Title: The next frontier in gravitational wave cosmology

Speakers: Jose Maria Ezquiaga

Series: Strong Gravity

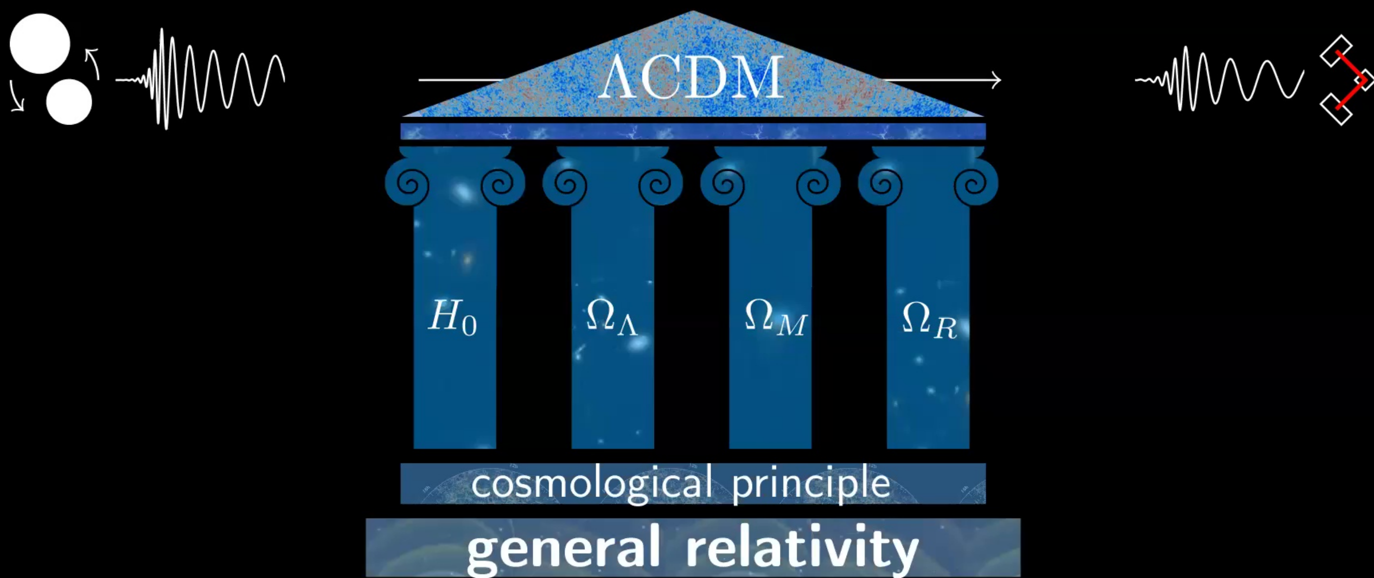
Date: October 07, 2021 - 1:00 PM

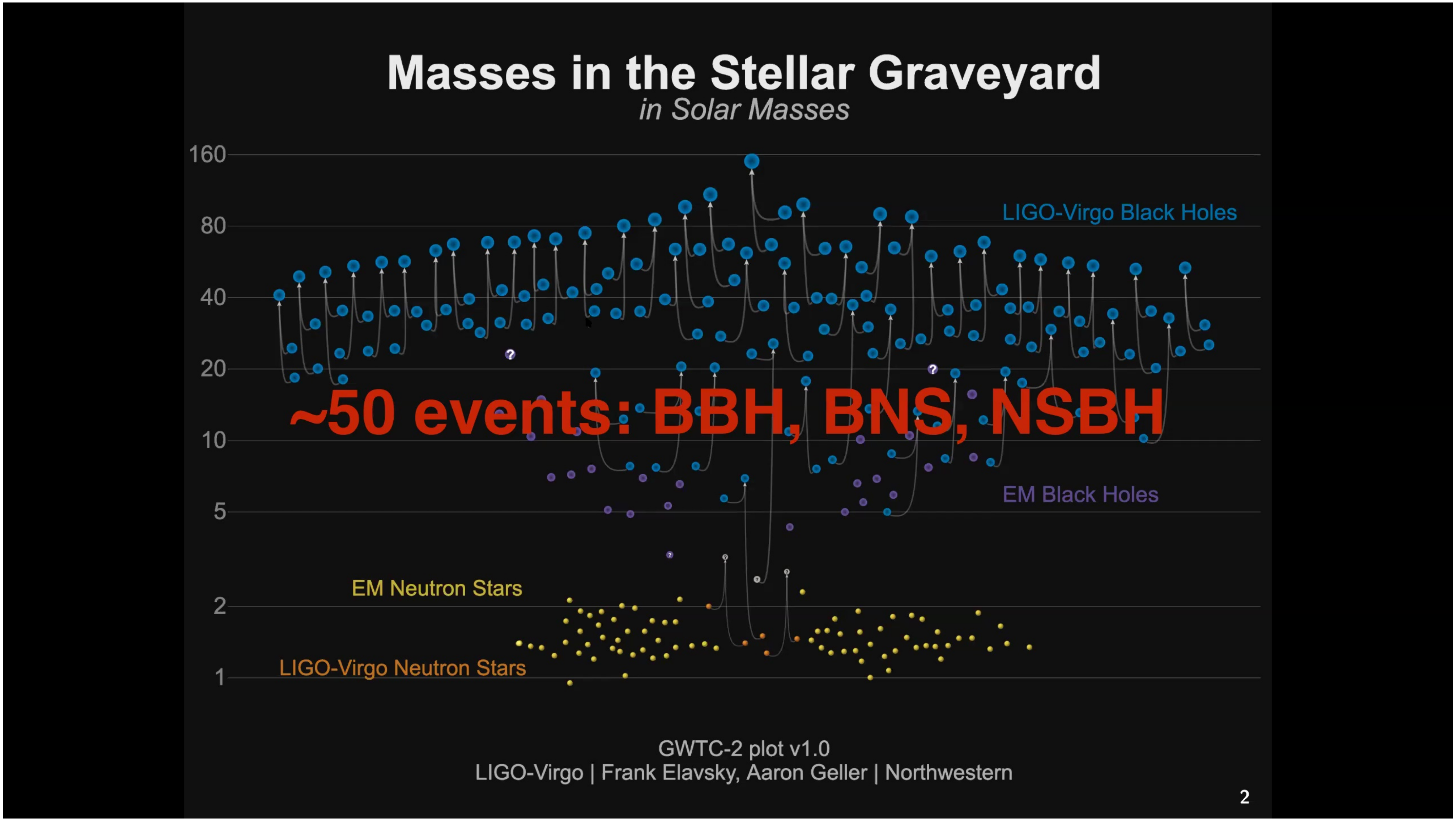
URL: https://pirsa.org/21100012

Abstract: Gravitational waves (GWs) are reshaping our understanding of the universe, and the more exciting discoveries are yet to come. In the next observing runs we will observe hundreds to thousands of events per year at increasingly higher redshifts, opening unique opportunities to test our cosmological model. In this talk I will focus on how this coming data could help probing gravity and dark energy, and what new information GW lensing will provide. In the first part of the talk I will describe how, without the need for electromagnetic counterparts or galaxy catalogs, the study of the binary black hole mass distribution can constrain LCDM and Einstein's gravity. Moreover, I will show that black hole mergers are also promising laboratories to bound GW interactions with other cosmological fields leading to waveform distortions and echoes. In the second part, I will discuss current searches for strongly lensed GWs and the importance of the GW phase measurement in this identification. Observing GW lensed events will allow us to probe the matter distribution in the universe and further constrain the laws of gravity. In both parts of the talk I will emphasize the important role of next generation ground- and space-based detectors.

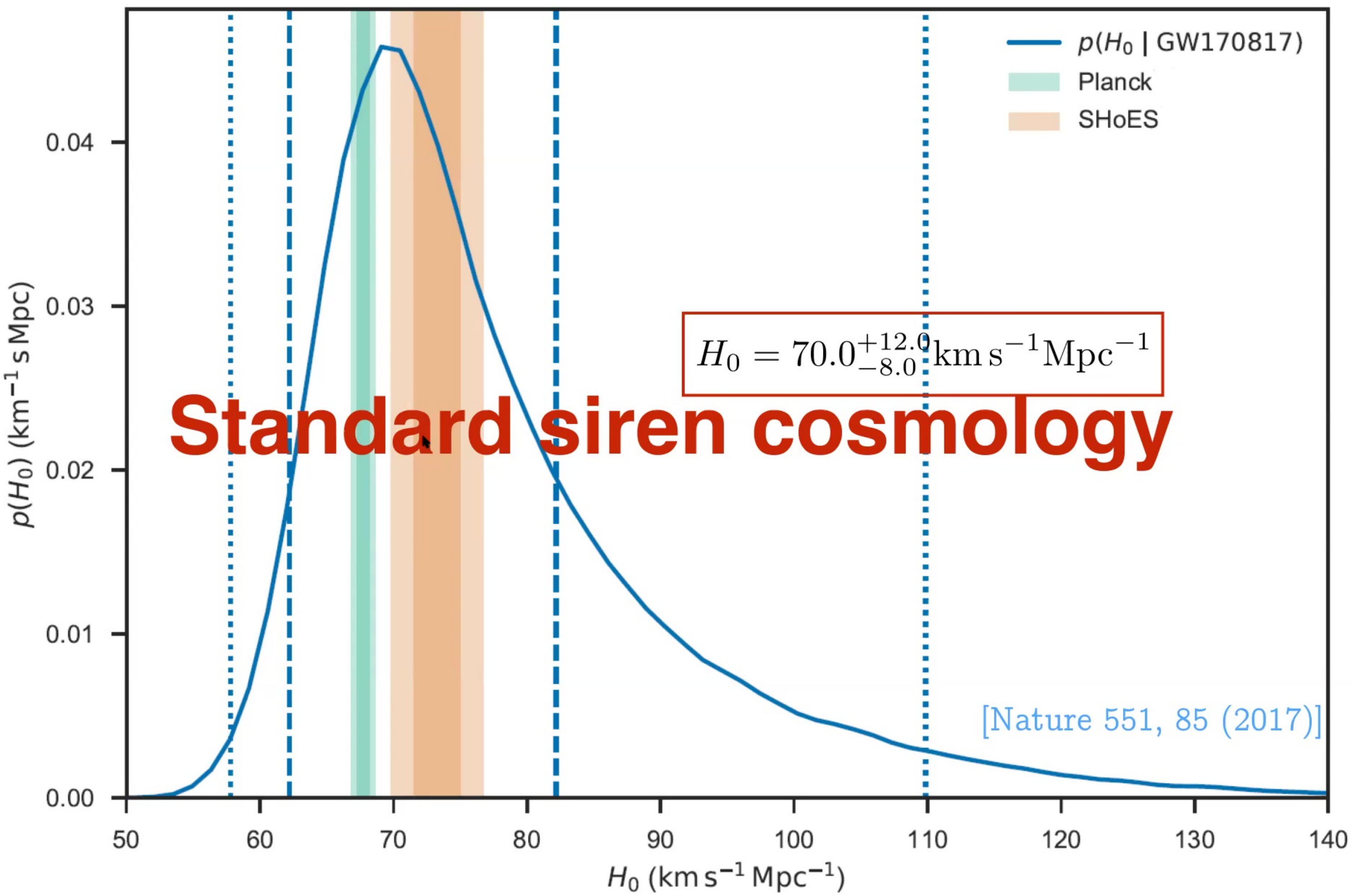
The next frontier in gravitational wave cosmology

Jose María Ezquiaga
NASA Einstein Fellow, UChicago, ezquiaga@uchicago.edu
ezquiaga.github.io

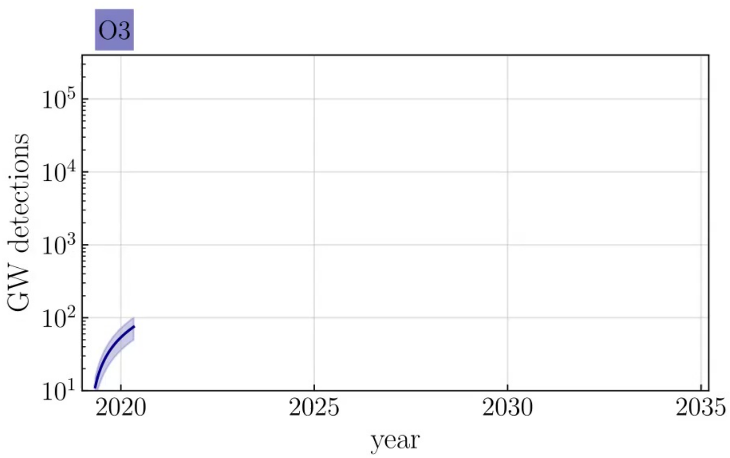


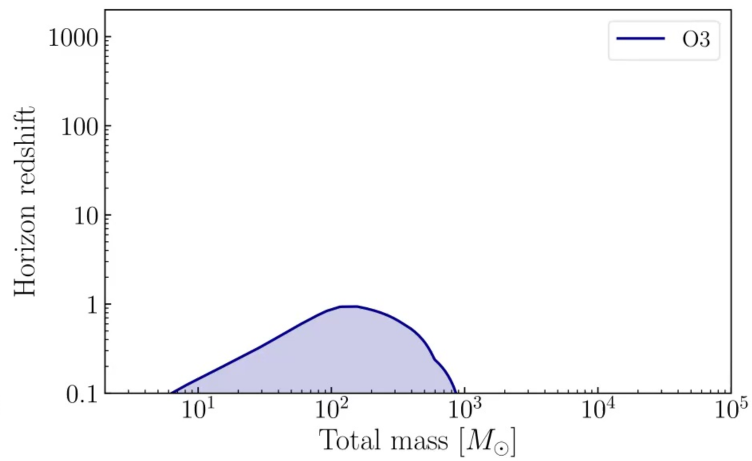

Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
~50 events: BBH, BNS, NSBH
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern
2

