Continuous Gravitational-Wave: the enchanting adventure towards their detection

ELBA 2019 – Lepton Interactions with Nucleons and Nuclei

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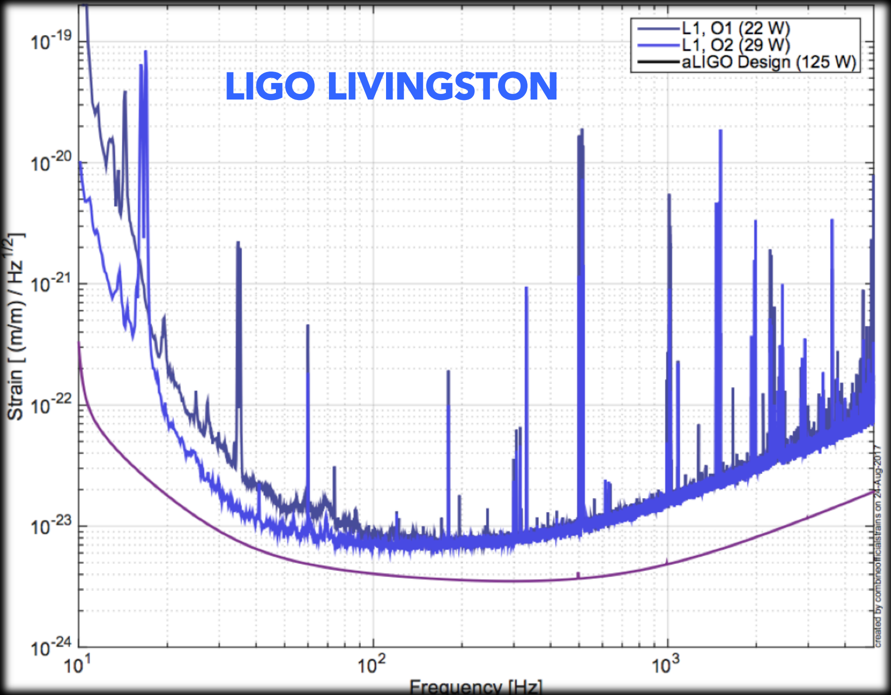
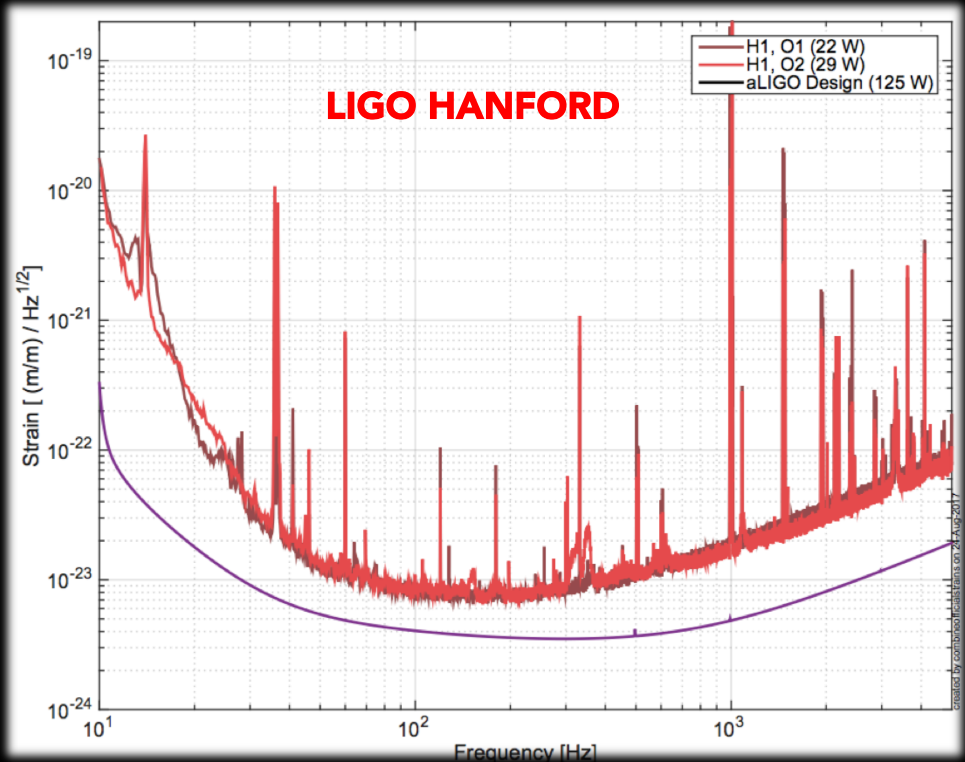
LIGO VIRGO

