Gravitational Wave Open Data Workshop
12-14 May 2025

Lecturers

Koustav

Alorika

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Tutors

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Alorika

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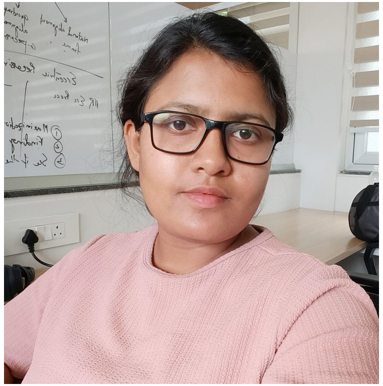

Priyanka

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Introduction to gravitational wave science

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12 May 2025

Overview

- ➢ Gravitational waves: ripples in spacetime
- ➢ Detectors: bars and interferometers
- ➢ Sources: heavy and fast things
- ➢ Waveforms: chirping binaries
- ➢ Gravitational wave astronomy
- ➢ Workshop overview

Gravitational waves [**GW**s]

Waves

$$A \cdot e^{2\pi\iota\, f\, t}$$

* At a fixed location, so no k.x

A: perturbation around a background

- ➢ Sound: Pressure fluctuations around 1 atm
- ➢ EM: EM field fluctuations around ~ 0
- ➢ ***GW: metric fluctuations around flat spacetime***

General Relativity 101: The metric of spacetime

➢ Metric is a rule that gives you distance between two points

$$ds^2 = \sum_\mu \sum_\nu g_{\mu\nu}\, dx^\mu\, dx^\nu$$

$$\begin{pmatrix} g_{00} & g_{01} & g_{02} & g_{03} \\ g_{10} & g_{11} & g_{12} & g_{13} \\ g_{20} & g_{21} & g_{22} & g_{23} \\ g_{30} & g_{31} & g_{32} & g_{33} \end{pmatrix}$$

$$\eta = \begin{pmatrix} -c^2 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$g_{\mu\nu} = \begin{bmatrix} -\left(1-\frac{2GM}{rc^2}\right) & 0 & 0 & 0 \\ 0 & \left(1-\frac{2GM}{rc^2}\right)^{-1} & 0 & 0 \\ 0 & 0 & r^2 & 0 \\ 0 & 0 & 0 & r^2\sin^2\theta \end{bmatrix}.$$

Credit: wikipedia

GWs as perturbations around flat metric

Metric perturbations => distances between free particles will oscillate

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu},\ h \ll 1$$

$$h_{\mu\nu} = A_{\mu\nu}\, e^{2\pi\iota f t}$$

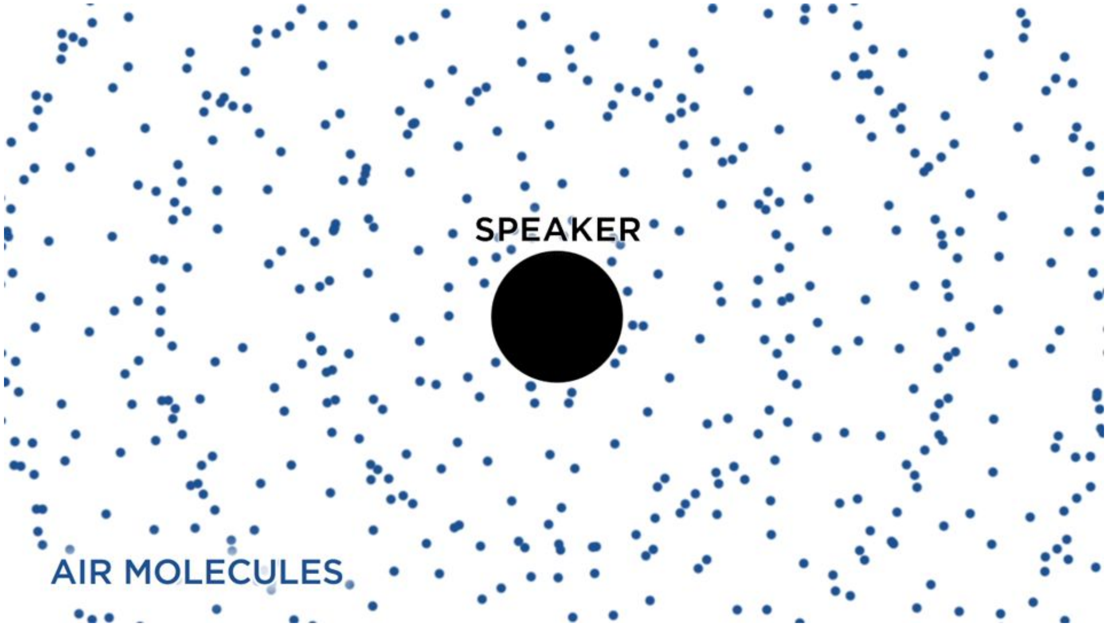
Credit: wikipedia

Wave

Action: longitudinal

Sound

$$p = p_{atm} + \delta p \, e^{2\pi \iota f t}$$



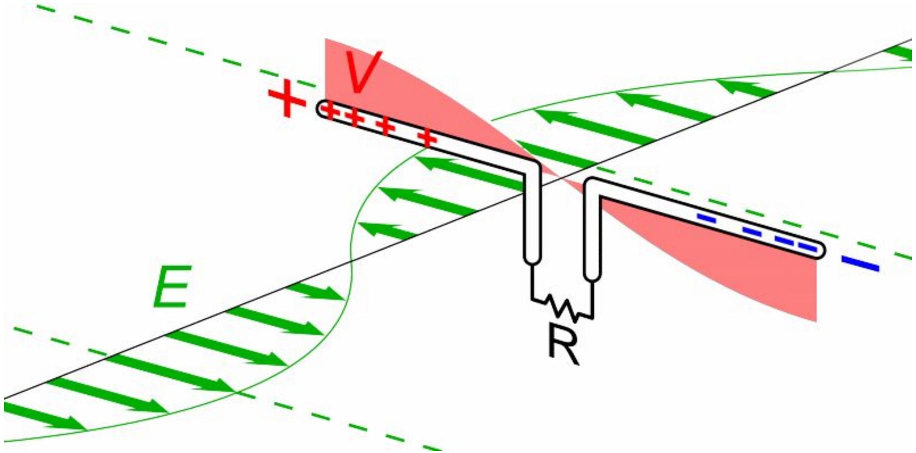
Credit: npr.org @pinterest

Wave

Action: transverse

Electromagnetic

$$\bar{E} = \bar{E}_0 \; e^{2\pi\iota f t}$$



2 polarizations

Credit: wikimedia

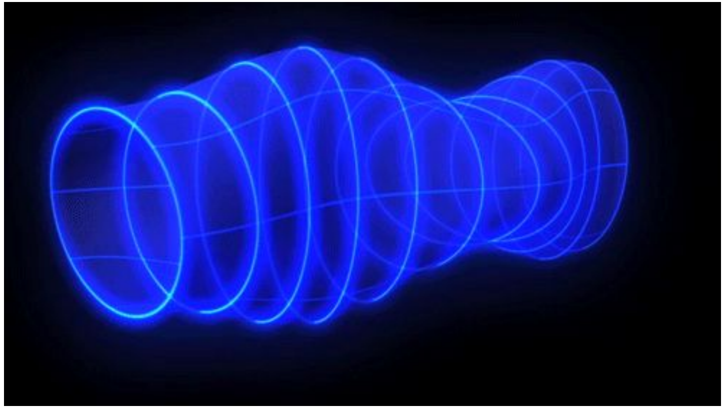
Wave

Gravitational

$$h_{\mu\nu} = A_{\mu\nu}\, e^{2\pi\iota f t}$$

2 polarizations

Action: transverse



Credit: ESA

Credit: wikipedia

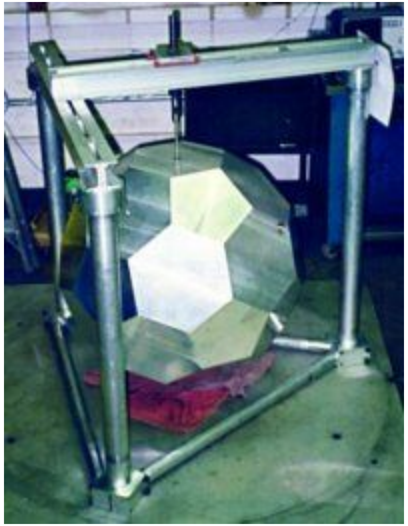
Detectors

A simple detector

- ➢ Something that the wave interacts with…
- ➢ … setting it into motion
- ➢ … resulting in something that we can measure

Weber’s Bar detector

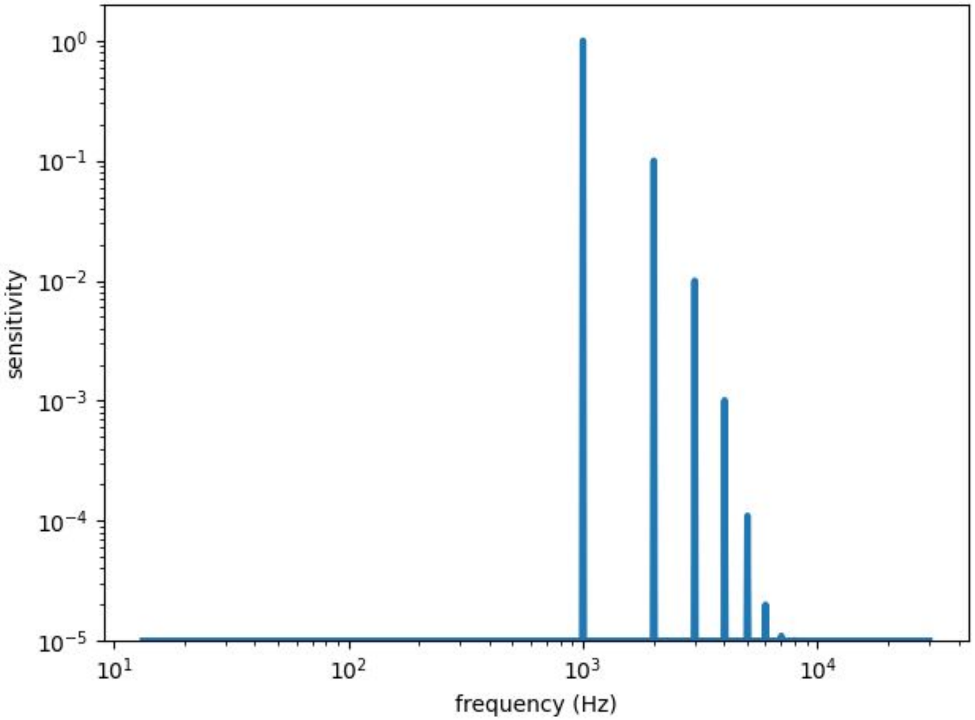
- ➢ A giant chunk of metal
- ➢ Strain gauges to measure GWs



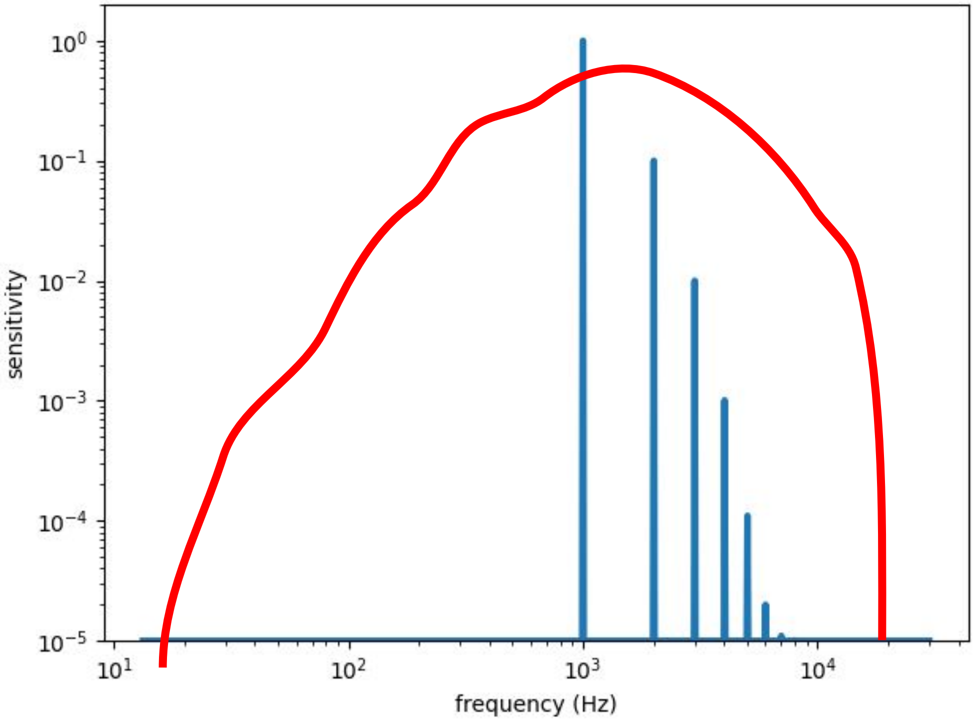
Credit: MIT

What is the difference between these two detectors?

Narrow vs broadband sensitivity



Narrow vs broadband sensitivity



Interferometers

In bound masses, gravity has to compete with EM forces

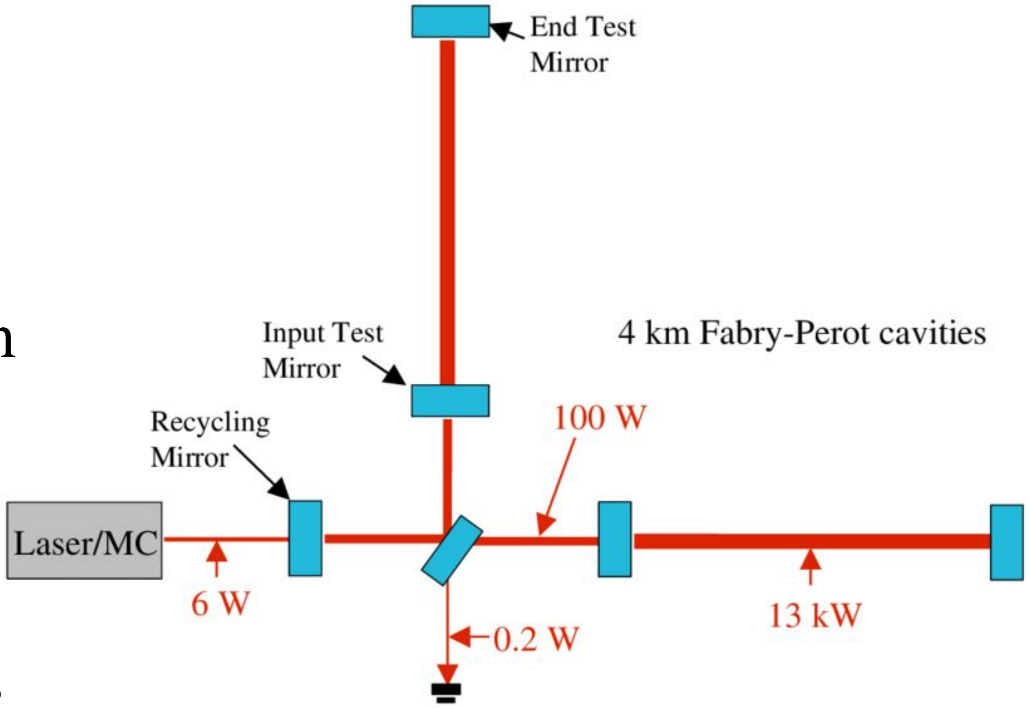
- ➢ Sensitive only at mechanical resonance

Free the masses, monitor their relative motion

[Michelson Interferometer]

The LIGO Interferometers

- ***Broadly*** sensitive to wavelengths of the order of the arm size
- Effective arm size ~ 10^6 m ~ 300 Hz
- Noise causes cut offs at low and high wavelengths