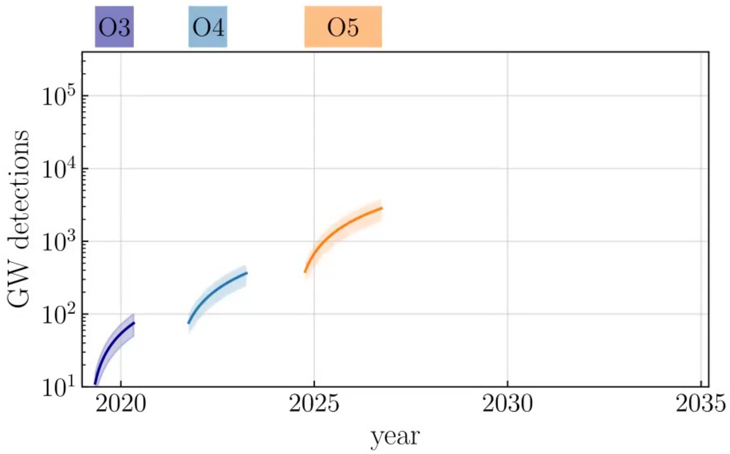
Standard siren cosmology

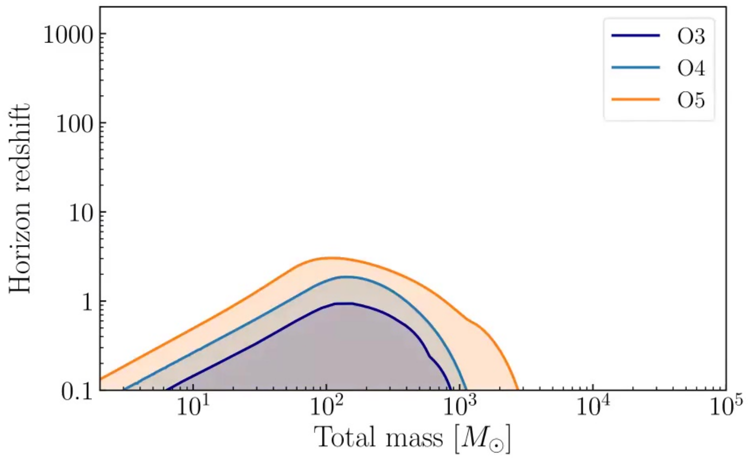


3

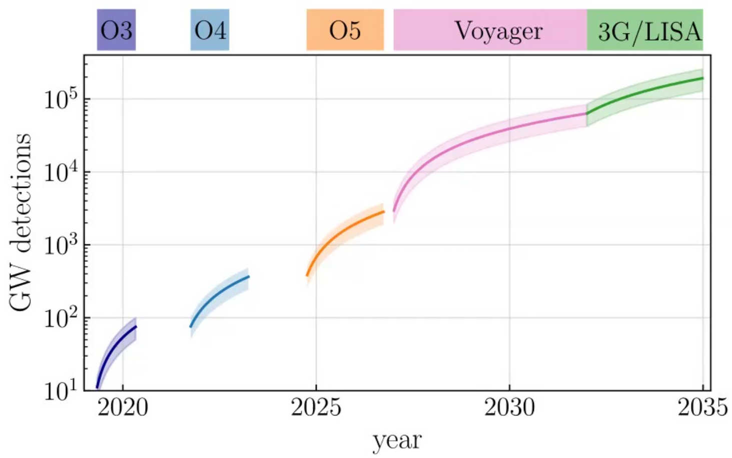

O3
GW detections
10^1
10^2
10^3
10^4
10^5
2020
2025
2030
2035
year

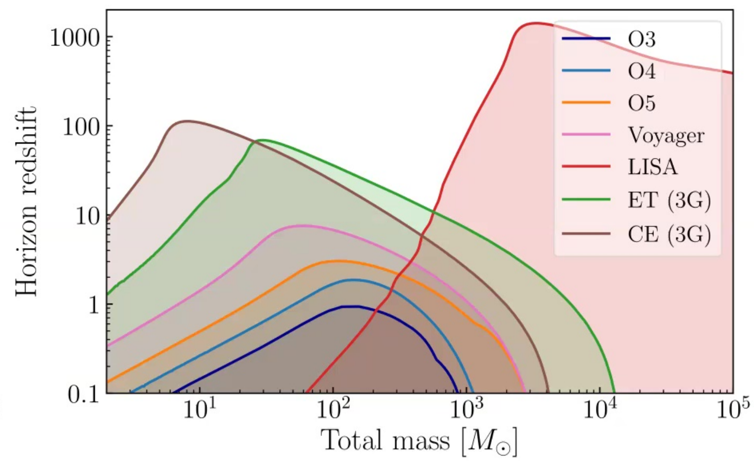

O3
Horizon redshift
0.1
1
10
100
1000
10^1
10^2
10^3
10^4
10^5
Total mass $[M_\odot]$


O3
O4
O5
GW detections
10^5
10^4
10^3
10^2
10^1
2020
2025
2030
2035
year

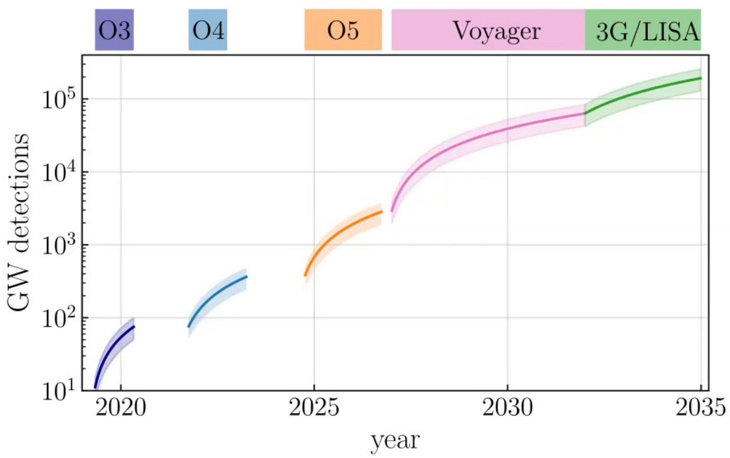

O3
O4
O5
Horizon redshift
1000
100
10
1
0.1
10^1
10^2
10^3
10^4
10^5
Total mass $[M_\odot]$

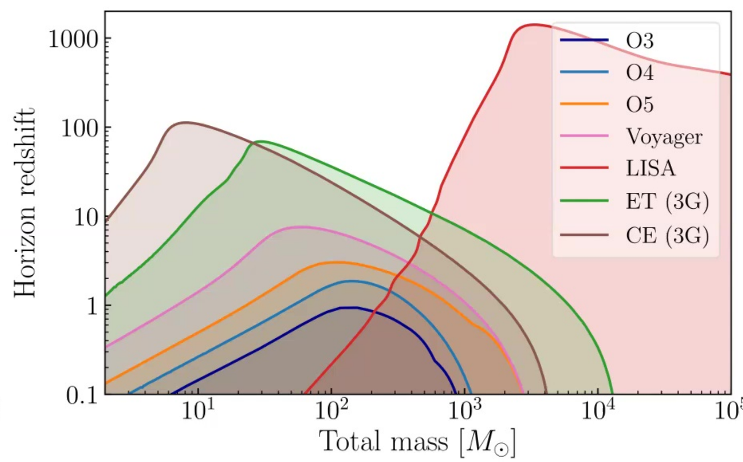
4


O3
O4
O5
Voyager
3G/LISA
GW detections
10^5
10^4
10^3
10^2
10^1
2020
2025
2030
2035
year


Horizon redshift
1000
100
10
1
0.1
10^1
10^2
10^3
10^4
10^5
Total mass $[M_\odot]$
O3
O4
O5
Voyager
LISA
ET (3G)
CE (3G)

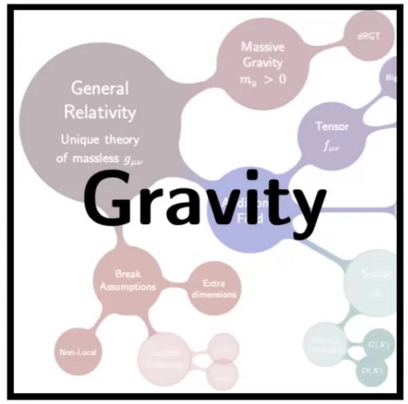
4





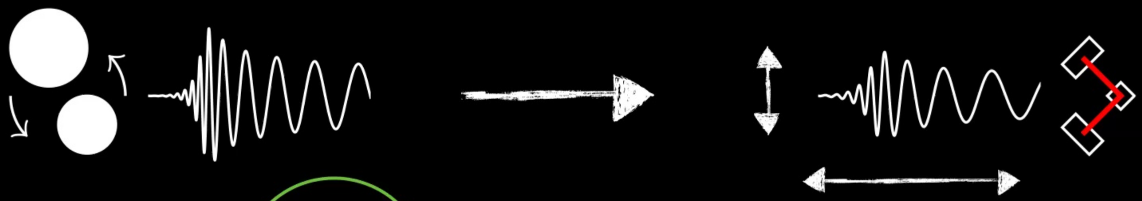
+ higher SNR, polarization


Cosmology


Gravity
General Relativity
Unique theory of massless $g_{\mu\nu}$
Massive Gravity $m_g > 0$
dRGT
Tensor $f_{\mu\nu}$
Break Assumptions
Extra dimensions
Non-Local


Lensing

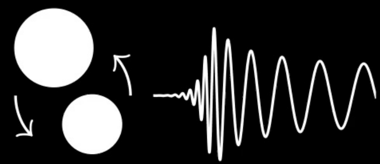
From GWs to astrophysics and cosmology

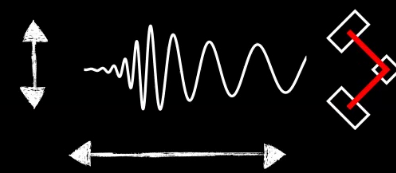


$$\{d_L^{\rm gw}(z), m_z = (1+z)m\}$$

6

From GWs to astrophysics and cosmology





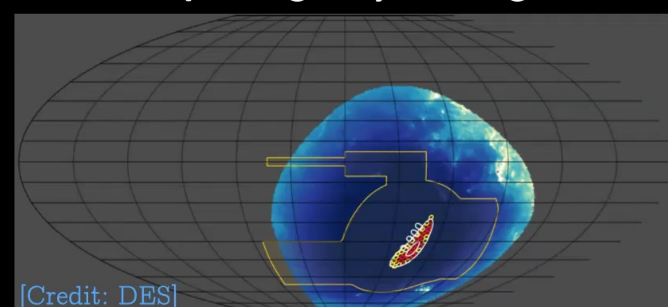
$d_L^{\mathrm{gw}}(z)$

Bright sirens

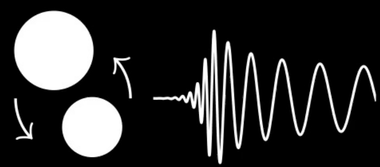
- Redshift from EM counterpart
- E.g. GW170817
- Need **neutron stars**!
- Bright counterpart at high-z?

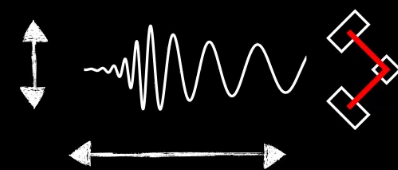
Dark sirens

- Statistically infer z from galaxies in localization volume
- E.g. GW170814
- Need good localization and **complete** galaxy catalogs!

