Chasing Whispers from the Cosmos: Detecting Continuous Gravitational Waves

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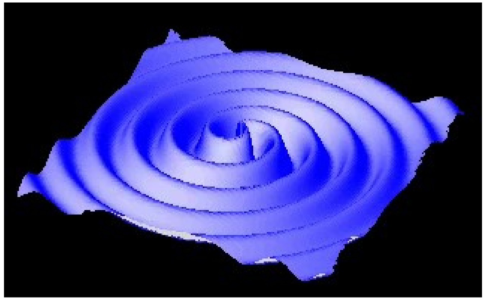
Summary

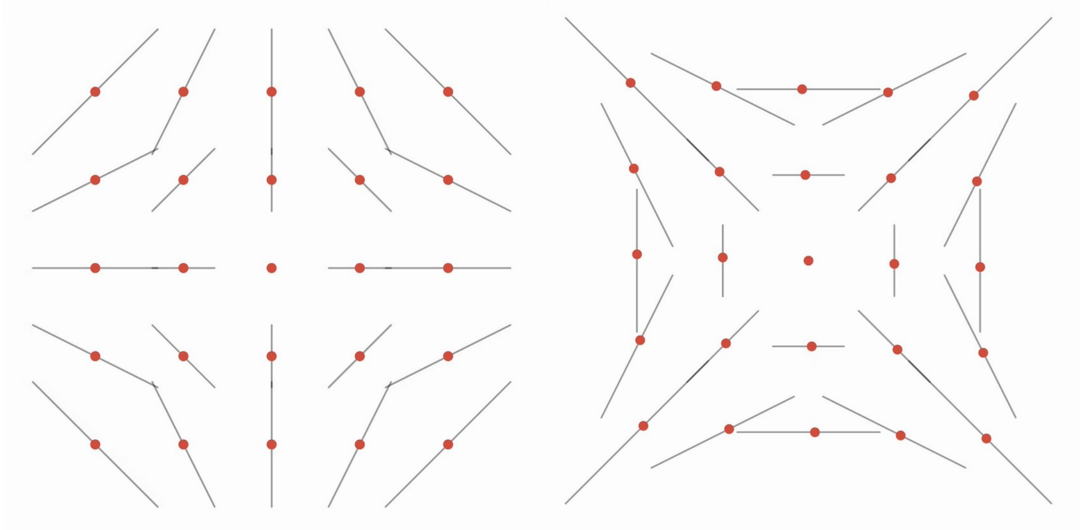
- Introduction
- **Continuous** Waves (CW) signal
- Current status
- Conclusions

Introduction: Gravitational Waves

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$



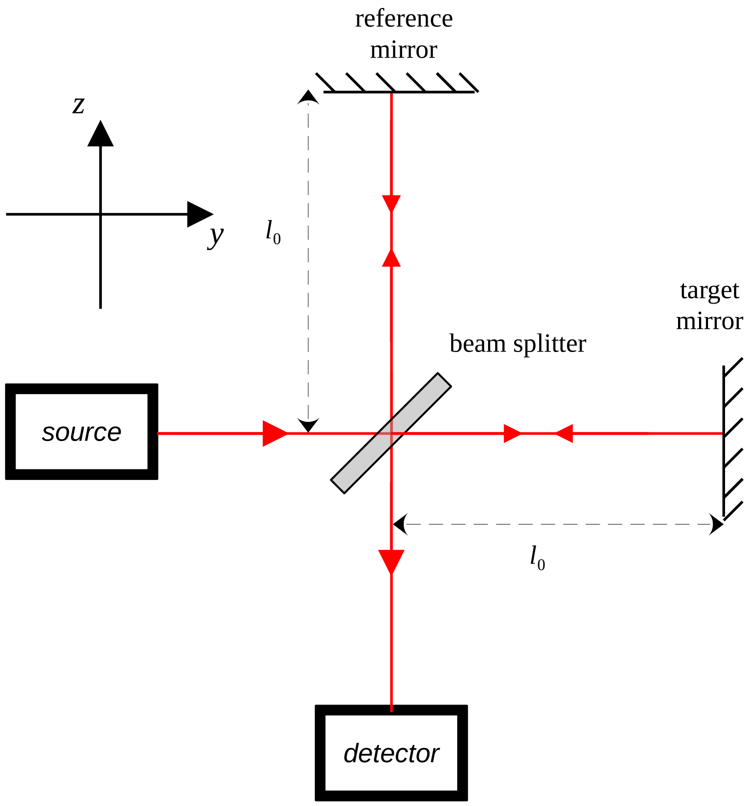
Spacetime tells matter how to move; matter tells spacetime how to curve (J.A. Wheeler)



- Einstein solution to GR equation that looks like waves
  - Quadrupole nature
  - Two indipendent polarizations
  - Transverse waves

Credits Victor Sanz Sanchis

Introduction: Interferometers



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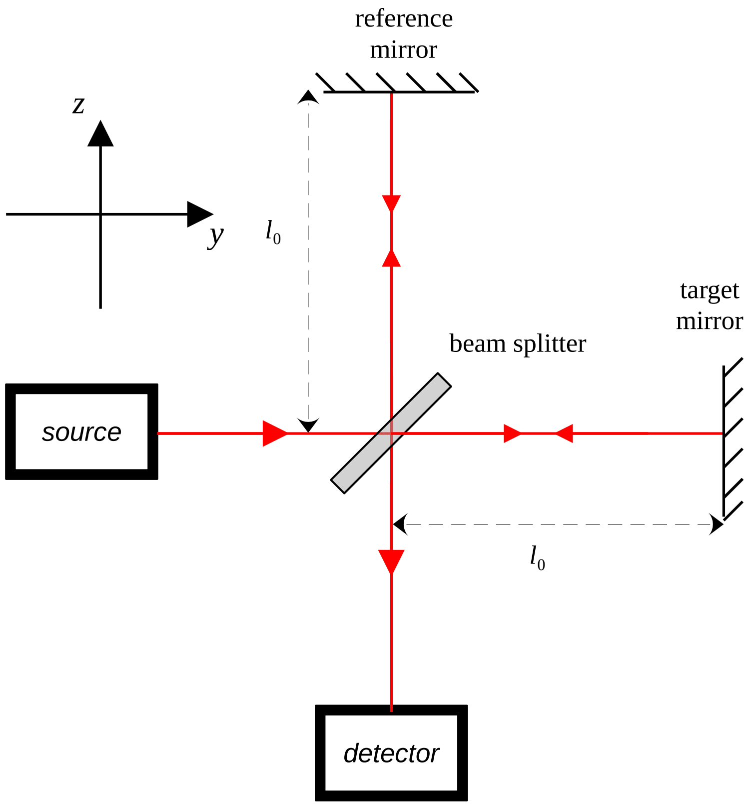