The most recent observing advanced LIGO-Virgo runs



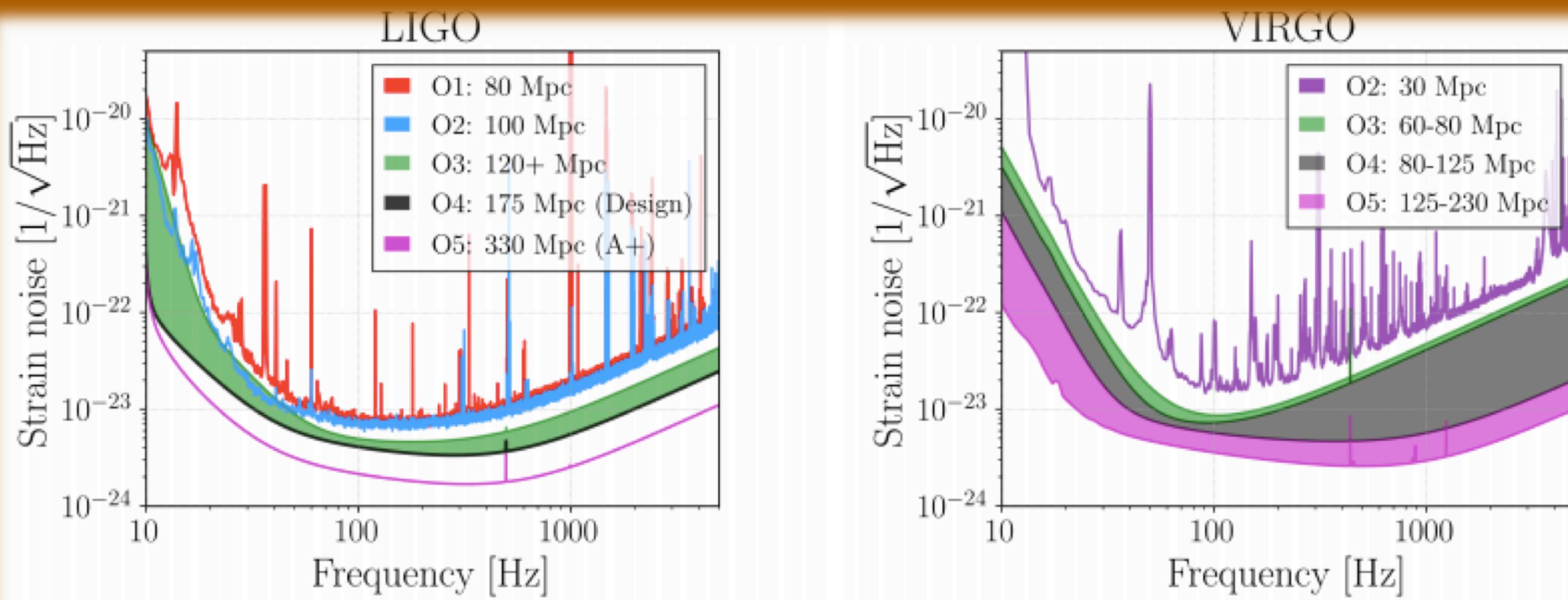
O1: Sept. 12, 2015 – Jan. 19, 2016

O2: Nov. 30, 2016 – August 25, 2017

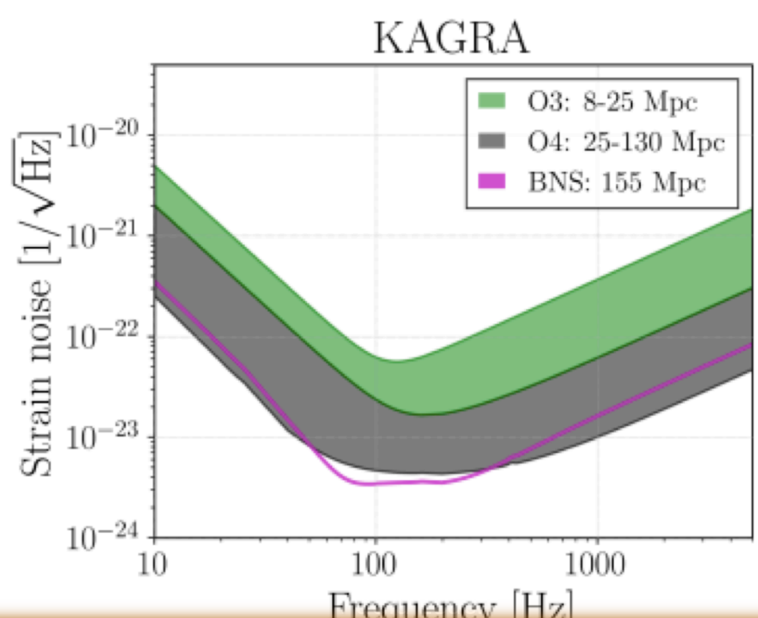


O3 has started on April 1, 2019

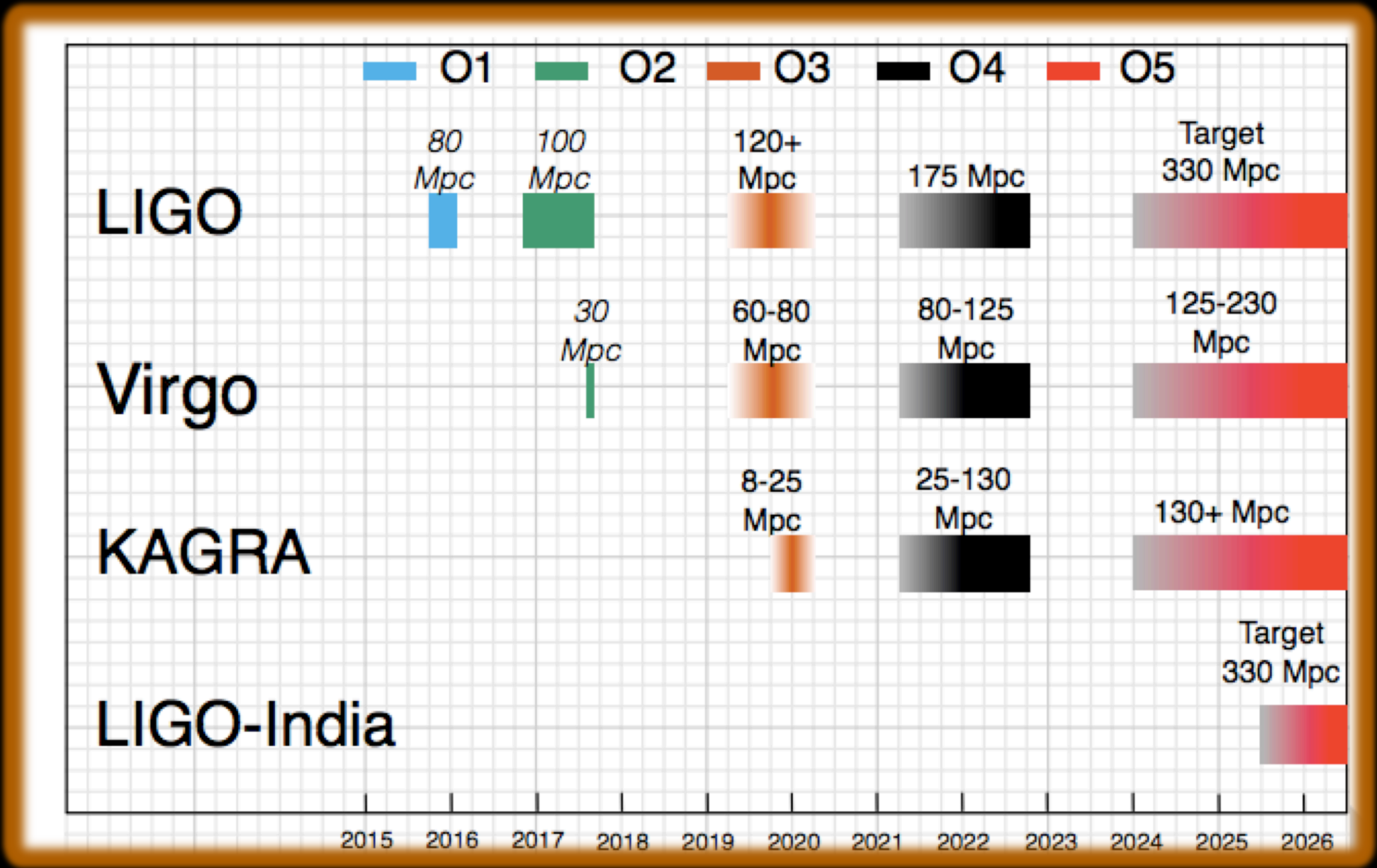
GW detector sensitivity progression I



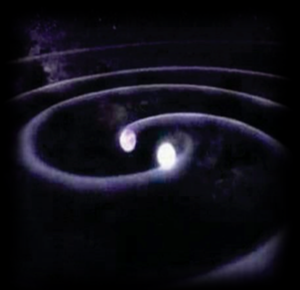
In preparation update of LVC, Liv. Rev. Rel., 21, 3 (2018)



GW detector sensitivity progression II



What are the missing Gravitational-Wave (GW) signals?

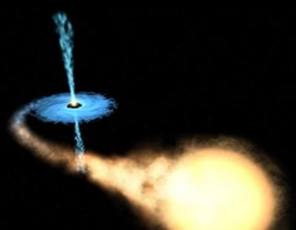


- Compact Binary Coalescing systems *(CBC)*, well modeled waveforms

Two Black Holes (BHs)	Two Neutron Stars (NSs)	BH-NS
✓	✓	X

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

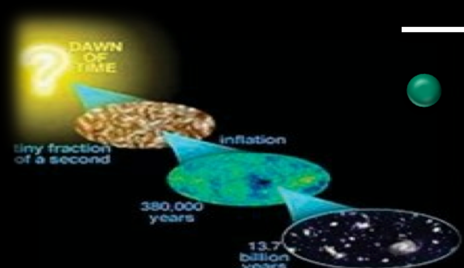
X



http://en.wikipedia.org/

- Fast-spinning NSs in our galaxy (either isolated or in binary systems); monochromatic waves; modeled waveform

X X



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

X

The Continuous-Wave (CW) signal I

- Quasimonochromatic waves with a slowly decreasing intrinsic frequency
- Constant amplitude, weak, but persistent over years of data taking
- Sensitivity increases with observation time
- Computation cost scales with a high power of the observation time
- More than 2800 observed NSs (mostly pulsars) and $O(10^8 - 10^9)$ expected to exist in the Galaxy
- To emit CWs a NS must have some degree of non-axisymmetry due to
  - deformation caused by elastic stresses or magnetic field not aligned to the rotation axis ($f_{GW} = 2 f_{rot}$)
  - free precession around rotation axis ($f_{GW} \sim f_{rot} + f_{prec}$; $f_{GW} \sim 2 f_{rot} + 2 f_{prec}$)
  - excitation of long-lasting oscillations (*e.g.* *r*-modes; $f_{GW} \sim 4/3\, f_{rot}$)
  - deformation due to matter accretion (*e.g.* LMXB; $f_{GW} \sim 2 f_{rot}$)

The CW signal II