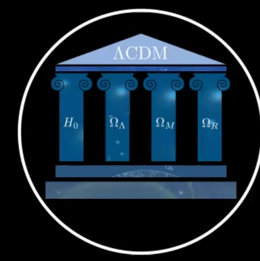


From GWs to astrophysics and cosmology

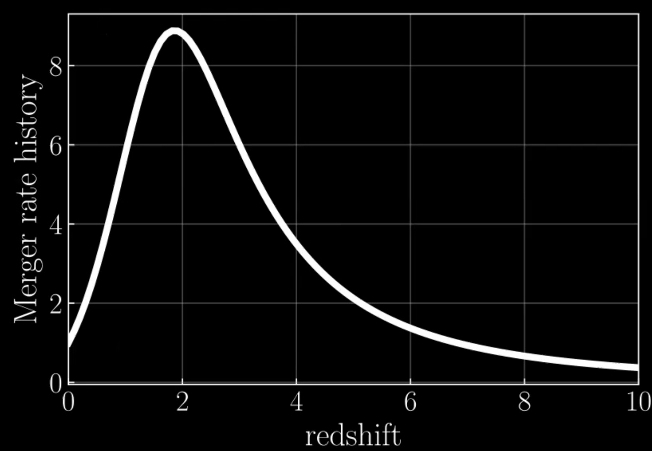


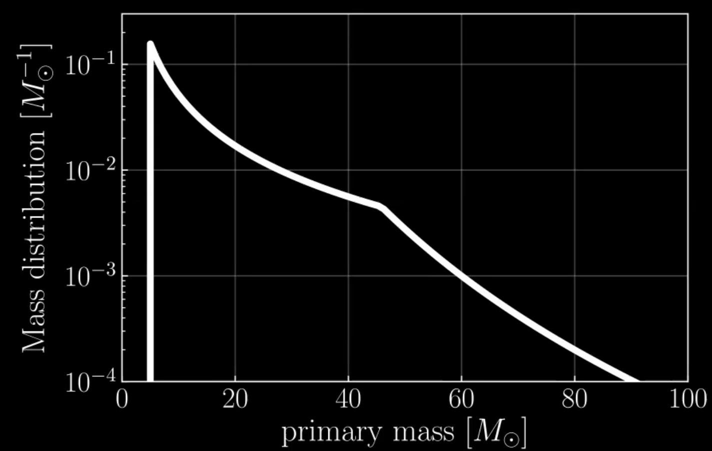


$$\{z, m_1, m_2\}$$

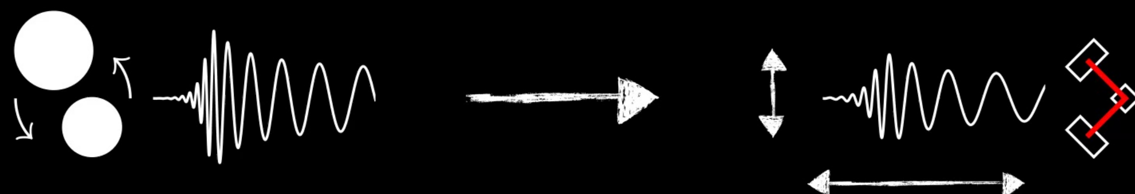


[see GWTC-2 astro pop]



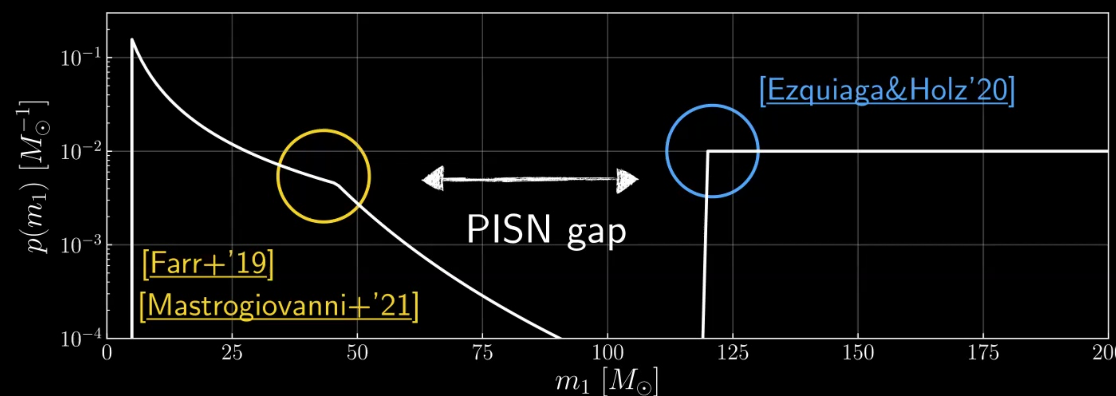


From GWs to astrophysics and cosmology



$$\{d_L^{\rm gw}(z), m_z = (1+z)m\}$$

Features in the source mass distribution are key!

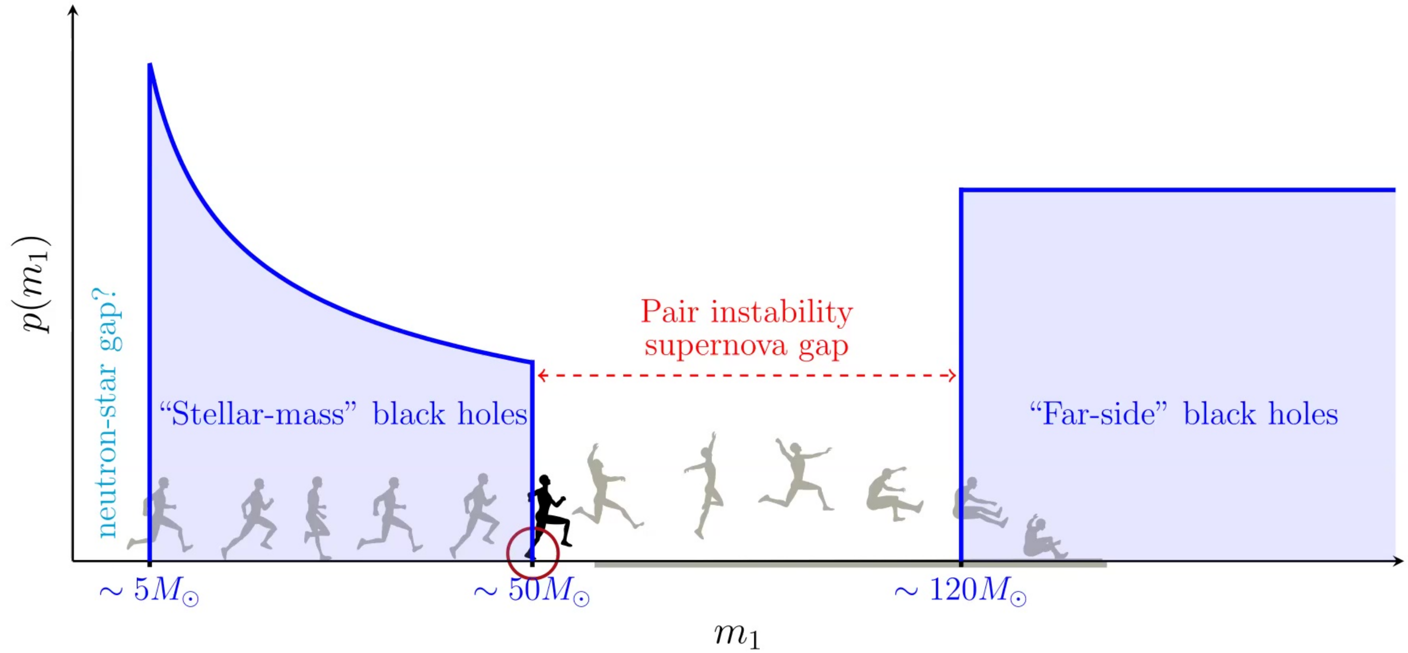


*PISN = Pair Instability SuperNova

9

Evidence for PISN gap?

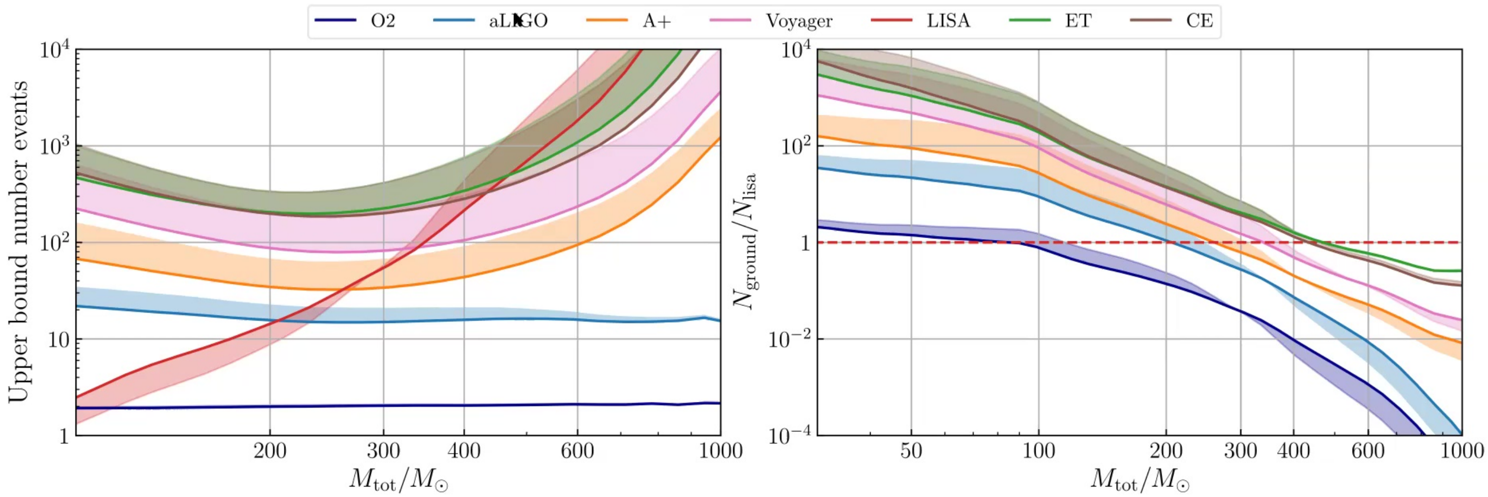
- LIGO-Virgo observations GWTC-2: only $2^{+3.4}_{-1.7}\%$ above $45 M_\odot$
- Pair instability supernova (PISN) gap expected range $\sim 50 M_\odot - 120 M_\odot$



Ezquiaga & Holz; *Jumping the gap* (ApJL, arXiv 2006.02211)

Detection rates *far-side* binaries

- With the present upper bound on the merger rate we can determine how many events ground- and space-based interferometers could detect

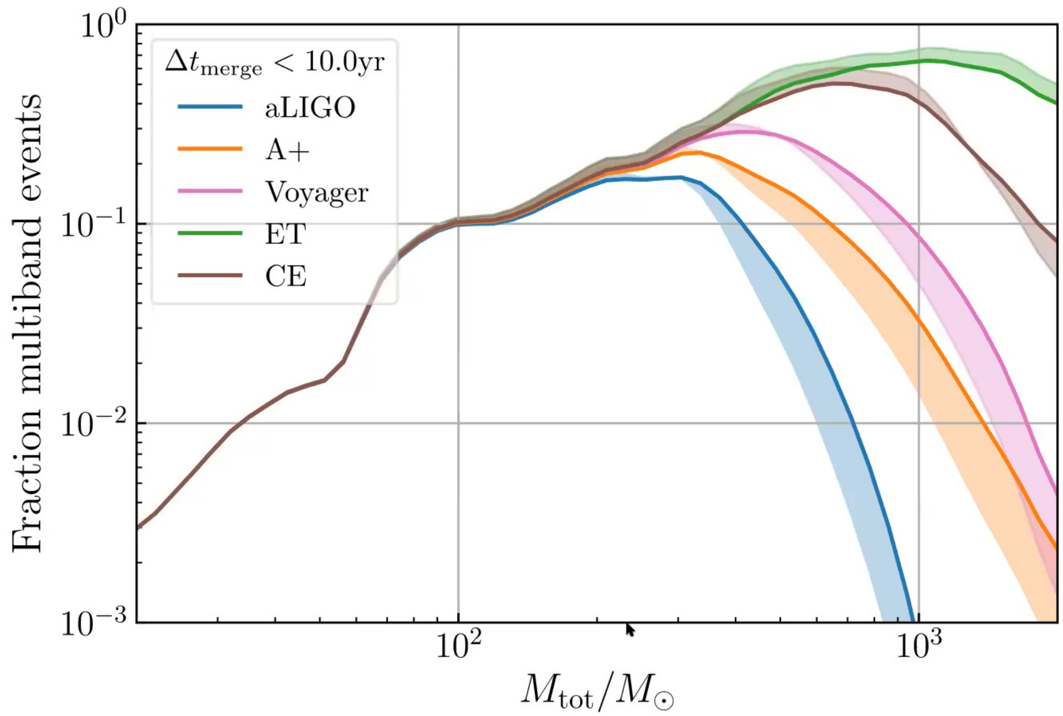


Comparing the number of events that LISA and ground-based detectors observe constrains the redshift evolution of the merger rate

Ezquiaga & Holz; *Jumping the gap* (ApJL, arXiv 2006.02211)

Multi-band events

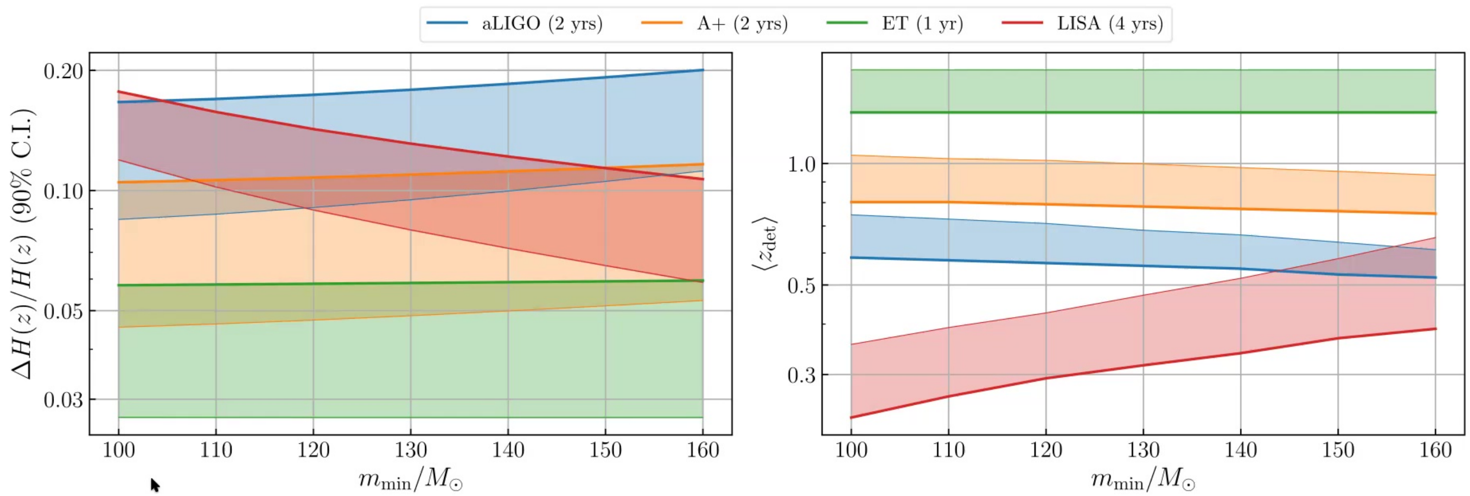
Far-side binaries could dominate the fraction of multi-band events



Ezquiaga & Holz; *Jumping the gap* (ApJL, arXiv 2006.02211)

Standardizable GW sirens

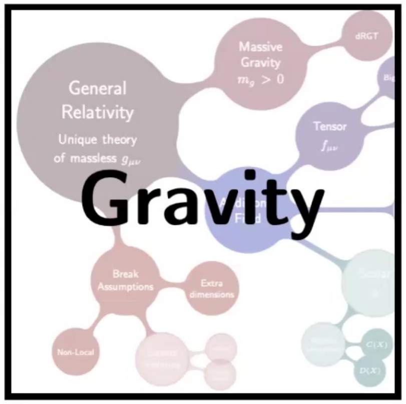
- Constrain the cosmic expansion at redshifts of ~ 0.4, 0.8 and 1.5 with LISA, aLIGO and ET respectively



Far-side binaries could allow LISA to constrain the local expansion rate at $\sim 10\%$ C.I. and cross-calibrate with LIGO BNS.

