

Exploring the uncharted Universe with Gravitational Waves

Jose María Ezquiaga

Niels Bohr Institute

jose.ezquiaga@nbi.ku.dk

ezquiaga.github.io

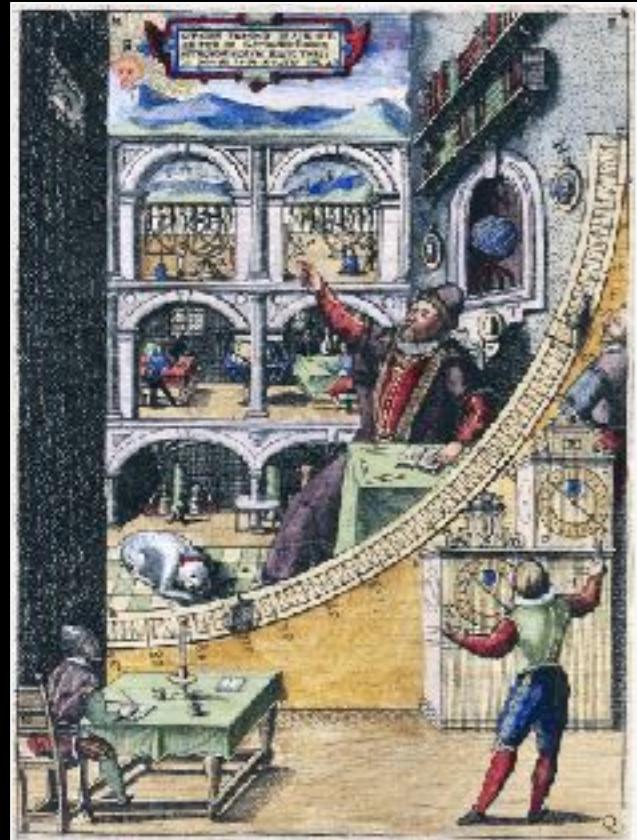
VILLUM FONDEN



[Kusama, Louisiana Museum]

KØBENHAVNS
UNIVERSITET

Every time that we have been able to look further...



[Tycho Brahe, 16th century]



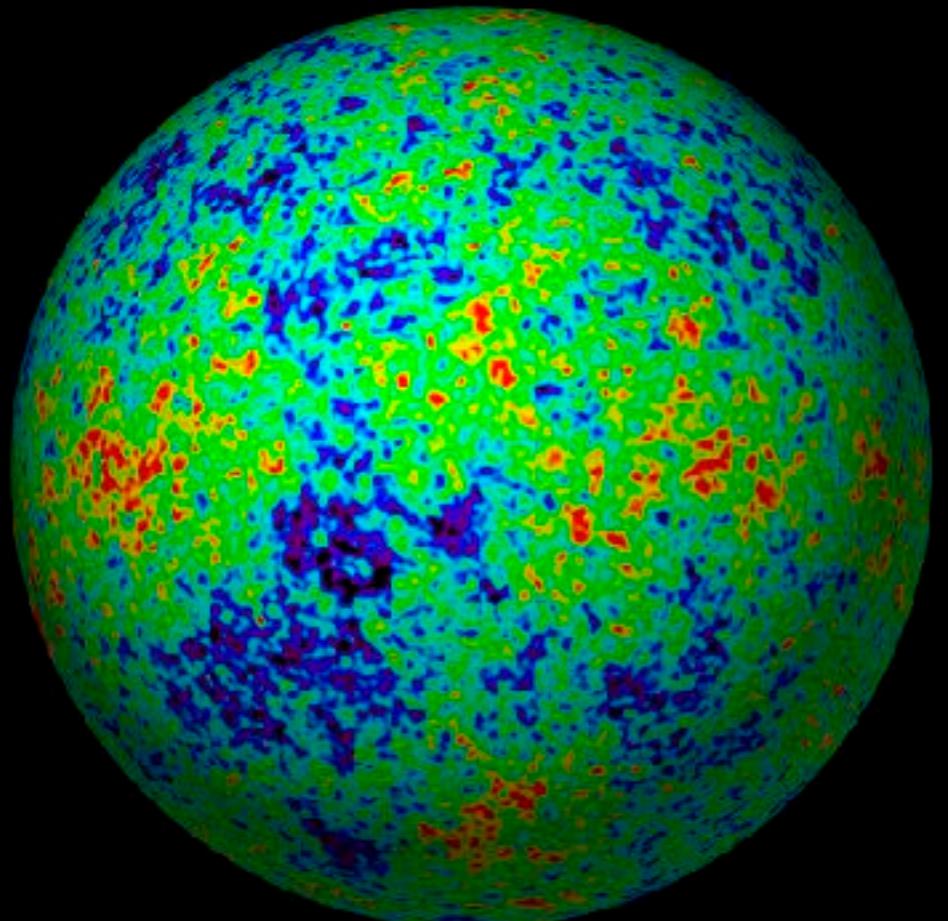
[Edwin Hubble, 20th century]



[Space Telescopes, 21st century]

...we have found fascinating surprises

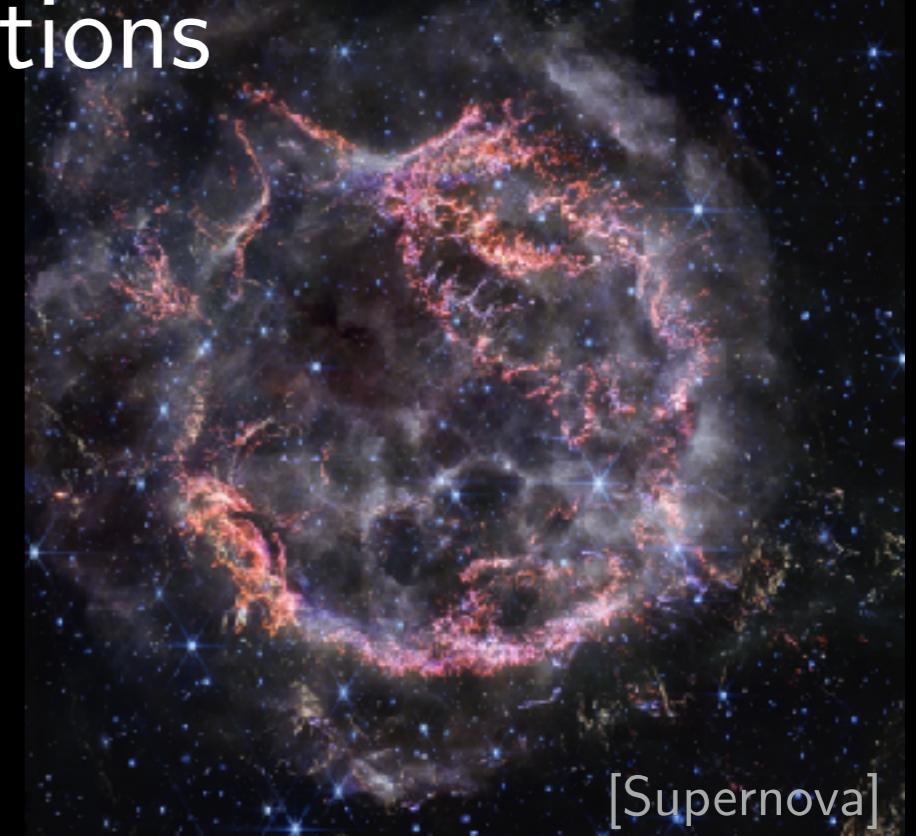
A plethora of cosmological observations



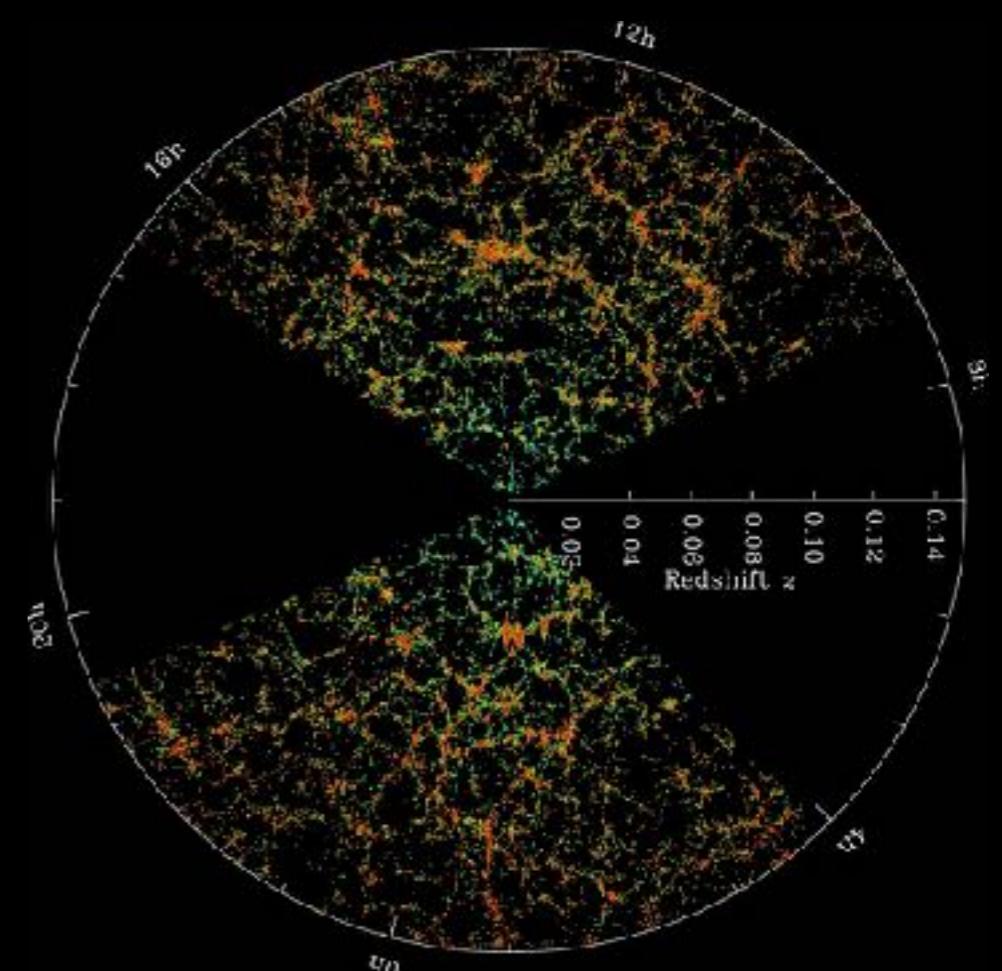
[Cosmic microwave background]



[Gravitational Lensing]

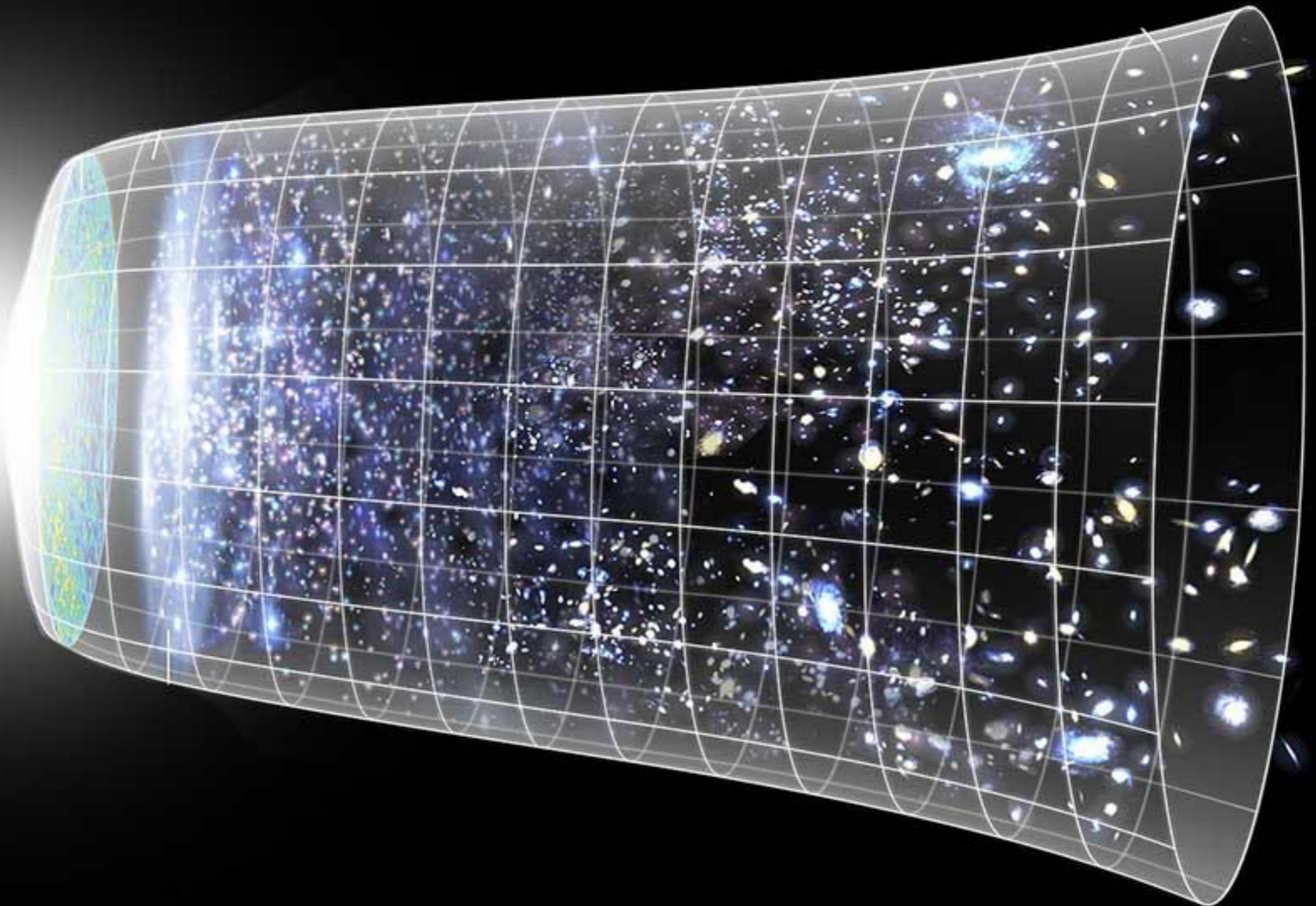


[Supernova]



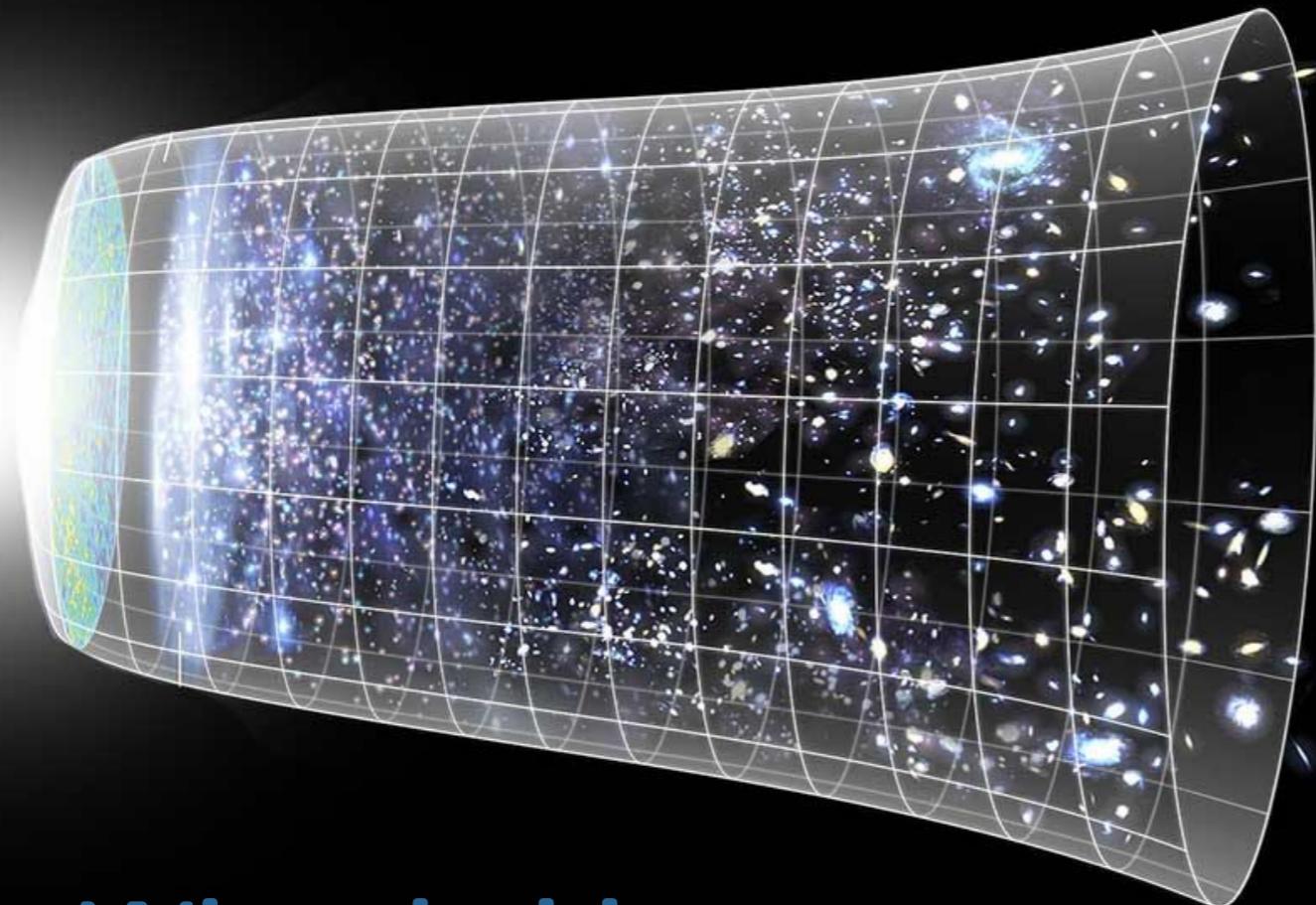
[Cosmic web]

The **standard** cosmological model...



