Investigating Unassociated Fermi-LAT sources for the search of Gamma ray Pulsars and Millisecond pulsars

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MOTIVATION

The aim is to identify potential Gamma-ray pulsars and Millisecond pulsars, offering new insights into the gamma-ray sky and enhancing our understanding of the unidentified gamma ray sources.

GOALS

To improve the sensitivity of the analysis by extending the observational time period (August 2008 to December 2023), allowing for more comprehensive data coverage and increasing the likelihood of detecting pulsar signals. [1]

To Test the pipeline on known pulsars using the extended observational time and increased photon counts, ensuring improved accuracy and performance in pulsar signal detection.

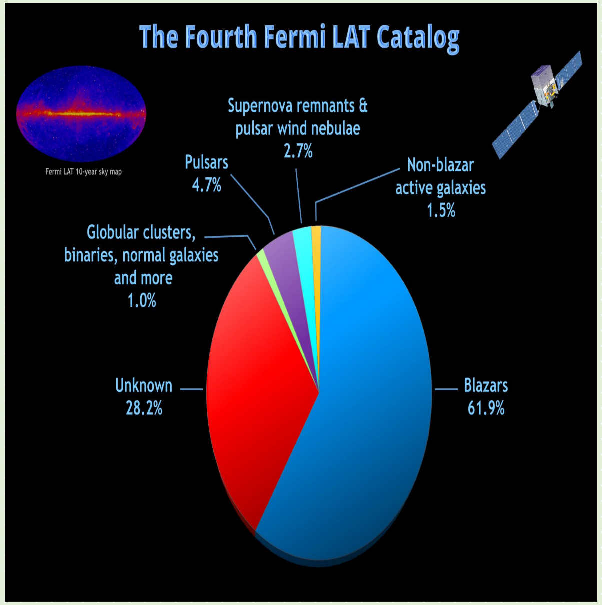
To perform the detailed analysis for unassociated sources of the Fermi catalog in search of potential Gamma ray pulsars and Millisecond pulsars.

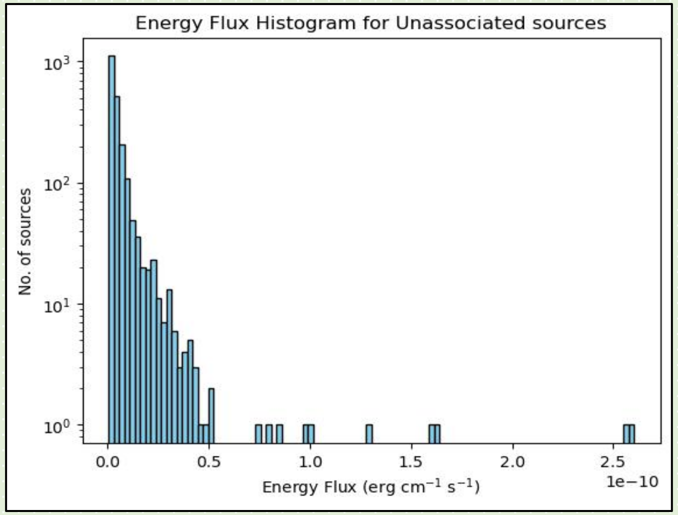
If pulsars are successfully identified through our analysis, submit eventual potential Neutron star candidates to the LVK community for further analysis to look into Gravitational waves counterpart.

[1] Analysis method adapted from the thesis "Adattamento alla ricerca di pulsar gamma di metodologie di analisi per segnali gravitazionali continui" - Dr. Maria Concetta Tringali

The pipeline was originally designed and implemented by Dr. Maria Concetta Tringali and Dr. Cristiano Palomba.

What are Unassociated Gamma ray sources?





4FGL DR3

Table 5. LAT 4FGL-DR3 Source Classes

Description	Identified		Associated	
	Designator	Number	Designator	Number
Galactic center	GC	1	...	...
Young pulsars, identified by pulsations	PSR	135	...	...
Young pulsars, no pulsations seen in LAT yet	...	...	psr	2
Millisecond pulsars, identified by pulsations	MSP	120	...	...
Millisecond pulsars, no pulsations seen in LAT yet	...	...	msp	35
Pulsar wind nebula	PWN	11	pwn	8
Supernova remnant	SNR	24	snr	19
Supernova remnant / Pulsar wind nebula	SPP	0	spp	114
Globular cluster	GLC	0	glc	35
Star-forming region	SFR	3	sfr	2
High-mass binary	HMB	8	hmb	3
Low-mass binary	LMB	2	lmb	6
Binary	BIN	1	bin	6
Nova	NOV	4	nov	0
BL Lac type of blazar	BLL	22	bll	1435
FSRQ type of blazar	FSRQ	44	fsrq	750
Radio galaxy	RDG	6	rdg	39
Nonblazar active galaxy	AGN	1	agn	8
Steep spectrum radio quasar	SSRQ	0	ssrq	2
Compact steep spectrum radio source	CSS	0	css	5
Blazar candidate of uncertain type	BCU	1	bcu	1491
Narrow-line Seyfert 1	NLSY1	4	nlsy1	4
Seyfert galaxy	SEY	0	sey	2
Starburst galaxy	SBG	0	sbg	8
Normal galaxy (or part)	GAL	2	gal	4
Unknown	UNK	0	unk	134
Total	...	389	...	4112
Unassociated	...	...	...	2157

NOTE—The designation 'spp' indicates potential association with SNR or PWN. 'Unknown' are $|b| < 10°$ sources solely associated with the likelihood-ratio method from large radio and X-ray surveys. Designations shown in capital letters are firm identifications; lower-case letters indicate associations.

The Third Fermi Large Area Telescope Catalog of Gamma-ray Pulsars
ApJ 2023 958 191 [arXiv:2307.11132]

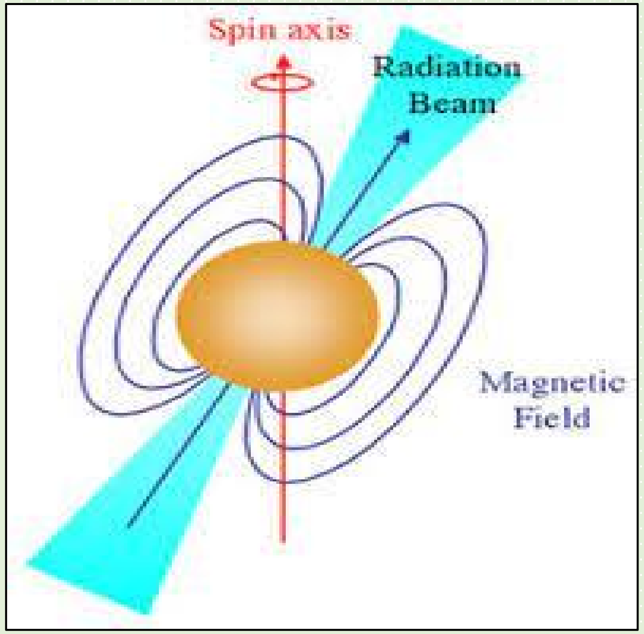
- **Unassociated sources** - Gamma-ray sources whose counterparts in other wavelengths (such as radio, X-ray, or optical) have not been identified.
- **Direct search Data Analysis Method (DSDA) -** This is an extension of a semicoherent pipeline used to analyse GW data of interferometers to the Fermi data.
- The DSDA method is being applied to the Unassociated sources of the Fermi catalog in search of potential Gamma ray pulsars and Millisecond pulsars (MSPs).

Why is it interesting to study Pulsars?

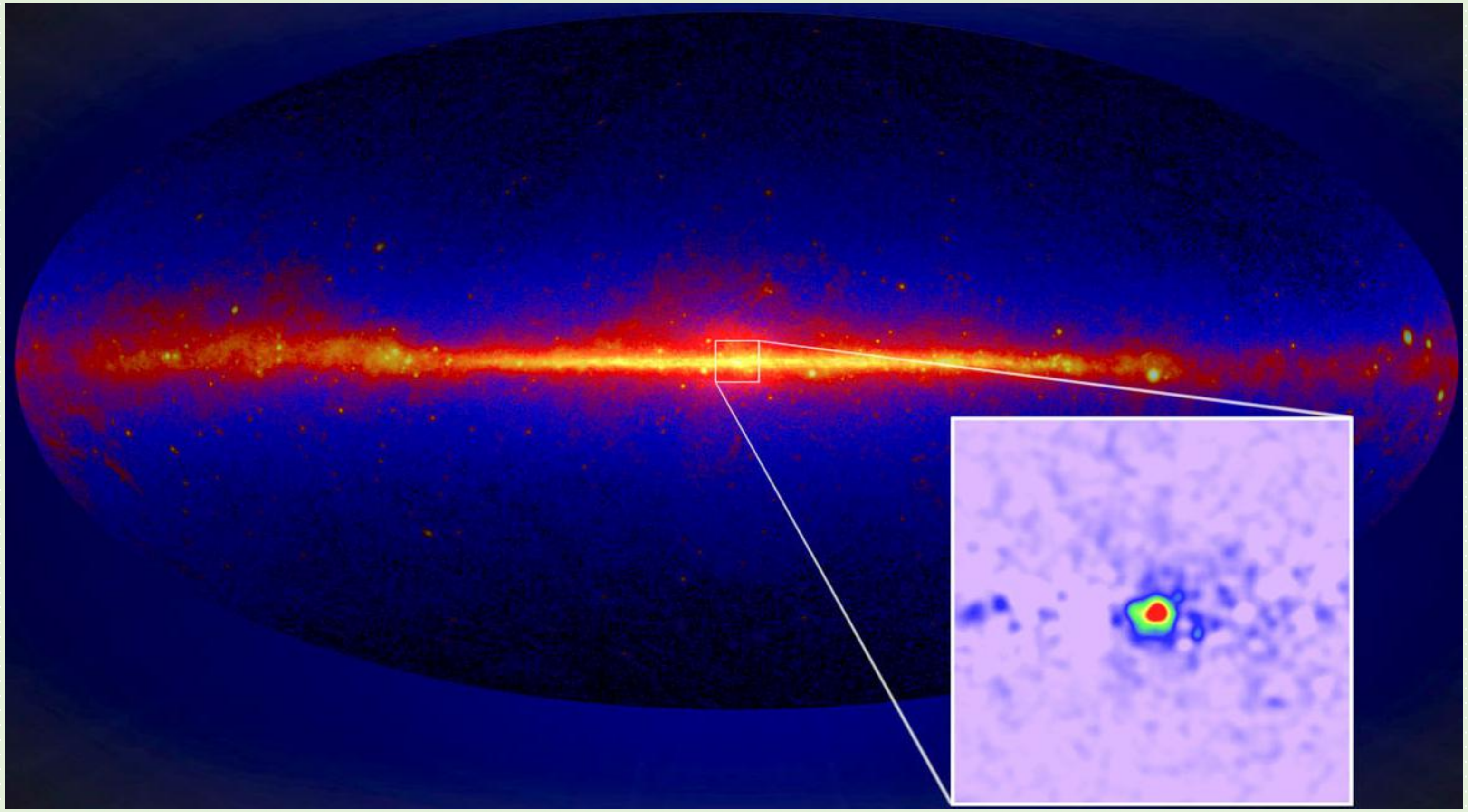
- Pulsars are rapidly rotating Neutron Stars (NS).
- Exceptional objects - they serve as natural laboratories for testing the extremes of physics, from strong gravitational and magnetic fields to high-density matter, all while being remarkably stable and observable across multiple wavelengths.
- Continuous GW signals - ellipticity (deformation) of the pulsars, which quantifies how much the neutron stars deviate from perfect symmetry.
- GWs give information on Equation of State (EOS)

$$\varepsilon = \frac{I_{eq} - I_p}{I_p}$$

  - ε is the ellipticity of the neutron star.
  - I_{eq} is the moment of inertia about the equatorial axis.
  - I_p is the moment of inertia about the polar axis.
- EM counterparts are crucial for understanding their magnetic fields, internal composition, rotational behavior, and the extreme environments they inhabit.



