Looking for gravitational-waves from poorly known neutron stars

S. Mastrogiovanni and the Rome Virgo group*

*P. Astone, S. D'Antonio, S. Frasca, G. Intini, I. La Rosa, P. Leaci, A. Miller, F. Muciaccia C. Palomba, O. J. Piccinni, A. Singhal

Sapienza Università di Roma
INFN Istituto Nazionale di Fisica Nucleare
VIRGO

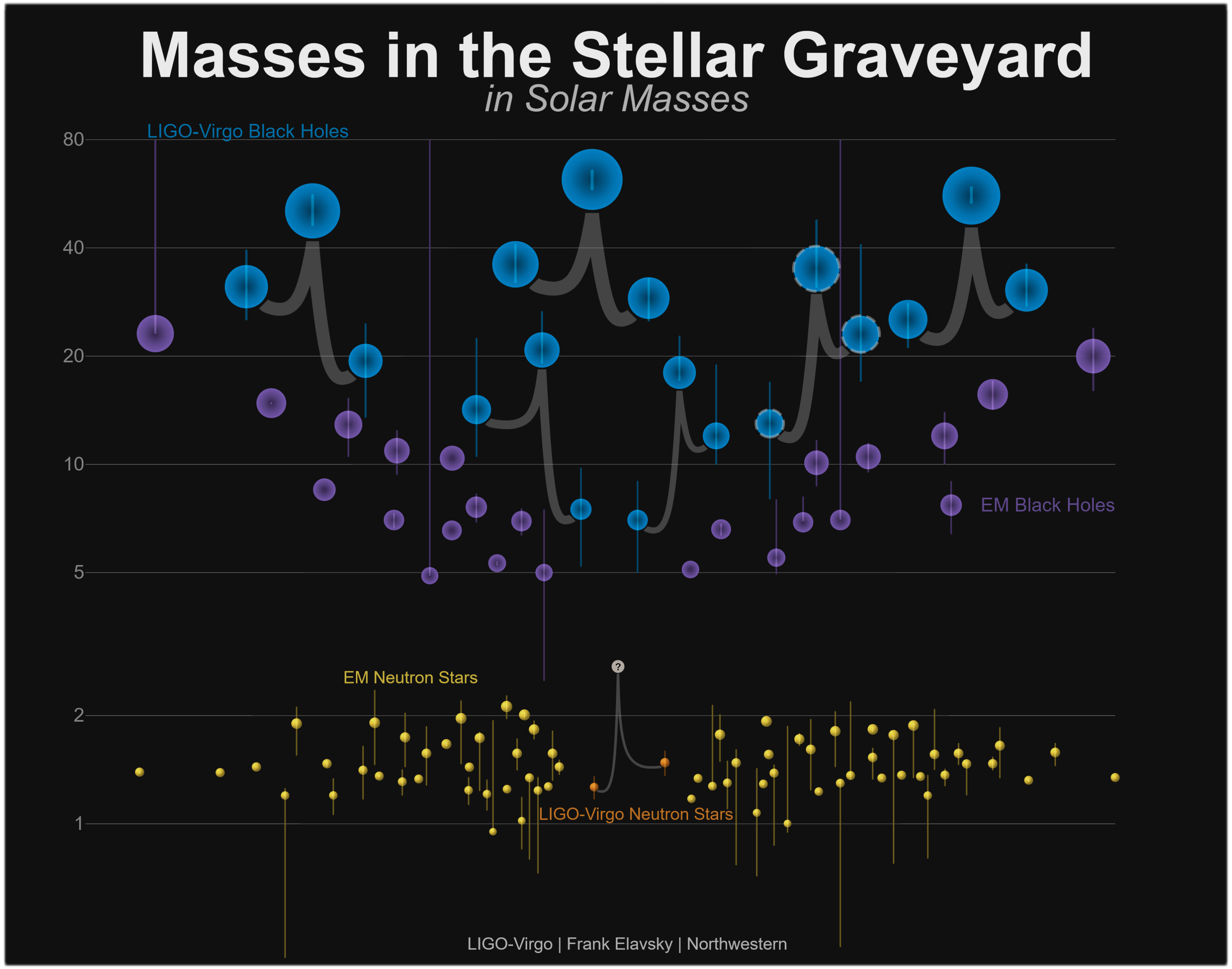
1

Outline

- Looking for continuous gravitational waves
- What makes a neutron star poorly known?
- Methodology of narrow-band search
- GW astronomy with narrow bands searches

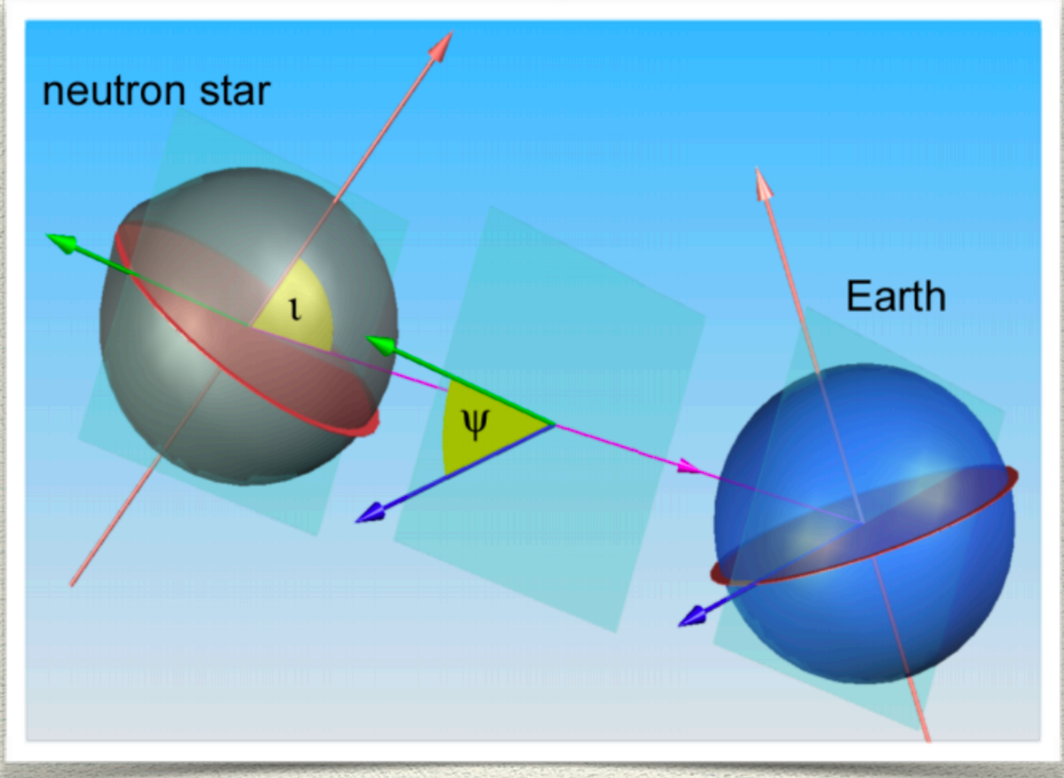
Looking for Continuous gravitational waves

The LVC collaboration has detected GWs emitted from compact binaries coalescences.



- Detected GWs arise from the orbital motion of compact objects.
- GW170817 is the only detection associated with the presence of at least a Neutron Star (NS) in the binary.
- Isolated and asymmetric spinning NSs are also expected to emit GW. The signal is however very different from the detected ones.

