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Prospects of continuous gravitational waves searches from Fermi-LAT sources

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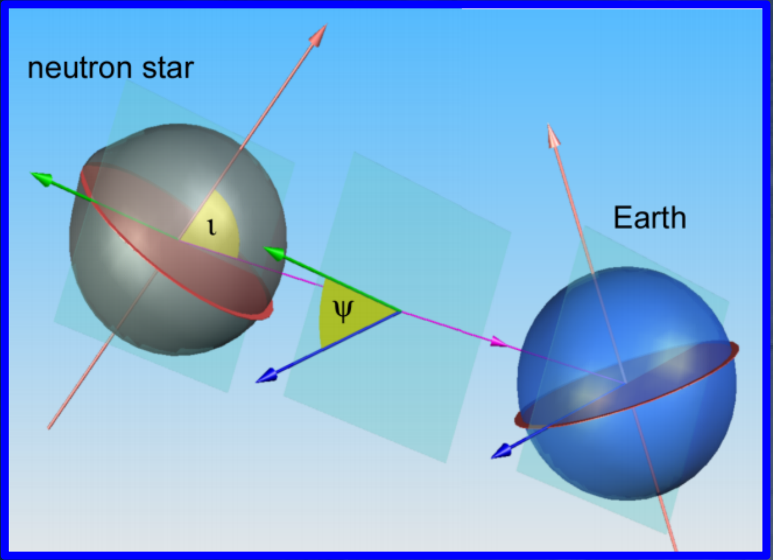
Outline

Aim of the talk: I would like to give you a general idea on how searches for continuous gravitational waves work.

- Gravitational waves (GW) from neutron stars
- Principles of gravitational waves detection
- Continuous GW searches
- Gamma-ray sources and Fermi-LAT
- GW searches from:
  - Known Pulsars
  - Supernova remnants and pulsar wind nebulae
  - Unassociated
- Perspectives
- What we can infer?
- Summary and conclusion

Gravitational waves from neutron stars

Asymmetric neutron stars (NS) are one of the expected sources of gravitational waves



$$h_+ = h_0 \frac{1+\cos^2\iota}{2}\cos(4\pi\nu_{NS}t)$$
$$h_\times = h_0 \cos\iota \sin(4\pi\nu_{NS}t)$$

$$h_0 = \frac{1}{r}\frac{16\pi^2 G}{c^4} I_{zz}\nu_{NS}^2\epsilon$$

In the standard NS configuration we expect a GW at two times the NS rotational frequency

Neutron stars are pretty peculiar astrophysical objects:

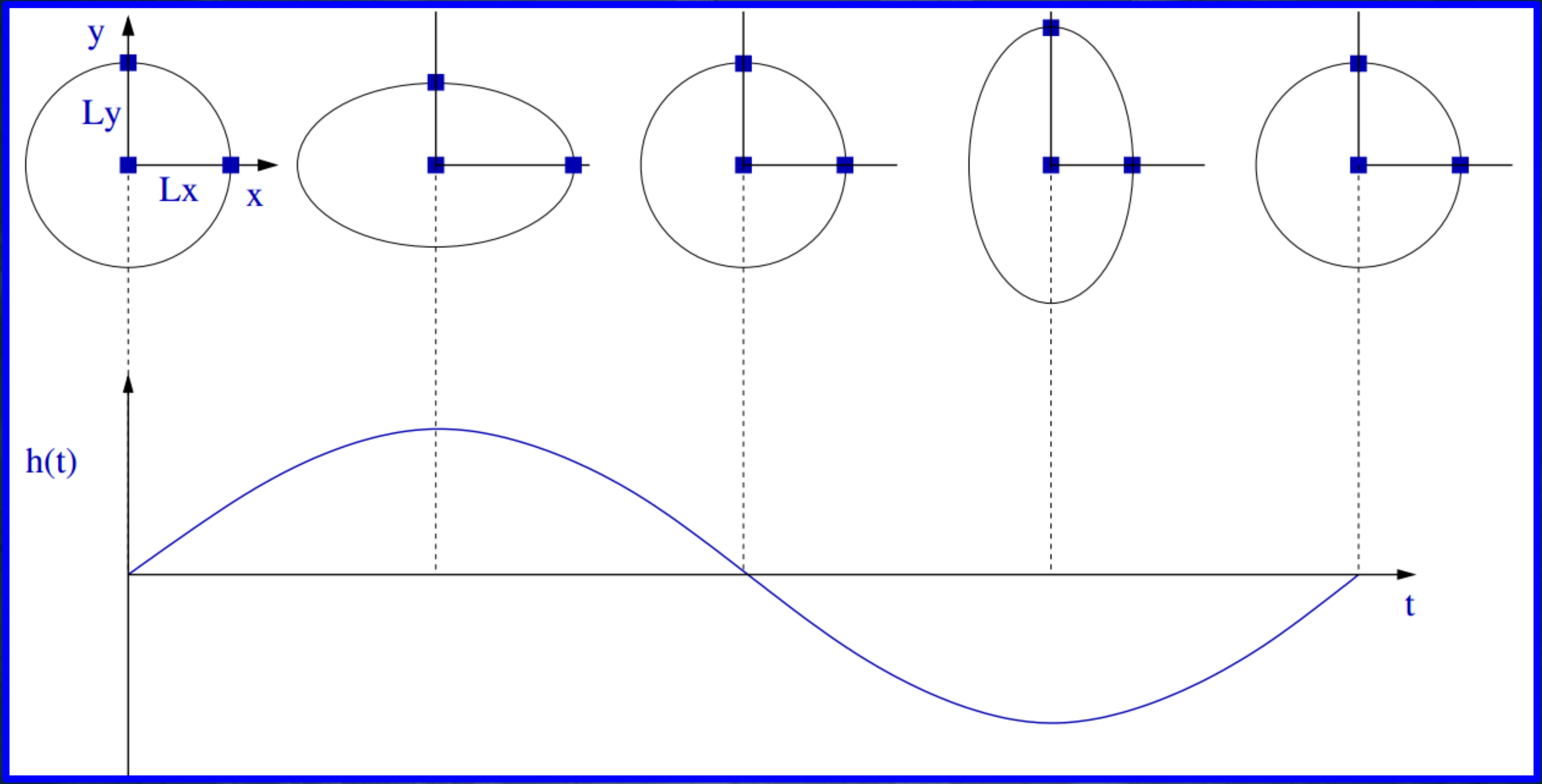
- High stability in rotation period (Spin-down ~10^{-12} Hz/s)
- For the *pulsars* sub-class it is possible in principle to infer the rotational parameters from electromagnetic observations
- Long-lived coherent signal (>months), depends on glitches
- Are supposed to be very dense (~10^{14} g/cm^3)
- Spin-down limit (absolute theoretical upper-limit):

$$h_0 \leq 8.06 \cdot 10^{-19}\left(\frac{I_{zz}}{kg\, m^2}\right)\sqrt{\left(\frac{\dot{\nu}}{Hz/s}\right)\left(\frac{Hz}{\nu}\right)}$$

This type of GW signal are called **continuous gravitational waves**

Principle of GW detection

A crossing GW changes the distance between two test masses.
LIGO and Virgo are experiments based on Michelson interferometry suitable to detect GWs

