[Yayoi Kusama, Lousiana Museum]

Exploring the Dark Universe with gravitational waves

Jose María Ezquiaga

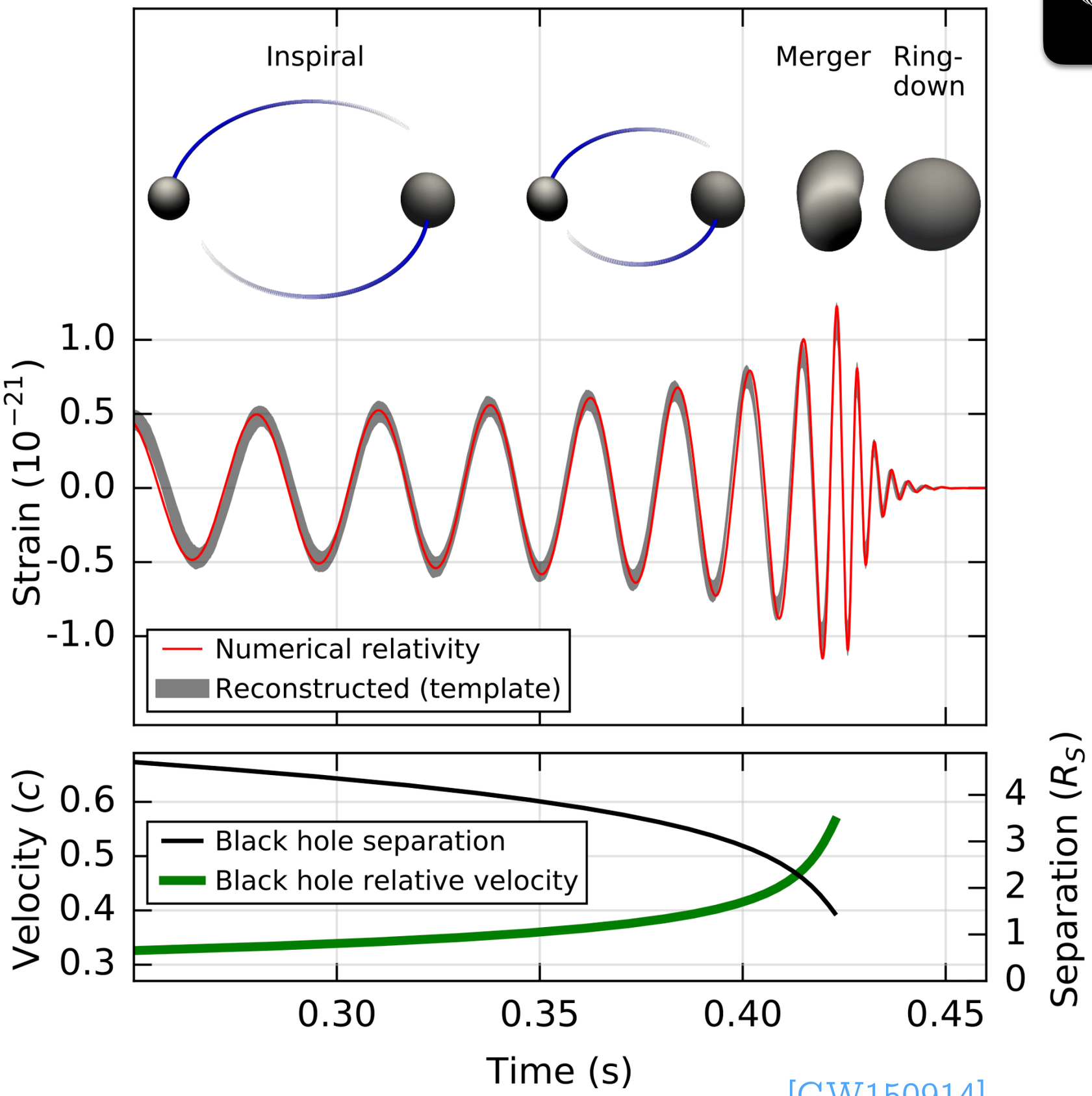
Niels Bohr Institute

jose.ezquiaga@nbi.ku.dk

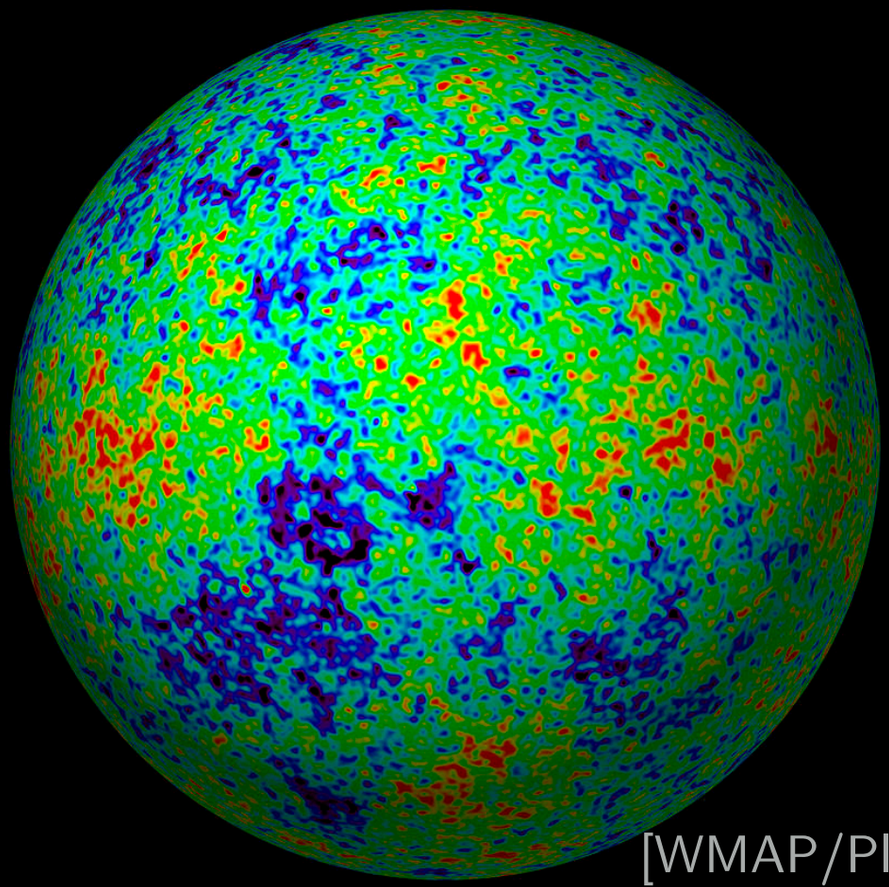
ezquiaga.github.io

VILLUM FONDEN

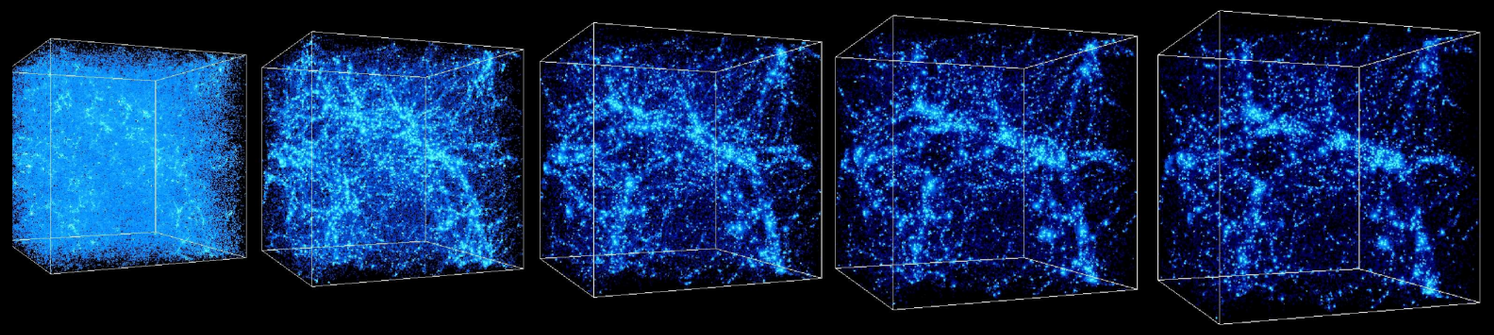
KØBENHAVNS UNIVERSITET


Inspiral
Merger
Ring-down
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
4
3
2
1
0
0.30
0.35
0.40
0.45
Time (s)

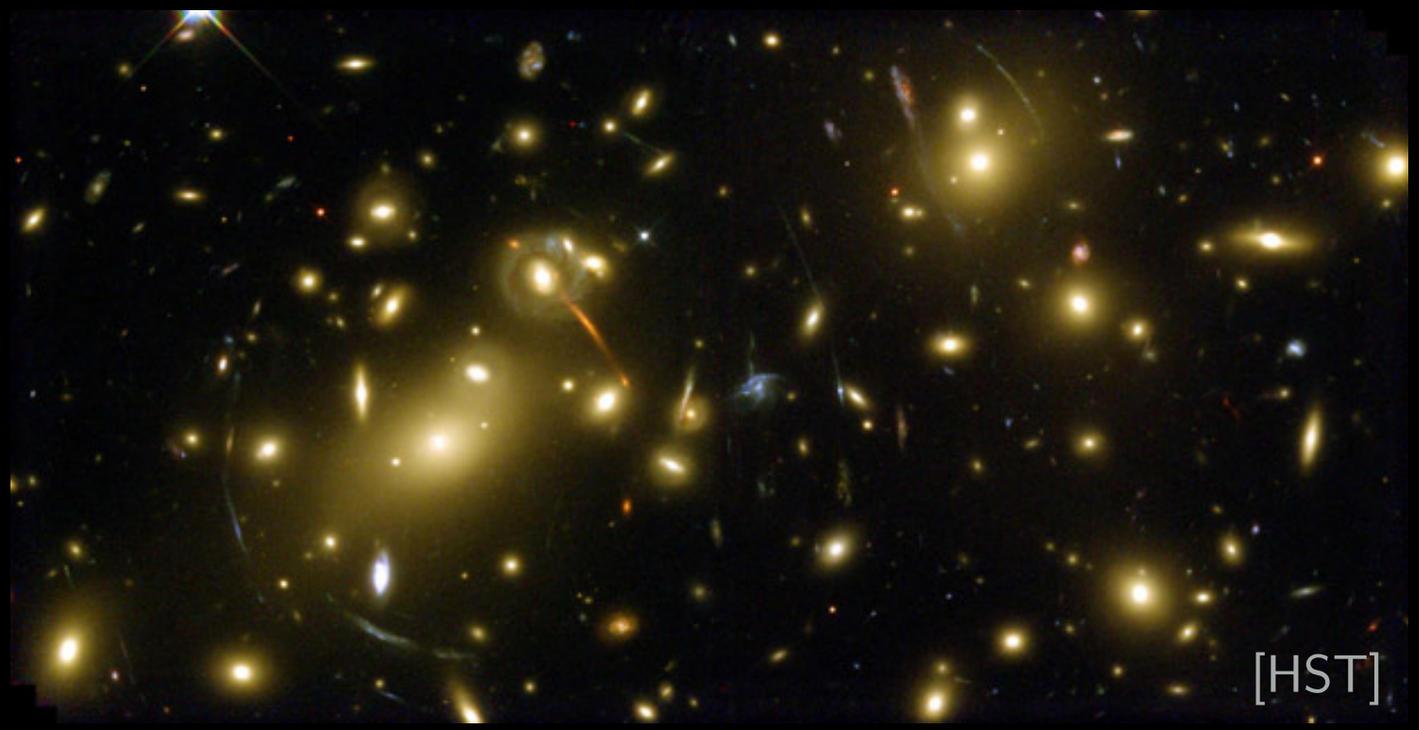
[GW150914]



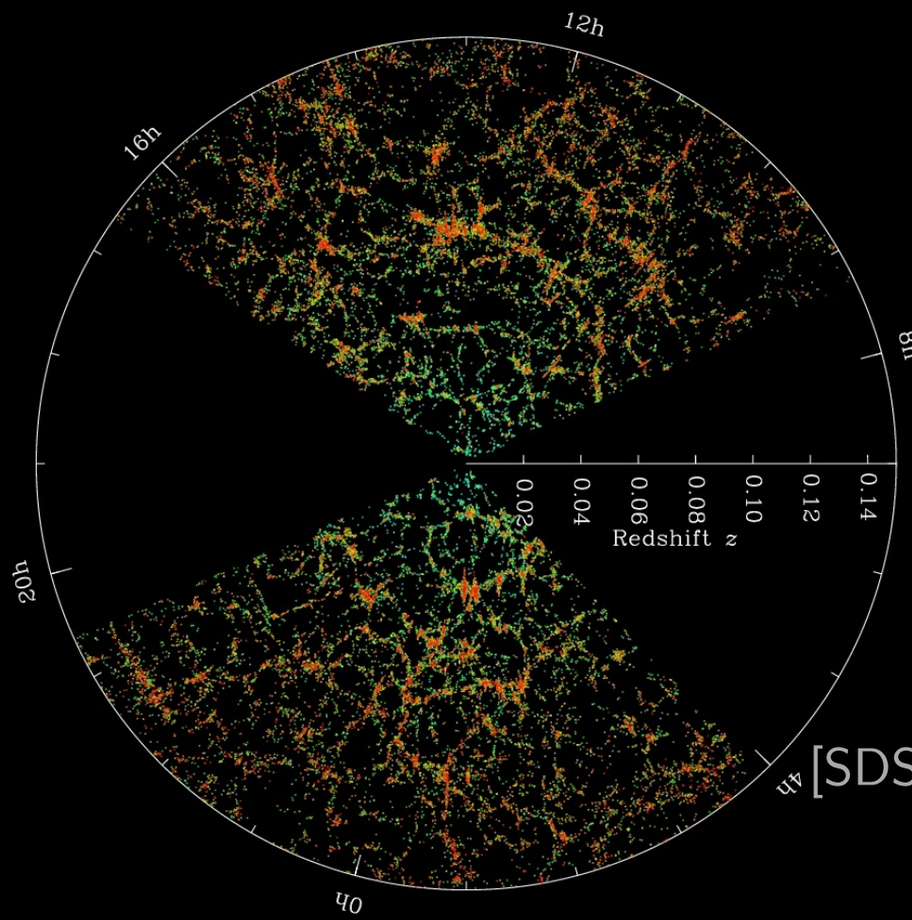
[WMAP/Planck]



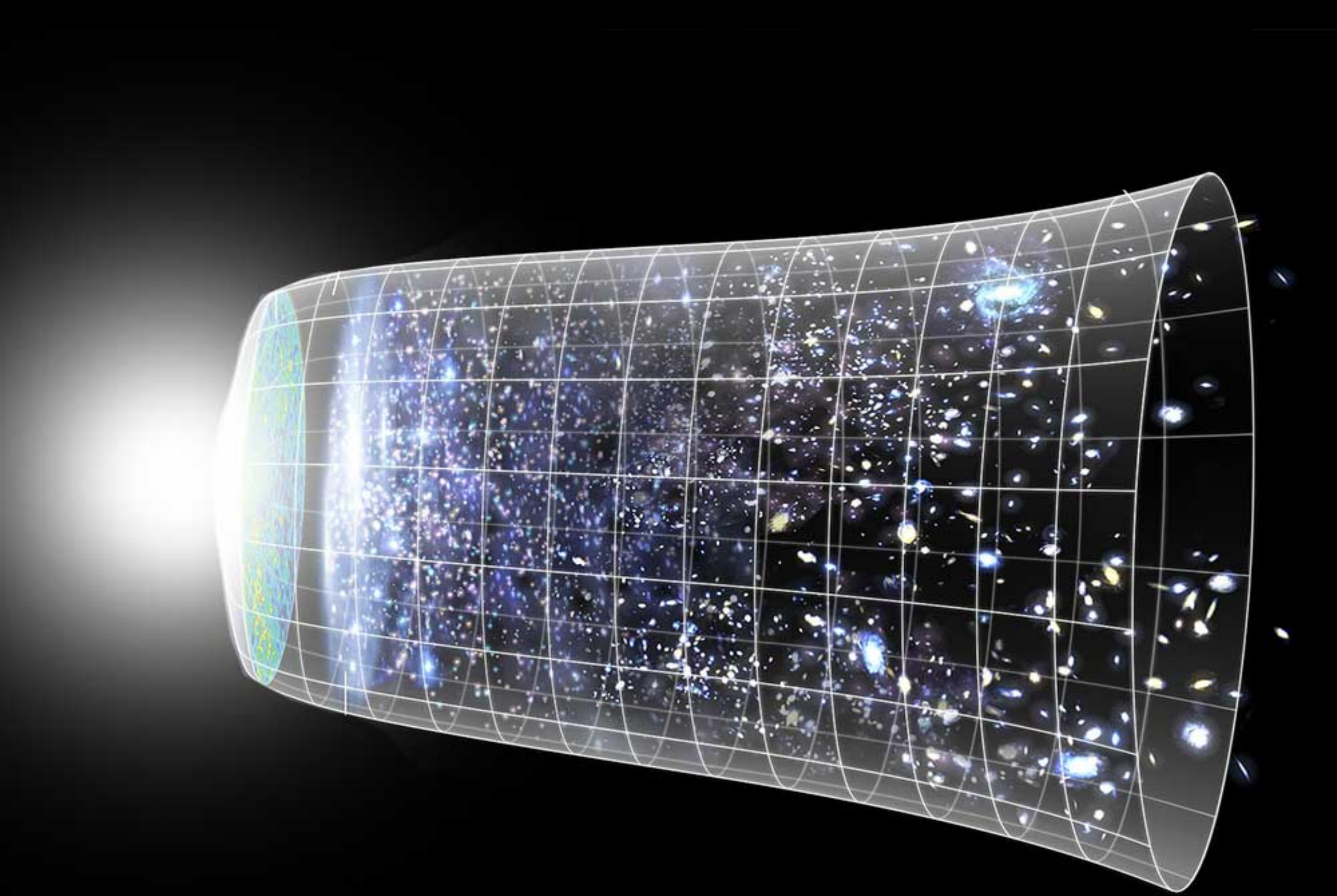
[Kravtsov]

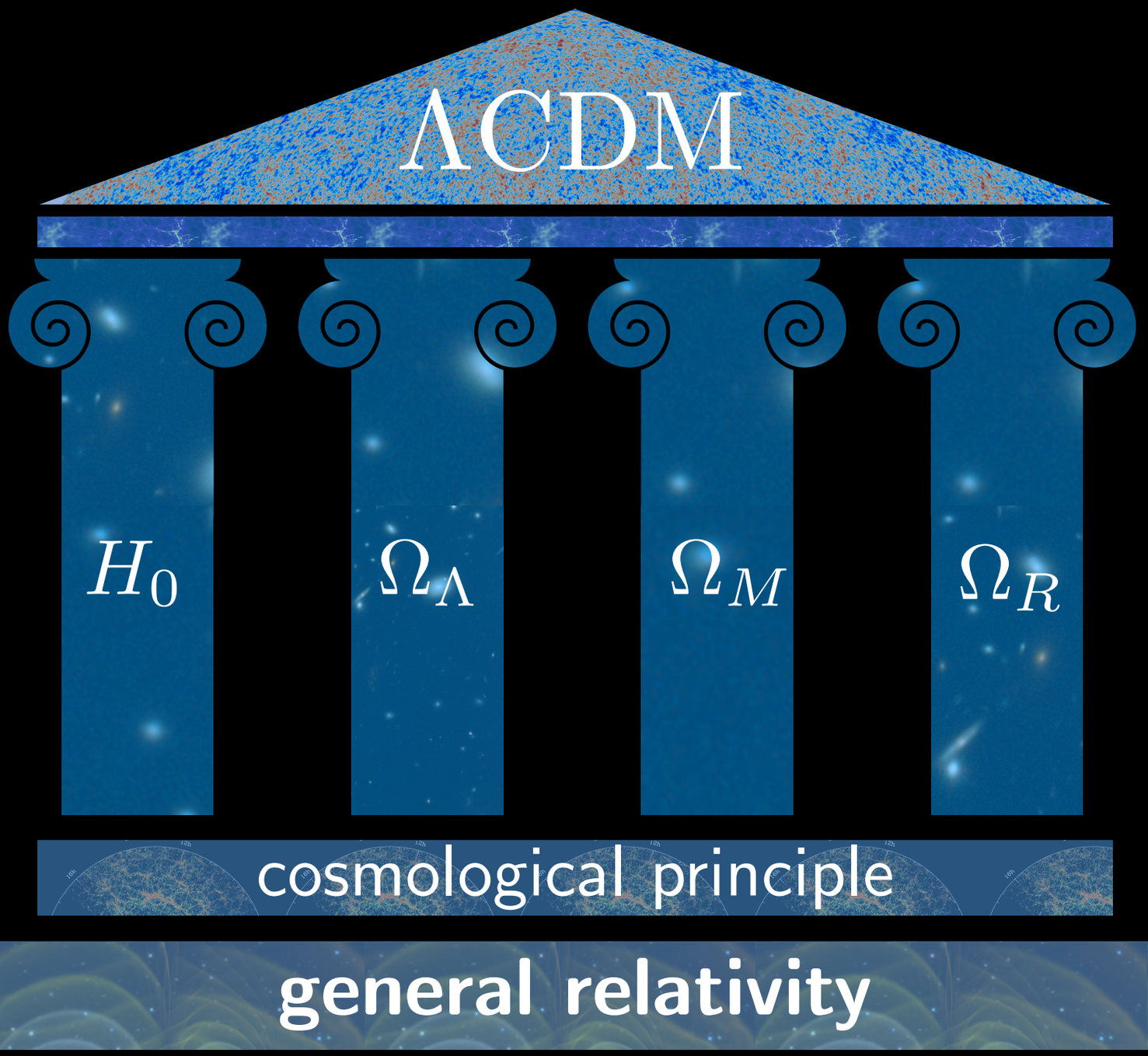


[HST]

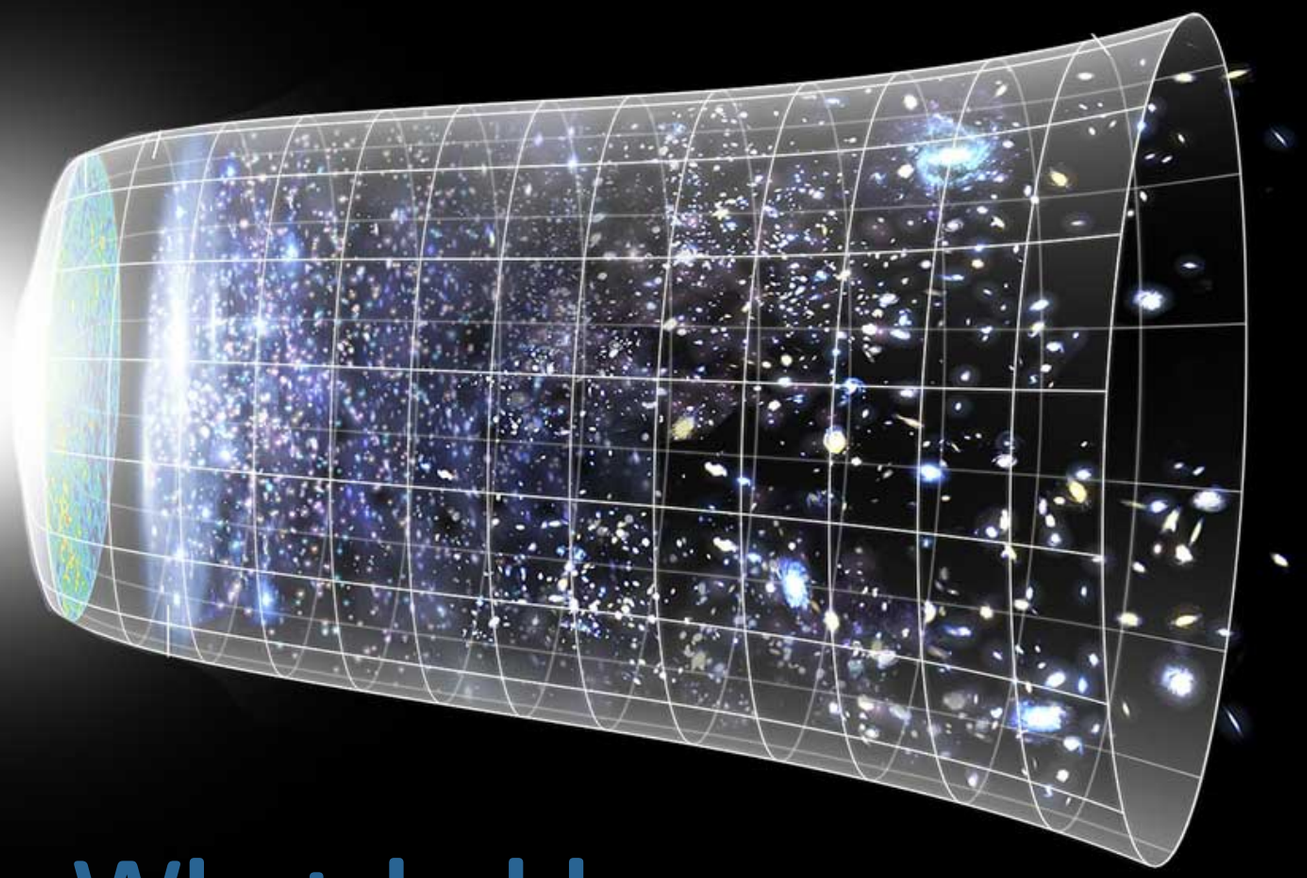


[SDSS]



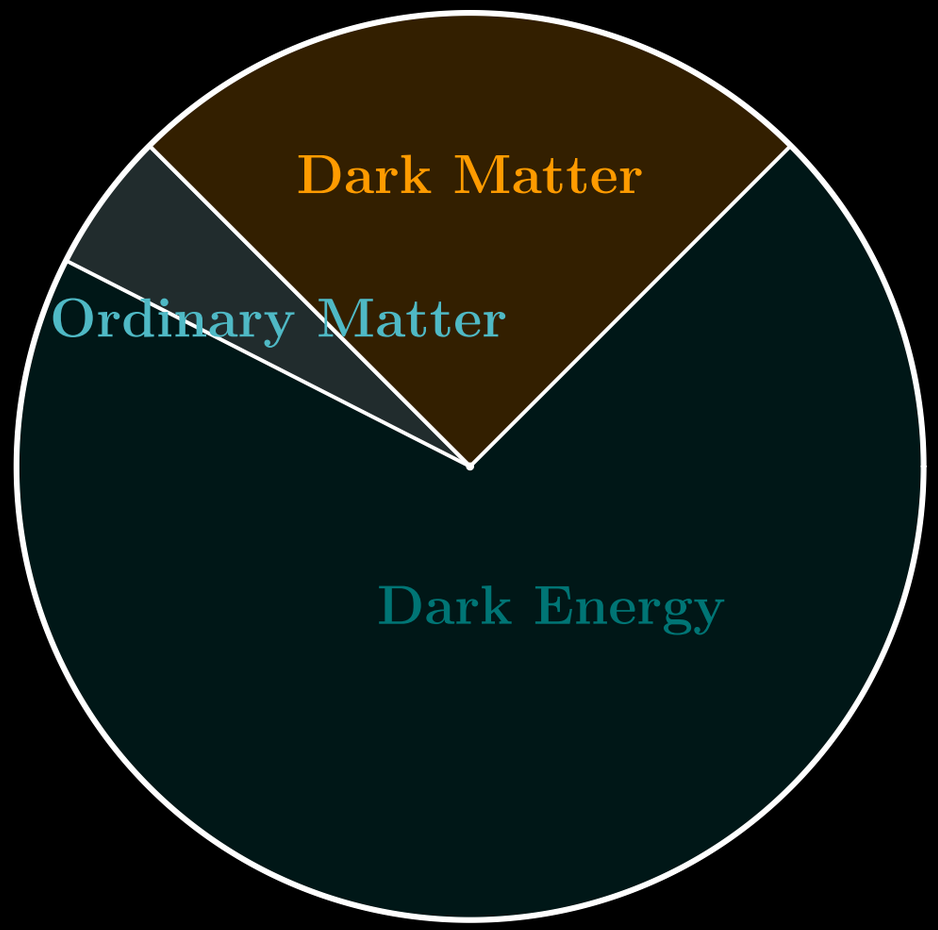

ΛCDM
H_0
Ω_Λ
Ω_M
Ω_R
cosmological principle
general relativity

We **don't** understand the basics of our Universe

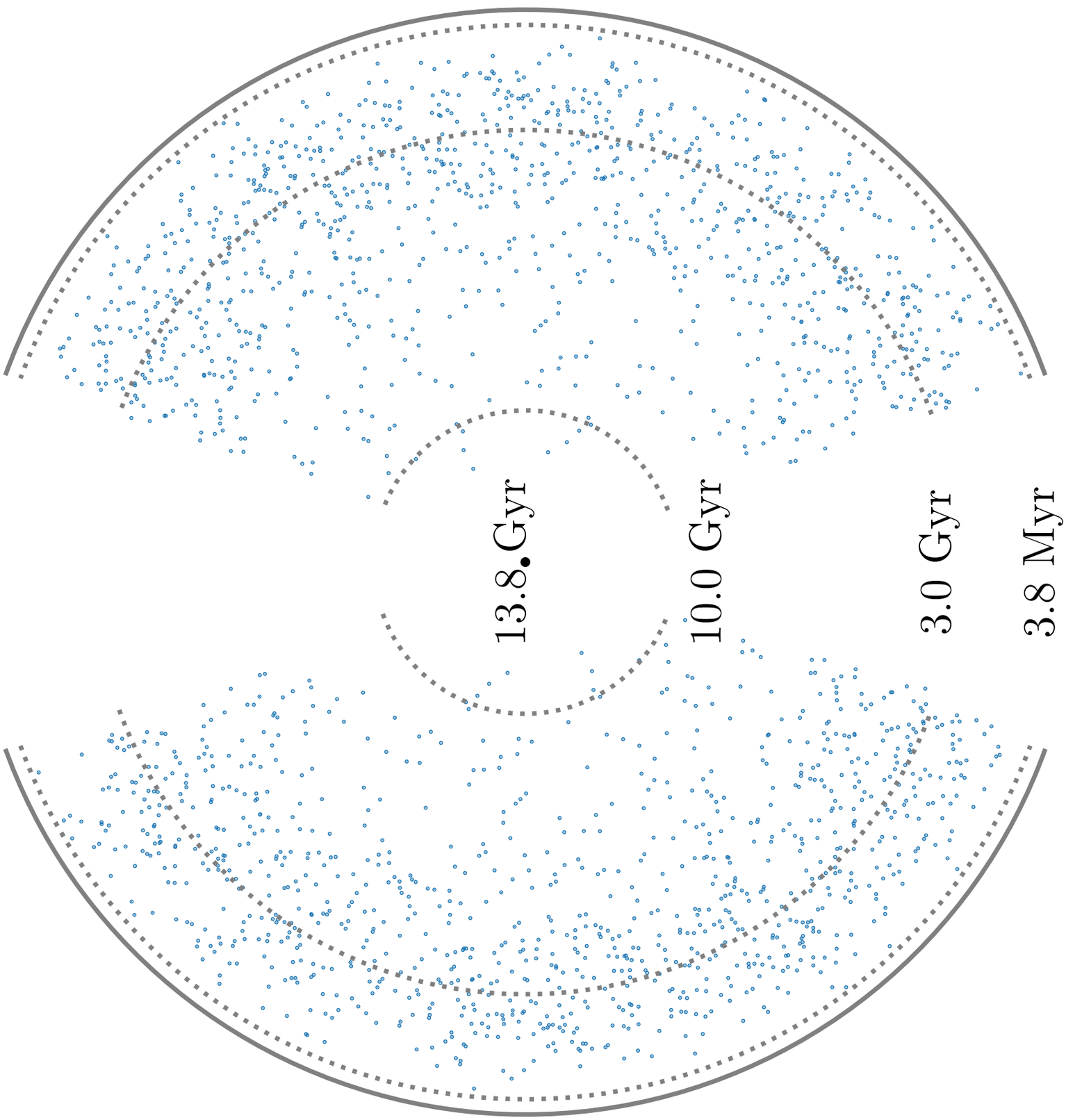


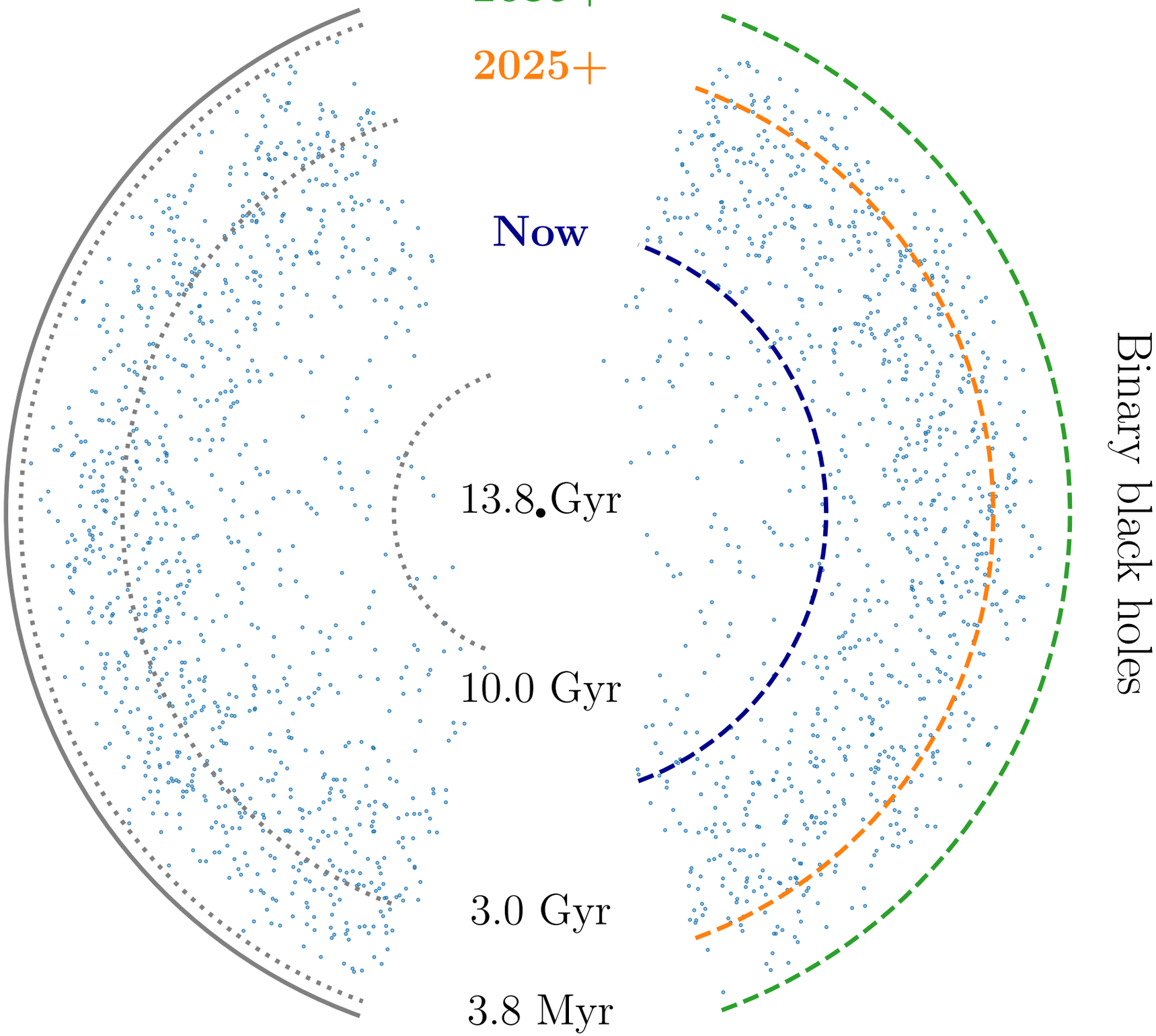
What holds galaxies together?

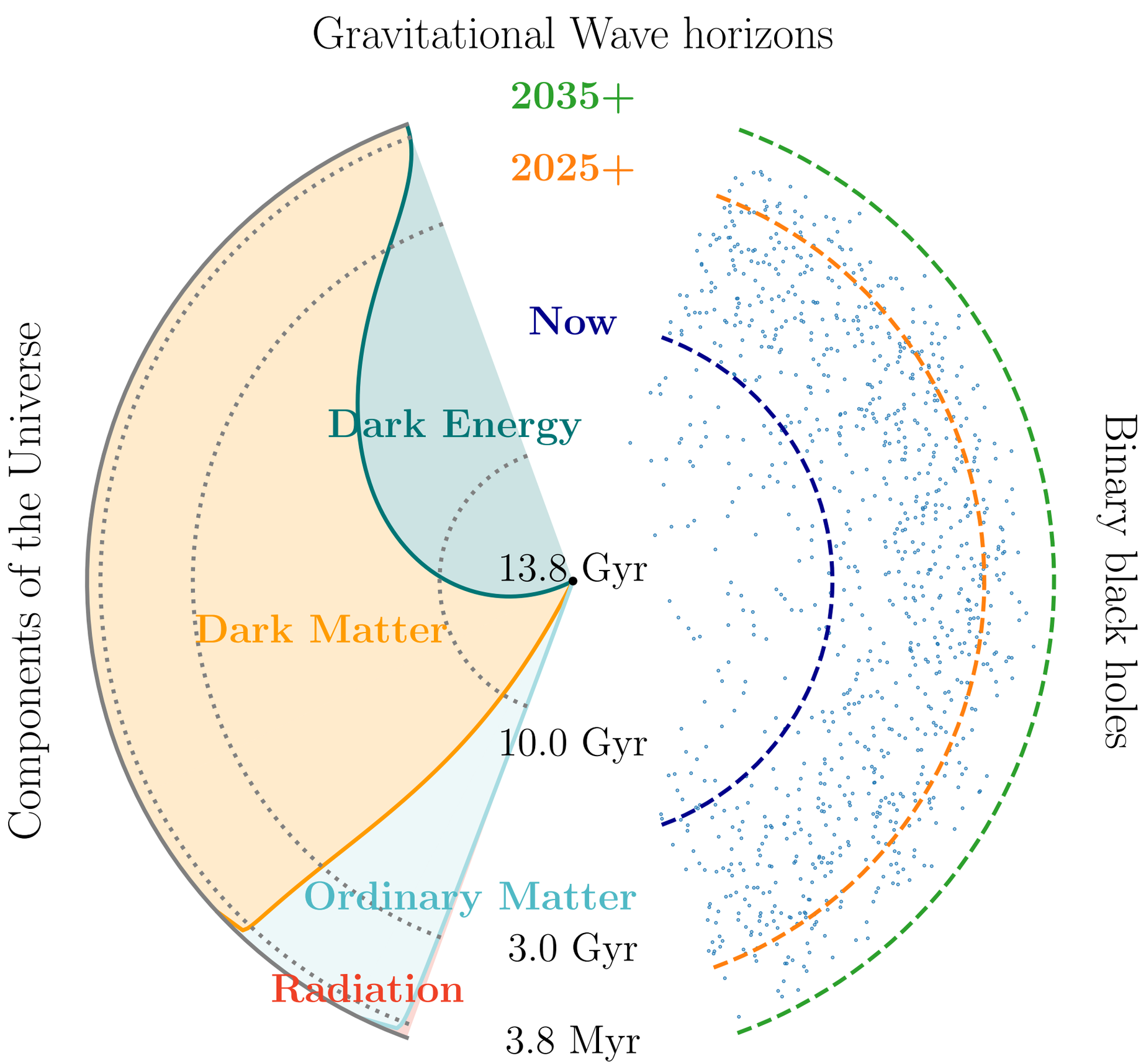
Why the Universe expands ever faster?