Galactic center GeV excess



The Fermi telescope has mapped the entire sky and found an excess of gamma-rays in the Galactic Centre. T. LINDEN/UNIVERSITY OF CHICAGO

The first evidence of the GeV excess was mentioned by V.Vitale, A.Morselli, Fermi Collaboration in "Indirect Search for Dark Matter from the center of the Milky Way with the Fermi-Large Area Telescope", arXiv:0912.3828 (2009)

Theories explaining GeV excess

- **Series of Leptonic Cosmic-Ray Outbursts**
  Cholis et al. arXiv:1506.05119

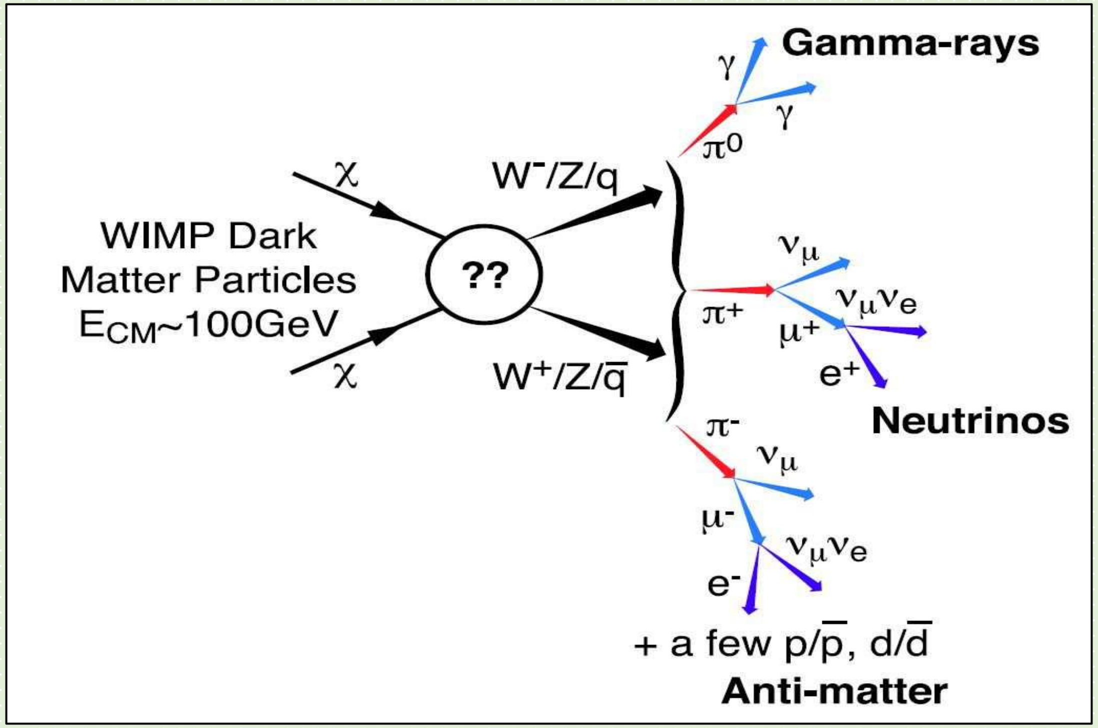
- **Stellar population of the X-bulge and the nuclear bulge**
  Macias et al. arXiv:1611.06644

- **Molecular Clouds in the disk**
  De Boer et al. arXiv:1610.08926, arXiv:1707.08653

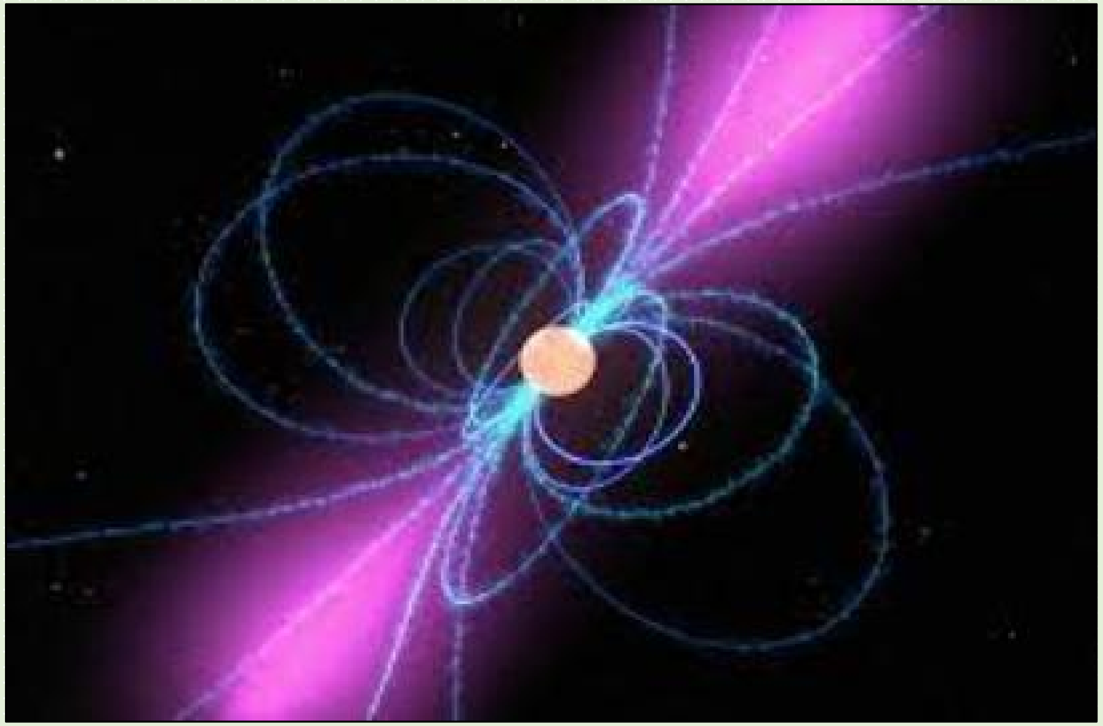
- **Population of pulsars in the Galactic bulge**
  Yuan and Zhang arXiv:1404.2318v1, Lee et al. arXiv:1506.05124, Bartels et.al. 1506.05104
  M.Ajello et al. [Fermi-LAT Coll.] Phys. Rev. D 95, 082007 (2017) [arXiv:1704.07195]

Leading theories

Self annihilating Dark Matter



Pulsar population



Although the Dark Matter scenario seems very attractive, it is very crucial to investigate the astrophysical alternatives of the excess, especially in view that direct detection experiments found no signal of Dark Matter collision in the corresponding mass ranges.

Strong Support for the Millisecond Pulsar Origin of the Galactic Center GeV Excess

Richard Bartels,[1,*] Suraj Krishnamurthy,[1,†] and Christoph Weniger[1,‡]

[1]GRAPPA Institute, University of Amsterdam, Science Park 904, 1090 GL Amsterdam, Netherlands

Phys. Rev. Lett. 116, 051102 arXiv:1506.05104 [astro-ph.HE] (9 Mar 2016)

Evidence for Unresolved Gamma-Ray Point Sources in the Inner Galaxy

Samuel K. Lee,[1,2] Mariangela Lisanti,[3] Benjamin R. Safdi,[4] Tracy R. Slatyer,[4] and Wei Xue[4]

[1]Princeton Center for Theoretical Science, Princeton University, Princeton, NJ 08544

[2]Broad Institute, Cambridge, MA 02142

[3]Department of Physics, Princeton University, Princeton, NJ 08544

[4]Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139

Phys. Rev. Lett. 116, 051103 arXiv:1506.05124 [astro-ph.HE] (Dated: 4 February 2016)

Robustness of the Galactic Center Excess Morphology Against Masking

Yi-Ming Zhong[1,2] and Ilias Cholis[3]

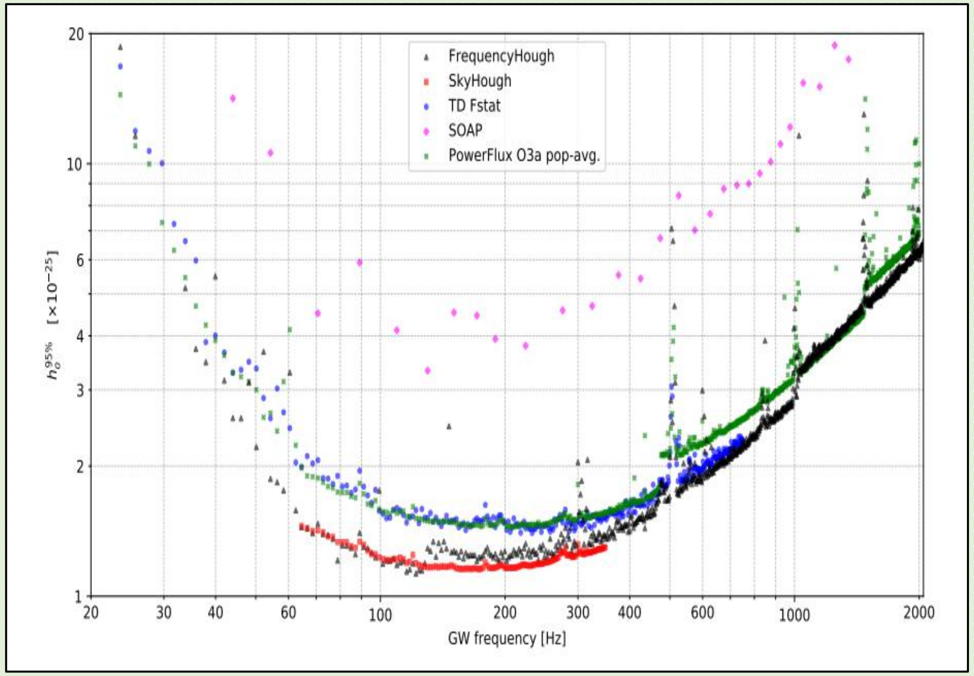
[1]*Department of Physics, City University of Hong Kong, Kowloon, Hong Kong SAR, China*[*]

