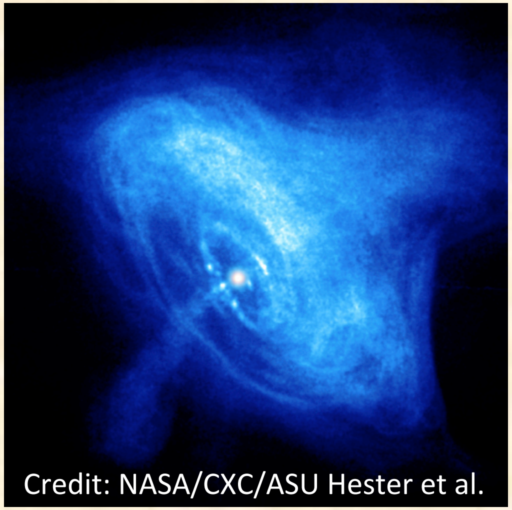
The search for continuous gravitational waves in LIGO and Virgo data

Cristiano Palomba (INFN Roma) for the **LIGO-Virgo Collaboration**


Credit: NASA/CXC/ASU Hester et al.

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Outline:

- Main aspects of CW searches
  - ✓ More details in Leaci/Mastrogiovanni/Piccinni talk/poster
- Highlights on initial detector results
- Some preliminary results from Advanced detectors

SciNeGHE– Pisa, October 18th -21th 2016

Sources of CW

- Asymmetric spinning neutron stars are the most obvious source of CW (for Earth-bound detectors).

- **We know that potential sources of CW exist**: 2400+ NS are observed (mostly pulsars) and O(10^8-10^9) are expected to exist in the Galaxy.

- A fraction of these is expected emit in the sensitivity band of detectors

- **We do not know the typical amplitude of the signals.**

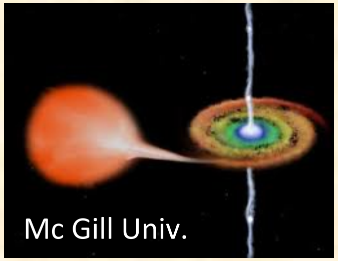
Signal amplitude: $$h_0 \cong 10^{-27}\left(\frac{I_{zz}}{10^{38}\,kg\cdot m^2}\right)\left(\frac{10kpc}{r}\right)\left(\frac{f}{100Hz}\right)^2\left(\frac{\varepsilon}{10^{-6}}\right)$$

ε : star ellipticity (adimensional number measuring the degree of asymmetry)

The ellipticity can be due to different mechanisms:

- ○ distortion due to elastic stresses or magnetic field ($f=2f_{rot}$);
- ○ distortion due to matter accretion, e.g. LMXB ($f=2f_{rot}$) ;
- ○ free precession around rotation axis ($f\sim k(f_{rot}+f_{prec})$, $k=1,2$);
- ○ excitation of long-lasting oscillations (e.g. r-modes, $f\sim 4/3f_{rot}$
- ○ …

Indiana Univ.



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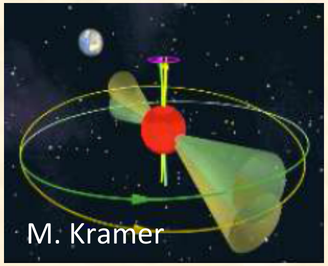


M. Kramer

Lamb, Rezzolla, Shapiro

- ○ Maximum value from $\sim 10^{-6}$ to $\sim 10^{-4}$ depending on the mechanism and on the star EOS

✧ **We do not know which are the typical values of ε.**

Searches for CW

- Main signal parameters: position in the sky, frequency, frequency derivative(s)
- signal duration very long respect to typical observation times! → S/N increases with time
- signals have very specific pattern in the time-frequency plane

  → "direct" power spectrum estimation (that would be ok for truly monochromatic signals) does not work

  → this helps in rejecting instrumental artifacts
- different algorithms depending on what we know about the source (targeted, directed, all-sky,… searches)

- We search for persistent signals of the form

$$h(t) = H_0\left(H_+A^+(t) + H_\times A^\times(t)\right)e^{j(2\pi f(t)+\varphi_0)}$$

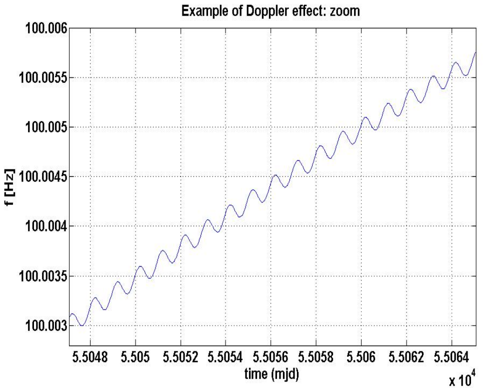
$$H_+ = \frac{\cos 2\psi - j\eta \sin 2\psi}{\sqrt{1+\eta^2}}$$

$$H_\times = \frac{\sin 2\psi + j\eta \cos 2\psi}{\sqrt{1+\eta^2}}$$

- The received frequency is a function of time due to:

- Doppler effect (+ relativistic effects)

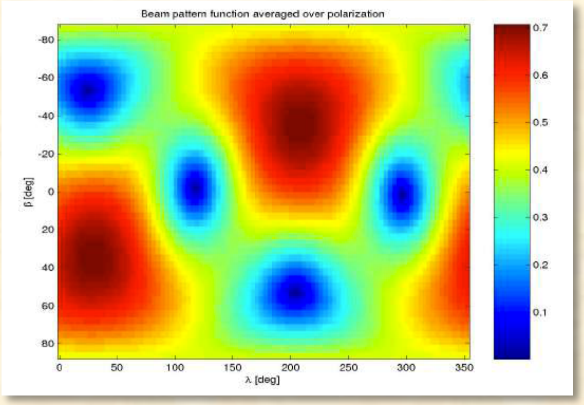
$$f(t) = f_0\left(1 + \frac{\vec{\mathbf{v}}\cdot\hat{n}}{c}\right), \quad \vec{\mathbf{v}} = \vec{\mathbf{v}}_{rev} + \vec{\mathbf{v}}_{rot}$$

