

Title: Gravitational Waves Experiments

Speakers: Jess McIver

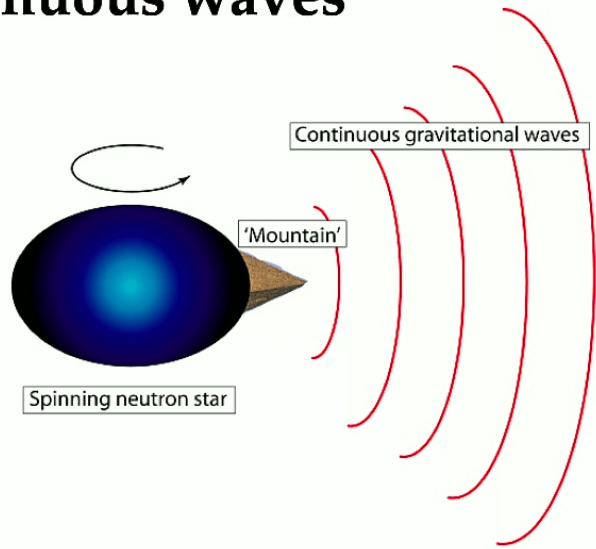
Collection: TRISEP 2023

Date: June 23, 2023 - 2:30 PM

URL: <https://pirsa.org/23060062>

Continuous waves

ANU



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

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

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

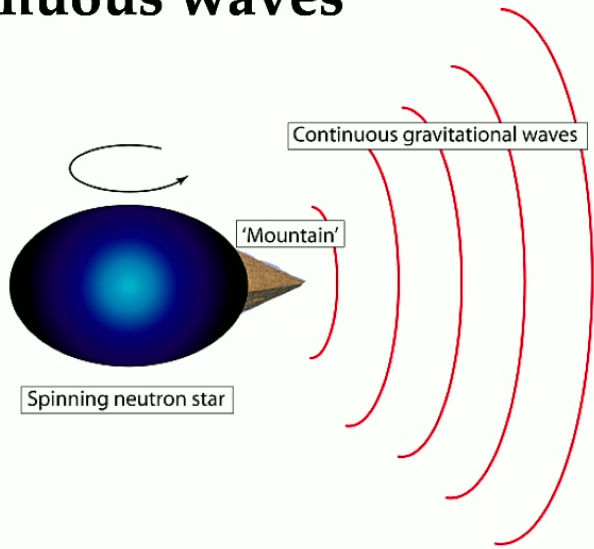
Equatorial ellipticity

Thought exercises...

Why is equatorial ellipticity required for GW generation?

Continuous waves

ANU

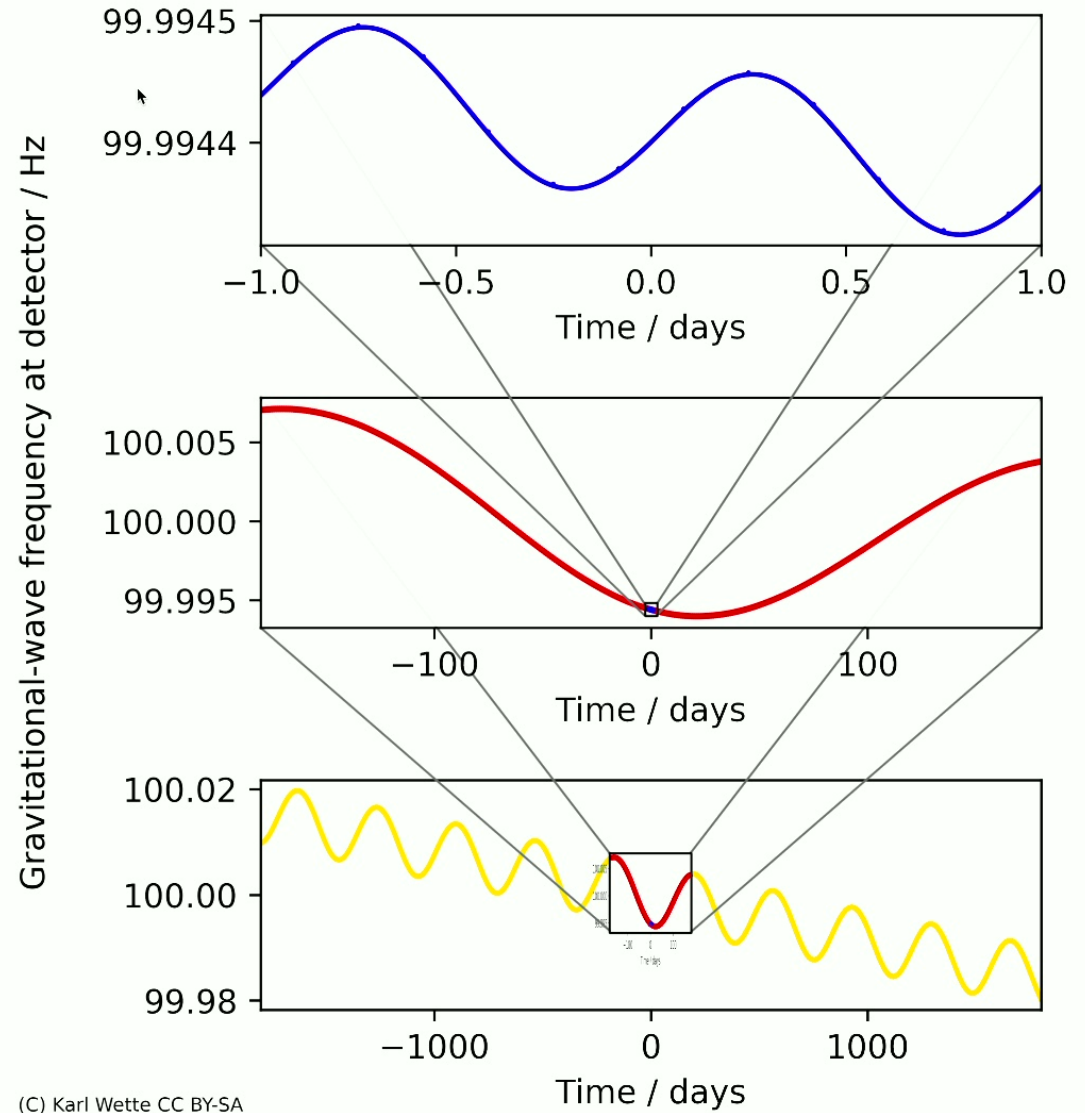


$$h \sim \frac{Gf_{GW}^2}{c^4 r} \epsilon$$

On the order of 10^{-24}
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Equatorial ellipticity



(C) Karl Wette CC BY-SA

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

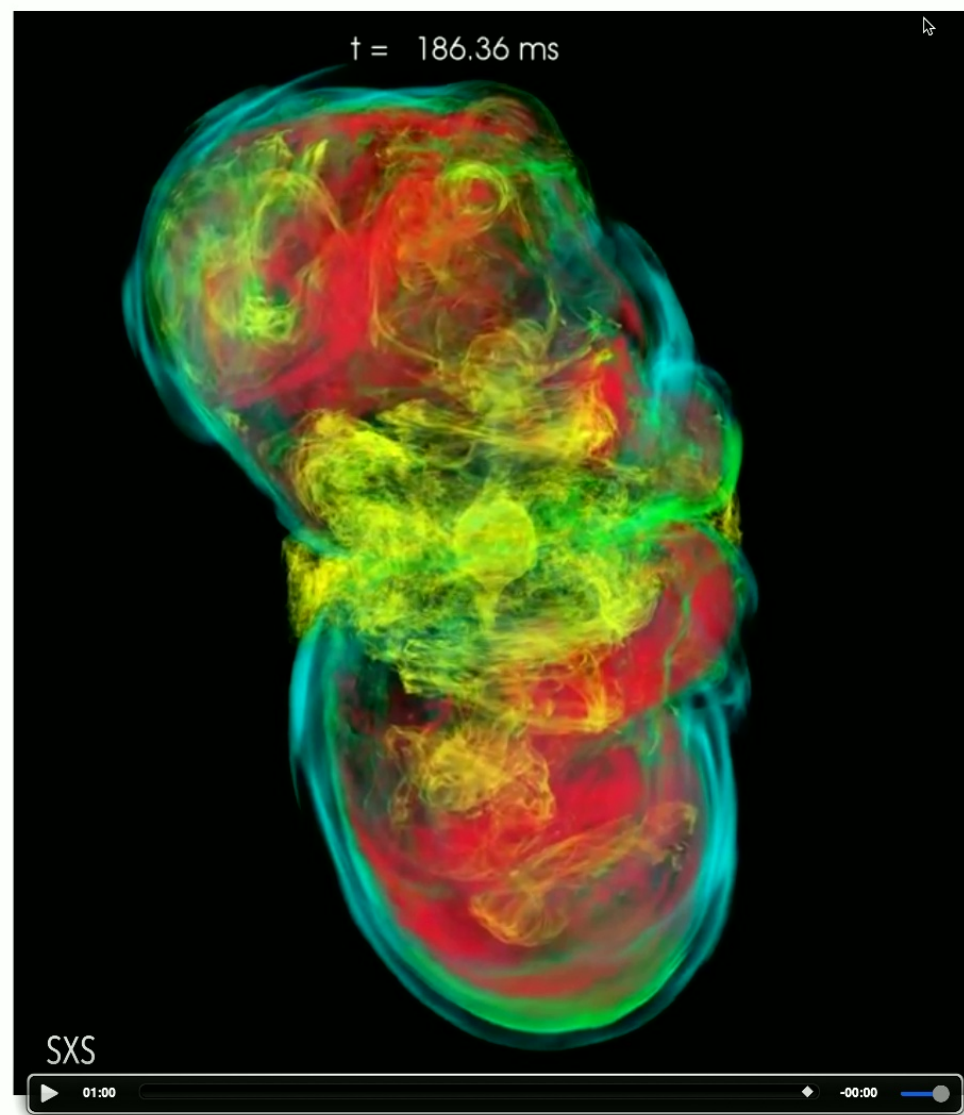
We can leverage the “burst equation”:

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

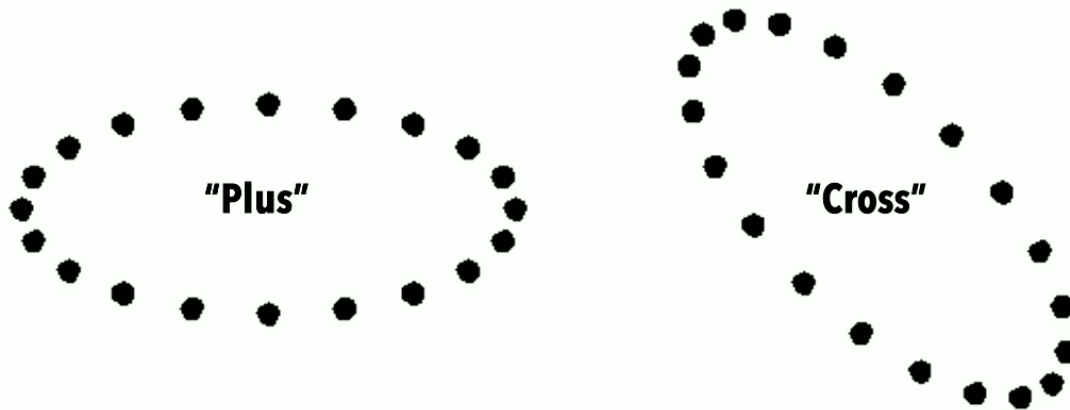
CCSNe emit most of their energy in neutrinos, and a small fraction ($\sim 0.1\%$) in GWs from asymmetrically accelerating mass.

