[Gustave Vidal, 1930]

Magnifying the gravitational-wave Universe

Jose María Ezquiaga

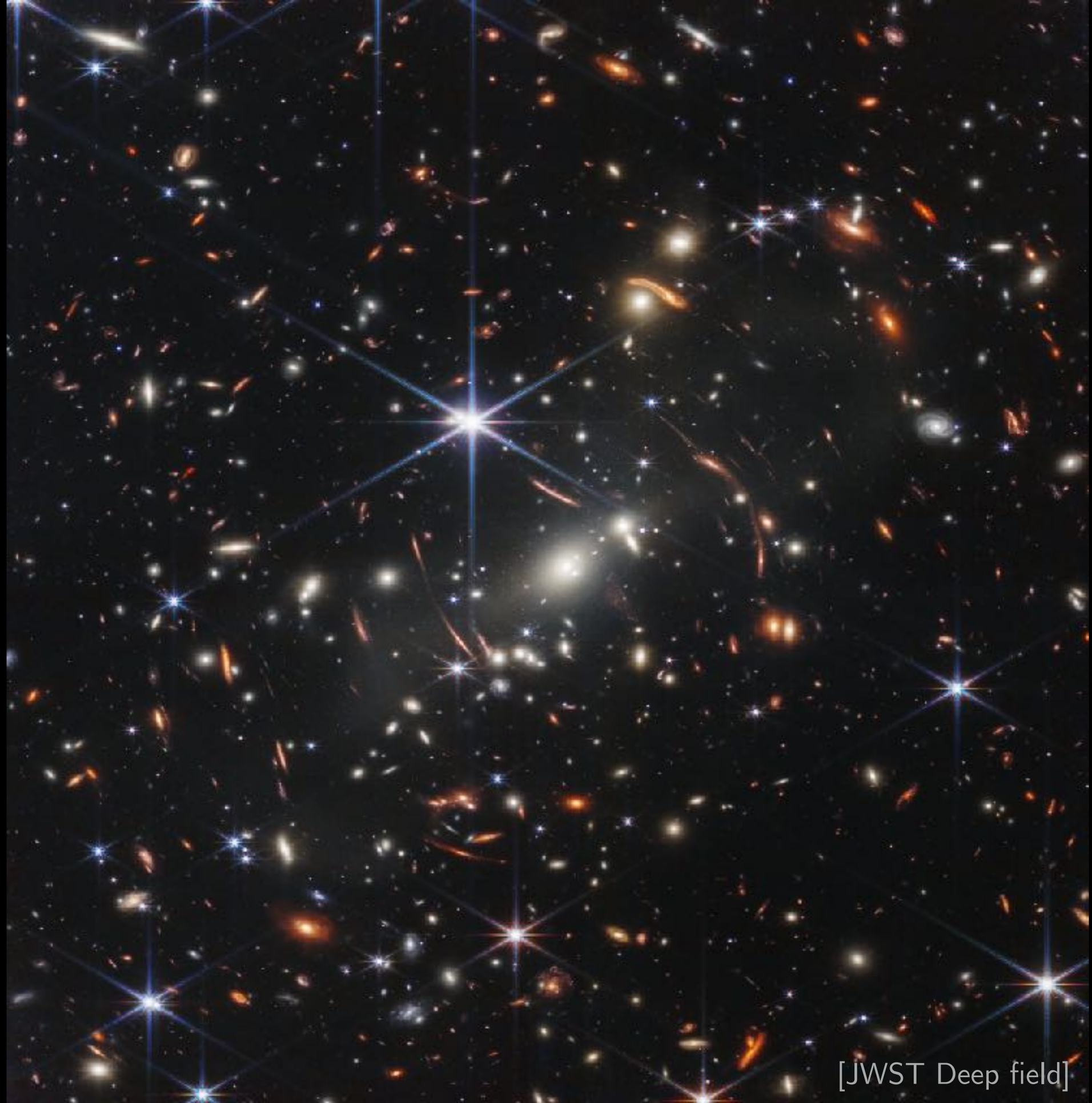
Niels Bohr Institute

jose.ezquiaga@nbi.ku.dk

