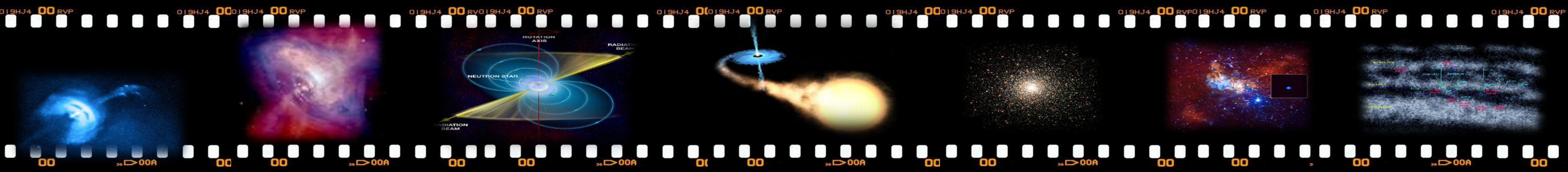
Build-a-Detector WORKSHOP

May 31 - June 11

Continuous Gravitational-Wave sources



Paola Leaci

paola.leaci@roma1.infn.it

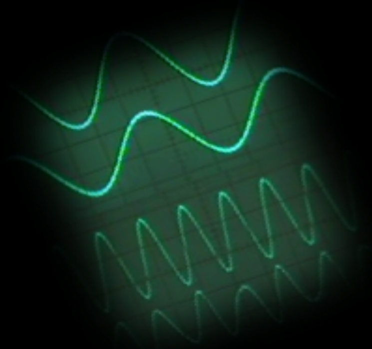
SAPIENZA UNIVERSITÀ DI ROMA

INFN Istituto Nazionale di Fisica Nucleare

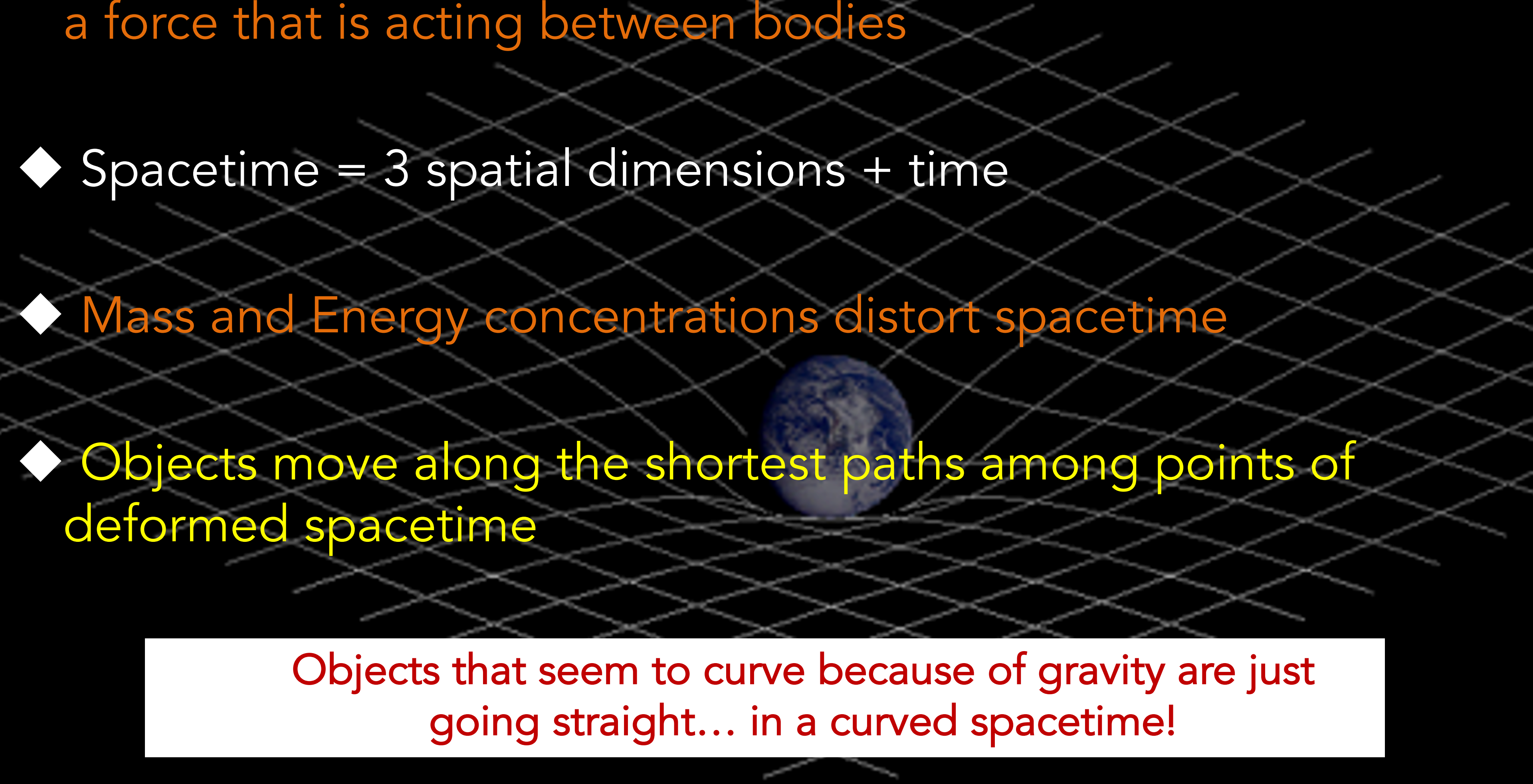
LIGO VIRGO

OUTLINE

- Gravitational-Wave (GW) Interferometry
- GW sources
- The Continuous Wave (CW) signal
- CW data analysis
- Hands-on session



General Relativity (GR): the essential idea



- Gravity can be looked at as curvature in space- time and not as a force that is acting between bodies
- Spacetime = 3 spatial dimensions + time
- Mass and Energy concentrations distort spacetime
- Objects move along the shortest paths among points of deformed spacetime

Objects that seem to curve because of gravity are just going straight… in a curved spacetime!