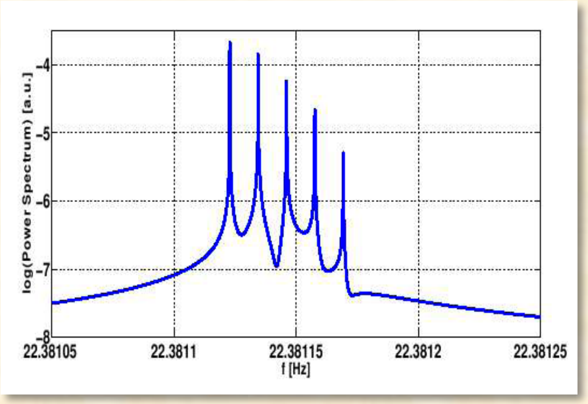


- Source spin-down

$$f(t) = f_0 + \sum_{n\geq 1} f^{(n)}\frac{(t-t_0)^n}{n!}$$

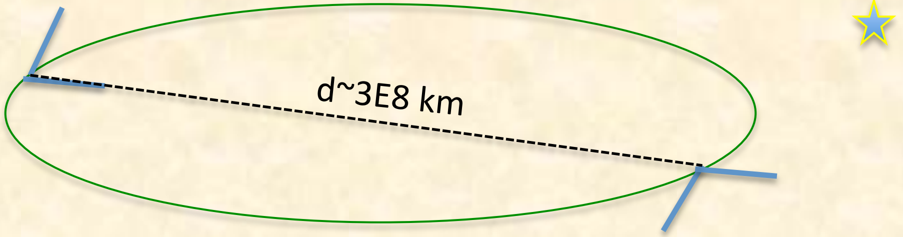
- There is also an amplitude and phase modulation, due to the detector sidereal response (encoded in A_+, A_x)

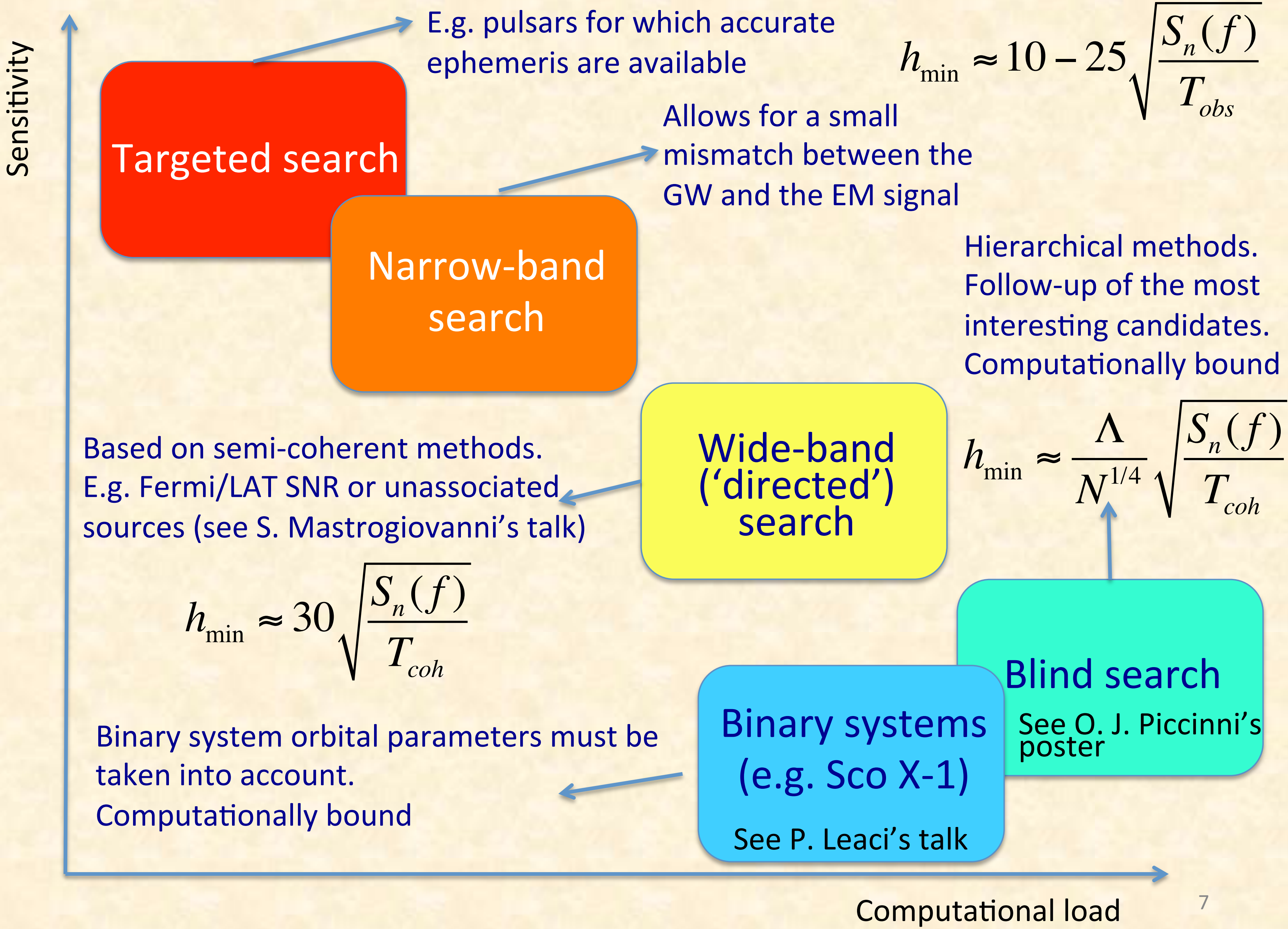




- Signal persistent nature allows to significantly increase the detection significance, and to pin down the NS parameters to extremely high accuracy **even with a single detector**