Ezquiaga & Holz; *Jumping the gap* (ApJL, arXiv 2006.02211)


Cosmology


Gravity
General Relativity
Unique theory of massless $g_{\mu\nu}$
Massive Gravity
$m_g > 0$
dRGT
Tensor
$f_{\mu\nu}$
Break Assumptions
Extra dimensions
Non-Local


Lensing

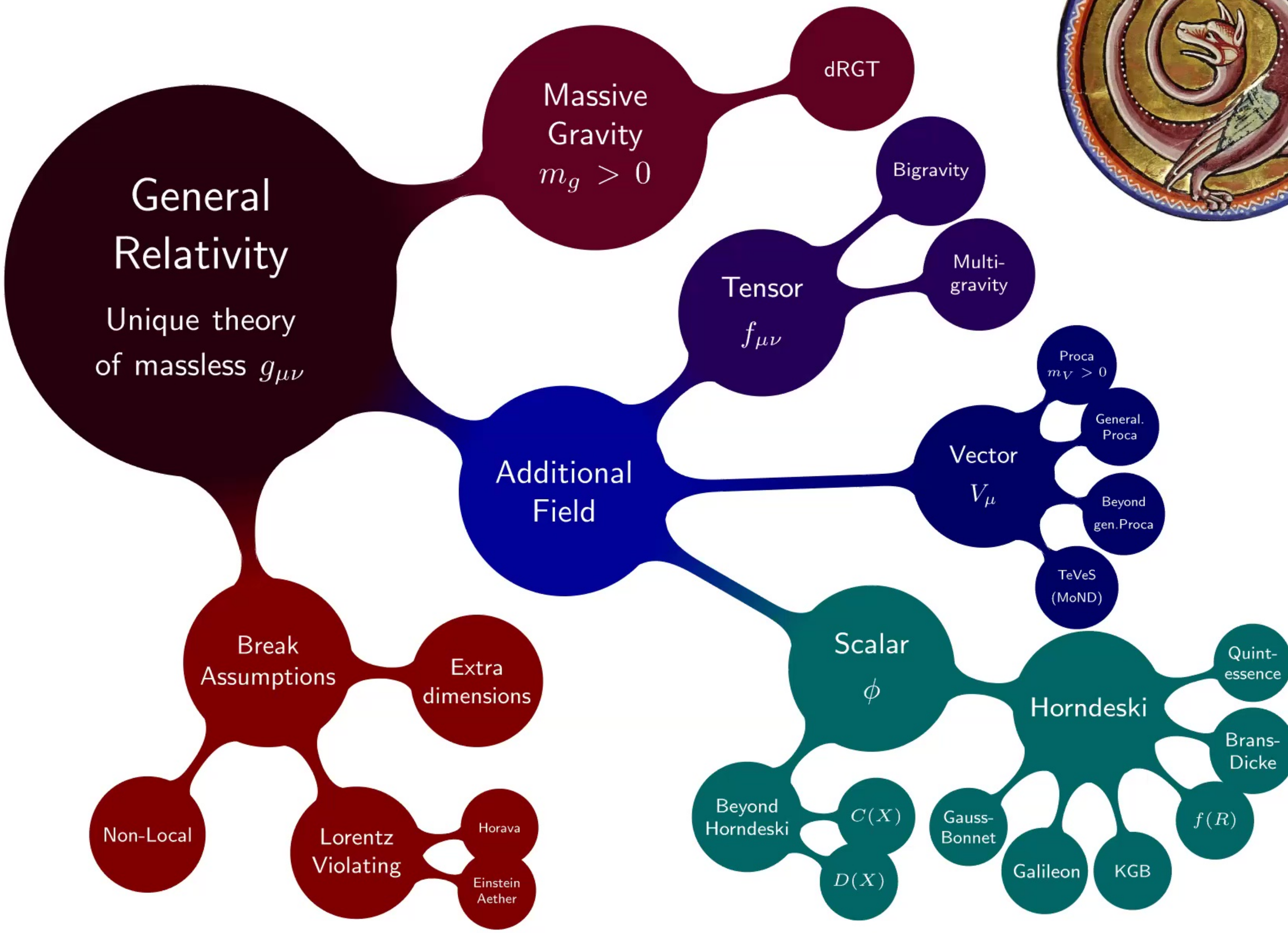
General
Relativity

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

Basic GW properties

- Propagate speed of light
- Amplitude scales with inverse of distance
- No dispersion
- Two tensor polarizations propagating equally

Modified gravity roadmap



GW luminosity distance

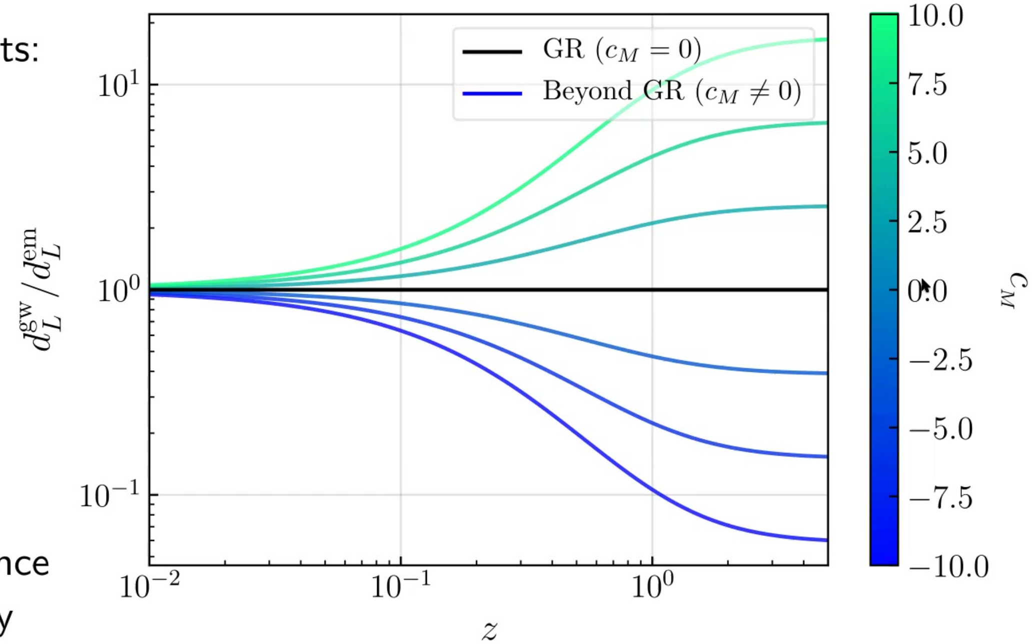
General relativity predicts:

$$d_L^{\mathrm{gw}} = d_L^{\mathrm{em}}$$

GW luminosity distance

General relativity predicts:

$$d_L^{\rm gw} = d_L^{\rm em}$$



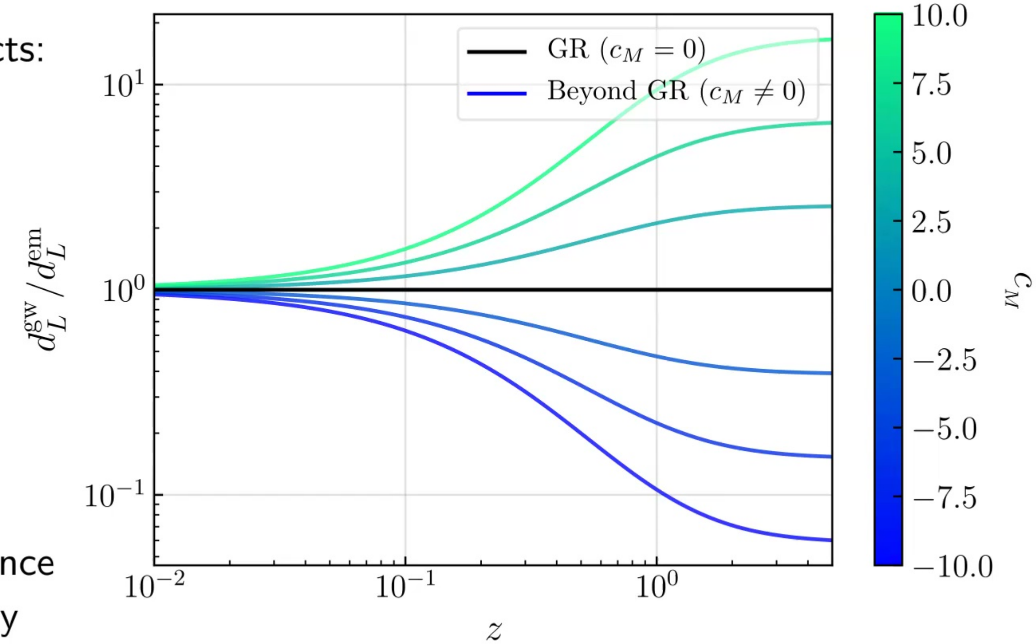
Modified luminosity distance triggered by dark energy

$$\frac{d_L^{\rm gw}}{d_L^{\rm em}} = \exp\left[\frac{c_M}{2}\int_0^z \frac{\Omega_{DE}(z')}{(1+z')\Omega_{DE}(0)}{\rm d}z'\right]$$

GW luminosity distance

General relativity predicts:

$$d_L^{\rm gw} = d_L^{\rm em}$$



Modified luminosity distance triggered by dark energy

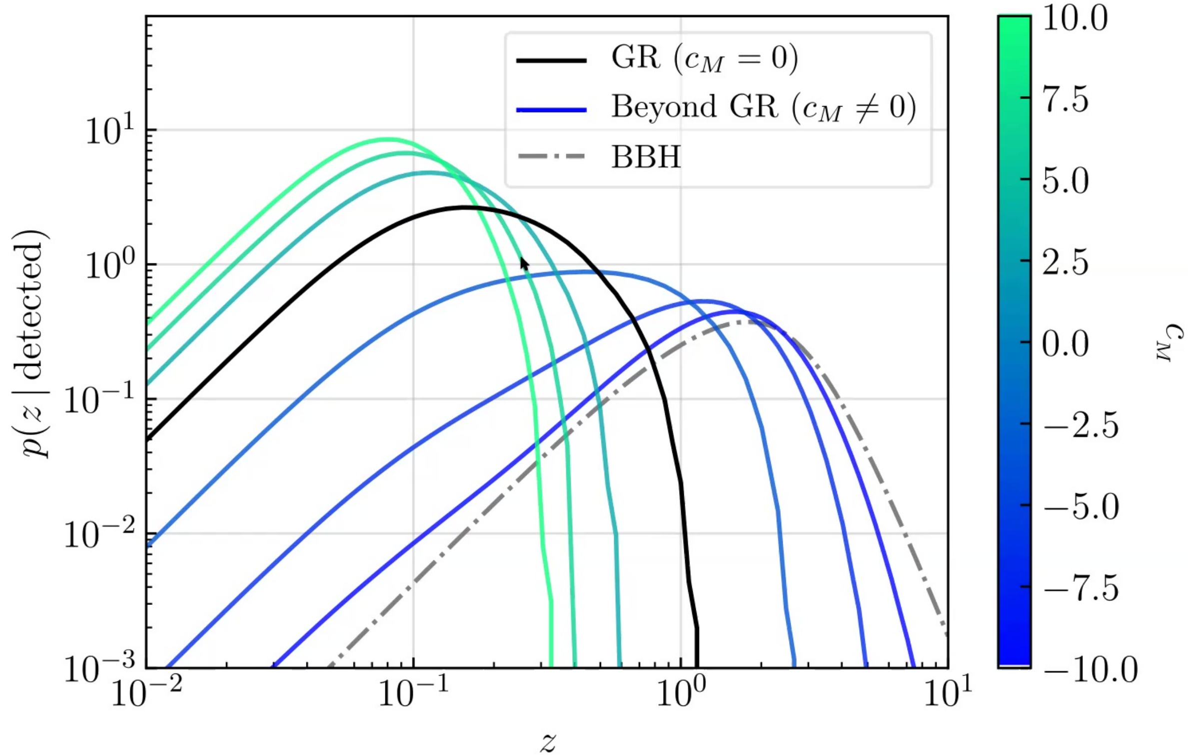
$$\frac{d_L^{\rm gw}}{d_L^{\rm em}} = \exp\left[\frac{c_M}{2}\int_0^z \frac{\Omega_{DE}(z')}{(1+z')\Omega_{DE}(0)}{\rm d}z'\right]$$

