STATUS AND PERSPECTIVES OF CONTINUOUS GRAVITATIONAL-WAVE SEARCHES WITH LIGO AND VIRGO

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BIST Barcelona Institute of Science and Technology

IFAE Pizza seminar, 16 Mar 2022

GRAVITATIONAL WAVE SOURCES

<table>
<tr><th></th><th>Modeled waveform</th><th>Unmodeled waveform</th></tr>
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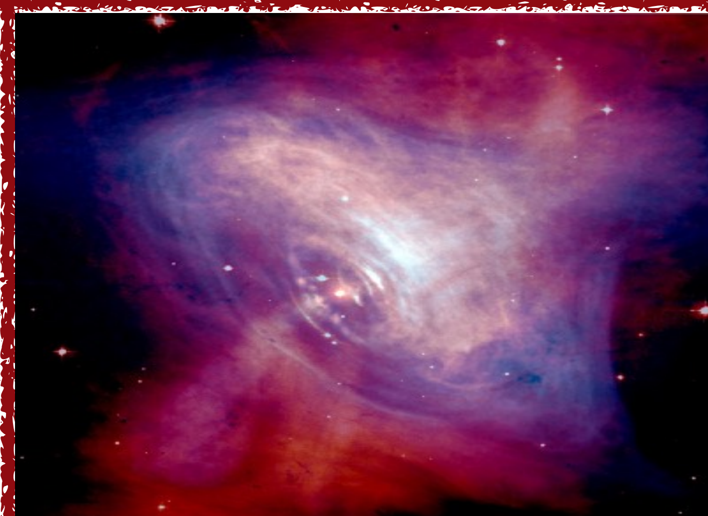
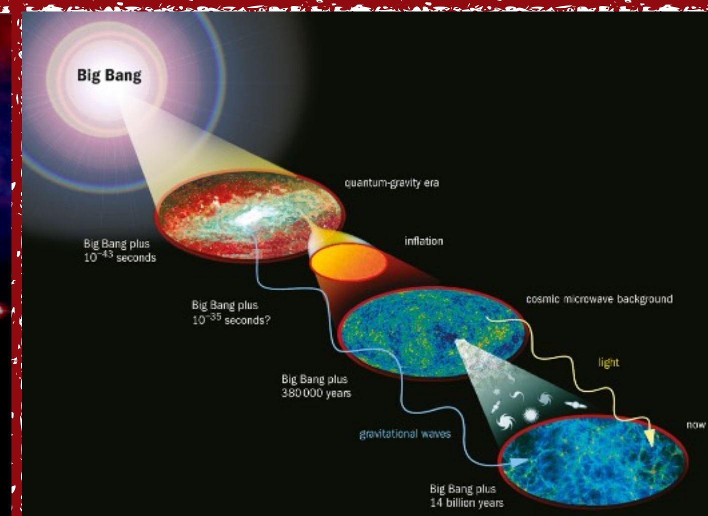
T ~ months or years</td><td></td><td>
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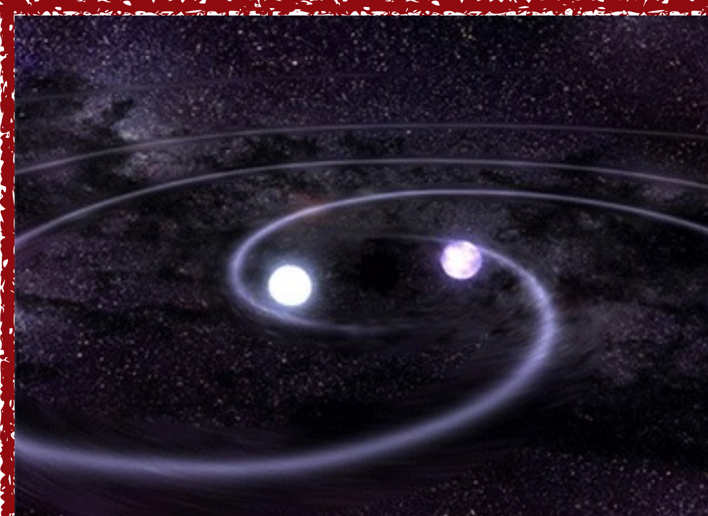
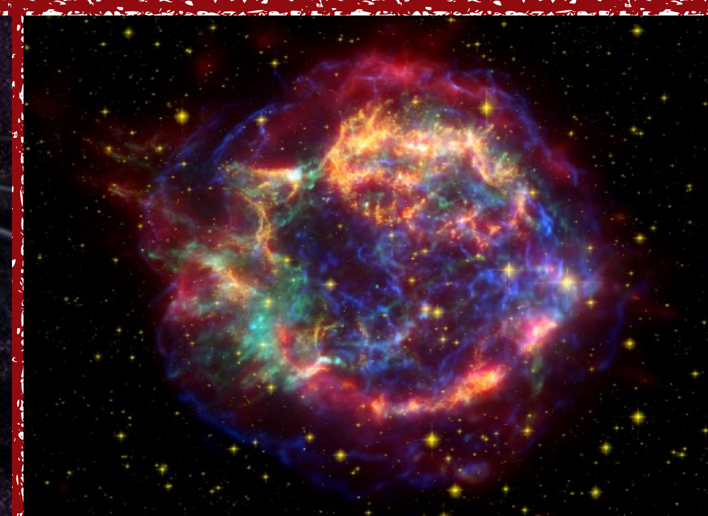
T ~ up to minutes</td><td></td><td></td></tr>
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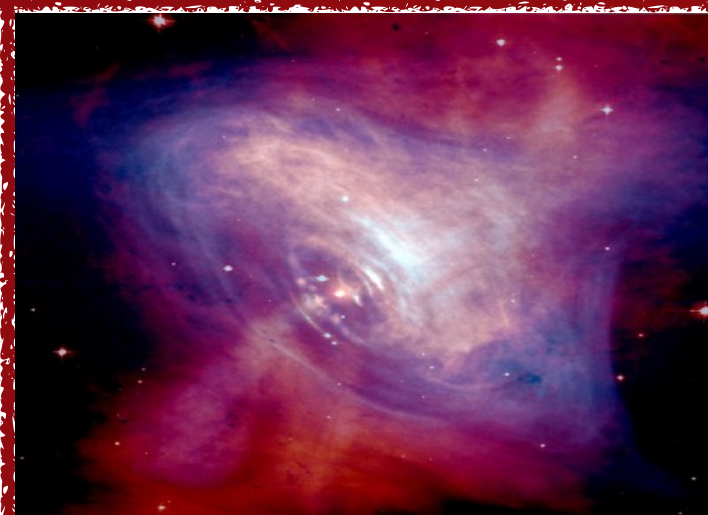
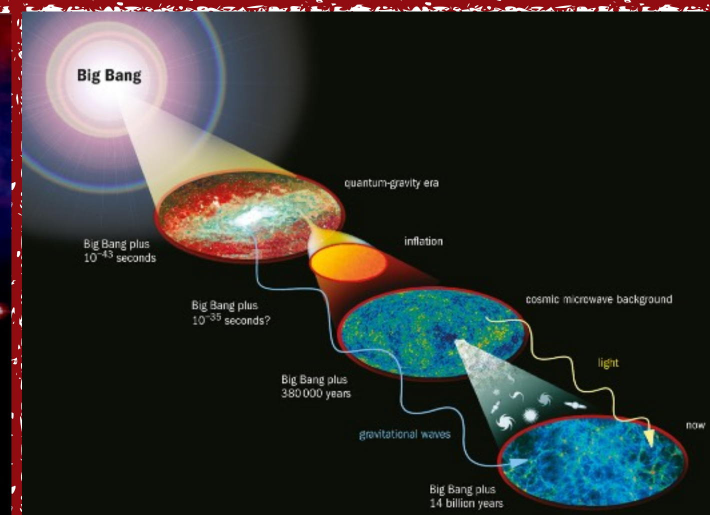
$T \sim$ months or years</td><td></td><td>
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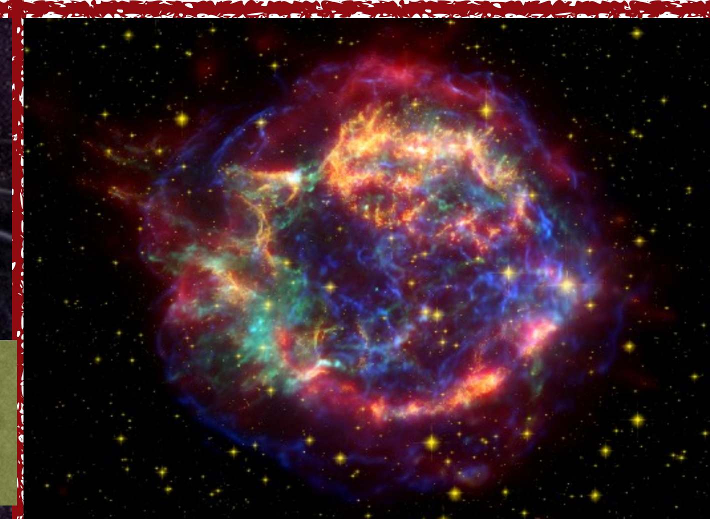
$h_0 \sim 10^{-21}$</td><td></td></tr>
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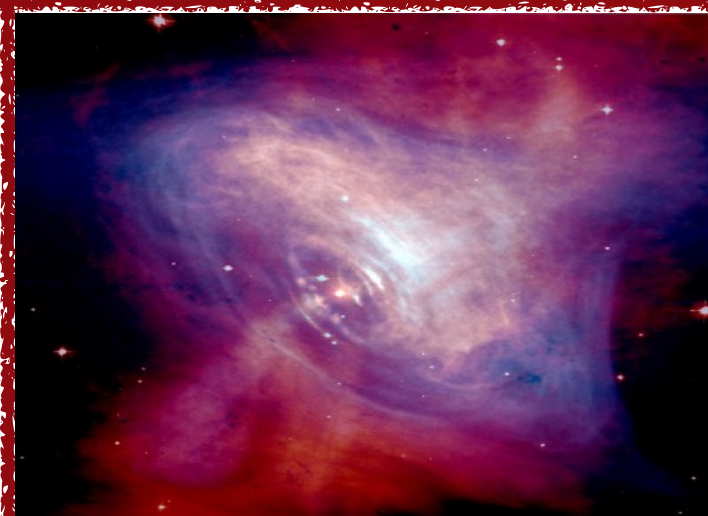
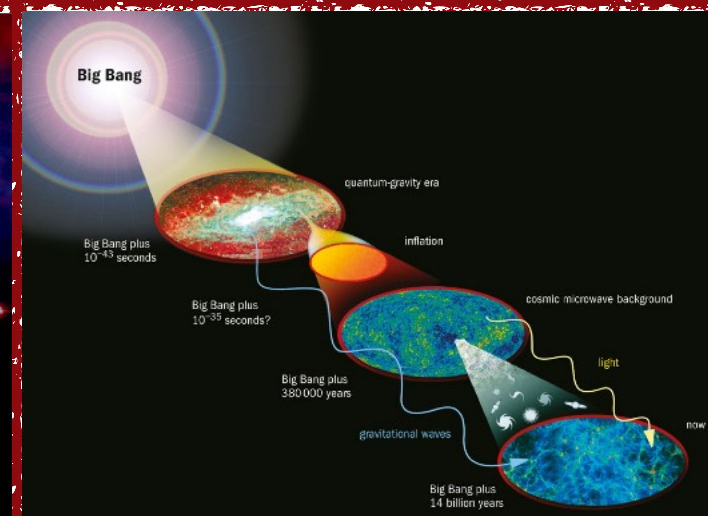
$T \sim$ months or years</td><td></td><td>
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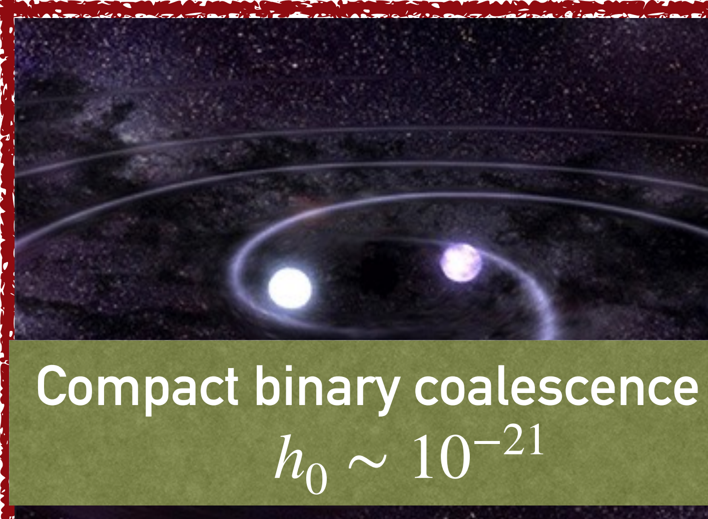
$T \sim$ up to minutes</td><td>
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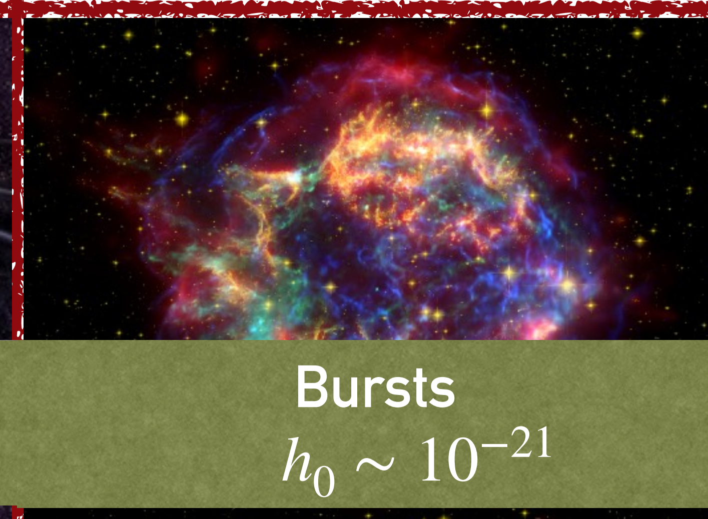
$h_0 \sim 10^{-21}$</td><td>
Bursts
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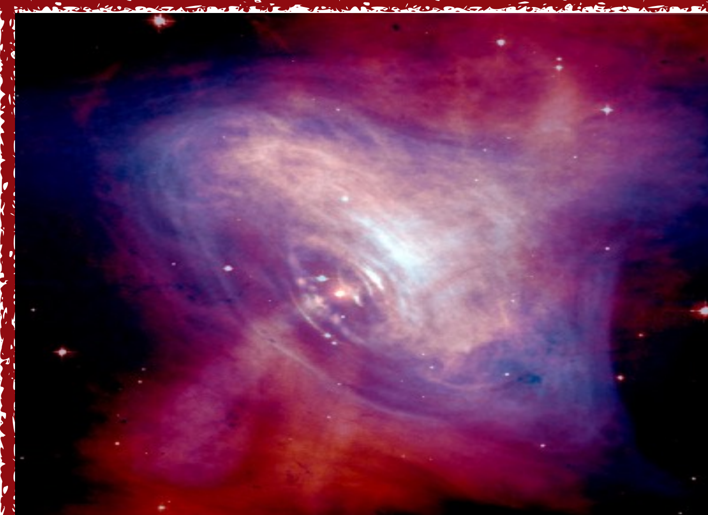
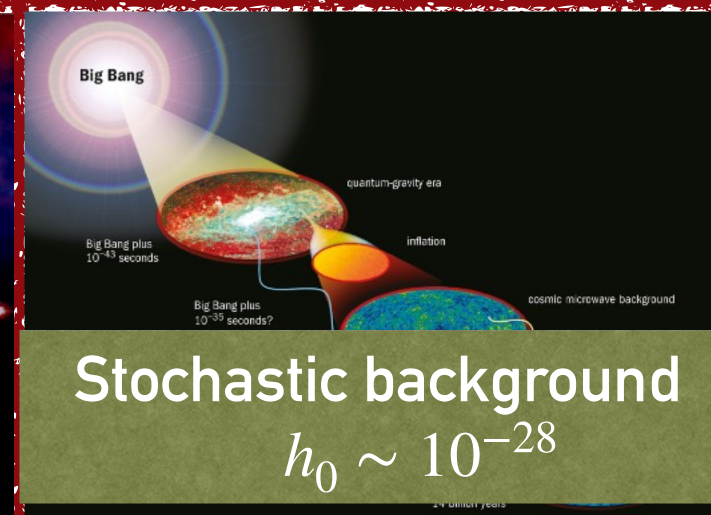
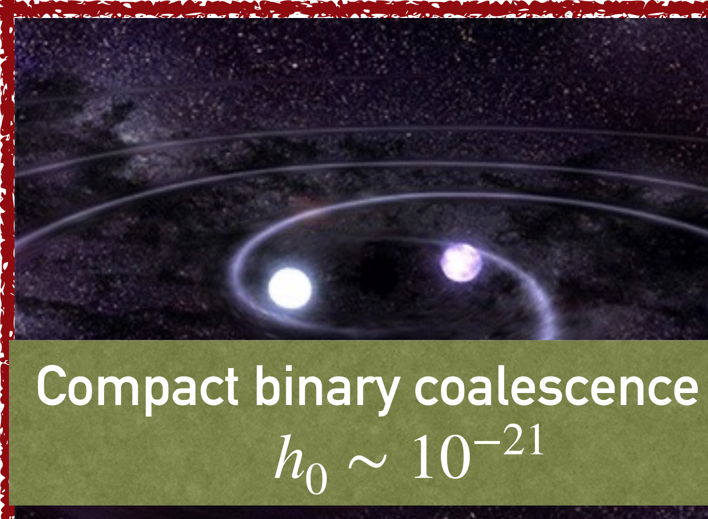
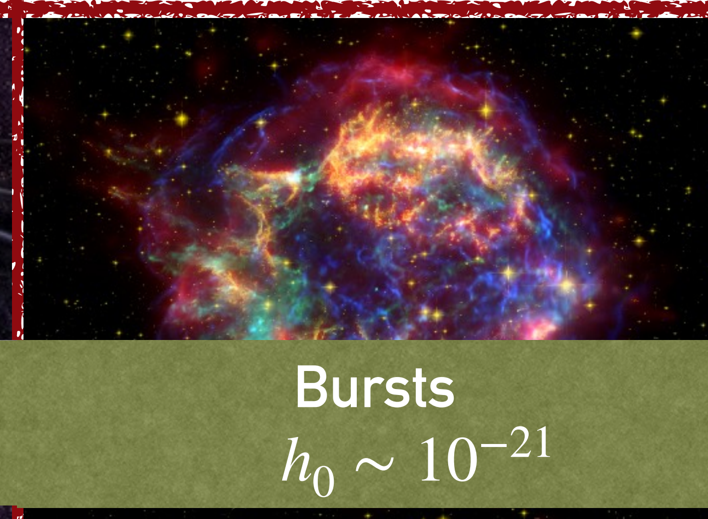
Long-lived *$T \sim$ months or years*		 Stochastic background $h_0 \sim 10^{-28}$
Transients *$T \sim$ up to minutes*	 Compact binary coalescence $h_0 \sim 10^{-21}$	 Bursts $h_0 \sim 10^{-21}$