In practice, the detector makes a very large baseline network with itself





Sensitivity

Targeted search

Based on matched filter.
E.g. pulsars for which accurate ephemeris are available

$$h_{\min} \approx 10-25\sqrt{\frac{S_n(f)}{T_{obs}}}$$

Narrow-band search

Allows for a small mismatch between the GW and the EM signal

Wide-band (‘directed’) search

Based on semi-coherent methods.
E.g. Fermi/LAT SNR or unassociated sources (see S. Mastrogiovanni’s talk)

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

Blind search

See O. J. Piccinni’s poster

Hierarchical methods.
Follow-up of the most interesting candidates.
Computationally bound

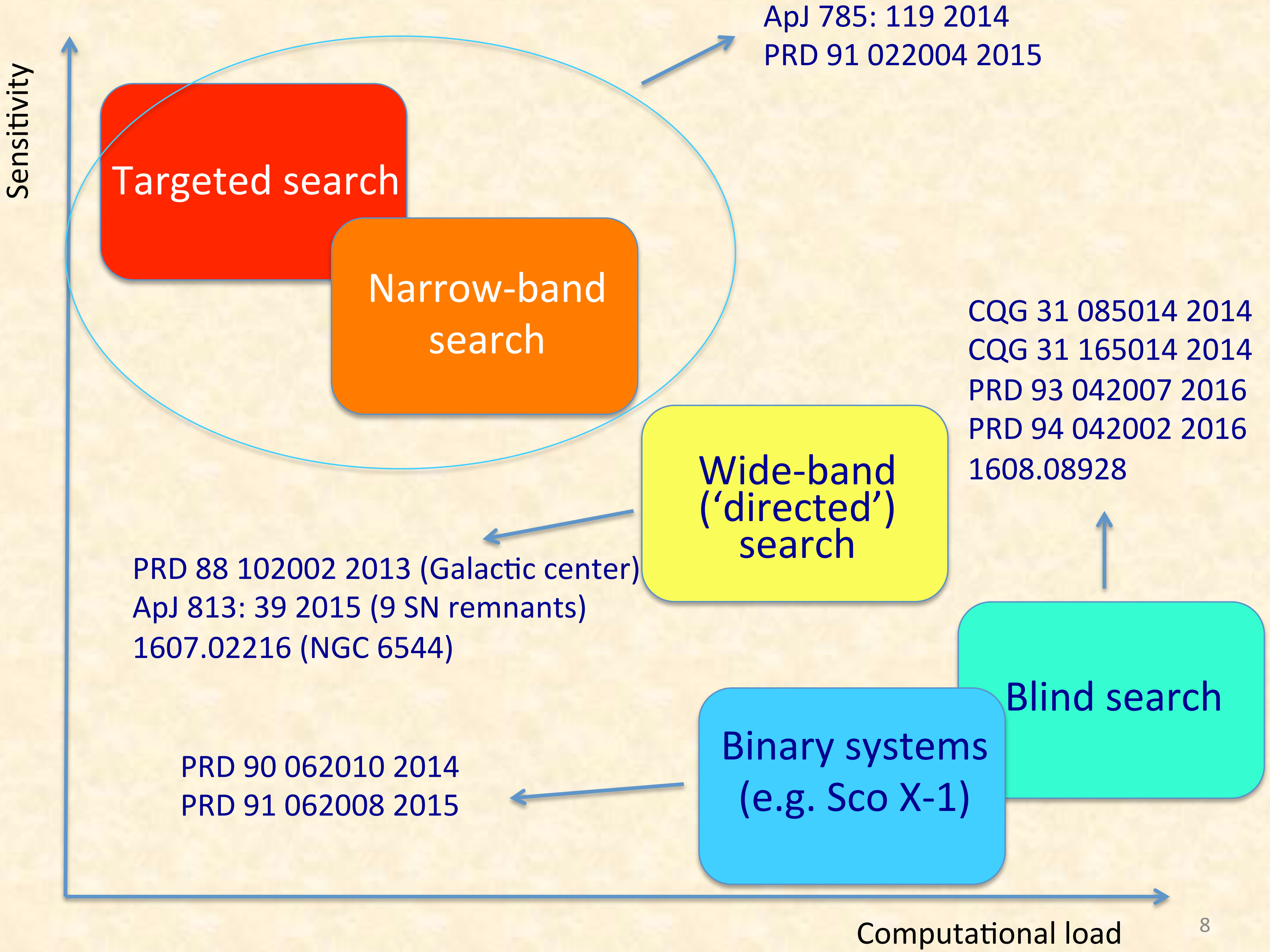
$$h_{\min} \approx \frac{\Lambda}{N^{1/4}}\sqrt{\frac{S_n(f)}{T_{coh}}}$$

Binary systems (e.g. Sco X-1)

See P. Leaci’s talk

Binary system orbital parameters must be taken into account.
Computationally bound

Computational load



Sensitivity

Targeted search

Narrow-band search

ApJ 785: 119 2014
PRD 91 022004 2015

Wide-band (‘directed’) search

PRD 88 102002 2013 (Galactic center)
ApJ 813: 39 2015 (9 SN remnants)
1607.02216 (NGC 6544)

