Detecting continuous-wave signals with advanced gravitational-wave detectors and beyond

Rocca di Sant'Apollinare, May 16-18 (2019)

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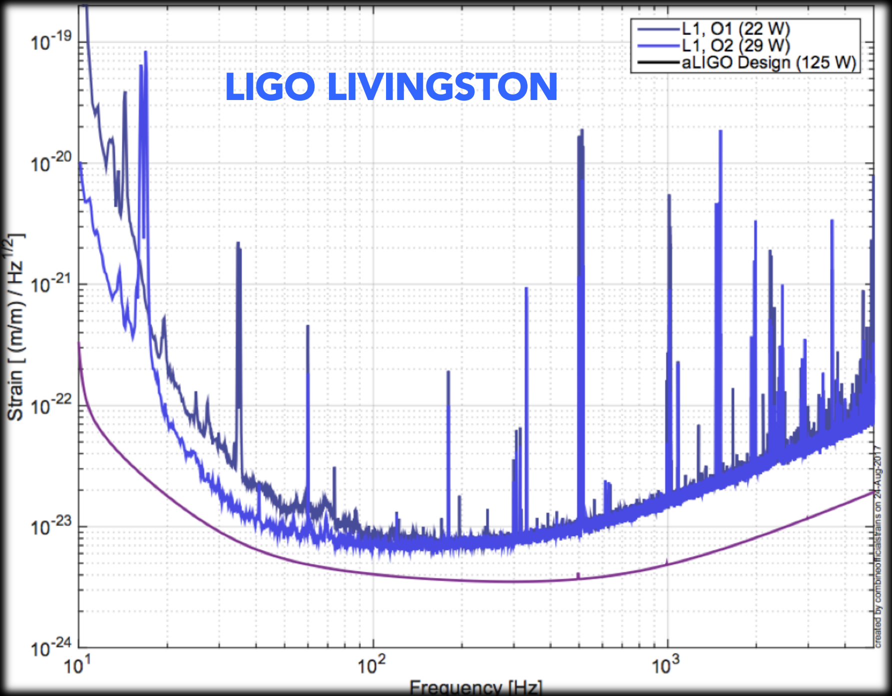
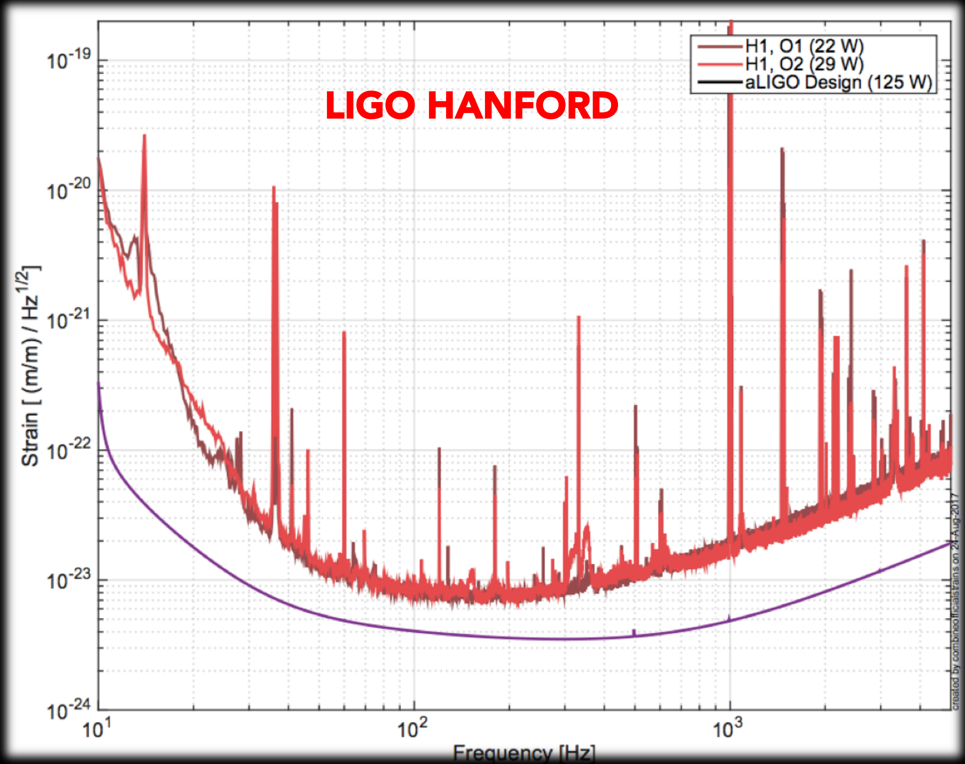
on behalf of the LIGO Scientific Collaboration and the Virgo Collaboration

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

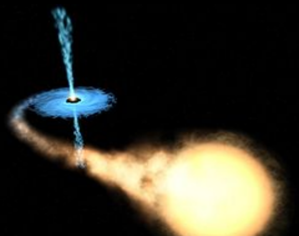
What are the missing Gravitational-Wave (GW) signals?

- 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

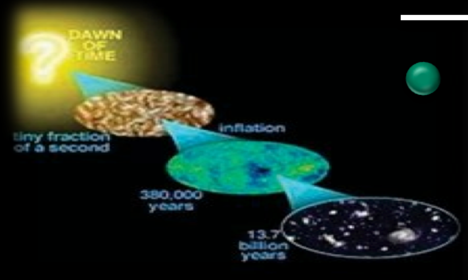
X



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 2500 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 ($f_{GW} \approx 2\, f_{rot}$)
  - 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

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

PRD 87, 129903 (2013)

○ $\varepsilon \leq 10^{-5}$ *normal NS*
○ $\varepsilon \leq 10^{-3}$ *hybrid (hadron-quark core) stars*
○ $\varepsilon \leq 10^{-1}$ *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.

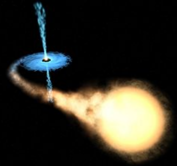
Type of searches

- 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)]