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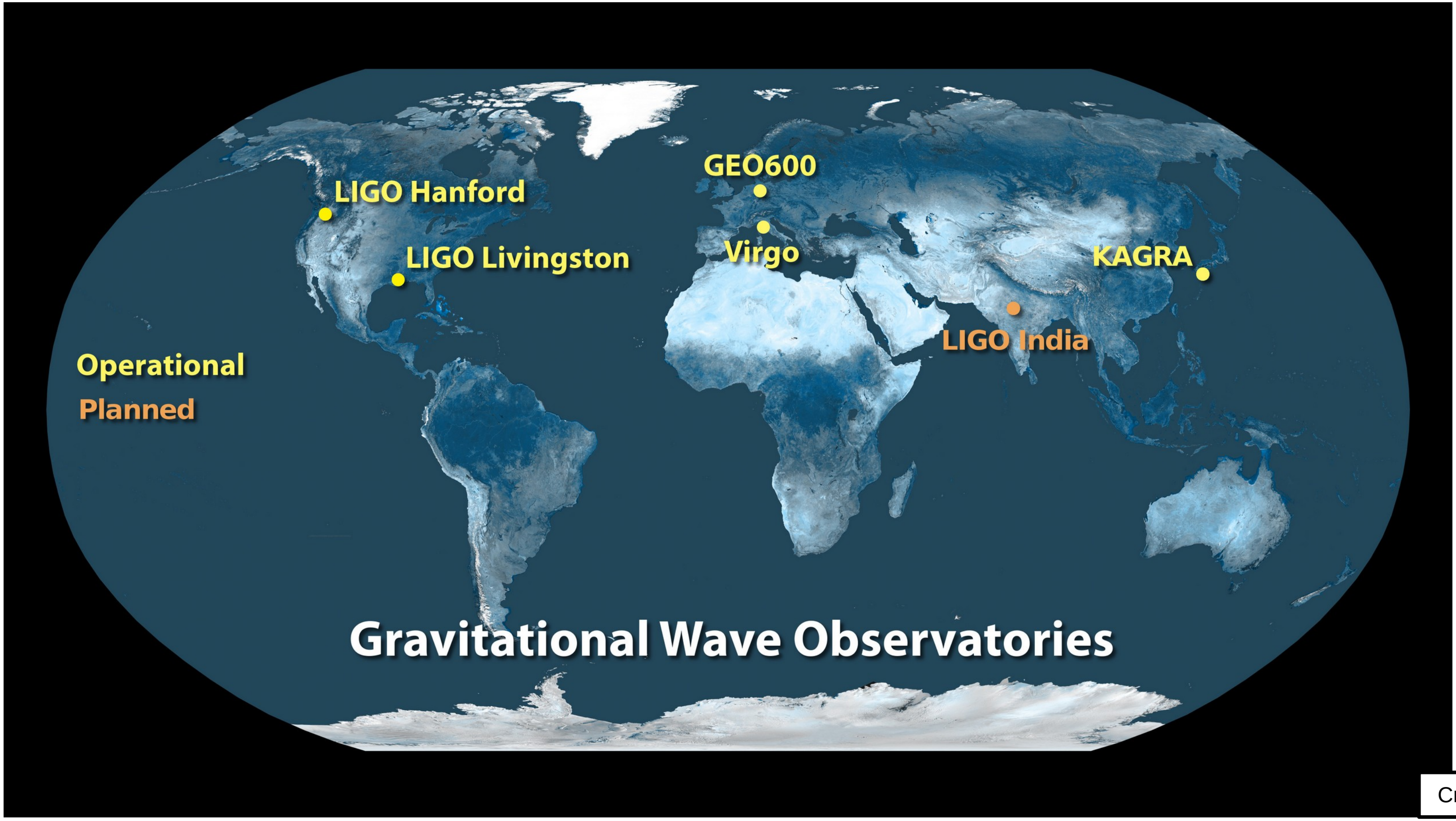
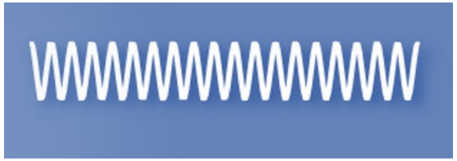


Credits: LIGO

Introduction: CW

Persistent

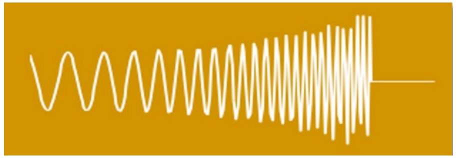


CONTINUOUS

STOCHASTIC

Transient

BURST

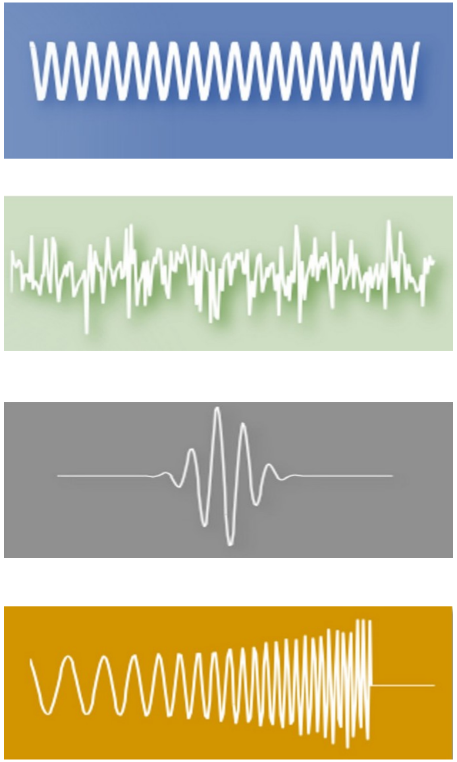


INSPIRAL

Introduction: CW

Persistent

Transient



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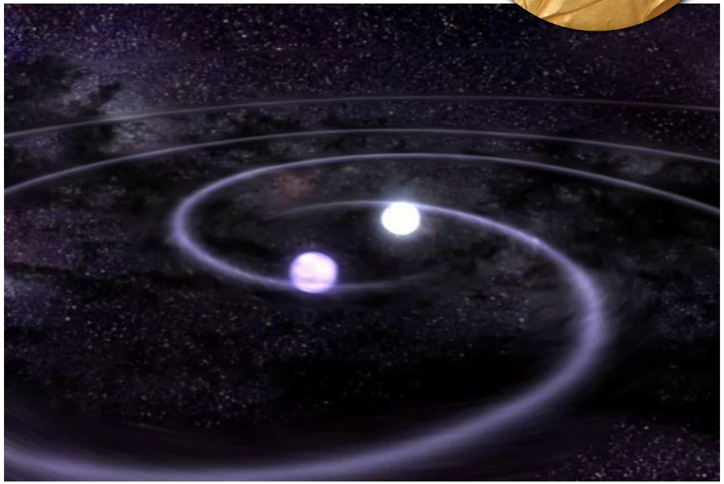
STOCHASTIC

BURST

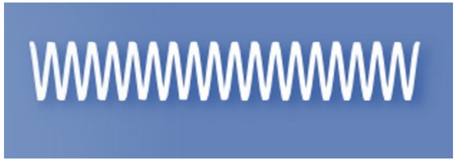
INSPIRAL



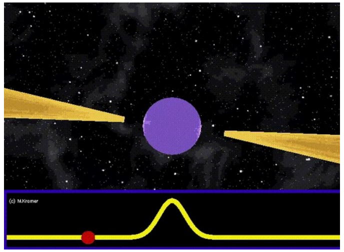
Credits LIGO

Introduction: CW – Neutron stars

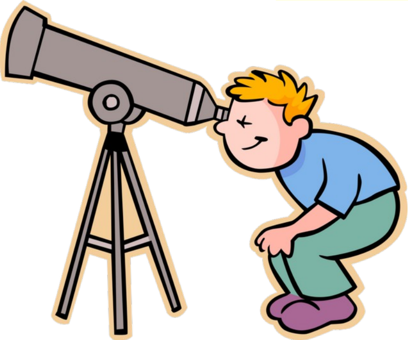
Persistent



CONTINUOUS



3200 known neutron stars known up to date!