Is Einstein gravity valid at cosmological scales?

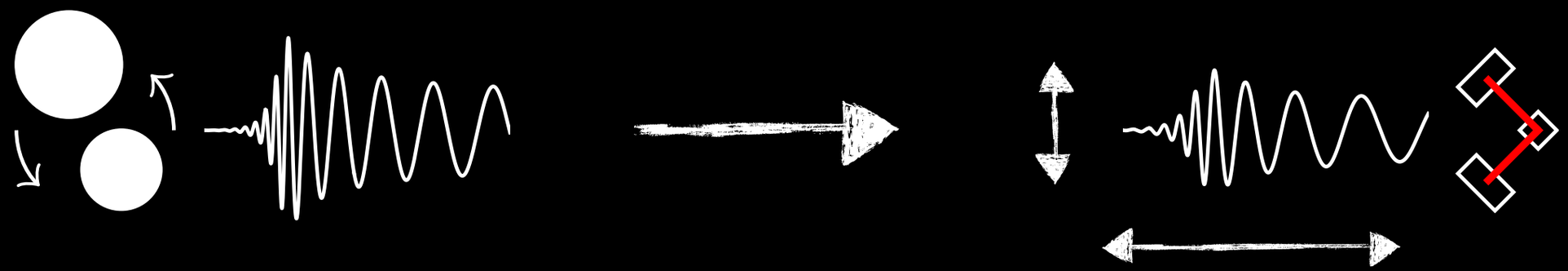

Binary black holes
13.8●Gyr
10.0 Gyr
3.0 Gyr
3.8 Myr
Age of the Universe

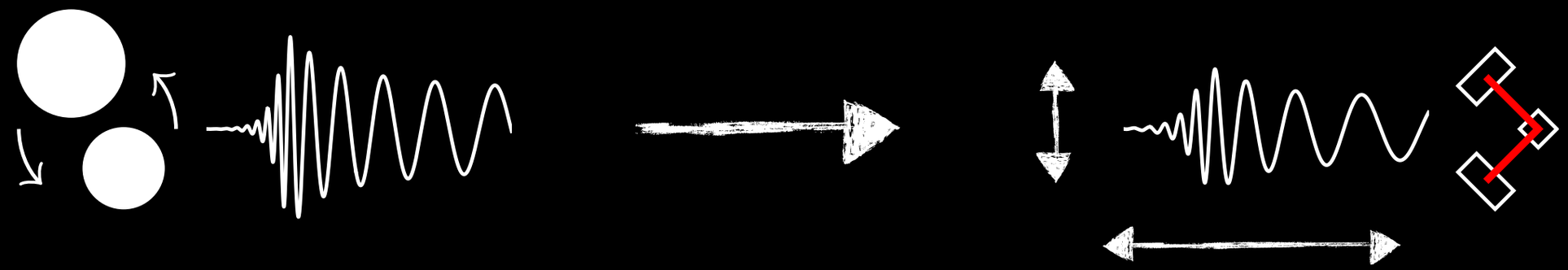

Gravitational Wave horizons
2035+
2025+
Now
13.8 Gyr
10.0 Gyr
3.0 Gyr
3.8 Myr
Binary black holes
Age of the Universe


Gravitational Wave horizons
2035+
2025+
Now
Dark Energy
13.8 Gyr
Dark Matter
10.0 Gyr
Ordinary Matter
3.0 Gyr
Radiation
3.8 Myr
Components of the Universe
Binary black holes
Age of the Universe

Standard Sirens

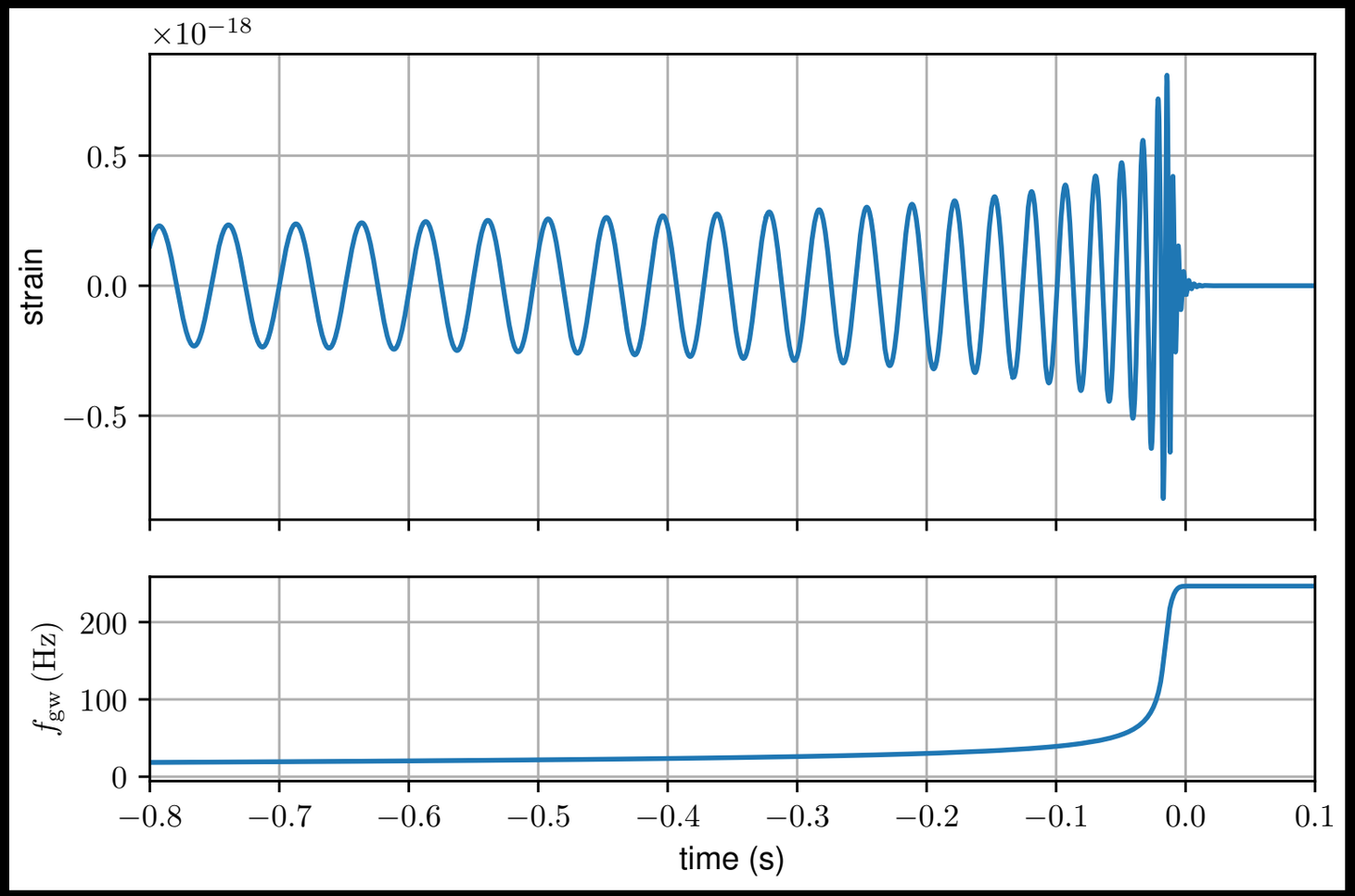
- *General relativity* predicts the waveform of a compact binary coalescence
- Gravitational waves *do not interact* with the medium
- Compact binaries are detected at *cosmological* distances





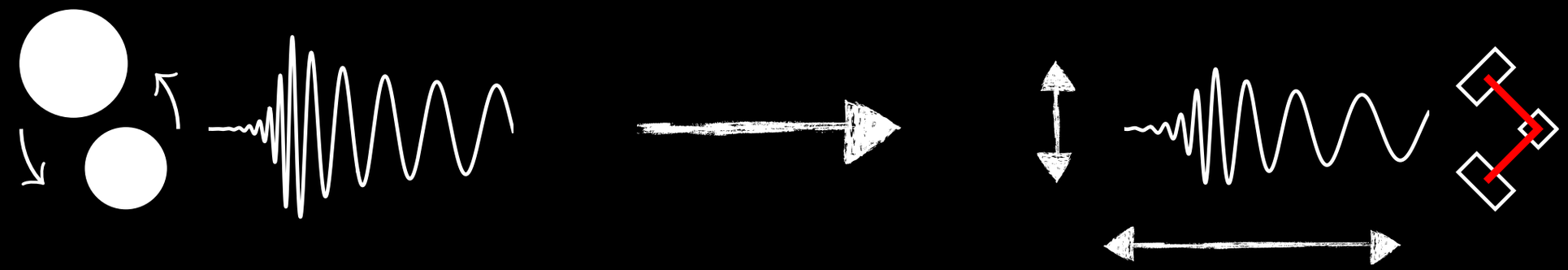
$$h \sim \frac{\mathcal{M}_{\rm det}^{5/3} f_{\rm det}^{2/3}}{d_L}$$

$$\dot{f}_{\rm det} \sim \mathcal{M}_{\rm det}^{5/3} f_{\rm det}^{11/3}$$



For more details see:

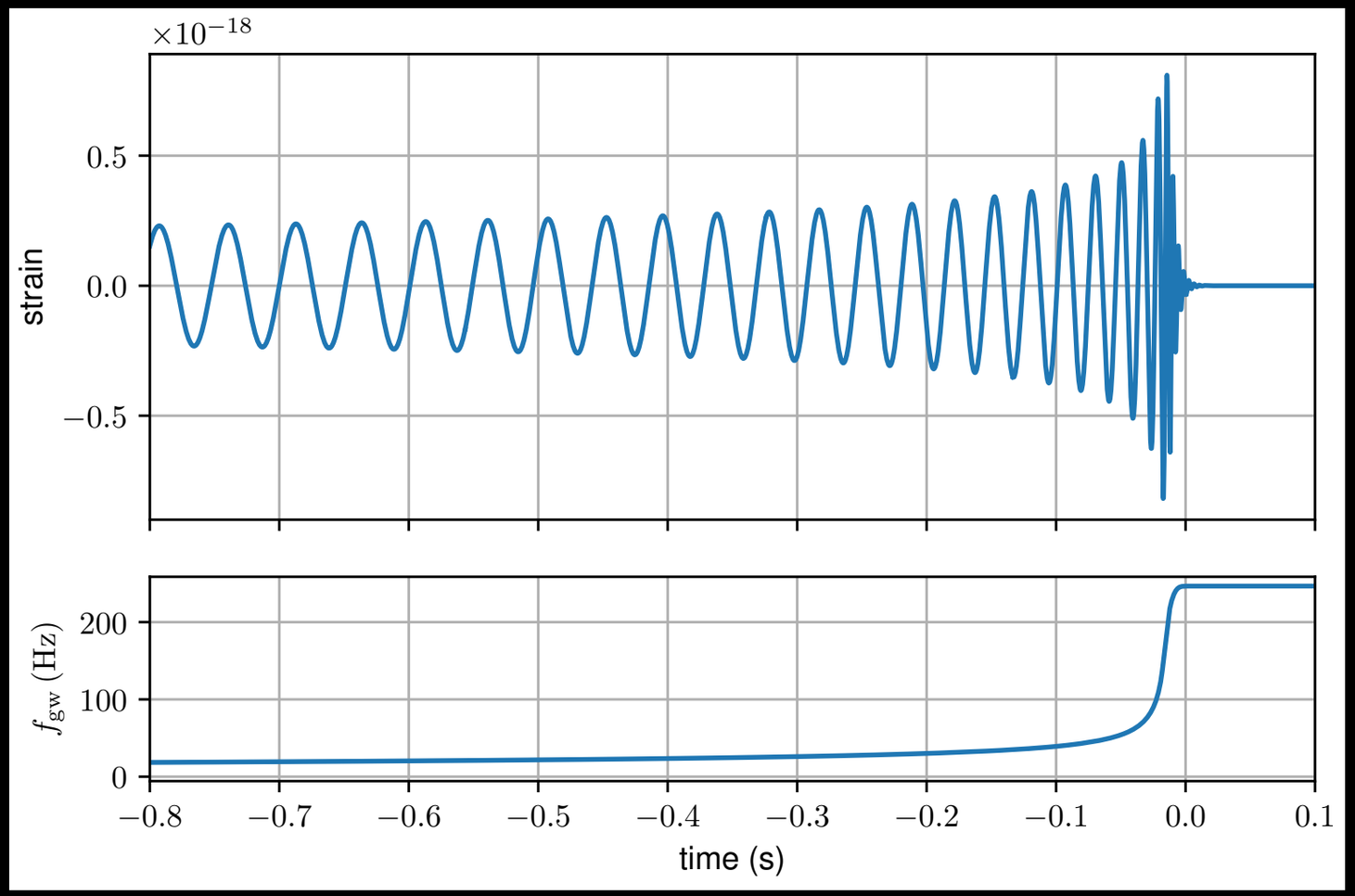
Gravitational Waves Vol. I, M. Maggiore



$$\{d_L(z), m_{\rm det} = (1+z)m\}$$

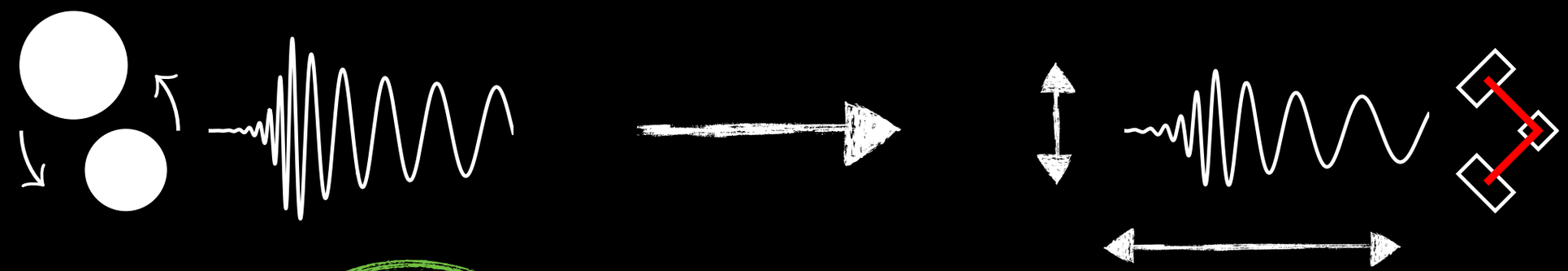
$$h \sim \frac{\mathcal{M}_{\rm det}^{5/3} f_{\rm det}^{2/3}}{d_L}$$

$$\dot{f}_{\rm det} \sim \mathcal{M}_{\rm det}^{5/3} f_{\rm det}^{11/3}$$



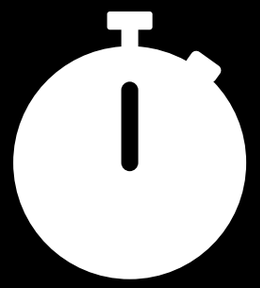
For more details see:

Gravitational Waves Vol. I, M. Maggiore



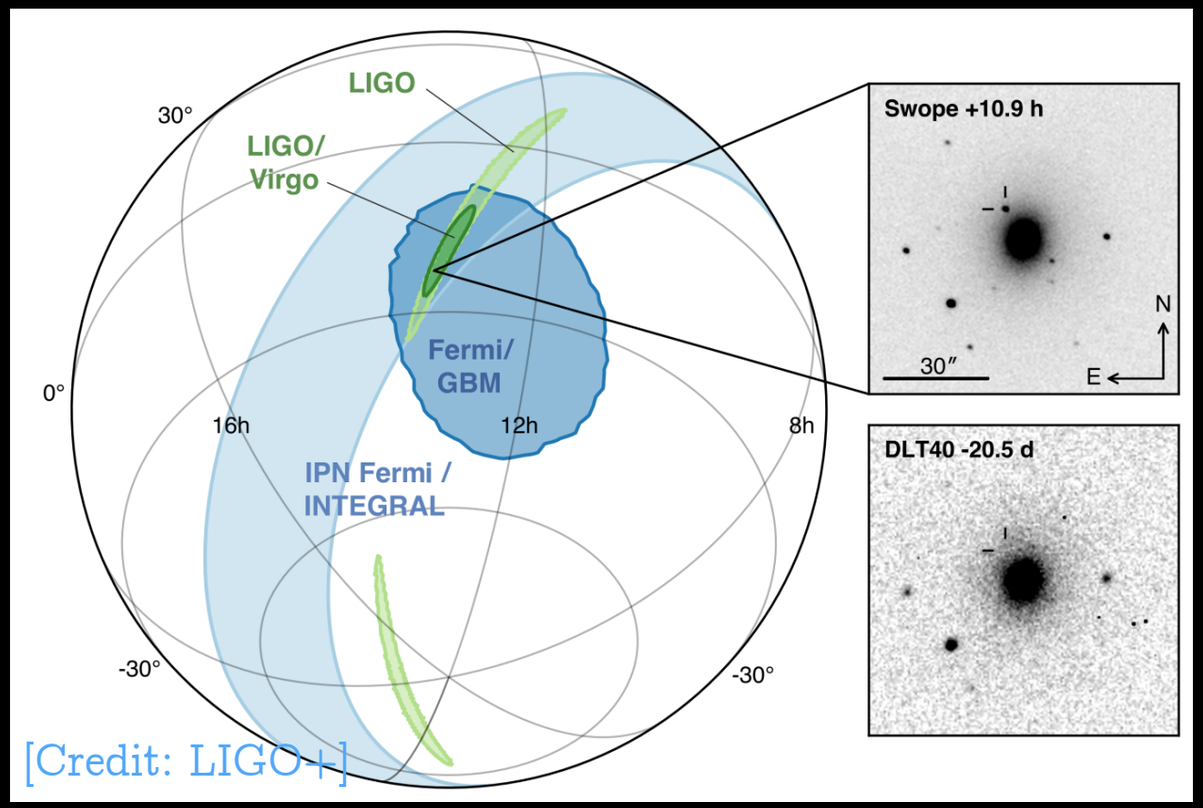
$$\{d_L(z)\, m_{\rm det} = (1+z)m\}$$

Gravitational waves give direct information of their distance, but to measure the expansion rate of the Universe we need some timing information



BRIGHT SIRENS

- Redshift from electromagnetic counterpart (e.g. identifying host galaxy)
- E.g. GW170817
- Need matter around merger: **neutron stars**!, AGN?
- Bright counterpart at high-z?



[Credit: LIGO+]


[Credit: D. Berry]

GraceDB Public Alerts Latest Search Documentation Login

Please log in to view full database contents.

LIGO/Virgo/KAGRA Public Alerts

- More details about public alerts are provided in the LIGO/Virgo/KAGRA Alerts User Guide.
- Retractions are marked in red. Retraction means that the candidate was manually vetted and is no longer considered a candidate of interest.
- Less-significant events are marked in grey, and are not manually vetted. Consult the LVK Alerts User Guide for more information on significance in O4.

O4 Significant Detection Candidates: **19** (24 Total - 5 Retracted)

O4 Low Significance Detection Candidates: **299** (Total)

Show All Public Events

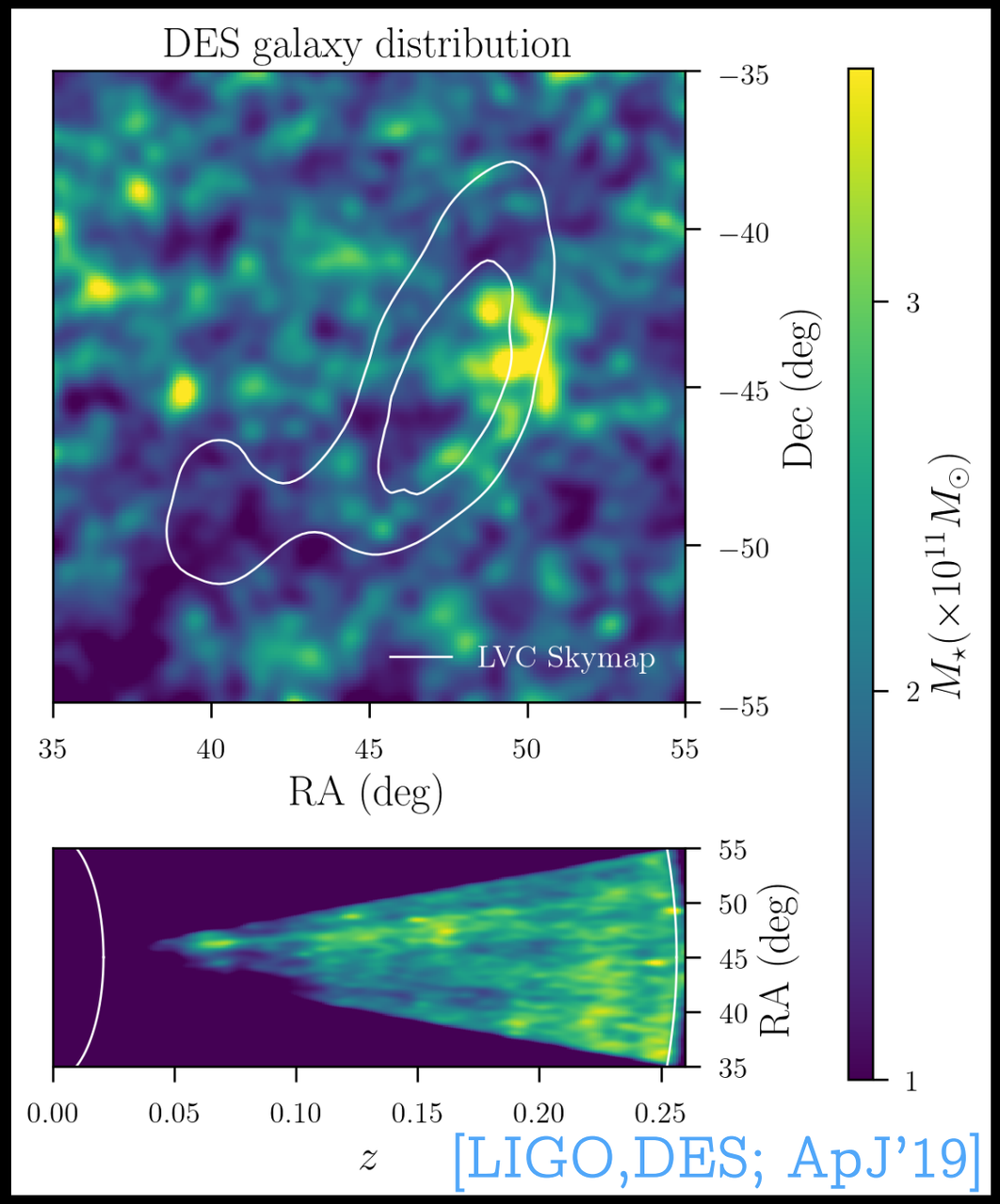
SORT: EVENT ID (A-Z)

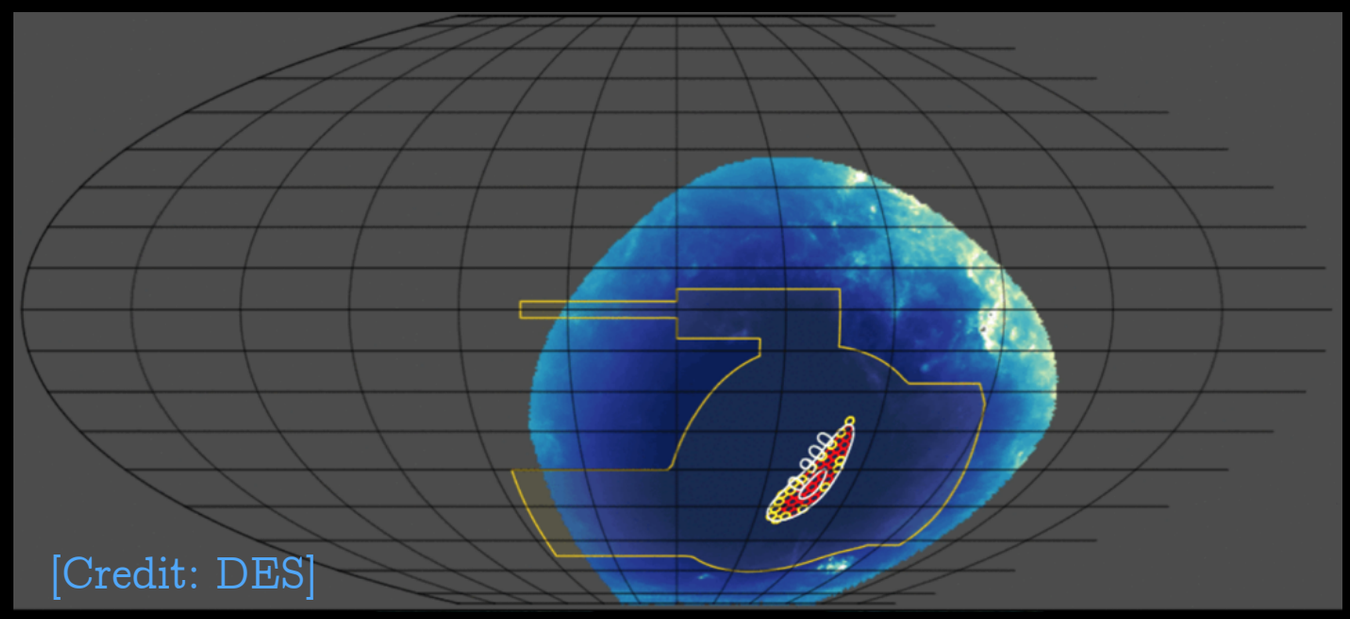
Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location
S230715bw	NSBH (91%), BBH (9%)	Yes	July 15, 2023 19:05:37 UTC	GCN Circular Query Notices | VOE	
S230712a	BBH (>99%)	Yes	July 12, 2023 00:53:57 UTC	GCN Circular Query Notices | VOE	
S230709bi	BBH (>99%)	Yes	July 9, 2023 12:27:27 UTC	GCN Circular Query Notices | VOE	

[GraceDB]

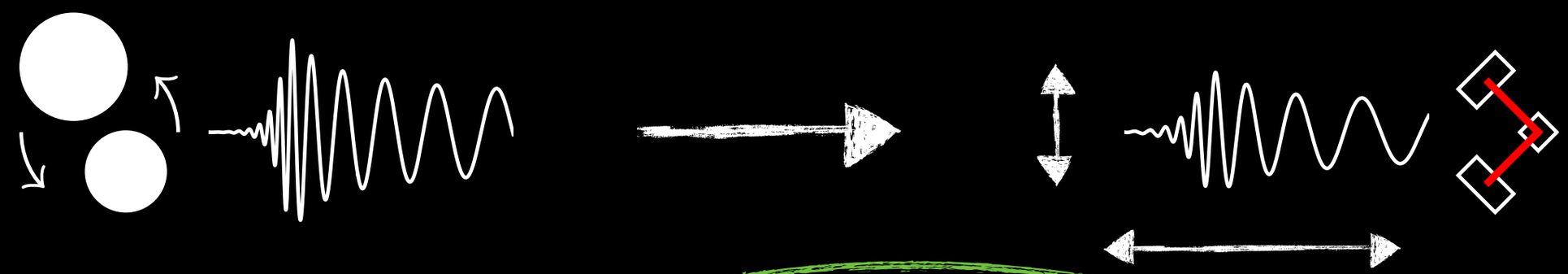
DARK SIRENS

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



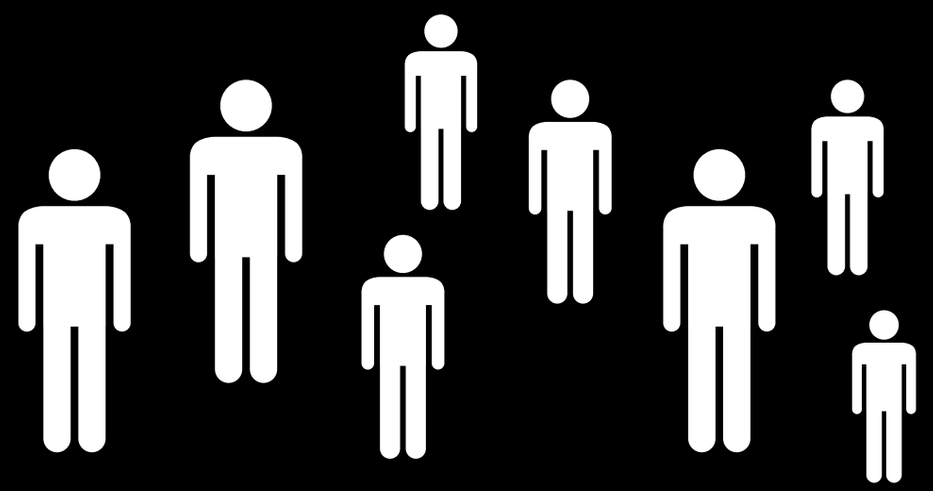


For more details see:
Hitchhiker guide GW galaxy catalog cosmo
(arXiv 2212.08694)



$$\{d_L(z), m_{\rm det} = (1+z)m\}$$

Gravitational waves alone can provide redshift information if studied as a population



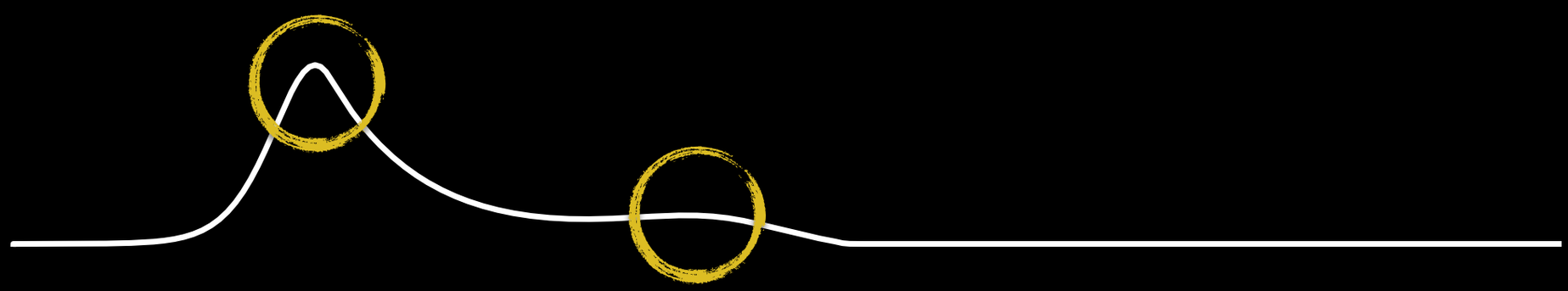
SPECTRAL SIRENS

$$\{d_L(z), m_{\rm det} = (1+z)m\}$$

log[Detector frame mass]

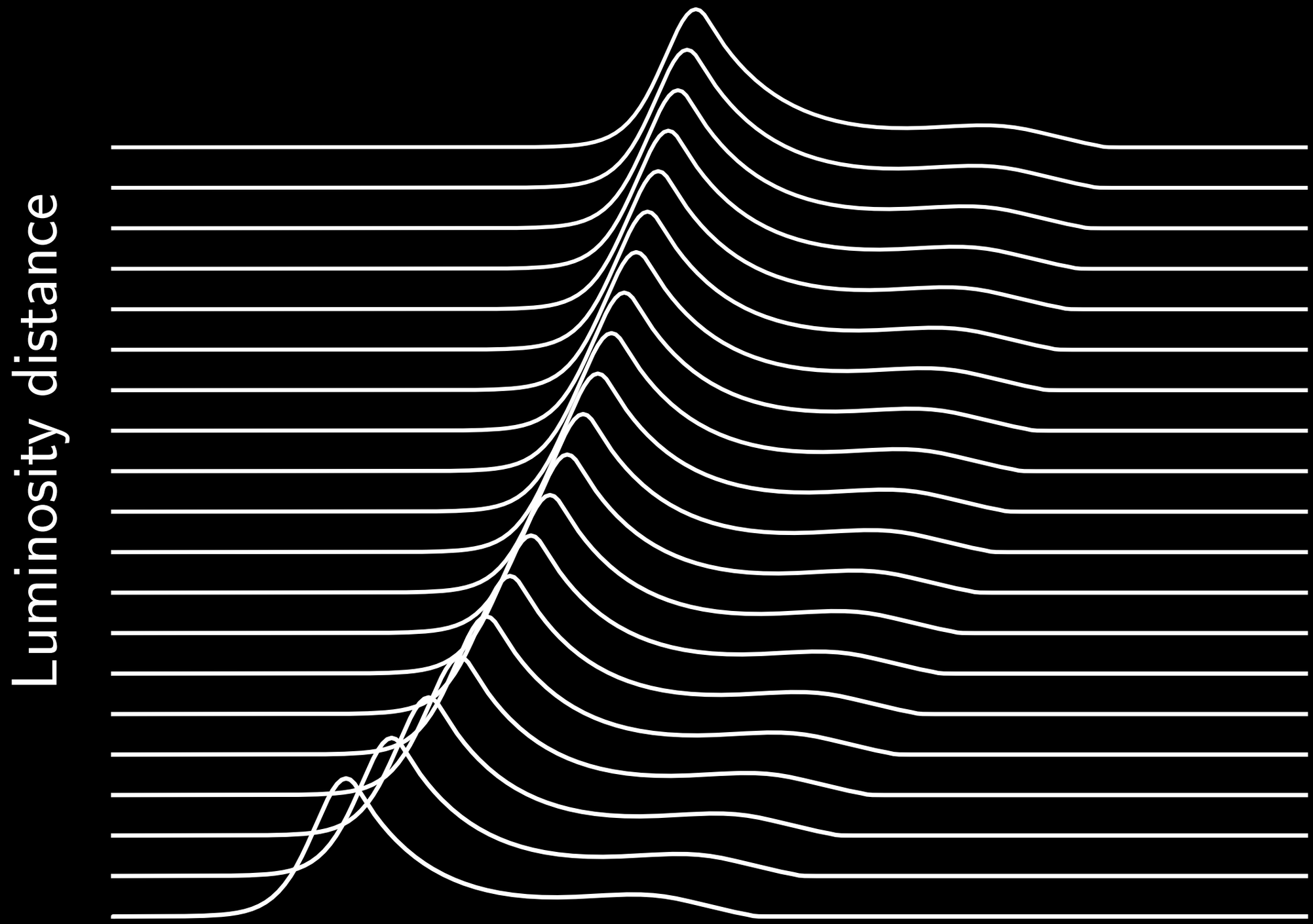
SPECTRAL SIRENS

$$\{d_L(z), m_{\rm det} = (1+z)m\}$$



log[Detector frame mass]