Global GW Interferometer (IFO) network

LIGO Livingston (LA, USA): 4 km dual recycled Fabry-Perot Michelson IFO

GEO600 (Hanover, GE):
600 m folded arms dual recycled Michelson
triple pendulum suspensions

VIRGO (Cascina, IT):
3 km power recycled
Fabry-Perot Michelson
super-attenuator
seismic isolation

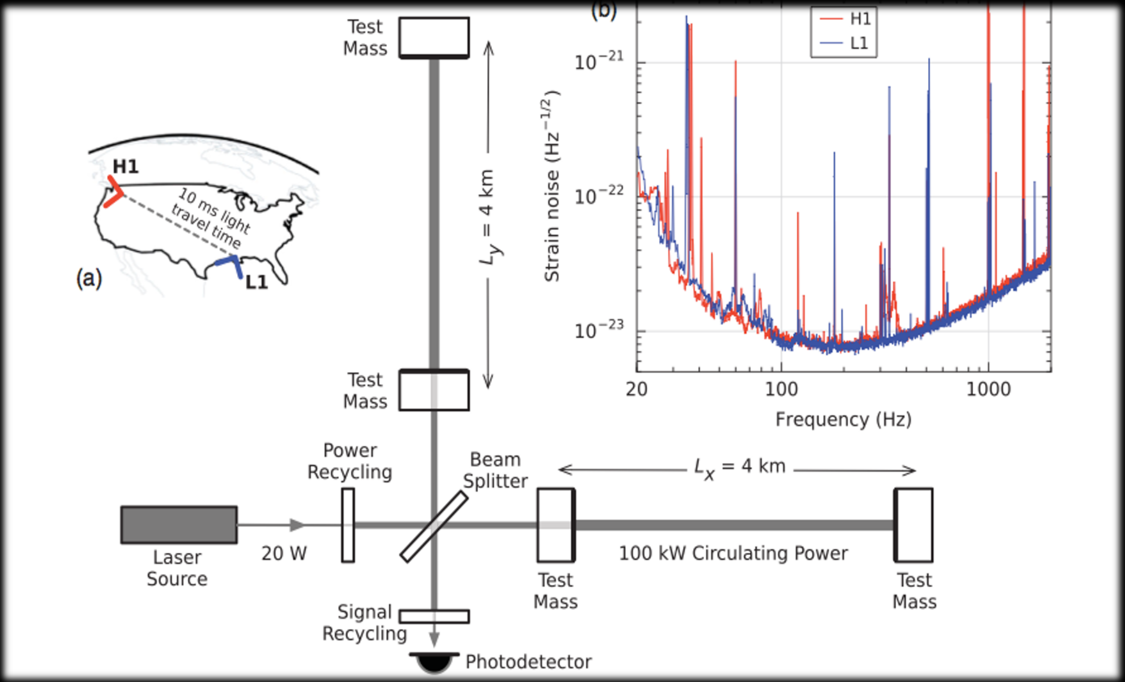
LIGO Hanford (WA, USA):
4 km dual recycled Fabry-Perot Michelson IFO

KAGRA (JP): 3 km dual recycled Fabry-Perot Michelson IFO
(2019+)

LIGO-India (IndIGO):
PLANNED (2025+)

GW Interferometry

- What we see at the photodetector of a Michelson IFO depends on the time difference taken by the light to go back and forth in the two arms, i.e. on the difference in arm length.



- The detected signal is originated by a phase shift of the laser light :

  $\Delta\Phi = \Delta t\, \omega = \Delta L\, 2\pi/\lambda$

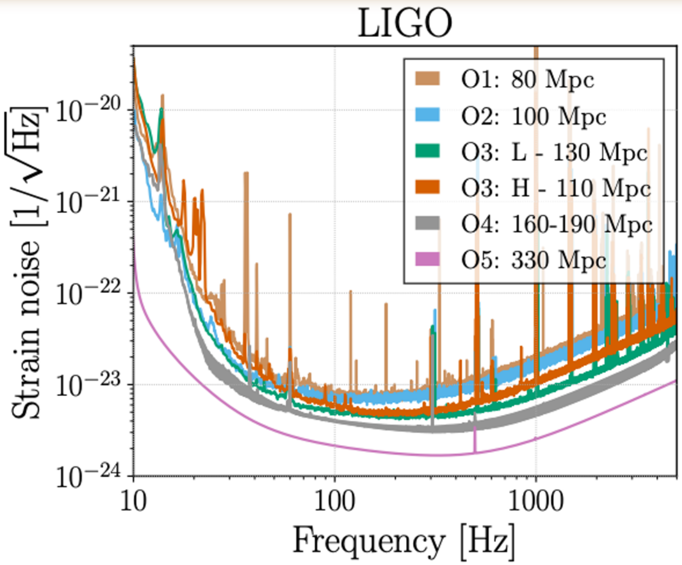
- The difference in arm length is given by