*Bounded by GW170817

$$c_M = -9^{+21}_{-28}$$

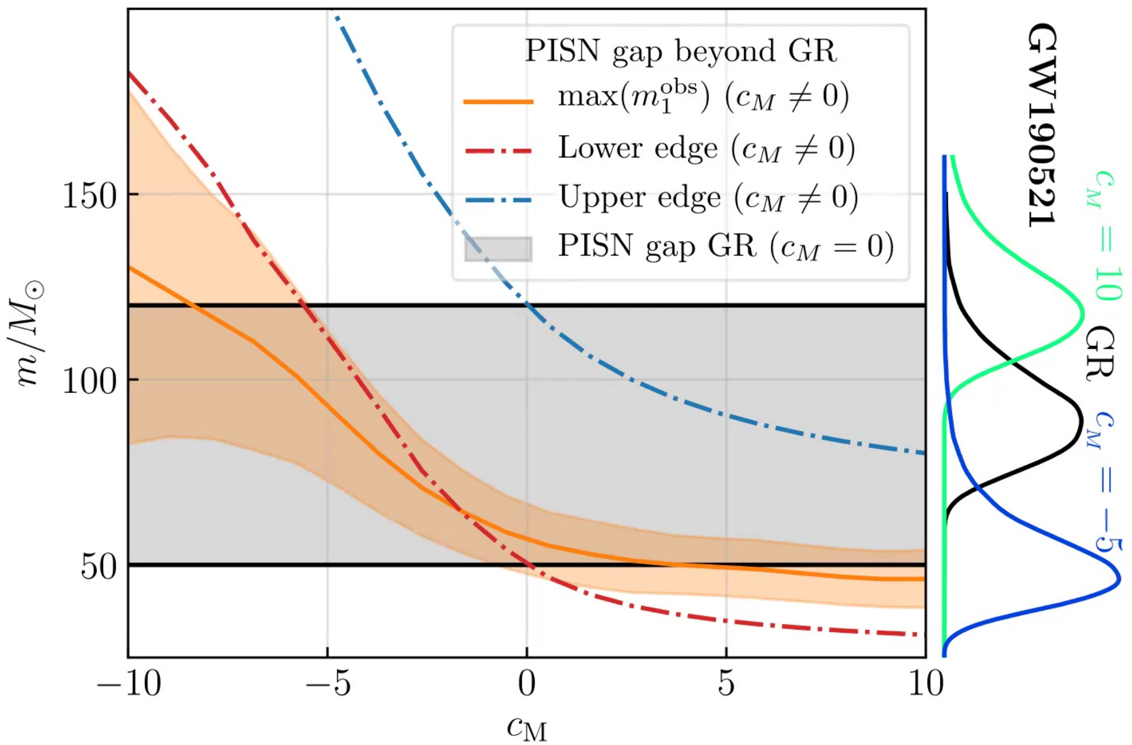
[Lagos+'19]

How far can we hear BBHs?



Ezquiaga; *Hearing gravity form the cosmos* (PLB, arXiv 2104.05139)

How is the PISN gap affected?



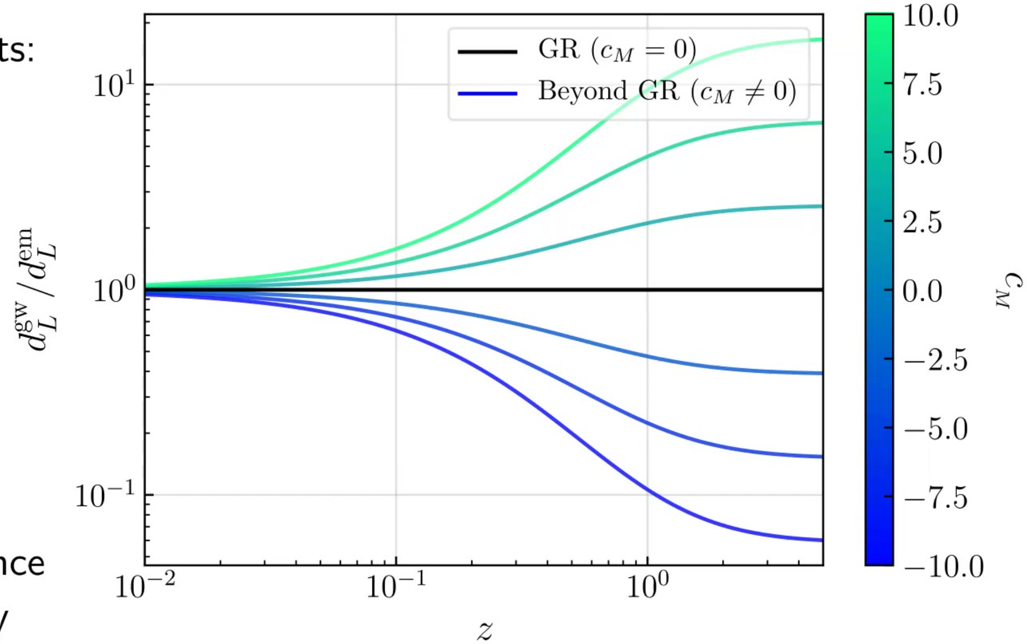
Ezquiaga; *Hearing gravity form the cosmos* (PLB, arXiv 2104.05139)

21

GW luminosity distance

General relativity predicts:

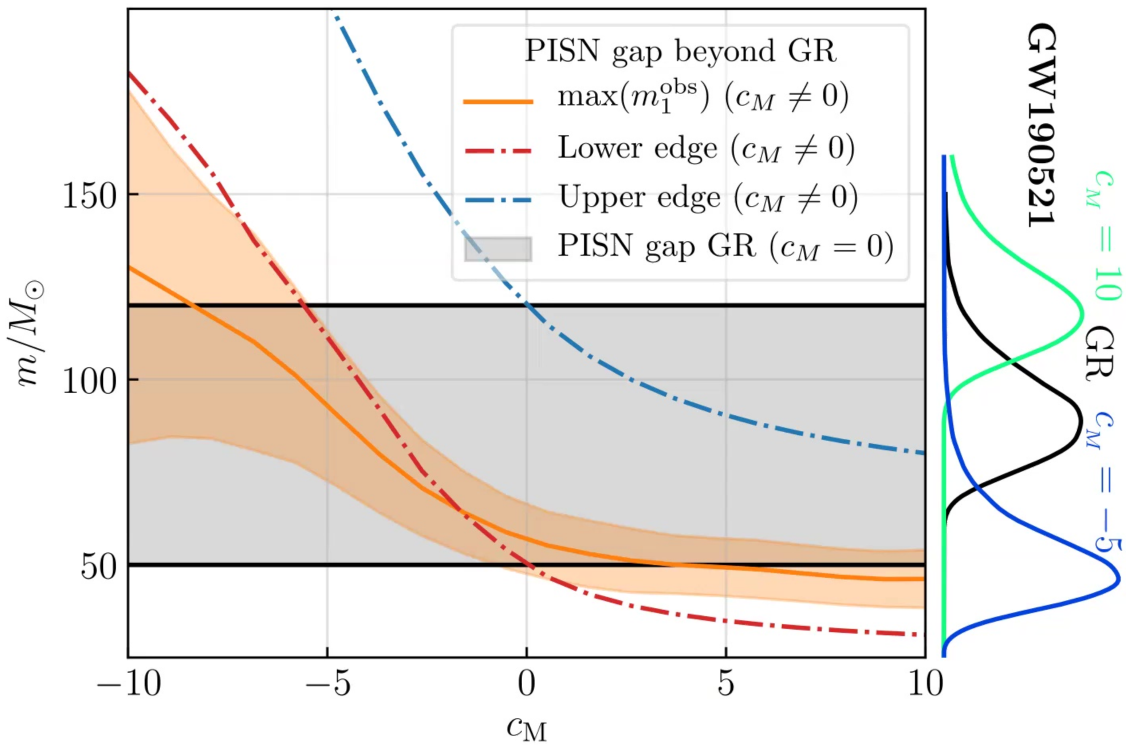
$$d_L^{\rm gw} = d_L^{\rm em}$$



Modified luminosity distance triggered by dark energy

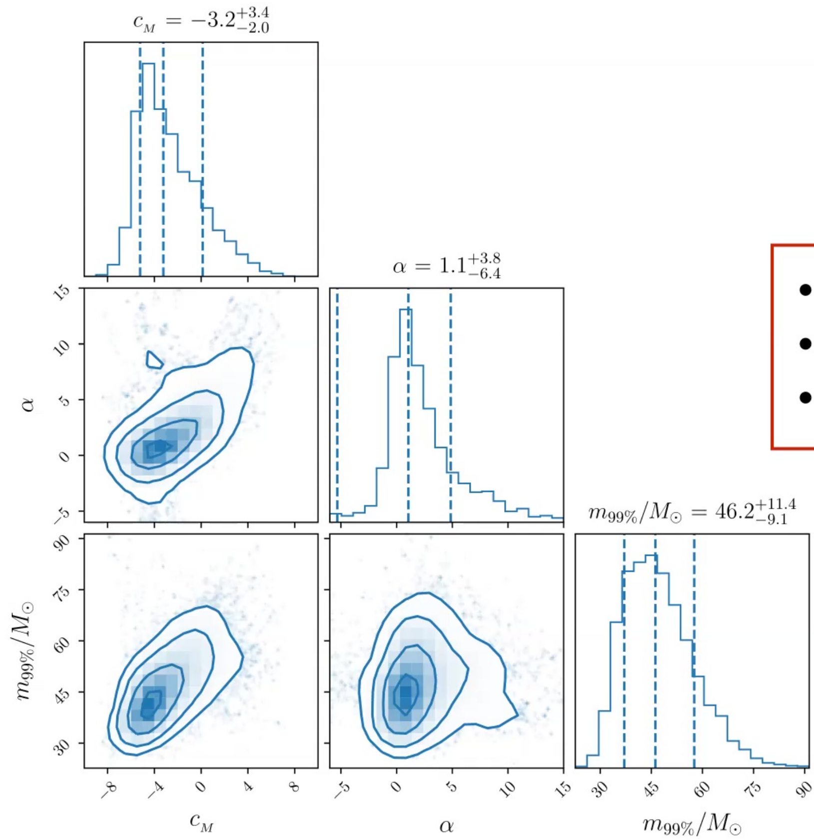
$$\frac{d_L^{\rm gw}}{d_L^{\rm em}} = \exp\left[\frac{c_M}{2}\int_0^z \frac{\Omega_{DE}(z')}{(1+z')\Omega_{DE}(0)} {\rm d}z'\right]$$

How is the PISN gap affected?



Ezquiaga; *Hearing gravity form the cosmos* (PLB, arXiv 2104.05139)

Results from GWTC-2



$$c_M = -3.2^{+3.4}_{-2.0}$$

- More constraining than GW170817
- Shifts $m_{99\%}$ to lower values
- GW data only!

