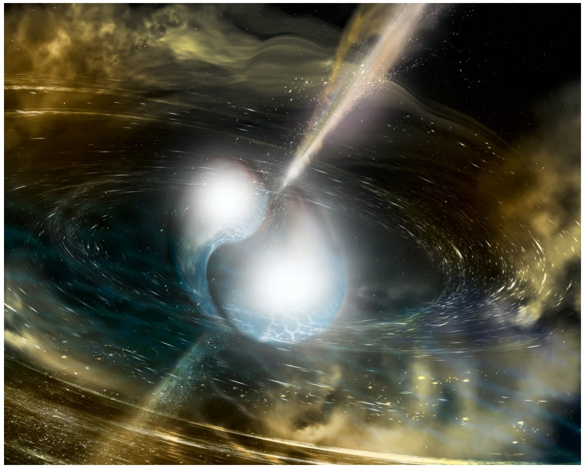


Sources of gravitational waves: A panorama

Chris Van Den Broeck

Utrecht University

LIGO VIRGO KAGRA

Nikhef

1st MaNiTou Summer School on Gravitational Waves, Marseille/Luminy, 4-8 July 2022

Detectable sources of gravitational waves

- Strength of gravitational wave signals: **quadrupole formula**

$$h_{ij} = \frac{G}{c^4}\frac{2}{r}\frac{d^2 Q_{ij}}{dt^2} \qquad\qquad Q_{ij} = \int \rho\, x_i x_j\, d^3x$$

- Back-of-the-envelope:

$$h \sim \epsilon \frac{G}{c^4}\frac{1}{r} M v^2$$

$\frac{G}{c^4} \simeq 8.3 \times 10^{-45} \frac{\mathrm{s}^2}{\mathrm{kg\,m}}$

ϵ : asymmetry of the source

M : mass

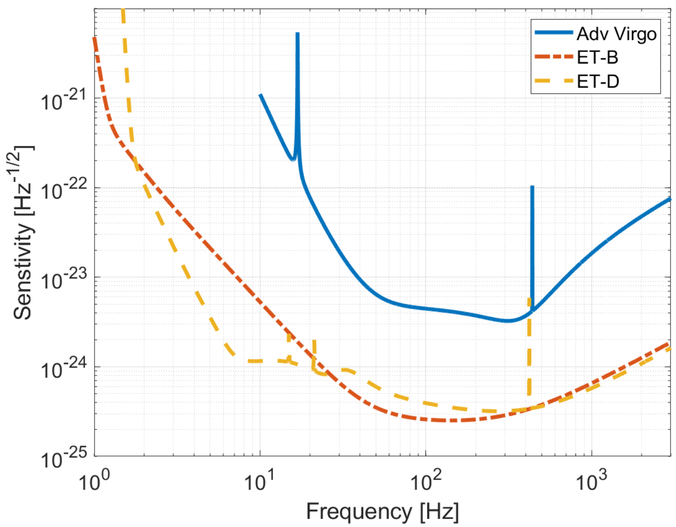
v : characteristic speed

r : distance to observer

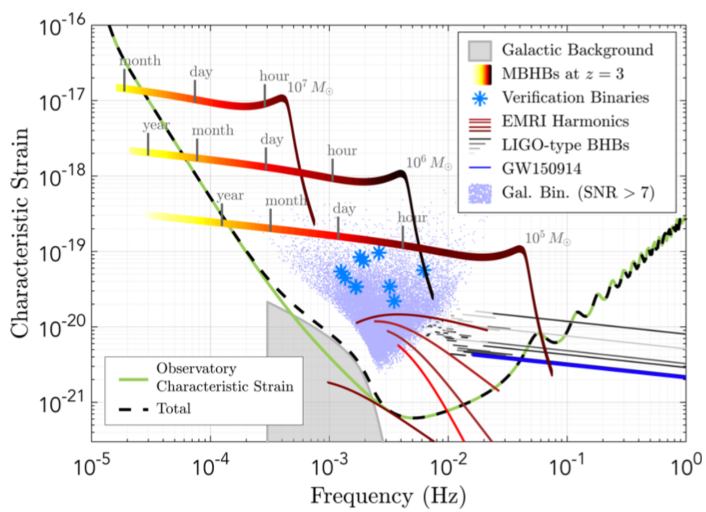
- Detectability of gravitational waves:
  - Limited by detector sensitivity
    - Current ground-based detectors, short-duration source: Need $h \gtrsim 10^{-22}$
    - Long signal of known shape: "signal-to-noise ratio" grows as $\propto T^{1/2}$ with T the observation time

Detectable sources of gravitational waves

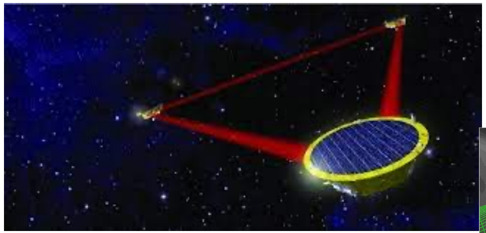
- Different detectors will be sensitive in different frequency ranges

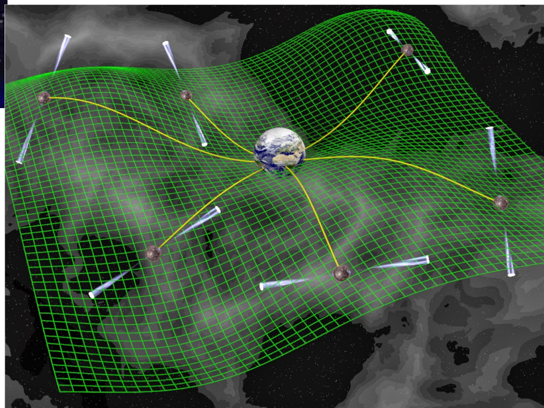


- Ground-based (LIGO, Virgo, …, Einstein Telescope): $f \sim 1 - 10^4\ \mathrm{Hz}$

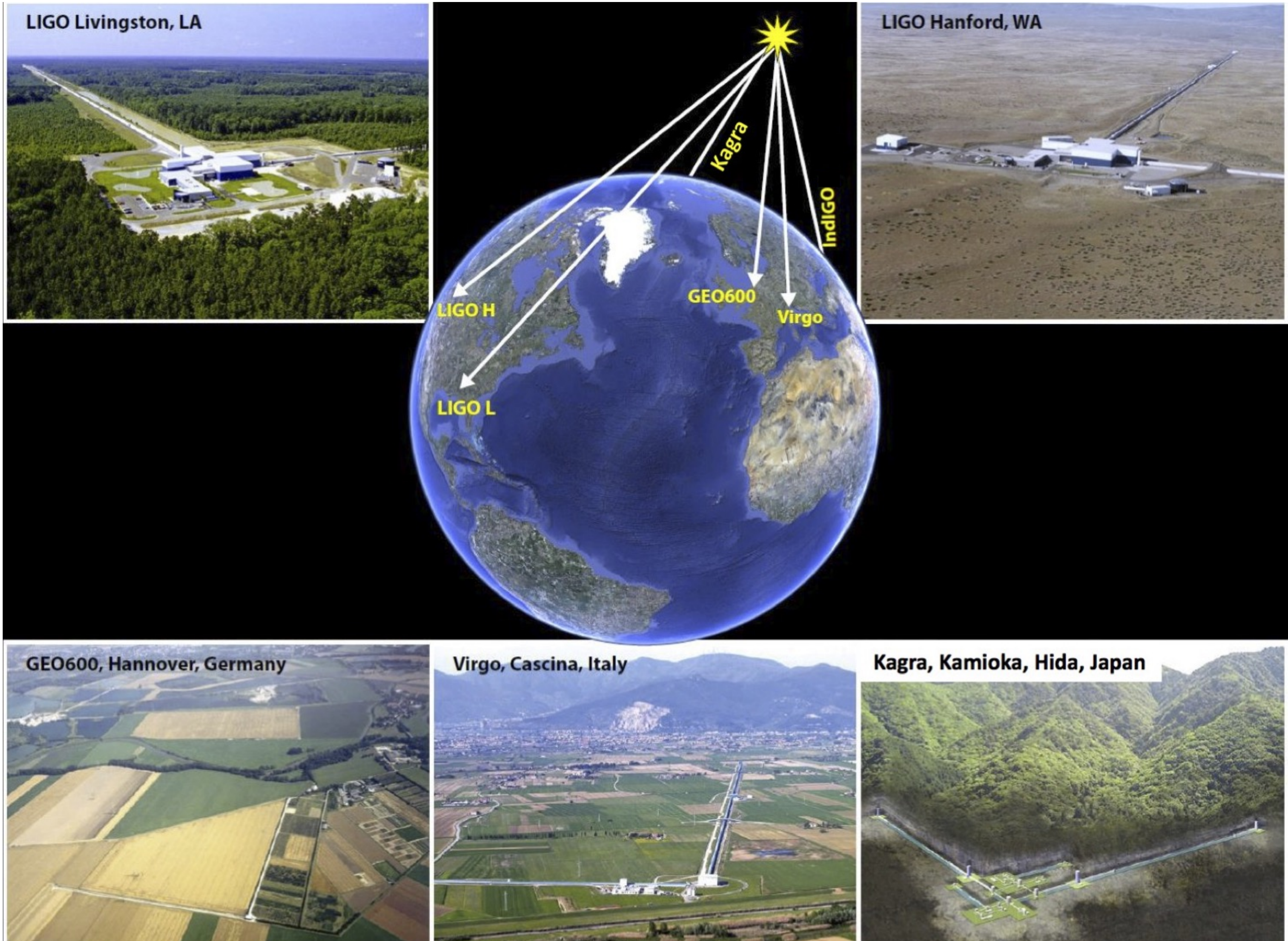


- Space-based LISA: $f \sim 10^{-4} - 10^{-1}\ \mathrm{Hz}$





- Pulsar timing arrays: down to $\sim 10^{-10}\ \mathrm{Hz}$

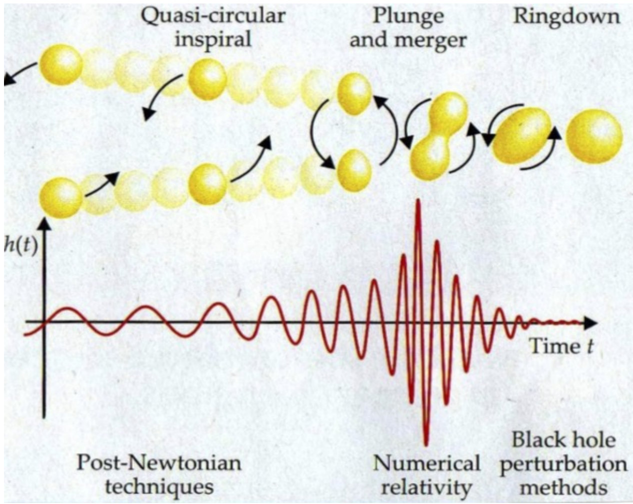


LIGO Livingston, LA
LIGO Hanford, WA
Kagra
IndIGO
GEO600
Virgo
LIGO H
LIGO L
GEO600, Hannover, Germany
Virgo, Cascina, Italy
Kagra, Kamioka, Hida, Japan

