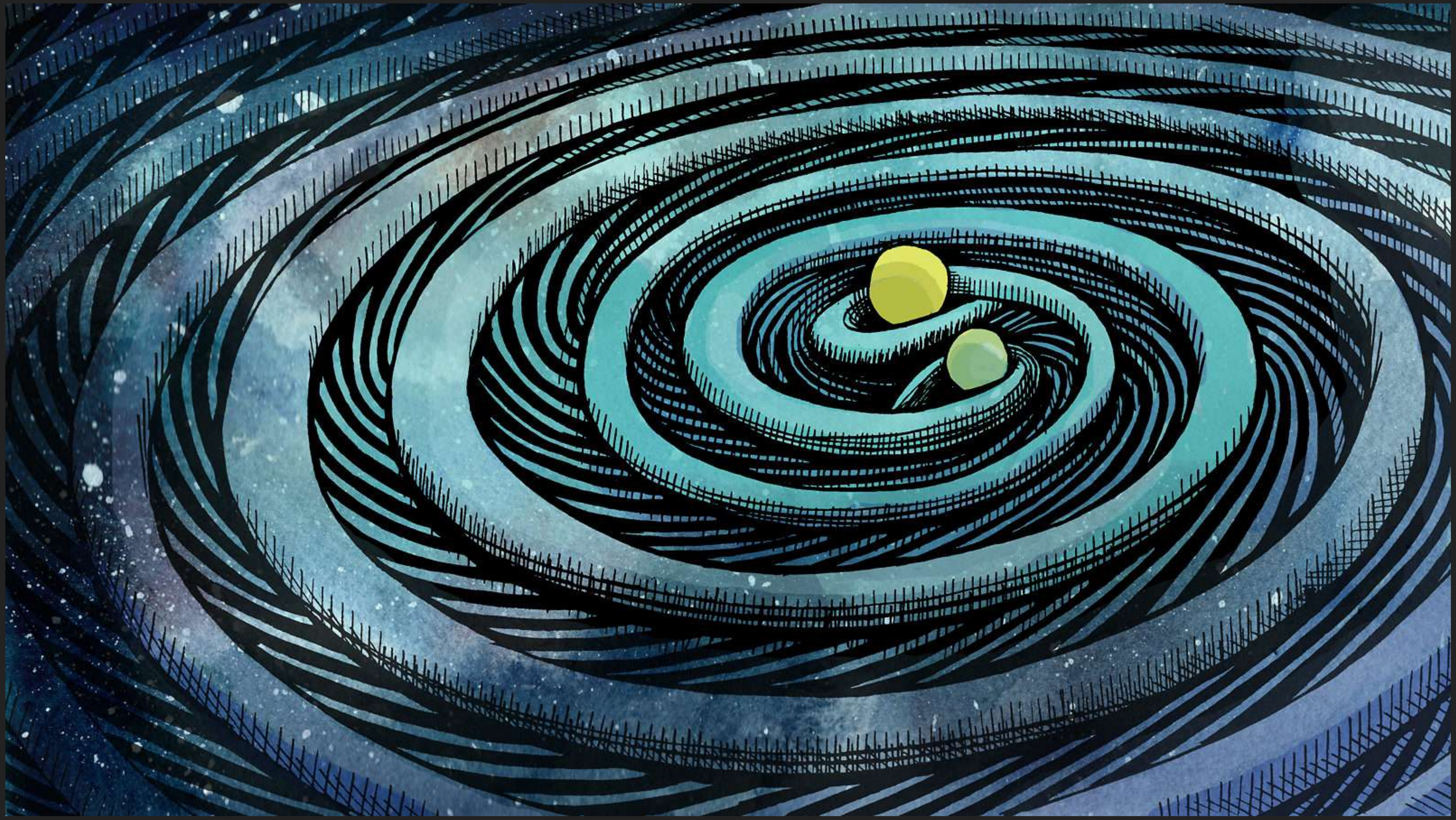
INTRODUCTION TO

GRAVITATIONAL WAVE SCIENCE



Artwork by Sandbox Studio, Chicago with Corinne Mucha

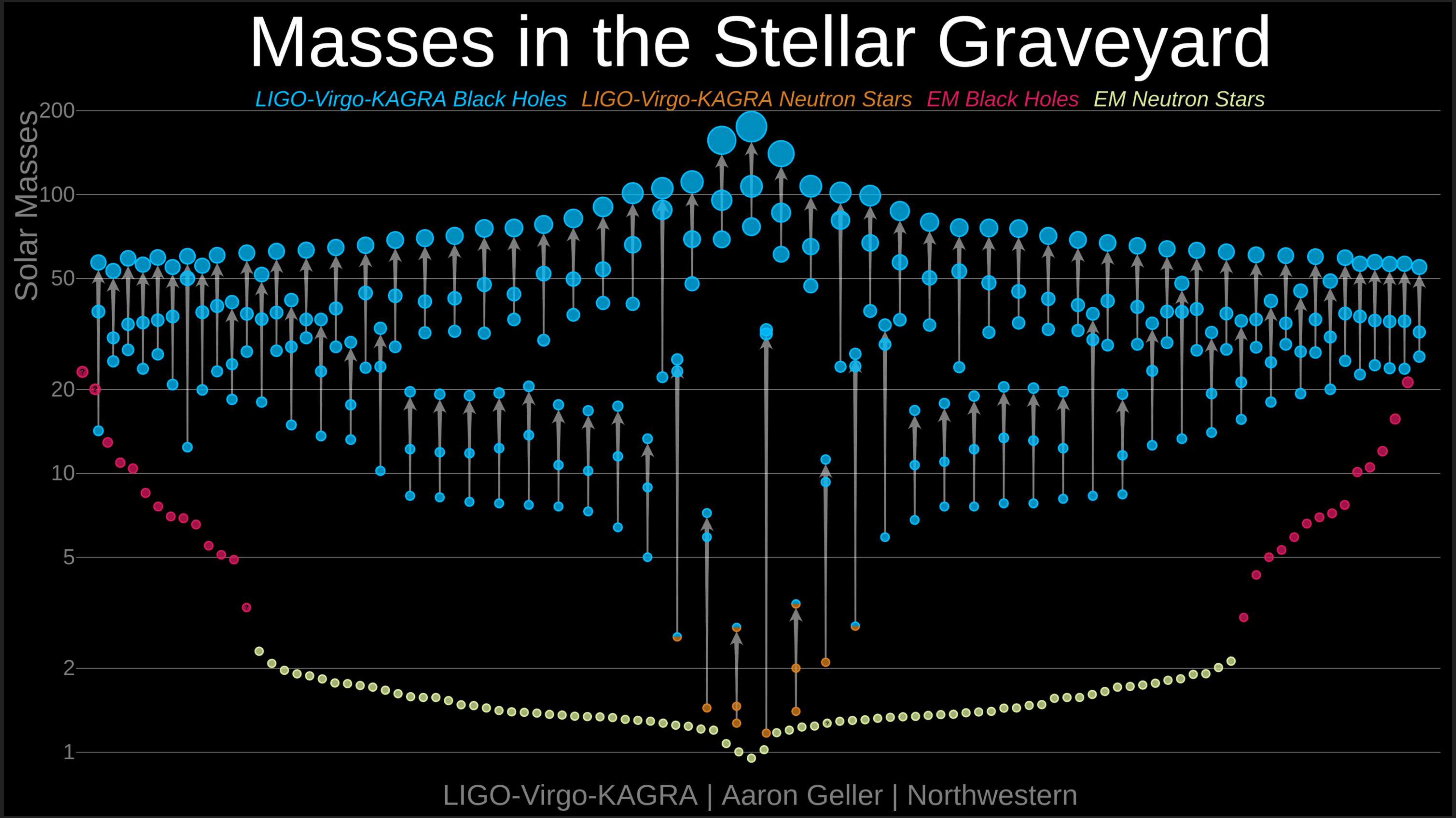
OUTLINE

- Why care?
- What are they?
- How do we detect them?
- How do we analyze them?
- What does the future hold?

INTRO TO GRAVITATIONAL WAVES

WHY YOU SHOULD CARE

A NEW ERA


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Electromagnetic Wave Windows

X-Ray

Optical

Radio

Credit: Laura Nuttall

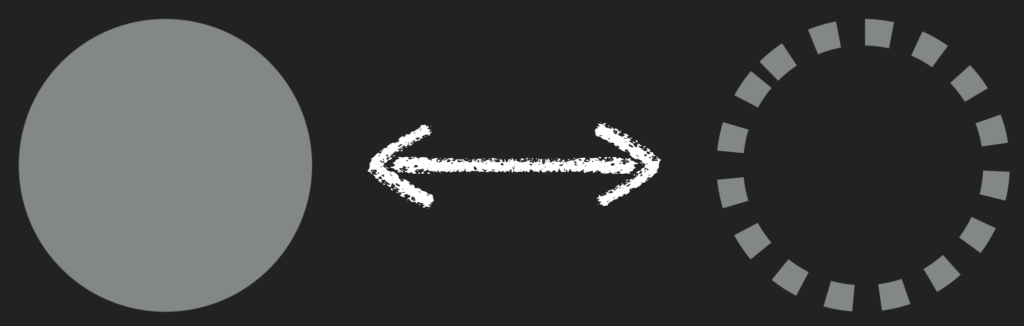
Gravitational Wave Periods

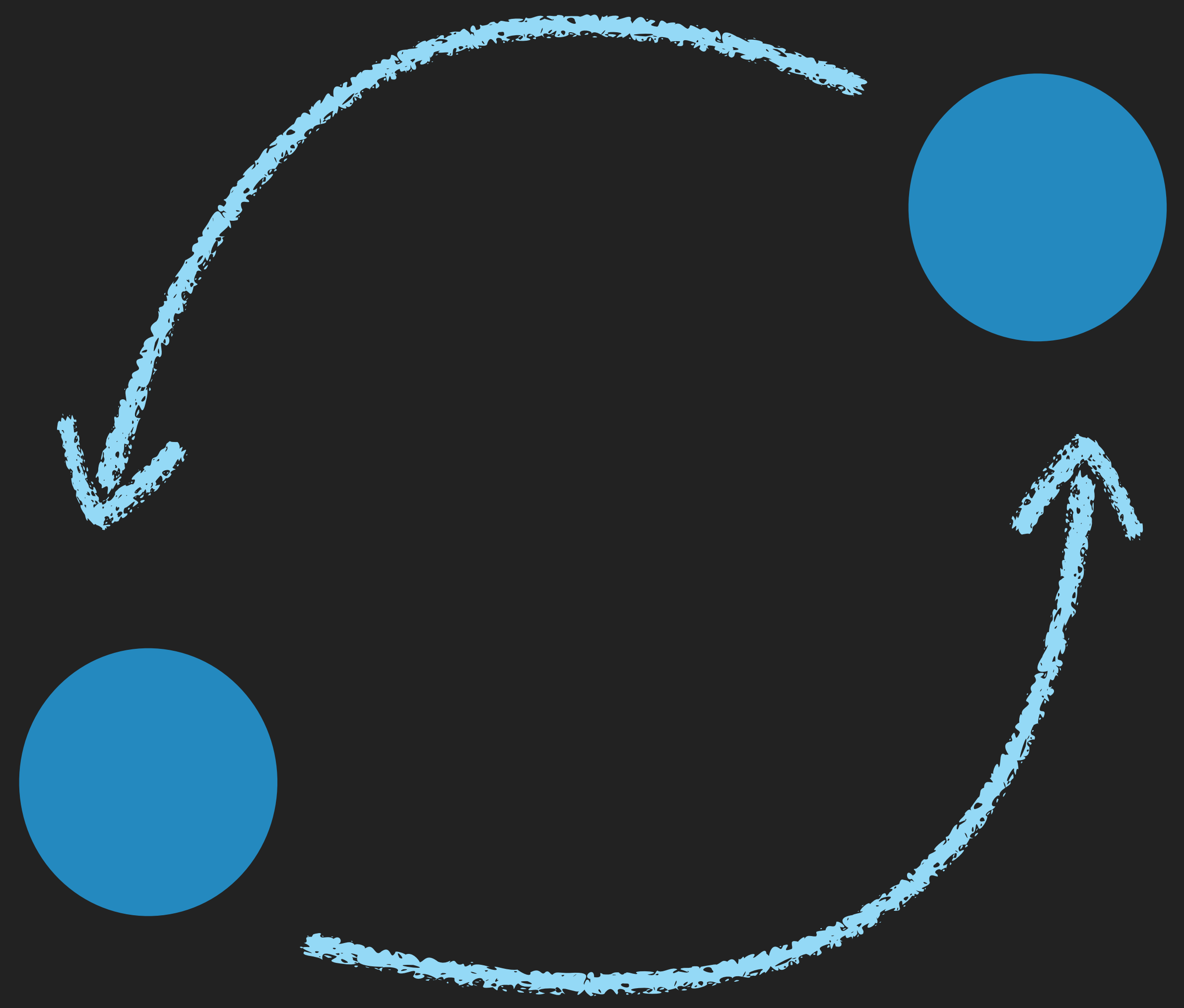
Milliseconds	Minutes to Hours	Years to Decades	Billions of Years

INTRO TO GRAVITATIONAL WAVES

WHAT ARE THEY?

GRAVITATIONAL RADIATION

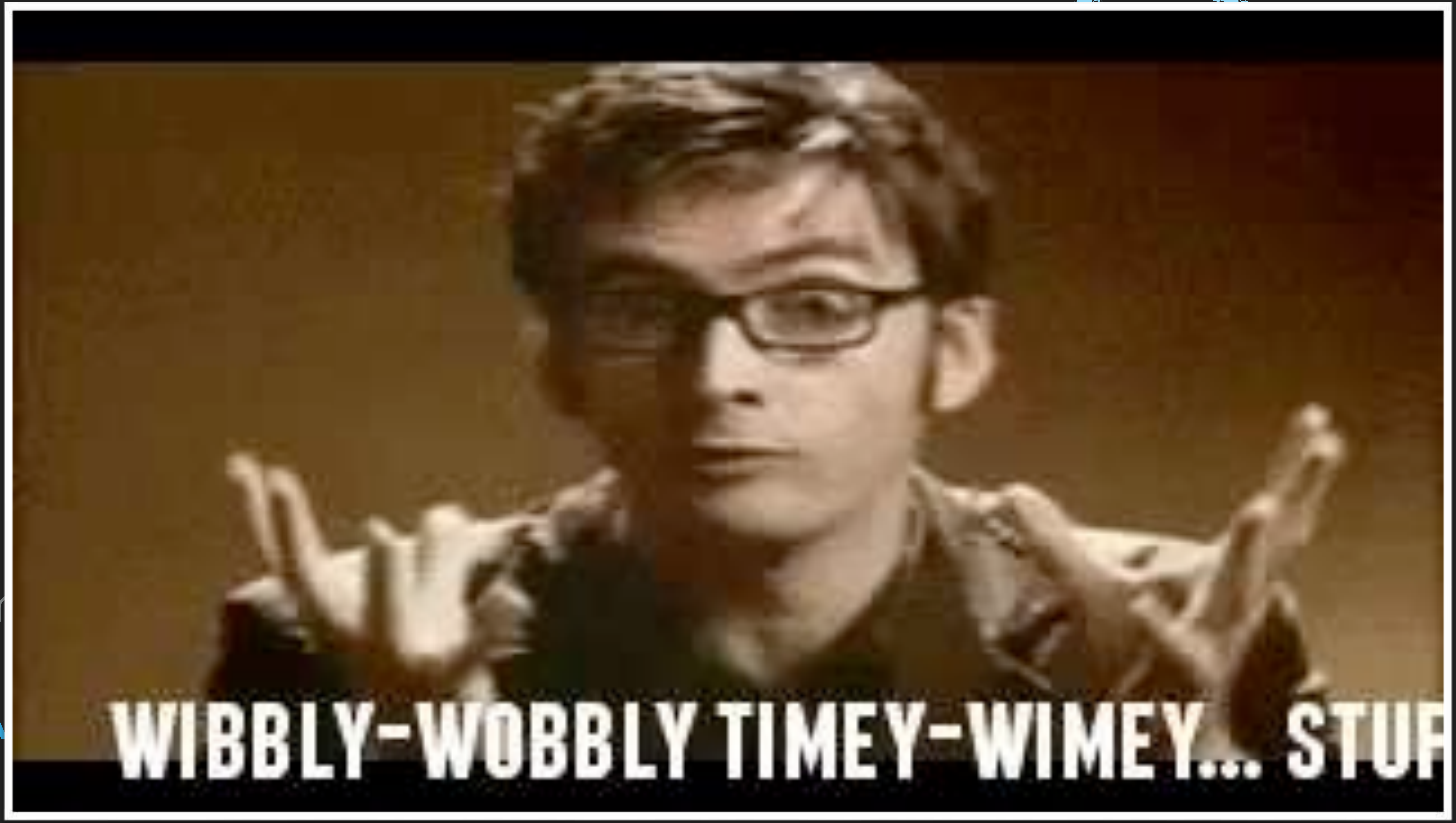




Asymmetric acceleration in **charge** == **Electromagnetic** radiation

Asymmetric acceleration in **mass** == **Gravitational** radiation

GRAVITATIONAL RADIATION



Asy … on

A

GW STRAIN

$$S = \int \left[\frac{1}{2\kappa}(R - 2\Lambda) + \mathscr{L}_{\mathrm{M}} \right] \sqrt{-g}\ \mathrm{d}^4x$$

$$\downarrow$$

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$\downarrow$$

$$\Box\, \bar{h}_{\mu\nu} = -\,16\pi T_{\mu\nu}$$

GW STRAIN

Emitted GW = Second time-derivative of **quadruple mass moment**

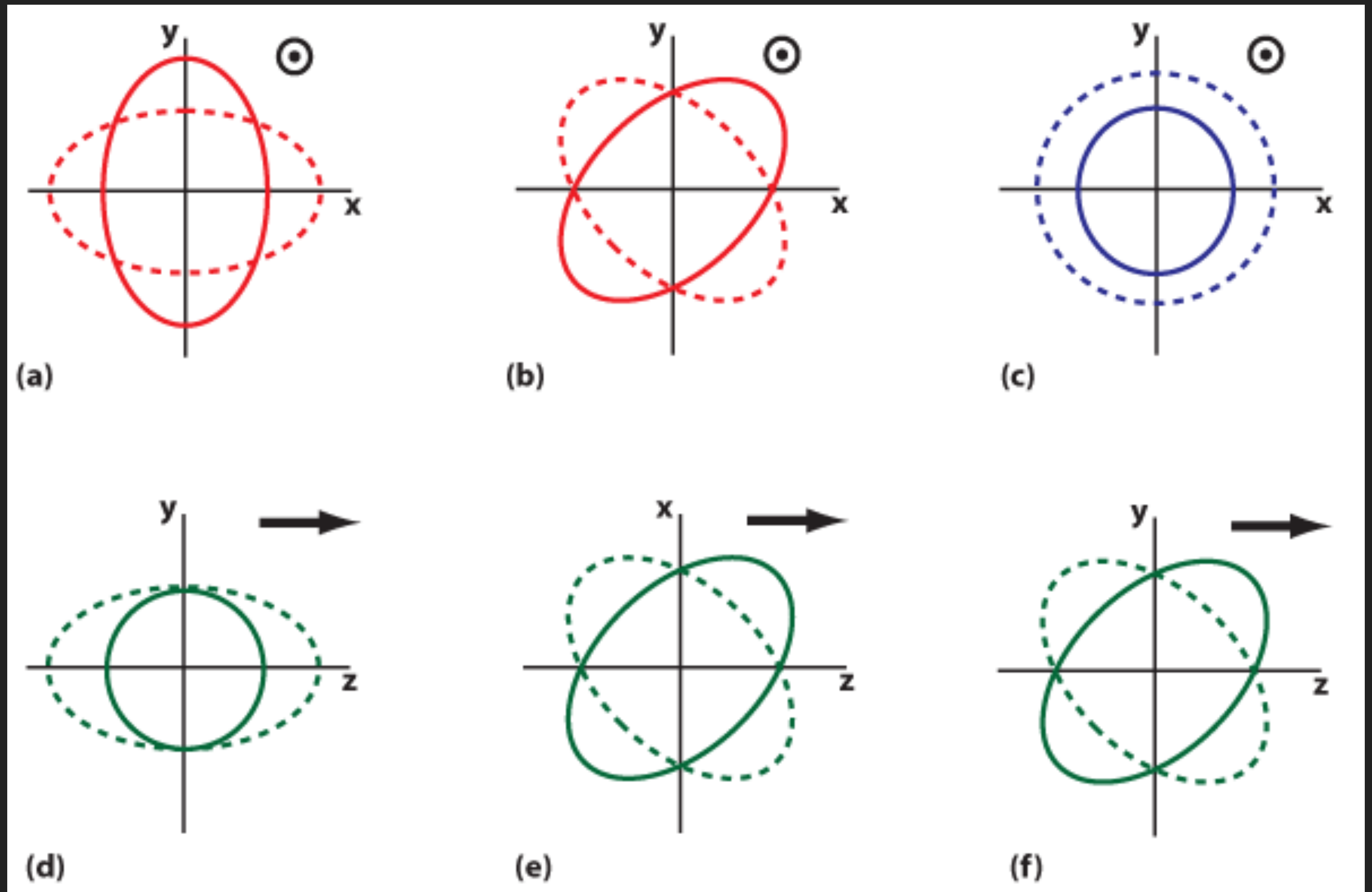
$$I_{ij}^{T} = \int \rho(\mathbf{x}) \left[r_i r_j - \frac{1}{3} r^2 \delta_{ij} \right] d^3 r$$

$$\bar{h}_{ij}(t, r) = \frac{2G}{c^4 r} \ddot{I}_{ij}(t - r/c)$$

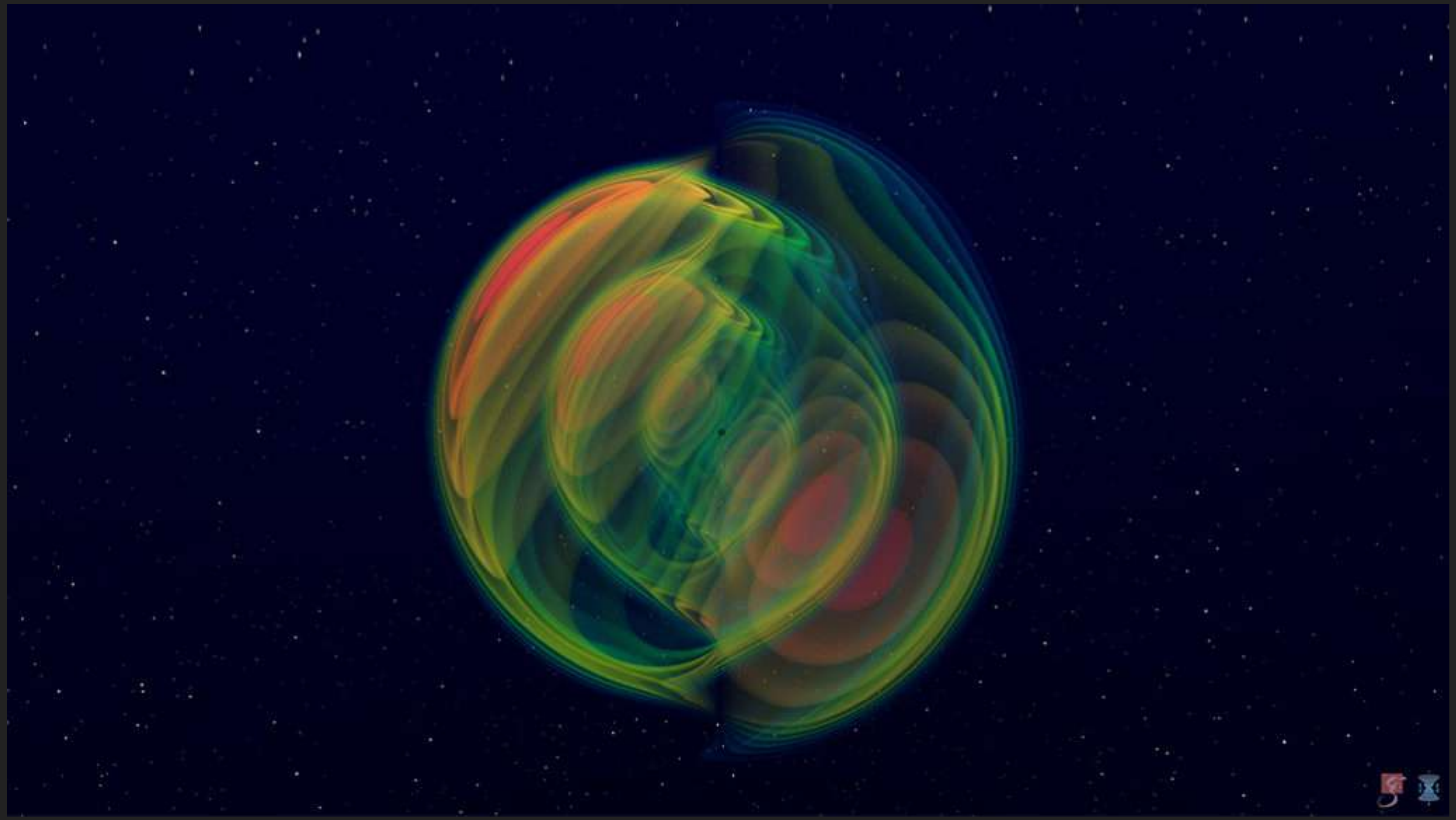
POLARIZATION & HARMONIC DECOMPOSITION

$$h = h_+ - ih_\times$$

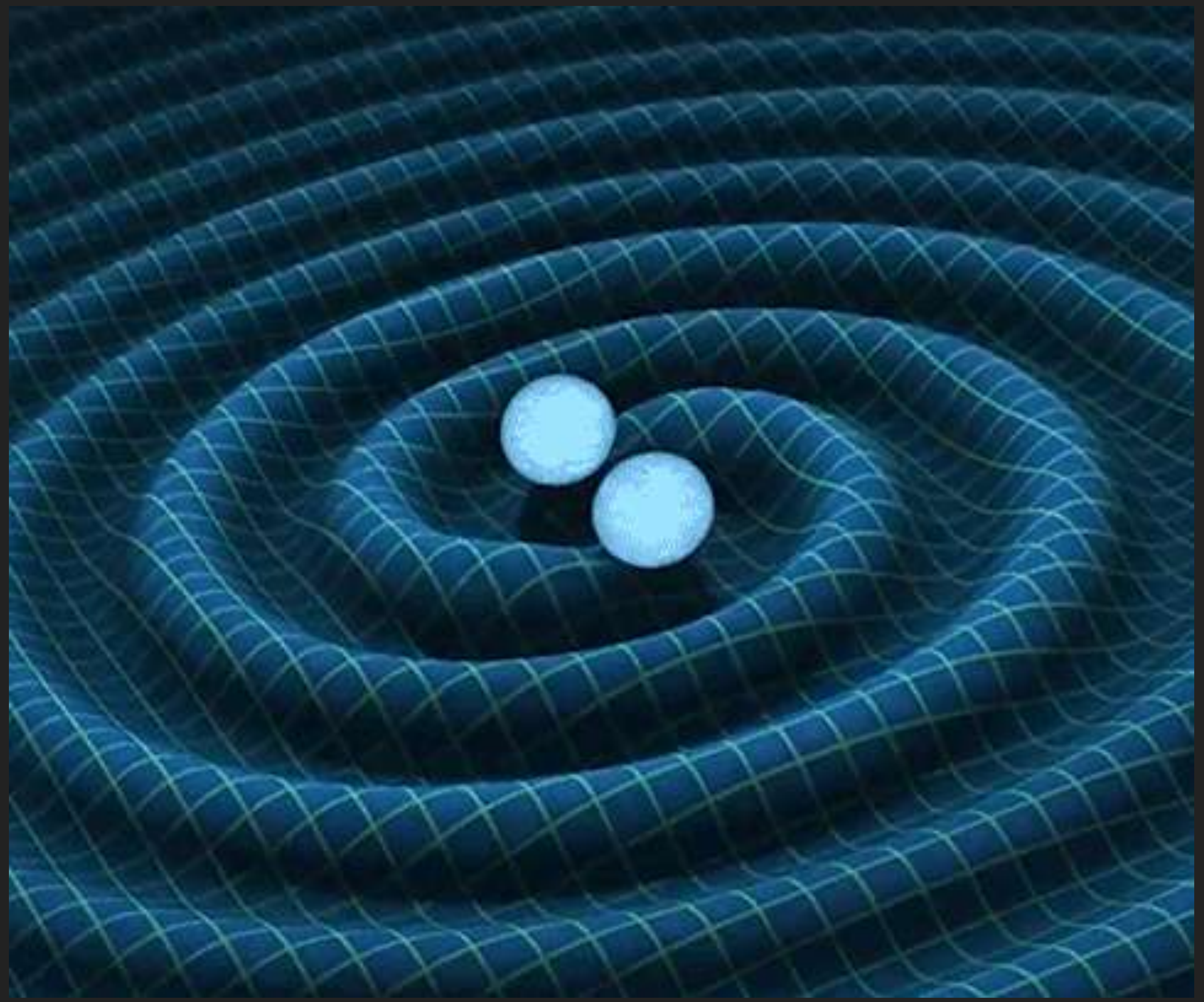
$$h_+ - ih_\times = \frac{1}{r}\sum_{\ell,m}\sqrt{(\ell+2)!\,/\,(\ell-2)!}\left(\Psi^{(e)}_{\ell m} + i\Psi^{(o)}_{\ell m}\right)\,{}_{-2}Y^{\ell m}(\theta,\phi)$$