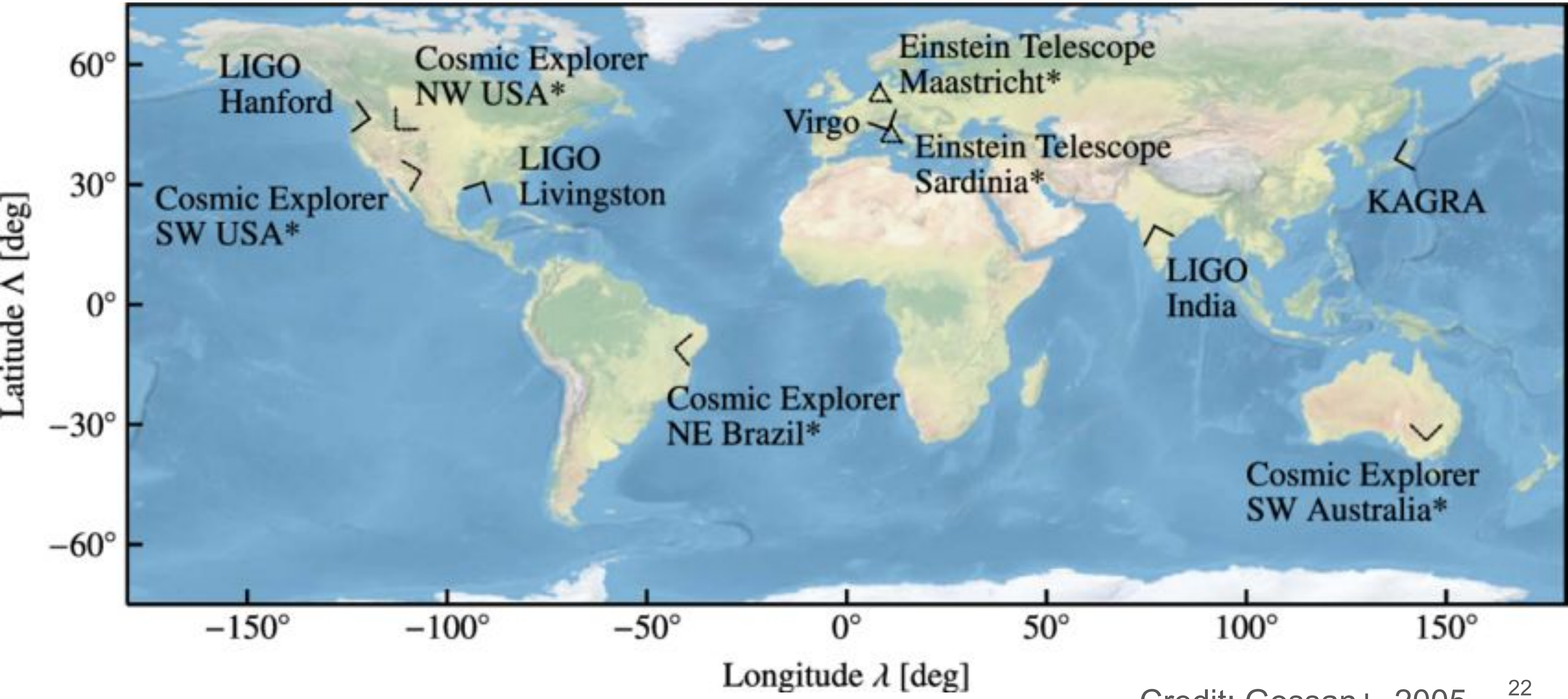


Credit: Hamilton+, 2005

Currently operational interferometric detectors

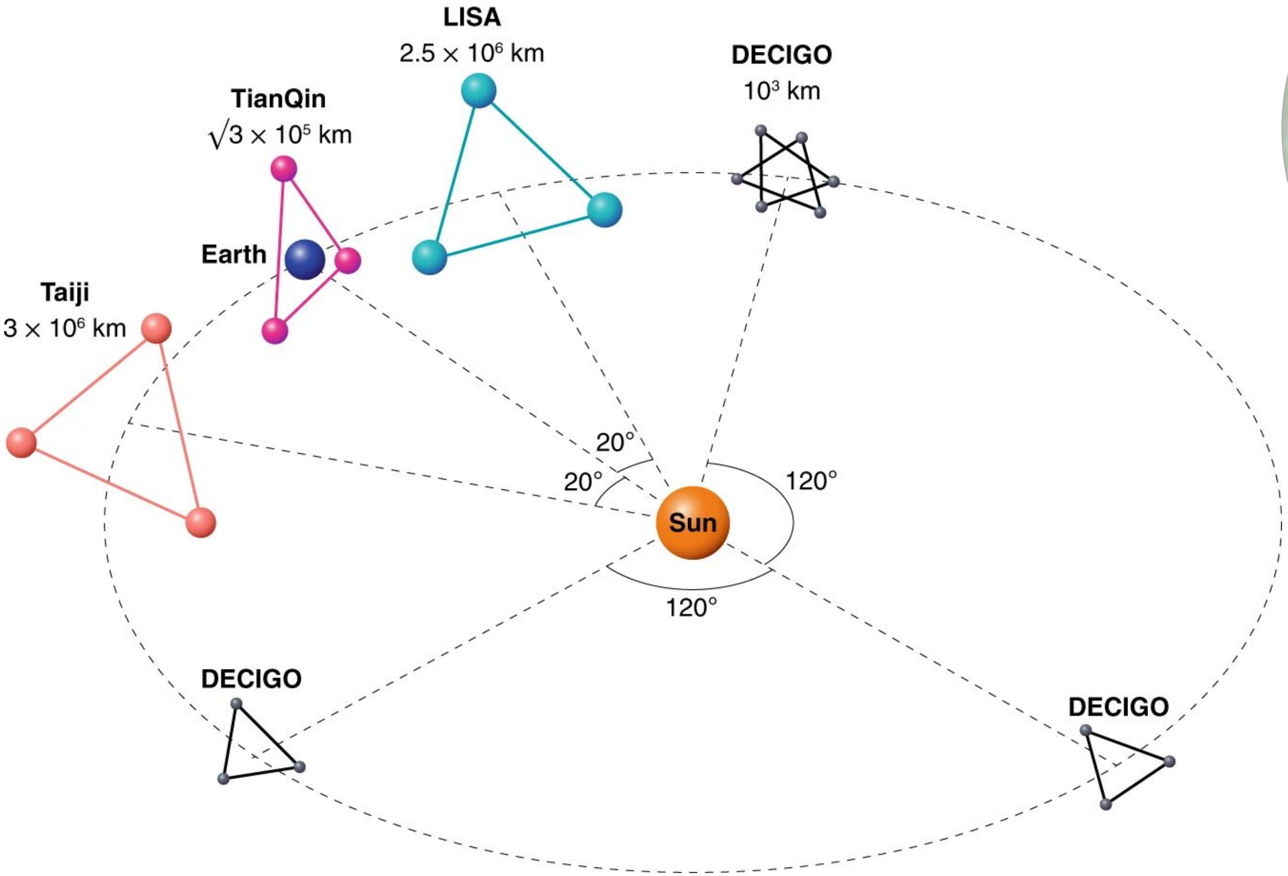
Credit: IUCAA

Proposed ground based detectors, 2-2k Hz



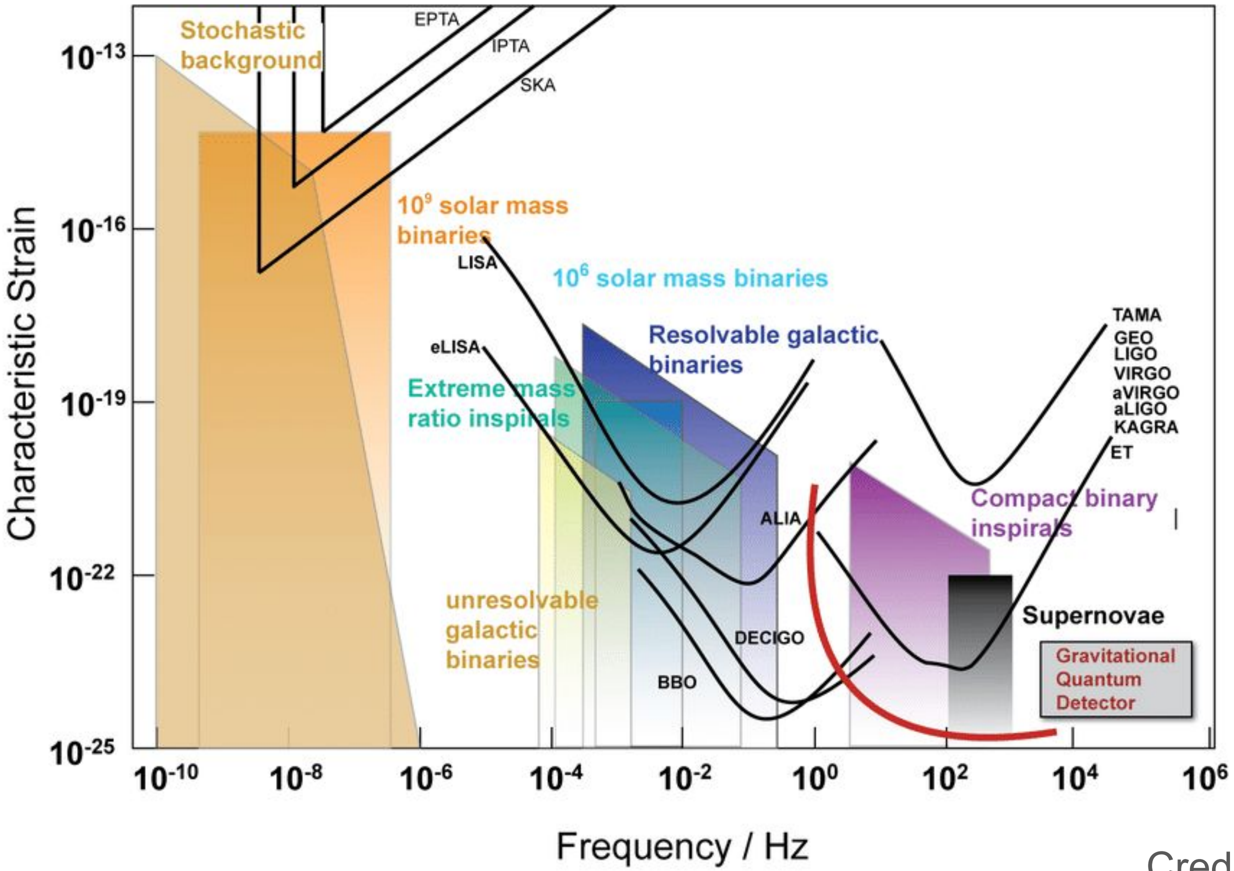
Credit: Gossan+, 2005

Proposed space based detectors



Credit: Gong+, 2021

Overview of GW detectors



Credit: Sabin+, 2015

Sources

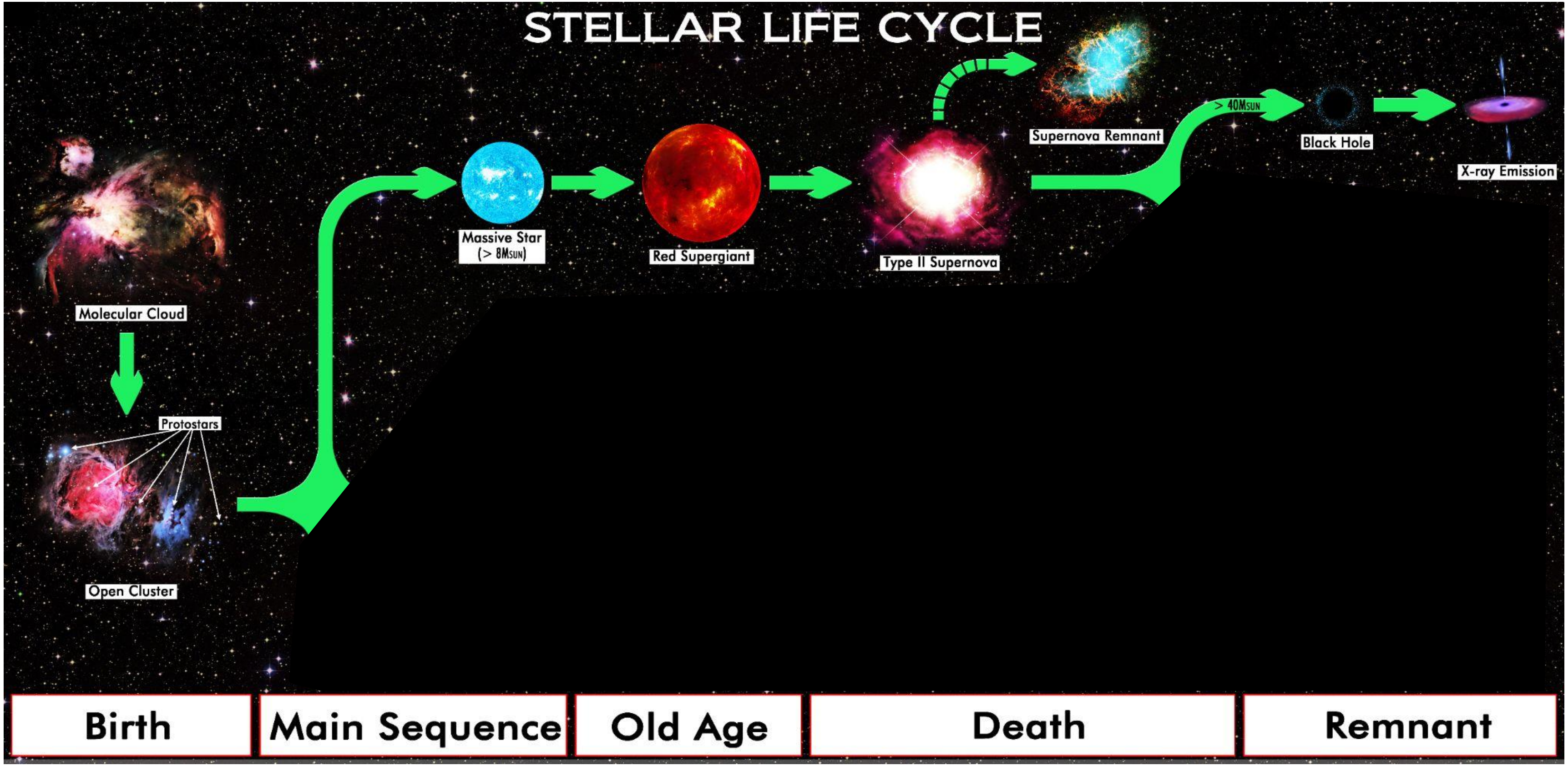
Anything that has changing mass asymmetry

- My hands: $h \sim 10^{-55}$ @ $f \sim 1$ Hz
- Nucleons: $h \sim 10^{-92}$ @ $f \sim 10^{22}$ Hz
- Galaxy cluster: $h \sim 10^{-11}$ @ $f \sim$ (1 / age of universe) Hz
- Binary Stars: $h \sim 10^{-21}$ @ $f \sim 100$ Hz
- The strongest sources are heavy and move quickly
  - They need to be ***compact,*** GM/Rc^2
  - 10^{-27}, 10^{-39}, 0.0027, 0.01