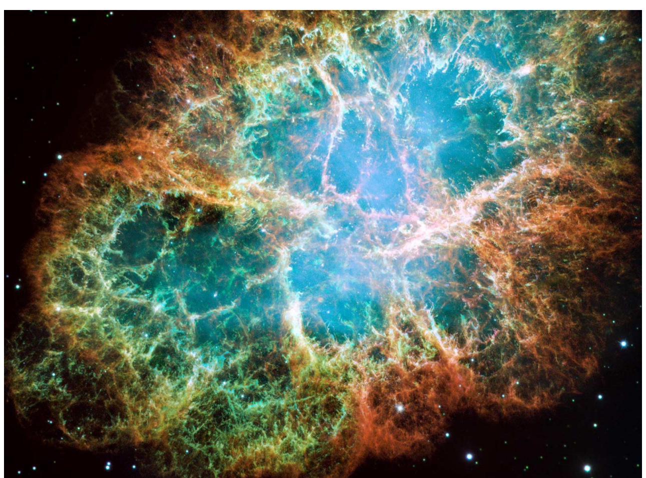
Detectable sources of gravitational waves

Transient signals

Merging neutron stars, black holes

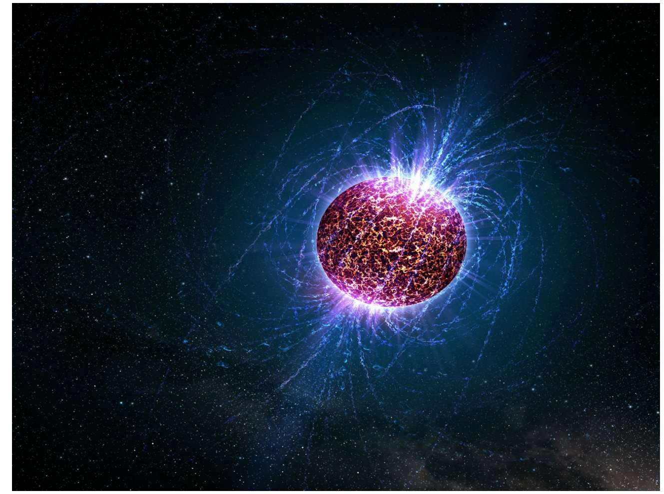


"Burst" sources

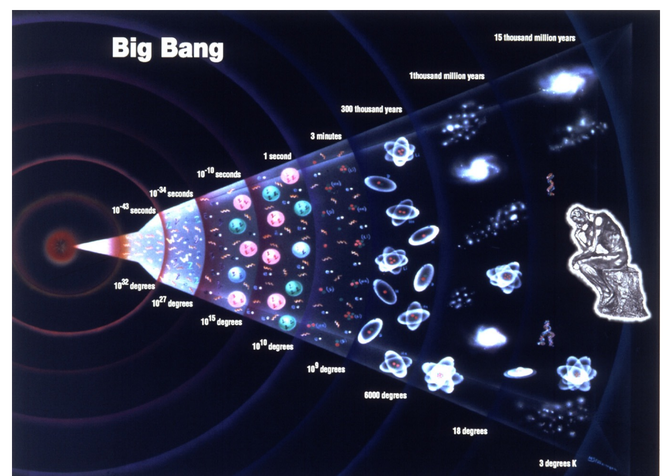


Continuous signals

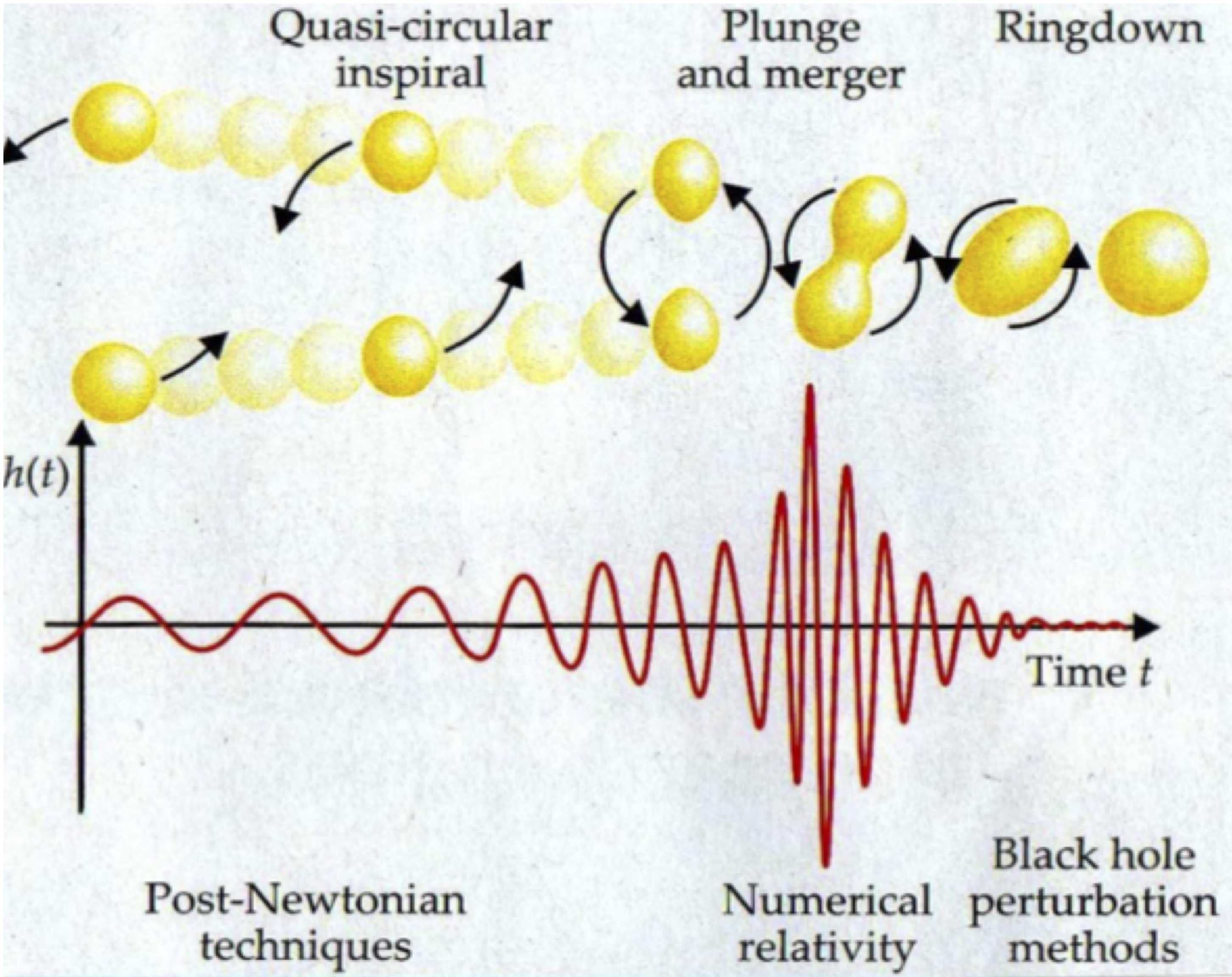
Fast-spinning neutron stars



Stochastic gravitational waves

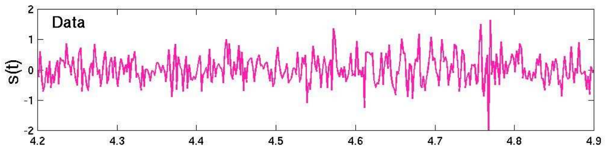


Inspiral, merger, and ringdown

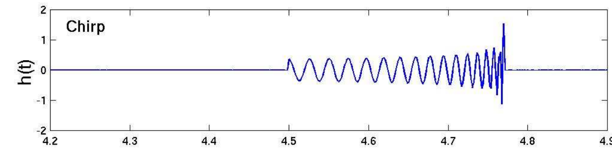


Detecting signals from coalescing binaries

➢ Matched filtering:

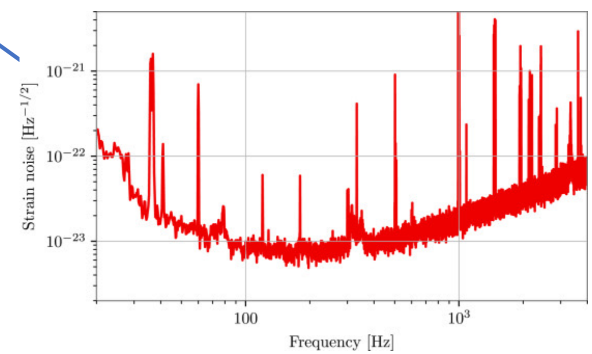


detector data

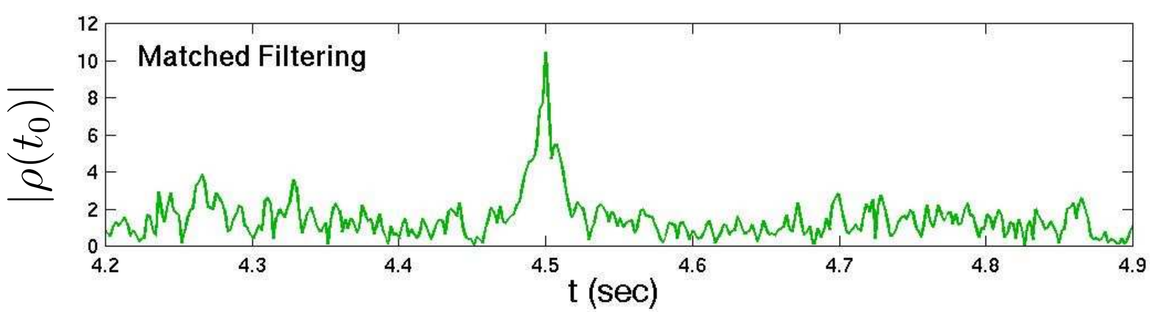


trial waveform at time t_0

$$\rho(t_0) = 4\Re \int_0^\infty \frac{\tilde{s}^*(f)\, \hat{h}(f)\, e^{2\pi i f t_0}}{S_n(f)} df$$



