Title: Gravitational Waves Experiments

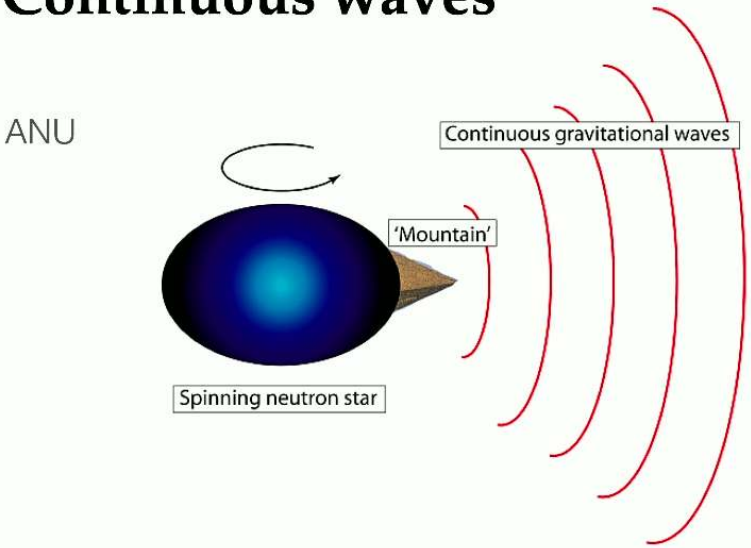
Speakers: Jess McIver

Collection: TRISEP 2023

Date: June 23, 2023 - 2:30 PM

URL: https://pirsa.org/23060062

Continuous waves



$$h \sim \frac{G f_{GW}^2}{c^4 r} \epsilon$$

On the order of 10^{-24} for a galactic source

$$\epsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$$

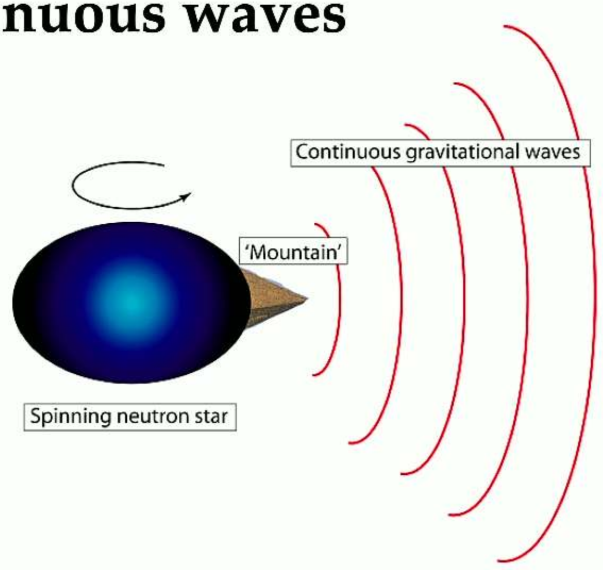
Equatorial ellipticity

Thought exercises…

Why is equatorial ellipticity required for GW generation?

Continuous waves

ANU

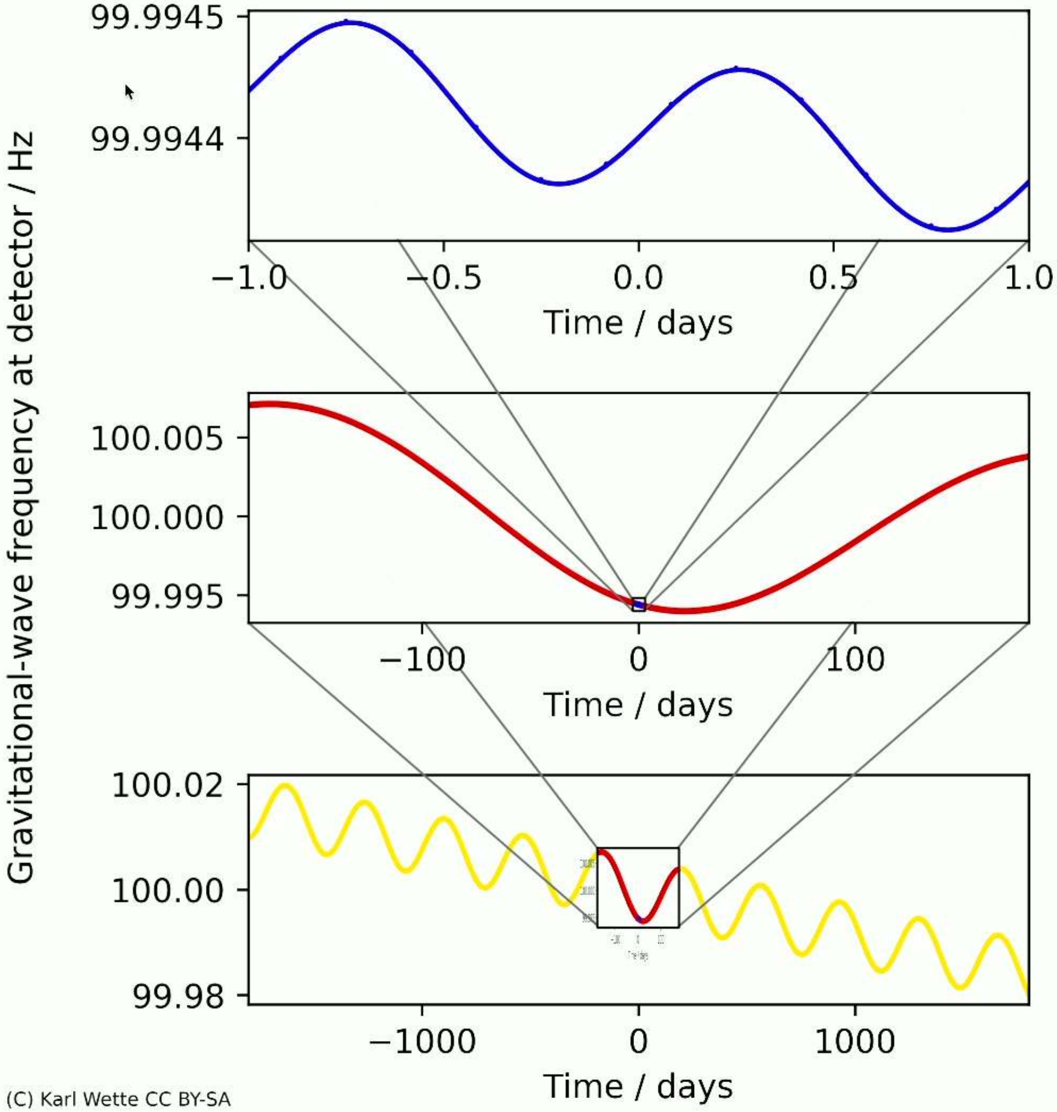


$$h \sim \frac{G f_{GW}^2}{c^4 r}\epsilon$$

On the order of 10^{-24} for a galactic source

$$\epsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$$

Equatorial ellipticity



When does a GW "end"?

CBCs

- CBC orbits will spiral inward, increasing in frequency until merger
- This is often called a "chirp"
- We can estimate the merger frequency as roughly the frequency of the **last stable orbit**, described by:

$$f_{LSO} \sim 220 \, \frac{20 \, M_{\odot}}{M} \, \text{Hz}$$

CWs

- Will spin down as the source loses angular momentum over time
- Will steadily *decrease* in frequency
- We can estimate this time scale with a strategy similar to "cool down" time for radiation:

$$t_{spindown} = \frac{E_K}{L_{GW}}$$

Core-collapse supernovae

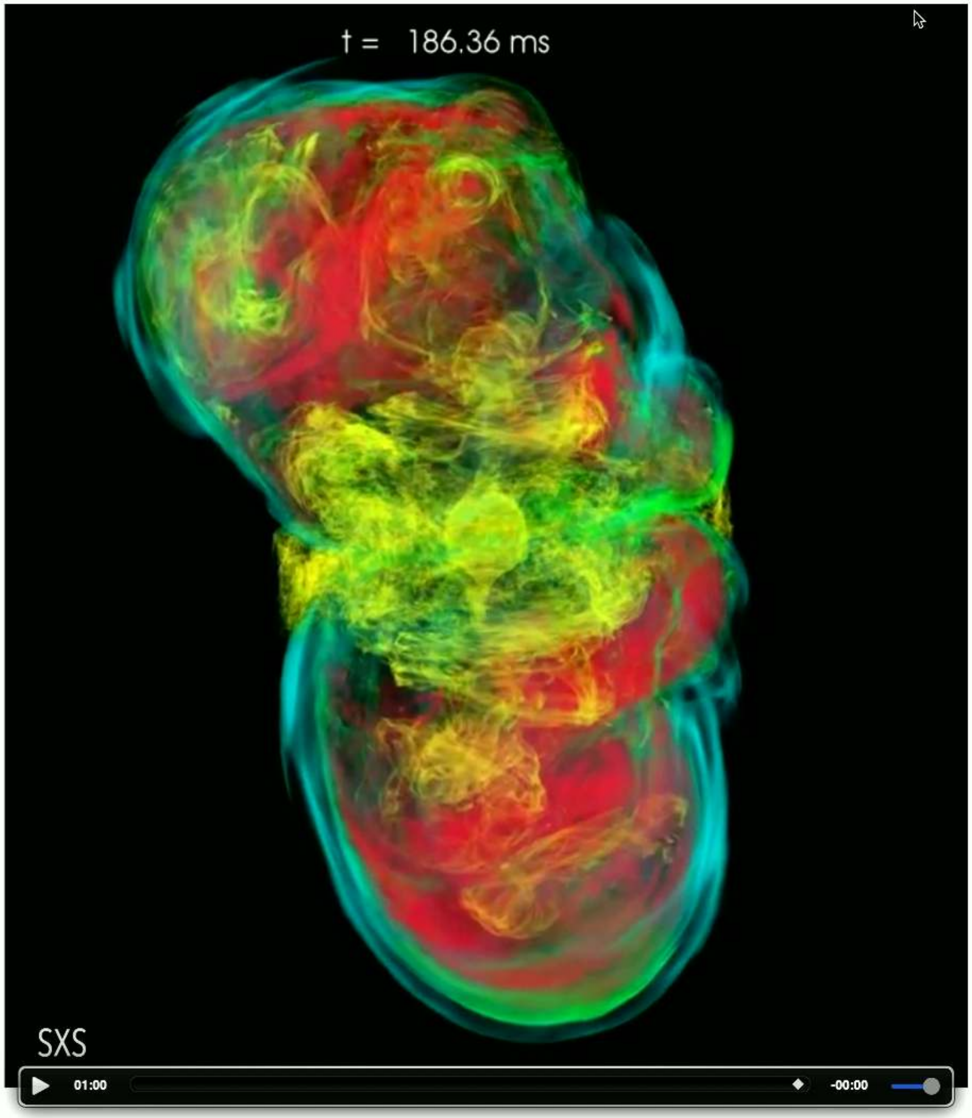
We can leverage the "burst equation":

$$h \approx 10^{-21}\left[\frac{E_{gw}}{0.01M_{\odot}c^2}\right]^{1/2}\left[\frac{r}{20\mathrm{Mpc}}\right]^{-1}\left[\frac{f}{1\mathrm{kHz}}\right]^{-1}\left[\frac{\tau}{1\mathrm{ms}}\right]^{-1/2}$$

