Continuous GWs from known and unknown sources: O3 observations and beyond

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dcc.ligo.org/G2201744

Outline

- ⋆ Astrophysical motivation
- ⋆ Methods and challenges
- ⋆ Current results
- ⋆ Plans for the future

Continuous GW sources vs other types of sources

(Hokusai "The Great Wave off Kanagawa")

One-time cataclysmic events, e.g. last moments of binary systems of

- ⋆ black holes (GW150914 etc.) and neutron stars (GW170817),

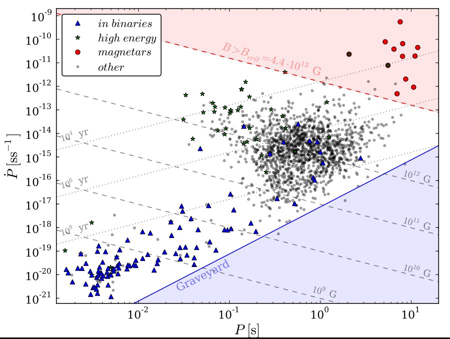
(Shoson "Cranes landing")

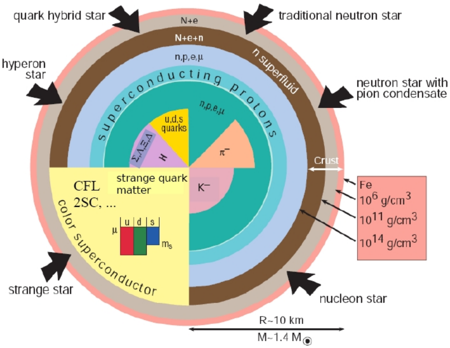
Periodic phenomena, e.g.

- ⋆ rotating asymmetric neutron stars ("*gravitational pulsars*"),
- ⋆ low-mass binary systems,
- ⋆ boson clouds.

Neutron stars = very dense, magnetized stars

The most relativistic **material** objects in the Universe: compactness $M/R \simeq 0.5$, observed in all EM spectrum as pulsars, magnetars, in supernovæ remnants, in accreting systems, in double neutron star binaries...





About 2500 NS observed to date, $\sim 10^8 - 10^9$ in the Galaxy.

Continuous GWs from spinning neutron stars

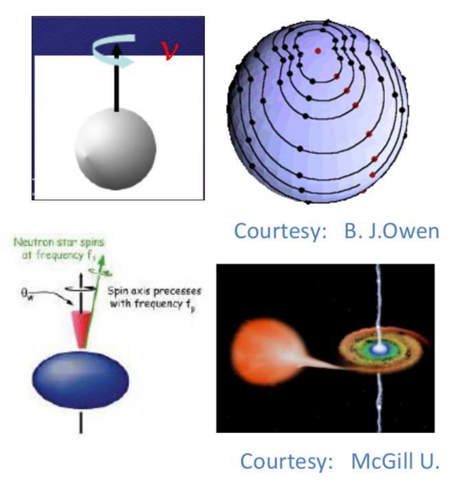
Characteristics:

- ⋆ Long-lived: $T > T_{obs}$,
- ⋆ Nearly periodic: $f_{GW} \propto f_{rot}$

Mechanisms that can create time-varying quadrupole moment:

- ⋆ "Mountains" (elastic and/or magnetic stresses, $f_{GW} = 2f_{rot}$),
- ⋆ Oscillations (r-modes, $f_{GW} = 4/3 f_{rot}$),
- ⋆ Free precession ($f_{GW} \propto f_{rot} + f_{prec}$)
- ⋆ Accretion (drives deformations from r-modes, thermal gradients, magnetic fields, $fGW \simeq f_{rot}$)

(see PASA **32**, 34 2015; Universe **5(11)**, 217 2019)



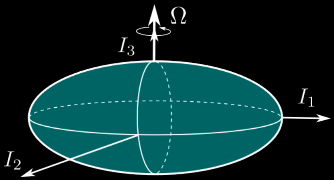
Courtesy: B. J.Owen

Courtesy: McGill U.