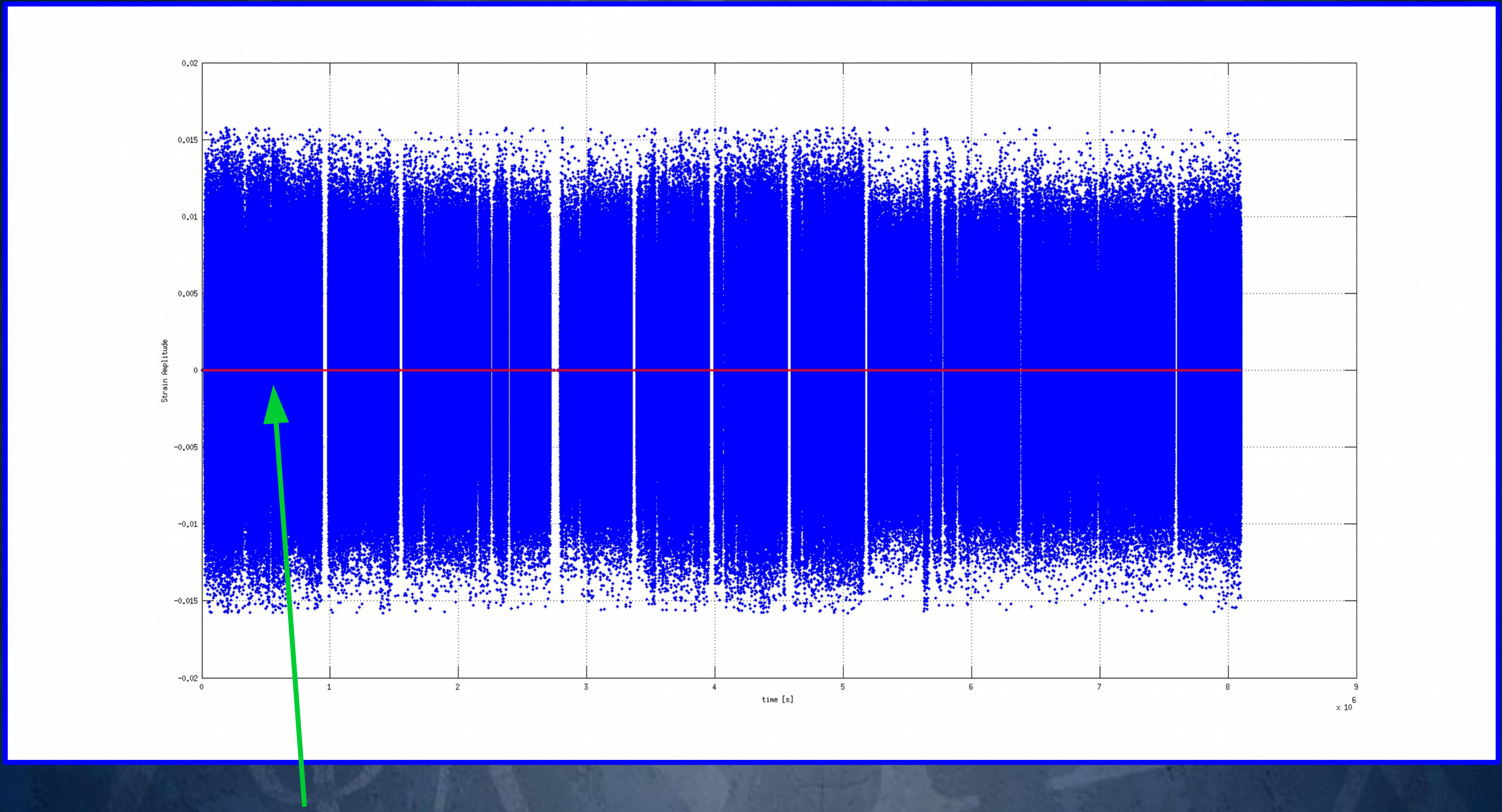


$$I(t) \propto h(t)$$

Seems simple...**but it's not**

Principle of GW detection

The typical length of Virgo and LIGO science Run is of order of several months, sampled at **4096 Hz.**



Hardware injection in VSR4, Amplitude= 8.4 x 10^{-24} (we can see it)

We expect a signal deeply buried into noise

Continuous GW searches

Doppler due to the Earth motion: It is needed to know with very high precision the location of the neutron star

$$f_d = f(t)\left(1 + \frac{\vec{v}\cdot\vec{n}}{c}\right)$$

Fix R.A. and declination

Neutron star frequency: It is needed to know with high precision the frequency and its derivatives of the neutron star

$$f(t) = \sum_{n=0}^{\infty} f^{(n)} \frac{(t - t_0)^n}{n!}$$

Fix frequency and spin-down

Antenna response: It is needed to know the source position and the interferometer position

$$F_+(\theta, \phi) = \frac{1}{2}(1 + \cos^2\theta)\cos 2\phi$$

$$F_\times(\theta, \phi) = \cos\theta \sin 2\phi$$

[Maggiore, 2008]

Fix the interferometer position with respect to the source

Signal buried in noise: Compute the analysis to extract the signal from the noise

Continuous GW searches

The simplest way to look for cGWs is to search for a monochromatic signal after that all the corrections have been applied.

From the basic theory of signal processing we know that the longer is the coherence time, the better I can see the signal in the spectrum

This procedure is not always suitable for several reasons but the more important is the computational costs of the analysis.

Analyzing 4 months of data means that our frequency and spin-down bins are:

$$\delta f \approx 10^{-7}\mathrm{Hz} \qquad \delta \dot{f} \approx 10^{-14}\mathrm{Hz/s}$$

Continuous GW se che

The simplest way to nochromatic signal
after that al

From th s the
coherence

This pro ore
im

An s
are:

$\delta f \approx 10^{-}$

www.jolyon.co.uk

Continuous GW searches

In order to look for GW we have to explore a 4+N dimensional space (R.A, decl, frequency, spin-down+Spin-down's derivatives)

Targeted searches: Based on the application of a matched filter, the knowledge of all the source parameters is mandatory.

$$h_{min} \approx 10\sqrt{\frac{S_n(f)}{T_{obs}}}$$

[Astone et al., 2010]

5-vectors pipeline
F-Statistic pipeline
Bayesan Heterodyne pipeline

Directed searches: Apply the matched filter on many shorter data chunks and then combine the detection statistic incoherently.

$$h_{min} \approx 30\sqrt{\frac{S(f)}{T_{coh}}}$$

[Aasi et al, 2016]

Directed *F-statistic*

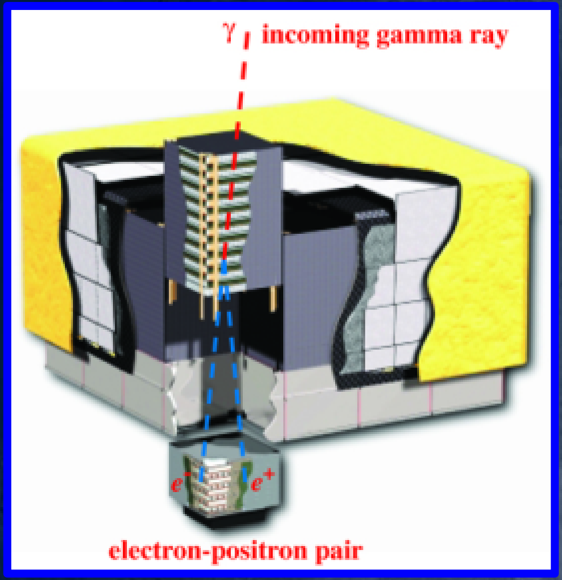
All-sky searches: Based on the incoherent combination of several data chunks.

$$h_{min} \approx \frac{\Lambda}{N^{1/4}}\sqrt{\frac{S_n(f)}{T_{coh}}}$$

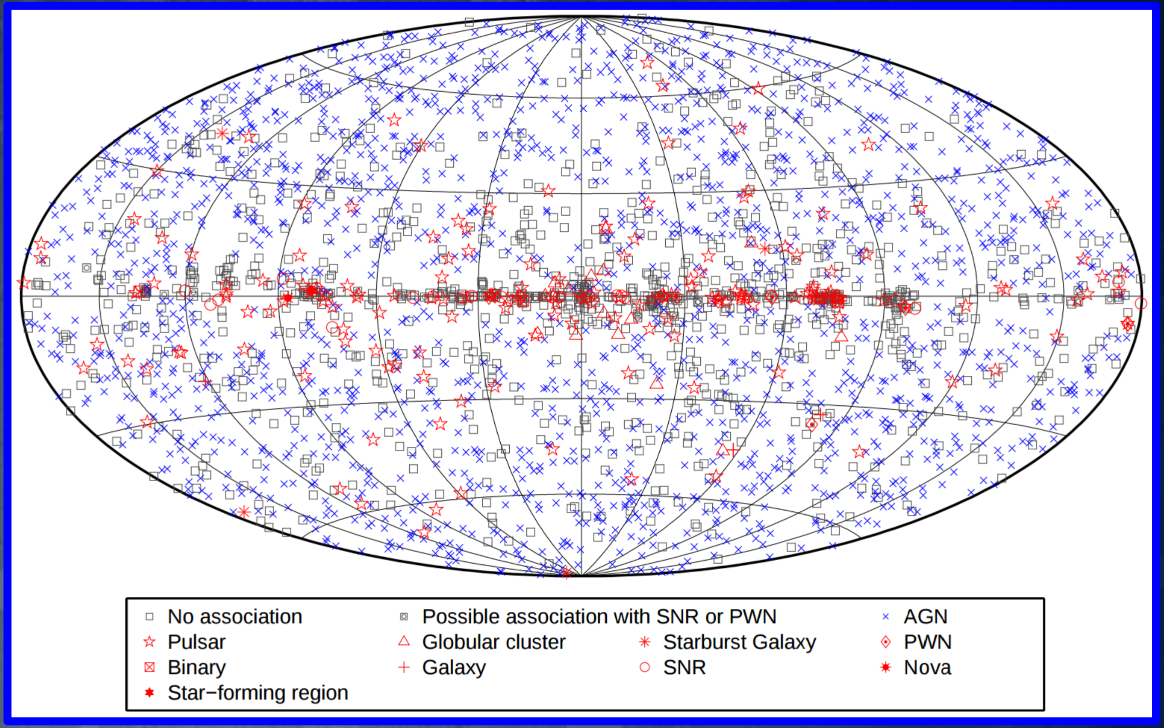
[Krishnan et al., 2004]

Sky Hough
Frequency Hough
PowerFlux
All-sky *F-stat*

Gamma-ray sources and Fermi-LAT



[Acero et. al, 2015]



- Detects gamma-ray in a range of 20 MeV to 300 GeV measuring times energy and directions.
- Fermi-LAT collaboration produced 3 source catalogs so far.
- The 3rd catalog covers the period from 2008 to 2012 (ApJ Supplement Series, 218:231)
- The LAT team distinguish between *Associated* and *Identified* sources

Gamma-ray sources and Fermi-LAT *[Acero et. al, 2015]*

Identified sources:

Source	Number	Frequency	Position	Search
Pulsar (flag: PSR)	143	Well known	Well known	Targeted
Pulsar Wind Nebula (flag: PWN)	9	Not-known	Known	Directed
Supernova remnant (flag: SNR)	12	Not-known	Known	Directed

Associated sources:

Source	Number	Frequency	Position	Search
Pulsar (flag: psr)	24	Not well known	Known	Narrow-band
Pulsar Wind Nebula (flag: pwn)	2	Not known	Not well known	All-sky
Supernova Remnant (flag: snr)	11	Not known	Not well known	All-sky
Potential pwn or snr (flag: spp)	49	Not known	Not well known	All-sky

Unassociated sources:

Sources for which we have only gamma-rays observation: 1010

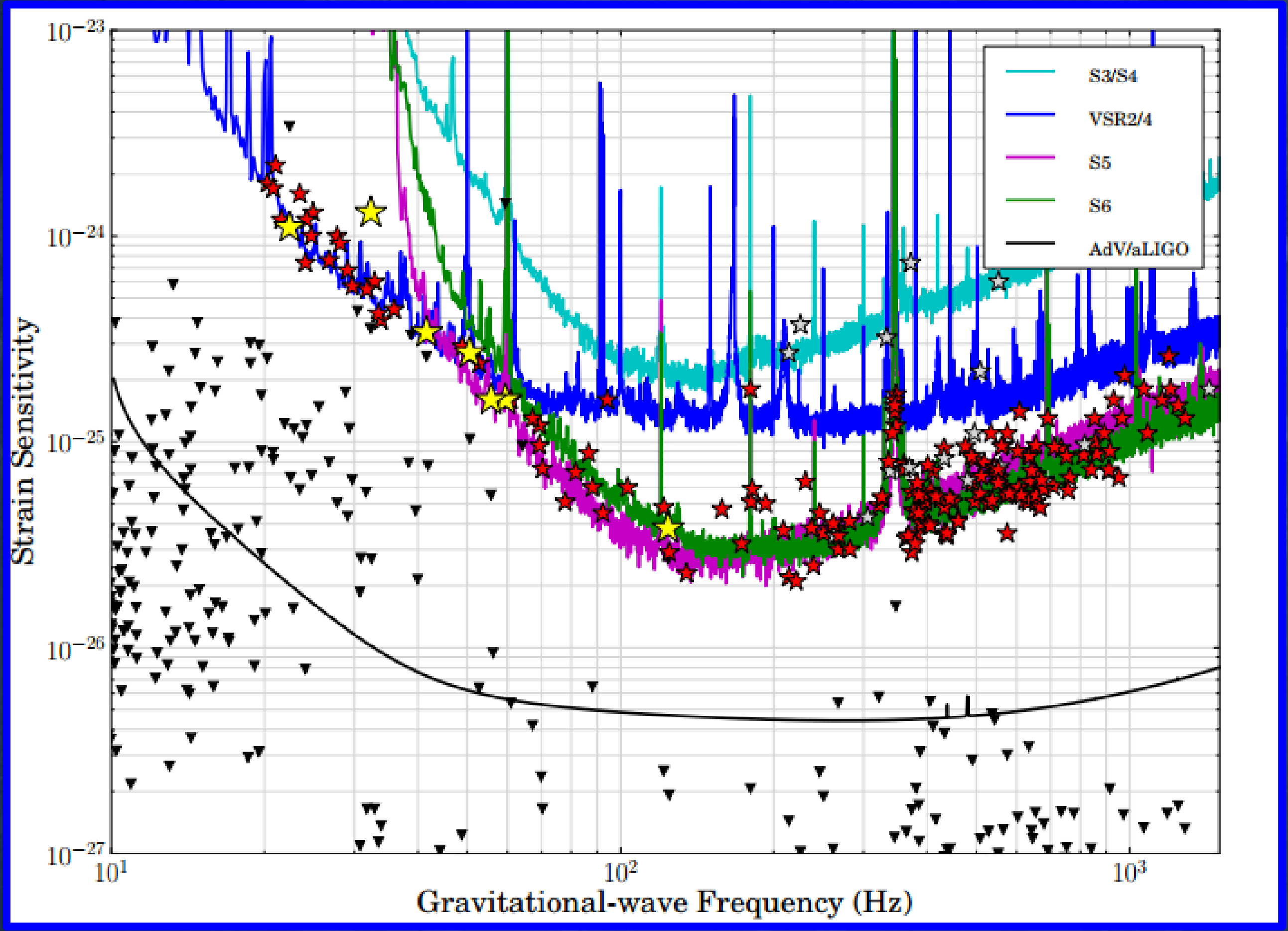
Mainly on the galactic plane

Depending on the knowledge of source parameters different searches can done

GW searches from: Known pulsars

Target searches applied to pulsars for which we have updated ephemeris and the knowledge of the rotational parameters

See C. Palomba’s talk.

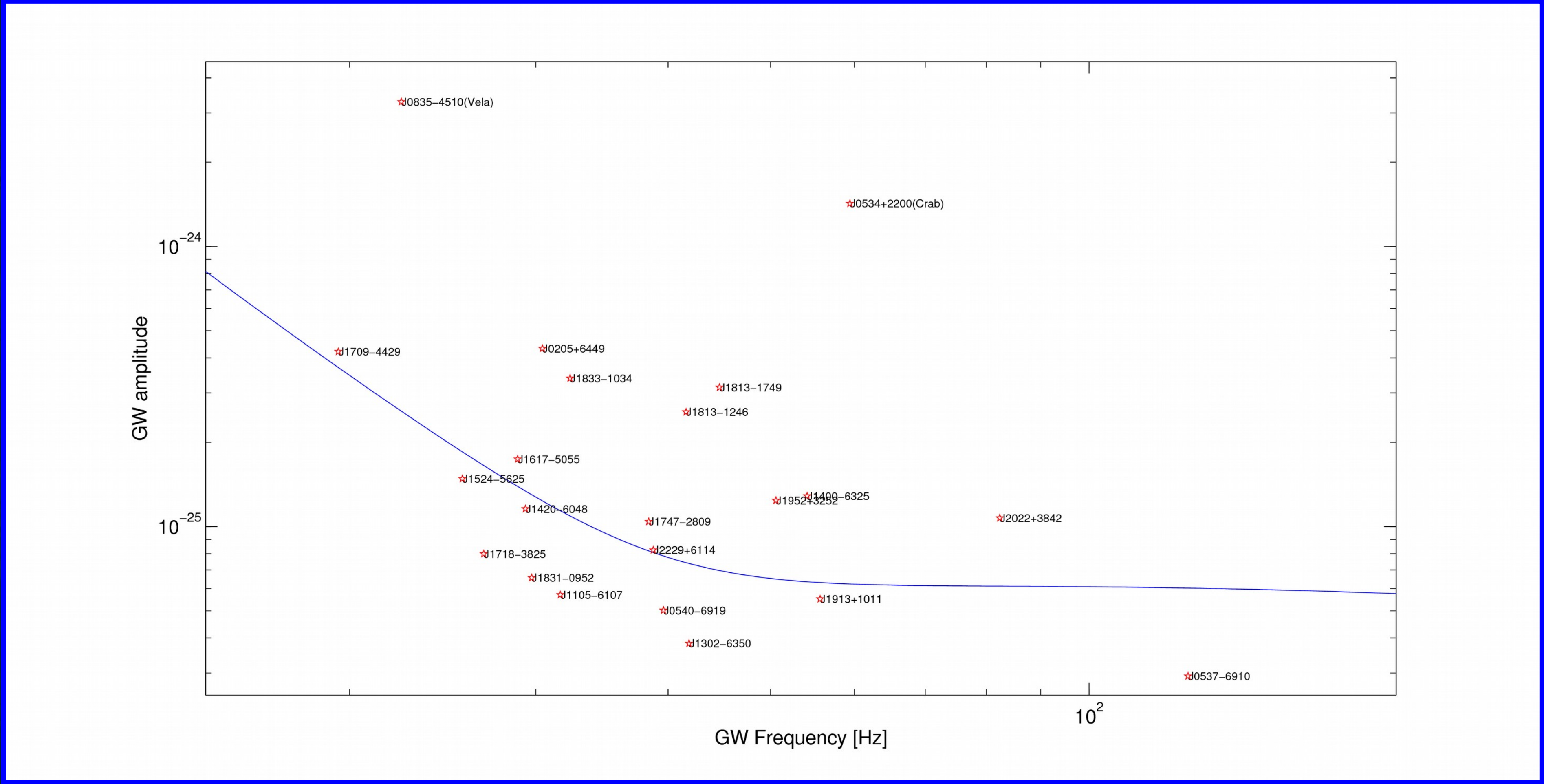


[Aasi et al, 2014]

GW searches from: Known pulsars

If we have some uncertainties on the rotational parameters or the ephemeris are not updated, narrow-band searches can be applied.

We have applied this typer of searches for 11 known pulsars using O1 data *(results under internal review, paper in preparation)*



