ALBERT EINSTEIN INSTITUTE HANNOVER
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CONTINUOUS GRAVITATIONAL WAVES

Continuous gravitational wave atlas.

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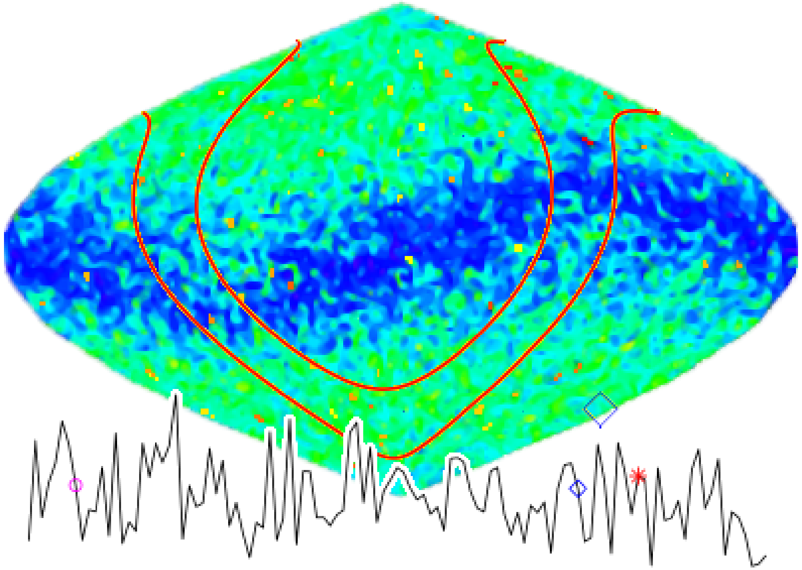
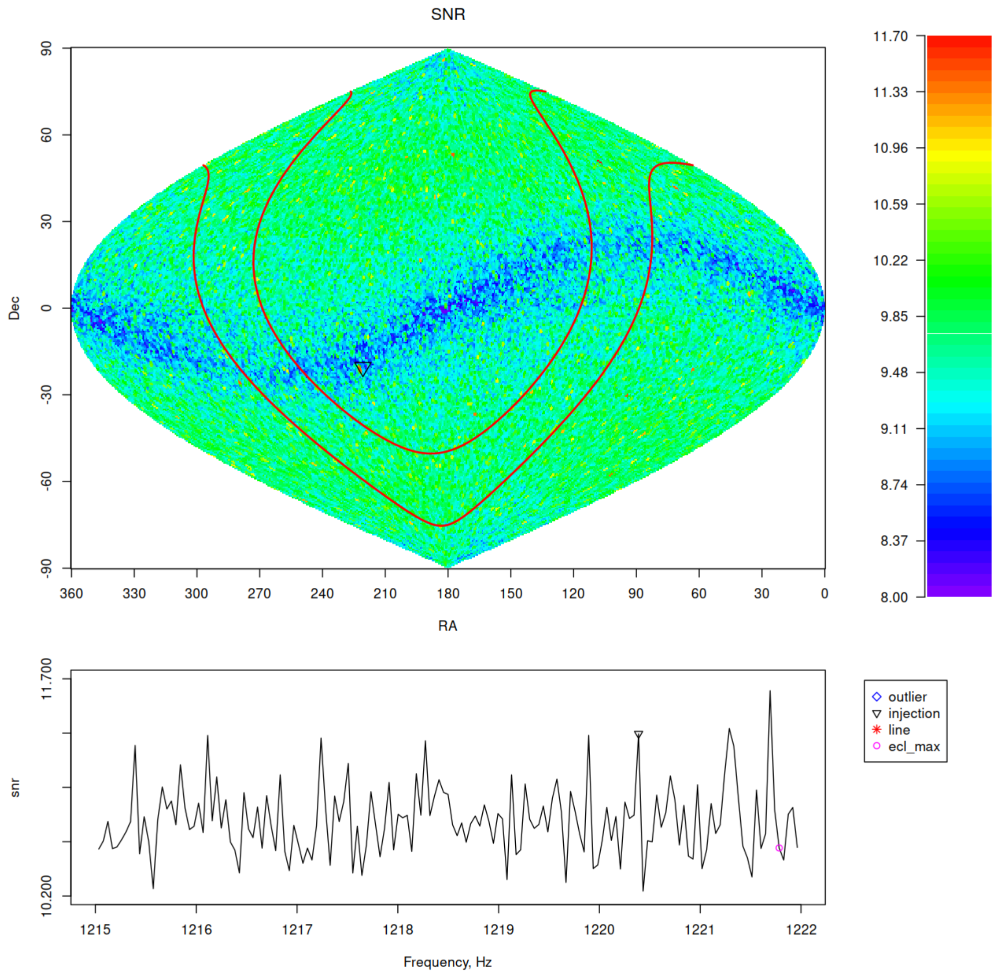


APS, 2024-Apr-4

Continuous gravitational wave atlas

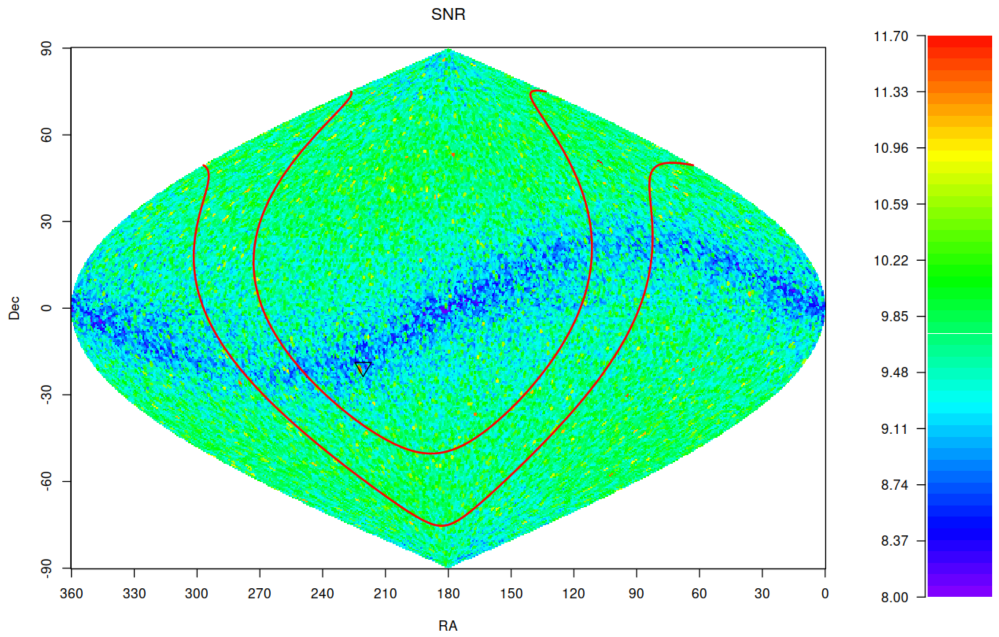
- An atlas is a collection of skymaps, such as shown on the right
- One skymap for each 45mHz frequency band and each metric