Blind search

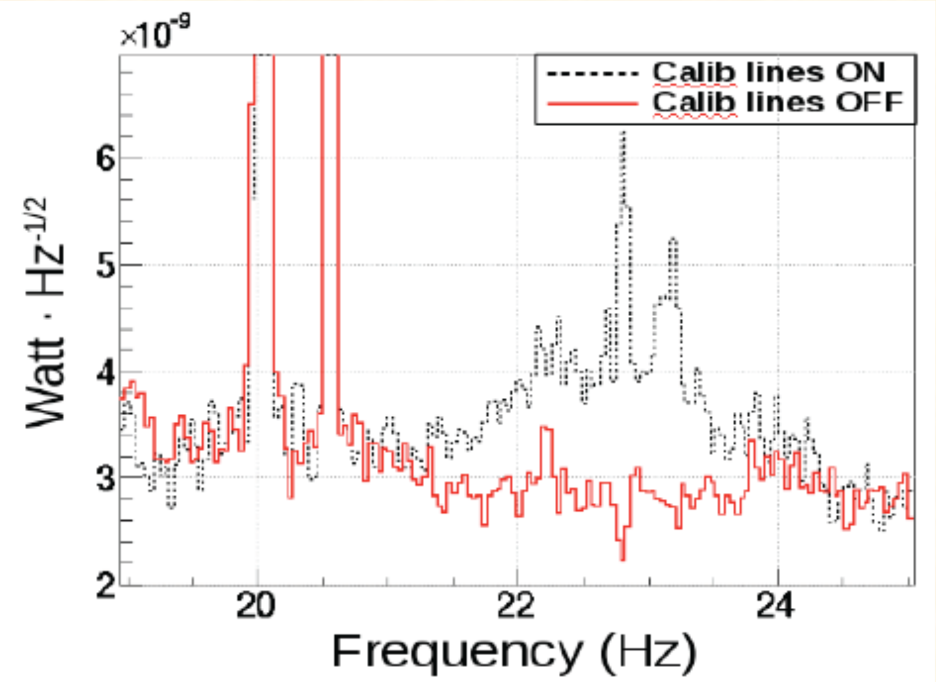
CQG 31 085014 2014
CQG 31 165014 2014
PRD 93 042007 2016
PRD 94 042002 2016
1608.08928

Binary systems (e.g. Sco X-1)

PRD 90 062010 2014
PRD 91 062008 2015

Computational load

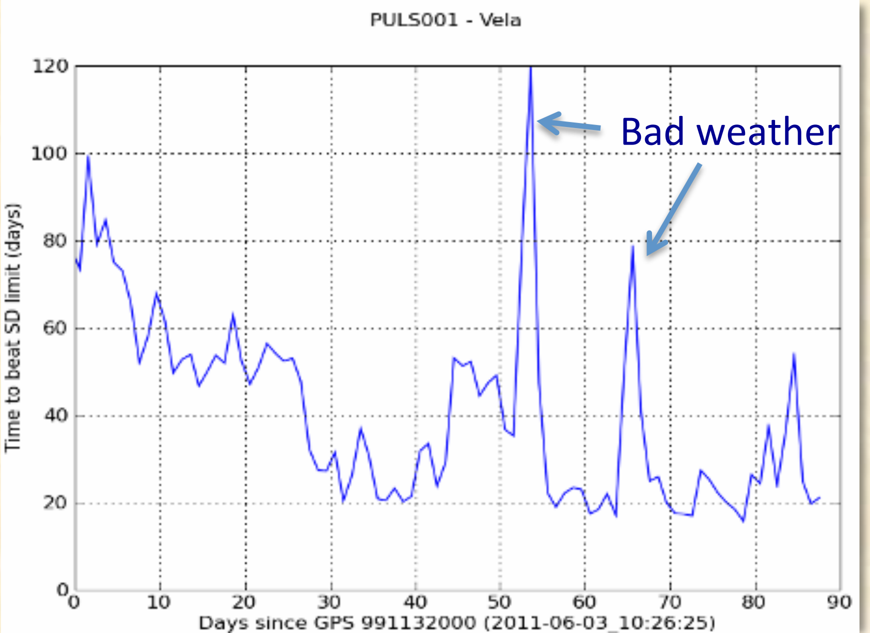
- Several types of disturbances affect real data. We must try as much as possible to identify and remove their source.



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

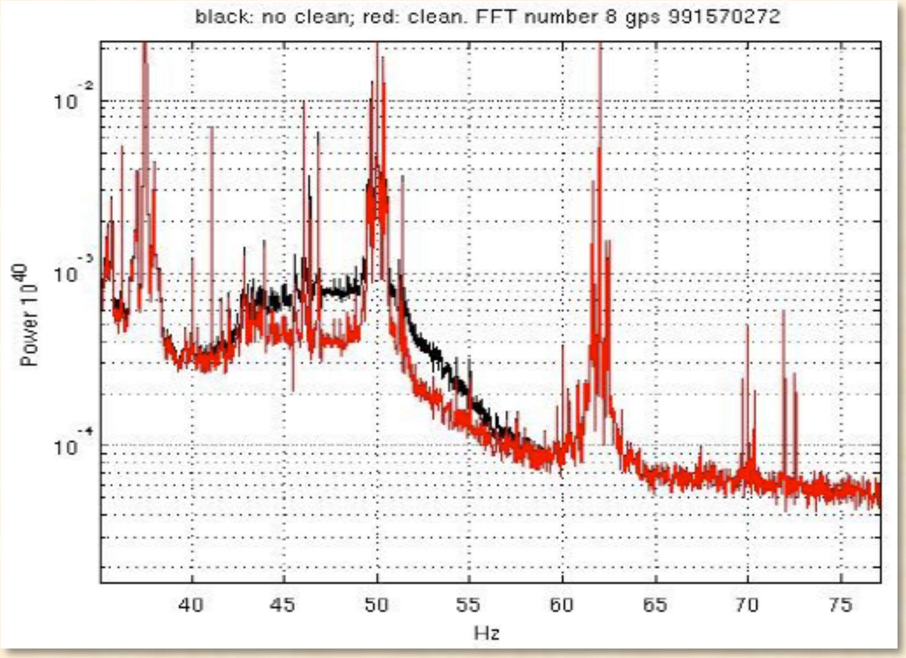
- Due to a complicate non-linear coupling between control and calibration lines.

