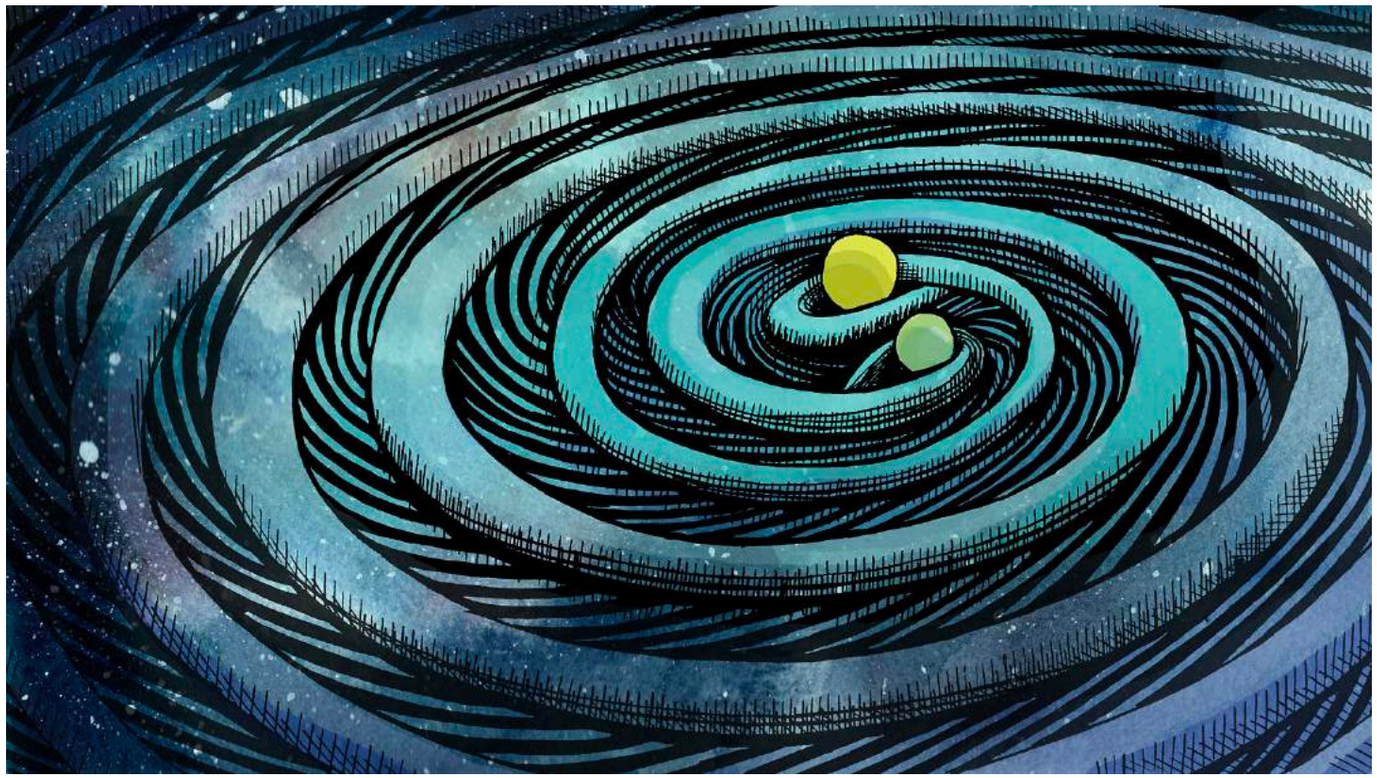
The Kavli Institute for Astronomy and Astrophysics at Peking University
北京大学科维理天文与天体物理研究所

GWs and Fundamental Physics

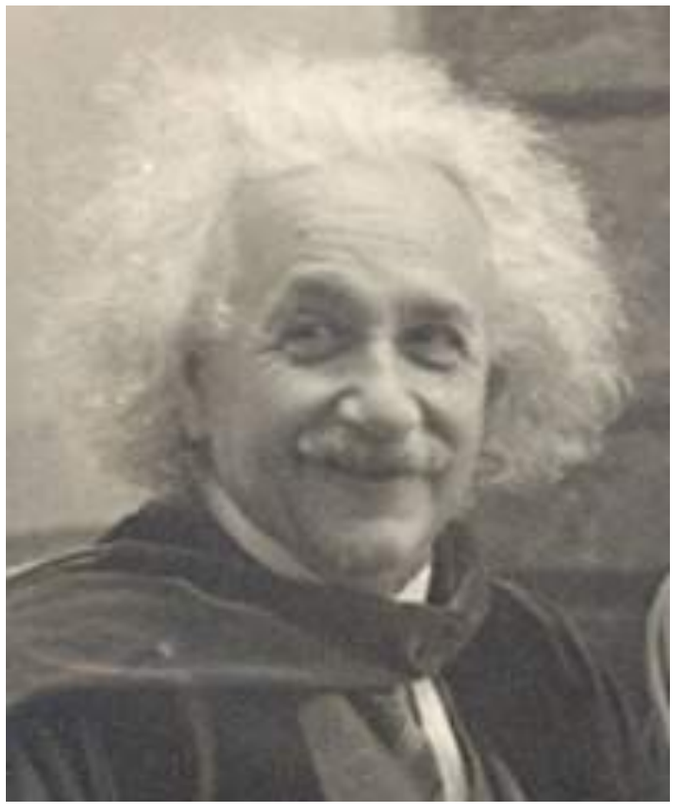


Lijing Shao (邵立晶)

Kavli Institute for Astronomy and Astrophysics, Peking University

Today's Goal: to understand why David Reitz is so excited?

General Relativity

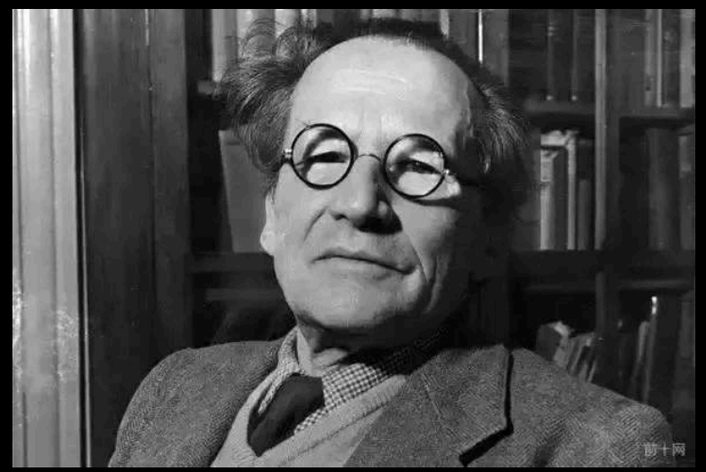


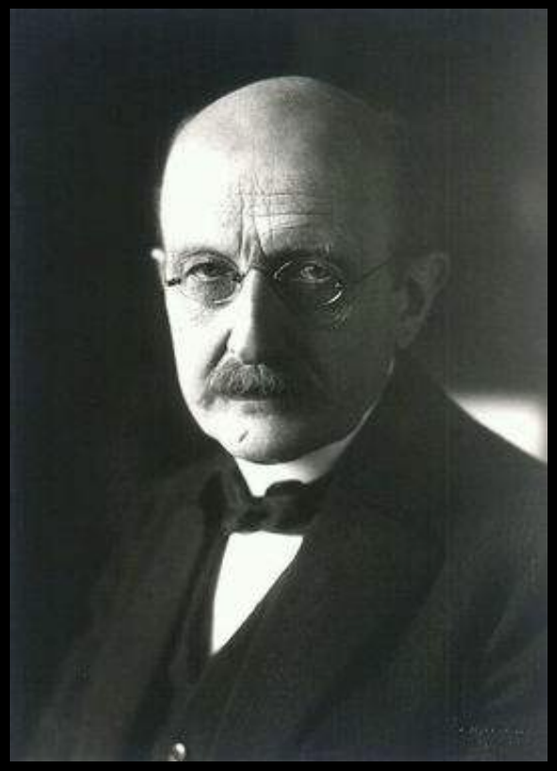
$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Albert Einstein (1915)

“[狭义相对论] 像光彩夺目的火箭，在黑暗的夜空里突然划出一道短促而又十分强烈的光辉，照亮了广阔的未知领域。”

德布罗意，1929 年获诺贝尔物理学奖





“现在一切都能明白地解释了，你为什么忙于另一个问题呢？”

普朗克，1918 年获诺贝尔物理学奖

My (personal) Favorite Equations

- **Equations deeply from the soul**

$$e^{i\pi} + 1 = 0$$ **Nope...**

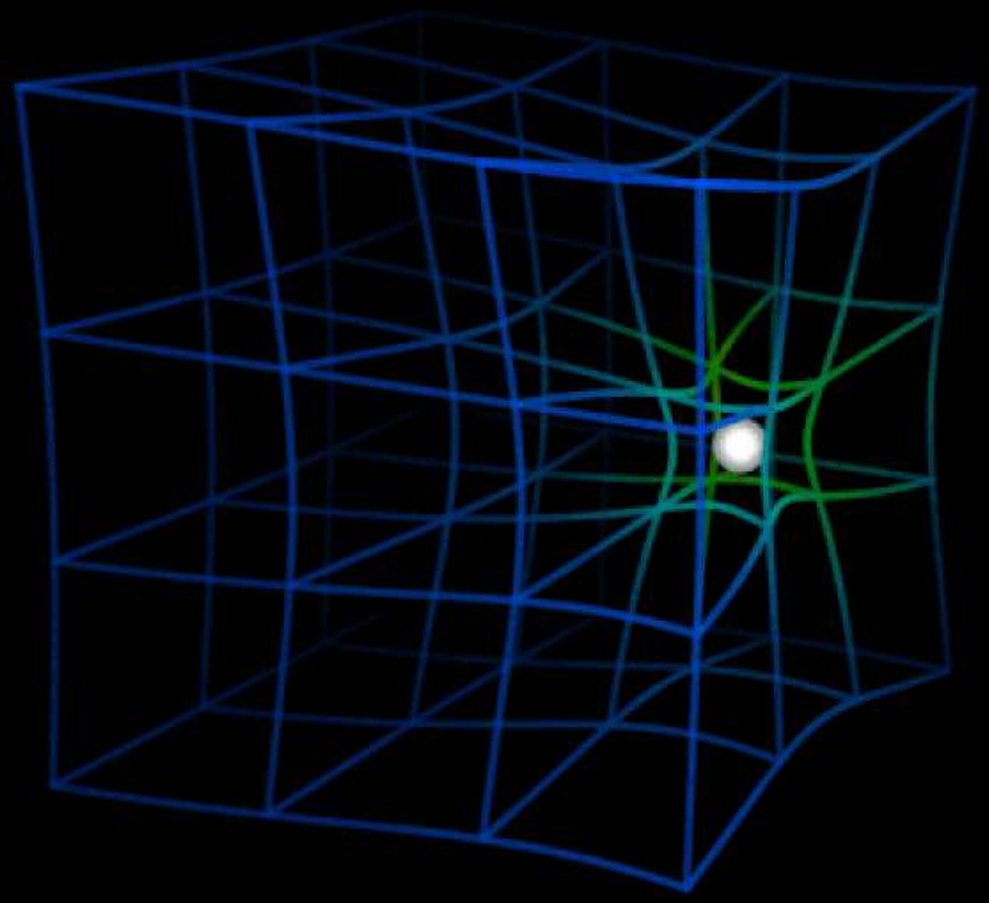
$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$ **Yes!**

$$\left(i\not{D}_{\mu} - m \right) \psi = 0$$ **Yes!**

广义相对论

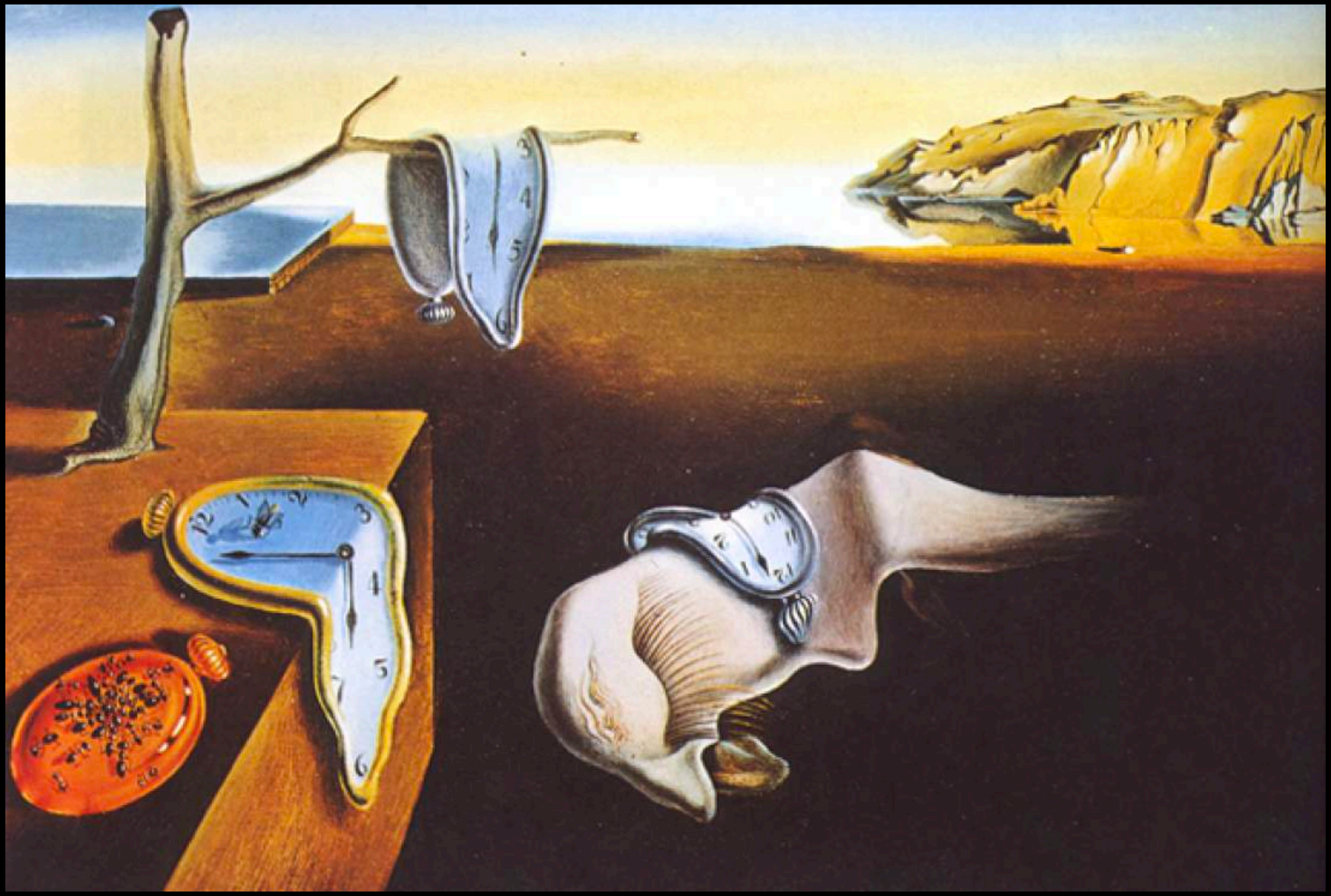
$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

时空几何　　物质



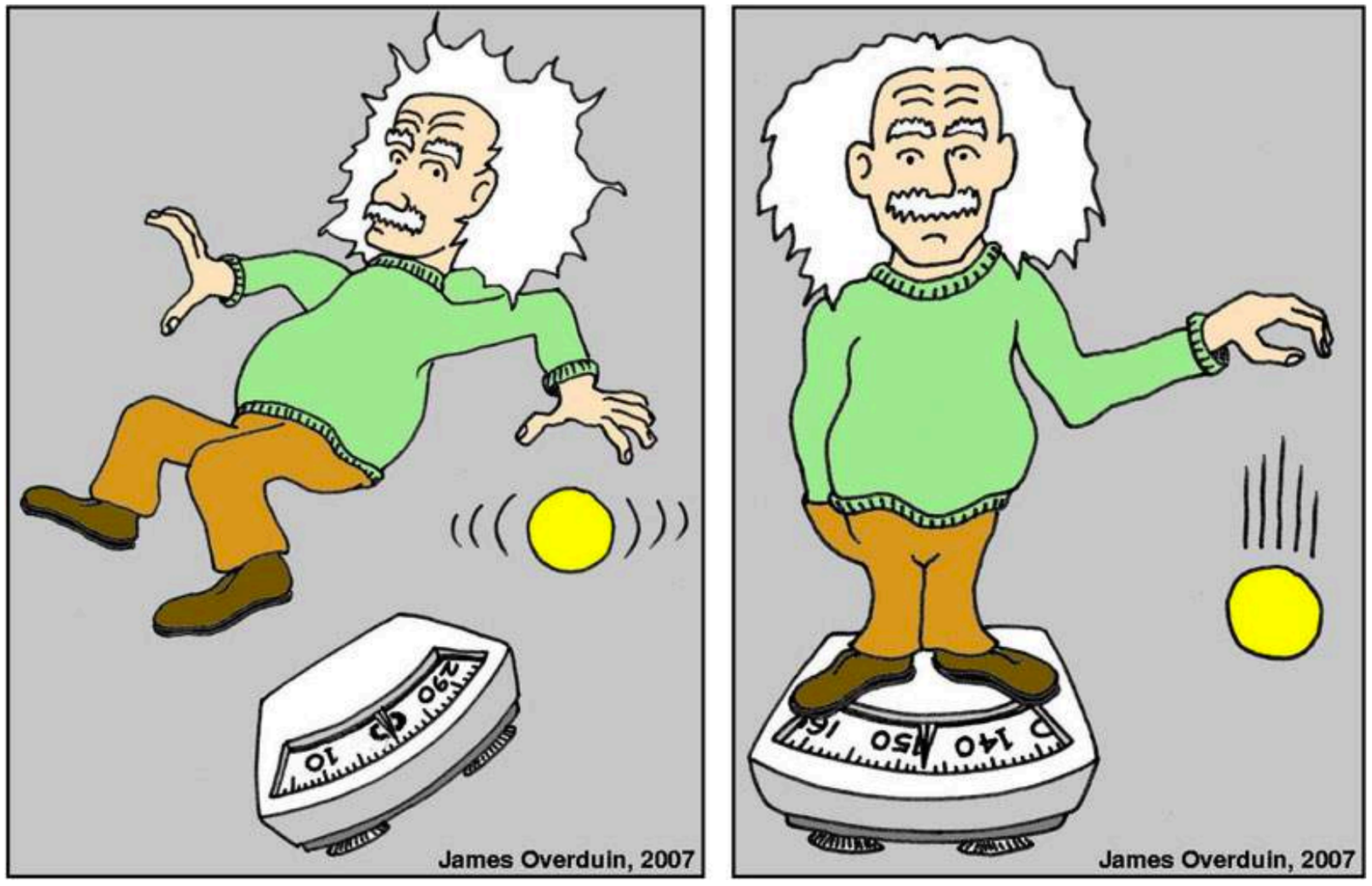
John A. Wheeler: *"Matter tells spacetime how to curve, and spacetime tells matter how to move."*