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

See Sathyaprakesh and Schutz’s [Living Review in Relativity](#)

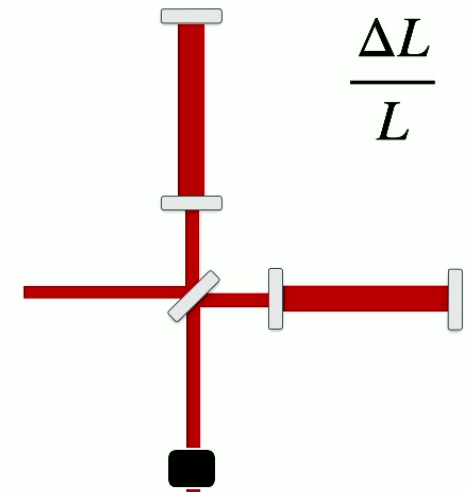


Gravitational wave propagation



Wikimedia

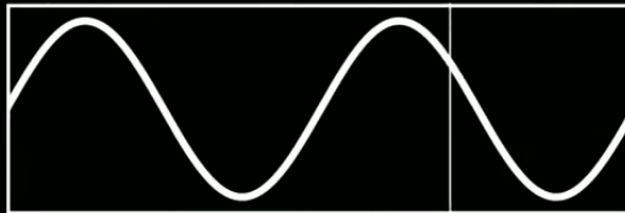
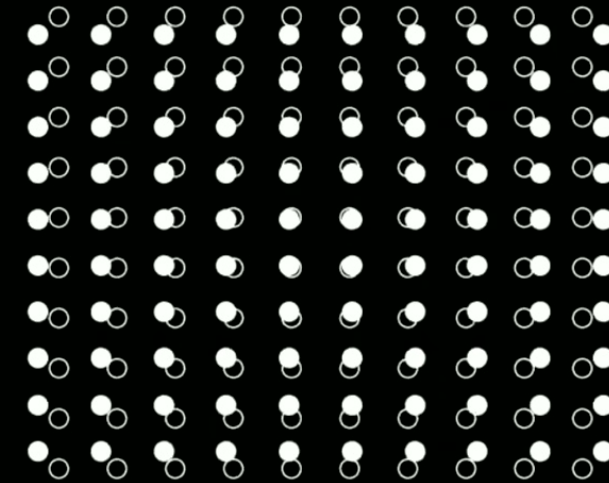
Measured spacetime strain $h(t)$:



Intro to GW interferometers

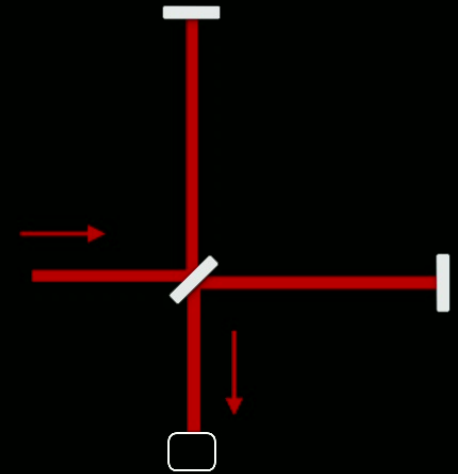
Induced
spacetime
strain $h(t)$

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



Measured
spacetime
strain $h(t)$

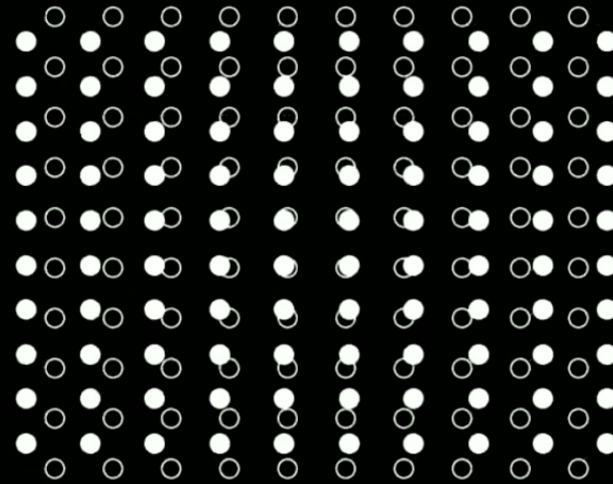
$$h(t) = \frac{\Delta L}{L}$$



How would you design a GW detector?

Induced
spacetime
strain $h(t)$

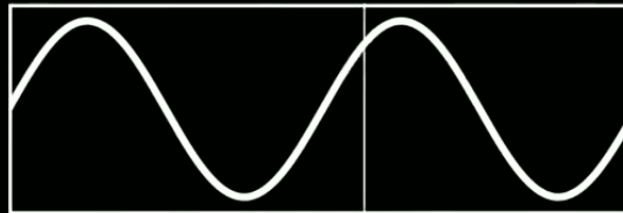
$$h_{ij}(t) \propto \frac{G}{c^4 r} \frac{d^2 I_{ij}}{dt^2}$$