(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

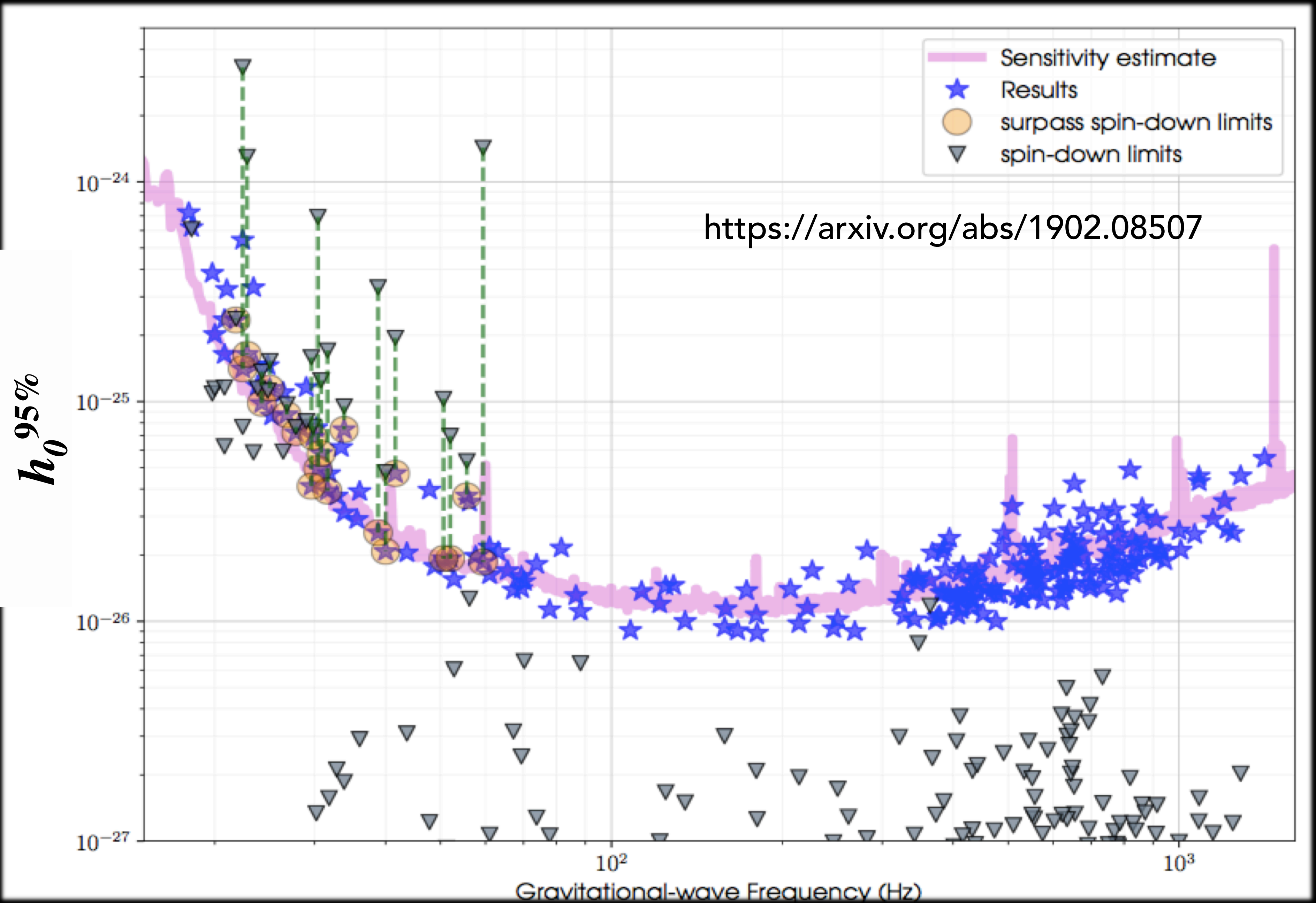
- Search for 221 pulsars
- Targeted emission at $f_{GW} = 2f_{rot}$ and $f_{GW} = f_{rot}$
- Three pipelines contributing:
  - **TD Bayesian** [PRD 72, 102002, 2005]
  - **TD F/G-Stat** [CQG 27, 194015, 2010]
  - **FD 5-vector** [CQG 27, 194016, 2010] (only on O2 data)

- 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



https://arxiv.org/abs/1902.08507

O2 Narrowband search

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

- Observational paper submitted to 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 All-Sky search

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

- Observational paper submitted to PRD & 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

O1 Directed search

- 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

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

- Best UL on NS ellipticity: 2e-9

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

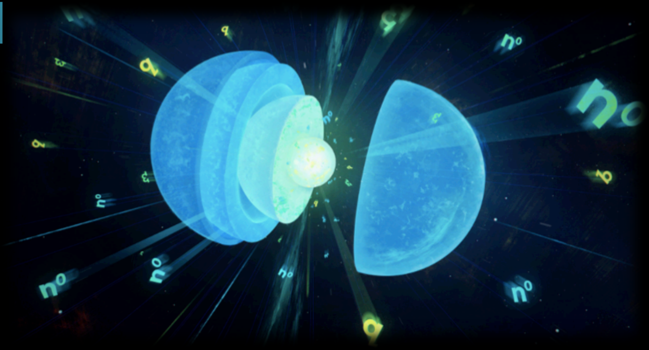
- Four pipelines contributing:
  - Stochastic Transient Analysis Multidetector Pipeline [PRD 83, 083004 (2011)] *(unmodeled)*
  - Hidden Markov Model [PRD 97, 043013 (2018)] *(unmodeled)*
  - Adaptive Transient Hough [arXiv:1901.01820] *(modeled)*
  - Generalized FrequencyHough [PRD 98, 102004 (2018)] *(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,…)
- 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

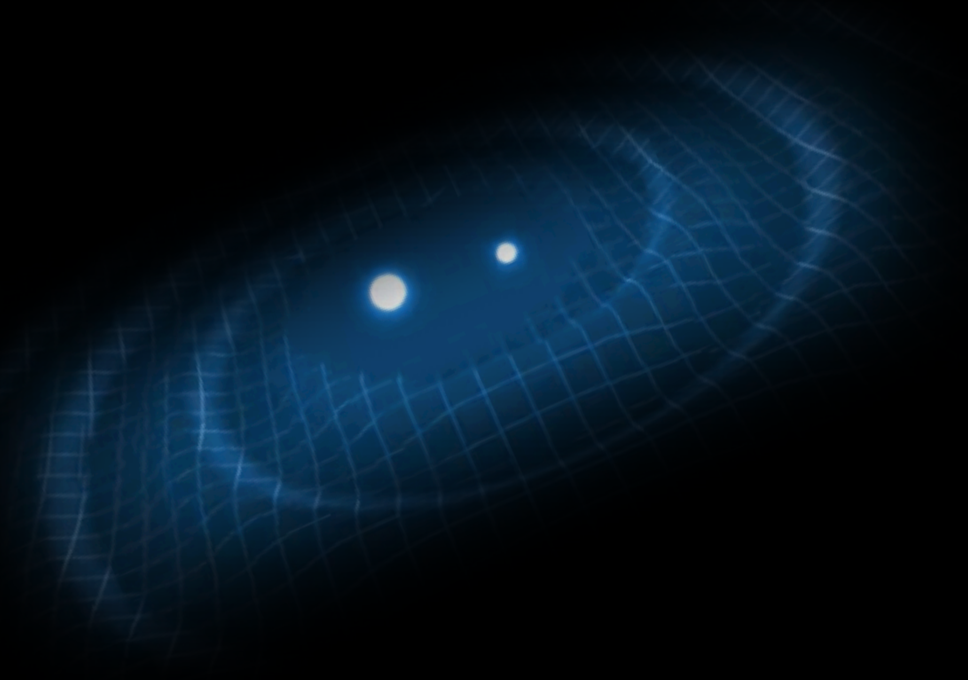


www.quantamagazine.org/

- 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:
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