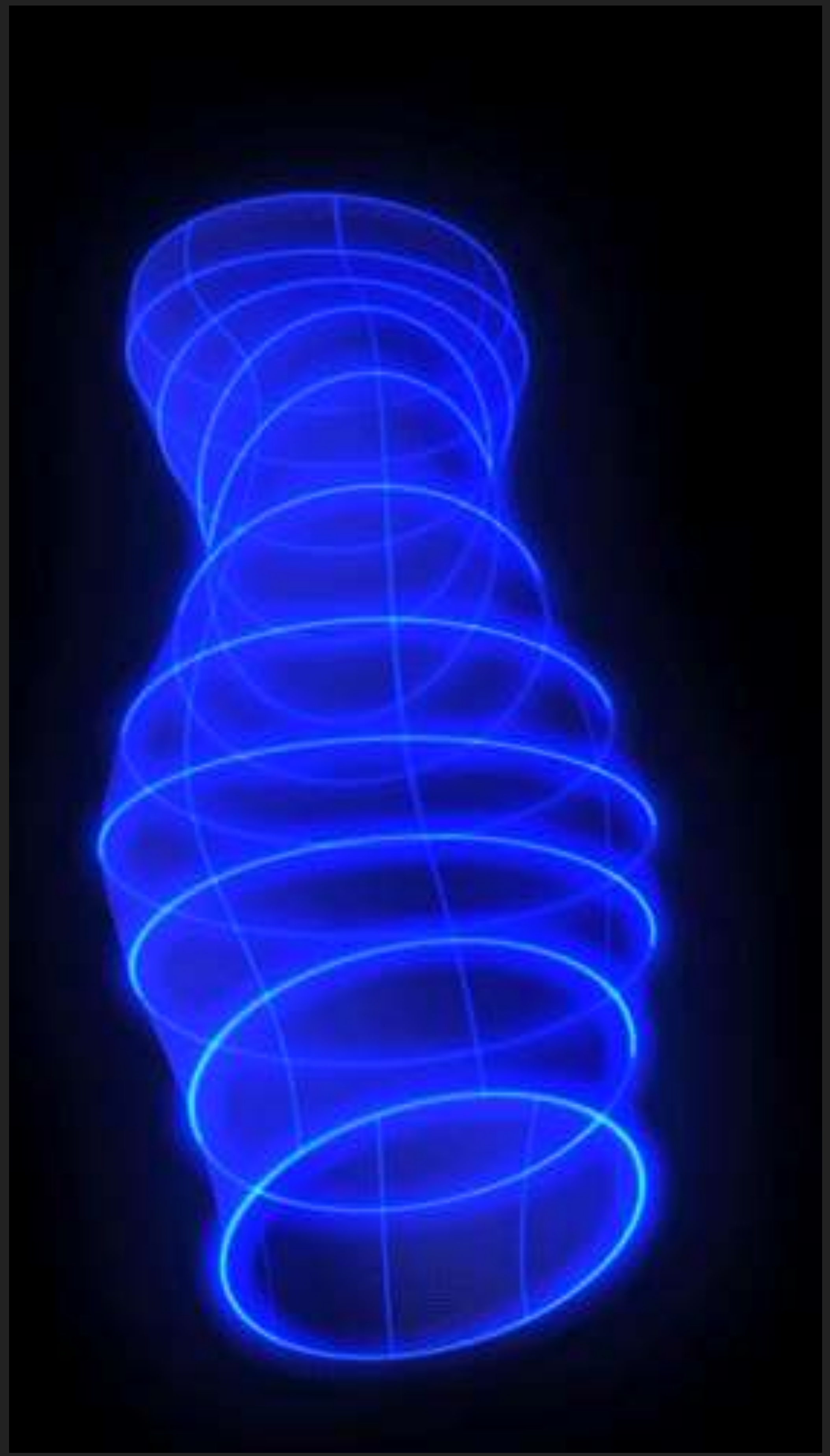
Credit: Gair et al., Living Rev. Relativity (2013)


Credit: SXS Collaboration

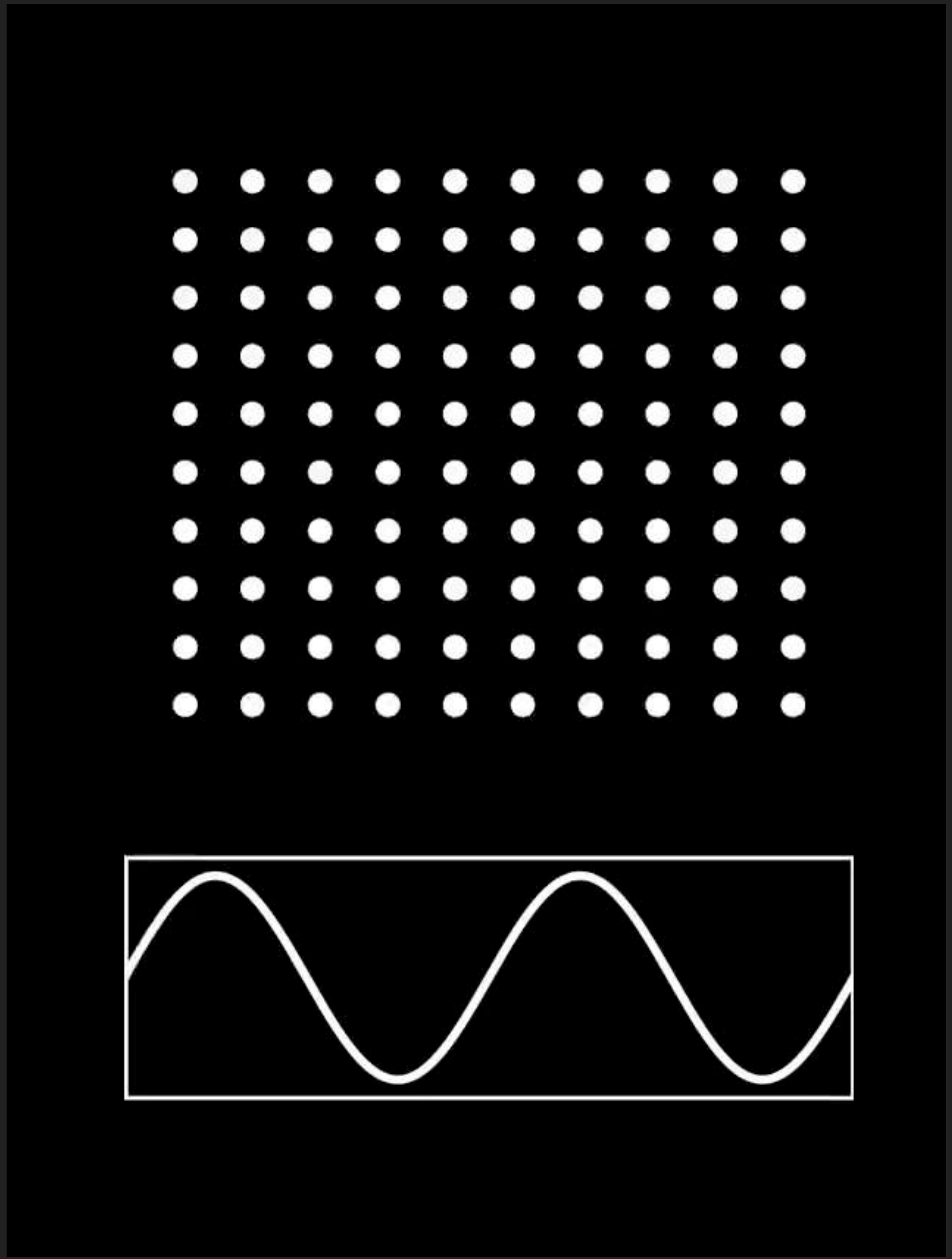
VISUALIZATIONS



Credit: LIGO/Caltech

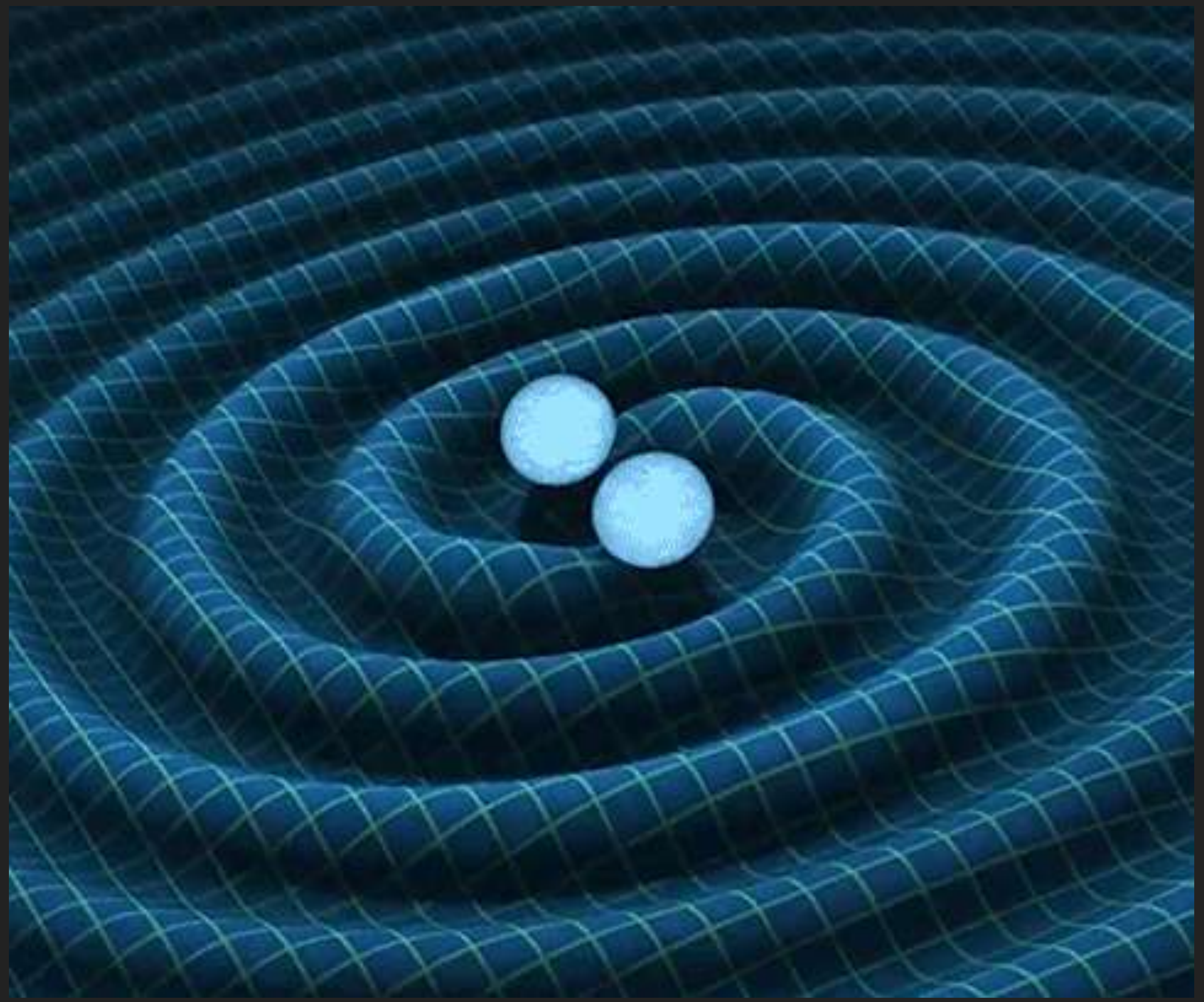


Credit: ESA



Credit: Carl Rodriguez

VISUALIZATIONS



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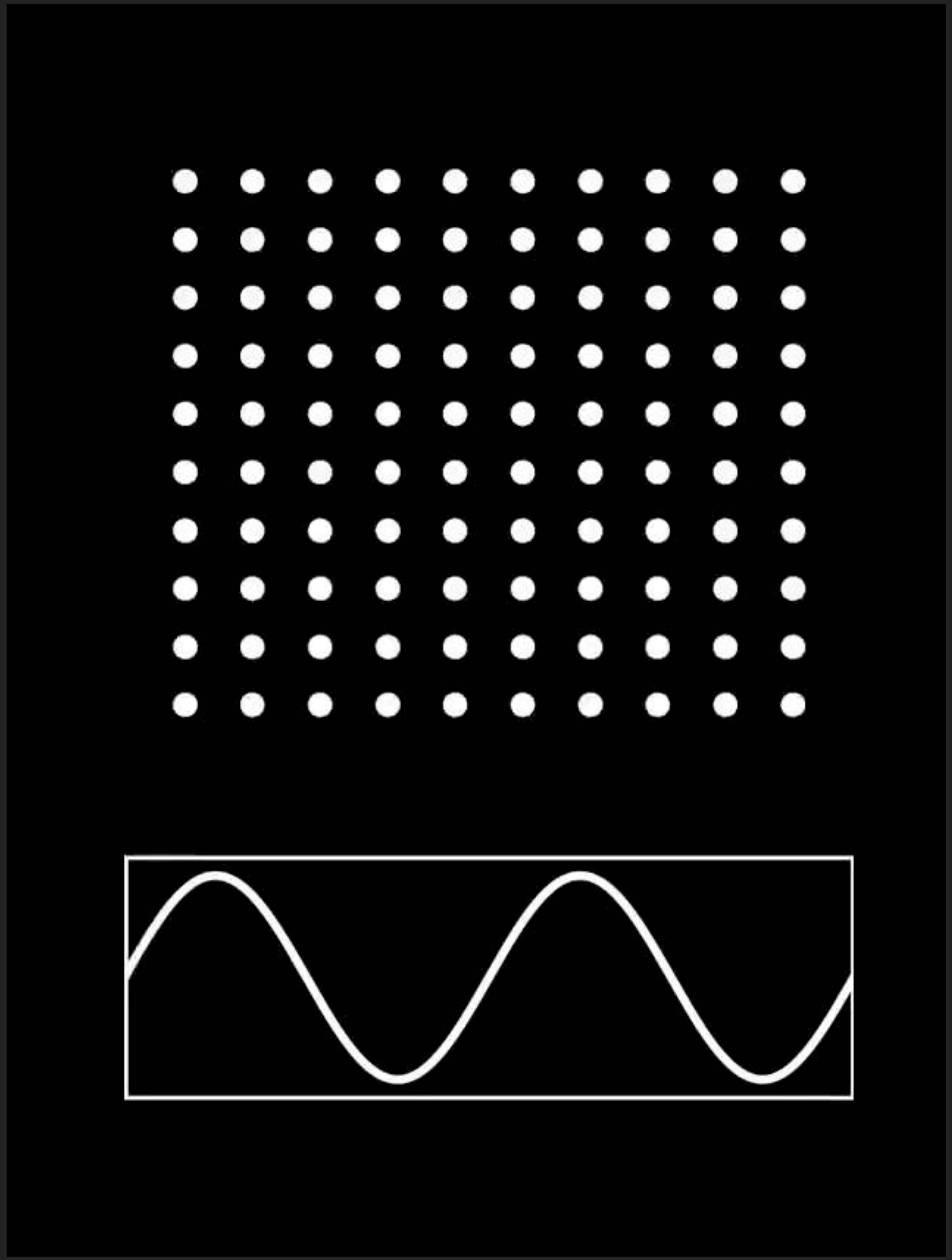
Credit: ESA



Credit: Carl Rodriguez

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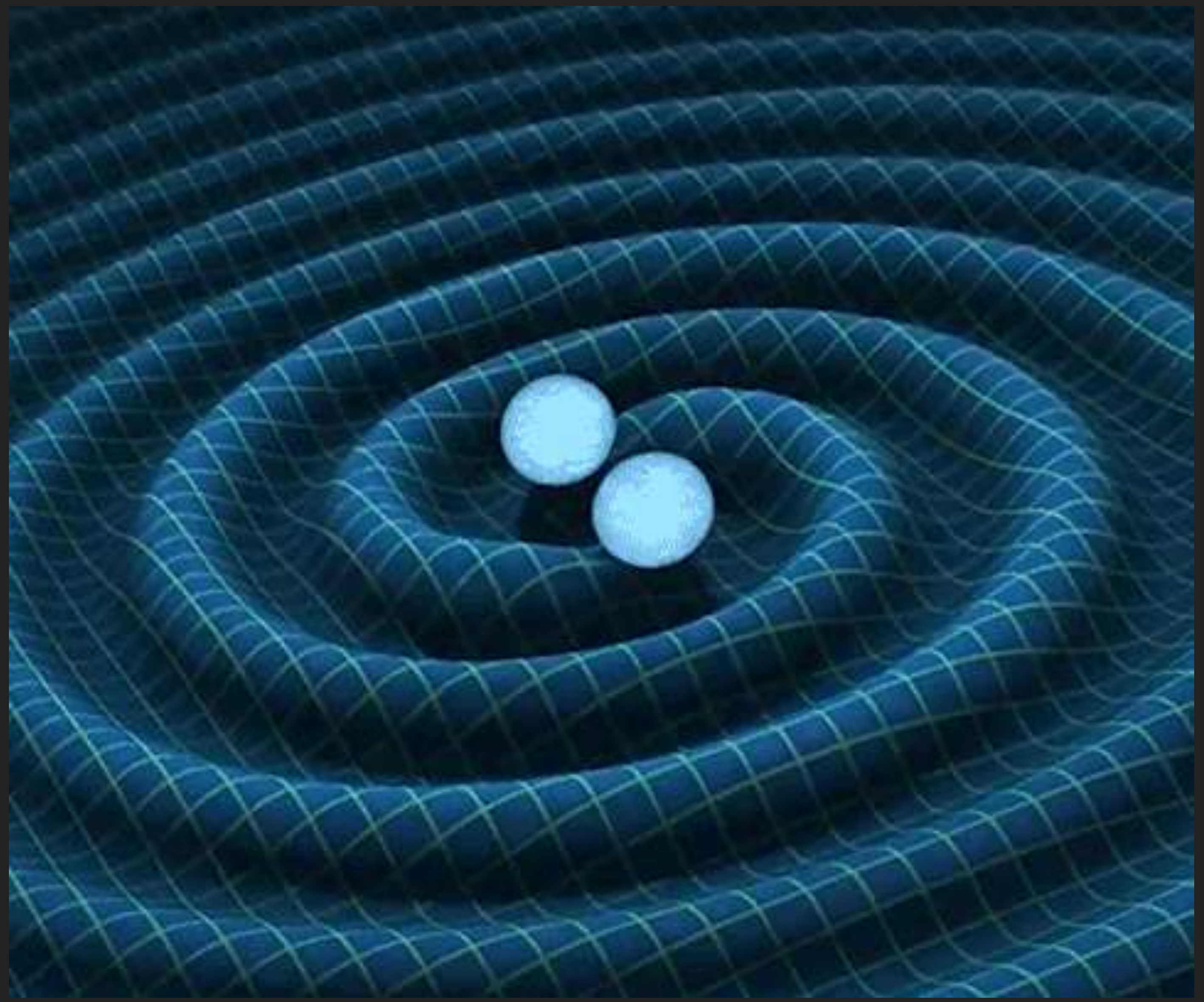
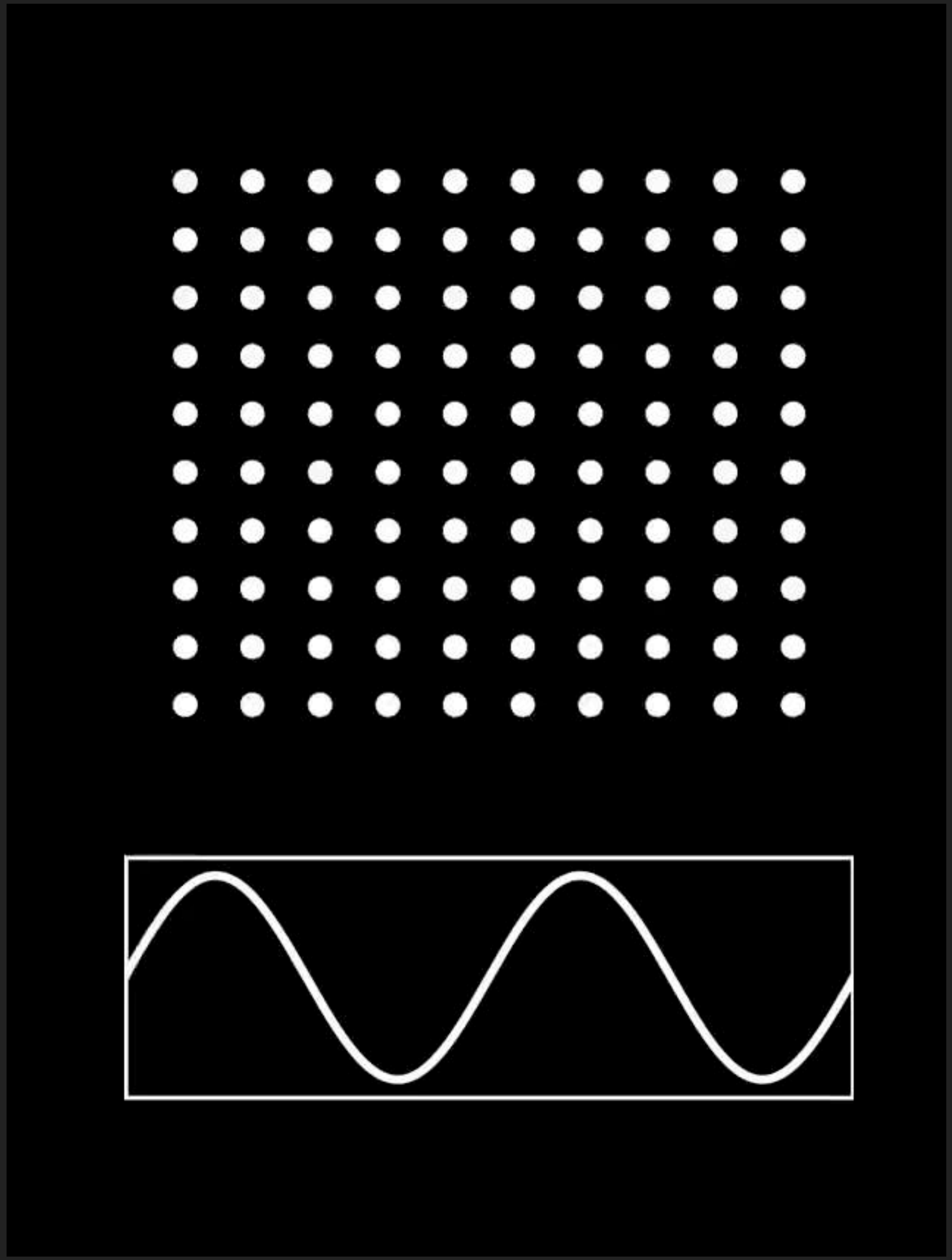


