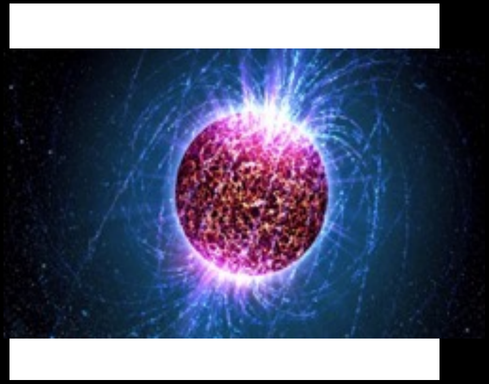
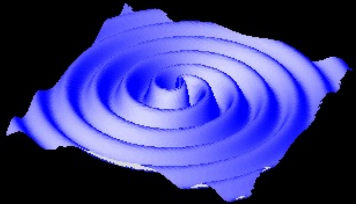
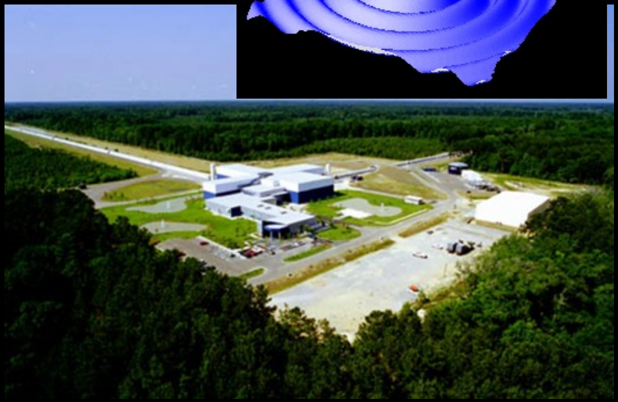
RECENT RESULTS AND FUTURE CHALLENGES FOR CONTINUOUS GRAVITATIONAL WAVE SEARCHES WITH A NETWORK OF TERRESTRIAL GRAVITATIONAL WAVE DETECTORS



Pia Astone, INFN Roma.

LVK collaboration





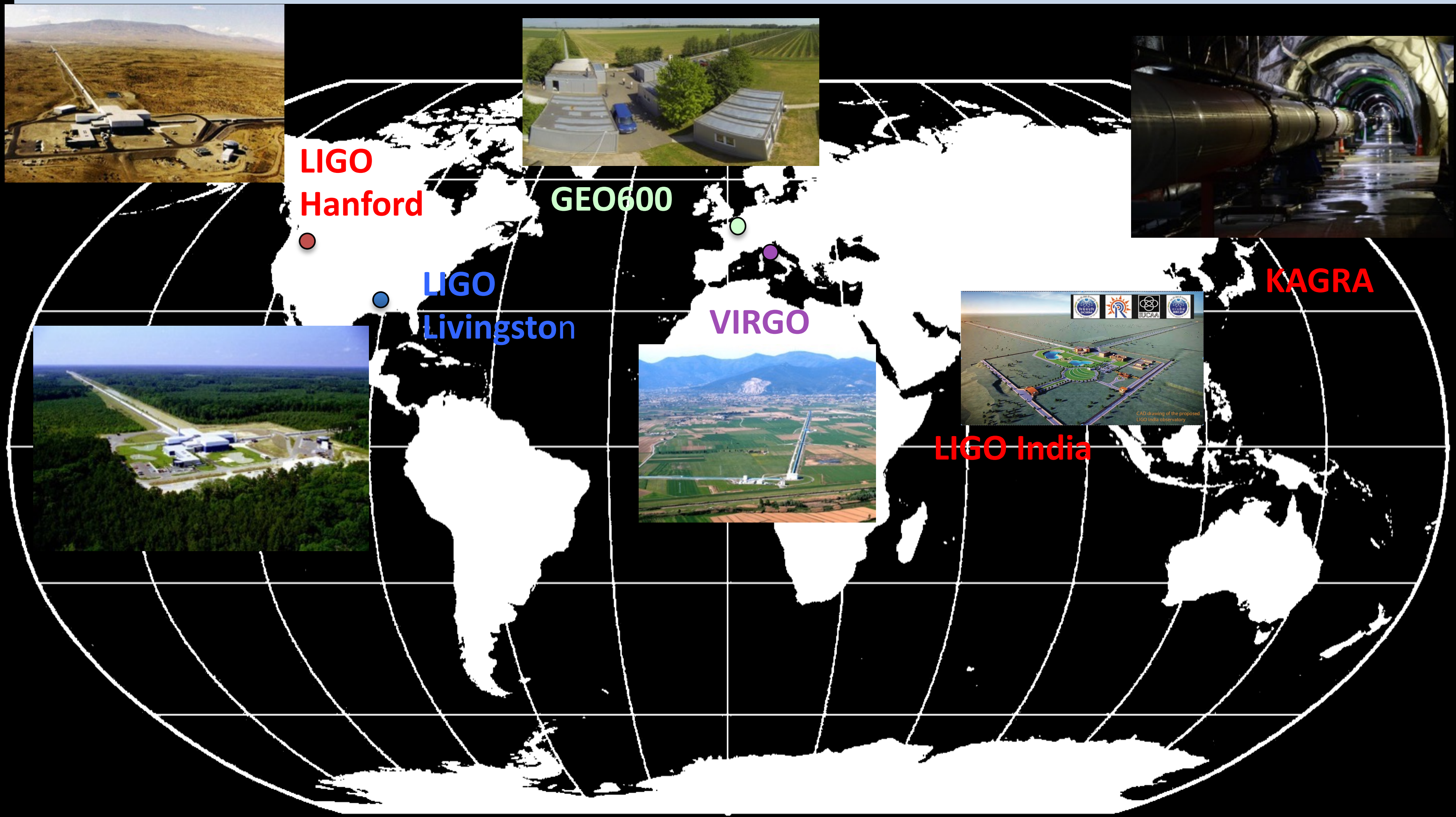
LIGO, Livingston (LSU)

Virgo, Cascina

LIGO, Hanford (Washington State)

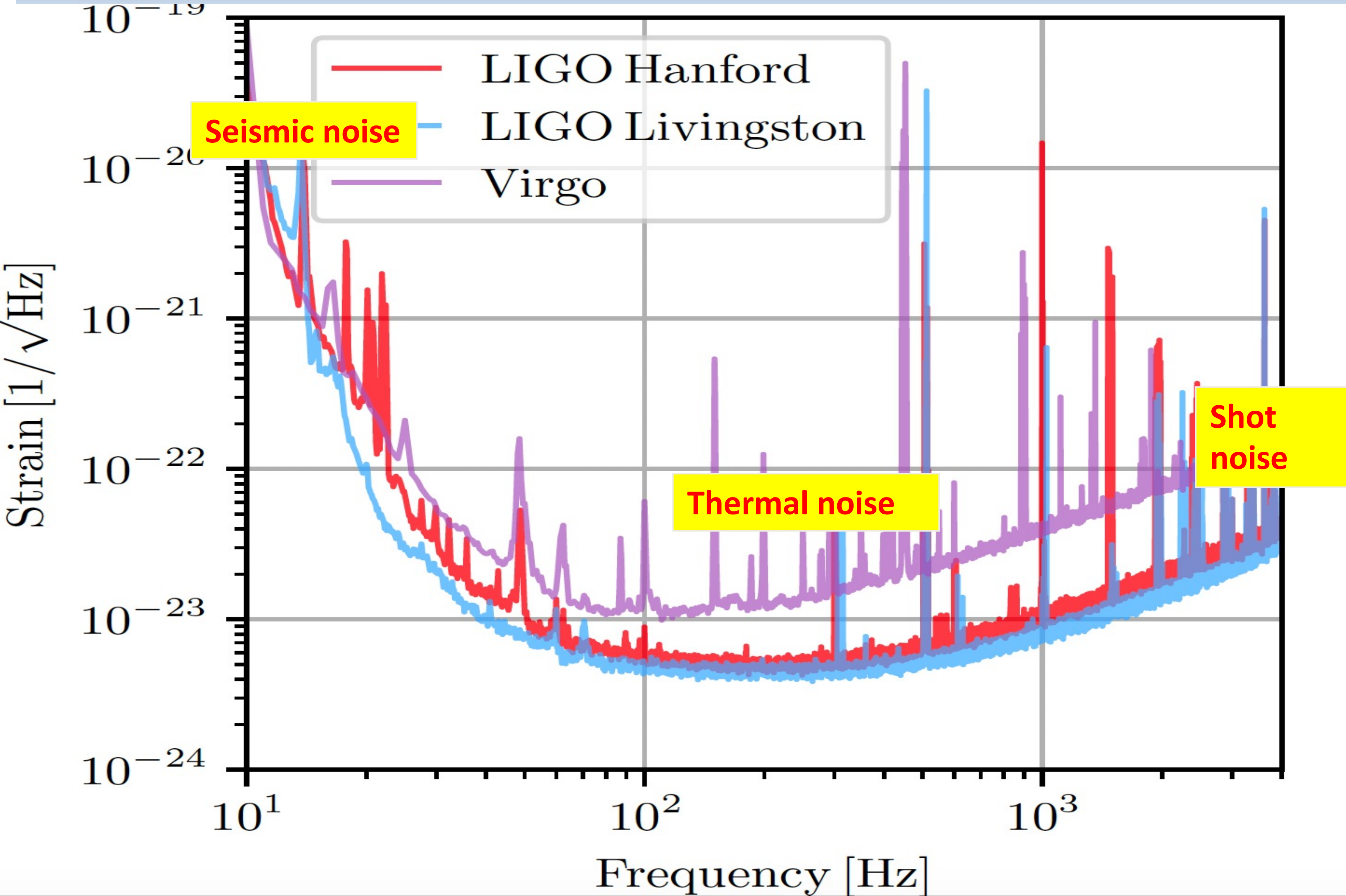
12th Iberian GW meeting 6-8 June

The current-near future terrestrial network of GW detectors



Next observing run: end of 2022/beginning of 2023

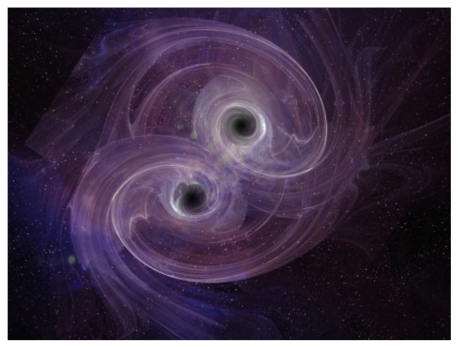
SCIENCE Run O3 detector's strain

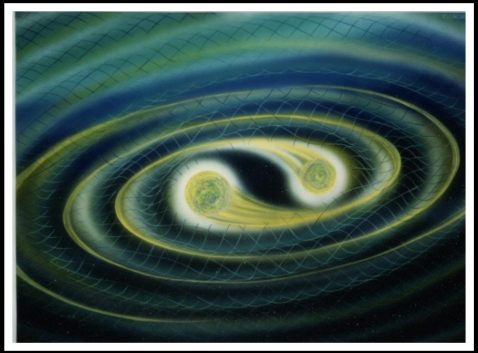


SOURCES, SIGNALS and SEARCH METHODS

CBC: Coalescence of binary system of neutron stars and/or stellar-mass black-holes

90 detections to date GWTC-3



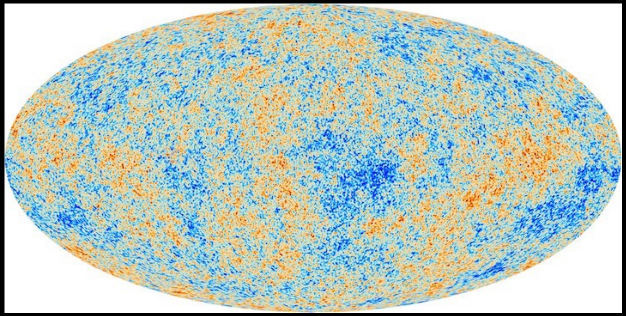


Matched-filter (MF) Modeled searches

Burst: Core-collapse of massive stars

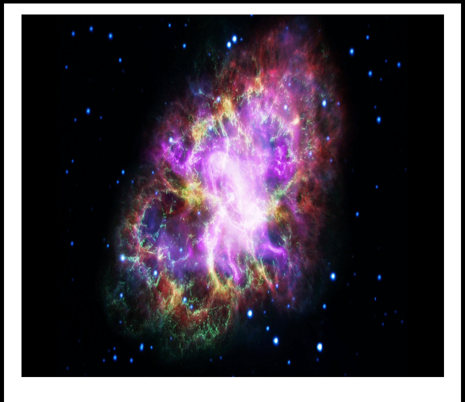
Unmodeled searches

Stochastic Background



Cross-correlations

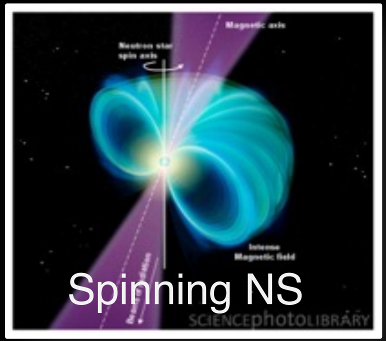
CW: Isolated or binary neutron stars



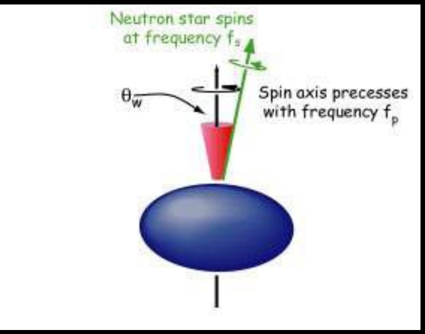
MF/FFT based and/or hierarchical searches

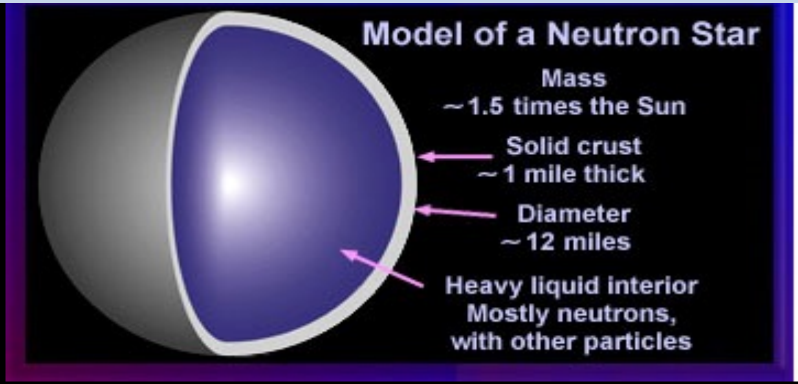
The basic problem of detecting CW sources

- **CBC** signals are of limited duration, well modeled and visible given the actual sensitivities , even if ”far” from us. GW170817 distance was ~ 40 Mpc from earth.
- **Continuous signals**, like those emitted by compact objects isolated or in binary systems, typically have long duration but strain amplitudes are much weaker , o(10^{-26}) compared to o(10^{-21})



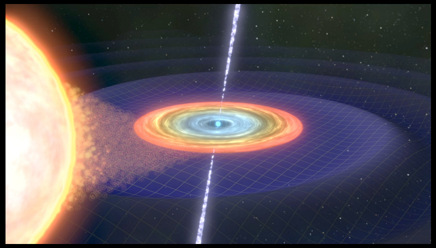
CONTINUOUS WAVES EMITTED BY NEUTRON STARS





$$h_0 \cong 10^{-26} \left(\frac{I_{zz}}{10^{38} kg \cdot m^2}\right)\left(\frac{10kpc}{d}\right)\left(\frac{f}{300\ Hz}\right)^2\left(\frac{\varepsilon}{10^{-6}}\right)$$

deformation due to elastic or magnetic stresses: $\mathbf{f_{GW} = 2\ f_{spin}}$
deformation due to (anisotropic) matter accretion (e.g., LMXB);
excitation of long-lived oscillations (e.g., r-modes): $\mathbf{f_{GW} = 4/3\ f_{spin}}$



Expected signals are not monochromatic at the detector. Frequency (and phase) are modified by various effects:

- Doppler effect due to the detector motion;
- Orbital motion for sources in binary systems;
- Source spin-down (rotation frequency decreases due to energy loss; relativistic effects; antenna pattern).

For isolated NS the maximum foreseen **ellipticity** depends on the star crust physics, the matter equation of state at supra-nuclear density and on the deformation mechanism.

ε_{max} ~ 10^{-5} for a 'standard' NS (fluid core, normal nuclear matter)

ε_{max} ~ 10^{-3} for 'hybrid' stars (hadron-quark core)

ε_{max} ~ 10^{-3} $(B/10^{16}\,G)^2$ deformation from the volume averaged magnetic field.

ε_{max} ~ 10^{-1} for quark star.

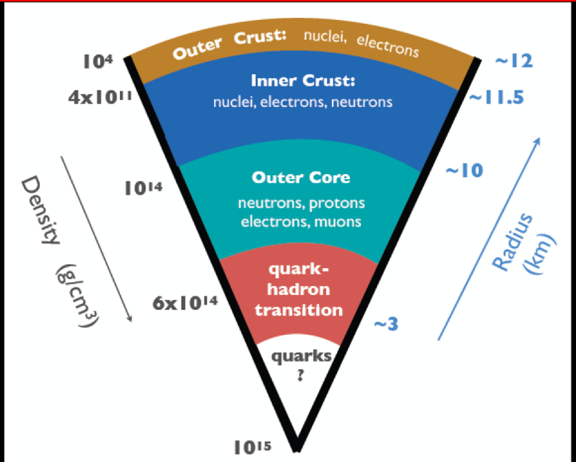
Lasky, Glampedakis, MNRAS 458 2016
N. Jonhson-McDaniel, B. Owen
PRD 86 063600 , PRD 87 129903

10^{-5} corresponds to a 'mountain' ~10 cm high!