SPECTRAL SIRENS



SPECTRAL SIRENS

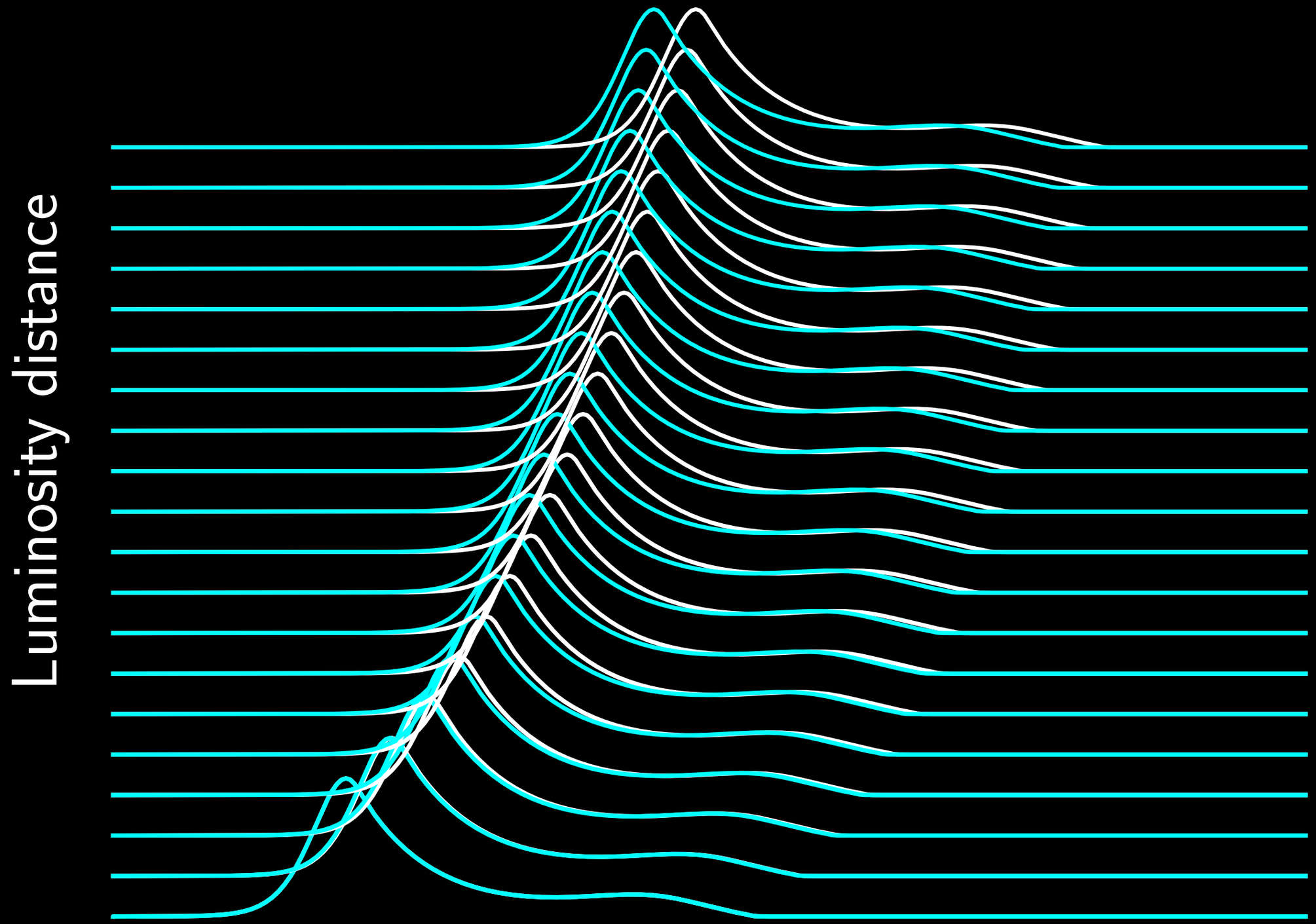
higher H_0

Luminosity distance

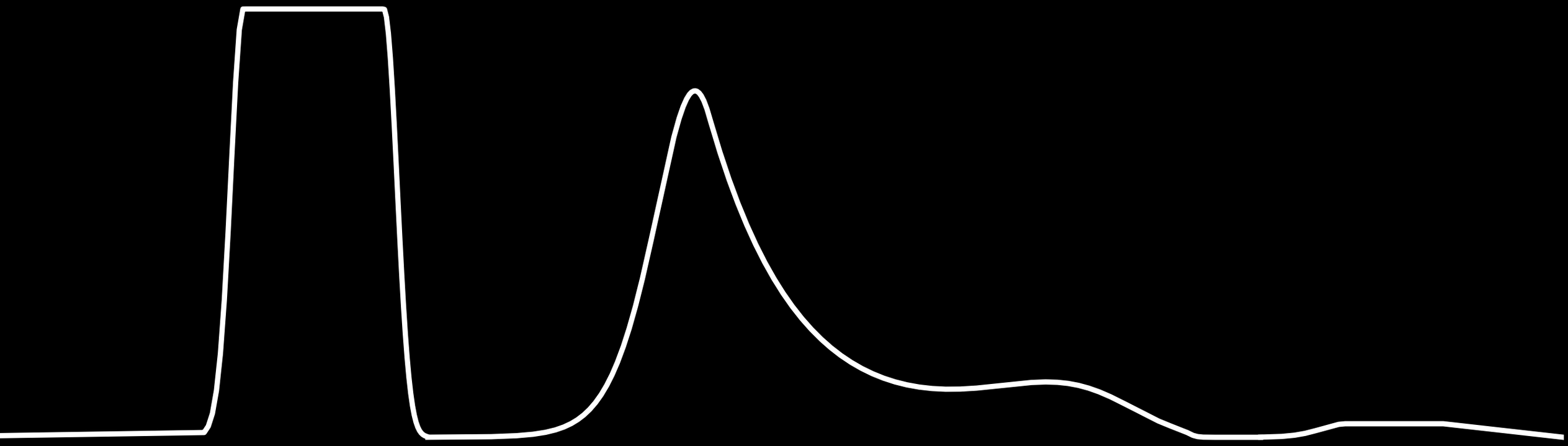
log[Detector frame mass]

SPECTRAL SIRENS

lower Ω_m

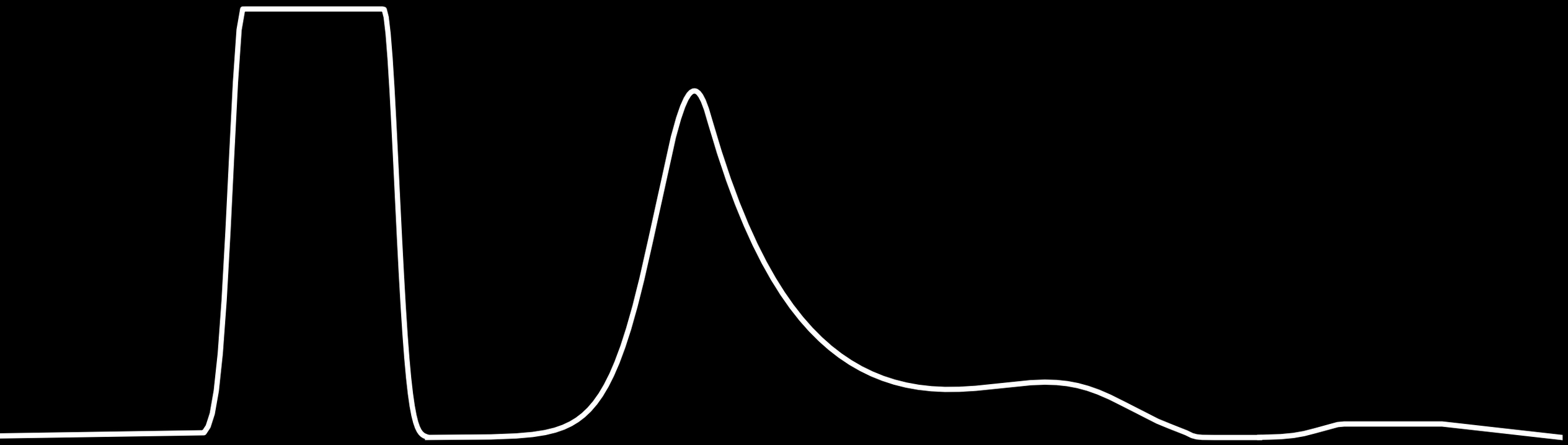


All compact binaries are standard sirens, no electromagnetic information is necessary



Binary neutron stars ***"Stellar-mass" binary black holes*** ***"Far-side" binaries***

All compact binaries are standard sirens, no electromagnetic information is necessary

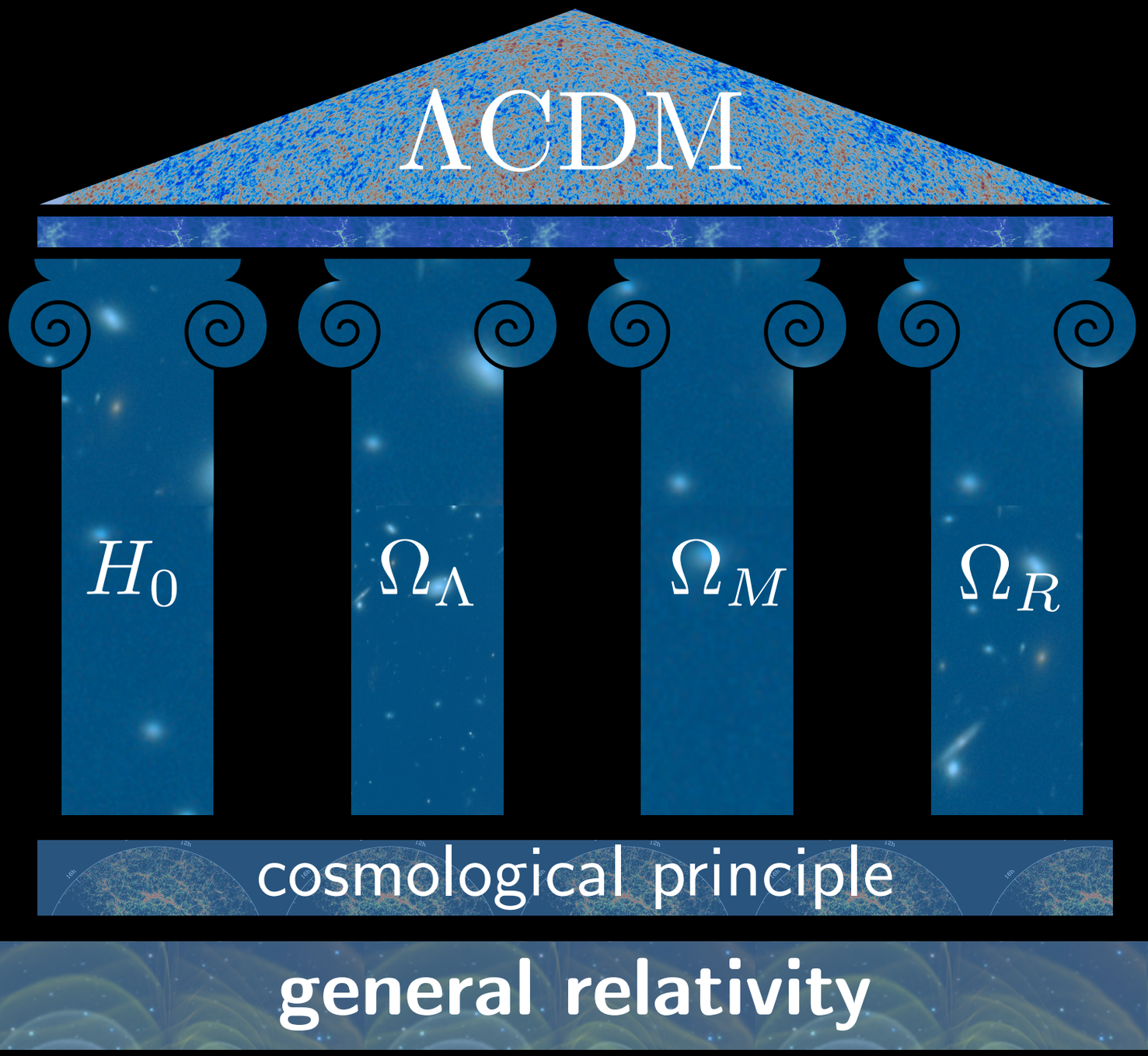


Binary neutron stars ***"Stellar-mass" binary black holes*** ***"Far-side" binaries***

Ezquiaga & Holz; *Spectral sirens: Cosmology from full mass distribution of compact binaries* (PRL'22, arXiv 2202.08240)

[Chernoff&Finn'93] [Farr+'19] [Mastrogiovanni+'21] **[Ezquiaga&Holz'20]**

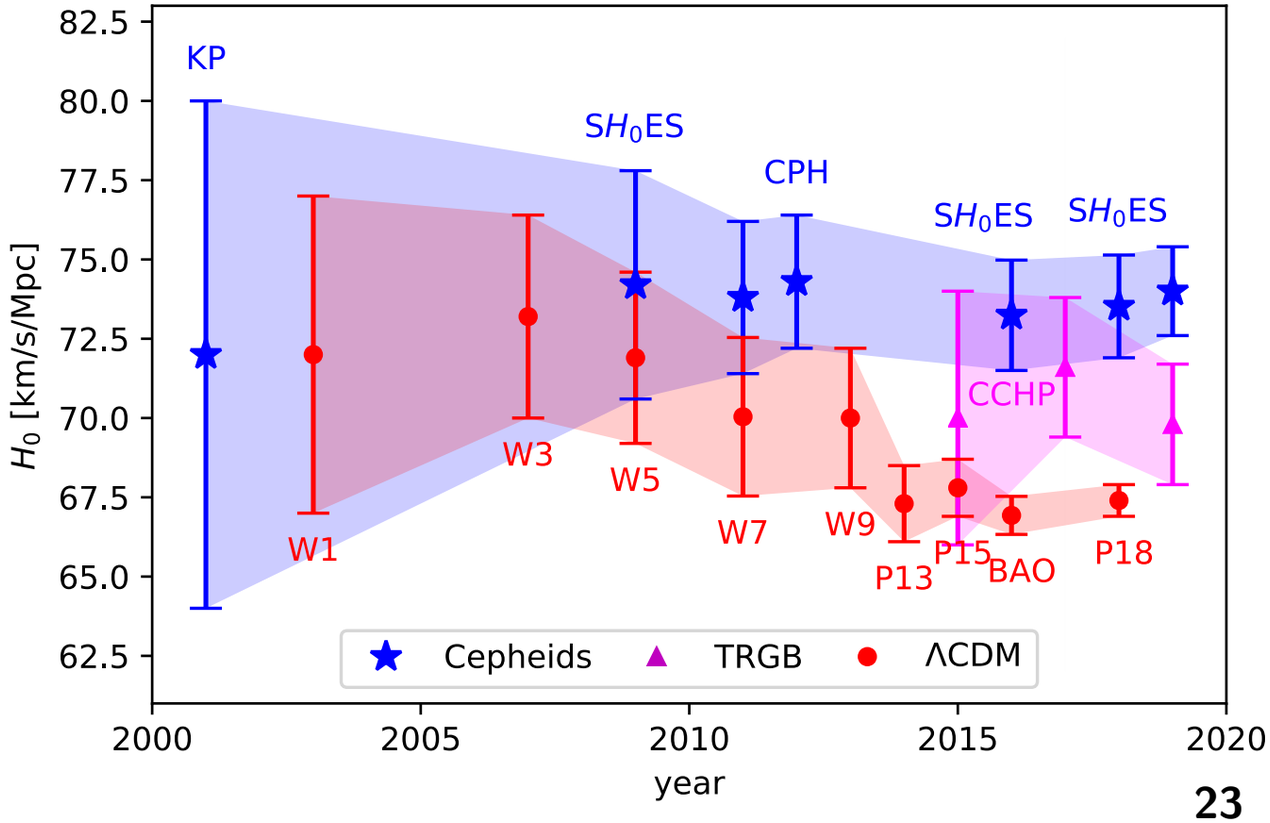
[Taylor+'11] [You+'20] [LVC Cosmo GWTC-3 '21]

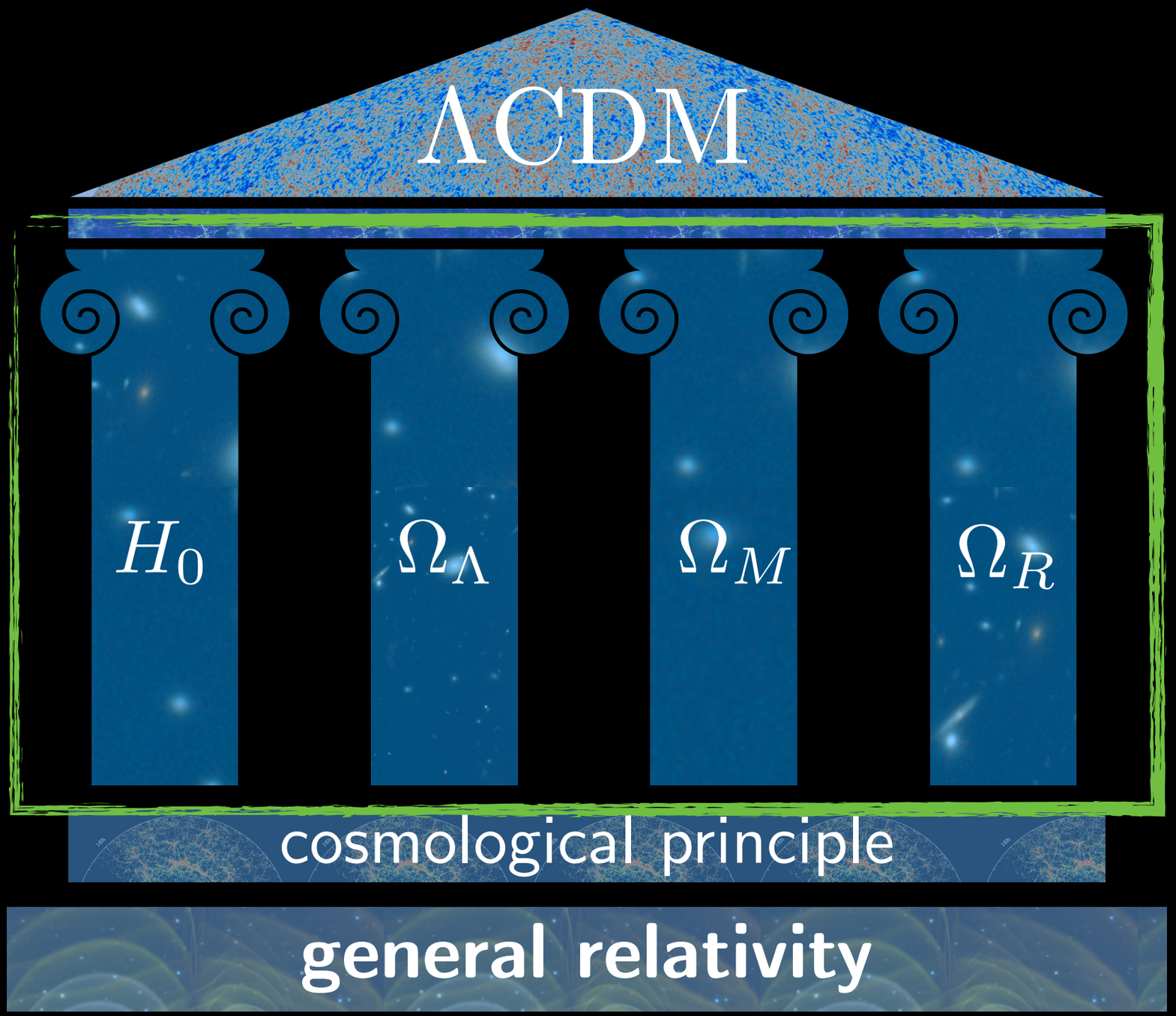

ΛCDM
H_0
Ω_Λ
Ω_M
Ω_R
cosmological principle
general relativity

The standard model of cosmology - open questions

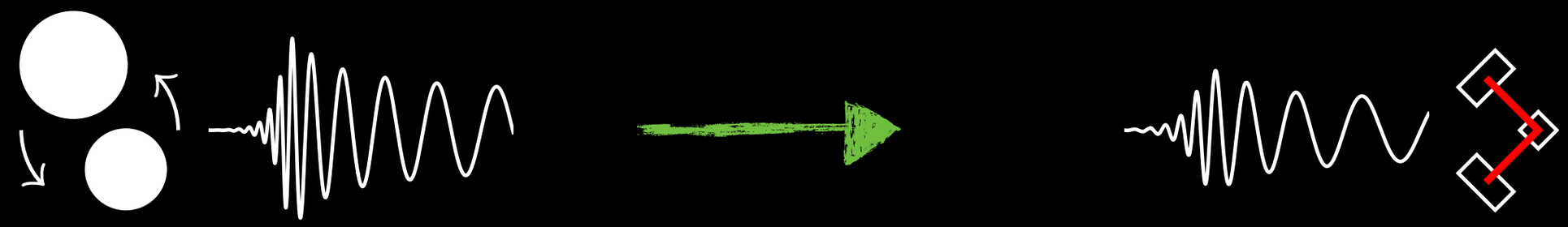
	Initial Conditions	Cosmic Structure	Late acceleration
New Physics?	Inflation Primordial GWs?	Dark Matter Primordial BHs?	Dark Energy Modified Gravity?
Standard	Metric Ansatz $ds^2 = -dt^2 + a(t)^2 d\vec{x}^2$ Maximal spatial symmetry	Standard Matter Atoms/baryons, photons, massive neutrinos	Theory of Gravity $G_{\mu\nu} = 8\pi G T_{\mu\nu}$ Einstein's GR

- *What drives the late time cosmic acceleration?*
- *Is GR valid at cosmological scales?*
- *Is there new physics associated to the tension in H_0?*



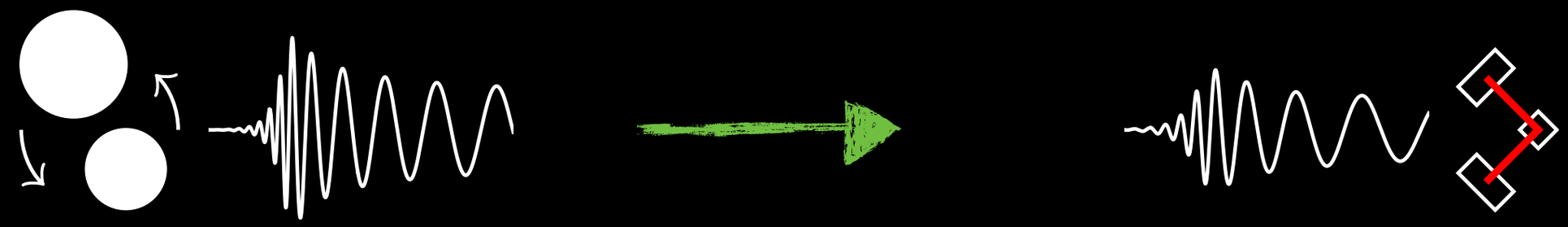

ΛCDM
H_0
Ω_Λ
Ω_M
Ω_R
cosmological principle
general relativity

Cosmological GW propagation



$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda + \Omega_r(1+z)^4}$$

Cosmological GW propagation



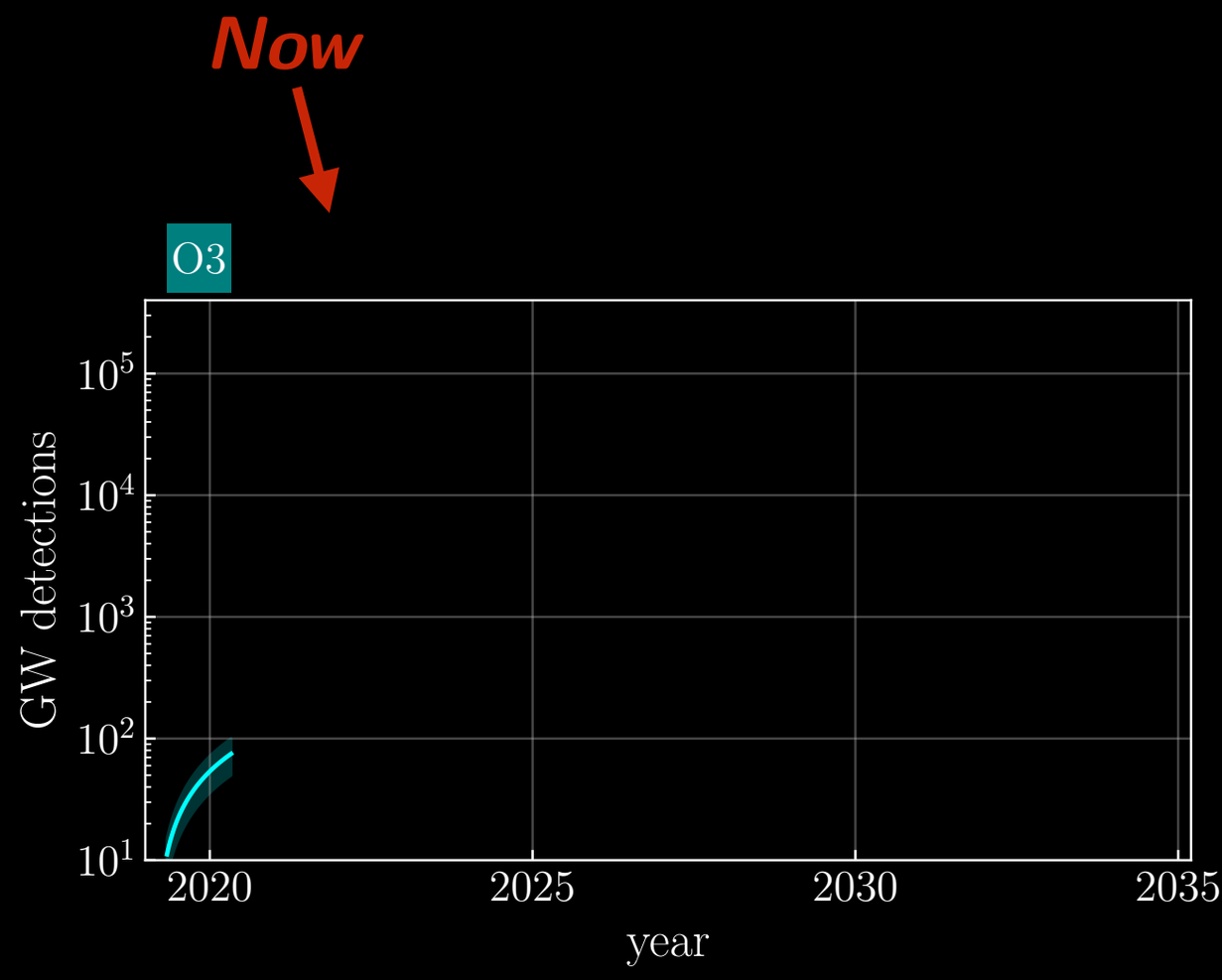
$$h''_A + 2\mathcal{H}h'_A + c^2k^2h_A = 0$$

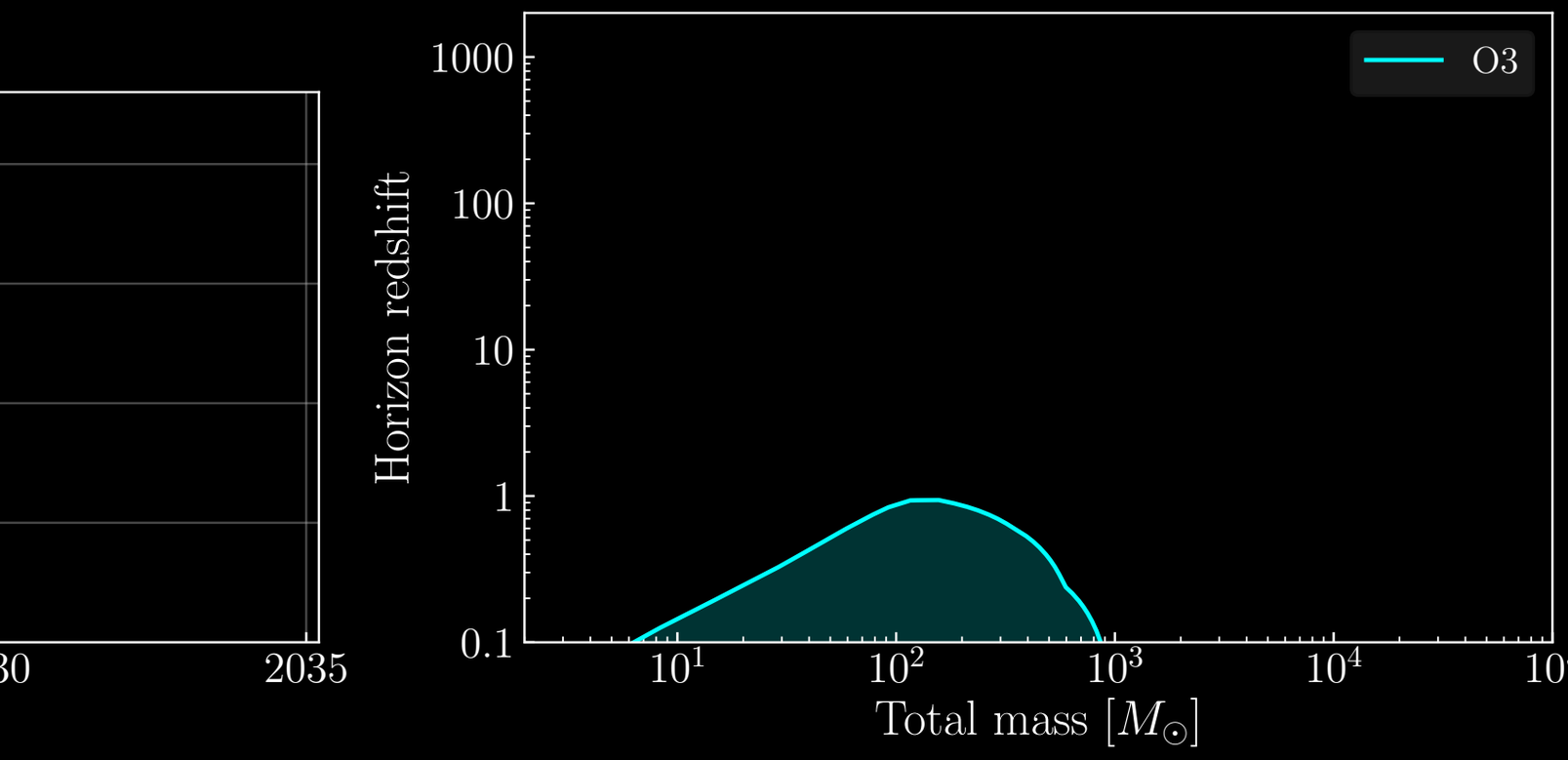
- Expansion rate: changes GW amplitude

$$d_L = (1+z)\int_0^z \frac{cdz}{H(z)}$$

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda + \Omega_r(1+z)^4}$$

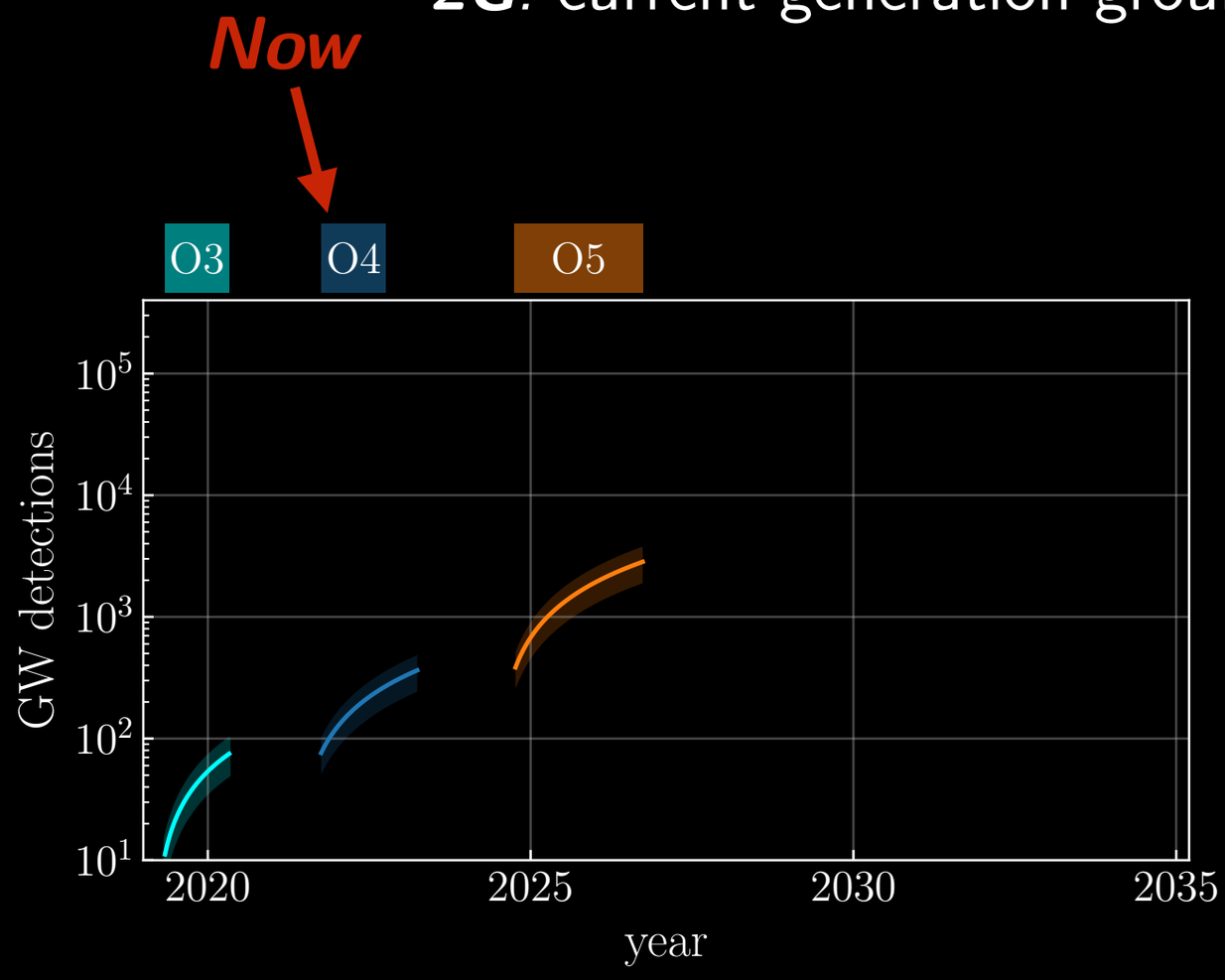
Gravitational wave detectors will constrain expansion history at different redshifts, measuring e.g. H_0, EoS of Dark Energy, Dark Matter

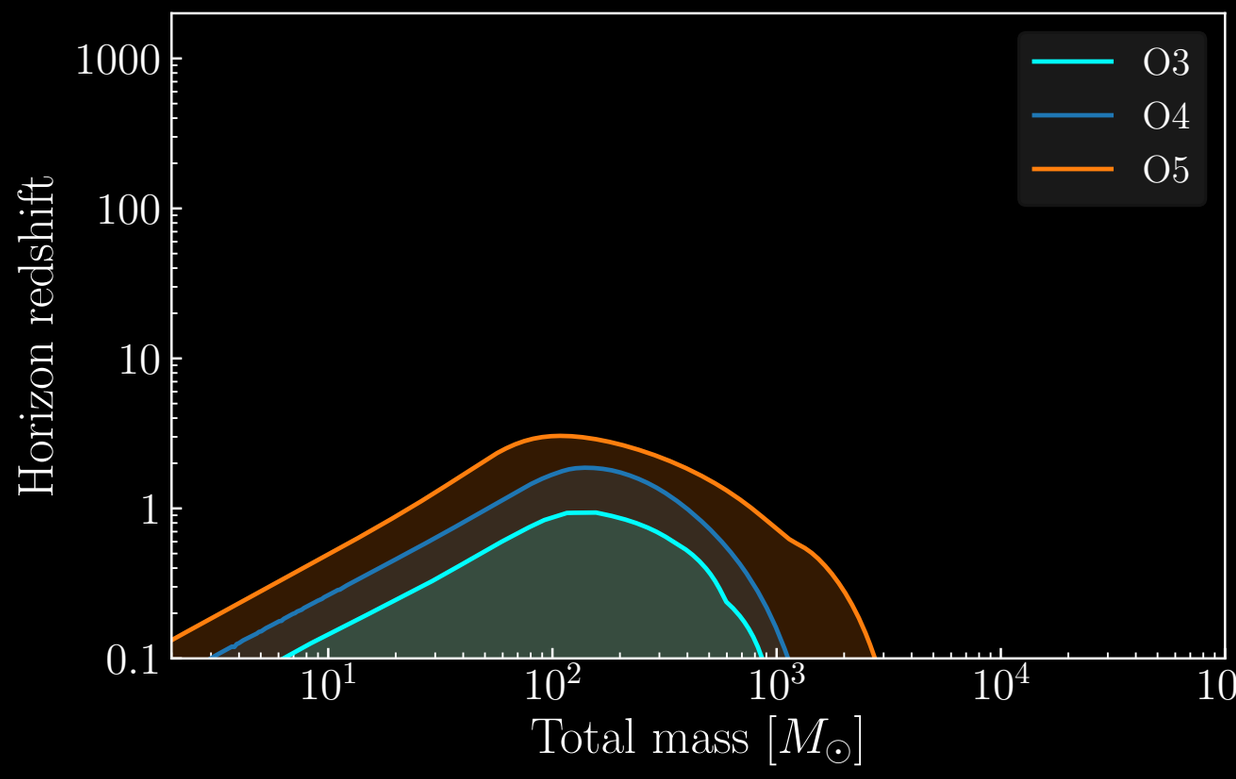




Approx. ***100***
events typically at
$z < 0.6$

***2G**: current generation ground-based GW detectors*





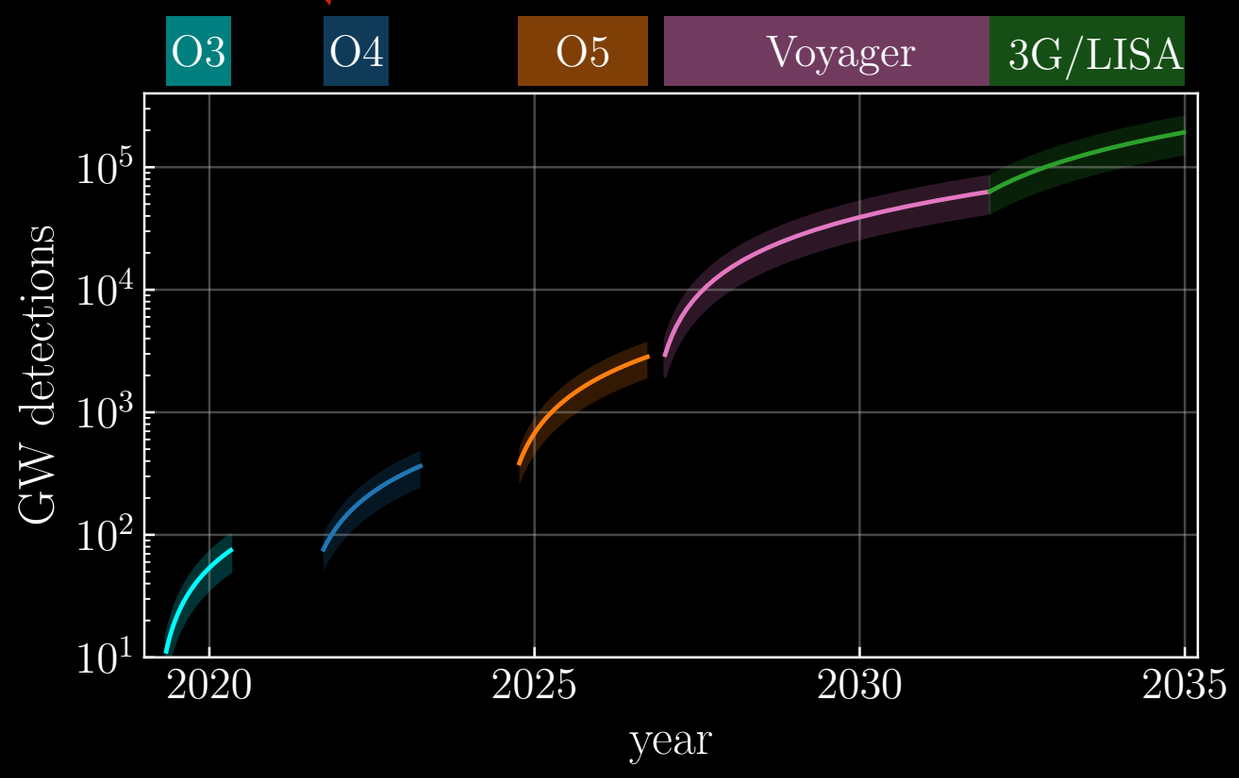
Approx. ***100***
events typically at
$z < 0.6$