Compact sources

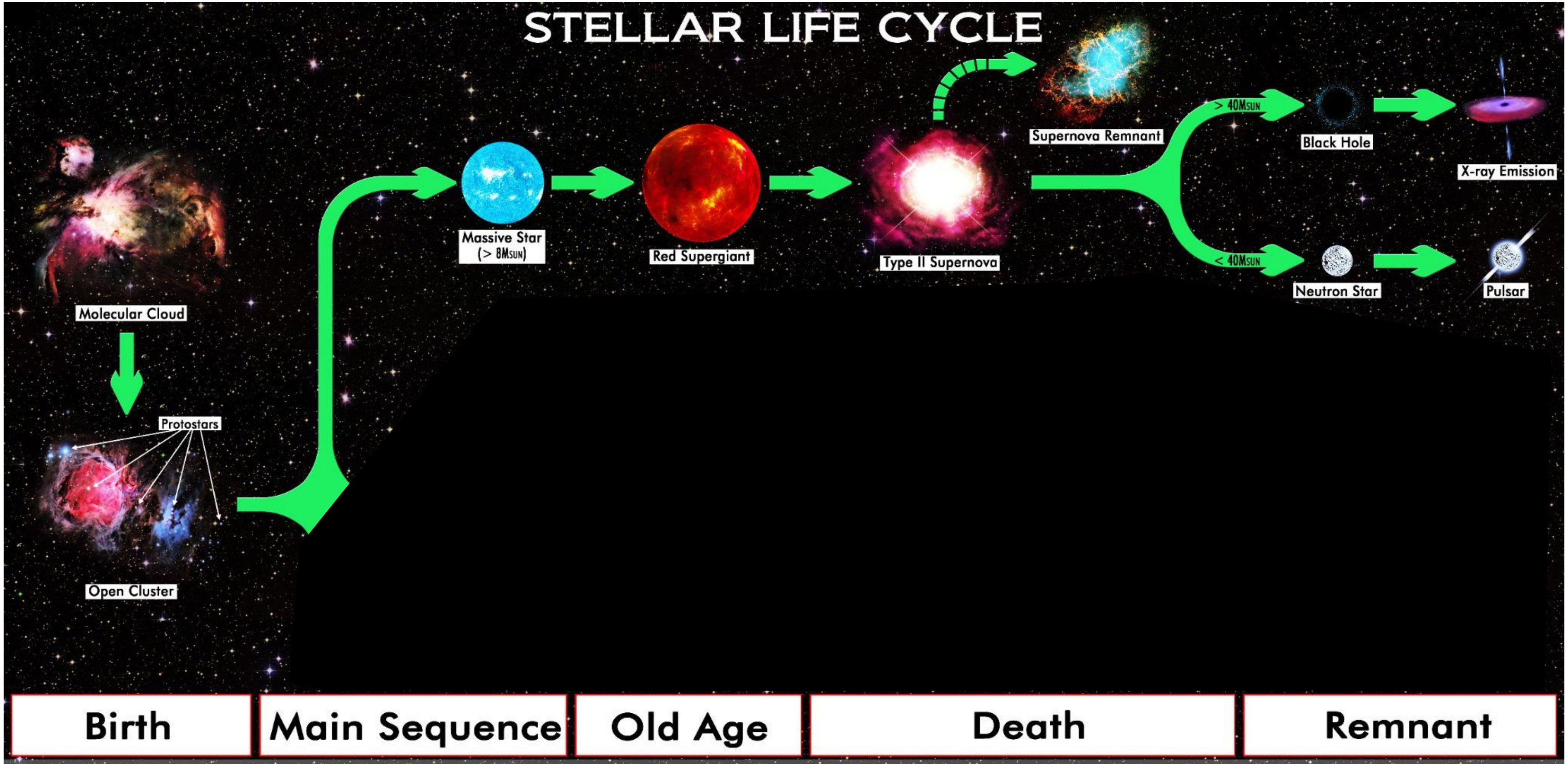
- Compact binaries:
  - BHs (3 km / Msun), NSs (~10 km), WDs (~10^4 km)
  - BBH, BNS, NSBH, …
- Spinning neutron stars having a “mountain” on them
- Supernova explosions
- Hyperbolic encounters
- Astrophysical foreground due to CBCs

From stars to compact objects



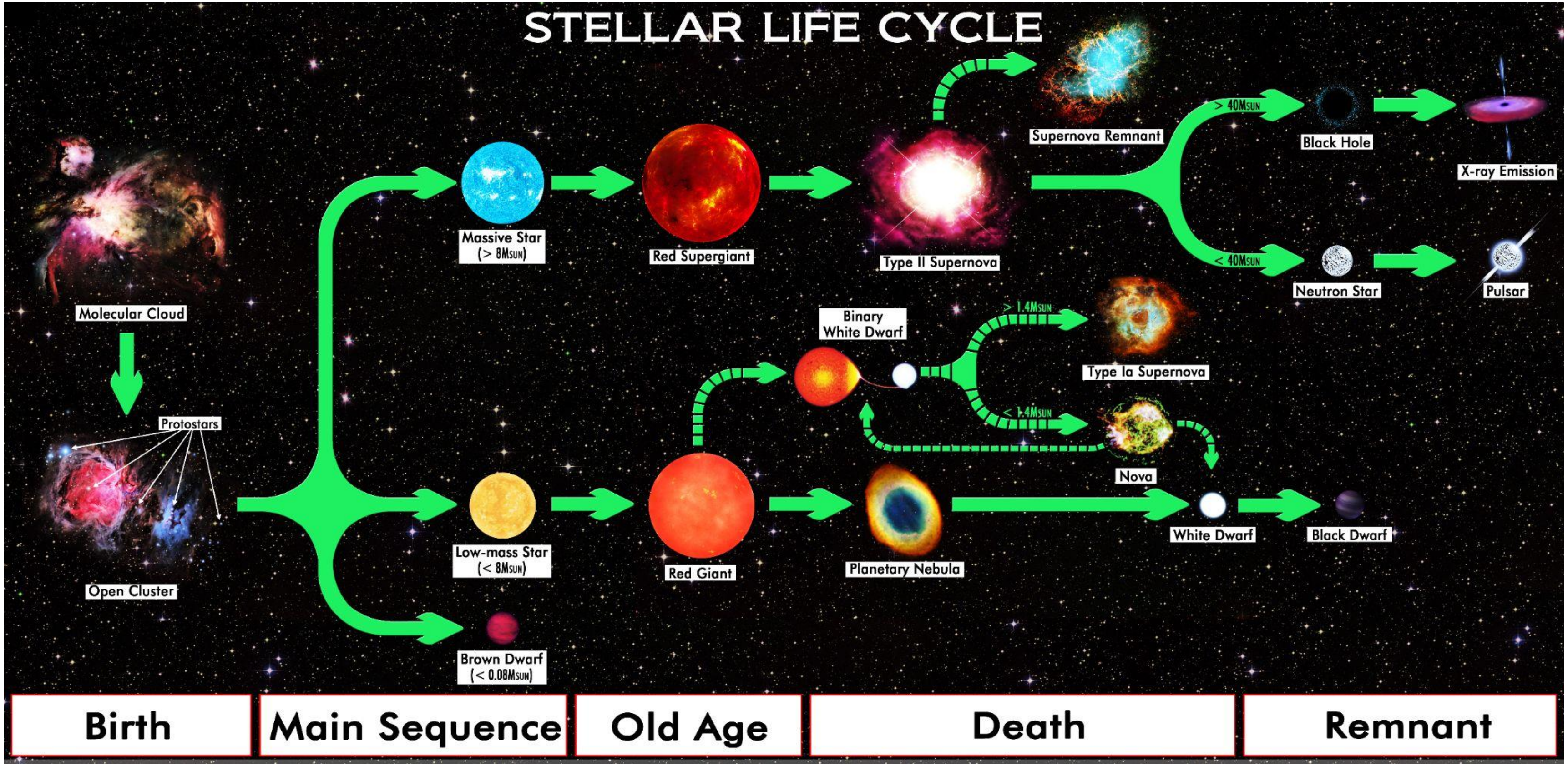
Credit: wikipedia

From stars to compact objects



Credit: wikipedia

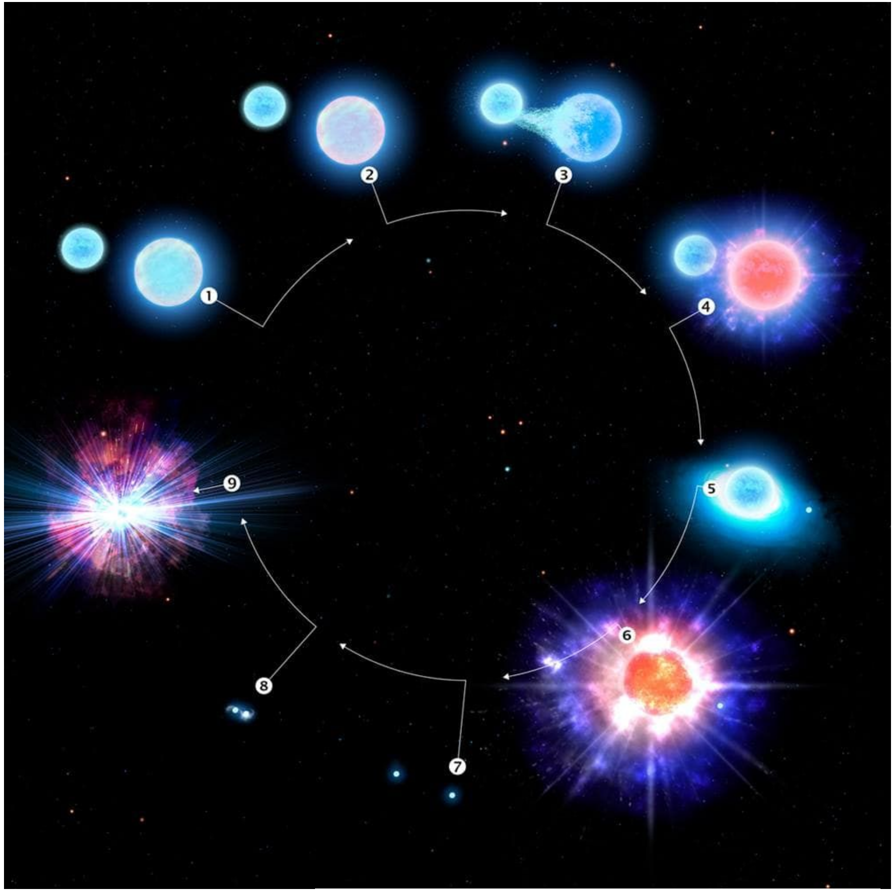
From stars to compact objects



Credit: wikipedia

Assembling compact objects into compact binaries

- Multiple possible formation channels
- Binary stars, evolve together, die together, merge



Credit: CTIO/NOIRLab/NSF/AURA/P. Marenfeld

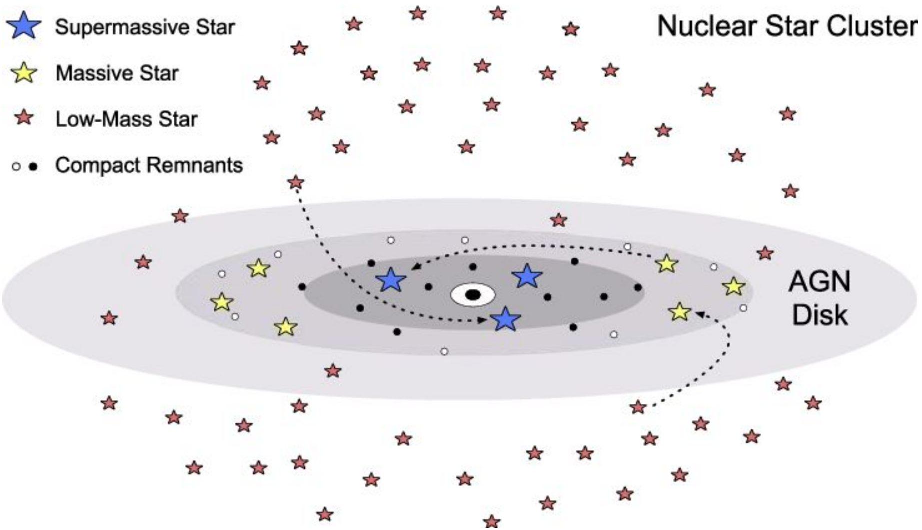
Assembling compact objects into compact binaries

- Multiple possible formation channels
- Binary stars, evolve together, die together, merge
- Dynamical capture in dense clusters

Credit: ICTS astro club

Assembling compact objects into compact binaries

- Multiple possible formation channels
- Binary stars, evolve, die, merge
- Dynamical capture in dense clusters
- Mergers assisted by AGN disks



Credit: Cantiello+, 2021

Waveforms

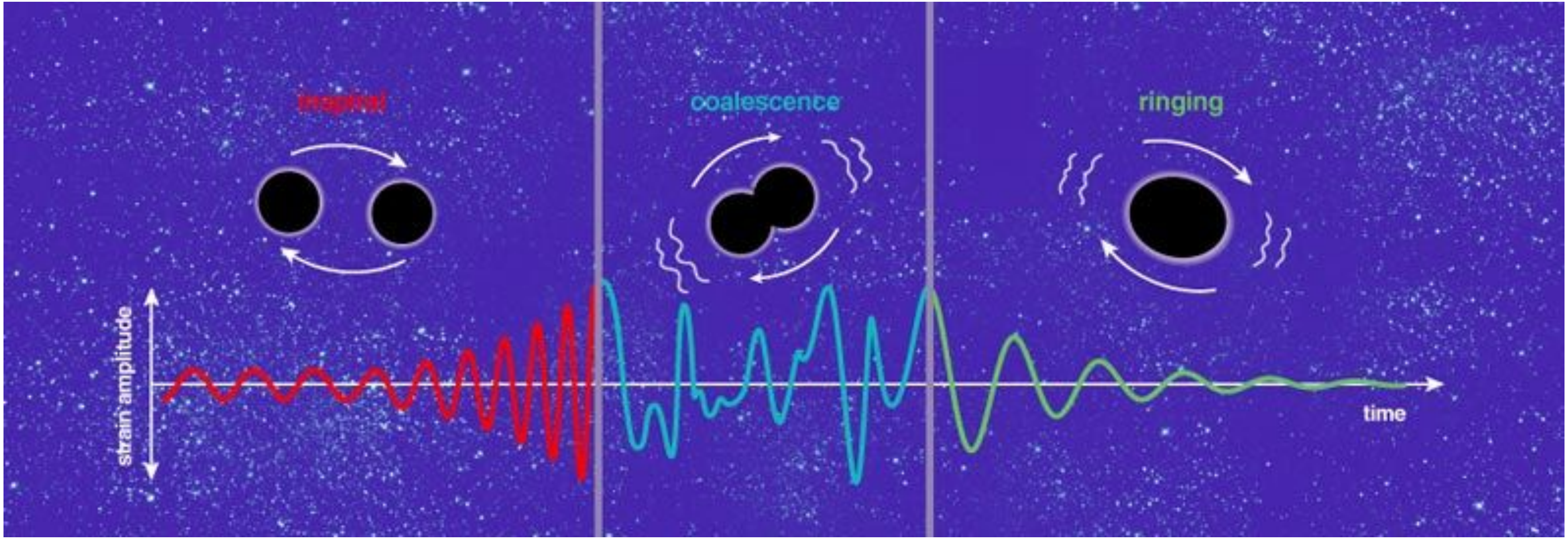
$h_+(t)$, $h_x(t)$ for compact binary coalescences (***CBC***s)

$$h_+(t) = A_+(t)\, e^{2\pi\iota f_+(t)t}$$

$$h_\times(t) = A_\times(t)\, e^{2\pi\iota f_\times(t)t}$$

Credit: NASA

$h_+(t)$, $h_x(t)$ for compact binary coalescences (***CBC***s)



← Thousands of years →   ← milliseconds →

Credit: Tom Dunne

Leading order inspiral waveform

Wide-ish binaries, slow speeds, weak fields, quasi-circular orbits

- ➢ Assume circular orbit and find rate of energy loss through GW

$$I_{()} \sim \mu R^2 e^{\iota \Omega t} \qquad h_{()} \sim \frac{G\ddot{I}_{()}}{c^4 d} \qquad \Omega^2 = GM/R^3$$

$$h_{()} \sim \frac{4G^2}{c^4}\frac{1}{d}\frac{\mu M}{R} \qquad L_{GW} = -\frac{dE}{dt} \sim 4\pi d^2 |\dot{h}_{()}|^2 \sim \frac{32G^4}{5c^5}\frac{\mu^2 M^3}{R^5}$$