Looking for Continuous gravitational waves



$$h_+ = h_0 \frac{1+\cos^2\iota}{2}\cos(4\pi\nu_{NS}t) \qquad \text{pol. +}$$

$$h_\times = h_0 \cos\iota \sin(4\pi\nu_{NS}t) \qquad \text{pol. x}$$

Theoretical upper-limit from energy conservation:

$$h_0 \leq 8.06 \times 10^{-19}\left(\frac{I_{zz}}{10^{38}\mathrm{kg\ m}^2}\right)\sqrt{\left(\frac{\nu_{NS}}{\mathrm{Hz}}\right)\left(\frac{\mathrm{Hz/s}}{\dot{\nu}_{NS}}\right)}$$

- High stability in the rotational period (~10^{-12} Hz/s)
- Emitted at two times the rotational frequency of the NS
- Ephemeris are inferred mainly from radio observations, as we will see later.
- Long-lived coherent signals (>months).
- NSs are expected to be very dense (10^{14} g/cm^3).
- Moment of inertia ~ 10^{38} kg m^2

Looking for Continuous gravitational waves

- **NS's rotational phase:** We need to take into account the neutron star rotational phase. We use the **frequency + its derivatives** **(1+N parameters)**

$$\nu_{\rm NS}(t) = \sum_{i=0}^{\infty} \nu_0^{(i)} \frac{(t-t_0)^i}{i!}$$

- **Romer phase shift:** In the detector reference frame, the signal is modulated by the Doppler effect due to the Earth motion. A good knowledge of the **sky-localisation (+2 parameters)**

$$f(t) = 2 \cdot \nu_{\rm NS}(t) \big(1 + \frac{\vec{v} \cdot \widehat{n}}{c}\big)$$

- **Sidereal modulation:** The GW detectors have a response to the GW polarisations encoded in the antenna pattern. This modulation depends on the sky-localisation.

The waveform depends on 8 parameters:

$$(h_0, \cos\iota, \psi, \phi_0) \qquad (f, \dot{f}, \alpha, \delta)$$

Looking for Continuous gravitational waves

The narrow-band search makes use of a statistic closely related to the famous F-statistic firstly defined in ***Jaranowski et al [Phys. Rev. D 58, 063001 (1998)]*** and later extended for multiple detectors in ***Cutler and Schutz [Phys. Rev. D 72, 063006, 2005]***. The data is modelled as a superposition of Gaussian noise and signal.

$$\mathcal{L}(h|x) \propto e^{\langle x-h|x-h\rangle}$$

[Jaranowski et al, Phys. Rev. D 58, 063001]

$$|h >= H_0(\beta) \sum_p H_p(\beta) |A_p(\lambda) >$$

We can define the 5-vector's detection statistic as

$$S = \sum_p \frac{\langle x|A_p\rangle}{\langle A_p|A_p\rangle} \langle A_p|A_p\rangle^2$$

P. Astone et al [CQG 27 194016]

It is possible to marginalise over the intrinsic parameters and that's what we usually do in GW searches. So only four parameters remain

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

Single template sensitivity

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

Multi-frequency templates sensitivity

What can we learn from CW?

The maximum ellipticity that a neutron star can sustain can be related to the equation of state and to the neutron star interior model, see ***B. Owen [Phys.Rev.Let 95, 211101]***.

In order to gain information on the equation of state, a joint measure of the NS's **radius, mass, magnetic field and ellipticity** is needed.

Some models:

- **Solid strange stars:** Fiducial maximum ellipticity 6×10^{-4}
- **Hybrid and meson condense stars:** Fiducial maximum ellipticity $3\text{-}9 \times 10^{-6}$
- **Canonical (NSs):** $2\text{-}6 \times 10^{-7}$

What makes a NS poorly known?

Waveforms computed for mismatched variables will result in a partial recovery of the signal-to-noise ratio.

The grid in the parameter space is built in such a way that for the correct waveform the power of the signal is entirely enclosed in one cell.

Sky angles: $\delta\lambda = \frac{1}{N_d \cos\beta}$ $\delta\beta = \frac{1}{N_d \sin\beta}$ $N_d = \frac{f_0 \Omega_{orb} R_{orb} T_{coh}}{c}$

Typical values for 4months of data are 10^{-5} deg

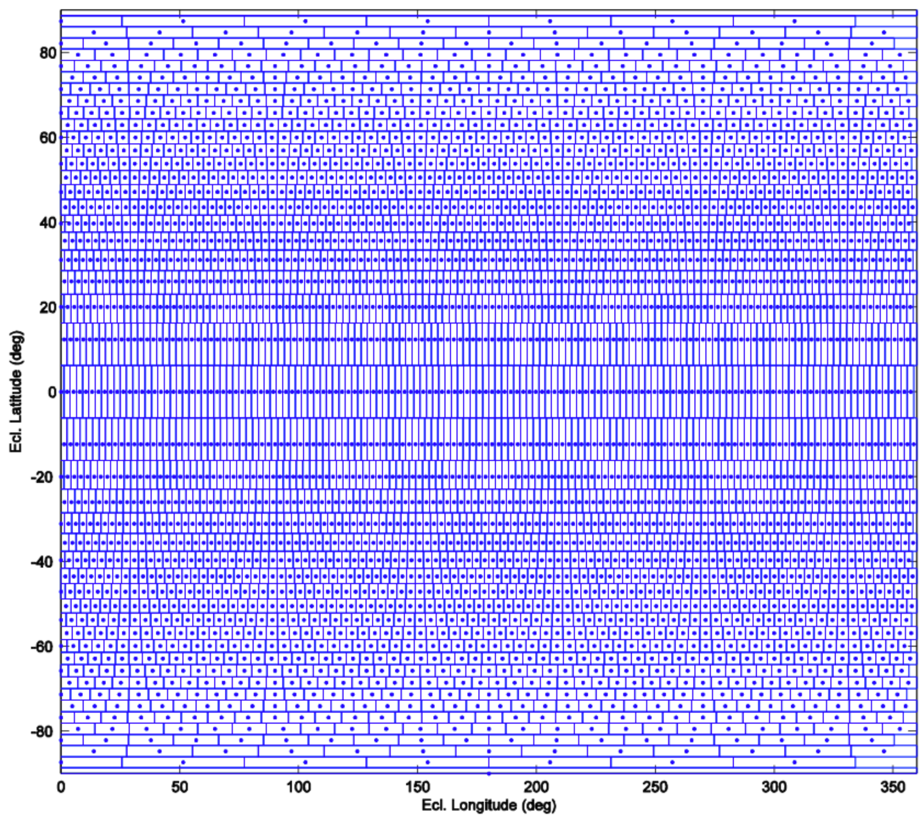
Searched frequency bin: $\delta f = \frac{1}{T_{coh}}$

