Searches for continuous gravitational waves: recent results in data from the LIGO and Virgo detectors

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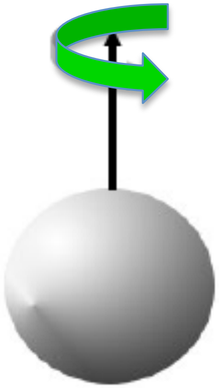
Outline

- Continuous Gravitational waves from spinning neutron stars
- Recent published results
- Advanced detector Era: future and prospects

Rotating neutron stars

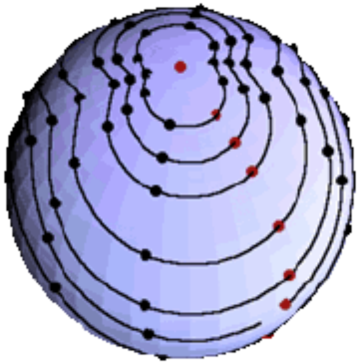
- Neutron stars can form from the remnant of stellar collapse.
- To emit continuous gravitational wave (GW) signals they must have some degree of asymmetry (ellipticity):
  - Deformation due to elastic stresses or magnetic field (in isolated or in accreting NS due to the accretion process);
  - Free precession of rotation axis of angular momentum;
  - Excitation of long-lasting oscillations (e.g. r-modes);…
- Typical size: radius=10 Km, and are about 1.4 solar masses.
- Some of these stars are observed as pulsars.
- Gravitational waves from neutron stars could tell us about the equation of state of dense nuclear matter.



Bumpy neutron star

Accreting neutron star

Precessing neutron star

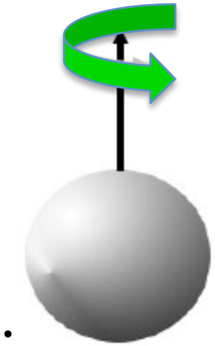


Oscillating neutron star

Continuous wave 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.
- For a triaxial neutron star rotating around a principal axis of inertia, the signal frequency is $f=2f_{rot}$.

Non-axisymmetric distortions



A non-axisymmetric neutron star at a distance *d*, rotating with frequency f_{rot} around the I_{zz} axis emits monochromatic GWs of frequency $f_{gw}=2f_{rot}$ received with an amplitude h_0:

$$h_0 = \frac{4\pi^2 G}{c^4} \frac{I_{zz}\epsilon f_{gw}^2}{d}$$

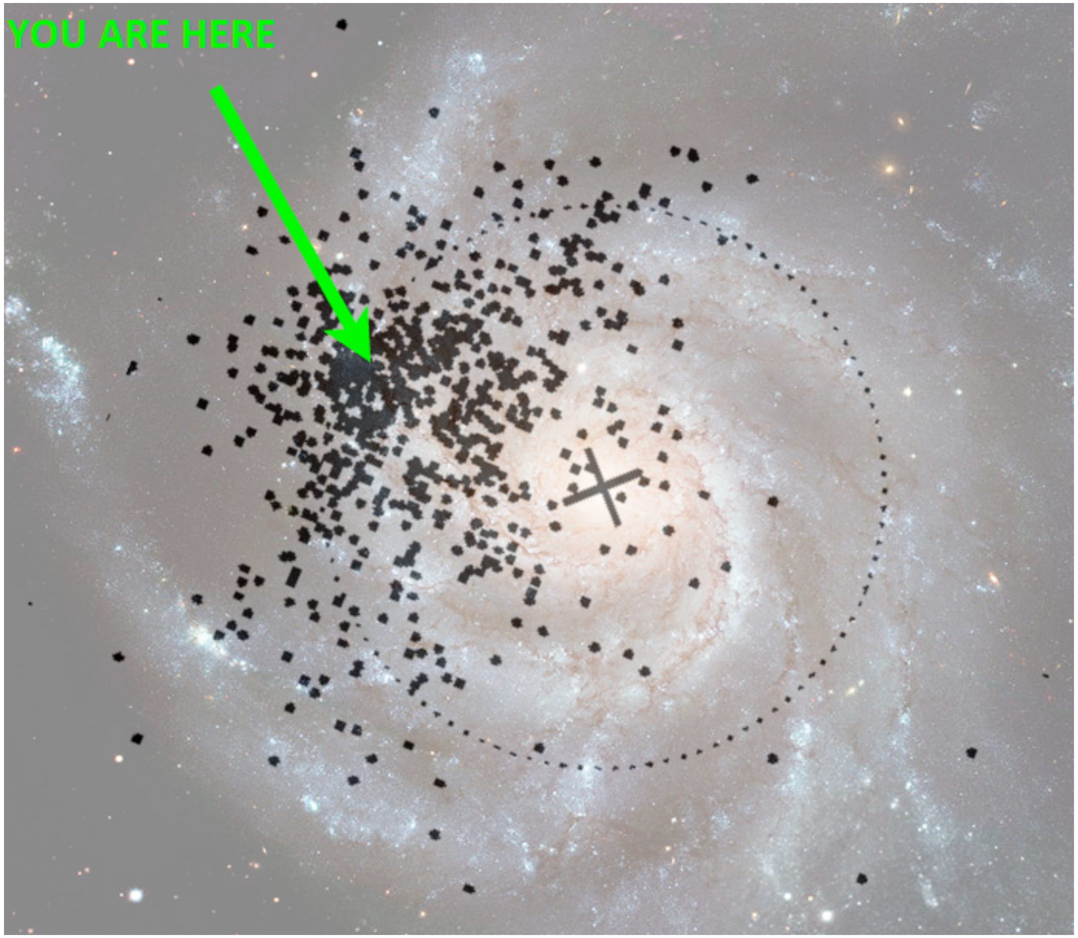
The strain amplitude h_0 refers to a GW from an optimally oriented source with respect to the detector.

The equatorial ellipticity, ε, is highly uncertain, $\varepsilon \sim 10^{-7}$. In the most speculative model can reach up to 10^{-4}.

$$\epsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$$

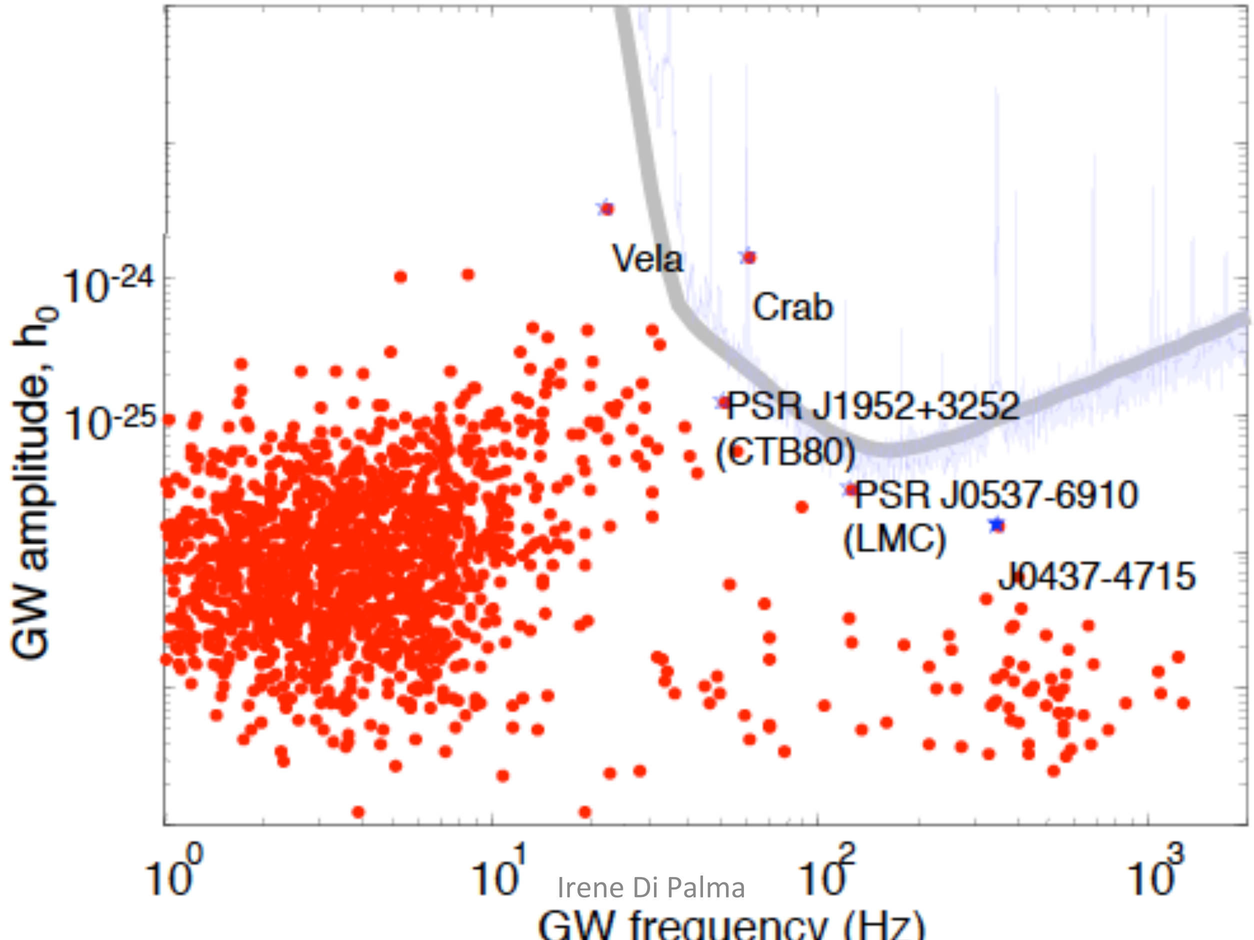
Neutron stars in the Galaxy

- There are probably $\sim 10^8$-10^9 neutron stars in the galaxy
  - $\sim 10^5$ are radio pulsars (we know of ~2300).
- We will see GWs from any neutron star that is
  - Sufficiently lumpy;
  - Sufficiently close;
  - Spinning at a rate that will appear in our band.



Important to search for unknown objects

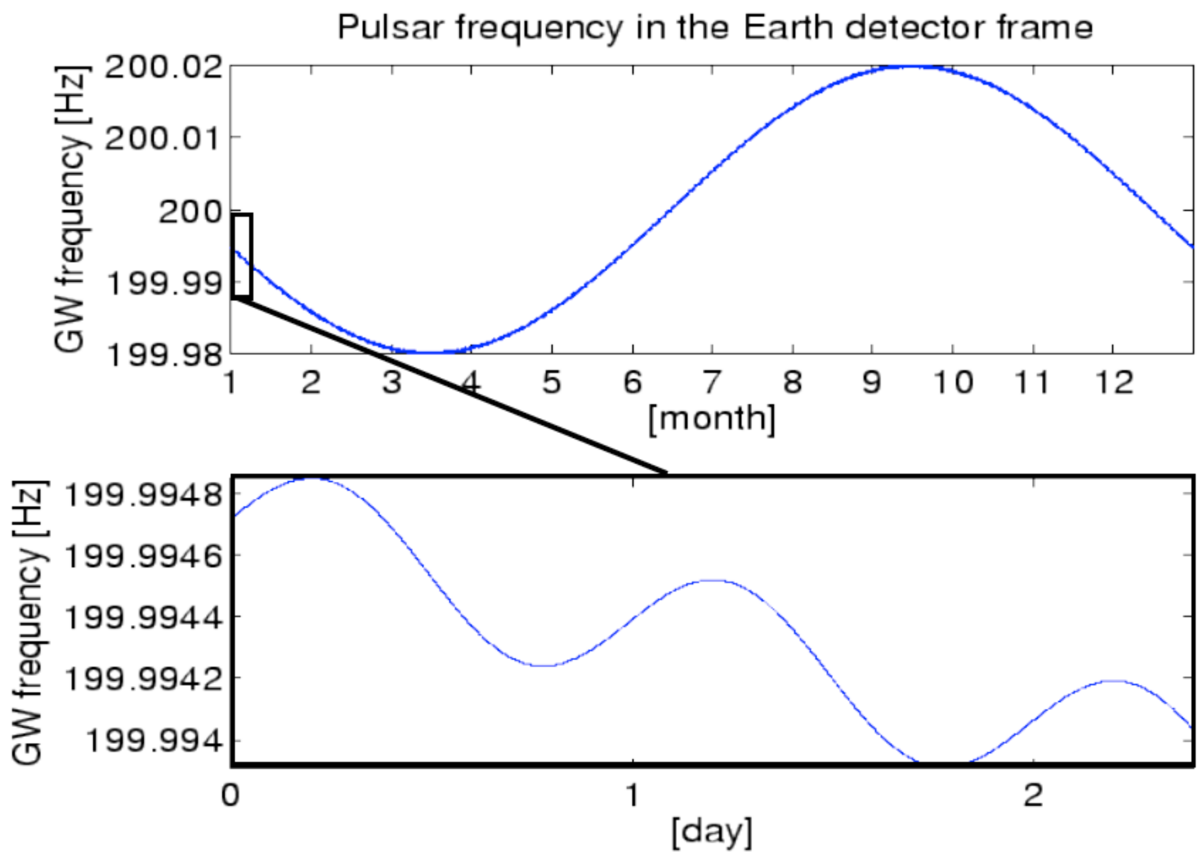
Most known (timed) pulsars are out of our band, and their maximum expected h_0 is below the initial LIGO/Virgo sensitivity (assuming 1 yr of coherent integration).



The signal at the detector

A gravitational wave signal from a NS will be:

- Frequency-modulated by the relative motion of the detector and source;
- Amplitude-modulated because of the time dependence of the sky-sensitivity pattern of the detector.



What is the “*direct spin-down limit*”?

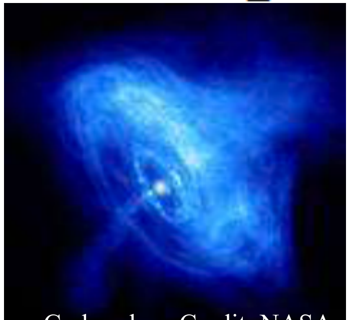
It is useful to define the “direct spin-down limit” for a known pulsar, under the assumption that it is a “gravitar”, i.e., a star spinning down only due to gravitational wave energy loss.

Unrealistic for known stars, but serves as a useful benchmark.

Equating “measured” rotational energy loss (from measured period increase and reasonable moment of inertia) to GW emission gives:

$$h_{SD} = 2.5 \times 10^{-25} \left[\frac{kpc}{d}\right] \sqrt{\left[\frac{1kHz}{f_{\mathrm{GW}}}\right]\left[\frac{-df_{\mathrm{GW}}/dt}{10^{-10}\,Hz/s}\right]\left[\frac{I}{10^{45}\,g \cdot cm^2}\right]}$$

Example:
Crab → $h_{SD} = 1.4 \times 10^{-24}$
(d=2 kpc, f_{GW} = 59.5 Hz, $df_{GW}/dt = -7.4 \times 10^{-10}$ Hz/s)



Crab pulsar. Credit: NASA

Recent results

The LIGO Scientific Collaboration and Virgo Collaboration have carried out joint searches in LIGO and Virgo data for periodic continuous gravitational waves. These searches can be broadly classified according to

- *Targeted* searches: known pulsars with timing from radio, X-ray or γ-ray observations can be used => *O(laptop).*
- *Directed* searches: known direction of the star but no frequency information => *O(cluster).*
- *All-sky* searches: no information about location or frequency. => *computing challenge.*

Analysis strategies depend critically on parameter space volume to be searched, which itself depends on high powers of the coherent times of integration steps used in the search.

