Searches for continuous gravitational waves in LIGO/Virgo data and the post-merger remnant following the binary neutron star merger GW170817

Evan Goetz

for the LIGO Scientific Collaboration and Virgo Collaboration

LIGO Hanford Observatory

LIGO-G1800355

Transient vs continuous gravitational wave signals

- **Compact binary coalescence** gravitational wave signals are **strong but transient**

- Cannot perform long duration studies of particular source

- **Continuous** gravitational wave signals are **weak but persistent** enabling long term studies of a source

Continuous gravitational waves (1)

- Radiation generated by time-varying quadrupolar mass-moment

$$h_{\mu\nu} = \frac{2G}{rc^4}\frac{d^2}{dt^2}\left[I_{\mu\nu}\right]$$

$I_{\mu\nu}$ Quadrupole moment of inertia tensor

r Distance to source

- Rapidly-rotating neutron star with equatorial ellipticity (tri-axial ellipsoid)

$$h \approx 1.1 \times 10^{-24} \left(\frac{r}{1\,\mathrm{kpc}}\right)^{-1} \left(\frac{f_{\mathrm{GW}}}{1\,\mathrm{kHz}}\right)^{2} \left(\frac{\varepsilon}{10^{-6}}\right) \left(\frac{I_{zz}}{10^{38}\,\mathrm{kg}\cdot\mathrm{m}^2}\right)$$

$$\varepsilon = \frac{|I_{xx} - I_{yy}|}{I_{zz}}$$ Equatorial ellipticity

$$f_{\mathrm{GW}} = 2 f_{\mathrm{rot}}$$

P. Jaranowski, A. Królak, B. Schutz, Phys. Rev. D **58** 063001

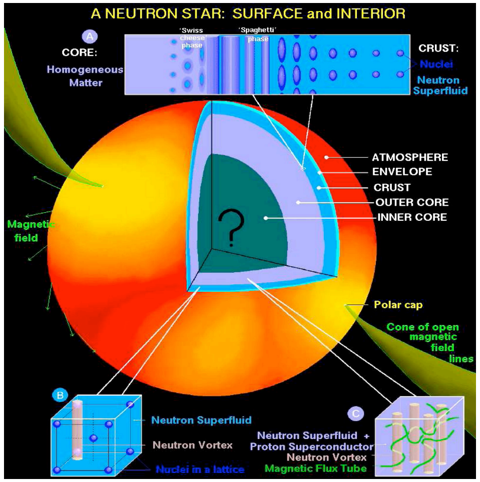
Continuous gravitational waves (2)

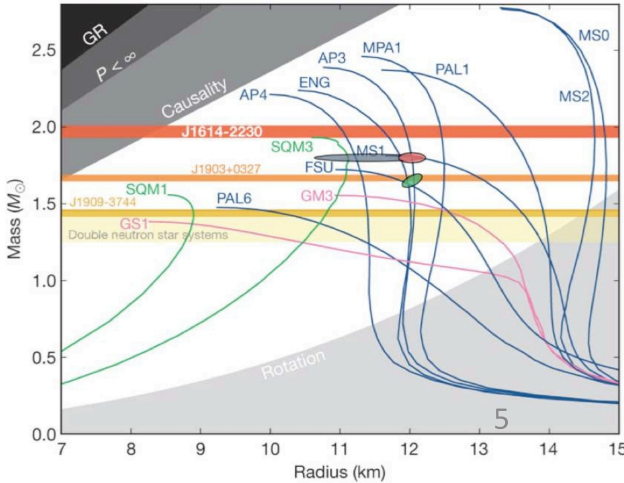
- Continuous GWs are nearly monochromatic sinusoidal waves
- Plausible breaking strain of NS matter:
  - Normal nuclear matter $\varepsilon < 10^{-5}$
  - Hybrid (hadron-quark core) $\varepsilon < 10^{-3}$
  - Quark star $\varepsilon < 10^{-1}$
- Gravitational wave emission strength and frequency depends on mechanism, ex:
  - Tri-axial ellipsoid $f_{\mathrm{GW}} = 2f_{\mathrm{rot}}$
  - r-mode fluid oscillations $f_{\mathrm{GW}} \simeq (4/3)f_{\mathrm{rot}}$
  - Free-precession $f_{\mathrm{GW}} = f_{\mathrm{rot}} \pm f_{\mathrm{prec}}$

