Probing the Fermi-LAT GeV excess with gravitational waves

Part I / Introduction

Seizing the multimessenger/GW revolution

Part II

The example of the gamma-ray excess at the Galactic Center

Part III

Multiwavelength & multimessenger (GW) counterpart:
model-independent and model-dependent implications

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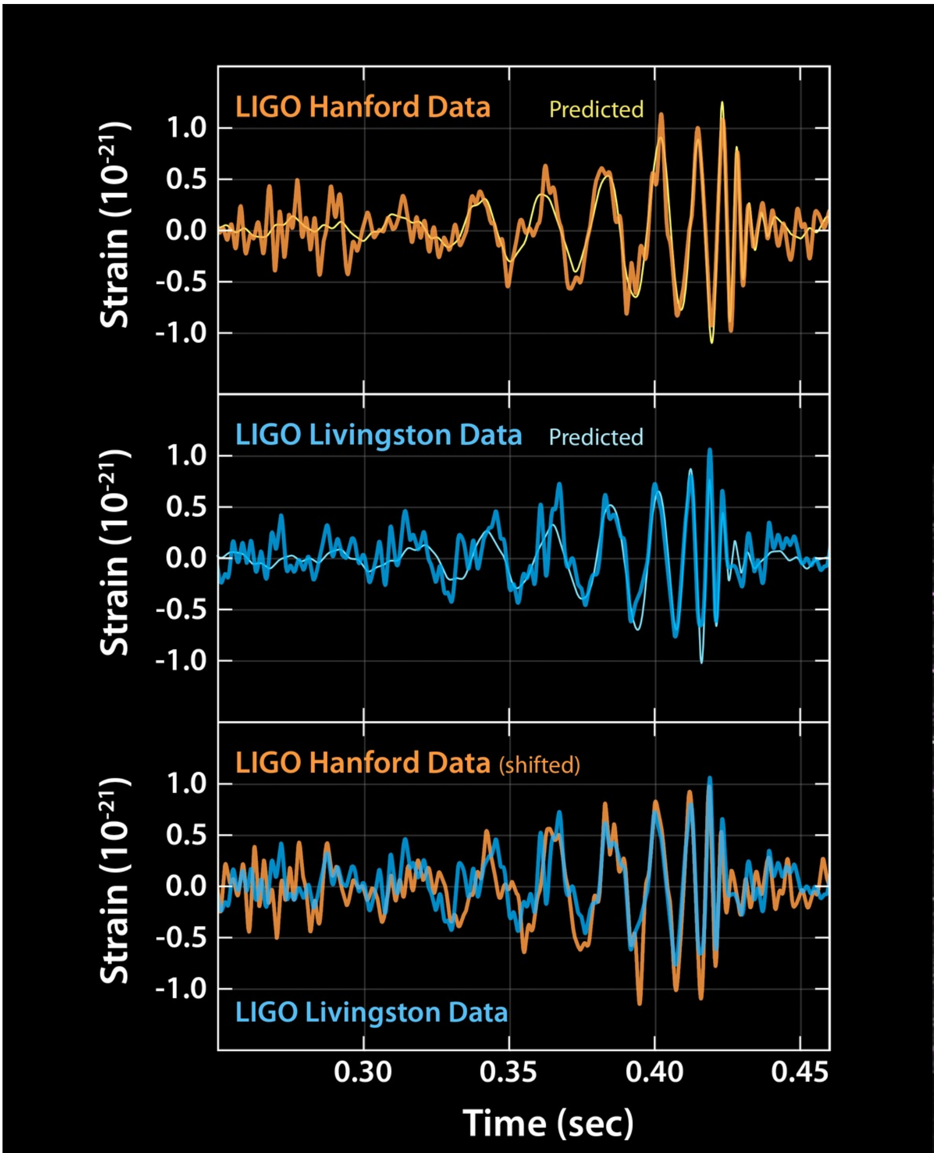
(Laboratoire d'Annecy-Le-Vieux de Physique Théorique)
DSU 2019 - Buenos Aires - 15/07/2019

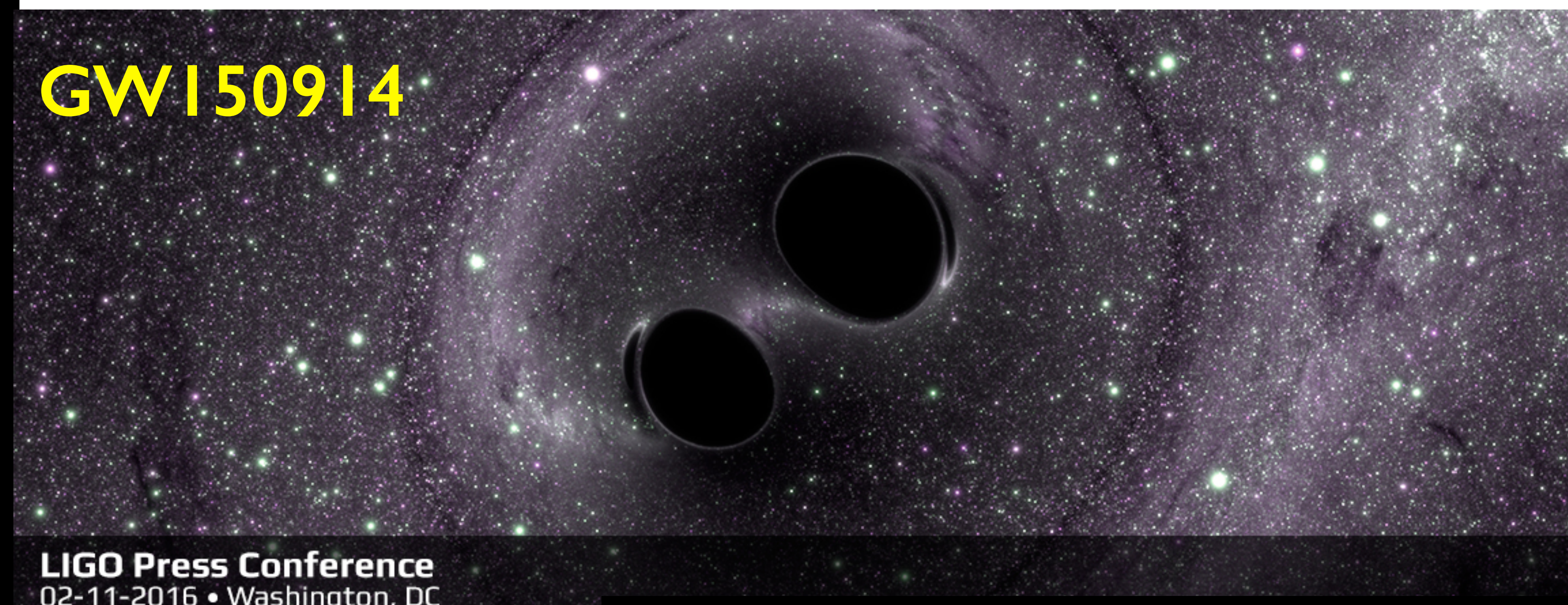
Part I: seize the revolution!

A frantic pace of discoveries, I



First Black Hole merger detection by LIGO interferometers in 2015, announced in 2016

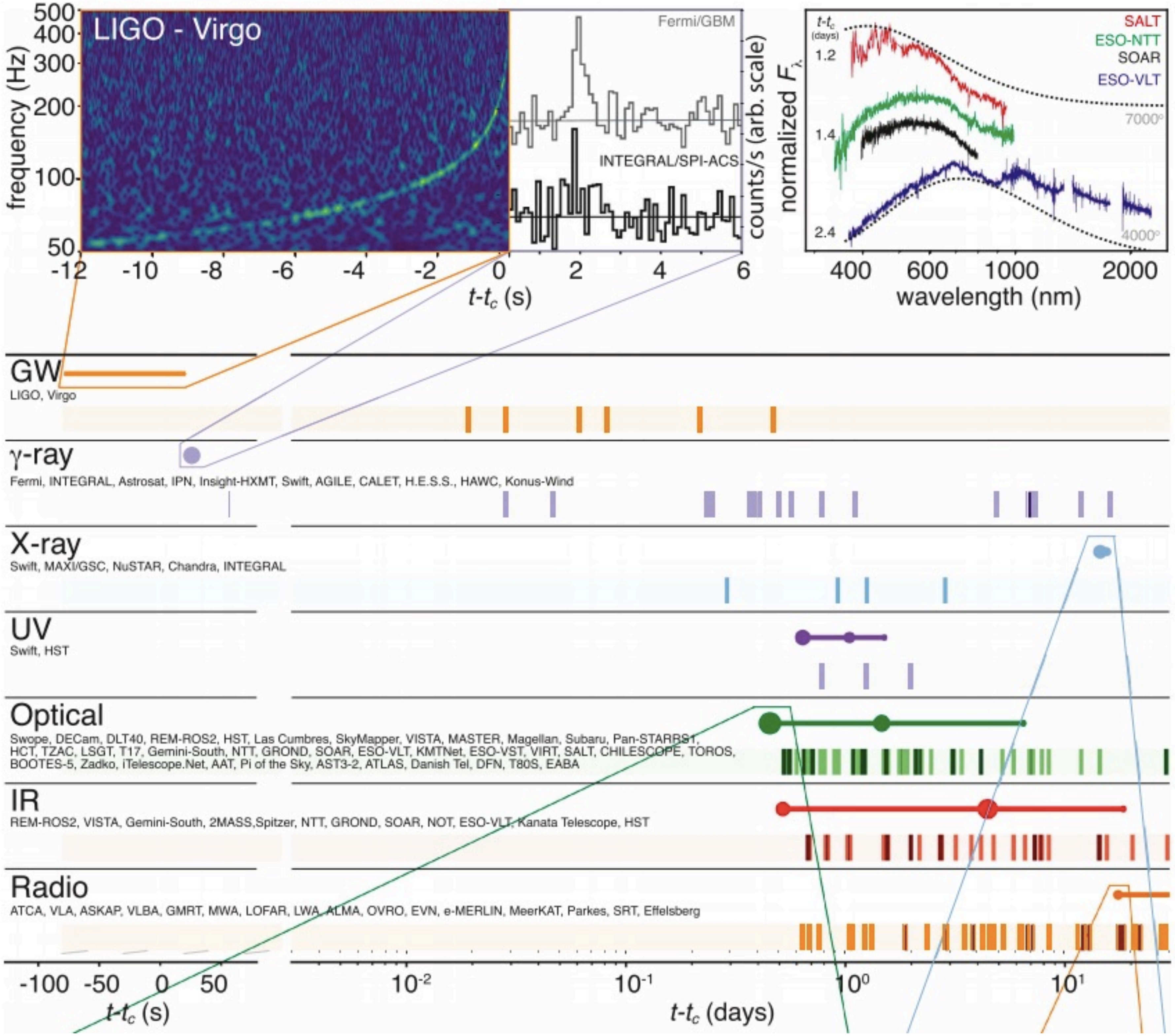
B.P. Abbott et al. [LIGO/Virgo collab], Phys. Rev. Lett. 116, 061102 (2016) [1602.03837]



Nobel Prize in 2017 "for decisive contributions to the LIGO detector & the observation of gravitational waves."

A frantic pace of discoveries, II

The birth of multi messenger astrophysics with GW!



Neutron star merger, announced

16/10/2017

Phys. Rev. Lett. 119, 161101 (2017) [1710.05832]

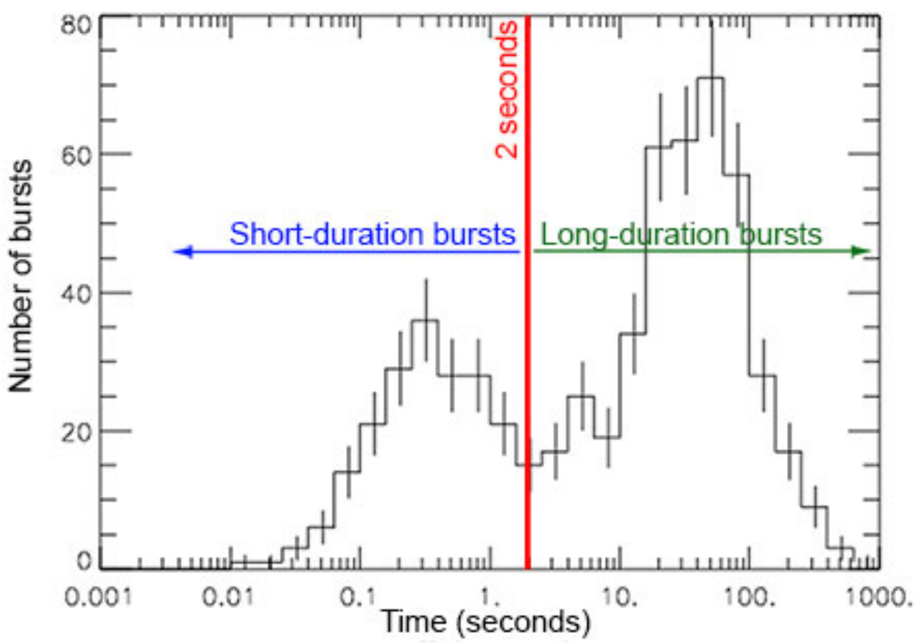
Many follow-up observations, from gamma-ray to radio

Astrophys.J. 848 (2017) no.2, L12

coauthored by ~4,000 astronomers (~1/3 of the worldwide community) from >900 institutions, using >70 observatories on all seven continents and in space

Impact of a single event!

