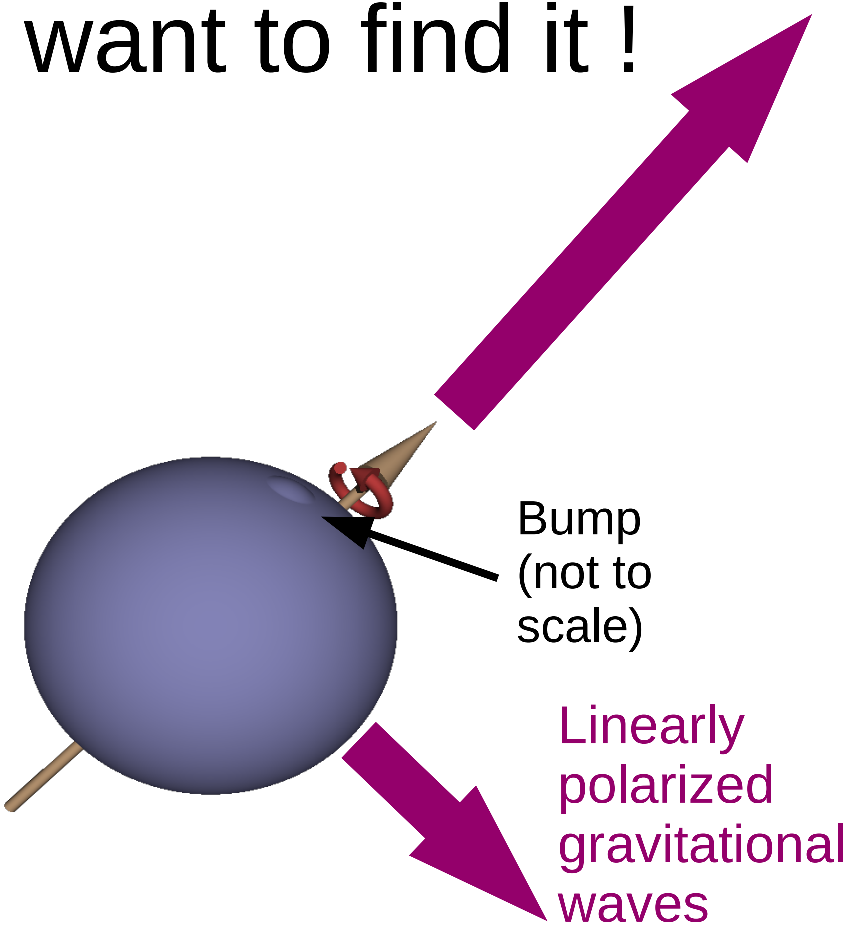
Results from all-sky searches for continuous waves

Vladimir Dergachev
Max Planck/AEI Hannover

GWPAW, 2021-Dec-15

Somewhere far away there is a neutron star...

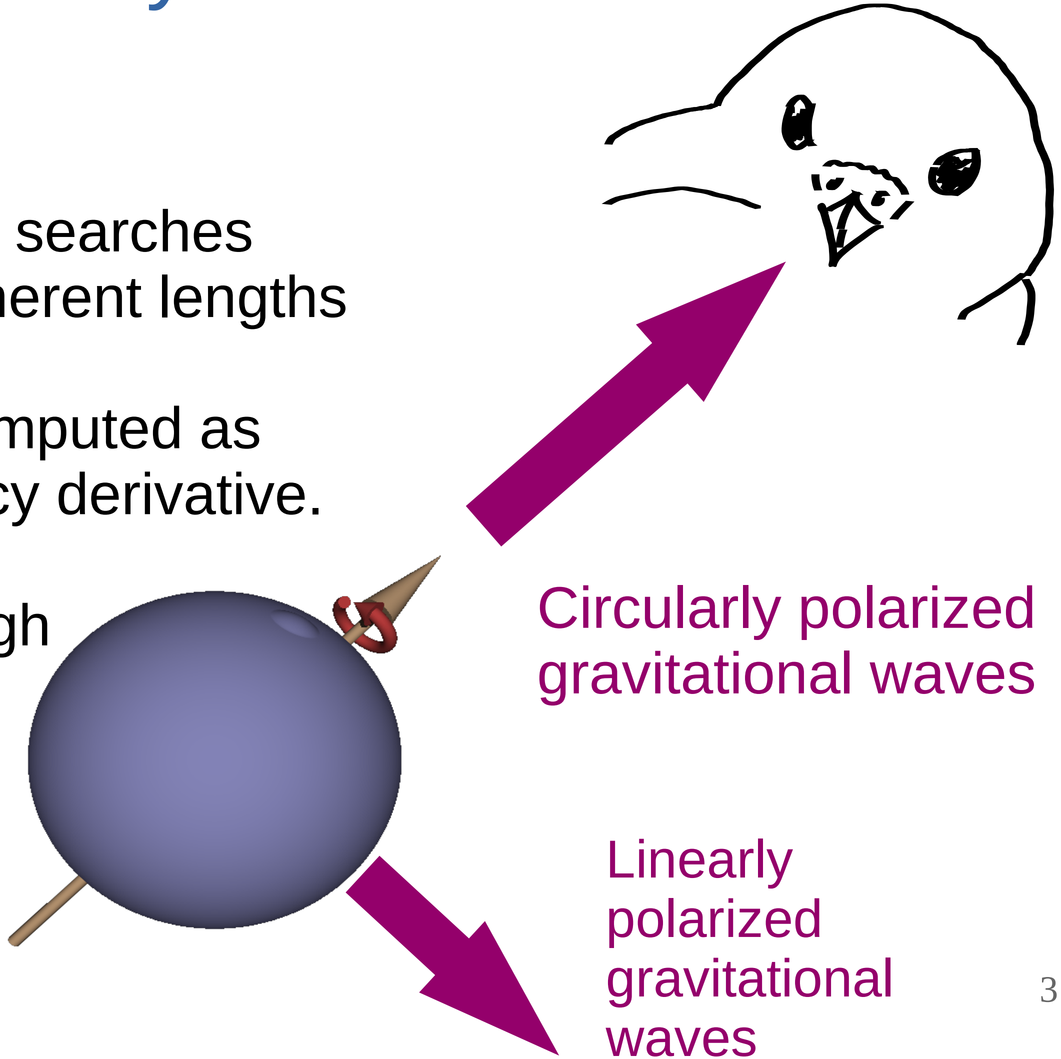
We want to find it !