GRAVITATIONAL WAVE SOURCES

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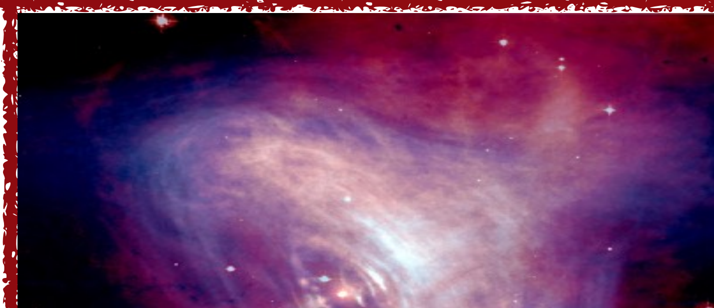
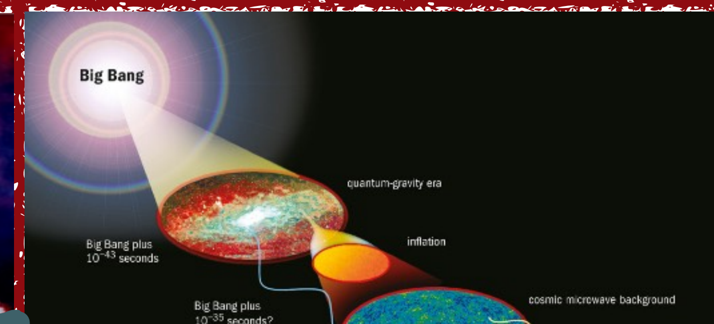
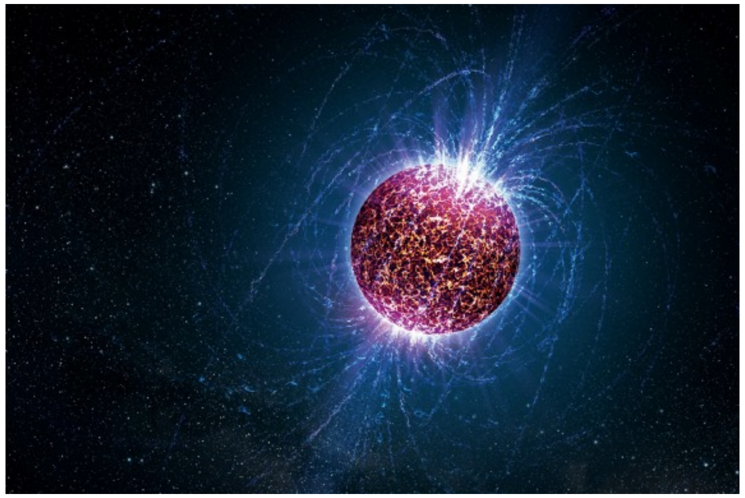
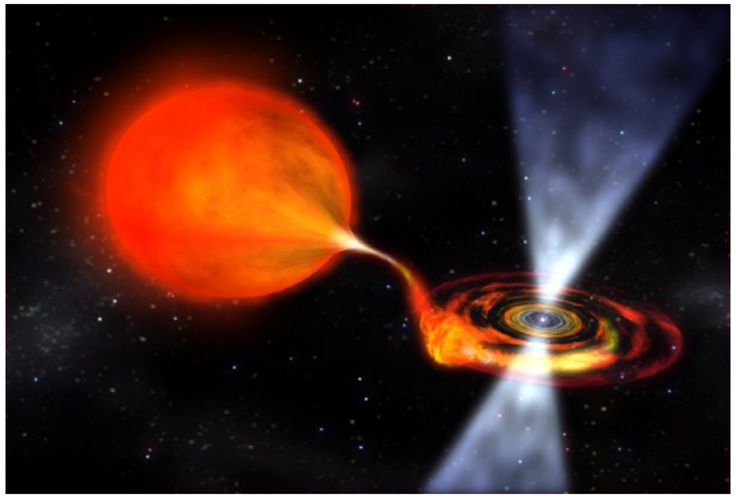
Long-lived $T \sim$ *months or years*	 **Continuous waves** $h_0 \leq 10^{-26}$	 **Stochastic background** $h_0 \sim 10^{-28}$
Transients $T \sim$ *up to minutes*	 **Compact binary coalescence** $h_0 \sim 10^{-21}$	 **Bursts** $h_0 \sim 10^{-21}$