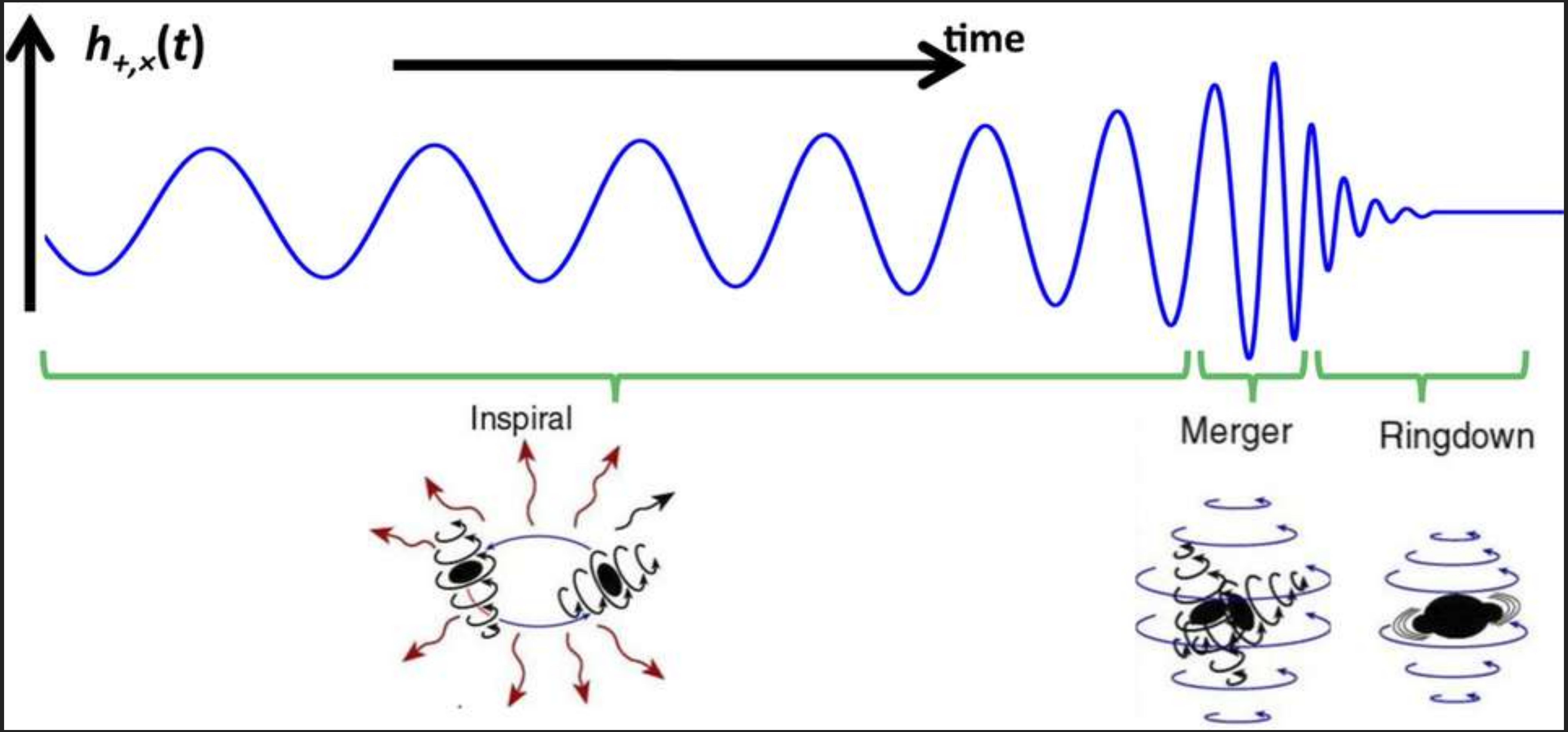
Credit: LIGO/Caltech

Credit: ESA



Credit: Carl Rodriguez

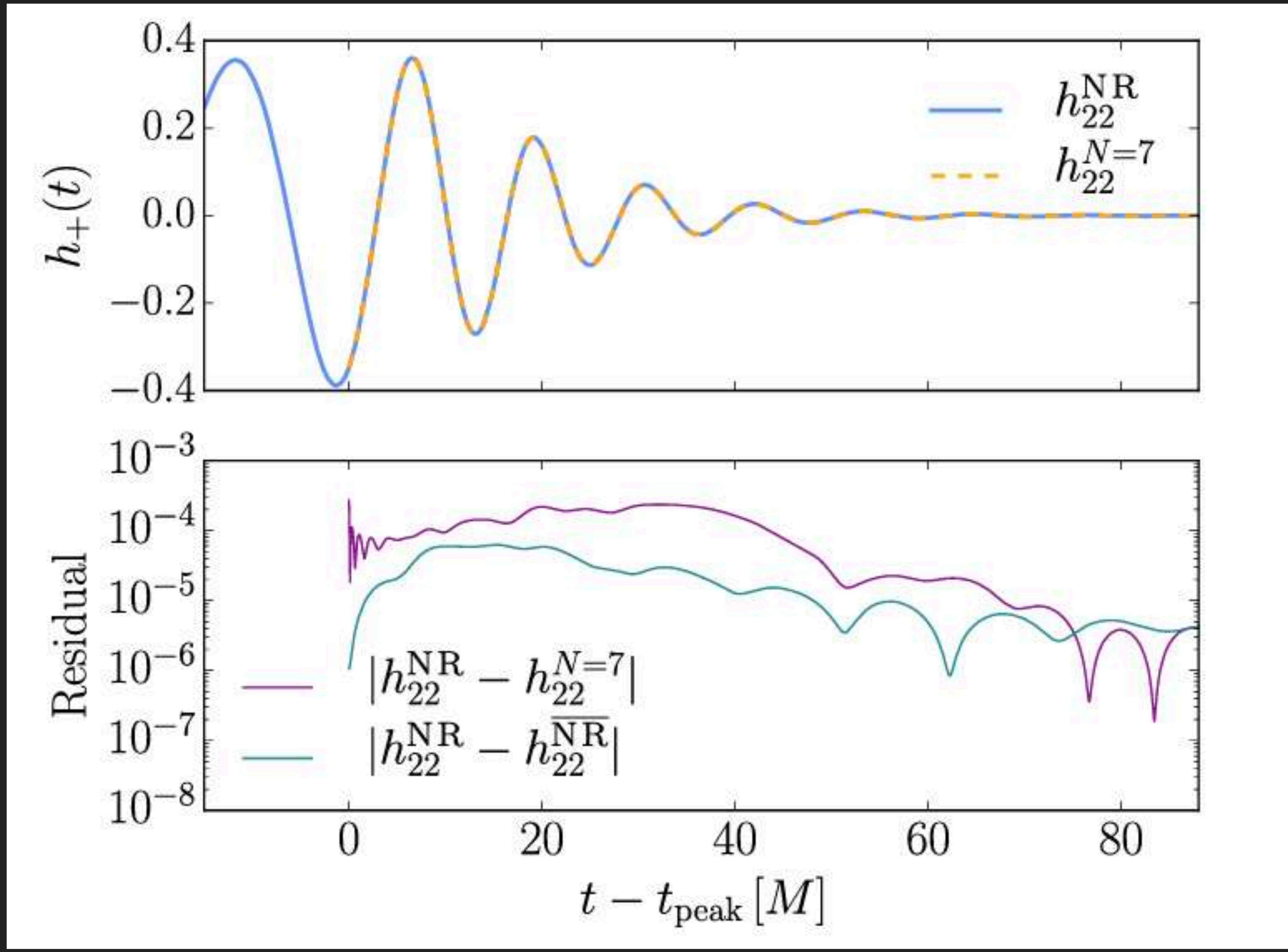
BINARY BLACK HOLE WAVEFORM



Credit: M. Favata/SXS/K. Thorne

PORTFOLIO OF OBSERVATIONS

- Binary Black Holes
- Binary Neutron Stars
- Neutron Star - Black Hole
- Evidence for:
  - Precession
  - Quasi-normal modes in ringdown



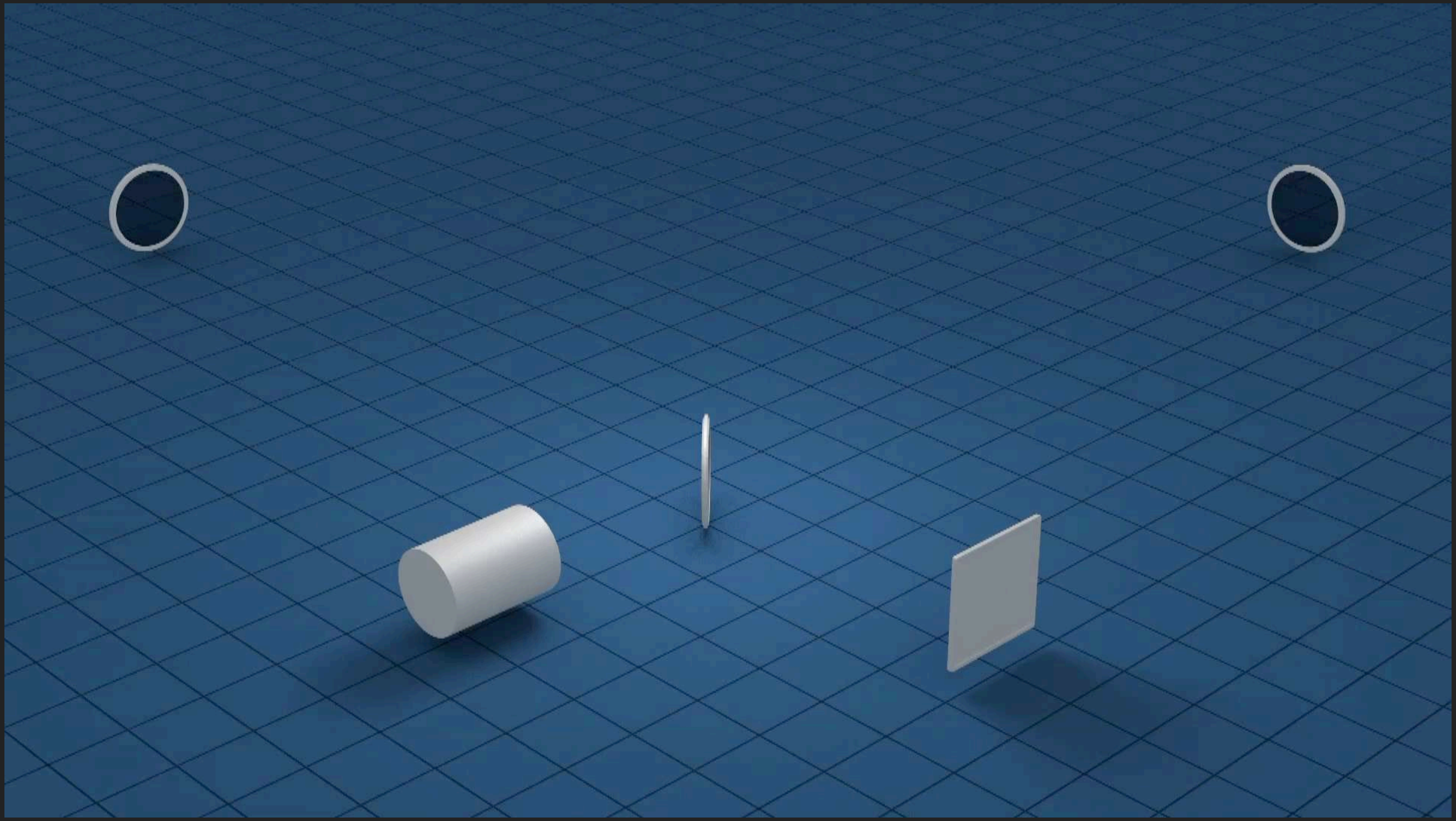
Credit: Giesler et al., Phys Rev. X (2019)

INTRO TO GRAVITATIONAL WAVES

HOW DO WE DETECT THEM?

MICHELSON INTERFEROMETER

$$h \propto \Delta L \,/\, L$$



Credit: LIGO/Caltech

MICHELSON INTERFEROMETER

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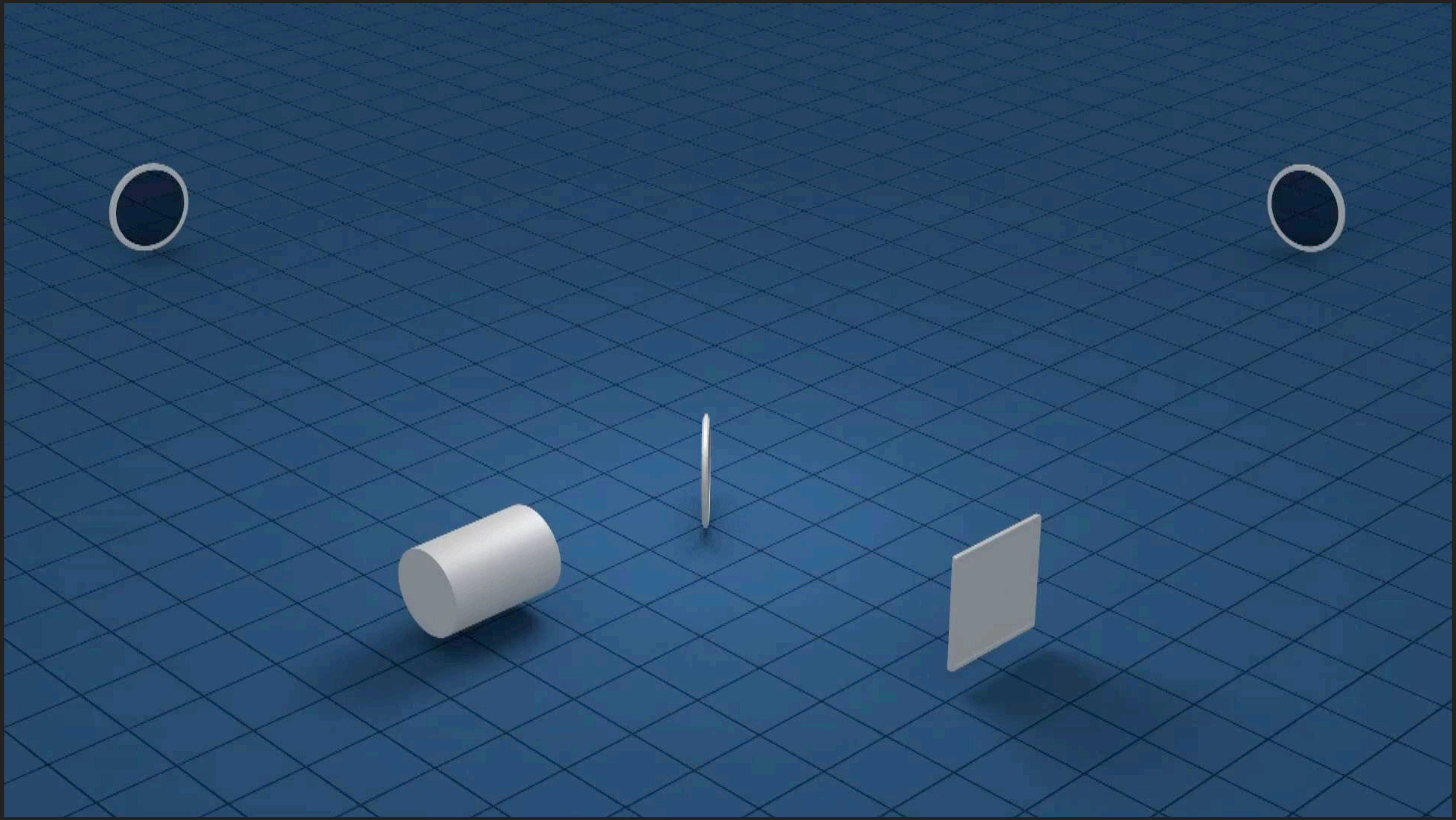
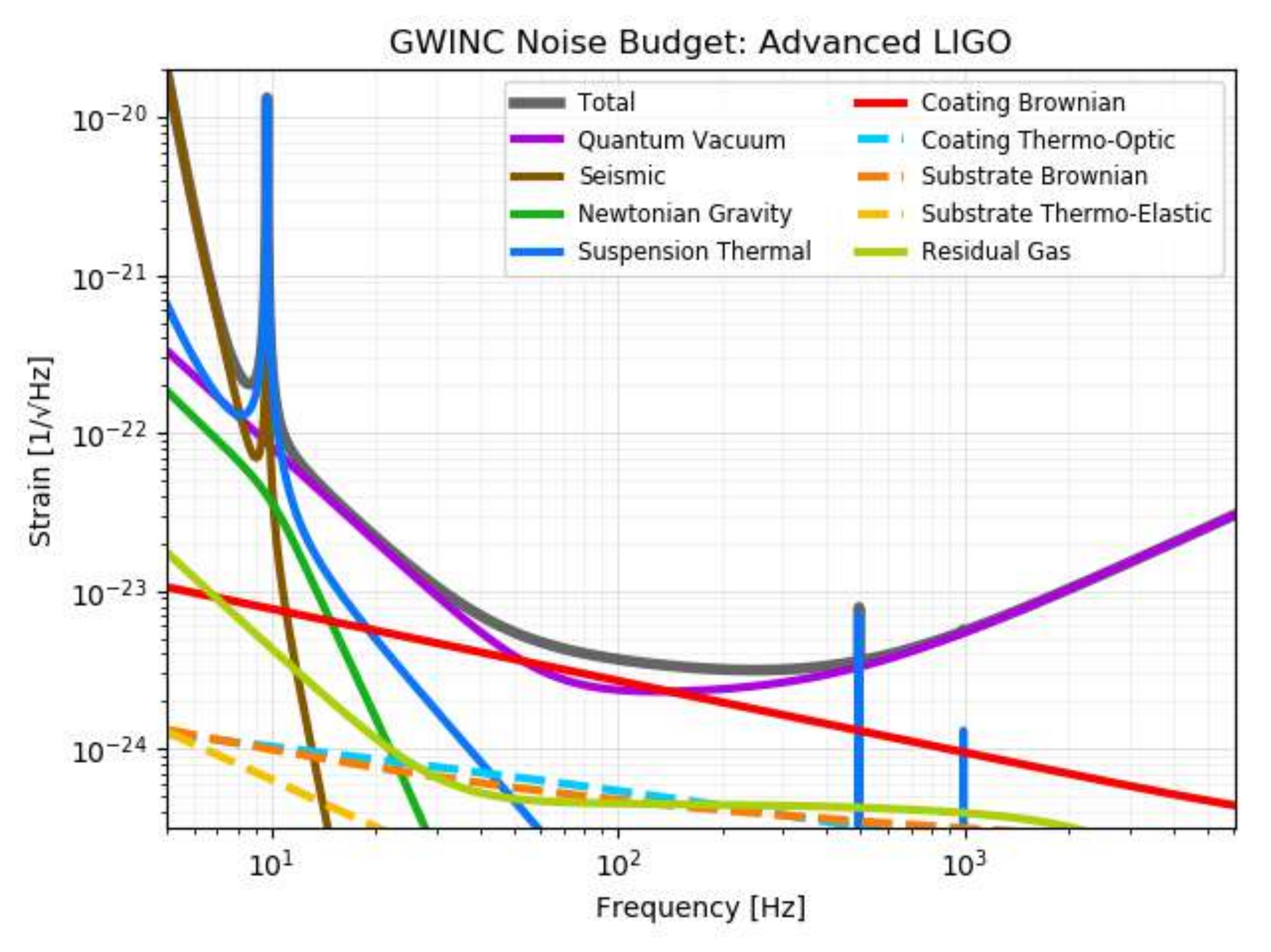


Credit: LIGO/Caltech

LIGO NOISE CURVE

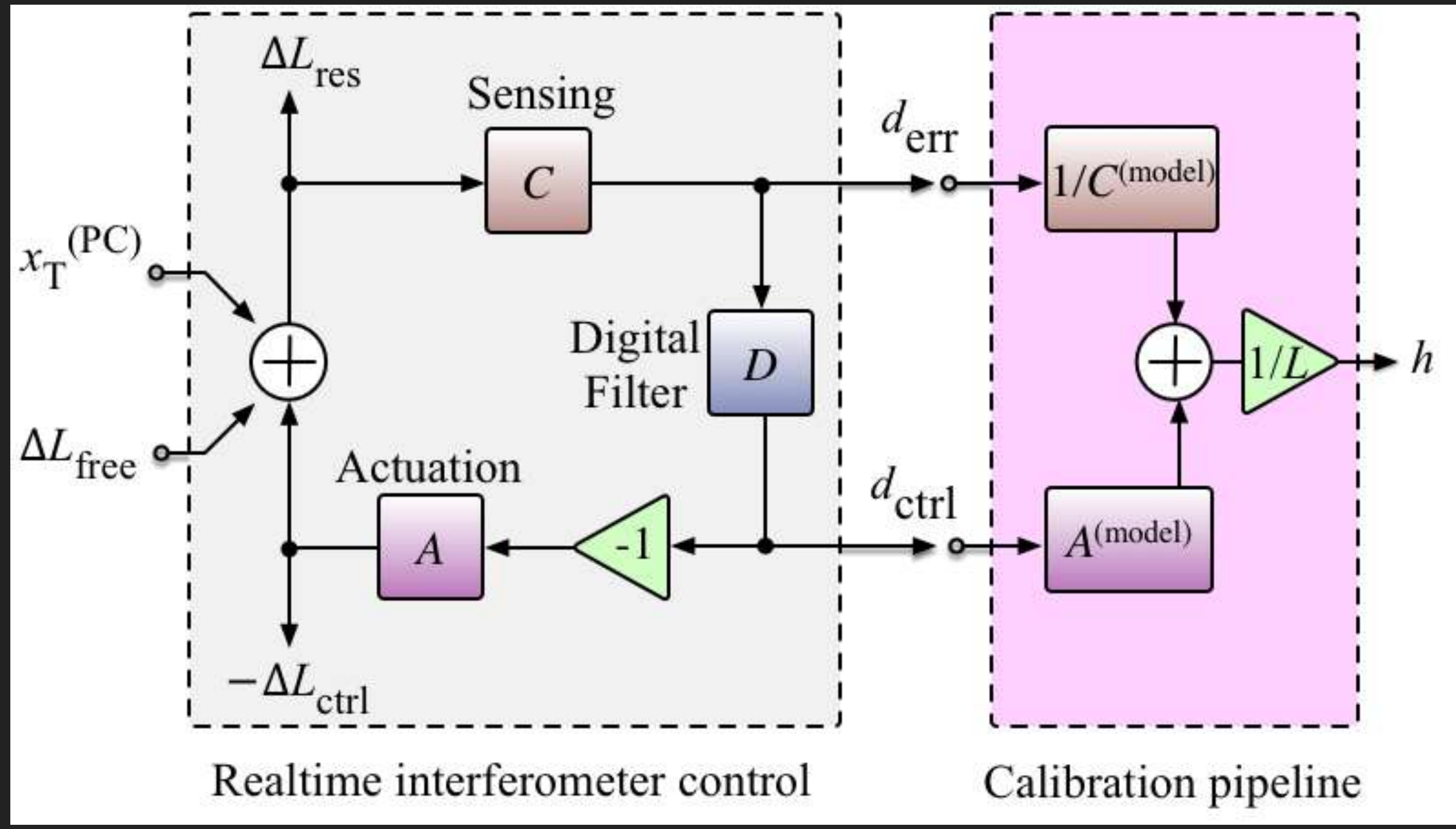
- Dominated by:
  - Seismic (low freqs)
  - Thermal (low freqs)
  - Quantum (higher freq)
- Light Squeezing
  - Uncertainty principle applied to time/freq



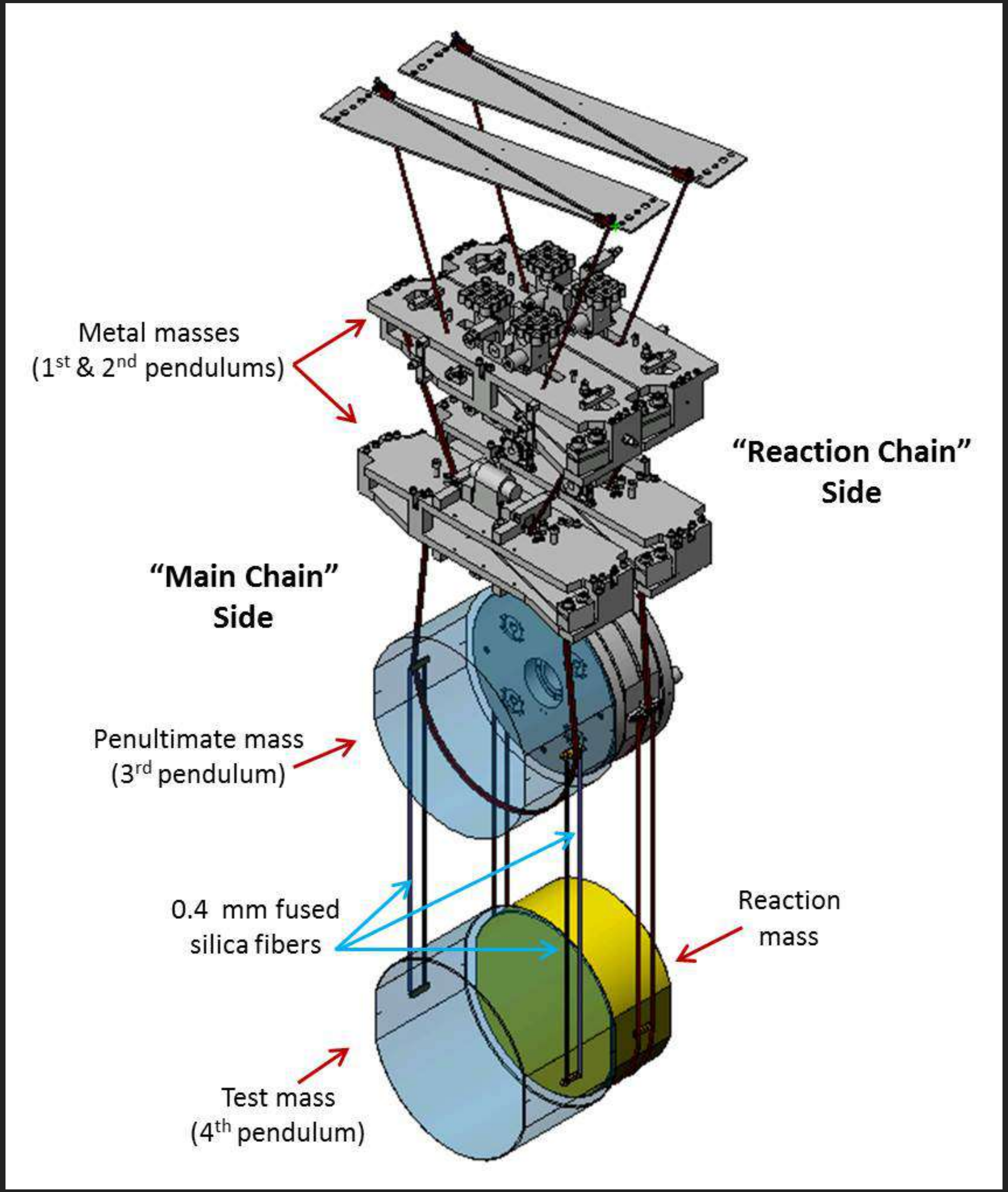
Credit: Wang et al., 2023

SEISMIC ISOLATION

- Mirrors suspended from seismic noise via quadruple pendulum system
- Actuators on reaction test mass
- Motion-dampening pads placed under pretty much everything

