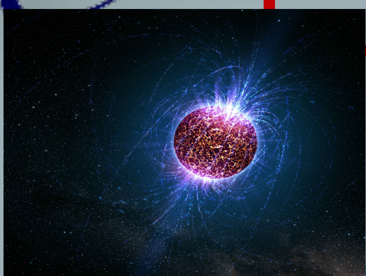
RECENT RESULTS AND FUTURE CHALLENGES FOR CONTINUOUS WAVES AND STOCHASTIC BACKGROUND SEARCHES WITH A NETWORK OF GRAVITATIONAL WAVE DETECTORS

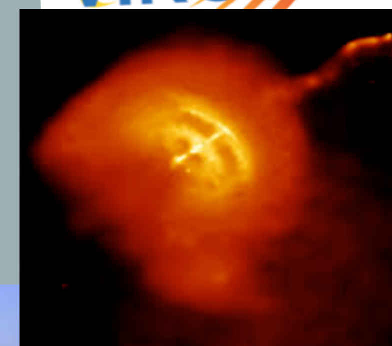
Pia Astone, INFN Roma 1

For the LIGO Scientific Collaboration
and the Virgo collaboration



Virgo, Cascina

LIGO, Hanford
(Washington State)

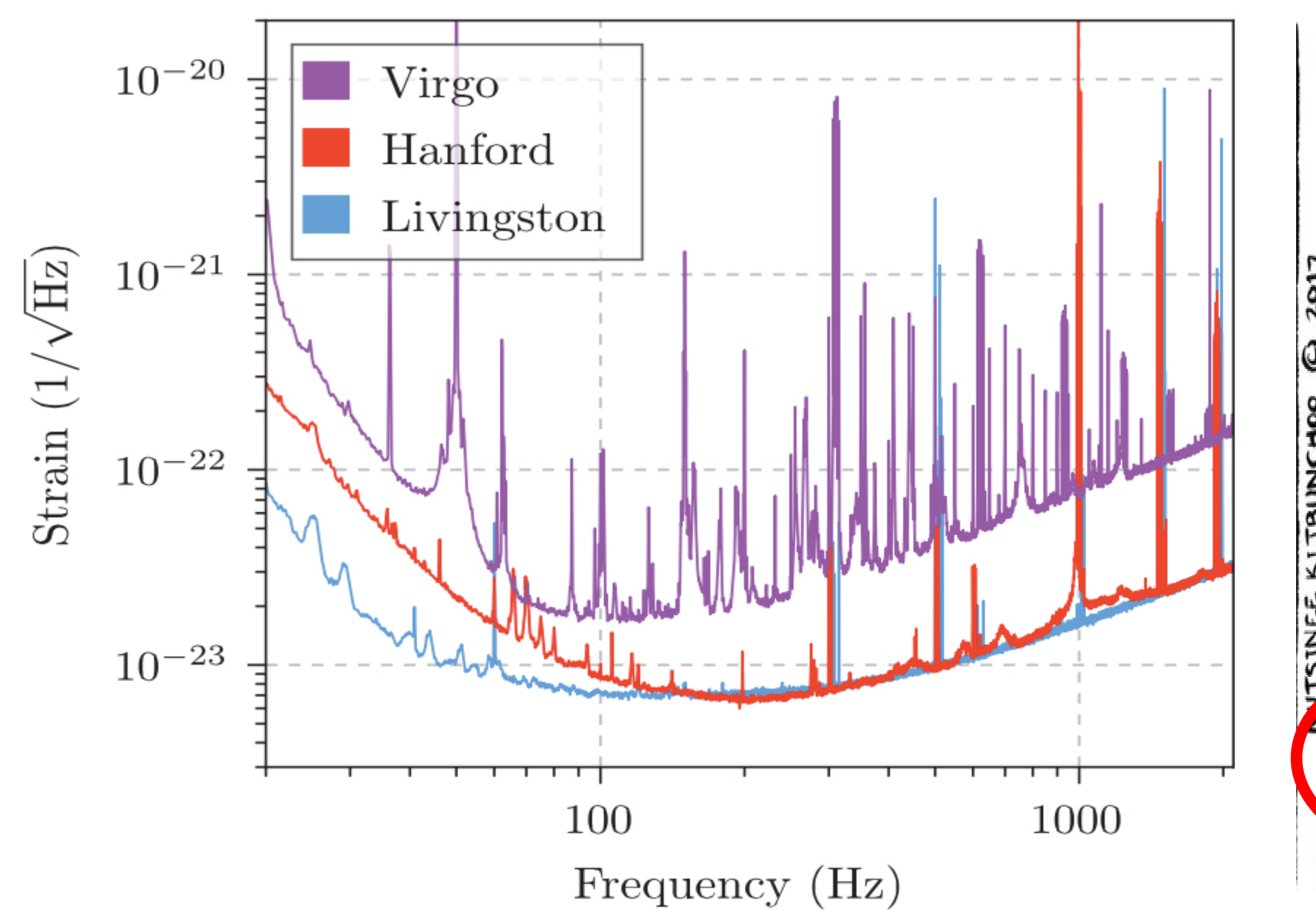


LIGO, Livingston (LSU)

GRAvitational waves Science-Technology Symposium " 2018/03/01-02

DCC document :G1800271

The LIGOs and Virgo O2 strain sensitivity

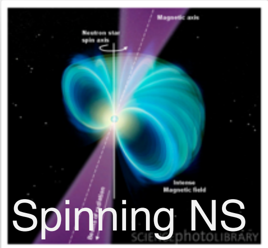


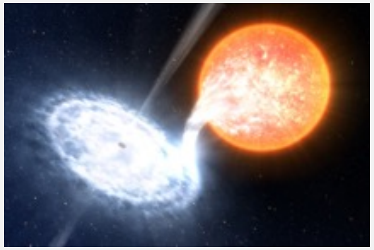
117 days of coincident LIGO data
15 days of coincident LIGO-Virgo data
LL LH run: 30/11/2016-25/08/2017
Virgo run: 01/08/2017-25/08/2017

Searches on O2 data are still in progress

THE BASIC PROBLEM OF DETECTING CONTINUOUS SOURCES OF GRAVITATIONAL WAVES -I-

- Observational GW astronomy begun with the observation of the binary BH coalescence on 2015 Sept. 14. Continued with BH systems, up to the detection of the BNS system on 2017 August 17, when the fantastic multi-messenger astronomy survey begun.
- CBC signals are of limited duration, well modeled and visible given the actual sensitivitivities , even if ”far” from us. GW170817 distance was ~ 40 Mpc from Earth.
- Continuous signals, like those emitted by compact object isolated or in binary systems, typically have long duration but strain amplitudes are much weaker , $O(10^{-26})$ compared to $O(10^{-21})$



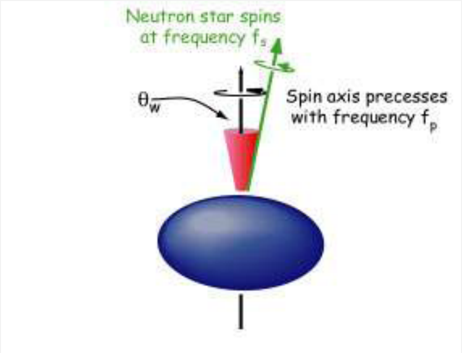


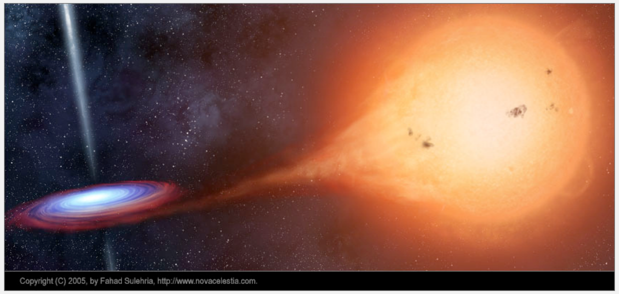
THE BASIC PROBLEM OF DETECTING CONTINUOUS SOURCES OF GRAVITATIONAL WAVES -II-

- To detect these signals we need to integrate over long times.
- Depending on our knowledge of the source parameters (frequency, frequency evolution, position in the sky, orbital parameters in the case of binary systems) the impact on the needed computing resources is relevant and limits the sensitivity of the search and/or the parameter search we can exploit.
- At the actual sensitivities our main target for continuous searches are galactic non-axisymmetric spinning NS, isolated or in binary systems, such that the frequency of the emitted GW, is in the band of our detectors ~[20-2000] Hz.
- **We know that potential sources of CW exist**: 2500+ NS are observed (mostly pulsars) and O(10^8 - 10^9) are expected to exist in the Galaxy.
- *Multi-messenger astronomy plays and will play an important role*