$$h_0 = 4\cdot 10^{-25}\left(\frac{\varepsilon}{10^{-5}}\right)\left(\frac{I_{zz}}{10^{45}\,\mathrm{g\,cm^2}}\right)\left(\frac{f_r}{100\ \mathrm{Hz}}\right)^2\left(\frac{1\,kpc}{d}\right)$$

- $\varepsilon \le 10^{-5}$ *normal NS* PRD 87, 129903 (2013)
- $\varepsilon \le 10^{-3}$ *hybrid (hadron-quark core) stars*
- $\varepsilon \le 10^{-1}$ *extreme quark stars*

$$h_0^{\mathrm{sd}} = \left(\frac{5}{2}\frac{G I_{zz}\dot{f}_{\mathrm{rot}}}{c^3 d^2 f_{\mathrm{rot}}}\right)^{1/2} = 8.06\times 10^{-19}\frac{I_{38}^{1/2}}{d_{\mathrm{kpc}}}\sqrt{\frac{|\dot{f}_{\mathrm{rot}}|}{f_{\mathrm{rot}}}}$$

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

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

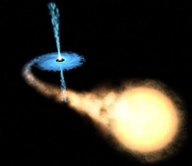
Type of searches

- Targeted
- Narrowband
- Directed
- All-Sky
- Post-merger

Main methods

- Time domain methods, including complex hetrodyne
- Matched filter
- 5-vector method relying on carrier frequency sidebands
- Power spectra analysis
- Hough transform

CWs from spinning NSs in binary systems



- A CW signal from a source in a binary system is frequency-modulated by the source's orbital motion, which in general is described by five unknown Keplerian parameters

- Accretion from a companion may cause an asymmetrical quadrupole moment of inertia of the spinning NS

- In some cases the accretion is asymmetric due to the sporadic observation of x-ray pulsations

- This asymmetry can lead to GW emission through various mechanisms:
  - temperature-dependent electron capture onto nuclei in the crust [ApJ 501, L89 (1998)]
  - magnetic funneling of accreted material [ApJ 623, 1044 (2005)]
  - sustained instability of rotational *r*-modes [ApJ 516, 307 (1999)]

- The most rapidly observed accreting NSs do not spin at very high frequencies, and this seems to suggest that their accretion torques are balanced by GW emission torque [ApJ 501, L89 (1998)]

SEARCHES FROM ISOLATED NSs

(O1+O2) Targeted searches I

- CW signals are assumed to be phase-locked to the pulsar beamed emission => *O*(workstation)