Typical values for 4months of data are 10^{-7} Hz

Searched spin-down bin: $\delta \dot{f} = \frac{1}{T_{coh}^2}$

Typical values for 4months of data are 10^{-14} Hz/s

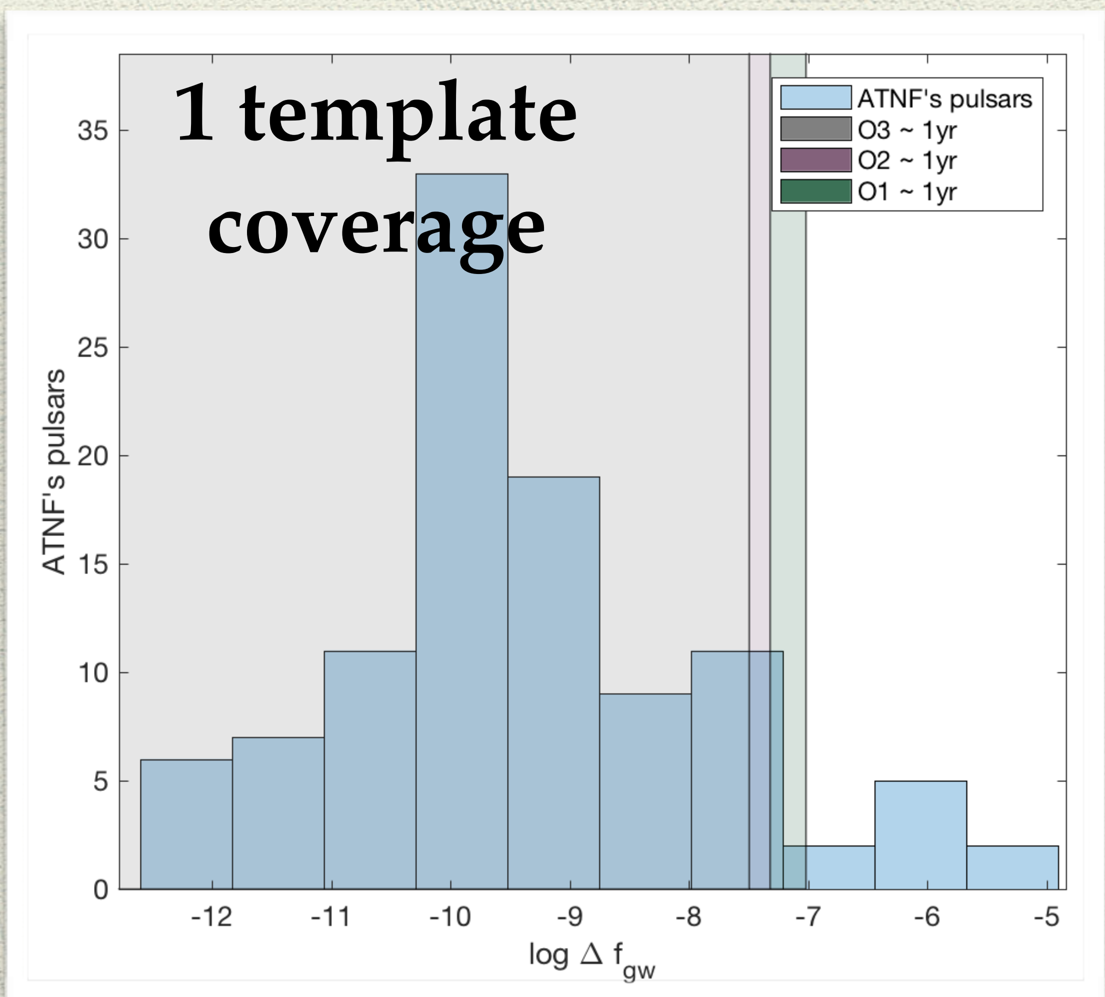
Sky-grid: T=1024s Freq=200 Hz

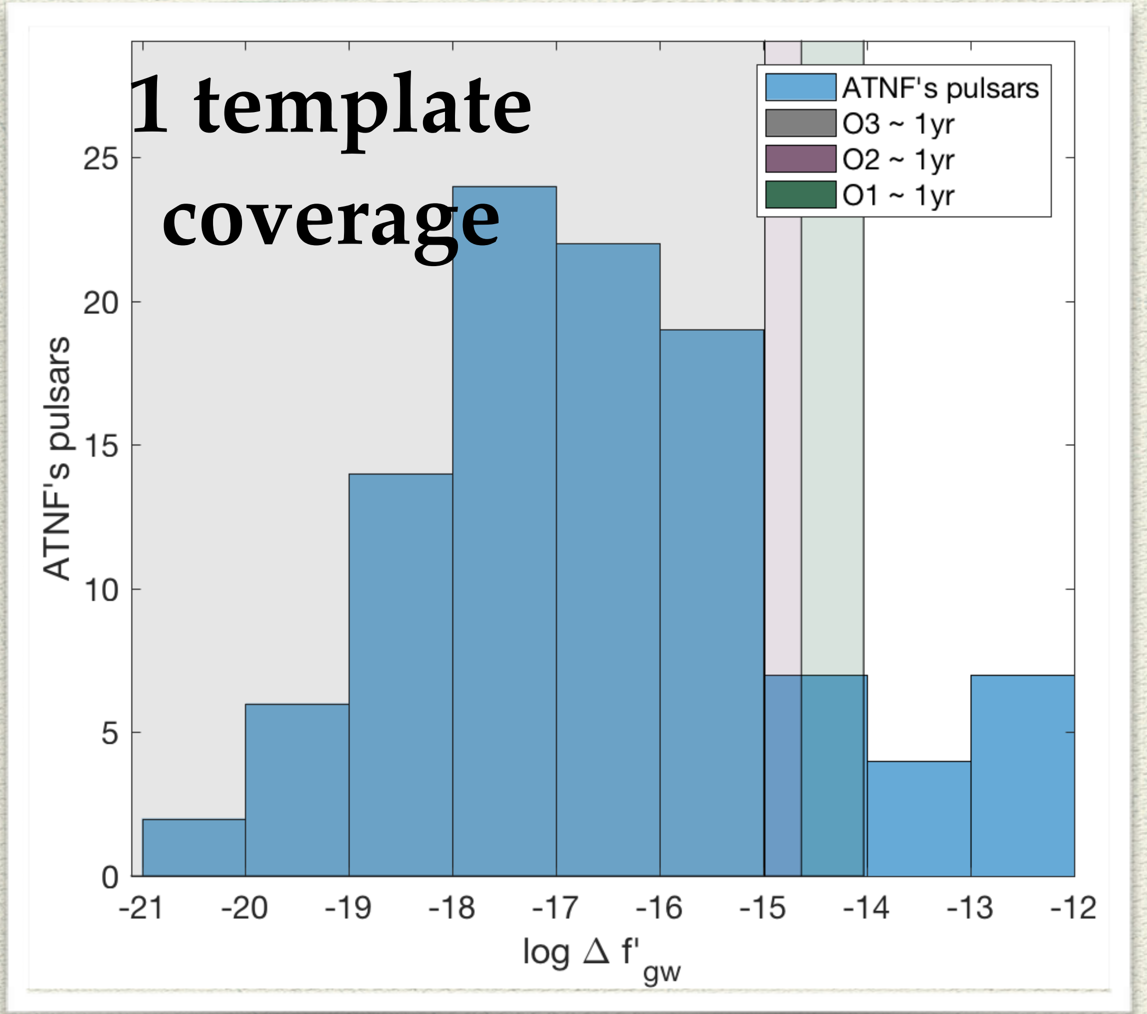


P. Astone et al [Phys. Rev. D 89, 062008]

What makes a NS poorly known?

Parameters needed for CW searches (position and frequency evolution) are usually estimated from electromagnetic observations.
However if the pulsar's timing is not accurate, this may result in the necessity of exploring many templates in our searches.





Uncertainties of rotational period for the isolated radio pulsars in the ATNF catalog (v1.58)

What makes a NS poorly known?

Different astrophysical scenarios for the NS may also play important roles in our ability to detect a signal (see D. I. Jones talk).

Freely precessing neutron stars may show a decoupling of the frequency inferred from EM observations and the GW emitted frequency.