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

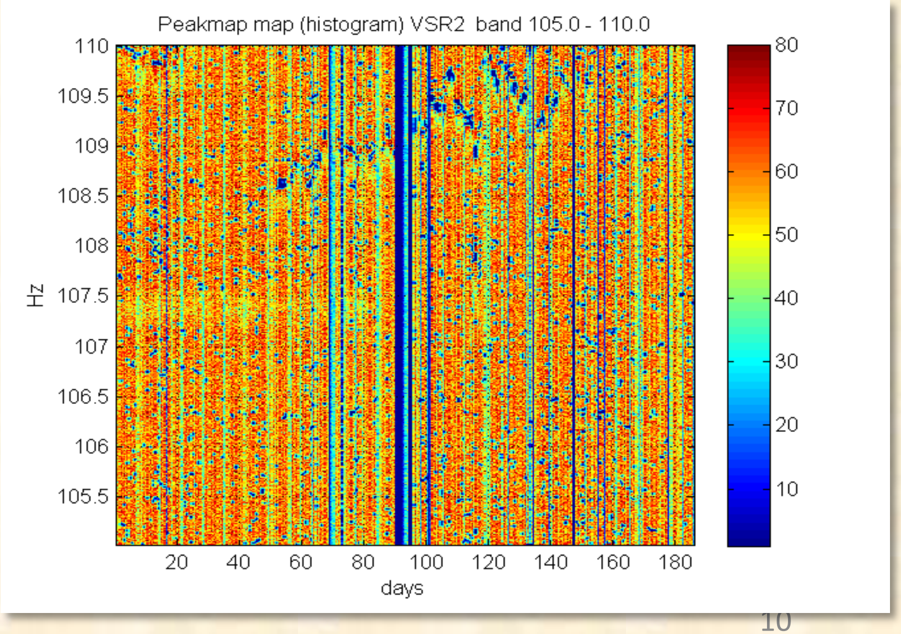


Bad weather

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

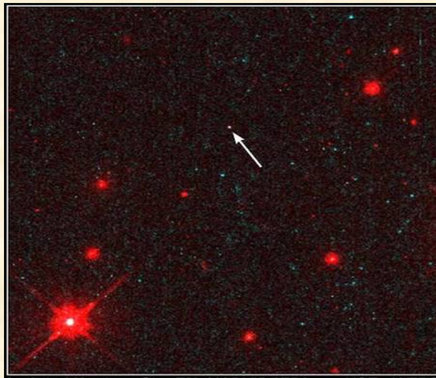


- "Lines" which have a recognized instrumental origin, or which clearly have a non-gravitational origin are also removed during the analysis:



Multi-messenger aspects of CW searches

- EM observations provide “alerts” on pulsar glitches.
- Updated pulsar ephemeris allows to make very sensitive targeted searches.
- EM observations can allow to restrict the parameter space for potential CW sources.



Isolated Neutron Star RX J185635-3754 HST • WFPC
PRC97-32 • ST Scl OPO • September 25, 1997
F. Walter (State University of New York at Stony Brook) and NASA

- They can also provide brand new potential CW sources. E.g. Fermi/LAT unidentified sources (see S. Mastrogiovanni’s talk).
- They can confirm GW sources after detection

Pay-off of detection

- Detection of CW would bring a lot of information:
  - Constraints on NS EOS
  - Evidence for differential rotation
  - Evidence for r-modes
  - Demography of "gravitars"
  - GR tests (number of polarizations, speed of gravitons, …)
  - Exotic processes (e.g. axion-black hole interaction)

- The persistent nature of CW would allow to make very accurate measures of the source parameters and to study tiny effects over long times

Some results from initial IFOs

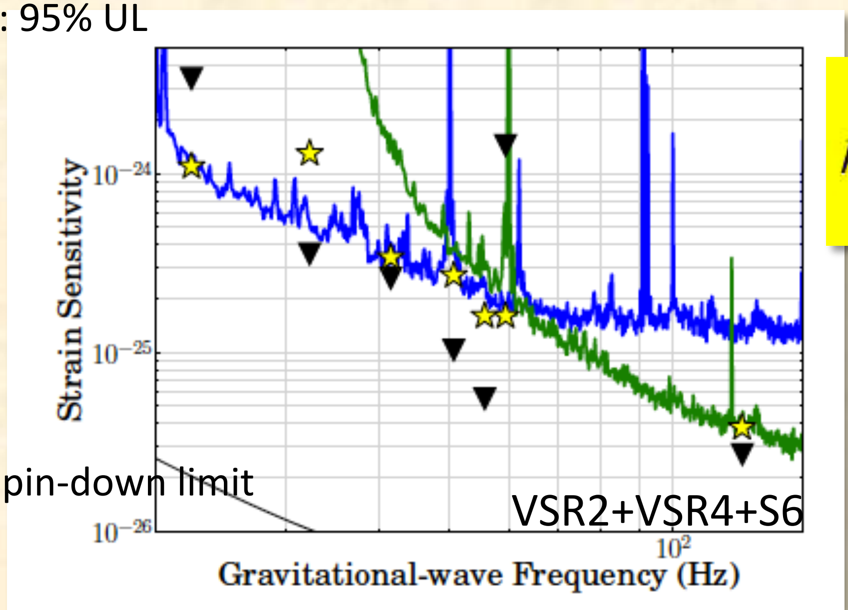
- The LVC has developed several pipelines to search for CW

- The cornerstones of CW searches are:
  - sensitivity
  - robustness with respect to signal uncertainties
  - computational load

- No detection so far, but some astrophysically interesting upper limits obtained.