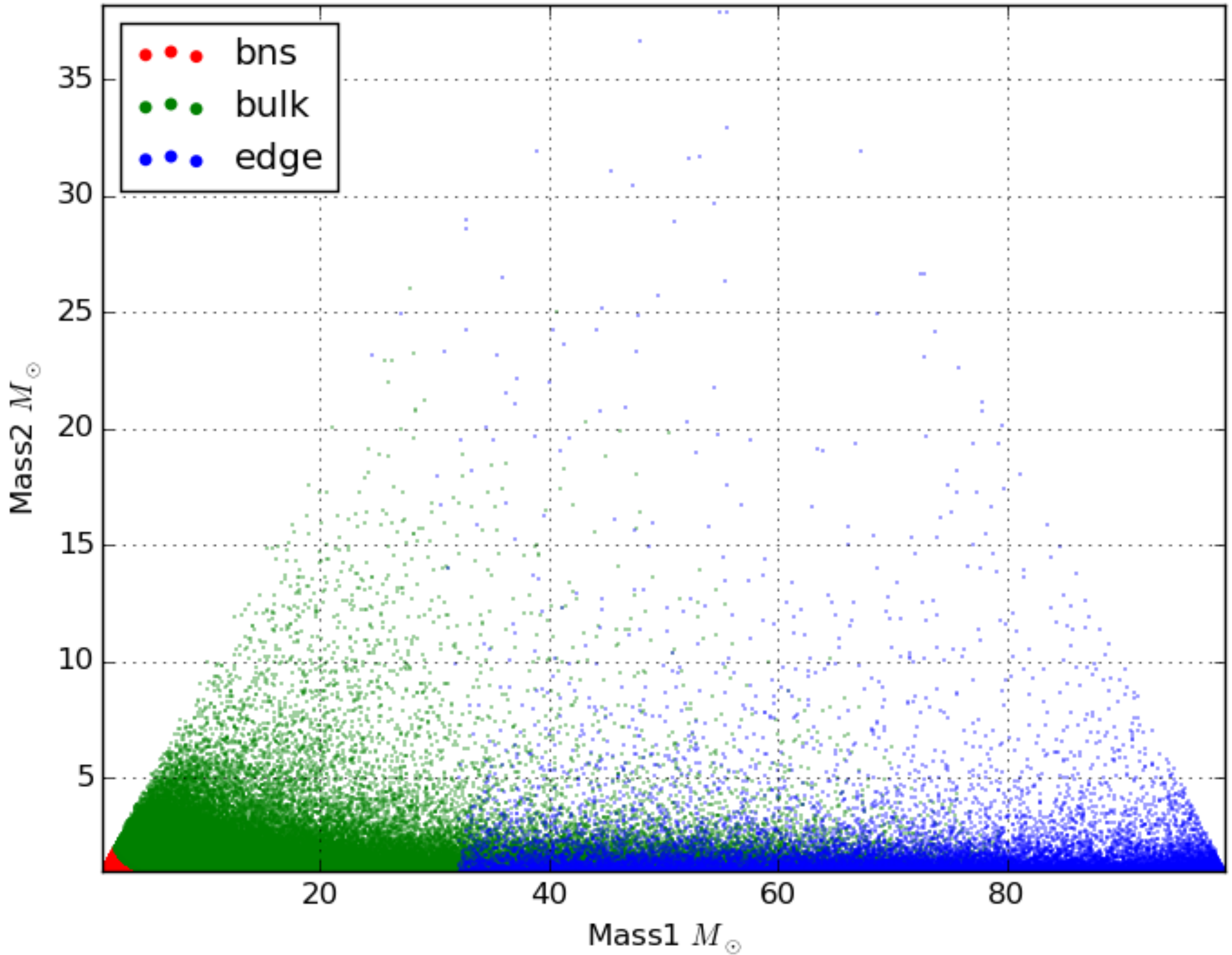
variance of the noise



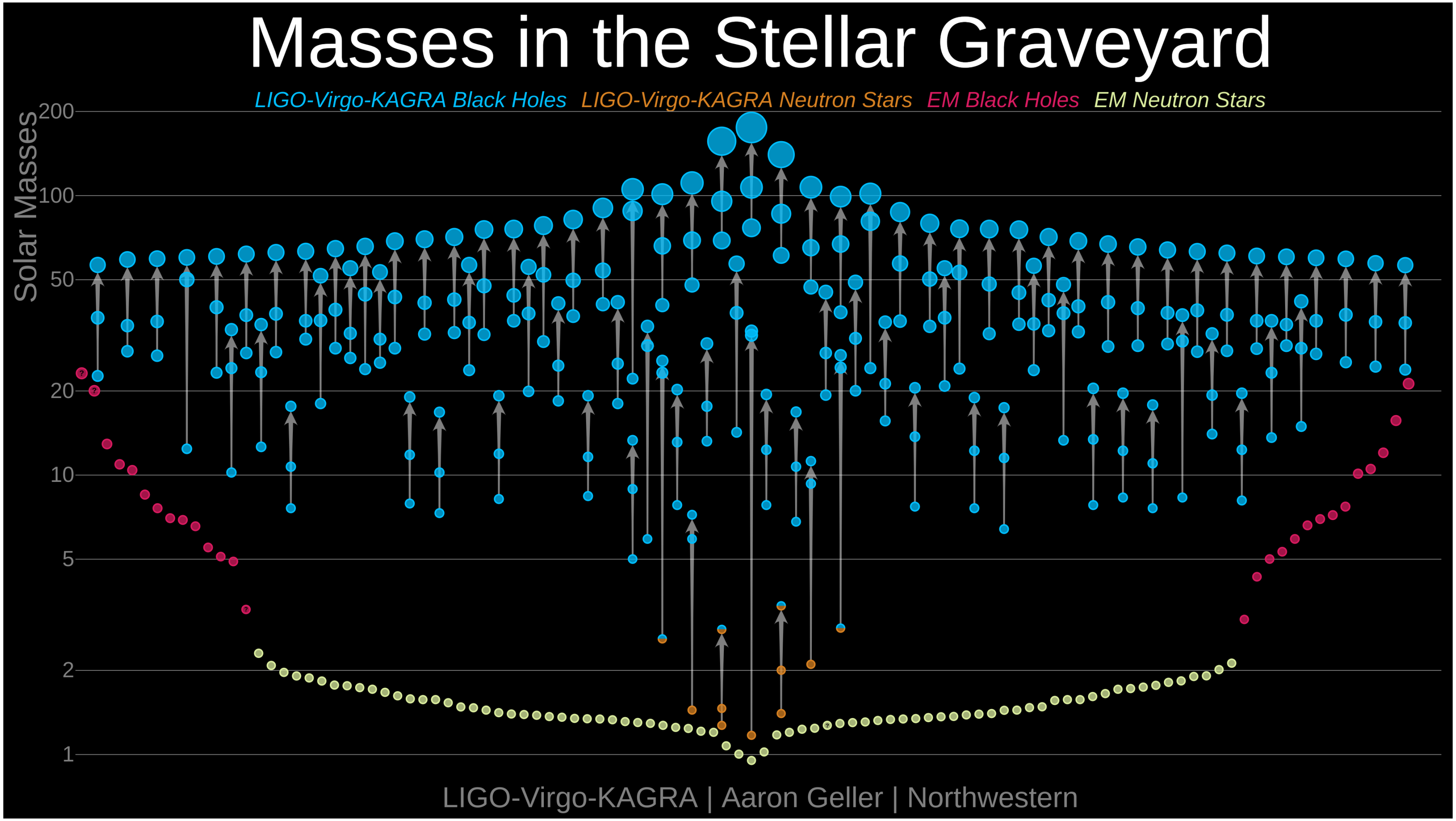
➢ Signal-to-noise ratio $\rho(t_0)$ peaks when a signal is present in the data

Detecting signals from coalescing binaries

- Many different choices for masses m_1, m_2 in the trial waveforms: "Template bank"



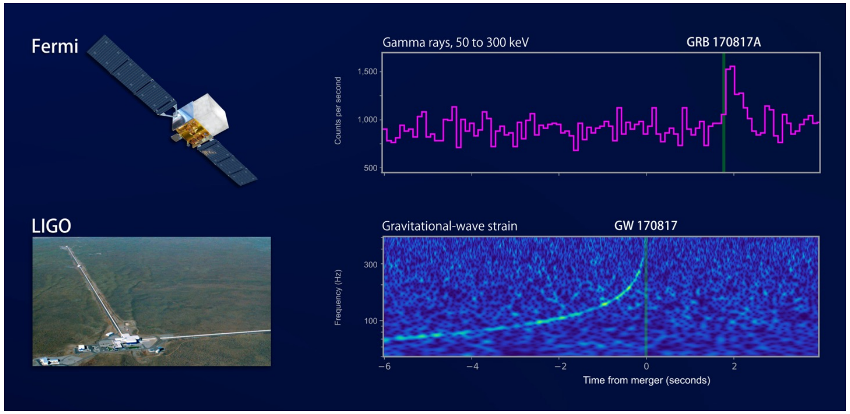
90 candidate detections so far

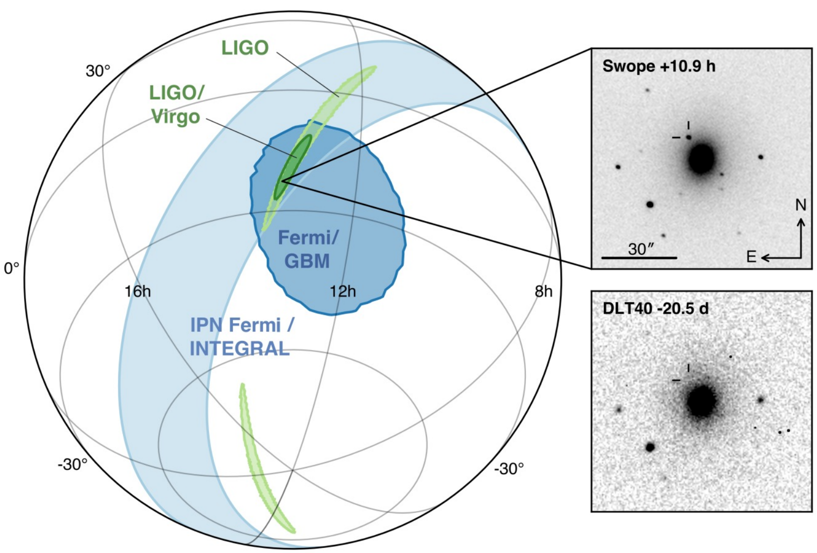


- Mostly binary black holes
- Binary neutron stars: GW170817, GW190425
- Neutron star-black hole: GW200105, GW200115

LIGO + Virgo+ KAGRA, arXiv:2111.03606

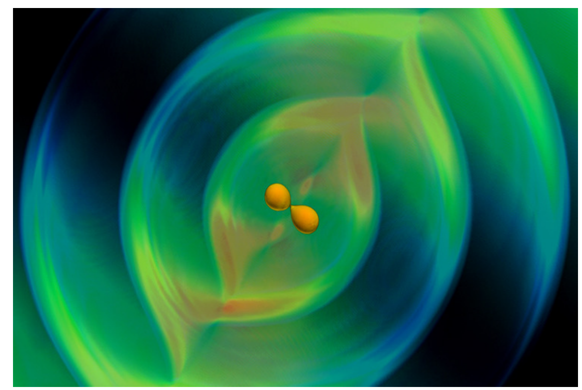
GW170817: binary neutron star inspiral





LSC, Virgo, arXiv:1710.05832

- Gamma ray counterpart
  - Origin of gamma ray bursts
- Thanks to LIGO-Virgo “triangulation”: Discovery of “kilonova” afterglow
  - Origin of heavy elements
- New cosmic distance markers
  - Novel way of doing cosmology
- Measurement of neutron star tides

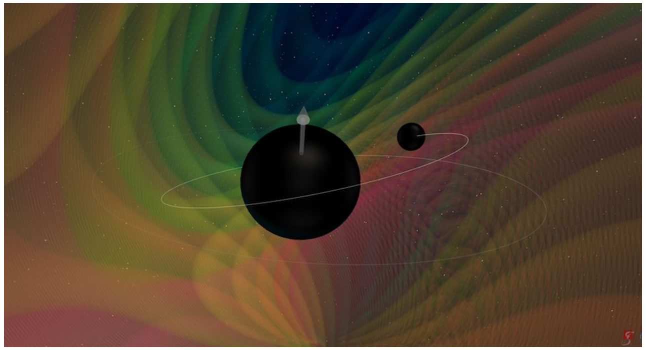


  - Structure of neutron stars

- Can we learn more about dense nuclear matter by also including information from heavy ion collision experiments on Earth?