N. Johnson-McDaniel and B. Owen, PRD 87 129903

Why we search for continuous gravitational waves

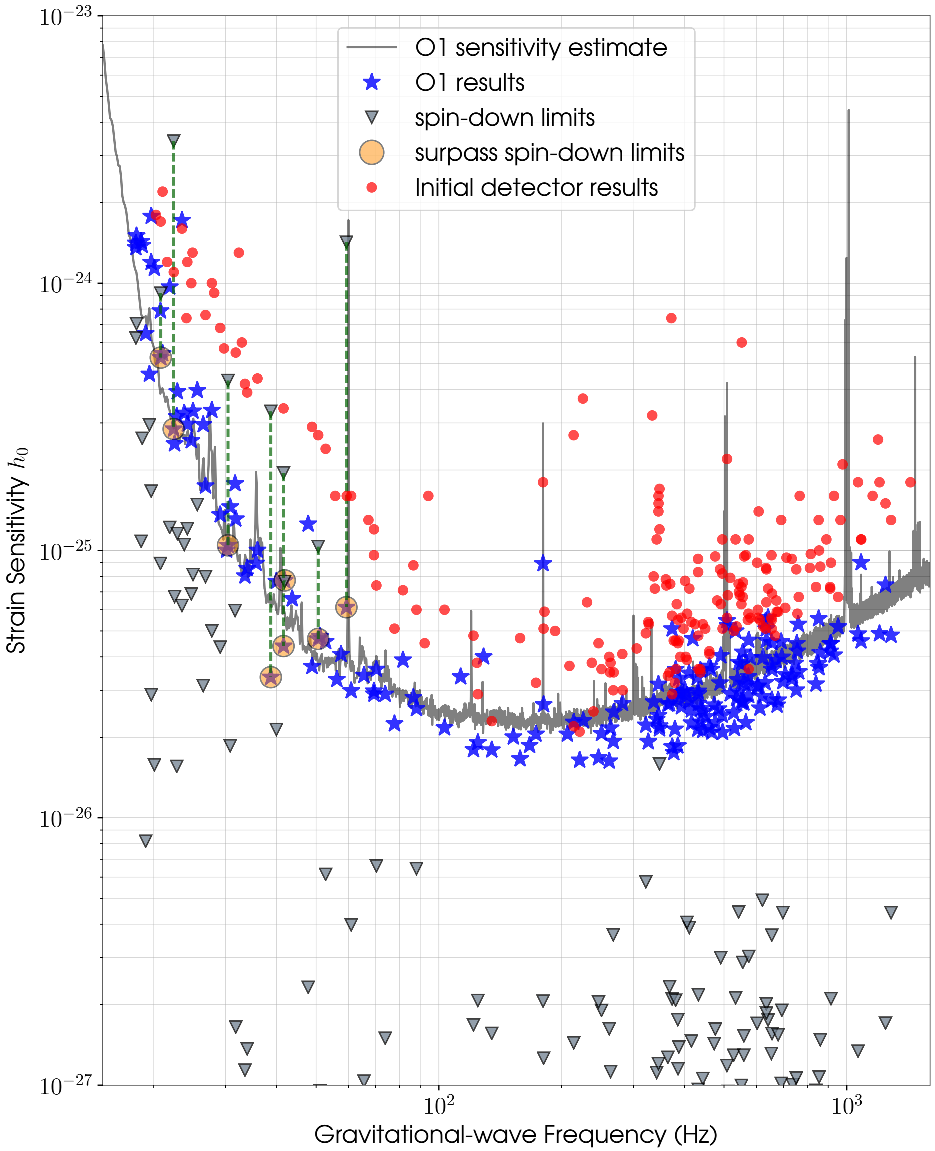
- Just one system would provide a rich laboratory!
  - Neutron star equation of state?
  - Maximum ellipticity?
  - Does NS have exotic states of matter?
  - Maximum mass of a neutron star?
  - How fast can a neutron star spin?
  - Other tests of General Relativity
  - NS dynamics
  - Implications for population models
  - Stochastic background of GWs from spinning neutron stars





Images:
http://www.mpifr-bonn.mpg.de/research/fundamental/forces
http://sci.esa.int/loft/49338-equation-of-state-for-neutron-stars/

Recent results: O1 targeted search



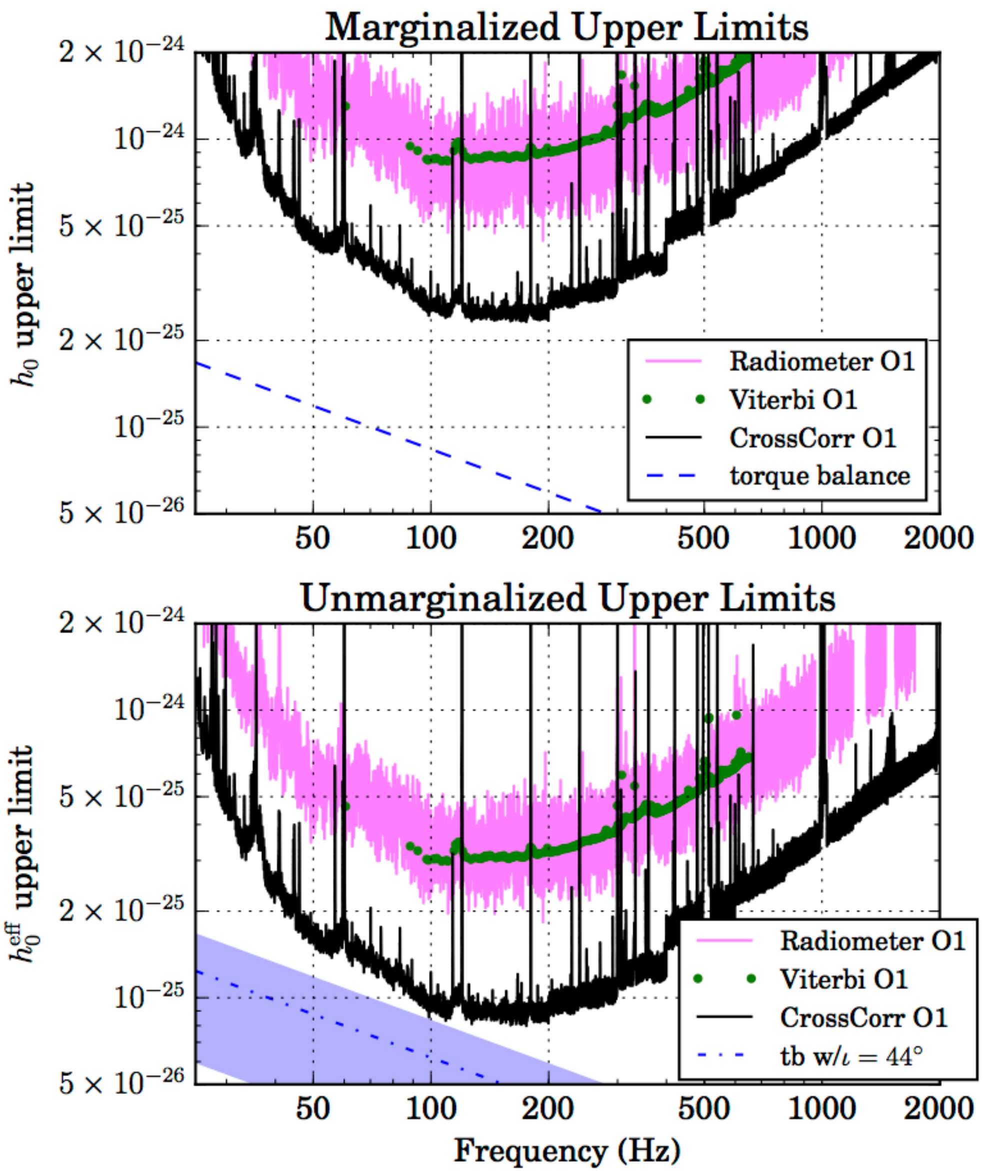
- Targeted search of 200 known pulsars in first Advanced LIGO observing run
- Results for 8 pulsars beat the "spin-down" limit
- Overall, 2x better than initial LIGO/Virgo results
- Crab limit at 0.2% of total energy loss
- Vela limit at 1% of total energy loss
- Smallest ellipticity limit:

$$\varepsilon < 1.3 \times 10^{-8}$$

- One of several targeted analyses

B. P. Abbott, et al. ApJ **839** 12

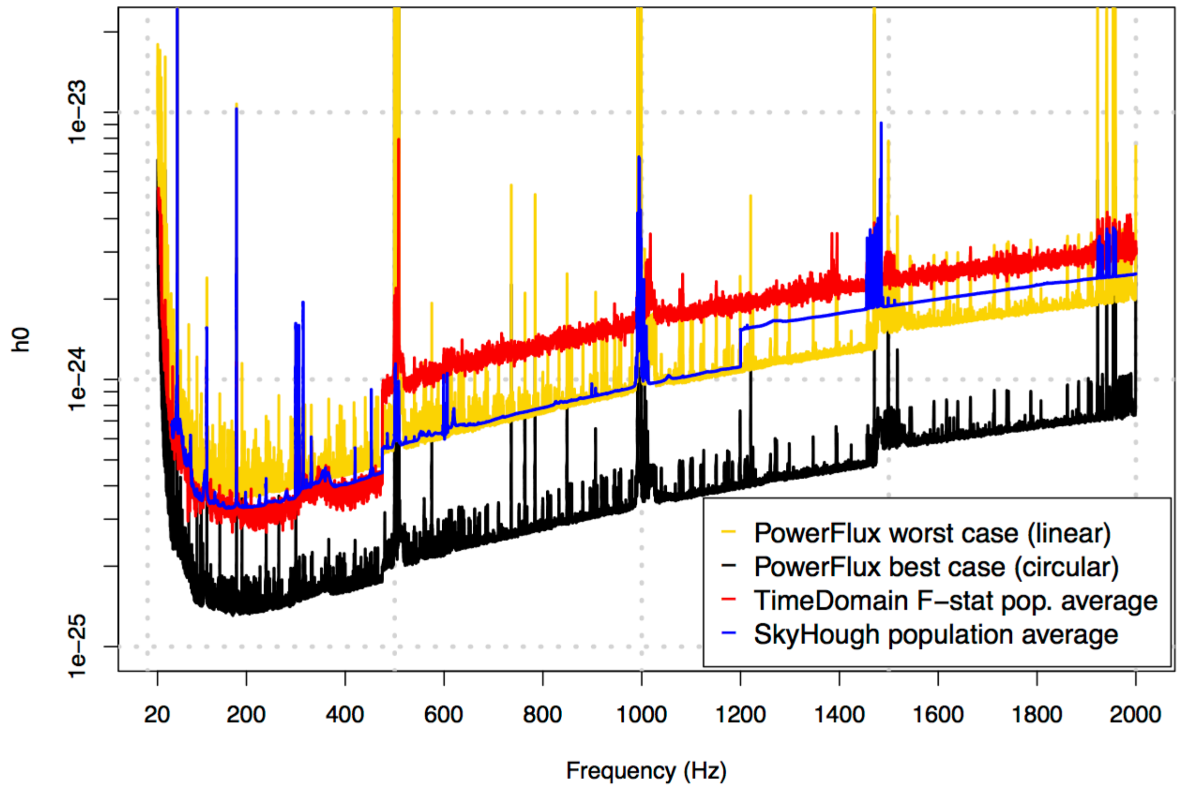
Recent results: O1 searches for Sco X-1



- Three different methods:
  - Unmodeled cross-correlation (radiometer)
  - Hidden Markov model tracking of spin-wandering signal (Viterbi)
  - Model-based cross-correlation (CrossCorr)
- Tightest limits nearly reach the torque-balance limit near 100 Hz
- Anticipate refined limits with additional data / improved detectors / advancements in methods