- Hard, computationally intensive problem
- Small parameter – equatorial deformation of neutron star ε
- Sensitivity scales as $(\text{coherence length})^{-0.25}(\text{frequency})^{2}$ and is proportional to ε
- Computing time scales as $(\text{coherence length})^{4}(\text{frequency})^{3}$ or faster

Falcon – Fast Loosely Coherent Search

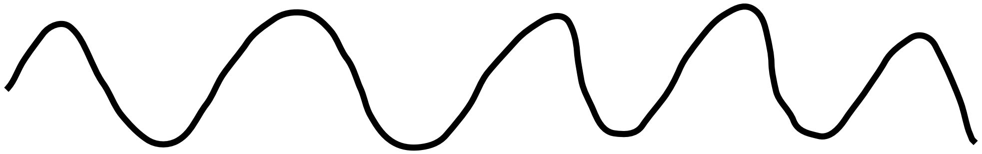
- Designed for wide band all-sky searches
- Optimized for analysis with coherent lengths from few hours to several days.
- Worst case upper limits are computed as maximum over sky and frequency derivative. They are valid for any subset
- Detection pipeline produces high quality outliers



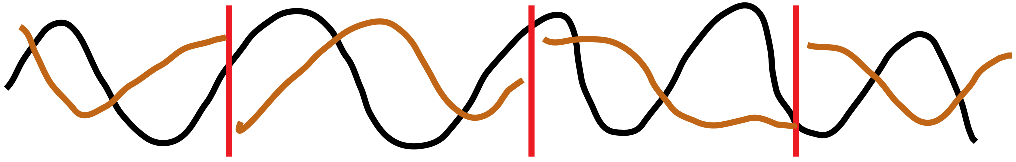
Phys. Rev. Lett. 123, 101101 (2019)
Phys. Rev. D 101, 022001 (2020)
Phys. Rev. Lett. 125, 171101 (2020)
Phys. Rev. D 103, 063019 (2021)

What is a loosely coherent search ?

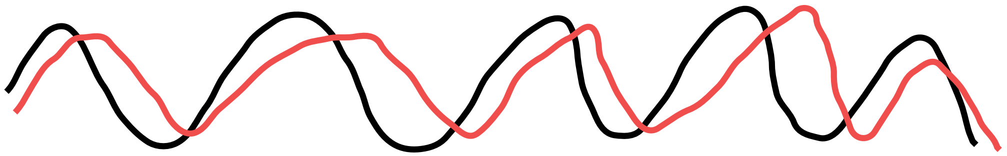
Conventional matched filter looks for one waveform at a time. Sensitive, but very large parameter space



Semi-coherent searches partition data and integrate results of analysis in each chunk. Sensitivity lost due to unphysical waveforms.



Loosely coherent search analyses sets of trajectories at a time. The set of allowed waveforms is controlled for best sensitivity and computational efficiency



Falcon search on O2 data, 500-2000 Hz

- 2x data compared to O1
- 3x initial coherence length
- Produce high-quality outliers with 6-day integration in the last stage of followup

Stage	Coherence length (hours)	Minimum SNR
0	12	6
1	24	7
2	48	8
3	144	16

TABLE I. Parameters for each stage of the search. The stage 3 outliers are subject to an additional consistency check.