- Observational paper accepted by APJ & https://arxiv.org/abs/1902.08507

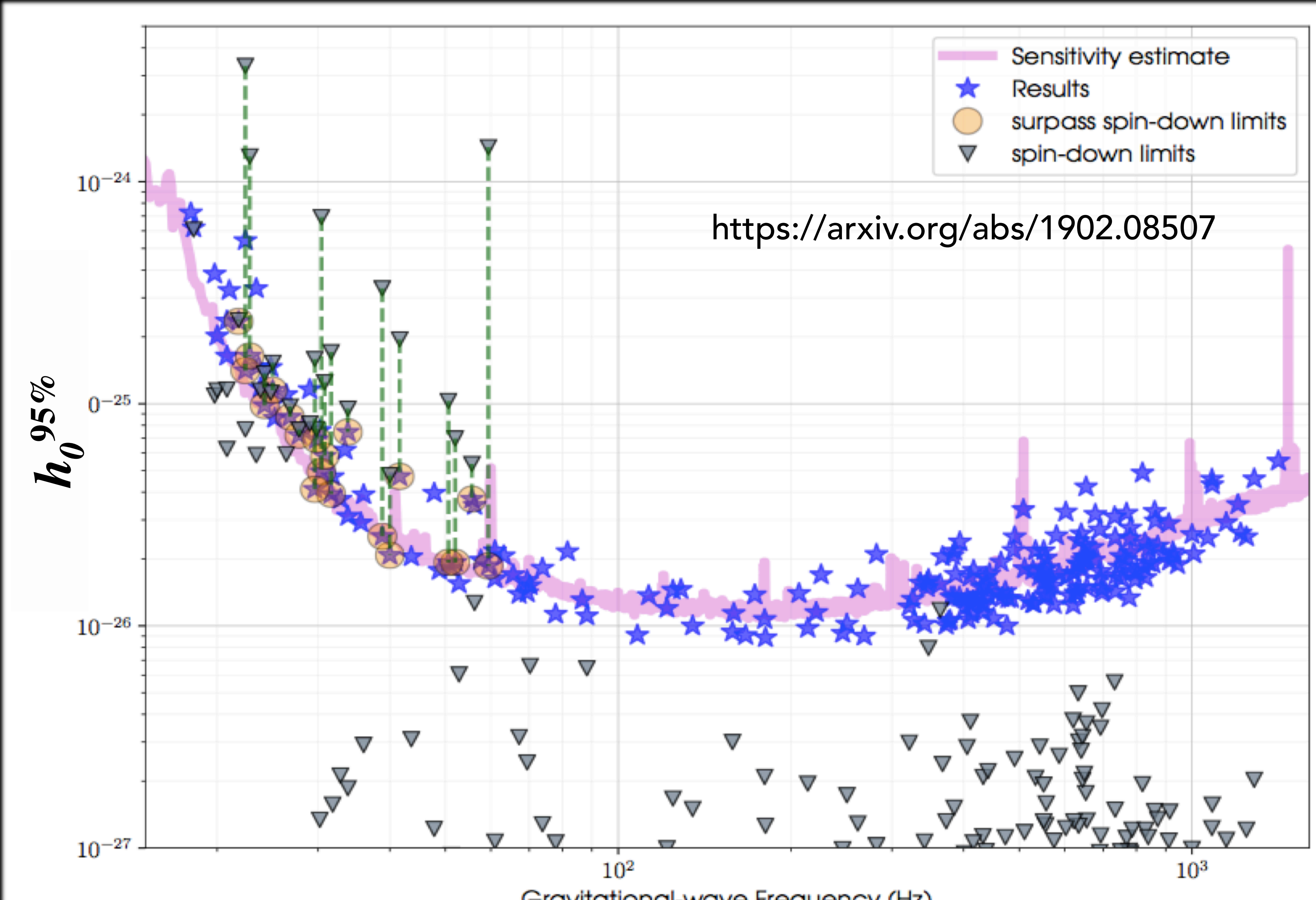
- Search for 221 pulsars
- Targeted emission at $f_{GW} = 2f_{rot}$ and $f_{GW} = f_{rot}$
- Three pipelines contributing:
  - **TD Bayesian** [PRD 72, 102002, 2005]
  - **TD F/G-Stat** [CQG 27, 194015, 2010]
  - **FD 5-vector** [CQG 27, 194016, 2010] (only on O2 data)

- Best 95% CL h_0 UL set to 1.4e-25 for the Vela pulsar.

- For the Crab and Vela pulsars our results constrain GW emission to account for less than 0.017% and 0.18% of the spin-down luminosity, respectively.

- Spindown limit surpassed for 20 young pulsars, including Crab and Vela

(O1+O2) Targeted searches II



O2 Narrowband search I

- Accounting for a small mismatch between the GW rotational parameters and those inferred from EM observations => *O*(workstation)