GW amplitude and the spindown limit

GW strain $h_0 = \frac{4\pi^2 G}{c^4} \frac{I_3 \epsilon f_{GW}^2}{d}$

with the distance d and the deformation $\epsilon = (I_1 - I_2)/I_3$. Depending on the dense matter model, $\epsilon_{max} = 10^{-3} - 10^{-6}$.



Rotational energy loss: $\dot{E}_{rot} \propto f\dot{f}$

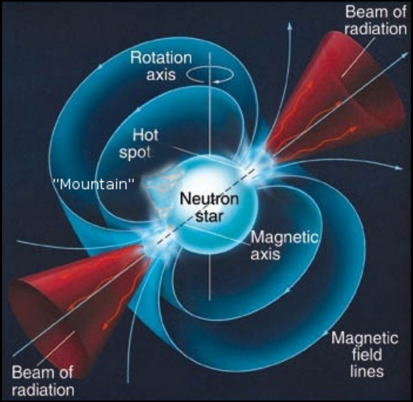
Energy emitted in GWs: $\dot{E}_{GW} \propto f^6 I_3^2 \epsilon^2$

Spindown upper limit: observed spindown fully due to GWs, $\dot{E}_{rot} = \dot{E}_{GW}$:

Assuming the knowledge of I_3 and d

$$\rightarrow \text{upper limit } h_0^{sd} = \frac{1}{d}\sqrt{\frac{5G}{2c^3}\frac{|\dot{f}|}{f} I_3}$$

$$\epsilon_{\mathrm{sd}} = 0.237\, I_{38}^{-1} \left[\frac{h_{\mathrm{sd}}}{10^{-24}}\right] \left[\frac{\mathrm{Hz}}{f_{\mathrm{rot}}}\right]^2 \left[\frac{d}{1\mathrm{kpc}}\right]$$

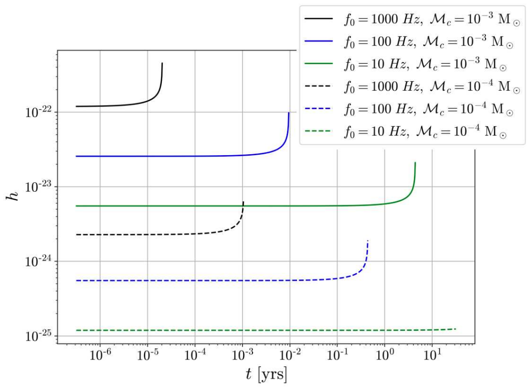


Other CW sources: low-mass primordial BHs

Inspiral of low-mass binary, with $\mathcal{M}_c = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5} \approx 10^{-3} - 10^{-5}\ M_\odot$ results in slow evolution of chirp frequency $\approx$ CW signal

Evolution of GW frequency:

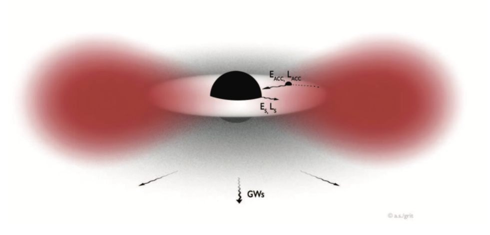
$$\frac{df}{dt} = \frac{96}{5}\pi^{8/3}\left(\frac{G\mathcal{M}_c}{c^3}\right)^{5/3} f^{11/3}$$
$$\times\,(1 + \text{PN corrections})$$



(Credit: Marc Andrés-Carcasona & Ornella Piccinni)

Other CW sources: boson clouds near BHs

- ⋆ CW emission from (hypothetical) light boson particles forming clouds around spinning BHs,
- ⋆ bosons will collide with each other over time, resulting in GW emission at almost constant frequency.



(Credit: Richard Brito, Vitor Cardoso, Paolo Pani)

(LVK analyses with O3 data: "Search for continuous gravitational wave emission from the Milky Way center in O3 LIGO-Virgo data", PRD **106**, 042003 2022, "All-sky search for gravitational wave emission from scalar boson clouds around spinning black holes in LIGO O3 data", PRD **105**, 102001 2022)

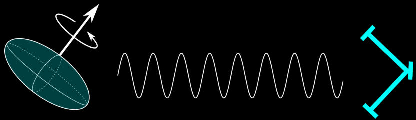
”Collider” vs ”table top” experiments

- ⋆ Many potential sources, but the GW ‘engine‘ is not guaranteed
  - ⋆ ”opposite problem” to transient compact binary coalescences (BH events).