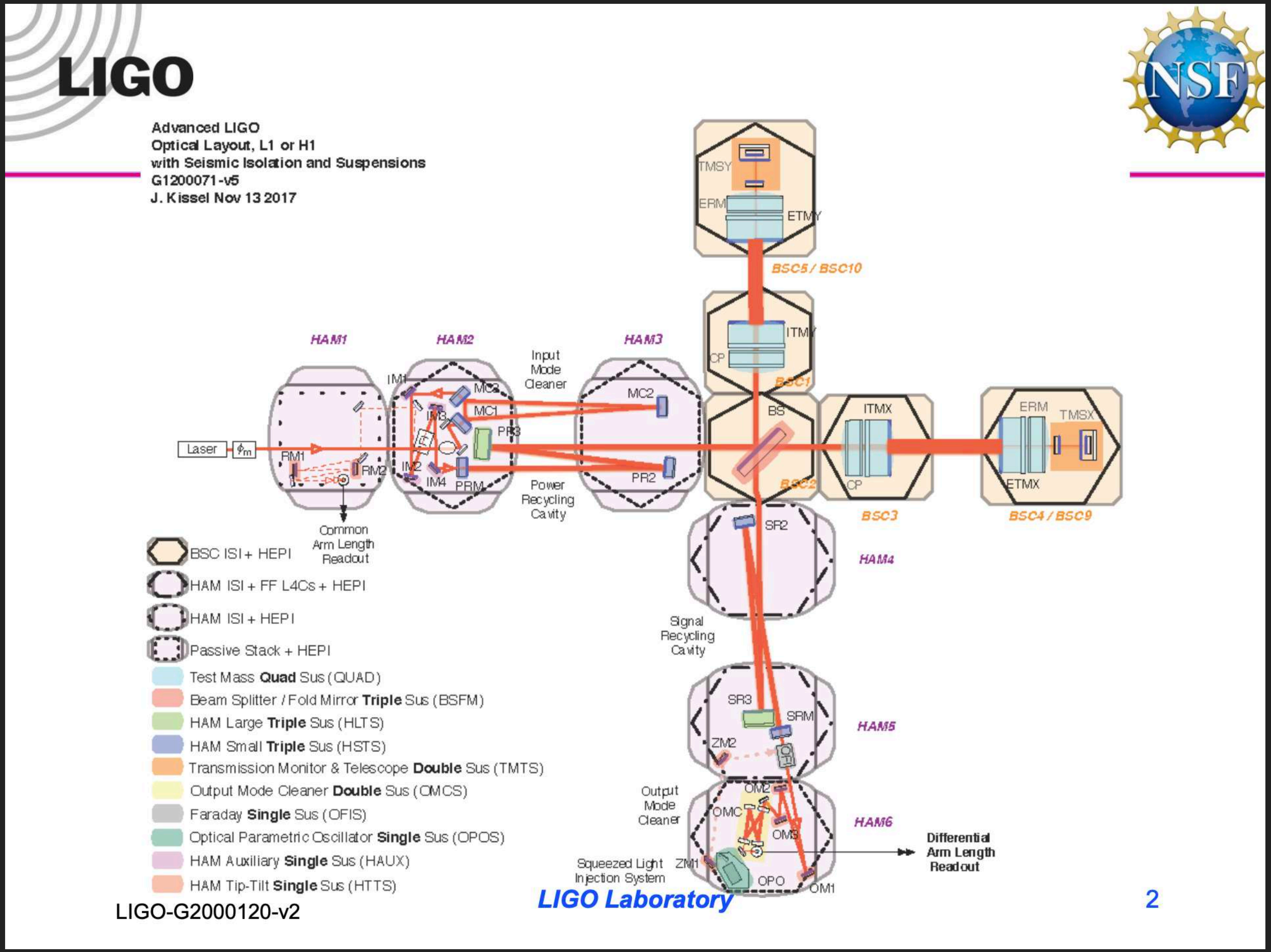


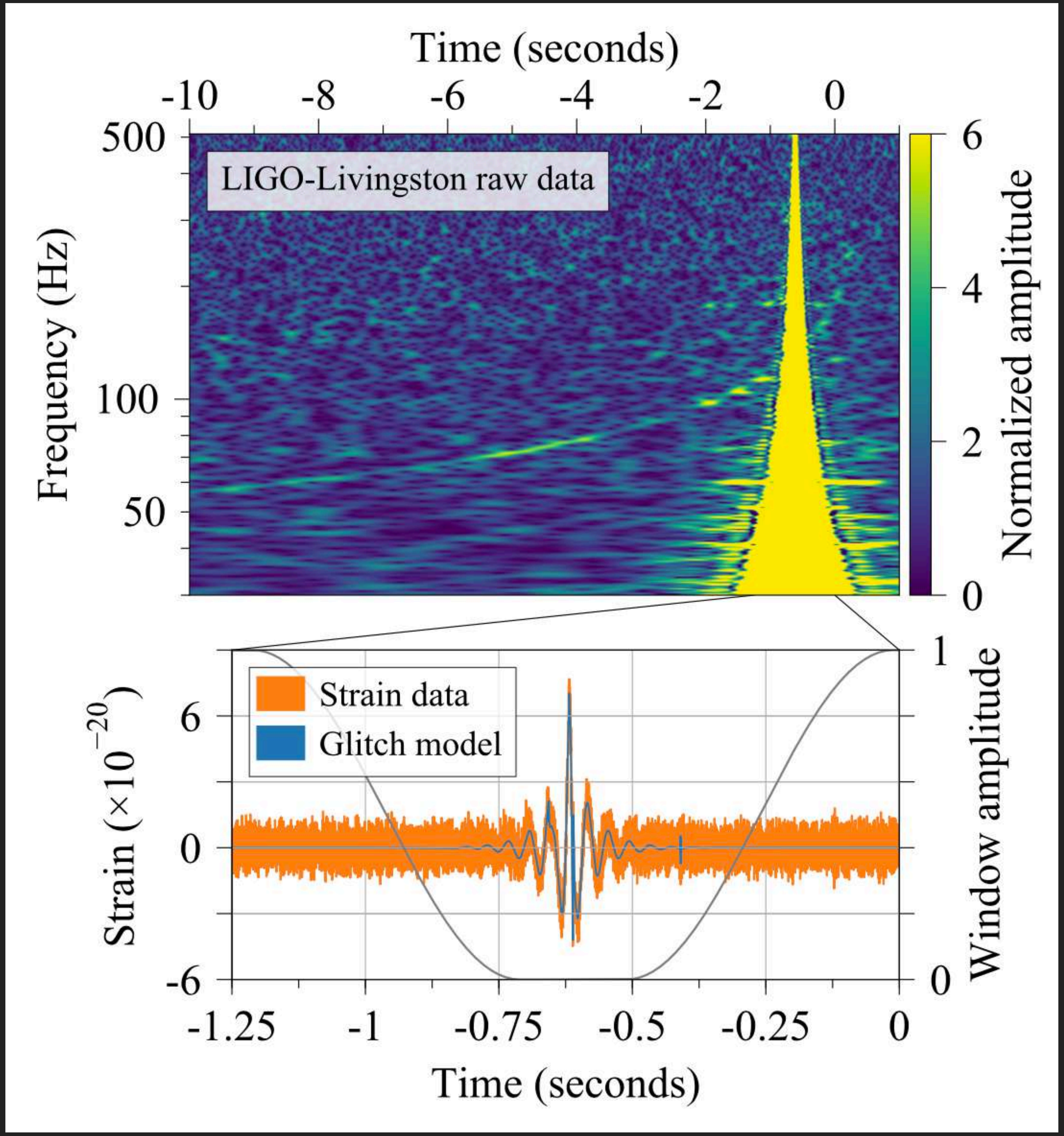
Credit: LIGO/Caltech



Credit: LIGO/Caltech

DETECTOR CHARACTERIZATION

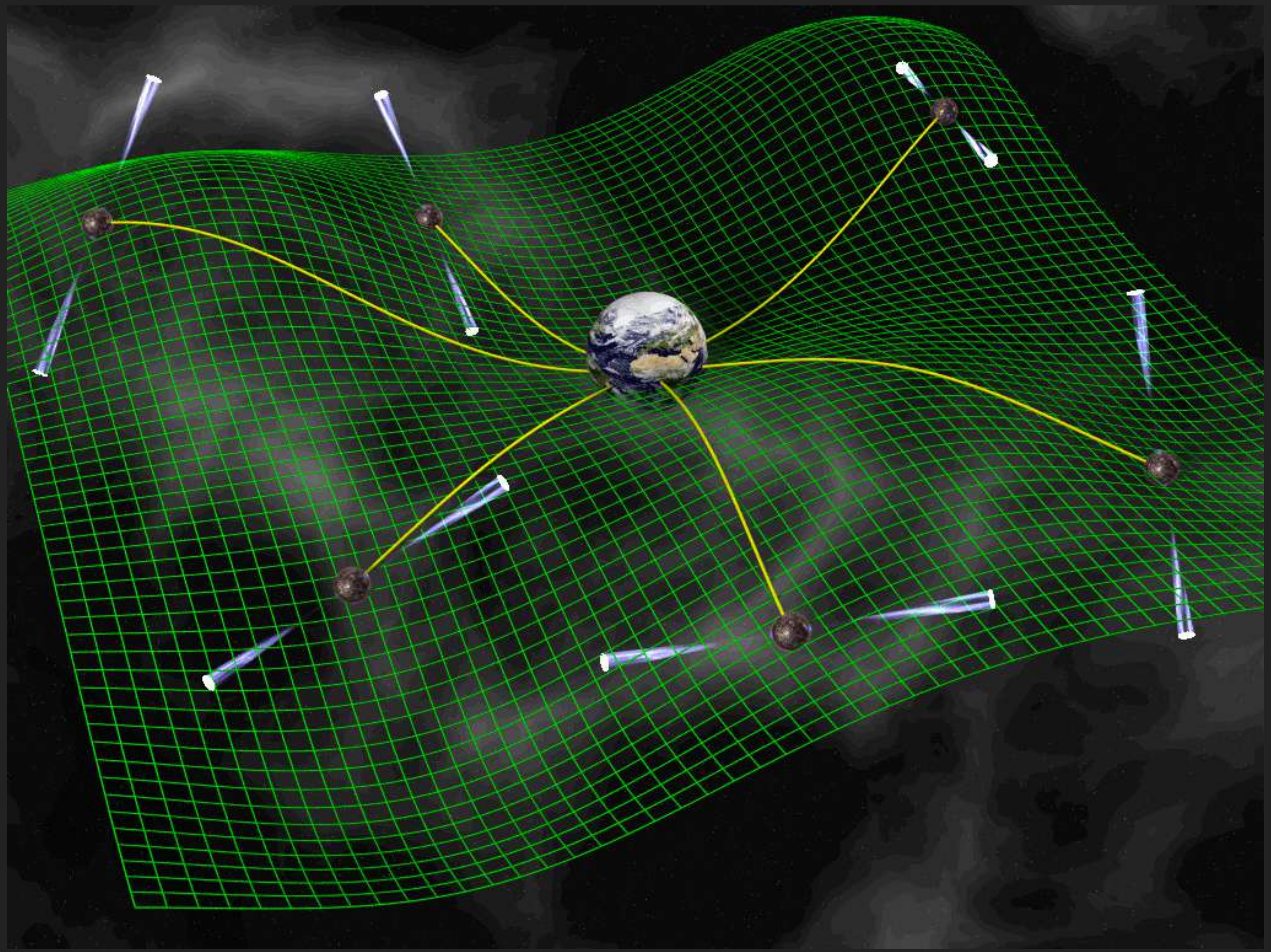




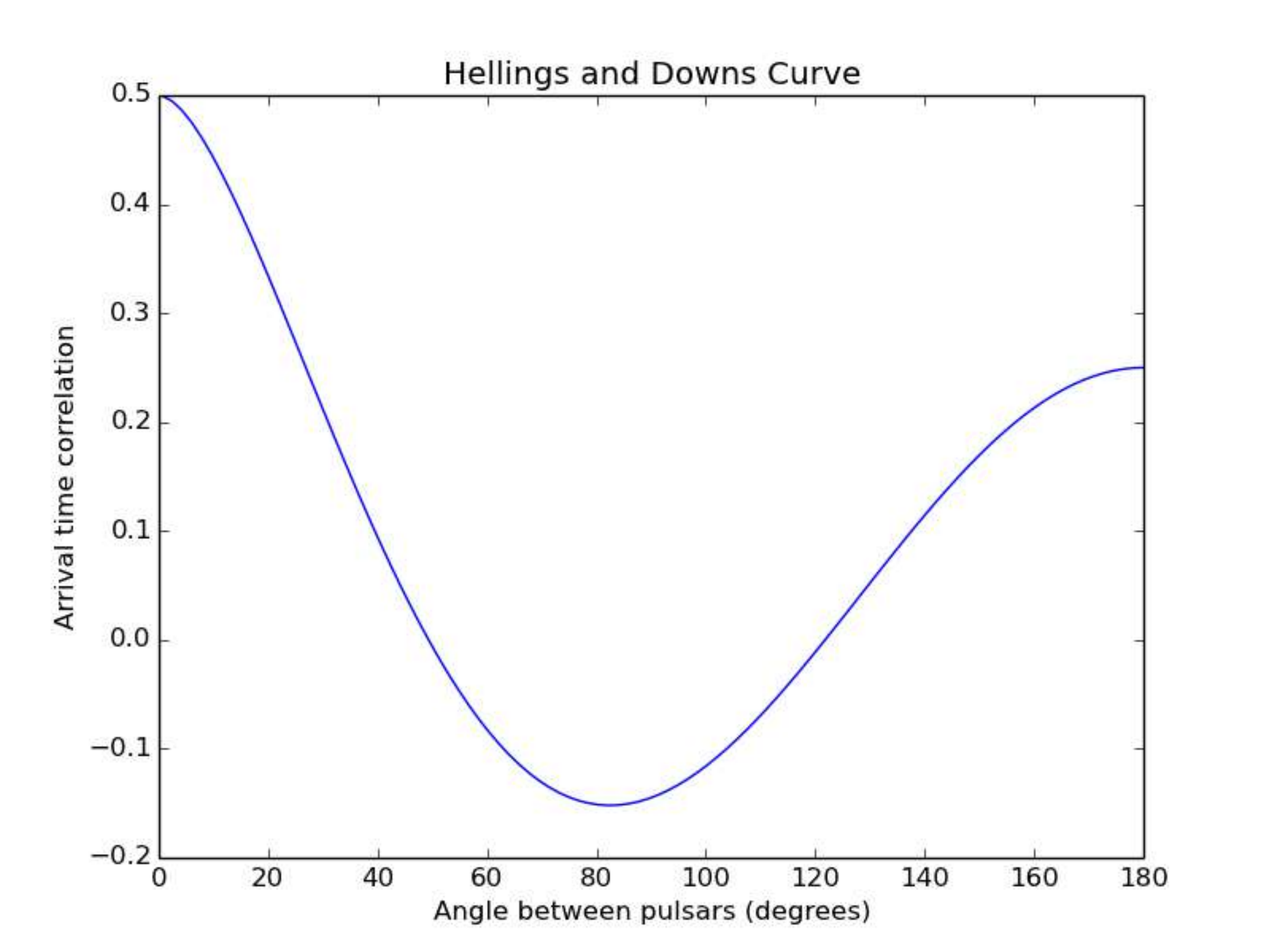
Credit: Abbott et al., 2017

PULSAR TIMING ARRAYS

- Measuring Stochastic Gravitational Wave Background



Credit: David J. Champion

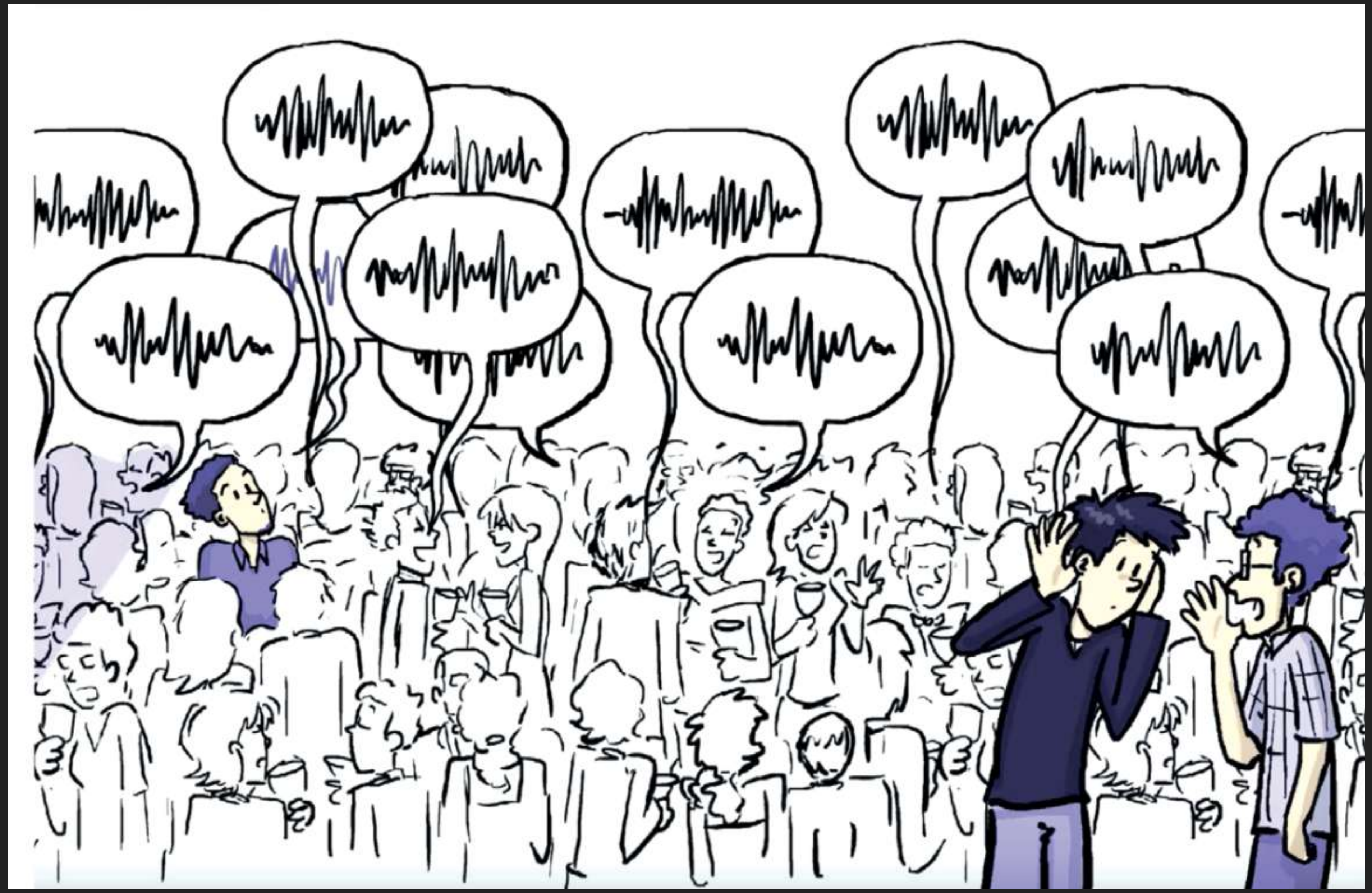


Credit: Michael Zevin, 2016

INTRO TO GRAVITATIONAL WAVES

HOW DO WE ANALYZE THEM?

WAVEFORM MODELING

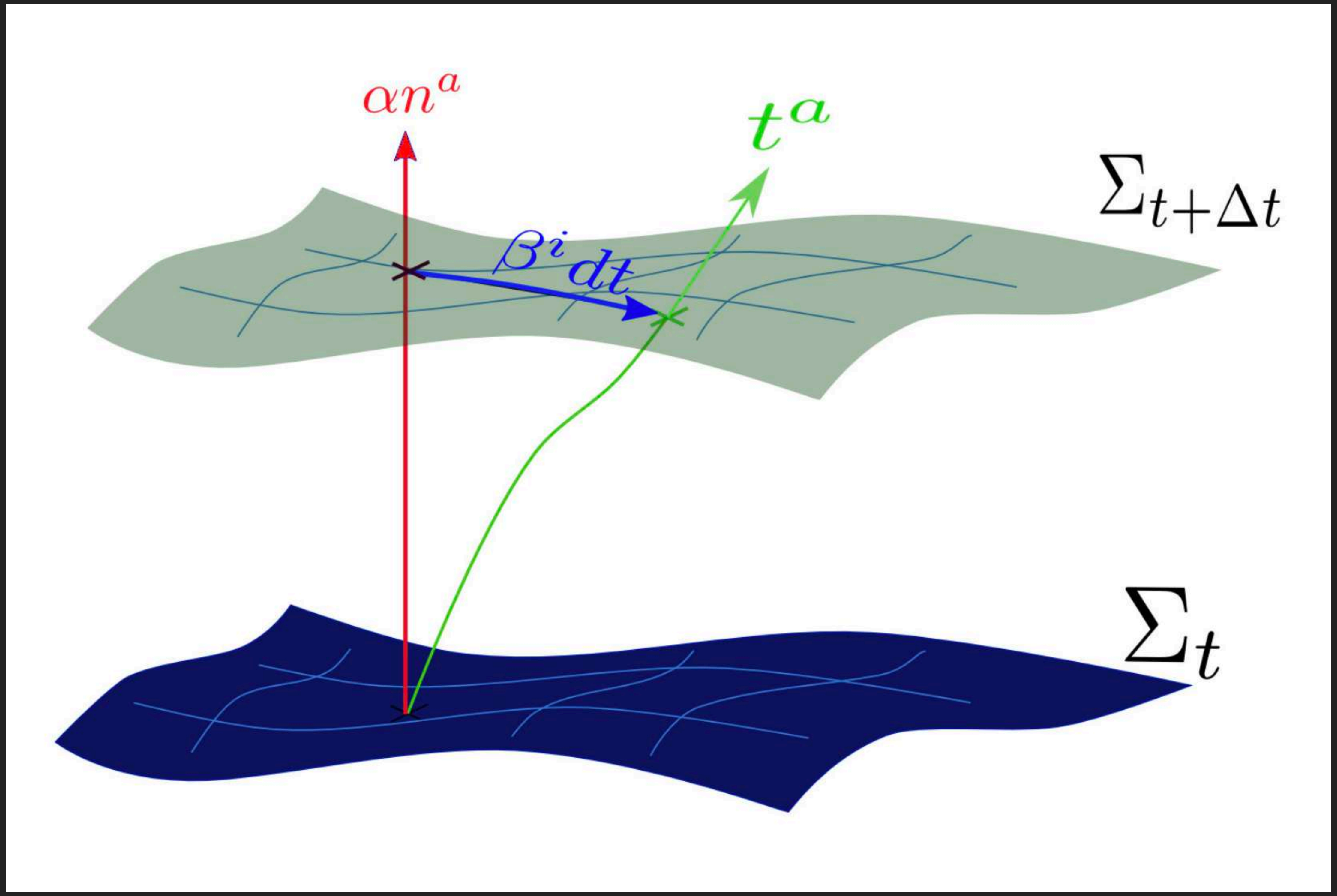


Credit: Jorge Cham, www.phdcomics.com

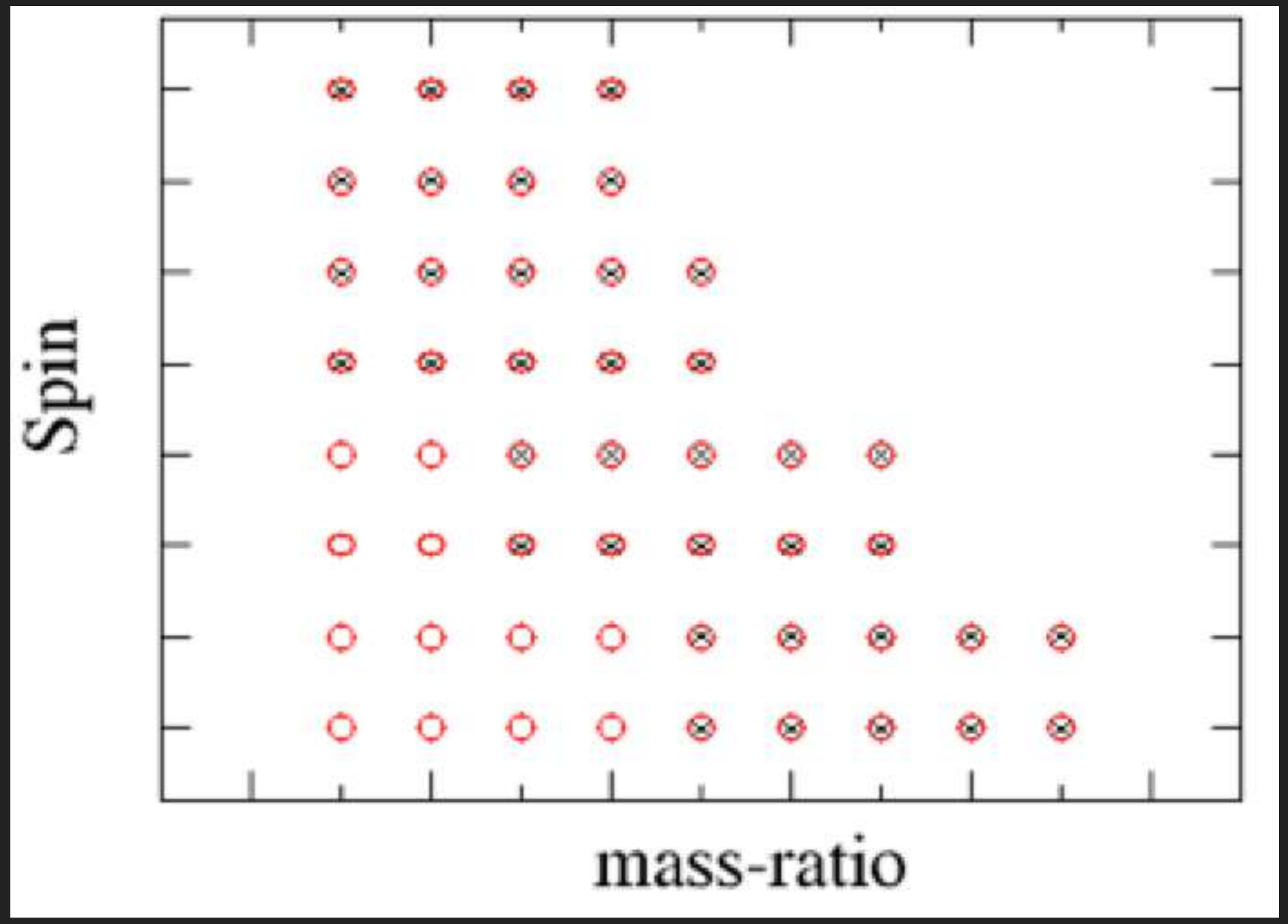
- **Waveforms** tell us what to look for
  - Low-latency match filtering
- Models:
  - Brute force - Numerical Relativity
  - Approximate: Effective-One-Body, Phenomenological, Surrogate Methods
- Estimating parameters of the binary system requires model comparison.