Abbott, et al., 2017 ApJ **847** 47

Recent results: O1 all-sky, isolated neutron star search

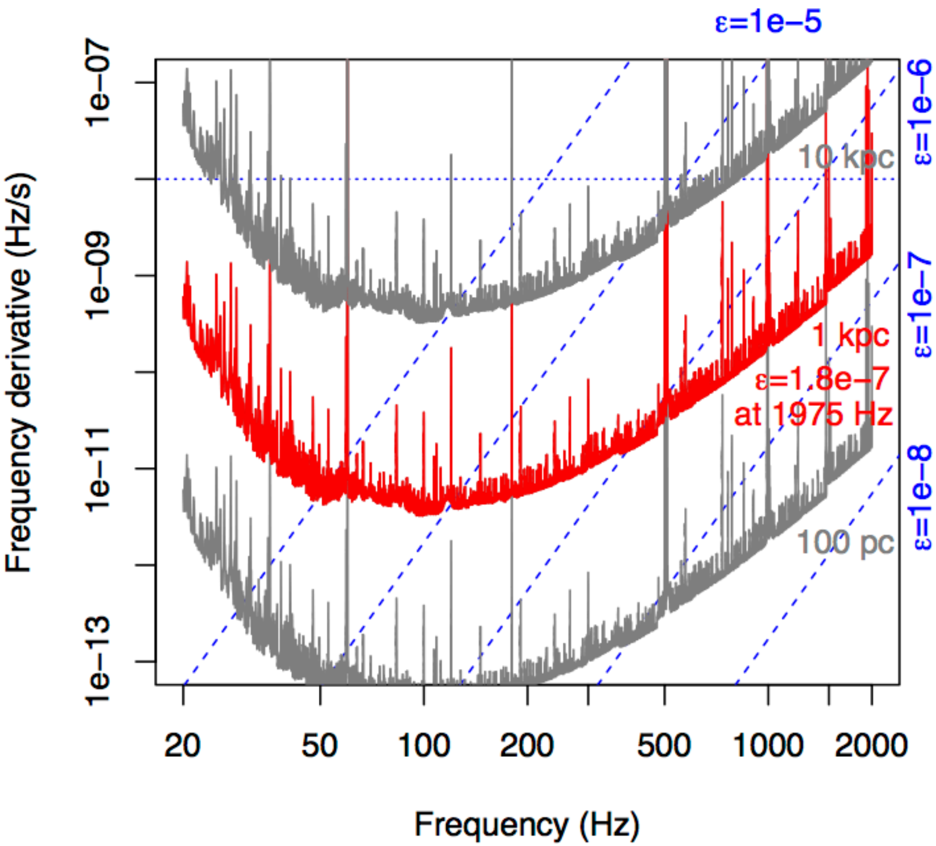


- 4 different pipelines: PowerFlux, time-domain F-statistic, Sky Hough and Frequency Hough
- Pipelines provide consistent results; confidence nothing has been missed
- Tightest limits $h_0 \simeq 1.5 \times 10^{-25}$ (circular polarization) near 170 Hz

arXiv:1802.05241 [gr-qc]

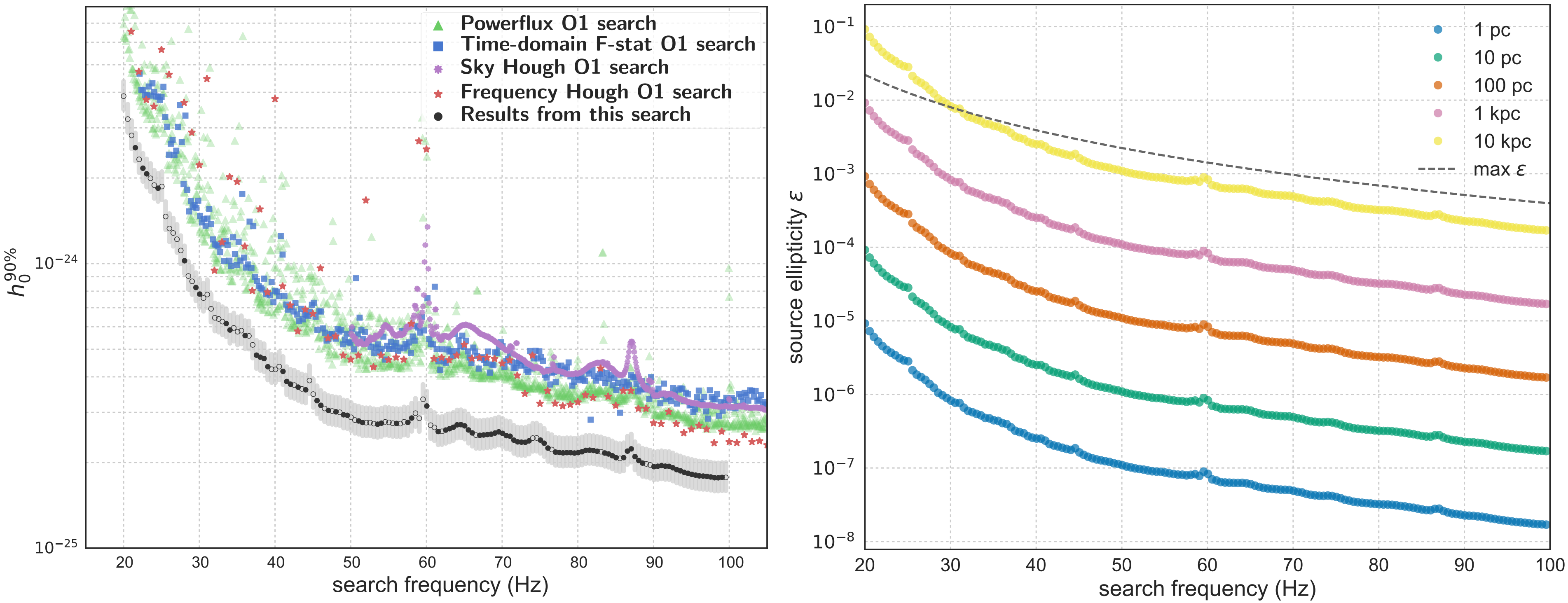
Recent results: O1 all-sky isolated neutron star search reach