BACKUP SLIDES

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

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

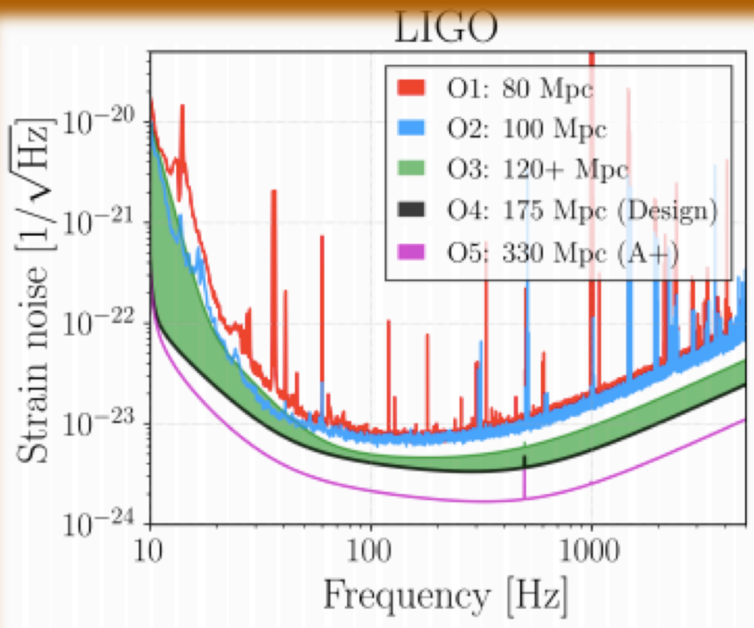
HIGHEST PRIORITY:

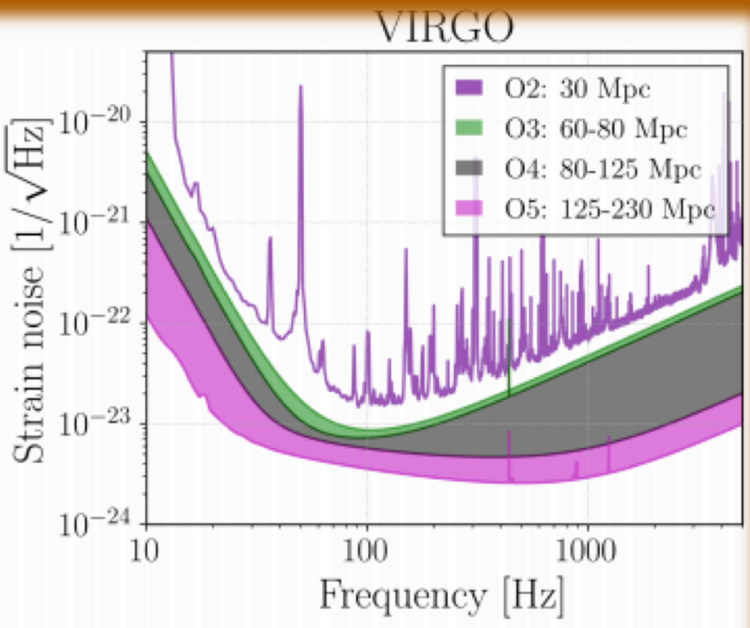
- ✷ All-Sky searches,
- ✷ Targeted searches (search at one and twice spin frequency)
- ✷ Narrowband searches (Vela, Crab,…)
- ✷ Directed searches (Galactic center, CasA, Vela Jr. and other young SNRs, FERMI-LAT/INTEGRAL sources, Scorpius X-1)

HIGH PRIORITY:

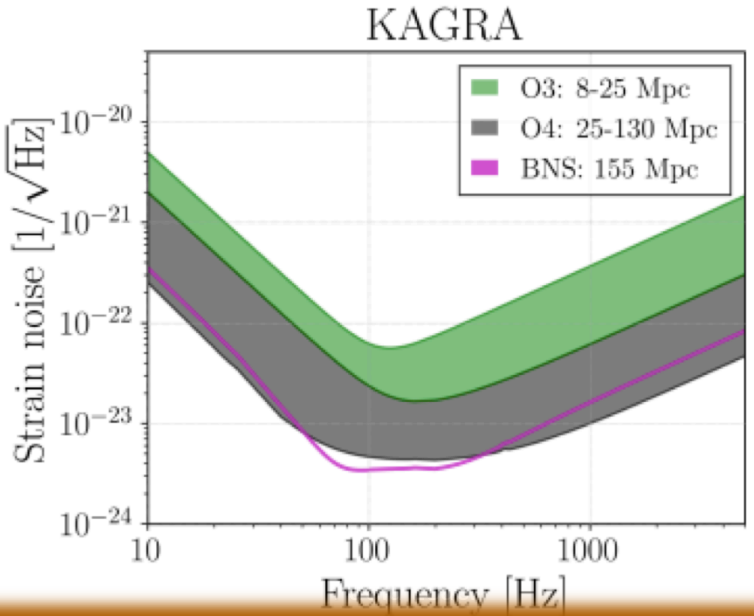
- ✷ Search for *r*-modes applying machine learning techniques (Crab pulsar, J0537-6910, which glitches every ~100 days, and it will be monitored by NICER in X-rays during O3)
- ✷ Stochastic and CW joint search
- ✷ Search for CWs from ultralight boson clouds around spinning BHs
- ✷ Post-merger transient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

