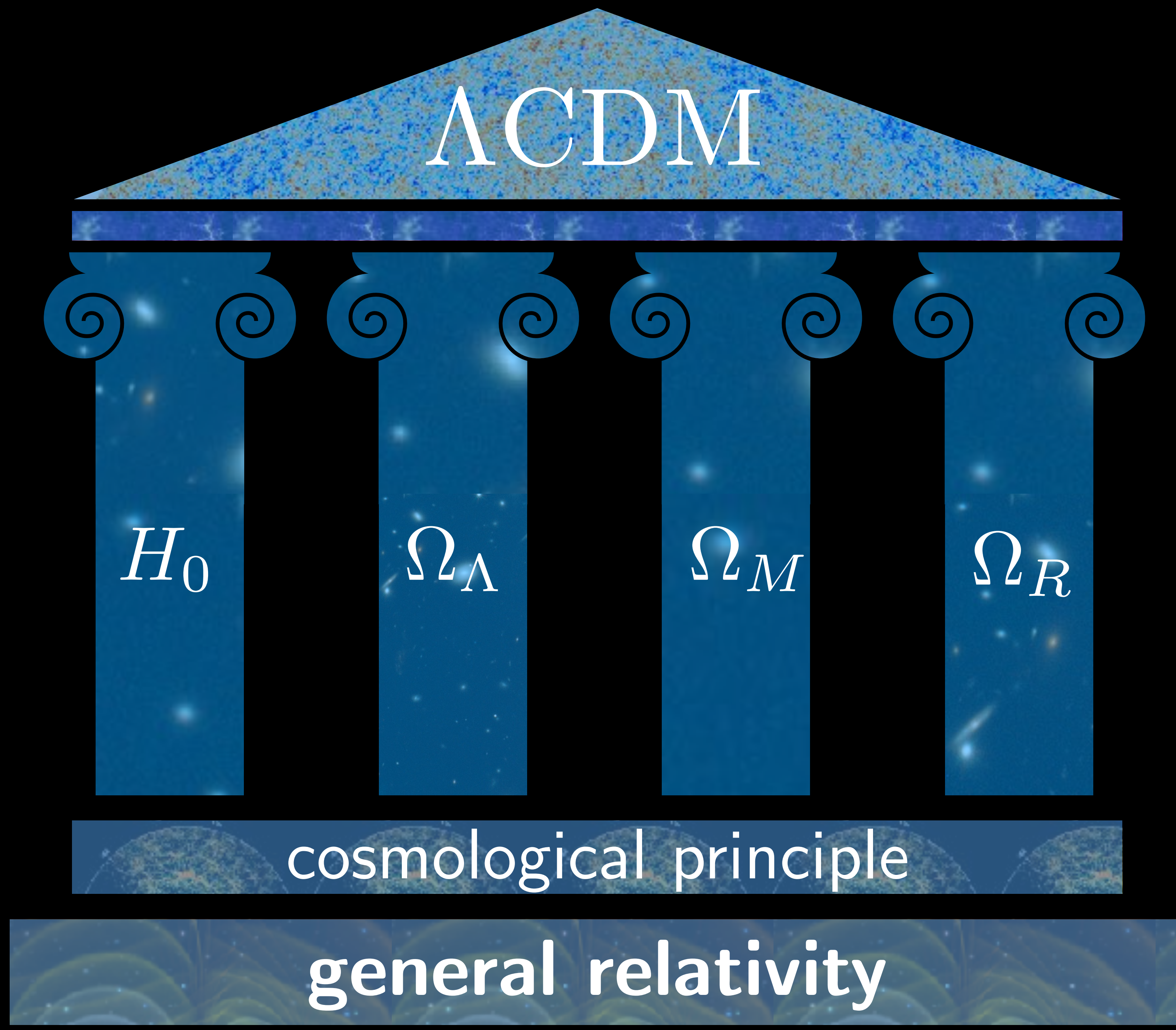
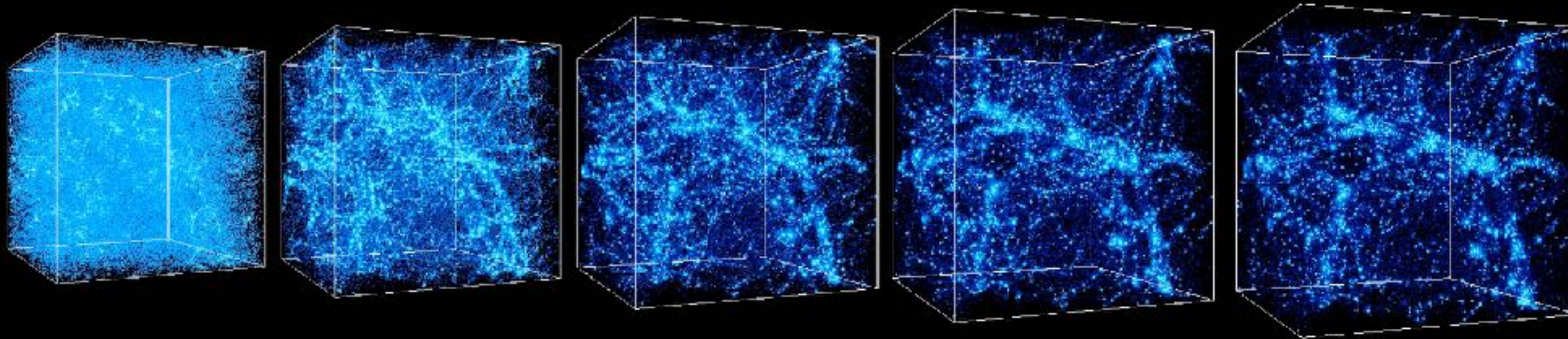
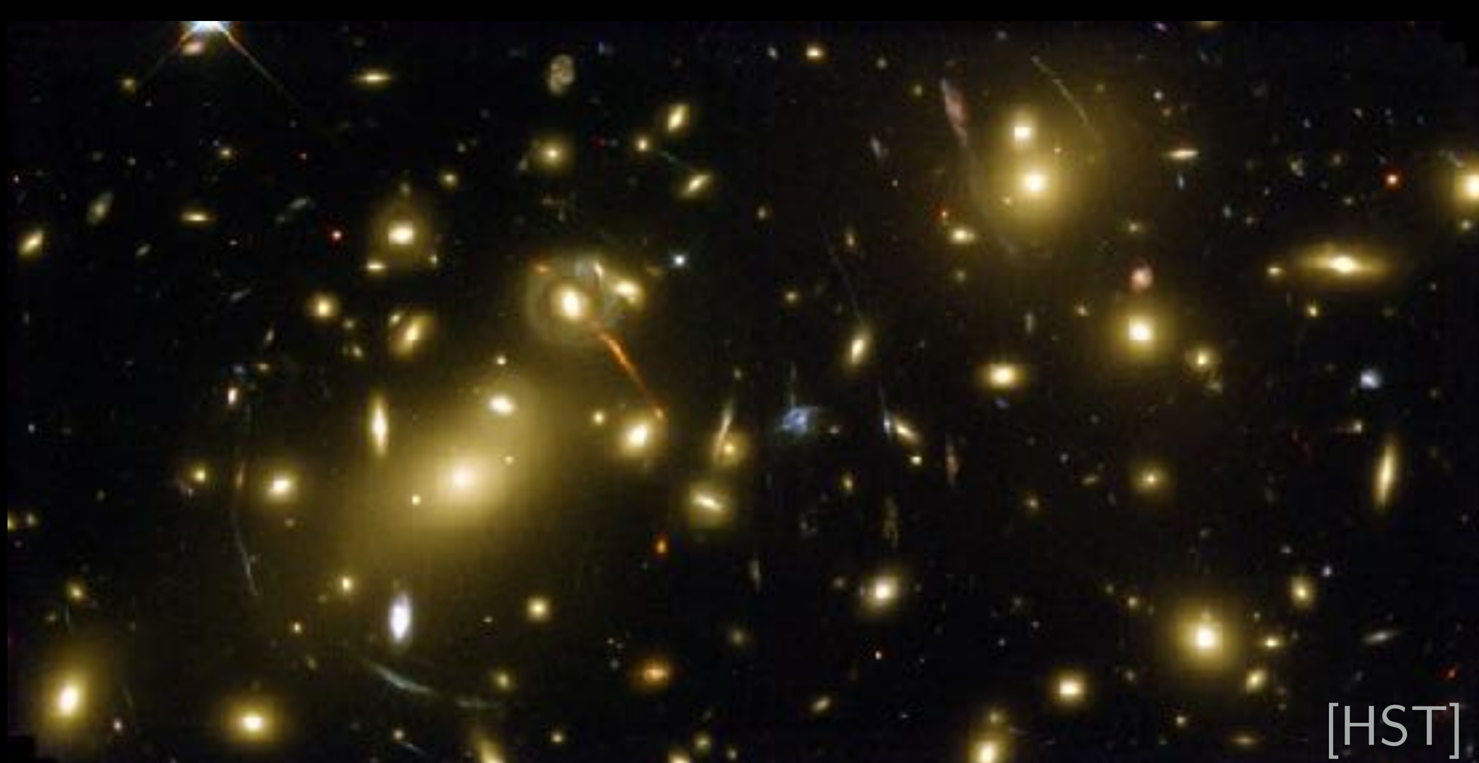
Testing LCDM with LISA

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

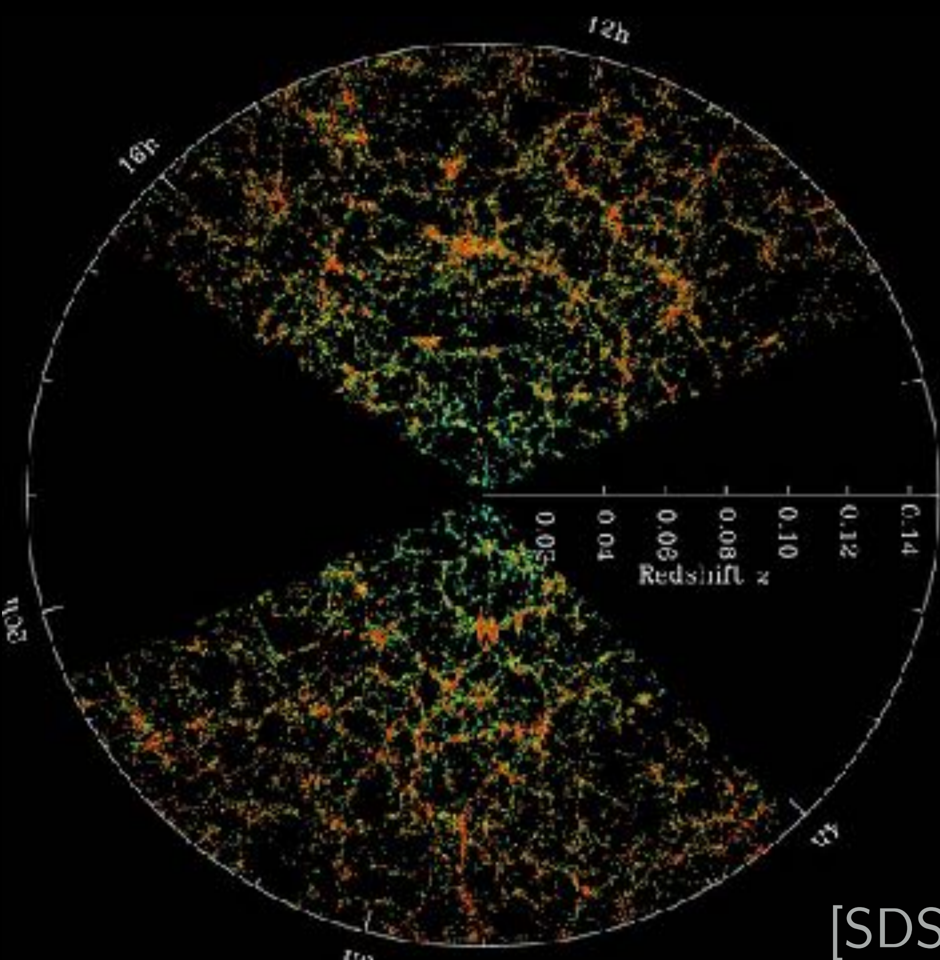

ΛCDM
H_0
Ω_Λ
Ω_M
Ω_R
cosmological principle
general relativity



[Kravtsov]

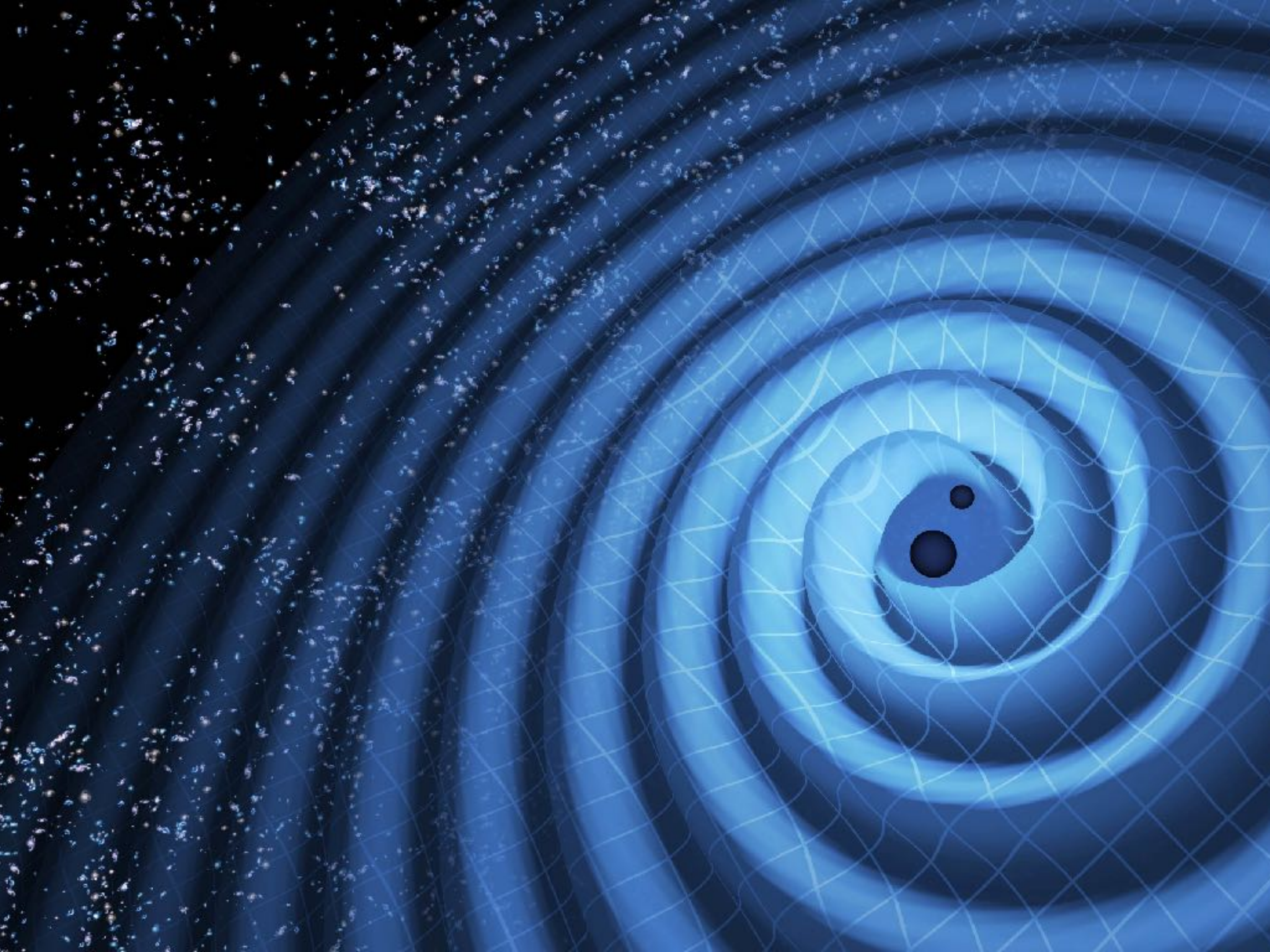


[HST]



[SDSS]

For a review see e.g. Ferreira'19



8. Interpretation, key-science projects

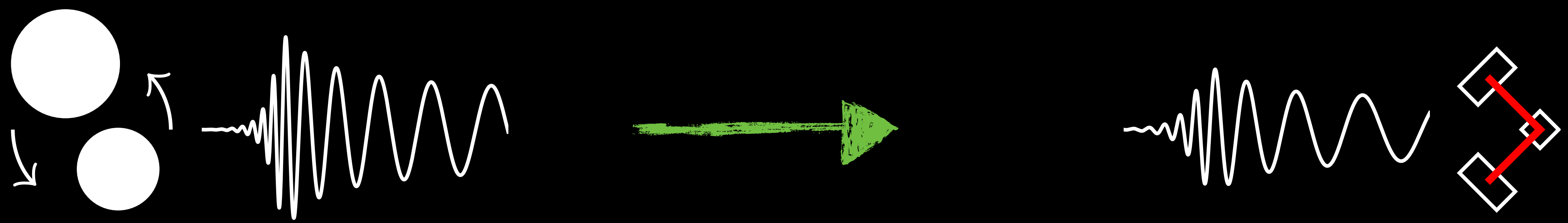
Galactic

Cosmology related

WP	Description	Priority
8.1	analysis of joint GW+EM observations of GBs (including VBs)	3
8.2	population studies of GW-only GBs	3
8.3	studies of seed black holes and BH formation mechanisms	3
8.4	studies of SMBHBs and connection to galaxy clustering	3
8.5	analysis of joint EM+GW SMBHB events	3
8.6	analysis of EMRI population	3
8.7	tests of GR and the nature of compact objects	3
8.8	analysis of IMBHBs and IMRIs	3
8.9	studies of SOBH populations	3
8.10	estimation of cosmological parameters	3
8.11	characterisation of backgrounds	3
8.12	analysis of detected unmodelled events	3

Table 8: Work packages on interpretation and key science questions.