- ⋆ GW amplitude is small: $\lessapprox 10^{-25}$ vs 10^{-21} (GW140915)

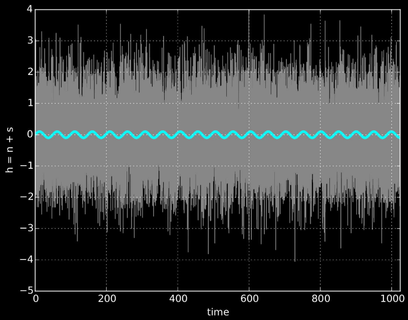
- ⋆ Discovery of a persistent source will be the capstone of GW astronomy:
  - ⋆ repeatable studies,
  - ⋆ access to ‘cold’ dense-matter equation of state of NSs, but also
  - ⋆ testing GR (polarizations etc.),
  - ⋆ searches for dark matter & exotic particles,
  - ⋆ detectors’ calibration, ”distance ladder”/cosmography.

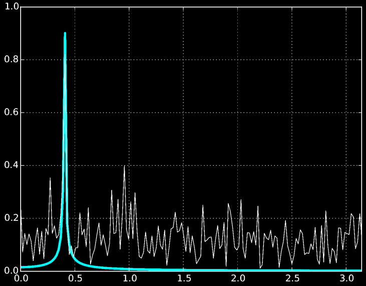
Example: a monochromatic signal



In this case a Fourier transform is sufficient to detect the signal (simplest matched filter method):

$$F = \left| \int_0^{T_0} x(t) \exp(-i\omega t) dt \right|^2$$



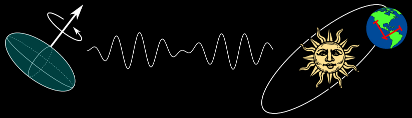


T_0 - time series duration, S_0 - spectral density of the data.

Signal-to-noise $SNR = h_0 \sqrt{\frac{T_0}{S_0}}$

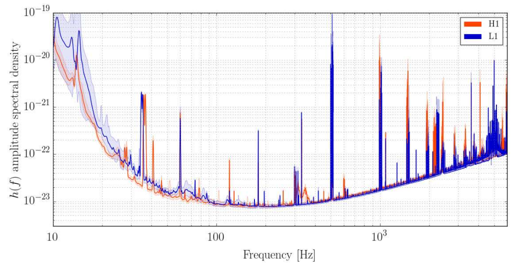
In reality: signal is modulated

Since the detector is on Earth, planets and Earth's rotation influences signal's amplitude and phase.



- ⋆ Signal is almost monochromatic: sources may slow down/spin up,
- ⋆ it has to demodulated (detector is moving),
- → precise ephemerides of the Solar System needed.

Detector movement distinguishes a real signal from detector's spectral artifacts ("lines").



Example: the $\mathcal{F}$-statistic

$\mathcal{F}$-statistic estimates how well the amplitude and phase modulated model matches the data $x(t)$

$$\mathcal{F} = \frac{2}{S_0 T_0}\left(\frac{|F_a|^2}{\langle a^2\rangle} + \frac{|F_b|^2}{\langle b^2\rangle}\right)$$

where S_0 is the spectral density, T_0 is the observation time, and

$$F_a = \int_0^{T_0} x(t)a(t)\exp(-i\phi(t))dt, \qquad F_b = \ldots$$

$a(t)$, $b(t)$ - amplitude modulation functions that depend on the sources' sky position $(\alpha,\ \delta)$,

$\phi(t)$ - phase modulation function that depends on $(f, \dot{f}, \alpha, \delta)$

(PRD **58**, 063001, 1998)

Taxonomy of search methods

- Targeted searches
  - based on matched filtering (data of length T_0 correlated with signal templates). Position, f and $\dot{f}$, sometimes source orientation, are known.