[2]*Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA*

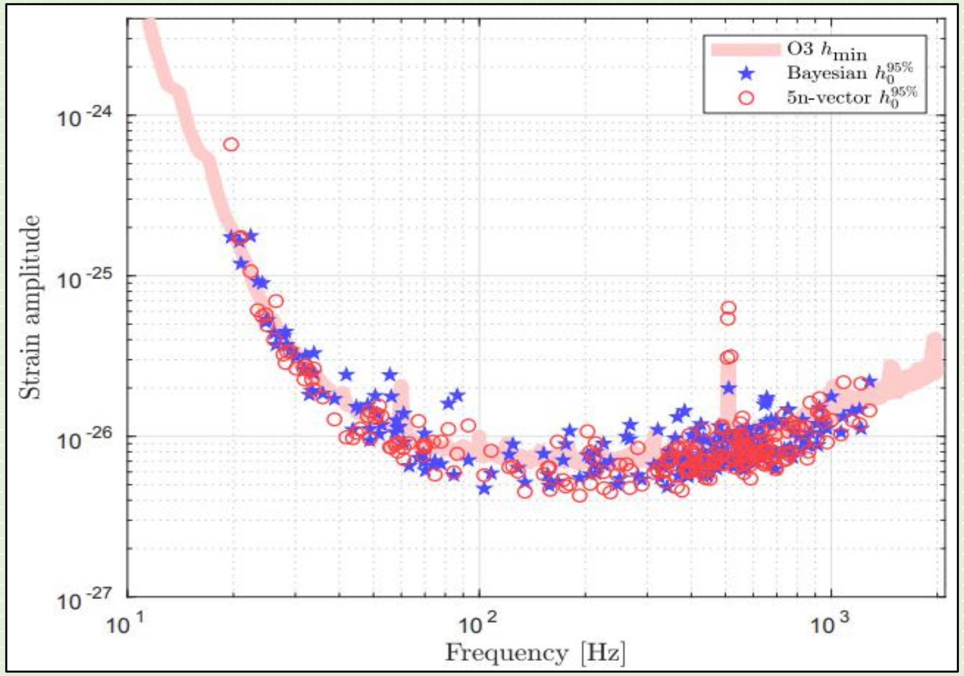
[3]*Department of Physics, Oakland University, Rochester, Michigan, 48309, USA*[†]

(Dated: June 13, 2024)

Gravitational waves signal from isolated pulsars



From "All-sky search for continuous gravitational waves from isolated neutron stars using Advanced LIGO and Advanced Virgo O3 data", LVK Collaboration. (arXiv:2201.00697v1 [gr-qc] 3 Jan 2022)



From "Search for gravitational wave signals from known pulsars in LIGO-Virgo O3 data using the 5n-vector ensemble method", Luca D'Onofrio et al. (https://arxiv.org/abs/2311.08229)

The study shows the results of an all-sky search for continuous gravitational waves from isolated pulsars. The upper limits on the gravitational wave strain were calculated using data from the LIGO and Virgo detectors during their third observing run. The most sensitive upper limit achieved was approximately $h0 \approx 1.1 \times 10^{-25}$.

The study presents a targeted search for continuous gravitational waves (CWs) from 201 known pulsars using data from the LIGO and Virgo O3 observing run. The paper sets 95% credible upper limits on the strain amplitude of the gravitational waves and the ellipticity (deformation) of the pulsars. The most sensitive upper limit achieved is approximately $h0 \approx 1.9 \times 10{-}27$.

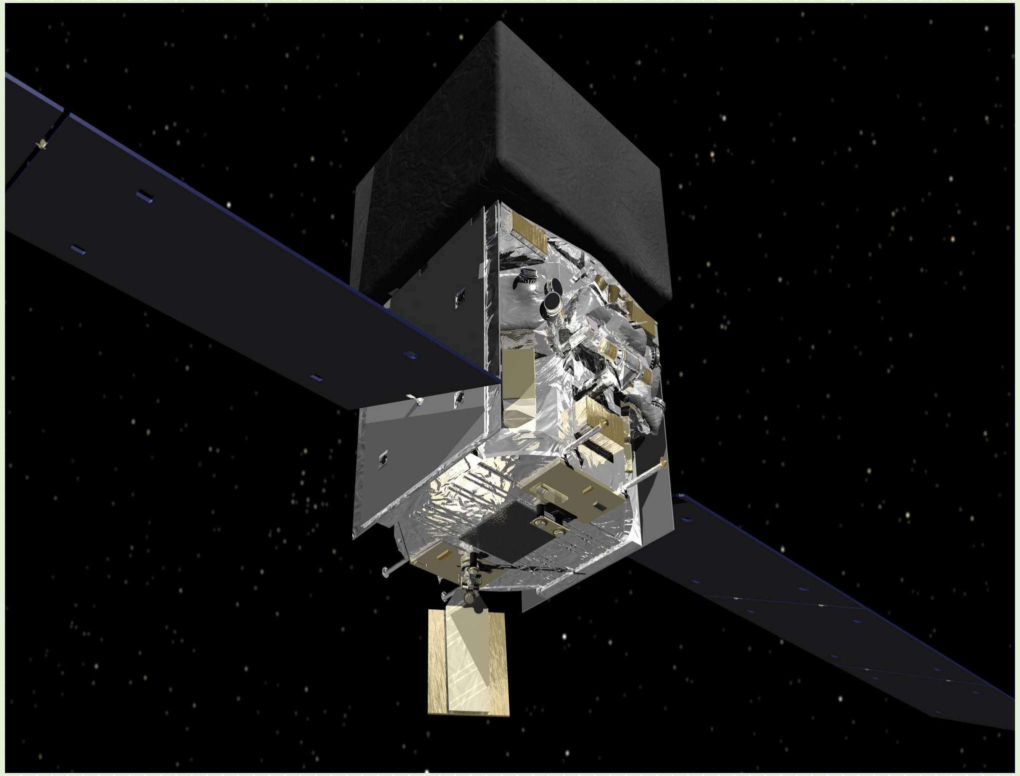
Why is EM-GW collaboration important?

EM

- Sky position
- Rotational frequency
- Spin-down

GW

- Hints on internal structure
- For sources not known from EM emission:
  - New NSs
  - Sky position
  - Rotational frequency
  - Spin-down



Large Area Telescope on top of the Fermi Gamma-ray Space Telescope.
credit: NASA

Bottom right Virgo, an international collaboration with a strong Italian contribution, and has a single interferometer in Cascina, in the province of Pisa. Above right, the first LIGO interferometer in Livingston, Louisiana, lower left, the second, in Hanford, Washington State.

Analysis technique

1. **Setting up input parameters and estimating lambda for frequency drift**
2. **Preparing for the sky grid point**
3. **Processing photon arrival times from a gamma-ray data set**
4. **Autocorelation spectrum calculation, statistical analysis and candidate selection**

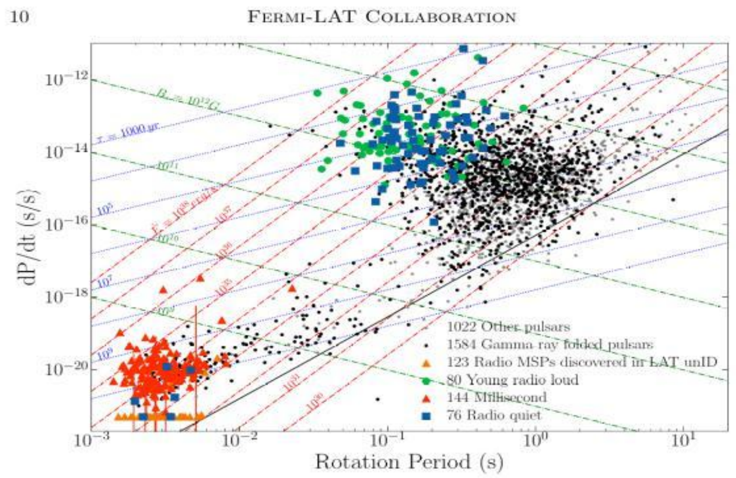
- Input parameters include sky position, radius of interest, time analysis window, time interval of the analysis, range of lambda etc.
- Some of the parameters are found in the catalog and other parameters are decided based on the known sources.
- The parameter λ is related to the pulsar's frequency evolution (specifically, how the frequency changes over time).

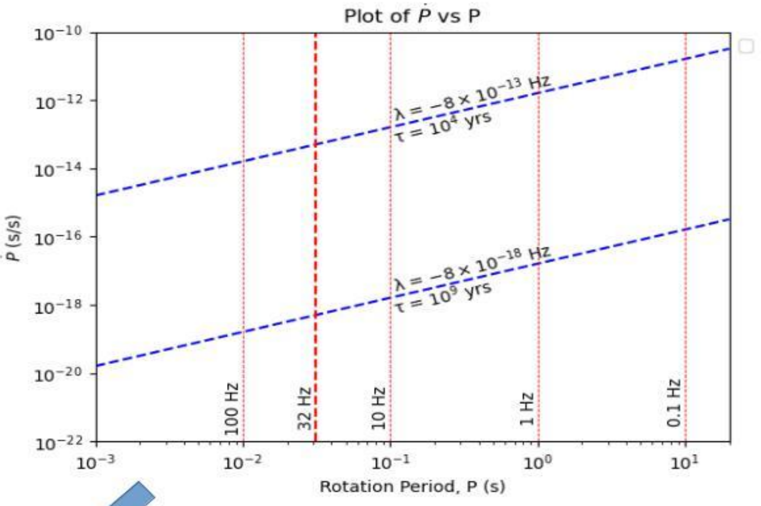
$$\lambda = \frac{\dot{f}}{2f}$$

Charactestic age of the Pulsar

$$\tau = \left|\frac{1}{4\lambda}\right|$$

Lambda range for Gamma- ray Pulsars





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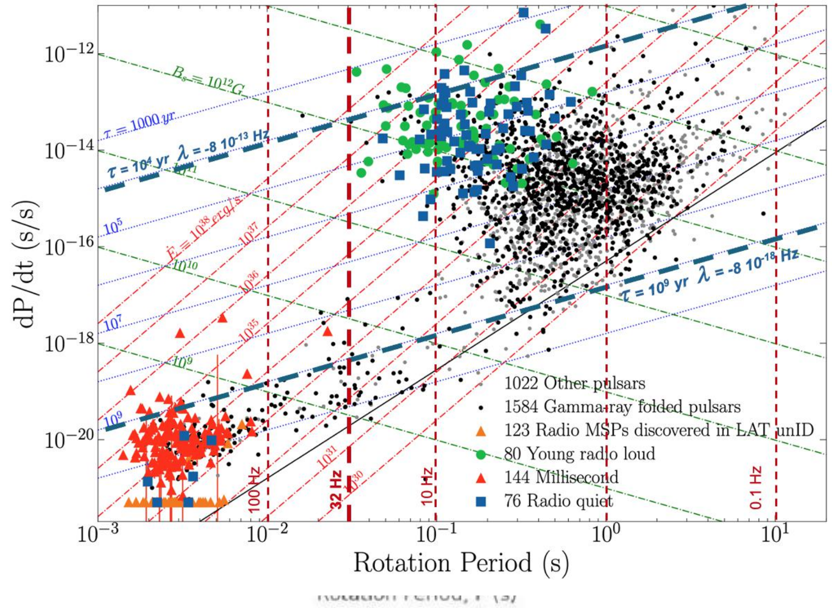
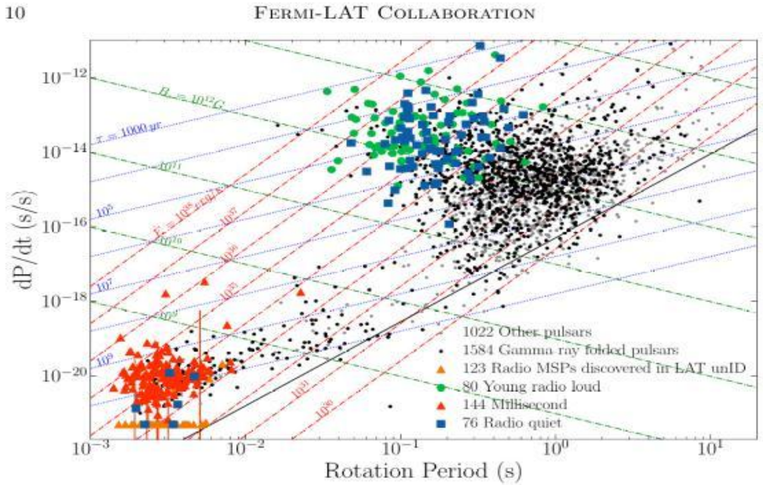
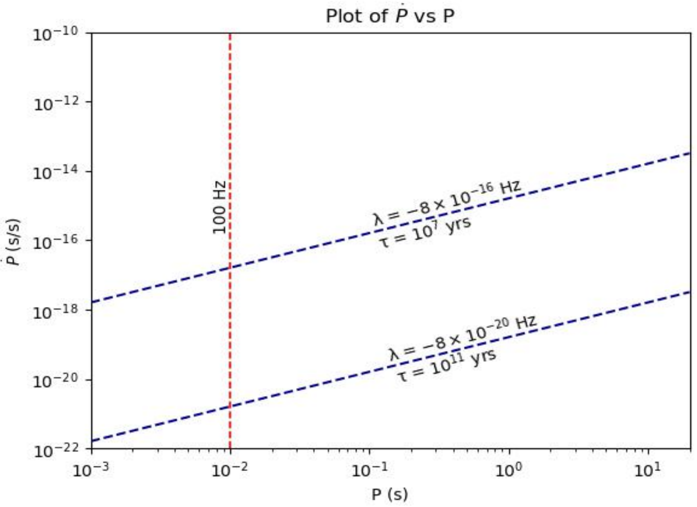
ApJ 2023 958 191 [arXiv:2307.11132]