GW detector sensitivity progression I

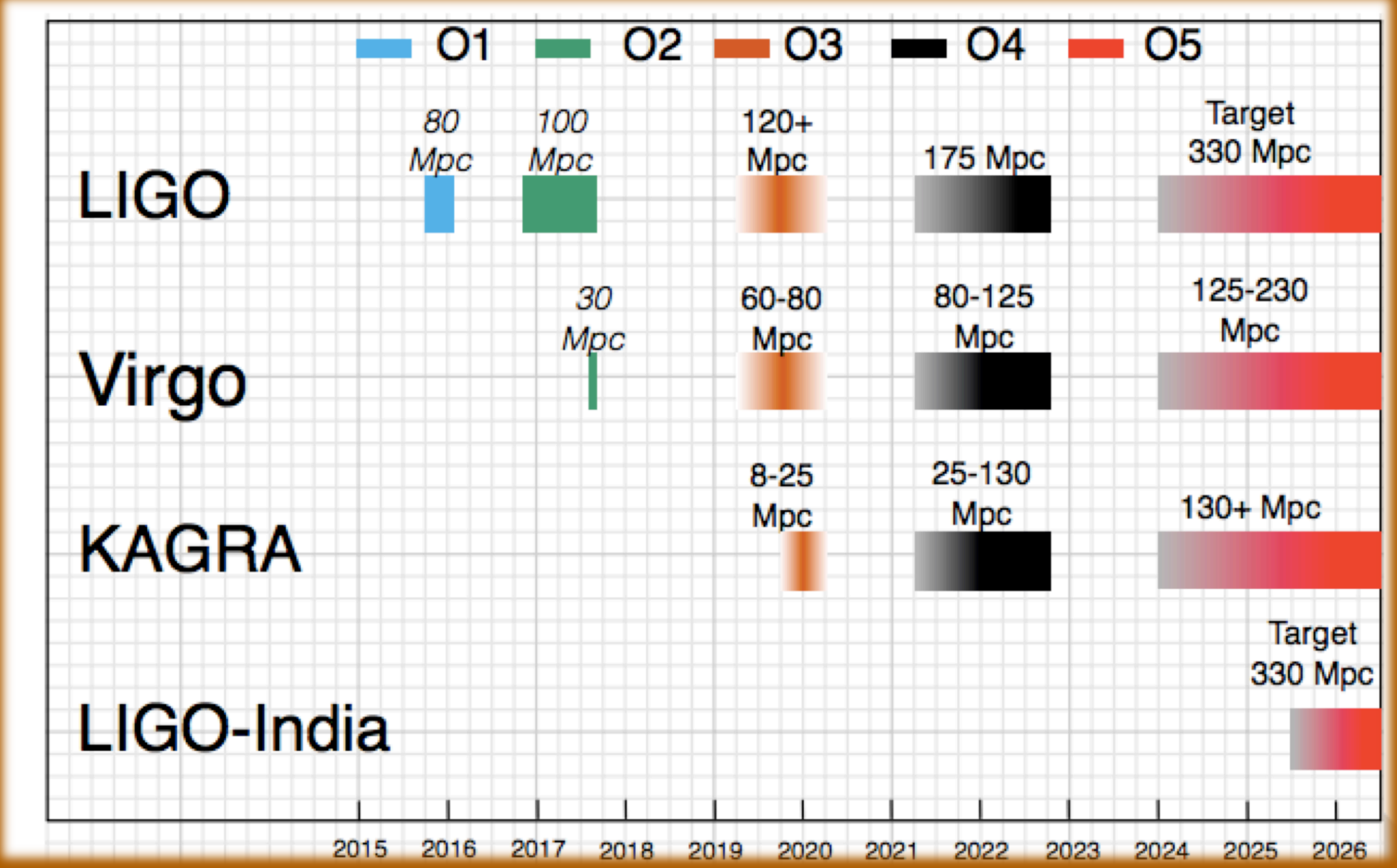




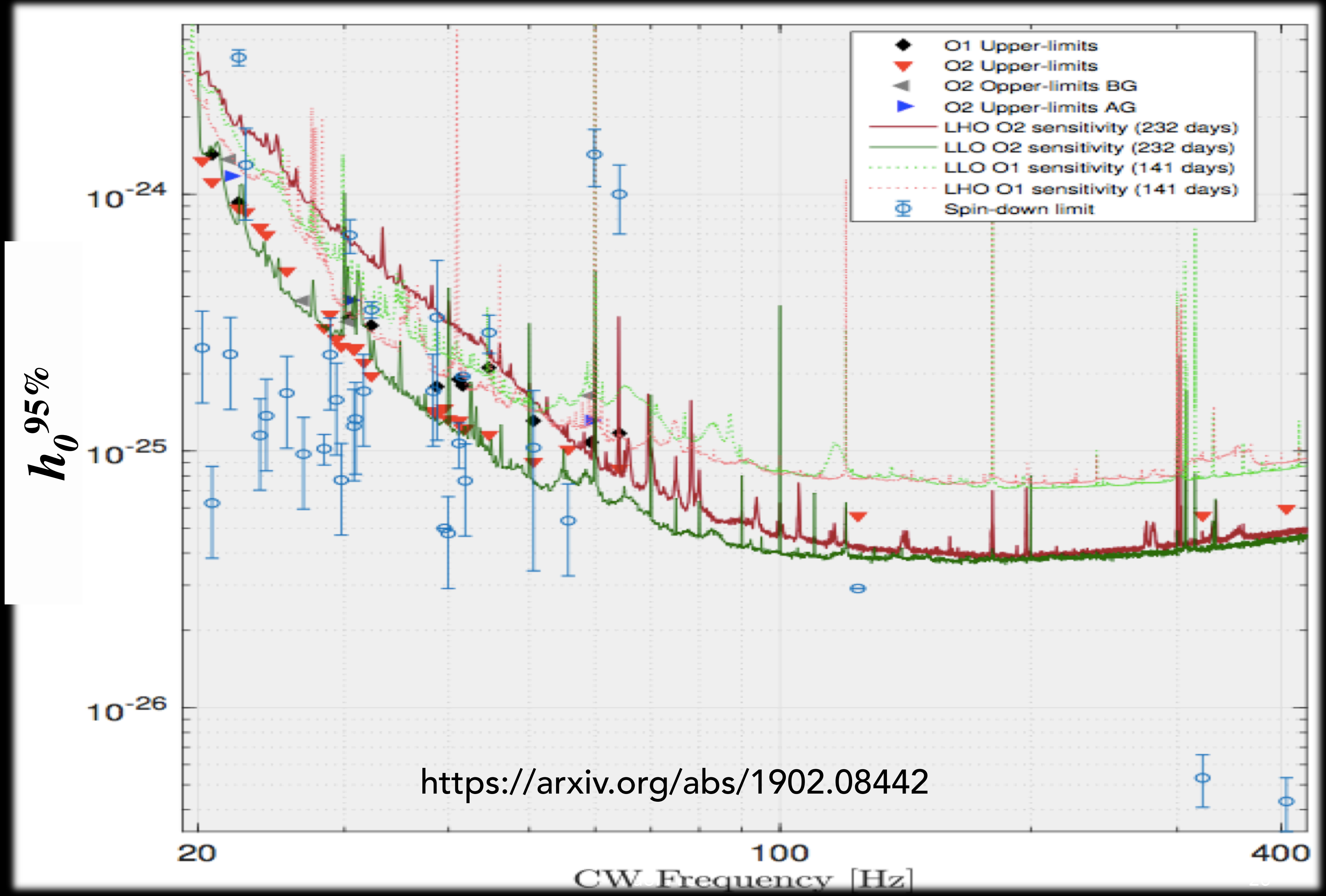
In preparation update of LVC, Liv. Rev. Rel., 21, 3 (2018)



