: spectrum compatible with the one of simulated MSPs



~1400 MSP candidates: contaminated by cataclysmic variables (CVs)

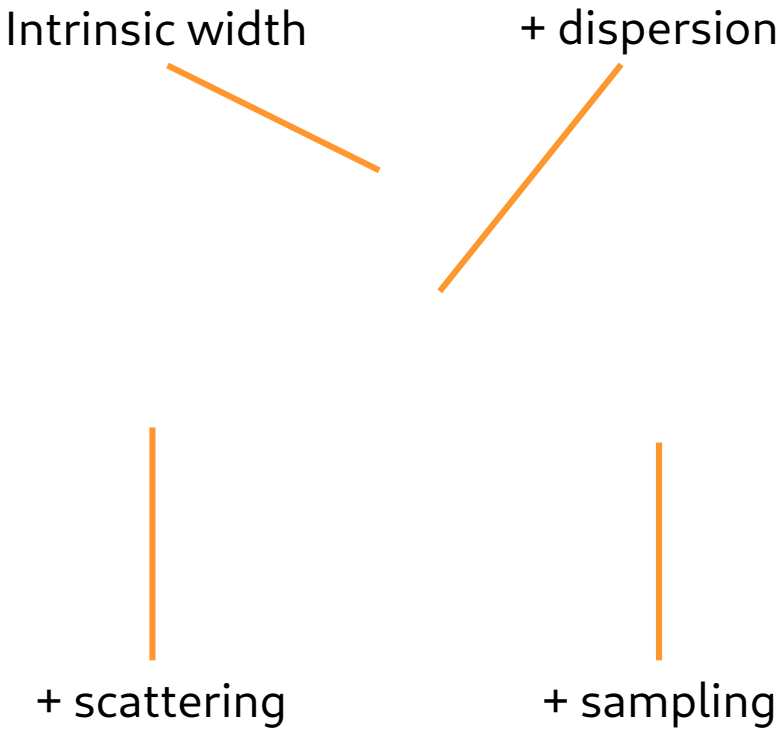
Radiometer equation

Radiometer equation:
→ minimum detectable flux S_{min}
→ as a function of pulsar period P

$$S_{min}(P)\,\alpha\sqrt{\frac{w}{T_{obs}(P-w)}}$$

Ridolfi et al. (2021)

Radiometer equation



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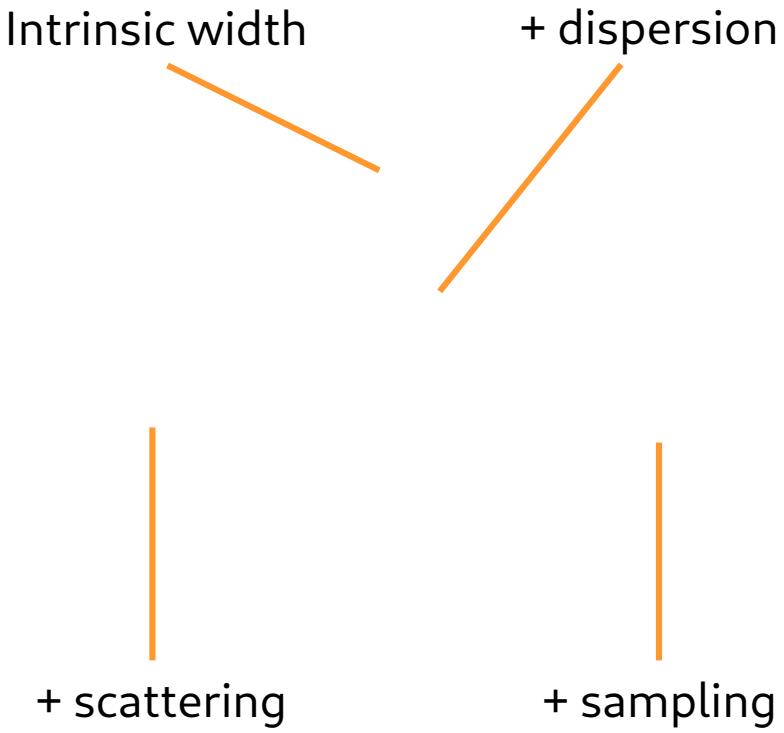


Radiometer equation:
→ minimum detectable flux S_{min}
→ as a function of pulsar period P

