Infinite-duration Continuous Gravitational Waves from neutron stars in binary systems

GraSP23

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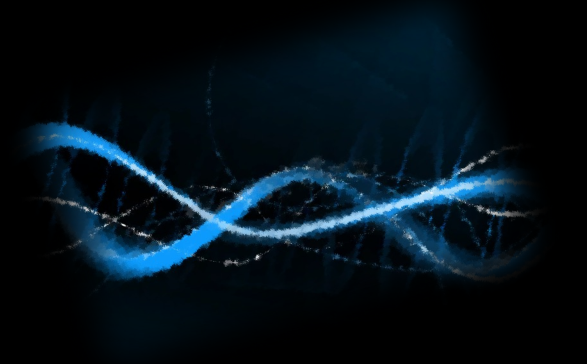
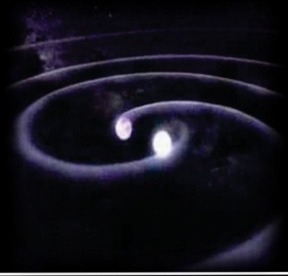
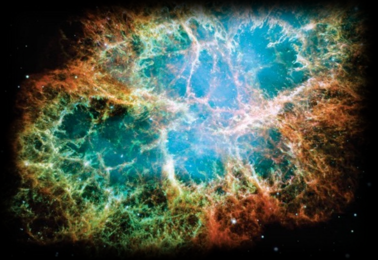
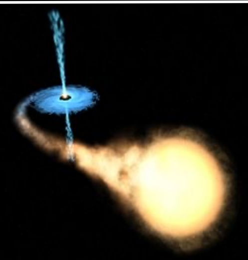
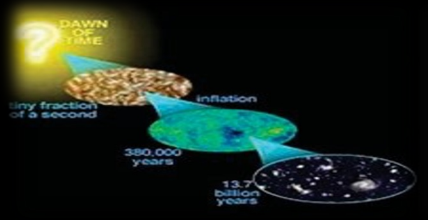
OUTLINE

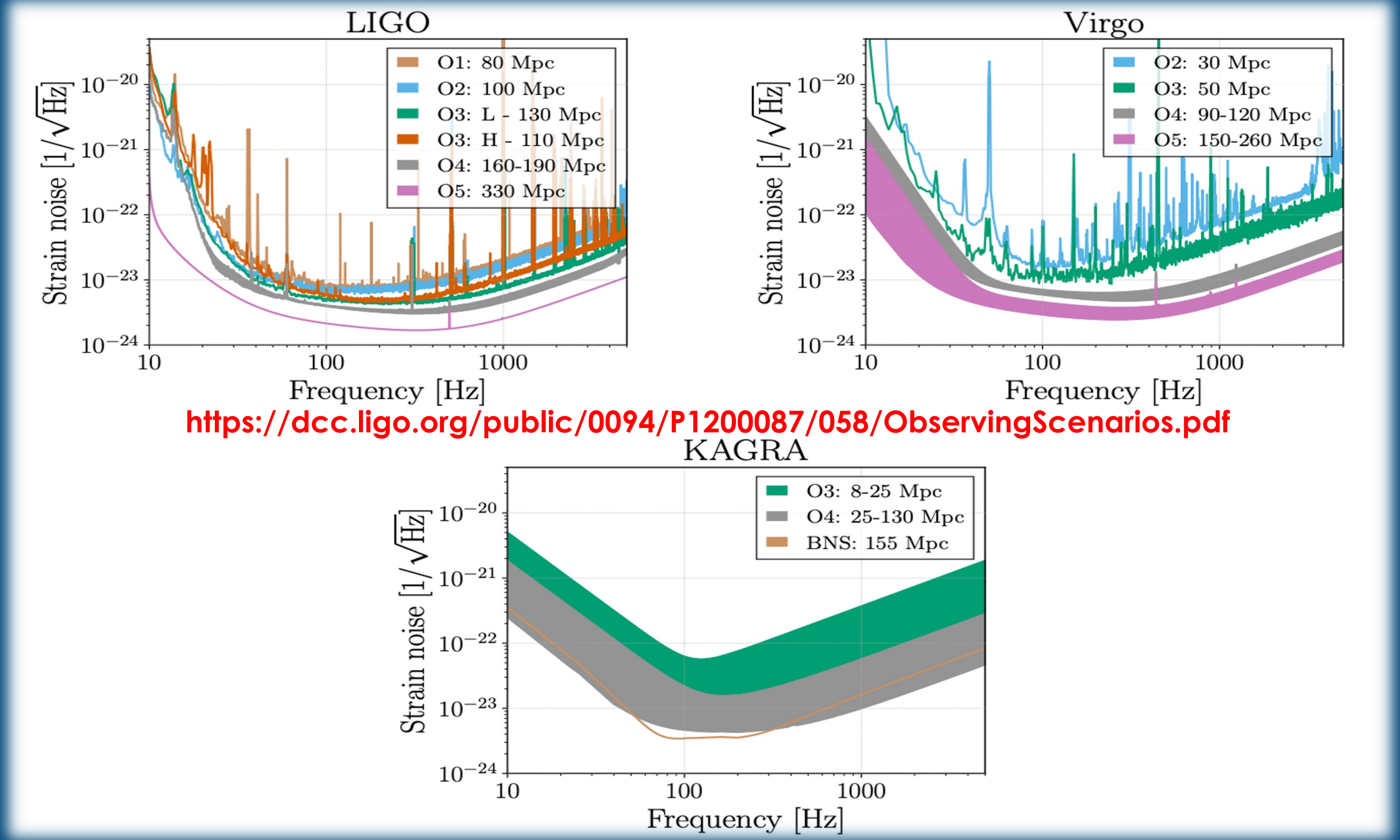
- Recap on Gravitational-Wave (GW) sources
- GW Advanced detector sensitivity progression
- Continuous-Wave (CW) signals: the BINARY case
- How to perform a search for CWs?
- CW search highlights from the third advanced LIGO-Virgo-KAGRA detector run
- Synergies with Multi-messenger astronomy
- Future Prospects



Recap on GW sources

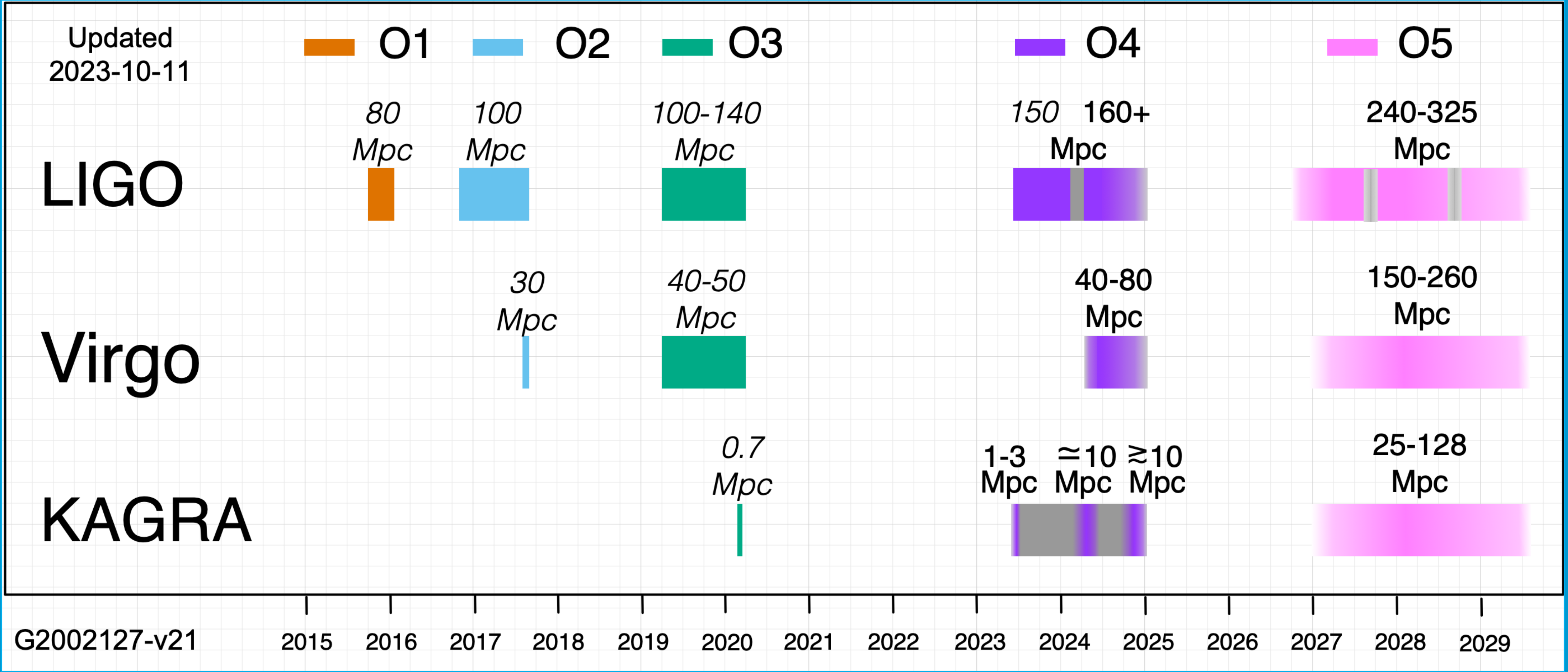
		Two Black Holes (BHs)	Two Neutron Stars (NSs)	BH-NS
Compact Binary Coalescing systems *(CBC)*, well modeled waveforms		✓	✓	✓
Supernovae, GRBs (*bursts*), unmodeled waveforms; short-duration GW events in coincidence with signals in electromagnetic (EM) radiation/neutrinos			X	
Fast-spinning NSs in our galaxy (either <u>isolated</u> or in <u>binary systems</u>); monochromatic waves; modeled waveform			X	X
Cosmological GW (*stochastic background*); A background of primordial and/or astrophysical GWs; unmodeled waveform			X	