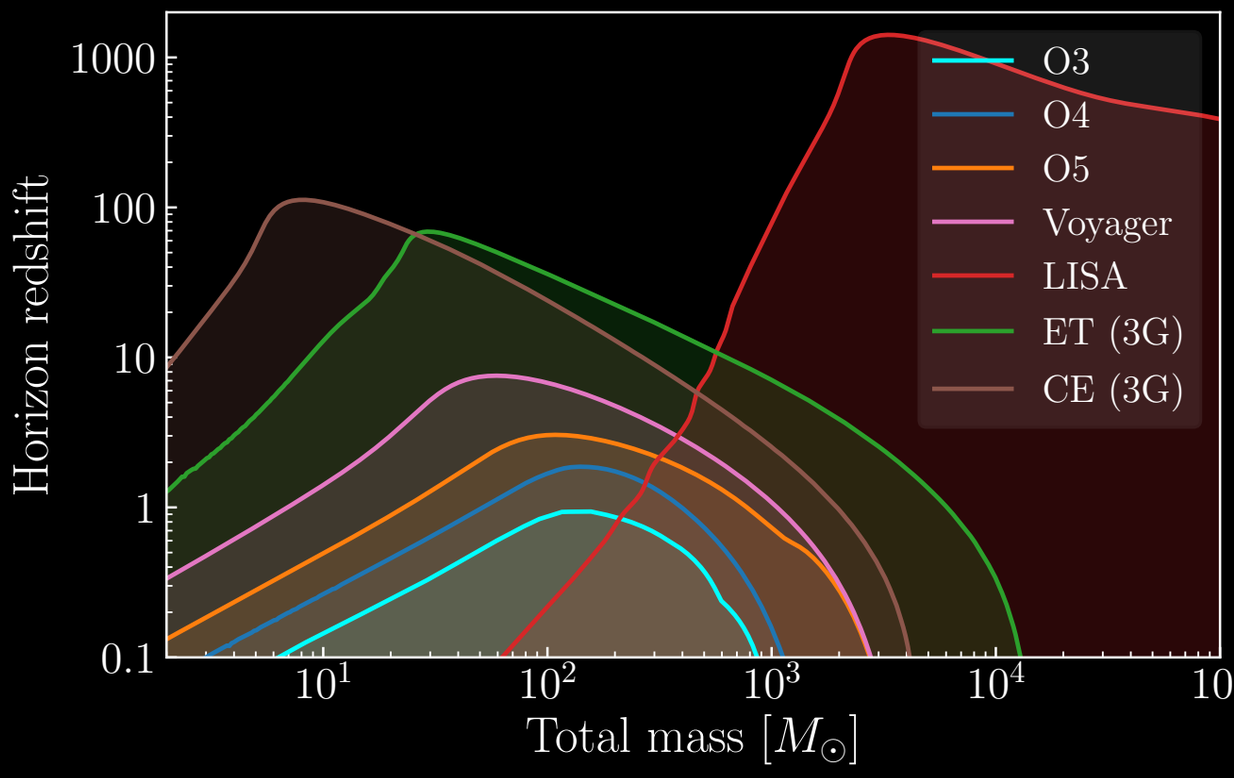
→

1000s / year
with some $z > 1$

***2G**: current generation ground-based GW detectors*

***3G**: next generation ground-based GW detectors*

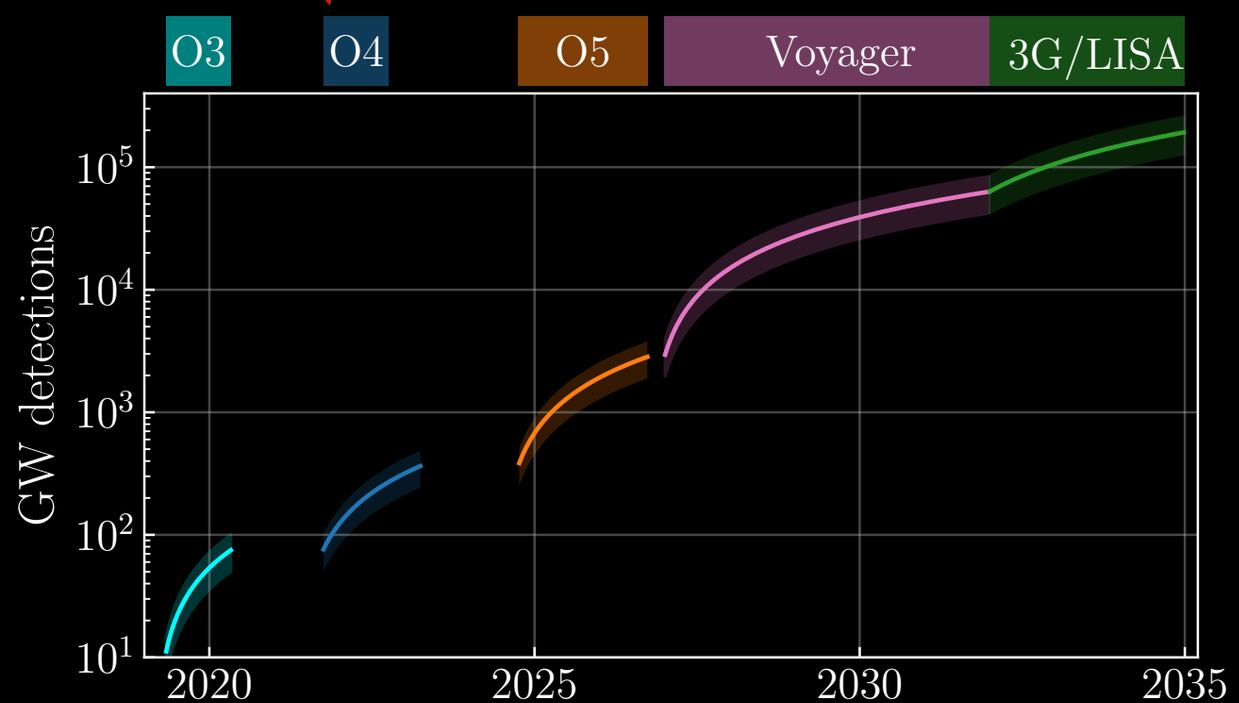


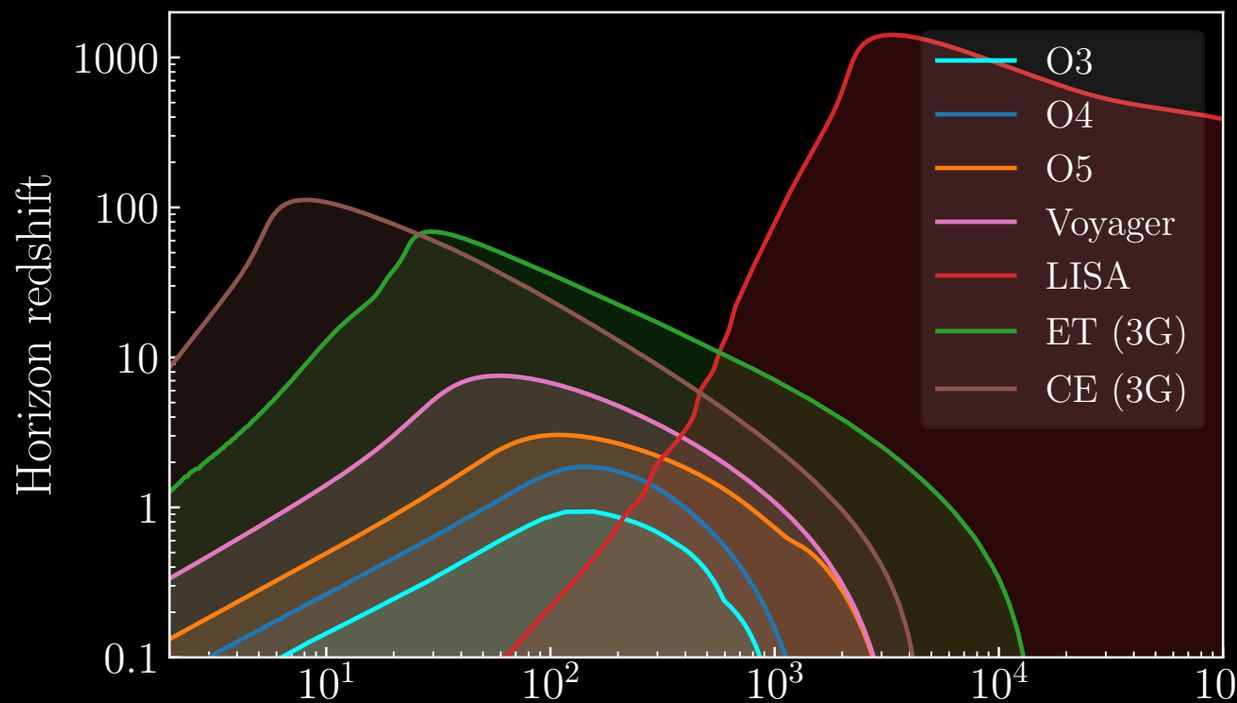


Approx. ***100*** events typically at $z < 0.6$ → ***1000s / year*** with some $z > 1$ → ***100,000s / year*** with most $z > 1$

***2G**: current generation ground-based GW detectors*

***3G**: next generation ground-based GW detectors*



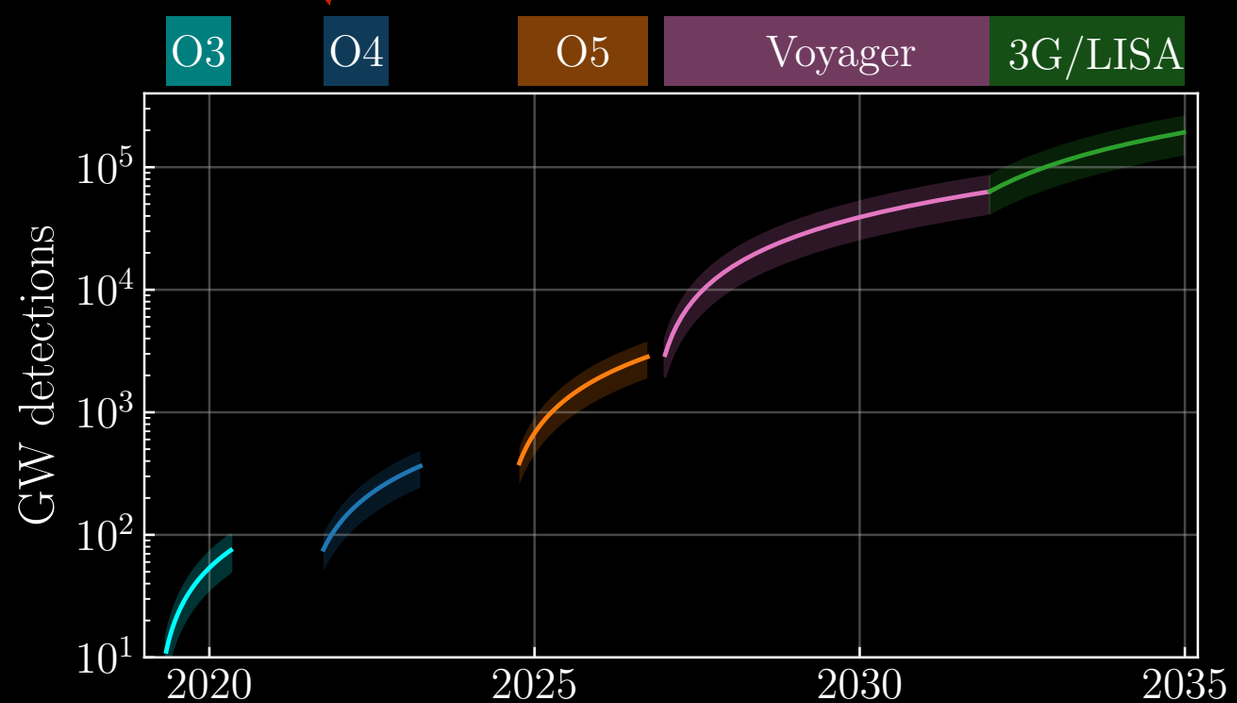


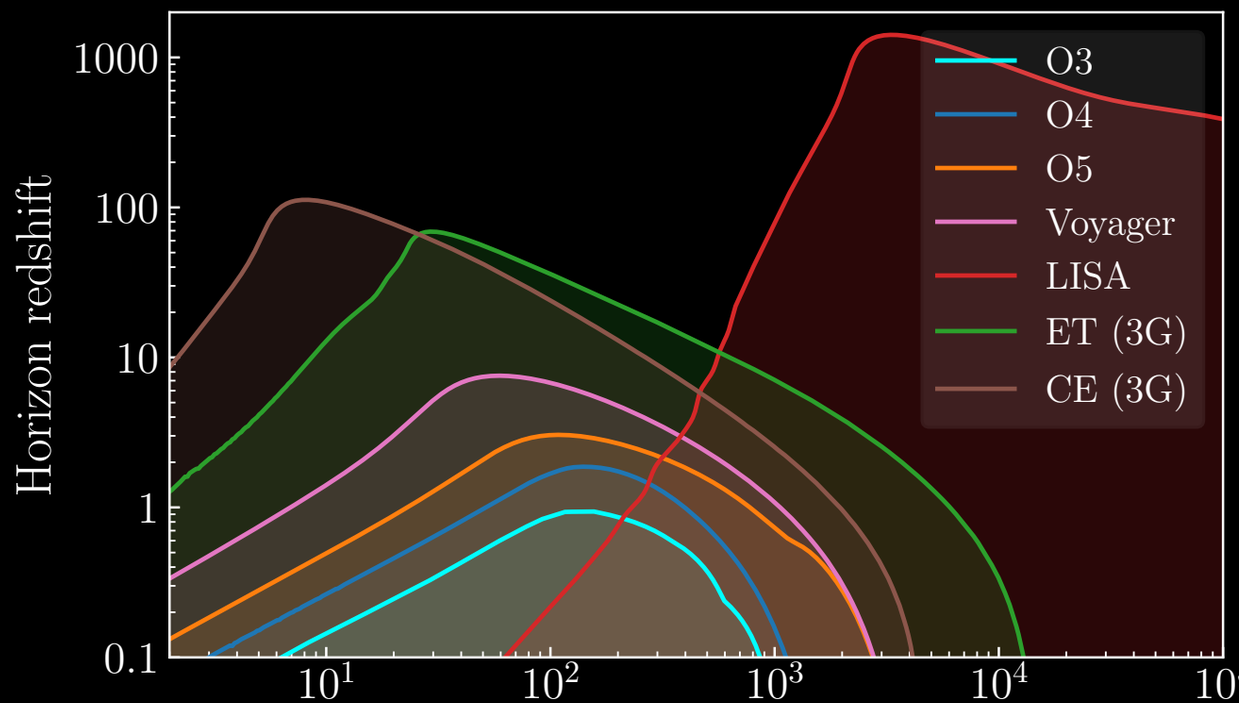
Approx. ***100*** events typically at $z < 0.6$ → ***1000s / year*** with some $z > 1$ → ***100,000s / year*** with most $z > 1$

***2G**: BNS constraints H_0, enough to help with Hubble tension?*

***2G**: current generation ground-based GW detectors*

***3G**: next generation ground-based GW detectors*





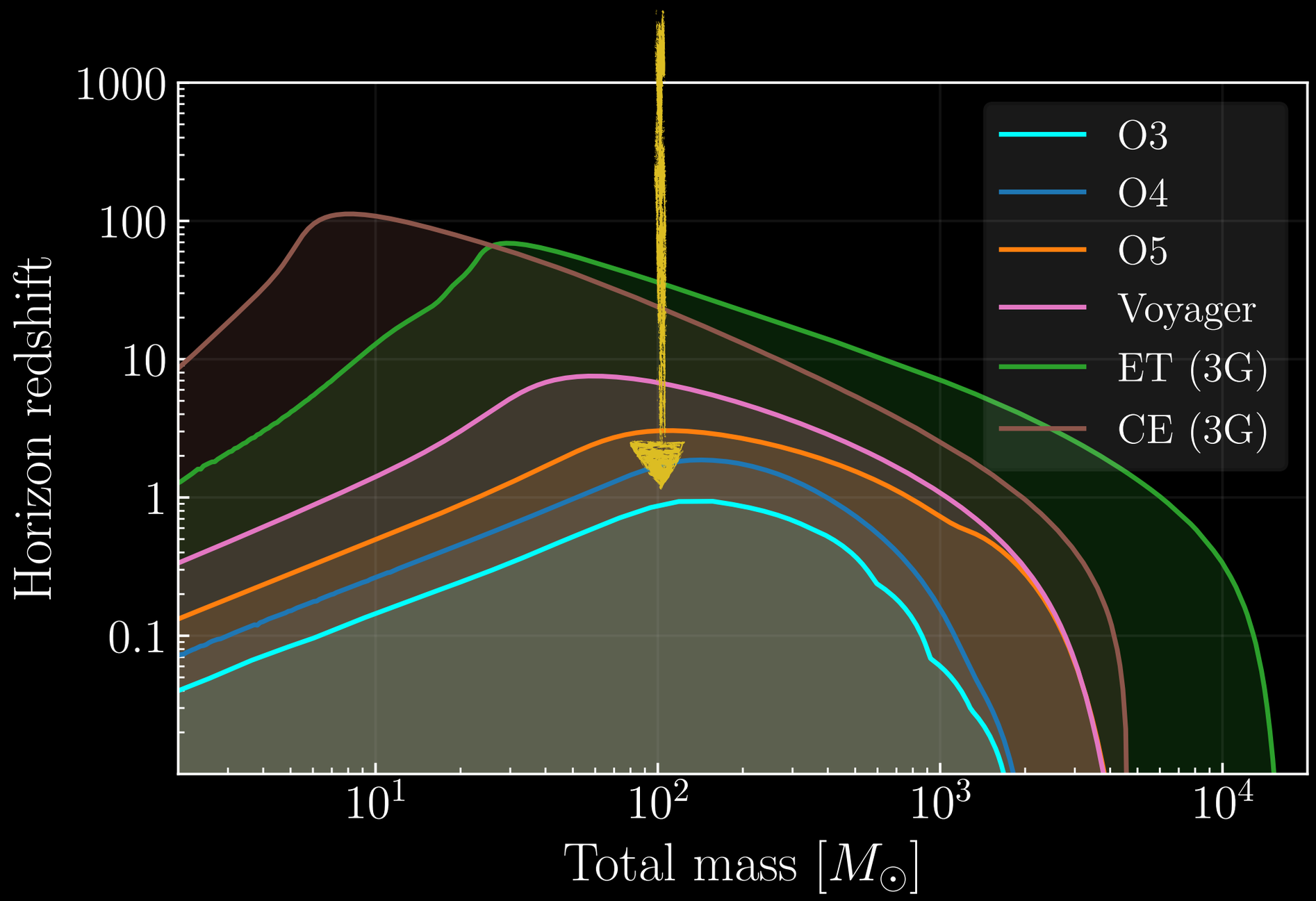
Approx. ***100*** events typically at $z < 0.6$ → ***1000s / year*** with some $z > 1$ → ***100,000s / year*** with most $z > 1$

***2G**: BNS constraints H_0, enough to help with Hubble tension?*

*3**G**: BBHs spectral sirens H(z>2), new physics?*

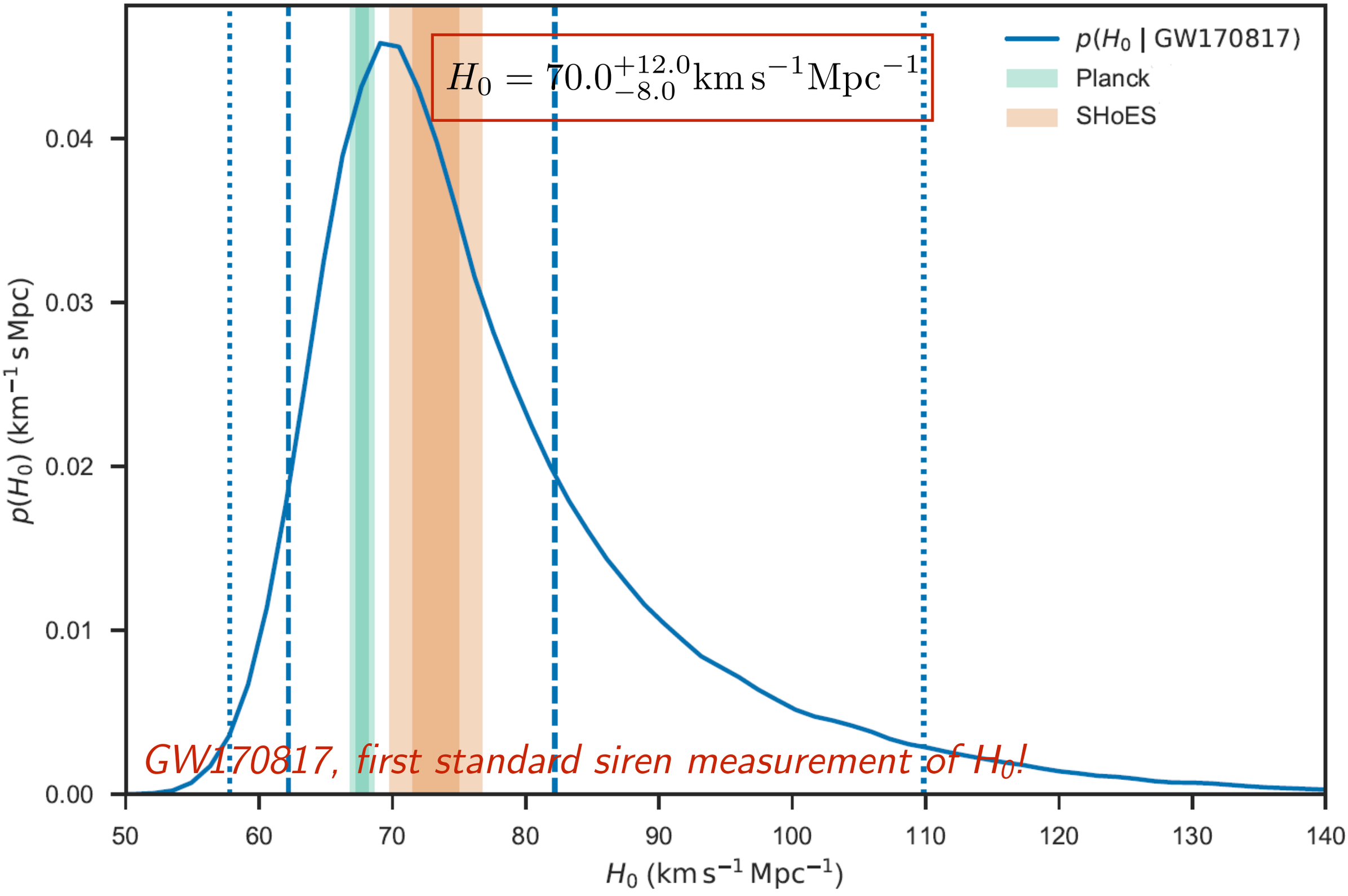
All compact binaries are standard sirens, no electromagnetic information is necessary

Currently, binary black holes most promising



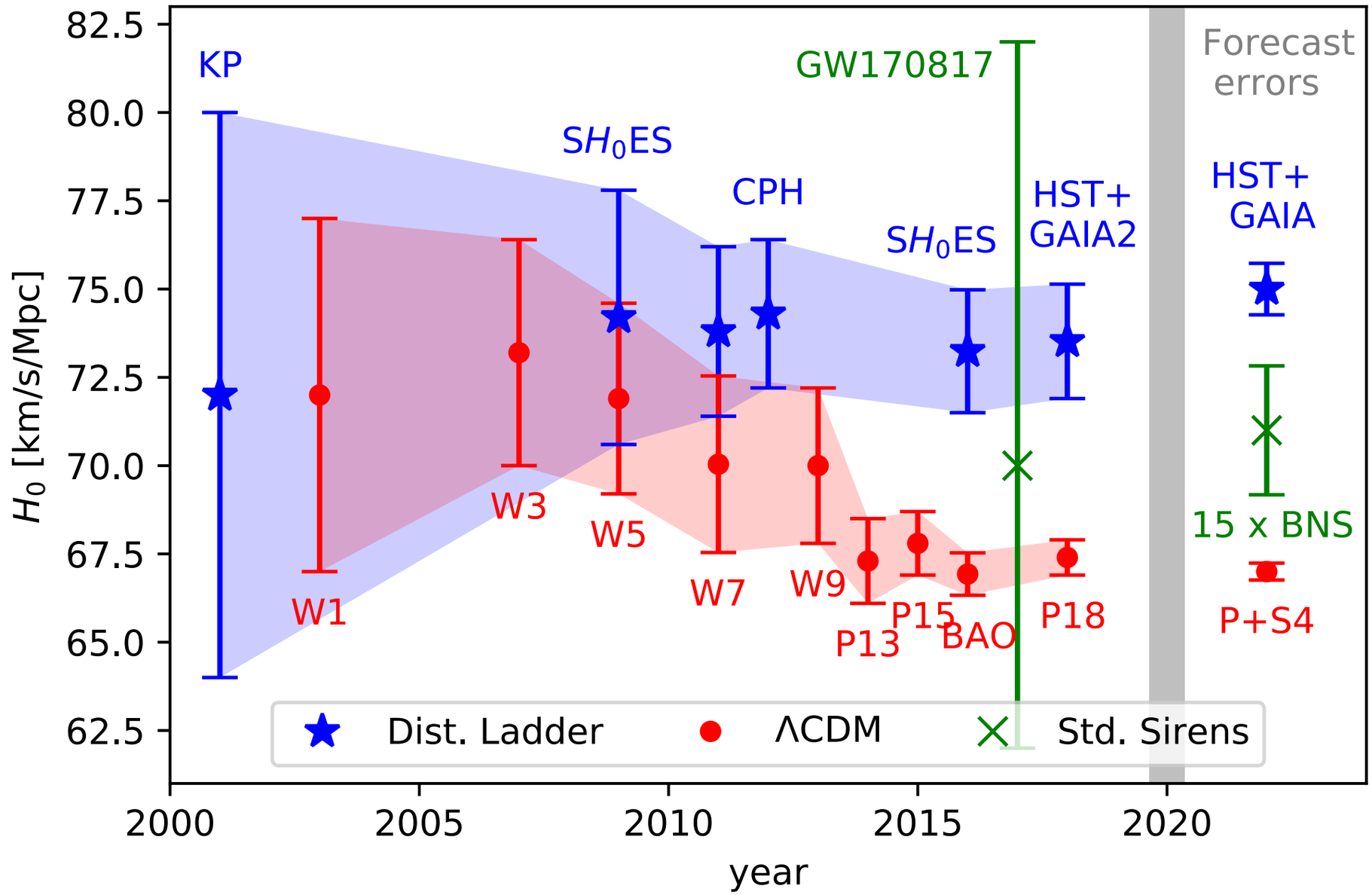
Bright sirens

[Nature 551, 85 (2017)]



GW170817, first standard siren measurement of H_0!

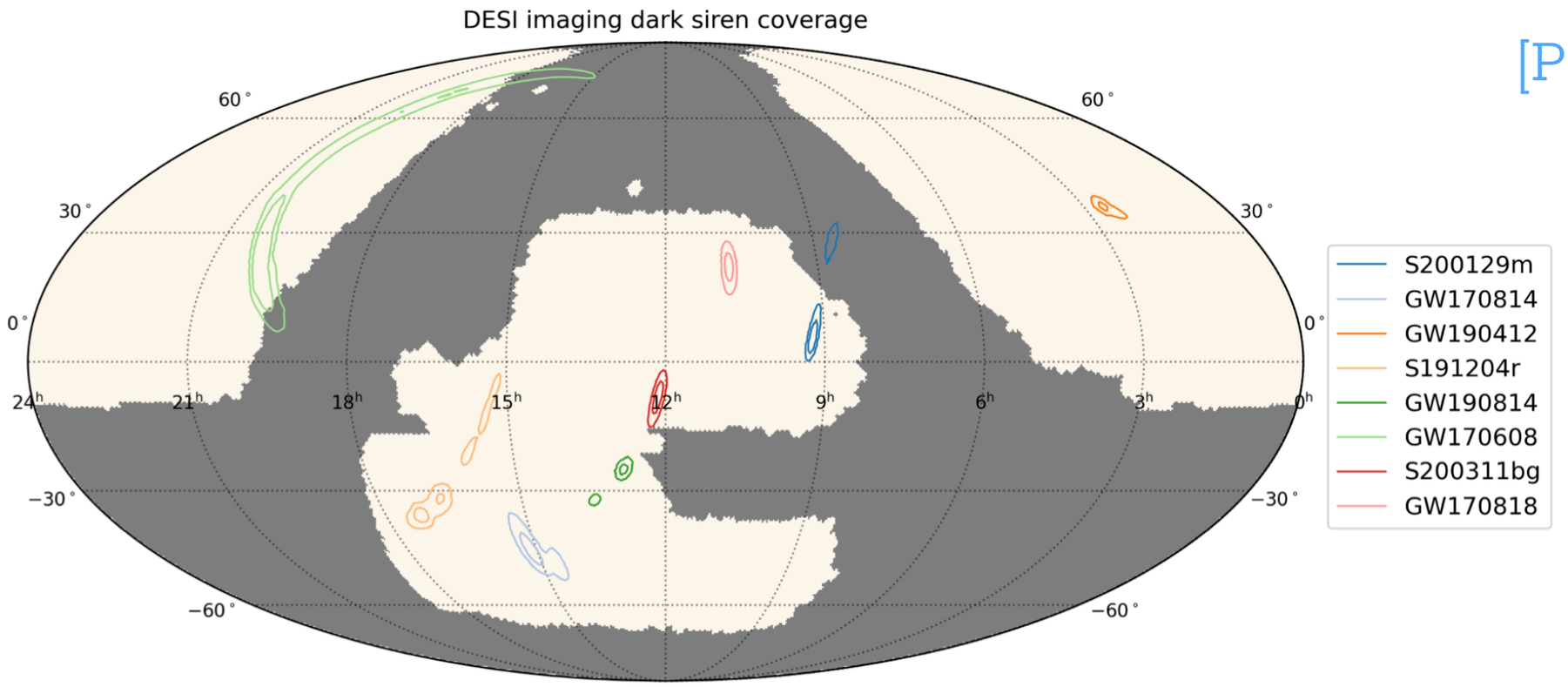
Solve Hubble tension?



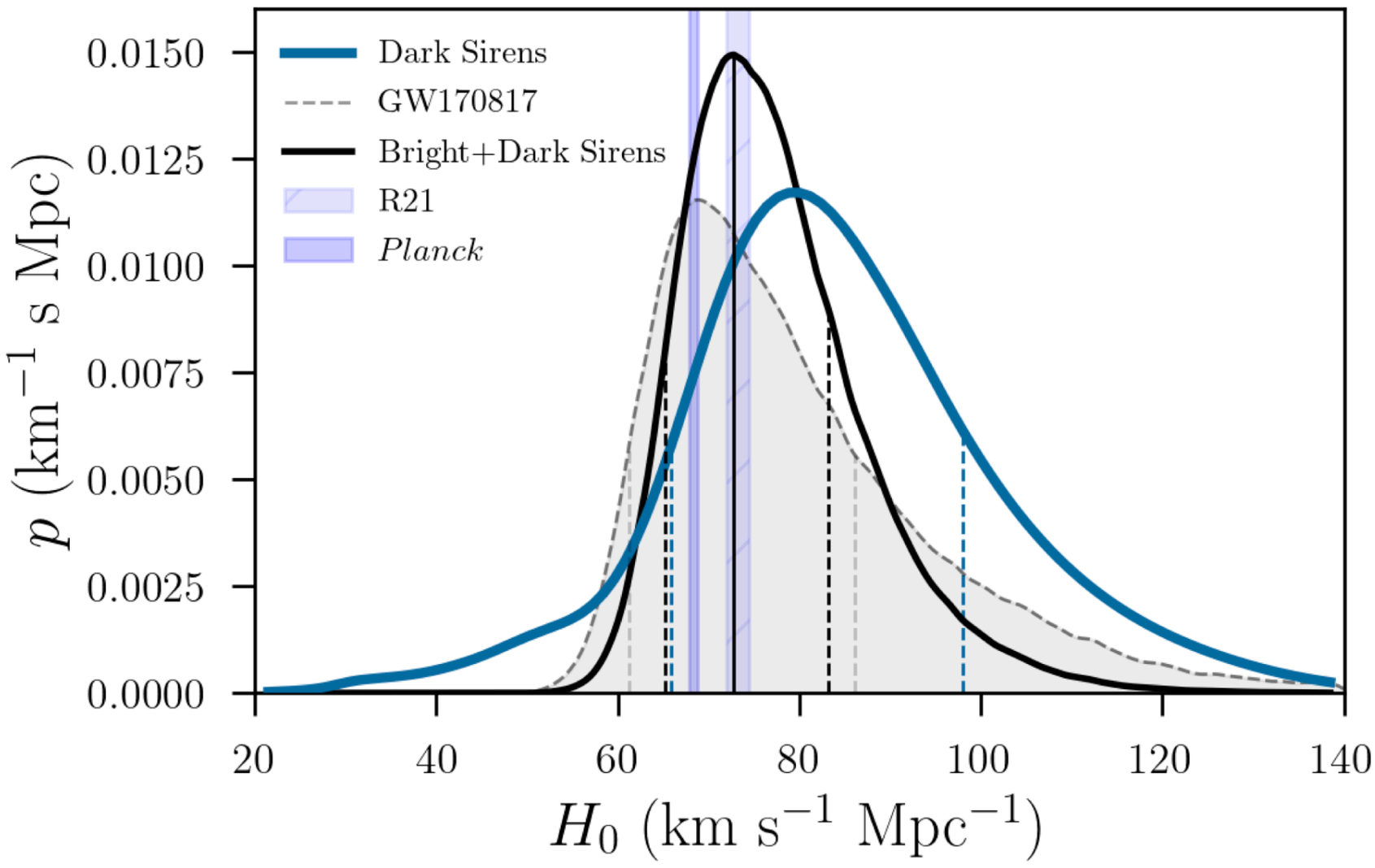
Predictions for O4: $7.7^{+11.9}_{-5.7}\mathrm{yr}^{-1}$ BNS

[2204.07592] 74% kilonova, 2% GRB

[Palmese et al., ApJ'23]

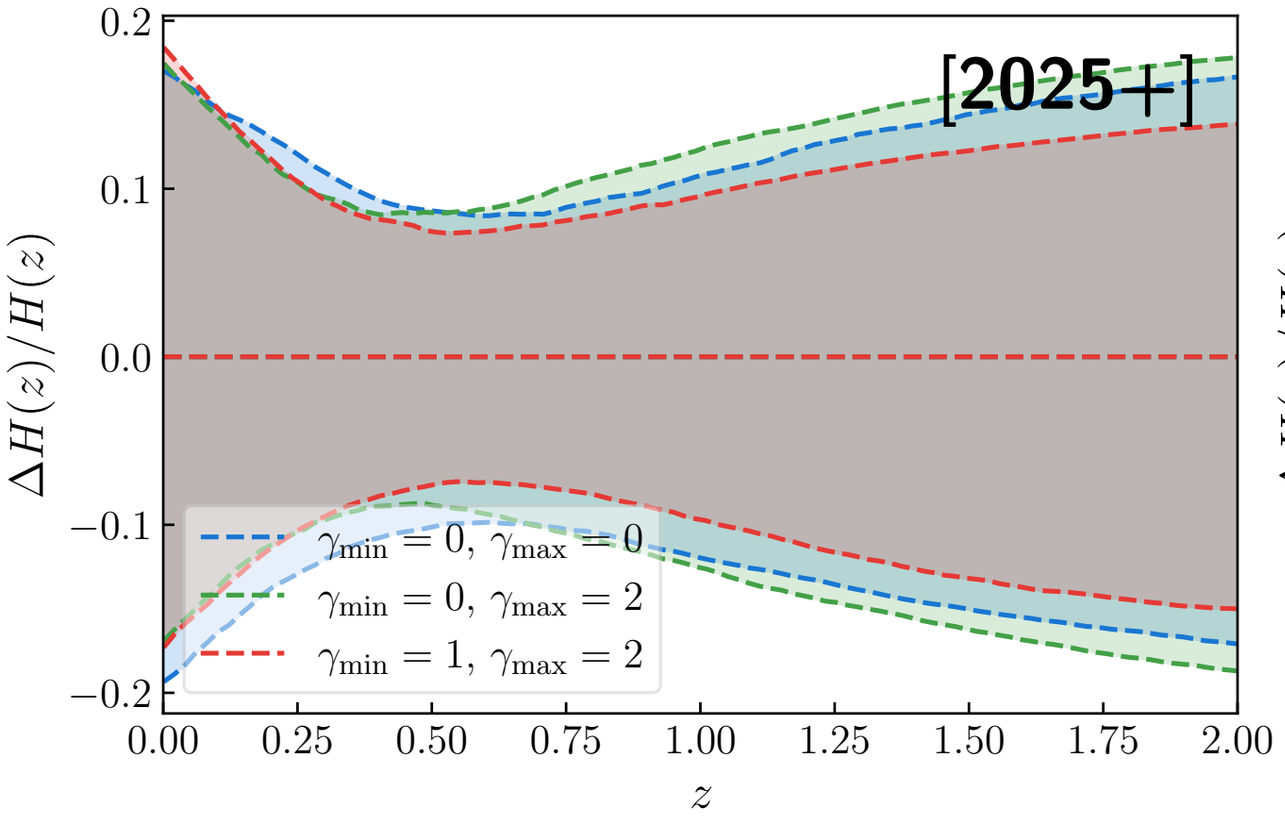


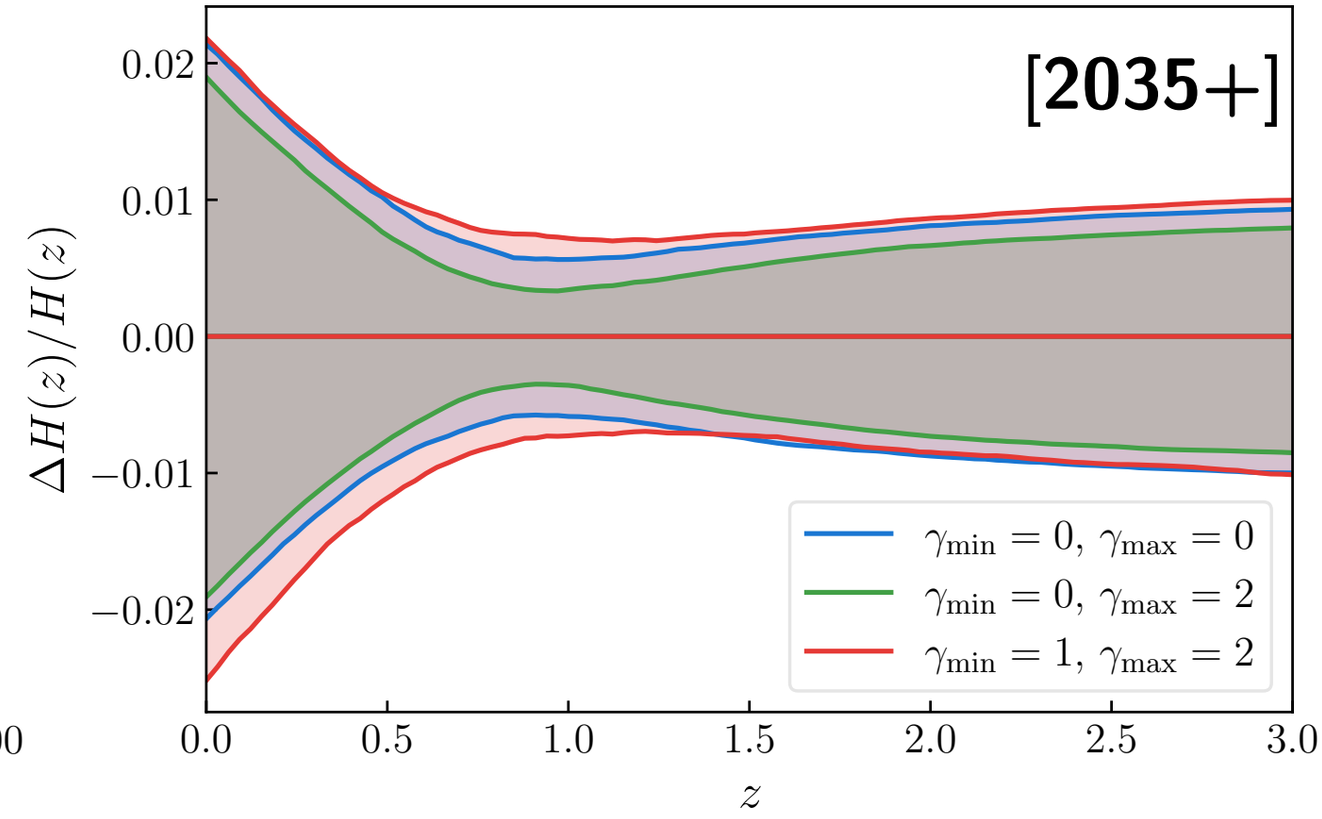
Dark sirens



Spectral sirens: forecasts

[**BBHs** between NSBH and PISN gap]