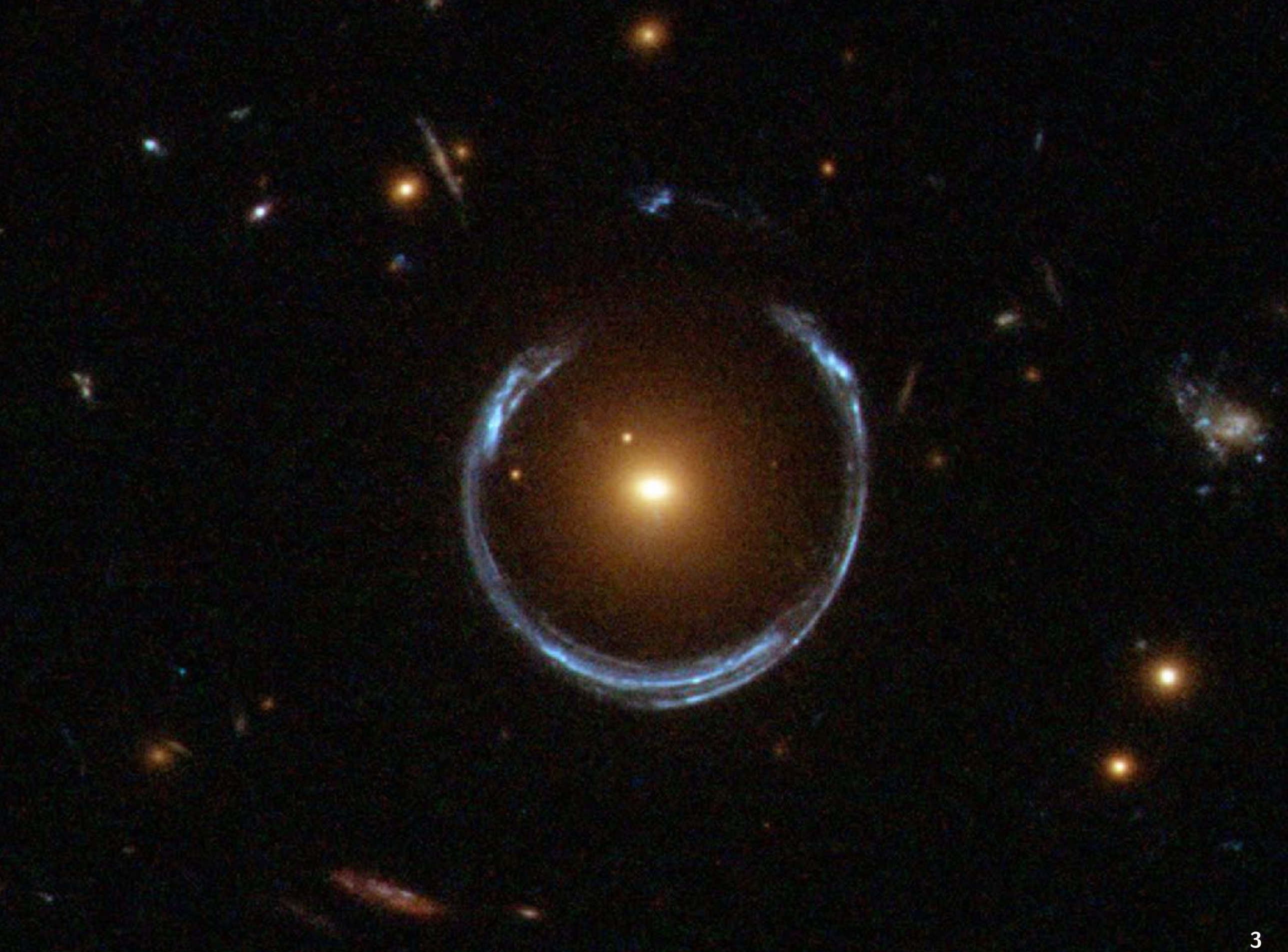
ezquiaga.github.io

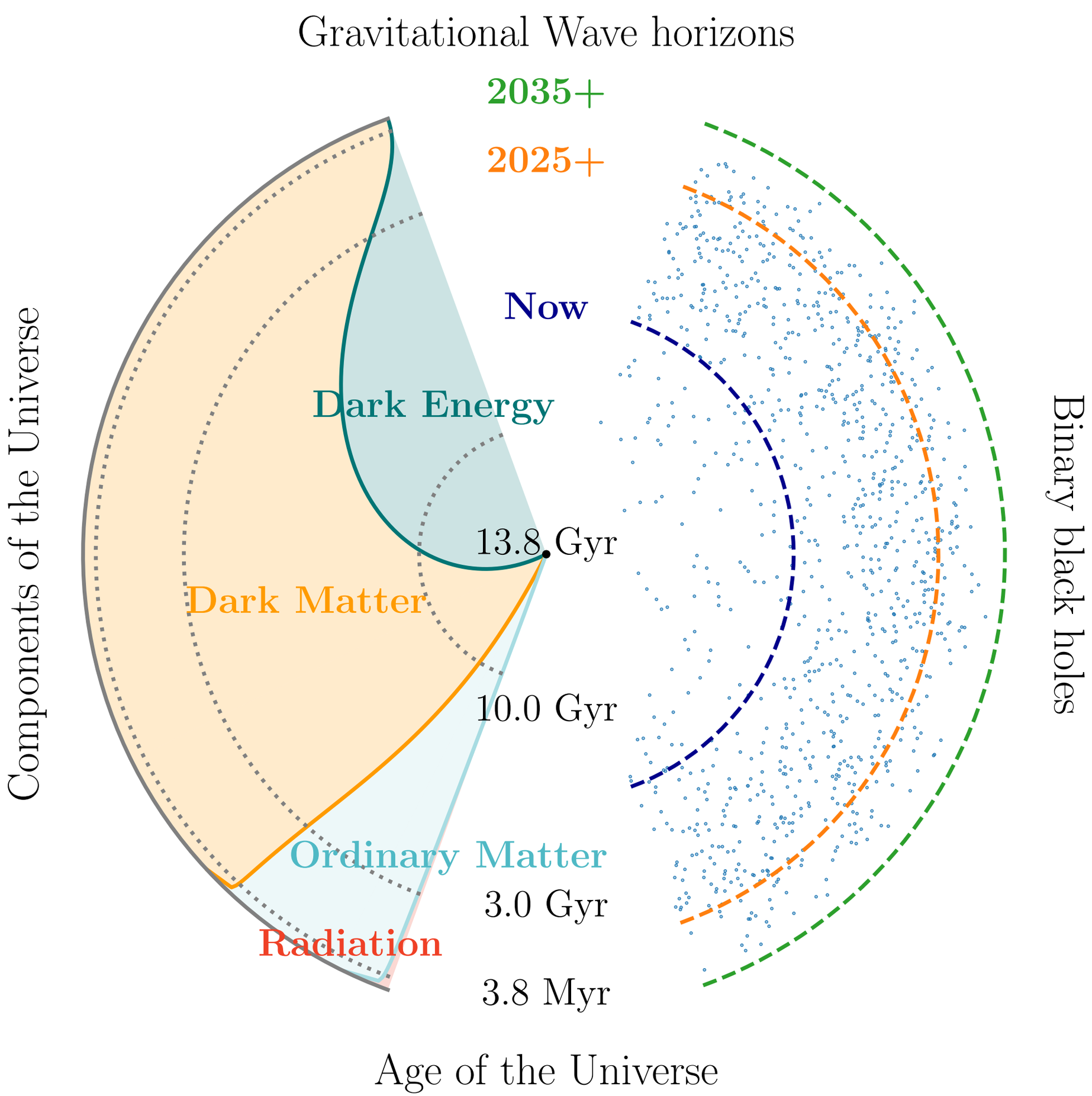
VILLUM FONDEN

