Searches for continuous gravitational waves in the advanced detector era

Evan Goetz
University of Michigan
for the LIGO Scientific Collaboration and Virgo Collaboration

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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

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

$I_{\mu\nu}$ 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

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

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

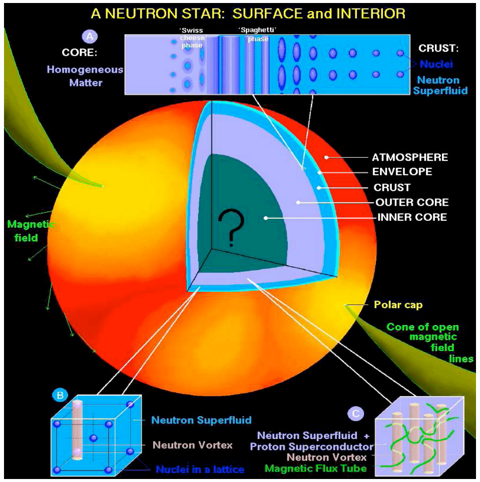
Continuous gravitational waves (2)

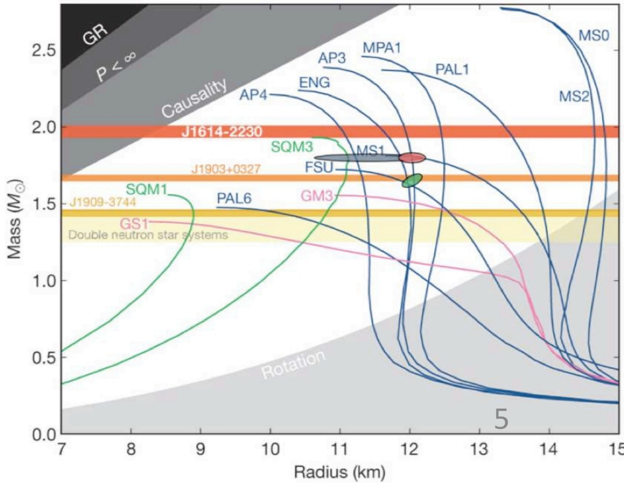
- Continuous GWs are nearly monochromatic sinusoidal waves
- Plausible breaking strain of NS matter:
  - Normal nuclear matter $\varepsilon < 10^{-5}$
  - Hybrid (hadron-quark core) $\varepsilon < 10^{-3}$
  - Quark star $\varepsilon < 10^{-1}$
- Gravitational wave emission strength and frequency depends 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/

Continuous wave search strategies

- Targeted search (known pulsars)
  - “Know everything” (in principle)

- Directed search (Cas A, galactic center, Sco X-1, etc.)
  - “Know something”

- All-sky (“blind”) search
  - “Know nothing”

