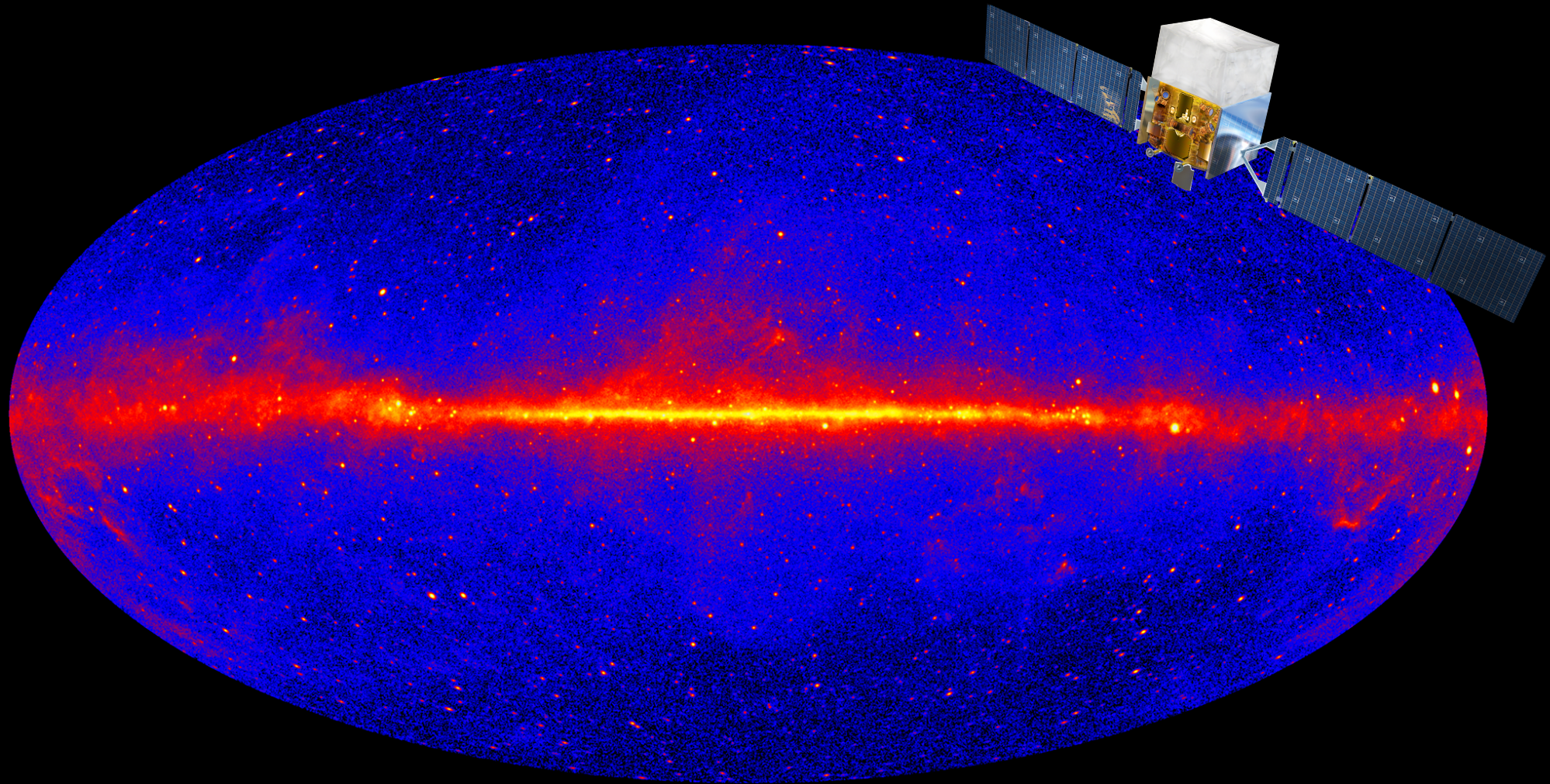


Investigating the γ -ray Galactic Center Excess with X-ray and radio data

Joanna Berteaud

Galactic Center Workshop, April 2023





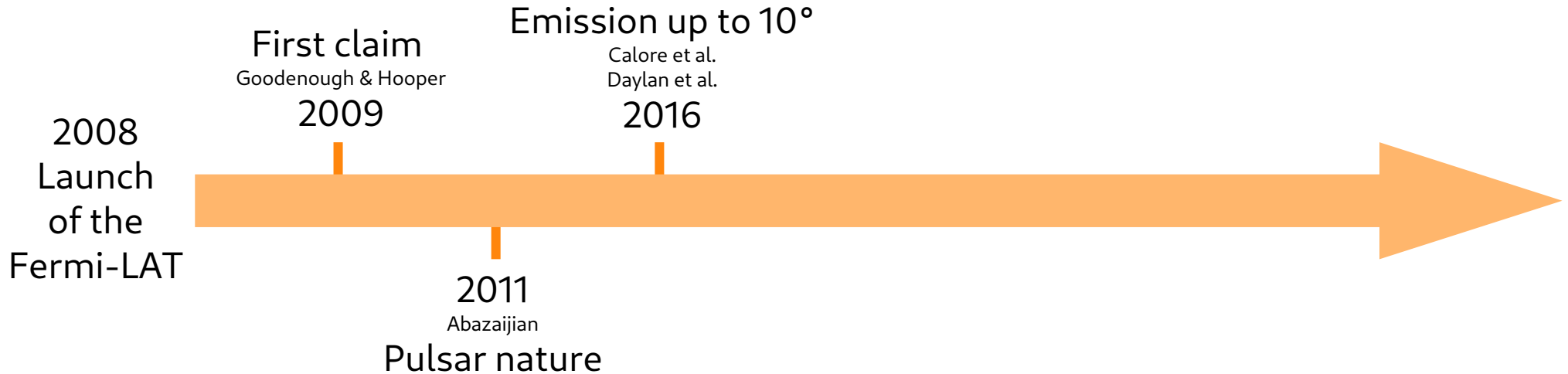
(Non-exhaustive) Timeline of the Fermi GeV excess



