Neutron Stars in Future Research, Bonn, 12/12/2017

Neutron stars as continuous gravitational wave emitters

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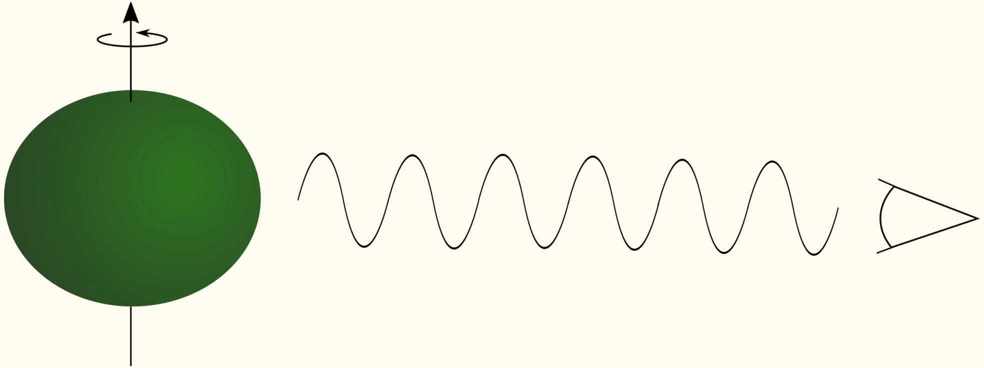
DCC: LIGO-G1702245

Continuous gravitational waves (CWs)