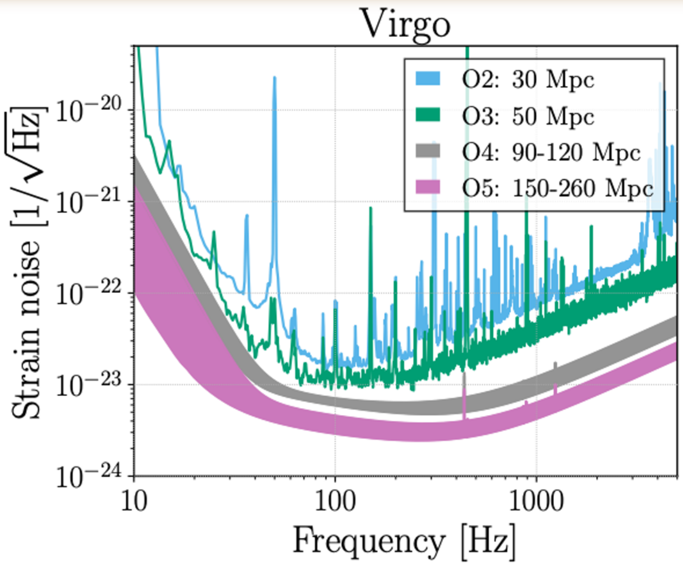
  $\Delta L \sim h\, L$

- The “deformation” the mirrors undergo is $\Delta L \sim 10^{-19}$ m

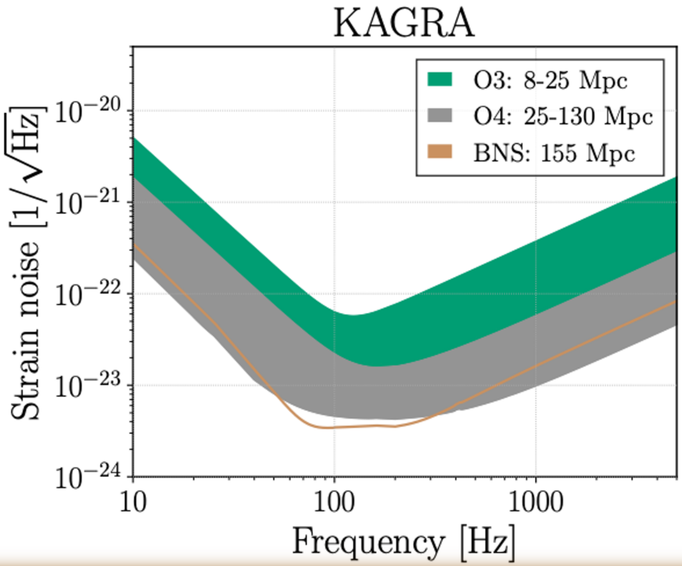
- Given h, the larger L, the larger ΔL

GW detector sensitivity progression I

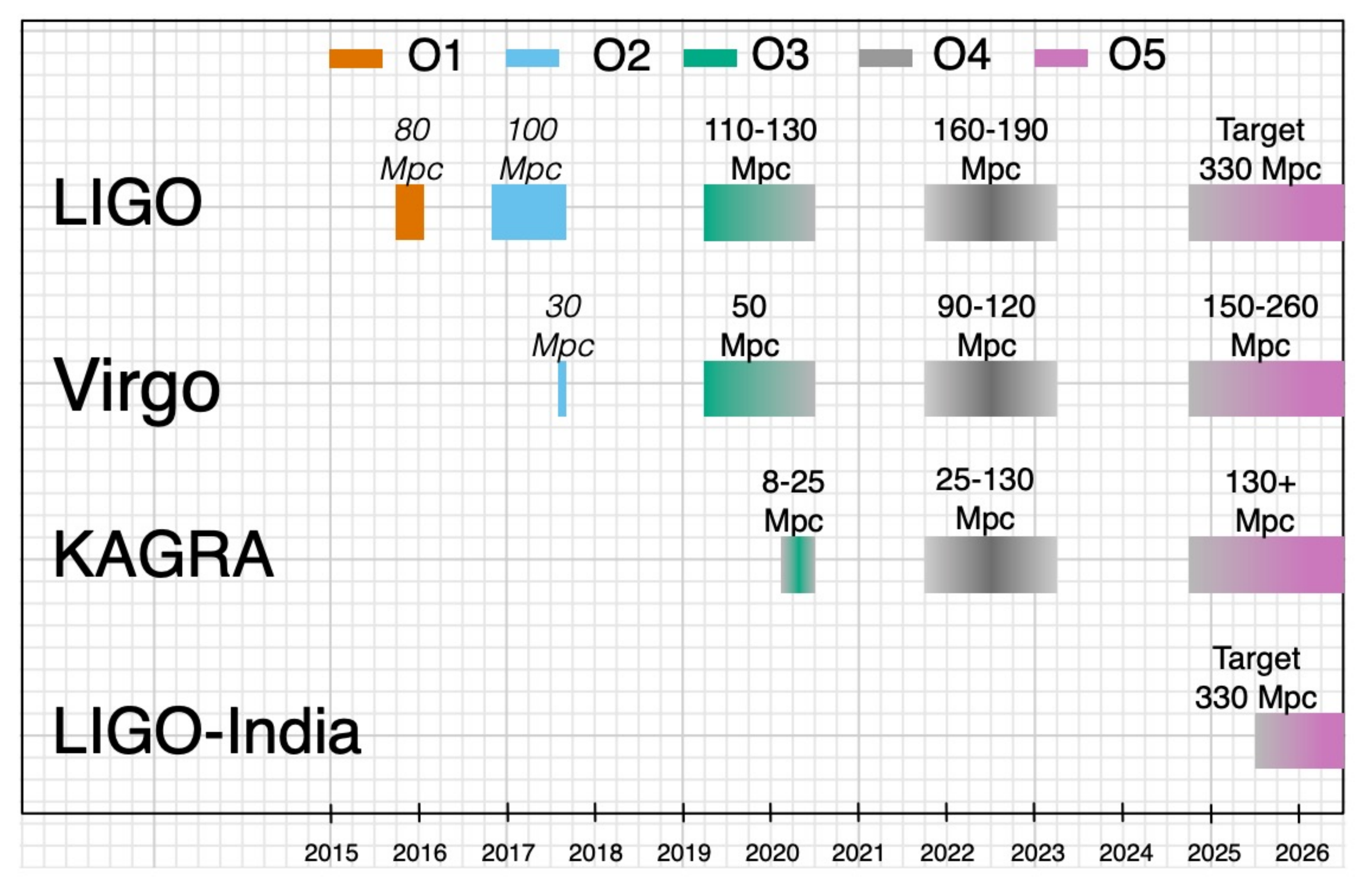




https://dcc.ligo.org/public/0094/P1200087/058/ObservingScenarios.pdf



GW detector sensitivity progression II



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

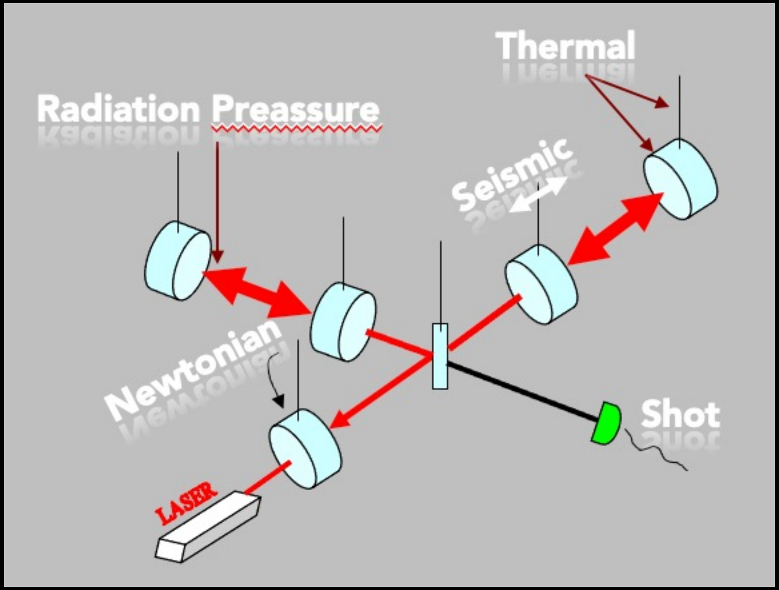
Main detector noise sources

- Quantum Noise (due to measurement and readout processes, strongly related to the quantum-nature of light):