$$h_0 \propto \sqrt{S(f)/T_0}$$

- Directed searches
  - Cases when some parameters are known, e.g. the position:

  → Supernovæ remnants, Sco X-1, the Galactic center, globular clusters etc.
- All-sky searches
  - Source parameters and position not known → parameter space is large → problem becomes computationally bound

  → *Hierarchical approach:* analysis of N data segments of length T_s coherently, combining the results incoherently

$$h_0 \propto \sqrt{S(f)/T_s}/N^{1/4}$$

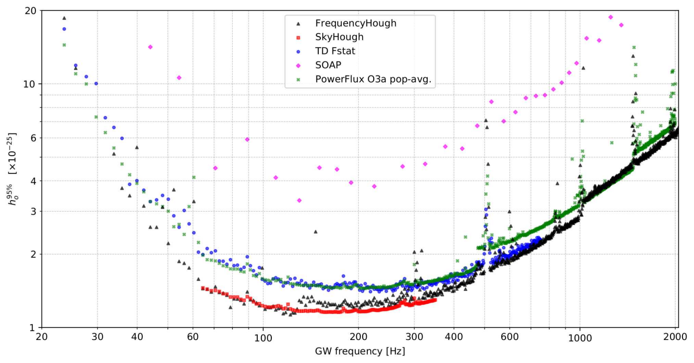
LIGO-Virgo-KAGRA O3 CW papers

Release Date	Title	Keywords (clear filter)	Science Summary	Journal citation	arXiv Preprint	Public Report
Sep 7, 2022 *Recent*	**Model-based cross-correlation search for gravitational waves from the low-mass X-ray binary Scorpius X-1 in LIGO O3 data** *(by LSC, Virgo and KAGRA)*	O3 CW LVK	-	*Submitted to ApJL*	2209.02863	P2100110
Apr 9, 2022	**Search for continuous gravitational wave emission from the Milky Way center in O3 LIGO-Virgo data** *(by LSC, Virgo and KAGRA)*	O3 CW LVK	summary	Phys. Rev. D **106**, 042003 (2022)	2204.04523	P2100437
Jan 25, 2022	**Search for gravitational waves from Scorpius X-1 with a hidden Markov model in O3 LIGO data** *(by LSC, Virgo and KAGRA)*	O3 CW LVK	summary	Phys. Rev. D **106**, 062002 (2022)	2201.10104	P2100405
Jan 3, 2022	**All-sky search for continuous gravitational waves from isolated neutron stars using Advanced LIGO and Advanced Virgo O3 data** *(by LSC, Virgo and KAGRA)*	O3 CW LVK	summary	*Submitted to PRD*	2201.00697	P2100367
Dec 21, 2021	**Narrowband searches for continuous and long-duration transient gravitational waves from known pulsars in the LIGO-Virgo third observing run** *(by LSC, Virgo, KAGRA plus 28 radio astronomers and NICER science team members)*	O3 CW LVK	summary	Astrophys. J. **932**, 133 (2022)	2112.10990	P2100267
Nov 30, 2021	**Search of the Early O3 LIGO Data for Continuous Gravitational Waves from the Cassiopeia A and Vela Jr. Supernova Remnants** *(by LSC and Virgo)*	O3 CW LV	summary	Phys. Rev. D **105**, 082005 (2022)	2111.15116	P2100298
Nov 30, 2021	**All-sky search for gravitational wave emission from scalar boson clouds around spinning black holes in LIGO O3 data** *(by LSC, Virgo and KAGRA)*	O3 CW LVK	summary	Phys. Rev. D **105**, 102001 (2022)	2111.15507	P2100343
Nov 25, 2021	**Searches for Gravitational Waves from Known Pulsars at Two Harmonics in the Second and Third LIGO-Virgo Observing Runs** *(by LSC, Virgo and KAGRA)*	O3 CW LVK	summary	Astrophys. J. **935**, 1 (2022)	2111.13106	P2100049
Sep 20, 2021	**Search for continuous gravitational waves from 20 accreting millisecond X-ray pulsars in O3 LIGO data** *(by LSC, Virgo, KAGRA plus A. C. Albayati, D. Altamirano, P. Bult, D. Chakrabarty, M. Ng, P. S. Ray, A. Sanna, and T. E. Strohmayer)*	O3 CW LVK	summary	Phys. Rev. D **105**, 022002 (2022)	2109.09255	P2100221
Jul 1, 2021	**All-sky search for continuous gravitational waves from isolated neutron stars in the Early O3 LIGO Data** *(by LSC and Virgo)*	O3 CW LV	summary	Phys. Rev. D **104**, 082004 (2021)	2107.00600	P2000334
May 27, 2021	**Constraints on dark photon dark matter using data from LIGO's and Virgo's third observing run** *(by LSC, Virgo and KAGRA)*	O3 CW LVK	summary	Phys. Rev. D **105**, 063030 (2022)	2105.13085	P2100098
May 25, 2021	**Searches for continuous gravitational waves from young supernova remnants in the early third observing run of Advanced LIGO and Virgo** *(by LSC, Virgo and KAGRA)*	O3 CW LVK	summary	Astrophys. J. **921**, 80 (2021)	2105.11641	P2000479
Apr 29, 2021	**Constraints from LIGO O3 data on gravitational-wave emission due to r-modes in the glitching pulsar PSR J0537-6910** *(by LSC, Virgo, KAGRA plus D. Antonopoulou, Z. Arzoumanian, T. Enoto, C. M. Espinoza, and S. Guillot)*	O3 CW J0537-6910 LVK	summary	Astrophys. J. **922**, 71 (2021)	2104.14417	P2100069
Dec 23, 2020	**Diving below the spin-down limit: Constraints on gravitational waves from the energetic young pulsar PSR J0537-6910** *(by LSC, Virgo, KAGRA plus D. Antonopoulou, Z. Arzoumanian, T. Enoto, C. M. Espinoza, and S. Guillot)*	O3 CW J0537-6910 LVK	summary	Astrophys. J. Lett. **913**, L27 (2021)	2012.12926	P2000407
Dec 22, 2020	**All-sky search in early O3 LIGO data for continuous gravitational-wave signals from unknown neutron stars in binary systems** *(by LSC and Virgo)*	O3 CW LV	summary	Phys. Rev. D **103**, 064017 (2021)	2012.12128	P2000298
Jul 28, 2020	**Gravitational-wave constraints on the equatorial ellipticity of millisecond pulsars** *(by LSC, Virgo, and radio astronomers)*	O3 CW LV	summary	Astrophys. J. Lett. **902**, L21 (2020)	2007.14251	P2000029