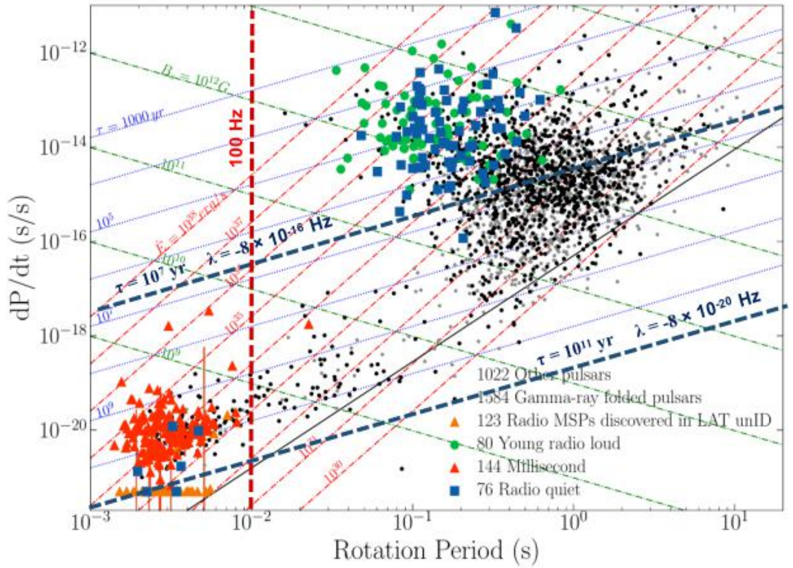


Lambda range for MSP

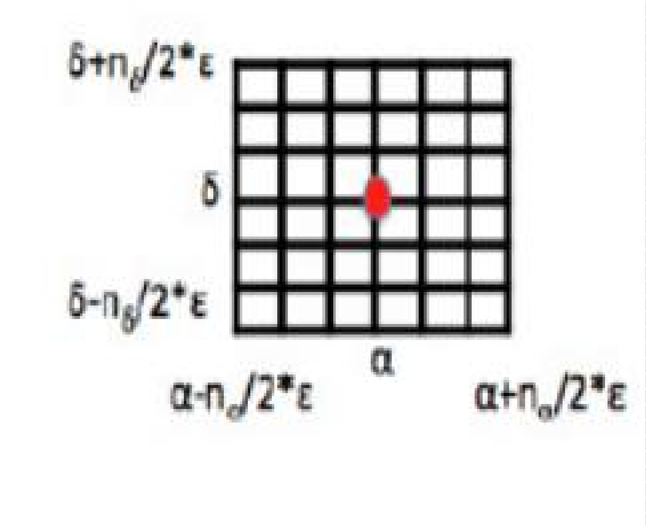


The Third Fermi Large Area Telescope Catalog of Gamma-ray Pulsars ApJ 2023 958 191 [arXiv:2307.11132]

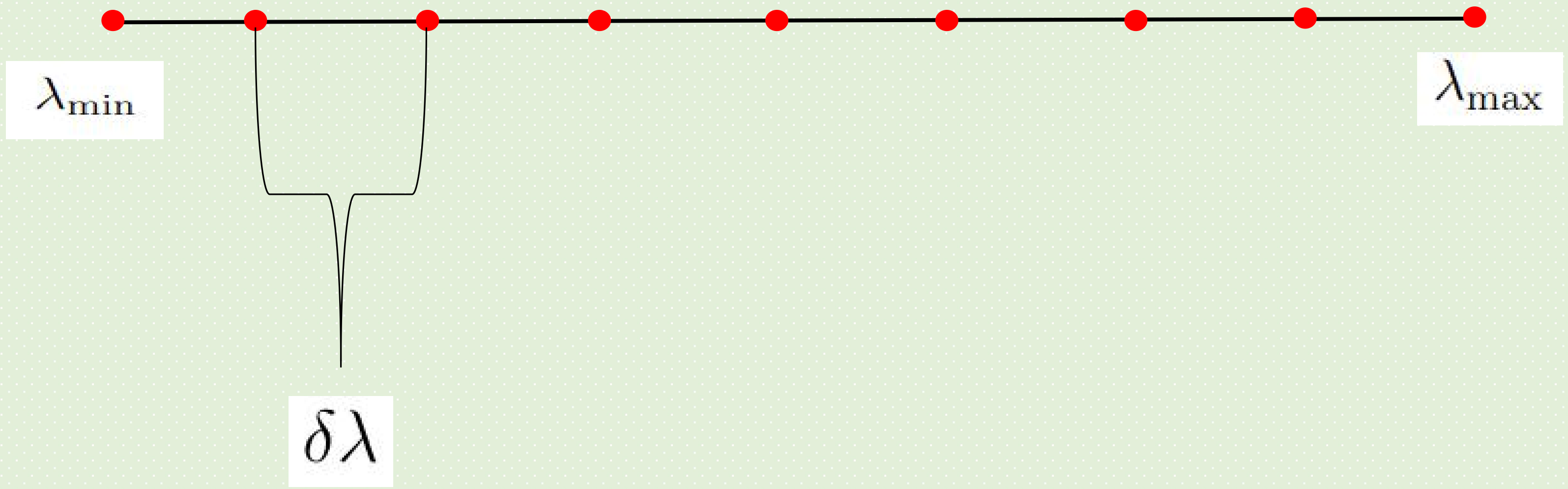




1. **Setting up input parameters and estimating lambda for frequency drift**
2. **Preparing for the sky grid point**
3. **Processing photon arrival times from a gamma-ray data set**
4. **Autocorelation spectrum calculation, statistical analysis and candidate selection**



- A grid is initialised around source's central coordinates, with a spacing determined by the epsilon (ε).
- ε depends on the time analysis window and sampling time.



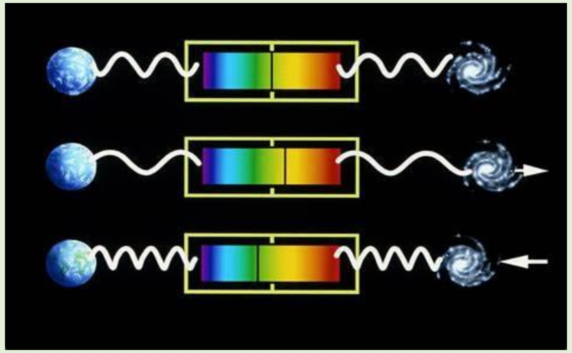
- A secondary scan over the λ parameter ranging from λ_{min} to λ_{max} takes place.
- It is incremented by $\delta\lambda$.
- $\delta\lambda$ depends on time analysis window, time interval and the maximum frequency used for the analysis.

Setting up input parameters and estimating lambda for frequency drift

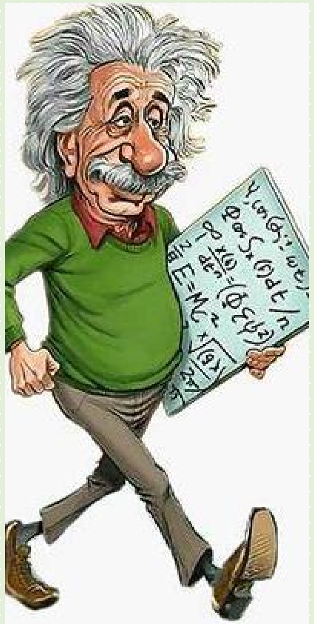
Preparing for the sky grid point

Processing photon arrival times from a gamma-ray data set

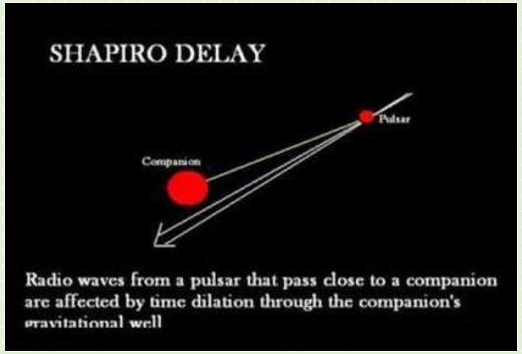
Autocorelation spectrum calculation, statistical analysis and candidate selection



Doppler correction



Einstein delay



Shapiro dalay

Setting up input parameters and estimating lambda for frequency drift

Preparing for the sky grid point

Processing photon arrival times from a gamma-ray data set

Autocorelation spectrum calculation, statistical analysis and candidate selection

Critical ratio is a measure that shows how far our signal deviates from the noise.