WHAT IS A CONTINUOUS WAVE (CW)?





Credit: C. Reed, Penn State/Mc Gill University

Persistent signal (long-lived)

Produced by a nearly **periodic** mass quadrupole moment variation

Expected sources

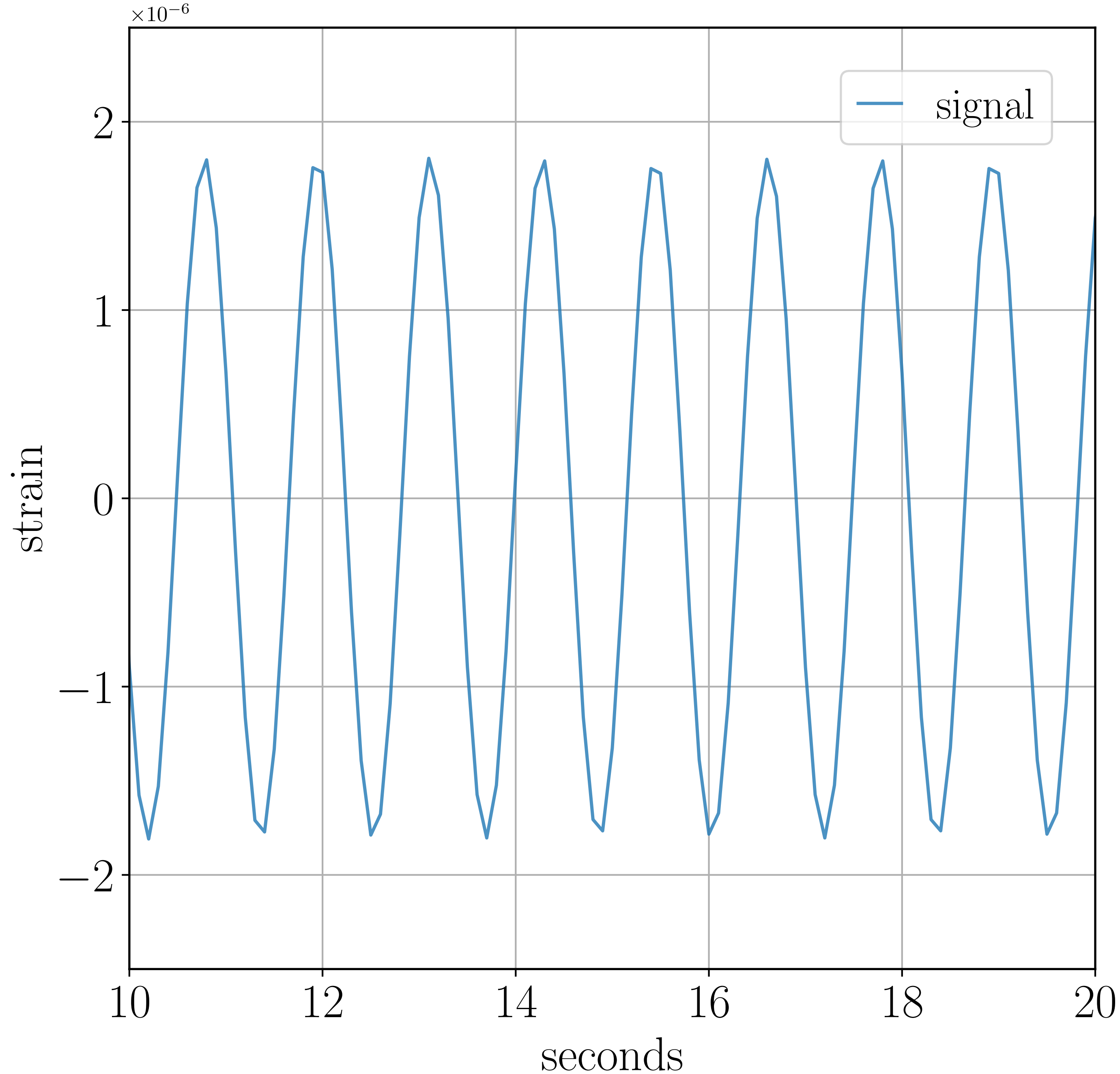
Non-axisymmetric isolated neutron stars (NS)
NSs in binary systems (e.g. in accreting systems)
More objects: bosons clouds around spinning BH, newborn NSs

Expected strain

$$h_0 \cong 10^{-27} \left(\frac{I_{zz}}{10^{38}\ \mathrm{kg\ m^2}} \right) \left(\frac{10\,\mathrm{kpc}}{d} \right) \left(\frac{f}{100\ \mathrm{Hz}} \right)^2 \left(\frac{\epsilon}{10^{-6}} \right) \ll h_{0_{CBC}}$$

[For a CW review: Lasky PASA 32, pp. 34 (2015); Riles Mod Phys Lett A 32, No. 39, 1730035 (2017); Piccinni, 2202.01088 (2022)]

WHAT WE ACTUALLY SEE IN THE DATA



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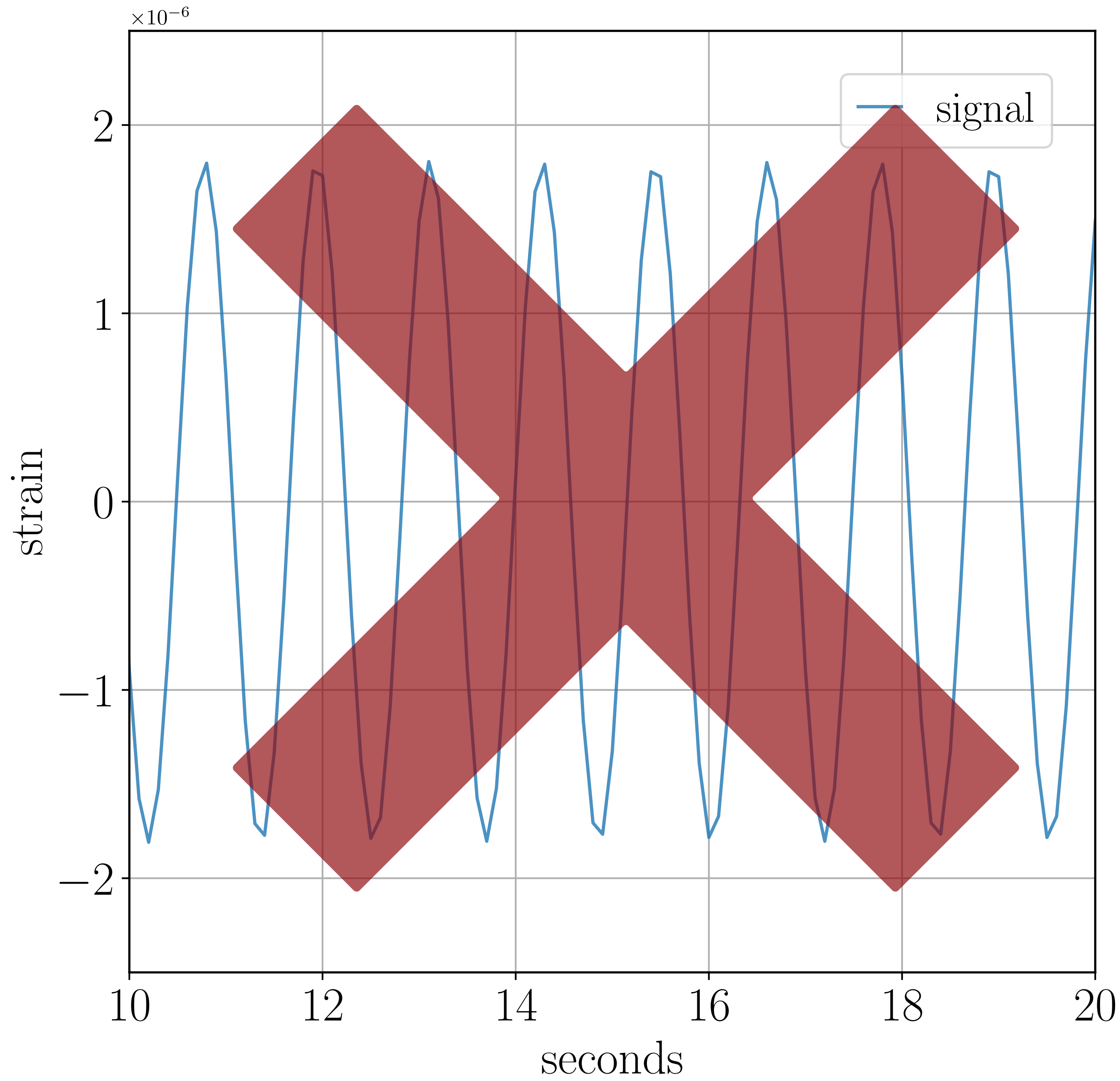