  - Radiation preassure ~ f^{-2} (Photons transfer their momentum to the mirror. They hit it with temporally inhomogeneous distribution => the force exerted onto the mirror shows time fluctuations => test-mass position fluctuations
  - Shot Noise ~ $P_{laser}^{1/2}$(Photons in a laser beam are not equally spaced in time but they follow a Poissonian distribution => photo-current time-series fluctuations)

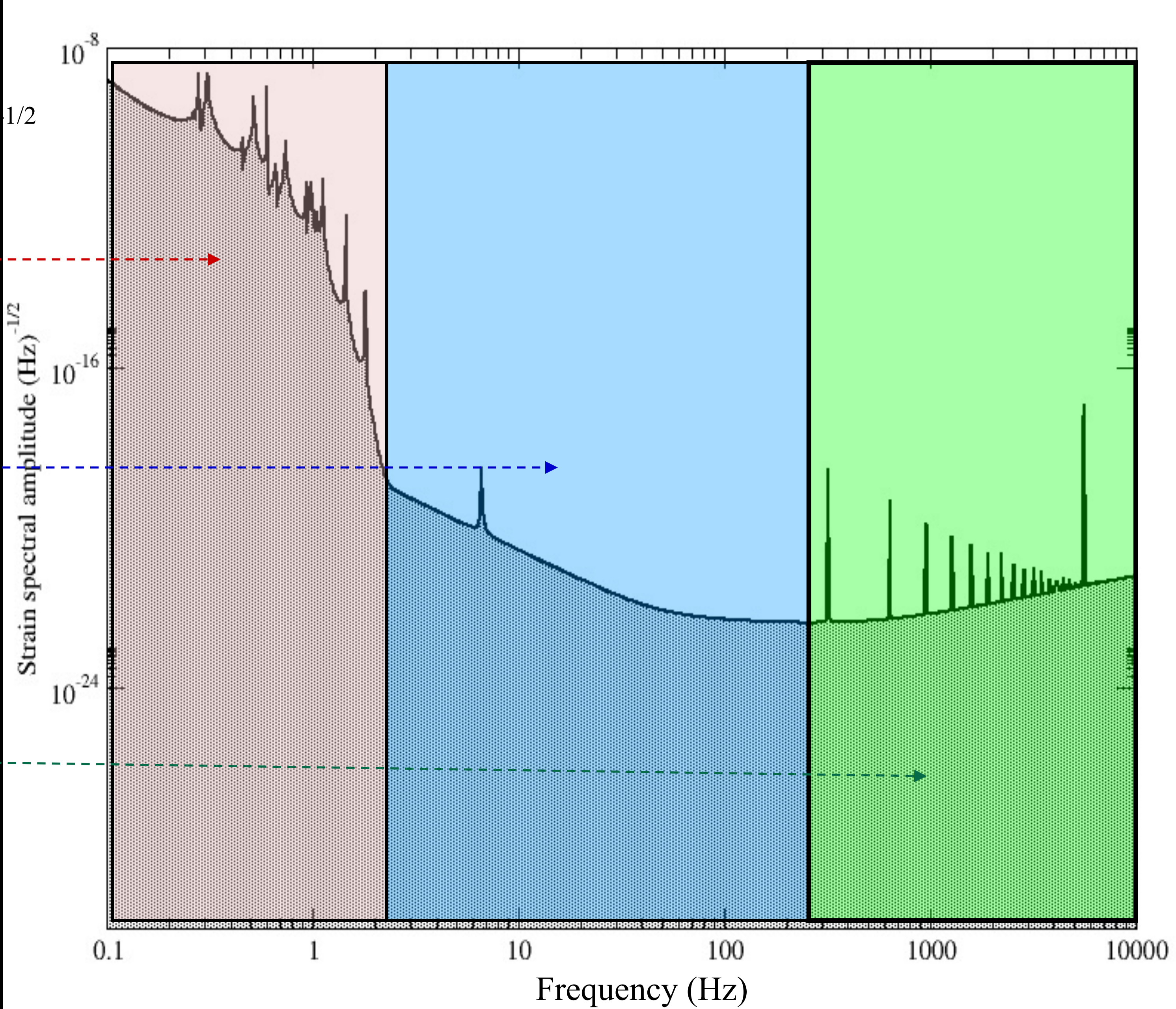
- Thermal Noise (thermal fluctuations in the electron density within a conductor)

- Newtonian Noise (due to transients in the local gravitational field; relevant from 1 Hz up to 10 Hz)

- Seismic Noise (due to human or wind activity, unwanted vibrations of the interferometer components) => reduced by using seismic isolation system