KØBENHAVNS UNIVERSITET

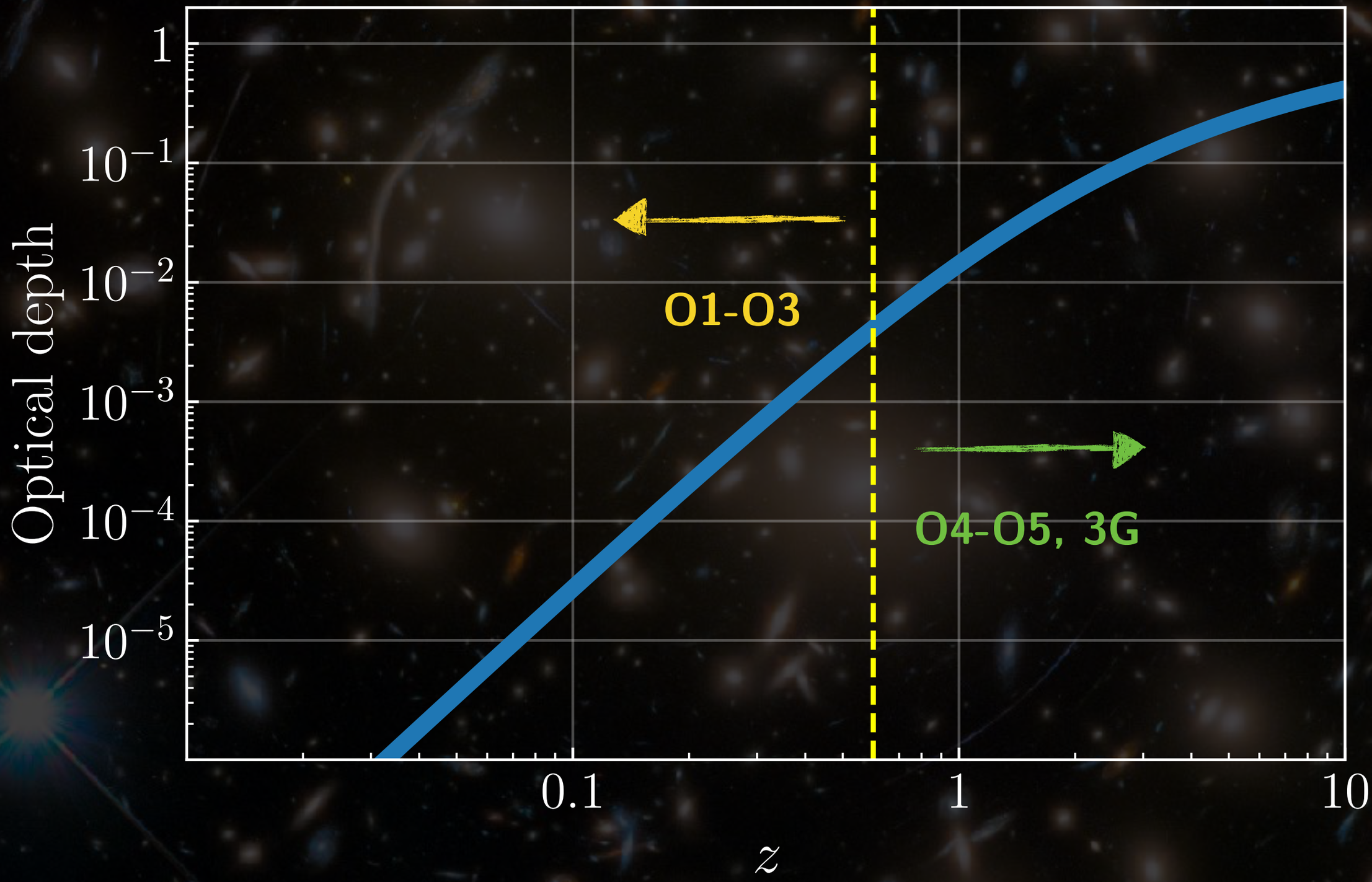


[JWST Deep field]