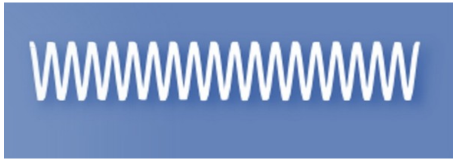
- **Quasi-monochromatic** waves with a slowly decreasing intrinsic frequency (spindown) in the source frame

- **Weak** but **persistent** over years of data taking

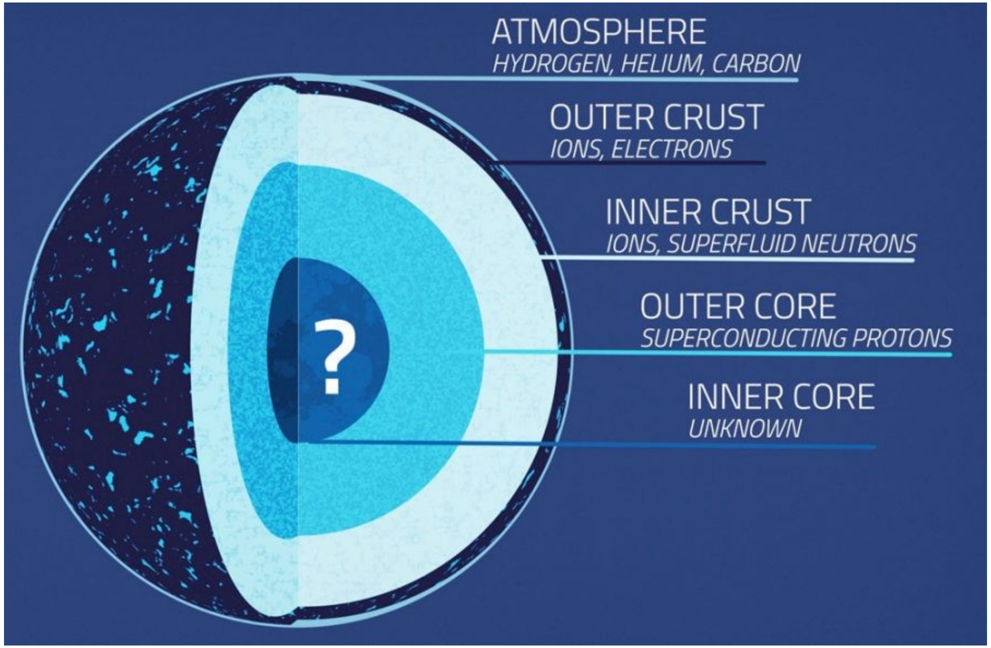
$$h_0 = \frac{16\pi^2 G}{c^4} \frac{\epsilon I f_{\mathrm{GW}}^2}{r}$$

Introduction: CW

Persistent



CONTINUOUS



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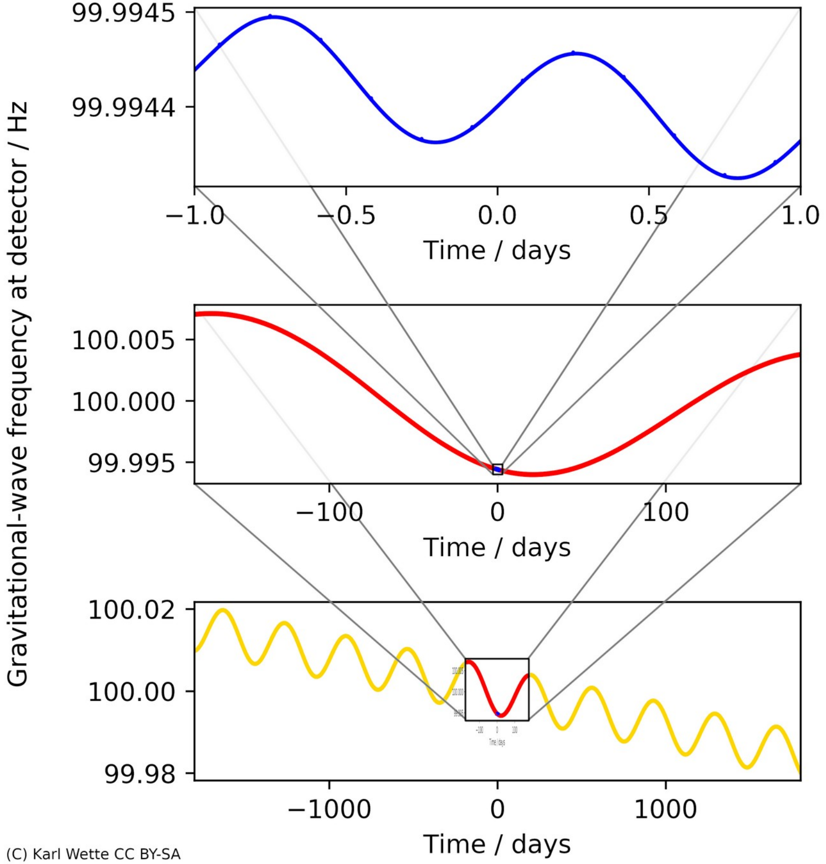
CW signal

- Signal model $h(t) \propto h_0 e^{i\Phi(t)}$

- At the source

$$\Phi^{\mathrm{NS}}(\tau) = \phi_0 + 2\pi f_{\mathrm{GW}} \cdot (\tau - \tau_0)$$



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Time delays

- Earth rotation
- Earth revolution
- **Neutron star binary revolution**
- Relativistic effects

- At the detector

$$\Phi(t) = \Phi_0 + 2\pi f_{\mathrm{GW}} \cdot (t + \Delta\tau(t) - \tau_0)$$

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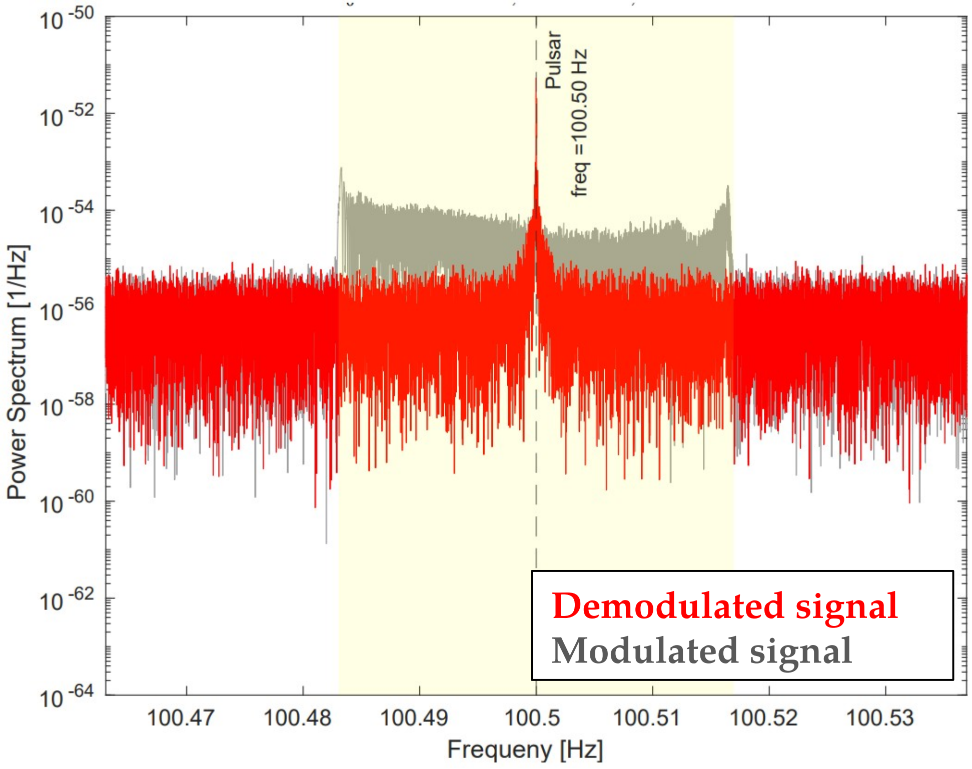
Artificial CW signal in 2 days Hanford O3 data



CW signal: Resampling technique

$$\Phi(t) = \Phi_0 + 2\pi f_{\mathrm{GW}}(t + \Delta\tau(t) - \tau_0)$$

Not a sinusoid

$$\Phi(\mathbf{t}') = \Phi_0 + 2\pi f_{\mathrm{GW}}(\mathbf{t}' - \tau_0)$$

A sinusoid!