Detector Intrinsic Noise Spectrum



Seismic

Passive and Active Attenuators

Thermal

Low dissipation materials for coatings, mirrors and suspensions

Shot

High Laser Power, Signal Recycling Techniques

Antenna Pattern: *directional response function*

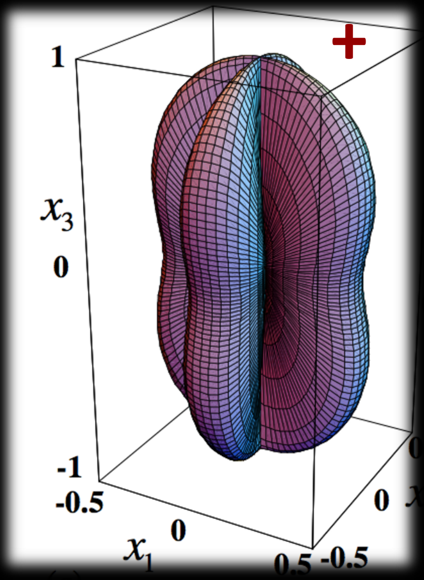
The received signal at the detector is

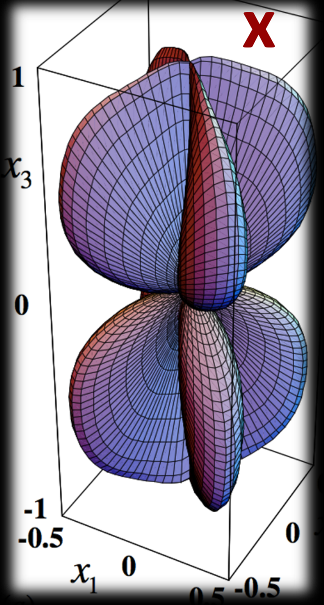
$$h(t) = F^{+}(t;\, \alpha, \beta, \Psi)\, h_{+}(t) + F^{\times}(t;\, \alpha, \beta, \Psi)\, h_{\times}(t)$$

Detector antenna patterns

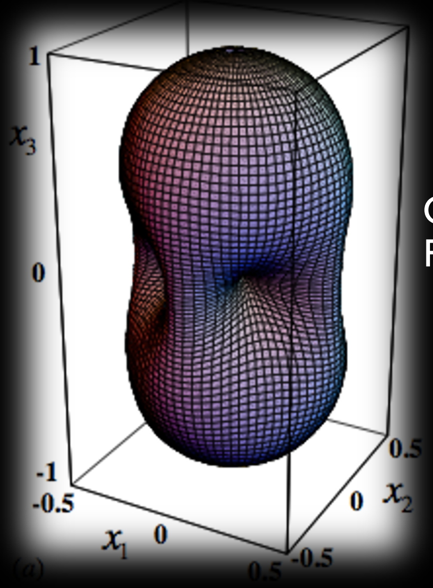
$$h_{+}(t) = A_{+} \cos\phi(t) \qquad A_{+} = \frac{1}{2} h_0 (1 + \cos^2 \iota)$$

$$h_{\times}(t) = A_{\times} \sin\phi(t) \qquad A_{\times} = h_0 \cos\iota$$





Detector arms oriented along the x_1 and x_2 axes



CIRCULAR POLARIZATION

Because of the diurnal motion of the Earth the beam patterns F^{+} and $F^{\times}$ are periodic functions of time with a period equal to one sidereal day

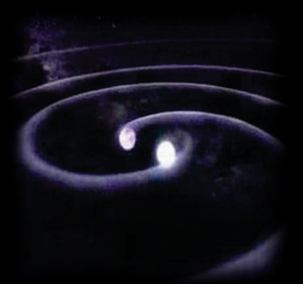
The distance from a point of the plot surface to the center of the box is just a measure of the GW sensitivity in this direction

GW sources

Two Black Holes (BHs)

Two Neutron Stars (NSs)

BH-NS

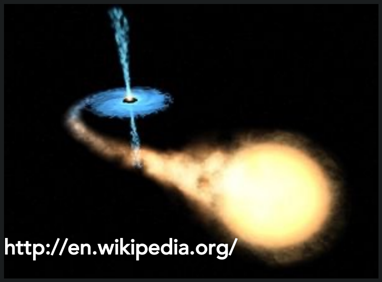


- Compact Binary Coalescing systems *(CBC)*, well modeled waveforms

✓ ✓ ✓

- Supernovae, GRBs (*bursts*), unmodeled waveforms. Short-duration GW events in coincidence with signals in electromagnetic (EM) radiation/neutrinos

X



http://en.wikipedia.org/

- Fast-spinning NSs in our galaxy (either isolated or in binary systems); monochromatic waves; modeled waveform

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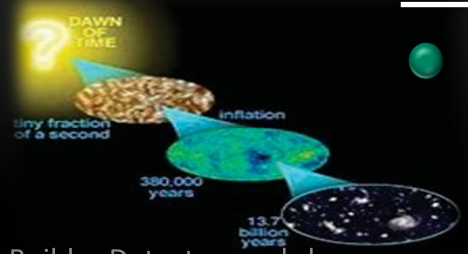


- Cosmological GW (*stochastic background*); A background of primordial and/or astrophysical GWs; unmodeled waveform

X

The Continuous-Wave (CW) signal I

- Quasimonochromatic waves with a slowly decreasing intrinsic frequency, which are expected to be emitted by
  - Rapidly rotating NSs with nonaxisymmetric deformations
  - Short periodic signals (~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 $\sim O(T^{1/2})$

- Sensitivity increases with observation time

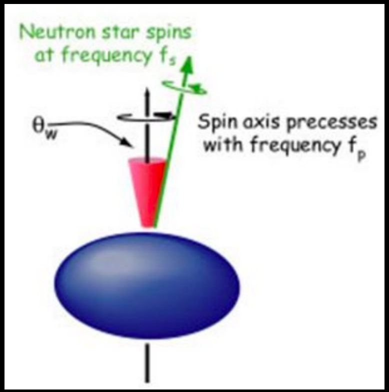
- Computation cost scales with a high power of the observation time