Targeted **searches**

When the source parameters:

✓ position,

✓ frequency,

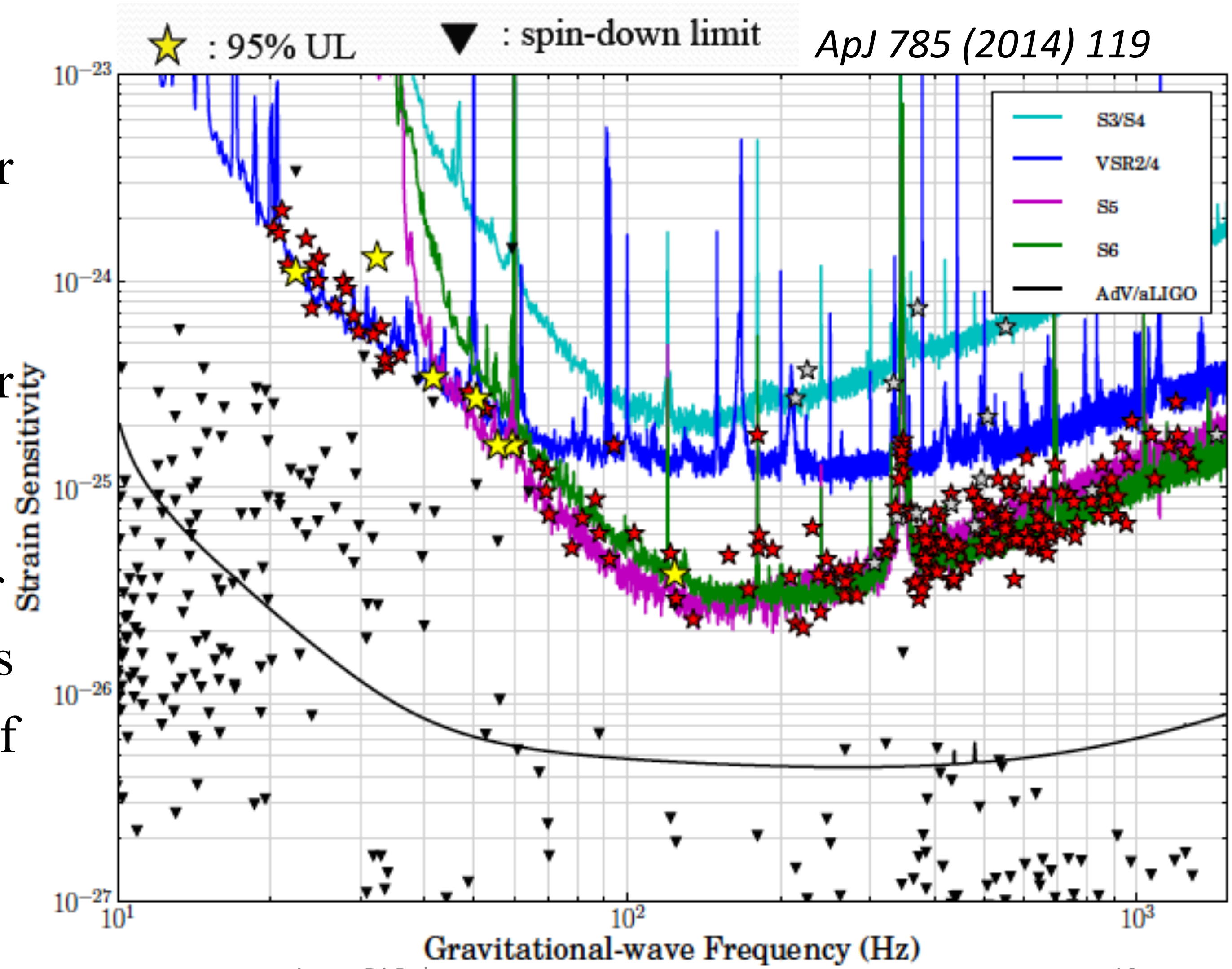
✓ spin-down,

are known with high accuracy *targeted* searches can be done using optimal analysis methods, based on matched filtering.

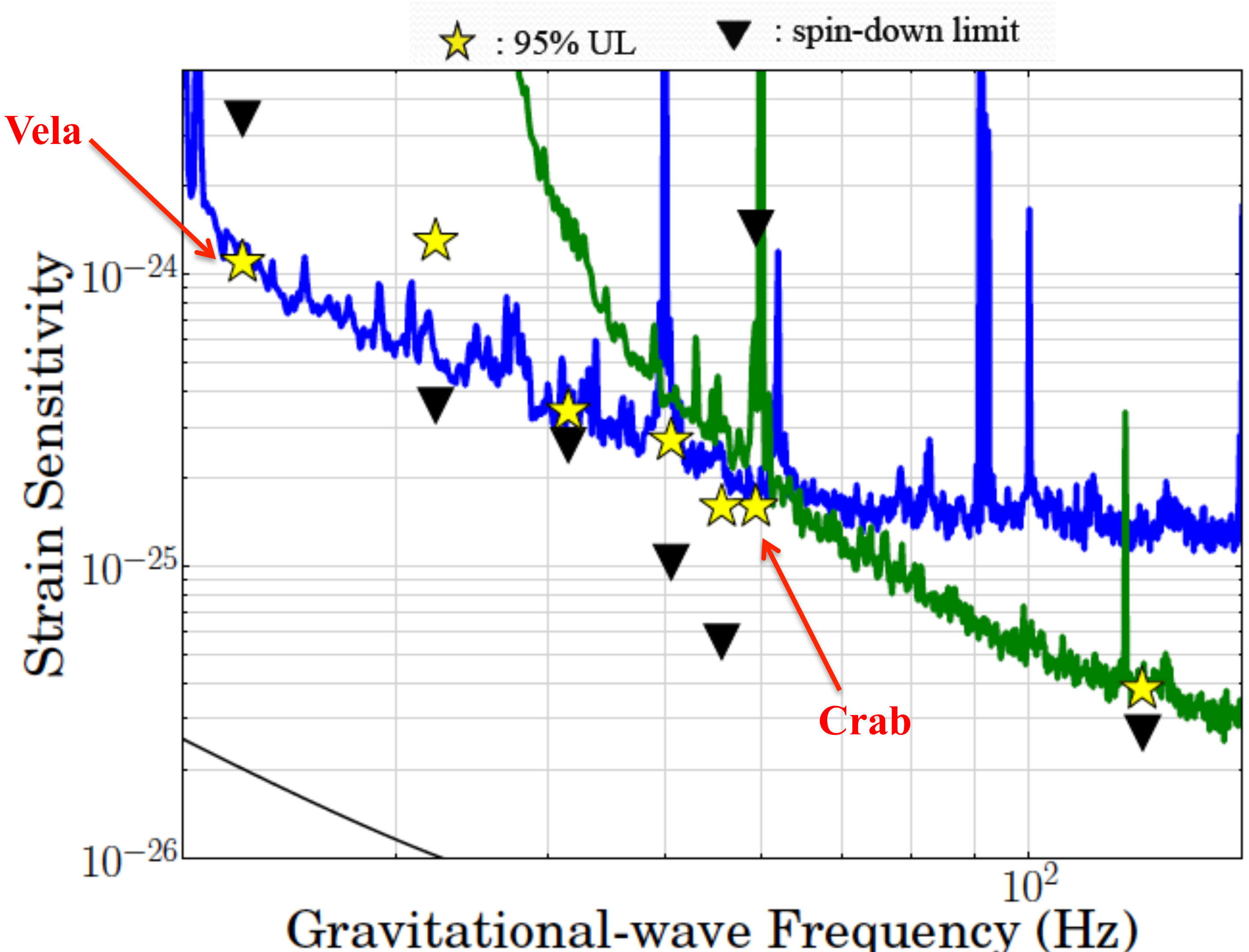
Targeted (matched filter) algorithm applied to **195 known pulsars** over LIGO S5/S6 and Virgo VSR2/VSR4 data

- Lowest (best) upper limit on strain: $h_0 < 2.1 \times 10^{-26}$
- Lowest (best) upper limit on ellipticity: $\varepsilon < 6.7 \times 10^{-8}$
- Crab limit at 1% of the total energy loss
- Vela limit at 10% of total energy loss

ApJ 785 (2014) 119

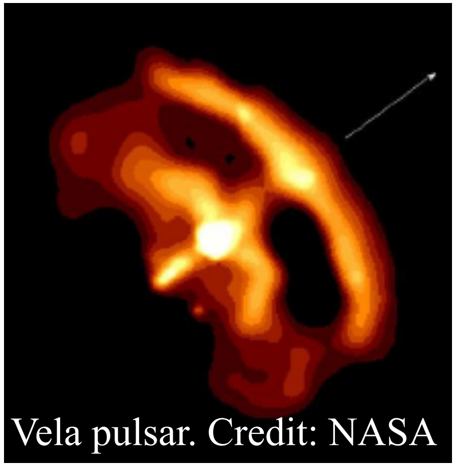


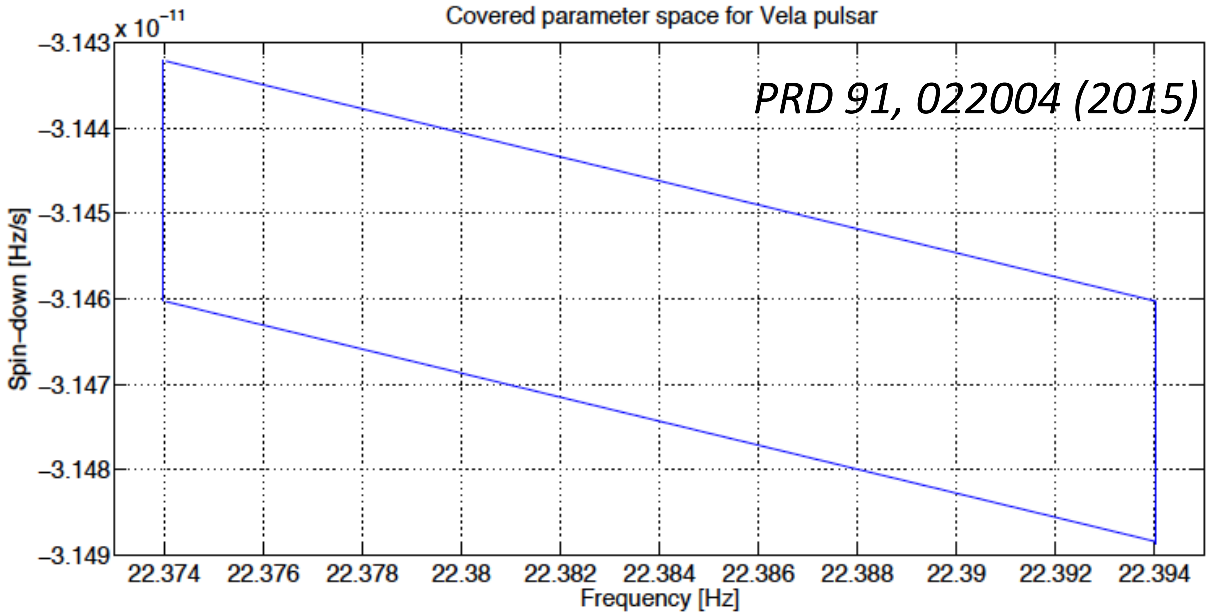
For seven of these 195 known pulsars we have produced Uls below or near the spin-down limit.



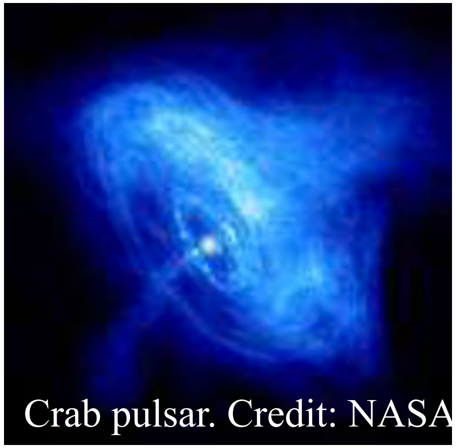
J0534+2200 (Crab)
J0537-6910
J0835-4510 (Vela)
J1813-1246
J1833-1034
J1913+1011
J1952+3252

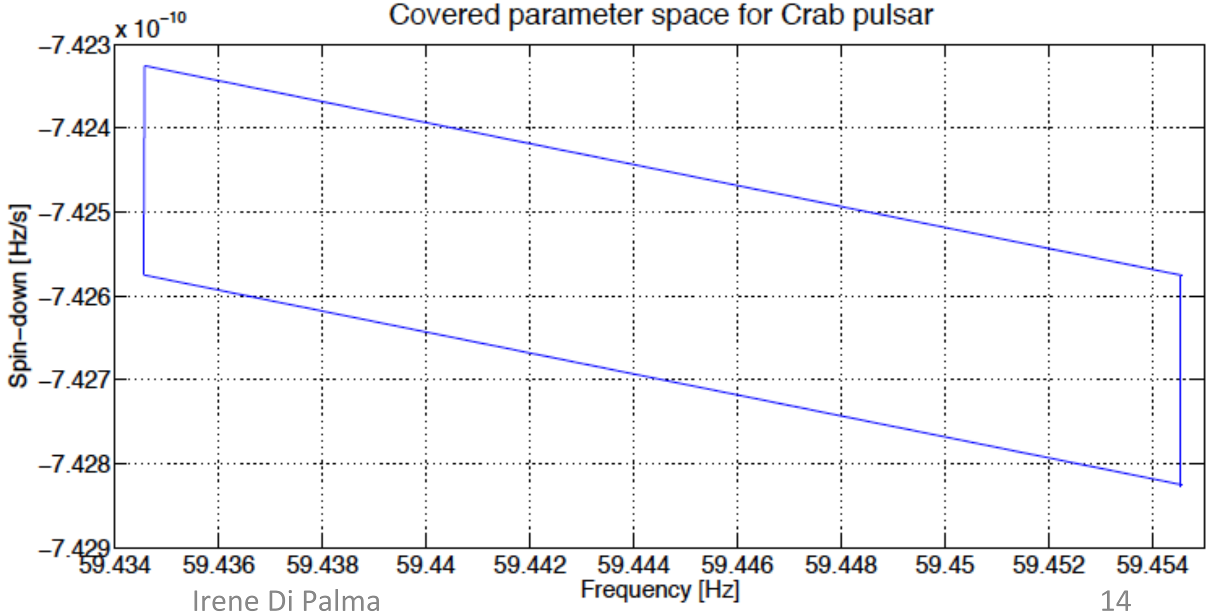
Targeted search for **Crab** and **Vela pulsars** on Virgo VSR4 data.





PRD 91, 022004 (2015)





For the **Crab** and **Vela pulsars** we are below the spin-down limit, constraint on the fraction of spin-down energy due to gravitational wave.