Falcon search on O2 data, 20-500 Hz

- 2x data compared to O1
- 12x initial coherence length
- Produce high-quality outliers with 16-day integration in the last stage of followup

Stage	Coherence length (days)	Minimum SNR
1	2	6
2	3	9
3	4	11
4	6	12
5	9	16
6	16	16
7	16	16

TABLE II. Parameters for each stage of the search. Stage 7 refines outlier parameters, and then subjects them to an additional consistency check.

Target low-ellipticity pulsars

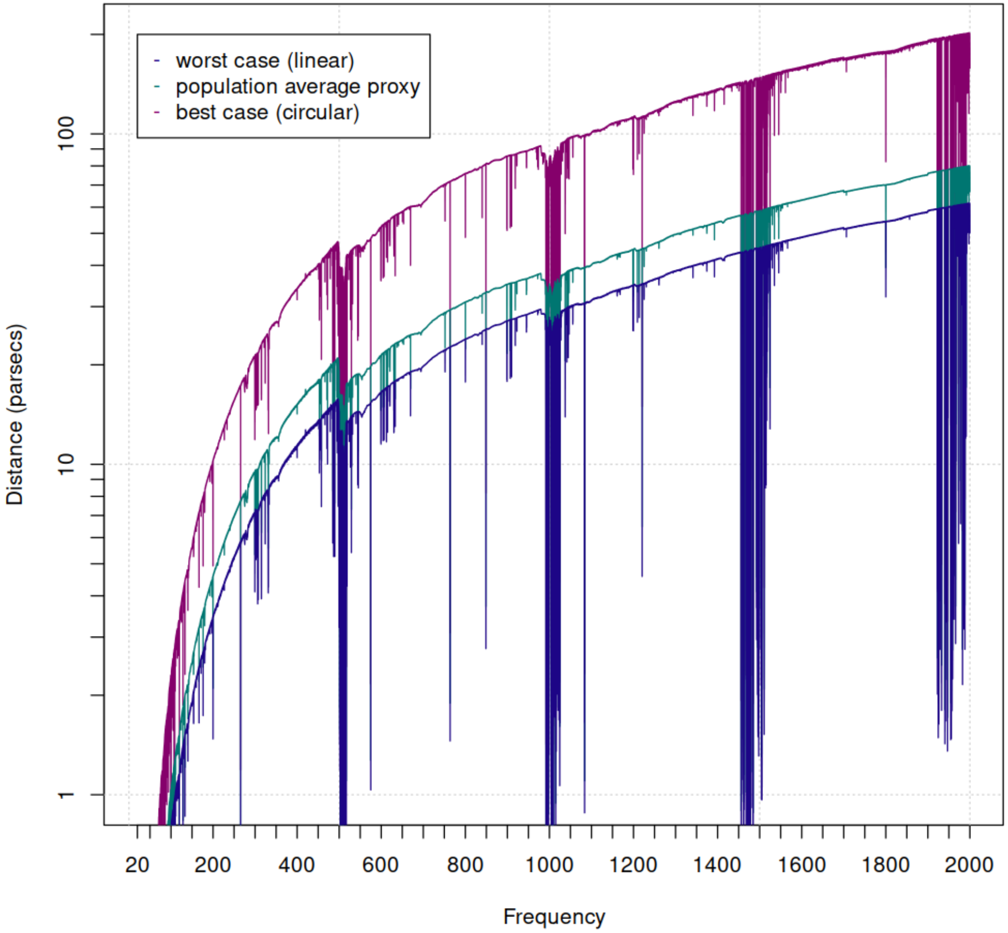
- It is known that neutron star crust can support ellipticities of $\approx 10^{-6}$
- But we do not know what physical process will produce them naturally
- No detections in previous searches
  - This might be due to lack of sensitivity, with signals just below noise floor
  - Or because natural sources do not perfectly follow assumed model

There are generic arguments that many known pulsars have ellipticities of 10^{-8} and that there is a minimum ellipticity of 10^{-9}
ApJ 863 2 G. Woan, M. D. Pitkin, B. Haskell, D. I. Jones, P. D. Lasky