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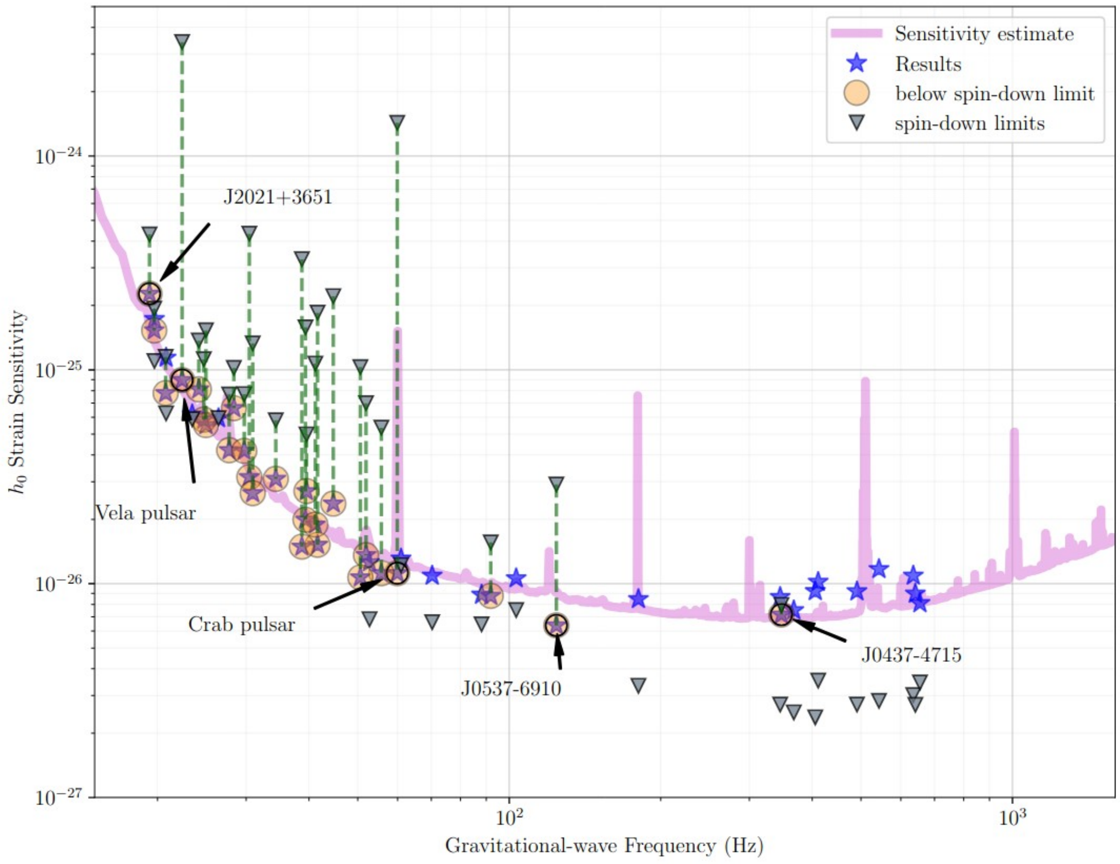
$\Delta\tau$ depends on $\{\alpha, \delta\} + \{P, a_p, e, \omega, t_p\}$