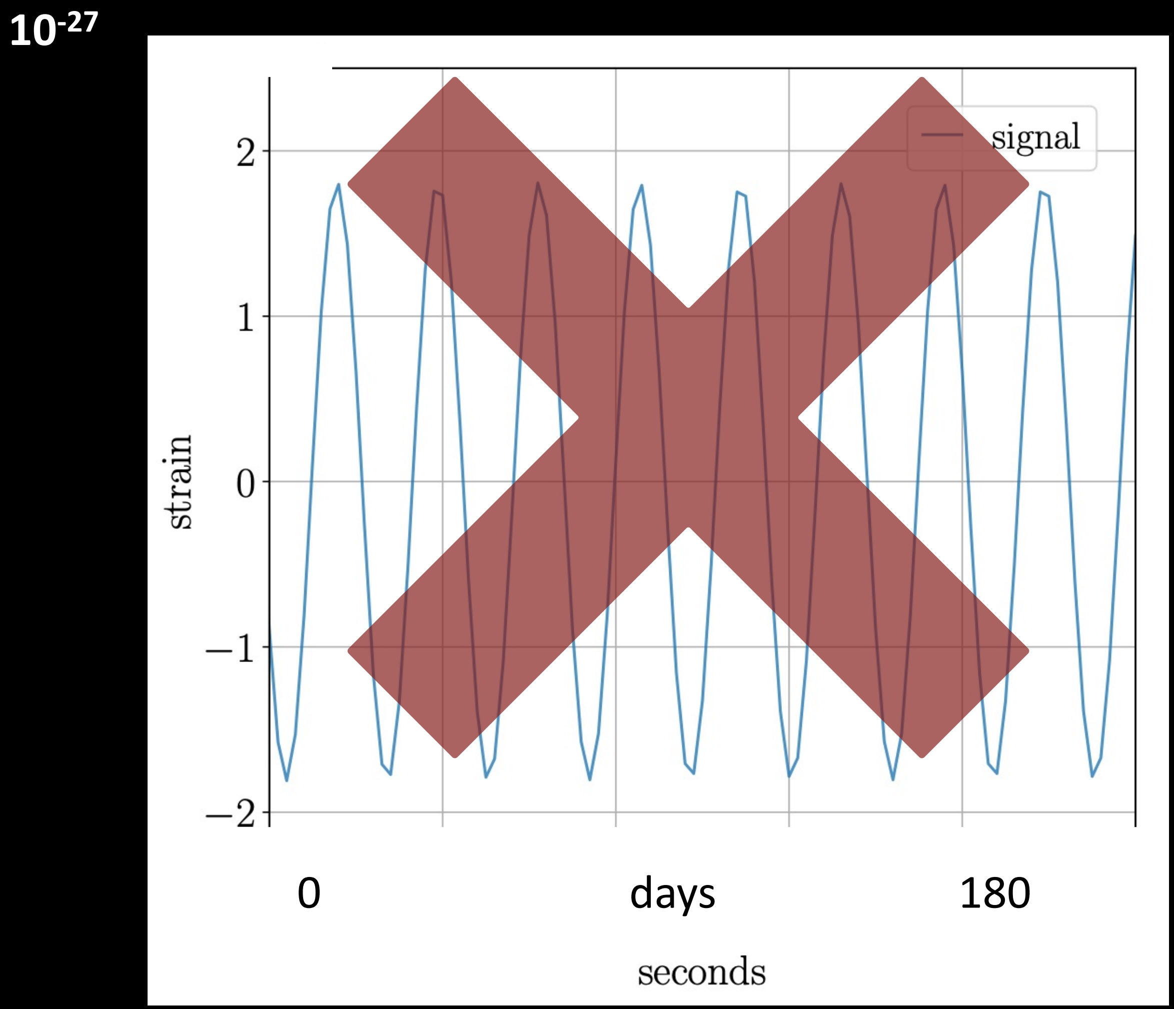
CW signals: What will a detections tell us?

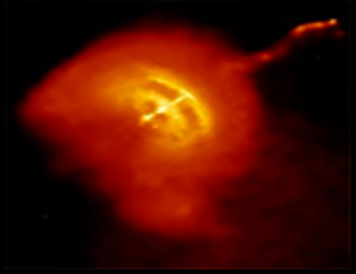
- NS internal structure (EOS, viscosity, superfluidity)
- Maximum spin allowed for a NS
- Intensity and geometry of interior magnetic field
- Accretion physics
- NS demography (including a possible population of ``exotic" stars) and implications for a stochastic background.
- Testing GR

Even a null result can be used to constrain NS parameters, like ellipticity or the internal magnetic field, and at least some of the EOS's.



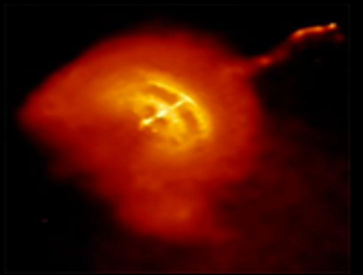
The continuous wave signal at the detector



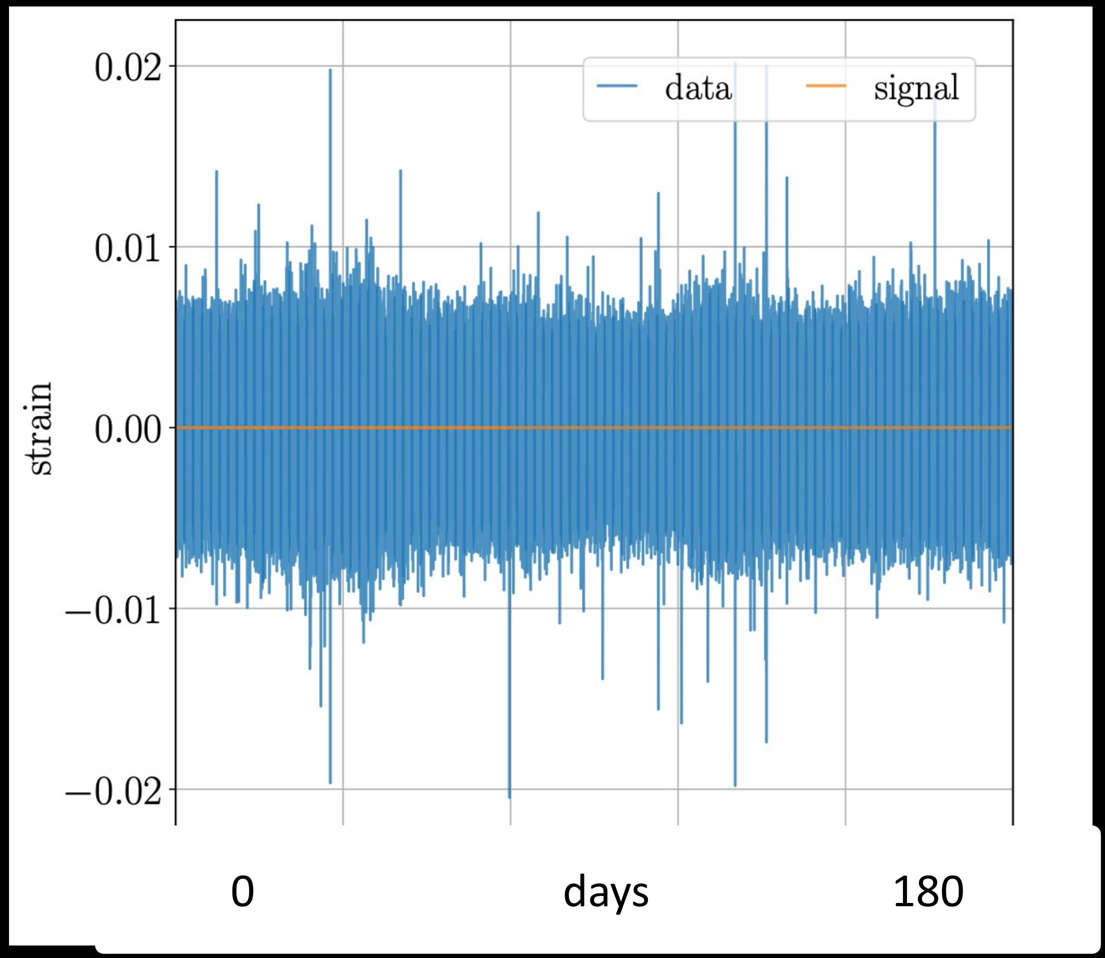


Values here are just to mark order of magnitues of the effects

The continuous wave signal in the detector noise



10^{-21}



Values here are just to mark order of magnitues of the effects

Neutron stars signal model

FOR ISOLATED NSs

A CW received at the detector is NOT exactly monochromatic

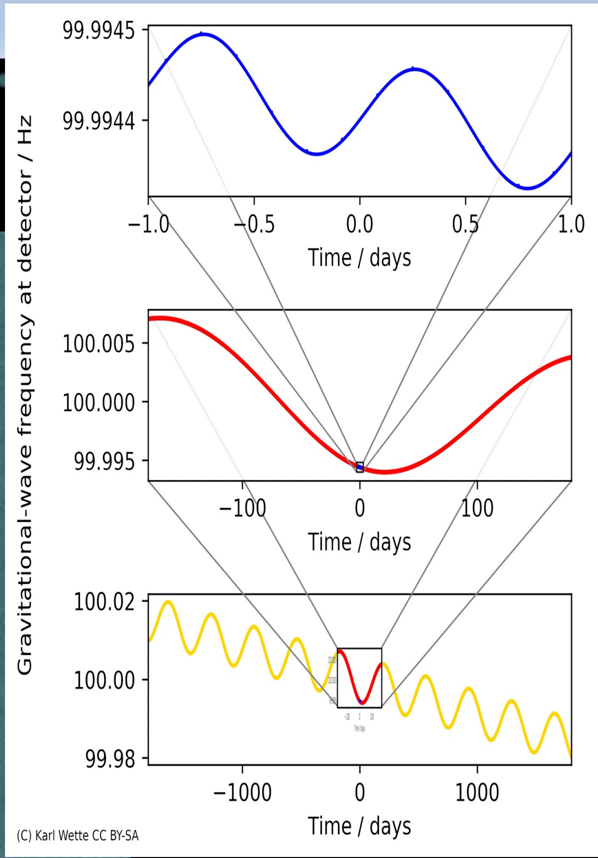
- SPIN-DOWN due to the loss of energy of the star

$$f_0(t) = f_0 + \dot{f}_0(t - t_0) + \frac{\ddot{f}_0}{2}(t - t_0)^2 + \cdots$$

- DOPPLER shift due to the motion of the Earth

$$f(t) = \frac{1}{2\pi}\frac{d\Phi(t)}{dt} = f_0(t)\left(1 + \frac{\vec{v}\cdot\hat{n}}{c}\right)$$

- SIDEREAL VARIATION of the amplitude



Long-term frequency evolution of a CW signal

PicturecCredit: K. Wette

The basic problem of detecting CW sources

To detect these signals, we need to integrate over long times.

At the actual sensitivities our main target for continuous searches are galactic non-axisymmetric spinning NS, isolated or in binary systems, such that the frequency of the emitted GW, is in the band of our detectors ~[20-2000] Hz.

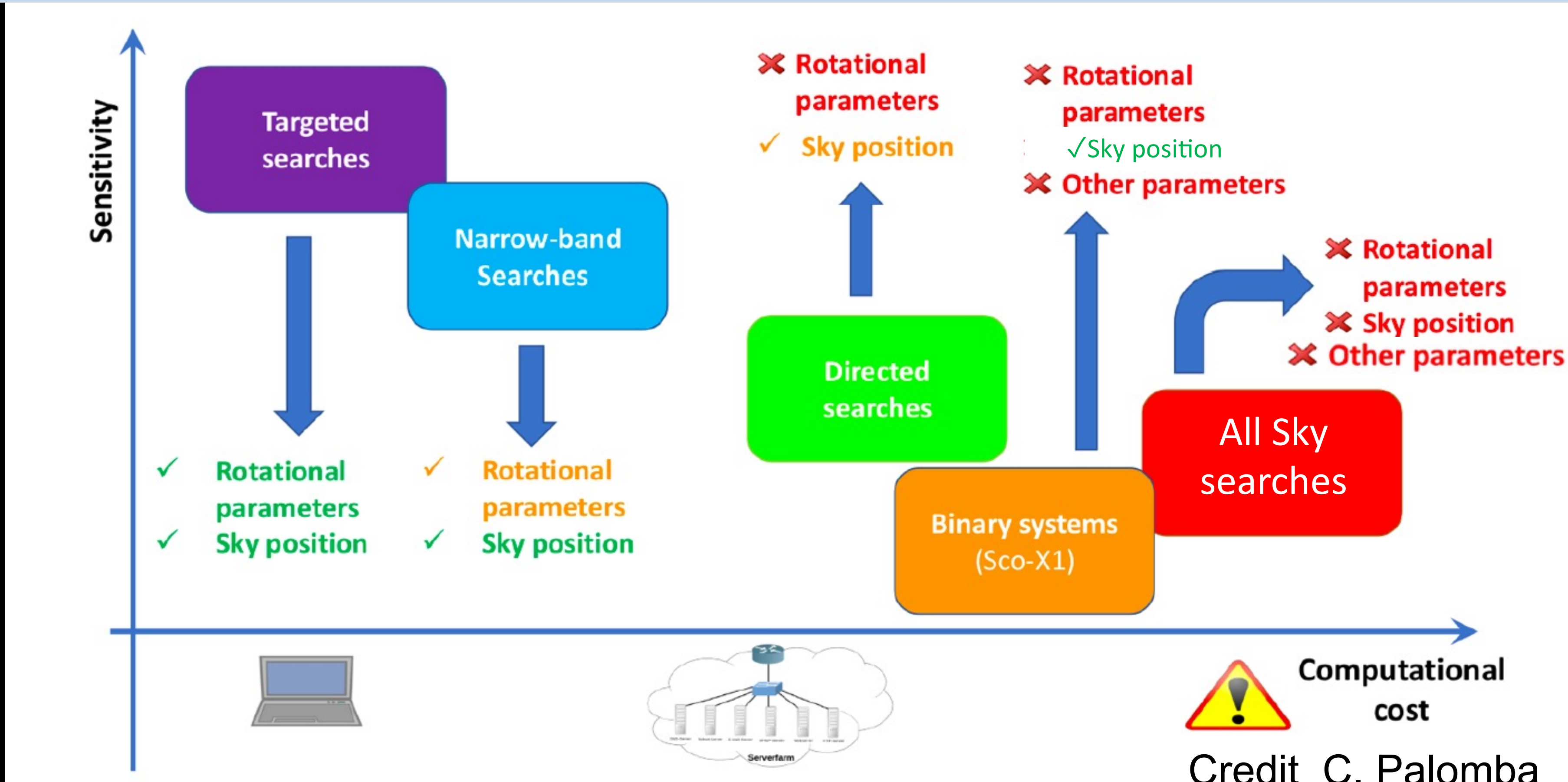
We know that potential sources of CW exist: **2500+ NS** are observed (mostly pulsars) and **O(10^8 - 10^9)** are expected to exist in the Galaxy.

In some cases, hierarchical procedures are needed

(compromise between sensitivity and computational problems)

Multimessenger astronomy plays a very important role

The computational problem

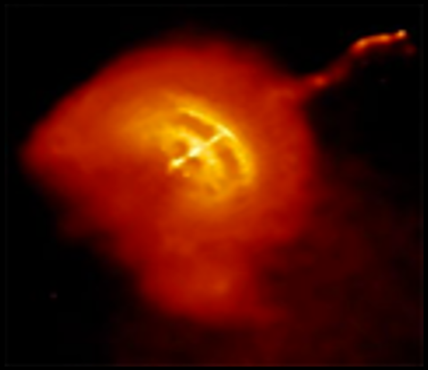


To give an example:

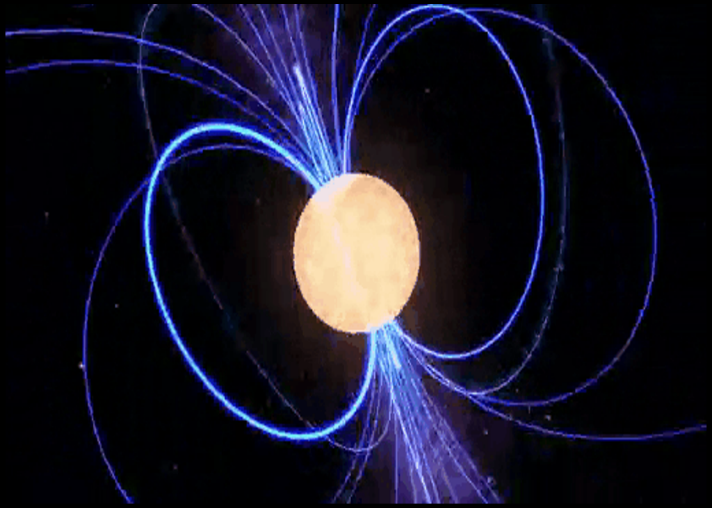
Order of magnitude estimation for the Frequency Hough hierarchical All Sky search (isolated NS) is: 1 year, 3 detectors.