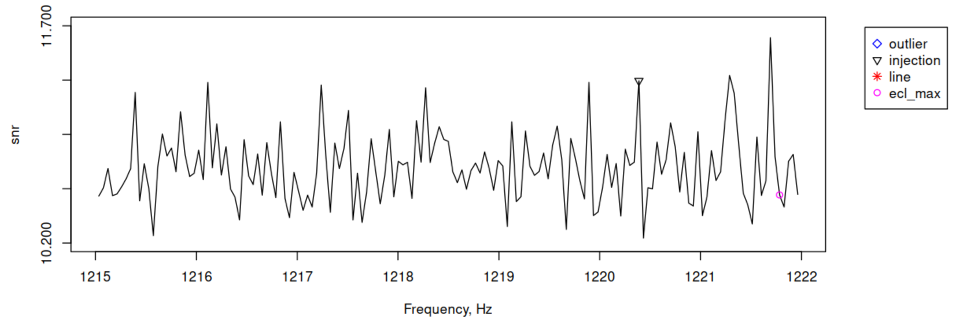


Continuous gravitational wave atlas

- **New early release (2023 Nov) while we are still analyzing outliers**
- 20-1500 Hz
- |fdot| < 5e-10 Hz/s

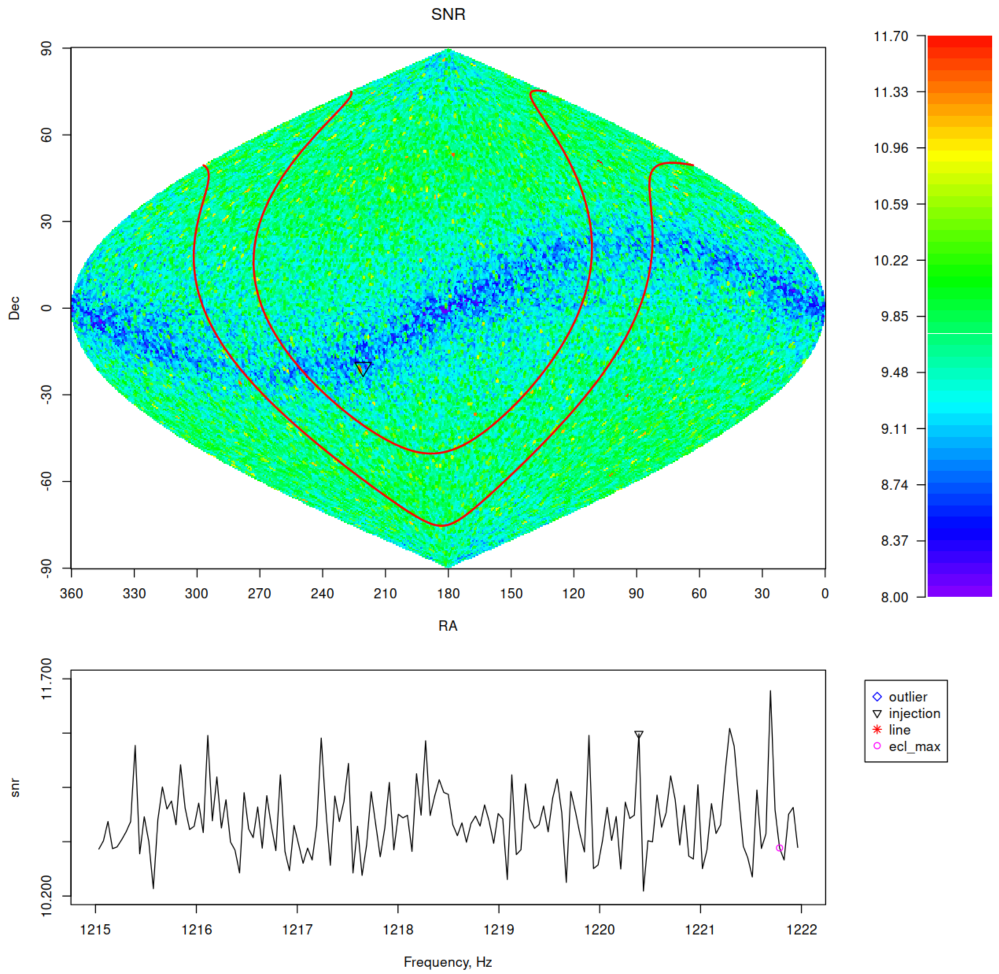
Phys. Rev. D 109, 022007 (2024)





Metrics

Each sky location and frequency band has the following metrics
- maximum SNR
- frequency and polarization where SNR was achieved
- upper limit on arbitrary polarized signals (“worst case”)
- upper limits for circularly polarized signals
- data to compute polarization specific upper limits