Current status: Results

arXiv:2501.01495



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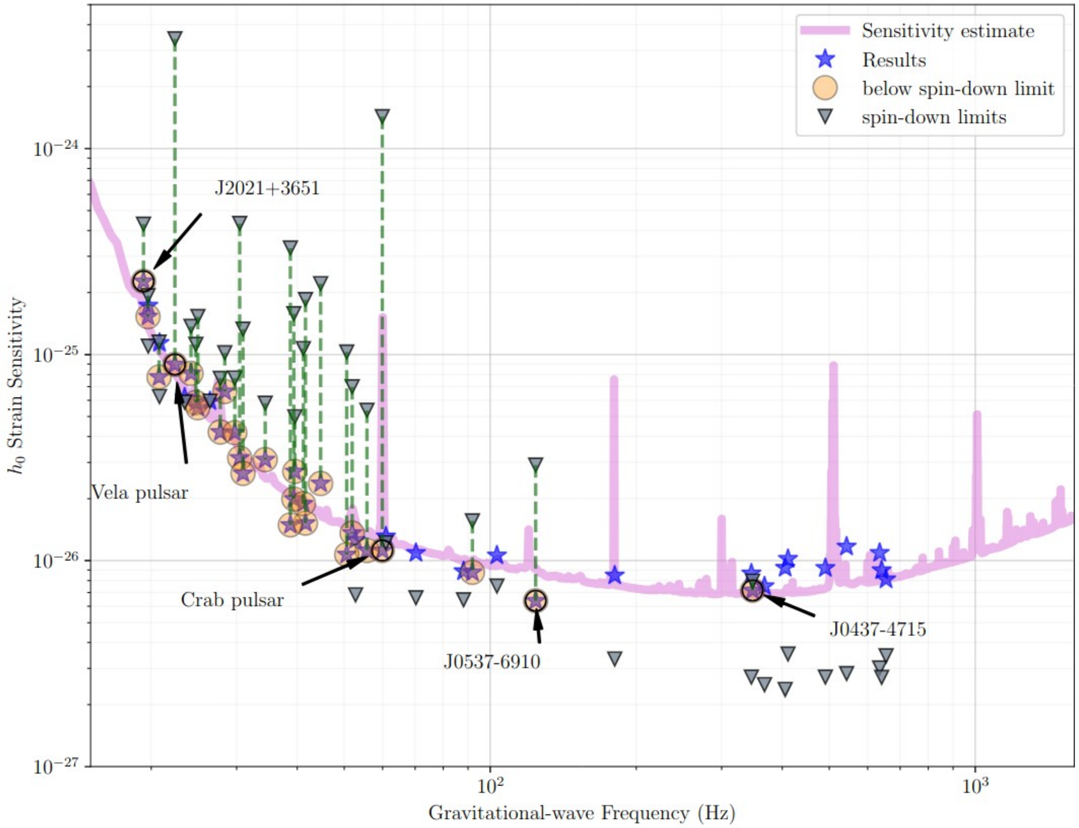
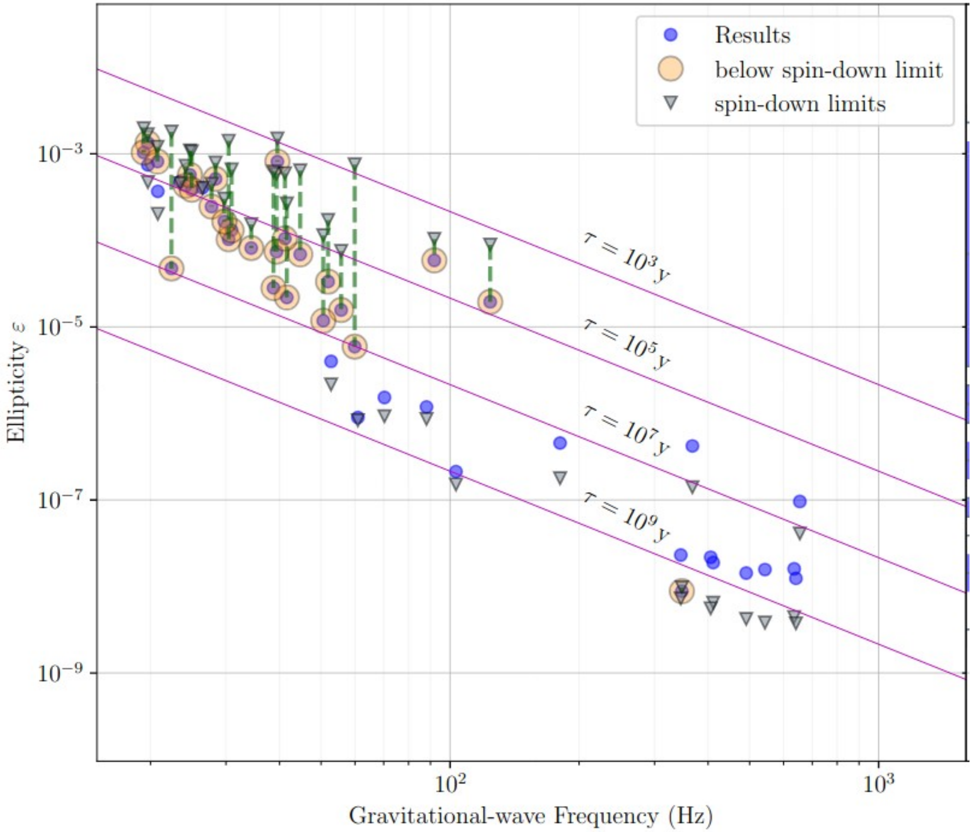
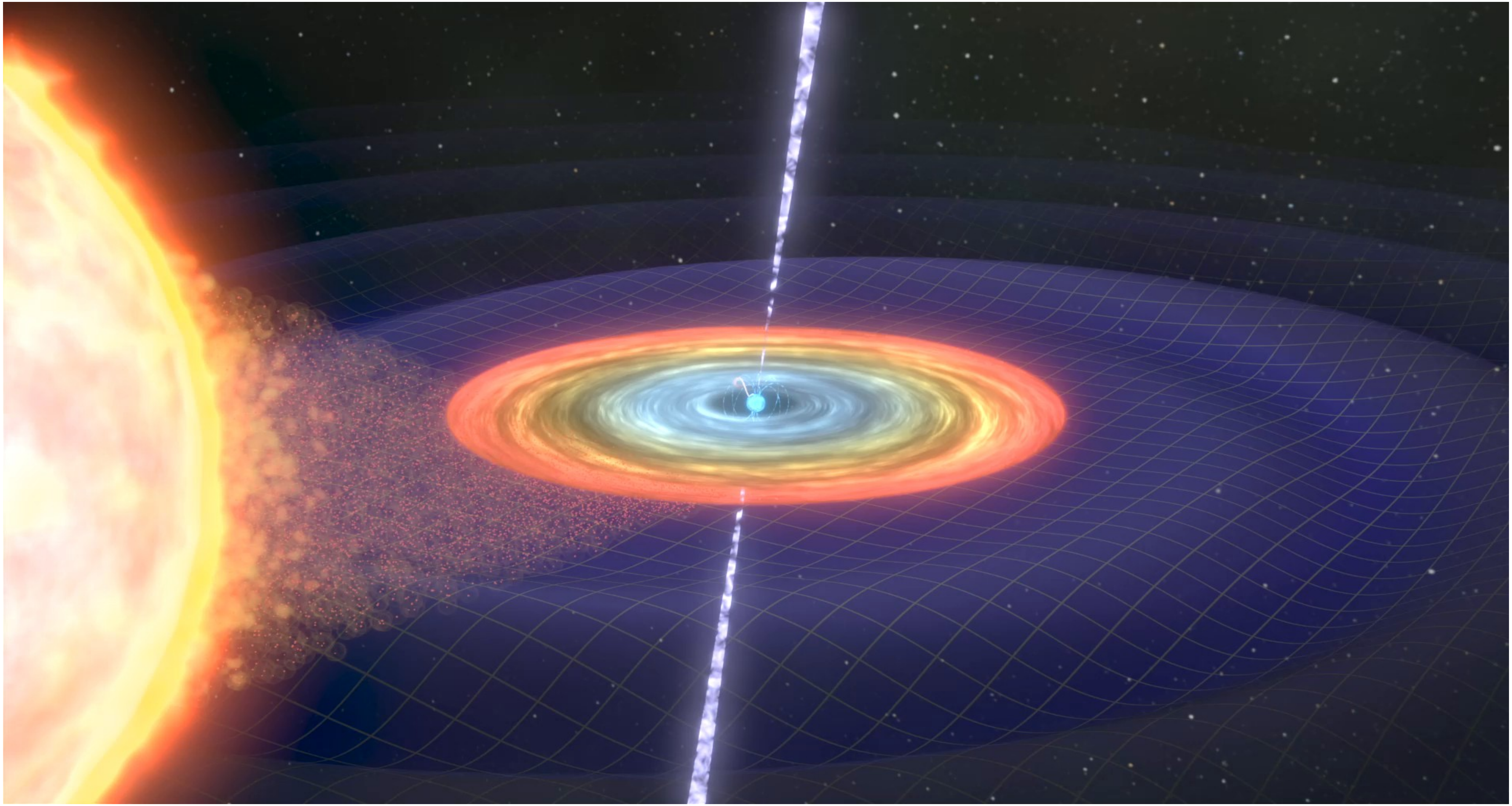
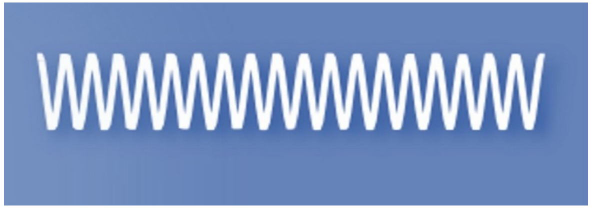






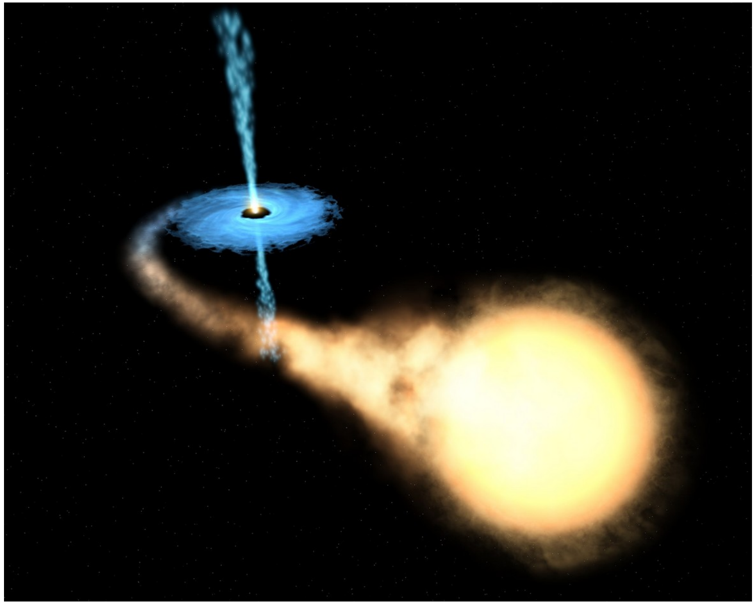
CW: Scorpius X-1



- Low Mass X-ray binaries (LMXBs) in a state of torque balance, could be a strong CW source with

$$h = 5 \times 10^{-27} \sqrt{\frac{300\ \mathrm{Hz}}{f_{\mathrm{rot}}}} \sqrt{\frac{\mathcal{F}_{\mathrm{Xray}}}{10^{-8}\ \mathrm{erg\ cm^{-2} s^{-1}}}}$$

- Scorpius X-1 is the **brightest** known LMXB
- **Unknown** frequency and its evolution



J. Papaloizou, J. E. Pringle (1978), Monthly Notices of the Roy al Astronomical Society, 184 (3), 501-508

Conclusions

- O4 is ongoing and it will last until October 2025

- Hopefully, we will be able to claim the first detection of Continuous Gravitational waves!