~ 80 million core-hours

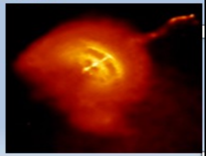
O3 CW group



SOME RECENT RESULTS

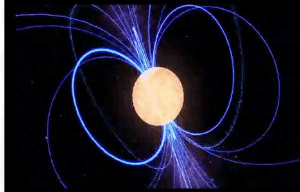


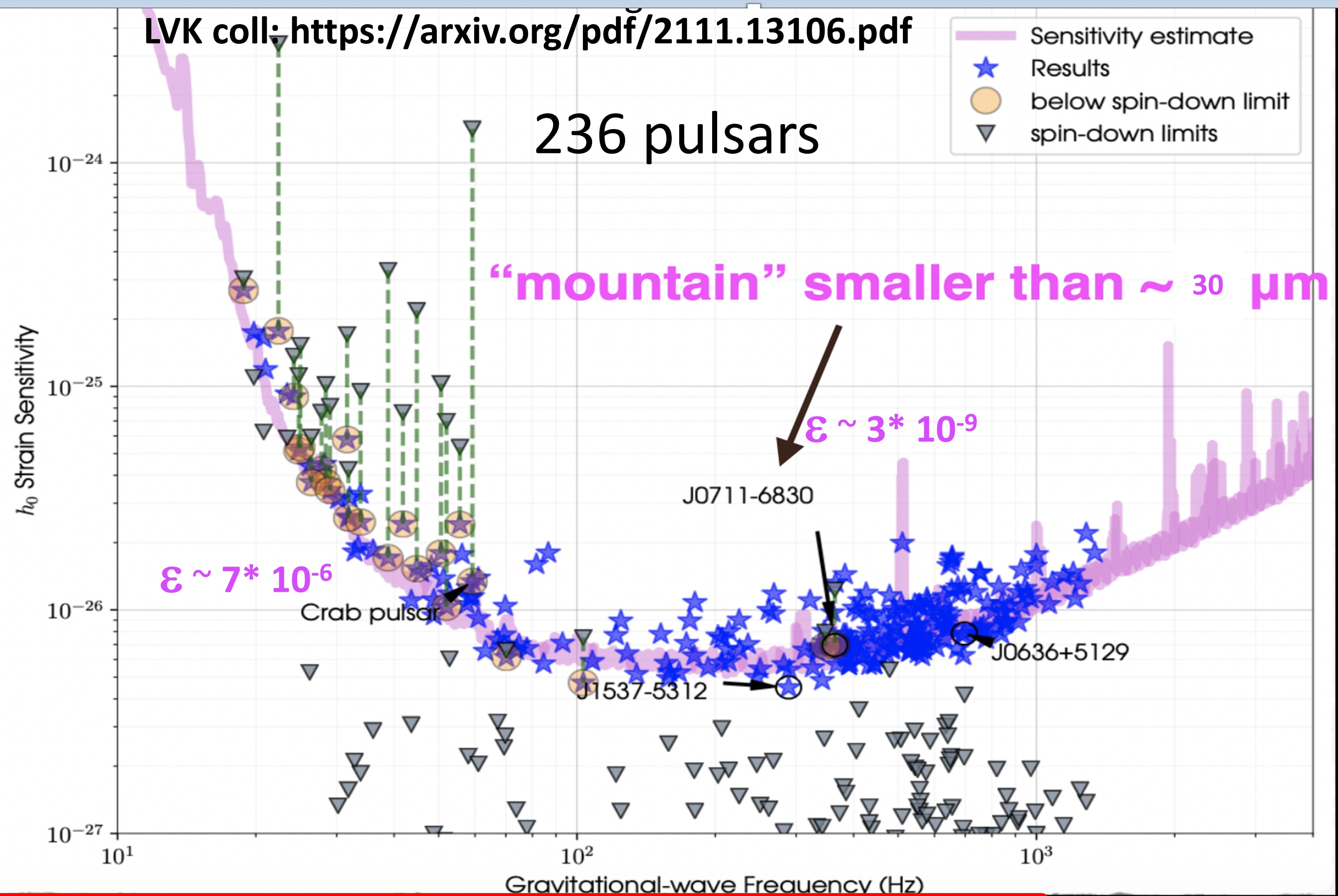
Searches for Gravitational Waves from Known Pulsars at Two Harmonics in the Second and Third LIGO-Virgo Observing Runs



LVK coll: https://arxiv.org/pdf/2111.13106.pdf

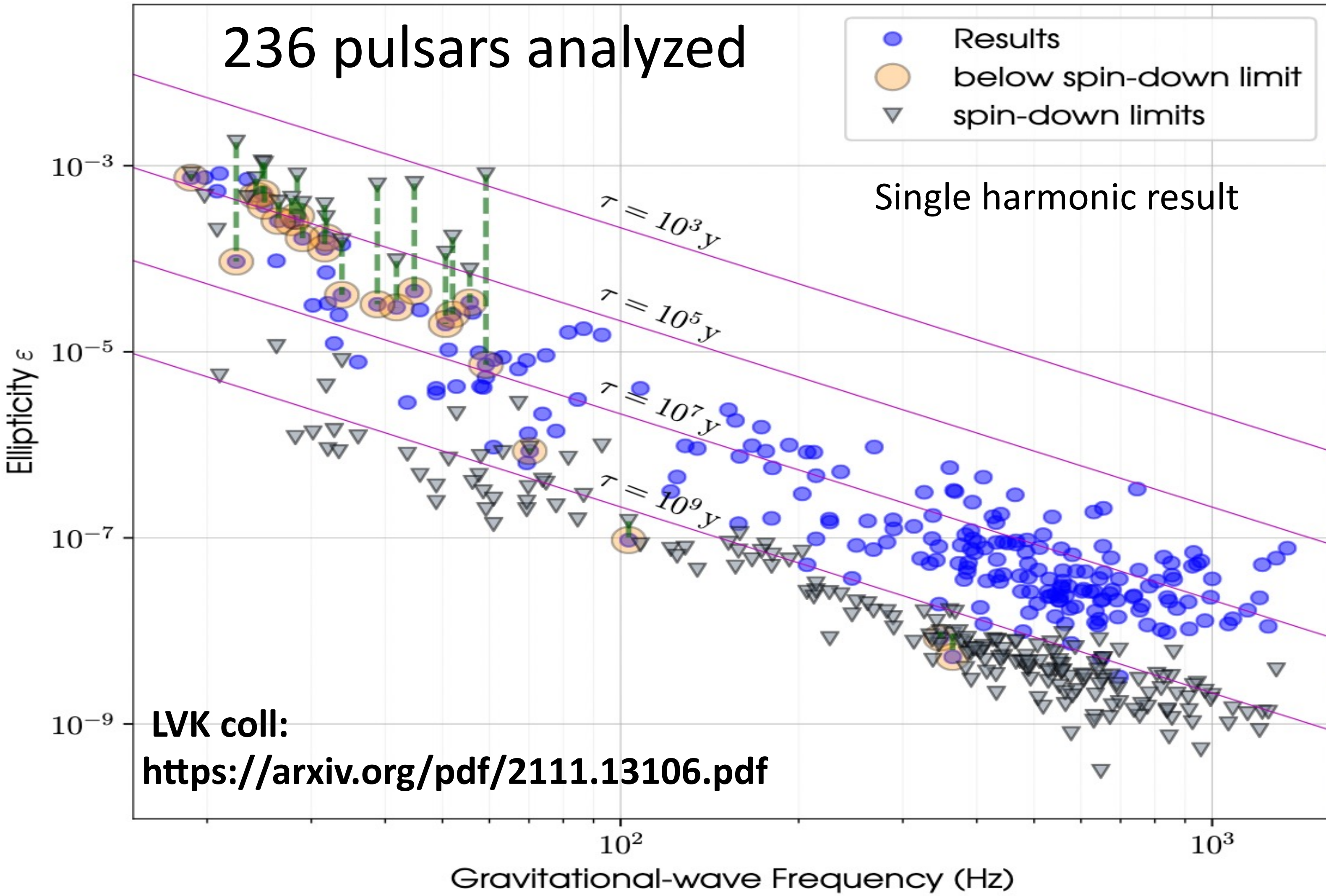
236 pulsars

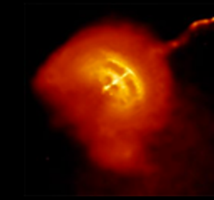


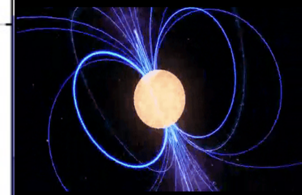


For the Crab and Vela pulsars limits are factors of ~ 100 and ~ 20 more constraining than spin-down limits

TARGETED







$$\epsilon^{sd} = 0.237 \left(\frac{h_0^{sd}}{10^{-24}} \right) I_{38}^{-1} (f_{rot}/\text{Hz})^{-2} d_{kpc}$$

pink contour: lines of equal characteristic age τ assuming that GW emission alone is causing spin-down

Search for continuous gravitational wave emission from the Milky Way center in O3 LIGO–Virgo data

https://arxiv.org/pdf/2204.04523.pdf

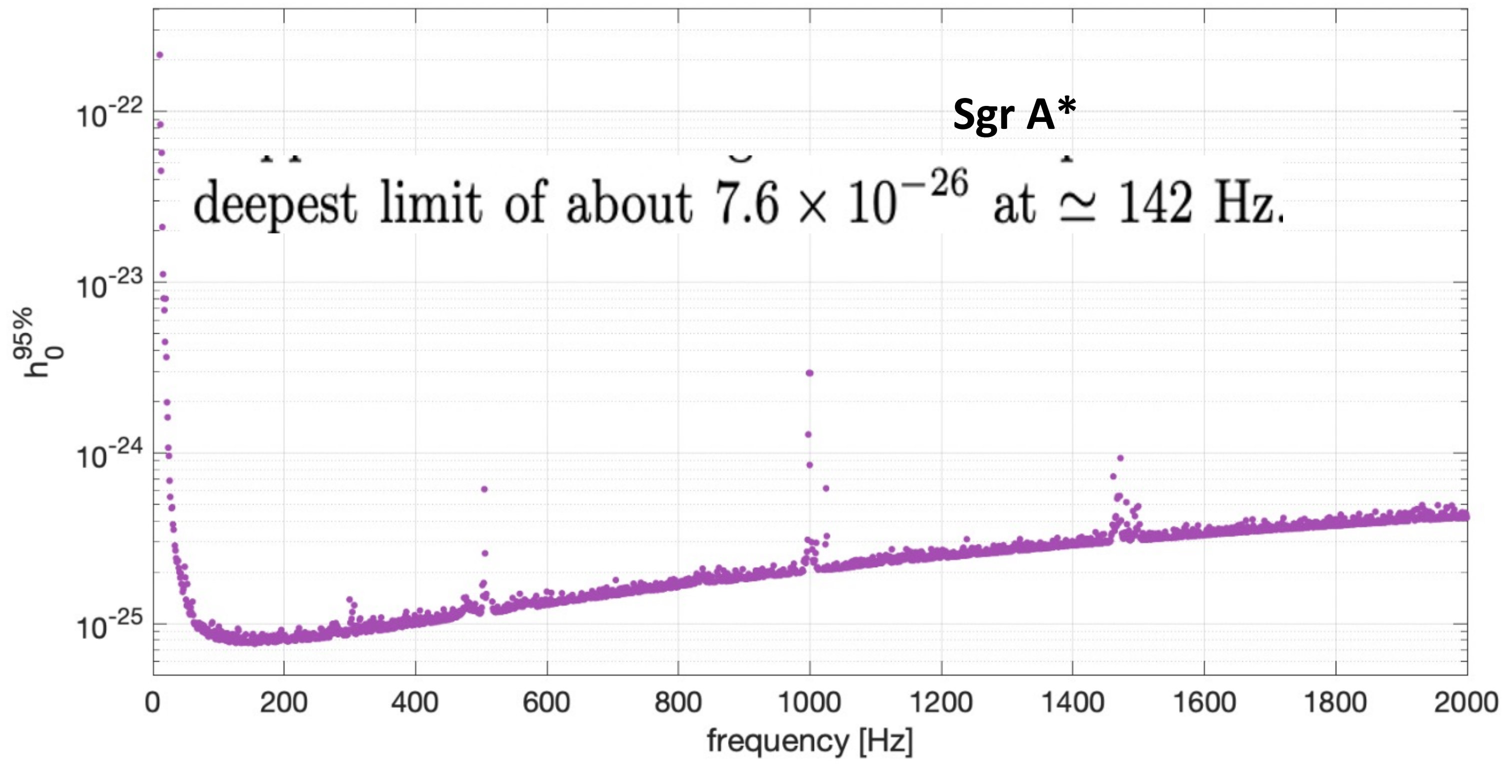


FIG. 2. Estimates of the 95 % C.L. strain upper limits, derived for the best combination HL in 1 Hz bands.

DIRECTED SEARCHES

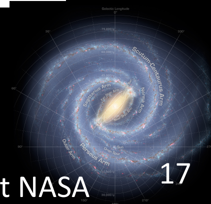


Image Credit NASA

Search for continuous gravitational wave emission from the Milky Way center in O3 LIGO–Virgo data

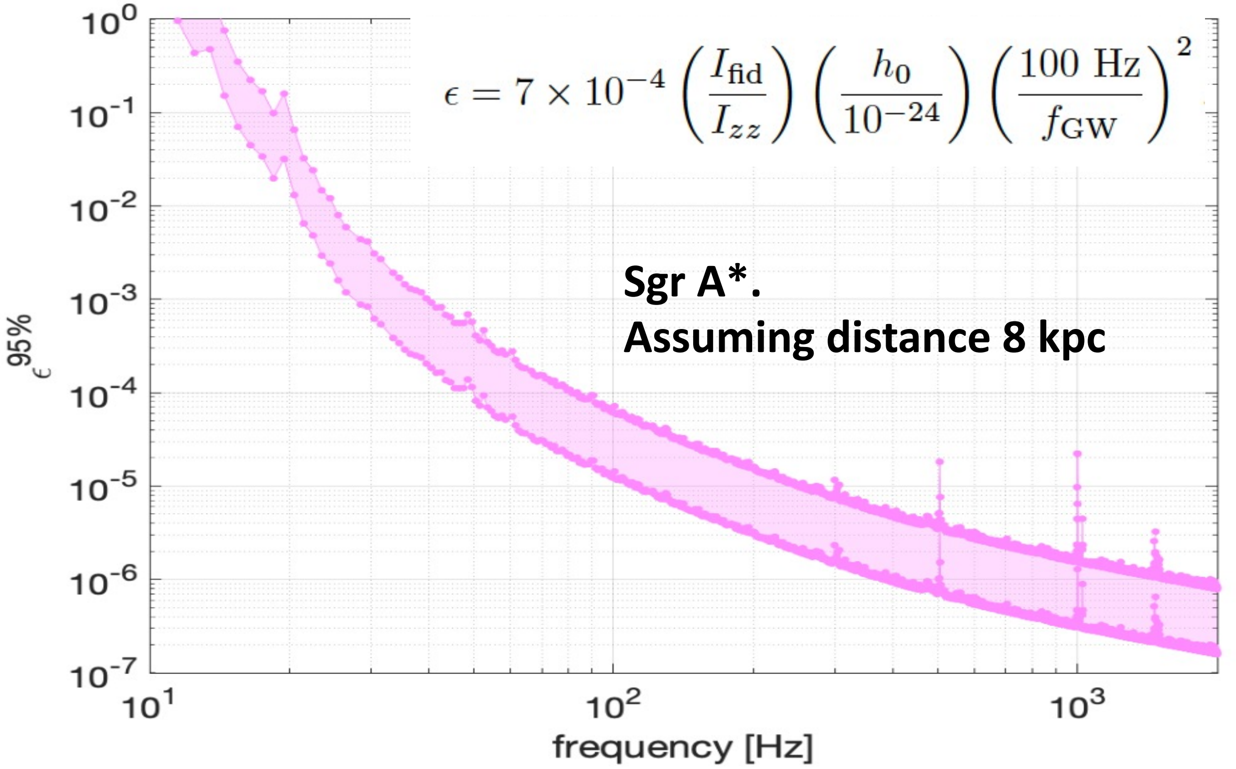


FIG. 3. Estimates of the 95 % C.L. ellipticity upper limits assuming a GC distance of 8 kpc. The shaded area between the two curves covers the possible values of the moment of inertia along z of the spinning star. The lower curve corresponds to a moment of inertia five times larger than the fiducial value $I_{\rm fid}$, sustainable by exotic objects.

$I_{\rm fid}$=

10^{38} kg*m^2

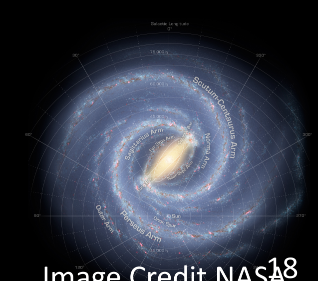


Image Credit NASA

Search for continuous gravitational wave emission from the Milky Way center in O3 LIGO–Virgo data. **R-mode searches**

https://arxiv.org/pdf/2204.04523.pdf

R mode emission frequency and amplitude

$$f_{\mathrm{GW}} = \frac{4}{3} f_{\mathrm{spin}}$$

$$\alpha \simeq 0.028 \left(\frac{h_0}{10^{-24}}\right) \left(\frac{d}{1\ \mathrm{kpc}}\right) \left(\frac{100\ \mathrm{Hz}}{f_{\mathrm{GW}}}\right)^3$$

R-mode amplitude

Long-lasting oscillations in the fluid that makes up most of the star ➔
a fluid wave travelling around the star and driven by the Coriolis force due to rotation

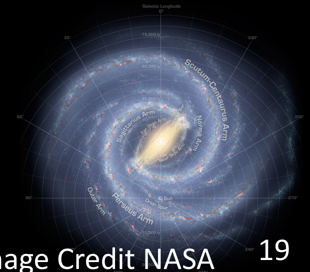


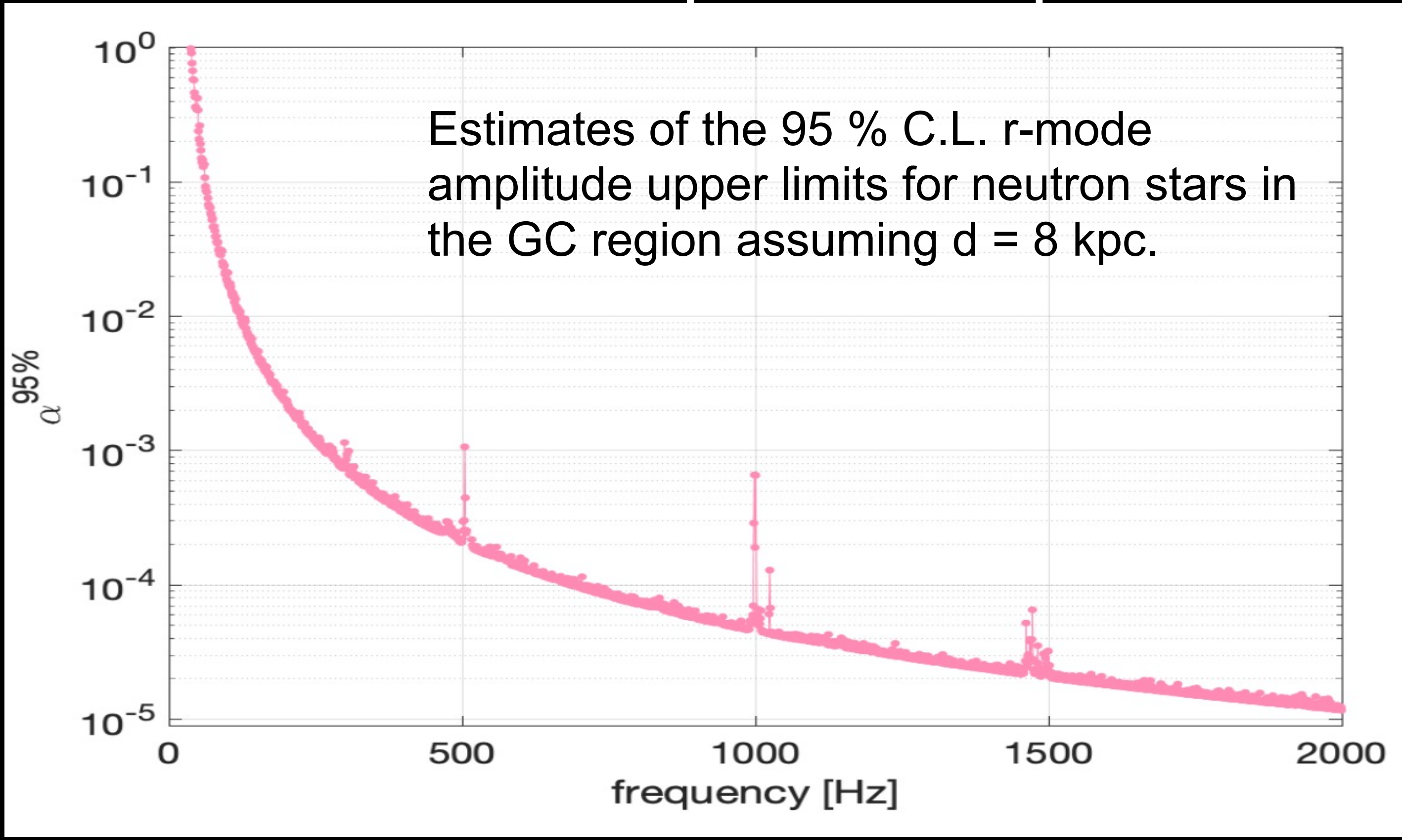
Image Credit NASA

DIRECTED SEARCHES

Search for continuous gravitational wave emission from the Milky Way center in O3 LIGO–Virgo data**. R-mode searches**

https://arxiv.org/pdf/2204.04523.pdf

Under some assumptions for parameters of the NS



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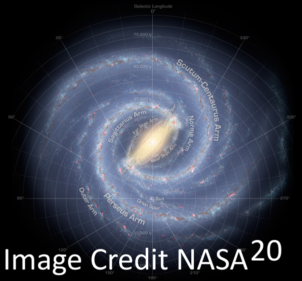


Image Credit NASA

Discovering new particles using GWs

If an ultralight boson exist, they will form clouds around spinning black holes (superradiance)

Clouds will emit nearly periodic, long-duration GWs
We can run searches pointing at known BH locations.