The split is estimated to being of the order

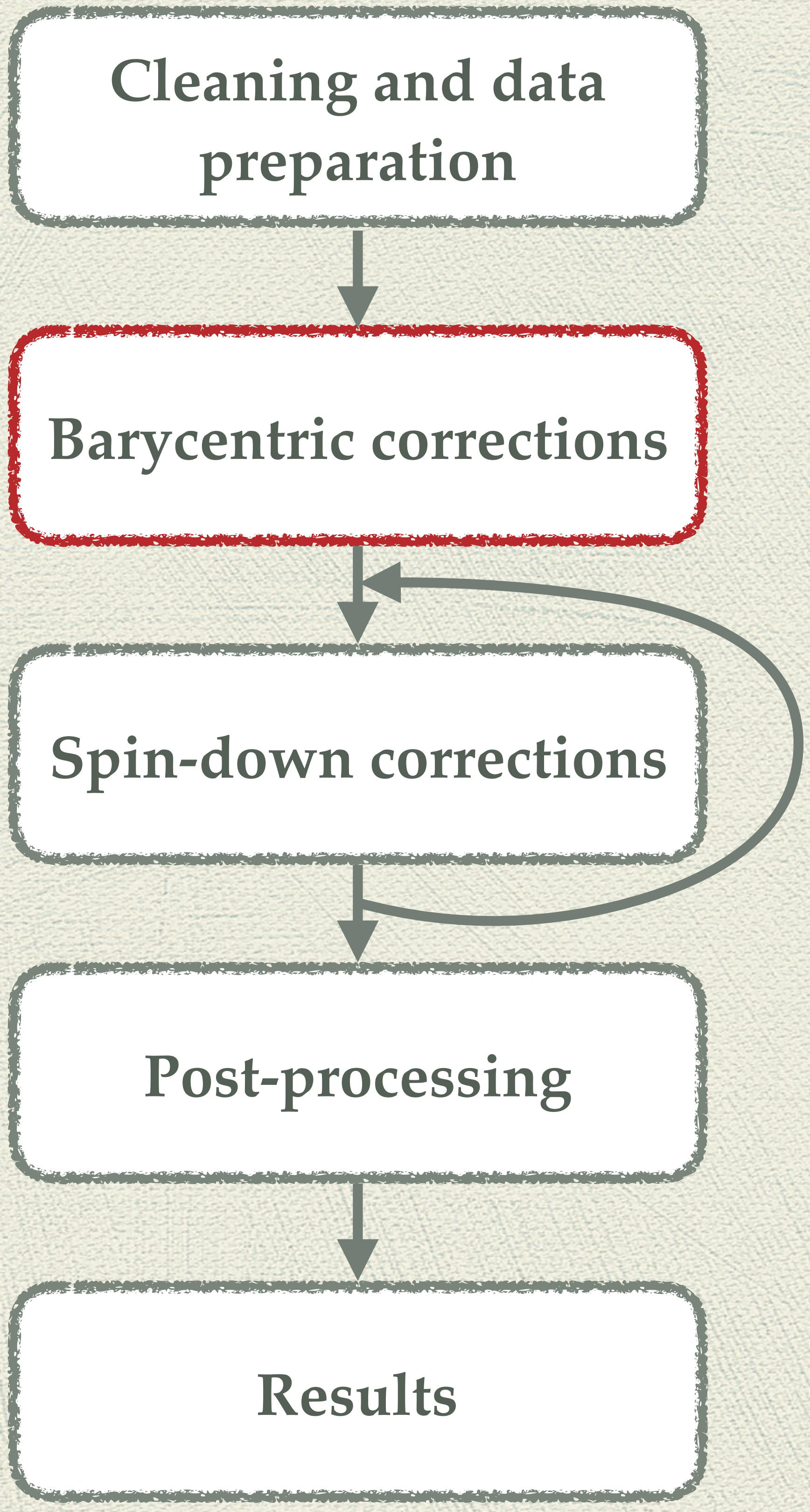
Rigidity parameter

$$\Delta f = 3 \cdot 10^{-5} \left(\frac{f_{\mathrm{gw}}}{100\,\mathrm{Hz}} \right)^3 \left(\frac{b}{10^{-5}} \right) \left(\frac{I/I_{\mathrm{crust}}}{10} \right)$$

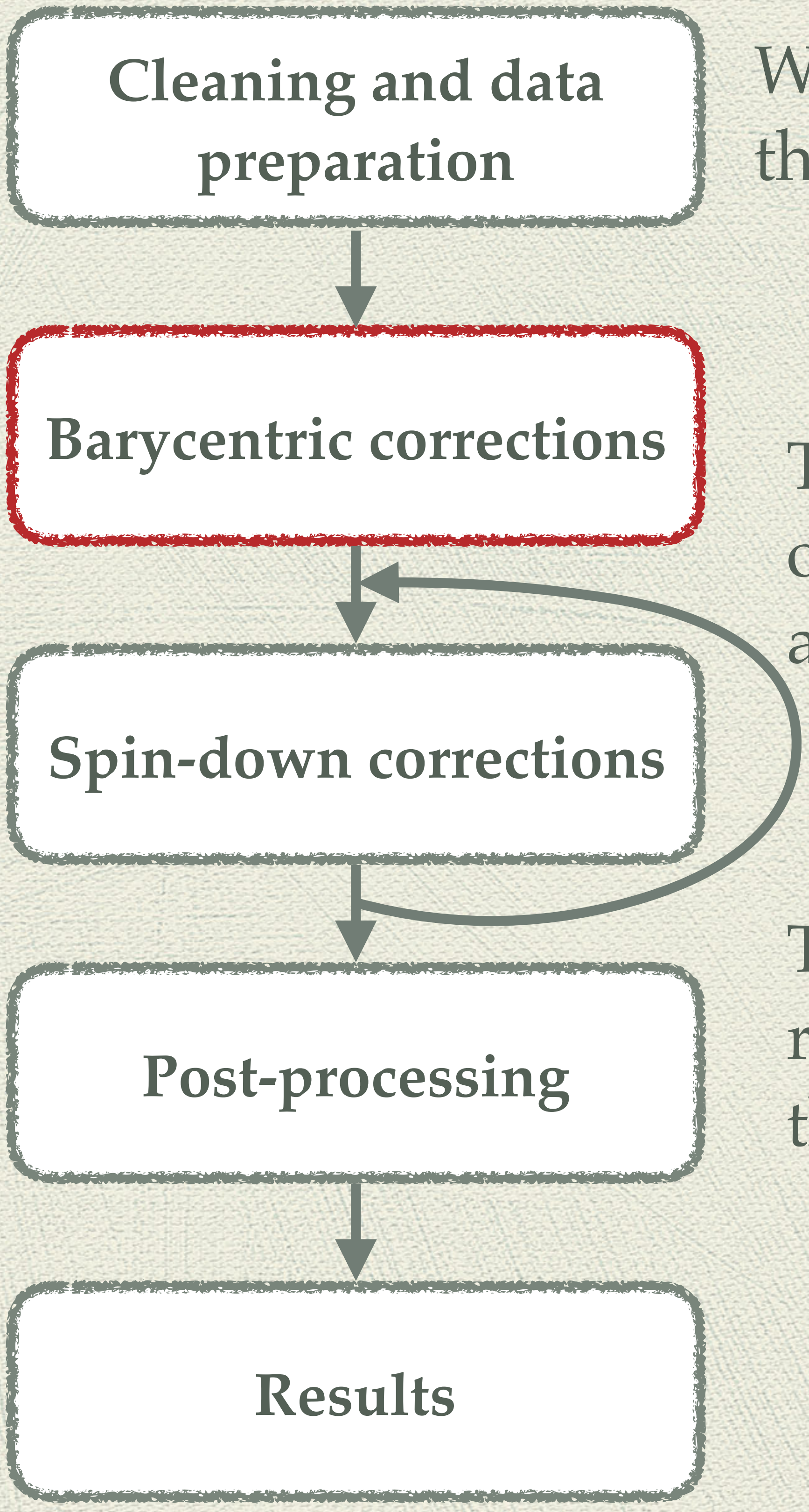
D. I. Jones and N. Andeerson (2002), MNRAS 331 1, 203-220

If we are looking at a freely precessing neutron star we may found a difference in EM pulse emission and GW emission.