$$Critical\ Ratio = \frac{y_{max} - \bar{y}_{noise}}{\sigma_{noise}}$$

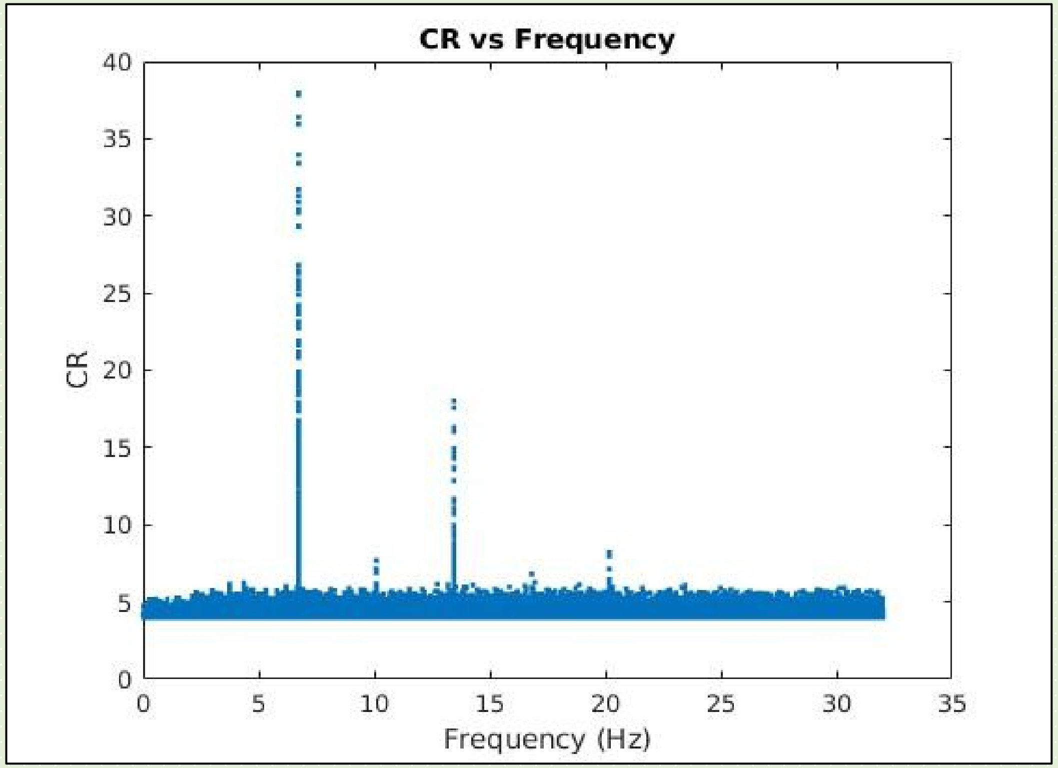
Results

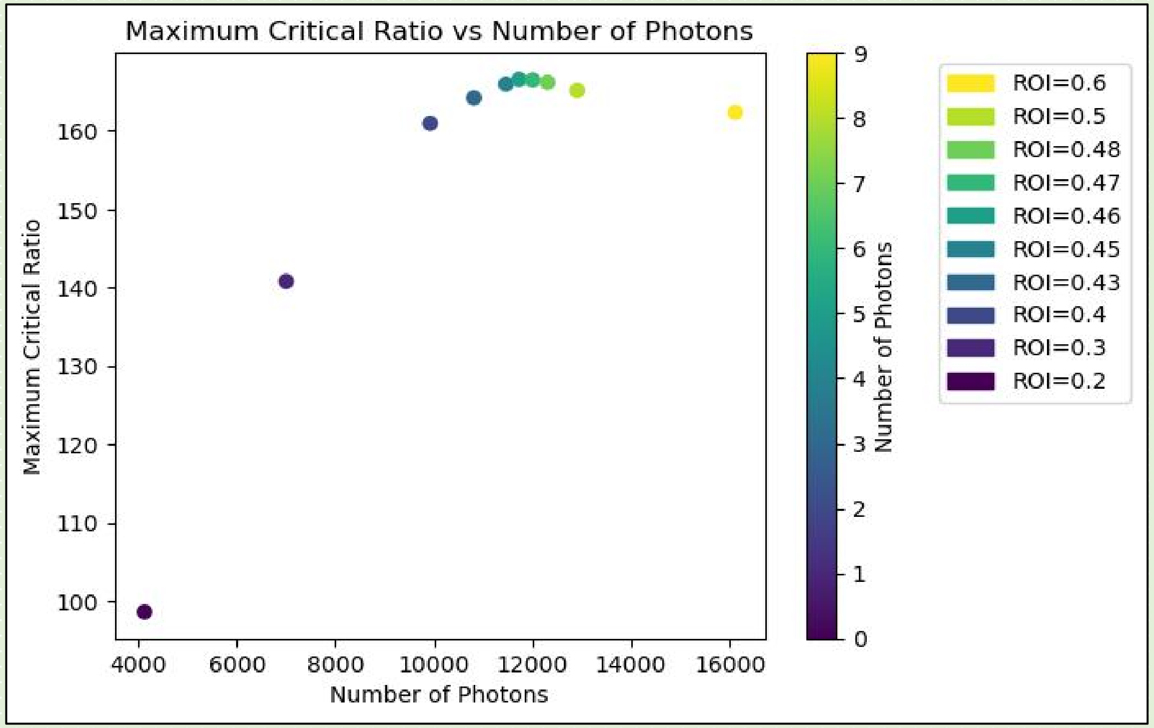
Pipeline tested on known Pulsar - J0633+0632

Input parameters:

- RA = 270.4239 deg
- DEC = -23.4345 deg
- Range of lambda covered in this run = -8.0e-18 to -7.0e-14 Hz
- ROI = 0.0389 deg
- Observation period = 4 August 2008 to 7 December 2023
- Time analysis window = 7 days
- Number of sky points = 2 * (ROI/epsilon) + 1

(epsilon is the step increment in the grid formation)



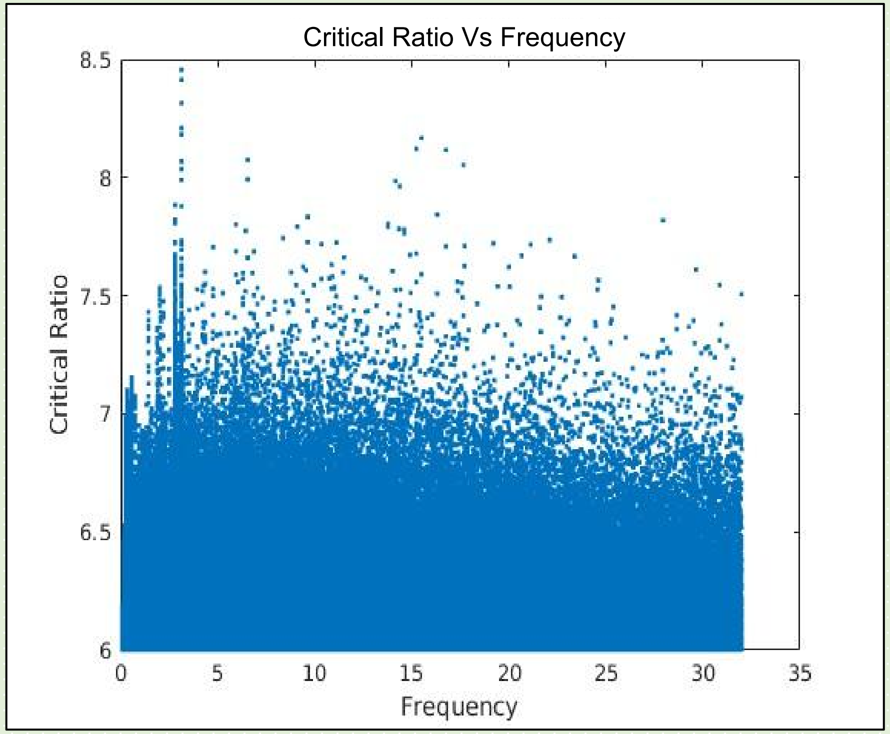


Detailed Analysis of 4FGLJ1801.6-2326 using DSDA

Input parameters:

- RA = 270.4239 deg
- DEC = -23.4345 deg
- Range of lambda covered in this run = -8.0e-18 to -7.0e-14 Hz
- ROI = 0.0389 deg
- Observation period = 4 August 2008 to 7 December 2023
- Time analysis window = 7 days
- Number of sky points = 2 * (ROI/epsilon) + 1

(epsilon is the step increment in the grid formation)



Output parameters:

- Average number of lambda (analyzed) = 29262
- Number of sky points (analyzed) = 21
- Time taken for the code execution = 1 month
- Total number of frequency candidates = 325,780
- CR value above which there is probability of finding a frequency candidate = 7.5
- Number of candidates above CR threshold 7.5 = 174

To find the value of Critical Ratio (c') above which there is probability of finding a frequency candidate

Let c denote a value for CR. For an interval between c' and ∞, we are looking for exactly 1 candidate

$$\int_{c'}^{\infty} n\phi(c)\,dc = 1 \tag{1}$$

- $\phi(c)$ is the probability density function.
- n is the total number of candidates (without any CR threshold).
- c' is a value of CR above which there is exactly 1 candidate.

$$\int_{c'}^{\infty} \phi(c)\,dc = \frac{1}{n} \tag{2}$$

- $\Phi(c)$ is the cumulative distribution function.

Also,

$$\int_{c'}^{\infty} \phi(c)\,dc = 1 - \Phi(c') \tag{3}$$

From (2) and (3)

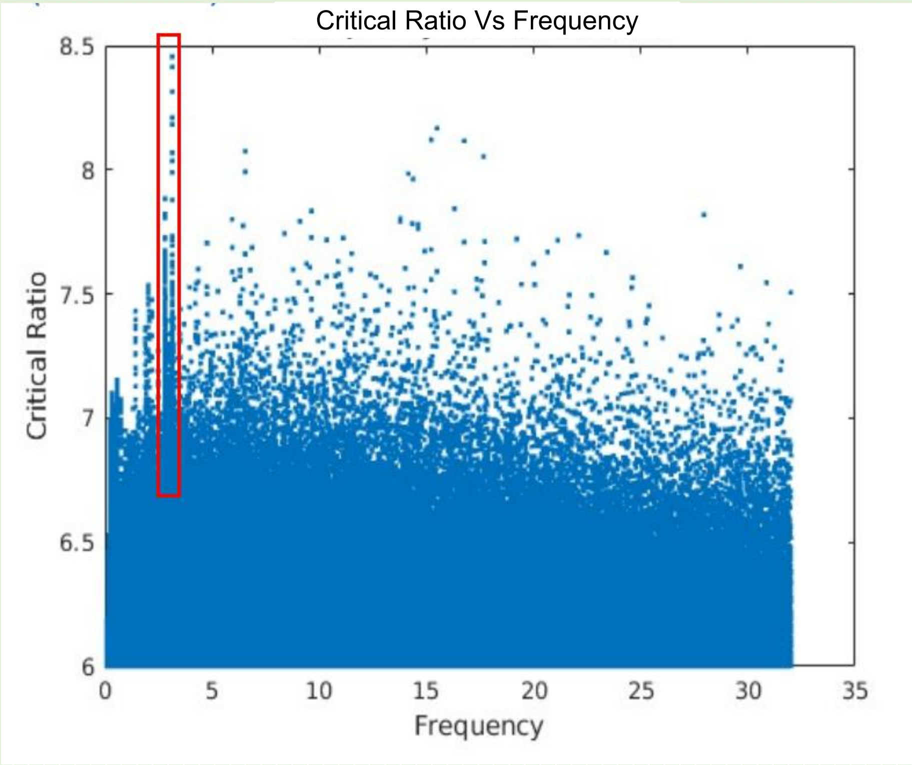
$$\Phi(c') = 1 - \frac{1}{n} \tag{4}$$

$$c' = \Phi^{-1}(1 - \frac{1}{n}) \tag{5}$$

For k number of candidates

$$c_k = \Phi^{-1}(1 - \frac{k}{n}) \tag{6}$$

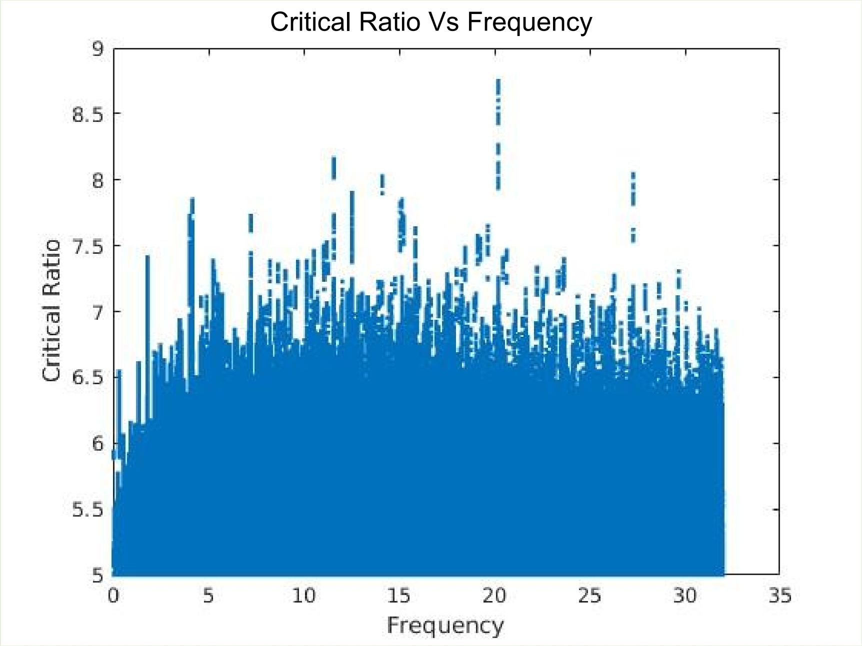
- The two ‘peak like structures’ were further analysed.
- The frequency values of these peak like structure were found to be **f1 = 2.7964 Hz** and **f2 = 3.1399 Hz**