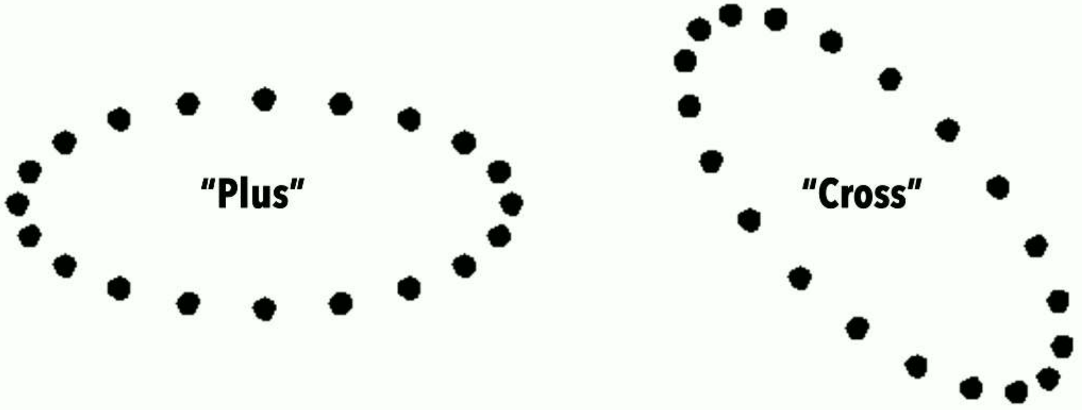
CCSNe emit most of their energy in neutrinos, and a small fraction ($\sim 0.1\,\%$) in GWs from asymmetrically accelerating mass.

Type 1a supernovae are not promising GW sources; generally much less accelerating mass.

See Sathyaprakesh and Schutz's Living Review in Relativity

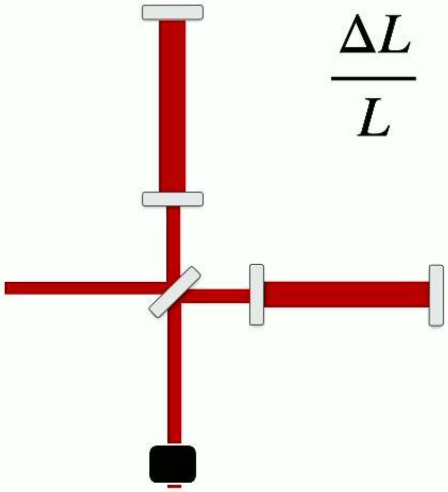


Gravitational wave propagation



Wikimedia

Measured spacetime strain h(t):

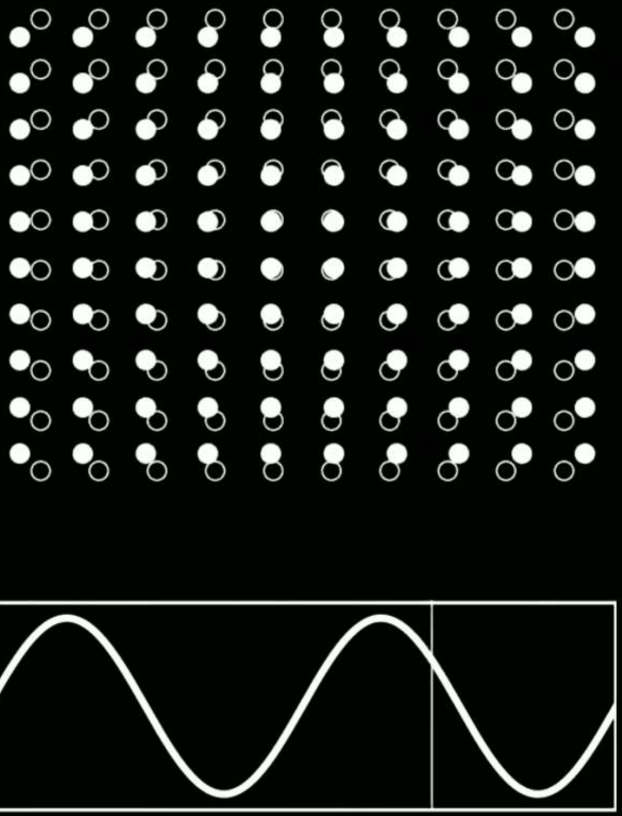


$$\frac{\Delta L}{L}$$

Intro to GW interferometers

Induced
spacetime
strain h(t)

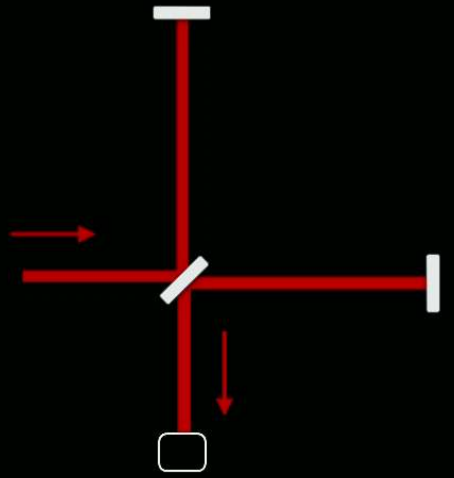
$$h_{ij}(t) \propto \frac{G}{c^4 r}\frac{d^2 I_{ij}}{dt^2}$$



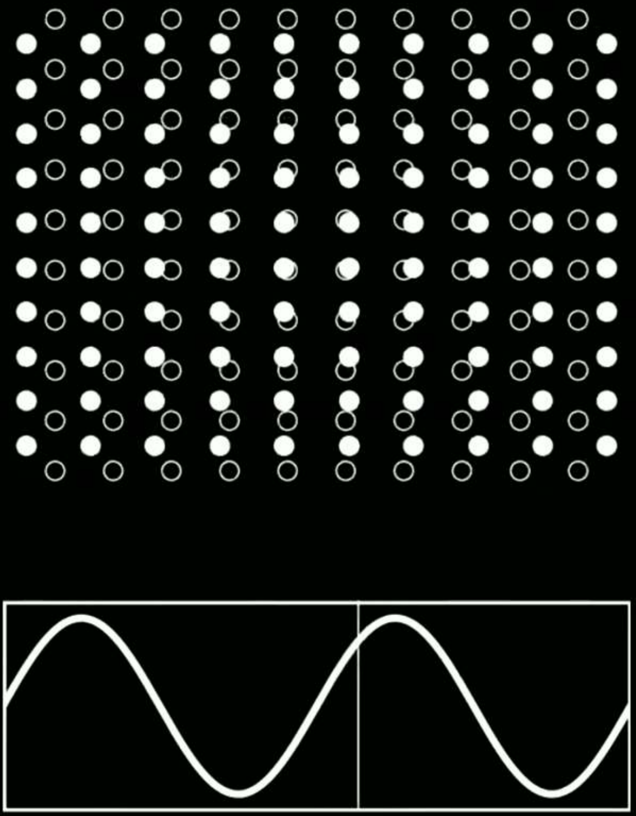
Movie: Carl Rodriguez

Measured
spacetime
strain h(t)

$$h(t) = \frac{\Delta L}{L}$$



How would you design a GW detector?



Induced spacetime strain h(t)

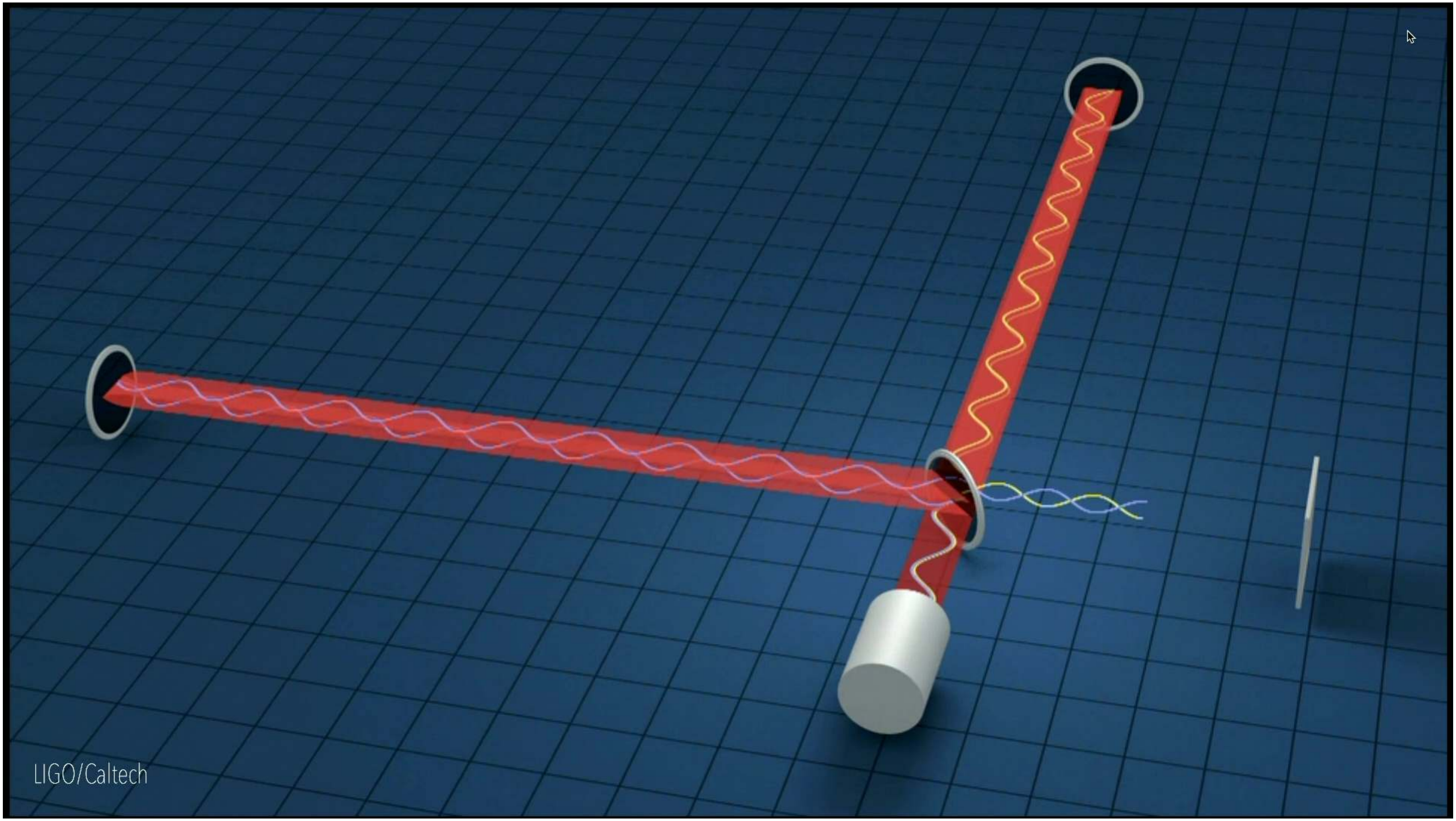
$$h_{ij}(t) \propto \frac{G}{c^4 r}\frac{d^2 I_{ij}}{dt^2}$$

Measured spacetime strain h(t)