GW Advanced detector sensitivity progression.I



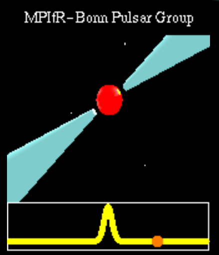
https://dcc.ligo.org/public/0094/P1200087/058/ObservingScenarios.pdf

GW Advanced detector sensitivity progression.II



https://observing.docs.ligo.org/plan/

CW signals



- Quasimonochromatic waves with a slowly decreasing intrinsic frequency, which are expected to be emitted by
  - *Rapidly rotating NSs with non-axisymmetric deformations*
  - *Short periodic signals (from ~hours-days) from NS r-modes*
  - *Clouds of ultra-light bosons that could form around Kerr black holes as a consequence of superradiance*

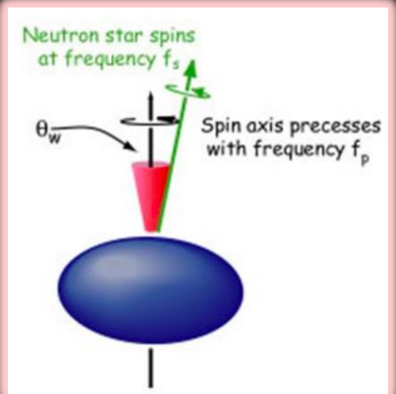
- Constant amplitude, weak (weaker than transient GW events), but persistent over years of data taking:
  - *Signal duration >> observation time*
  - *Due to the weakness of CWs, we have to integrate for a longer time to increase the signal-to-noise-ratio (SNR) ~O($T^{1/2}$)*

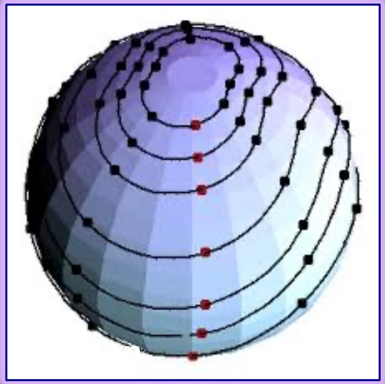
- Sensitivity increases with observation time

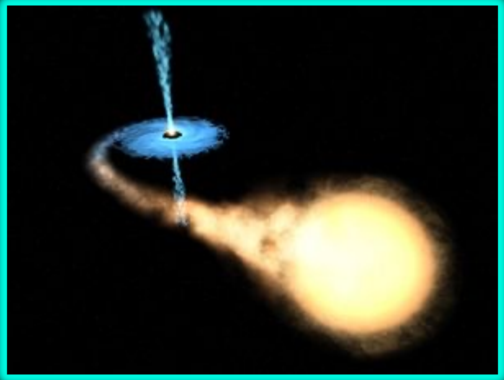
- Computation cost scales with a high power of the observation time

CW signals

- More than 3000 observed NSs (mostly pulsars) and $O(10^8 - 10^9)$ expected to exist in the Galaxy
- To emit CWs a NS must have a certain degree of non-axisymmetry due to
  - deformation caused by elastic stresses or magnetic field not aligned to the rotation axis ($f_{GW} = 2 f_{rot}$)
  - free precession around rotation axis ($f_{GW} \sim f_{rot} + f_{prec}$; $f_{GW} \sim 2f_{rot} +2 f_{prec}$)
  - excitation of long-lasting oscillations (*e.g.* *r*-modes; $f_{GW} \sim 4/3 f_{rot}$)
  - deformation due to matter accretion (*e.g.* LMXB; $f_{GW} \sim 2 f_{rot}$)







http://en.wikipedia.org/

CW signals:
CWs from rotating NSs

The measured strain amplitude h_0 on Earth is given by

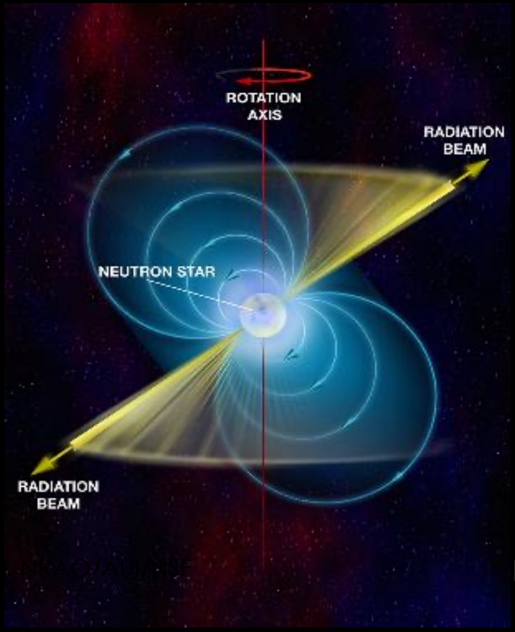
$$h_0 = \frac{4\pi^2 G}{c^4}\frac{I_{zz} f^2 \varepsilon}{d} \quad \Rightarrow \quad h_0 = 4\cdot 10^{-25}\left(\frac{\varepsilon}{10^{-5}}\right)\left(\frac{I_{zz}}{10^{45}\,\mathrm{g\,cm^2}}\right)\left(\frac{f_r}{100\ \mathrm{Hz}}\right)^2\left(\frac{1\ \mathrm{kpc}}{d}\right)$$

with d distance to the source, $\varepsilon = (I_{xx}-I_{yy})/I_{zz}$ being the equatorial non-axisymmetry and I_{ab} the moments of inertia

MAXIMUM DEFORMATION

- Normal NS ⟶ $\varepsilon \leq 10^{-5}$
- Hybrid (hadron-quark core) ⟶ $\varepsilon \leq 10^{-3}$
- Extreme quark stars ⟶ $\varepsilon \leq 10^{-1}$

PRD 87, 129903 (2013)]



CW signals:
The spindown limit

A rotating NS spins down losing energy:

$\varepsilon = \epsilon$

- $\dot{E}_{rot} \propto I_{zz} f_{rot} \dot{f}_{rot}$ ROTATIONAL ENERGY LOSS
- $\dot{E}_{GW} \propto I_{zz}^2 f_{rot}^6 \epsilon^2$ GRAVITATIONAL ENERGY LOSS
- If we assume that all the loss of energy of a spinning NS is caused by GW emission, i.e., that the observed star spindown, which is the decrease of the rotation period, is due to GWs, we get

$$\dot{E}_{rot} = \dot{E}_{GW} \implies \epsilon_{sd} \propto \sqrt{\frac{1}{I_{zz}} \frac{|\dot{f}_{rot}|}{f_{rot}^5}}$$

