Galactic center GeV excess: dark matter annihilation vs millisecond pulsars

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Synergies in Non-Thermal Astrophysics, 29.07 – 02.08 2024

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Dark Matter in the Galactic center

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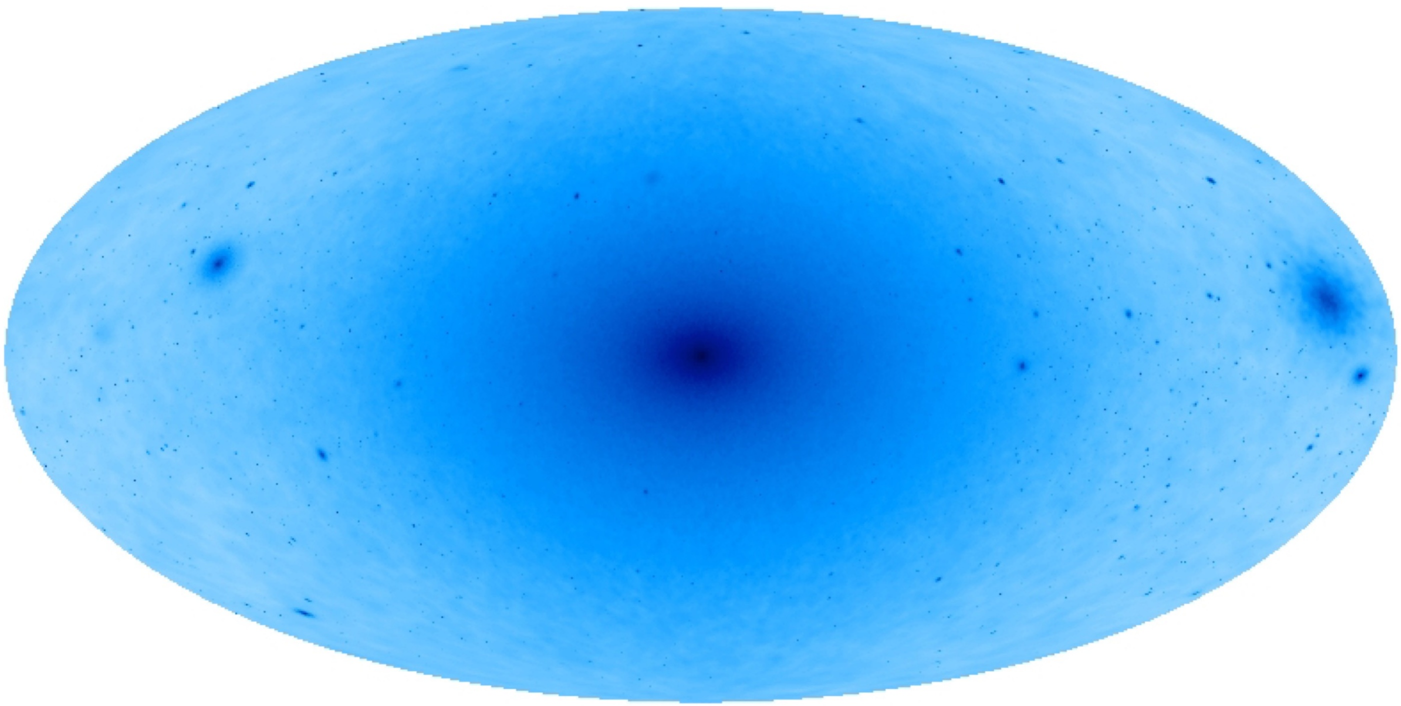
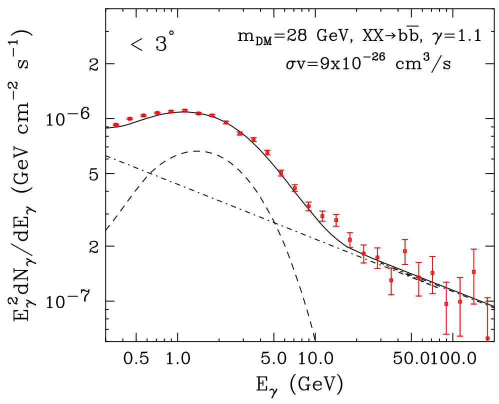
- Dark matter annihilation signal in a Milky Way-like galaxy
  - Galactic center is the strongest possible source of DM annihilation



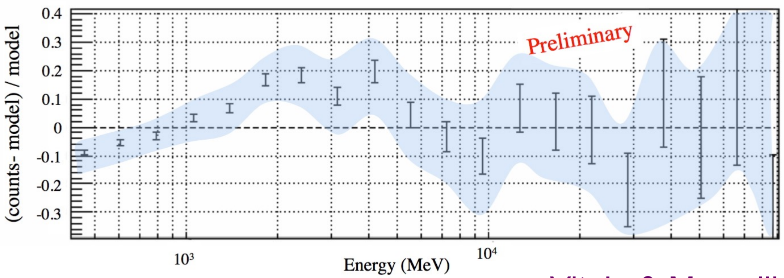
Via Lactea II, Kuhlen et al, Science, 325 (2009)

Galactic center excess

- Detected two months after the Fermi-LAT gamma-ray data became public

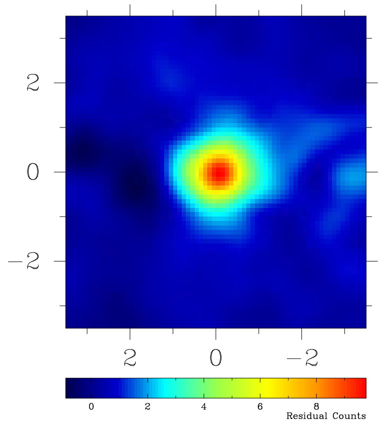


Goodenough & Hooper
arxiv:0910.2998

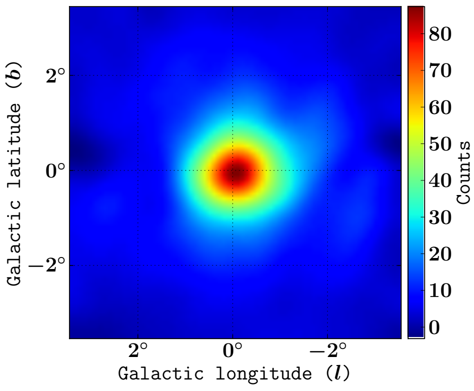


Vitale & Morselli
arxiv:0912.3828

- Spherical morphology – dark matter annihilation?