Ezquiaga; *Hearing gravity form the cosmos* (PLB, arXiv 2104.05139)

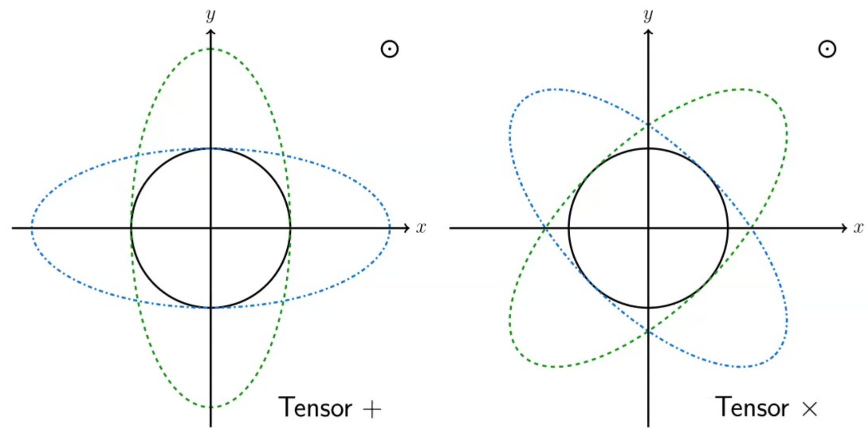
Dispersion and polarization

General relativity predicts:

$$\omega(k) = c \cdot k$$

$$h_+ , \quad h_\times$$

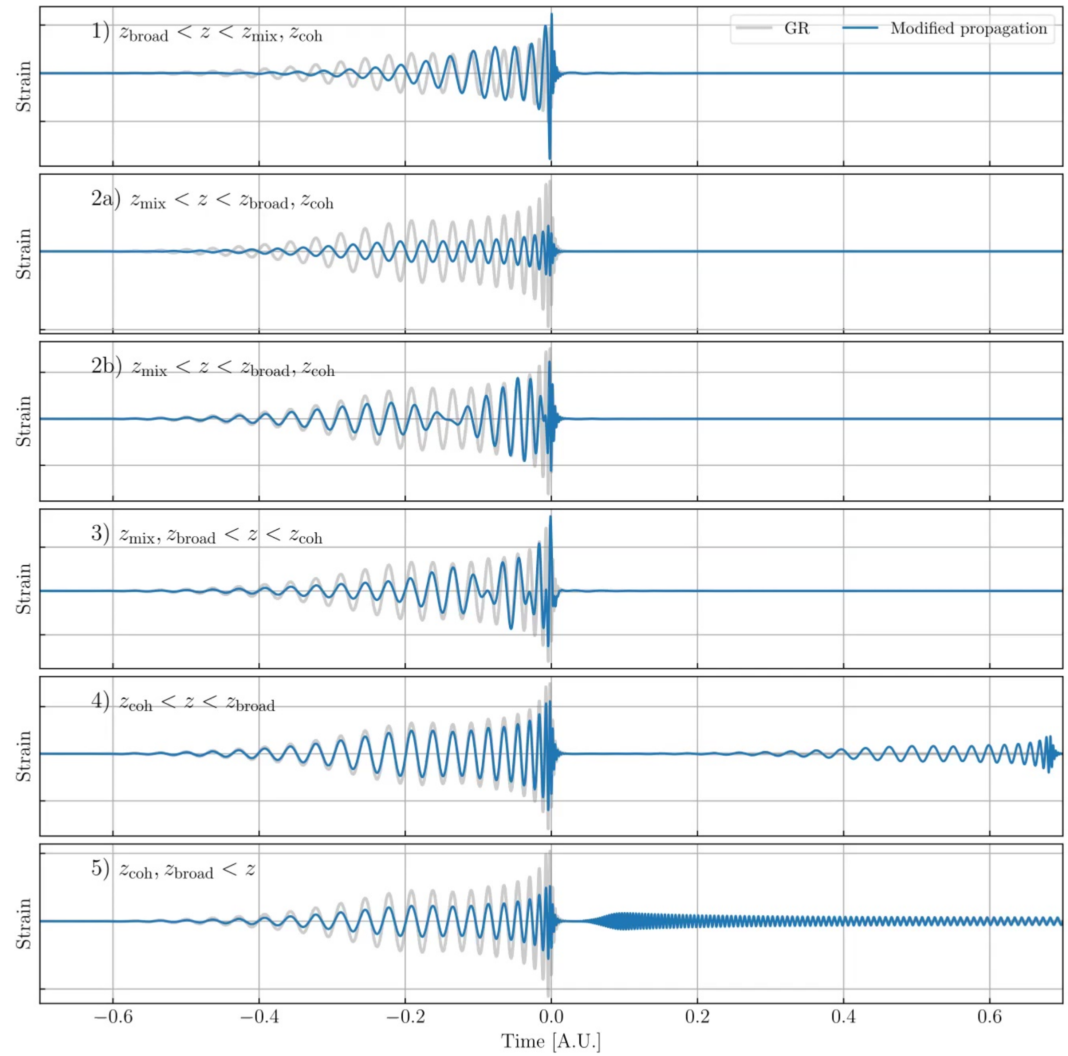
Gravitational Wave Polarizations



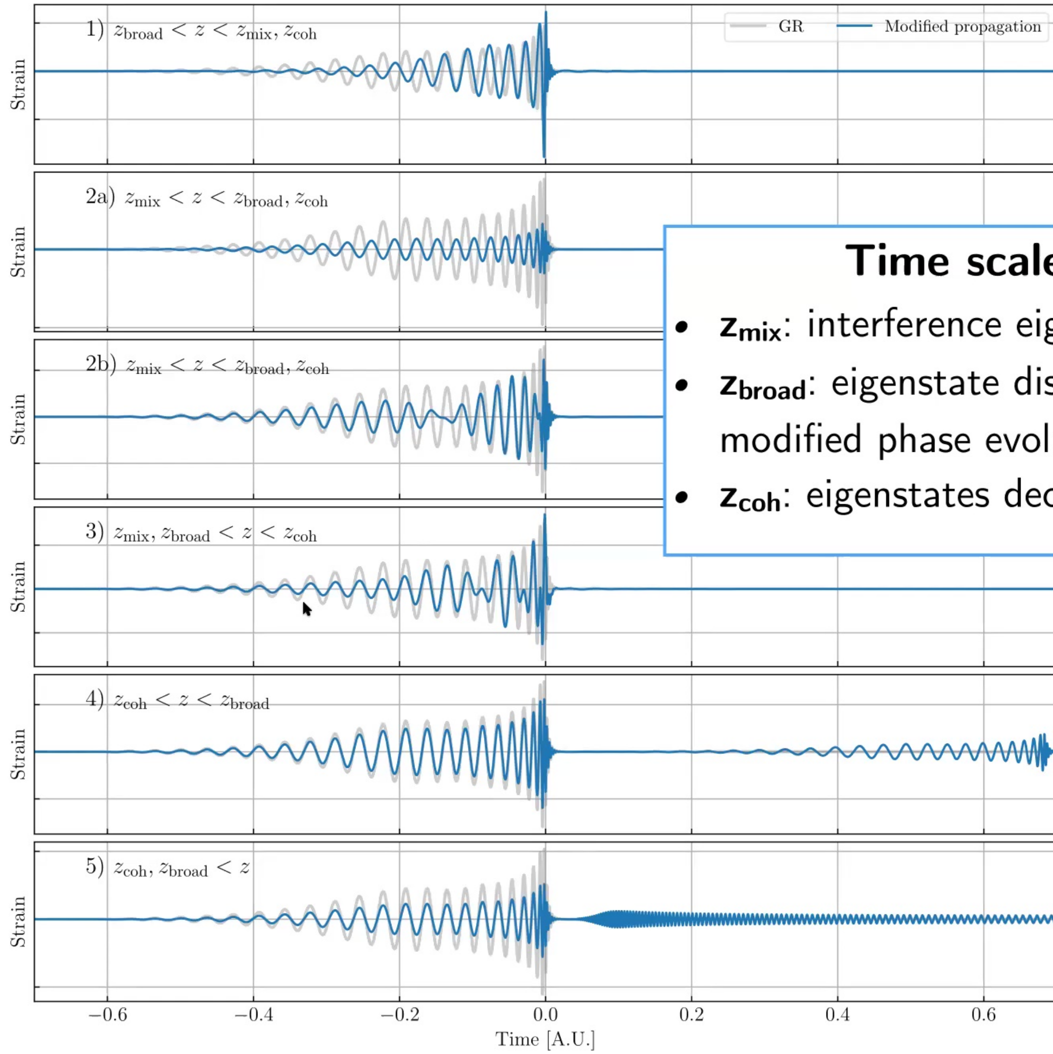
Mixing cosmological tensor fields (similar to neutrino oscillations)

$$\left[\hat{I}\left(\frac{d^2}{d\eta^2} + (ck)^2\right) + \begin{pmatrix} m_h^2 & m_{hs}^2 \\ m_{hs}^2 & m_s^2 \end{pmatrix}\right]\begin{pmatrix} h_{+,\times} \\ s_{+,\times} \end{pmatrix} = 0$$

23



Ezquiaga, Hu, Lagos and Lin; *GW propagation beyond GR* (arXiv 2108.10872)

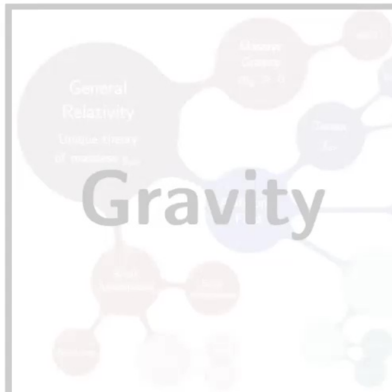


Time scales

- $\mathbf{z_{mix}}$: interference eigenstates
- $\mathbf{z_{broad}}$: eigenstate distorted modified phase evolution
- $\mathbf{z_{coh}}$: eigenstates decohere

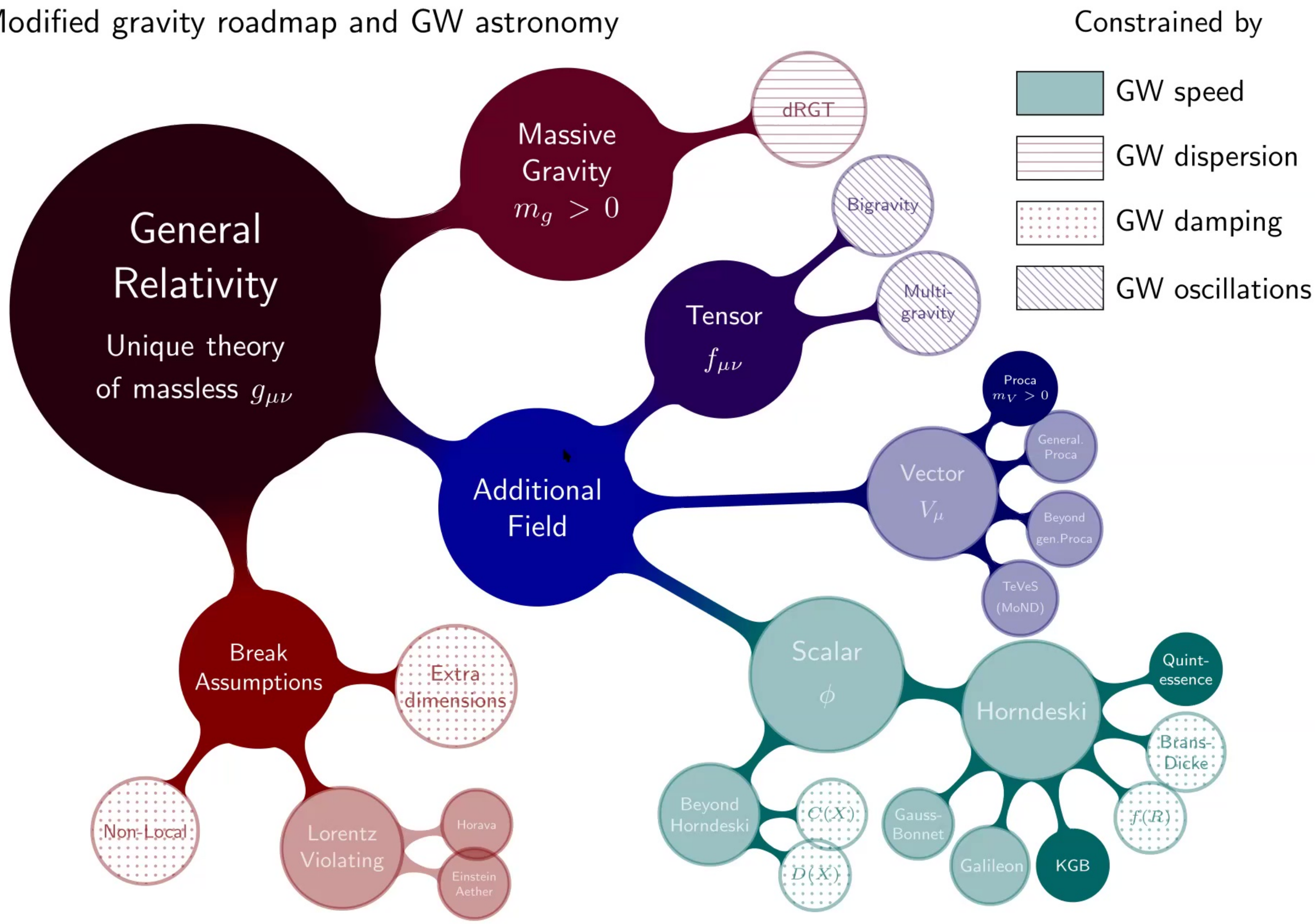
Ezquiaga, Hu, Lagos and Lin; *GW propagation beyond GR* (arXiv 2108.10872)