Neutron star mergers as (one of the) origin(s) of mysterious (short) gamma-ray bursts



Constraint to the equation of state of *nuclear matter*

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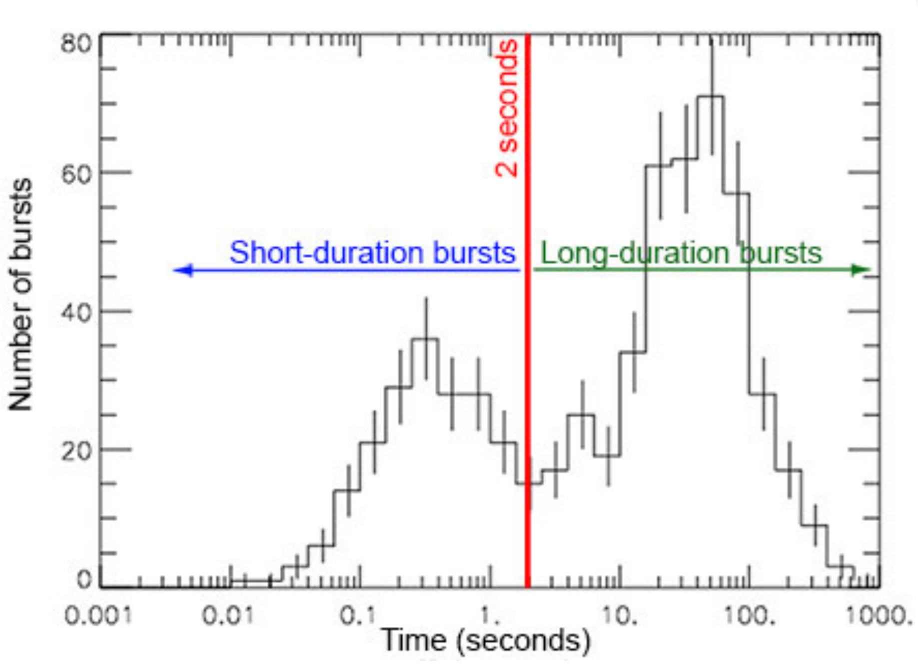
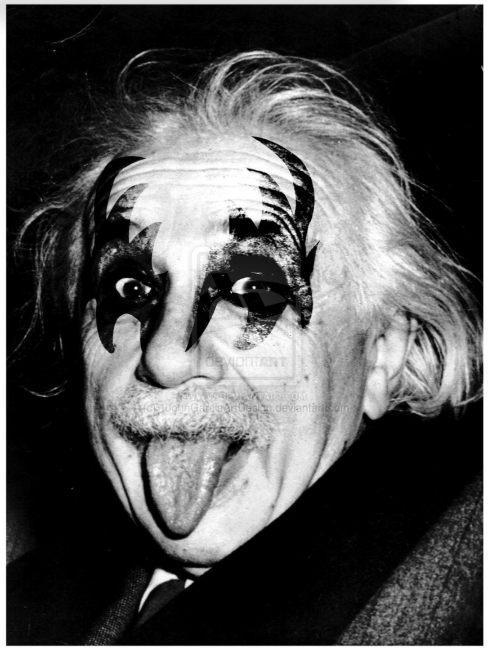
(Main) site of nucleosynthesis of heavy (*r-process*) elements, like ***gold*** and platinum





Constraint to the equation of state of ***nuclear matter***

Limits on the difference between the speed of light and that of gravity, excluding many ***alternatives to general relativity*** (including "***dark matter*** emulators")

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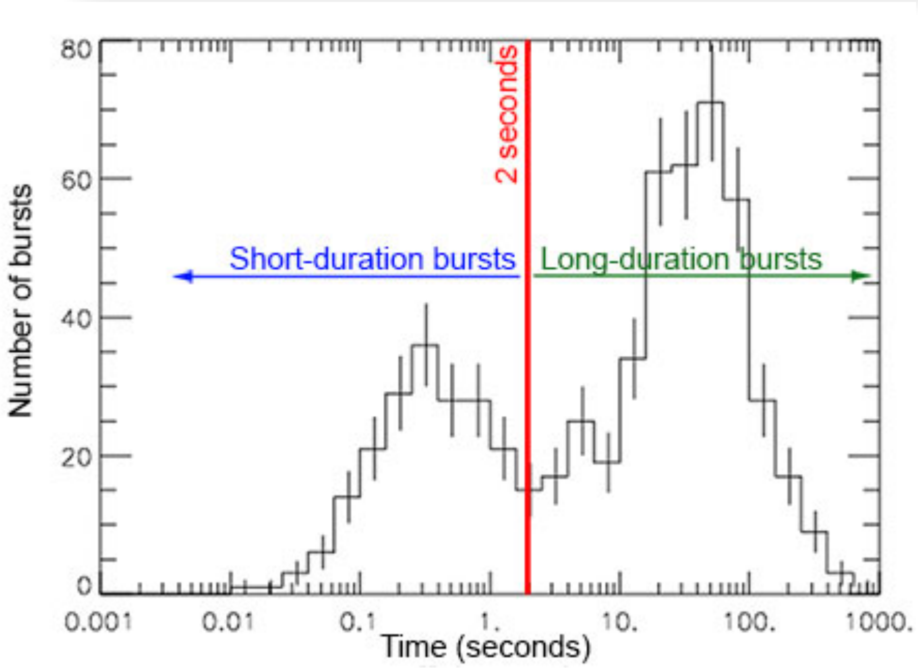
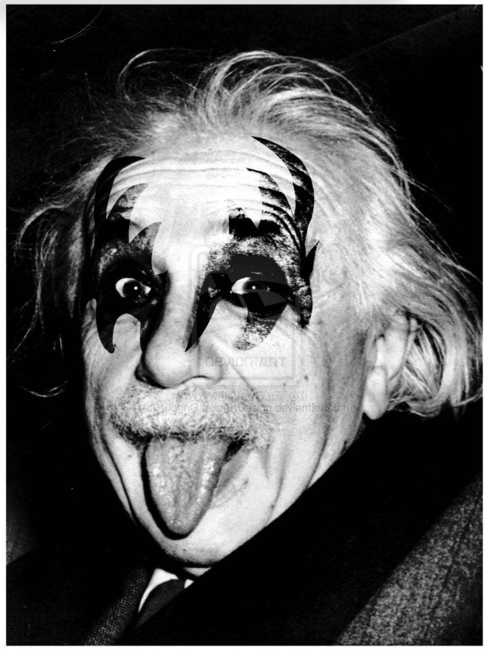




Constraint to the equation of state of ***nuclear matter***

Limits on the difference between the speed of light and that of gravity, excluding many ***alternatives to general relativity*** (including "***dark matter*** emulators")

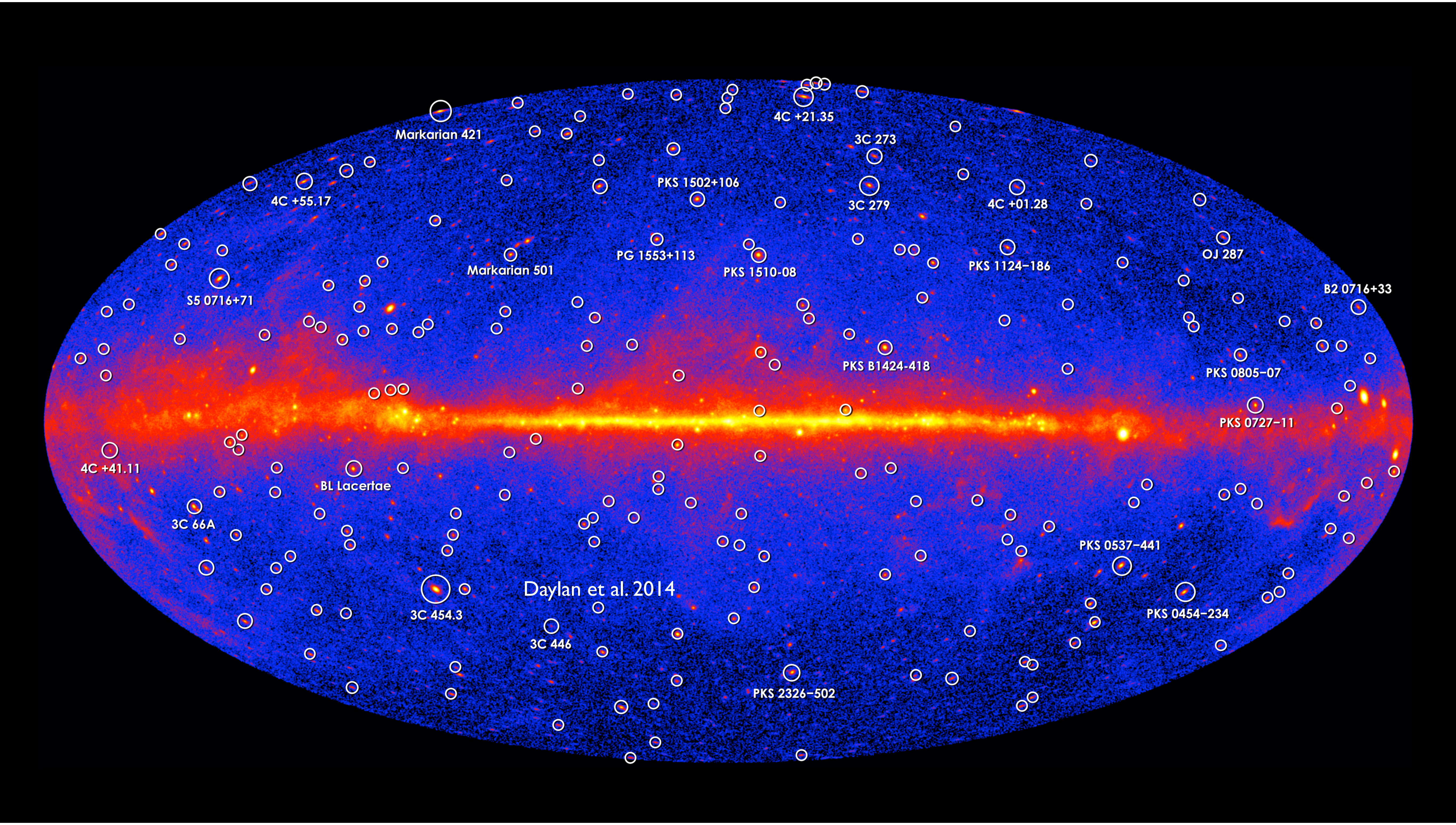
What other opportunities wait to be unveiled?

Learn to "think multimessenger" to tackle some mysteries!

What follows is an illustrative example

Part II: The Galactic Center Excess

The Fermi sky in the GeV energy range



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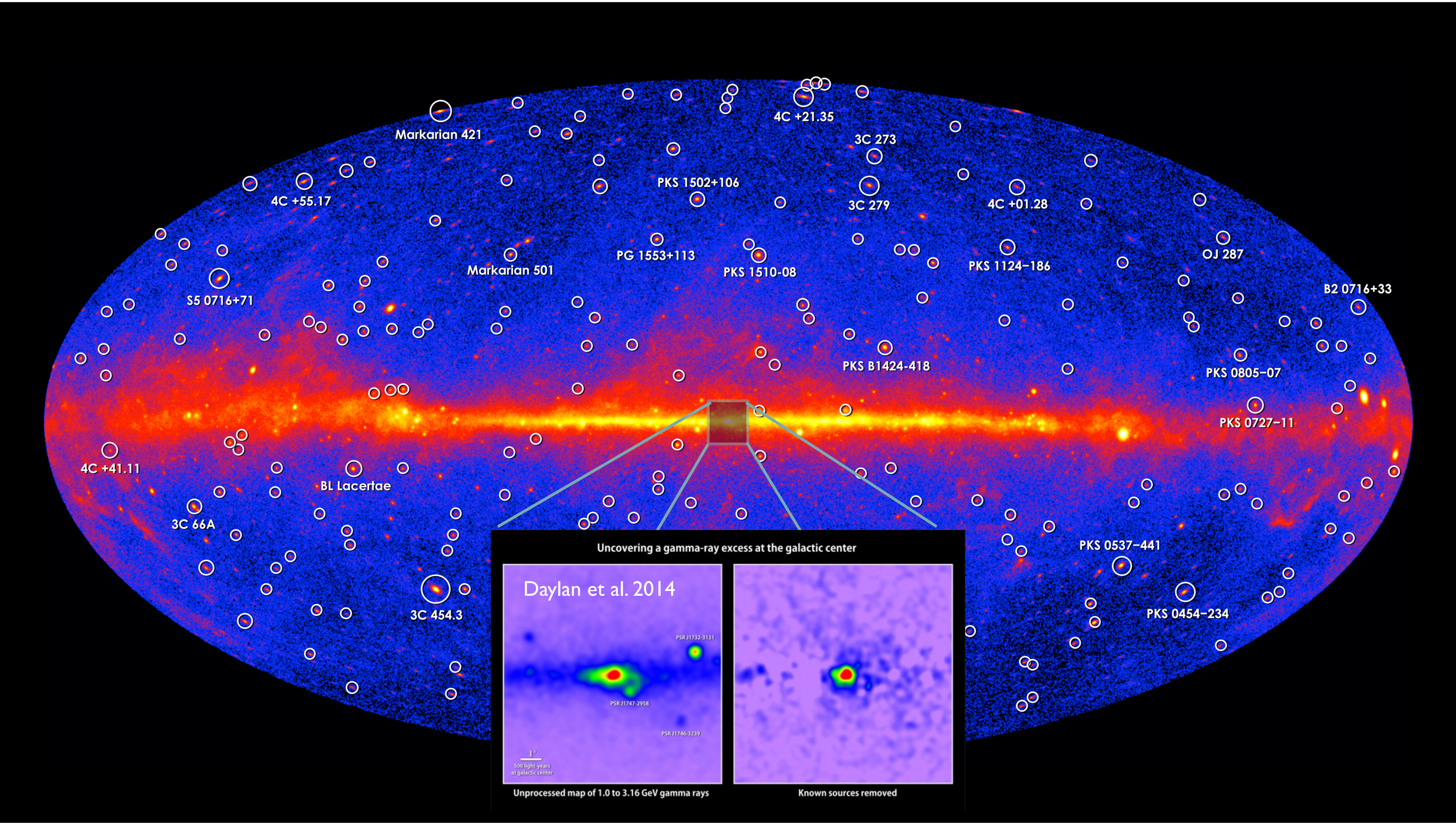


In the past decade, a statistically significant γ-ray excess over diffuse emission *model* + *known* astrophysical sources has been unveiled

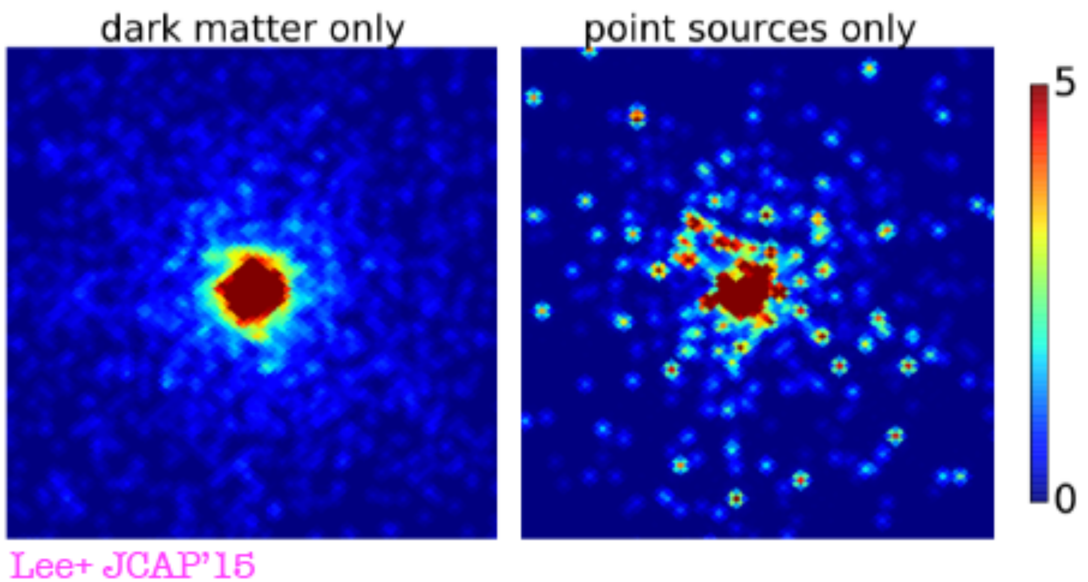
What could it be?

