Ecole de Physique des Astroparticules

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OHP, Saint Michel l'Observatoire

Search for continuous gravitational wave signals

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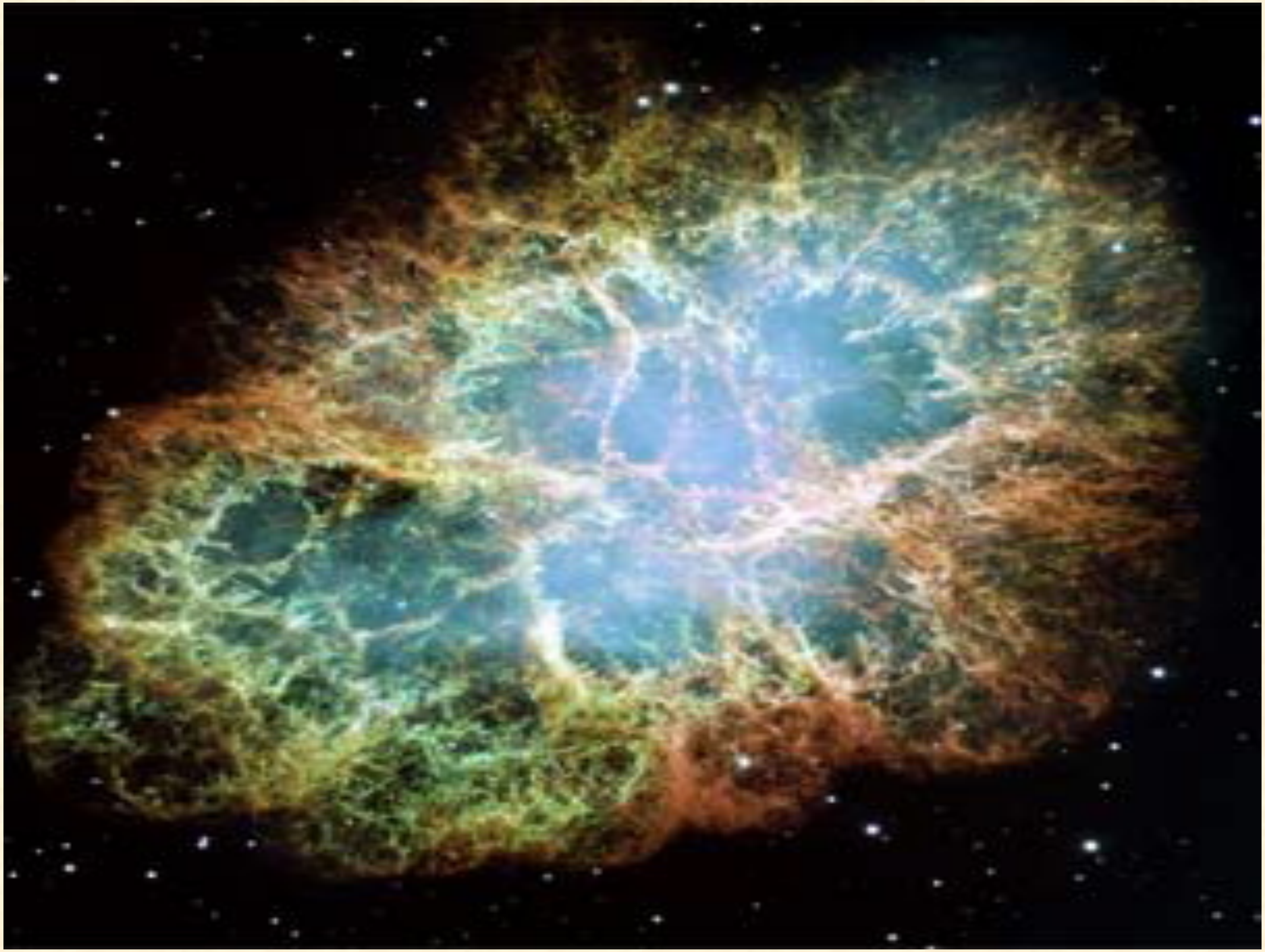
Outline

- Source characterization
- Signal characterization
- Basics of analysis methods
- Detection and Upper limits
- Link to electromagnetic astronomy
- Some recent results and their astrophysical interpretation
- Expectations from Advanced detectors era and beyond

Source characterization



- ✧ We classify as *continuous* those GW signals with duration much longer than the typical observation time of detectors.

- ✧ CW are typically emitted by sources with a mass quadrupole moment varying in time in a quasi-periodical way.

- ✧ For Earth-bound detectors the most interesting sources of CW involve *deformed* neutron stars (NS), isolated or in binary systems.

We know that potential sources of CW exist: 2000+ NS are observed (mostly pulsars) and $O(10^9)$ are expected to exist in the Galaxy.

We do not know the typical amplitude of emitted signals.

To emit CW a NS must have some degree of asymmetry, i.e. an ellipticity:

- deformation due to elastic stresses or magnetic field;
- deformation due to matter accretion (e.g. LMXB);
- free precession around rotation axis;
- excitation of long-lasting oscillations (e.g. r-modes); …

For isolated NS, the maximum foreseen ellipticity depends on the star crust physics, the matter equation of state at supra-nuclear density and on the deformation mechanism.

$\varepsilon_{max} \sim 10^{-5}$ for a 'standard' NS (fluid core)

$\varepsilon_{max} \sim 10^{-4}$-$10^{-3}$ for 'exotic' stars (solid phase in the core)

$\varepsilon_{max} \sim 10^{-4}$-$10^{-3}$ in presence of strong magnetic field and a superconducting core

$\varepsilon \sim 10^{-12} (B/10^{12}\,G)^2$ minimal deformation from mag. field

$\varepsilon \sim 10^{-6}$ expected for large toroidal fields

But we do not know which are the **typical** values.

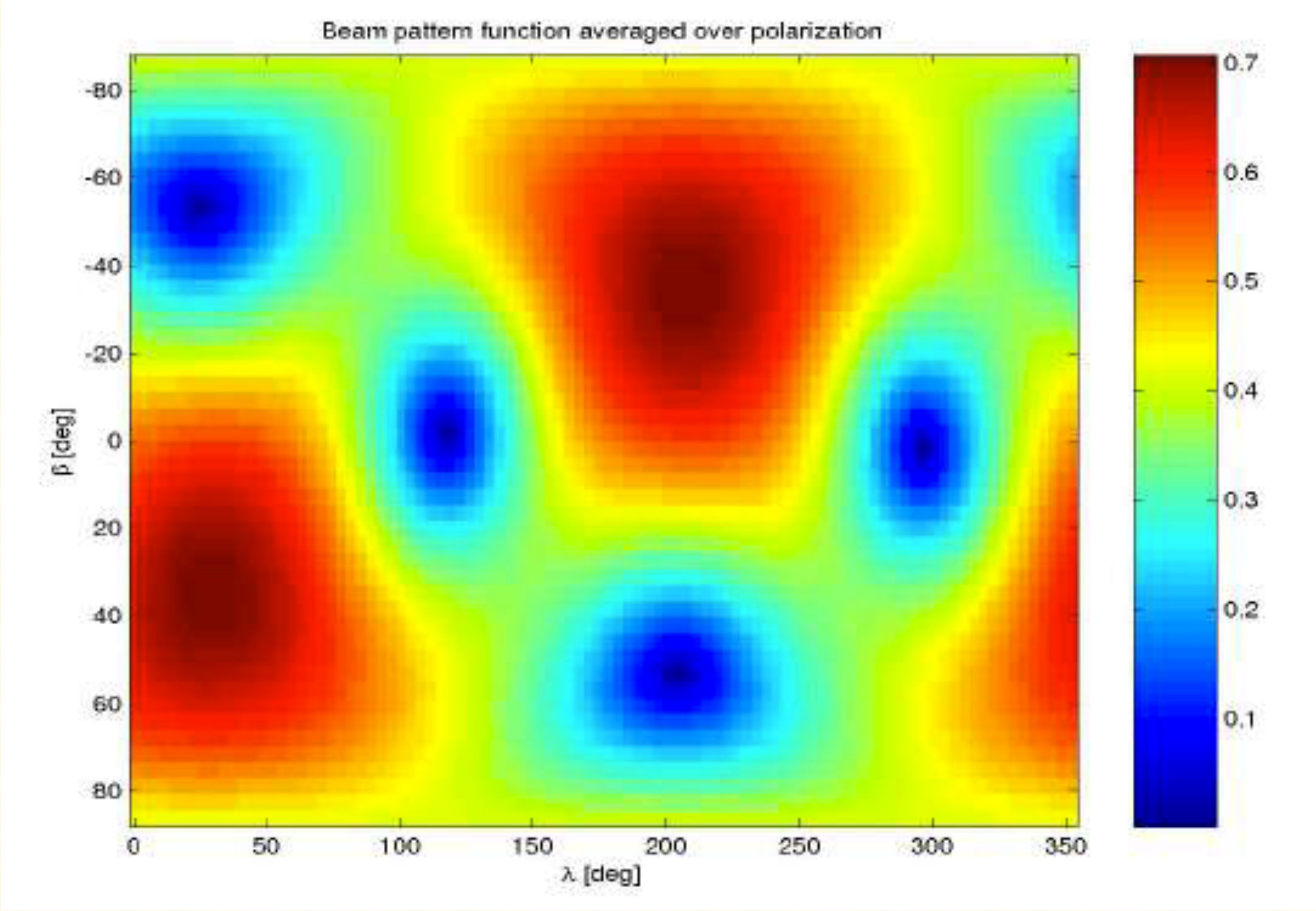
Note that 10^{-5} corresponds to a 'mountain' ~10 cm high!

What could detections tell us?

- NS internal structure (EOS, viscosity)
- Inner magnetic field intensity
- Mechanism operating in accreting systems
- Interplay between inner superfluid and crust
- NS demography (e.g. existence of a *gravitar* population)

- Non-detections (i.e. upper limits) **cannot** be used to exclude some equations of state…
- … But can constrain internal magnetic field

CW signal characterization



The signal emitted by a spinning neutron star is nearly monochromatic, with a frequency slowly varying in time. The signal amplitude depends on the frequency, the ellipticity, the distance and the star moment of inertia.

The details depend on the specific emission mechanism.

E.g. for a tri-axial neutron star rotating around a principal axis of inertia, the signal frequency is $f=2f_{rot}$ and the signal amplitude can be parametrized as

$$\mathbf{h}(t) = h_+(t)\,\mathbf{e}_+ + h_\times(t)\,\mathbf{e}_\times$$

$$\begin{aligned} h_+(t) &= h_0 \left(\frac{1+\cos^2\iota}{2}\right)\cos\Phi(t) \\ h_\times(t) &= h_0 \cos\iota \sin\Phi(t). \end{aligned}$$

$$h_0 \cong 10^{-27}\left(\frac{I_{zz}}{10^{38}\,kg\cdot m^2}\right)\left(\frac{10kpc}{d}\right)\left(\frac{f}{100Hz}\right)^2\left(\frac{\varepsilon}{10^{-6}}\right)$$

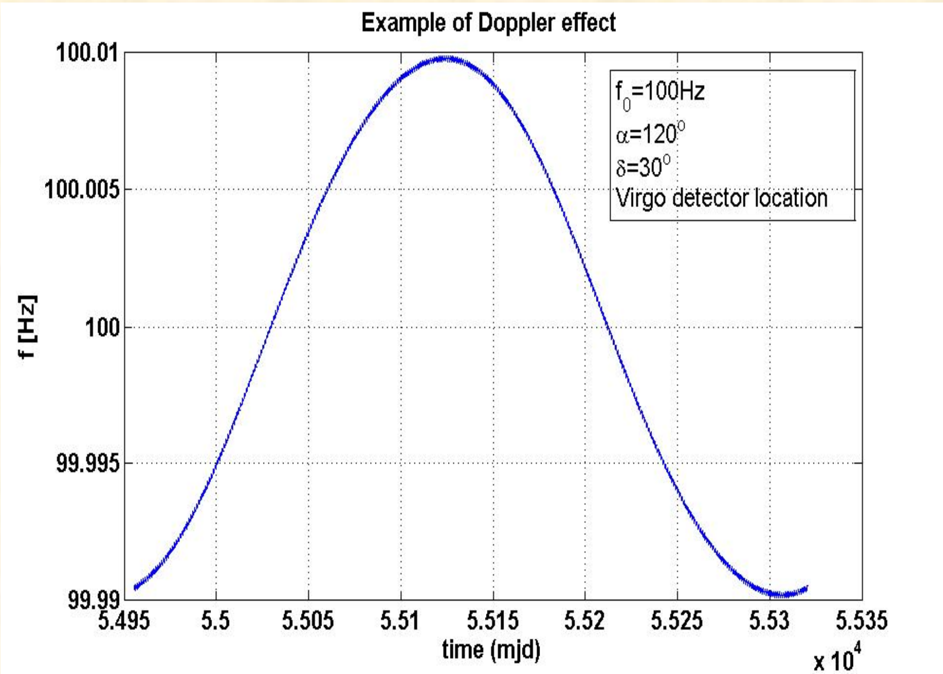
Expected signals are not exactly monochromatic at the detector. Frequency (and phase) are modified by various effects:

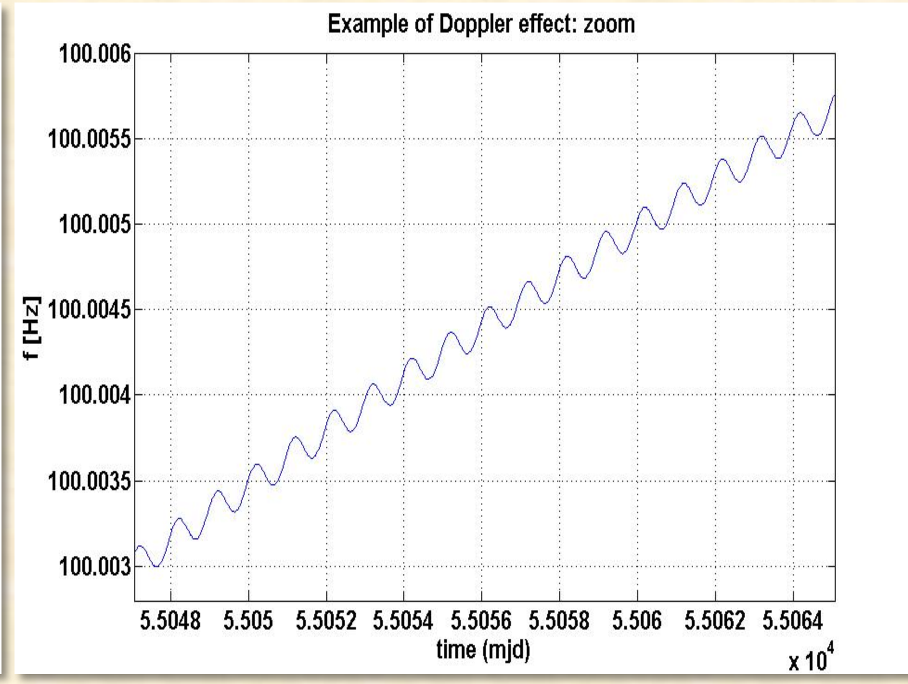
- (Non-relativistic) **Doppler effect** due to the detector motion

$$f(t) = f_0\left(1 + \frac{\vec{\mathbf{v}}\cdot\hat{n}}{c}\right), \quad \vec{\mathbf{v}} = \vec{\mathbf{v}}_{rev} + \vec{\mathbf{v}}_{rot}$$

$|\vec{\mathbf{v}}_{rev}| \approx 30 km/s$ (directed along the ecliptic; period of 1 sidereal year)

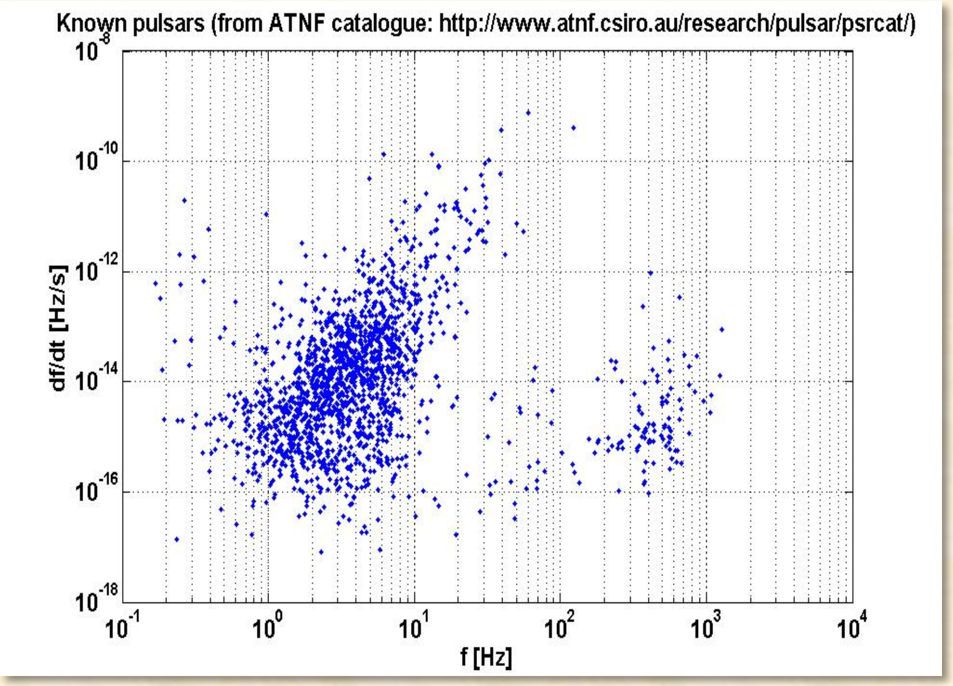
$|\vec{\mathbf{v}}_{rot}| \approx 0.32 km/s$ (at 45 deg latitude; tilted by ~23.4 degree respect to the orbital plane; period of 1 sidereal day)





For sources in binary systems there are further terms in the Doppler formula due to the orbital motion.