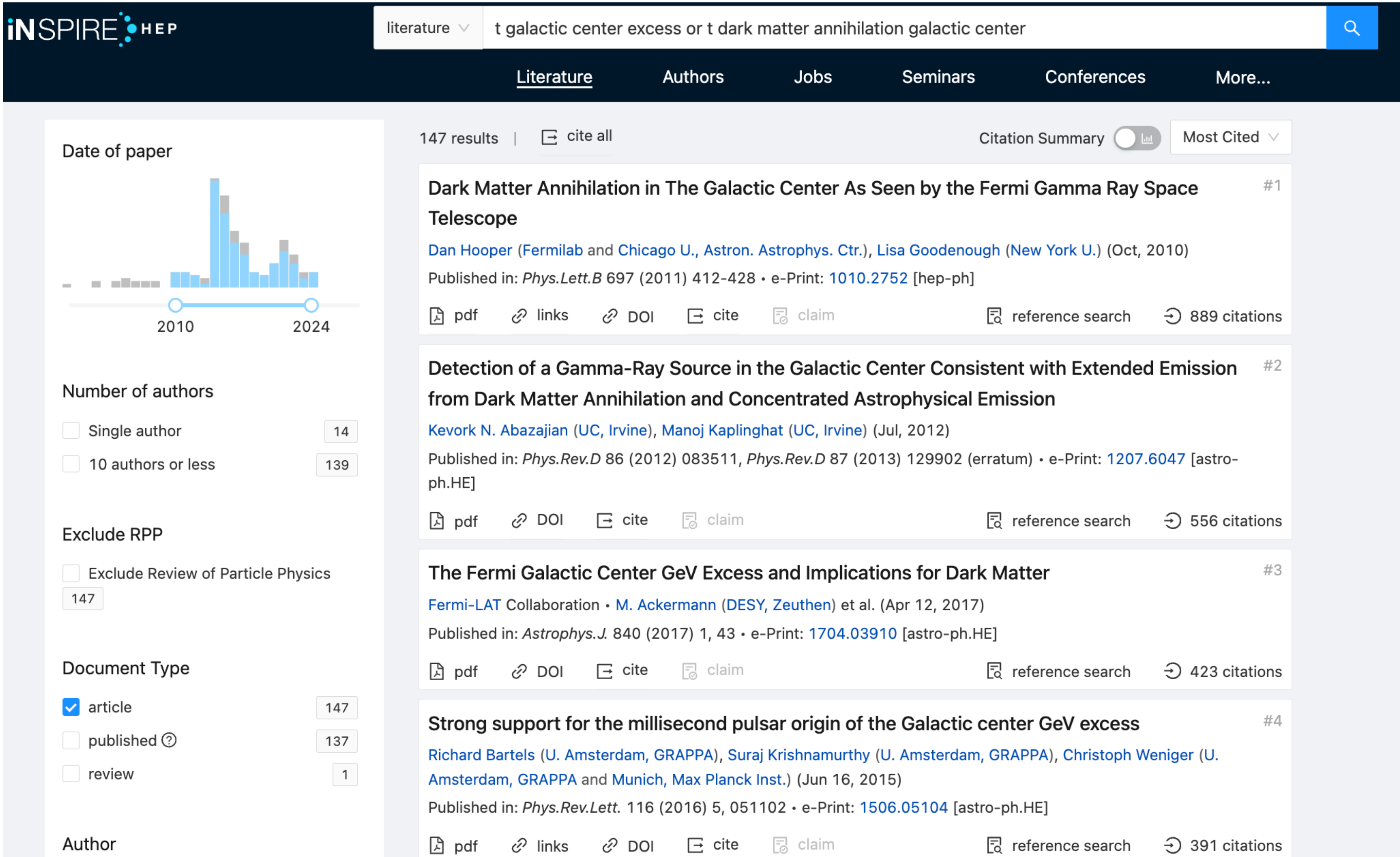


Abazajian & Kaplinghat
PRD 87 (2012)



Gordon & Macias
PRD 88 (2013)

Possible interpretations



Millisecond pulsars (MSPs)

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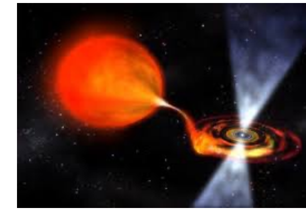
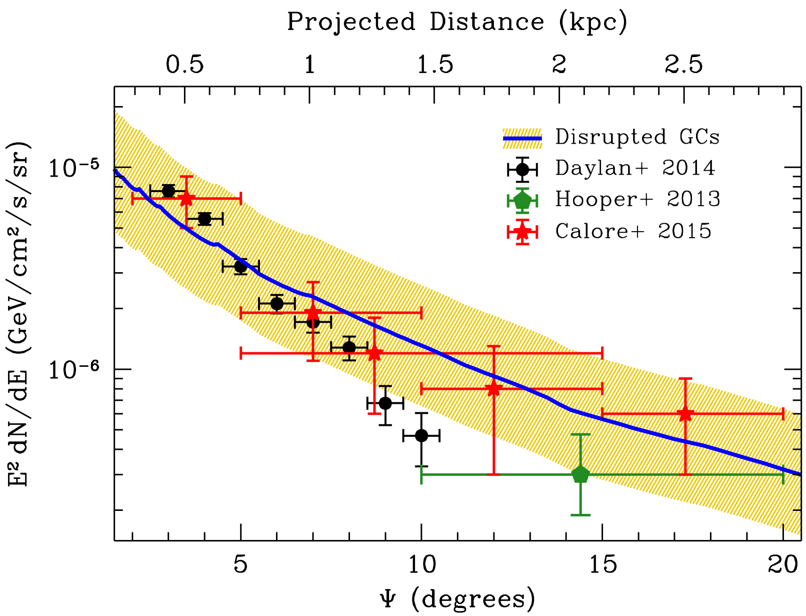
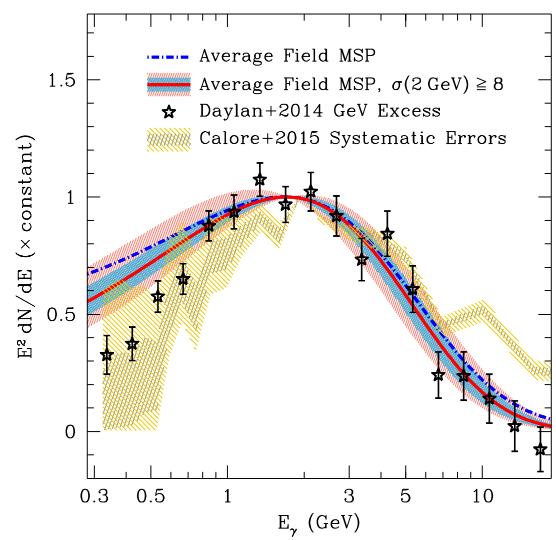