(see `pnp.ligo.org/ppcomm/Papers.html` for details)

All-sky CW search in LIGO O3a and O3 data

(PRD **103**, 064017 2021, `arXiv:2201.00697`)

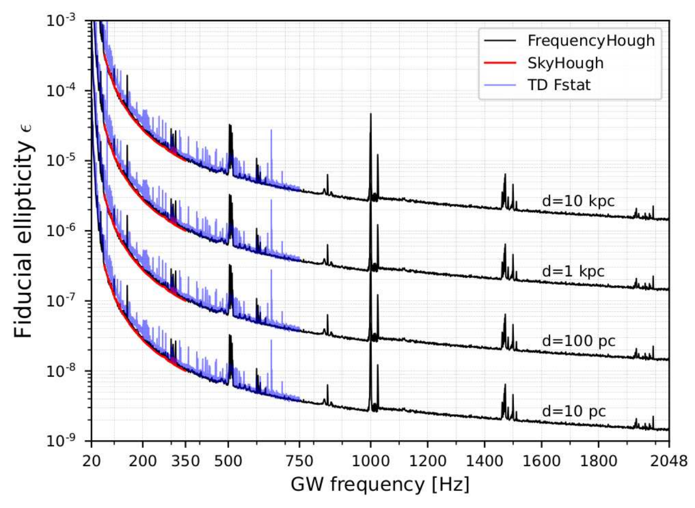


Sensitivity comparison of methods used:

- ⋆ PowerFlux (PRD **94**, 042002, 2016)
- ⋆ FrequencyHough (PRD **90**, 042002, 2014)
- ⋆ SkyHough (CQG **31**, 085014, 2014)
- ⋆ Time domain $\mathcal{F}$-statistic (CQG **31**, 165014, 2014)
- ⋆ SOAP (PRD **100**, 023006, 2019)