广义相对论也催生了全新的艺术作品



Principles behind GR

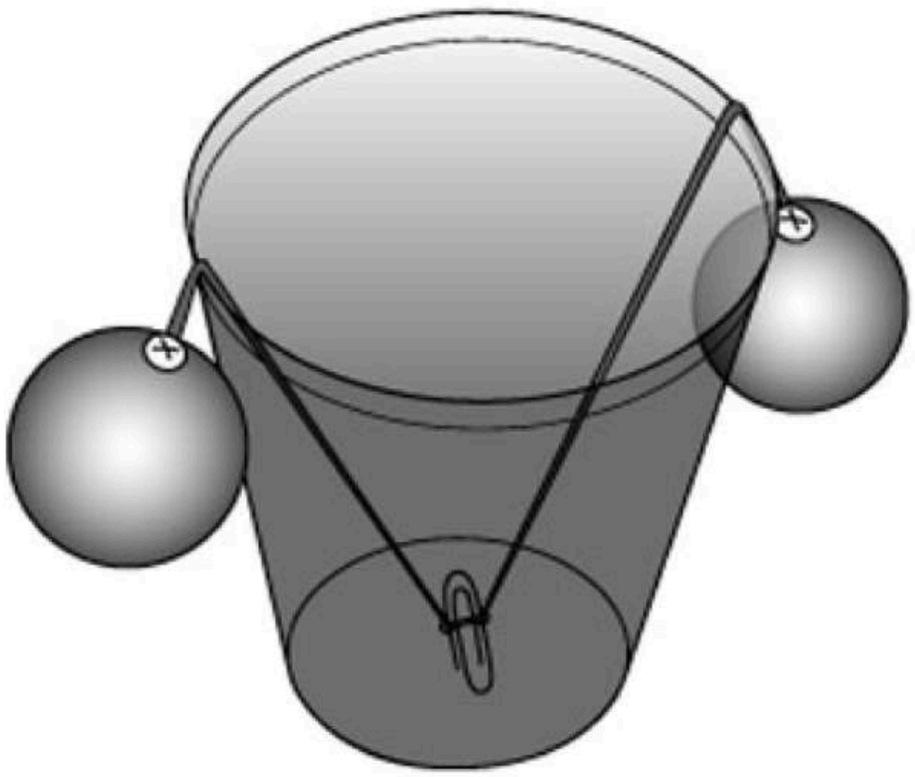
- ✦ 相对性原理
- ✦ 等效原理：来自实验

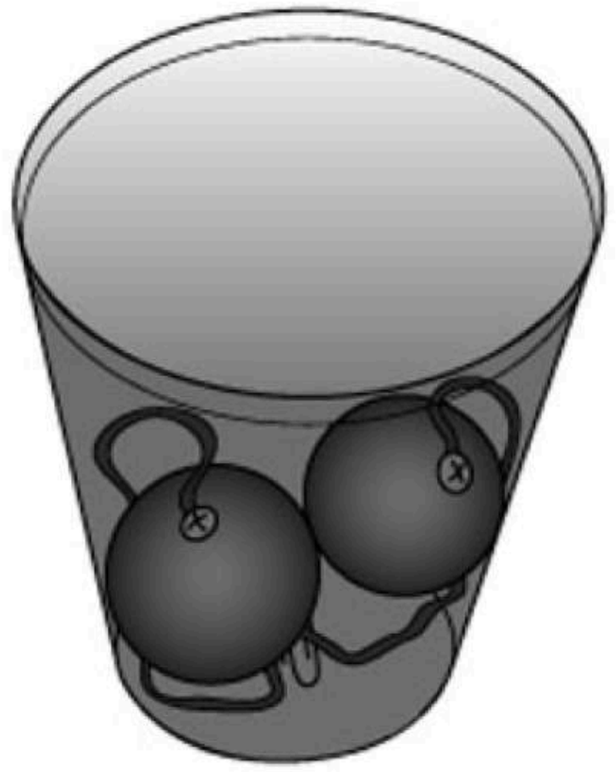


广义相对论是描述引力的理论，它的精髓在于指出：其实并没有“引力”！

引力 = 非惯性系 = 时空 （= 没有“引力”！）

爱因斯坦的玩具

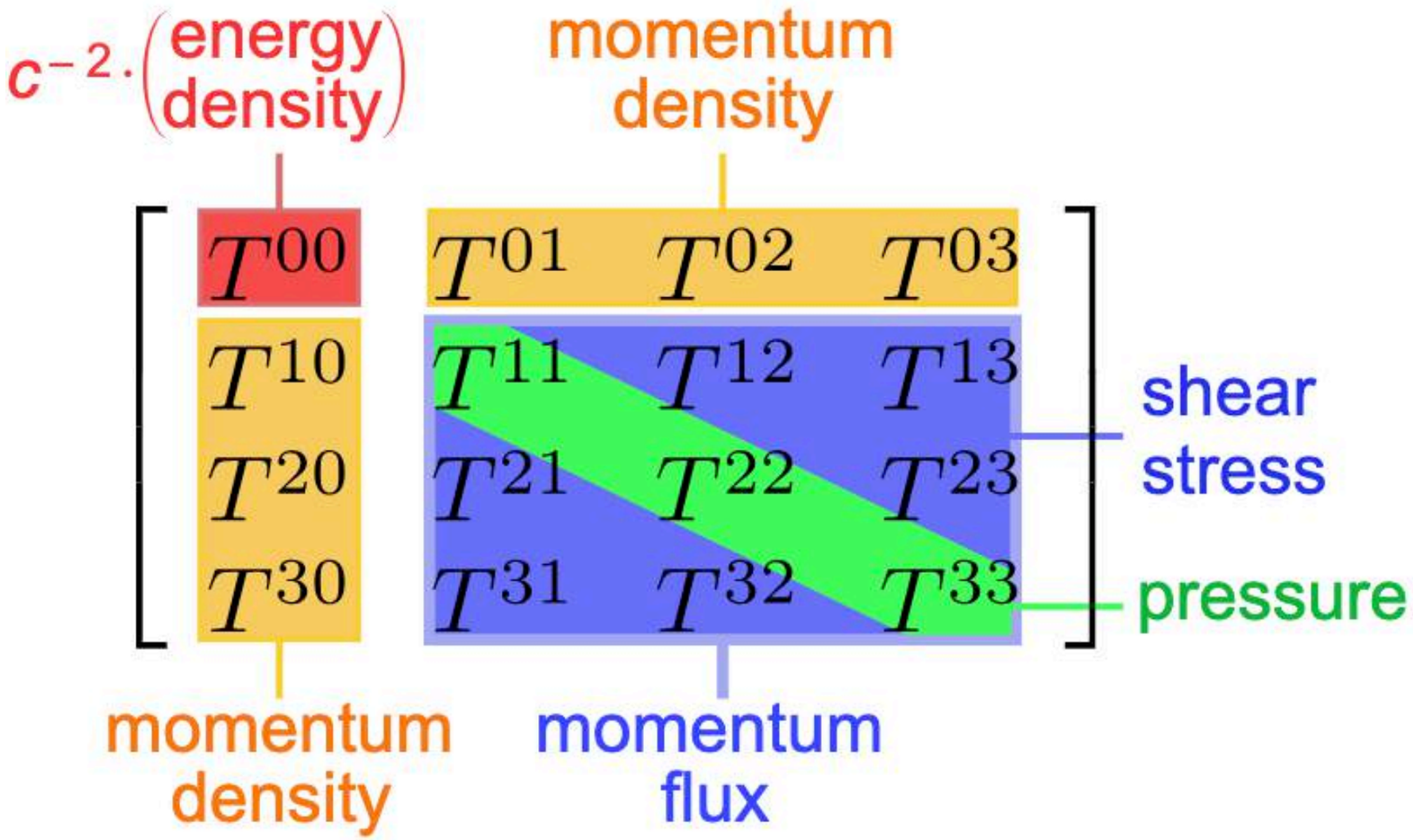




76 岁时的生日礼物

General Relativity: stress-energy tensor

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



General Relativity: geometry

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

Metric: $g_{\mu\nu}$ **describes distance** $\mathrm{d}s^2 = g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu$ 求和法则

Connection: $\Gamma^\mu_{\nu\alpha} = \frac{1}{2} g^{\mu\sigma}\left(\partial_\nu g_{\alpha\sigma} + \partial_\alpha g_{\nu\sigma} - \partial_\sigma g_{\alpha\nu}\right)$ 一阶导数

Riemannian tensor: $R^\alpha_{\beta\gamma\delta} \equiv \partial_\gamma \Gamma^\alpha_{\beta\delta} - \partial_\delta \Gamma^\alpha_{\beta\gamma} + \Gamma^\nu_{\beta\delta}\Gamma^\alpha_{\nu\gamma} - \Gamma^\nu_{\beta\gamma}\Gamma^\alpha_{\nu\delta}$ 二阶导数

Ricci tensor: $R_{\alpha\beta} \equiv R^\gamma_{\alpha\gamma\beta}$ “缩并”

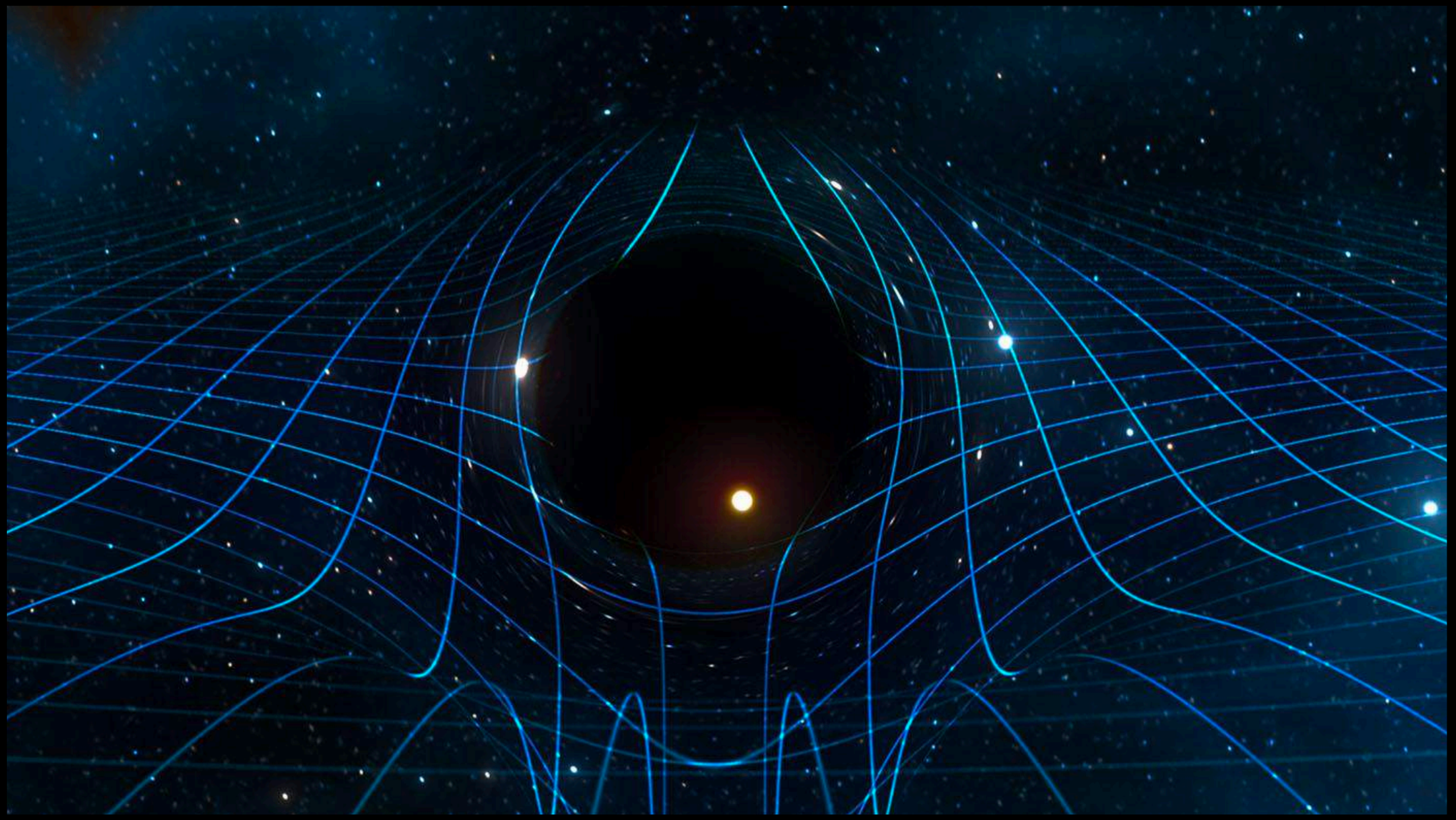
Ricci scalar: $R \equiv R^\alpha_\alpha$

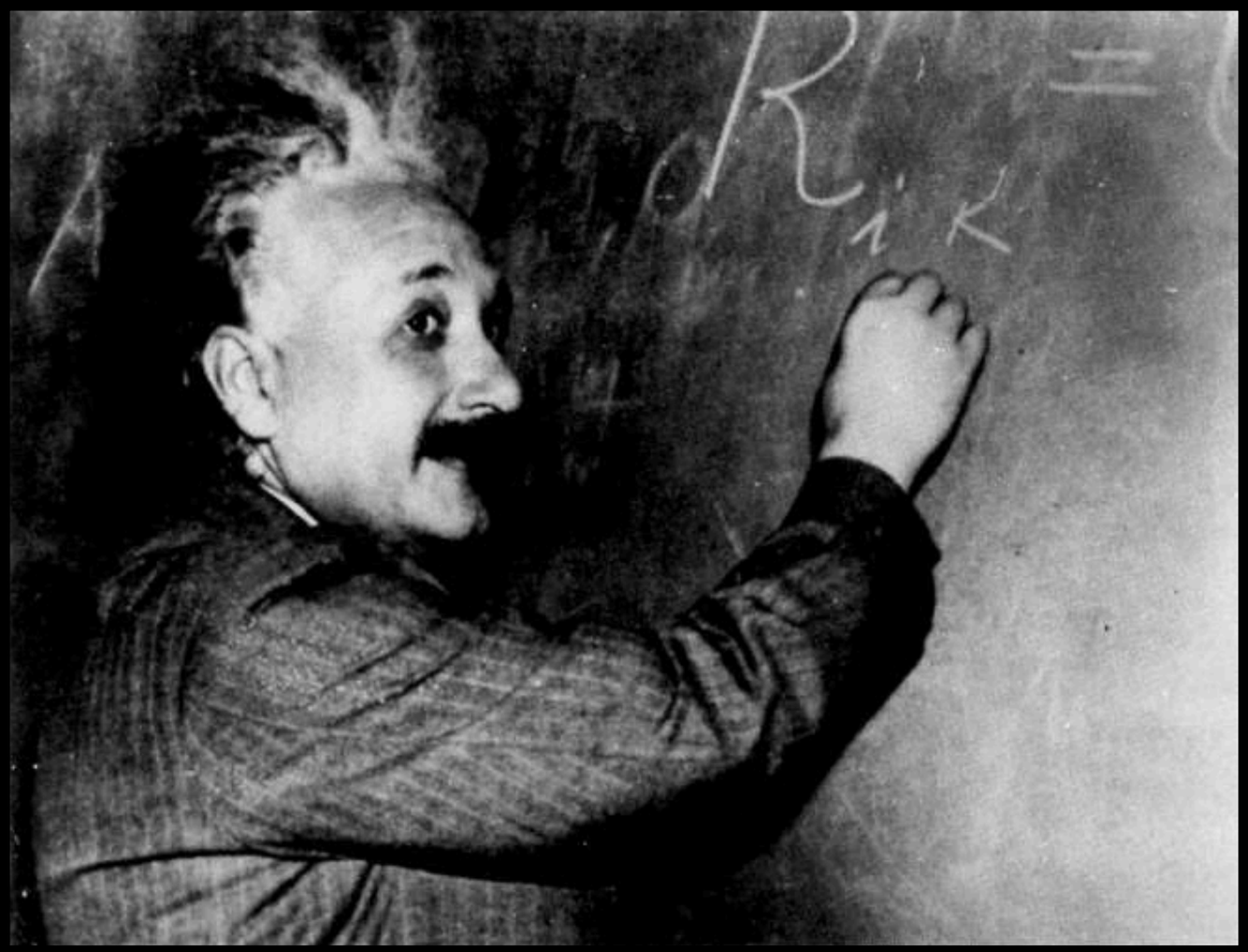
Summary: LHS contains first & second derivatives of the metric, that is all!