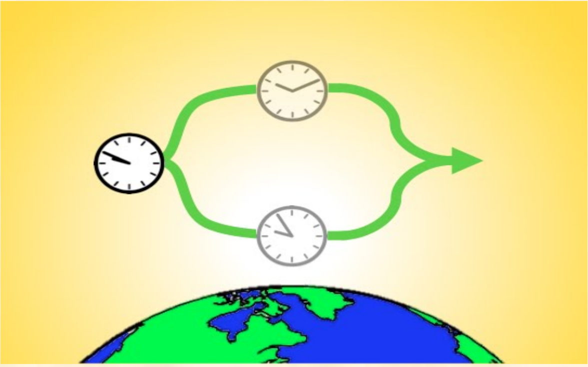
- **Source spin-down**: the rotation frequency, and then the emitted signal frequency, slowly decreases due to the energy loss of the source (EM, GW hopefully…)

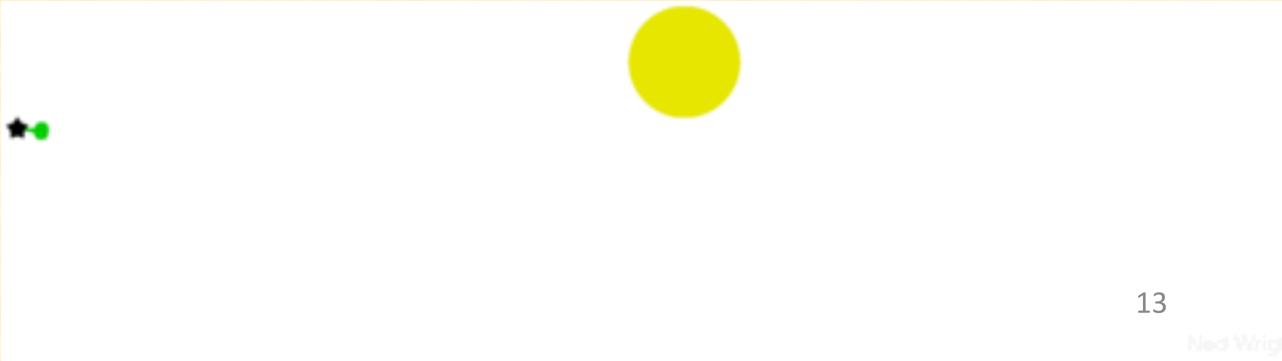


There are also smaller effects which, however, can be necessary to take into account when making coherent analysis over long times:

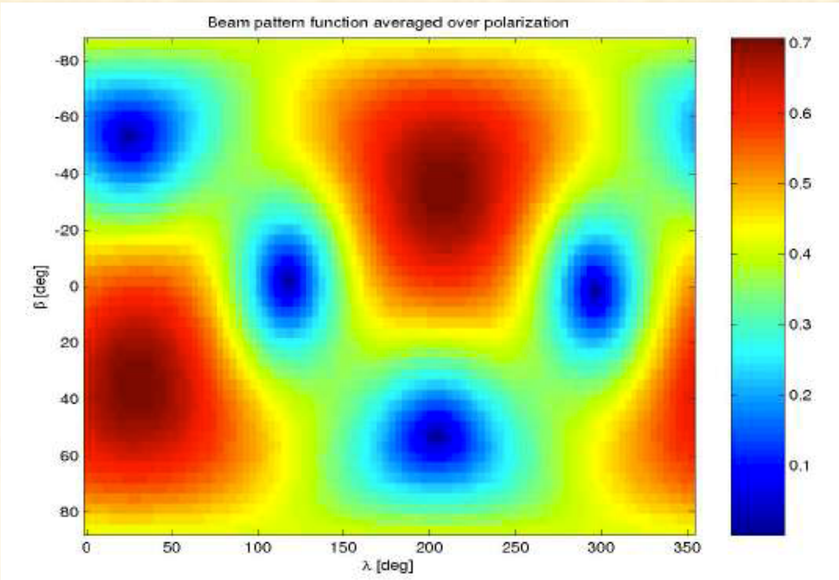
- **Einstein delay**: it is the time delay caused by the detector motion (SR) and the gravitational redshift due to the bodies in the Solar system (or the binary companion)

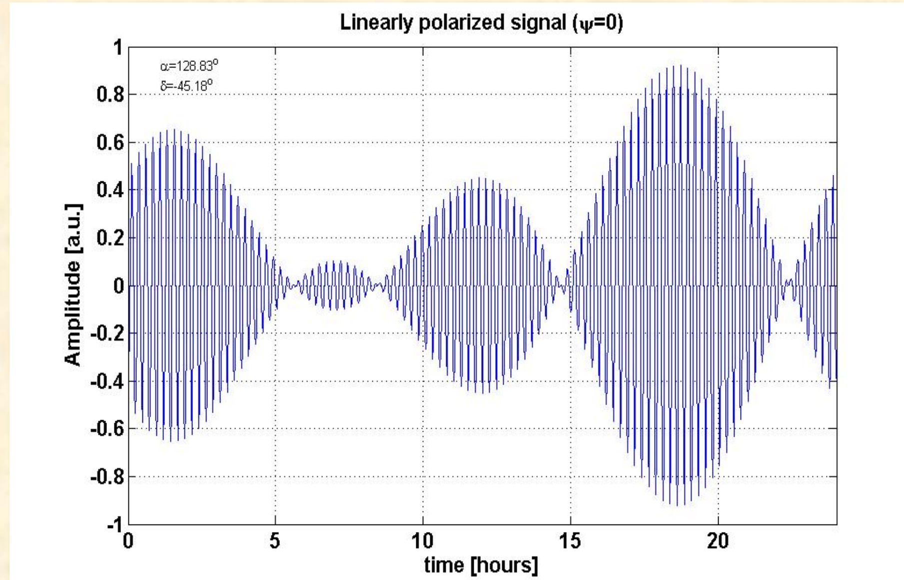
- **Shapiro delay**: it is the time delay due to the curvature of space-time caused by the masses in the Solar system (or binary companion)





Moreover, the signal at the detector is amplitude and phase modulated by the non-uniform antenna sensitivity pattern.

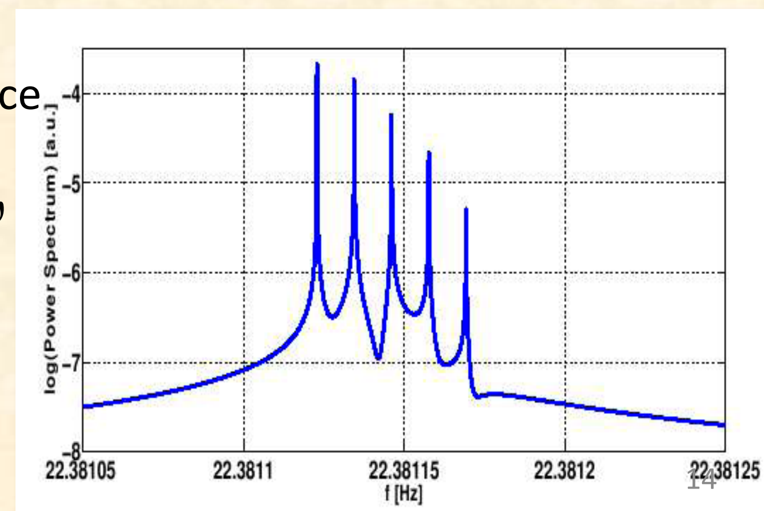




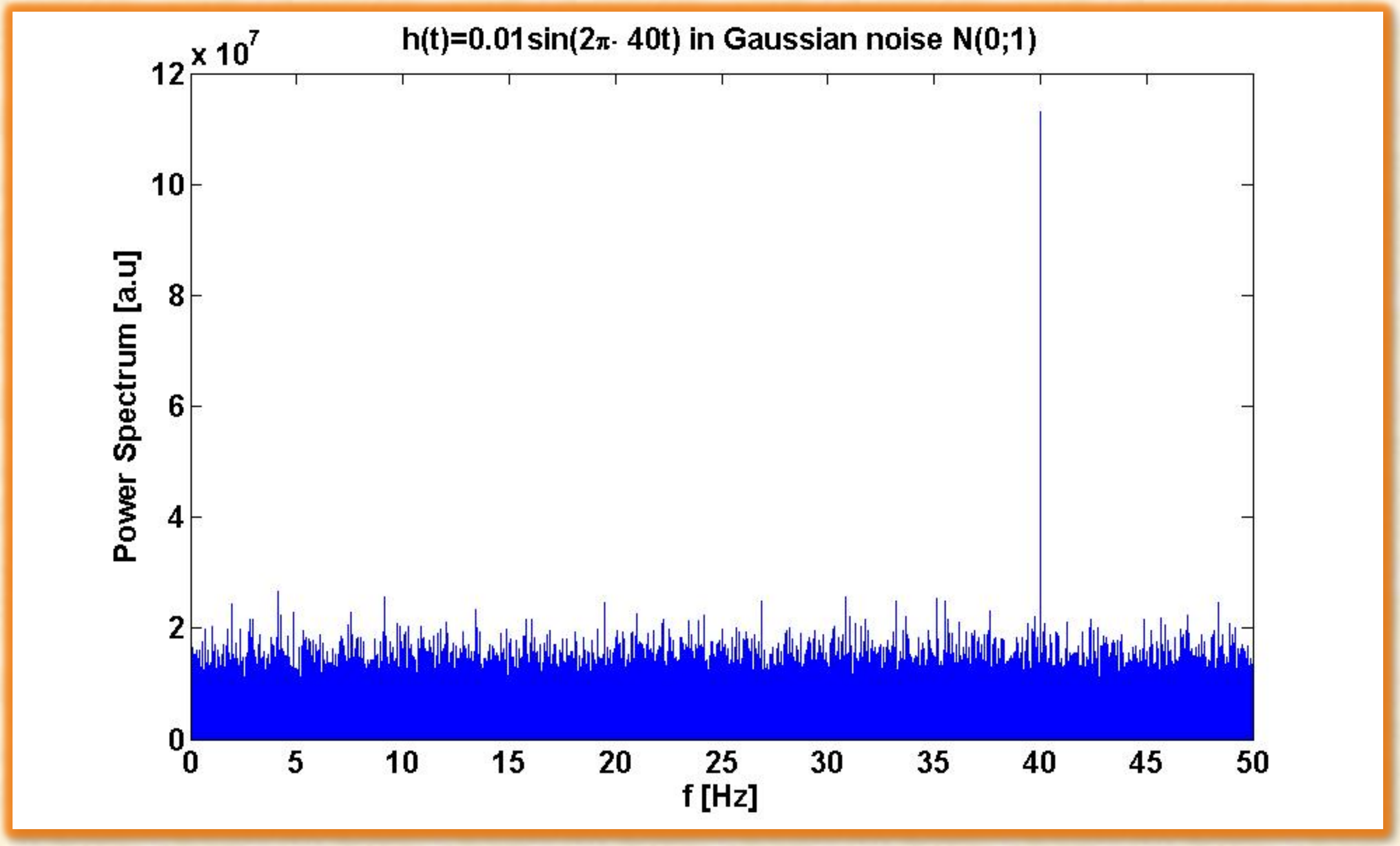
$$h(t) = h_+ F_+ + h_\times F_\times$$

depend on the source position and wave polarization angle ψ

→ There is a split of the power of a monochromatic signal among five frequencies.



Data analysis basics



The best sensitivity of current detectors corresponds to a strain of $\sim 10^{-21}$

On the other hand for a source with f_0=100 Hz, $\varepsilon=10^{-5}$, d=1 kpc we find $h_0 \sim 10^{-25}$:

$$h_0 \cong 10^{-27}\left(\frac{I_{zz}}{10^{38}\,kg\cdot m^2}\right)\left(\frac{10kpc}{d}\right)\left(\frac{f}{100Hz}\right)^2\left(\frac{\varepsilon}{10^{-6}}\right)$$

→ signals are deeply buried into the noise!

BUT

→ signal duration very long respect to typical observation times! → Signal-to-noise ratio increases with time

→ signals have very specific pattern in the time-frequency plane → This helps also in rejecting noise artifacts

This can be exploited to develop data analysis strategies able to detect such kind of signals and to estimate their parameters.

We distinguish two main kinds of analysis:

- ✧ Search for known neutron stars (e.g. pulsars) for which position and rotational parameters are known with high accuracy → coherent methods (like Bayes factor or "matched filter")

- ✧ Blind searches for unknown NS → incoherent methods

(Plus intermediate cases...)

For each kind several implementations, based on different algorithms, exist.

Schematically, a typical search consists of 3 main steps:

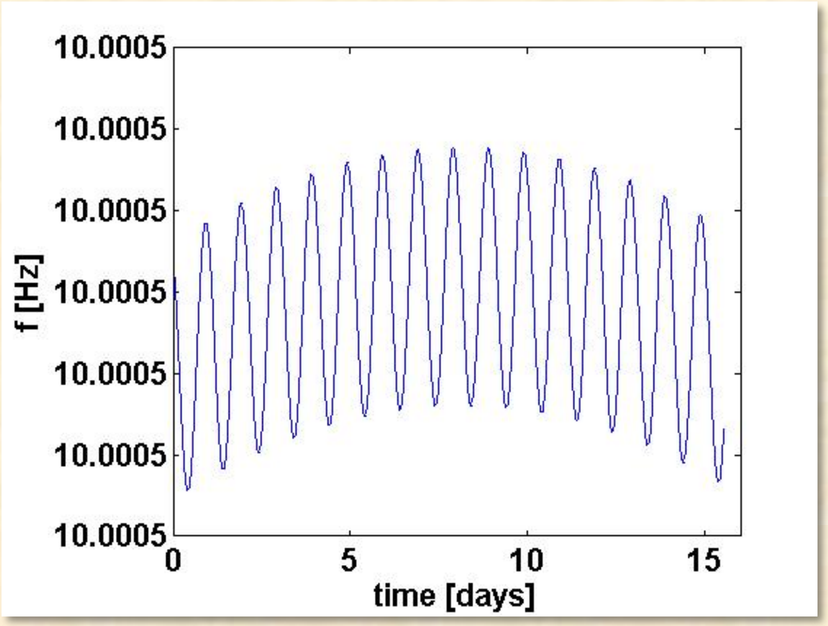
- **Data reduction**, in which the starting data are processed in order to increase the SNR of a signal respect to the background noise;

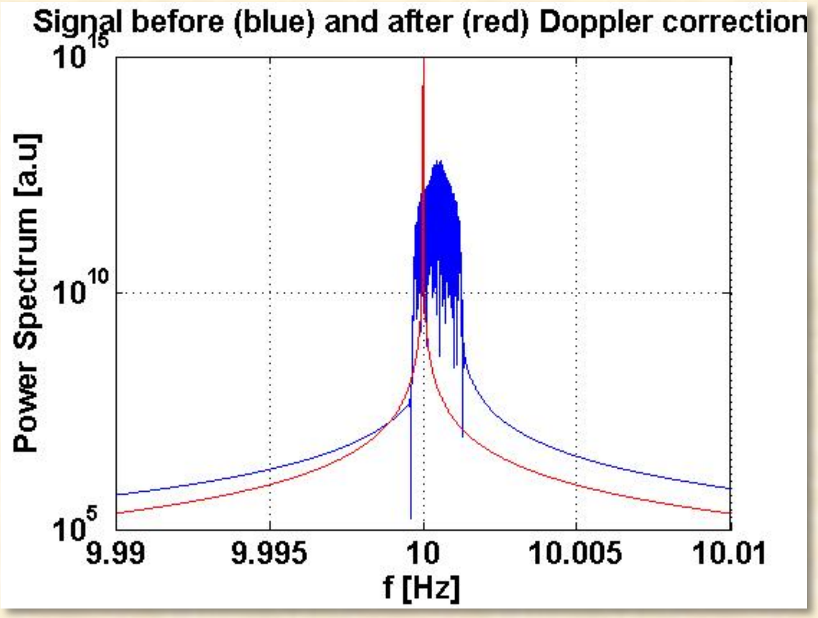
- **Detection assessment**;

- **Signal parameter estimation** (in case of detection) or **upper limit computation**.

Each analysis pipeline can be characterized by its **sensitivity**: the minimum signal amplitude detectable in a given dataset with a given statistical confidence.

Data reduction consists in properly taking into account Doppler, spin-down (+ Einstein delay and Shapiro effect), and signal amplitude modulation to increase the search sensitivity.





Not doing this properly causes a smearing of the signal which reduces the detection probability.

There are different ways of taking into account the frequency modulations. A nice way, often also used in EM pulsar searches, is to properly re-sample the data.

The received signal phase is affected by the various effects. E.g. for the Doppler:

$$\varphi(t) = \varphi_0 + \int_{t_0}^{t} f(t')dt' = \varphi_0 + \int_{t_0}^{t} f_0\left(1 + \frac{\vec{\mathbf{v}}(t')\cdot\hat{n}}{c}\right)dt'$$

We can introduce a new time variable in which the signal phase is that of a monochromatic signal:

$$\varphi(\tilde{t}) = \varphi_0 + 2\pi f_0 \tilde{t}$$

$$\tilde{t} = t + \frac{\hat{n}}{c}\cdot\left[\vec{r}(t) - \vec{r}(t_0)\right]$$

Romer delay

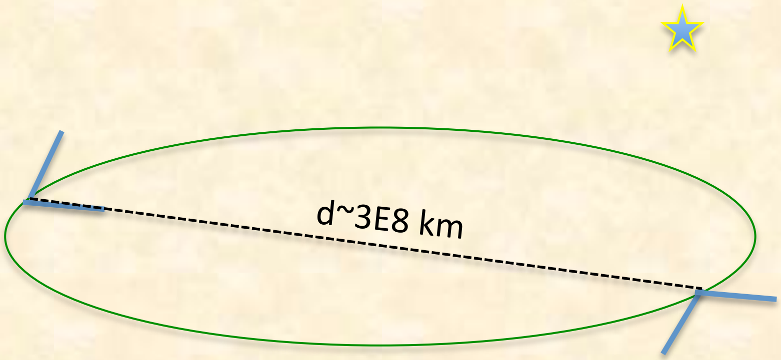
Similarly for spin-down:

$$\hat{t} = t + \frac{\dot{f}_0}{2f_0}(t-t_0)^2 + \frac{\ddot{f}_0}{6f_0}(t-t_0)^3 + \ldots$$

This implies we accurately know source position and rotational parameters! → *targeted* searches
Or we need to apply the corrections for many trial values of the parameters. → *directed* or *semi-blind* or *blind* searches

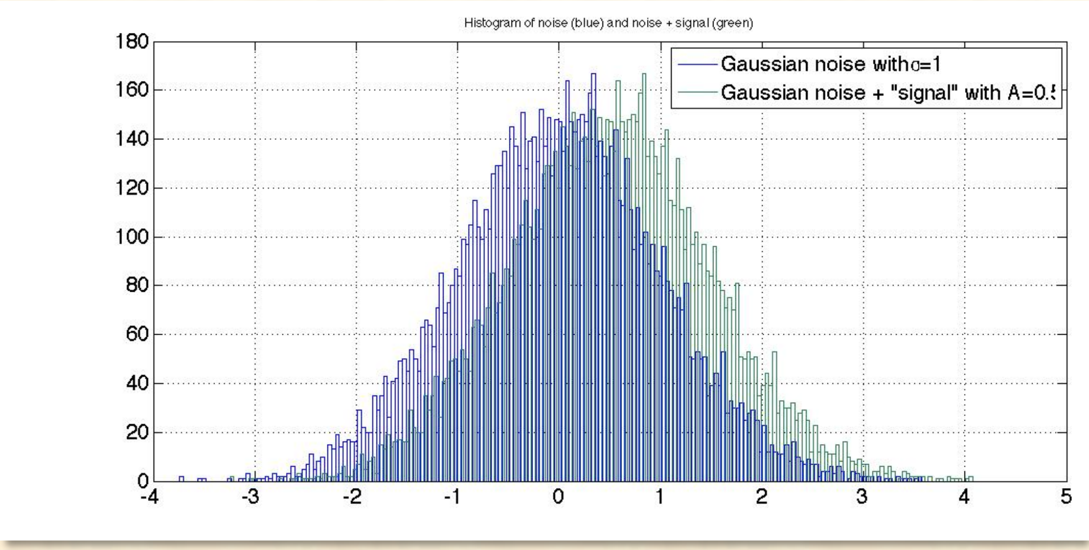
Integrating over a long time allows to pin down the NS parameters to extremely high accuracy **even with a single detector and even for sources with no EM counterpart**:

in practice the detector makes a very large baseline network with itself



At some point also the NS intrinsic transverse velocity must be taken into account.

On a general ground, the **detection assessment** is based on the fact that the probability distribution of some quantities is different if the data at hand consist of noise only or if they contain also a signal.



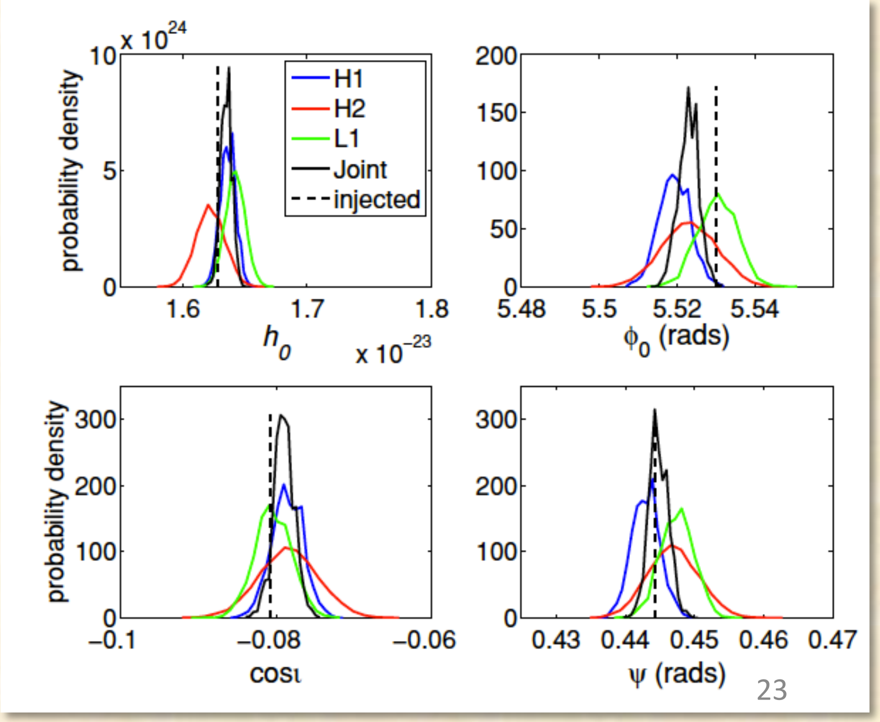
What quantity is better to consider can depend on the specific case and is even a matter of ‘philosophical’ debate (Bayesian vs frequentist struggle!).

E.g. in the **Bayesian** framework the posterior probability distribution of the signal amplitude (and other parameters) is computed, given the data and all the available prior information.

Signal detection corresponds to a distribution peaked significantly off zero.