Reference: Shapiro & Baumgarte, Num Rel, 2021

Leading order inspiral waveform

Wide-ish binaries, slow speeds, weak fields, quasi-circular orbits

- ➢ If it is losing energy, can't remain circular: correct the orbit by reducing orbital separation R

$$-\frac{dE}{dt} \cong \frac{32G^4}{5c^5} \frac{\mu^2 M^3}{R^5}$$

$$E_{eq} = -\frac{G}{2} \frac{\mu M}{R}$$

$$\frac{dR}{dt} = \frac{dE/dt}{dE_{eq}/dR} \cong -\frac{64G^3}{5c^5} \frac{\mu M^2}{R^3}$$

Reference: Shapiro & Baumgarte, Num Rel, 2021

Leading order inspiral waveform

Wide-ish binaries, slow speeds, weak fields, quasi-circular orbits

- ➢ Compute the trajectory: integrate to get R(t)

$$\frac{dR}{dt} = \frac{dE/dt}{dE_{eq}/dR} \cong -\frac{64G^3}{5c^5}\frac{\mu M^2}{R^3}$$

$$R(t) = \left(\frac{256G^4}{5c^{10}}\mu M^2(T-t)\right)^{1/4}$$

Reference: Shapiro & Baumgarte, Num Rel, 2021

Leading order inspiral waveform

Wide-ish binaries, slow speeds, weak fields, quasi-circular orbits

- ➢ Compute the frequency evolution: substitute R by f_{GW}

$$\Omega^2 = GM/R^3 \qquad f_{GW} = 2f_{orb} = \Omega/\pi$$

$$f_{\mathrm{GW}} = \frac{5^{3/8}}{8\pi}\left(\frac{c^3}{G\mathcal{M}}\right)^{5/8}\frac{1}{(T-t)^{3/8}} \simeq 155.7\,\mathrm{Hz}\left(\frac{M_\odot}{\mathcal{M}}\right)^{5/8}\left(\frac{1\,\mathrm{s}}{T-t}\right)^{3/8}$$

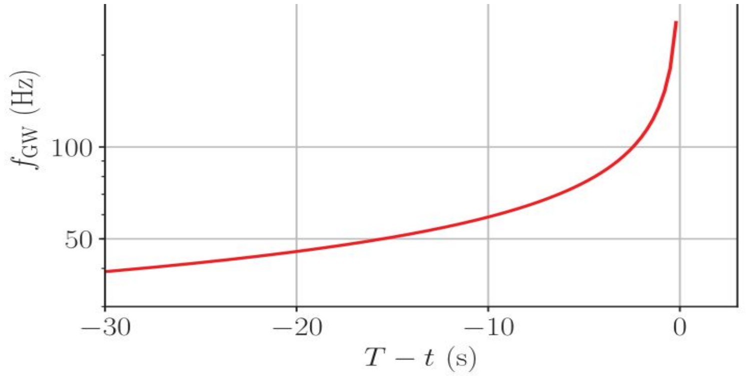
$$\mathcal{M} = \mu^{3/5}M^{2/5}$$

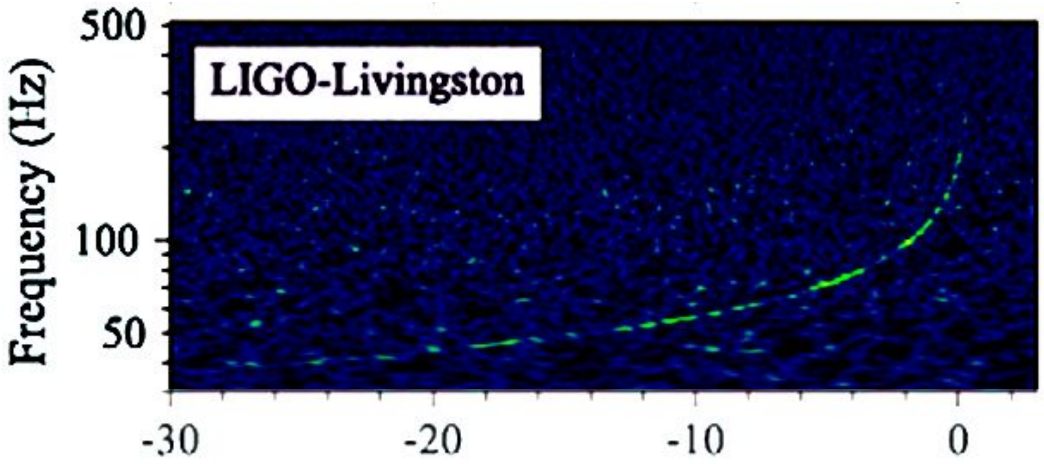
Reference: Shapiro & Baumgarte, Num Rel, 2021

Leading order inspiral waveform

Wide-ish binaries, slow speeds, weak fields, quasi-circular orbits

- ➢ Validity of $f_{\mathrm{GW}} \simeq 155.7\,\mathrm{Hz}\left(\frac{M_\odot}{\mathcal{M}}\right)^{5/8}\left(\frac{1\,\mathrm{s}}{T-t}\right)^{3/8}$





Reference: Shapiro & Baumgarte, Num Rel, 2021

Leading order inspiral waveform

Wide-ish binaries, slow speeds, weak fields, quasi-circular orbits

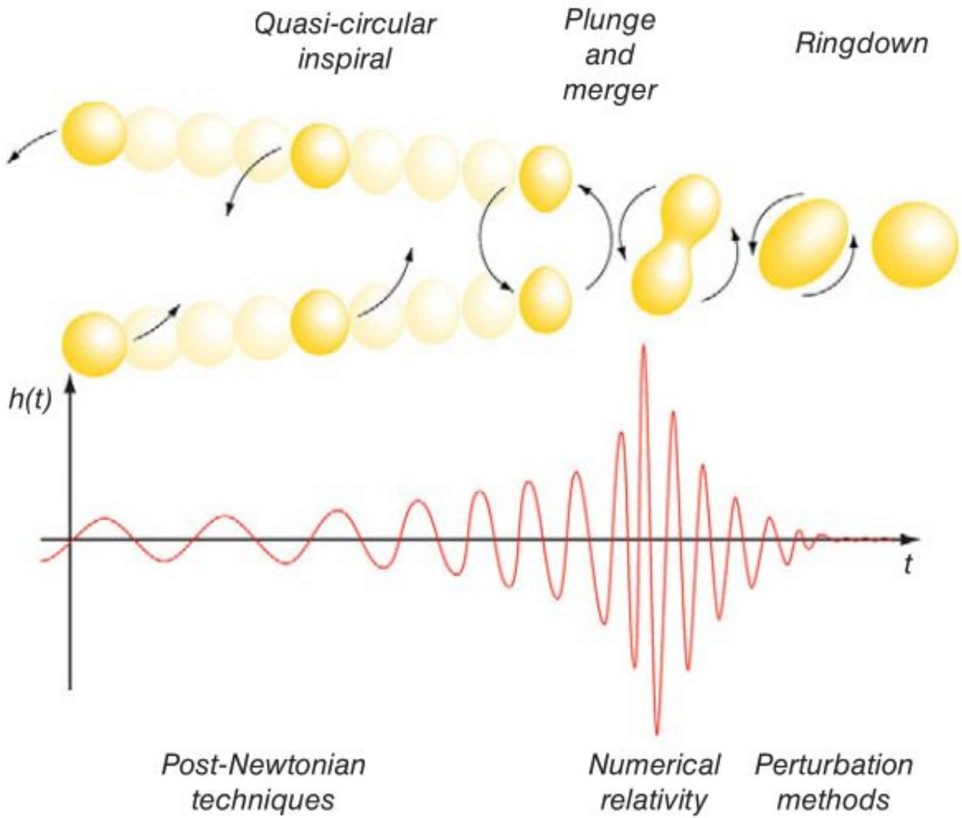
- ➢ Late inspiral: decay too fast to be quasi circular

$$\tau_{\rm GW} = \left| \frac{R}{dR/dt} \right| = P_{\rm orb} = 2/f_{\rm GW}$$

$$f_{\rm GW}^{\rm crit} \simeq 4.9\,{\rm kHz} \left(\frac{M_\odot}{\mathcal{M}} \right) \quad \boxed{h^{\rm crit} \simeq 3.3 \times 10^{-20} \left(\frac{\mathcal{M}}{M_\odot} \right) \left(\frac{\rm Mpc}{d} \right)}$$

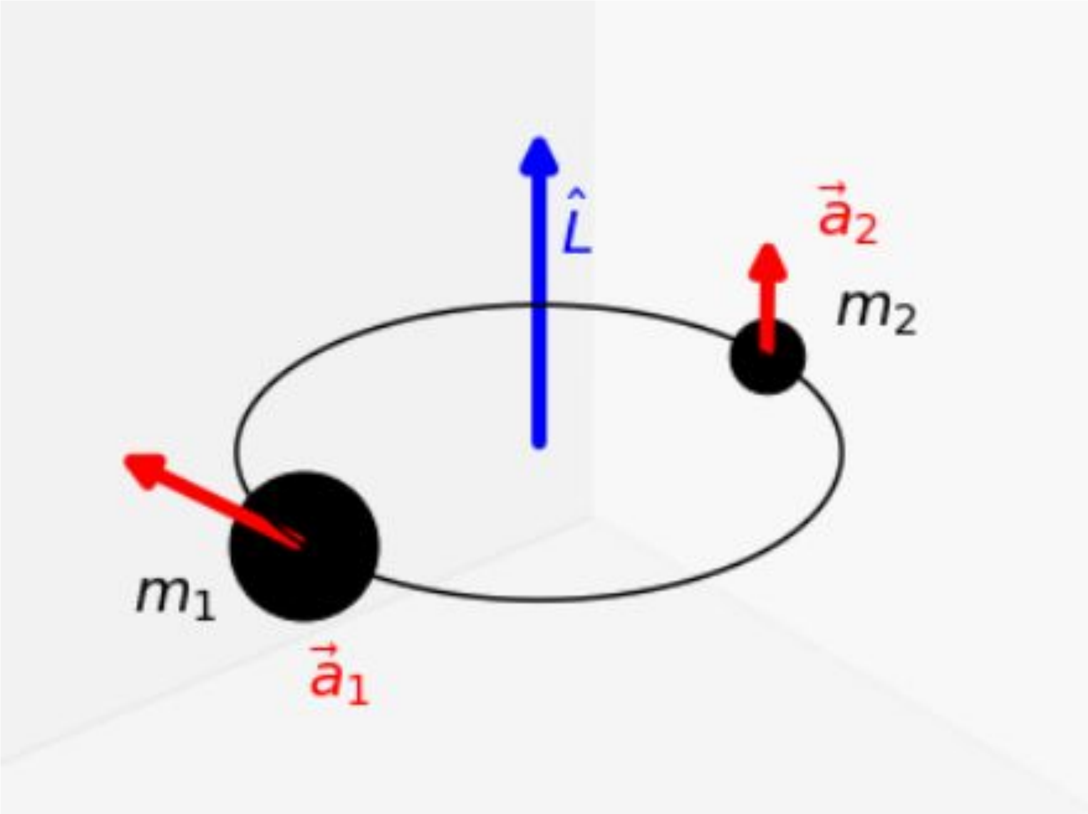
Reference: Shapiro & Baumgarte, Num Rel, 2021