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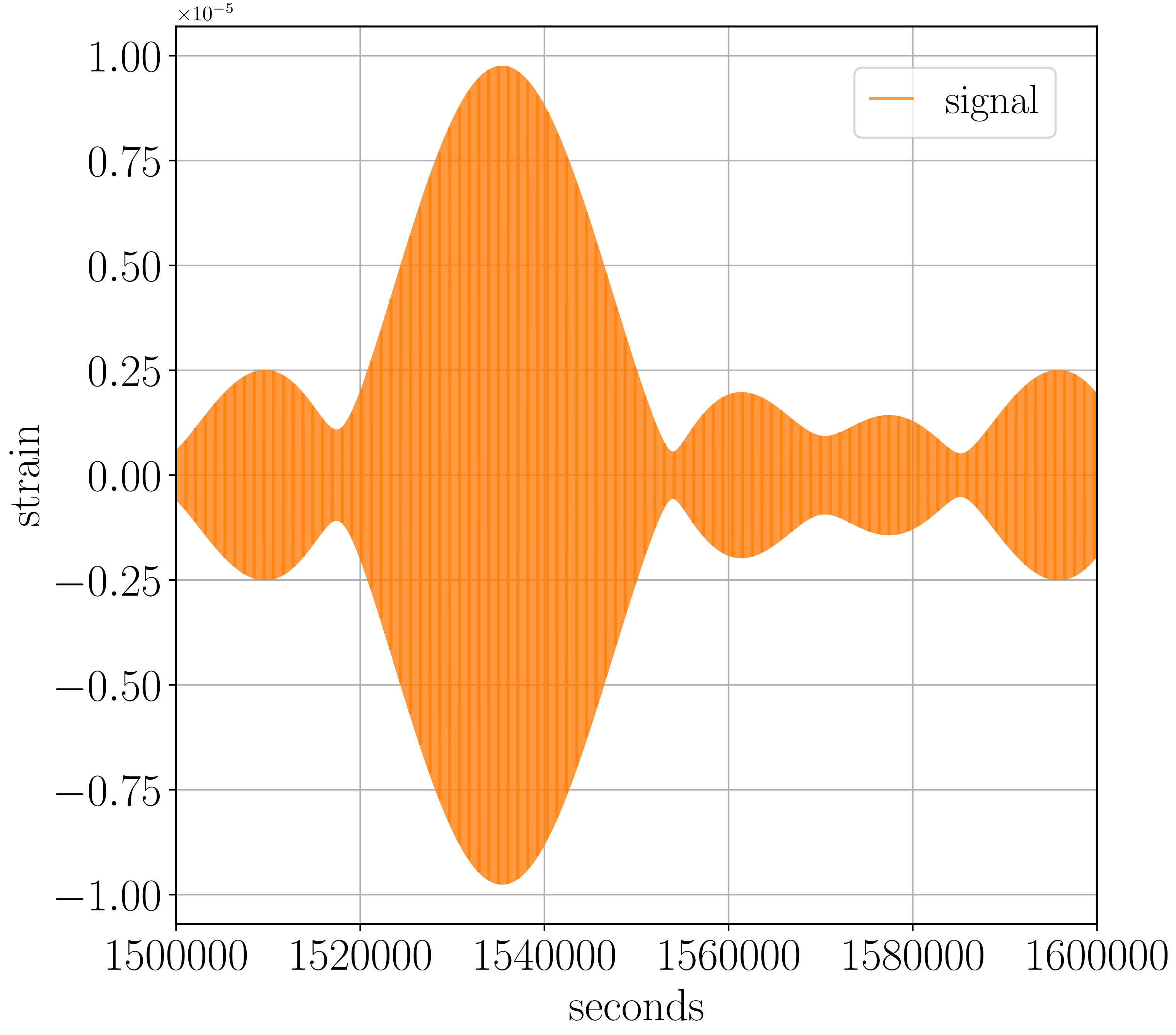

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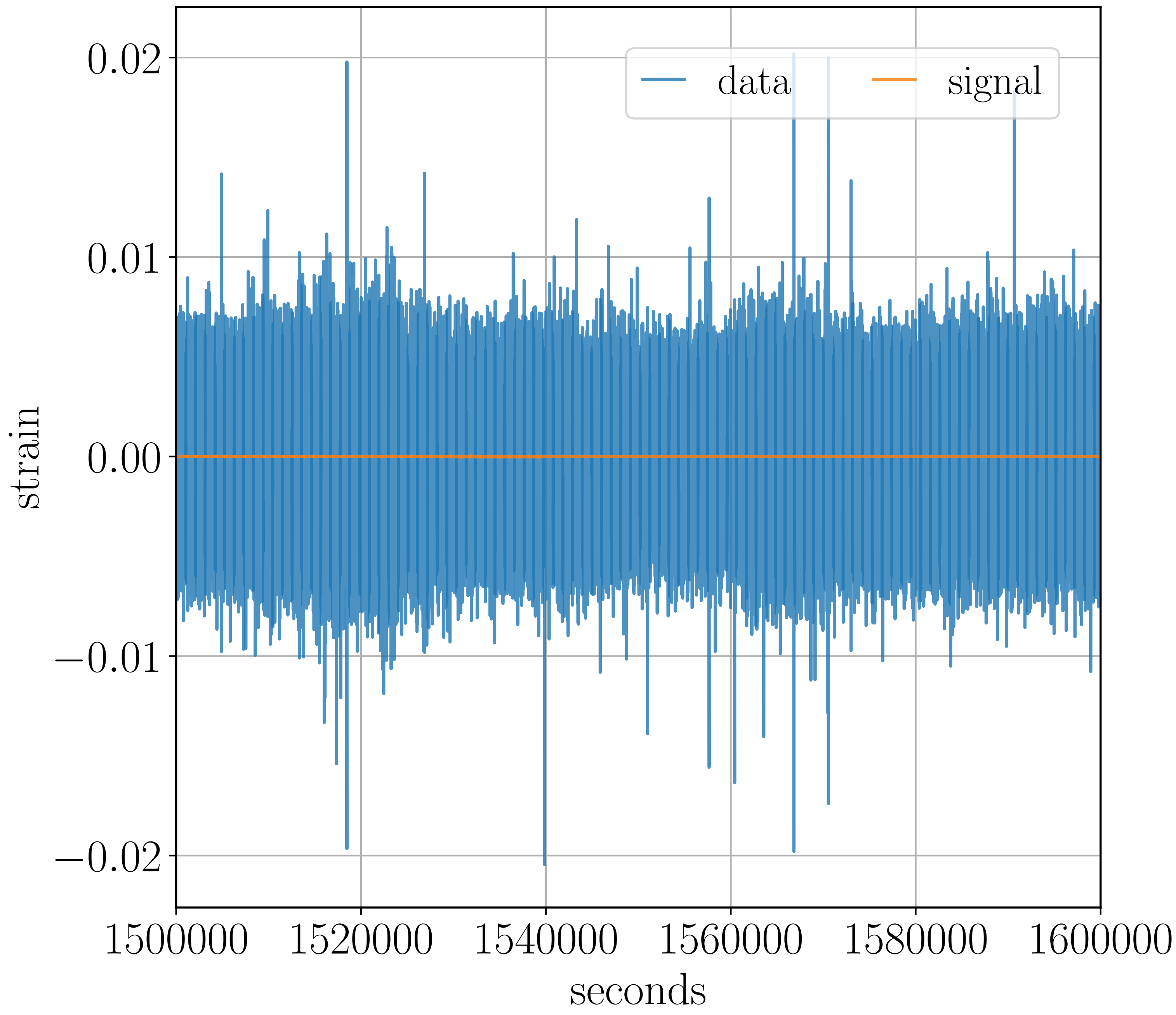


HOW THE SIGNAL LOOKS LIKE

A CW received at the detector is NOT exactly monochromatic

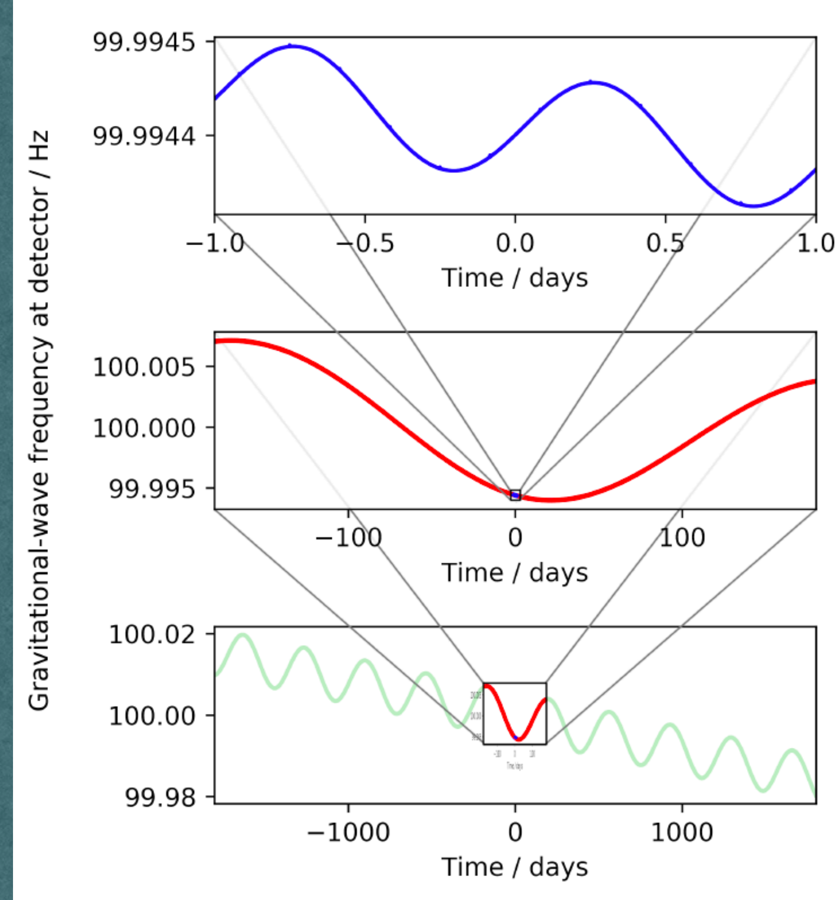
- SPIN-DOWN (or SPIN-UP)

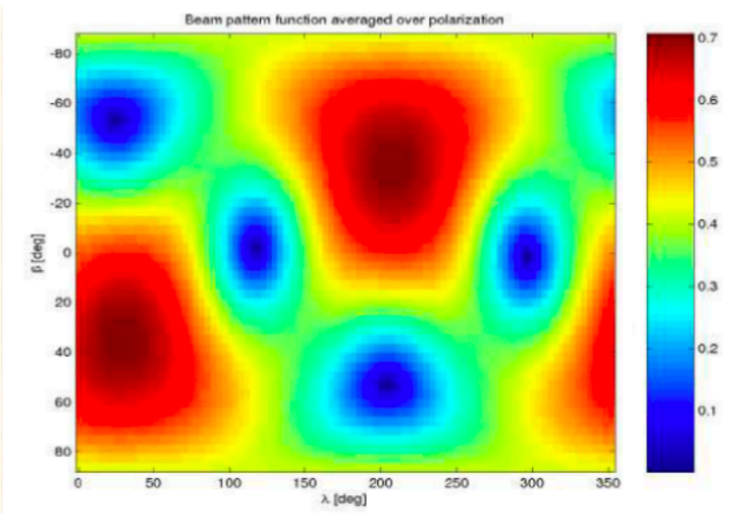
$$f_0(t) = f_0 + \dot{f}_0\left(t - t_0\right) + \frac{\ddot{f}_0}{2}\left(t - t_0\right)^2 + \ldots$$