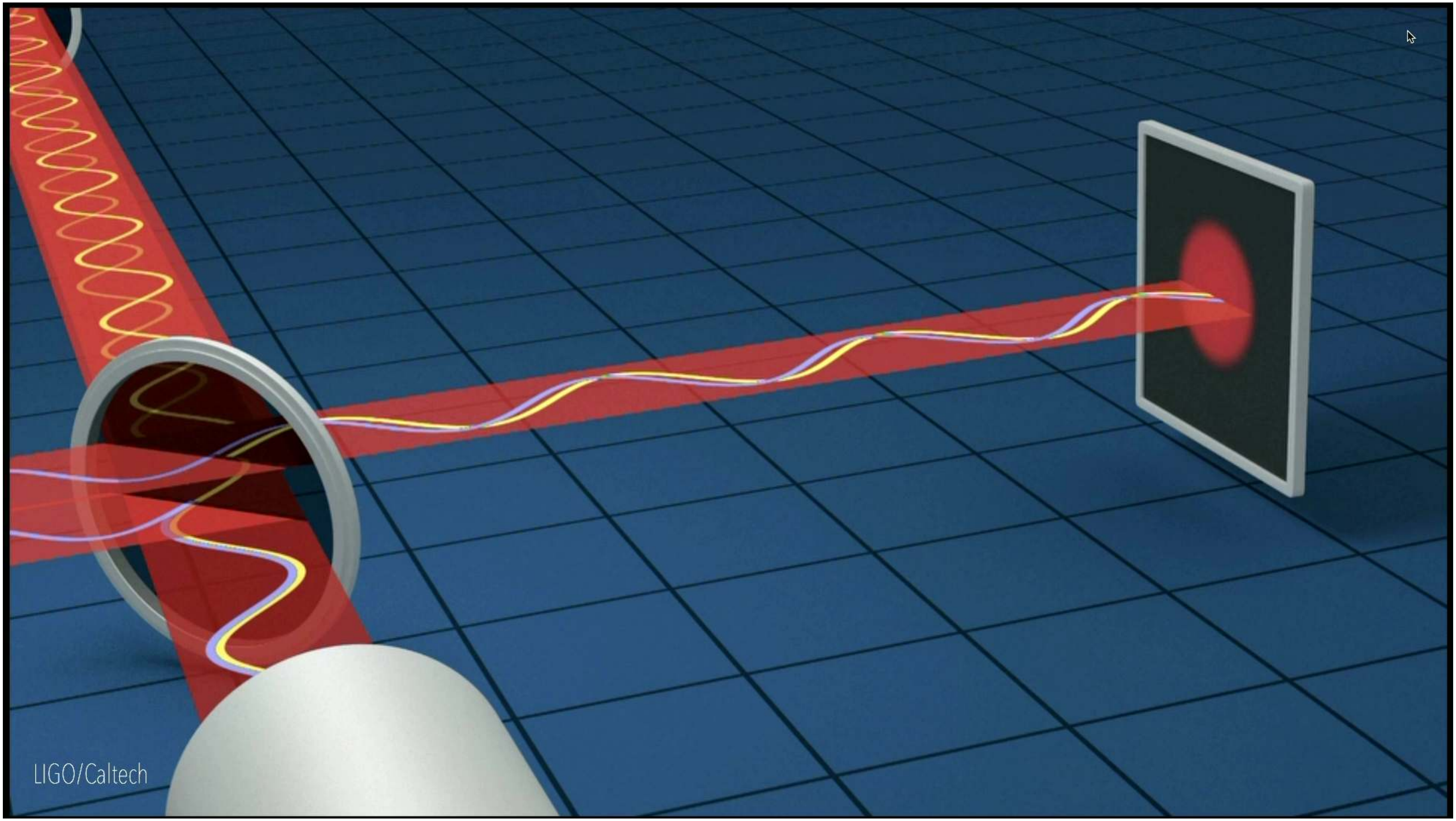
$$h(t) = \frac{\Delta L}{L}$$

How long do you want your arm length, L?