- Ellipticity of a NS at a given distance for which circularly polarized waves could be detected using, e.g. PowerFlux algorithm
- Ex: at 1 kpc, can exclude sources emitting at $f_{\mathrm{GW}} > 400\,\mathrm{Hz}$ with $\varepsilon = 10^{-6}$
- Tightest constraint $\varepsilon = 1.8 \times 10^{-7}$ at $f_{\mathrm{GW}} = 1975\,\mathrm{Hz}$



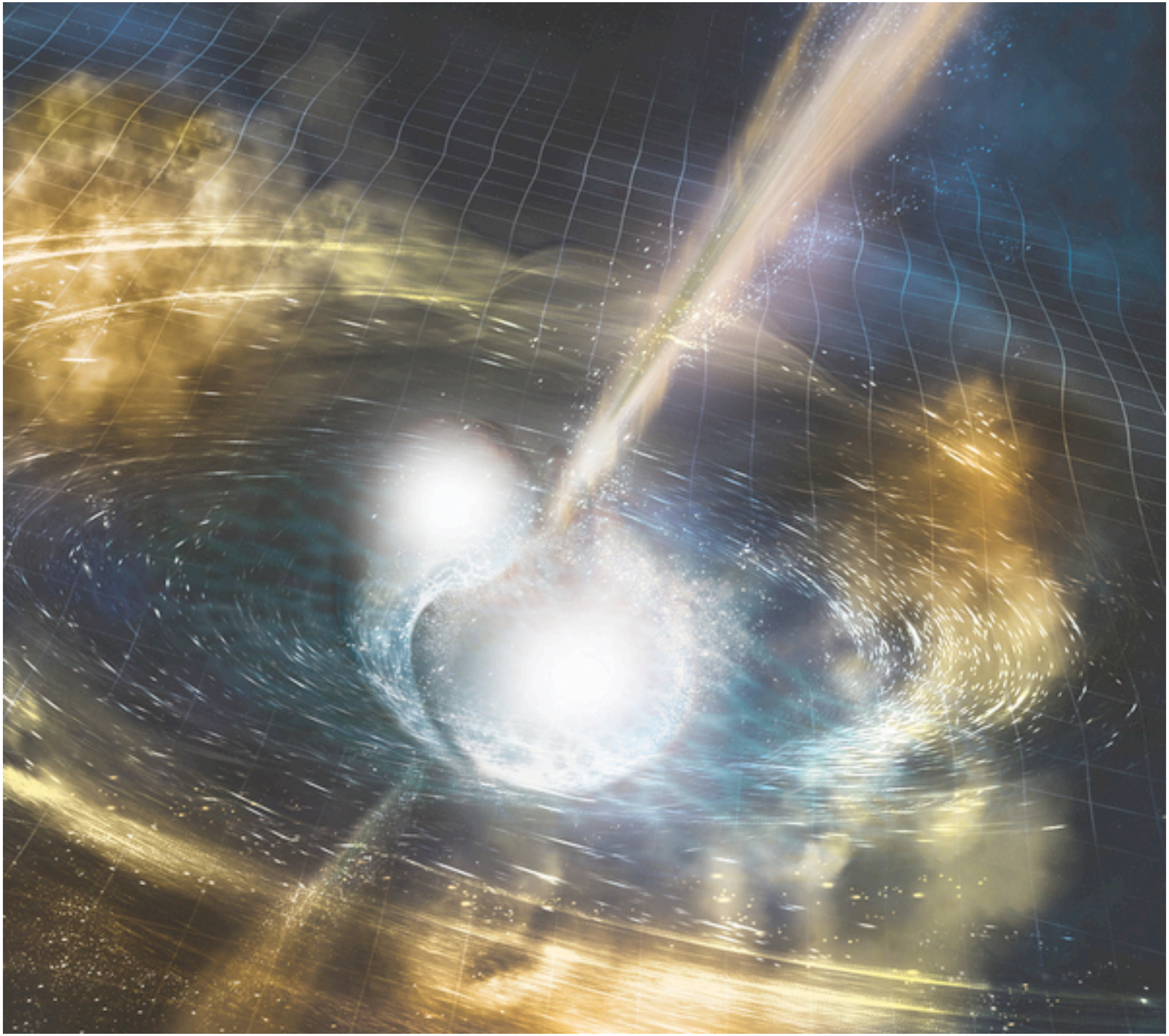
arXiv:1802.05241 [gr-qc]