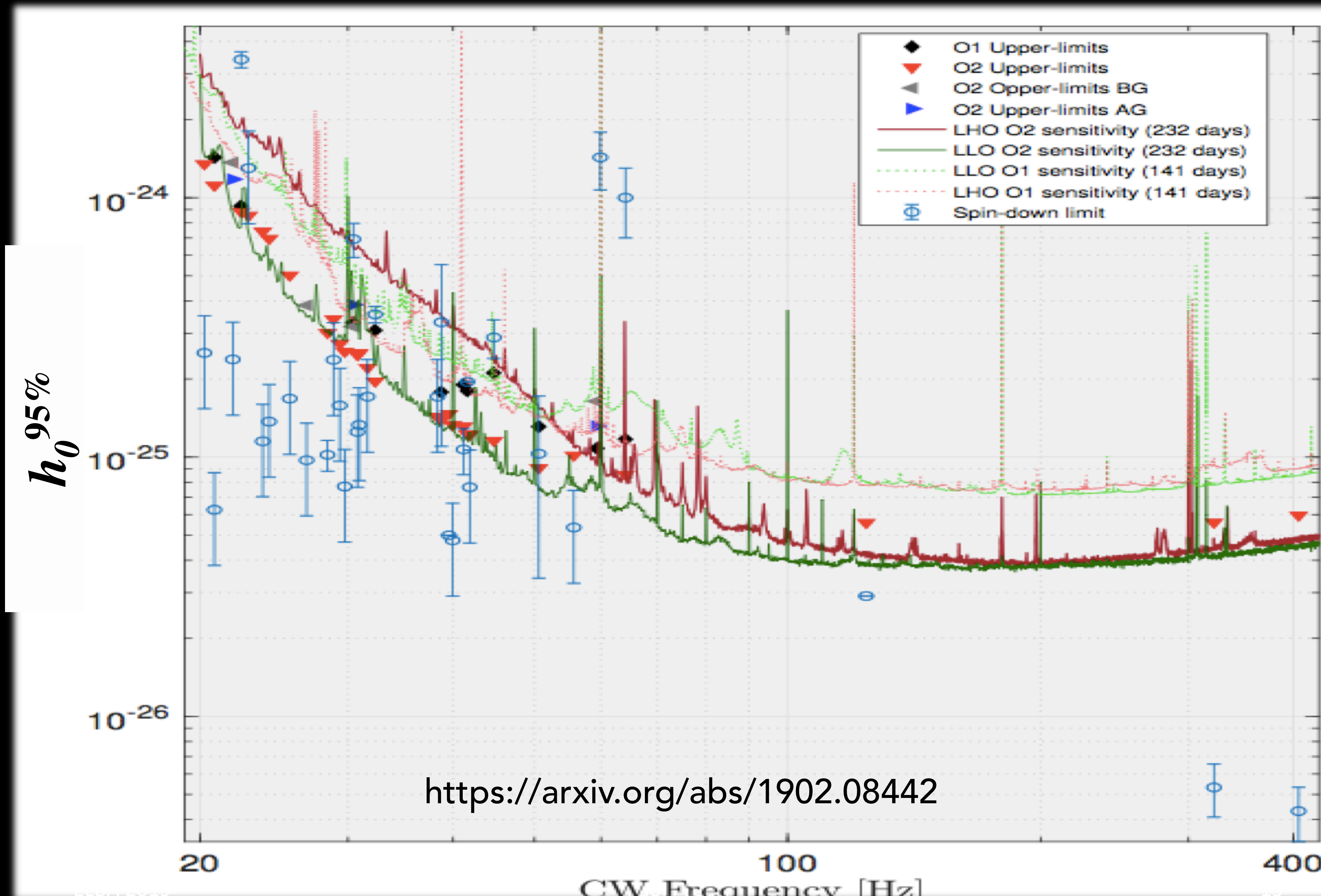
- Observational paper accepted by PRD & https://arxiv.org/abs/1902.08442
- Search parameter space: 33 pulsars, f_{GW} (1+ 1e-3), df_{GW}/dt (1+ 1e-3)

- Best 95% CL h_0 UL set for the 3 millisecond pulsars J0537-6910, J1300+1240 and J2124-3358 and are of the order of 5.5e-26 (above the spin-down limit). The lowest ellipticity UL has been set for J1300+1240, of about 3.3 × 10−7.

- Spindown limit surpassed for 6 pulsars, including Crab (~ 60 Hz) and Vela (~22 Hz).

- The UL on the Vela and Crab pulsars has improved *wrt* O1 result by 10% and by a factor of 2, respectively.

O2 Narrowband search II



https://arxiv.org/abs/1902.08442

O2 All-Sky search I

- **Unknown isolated NSs => computationally expensive (Cloud – Grid Infrastructures)**

- Observational PRD paper (in press) & https://arxiv.org/abs/1903.01901
- Search parameter space: [20, 1922] Hz; [-1, 0.2] x 10^{-8} Hz/s

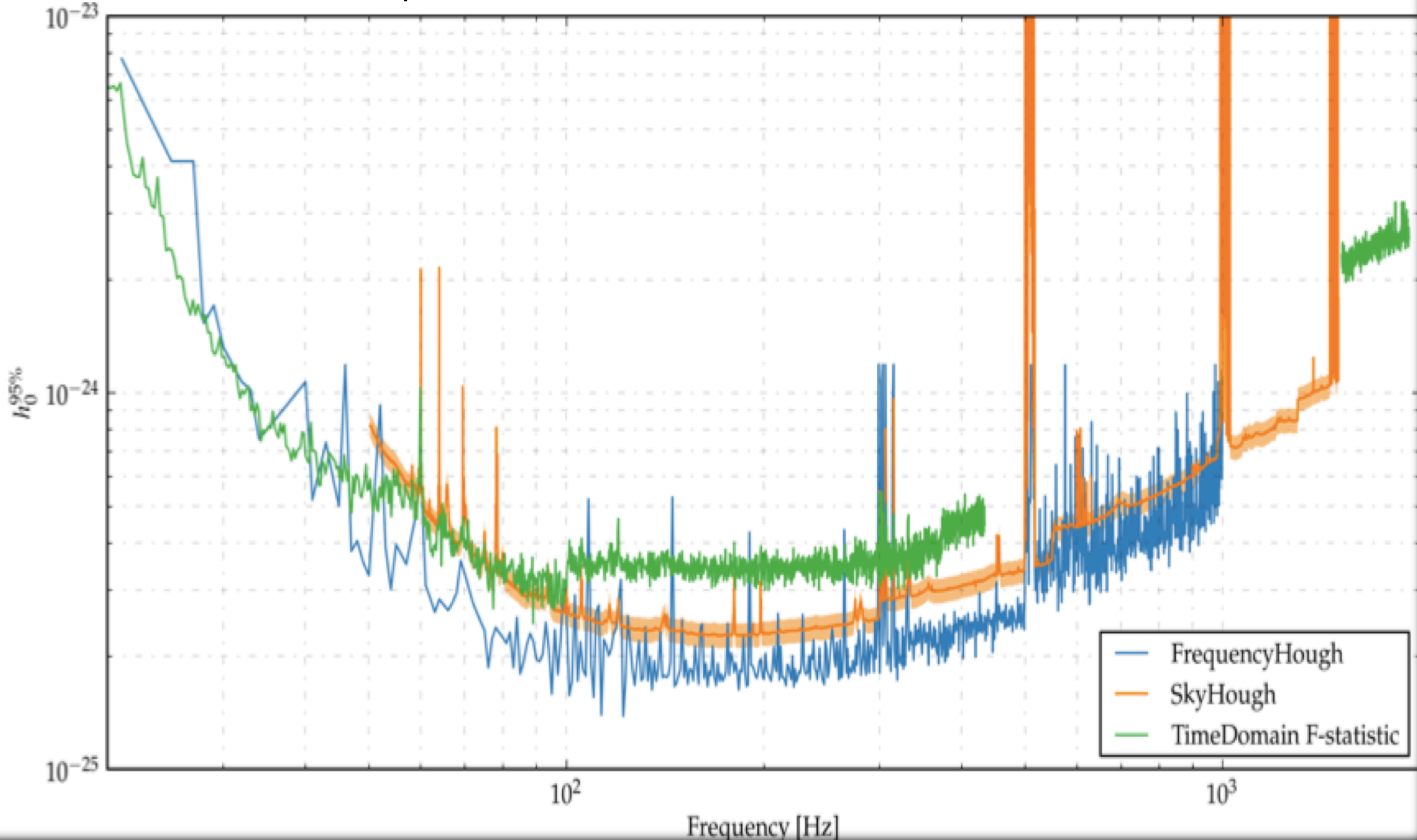
- Three pipelines contributing:
  - Frequency Hough [PRD 90, 042002 (2014)]
  - Sky Hough [CQG 31, 085014 (2014)]
  - Time-Domain F-Statistic [CQG 31, 165014 (2014)]