Movie: Carl Rodriguez

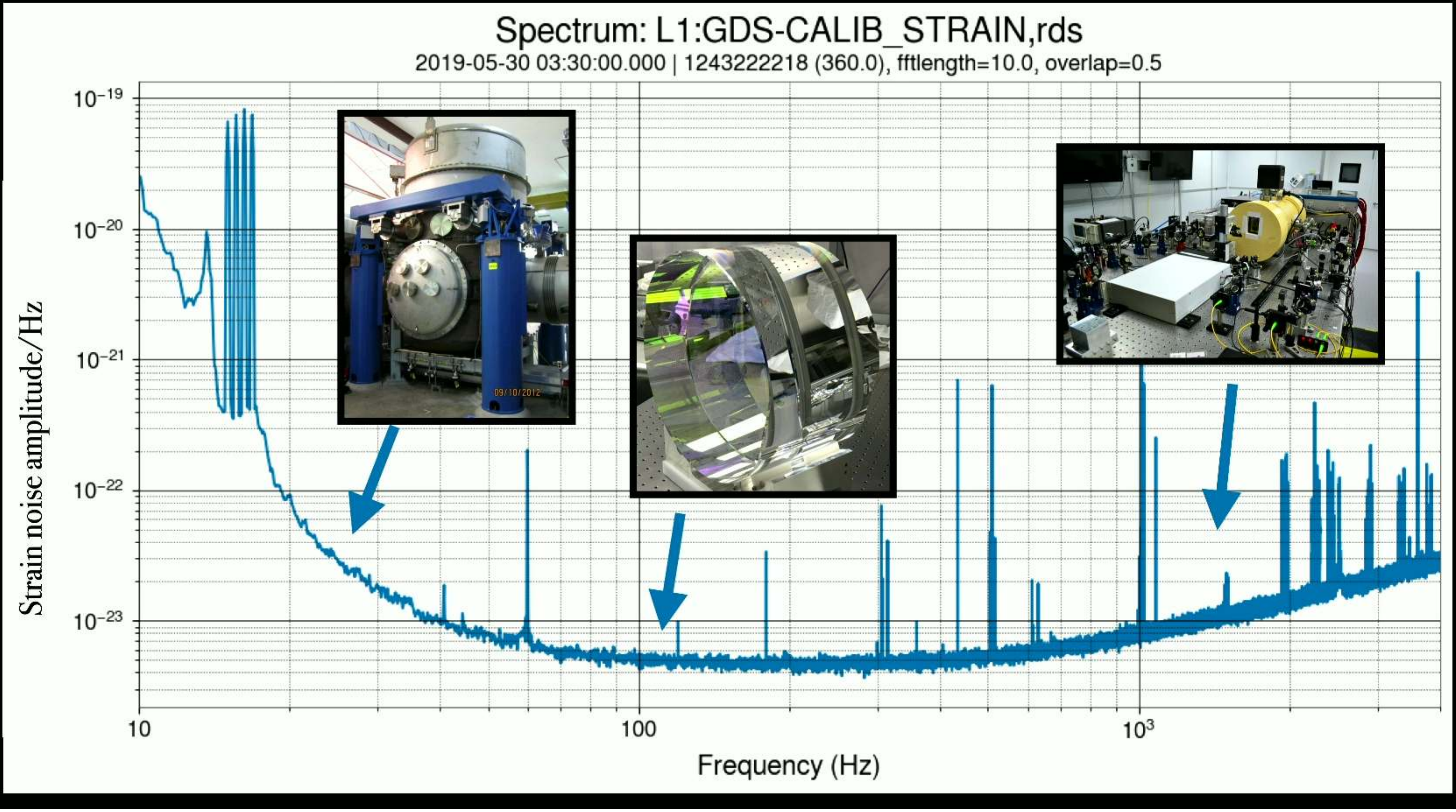


LIGO/Caltech

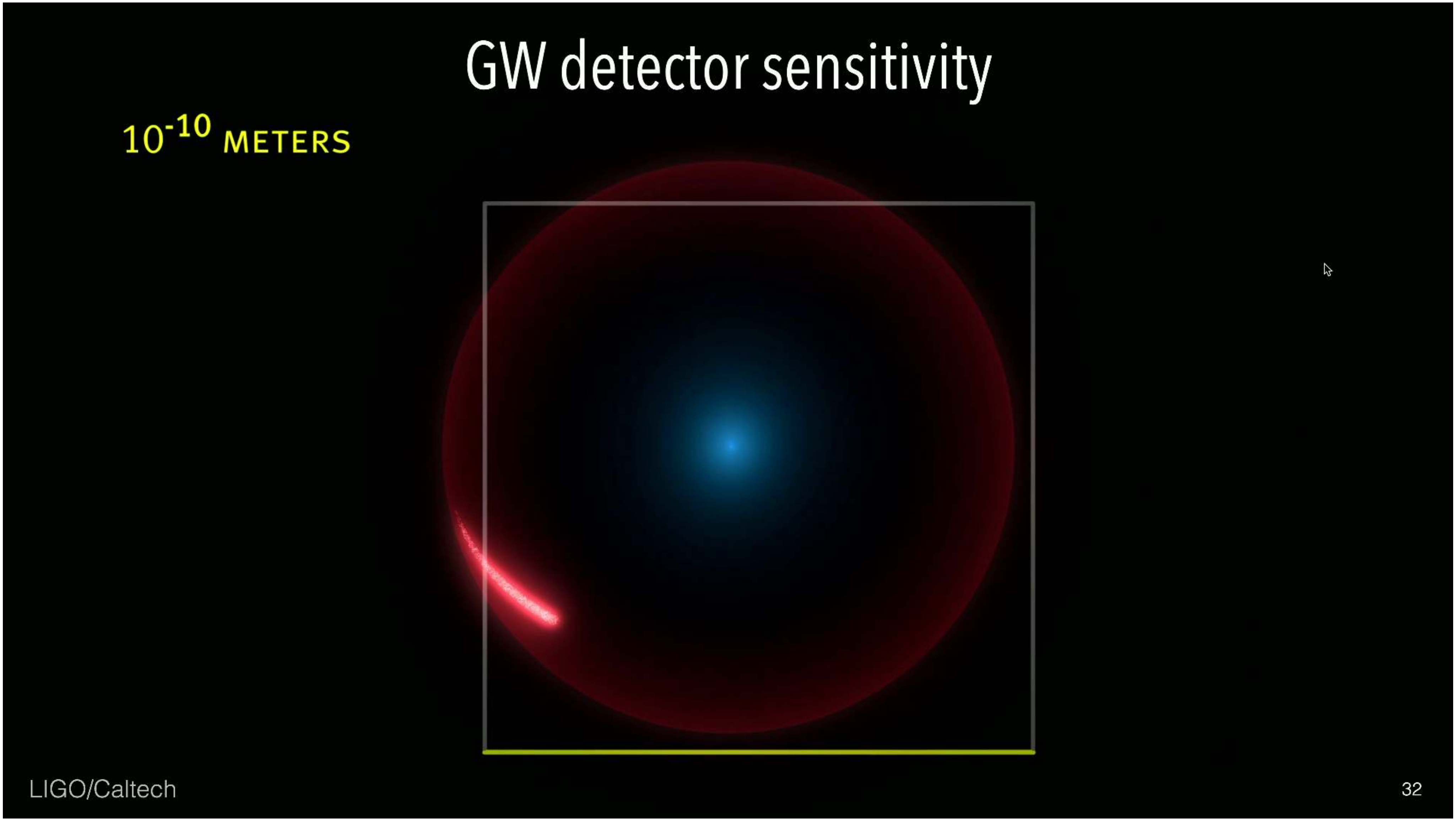

LIGO/Caltech


Kai Staa

Advanced LIGO noise

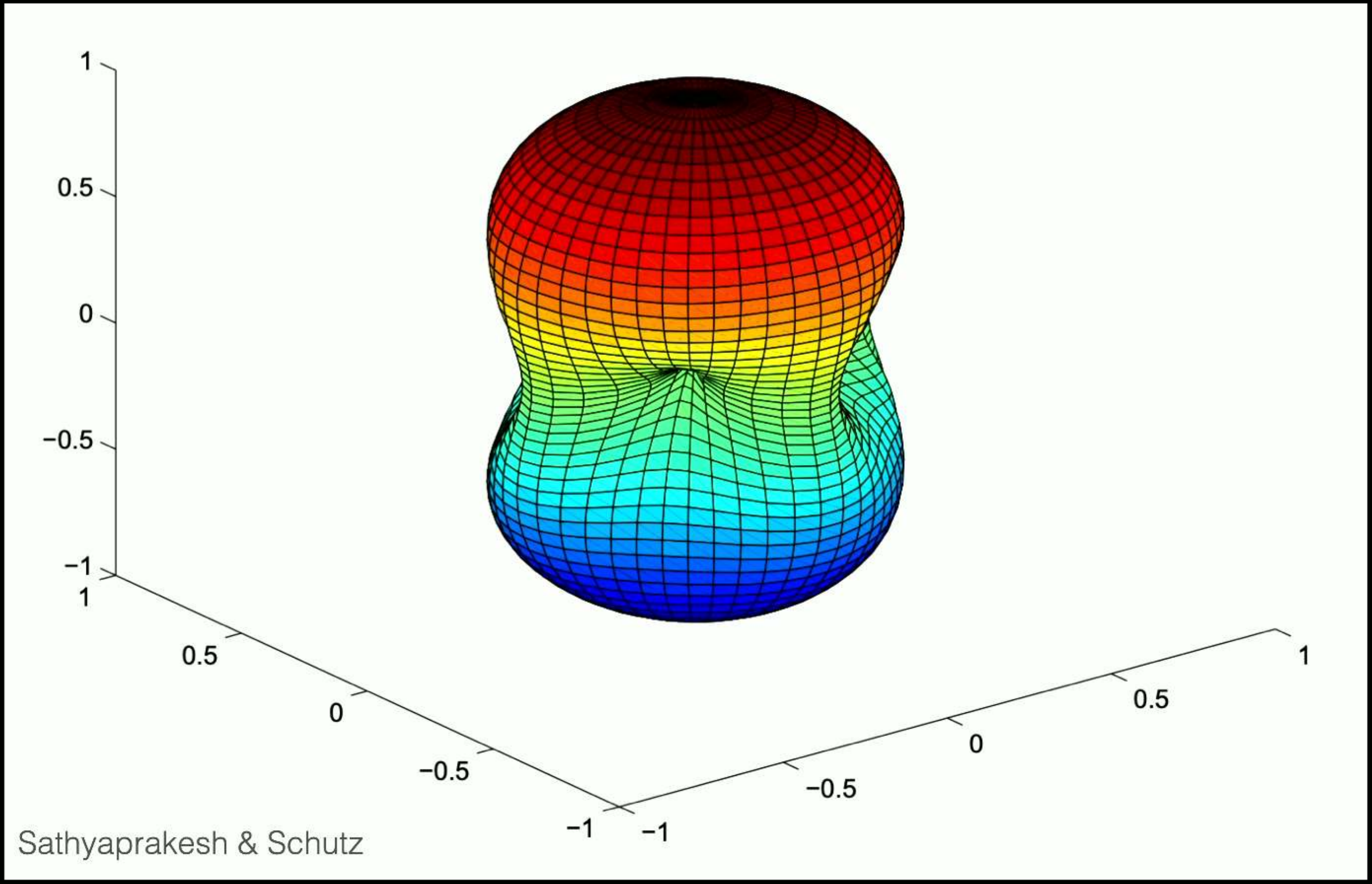


GW detector sensitivity

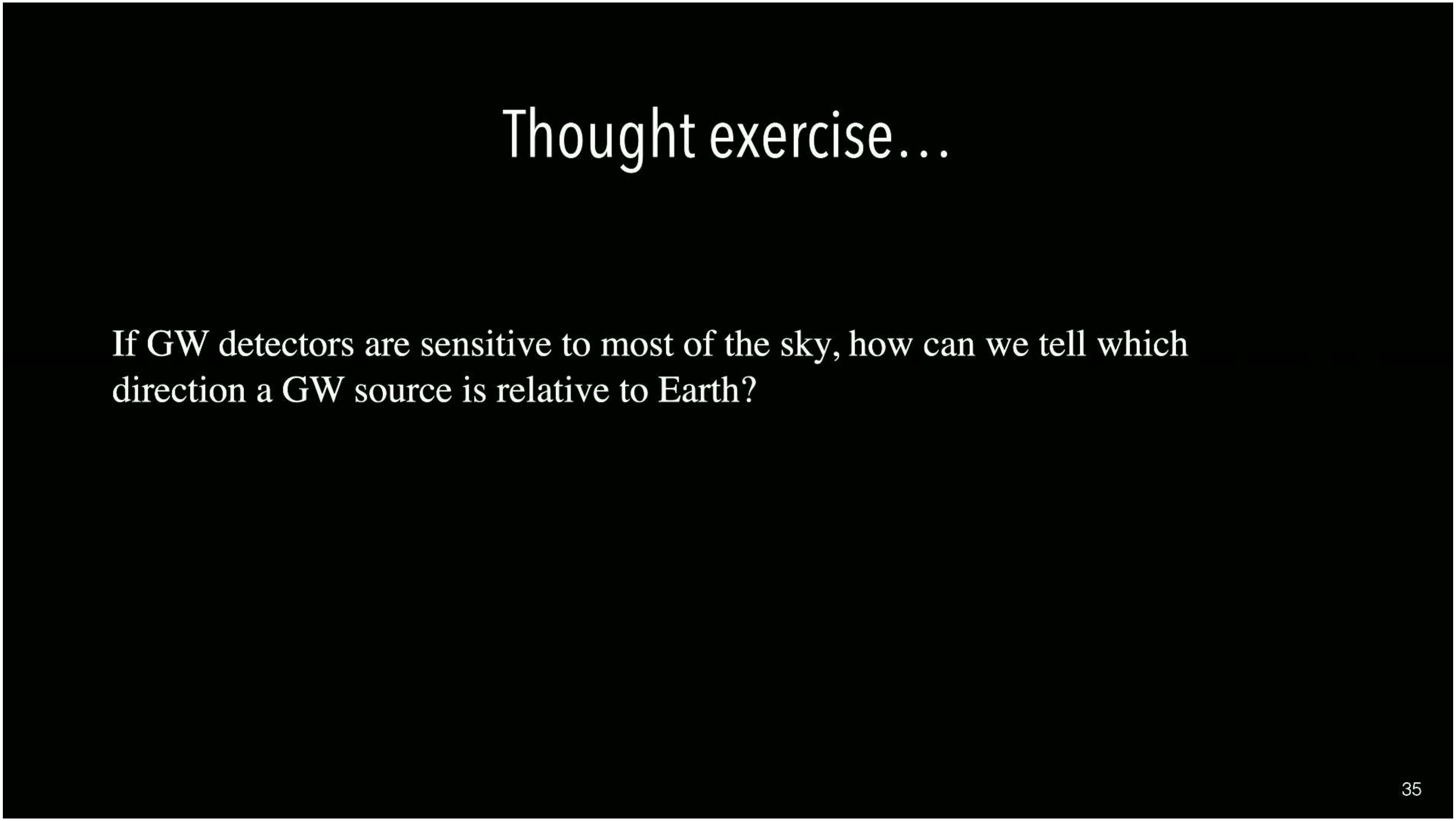


LIGO/Caltech

GW detector "antenna pattern"