Parameterizing $h_+(t)$, $h_x(t)$ for CBC



Credit: Shapiro+, 2021

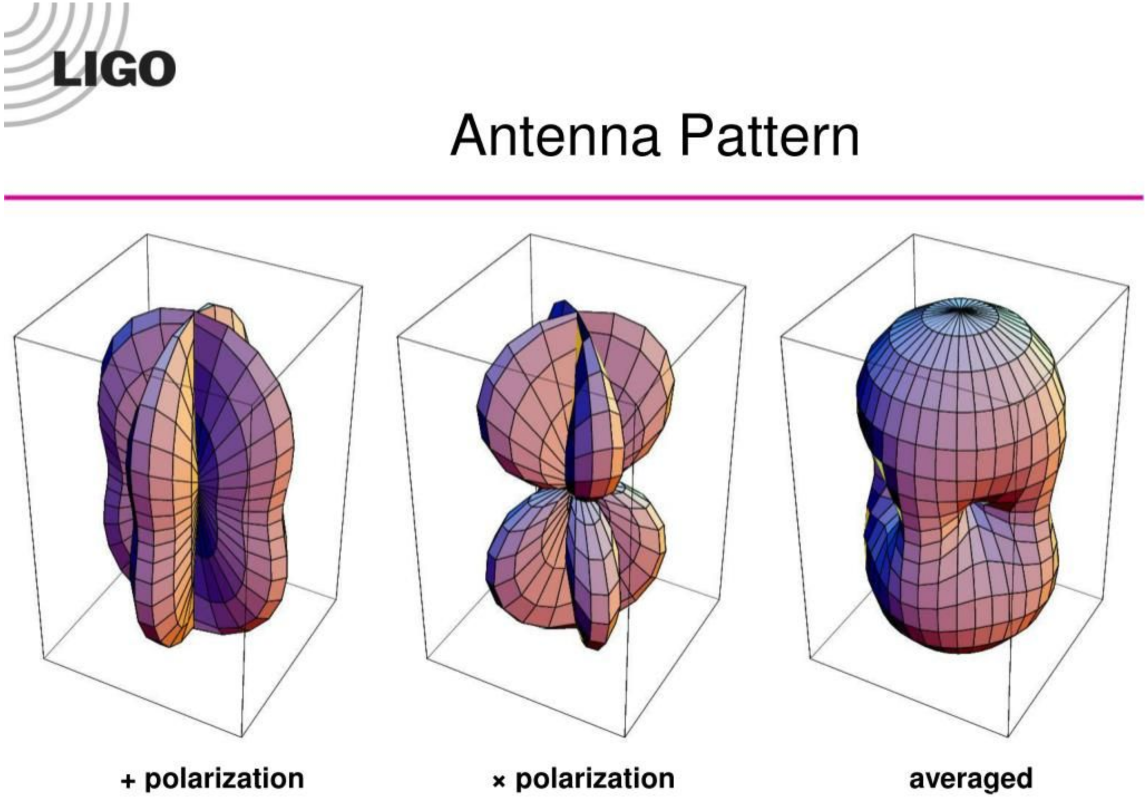
Intrinsic parameters

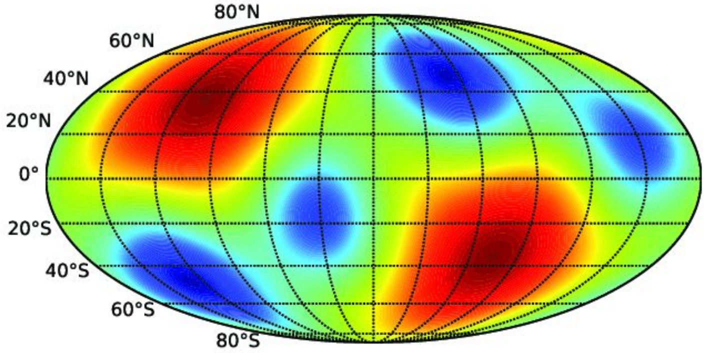


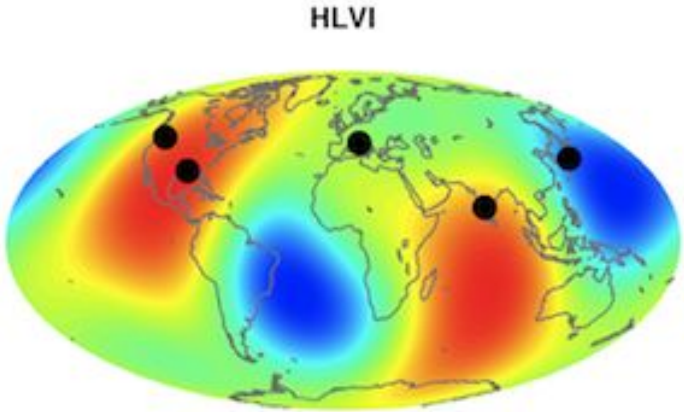
Credit: Adria Medina i Diez, 2020

Orientation parameters: source

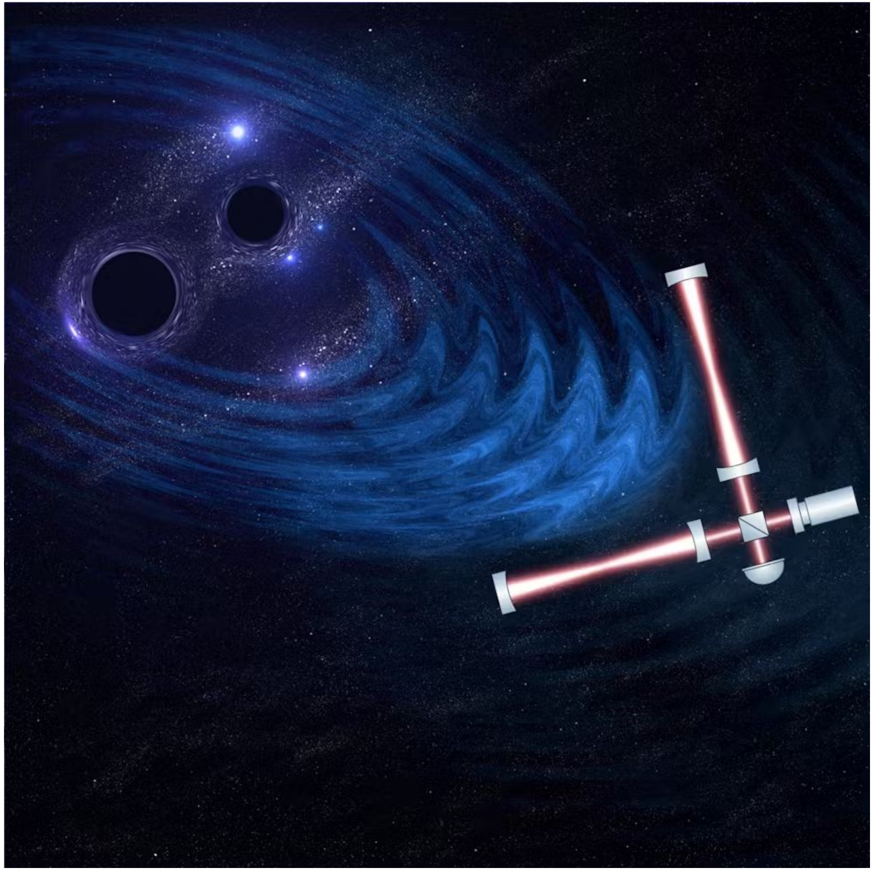
Orientation parameters: detector







Location parameters



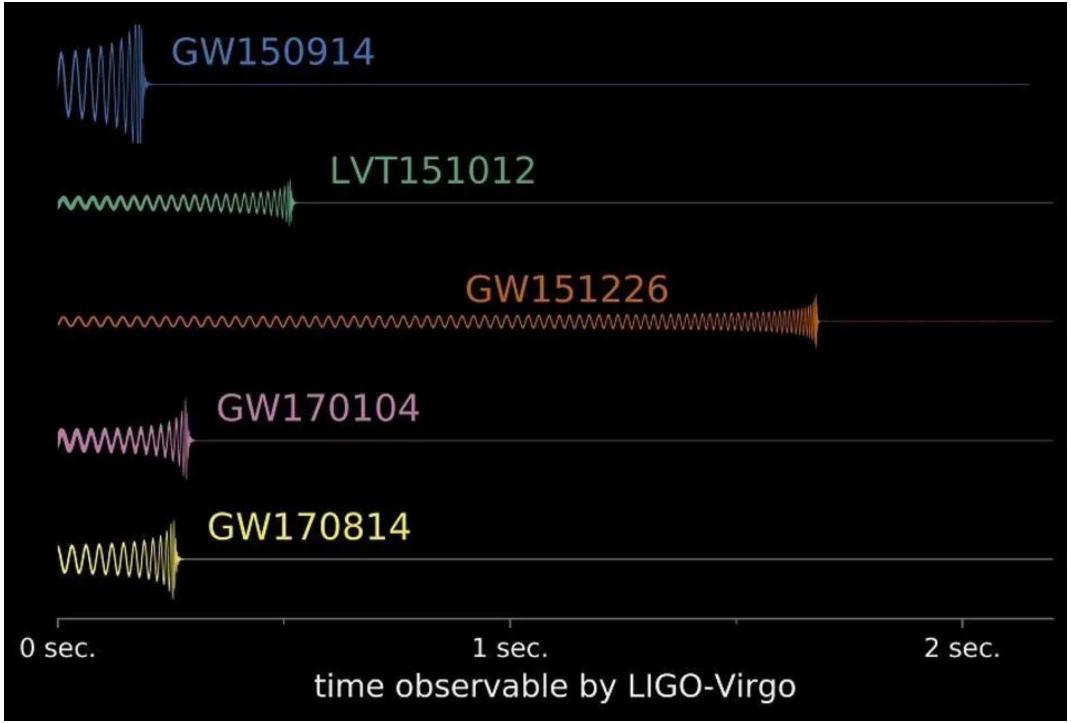
Credit: Christopher Berry

Parameterized waveforms

- Waveform parameters **[15D]**:
  - t or f
  - $m_1, s_{1x}, s_{1y}, s_{1z}, m_2, s_{2x}, s_{2y}, s_{2z}$
  - inclination, coalescence phase, polarization
  - RA, DEC, d_L, t_c
- Additionally: eccentricity, deformability, magnetic fields…

CBC waveform models

- Take 15 params; return
  $h(t \text{ or } f) = F_+ h_+ + F_x h_x$
- IMRPhenom family:
  - Stitching ***I***nspiral, ***M***erger, ***R***ingdown ***Phenom***enologically



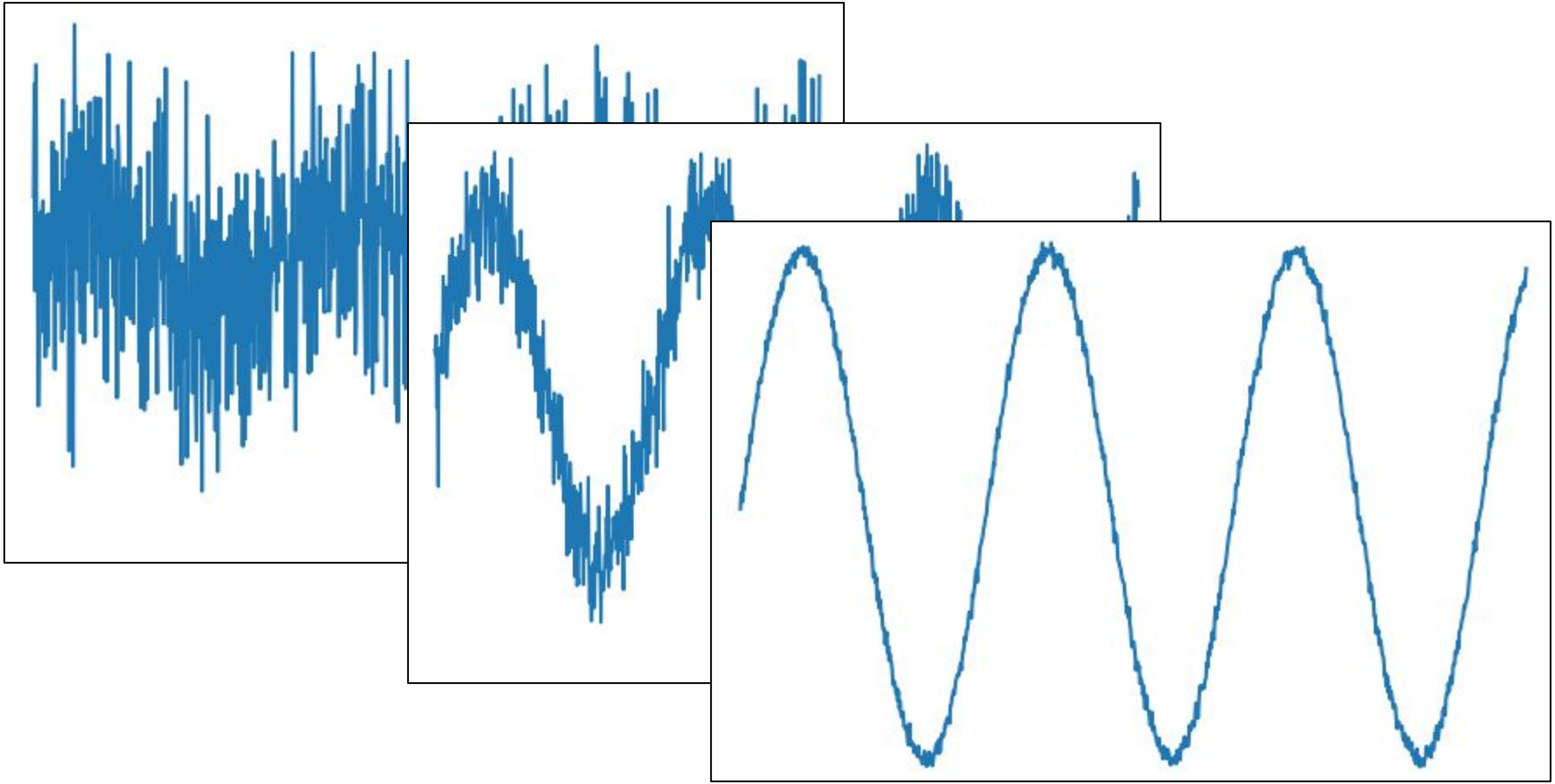
Credit: LVK, B. Farr

GW astronomy

GW astronomy

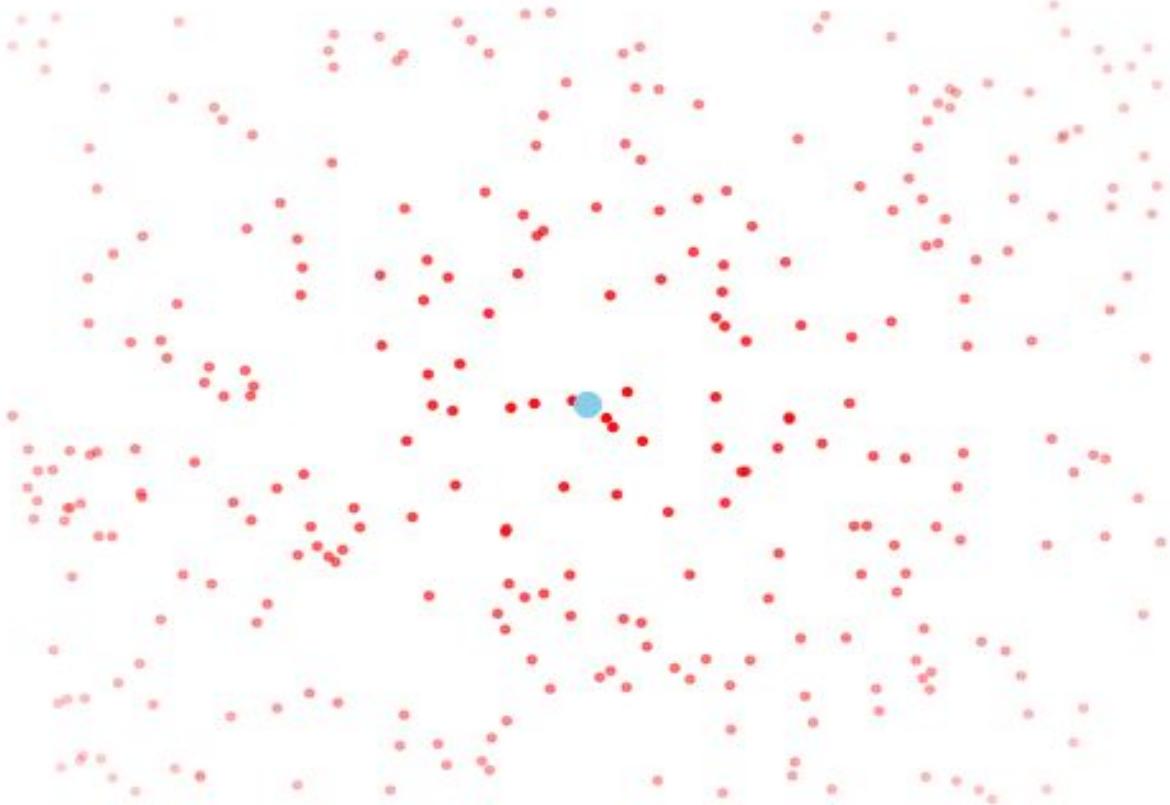
- Answering questions about the universe using GWs
- Unlike EM, no attenuation
  - can propagate long distances without significant changes to the waveform: **study stuff far away**
  - may undergo *refraction*, “gravitational lensing” of GWs: **study stuff in between**
- But there are challenges…

Loudness of a signal relative to noise



More sensitive = farther reach

$$h^{\text{crit}} \simeq 3.3 \times 10^{-20} \left(\frac{\mathcal{M}}{M_\odot}\right)\left(\frac{\text{Mpc}}{d}\right)$$

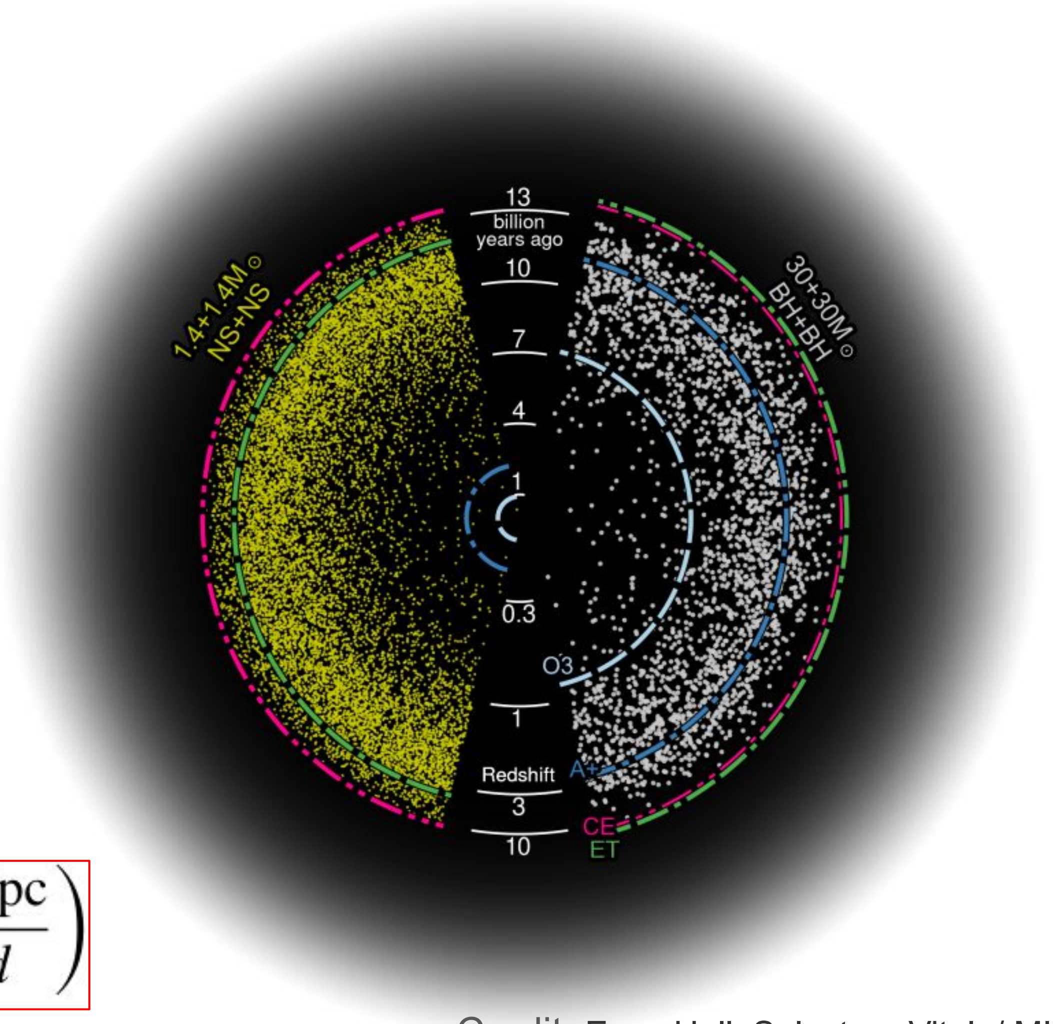


Detection range

How far can a source lie and still be detectable?