- From h_0 we can also express a theoretical upper limit for the GW amplitude: $h_{sd} \propto \frac{1}{r} \sqrt{I_{zz} \frac{|\dot{f}_{rot}|}{f_{rot}}}$

Going below the spindown limit means we are putting a constraint on the fraction of spindown energy due to the emission of GWs

CW signals:
Signal characteristics

- A CW signal is not exactly monochromatic, but it has a spindown due to the loss of energy (in a few cases a spinup may be present)

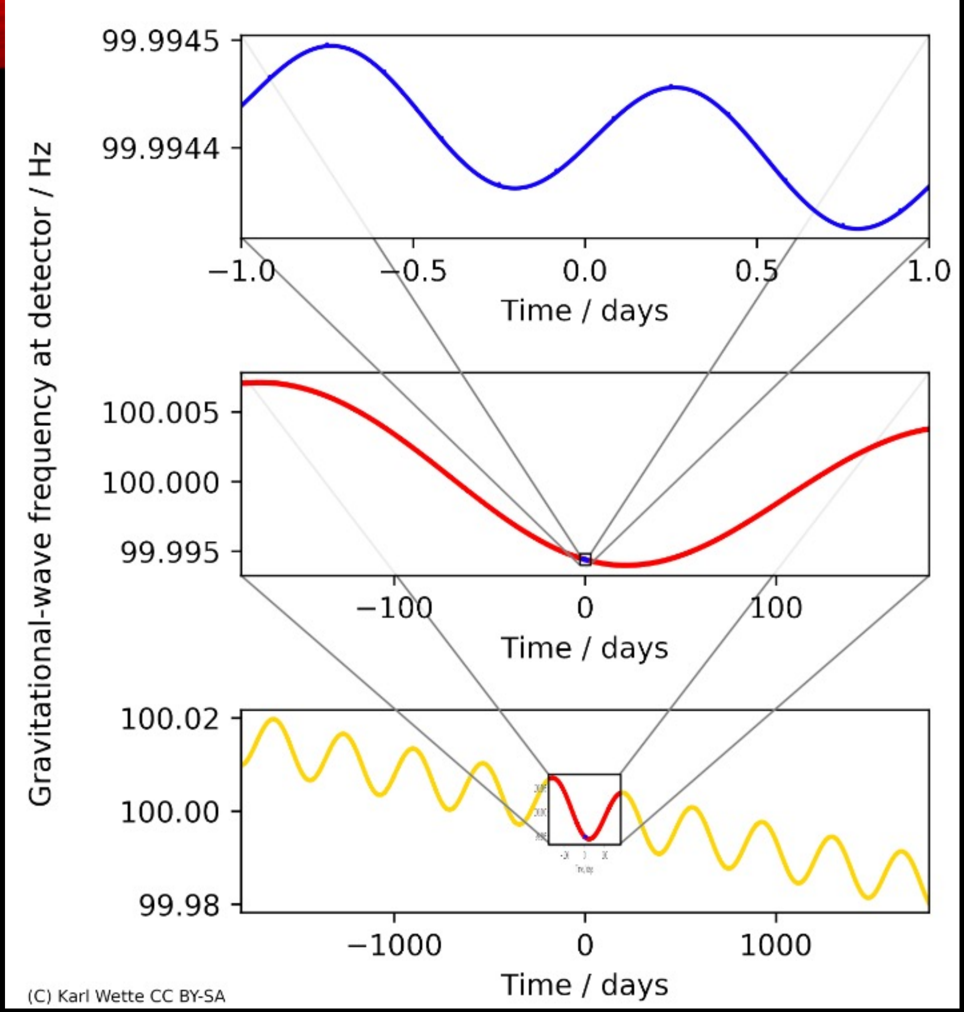
$$f_0(t) = f_0 + \dot{f}_0(t - t_0) + \frac{\ddot{f}_0}{2}(t - t_0)^2 + \dots$$

- Due to both the Earth orbital and rotational motions, we have that the signal frequency is Doppler shifted, depending on the direction of the source in the sky, and –if the signal is in an binary system– we have a further Doppler modulation due to the orbit motion of the companion

$$f(t) = \frac{1}{2\pi}\frac{d\Phi(t)}{dt} = f_0(t)\left(1 + \frac{\vec{v}\cdot\widehat{n}}{c}\right), \quad \vec{v} = \vec{v}_{orb} + \vec{v}_{rot}$$

- Due to the variation of the source direction in the detector frame, a sidereal day variation of the signal phase and amplitude is present
- Glitches (i.,e., sudden variations of the rotational frequency of the star) can also occur

CW signals:
The Doppler shift



Frequency changing with a daily cycle due to the Earth rotation

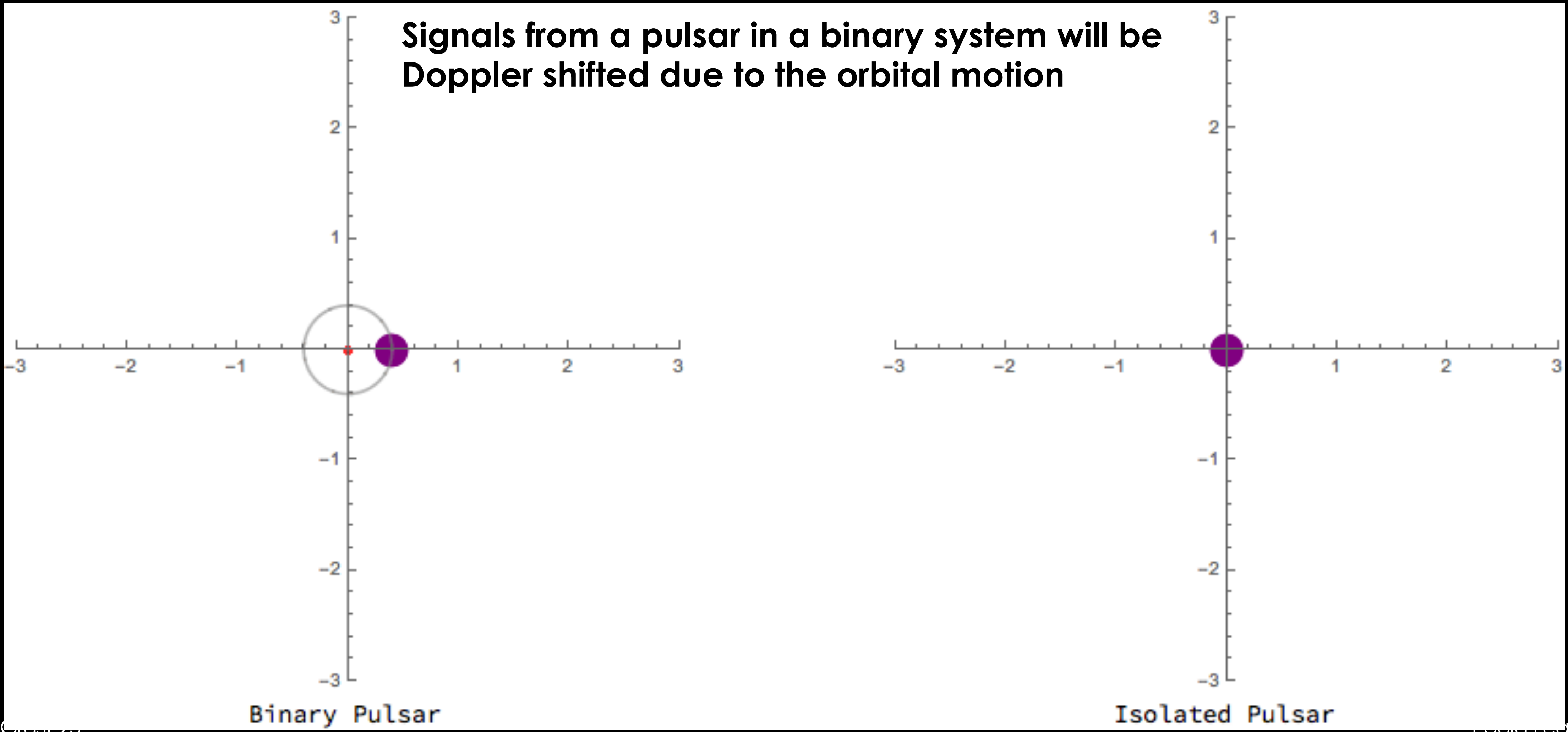
Zoom out of the frequency changing on a year's time scale due to the orbit of the Earth around the Sun