For f1 = 2.7964 Hz, the lambda ranges from -2.0538e-13 to -2.0514e-13 Hz

Input parameters

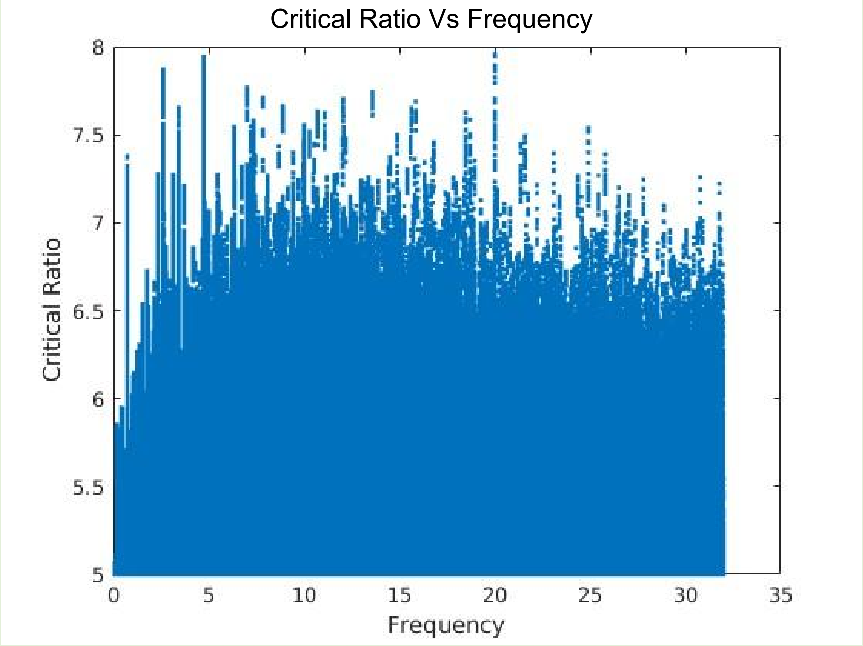
- RA = 18:01:41.73599 (hh:mm:ss)
- DEC = [-23 26 04.1999] (hh:mm:ss)
- ROI = 0.0389 deg
- CR threshold = 5
- Time analysis window = 30 days
- Time interval of the analysis = 4th August 2008 to 7th December 2023
- Lambda range = -2.0538e-13 to -2.0514e-13 Hz



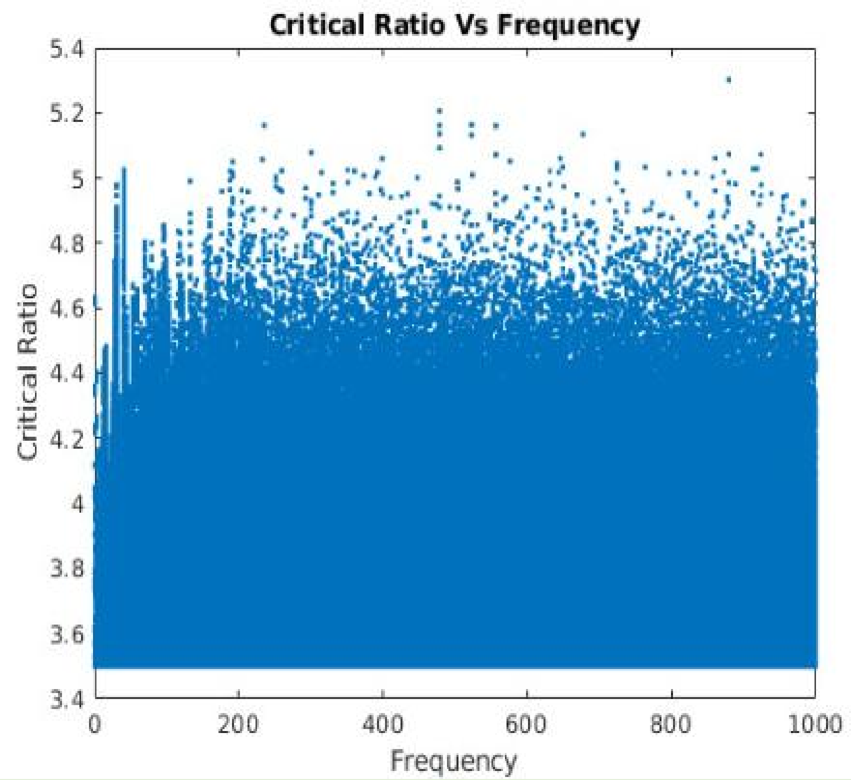
For f2 = 3.1399 Hz, the lambda ranges from -3.7568e-13 to -3.7533e-13 Hz

Input parameters

- RA = 18:01:41.73599 (hh:mm:ss)
- DEC = [-23 26 04.1999] (hh:mm:ss)
- ROI = 0.0389
- CR threshold = 5
- Time analysis window = 30 days
- Time interval of the analysis = 4th August 2008 to 7th December 2023
- Lambda range = -3.7568e-13 to -3.7533e-13 Hz



Analysis of 4FGLJ1801.6-2326 in the lambda range of MSP



Input parameters

- RA = deg = '18:01:41.73599' (hh:mm:ss)
- DEC -23.4345 deg = -23:26:04.1999 (hh:mm:ss)
- ROI = 0.0389 deg
- Time analysis window = 0.2 days
- Observation period = 4 August 2008 to 7 December 2023
- Range of lambda covered in this run = -8.0e-16 to -8.0e-20

Output parameters

- Average number of lambda (analyzed) = 351
- Number of sky points (analyzed) = 29
- Time taken for the code execution = 1 day
- Total number of frequency candidates = 1.2130e+10
- CR' = 6.4
- Number of candidates above CR' = 0

Summary

- The analysis technique involves setting up a parameter space (sky positions and lambda values) and processing gamma-ray photon data to search for pulsar-like signals.

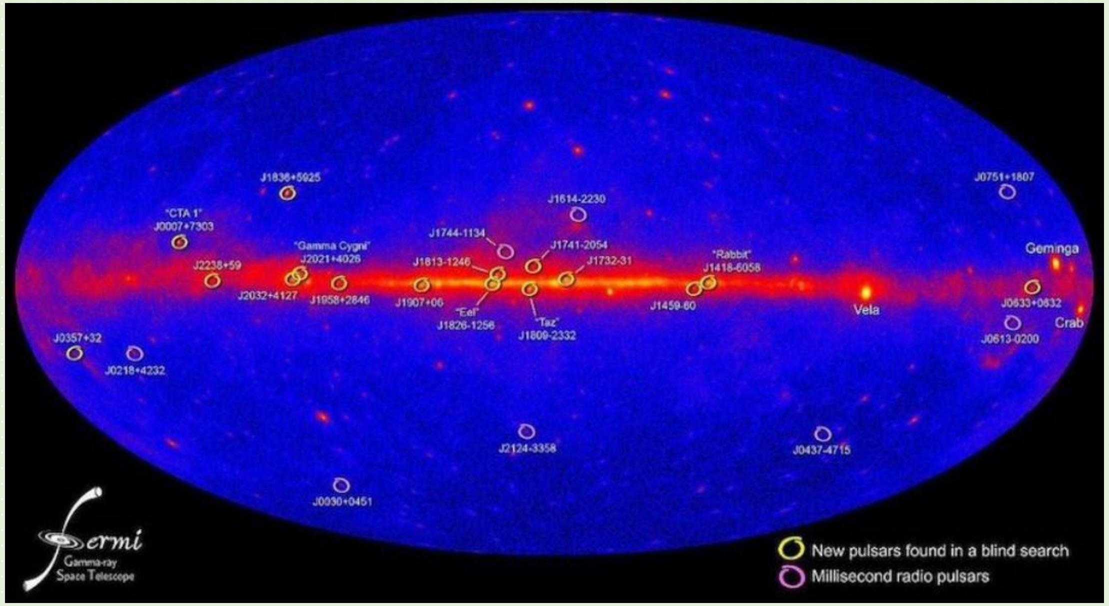
- This structured approach improves the chances of finding weak pulsar signals in the vast parameter space.

- The aim is to add sources to the Fermi catalog which will then be analysed with the data of the interferometric detectors.

- The pipeline was tested on 5 known pulsars. Number of Unassociated sources analysed so far is 8.

- By discovering more gamma-ray pulsars, particularly in regions close to the Galactic center, the contribution of pulsars to the GeV excess can be modelled in a better way.

- Detecting more gamma-ray pulsars significantly increases the possibility of a direct gravitational wave (GW) search, enhancing both the detection prospects and scientific understanding.



Map of the sky - showcasing new pulsars and millisecond pulsars. Credit: NASA/DOE/FERMI LAT COLLABORATION.

Analysed sources

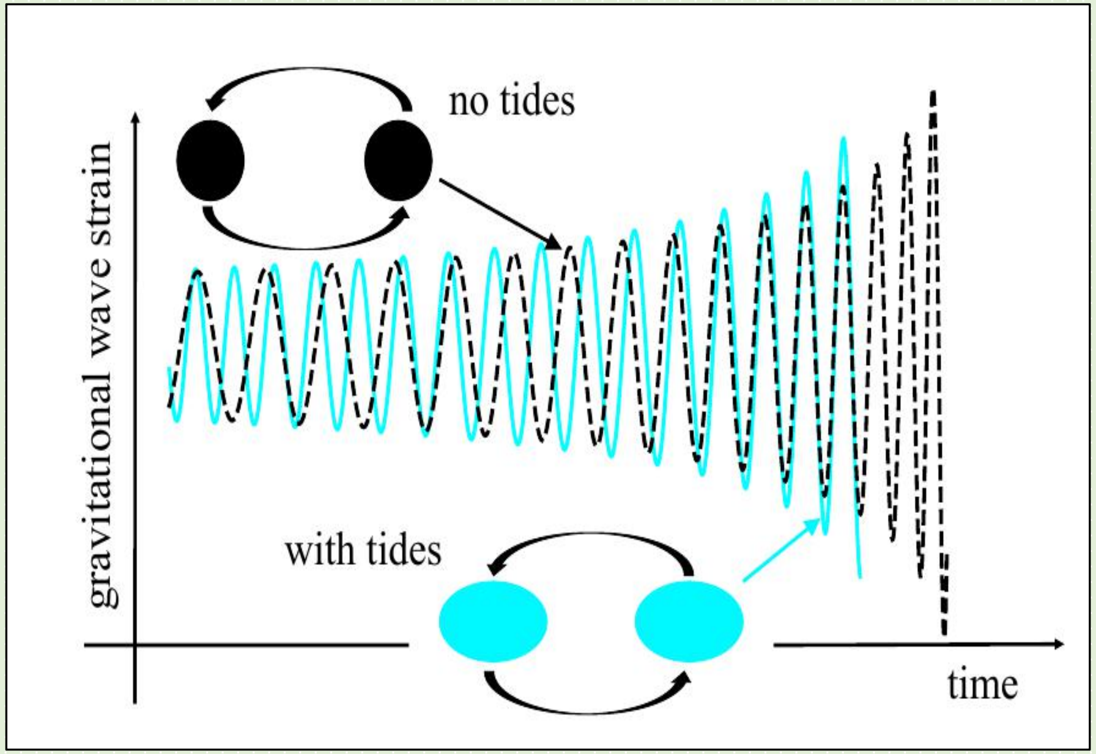
Source Name	Analysed for
4FGL J1801.6-2326	Gamma ray Pulsar and MSP
4FGL J1823.3-1340	Gamma ray Pulsar and MSP
4FGL J1653.2-4349	Gamma ray Pulsar and MSP
4FGL J1753.8-2538	Gamma ray Pulsar and MSP
4FGL J0340.4+5302	Gamma ray Pulsar and MSP
4FGL J0426.5+5434	Gamma ray Pulsar and MSP
4FGL J0616.5+2235	Gamma ray Pulsar
4FGL J0039.1+6257	Gamma ray Pulsar