Polarization specific upper limits

- The functional form shown on the right produces upper limits values for each i and ψ
- The coefficients c_1-c_{14} are chosen large enough that upper limits are always valid
- It is possible to choose them so that the overestimate is small (~5%) for noise dominated data

$$
\begin{aligned}
\widehat{\mathrm{UL}}^2 = &\left(c_1 + f_{pp}c_2 + f_{pc}c_3 + f_{cc}c_4 + f_{impc}c_5 + f_{pp}^2 c_6 + \right.\\
&+ f_{cc}^2 c_7 + f_{pc}^2 c_8 + f_{impc}f_{pp}c_9 + f_{impc}f_{pc}c_{10} + \\
&+ f_{impc}f_{cc}c_{11} + f_{pp}f_{pc}c_{12} + f_{cc}f_{pc}c_{13} + \\
&\left. + f_{pp}f_{cc}c_{14}\right) / \left(f_{pp} + f_{cc}\right)
\end{aligned}
$$

$$
\begin{aligned}
a_+ &= \frac{\left(1+\cos^2\iota\right)^2}{4} \\
a_\times &= \cos^2\iota \\
f_{pp} &= 2|\tilde{w}_1|^2 = \frac{1}{4}\left(a_+ + a_\times + (a_+ - a_\times)\cos 4\psi\right) \\
f_{pc} &= 4\mathrm{Re}\,\tilde{w}_1\tilde{w}_2^* = \frac{1}{2}\left((a_+ - a_\times)\sin 4\psi\right) \\
f_{cc} &= 2|\tilde{w}_2|^2 = \frac{1}{4}\left(a_+ + a_\times - (a_+ - a_\times)\cos 4\psi\right) \\
f_{impc} &= 2\mathrm{Im}\,\tilde{w}_1\tilde{w}_2^* = \frac{1}{4}\left(1 + \cos^2\iota\right)\cos\iota
\end{aligned}
$$

arXiv:2311.09911

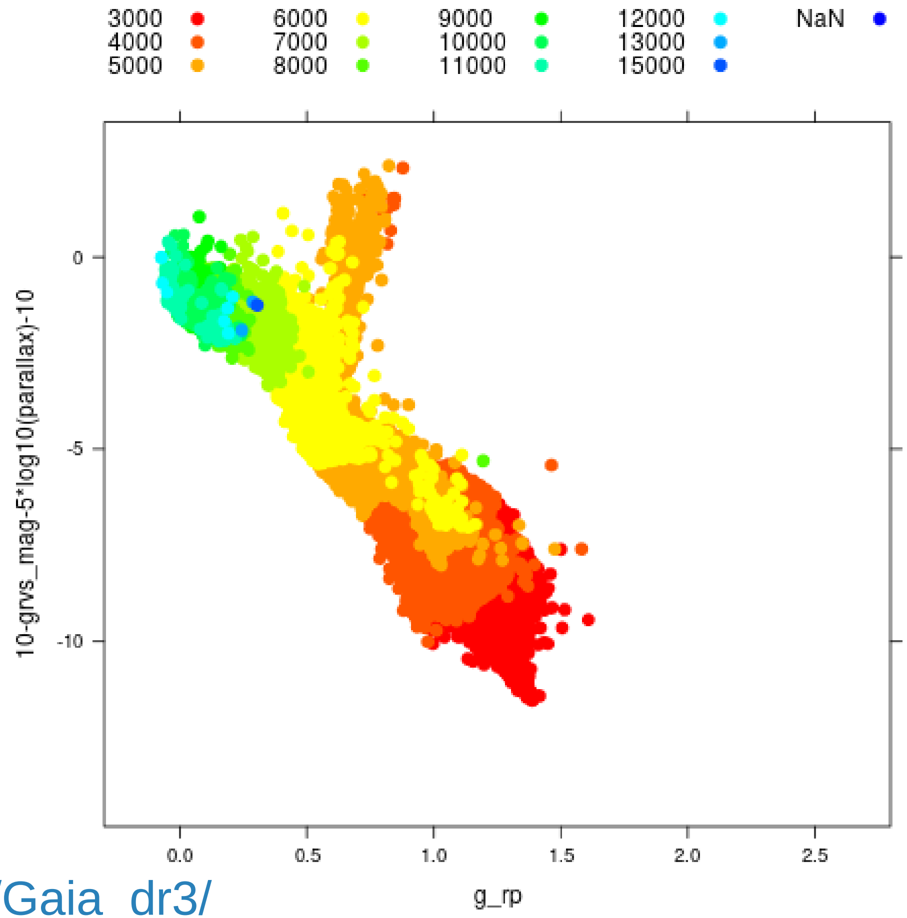
Example: hardware injections

TABLE I. This table shows parameters of the hardware-injected continuous wave signals and atlas data for their locations and frequencies. The upper limits for the injections are polarization specific and were computed using ι and ψ of each injection. We show all the hardware injections within 20–1500 Hz range, including those outside of our search space, as indicated by the "In" column. We use the reference time (GPS epoch) $t_0 = 1246070000$ (2019 Jul 2 02:33:02 UTC).

Label	f Hz	$\dot{f}$ Hz/s	Binary	SNR	UL/h_0 %	Δf mHz	In
ip0	265.57505	-4.15×10^{-12}	No	28.5	122.5	−0.1	Yes
ip1	848.93498	-3×10^{-10}	No	393.0	119.9	−0.1	Yes
ip2	575.16351	-1.37×10^{-13}	No	39.3	138.5	0.0	Yes
ip3	108.85716	-1.46×10^{-17}	No	23.7	141.6	0.1	Yes
ip4	1390.60583	-2.54×10^{-8}	No	7.6	21.3	−7.7	No
ip5	52.80832	-4.03×10^{-18}	No	155.9	130.2	0.0	Yes
ip6	145.39178	-6.73×10^{-9}	No	8.4	25.0	−11.2	No
ip7	1220.42586	-1.12×10^{-9}	No	7.3	68.1	3.6	No
ip8	190.03185	-8.65×10^{-9}	No	8.9	83.8	−2.9	No
ip9	763.84732	-1.45×10^{-17}	No	39.1	135.1	0.1	Yes
ip10	26.33210	-8.5×10^{-11}	No	63.9	124.9	0.0	Yes
ip11	31.42470	-5.07×10^{-13}	No	93.2	400.9	−12.1	Yes
ip12	37.75581	-6.25×10^{-9}	No	14.0	156.5	4.0	No
ip16	234.56700	0	Yes	8.3	29.6	42.7	No
ip17	890.12300	0	Yes	8.1	103.6	23.6	No