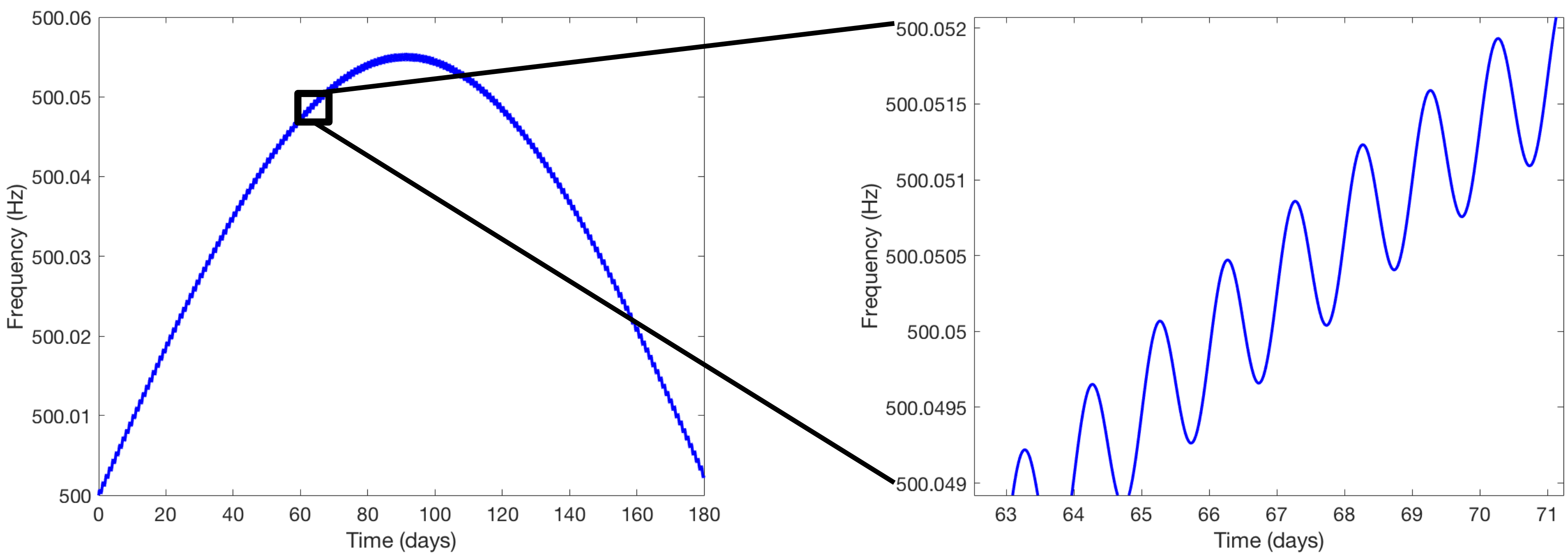
?

Increasing computational costs

Images: NASA/STSci/ESA

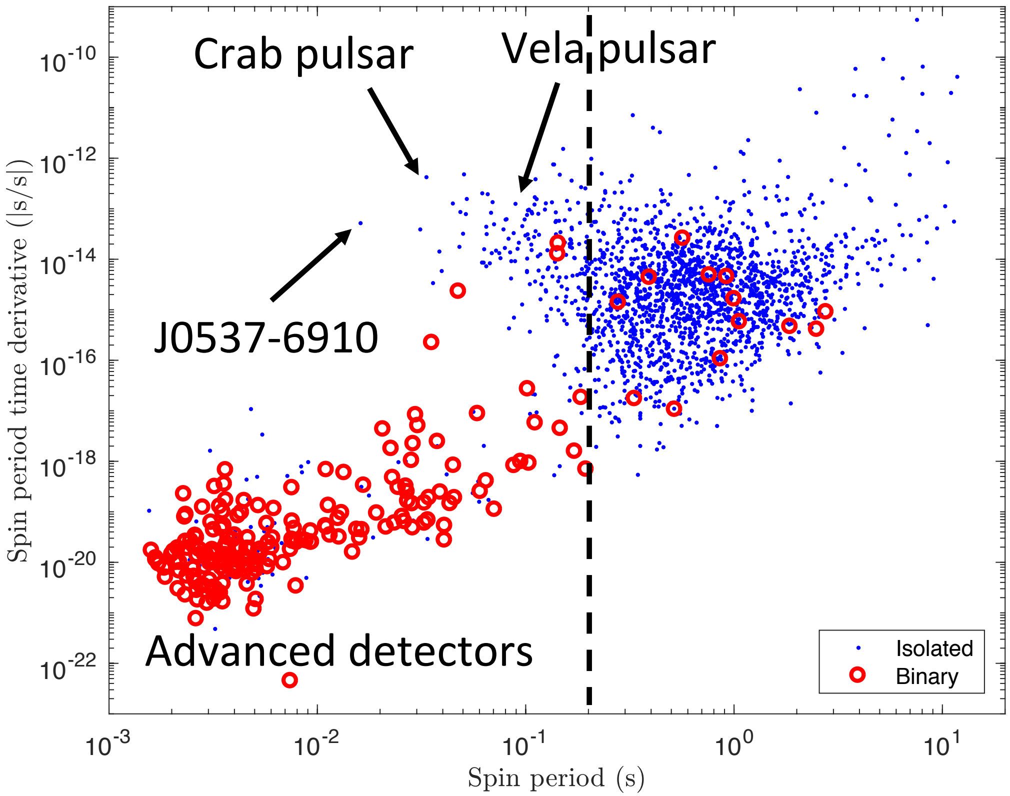
Continuous wave analysis considerations

- GW detectors are on the Earth: Doppler effect
  - Correct for the rotation and orbit of the Earth for every sky location you want to observe