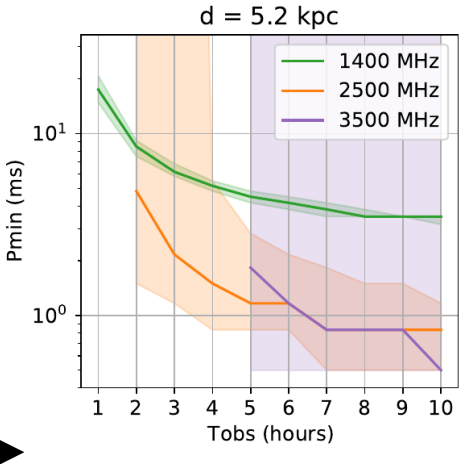
Hardest detections:

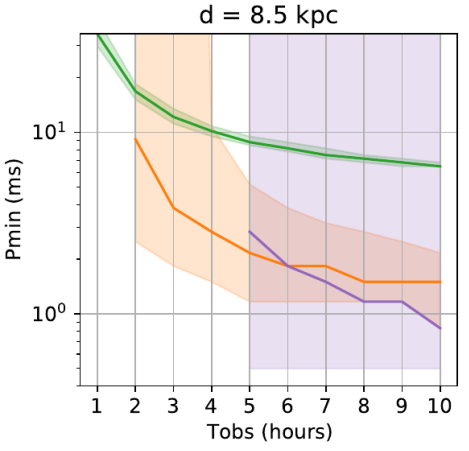
- High electron column density (DM)
- Short pulsar period
- Binary system
- Low flux

See also Calore et al. (2016)

Observations with Parkes, the GBT and the NRT

$$S_{min}(P)\,\alpha\,\sqrt{\frac{w}{T_{obs}(P-w)}}$$





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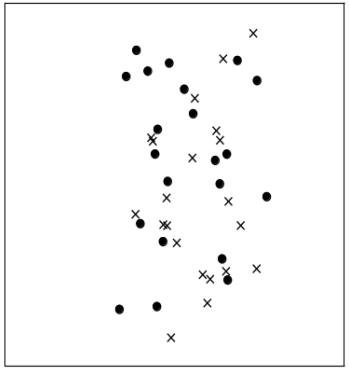

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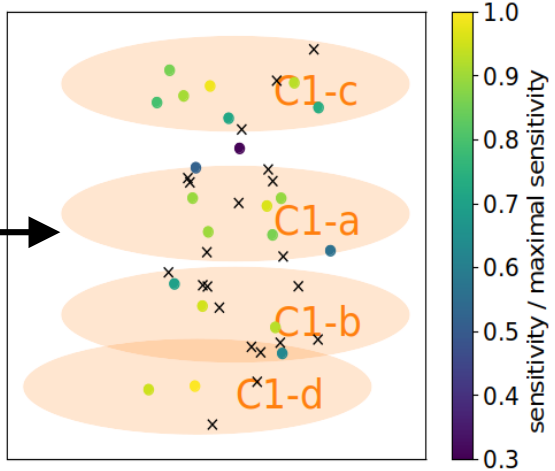