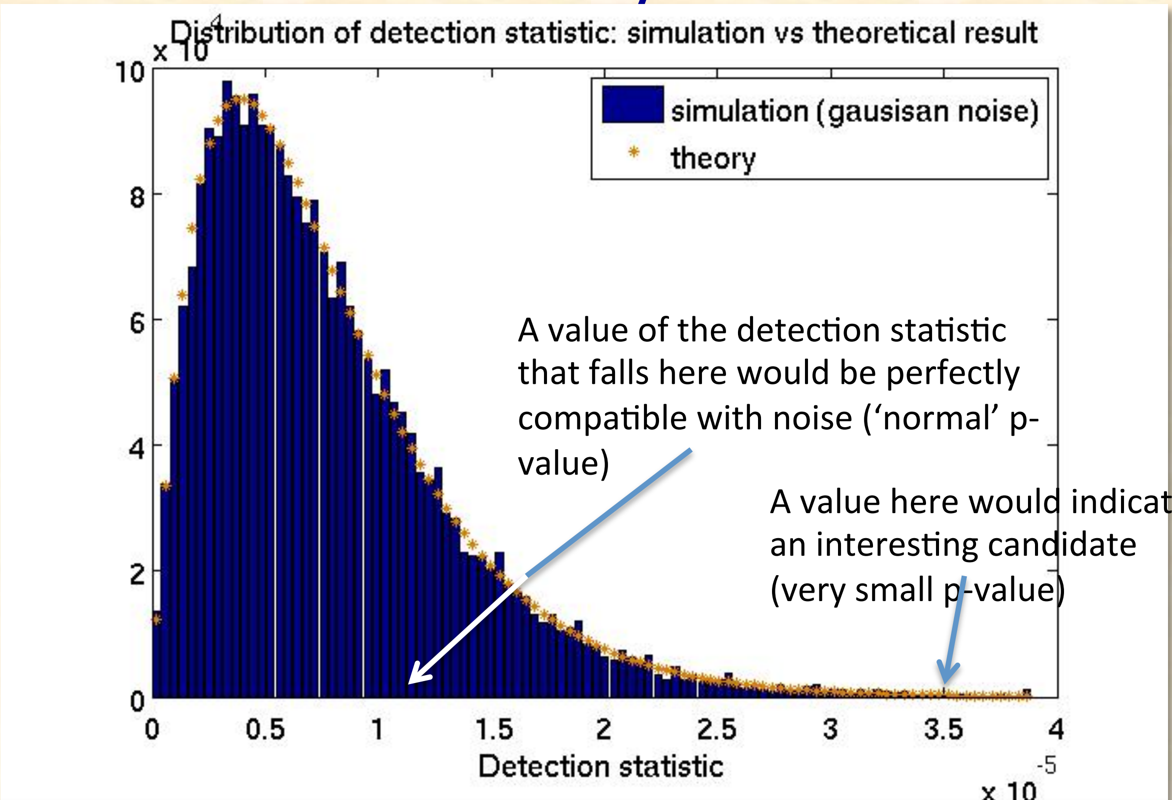
The position if the peak gives the parameter estimatation.

Hardware injection in S5 data (Abbott et al, Apj, 2010)



In the **frequentist** framework a *detection statistic* , which is a function of the data, is computed and used to assess detection significance by computing the *p-value* which measures the agreement with its noise-only distribution.

In case of detection signal parameters are computed through suitable estimators



p-value: probability that noise alone can produce a value of the detection statistic equal or larger to that actually observed.

In principle, one would take a threshold value p_{thr} (e.g.1%):

if $p>p_{thr}$ ⟶ our result is compatible with noise

if $p<p_{thr}$ ⟶ we have an interesting candidate

A very nice feature of CW searches:
if we have an interesting candidate, or even if we detect 'something' at low SNR, the detection significance can be increased 'arbitrarily' by analyzing more and more data.

If no statistically significant candidate is found in a given analysis, then an **upper limit** is computed.

Again, frequentist and Bayesian frameworks provide different ways to compute it.

From the upper limit we can try to derive some constraint on a single source characteristics (targeted search) or on the properties of a whole class of sources (all-sky search).

With current detectors data we are starting to enter into a regime of astrophysical interest → see later

Targeted searches

If we know with high accuracy the main source parameters, i.e. **position**, **frequency**, **frequency derivative(s)**, we can correct the Doppler effect, the spin-down, the other relativistic effects over long times.

Analysis methods of this kind are called <u>**coherent**</u> because are based on the assumption that the signal phase can be accurately "followed" over the full observation period.

Coherent methods are the most sensitive but their computational cost rapidly increases with volume of parameter space to be explored.

$$\boxed{h_{0,\min} \approx 11\sqrt{\frac{S_n}{T_{obs}}}}$$

1% FAP, 10% FDP

Highly accurate measures of source position and rotational parameters is a key point for the use of coherent methods over long times. Otherwise a sensitivity loss happens.

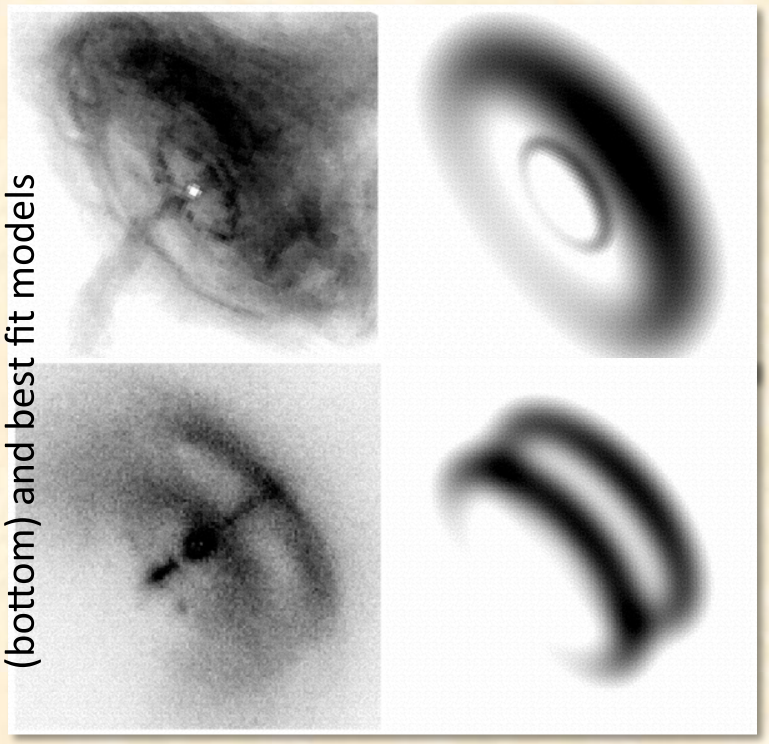
Also source intrinsic velocity can be an issue.

By imposing e.g. that the phase error remains well below one cycle over 1 year for a signal with f_0~100 Hz and df_0/dt ~ 10^{-10} Hz/s we find, for the spin-down correction, $\Delta f_0 \approx 10^{-5} Hz$ and $\Delta \dot{f}_0 \approx 10^{-16} Hz/s$

EM observations provide very accurate position and rotational parameters of many NS, especially radio pulsars.

On the other hand, **polarization parameters** ι, ψ are generally not known, even for standard pulsars.

In fact, for a few pulsars an estimation has been derived by fitting 3D models to X-ray data for the observed equatorial torus of PWN (Ng &Romani, ApJ 2004; 2008)

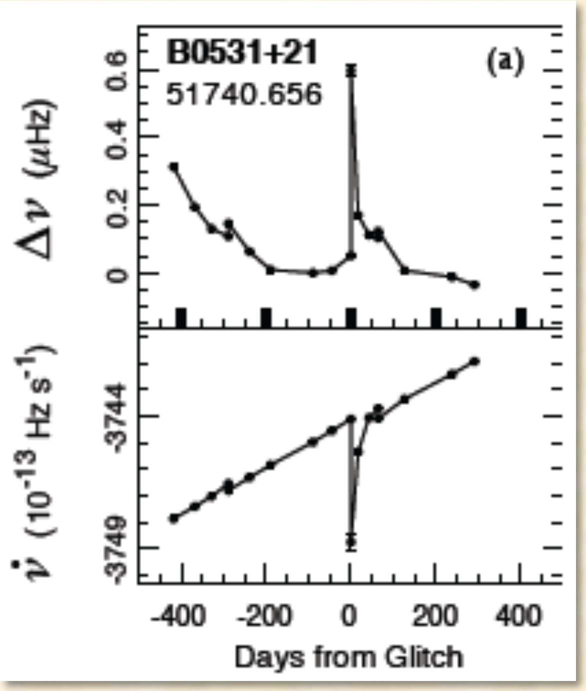


Chandra images: Crab (top), Vela (bottom) and best fit models

object	$\Psi(^\circ)$	$\zeta(^\circ)$
Crab (inner)	$124 \pm 0.1 \pm 0.1$	$61.3 \pm 0.1 \pm 1.1$
Crab (outer)	$126.31 \pm 0.03 \pm 0.11$	$63.03^{+0.02}_{-0.03} \pm 1.3$
Vela	$130.63^{+0.05}_{-0.07} \pm 0.05$	$63.6^{+0.07}_{-0.05} \pm 0.6$
J1930+1852	$91^{+4}_{-5} \pm 1.1$	$147 \pm 3 \pm 3$
J2229+6114	$103 \pm 2 \pm 1.6$	$46 \pm 2 \pm 6$
B1706−44	$163.6 \pm 0.7 \pm 1.6$	$53.3^{+1.6}_{-1.4} \pm 2.9$
J2021+3651	$45 \pm 1.3 \pm 0.6$	$79 \pm 1 \pm 2$
J0205+6449 (inner)	$90.3^{\dagger} \pm 0.2 \pm 0.4$	$91.6 \pm 0.2 \pm 2.5$
J0205+6449 (outer)	$90.3^{\dagger} \pm 0.2 \pm 0.4$	$90.56^{+0.07}_{-0.05} \pm 0.01$
J0537−6910	$131 \pm 2 \pm 0.9$	$92.8^{+0.7}_{-0.8} \pm 0.5$
B0540−69	$144.1 \pm 0.2 \pm 0.8$	$92.9 \pm 0.1 \pm 0.6$
J1124−5916	16 ± 3	105 ± 7
B1800−21	44 ± 4	90 ± 2
J1833−1034	45 ± 1	$85.4^{+0.2}_{-0.3}$

Rotating neutron stars are, in general, very stable rotators but can be affected by two kinds of irregularity, especially in the case of young objects: **glitches** and **timing noise**.

A glitch may produce a 'jump' in the phase of the GW signal: coherent analysis across the glitch time may not be possible (unless the jump can be estimated or if it does not affect the GW signal).



EM alerts on glitch occurrence for the most interesting targets are extremely important for CW analysis.

Timing noise is a random fluctuation of the pulsar rotational phase which affects especially young pulsars

$$\varphi(t) = \varphi_0 + 2\pi\left[f_0(t-t_0) + \frac{1}{2}\dot{f}_0(t-t_0)^2 + \frac{1}{6}\ddot{f}_0(t-t_0)^3 + \dots \right]$$

First term containing significant timing noise

Extrapolating over a long observation time the source ephemeris computed at a given epoch can produce a large loss if timing noise is large enough.

Assuming the timing noise affects also the GW signal (i.e. it is phase locked to the EM one), it is important to have updated ephemeris covering the actual times of the analysis.

Hobbs et al, 2010

The typical CW searches assume $f=2f_{rot}$ (or $f=f_{rot}$) , and similarly for spin-down.
This assumption may well be not valid (e.g. if the GW signal is due to the core rotating at a slightly different rate respect to the crust, or if there is precession).

Moreover, if not properly taken into account also timing noise can negatively impact on a search at a single frequency.

→ Then '**narrow-band**' searches around the EM-inferred rotational parameters are also important .

A narrow band search could reasonably explore a fraction of Hertz around the central frequency.

Coherent methods still usable but with less sensitivity due to the '*look elsewhere*' effect:

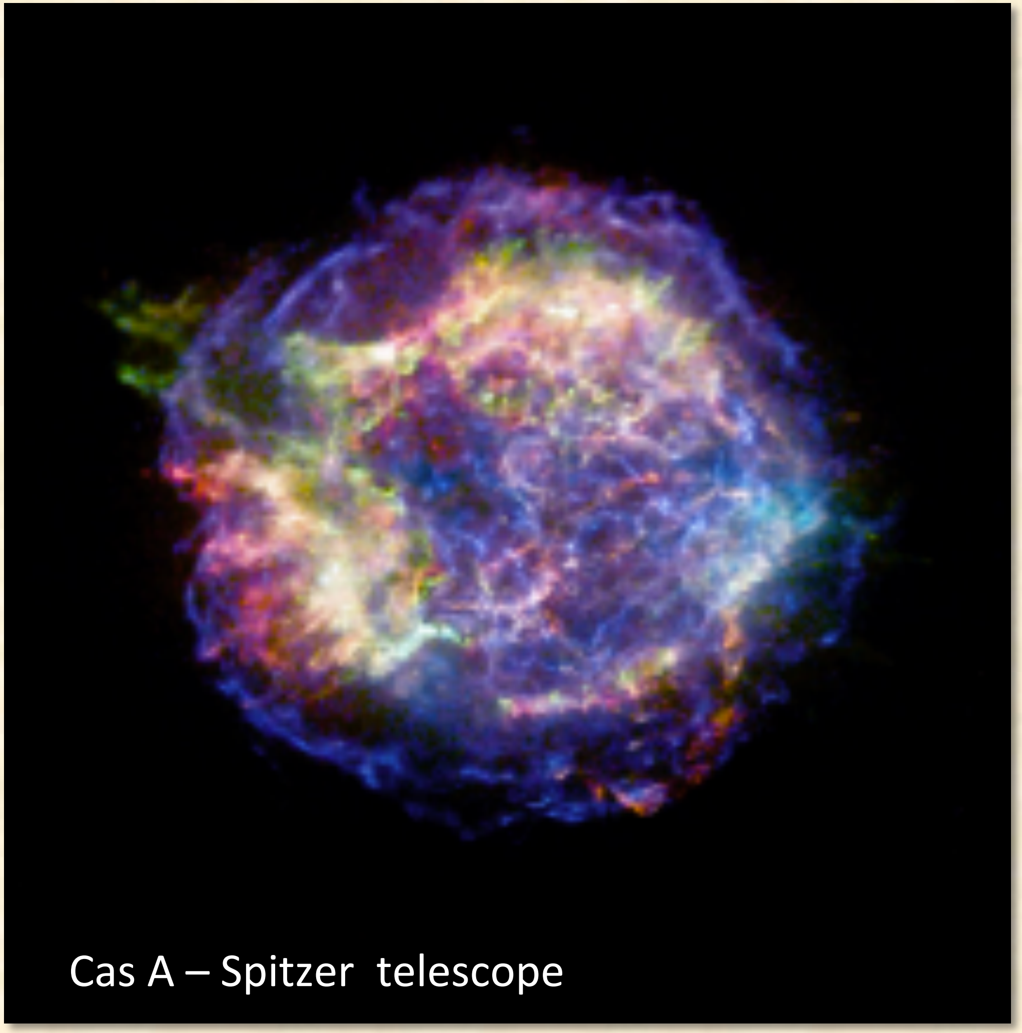
$$\boxed{h_{0,\min} \approx 34\sqrt{\frac{S_n}{T_{obs}}}}$$

Larger probability that a noise fluctuation can give a candidate at a given confidence level.

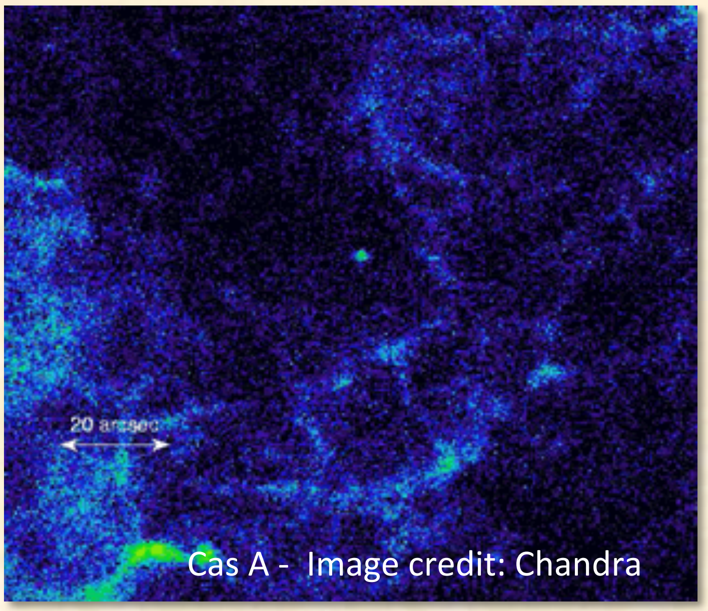
Still relatively little attention given to this kind of search:

- Abbott et al, ApJ 2008 (Crab) ;
- improved method recently developed in our group.

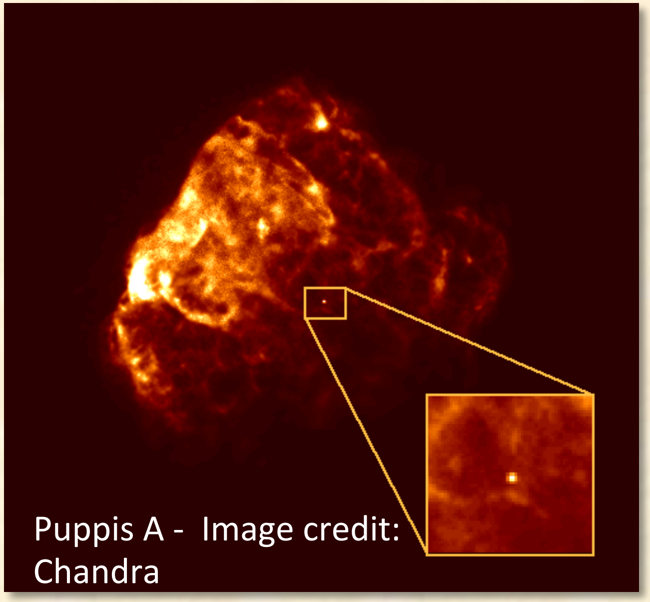
Directed searches

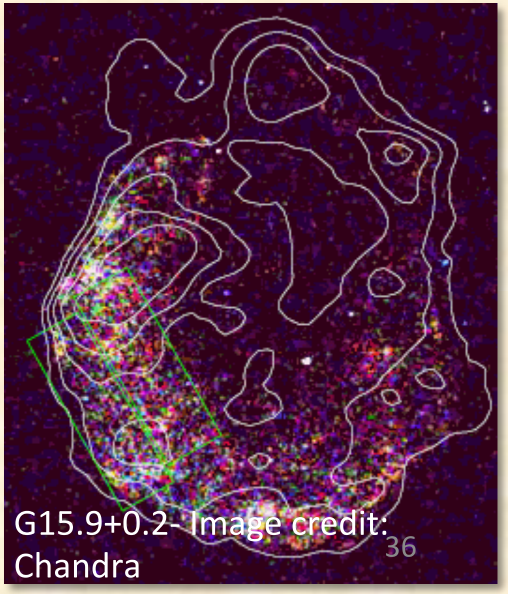


In some cases rotational parameters are not well constrained: e.g. for CCO the position is known fairly well but rotational parameters can be completely unknown (because no pulsation is observed).



Cas A - Image credit: Chandra


Puppis A - Image credit: Chandra

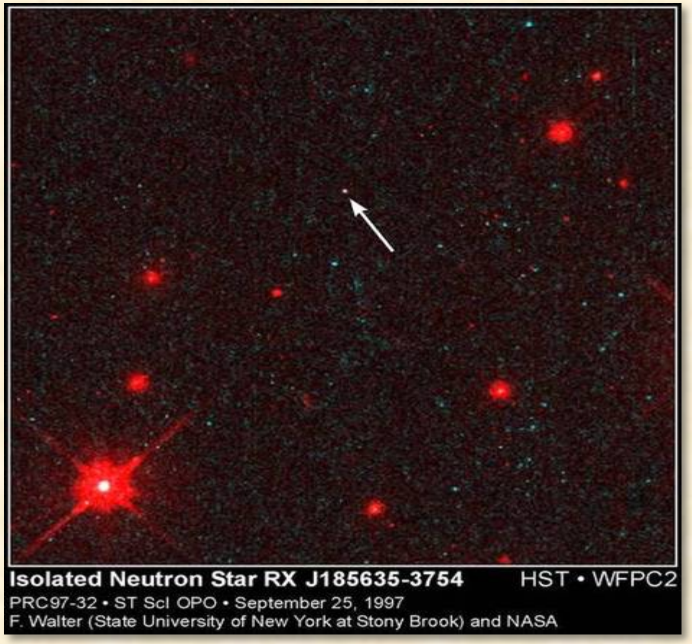

G15.9+0.2- Image credit: Chandra

In such cases coherent GW searches can be computationally feasible only using a few days of data if a large frequency band is considered.