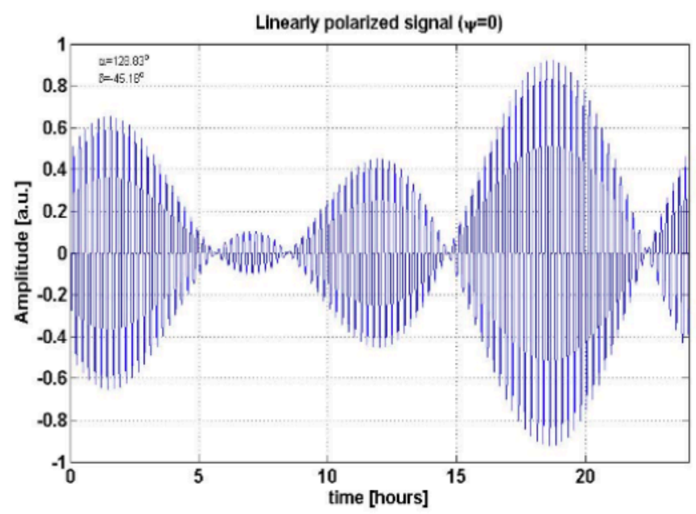
- DOPPLER

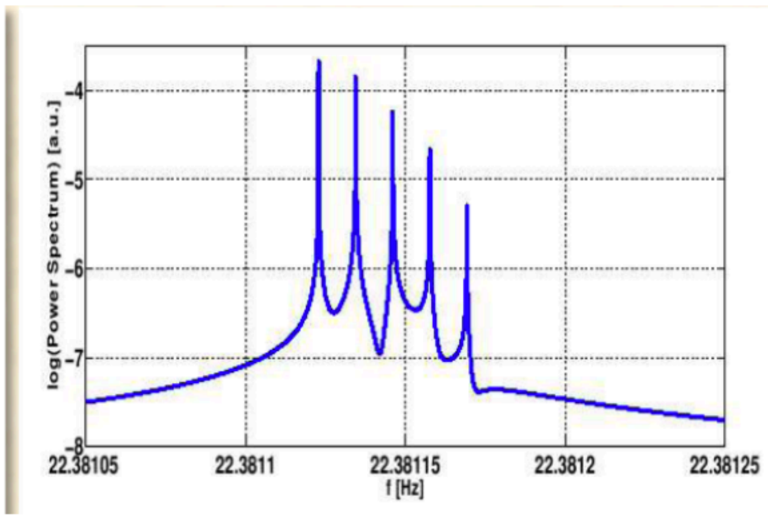
$$f(t) = \frac{1}{2\pi}\frac{d\Phi(t)}{dt} = f_0(t)\left(1 + \frac{\vec{v}\cdot\hat{n}}{c}\right)$$

- SPIN WANDERING
- SIDEREAL VARIATION of the amplitude

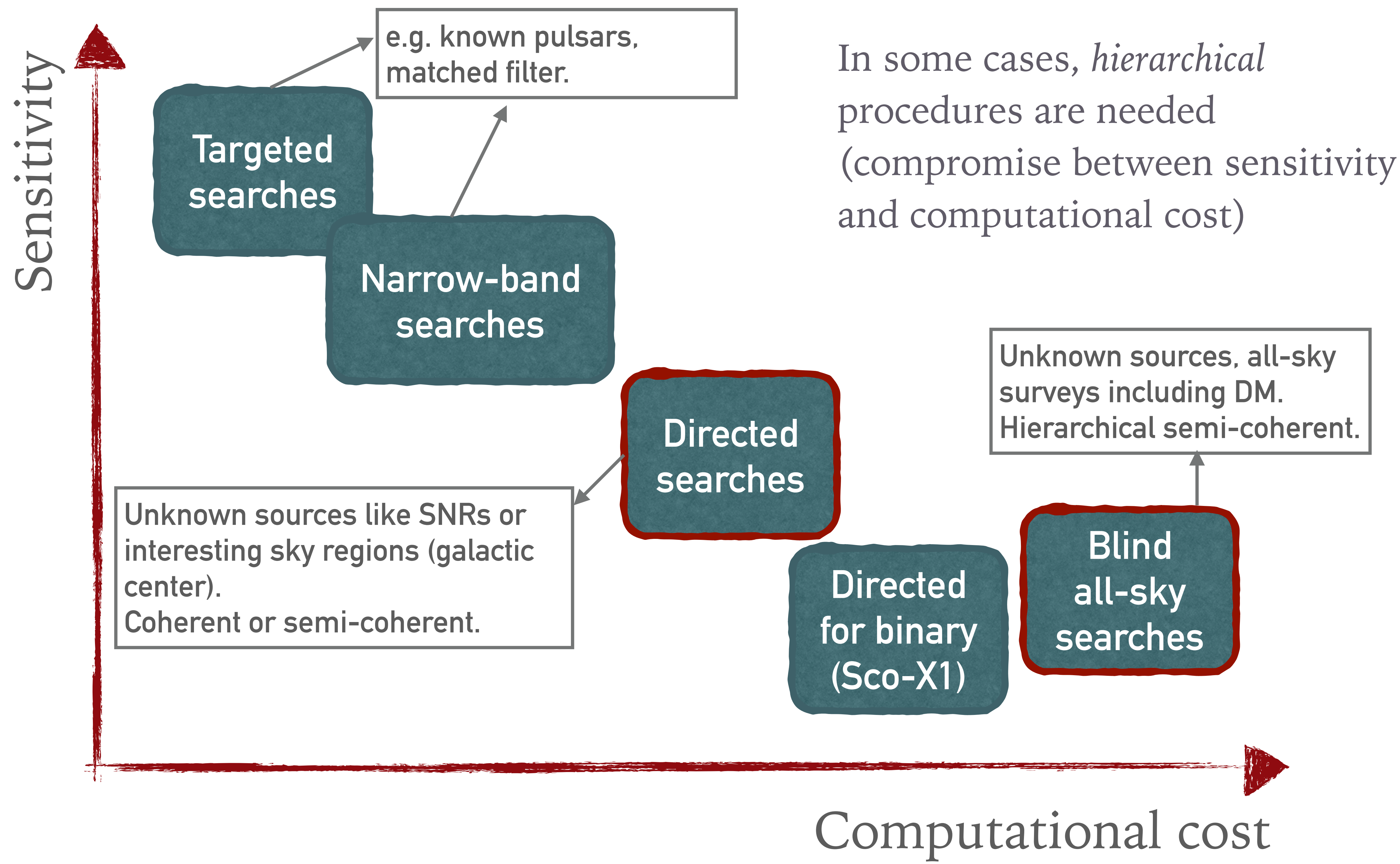








TYPE OF CW SEARCHES

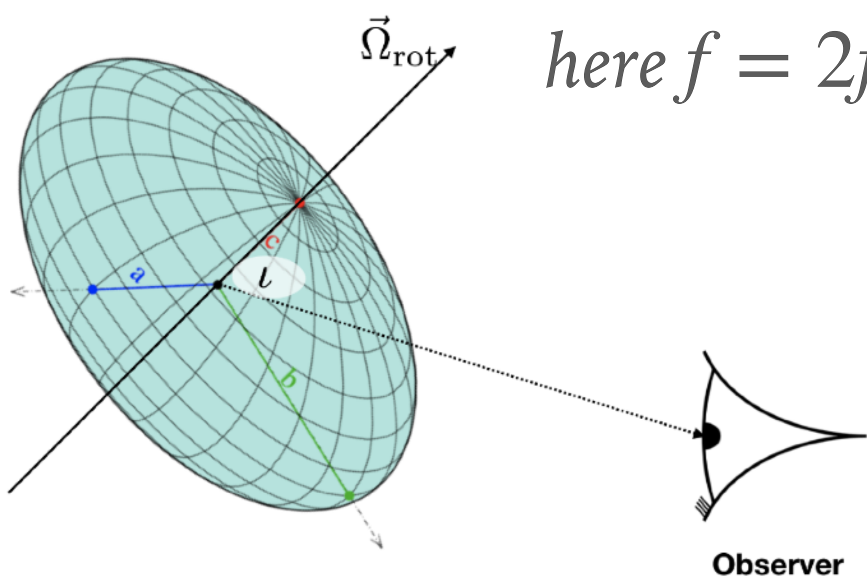


In some cases, *hierarchical* procedures are needed (compromise between sensitivity and computational cost)

STANDARD CASE: ISOLATED NEUTRON STAR

$$h_0 \cong 10^{-27}\left(\frac{I_3}{10^{38}\ \mathrm{kg\,m^2}}\right)\left(\frac{10\,\mathrm{kpc}}{d}\right)\left(\frac{f}{100\ \mathrm{Hz}}\right)^2\left(\frac{\epsilon}{10^{-6}}\right) \ll h_{0_{CBC}}$$

non-precessing, rotating around one of the axes



Tri-axial spinning neutron star

Credit: S. Mastrogiovanni

here $f = 2f_\star z$

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

I_3: moment of inertia

ϵ: ellipticity

$$\epsilon = \left|\frac{I_1 - I_2}{I_3}\right|$$

What is the actual value of ϵ?

$$\epsilon < 2\times10^{-5}\left(\frac{u_{\rm break}}{0.1}\right) \text{ crustal strain} \qquad \epsilon \approx 10^{-12}\left(\frac{B}{10^{12}\ \mathrm{G}}\right)^2 \text{ magnetic field}$$

N. Andersson et al. 2011

ESTIMATES ON THE ELLIPTICITY

Theoretical models K. Glampedakis & L. Gualtieri [Astro. and Space Science Lib., vol 457. Springer, 2018]

- Solid strange stars: $\epsilon \leq 6 \times 10^{-4}$
- Hybrid and meson condensates stars: $\epsilon \leq 3 - 9 \times 10^{-6}$
- Canonical magnetic deformations: $\epsilon \leq 2 - 7 \times 10^{-7}$
- Buried magnetic field in MSPs: $\epsilon_{fid} \sim 10^{-9}$ and a buried magnetic field of 10^{11} G. Woan+[ApJL,863:L40, 2018]

Above models more stringent than older results Johnson-McDaniel+ [PRD 88, 044004 (2013)]

- normal NS matter: $\epsilon \leq 10^{-5}$
- hybrid stars: $\epsilon \leq 10^{-3}$
- extreme quark stars: $\epsilon \leq 10^{-1}$