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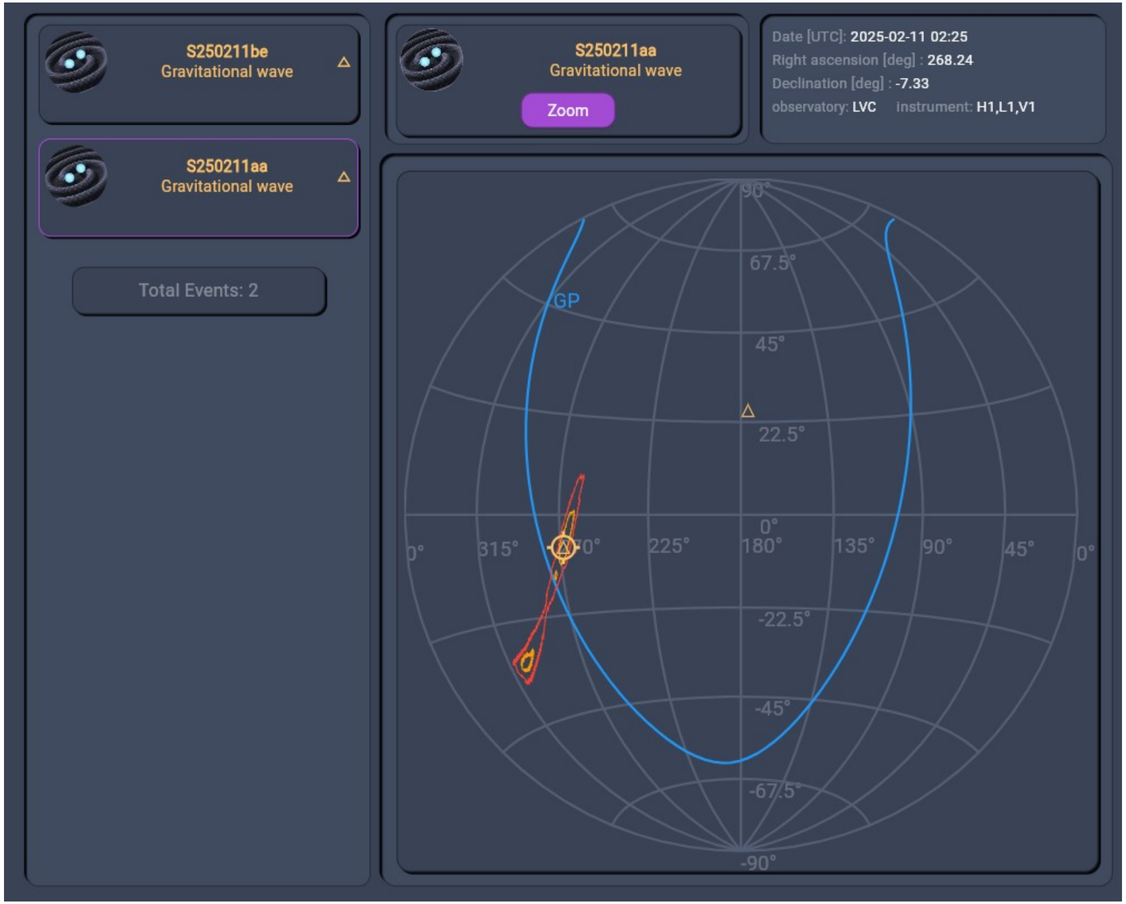
- In the meantime…

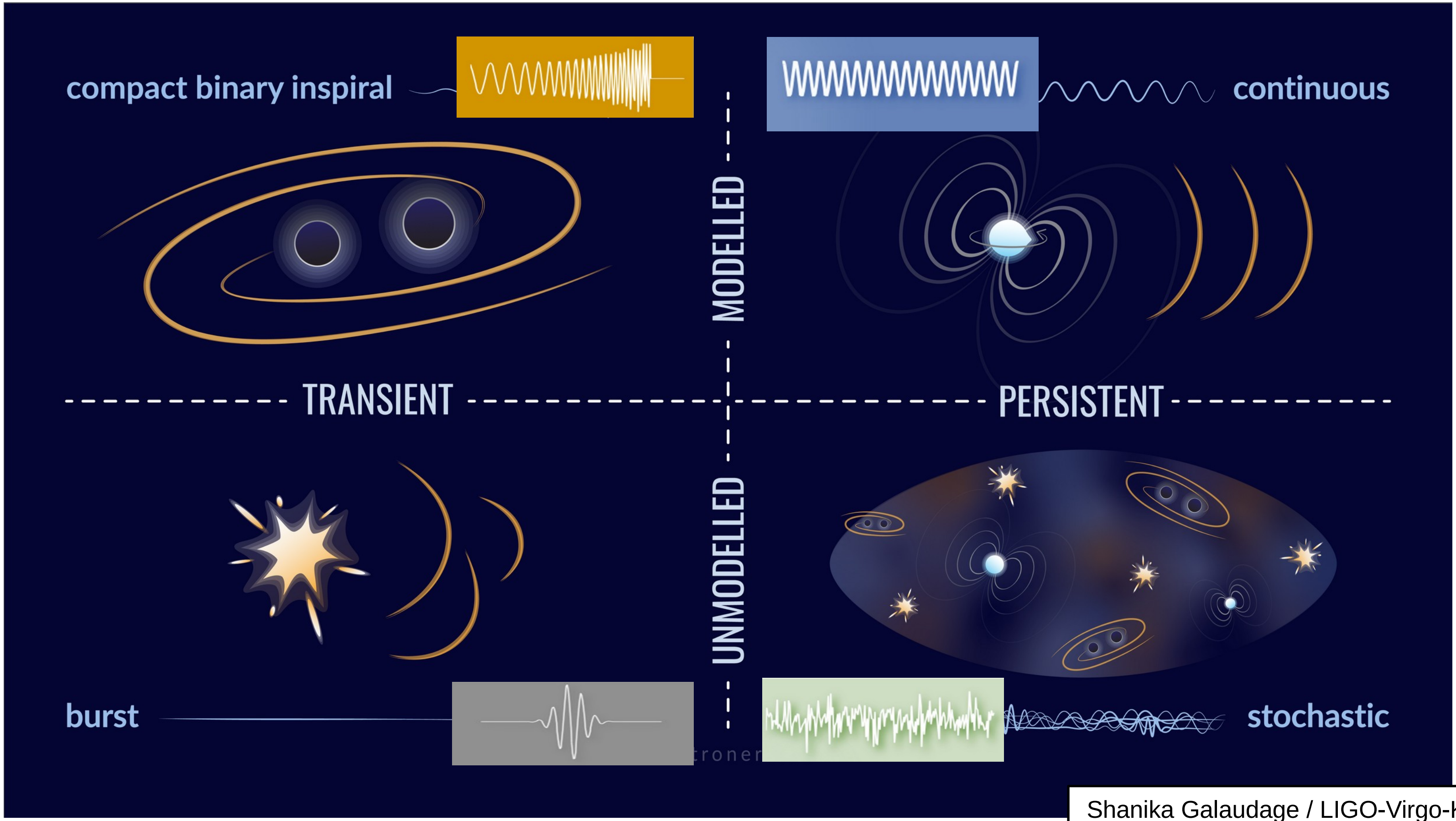


Bibliography

Some of the papers used as reference in the presentation are here collected:

- B. P. Abbott et al Phys. Rev Lett 116, 061102 (2016)
- A Singhal et al 2019 Class. Quantum Grav. 36 205015
- P Astone et al 2010 Class. QuantumGrav. 27 194016
- Robert V. Wagoner, The Astrophysical Journal, 278:345-348, (1984)
- Mark Zimmermann and EugeneSzedenits, Jr.,Phys. Rev. D 20, 351 (1979)
- Pia Astone et al. (2014)Phys Rev. D 89, 062008
- PaolaLeaciand Reinhard Prix (2015).Phys. Rev. D, 91:102003.
- Abac, A. G., et al. "Search for continuous gravitational waves from known pulsars in the first part of the fourth LIGO-Virgo-KAGRA observing run." arXiv preprint arXiv:2501.01495 (2025).