Further zoom out to show the slowly frequency decreasing due to the rotation of the NS, which slows down over several years

Tracking all possible frequency changes is what makes the CW detection a computational challenge

CW signals:
The Doppler shift

Signals from a pulsar in a binary system will be Doppler shifted due to the orbital motion



CW signals:
Further modulation effects

We have the following relativistic wave-propagation effects:

EINSTEIN DELAY quantifies the change in arrival times due to variations in clocks at the observatory and the Solar System Baricenter due to changes in the gravitational potential of the Earth and the Earth's motion

SHAPIRO DELAY time delay caused by the passage of the pulse through large gravitational fields (*radar signals passing near a massive object take slightly longer to travel to a target and longer to return than they would if the mass of the object were not present*)

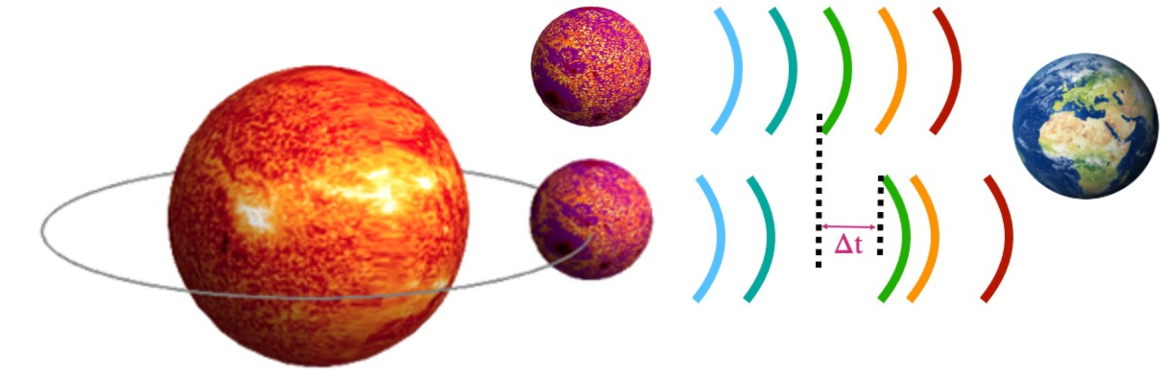
CW signals:

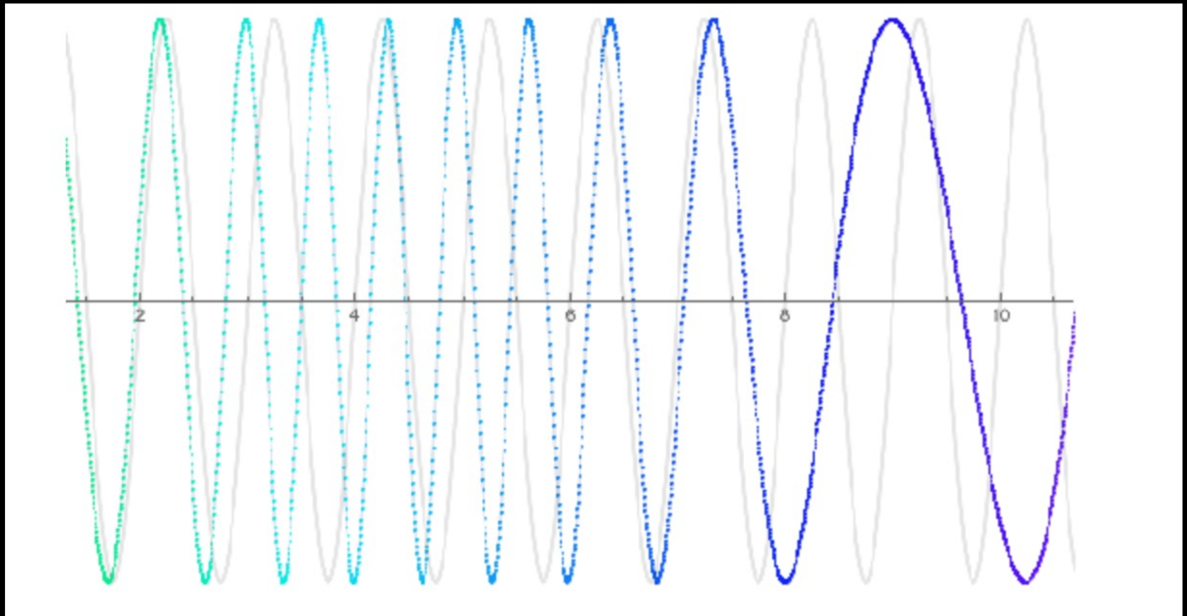
How can we remove these modulation effects?

- Due to the signal frequency variation, the CW energy is spread across more than a single frequency, thus reducing the SNR
- Assuming we know the frequency variation, or that we can model it by a set of templates, we can correct for it
- The frequency correction can be achieved with a variety of methods using *ad hoc* techniques:
    - re-sampling
    - heterodyne
    - standard frequency shift

The Resampling technique

- The time series is downsampled (using a non-uniform sampling time) at an irregular interval where the phase behaves linearly: *if the sampling frequency is proportional to the (varying) received frequency, the samples, seen as uniform, represent a constant frequency sinusoid*
- A regular spacing of the downsampled data results into demodulating the signal (*gray curve on the right*)





Singhal, Leaci *et al.*, CQG 36, 205015 (2019)

The Heterodyne technique

- We can multiply the data by a phase shift to correct the signal
- For a source with a known frequency and frequency evolution, the Doppler correction phase factor is

$$\phi_{dc}(t) = \frac{2\pi}{c} \cdot p_{\hat{n}} \cdot f_0(t)$$

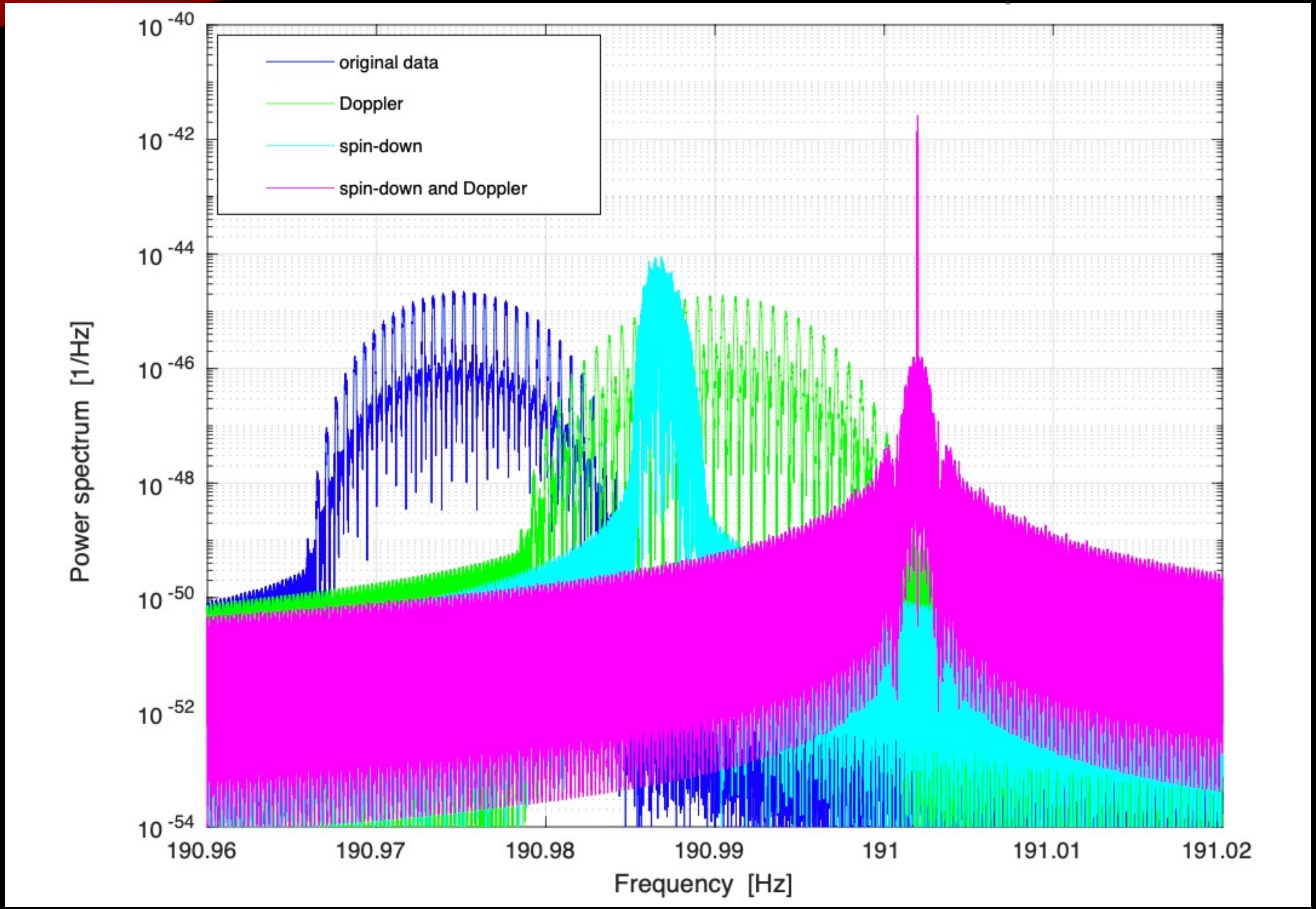
$$f_0(t) = f_0 + \dot{f}_0(t - t_0) + \frac{\ddot{f}_0}{2}(t - t_0)^2 + \dots$$