Black Hole Spacetimes

Schwarzschild 1916
Kerr 1963

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G T_{\mu\nu}}{c^4} = 0$$





Einstein (1916): 引力波解

Gravitational Waves

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

To leading order in $h_{\mu\nu}$

$$\Gamma^{\nu}_{\mu\rho} = \frac{1}{2}\eta^{\nu\lambda}\left(\partial_\rho h_{\lambda\mu} + \partial_\mu h_{\lambda\rho} - \partial_\lambda h_{\mu\rho}\right)$$

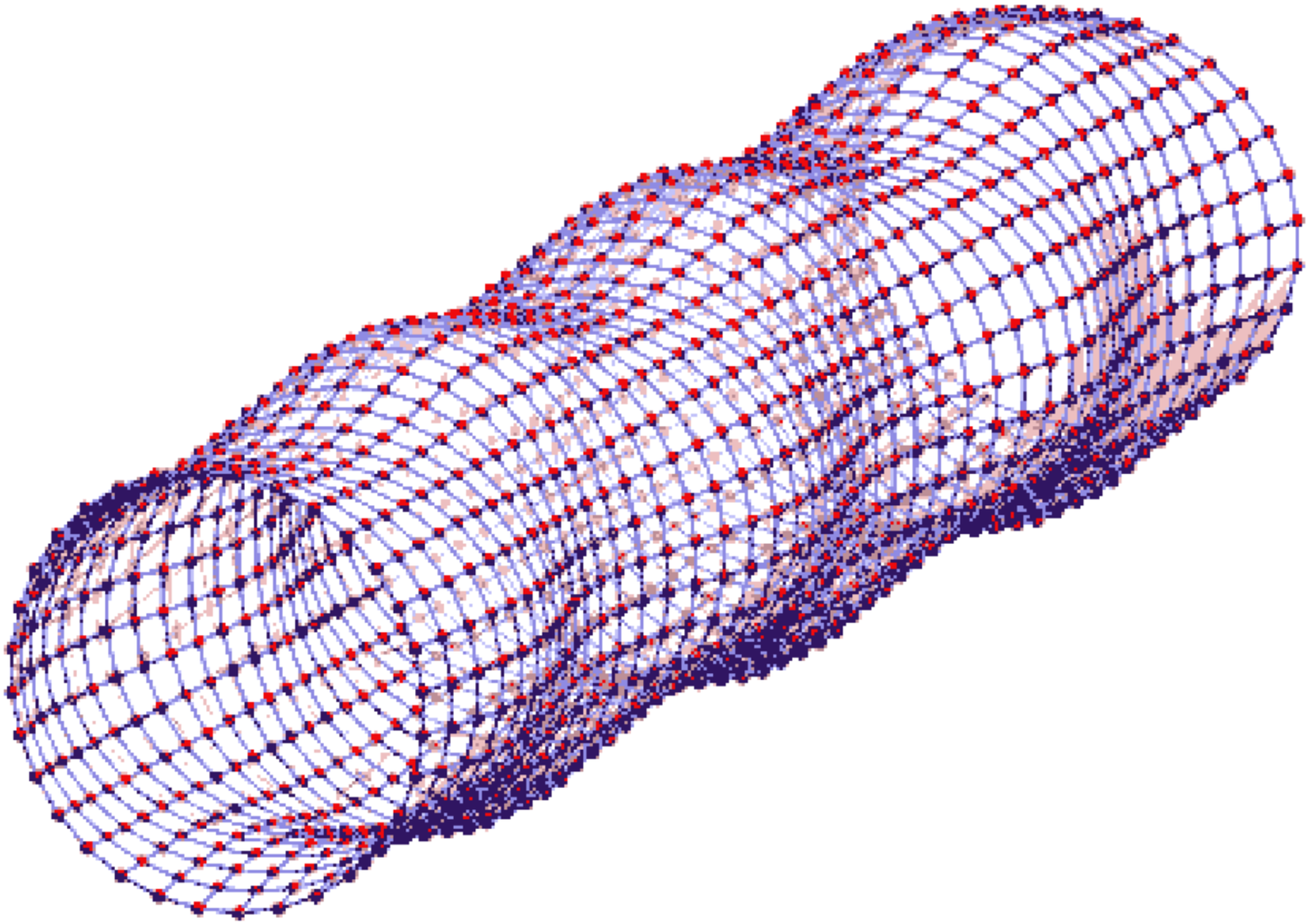
$$R_{\mu\nu\rho\sigma} = \frac{1}{2}\left(\partial_{\rho\nu} h_{\mu\sigma} + \partial_{\sigma\mu} h_{\nu\rho} - \partial_{\rho\mu} h_{\nu\sigma} - \partial_{\sigma\nu} h_{\mu\rho}\right)$$

Define $\bar{h}^{\mu\nu} = h^{\mu\nu} - \frac{1}{2}\eta^{\mu\nu}h$ **Choose gauge** $\partial_\nu \bar{h}^{\mu\nu} = 0$

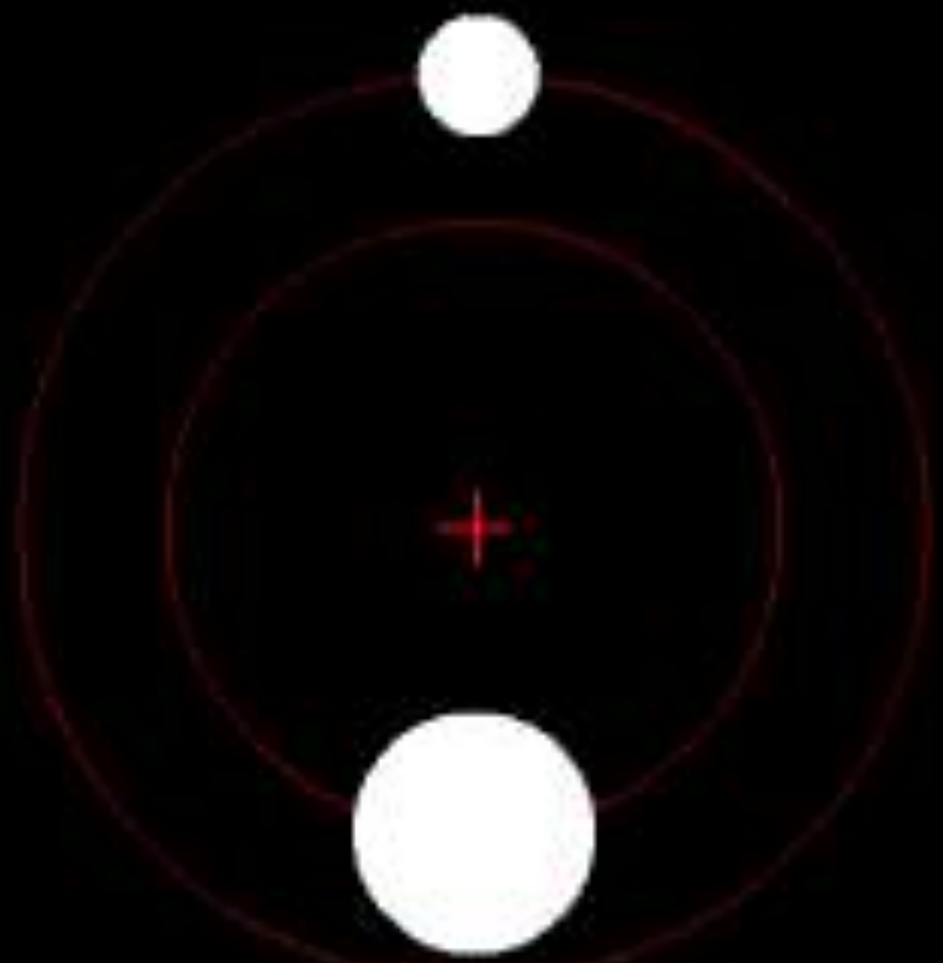
$$\Box \bar{h}_{\nu\sigma} = -\frac{16\pi G}{c^4} T_{\nu\sigma}$$

Metric perturbative satisfies a wave equation

GWs



开普勒轨道



time(ms)=337.5

Kerr黑洞

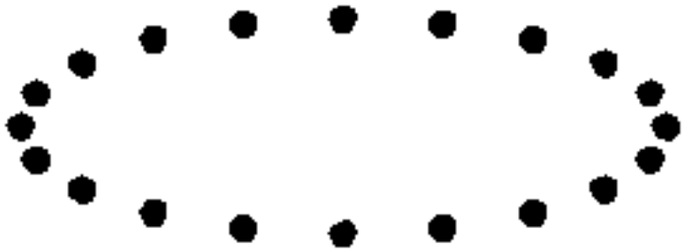
Chirp

Inspiral, merger, and ringdown

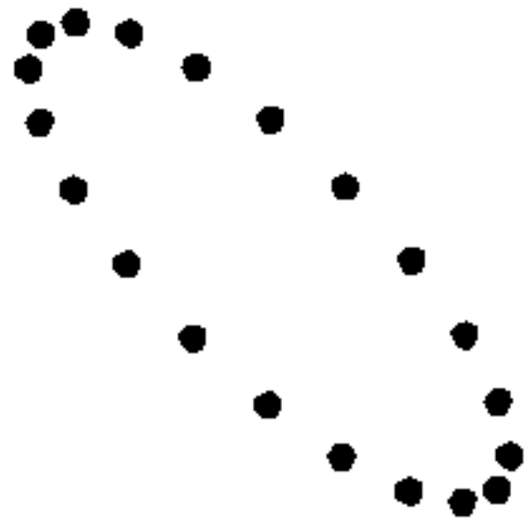
https://www.youtube.com/watch?v=L9H9xawSg_c

GW Polarizations

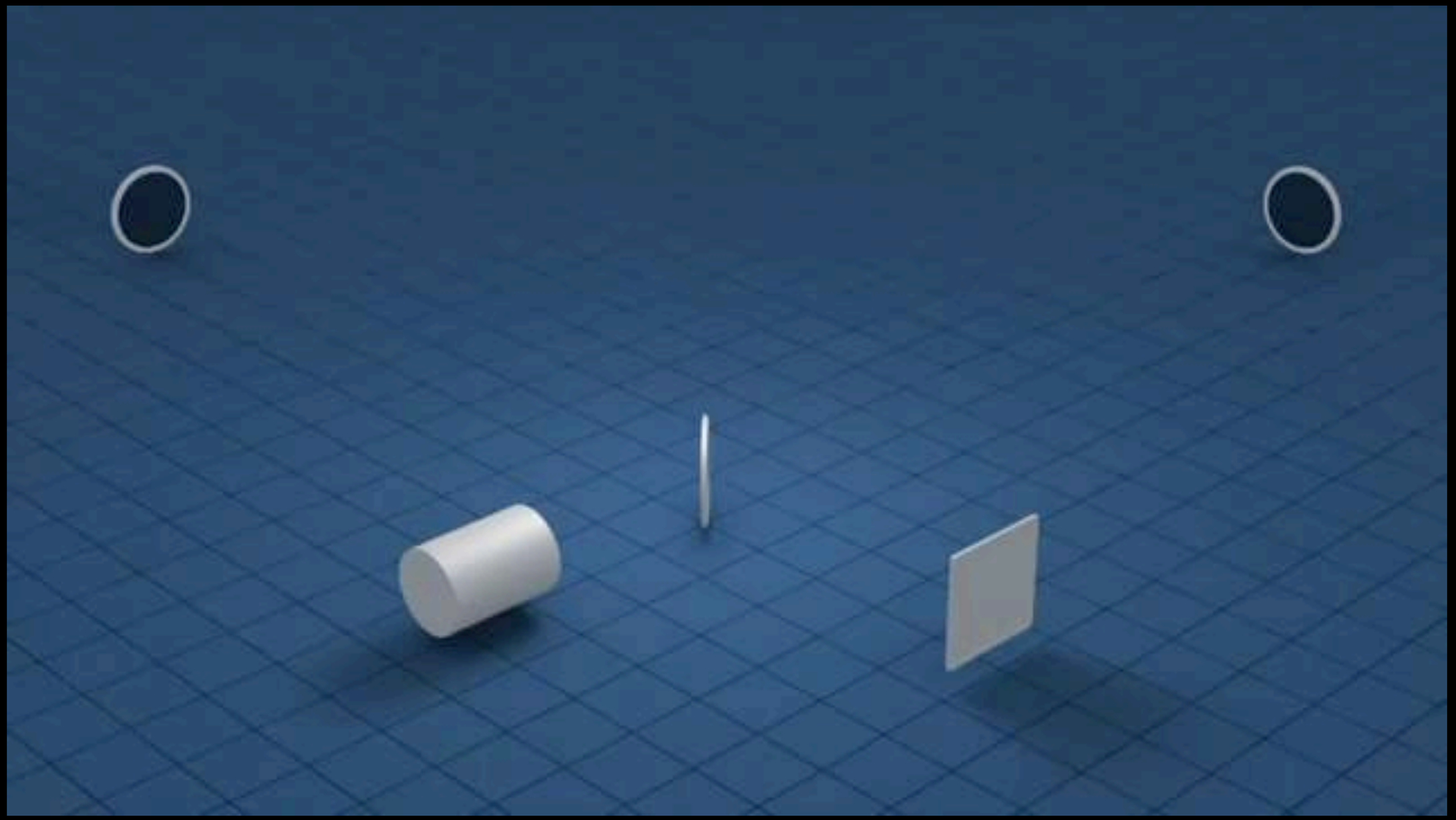
GWs in GR have two polarizations: plus (+) and cross (x)



Plus



Cross

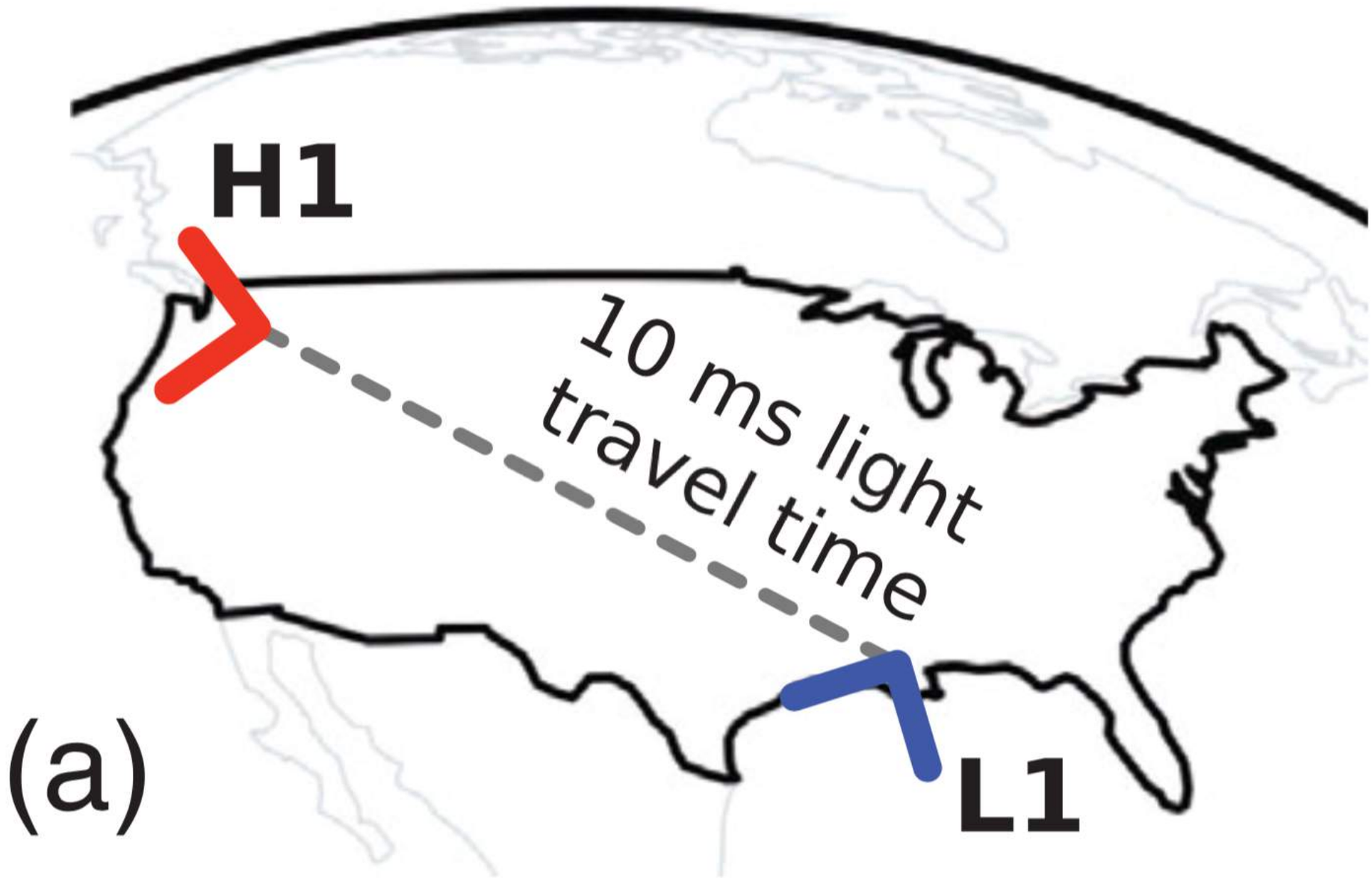


LIGO

PRL 116, 061102 (2016) Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS
week ending
12 FEBRUARY 2016

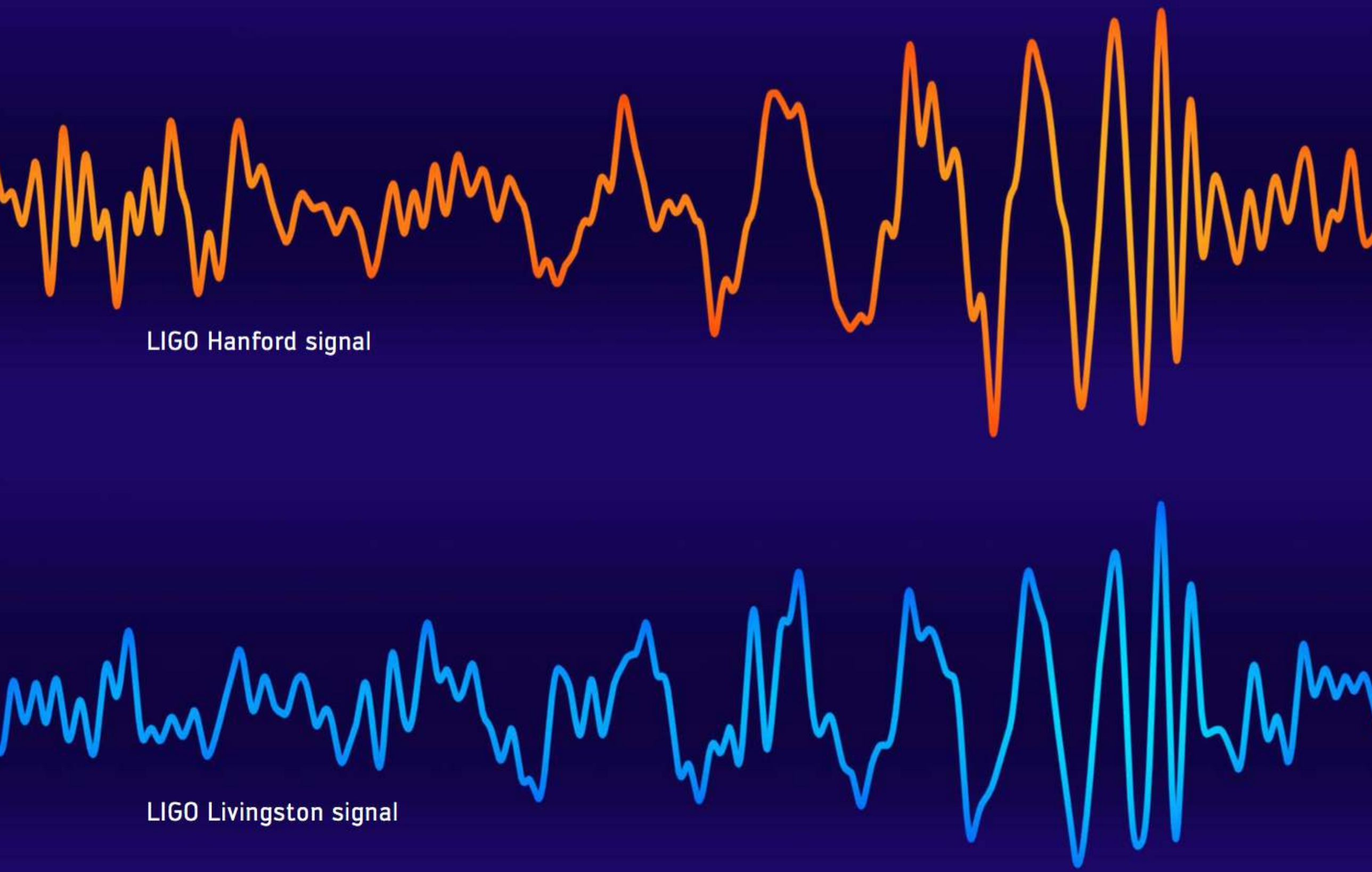
Observation of Gravitational Waves from a Binary Black Hole Merger