ASTROPHYSICAL REACH



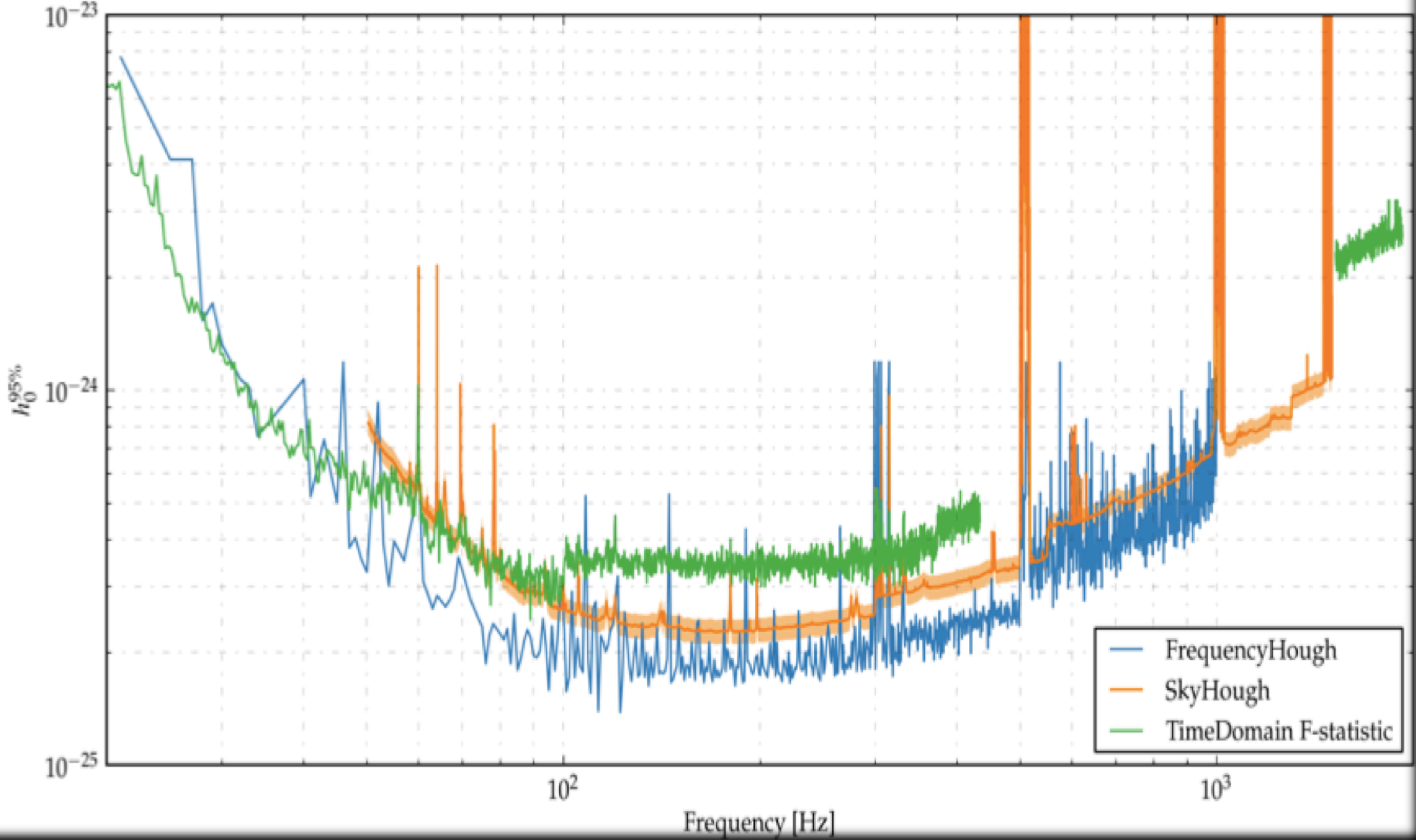
O2 Narrowband search II



https://arxiv.org/abs/1902.08442

O2 All-Sky search II

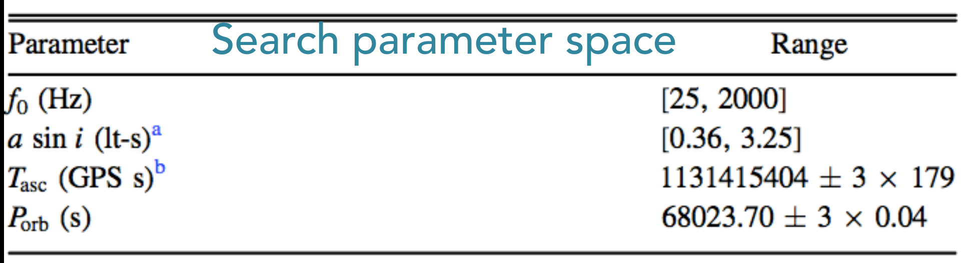
https://arxiv.org/abs/1903.01901



O1 Directed search from Scorpius X-1 I

- Observational paper:
  ApJ 847, 47 (2017)

Search parameter space



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

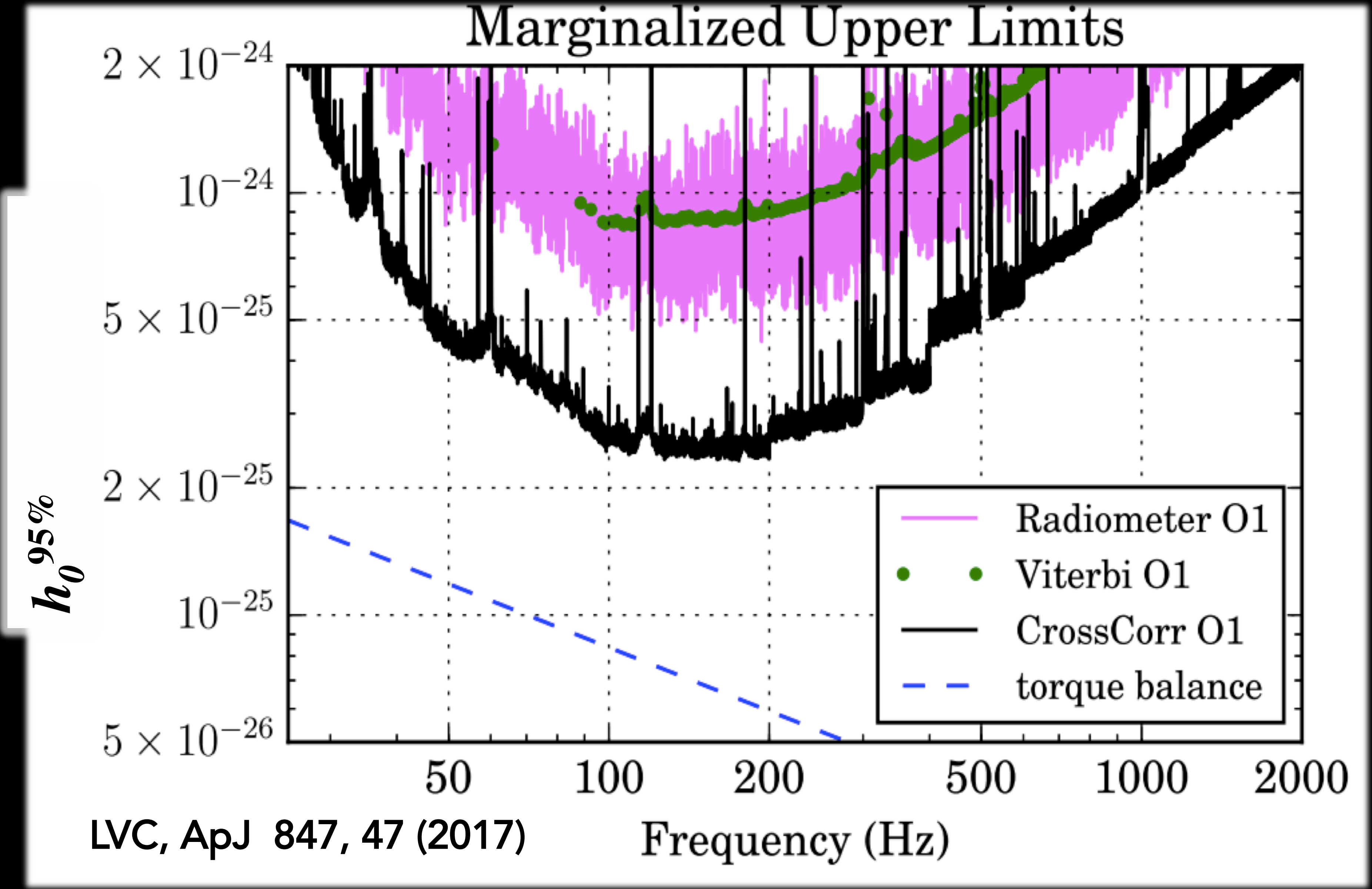
- Three pipelines contributing:
  - New Viterbi Sideband [PRD 95, 122003 (2017)]
  - The CrossCorr method [ApJ 847, 47 (2017)]
  - Radiometer search (including also other targets) [PRL 118, 121102 (2017)]