Electromagnetically observed pulsars

- ATNF catalog (as of July 2017): 623 pulsars spinning faster than 5 Hz
- Of these, 258 are in binary systems (>40%)
- Emission of gravitational waves (>10 Hz) is in the most sensitive region of the LIGO/Virgo frequency band



Source: ATNF pulsar catalog (July 2017)

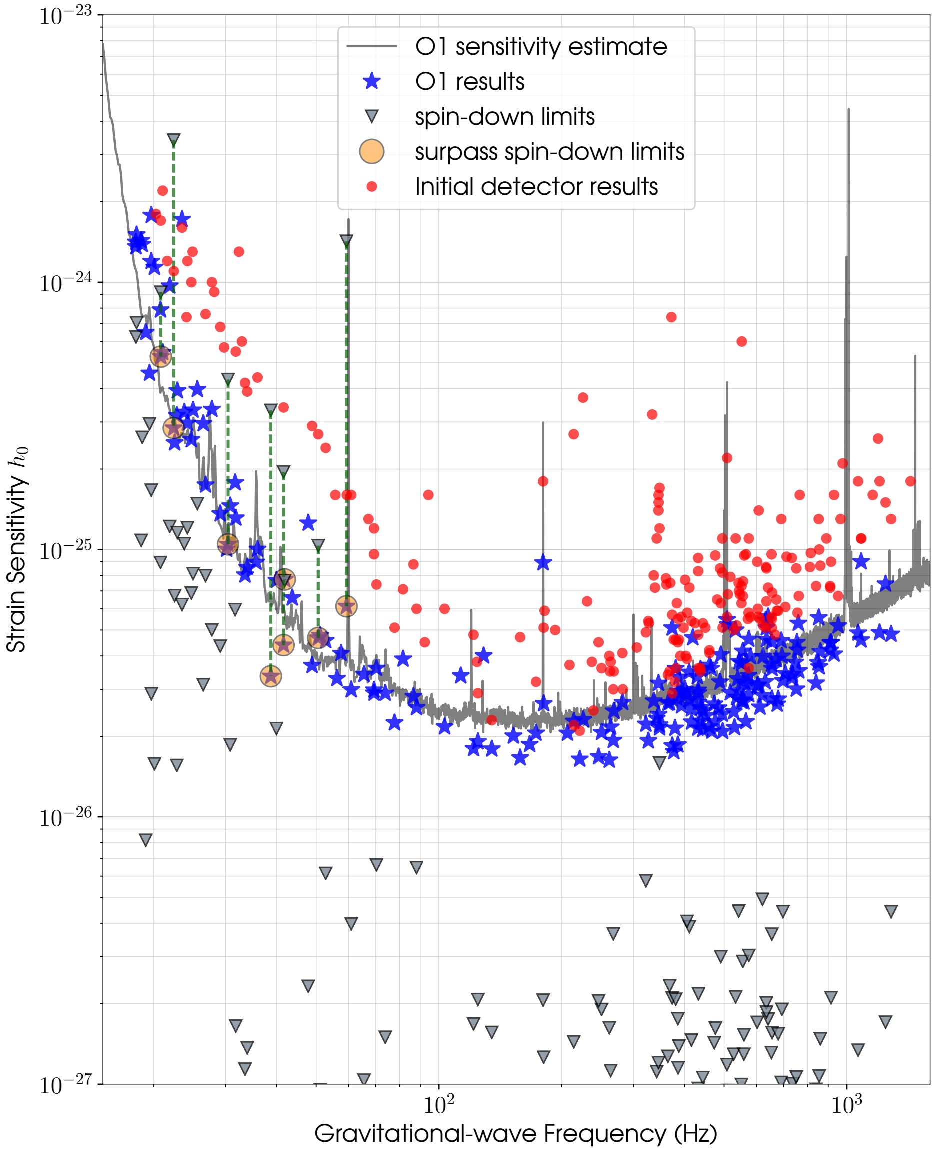
Spin-down limit on GW emission

- Neutron stars spin down (lose energy)
- Equate rate of radiated energy to the energy of a gravitational wave from tri-axial ellipsoid