Gravitational waves with ~ constant source amplitude over long timescales



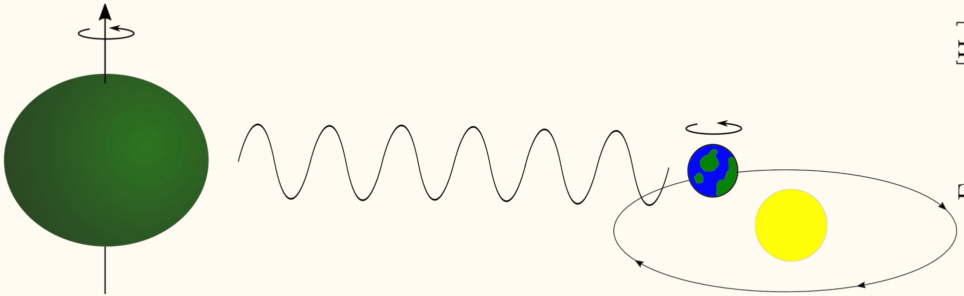
Not yet detected

Potential science

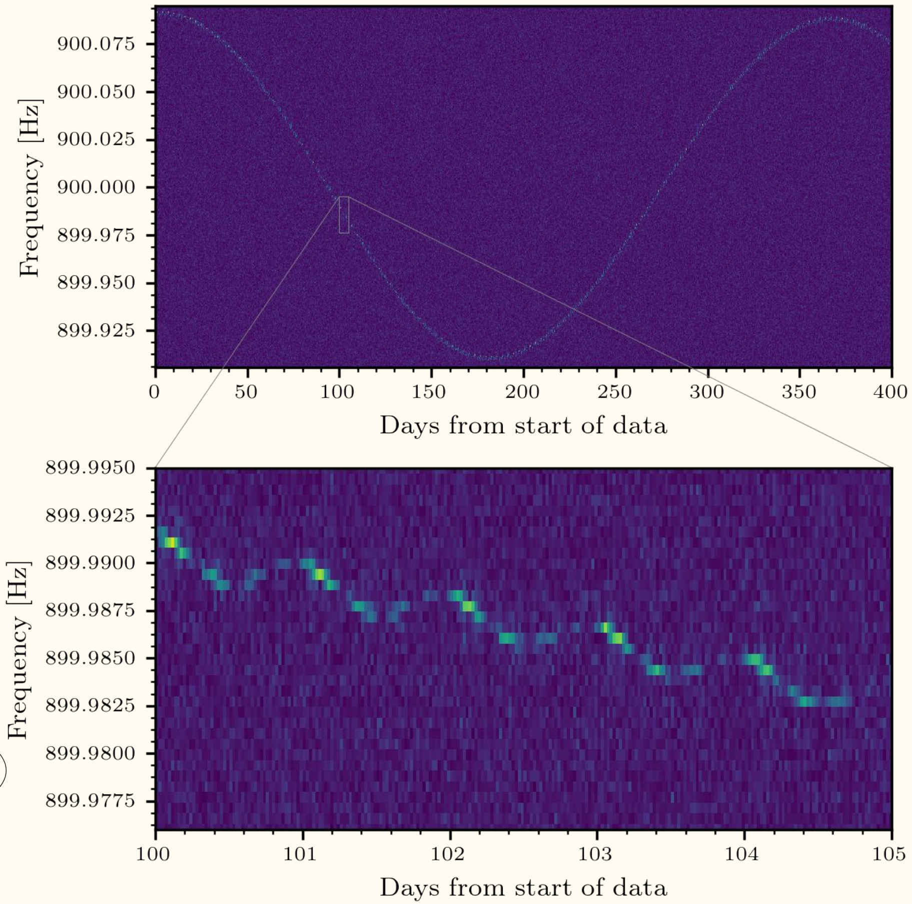
- Neutron star interior
- Multimessenger view, e.g. glitch pulsar also seen as CW source
- Tests of GR (e.g. non tensorial modes: LVC, 2017, arxiv:1709.09203)

Searching for CWs

- Optimistic amplitudes remain buried in advanced LIGO/Virgo noise
- Need **matched-filter** searches with accurate models of source phase evolution
- Track signal over Earth spin & orbit



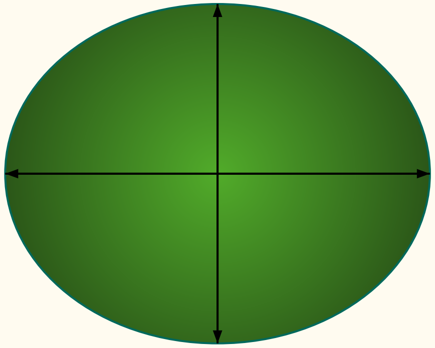
Example of detector response



Emission mechanisms

Non-axisymmetric distortions “Mountains”

Rotating aligned isolated non-axisymmetric neutron star



Rotation about the z-axis: $\epsilon = \dfrac{I_{xx} - I_{yy}}{I_{zz}}$

Produces CW at f_{GW}~2ν and ν if precessing (Zimmermann & Szedenits 1979)

The amplitude of the wave is given by

$$h_0 = \frac{4\pi^2 G}{c^4}\frac{I_{\rm zz} f_{\rm gw}^2}{d}\epsilon = 10^{-26}\left(\frac{\epsilon}{10^{-6}}\right)\left(\frac{f_{\rm gw}}{100\ \rm Hz}\right)^2\left(\frac{d}{1\ \rm kpc}\right)^{-1}$$

This is much smaller than compact binary coalescence events!

Mountains - size and source of the deformations

Maximum ellipticity proportional to breaking strain: $\varepsilon_{max} \propto \sigma$

Assuming σ=0.1 (Horowitz & Kadau, 2009):

- Normal $\varepsilon_{max} \sim 10^{-5}$
- Hybrid $\varepsilon_{max} \sim 10^{-3}$
- Extreme quark stars $\varepsilon_{max} \sim 10^{-1}$

(Johnson-McDaniel & Owen, 2013)

Why should NS be deformed up to this limit?