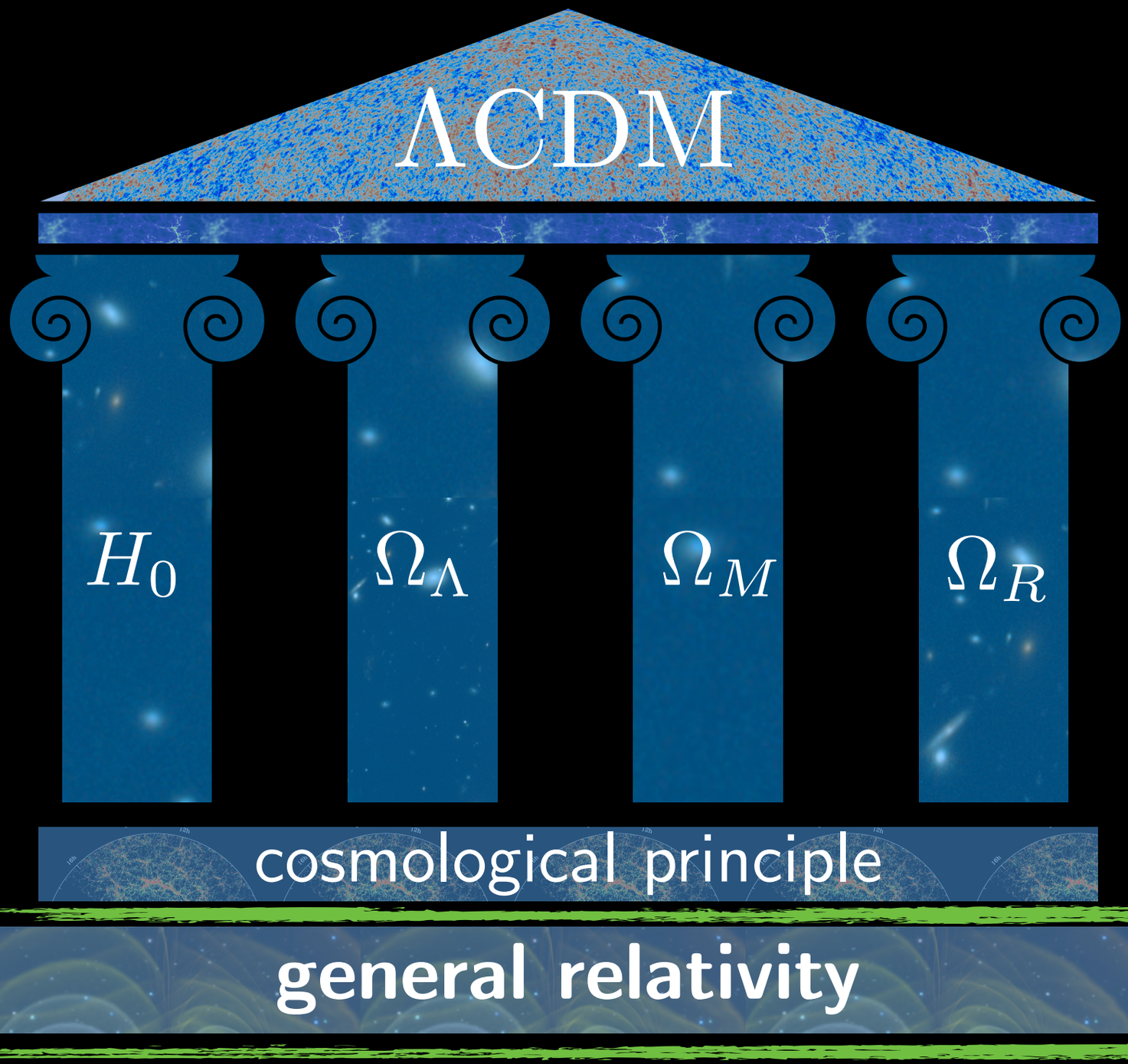




2G: **<10%** within 1 year at approx. z=0.7

3G: **Sub-percent** within 1 month. High-redshift!

Ezquiaga & Holz; *Spectral sirens: cosmology from full mass distribution* (PRL, arXiv 2202.08240)


ΛCDM
H_0
Ω_Λ
Ω_M
Ω_R
cosmological principle
general relativity

General Relativity

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

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

General Relativity

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

Massive Gravity $m_g > 0$

dRGT

Additional Field

Tensor $f_{\mu\nu}$

Bigravity

Multi-gravity

Vector V_μ

Proca $m_V > 0$

General. Proca

Beyond gen.Proca

TeVeS (MoND)

Scalar ϕ

Horndeski

Quint-essence

Brans-Dicke

$f(R)$

KGB

Galileon

Gauss-Bonnet

Beyond Horndeski

$C(X)$

$D(X)$

Break Assumptions

Extra dimensions

Non-Local

Lorentz Violating

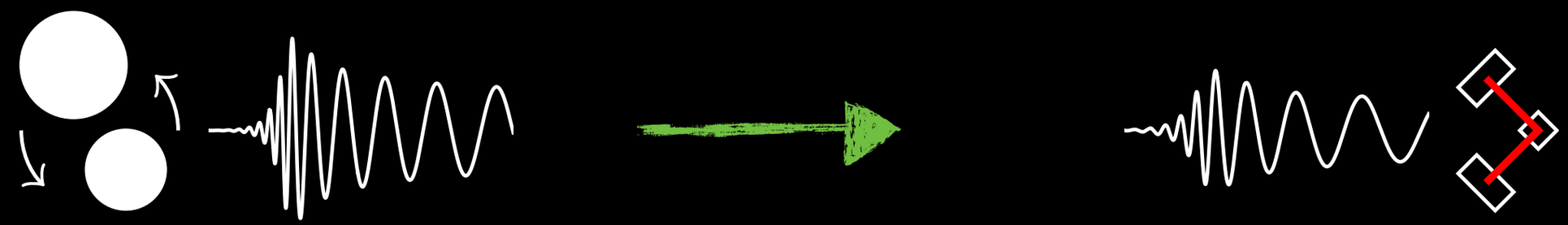
Horava

Einstein Aether

For a review see:

Ezquiaga & Zumalacárregui; *Dark energy in light of GW astronomy* (Frontiers, arXiv 1807.09241)

Modified GW propagation



$$h_A'' + (2+\nu)\mathcal{H}h_A' + (c_g^2 k^2 + \Delta\omega)h_A = \mathcal{O}_{AB}h_B$$

- Speed: changes arrival time
- Amplitude: modifies luminosity distance
- Phase: may produce waveform distortions
- Polarization: birefringence, additional tensor modes

Small deviations accumulate over cosmological propagation times!

For propagation effects beyond cosmological backgrounds:
Ezquiaga & Zumalacárregui; *GW lensing beyond GR* (PRD, arXiv 2009.12187)

The speed of GWs

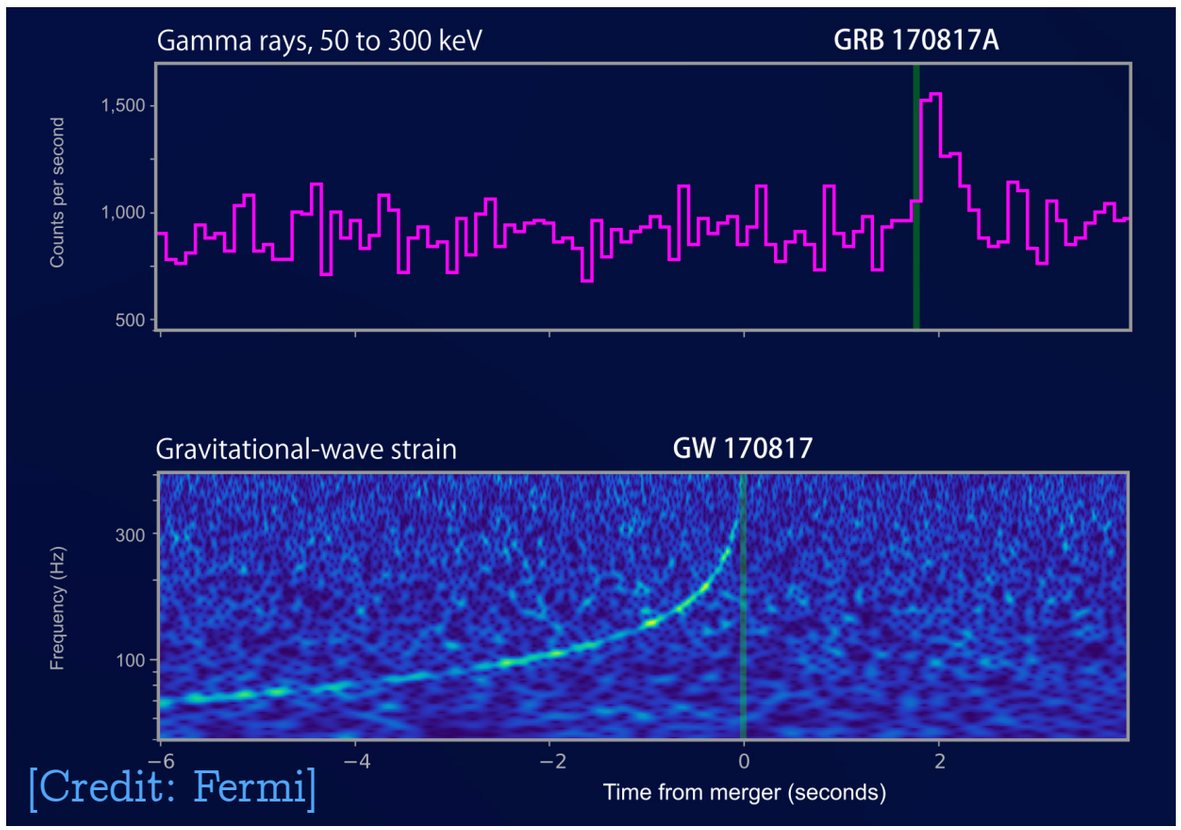
General relativity predicts: $\boxed{c_g = c}$

The speed of GWs

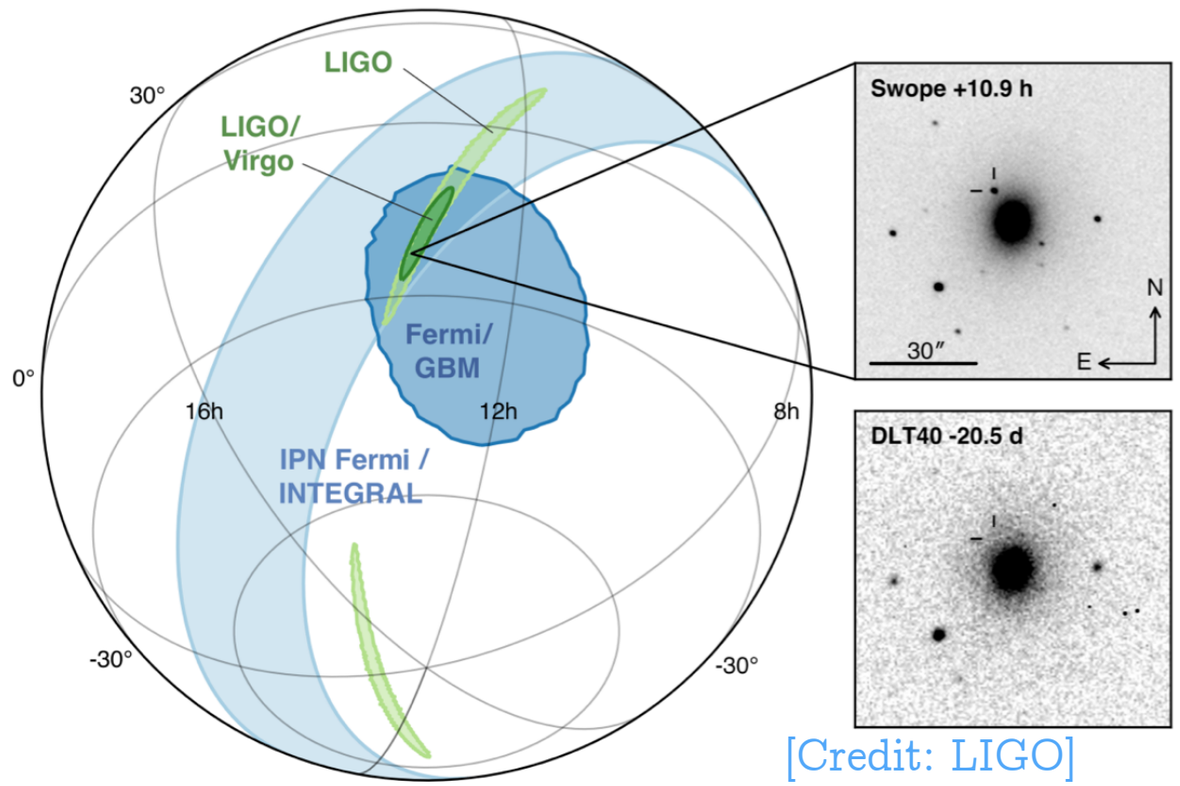
General relativity predicts: $c_g = c$

GW170817: *multi-messenger* event [LVC, Fermi, INTEGRAL'17]

$$-3 \cdot 10^{-15} \leq c_g/c - 1 \leq 7 \cdot 10^{-16}$$



[Credit: Fermi]

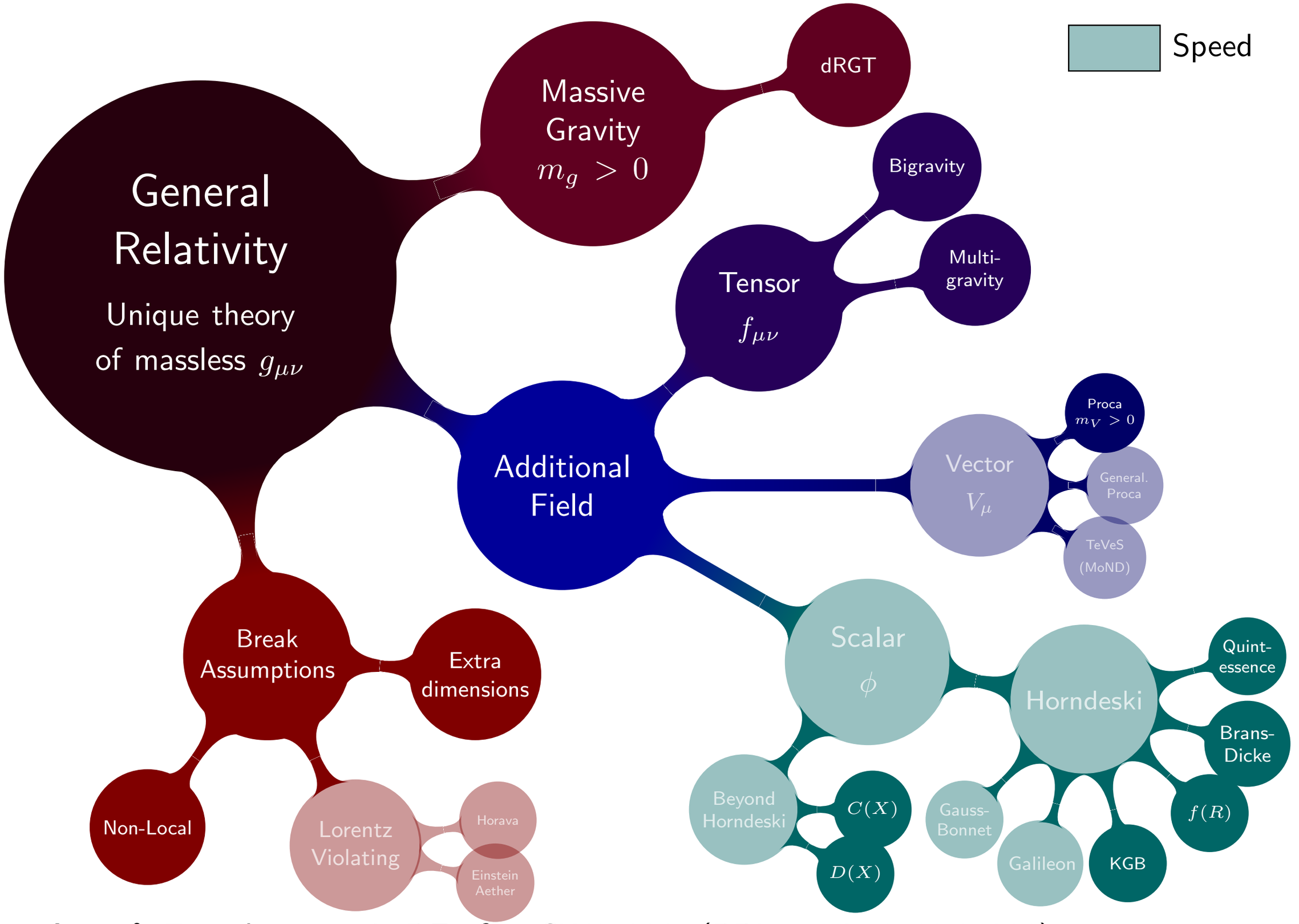


[Credit: LIGO]

Modified gravity roadmap and GW astronomy

Constrained by

Speed



Ezquiaga & Zumalacárregui; *DE after GW170817* (PRL, arXiv 1710.05901)

GW luminosity distance

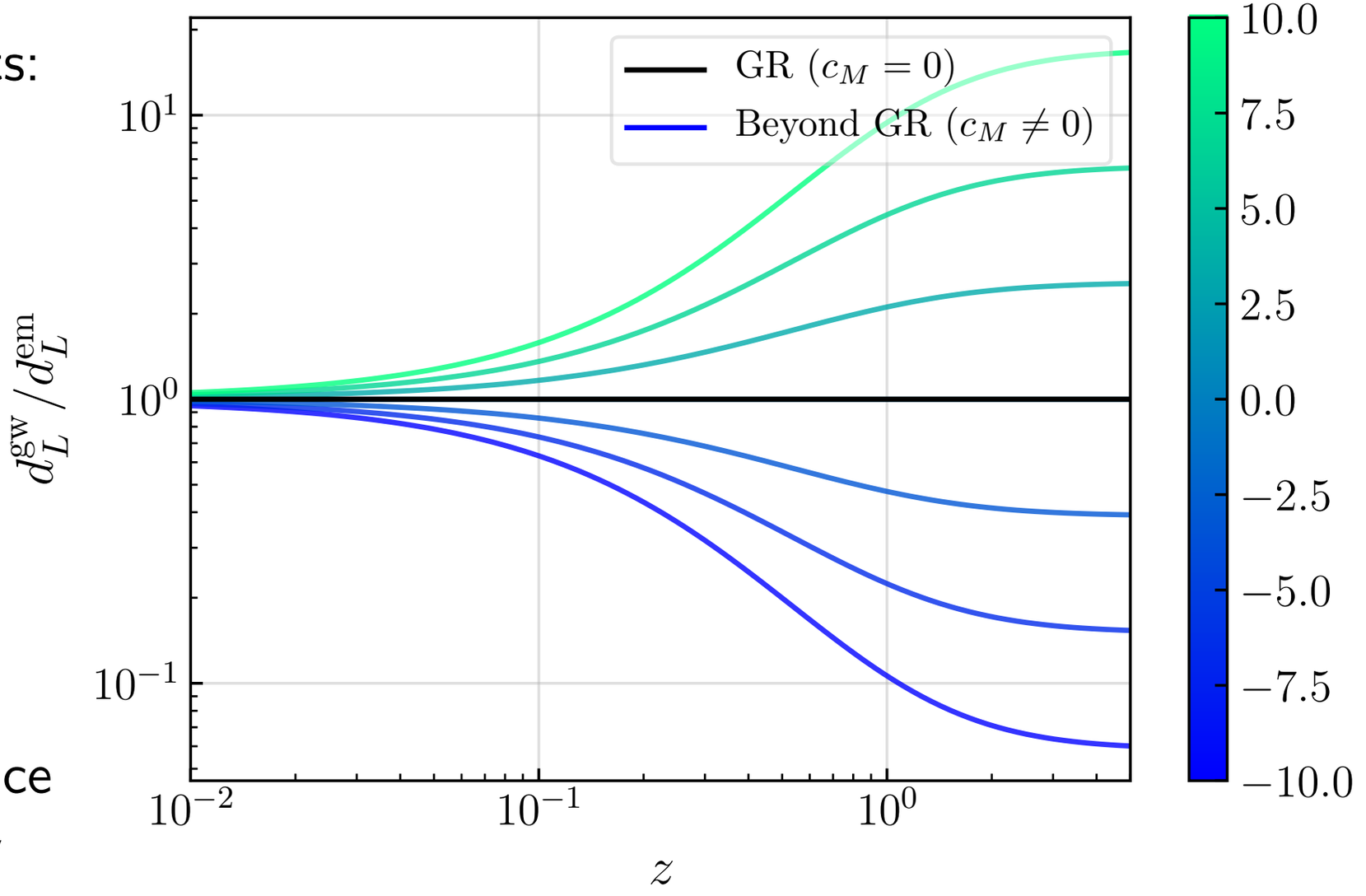
General relativity predicts:

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

GW luminosity distance

General relativity predicts:

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



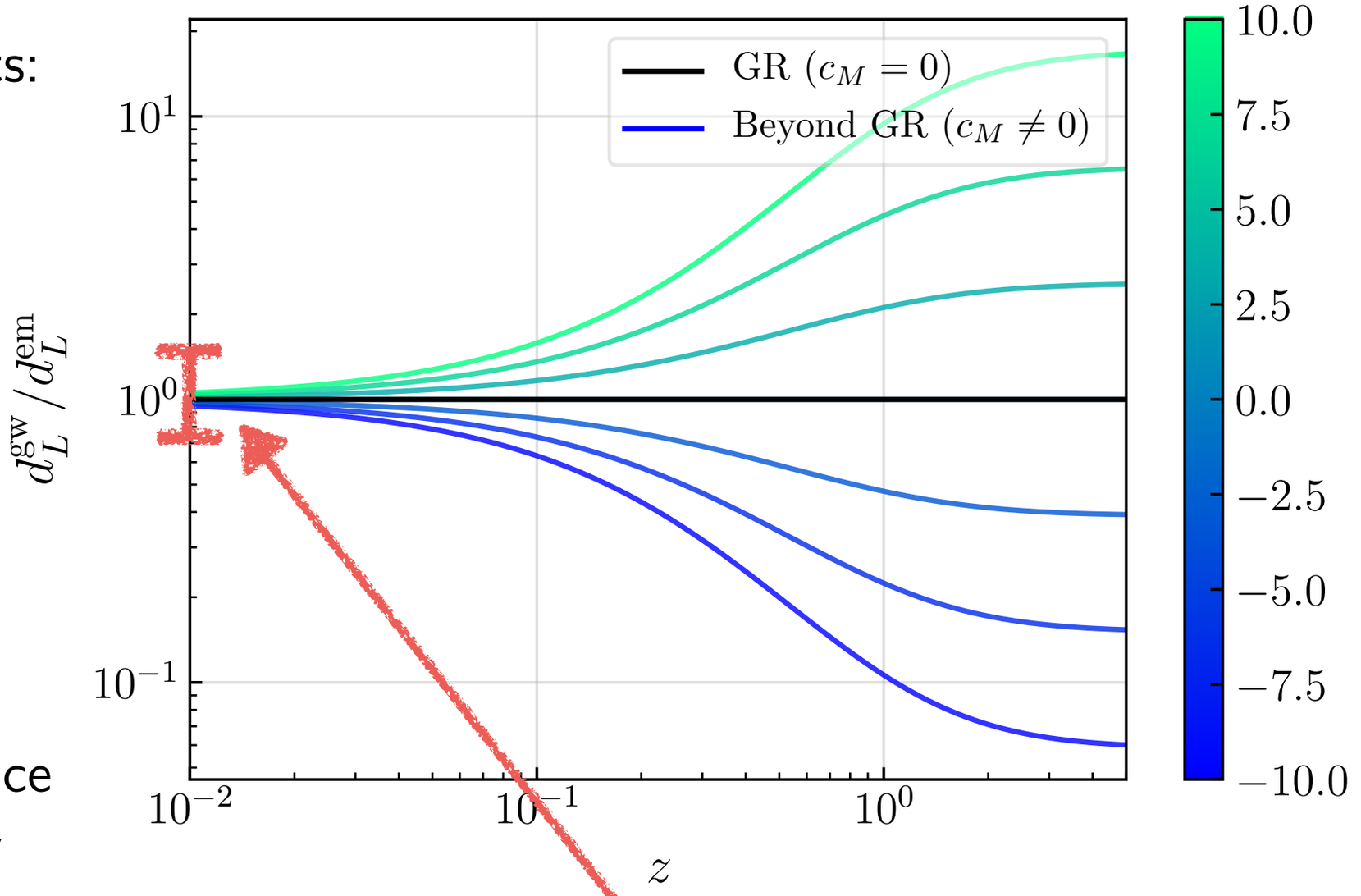
Modified luminosity distance triggered by dark energy

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

GW luminosity distance

General relativity predicts:

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



Modified luminosity distance triggered by dark energy

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

Bright sirens (GW170817)

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

[Lagos+'19]

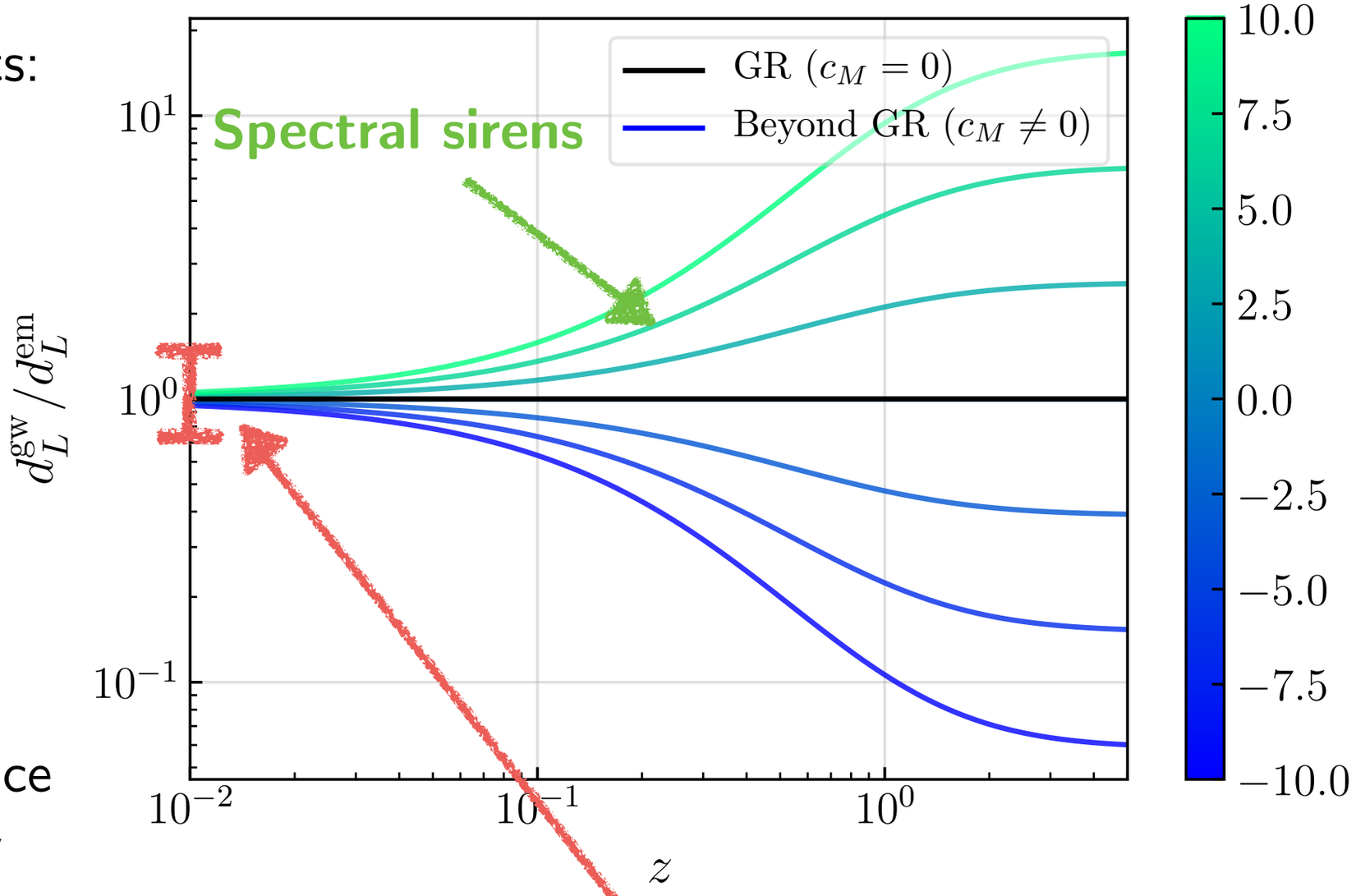
GW luminosity distance

General relativity predicts:

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

Modified luminosity distance triggered by dark energy

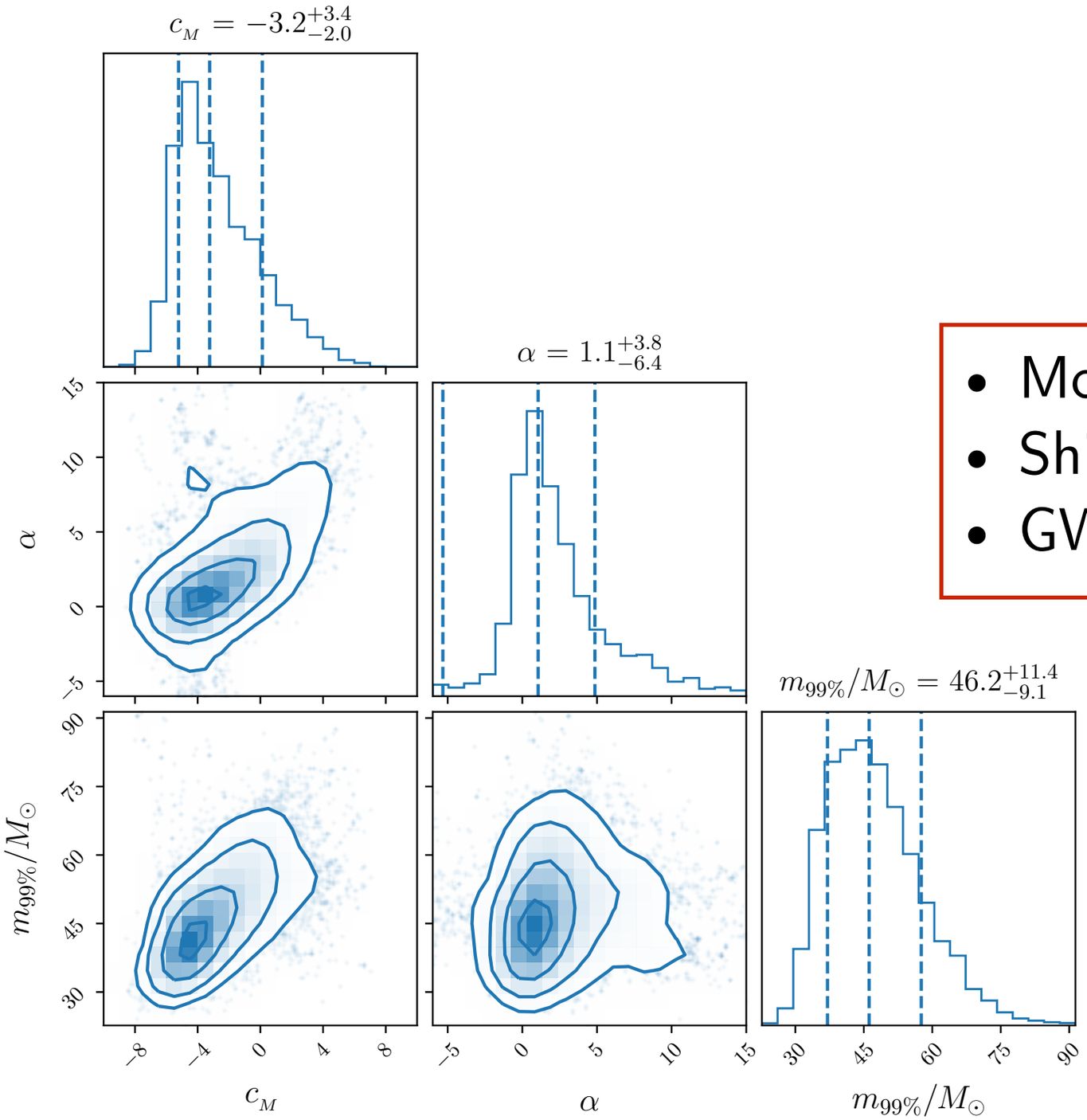
$$\frac{d_L^{\rm gw}}{d_L^{\rm em}} = \exp\left[\frac{c_M}{2}\int_0^z \frac{\Omega_{DE}(z')}{(1+z')\Omega_{DE}(0)}{\rm d}z'\right]$$



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

[Lagos+'19]

Results from GWTC-2



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

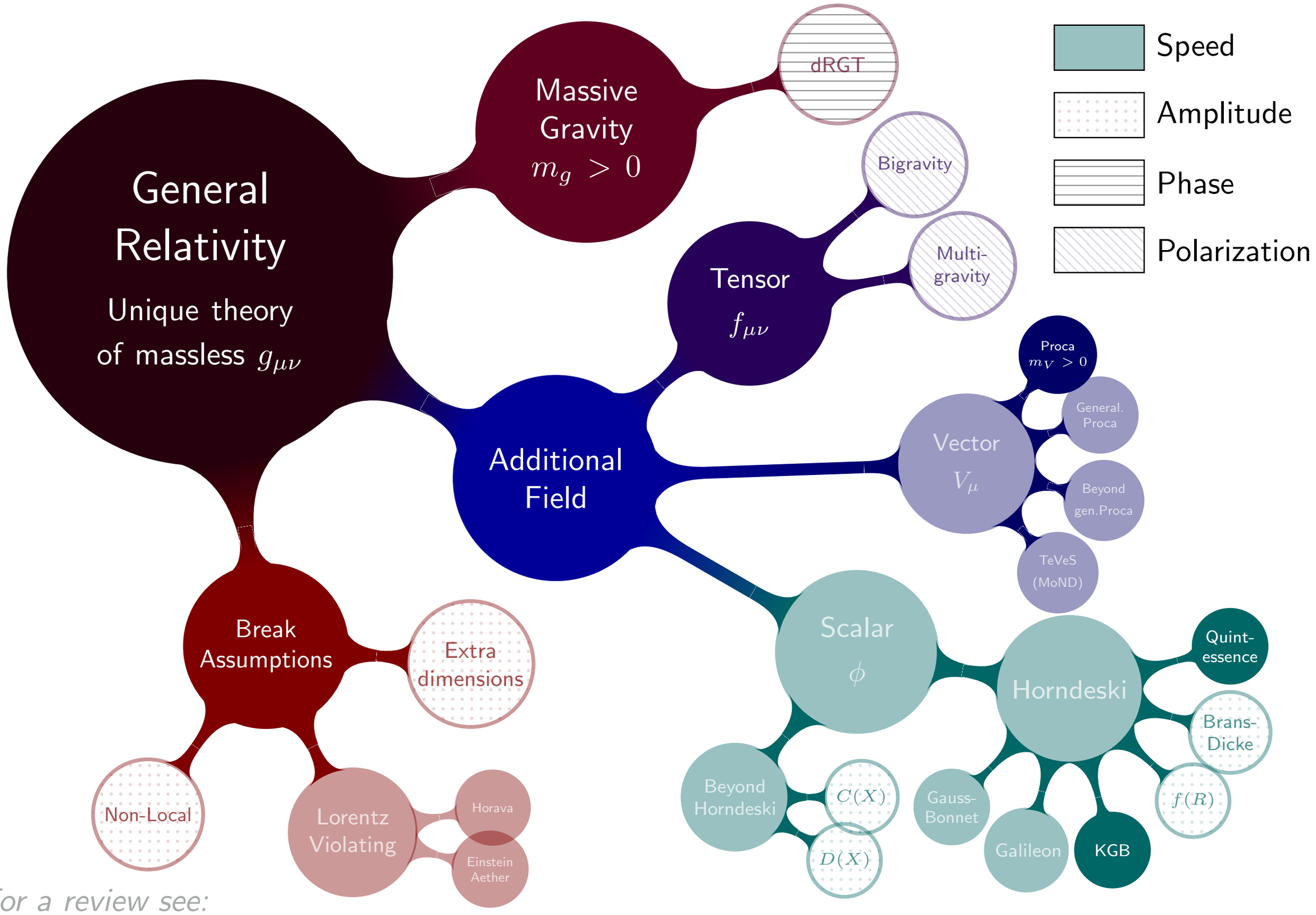
- More constraining than GW170817
- Shifts $m_{99\%}$ to lower values
- GW data only!