This means a reduction in sensitivity!

Discovery of EM pulsations have a great impact on the search of CW.

E.g. Calvera for which X-ray pulsations were found only in 2010 (P~59.2ms)



The spin-down limit

Assuming that the measured spin-down of a pulsar is totally due to the emission of GW, we compute an upper limit on the signal amplitude, the so-called ***spin-down limit***:

$$h_{sd} = 8 \cdot 10^{-25} \sqrt{\left(\frac{|\dot{f}|}{10^{-10}\,Hz/s}\right)\left(\frac{f}{100Hz}\right)^{-1}}\left(\frac{d}{1kpc}\right)^{-1}$$

This would be the actual amplitude for a *gravitar*

Going below the spin-down limit is an important milestone in the search for CW from known NS.

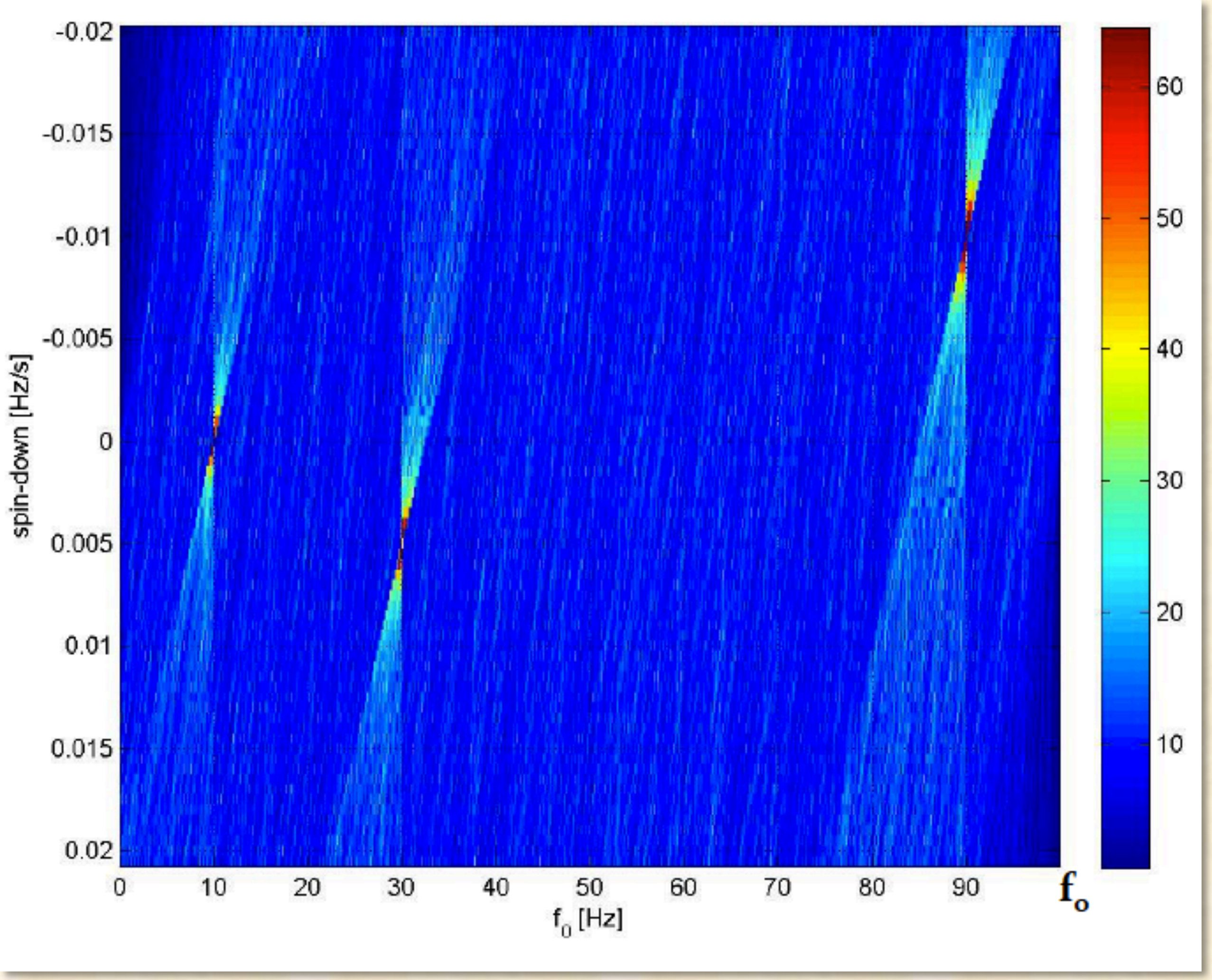
→ **Set a constraint on the fraction of spin-down energy due to the emission of GW.**

$$\epsilon^{\rm sd} = 0.237\left(\frac{h_0^{\rm sd}}{10^{-24}}\right) I_{38}^{-1}(f_{\rm rot}/{\rm Hz})^{-2}\, d_{\rm kpc}$$

If the rotational parameters are not known, an *indirect limit* can be computed if the NS age is known:

$$h_{il} = 2.2 \cdot 10^{-24}\left(\frac{\tau}{1kyr}\right)^{-\frac{1}{2}}\left(\frac{d}{1kpc}\right)^{-1}$$

Blind searches



In blind searches we try to explore a portion of the source parameter space as large as possible:

- All-sky
- Frequency up to 1.5-2kHz
- Spin-down age $\tau = \frac{f}{\dot{f}}$ as small as possible (e.g < 10^3 – 10^4 years)

This cannot be done with fully coherent methods that are computationally unfeasible because the number of points is huge (~10^{31}).

$$N_f = \frac{t_{obs}}{2 \cdot \Delta t}$$

number of frequency bins (Dt is the sampling time)

$$N_{DB}(f) = 10^{-4} \cdot f \cdot t_{obs}$$

number of frequency bins in the Doppler band of the frequency f

$$N_{sky}(f) = 4\pi \cdot N_{DB}^2$$

number of points in the sky for the frequency f

$$N_{sky,tot} = 4\pi \cdot 10^{-8} \sum_{i=1}^{N_f} i^2 \approx \frac{4\pi}{3} 10^{-8} \cdot N_f^3$$

total number of points in the sky (all frequencies)

$$N_{SD}^{(j)} = 2N_f \left(\frac{t_{obs}}{\tau_{\min}} \right)^j$$

number of values of spin-down parameter of order j

$$N_{tot} = N_{sky,tot} \cdot \prod_{j:N_{SD}^{(j)} \geq 1} N_{SD}^{(j)}$$

total number of points in the parameter space

$$N_{tot} \approx \frac{10^{-8}\pi}{6} \frac{t_{obs}^8}{\Delta t^5 \cdot \tau_{\min}^3} = 2.28 \cdot 10^{31} \left(\frac{t_{obs}}{4 \text{ months}} \right)^8 \left(\frac{\Delta t}{2.5 \cdot 10^{-4} s} \right)^{-5} \left(\frac{\tau_{\min}}{10^4 \text{ years}} \right)^{-3}$$

Alternative **hierarchical** approaches have been developed which try to satisfy two requirements:

- drastically reduce the computing power needed;
- not loose too much in sensitivity

The key idea is that of dividing data in a number of shorter segments and combine them incoherently.

In the incoherent step a rough exploration of the parameter space is done and some candidates are selected.

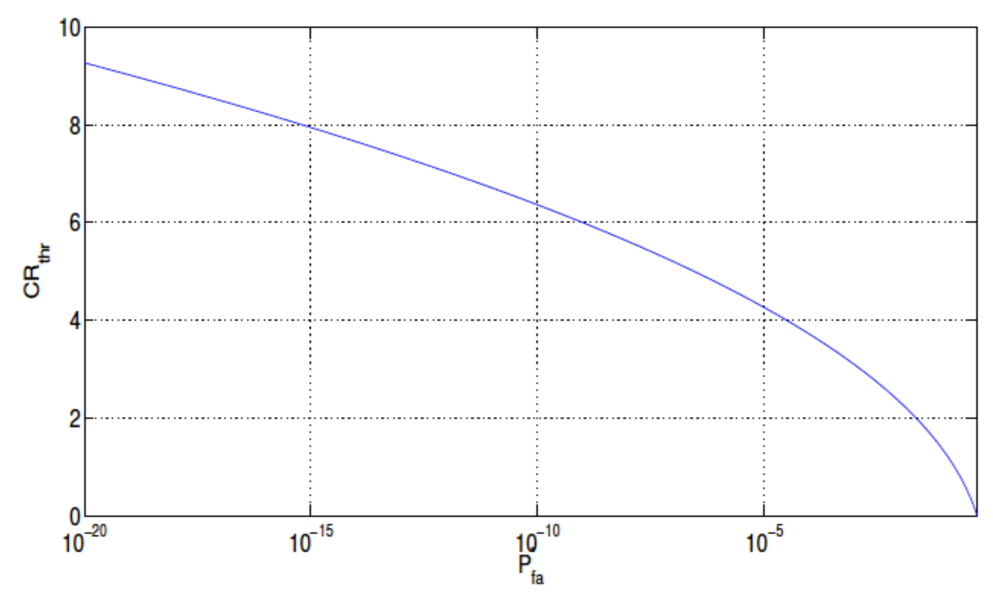
Candidates are followed with a more refined search.

$$\boxed{h_{0,\min} \approx \frac{10}{N^{1/4}}\sqrt{\frac{S_n}{T_{FFT}}}}$$

N: number of segments
T_{FFT}: length of short pieces

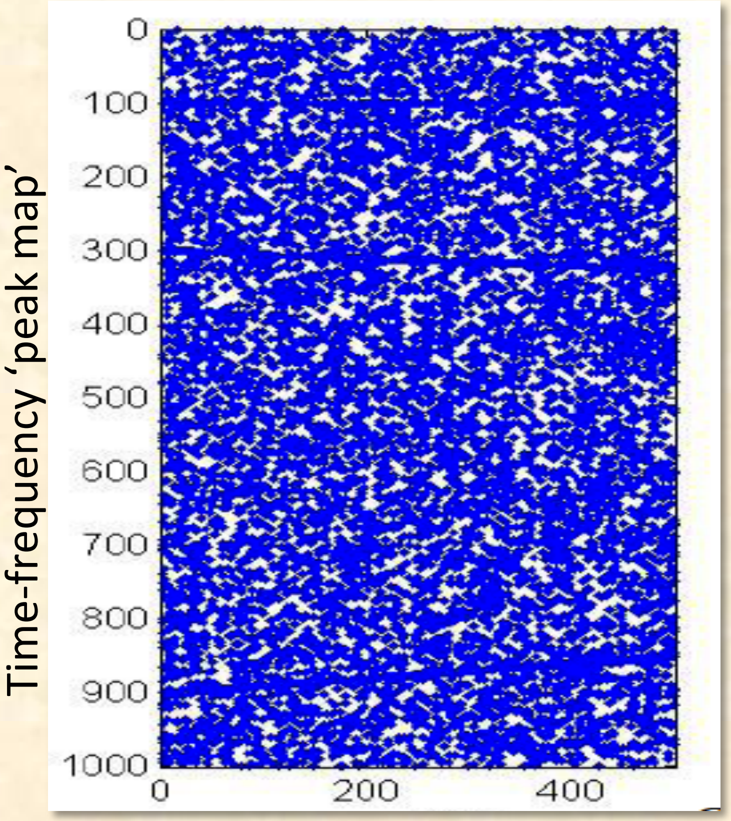
In fact, the exact value of the coefficient depends also on the specific parameter choice, e.g. the number of candidates that are selected.

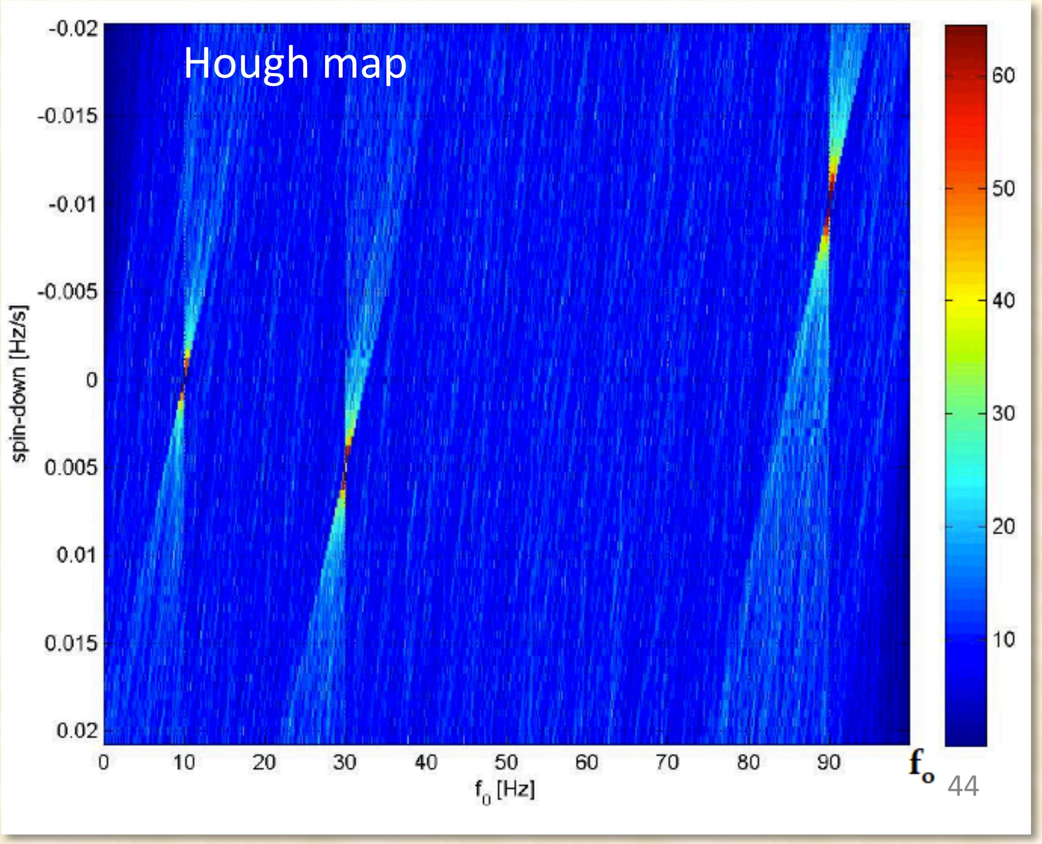
$$CR_{thr} = \sqrt{2}\,\mathrm{erfc}^{-1}\left(2\frac{N_{cand}}{N_{tot}}\right)$$



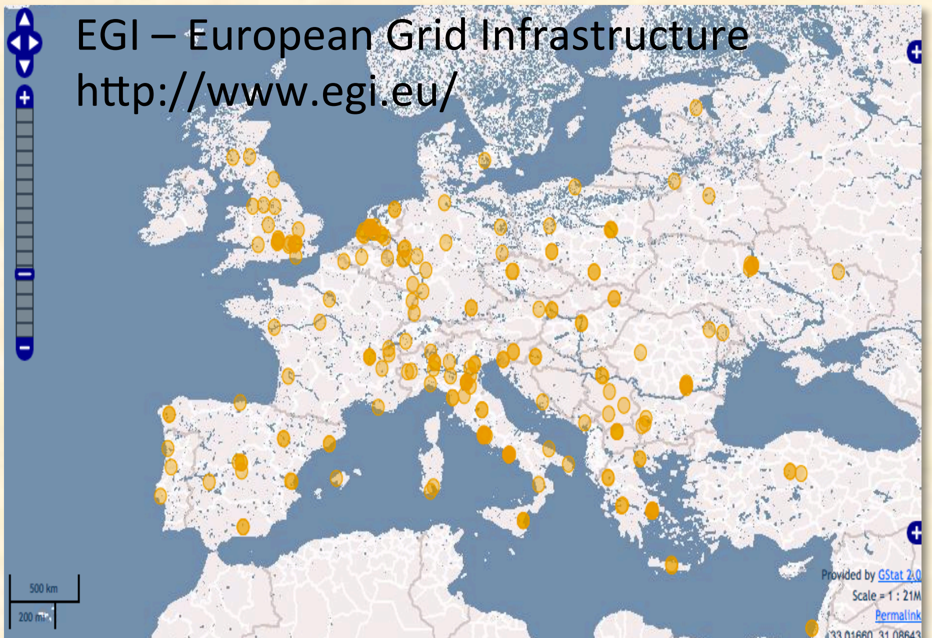
An example of incoherent step is the **Hough transform**, a pattern recognition method originally developed in the 60’ to analyze tracks in bubble chambers.

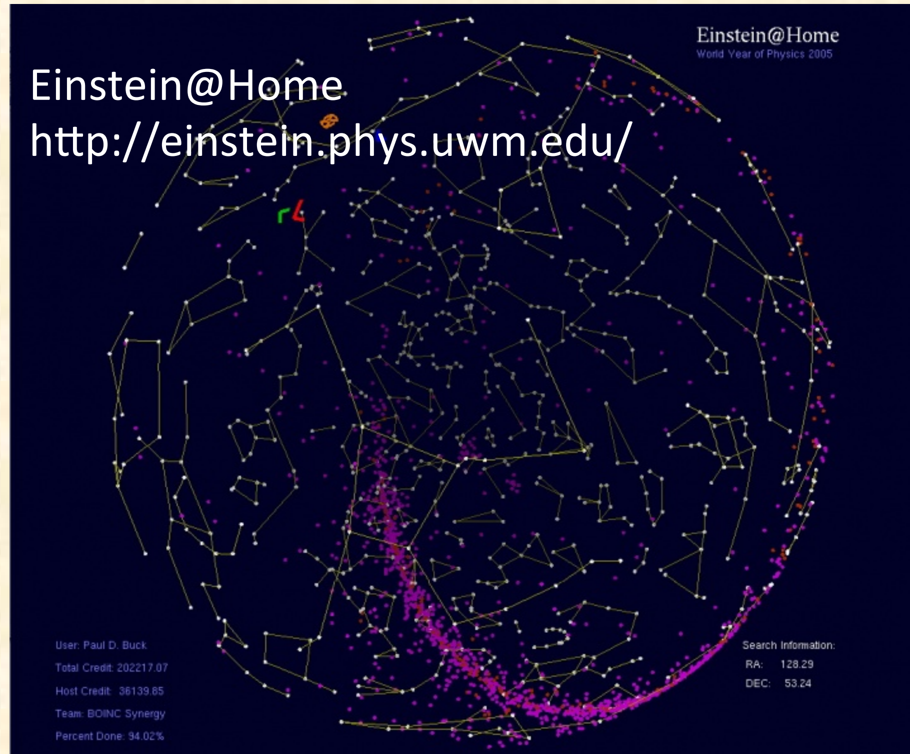
It realizes a mapping between the time-frequency plane and the source parameter space.





All-sky searches are computationally-bounded: the larger is the available computing power and the deeper is the search that can be done.