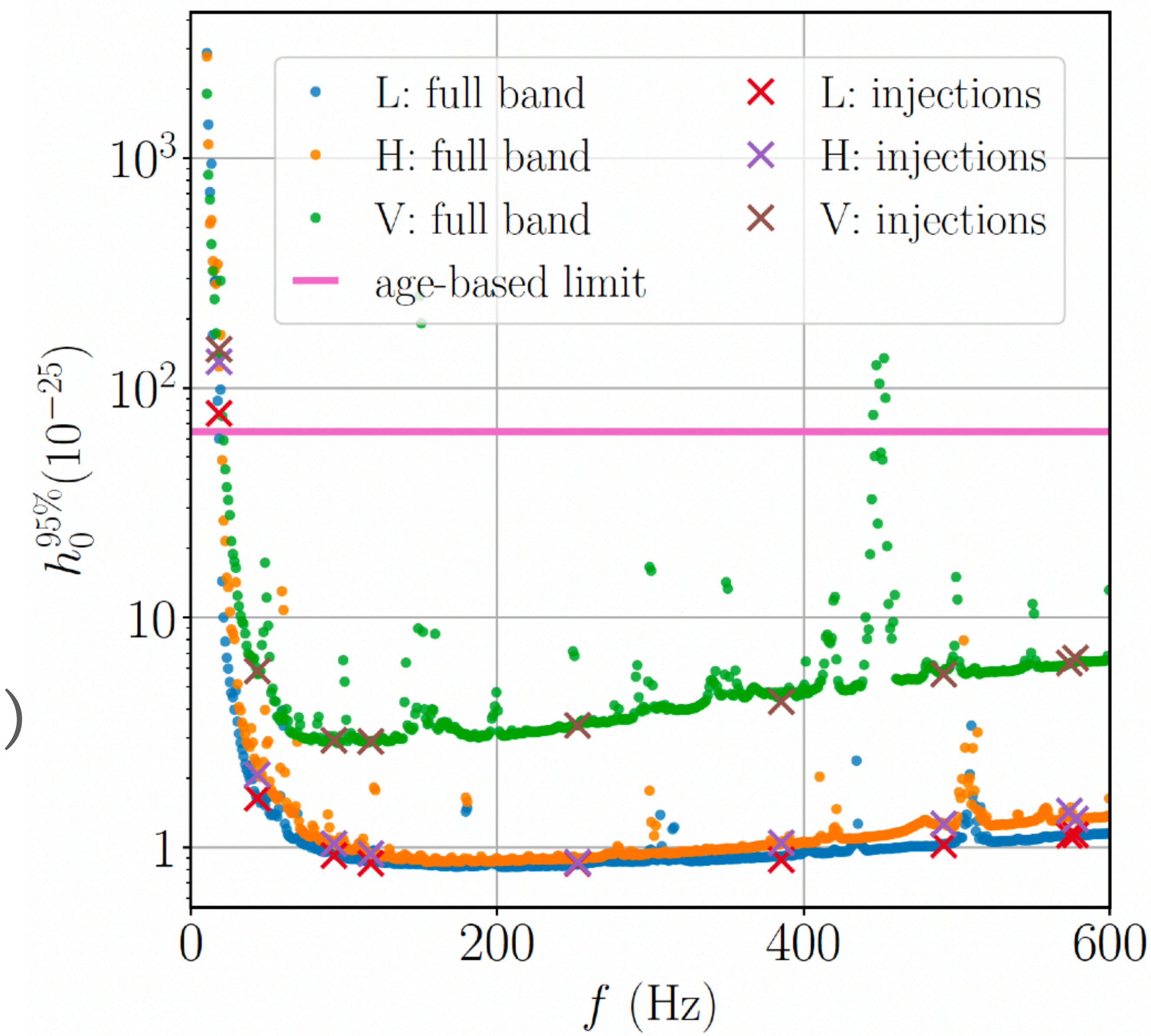
A more exotic object could sustain bigger ellipticities?

RESULTS – SNR O3A

LVK, R. Abbott *et al* 2021 *ApJ* **921** 80

- Directed search in O3a LIGO/Virgo
- Three complementary pipelines
  - Band-Sampled-Data directed
  - Single harmonic Viterbi
  - Dual harmonic Viterbi
- 15 targets investigates
- Best result 7.7×10^{-26} (G39.2-0.3) for the BSD, similar for other targets

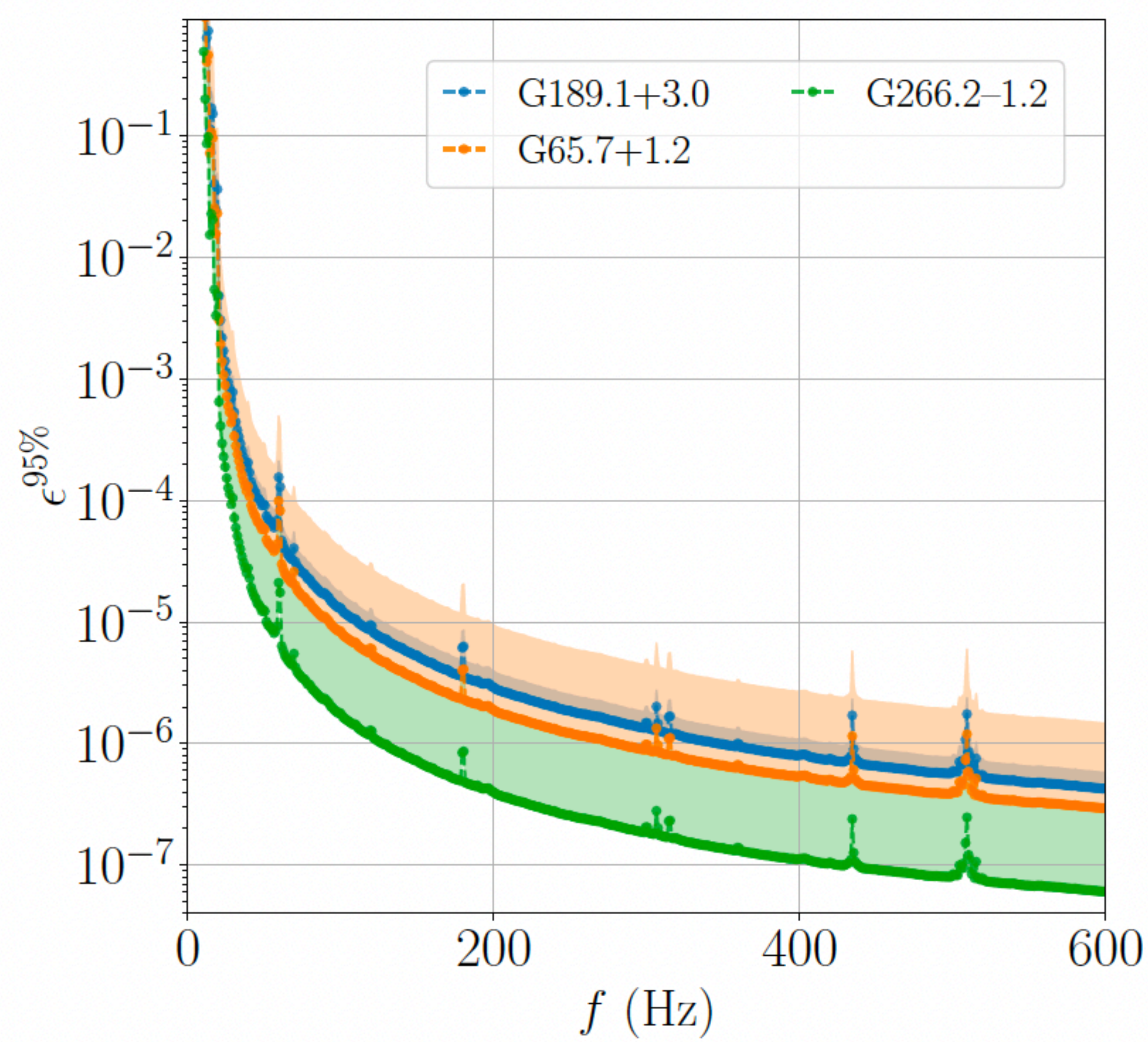
$$h_0^{\rm age} = 2.2 \times 10^{-24} \left(\frac{1\,{\rm kpc}}{d}\right) \left(\frac{1\,{\rm kyr}}{t_{\rm age}}\right)^{1/2} \left(\frac{I_3}{10^{38}\ {\rm kg\ m^2}}\right)^{1/2}$$



(c) G266.2–1.2/Vela Jr.

ELLIPTICITY (AND R-MODE) – SNR O3A

LVK, R. Abbott *et al* 2021 *ApJ* **921** 80



$$\epsilon = 9.5 \times 10^{-5} \left(\frac{h_0}{10^{-24}}\right) \left(\frac{d}{1\text{kpc}}\right) \left(\frac{100\text{ Hz}}{f}\right)^2$$

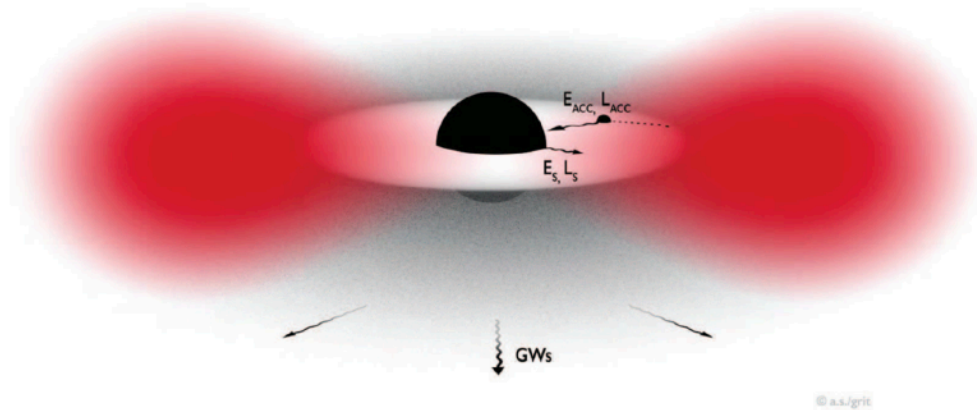
- Ellipticity $\epsilon < 10^{-6}$ for most of the sources; less than theoretical limit for normal neutron stars (Johnson-McDaniel & Owen 2013), 6×10^{-8} for the closest source Vela Jr

OTHER CW SIGNALS

- Typical CW signals are emitted by isolated neutron stars, other:
  - accreting binaries (spin-wandering)
  - unstable newborn NS, strongly magnetized, it emits "long-transients" CW signals (high spin-down rate)
- Other astrophysical scenarios where the emission is still expected to be monochromatic and includes DM (Bertone+, 1907.10610):
  - **Boson clouds around spinning BHs**
  - Primordial BH coalescences (long-transients)
  - **"Dark photons" coupling with the detector**
- Some of these searches are carried on in the BSD framework (Piccinni+ CQG, **36** 015008 (2019)) and/or CW techniques can be easily applied

BOSON CLOUDS AROUND BH

Brito+, 1501.06570



Ultra-light bosonic particles like axions can form *clouds* around spinning BH, due to a *superradiant* instability process