❑ Targeted searches

☆: 95% UL



▼ : spin-down limit

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

J0534+2200
J0835-4510
J0537-6910
J1813-1246
J1833-1034
J1913+1011

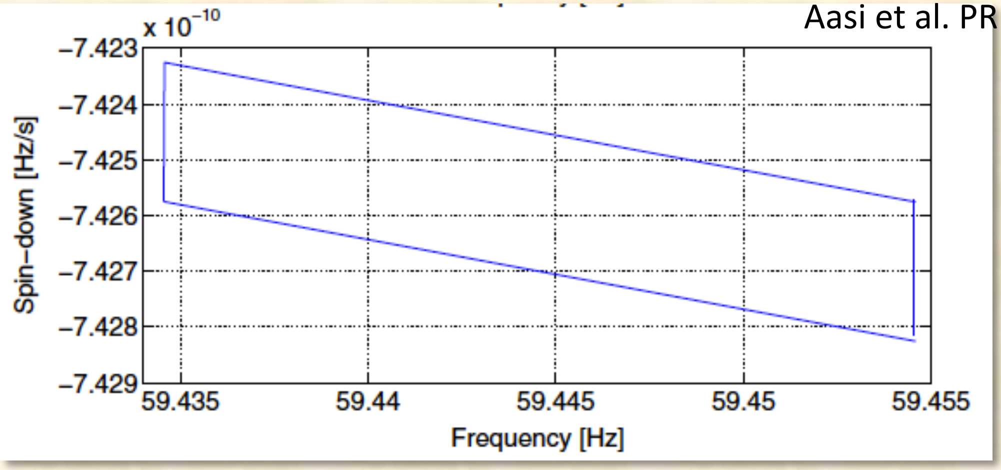
- **For Crab and Vela pulsars we are below the "spin-down limit"**: constraint the fraction of spin-down energy due to GW

Aasi et al., Apj 2014

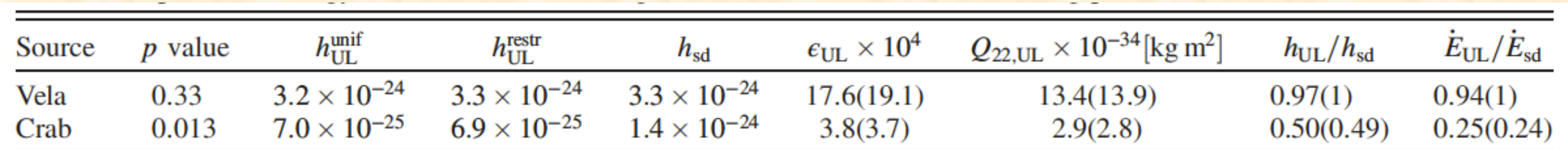
	$h_0^{95\%}$	ε	$h_0^{95\%}/h_0^{\rm sd}$	$\dot{E}_{\rm gw}/\dot{E}$ %
J0534+2200	1.8(1.6)x10^{-25}	9.7(8.6)x10^{-5}	0.12(0.11)	1.4(1.2)
J0835-4510	1.1(1.0)x10^{-24}	6.0(5.5)x10^{-4}	0.33(0.30)	11(9.0)

❑ Narrow-band search for Crab and Vela (VSR4)

- Possible mismatch between the GW frequency and 2 times the EM-inferred rotational frequency of the star



Aasi et al. PRD 022004 (2015)

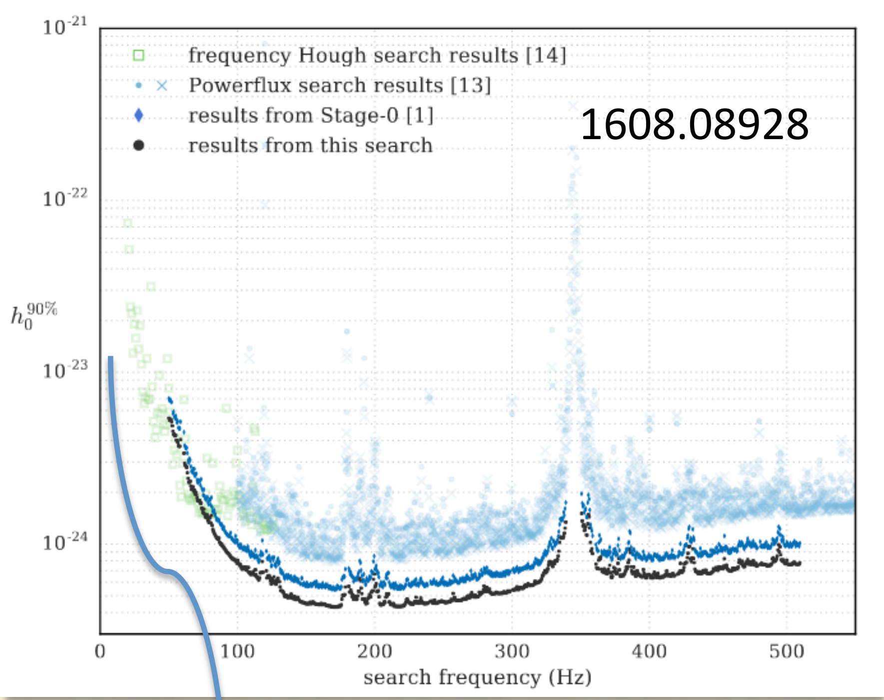


Source	p value	$h_{\mathrm{UL}}^{\mathrm{unif}}$	$h_{\mathrm{UL}}^{\mathrm{restr}}$	h_{sd}	$\epsilon_{\mathrm{UL}} \times 10^4$	$Q_{22,\mathrm{UL}} \times 10^{-34}[\mathrm{kg\ m}^2]$	$h_{\mathrm{UL}}/h_{\mathrm{sd}}$	$\dot{E}_{\mathrm{UL}}/\dot{E}_{\mathrm{sd}}$
Vela	0.33	3.2×10^{-24}	3.3×10^{-24}	3.3×10^{-24}	17.6(19.1)	13.4(13.9)	0.97(1)	0.94(1)
Crab	0.013	7.0×10^{-25}	6.9×10^{-25}	1.4×10^{-24}	3.8(3.7)	2.9(2.8)	0.50(0.49)	0.25(0.24)

