Multi-wavelength probes of the Fermi GeV excess:

A multi-wavelength search for bulge millisecond pulsars

Journées PNHE
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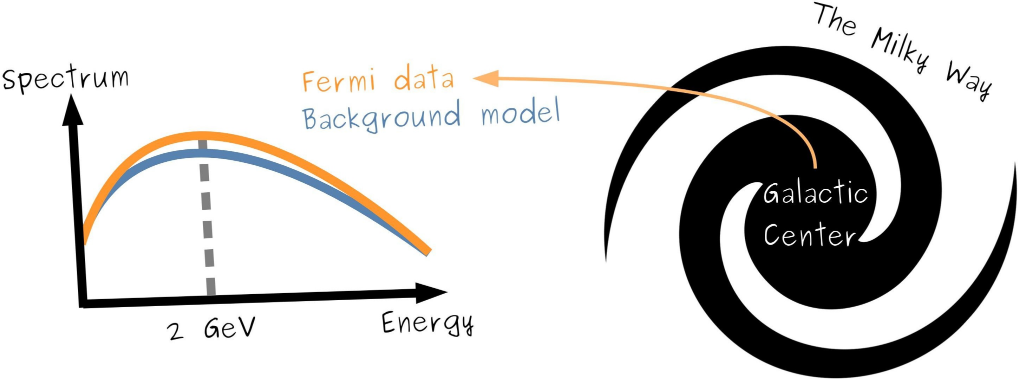
Joanna Berteaud

Francesca Calore
Maïca Clavel

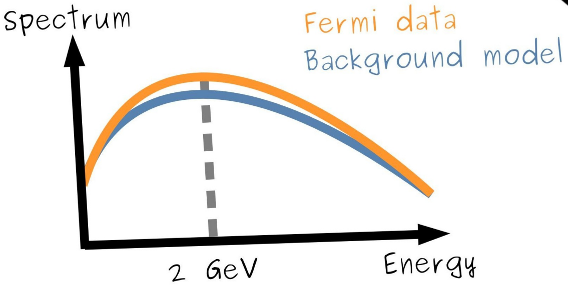
Introduction

What is the Fermi GeV excess?



Goodenough+09

Introduction
What is the Fermi GeV excess?



Abazadjian10

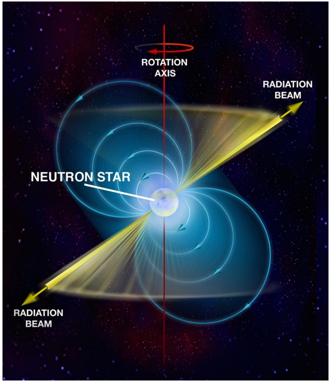
Introduction
Why millisecond pulsars?

Millisecond pulsars:

- **Pulsars**: fast rotating neutron stars, γ-ray emitters
- Rotation period shorter than 30 **milliseconds**
- Older than normal pulsars

Excess:

- Same spectrum as globular clusters hosting MSPs
- Morphology traces old stars in the Galactic bulge



Credit: B. Saxton, NRAO/AUI/NSF.

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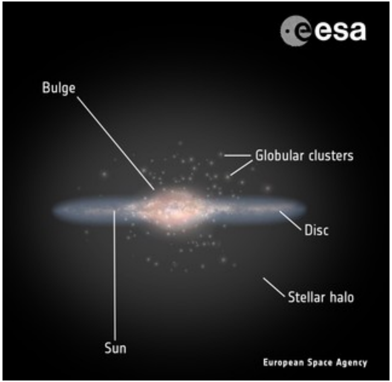
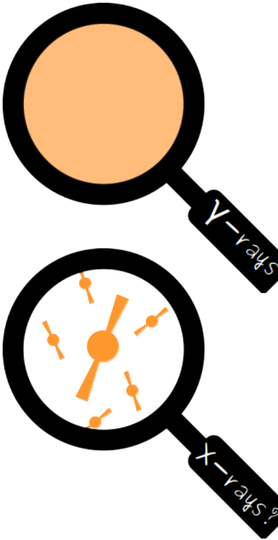


ESA, ESA/ATG medialab.

Introduction
X-ray detectability of the MSP population

Could the MSP population be seen in X-rays?