...13.8 billion years of cosmic history

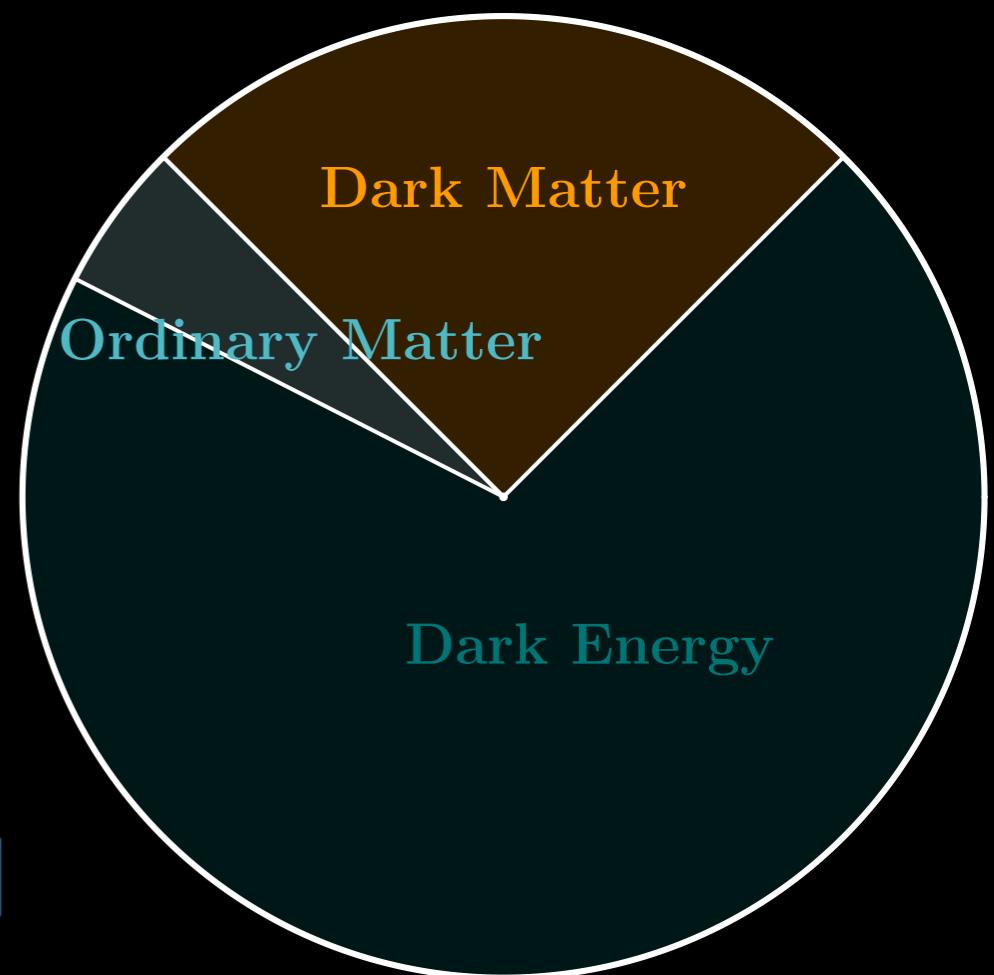
We don't understand the basics of our Universe



What holds
galaxies together?

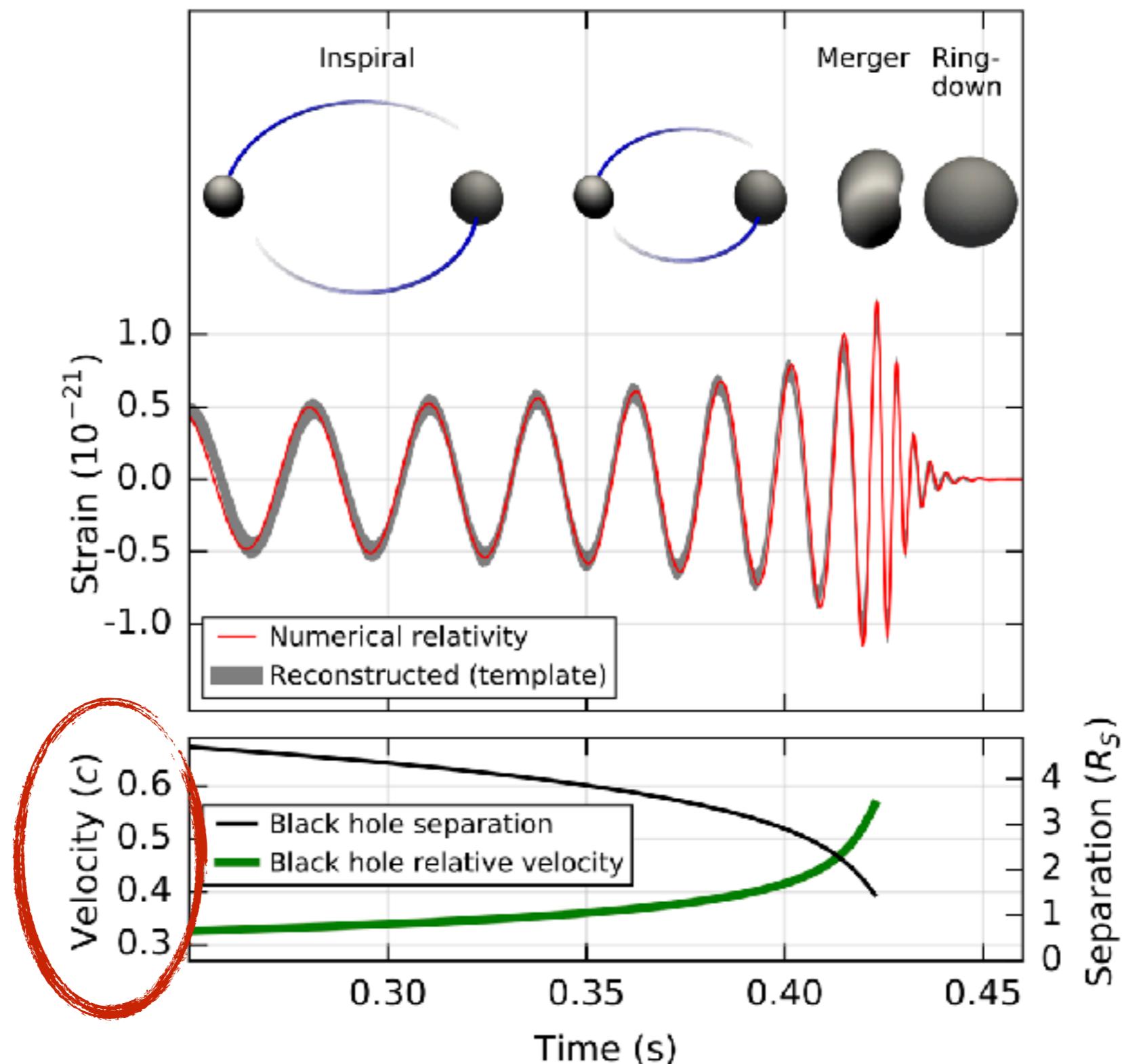
Is Einstein gravity valid
at cosmological scales?

Why the Universe
expands ever faster?



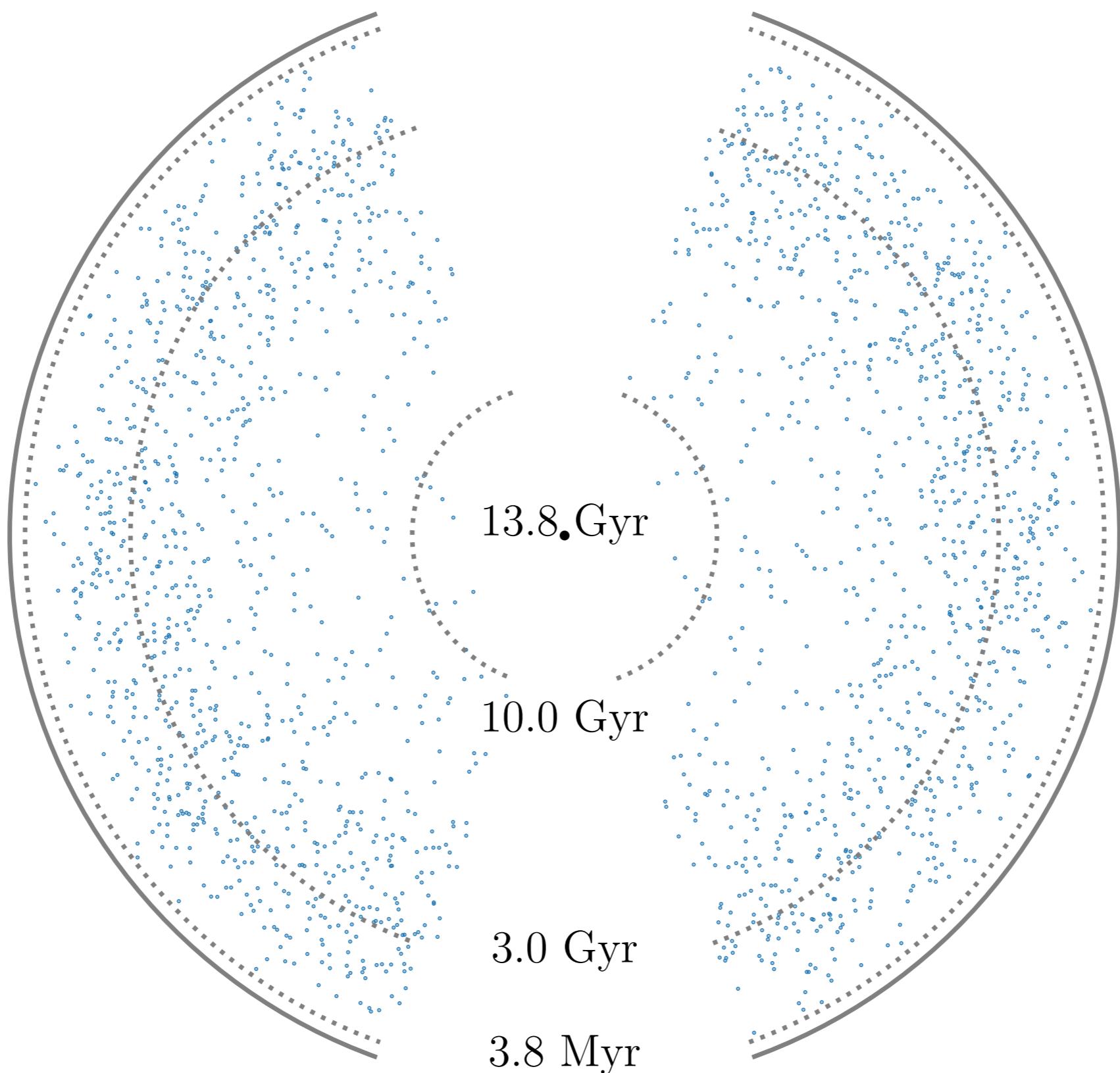
Gravitational waves are new cosmic messengers

Gravitational waves from stellar-mass **binary black holes**



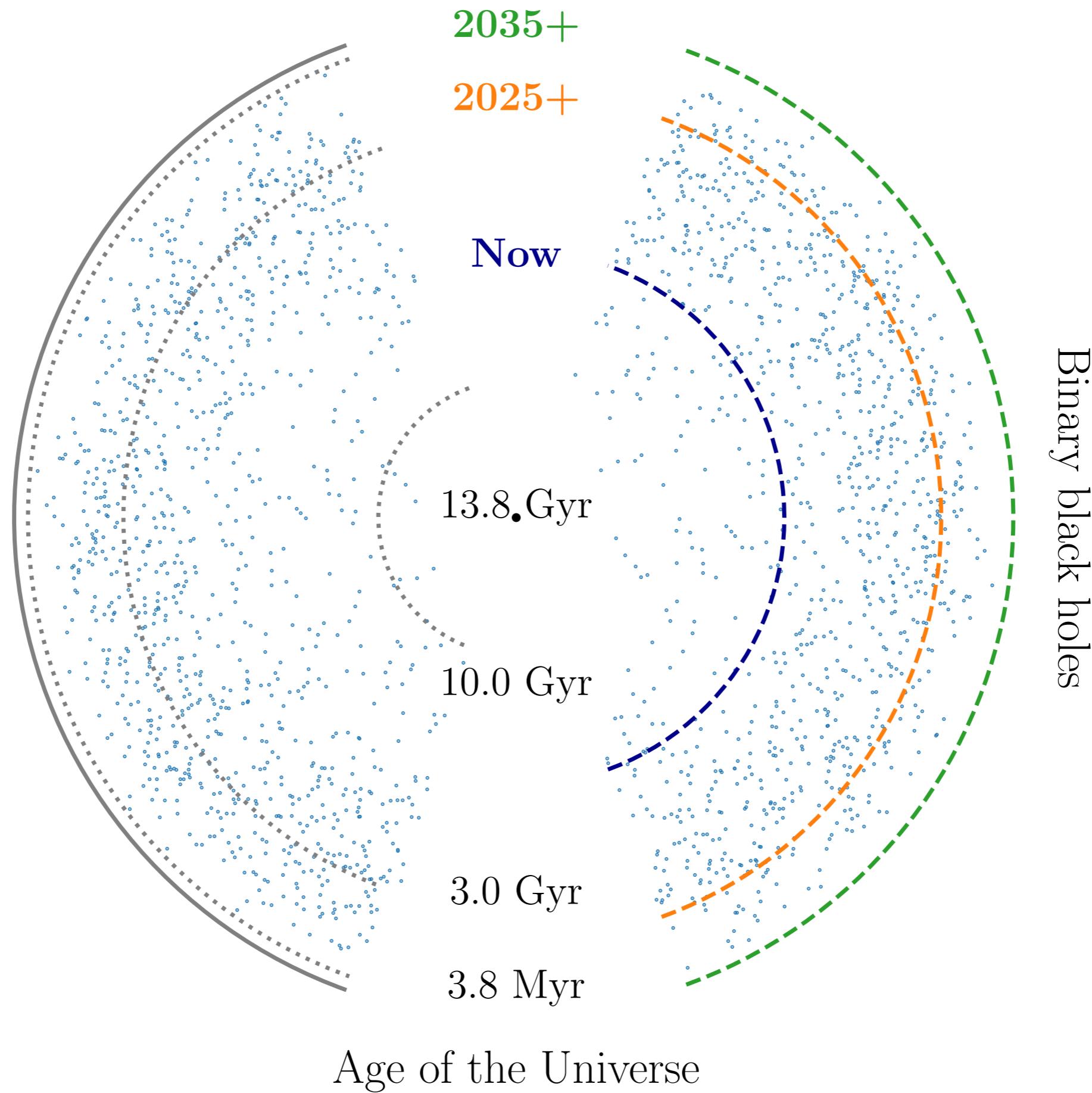
[First detection, GW150914]