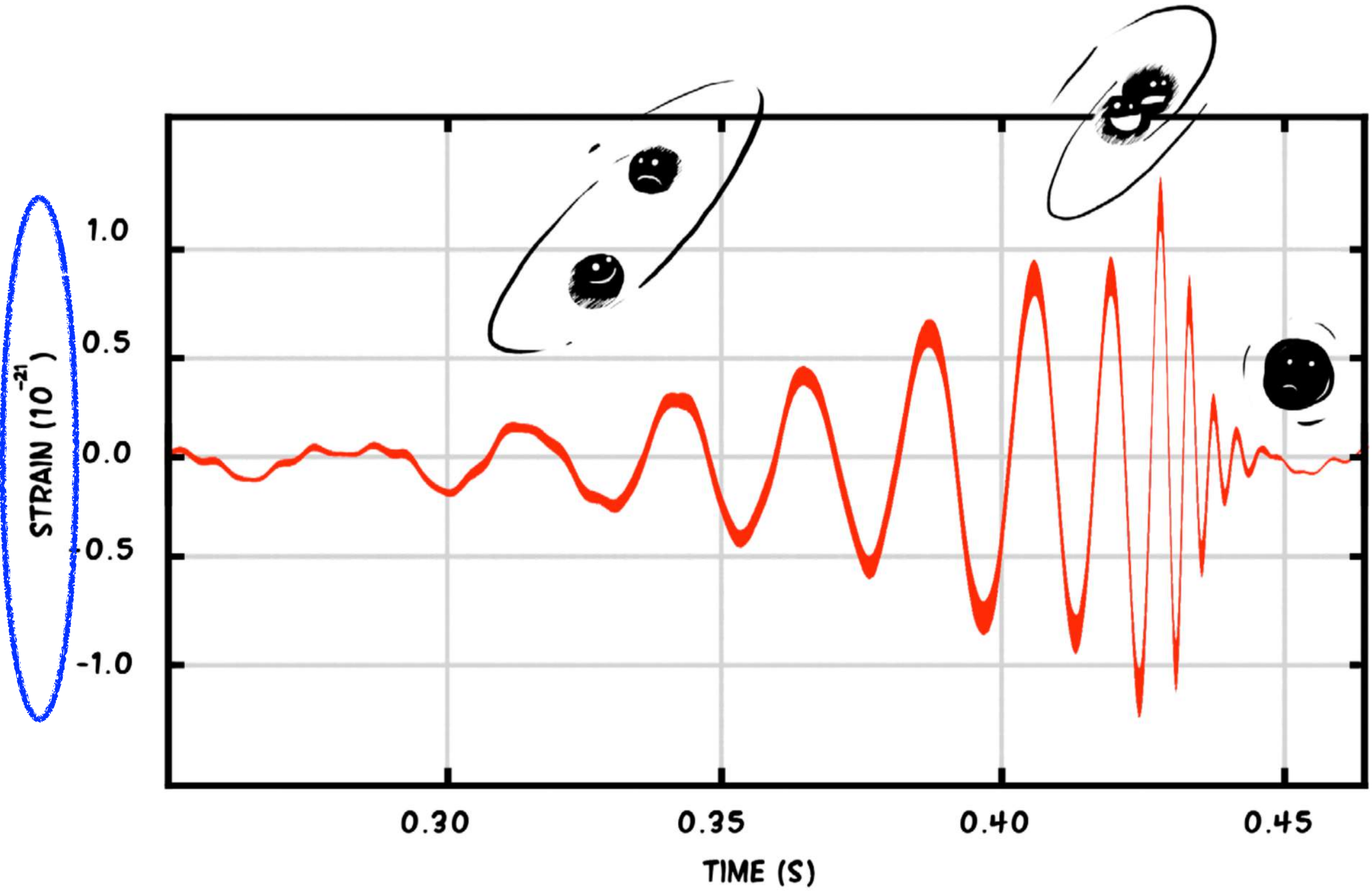
B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)



First detection!

9:50:45 UTC, 14 September 2015

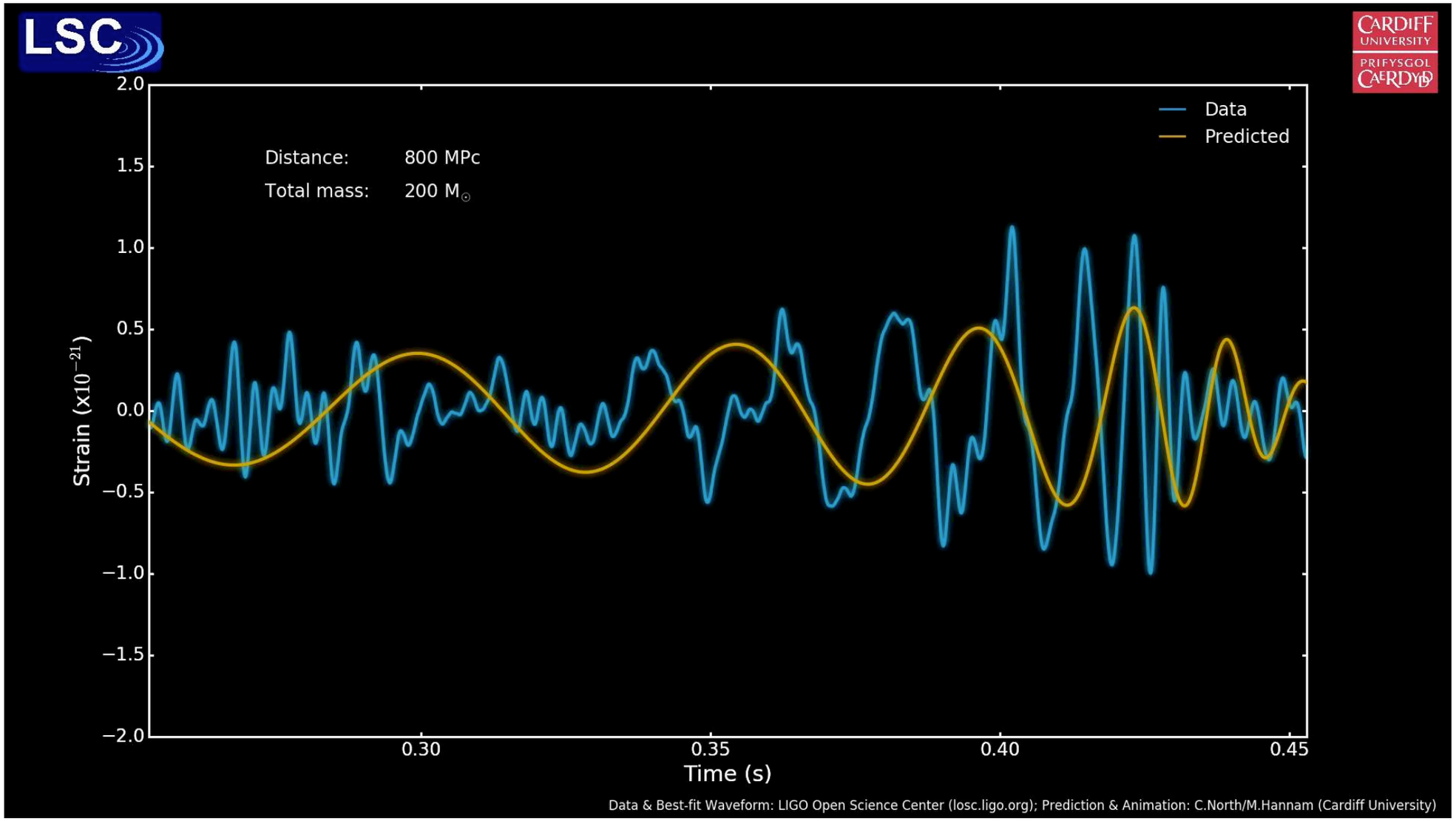




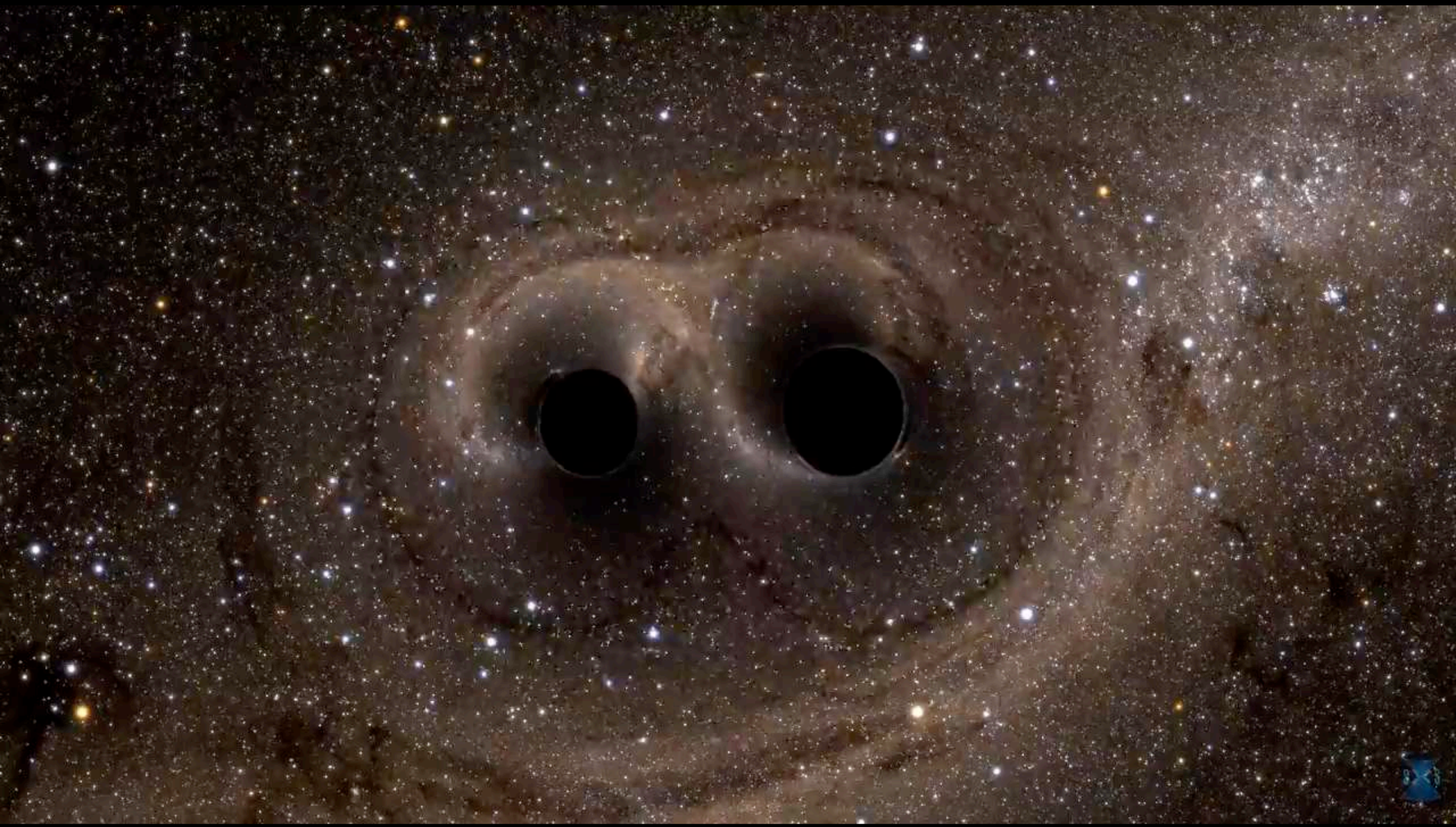
LIGO magazine

LIGO看到了什么?

GW Data Analysis: matched filtering



$$\left(\mathbf{g}\middle|\,\mathbf{k}\right) \equiv 2\int_0^\infty \frac{\tilde{g}^*(f)\tilde{k}(f)+\tilde{g}(f)\tilde{k}^*(f)}{S_n(f)}\mathrm{d}f$$



EVOLUTION OF STARS

Small Star

Red Giant

Planetary Nebula

White Dwarf

Stellar Cloud with Protostars

Large Star

Red Supergiant

Supernova

Neutron Star

Black Hole

IMAGES NOT TO SCALE

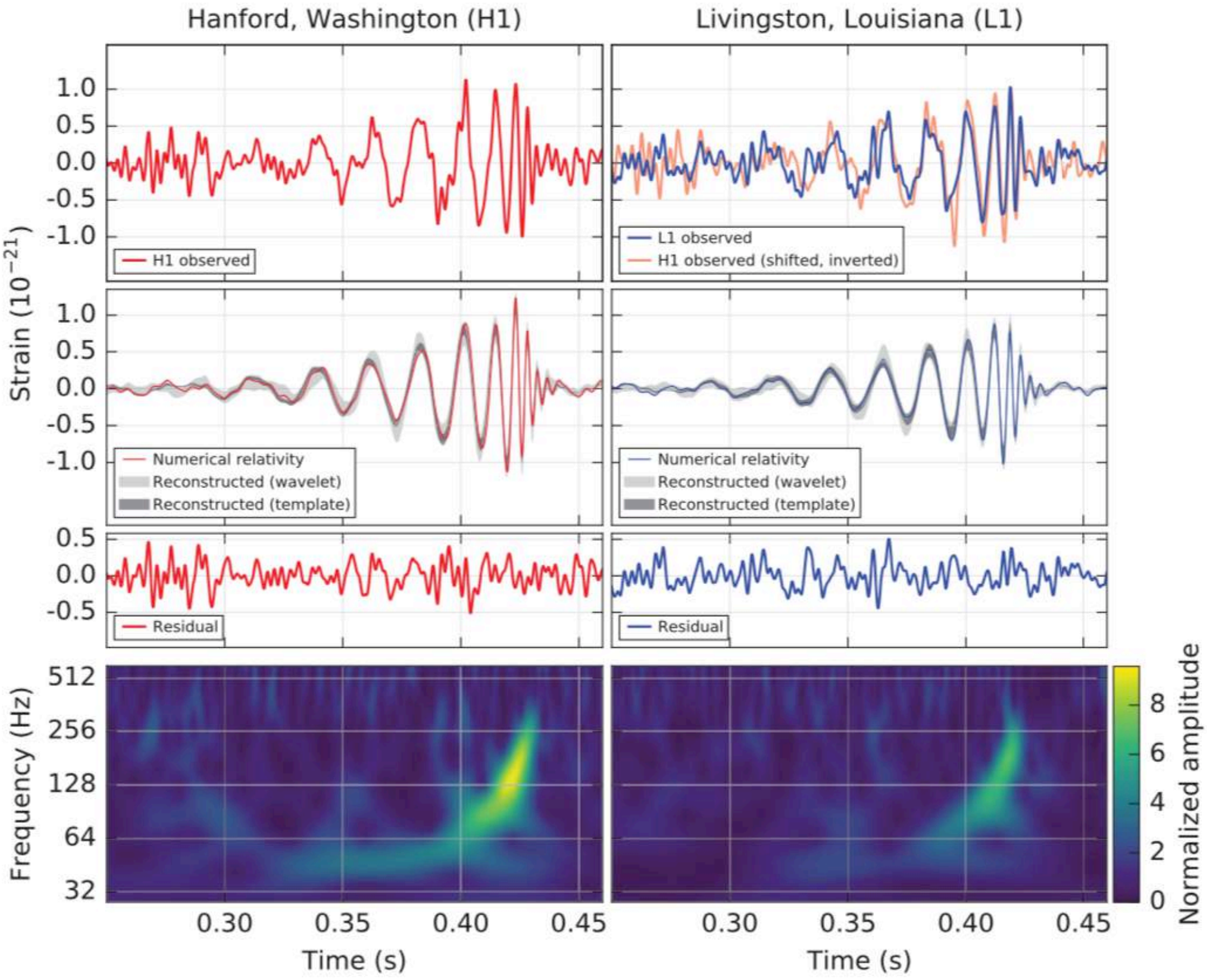
https://www.youtube.com/watch?v=aysiMbgml5g