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:





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

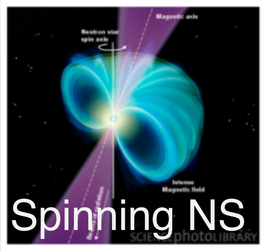
- deformation due to elastic stresses or magnetic field;
- deformation due to matter accretion (e.g. LMXB);
- free precession around rotation axis;
- excitation of long-lasting oscillations (e.g. r-modes); …

- Expected signals are not monochromatic at the detector. Frequency (and phase) are modified by various effects:
    - Doppler effect due to the detector motion;
    - orbital motion for sources in binary systems;
    - source spin-down (rotation frequency decreases due to energy loss; relativistic effects; antenna pattern).

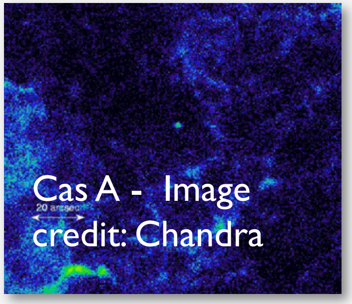
OPTIMISTIC LIMITS FOR CONTINUOUS SIGNALS

- **Spin down limit:** uses the measured f and spin down of a known NS. Assume that the measured spin down of the source is totally due to the emission of GW

$$h_0 \cong 8 \cdot 10^{-25} \cdot \left(\frac{d}{1kpc}\right)^{-1} \cdot \sqrt{\left(\frac{I}{10^{38} kg \cdot m^2}\right)\left(\frac{|\dot{f}|}{10^{-10} Hz/s}\right)\left(\frac{f}{100 Hz}\right)^{-1}}$$

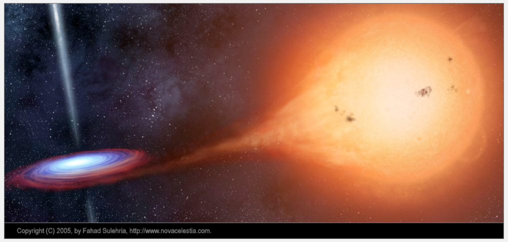


- **Age-based limit:** uses the age of a known NS with unknown spin frequency.



$$h_{IL} \cong 2.3 \cdot 10^{-24} \cdot \left(\frac{d}{1kpc}\right)^{-1} \cdot \sqrt{\left(\frac{I}{10^{38} kg \cdot m^2}\right)\left(\frac{10^3 yr}{\tau_{sd}}\right)}$$

- **Torque-balance limit** (accreting binaries)



$$h_0 = 5\ 10^{-27} \sqrt{\frac{X\ rays\ Flux}{10^{-8}\frac{erg}{cm^2 s}}} \cdot \sqrt{\frac{600\ Hz}{f}}$$

- 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.

ε_{max} ~10^{-5} for a 'standard' NS (fluid core, normal nuclear matter)

ε_{max} ~ 10^{-3} for 'hybrid' stars (hadron-quark core)

ε ~10^{-6} $(B/10^{15}\,G)^2$ minimal deformation from magnetic field. B is the volume averaged magnetic field inside the star (Cutler, PRD 66 084025, 2002. Lasky, Glampedakis, MNRAS 458 2016)

ε < 10^{-1} for quark star.

(N. Jonhson-McDaniel, B. Owen PRD 86 063600 , PRD 87 129903)

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

Tri-axial ellipsoid	$f_{GW} \hat{=} 2 f_{rot}$
r-mode fluid oscillations	$f_{GW} \simeq (4/3) f_{rot}$
Free-precession	$f_{GW} \hat{=} f_{rot} \pm f_{prec}$

What could detections tell us?

- NS internal structure (EOS, viscosity)
- Maximum ellipticity
- Maximum spin allowed for a NS
- Inner magnetic field intensity
- Mechanism operating in accreting systems
- Interplay between inner superfluid and crust
- NS demography (gravitar population or other compact objects) and implications for a stochastic background of signals from NS
- GR predictions (e.g. tests for non-tensorial g.w.)
-

➢ Non-detections (i.e. upper limits) **cannot** be used to exclude some EOS

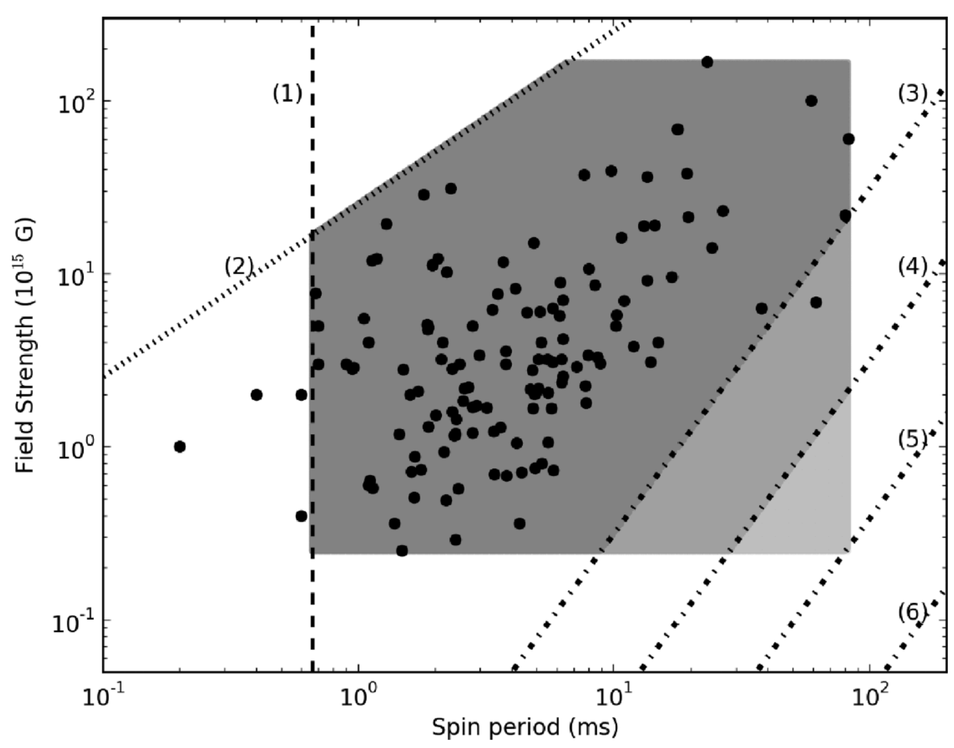
➢ But even with a null result we can constrain other parameters, like ellipticity and the internal magnetic field .

➢ Or, on the other side..,see next slide:

CONSTRAINING NS PROPERTIES USING SGRB

- Rowlingson et al, MNRAS 443, 1779–1787 (2014)
- *An intrinsic correlation has been identified between the luminosity and duration of plateaus in the X-ray afterglows of gamma-ray bursts suggesting a central engine origin. The magnetar central engine model predicts an observable plateau phase, with plateau durations and luminosities being determined by the magnetic fields and spin periods of the newly formed magnetar.*

Vertical line at 0.66 ms represents the minimum spin period allowed before breakup of a 2.1 M neutron star.



GW EMISSION FROM POST-MERGER REMNANT

- The outcome of the BNS coalescence can be:
  - BH prompt formation. Favored by soft EOS.
  - Hypermassive NS, that collapses to a BH in < 1s (burst-like signal)
  - Supramassive NS, that collapses to a BH in 100-10000 s (long-transient signal)
  - Stable NS (continuous signal)
  - Which of these possibilities occurs depends on how much mass remains in the resulting object, as well as the composition and properties of matter inside neutron stars.
  - Knowing the masses of the original two neutron stars before they merged, which can be measured from a possible gravitational wave signal detected, and under some assumptions about the compactness of neutron stars, one can guess the nature of the resulting object
- Searches for short (<1 s) , medium (< 500 s) , long (hours, days) duration gw signals might be done.