- In the case of the Crab pulsar the upper limits on signal strain amplitude are about 2 times below the spin-down limit, with a corresponding constraint of about 25% on the fraction of spin-down energy due to gravitational waves.
- The upper limit on signal strain can be converted into an upper limit on star ellipticity of about ε~3.7 x 10^{-4}, assuming the neutron star moment of inertia is equal to the canonical value of 10^{38} kg m^2

Source	p-value	h_{UL}^{unif}	h_{UL}^{restr}	h_{sd}	$\epsilon_{UL} \times 10^4$	$Q_{22,UL} \times 10^{-34}$ [kg m^2]	h_{UL}/h_{sd}	$\dot{E}_{UL}/\dot{E}_{sd}$
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)

Pulsar ephemerides provided by several telescopes

Robert C. Byrd Green Bank Radio Telescope

Parkes radio telescope

15 m XDM Telescope at Hartebeesthoek

Lovell Radio Telescope at Jodrell Bank

Nançay Decimetric Radio Telescope

Giant Metrewave Radio Telescope

Directed searches

In these searches the sky localization is known but the frequency and other parameters are not.

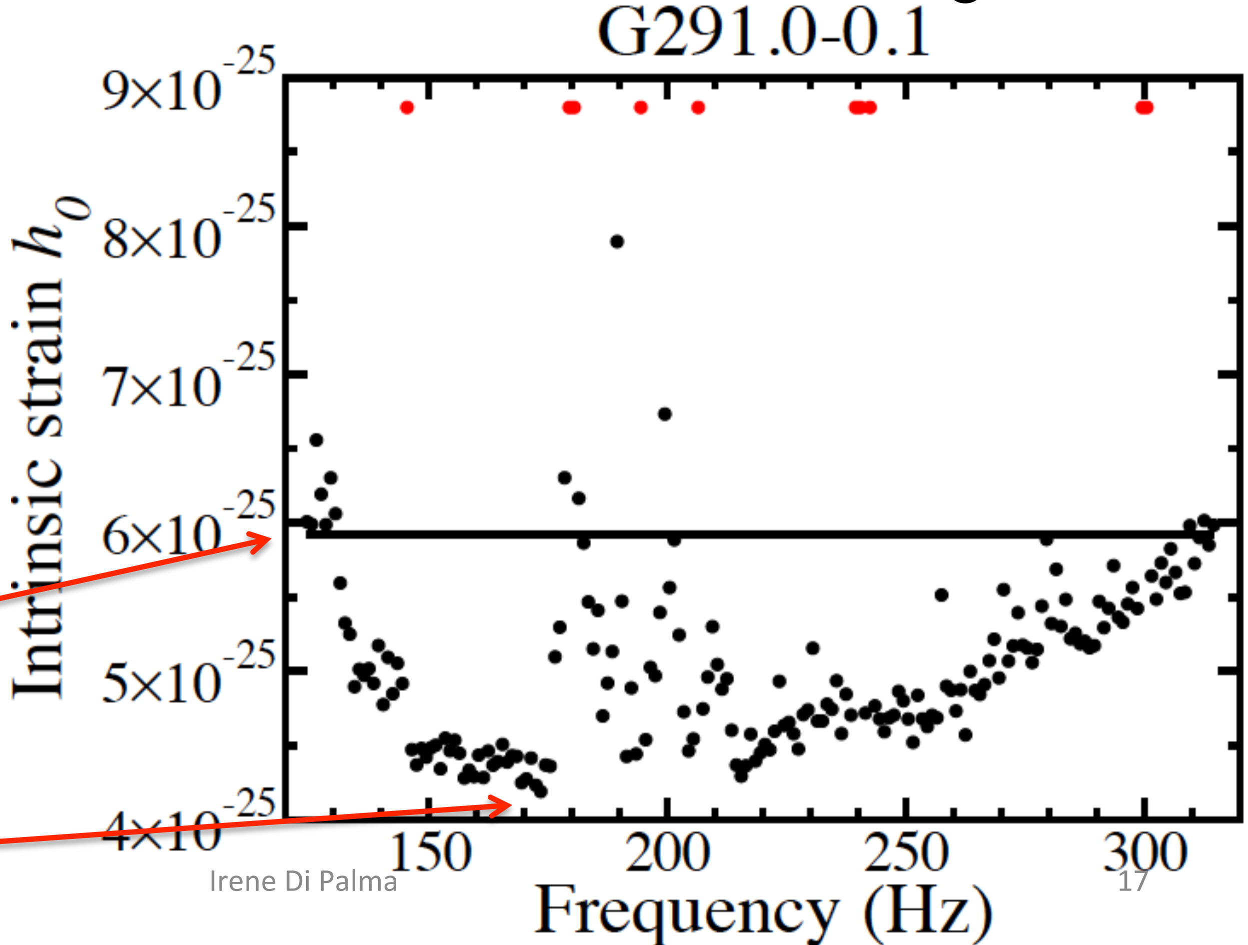
Directed searches for Continuous Gravitational Waves from:

- 9 young supernovae remnants (*arXiv:1412.5942*);
- Galactic Center region (*PRD 88, 102002 (2013)*);
- Cassiopeia A (*ApJ 722 (2010) 1504*);
- Low Mass X-ray binary Scorpius X-1 (*PRD 91, 062008 (2015)*).

Directed search for CWs from **9 young supernovae remnants,** not associated with pulsars, with known position and unknown rotational parameters.

arXiv:1412.5942, submitted to ApJ

- ✓ Integration time in the range 5-25 days.
- ✓ Upper limit is below indirect limit based on distance and age.
- ✓ 95% confidence upper limits as low as 4×10^{-25} on instrinsic strain and 2×10^{-7} on fiducial ellipticity, and 4×10^{-5} on r-mode amplitude.



Indirect upper limit based on age of and distance to the remnants

Best upper limit @170 Hz
$h_0 = 4.2 \times 10^{-25}$

Directed search for CWs from unknown, isolated neutron stars in the direction of the **Galactic Center.**

- At least three stellar clusters in the GC region contain massive stars, making this a promising target.
- Because of this overabundance of massive stars, it is assumed to contain also a large number of neutron stars.
- Massive stars are believed to be the progenitors of neutron stars: the star undergoes a supernovae explosion and leaves behind the neutron star.

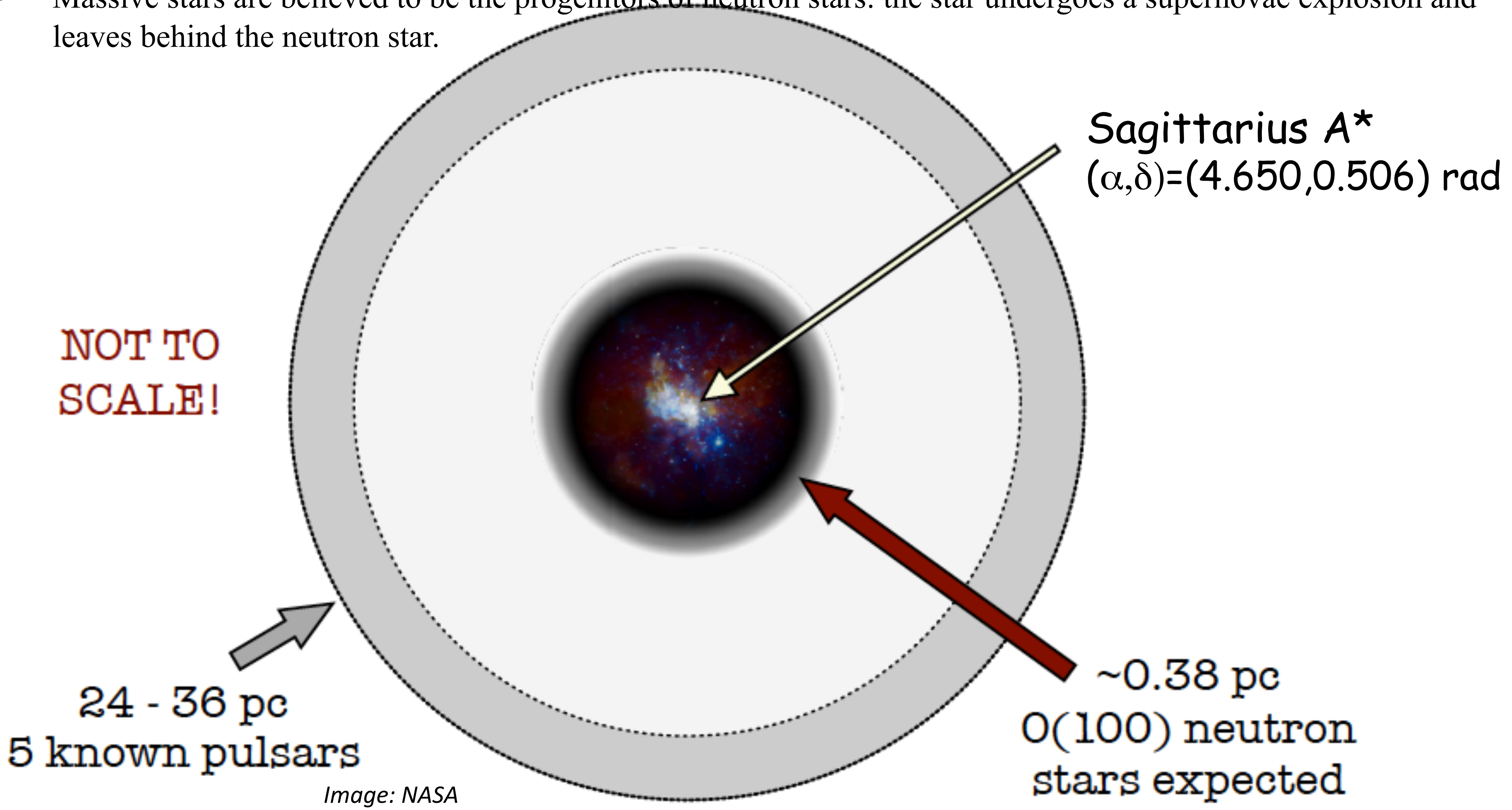
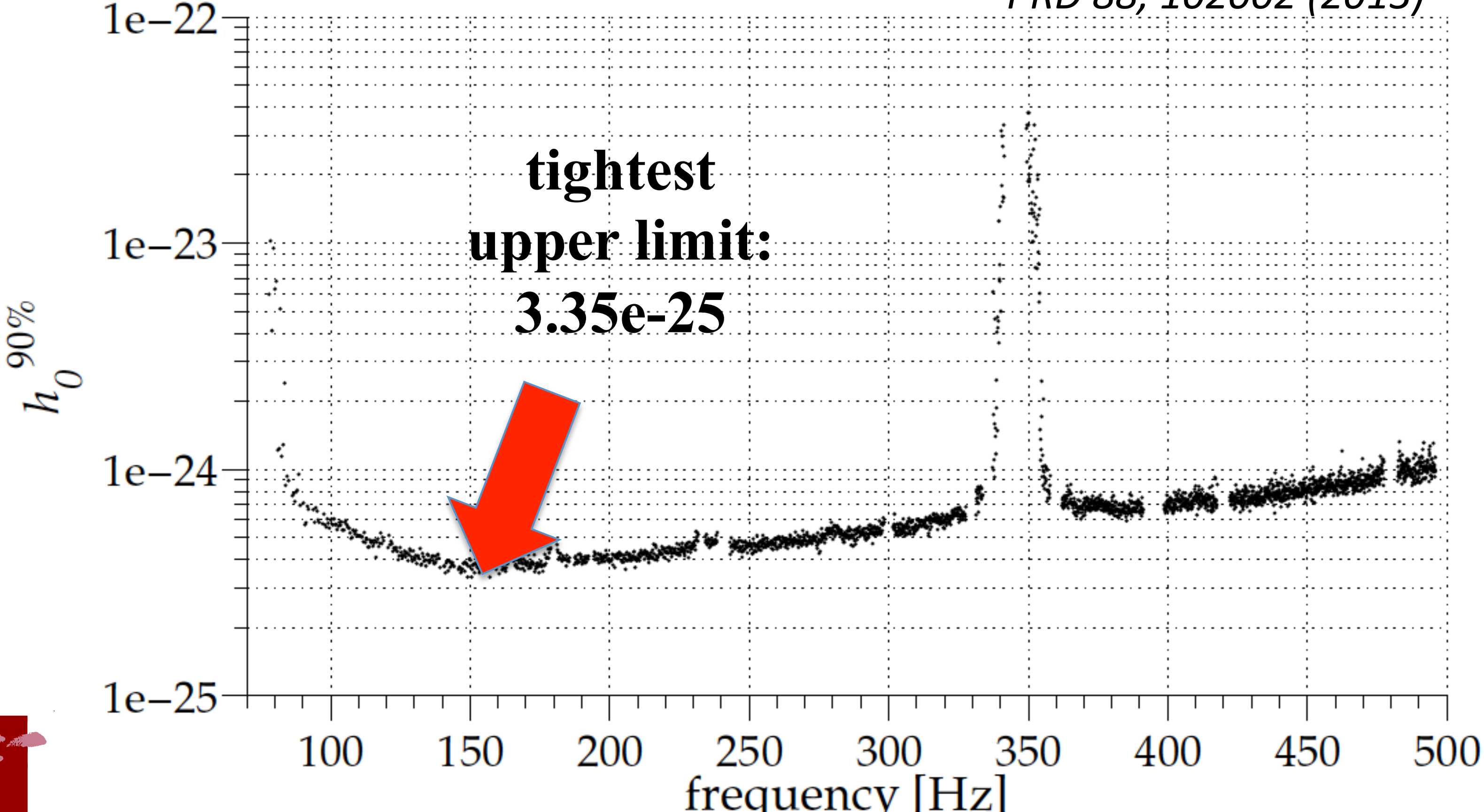


Image: NASA

Directed search algorithm applied to the **Galactic center** using LIGO S5 data.

The search uses a semi-coherent approach, analyzing coherently 630 segments, each spanning 11.5 hours, and then incoherently combining the results of the single segments.