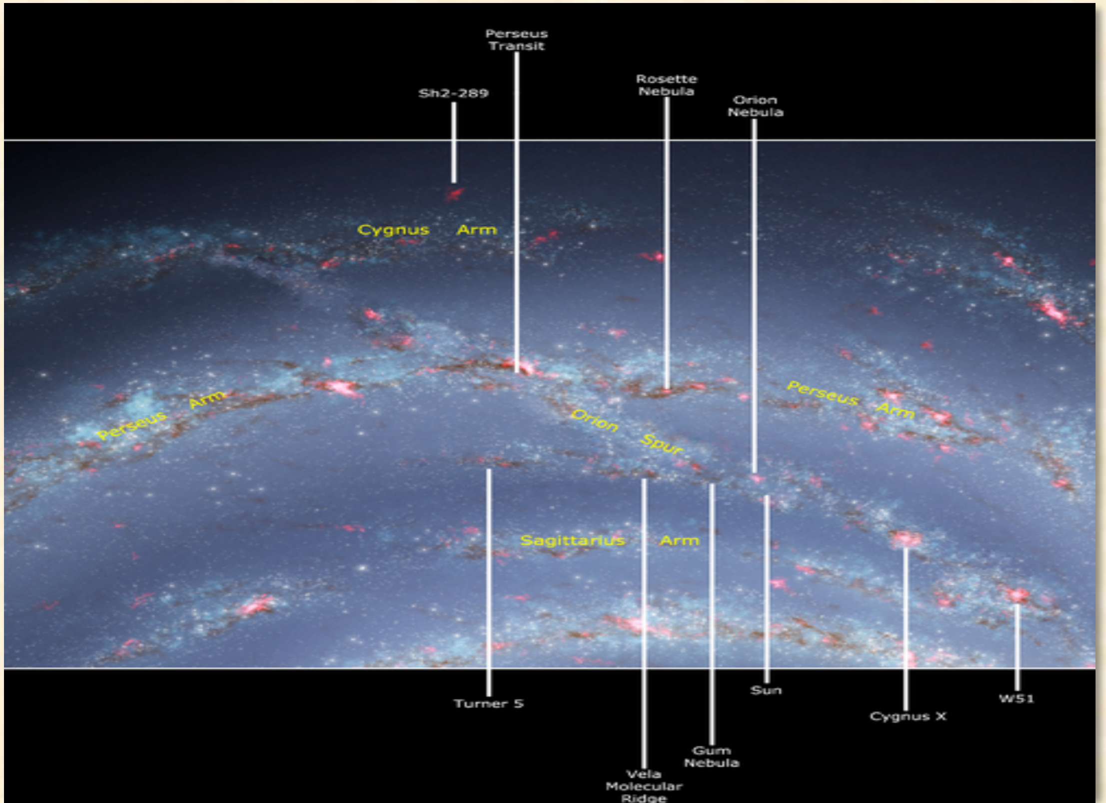


+ efforts for porting some pipelines on GPU

In particular, going to smaller spin-down age means searching for younger, and then possibly more deformed, objects.

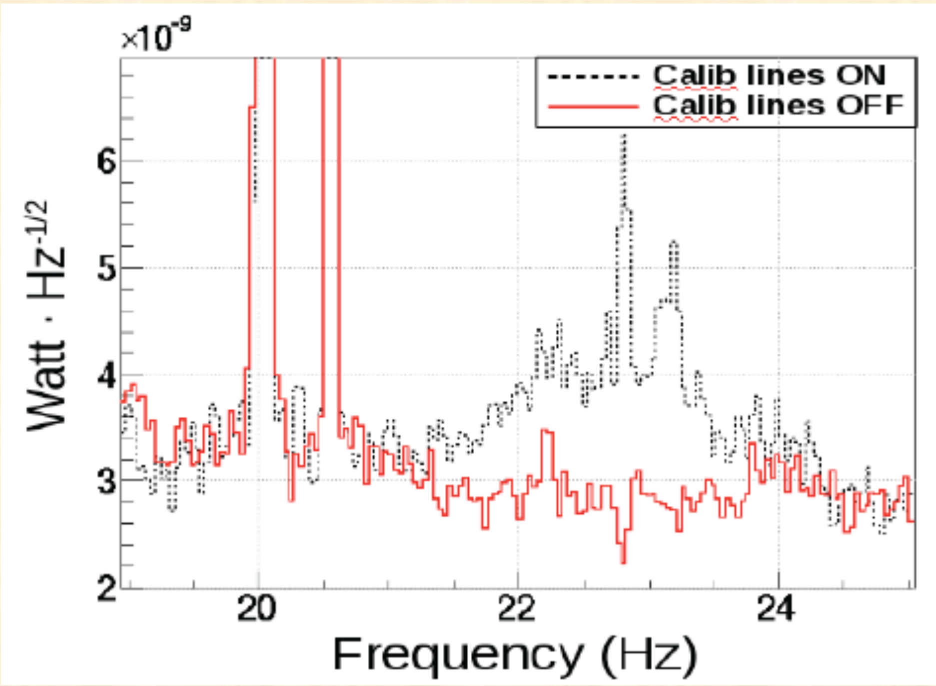
In principle blind searches do not want to rely on photon astronomy: **search for the unexpected!**

On the other hand, photon astronomy can provide interesting spots (like regions with high massive star birth rate) where to bet for a deep 'semi-blind' search.



Real data life

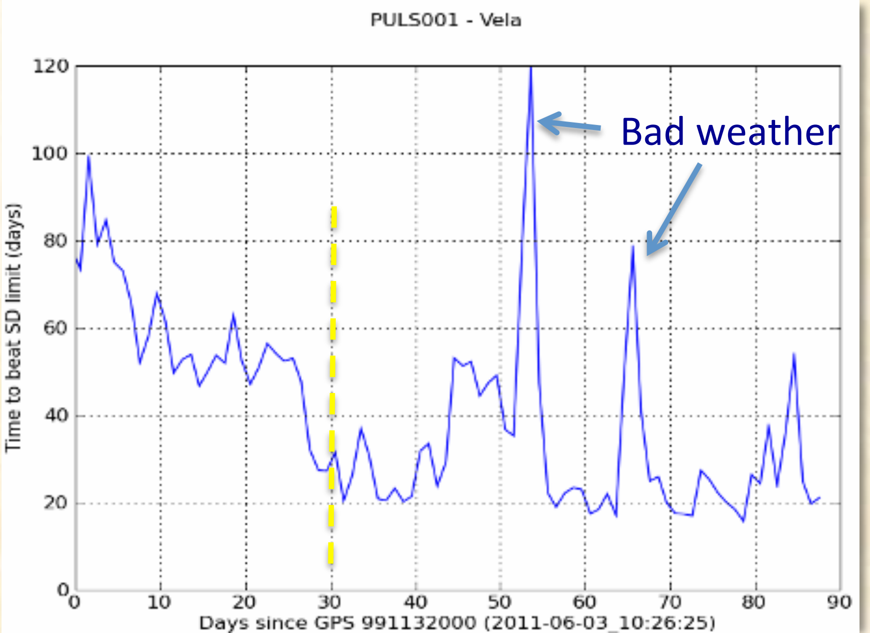
Disturbances affect real data. We must try as much as possible to identify and remove their source.



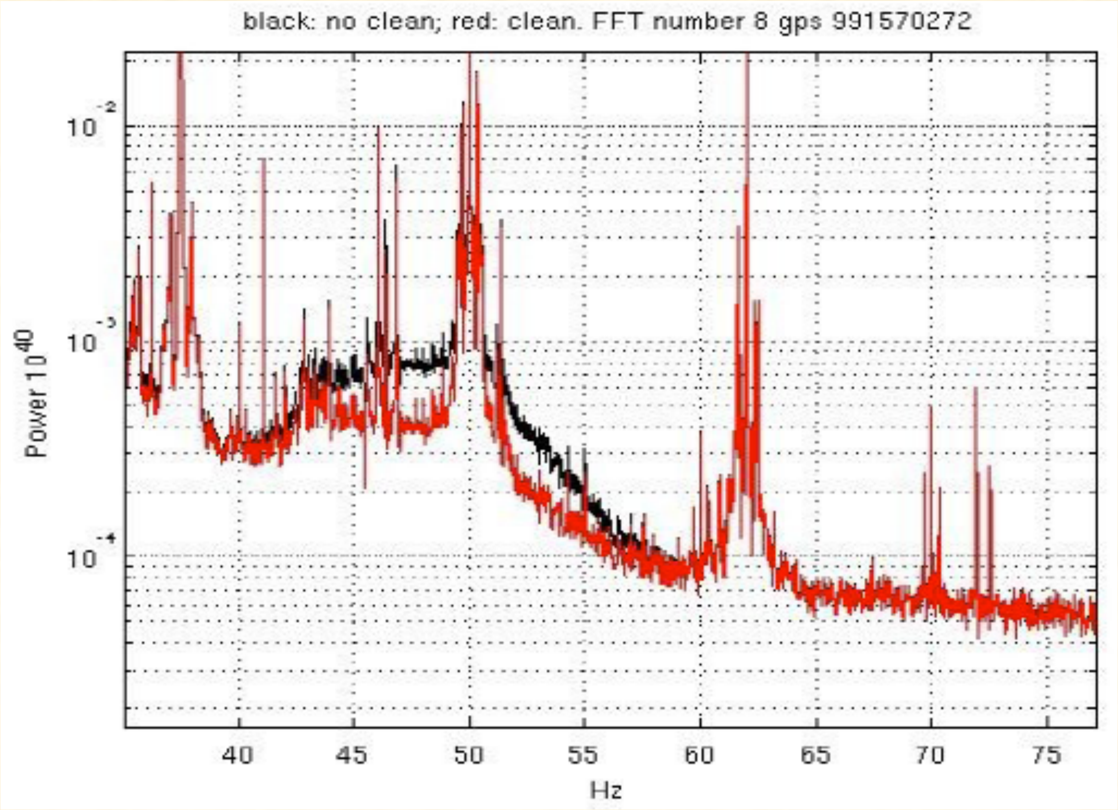
E.g. this a disturbance affecting the first month of Virgo VSR4 run.

- Due to a complicate non-linear coupling between control and calibration lines.

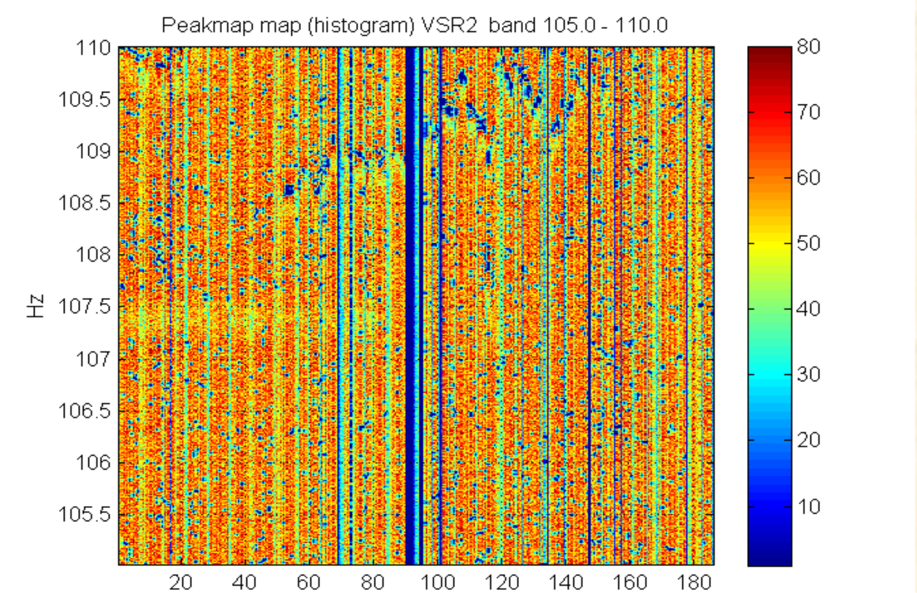
- Eliminated moving frequency of calibration lines and reducing their amplitude.



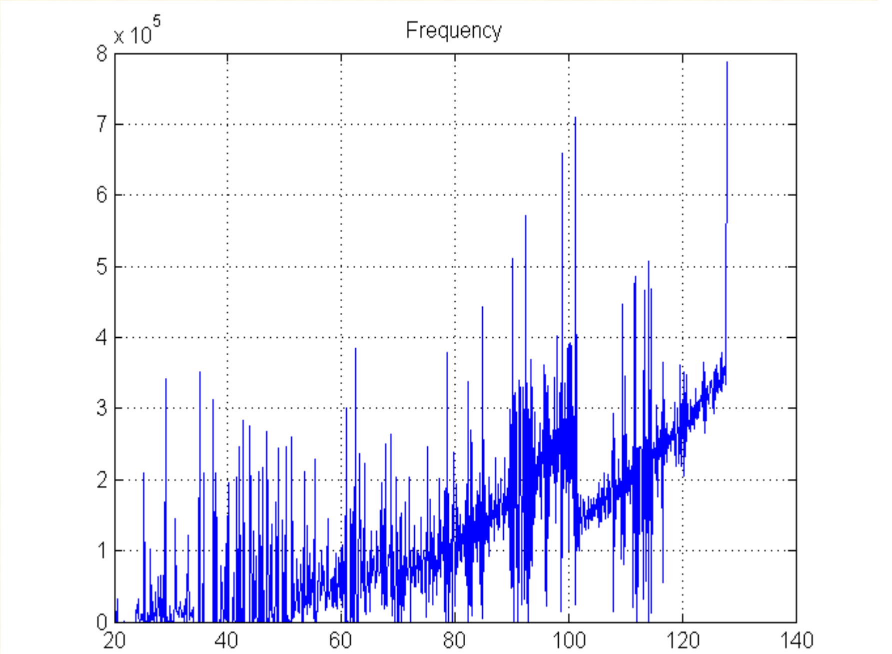
Short time domain disturbances are removed in pre-processing. They can increase the overall noise level.

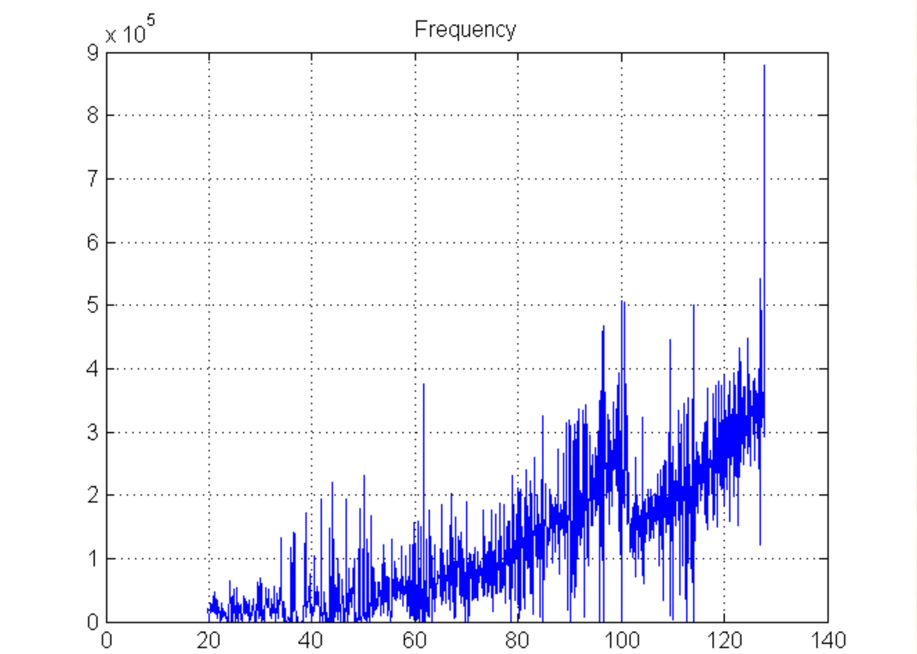


“Lines” which have a recognized instrumental origin, or which clearly have a non-gravitational origin are also removed during the analysis:

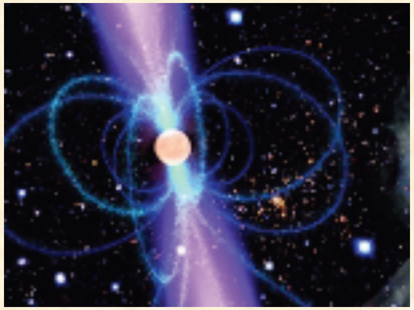


This process has a large impact on the number of candidates in a blind search:





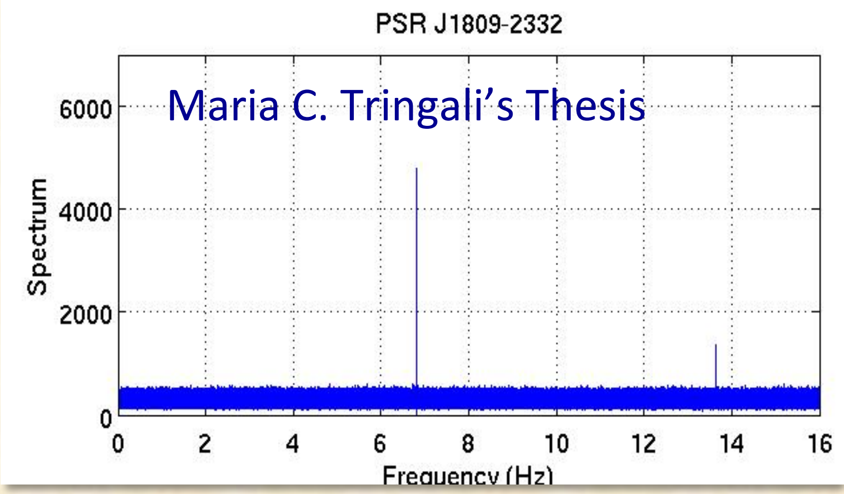
GW methods for pulsar search



There are several similarities between the search for continuous GW and the search of pulsars in the EM band

This is especially true for gamma-ray pulsars, for which long observation times are needed to collect a sufficient number of photons.

→ **We can adapt GW algorithm to search for pulsars!**



One effort in this direction (led by LSC-AEI Hannover group) is producing great results!

~10 new pulsars found among which the first MSP in a blind search! (Pletsch et al. ApJ 2012, Science 2012). More discoveries expected!