Sources of asymmetry for isolated systems:

- Residual crust deformation
- Non-axisymmetric distribution of magnetic field energy
- Pinned NS superfluid in the interior

Other mechanisms

Normal modes of oscillation, e.g. r-modes $f_{GW} \sim 4\nu/3$

- Intriguing evidence from J0537-6910 of n~7 (Andersson et al., 2017, arxiv:1711.05550)
- New born stars may immediately spin-down due to r-modes (e.g. Alford & Schwenzer, ApJ 781, 2014)

Binary systems

- Mountains built during accretion (Bildsten, L.: 1998, ApJ 501, L89)
- Recent observations of PSR J1023+0038 intriguing, but undetectable (Haskell & Patruno, 2017, arxiv:1703.08374)

Other transient-continuous gravitational waves

- After glitches (van Eysden & Melatos, CQG 25, 225020 (2008); Keer & Jones, MNRAS 446, 865 (2015); Singh, PRD 95, 024022 (2017))
- Post-merger remnant of a compact binary coalescence (e.g. LVC, 2017, arxiv:1710.09320)

And many more

Continuous gravitational wave searches

Searches

$$h(t) = h(\text{sky-location}, \underbrace{\text{phase-evolution}}_{f,\dot{f},\ldots+\text{binary}}, \underbrace{\text{amplitude-params}}_{h_0,\cos\iota,\psi,\phi})$$

Targeted search
- Known pulsars

Narrow-band searches
- Known pulsars with uncertain phase evolution

Directed search
- Pulsar wind nebulae
- Supernova remnant
- Galactic centre
- Accreting NSs in LMXBs

All-sky search
- Nothing known a priori
- Gravitars
- Off-axis pulsars

→ Computational cost →

Transient-CWs
- CW search adapted for signals lasting O(hours→months)

Selected O1 results

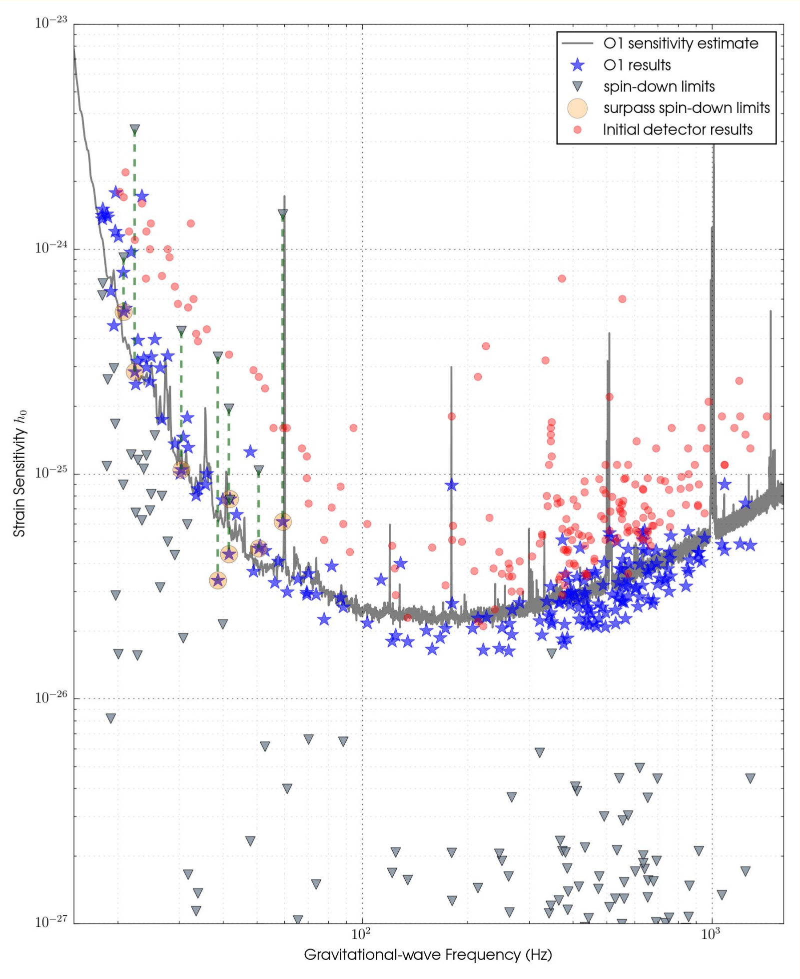
O1 known-pulsars

O1 targeted known-pulsar search
(LVC, ApJ 839, 2017, 12)