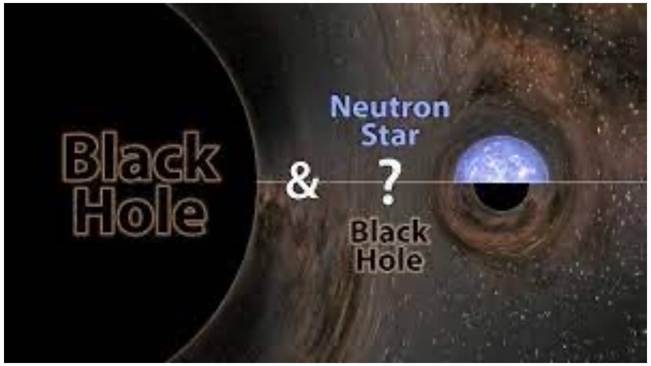
E.g. Huth et al, arXiv:2107.06229

Other "special events"



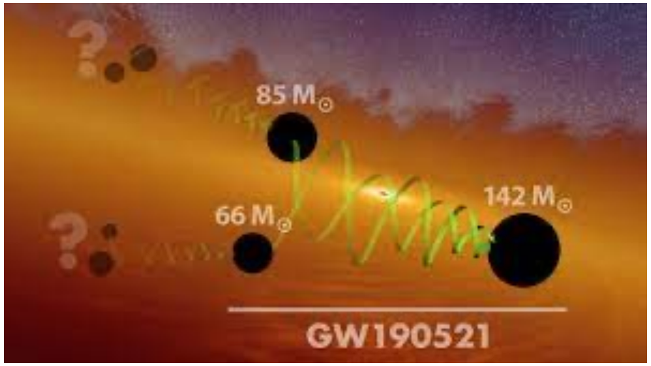
- GW190412
  - Binary black hole with significantly different masses (8 and 30 solar masses)
  - First observation of **harmonics** of the basic signal

LSC, Virgo, arXiv:2004.08342



- GW190814
  - Black hole of 23 solar masses + a mystery object of **2.6 solar masses**
    - Neutron star, or black hole?

LSC, Virgo, arXiv:2006.12611

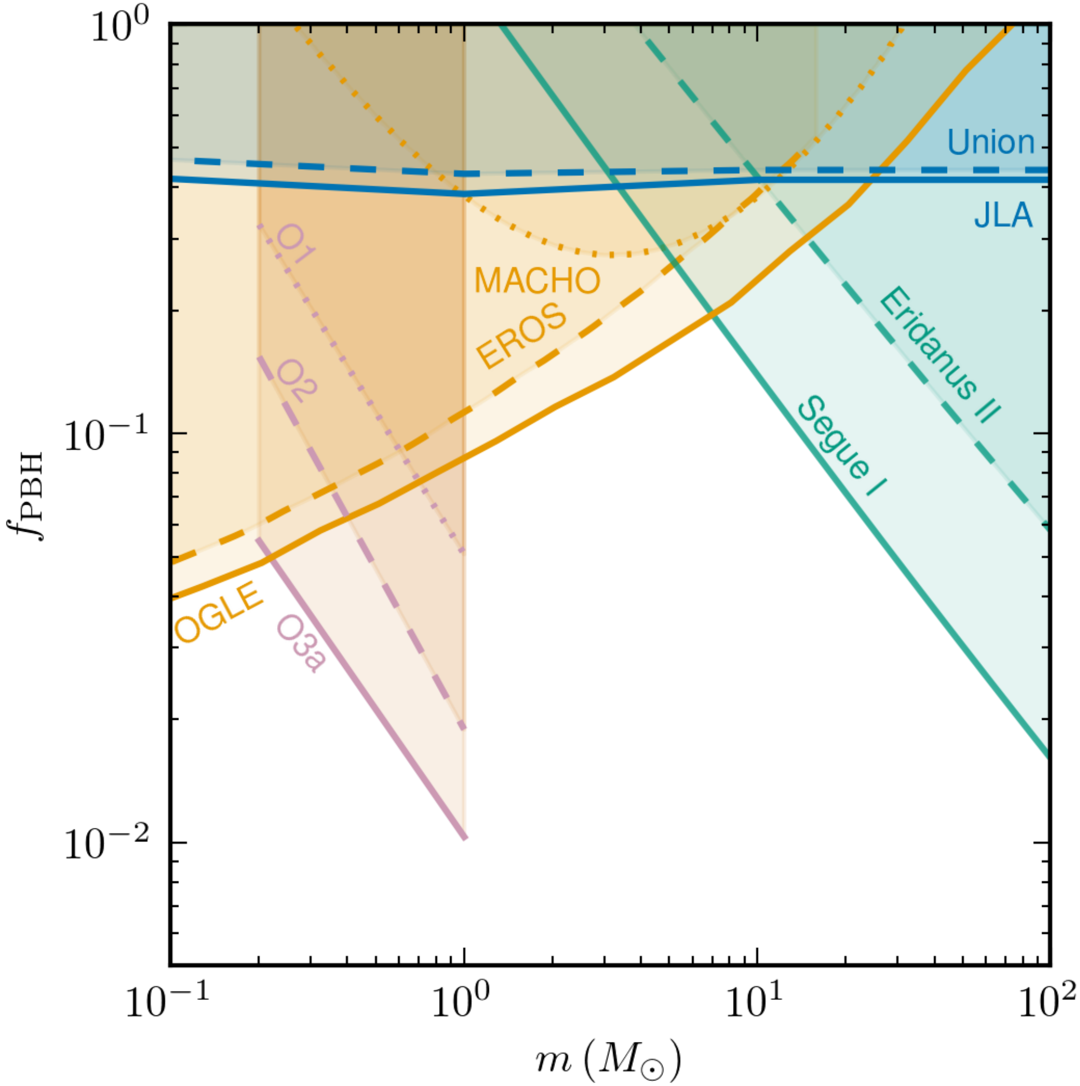


- GW190521
  - Binary black hole, 66 + 85 solar masses
  - **Can not have been formed directly from stars!**
    - Resulting from earlier mergers?
  - Remnant black hole: 142 solar masses

LSC, Virgo, arXiv:2009.01075

Searching for sub-solar mass black holes

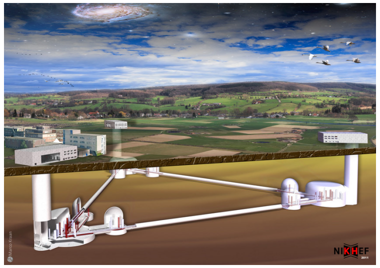
- If black holes with mass significantly below 1 solar mass: most likely **primordial**