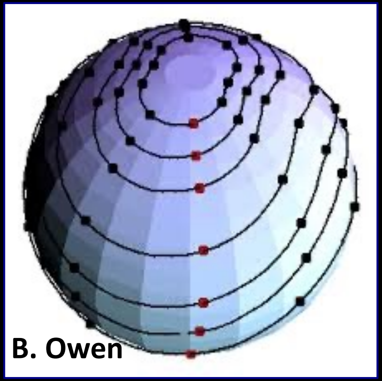
The CW signal II

- More than 2000 observed NSs (mostly pulsars) and $\mathcal{O}(10^8 - 10^9)$ expected to exist in the Galaxy

- To emit CWs a NS must have some 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 ($f_{GW} \sim f_{rot} + f_{prec}$; $f_{GW} \sim 2 f_{rot} + 2\, f_{prec}$)
  - 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://www.indiana.edu/

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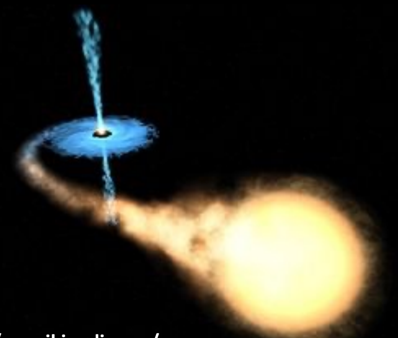

http://en.wikipedia.org/

CWs from rotating NSs

The measured strain amplitude h_0 on Earth is given by

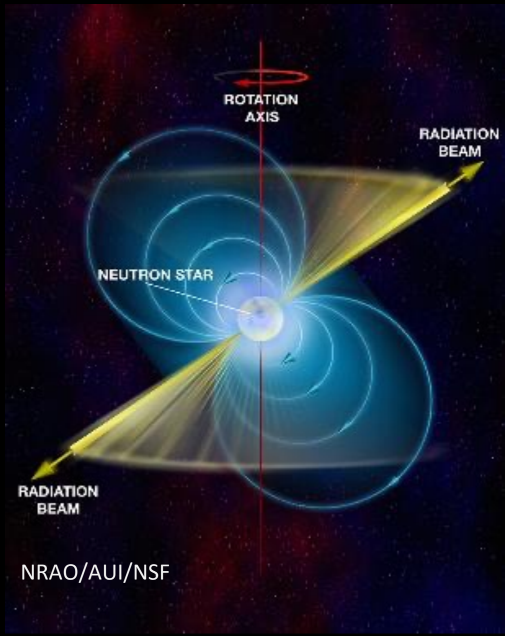
$$h_0 = \frac{4\pi^2 G}{c^4} \frac{I_{zz} f^2 \varepsilon}{d} \quad \Rightarrow \quad h_0 = 4 \cdot 10^{-25} \left(\frac{\varepsilon}{10^{-5}}\right) \left(\frac{I_{zz}}{10^{45}\,\mathrm{g\,cm}^2}\right) \left(\frac{f_r}{100\ \mathrm{Hz}}\right)^2 \left(\frac{1\ \mathrm{kpc}}{d}\right)$$

with d distance to the source, with $\varepsilon = (I_{xx}-I_{yy})/I_{zz}$ 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)]



NRAO/AUI/NSF

The spin-down limit

A rotating NS spins down losing energy:

ε = ϵ

- $\dot{E}_{rot} \propto I_{zz} f_{rot} \dot{f}_{rot}$ 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 spin-down, which is the decrease of the rotation period, is due to GWs, we get

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

- 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 spin-down limit means we are putting a constraint on the fraction of spin-down energy due to the emission of GWs

CW signal characteristics

- A CW signal is not exactly monochromatic, but it has a spin-down due to the loss of energy (in some cases a spin-up could be present)

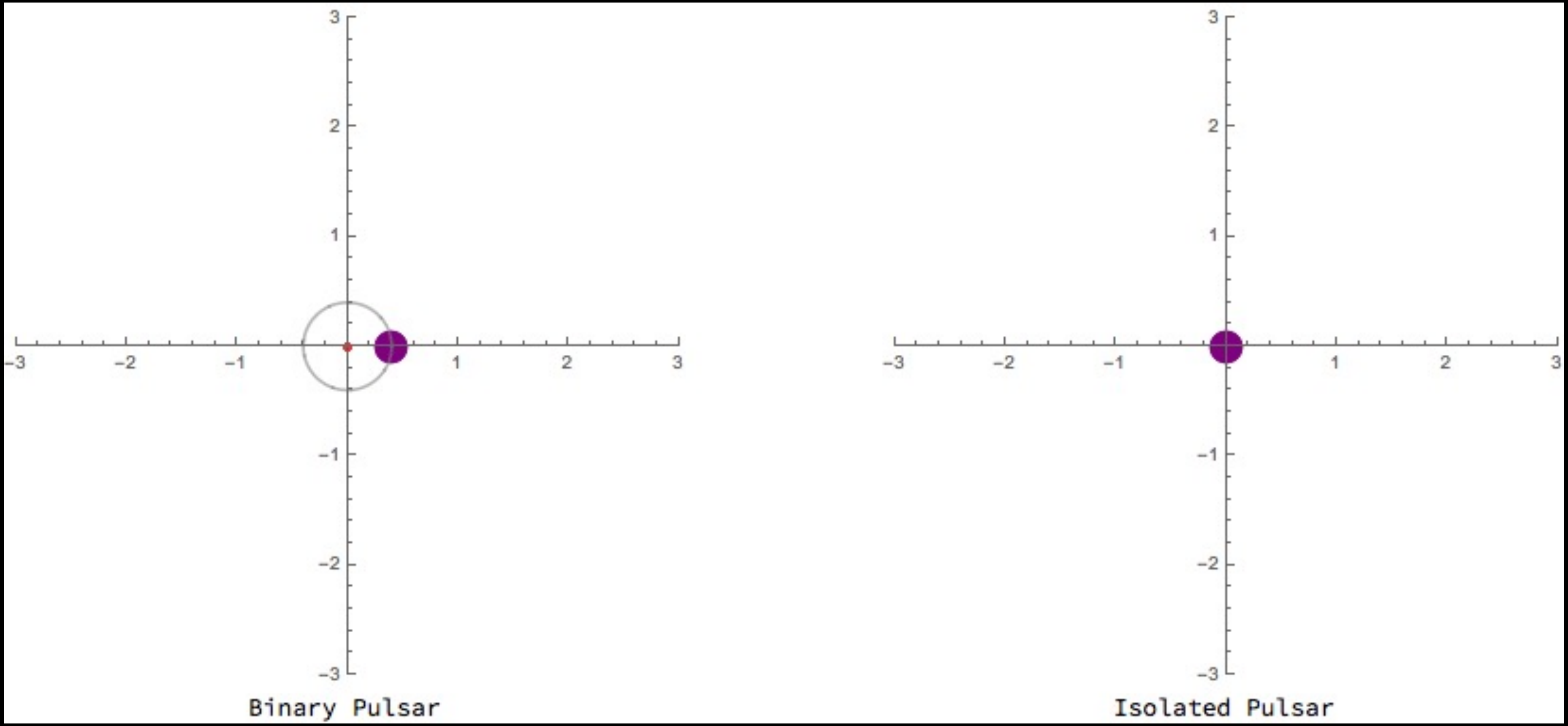
$$f_0(t) = f_0 + \dot{f}_0(t - t_0) + \frac{\ddot{f}_0}{2}(t - t_0)^2 + \ldots$$