$$h_{\mathrm{SD}} \approx 2.5 \times 10^{-25} \left(\frac{r}{1\,\mathrm{kpc}}\right)^{-1} \left(\frac{f_{\mathrm{GW}}}{1\,\mathrm{kHz}}\right)^{-1/2} \left(\frac{\dot{f}_{\mathrm{GW}}}{10^{-10}\,\mathrm{Hz/s}}\right)^{1/2} \left(\frac{I}{10^{45}\,\mathrm{g}\cdot\mathrm{cm}^2}\right)^{1/2}$$

- Useful benchmark “spin-down limit”

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

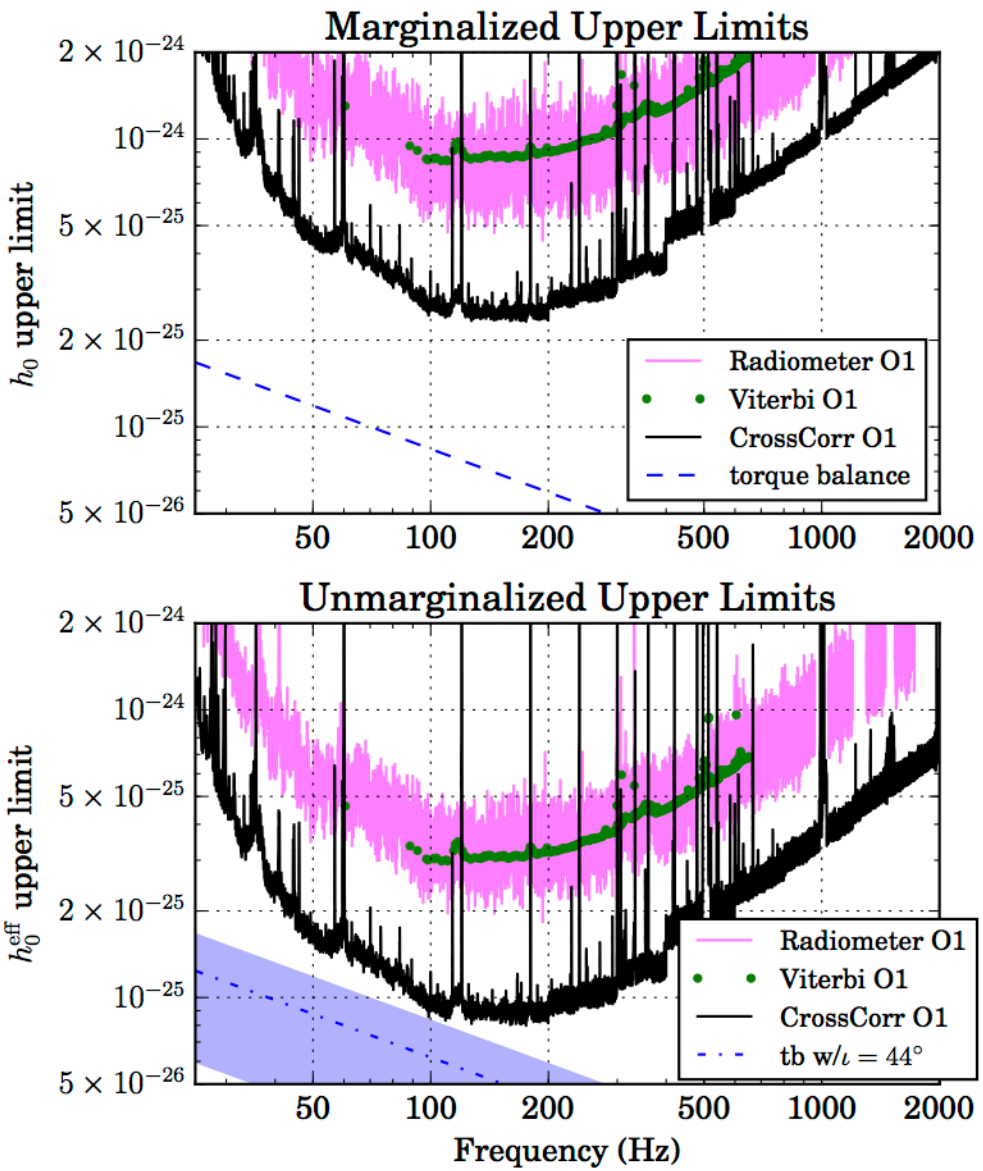
Torque-balance limit

- For actively accreting NS, the in-falling matter spins up the NS <--> GW emission spins down the NS
- Assume the two mechanisms are in balance for a tri-axial ellipsoid NS

$$h_{\rm TB} \approx 2.7 \times 10^{-26} \left(\frac{f_{\rm GW}}{800\,{\rm Hz}}\right)^{-1/2} \left(\frac{F_{\rm x}}{3.9 \times 10^{-7}\,{\rm erg\,cm^{-2}\,s^{-1}}}\right)^{1/2}$$

- Those NS accreting most rapidly would have the largest amplitude GWs
- Brightest (non-solar) x-ray source is Sco X-1