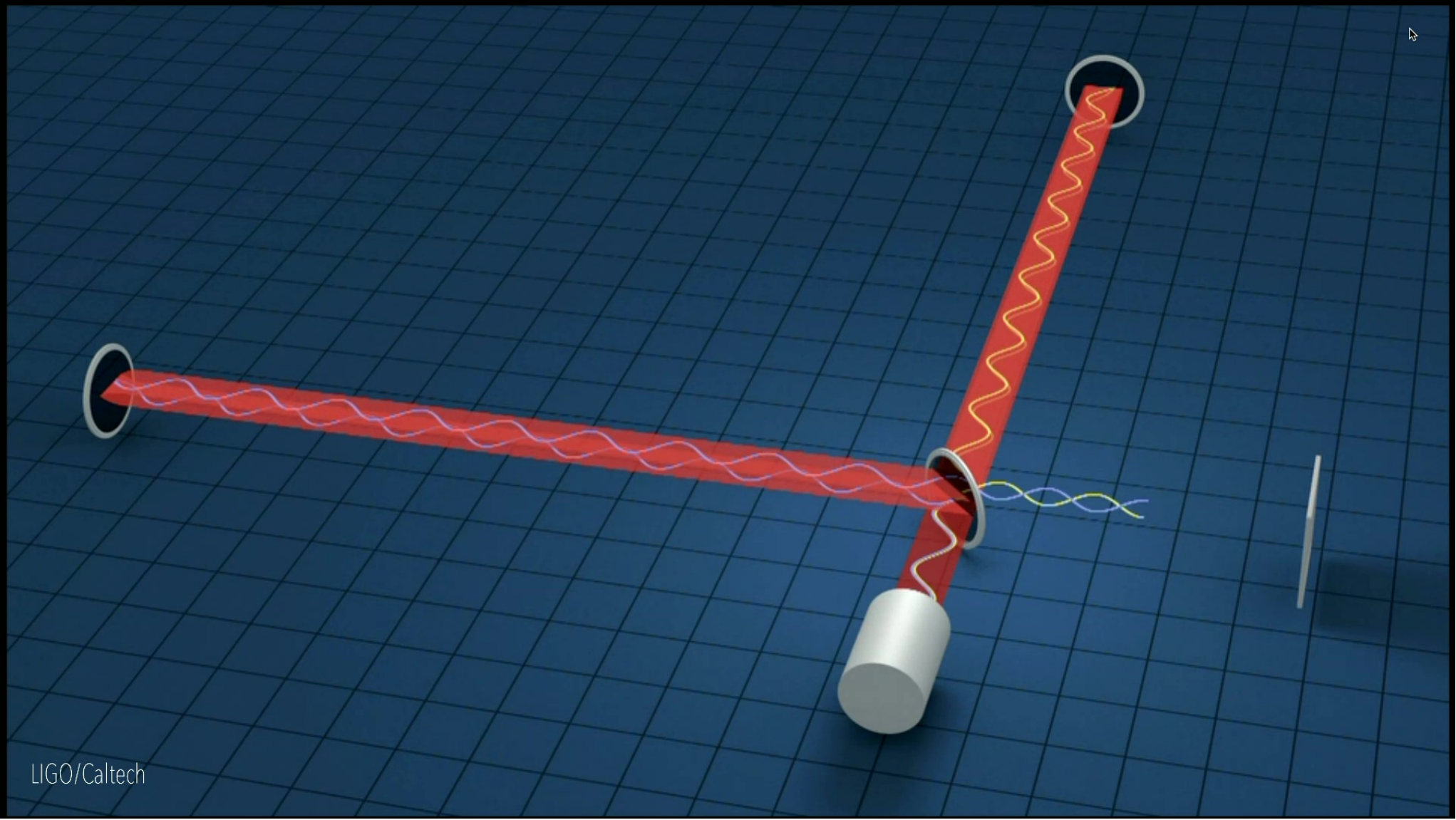


Measured
spacetime
strain $h(t)$

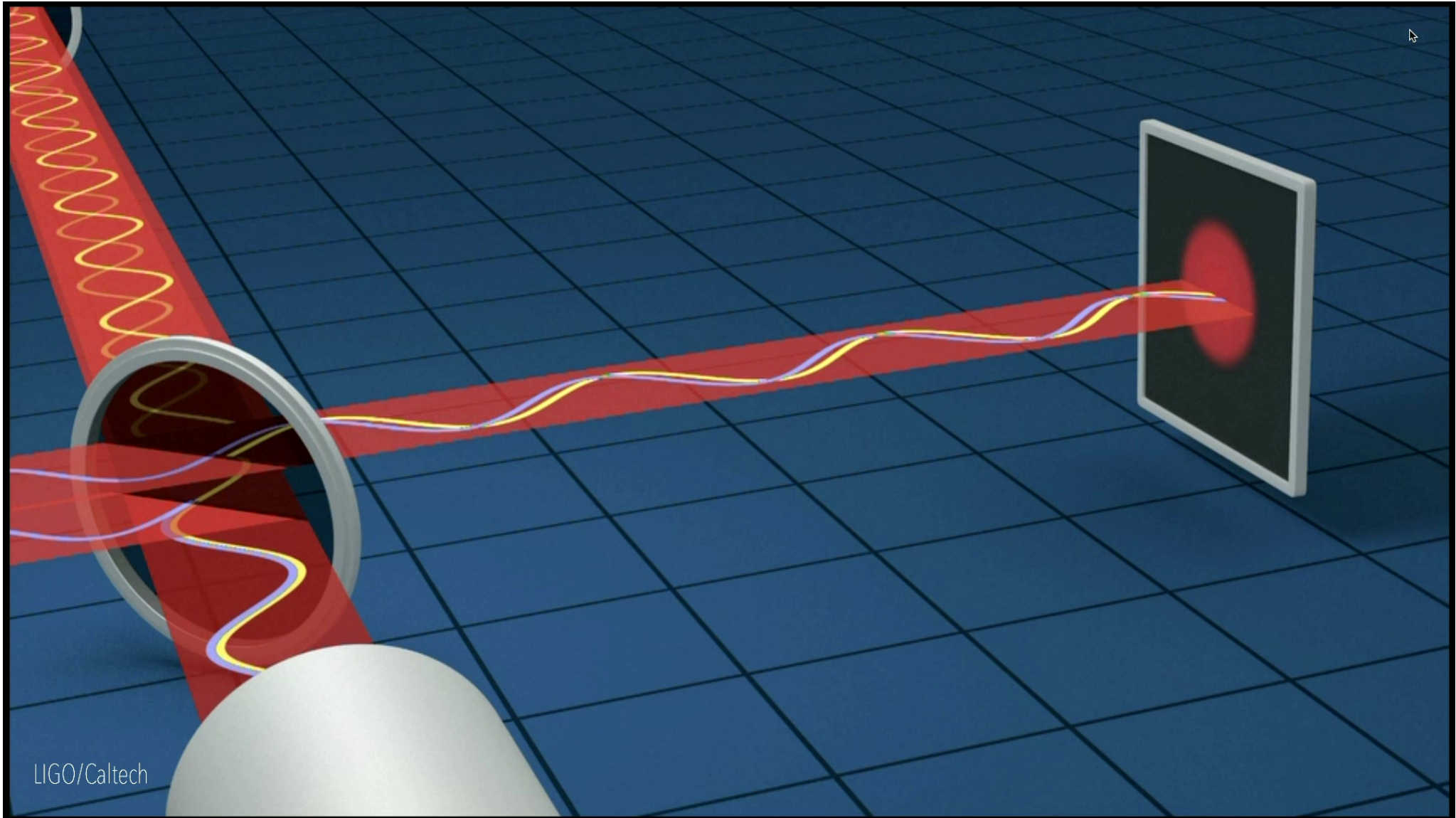
$$h(t) = \frac{\Delta L}{L}$$

How long do
you want your
arm length, L ?