Target low-ellipticity pulsars

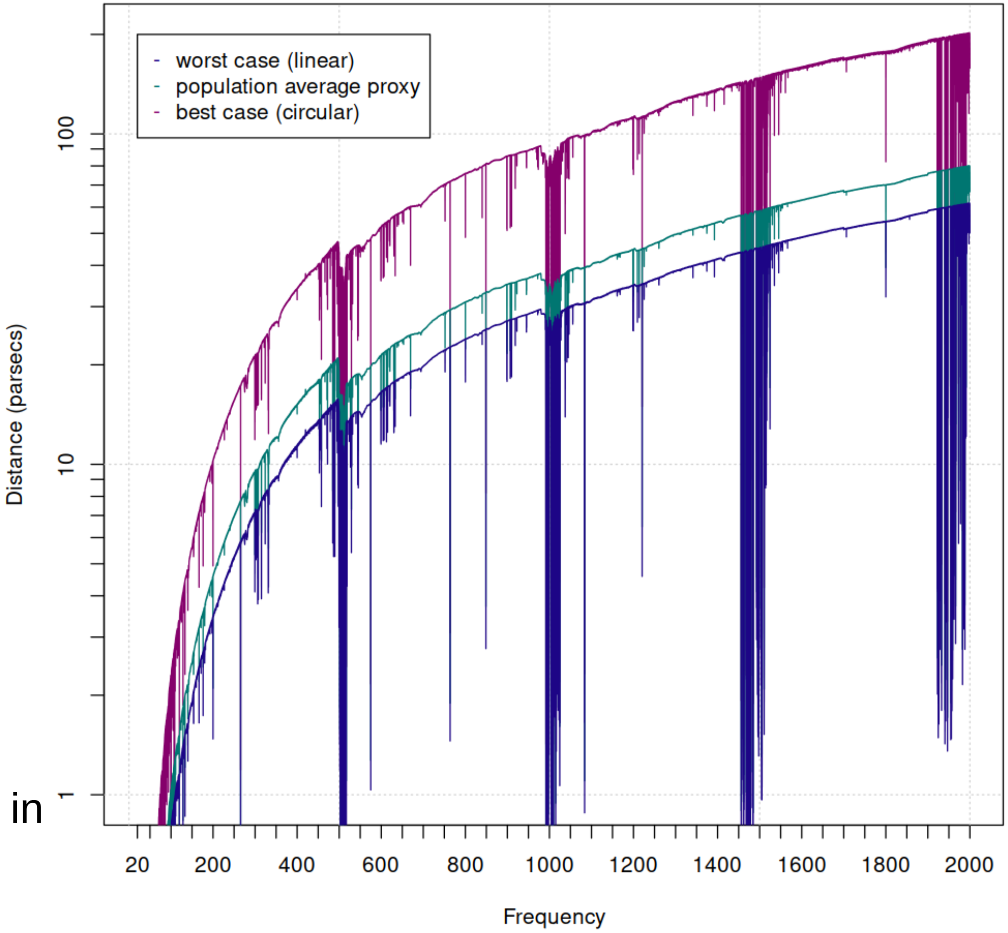
- Plot on the right shows distance to pulsars with ellipticity of 10^{-8}
- We are sensitive to sources up to 200 pc away
- Population average proxy has been tested with injections

Phys. Rev. Lett. 125, 171101 (2020)
Phys. Rev. D 103, 063019 (2021)



Why three curves ?

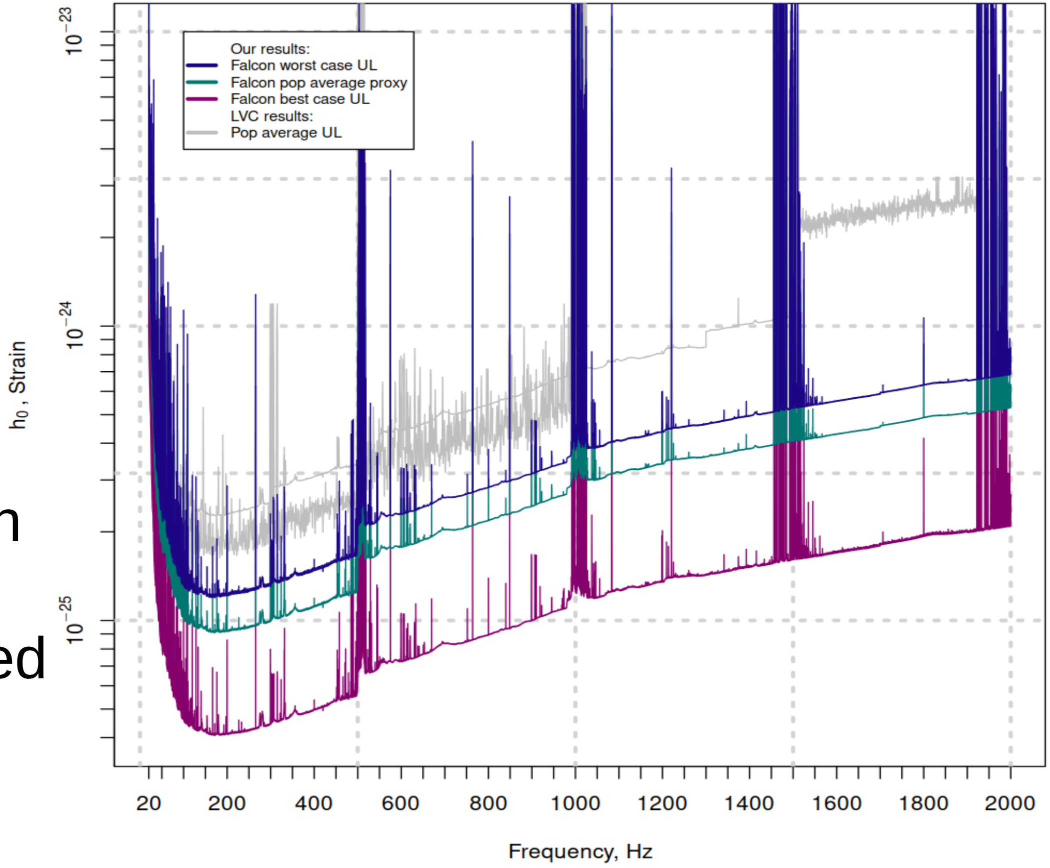
- The **bottom** curve is hard (or worst-case) upper limit – if there was a source closer than this we would have seen it. It is produced using *Universal Statistics* algorithm, which guarantees 95% CL in **any noise** and remains valid after **any subset** of initial parameter space.
- **Middle** curve is a population average *proxy* – it approximates a population average upper limit that is normally done with very expensive injections in other pipelines.
- **Top** curve shows hard upper limit when we assume the source is circularly polarized – the most favorable orientation.