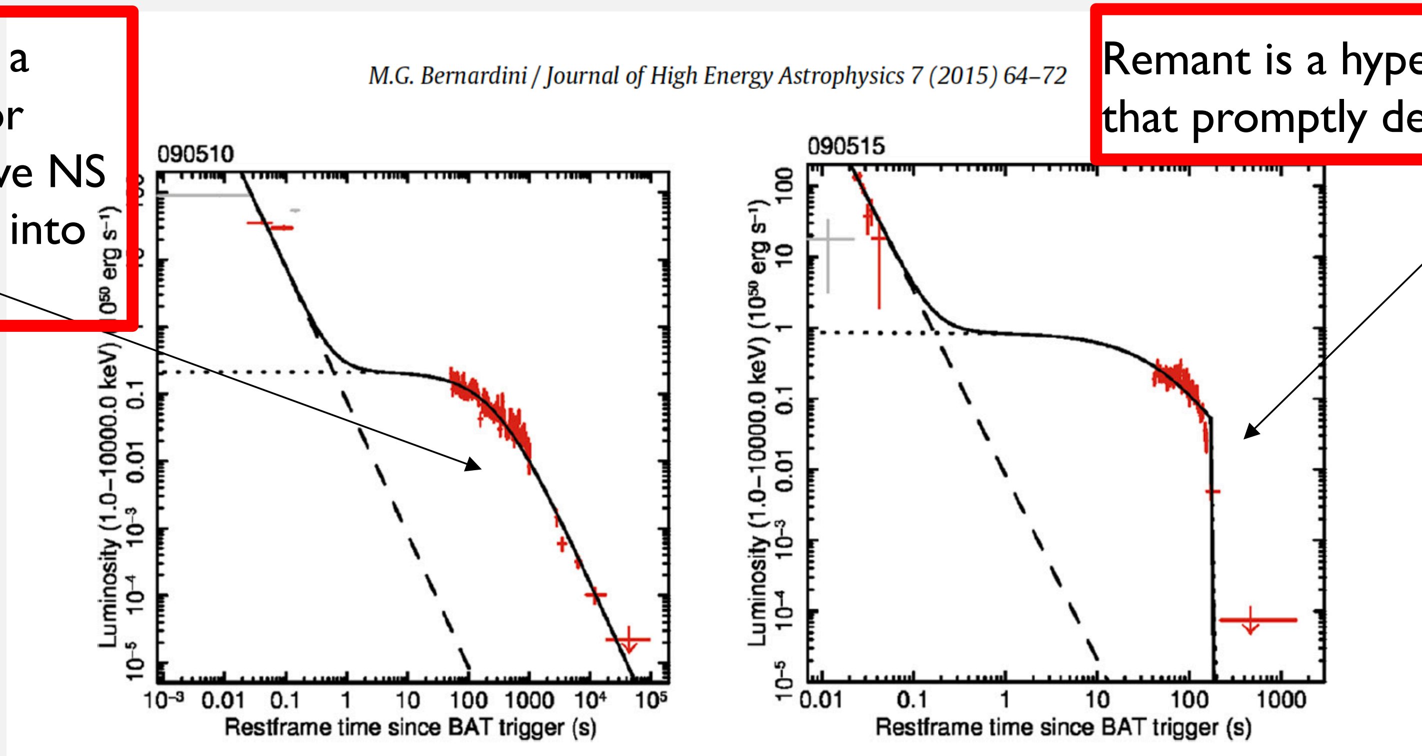
Constraining GW emission using SGRB properties

- Chances to detect a long duration transient from the remnant of GW170817 is small (due to 40 Mpc), and to the fact that model uncertainties are large.

- X-ray light curves from short GRBs can constrain GW emission !

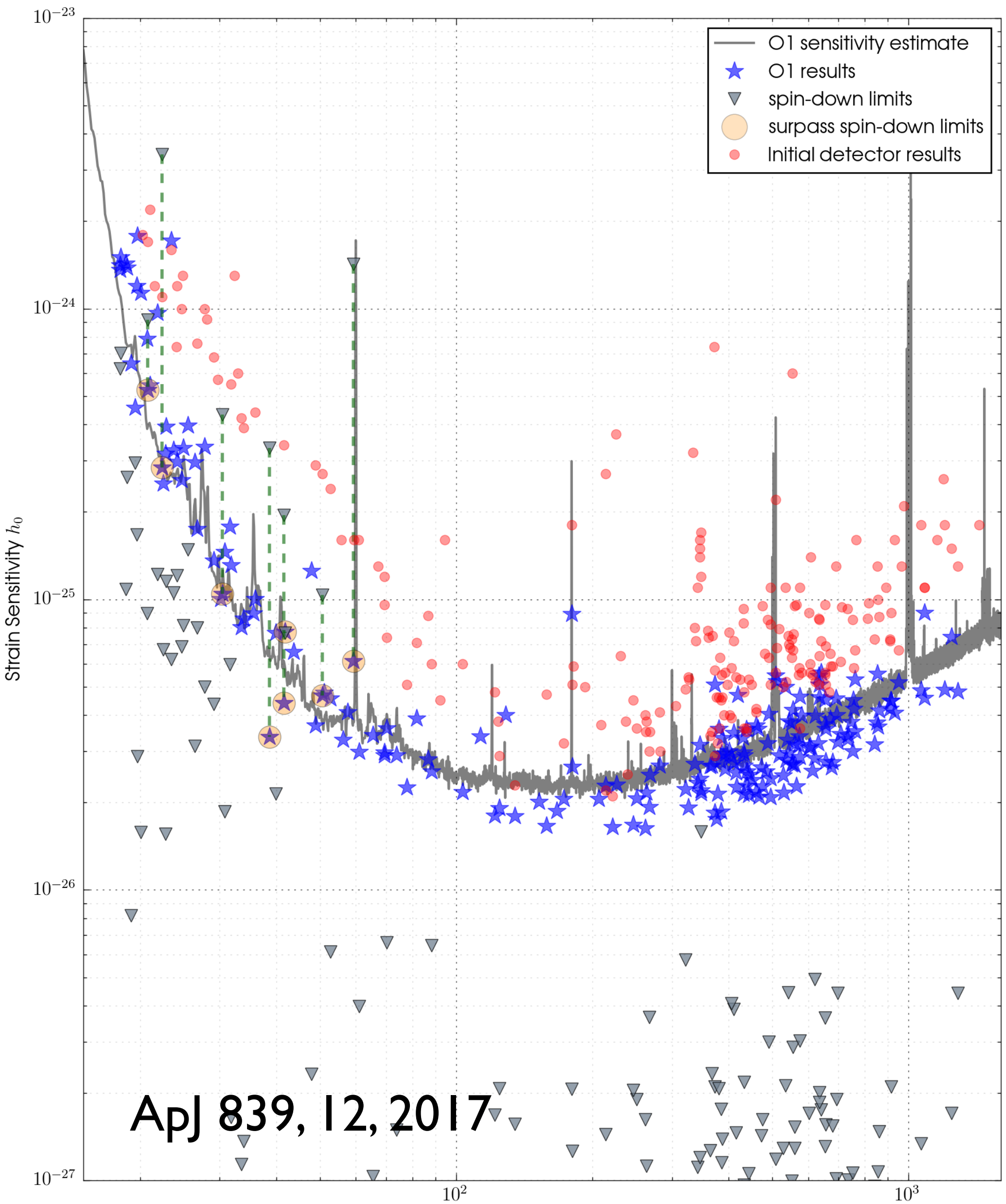
Remnant is a stable NS or supramassive NS that decays into a BH

Remant is a hypermassive NS that promptly decays to BH



Examples of X-ray plateaus and power laws in short GRBs (from Rowlinson et al., 2013)

RESULTS: O1 TARGETED SEARCH FOR KNOWN PULSARS



- This search needs accurate ephemerides
- 200 known pulsars analyzed (out of ~400 in the sensitive band)
- Spin down limit broken for 8 pulsars
- Crab limit at 0.2% of total energy loss
- Vela limit at 1% of total energy loss

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

O1 NARROW BAND SEARCH RESULTS

Search over narrow frequency band.