LIGO/Caltech



LIGO/Caltech

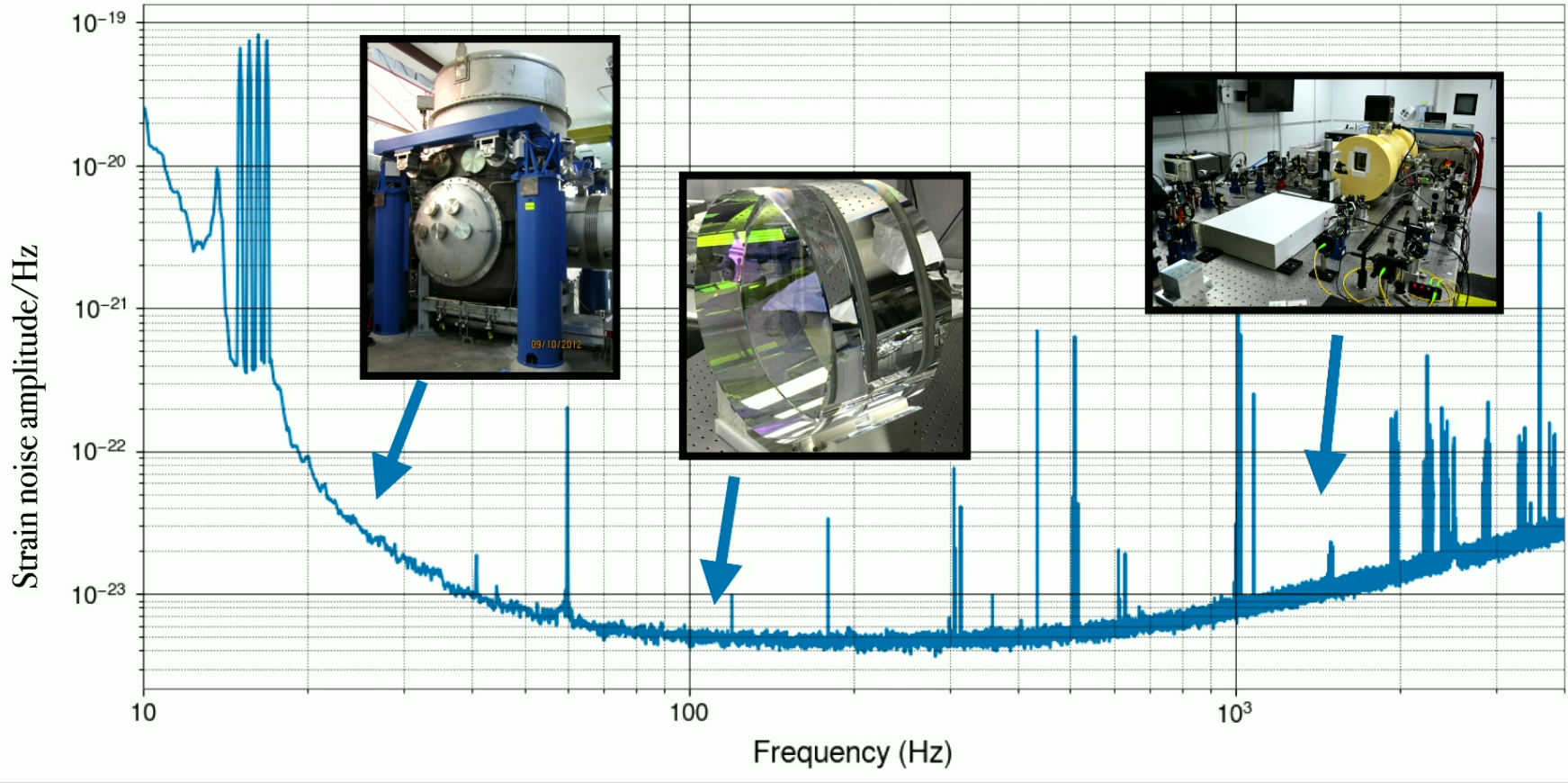


Kai Staar

Advanced LIGO noise

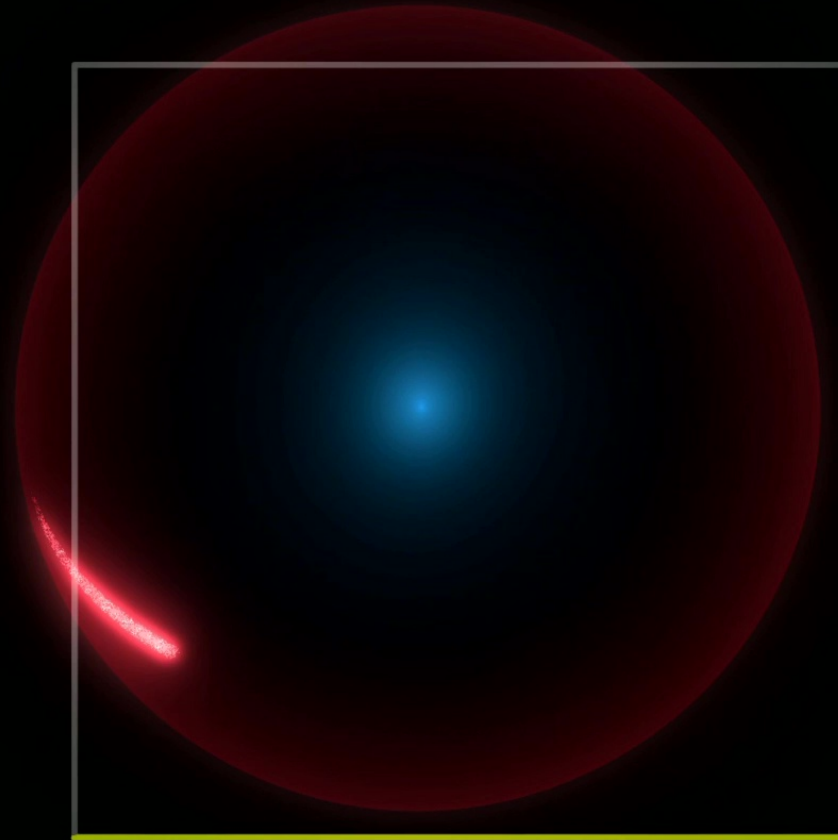
Spectrum: L1:GDS-CALIB_STRAIN,rds

2019-05-30 03:30:00.000 | 1243222218 (360.0), fftlength=10.0, overlap=0.5

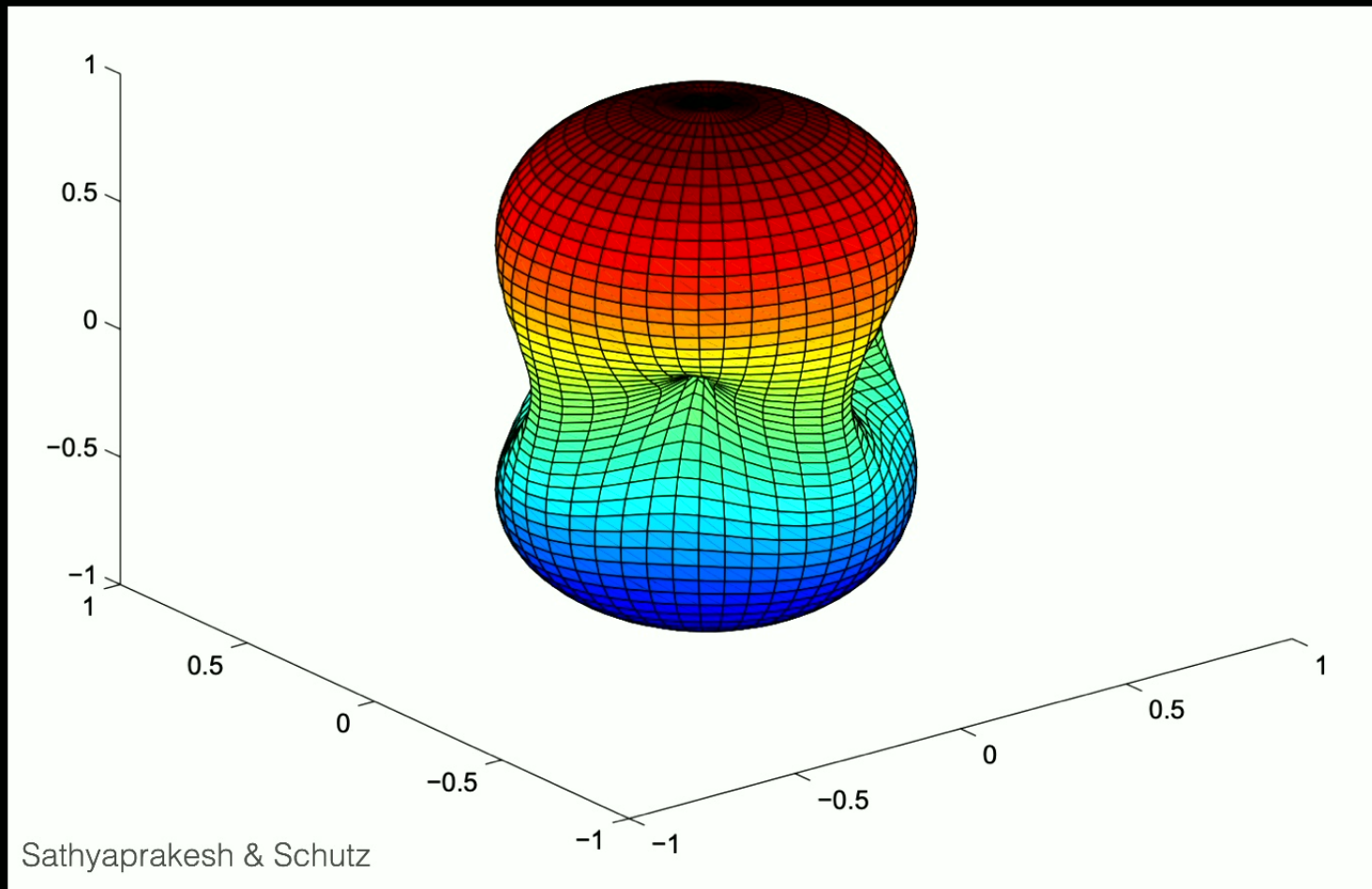


GW detector sensitivity

10^{-10} METERS



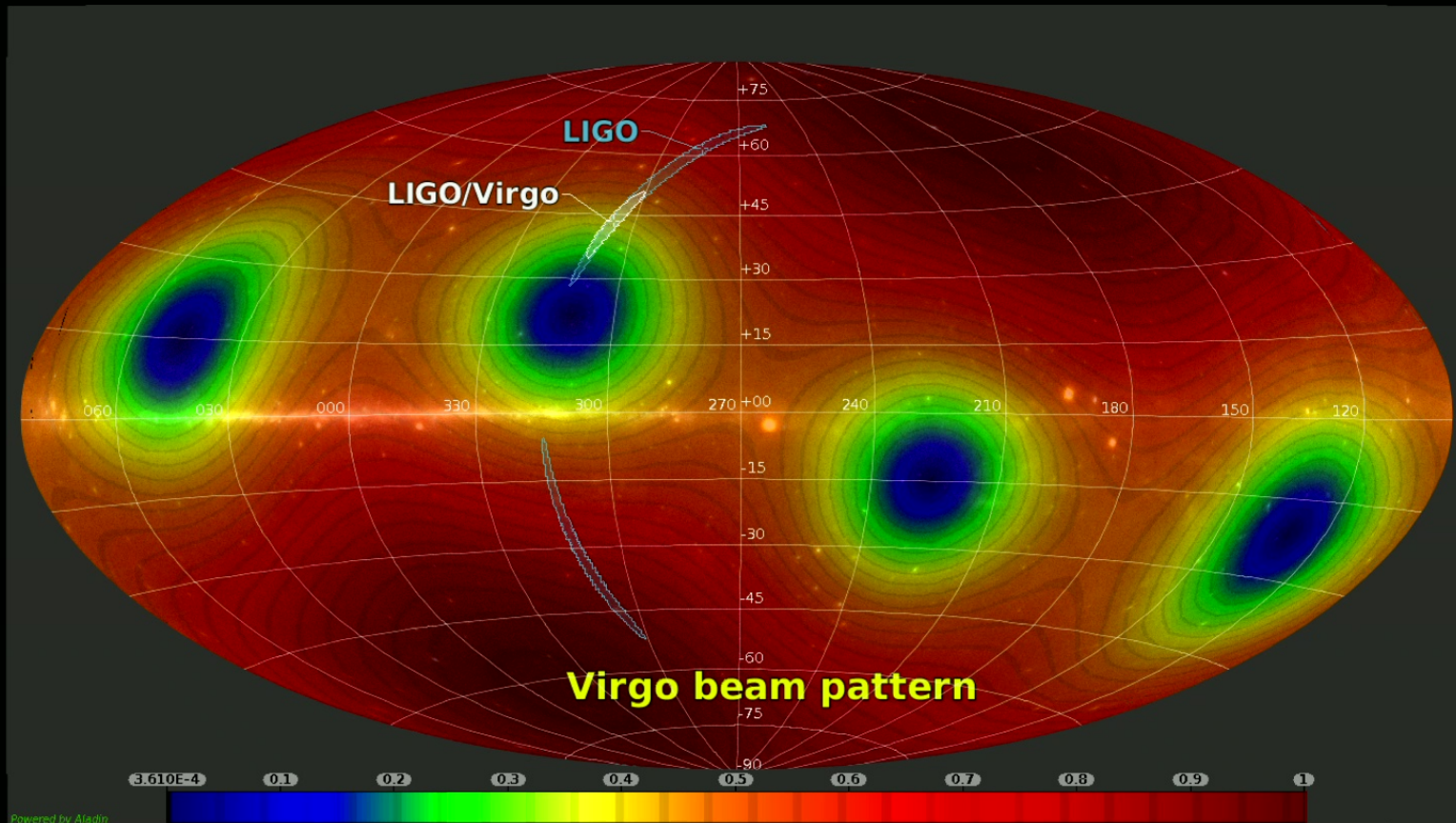
GW detector "antenna pattern"



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

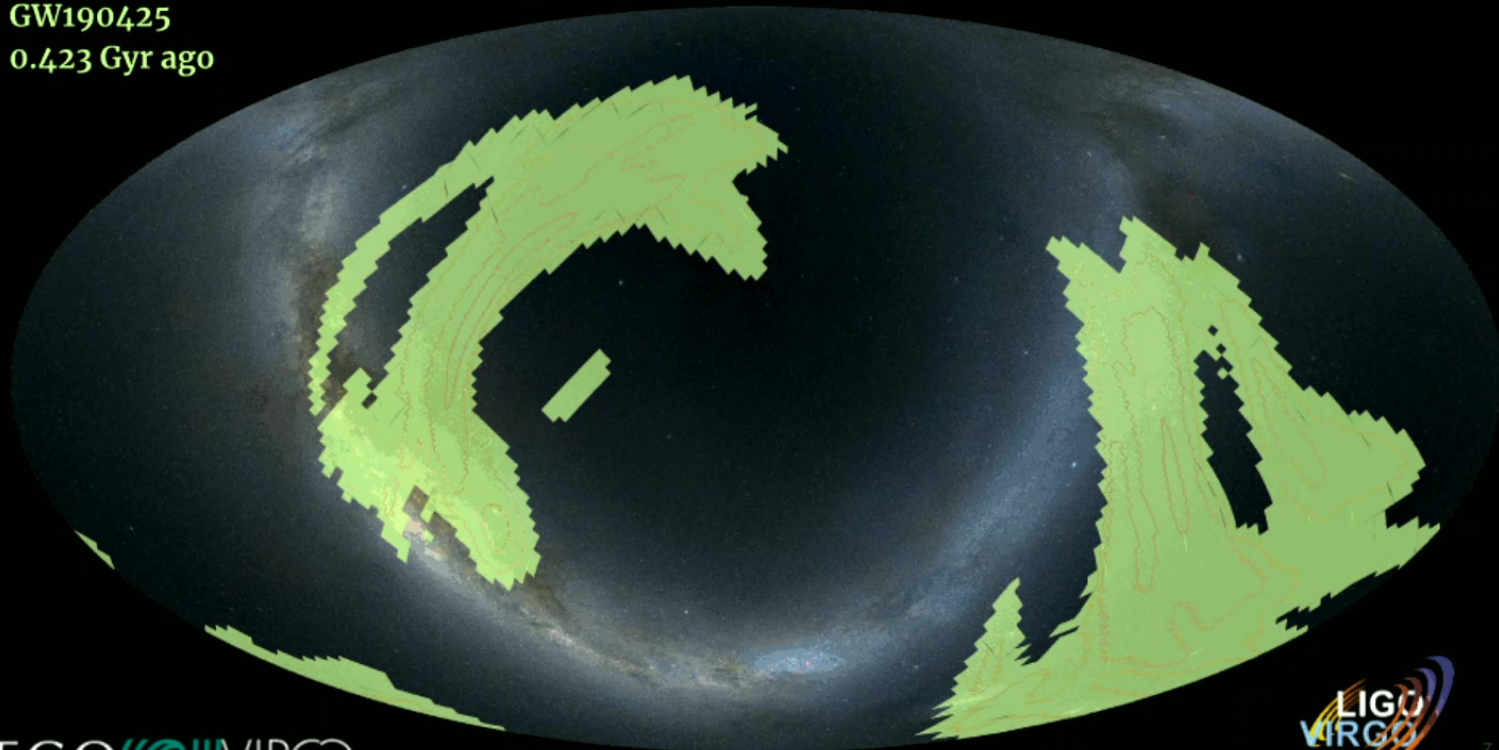


LIGO-Virgo/Greco, Arnaud, Vicerè

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Typical GW sky localizations (examples from GWTC-2)