Arvanitaki+, PRD 91, 084011 (2015)
Brito+, PRD96, 064050 (2017)

Existing continuous-wave search methods are applicable to these sources, for stellar mass BHs and mass range $10^{-13} \leq \mu/\mathrm{eV} \leq 10^{-11}$

Isi, Sun, Brito, Melatos, PRD 99, 084042 (2019) and Sun, Brito, Isi arXiv:1909.11267 (2019)

$$f_{\rm gw} \simeq 483\,{\rm Hz}\left(\frac{m_{\rm b}}{10^{-12}\ {\rm eV}}\right) \times \left[1 - 7\times 10^{-4}\left(\frac{M_{\rm BH}}{10M_\odot}\frac{m_{\rm b}}{10^{-12}\ {\rm eV}}\right)^2\right]$$

$$\tau_{\rm gw} \simeq 6.5\times 10^4\left(\frac{M_{\rm BH}}{10M_\odot}\right)\left(\frac{\alpha}{0.1}\right)^{-15}\left(\frac{1}{\chi_i}\right)\ {\rm years.}$$

$$\alpha = \frac{GM_{\rm BH}}{c}\frac{m_b}{\hbar}$$

$$\dot{f}_{\rm gw} \approx 7\times 10^{-15}\left(\frac{m_{\rm b}}{10^{-12}\ {\rm eV}}\right)^2\left(\frac{\alpha}{0.1}\right)^{17}\ {\rm Hz/s.}$$

$$h_0 \approx 6\times 10^{-24}\left(\frac{M_{\rm BH}}{10M_\odot}\right)\left(\frac{\alpha}{0.1}\right)^7\left(\frac{1\,{\rm kpc}}{r}\right)(\chi_i - \chi_c)$$

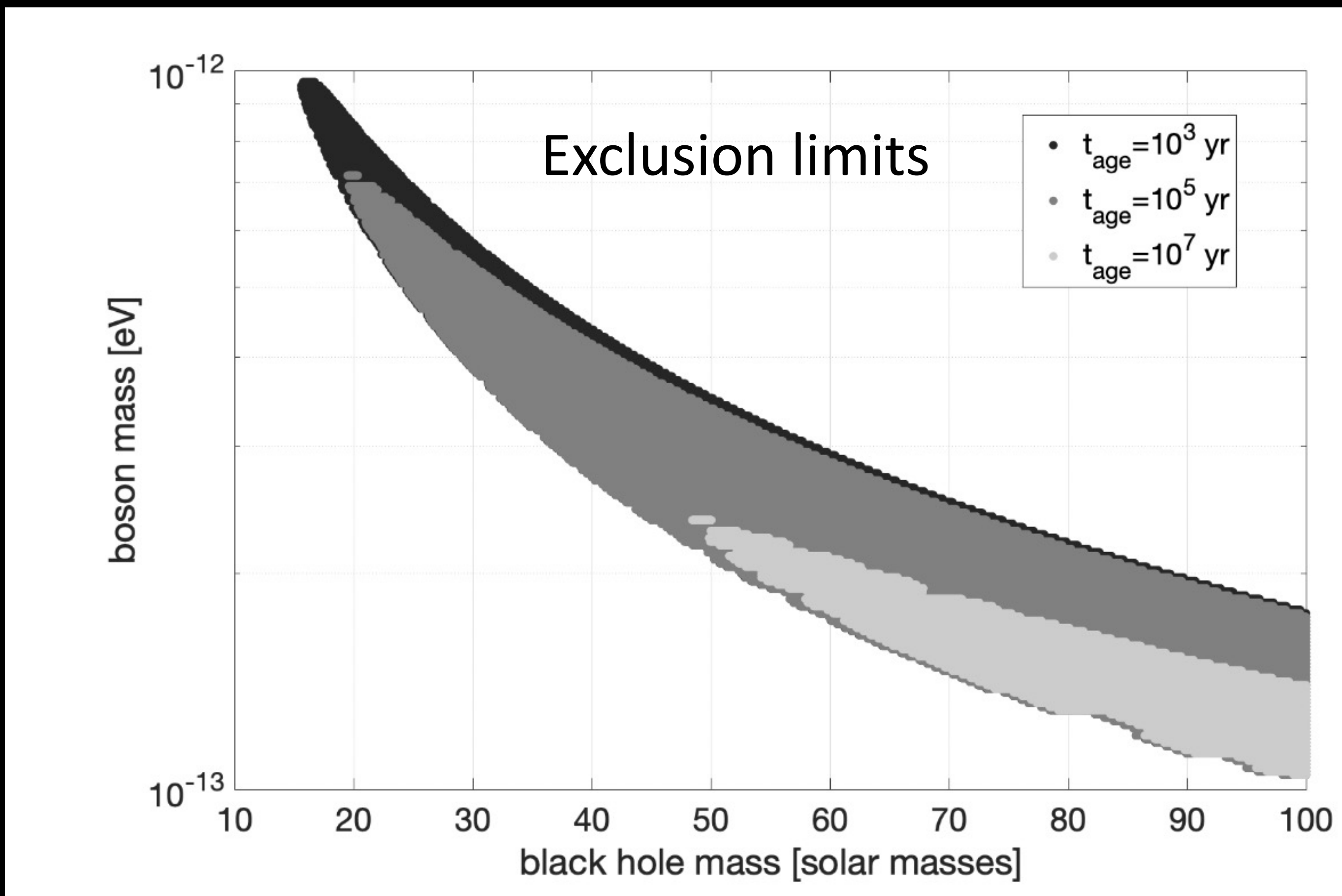
$$h(t) = \frac{h_0}{1+\frac{t}{\tau_{\rm gw}}}.$$

Black hole and boson masses

https://arxiv.org/abs/2111.15507
(includes results using All Sky O3 data analysis)

Search for continuous gravitational wave emission from the Milky Way center in O3 LIGO–Virgo data. **Boson clouds searches**

https://arxiv.org/pdf/2204.04523.pdf



Black hole dimensionless spin $\chi_i = 0.5$

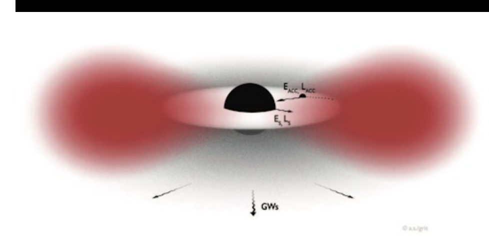


Figure Credit: Brito, Cardoso, Pani

DM DIRECTED SEARCHES

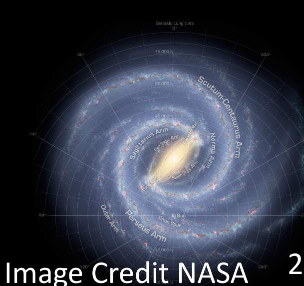


Image Credit NASA

Search for gravitational waves from Scorpius X-1 with a hidden Markov model in O3 LIGO data

https://arxiv.org/pdf/2201.10104.pdf

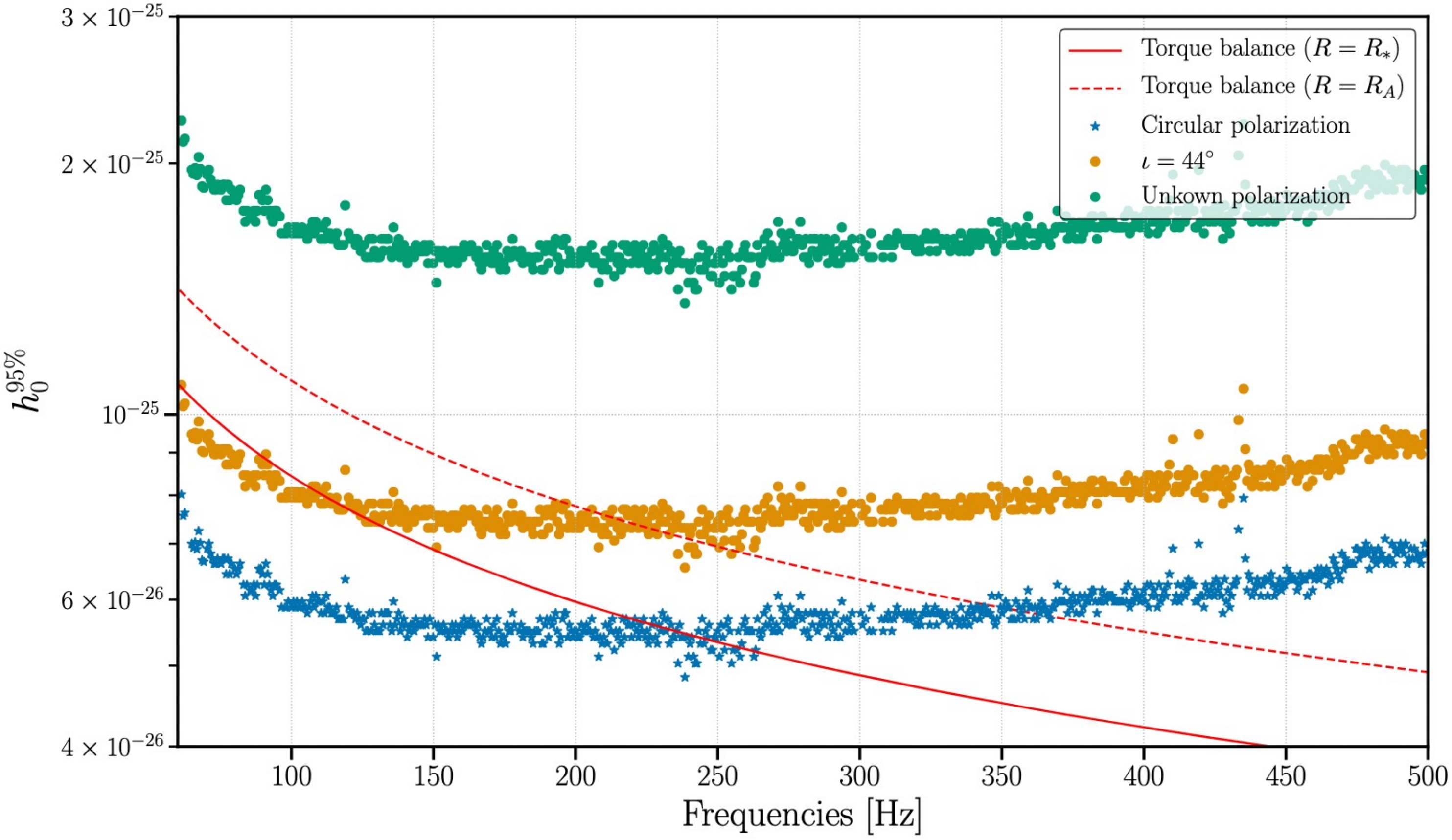


FIG. 4. Frequentist effective wave strain upper limits at 95% confidence as a function of sub-band frequency, for three scenarios: circular polarization with $\iota = 0$ (blue stars), $\iota \approx 44°$ based on the electromagnetic measurements (see Ref. [51]; orange dots), and a flat prior on $\cos \iota$ (green dots). Indirect torque-balance upper limits (see Section V C) for two torque lever arms are also shown: the stellar radius (red solid line) and the Alfvén radius (dashed red line).

Search for gravitational waves from Scorpius X-1 with a hidden Markov model in O3 LIGO data

https://arxiv.org/pdf/2201.10104.pdf

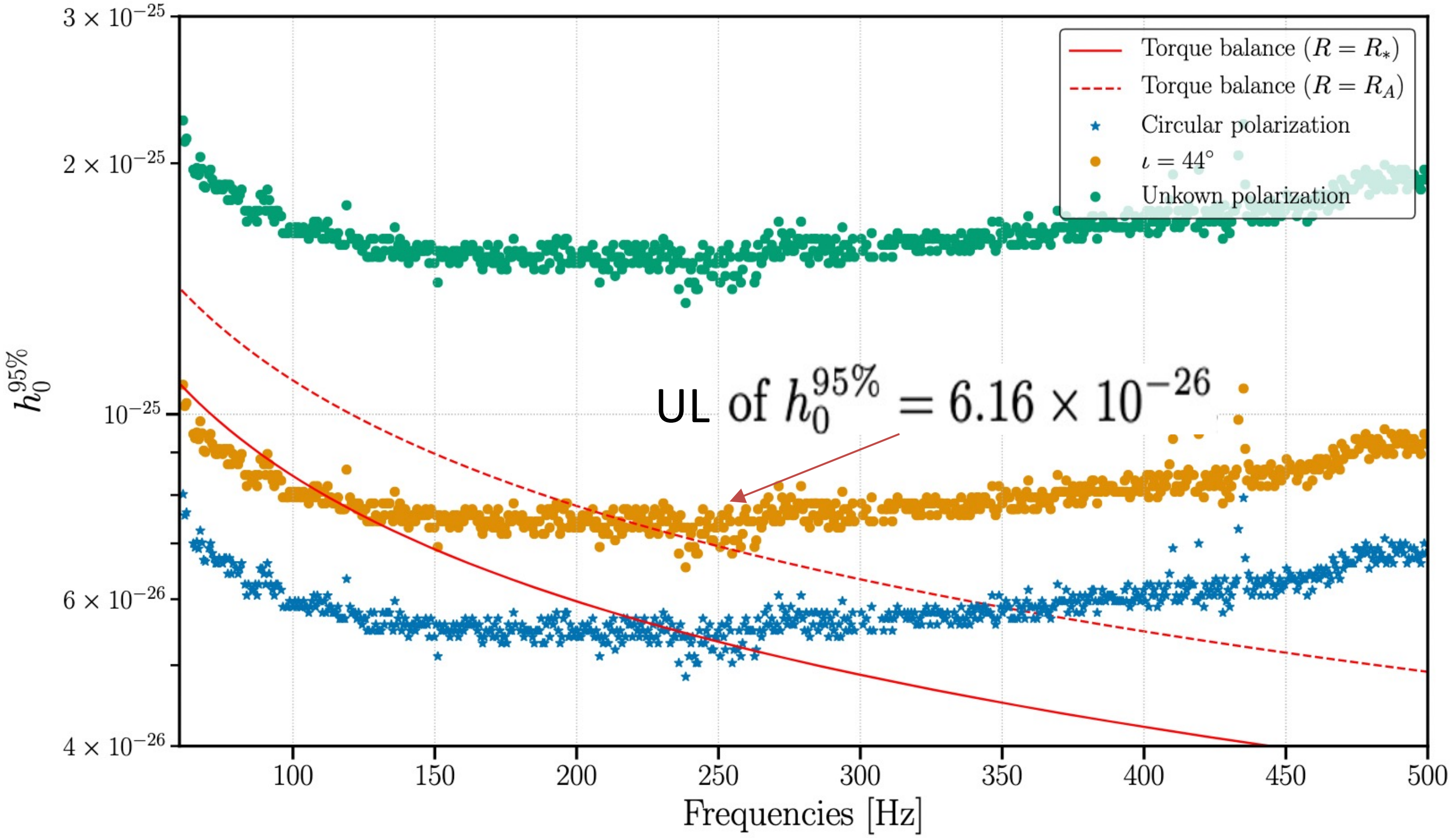
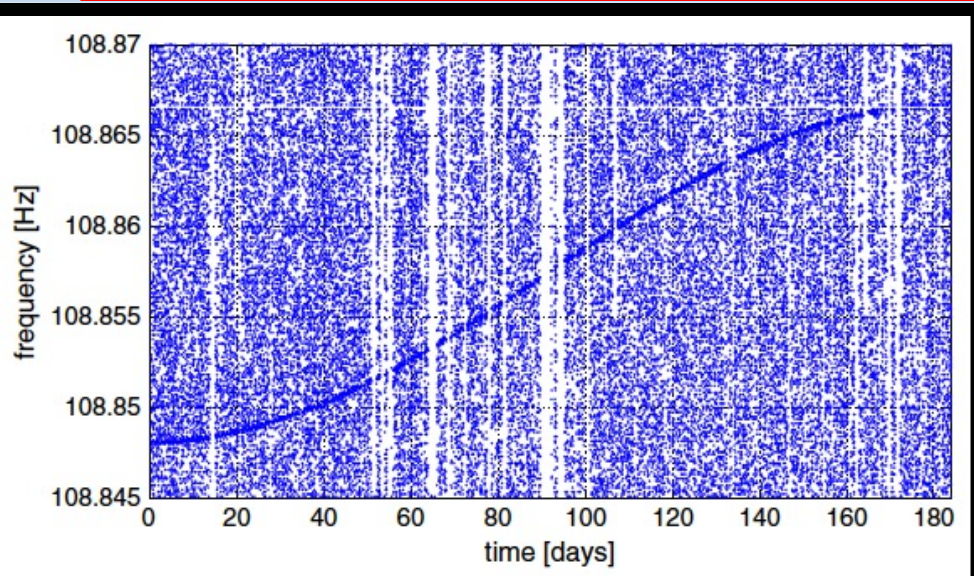


FIG. 4. Frequentist effective wave strain upper limits at 95% confidence as a function of sub-band frequency, for three scenarios: circular polarization with $\iota = 0$ (blue stars), $\iota \approx 44°$ based on the electromagnetic measurements (see Ref. [51]; orange dots), and a flat prior on $\cos\iota$ (green dots). Indirect torque-balance upper limits (see Section V C) for two torque lever arms are also shown: the stellar radius (red solid line) and the Alfvén radius (dashed red line).