Atlas data uses MVL file format

- Designed for efficient access by memory mapping
- Useful for interactive and scripted analysis of large data
- In addition to Falcon atlas, there is also a Gaia DR3 dataset in MVL format
- Examples of common searches using Falcon atlas and Gaia data



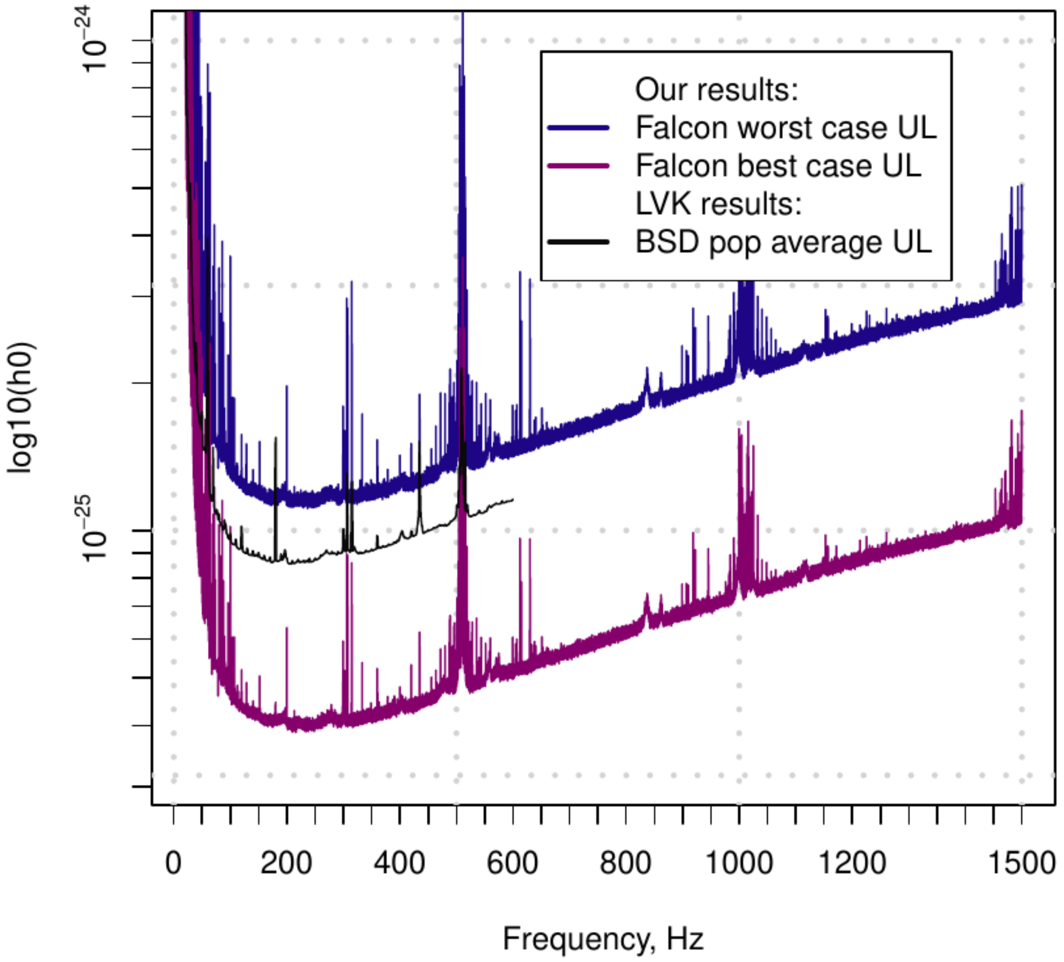
https://www.atlas.aei.uni-hannover.de/work/volodya/Gaia_dr3/

MySQL/MariaDB/sqlite vs MVL files

Mysql/MariaDB/sqlite/Postgresql	MVL
Collection of tables, each table consists of fixed length rows	Can store tables, but also lists, trees and other complex data structures
Lookup based indices, usually log(N) scaling	Hash based indices – O(1) scaling with length
	Spatial indices - find objects near query
Needs setup, dedicated server	Just files – use as is
Server needs to be large enough to support cluster usage	Files are memory mapped and just need a fast enough file system.
	Loaded data is shared between processes
Supports bulk data storage as well as frequently changed data, such as created by transactions	Focused on large data storage, optimized for solid state drives

Example: directed searches

- G189.1+3.0 – data on the right is an extract from Falcon atlas
- Latest LVK results shown for comparison



Summary

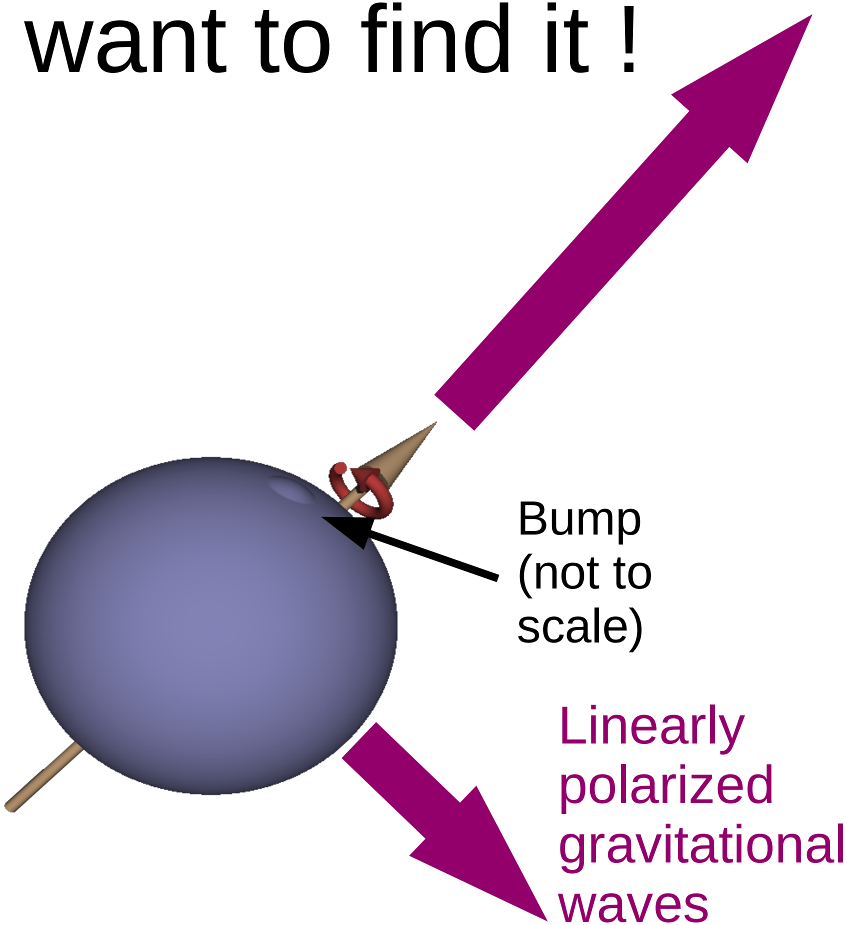
- All-sky searches for gravitational waves probe low ellipticity neutron stars.
- Early release of all-sky, spectrally resolved data for continuous gravitational wave sources – a starting point for new searches
- New MVL file format for large scale data analysis
- Ready to use examples of searches using Falcon atlas and Gaia DR3 data
- Get the data !