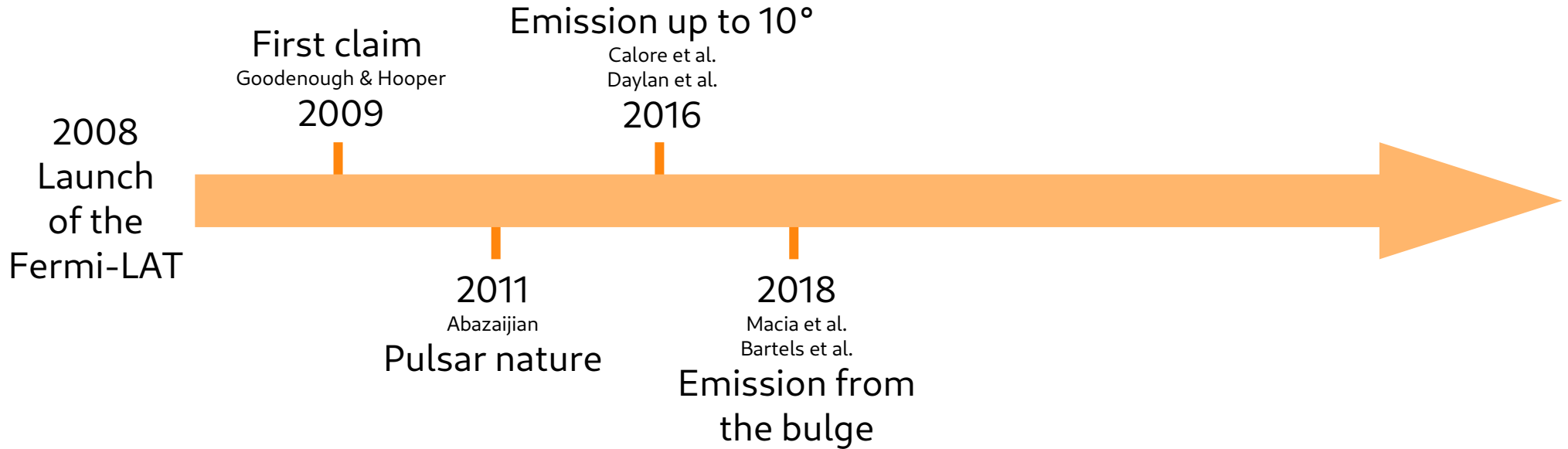
(Non-exhaustive) Timeline of the Fermi GeV excess



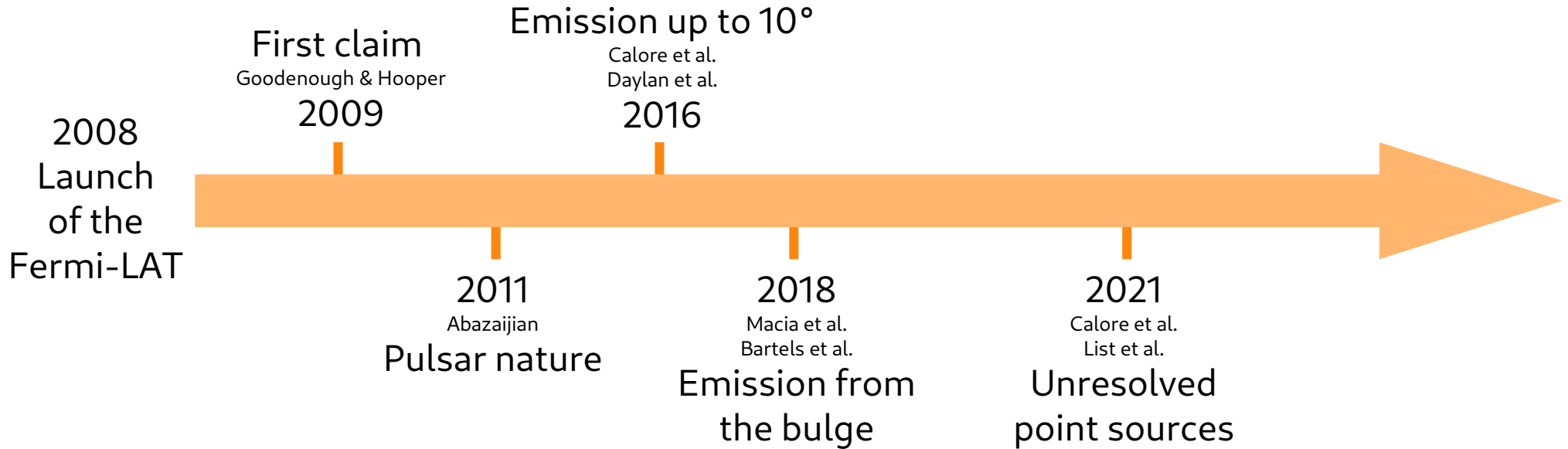
(Non-exhaustive) Timeline of the Fermi GeV excess



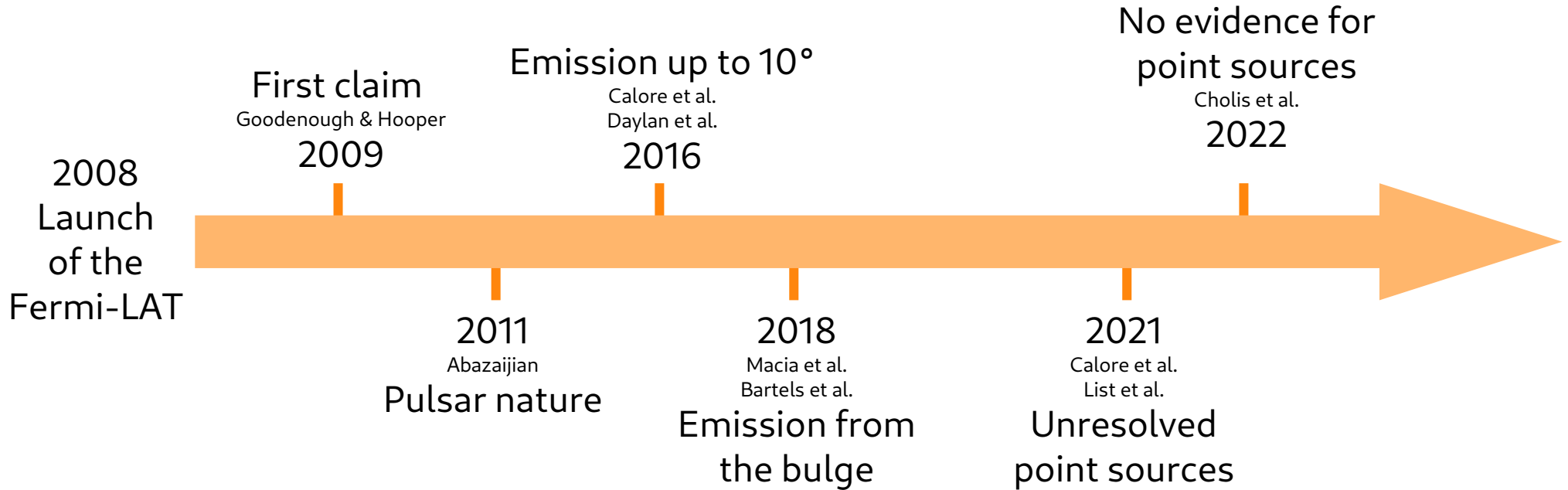
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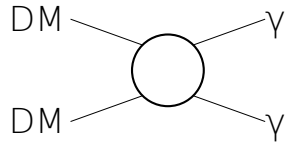
(Non-exhaustive) Timeline of the Fermi GeV excess



(Non-exhaustive) Timeline of the Fermi GeV excess



Dark Matter (DM) versus Millisecond Pulsars (MSP)

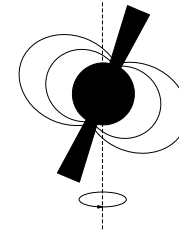


Spherically symmetric morphology

DM annihilation spectrum

Not enough LMXBs

...