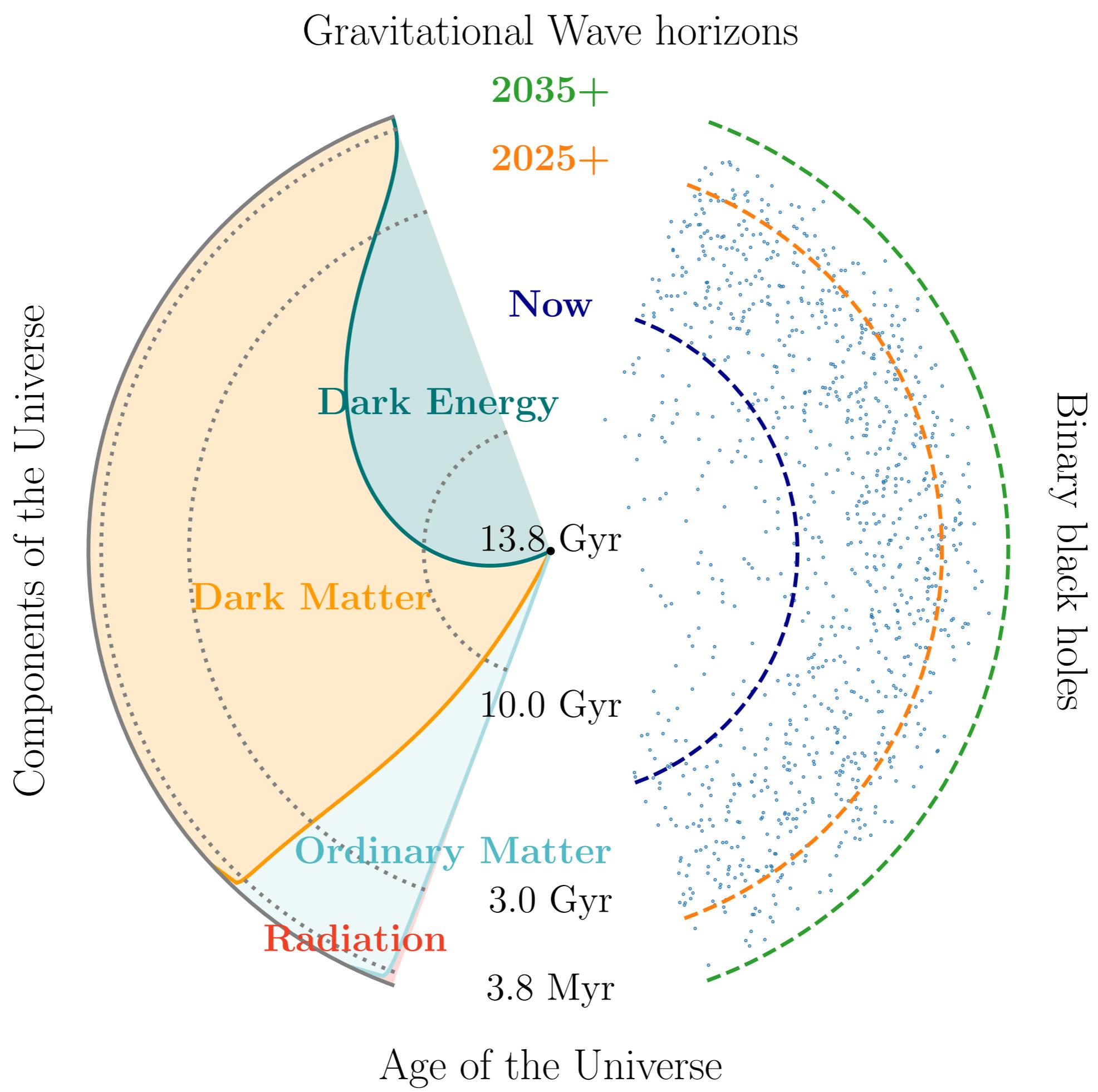
Binary black holes



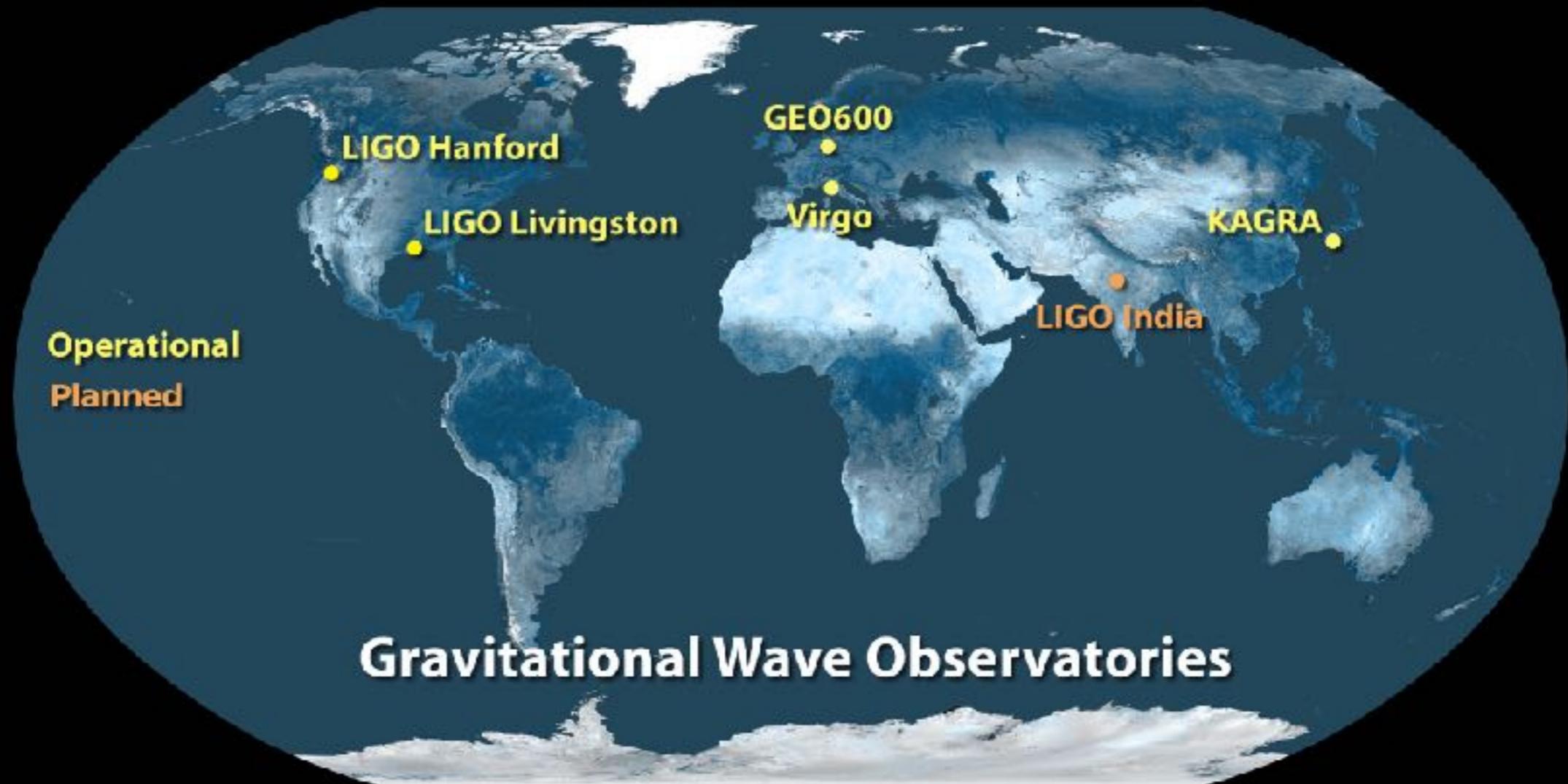
*stellar mass
binary black holes

Gravitational Wave horizons





The era of gravitational wave astronomy is here!



[Hanford, US]



[Livingston, US]

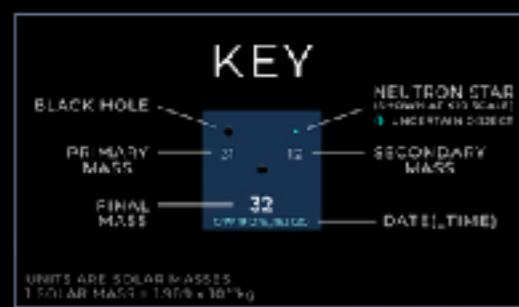
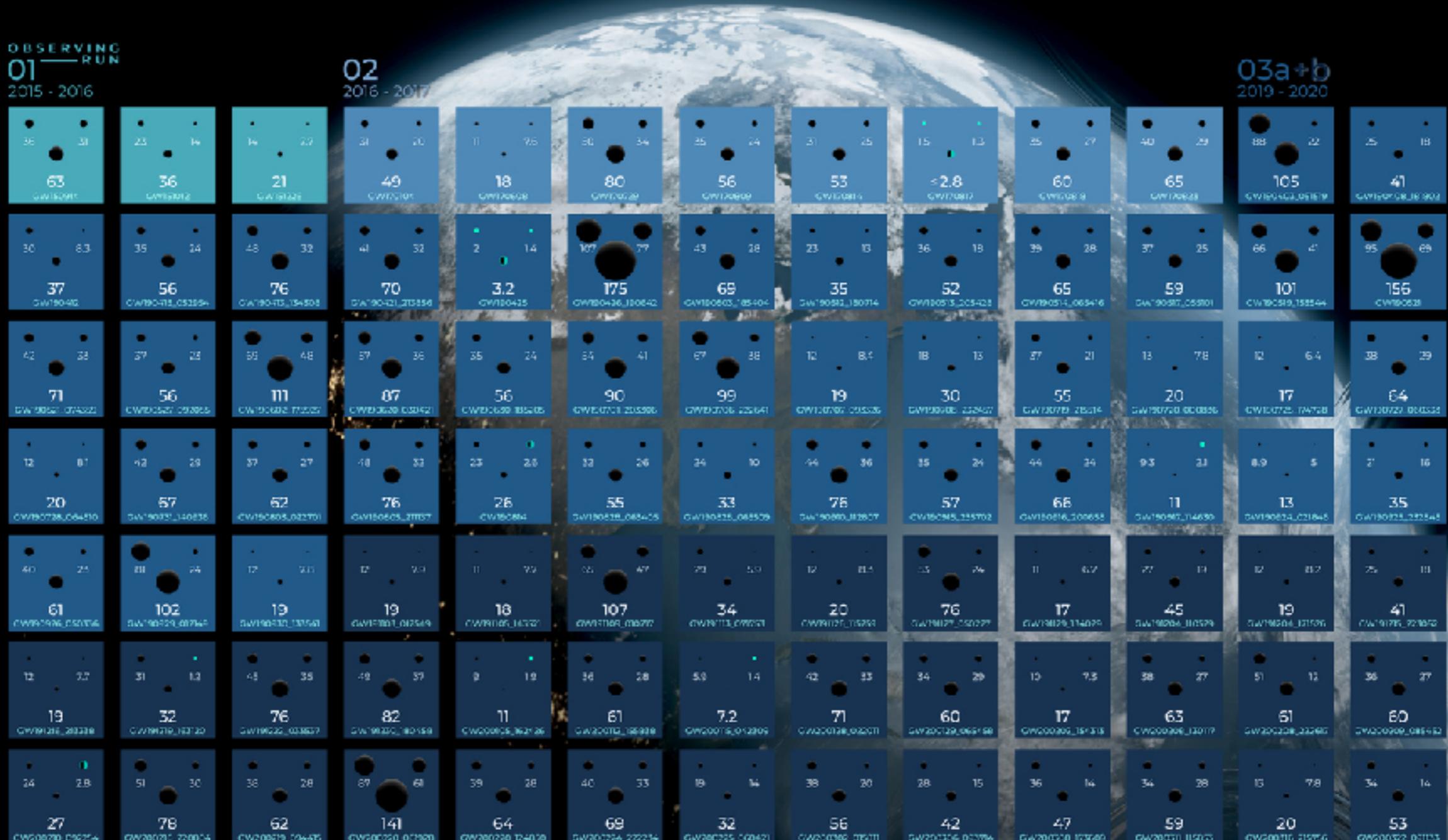


[Virgo, Italy]



[KAGRA, Japan]

The era of gravitational wave astronomy is here!

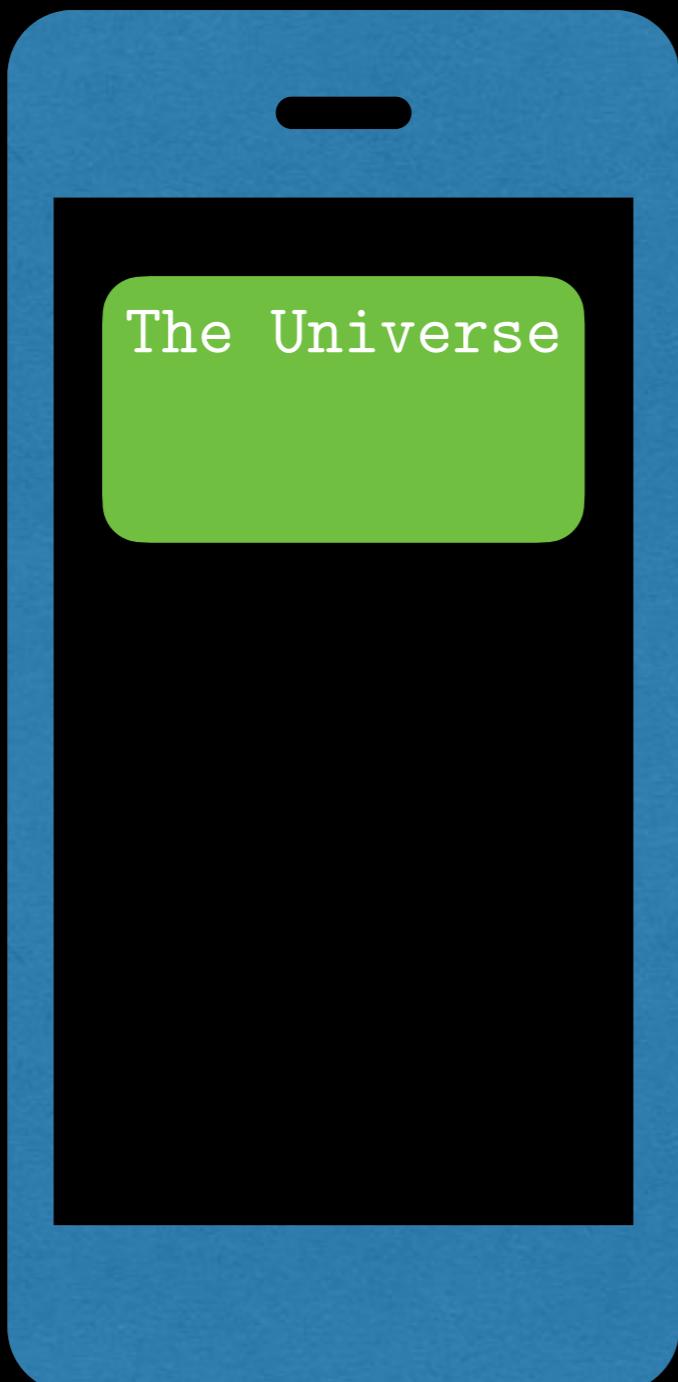


GRAVITATIONAL WAVE MERGER DETECTIONS — SINCE 2015 —



O4 is happening!