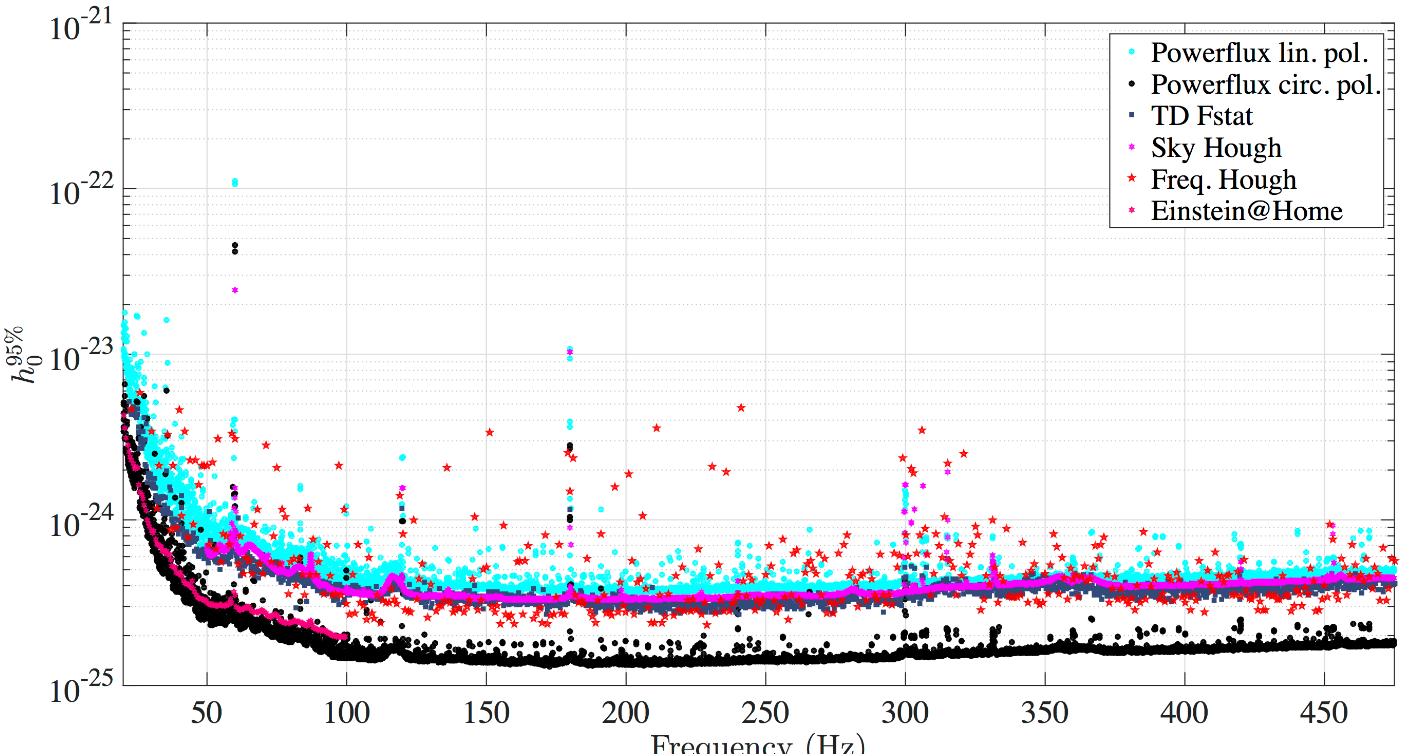
Recent results: O1 searches for Sco X-1



- 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

arXiv:1706.03119 [astro-ph.HE]

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

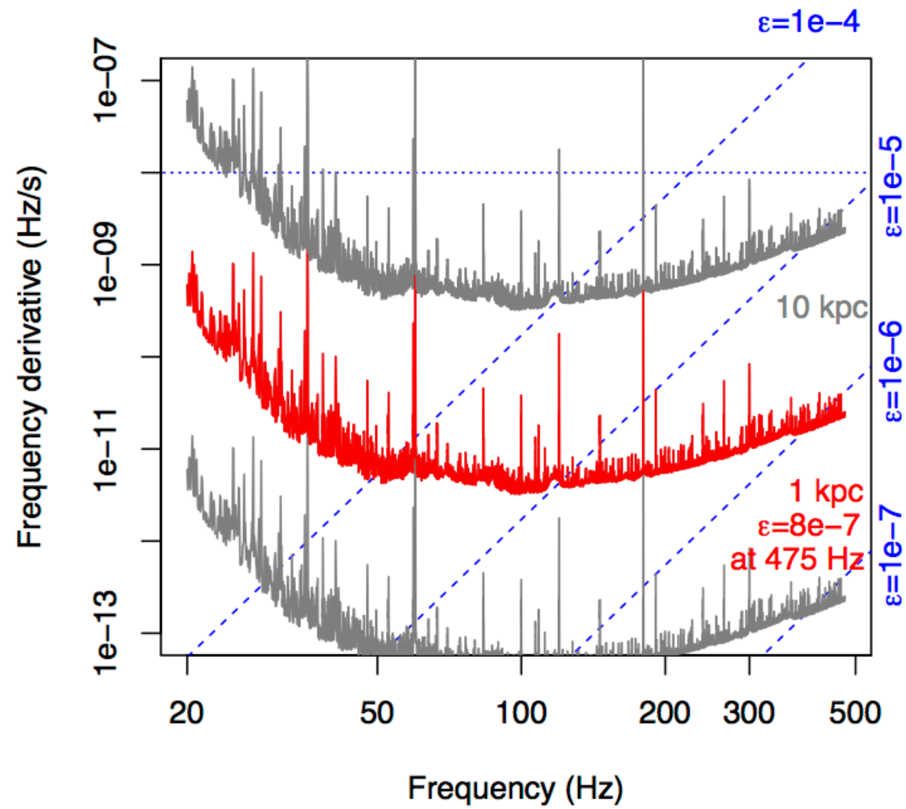


- 4 different pipelines: PowerFlux, time-domain F-statistic, Sky Hough and Frequency Hough (+ comparison to F-stat on Einstein@Home)
- Pipelines provide consistent results; confidence nothing has been missed
- Tightest limits $h_0 \simeq 1.5 \times 10^{-25}$ (circular polarization) near 170 Hz