GWTC-2 = O1+O2+O3a
GWTC-3 = O1+O2+O3a+O3b

See Mancarella et al.'21 and Leyde et al.'22 for GWTC-3 constraints!

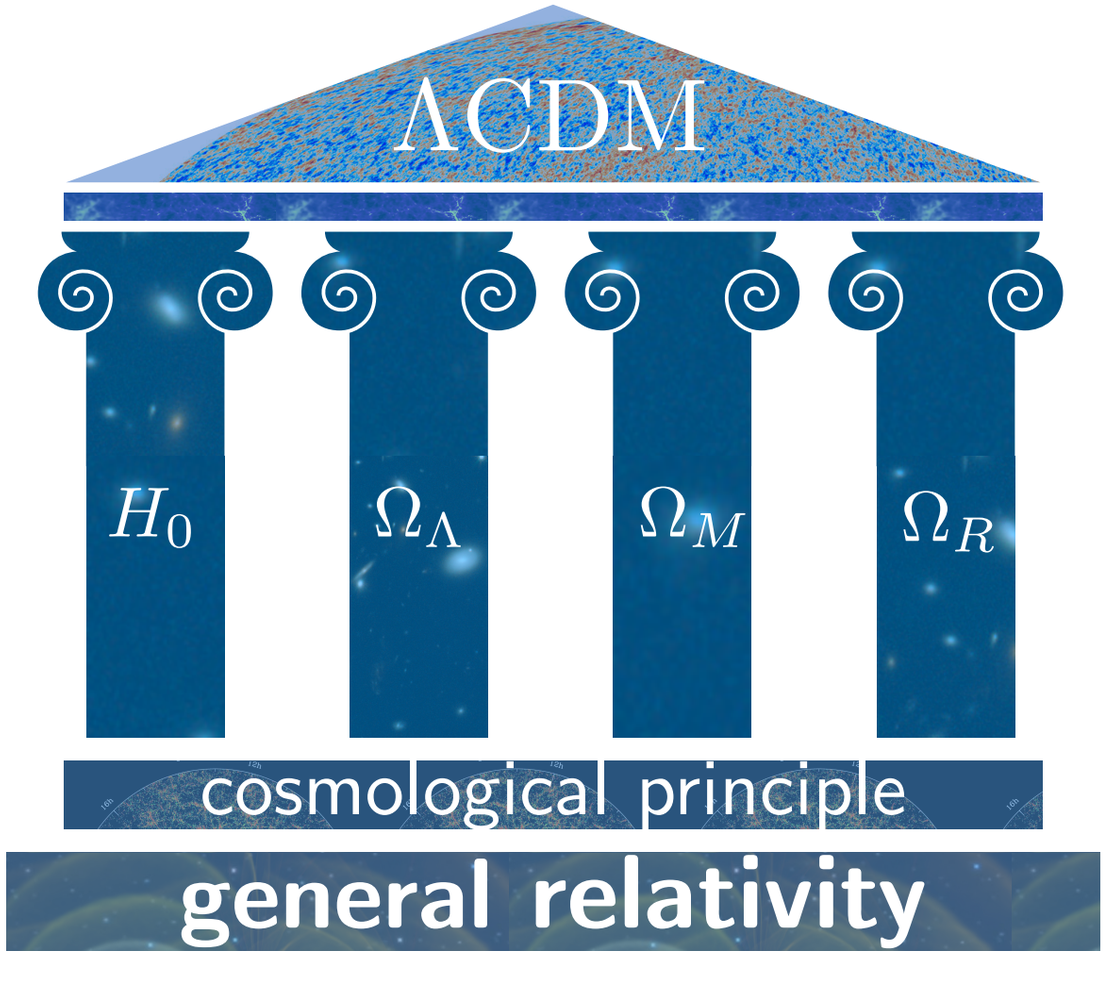
Ezquiaga; *Hearing gravity form the cosmos* (Phy.Lett.B, arXiv 2104.05139)

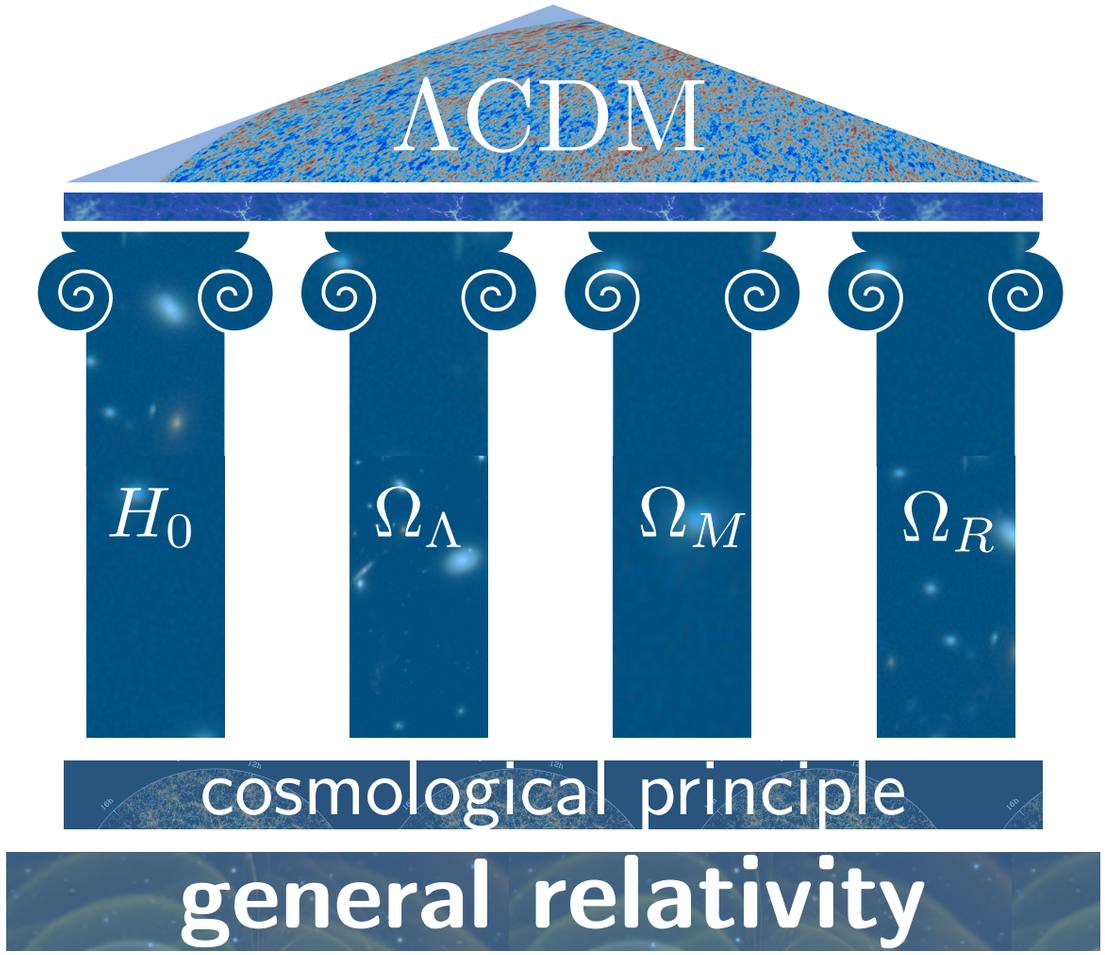
Modified gravity roadmap and GW astronomy

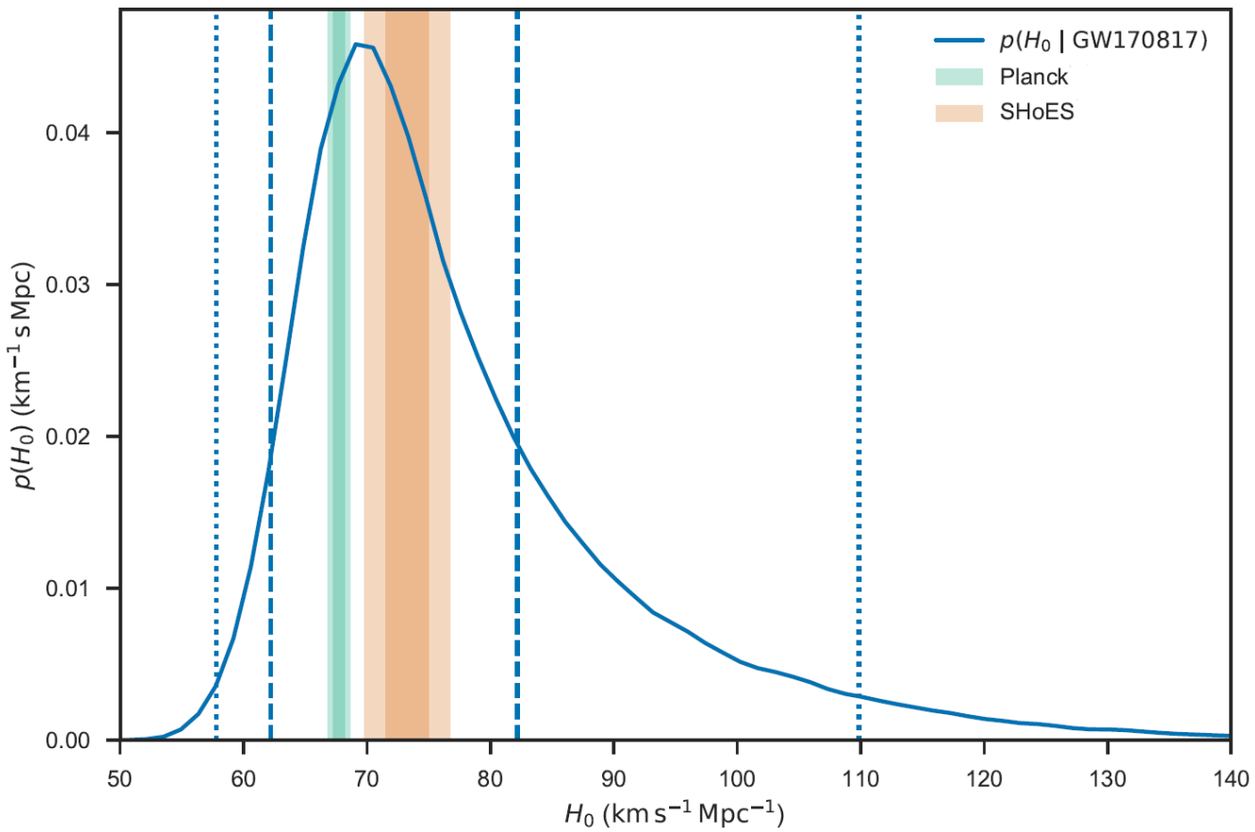


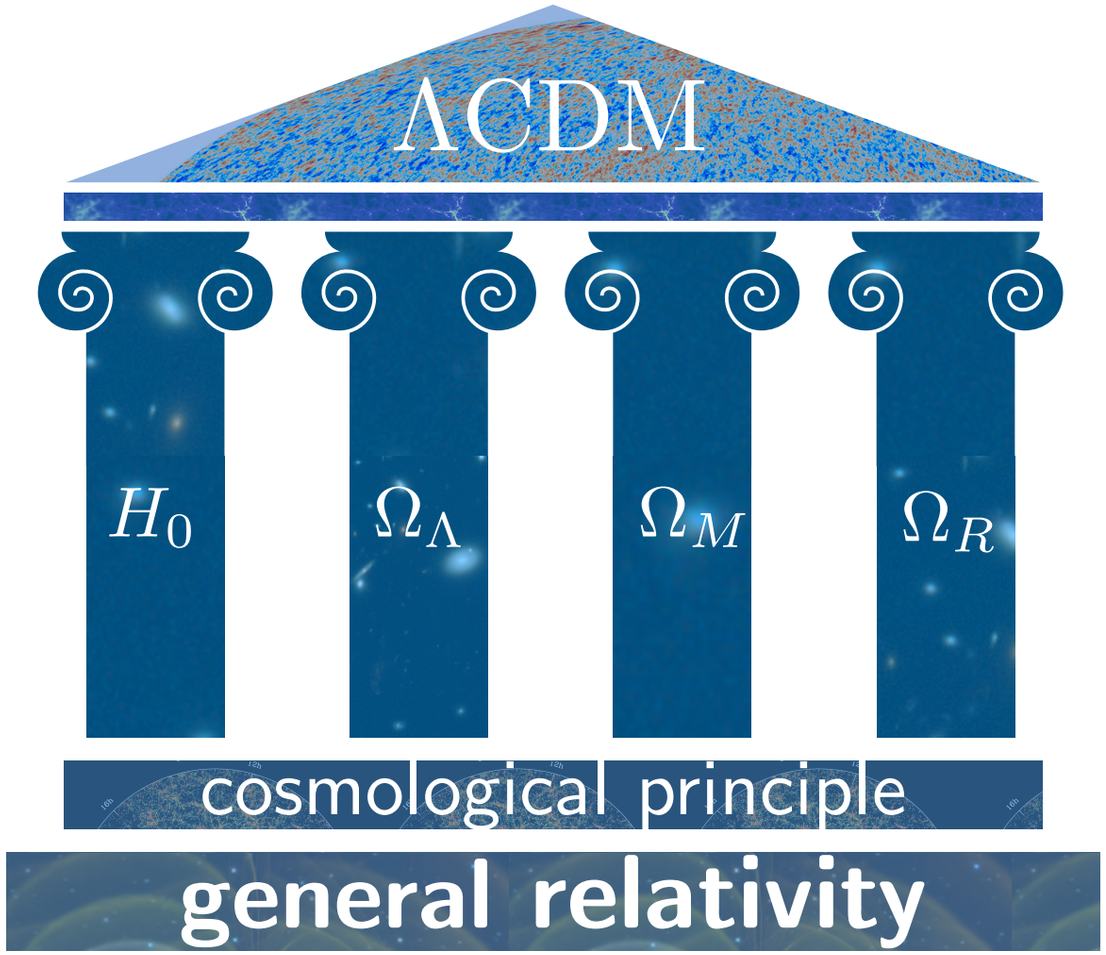
For a review see:

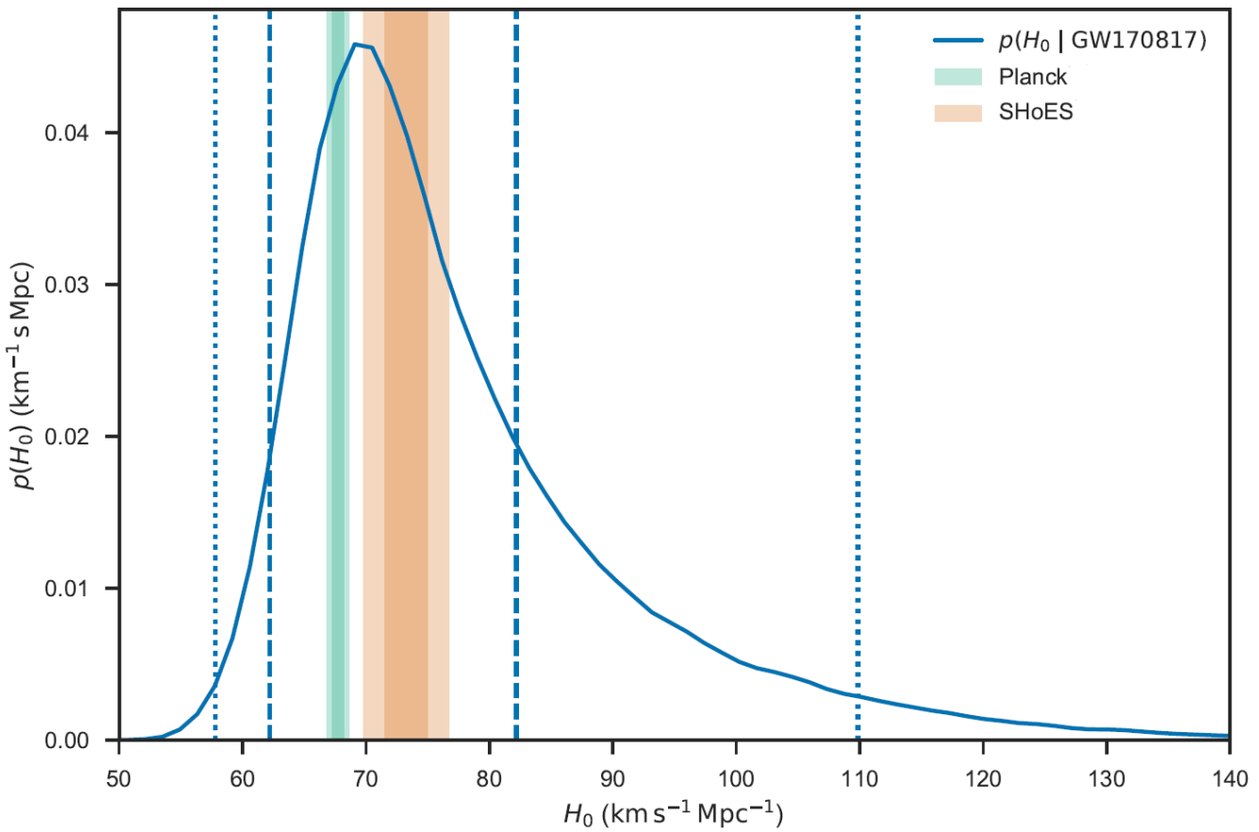
Ezquiaga & Zumalacárregui; *Dark energy in light of GW astronomy* (Frontiers, arXiv 1807.09241)

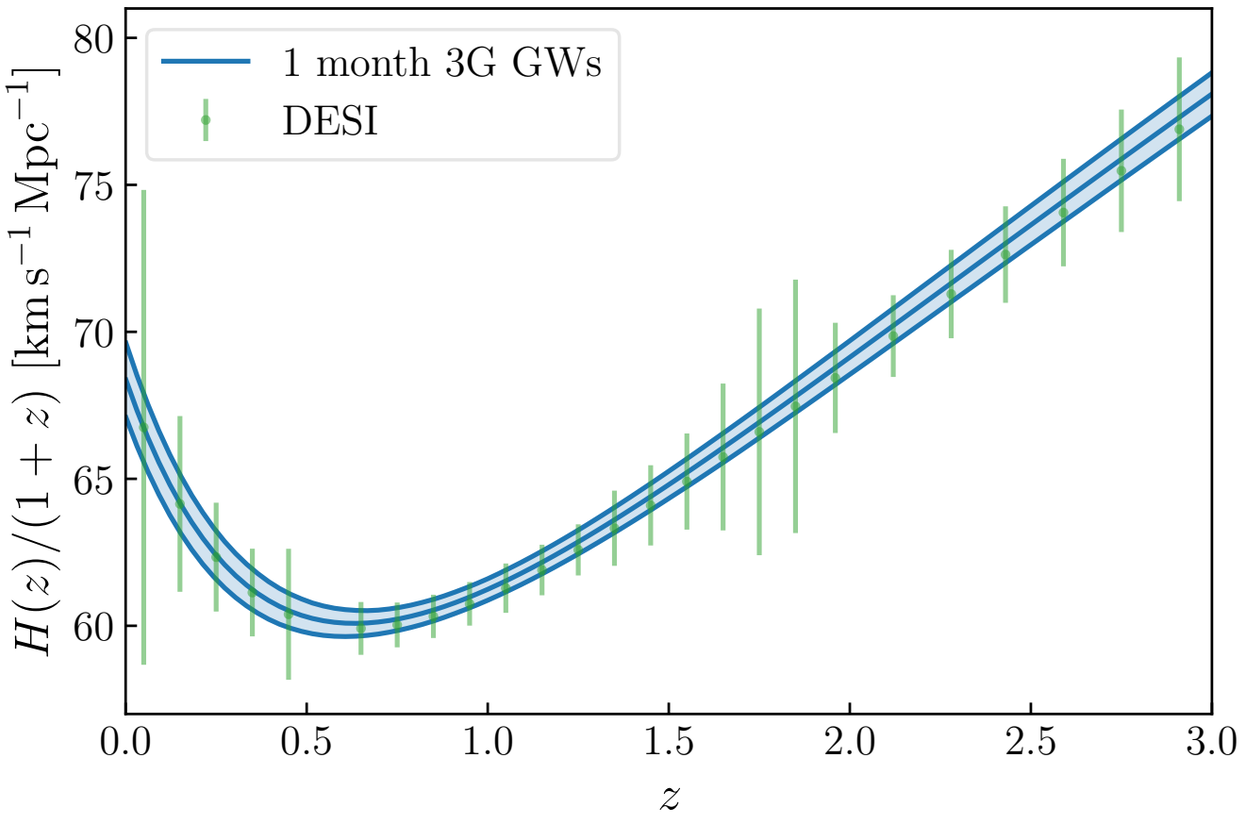

ΛCDM
H_0
Ω_Λ
Ω_M
Ω_R
cosmological principle
general relativity

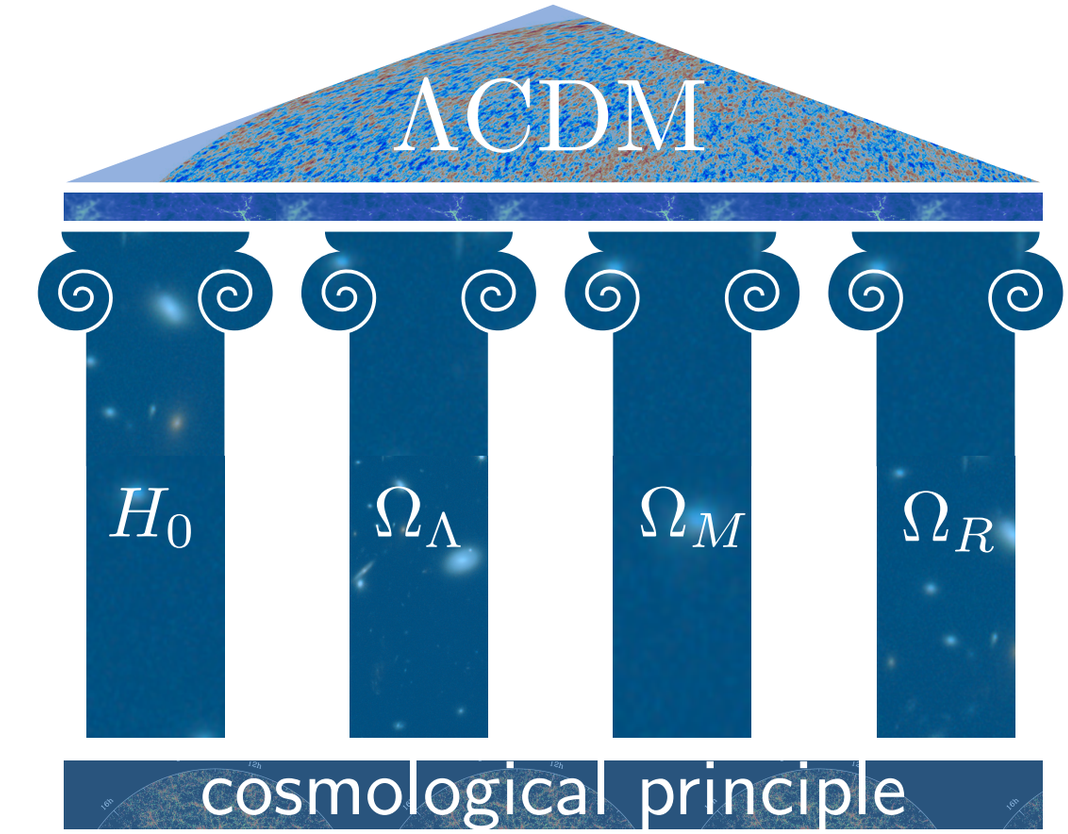

ΛCDM
H_0
Ω_Λ
Ω_M
Ω_R
cosmological principle
general relativity

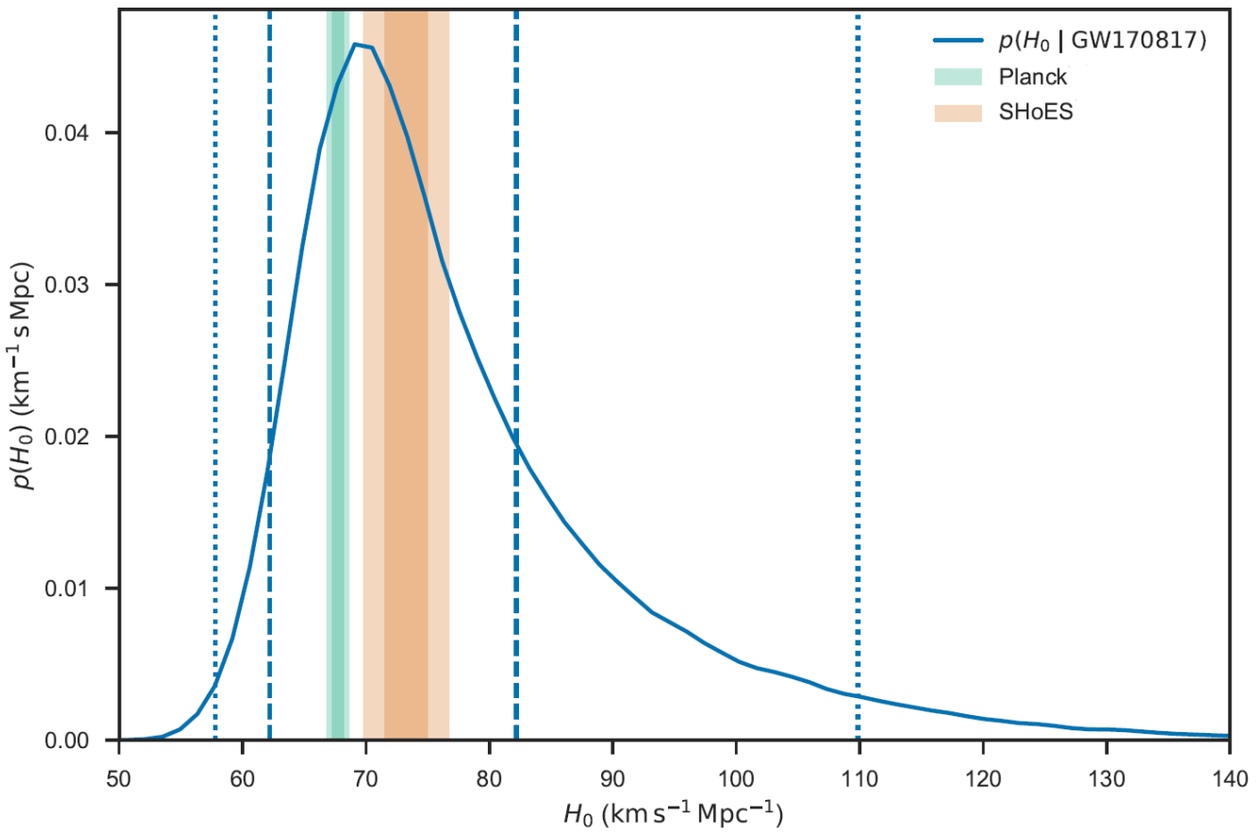

$p(H_0 \mid \mathrm{GW170817})$
Planck
SHoES
$p(H_0)$ (km^{-1} s Mpc)
H_0 (km s^{-1} Mpc^{-1})
0.00
0.01
0.02
0.03
0.04
50
60
70
80
90
100
110
120
130
140

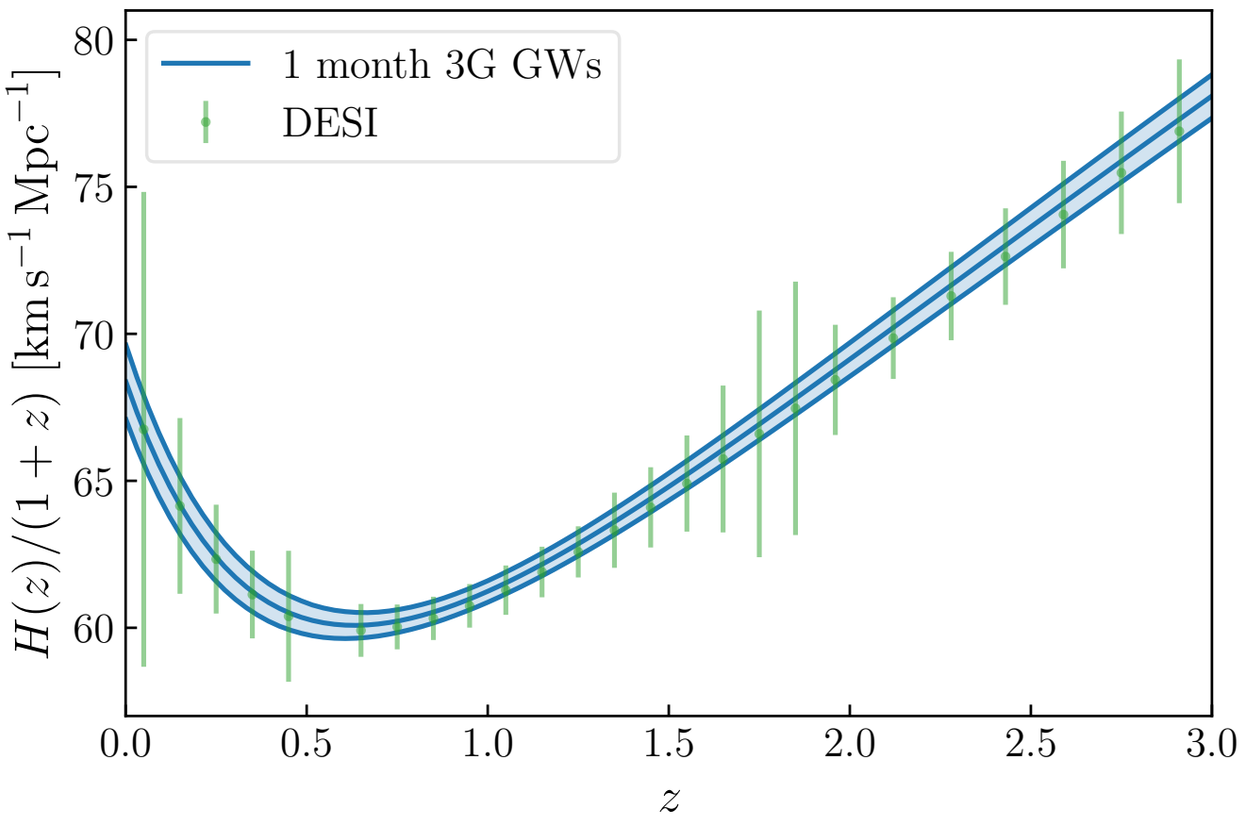

ΛCDM
H_0
Ω_Λ
Ω_M
Ω_R
cosmological principle
general relativity

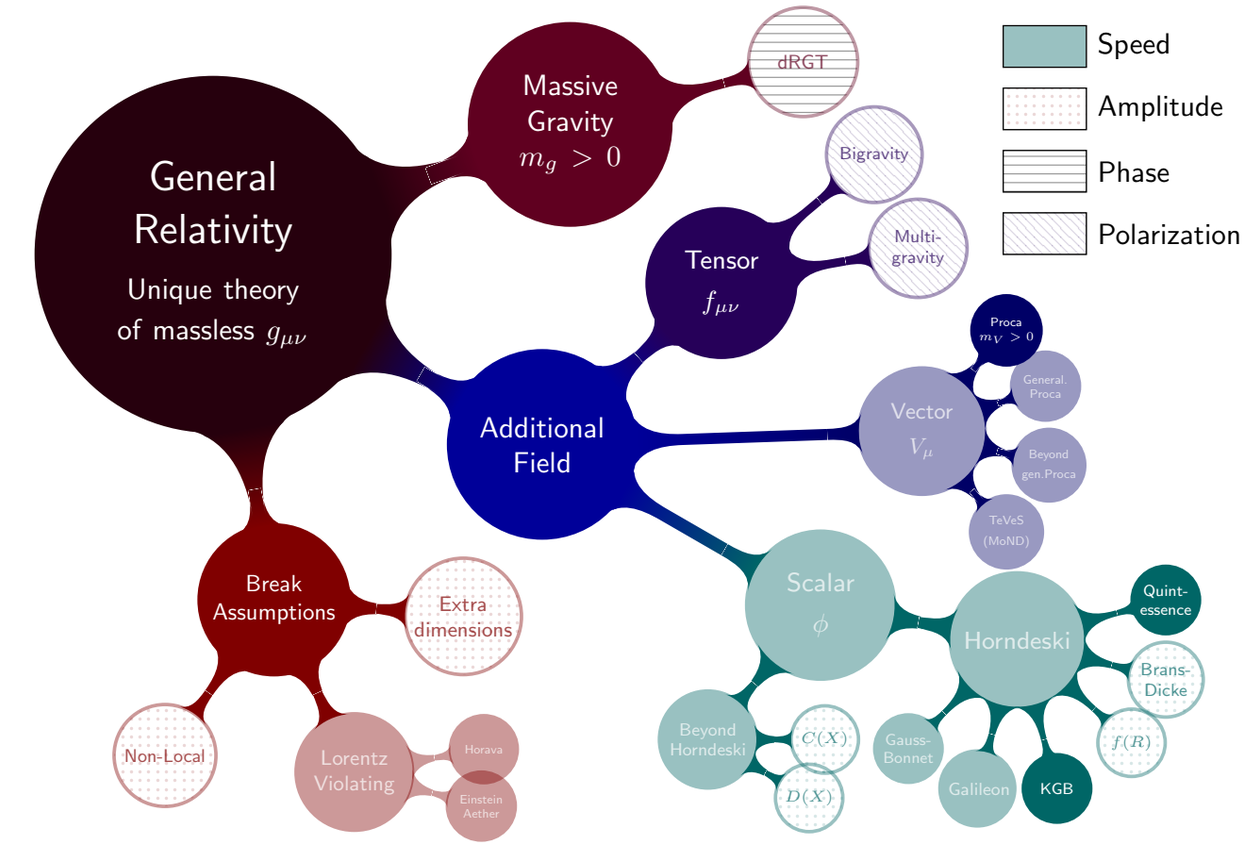

$p(H_0 \mid \mathrm{GW170817})$
Planck
SHoES
$p(H_0)$ (km^{-1} s Mpc)
H_0 (km s^{-1} Mpc^{-1})
0.00
0.01
0.02
0.03
0.04
50
60
70
80
90
100
110
120
130
140


1 month 3G GWs
DESI
$H(z)/(1+z)$ [km s^{-1} Mpc^{-1}]
z
60
65
70
75
80
0.0
0.5
1.0
1.5
2.0
2.5
3.0


ΛCDM
H_0
Ω_Λ
Ω_M
Ω_R
cosmological principle
general relativity


$p(H_0 \mid \mathrm{GW170817})$
Planck
SHoES
$p(H_0)$ (km^{-1} s Mpc)
H_0 (km s^{-1} Mpc^{-1})
0.00
0.01
0.02
0.03
0.04
50
60
70
80
90
100
110
120
130
140


1 month 3G GWs
DESI
$H(z)/(1+z)$ [km s^{-1} Mpc^{-1}]
z
60
65
70
75
80
0.0
0.5
1.0
1.5
2.0
2.5
3.0


Modified gravity roadmap and GW astronomy
Constrained by
Speed
Amplitude
Phase
Polarization
General Relativity
Unique theory of massless $g_{\mu\nu}$
Massive Gravity $m_g > 0$
dRGT
Bigravity
Multi-gravity
Tensor $f_{\mu\nu}$
Additional Field
Vector V_μ
Proca $m_V > 0$
General. Proca
Beyond gen.Proca
TeVeS (MoND)
Scalar ϕ
Horndeski
Quint-essence
Brans-Dicke
$f(R)$
KGB
Galileon
Gauss-Bonnet
Beyond Horndeski
$C(X)$
$D(X)$
Break Assumptions
Extra dimensions
Non-Local
Lorentz Violating
Horava
Einstein Aether

Medfinansieret af Den Europæiske
Unions Connecting Europe-facilitet

Join us!