Introduction: Type of GW



Shanika Galaudage / LIGO-Virgo-KAGRA collaboration

Resampling: Signal at detector

$$h(t) = h_0 \left(H_+ A_+(t) + H_\times A_\times(t)\right) e^{i\Phi(t)}$$

Fast term

Amplitude modulation term

- $H_{+,\times}$ are the complex polarization amplitudes
- $A_{+,\times}(t)$ are the time-dependent **sidereal** detector response functions

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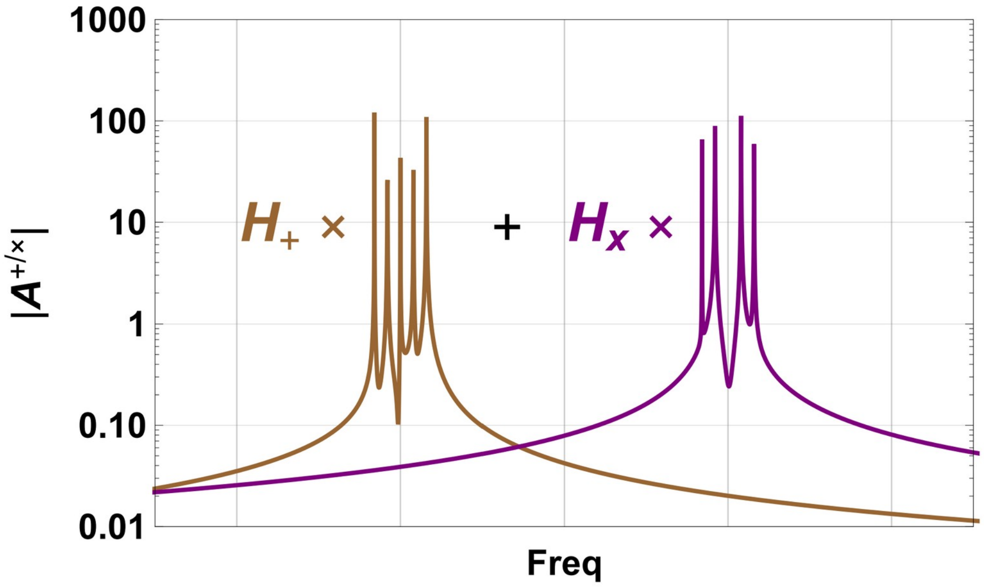
A Singhal (2019) *PhD thesis*



P Astone *et al* 2010 *Class. Quantum Grav.* **27** 194016

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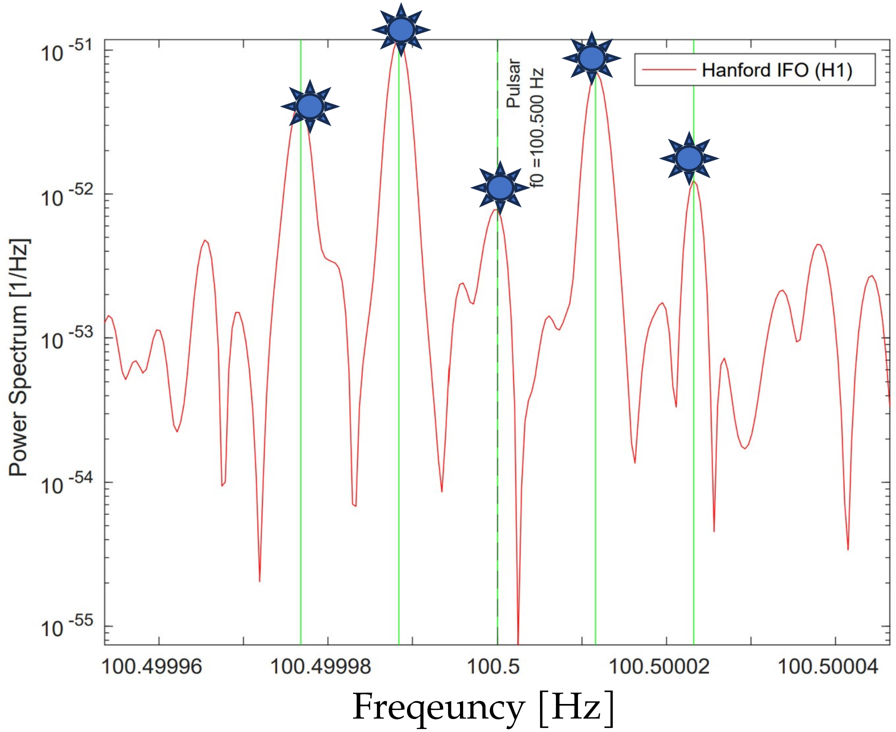

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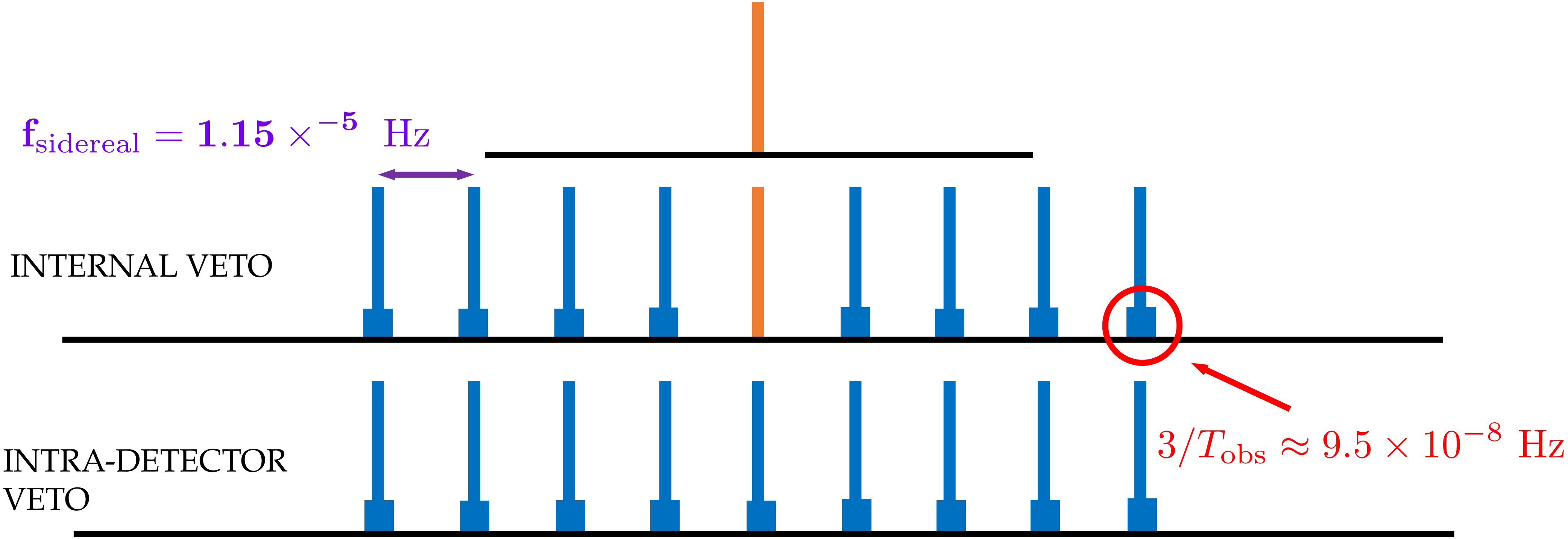
P Astone *et al* 2010 *Class. Quantum Grav.* **27** 194016