Position of the detector in the Solar System Baricenter, projected along a sky direction

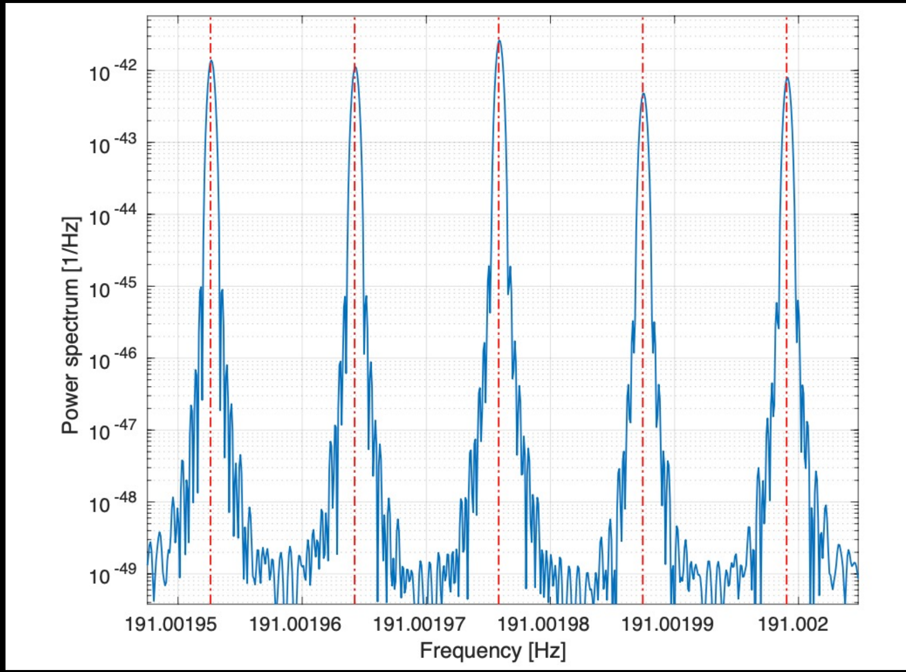
- If we denote the frequency variation due to the spindown as $sd(t) = \dot{f}_0 \cdot (t - t_0) + \dots$ the spindown phase correction term is given by

$$\phi_{sd}(t) = 2\pi \cdot \int_{t_0}^{t} sd(t')dt'$$

The Heterodyne technique



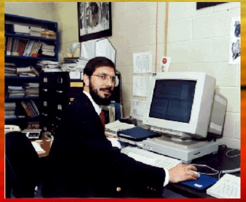
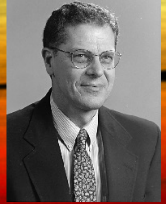
ZOOM OF THE PEAK



CW signals.VII:
CWs from spinning NSs in binary systems

- A CW signal from a source in a binary system is frequency-modulated by the source orbital motion, which in general is described by five unknown Keplerian parameters
- Accretion from a companion may cause an asymmetrical quadrupole moment of inertia of the spinning NS
- In some cases the accretion is asymmetric due to the sporadic observation of X-ray pulsations
- This asymmetry can lead to GW emission through various mechanisms:
  - *temperature-dependent electron capture onto nuclei in the crust [ApJ 501, L89 (1998)]*
  - *magnetic funneling of accreted material [ApJ 623, 1044 (2005)]*
  - *sustained instability of rotational r-modes [ApJ 516, 307 (1999)]*
- The most rapidly observed accreting NSs do not spin at very high frequencies, and this seems to suggest that their accretion torques are balanced by GW emission torque [ApJ 501, L89 (1998)]
- Maximal Doppler modulation due to the source orbital motion depends on orbital parameters