Cosmological GW propagation



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

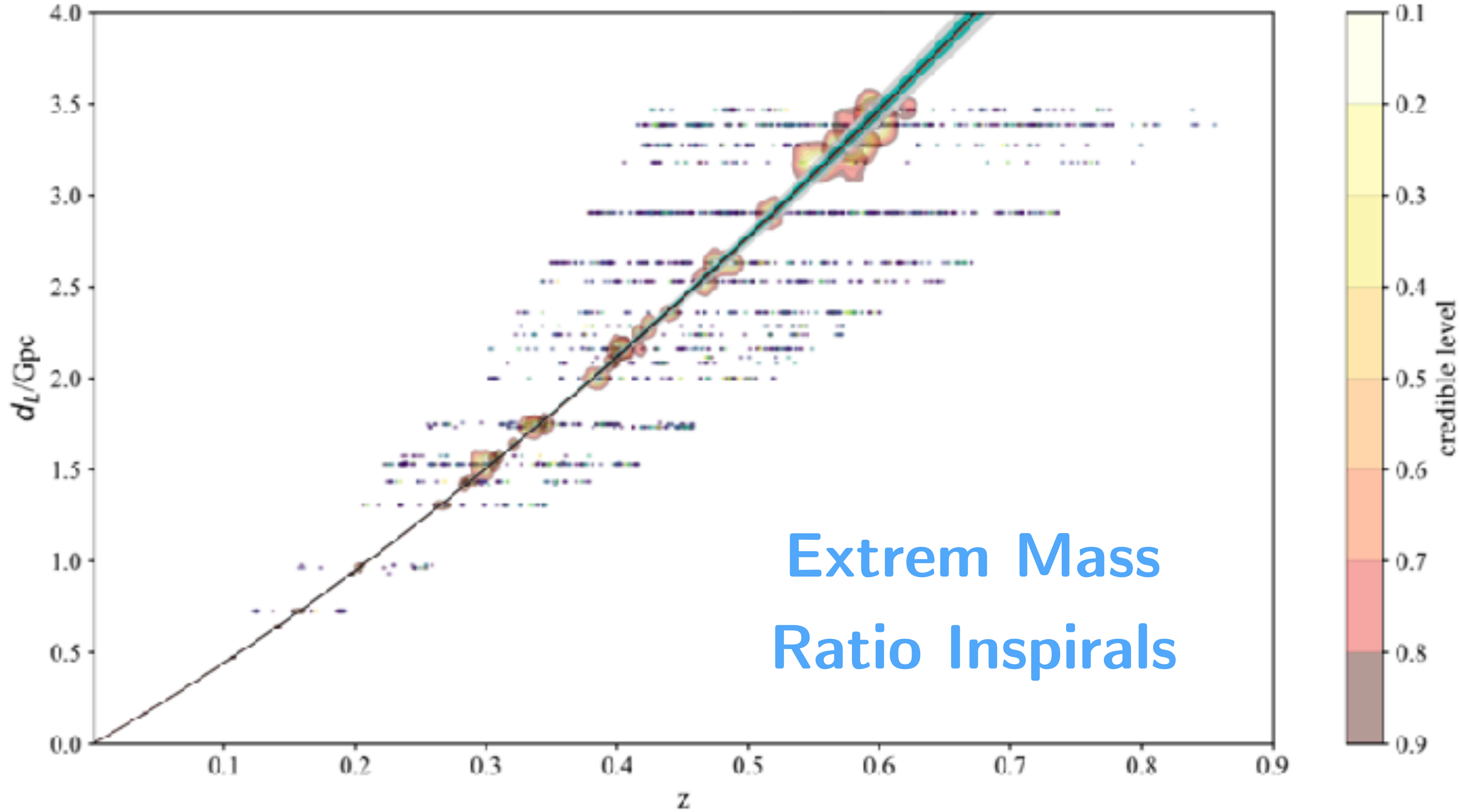
- Expansion rate: changes GW amplitude

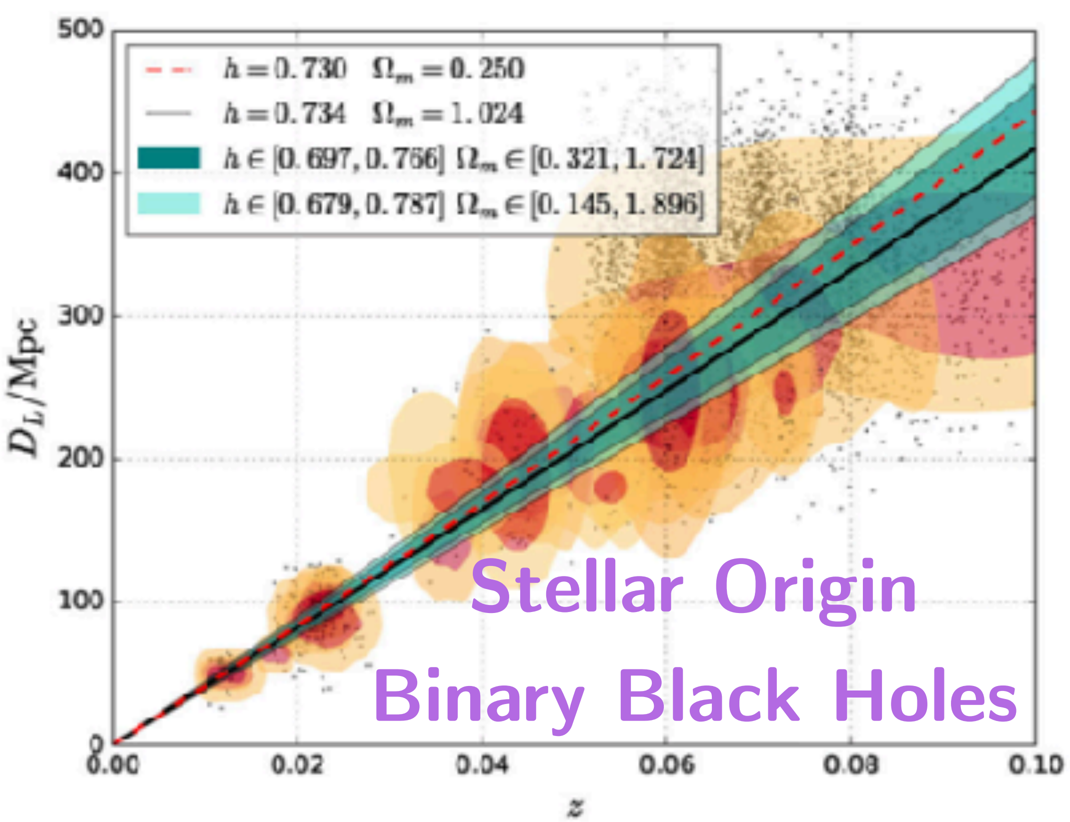
$$d_L = (1+z)\int_0^z \frac{c\,dz}{H(z)}$$

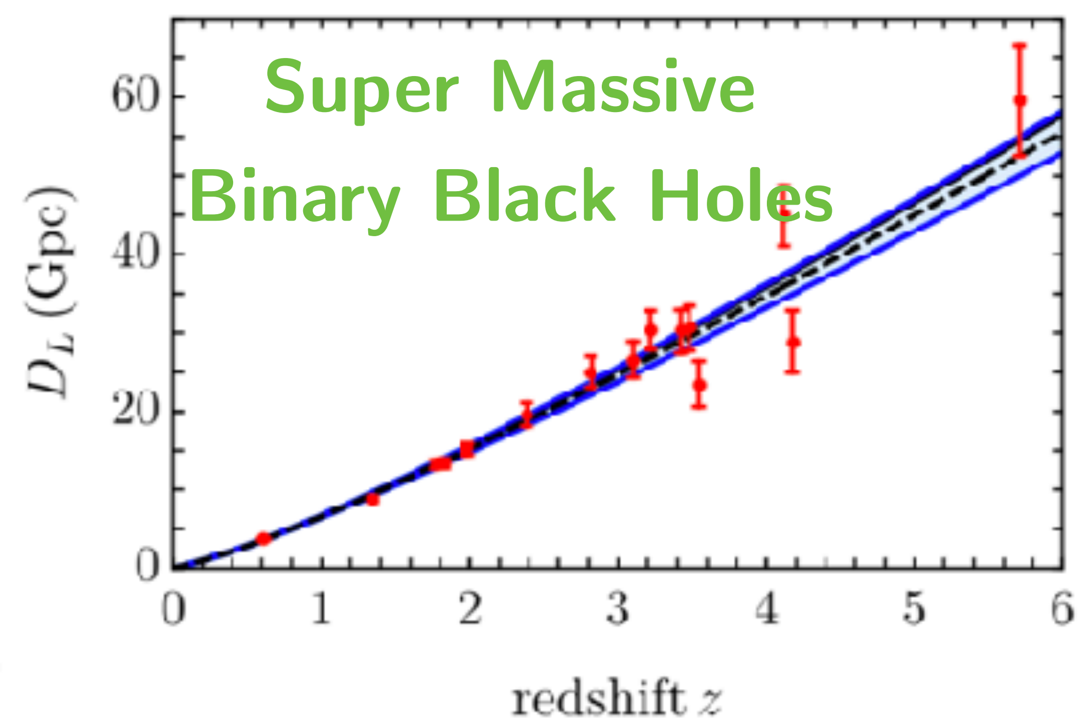
LISA will constrain expansion history at different redshifts, e.g. H_0, EoS of DE, DM

For more details see:

LISA Cosmology White Paper (arXiv 2204.05434)

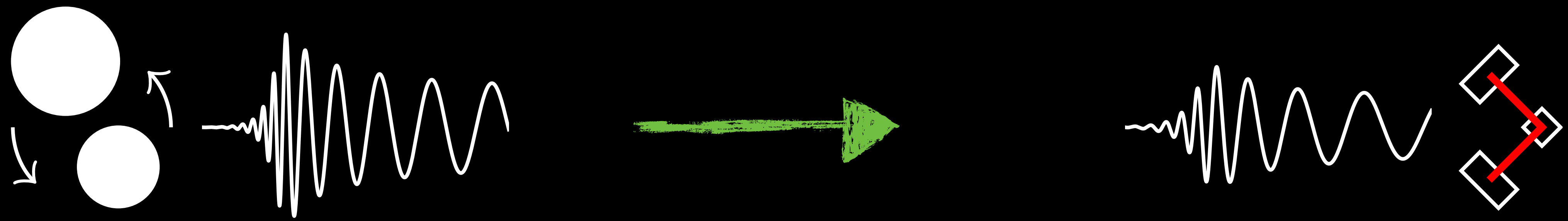






LISA Cosmo WG white paper (arXiv 2204.05434)

Modified GW propagation



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

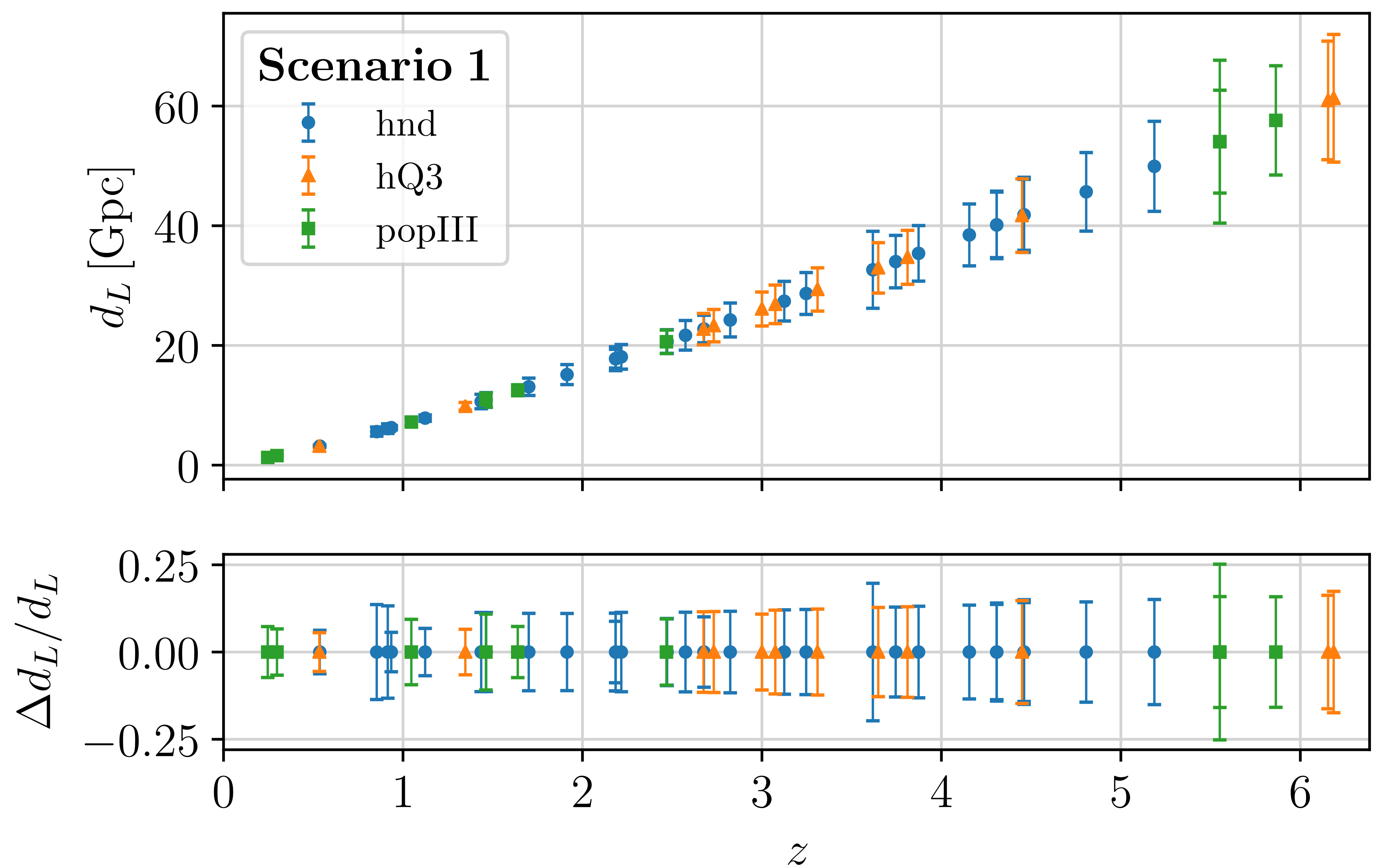
- Speed: changes arrival time
- Amplitude: modifies luminosity distance
- Phase: may produce waveform distortions
- Polarization: birefringence, additional tensor modes

Small deviations accumulate over cosmological propagation times!