- 200 targets with ephemeris thanks to EM partners
- 8 pulsars surpass indirect spin-down limit
- Crab $\dot{E}_{GW}/\dot{E} \lesssim 2\times10^{-3}$ and $\epsilon \lesssim 3\times10^{-5}$
- Vela $\dot{E}_{GW}/\dot{E} \lesssim 1\times10^{-2}$ and $\epsilon \lesssim 1\times10^{-4}$

O1 Narrow-band known-pulsar search
(LVC, arXiv:1710.02327)

- Upper limits marginally larger, but comparable to targeted search
- Robust to non-standard signals

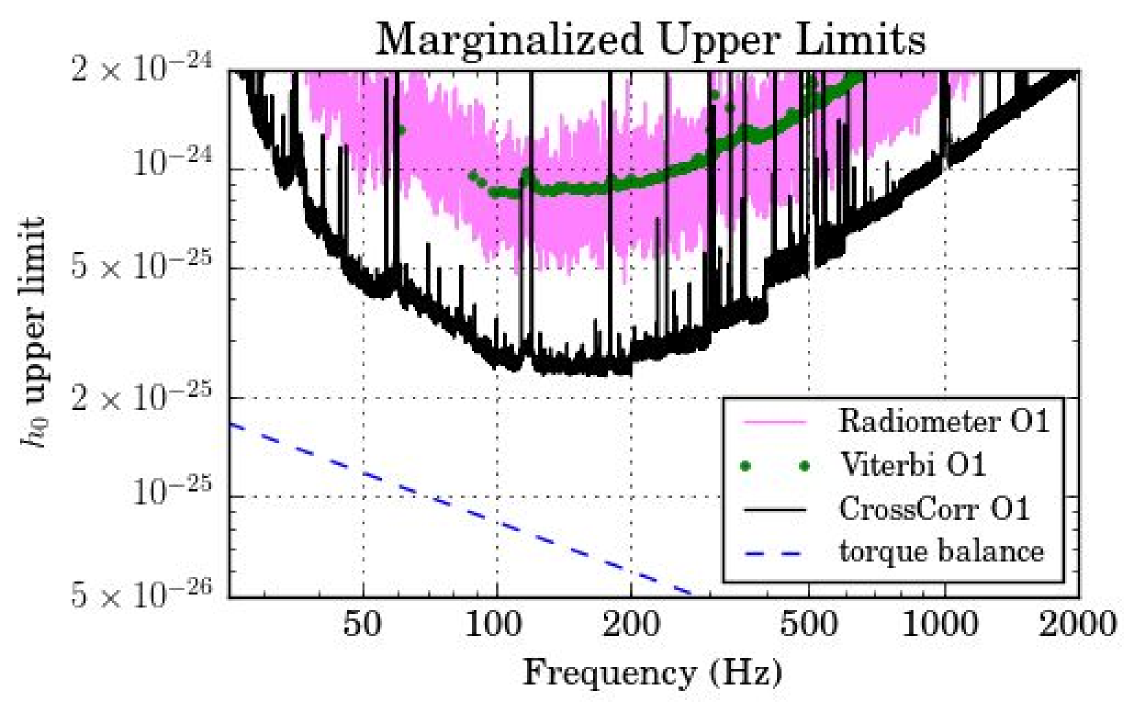


Low Mass X-ray Binary: O1 Scorpius X-1

Unknown frequency

Searches starting to approach the *torque balance* limit

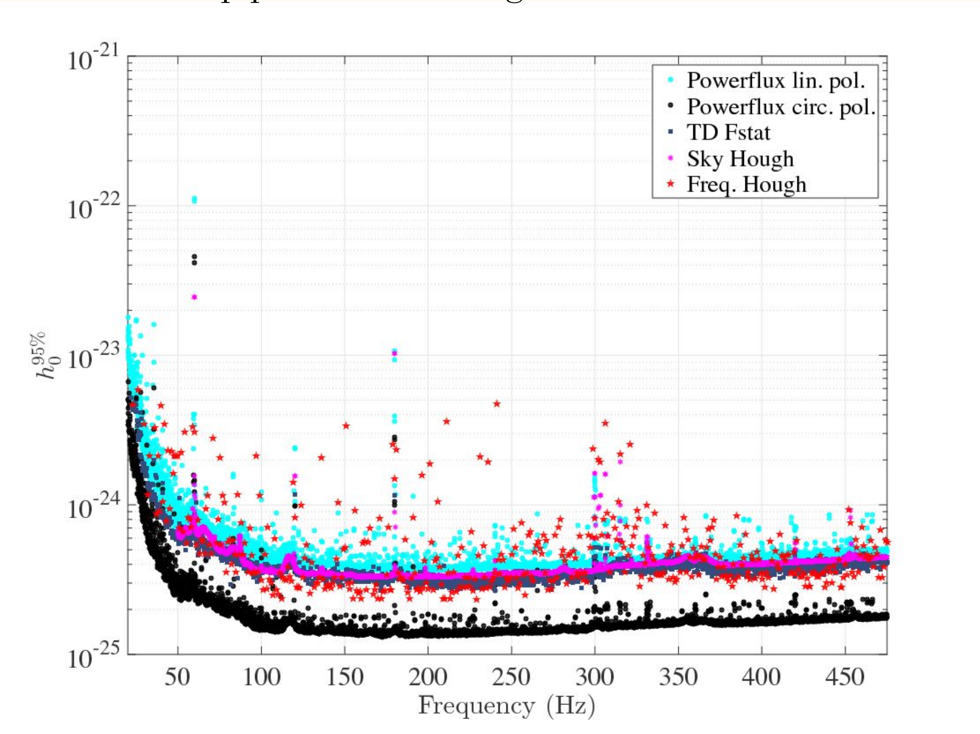
Spin-wandering ([Mukherjee et al., 2017, arxiv:1710.06185](https://arxiv.org/abs/1710.06185))



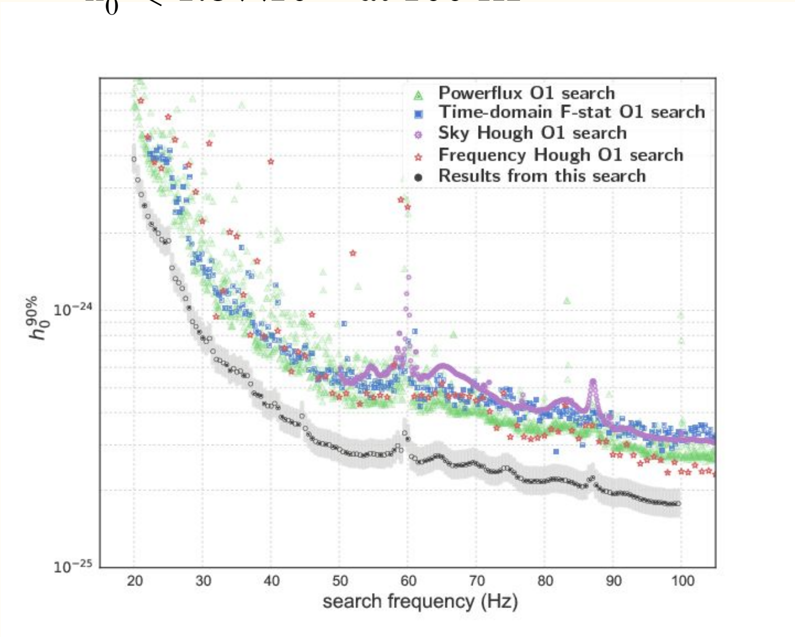
(LVC, ApJ 847 (2017)47; LVC, PRD 95 (2017) 122003; LVC PRL 118 (2017) 121102)