PRD 88, 102002 (2013)



Directed search for CWs from the neutron star in the supernovae remnant **Cassiopeia A** with LIGO S5 data

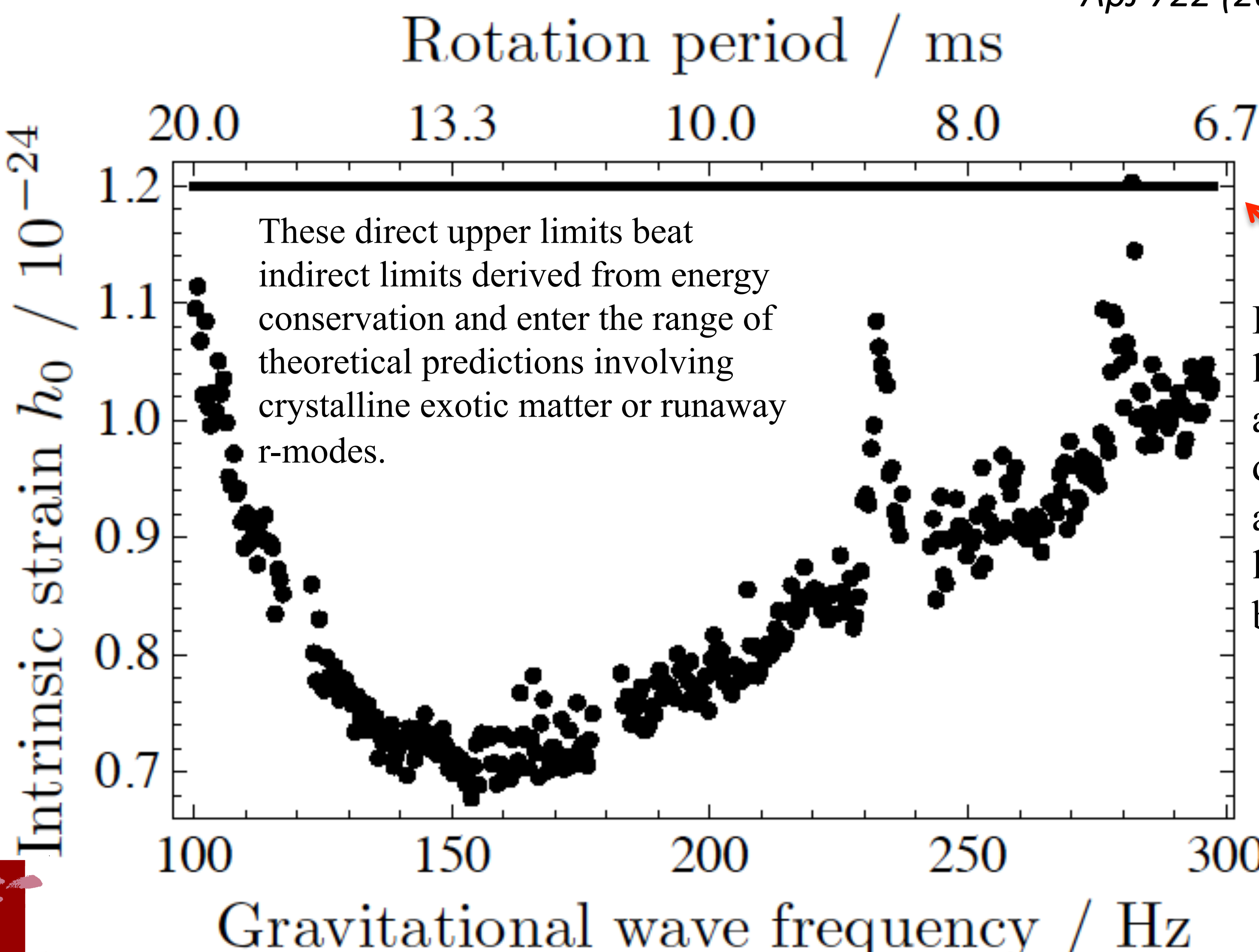
- There is a compact central object in the supernovae remnant Cassiopeia A.
- Birth observed in 1681. One of the youngest neutron stars known.
- Star is observed in X-rays, but not pulsation observed.
- Search for Cassiopeia A – young age (~300 years) requires search over 2nd frequency derivative over 12 day observation.


Cassiopeia A. Credit: NASA

- If the Central Compact Object in Cas A is an anti-magnetar (low surface magnetic field), it may be spinning fast enough to emit periodic gravitational waves above 100 Hz, where LIGO is most sensitive.

Directed search for CWs from the neutron star in the supernovae remnant **Cassiopeia A** with LIGO S5 data

ApJ 722 (2010) 1504



Indirect upper limit (based on age and distance), assuming energy loss dominated by GW emission.

Directed search for CWs from the brightest low-mass x-ray binary, **Scorpius X-1**

- The semicoherent analysis covers 10 days of LIGO S5 data ranging from 50–550 Hz.
- All candidates not removed at the veto stage were found to be consistent with noise at a 1% false alarm rate.
- No evidence was found to support detection of a signal with the expected waveform.

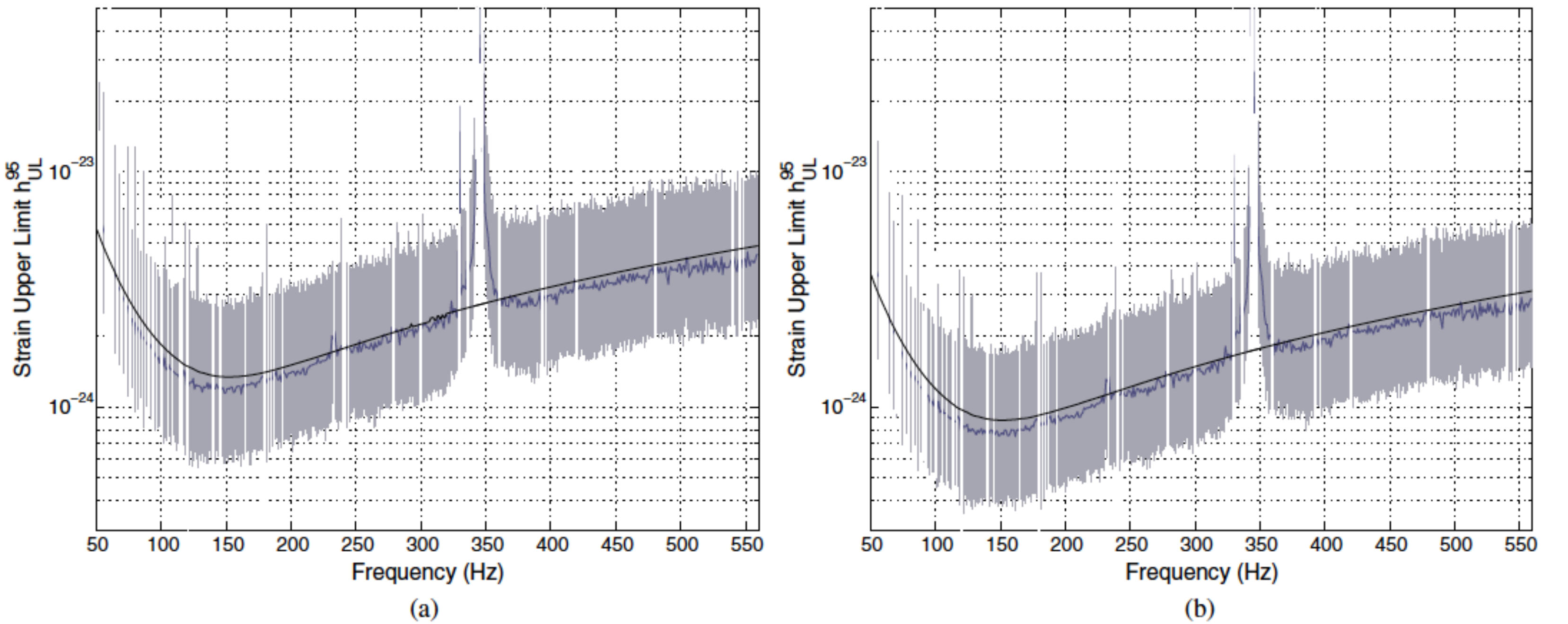


FIG. 5 (color online). Gravitational-wave strain 95% upper limits for H1L1 data from 21–31 Aug 2007 for (a) the standard search with flat priors on $\cos\iota$ and ψ (left panel) and (b) the angle-restricted search with $\iota = 44^\circ \pm 6^\circ$ and $\psi = 234^\circ \pm 4^\circ$ (right panel). 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.

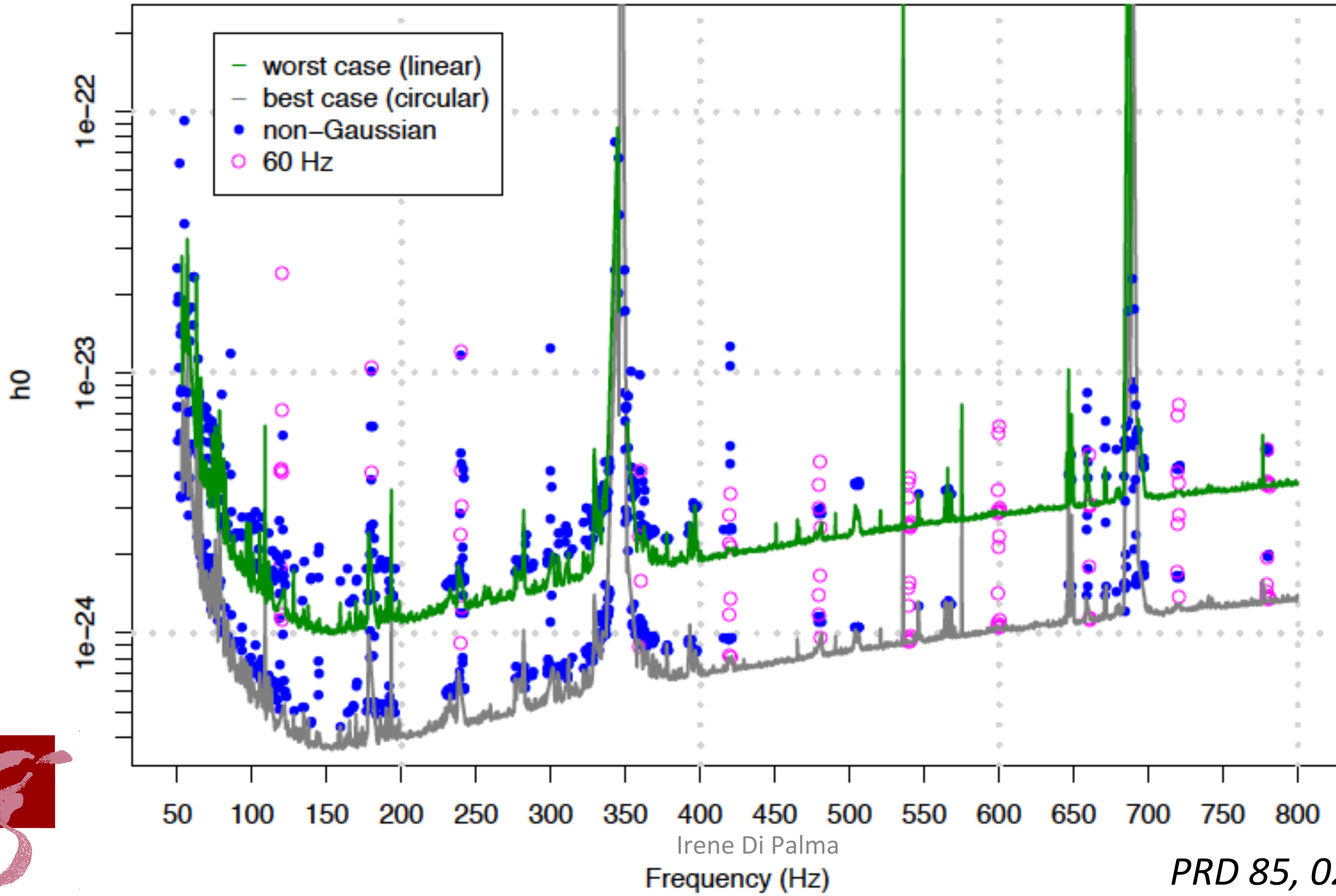
PRD 91, 062008 (2015)

All-sky searches

All-sky searches are computationally bound – cannot carry out coherent integrations over full observation time. Various semicoherent algorithms used in searches, with coherence times ranging from 30 minutes (e.g., PowerFlux, *PRD 85, 022001 (2012)*) to ~30 hours (Einstein@Home *PRD 87, 042001 (2013)*).

All-sky search for CWs in LIGO S5 data

- The search covers the frequency range between 50 and 800 Hz.
- Such a signal could be produced by a nearby spinning and slightly non-axisymmetric isolated neutron star in our galaxy.
- Semi-coherent stacks of 30-minute, demodulated power spectra ("PowerFlux").

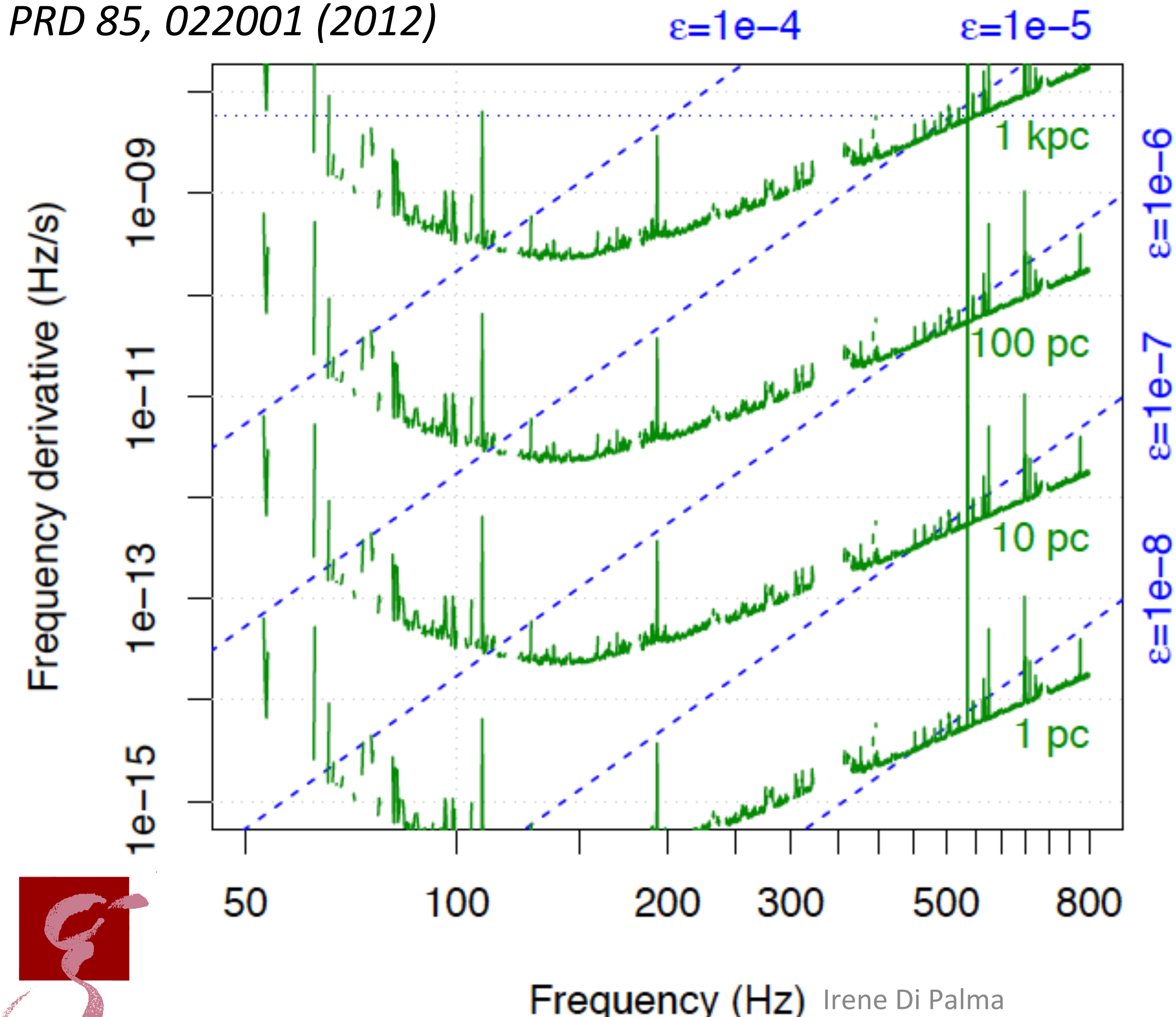


PRD 85, 022001 (2012)

All-sky search for CWs in LIGO S5 data

Range of the PowerFlux search for neutron stars spinning down solely due to gravitational radiation.