- First time the spin-down limit has been significantly beaten in a narrow-band search

☐ All-sky searches:

- several pipelines
- most sensitive search to date by Einstein@Home



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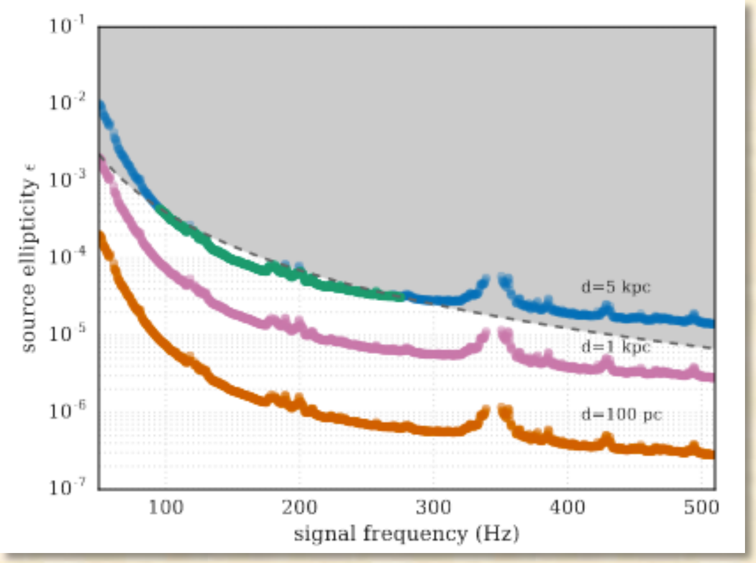


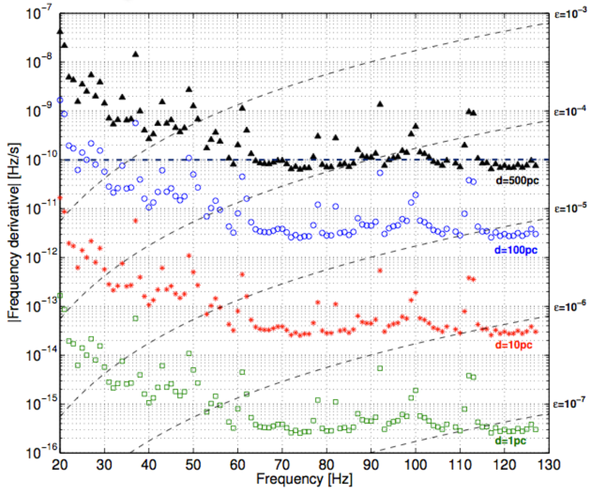


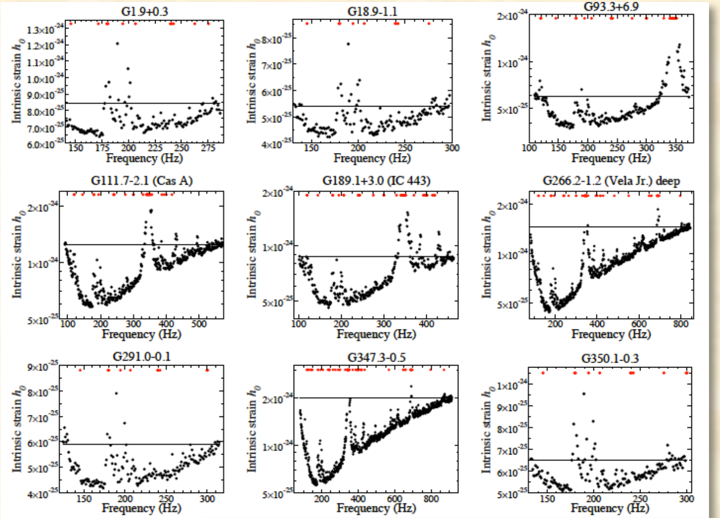
FIG. 13. Astrophysical reach of the search. The sets of points gives the relation between the frequency derivative and the frequency of a signal emitted by a detectable source placed at various distances. The triangles correspond to a distance of 500 pc; the circles to a distance of 100 pc; the stars to a distance of 10 pc and the squares to a distance of 1 pc. The dashed lines represents lines of constant ellipticity. The horizontal dot-dashed line indicates the maximum spin-down values searched in the analysis.

Low-frequency search on Virgo VSR2/VSR4 data

(PRD 93 042007 (2016))

- Directed searches for 9 SNR

ApJ 813 39 (2015)



- Directed search to the Galactic center

PRD88 102002 (2013)

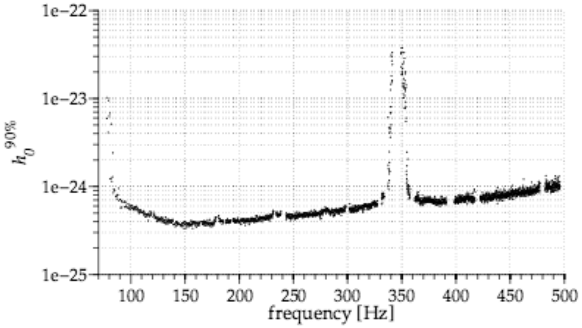
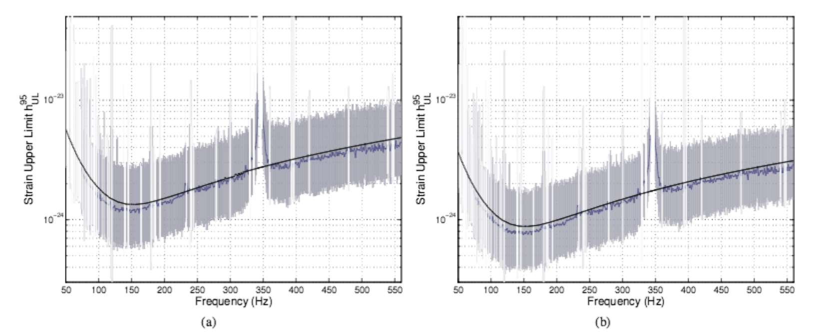