<https://gracedb.ligo.org/superevents/public/O4/#>



[Resonance, D. Teocharis]

NBI LIGO group



Jose M. Ezquiaga



Rico Lo



Luka Vujeva



Asta Heinesen



Juno Chan



Miao Shang



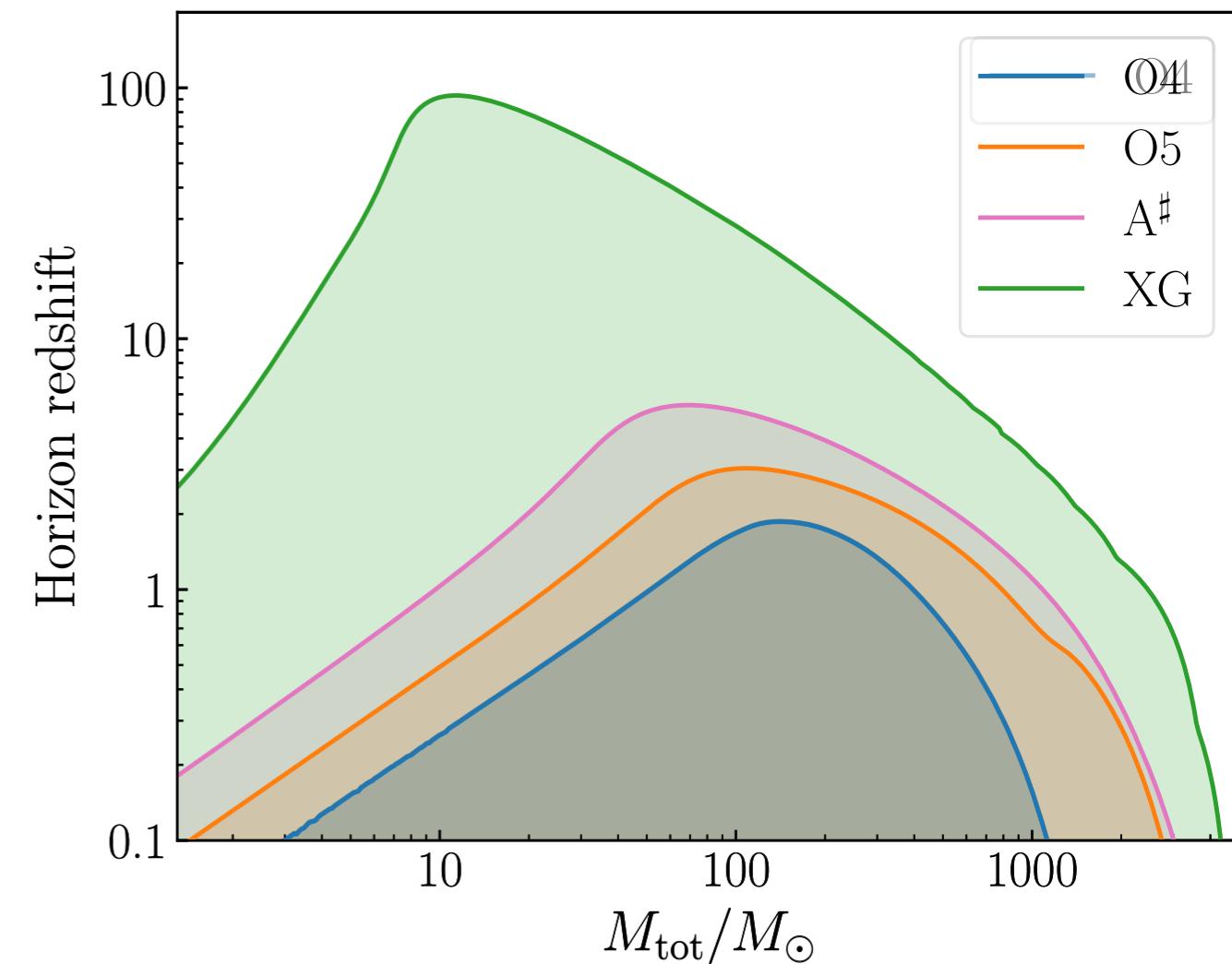
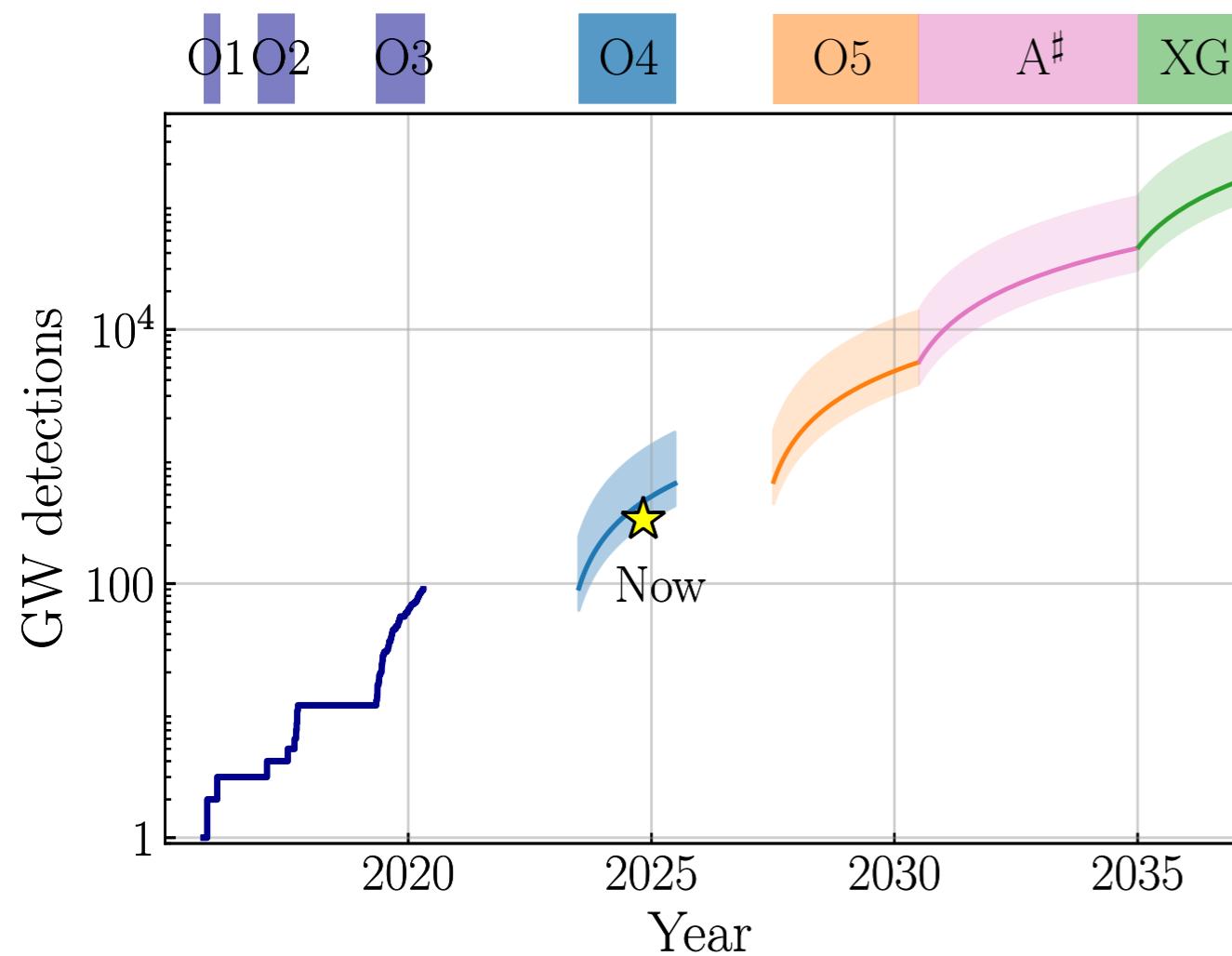
Lorena Magaña



Matilde García

+ YOU?

The future: “big data” & distant Universe



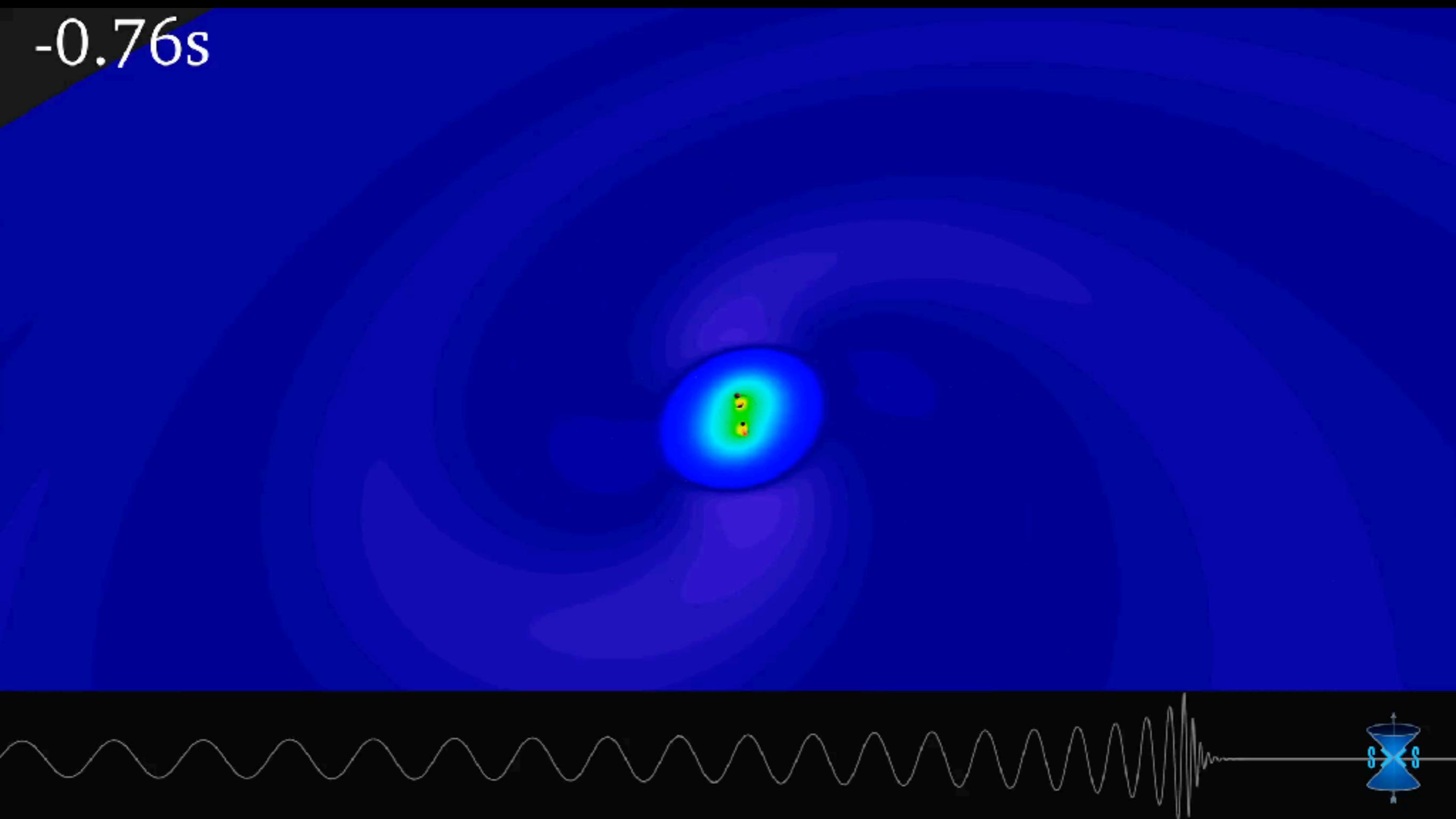
Gravitational waves are standard sirens



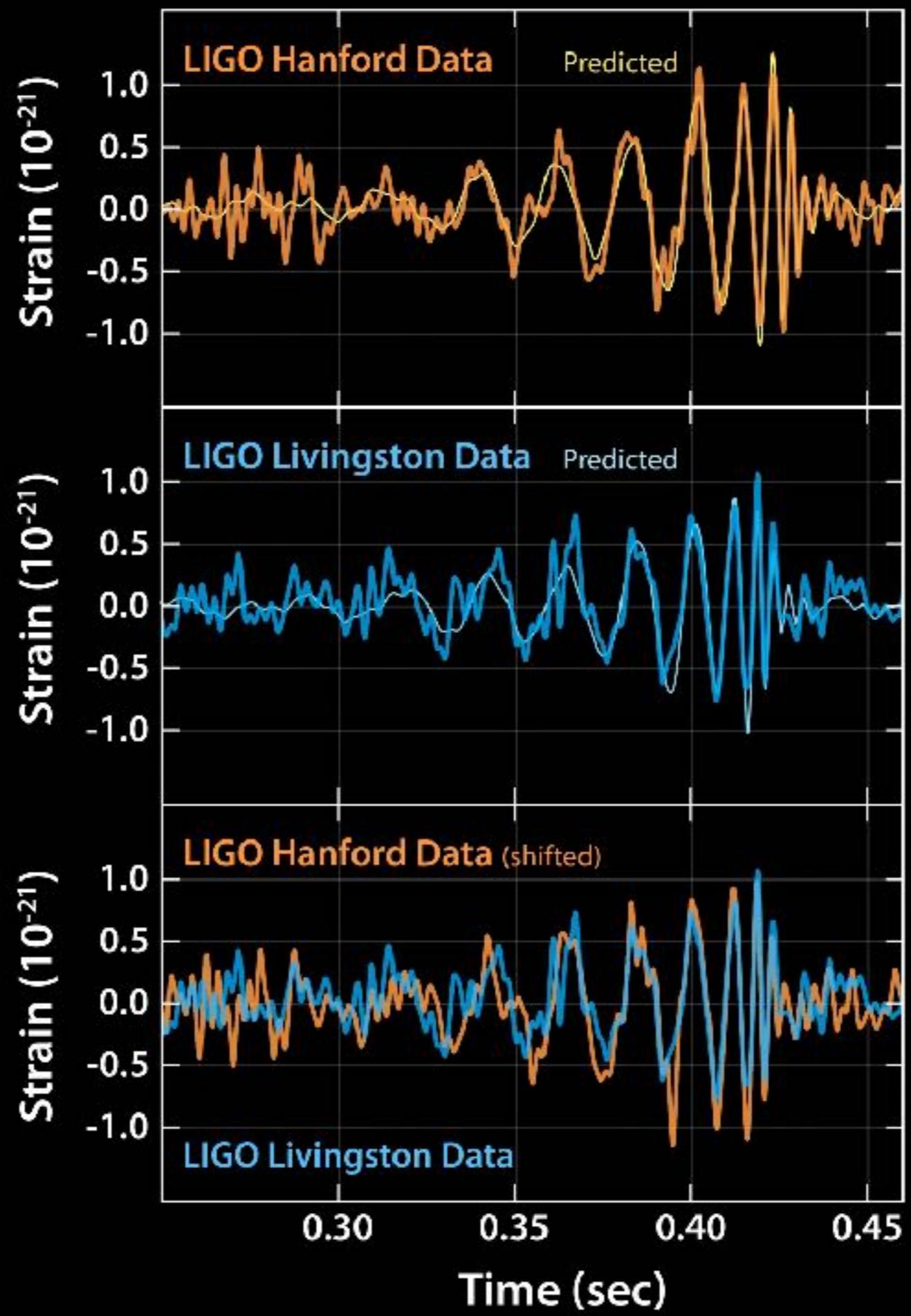
[general relativity predicts waveform]

Numerical simulation of a binary black hole merger

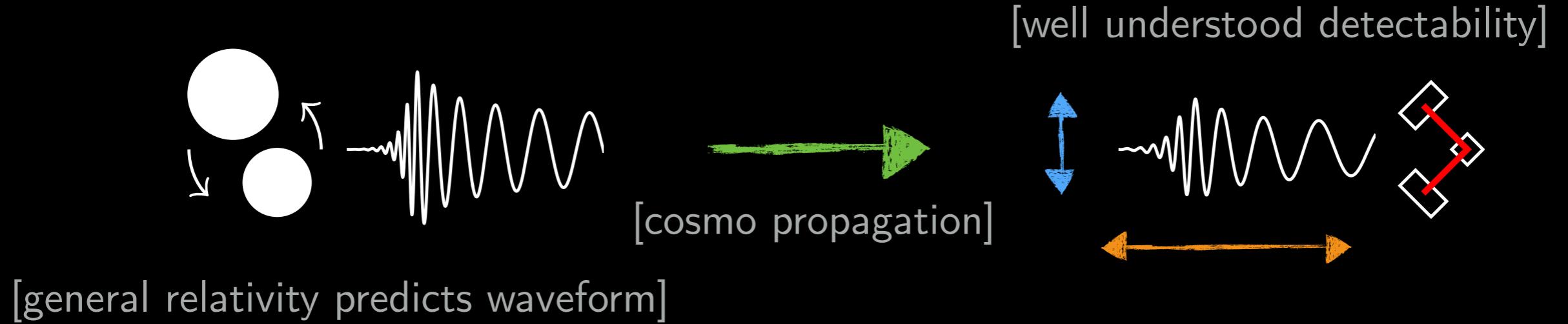
-0.76s

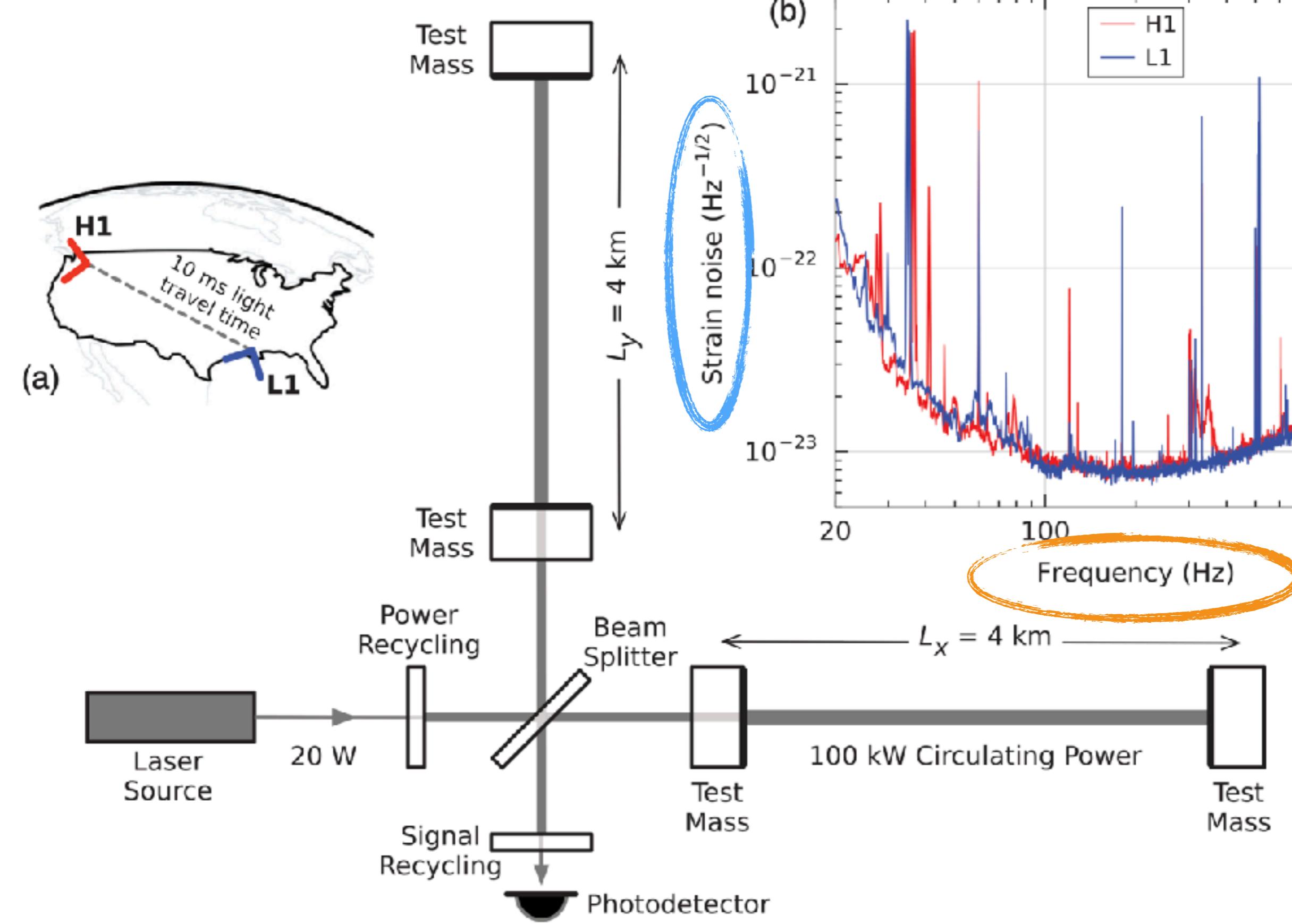


[Credit: SxS Collaboration]