Recent results: O1 all-sky isolated low-frequency Einstein@home search



- Einstein@home distributed computing project results
- 20 – 100 Hz, "deep search" (restricted spindown search compared with other searches)
- Tightest limits: $h_0 \simeq 1.8 \times 10^{-25}$ (marginalized over NS orientation); above 55 Hz, can exclude sources with $\varepsilon > 10^{-5}$ within 1 kpc of Earth

Abbott, et al., Phys. Rev. D **96** 122004



Plausible signal of post-merger remnant from GW170817

- Bar-mode instabilities?
- Magnetar like waveforms?
- r-mode oscillations/instabilities?

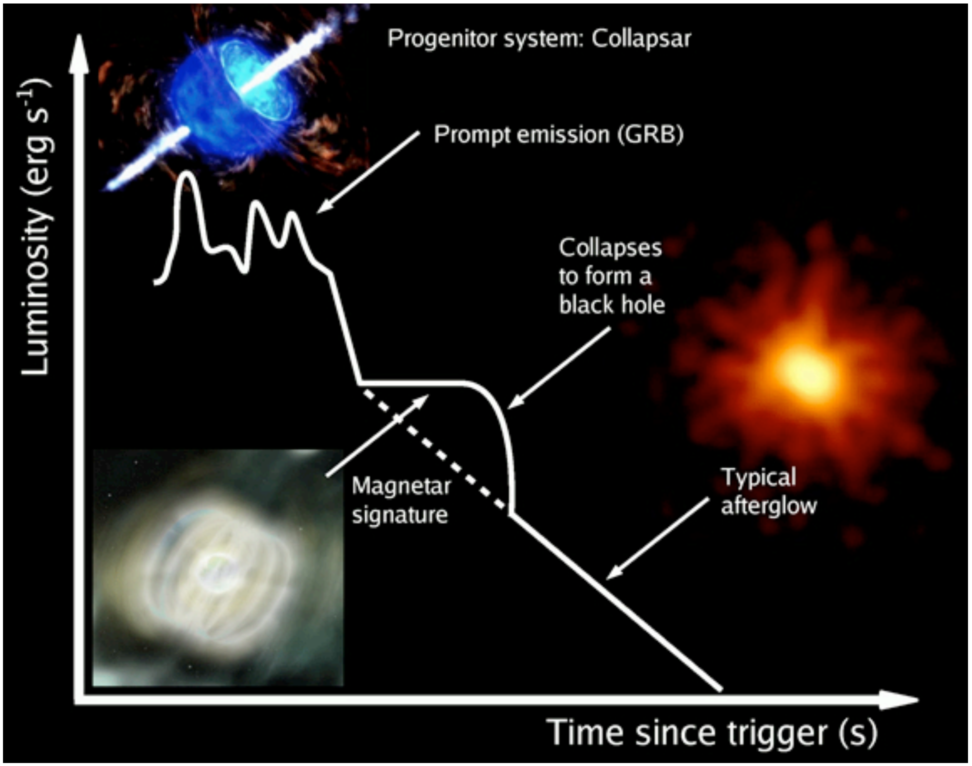
- First non-detection results for signals <500s

- Challenges for longer-duration search:
  - Unknown GW emission frequency and (rapid) signal evolution
  - Distance is far for traditional CW searches