PRD 96, 122006, 2017

Position is known, but allows EM and GW phases evolution to not be completely phase-locked.

Ephemeris, doesn't need to be up to date.

$$\Delta f = 2 f_0 \delta$$

$$\Delta \dot{f} = 2 \dot{f}_0 \delta,$$

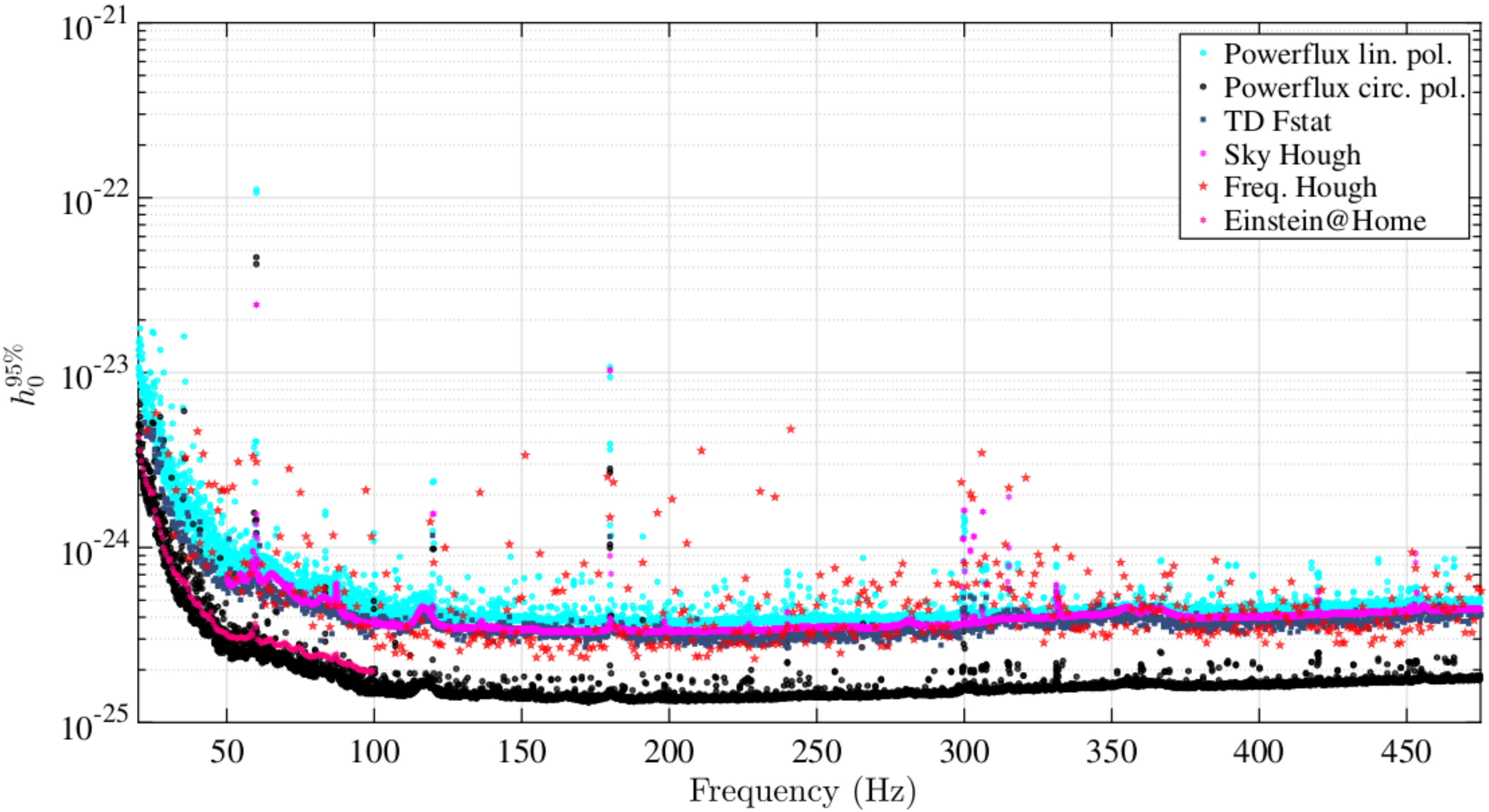
With $\delta \sim 10^{-4} - 10^{-3}$

TABLE VI. Median over the analyzed frequency band of the upper limits obtained on the GW amplitude for the 11 known pulsars. In the fourth column we report the ratio between the spin-down limit listed in Table II and the median of the upper limit; uncertainties correspond to the 1σ confidence level and are due to the uncertainties on the pulsars' distances. The last column reports the median upper limit on the fraction of rotational energy lost due to GW emission.

Name	$h_{ul} \times 10^{-25}$	$\epsilon_{ul} \times 10^{-4}$	h_{ul}/h_{sd}	$\dot{E}_{rot}/\dot{E}_{GW}$
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