Bulge-like morphology

Globular cluster spectrum

Accretion-induced collapse

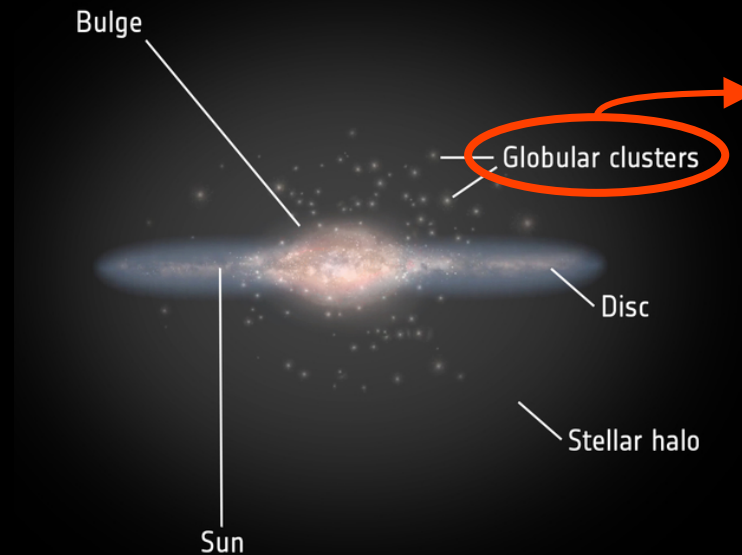
Photon-count statistics

...

Almost 15 years of debate!

Resolve the MSP population would finally settle the debate.

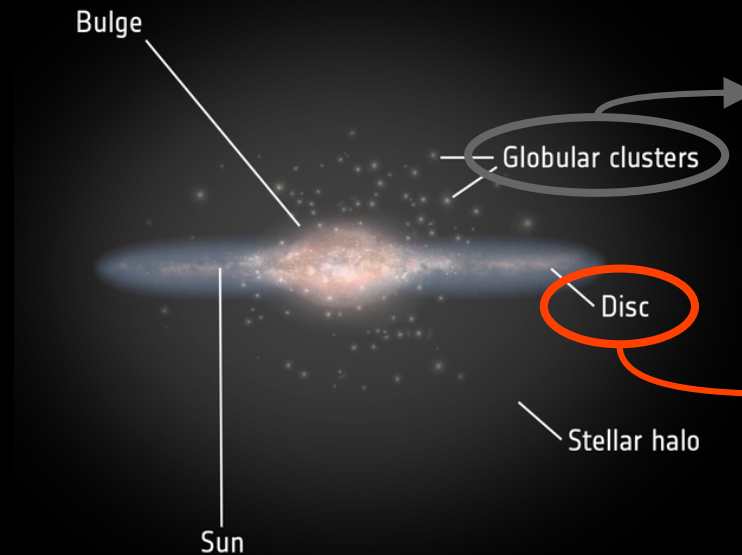
The Galactic MSP population



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

European Space Agency

The Galactic MSP population



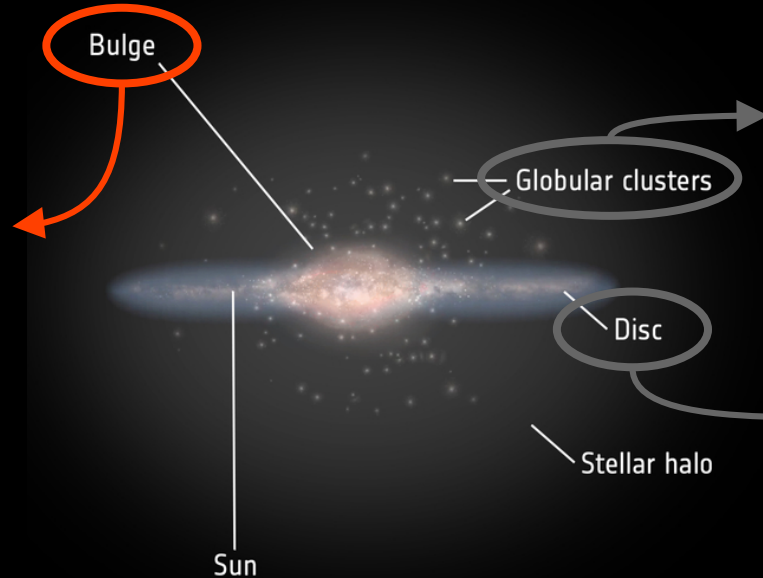
- More than 250 MSP pulsation detected in radio
- Diffuse γ -ray emission seen by the Fermi-LAT

- The rest, more than 300

European Space Agency

The Galactic MSP population

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



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

- The rest, more than 300

European Space Agency

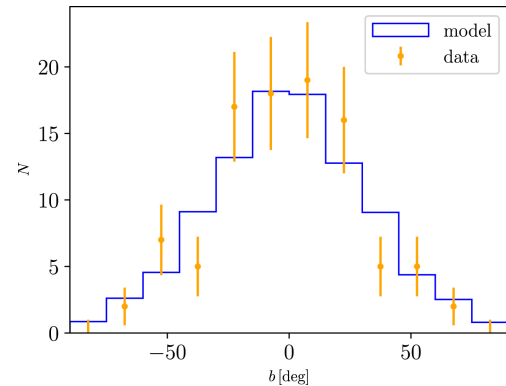
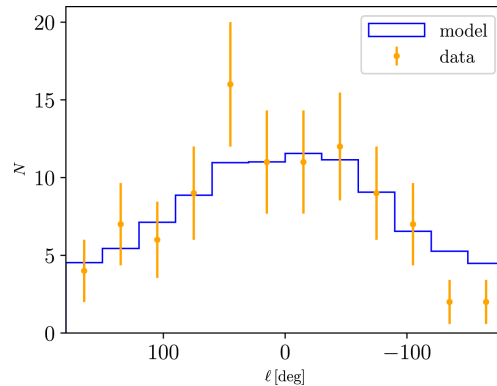
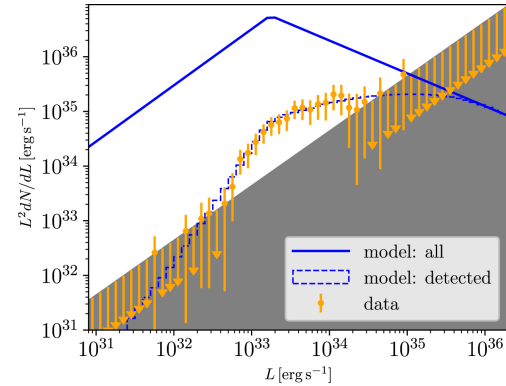
Simulation of the Galactic MSP population