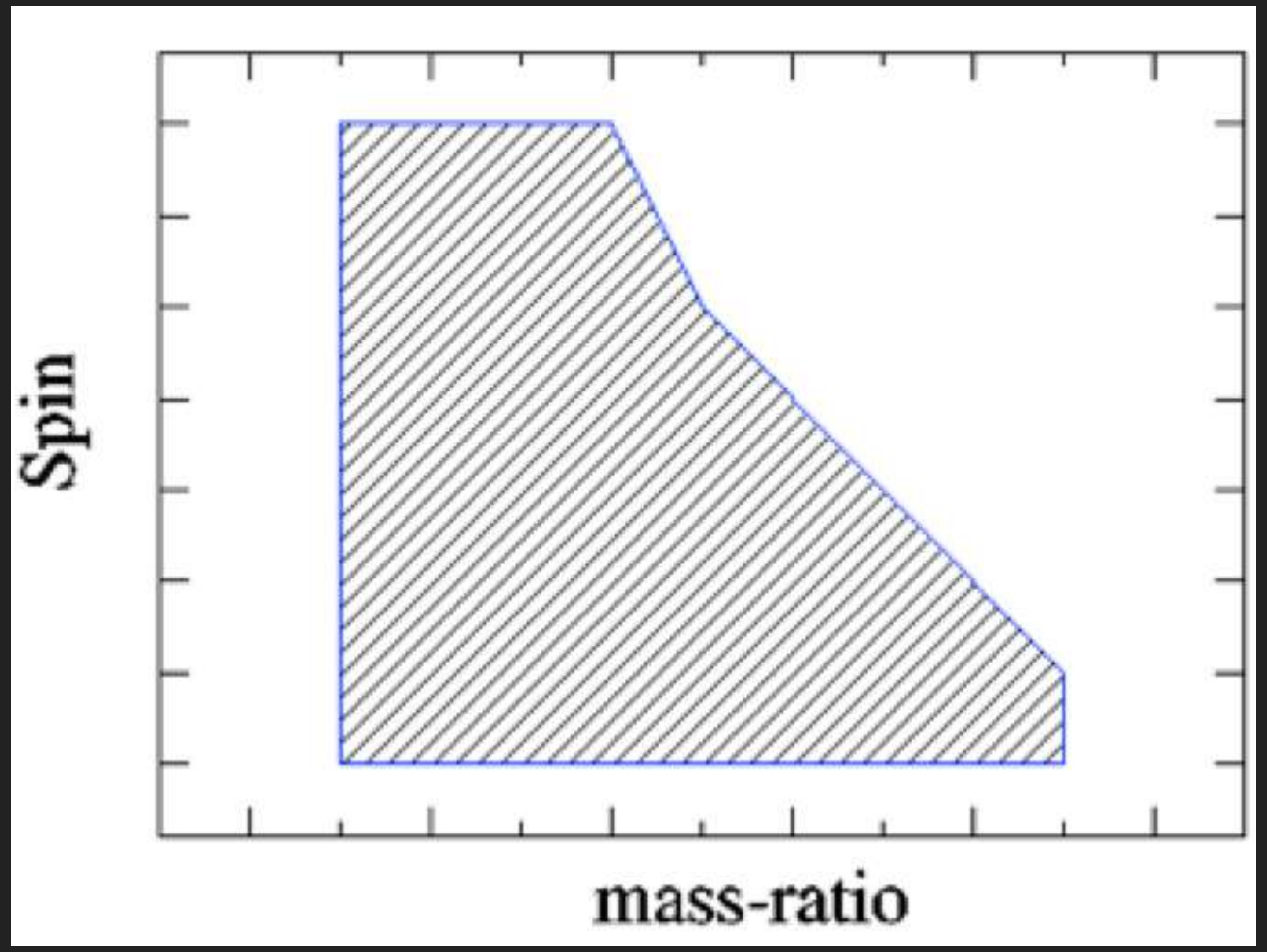
NUMERICAL RELATIVITY

- Directly solving Einstein Field Eqns



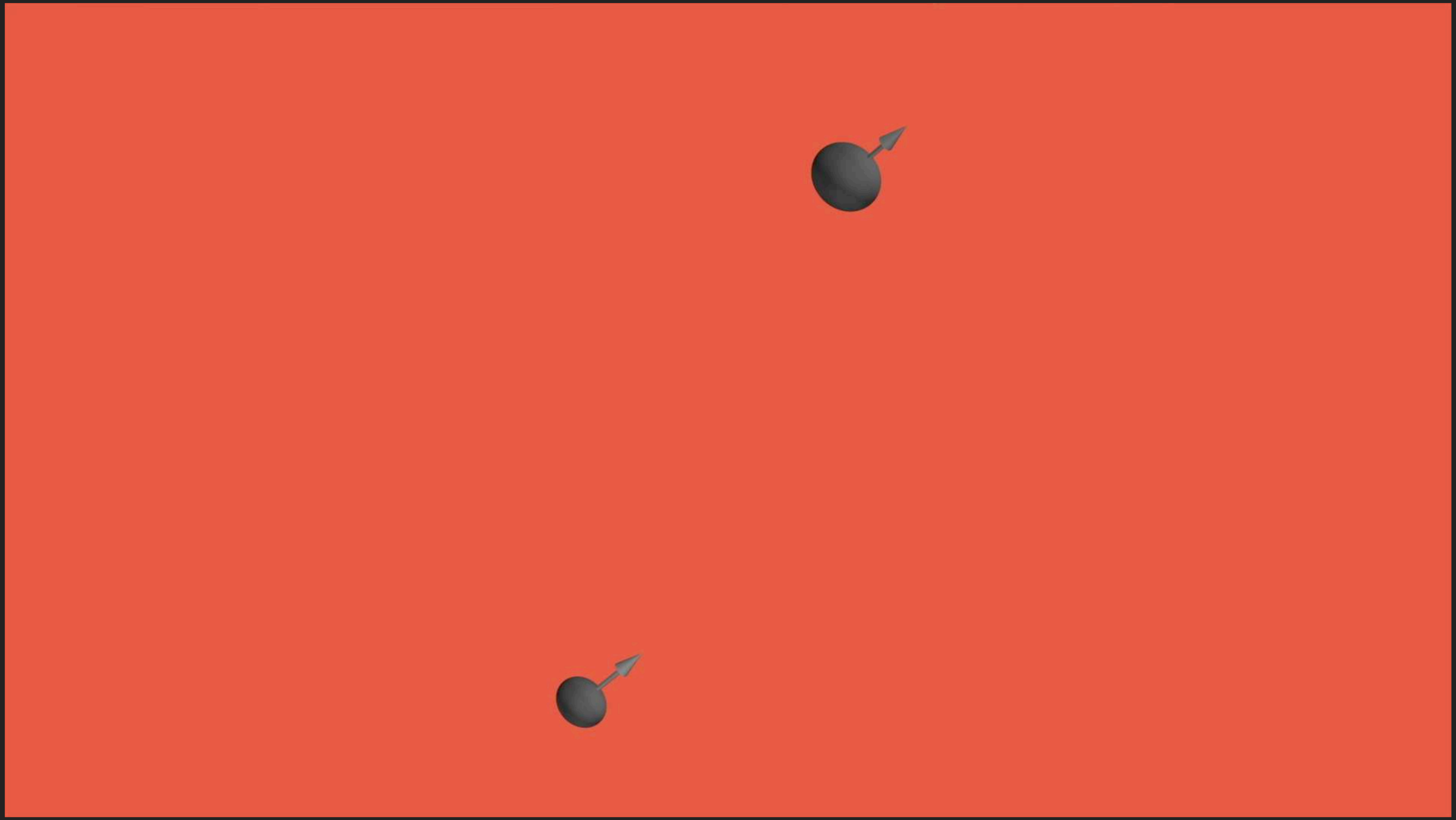
Credit: Carlos Palenzuela



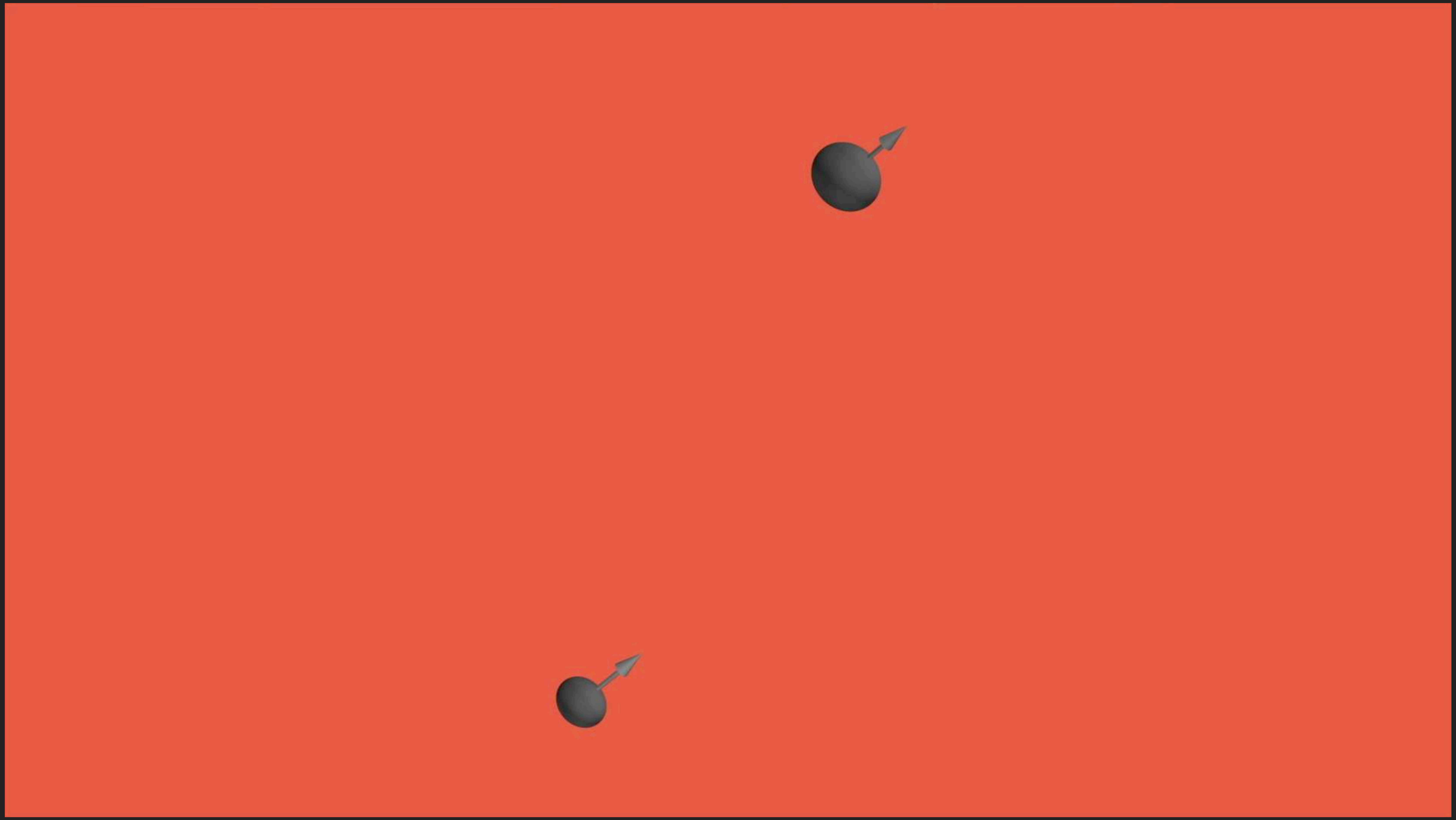


Borrowed with permission from Deirdre Shoemaker

MAYAWAVES

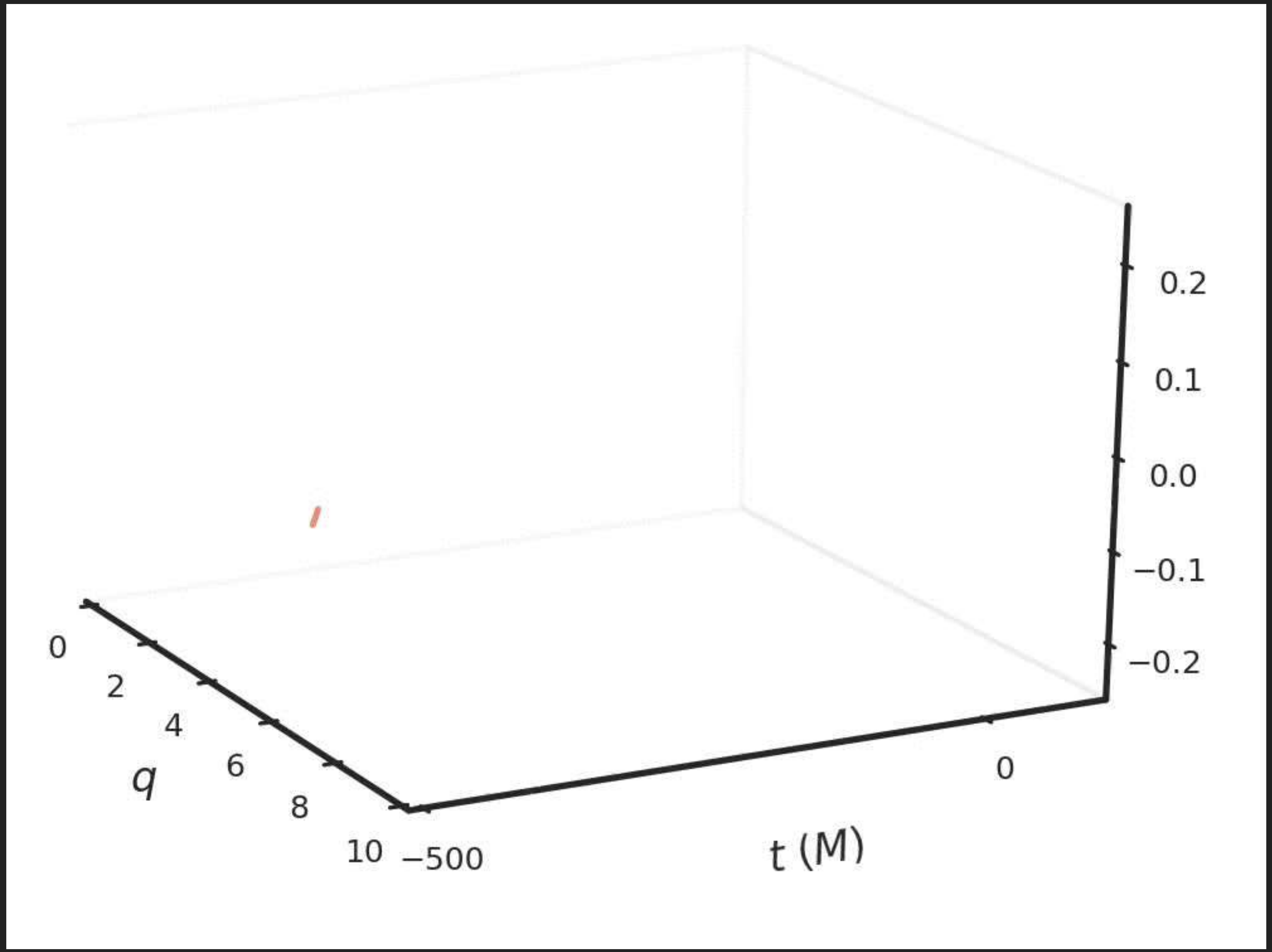


MAYAWAVES



SURROGATE MODELING

- Build a reduced basis of training waveforms
- Empirically interpolate to reduce time nodes
- Find parametric fit across parameter space



Credit: Vijay Varma

$$h_S(t,\theta,\phi;q,\chi) = \sum_{\ell,m} h_S^{\ell,m}(t;q,\chi)\,{}_{-2}Y_{\ell m}(\theta,\phi)$$

$$h_S^{\ell,m}(t;q,\chi) = A_S^{\ell,m}(t;q,\chi)\exp\left(-i\phi_S^{\ell,m}(t;q,\chi)\right)$$

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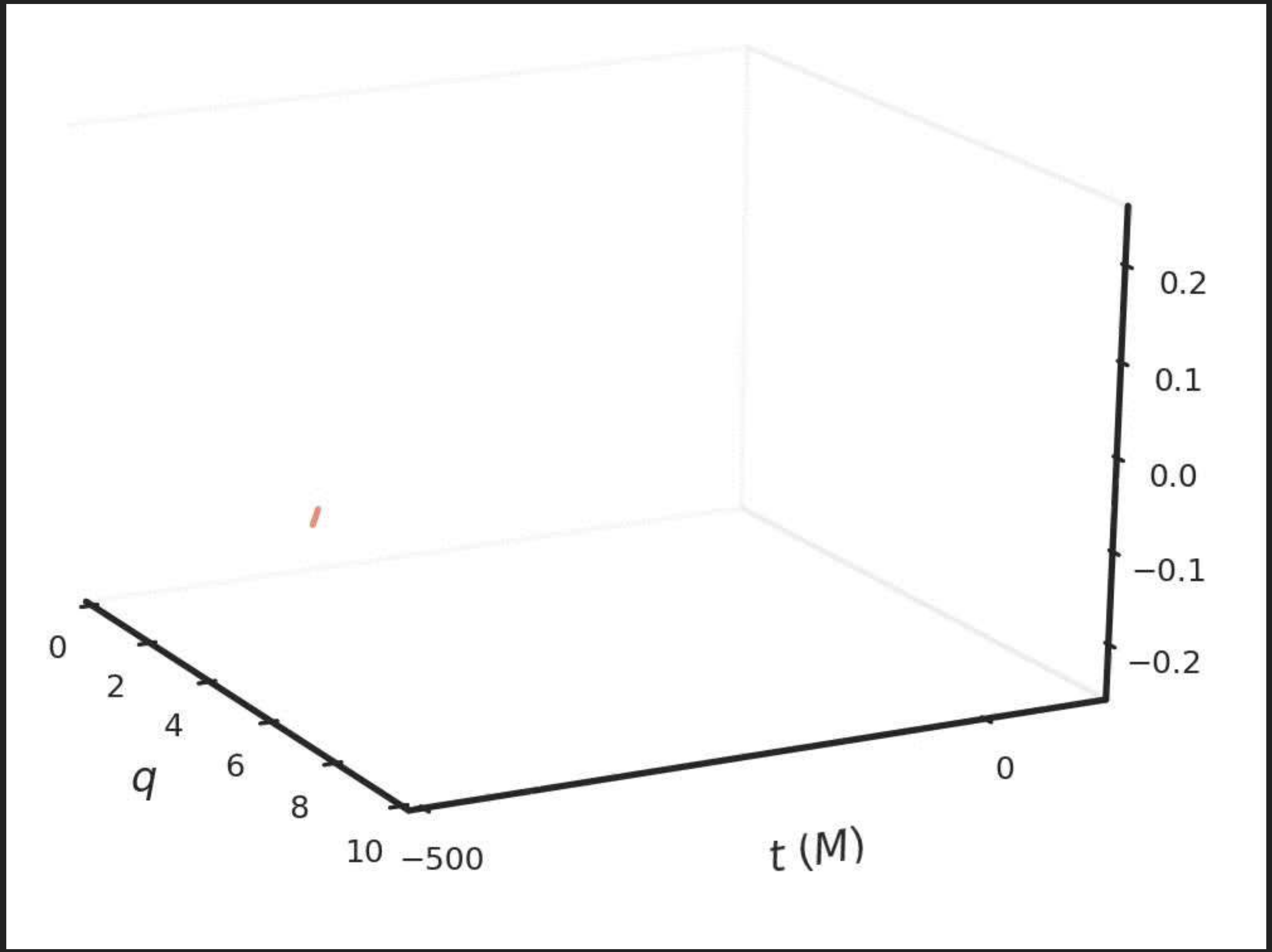

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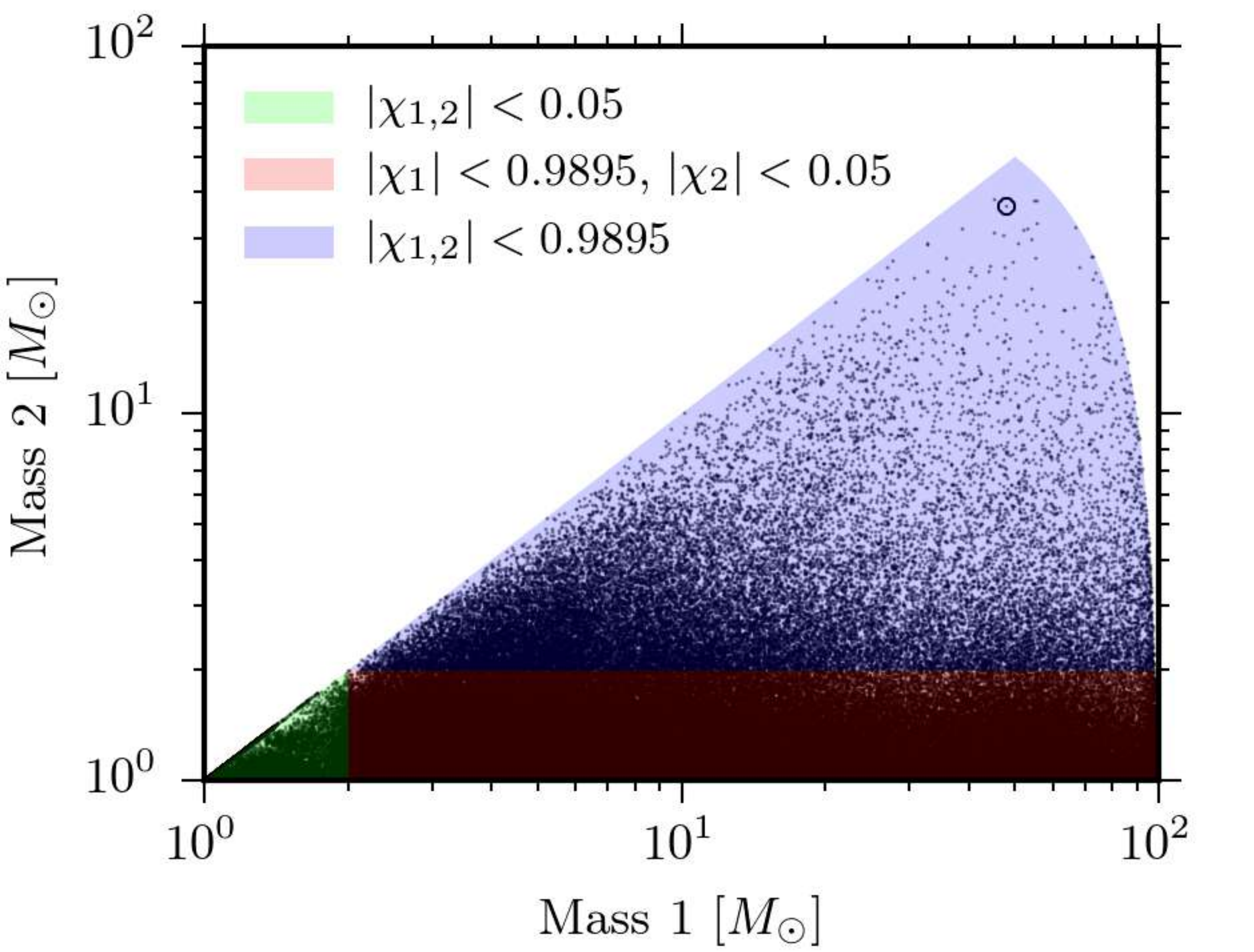
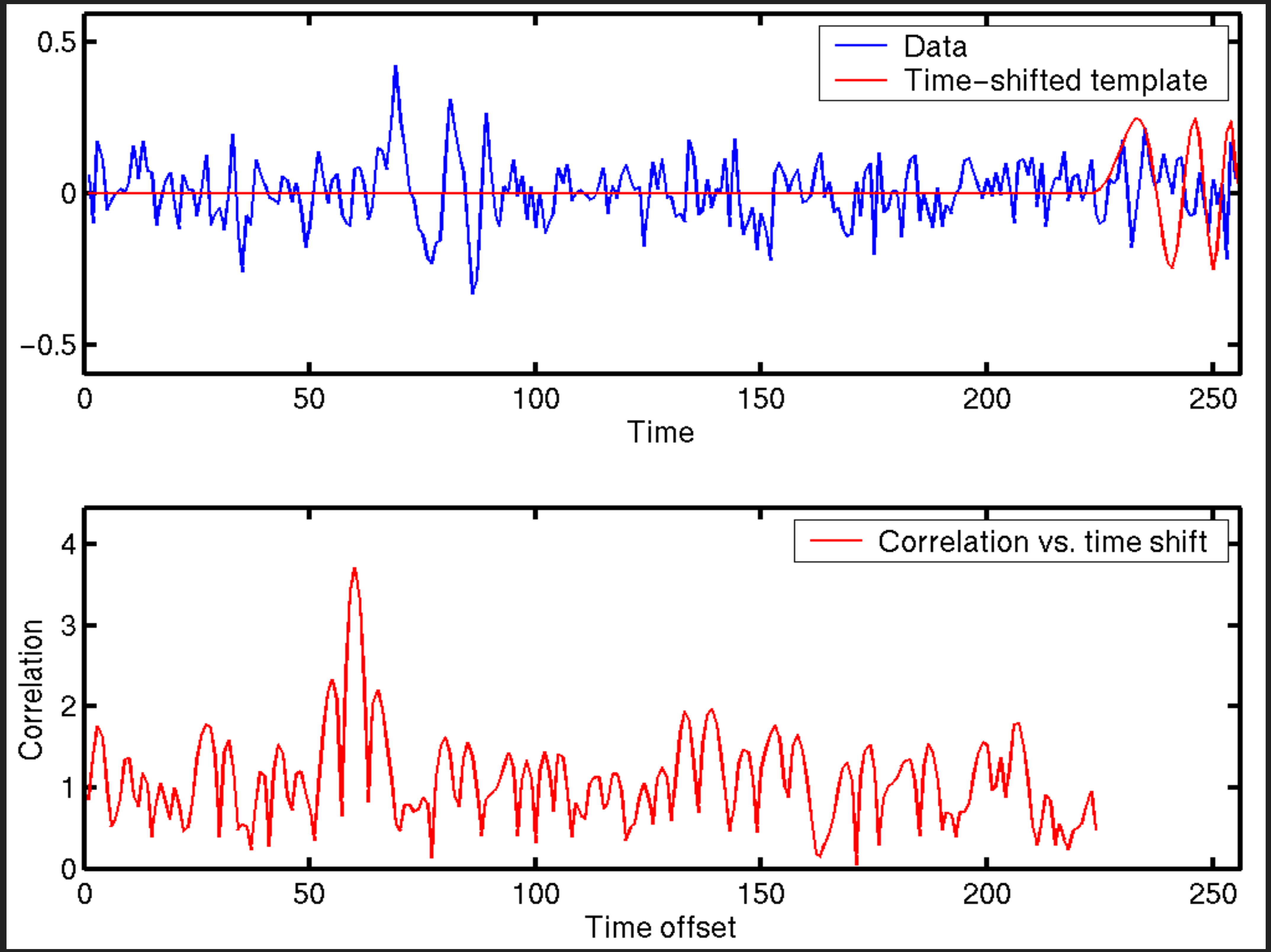
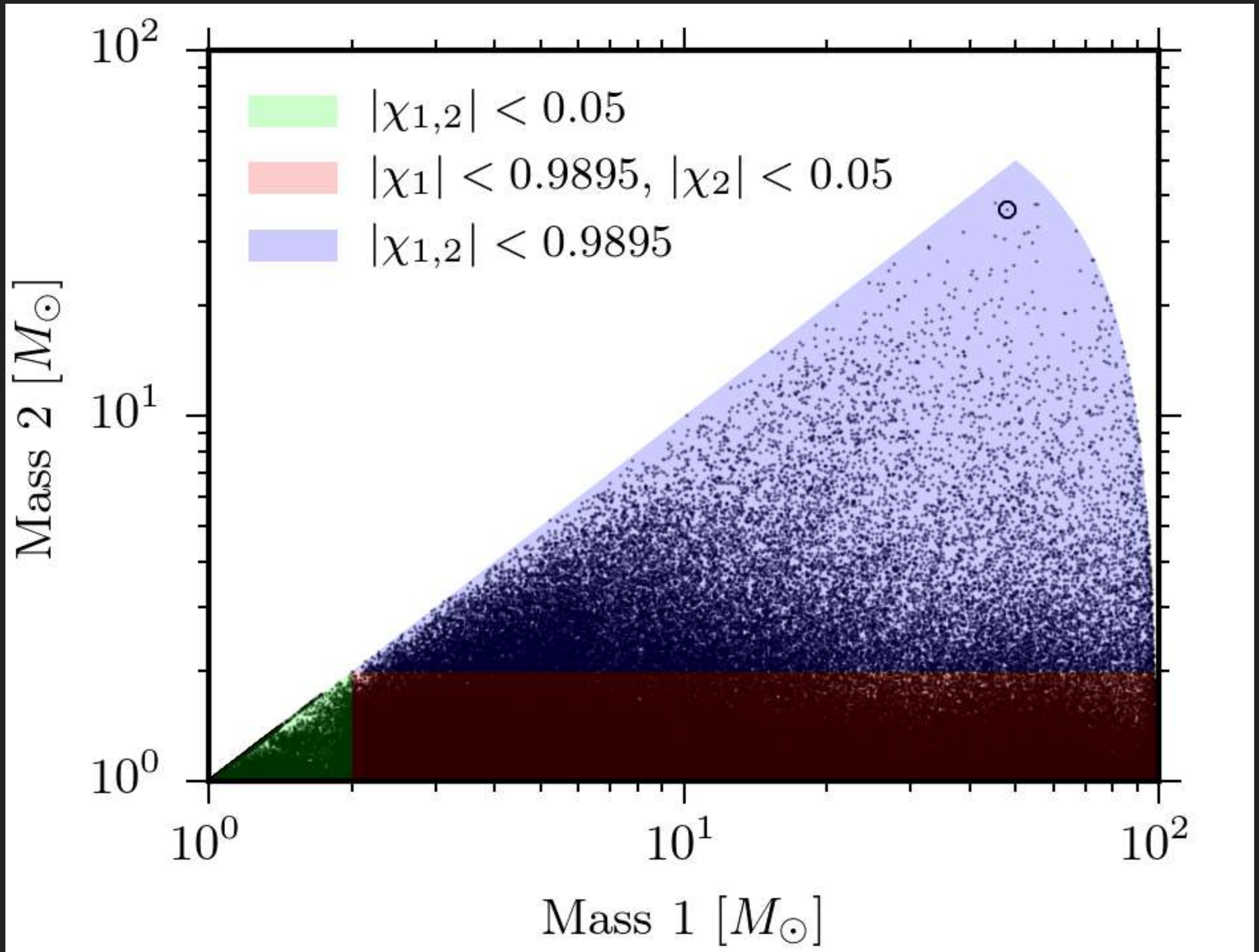
TEMPLATE BANK