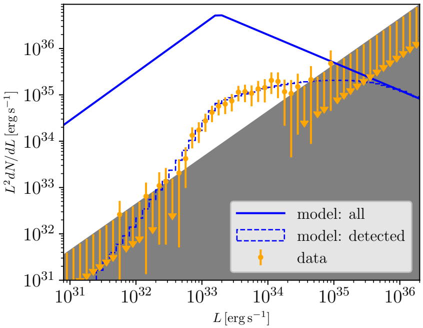
1. Simulate an MSP population having the properties of the excess
2. Find a relation between the γ- and X-ray emission of observed MSPs
3. Compare the simulated X-ray emission to an X-ray telescope sensitivity
4. Look for MSP candidates in X-ray data



Introduction

X-ray detectability of the MSP population: simulate an MSP population

We know a bit about MSPs, a lot about the excess:



Bartels+18.

$$L_\gamma^{excess} = 2 \times 10^{37} erg/s$$

$$n(x,y,z) = K_0 \left(\left[\left[\left(\frac{x}{x_0}\right)^2 + \left(\frac{y}{y_0}\right)^2 \right]^2 + \left(\frac{z}{z_0}\right)^4 \right]^{\frac{1}{4}} \right)$$

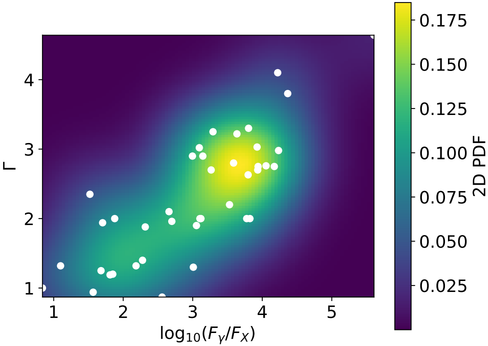
More details in Berteaud+21

$\Longrightarrow$ **Monte Carlo simulations**

Introduction

X-ray detectability of the MSP population: find a relation between the γ- and X-ray emission

- Calculation of the γ-to-X flux ratio of 40 observed MSPs
- Ratio correlated with the X-ray spectral index Γ
- Computation of a 2D probability density function



Berteaud+21.

$\Longrightarrow$ **Monte Carlo simulations**

Introduction

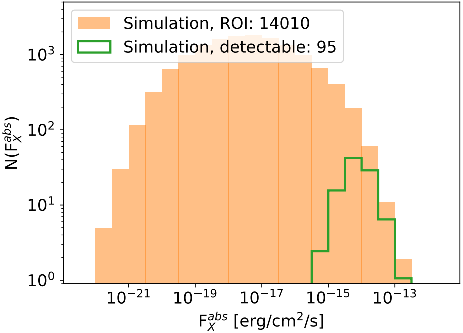
X-ray detectability of the MSP population: compare the X-ray emission to an X-ray telescope sensitivity

Chandra X-ray observatory:

- High spatial resolution
- Low instrumental background

Detectability of the MSP population:

- Region of interest: $6^\circ \times 6^\circ$ around the Galactic Center
- MSP flux > Chandra sensitivity $\Longrightarrow$ detectable
- A few hundred of detectable MSPs



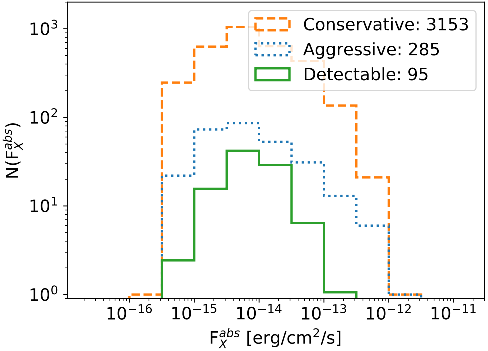
Berteaud+21.

Introduction

X-ray detectability of the MSP population: look for MSP candidates in X-ray data

Comparison with data:

- Chandra data: unidentified sources
- MSP candidate properties:
  1. Power-law X-ray spectrum
  2. Intermediate distance
  3. Very faint or no optical counterpart
- MSP hypothesis not excluded by the data
- Few hundreds of **promising candidates** kept for follow-up studies



Berteaud+21.

Multi-wavelength cross-matches
MSP criteria

For bulge MSPs, we expect:

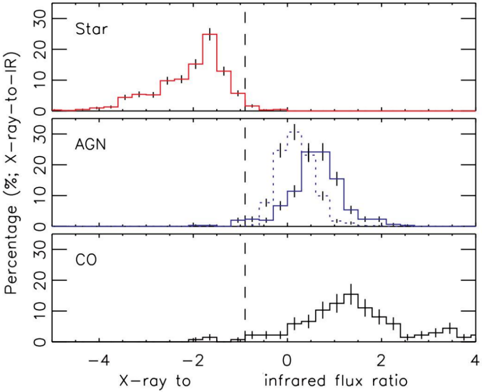
1. No optical counterpart (Antoniadis20)

2.a No IR counterpart **or**

2.b Faint IR counterpart (Lin+12):

$$\log_{10}(F^{abs}_{0.1;10keV}/F_{IR}) > 0.5$$

3. No UV counterpart



Lin+12.