Monte Carlo simulation: sequence of random numbers distributed according to a PDF
Available on [Zenodo!](#)

D
I
S
K

Bartels et al. (2018b):

- ~100 γ -ray detected (disk) MSPs
- γ -ray luminosity function
- disk number density



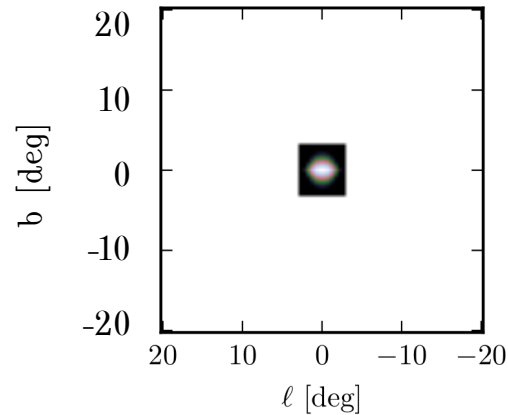
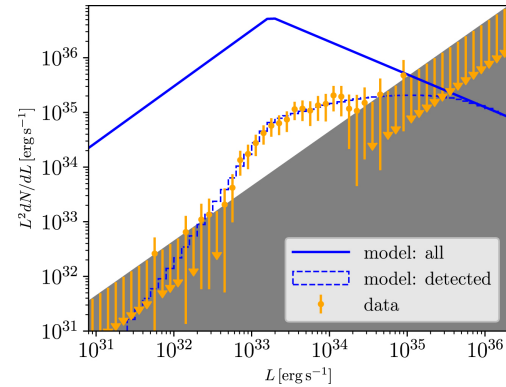
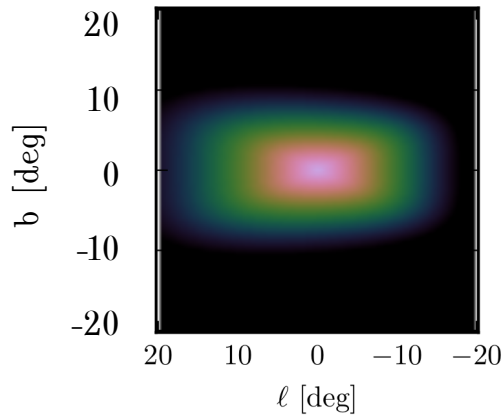
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B
U
L
G
E

Bartels et al. (2018a):

- boxy bulge (Cao et al. 2013)
- nuclear bulge (Launhardt, 2002):
 - nuclear stellar disk
 - nuclear stellar cluster



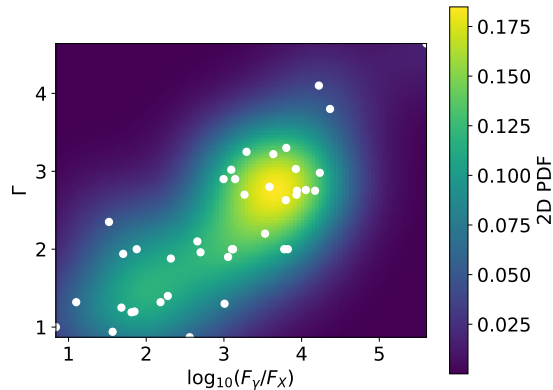
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to
X

Berteaud et al. (2021):