  https://www.atlas.aei.uni-hannover.de/work/volodya/O3a_2_atlas/

END OF TALK

Somewhere far away there is a neutron star...

We want to find it !

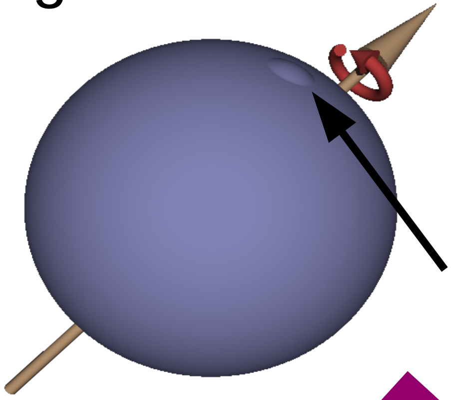


- Hard, computationally intensive problem
- Small parameter – equatorial deformation of neutron star ε
- Sensitivity scales as (coherence length)$^{-0.25}$(frequency)^{2} and is proportional to ε
- Computing time scales as (coherence length)^{4}(frequency)^{3} or faster

Continuous gravitational waves

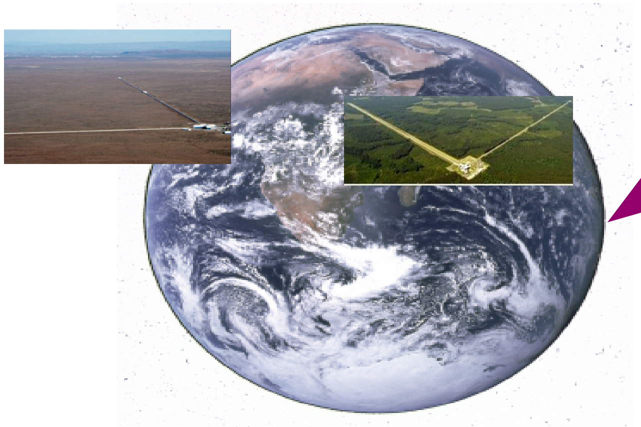
- Need a rotating star with non-zero equatorial second moment
- Gravitational radiation is expected to be emitted at twice the rotation frequency
- Continuous wave signals have very narrow bandwidth
- The only signal that can be measured again, months and years after detection

Rotating neutron star



Bump (not to scale)