VILLUM FONDEN

ezquiaga.github.io/joinus

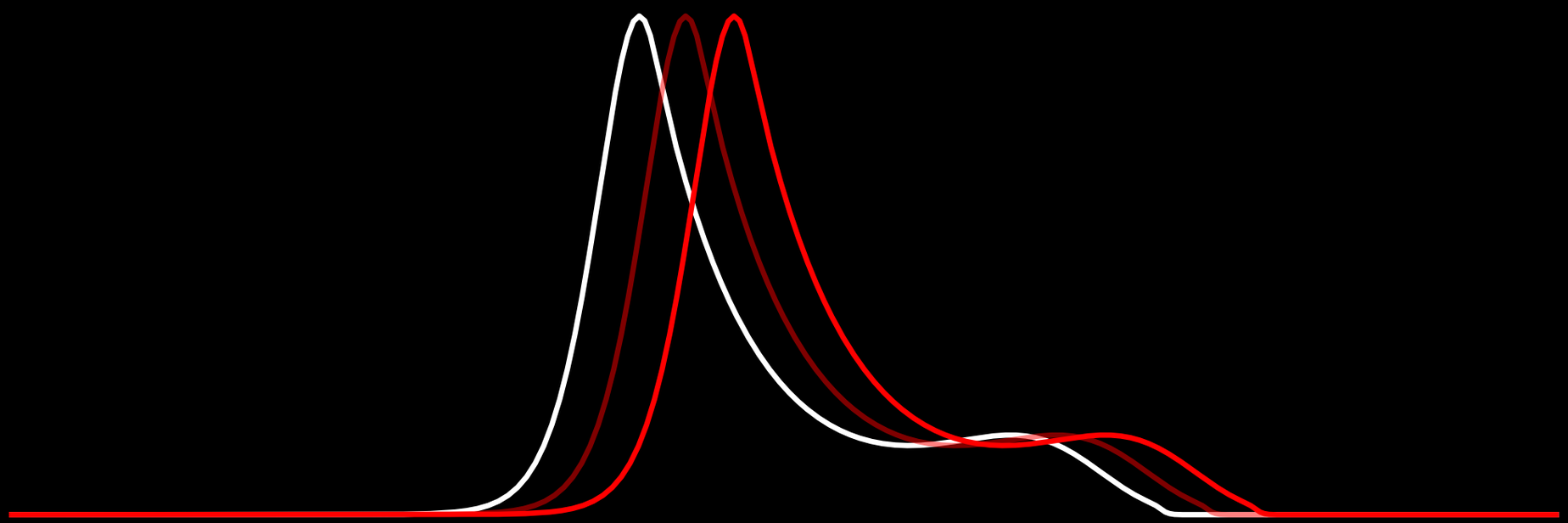
Medfinansieret af Den Europæiske
Unions Connecting Europe-facilitet

VILLUM FONDEN

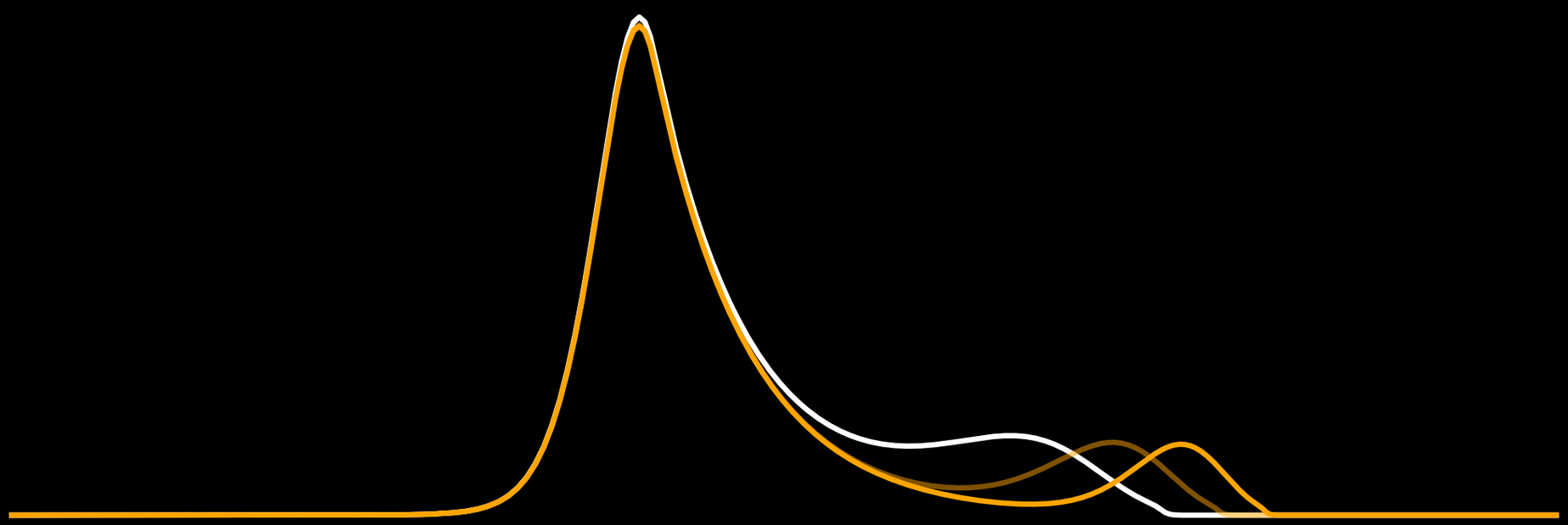
INTERACTIONS

Supplemental material

Cosmology

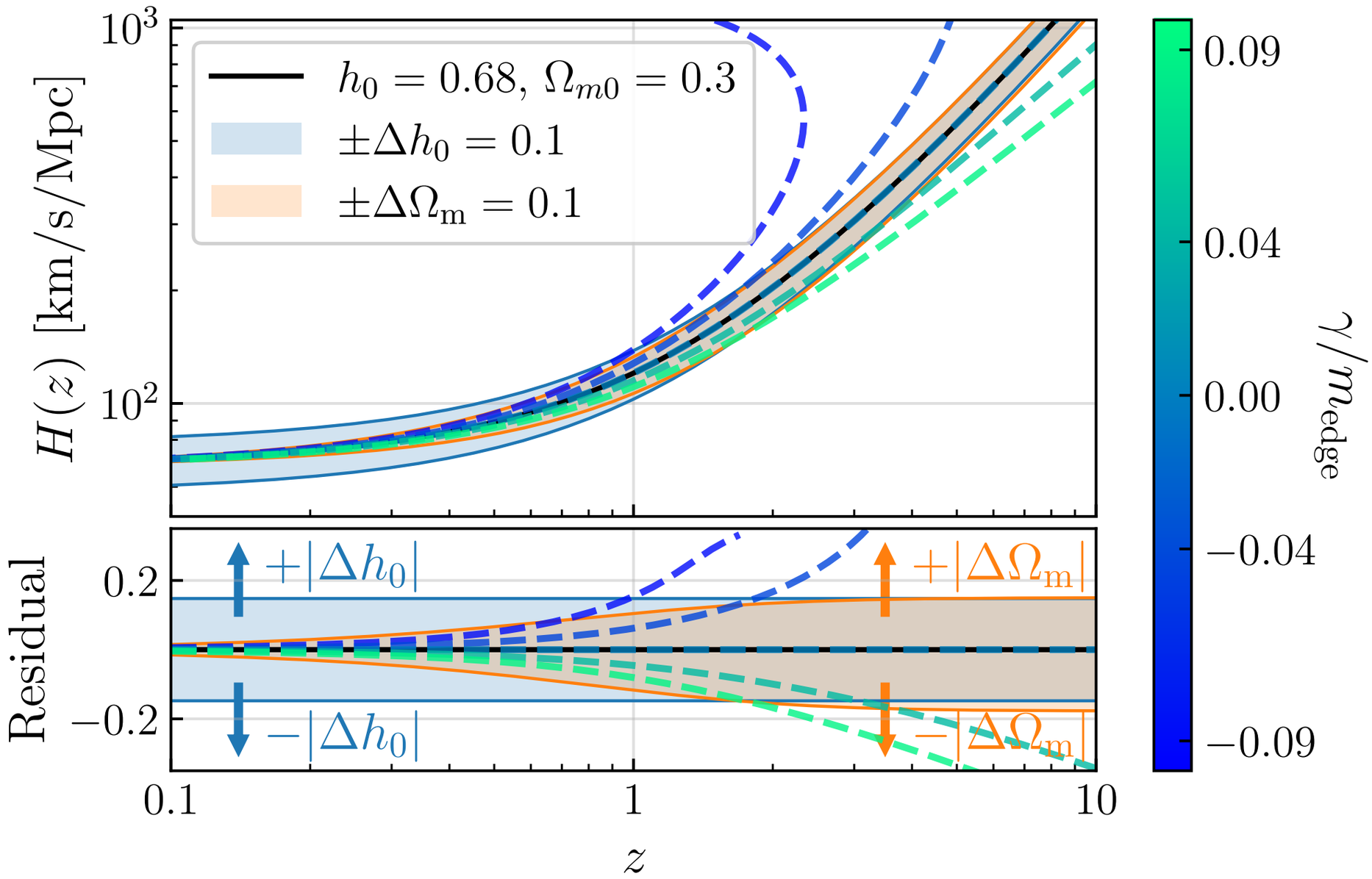


Astrophysics



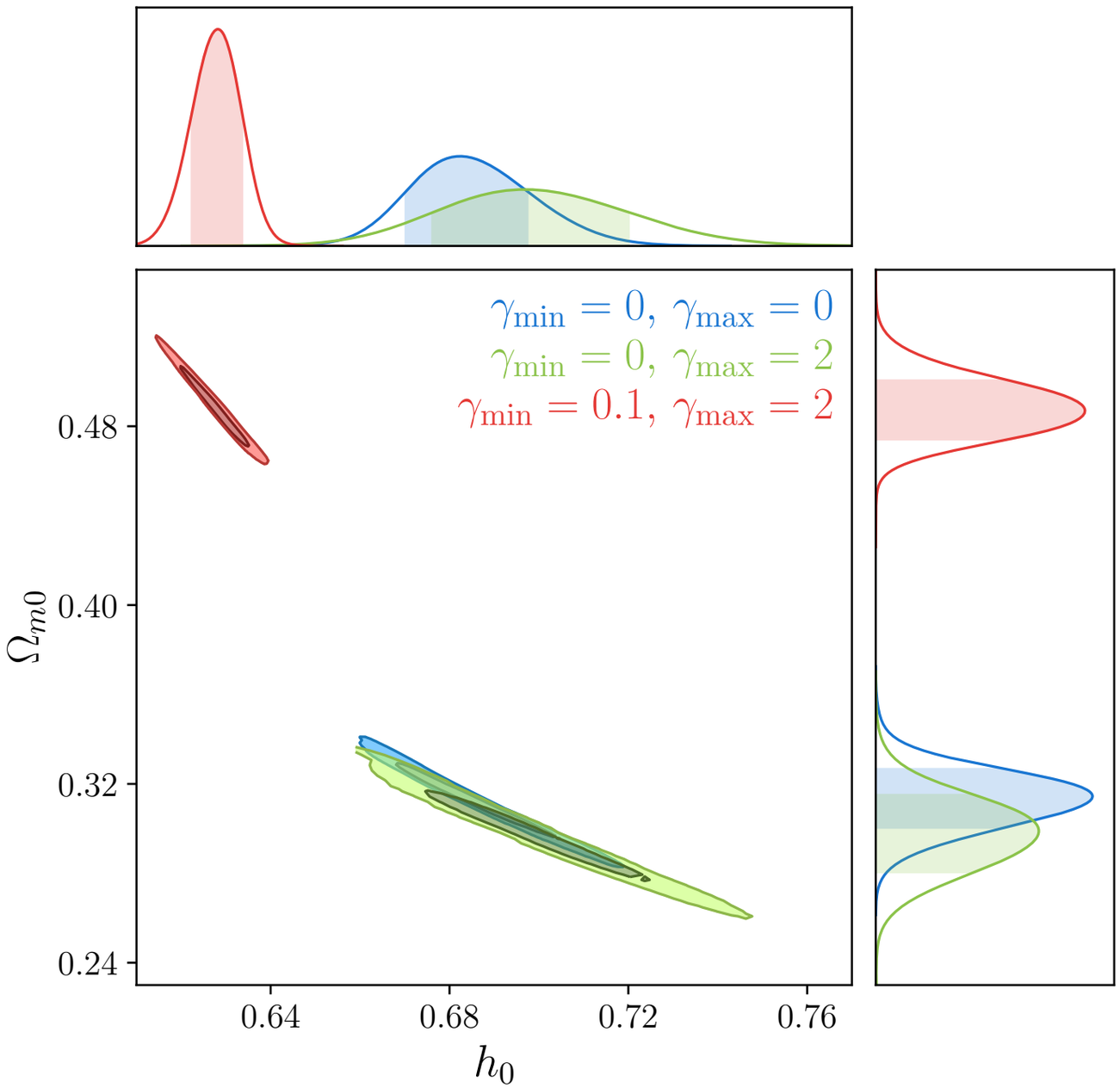
log[Detector frame mass]

"By using the full mass distribution, we demonstrate that ***degeneracies*** *between mass evolution and cosmological evolution* ***can be broken****, unless an astrophysical conspiracy shifts all features of the full mass distribution simultaneously following the (non-trivial) Hubble diagram evolution."*



Example: 3G cosmo inference

[10,000 **BBHs** between NSBH and PISN gap (1 month)]



Without evolution in the model:
cosmology can be biased

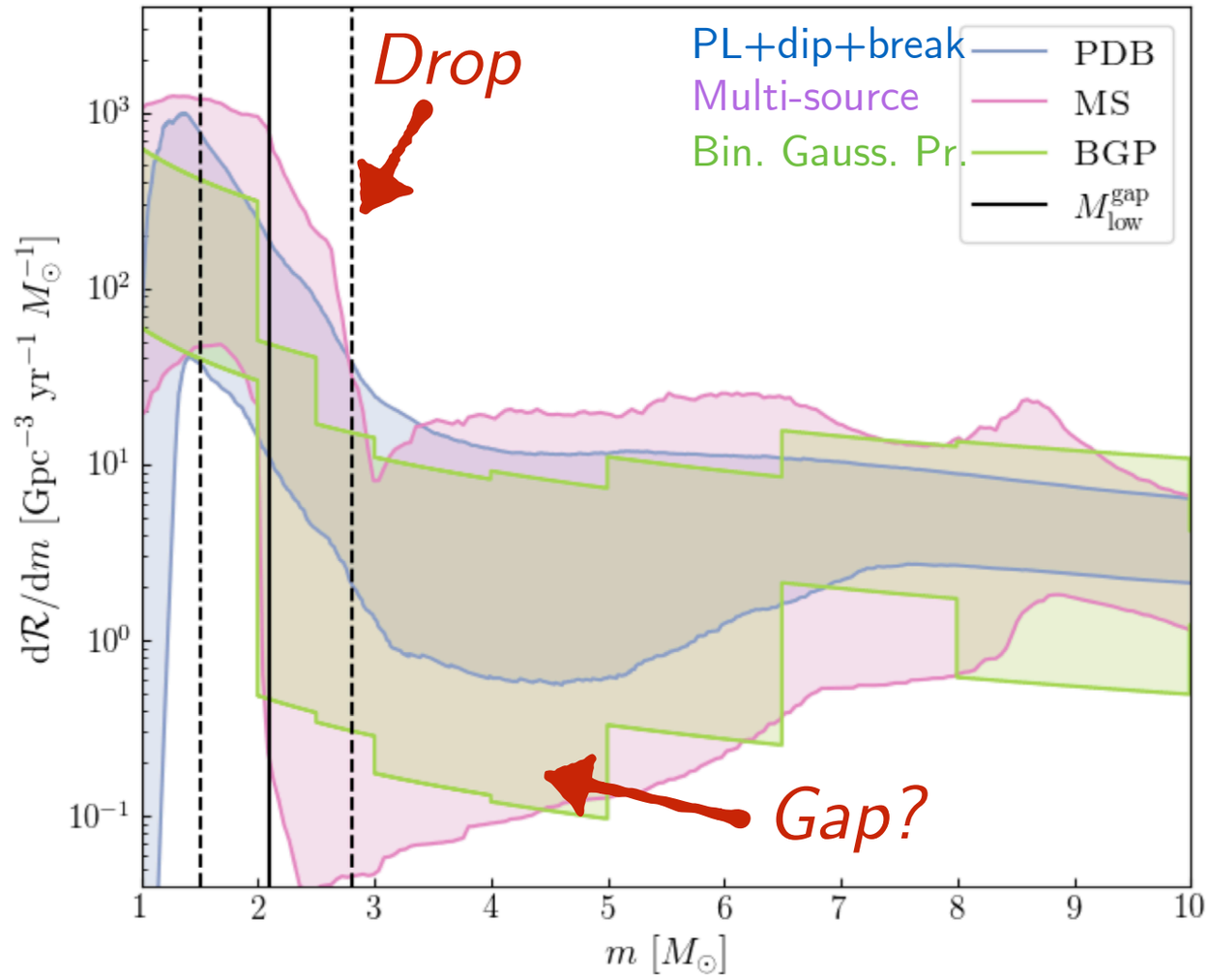
Ezquiaga & Holz; *Spectral sirens: cosmology from full mass distribution* (arXiv 2202.08240)

GWTC-3

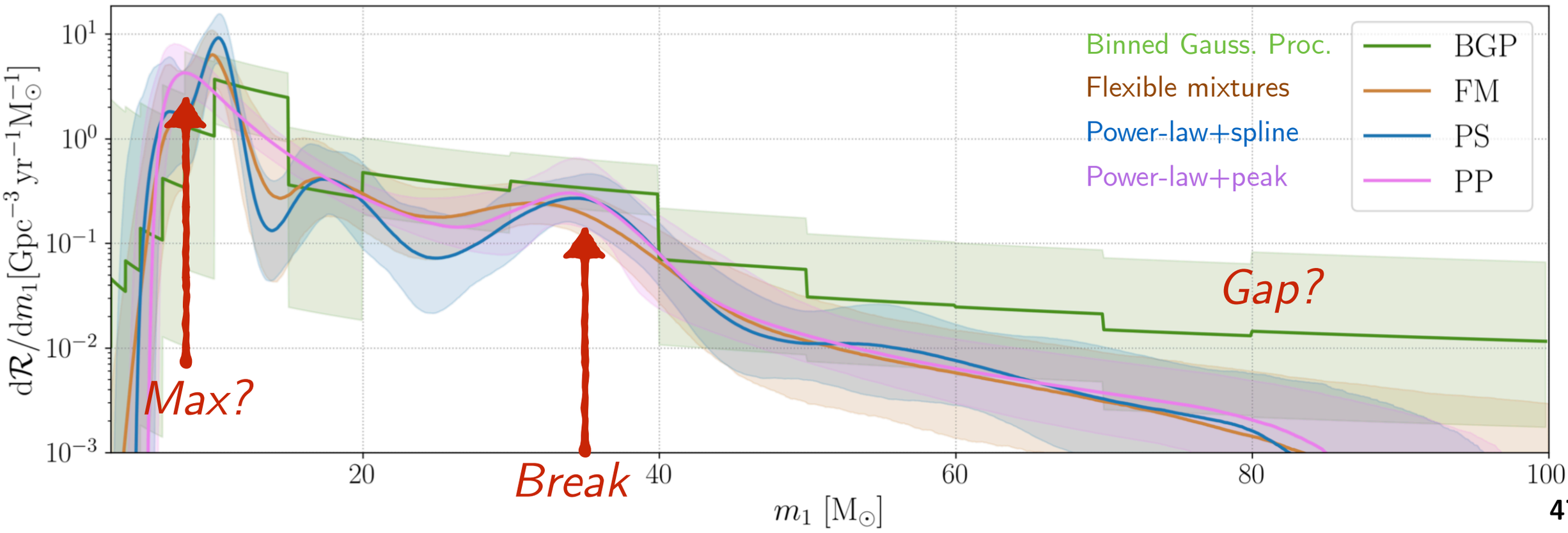
[latest LIGO-Virgo catalog]

[LVC GWTC-3 '21]

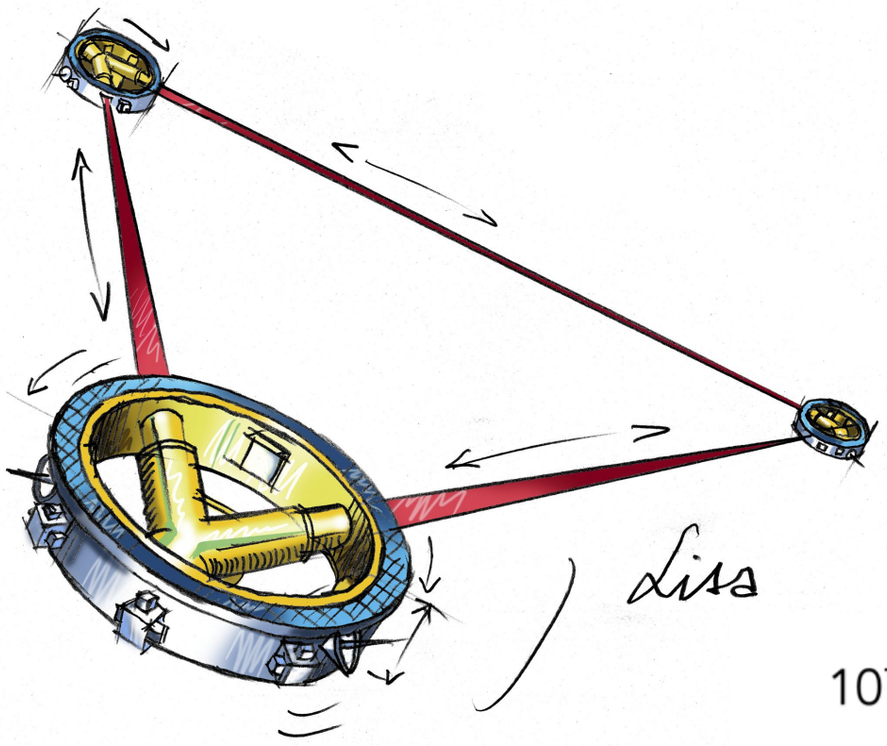
Low-mass mass distribution

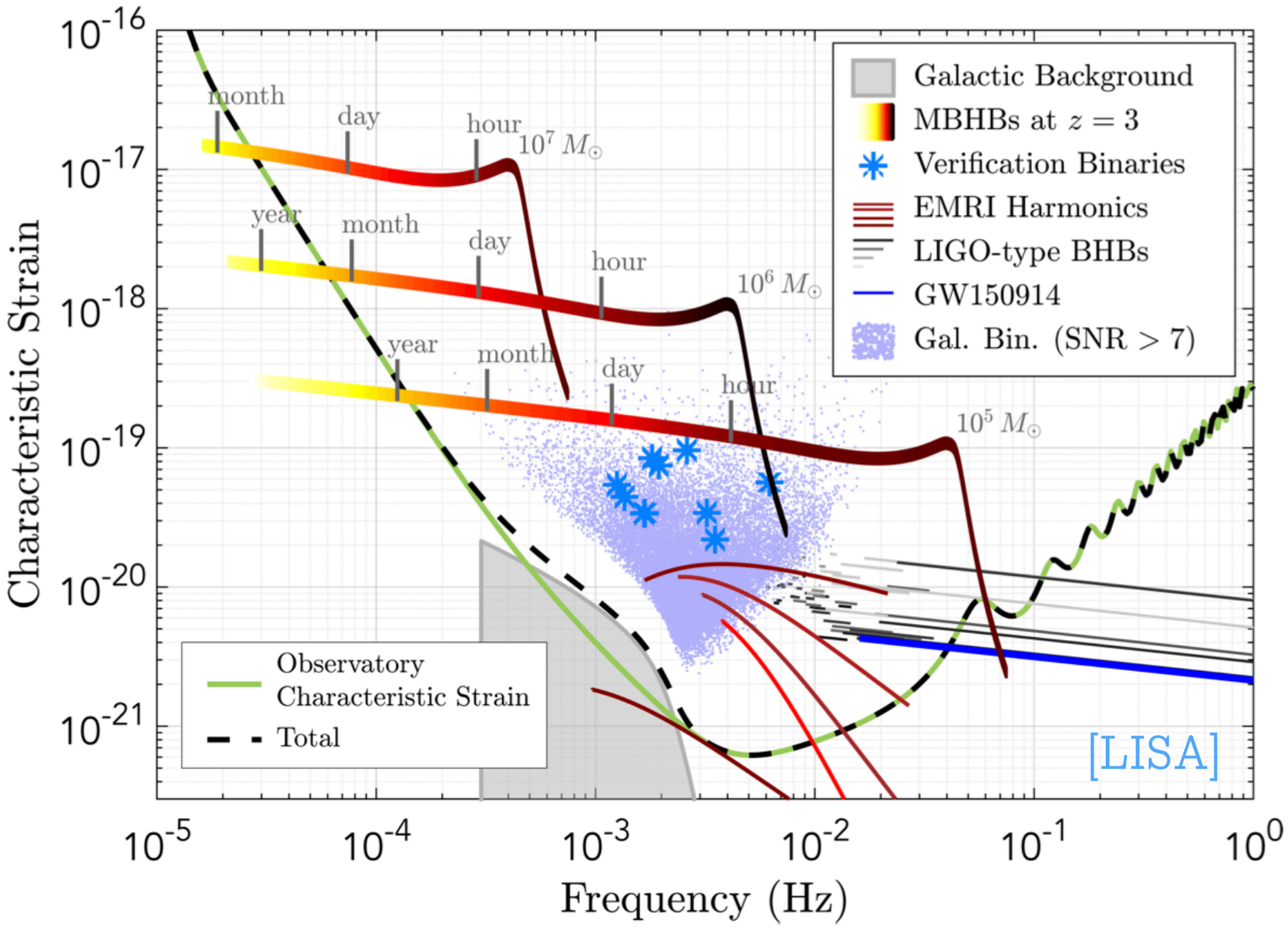


BBH mass distribution



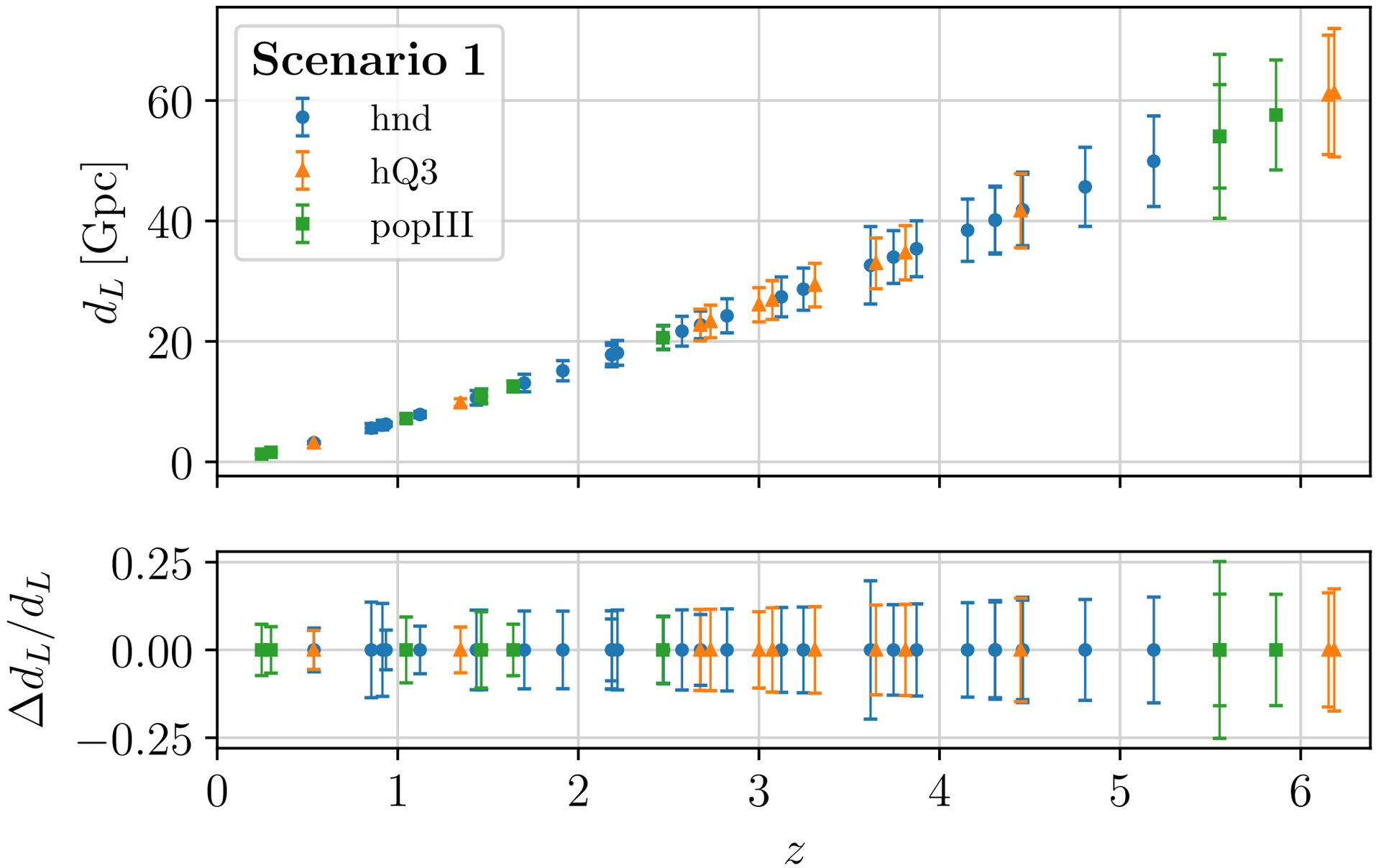
LISA's perspective





LISA forecasts: SMBBHs

[approx. 10-30 **bright sirens** (4 yrs)]



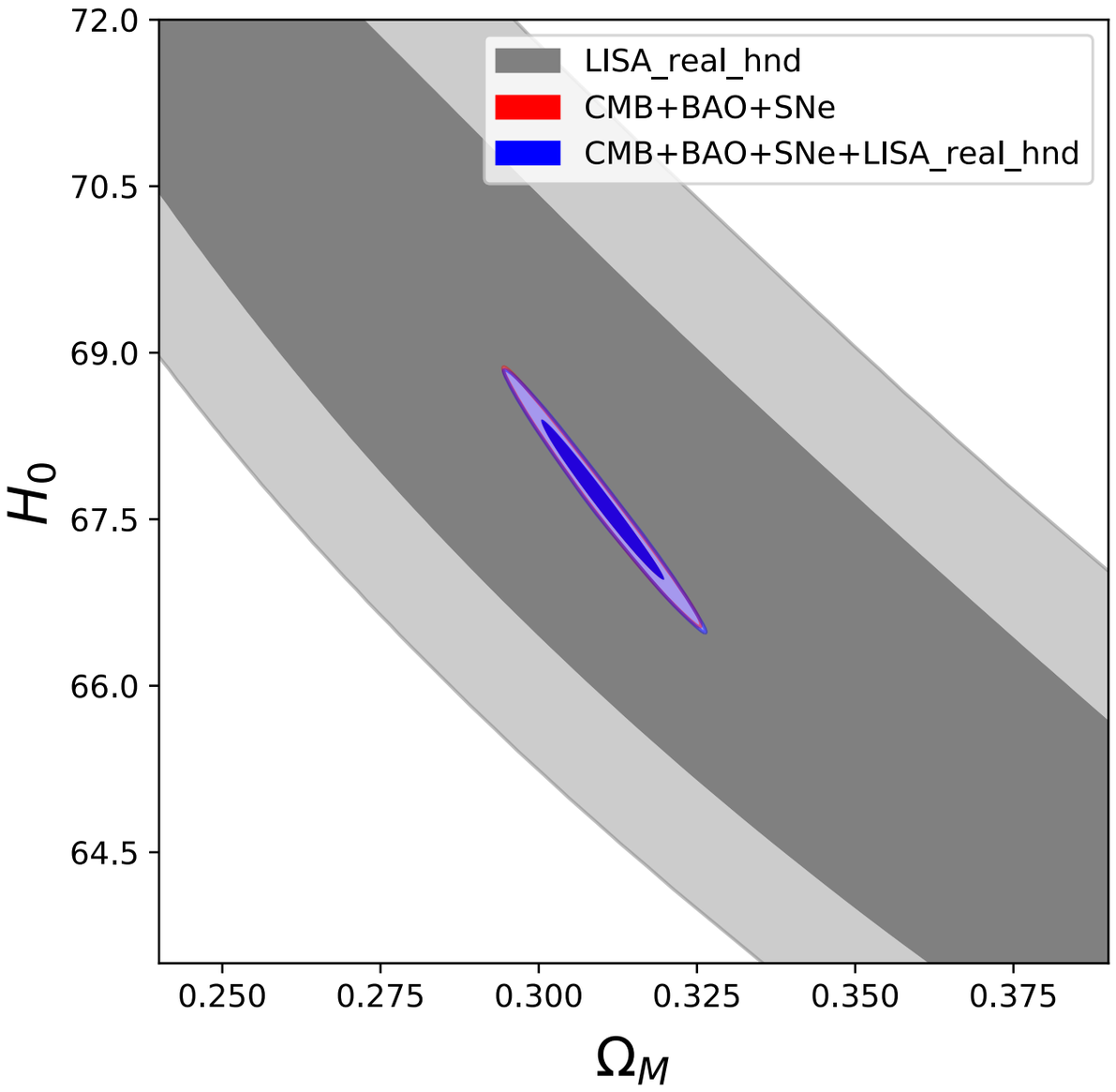
hnd: heavy seeds no delay

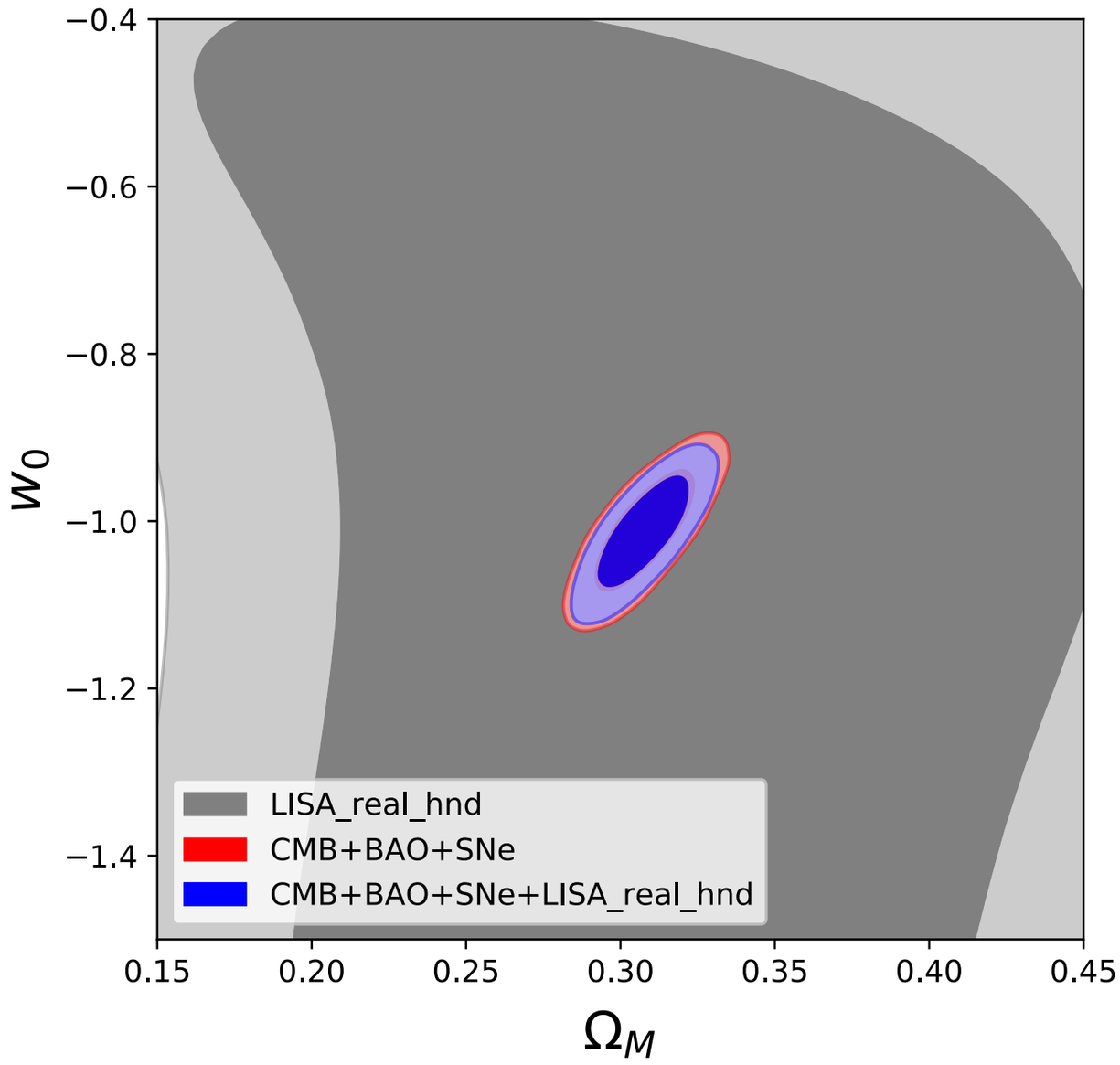
hQ3: heavy seeds with delay

popIII: light seeds

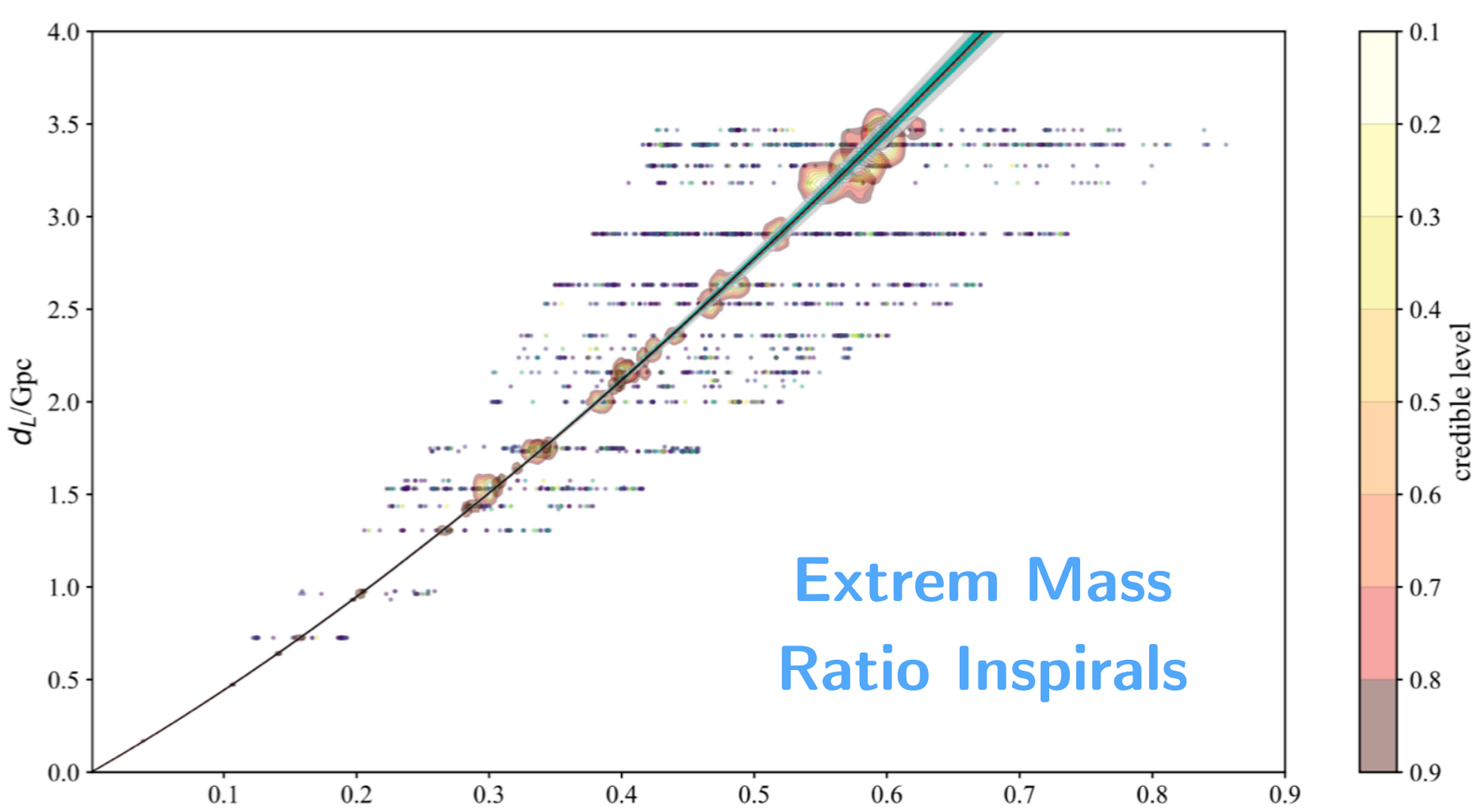
Belgacem *et al.*; *Testing modified gravity at cosmological distances with LISA* (arXiv 1906.01593)