- 4FGL
- X-ray MSPs (Lee et al. 2018)
- 40 MSPs detected in X- and γ -rays



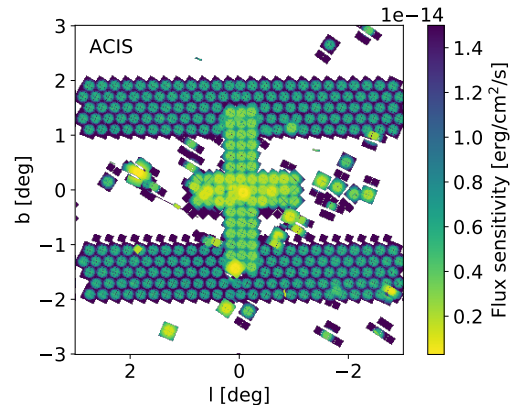
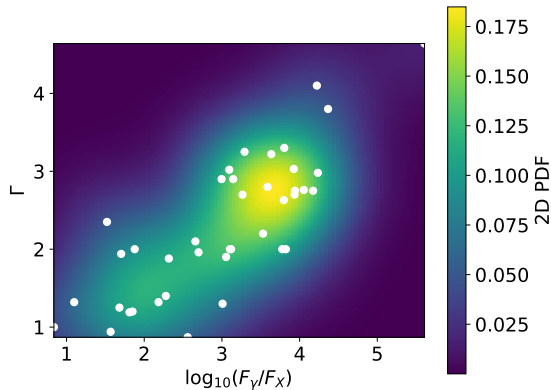
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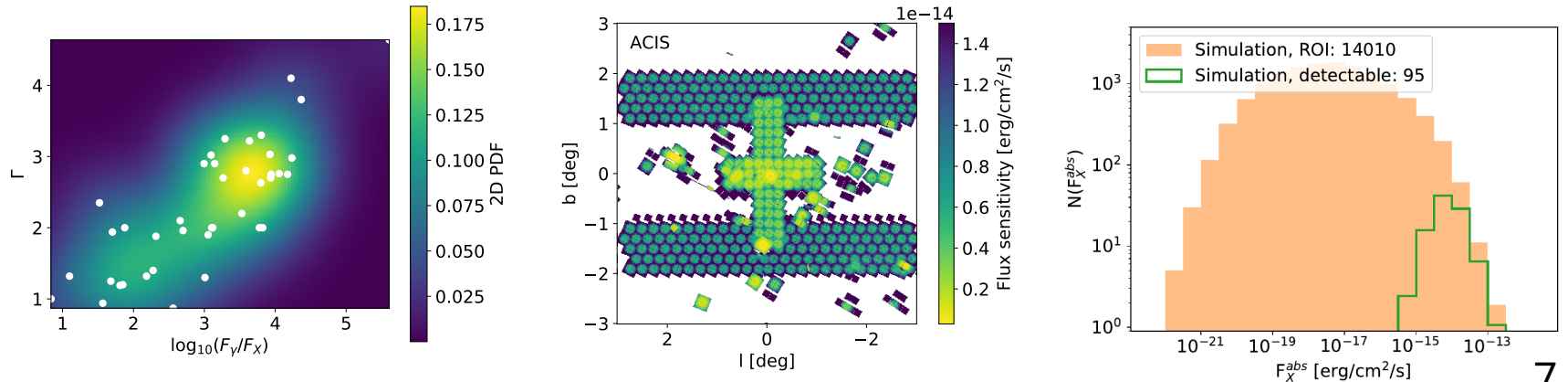
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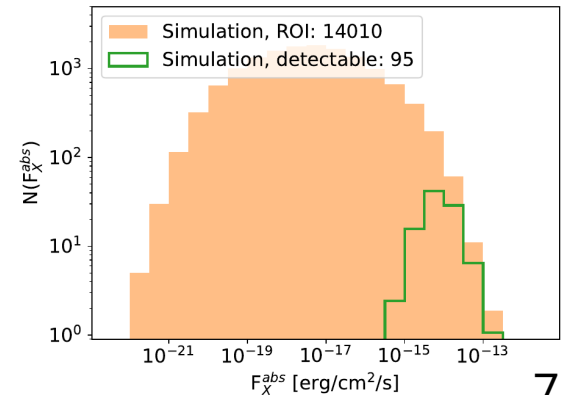
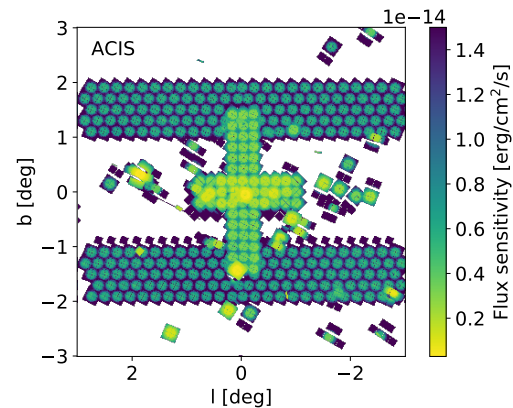
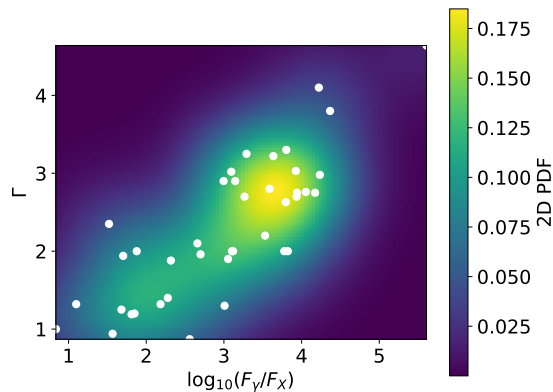
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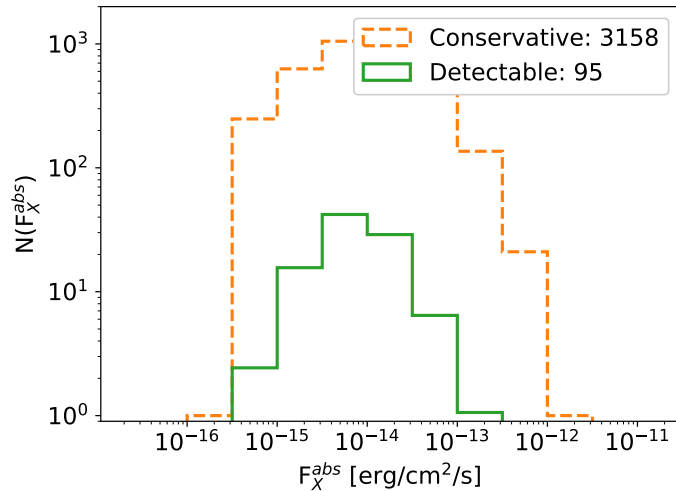
- 4FGL
- X-ray MSPs (Lee et al. 2018)
- 40 MSPs detected in X- and γ -rays

**Some bulge MSPs
have likely been detected
in past Chandra observations!**



Selection of MSP candidates

Berteaud et al. (2021, 2022)



1. From the Chandra catalog:

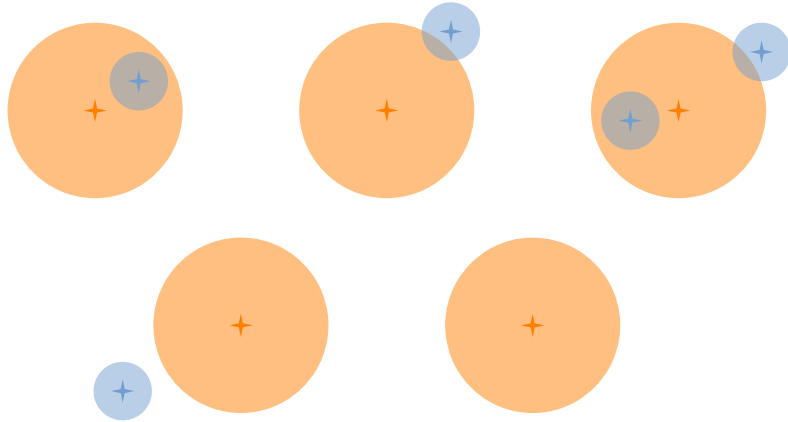
- Non-variable
- Non-extended
- Hard sources

2. Optical constraints with Gaia:

- at bulge distance (Bailer-Jones, 2021)
→ **3158** candidates > 95 expected
- no counterpart → **2358**

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- at bulge distance (Bailer-Jones, 2021)
→ **3158** candidates > 95 expected
- no counterpart → **2358**

4. IR constraints with 2MASS, VVV, etc:

- no counterpart or
- compact objects (CO, Lin et al. 2012):