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

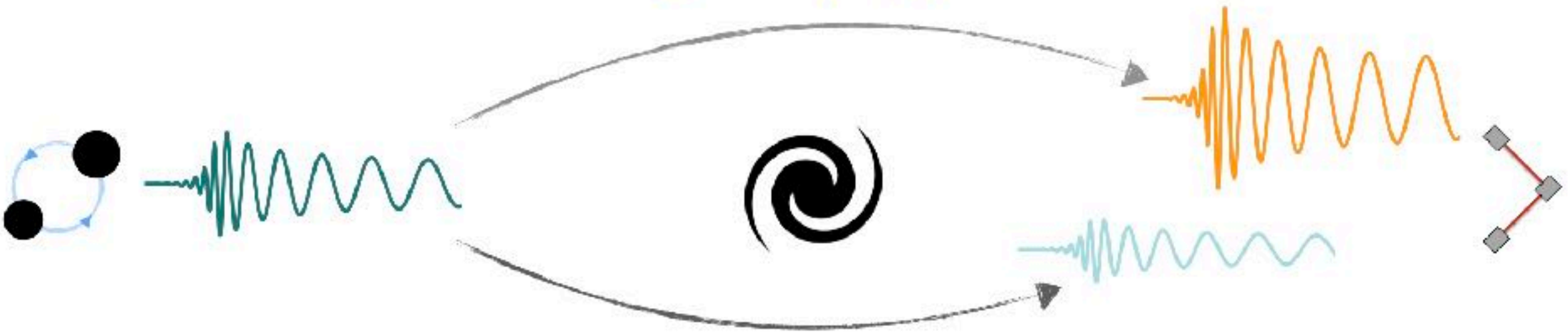
Gravitational lensing



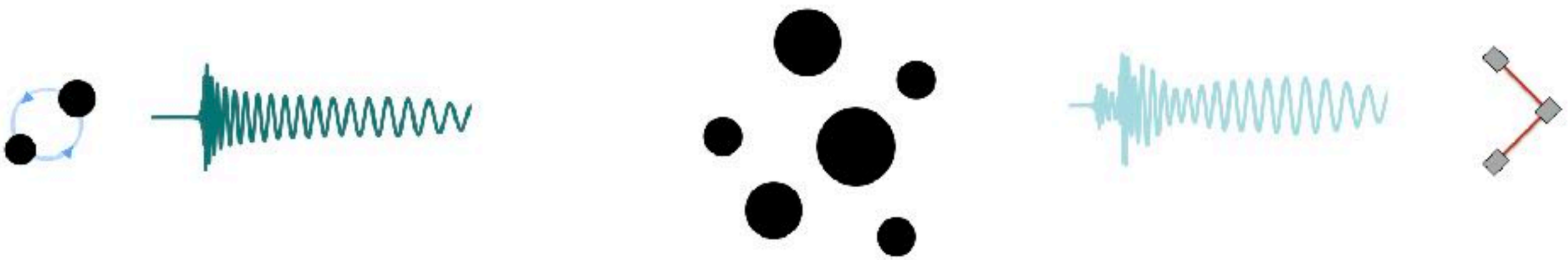
Gravitational lensing of gravitational waves

- Clean signals, not affected by the medium
- All-sky coverage, high redshifts, large wavelengths
- Well understood selection effects of detectors