Image credit: NASA

- Fast-rotating pulsars often found in binaries
  - Spin up due to accretion from the companion
  - Can emit gamma-rays for billions of years
- A population of MSPs near the GC from disrupted globular clusters can fit the spatial profile and energy spectrum



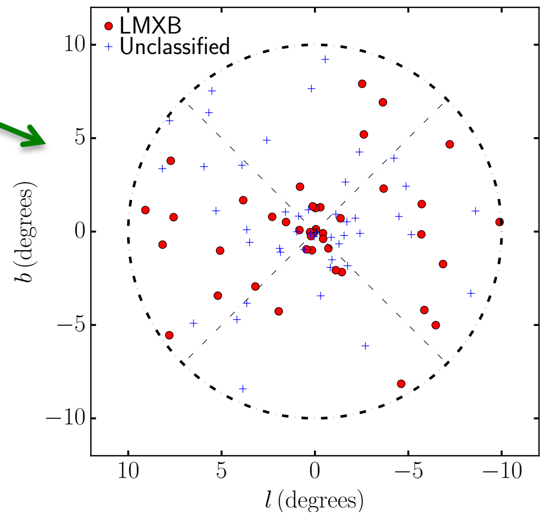


Brandt & Kocsis ApJ 812 (2015)

Are there enough MSPs?

- Hooper & Linden (2016)
  - Study the gamma-ray flux from globular clusters (dominated by MSPs)
  - Model the MSP luminosities
  - Can account for 30%, but 10 – 50 MSPs should have been detected by Fermi LAT near the GC
  - Taking into account spin-down evolution gives ~ 2% of GCE
- Haggard et al. (2017)
  - Low mass X-ray binaries (progenitors of MSPs)
  - LMXBs detected with INTEGRAL near GC
  - < 14% (28%) of GCE can be attributed to MSPs at 95% confidence taking into account only LMXBs (LMXBs + unclassified sources)
- There are 4 MSPs and 8 globular clusters within 10° from the GC in 4FGL-DR4

  Ballet et al. (2023)



Haggard et al., JCAP 056 (2017)

Statistical and DNN methods

- Main idea: point-like sources give larger fluctuations than Poisson fluctuations for smooth diffuse emission
  - Typically favor MSP interpretation of GCE
- Filtering – wavelets

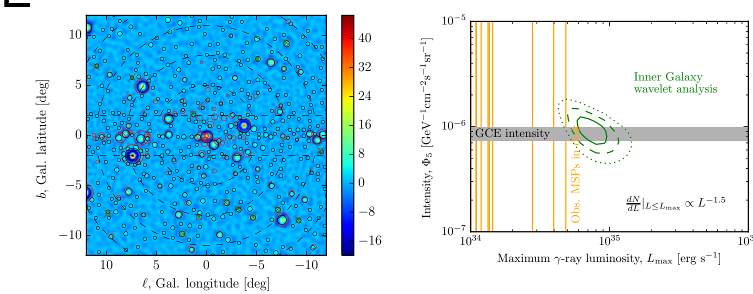
  Bartels et al. (2016), Zhong et al. (2020)
- Statistical
  - Non-poissonian templates

    Lee et al. (2015, 2016)
  - 1pt PDF

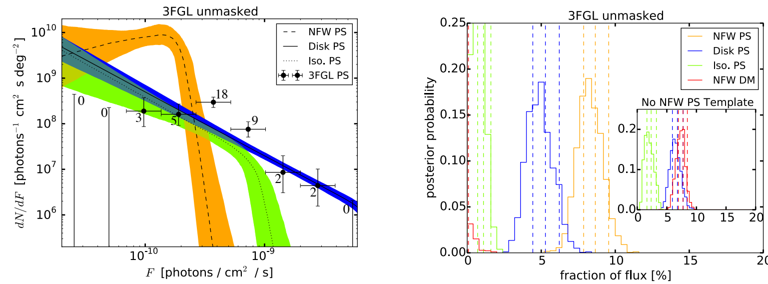
    Calore et al. (2021), Manconi et al. (2024)
  - However, sensitive to diffuse emission uncertainties

    Leane & Slatyer (2019, 2020, 2020)
- Deep learning

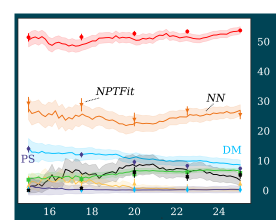
  List et al. (2020), Mishra-Sharma & Cranmer (2022)
  - However, "mind the gap", Caron et al. (2023)



Bartels et al., PRL 116 (2016)



Lee et al., JCAP 5 (2015)



List et al., PRL 24 (2020)

Unassociated sources near the GC?