Multi-wavelength cross-matches

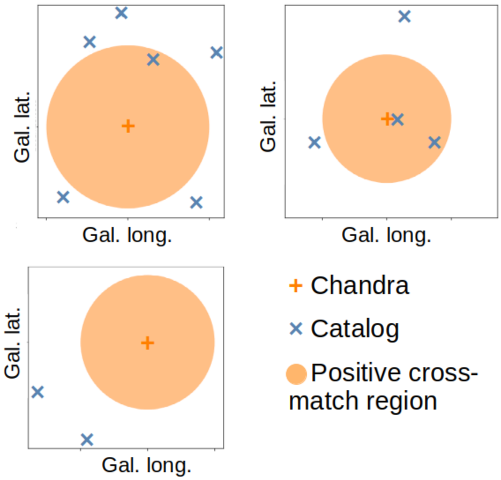
Goal and method

The goal of the multi-wavelength cross-matches is:

- **not** to find the true counterpart
- to exclude all candidates that **potentially** don't respect our criteria
- to keep only the most promising candidates

Method:

- Positive cross-match according to the angular separation
- Maximum separations depend on the positional uncertainties



Multi-wavelength cross-matches
Results

Ultraviolet:

- XMM-OM: 7 positive cross-matches

- 7 exclusions

Infrared:

- 2MASS: 10 positive cross-matches, no compact object
- VVV: 23 positive cross-matches, no compact object
- GLIMPSE: 5 positive cross-matches, no compact object

- 38 exclusions

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The 158 remaining promising candidates are only detected in X-rays so far.

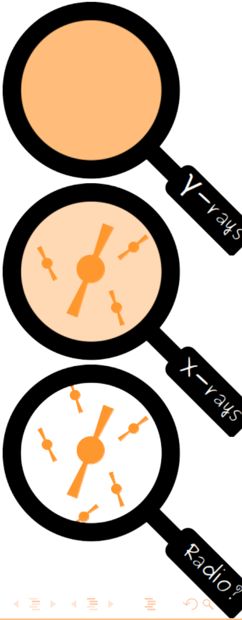
Future radio observations
Radio emission predictions

Motivations:

- The detection of a pulsation would identify a candidate as pulsar
- More chances to detect a radio pulsation than an X-ray pulsation
- Demonstrating that a candidate is radio detectable can motivate observations

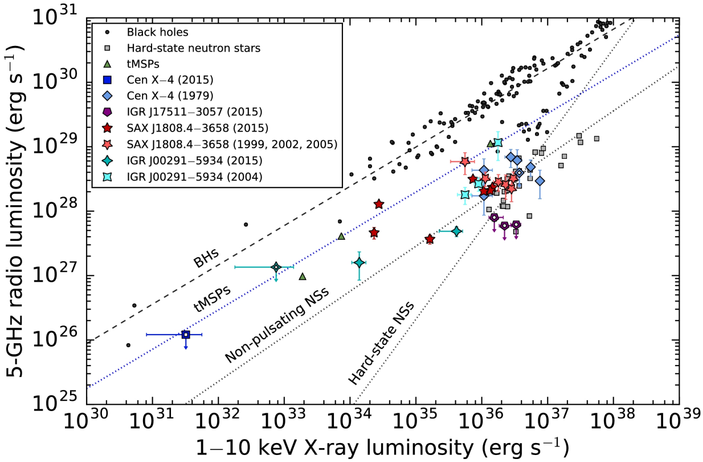
Method:

- Find a relation between the X-ray and radio luminosity of observed MSPs
- Use Chandra X-ray data of the candidates to estimate their radio emission



Future radio observations

$L_X - L_R$ relation: known correlations for other type of objects

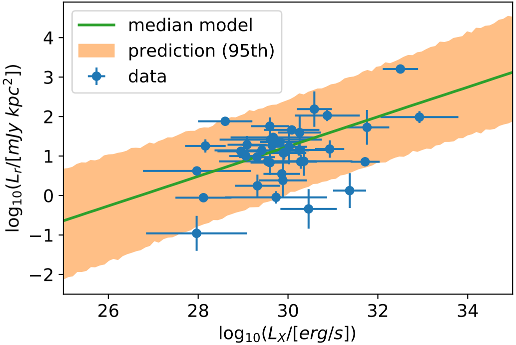


Tudor+17.