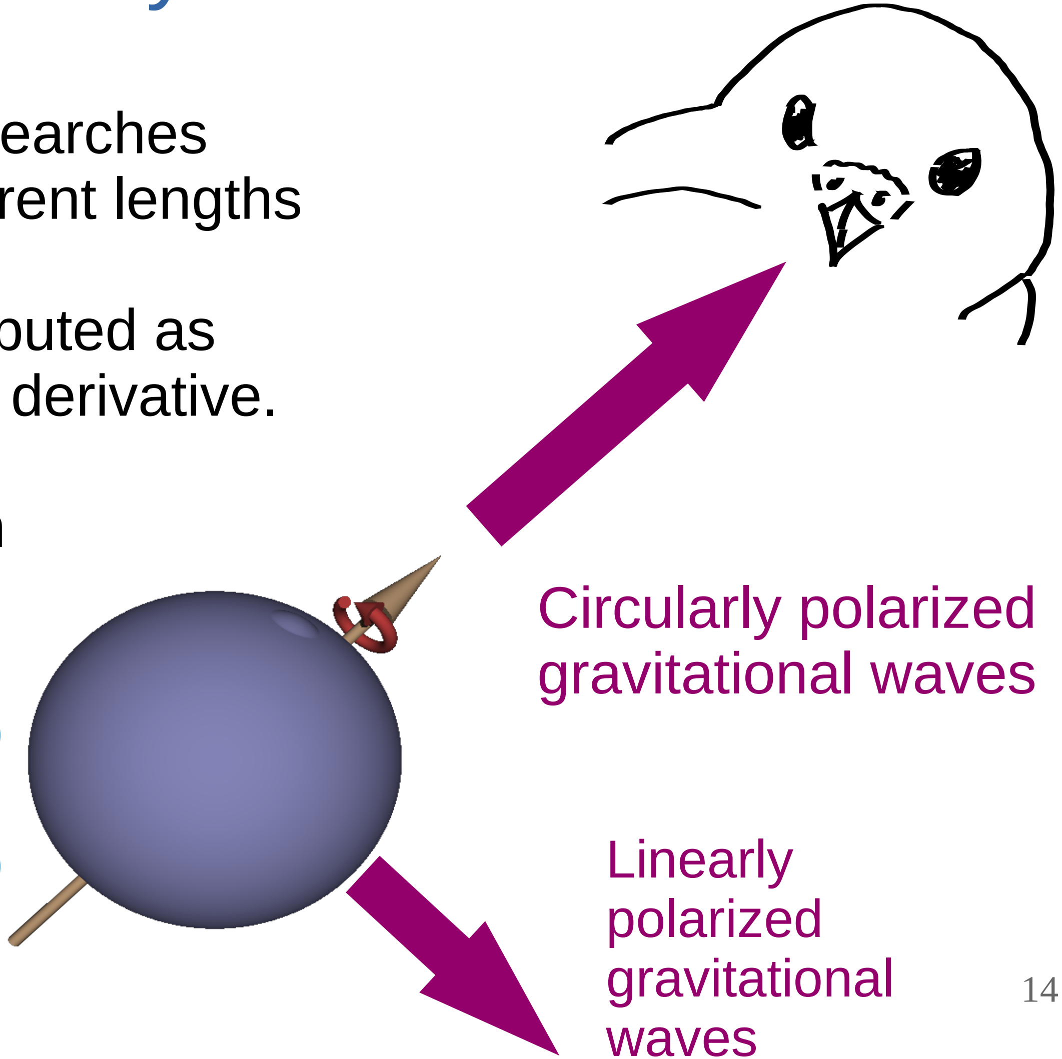
Linearly polarized gravitational waves



Circularly polarized gravitational waves

Falcon – Fast Loosely Coherent Search

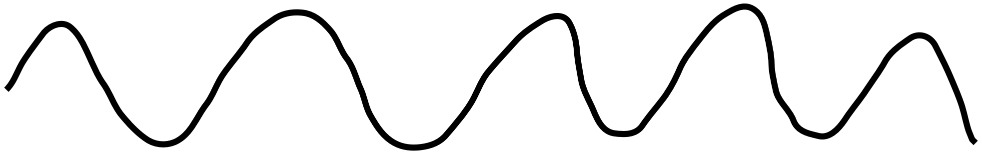
- Designed for wide band all-sky searches
- Optimized for analysis with coherent lengths from few hours to several days.
- Worst case upper limits are computed as maximum over sky and frequency derivative. They are valid for any subset
- Detection pipeline produces high quality outliers



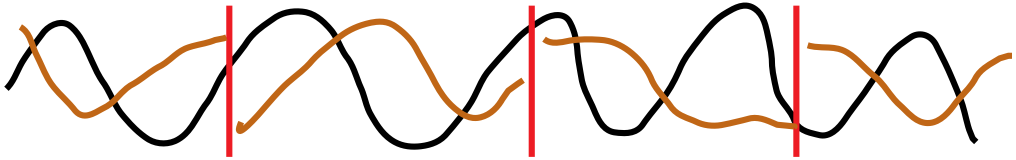
Phys. Rev. Lett. 123, 101101 (2019)
Phys. Rev. D 101, 022001 (2020)
Phys. Rev. Lett. 125, 171101 (2020)
Phys. Rev. D 103, 063019 (2021)
2202.10598, accepted to PRX

What is a loosely coherent search ?

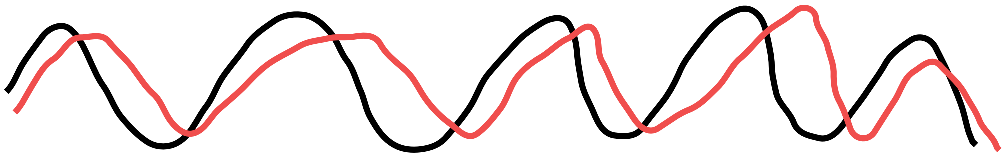
Conventional matched filter looks for one waveform at a time. Sensitive, but very large parameter space