A Novel Universal Statistic for Computing Upper Limits in Ill-behaved Background, V. Dergachev
Phys. Rev. D 87, 062001 (2013)

Upper limits also apply to boson condensate sources

- If ultralight bosons exist, they will form clouds around rotating black holes via superradiance instability and through annihilations and level transitions will emit continuous gravitational waves
- Results depend on model
- For example, assuming model with O(10^8) with maximum mass of 30Msol and spin uniformly distributed in [0,1], we exclude bosons with mass in range [1-3]*10^{-12}eV



Public O2 data has known issues with amplitude calibration

- Calibration of O2 data was performed in two steps – first an absolute calibration was established with a careful process
- The resulting data was then "cleaned" to remove detector artifacts, that were especially prominent at low frequencies.
- While original cleaning procedure was conservative and meant for transient analysis, the publicly released data was subjected to much more aggressive cleaning, that regressed on too many channels.
- No way to fix as public data is missing necessary channels.

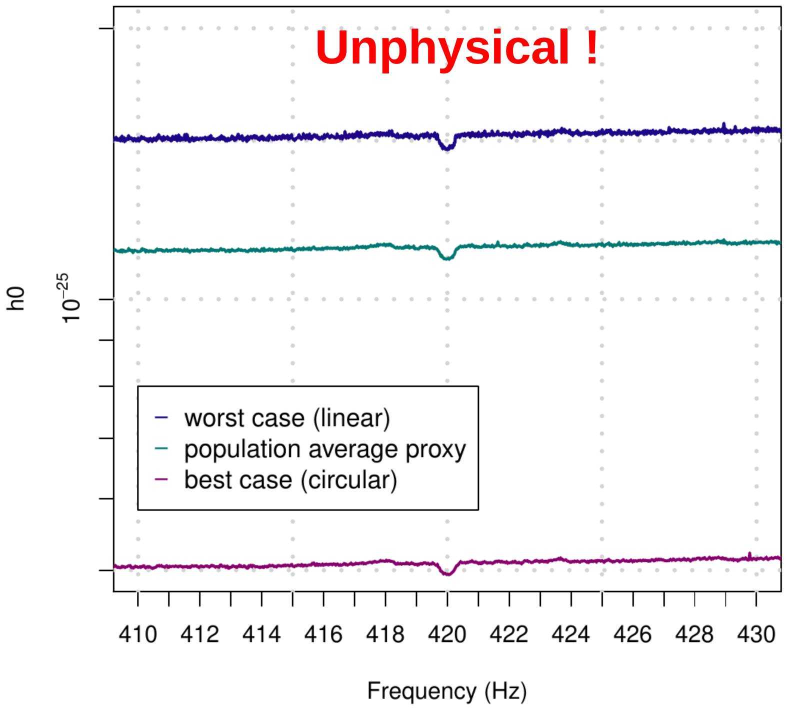
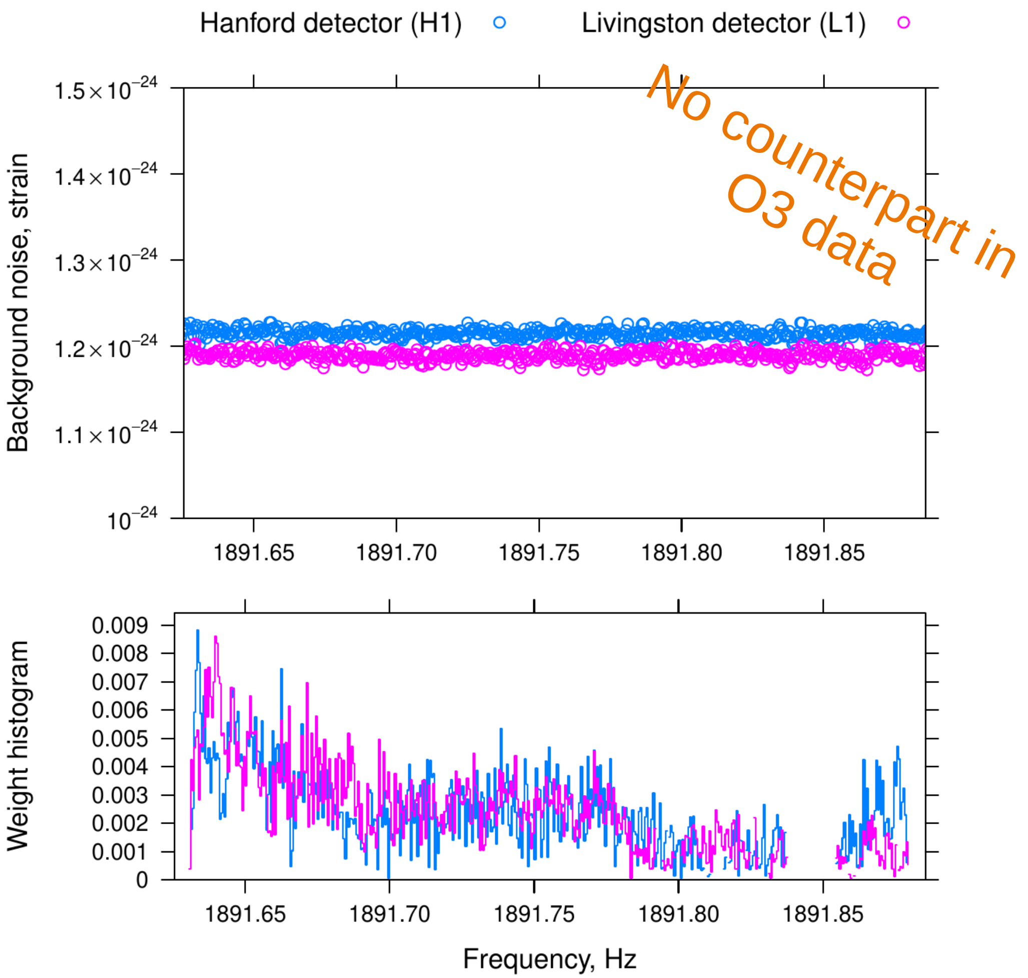


FIG. 3. One of anomalies in our upper limits due to errors in public data. At these high frequencies the shot noise is dominant. A 60 Hz power line harmonic can add to it, but a dip below shot noise is completely unphysical. It is there because

Are there outliers ? - Yes !!

- Many from hardware injections
- Many from low-frequency combs
- But also many clean outliers with no identifiable detector artifacts
- Plot shows amplitude spectral density around high frequency clean outlier at 1891.75 Hz
- Doppler shifts spread out the signal, forming a unique pattern whose length grows with frequency and coherence length



Phys. Rev. Lett. 125, 171101 (2020)
Phys. Rev. D 103, 063019 (2021)

Summary

- All-sky searches for gravitational waves from low ellipticity neutron stars find interesting outliers
- Placed upper limits on potential sources; applicable to potential signals from boson condensates.
- Numerical search results available as supplementary materials to our papers and at https://www.aei.mpg.de/continuouswaves/
- No investigations in auxiliary channels because they are missing in public data.
- O2 data has known problems affecting calibration of publicly released data; public data is missing channels to fix this.
- Looking forward to new results from O3 data.

END OF TALK

Population average proxy test

- Yellow bars show percent of found injections
- Each injection had strain equal to population average proxy, with other parameters chosen randomly
- An injection was considered recovered if the pipeline produced an outlier with location, spindown and frequency close to true values
- 90% recovery everywhere, 95% outside violin mode region – when there is a signal, we find it !