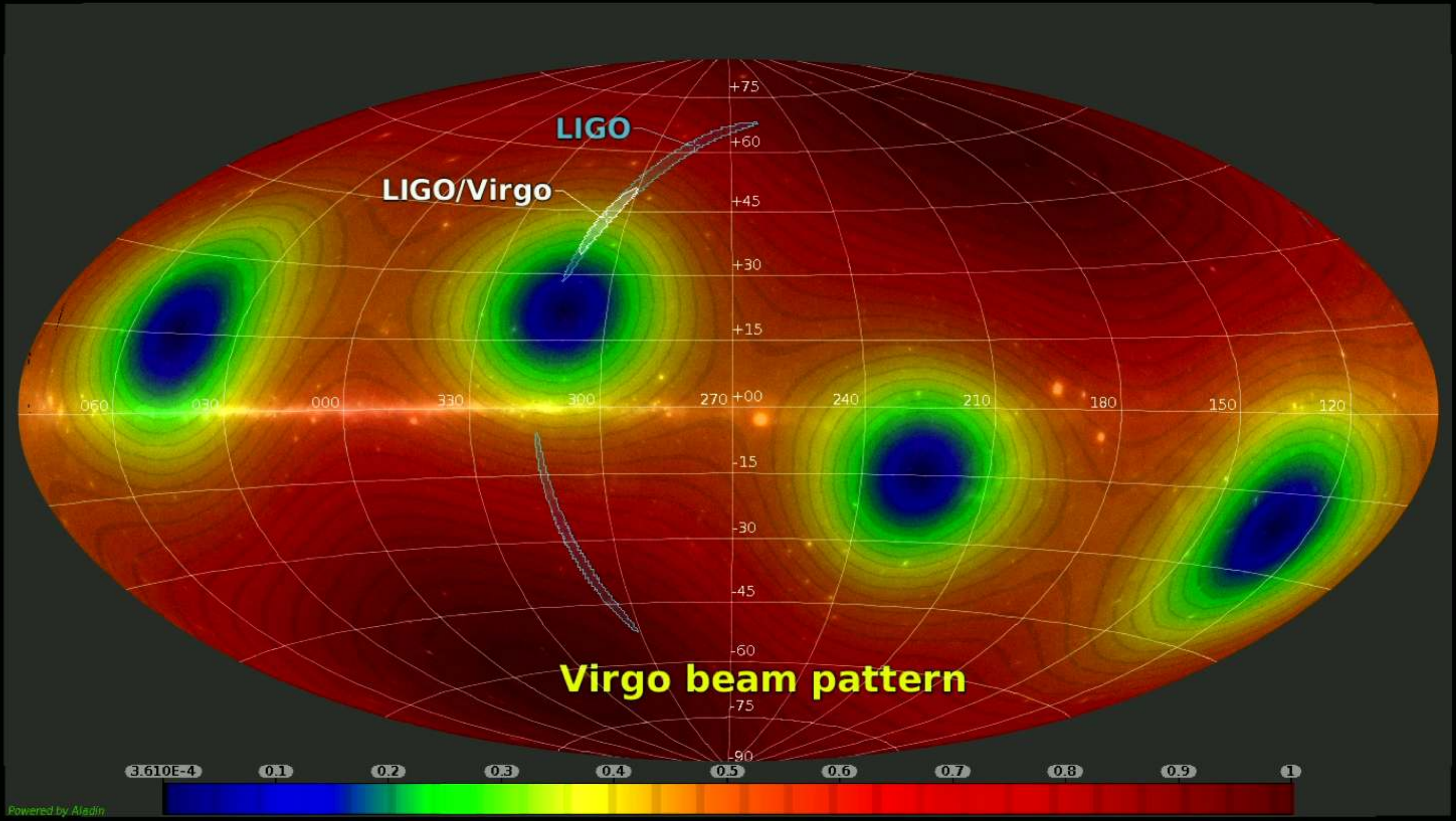
Sathyaprakesh & Schutz



Thought exercise…

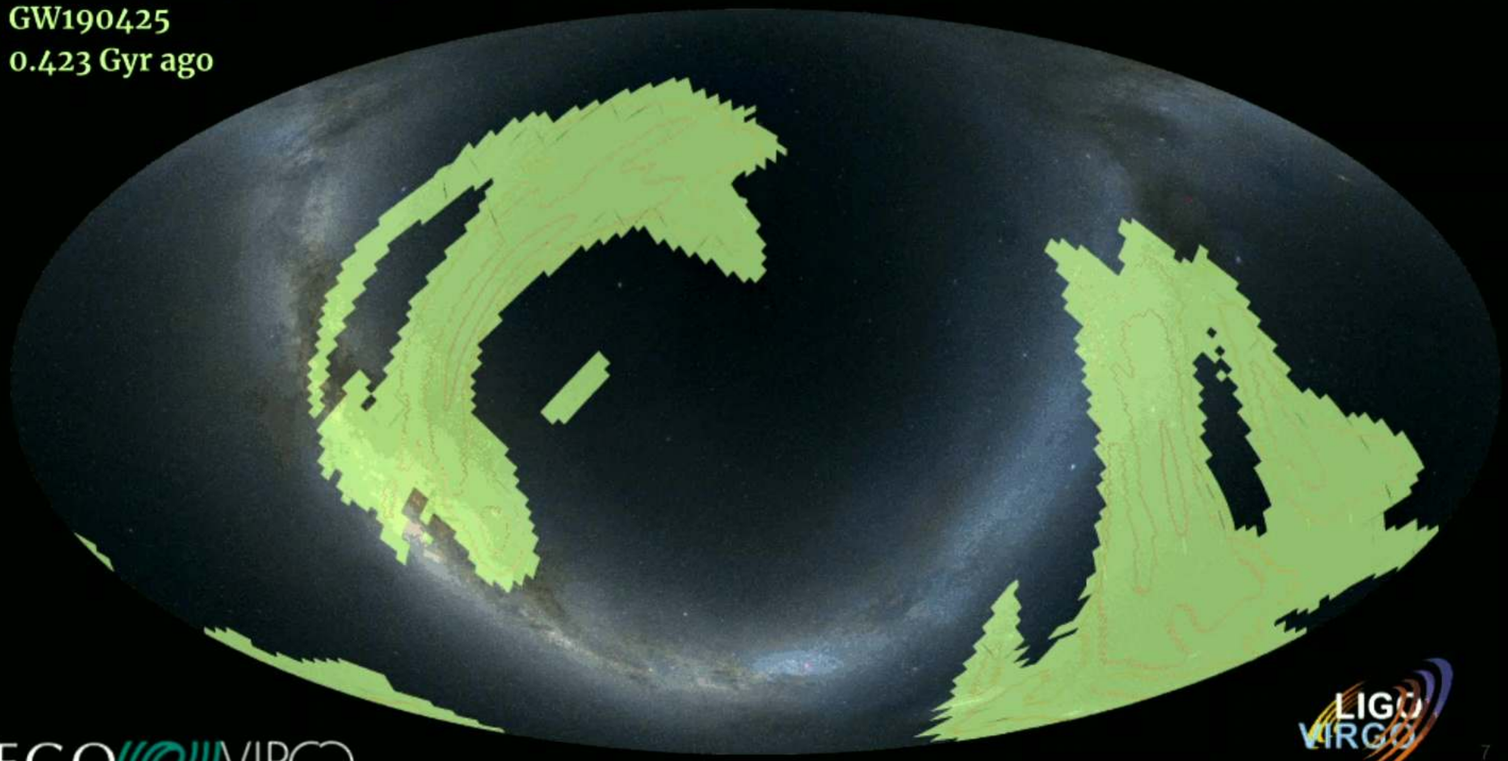
If GW detectors are sensitive to most of the sky, how can we tell which direction a GW source is relative to Earth?

Inferring sky location from antenna pattern



LIGO-Virgo/Greco, Arnaud, Vicerè

Typical GW sky localizations (examples from GWTC-2)

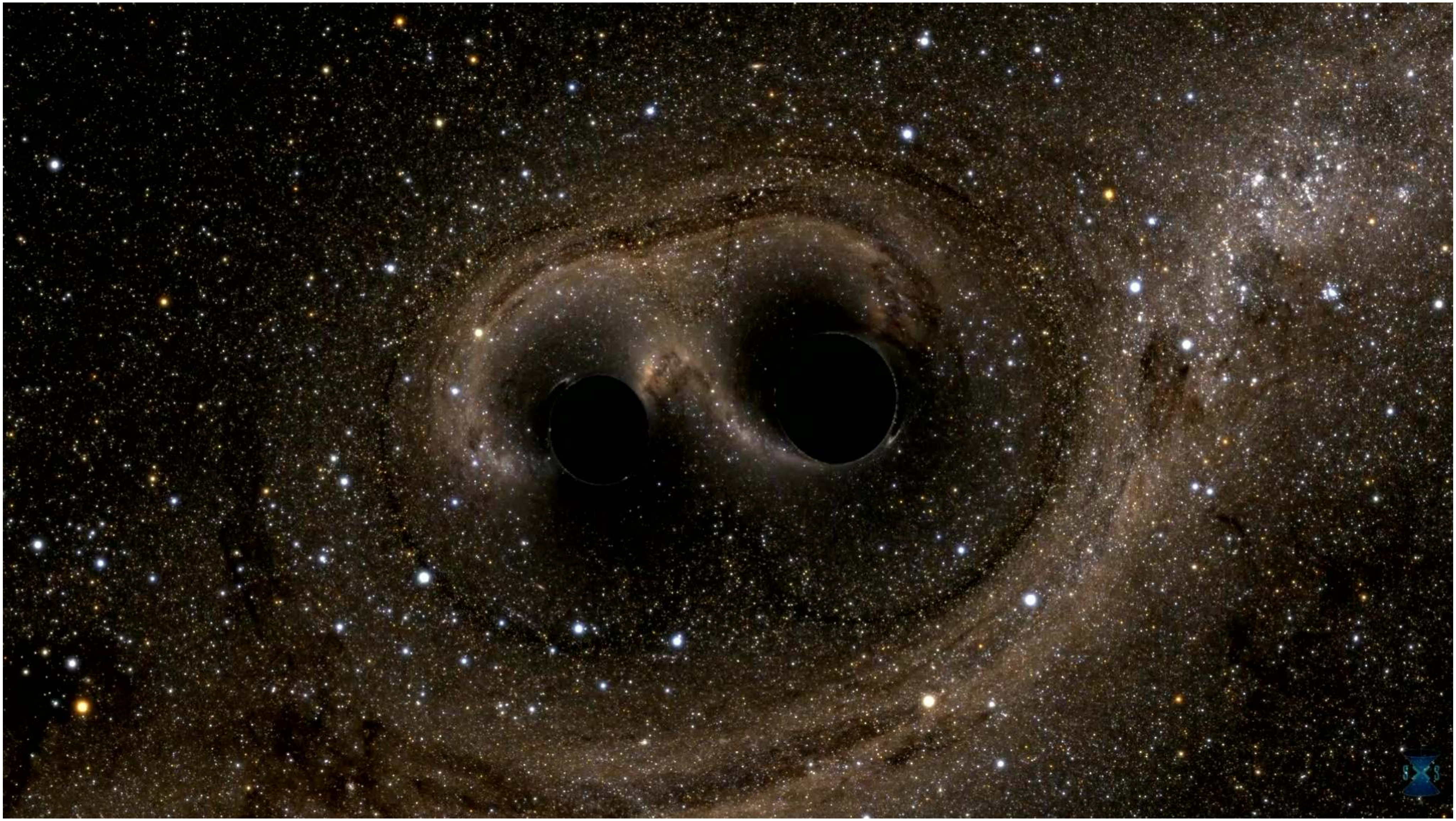


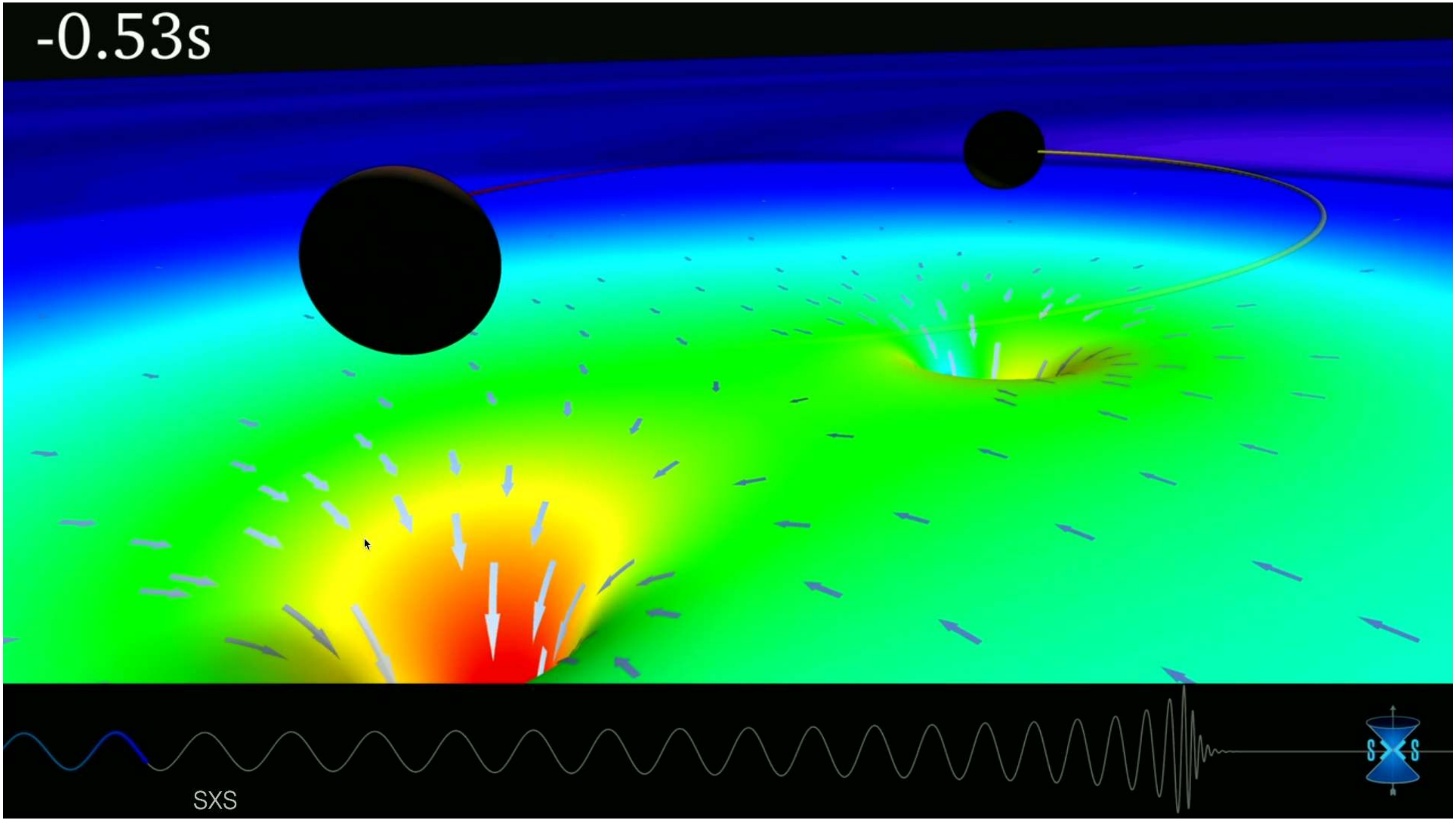
April 25, 2019 08:18:05 UTC
GW190425
0.423 Gyr ago