- 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

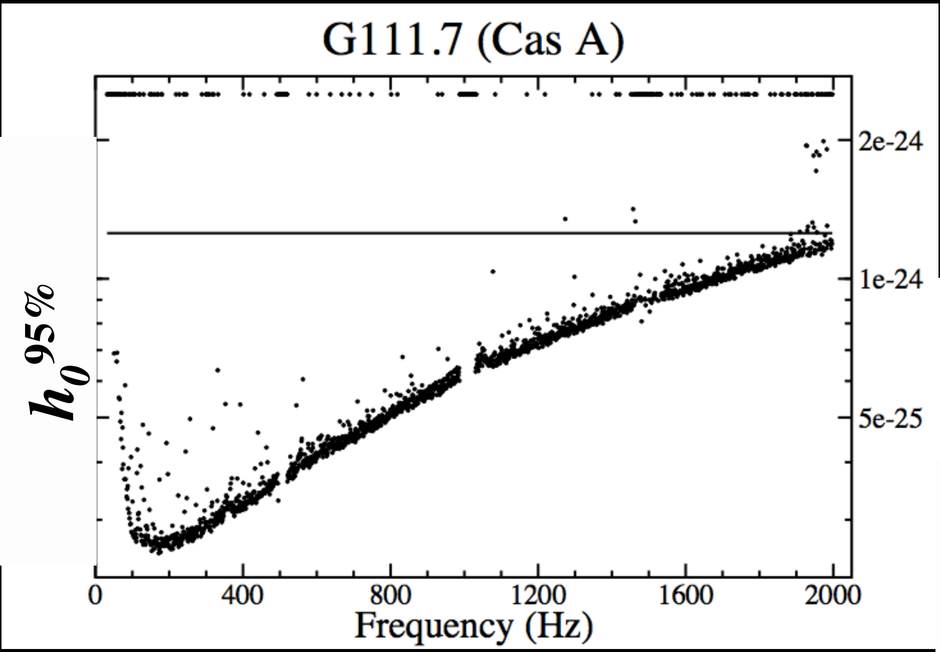
$$h_0 \sim 3.5 \times 10^{-26} \sqrt{\frac{300\ \mathrm{Hz}}{\nu}}$$

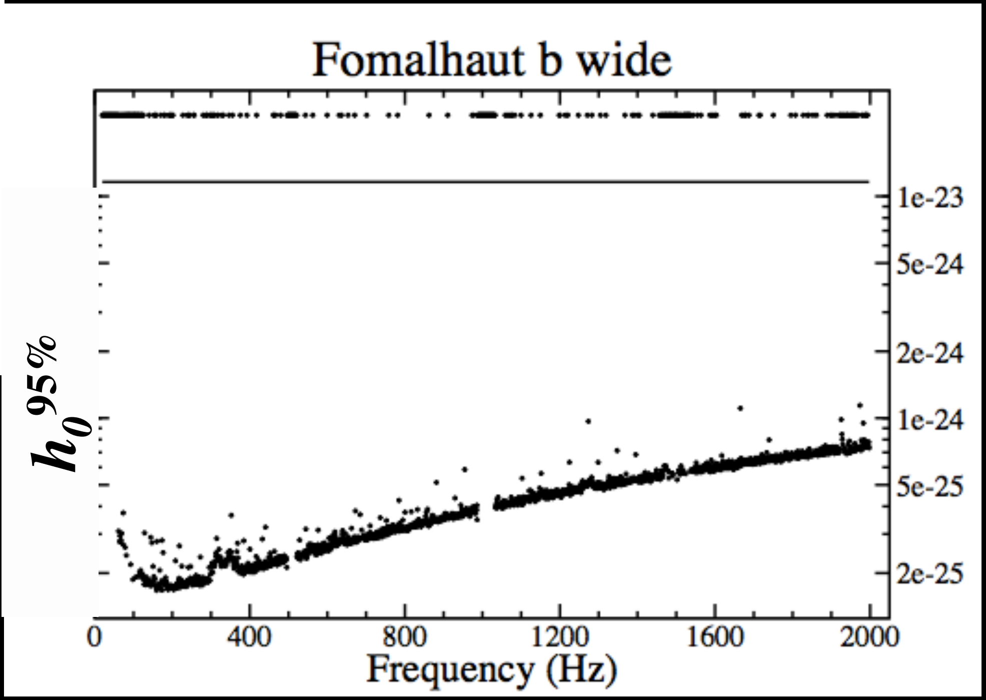
O1 Directed search from Scorpius X-1 II



LVC, ApJ 847, 47 (2017)