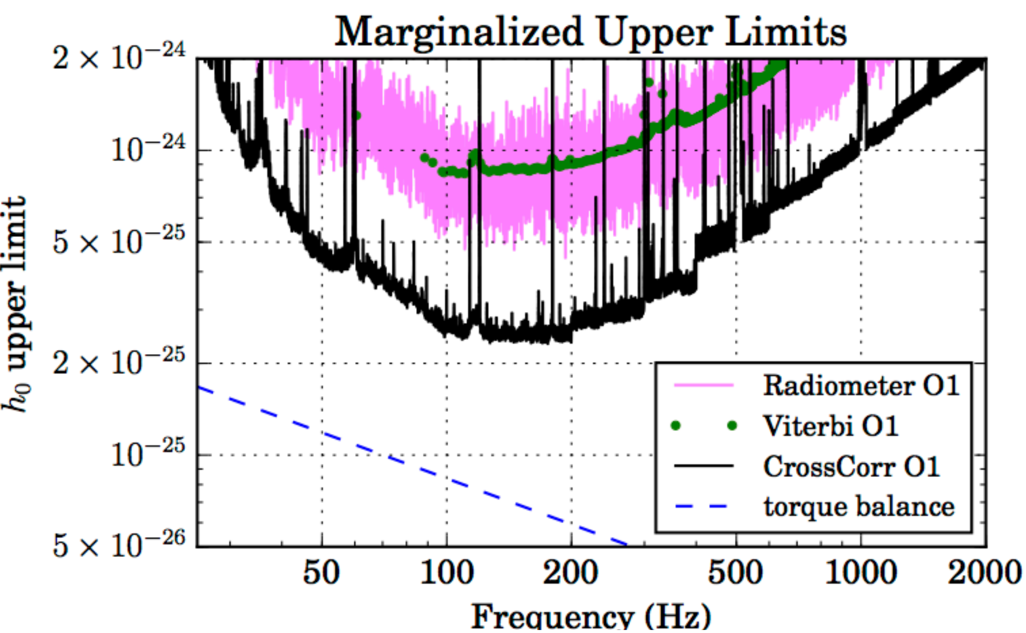
RESULTS: ALL-SKY SEARCHES IN O1 DATA

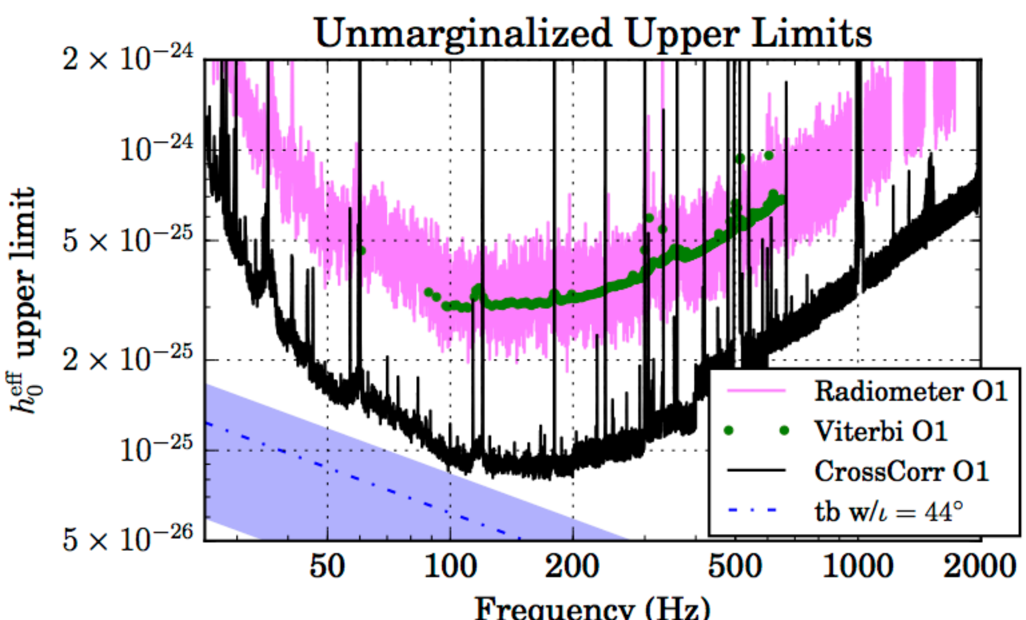
PRD96, 062002 (2017). Up to 475 Hz.
PRD 96 12004 (2017). E@H up to 100 Hz. Restricted sd range
arXiv 1802.05241, Feb 2018..Submitted to PRD. From 475 to 2000 Hz



RESULTS: O1 DIRECTED SCORPIUS X-1 SEARCHES.

APJ 847, 1 (Sept 2017)



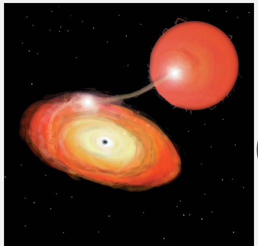


No evidence for a continuos wave signal in the range 25 Hz-2kHz. We have done three different analysis.

The torque balance line is an optimistic expected signal strength inferred from the X-ray flux from Sco X-1

Tightest limits nearly reach the torque-balance limit near 100 Hz (a factor ranging between 1.2 and 3.5)

Additional and more sensitive data together with the expected improvements in the methods will lead to possibly beat the Torque balance limit



RESULTS: SEARCH FOR A POST-MERGER SIGNAL (APJL, 851:L16 (2017))

Analysis done using two pipelines, called cWB and STAMP.

Both are based on the measure of excess power in time/frequency bins.

Search for short ($\lesssim 1$ s) and intermediate-duration ($\lesssim 500$ s) signals, which includes gravitational-wave emission from a hypermassive NS or supramassive NS

No signal was found from the post-merger remnant.
The strain upper limits are more than an order of magnitude larger than those predicted by most models.

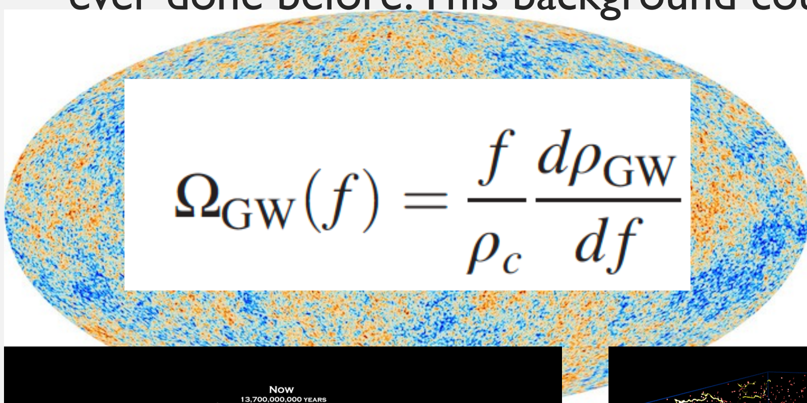
For short signals, our best upper limit of the gravitational-wave strain emitted from [1-4] kHz is $h_{50\%\mathrm{rss}} = 2.1*10^{-22}$ Hz$^{-1/2}$.

For intermediate-duration signals, our best upper is
$h_{50\%\mathrm{rss}} = 8.4*10^{-22}$ Hz$^{-1/2}$ for a millisecond magnetar model,
and is $h_{50\%\mathrm{rss}} = 5.9*10^{-22}$ Hz$^{-1/2}$ for a bar-mode model.

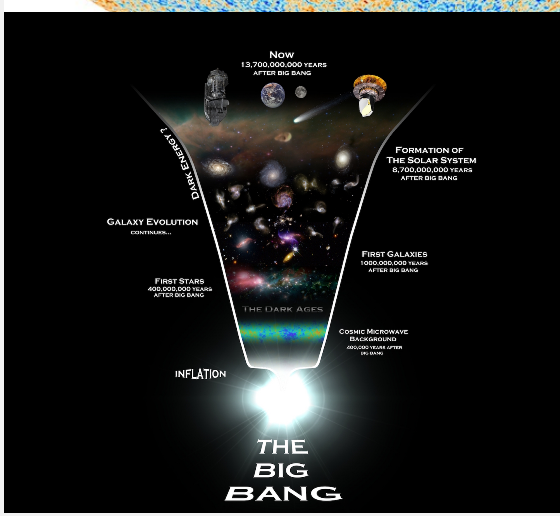
STOCHASTIC G.W. BACKGROUND

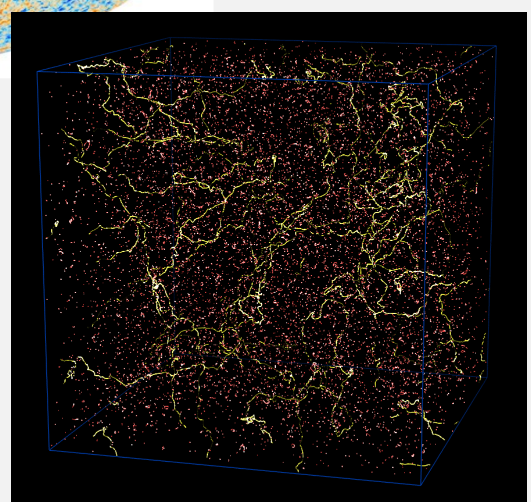
There are many colliding black hole events that g.w. detectors are unlikely to hear because they are too far away. We can hear their collective singing as a stochastic background. There are several other kinds of astrophysical objects that could contribute to this background, like neutron stars and supernovae.

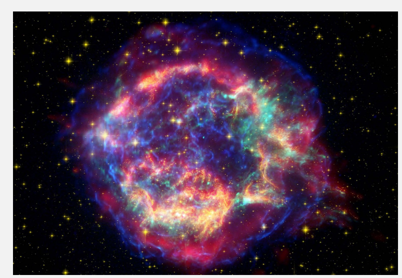
It is also thought that ripples from a tiny fraction of a second after the Big Bang can grow into gravitational waves that are detectable as a stochastic background today. Detecting these backgrounds would allow us to 'hear' further back into cosmic history than we have ever done before. This background could potentially be revealed with future detectors



$$\Omega_{\mathrm{GW}}(f) = \frac{f}{\rho_c}\frac{d\rho_{\mathrm{GW}}}{df}$$







THE BASIC PROBLEMS OF DETECTING A STOCHASTIC GW BACKGROUND.