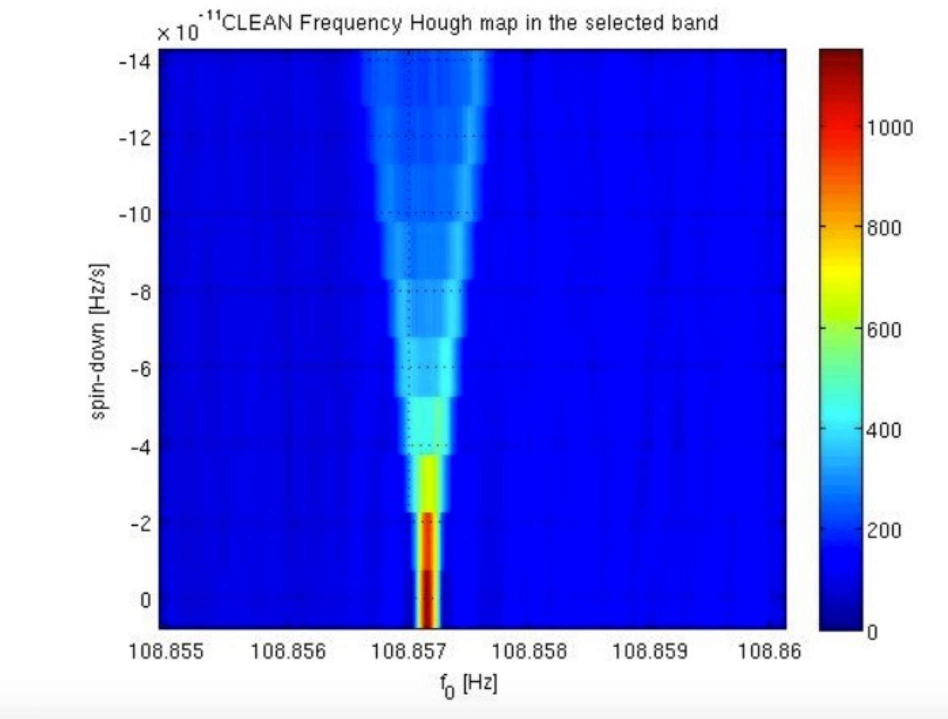
All-Sky searches: The "Frequency Hough" procedure



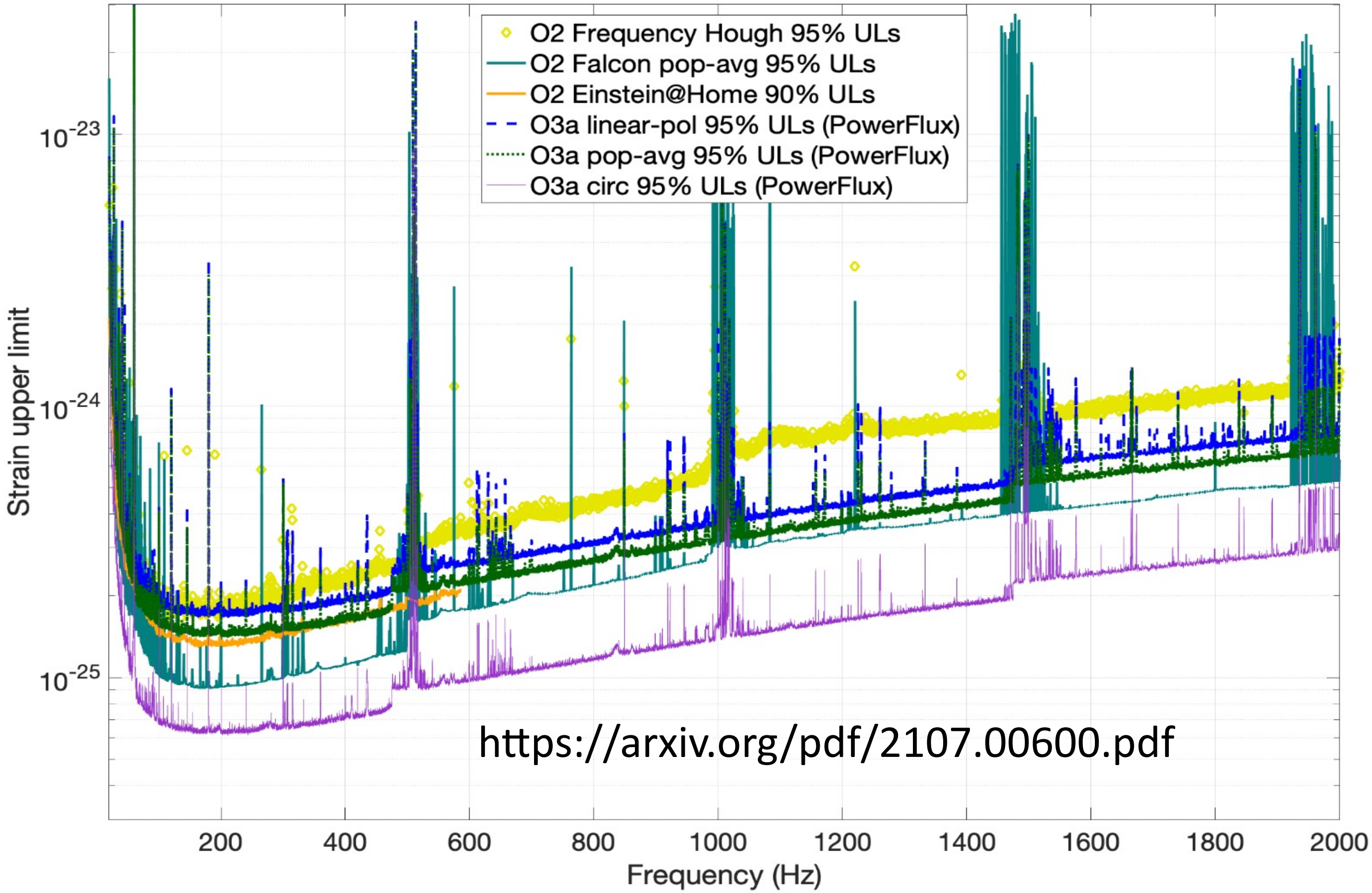
<u>An example</u> *of hierarchical procedure used in All-Sky searches.*

This is ***one of*** *the LIGO/Virgo official pipelines*

ALL – SKY SEARCHES



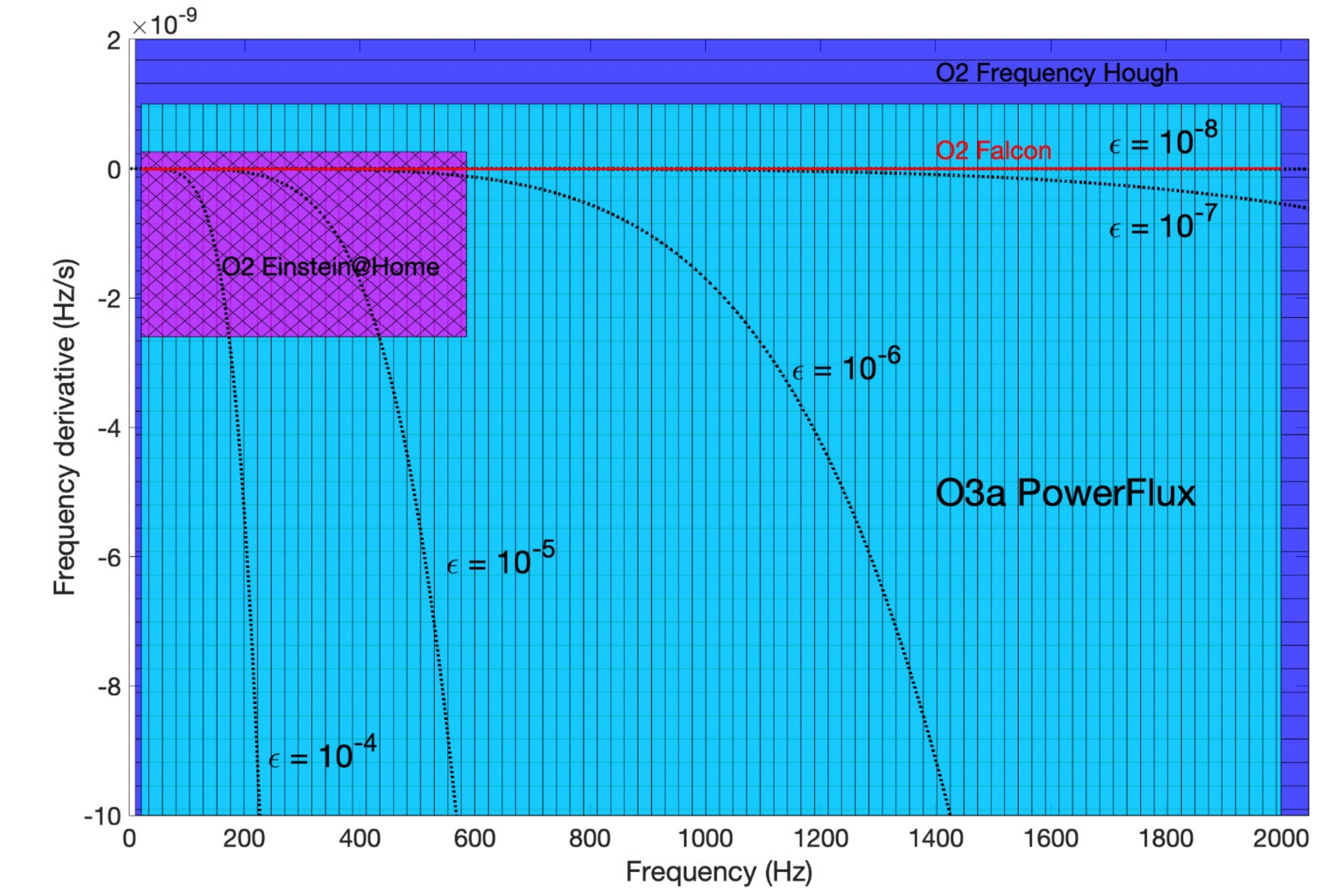
All-sky Search for Continuous Gravitational Waves from isolated Neutron Stars in the Early O3 LIGO Data



Upper limits on gravitational strain amplitude for O3a analysis and for previous O2 analyses.

ALL – SKY SEARCHES

All-sky Search for Continuous Gravitational Waves from isolated Neutron Stars in the Early O3 LIGO Data



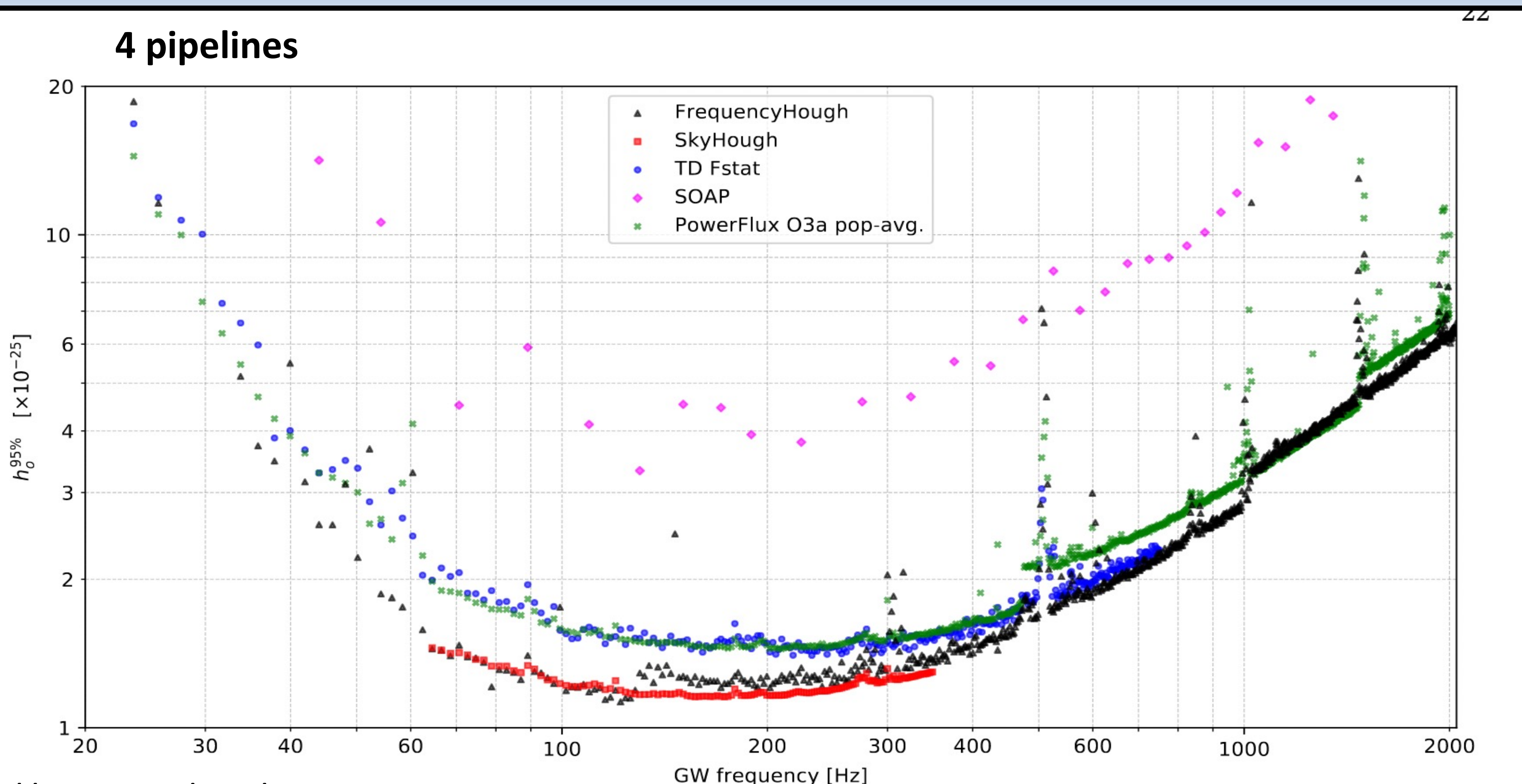
Covered Parameter space in O3a analys and in previous O2 analyses.

https://arxiv.org/pdf/2107.00600.pdf

ALL – SKY SEARCHES

All-sky search for continuous gravitational waves from isolated neutron stars using Adv LIGO and Adv Virgo O3 data

4 pipelines

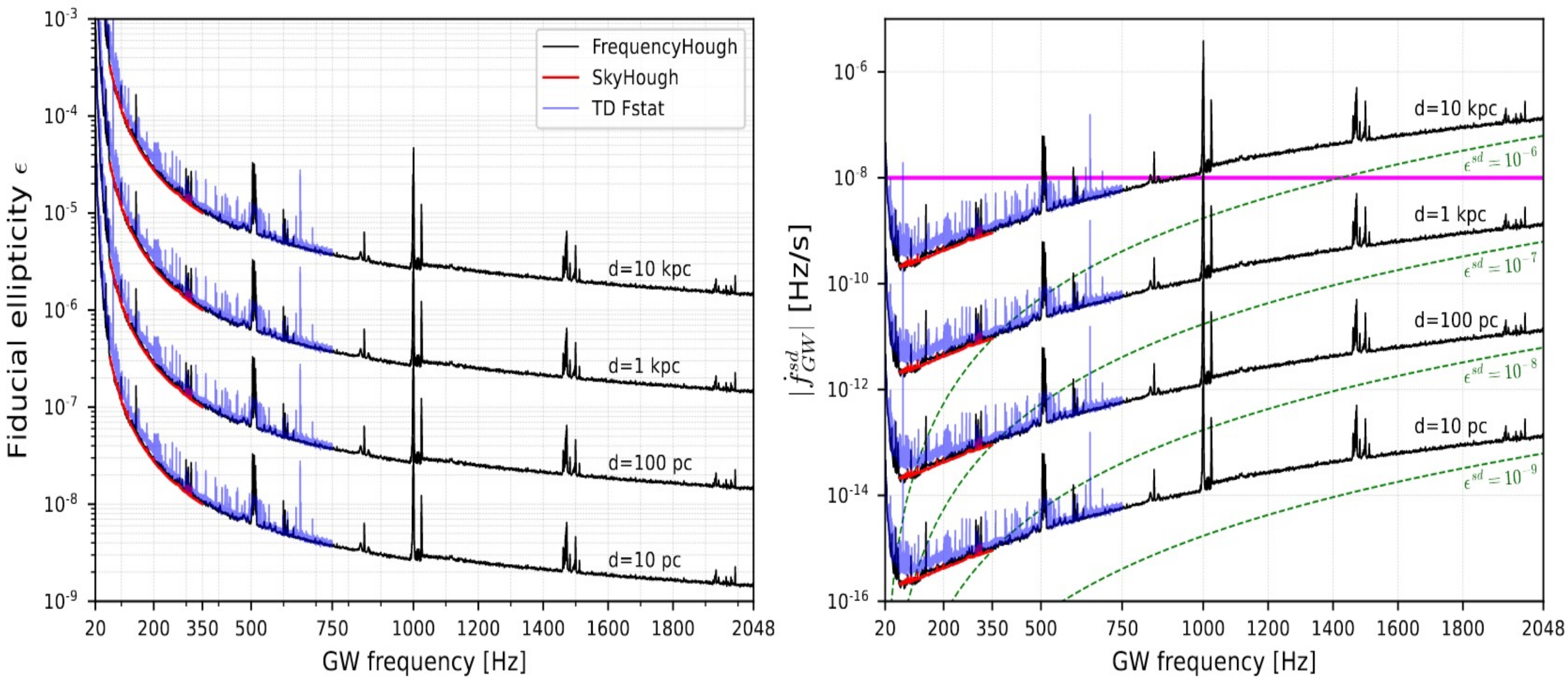


https://arxiv.org/pdf/2201.00697.pdf

FIG. 15. Comparison of 95% confidence upper limits on GW amplitude h_0 obtained by the *FrequencyHough* pipeline (black triangles), the *SkyHough* pipeline (red squares), the *Time-Domain $\mathcal{F}$-statistic* pipeline (blue circles), and the *SOAP* pipeline (magenta diamonds). Population-averaged upper limits obtained in [101] using the O3a data are marked with dark-green crosses. To enhance visibility, we do not show the error estimates of h_0 in this plot; additionally, the data is divided in 2 Hz bins, and the median of h_0 values within each bin is presented.