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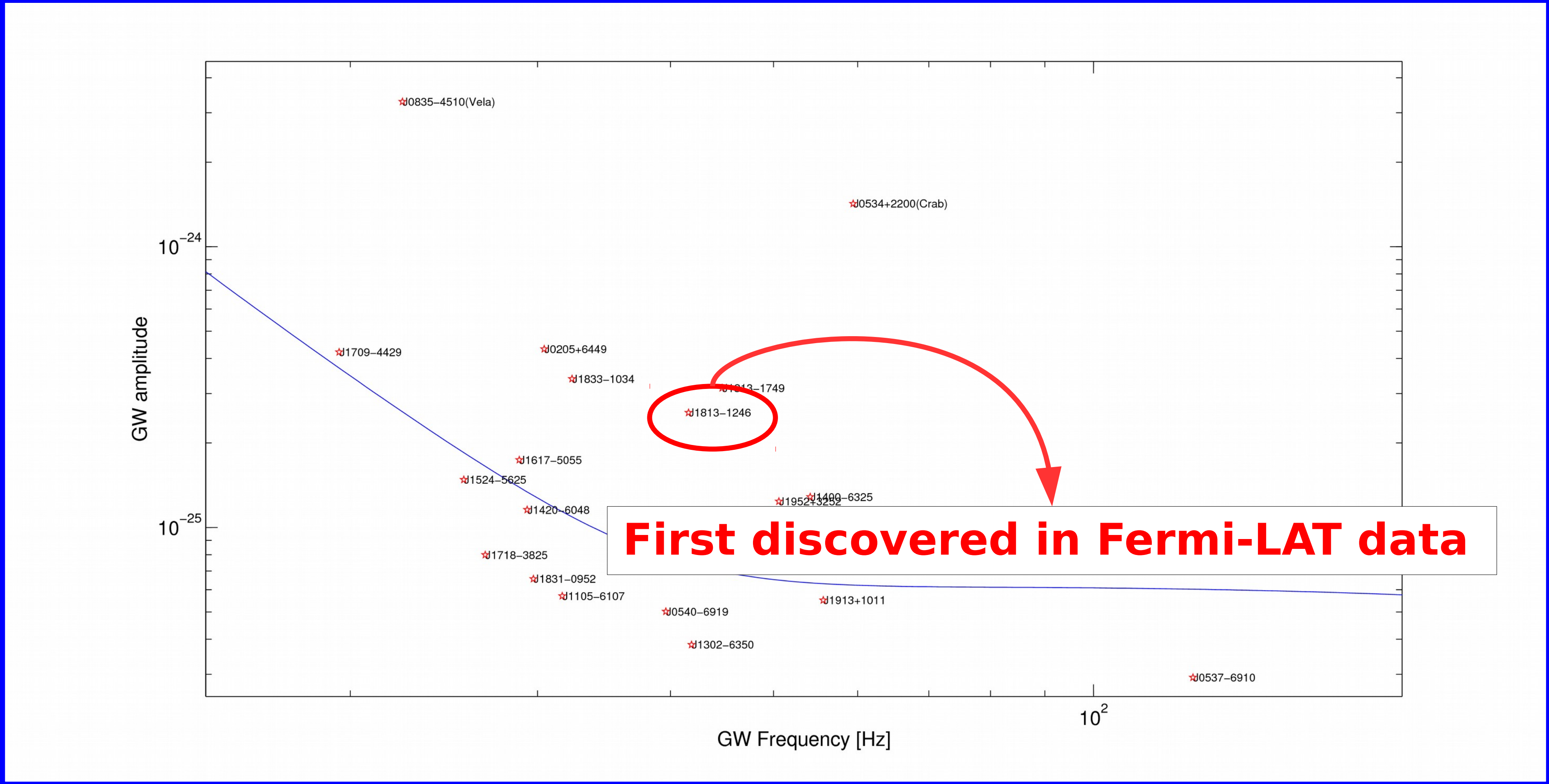
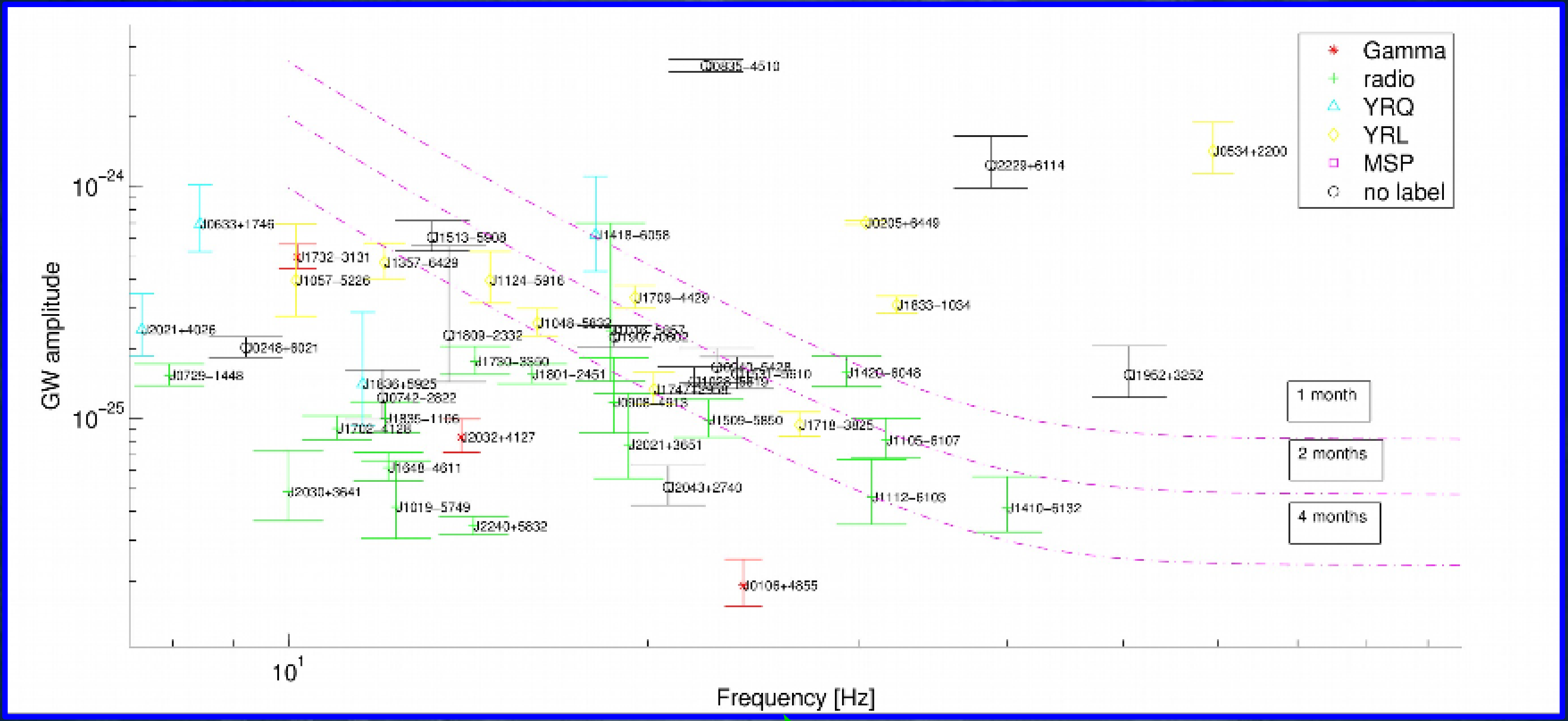


First discovered in Fermi-LAT data

GW searches from: Known pulsars

Moreover with the future runs of the advanced detectors we will be able to beat the spin-down limit for several pulsars in the second *Fermi-LAT pulsars catalog*



Spin-down limit predicted for the low frequency pulsars present in the catalog

GW searches from: Known pulsars

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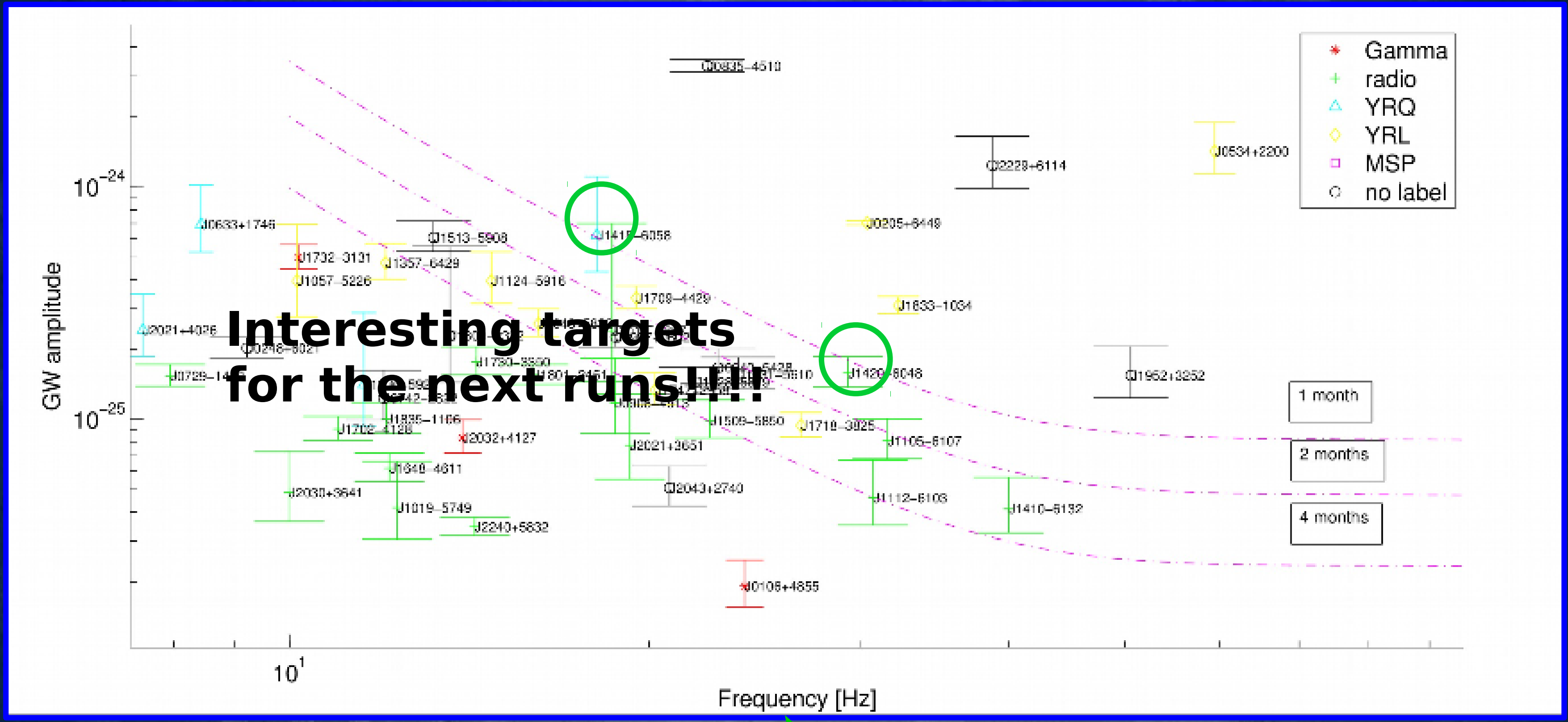


Interesting targets for the next runs!!!!