- Challenges
  - Population studies rely on associated sources (mostly bright)
  - Statistical methods determine an overall dN/dS distribution of sources including sources below the detection threshold but
    – not specific to MSPs
    – use integrated spectrum in a large energy bin
- However, there are many unassociated Fermi-LAT sources (200 within 10^{o} from the GC)
  - Can we use them to learn something about the population of MSPs near the GC
- This work
  - Use machine learning (ML) trained on associated sources to classify unassociated sources near the GC
  - Test the MSP hypothesis

ML classification of Fermi-LAT sources

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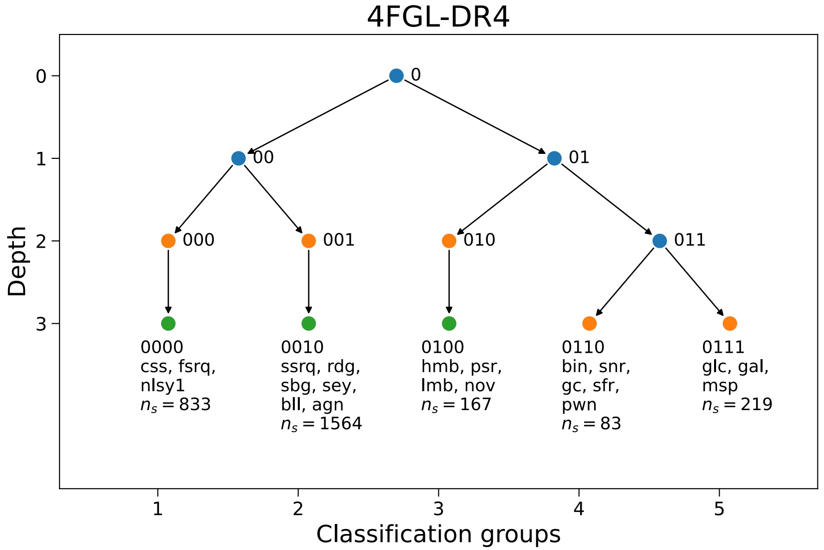
- Challenges in going beyond two classes
  - Many physical classes (> 20)
  - Some classes are small (> 10 classes have < 10 associated sources)
- Separate classes in large groups with similar properties
  - Malyshev & Bhat, MNRAS 521 (2023)
  - This work: 5-class classification (dominated by FSRQs, BL Lacs, pulsars, supernova remnants + pulsar wind nebulae, and MSPs)
- Input features:
  - spectral parameters, variability, source significance
  - No source coordinates
- Classification: random forest (also tested neural networks)



Malyshev, arXiv:2401.04565

Probabilistic classification

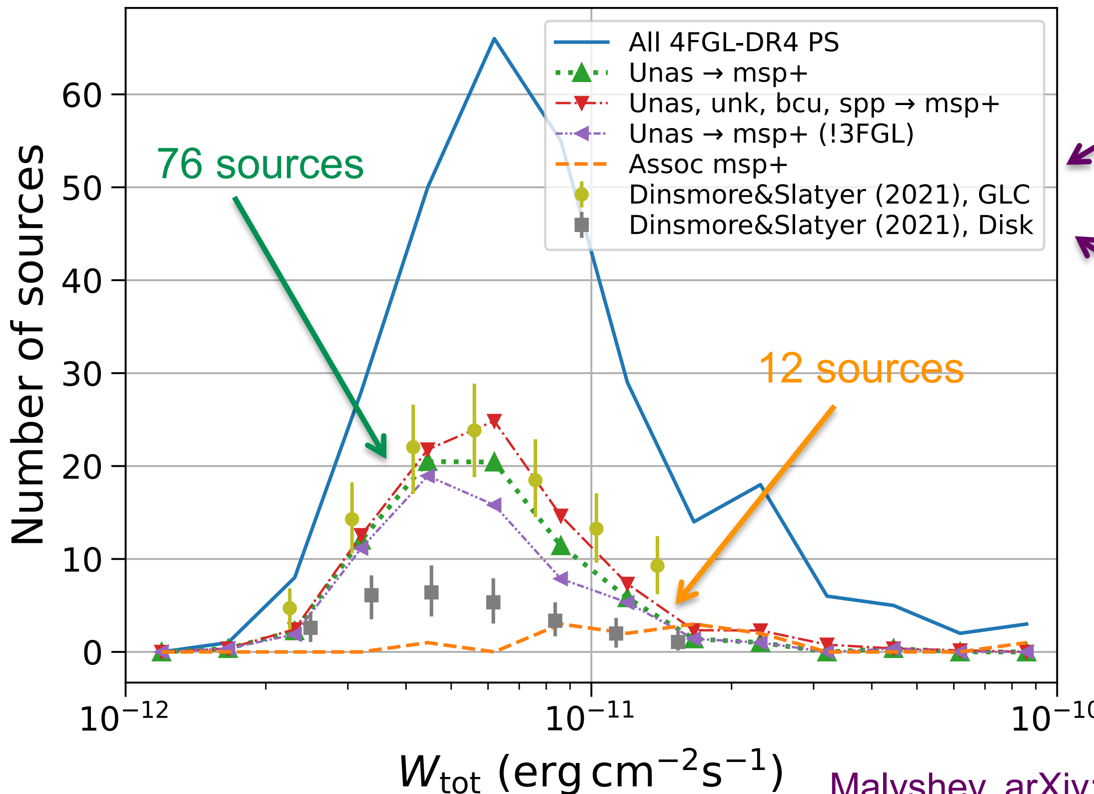
- ML: input features (X) → class probabilities p(Y)
- Use class probabilities, e.g., to determine the expected number of MSP-like sources among the unassociated ones within 10° from the GC:

$$N_{\rm MSP} = \sum_{i \in {\rm unas}, <10^\circ} p^i_{\rm MSP}$$

  which gives ~76 MSP-like sources expected near the GC
- There are 200 unassociated and 94 associated sources within 10° from the GC
- If we sum over unassociated sources in flux bins, then we can determine the expected number of MSP-like sources as a function of flux

Source count of MSPs near the GC

- Calculate expected number of MSPs within 10° from the GC as a function of energy flux above 100 MeV



Based on Hooper & Linden JCAP 018 (2016)

Based on Bartels et al., MNRAS 481 (2018)