Truly diffuse processes

DM annihilation
Inverse Compton of e± onto interstellar light (impulsive or steady state)
…

Unresolved point sources

Millisecond pulsars
Young pulsars
…



How to discriminate?

Difference in the statistics of the photon counts

Correlations with astro tracers

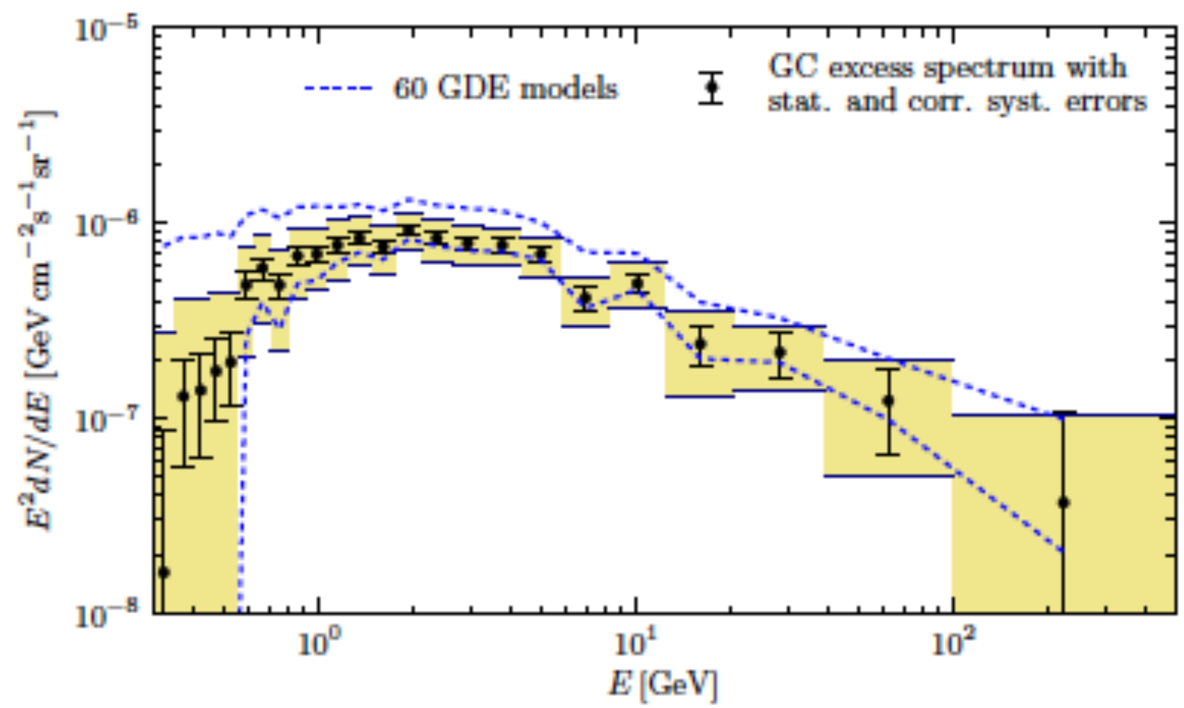
Multimessenger signals

Basic reasons for the DM interpretation

Spectrum: Well fit by a 40-70 GeV particle annihilating to quarks, roughly uniform across the Inner Galaxy

Morphology: Roughly spherically symmetric, with a flux falling as $\sim r^{-2.4}$ out to at least $\sim 10^{o}$, consistent with a DM halo only slightly steeper than the benchmark NFW profile suggested by DM-only simulations

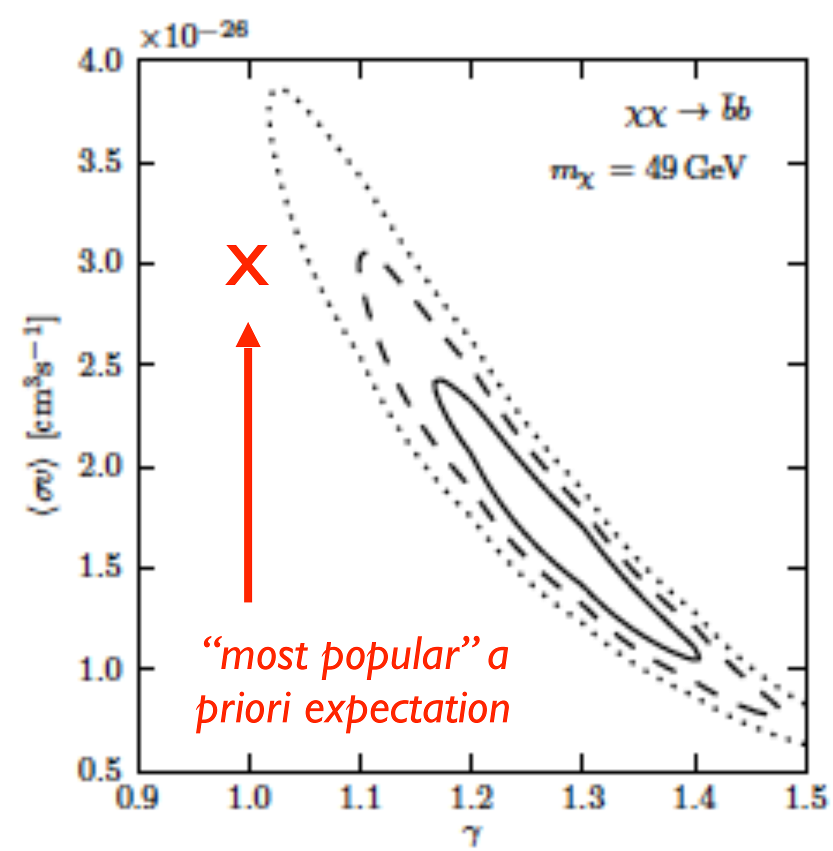
Intensity: Requires an annihilation cross section of $\langle\sigma v\rangle \sim 2\ 10^{-26}$ cm^3/s, near the value of a thermal relic



some key references

T. Daylan et al. "The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter", 1402.6703

F. Calore, I. Cholis and C. Weniger, "Background model systematics for the Fermi GeV excess," 1409.0042

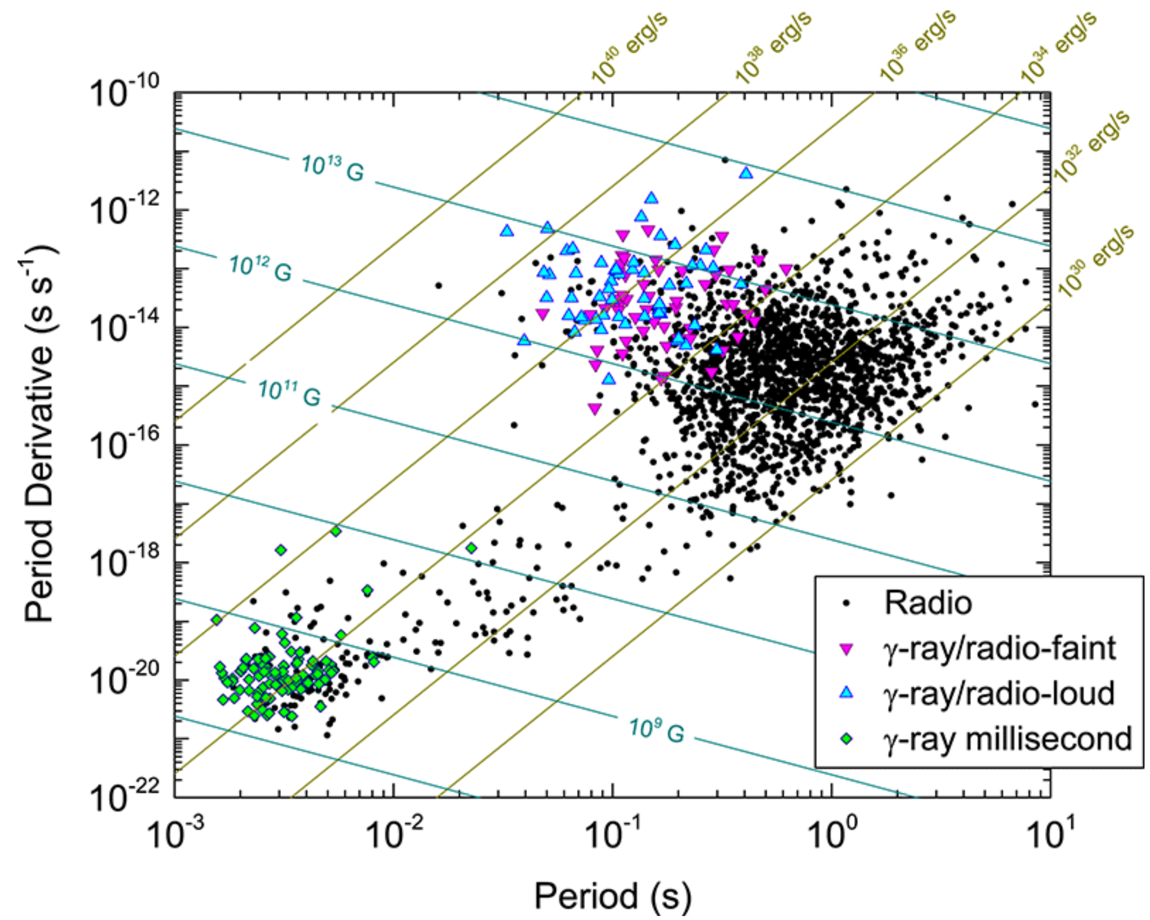


Main reasons for MSP interpretation

✓ **Millisecond pulsars exist (and γ-abundant)**

✓ **Spectrum** of both isolated MSP and of Glob. Clusters similar to the Gal. Center one!

K.N. Abazajian, JCAP 1103 (2011) 010 [1011.4275]



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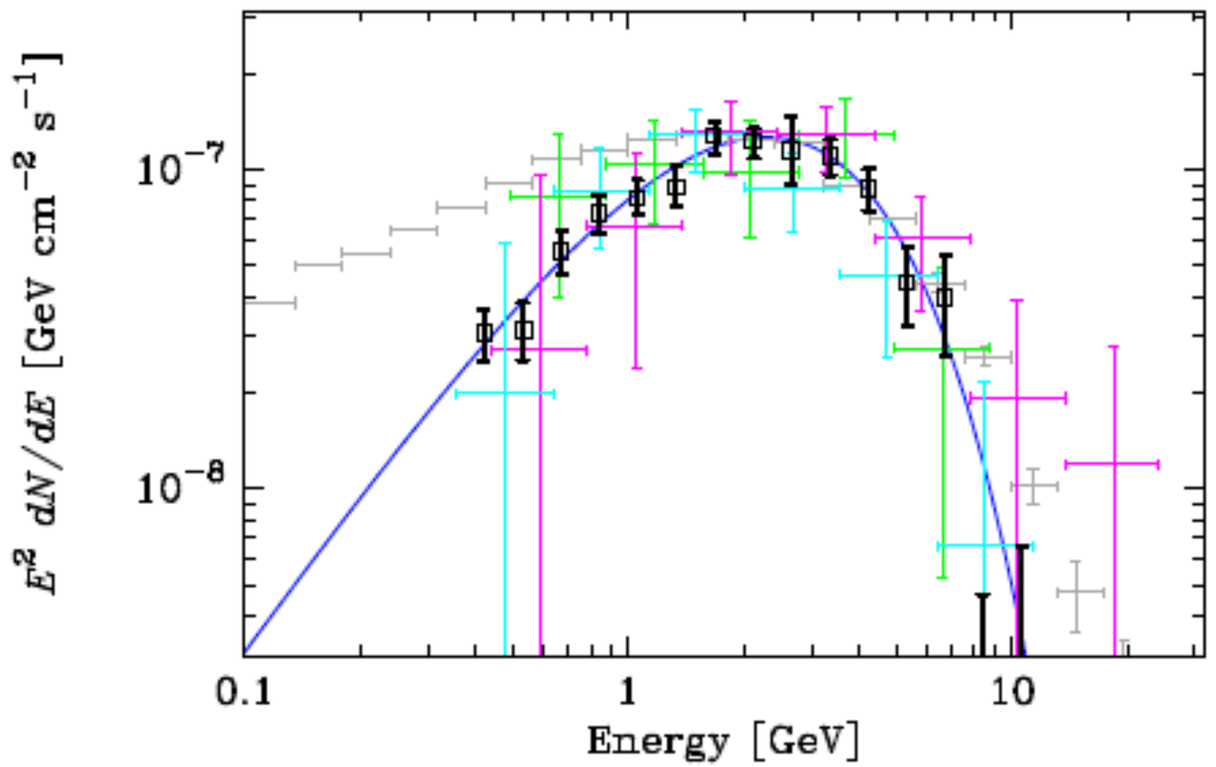