Results of O3 analysis for CW All-Sky searches

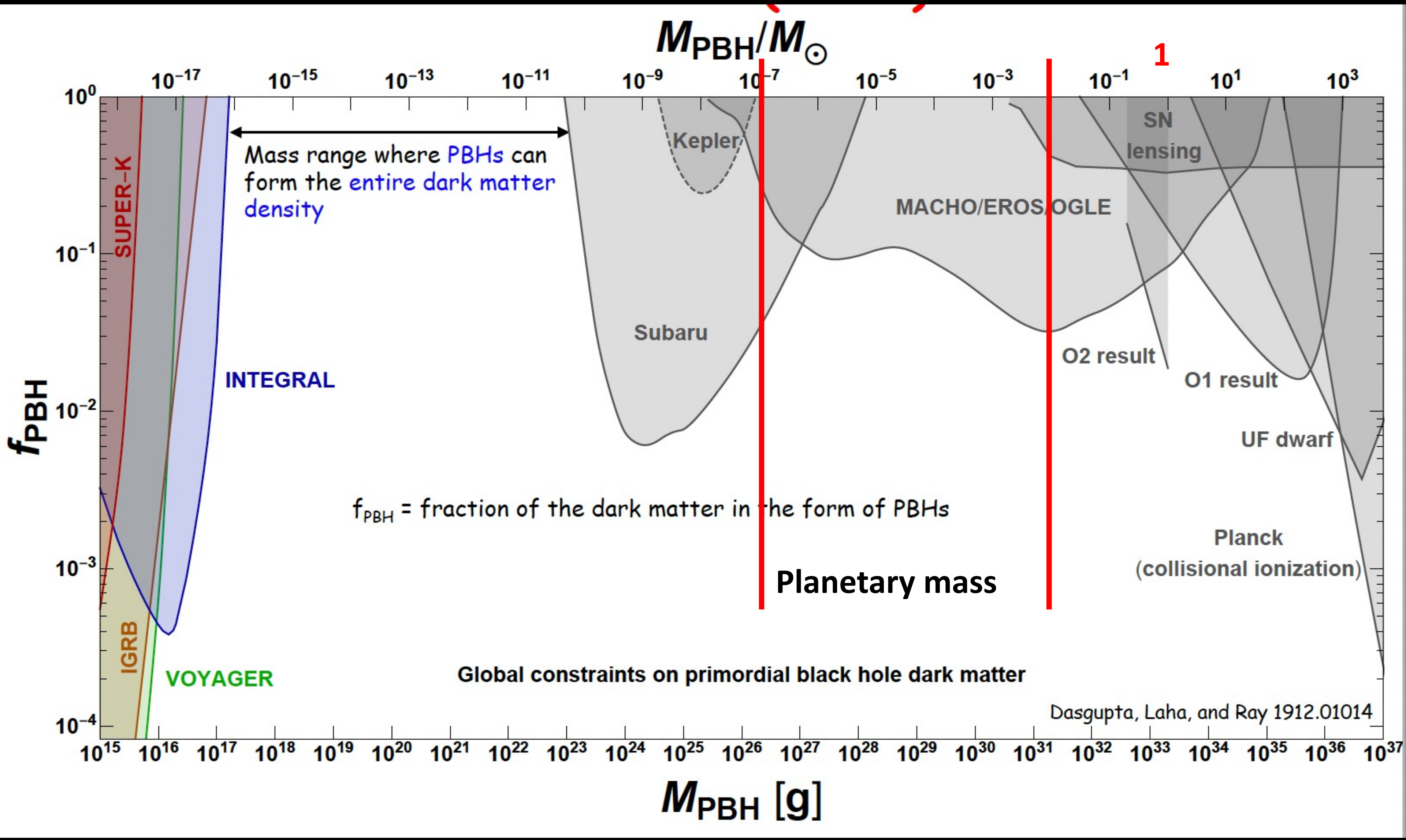
https://arxiv.org/pdf/2201.00697.pdf



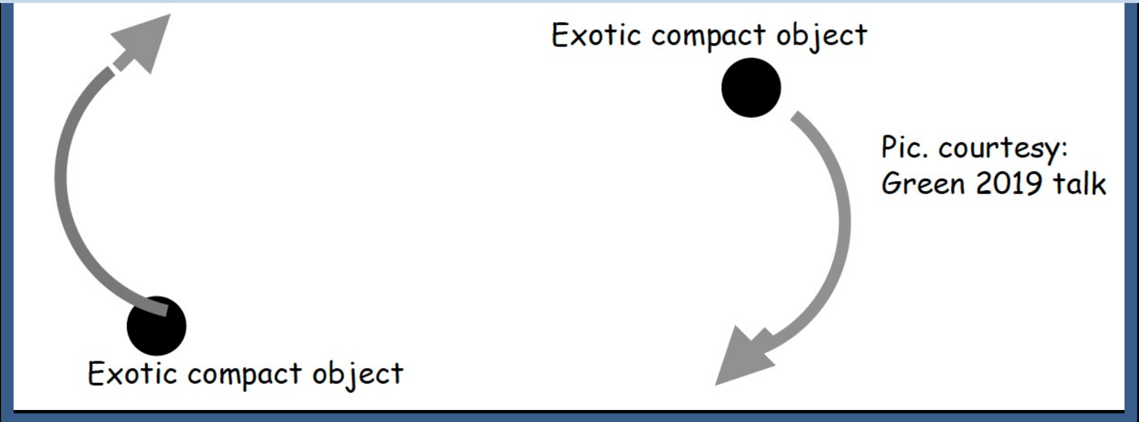
Assuming all rotational energy goes into GW

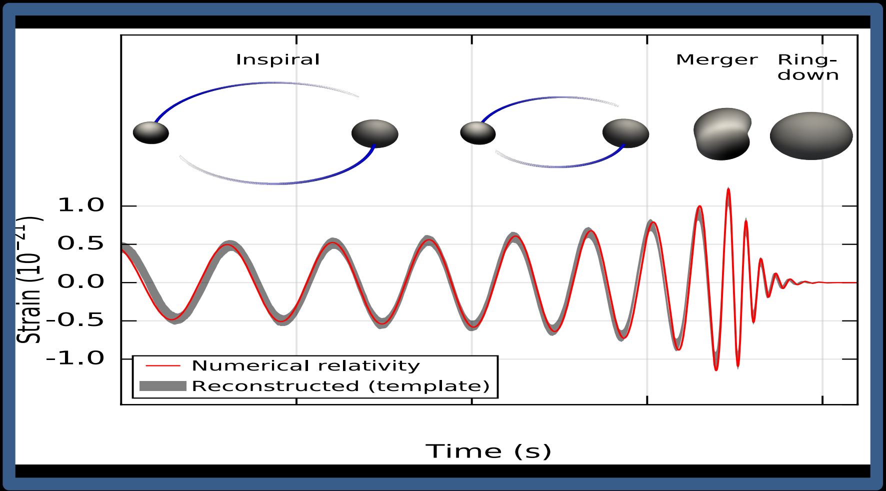
$$\epsilon = \frac{c^4}{4\pi^2 G}\frac{h_0 d}{I_{zz} f^2}.$$

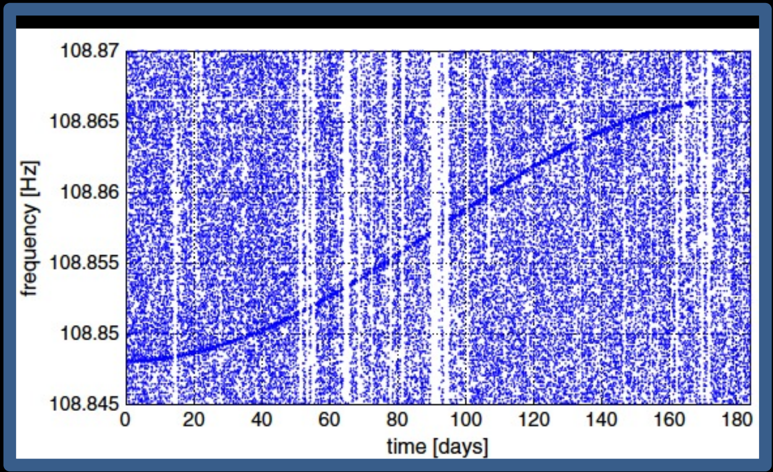
Searches for sub-solar mass black holes



Searches for sub-solar mass black holes







Seconds – Minutes - Hours - Days – Months - Years

(10^{-1} – 10^{2}) $M_\odot$

(10^{-7} – 10^{-2}) $M_\odot$

Results of O3 analysis for CW All-Sky searches:

PBHs searches

https://arxiv.org/pdf/2201.00697.pdf

We also place constraints on the rates and abundances of nearby inspiraling **planetary- and asteroid-mass primordial black holes** that could give rise to CW signals.

GW signals from inspiraling PBH binaries with chirp masses less than $O(10^{-5})$ solar masses and GW frequencies less than 250 Hz would be identical to those arising from non-axisymmetric rotating NSs.

PRD 100, 024004 (2019)

Using the Frequency Hough upper limits, which cover the widest range of spin-down/spin-up, we obtain constraints on highly asymmetric mass ratio binary systems, assuming that one object in the binary has a mass m1 = 2.5 solar masses

The analysis done is a good starting point for future detectors

All-sky search in early O3 LIGO data for continuous gravitational-wave signals from unknown neutron stars in binary systems

Phys. Rev. D 103, 064017 – 12 March 2021

The search analyses the most sensitive frequency band of the LIGO detectors, **50–300 Hz.**

Binary orbital parameters are split into four regions, comprising **orbital periods of 3 to 45 days** and **projected semimajor axes of 2 to 40 light seconds.**

PRD 100, 024004 (2019)

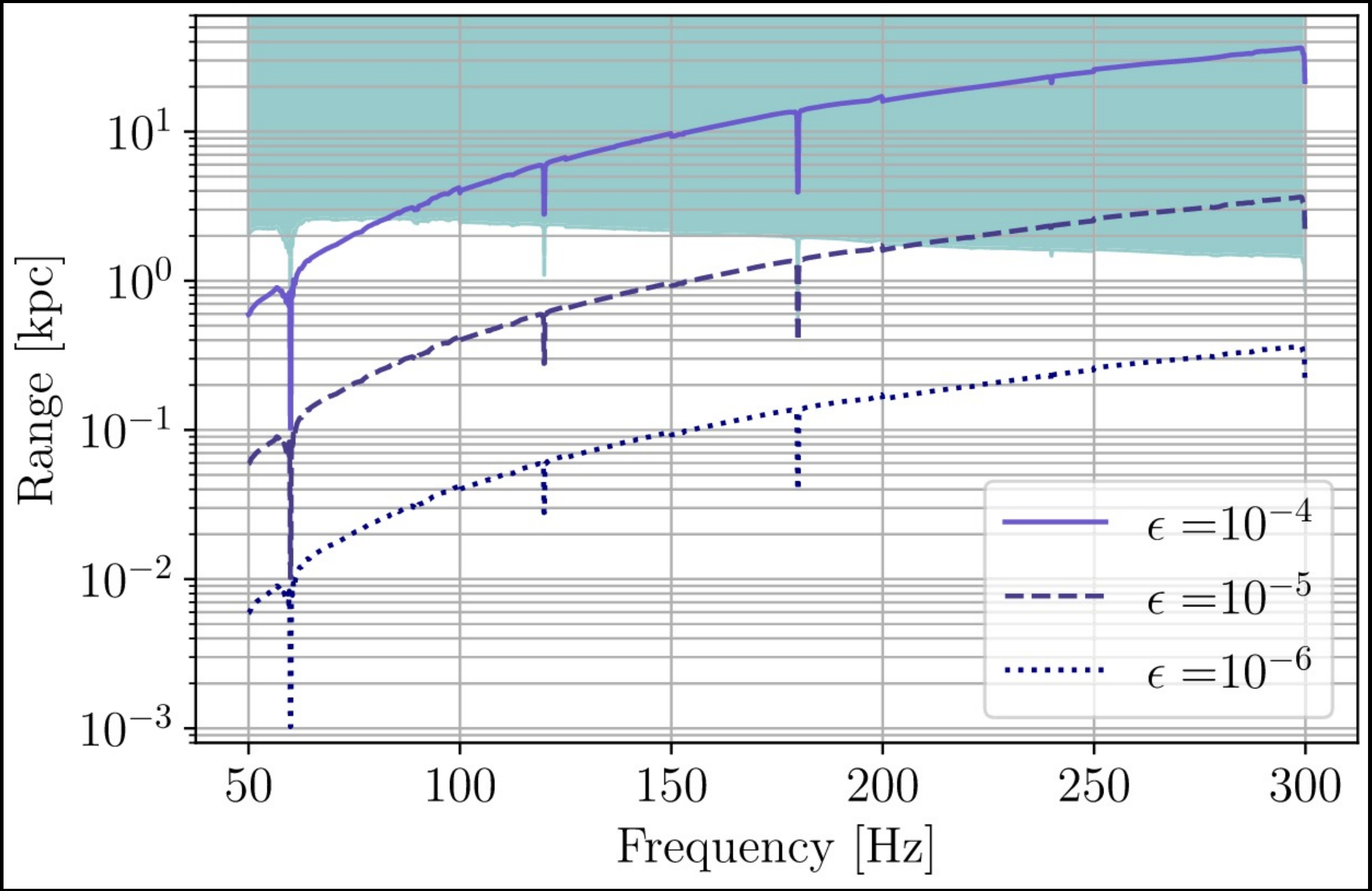
No detections are reported.

We estimate the **sensitivity** of the search using simulated CW signals, achieving the most sensitive results to date across the analyzed parameter space.

ALL – SKY BINARY SEARCHES

All-sky search in early O3 LIGO data for continuous gravitational-wave signals from unknown neutron stars in binary systems

Phys. Rev. D 103, 064017 – 12 March 2021



ALL – SKY BINARY SEARCHES

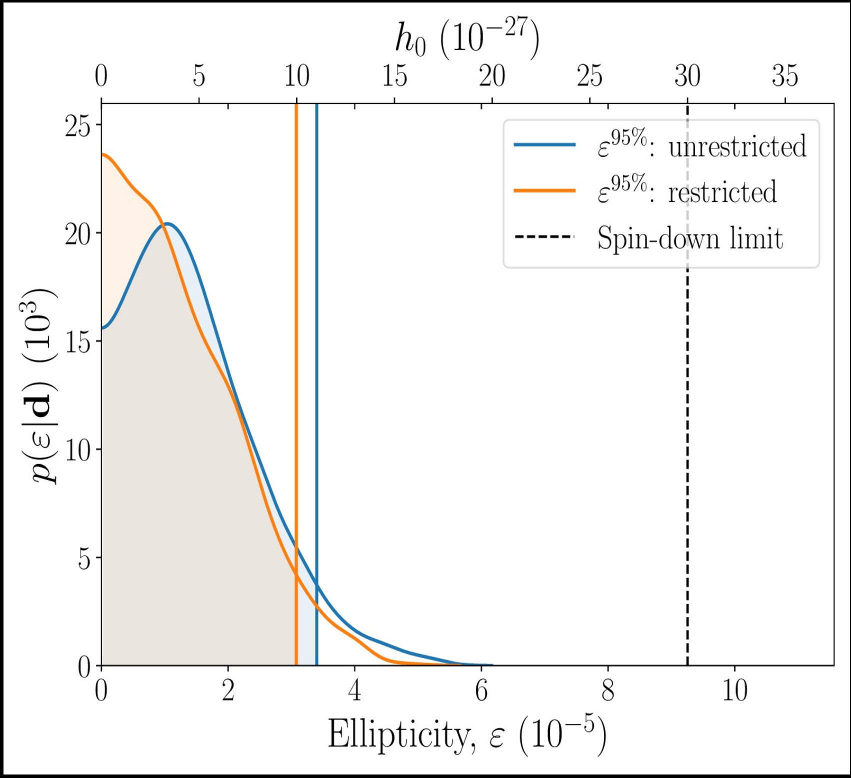
Other interesting results

Energetic young pulsar PSR J0537-6910 (“The Big Glitcher”). *ApJL 913, L27 (2021)*