Malyshev, arXiv:2401.04565

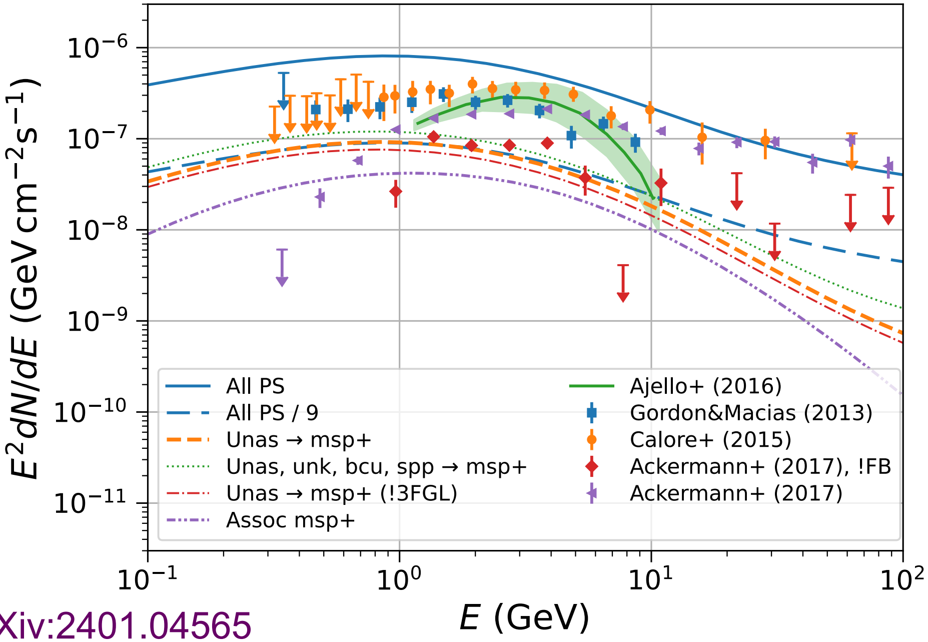
Spectrum

- Using probabilistic classification, we can also determine the expected spectrum from the MSP-like unassociated sources

$$F_{\rm MSP}(E) = \sum_{i \in {\rm unas},\, <10^\circ} p^i_{\rm MSP} F_i(E)$$

- It's a factor 3 below the typical GCE spectra

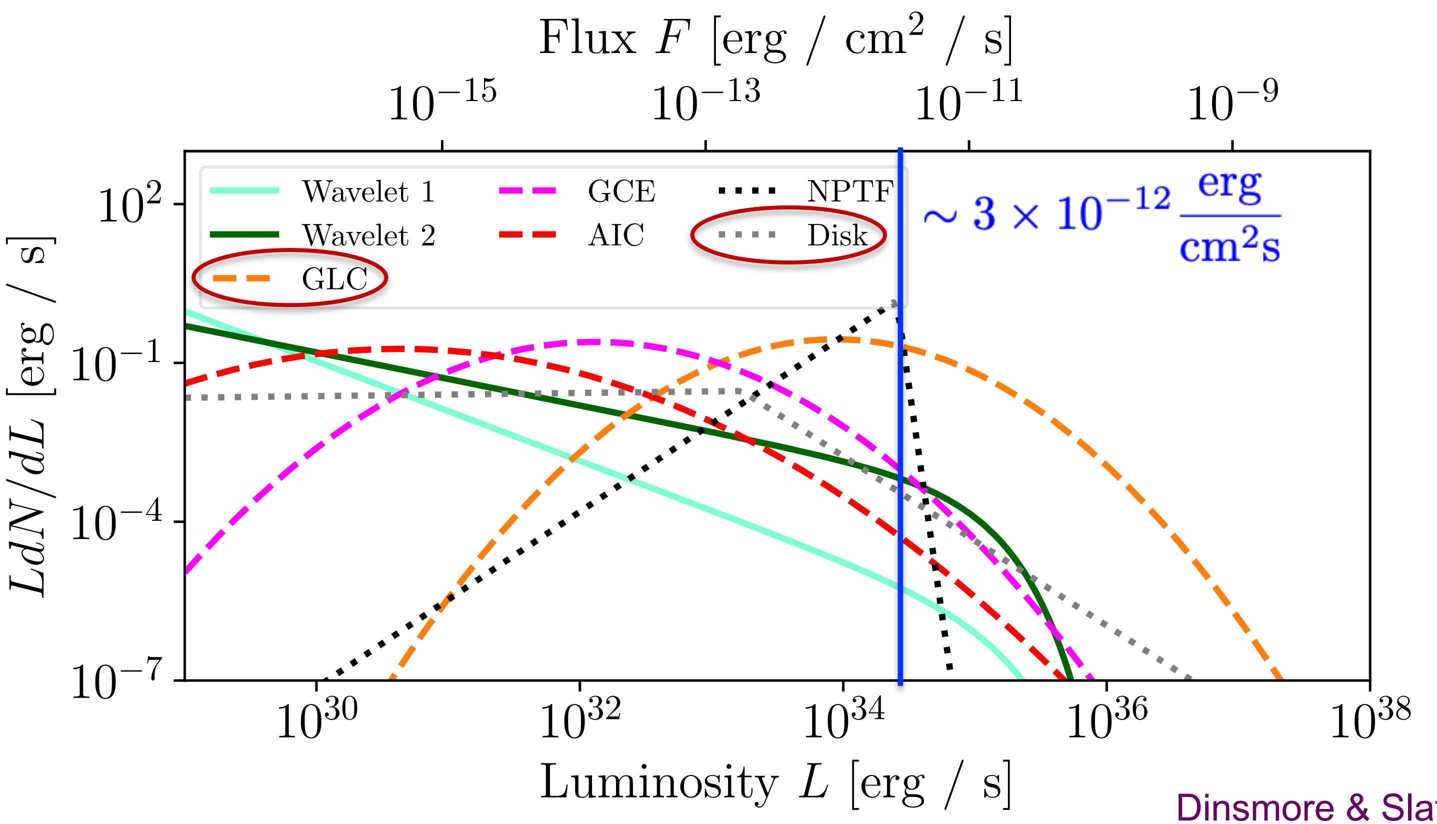
- Similar to remaining GCE after a model of FBs has been subtracted