Methodology of narrow-band search:



Methodology of narrow-band search:



We want to demodulate the Romer modulation from the signal

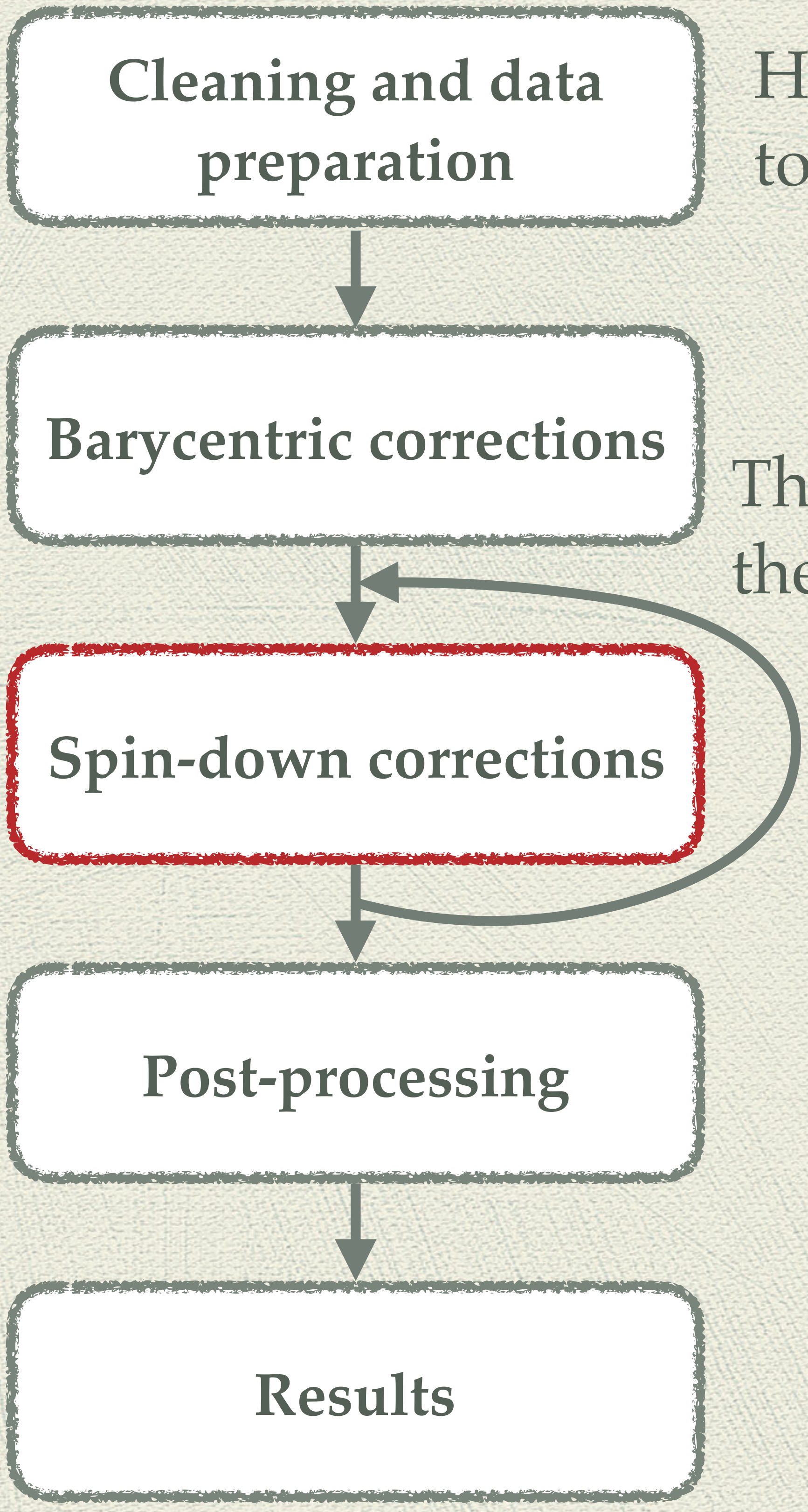
$$f(t) = 2 \cdot \nu_{\mathrm{NS}}(t)\Big(1 + \frac{\vec{v} \cdot \widehat{n}}{c}\Big)$$

This can be done by a non-uniform resampling of our data, defining a new time which takes into account all the possible time delays.

$$\tau = t + \Delta_R + \Delta_E - \Delta_s$$

The process can be though as sampling in a reference frame that does not move with respect to the NS.

Methodology of narrow-band search:



Here we wish to correct the intrinsic modulation due to the spin-down of the source.

$$\nu_{\mathrm{NS}}(t) = \sum_{i=0}^{\infty} \nu_0^{(i)} \frac{(t-t_0)^i}{i!}$$

This is done with the sub-heterodyne, i.e. correcting the phase of our time-series.

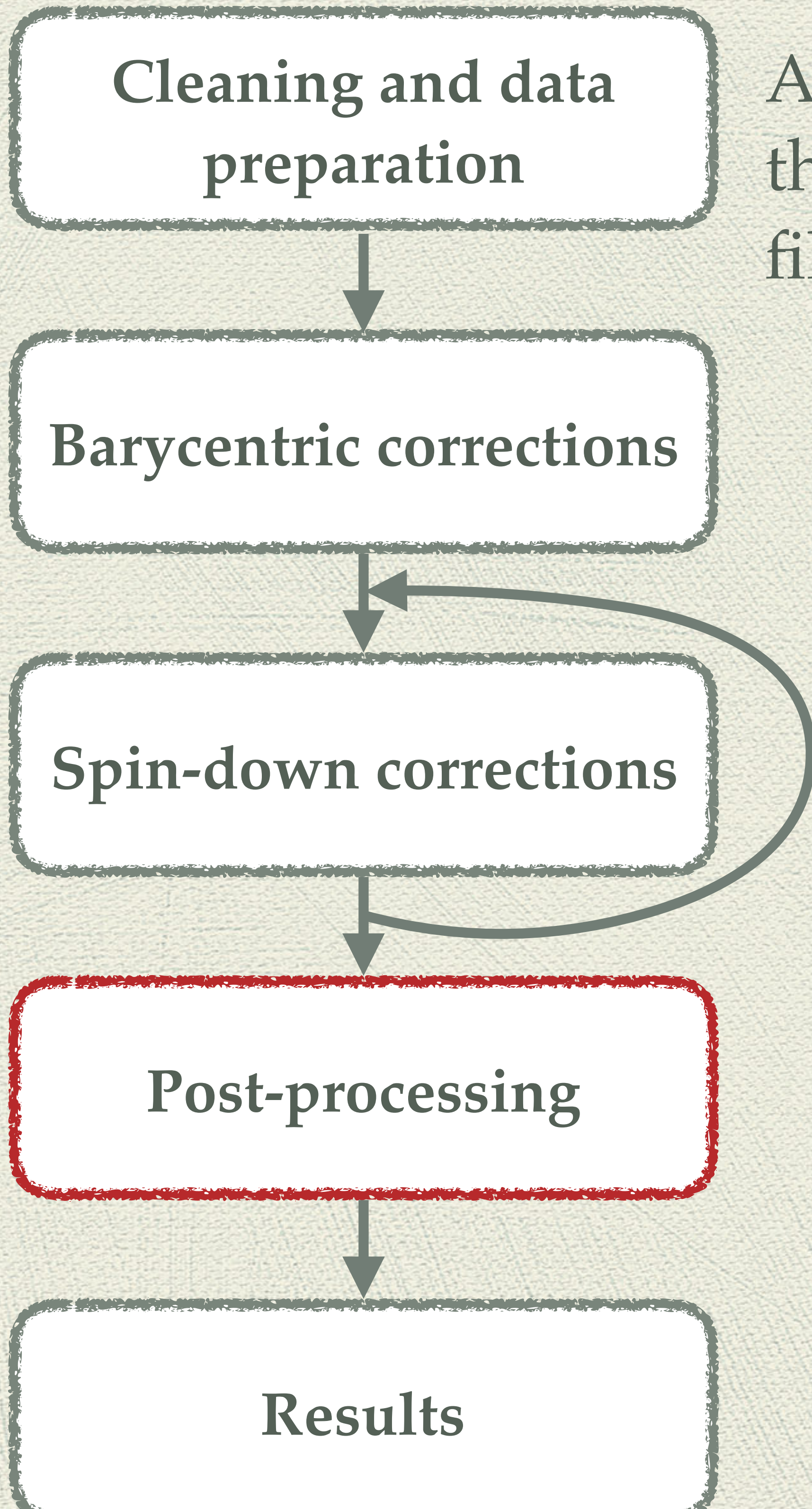
$$\phi_{\mathrm{sd}}(t) = 2\pi \sum_i \frac{2}{(i+1)!} \frac{\partial \nu_{\mathrm{NS}}}{\partial t}\bigg|_{t=t_0} (t-t_0)^{i+1}$$