FIG. 1. This plot shows the 90% confidence upper limits on the intrinsic GW strain h_0 from a population of signals with parameters within the search space. The tightest upper limit is $\sim 3.35 \times 10^{-25}$ at $\sim$ 150 Hz. The large value upper limit values close to 350 Hz are due to residual spectral of the detectors' violin modes.

- Semi-coherent search for Sco-X1



(a)

(b)

FIG. 5. Gravitational wave strain 95% upper limits for H1L1 data from 21–31 Aug 2007 for (a) the standard search with flat priors on $\cos\iota$ and ψ (left panel) and (b) the angle-restricted search with $\iota = 44° \pm 6°$ and $\psi = 234° \pm 4°$ (right panel). The grey region extends from the minimum to the maximum upper limit in each 1-Hz sub-band. The median upper limit in each sub-band is indicated by a solid, thick, blue-grey curve. The expected upper limit for Gaussian noise at the S5 design sensitivity is shown for comparison (solid, thin, black curve). Whited regions of the grey band indicate bands that have been excluded (due to known contamination or vetoed out bands). No upper limits are quoted in these bands.

PRD91 062008 (2015)

CW searches in Advanced detector data

- O1 data are being analyzed by different pipelines, searching for CW. In particular, targeted searches for known pulsars have been done.
- For a few targets an upper limit on signal strain amplitude below the spin-down limit has been obtained

Spin-down limit:

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

- In these cases we are able to put a non-trivial constrain on the fraction of rotational energy lost by the pulsars through GWs
- These new results represent a significant improvement with respect to past analysis (cfr. ApJ 785:119 (2014))-> see slide 11

These numbers must be considered as PRELIMINARY!

	f_{GW} [Hz]	$UL_{90\%}$ (uniform priors)	$UL_{90\%}$ (restricted priors)	$E_{dot,GW}/E_{dot,rot}$	ε_{UL}
Crab	59.43	5.2E-26	5.0E-26	0.001	2.7E-5
Vela	22.39	2.9E-25	2.9E-25	0.007	1.5E-4
J1952+3252	50.59	3.7E-26	3.9E-26	0.09	3.4E-5
J2229+6114	38.74	5.6E-26		0.03	1.1E-4
J0205+6449	30.43	7.3E-26		0.03	2.4E-4
J1813-1246	41.60	5.5E-26		0.08	1.6E-3
J2043+2740	20.80	6.0E-25		0.42	1.5E-3

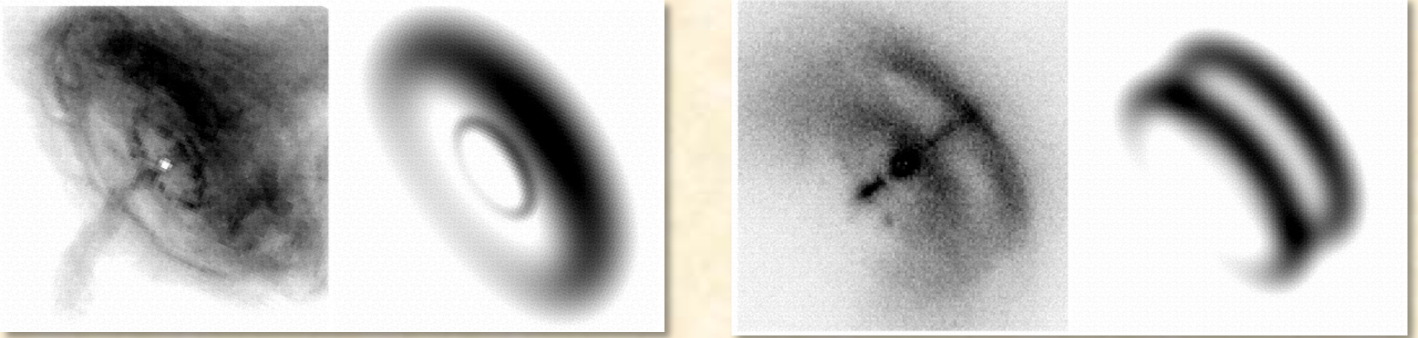
- Ephemerides covering O1 time span provided by various telescopes


Lovell Radio Telescope at Jodrell Bank


15 m XDM Telescope at Hartebeesthoek


Fermi/LAT

- "Restricted priors" ULs computed using an estimation of the signal polarization parameters deduced from X-ray observation of the PWN (Ng&Romani 2004, 2008)



Chandra images: Crab (left), Vela (right) and best fit models

- For Crab and Vela there is an improvement of a factor ~4 with respect to past analyses
- For Crab we can constrain the fraction of rotational energy lost to GW to about 1 part over 1000 (with corresponding limit on ellipticity in the 10^{-5} range)!
- J0205+6449 had a glitch around MJD 57345. Separate coherent analysis for the pre-glitch and post-glitch period, and incoherent combination of the two results

Conclusions

- A lot of physics and astrophysics can be done with CW.
- We are developing more sensitive, more robust and faster analysis pipelines (e.g. see O J Piccinni's poster).
- Input from photon astronomers is crucial to make better searches.
- More results on CW searches will be out in the next months.
- **Detection of CW from spinning neutron stars could be the next surprise of GW astronomy!**