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

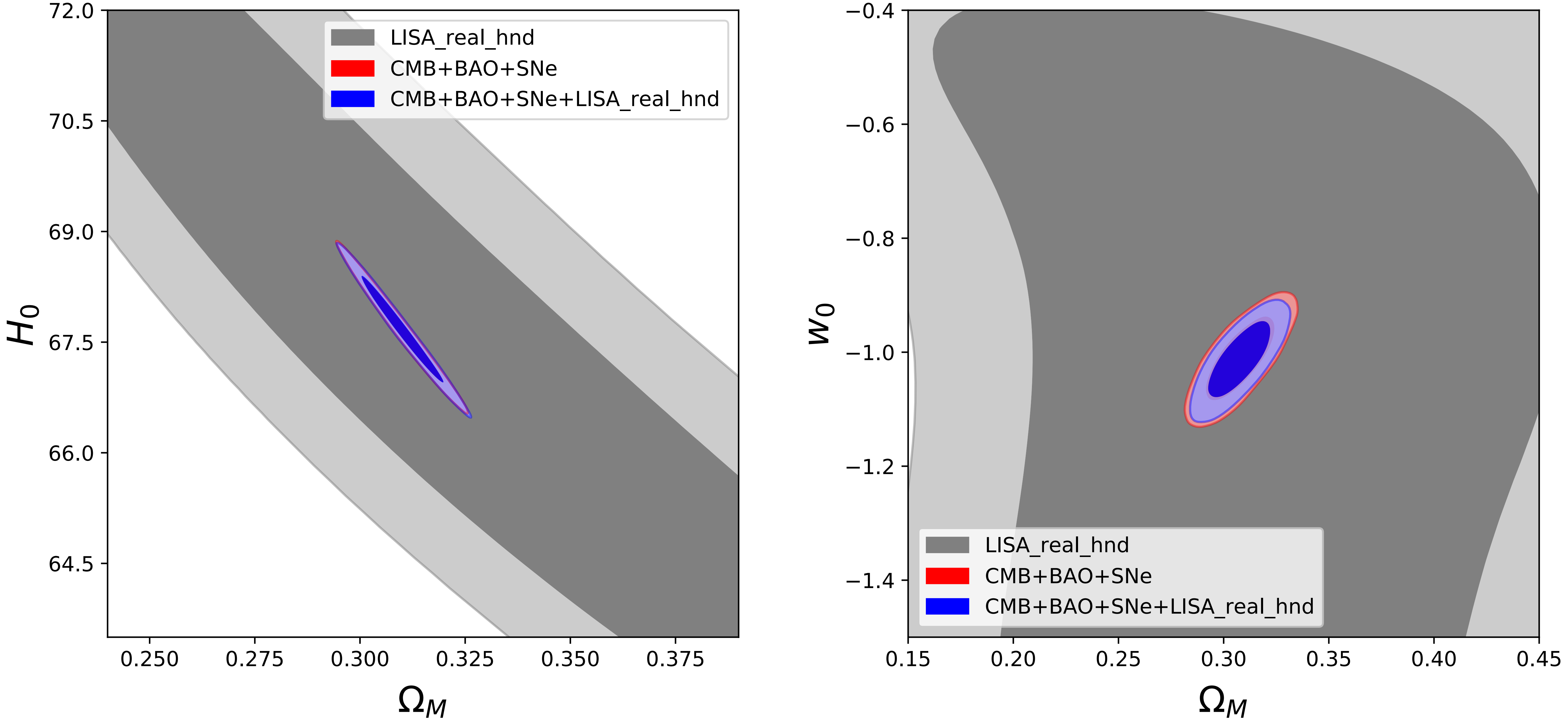
LISA forecasts: SMBBHs

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



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

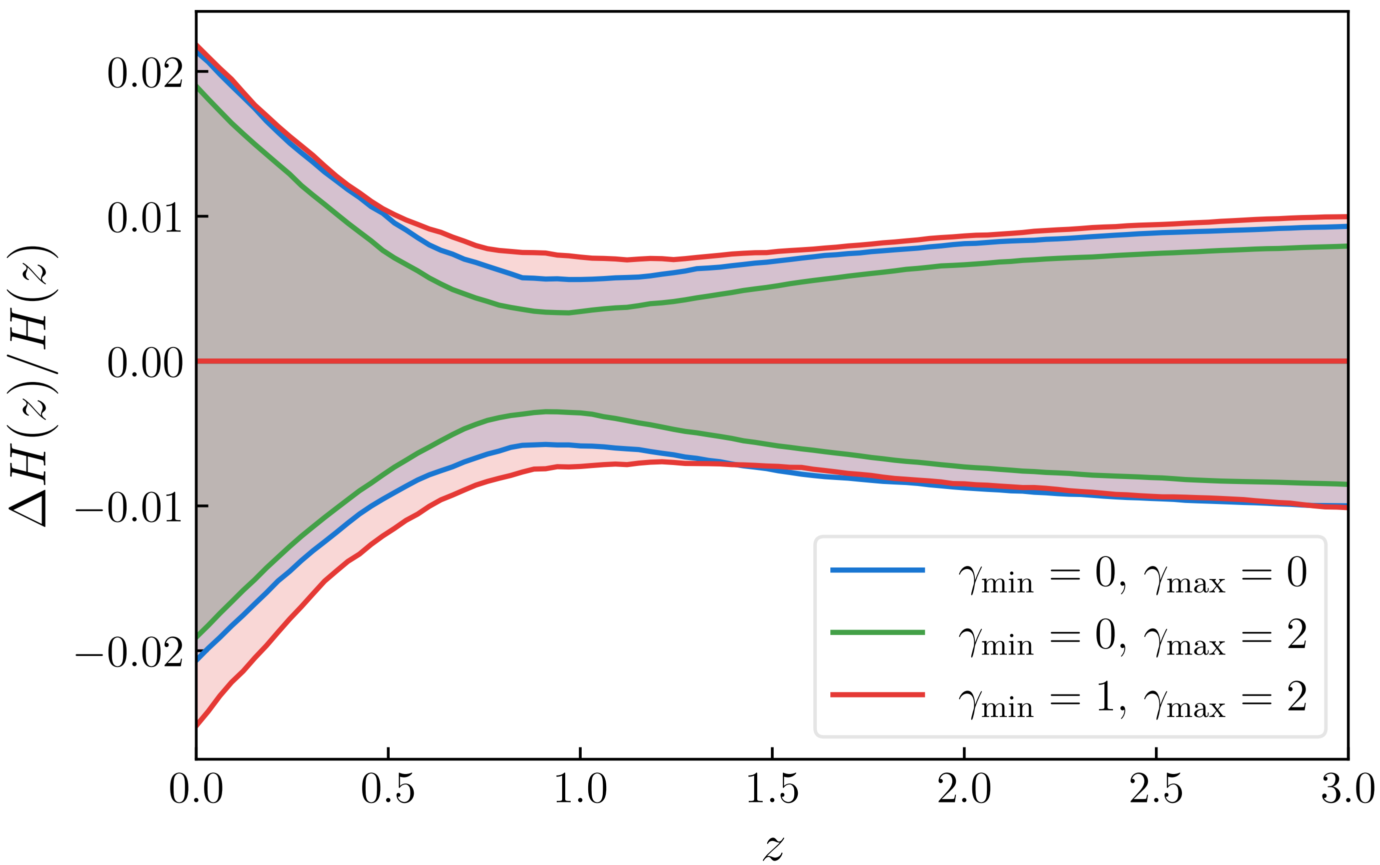
LISA forecasts: SMBBHs

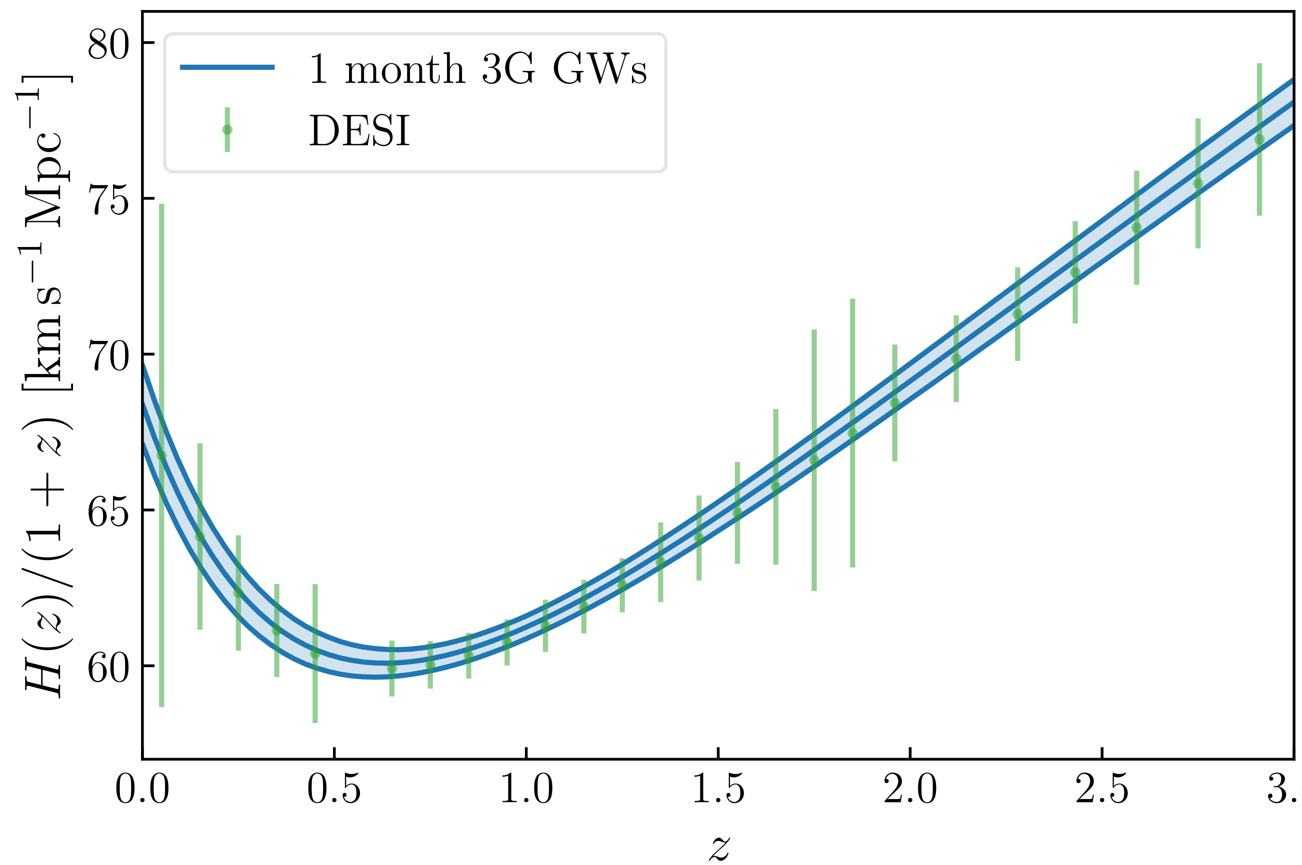


Belgacem *et al.*; *Testing modified gravity at cosmological distances with LISA* (arXiv 1906.01593)

3G cosmo inference

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



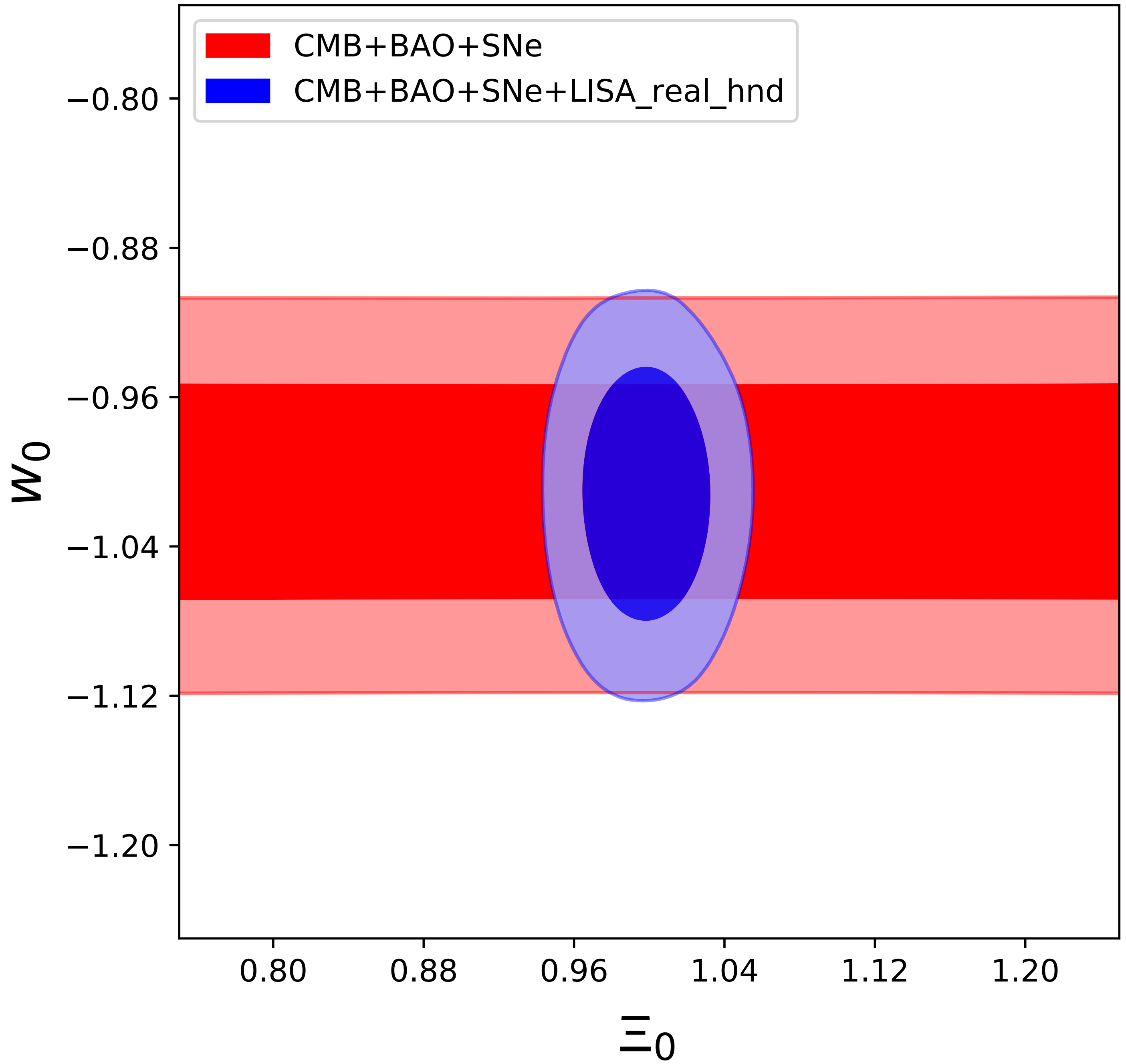


Sub-percent within 1 month. High-redshift!

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

LISA forecasts: SMBBHs

$$\frac{d_L^{\rm gw}}{d_L^{\rm em}} = \Xi_0 + \frac{1 - \Xi_0}{(1+z)^n}$$



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

Modified dispersion relation (MDR)

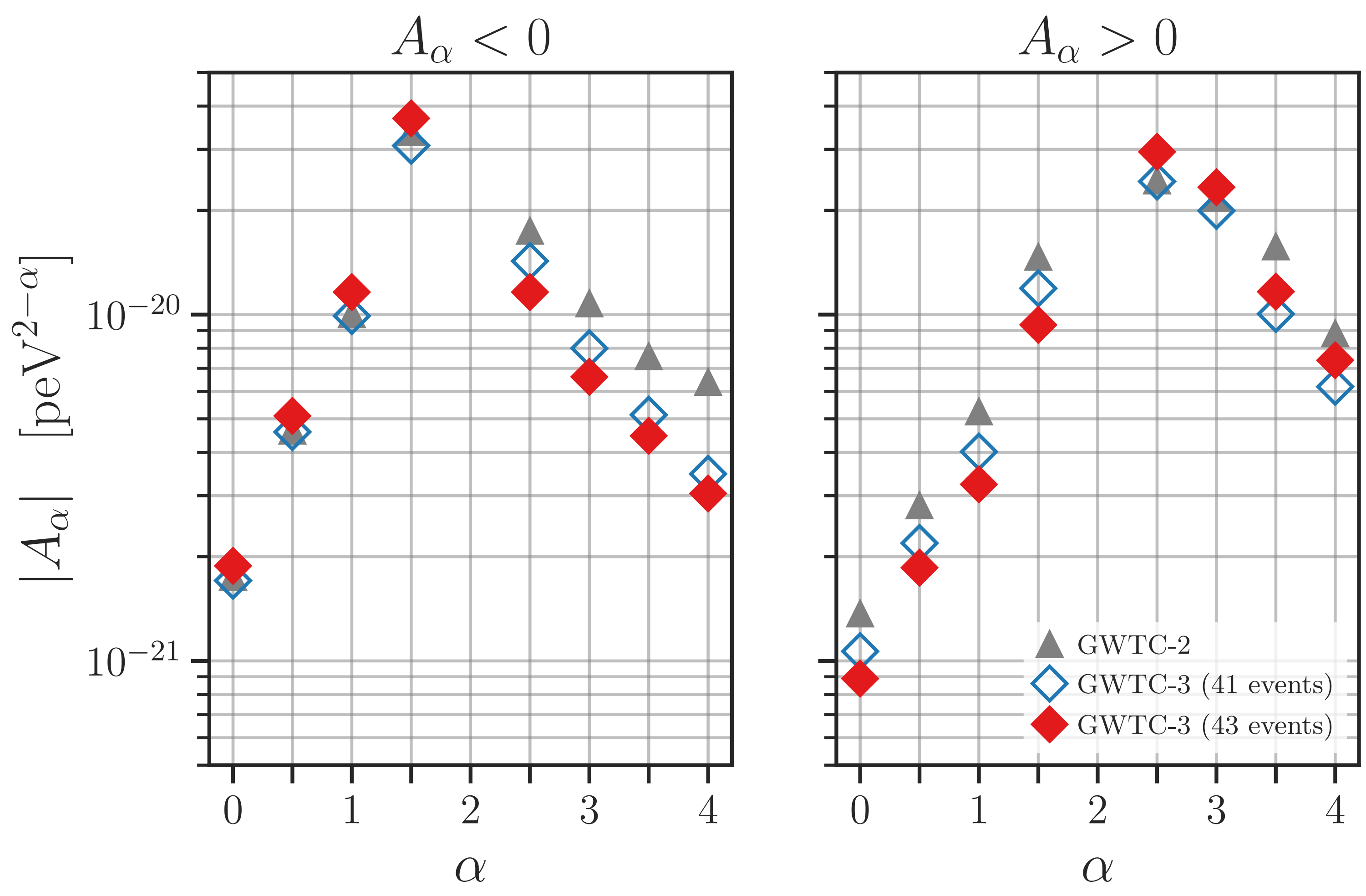
General relativity predicts: $\omega(k) = c \cdot k$