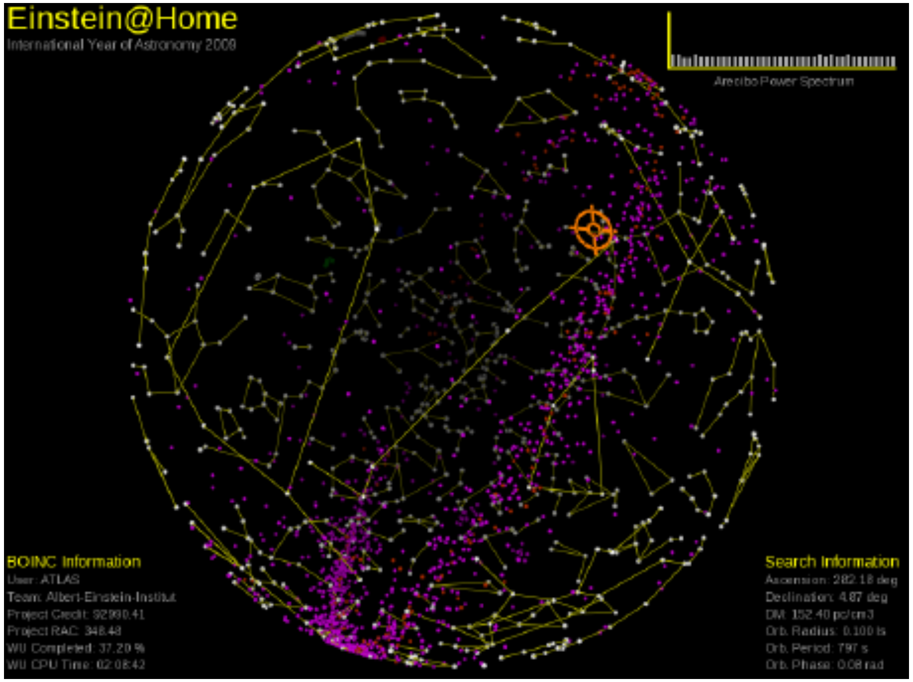
PRD 85, 022001 (2012)



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 fdot. The dashed lines are contours of the corresponding ellipticity (f; fdot). The fine dotted line marks the maximum spin-down searched. Together these quantities tell us the maximum range of the search in terms of various populations.

Einstein@Home

- The Einstein@Home project is built upon the BOINC (Berkeley Open Infrastucture for Network Computing) architecture, a system that exploits the idle time on volunteer computers to solve scientific problems that require large amount of computing power.
- O(10^5) active users contribute about 1 petaFLOP of computational power.
- The computational work of a typical CW search is partitioned into millions of independent computing tasks, so-called Work-Unit, analyzed by machines owned by volunteers.
- It's also available on Android devices!



Einstein@Home *all-sky* search for CWs in LIGO S5 data

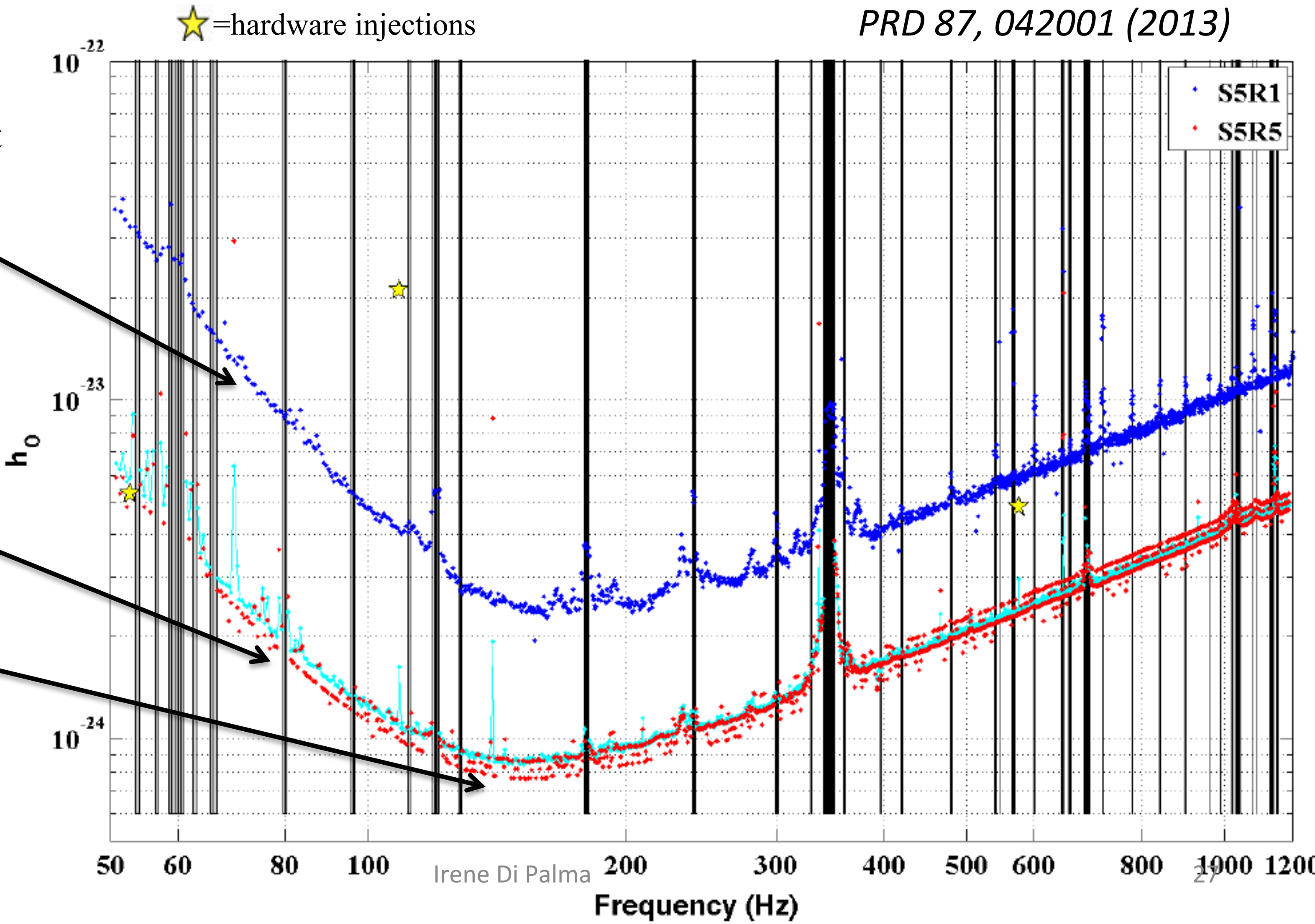
- The search uses a non-coherent Hough-transform method to combine the information from coherent searches on timescales of about one day, in the frequency range (50, 1190) Hz.
- Post-processing identifies eight candidate signals; deeper follow-up studies rule them out.

PRD 87, 042001 (2013)

Search over fist two months.

Search over 2 years of data.

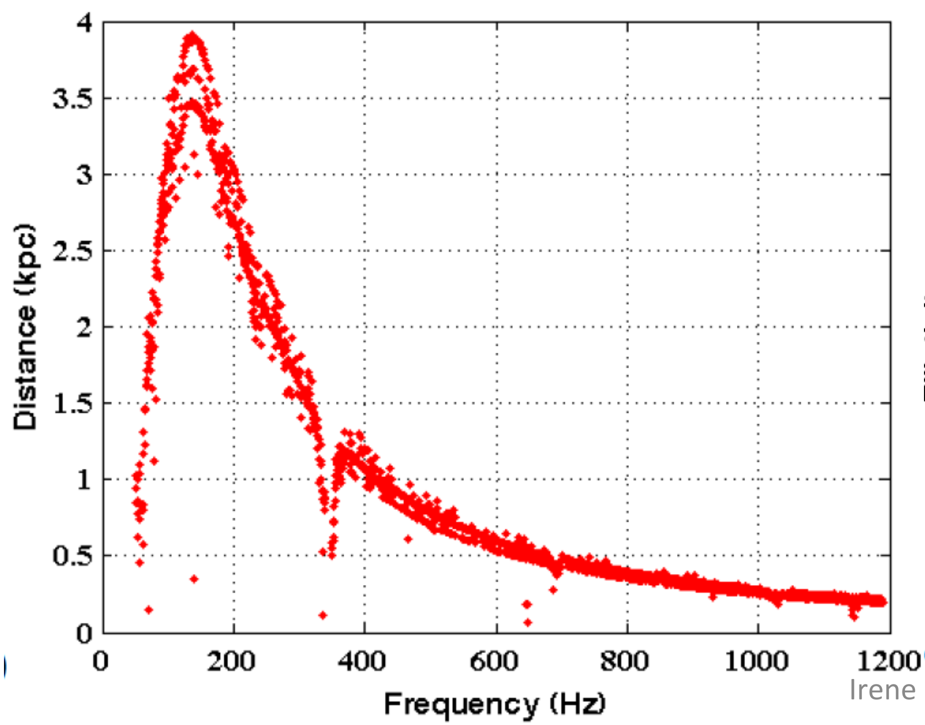
Best upper limit $h_0 \lesssim 7.6 \times 10^{-25}$



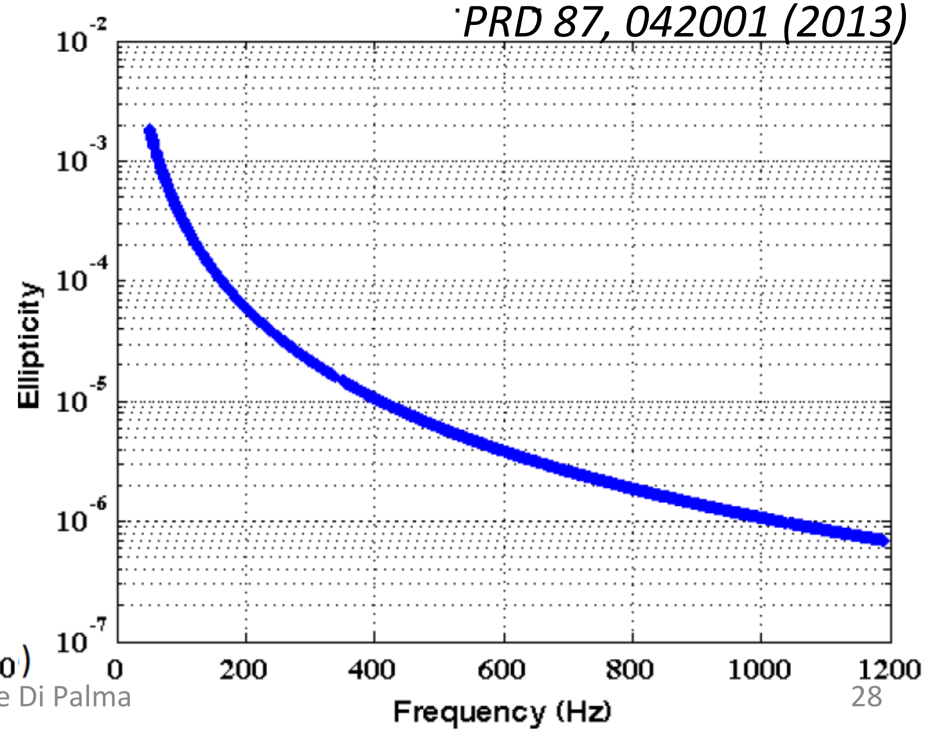
Einstein@Home *all-sky* search for CWs in LIGO S5 data

The maximum distance of a source emitting a CW signal with a strain that we could have detected. The source is assumed to be spinning down at the maximum spindown rate of the search (~ 2 x 10^{-9} Hz/s), and emitting all the lost angular energy in gravitational waves.

The plot shows what ellipticity values, as a function of the frequency, the source of the adjacent plot would need in order to emit in gravitational waves all the energy lost while spinning down at a rate of ~ -2 x 10^{-9} Hz/s.



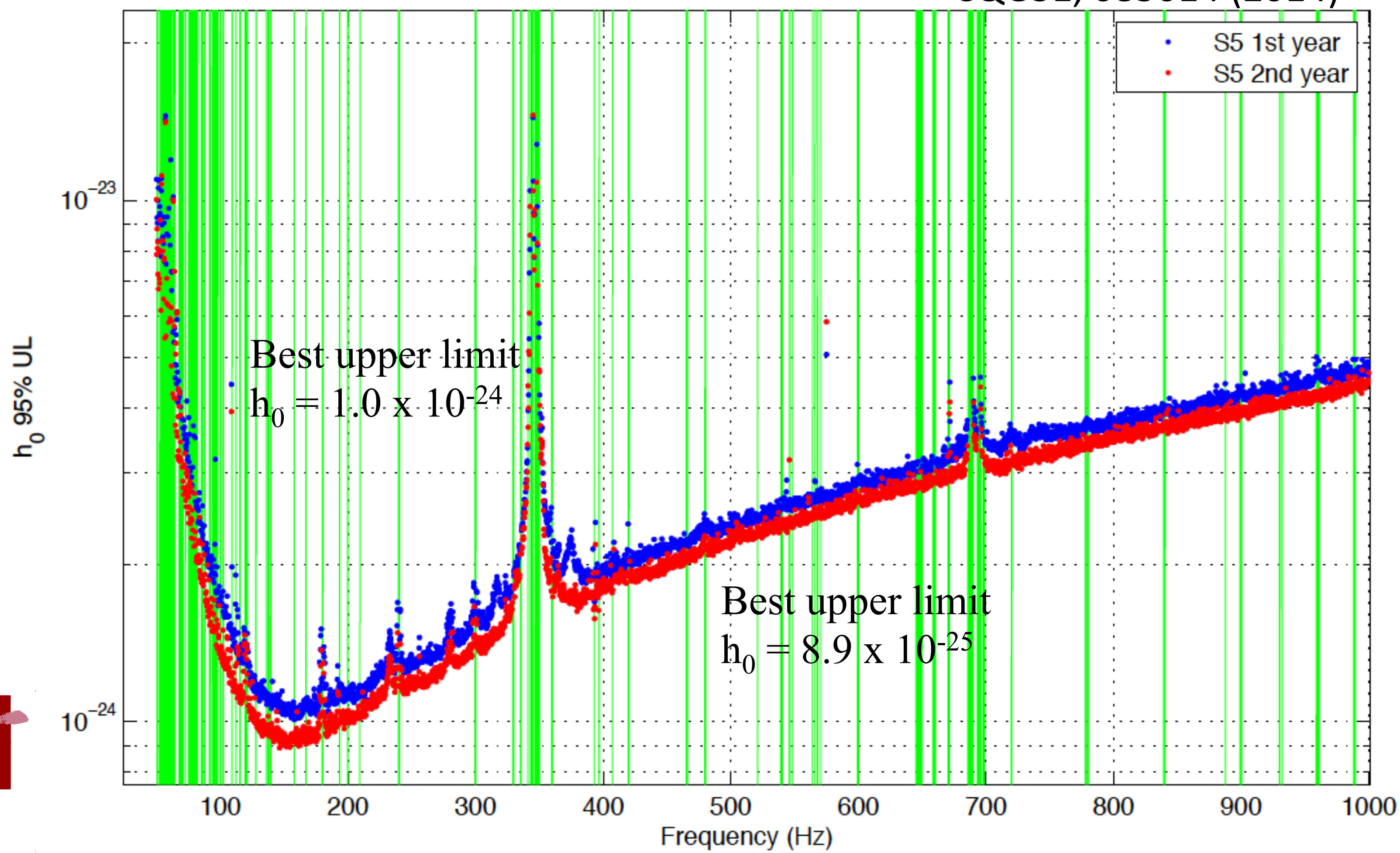
PRD 87, 042001 (2013)