Arvanitaki+, PRD 91, 084011 (2015)
Brito+, CQG, 32, 134001 (2015) and PRD96, 064050 (2017)

- We need: boson angular frequency < BH's outer horizon angular frequency
- The instability stops at the saturation
- Then a (quasi)-monochromatic emission happens at a GW frequency given by

$$f_{\mathrm{GW}} = \frac{c^3}{\pi G}\mu \left[1 - \frac{1}{8}\left(M_{\mathrm{bh}}\mu\right)^2\right]$$

$$\mu \sim 10^{-13}\ \mathrm{eV}, \mathrm{M_{bh}} > 10\ \mathrm{M_\odot} \rightarrow 50\,\mathrm{Hz}$$

$$\mu \sim 10^{-12}\ \mathrm{eV}, \mathrm{M_{bh}} < 70\mathrm{M_\odot} \rightarrow 500\,\mathrm{Hz}$$

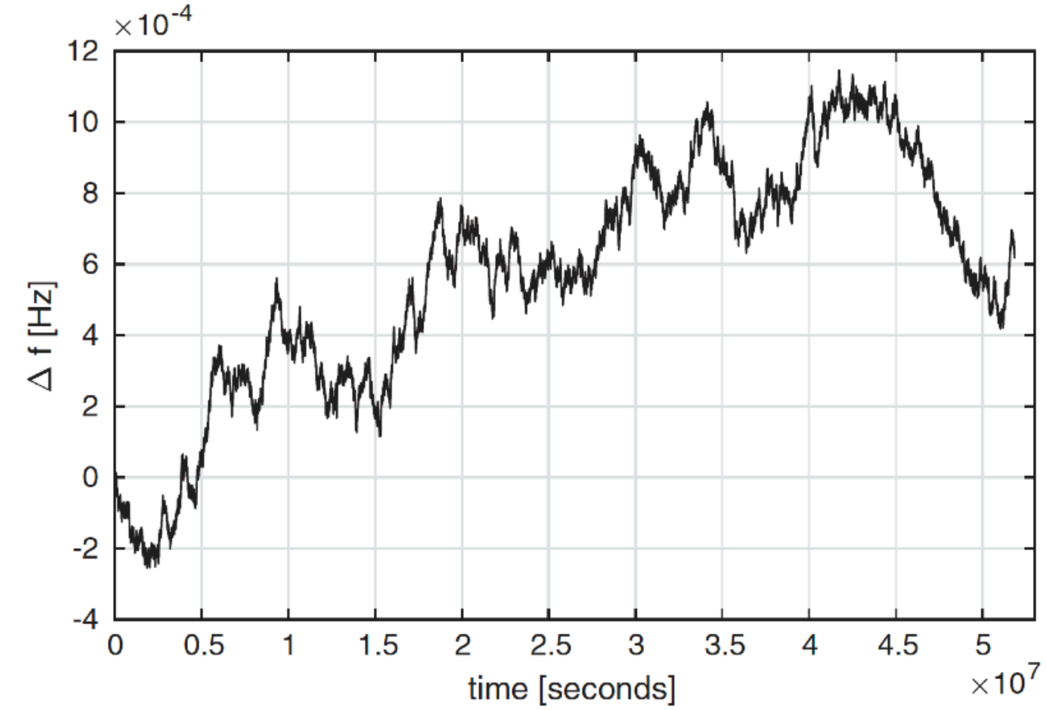
D'Antonio+, PRD, 98, 103017 (2018)

BOSON CLOUDS AROUND BH

Small spin-up are expected in this case, almost negligible

$$\dot{f}_{GW} \approx 10^{-16} \left(\frac{f_{GW}}{100\ \mathrm{Hz}}\right) \left(\frac{10^6\ \mathrm{yr}}{\tau_{GW}}\right) \left(\frac{2\times 10^{18}\ \mathrm{GeV}}{\mathrm{F_a}}\right)^2 \frac{\mathrm{Hz}}{\mathrm{s}}$$

In the search setup we need to consider this constraint ($T_{coh} = 1/\Delta f$)



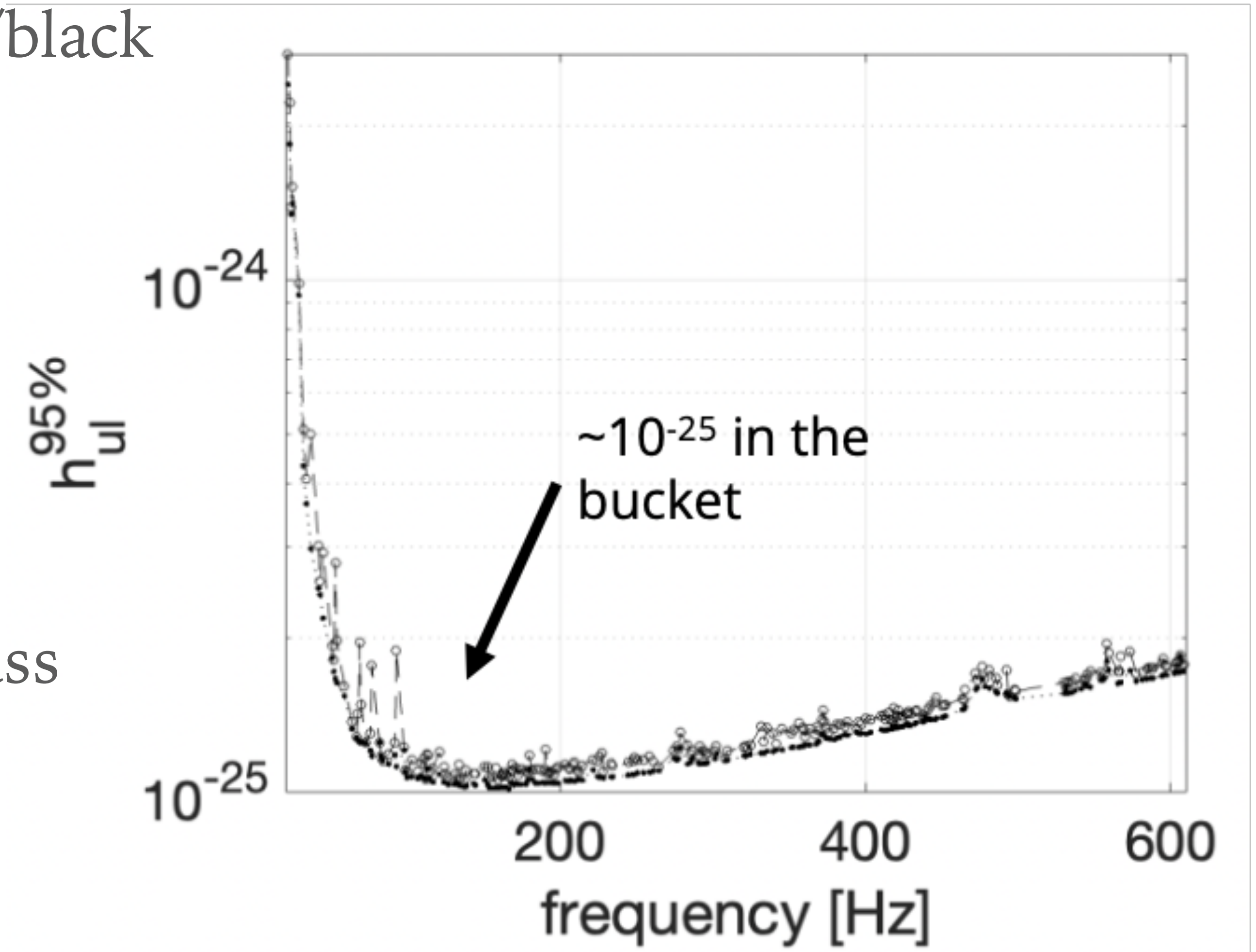
The GW strain depends on the initial cloud mass $M_0\left(M_{bh}, \mu, \chi\right)$

$$h_0(t) \approx 9\times 10^{-24} \left(\frac{M_0}{M_\odot}\right)^{1/2} \left(\frac{M_{bh}}{40 M_\odot}\right)^{7} \left(\frac{\mu}{5\times 10^{-13}\mathrm{eV}}\right)^{13/2} \chi^{1/2} \left(\frac{d}{10\mathrm{kpc}}\right)^{-1} \left(1+\frac{t}{\tau_{GW}}\right)^{-1}$$

D'Antonio+, PRD, 98, 103017 (2018)

BOSON CLOUDS AROUND BH (O3 - ALL SKY RESULTS)

- First all-sky survey for boson clouds/black holes systems
- No CW signal found
- Upper limits on the strain:
- Astrophysical implications:
  - exclusion region on the boson mass particle can be derived
  - Astrophysical reach of the search