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



EGO VIRGO

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





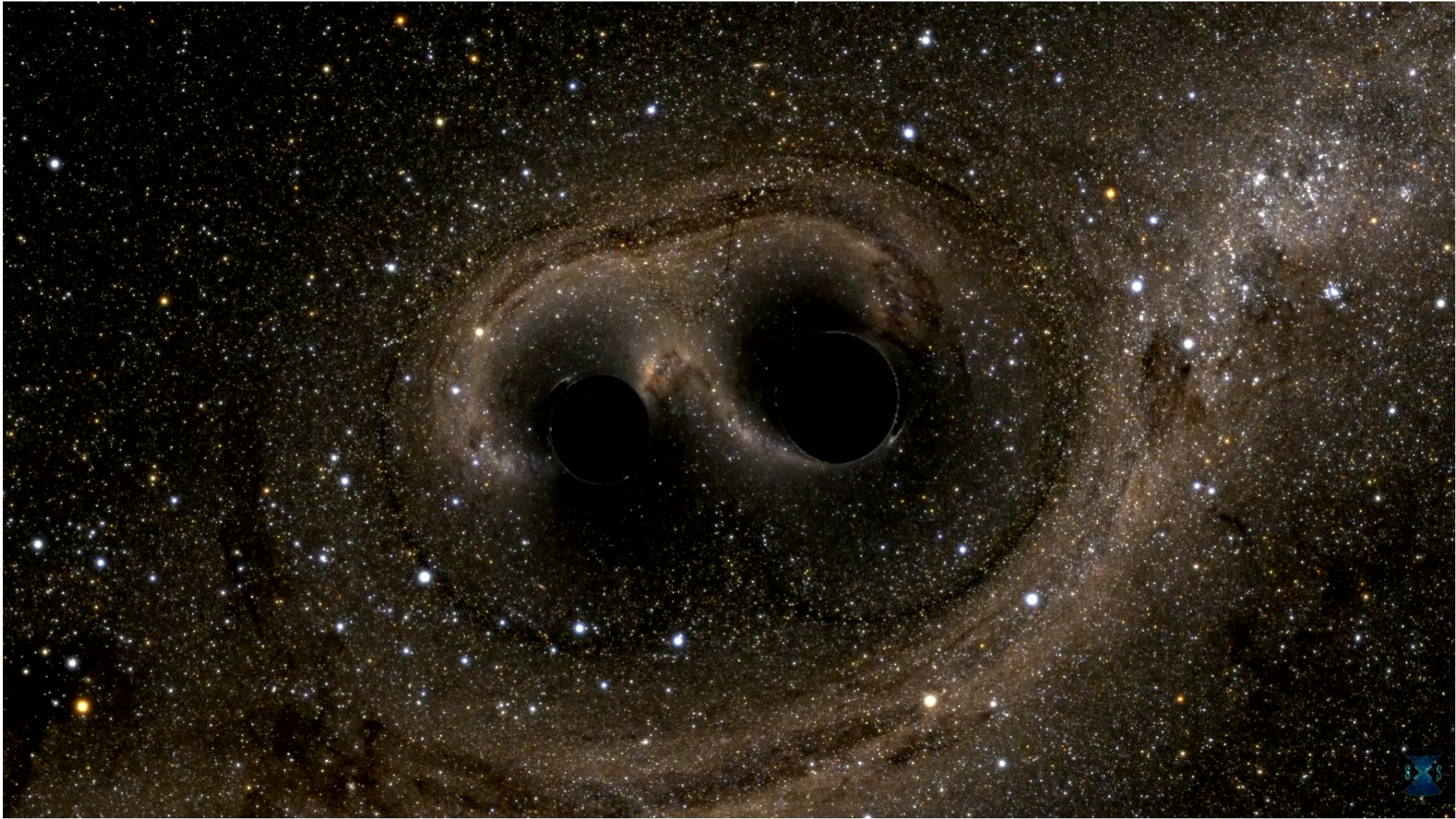
LIGO-Virgo

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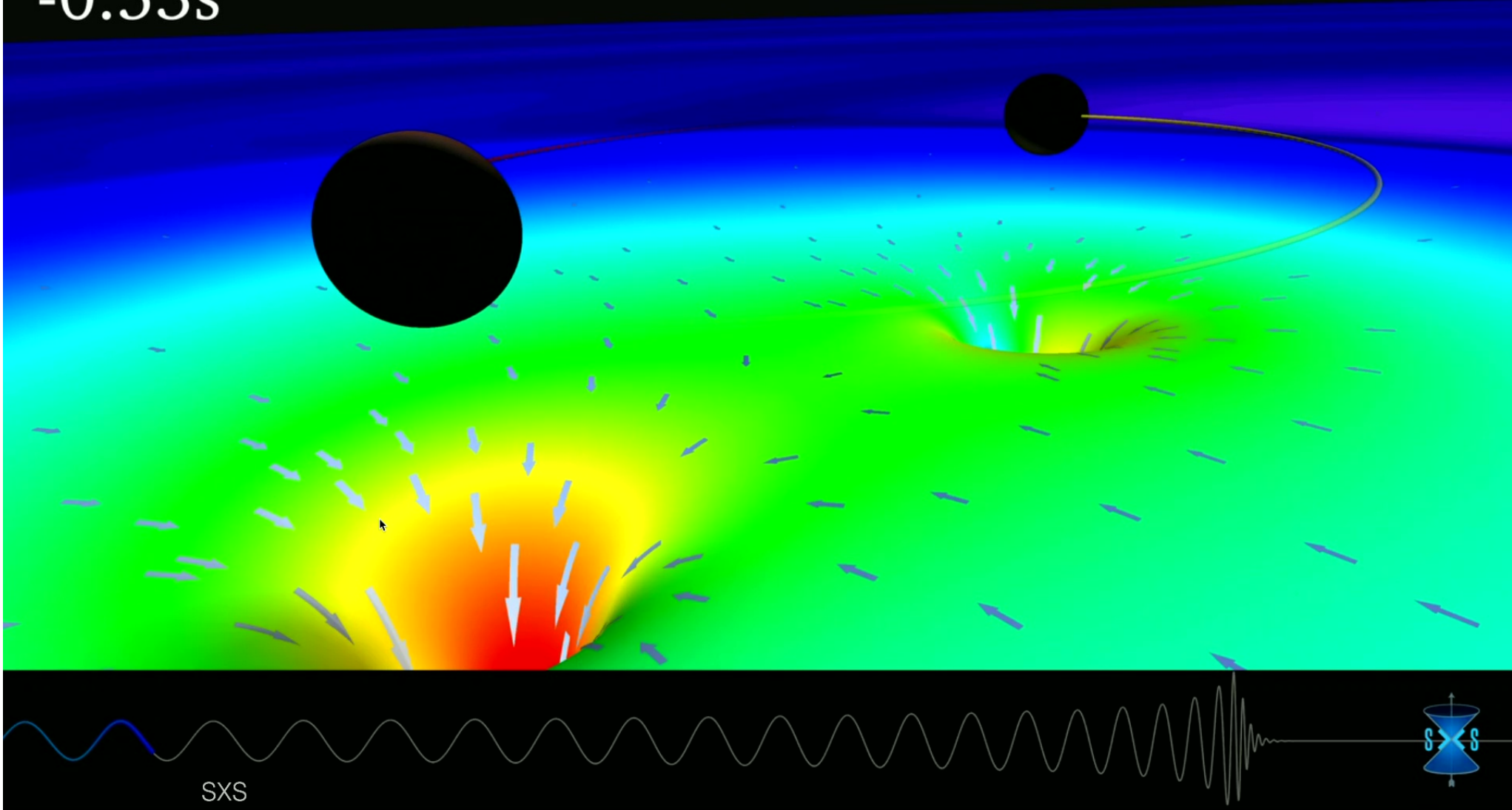
Let's move!