Cosmology


General Relativity
Gravity


Lensing

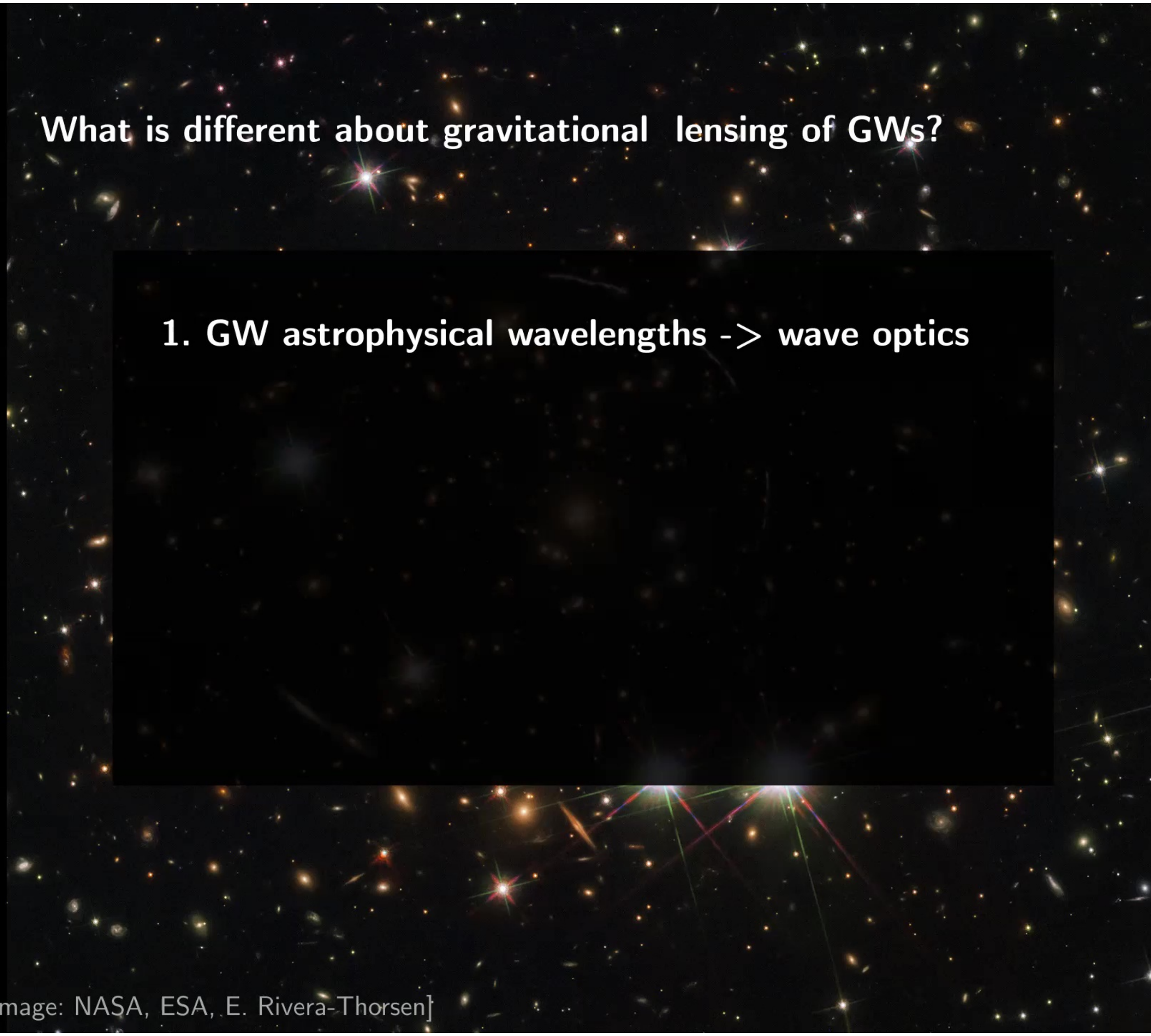
Modified gravity roadmap and GW astronomy



Ezquiaga & Zumalacárregui; *DE in light multi-messenger GW astronomy* (review, arXiv 1807.09241)

What is different about gravitational lensing of GWs?

1. GW astrophysical wavelengths -> wave optics



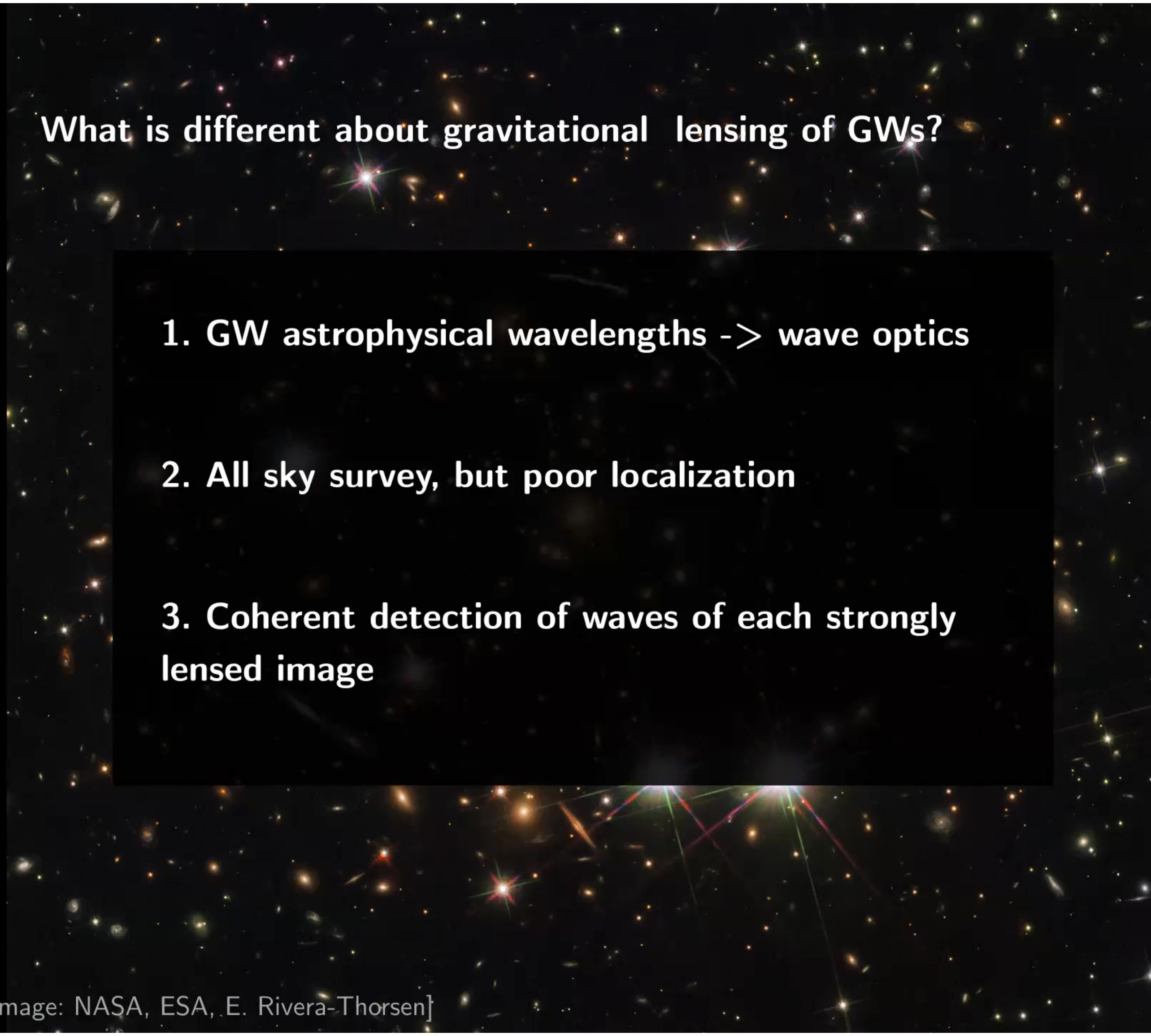
[credit image: NASA, ESA, E. Rivera-Thorsen]

What is different about gravitational lensing of GWs?

1. GW astrophysical wavelengths -> wave optics

2. All sky survey, but poor localization

3. Coherent detection of waves of each strongly lensed image



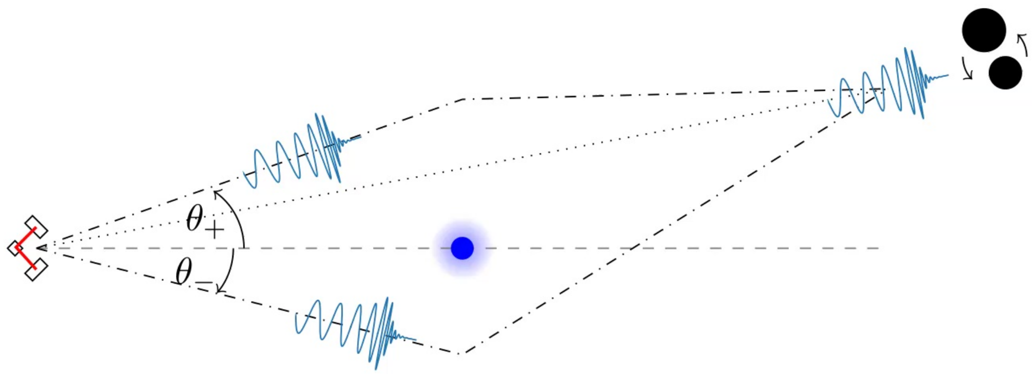
[credit image: NASA, ESA, E. Rivera-Thorsen]

[see also Schneider et al.'92, Dai&Venumadhav'17]

Lensing phase shifts

- Strong lensing amplification factor:

$$F \approx \sum_j |\mu(\vec{\theta}_j)|^{1/2} \exp\left(i\omega t(\vec{\theta}_j) - i\pi \text{sign}(\omega) n_j\right)$$



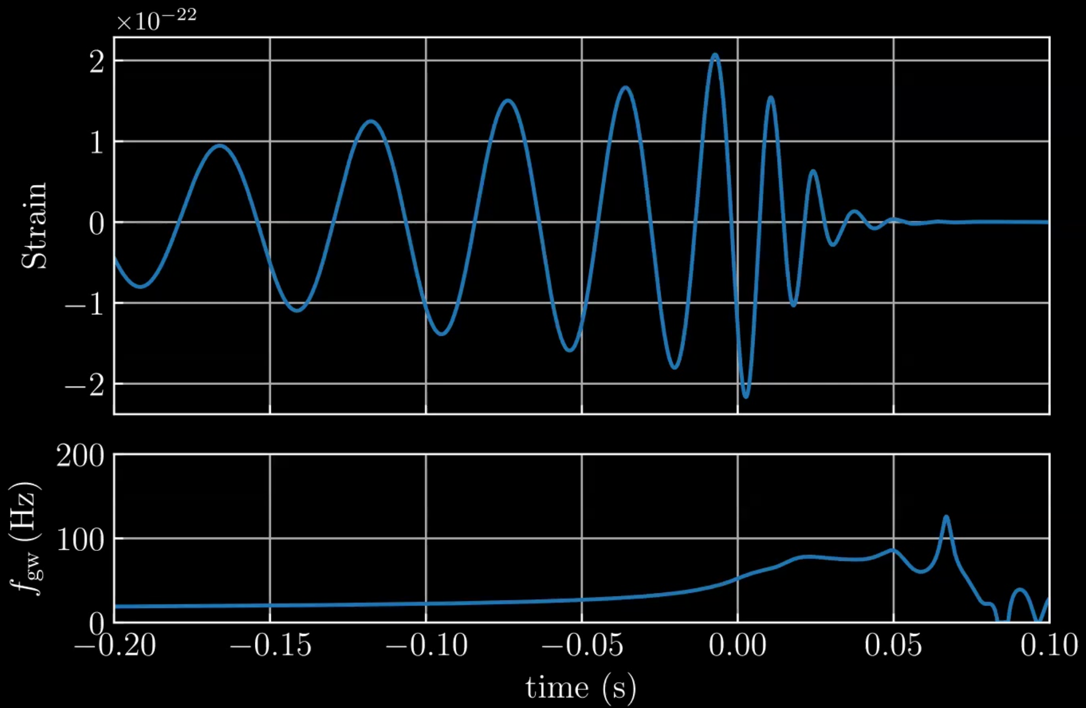
Amplitude/distance
Time delay
Phase shift

Type I: $n_j = 0$
Type II: $n_j = 1/2$
Type III: $n_j = 1$

GW detectors register waves coherently, being directly sensitive to the phase!

Ezquiaga *et al.*; *Phase effects from strong lensing of GWs* (PRD, arXiv 2008.12814)

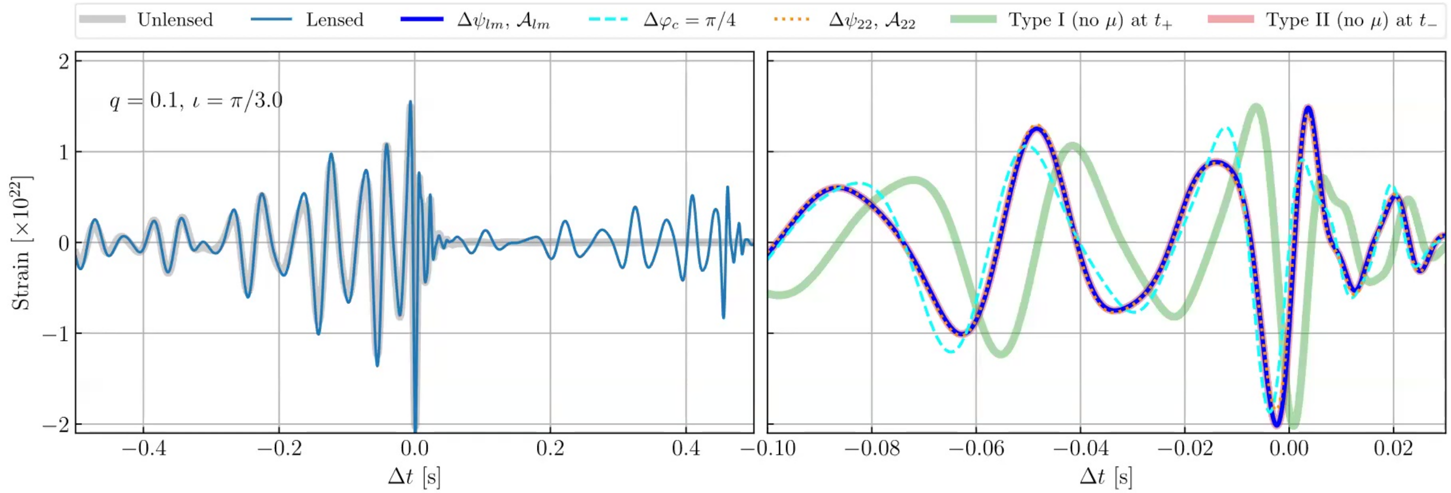
$$h = \sum_{l,m} \mathcal{A}_{lm} \cos\left[m(\Omega t + \varphi_c) - 2\chi_{lm}\right]$$