Malyshev, arXiv:2401.04565

Detection threshold

- Most of flux comes from MSPs below detection threshold, even in models dominated by bright MSPs



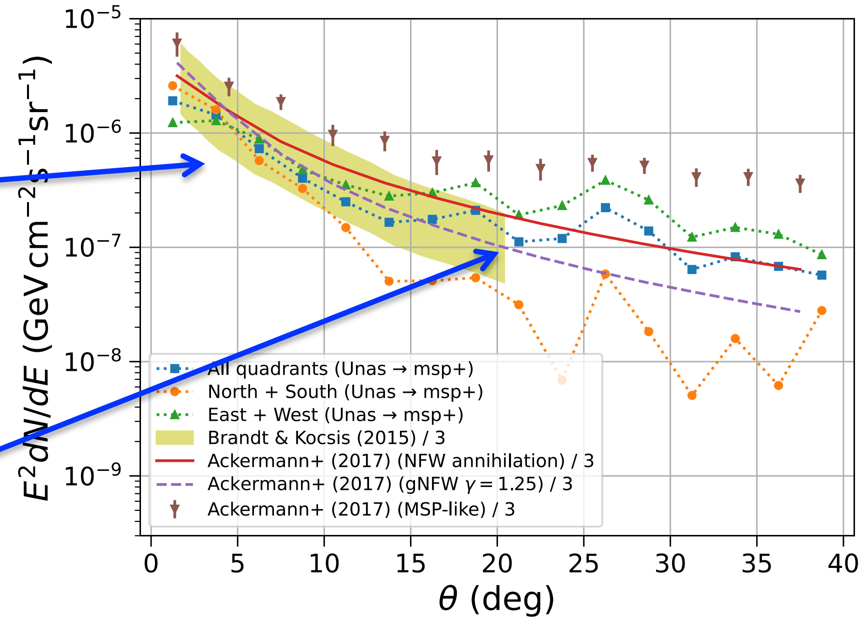
Dinsmore & Slatyer, JCAP 025 (2022)

Radial profile

- Calculate intensity at 2 GeV in rings around the GC

$$I_{\rm MSP}(\theta) = \frac{1}{\Omega} \sum_{i \in {\rm unas},\ \theta_i \in (\theta_1,\ \theta_2)} p^i_{\rm MSP} F_i(E = 2\ {\rm GeV})$$

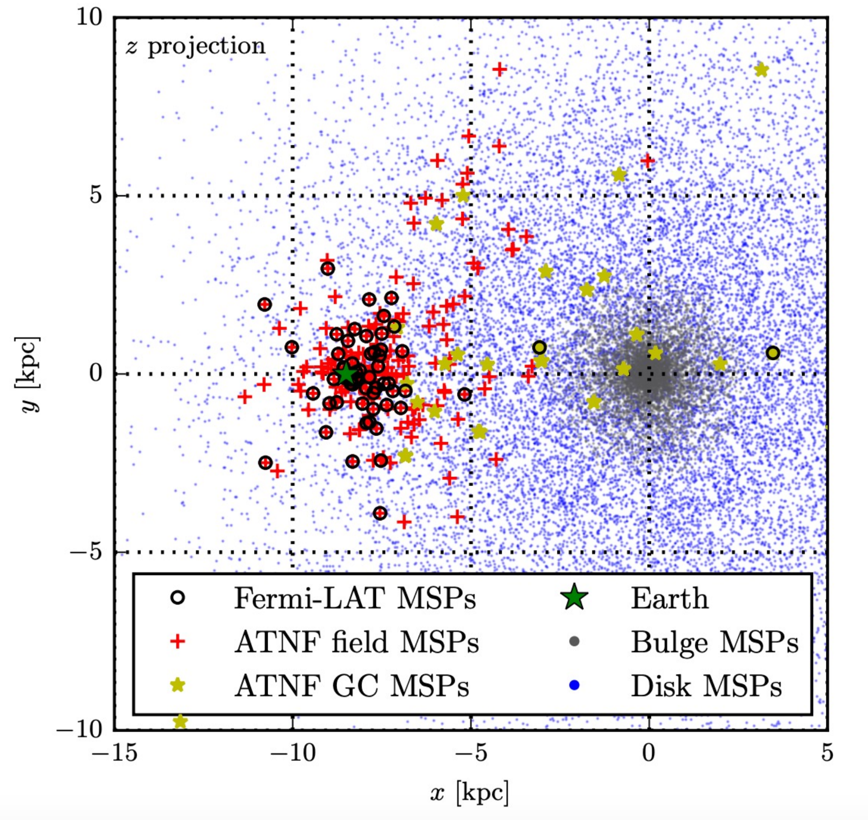
- The profile is consistent with gNFW profile within about 10° from the GC
  - Dominated by a spherical distribution of PS
- At larger angles the population of MSPs in the Galactic plane dominates the emission



Malyshev, arXiv:2401.04565

Radio searches for MSPs

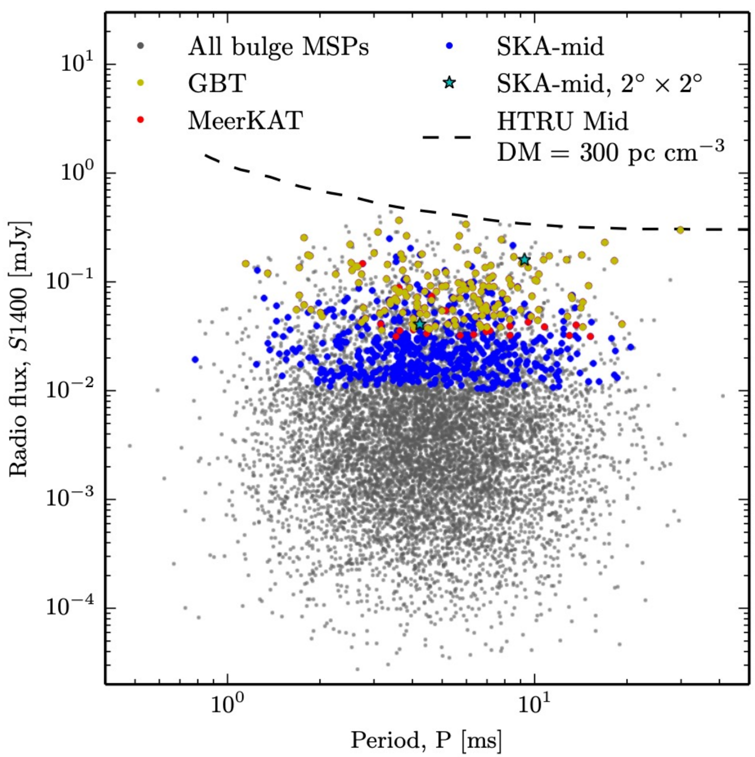
- Can we prove that the MSP candidates determined by machine learning are actually MSPs?
  - Detection of pulsed emission with radio telescopes is needed!