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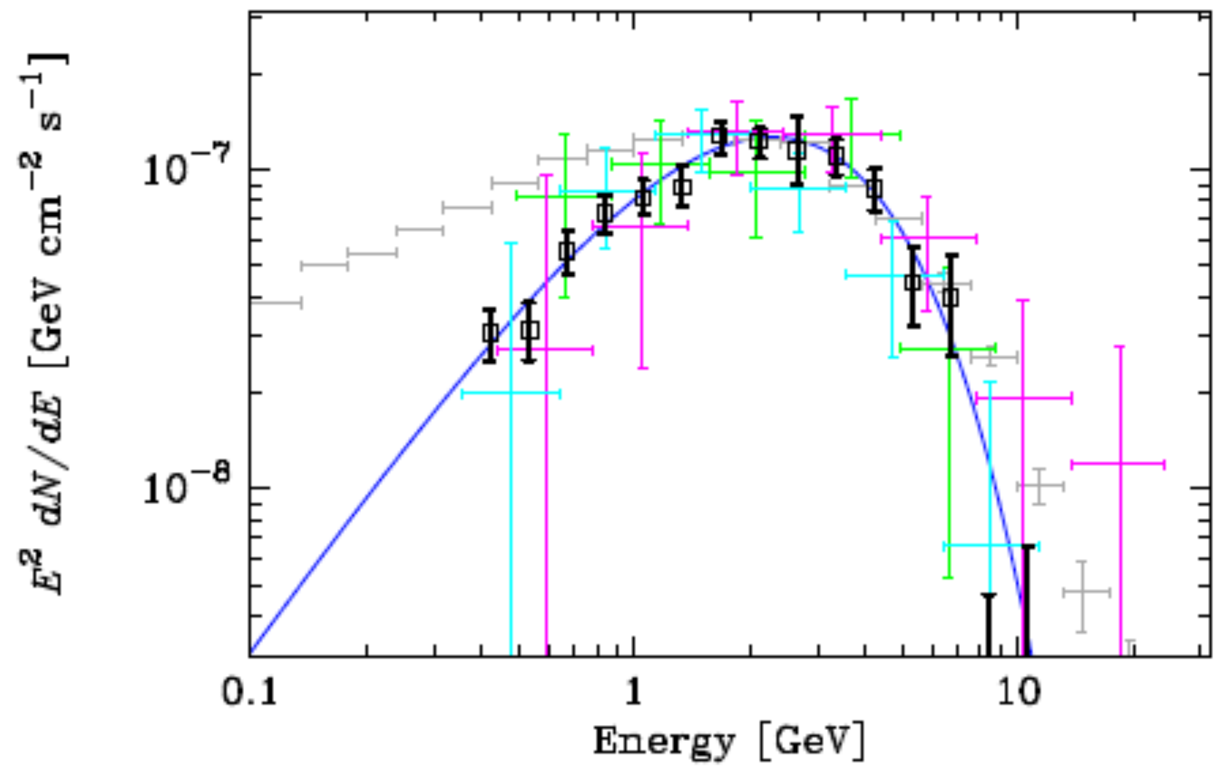
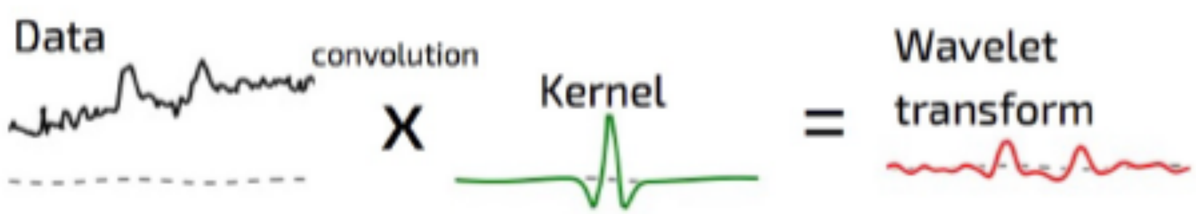
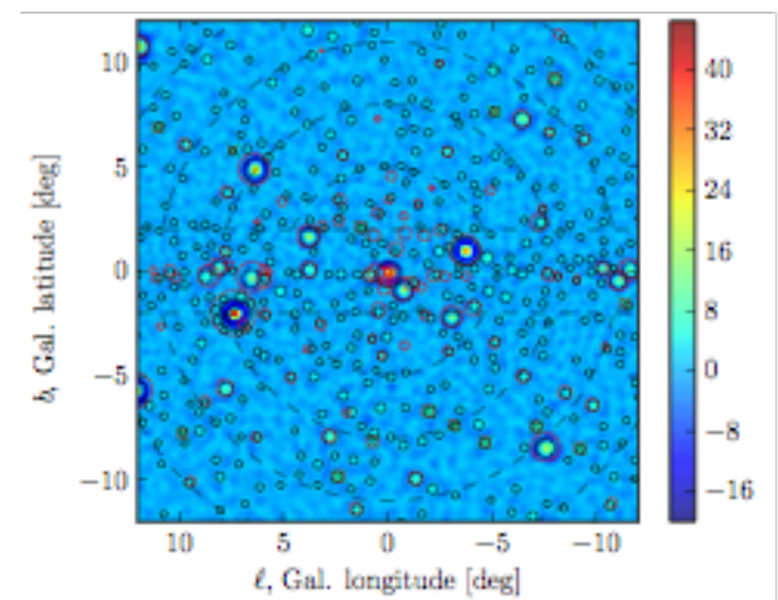


✓ Support for unresolved point sources from Wavelet transform



Excess power at small scales, no background modeling, constraint on spatial and luminosity distribution



R. Bartels, S. Krishnamurthy and C. Weniger, PRL 116, 051102 (2016) [1506.05104]

Similar evidence from pixel statistics reported in *S. K. Lee et al. PRL, 116, 051103 (2016) [1506.05124]*

retracted due to proof that the method used is not truly sensitive *Leane & Slatyer 1904:08430*

Playing devil's advocate

Hard to tell whether these clustered gamma-rays result from unresolved sources or from backgrounds that are less smooth than being modeled

Dan Hooper, TeVPA 2018

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True… however, GCE traces *stellar* density!

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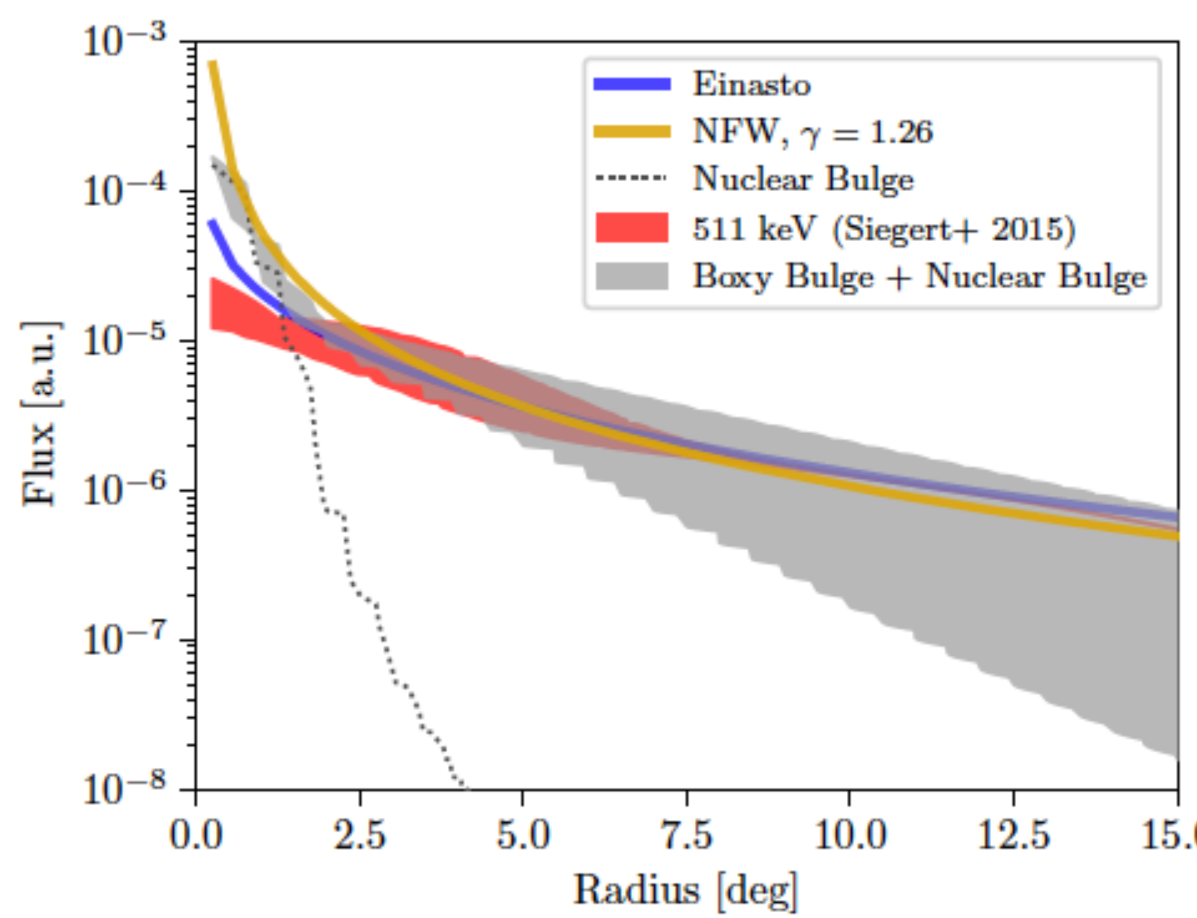
"Stellar mass templates are preferred over conventional DM profiles with high statistical significance"



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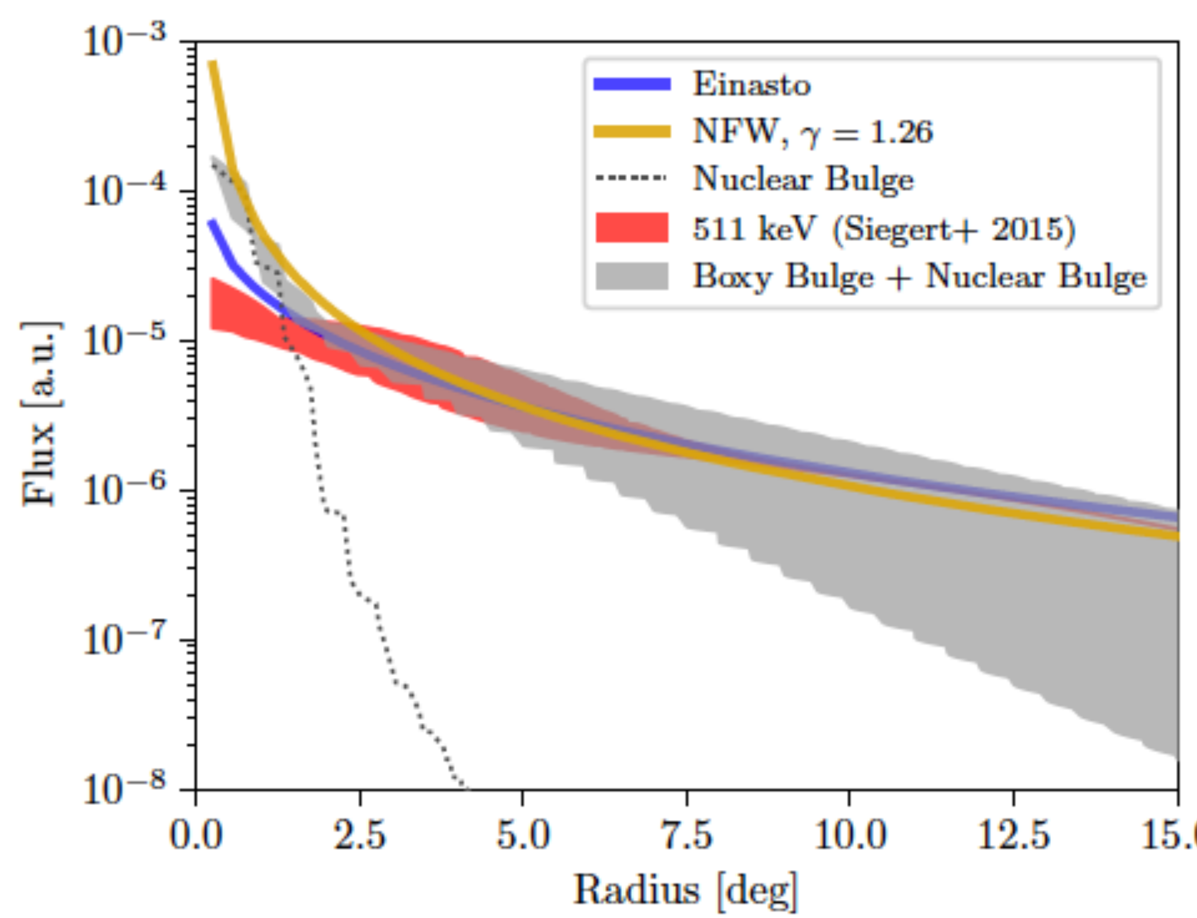
"Stellar mass templates are preferred over conventional DM profiles with high statistical significance"

Also, a not so well-known fact

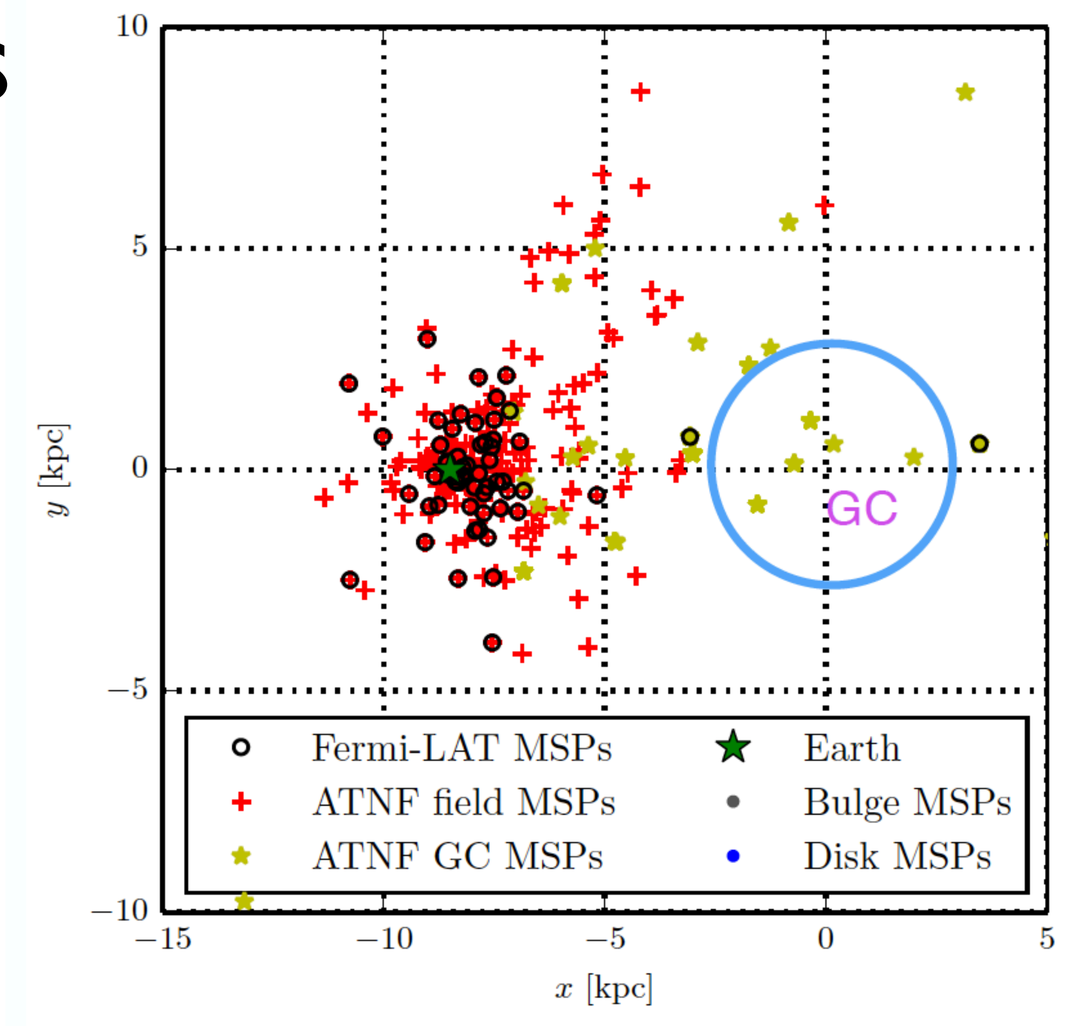
Just rescaling the measured local MSP/star ratio in the disk to the stars in the bulge, ~10% to ~200% of the GCE be accounted for by MSP!!!