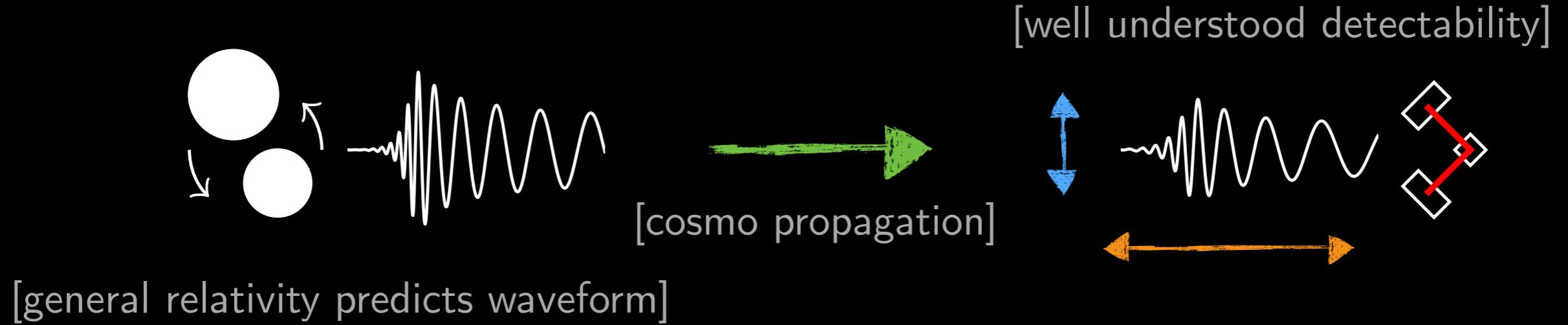
Gravitational waves are standard sirens





[Credit: LIGO]

Gravitational waves are standard sirens

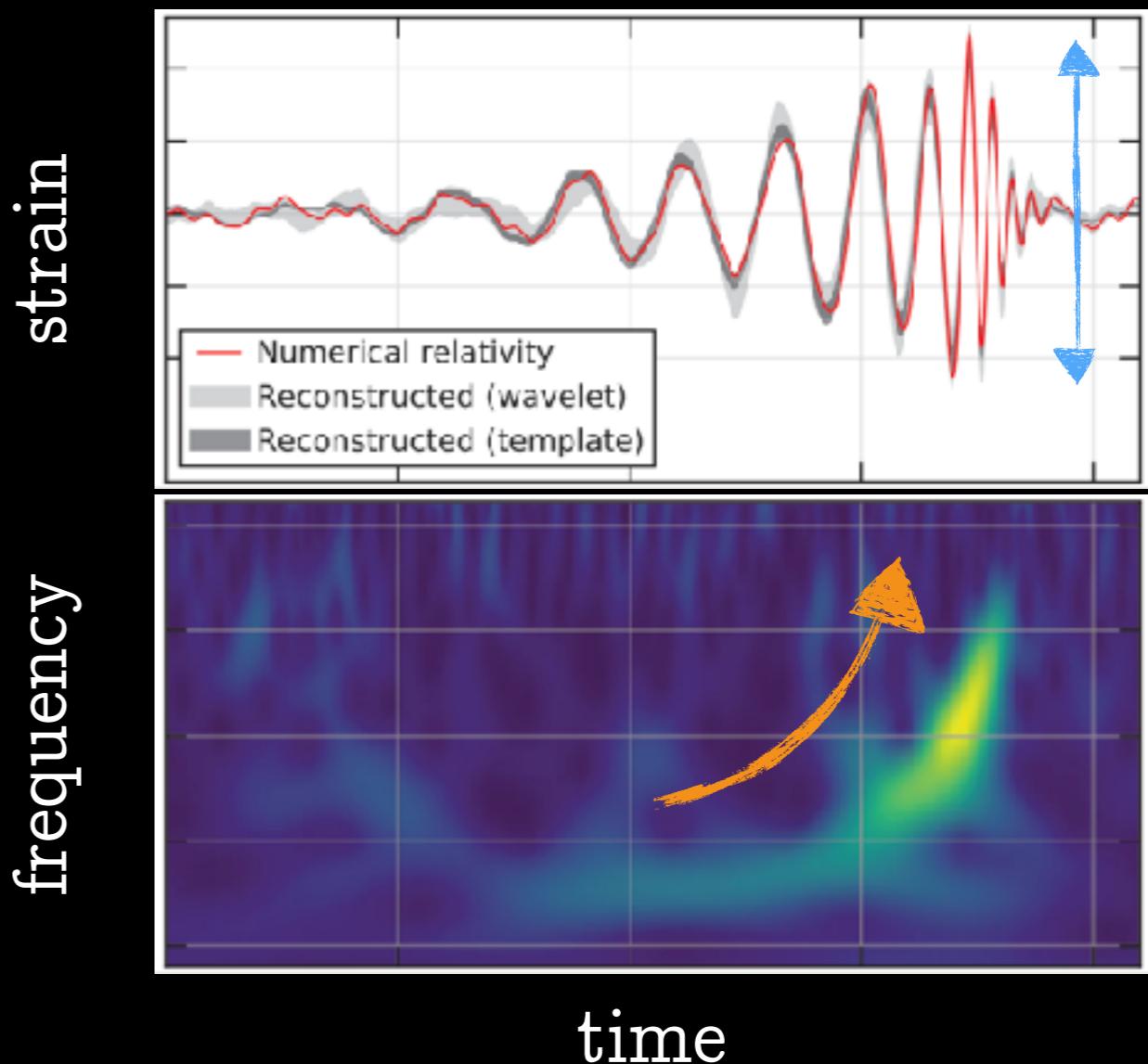


$$d_L(z)$$

[GW Hubble diagram]

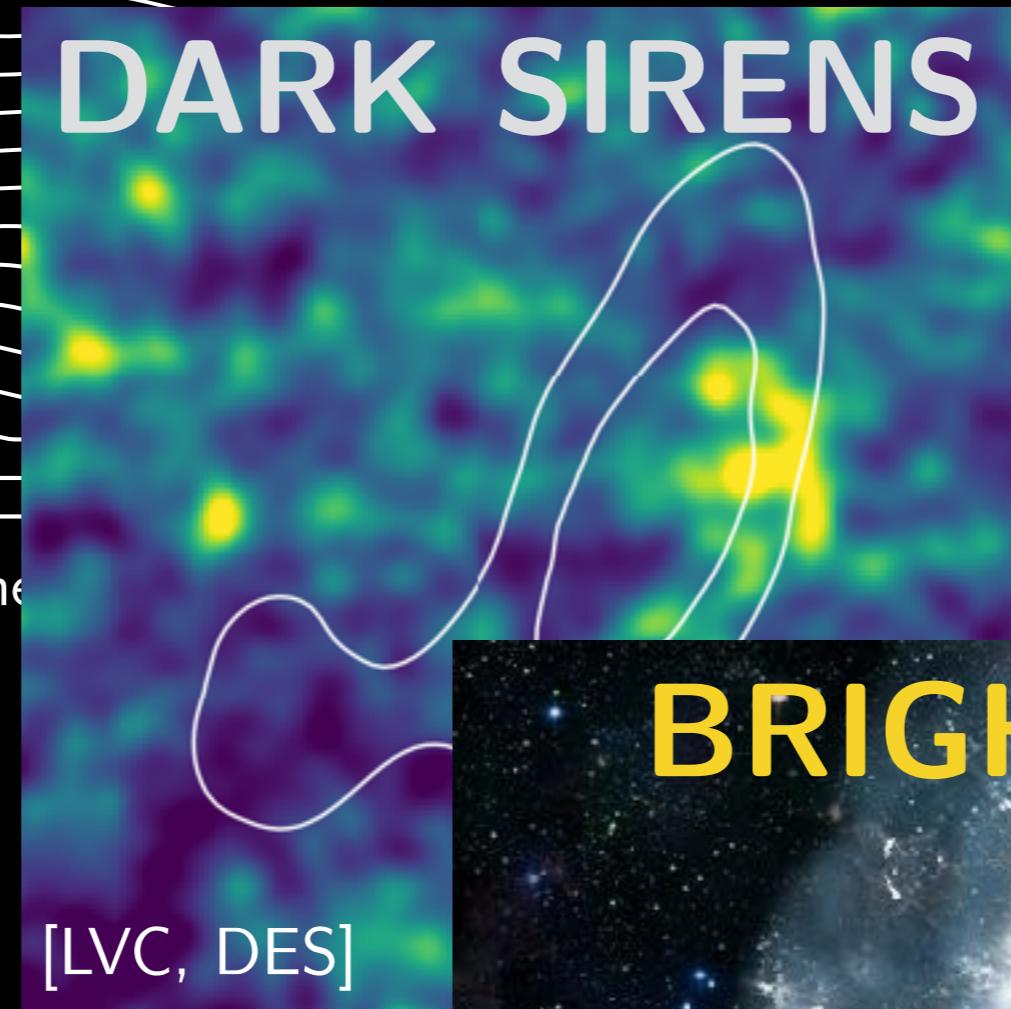
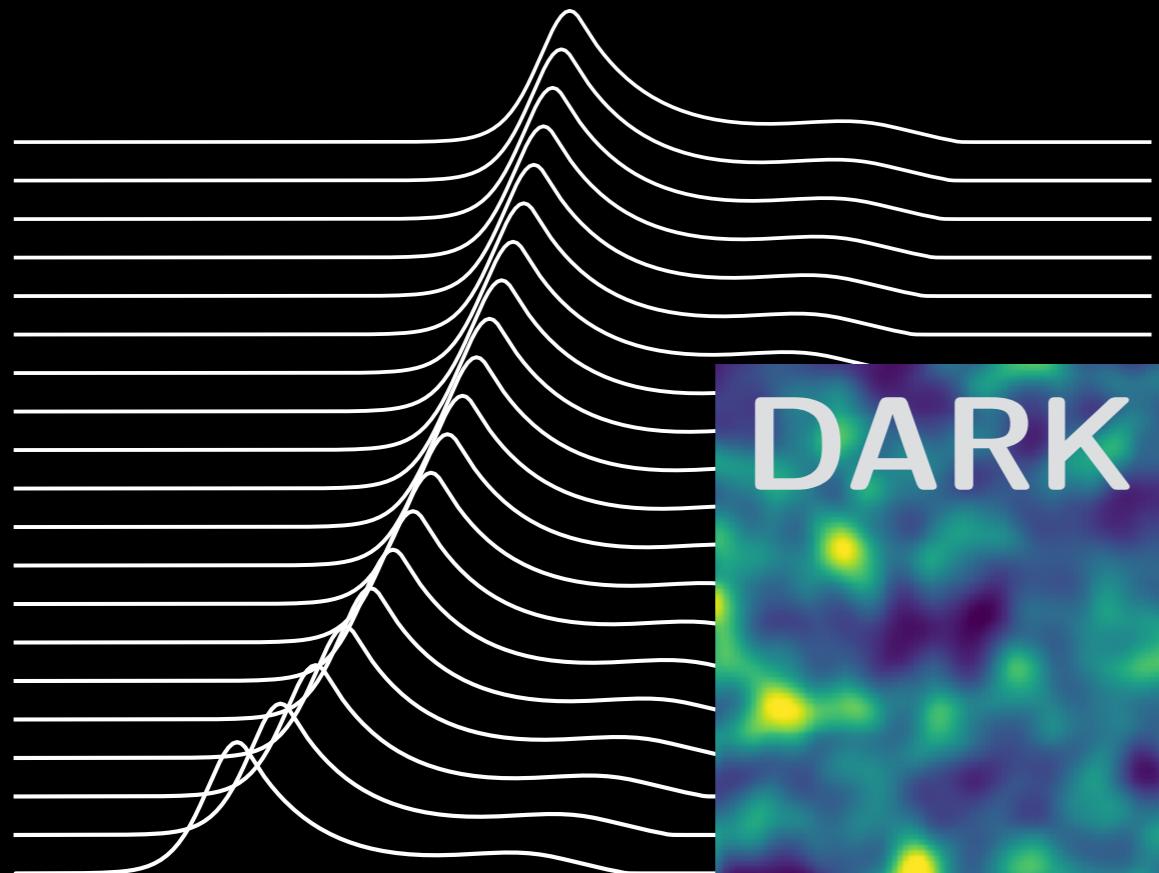
$$m_{\text{det}} = (1 + z)m$$

[Interplay with astrophysics]