- 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

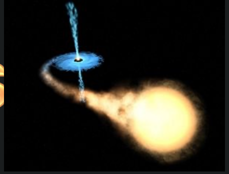
$$f(t) = \frac{1}{2\pi}\frac{d\Phi(t)}{dt} = f_0(t)\left(1 + \frac{\vec{v}\cdot\widehat{n}}{c}\right), \qquad \vec{v} = \vec{v}_{orb} + \vec{v}_{rot}$$

- 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

The Doppler Effect: *a concrete signature for the detection of real CWs*



CWs from spinning NSs in binary systems



- A CW signal from a source in a binary system is frequency-modulated by the source's 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

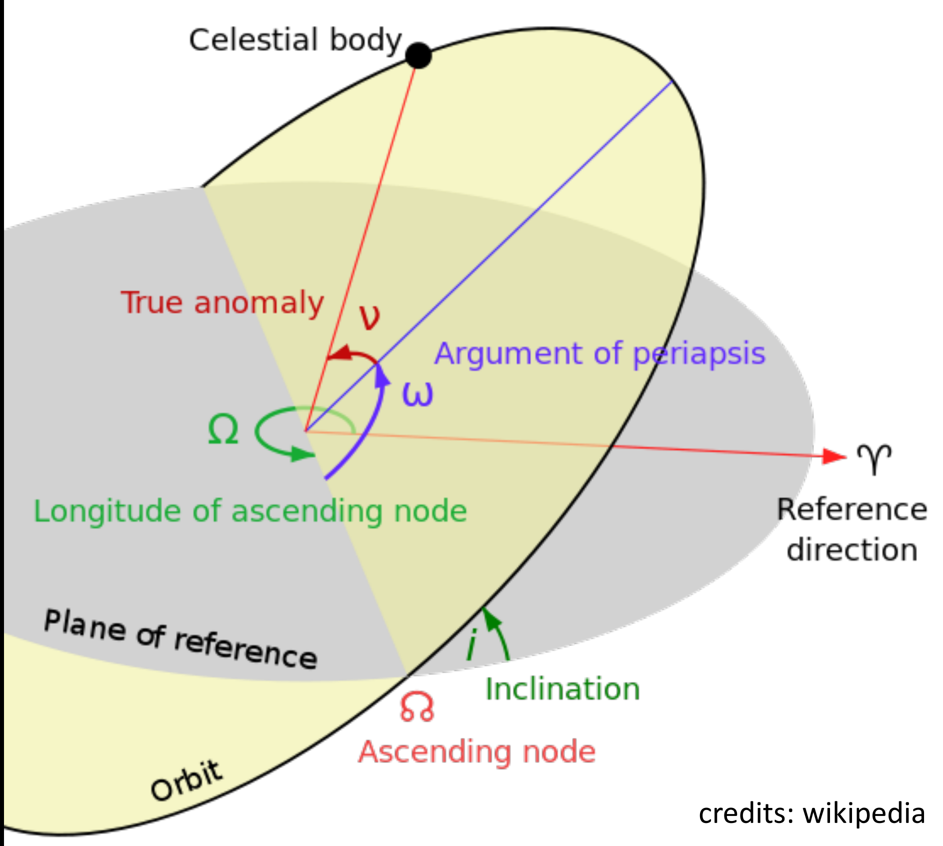
- In some cases the accretion is asymmetric due to the sporadic observation of X-ray pulsations

- 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)]

Binary system orbital parameters

- Period : P
- Semi-major axis : a
  - a_p Projection (time) : a sin i /c
- Inclination : *i*
- eccentricity : e
- Argument of periapsis : ω
- Time of periapsis : t_p

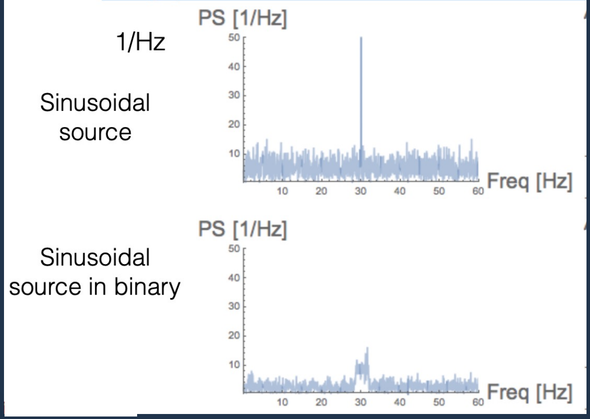


credits: wikipedia

- *Other search parameters:*
  - *Sky location, Frequency, Spin-down terms*

Binary systems

- CWs from a binary system will be further Doppler shifted due to the orbital motion