C. Eckner et al., Astrophys. J. 862, no. 1, 79 (2018) [1711.05127]



Part III:
Multiwavelength and multimessenger probes

Challenges



To nail down GCE origin, actual population of sources should be identified and characterized

Strong selection effects in known MSP pulsar catalogues
(~370 radio sources with P<30 ms):
mostly detected within (3-4 kpc from Earth),
remote ones only 'collectively' via Globular Cluster emission

Bagchi+MNRAS'11 Calore+ ApJ'16

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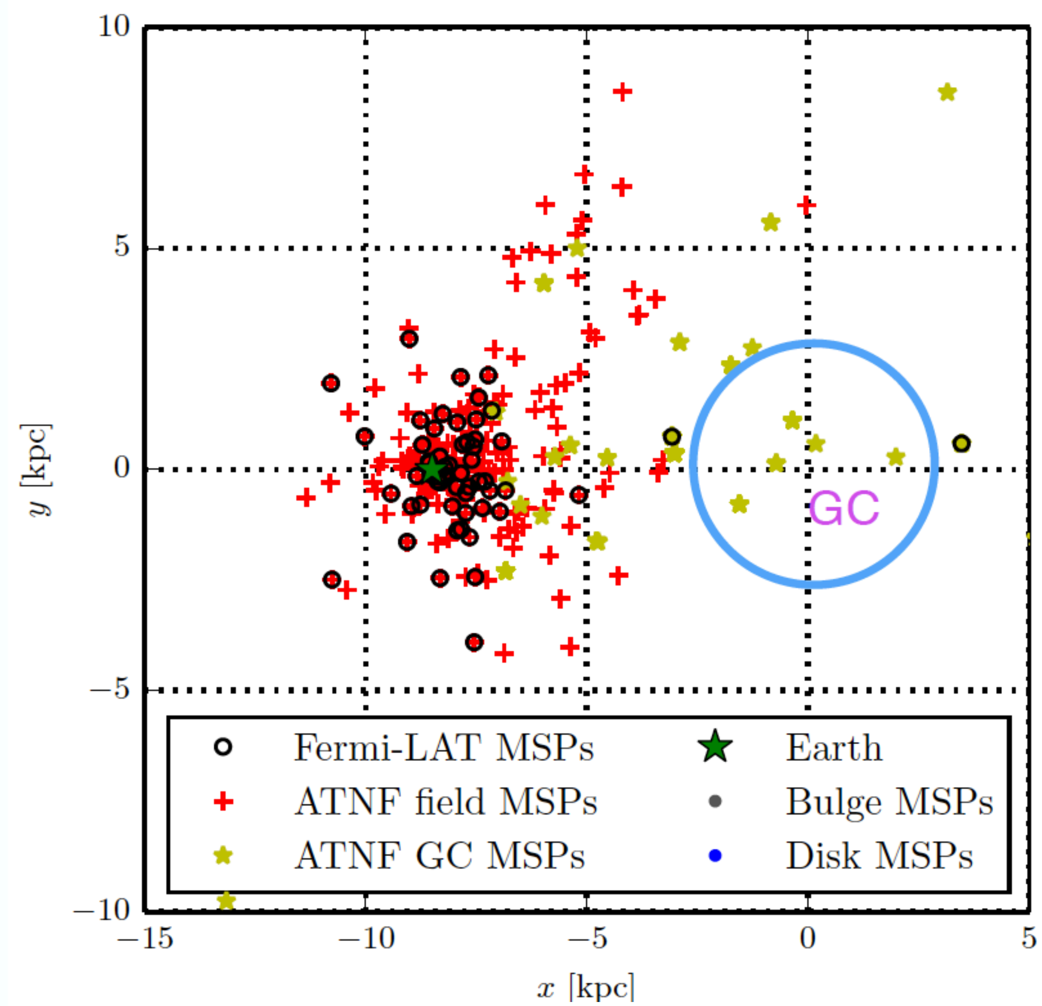
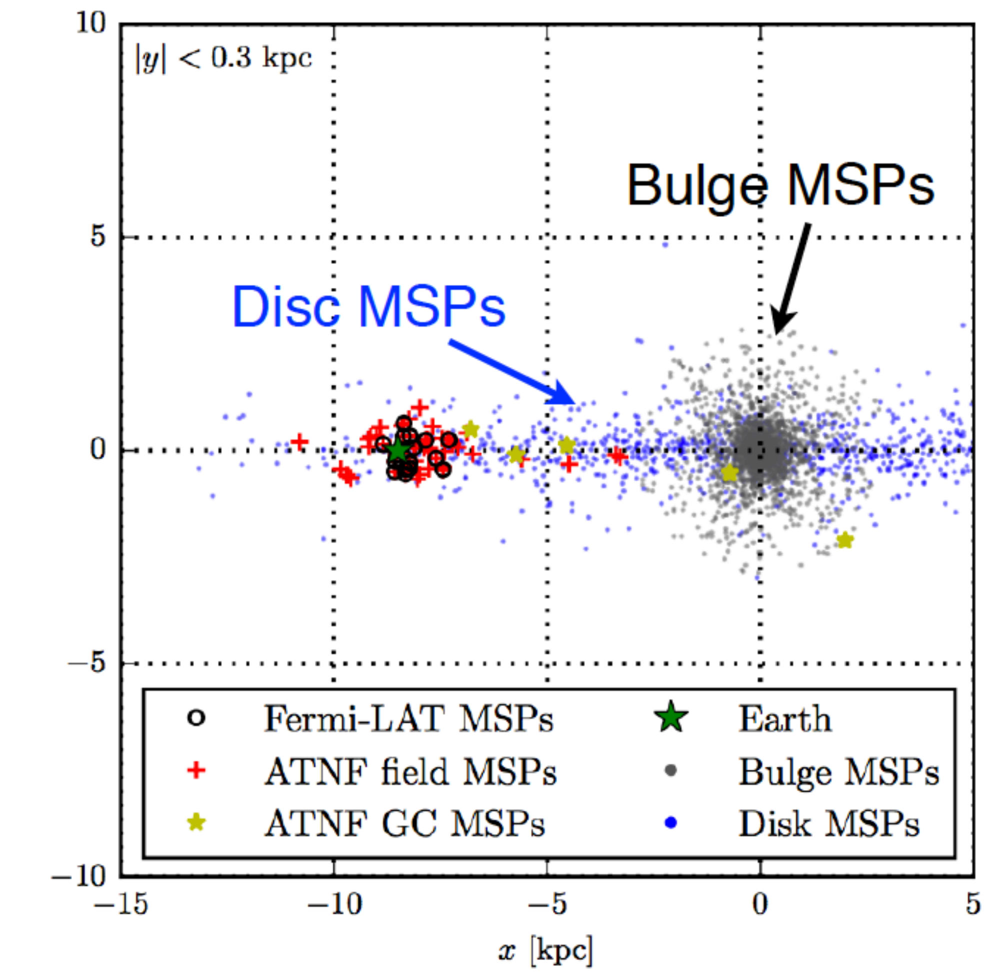


Predictions require some (mild) model assumptions

- Use Fermi GCE spatial & spectral features;
- Compare GCE intensity with Globular Clusters emission (assumed dominated by MSP) to 'normalize'

→ ~10^4 MSP expected in the bulge, only a factor a few less than in the whole disk!

$$\propto r^{-2.5} \exp\left(-\frac{r}{3\,\mathrm{kpc}}\right)$$



Radio surveys

1. Not surprising that currently undetected

Mid-latitude past surveys (|b| >5°) not optimal for MSPs searches at the GC (too shallow, ca 200 sec); huge dispersion and scattering effects too close to the GC!

2. Ongoing TRAPUM survey @ MeerKat (SKA precursor) could be enough for discovering some tens of objects

provided that optimal deep surveys are performed, and best-fits not too far from truth.

F. Calore et al." Radio detection prospects for a bulge population of millisecond pulsars as suggested by Fermi LAT observations of the inner Galaxy," Astrophys. J. 827, no. 2, 143 (2016) [1512.06825]

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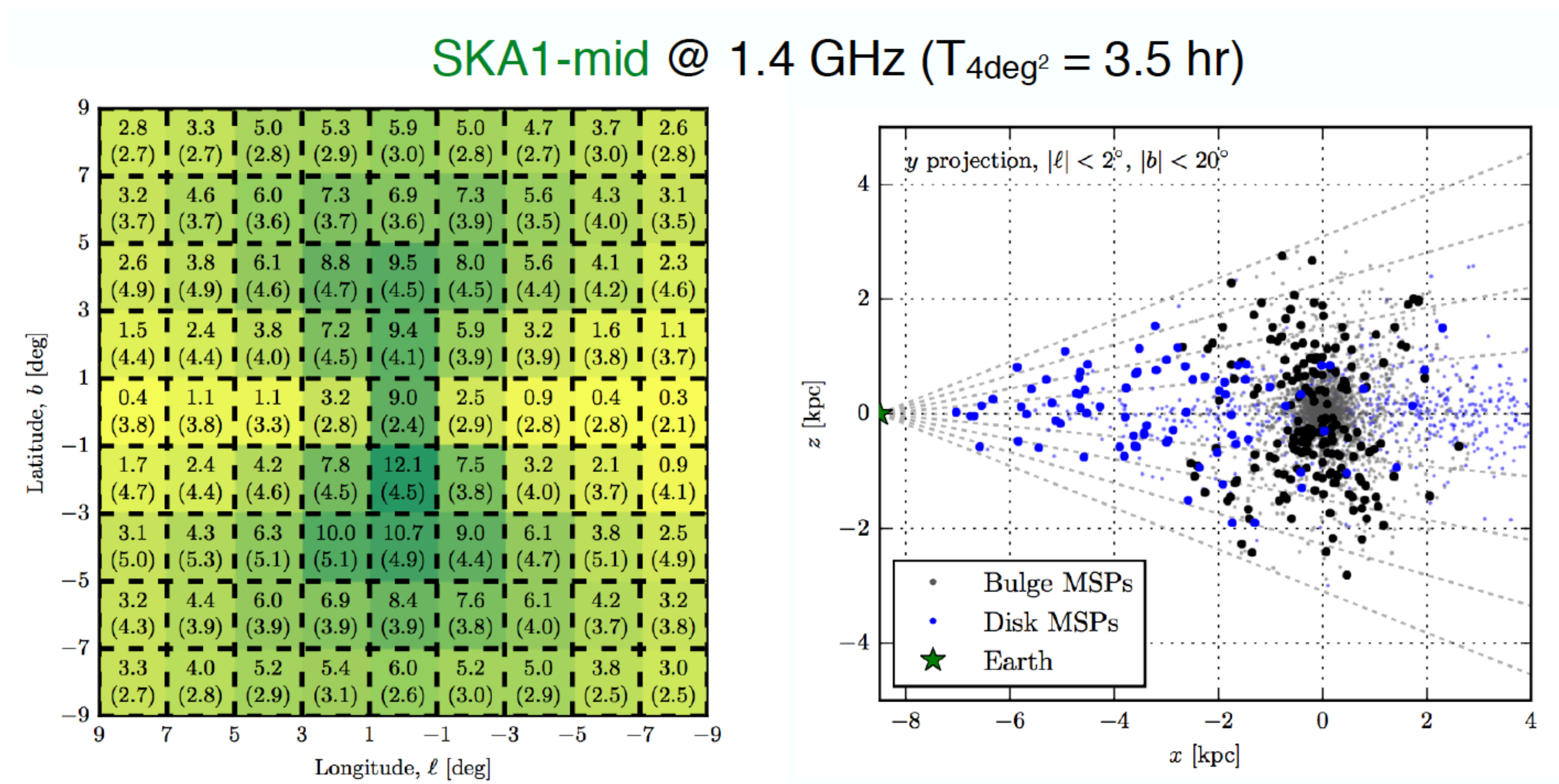
3. Future SKA-mid needed for definite discovery and characterization



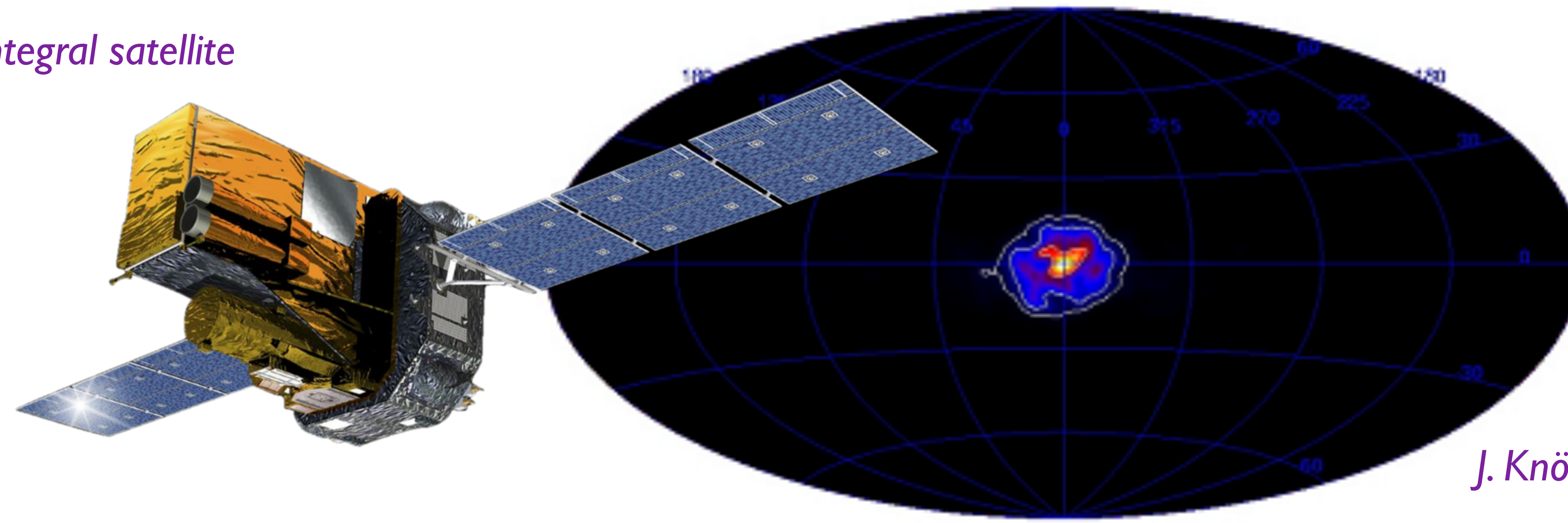
F. Calore et al." Radio detection prospects for a bulge population of millisecond pulsars as suggested by Fermi LAT observations of the inner Galaxy," Astrophys. J. 827, no. 2, 143 (2016) [1512.06825]

X-ray alternative?