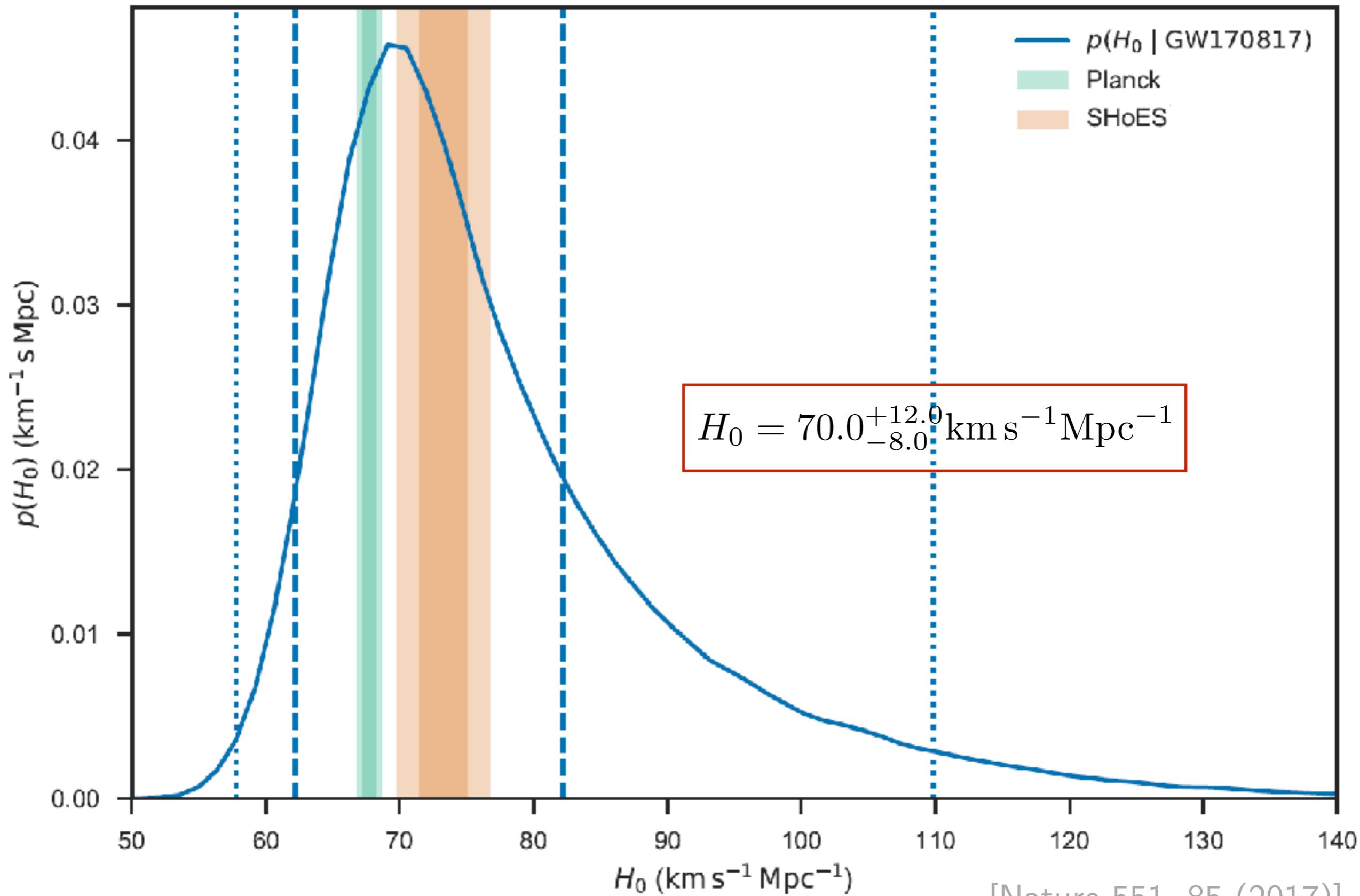
SPECTRAL SIRENS

Luminosity distance



Love sirens

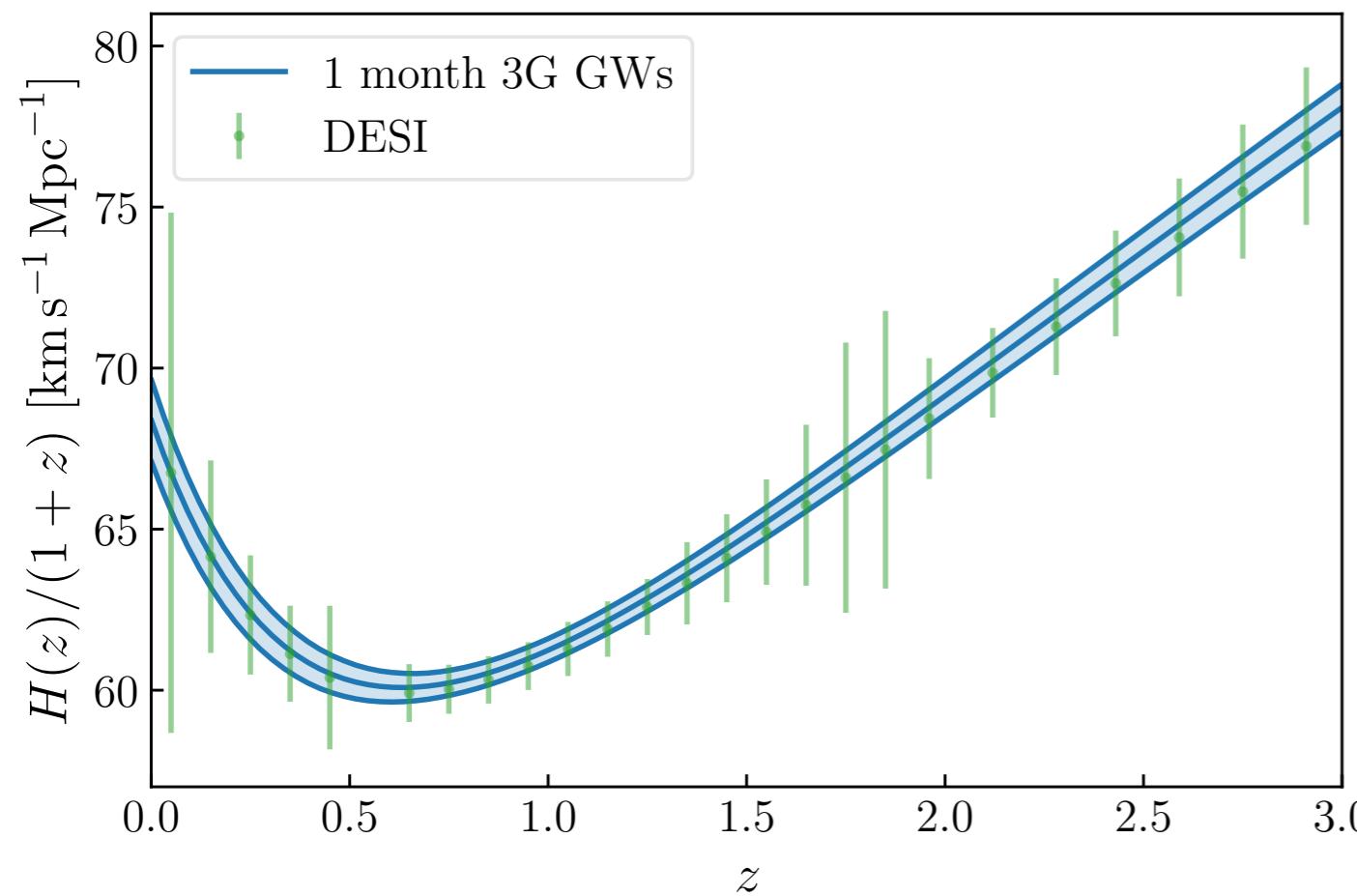
Bright sirens



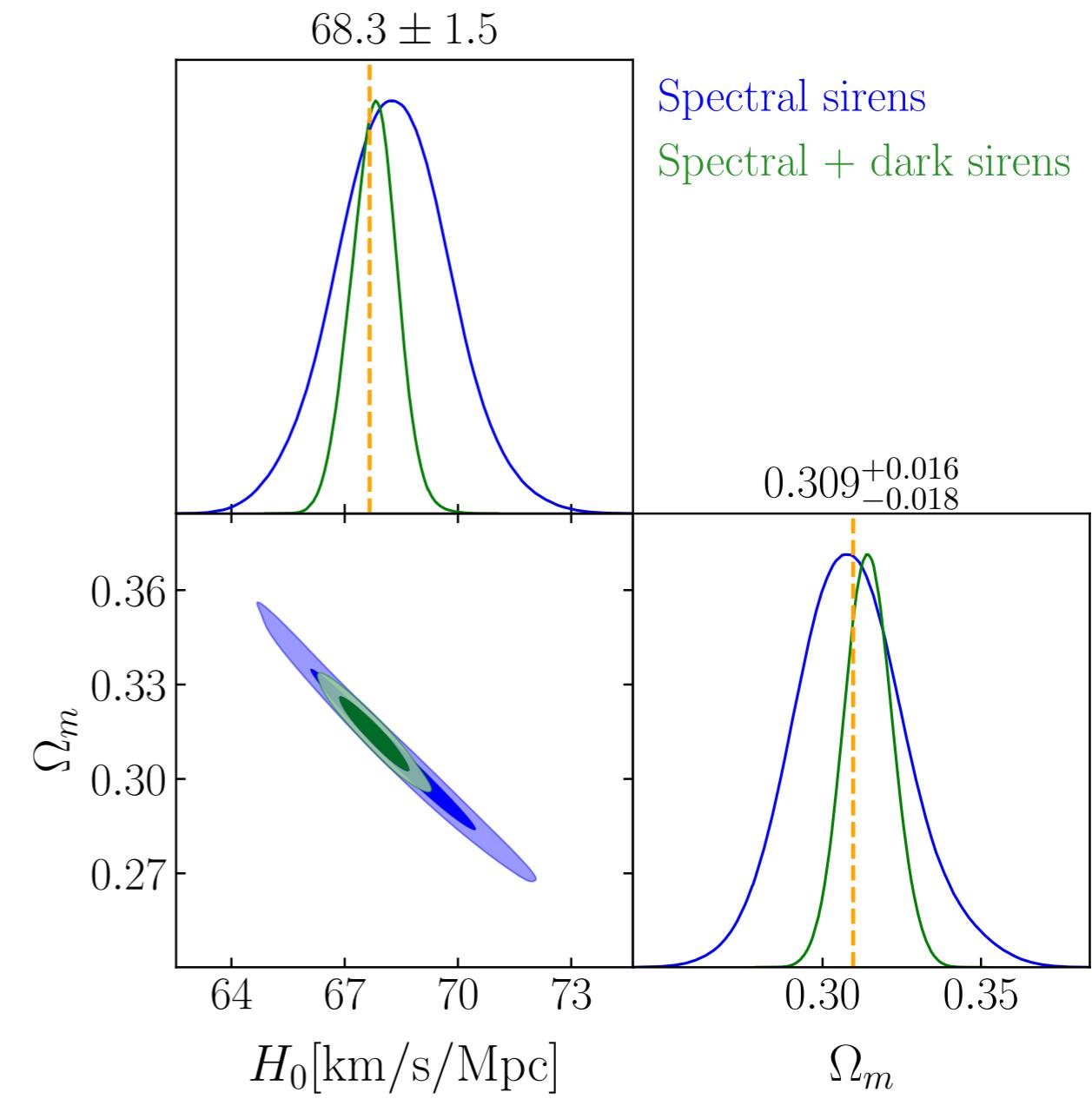
Expansion rate at high redshift $H(z)$

Combining sirens **sub-percent** precision across cosmic history!

Spectral sirens are competitive
with cosmic surveys



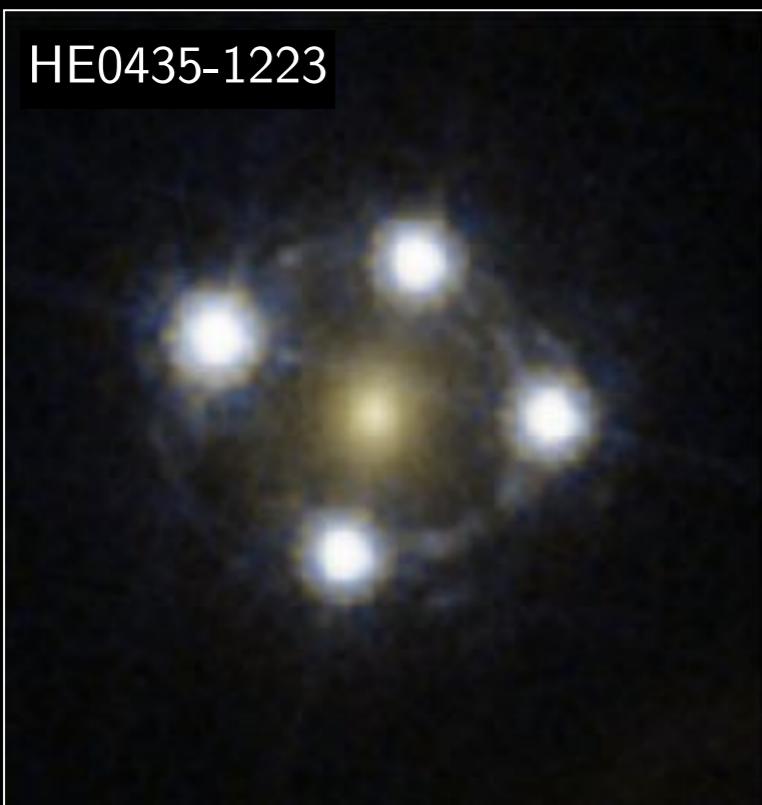
[Ezquiaga & Holz (PRL'22)]



[Chen, Ezquiaga & Gupta (CQG'24)]

Gravitational waves are *only* altered by
gravitational interactions with cosmic structures

Gravitational lensing - electromagnetic spectrum



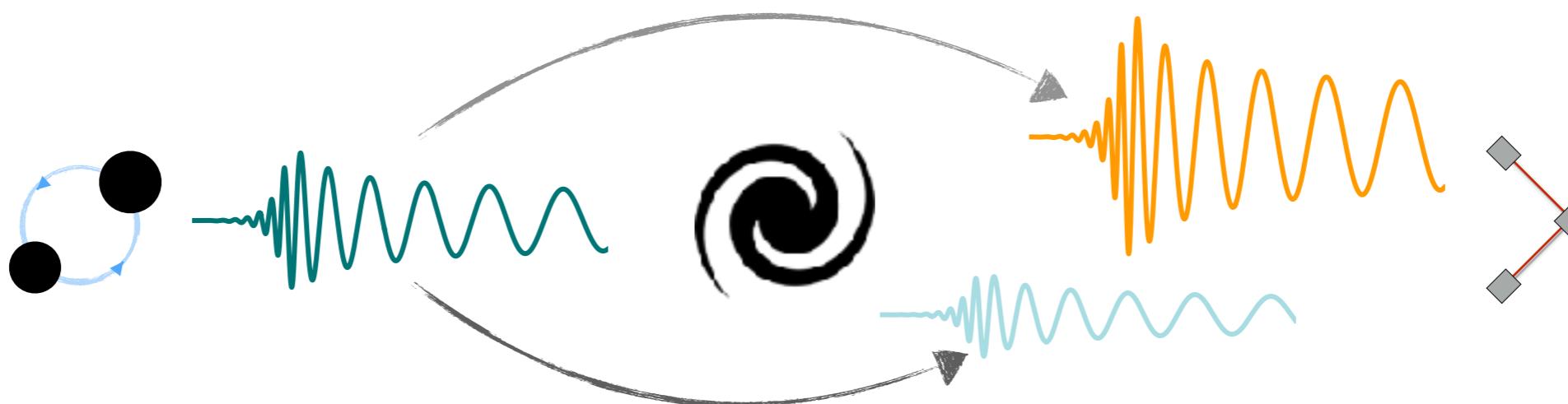
[multiple images]



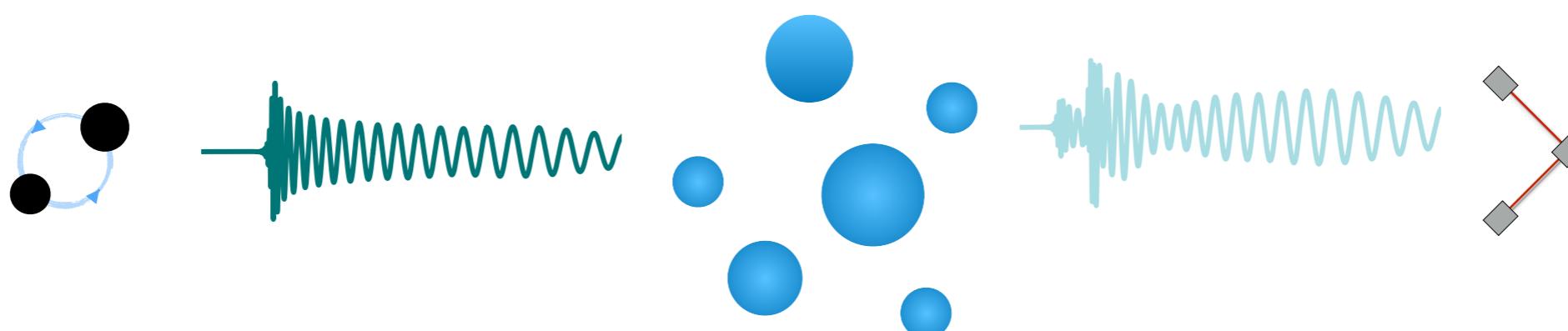
[arcs and rings]