- The signal is continuous and weak. No detection is expected, at the actual sensitivities (in a next slide this will be shown).
- Background characterization is of paramount relevance. Much work done, but improvements still possible.
- But, as the advanced detectors reach design sensitivity, there is a reasonable possibility of detecting the background due to BBHs.
- Even if no detection is made with (close) future searches, the searches will be able to constrain important cosmological and astrophysical background models.
- A wide variety of astrophysical and cosmological sources are expected to contribute to a stochastic gravitational-wave background. Following the observations of GW150914 and GW151226, the rate and mass of coalescing binary black holes appear to be greater than many previous expectations. As a result, the stochastic background from unresolved compact binary coalescences is expected to be louder than it was thought.

$$\Omega_{\mathrm{GW}}(f) = \Omega_\alpha \left(\frac{f}{f_{\mathrm{ref}}} \right)^\alpha$$

Reference frequency is assumed to be 25 Hz
α= 0, 3 (cosmologically and astrophysically motivated)
And α=2/3 (compact binary motivated model)

SUMMARY OF RECENT RESULTS. O1 DATA

PRL 118, 121101 (2017)

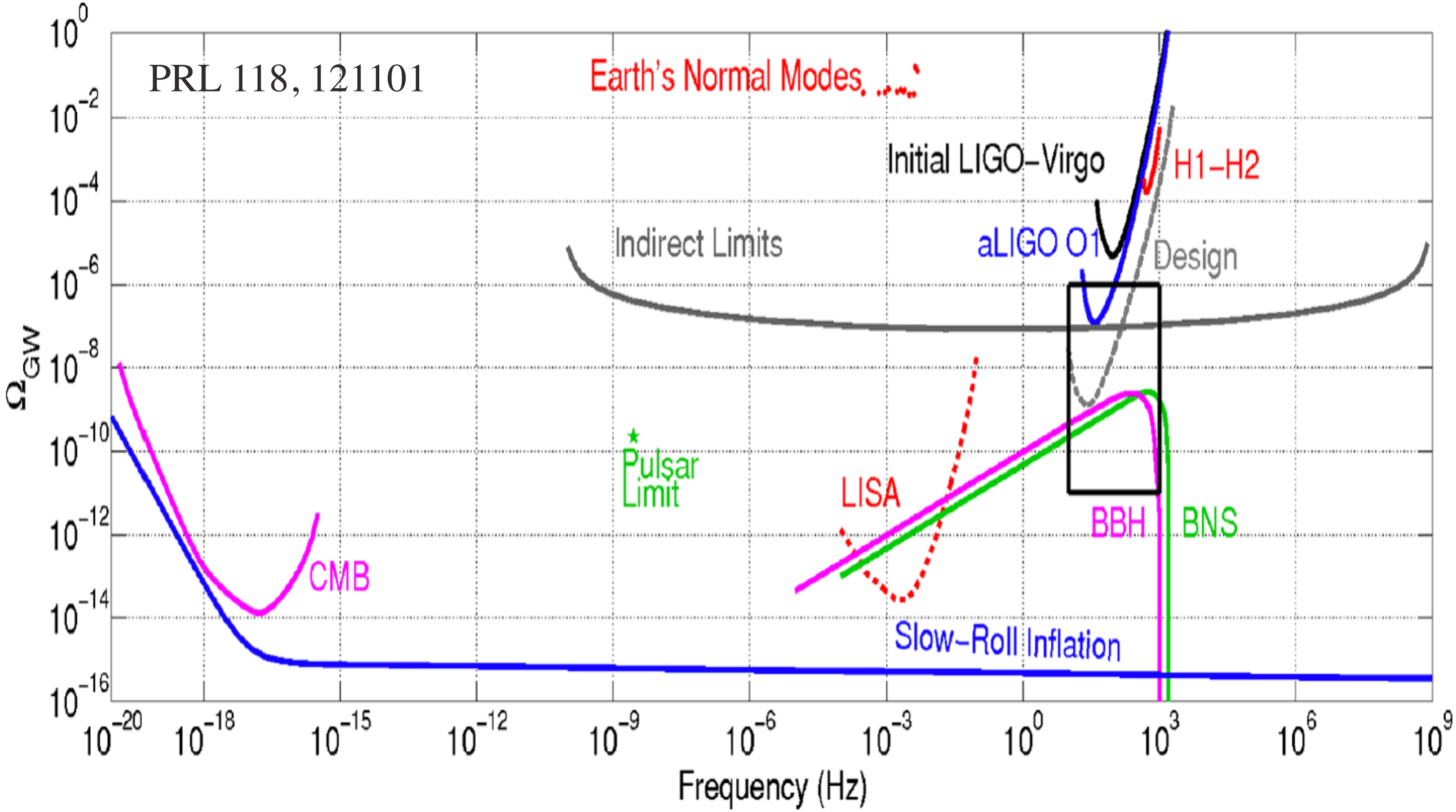
Isotropic search: While no evidence of the background was heard, Advanced LIGO was able to place limits on its loudness (the dimensionless gravitational wave energy density of the background). The limit on the total energy density is 33 times better than earlier limits obtained from analysis of initial detectors data.
A significant effort was put into understanding the data to ensure that any background that is detected comes from astrophysical sources, not from the detectors.

$$\Omega_0 < 1.7 \times 10^{-7}$$

Assuming a flat energy density spectrum
20-86 Hz
95% confidence

TABLE I. The frequency bands with 99% of the sensitivity are shown, along with the point estimate and standard deviation for the amplitude of the background, and 95% confidence level upper limits using O1 data for three values of the spectral index, $\alpha = 0, 2/3, 3$. We also show the previous upper limits using Initial LIGO-Virgo data.

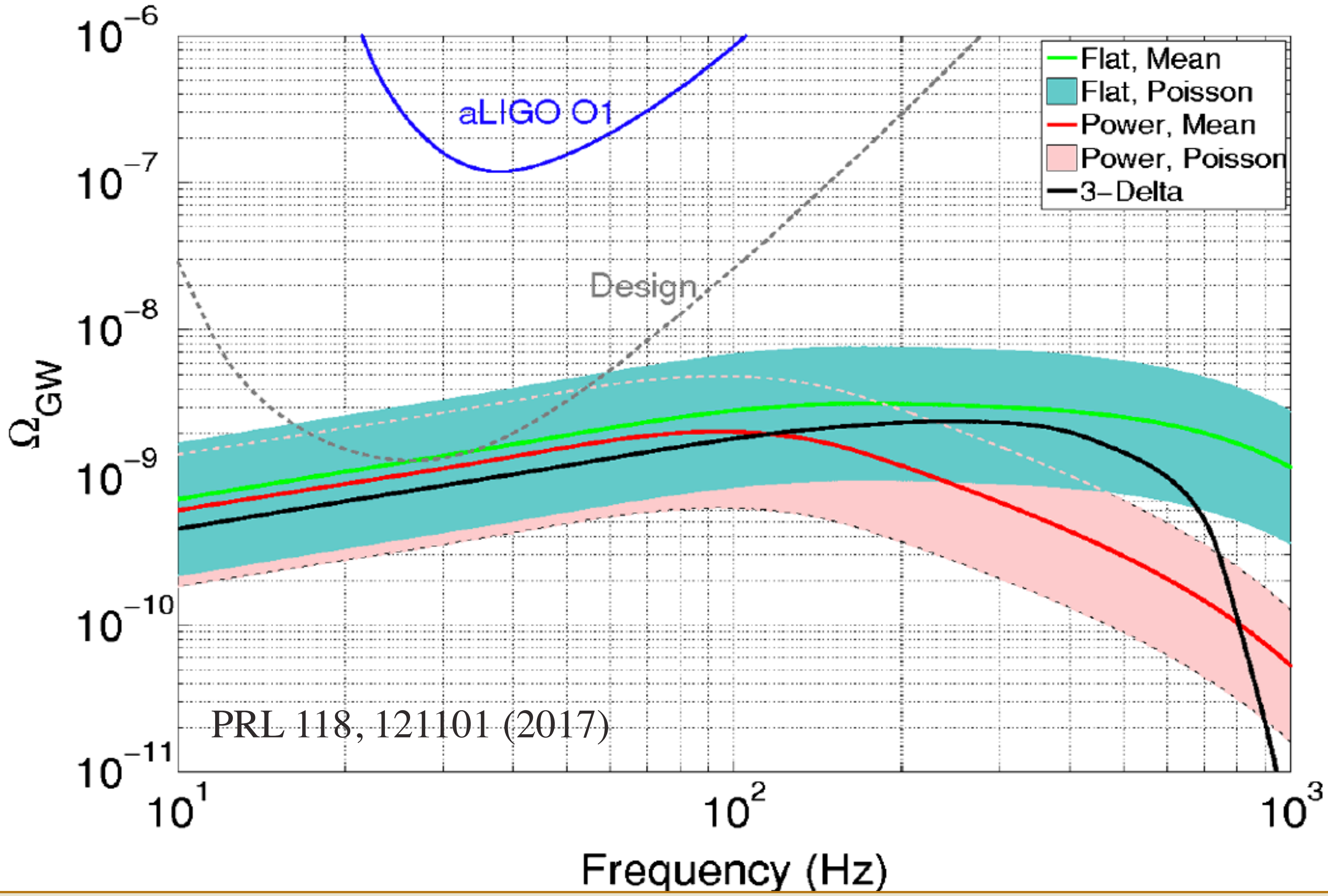
Spectral index α	Frequency band with 99% sensitivity	Amplitude Ω_α	95% C.L. upper limit	Previous limits [36]
0	20–85.8 Hz	$(4.4 \pm 5.9) \times 10^{-8}$	1.7×10^{-7}	5.6×10^{-6}
2/3	20–98.2 Hz	$(3.5 \pm 4.4) \times 10^{-8}$	1.3×10^{-7}	–
3	20–305 Hz	$(3.7 \pm 6.5) \times 10^{-9}$	1.7×10^{-8}	7.6×10^{-8}



Constraints on the background, compared to models

In a classical scenario, the measure of the astrophysical BBH background provides the most promising candidate for the first detection of the background.