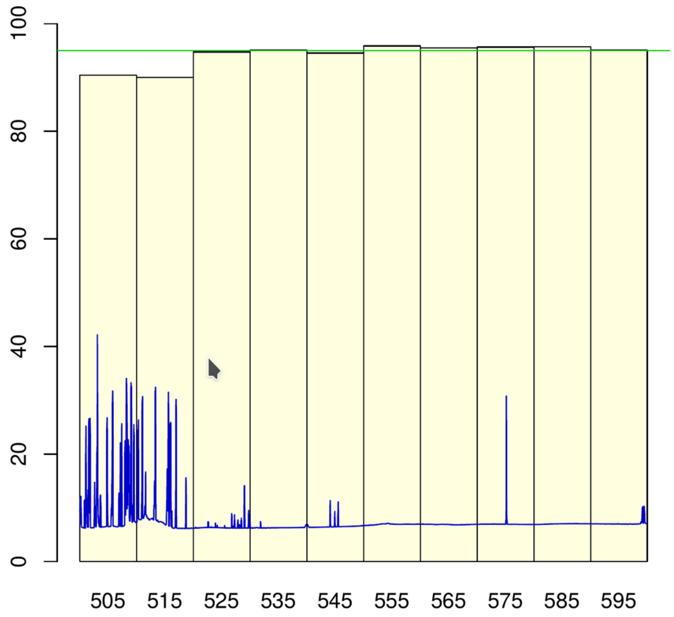
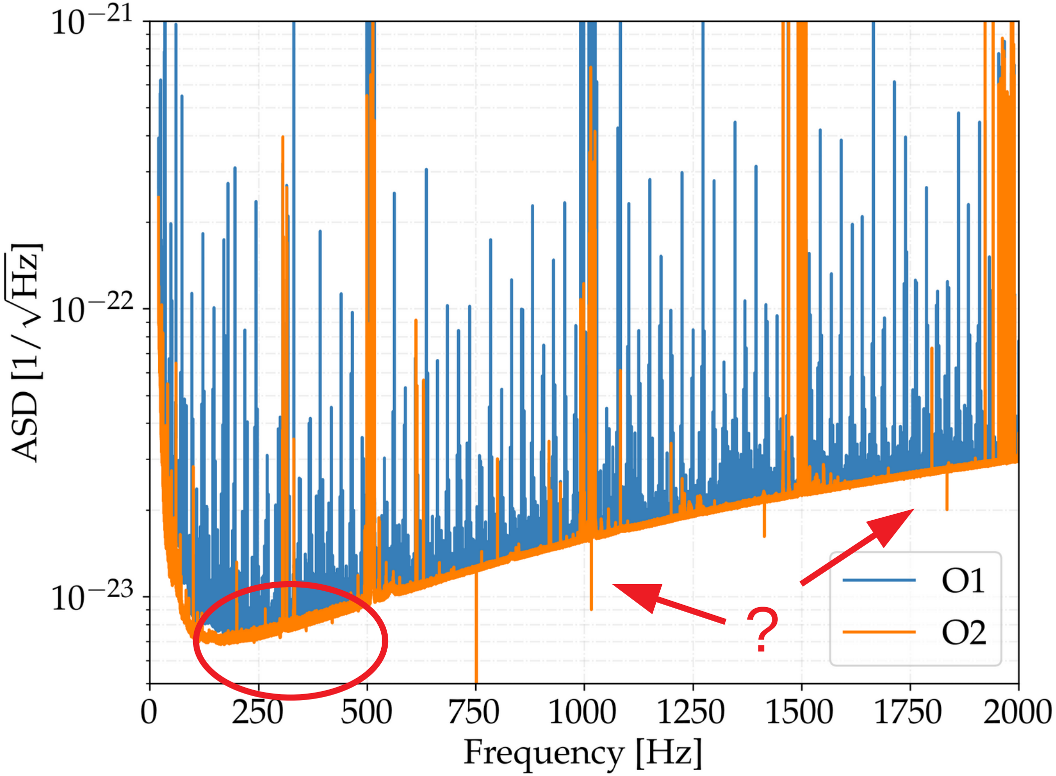


FIG. 3. The yellow bars show the detection efficiency of signals with amplitude at the population average (proxy) upper limit level, measured in 10 Hz bands. In each band we consider $\gtrsim 530$ fake signals. The top (green) line marks the 95% level. The blue curve on the bottom shows population average upper limits. We see that even in the heavily contaminated bands the detection efficiency is never lower than 90%.

Unphysical features in O2 data

O2 data has been released in February 2019
The strain data was subjected to cleaning procedure that removed a lot of instrumental noise, especially at low frequencies.
However, the coefficients were estimated from the same data on short time scales.
This procedure removes a portion of GW signal and shot noise, sometimes spectacularly.