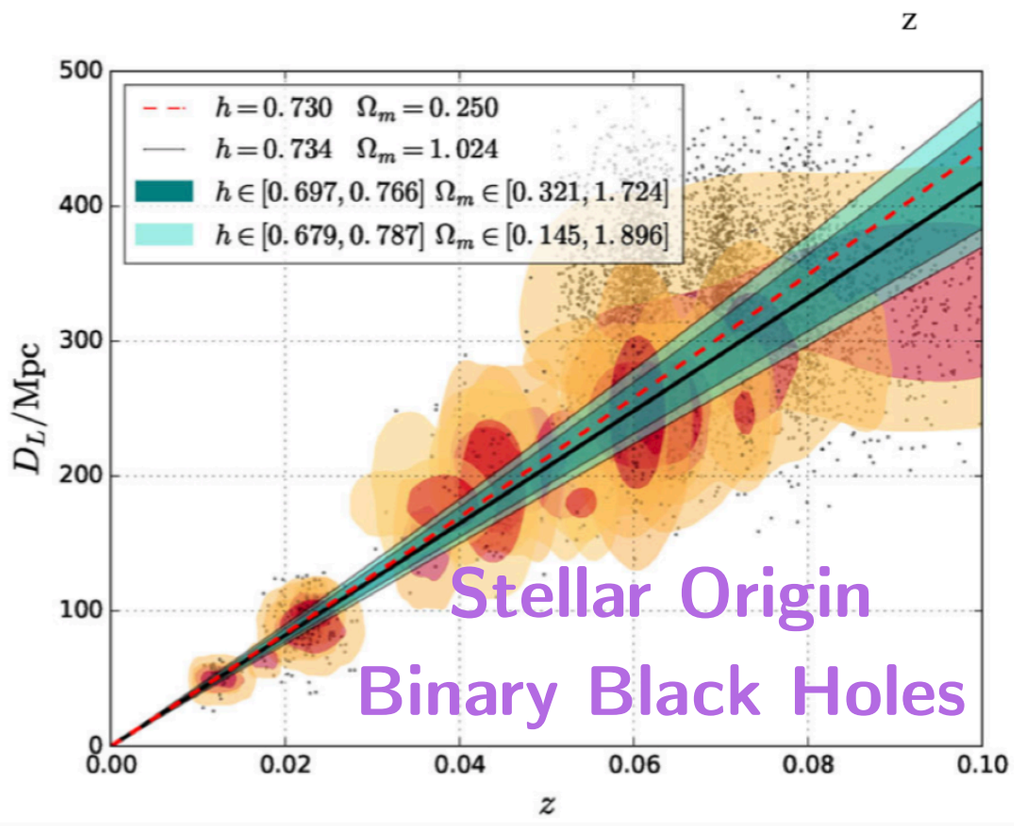
LISA forecasts: SMBBHs

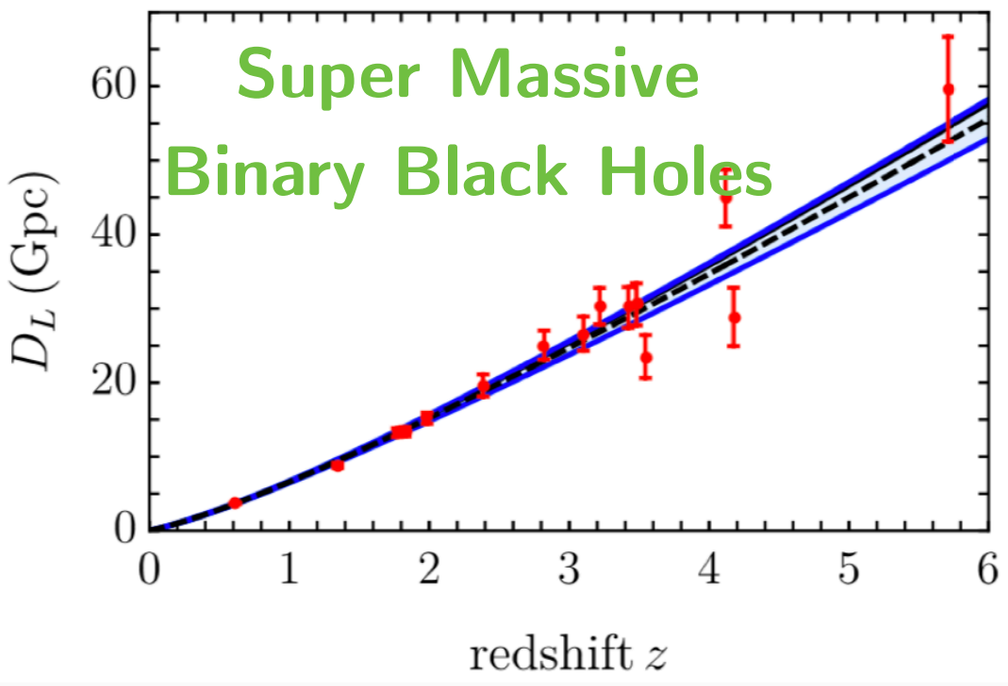




Belgacem *et al.*; *Testing modified gravity at cosmological distances with LISA* (arXiv 1906.01593)







LISA Cosmo WG white paper (arXiv 2204.05434)

Modified dispersion relation (MDR)

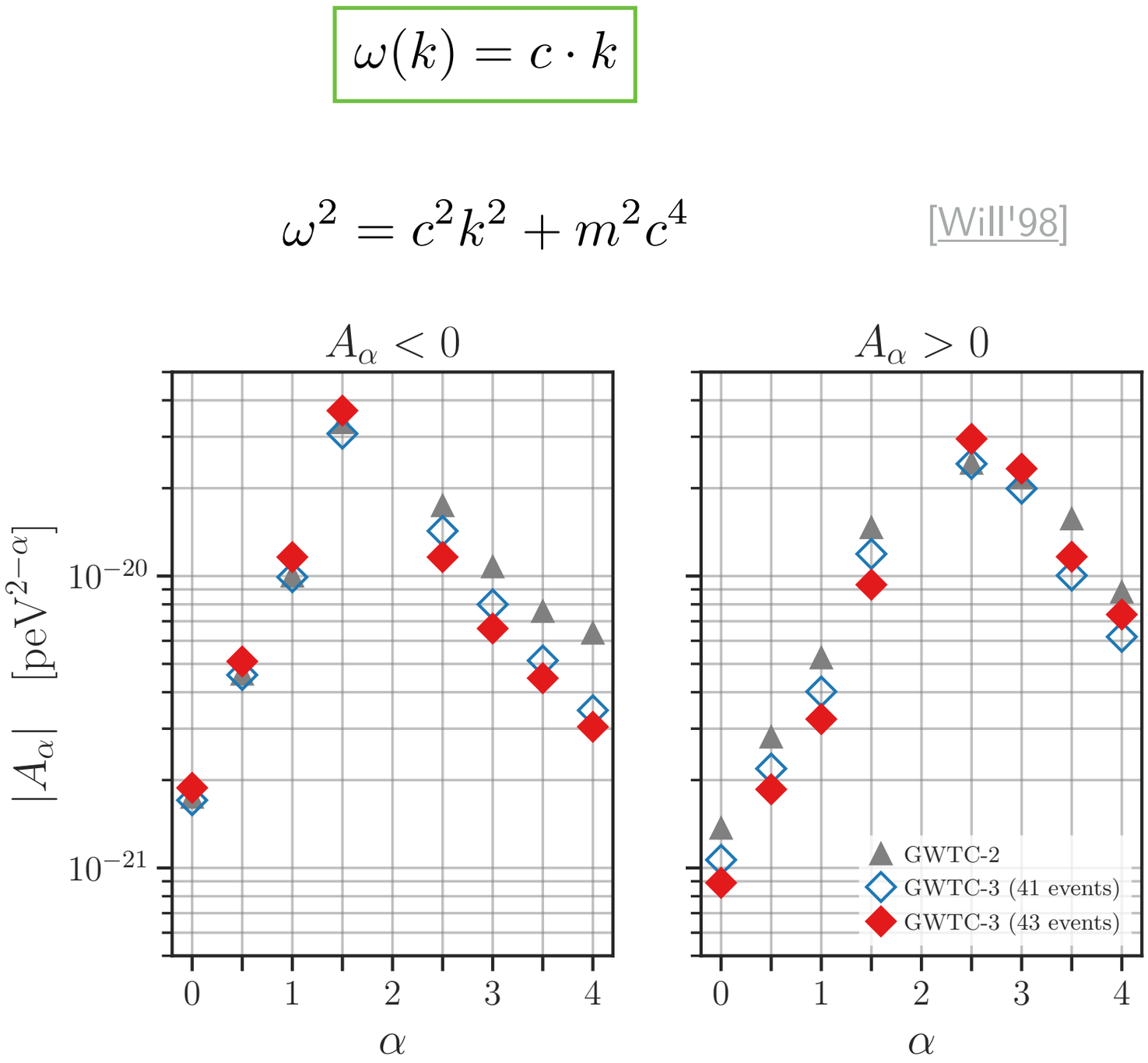
General relativity predicts: $\omega(k) = c \cdot k$

Massive graviton: $\omega^2 = c^2 k^2 + m^2 c^4$ [Will'98]

General MDR:

$$\omega^2 = c^2 k^2 + \mathbb{A}(ck)^\alpha$$

[Mirshekari et al.'11]



[LVK TGR GWTC-3]

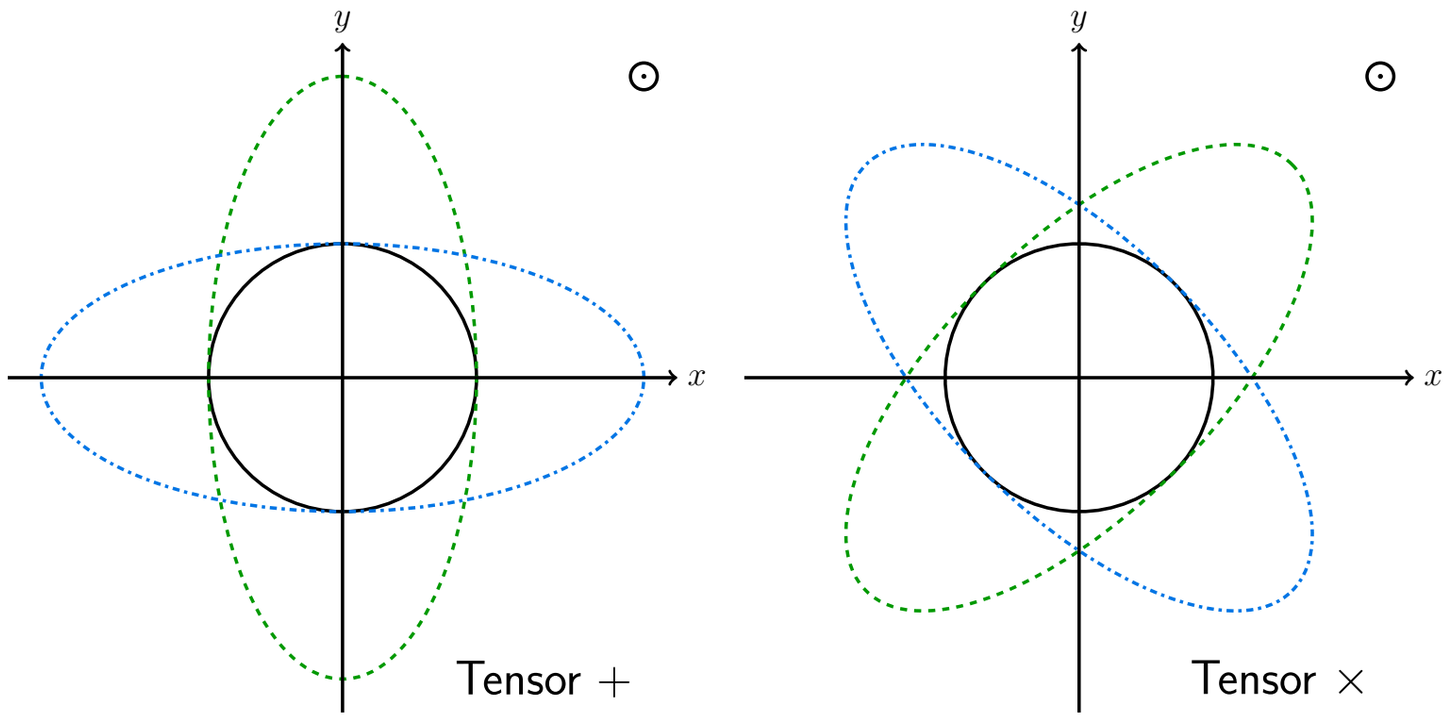
Tensor polarizations

General relativity predicts:

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

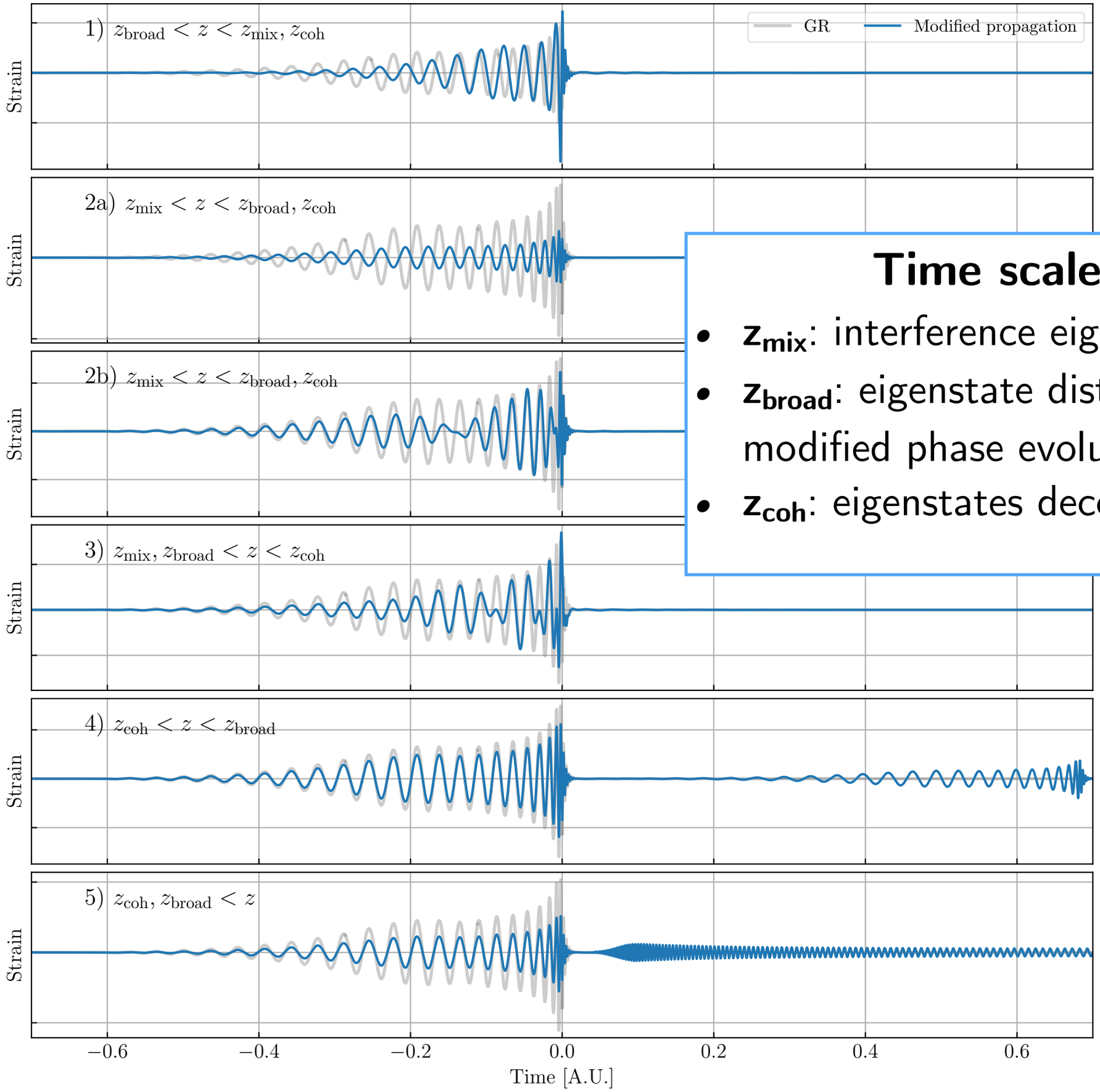
$$\Box h_{+,\times} = 0$$

Gravitational Wave Polarizations



Mixing cosmological tensor fields (similar to neutrino oscillations)

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

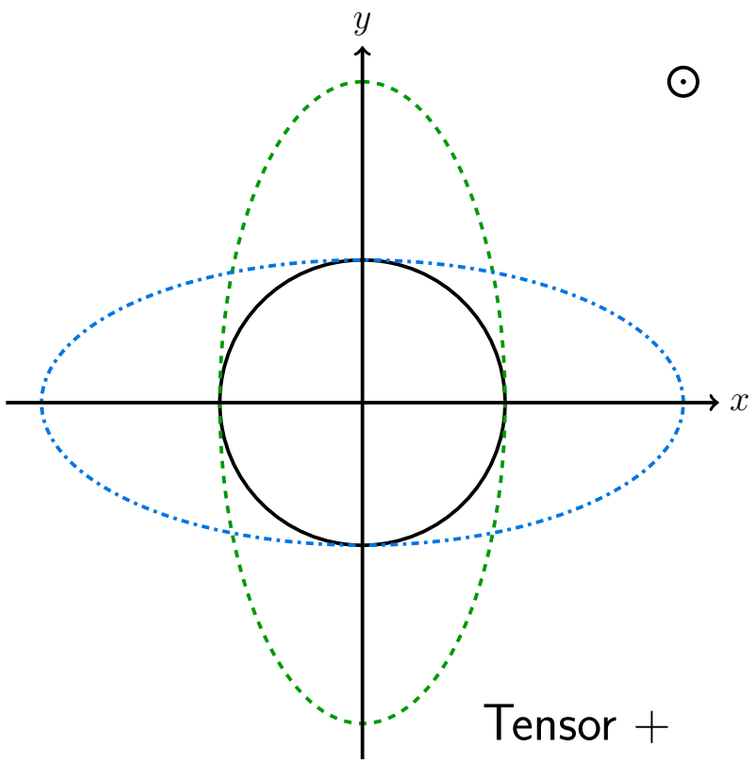


Time scales

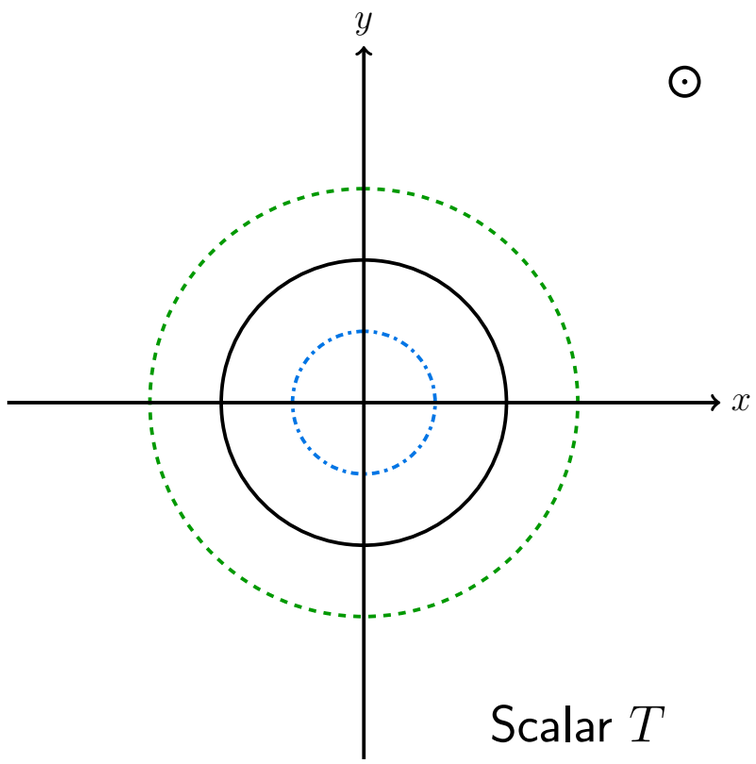
- $z_{\rm mix}$: interference eigenstates
- $z_{\rm broad}$: eigenstate distorted modified phase evolution
- $z_{\rm coh}$: eigenstates decohere

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

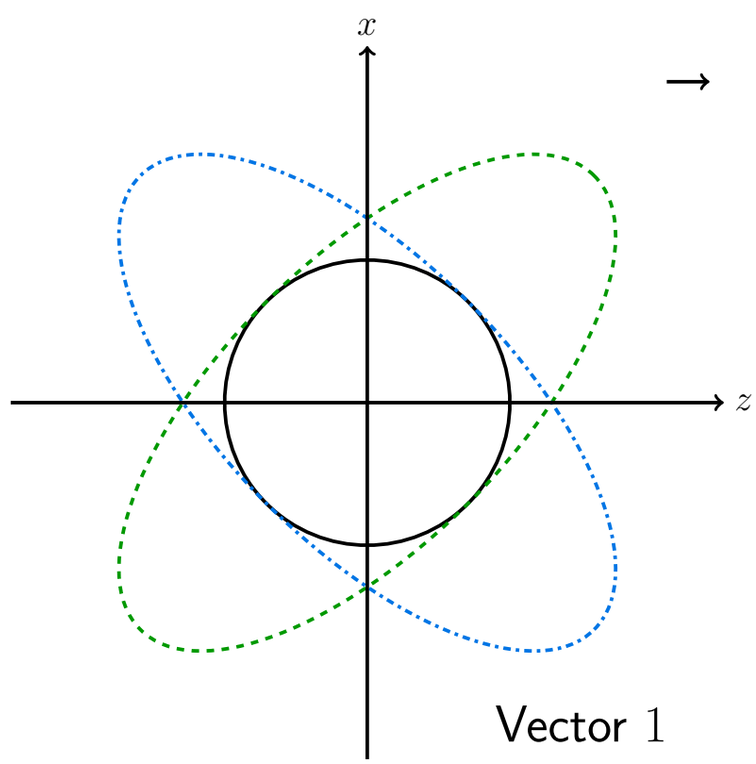
Gravitational Wave Polarizations



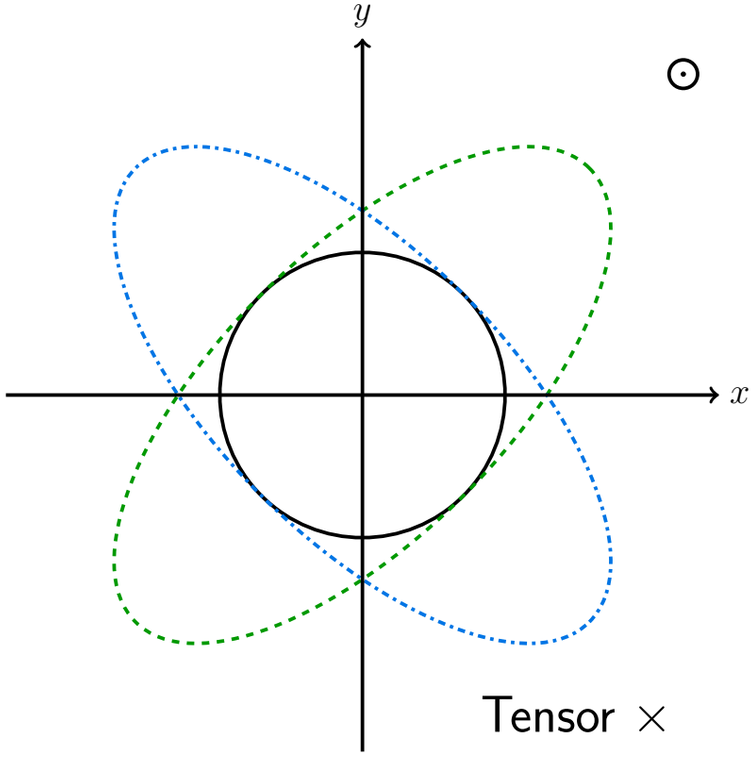
Tensor $+$



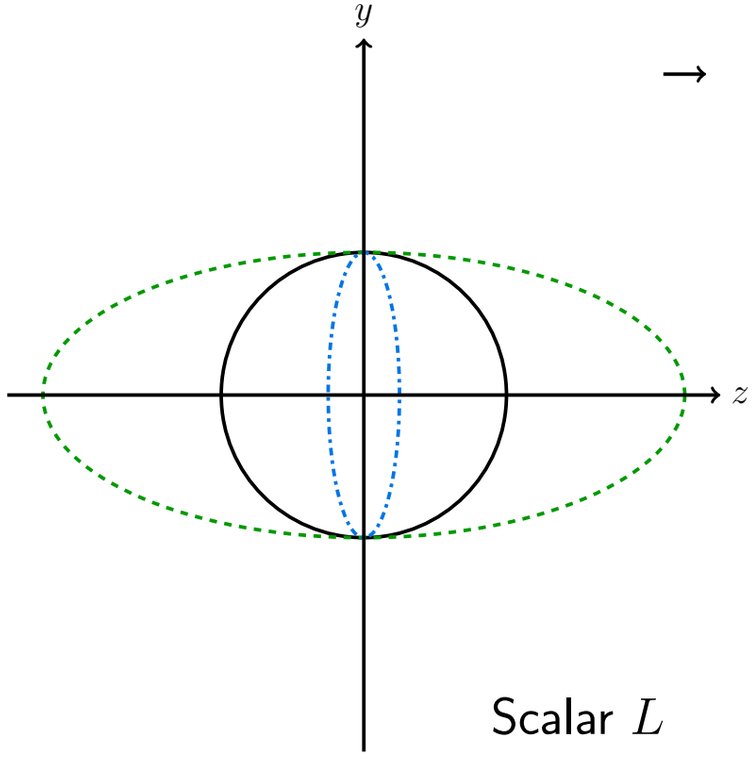
Scalar T



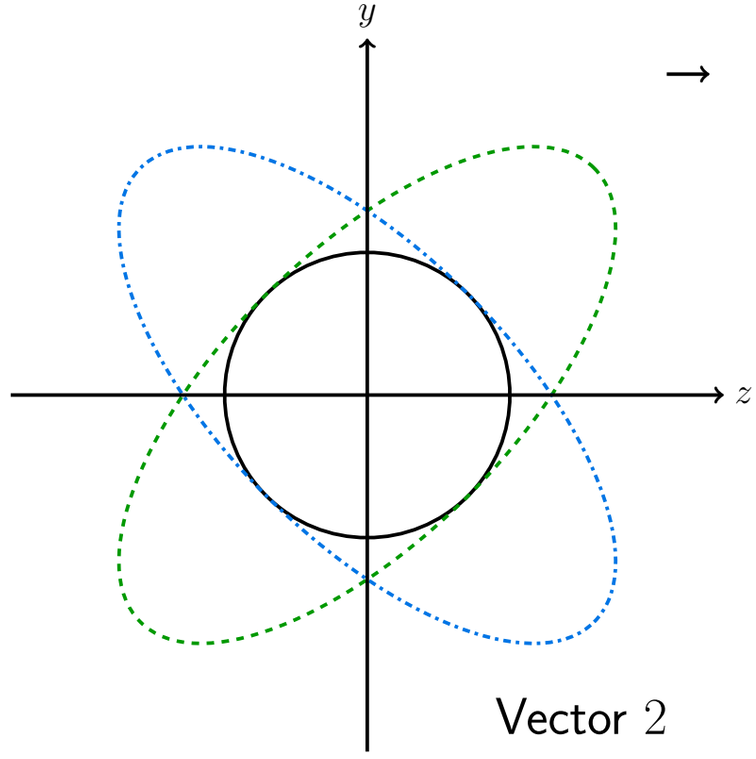
Vector 1



Tensor $\times$



Scalar L

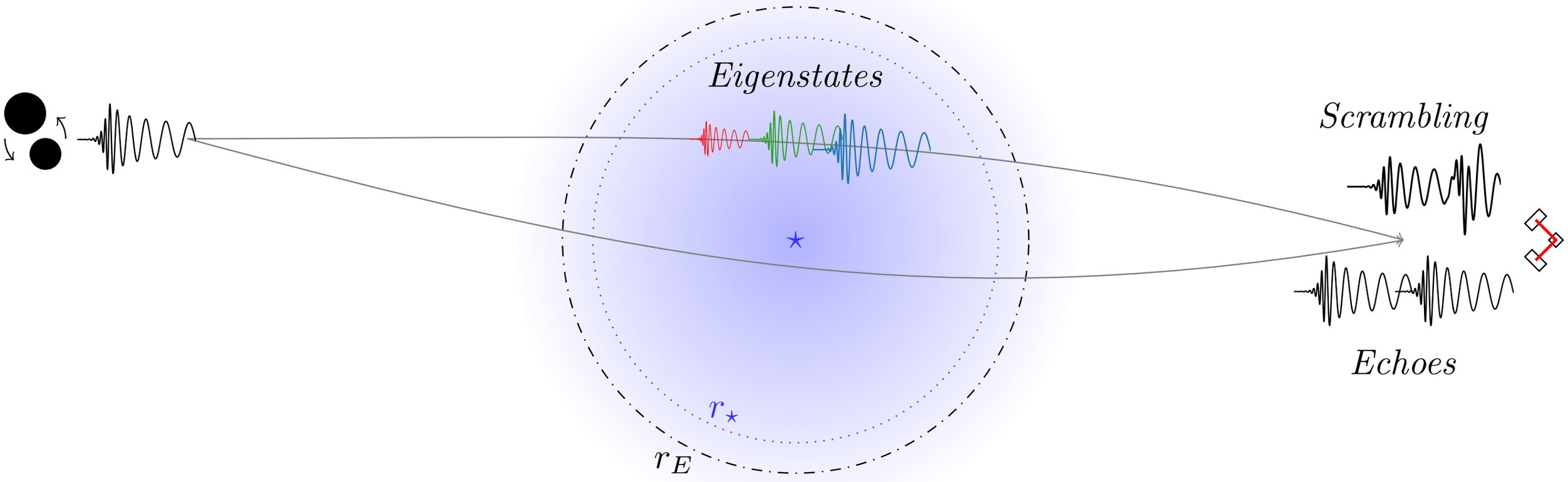


Vector 2

— $\omega\, t = 0, \pi$ ---- $\omega\, t = \pi/2$ ····· $\omega\, t = 3\pi/2$

GW lensing beyond GR

- Beyond GR the background of the additional fields $\phi(r)$ modify propagation (besides the change in gravitational potential)



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

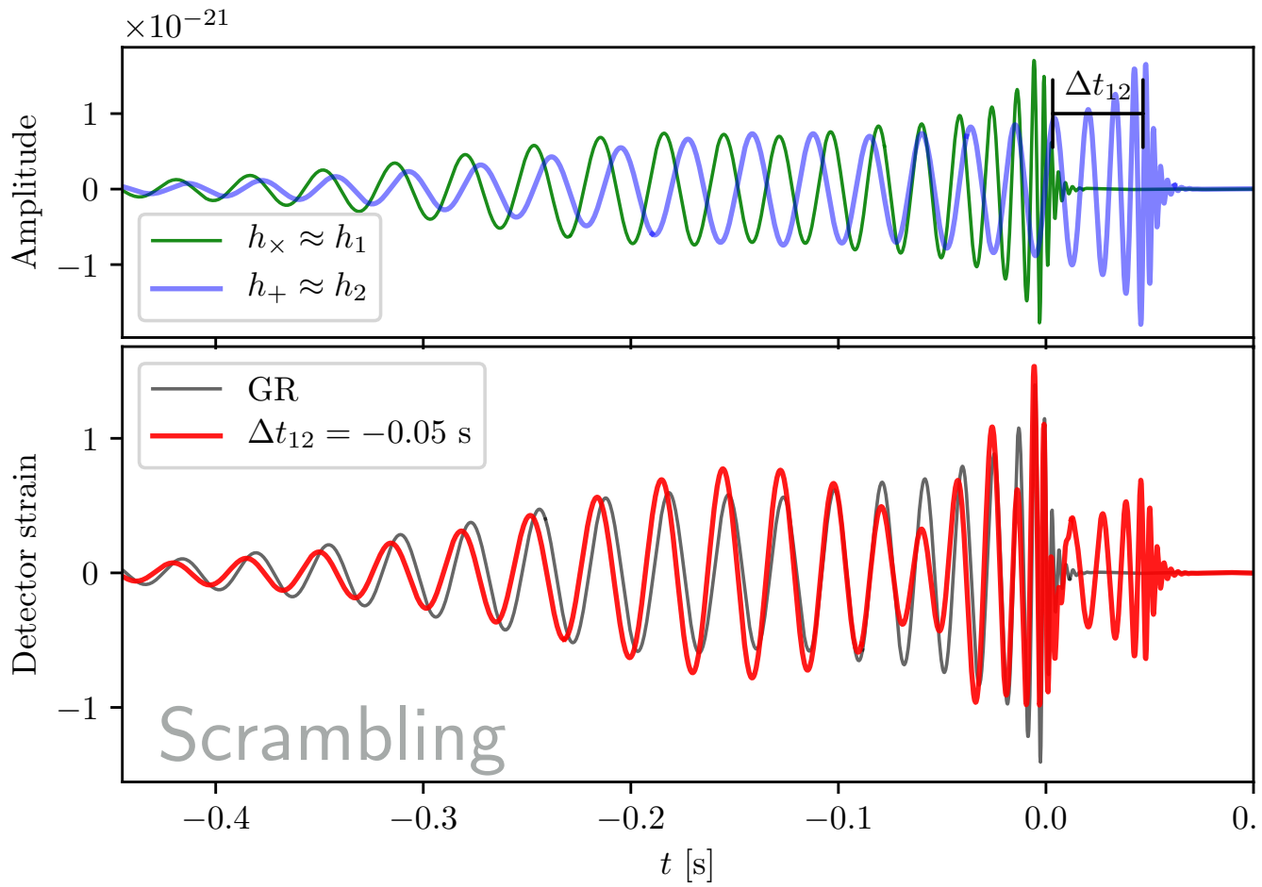
Ezquiaga & Zumalacárregui; *GW lensing beyond GR* (PRD, arXiv 2009.12187)

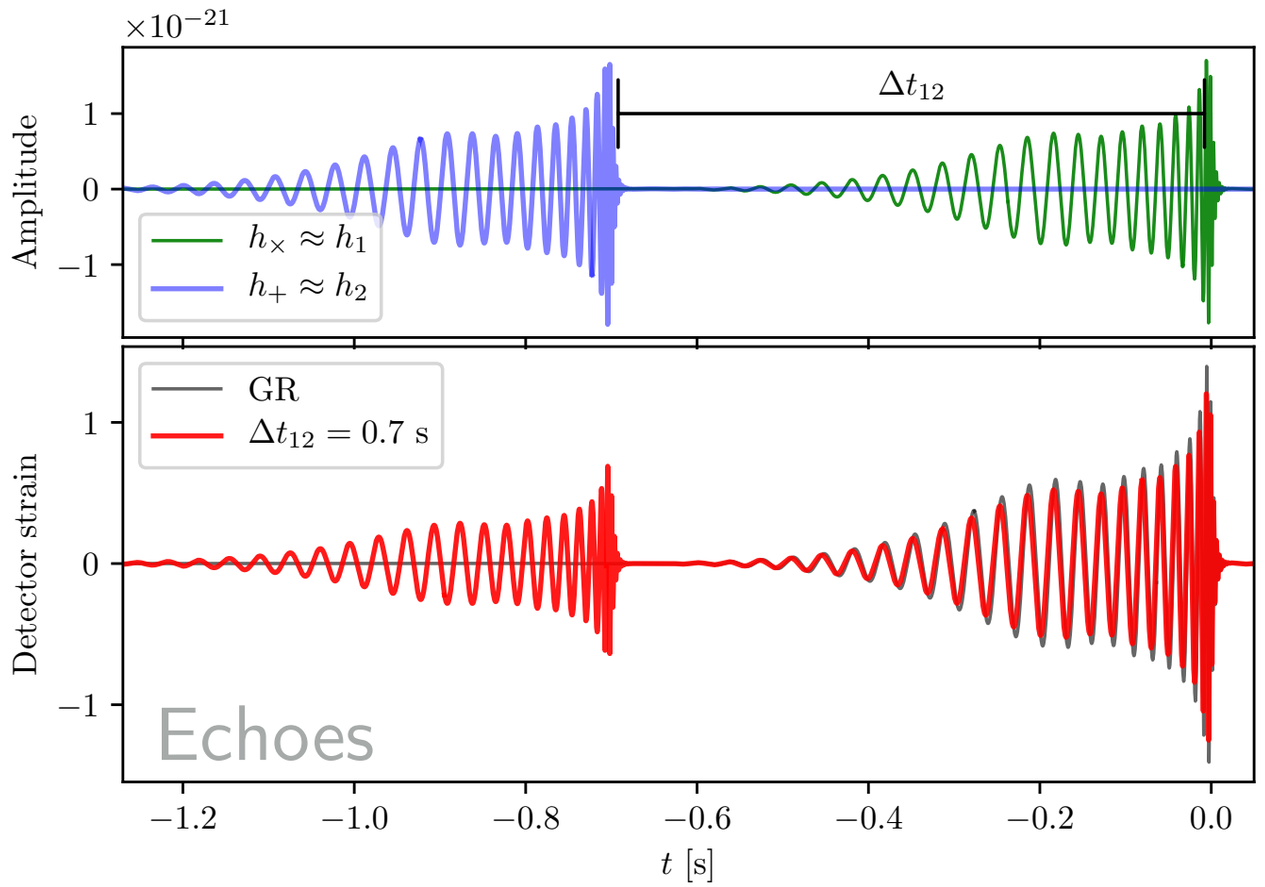
GW lensing beyond GR

Modified effective metric for each eigenstate and polarization mixing

Time delays

Birefringence





- No need of EM counterpart! Extend cosmological test GW propagation!

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