GWTC-2: Gravitational-Wave Transient Catalog - Sky Localizations


LIGO-Virgo

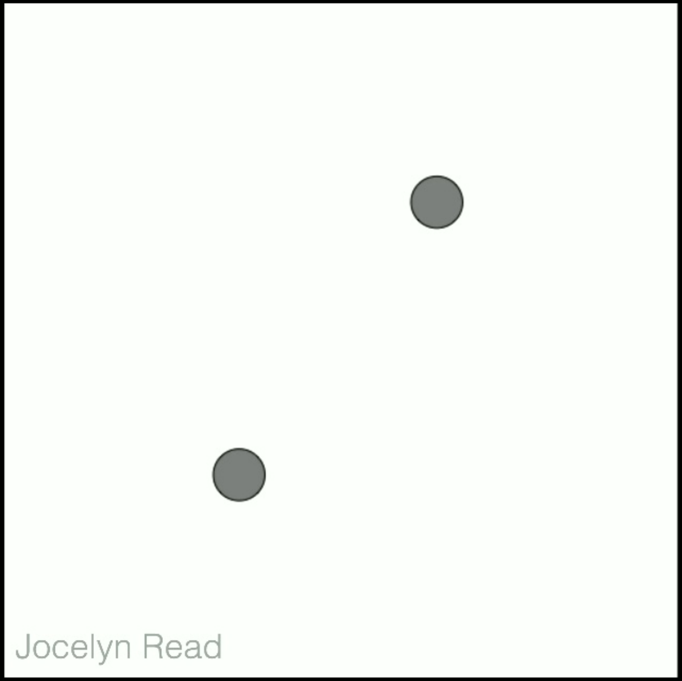
Let’s move!