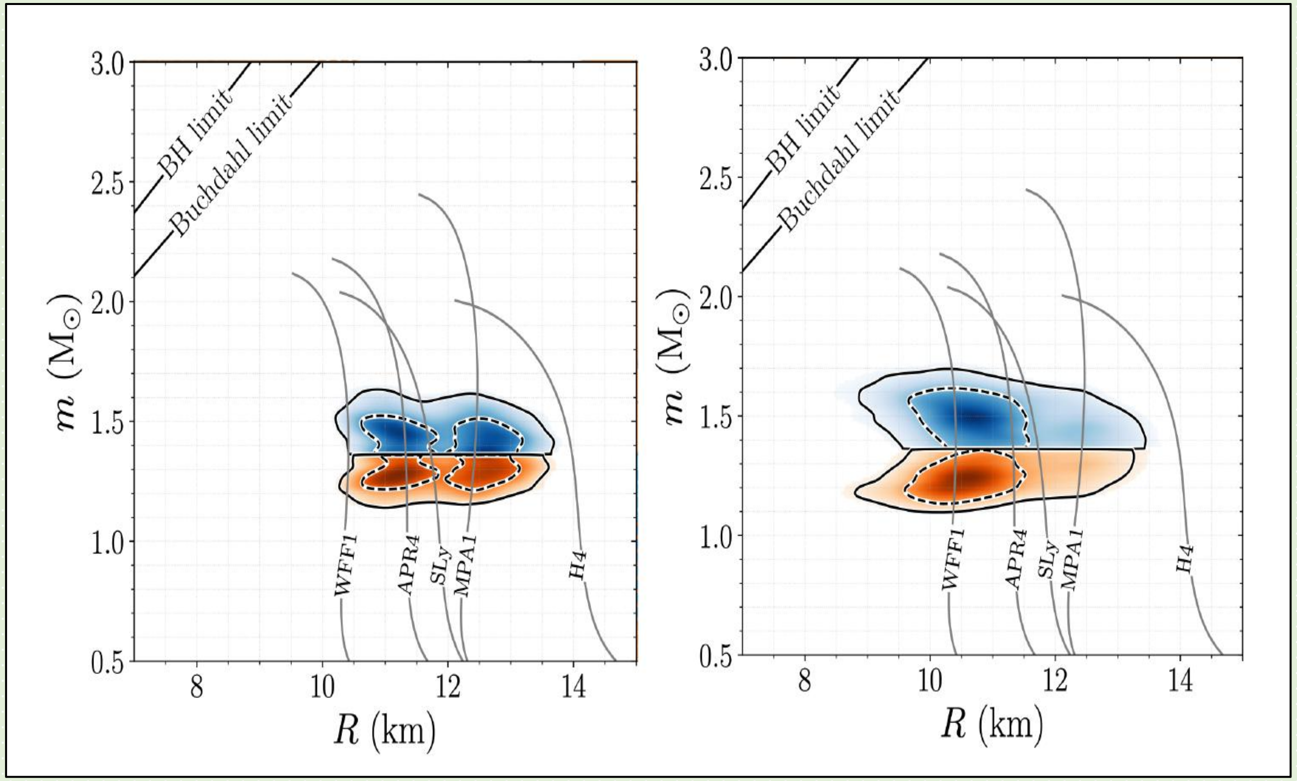
Thank You

Time for some discussion

Extra slides

Multimessenger study can explain EOS of NS

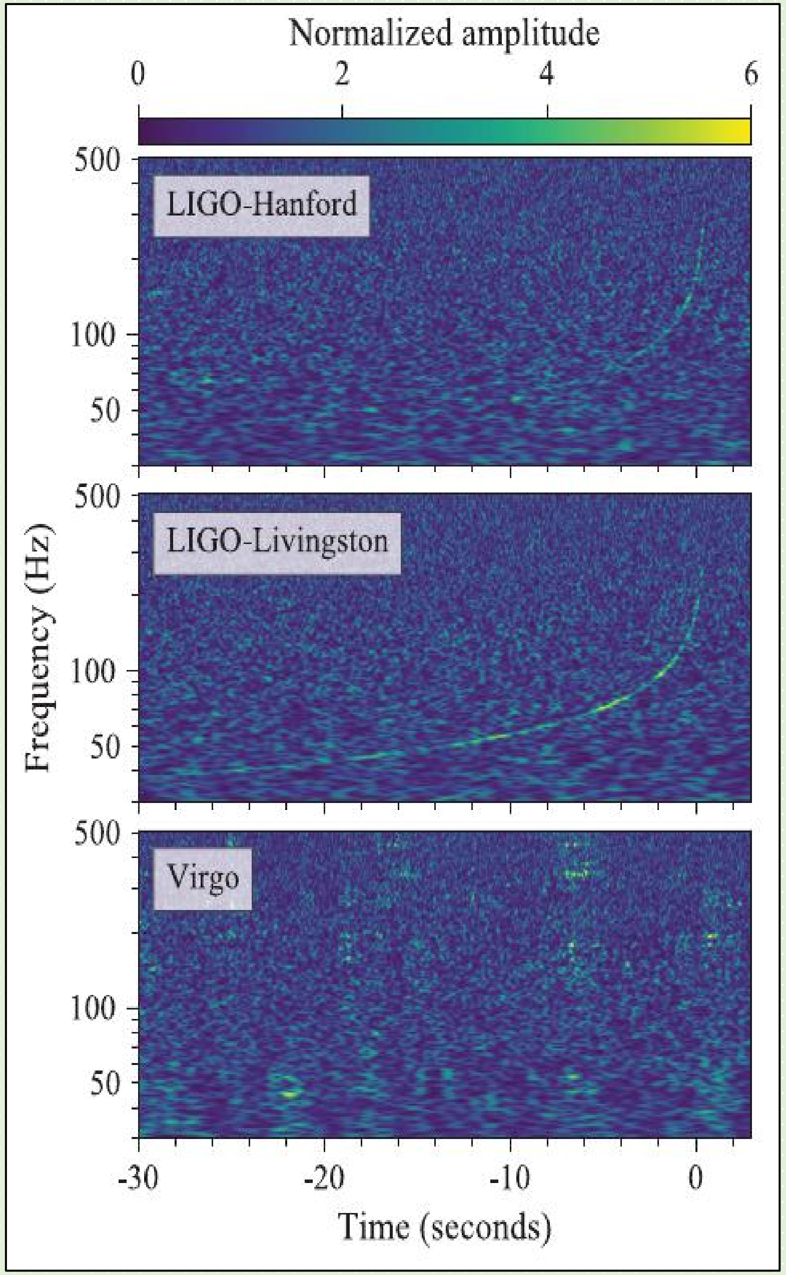


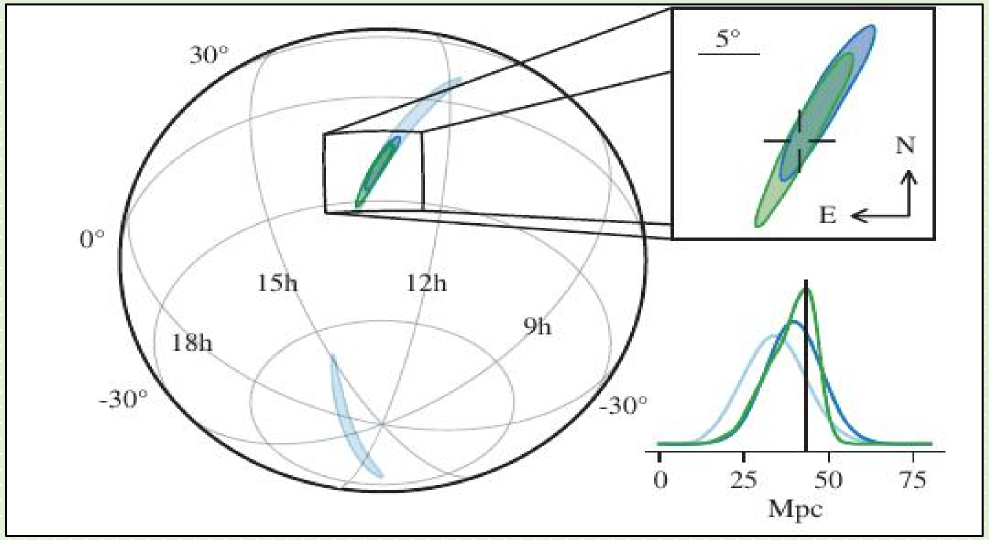


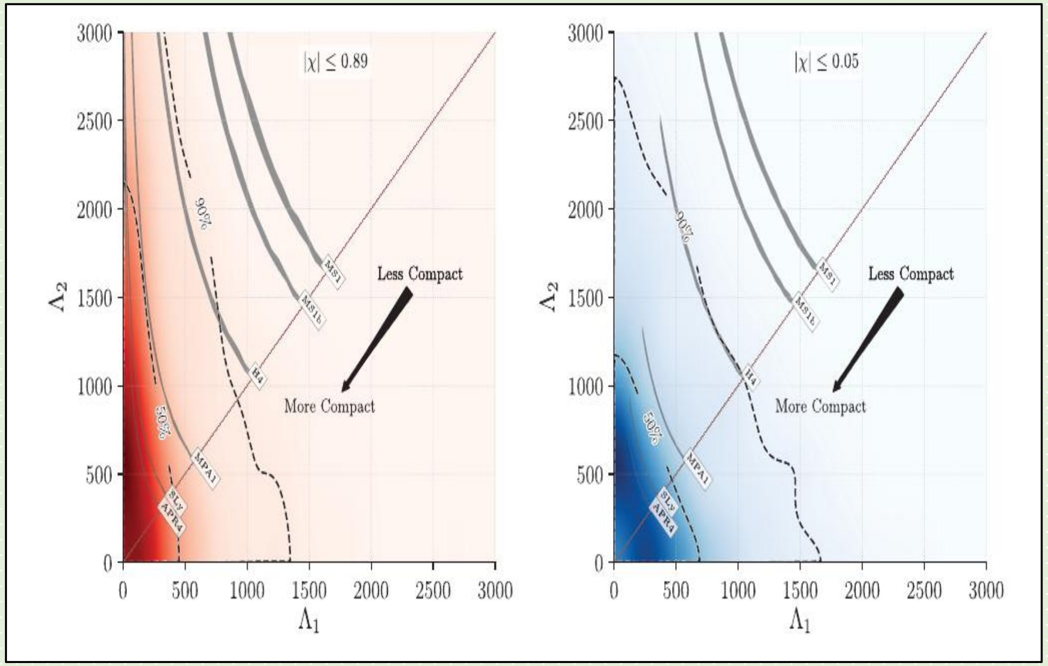
From “Gravitational-Wave and X-ray Probes of the Neutron Star Equation of State”, Yunes et al. (arXiv:2202.04117v1 8 Feb 2022)

The figure shows how gravitational waveforms differ based on whether tides are present or absent during a compact binary inspiral.