arXiv:XXXX.XXXXX

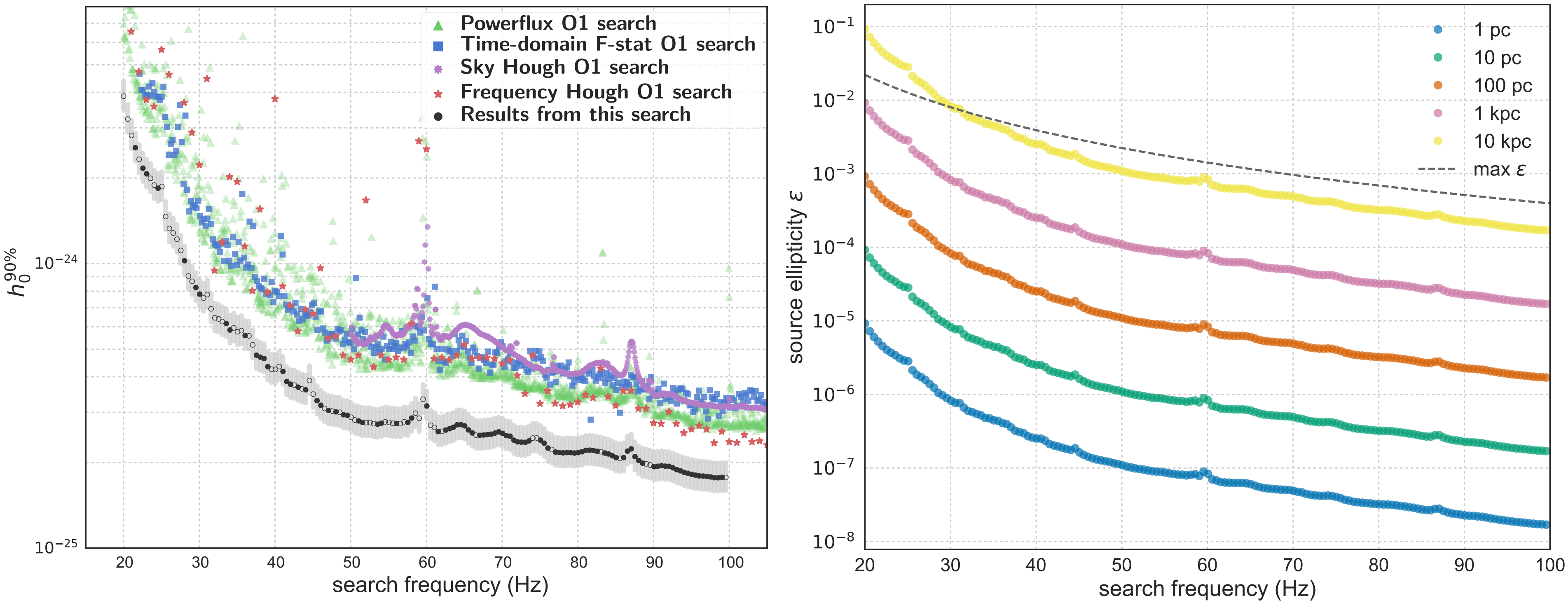
Recent results: O1 all-sky isolated neutron star search reach

- 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 $f_{\mathrm{GW}} > 120\,\mathrm{Hz}$ with $\varepsilon = 10^{-5}$
- Tightest constraint $\varepsilon = 8 \times 10^{-7}$ at $f_{\mathrm{GW}} = 475\,\mathrm{Hz}$



arXiv:XXXX.XXXXX

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

arXiv:XXXX.XXXXX

Other works in progress

- O1 analyses in the pipeline:
  - Searches for SNRs (plausible NSs)
  - High-frequency all-sky searches
  - All-sky searches for NSs in binary systems
  - “Narrowband” searches for GWs from known pulsars
  - “Spotlight” directional searches (e.g. Orion spur, galactic center)
  - Searches for non-tensoral GWs from known pulsars

Outlook

- Currently planned LIGO O2 observing run longer than O1 (9 months vs 4 months)
  – LIGO site hardware changes have mitigated some of the combs of lines present in O1 data
  – Sensitivity improvements, especially at low frequency at LIGO Livingston
- Investigations of algorithm enhancements, e.g. narrowband, Viterbi, TwoSpect search algorithms

See talk by K. Kawabe
S. Mastrogiovanni, et al. CQG 34 135007
E. Goetz and K. Riles, CQG 33 085007

Conclusions

- LIGO and Virgo Collaborations have set forth a robust program to detect continuous gravitational waves
- Detecting one source would provide rich laboratory
- 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