$$\Delta M = \frac{a_p \Omega}{1 - e}$$

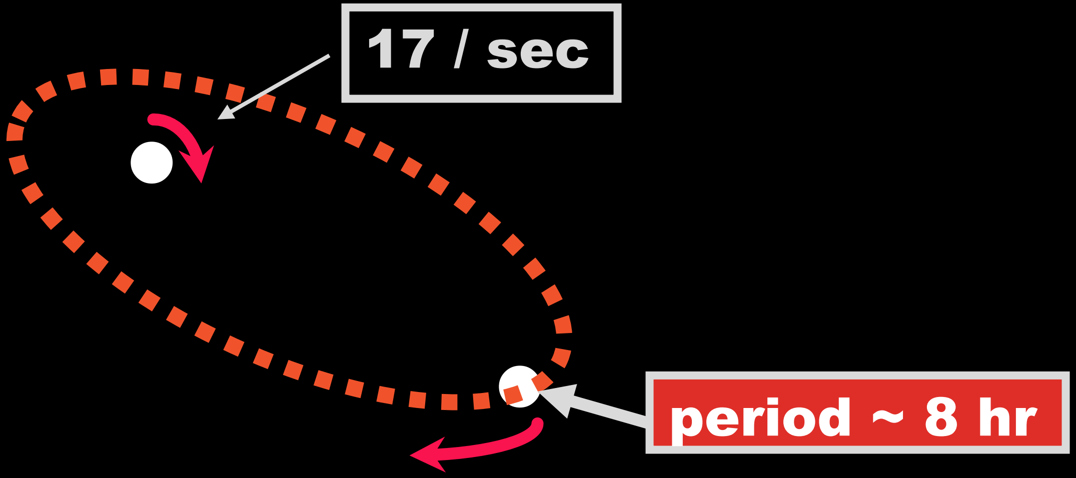



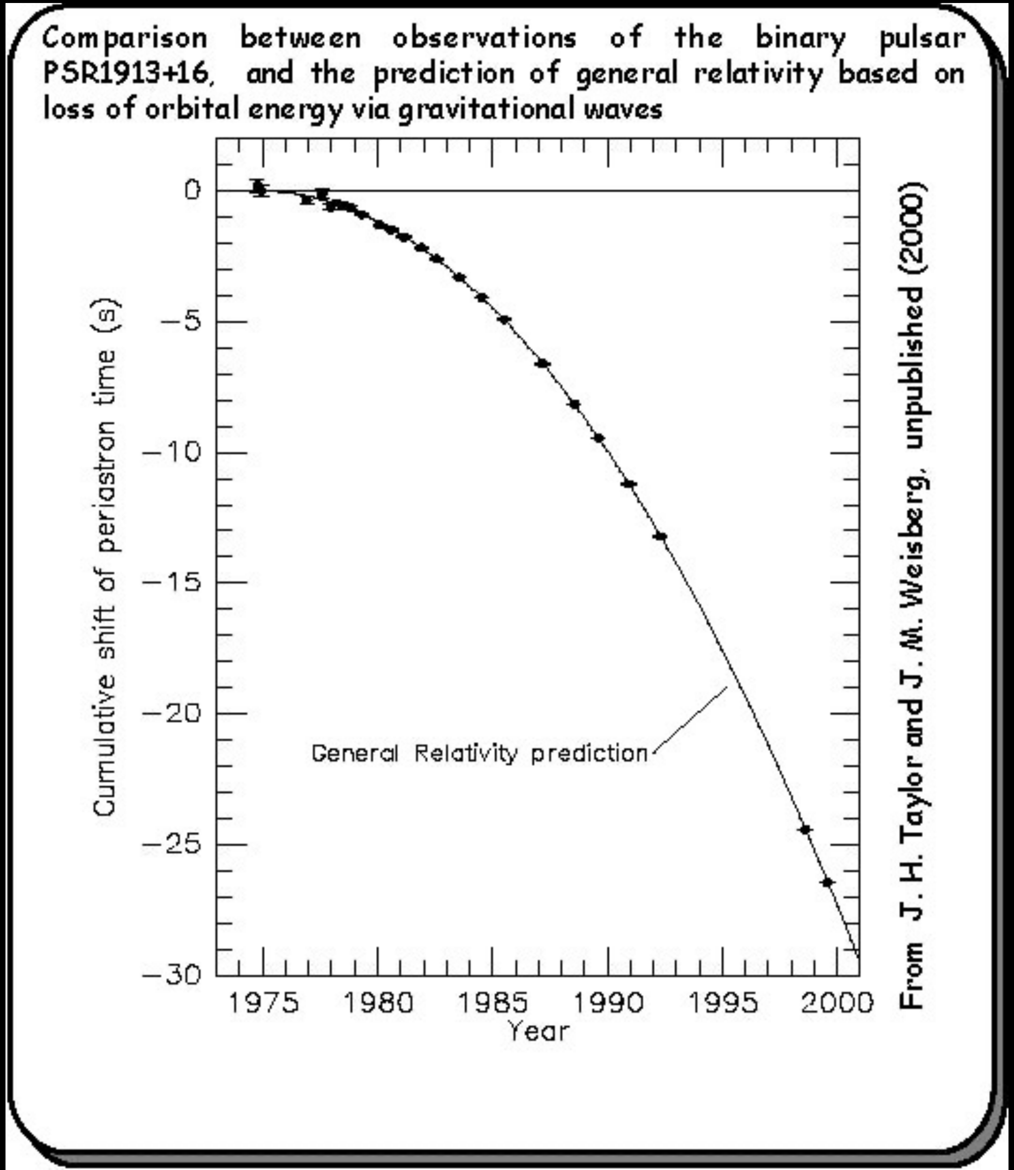
R. Hulse J. Taylor

Indirect GW Observation

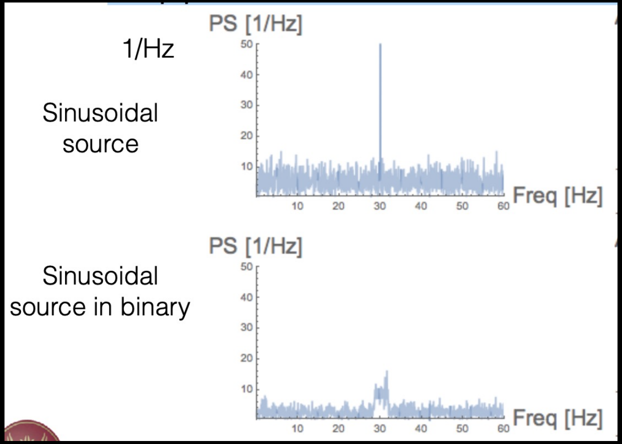
In 1974 they discovered, by using ARECIBO Radio Telescope, the first radio pulsar in a binary system: PSR 1913 + 16

Its orbital period decreased accordingly to what predicted by GR theory as regards GW emission!





Binary Systems



- The signal phase model is

$$\phi(t) = 2\pi f\{\Delta t - a_p[\sin\omega(\cos E(t) - e) + \cos\omega \sin E(t)\sqrt{1-e^2}]\},$$

Eccentric orbits

$$\phi(t) \approx 2\pi f\left\{\Delta t - a_p\left[\sin\psi + \frac{\kappa}{2}\sin 2\psi - \frac{\eta}{2}\cos 2\psi - \frac{3\eta}{2}\right]\right\}$$

Small-eccentricity approximation

$$\psi(t) \equiv \Omega(t - t_{\mathrm{asc}}),$$

$$\kappa \equiv e\cos(\omega), \quad \eta \equiv e\sin(\omega),$$

$$e = \sqrt{\kappa^2 + \eta^2} \text{ and } \omega = \arctan(\eta/\kappa),$$

$$t_{\mathrm{asc}} \equiv t_p - \frac{\omega}{\Omega}$$

$$\Delta M = \frac{a_p \Omega}{1 - e}$$

Maximal Doppler modulation due to orbital motion

$$\Omega = \frac{2\pi}{P}$$ ***mean orbital angular velocity***

Leaci & Prix: https://arxiv.org/abs/1502.00914
Leaci et al.: https://arxiv.org/abs/1607.08751

What's the best approach to search for CWs?

- The perfect search algorithm should be characterized by:
  - a high sensitivity (which can be translated into a high SNR coming from a long coherence time)
  - robustness with respect to signal uncertainties and noise artifacts (i.e., It should help reducing as much as possible the selection of noise candidates and it should be "model independent")
  - computational feasibility

- We need to find a TRADE-OFF between sensitivity and computing cost, filtering out annoying disturbances

How to perform a search for CWs?

The way to search for CWs depends on how much about the source is known. There are three main different types of searches:

- TARGETED/narrowband searches for observed NSs. The source parameters (sky location, frequency & frequency derivatives) are assumed to be known with great/enough accuracy (*e.g.* the Crab and Vela pulsars) => *O*(laptop)

$$h_{0_{min}} \approx 10\sqrt{\frac{S_n(f)}{T_{coh}}}$$

- DIRECTED searches, where sky location is known while frequency and frequency derivatives are unknown (*e.g.* Cassiopeia A, SN1987A, Scorpius X-1, galactic center, globular clusters) => *O*(cluster)

$$h_{0_{min}} \approx \alpha\sqrt{\frac{S_n(f)}{T_{coh}}}$$

- ALL-SKY searches for unknown pulsars => computing challenge (grid/cloud infrastructures)

$$h_{0_{min}} \approx \frac{\Lambda}{N^{1/4}}\sqrt{\frac{S_n(f)}{T_{coh}}}$$

Various approaches for CWs from binary systems

- Performance comparison of various pipelines -> Messenger et al., PRD 92, 023006 (2015)

- Parameter-space metric for Scorpius-X1 like searches ->
  - Leaci & Prix, PRD 91, 102003 (2015)
  - S. Suvorova et al., PRD 93, 123009 (2016)
  - LVK, Phys. Rev. D 106, 062002 (2022)
  - Whelan et al., ApJ 949, 117 (2023)

- Novel (directed) search strategy to detect continuous GWs from NSs in low- and high-eccentricity binary systems -> Leaci et al., PRD 95, 122001 (2017)