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]

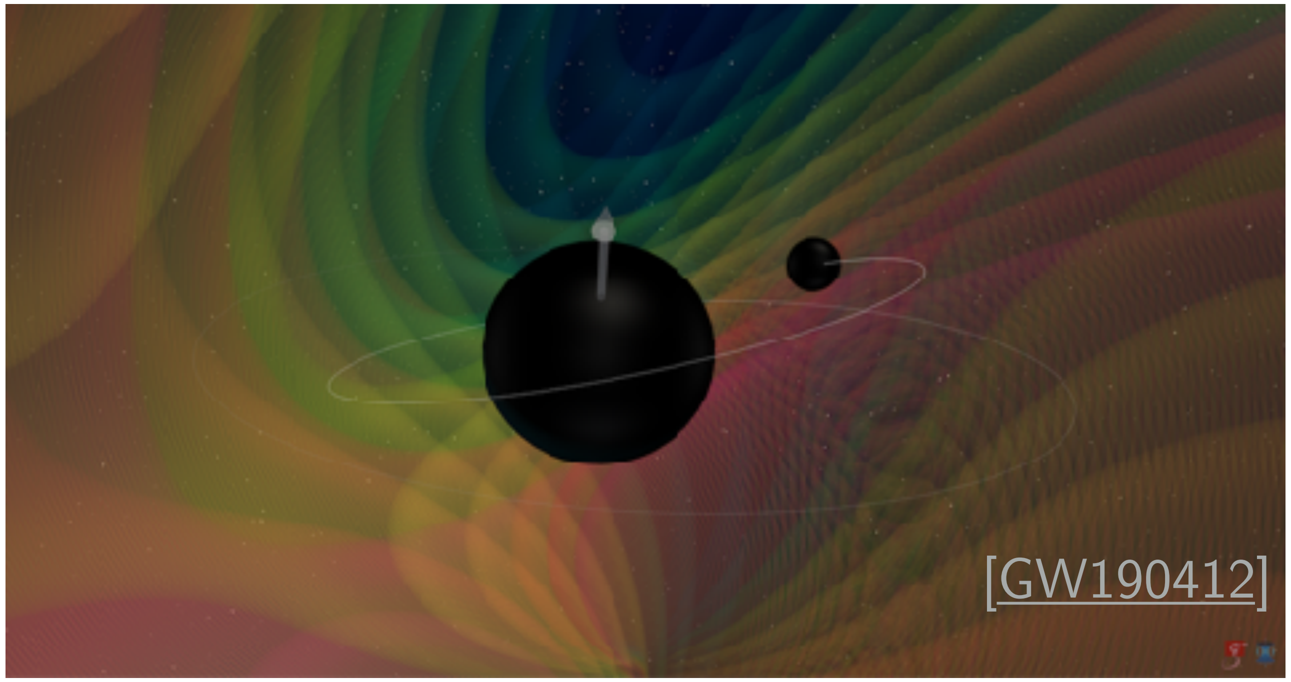


[LVK TGR GWTC-3]

MDR with higher modes

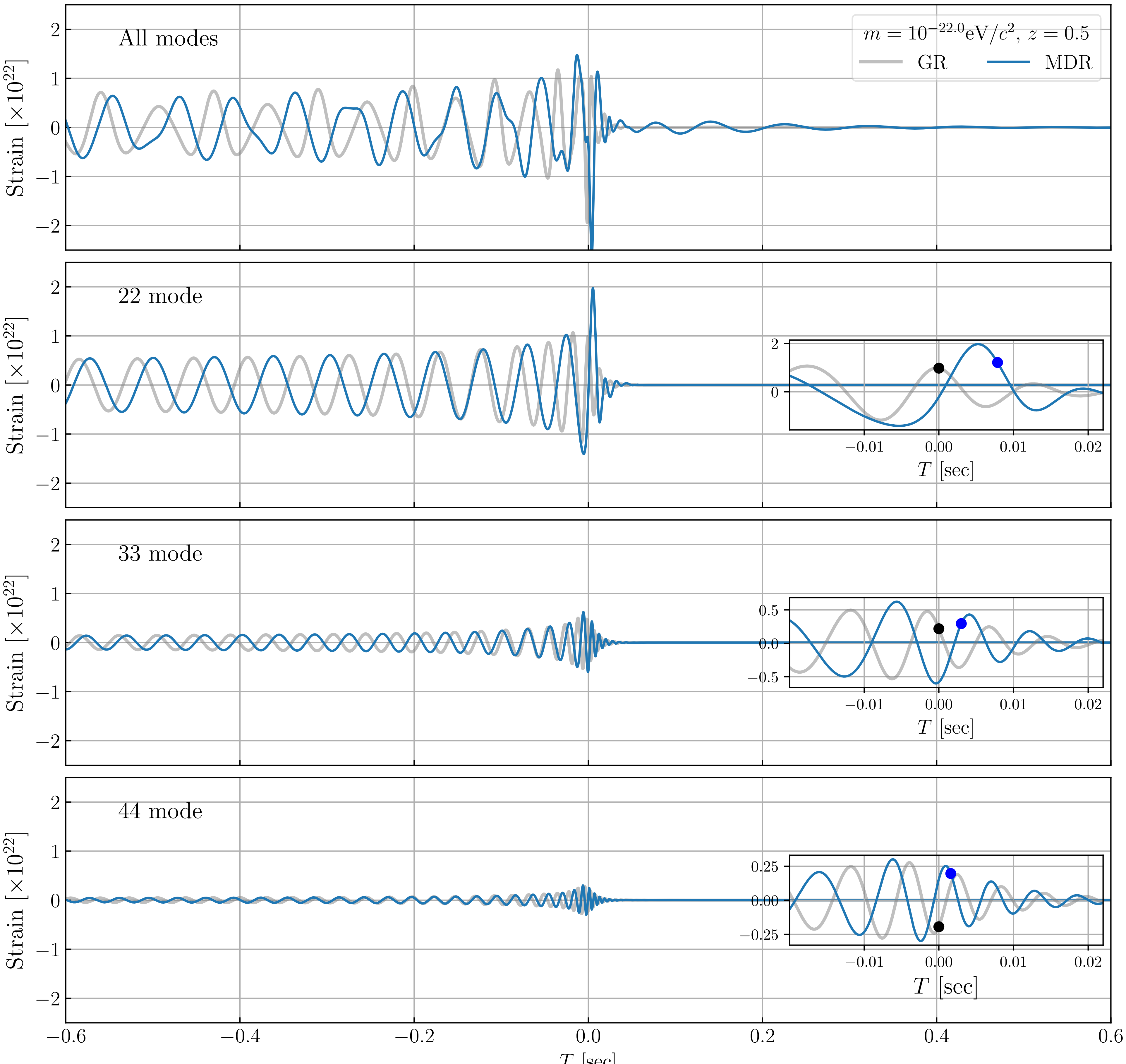
Previously, only dominant quadrupole (*l,m=2,2*) mode included.
Frequency-independent phase shifts are *degenerate* with coalescence phase

We have now events with evidence of HMs, *definitely* more with LISA



Each higher modes gets a different time delay and phase shift!

Ezquiaga, Hu, Lagos, Lin, Xu; *Modified GW prop with higher modes* (arXiv 2203.13252)



Ezquiaga, Hu, Lagos, Lin, Xu; *Modified GW prop with higher modes* (arXiv 2203.13252)

MDR with higher modes

Solving the propagation equations using ***WKB*** allows for arbitrary initial conditions [Ezquiaga et al.'21]

$$h_{\rm mg} \sim h_{\rm gr}\, e^{-i\int \Delta\omega {\rm d}z/H(z)} \equiv h_{\rm gr}\, e^{i\Delta\Psi} \qquad \Delta\Psi(f) = -\frac{\mathbb{A}}{2} D_\alpha (2\pi f_s)^{1-\alpha}$$

WKB approach is equivalent to the stationary phase approximation (SPA) with time delays computed with the **group velocity**

This is different to the SPA with **particle velocity**

E.g. $\omega^2 = c^2k^2 + \mathbb{A}ck$:

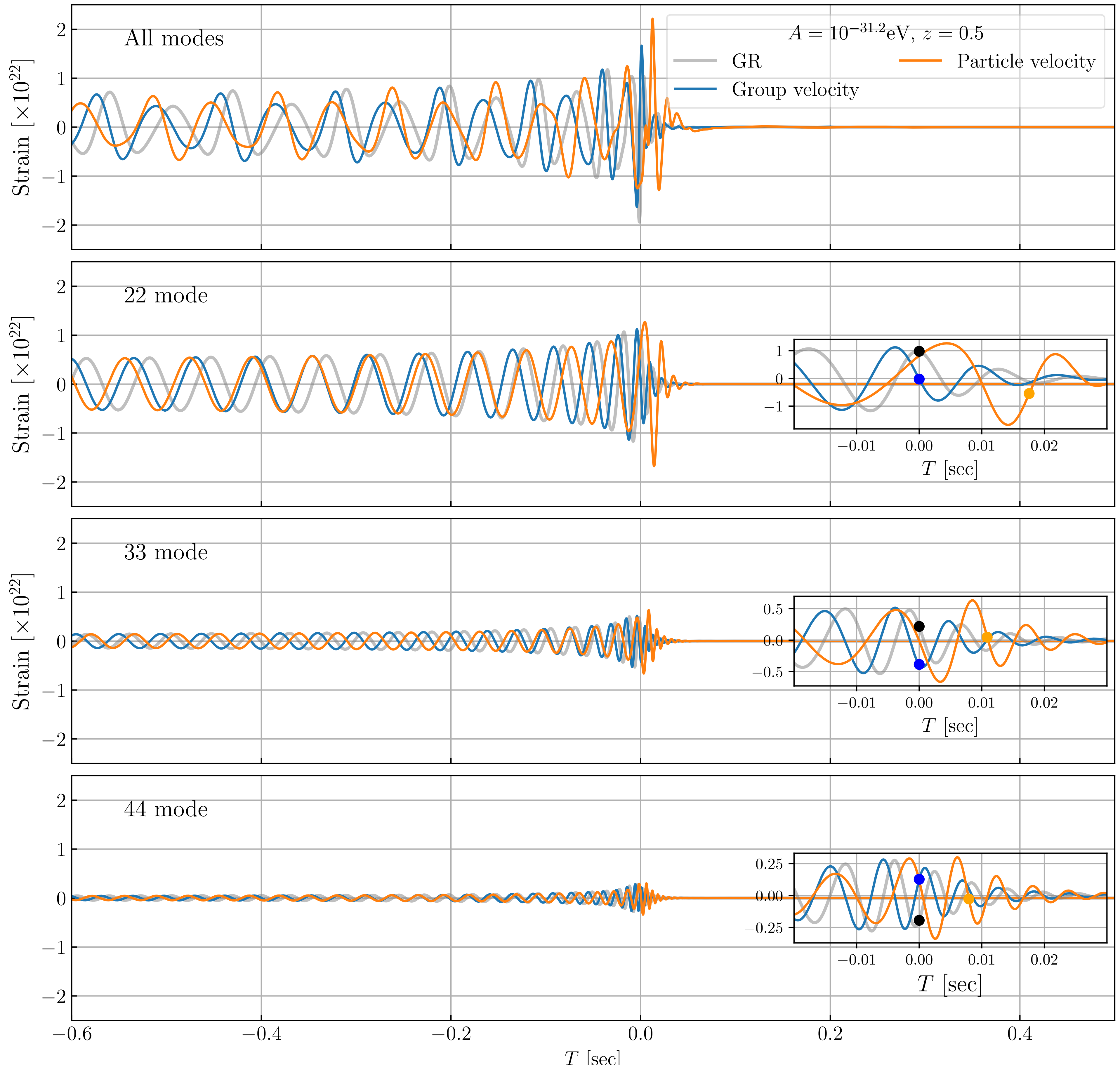
$$\Delta\Psi(f) = -\frac{1}{2}\mathbb{A}D_1$$

group velocity

$$\Delta\tilde{\Psi}(f) = \frac{1}{2}\mathbb{A}D_1 \ln\left(\frac{ef}{f_0}\right)$$

particle velocity

Ezquiaga, Hu, Lagos, Lin, Xu; *Modified GW prop with higher modes* (arXiv 2203.13252)

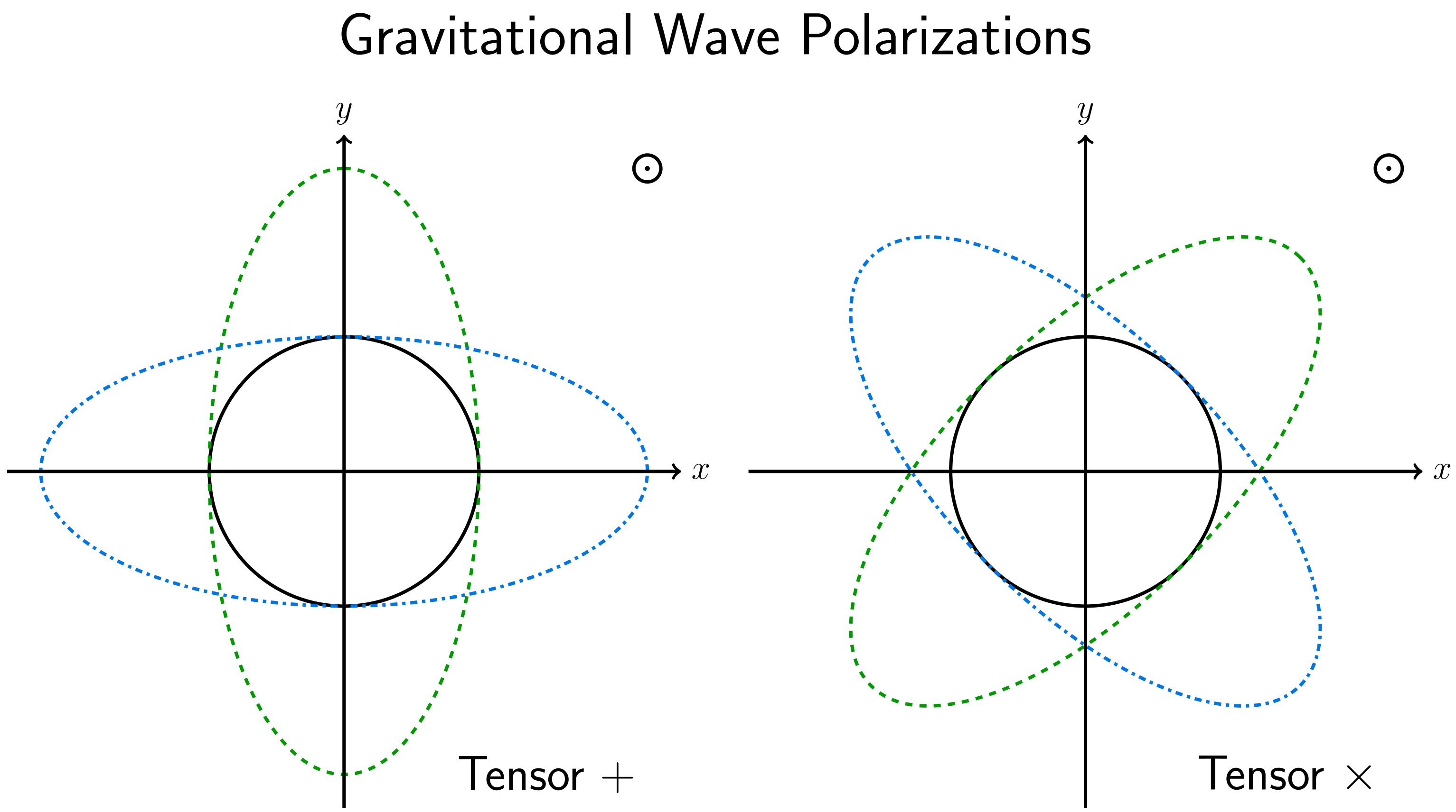


Ezquiaga, Hu, Lagos, Lin, Xu; *Modified GW prop with higher modes* (arXiv 2203.13252)

Polarization

General relativity predicts:

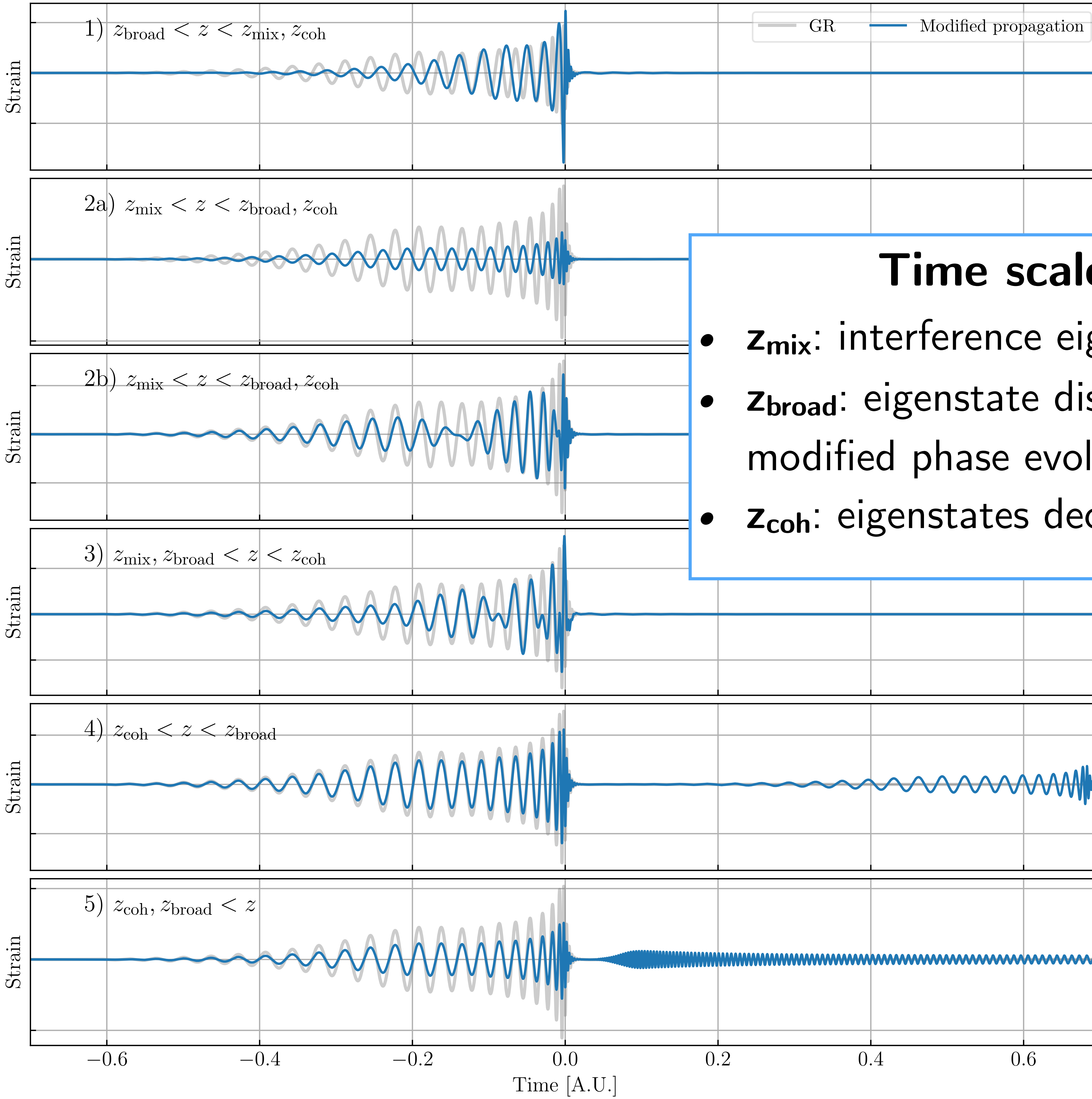
$$h_+ \,, \quad h_\times$$



Mixing cosmological tensor fields (similar to neutrino oscillations)

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

Beltrán, **Ezquiaga**, Heisenberg; *Probing cosmo fields with GWs* (arXiv 1912.06104)



Time scales

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

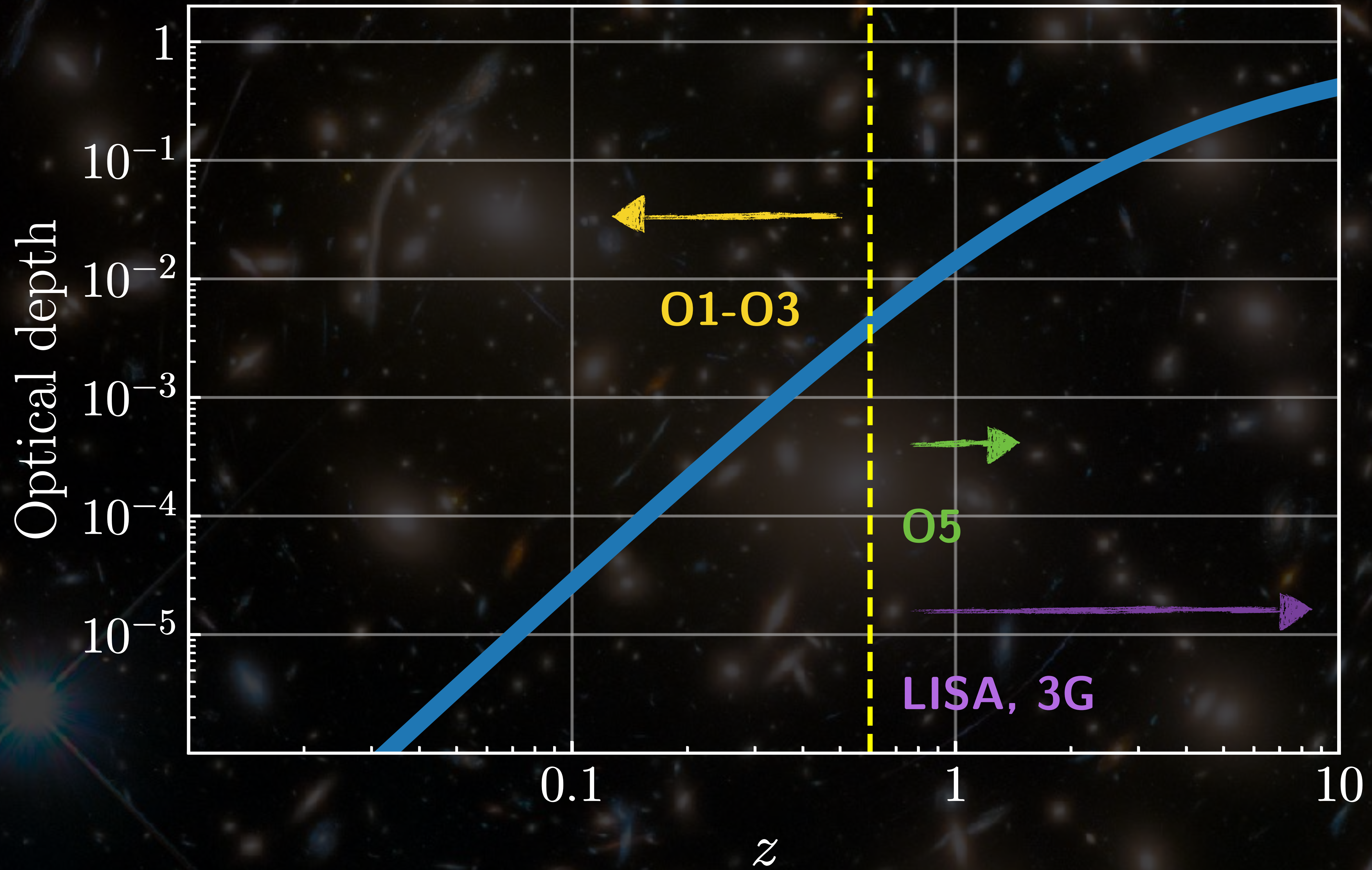
Ezquiaga, Hu, Lagos and Lin; *GW propagation beyond GR* (JCAP, arXiv 2108.10872)

Open questions

What are we learning about dark energy with these parameterizations?

Can we treat each effect separately?
E.g. luminosity distance vs modified dispersion relation

Propagation effects will likely dominate, but can waveform distortions at emission bias these analyses? Screening!



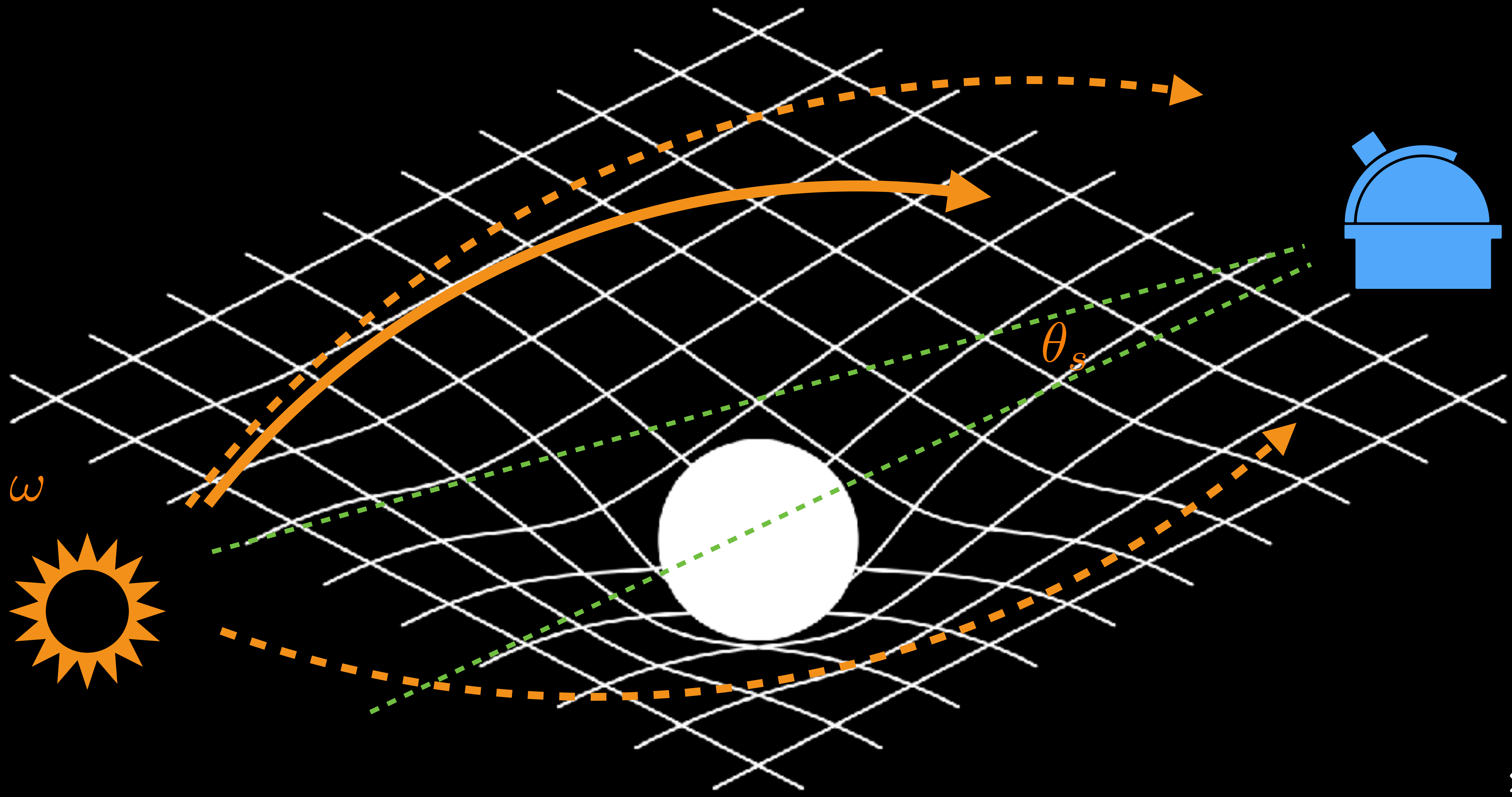
Optical depth
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
O1-O3
O5
LISA, 3G
0.1
1
10
z

Solving lensing

$\Delta t_d \cdot \omega$

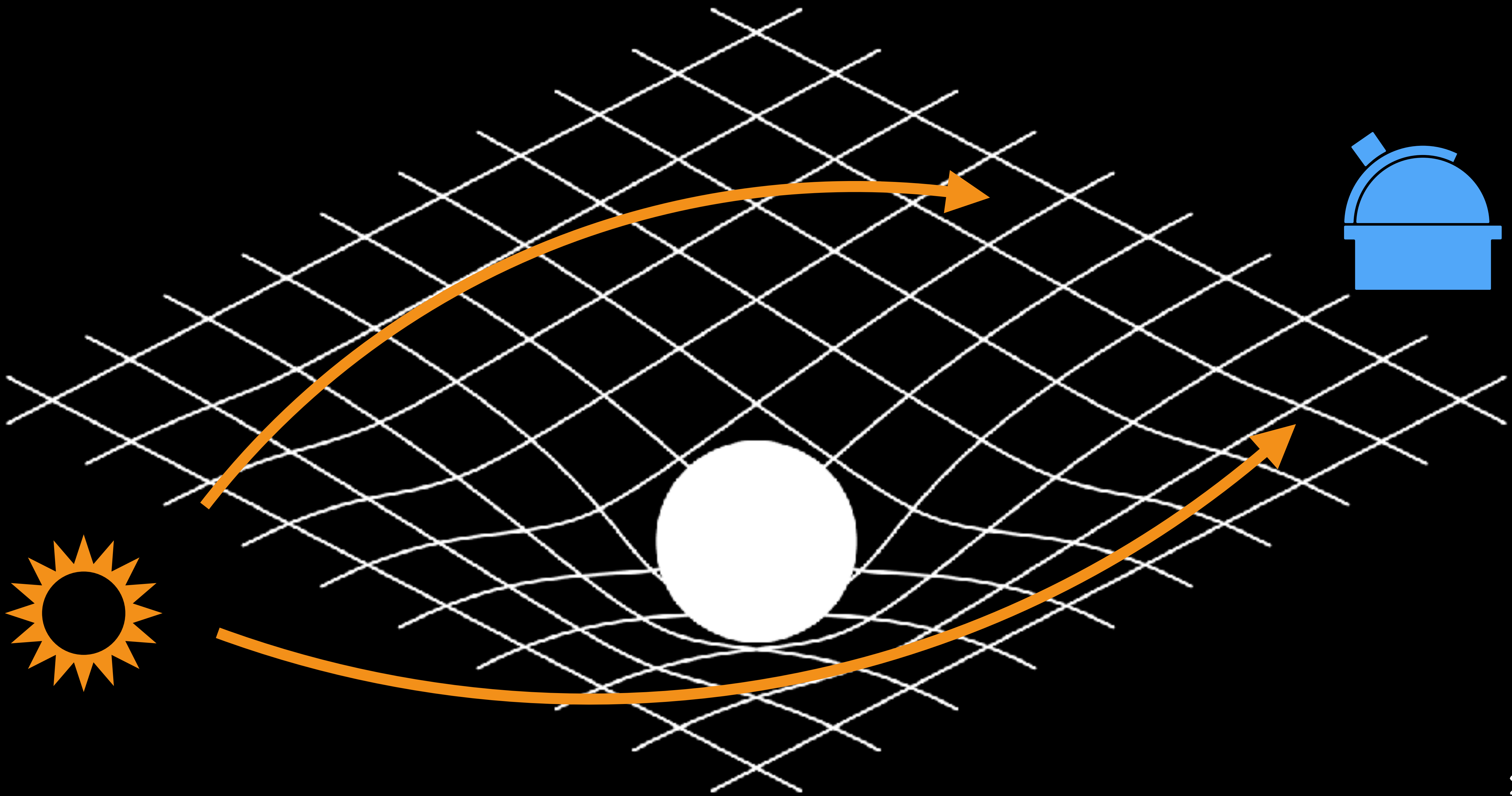
$$h_L(\omega, \theta_s) = F(\omega, \theta_s) h(\omega)$$