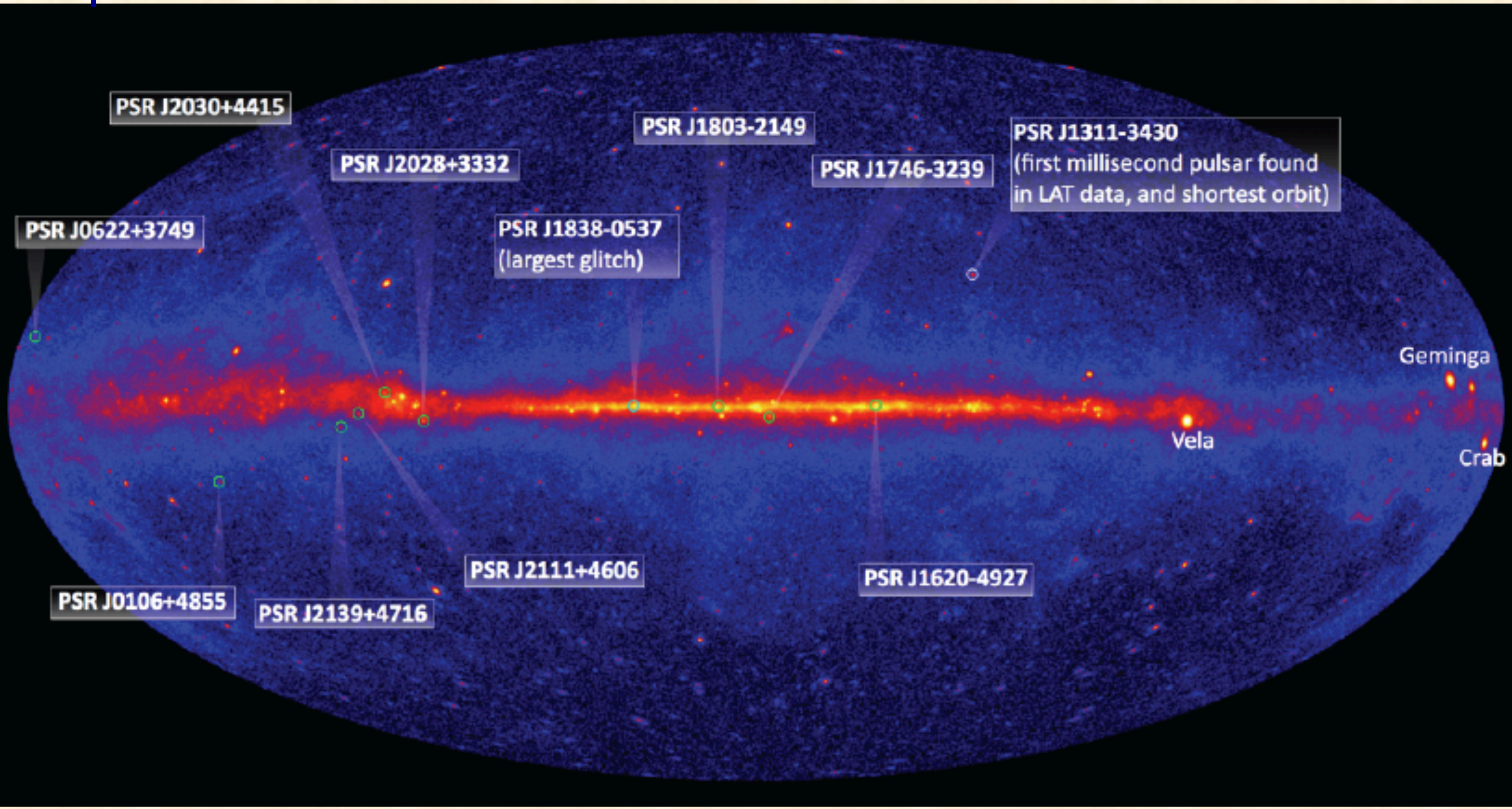
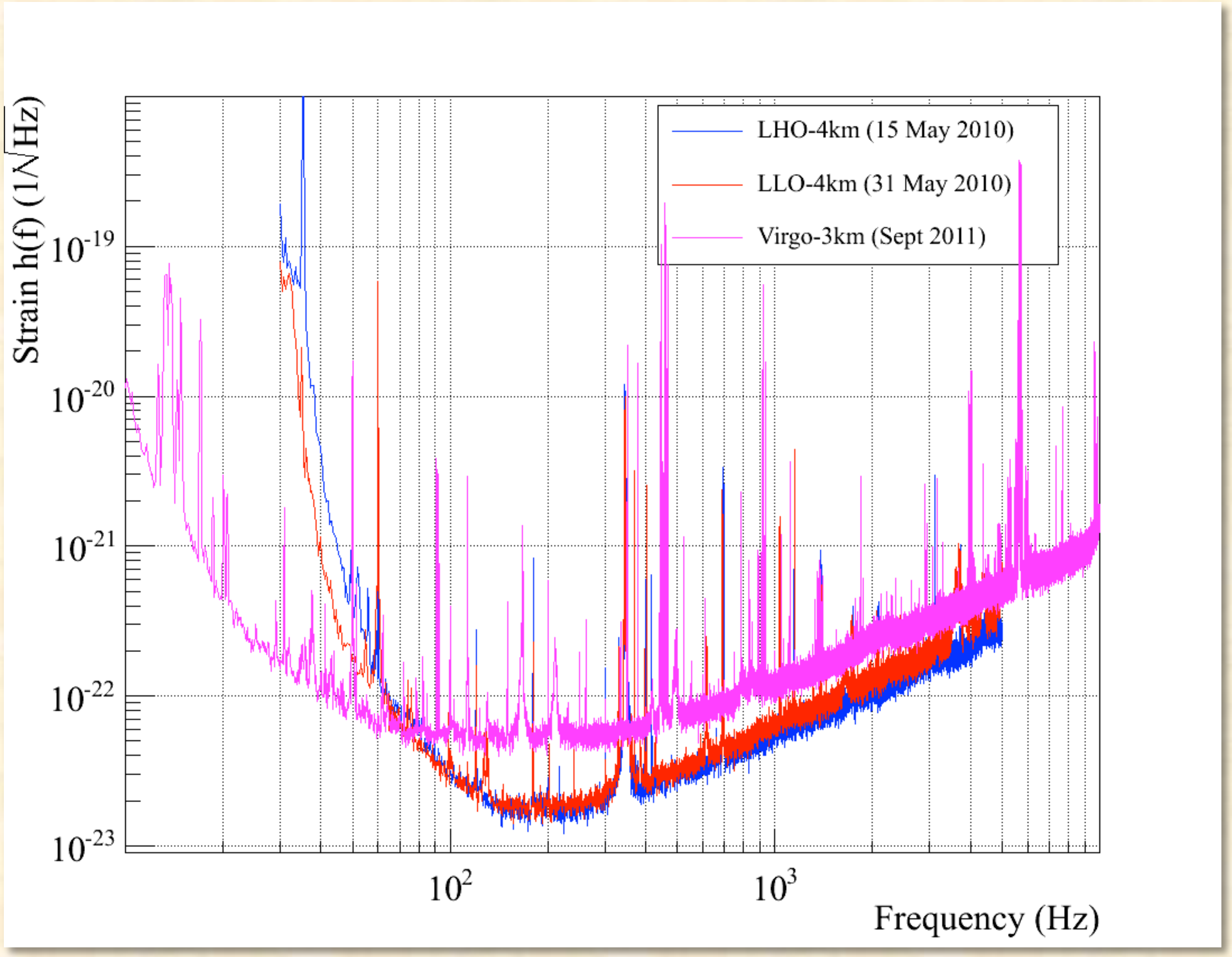


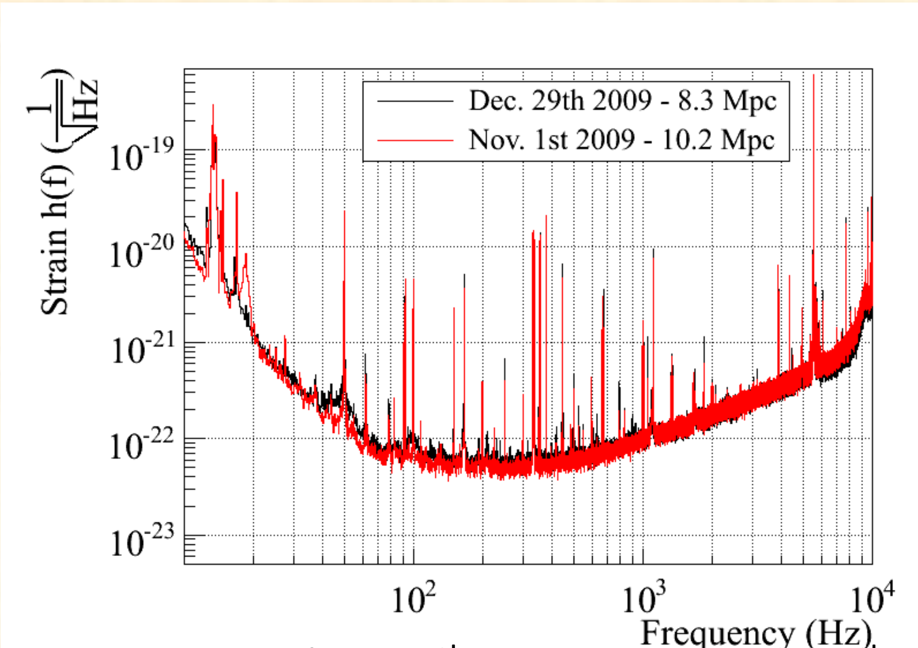
figure stolen from H. Pletsch's talk at 2013 VESF School

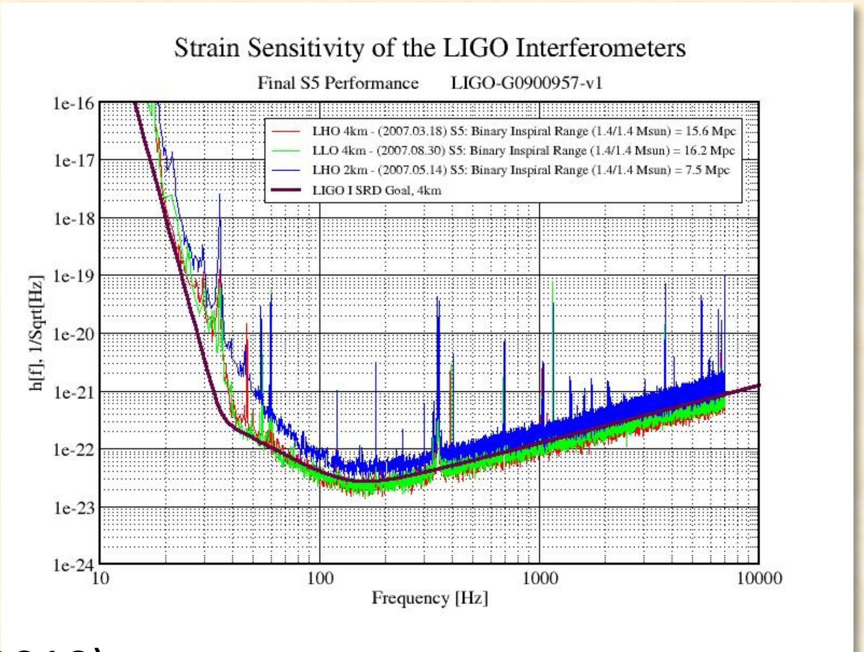
Some results on CW searches



No detection has been done in both targeted and blind searches, but interesting astrophysical constraints have been established in a few cases.

Latest published results concern the analysis of Virgo VSR2 and LIGO S5 data. VSR4/S6 results near to publication.





Virgo VSR2 (July 7th, 2009 – January 8th, 2010)
LIGO S5 (November 24th, 2005 – September 30th, 2007)

Crab

Abbott et al ApJ 2010

Analysis done over LIGO S5 data both assuming the polarization parameters (ι, ψ) are unknown ("uniform priors") and that are known ("restricted priors") .

95% "degree of belief" upper limits

	h_{ul}	eps_{ul}	h_{ul}/h_{sd}
Uniform priors	2.4×10^{-25}	1.3×10^{-4}	0.15
Restricted priors	1.9×10^{-25}	1.0×10^{-4}	0.13

These results refer to data after MJD=53970 when a glitch occurred.

Crab ephemeris valid for the whole observation period have been obtained by a fit over the monthly ephemeris published by Jodrell Bank (http://www.jb.man.ac.uk/pulsar/crab.html).

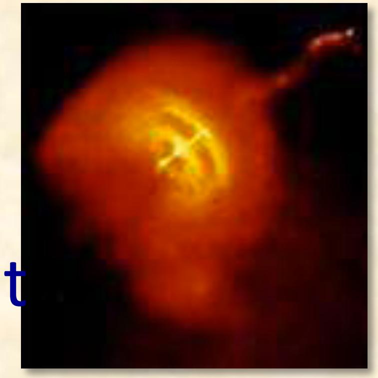
These upper limits corresponds to a maximum fraction of spin-down energy emitted as GW of ~2%.

The corresponding ellipticity is large respect to the maximum value foreseen by standard models, but comparable or below those estimated in some 'exotic' models.

Also constrains inner B field to be $<10^{16}$ G.

Abbott et al ApJ 2011

Vela



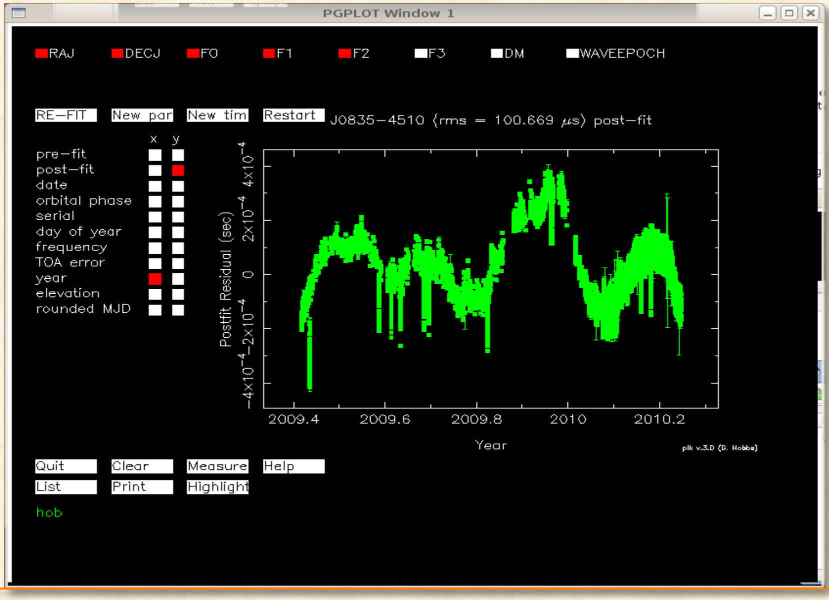
Analysis of Virgo VSR2 data done with three independent methods, which provide consistent results. For each method two analyses: one considering (ι, ψ) unknown and one taking x-ray estimations

Vela: 95% ‘confidence level’ upper limits

	h_{ul}	eps_{ul}	h_{ul}/h_{sd}
Method 1			
2 d.o.f.	1.9×10^{-24}	1.03×10^{-3}	0.58
4 d.o.f.	2.2×10^{-24}	1.19×10^{-3}	0.67
Method 2			
G-statistic	2.2×10^{-24}	1.19×10^{-3}	0.67
F-statistic	2.4×10^{-24}	1.30×10^{-3}	0.73
Method 3			
restricted priors	2.1×10^{-24}	1.14×10^{-3}	0.64
uniform priors	2.4×10^{-24}	1.30×10^{-3}	0.73

Two frequentist upper limits and one Bayesian.

Updated ephemeris covering VSR2 time span have been obtained using TEMPO2 from a set of TOAs of the EM pulses observed by Hartebeesthoek and Hobart radio-telescopes (post-fit residuals rms of ~ $100\mu s$).

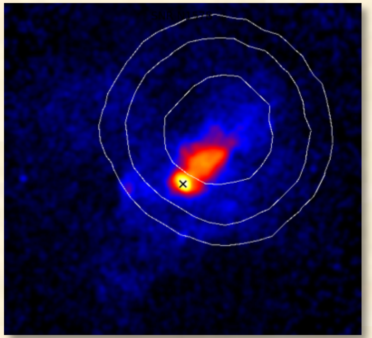


Courtesy by Matt Pitkin

The found upper limits constrain the fraction of spin-down energy due to GW to ~35%.

The upper limit on ellipticity is comparable to the maximum values foreseen by some 'exotic' models or produced by a very high inner magnetic field.

J0537-6910



This is an X-ray pulsar (~62Hz).
Analysis of LIGO S5 data using ephemeris from RXTE (7 inter-glitch segments).

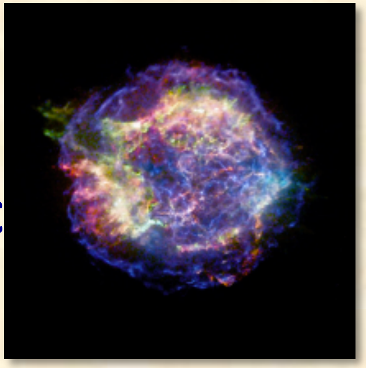
Phase jump among glitches treated as a further unknown parameter.

95% "degree of belief" upper limits

	h_{ul}	eps_{ul}	h_{ul}/h_{sd}
Uniform priors	4.1×10^{-26}	1.2×10^{-4}	1.4
Restricted priors	4.6×10^{-26}	1.4×10^{-4}	1.5

Spin-down limit nearly reached, but given the uncertainty on the glitch effects this result should be considered less robust than previous ones.

Cas A



12 days of LIGO S5 data used for a coherent search for CW from Cas-A supernova remnant. Abadie et al ApJ 2010

Known position, but unknown frequency.

Freq. band: 100-300 Hz and a range of 1st and 2nd frequency derivative.

Upper limit below indirect limit based on energy conservation and age.

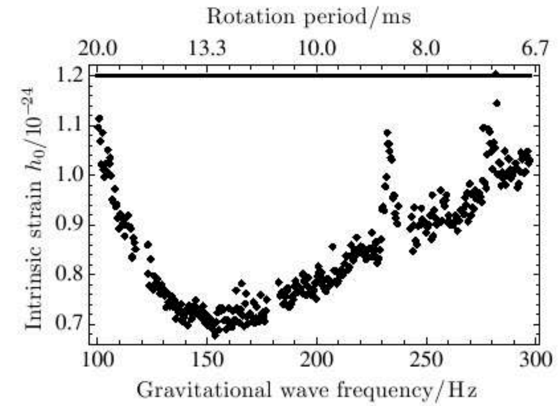


Figure 3. Upper limits at 95% confidence (dots) on the intrinsic strain h_0 of gravitational waves from Cas A and the indirect limit (line). The gravitational-wave frequency is assumed to be twice the rotation frequency. Systematic uncertainties are not included; see Section 3 for discussion.

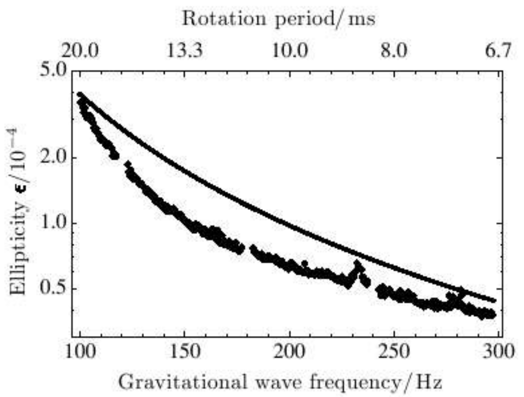


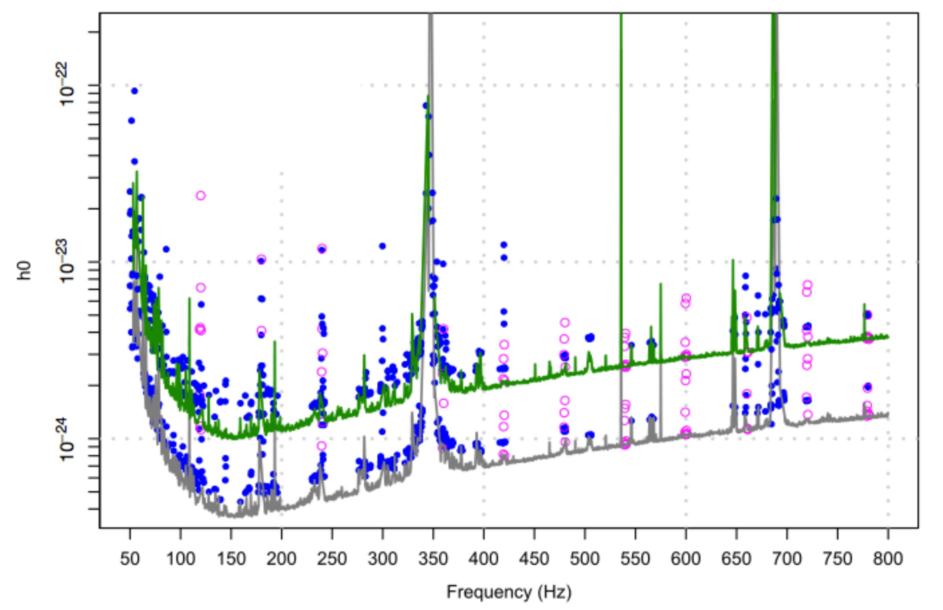
Figure 4. Upper limits at 95% confidence (dots) on the equatorial ellipticity ϵ of Cas A and the indirect limit (line). The gravitational-wave frequency is assumed to be twice the rotation frequency. Systematic uncertainties are not included; see Section 3 for discussion.

Also first upper limit on r-modes amplitude (search at $4/3f_{rot}$).