All-sky CW search in LIGO O3a and O3 data

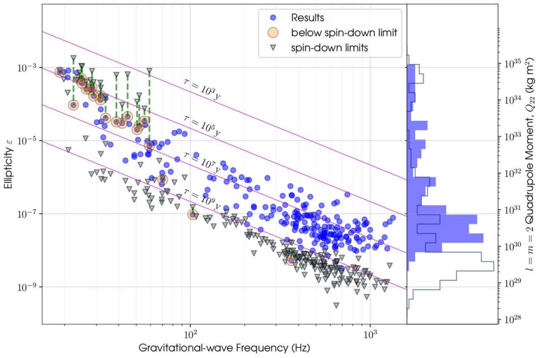
(PRD **103**, 064017 2021, `arXiv:2201.00697`)



O3 search for GWs from known pulsars (ApJ **935**, 1 2022)

236 known pulsars analyzed at $l = m = 2$ and $l = 2, m = 1$ mode.

- ⋆ 23 targets surpass the spin-down limit. Highlights:
  - ⋆ Crab: less than $0.009\% \dot{E}_{rot}$ in GW,
  - ⋆ Vela: less than $0.052\% \dot{E}_{rot}$.



⋆ Two millisecond pulsars below the spin-down limit, including J0711-6830 with $f_{rot} \simeq 182$ Hz $\rightarrow$ ellipticity $\epsilon < 5.26 \times 10^{-9}$,

⋆ Limits for dipole GW emission in the Brans-Dicke theory.

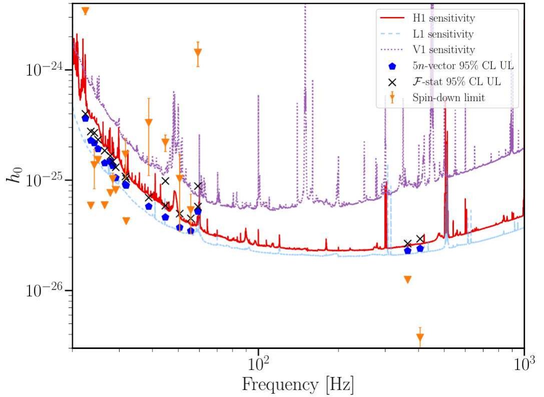
O3 narrowband known pulsars search (ApJ **932**, 133 2022)

Usually assumed that GW signal is phase-locked with the pulsar EM emission.

Here, a small possible mismatch between the assumed and true signal phase evolution:

$\Delta f_{gw} = f_{gw}\,(1+\delta)\,,$
$\delta \sim 10^{-3} - 10^{-4}$

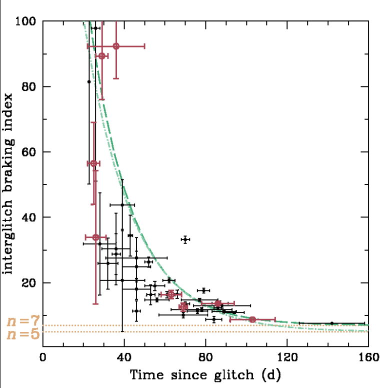
- ⋆ 18 pulsars, 7 surpassing the spin-down limit,
- ⋆ 6 glitching pulsars targeted for long-duration (hours-months) transient GWs



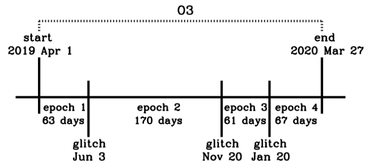
Frequently glitching X-ray pulsar J0537-6910

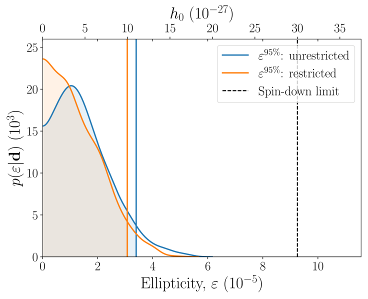
J0537 is an energetic X-ray pulsar rotating at $f = 62$ Hz & rapidly spinning-down. Is some of the spin-down due to GW emission?