Credit: LIGO Scientific Collaboration

TEMPLATE BANK

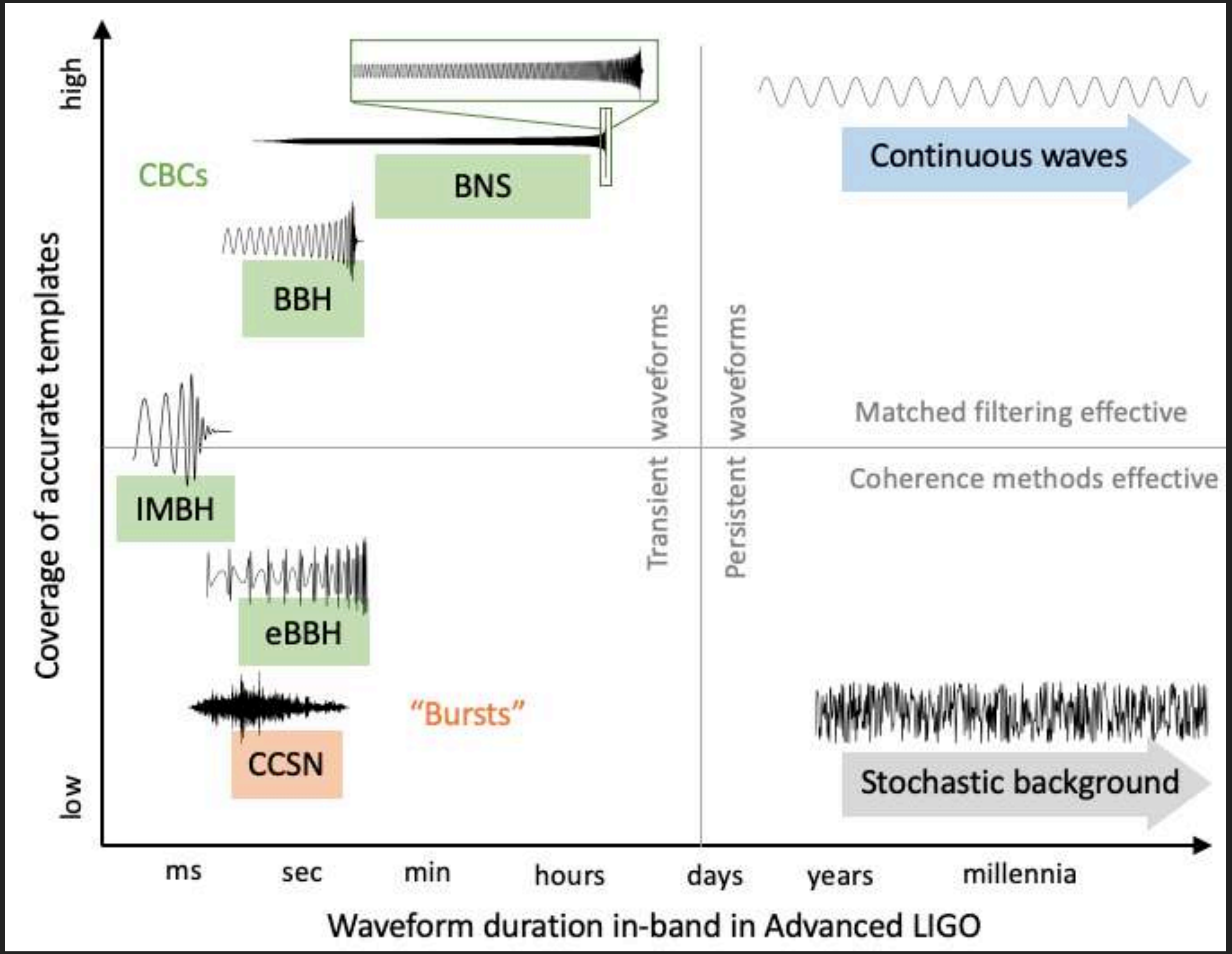




Credit: LIGO Scientific Collaboration

WHAT ELSE CAN WE LOOK FOR?

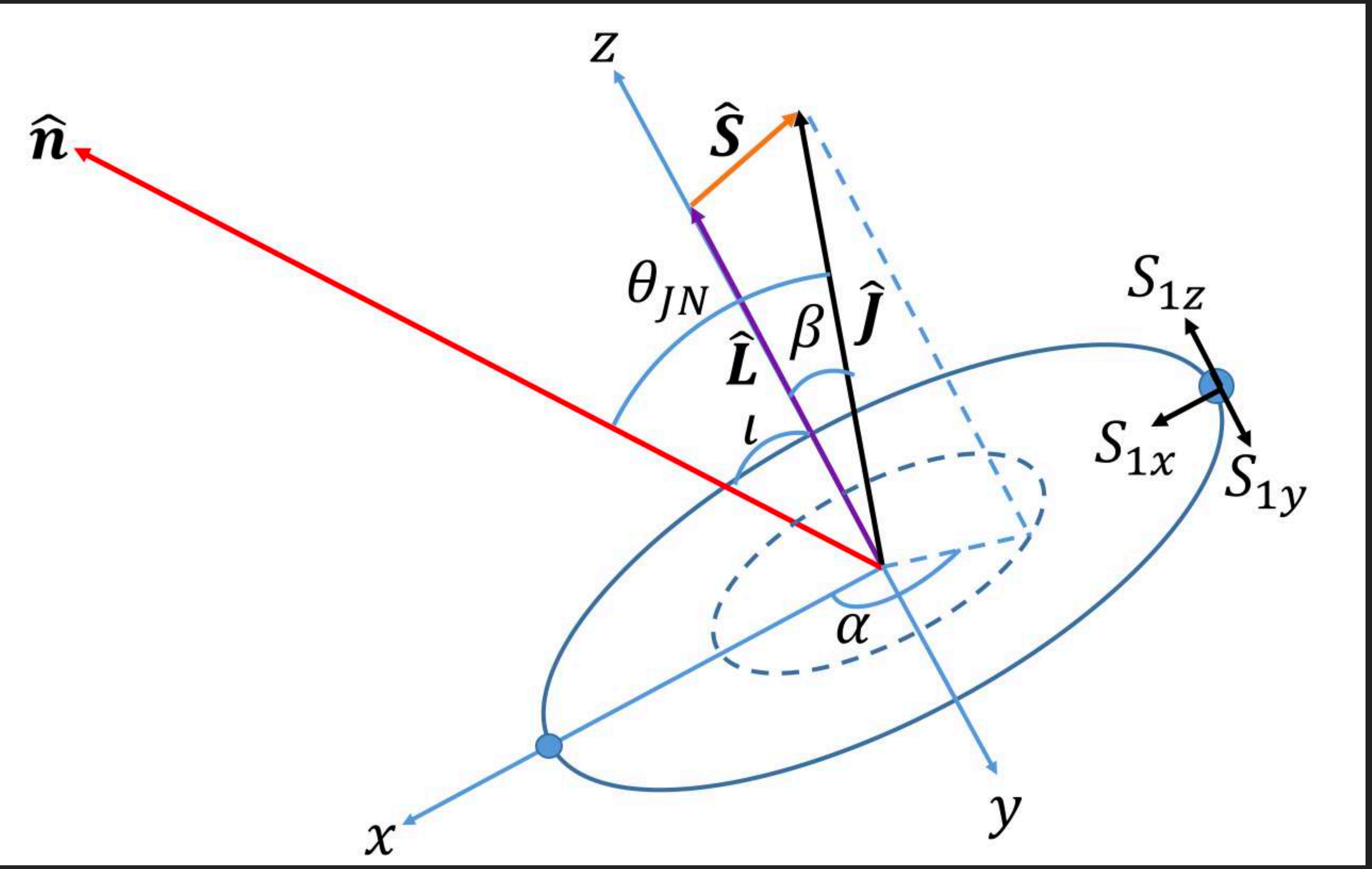
- **Un-modelled sources**
  - Burst Searches
    - Supernova
- **Mass gaps**
  - BHs b/w $\sim 150 - 100{,}000\ M_\odot$
  - New object b/w BHs and NSs?
    - $\sim 2.1 - 3\ M_\odot$
- **Continuous waves**
- **Stochastic background**



Credit: McIver and Shoemaker, 2021

PARAMETER ESTIMATION

- 15-dimensional parameter space

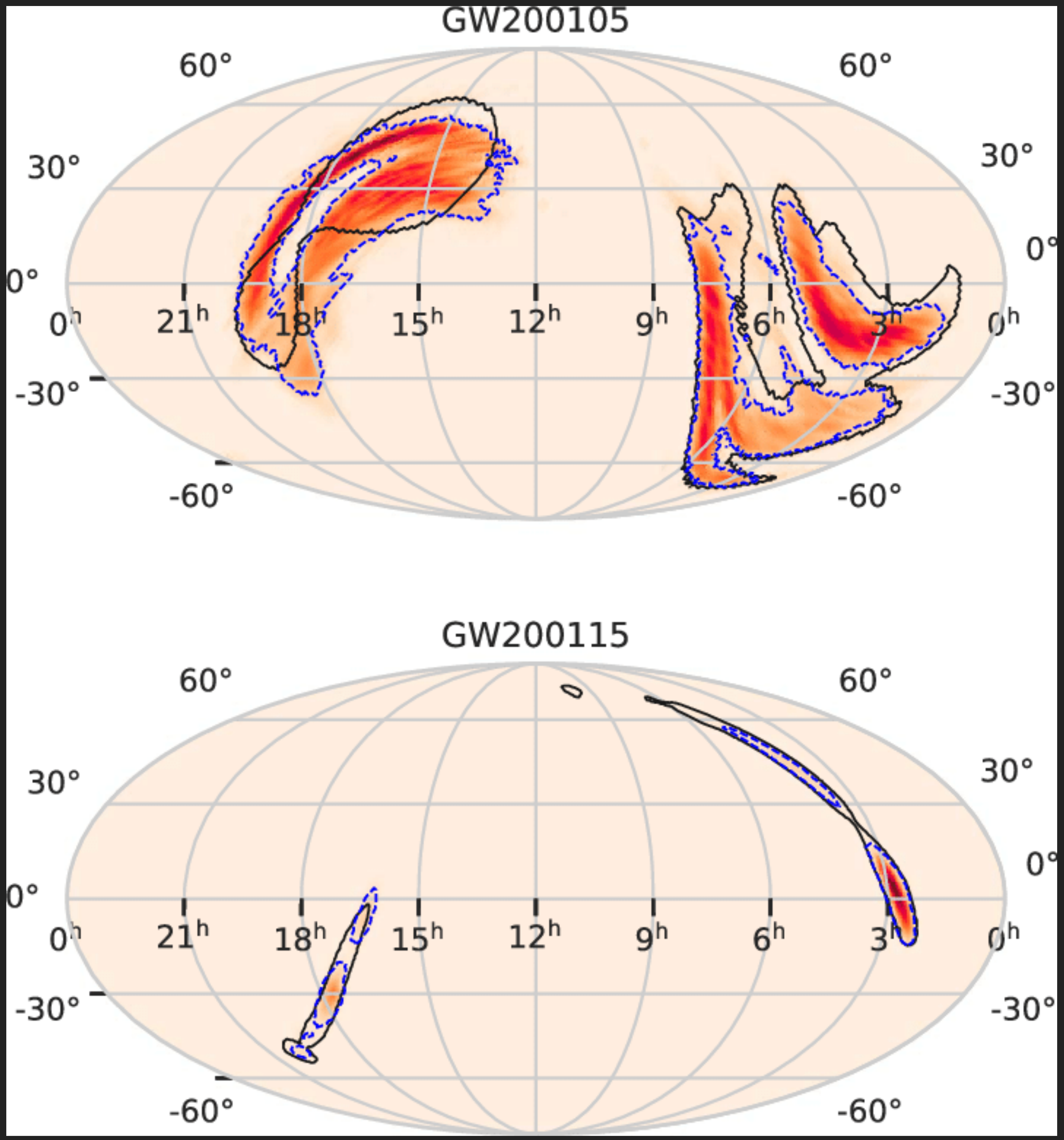


Credit: Green et al., Phys Rev D (2021)

Intrinsic	Extrinsic
Mass 1	Distance
Mass 2	Right Ascension
Spin 1x	Declination
Spin 1y	Inclination
Spin 1z	Rotation
Spin 2x	Reference time
Spin 2y	Reference phase
Spin 2z	

SKY LOCALIZATION

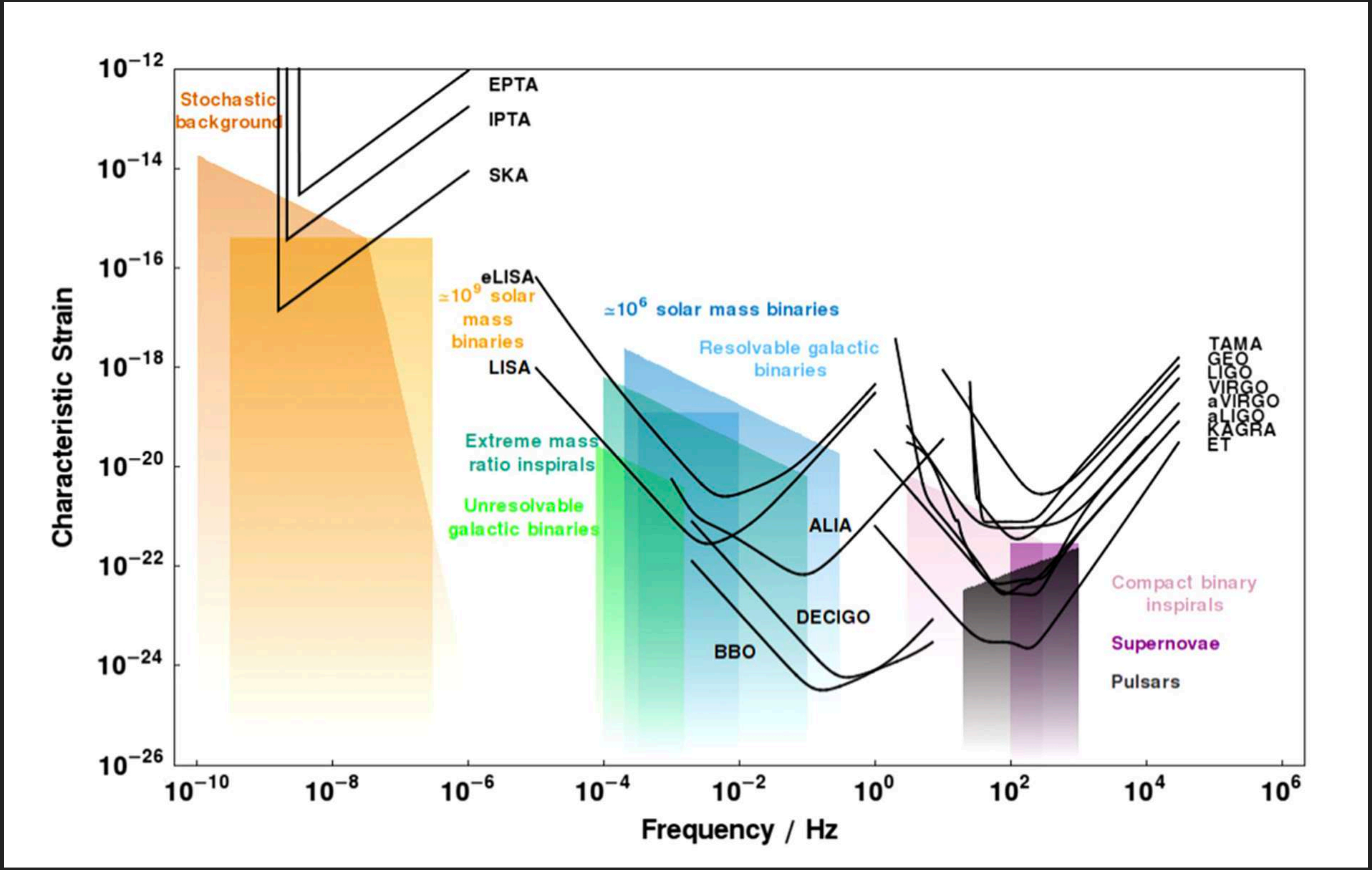
- Amplitude of each polarization depends on angle at which the wavefront hits the detector
  - Two polarizations and 2-3 detectors allows us to triangulate source's location to within ~10 degrees.
- Important for rapid electromagnetic follow-up



Credit: LIGO Scientific Collaboration, ApJ (2021)

INTRO TO GRAVITATIONAL WAVES

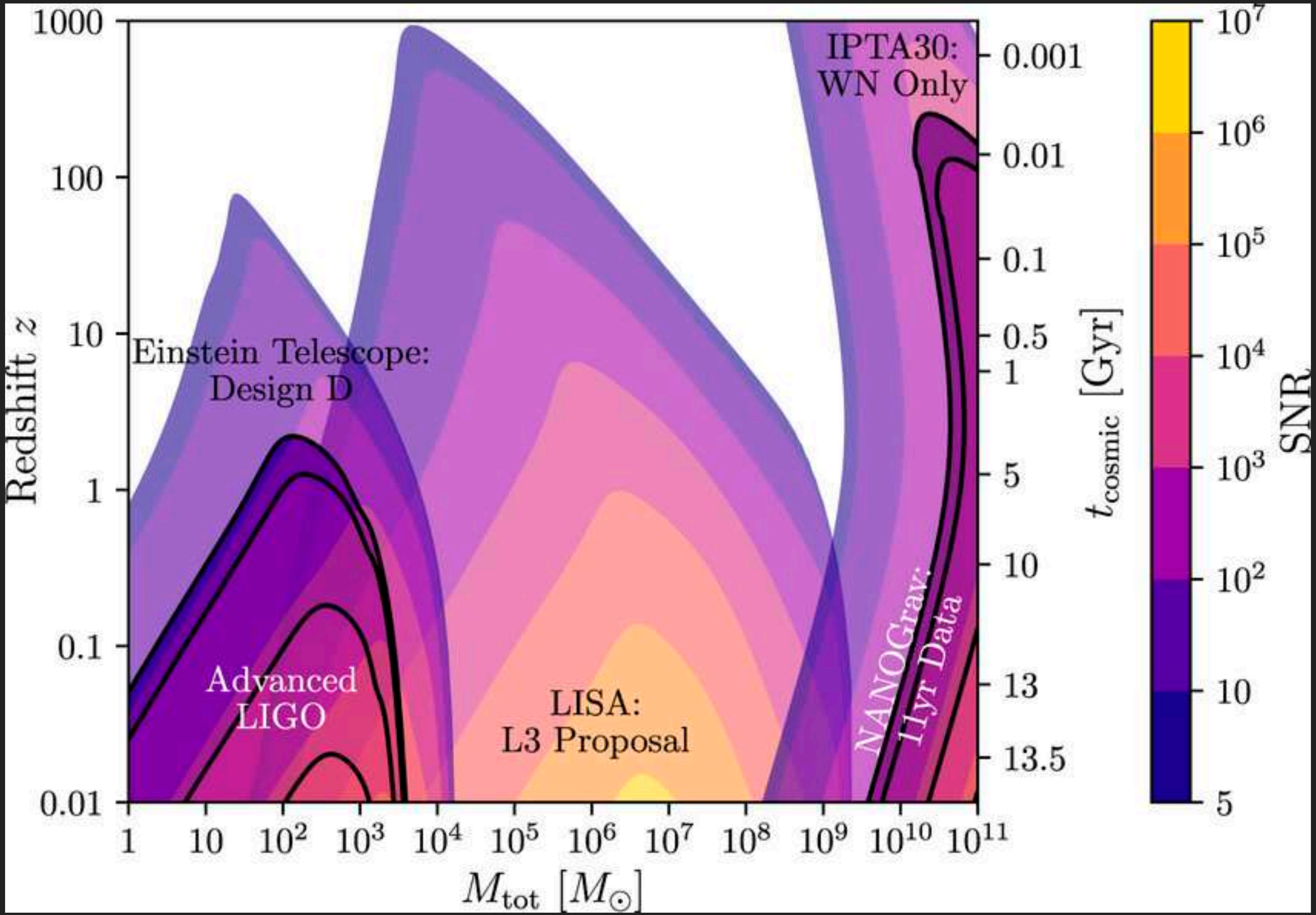
WHAT DOES THE FUTURE HOLD?



Credit: C J Moore et al., 2015

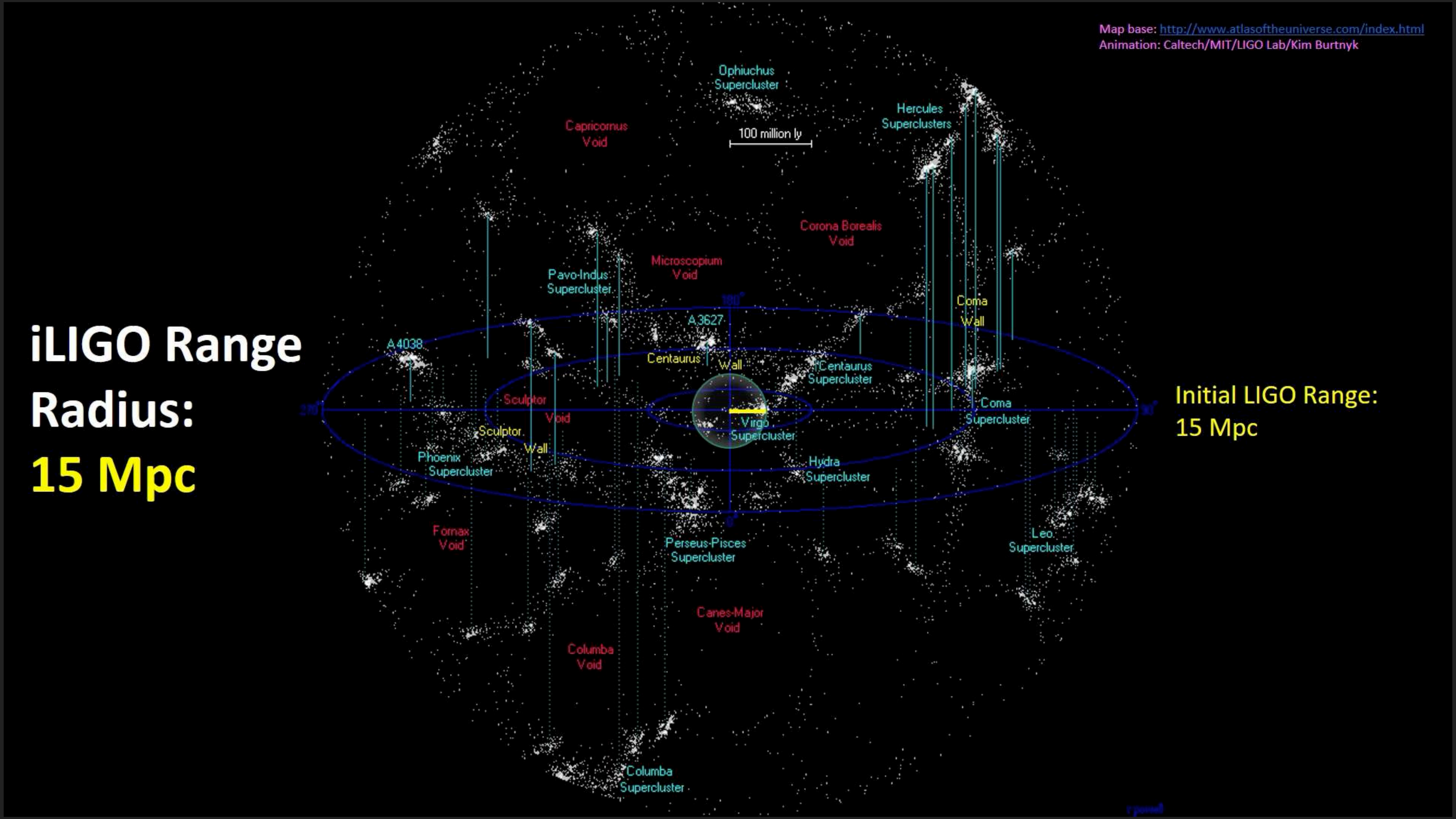
HOW WILL WE DETECT MORE?