Depends on the type of source

$$h^{\mathrm{crit}} \simeq 3.3 \times 10^{-20} \left(\frac{\mathcal{M}}{M_\odot}\right)\left(\frac{\mathrm{Mpc}}{d}\right)$$



Credit: Evan Hall, Salvatore Vitale/ MIT

Data analysis challenge

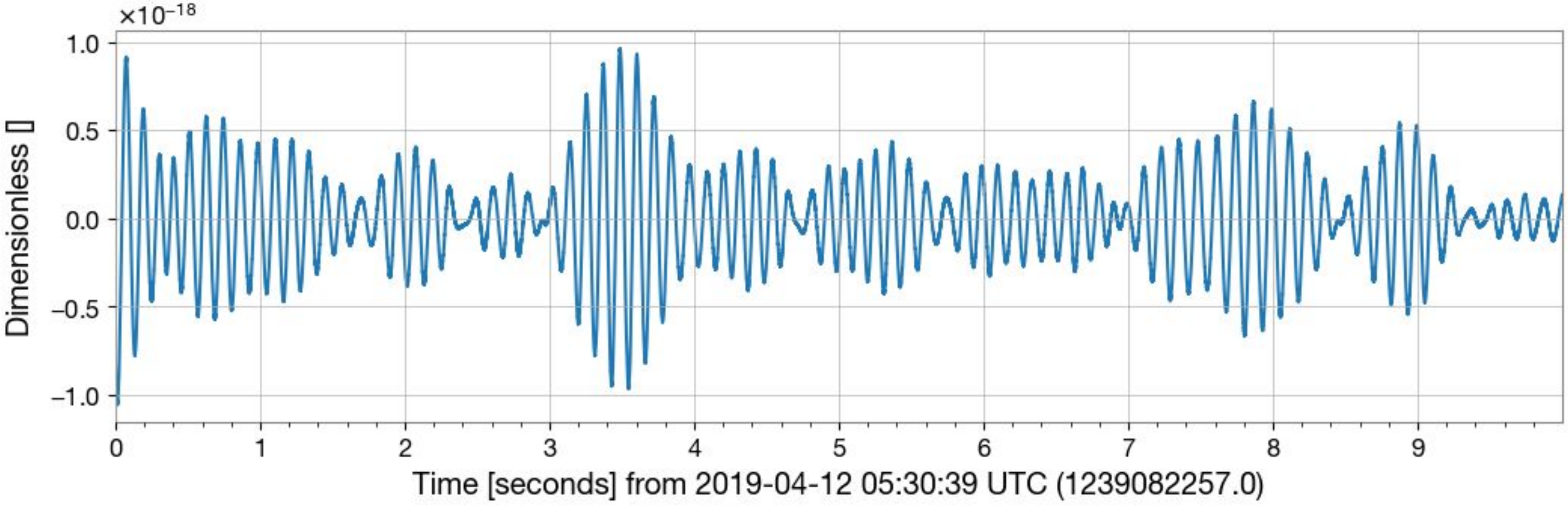
- For at least another decade
    - There will always be faint signals in the data
    - They will be more abundant than loud ones
- To fully enable GW astronomy, we need to be able to
    - Search for them *(I am __ confident that there is a signal here)*
    - Characterize them *(That signal came from IMR of 2 objects of masses __, spins __, that were __ far away, ...; with __ error on the estimates)*

Workshop Overview

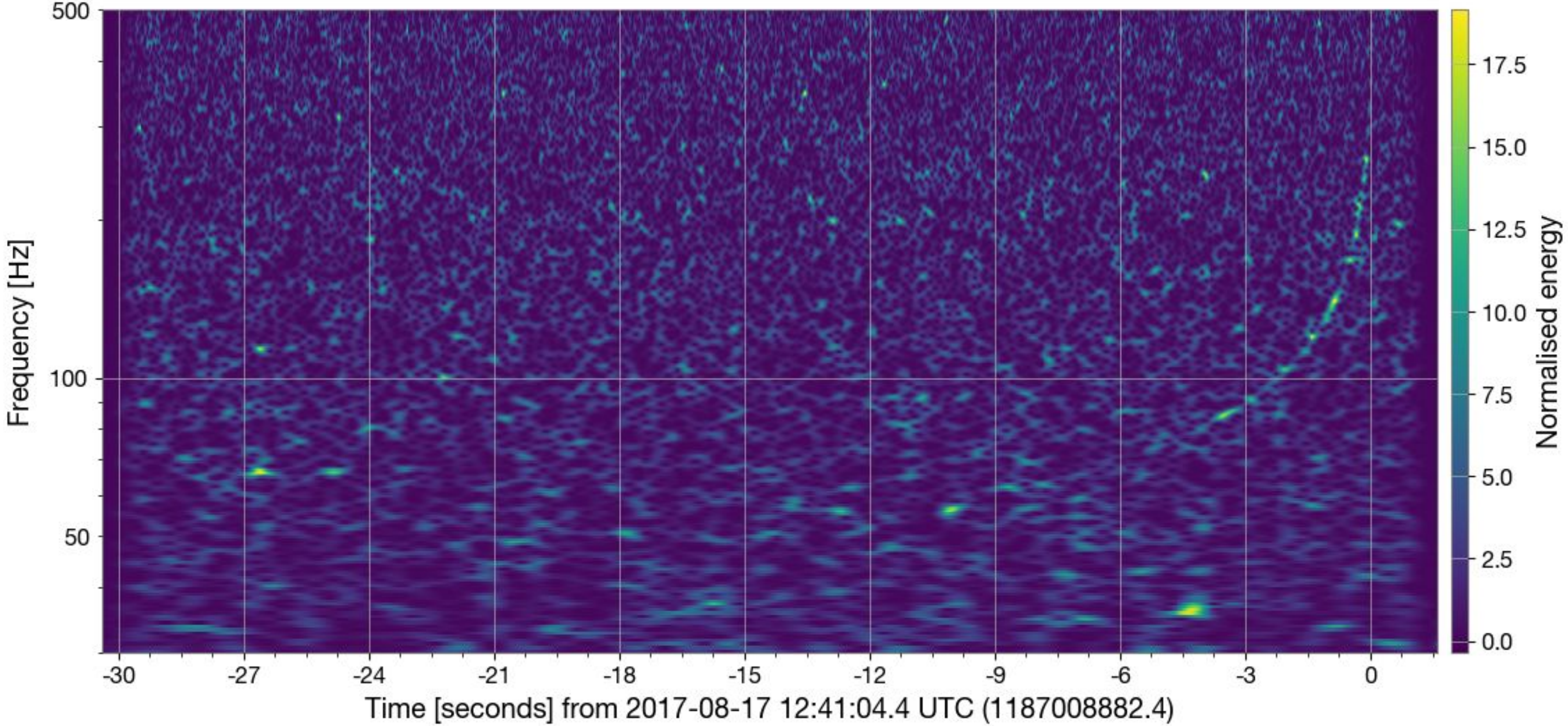
Introduction to open data

```
#-- Print all the GW events from the GWTC-1 catalog
gwtc1 = datasets.find_datasets(type='events', catalog='GWTC-1-confident')
print('GWTC-1 events:', gwtc1)
print("")
```

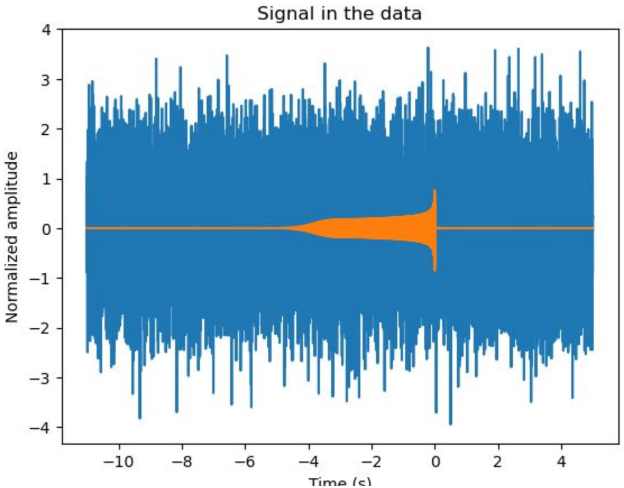
```
GWTC-1 events: ['GW150914-v3', 'GW151012-v3', 'GW151226-v2', 'GW170104-v2', 'GW170608-v3', 'GW170729-v
1', 'GW170809-v1', 'GW170814-v3', 'GW170817-v3', 'GW170818-v1', 'GW170823-v1']
```