Search for 1f and 2f GW emission (ApJL **913**, L27 2021):



Interglitch braking index n, $\dot{f} \propto -f^n$

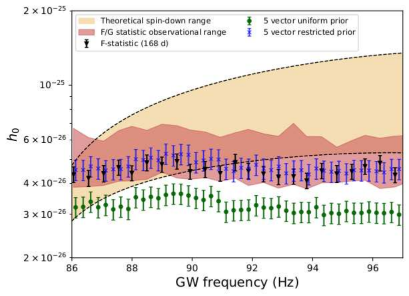


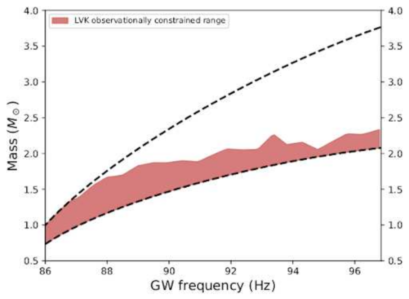


Frequently glitching X-ray pulsar J0537-6910

J0537 is an energetic X-ray pulsar rotating at $f = 62$ Hz & rapidly spinning-down. Is some of the spin-down due to GW emission?

Search for r-modes, $f_{GW} \approx 4/3f \in 86 - 97$ Hz GW emission (ApJ **922**, 71 2021):





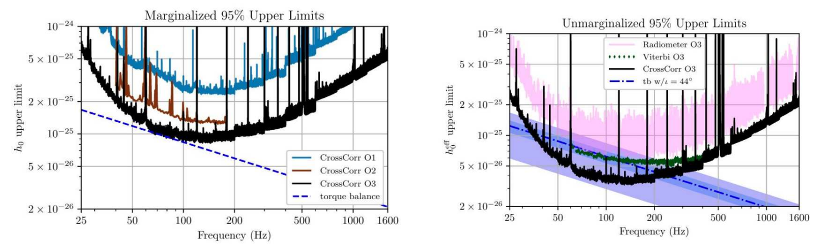
GW frequency of r-mode is a function of mass and radius of the NS $\rightarrow$ equation of state.

Sco X-1

Two searches for GWs from the low-mass X-ray binary Scorpius X-1 (NS in a binary system, with unknown orientation and frequency parameters):

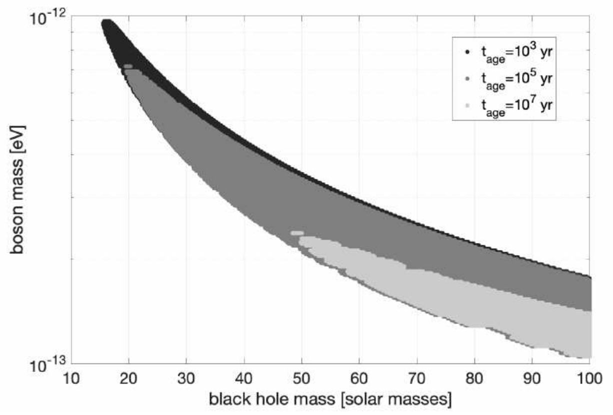
- ⋆ PRD **106**, 062002 (2022) - Hidden-Markov model search
- ⋆ `arXiv:2209.02863` - semi-coherent CrossCorrelation search with stronger astrophysical model assumptions

Polarization-averaged upper limit reaches conservative torque balance prediction. (“accretion from binary companion is completely balanced by GWs”)



O3 constraints on boson clouds

"Search for continuous gravitational wave emission from the Milky Way center in O3 LIGO-Virgo data", PRD **106**, 042003 2022



Constraints in the BH mass–boson mass plane for sources at the Galactic center. Clouds with different ages are considered (younger clouds emit stronger GWs). Shaded areas are excluded by observations.