- Best 95% CL h_0 UL: ~ 1.7e-25 at 123 Hz

- ASTROPHYSICAL range: At ~500 Hz we are sensitive to NSs with equatorial ellipticity ε >~ 10^{-6} and as far away as 1 kpc

O2 All-Sky search II

https://arxiv.org/abs/1903.01901



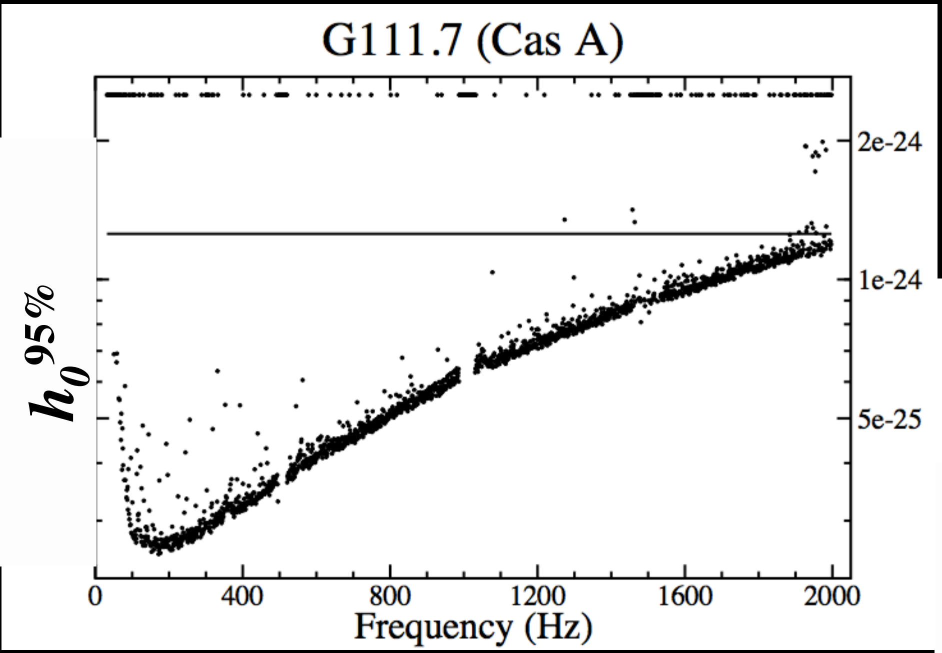
O1 Directed search I

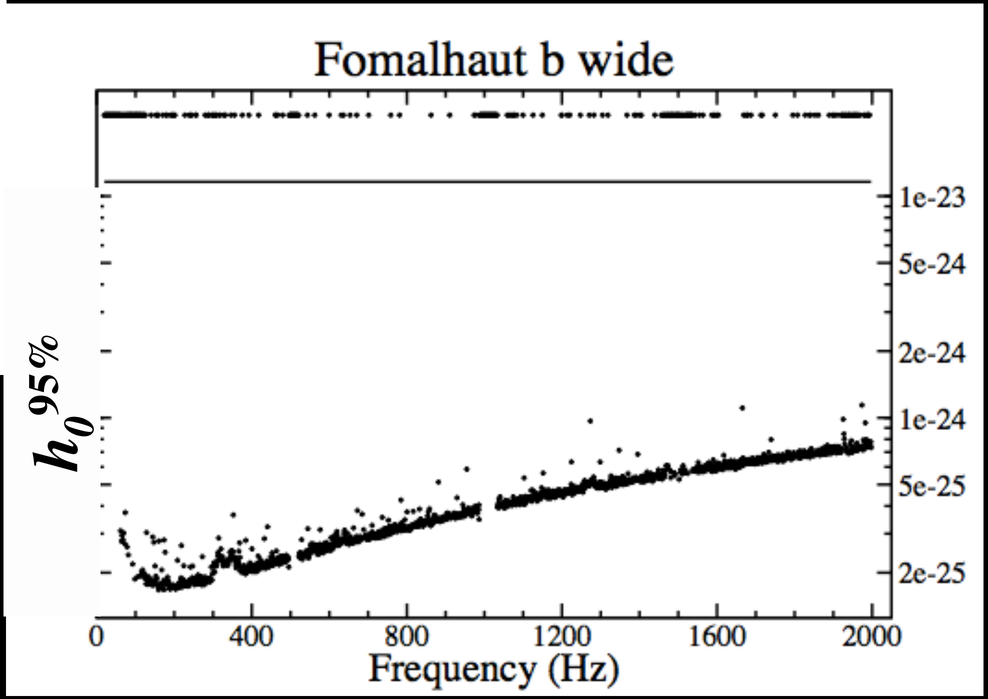
- Known sky location, but unknown frequency evolution (*e.g.* Cassiopeia A, SN1987A, Scorpius X-1, galactic center, globular clusters) => *O*(cluster)

- Observational APJ paper in press & https://arxiv.org/abs/1812.11656
- Search parameter space: 15 SNRs (including CasA and Vela Jr.) and Fomalhaut B
- Pipeline based on multi-IFO *F*-statistic (PRD 58, 063001, 1998; PRD 72, 063006, 2005)
- Best h_0 UL: it approaches 2e-25 for many targets and approaches 1e-25 for one
- Best UL on *r*-mode amplitude: α~3e-8
- Best UL on NS ellipticity: 2e-9

$$\alpha = 0.28 \left(\frac{h_0}{10^{-24}}\right)\left(\frac{100\ \mathrm{Hz}}{f}\right)^3\left(\frac{D}{1\ \mathrm{kpc}}\right)$$