Non standard inflation models or cosmic strings background might bring to surprises !



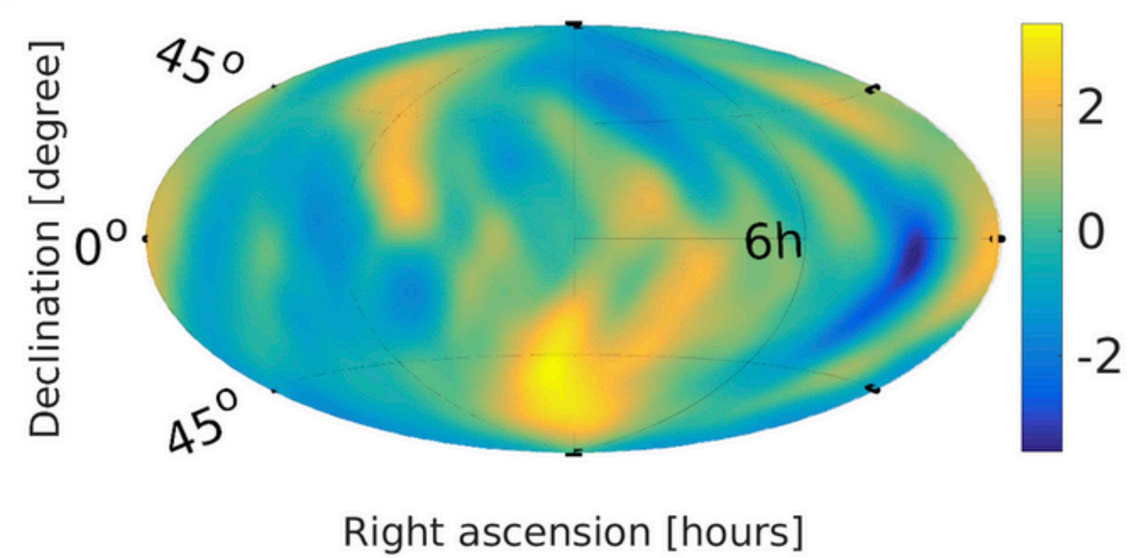
Range of potential spectra for a BBH background, using the flat-log, power-law, and three-delta mass distribution models, with the local rate inferred from the O1 detections.

For the flat-log and power law distributions, we show the 90% Poisson uncertainty band due to the uncertainty in the local rate measurement.

SUMMARY OF RECENT RESULTS

PRL 118, 121102 (2017). A 3 step search method based on a radiometer search method, optimized to search for a small number of resolvable point sources. The motivation is to search for persistent GW that might be difficult to detect with CW analyses.

- Directional search:
- Three search methods capable of detecting a wide range of possible signals with only minimal assumptions about the signal morphology.
- No evidence of persistent gravitational waves.
- Set upper limits on broadband emission of gravitational waves as a function of sky position. And set narrowband limits as a function of frequency for the three selected sky positions (Sco X-1, SN1987A and the Galactic Centre)
- Most sensitive strain amplitude upper limits on Sco X-1, SN1987A and the Galactic Centre



This map shows the radiometer signal-to-noise ratio for each point on the sky when looking for a GW background dominated by compact binary mergers. The values detected are not significant, and are consistent with the natural variations in measured SNR from a sky that contains purely noise.

PRL 118, 121102 (2017)

SNR for points in the Sky looking for a background dominated by compact binary mergers

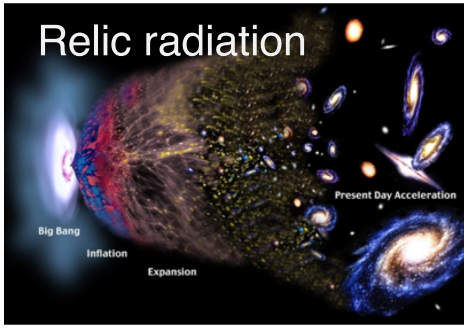
Sky maps are a useful tool to study the energy density of the gravitational wave sky.

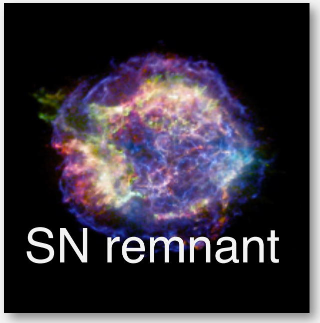
Finding structure in the gravitational wave background could uncover a richer, and even more exciting, infant universe.

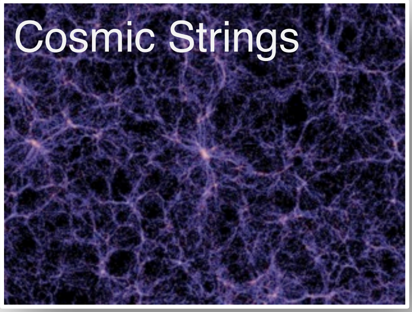
Also, scanning the gravitational wave sky, while making minimal assumptions about the type of signals we are looking for, could help us find things that we were not expecting.

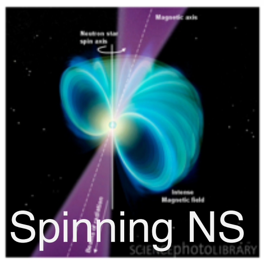
CONCLUSIONS

- We live highly exciting times, many interesting progresses and results, also ignoring the detections !, have been made in the past years.
- A strong effort is ongoing to unveil sources whose fingerprint is hidden in the data, and this is based on joint experimental, data analysis and theoretical work
- Multi messenger astronomy has, in many cases, an important role
  - provide ephemerides for the known sources
  - help in reducing the searches parameter space
  - confirm a result, in the case of a discovery of a persistent signal from an unknown source





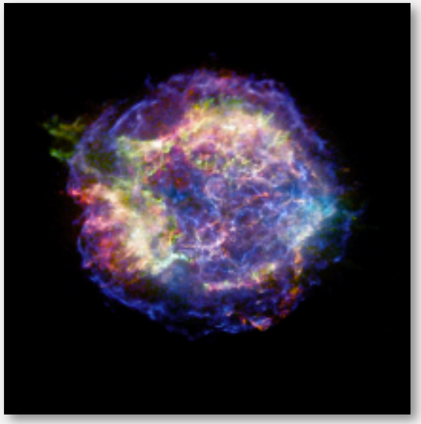




BACKUP

Directed searches on LIGO S5,S6 data

- **Search for CW from 9 supernova remnants**, not associated with pulsars, with known position and unknown rotational parameters. (arXiv:1412.5942, submitted to ApJ) S6 data.
- Integration time in the range 5-25 days
- Upper limit below indirect limit based on distance and age.