我的天呐！

双黑洞合并过程的峰值时，引力波
的功率释放大于宇宙中所有恒星的
辐射功率之和！

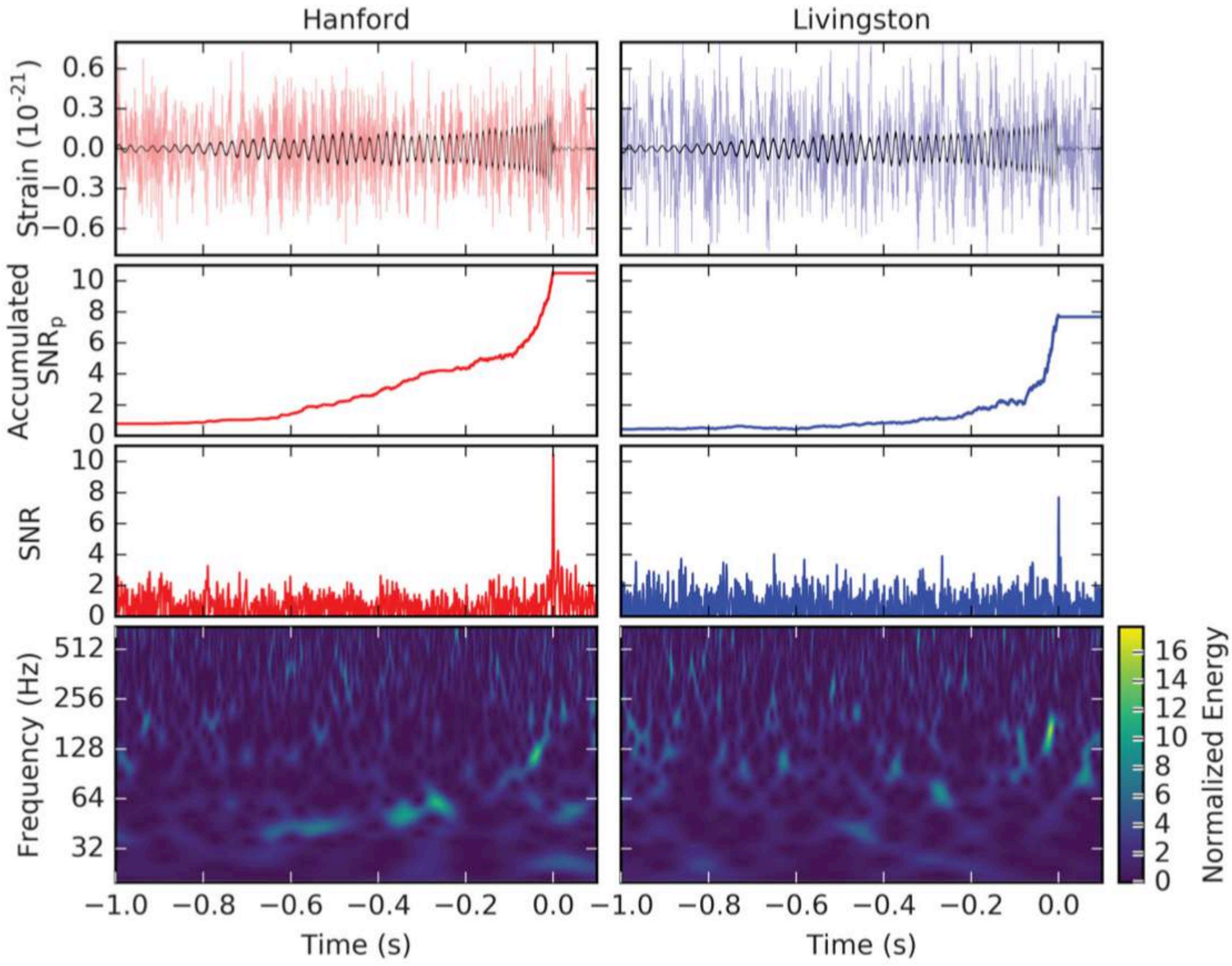
GW150914

LIGO/Virgo 2016



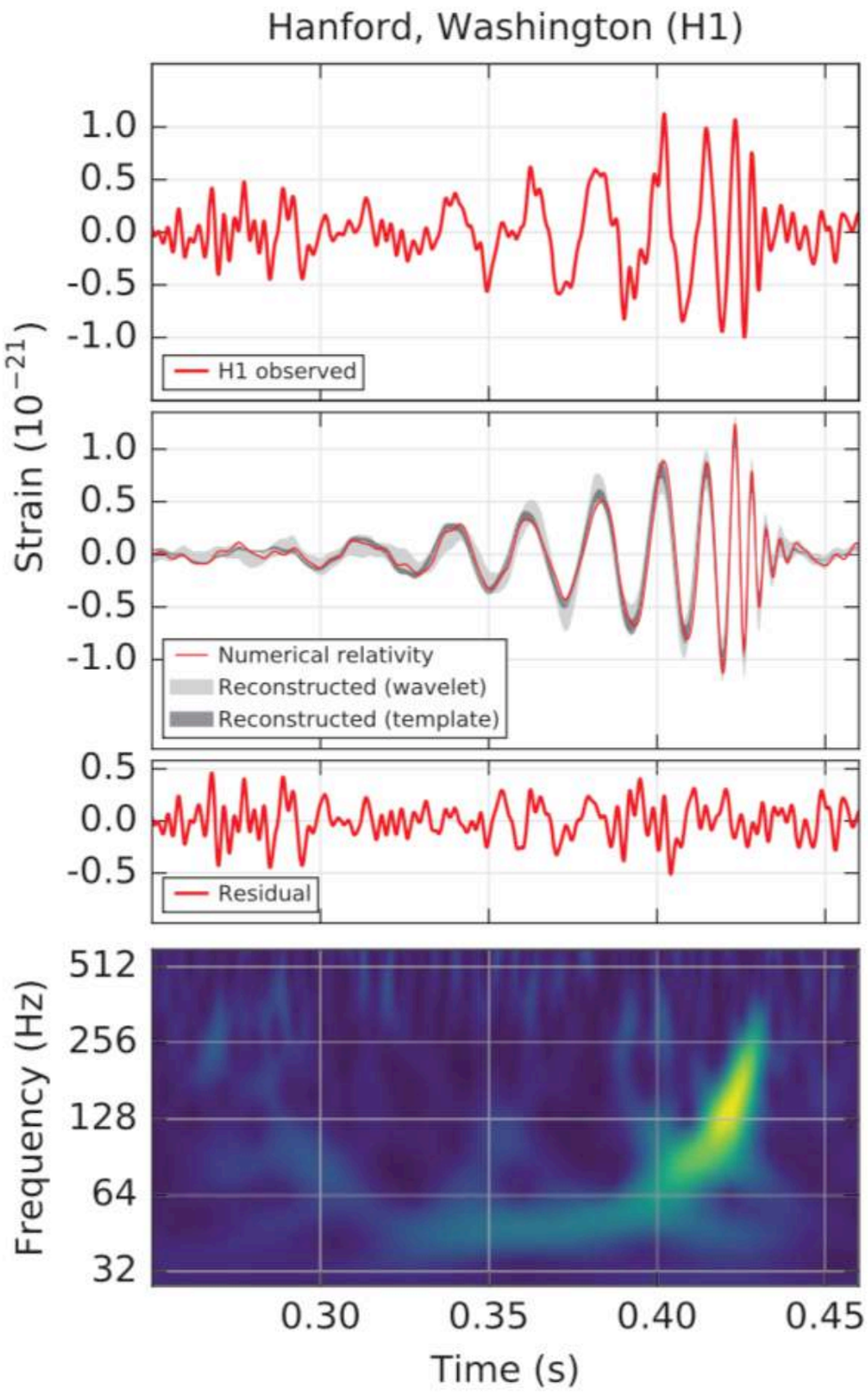
GW151226

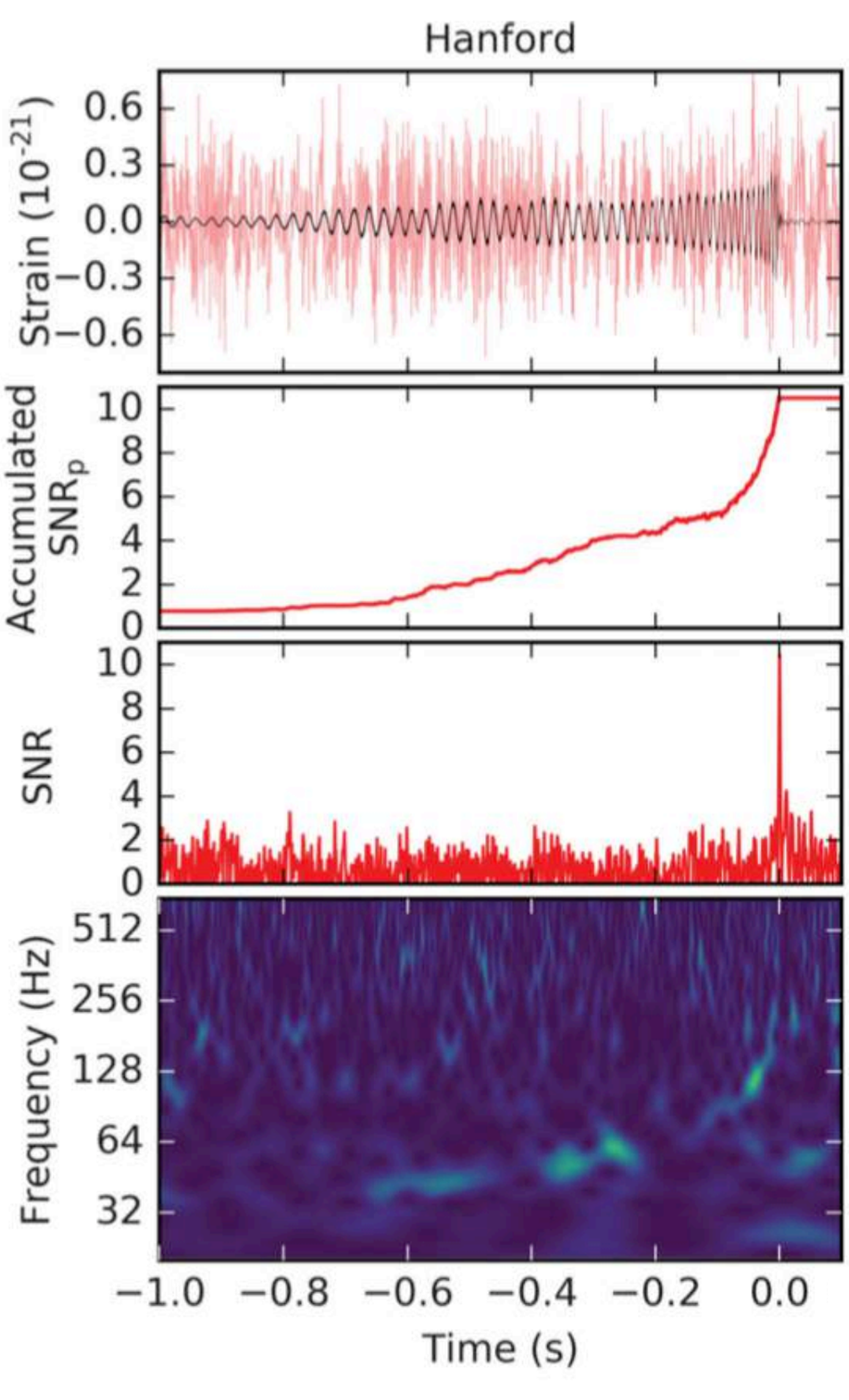
LIGO/Virgo 2016



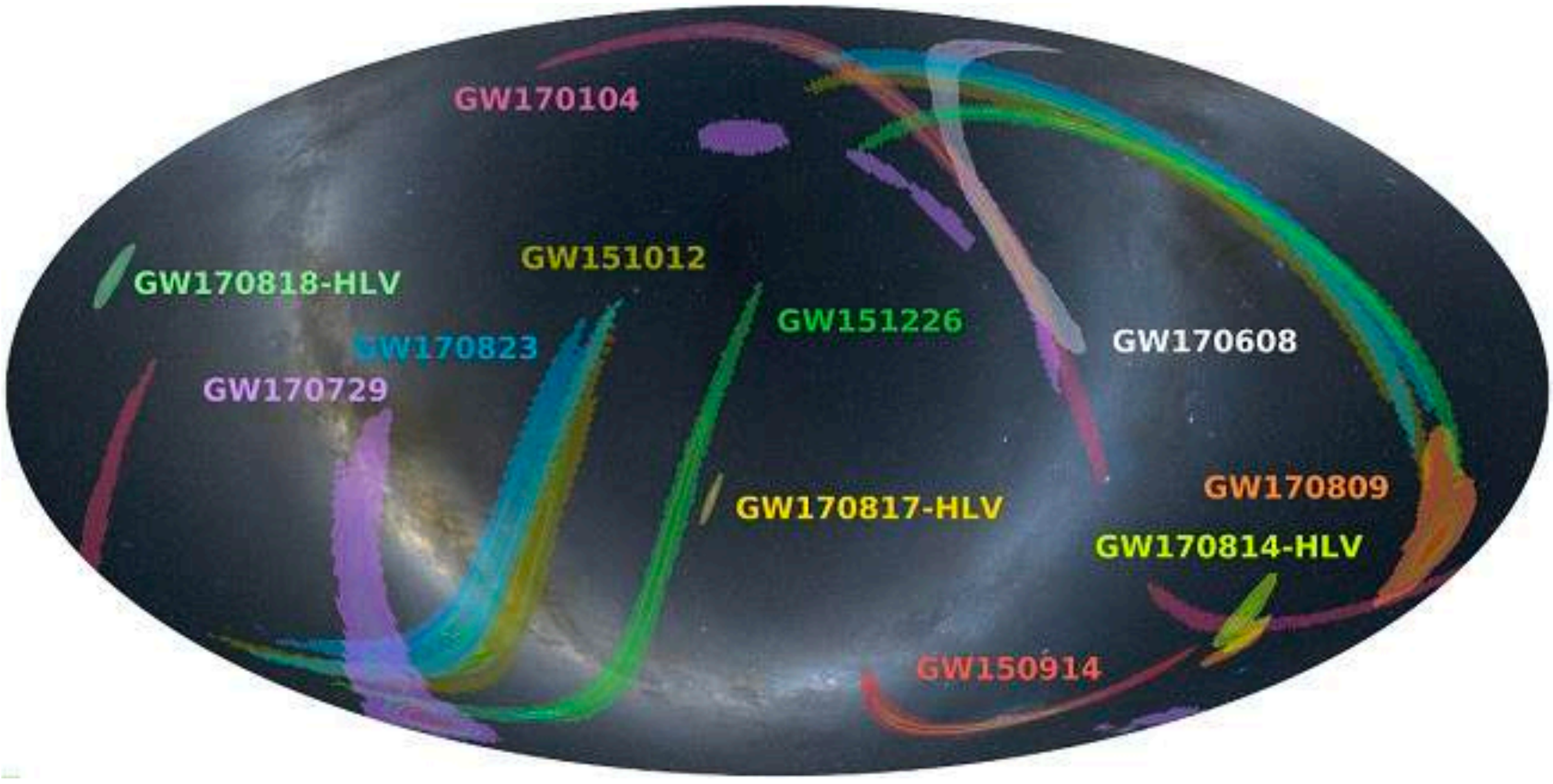
Tell the difference: GW150914 vs GW151226

Why?





GW Era: gravitational-wave transient catalog (GWTC-1)