O1 all-sky search

(LVC, PRD 96, 2017, 062002)
Four robust pipelines searching over 20 - 475 Hz

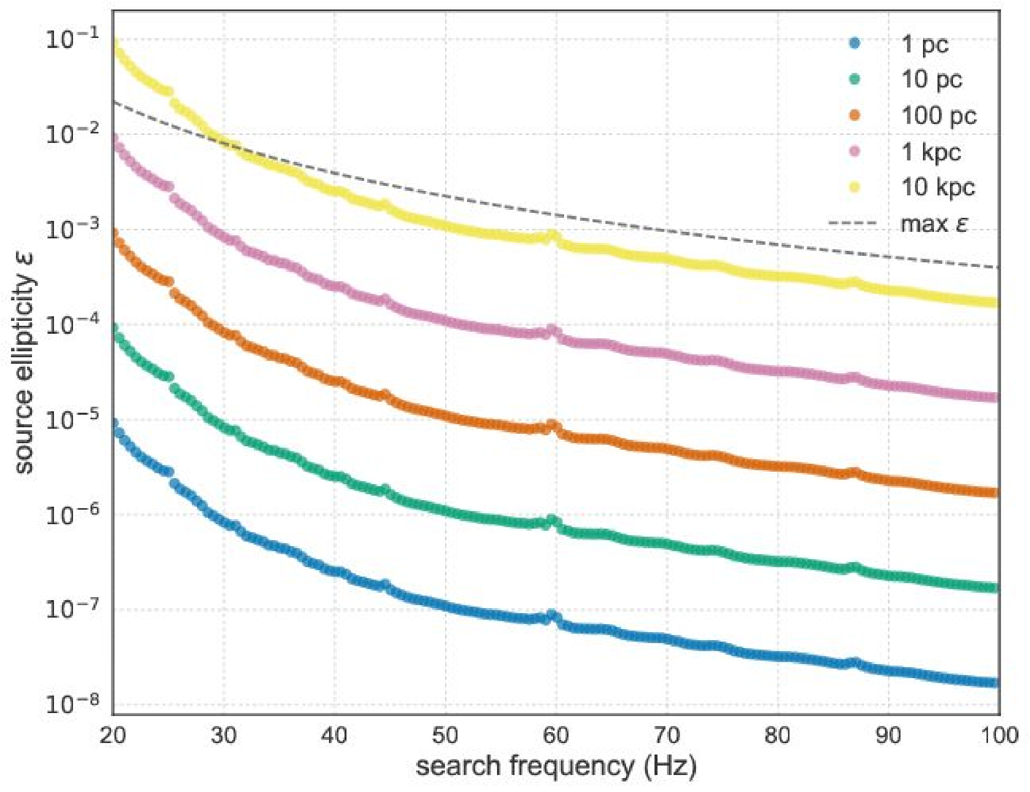


(LVC, (2017) arXiv:1707.02669)
In depth search on 20-100 Hz
Best marginalised 90% limits:
$h_0 < 1.8 \times 10^{-25}$ at 100 Hz



Ellipticity limits

(LVC, (2017) arXiv:1707.02669)



Outlook

Pulling signals out of the data

Continuous gravitational waves are expected to be in the data - we just don't know where or how loud

For a coherent search: $$h_0^{\text{single-trial}} \approx \sqrt{\frac{\text{Strain noise}}{\text{Observation span}}}$$