Gravitational lensing - gravitational wave spectrum

Repeated chirps due to strong lensing



Waveform distortions by substructures

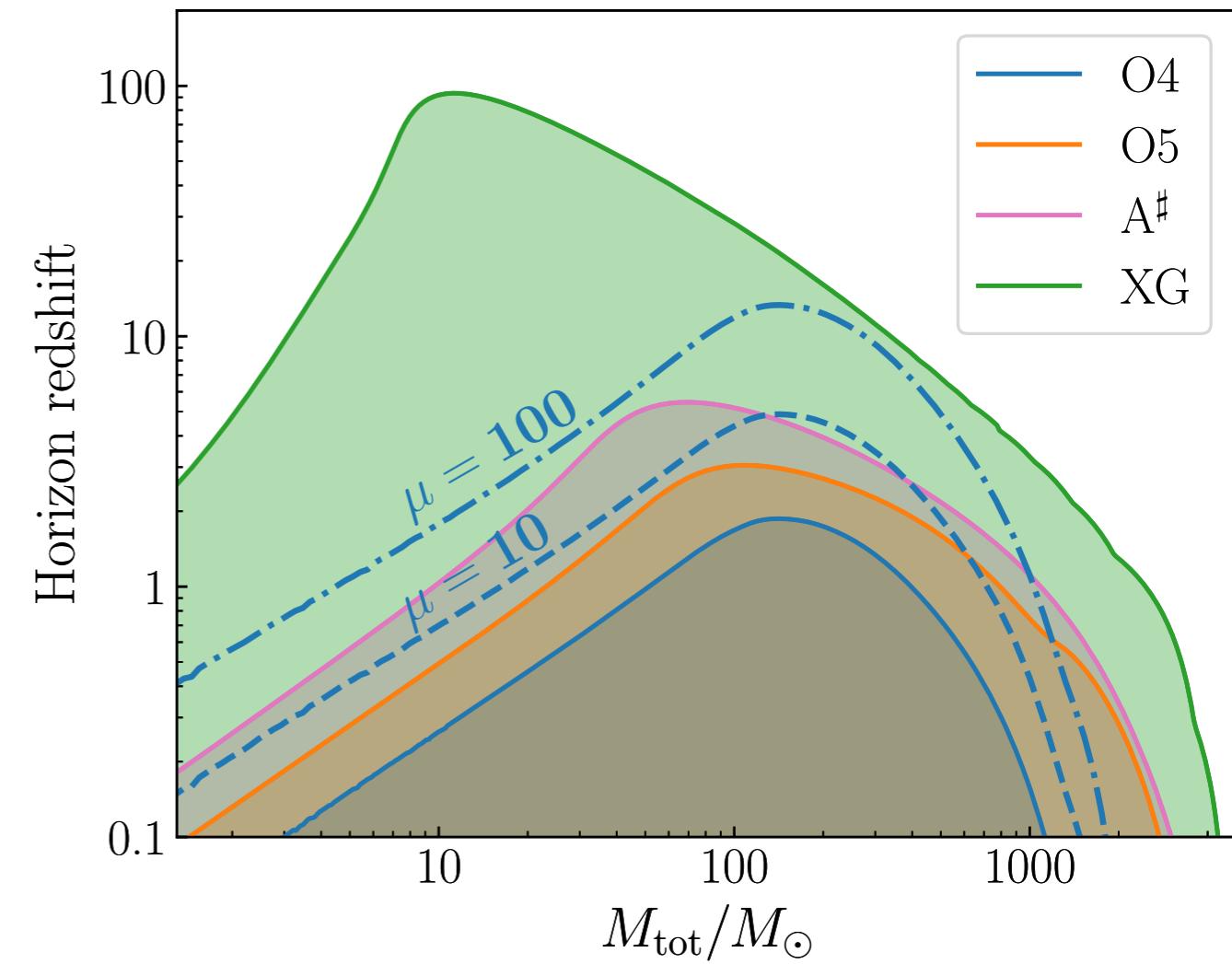
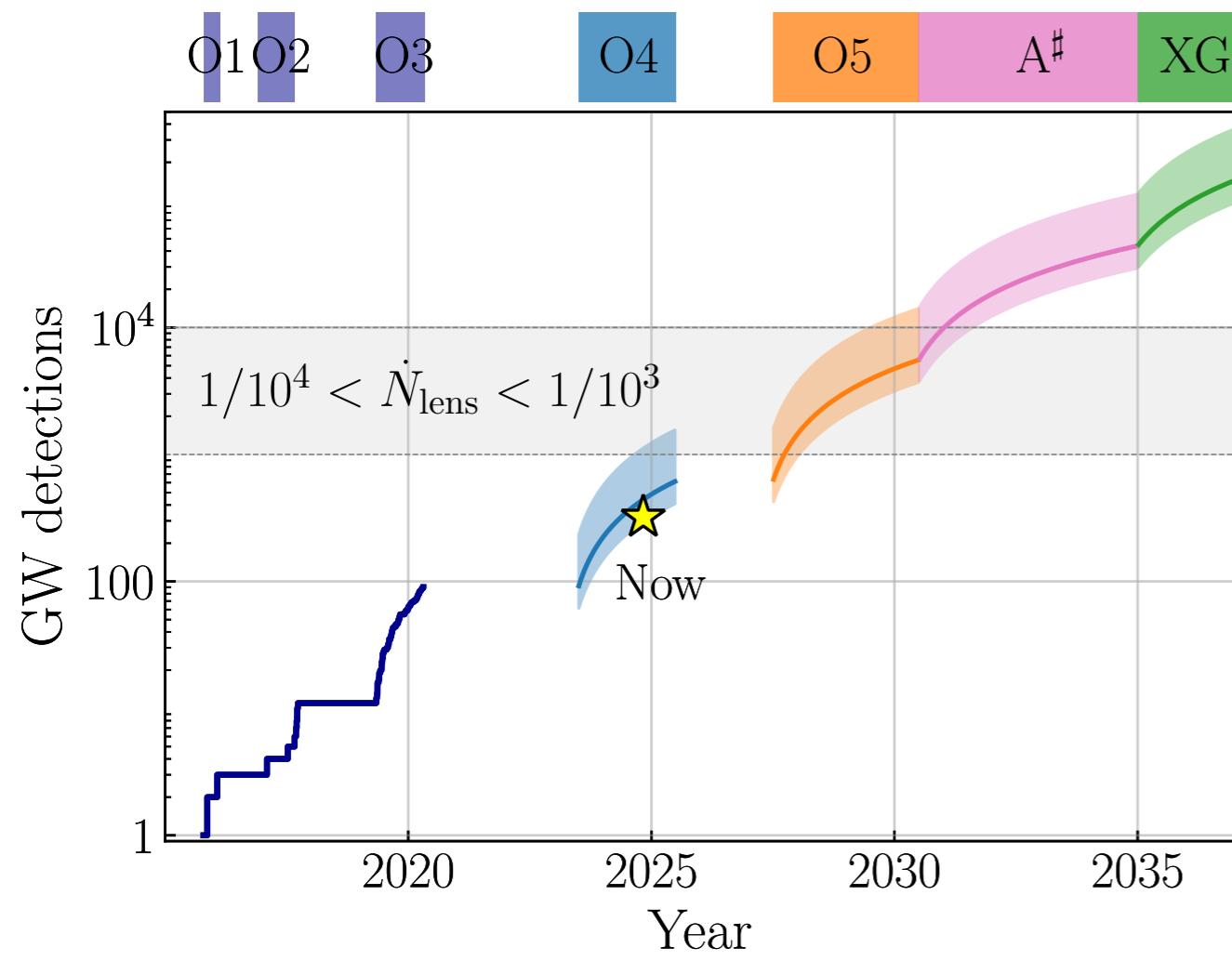


Source

Lens

Detector

Gravitational wave lensing: expanding *horizons*

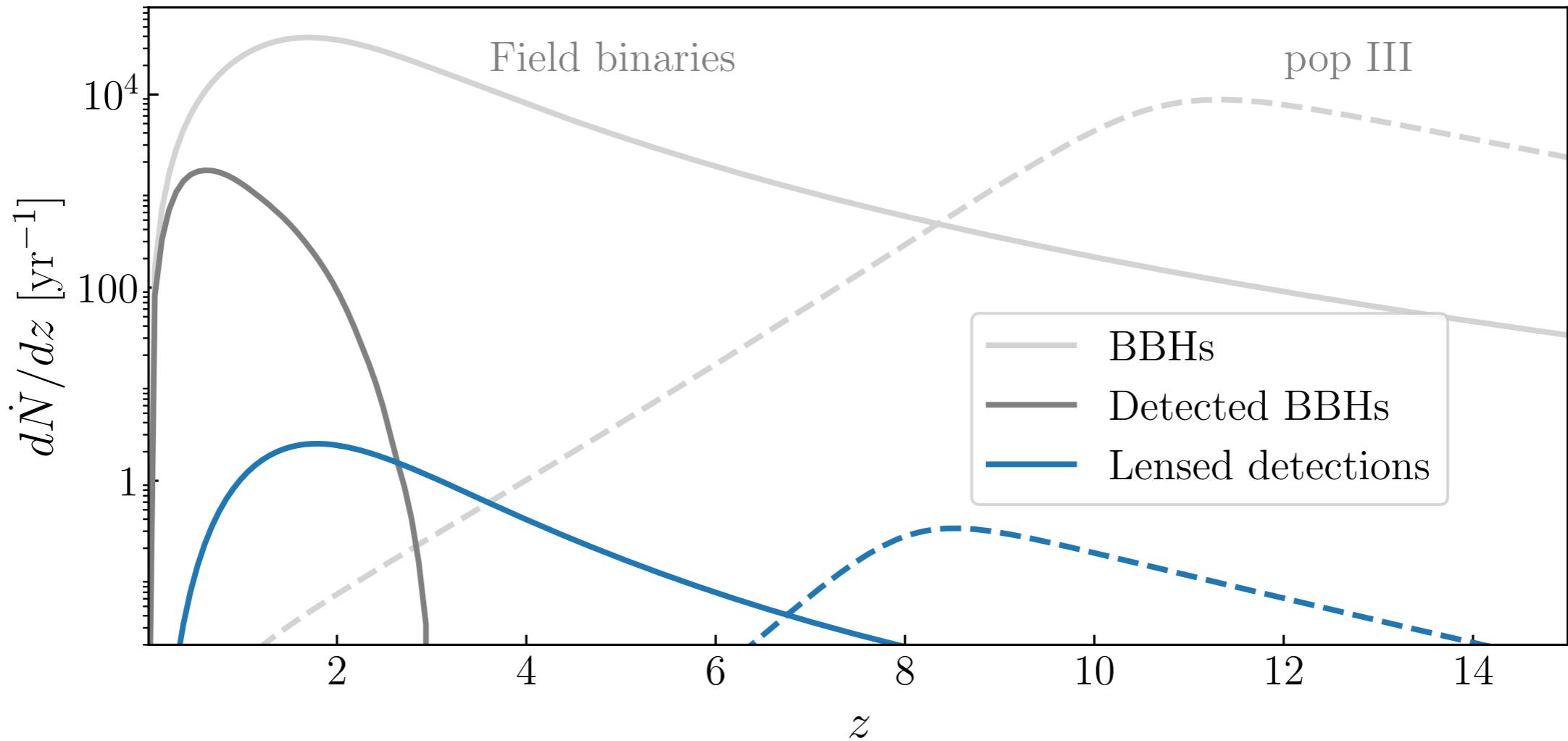


[Xu, Ezquiaga, Holz; ApJ'21]

[Lo, Vujeva, Ezquiaga, Chan; 2024]

Gravitational wave lensing: expanding *horizons*

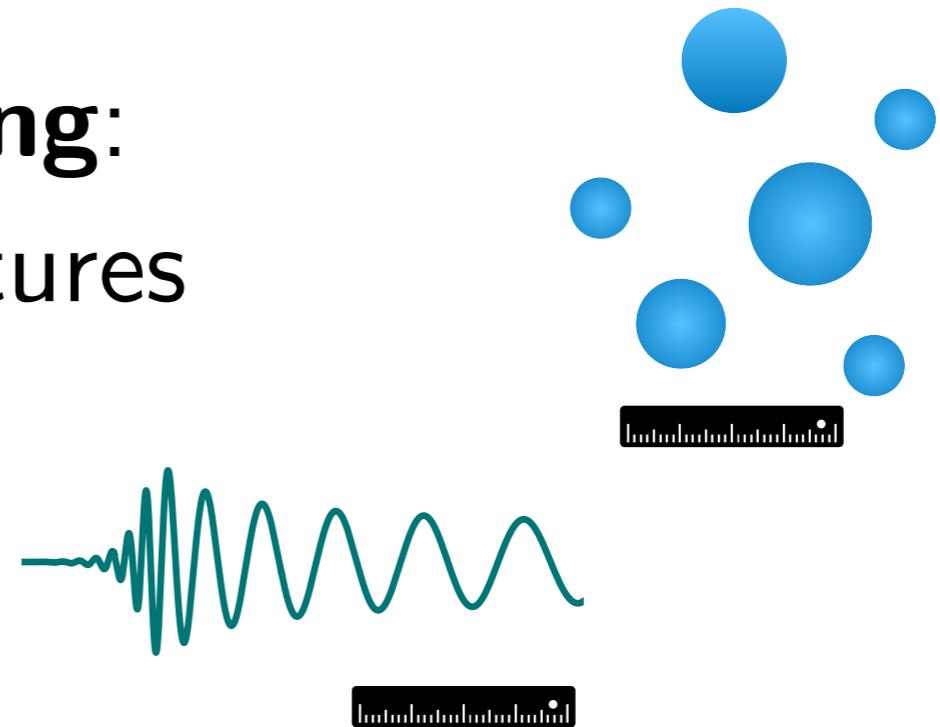
E.g. discover new populations of black holes



“field”: 100,000 merg./yr; [O5] 1500 det./yr, 5 lensed det./yr

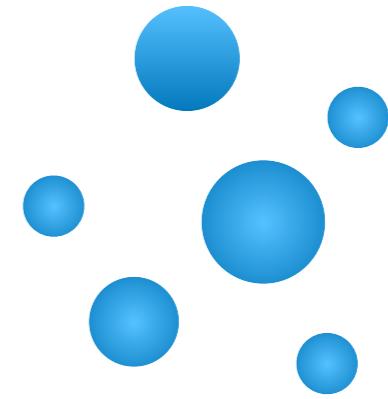
“pop-III”: 35,000 merg./yr; [O5] 0 det./yr, 1 lensed det./yr

Gravitational wave lensing: probing *dark matter* structures



$$\lambda_{\text{gw}} \sim 10^3 \text{ km} \left(\frac{M_{\text{bbh}}}{10 M_\odot} \right)$$

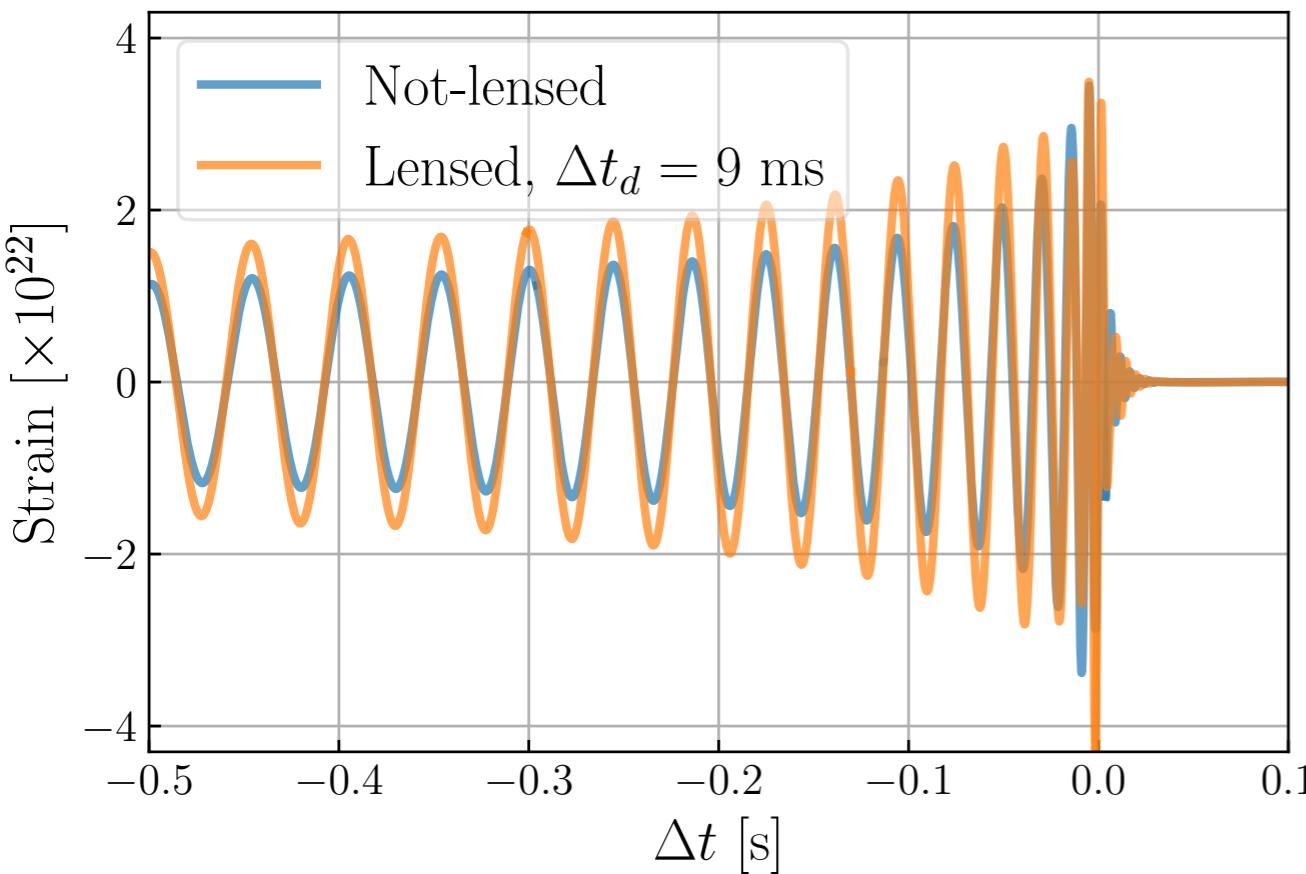
Gravitational wave lensing: probing dark matter structures