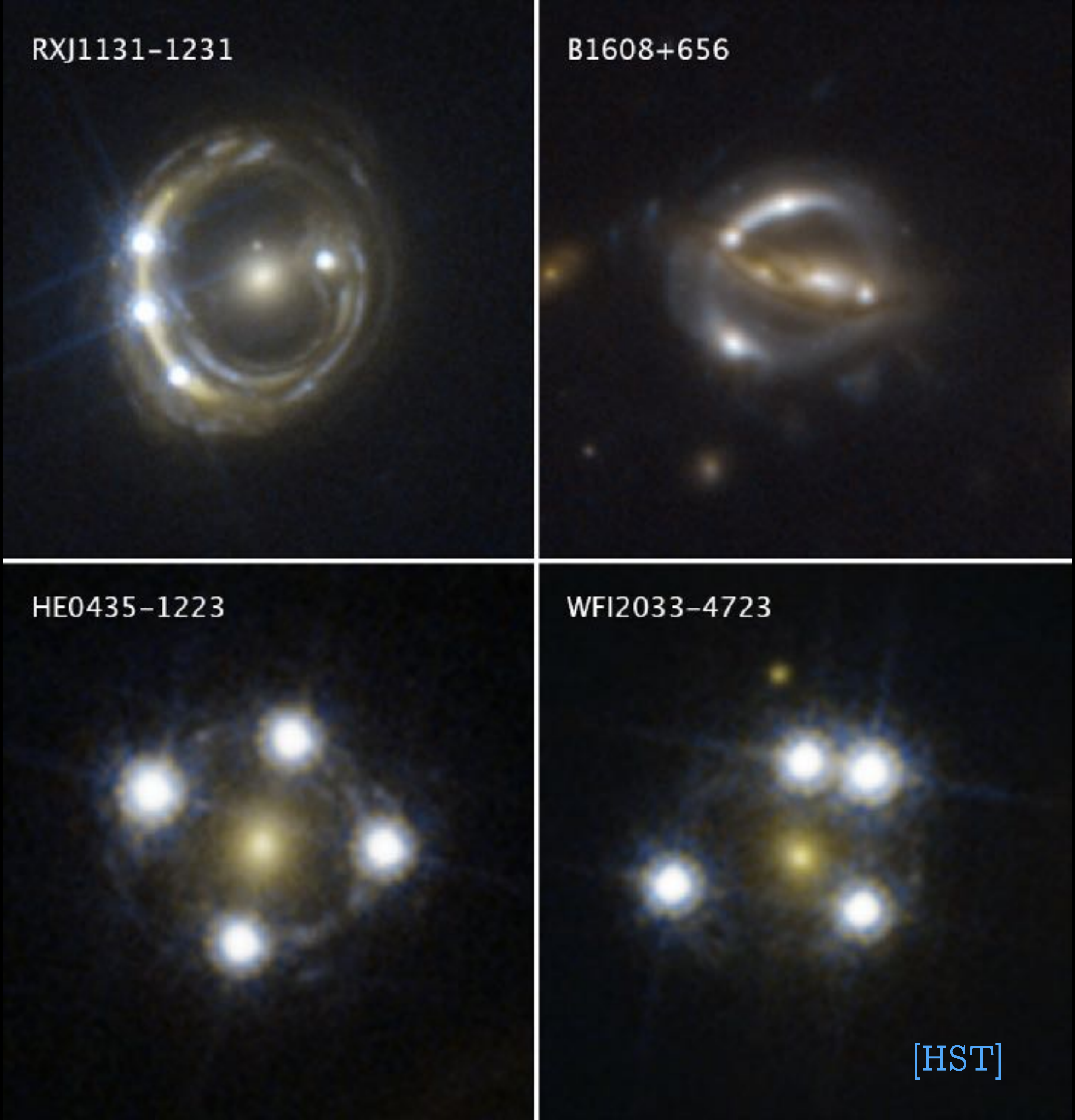
$$F(\omega, \theta_s) \sim \int \mathrm{d}^2\theta e^{i\omega t_d(\theta, \theta_s)}$$



Strong lensing

$\Delta t_d \cdot \omega \gg 1$



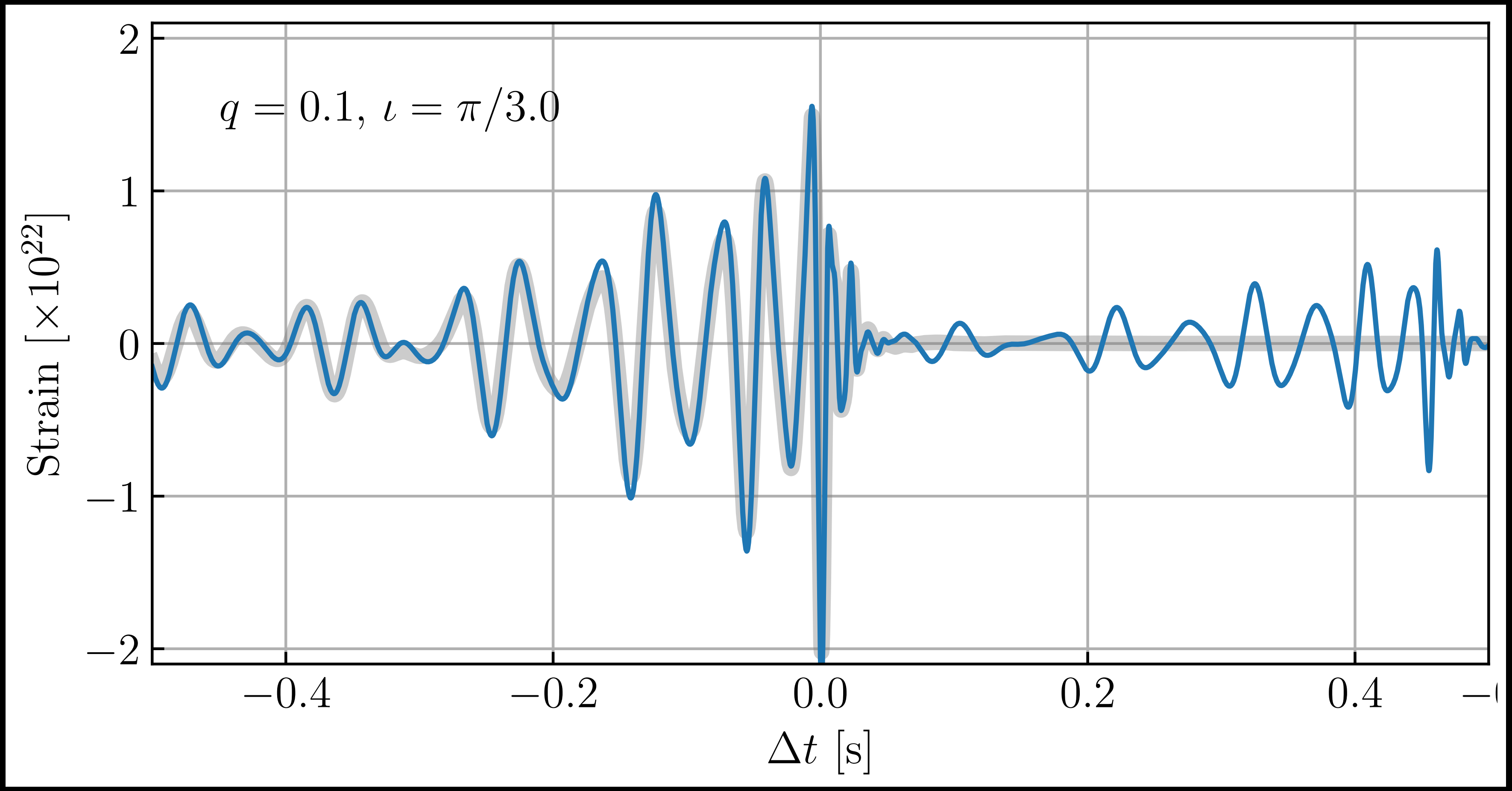

RXJ1131-1231
B1608+656
HE0435-1223
WFI2033-4723
[HST]

Strong lensing

$\Delta t_d \cdot \omega \gg 1$

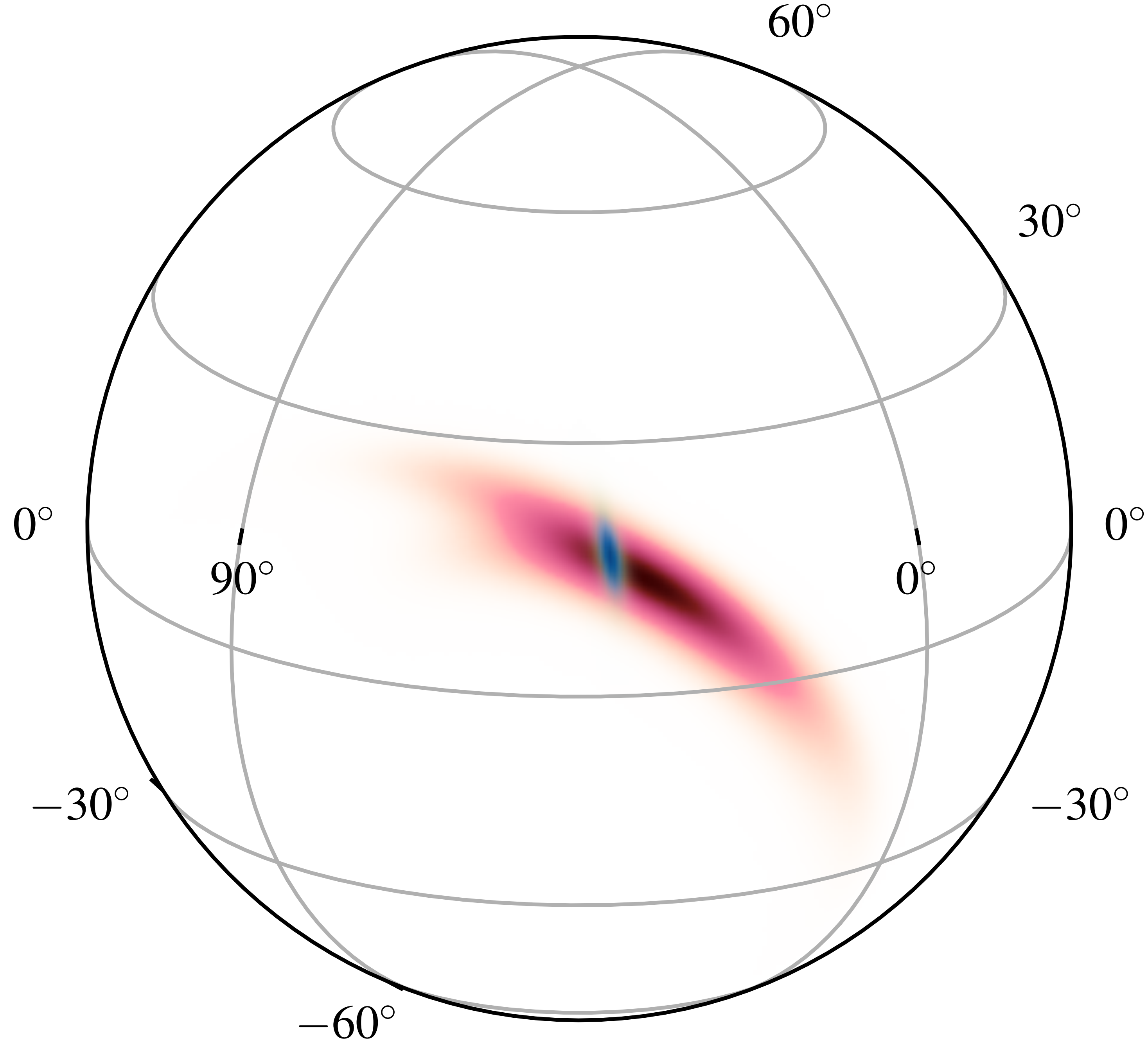
$$F \approx \sum_j |\mu_j|^{1/2} \exp\left(i\omega t_j - i\pi n_j\right)$$

Magnification
Time delay
Phase shift



GW sky localization

$$\theta_E \sim 1'' \sqrt{\frac{M}{10^{12} M_\odot}} \sqrt{\frac{1\text{Gpc}}{D}}$$



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Magnification
Time delay
Phase shift

- Each image type acquire a different phase shift

$$n_j = 0,\ 1/2,\ 1$$

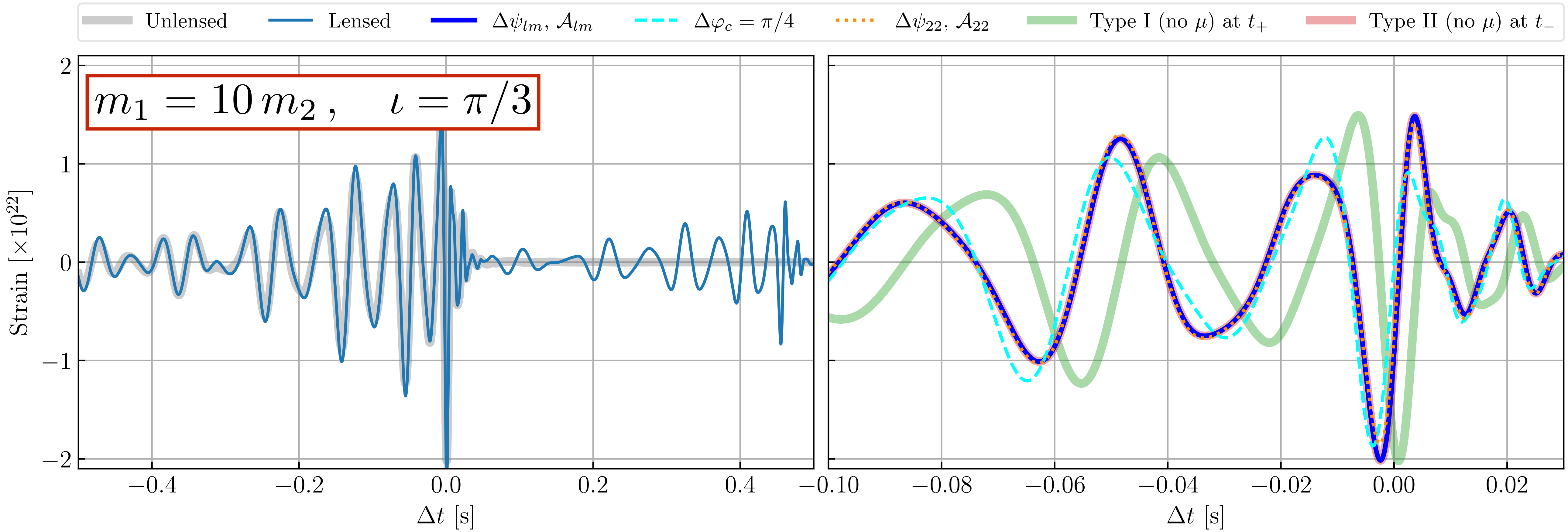
- A frequency independent phase shift is equivalent to a frequency dependent time delay

$$\Delta t_j = \pi n_j / \omega$$

Waveform distortions

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

$$\Delta t = n_j \pi / |\omega|$$



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

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

Strong lensing

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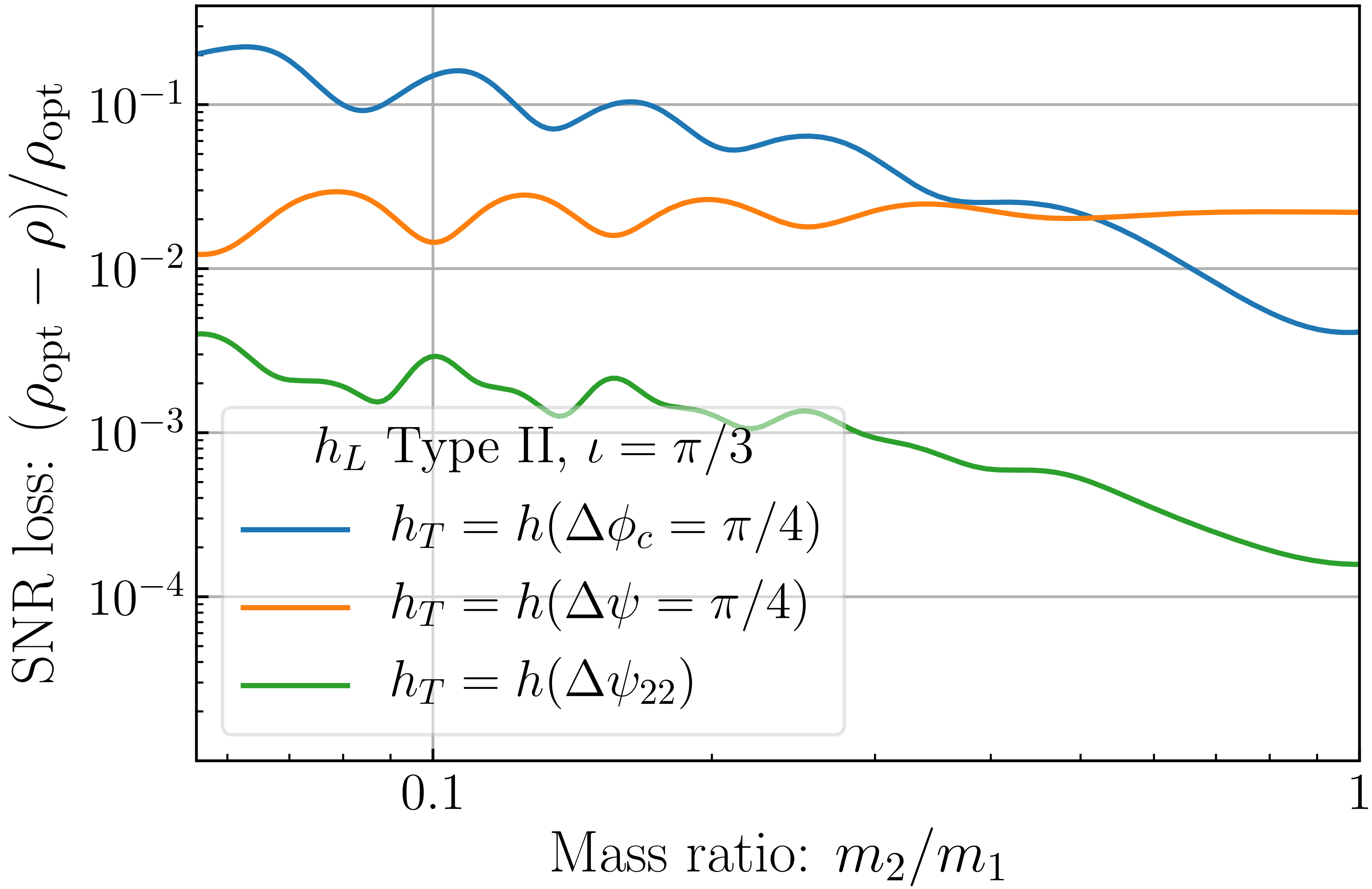
$$\Delta t_j = \pi n_j / \omega$$