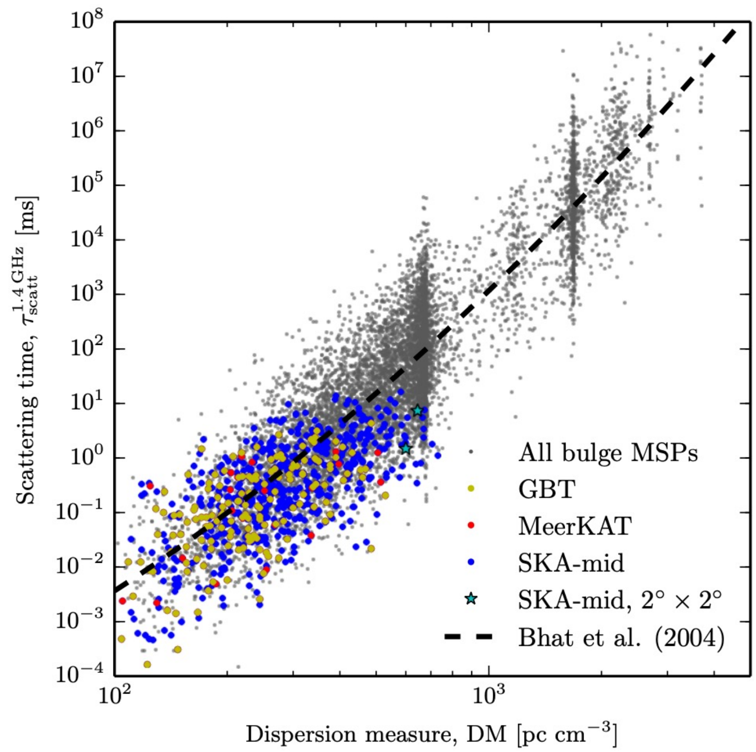


Calore et al, ApJ 827 (2016)

Radio flux and dispersion

- Two main limiting factors:
  - radio flux;
  - dispersion that smears the pulsed radio emission.





Calore et al, ApJ 827 (2016)

Expected detections in a survey

- Survey 108 deg^2 around the GC
  - Bottom row: expected number of MSPs in the bulge (Galactic plane)

Radio searches for bulge MSPs from Fermi diffuse observations

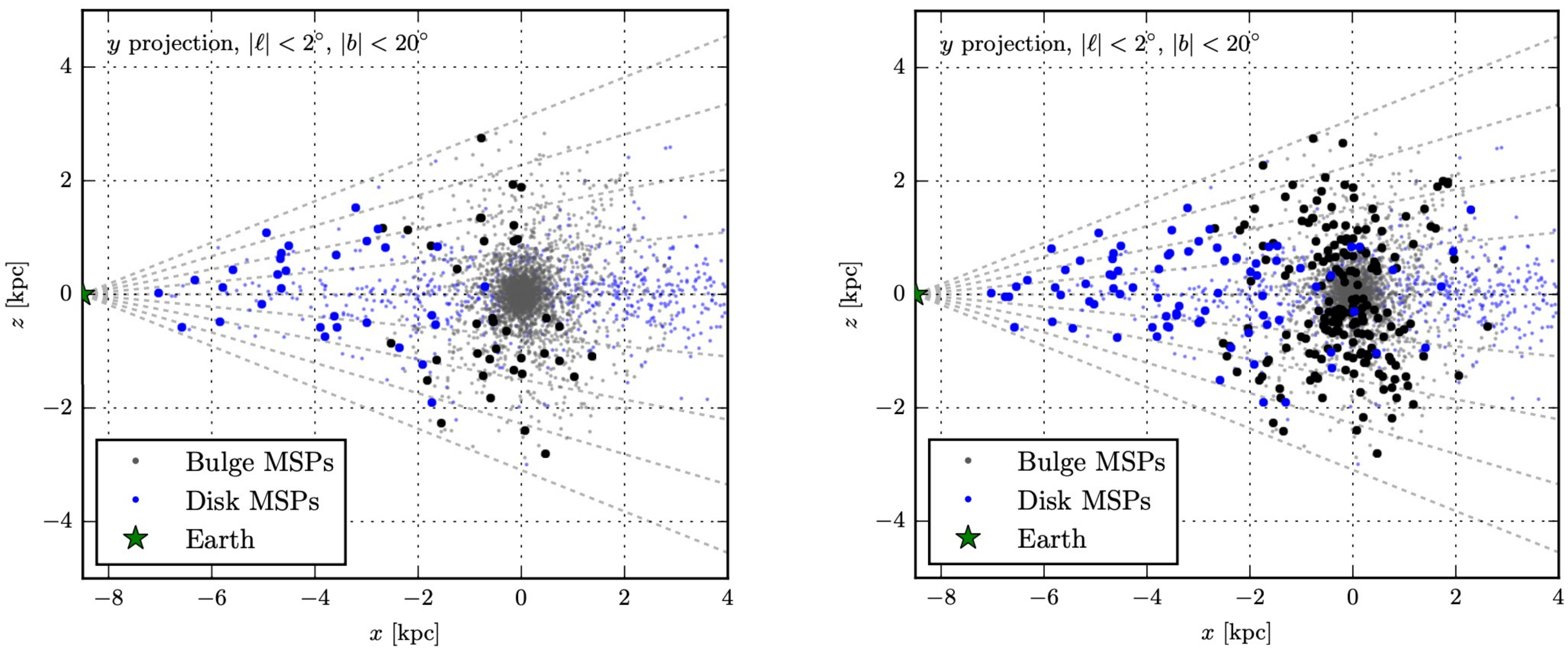
Parameters	HTRU (mid)	GBT	MeerKAT	SKA-mid
ν [GHz]	1.35	1.4	1.4	1.67
$\Delta\nu$ [MHz]	340	600	1000	770
t_{samp} [μs]	64	41	41	41
$\Delta\nu_{\mathrm{chan}}$ [kHz]	332	293	488	376
T_{rx} [K]	23	23	25	25
G [K/Jy]	0.74	2.0	2.9	15
Max. Base. Used [km]	–	–	1.0	0.95
Eff. G sub-array [K/Jy]	0.74	2.0	2.0	8.5
Ele. θ_{FWHM} [arcmin]	14	8.6	65	49
Ele. FoV [deg^2]	0.042	0.016	0.92	0.52
Beam θ_{FWHM} [arcmin]	14	8.6	0.88	0.77
Beam FoV [deg^2]	0.042	0.016	0.00017	0.00013
# Beams	13	1	3000	3000
Eff. FoV [deg^2]	0.55	0.016	0.51	0.39
T_{point} [min]	9	20	20	20
$T_{108\,\mathrm{deg}^2}$ [h]	29	2250	71	92
# Bulge(Foreground) MSPs	1(6)	34(37)	40(41)	207(112)