O1 Directed search II





https://arxiv.org/abs/1812.11656

SEARCHES FROM NSs IN BINARY SYSTEMS

O1 Directed search from Scorpius X-1 I

- Observational paper:
  ApJ 847, 47 (2017)

Parameter	Search parameter space	Range
f_0 (Hz)		[25, 2000]
$a \sin i$ (lt-s)[a]		[0.36, 3.25]
T_{asc} (GPS s)[b]		$1131415404 \pm 3 \times 179$
P_{orb} (s)		$68023.70 \pm 3 \times 0.04$

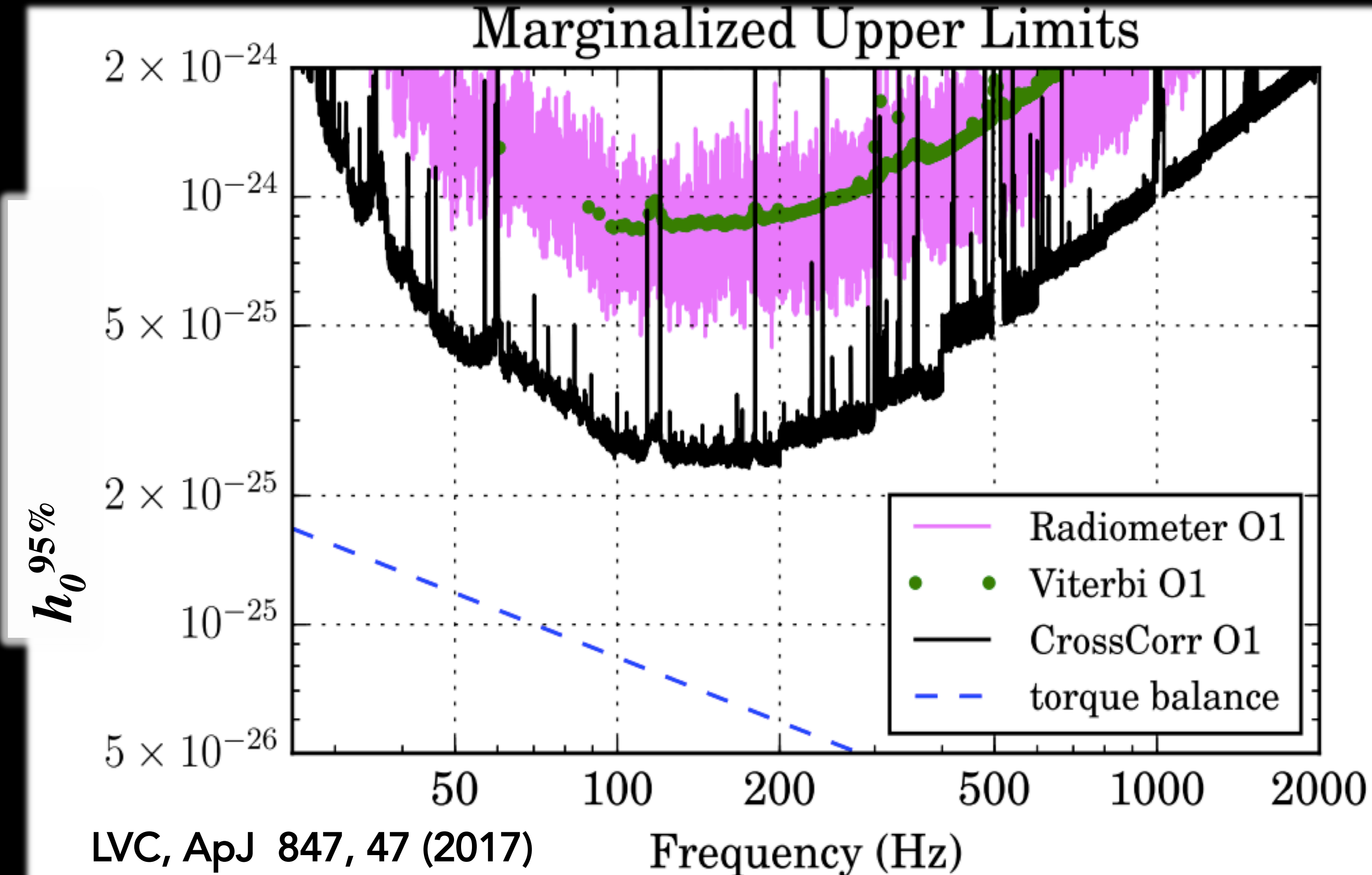
- Three pipelines contributing:
  - New Viterbi Sideband [PRD 95, 122003 (2017)]
  - The CrossCorr method [ApJ 847, 47 (2017)]
  - Radiometer search (including also other targets) [PRL 118, 121102 (2017)]

- Best h_0 UL: 2.3e-25 in [100-200] Hz

- At 100 Hz the limits are a factor of ~ 1.2 - 3.5 above the predictions of the torque balance model, depending on the inclination angle

$$h_0 \sim 3.5 \times 10^{-26} \sqrt{\frac{300\ \text{Hz}}{\nu}}$$

O1 Directed search from Scorpius X-1 II



LVC, ApJ 847, 47 (2017)

OTHER SEARCHES

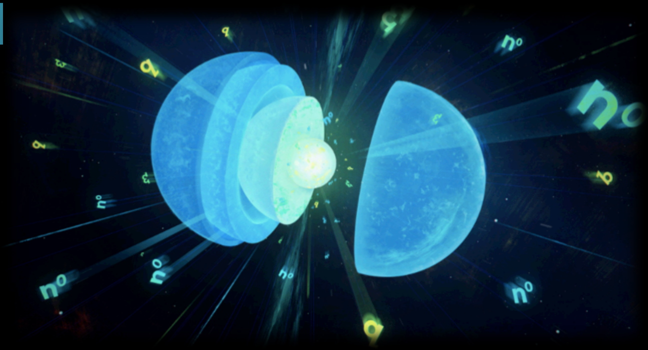
O2 GW170817 post-merger remnant search

- **Search for signal of post-merger remnant; Unknown frequency and frequency evolution**

- Observational paper: APJ 875, 2 (2019) & https://arxiv.org/abs/1810.02581
- Signal duration from 100 s up to 8.5 d after the merger
- Four pipelines contributing:
  - Stochastic Transient Analysis Multidetector Pipeline [PRD 83, 083004 (2011)] *(unmodeled)*
  - Hidden Markov Model [PRD 97, 043013 (2018)] *(unmodeled)*
  - Adaptive Transient Hough [arXiv:1901.01820] *(modeled)*
  - Generalized FrequencyHough [PRD 98, 102004 (2018)] *(modeled)*
- Waveform model of emitted radiation follows the power law $\dot{f} = -kf^n$
- Distance ~ 40 Mpc => Detection not expected for CW searches, but it is worthwhile to have pipelines ready to perform the search

Why CW searches are relevant to us?