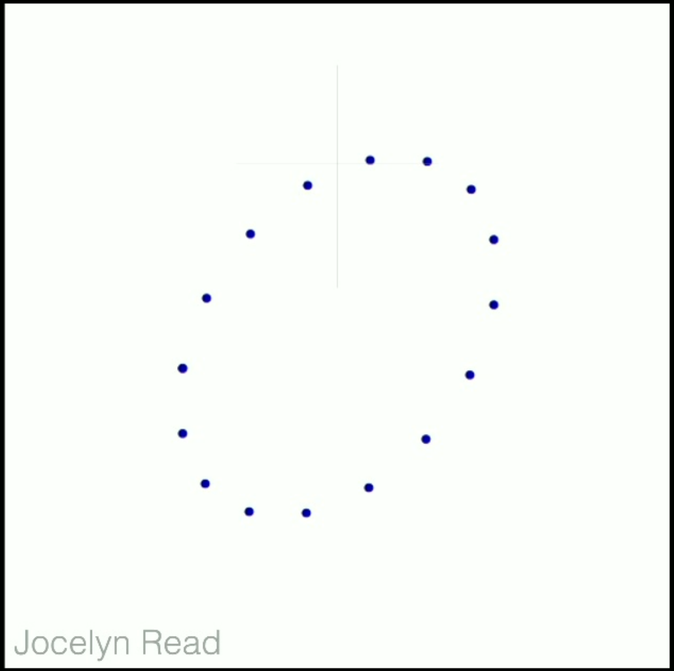

-0.53s
SXS

Compact binary sources

Massive objects orbit


Jocelyn Read

Spacetime response above orbital plane


Jocelyn Read

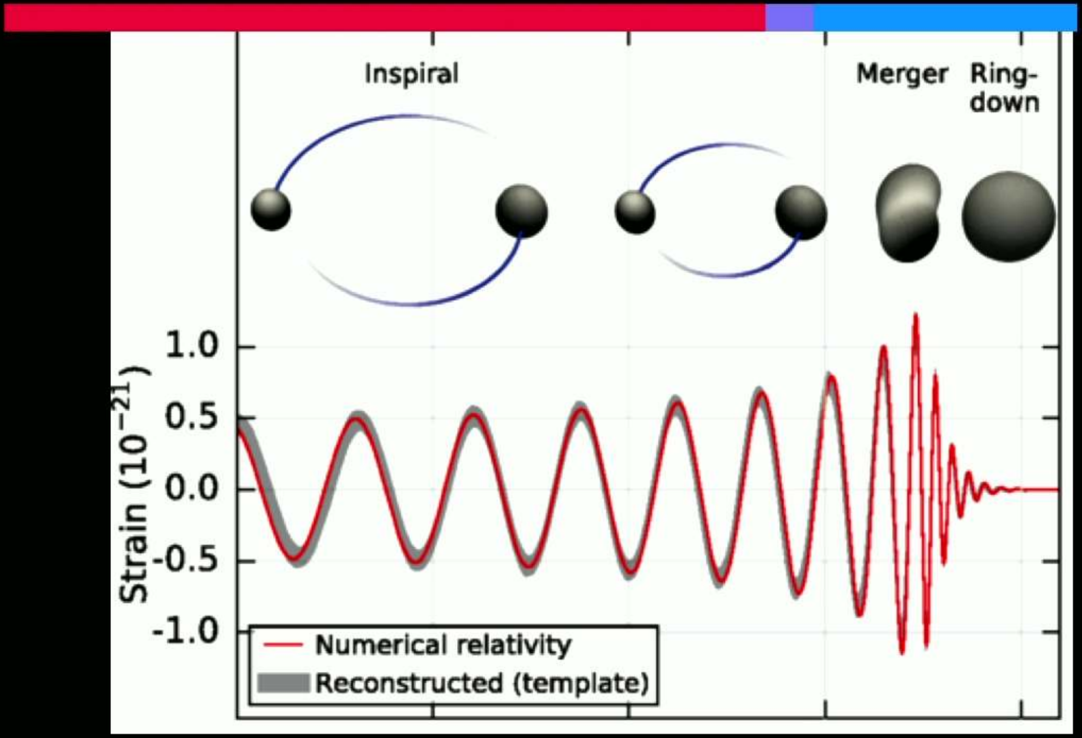
Constructing templates

Post-Newtonian point approximations

Valid for v << c

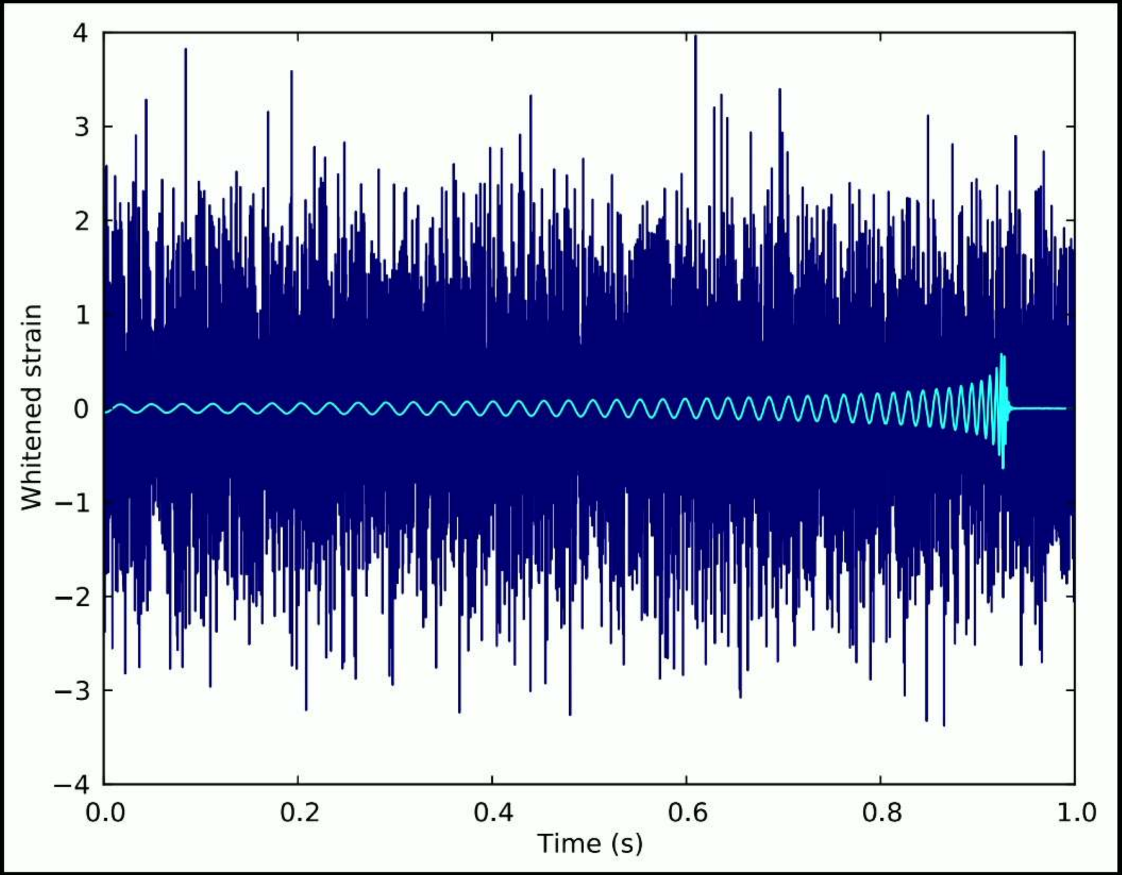
Numerical Relativity

Valid everywhere - very very expensive to generate



B.P. Abbott et al, PRL 2016

The challenge: find a quiet signal in noisy data



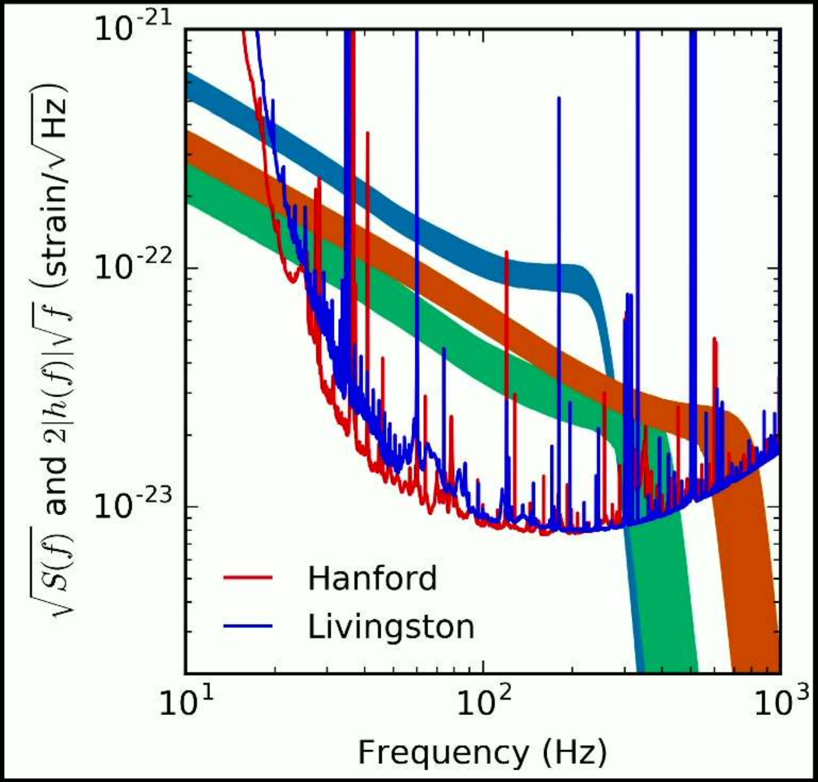
Heather Fong

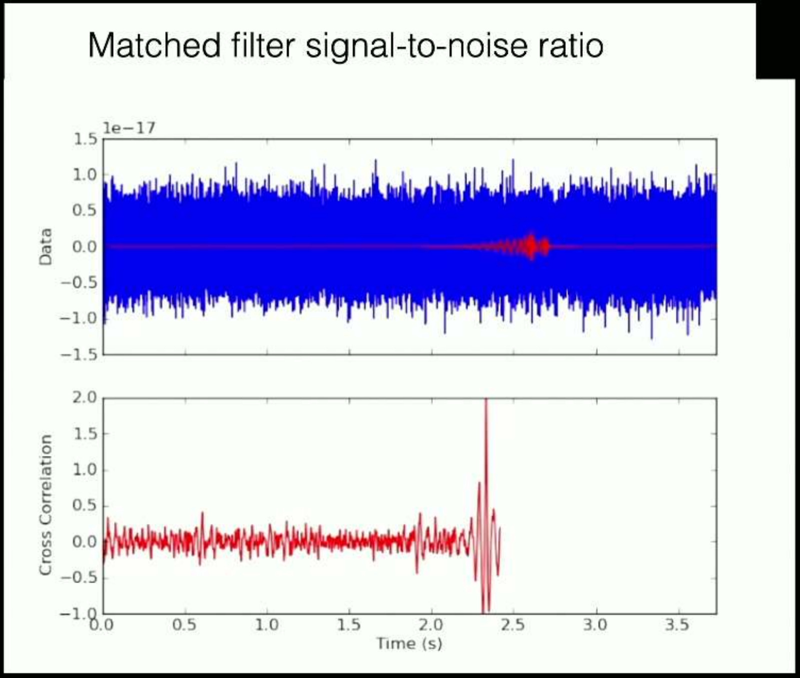
Searching for signals with matched filtering

Slide adapted from S. Caudill

$$\rho^2(t) = \left[\langle s|h_c\rangle^2(t) + \langle s|h_s\rangle^2(t) \right]$$

$$\langle s|h\rangle = 4\mathrm{Re}\int_0^\infty \frac{\tilde{s}(f)\tilde{h}^*(f)}{S_n(f)} e^{2\pi i f t} df$$

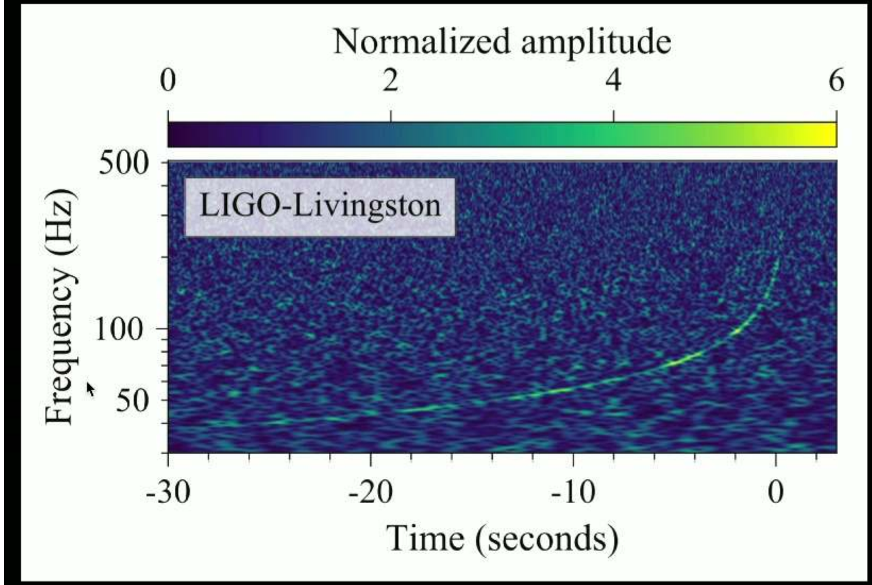


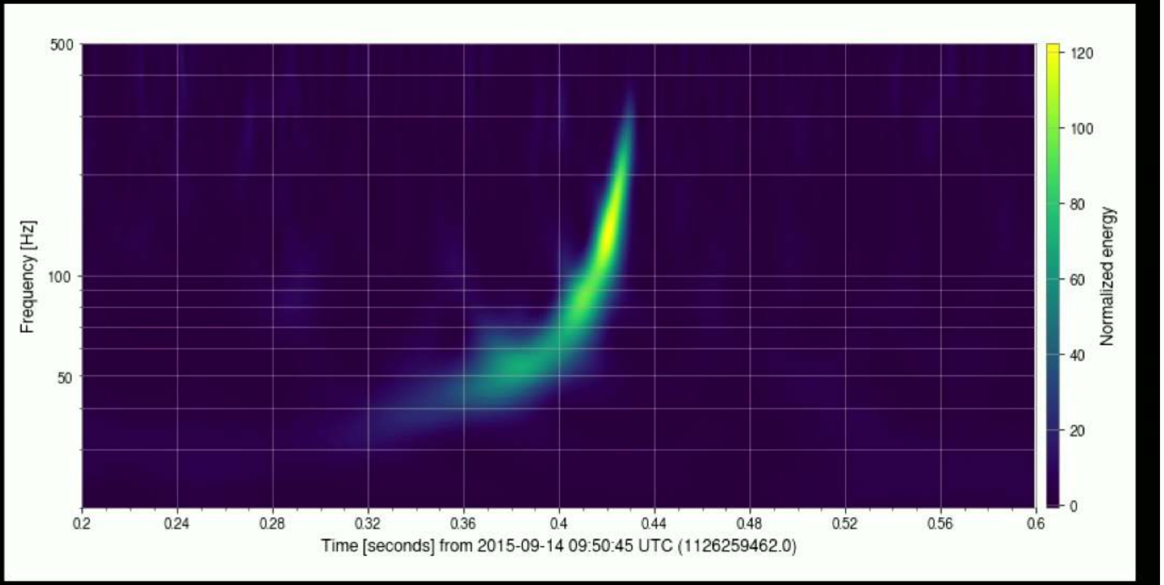

Matched filter signal-to-noise ratio

B. P. Abbott et al. Phys. Rev. X (2016)

Breakout question

Which of these signals has a higher (single detector) matched filter SNR?



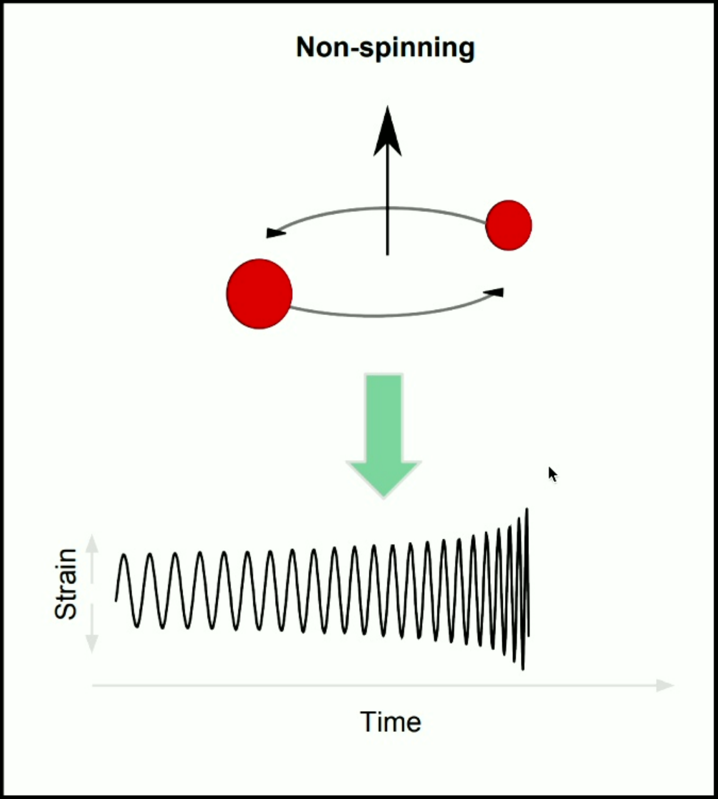


Constructing templates: spin

Breakout question

If the component objects have spin aligned with the orbital angular momentum, will that make the signal template:

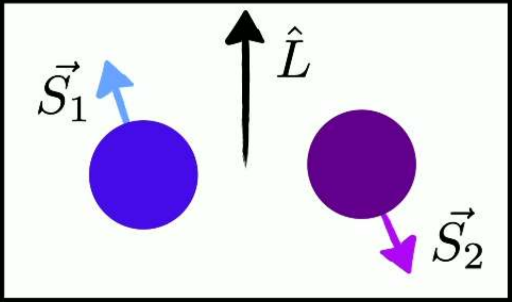
1. Longer
2. Shorter
3. The same

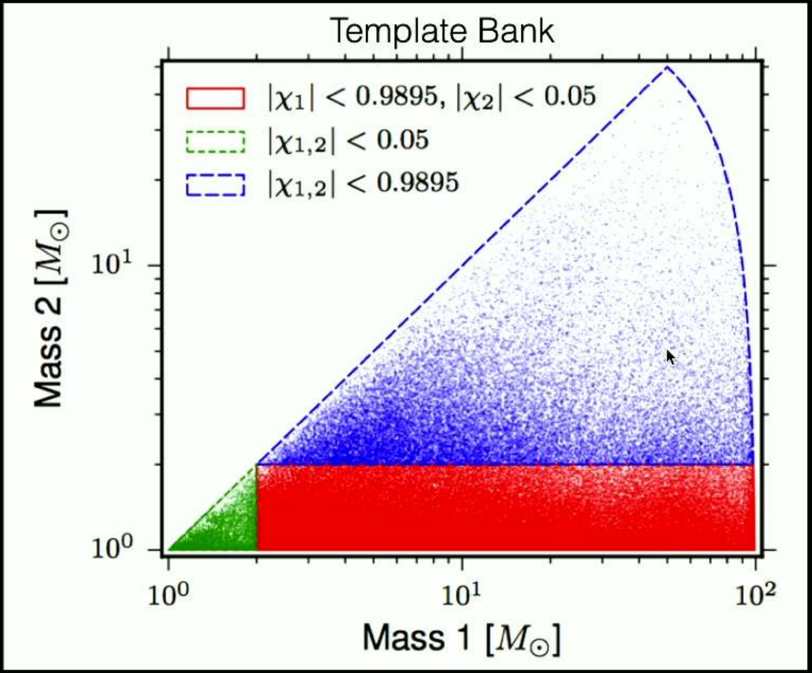


Images by Alex Nitz

Building a template bank

$$\chi_{1,2} \propto \vec{S_{1,2}} \cdot \hat{L}$$





B. P. Abbott et al. Phys. Rev. X (2016)

Dr. Heather Fong

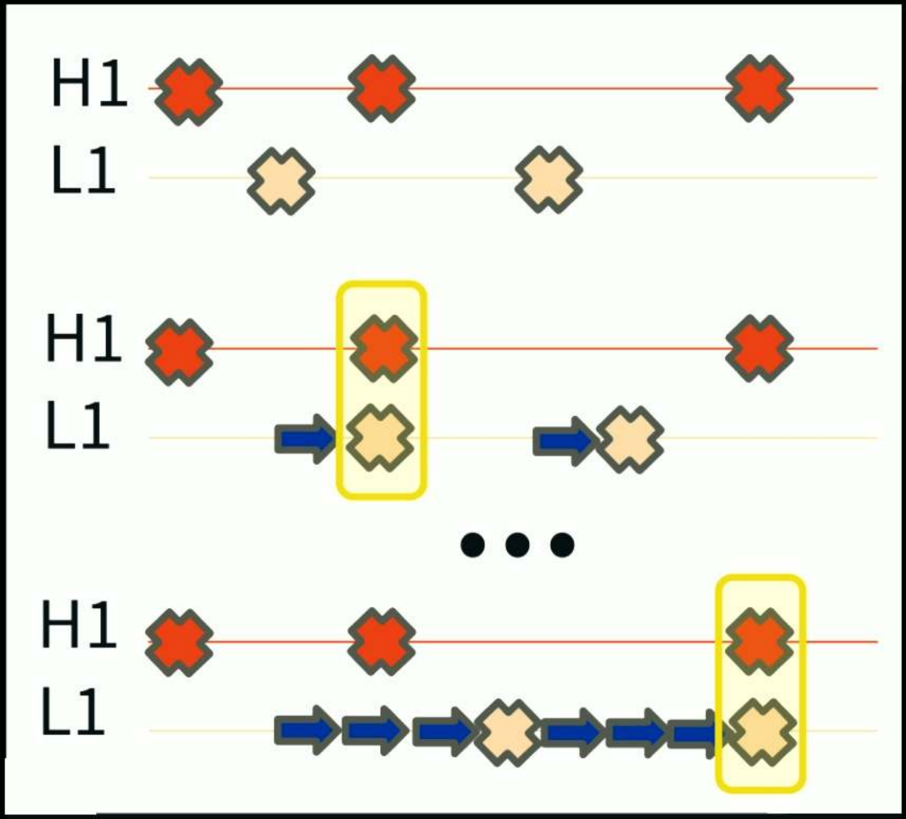
Calculating the foreground

Look for trigger coincidence within gravitational wave travel time between triggers

Network SNR is quadrature sum of single detector SNRs $$\rho_c = \sqrt{\rho_H^2 + \rho_L^2}$$

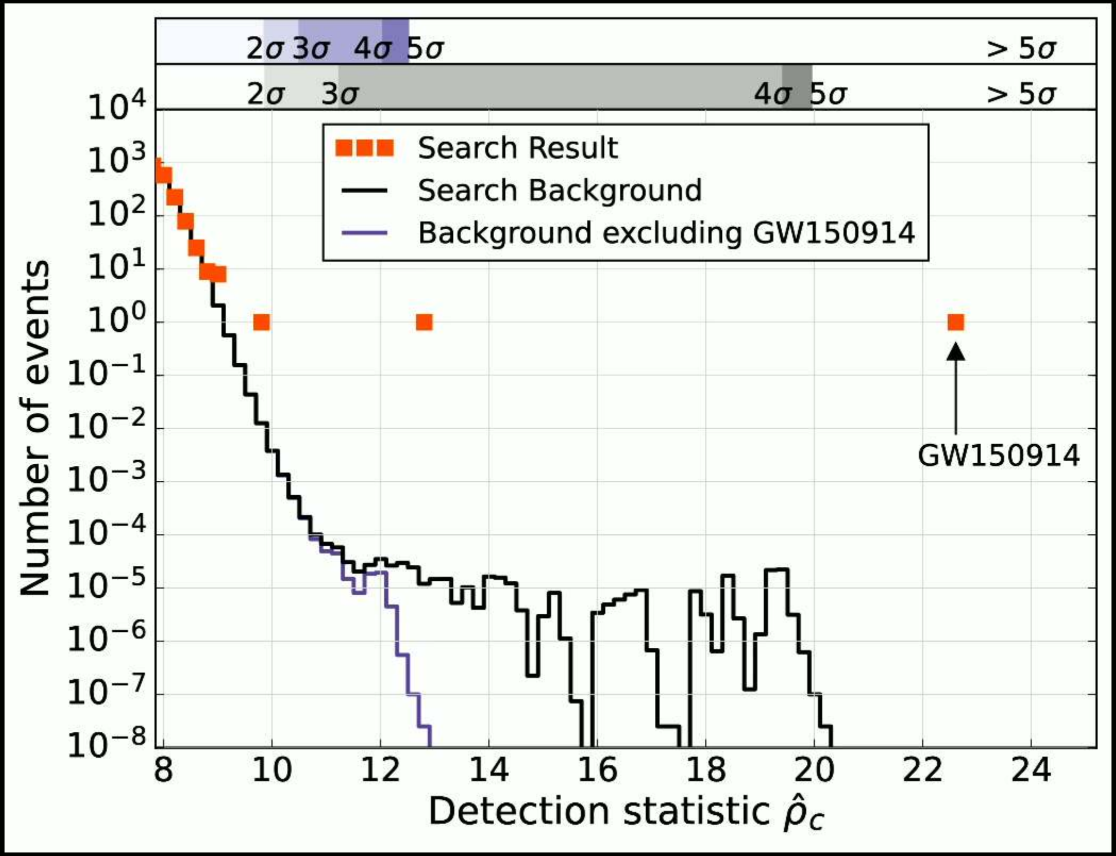
Graphic by Alex Nitz

Calculating the noise background



Graphic by Alex Nitz

Calculating the noise background



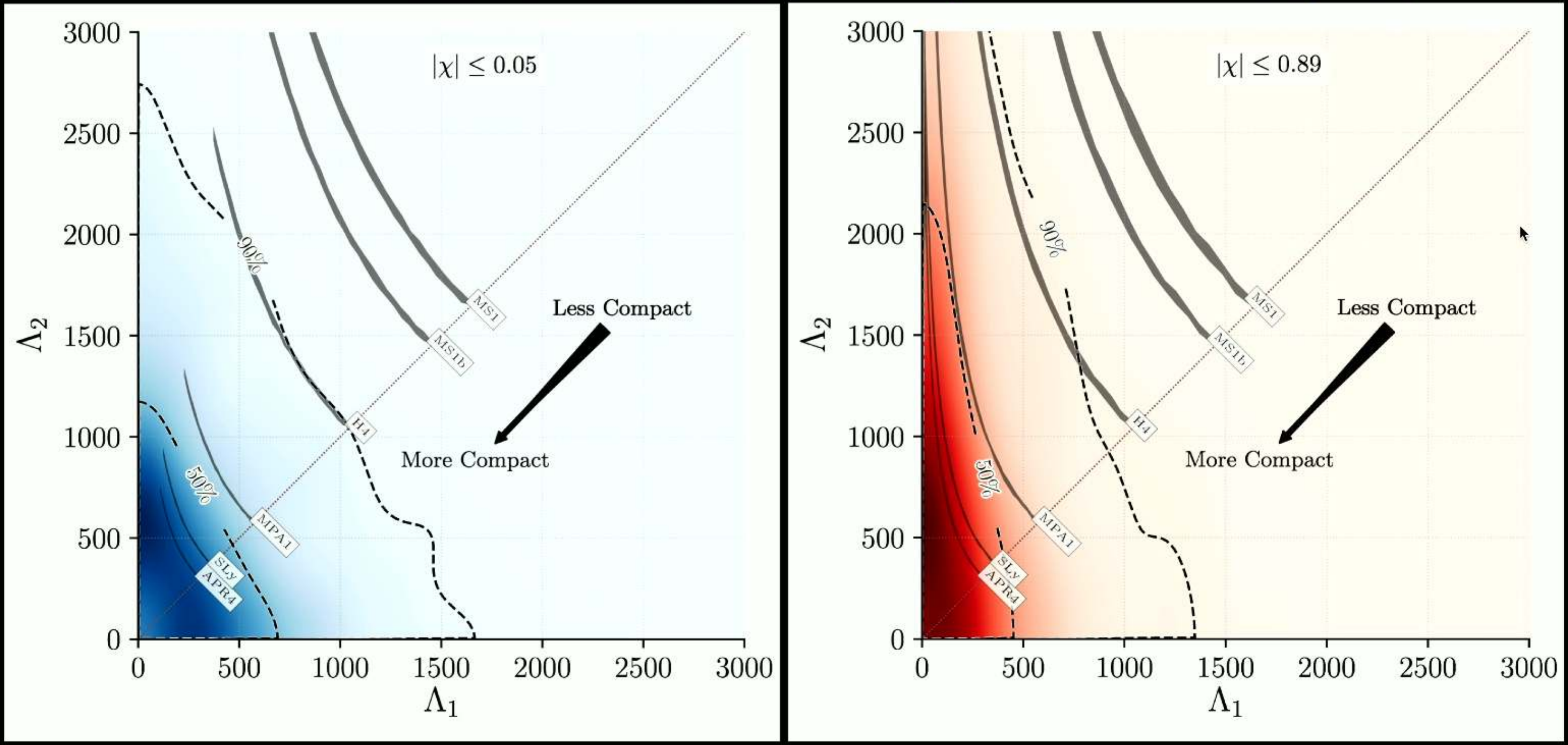
B. P. Abbott et al. Phys. Rev. X (2016)

From GWs: tidal deformability and constraining NS EoS

Tidal deformability $\Lambda = \frac{2}{3}k_2\left(\frac{c^2R}{GM}\right)^5$

k_2 is the gravitational “Love” number, with typical values around 0.2-0.3; $\propto \approx 1/M$

Great overview of Λ and love numbers by Katerina Chatziioannou (Caltech): arXiv 2006.03169



B.P. Abbott et al PRL. (2017)

NASA/Goddard Space Flight Center/CI Lab