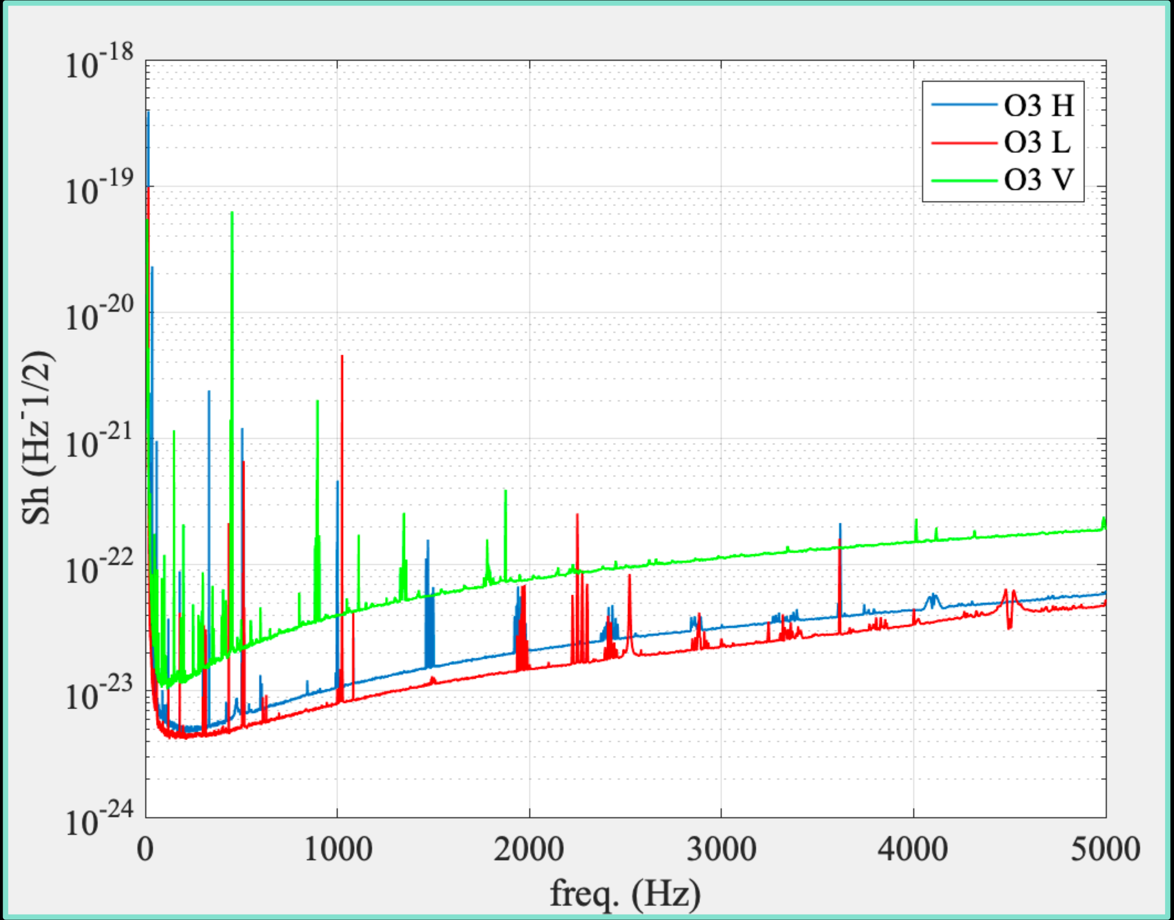
- All-sky approach: LVK, Phys. Rev. D 103, 064017 (2021)

CW search highlights from the third advanced LIGO-Virgo detector run

The third advanced LIGO-Virgo detector run O3

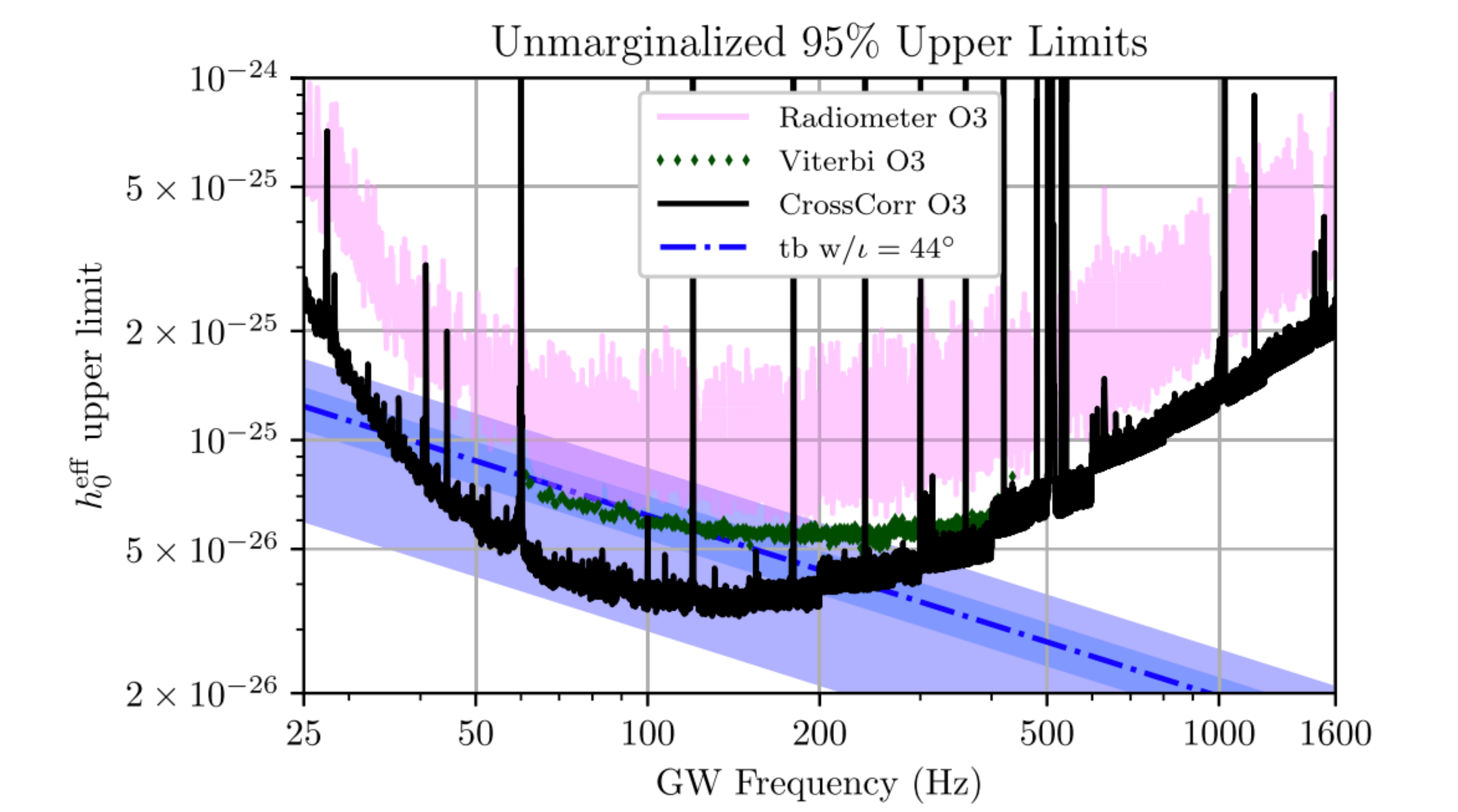
O3 observing run:
April 1, 2019 – March 27, 2020

Commissioning break:
October 1-31, 2019



Model-based Cross-correlation Search for GWs from Scorpius X-1 in O3 data

- Search frequency region: [25-1600] Hz
- Orbital period: 19h; Projected semimajor axis: [1.44 – 3.25] ls
- The blue dotted–dashed line corresponds to the assumption that the NS spin is aligned to the most likely orbital angular momentum and $\iota \sim 44$ degrees