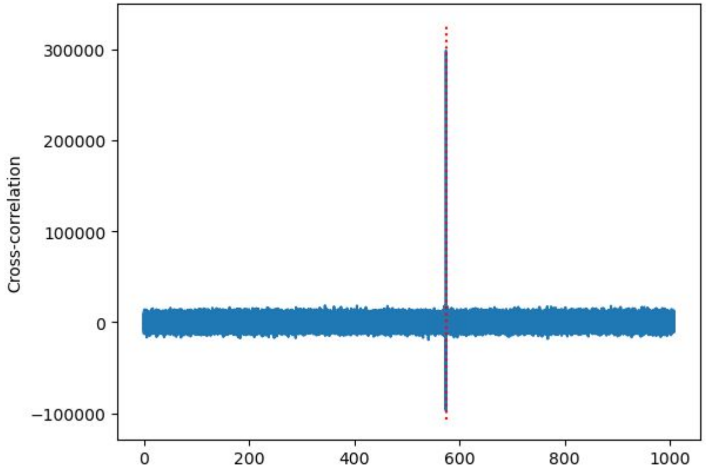


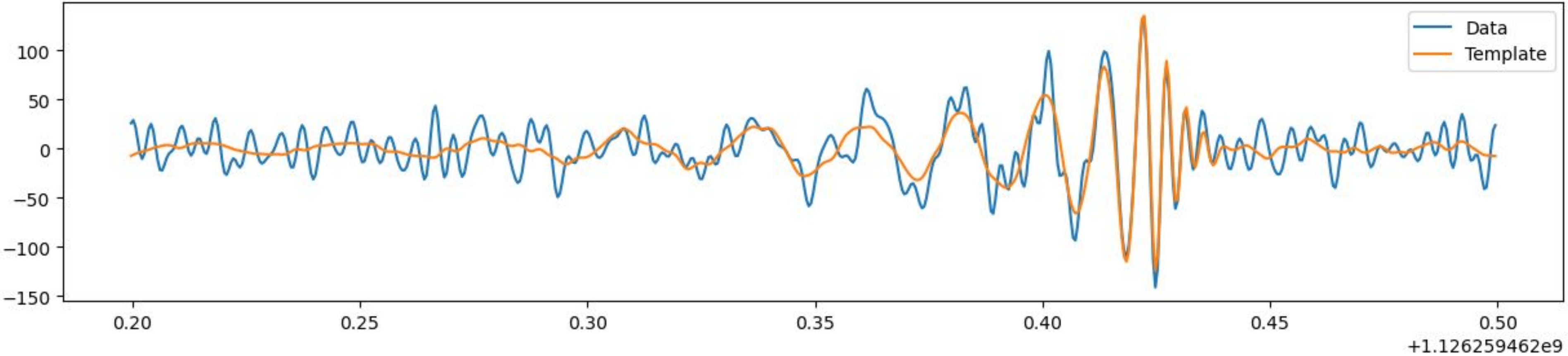
Visualization



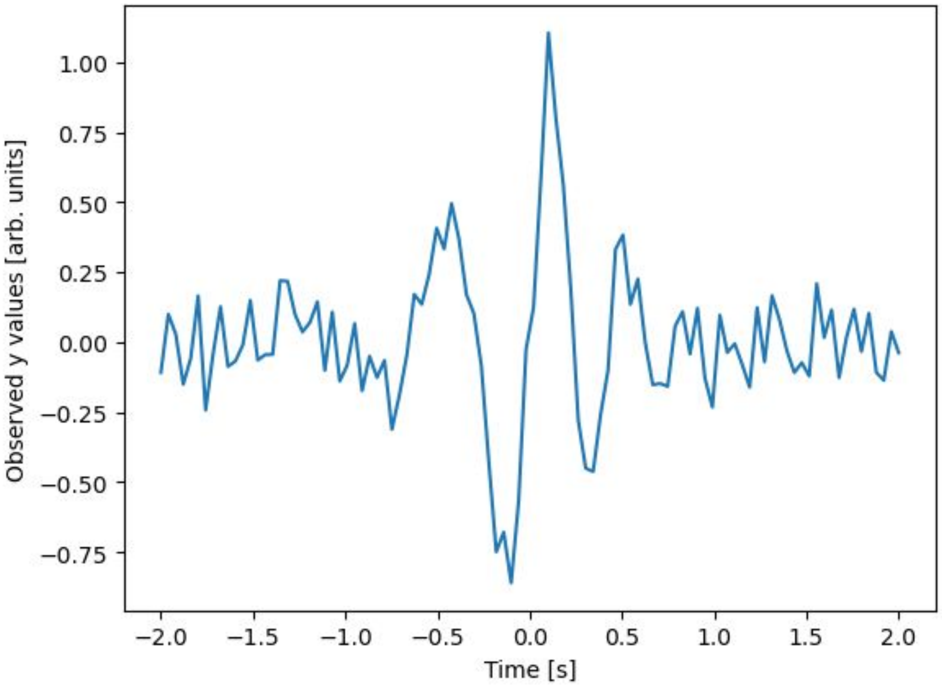
Searching for signals

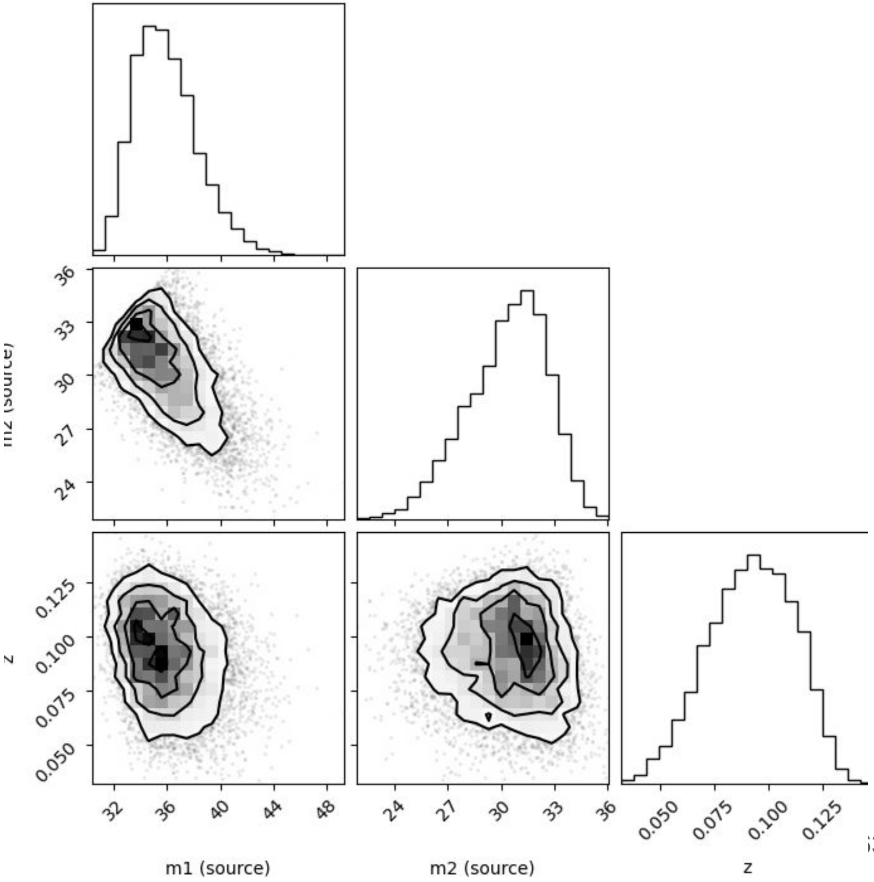






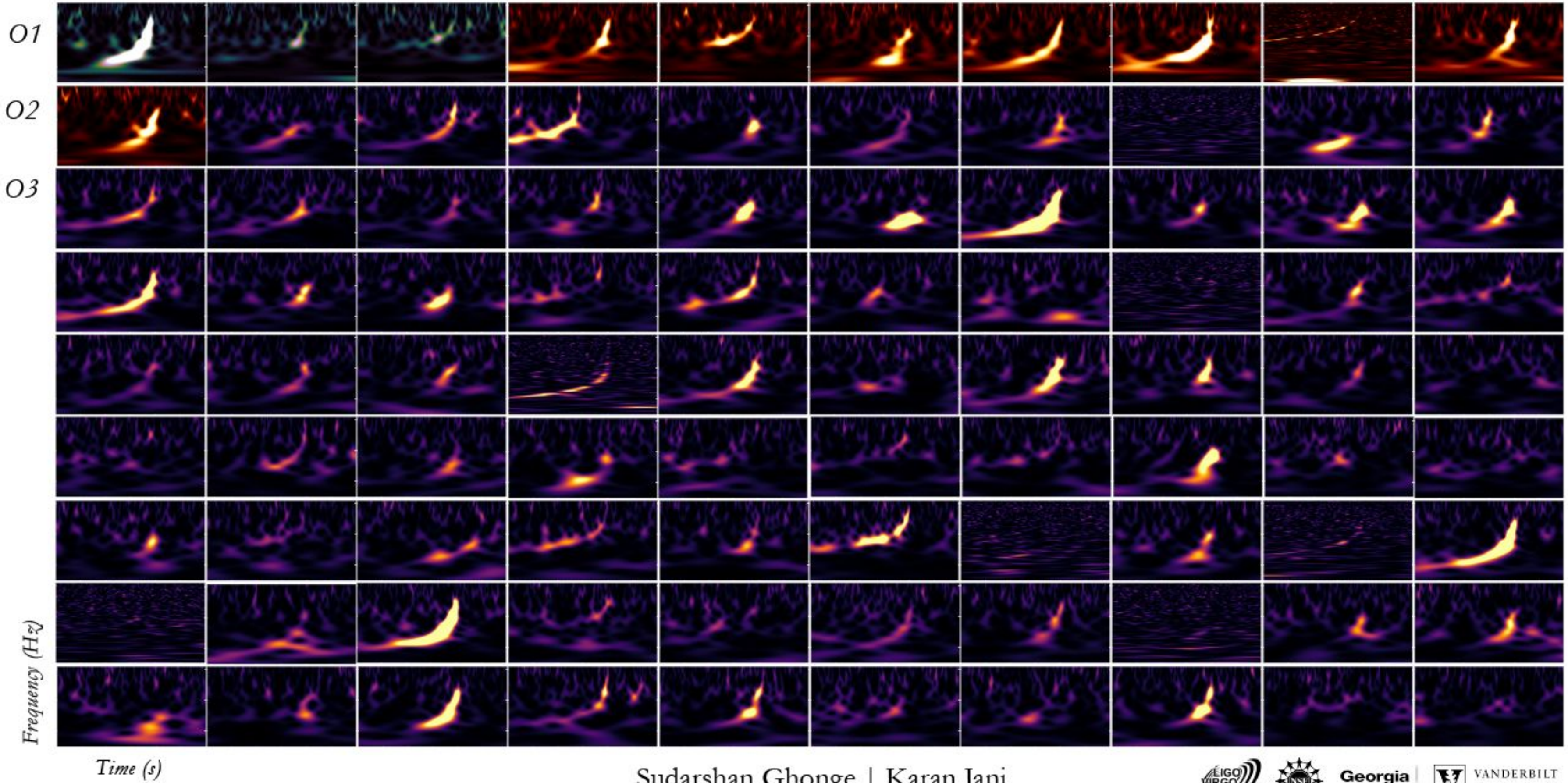
Measuring signal properties





Gravitational-Wave Transient Catalog

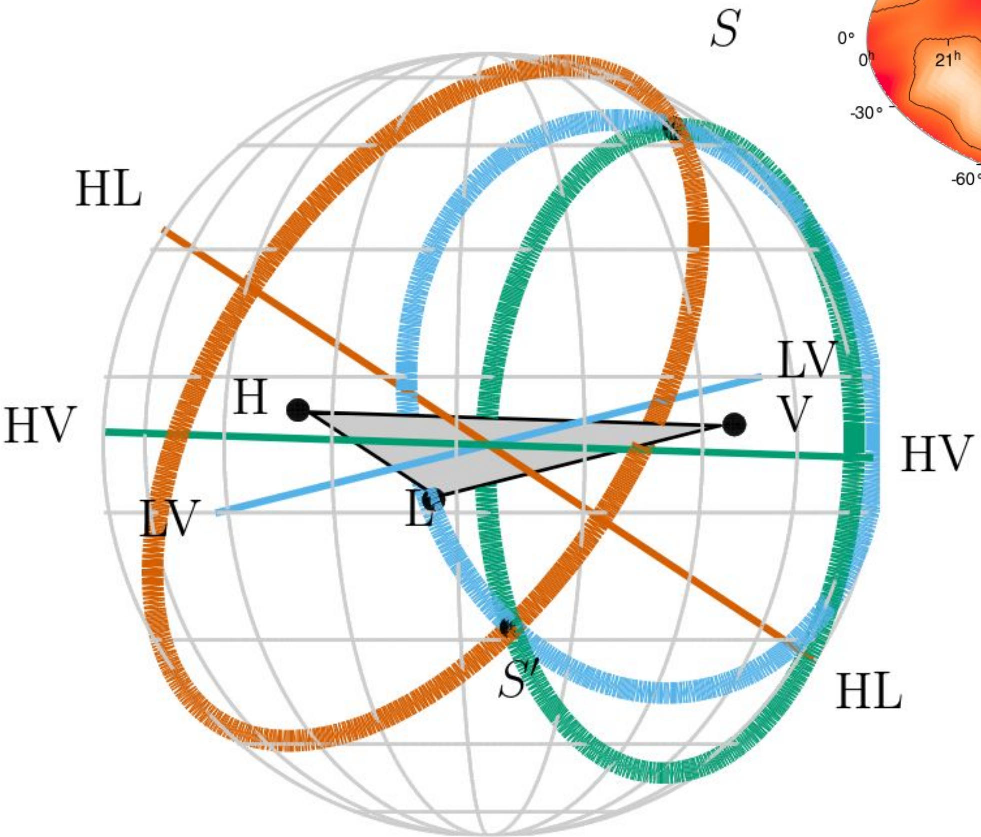
Detections from 2015-2020 of compact binaries with black holes & neutron stars



Sudarshan Ghonge | Karan Jani

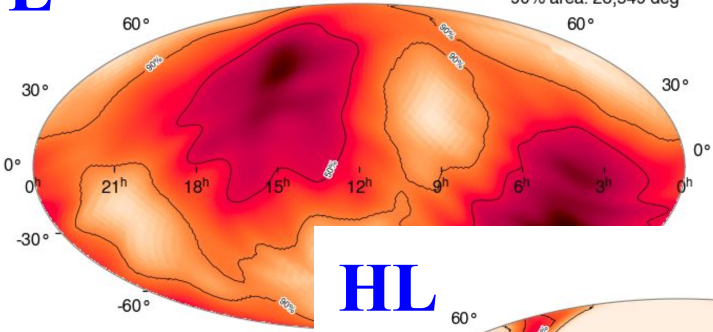
LIGO VIRGO KAGRA | NSF | Georgia Tech | VANDERBILT UNIVERSITY