Strong lensing by galaxies

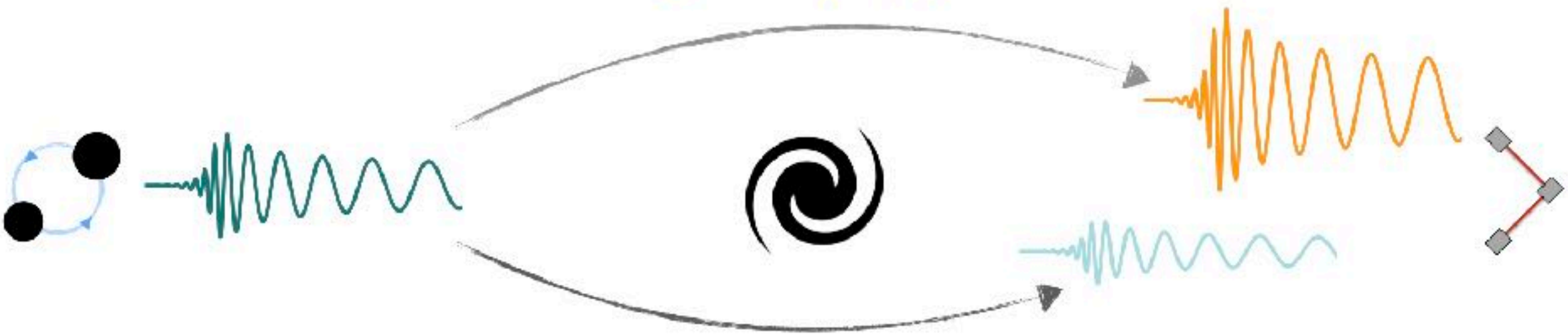


Interference effects by compact lenses

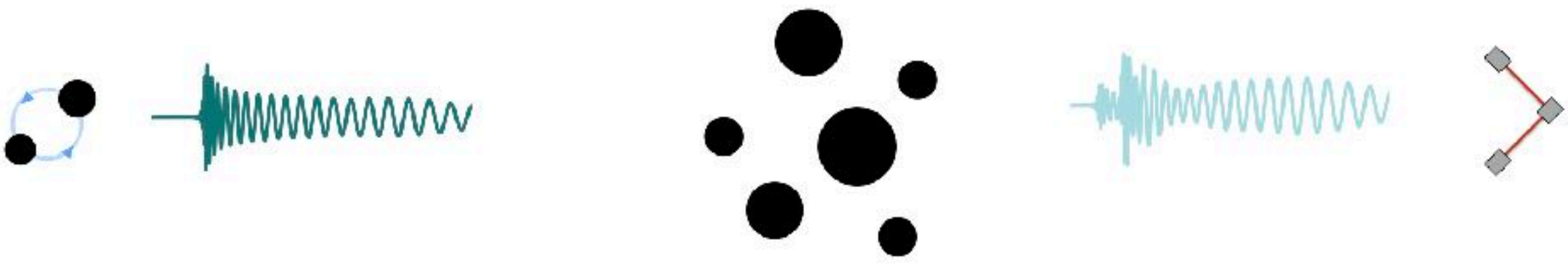


Source Lens Detector

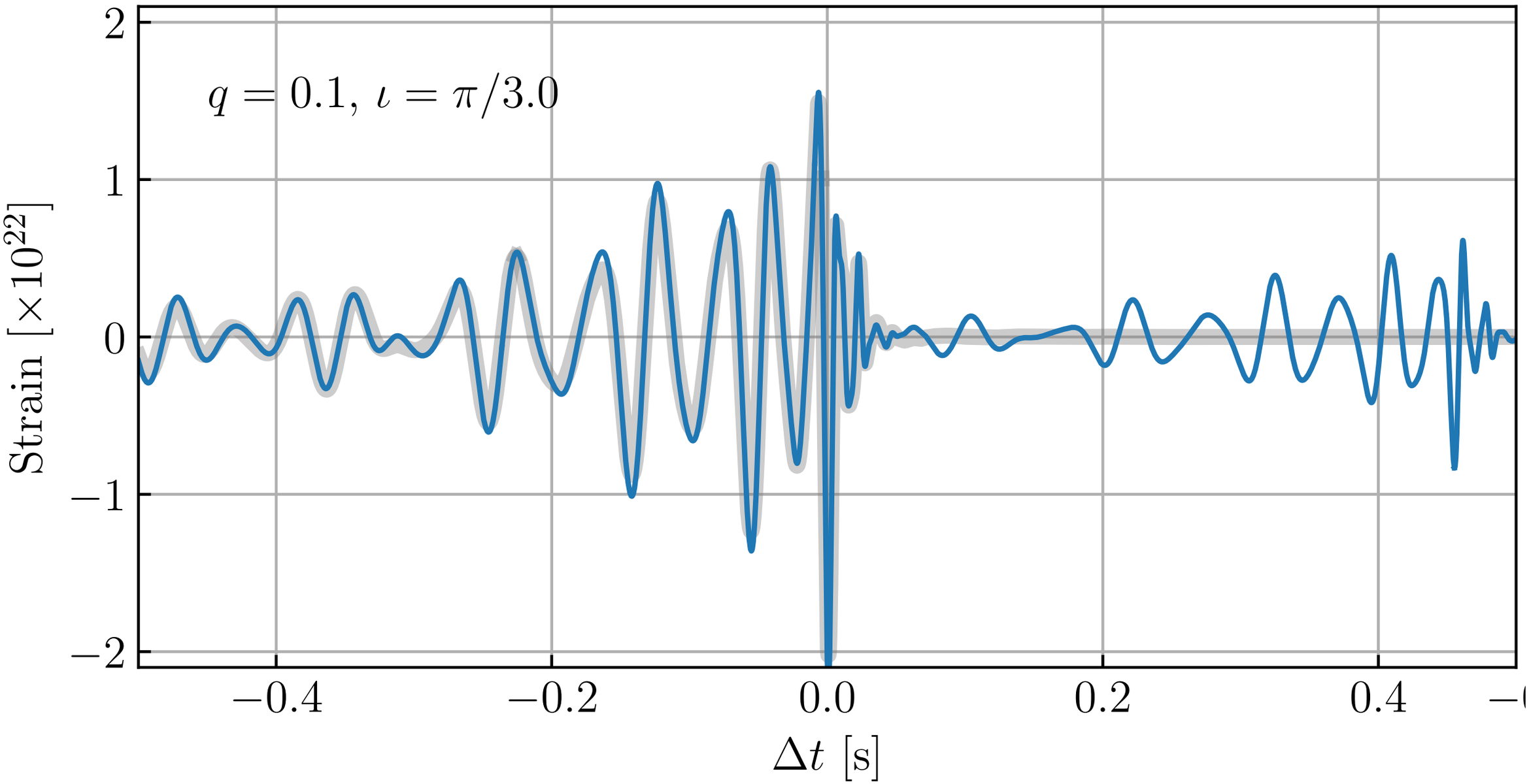
Strong lensing by galaxies



Interference effects by compact lenses

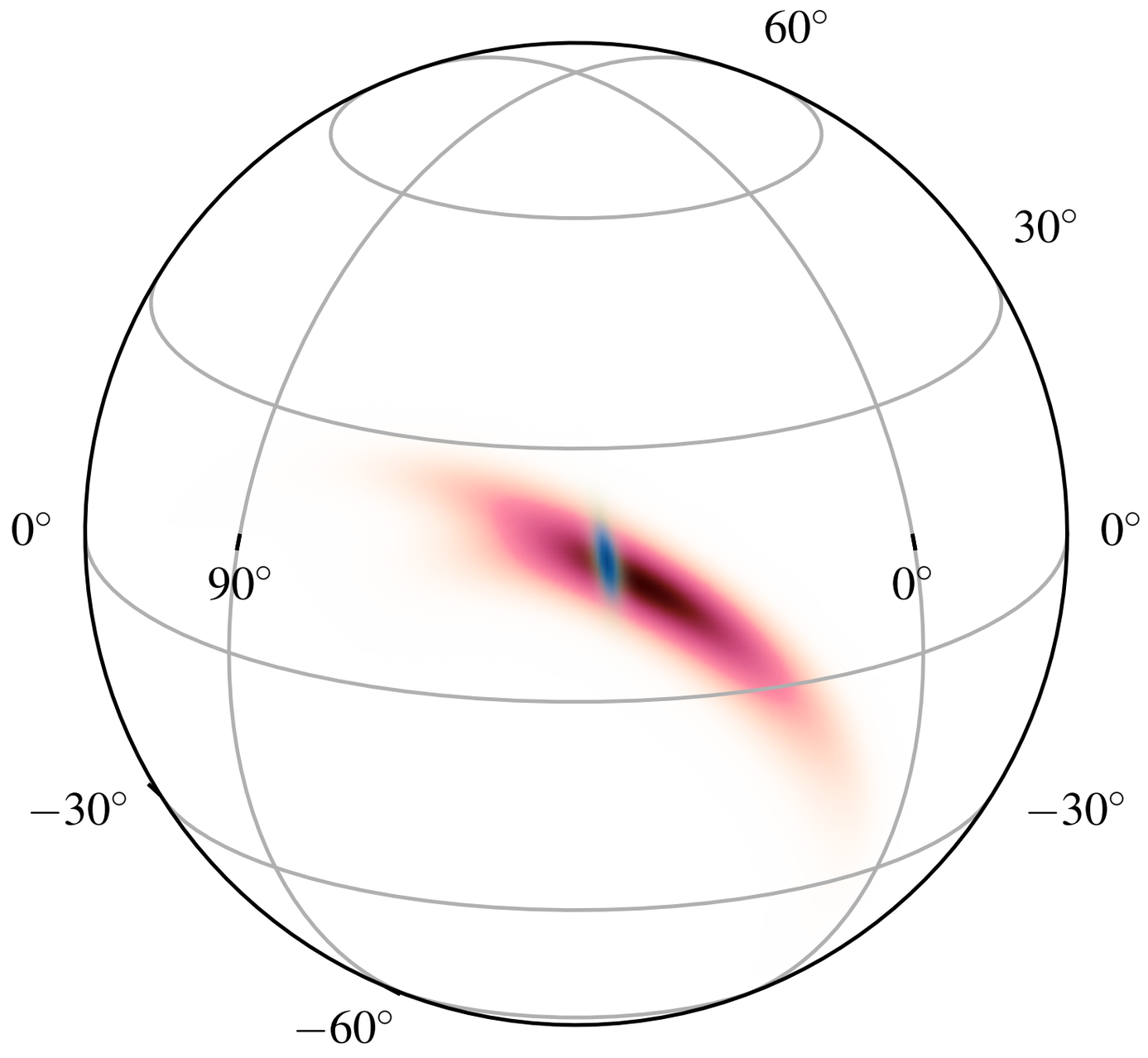


Repeated signals



GW sky localization

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



Gravitational lensing of gravitational waves

- Clean signals, not affected by the medium