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



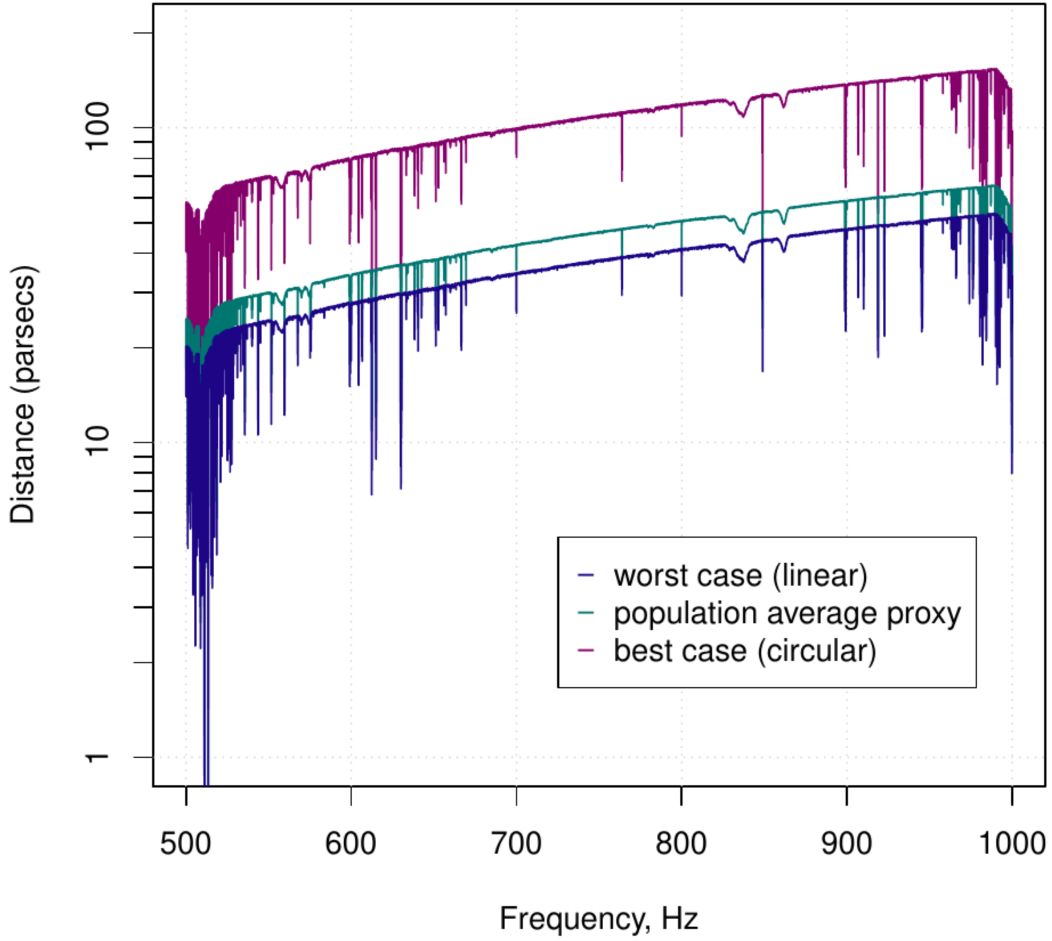
Target low-ellipticity pulsars

- 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 150 pc away
- Frequency derivatives up to $\pm 5 \cdot 10^{-11}$
- +50% sensitivity compared to O2



2202.10598, accepted to PRX

O3 Falcon search: first release of skymap data

Previous papers only provided coarse frequency upper limits and a few outliers

New data makes science possible for smaller groups without large compute.

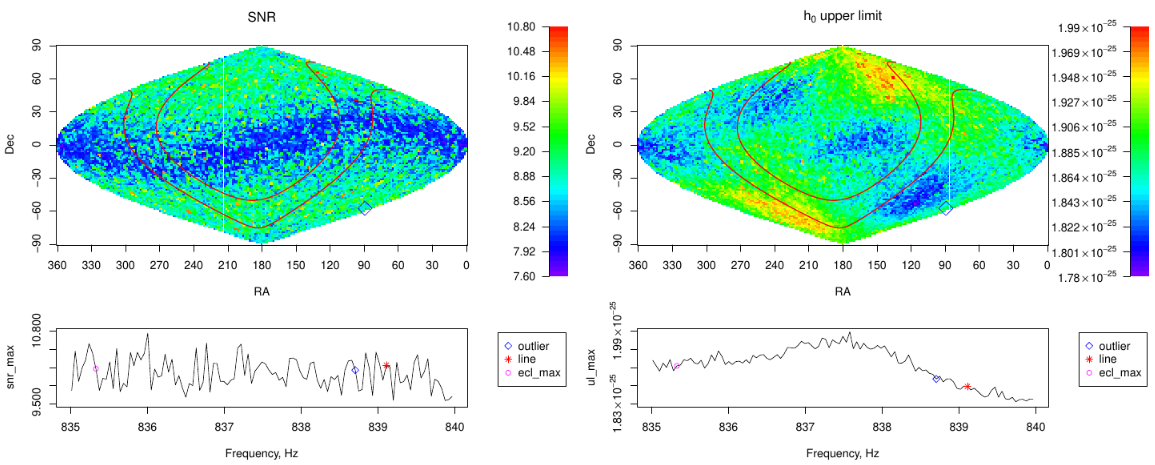


FIG. 3. Summary of atlas data from the bins between 835-840 Hz. The top panels show the highest SNR (left) and upper limit values (right) across the frequency band, for each pixel of the sky map, using equatorial coordinates. The red lines denote the galactic plane. The blue diamond shows the location of the outlier that is discarded based on the analysis of O3a+b data. The blue band of smaller SNRs near the ecliptic equator is due to large correlations between waveforms of sources in that region. The blue regions in the upper limit plot are due to the lower-SNR values in the ecliptic plane, and also occur near the ecliptic poles that are favored by the antenna pattern of the detectors. The bottom panels show the same data as a function of frequency and with the maximum taken over the sky. We mark the frequency of the band where the outlier mentioned above was found, the location of the only known line from the O3 line list in that band, and the band where we the maximum SNR is achieved in the ecliptic pole region - a region strongly affected by instrumental lines. The data and code used to produce this plot is available [21].

https://www.atlas.aei.uni-hannover.de/work/volodya/O3a_atlas/

O3 Falcon search: most sensitive to date

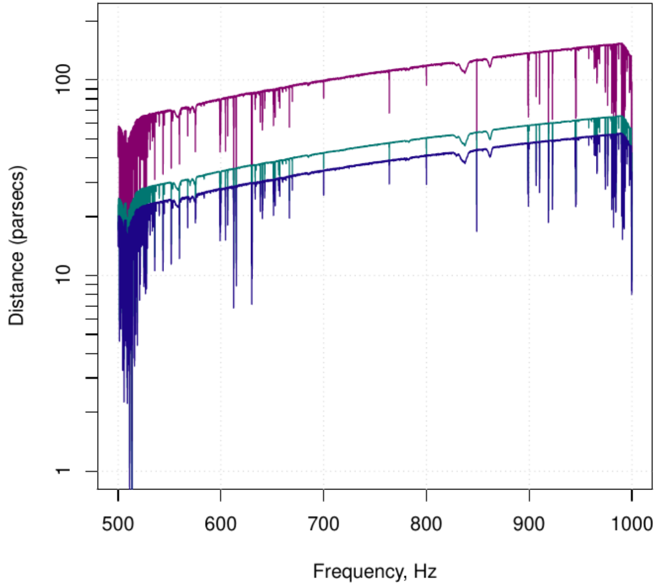


FIG. 2. Reach of the search for stars with ellipticity of 10^{-8}. The search is also sensitive to sources with ellipticities of 10^{-7} with a distance from Earth that is 10 times higher. The X axis is the gravitational wave frequency, which is twice the pulsar rotation frequency for emission due to an equatorial ellipticity. R-modes and other emission mechanisms give rise to emission at different frequencies. The top curve (purple) shows the reach for a population of circularly polarized sources; The middle curve (cyan) holds for a population of sources with random orientations; The bottom curve (blue) holds for linearly polarized sources.