Intriguing hints of morphological similarity with 511 keV bulge emission as well:

Crocker et al. Nature Astronomy 1, 0135 (2017) [1607.03495]
R. Bartels, F. Calore, E. Storm and C.Weniger MNRAS 2018[1803.04370]

Integral satellite



J. Knödlseder - CESR

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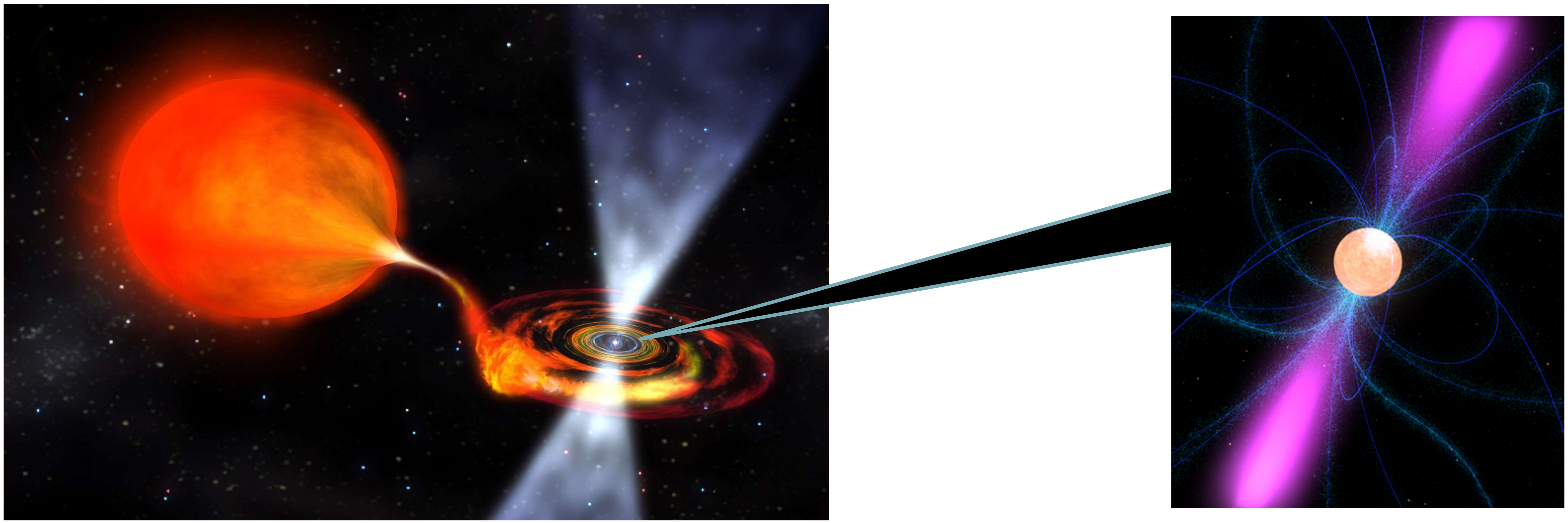


Scenario

'recycled' MSP causing GeV excess could have as progenitors dim Ultra-Compact X-ray binaries with neutron star partners (10^5 predicted in the bulge according to *van Haaften et al. A&A'13,'15*); UCXB could emit positrons from cold and mildly relativistic leptonic jets.

Guessoum et al. A&A'06; Bandyopadhyay et al. MNRAS'09; Siegert et al. A&A'16

Relies more on population synthesis and acceleration models, yet associate predictions on UCXB testable

A serendipitous consequence for GW

MSP are expected to emit GW, and their unresolved emission is considered the dominant Galactic background for ground-based interferometers like LIGO/Virgo

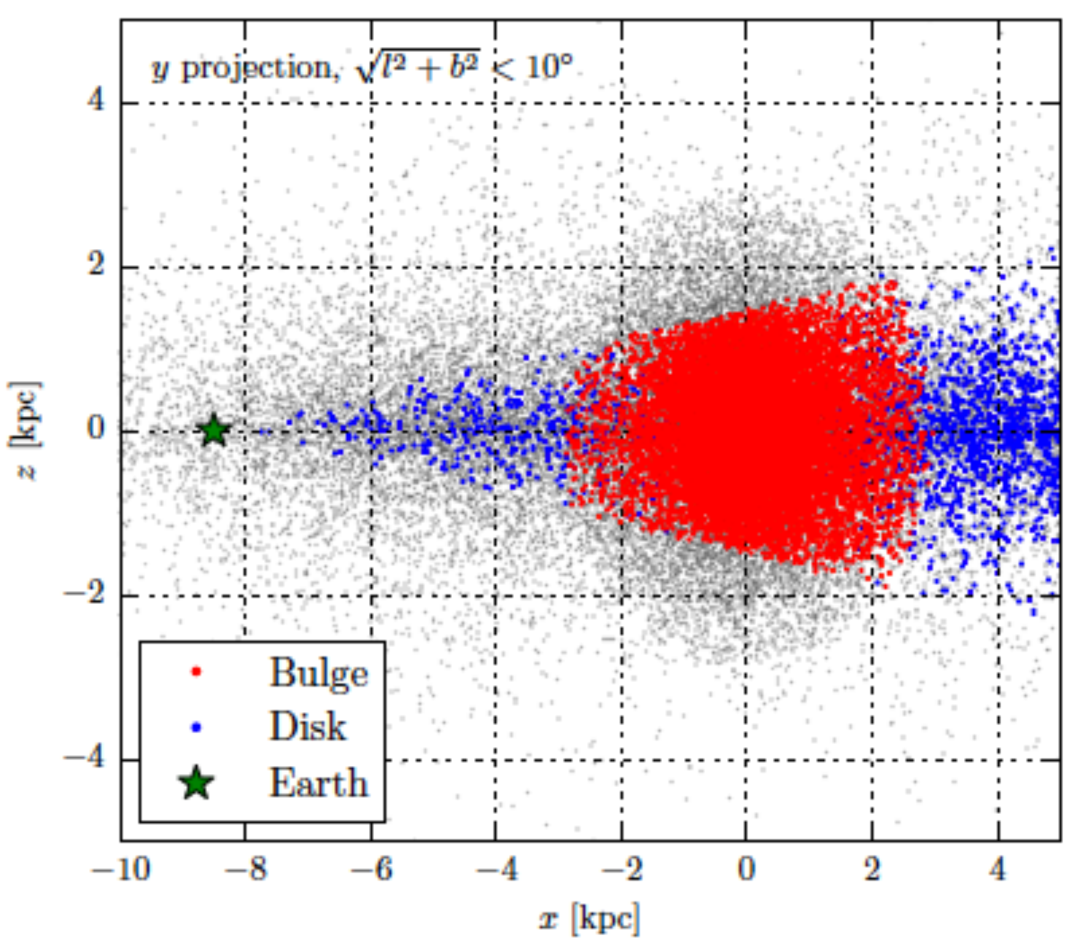
(bear with me, more on this later)

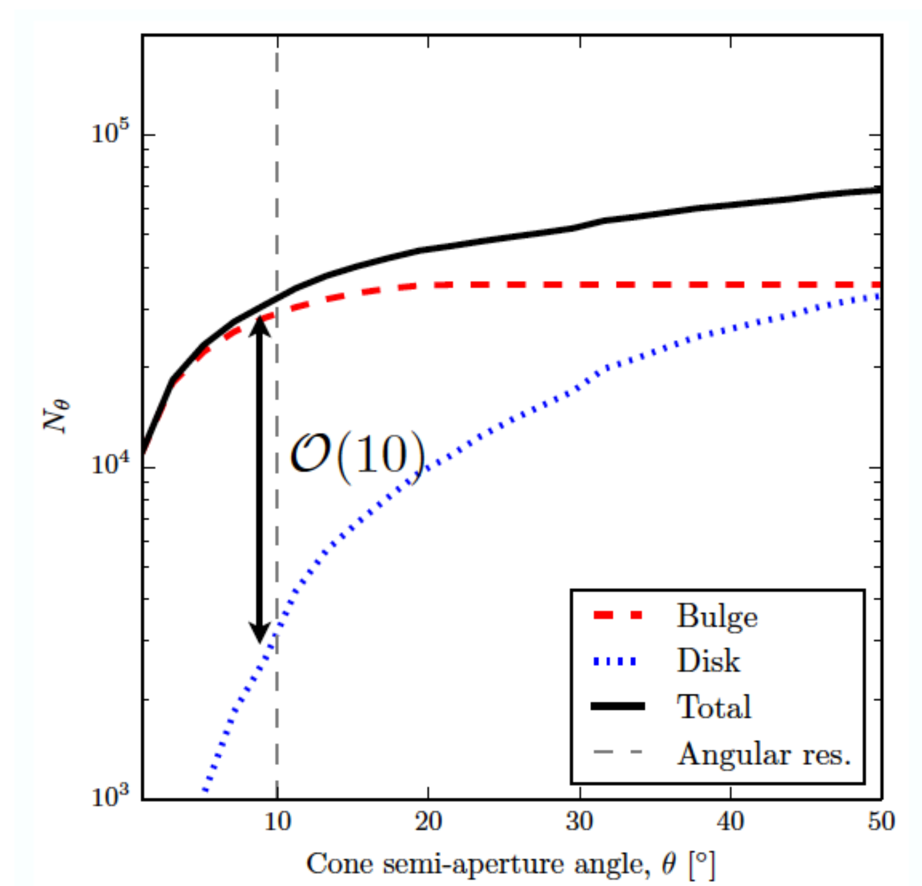
If the MSP origin of the "GCE" true

→ the differential signal much bigger than thought & focused towards the inner Galaxy!

→ Change in the optimal search strategy *(rather model-independent conclusion)*

F. Calore, T. Regimbau and P. D. Serpico, Phys. Rev. Lett. 122, 081103 (2019) [arXiv:1812.05094]





GW from (millisecond) Pulsars

mechanism considered dominant and most common:

If not perfectly spherical (asphericity parameterized by ε), MSP are expected to emit GW (triaxial rapidly rotating star of period *P*)

monochromatic at $f = 2/P$

Depends on **ellipticity** ($\propto$ quadrupole moment)

$$\varepsilon \equiv \frac{I_{xx} - I_{yy}}{I_{zz}} \propto Q$$

(more later on 'reasonable' values)

originate from elastic strains in the crust or strong internal B fields *Mastrano et al. MNARS '11,'12*

GW Luminosity

$$L_{\rm GW} = \frac{2048\pi^6 G}{5c^5}\frac{I^2\varepsilon^2}{P^6} \quad (|\epsilon| \ll 1 \quad I_{xx} \simeq I_{yy} \simeq I_{zz} = I)$$

Note: Other mechanisms known that can induce GW, e.g. instability in the r-modes of the rotating star (not considered in the following)

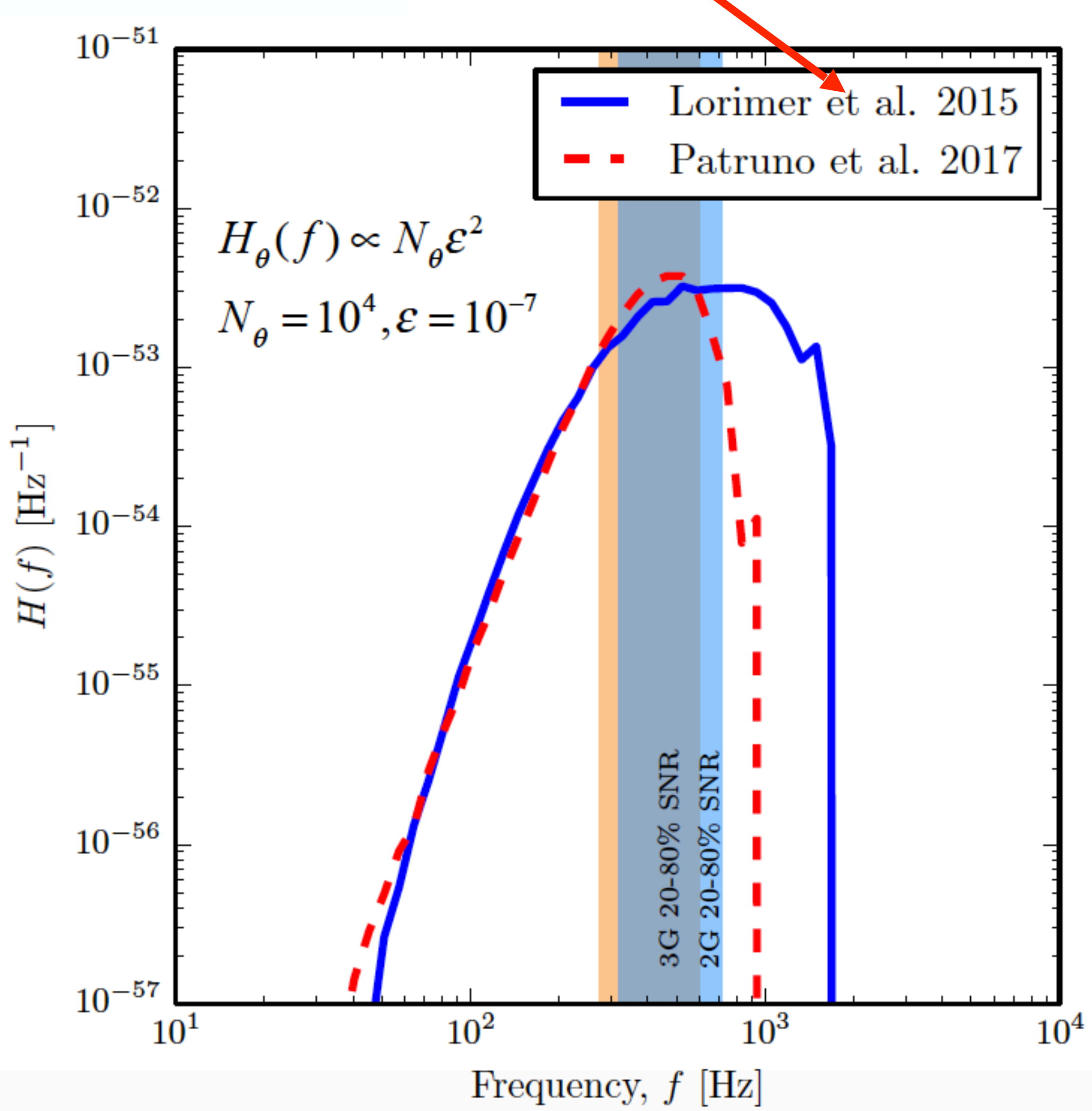
Andersson et al. ApJ 98; Owen et al Phys. ReV. D 98