Hough* search on data from the 5th LIGO science run

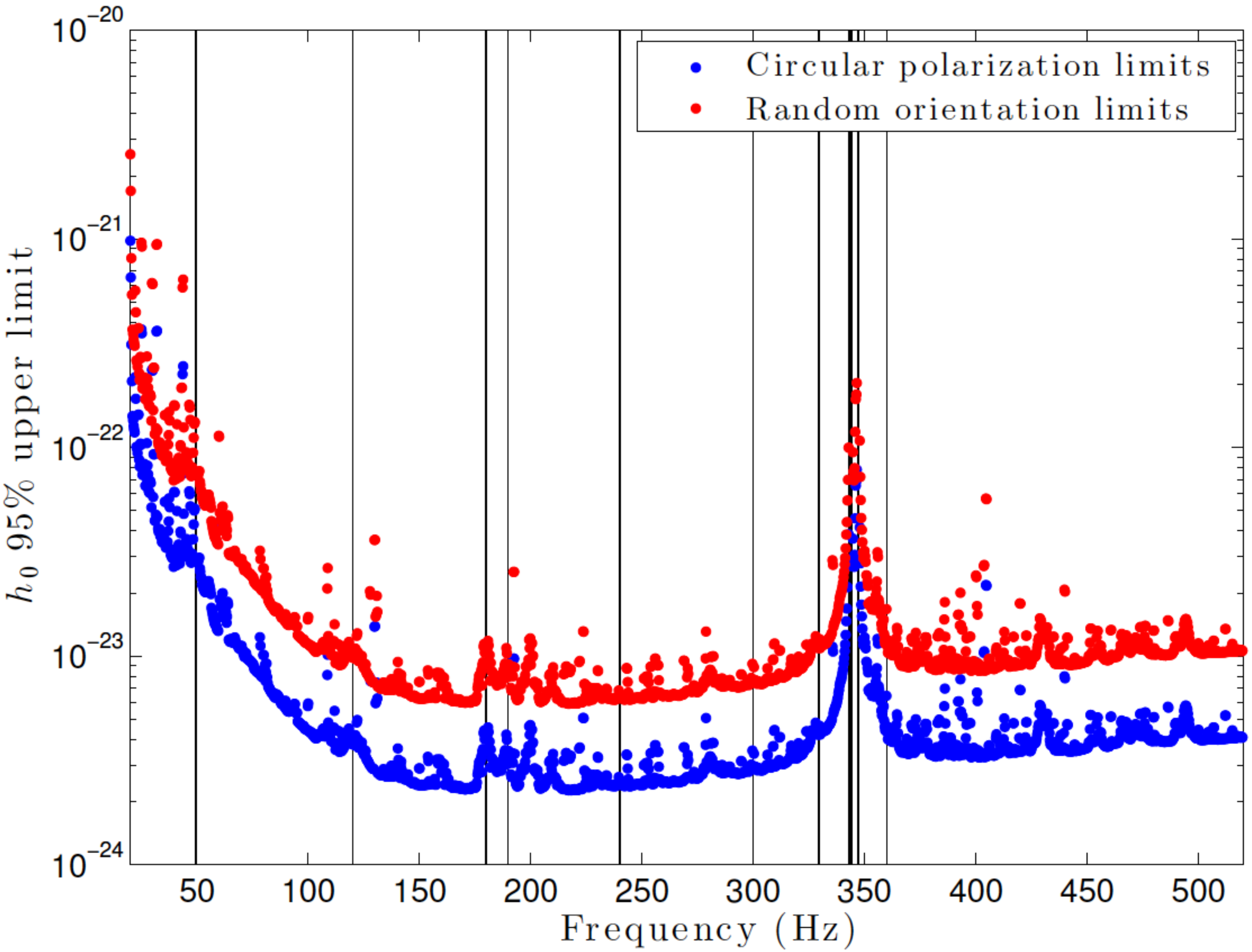
- *All-sky* search for periodic gravitational waves in the frequency range (50, 1000) Hz.
- The search employs the Hough transform technique, introducing a χ^2 test and analysis of coincidences between the signal levels in years 1 and 2 of observations that offers a significant improvement in the product of strain sensitivity with compute cycles per data sample compared to previously published searches.(*PRD 70, 082001, 2004).

CQG31, 085014 (2014)



First *all-sky* search for unknown binary CW sources

- The search was carried out on data from the sixth LIGO Science Run and the second and third Virgo Science Runs, employing the TwoSpect algorithm. The search covers a range of frequencies from 20 Hz to 520 Hz.



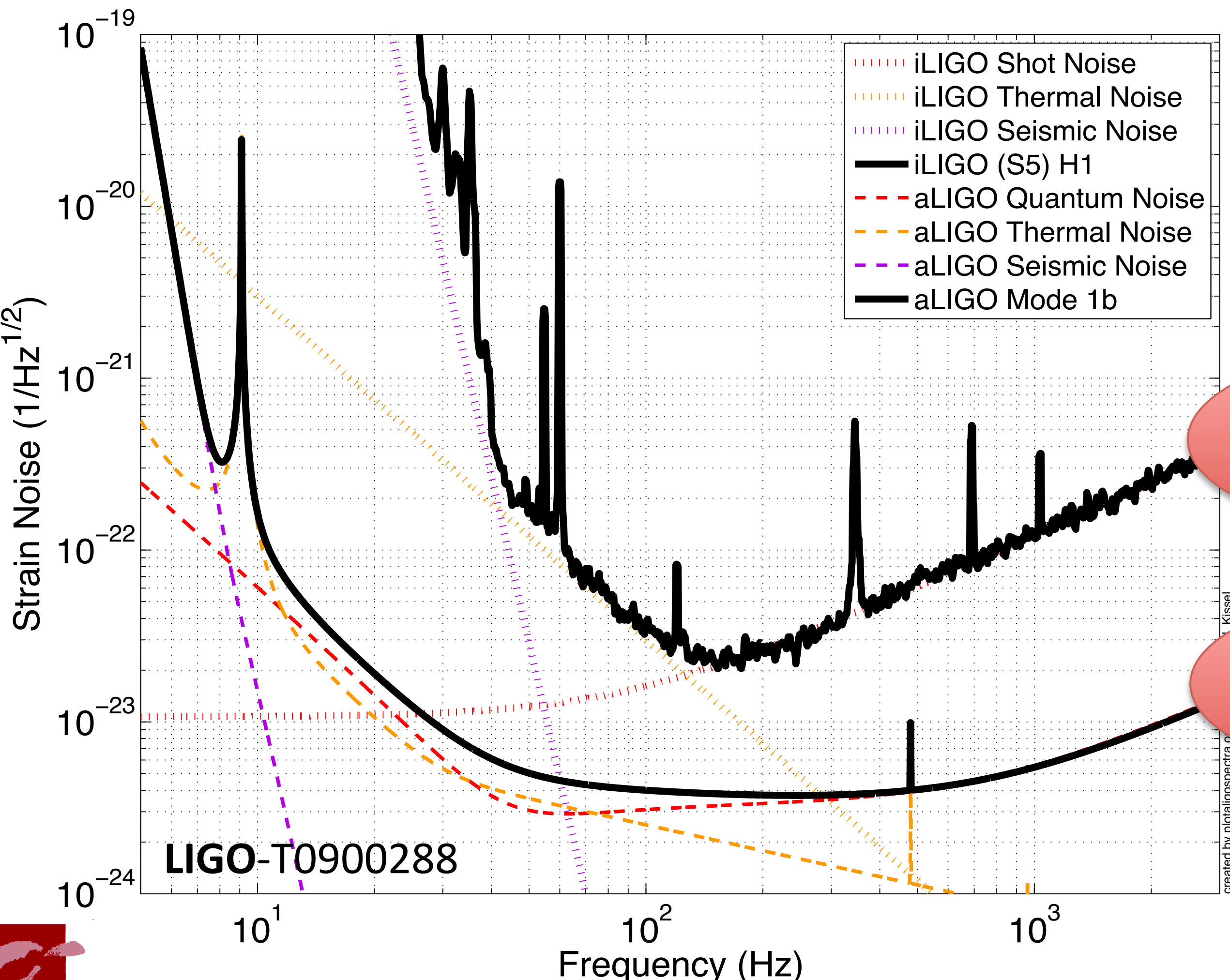
The blue dots show the upper limits on the circularly polarized gravitational wave strain amplitude.

The red dots show the upper limit on the randomly polarized gravitational wave strain amplitude.

PRD 90, 061010 (2014)

Ground-based interferometers

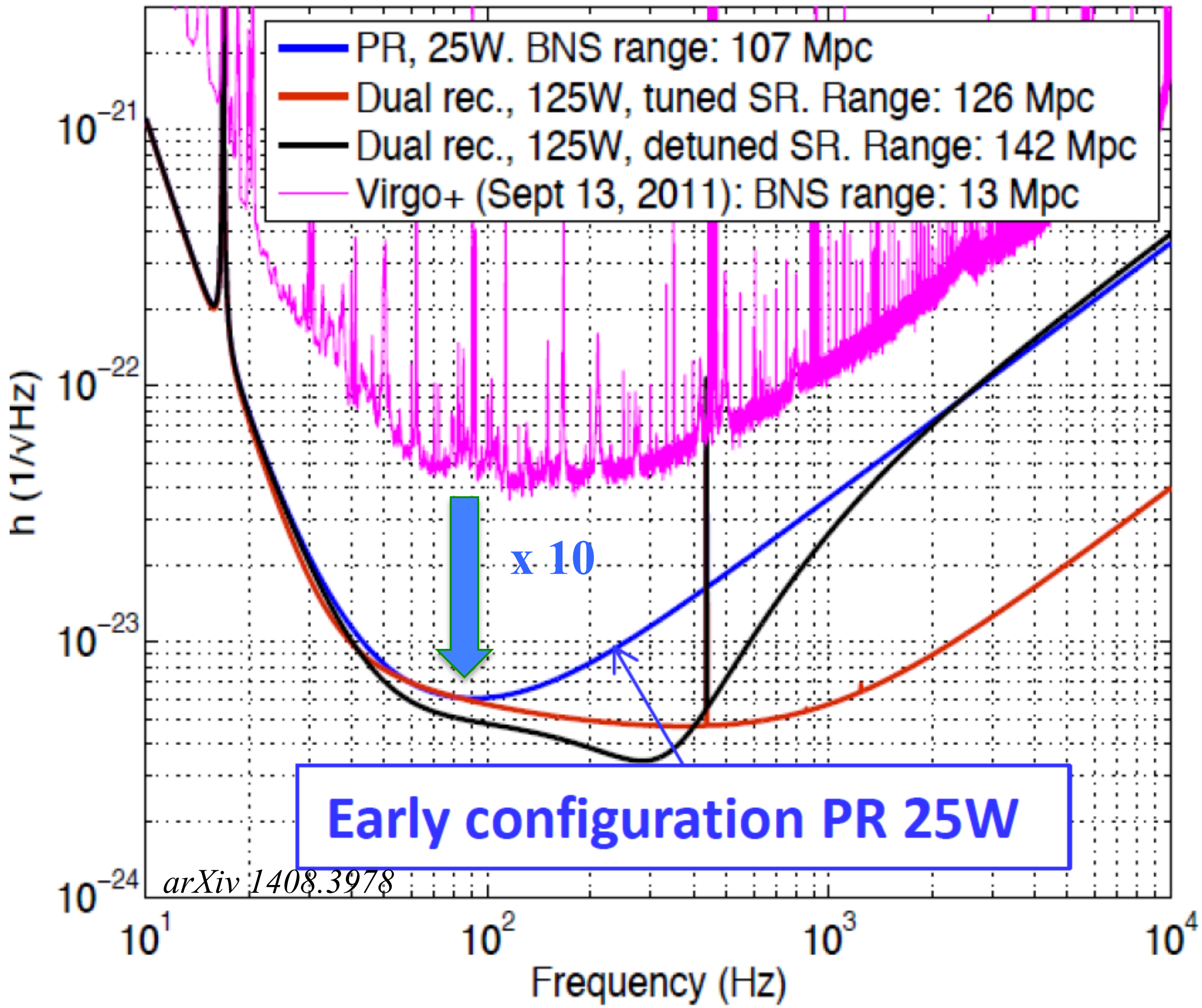
Advanced LIGO vs. Initial LIGO

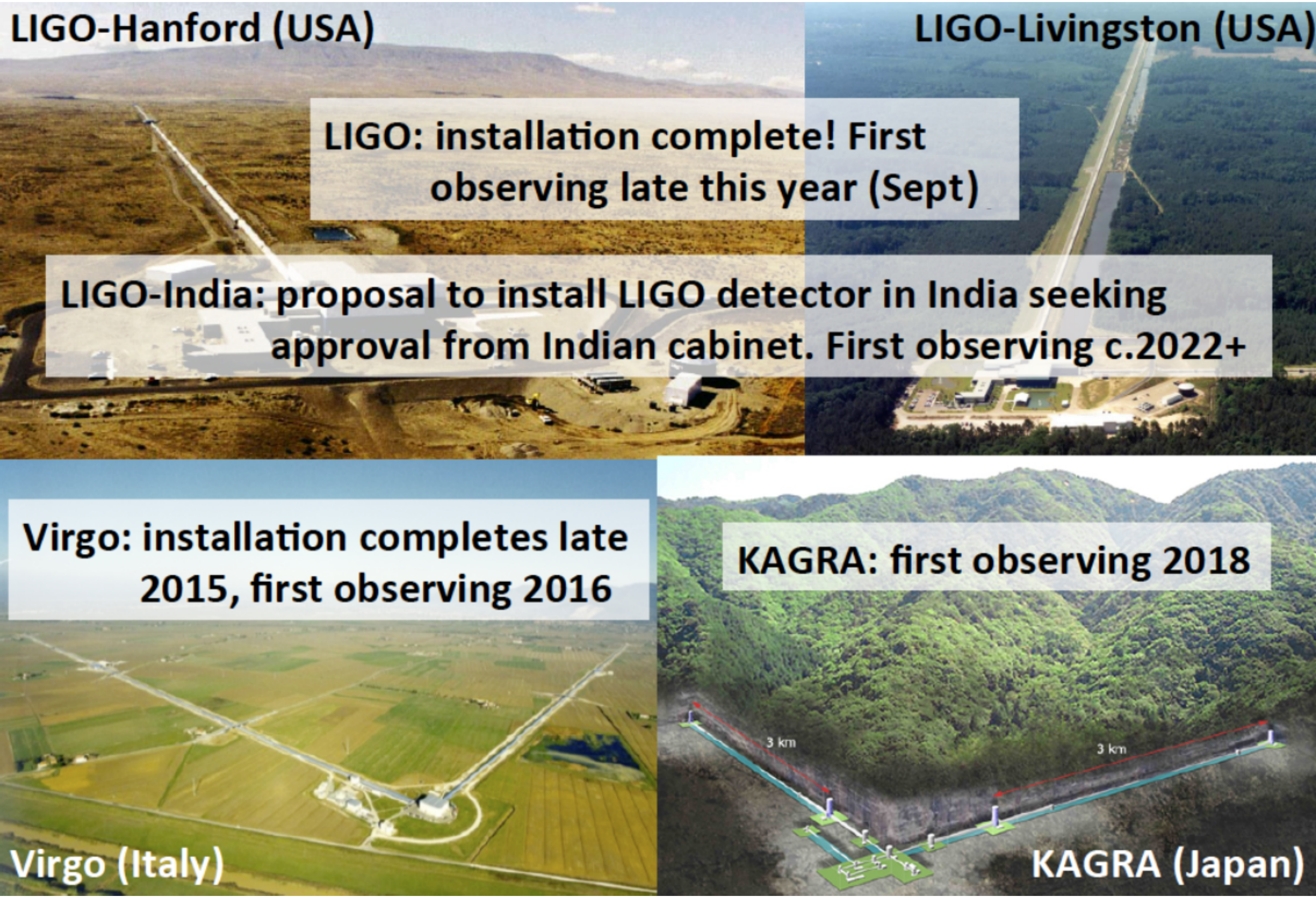


15-20 Mpc BNS inspiral range

~200 Mpc BNS inspiral range

Advanced Virgo vs. Virgo+




LIGO-Hanford (USA)
LIGO-Livingston (USA)
LIGO: installation complete! First observing late this year (Sept)
LIGO-India: proposal to install LIGO detector in India seeking approval from Indian cabinet. First observing c.2022+
Virgo: installation completes late 2015, first observing 2016
KAGRA: first observing 2018
3 km
3 km
Virgo (Italy)
KAGRA (Japan)

Conclusions

- The search for CWs from known NSs 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 with respect to parameter uncertainty, search at $f \neq 2f_{rot}$, wandering frequency (e.g. Sco-X1), 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.
- Large improvements in the number of interesting targets and in the relevance of results are expected for the Advanced Detector era.