Triangulation

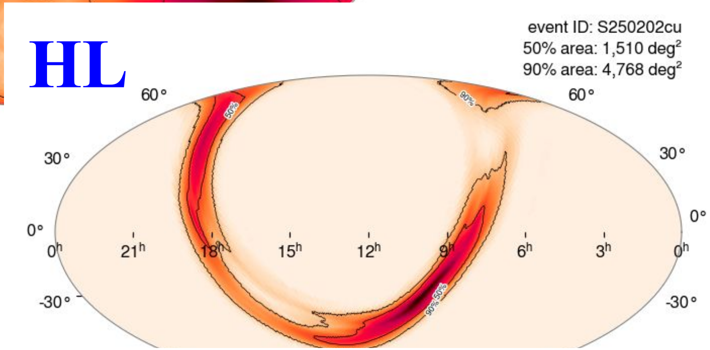


Credit: Abbott+, 2021

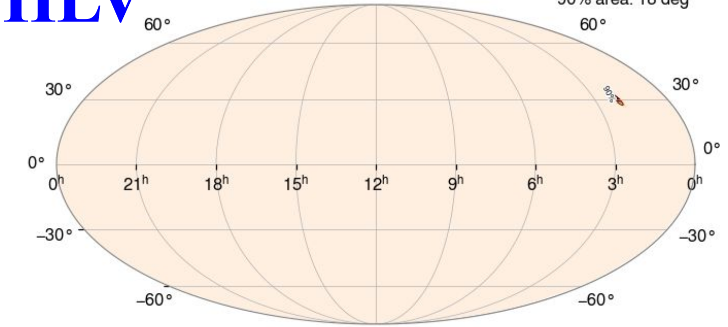
L



HL

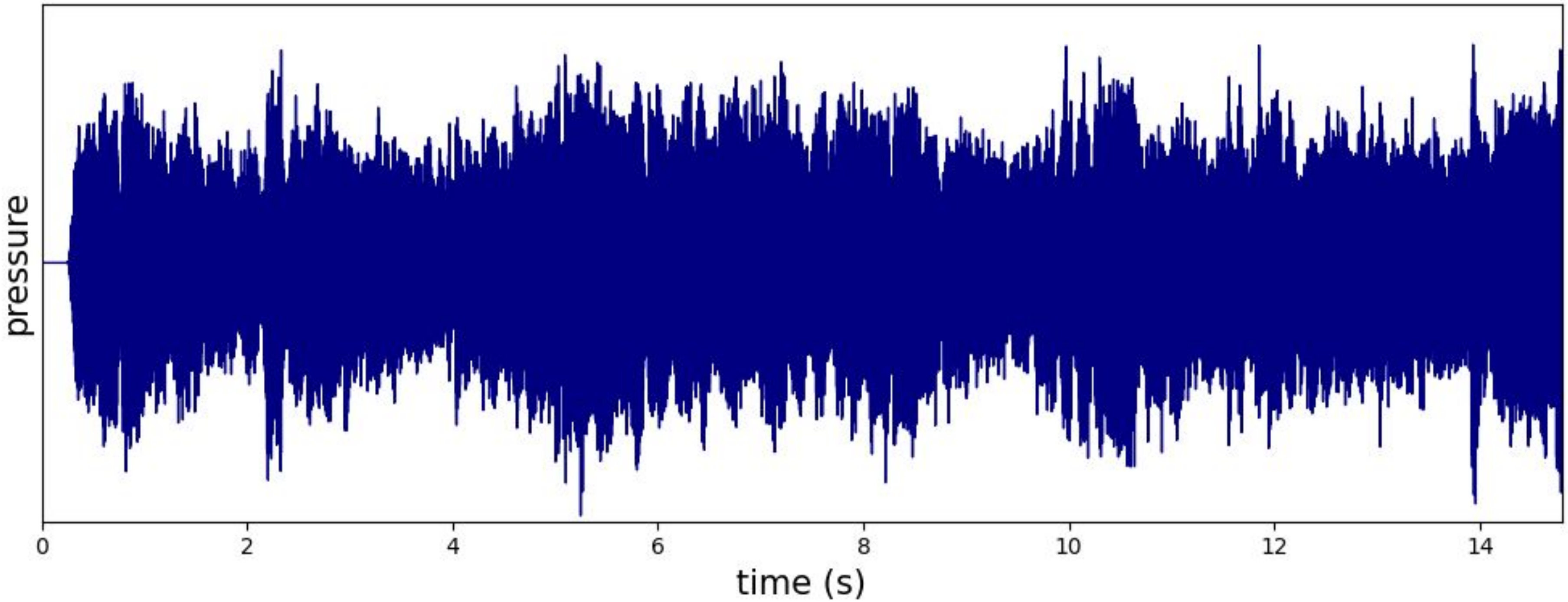


HLV

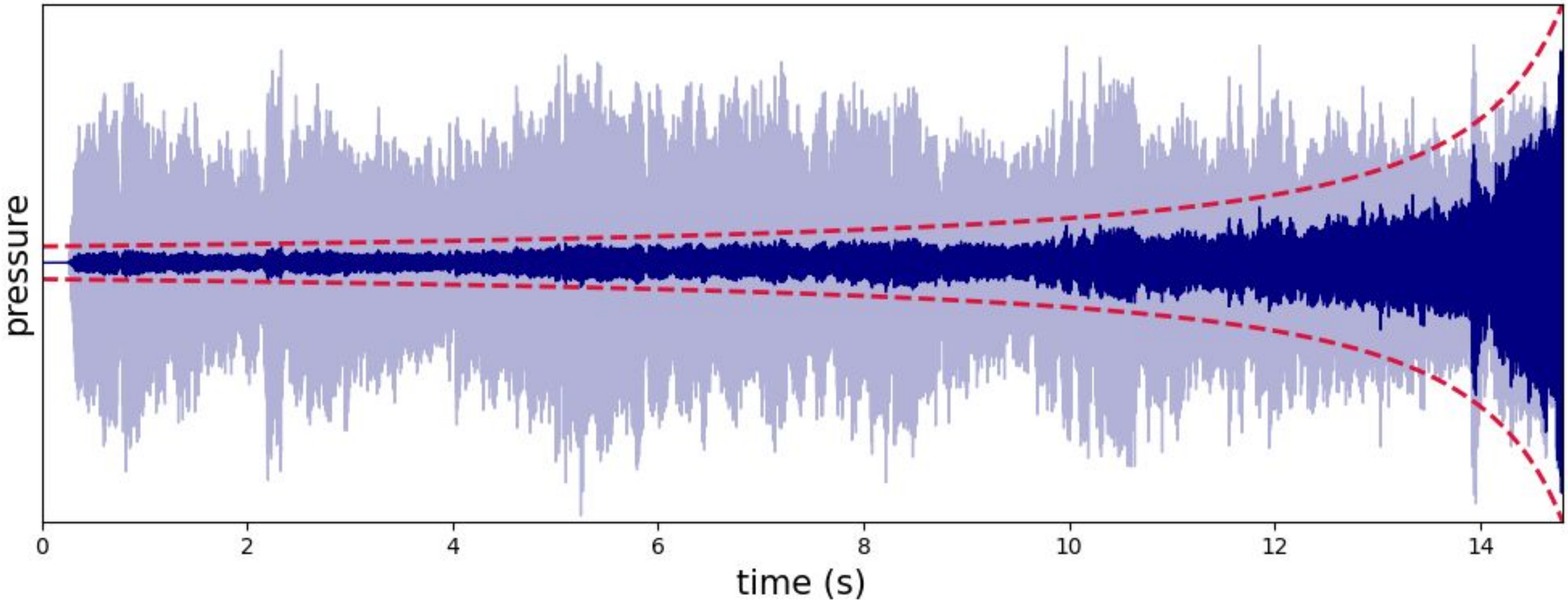


Credit: gracedb

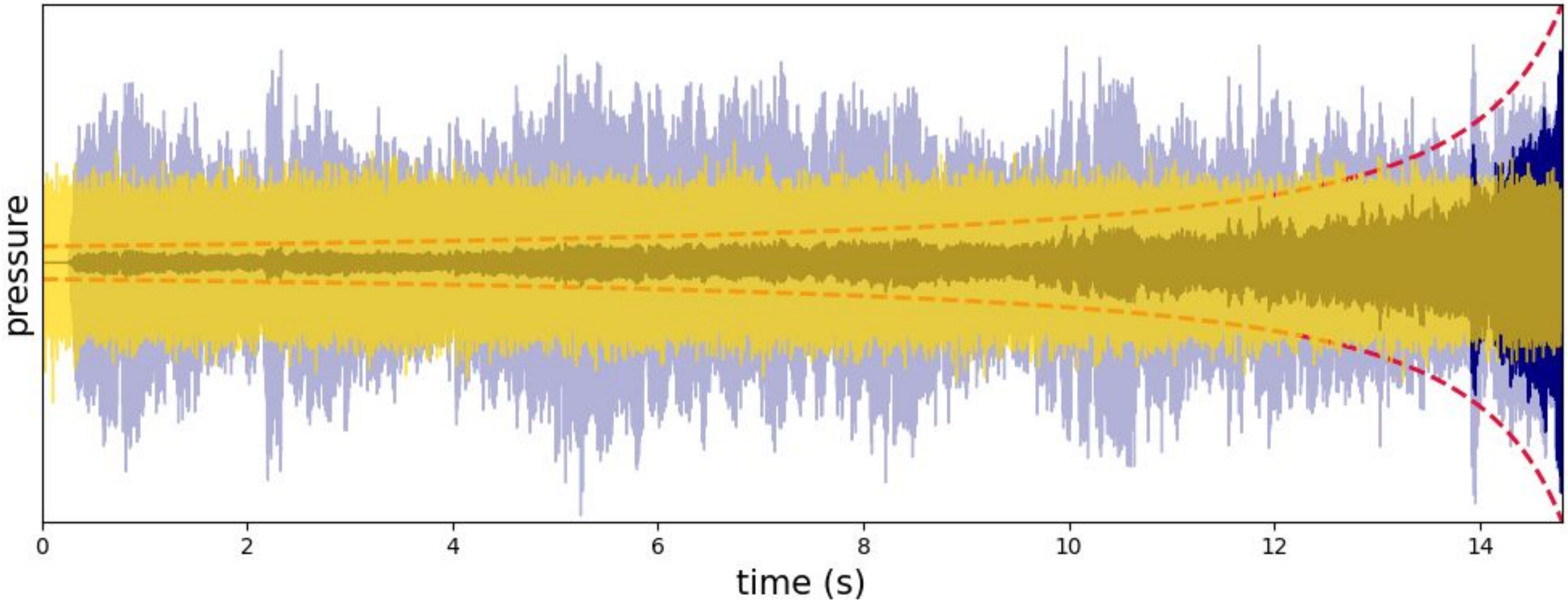
Messing with a song



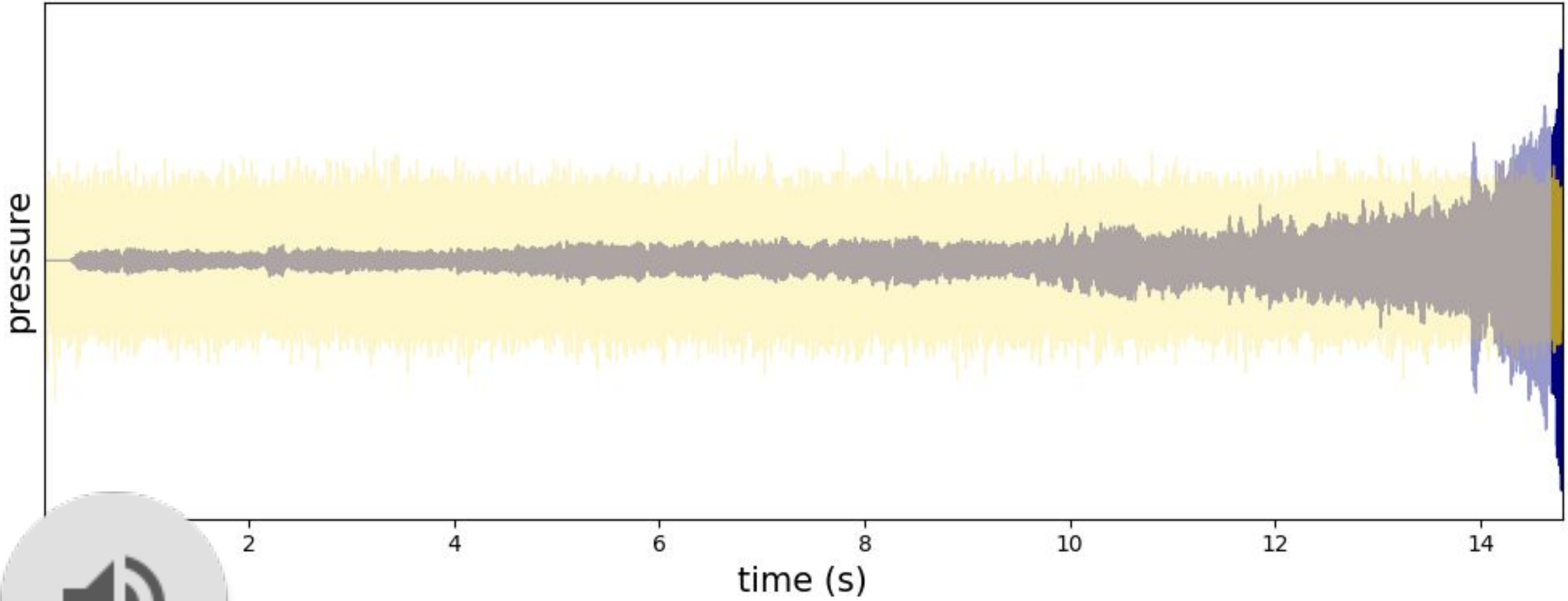
Messing with a song



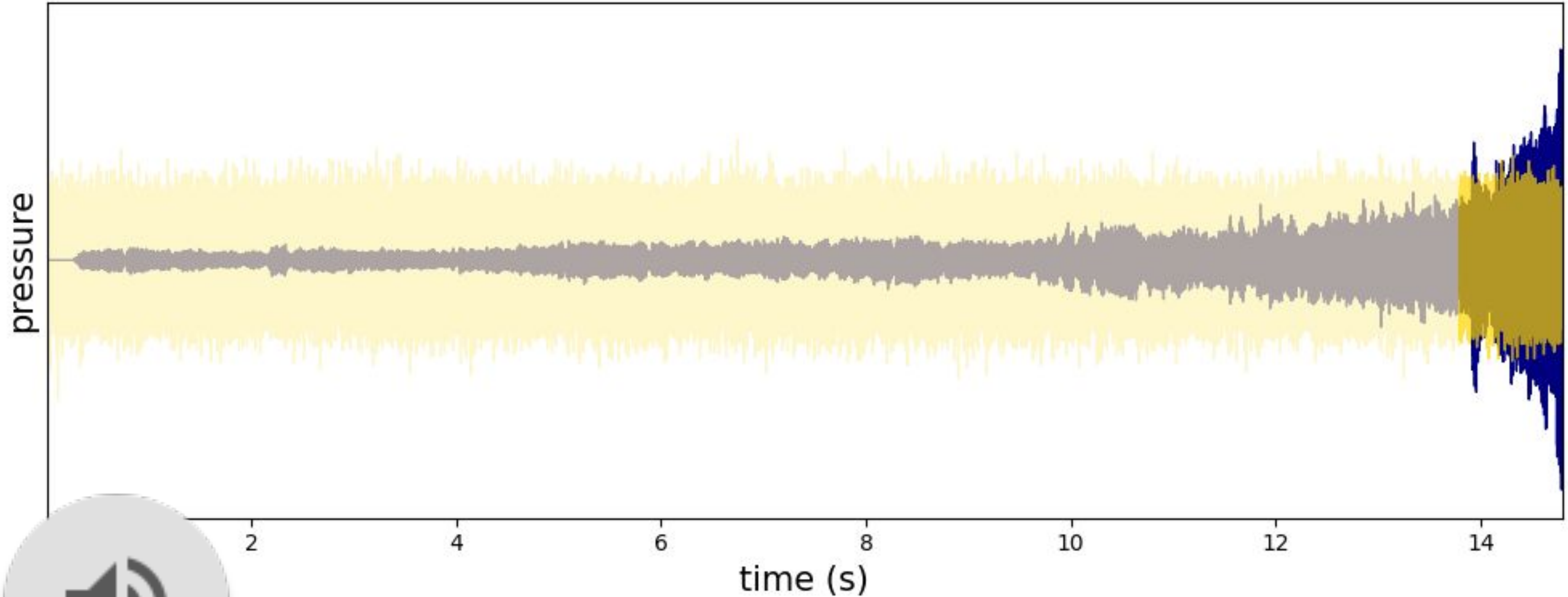
Messing with a song



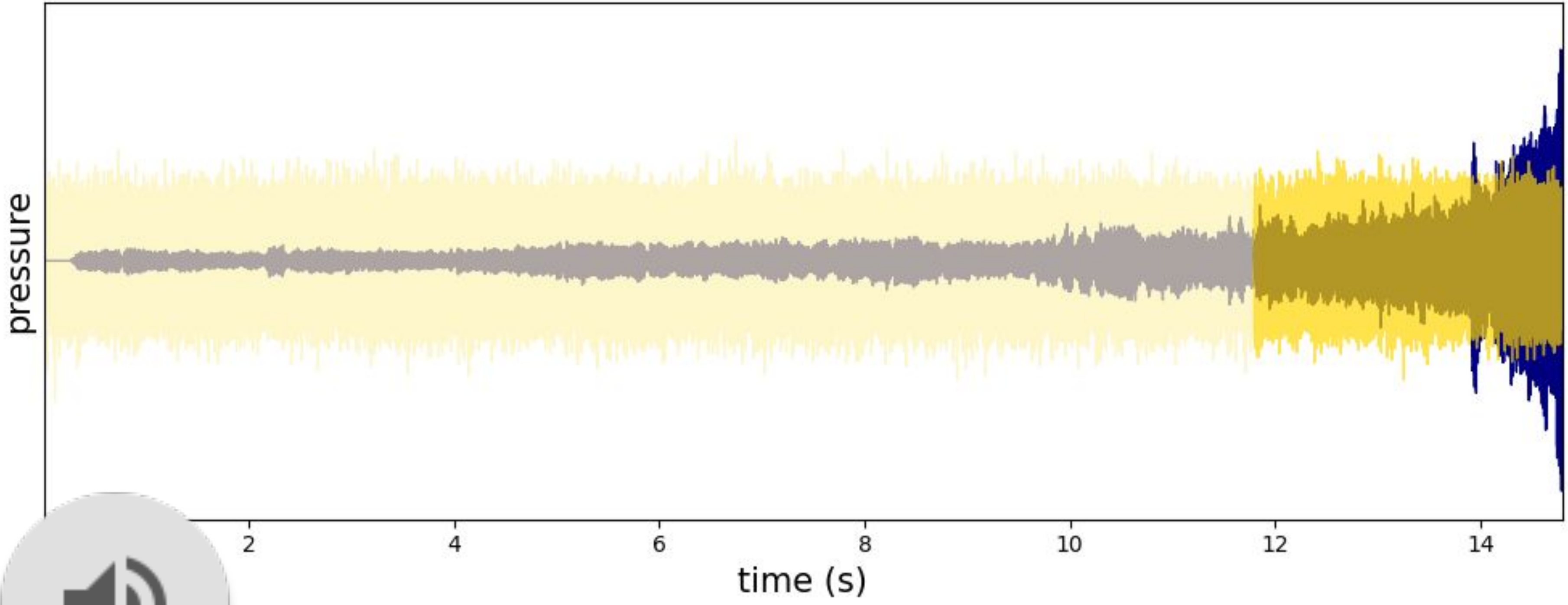
Identify the song: loudest 0.1s



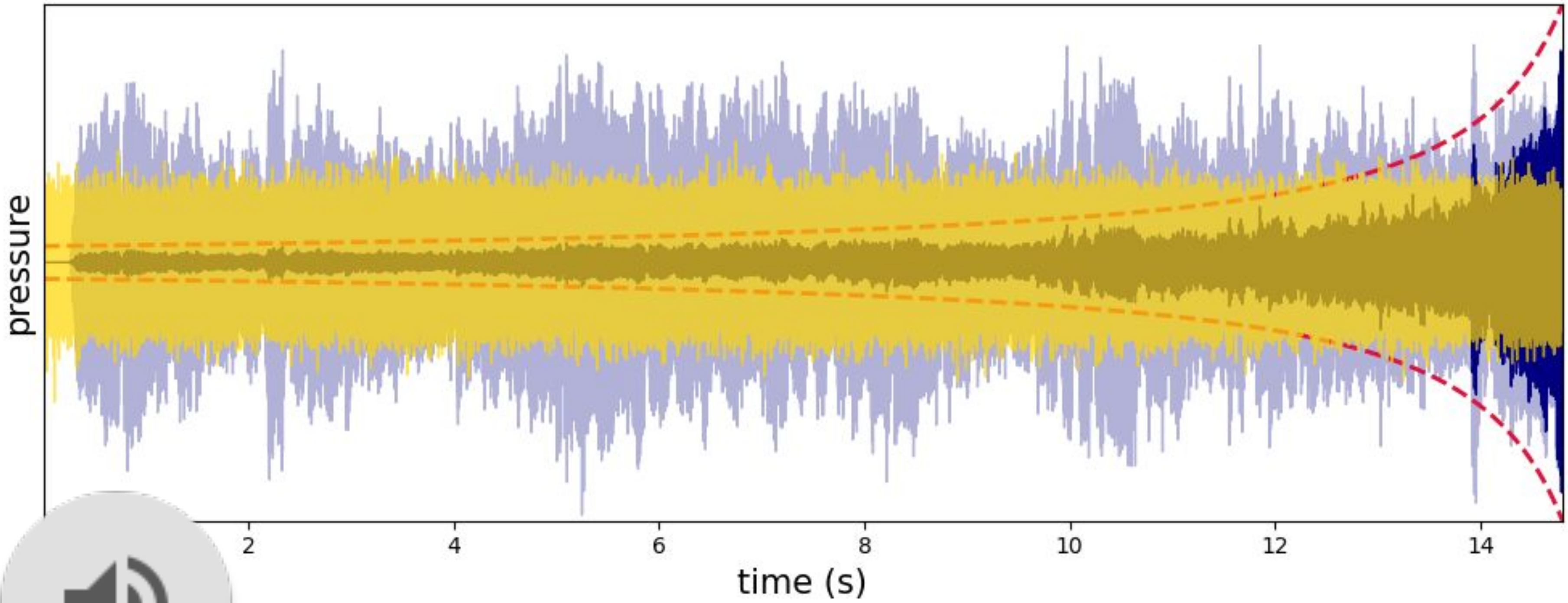
Identify the song: loud 1s



Identify the song: last 3s



Identify the song: full



Matched filtering

- A high amplitude isn't everything!
- What matters more is the accumulated phase above noise