The signal from the GC population

GW power spectral density in a cone of semi-aperture θ

$$H_\theta(f) = \frac{32\pi^4 G^2}{5c^8}\varepsilon^2 I^2 f^4 \mathscr{P}(f) \int_{\mathrm{l.o.s.}} \frac{\mathscr{N}_\theta(s)}{s^2}\mathrm{d}s$$

two different models for the MSP period distribution



assuming everything concentrated at GC

$$\mathscr{N}_\theta(s) = N_\theta \delta\left(s - d_{\mathrm{GC}}\right)$$

$$N_\theta \equiv d_{\mathrm{GC}}^2 \int_{\mathrm{l.o.s.}} \frac{\mathscr{N}_\theta(s)}{s^2} ds$$

Approx ok, given the poor angular resolution of GW detectors (estimated diffraction-limited spot size~7°)

Detectability with radiometer search

Search relies on excess coherence in the cross-correlated data streams from multiple detectors

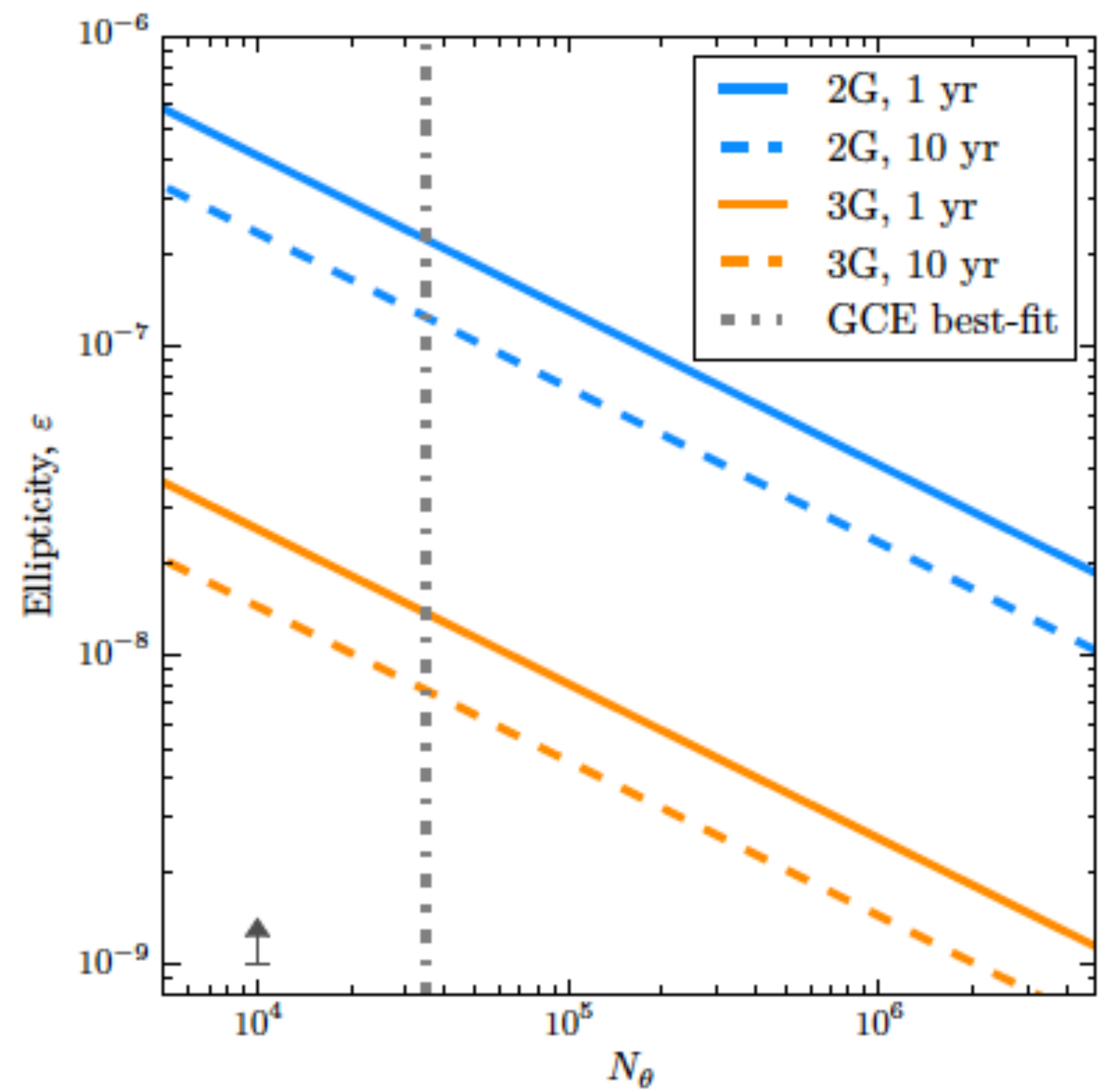
Method: GW radiometer — by applying appropriate time-varying delays between detectors possible to estimate directional sensitivity (here direction of GC)

signal to noise scales as

$$SNR \simeq 0.18\{46\}\frac{N_\theta}{10^4}\left(\frac{\epsilon}{10^{-7}}\right)^2\sqrt{\frac{T}{1\mathrm{yr}}}$$

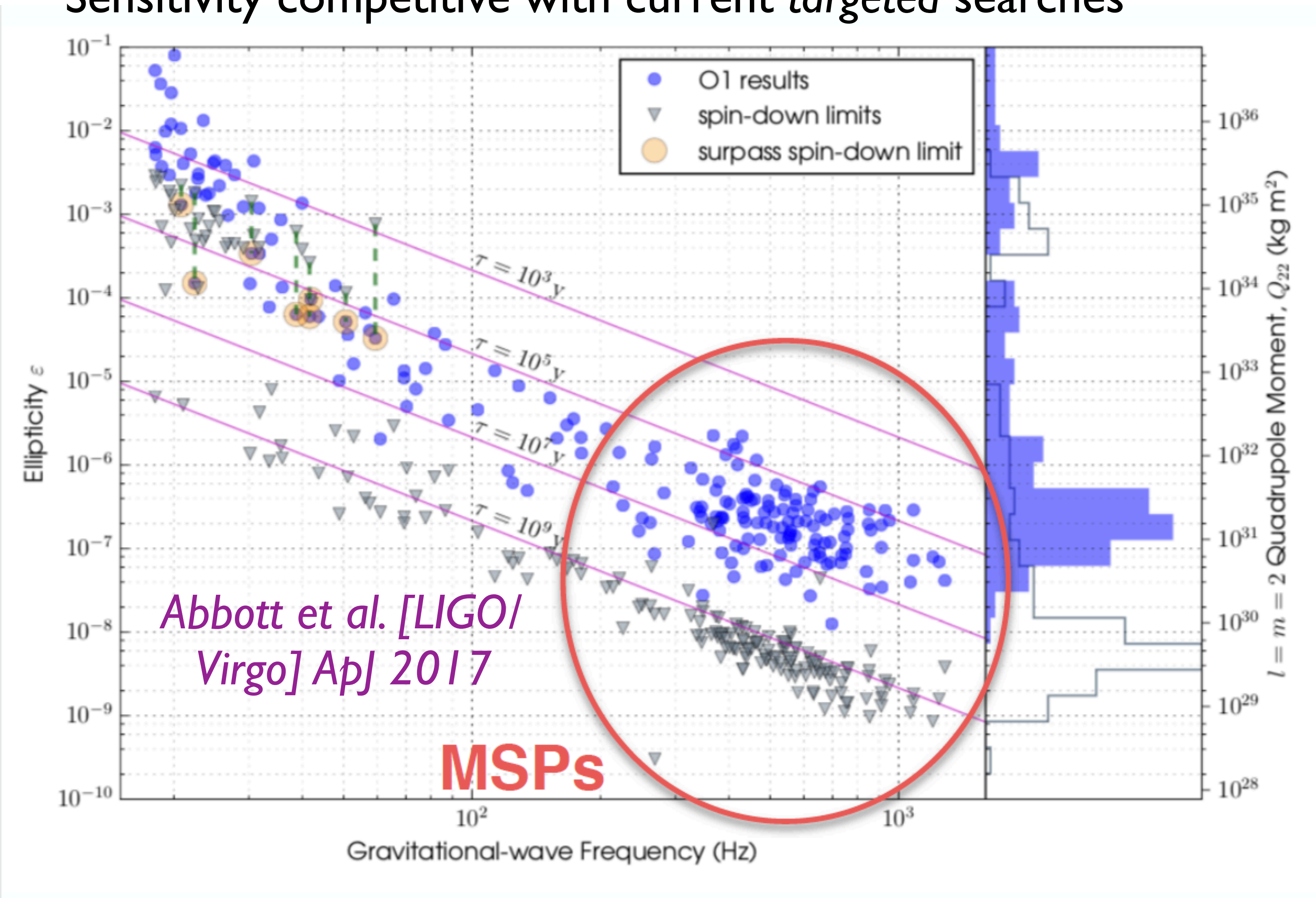
2G: current generation (2 LIGO det @ Hanford & Livingston + Virgo @ Pisa) at design sensitivity

3G: 2 Cosmic explorer at actual LIGO site plus Einstein Telescope at actual Virgo site



“Reasonable" ellipticities

Sensitivity competitive with current *targeted* searches



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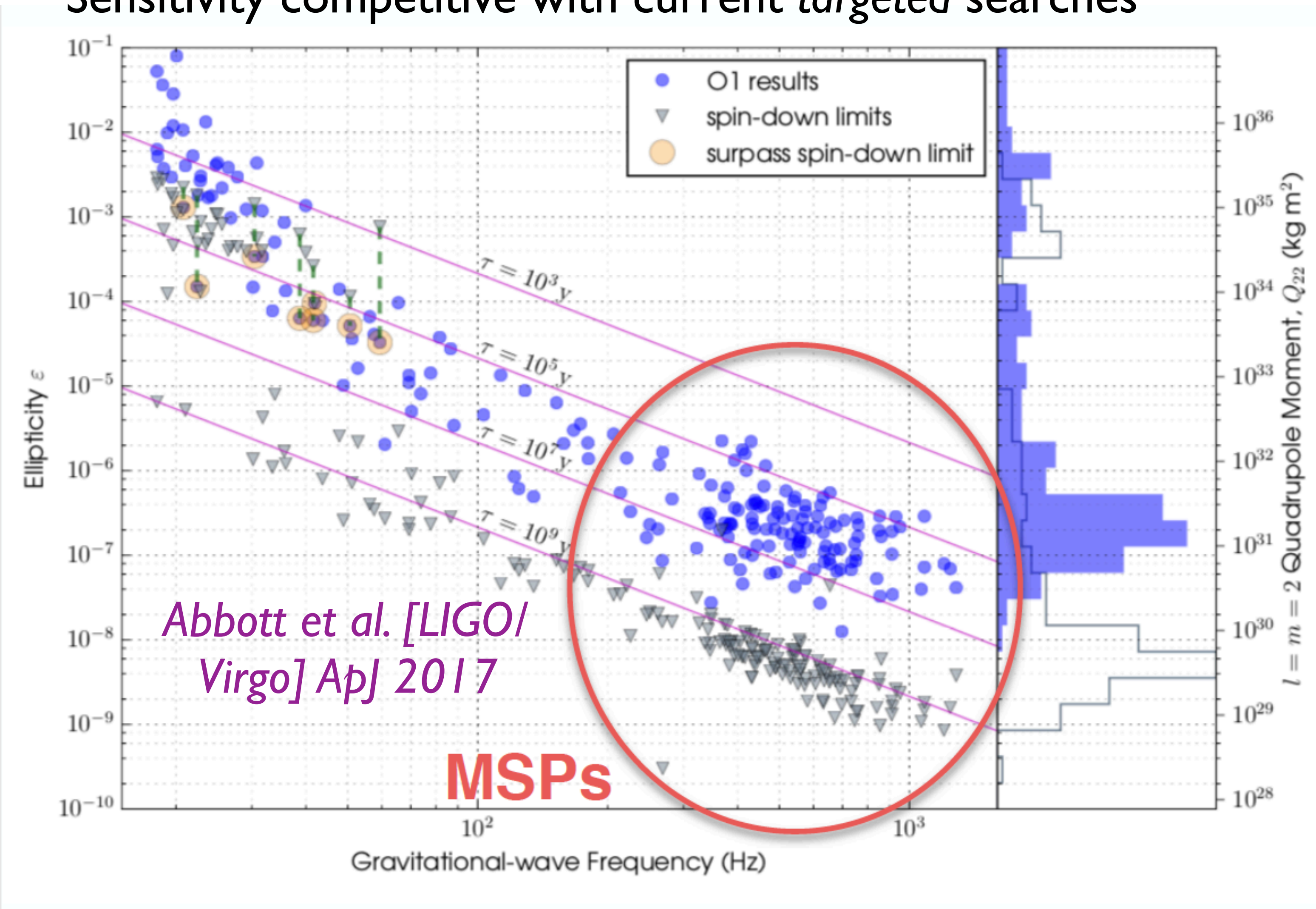
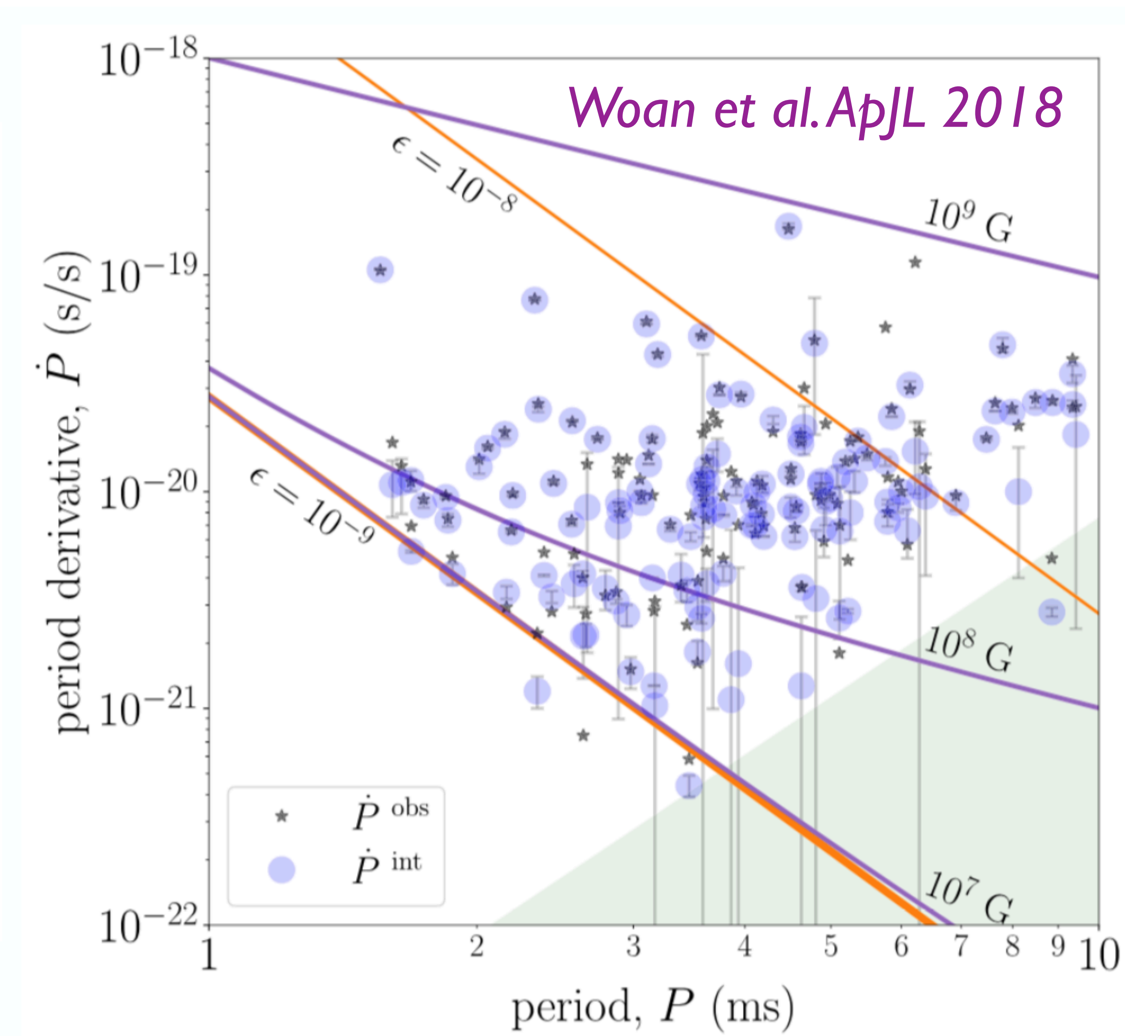