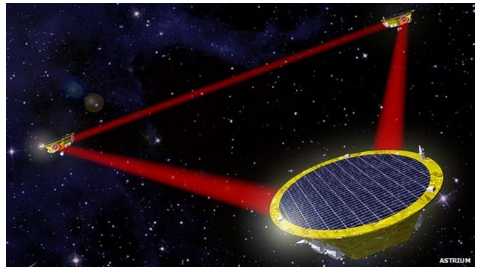
LSC, Virgo, KAGRA, arXiv:2109.12197

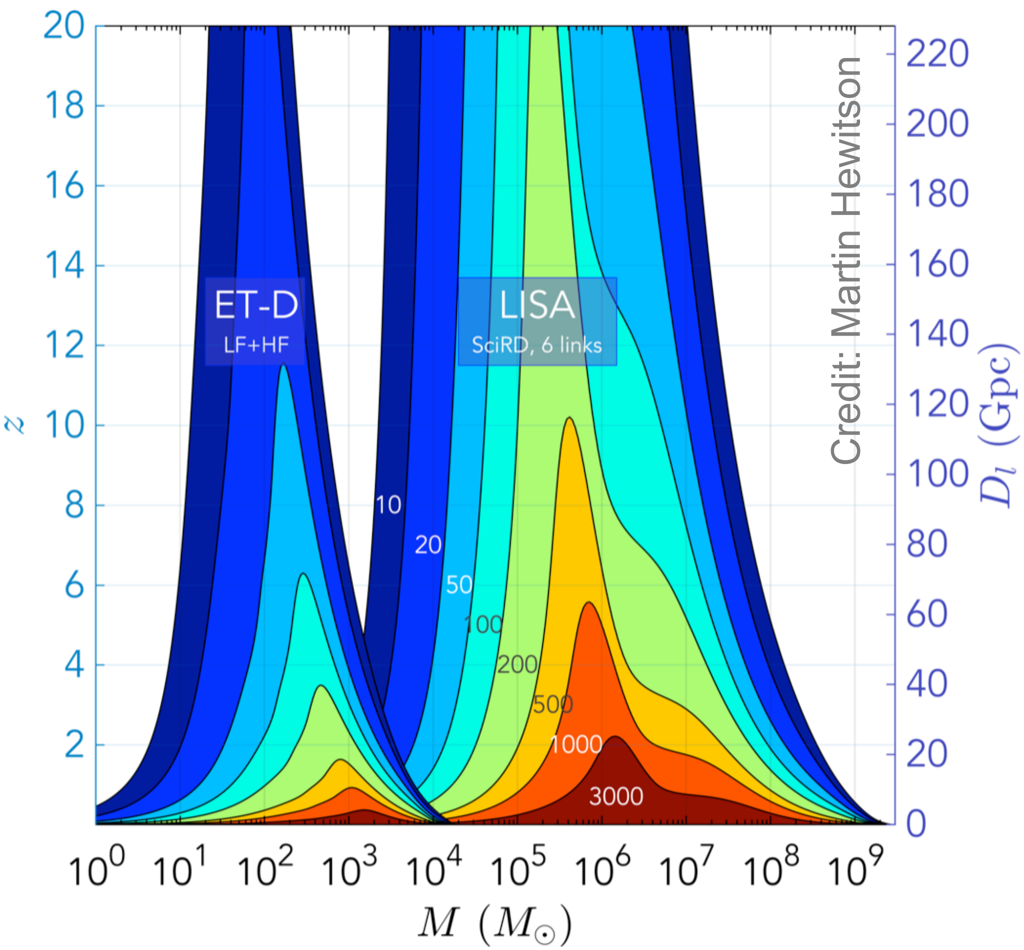
Future detectors

Einstein Telescope

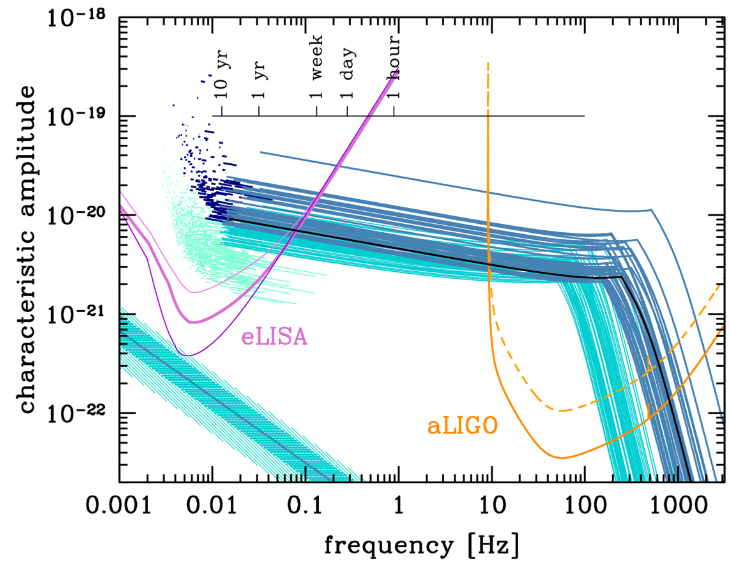


LISA

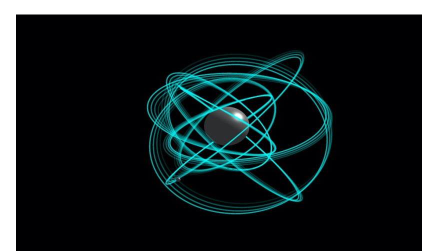




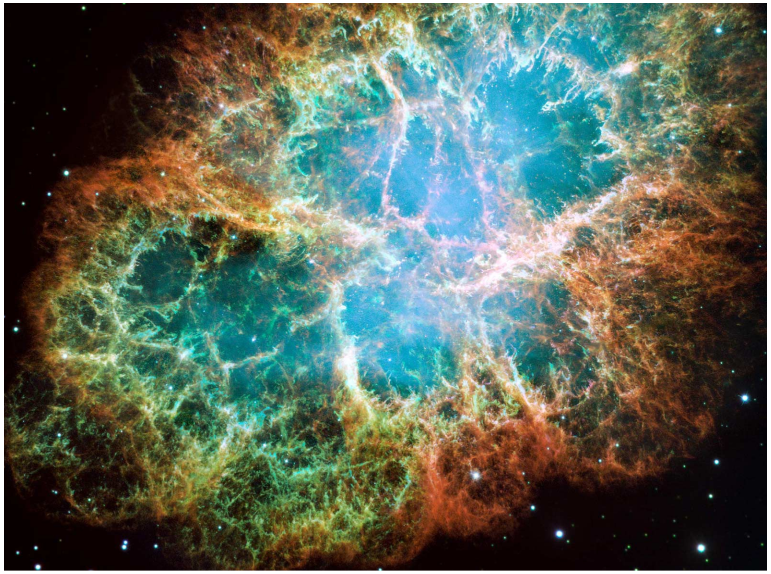
- Overlap between Einstein Telescope and LISA
  - Intermediate mass binary black holes $M \sim 10^2 - 10^4\, M_\odot$

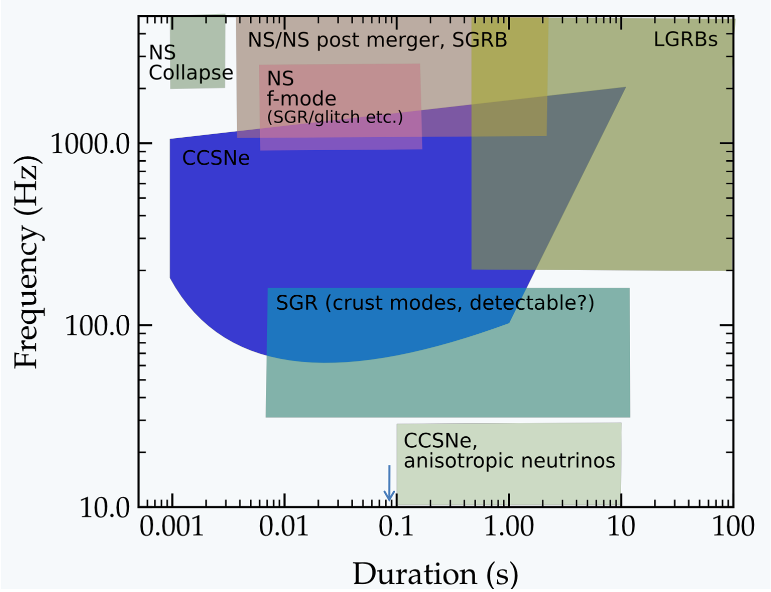


- New sources for LISA
  - Supermassive binary black holes $M \sim 10^5 - 10^9\, M_\odot$
  - Extreme mass ratio inspirals, e.g. $M = 10^6\, M_\odot + 10\, M_\odot$



"Burst" sources

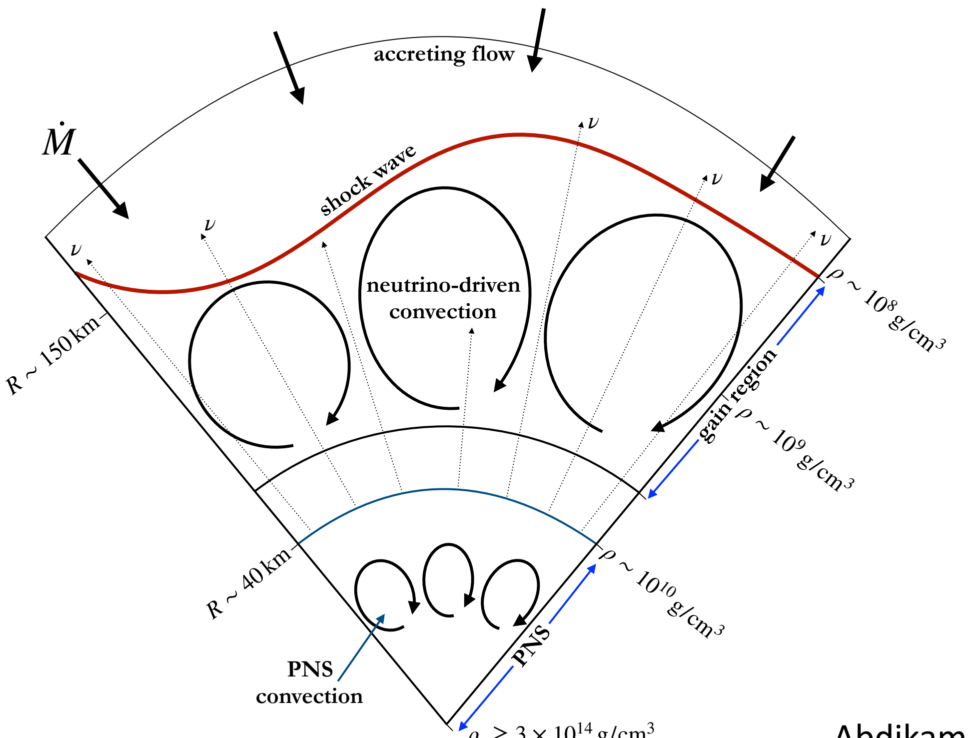


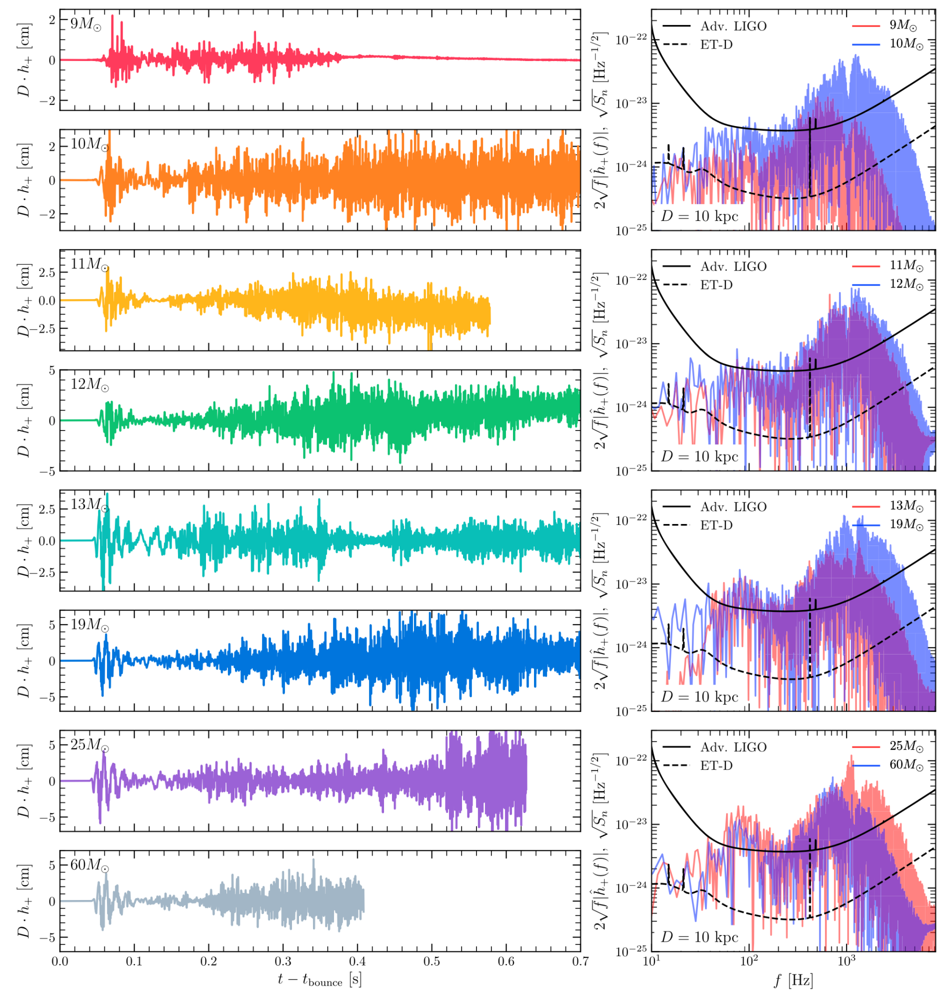


- Any source that is short(ish) in time
  - Compact binary coalescences
  - Supernovae in or near our galaxy
  - Neutron star instabilities
  - Cosmic strings
  - Long gamma ray bursts
  - Soft gamma-ray repeater giant flares
  - Accretion disk instabilities
  - …
  - **The unknown**
- Many of these are poorly modeled
  - Can't necessarily used matched filtering
  - Look for "coherent power" in multiple detectors
    - Common features in different detector outputs around the same time, consistent with a single sky location