- EM observations alone cannot help us to understand NS composition (highly condensed matter, crystalline structure, viscosity,…)



www.quantamagazine.org/

- Information on NS quadrupolar deformation (ellipticity) will be very valuable to understand whether NSs are composed by only neutrons, quarks, exotic matter, and so on

- Other NS properties (the range of NS masses, radii, sky locations, maximum NS spin frequency, population models, cold dense matter EOS properties)

- Detecting deviations from General Relativity (speed of GWs, existence of other polarizations)

Outlook I: What are we doing to keep detecting CWs?

- Getting started to analyze O3 data (LHO, LLO, Virgo):

HIGHEST PRIORITY:

- All-Sky searches,
- Targeted searches (search at one and twice spin frequency)
- Narrowband searches (Vela, Crab,…)
- Directed searches (Galactic center, CasA, Vela Jr. and other young SNRs, FERMI-LAT/INTEGRAL sources, Scorpius X-1)

HIGH PRIORITY:

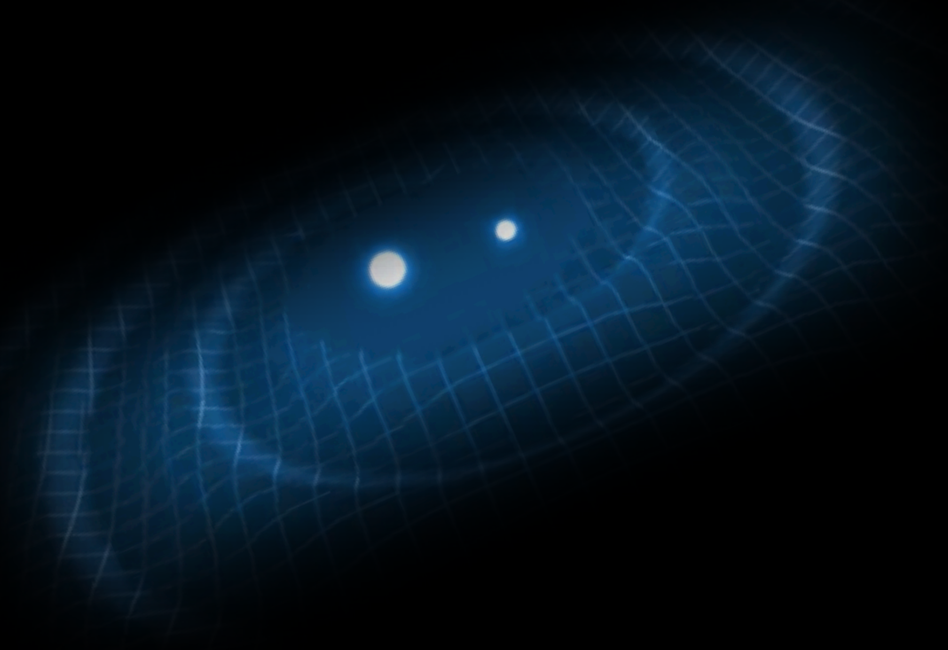
- Search for *r*-modes applying machine learning techniques (Crab pulsar, J0537-6910, which glitches every ~100 days, and it will be monitored by NICER in X-rays during O3)
- Stochastic and CW joint search
- Search for CWs from ultralight boson clouds around spinning BHs
- Post-merger transient search
- Search for non-tensorial polarizations
- Algorithm optimization (including candidate follow up)

Outlook II: What are we doing to keep detecting CWs?

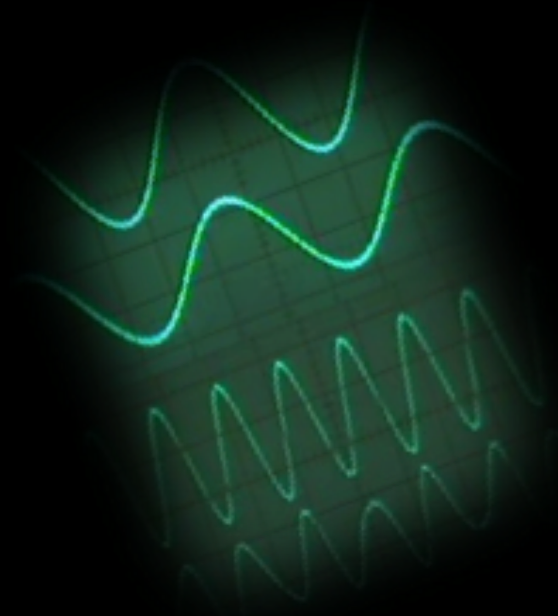
- Finish analyzing O2 data
  - Galactic center, SNRs directed searches
  - Scorpius X-1 directed search
  - Subthreshold all-sky search
  - Search for CWs in binary systems
  - Boson cloud searches

Outlook III:
What do we need to facilitate the CW detection?

- UPDATED EPHEMERIS as fully coherent searches for CWs from known pulsars rely on coherent phase models and wrong ephemeris can introduce phase errors, which would result in a loss of signal-to-noise ratio
- RADIO OBSERVATORIES able to monitor the vast majority of radio pulsars, mainly those with high spindown, which translates into a strong CW emission (e.g. PSRs J1952+3252 and J1913+1011)
- GAMMA/X-RAY observations
- NEW PULSAR DISCOVERIES (in all of EM bands)
- ROBUST ALGORITHMS able to detect both our standard signal models and the unexpected!
- … and of course (more) SENSITIVE GW DETECTORS



TRANSIENT GWs have been already detected!



We continue hunting for CW signals…

THANKS FOR LISTENING