Blind searches

Full S5 analysis with two different methods

"PowerFlux", Abadie et al. PRD 2012



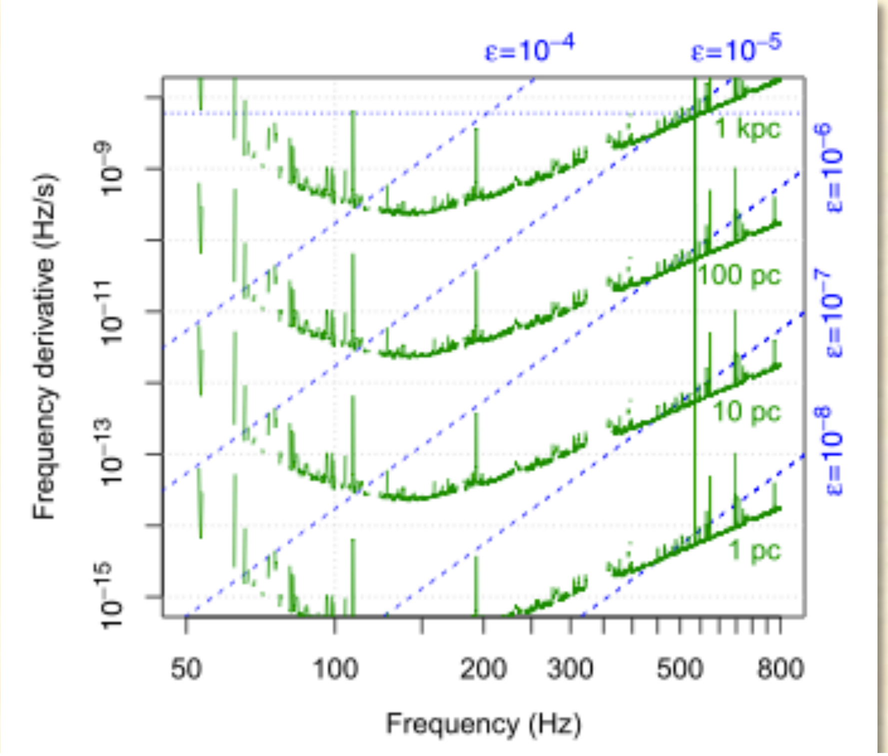
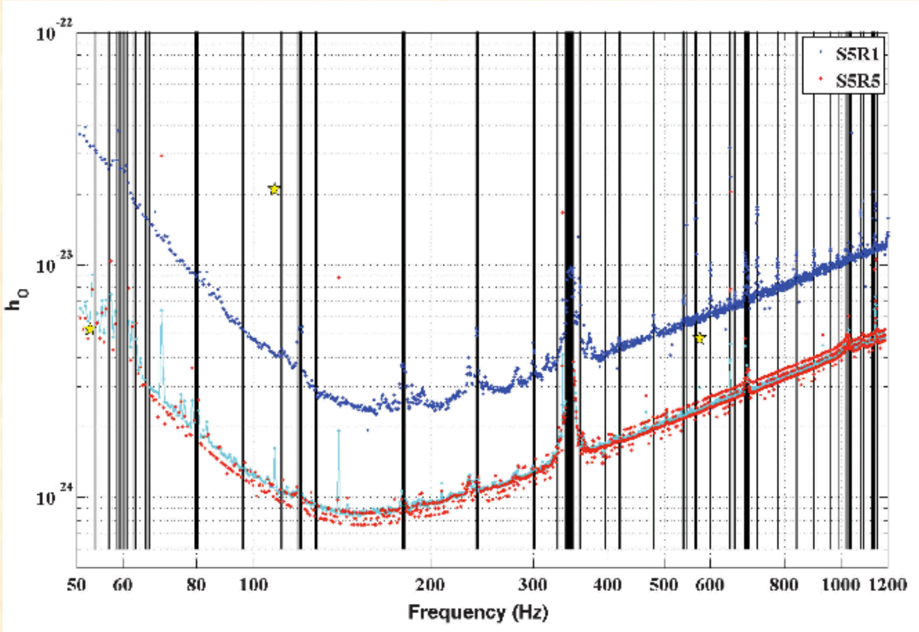
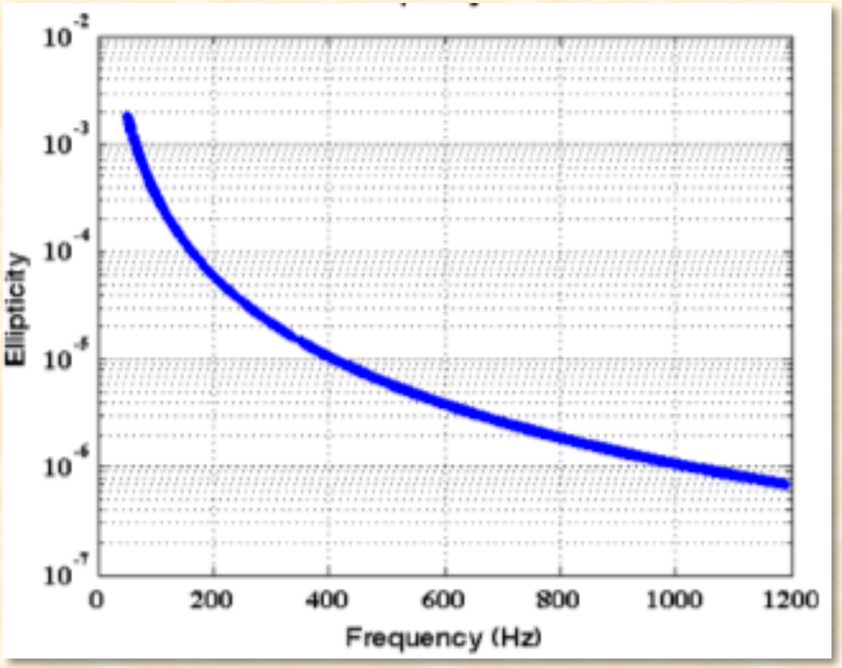
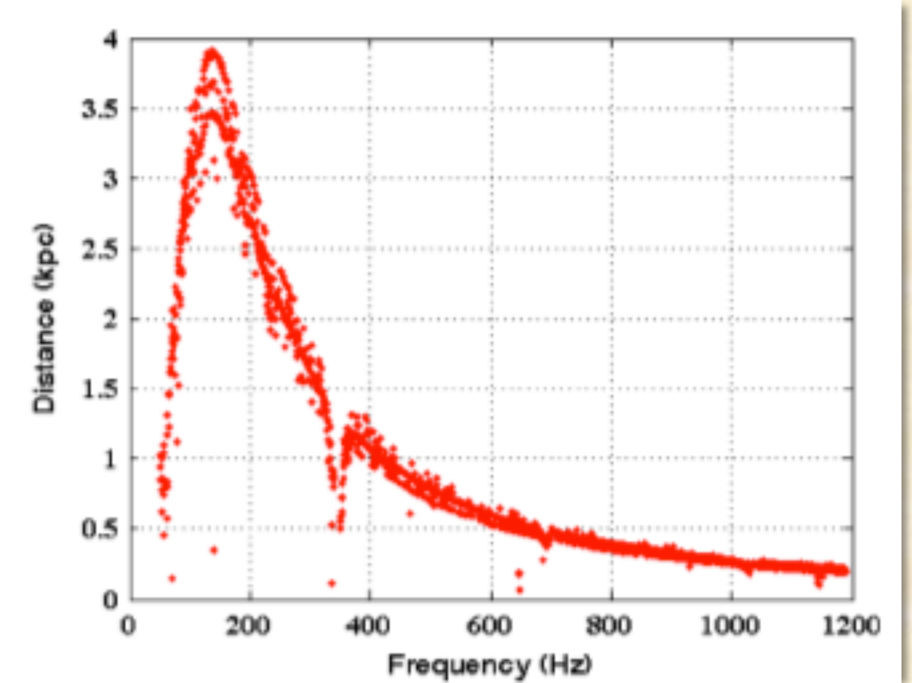


FIG. 13: Range of the PowerFlux search for neutron stars spinning down solely due to gravitational radiation. This is a superposition of two contour plots. The green solid lines are contours of the maximum distance at which a neutron star could be detected as a function of gravitational-wave frequency f and its derivative $\dot{f}$. The dashed lines are contours of the corresponding ellipticity $\epsilon(f, \dot{f})$. The fine dotted line marks the maximum spindown searched. Together these quantities tell us the maximum range of the search in terms of various populations (see text for details) (color online).

E@H, Aasi et al PRD 2013

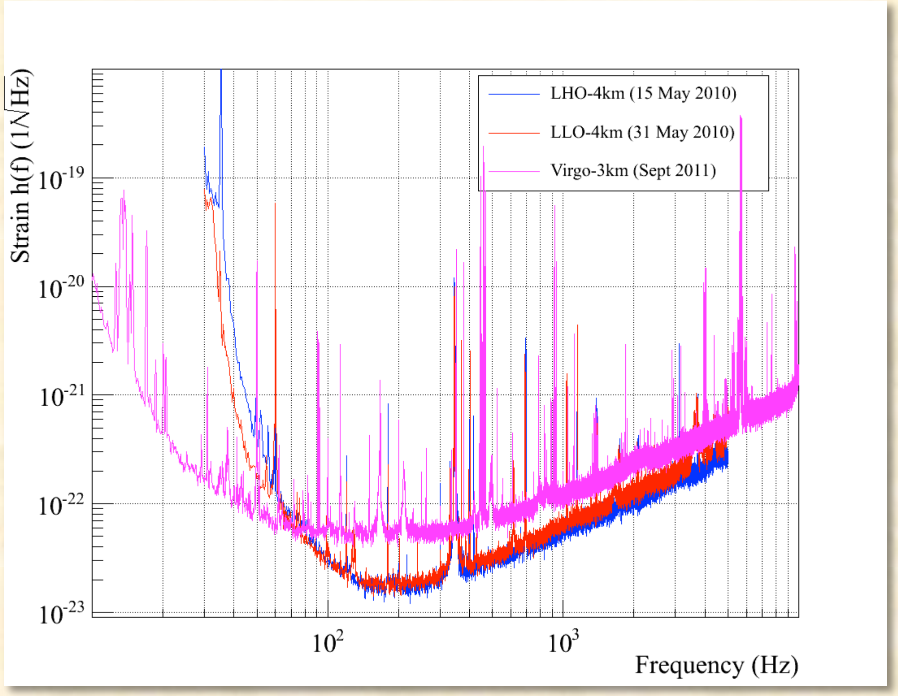






Current searches

Improvement expected due to the better sensitivity



Virgo VSR4 (June 3rd, 2011 – September 5th, 2011):
LIGO S6 (July 7th, 2010 – October 20th, 2011):

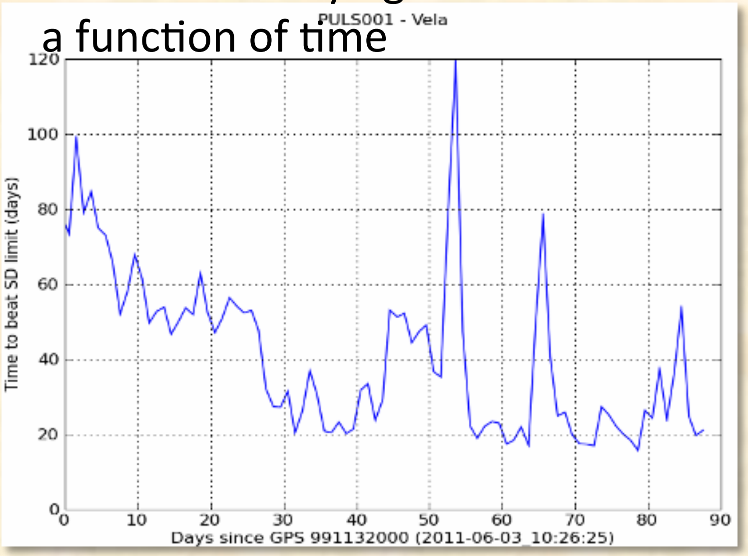
Vela search in Virgo VSR4 data:

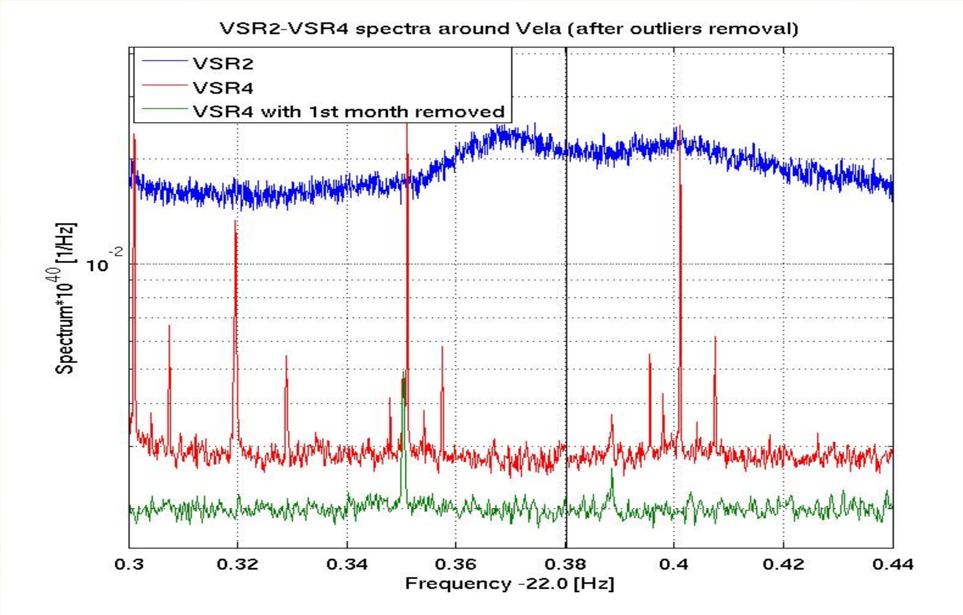
Sensitivity gain: ~2.6

Integrated sensitivity improvement: ~1.8

First month very noisy!

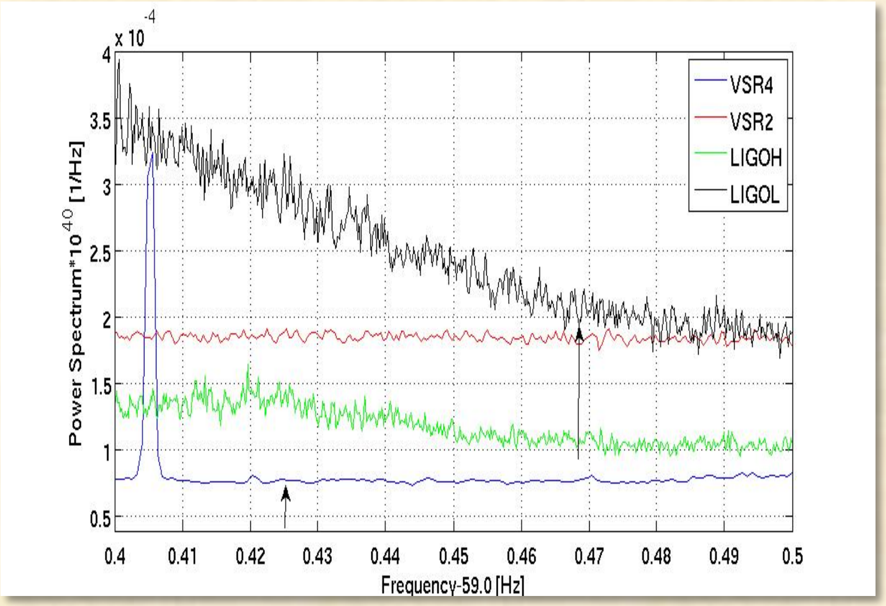
VSR4 sensitivity figure of merit as a function of time





Updated ephemeris got from Hartebeesthoek radio-telescope (S. Buchner)

Crab search in VSR2/VSR4/S6 data



Both Virgo VSR4 and LIGOH S6 have a better sensitivity than S5 but a smaller effective observation time.

By the joint analysis of VSR2/VSR4/S6 data we can expect an improvement of a factor ~1.3.

Other potentially interesting targets for which the spin-down (or the indirect) limit could be approached:

- Pulsars:

J0205+6449 (~30.42Hz) [no ephemeris]

J1833+1034 (~32.31Hz) [GMRT]

J1813-1246 (~41.60Hz) [Fermi LAT]

J1813-1749 (~44.74Hz) [no ephemeris]

J1952+3252(~50.58Hz) [Nancay]

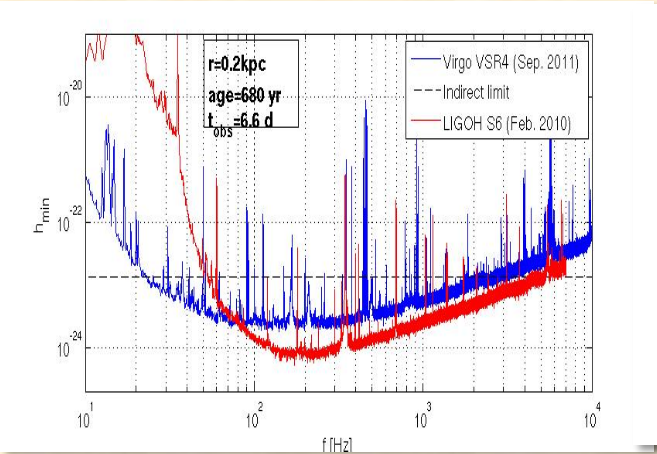
J1913-1011 (~55.68Hz) [Jodrell Bank]

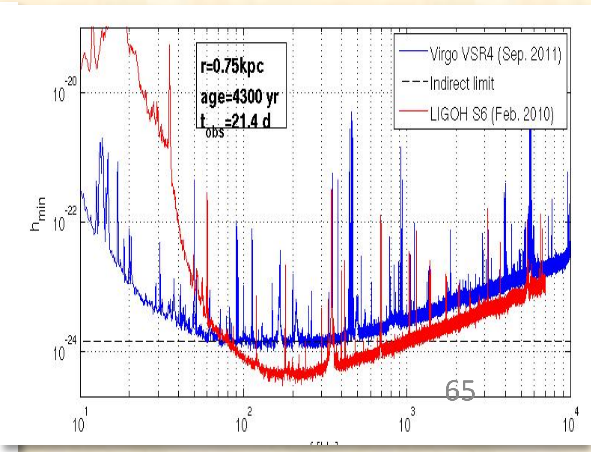
J0537-6910(~123.94Hz) [RXTE]

- Several among CCO.

(eg G266.2-1.2 - Vela Junior)

Distance and age uncertain





We are already heavily relying on the input from photon astronomers!