Anatomy of a bright pulsar detection with PRESTO

Well-identified pulses

Seen at all frequencies

Well-defined period and period derivative

Seen during the whole observation

Well-defined dispersion measure

Anatomy of a faint pulsar candidate

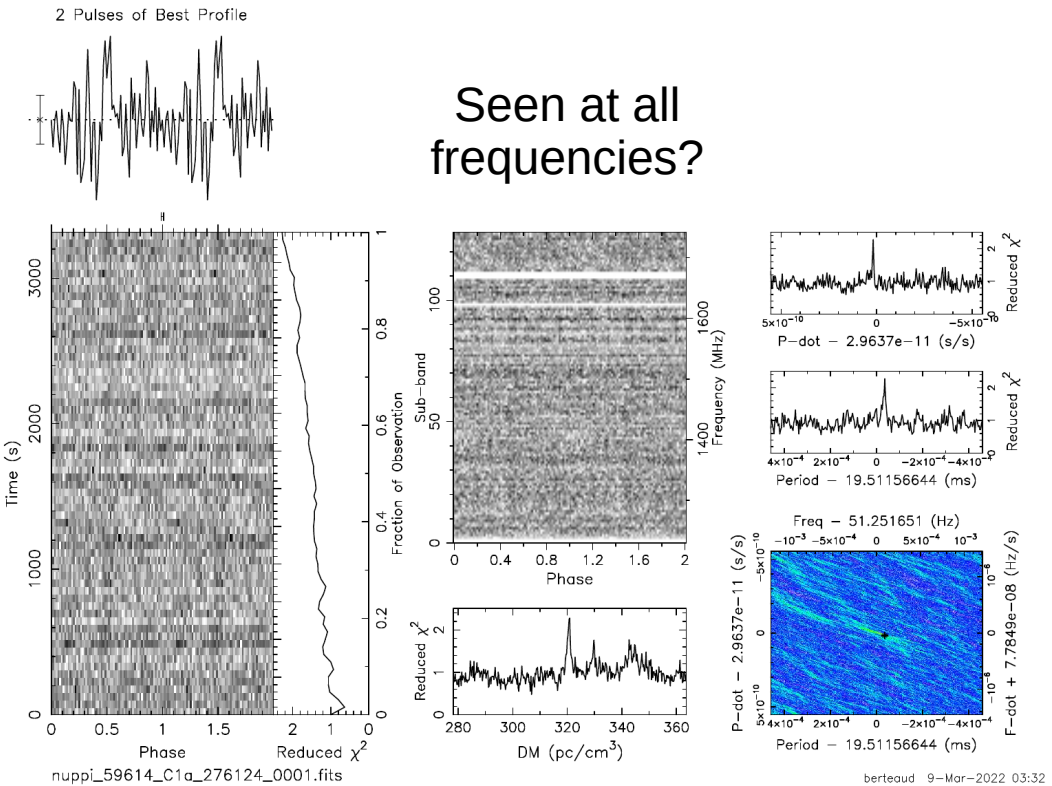
Well-identified pulses?

Seen during the whole observation?

Seen at all frequencies?

Well-defined period and period derivative?

Well-defined dispersion measure?



Anatomy of a faint pulsar candidate

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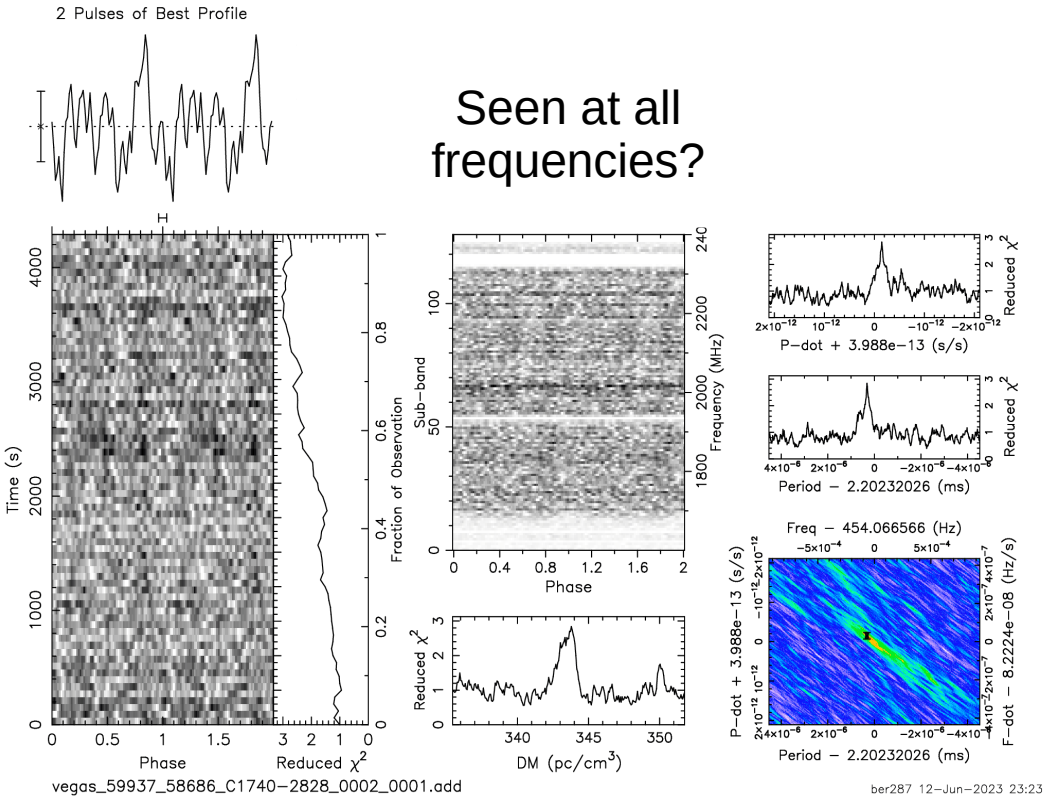

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