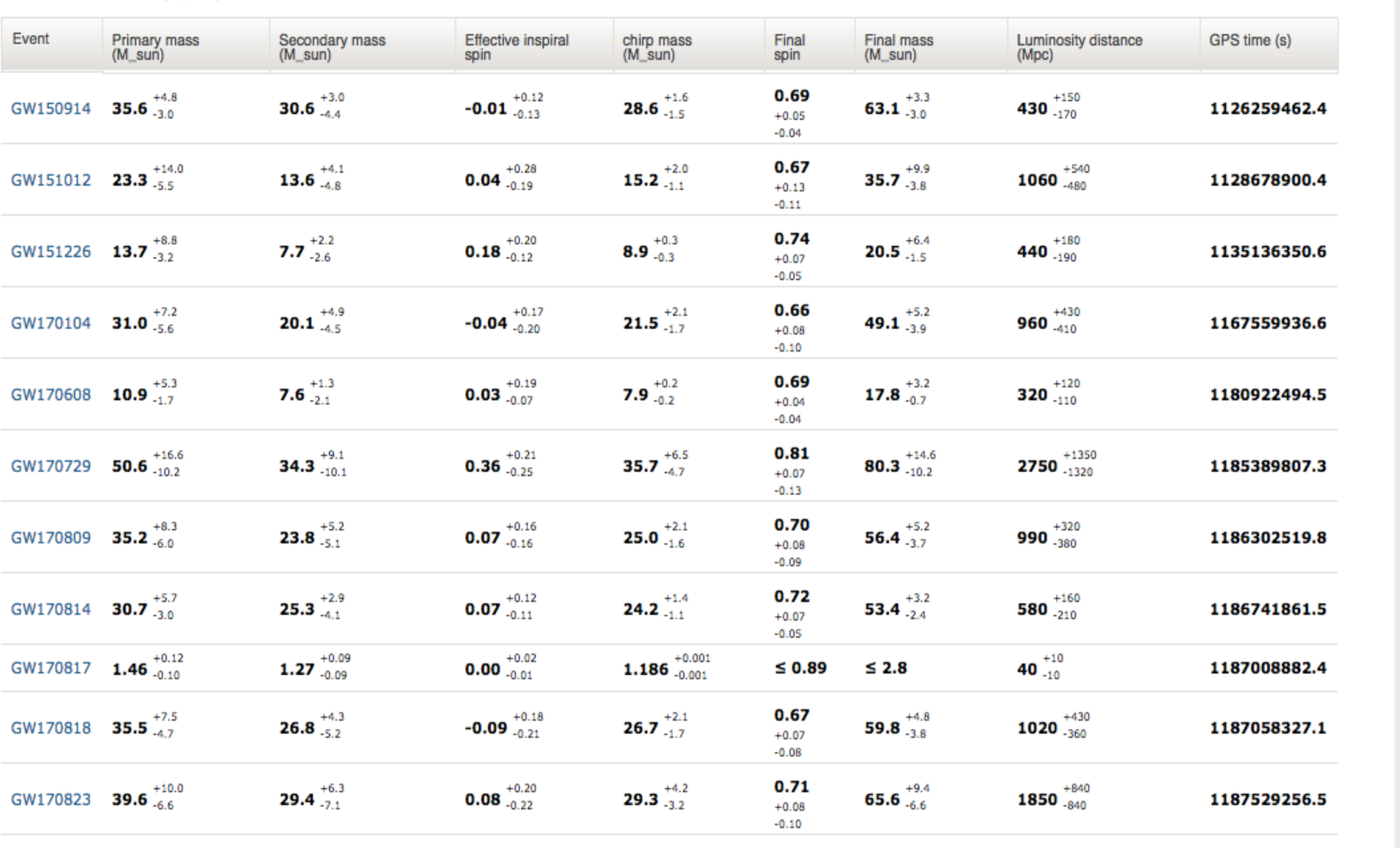
O1 Directed search II





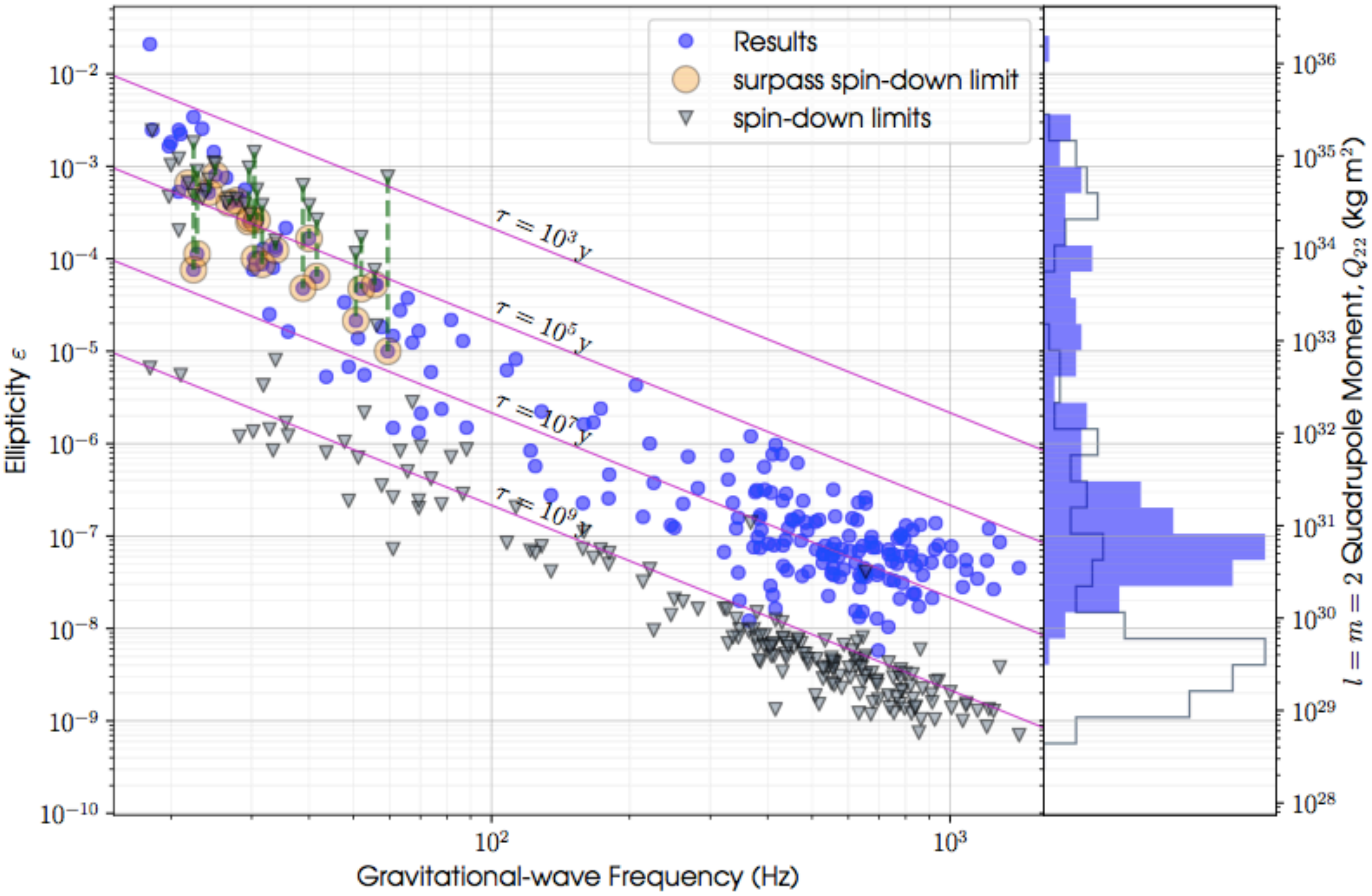
https://arxiv.org/abs/1812.11656

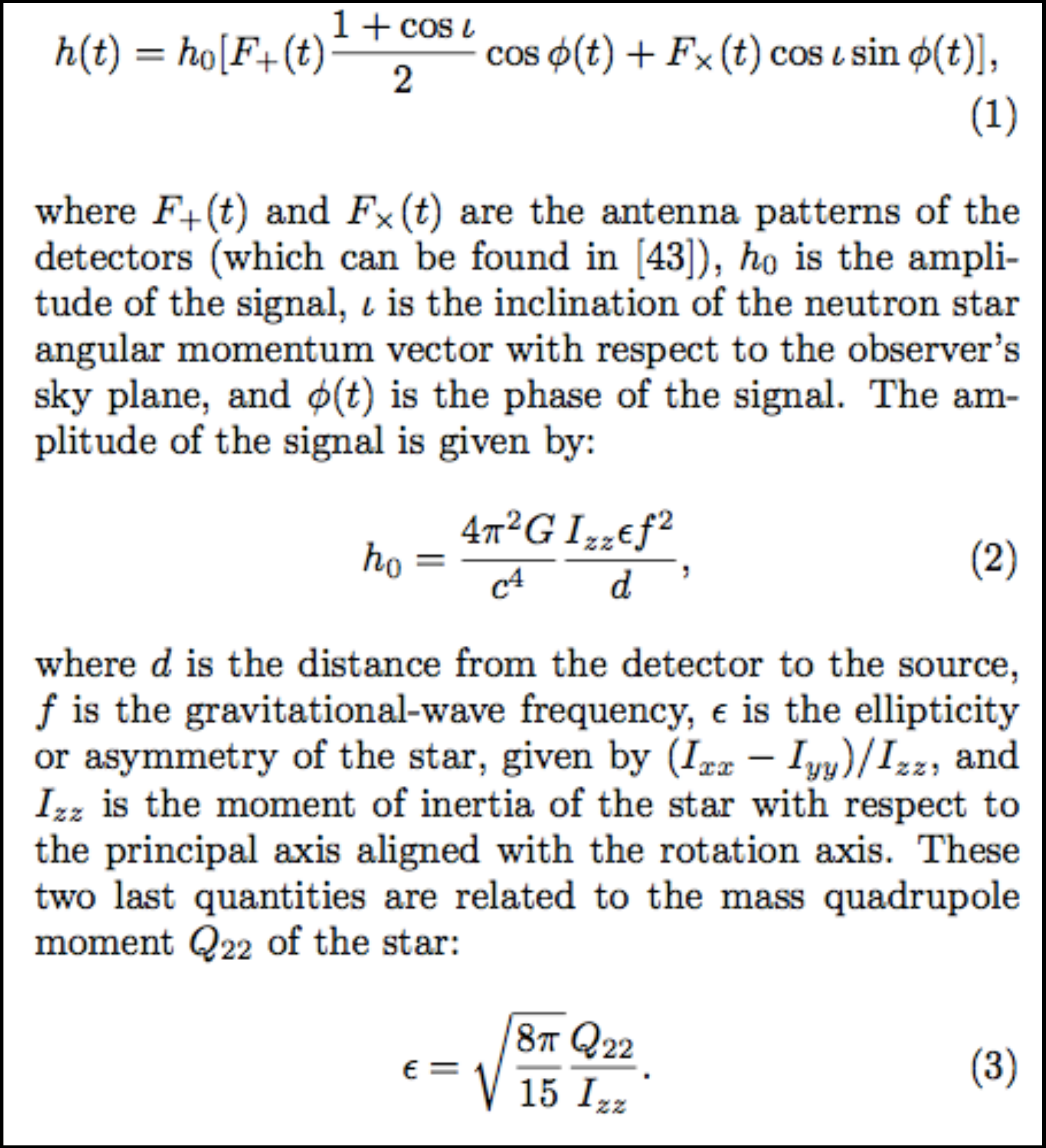
Gravitational Wave Open Science Center



Event	Primary mass (M_sun)	Secondary mass (M_sun)	Effective inspiral spin	chirp mass (M_sun)	Final spin	Final mass (M_sun)	Luminosity distance (Mpc)	GPS time (s)
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$-0.01^{+0.12}_{-0.13}$	$28.6^{+1.6}_{-1.5}$	$0.69^{+0.05}_{-0.04}$	$63.1^{+3.3}_{-3.0}$	430^{+150}_{-170}	1126259462.4
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$0.04^{+0.28}_{-0.19}$	$15.2^{+2.0}_{-1.1}$	$0.67^{+0.13}_{-0.11}$	$35.7^{+9.9}_{-3.8}$	1060^{+540}_{-480}	1128678900.4
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$0.18^{+0.20}_{-0.12}$	$8.9^{+0.3}_{-0.3}$	$0.74^{+0.07}_{-0.05}$	$20.5^{+6.4}_{-1.5}$	440^{+180}_{-190}	1135136350.6
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$-0.04^{+0.17}_{-0.20}$	$21.5^{+2.1}_{-1.7}$	$0.66^{+0.08}_{-0.10}$	$49.1^{+5.2}_{-3.9}$	960^{+430}_{-410}	1167559936.6
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$0.03^{+0.19}_{-0.07}$	$7.9^{+0.2}_{-0.2}$	$0.69^{+0.04}_{-0.04}$	$17.8^{+3.2}_{-0.7}$	320^{+120}_{-110}	1180922494.5
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$0.36^{+0.21}_{-0.25}$	$35.7^{+6.5}_{-4.7}$	$0.81^{+0.07}_{-0.13}$	$80.3^{+14.6}_{-10.2}$	2750^{+1350}_{-1320}	1185389807.3
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$0.07^{+0.16}_{-0.16}$	$25.0^{+2.1}_{-1.6}$	$0.70^{+0.08}_{-0.09}$	$56.4^{+5.2}_{-3.7}$	990^{+320}_{-380}	1186302519.8