From known MSP P-dotP, argued that $\epsilon \gtrsim 10^{-9}$



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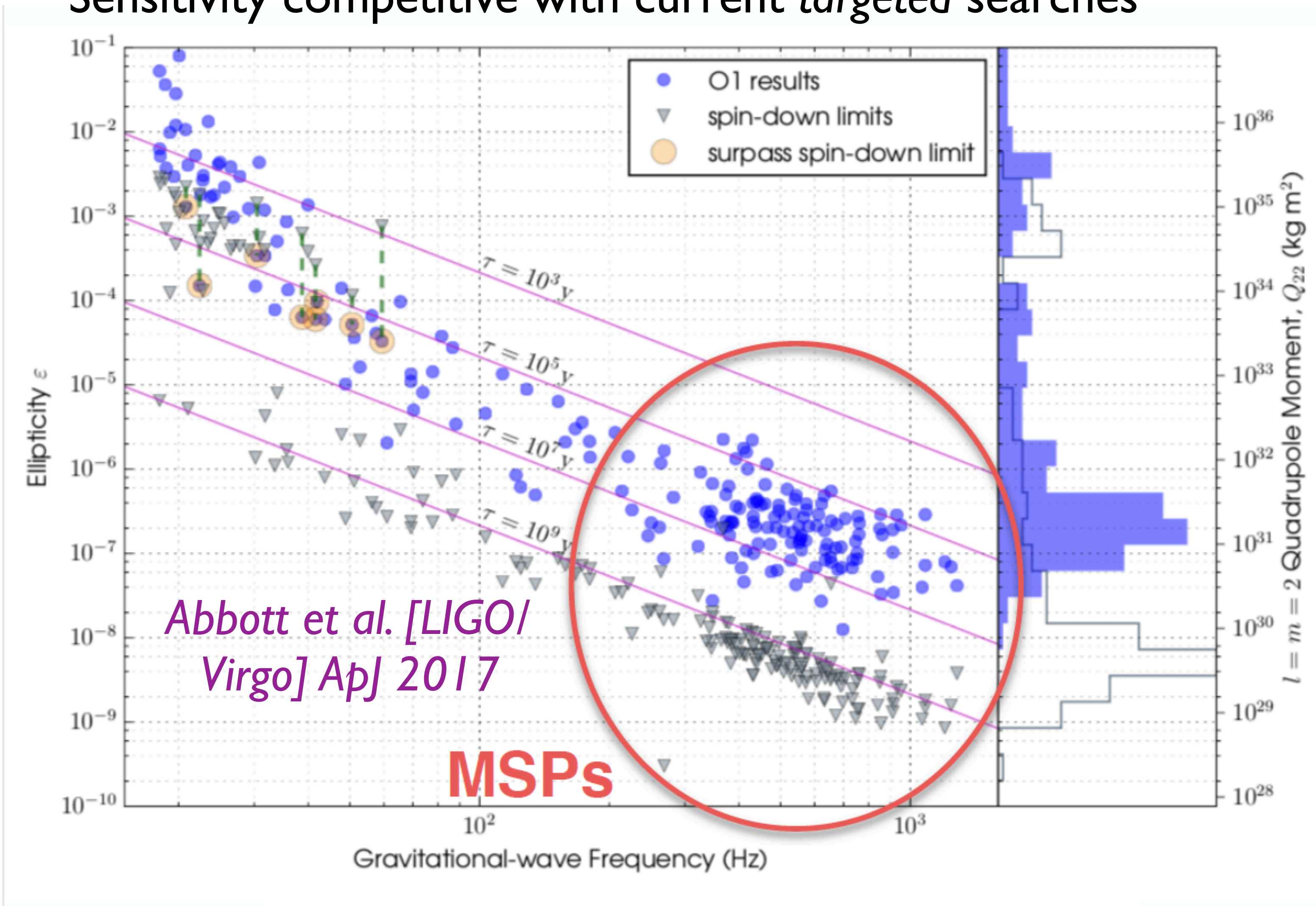

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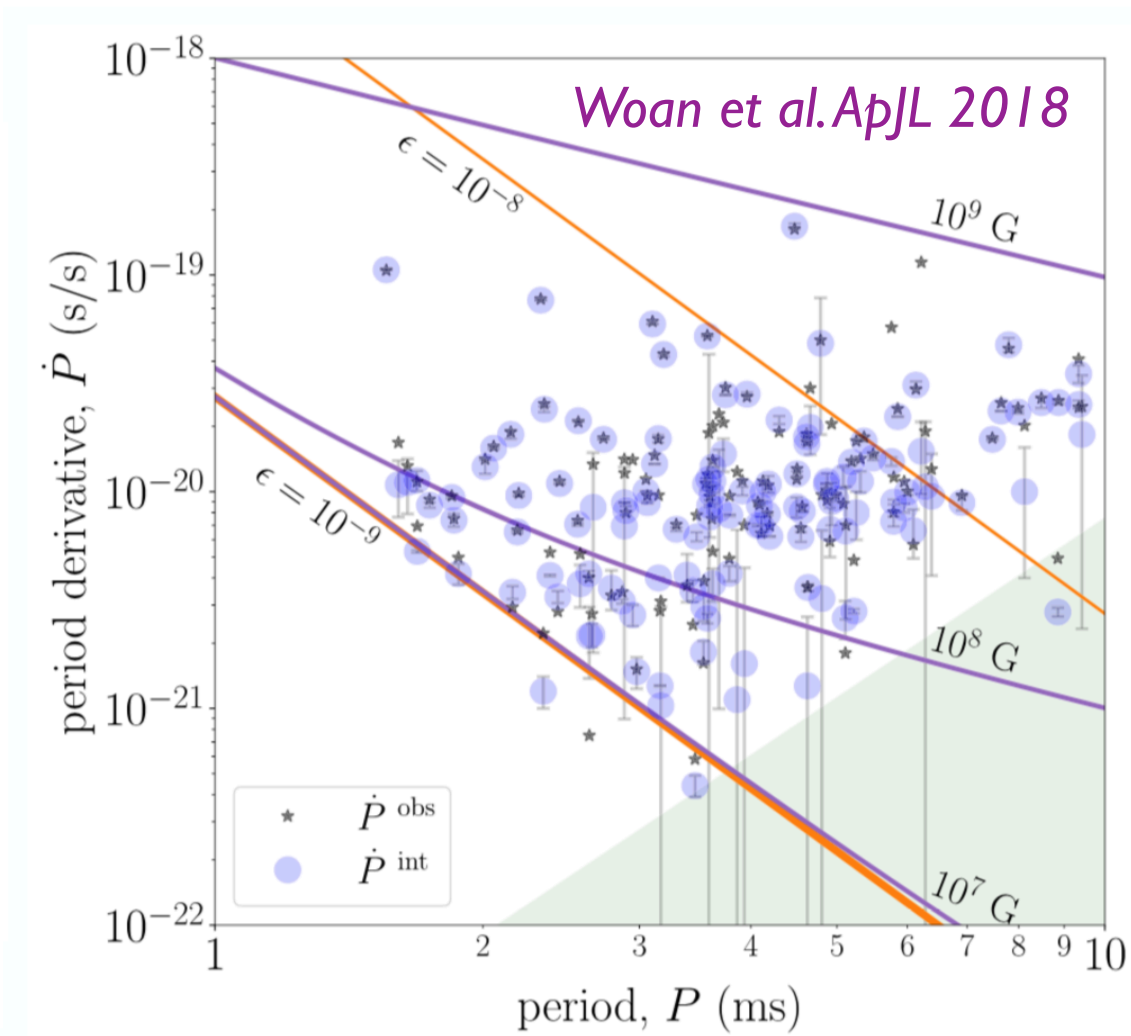

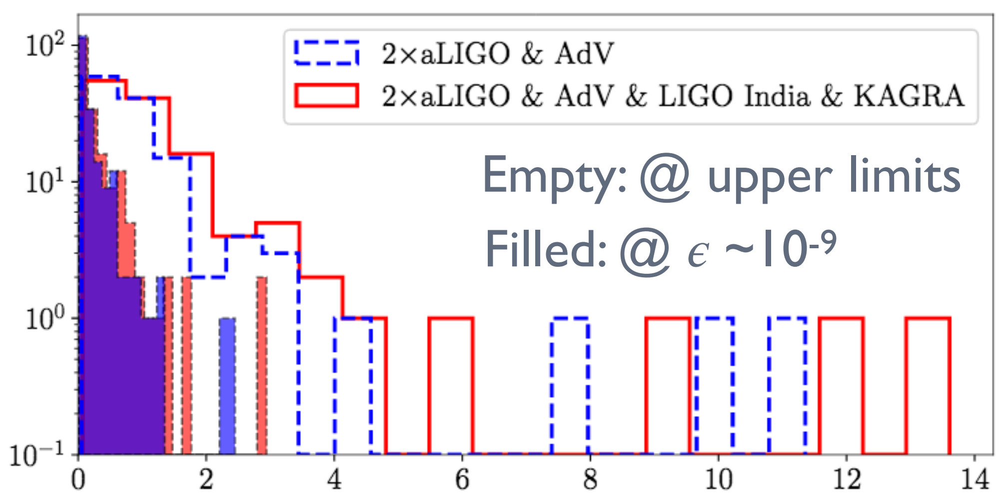

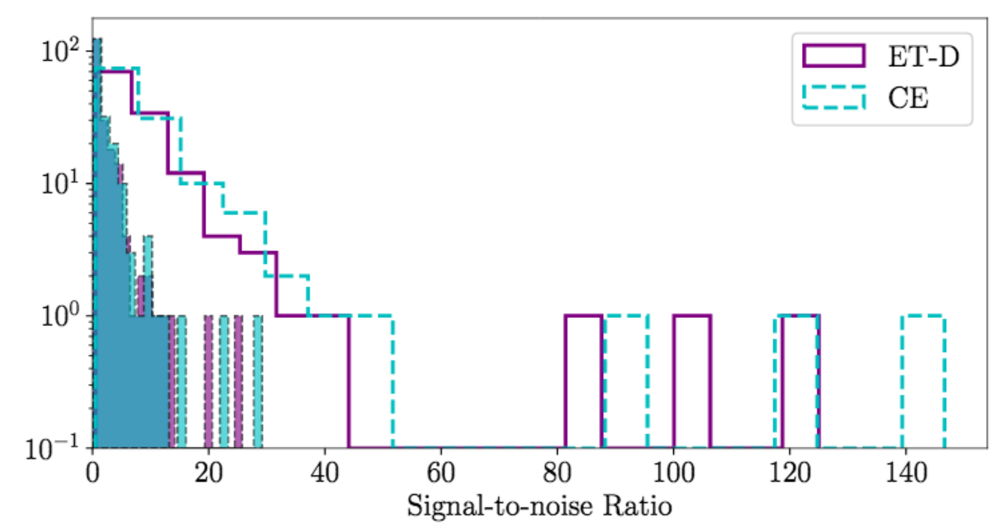

If single pulsars detected in forthcoming years, diffuse detectable at 3G (which we'll have otherwise to wait for to detect a few objects, or invalidate the paradigm of GW’s from MSP)

Summary and conclusions

- After decades of 'dreams' about it, the **multimessenger frontier is a reality** and promises rich rewards, as illustrated by GW170817

- Can we adopt a **similar strategy** to learn **about other contemporary mysteries?** I presented the case of the **Galactic Center Excess** revealed at GeV energies in Fermi-LAT data.

- I stressed the **growing** albeit indirect **indications for** an **unresolved** population of **sources** at its origin, and the **challenges** to reveal them explicitly (**radio, X-rays**…)

- **GWs offer another handle** on the issue. I argued that, if MSP are at the origin of the GCE:

  i) their collective emission should dominate the 'Galactic background' of GW sources in the LIGO/Virgo band *(rather model-independent)*

  ii) already *interesting sensitivity*; if nearby MSP detection in a few year, stochastic signal towards the GC detectable at future ground based detectors (~2030?), a timescale comparable with definite tests via SKA-mid in the radio band.