Summary and O4 outlook

- Searches for signals with more complicated morphology, transient aspects, loosely-coherent approach:
  - accounting for NSs glitches (sudden changes in spin frequency),
  - hierarchical follow-up of transient CW-like candidates,
  - using machine-learning algorithms.
  - NS spin frequency wandering,
  - mismatch between the GW frequency (and spindown) and the parameters inferred from EM observations
  - Focus on interesting targets like Sco X-1, supernovæ remnants (CasA, Vela Jr, G347, Crab)
  - GWs from r-modes and at multiple frequencies at once,
  - post-merger emission,
  - Dark matter constituents (also dark photon dark matter interacting directly with the detectors (as in PRD **105**, 063030 2022)
  - non-tensorial GWs.

(Astro)physics questions

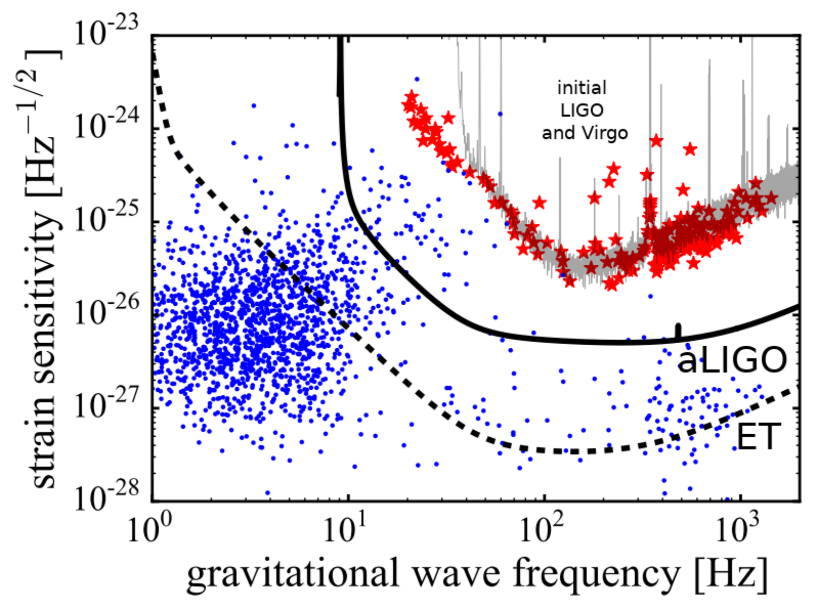
- $\star$ Magneto-elastic ‘mountains’: elastic properties of the crust, braking strain,
- $\star$ Thermally induced quadrupole: accretion processes, heating reactions in the crust,
- $\star$ Instabilities (r-modes): heating & cooling, rotational evolution,
- $\star$ Superfluidity.

- $\star$ Conditions at birth: SN $\leftrightarrow$ NS deformation connection,
- $\star$ Long-term evolution of NS asymmetry,

- $\star$ Dark matter: PBHs, boson clouds, dark photons…

Stay tuned to `cw.docs.ligo.org/public`

Extra slides



(PASA **32**, 34, 2015)

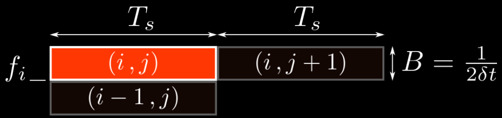
Example: computational cost for an all-sky search

In order to optimally cover a range of $(f, \dot{f}, \alpha, \delta)$ parameters,

$$\text{computing power} \propto \underbrace{T_0^2}_{\dot{f}} \times \underbrace{T_0^{[0-3]}}_{\alpha,\delta} \times \underbrace{T_0 \log(T_0)}_{f \text{ by FFT}} = T_0^{[3-6]} \log(T_0).$$

(see PRD **90**, 122010, 2014). Coherent search of $T_0 \simeq 1\ yr$ of data would require zettaFLOPS (10^{21} FLOPS) scale computers $\rightarrow$ currently impossible $\frown$

Solution: divide data into shorter length time frames ($T_s \simeq$ days)



- ⋆ Perform a search in narrow frequency bands: sampling time $\delta t = 1/2B$, number of data points $N_p = T_s/\delta t = 2T_sB$

$\rightarrow$ feasible on a petaFLOP computer.

Second stage: look for coincidences between different T_s segments.

Third stage: Analyze interesting outliers ("targeted search").