Table 3

Calore et al, ApJ 827 (2016)

Monte Carlo of detections

- Possible MSP detections for disk (blue) and bulge (black) MSPs for MeerKAT (left plot) and SKA-mid (right plot)
  - SKA is expected to detect a lot of MSPs, but the number of possible detections for MeerKAT is already quite good



Calore et al, ApJ 827 (2016)

Targeted observations

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- Instead of a survey, one can target high probability MSP candidates determined, e.g., using ML methods
  - Several MSPs can be detected with MeerKAT and SKA-mid after a few tens of hours of observations

Instrument	$t_{\rm obs}$ total	Detection of MSP candidates Probability	Number (20 total)
GBT	20 h	18.4%	3.7
MeerKAT	20 h	20.5%	4.1
SKA-mid	20 h	40.8%	8.2

Table 4
Projected number of detections for follow-up radio searches in 20 MSP candidates, assuming that all of the MSP candidates are indeed gamma-ray luminous MSPs in the bulge region. The radio luminosity of gamma-ray luminous MSPs is estimated from a flux limited sample of high-latitude MSPs and unassociated sources. Although the results were obtained in an observation-driven approach, they are uncertain by at least a factor of two and of indicative value only. Caveats are discussed in the text.

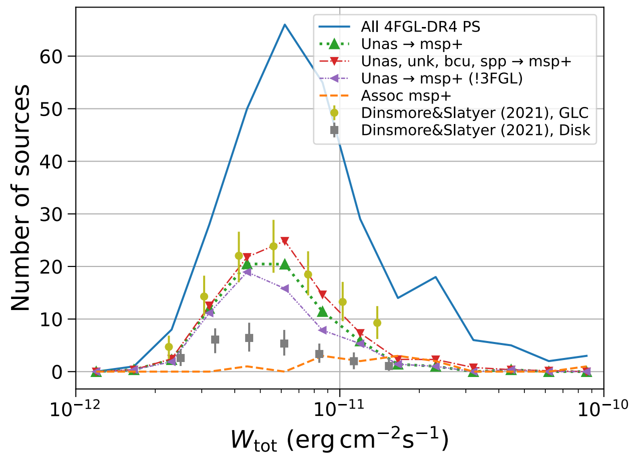
Calore et al, ApJ 827 (2016)

Probabilistic catalogs

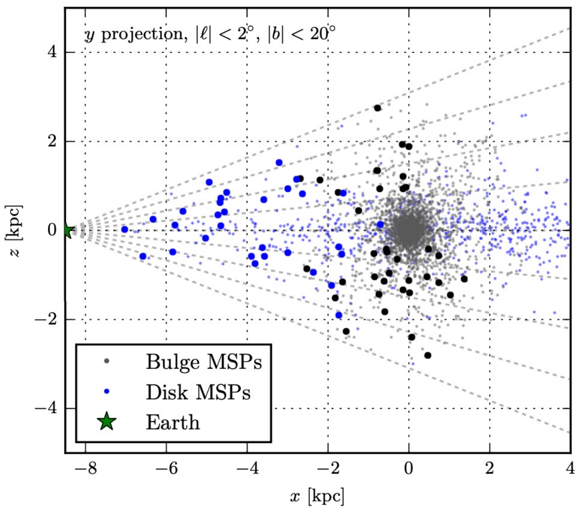
- Class probabilities for all sources
  - including the associated ones – obtained from testing datasets
- Based on 4FGL-DR3
  - Malyshev & Bhat, MNRAS 521 (2023), arXiv:2301.07412
  - Construction of multi-class classification, 6 or 9 classes
  - https://zenodo.org/records/7538664
- Based on 4FGL-DR4
  - Malyshev, RASTI 2 (2023), arXiv:2307.09584
  - Effect of covariate shift, 6 classes
  - https://zenodo.org/records/10452672
- Based on 4FGL-DR4 (still preliminary!)
  - Malyshev, arXiv:2401.04565
  - No coordinate features, no BCU or SPP classes in training, 5 classes
  - Application for MSPs near the GC
  - https://zenodo.org/records/10458464

Conclusions

- Machine learning methods have been used to determine MSP-like candidates near the GC
  - The spatial and spectral distribution of the MSP-like sources is consistent with the MSP interpretation of the Galactic center excess
- Radio observations with MeerKAT and SKA can detect a few MSPs near the GC after a few tens up to ~ 100 hours of observations
  - Radio detection of MSPs can support the MSP hypothesis of the GCE



Malyshev, arXiv:2401.04565



Calore et al, ApJ 827 (2016)