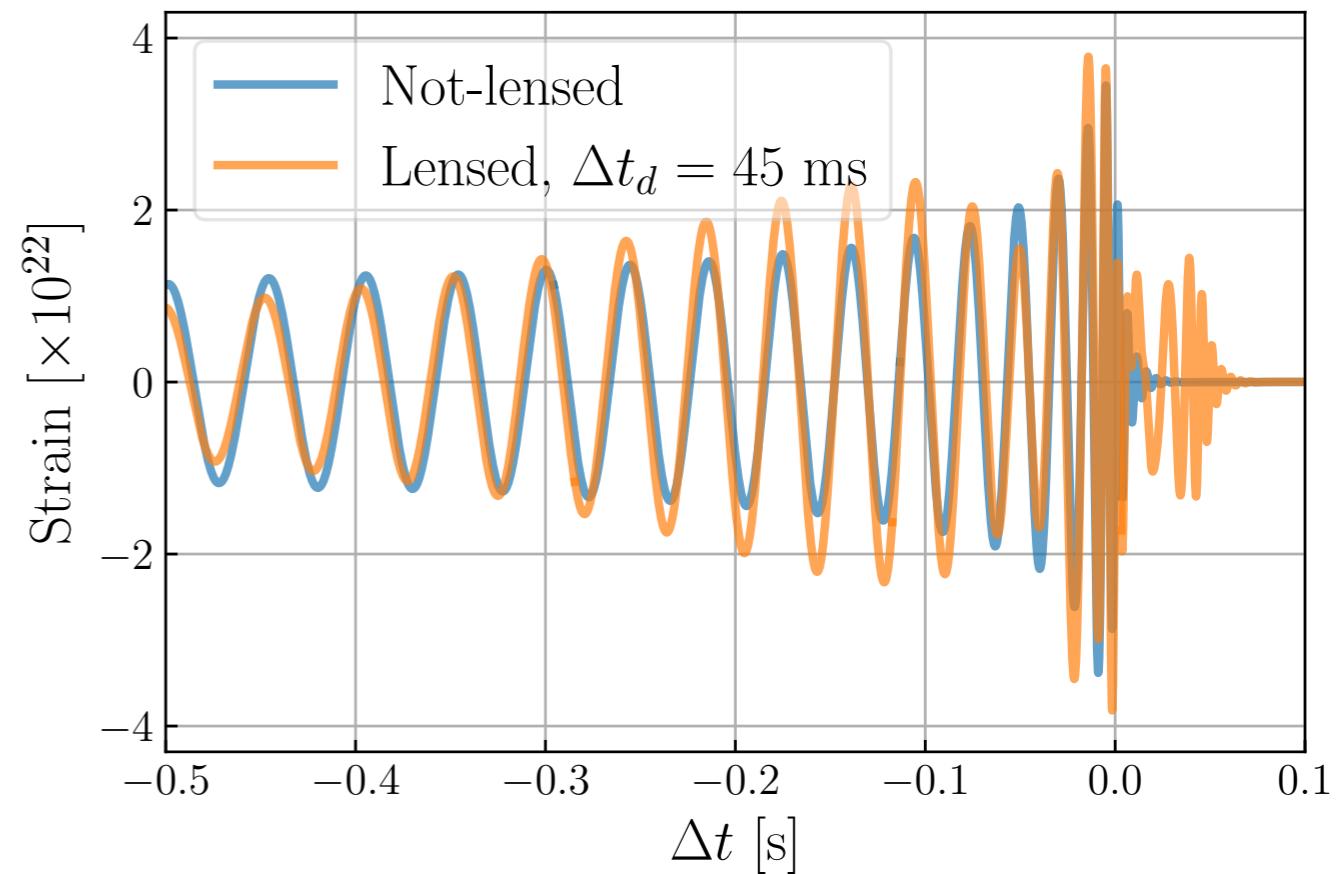
E.g. compact (point) lenses

$$\Delta t_d(y=1) \simeq 4 \left(\frac{(1+z_L)M_L}{100M_\odot} \right) \text{ ms}$$

Diffraction

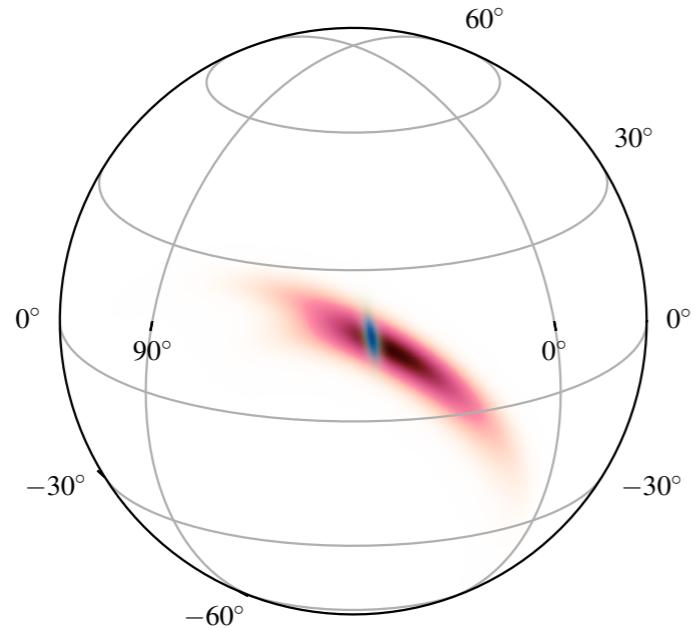


Interference

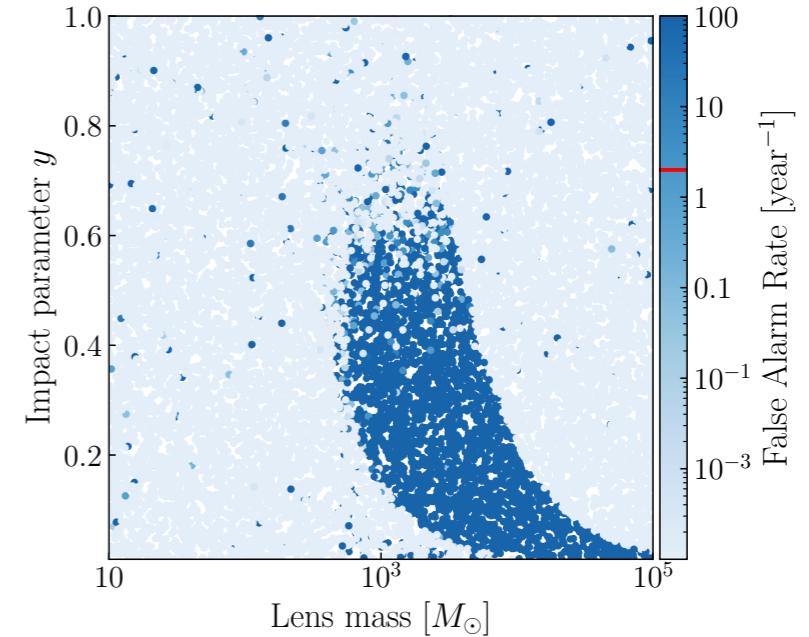


Our main goals

- Enable *first detection* of gravitational wave lensing

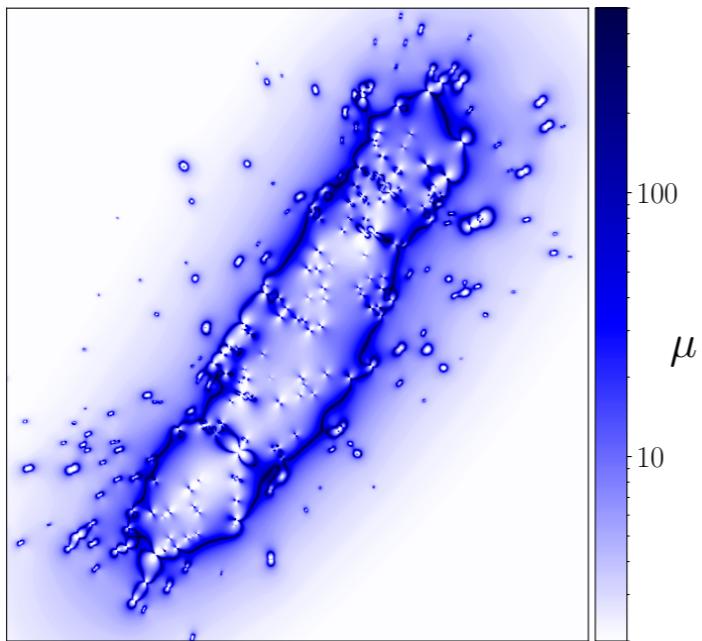


Identify multiple images



Distorted lensed waveforms

- Probe *dark matter* and test *gravity* in new regimes



Lensing with substructures



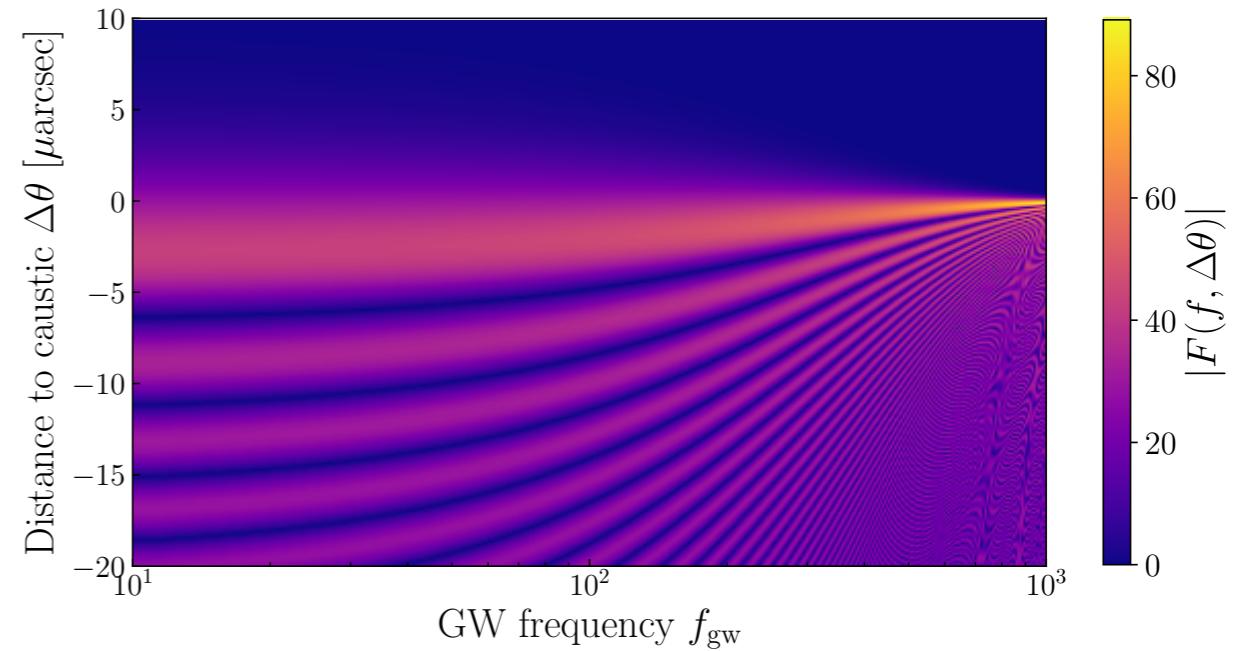
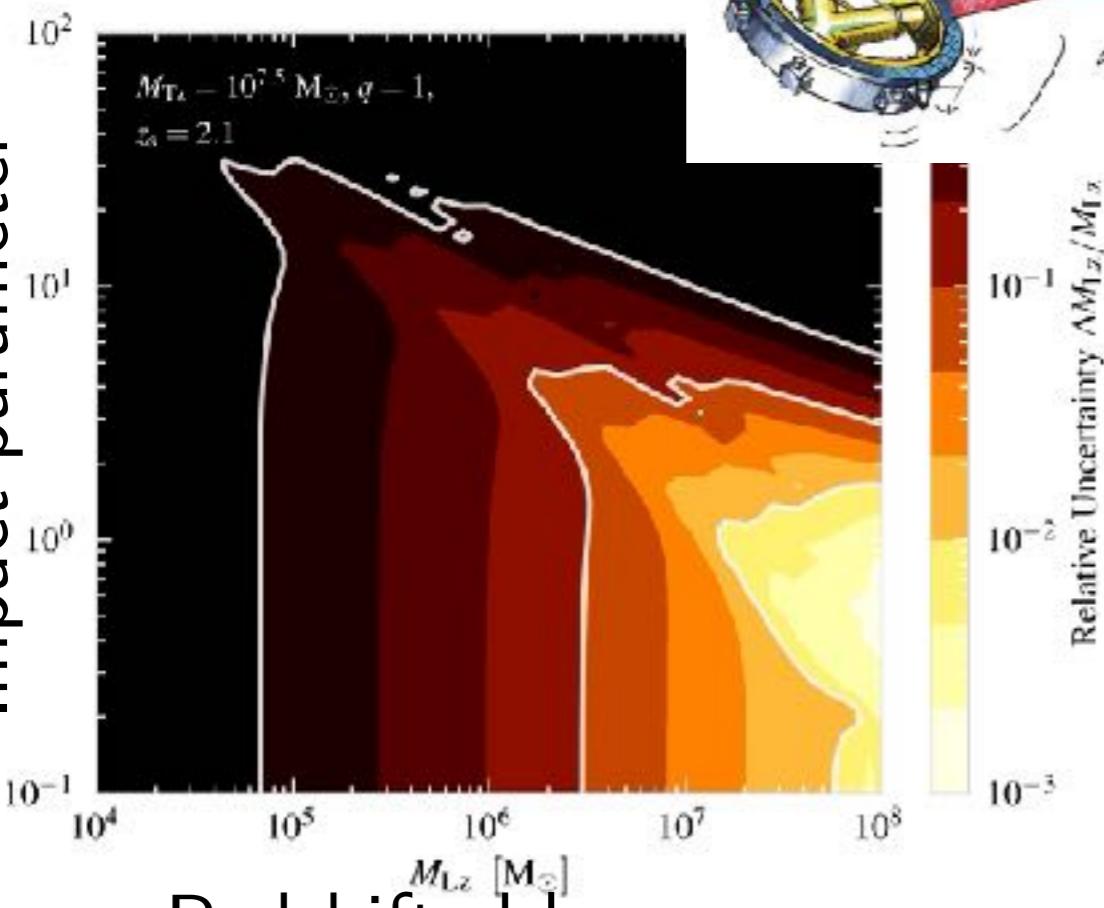
Strong-field wave optics lensing

And there is much more!

[Lo, Vujeva, Ezquiaga, Chan; 2024]

[Çalışkan et al.; PRD'23]

Impact parameter



Modified gravity roadmap and GW astronomy

General Relativity
Unique theory
of massless $g_{\mu\nu}$

Massive
Gravity
 $m_g > 0$

Tensor
 $f_{\mu\nu}$

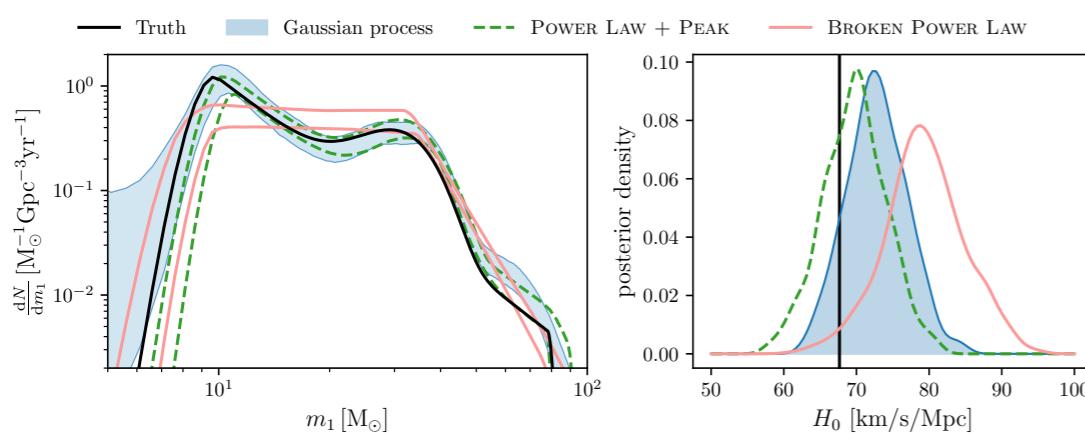
Additional
Field

Constrained by
Speed
Amplitude
Phase
Polarization

Break Assumptions
Non-Local
Lorentz Violating
Einstein Aether

Extra dimensions

Scalar ϕ
Horndeski
Brans-Dicke
Quintessence
 $f(R)$
Galileon
KGB
Gauss-Bonnet
 $C(X)$
 $D(X)$
Beyond Horndeski
General Proca
Beyond gen. Proca
TeVeS (MoND)
General Proca
dRGT
Bigravity
Multi-gravity
Proca $m_V > 0$



[Farah et al.; Astrophysics-free GW cosmology 2024]

[Ezquiaga & Zumalacárregui, Front.'18]

Conclusions

Gravitational waves are precious cosmological probes:

- Well understood signals from general relativity
- Coherent detection of waveform
- Expansion rate at high redshift $H(z)$ with **binary black holes** mergers
- Probing origin of the observed black holes and dark matter substructures via **lensing**
- Future of gravitational wave astronomy is exciting.
Join us!





Medfinansieret af Den Europæiske
Unions Connecting Europe-facilitet

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Join us!

ezquiaga.github.io/joinus