Spin-down limit predicted for the low frequency pulsars present in the catalog

GW searches from:

Pulsars are not the only interesting candidates for GW in Fermi-LAT catalogs. There are a lot of sources that are difficult to analyze with the current pipelines but are very promising under a GW point of view.

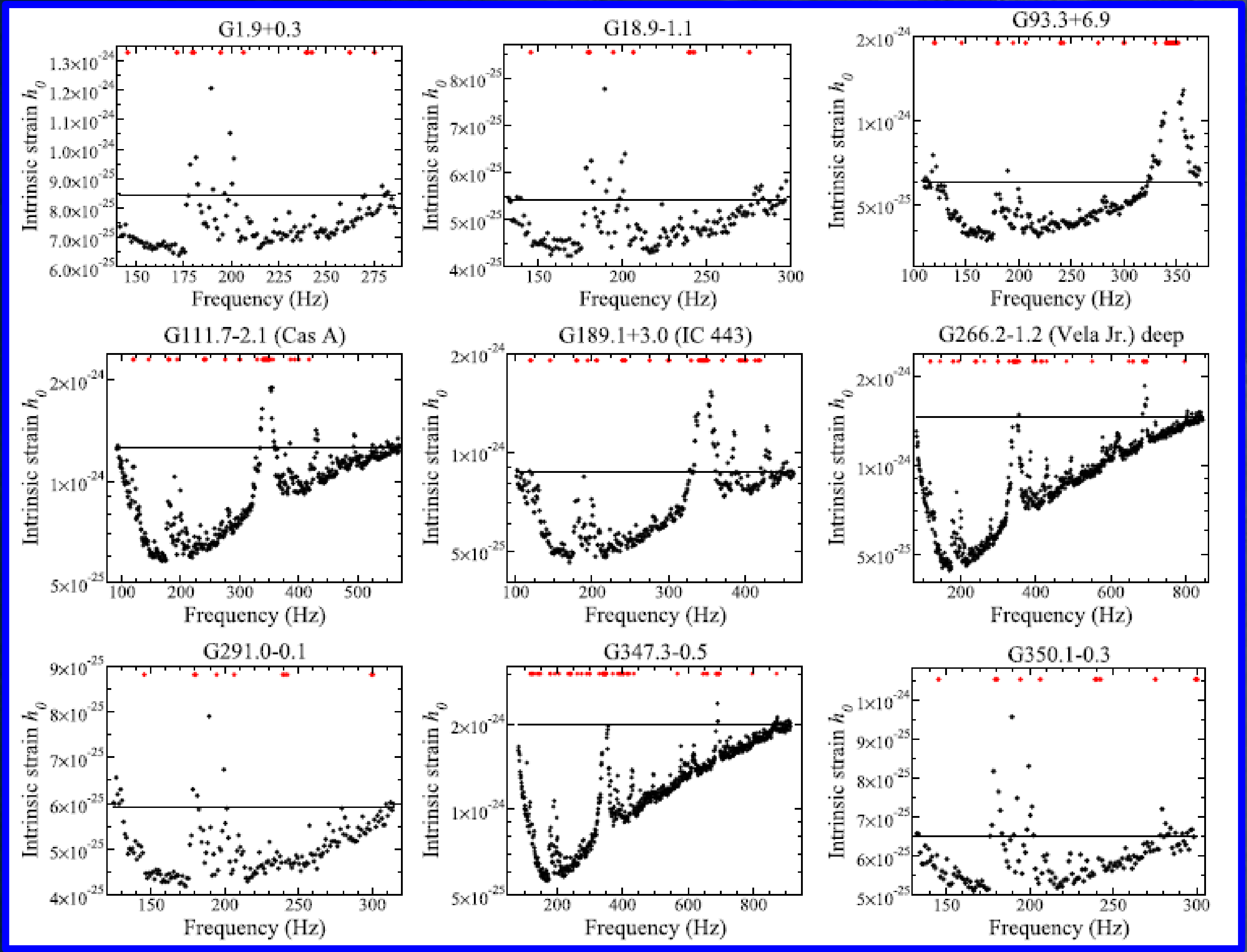
Supernova Remnant & PWN: For this type of sources the position is accurately known (in most of the cases) but the rotational parameters are completely unknown.

➡ **We need to explore 1 sky bin e many frequency bins**

Unassociated sources: Besides the fact that they are the 33% of the 3FGL, the unassociated sources are expected to be a large population of NS. This sources have a narrow-localization in the sky and their rotational parameters are unknown.

➡ **We need to explore several sky bins and many frequency bins**

GW searches from: SNR and PWN (past)



- Analysis performed for 9 SNR observed in many wavelengths using S6 data
- Semi-coherent analysis on chunks long 1800s
- 140 000 CPU hours
- Upper-limit set ever 5 Hz

[Aasi et al, 2016]

We can estimate the spin-down limit using the age of the remnant

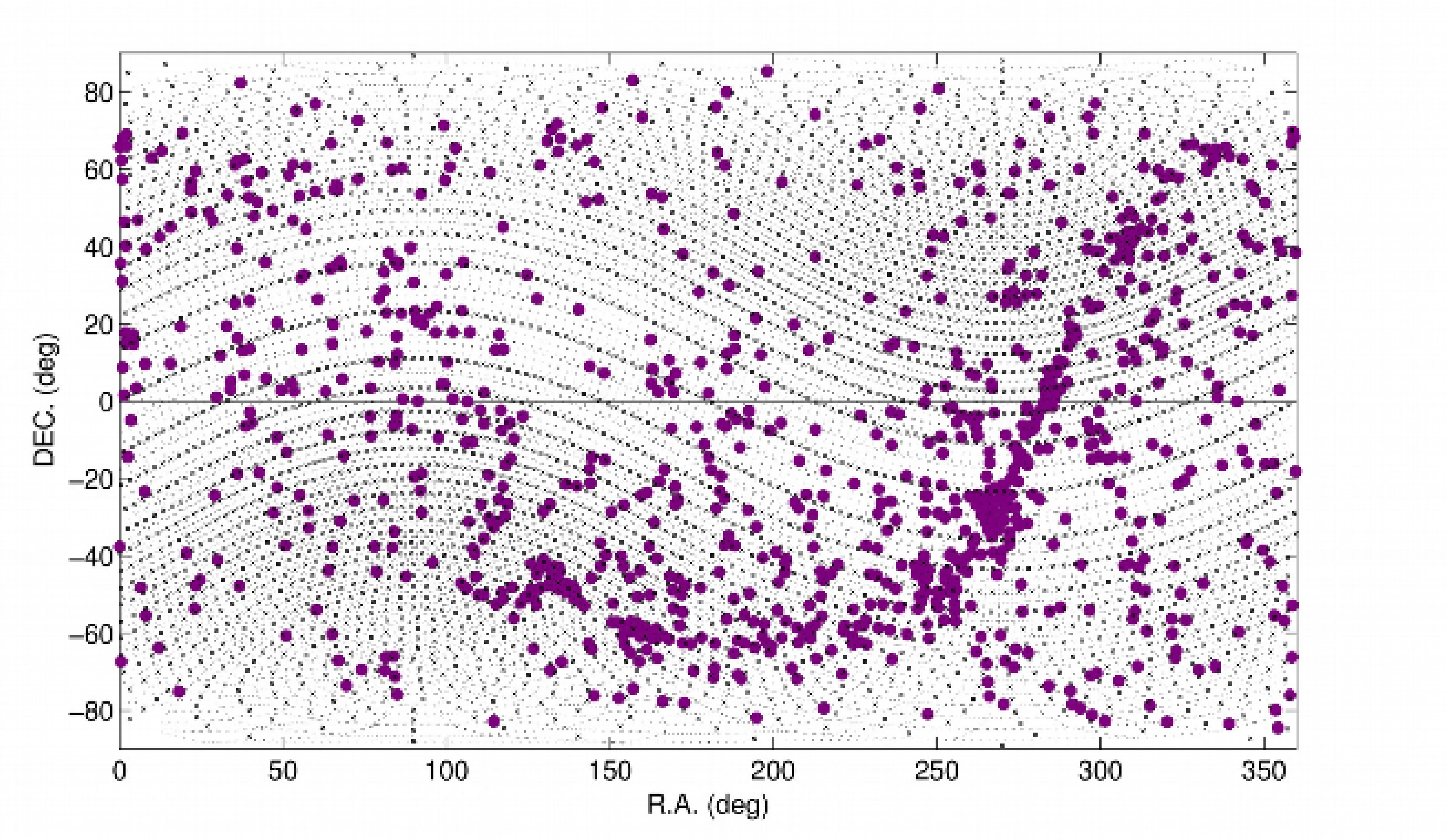
$$h_0 \leq 1.24 \cdot 10^{-24} \left(\frac{3.8\mathrm{kpc}}{d}\right) \sqrt{\left(\frac{I_{zz}}{10^{38}\mathrm{kg}}\right)\left(\frac{300\mathrm{yr}}{\tau}\right)}$$

GW searches from: unassociated

Fermi -LAT unassociated sources are really interesting.