- Lensed GWs *can differ* from (unlensed) GR wave-forms
- *Identify* strong lensing with *single image*

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

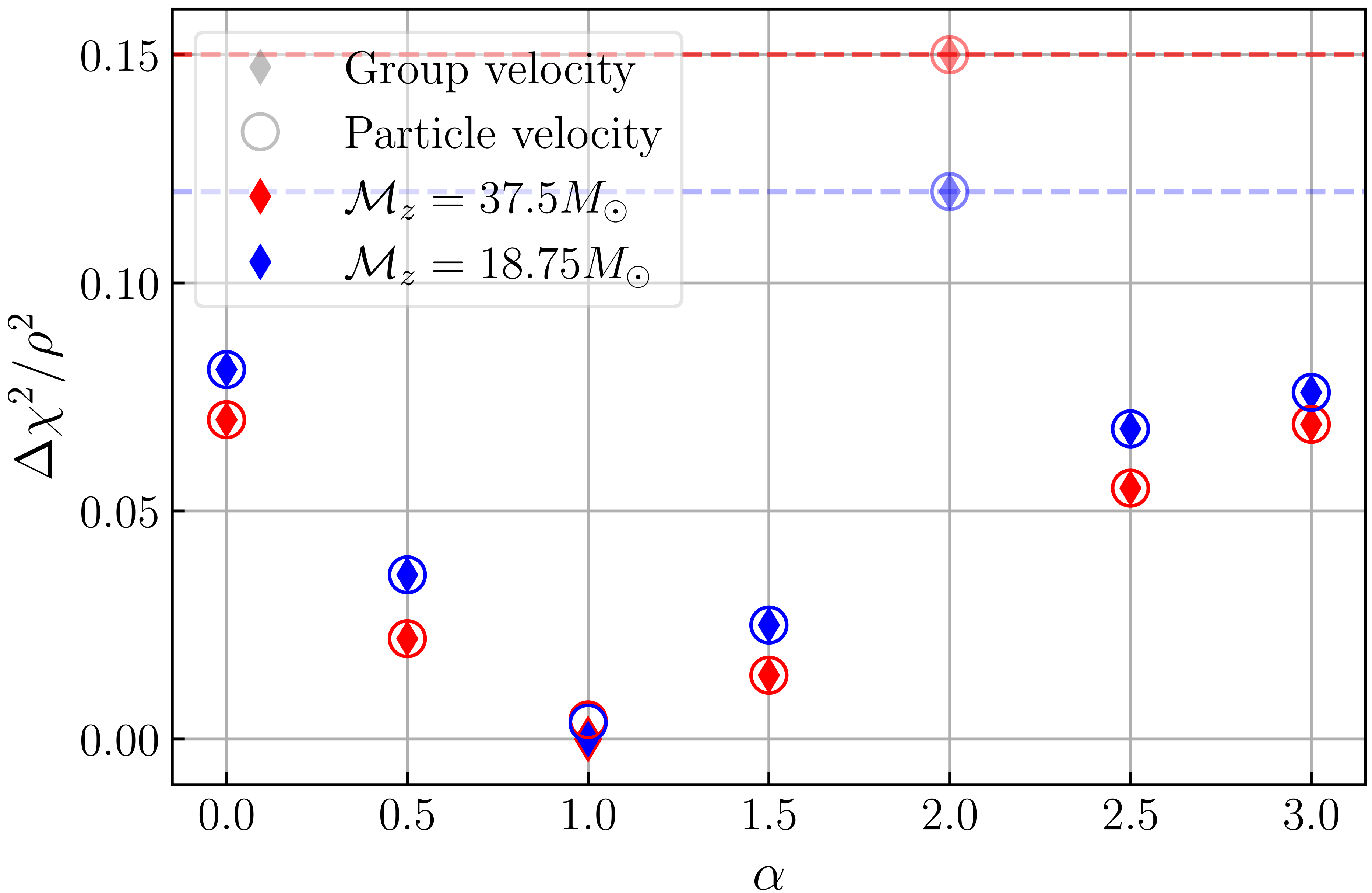
Effect on the SNR



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

Degeneracies with lensing

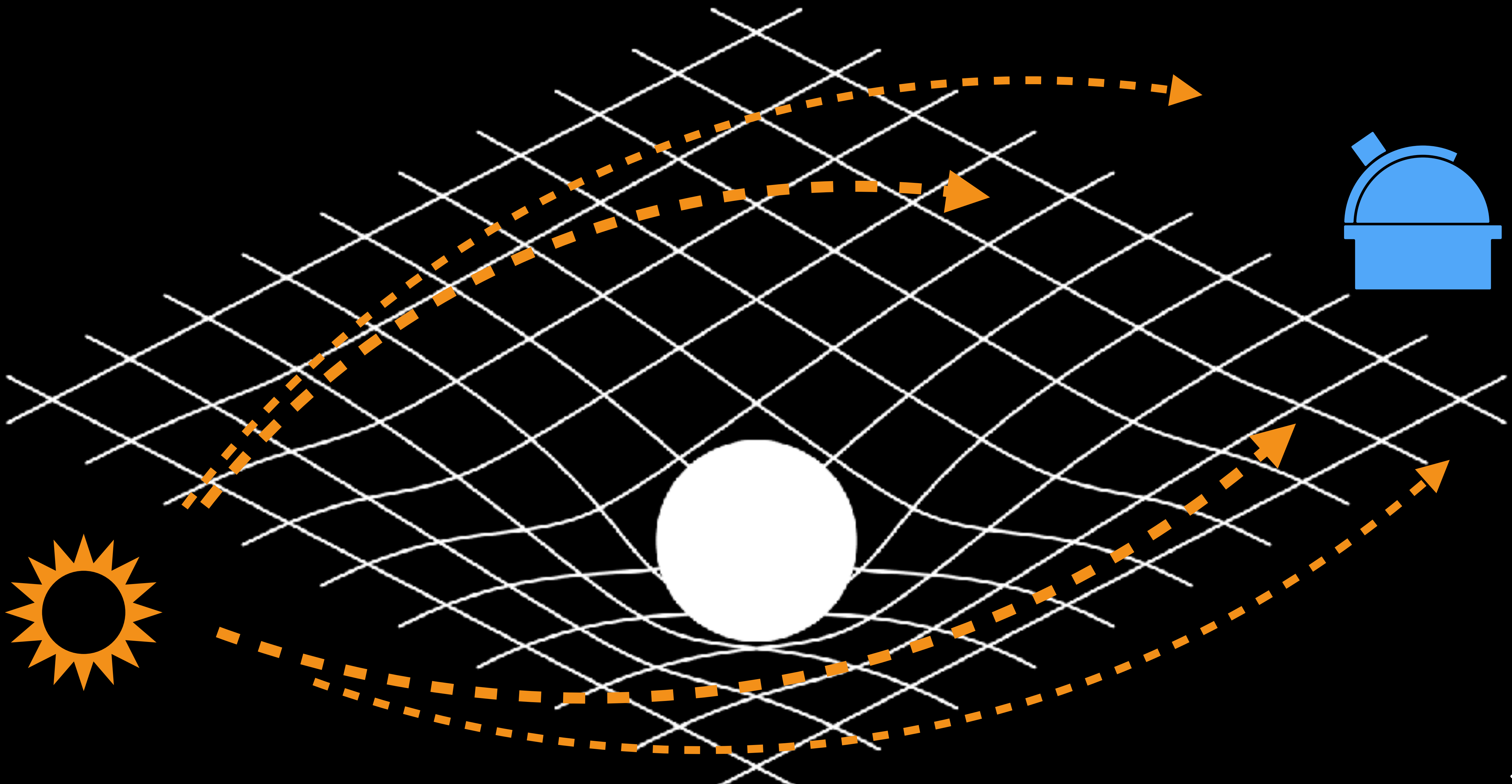
- Strong lensing: $$F \approx \sum_j |\mu(\vec{\theta}_j)|^{1/2} \exp\left(i\omega t(\vec{\theta}_j) - i\pi \mathrm{sign}(\omega) n_j\right)$$



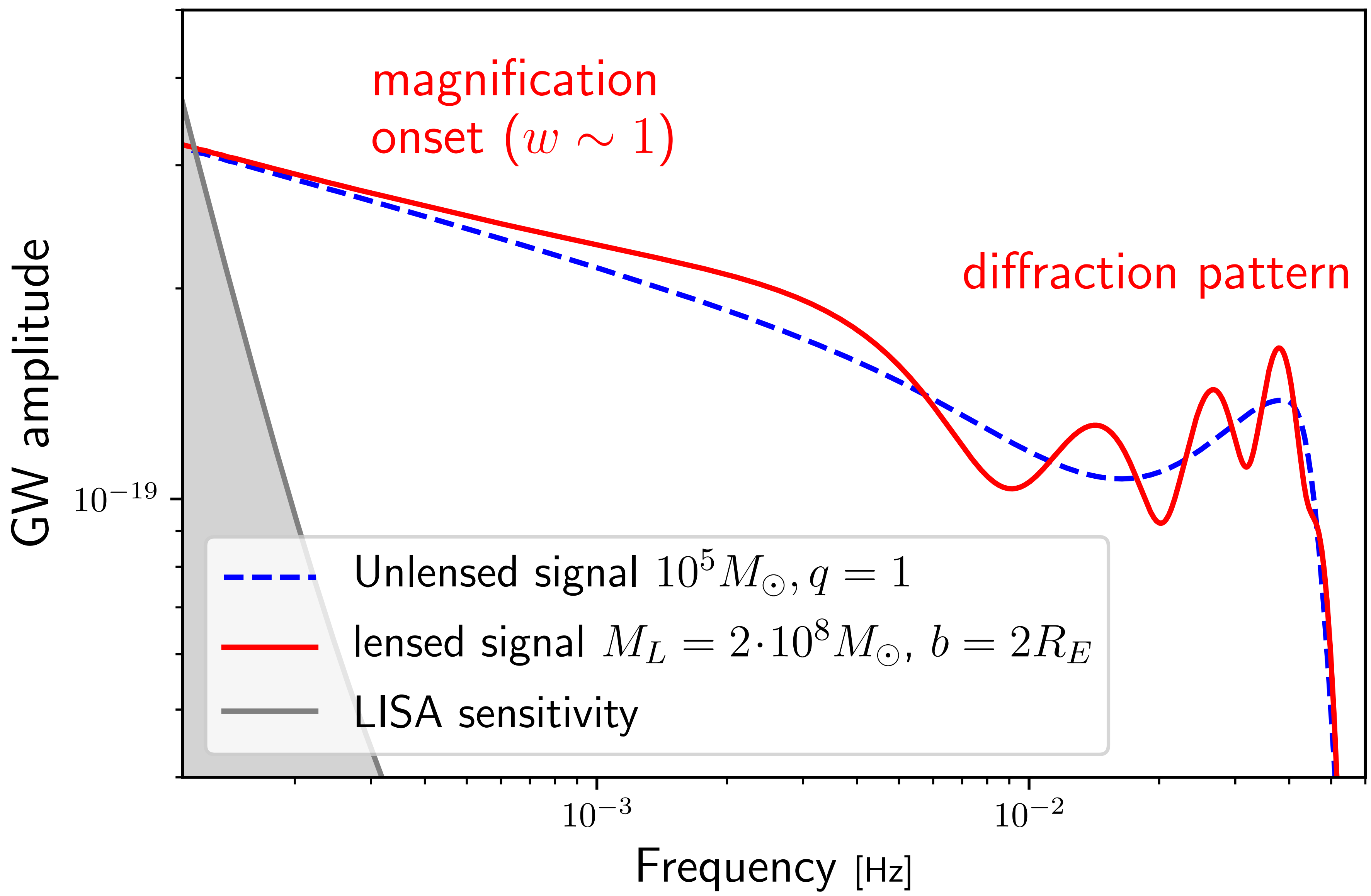
Ezquiaga, Hu, Lagos, Lin, Xu; *Modified GW prop with higher modes* (arXiv 2203.13252)

Wave effects

$\Delta t_d \cdot \omega \lesssim 1$

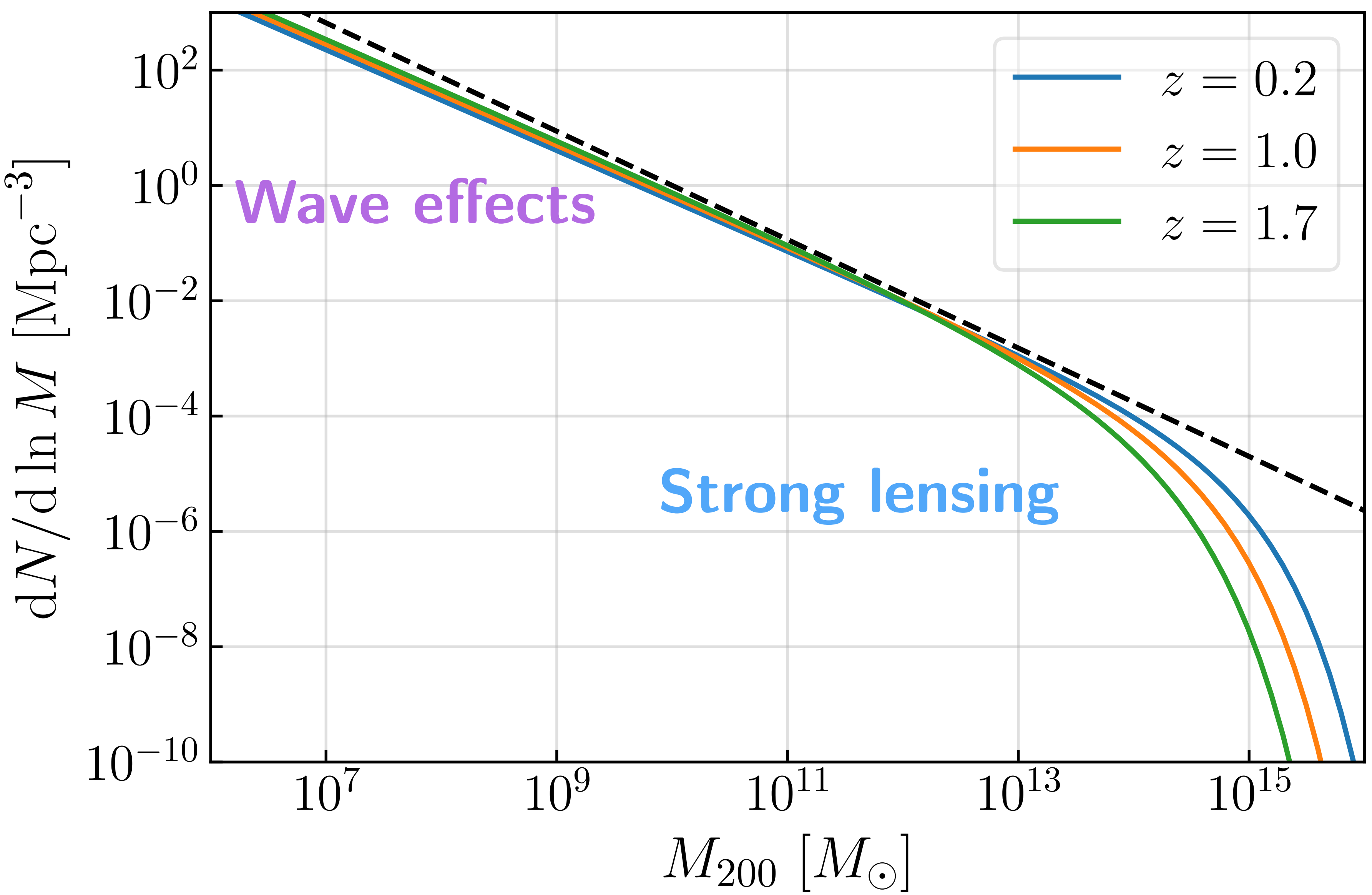


Wave effects



LISA Cosmo WG white paper (arXiv 2204.05434)

Probing matter distribution



Open questions

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Can we treat each effect separately?
E.g. luminosity distance vs modified dispersion relation

Propagation effects will likely dominate, but can waveform distortions at emission bias these analyses? Screening!