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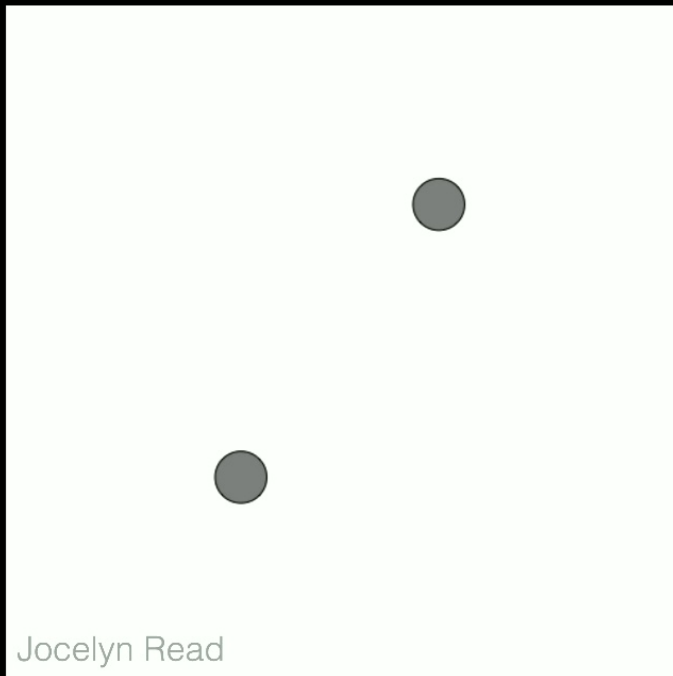


-0.53s

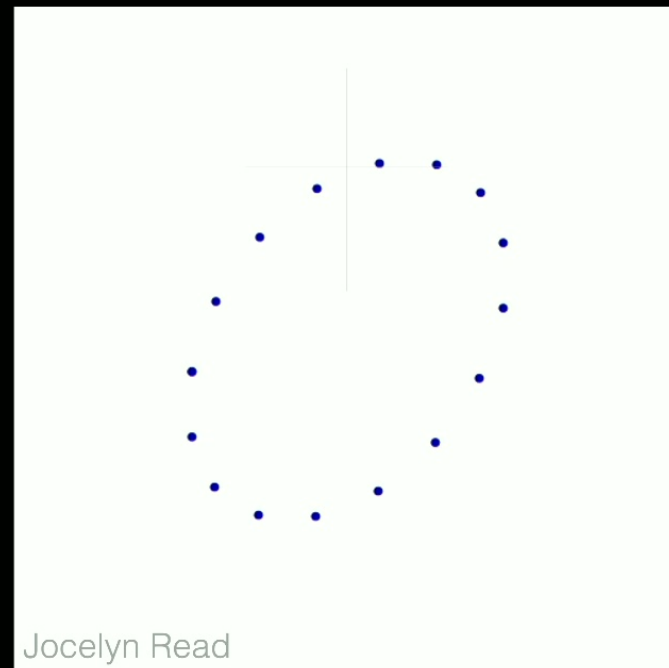


Compact binary sources

Massive objects orbit



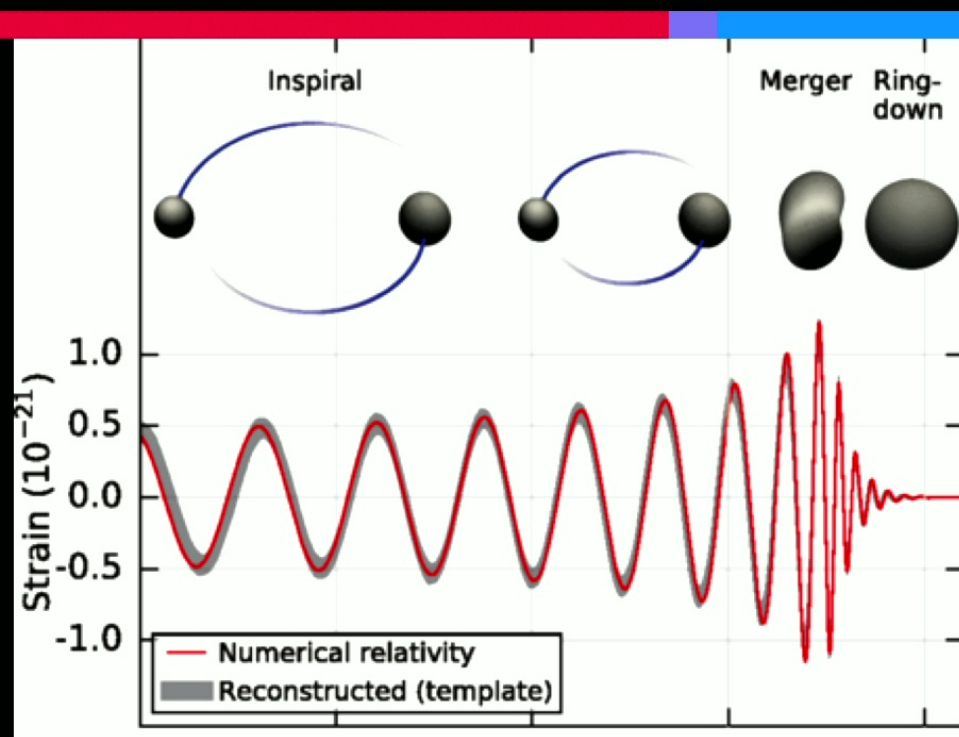
Spacetime response
above orbital plane



Constructing templates

Post-Newtonian point approximations
Valid for $v \ll c$

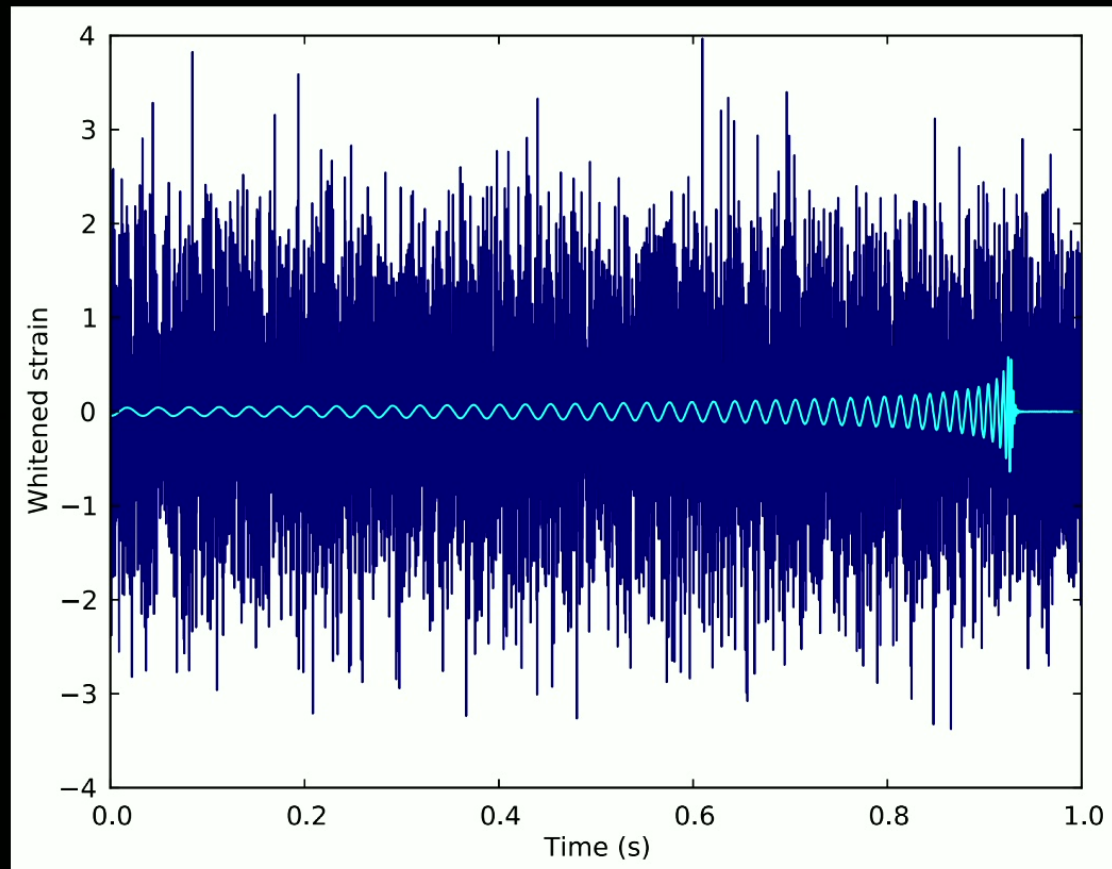
Numerical Relativity
Valid everywhere - very very expensive to generate



B.P. Abbott et al, PRL 2016

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The challenge: find a quiet signal in noisy data



Heather Fong

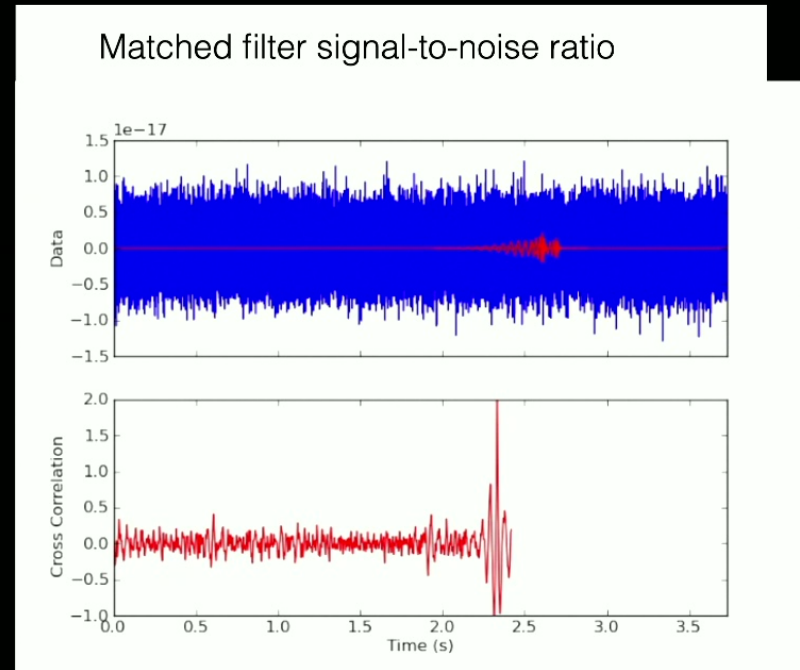
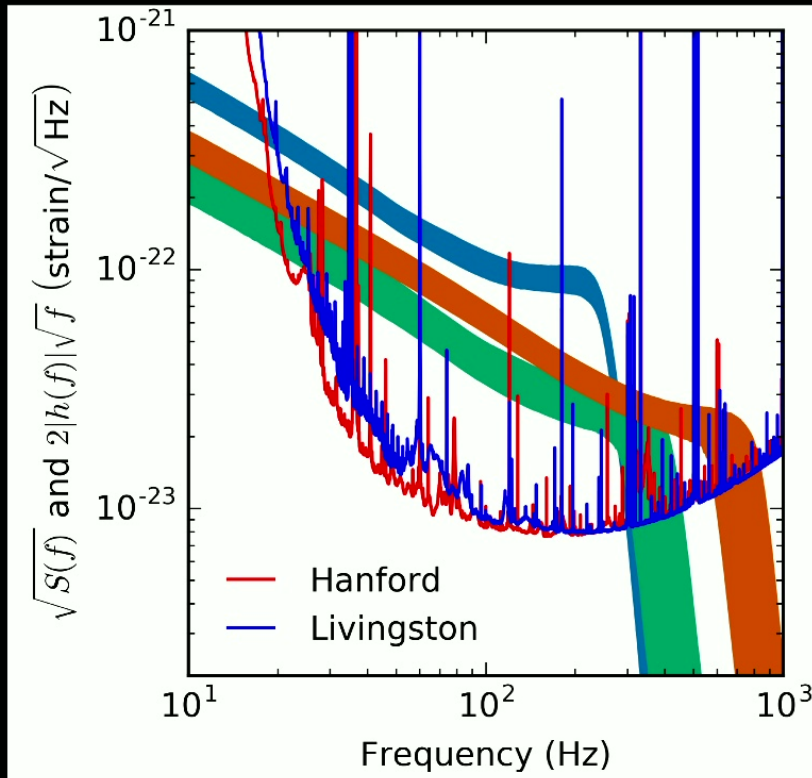
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Searching for signals with matched filtering