$$d = 40^{+8}_{-14}\,\mathrm{Mpc}$$

Abbott, et al., 2017 ApJL **851** L16

Bar-mode instabilities

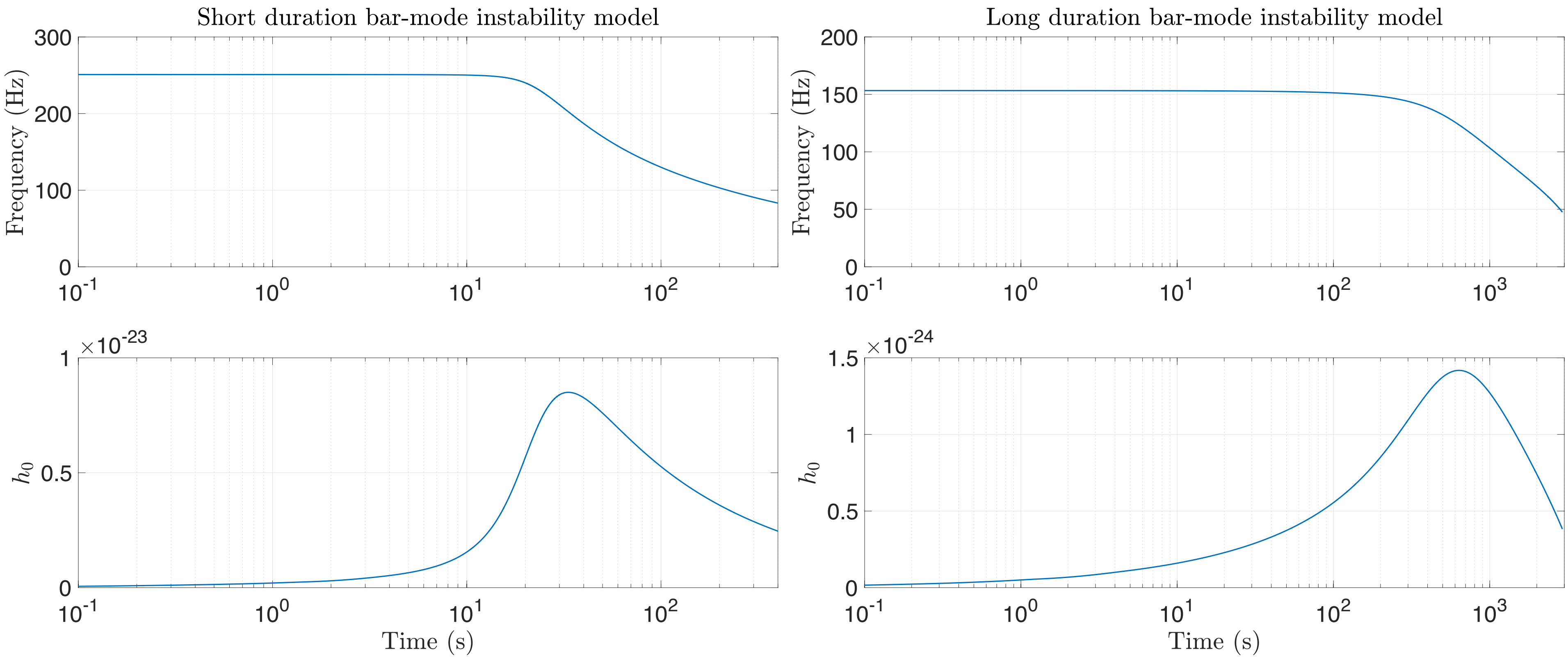


Reich, Nature 468, 15 (2010)

- NS becomes deformed into tri-axial ellipsoid
- Magnetar undergoing secular bar-mode instability might explain plateau in GRB light curves

Lai & Shapiro 1995
Corsi & Meszaros 2009

Bar-mode instability model waveform examples



"Typical" GRB magnetar: 1.4 Msun, 20 km radius, 1e14 G, n = 1

Corsi & Meszaros 2009
Coyne et al. 2016

Magnetar-like emission

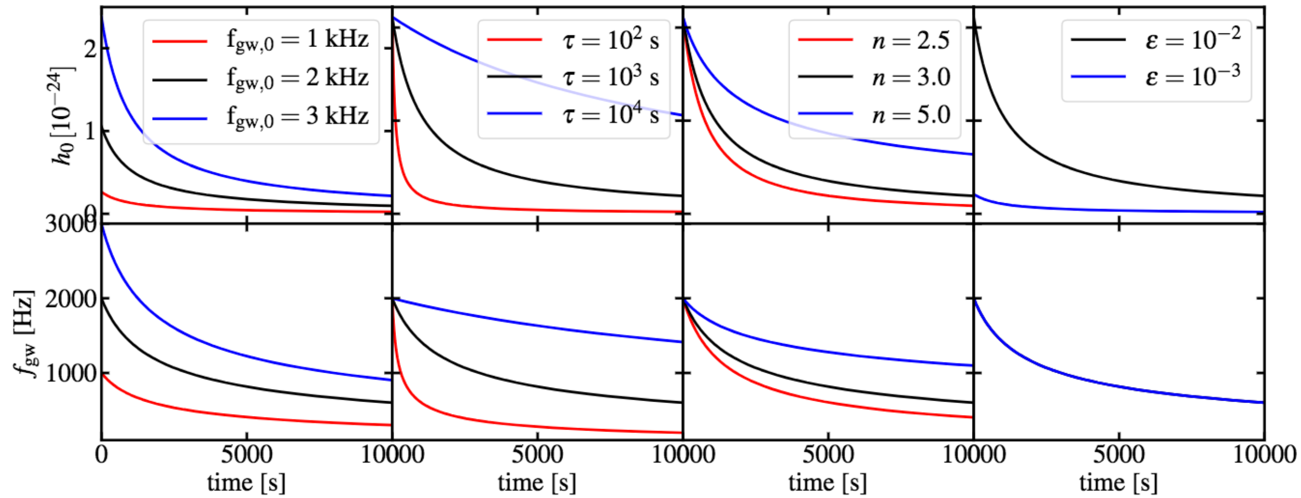
- Spindown $\dot{\Omega} = -k\Omega^n$
  - GW emission $n = 5$
  - Dipole EM emission $n = 3$
  - r-mode emission $n = 7$
- Observed EM spindown $n \lesssim 3$