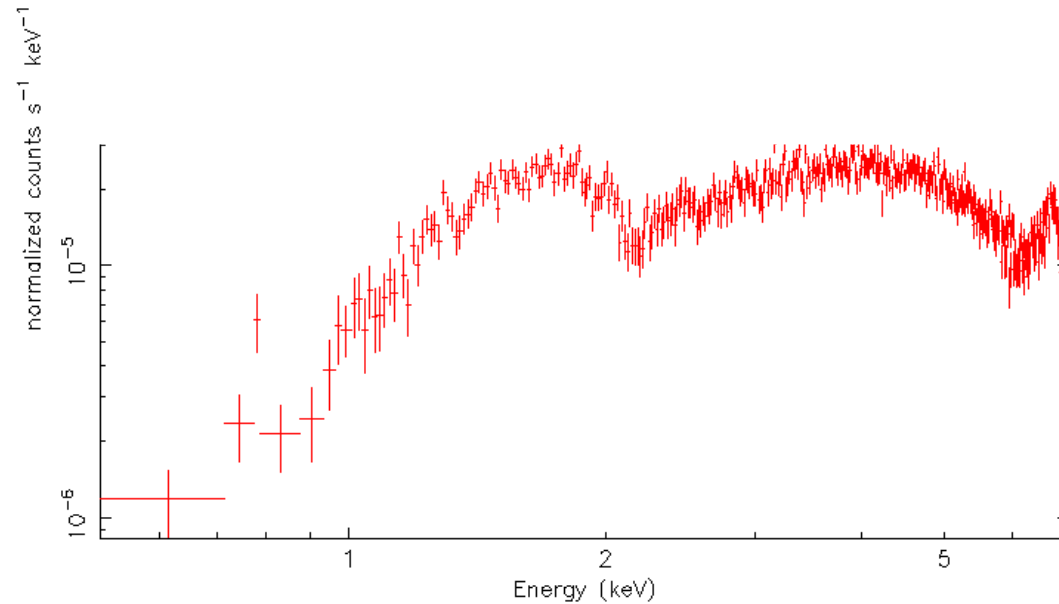
$$\log_{10}(F_X/F_K) > 0.5$$

→ **1421**

3. UV constraints with XMM-OM:

- no counterpart → **2298**

Cumulative X-ray emission of MSP candidates

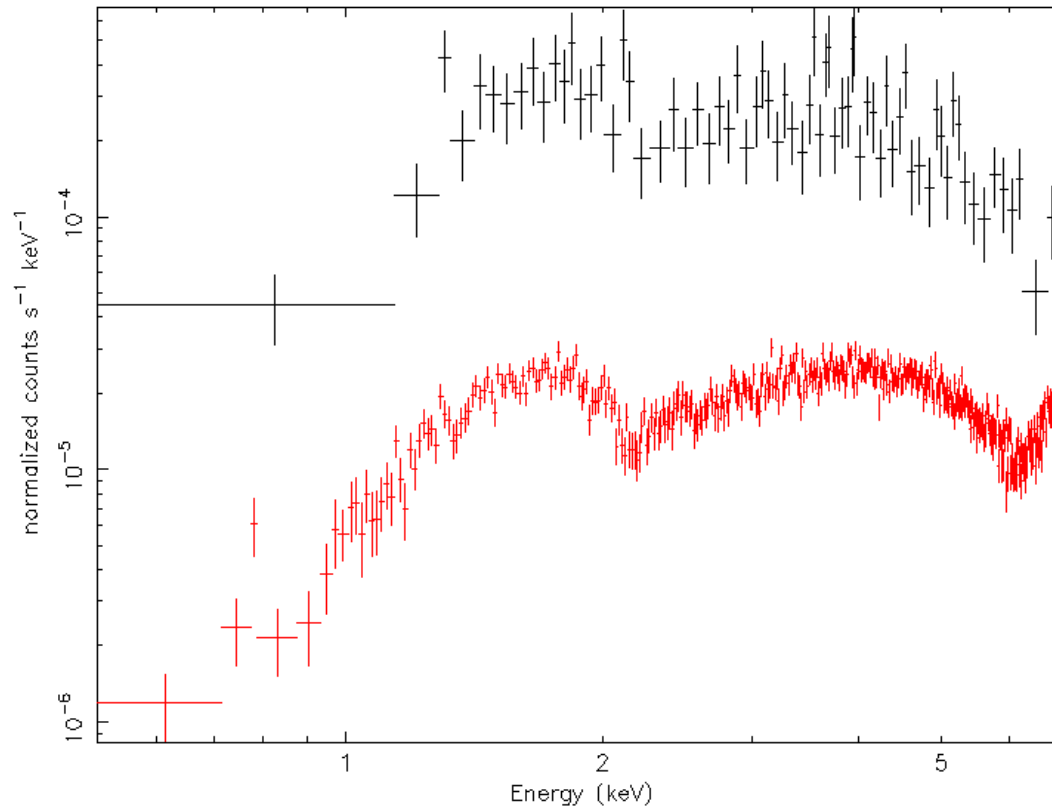


Whole population
is (unsurprisingly)
contaminated by
cataclysmic
variables (CVs)

What are the X-ray sources without optical/UV/IR counterpart apart from CVs?

Cumulative X-ray emission of MSP candidates

Spectrum of CO candidates compatible with the cumulative emission of detectable MSPs from the simulation