Slide adapted from S. Caudill

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

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

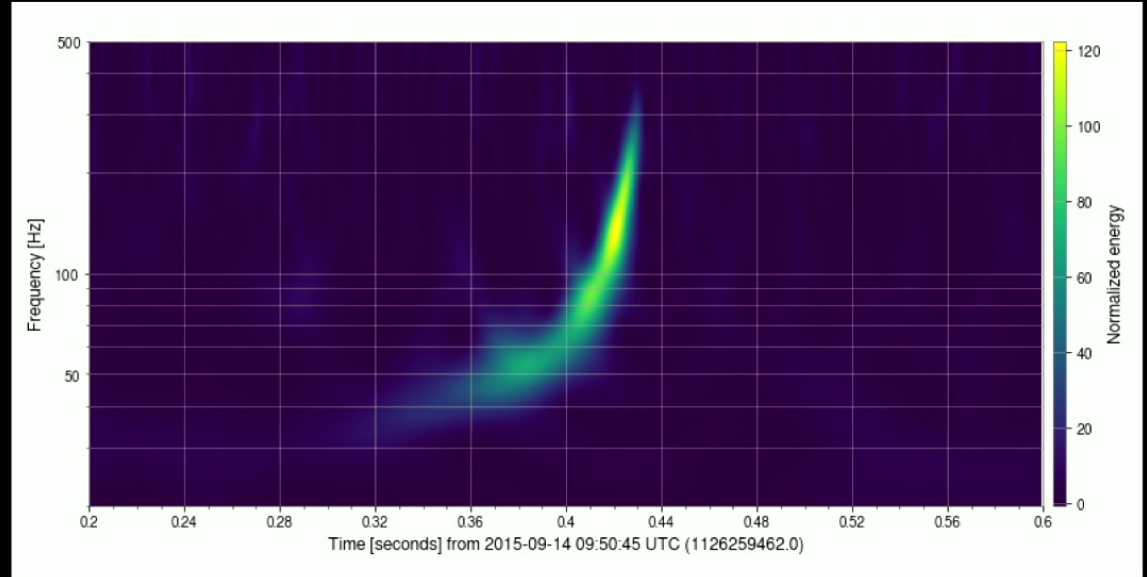
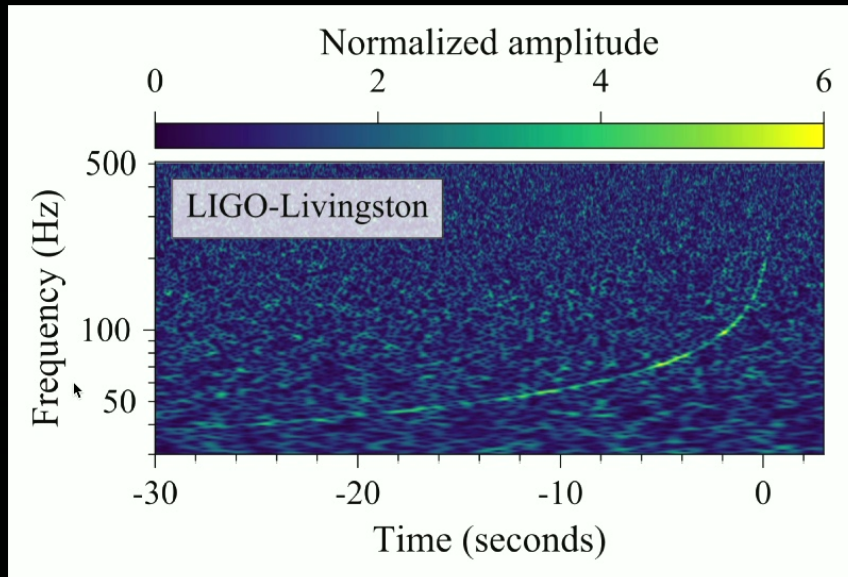


B. P. Abbott et al. Phys. Rev. X (2016)

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Breakout question

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

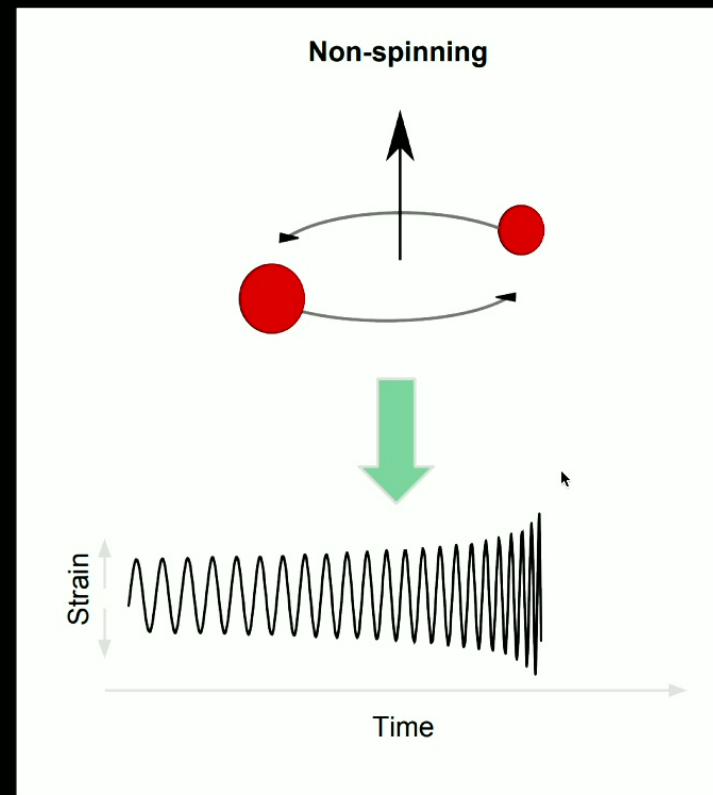


Constructing templates: spin

Breakout question

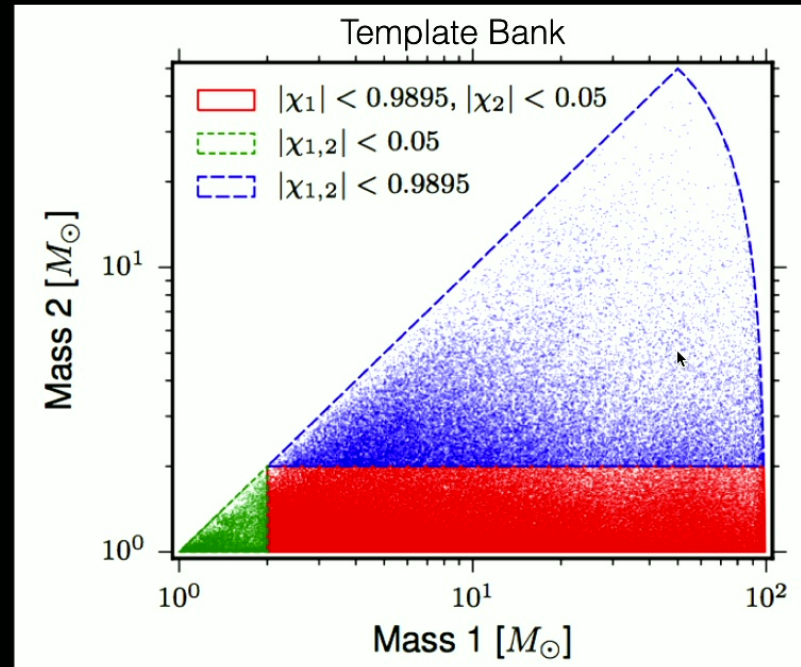
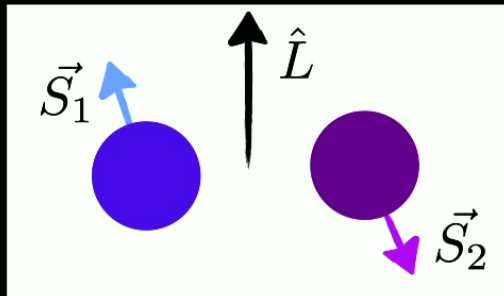
If the component objects have spin aligned with the orbital angular momentum, will that make the signal template:

1. Longer
2. Shorter
3. The same



Building a template bank

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



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

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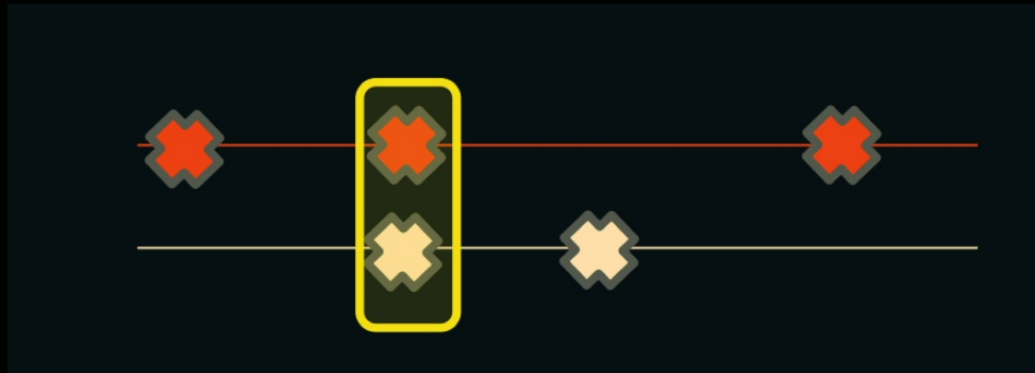