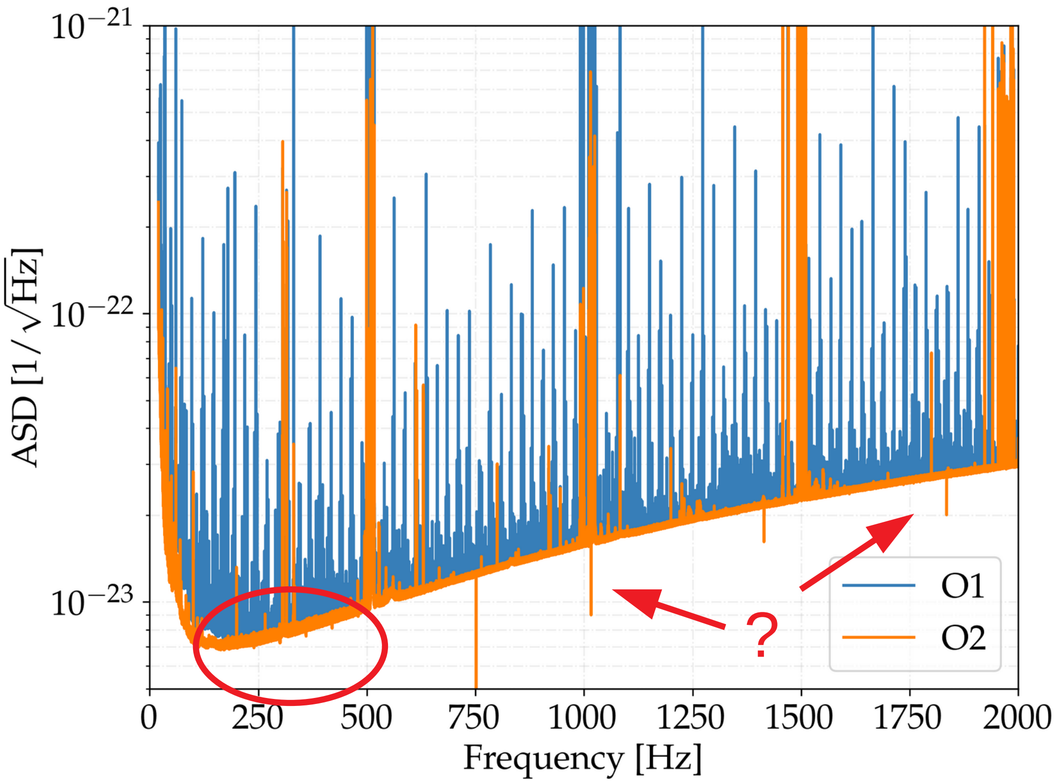
All-sky search for continuous gravitational waves from isolated neutron stars using Advanced LIGO O2 data, LSC, PRD 100, 024004

Unphysical features in O2 data

O2 data has been released in February 2019

The cleaning procedure removes a portion of GW signal and shot noise, sometimes spectacularly.

Any analysis on O2 data needs to address this. But public data is missing necessary channels !



All-sky search for continuous gravitational waves from isolated neutron stars using Advanced LIGO O2 data, LSC, PRD 100, 024004

Comparison with LVC results

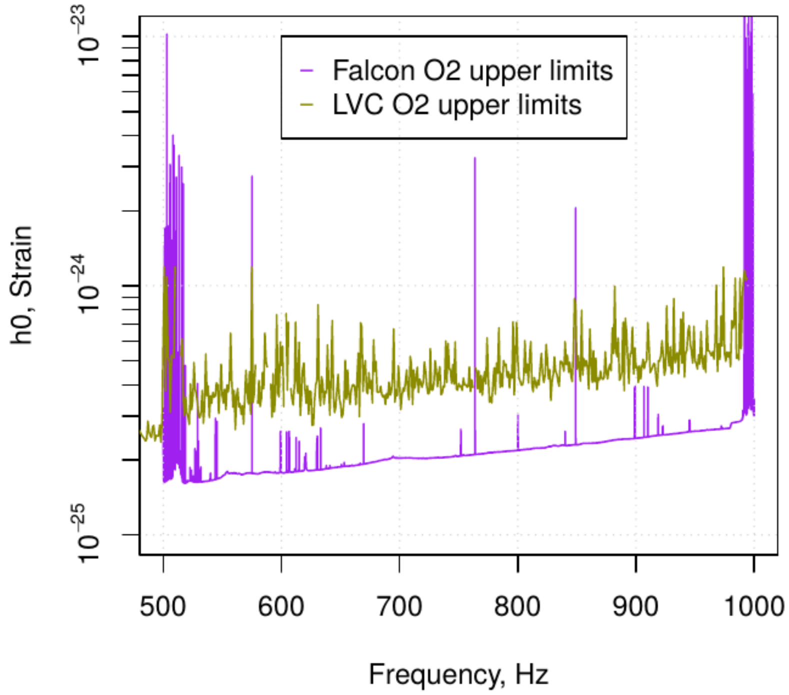


FIG. 4. Comparison of the Falcon O2 population-average upper limits (lower curve with tall spikes) and the LIGO-Virgo collaboration results [12] (upper curve). The dimensionless strain (vertical axis) is plotted against signal frequency.