THANK YOU

Please sign up your computers to Einstein@Home: http://einstein.phys.uwm.edu/

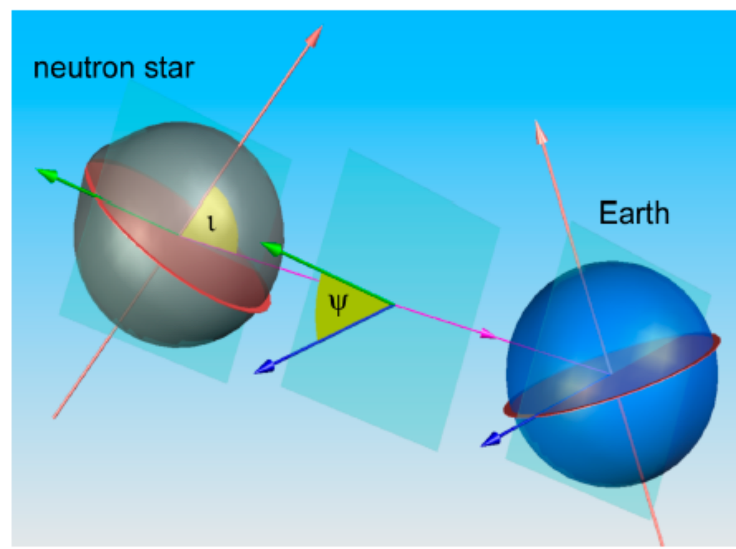
Periodic Continuous Gravitational waves

- The GW signal from a triaxial pulsar can be modelled as

$$h(t) = \frac{1}{2}F_{+}(t;\psi)h_0(1+\cos^2\iota)\cos 2\Psi(t) + F_{\times}(t;\psi)h_0\cos\iota\sin 2\Psi(t)$$

- The unknown parameters are
    - h_0 - amplitude of the gravitational wave signal
    - ψ - polarization angle of signal; embedded in $F_{x,+}$
    - ι - inclination angle of the pulsar
    - ϕ_0 - initial phase of pulsar $\Phi(0)$

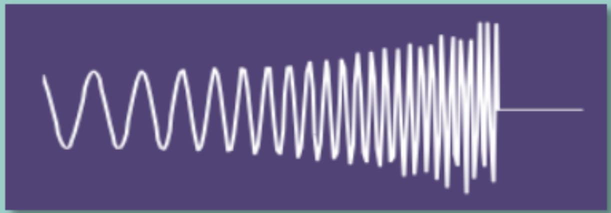
- In the known pulsar searches we usually look for signals at twice the rotation frequency of the pulsars
- For blind searches for isolated neutron stars the location in the sky and the source's frequency and its evolution are search parameters.



GW sources

TRANSIENT SIGNALS

- **Compact binary inspiral (*chirps*)**
  The inspiral, merger and ring-down of binary NSs and Black Holes



- **Supernovae, GRBs (*bursts*)**
  Short-duration GW events in coincidence with signals in electromagnetic radiation/neutrinos

CONTINUOUS SIGNALS

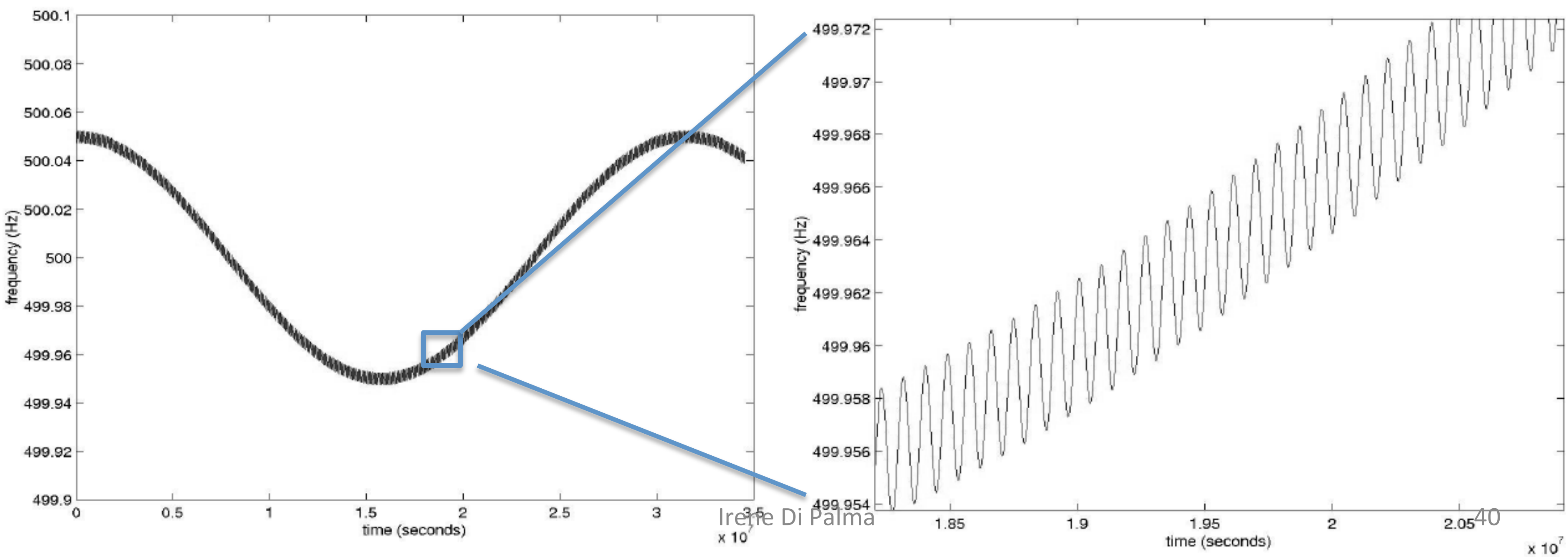
- **Cosmological GW (*stochastic background*)**
  A background of primordial and/or astrophysical GWs

- **Pulsars in our galaxy (CWs)**
  e.g. non-axisymmetric spinning NSs

The signal at the detector

A gravitational wave signal from a NS will be:

- Frequency-modulated by the relative motion of the detector and source;
- Amplitude-modulated because of the time dependence of the sky-sensitivity pattern of the detector.



Spin-down LIMIT

- **Assuming that the measured spin-down of the source is totally due to GW emission, we get an upper limit on the signal amplitude**

$$h_0^{\rm sd} = 8.06\times 10^{-19}\, I_{38}\, d_{\rm kpc}^{-1} \sqrt{\frac{|(\dot{f}_{\rm rot}/{\rm Hz\,s^{-1}})|}{(f_{\rm rot}/{\rm Hz})}}$$

Going below the spin-down limit means we are putting a constraint on the fraction of spin-down energy due to the emission of GWs.

- **The spin-down limit on the signal amplitude corresponds to an upper limit on the star's ellipticity given by**

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

Spin-down limit beaten for Vela & Crab!

What is the "indirect spindown limit"?

If a star's age is known (e.g., historical SNR), but its spin is unknown, one can still define an indirect spindown upper limit by assuming gravitar behavior has dominated its lifetime:

$$\tau = \frac{f}{4\,(df\,/\,dt)}$$

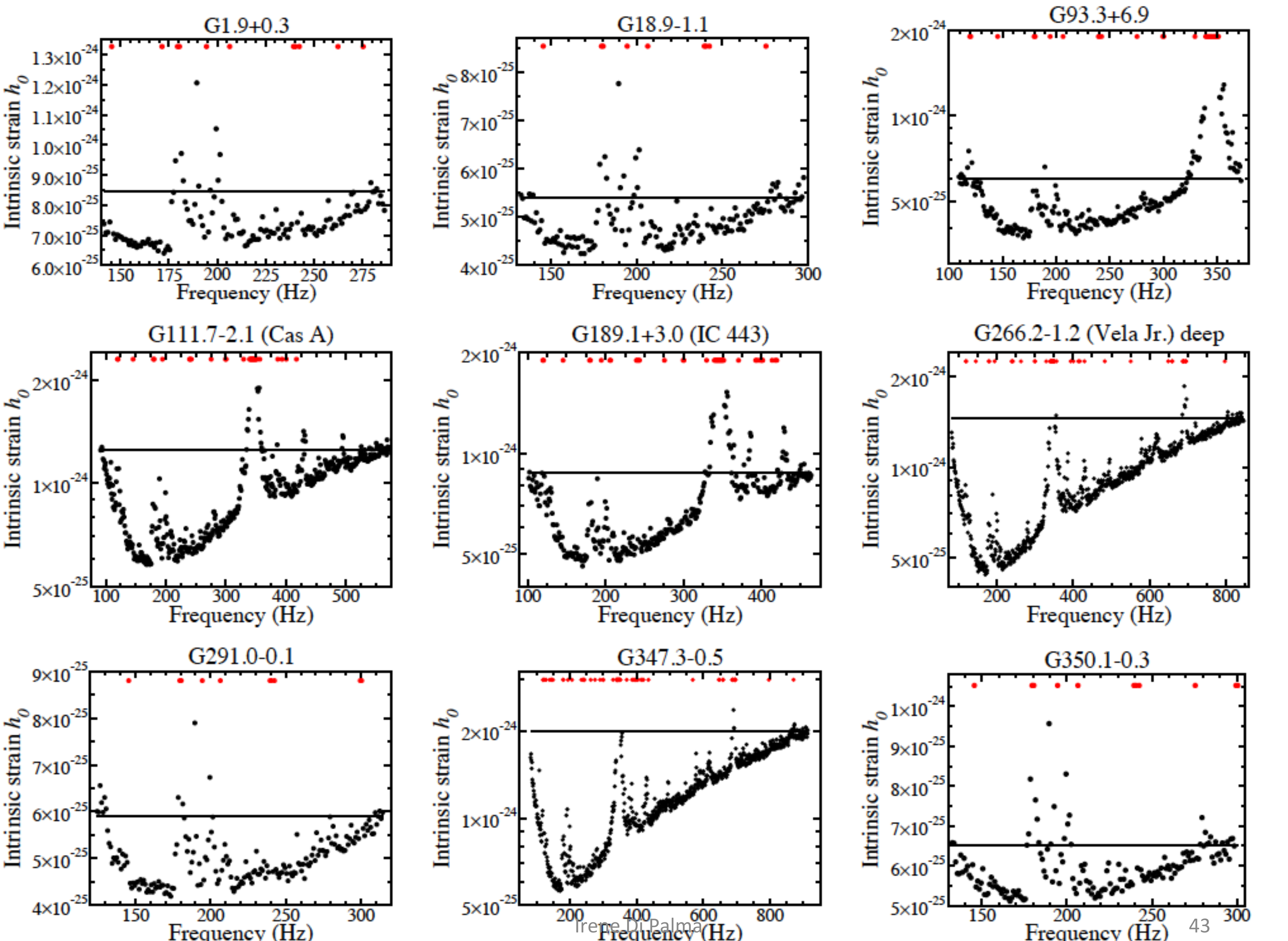
And substitute into h_{SD} to obtain
[K. Wette, B. Owen,… CQG 25 (2008) 235011]

$$h_{ISD} = 2.2\times 10^{-24}\left[\frac{kpc}{d}\right]\sqrt{\left[\frac{1000\,yr}{\tau}\right]\left[\frac{I}{10^{45}\,g\cdot cm^2}\right]}$$

Example:

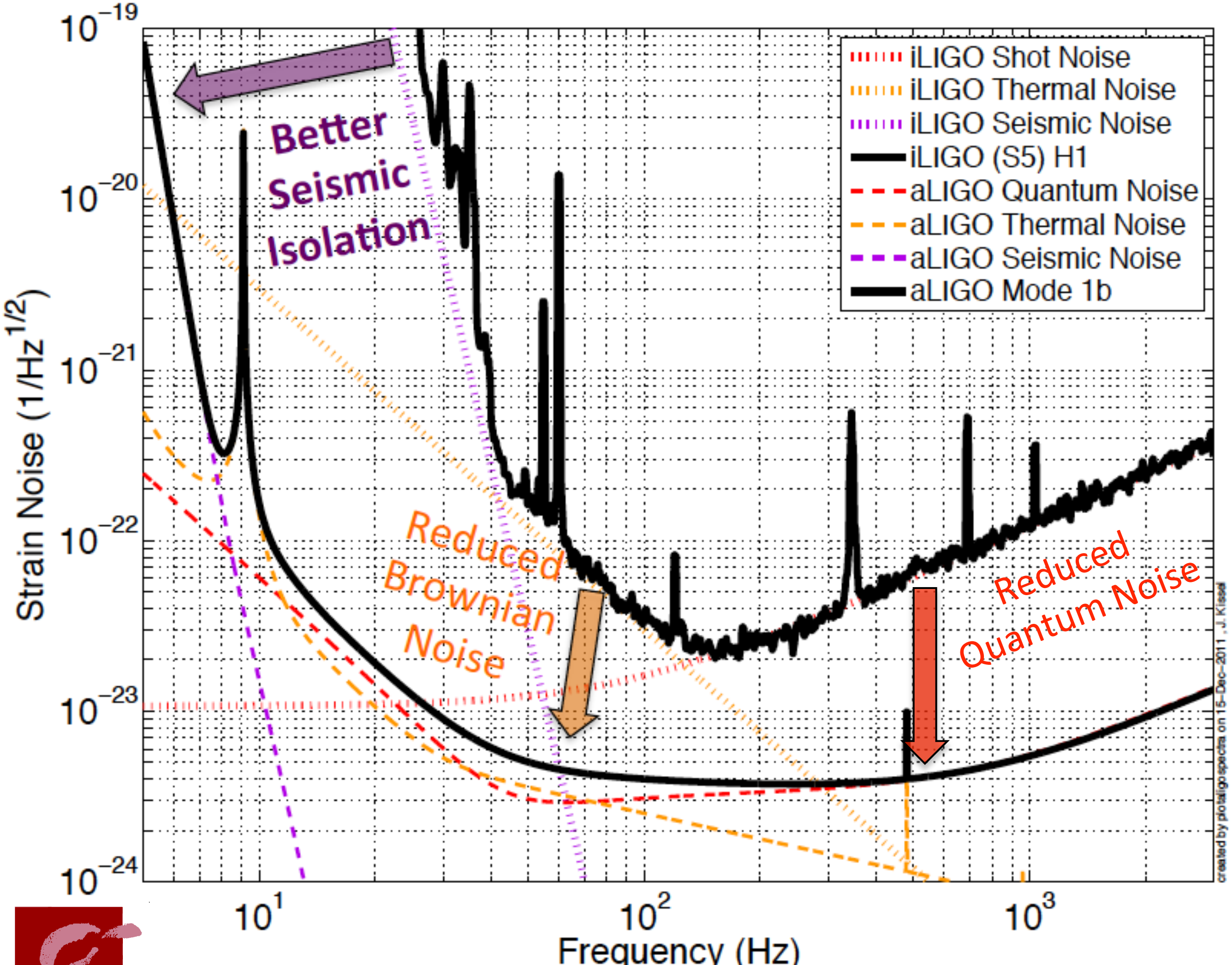
Cassiopeia A → **$h_{ISD} = 1.2 \times 10^{-24}$**

(d=3.4 kpc, τ=328 yr)



arXiv:1412.5942, submitted to ApJ

Advanced LIGO vs. Initial LIGO

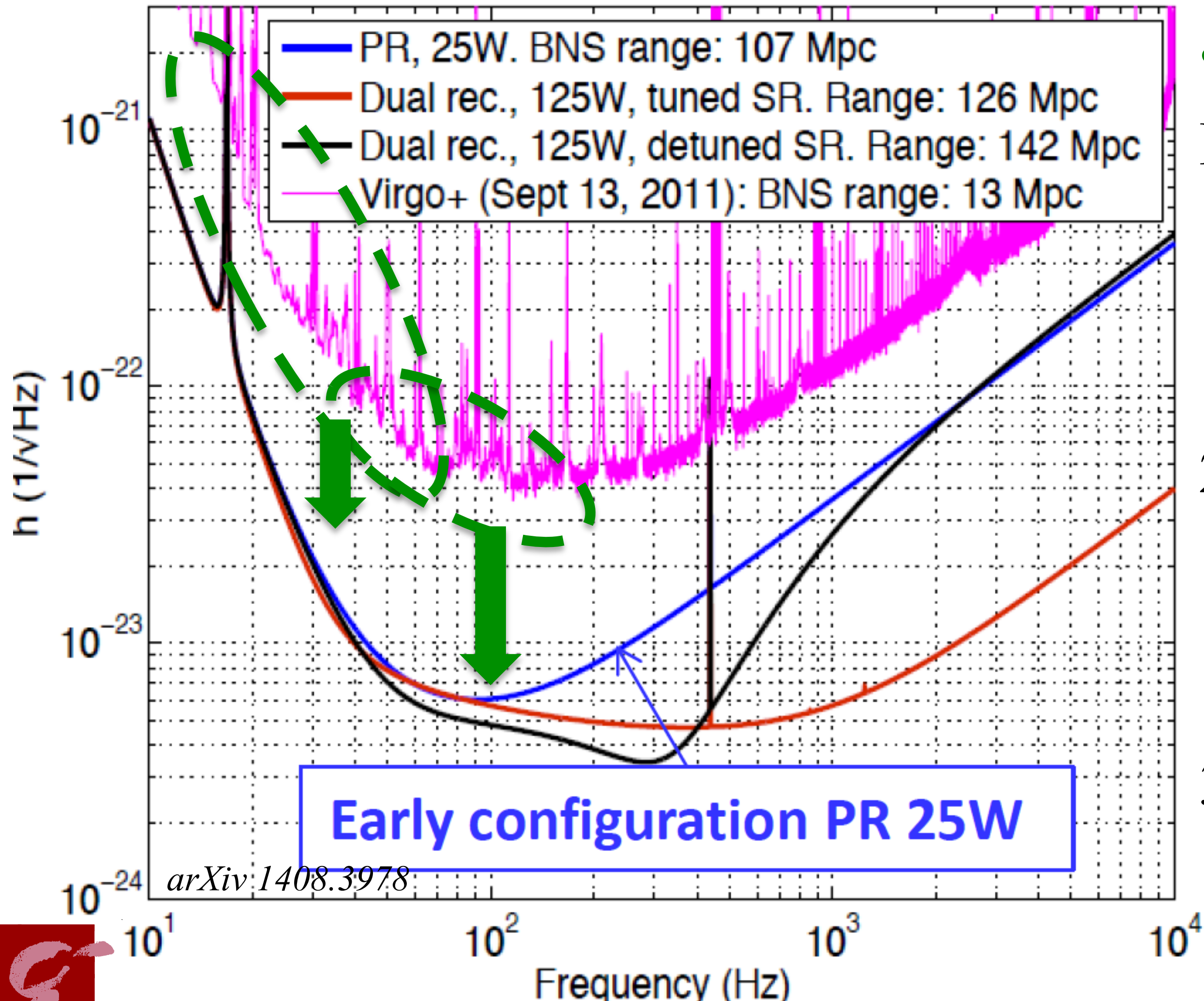


– **Seismic Noise:**
Test masses are suspended from seven stages of passive and active isolation systems.

– **Brownian Noise:**
Last two suspension stages are monolithic to improve thermal noise.

– **Quantum Noise:**
180W Laser
40 kg test masses
Signal Extraction Cavity

Advanced Virgo vs. Virgo+

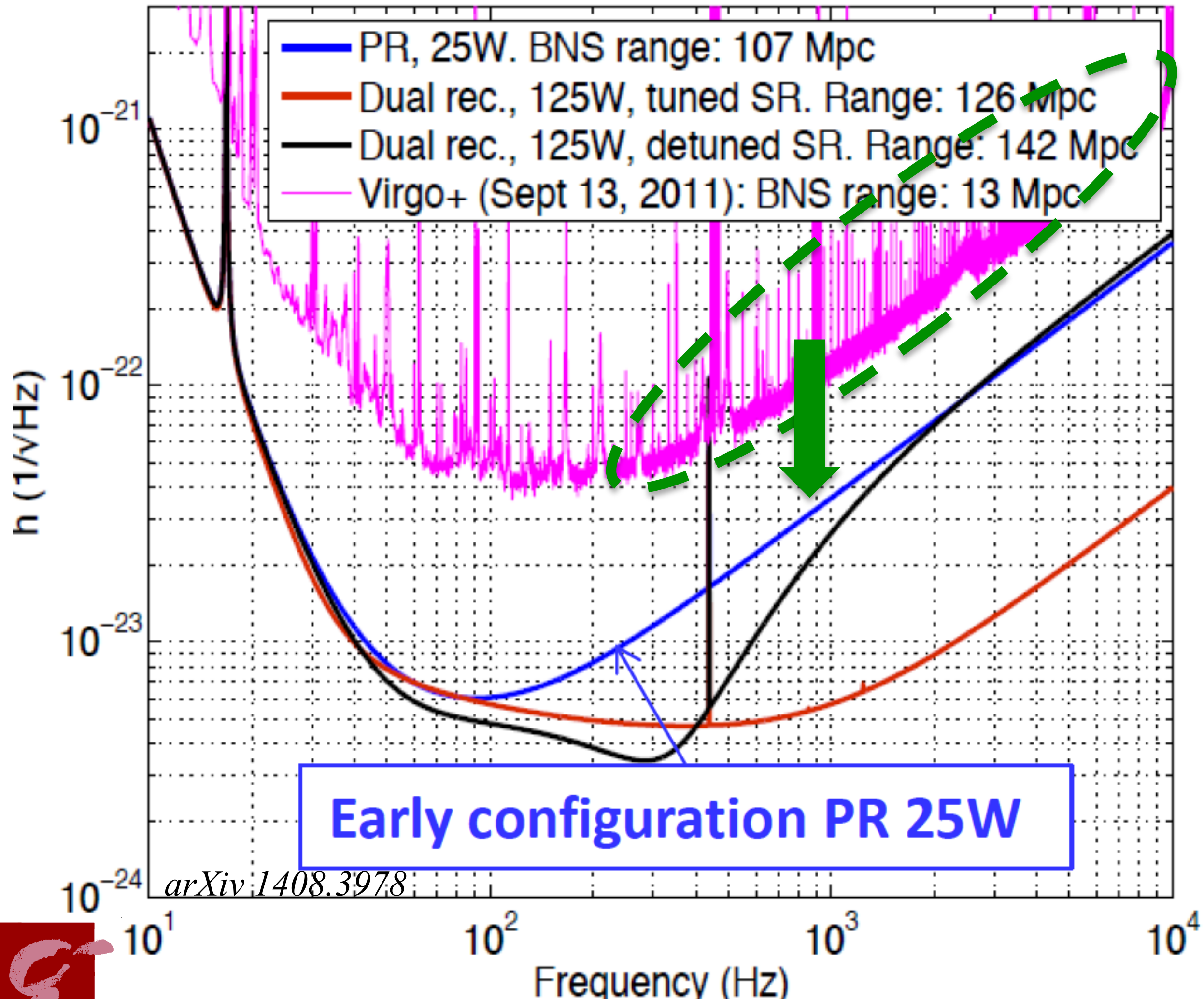


- **Thermal noise:**

Improved with

1. Optical configuration: larger beam spot
2. Test masses suspended by fused silica fibers (low mechanical losses)
3. Mirror coatings engineered for low losses

Advanced Virgo vs. Virgo+



- **Laser shot noise:**

Improved with

1. Higher laser power: 125 W injected
2. Higher finesse of the arm cavities
3. Optical configuration: signal recycling

Estimated observing scenario

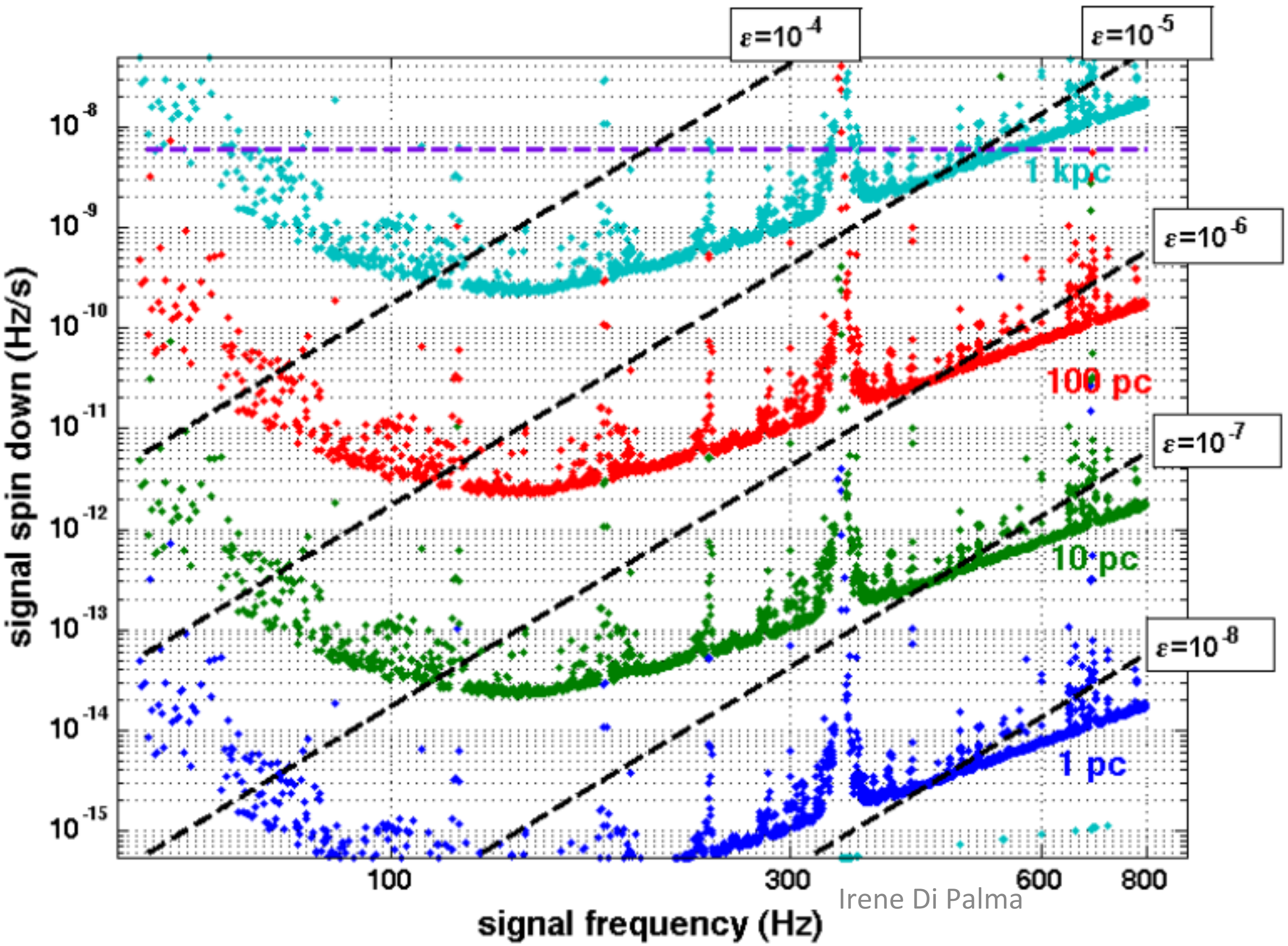
Epoch	Estimated Run Duration	$E_{\mathrm{GW}} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

Table 1: Summary of a plausible observing schedule, expected sensitivities, and source localization with the advanced LIGO and Virgo detectors, which will be strongly dependent on the detectors' commissioning progress. The burst ranges assume standard-candle emission of $10^{-2} M_{\odot} c^2$ in GWs at 150 Hz and scale as $E_{\mathrm{GW}}^{1/2}$. The burst and binary neutron star (BNS) ranges and the BNS localizations reflect the uncertainty in the detector noise spectra shown in Fig. [1]. The BNS detection numbers also account for the uncertainty in the BNS source rate density [28], and are computed assuming a false alarm rate of $10^{-2}\,\mathrm{yr}^{-1}$. Burst localizations are expected to be broadly similar to those for BNS systems, but will vary depending on the signal bandwidth. Localization and detection numbers assume an 80% duty cycle for each instrument.

arXiv 1304.0670

All-sky search in LIGO S5 data

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 fdot. The dashed lines are contours of the corresponding ellipticity (f; fdot). 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.