Heterodyned data

Phase shift

$$h'(t) = h(t) \cdot e^{-i\phi_{\mathrm{sd}}}$$

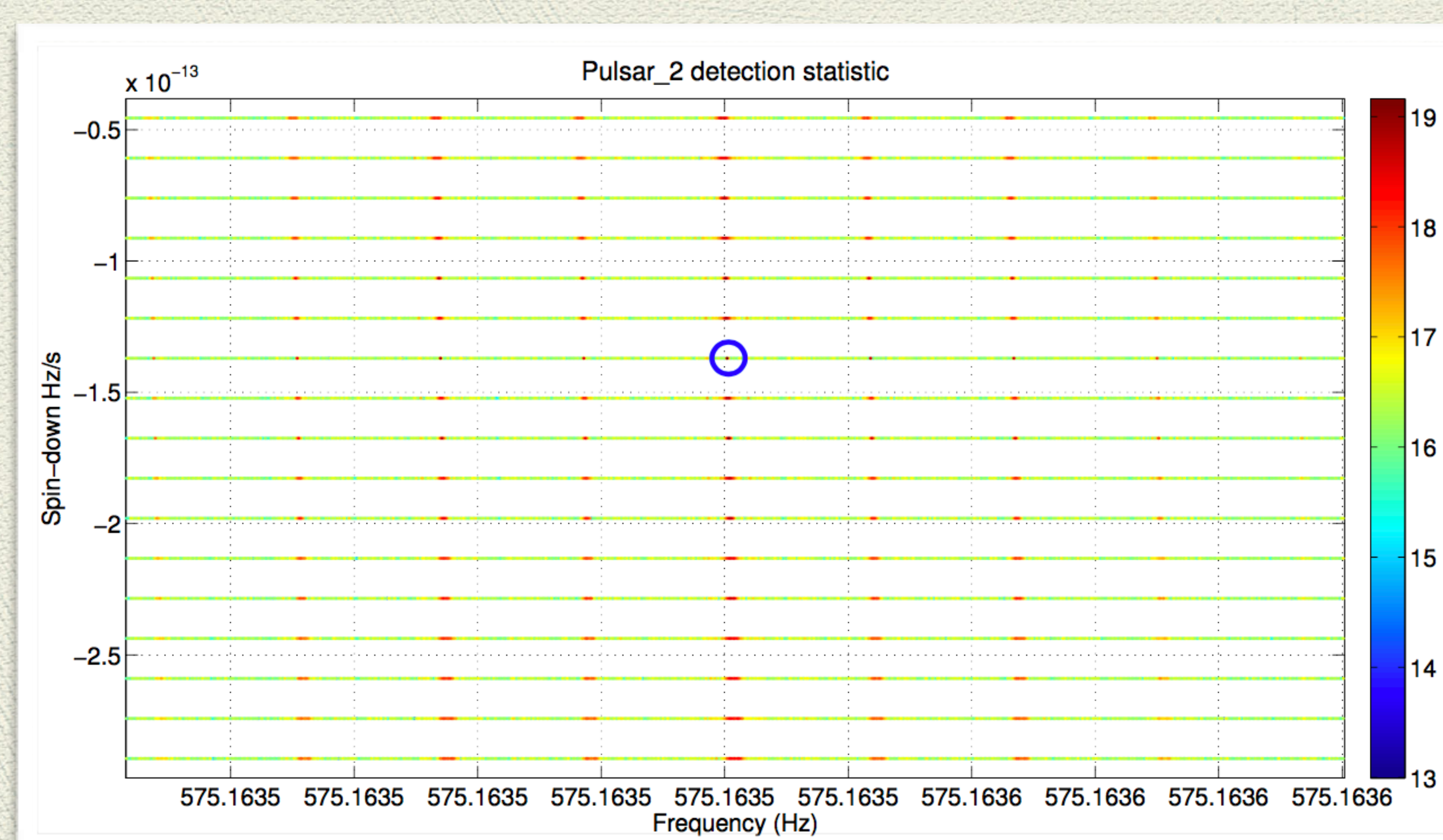
Methodology of narrow-band search:



After all corrections have been applied, we compute the 5-vector's detection statistic using two matched filters.

$$S = \sum_{p}^{+,\times} \frac{\sum_j^{\mathrm{IFO}} \langle x | A_p^j \rangle}{\sum_j^{\mathrm{IFO}} \langle A_p^j | A_p^j \rangle} \sum_j^{\mathrm{IFO}} \langle A_p^j | A_p^j \rangle^2$$

P. Astone et al CQG 27 194016



GW astronomy with Narrow-band

On the method:

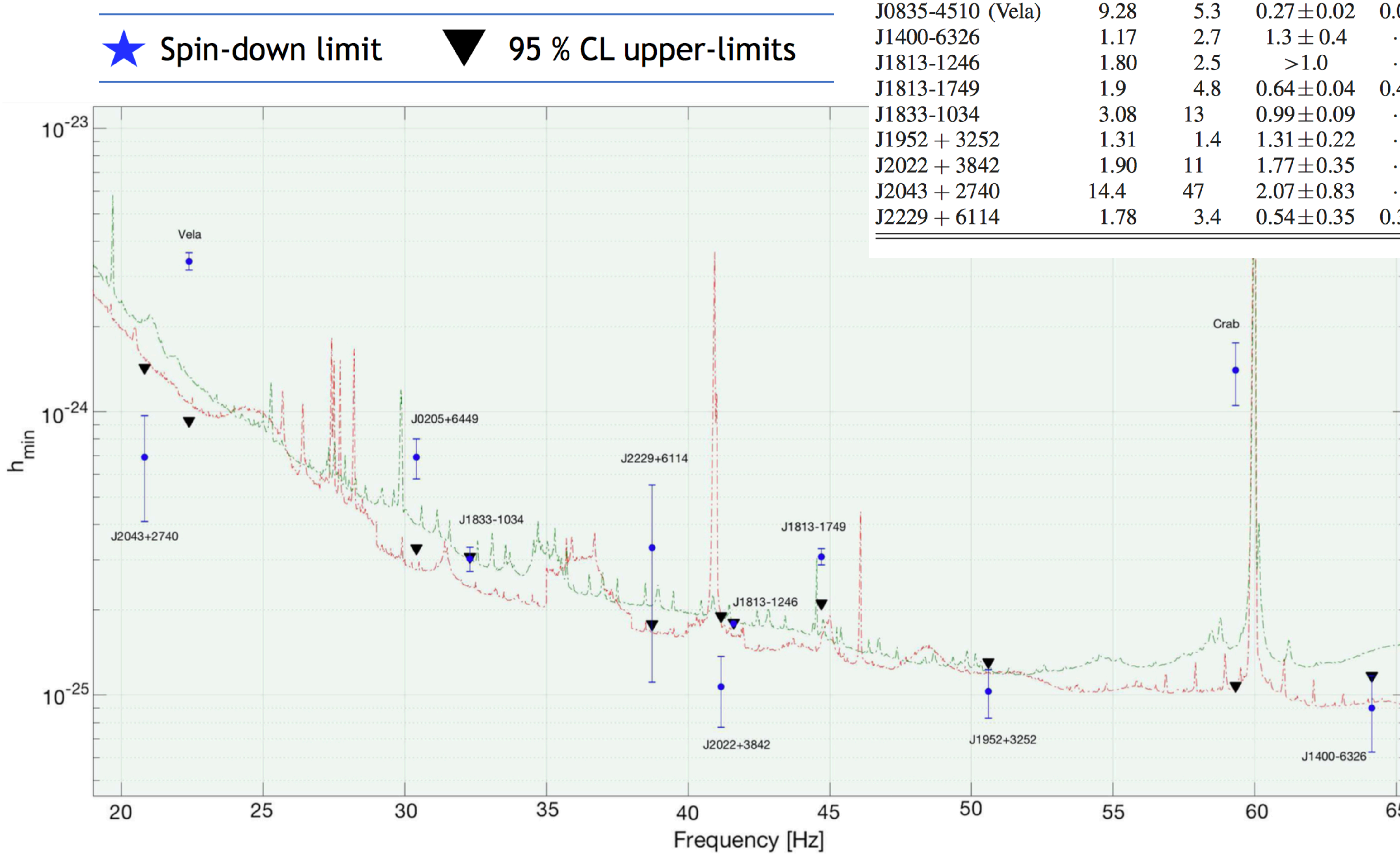
- The method was initially developed in ***P. Astone et al [Phys. Rev. D 89, 062008, 2010],*** and it is able to explore ~ 10^6 waveforms in ~ 330 CPU hours.
- The method was recently extended and optimised for wider space searches granting an improvement on the computational load of ~1000 in ***Mastrogiovanni et al. [CQG 135007, 2017]*** .

Application to LVC data:

- Applied for the first time looking for CW from the Crab and Vela pulsar using the VSR4 run. Explored ~ 10^6 waveforms in ***J. Aasi et al [Phys. Rev. D 91, 022004].***
- After the optimisation the method has been applied to O1-LLO/LHO datasets. 11 pulsars have been targeted (see results later) in ***B. P. Abbot et al. [Phys. Rev. D 96, 122006].***
- The method will be applied also to O2 data targeting ~20 pulsars for which it is expected to beat or closely approach the spin-down limit.

GW astronomy with narrow bands: O1

Name	$h_{\mathrm{ul}} \times 10^{-25}$	$\epsilon_{\mathrm{ul}} \times 10^{-4}$	$h_{\mathrm{ul}}/h_{\mathrm{sd}}$	$\dot{E}_{\mathrm{rot}}/\dot{E}_{\mathrm{GW}}$
J0205 + 6449	3.76	7.7	0.54 ± 0.09	0.29
J0534+2200 (Crab)	1.08	0.58	0.07 ± 0.02	0.005
J0835-4510 (Vela)	9.28	5.3	0.27 ± 0.02	0.07
J1400-6326	1.17	2.7	1.3 ± 0.4	…
J1813-1246	1.80	2.5	>1.0	…
J1813-1749	1.9	4.8	0.64 ± 0.04	0.41
J1833-1034	3.08	13	0.99 ± 0.09	…
J1952 + 3252	1.31	1.4	1.31 ± 0.22	…
J2022 + 3842	1.90	11	1.77 ± 0.35	…
J2043 + 2740	14.4	47	2.07 ± 0.83	…
J2229 + 6114	1.78	3.4	0.54 ± 0.35	0.30



B. P. Abbott et al (2017), Phys. Rev. D 96, 122006

GW astronomy with narrow bands: O1

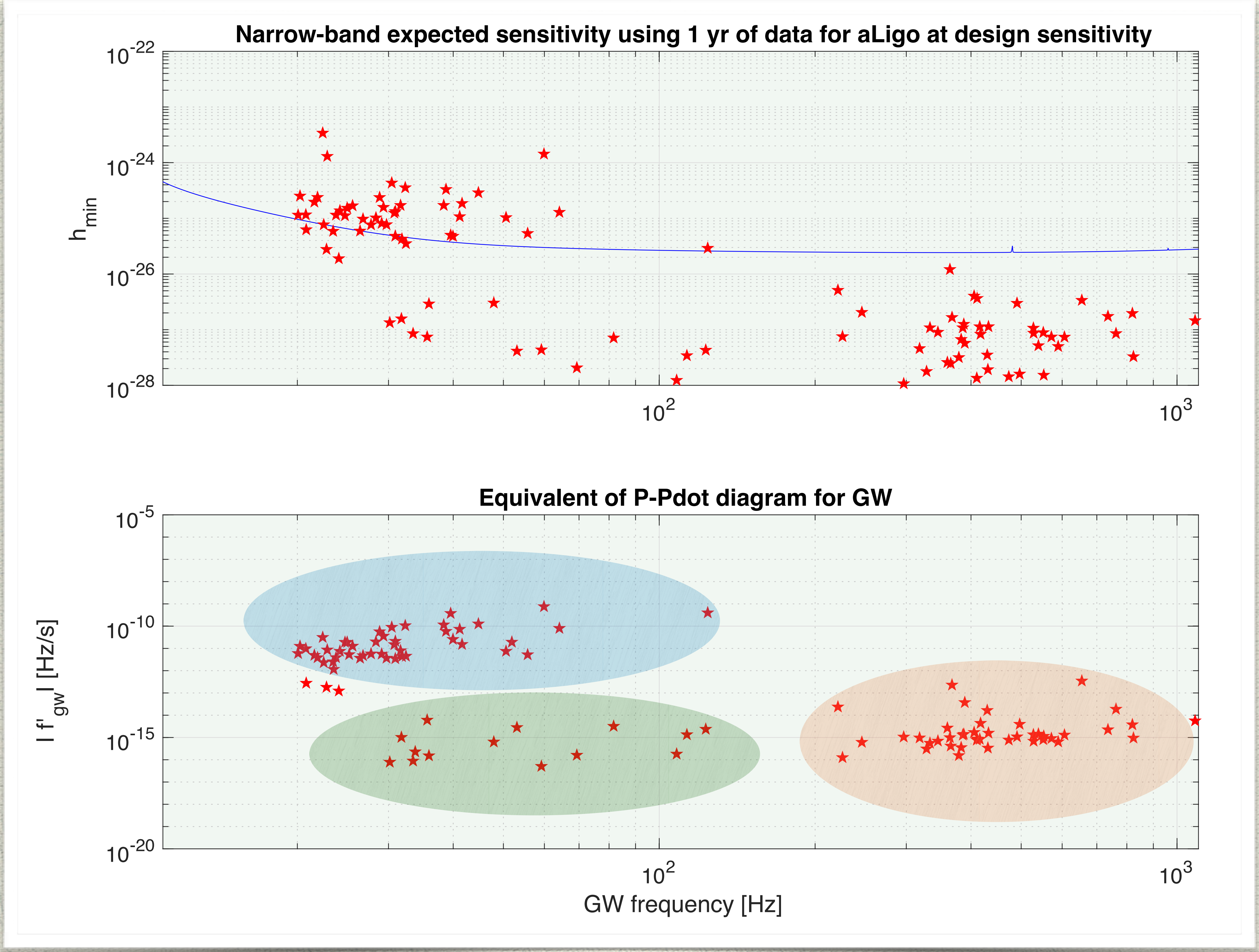
- Beaten the spin-down limit for 4 pulsars: Crab, Vela, J1813-1749 and J2229+6114.
- Improvement on Crab and Vela upper-limits by a factor 7 and 3.5 respectively.
- Spin-down beaten for the first time for J1813-1749. Previously not analysed due to the lack of accurate ephemeris.
- For 4 pulsars (J0205+6449, J1400-6326, J1813-1246 and J1833-1034) a large fraction of the upper-limits were below the spin-down limit.