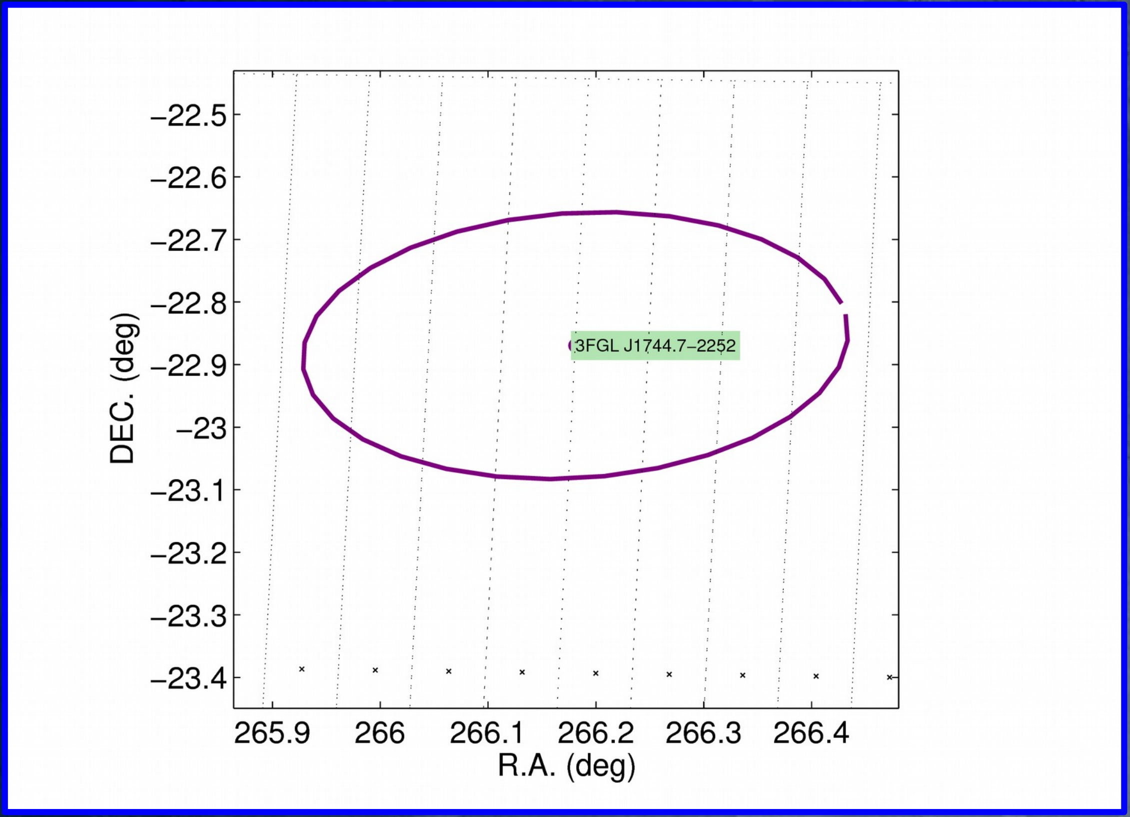
These sources lie on the galactic plane covering many sky-bins and many of them are present also in the previous catalogs

47 % are expected to be unseen neutron stars



GW searches from: unassociated

A typical *unassociated* source is the one shown below



Coherence time:

86400 s

Max Search frequency:

100 Hz

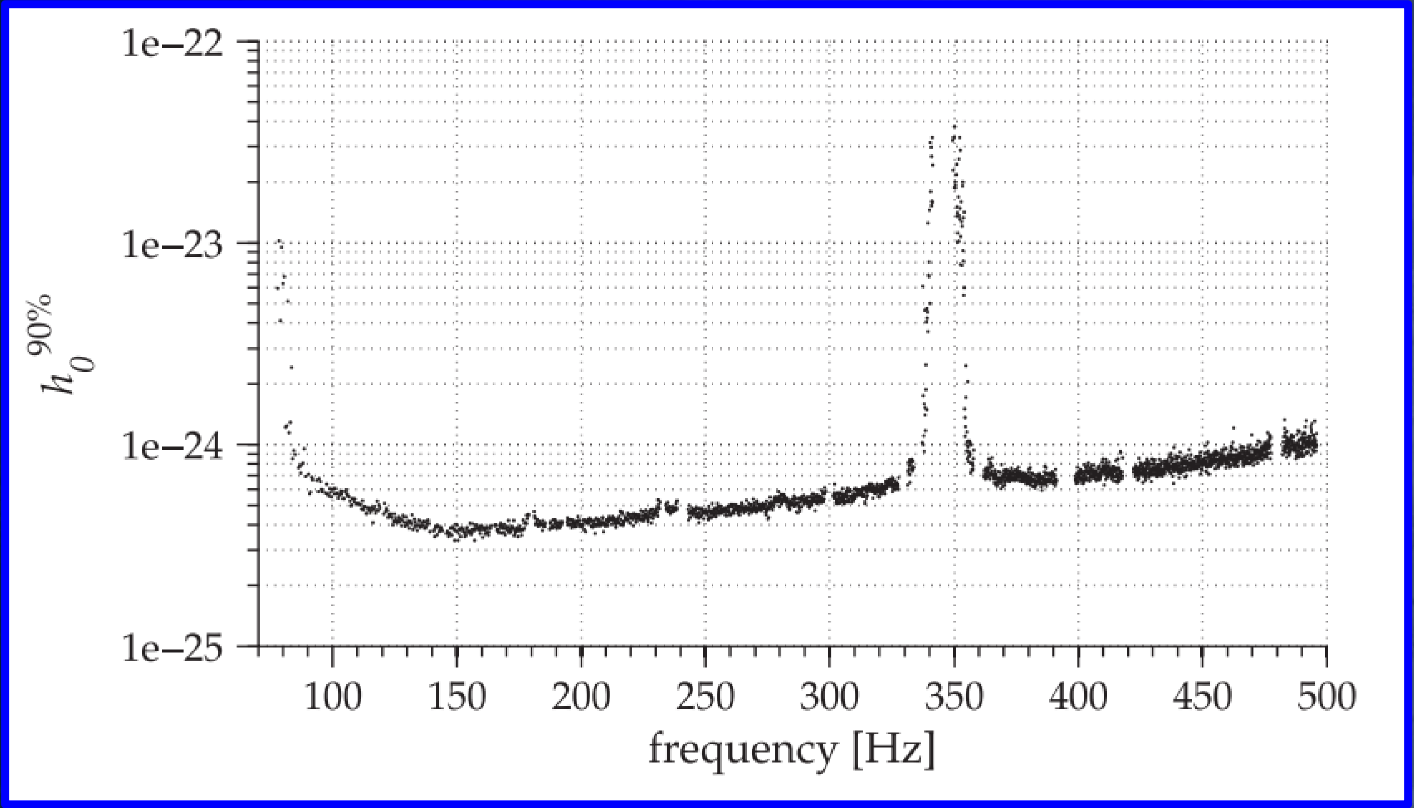
For this type of sources we would explore about 500 Hz on the frequency band and several sky-bins

For just one source

This type of analysis would be very heavy for a computational point of view with current methods

GW searches from: unassociated

- A GW search from the galactic center was performed
- Semi-coherent analysis on chunks long 1800s
- 1 milion CPU hours
- Upper limit every 1 Hz- band 20 Hz to 498 Hz



[Aasi et al, 2013]

We are currently performing all-sky analysis. No search of GW from the unassociated sources of LAT is ongoing

Perspectives

We are working to develop new method to analyze Fermi-LAT sources

The new starting point will be the **Band Sampled Data collection (BSD)** (*see Piccini O.J. poster)*

⬇

Allows to increase the coherence time in a computational cheap way

Unassociated:

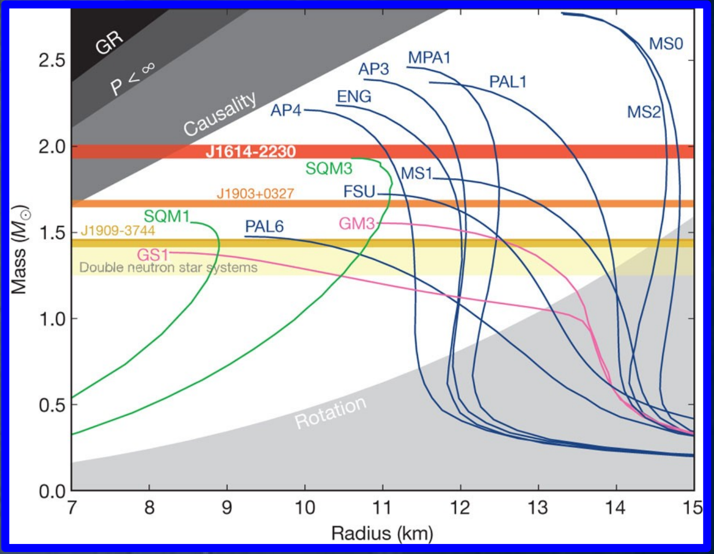
- GW flag in your catalog?
- Longer FFTs to improve the sensitivity
- Incoherent methods in the neighborhood of the source position (e.g. Hough transform)
- Fast follow-up methods
- New type of algorithms ?

SNR and PWN:

- Improvements of semi-coherent methods
- Fast follow-up methods
- New type of algorithms ?

What can we infer?

- According to standard stellar evolution, we expect $O(10^8)$ NS be hosted in the Galaxy, but only ~2500 have been observed.
- Many of them can be hidden in their supernova remnant (Ex: Cas A, 1987a)
  Or totally unseen
- NS demography
- Infer information on the internal magnetic field through the deformation
  [Owen et al., 2006]
- Moreover GW can probe the NS internal structure, I.e the equation of state (EOS).