- The signal phase model

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

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

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

$$\kappa \equiv e\cos(\omega),$$

$$\eta \equiv e\sin(\omega),$$

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

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

Maximal Doppler modulation due to orbital motion

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

Leaci & Prix: https://arxiv.org/abs/1502.00914

Leaci et al.: https://arxiv.org/abs/1607.08751

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

CW Data Analysis I

CWs can be detected by a single gravitational-wave interferometer, and –in case of detection– CWs will be persistently present into the data set to be further studied and confirmed by ad hoc and deep follow-up studies

Main methods

- Time domain methods, including re-sampling, complex hetrodyne
- Matched filter
- 5-vector method relying on carrier frequency sidebands
- Power spectra analysis
- Hough transform

Type of searches

- Targeted
- Narrowband
- Directed
- All-Sky
- Post-merger
- GR tests

CW Data Analysis II

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

- TARGETED/narrowbanded 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) => $\mathcal{O}$(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) => $\mathcal{O}$(cluster)

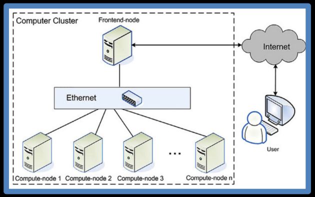
$$h_{0_{min}} \approx \alpha\sqrt{\frac{S_n(f)}{T_{coh}}}$$

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

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

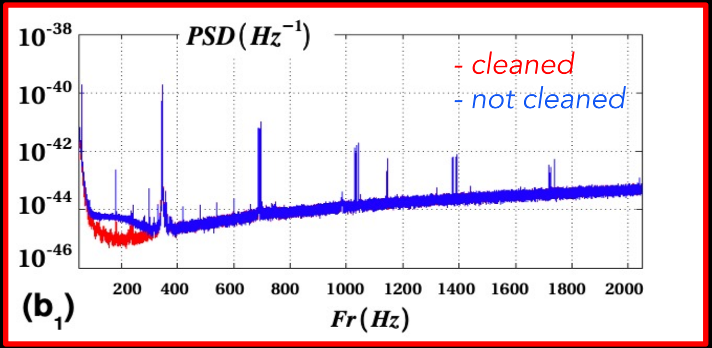
What we would like and what we have …

- Good search sensitivity, which we can get with long coherence time to increase the signal-to-noise ratio
- Robustness with respect to signal uncertainties and instrumental noise (we want to reduce as much as we can the selection of noise candidates)
- Speed up and low computational cost



10.1016/j.ins.2018.05.031

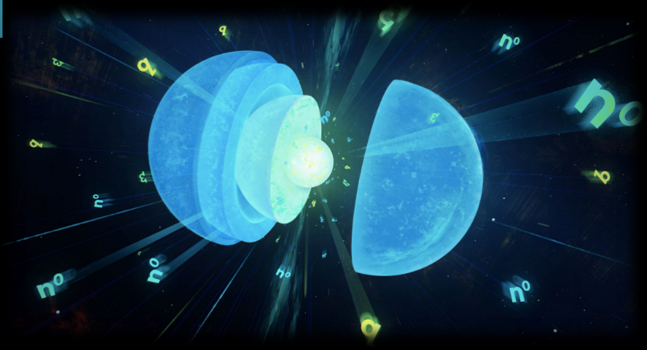
- Trade-off between sensitivity and computational cost
- Different kind of instrumental noise affect our data set
- Need to resort to ad hoc veto schemes to filter out false CW candidates



Why CW searches are relevant to us?

- 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



www.quantamagazine.org/

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

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

What are we doing to keep detecting CWs?

- Analyze the most recent and available data set from LIGO, VIRGO and KAGRA:
  - All-Sky searches,
  - Targeted searches (search at one and twice spin frequency)
  - Narrowband searches (Vela, Crab,…)
  - Directed searches (Galactic center, CasA, Vela Jr. and other young SNRs, FERMI-LAT/INTEGRAL sources, Scorpius X-1)
  - Search for *r*-modes applying machine learning techniques
  - Stochastic and CW joint search
  - Search for CWs from ultralight boson clouds around spinning BHs
  - Post-merger transient search
  - Search for non-tensorial polarizations
  - Algorithm optimization (including candidate follow up)

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 signal-to-noise ratio
- RADIO OBSERVATORIES able to monitor the vast majority of radio pulsars, mainly those with high spin down, 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

A few questions for you

- What’s the waveform that can better describe a CW signal?
- What’s the duration of a CW signal?
- What’s the Doppler effect and why it does not affect other types of GW signals, such as bursts?
- How many types of GW signals have been detected so far?
- Was a CW signal ever seen? If yes, when? Otherwise, why not?
- Why is it crucial to know as many details as possible on a CW source?
- What are the similarities and discrepancies between CWs and the other types of GW signals?
- What role does the detector sensitivity play in the context of CW searches?

Hands-on session: How to estimate the source orbital period?

- We will use the periodogram estimate, which is well suited to the problem of detecting a periodic signal in the presence of noise, and is the most common method to estimate the power spectrum of evenly and unevenly spaced data

- Codes: MATLAB/Python/Octave (or any other programming language)

- Download SNAG at https://www.sergiofrasca.net/wp-content/wwwContent/_Phys/snag.htm and give a look at peak_spec.m

- **Theory (Leaci et al., https://arxiv.org/abs/1607.08751)**

- Download the data containing a simulated binary CW signal from https://www.dropbox.com/sh/ujto25oen6v0o8m/AAB8-s2LHAOnCawm9uJnZn9sa?dl=0 -> GDpeakspec_results_[189-190]Hz.mat (focus on the peakspectrum values)

- Download the MATLAB code https://www.dropbox.com/sh/ujto25oen6v0o8m/AAB8-s2LHAOnCawm9uJnZn9sa?dl=0 -> OrbitalPeriodEstimation.m

QUESTIONS ARE WELCOME