X-ray pulsar, largest spin-down luminosity, frequent and strong glitches

In the analysis,
we have used NICER timing ephemeris

NICER:
Neutron star Interior Composition Explorer



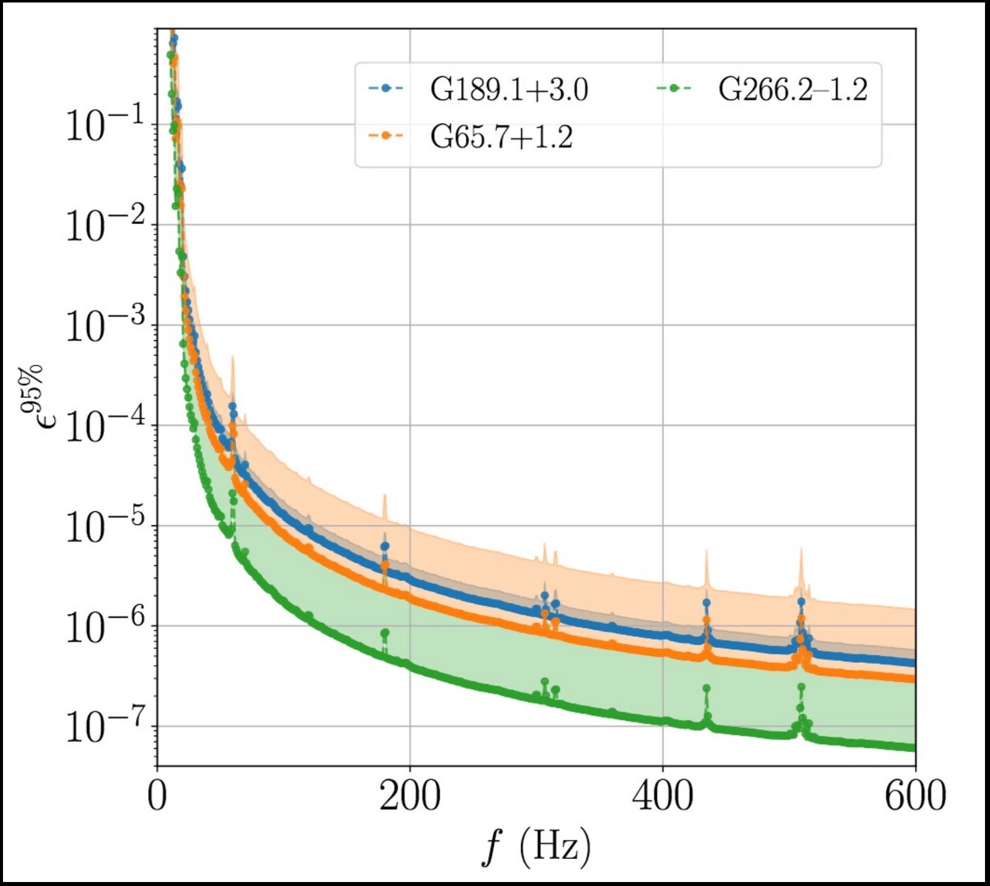
TARGETED SEARCHES

Other interesting results

Search for 15 young supernova remnants in frequency bands within [10, 2000] Hz

O3a HLV, ApJ 921, 80 (2021)
O3a HL, PRD 105, 082005 (2022)

No detections.
Constraints placed on ellipticities and
r-mode oscillation amplitudes

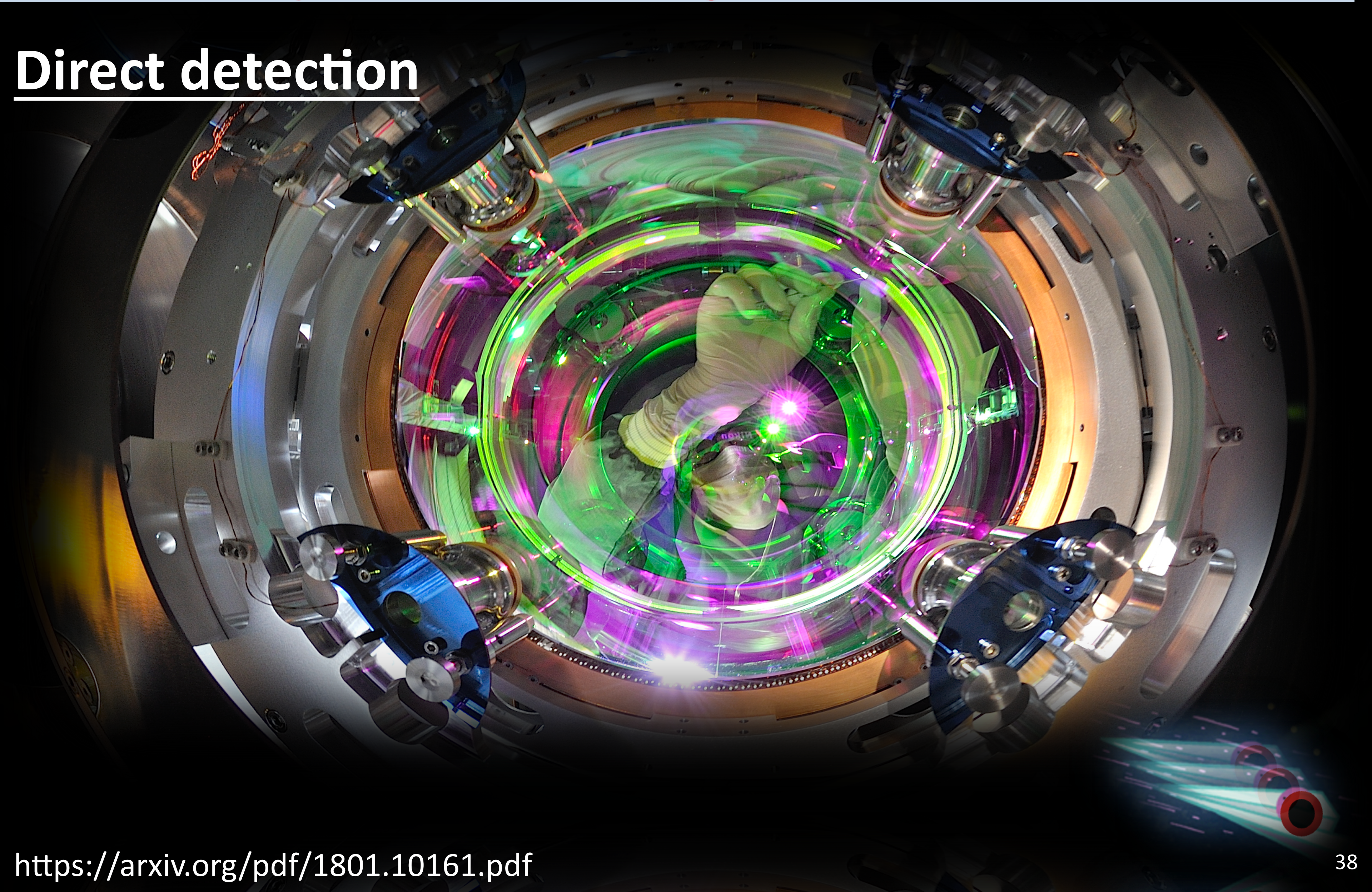


DIRECTED SEARCHES

Other interesting results

Dark photons: ultra-light dark matter

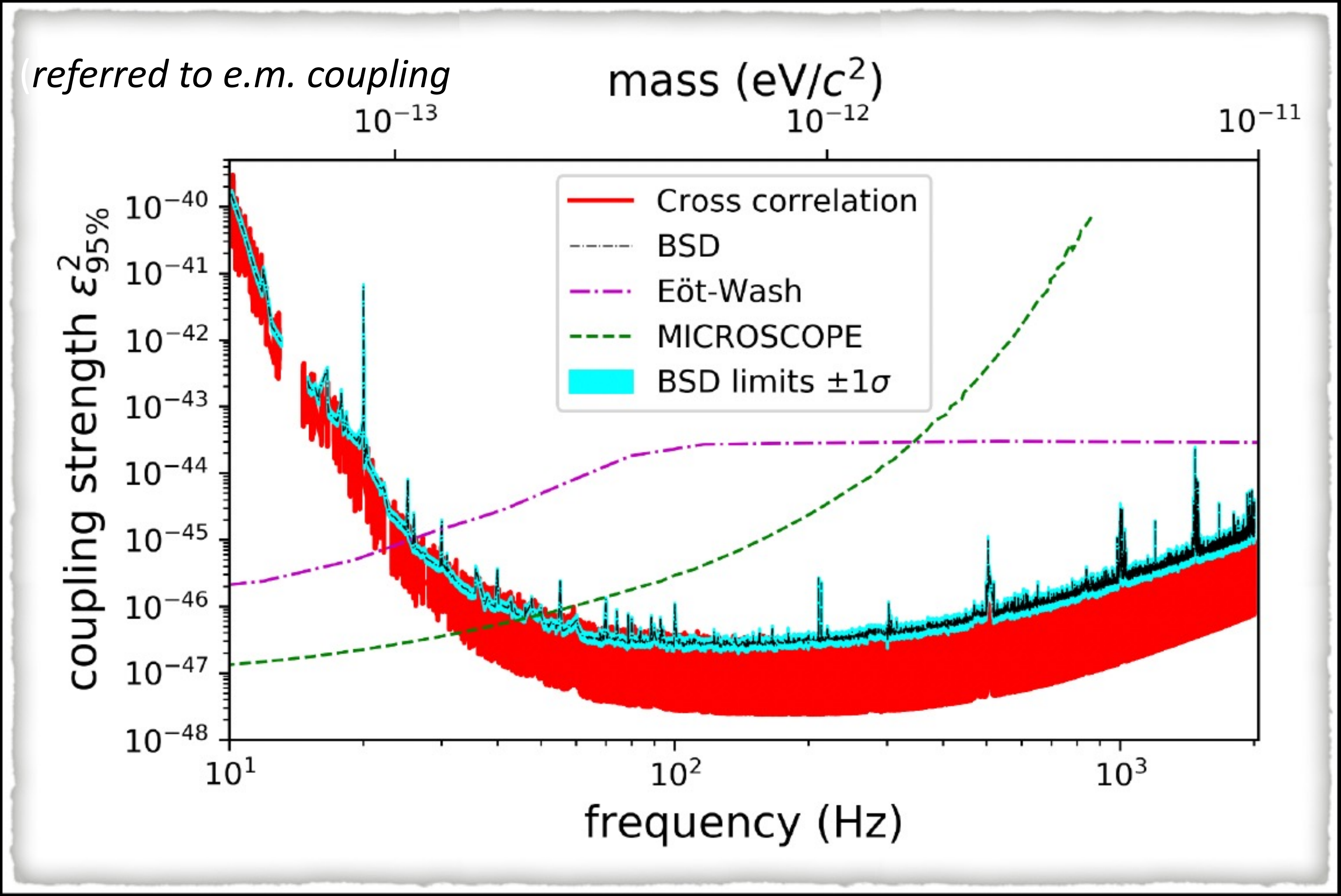
Direct detection



https://arxiv.org/pdf/1801.10161.pdf

Other interesting results: O3 searches for **Dark photons**

https://arxiv.org/abs/2105.13085



The explored dark photon mass range: $10^{-14} – 10^{-11}$ eV/c^2

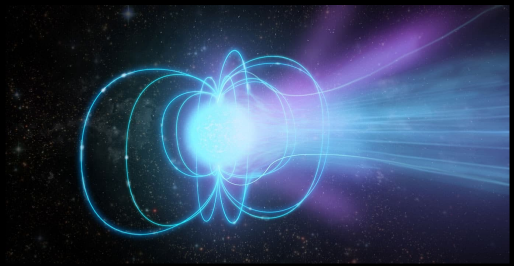
Post merger: what after GW170817 ?

- ***ApJL, 851:L16 (2017).*** We searched for short ($\lesssim$1 s) and intermediate-duration ($\lesssim$500 s) signals, which includes gravitational-wave emission from a hypermassive NS or supramassive NS, respectively.

- ***ApJ 875:160 (2019).*** Here we focused on longer signal durations up until the end of the Second Advanced LIGO-Virgo Observing run, 8.5 days. The main physical scenario for such emission is the power-law spindown of a massive magnetar-like remnant.

In both cases, in agreement with theoretical estimates, we did not find significant signal candidates.

GW astronomy and the key to magnetar formation

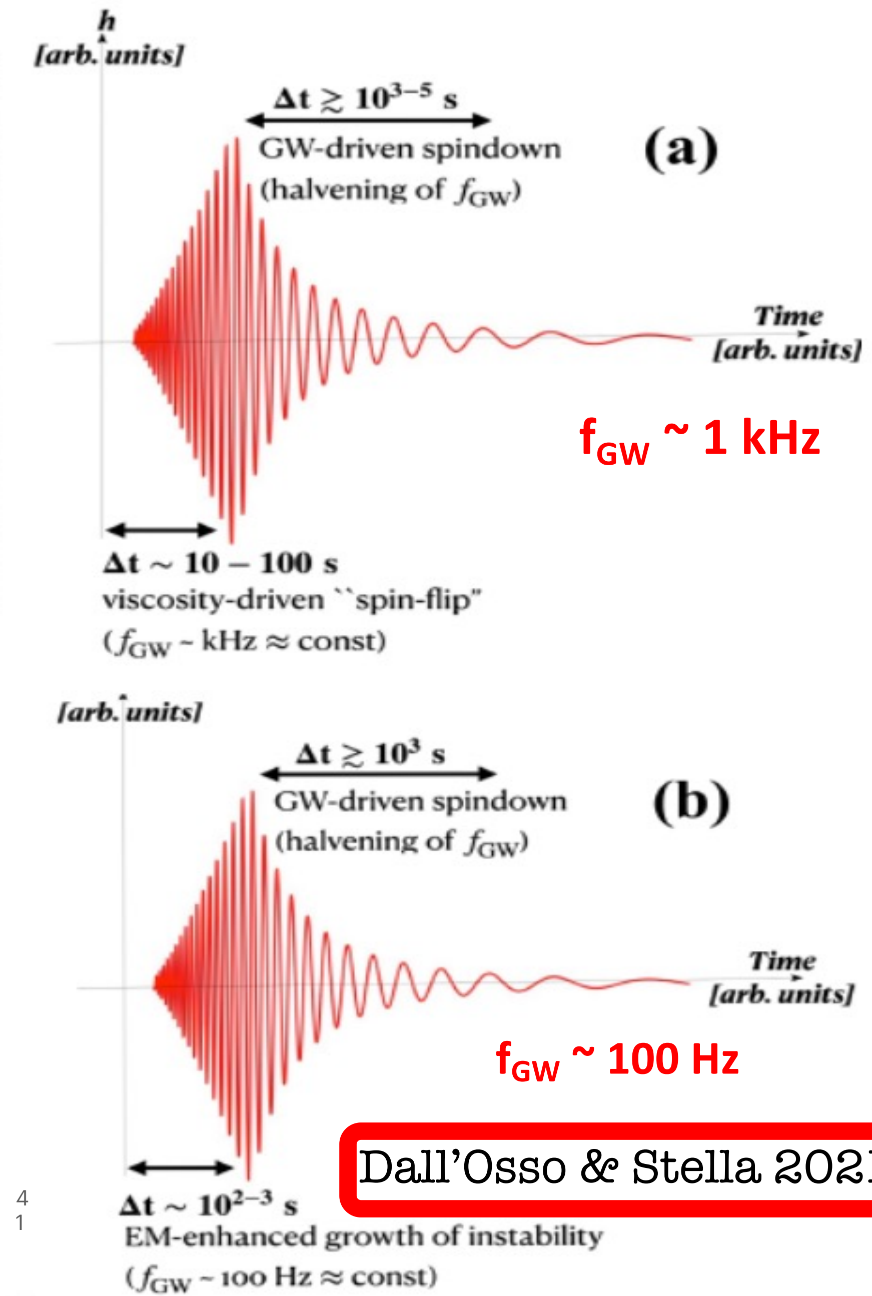


Mechanism 1

KEY GOAL:

developing ad-hoc search strategies
with maximal sensitivity
(horizon of a few Mpc)

Mechanism 2

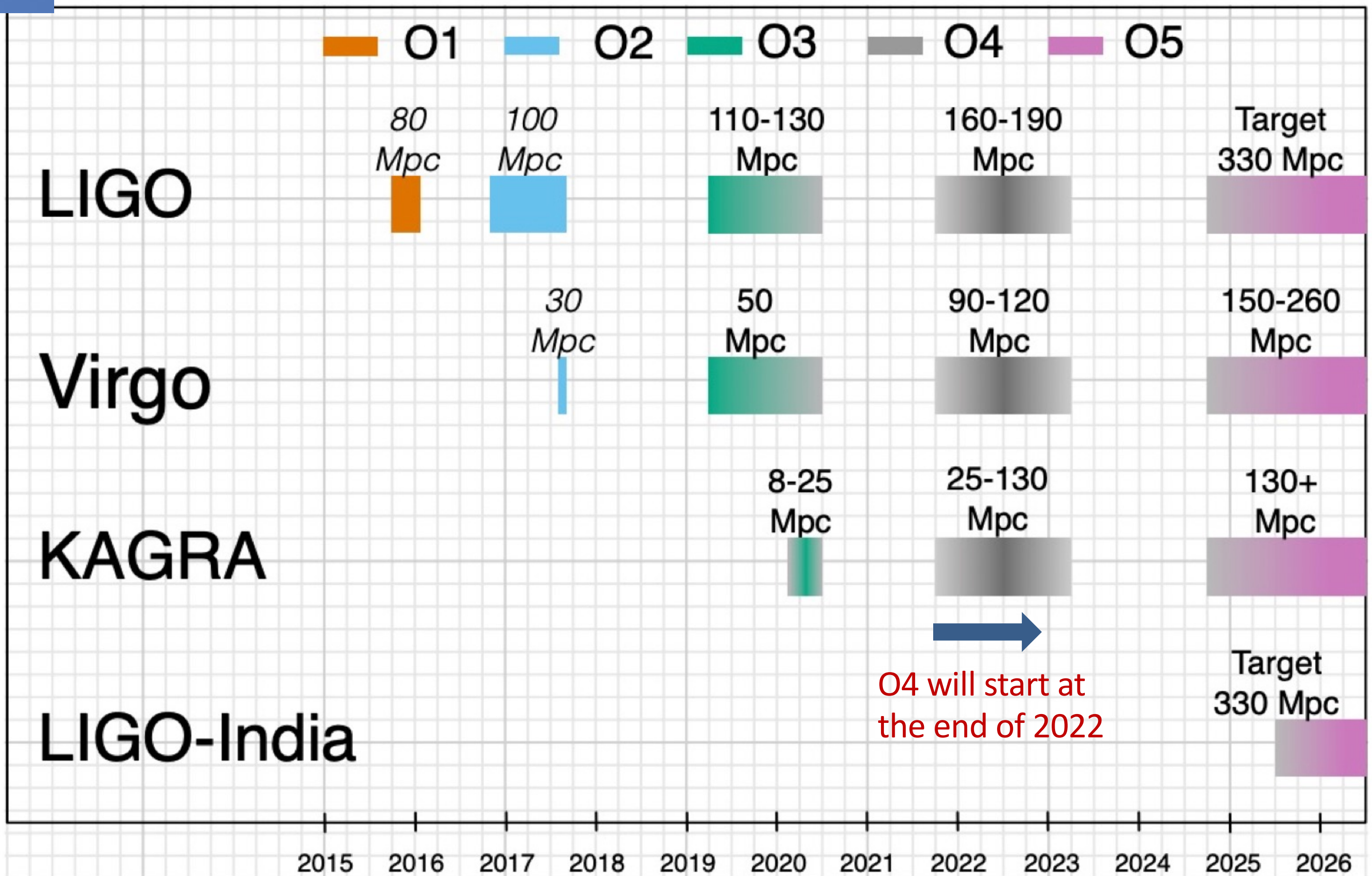


Dall'Osso & Stella 2021

More results from the LVK continuous wave group in upcoming talk by **David Keitel**