29

Asymmetric masses

- Lensed higher modes introduce distortions w.r.t unlensed GR wave-form

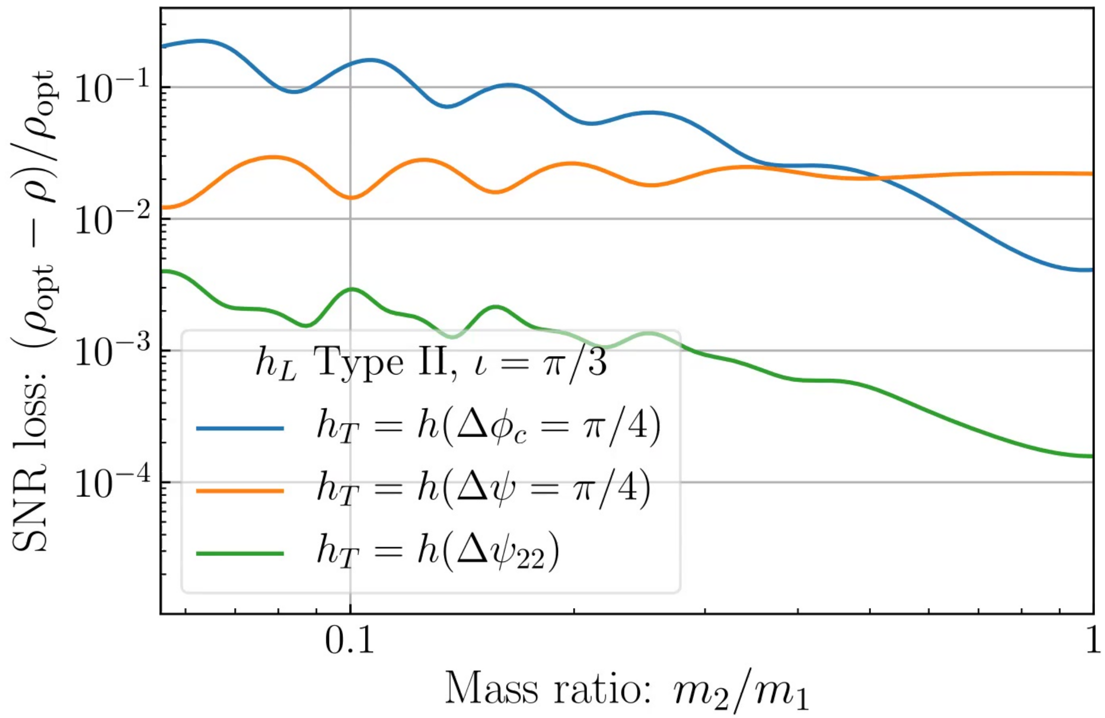


*Partial degeneracy with coalescence phase and orientation angle

*Similar effects happen for precessing and eccentric binaries

Ezquiaga *et al.*; *Phase effects from strong lensing of GWs* (PRD, arXiv 2008.12814)

Effect on the SNR



Ezquiaga *et al.*; *Phase effects from strong lensing of GWs* (PRD, arXiv 2008.12814)

Typical lensed compact binaries will not be missed

32

No evidence of lensing so far...

Search for lensing signatures in the gravitational-wave observations from the first half of LIGO-Virgo's third observing run

THE LIGO SCIENTIFIC COLLABORATION AND THE VIRGO COLLABORATION

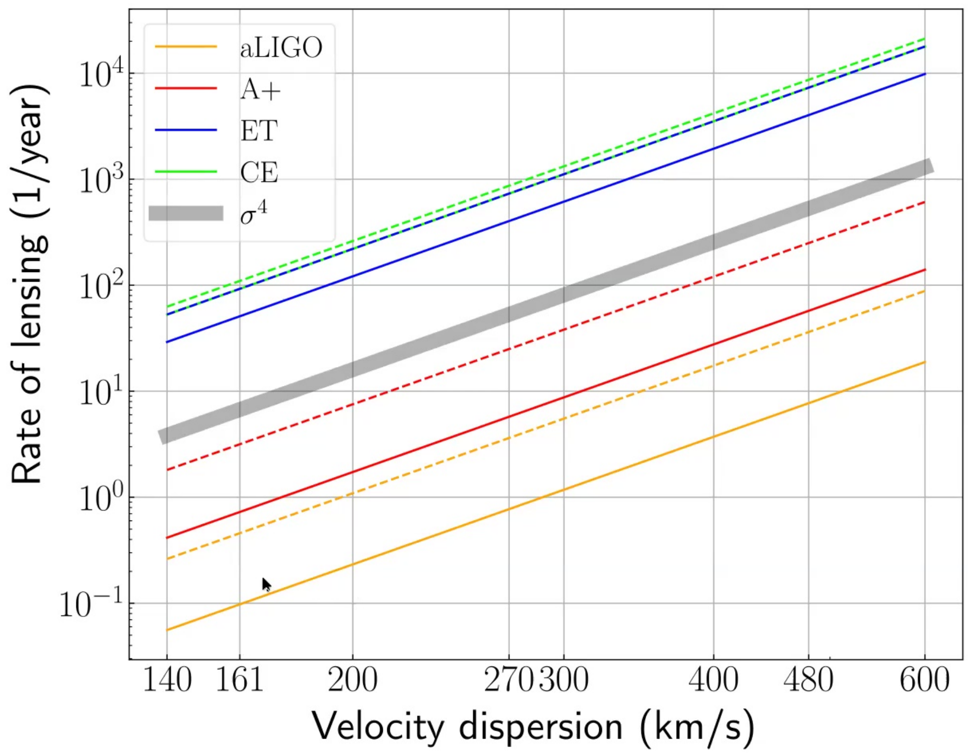
(Dated: 13 May 2021)

ABSTRACT

We search for signatures of gravitational lensing in the gravitational-wave signals from compact binary coalescences detected by Advanced LIGO and Advanced Virgo during O3a, the first half of their third observing run. We study: 1) the expected rate of lensing at current detector sensitivity and the implications of a non-observation of strong lensing or a stochastic gravitational-wave background on the merger-rate density at high redshift; 2) how the interpretation of individual high-mass events would change if they were found to be lensed; 3) the possibility of multiple images due to strong lensing by galaxies or galaxy clusters; and 4) possible wave-optics effects due to point-mass microlenses. Several pairs of signals in the multiple-image analysis show similar parameters and, in this sense, are nominally consistent with the strong lensing hypothesis. However, taking into account population priors, selection effects, and the prior odds against lensing, these events do not provide sufficient evidence for lensing. Overall, we find no compelling evidence for lensing in the observed gravitational-wave signals from any of these analyses.

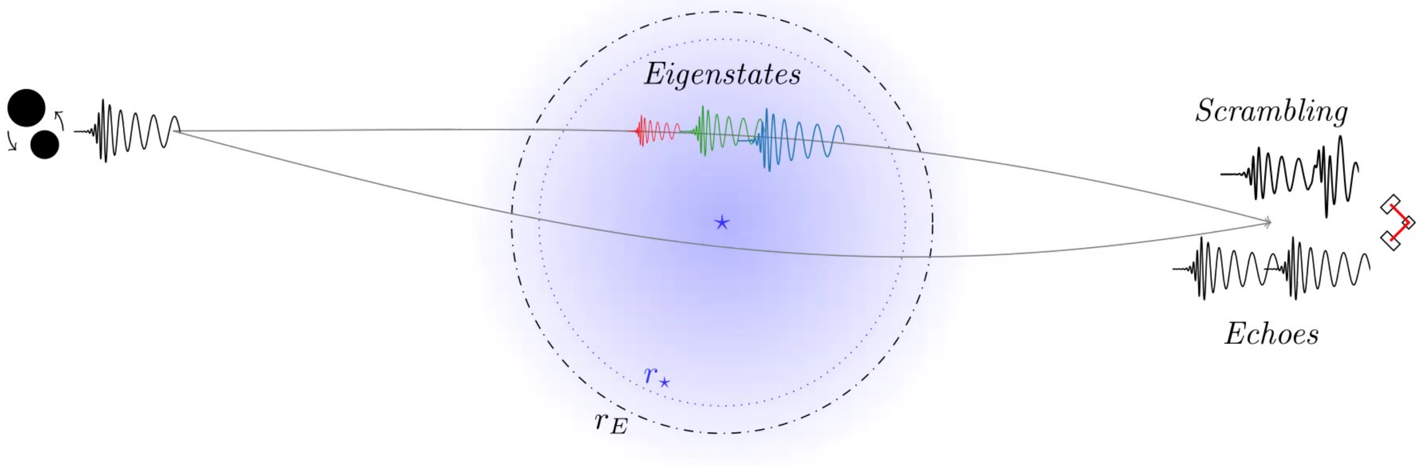
LVC (incl. **Ezquiaga**); *Search GW lensing O3a* (arXiv 2105.06384)

... but we are getting closer



<u>*Xu*</u>, **Ezquiaga** and Holz; *Strong lensing probes compact and galaxy pop* (arXiv 2105.14390) **34**

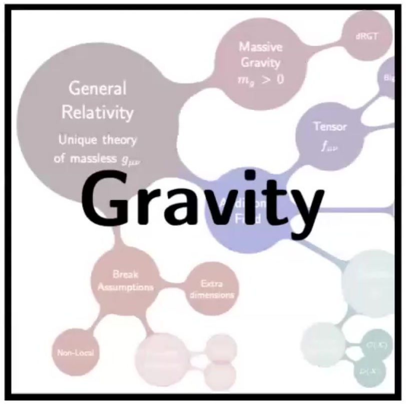
GW lensing beyond GR



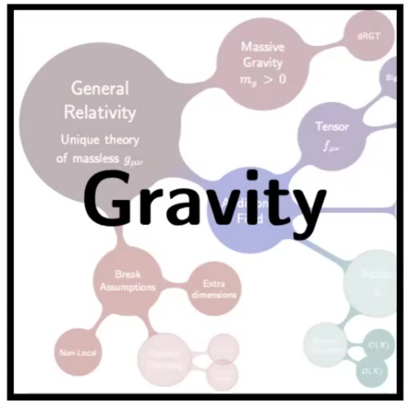
GWs can mix with the additional fields. The propagation eigenstates may have different speeds, splitting or distorting each image

Ezquiaga & Zumalacárregui; *GW lensing beyond GR* (PRD, arXiv 2009.12187)


Cosmology


Gravity
General Relativity
Unique theory of massless $g_{\mu\nu}$
Massive Gravity $m_g > 0$
dRGT
Tensor $f_{\mu\nu}$
Break Assumptions
Extra dimensions
Non-Local


Lensing



"Far-side binaries" above PISN gap have great science potential!

- At reach with LIGO/ Virgo and future multi-band LISA+3G
- Standard siren cosmology, imprint SGWB

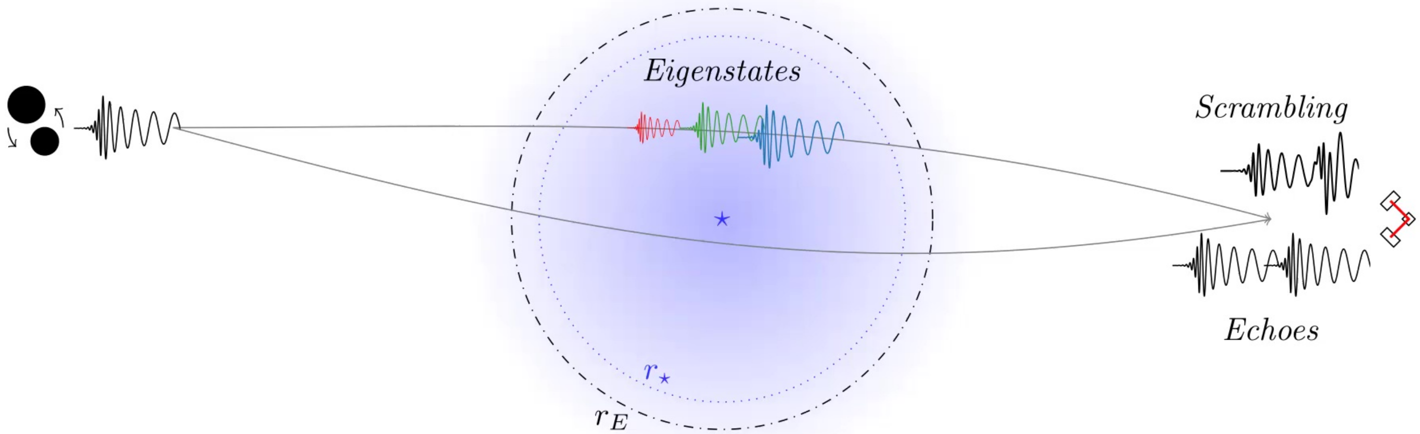
Probing gravity at cosmological scales without counterparts

- Luminosity distance constrained by BBH population in GWTC-2
- Tensor mixings bounded by waveform distortions and echoes

Lensed GWs can differ from (unlensed) general relativity wave-forms

- First detection possibly soon!
- Probing the galaxy and source populations
- Rich phenomenology of lensing beyond GR

GW lensing beyond GR



GWs can mix with the additional fields. The propagation eigenstates may have different speeds, splitting or distorting each image

Ezquiaga & Zumalacárregui; *GW lensing beyond GR* (PRD, arXiv 2009.12187)