Resampling: Coincidence veto

A Singhal *et al* 2019 *Class. Quantum Grav.* **36** 205015

For every **candidate above threshold** in a given detector, **coincidence candidates** are searched for in 9 intervals in the other detector, having widths outlined below



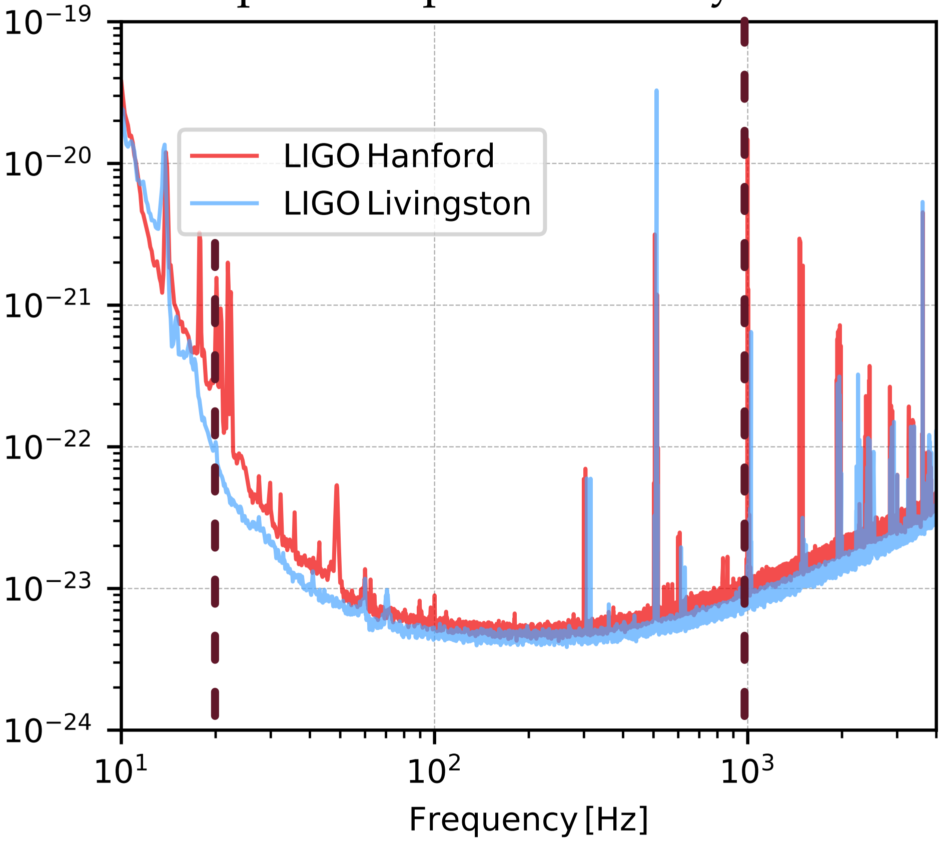
Introduction: Interferometers

- O3 data taking (https://gwosc.org/O3/) :
  - Start: April 1, 2019
  - End: March 27, 2020

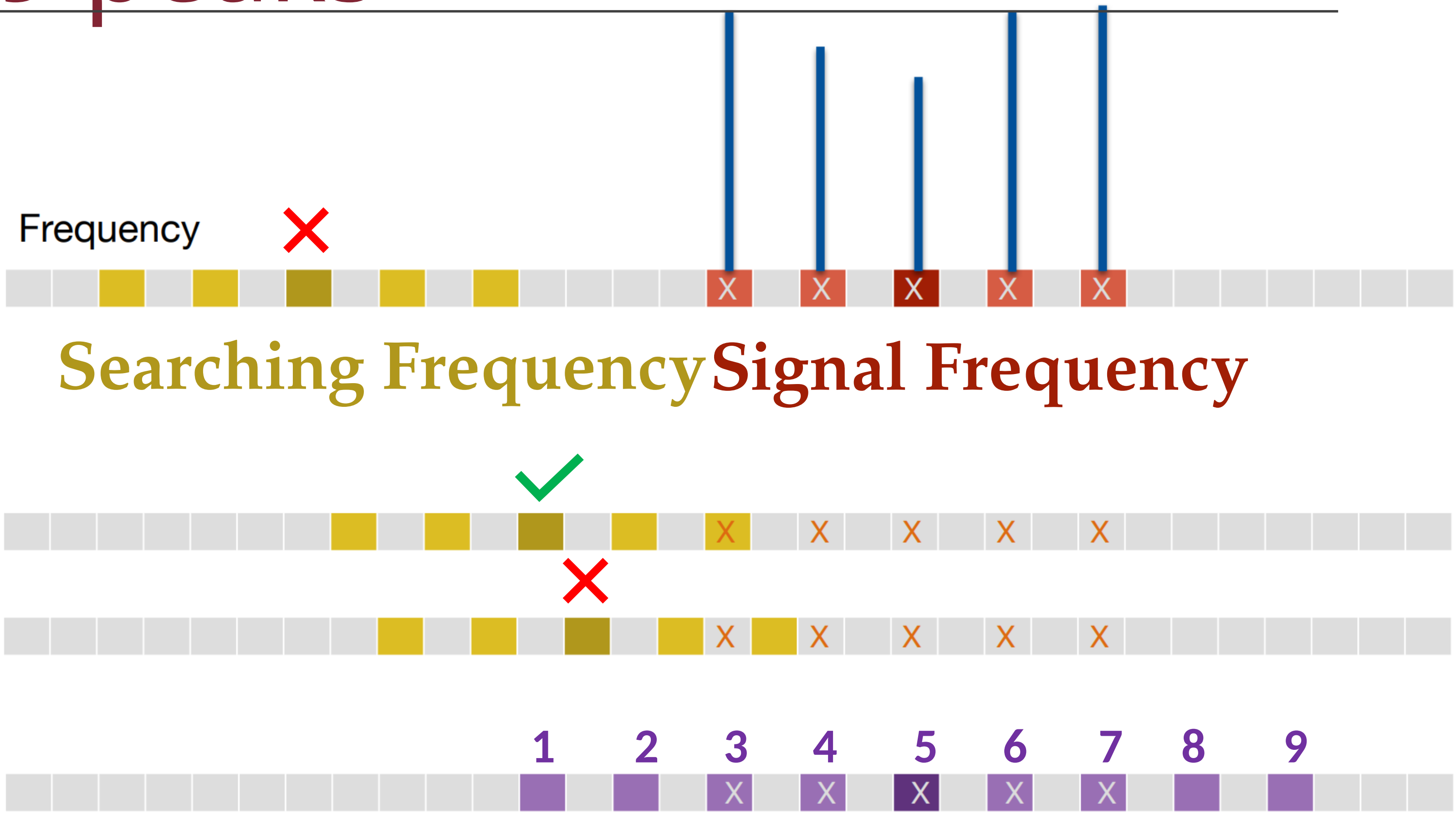
Search frequency range:

$f \in [10, 1000]$ Hz

O3 amplitude spectral density curves



DS: 9 peaks


Frequency
Searching Frequency
Signal Frequency
1
2
3
4
5
6
7
8
9

Resampling: Coincidence veto