Narrowband searches for continuous and long-duration transient gravitational waves from known pulsars in the LIGO-Virgo third observing run - David Keitel ()

- Relax the assumption that GW emission is phase-locked to EM emission, allowing the GW frequency to vary from EM expectation in a narrow band +
- Search for long-duration (hours–months) transient GWs after pulsar glitches for 6 targets



Post-O5 2027-2034

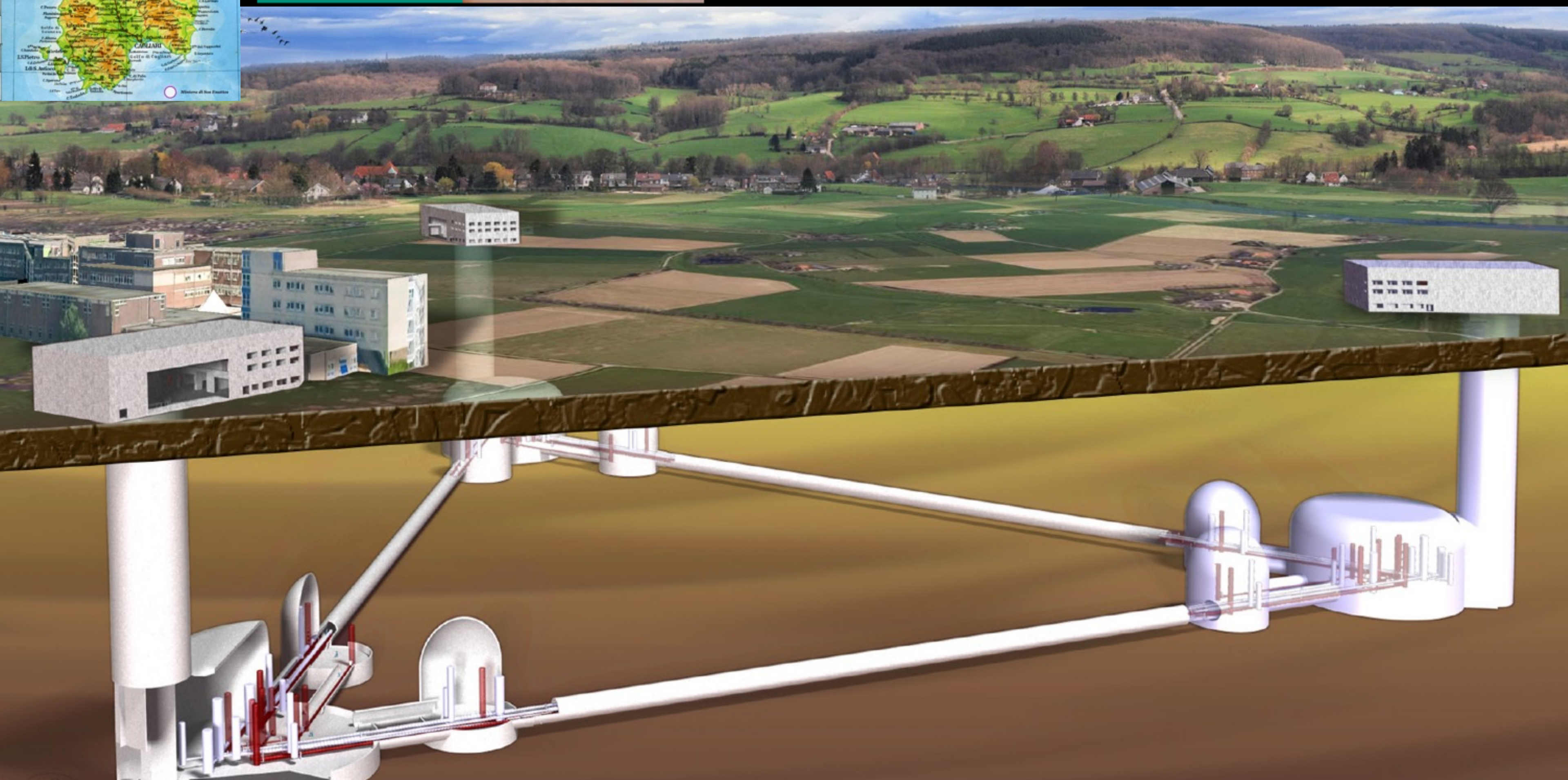
ET/Cosmic Explorer 2034 -

https://dcc.ligo.org/public/0094/P1200087/058/ObservingScenarios.pdf

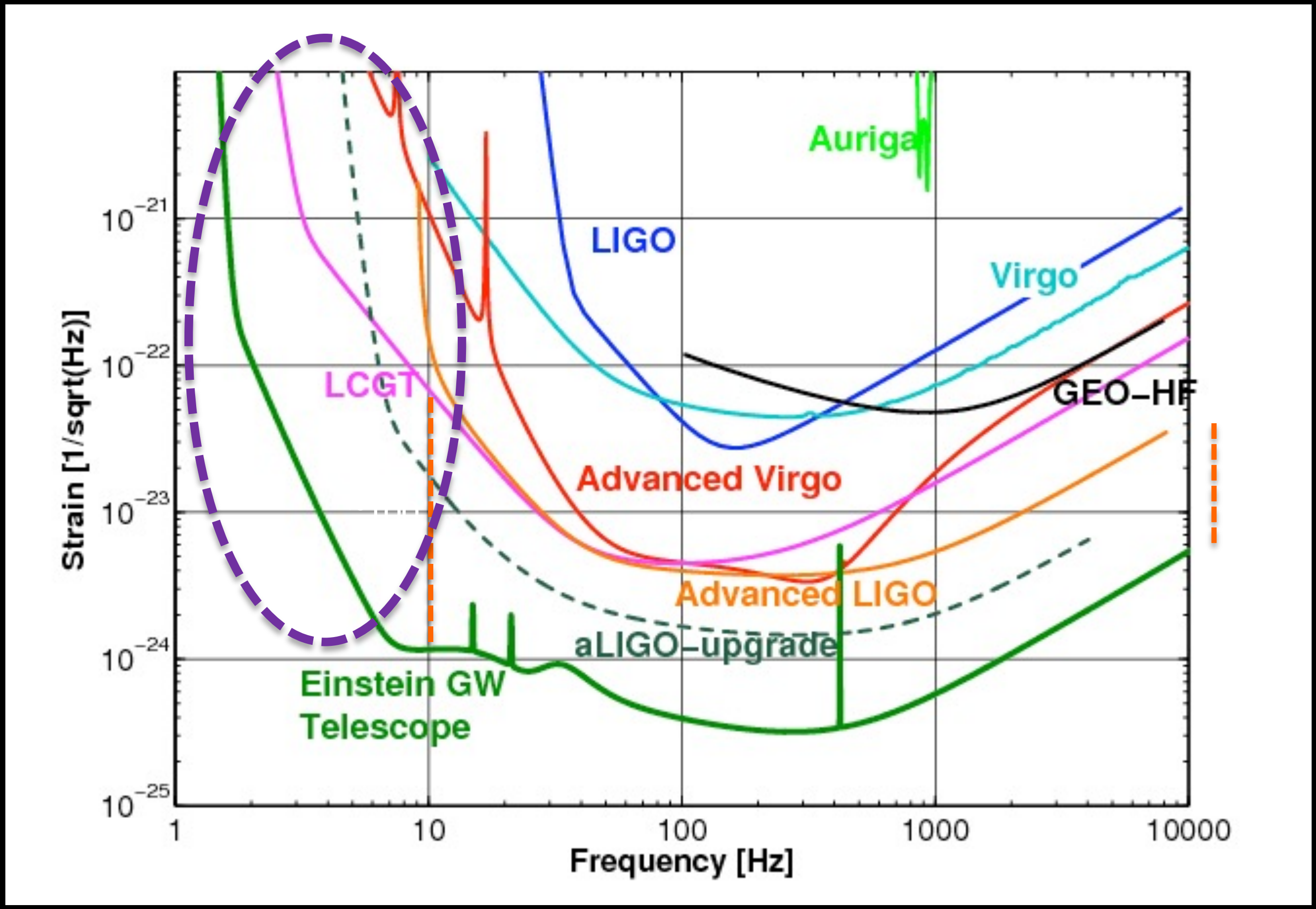
Einstein telescope

ET EINSTEIN TELESCOPE

Our work is clearly fundamental in particular to be ready with robust and sensitive procedures in view of 3rd generation detectors



> ~ 2030



Auriga
LIGO
Virgo
GEO–HF
LCGT
Advanced Virgo
Advanced LIGO
aLIGO–upgrade
Einstein GW
Telescope
Strain [1/sqrt(Hz)]
Frequency [Hz]
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
1
10
100
1000
10000

ET science case

https://arxiv.org/abs/1912.02622

- **Neutron star properties**
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- **Detection of new astrophysical sources**
  - core collapse supernovae
  - isolated neutron stars
  - stochastic background of astrophysical origi
- **The nature of compact objects**
  - near-horizon physics
  - tests of no-hair theorem
  - exotic compact objects
- **Multi-band and -messenger astronomy**
  - joint GW/EM observations (GRB, kilonova,...)
  - multiband GW detection (LISA)
  - neutrinos
- **Black hole properties**
  - origin (stellar vs. primordial)
  - evolution, demography
- **Dark matter**
  - primordial BHs
  - axion clouds, dark matter accreting on compact objects
  - Dark photons
  - Machos from microlensing
- **Tests of General Relativity**
  - post-Newtonian expansion
  - strong field regime
- **Stochastic backgrounds of cosmological origin**
  - inflation, phase transitions, cosmic strings
- **Dark energy and modifications of gravity on cosmological scales**
  - dark energy equation of state
  - modified GW propagation

Credit: Cristiano Palomba

Next science run will begin at the end of 2022/beginning of 2023.

Will last 1 year.
LVK analysis will be prepared and tested in the period 2022-2023 and done during 2024.

Some CW analysis might run after 3-6 months, producing results during the second part of 2023

Credit NASA

GWOSC : GW open Science Center

https://www.gw-openscience.org/

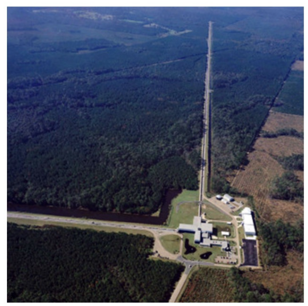
Gravitational Wave Open Science Center

Data▾ Software▾ Online Tools▾ Learning Resources▾ About GWOSC▾

The Gravitational Wave Open Science Center provides data from gravitational-wave observatories, along with access to tutorials and software tools.

LIGO Hanford Observatory, Washington

(Credits: C. Gray)



LIGO Livingston Observatory, Louisiana

(Credits: J. Giaime)

Virgo detector, Italy

(Credits: Virgo Col

News | Detections | Our science explained | Multimedia | Educational resources

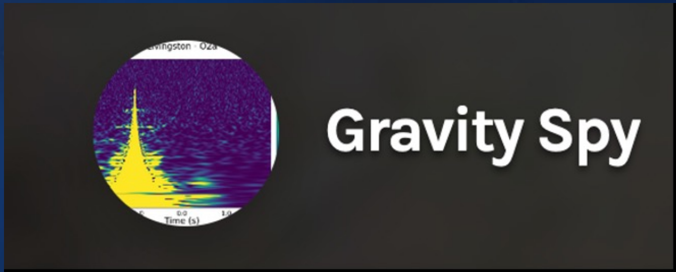
Intro to LIGO & Gravitational Waves | Science Summaries | Popular Articles | Fr

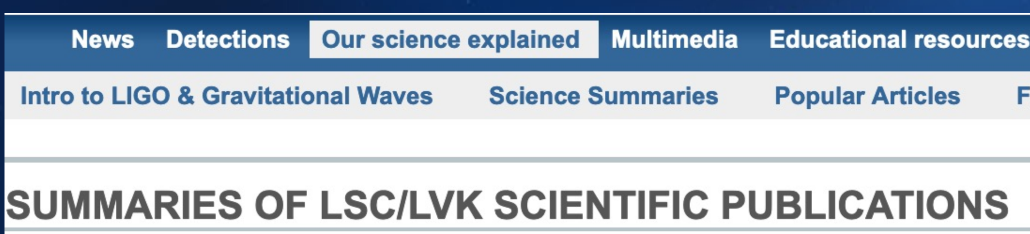
SUMMARIES OF LSC/LVK SCIENTIFIC PUBLICATIONS

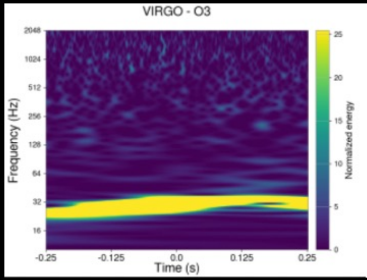
- **O3 Bulk Data Now Available (O3a+O3b+O3GK)**
- **GWTC-3 Catalog Data Now Available**
- **Start with a Learning Path**
- **Browse the Event Portal**
- **Join the email list**
- **Attend an Open Data Workshop**

GWOSC : GW open Science Center

https://www.gw-openscience.org/

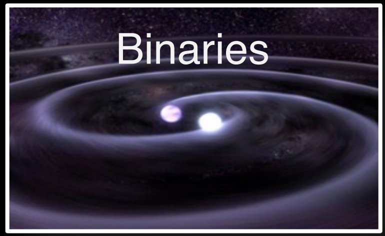




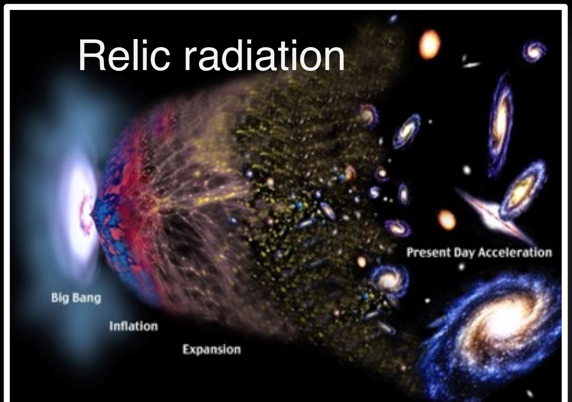


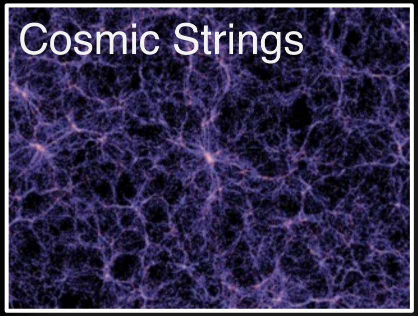
Conclusions

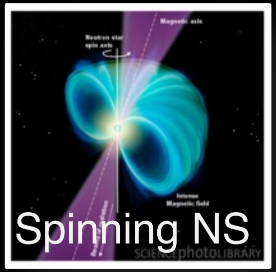
- We live in highly exciting times, many interesting progresses and results have been made in the past years.
- A strong effort is ongoing to unveil sources whose fingerprint is hidden in the data, and this is based on joint experimental, data analysis and theoretical work



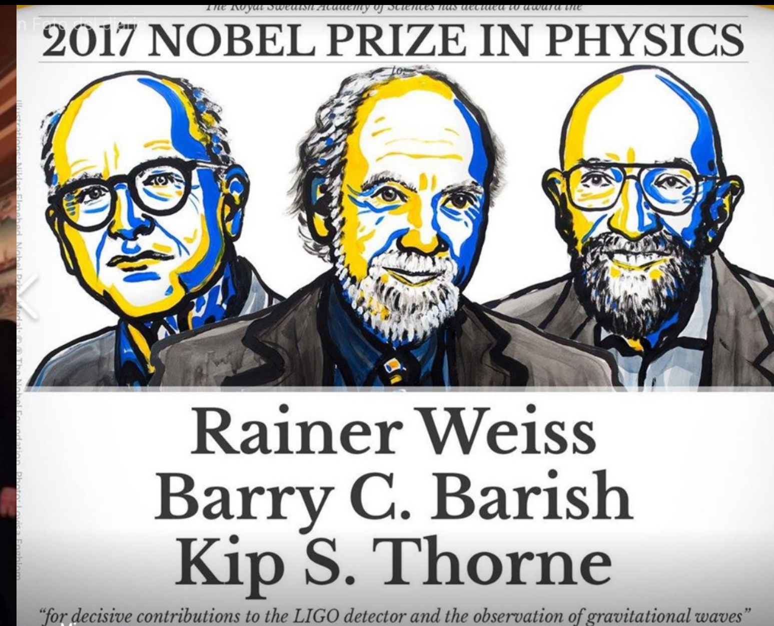
- Multi messenger astronomy has an important role in many cases



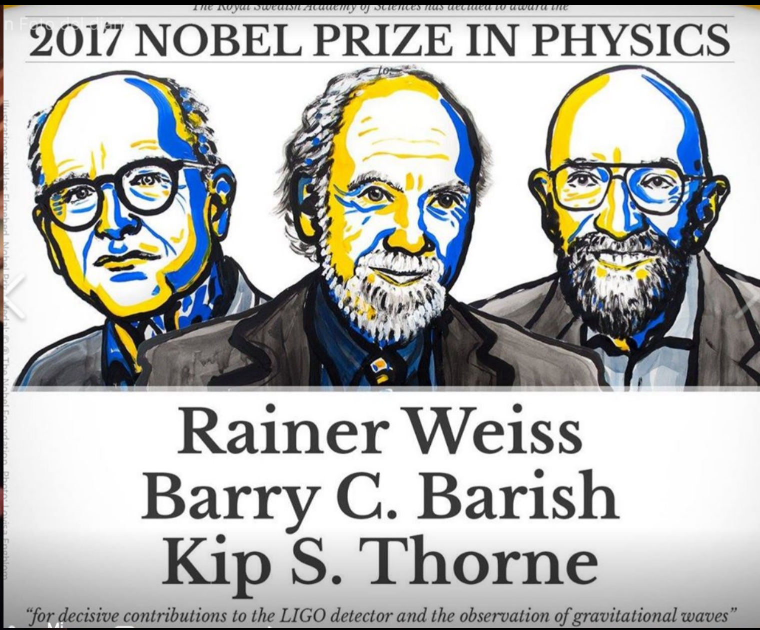




December 2017




December 2017


2017 NOBEL PRIZE IN PHYSICS
Rainer Weiss
Barry C. Barish
Kip S. Thorne
"for decisive contributions to the LIGO detector and the observation of gravitational waves"

Stay tuned !