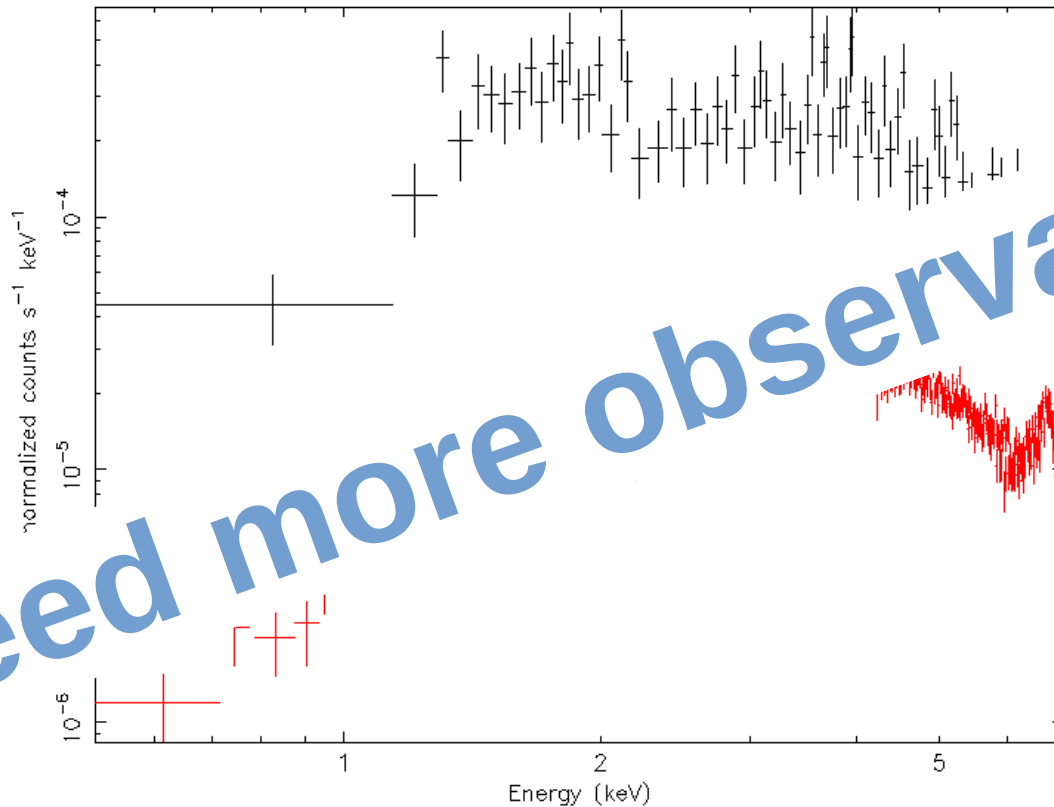


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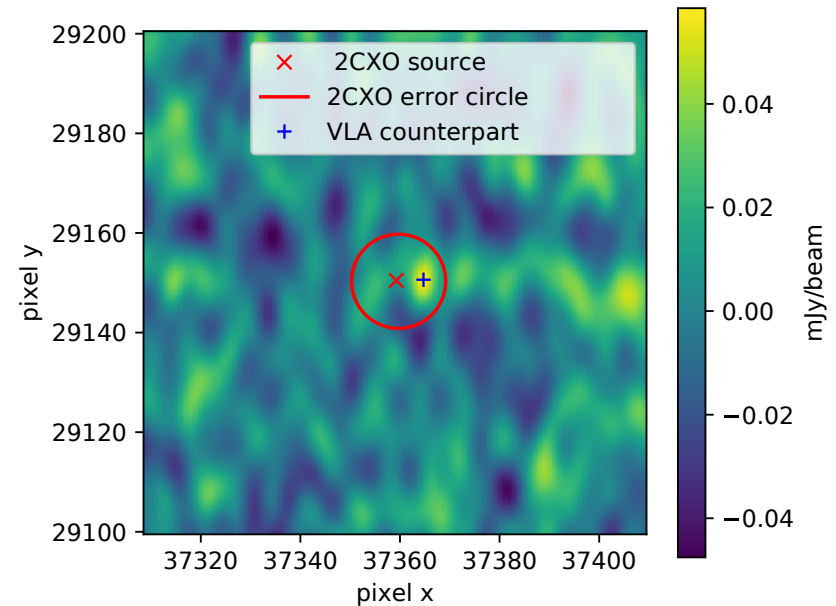
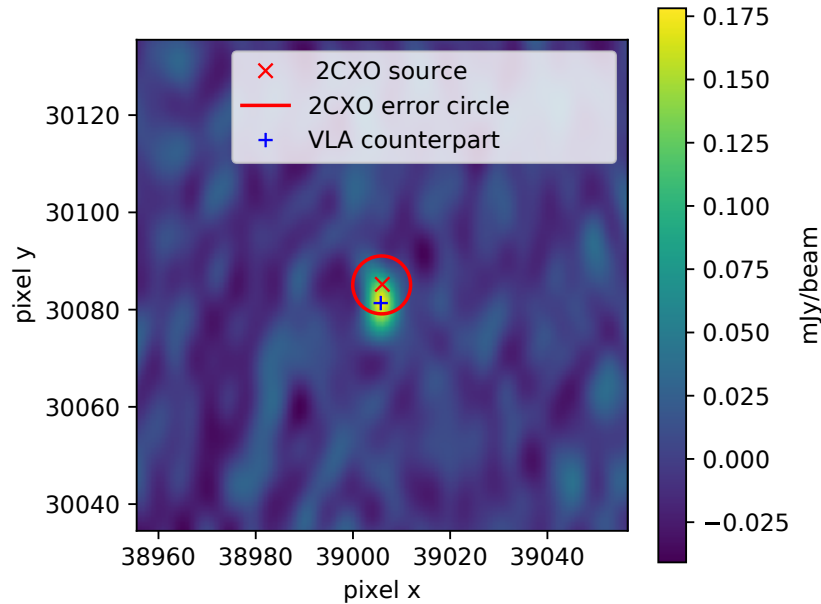


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What are the X-ray sources without optical/UV/IR counterpart apart from CVs?
What are the compact objects if not MSPs?

Radio counterparts

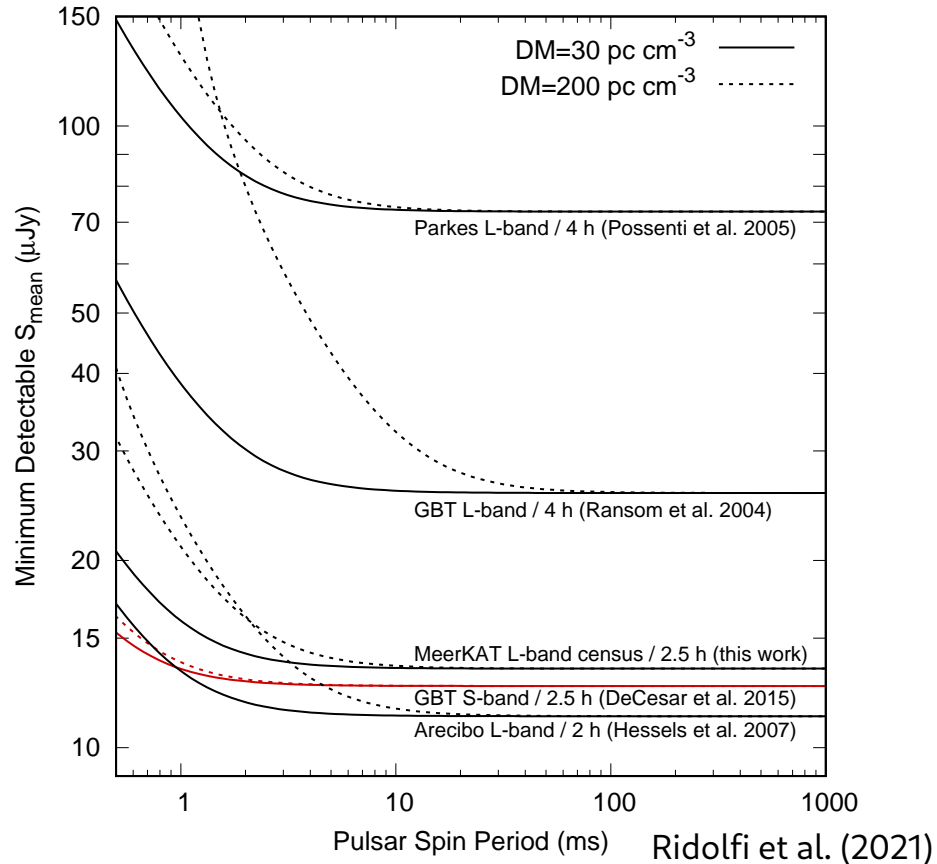
VLA L-band imaging data: 18 positive cross-matches, 6 suitable MSP candidates



Sobey et al. (2022): candidates = radio sources without optical/IR counterpart
→ 2 new disc pulsars!