- Einstein Telescope
  - 10 km (3 arms)
- Cosmic Explorer
  - 40 km (2 arms)
- LISA
  - 2.5 million km (3 arms)
- Advanced LIGO



Credit: A. R. Kaiser and S. T. McWilliams, 2021

ADVANCED LIGO



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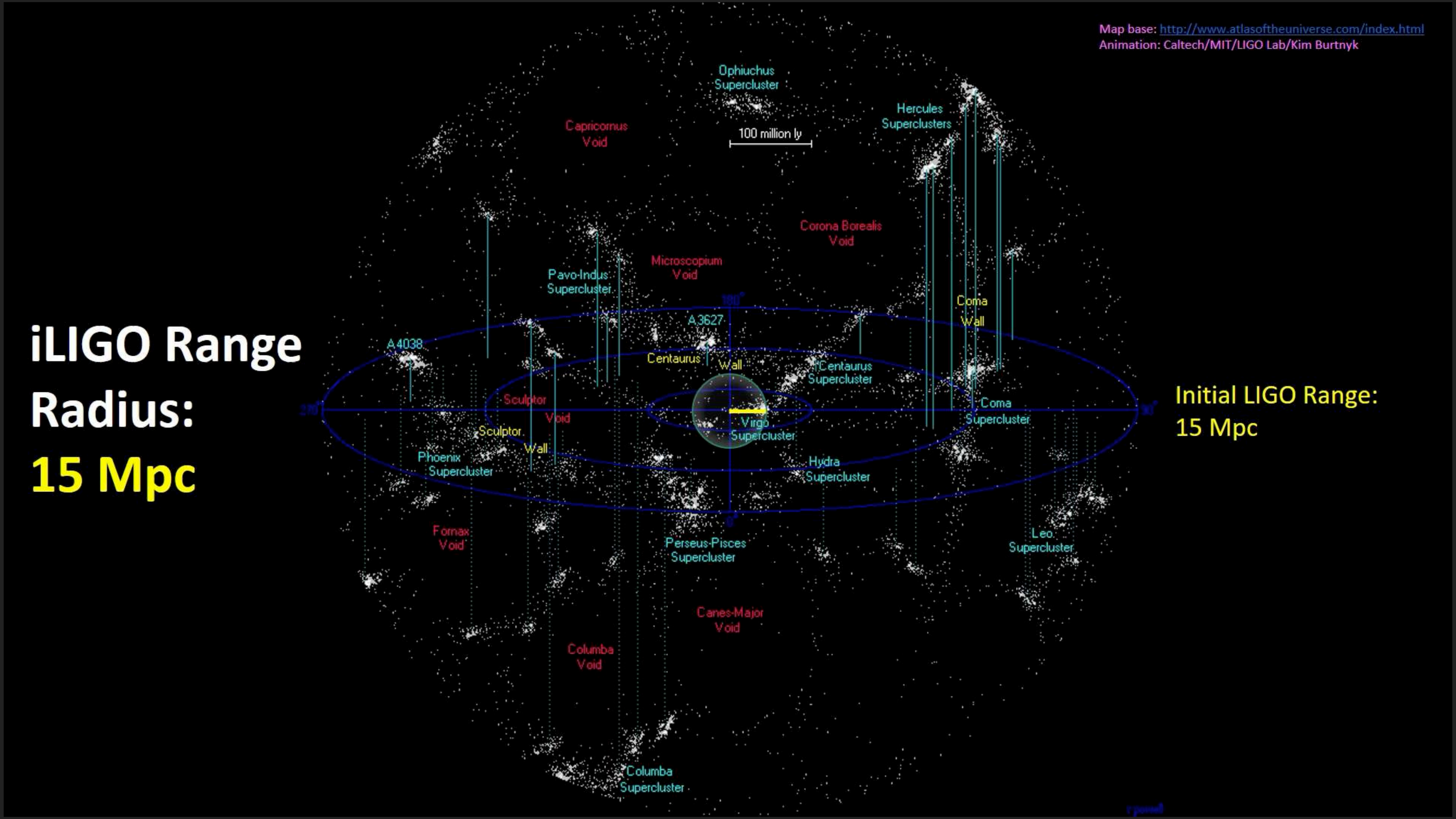
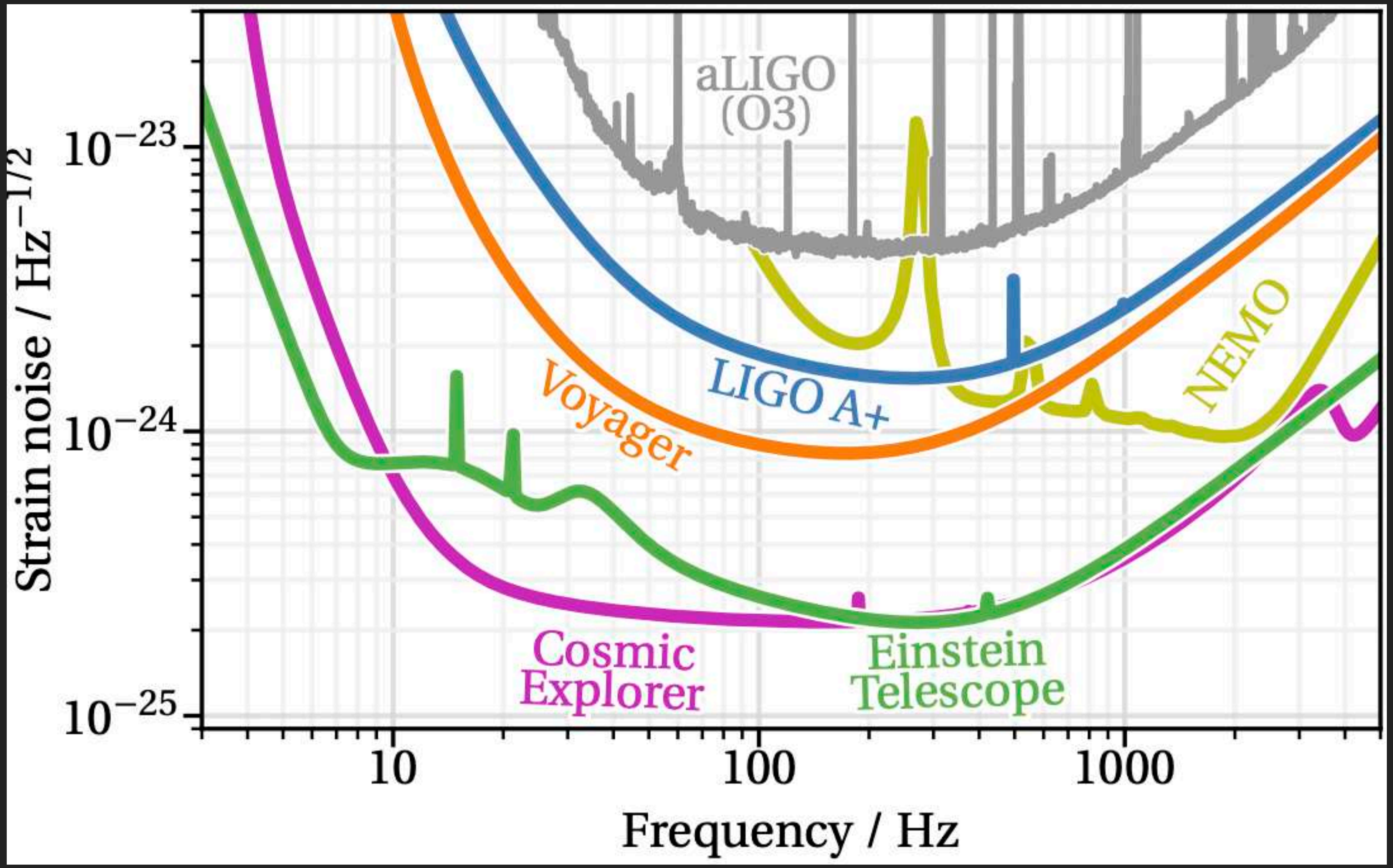
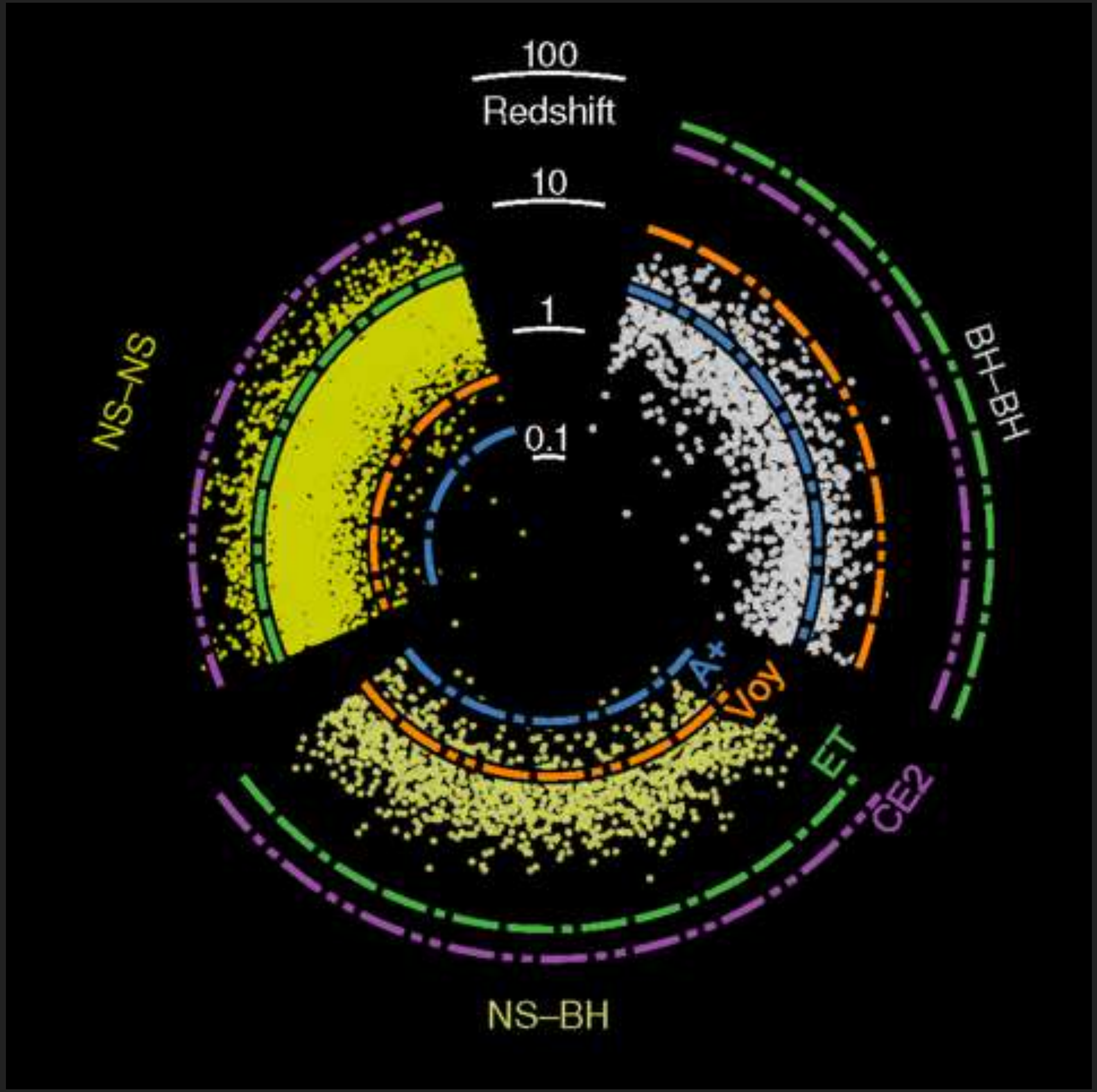


COSMIC EXPLORER

- LIGO scaled by 10

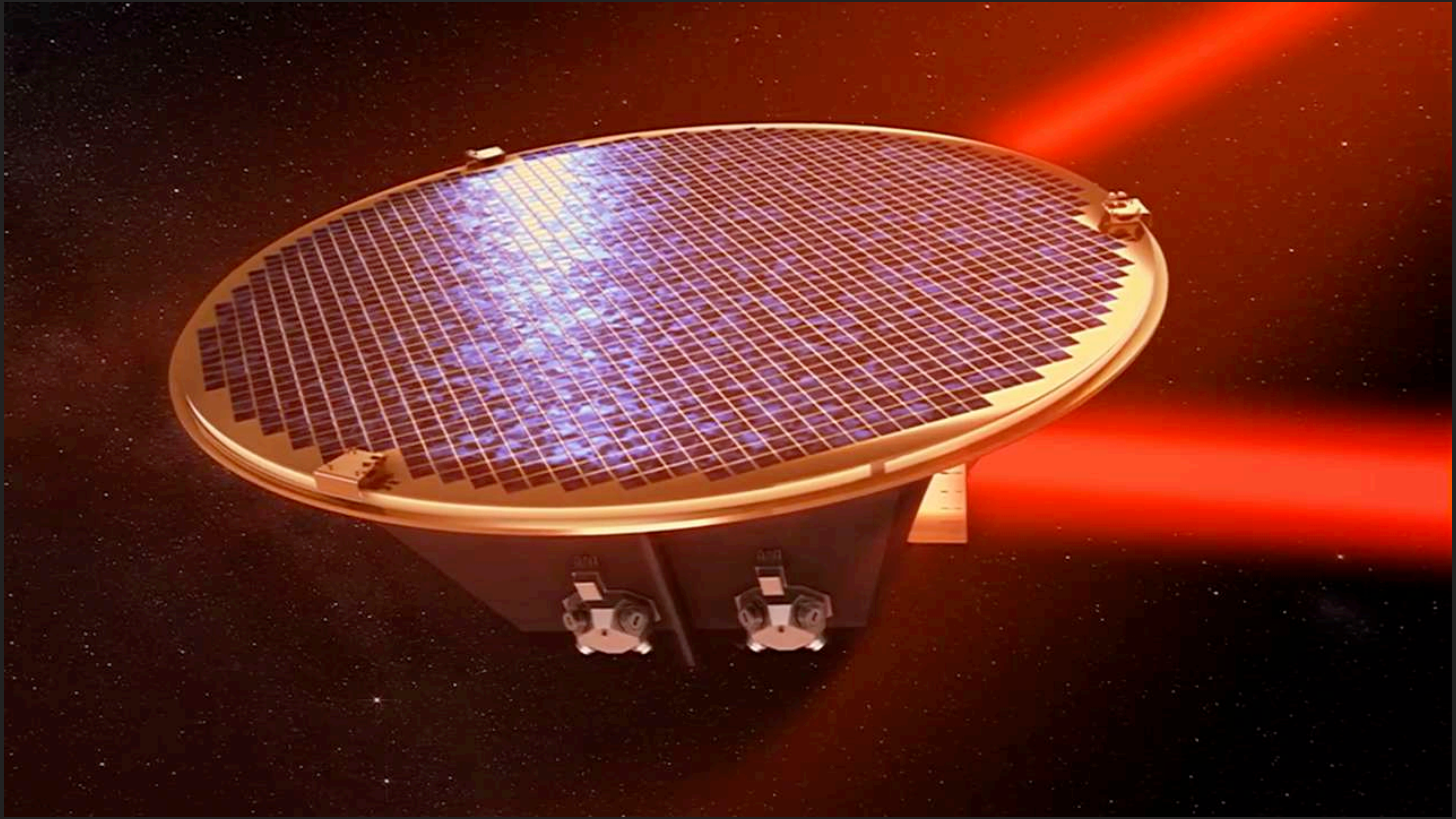


Credit: Cosmic Explorer Consortium



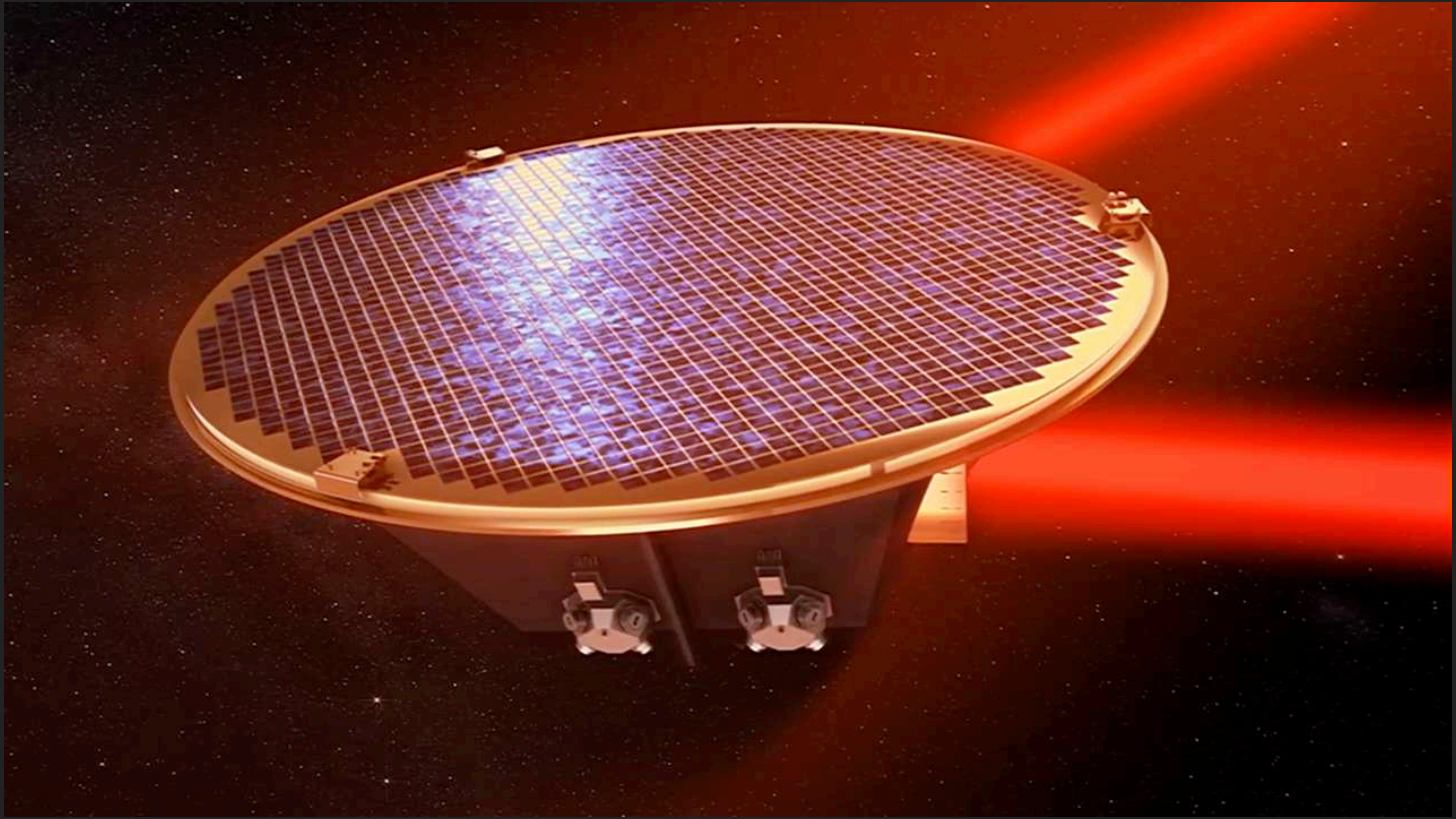
Credit: Cosmic Explorer Consortium

LISA



Credit: NASA/ESA

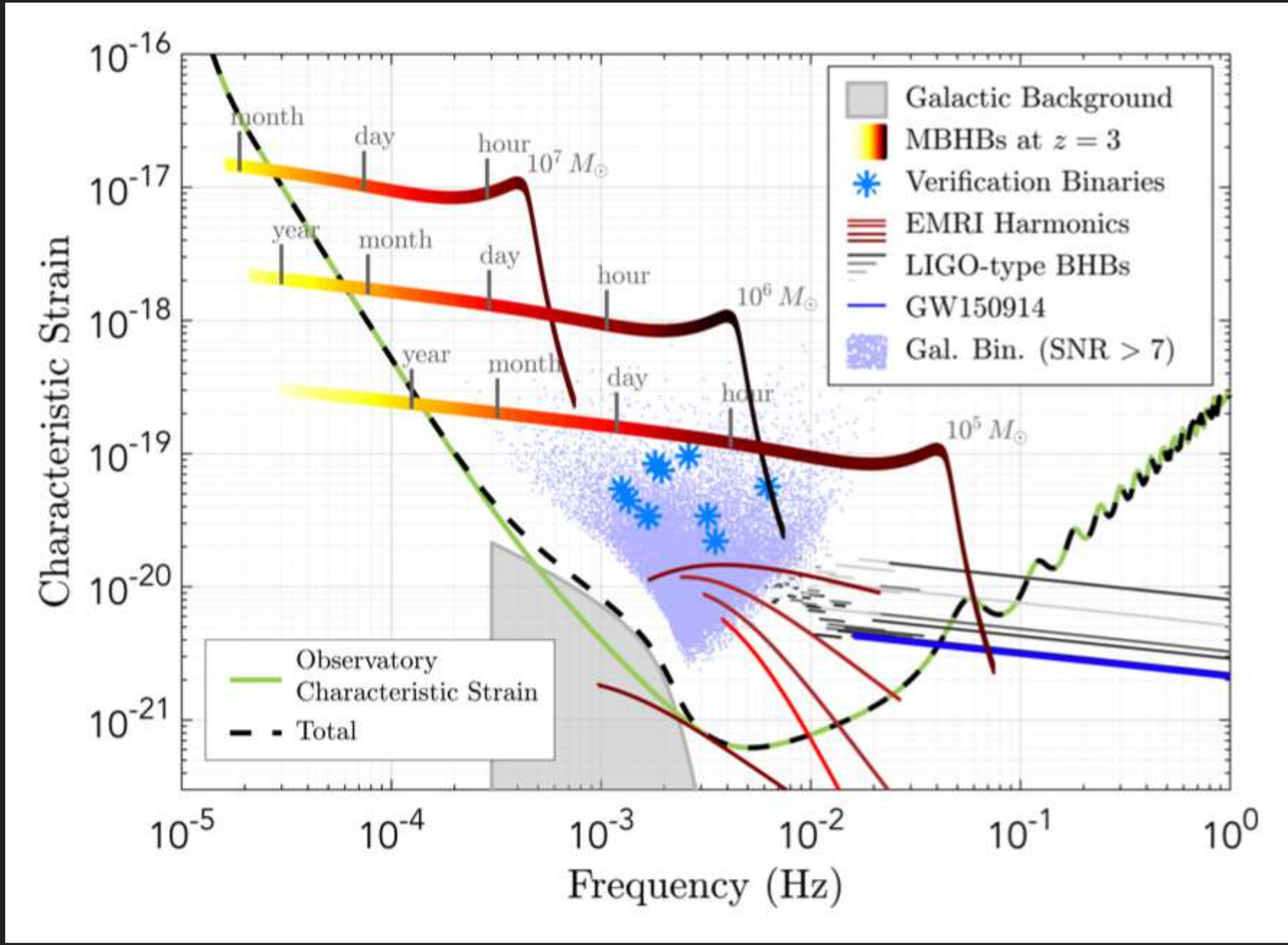
LISA



Credit: NASA/ESA

LISA

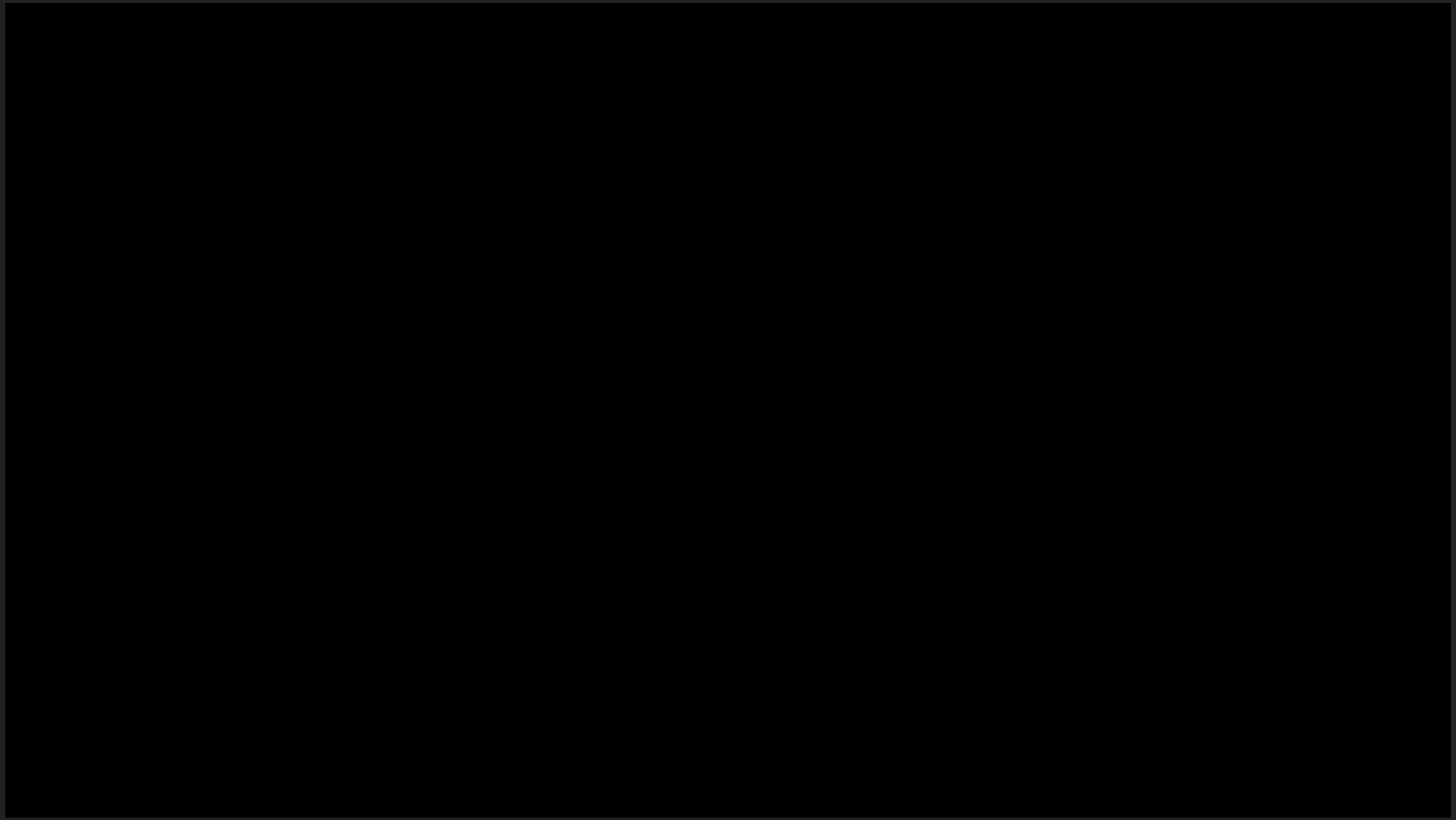
- Sources:
  - Supermassive Binary BHs
  - Extreme Mass-Ratios
  - Galactic White Dwarfs
  - Cosmic strings?
  - Early Universe phase transitions?
- Challenges:
  - Long signal duration
  - Lots of overlap
  - Global fit?



Credit: LISA Consortium, 2017

THANK YOU!