Improvements to search pipelines

- Ongoing work within LVC

Longer running times

Improvements to the detector

- HLV currently undergoing improvements read for O3

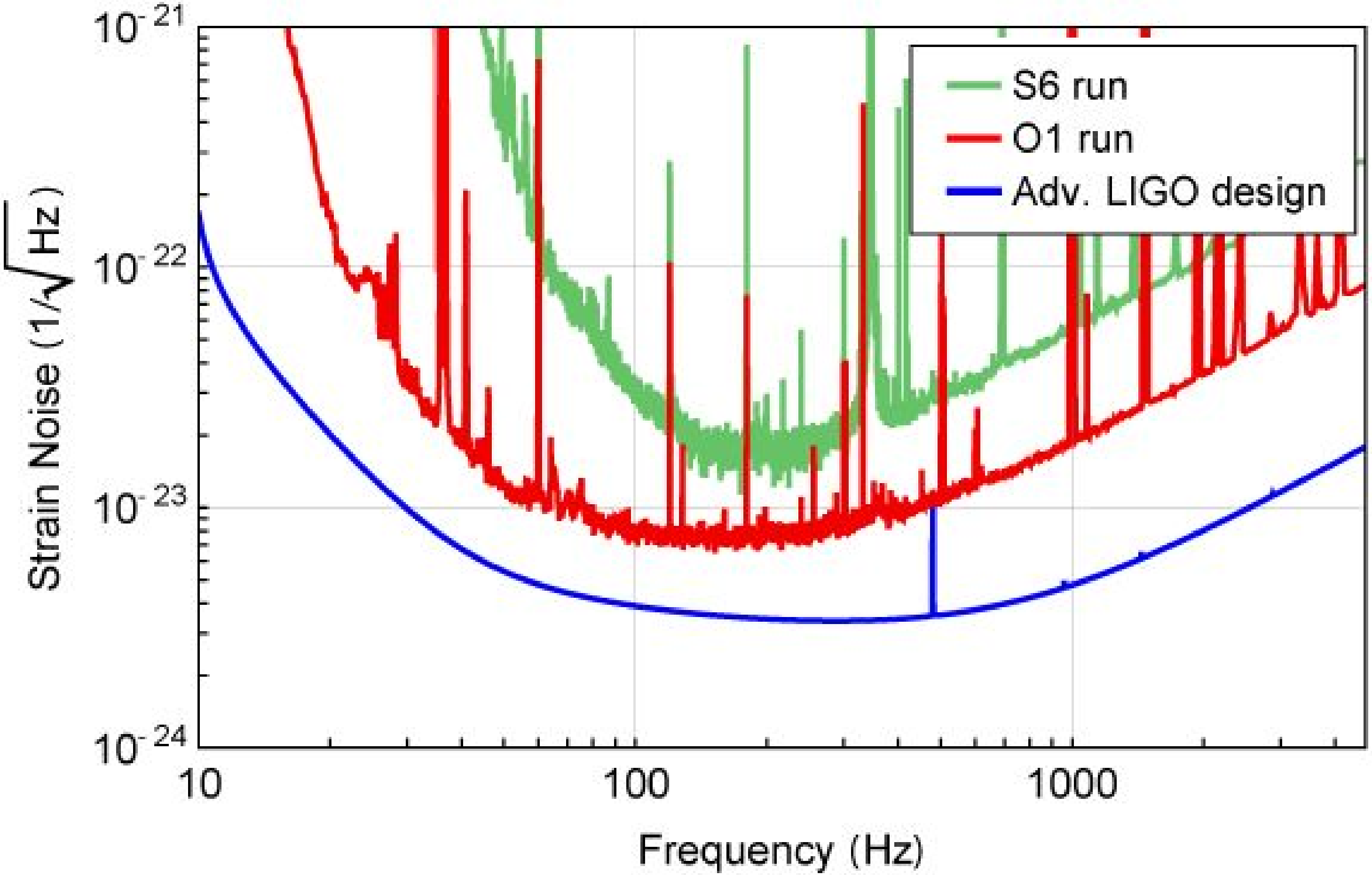
Improvements result in sensitivity to weaker signals