"Burst" sources

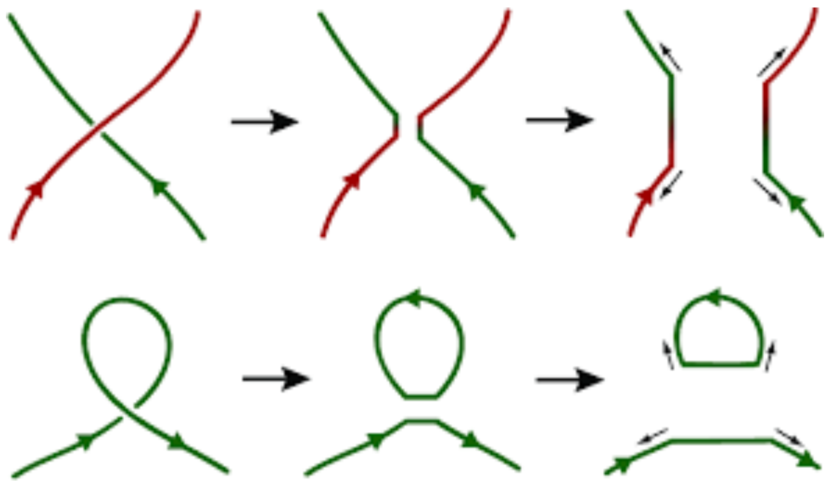
- **Core collapse supernovae**:
  - For collapsing stars of $M \gtrsim 9\,M_\odot$: Formation of a proto-neutron star
  - Convection
  - Standing-accretion shock: Large non-radial oscillations

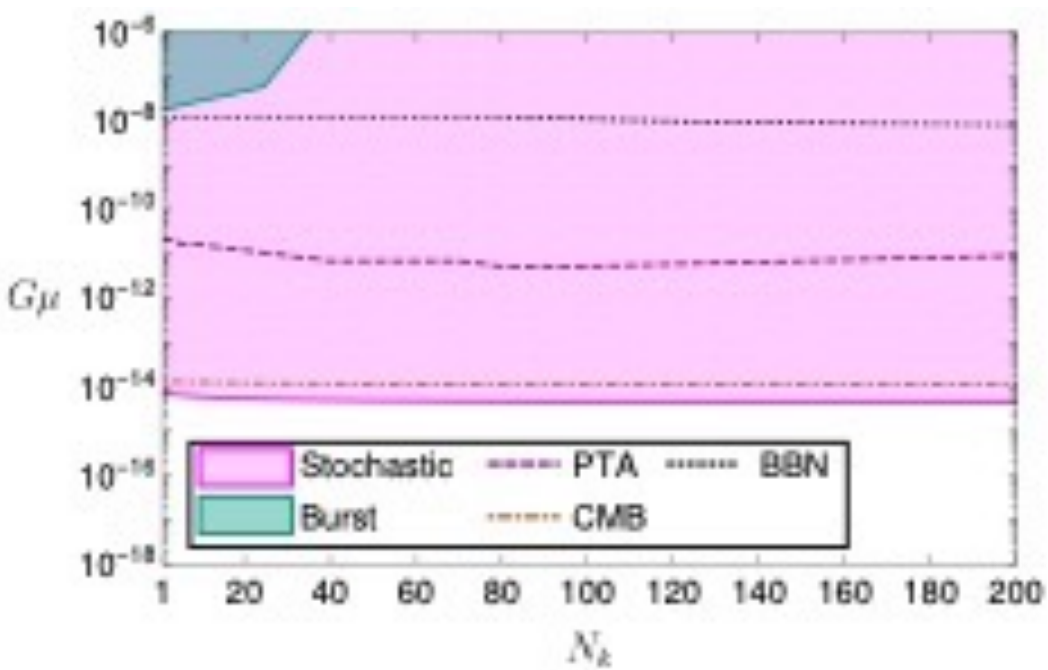




Abdikamalov et al., arXiv:2010.04356

"Burst" sources

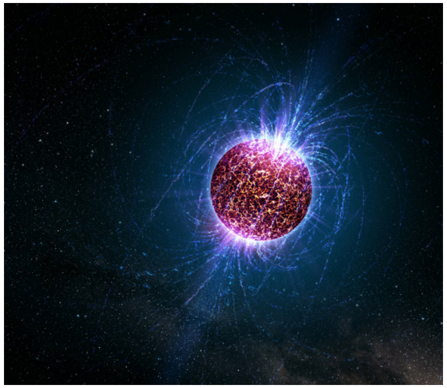


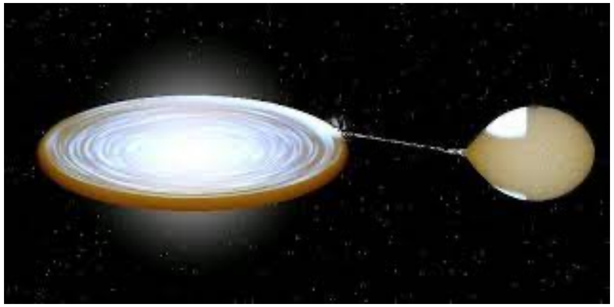


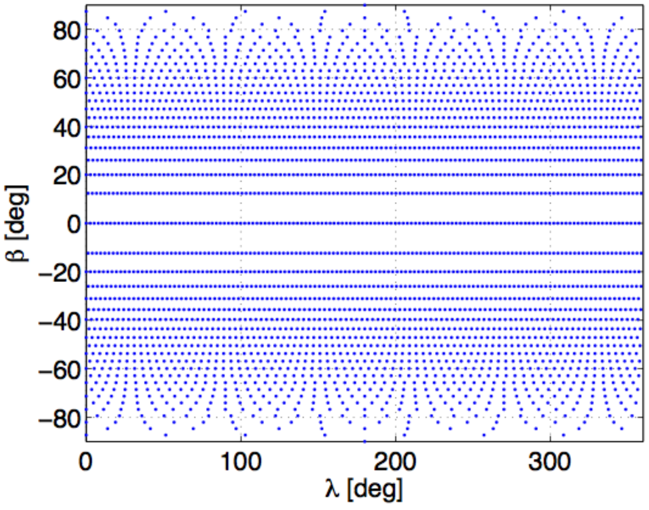
- **Cosmic strings**:
  - Formation of "cusps" that briefly travel at nearly speed of light: $h \propto f^{-4/3}$
  - Formation of "kinks" through the interaction of two strings: $h \propto f^{-5/3}$
  - Non-detection enables upper limits on the string tension
  - Accumulation of GW bursts from cusps and kinks can lead to **stochastic background**

LSC, Virgo, KAGRA, arXiv:2101.12248

Continuous waves







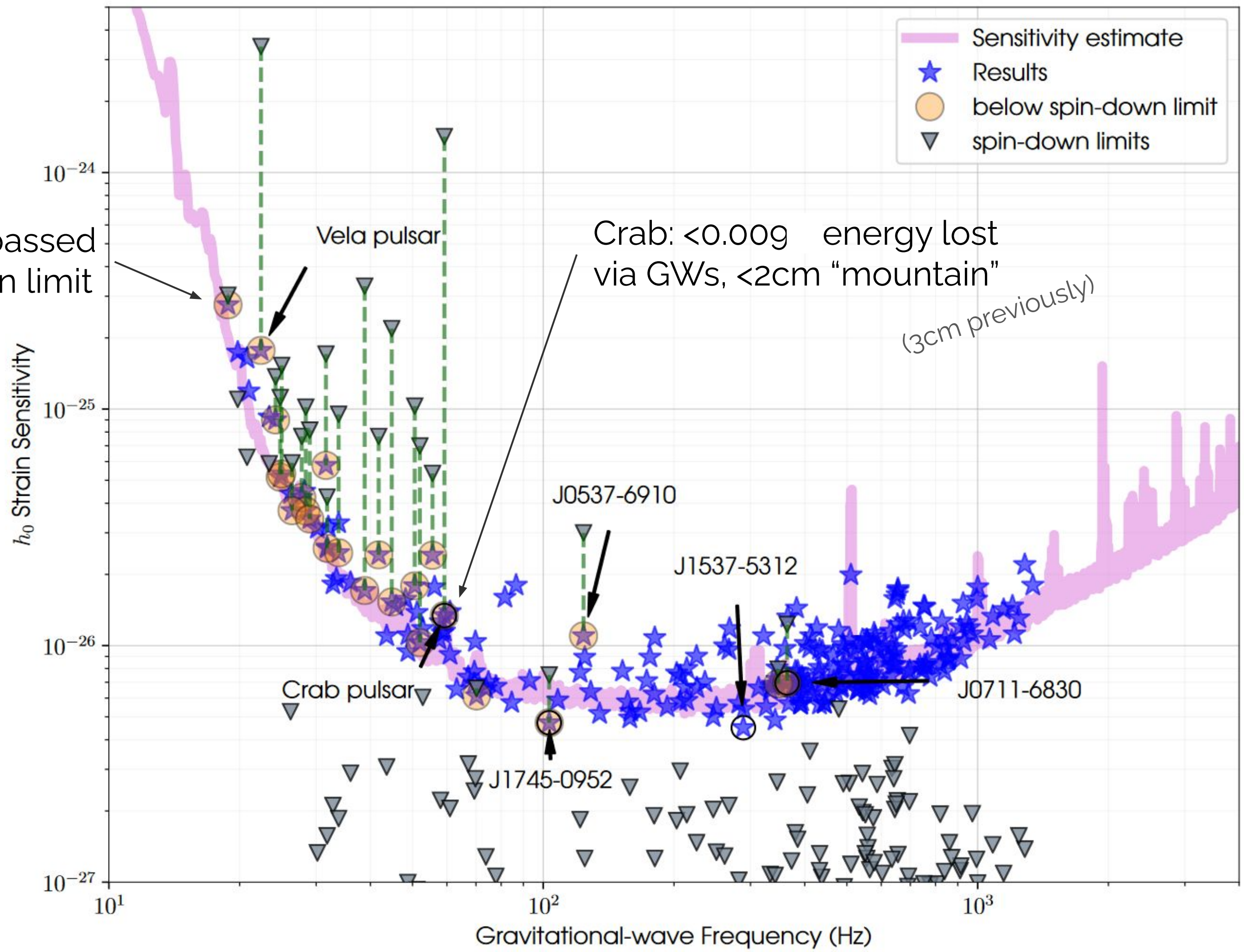
- Emission by fast-spinning neutron stars
  - Isolated neutron stars: Asymmetry due to "starquakes"
  - Neutron stars in binaries: Accretion
- The signals are weak!

$$h \sim 10^{-25} \left(\frac{10\,\mathrm{kpc}}{r}\right) \left(\frac{mR^2}{10^{38}\,\mathrm{kg\,m^2}}\right) \left(\frac{f}{1\,\mathrm{kHz}}\right)^2 \left(\frac{\epsilon}{10^{-6}}\right)$$

  - But, for very long-lived signals, signal-to-noise ratio $\propto T^{1/2}$
- Targeted searches when sky position and pulsar frequency known: Crab pulsar, Vela pulsar, …
- Computationally challenging to perform all-sky searches
  - Signals Doppler-modulated due to motion of Earth
  - Need to search over **sky position** in addition to other parameters