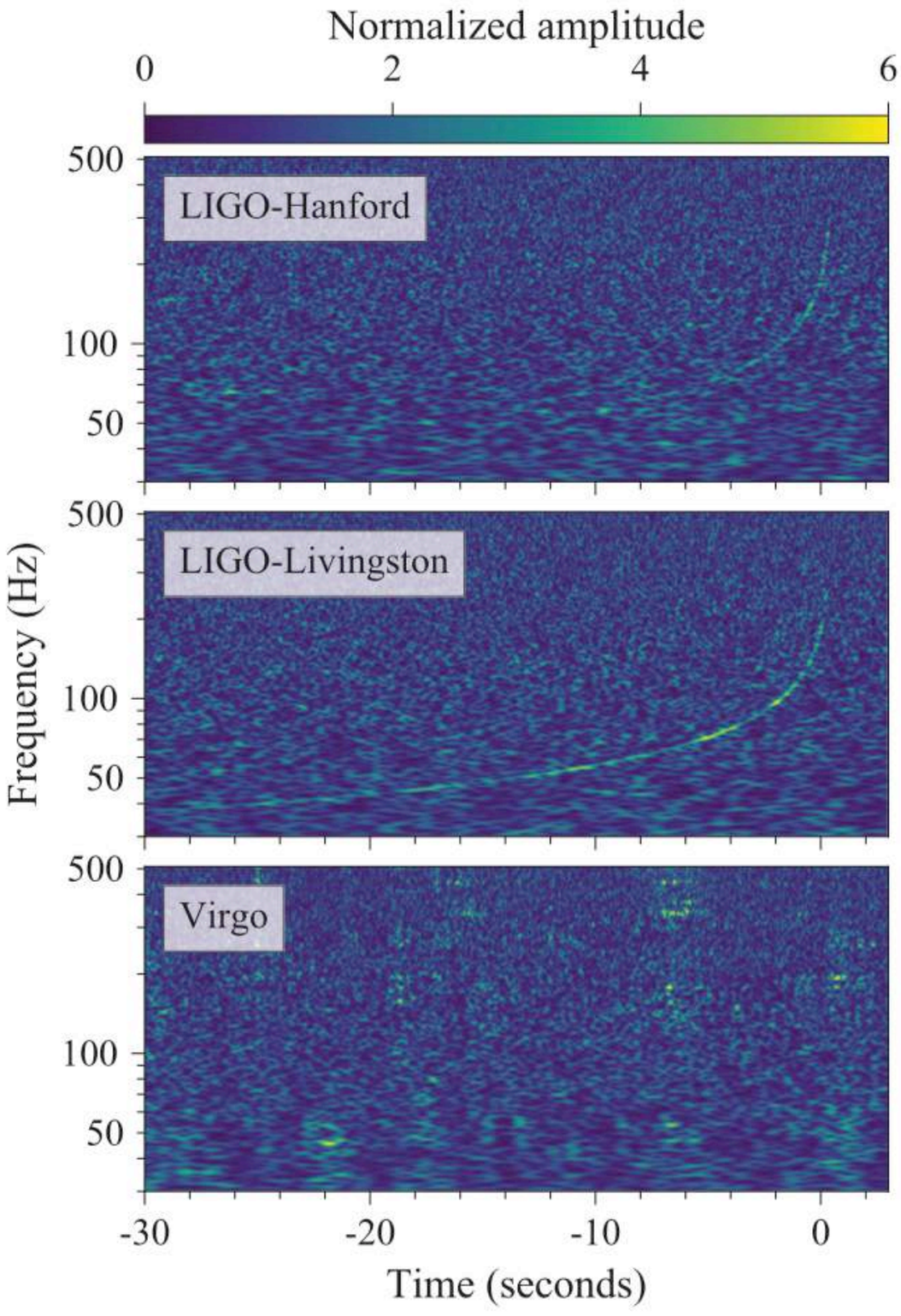


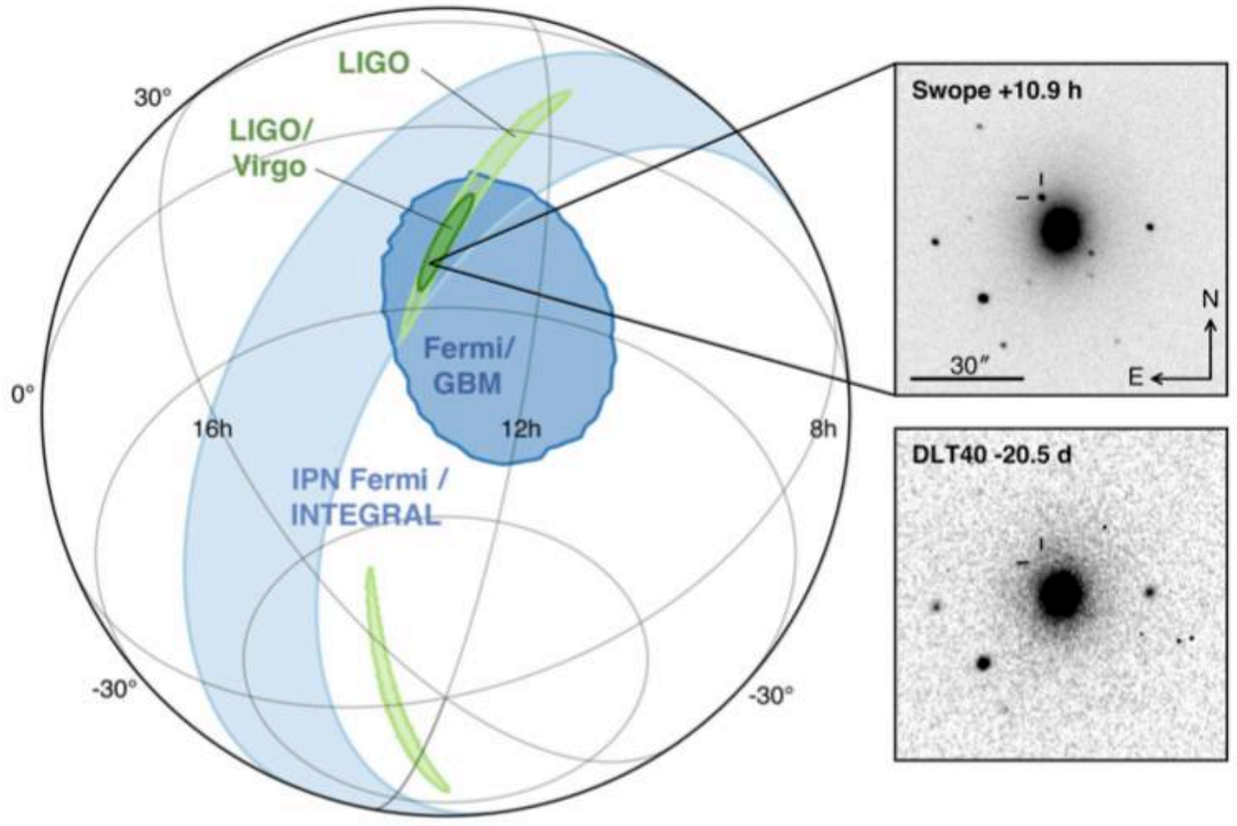
LIGO/Virgo

Binary Neutron Star (BNS) Merger

GW170817

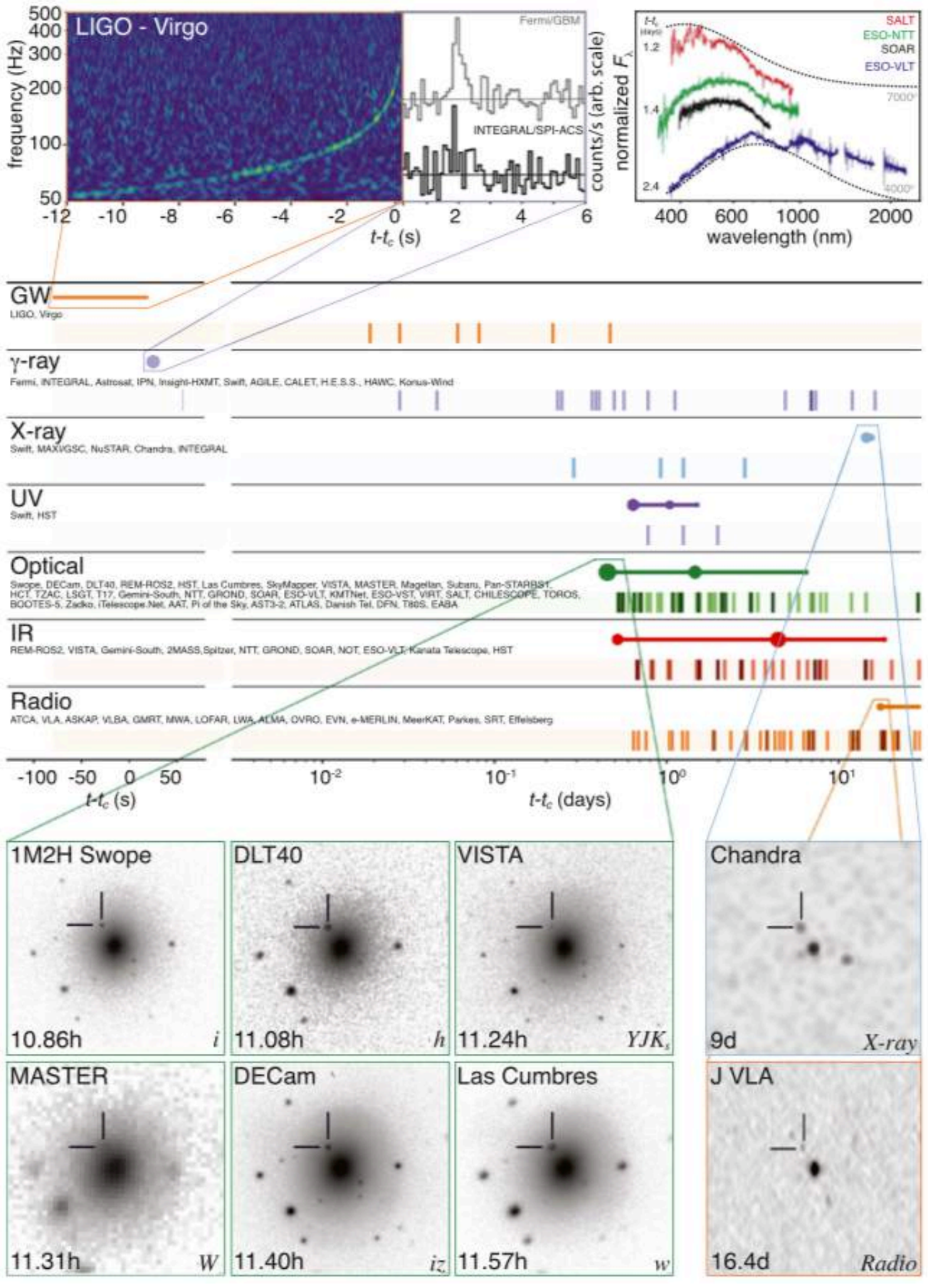
LIGO/Virgo 2017





Multimessenger Era

LIGO/Virgo, et al. 2016



Gamma-ray bursts

Kilonovae

Host galaxies

...

Prof. Li-Xin Li / KIAA

Why are GWs useful?

Living Rev. Relativity, **12**, (2009), 2
http://www.livingreviews.org/lrr-2009-2

LIVING REVIEWS in relativity

Physics, Astrophysics and Cosmology with Gravitational Waves

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Bernard F. Schutz
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and
Max Planck Institute for Gravitational Physics
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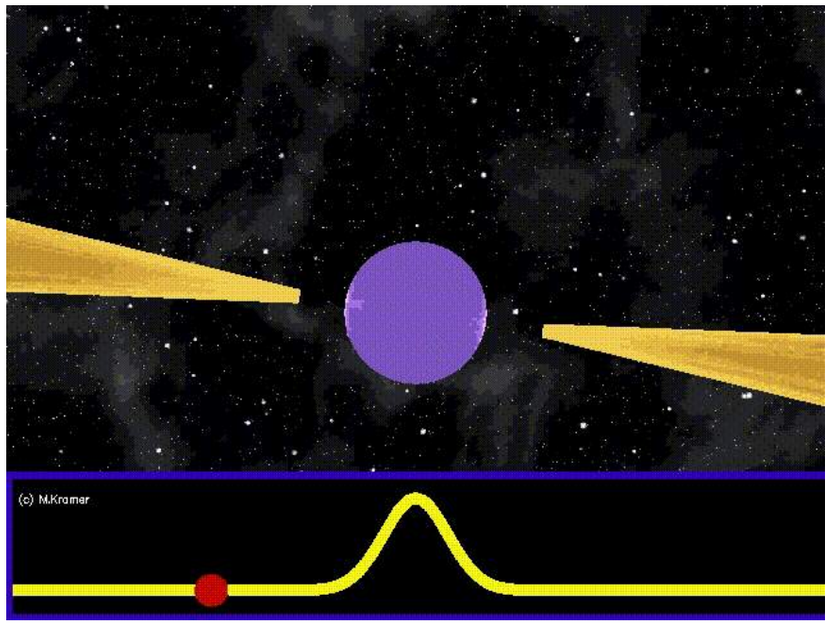
GW Astrophysics



Are there mountains on the NSs?

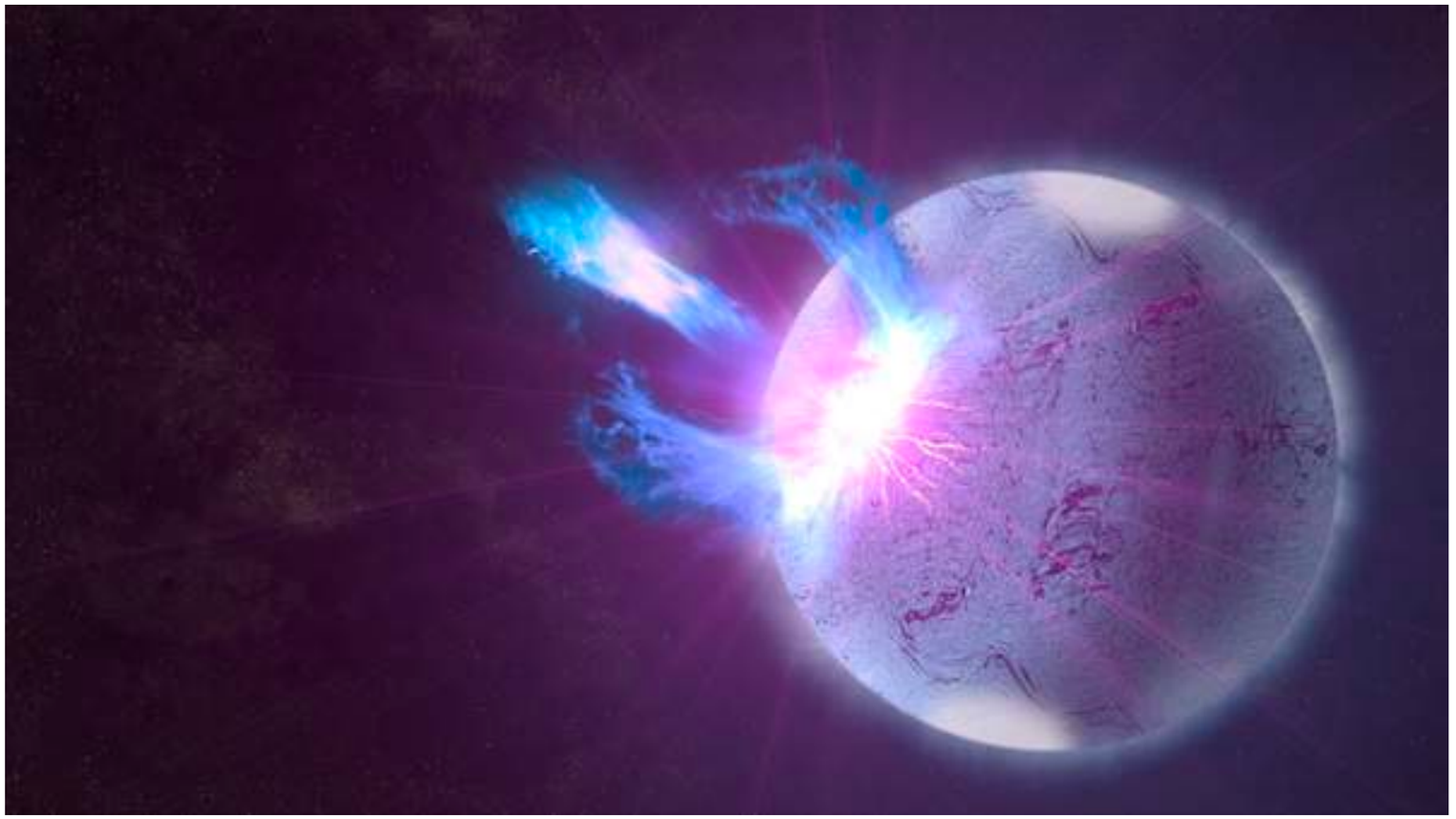
Continuous GWs

moment of inertia $I_{\rm NS} \sim \frac{2}{5} MR^2$

mass m **on the surface** $\Delta I = mR^2$

Fractional asymmetry

$$\epsilon \sim \frac{5}{2}\frac{m}{M} \lesssim 10^{-6} \ (???)$$

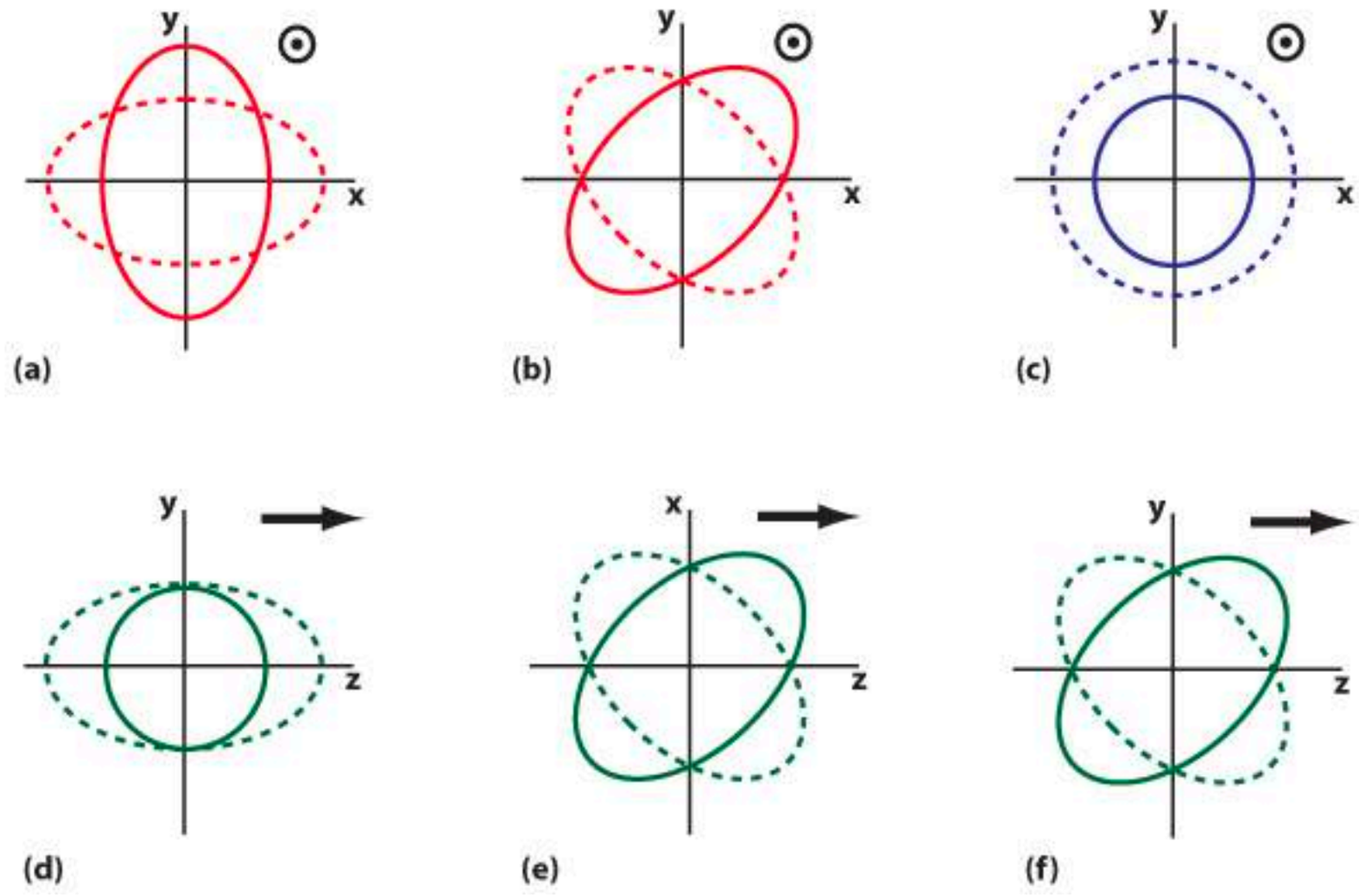


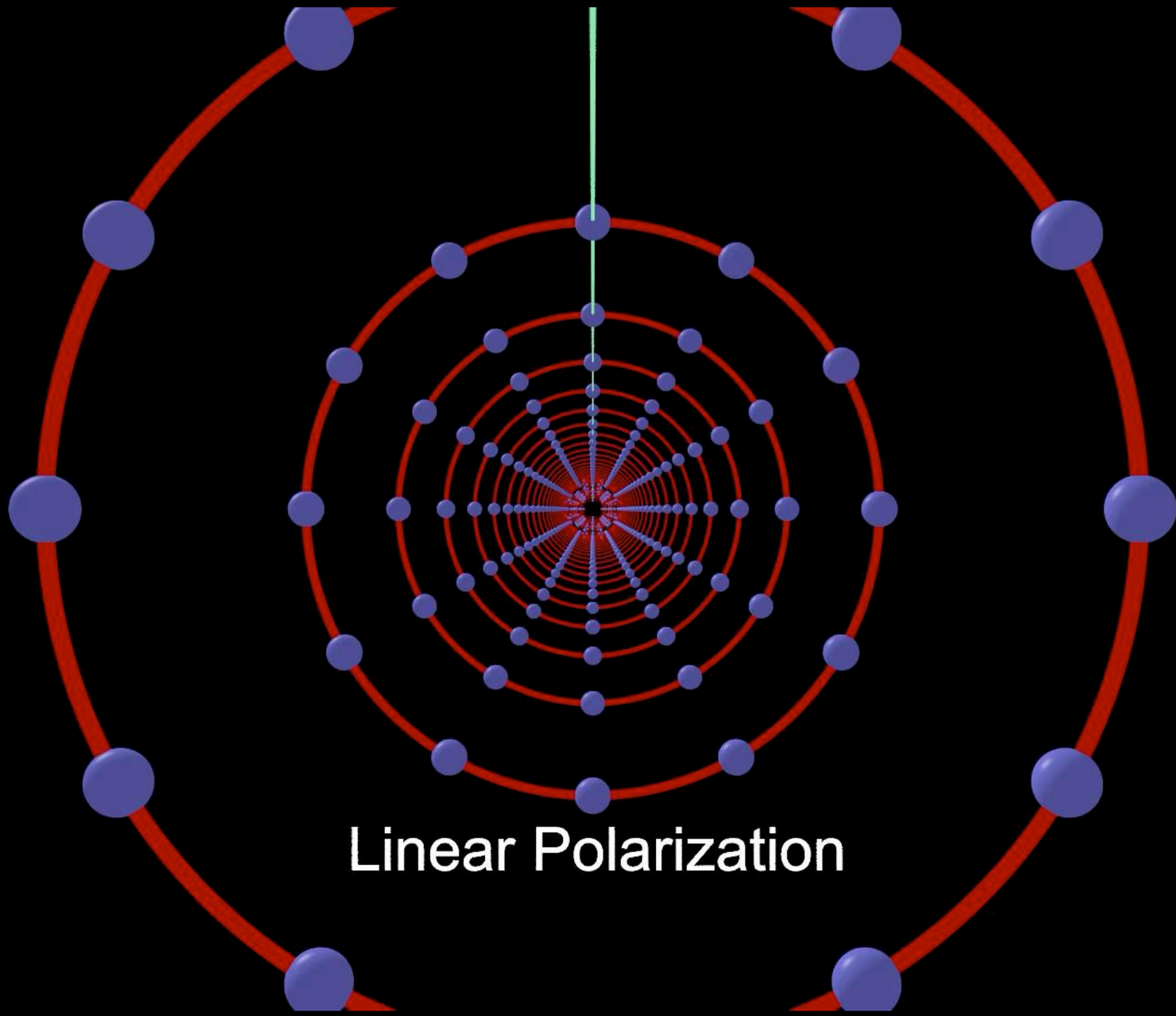
Closely related to NSs' equation of state of supranuclear matter

(Nonperturbative QCD)

GW Polarizations

- In GR, 2 polarizations
- Beyond GR, 6 polarizations at most

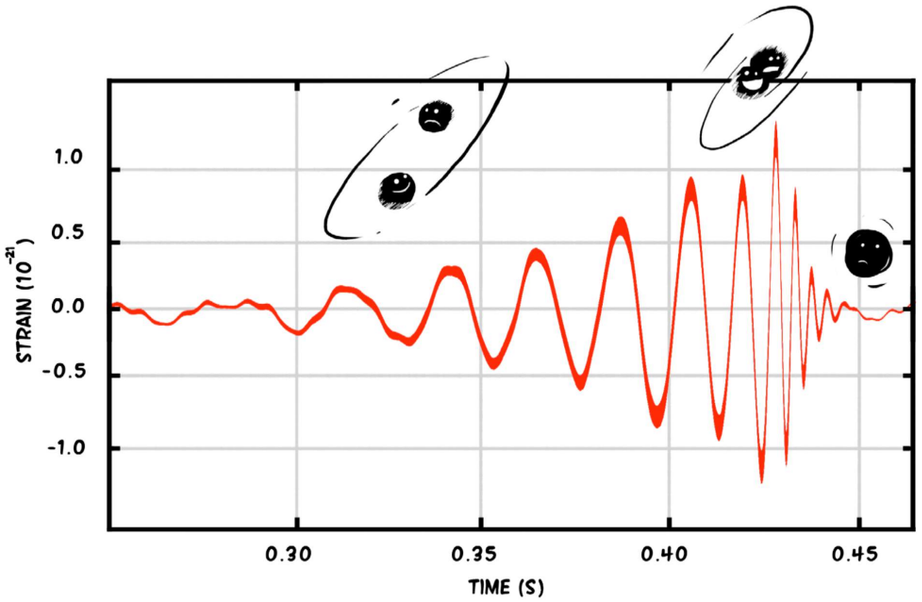


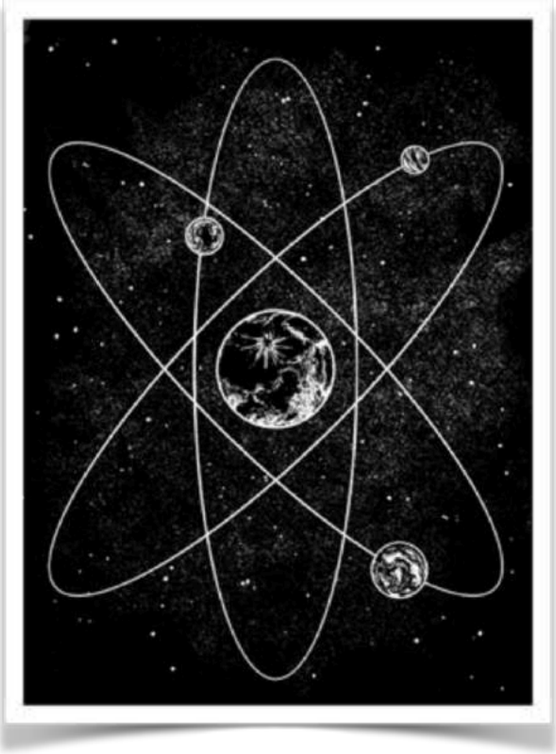


https://youtu.be/F4stTzxYrN0

BH Spectroscopy: quasinormal modes

- A sum of damped exponentials with unique frequencies and damping times
- No-hair theorem and uniqueness
- “gravitational atom”





“After the advent of gravitational wave astronomy, the observation of [the black hole’s] resonant frequencies might finally provide direct evidence of black holes with the same certainty as, say, the 21 cm line identifies interstellar hydrogen.”