The mass and radius estimates for the components of GW170817





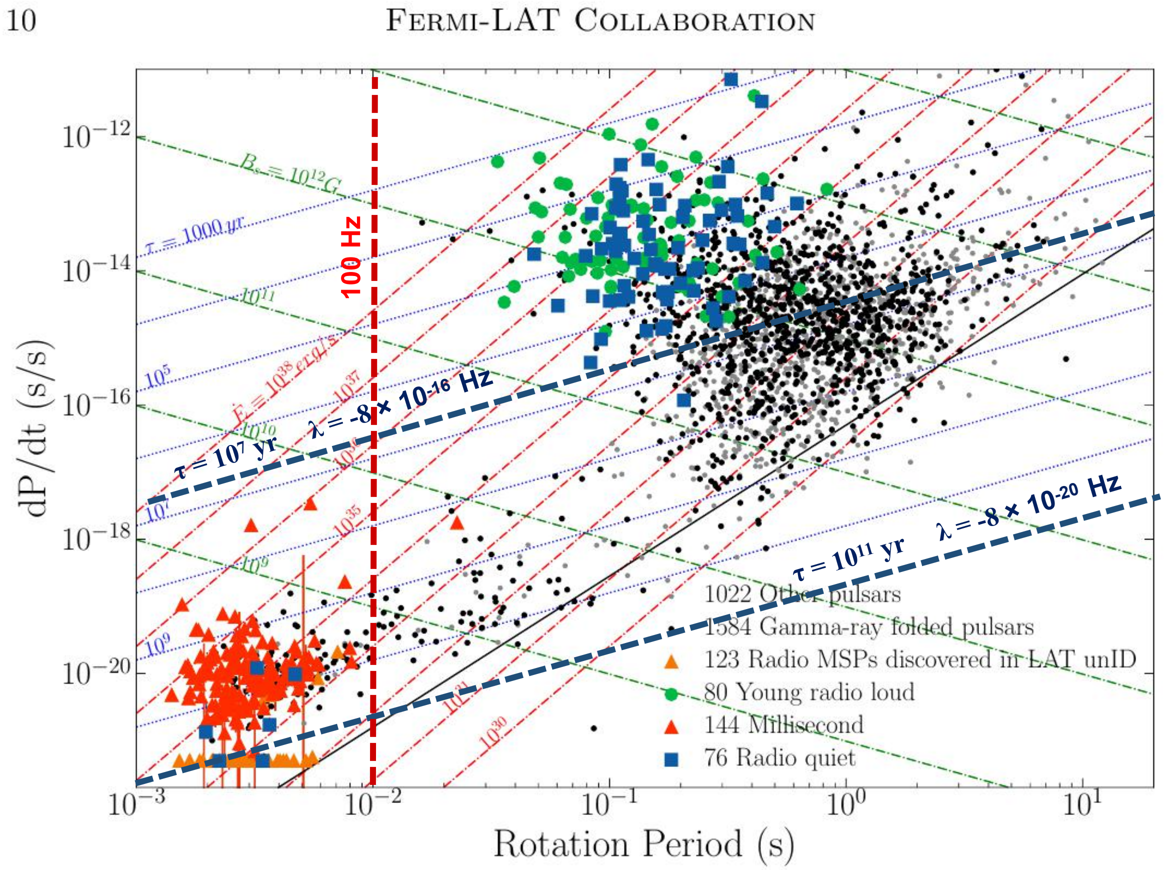


- The figures show the time-frequency data representation of the gravitational-wave event GW170817 observed by LIGO-Hanford, LIGO-Livingston, and Virgo detectors.
- The signal is clearly visible, indicating the inspiral and merger of a binary neutron star system.
- The sky localization of GW170817 shows how quickly the source was localized for follow-up observations. It also includes a luminosity distance distribution, which helps estimate the distance to the source.
- The posterior distributions of tidal deformabilities (Λ1 and Λ2) for the two neutron stars in GW170817. The contours reflect the 90% and 50% credible regions based on the gravitational-wave data and EOS models.

From “GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral”, Abbott et al (PRL 119, 161101 (2017))

Identifying new pulsars in the Fermi data to enable direct searches for gravitational wave signals with Virgo and LIGO

DOI: 10.1103/PhysRevLett.119.161101



$\tau = 10^7$ yr $\lambda = -8 \times 10^{-16}$ Hz

$\tau = 10^{11}$ yr $\lambda = -8 \times 10^{-20}$ Hz

Similarities in search of Gamma ray pulsars and search of continuous GW

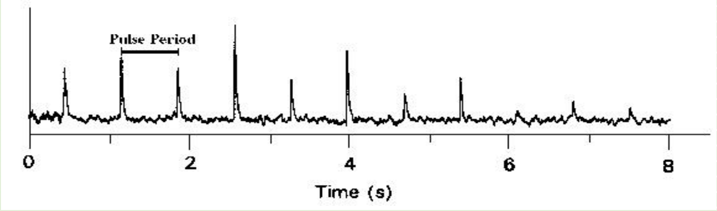
1) Periodic Nature of the Signals

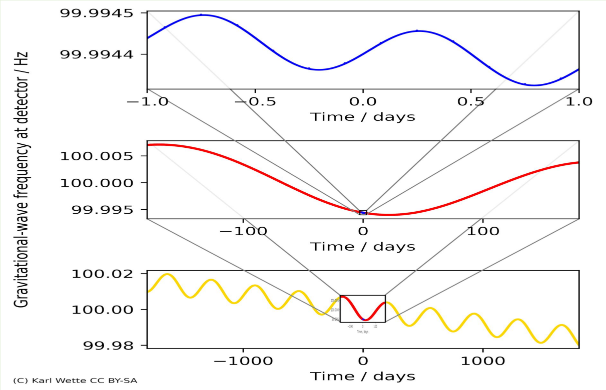
2) Signal weakness

3) Data analysis techniques

4) Parameter Space Searches

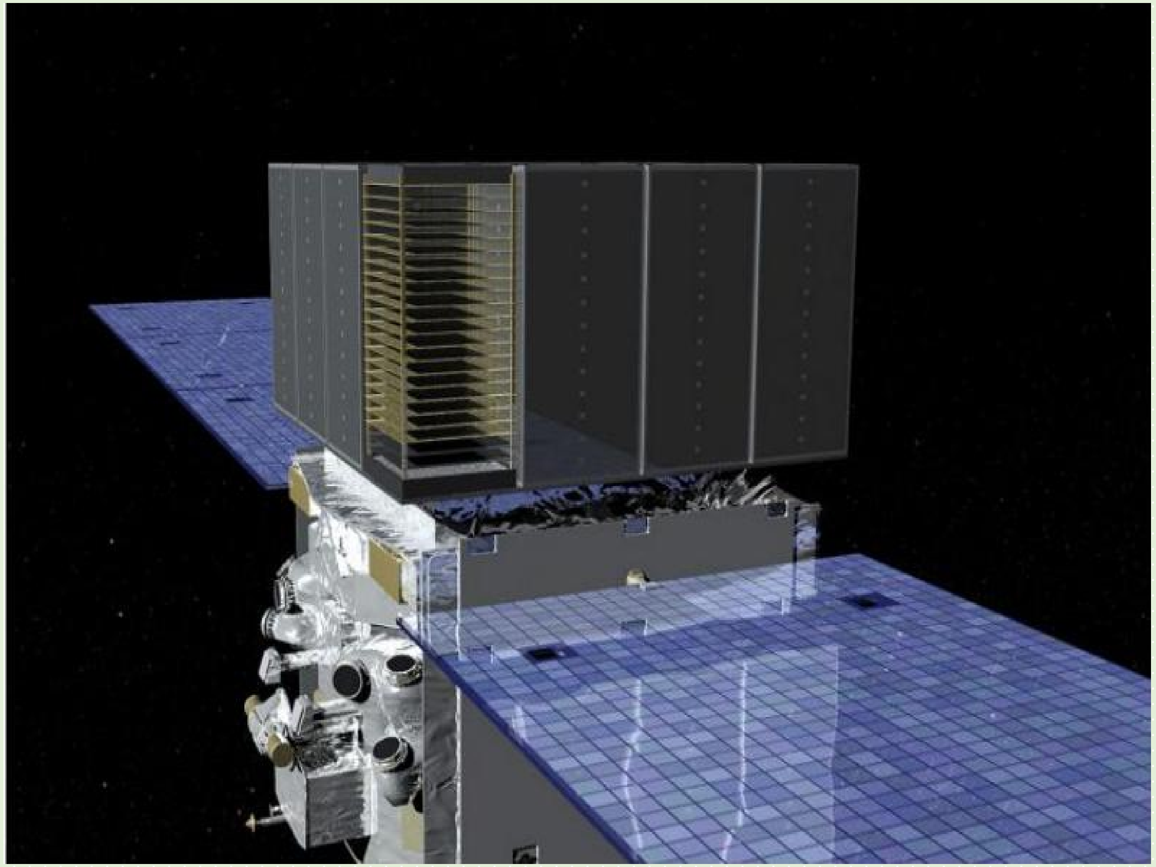
5) Coherent and Semi-Coherent Search Methods





Fermi Large Area Telescope

- Collaboration of Swedish, French, Italian and Japanese Space agencies.
- Gamma ray observatory
- Provides an important window into the most extreme phenomena of the Universe



Conferences, Schools and Workshops

- Colloquim at Christ University
  - Conducted on 29th August 2024
  - Presented a talk on the topic “Exploring the Universe through Multimessenger Astronomy: Insights from Fermi-LAT and the enigmatic unassociated gamma-ray sources”

- Physics and Astrophysics at the eXtreme workshop (PAX IX)
  - July 23−25 2024, King’s College London, UK.
  - Presented a talk on the topic ‘Probing Unassociated Fermi-LAT Sources for Potential Gamma Ray Pulsar Detection’.

- Gravitational Wave Open Data Workshop 7 (2024)
  - April 18−20, 2024

- IV Gravi-Gamma-Nu Workshop
  - October 4−6 2023, Gran Sasso Science Institute L’Aquila, Italy.

- AVENGe - Advances in Very-High Energy Astrophysics with Next-Generation Cherenkov Telescopes
  - May 29-31 2023, Rome Italy.

- Status and Prospects of Astroparticle Physics
  - January 25 2023, Physics Department Sapienza University Rome, Italy.

- Amaldi Research Center Summer School
  - September 5−9 2022 Paestum, Italy.

- Attented a course on Multimessenger astronomy that was organised by Prof. Viviana Fafone and Dr. Aldo Morselli during May - June 2023

- **Participation in forthcoming conference:**

I will be participating in Roma International Conference on AstroParticle Physics (RICAP-24). The participation will be through a presentation followed by the paper proceeding, communicationg my results.