Future radio observations
$L_X - L_R$ relation

PRELIMINARY

- MSP **data and errors**:
  X-ray, from Lee+18 (2-10 keV)
  Radio, from the ATNF pulsar catalog (1.4 GHz)
- Correlation coefficient: 0.45
- Not as correlated as for BHs

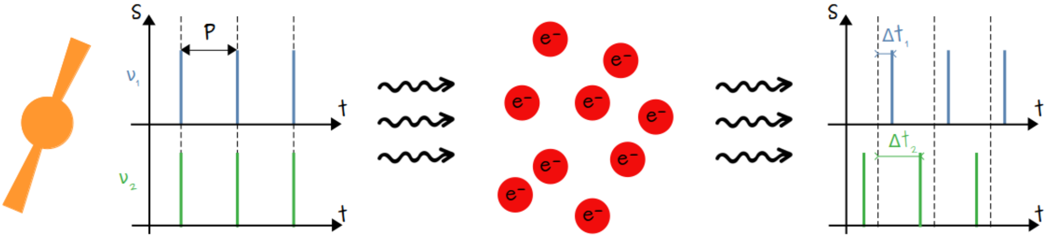


`Pystan`:

- **Linear model** with additional systematic
- **Prediction interval**

Future radio observations
Pulsation detection challenges

Dispersion in a tenuous plasma

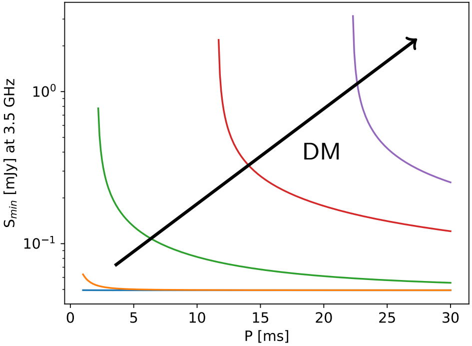


$$\Delta t = |\Delta t_1 - \Delta t_2| \propto \int_0^D n_e(l)\, dl = DM$$

D: pulsar distance
n_e: density of electrons
DM: dispersion measure, column density of electrons

Future radio observations
Pulsation detection challenges

- Minimal detectable flux density S_{min} increases when:
  1. pulsar DM increases
  2. pulsar period P decreases
  3. the frequency decreases
- Explains why Galactic Center MSPs are hard to detect
- But more chances with the Galatic bulge:
  - Lots of detectable MSPs between 5 and 8 kpc
  - DM lower at $|b| > 1^\circ$ than $b = 0^\circ$



Future radio observations

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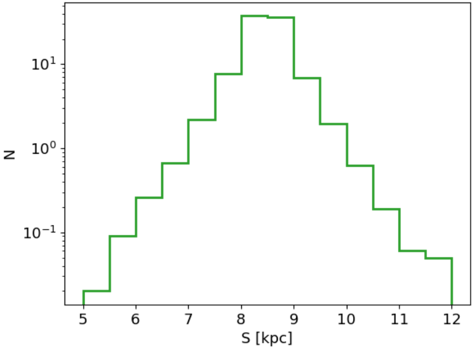
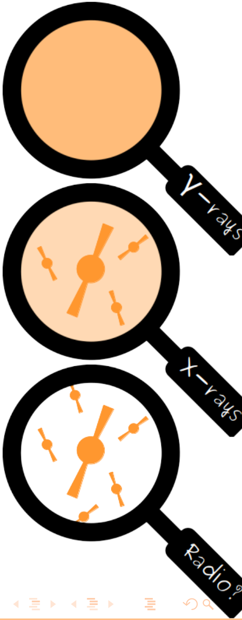


Conclusion and future prospects

- Some bulge MSP, unresolved in γ-rays, could be seen in X-rays
- The MSP hypothesis explaining the GeV excess is consistent with Chandra data

- More than 3000 possible MSP candidates found among Chandra unidentified sources
- About 160 promising candidates found, only seen in X-rays so far

- A pulsation detection at radio wavelength would identify a candidate as a pulsar
- Ongoing searches with current radio telescopes
- A relation between the X-ray and radio emission exists for BHs, could exist for MSPs
- Galactic Center MSPs might be hard to detect but Galactic bulge MSPs offer more opportunities!



Bibliography

Thank you for your attention!

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- Antoniadis20: arXiv:2011.08075
- Lee+18: 2018 ApJ 864 23
- Tudor+17: 1705.05071