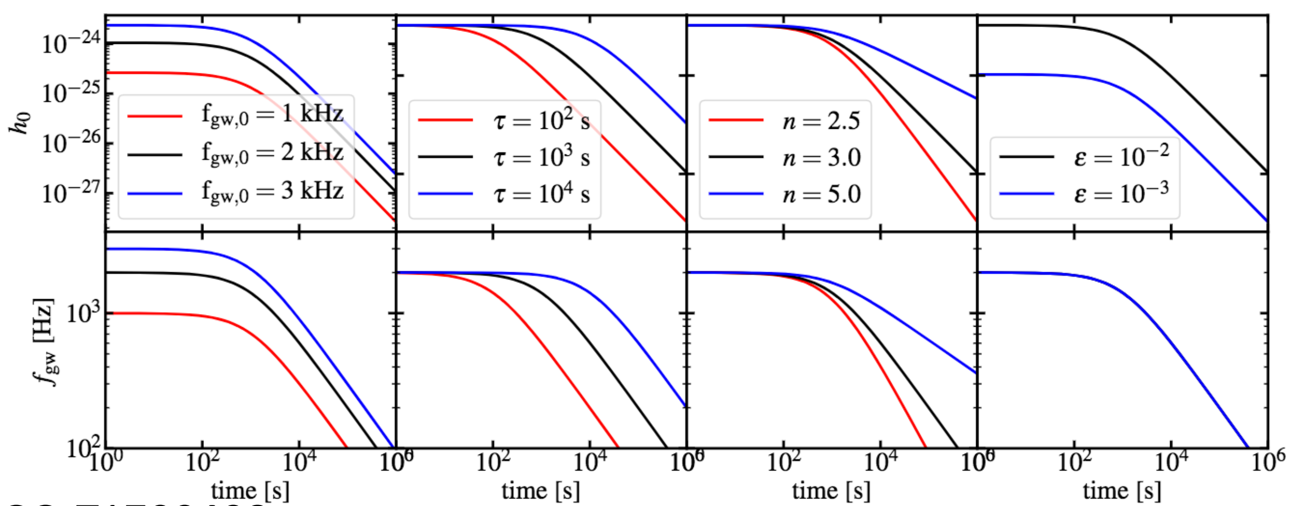
- GW frequency

$$f_{\rm gw}(t) = f_{\rm gw,0}\left(1 + \frac{t}{\tau}\right)^{\frac{1}{1-n}} \qquad \tau = \frac{-\Omega_0^{1-n}}{k(1-n)}$$

Lasky, et al., LIGO-T1700408

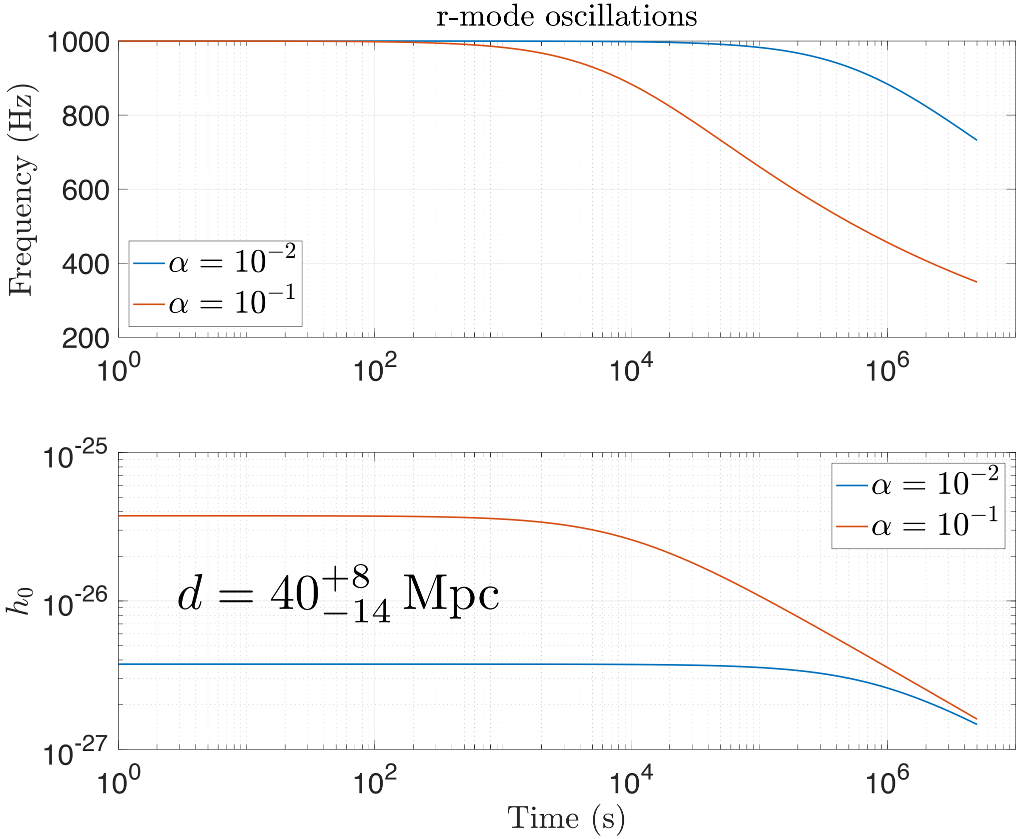
Magnetar-like emission waveform examples





Lasky, et al., LIGO-T1700408

r-mode oscillations?



- Toroidal pulsations of NS are unstable – most likely some damping reaching a saturation amplitude
- r-mode saturation amplitude depends on NS EOS

Mytidis, et al. 2015 ApJ **210** 27

CW search methods adapted

- Viterbi / Hidden Markov Model – previously used for Sco X-1 searches
- Tuned SkyHough / FrequencyHough / F-stat – methods adapted from all-sky searches
- STAMP-VLT – adapted from short duration cross-correlation burst searches

Conclusions

- LIGO and Virgo Collaborations have set forth a robust program to detect continuous gravitational waves
- Detecting one source would provide rich laboratory − including post-merger remnant searches!
- Critically important: improved detectors, sensitive algorithms, and continued collaboration with EM partners
- No detections yet, but we are searching hard
- Non-detections are probing interesting astrophysics