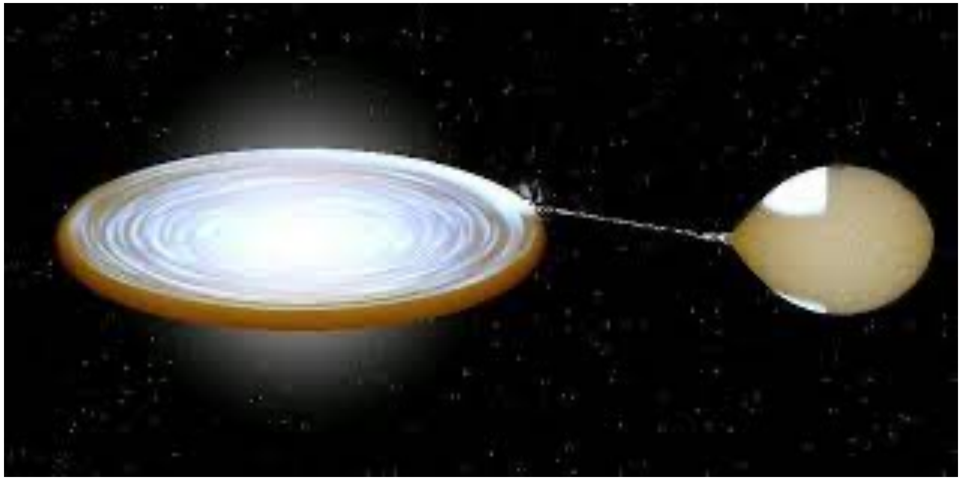
Continuous waves

23 pulsars surpassed their spin-down limit

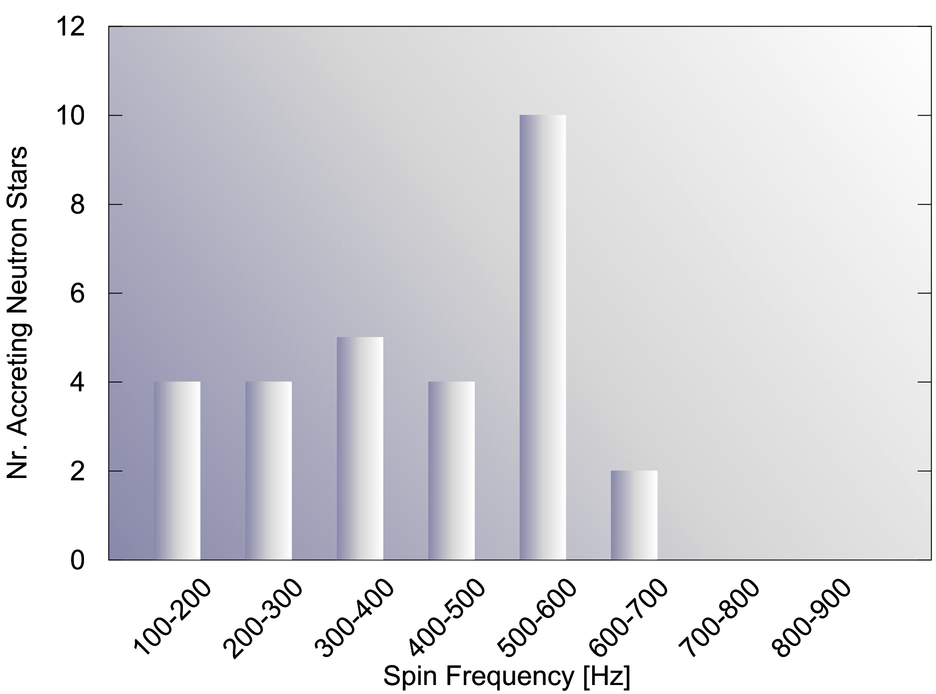


LSC, Virgo, KAGRA, arXiv:2111.13106

Continuous waves



- X-ray observations of neutron stars accreting matter from a companion star

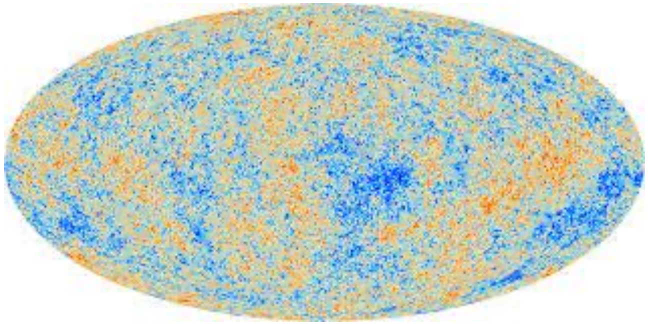


- No neutron stars in X-ray binaries spinning faster than ~700 Hz
  - Spinning-up due to accretion being counteracted by gravitational wave emission?

Patruno & Watts, arXiv:1206.2727

Stochastic gravitational wave backgrounds

- Recall the cosmic microwave background
  - Electromagnetic radiation
  - Generated ~300,000 years after the Big Bang, when first atoms formed



- There may also exist stochastic backgrounds of gravitational waves
  - **Astrophysical**:
    - Superposition of periodic signals from all the pulsars stars in the Milky Way
    - Superposition of signals from binary black hole and neutron star mergers throughout the Universe
  - **Primordial**:
    - Phase transitions in the early Universe
    - End of inflation (decay of the inflaton)
    - Superposition of bursts from cosmic strings

  Typically involve energies that are inaccessible to e.g. particle colliders
- Convenient to define

$$\Omega_{\mathrm{GW}}(f) = \frac{1}{\epsilon_c} \frac{d\epsilon_{\mathrm{GW}}}{d\ln f}$$

ϵ_{GW} : energy density of GW background

ϵ_c : critical density needed to close the Universe

Stochastic gravitational wave backgrounds

- Stochastic background takes the form of **correlated noise** between multiple detections

- Search for cross-correlations between detectors:

$$Y = \int \tilde{s}^*(f)\,\tilde{Q}(f)\,\tilde{s}_2(f)\,df$$

… which is similar to matched filtering but now using two detector outputs

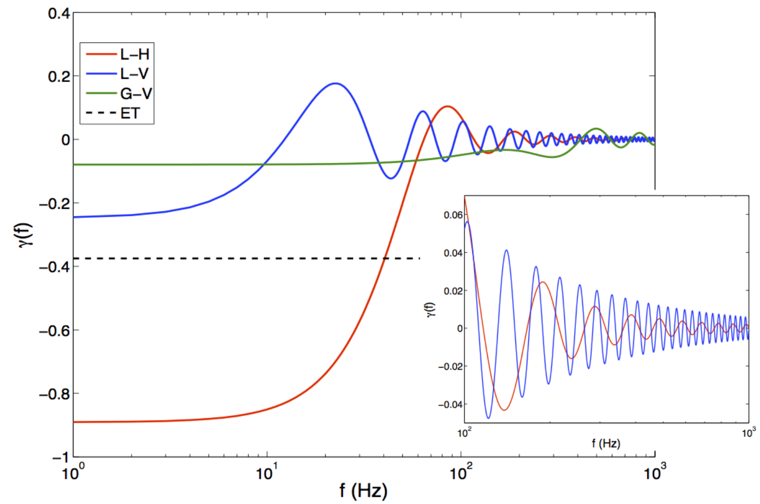
- Optimal filter:

$$\tilde{Q}(f) \propto \frac{\gamma(f)\,\Omega_{\rm GW}(f)}{f^3 S_1(f)\,S_2(f)}$$ where $\gamma(f)$ "overlap reduction function"

- Need to make a choice for the form of $\Omega_{\rm GW}(f)$
  - For many types of background, within the sensitive frequency range can be approximated by a power law:

    $$\Omega_{\rm GW}(f) = \Omega_0 f^\alpha$$

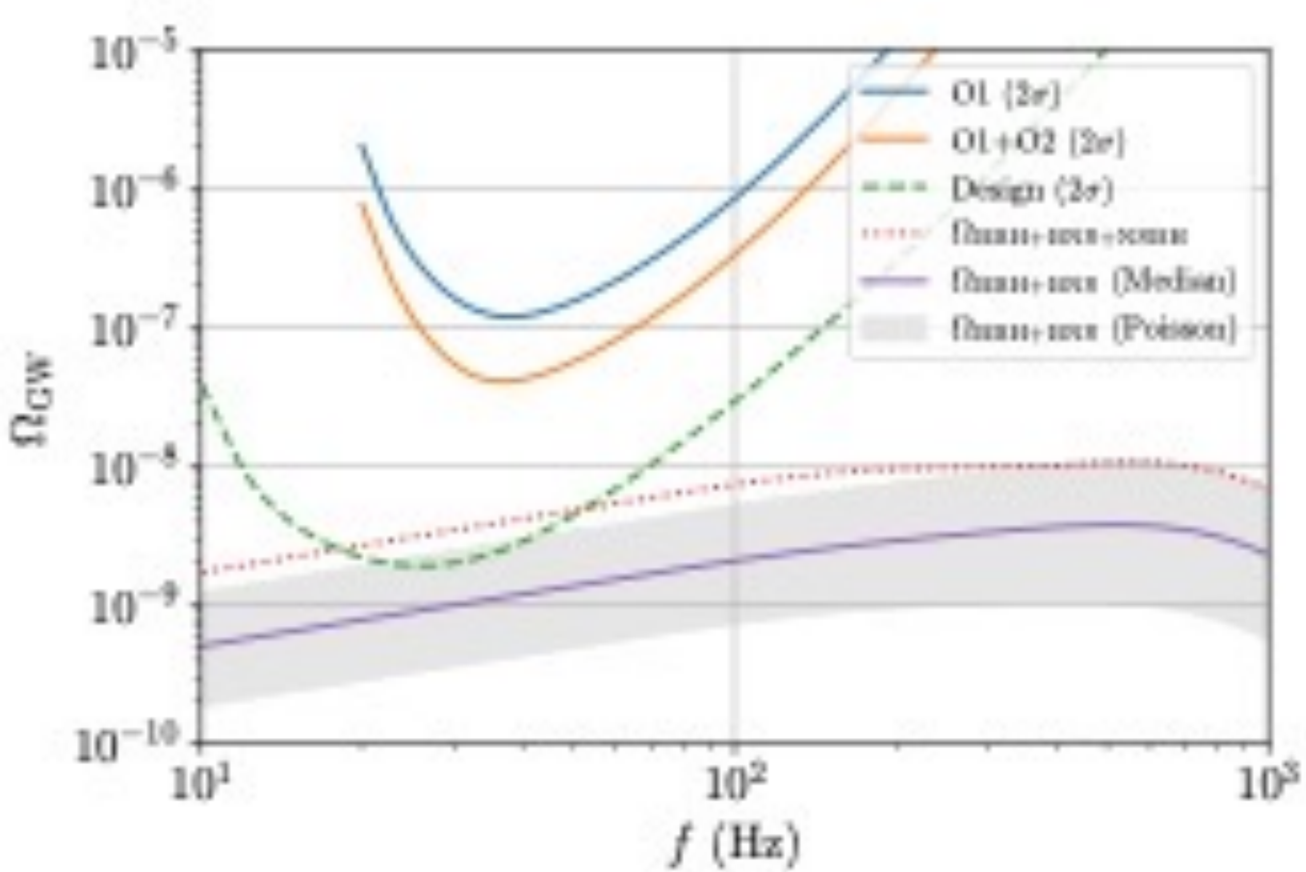
  - E.g. background from binary coalescences: $\alpha = 2/3$