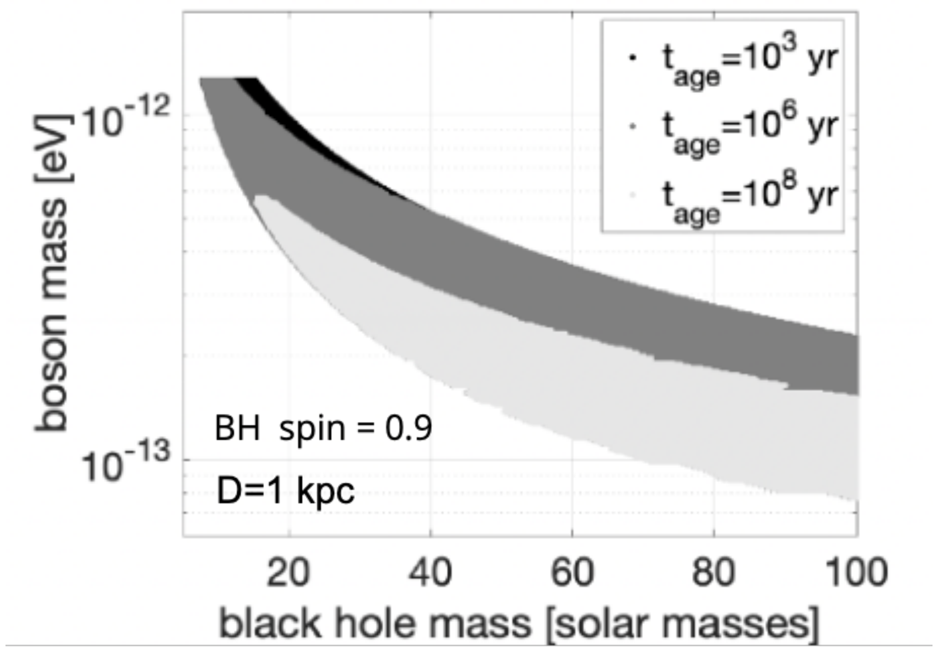


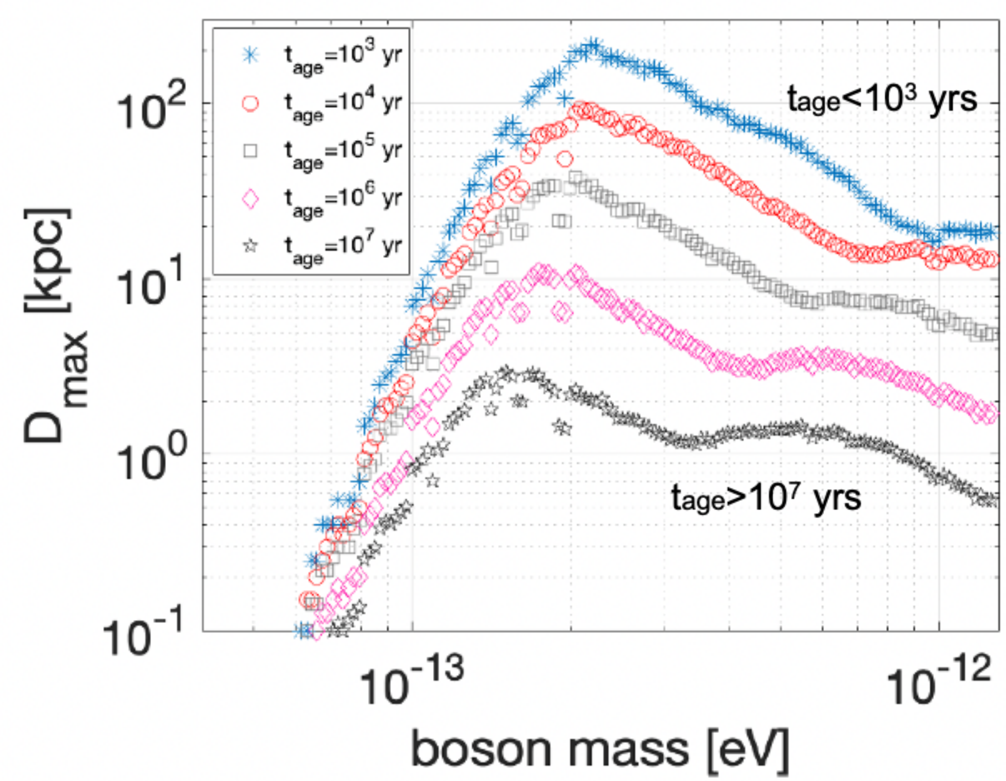
R. Abbott et al. - arXiv:2111.15507

BOSON CLOUDS AROUND BH (O3 – ALL SKY RESULTS)

- Astrophysical implications:
  - exclusion region on the boson mass particle can be derived
    - assuming a given spin, distance and age
  - Astrophysical reach of the search: maximum distance at which a given BH–boson cloud system, with a certain age, is not emitting CWs, as a function of the boson mass
    - by simulating a BH population with a given mass and spin distribution

Mass distribution (Kroupa): [5, 100] $M_\odot$
Spin distribution (uniform): [0.2, 0.9].





DARK MATTER CANDIDATES: VECTOR BOSONS "DARK PHOTONS"

- Ultralight vector bosons directly interacting with the detector
- Massive vector field coupling with baryons/baryons minus leptons current in the materials (fused silica) -> coherent oscillating field
- The time-dependent force acting on the test masses, produces a strain oscillating at the same frequency and phase as the DM field
- A spatial gradient is present, different forces at each mirror location (h_D)
- Additional effect due to the finite light travel time (h_C)
- No detection → limits on coupling ε

Total strain = sum of the two

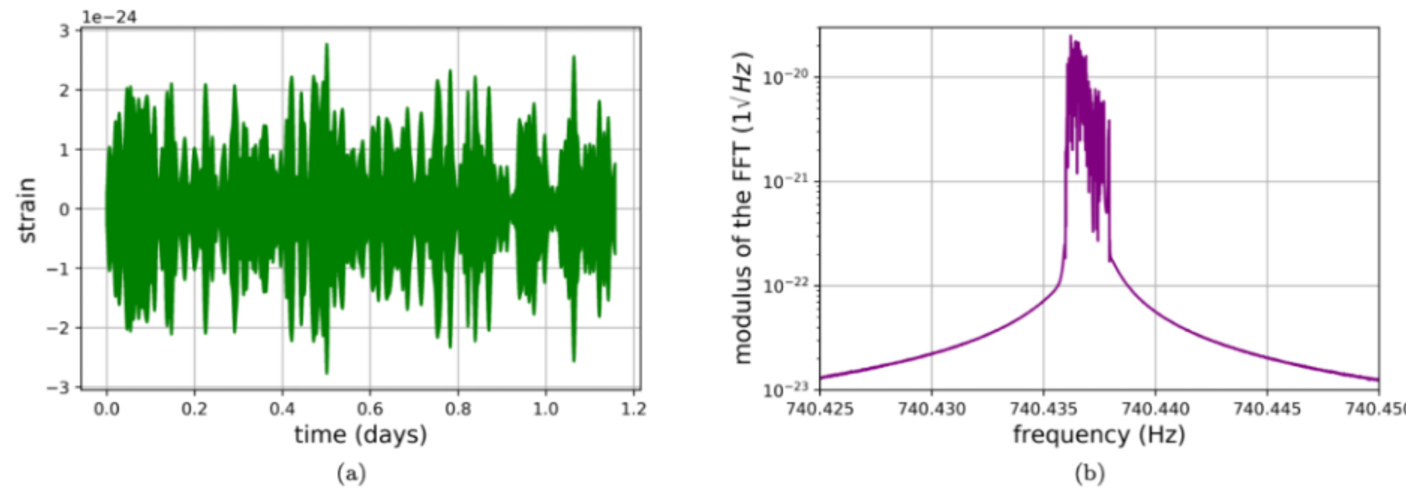
$$\sqrt{\langle h_D^2 \rangle} = C \frac{q}{M} \frac{e\epsilon}{2\pi c^2} \sqrt{\frac{2\rho_{DM}}{\epsilon_0}} \frac{v_0}{f_0} = 6.28 \times 10^{-27} \left(\frac{\epsilon}{10^{-23}} \right) \left(\frac{100 \text{ Hz}}{f_0} \right)$$

$$\sqrt{\langle h_C^2 \rangle} = \frac{\sqrt{3}}{2} \sqrt{\langle h_D^2 \rangle} \left(\frac{2\pi f_0 L}{v_0} \right) \simeq 6.21 \times 10^{-26} \left(\frac{\epsilon}{10^{-23}} \right)$$

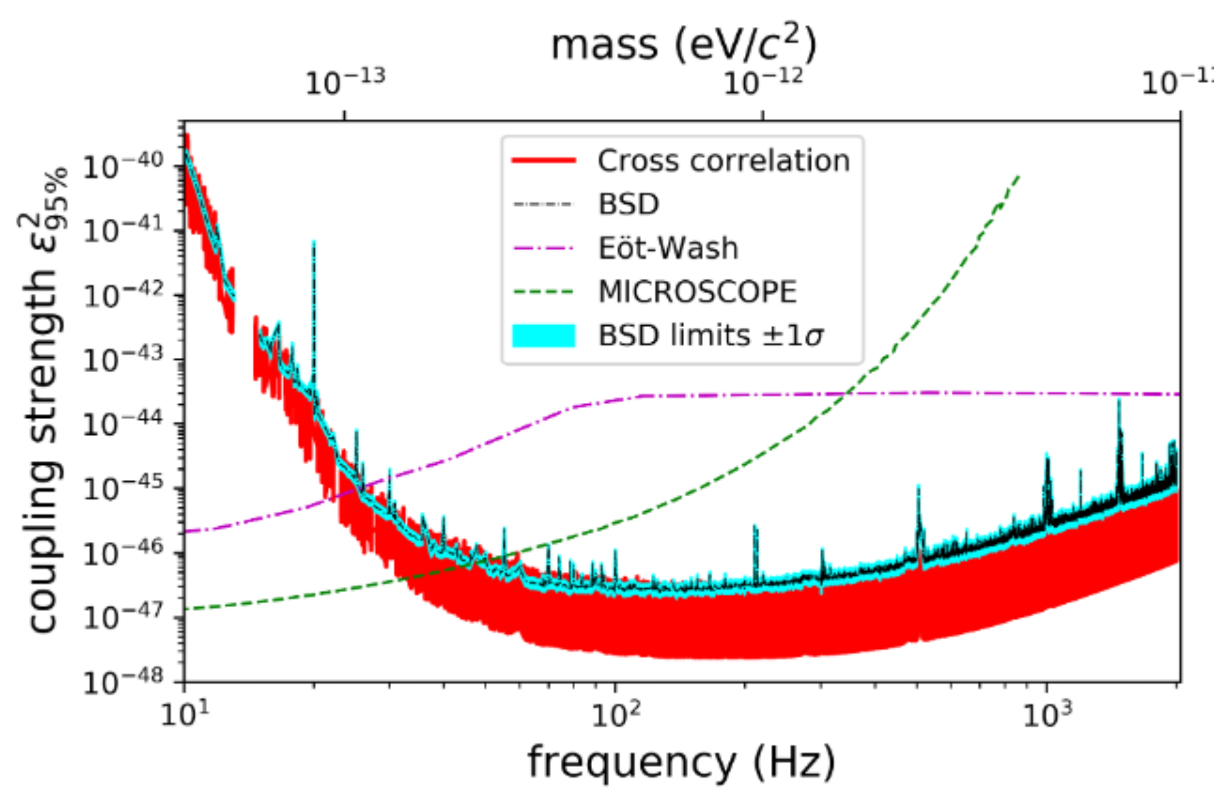
Averages over polarizations and propagations directions

DARK MATTER CANDIDATES: VECTOR BOSONS "DARK PHOTONS"

- Cross-correlation:
  - ○ Analyze detector data simultaneously, look for identical signals in both detectors.
  - ○ Fix T_{coh} length to be 1800 s.



- Excess power (BSD): analyze each detector's data separately.
  - ○ Change T_{coh} as a function of the boson mass considered.
  - ○ Look for strong, coincident candidates.



R. Abbott et al. - arXiv:2105.13085

CONCLUSION 1/2

- CW data analysis methods can be tuned to look for different signals, including Dark matter CW emitters
- Algorithms developed for CW searches are getting interesting role in the study of Dark matter candidates
- The BSD framework is a fundamental tool to enhance existing methods and it has been widely used for new searches
- An increasing number of pipelines are using the BSD framework to look for CW signals, especially DM ones

CONCLUSION 2/2

- CW could be the next surprise in GW astronomy given the enhanced sensitivity of the detectors, noise characterization is fundamental
- Efforts ongoing to increase the sensitivity of the pipelines
- For the standard NS case scenario we are probing ellipticities very close to the lowest estimates
- Exciting times especially if a joint CW and EM observation occurs (constraints on NS interior), remarking the importance of MMA.
- Searches for CWs emitted by standard and unconventional sources are almost completed for O3 data
- We expect (and hope) to find several surprises in O4