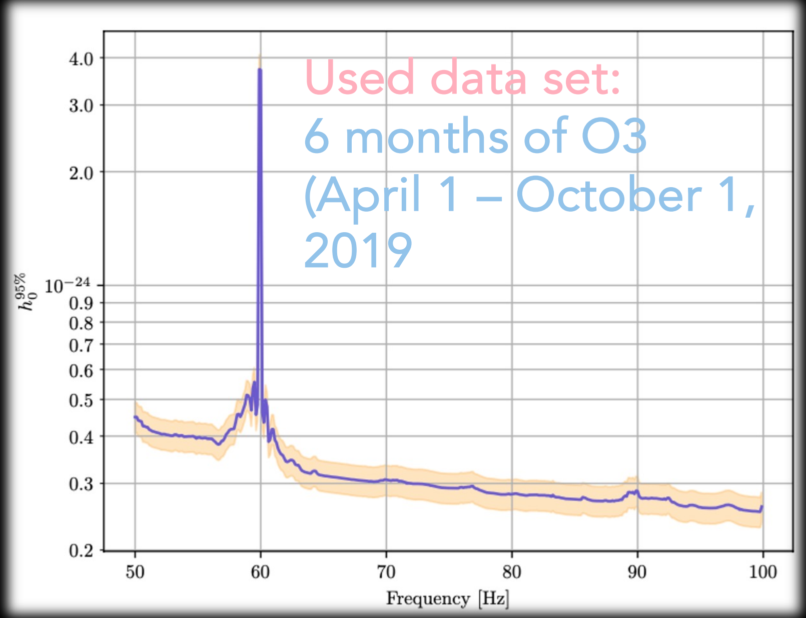


LVK, ApJ 941, 2022

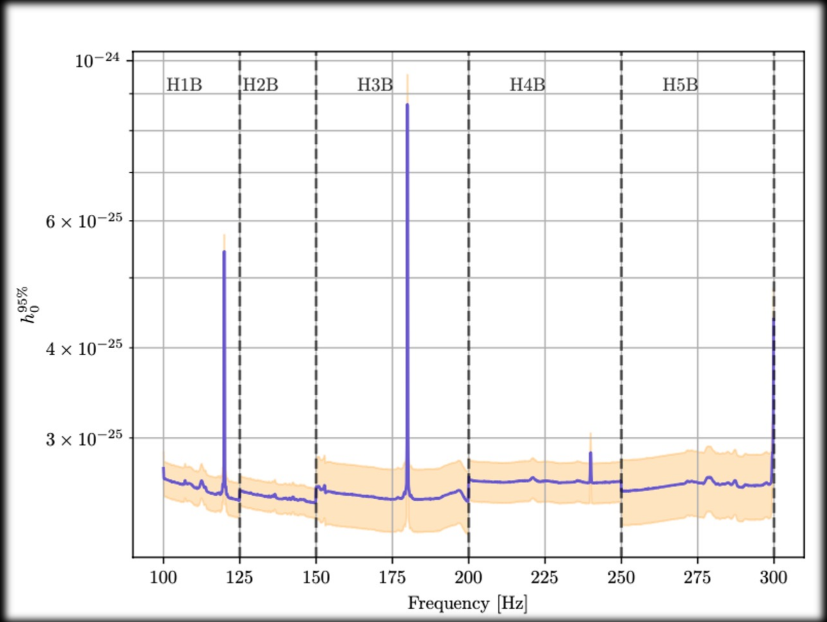
All-sky search for CWs from unknown NSs in binary systems

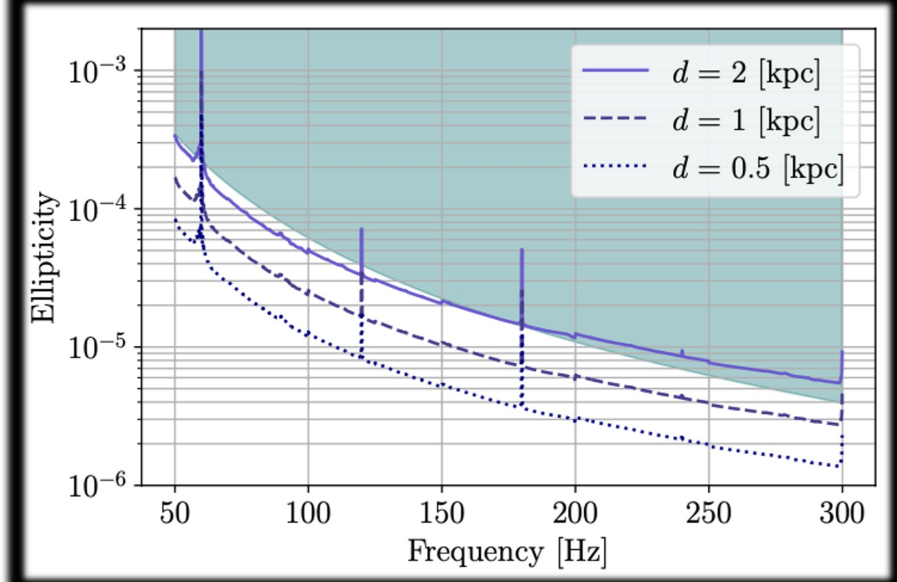
PRD 103, 064017 (2021)

- Search frequency region: [50-300] Hz
- Binary orbital parameters are split into four regions, including Orbital period: [3 – 45] days; Projected semimajor axis: [2 – 40] ls
- Search sensitivity estimated in terms of the GW amplitude corresponding to the interpolated 95% detection efficiency using a simulated population of signals



Used data set:
6 months of O3 (April 1 – October 1, 2019





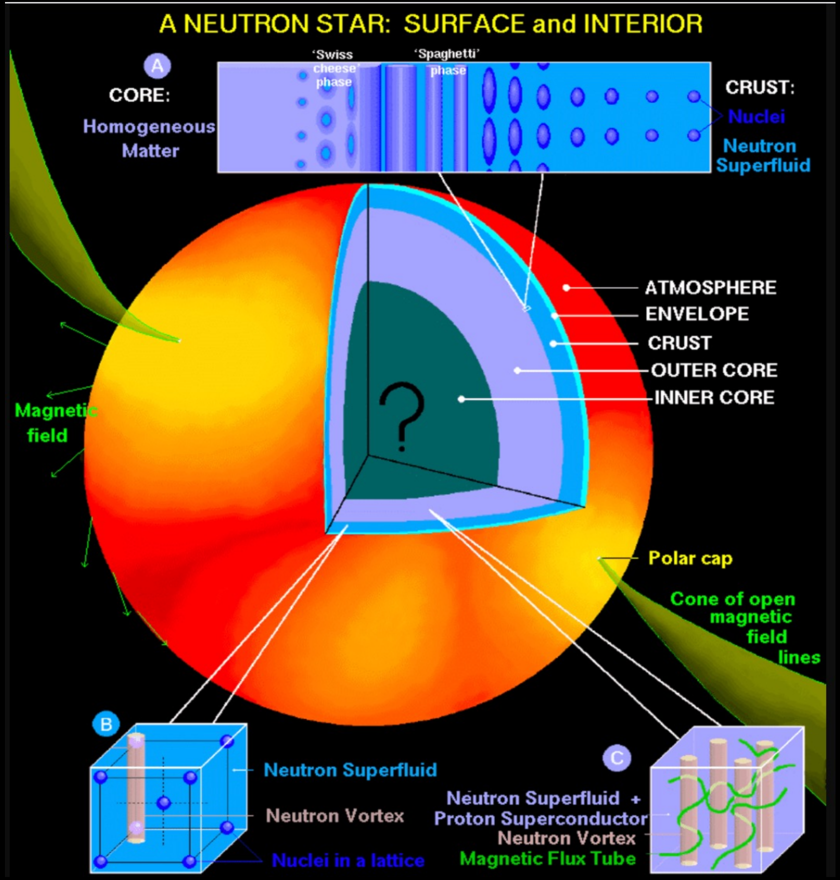
No detection can be claimed

Synergies with Multi-messenger astronomy

- EM observations alone cannot help to understand NS composition (highly condensed matter, crystalline structure, viscosity,…)

- Information on NS quadrupolar deformation (ellipticity) will be very valuable to understand whether NSs are composed by only neutrons, quarks, exotic matter, and so on

- Other NS properties (the range of NS masses, radii, sky locations, maximum NS spin frequency, population models, cold dense matter EOS properties)

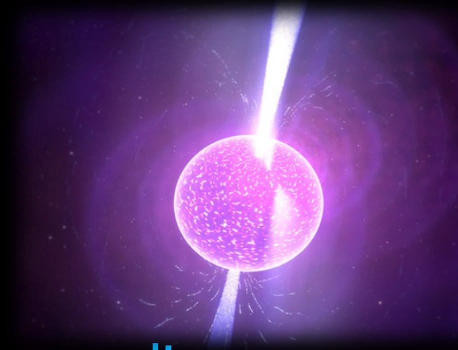


Credit: Dany P Page, Phys.org

- Detecting deviations from GR (speed of GWs, existence of other polarizations)

What do we need to facilitate the CW detection?

- UPDATED EPHEMERIS as fully coherent searches for CWs from known pulsars rely on coherent phase models and wrong ephemeris can introduce phase errors, which would result in a loss of SNR
- RADIO OBSERVATORIES able to monitor the vast majority of radio pulsars, mainly those with high spindown, which translates into a strong CW emission (e.g. PSRs J1952+3252 and J1913+1011)
- GAMMA/X-RAY observations
- NEW PULSAR DISCOVERIES (in all of EM bands)
- ROBUST ALGORITHMS able to detect both our standard signal models and the unexpected!
- … and of course (more) SENSITIVE GW DETECTORS



Credit: Kevin Gill

Future Prospects

- O3 data has been thoroughly analyzed
- Optimizing search algorithms (porting to GPUs/Machine Learning)
- Improving Follow-up methodologies (to be more computationally efficient)
- O4 started on May 27, 2023 and it exhibits an improved sensitivity with respect to O3; planned duration: 20 months
- Getting ready for O4+ and the 3rd generation GW detectors (e.g., Einstein Telescope and LIGO Cosmic Explorer)

QUESTIONS ARE WELCOME