Stochastic gravitational wave backgrounds

- The observed binary black hole coalescences are giving us access to merger rates and mass distributions

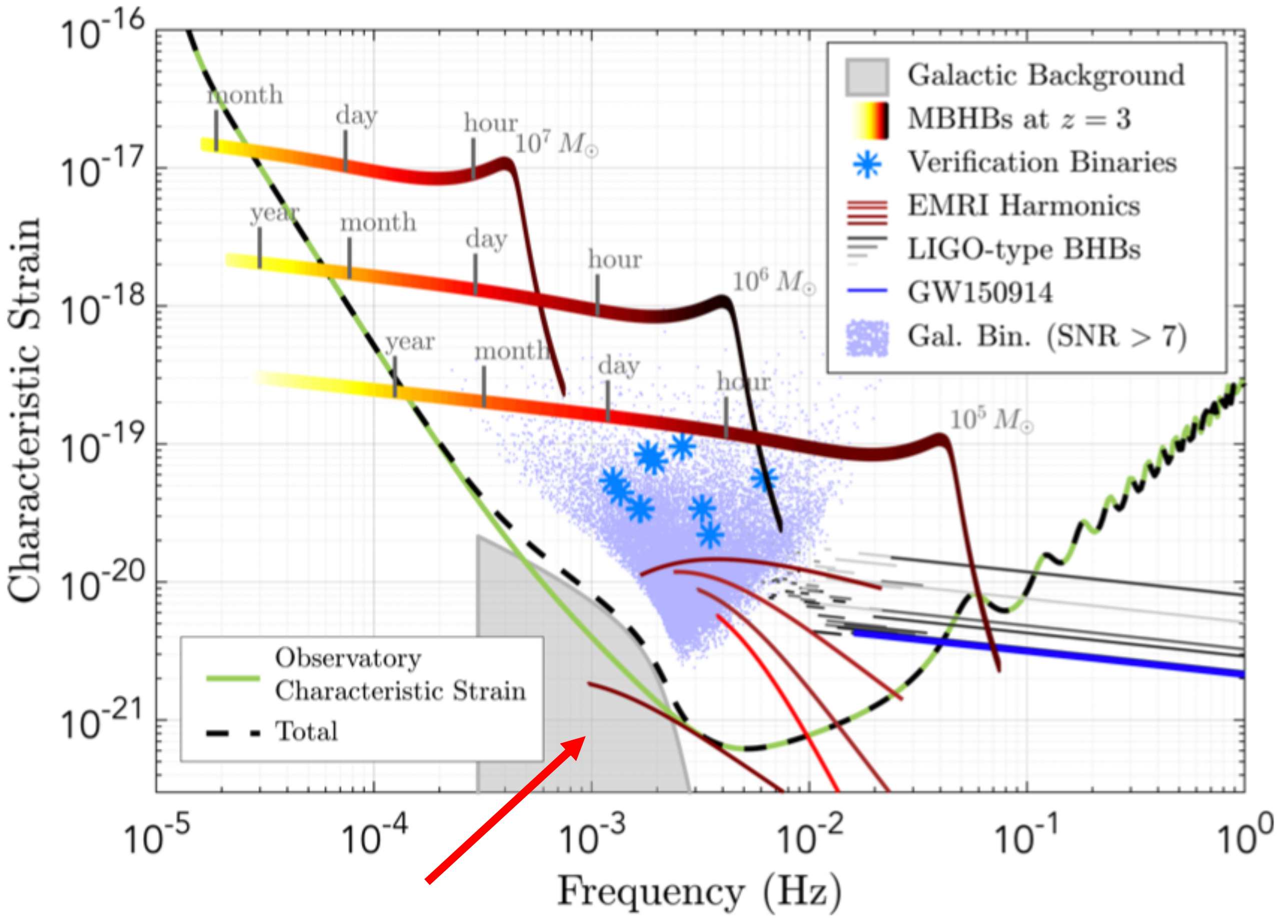
- From these, can estimate $\Omega_{\mathrm{GW}}(f)$ for all binary black hole coalescences in the visible Universe



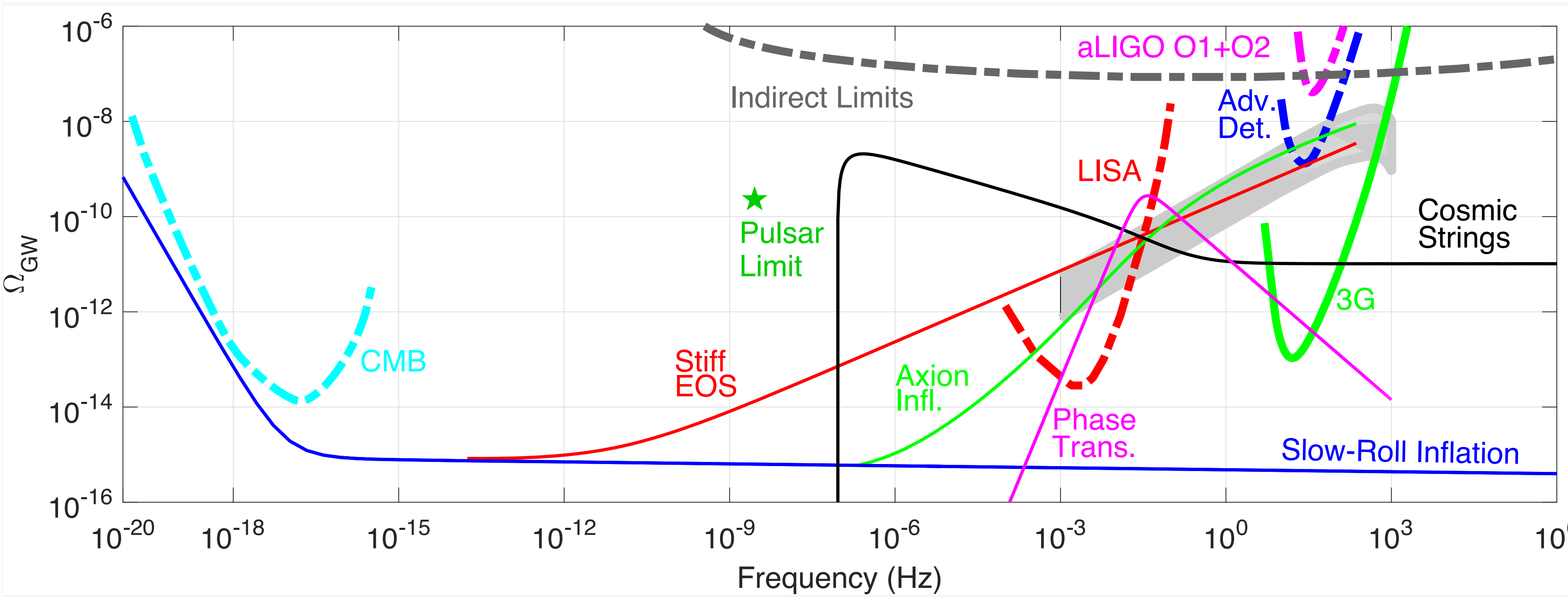
LSC, Virgo, arXiv:1903.02886

Stochastic gravitational wave backgrounds

- For LISA: background from all **white dwarf binaries** in the Milky Way
- When searching for other sources (e.g. supermassive binary black holes), effectively becomes a contribution to the noise



Primordial stochastic backgrounds

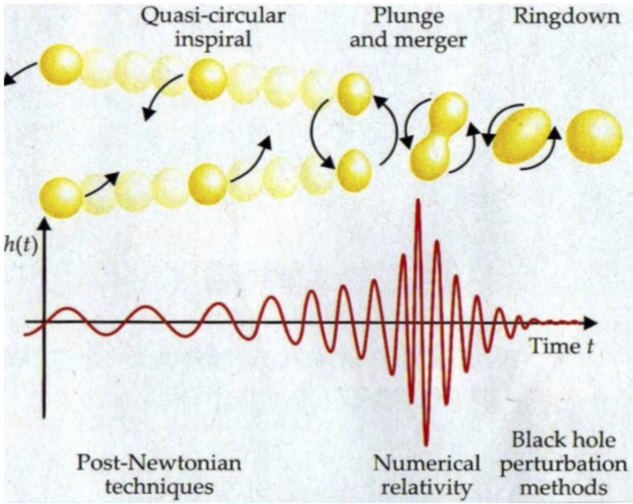


Kalogera et al., arXiv:2111.06990

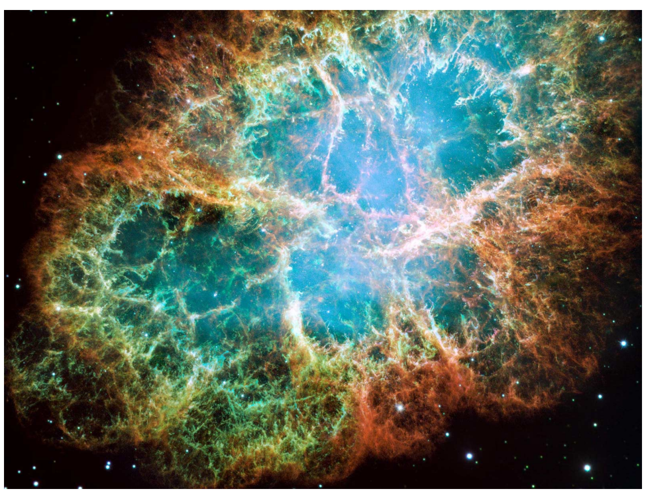
Detectable sources of gravitational waves

Transient signals

Merging neutron stars, black holes

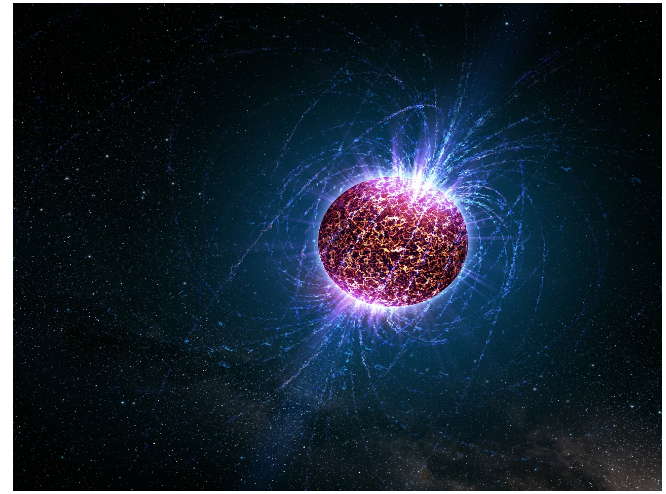


“Burst” sources



Continuous signals

Fast-spinning neutron stars



Stochastic gravitational waves