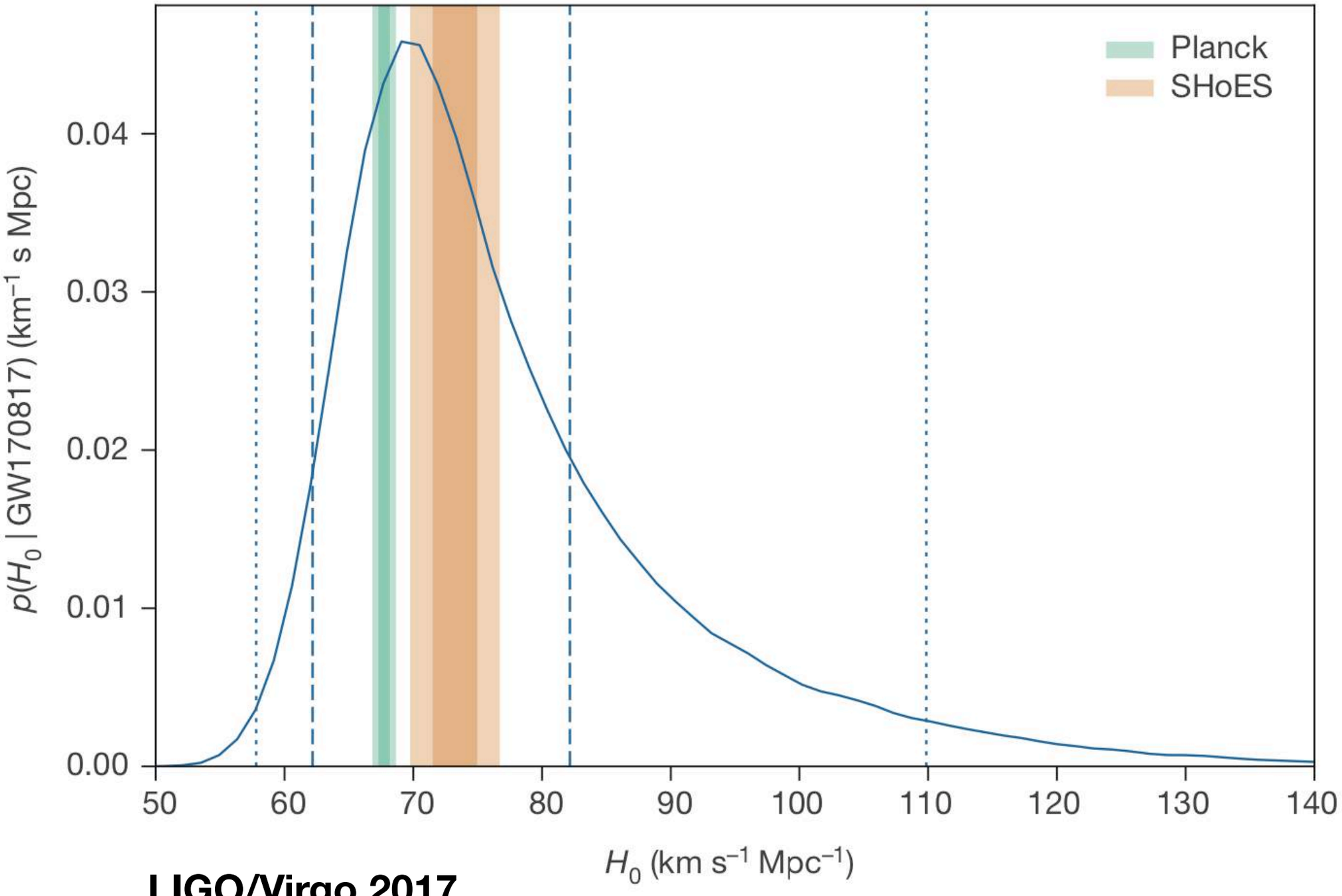
Detweiler 1980

GW Cosmology

The ultimate goal is to detect the cosmic relic GWs

Hubble Constant

Cosmology is about distance as a function of redshift



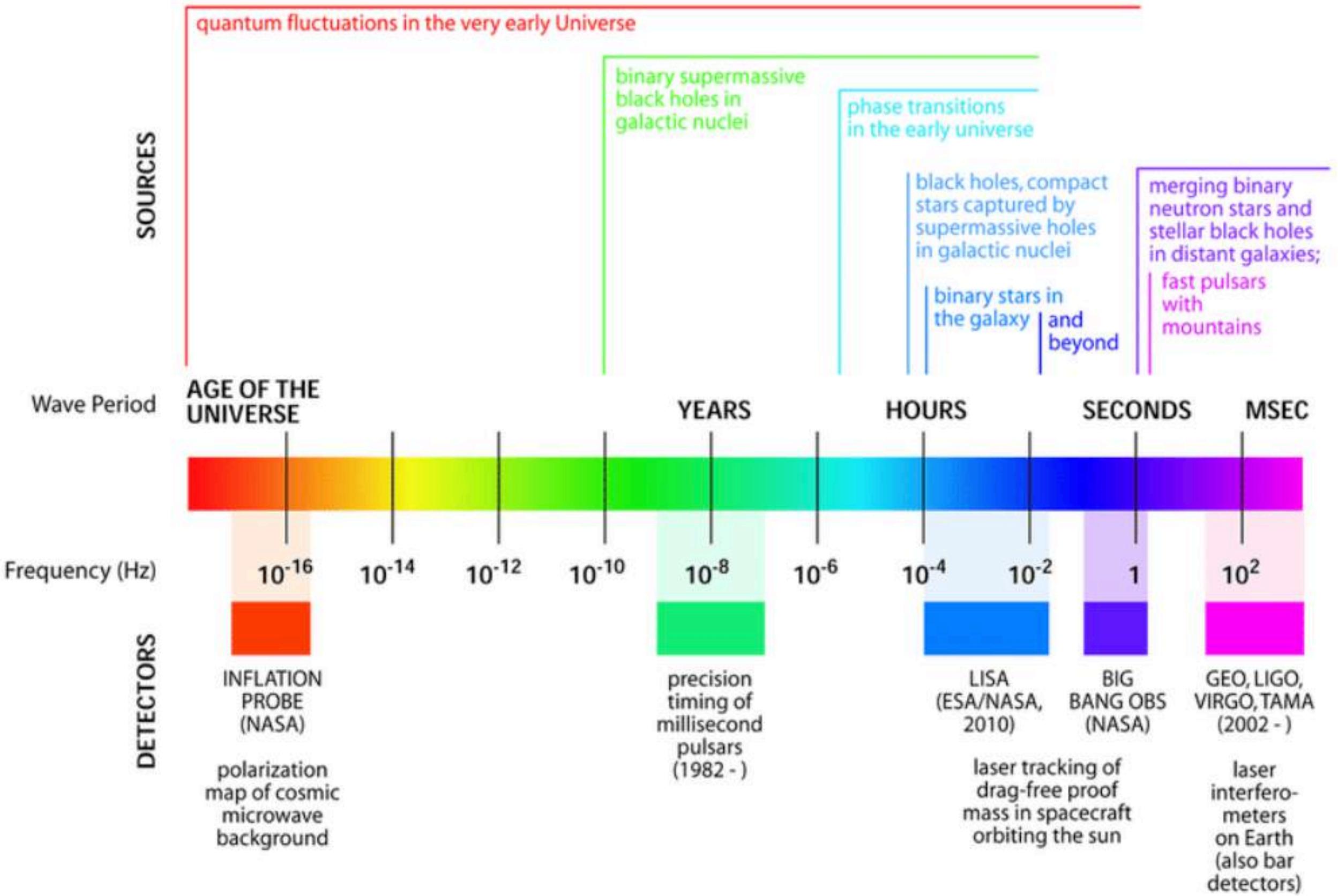
LIGO/Virgo 2017

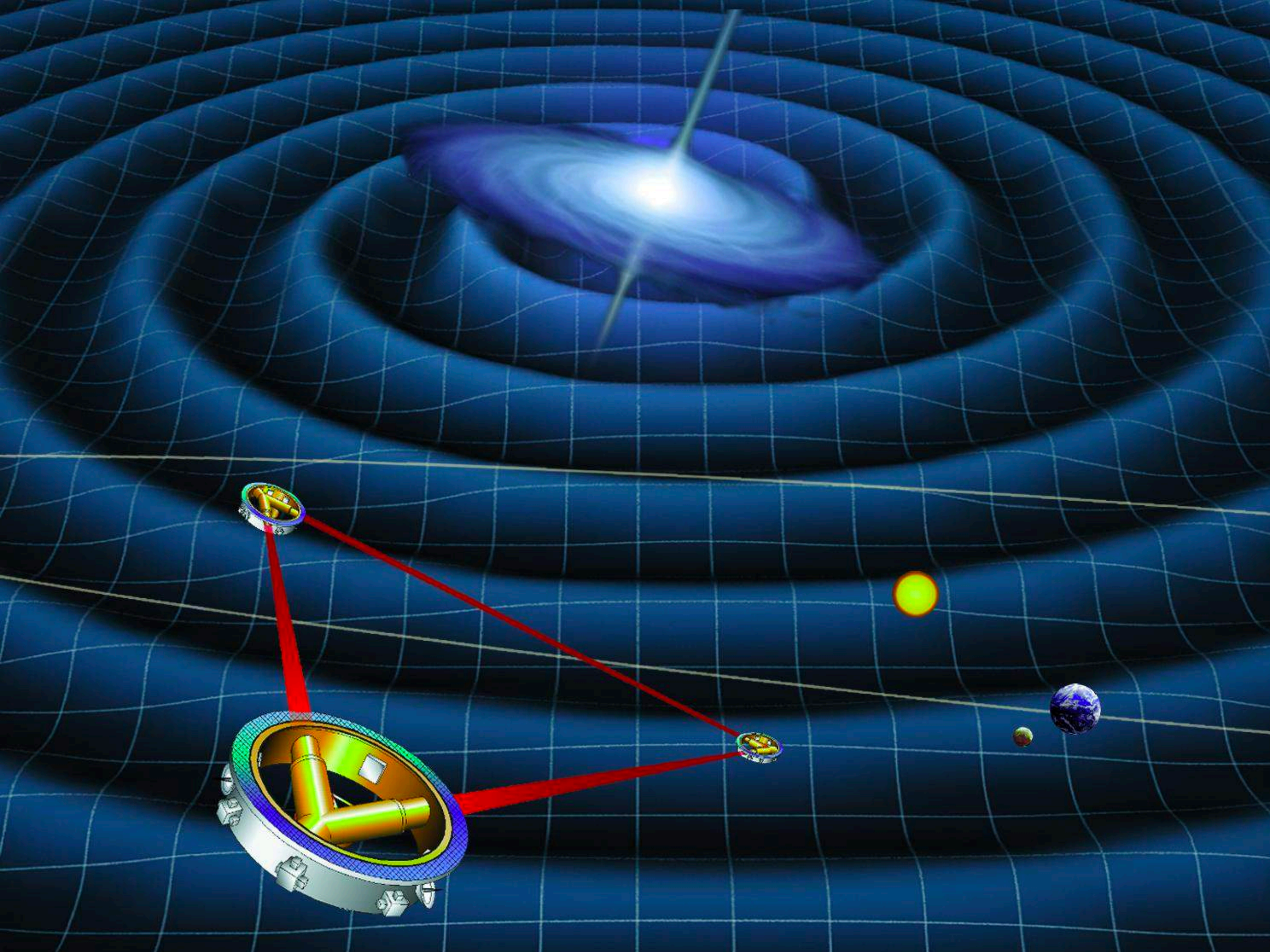
What we have talked about were only

focusing on ground-based detectors,

while there are more…

GW Spectrum

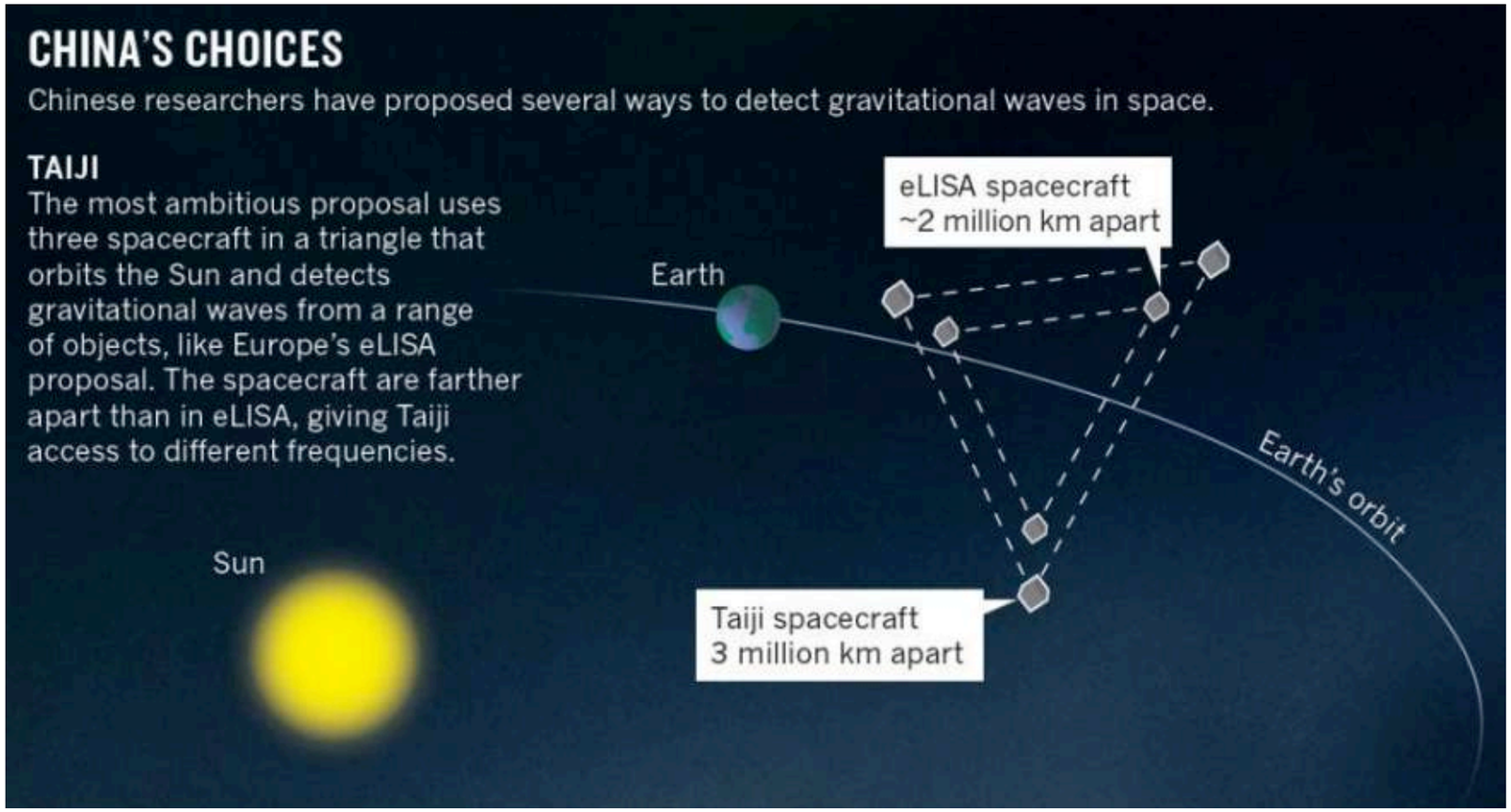

SOURCES
quantum fluctuations in the very early Universe
binary supermassive black holes in galactic nuclei
phase transitions in the early universe
black holes, compact stars captured by supermassive holes in galactic nuclei
binary stars in the galaxy
and beyond
merging binary neutron stars and stellar black holes in distant galaxies;
fast pulsars with mountains
Wave Period
AGE OF THE UNIVERSE
YEARS
HOURS
SECONDS
MSEC
Frequency (Hz)
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
DETECTORS
INFLATION PROBE (NASA)
polarization map of cosmic microwave background
precision timing of millisecond pulsars (1982 -)
LISA (ESA/NASA, 2010)
BIG BANG OBS (NASA)
laser tracking of drag-free proof mass in spacecraft orbiting the sun
GEO, LIGO, VIRGO, TAMA (2002 -)
laser interfero-meters on Earth (also bar detectors)