Dr. Heather Fong

Calculating the foreground

Look for trigger coincidence within gravitational wave travel time between triggers

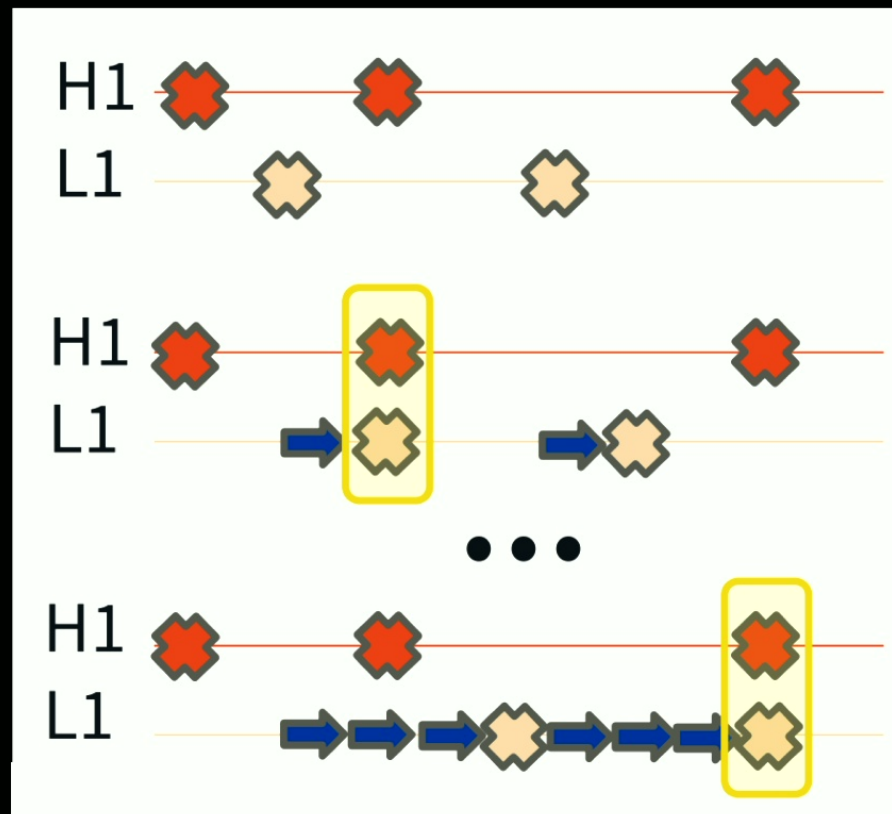
Network SNR is quadrature sum of single detector SNRs $\rho_c = \sqrt{\rho_H^2 + \rho_L^2}$



Graphic by Alex Nitz

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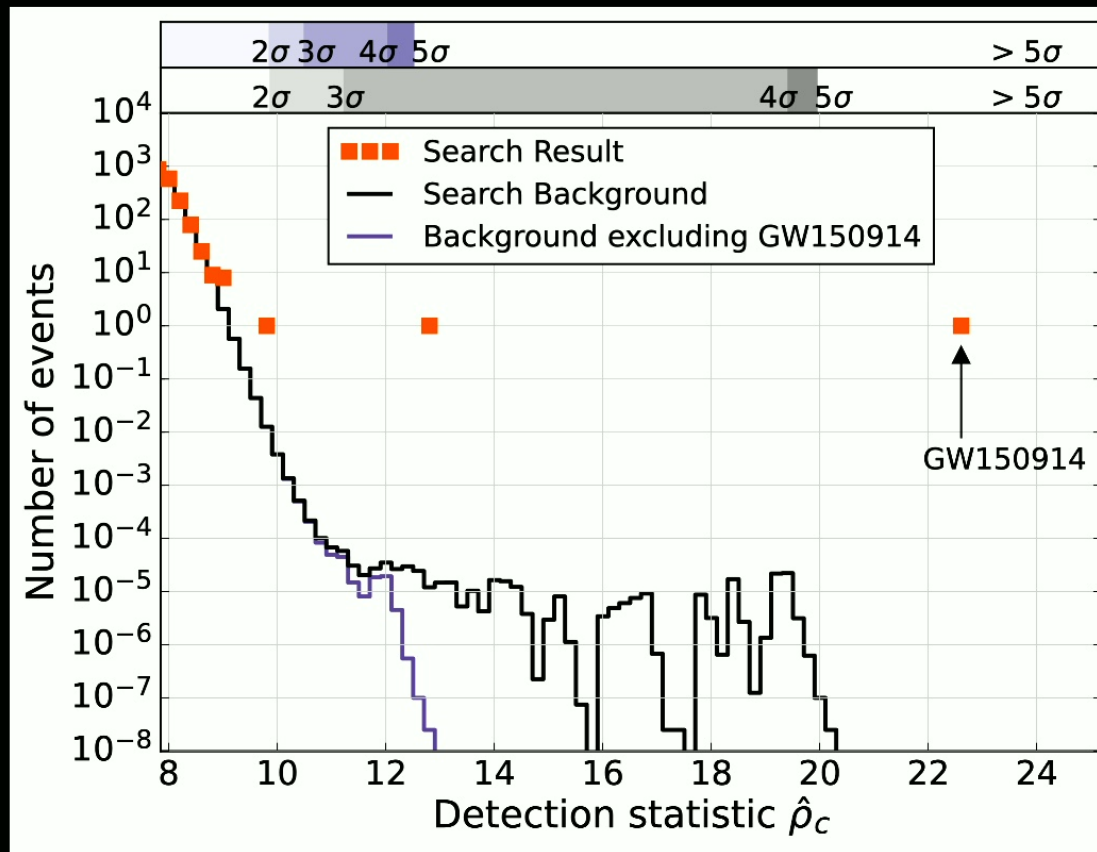
Calculating the noise background



Graphic by Alex Nitz

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Calculating the noise background



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

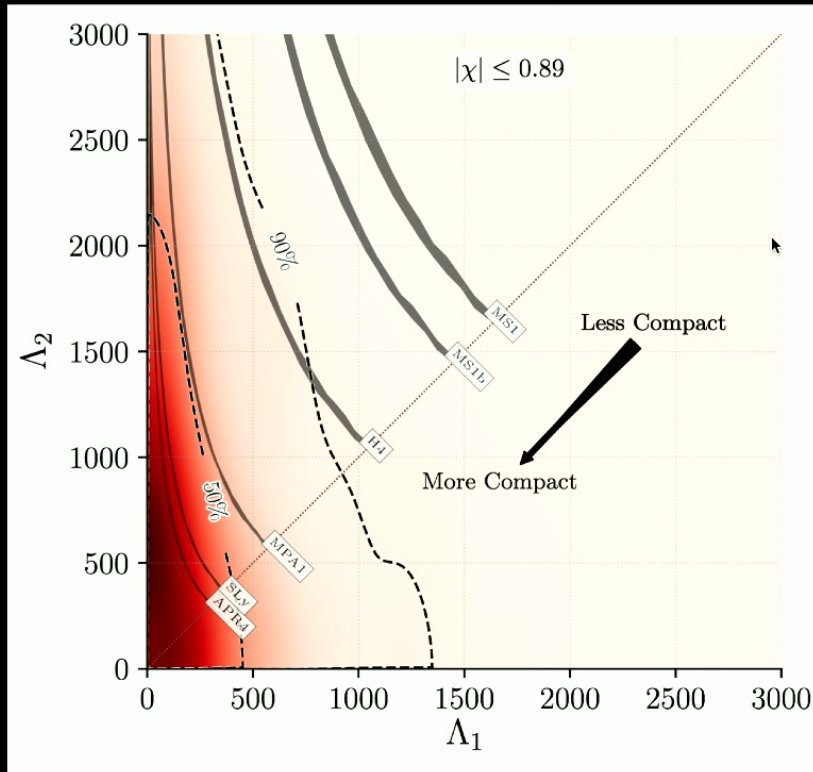
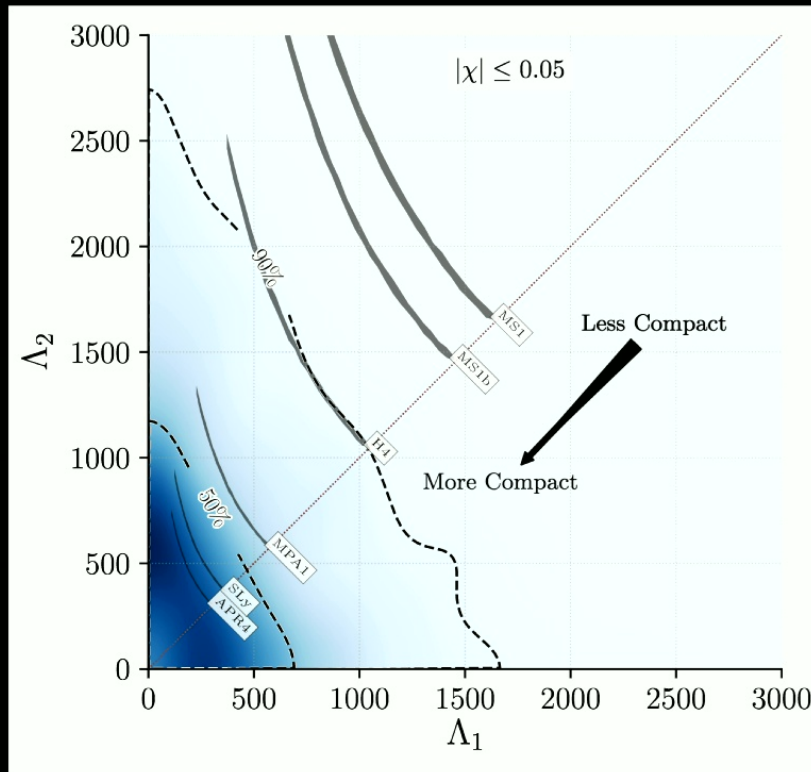
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From GWs: tidal deformability and constraining NS EoS

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

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

Great overview of Λ and love numbers by Katerina Chatziioannou (Caltech): [arXiv 2006.03169](https://arxiv.org/abs/2006.03169)



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



NASA/Goddard Space Flight Center/CI Lab

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