Name	$\mathbf{f_0}$ [Hz]	$\mathbf{\Delta f}$ [Hz]	$\dot{\mathbf{f}}_0$ [Hz/s]	$\mathbf{\Delta \dot{f}}$ [Hz/s]	$\mathbf{n_f}$	$\mathbf{n_{\dot f}}$
J0205+6449	30.4095820	0.03	$-8.9586 \cdot 10^{-11}$	$1.75 \cdot 10^{-13}$	$3.1 \cdot 10^5$	19
J0534+2200 (Crab)	59.32365204	0.10	$-7.3883 \cdot 10^{-10}$	$1.48 \cdot 10^{-12}$	$1.0 \cdot 10^6$	161
J0835-4510 (Vela)	22.3740981	0.03	$-3.1191 \cdot 10^{-11}$	$6.43 \cdot 10^{-14}$	$3.1 \cdot 10^5$	7
J1400-6326	64.1253722	0.07	$-8.0017 \cdot 10^{-11}$	$1.75 \cdot 10^{-13}$	$7.3 \cdot 10^5$	19
J1813-1246	41.6010333	0.04	$-1.2866 \cdot 10^{-11}$	$6.43 \cdot 10^{-14}$	$4.1 \cdot 10^5$	7
J1813-1749	44.7128464	0.05	$-1.5000 \cdot 10^{-10}$	$3.03 \cdot 10^{-13}$	$5.2 \cdot 10^5$	33
J1833-1034	32.2940958	0.04	$-1.0543 \cdot 10^{-10}$	$2.11 \cdot 10^{-13}$	$4.1 \cdot 10^5$	23
J1952+3252	50.5882336	0.05	$-7.4797 \cdot 10^{-12}$	$6.43 \cdot 10^{-14}$	$5.2 \cdot 10^5$	7
J2022+3842	41.1600845	0.04	$-7.2969 \cdot 10^{-11}$	$1.60 \cdot 10^{-13}$	$4.1 \cdot 10^5$	17
J2043+2740	20.8048628	0.05	$-3.4390 \cdot 10^{-11}$	$6.43 \cdot 10^{-14}$	$5.2 \cdot 10^5$	7
J2229+6114	38.7153156	0.06	$-5.8681 \cdot 10^{-11}$	$1.19 \cdot 10^{-13}$	$6.2 \cdot 10^5$	13

B. P. Abbott et al (2017), Phys. Rev. D 96, 122006

GW astronomy with narrow bands: >=O2

Pulsars for which we expect to put interesting upper-limits (single IFO)



Energetic radio pulsars

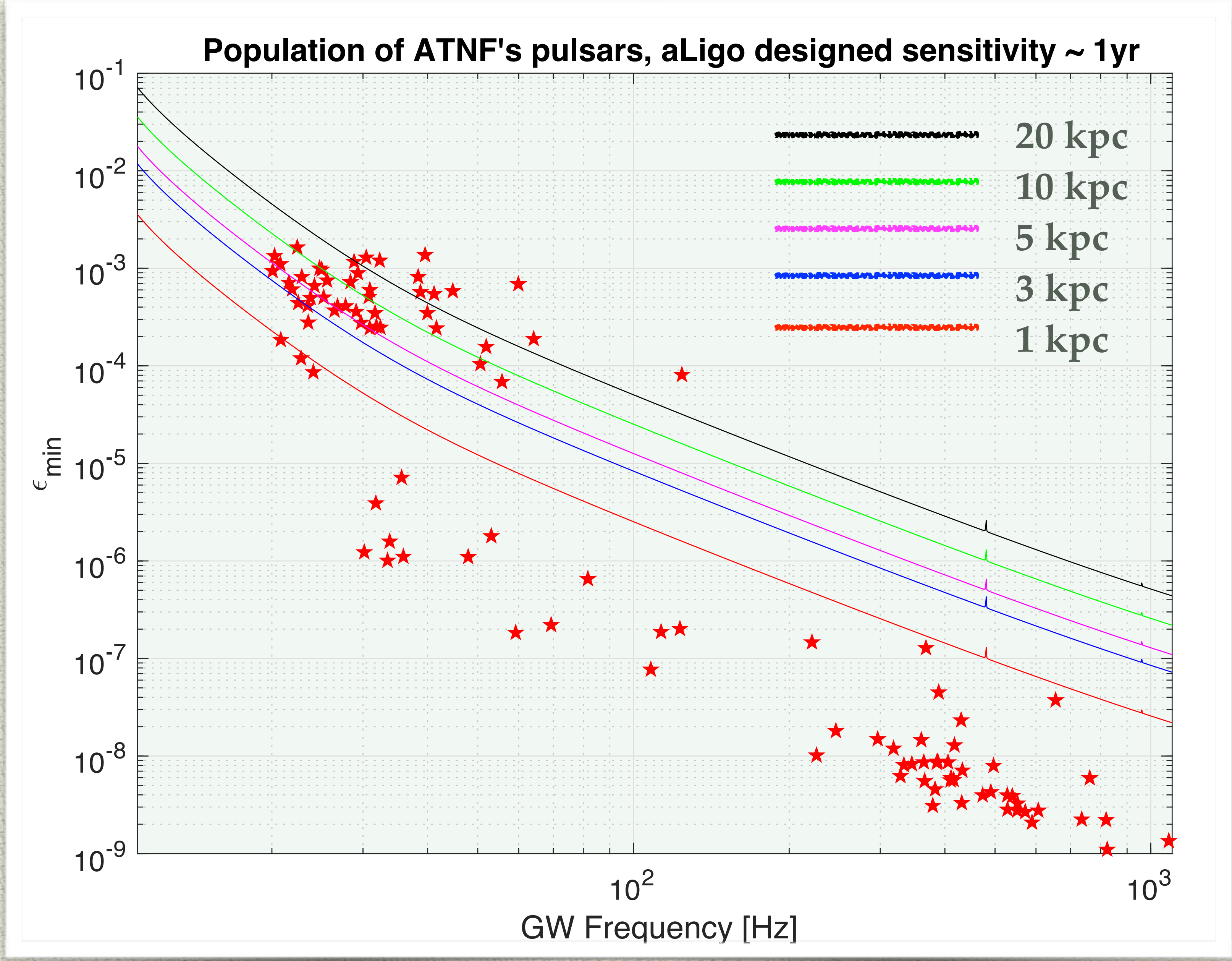
Transient radio pulsars

Recycled or millisecond pulsars

*Pulsars' parameters from ATNF catalogue v1.58

GW astronomy with narrow bands: >=O2

Minimum ellipticity detectable by LIGO at designed sensitivity using 1 yr of full-coherent integration and a single (IFO)



*Pulsars' parameters from ATNF catalogue v1.58

Conclusions

- Gravitational waves detectors are approaching their design configuration.
- With more sensitive and longer runs, data analysis pipelines require very accurate template waveforms.
- Ephemerides from EM partners may not be enough for the application of just 1 template.
- Narrow-band searches can overcome the computational load of the analysis while offering a sensitivity comparable to a full matched filter technique.
- Combining coherently several IFOs will improve the search sensitivity.
- Narrow-band searches may play an important role in gravitational-waves astronomy.