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$0.07^{+0.12}_{-0.11}$	$24.2^{+1.4}_{-1.1}$	$0.72^{+0.07}_{-0.05}$	$53.4^{+3.2}_{-2.4}$	580^{+160}_{-210}	1186741861.5
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$0.00^{+0.02}_{-0.01}$	$1.186^{+0.001}_{-0.001}$	≤ 0.89	≤ 2.8	40^{+10}_{-10}	1187008882.4
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$-0.09^{+0.18}_{-0.21}$	$26.7^{+2.1}_{-1.7}$	$0.67^{+0.07}_{-0.08}$	$59.8^{+4.8}_{-3.8}$	1020^{+430}_{-360}	1187058327.1
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$0.08^{+0.20}_{-0.22}$	$29.3^{+4.2}_{-3.2}$	$0.71^{+0.08}_{-0.10}$	$65.6^{+9.4}_{-6.6}$	1850^{+840}_{-840}	1187529256.5

(O1+O2) Targeted Search: fiducial ellipticity ULs





$$h(t) = h_0[F_+(t)\frac{1+\cos\iota}{2}\cos\phi(t) + F_\times(t)\cos\iota\sin\phi(t)], \tag{1}$$

where $F_+(t)$ and $F_\times(t)$ are the antenna patterns of the detectors (which can be found in [43]), h_0 is the amplitude of the signal, ι is the inclination of the neutron star angular momentum vector with respect to the observer's sky plane, and $\phi(t)$ is the phase of the signal. The amplitude of the signal is given by:

$$h_0 = \frac{4\pi^2 G}{c^4}\frac{I_{zz}\epsilon f^2}{d}, \tag{2}$$

where d is the distance from the detector to the source, f is the gravitational-wave frequency, ϵ is the ellipticity or asymmetry of the star, given by $(I_{xx} - I_{yy})/I_{zz}$, and I_{zz} is the moment of inertia of the star with respect to the principal axis aligned with the rotation axis. These two last quantities are related to the mass quadrupole moment Q_{22} of the star:

$$\epsilon = \sqrt{\frac{8\pi}{15}}\frac{Q_{22}}{I_{zz}}. \tag{3}$$

O2 All-Sky search

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