[Read et al., 2009]

What can we infer?

Only detection:

- The rotational parameters, i.e. frequency and spin-down
- The position of the source in the sky, hence if a compact object is present in a remnant or in a unassociated source

Studying the signal:

- The amplitude of the GW
- The polarization angle
- The line of sight angle
- Upper-limit on ellipticity

Studying the signal jointly with EM observation:

- Age of the neutron star
- Braking Index study
- Possible mismatches in EM and GW frequencies
- Distance

GW can carry out a lot of information...so let's keep going!

Summary and conclusions

- Continuous gravitational waves are good probes to spot and study NS
- Fermi-LAT pulsars and supernova remnants are good targets for GW searches
- Current pipelines are limited by the computational load (Only 9 supernova remnant were studied so far)
- *Unassociated sources* are also interesting possible GW sources
- Hopefully we will see the first detection of a continuous gravitational waves from NS in the next runs of the advanced detectors
- However more work is needed to develop pipeline and methods suitable to the analysis of sources with some uncertainties like the ones in Fermi Catalog

So.....

Brace yourself multi-messenger astronomy is coming

Thanks for the attention

Questions?

References

- M. Maggiore, *Gravitational waves Vol.1* (2008)
- P. Astone et al., *Method for narrow-band search of continuous gravitational wave signals,* **Phys. Rev. D 89, 062008 (2014)**
- P. Astone et al., *A method for detection of known sources of continuous gravitational wave signals in non-stationary data*, **Class. Quantum Grav. 27 194016(2010)**
- B. Krishan et al., *Hough transform search for continuous gravitational waves*, **Phys. Rev. D 70, 082001 (2004)**
- J.S. Read et al., *"Constraints on a phenomenologically parametrized neutron-star equation of state",* **Phys. Rev. D 79, 124032 (2009)**
- Acero et al., *Fermi Large Area Telescope third source catalog,* **ApJS 218 23 (2015)**
- S. Walsh, "*A comparison of methods for the detection of gravitational waves from unknown neutron stars"*, arXiv:1606.00660 **(2016)**
- B. Owen, "*Detectability of periodic gravitational waves by initial Interferometers*", **Class. Quantum Grav. 23 S1**
- J. Aasi et al., "*Gravitational waves from known neutron stars: results from the initial detector era*", **ApJ 785 119 (2014)**
- J. Aasi et al., "*Searches from continuous gravitational waves from nine young supernova remnants*", **ApJ 813 39 (2015)**
- J. Aasi et al., "*Directed search for continuous gravitational waves from the Galactic center*", **Phys. Rev. D 88, 102002 (2013)**
- A. Abdo et al., "*The second Fermi-LAT catalog of gamma-ray pulsars*", **ApJS 208 17 (2013)**

Backup slides

Spin-down limit

Assume that all the rotational energy is lost due to GW

$$L_{GW} = \frac{32G}{5c^5}\Omega^6 I_{zz}^2 \epsilon^2$$

$$(2\pi)^2 \nu\dot{\nu} = L_{GW}$$

→

$$\dot{\nu} = \frac{32G}{5c^4}(2\pi)^4 \nu^5 I_{zz} \epsilon^2$$

Some rotational parameters

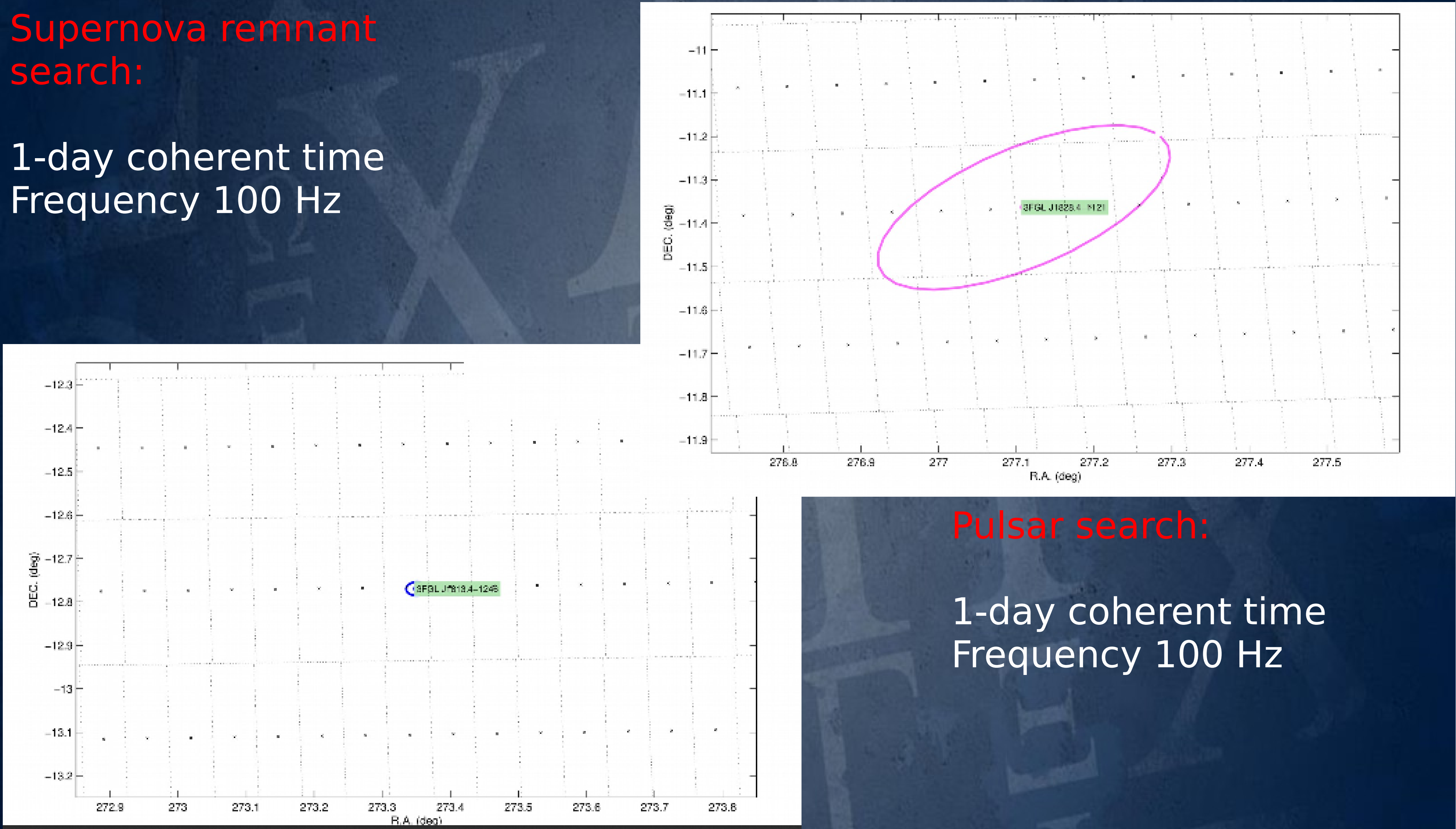
	Freq [Hz]	spin-down [Hz/s]
Crab	*59.32365204*	*-7.3883e-10*
J0205+6449	*30.40958196*	*-8.9586e-11*
J1813-1246	*41.60103328*	*-1.2866e-11*
J1813-1749	*44.71284639*	*-1.5000e-10*
J1833-1034	*32.29409580*	*-1.0543e-10*
J1952+3252	*50.58823360*	*-7.4797e-12*
J2043+2740	*20.80486277*	*-2.7415e-13*
J2229+6114	*38.71531561*	*-5.8681e-11*
Vela	*22.37409813*	*-3.1191e-11*
J1400-6326	64.12537215	-8.0017e-11
J2022+3842	41.16008453	-7.2969e-11

Computational efficency

Frequency bin $= \dfrac{1}{T_{coh}}$ Spin-down bin $= \dfrac{1}{T_{coh}^2}$ Sky bin $\propto \dfrac{1}{T_{coh}^2}$

Supernova remnant search:

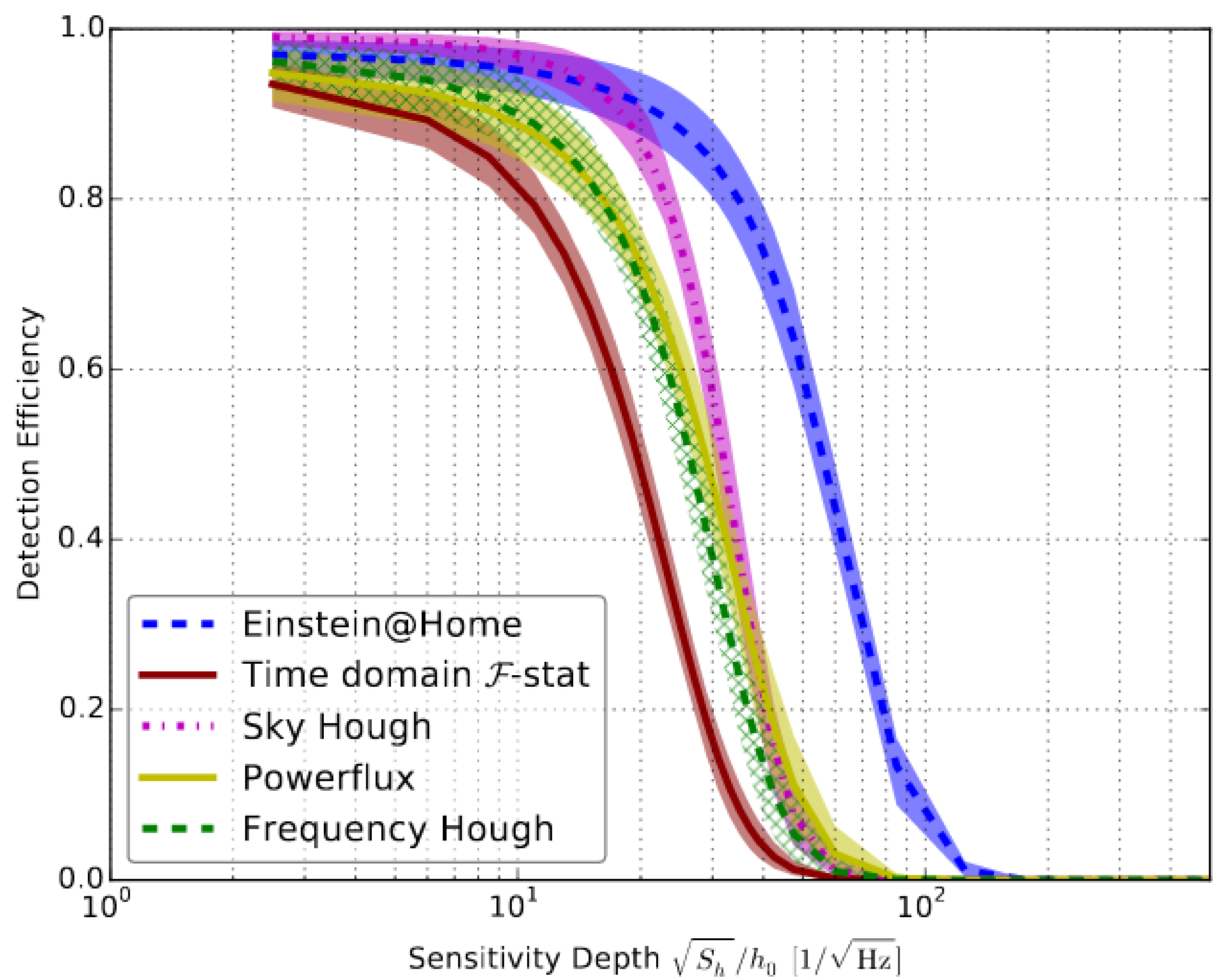
1-day coherent time
Frequency 100 Hz



Pulsar search:

1-day coherent time
Frequency 100 Hz

Computational efficency- Coherence time



[Walsh, 2016]

E@Home:
60 hours

Time-domain *F*:
48 hours

Sky-Hough:
1800 s

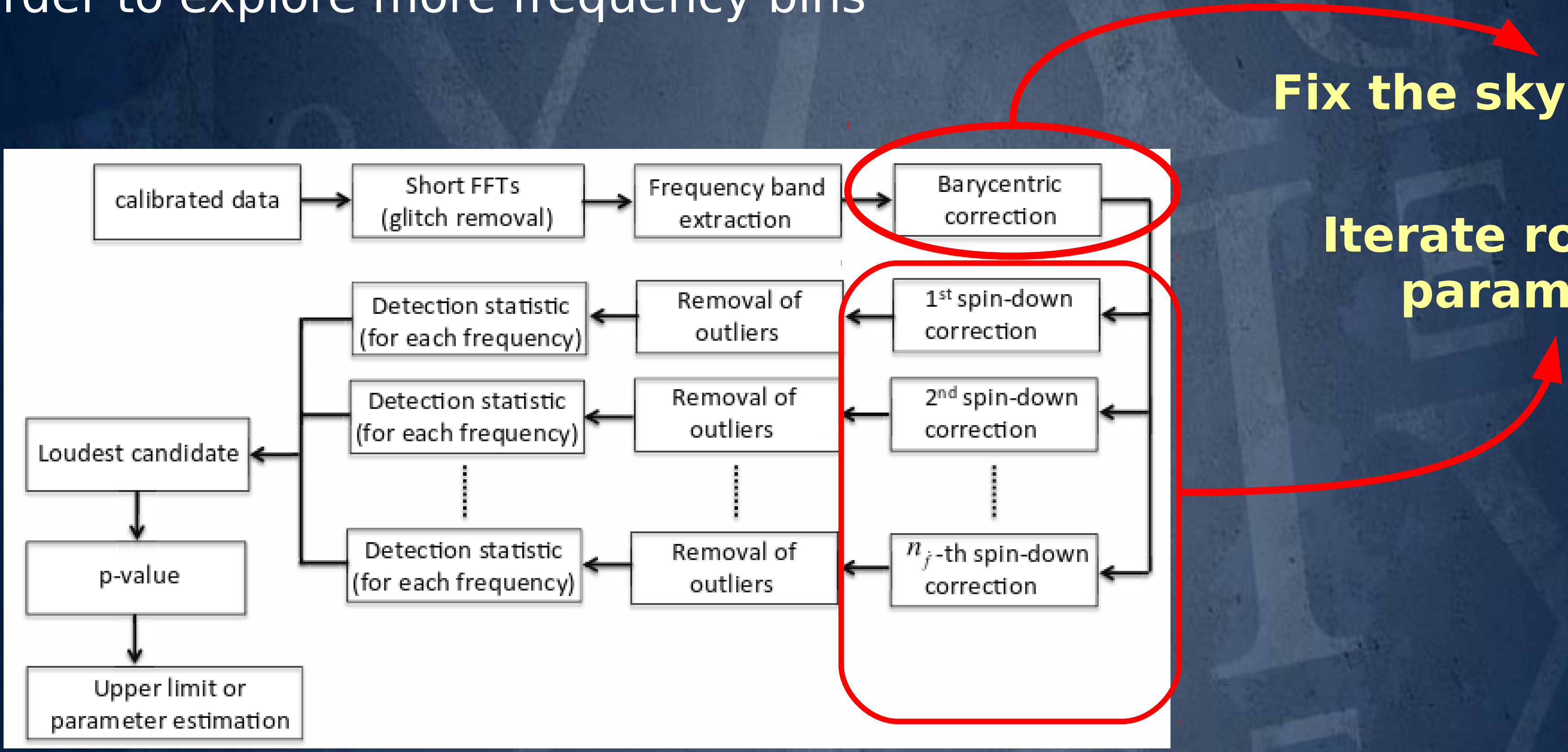
Power flux:
900 s

Frequency Hough:
1024 s

Continuous GW searches

Targeted and directed searches: This type of searches assume known the position and search for GW for different frequency and spin-down values

Directed searches divide the observation time in shorter data-chunks in order to explore more frequency bins



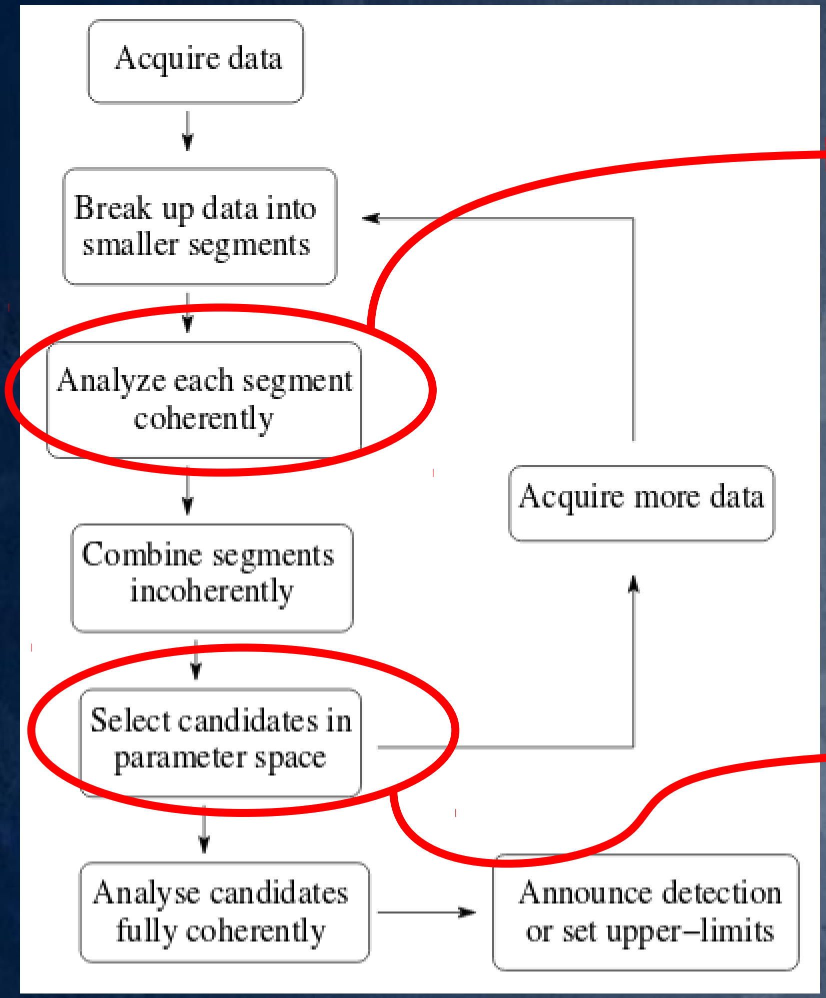
Fix the sky location

Iterate rotational parameters

[Astone et al., 2014]

Continuous GW searches

All-sky searches: Don’t use the matched filter technique and explore a wide range in the parameter space



[Krishnan et al., 2004]

No matched filter,other techniques:
Hough transform
Correlation
Incoherent summation

Select candidates to follow up