Type II image identification with LISA

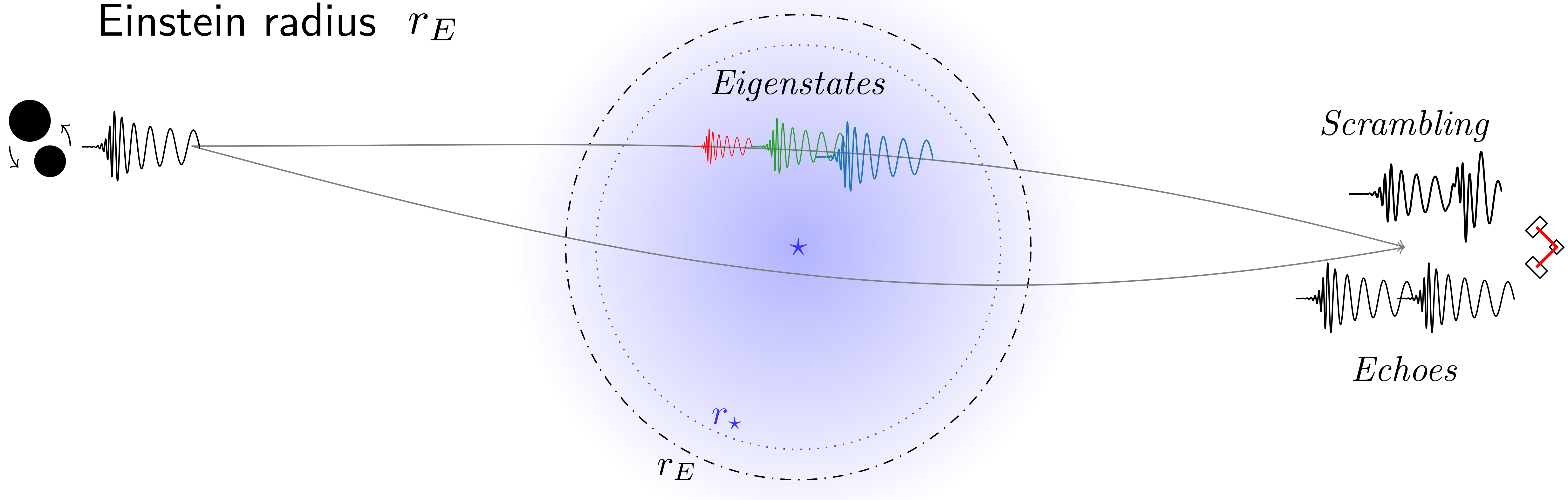
What types of dark matter halos can be probed?

Sereno *et al.* (arXiv 1011.5238) strong lensing forecasts < 5 events, wave optics negligible

Gao *et al.* (arXiv 2102.10295) wave optics forecasts: 0.1-1.6% of events

GW lensing beyond GR

- Beyond GR the background of the additional fields $\phi(r)$ modify propagation (besides the change in gravitational potential)
- The relevant scale for the modifications $r_\star$ might be different from the Einstein radius r_E



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

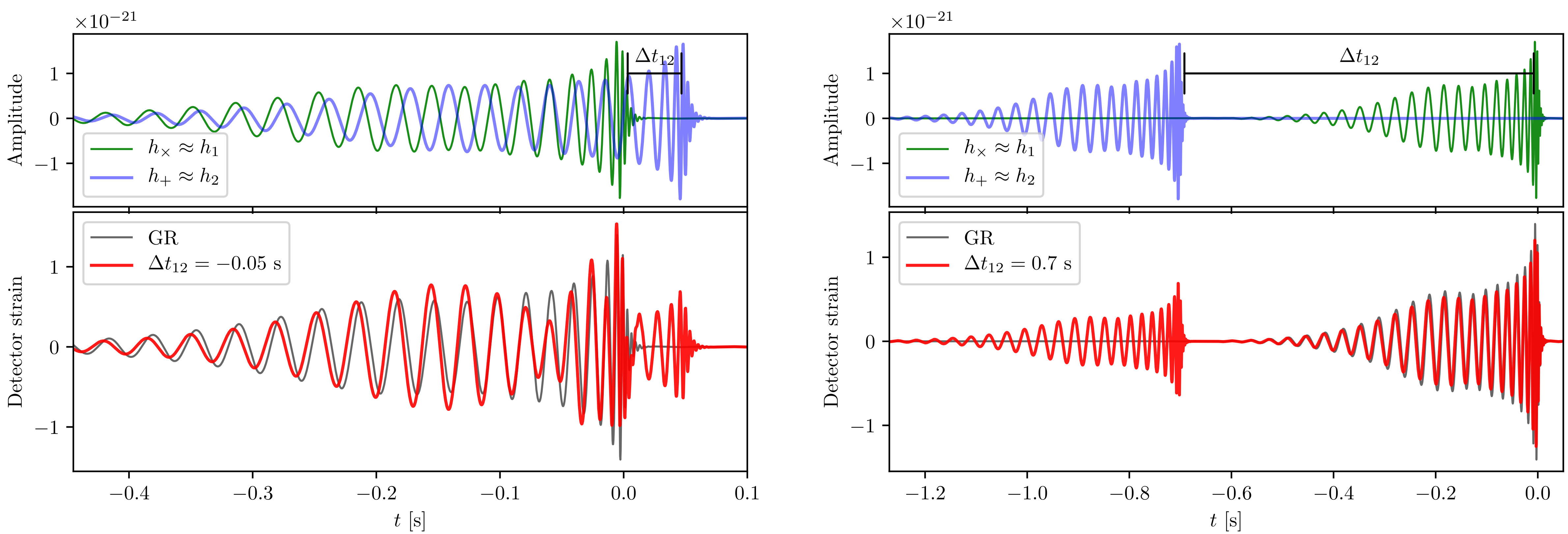
Ezquiaga & Zumalacárregui; *GW lensing beyond GR* (arXiv 2009.12187)

Main effects

Modified effective metric for each eigenstate and polarization mixing

Time delays | *Birefringence*

- For each lensed image there could be scrambling or echoes
- No need of EM counterpart! Extend cosmological test GW propagation!



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

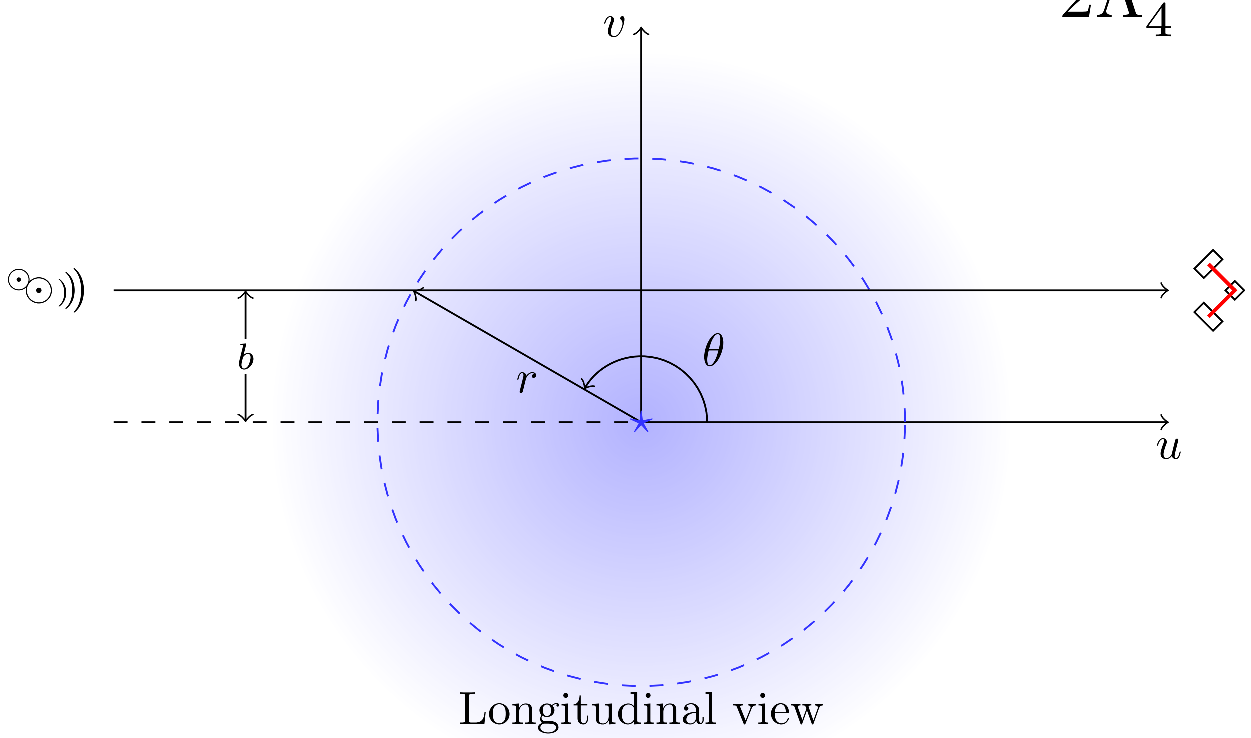
Screening in Horndeski

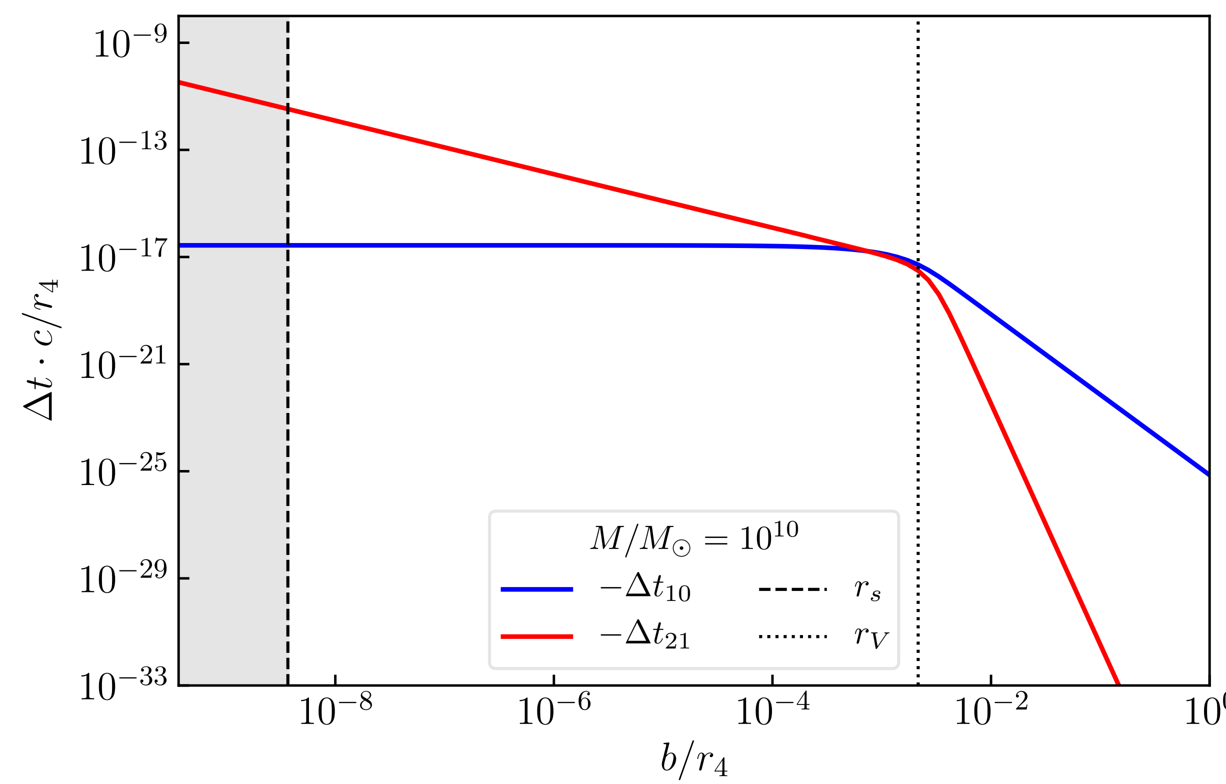
- Let us consider the effect of screening in the GW propagation for a quartic Horndeski theory

$$\mathcal{L} \sim \mathcal{L}_{\text{shift-sym}} + p_{4\phi}\phi M_{\text{Pl}} R \qquad G_4 \sim \frac{M_{\text{Pl}}^2}{2}\left(1 + p_{4X}\frac{(\partial\phi)^2}{M_{\text{Pl}}^2\Lambda_4^2}\right)$$

- Relevant scales: quartic term length scale and Vainshtein radius

$$(r_4)^3 = \frac{r_s}{2\Lambda_4^2} \qquad r_V = p_{4\phi}^{1/3} r_4$$





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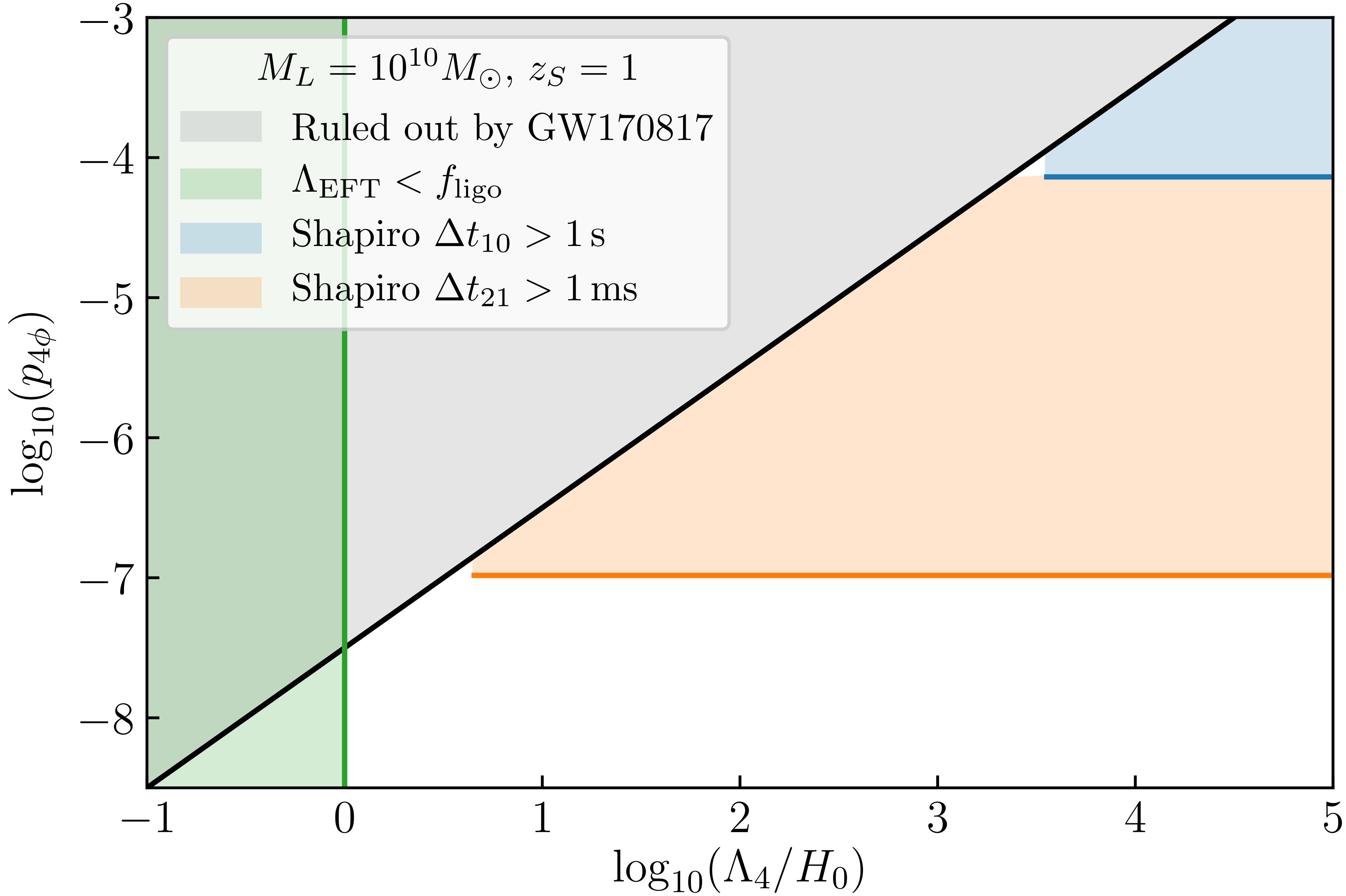
Screening in Horndeski

GW lensing beyond GR can probe regions of the parameter space unconstrained by GW170817



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

LISA cosmology: final thoughts

ezquiaga@uchicago.edu

We need to anticipate the interesting science in *2034+*

Likely not the same as today, *e.g.* current H0 tension

We need to anticipate what LISA will do *uniquely*

Build *synergies,* not repetition

Competition both with EM surveys *and* 3G GW detectors

Many tools can be borrowed from current ground-based GW pipelines

Let's not duplicate efforts and create flexible, public codes!

... but LISA is different

Overlapping signals, high SNR...

Connecting theories modifying emission and propagation...

LISA cosmology: open questions

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