But, this relies on us knowing the signal model exactly

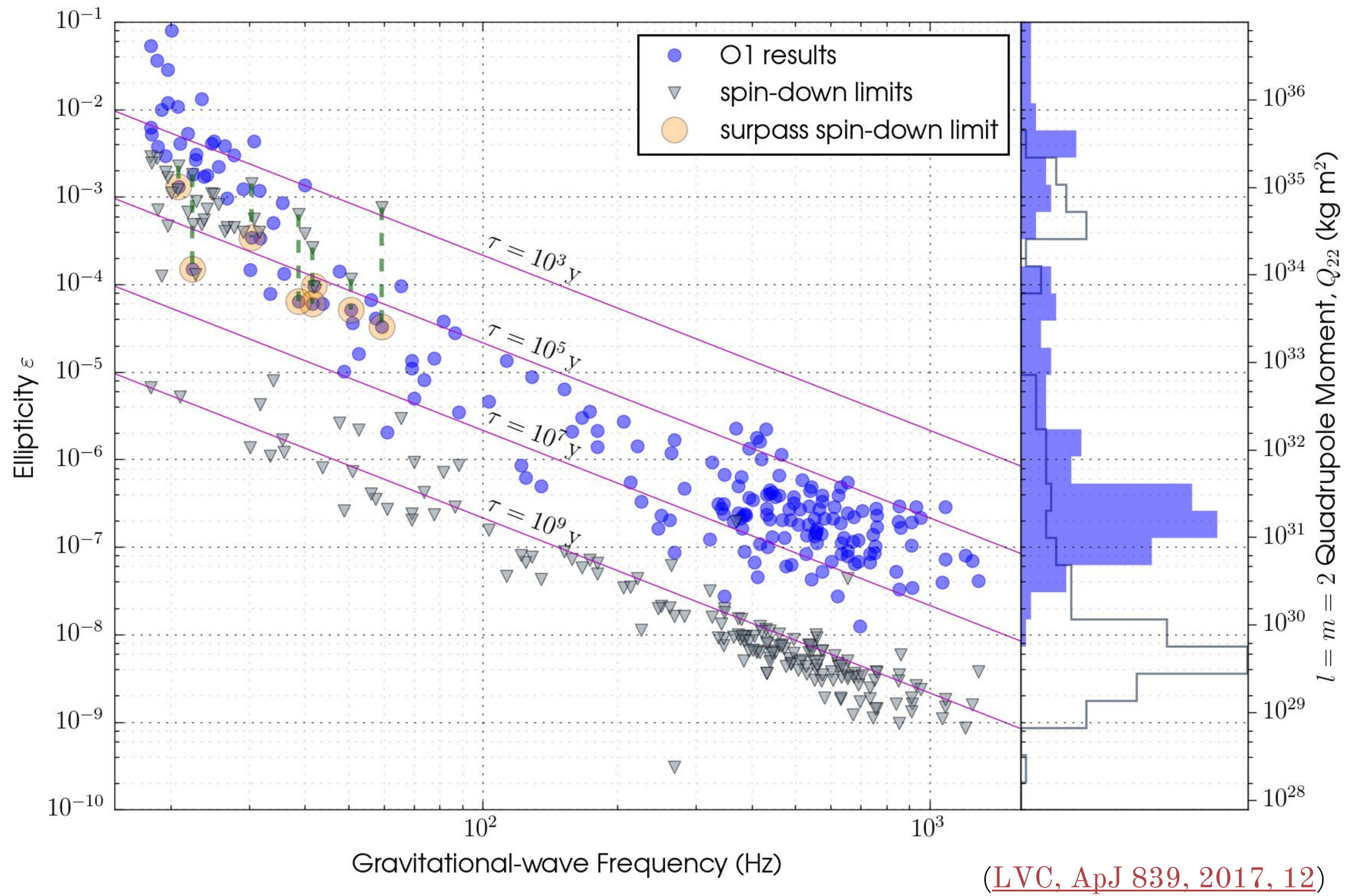
Improving our chances: questions and challenges

- Spin-wandering need robust search (e.g. Viterbi - Suvorova et al., PRD 93, 2016, 123009)
- For r-modes (or other sources) - What is the frequency relation to the rotation period? Is that exact, or approximate and if so by how much?
- Narrow-band searches look in a small band, but should we also look elsewhere?
- Glitches problematic for blind searches (Ashton et al., PRD 96, 2017, 063004)
- Ephemeris greatly improves sensitivity, can we obtain this for sources like J0537-6910?

Thanks for listening



https://www.advancedligo.mit.edu/adligo_news.html



(LVC, ApJ 839, 2017, 12)