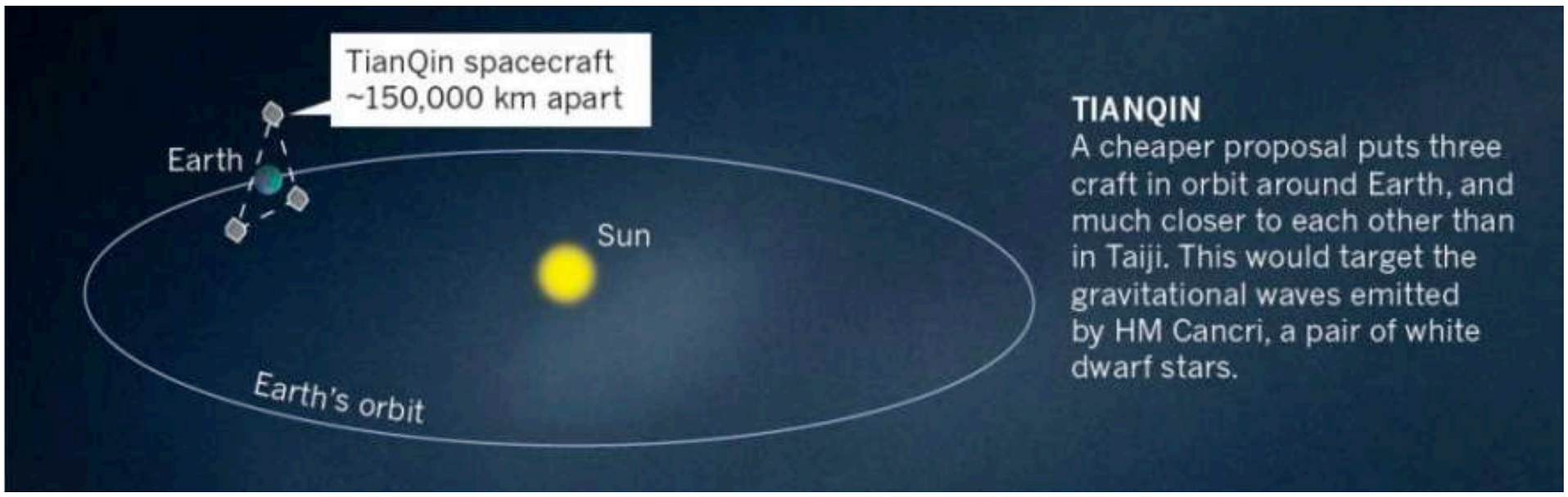


Laser Interferometer Space Antenna

Space-based GW Detectors in China

太极

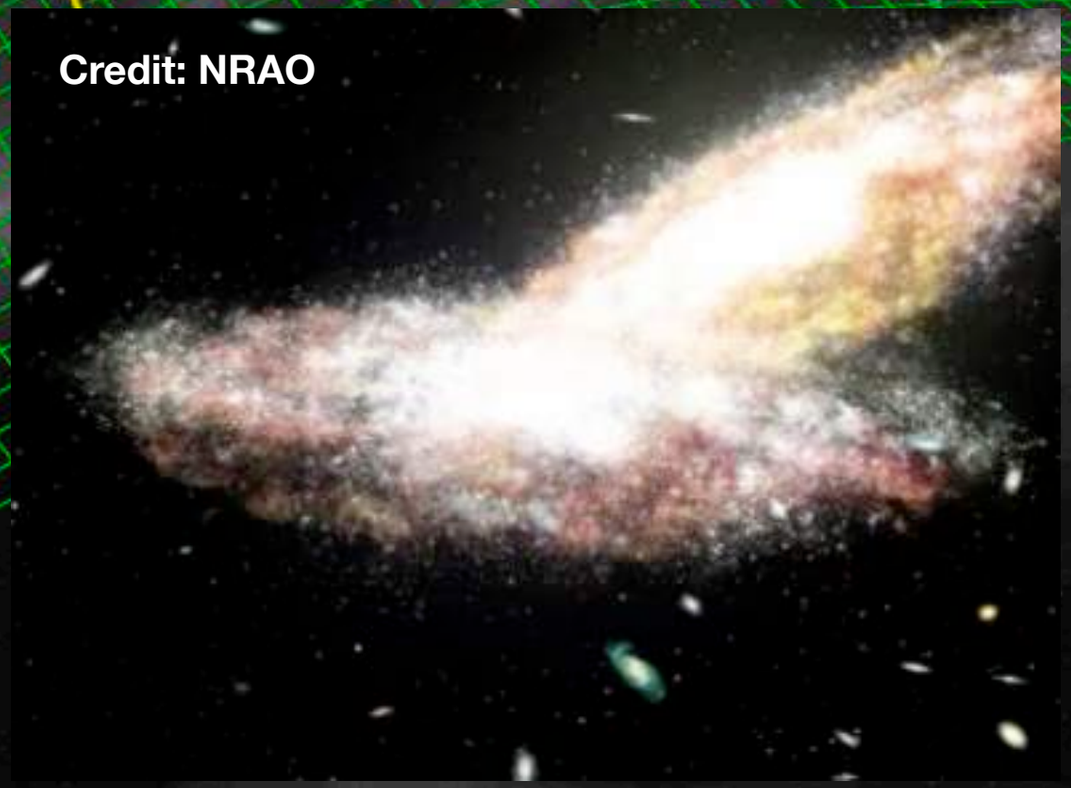




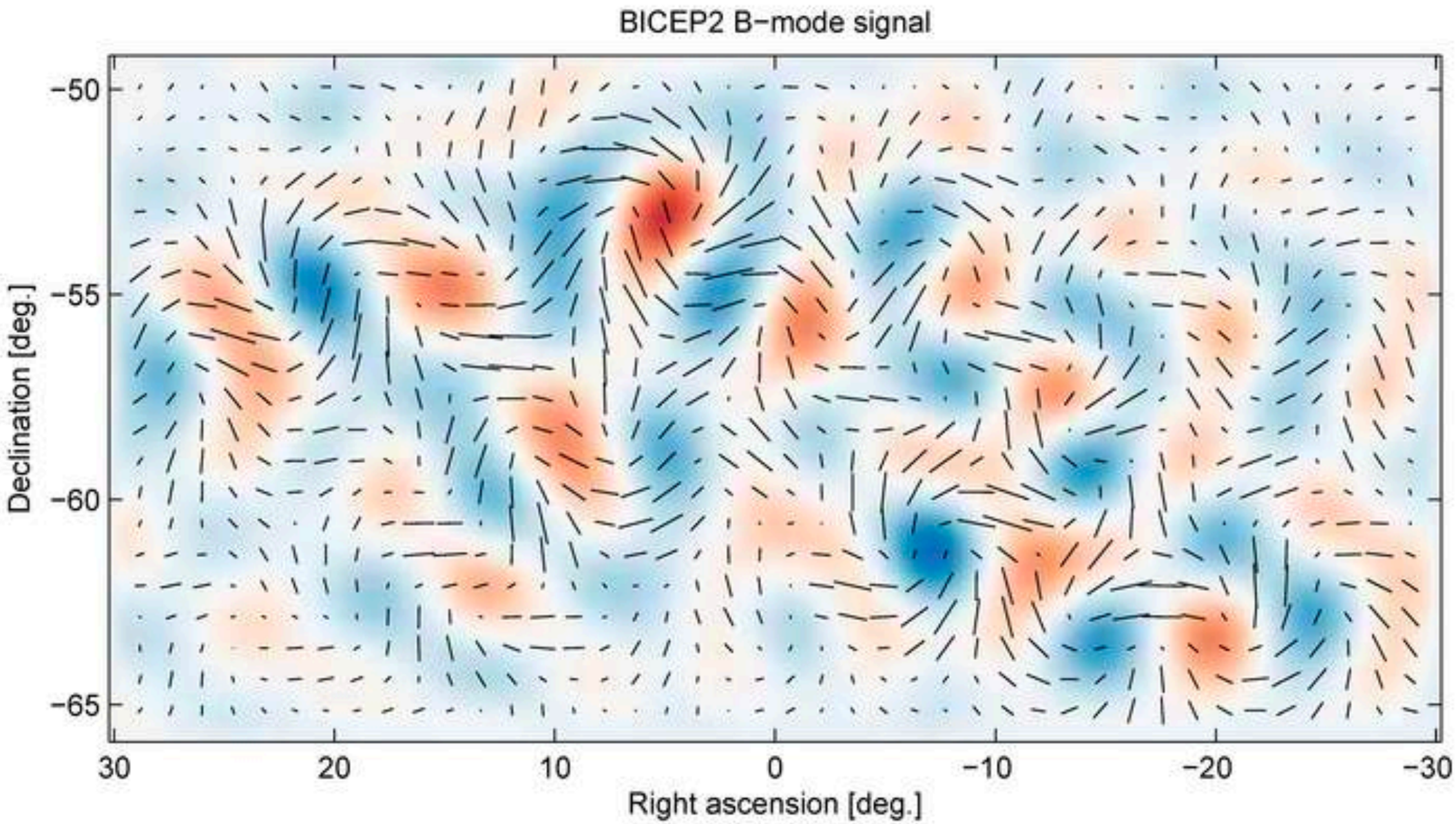
天琴

Credit: D.J. Champion

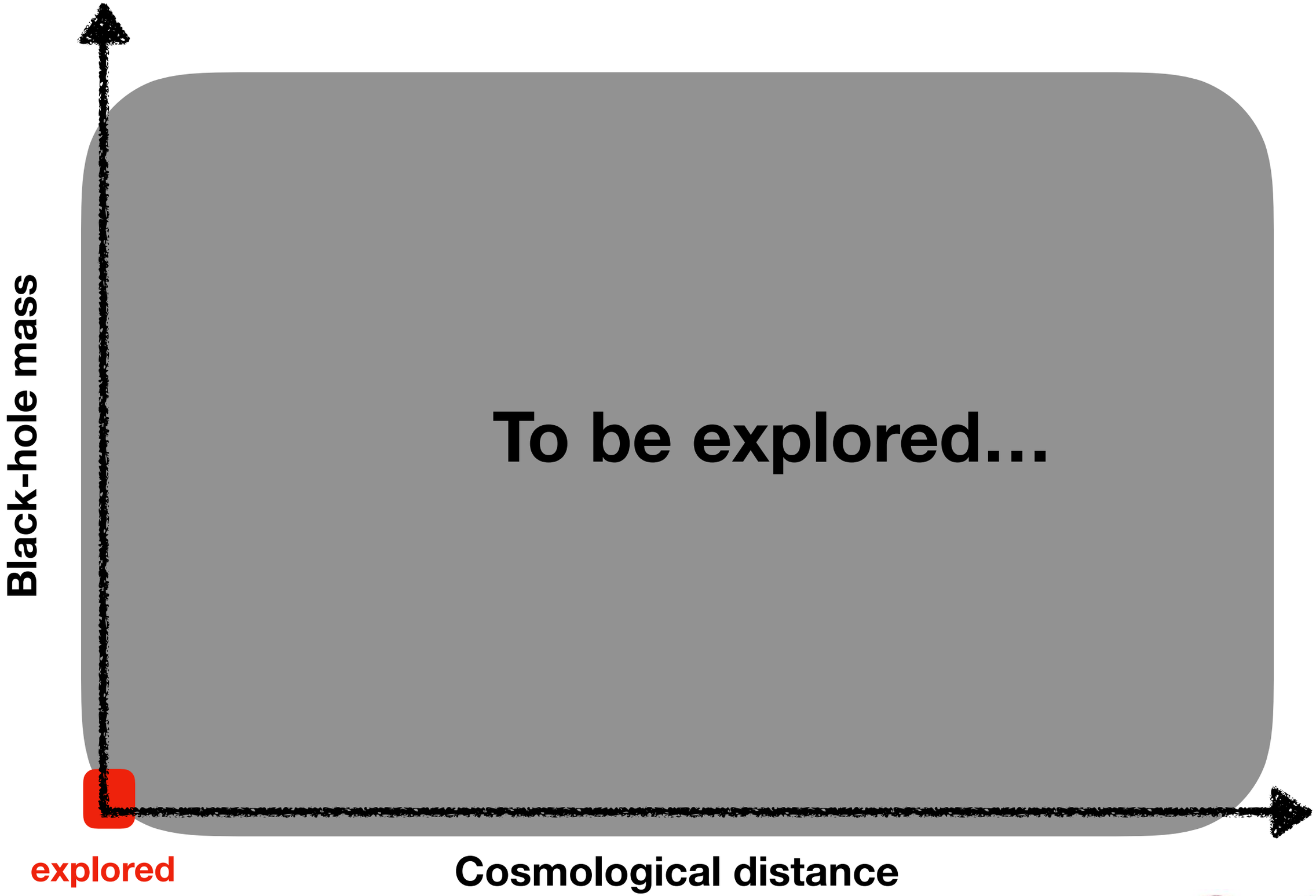
Credit: D.J. Champion



CMB B-mode Polarization

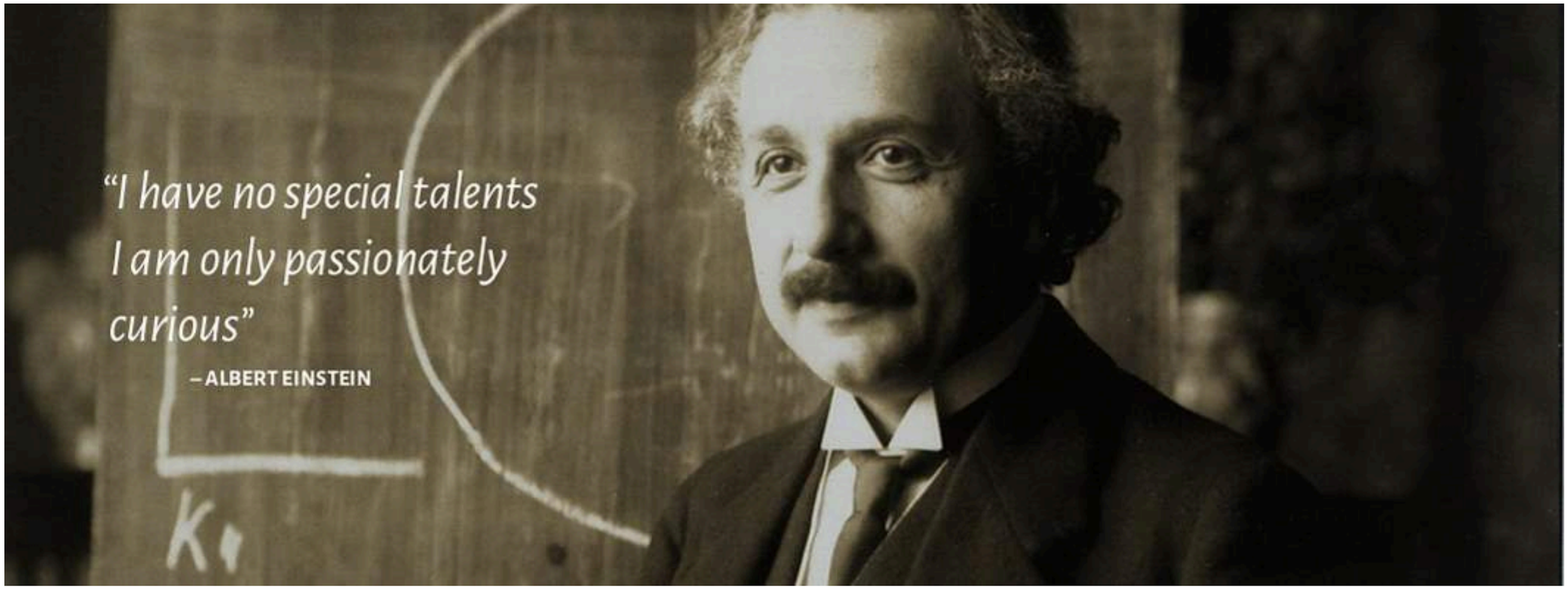


Where are we?

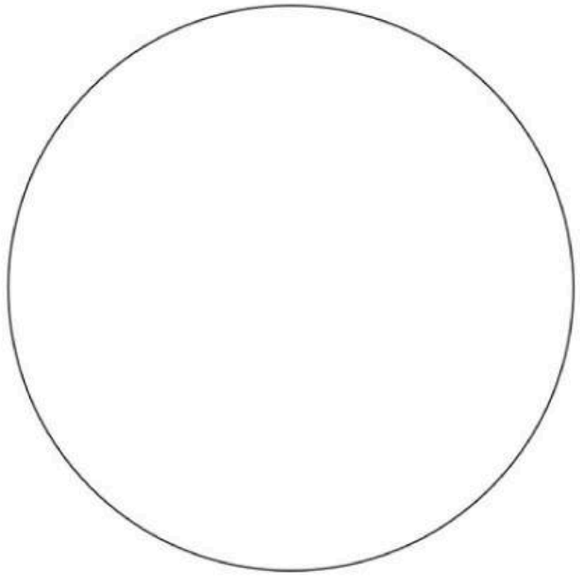


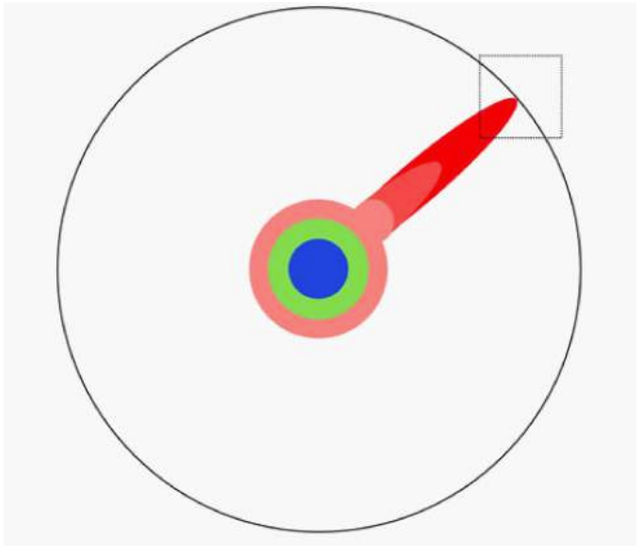
格物而后知至。

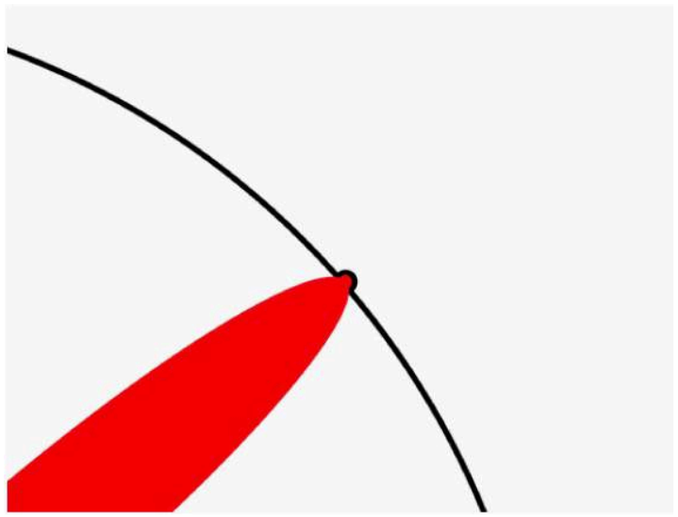
——《大学》

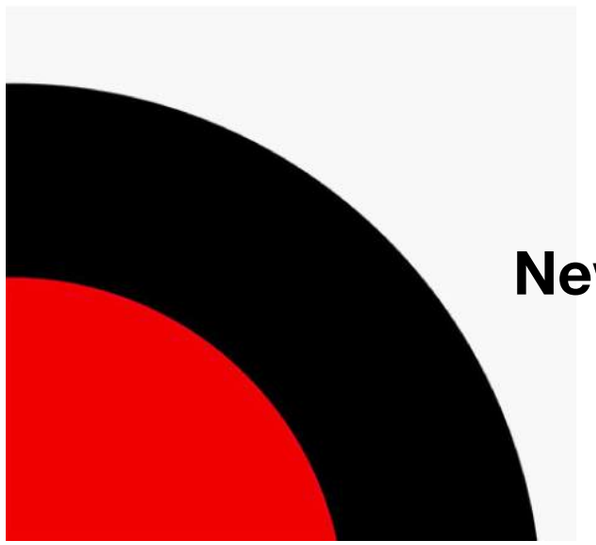

"I have no special talents
I am only passionately
curious"
– ALBERT EINSTEIN

Doing Research









New knowledge to human!

Explore Unknowns