- Why care? …
- What are they?
- Asymmetric acceleration in mass
- How do we detect them?
- Correlation b/w 2+ Interferometers
- How do we analyze them?
- Compare to waveform models
- What does the future hold?
- Longer, underground, and space, oh my!
- Young and exciting field rich in discovery space



Credit: LIGO Scientific Collaboration

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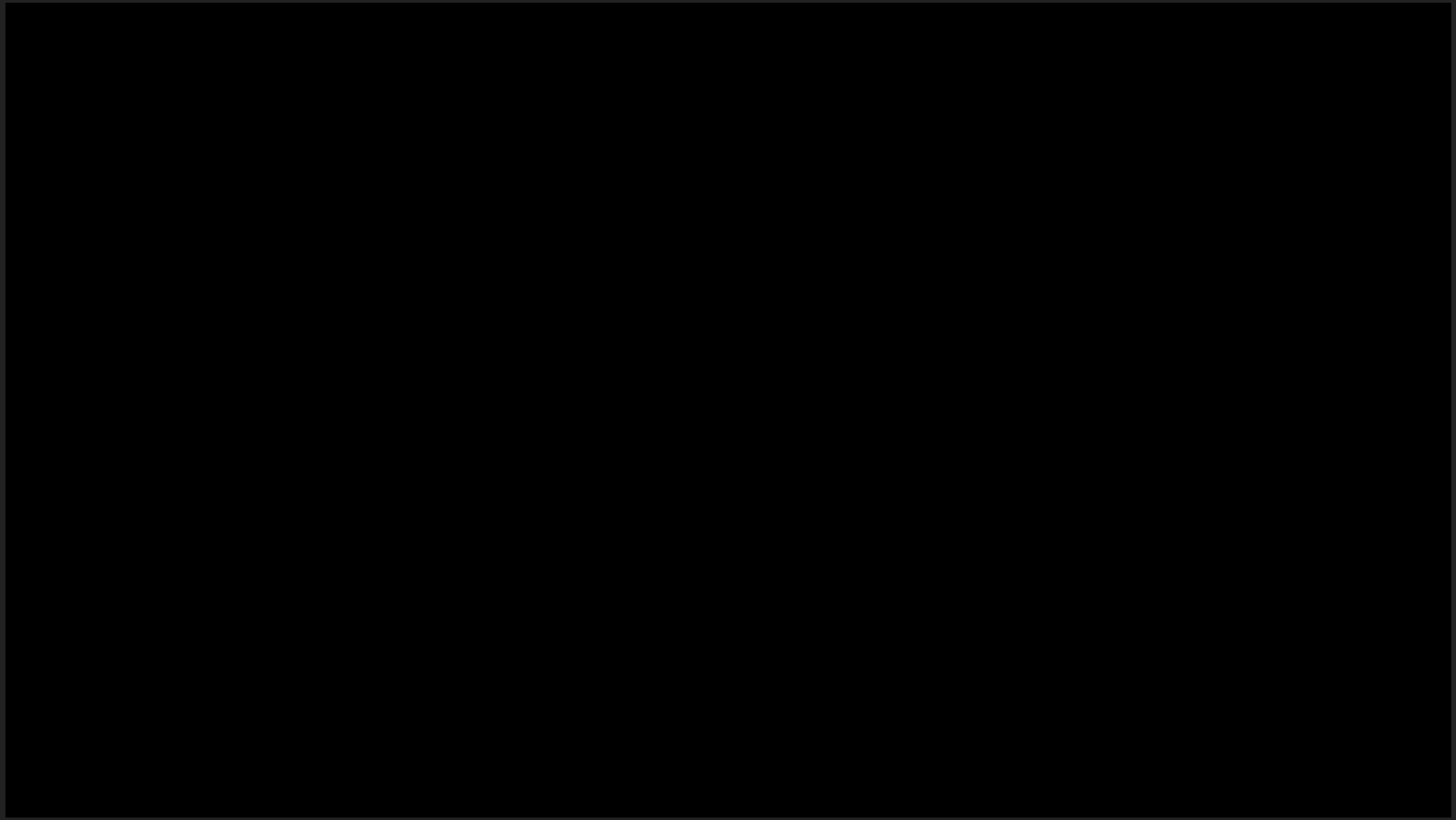

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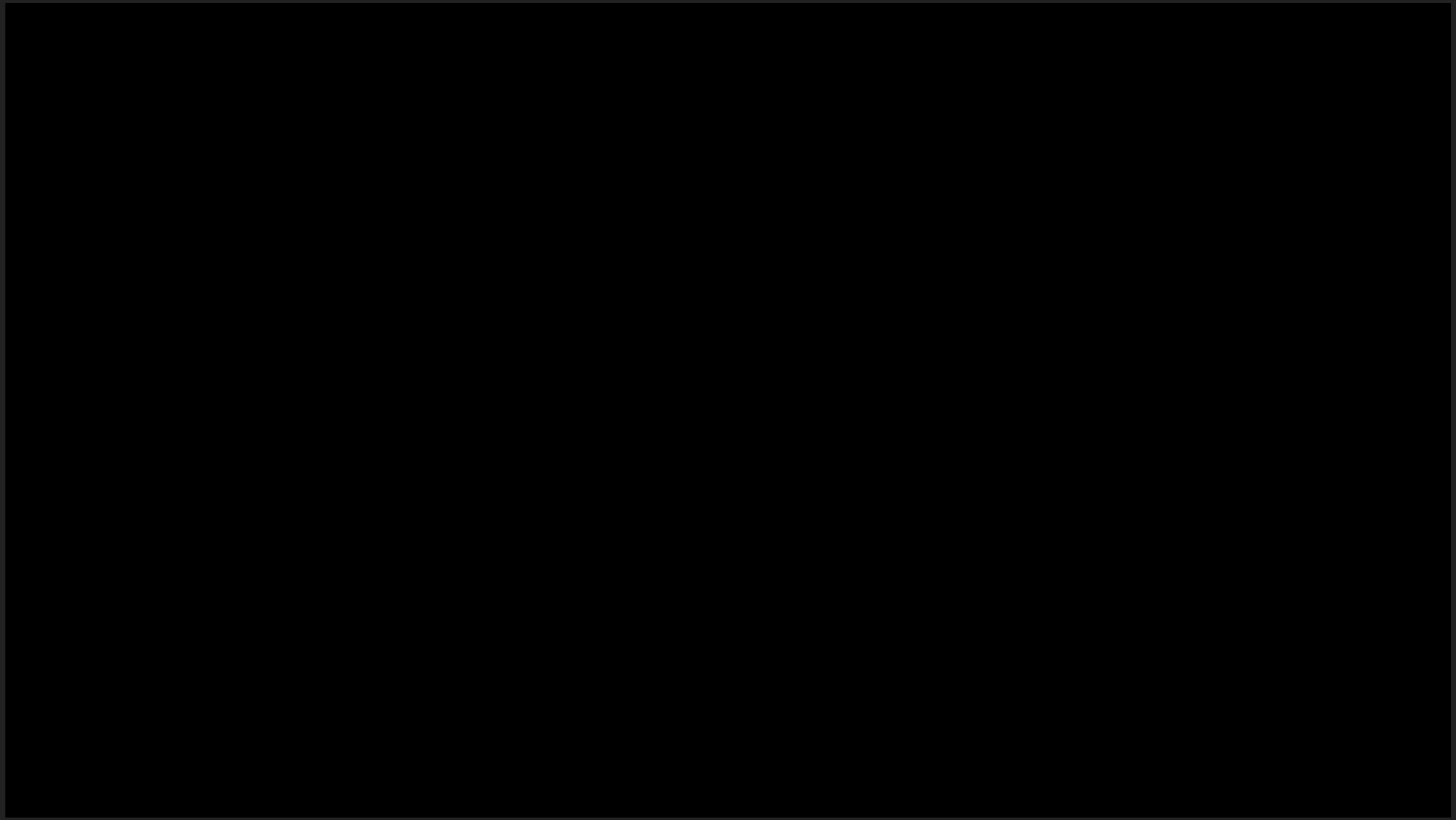
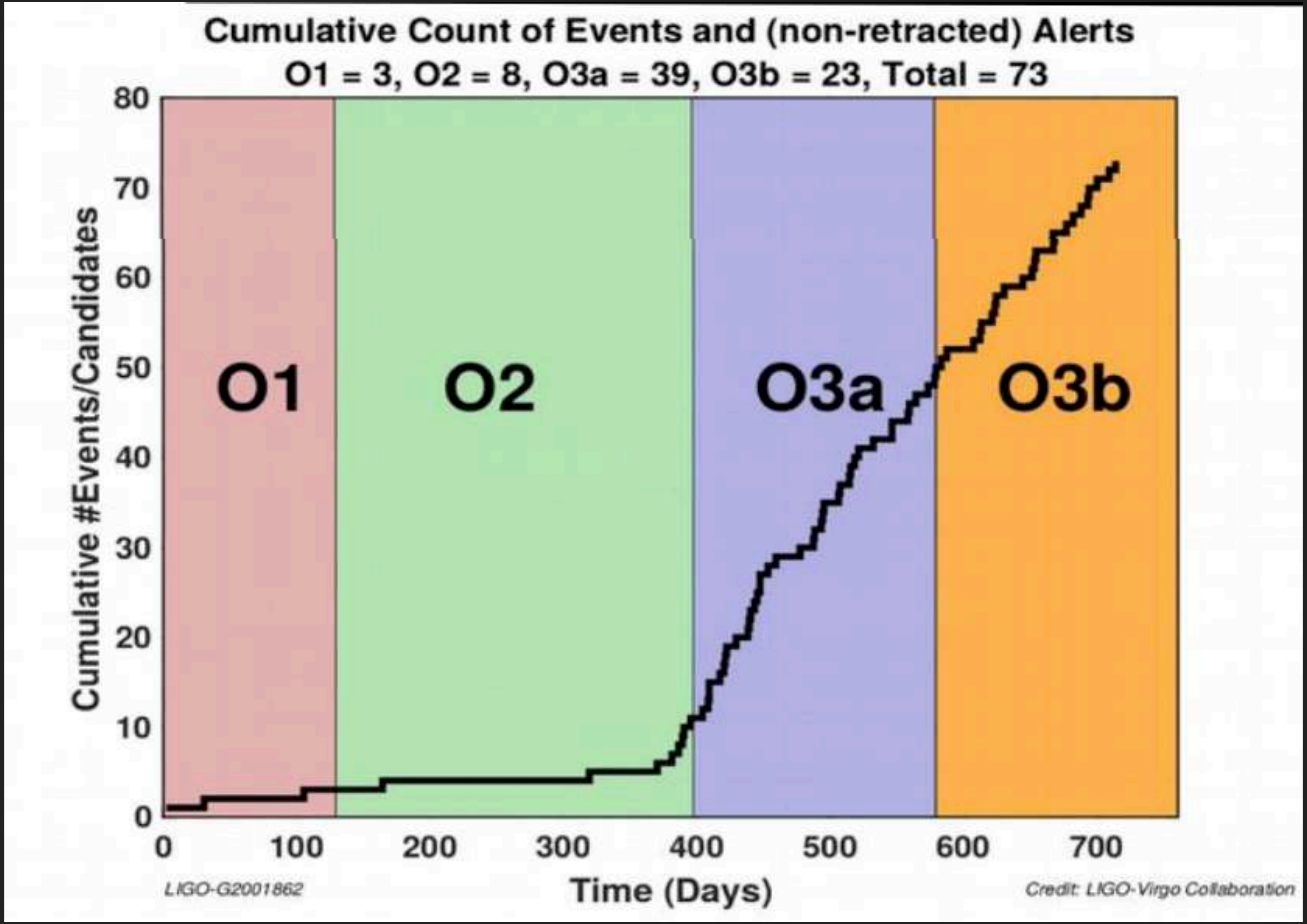
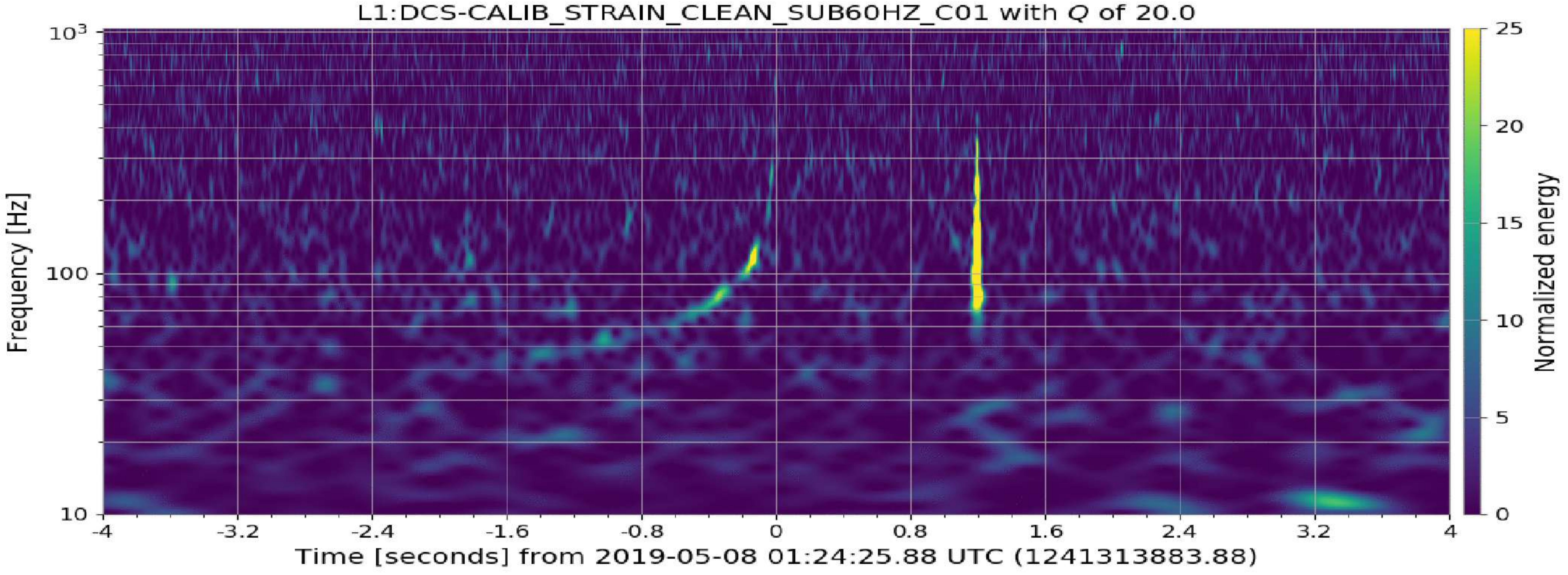
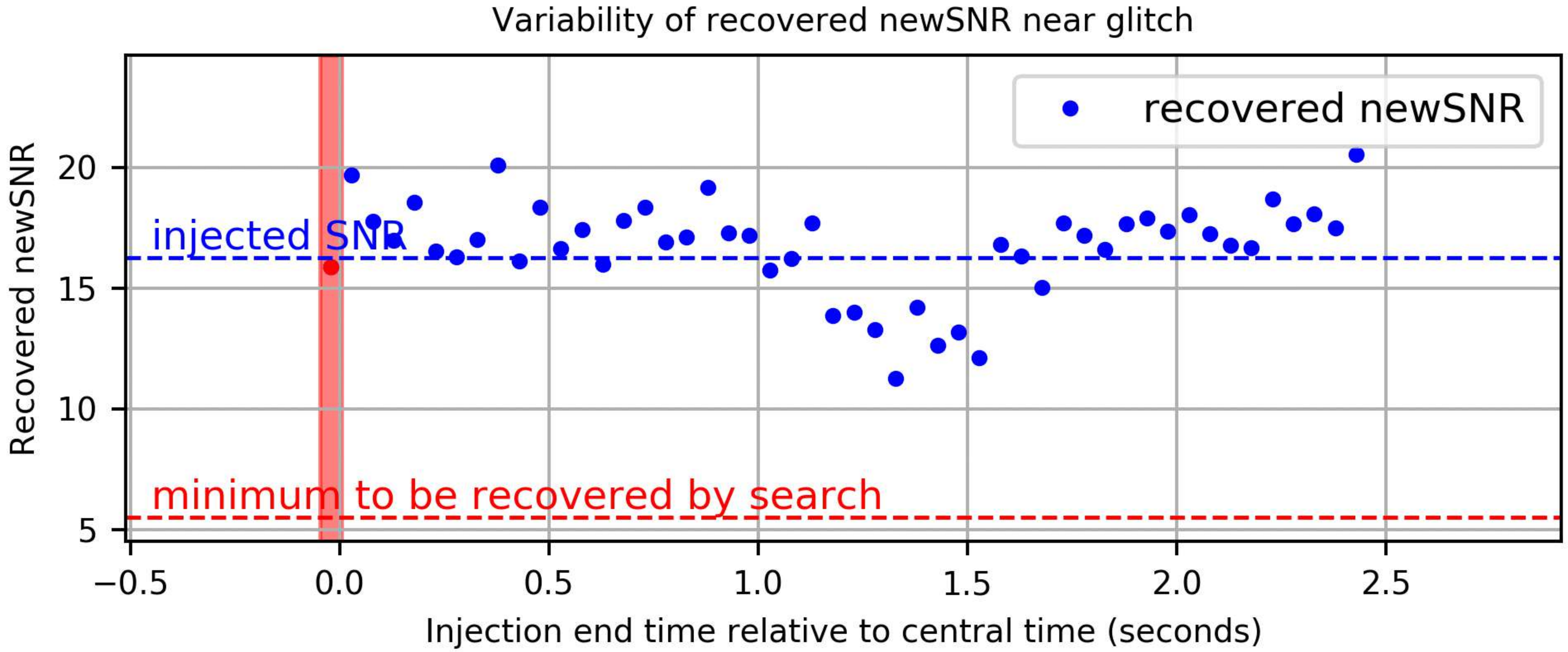


Credit: LIGO Scientific Collaboration

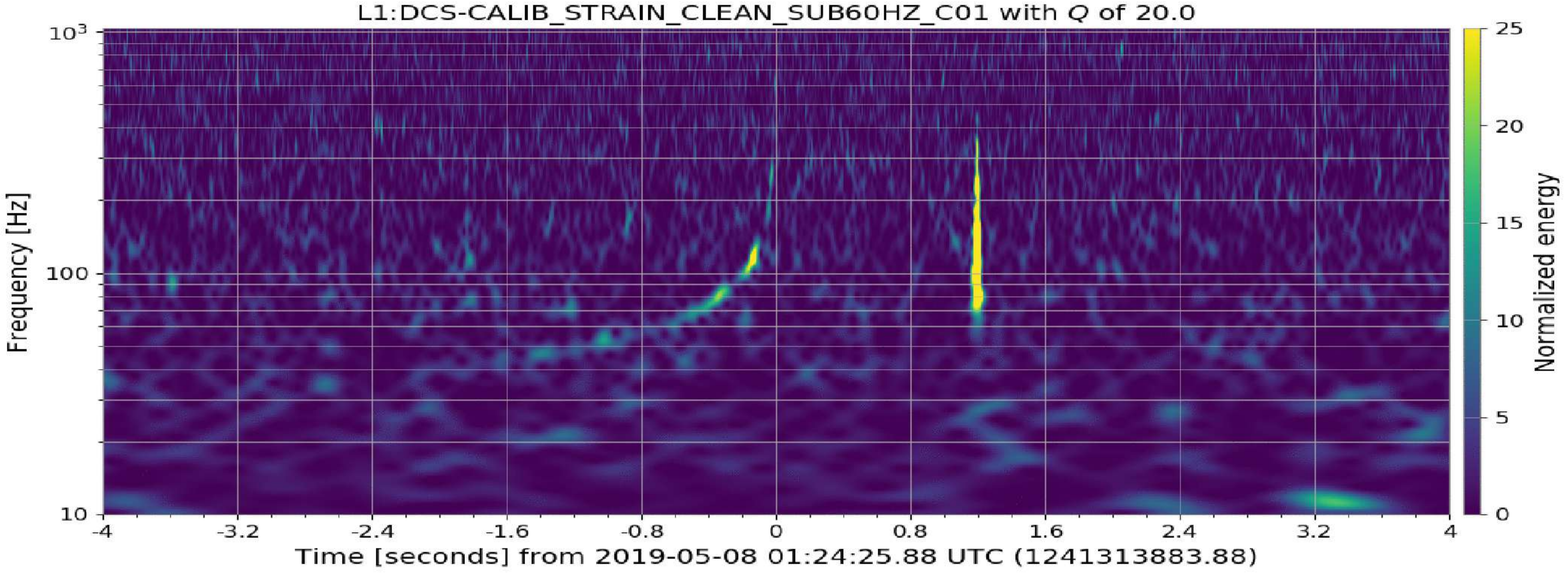
BACK-UP SLIDES

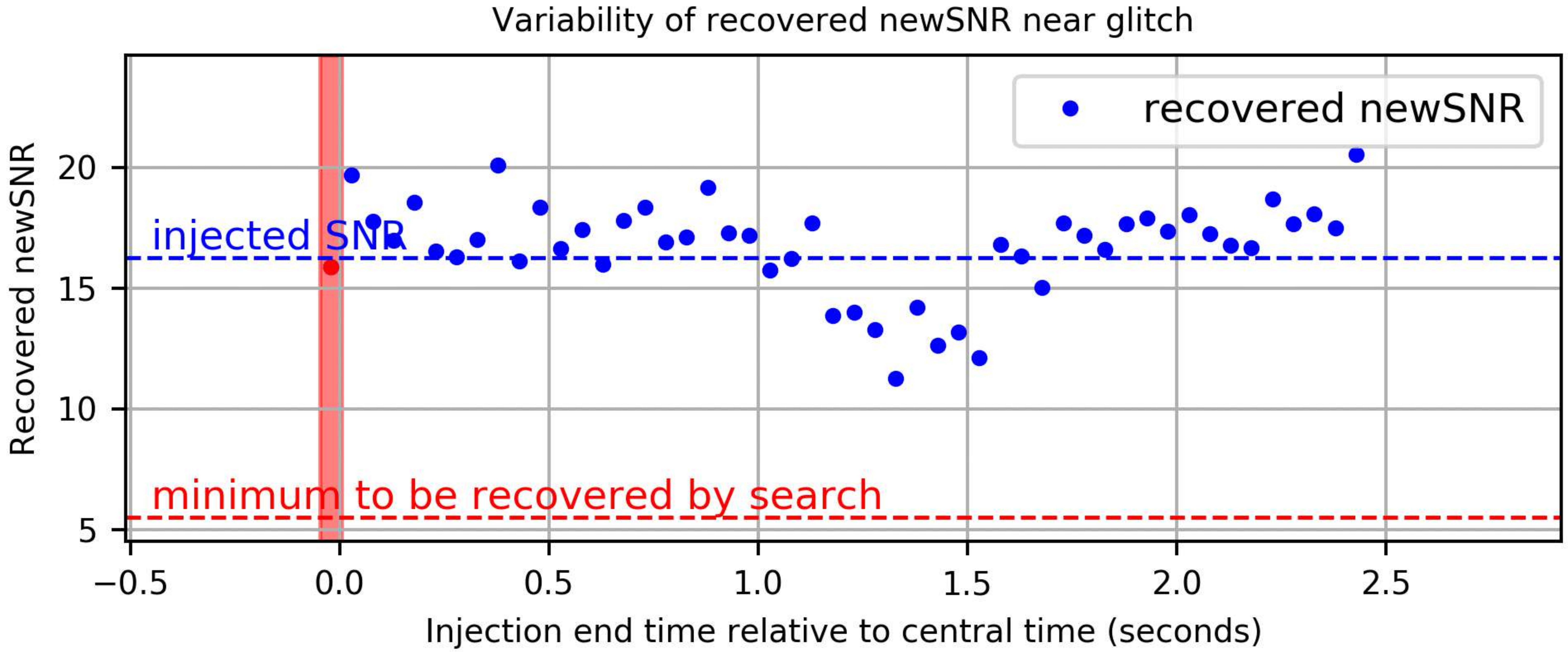

Cumulative Count of Events and (non-retracted) Alerts
O1 = 3, O2 = 8, O3a = 39, O3b = 23, Total = 73
Cumulative #Events/Candidates
Time (Days)
O1
O2
O3a
O3b
0
10
20
30
40
50
60
70
80
0
100
200
300
400
500
600
700
LIGO-G2001862
Credit: LIGO-Virgo Collaboration



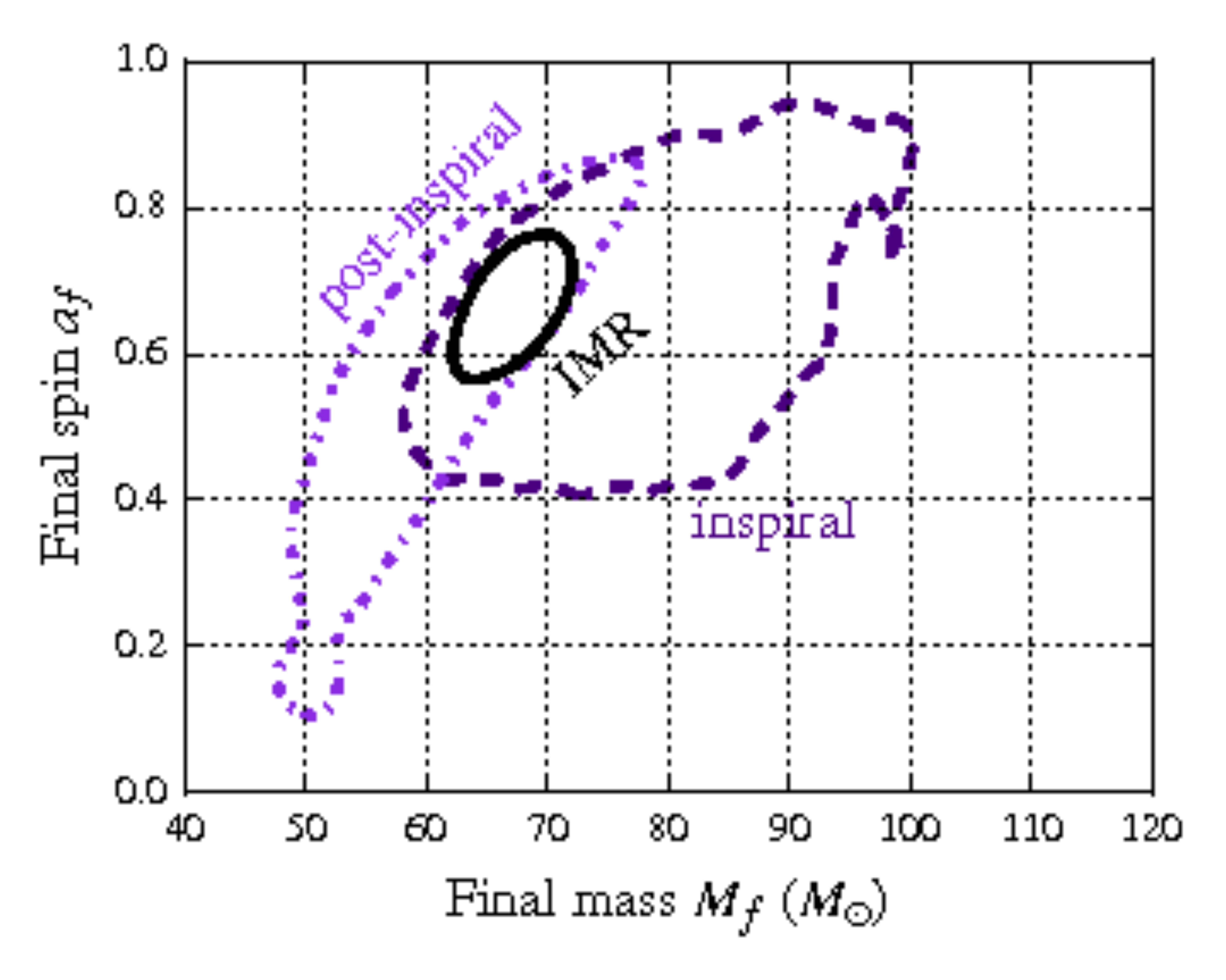


Credit:
Yannick Lecoeuche





Credit:
Yannick Lecoeuche



Credit: Breschi et al., Classical & Quantum Gravity (2019)