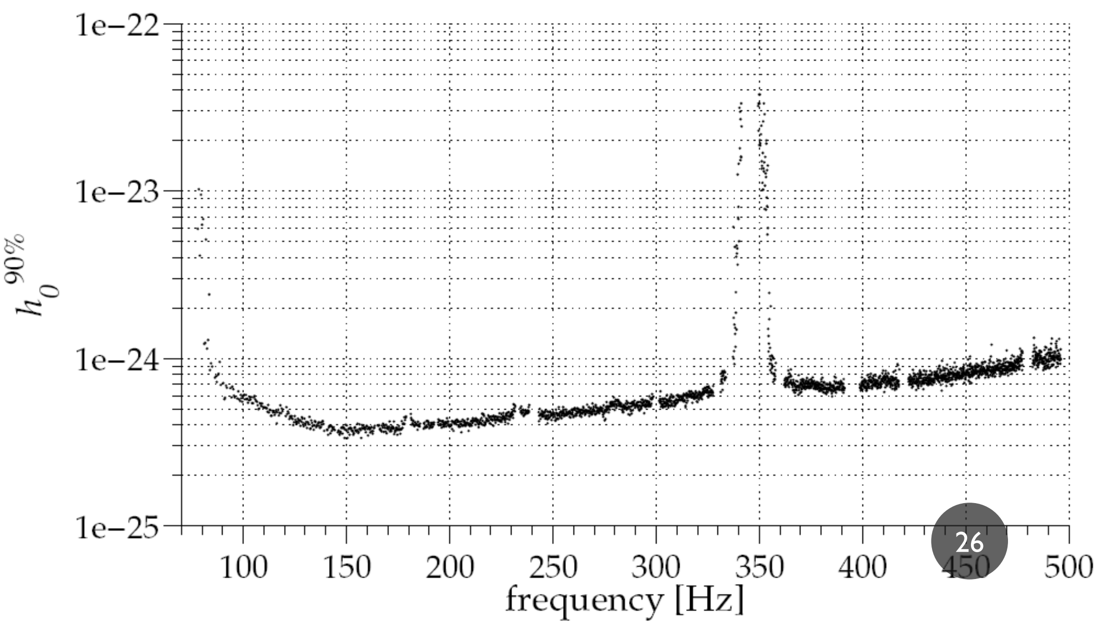
$$h_{IL} \cong 2.3 \cdot 10^{-24} \cdot \left(\frac{d}{1kpc}\right)^{-1} \cdot \sqrt{\left(\frac{I}{10^{38} kg \cdot m^2}\right)\left(\frac{10^3 yr}{\tau_{sd}}\right)}$$

- 95% confidence upper limits as low as 4×10^{-25} on intrinsic strain, 2×10^{-7} on fiducial ellipticity, and 4×10^{-5} on r-mode amplitude

- **Galactic center semi-coherent search**

PRD 88, 102002 (2013). S5 data

Hierarchical search in a 3 pc region around Sgr A*



SEARCH FOR BINARY SYSTEMS : DIRECTED SEARCH FOR GRAVITATIONAL WAVES FROM SCORPIUS X-1 WITH INITIAL LIGO DATA. PRD 91, 062008 (2015).

POTENTIALLY THE MOST POWERFUL CONTINUOUS GW EMITTER, DUE TO PROXIMITY AND HIGH ACCRETION RATE

- No evidence was found to support detection of a signal with the expected waveform.
- Semi coherent analysis covering 10 days of LIGO S5 data, from 50–550 Hz. Incoherent sum of coherent $\mathcal{F}$-statistic power distributed amongst frequency-modulated orbital sidebands.
- All candidates not removed at the veto stage were found to be consistent with noise at a 1% false alarm rate.
- Median strain upper limits of 1.3×10−24 and 8×10−25 at 150 Hz (for the standard and angle-restricted searches)

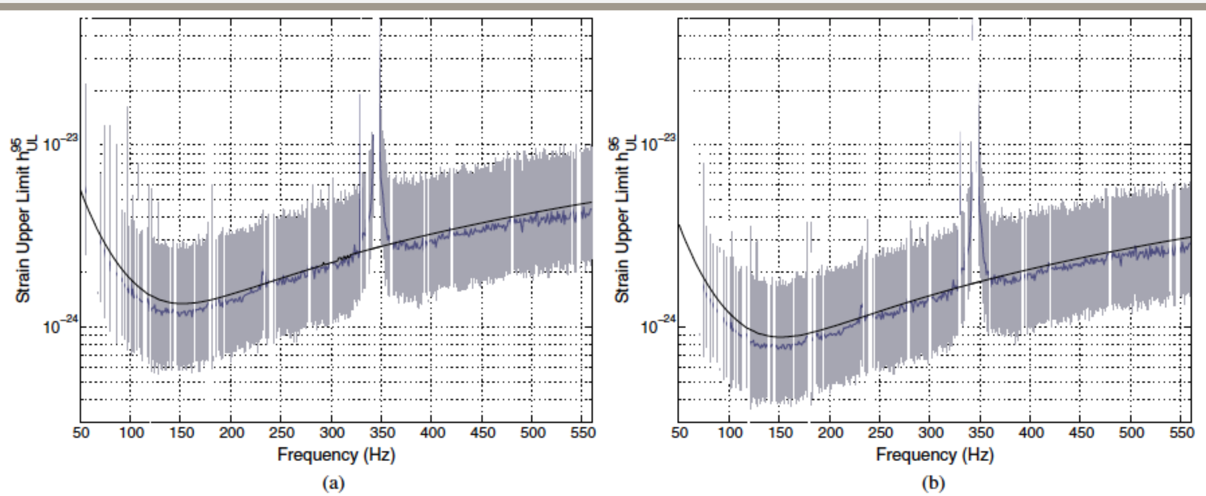


FIG. 5 (color online). Gravitational-wave strain 95% upper limits for H1L1 data from 21–31 Aug 2007 for (a) the standard search with flat priors on $\cos\iota$ and ψ (left panel) and (b) the angle-restricted search with $\iota = 44^\circ \pm 6^\circ$ and $\psi = 234^\circ \pm 4^\circ$ (right panel).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

THE FIRST ALL-SKY SEARCH FOR CONTINUOUS UNKNOWN G.W. SOURCES IN BINARY SYSTEMS. PRD 90,062010 (2014)

- On LIGO S6 and Virgo VSR2 and VSR3 data
- Frequencies from 20 to 520 Hz. Orbital periods from 2 to 2254 hours.
- Frequency and period dependent range of frequency modulation depths from 0.277 to 100 mHz.
- No plausible G.W. candidate events survive

The most sensitive 95% UL on

GW strain is 2.3 * 10^{-24} at 217 Hz,

assuming source waves circularly polariz

- An UL on SCO-X1 was also placed,

from 20 to 57.25 Hz.

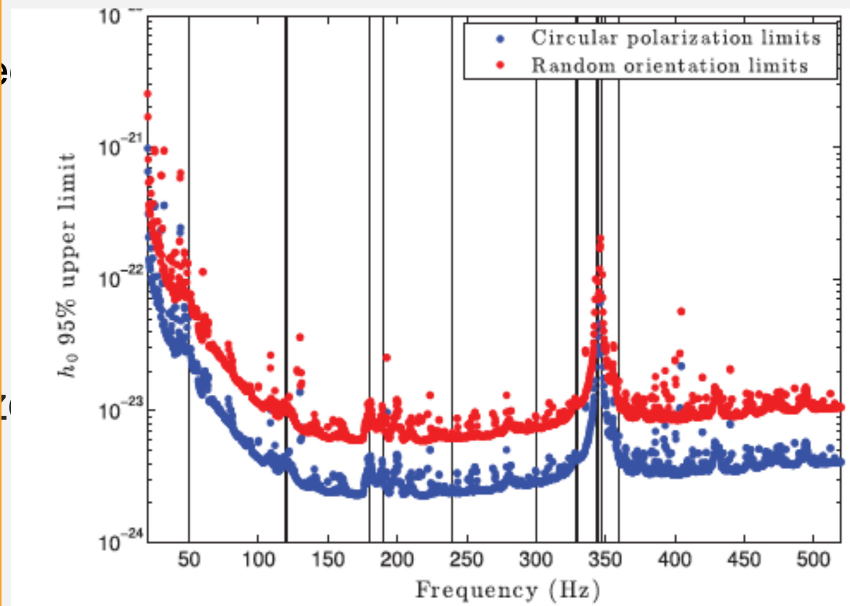


FIG. 2 (color). All-sky strain upper limit results of S6/VSR2-3 for continuous gravitational waves assuming the source waves are circularly polarized (blue points) or randomly polarized from randomly oriented sources (red points). The vertical black lines indicate 0.25 Hz frequency bands in which no upper limits have been placed. The smoothness of the curve is interrupted due to various instrumental artifacts, such as the violin resonances of the mirror suspensions near 350 Hz.