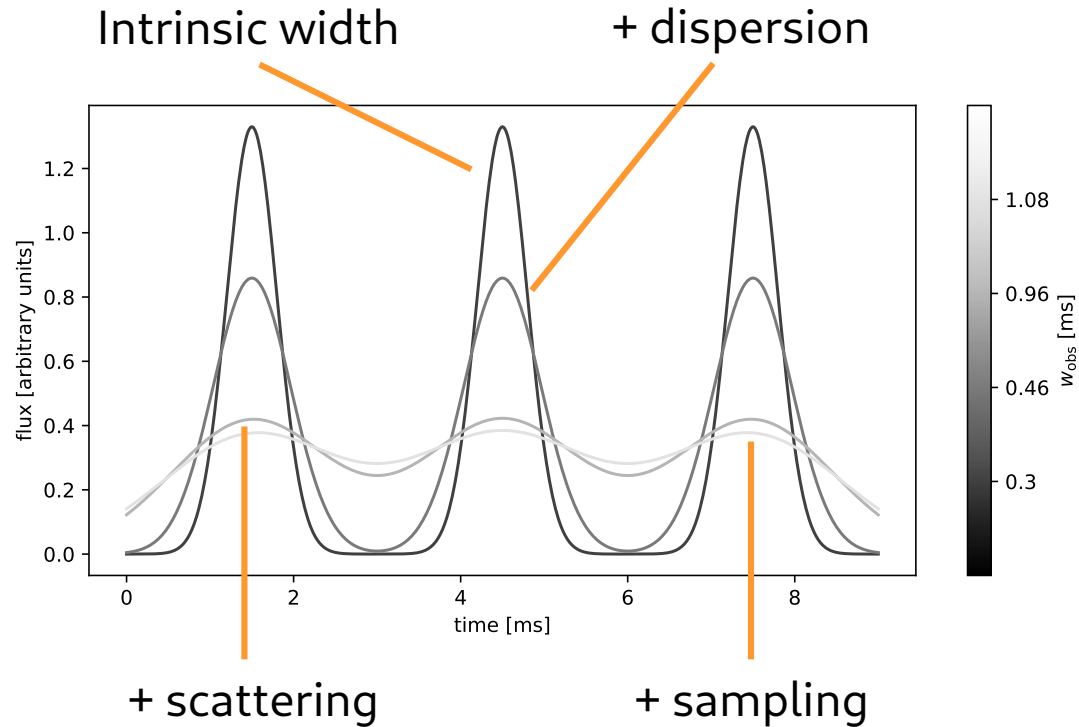
Let's observe!

Radio follow-ups



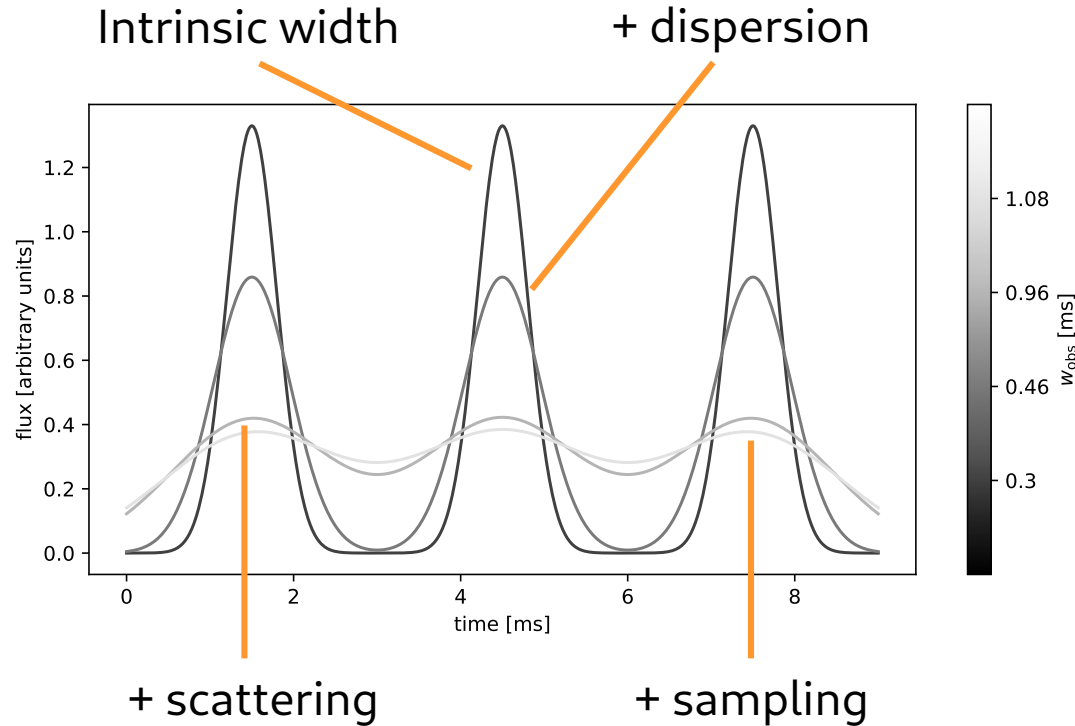
Radiometer equation: minimum detectable flux as a function of pulsar period, observing time

Radio follow-ups



Radiometer equation: minimum detectable flux as a function of pulsar period, observing time

Radio follow-ups



Radiometer equation: minimum detectable flux as a function of pulsar period, observing time

Hardest detections:

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

See also Calore et al. (2016)

Radio follow-ups



- Deep targeted timing observation proposals
- ~70h granted with:
 - the Nançay Radio Telescope
 - Parkes
 - the Green Bank Telescope (ongoing)

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- Multiple detections are needed for confirmation

Radio follow-ups



We need more observations!

...submitting observation proposals

...started with:

...the Nançay Radio Telescope

- Parkes
- the Green Bank Telescope (ongoing)

- No obvious detections but faint candidates
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Take-home messages

- Bulge MSPs are very serious candidates for the Galactic Center Excess
→ See talk by Andrew Miller
- Chandra likely detected some of them in the past
- Many sources are suitable MSP candidates

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Thank you for your attention!