Robert C. Byrd Green Bank Radio Telescope


Parkes radio telescope


15 m XDM Telescope at Hartebeesthoek


Rossi X-ray Timing Explorer


Lovell Radio Telescope at Jodrell Bank

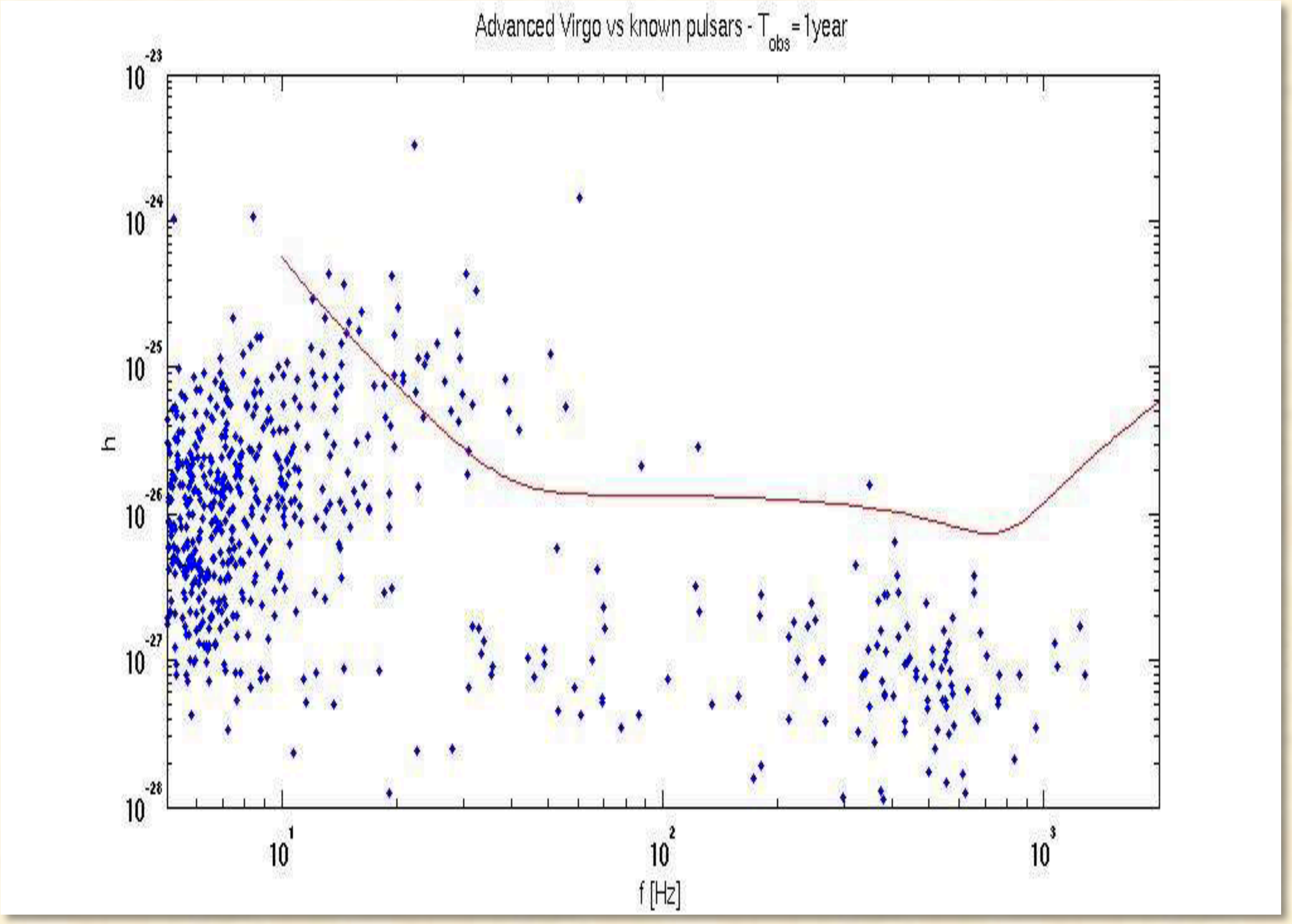

Nançay Decimetric Radio Telescope


Giant Metrewave Radio Telescope


Fermi Gamma-ray Space telescope

Pictures stolen from Matt Pitkin’s talk at last LVC meeting

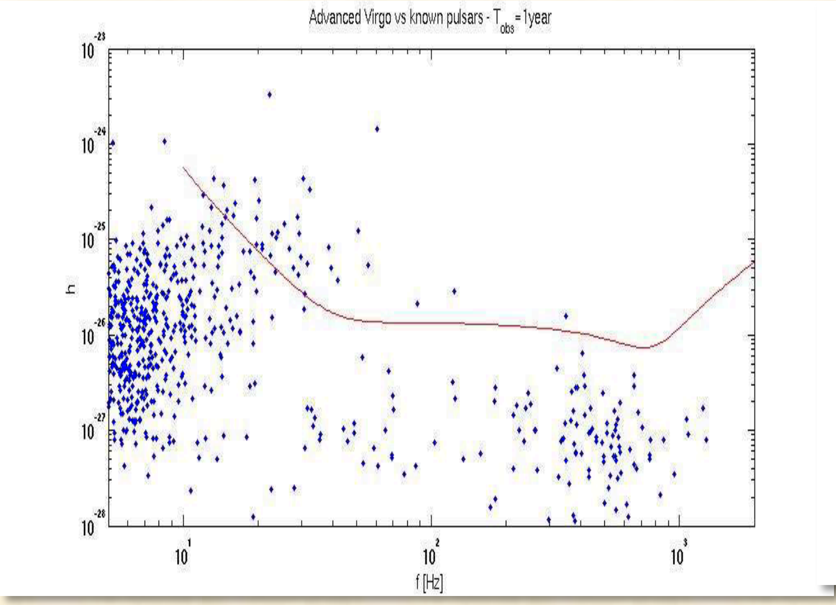
Expectations for the future

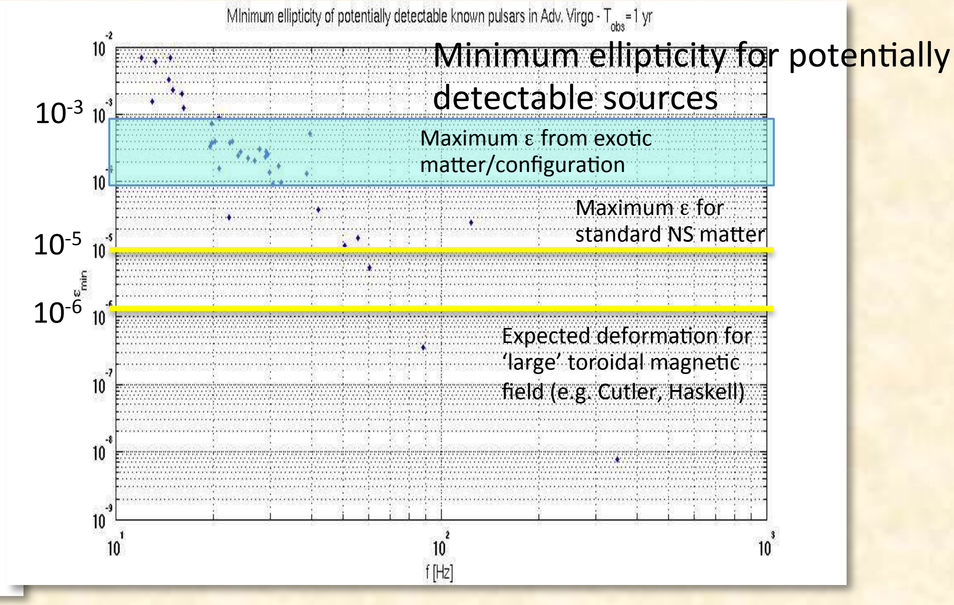


Advanced Virgo and LIGO detectors will start taking data around 2015-2016 (sensitivity ~1 order of magnitude better than 1st generation detectors over a wide frequency range).

Several new ‘accessible’ targets among currently known NS

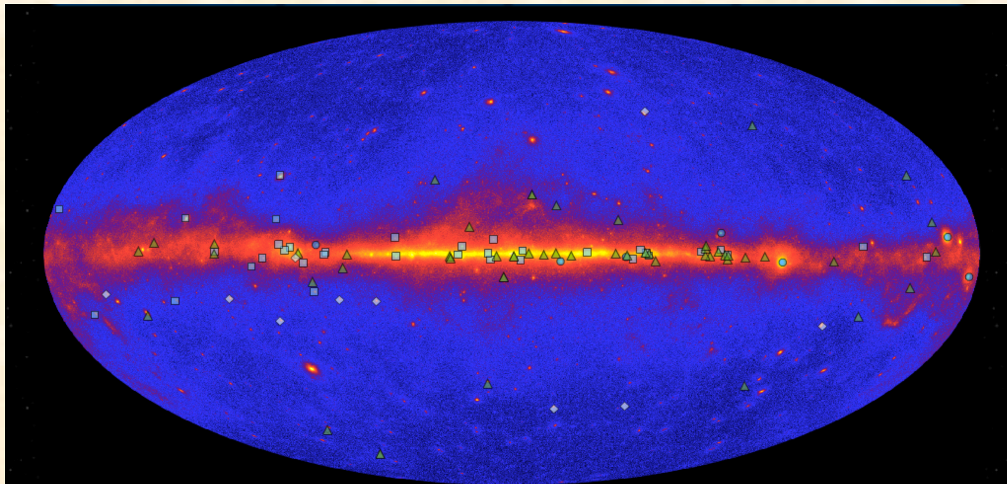
For a few objects a detection would be plausible!





Several new targets will be discovered in the meanwhile by telescopes on the Earth and in space, like Fermi-LAT.

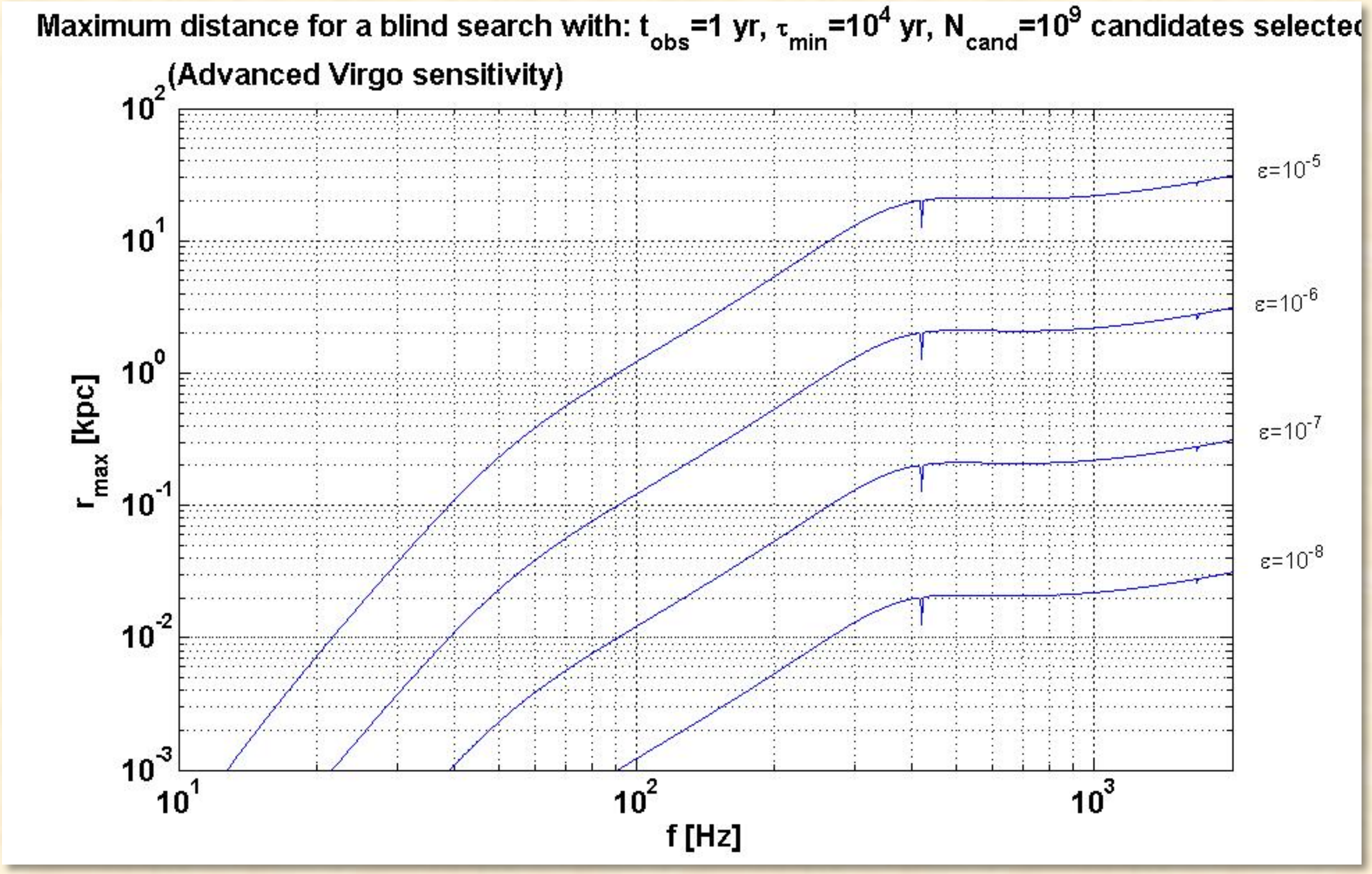
Fermi-LAT has already discovered several tens of previously unknown pulsars.



Abdo et al. Science 325, 840, 2009

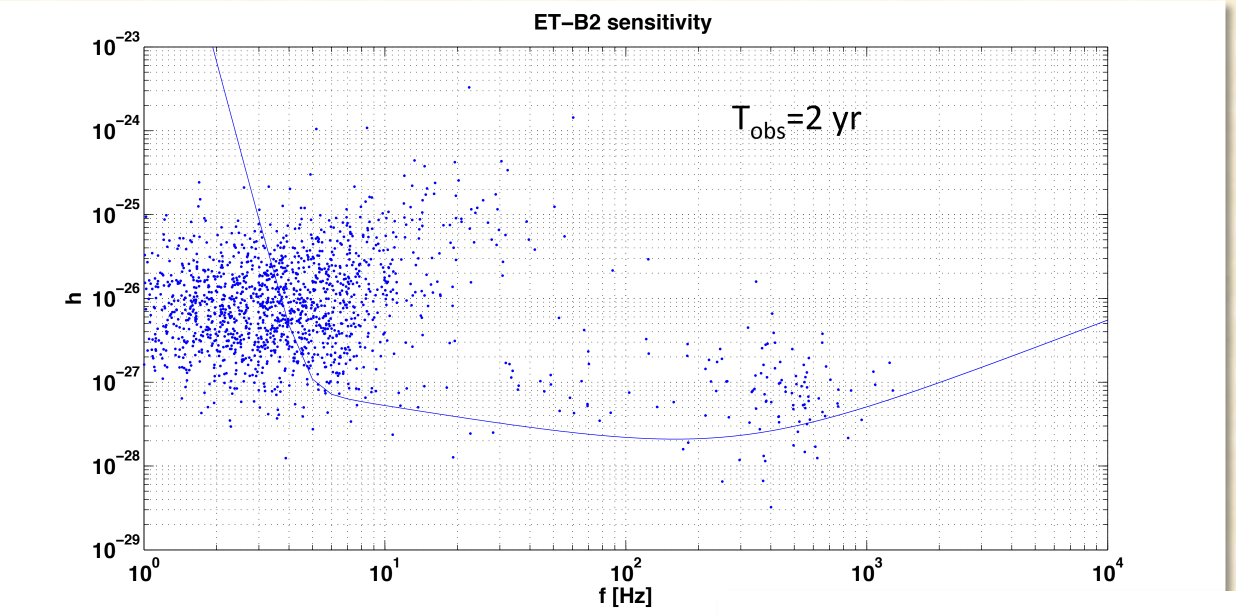
Many young pulsars are in the band of interferometers (if $f=2f_{rot}$):

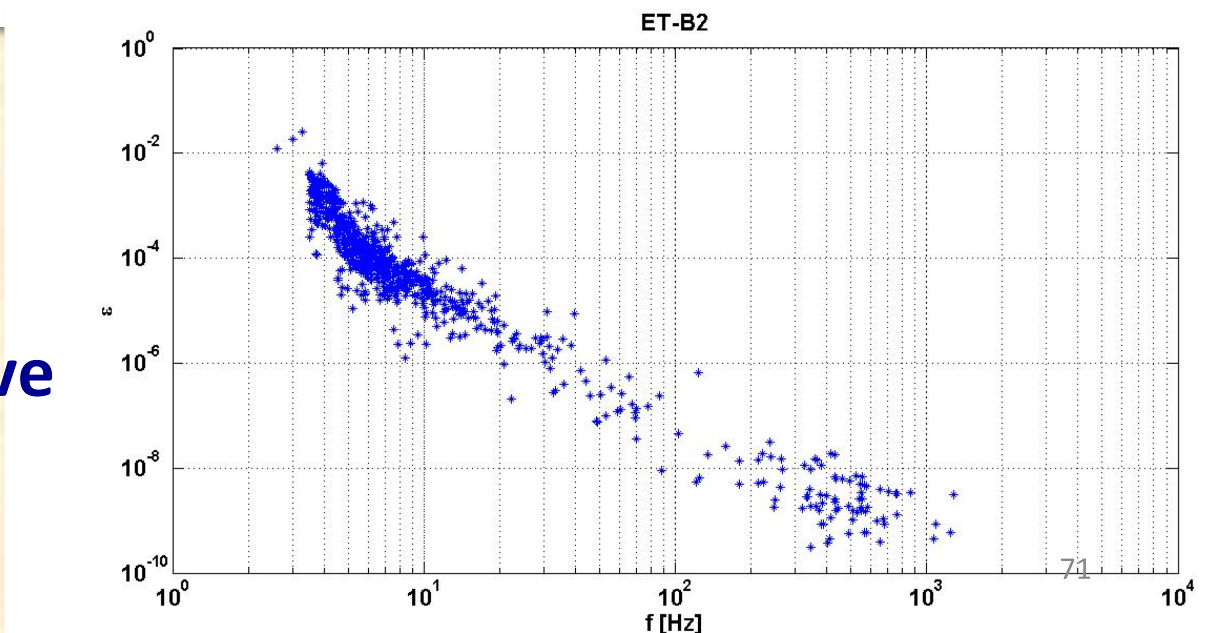
LAT PSR	n_γ	F_{35} (10^{-8} cm^{-2} s^{-1})	f (Hz)	$\dot{f}$ (-10^{-12} Hz s^{-1})	τ (years)
J0007+7303	1509	6.14(27)	3.1658891845(5)	3.6133(3)	13,900
J0357+32	294	0.64(10)	2.251723430(1)	0.0610(9)†	585,000
J0633+0632	648	1.60(17)	3.3625440117(3)	0.8992(2)	59,300
J1418−6058	3160	5.42(38)	9.0440257591(8)	13.8687(5)	10,300
J1459−60	1089	1.26(19)	9.694596648(2)	2.401(1)	64,000
J1732−31	2843	3.89(33)	5.087952372(2)	0.677(1)	119,000
J1741−2054	889	1.31(17)	2.417211371(1)	0.0977(7)	392,000
J1809−2332	2606	5.63(31)	6.8125455291(4)	1.5975(3)	67,600
J1813−1246	1832	2.79(24)	20.802108713(5)	7.615(4)	43,300
J1826−1256	4102	5.76(37)	9.0726142968(4)	9.9996(3)	14,400
J1836+5925	2076	8.36(31)	5.7715516964(9)	0.0508(6)	1,800,000
J1907+06	2869	3.74(29)	9.378101746(2)	7.682(1)	19,400
J1958+2846	1355	1.29(18)	3.443663690(2)	2.493(1)	21,900
J2021+4026	4136	10.60(40)	3.769079109(1)	0.7780(7)	76,800
J2032+4127	2371	3.07(26)	6.9809351235(8)	0.9560(4)	115,800
J2238+59	811	0.96(11)	6.145017519(3)	3.722(2)	26,200



With advanced ITF we can detect signals as far as the galactic centre and at high frequency.

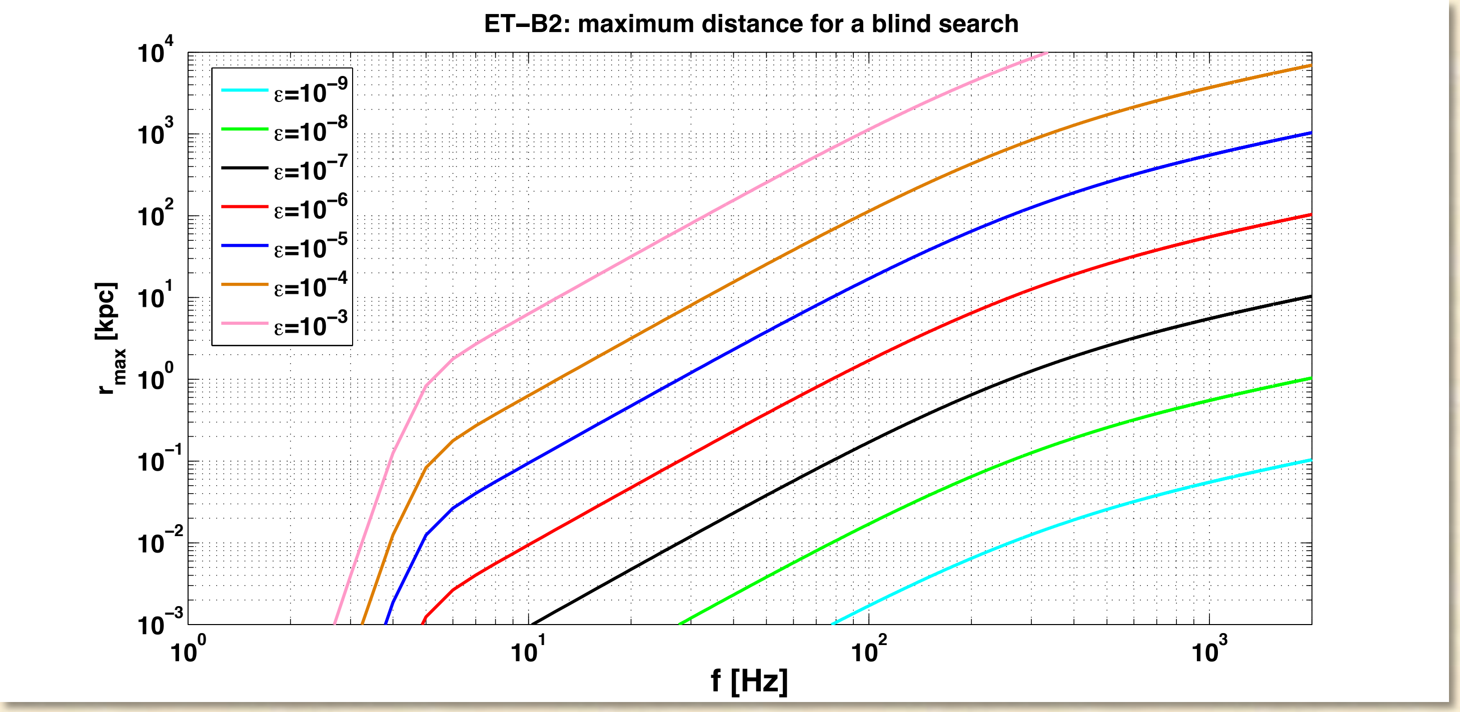
Expectation of detection are clearly still better for 3rd generation detectors, like the Einstein Telescope (~2025)





GW from several millisecond pulsars detectable if they have ellipticity >10^{-10} !!

Einstein Telescope will be able to detect fast unknown NS everywhere in the Galaxy with ellipticity ~10^{-7}



Close NS (say <1kpc) detectable with ellipticity < 10^{-8}

Conclusions

- The search for CW from known NS in data of current detectors has already provided some astrophysically interesting results (although no detection);

- The development of more effective GW analysis methods will continue: robustness respect to parameter uncertainty, search at $f \neq 2f_{rot}$, wandering frequency, analysis speed,…;

- Input from EM observations already play a fundamental role and will be even more important in the future: establishing a tighter link with EM observatories is crucial;

- EM observations will likely improve knowledge of parameters for many non-pulsing objects, thus reducing the parameter space to be explored in the search for GW. This will be particularly important e.g. for accreting LMXBs (like Sco X-1).

- Large improvements both in the number of interesting targets and in the relevance of results are expected for the advanced detector era and the next;

- **We must get ready to fully exploit GW and EM data!**