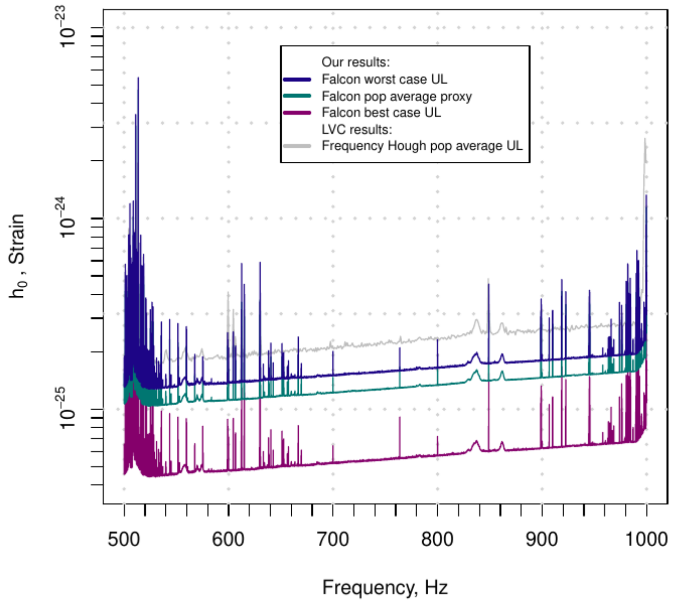


FIG. 1. Gravitational wave intrinsic amplitude h_0 upper limits at 95% confidence as a function of signal frequency. The upper limits are a measure of the sensitivity of the search. We introduce a "population average" proxy upper limit in order to compare with the latest LIGO/Virgo all-sky results [11]. In this frequency range [11] are a factor $\gtrsim 1.65$ less constraining than ours, albeit able to detect sources with much higher deformations.

Example: directed searches

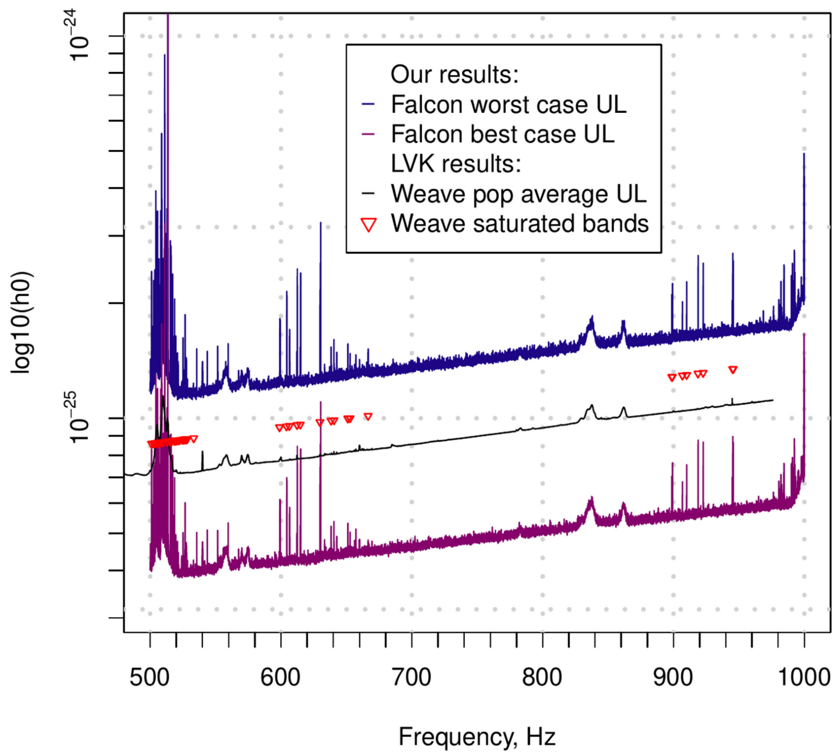


FIG. 6. This plot shows upper limits similar to those shown in Figure 2, but for the location of Vela Jr. Latest LIGO/Virgo/KAGRA results [50] are shown for comparison. The triangles mark saturated bands for which the Weave results are invalid.

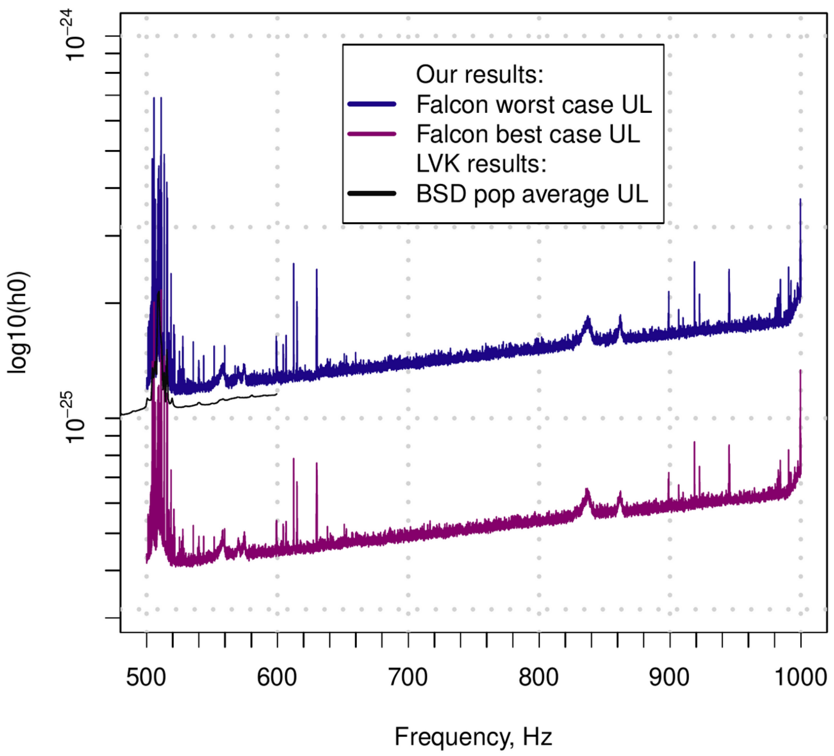


FIG. 7. This plot shows upper limits similar to those shown in Figure 2, but for the location of G189.1+3.0. Latest LIGO/Virgo/KAGRA results [51] are shown for comparison. The LVK upper limit curve was computed as minimum of Hanford, Livingston and Virgo data.