- All-sky coverage, high redshifts, large wavelengths
- Well understood selection effects of detectors
- Precise timing information
- Poor sky localization
- Coherent detection of waveform

Strong lensing

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

$$h_L(\omega) = F(\omega, \theta_S) \cdot h(\omega)$$

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

Magnification
Time delay
Phase shift

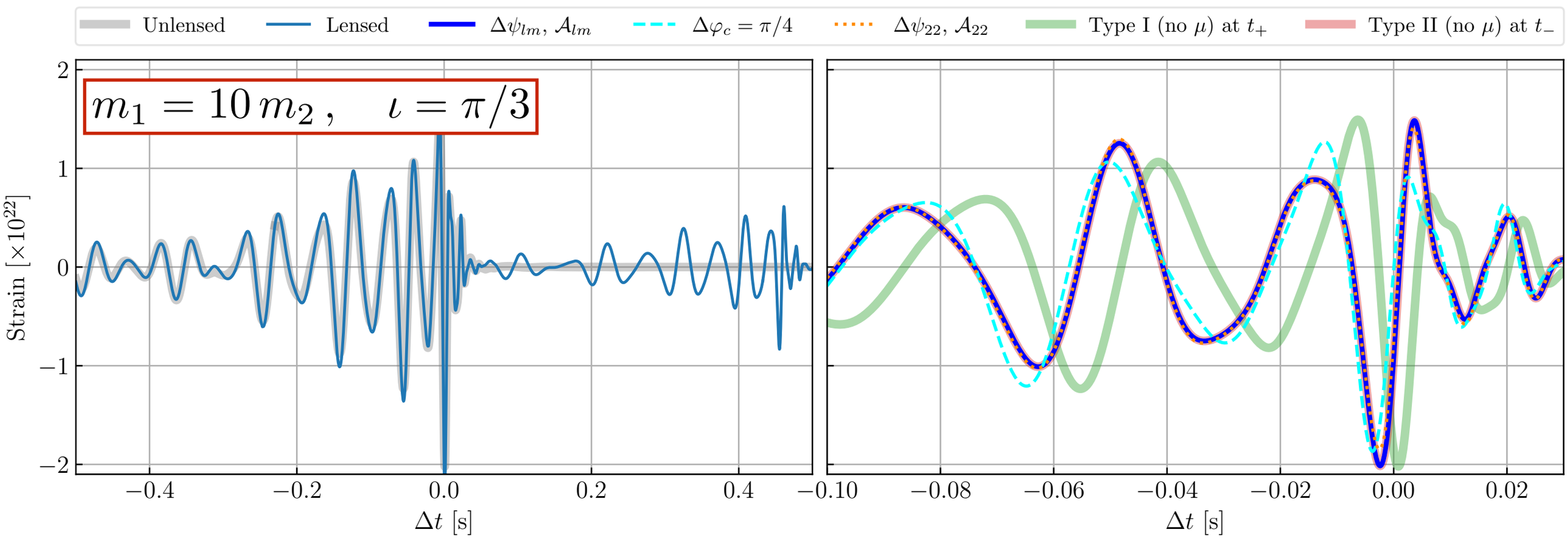
- Each image type (I, II and III) acquire a different phase shift

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

Waveform distortions in **type II** images

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

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



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

Strong lensing

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

$$h_L(\omega) = F(\omega, \theta_S) \cdot h(\omega)$$

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

Magnification
Time delay
Phase shift

- Each image type (I, II and III) acquire a different phase shift

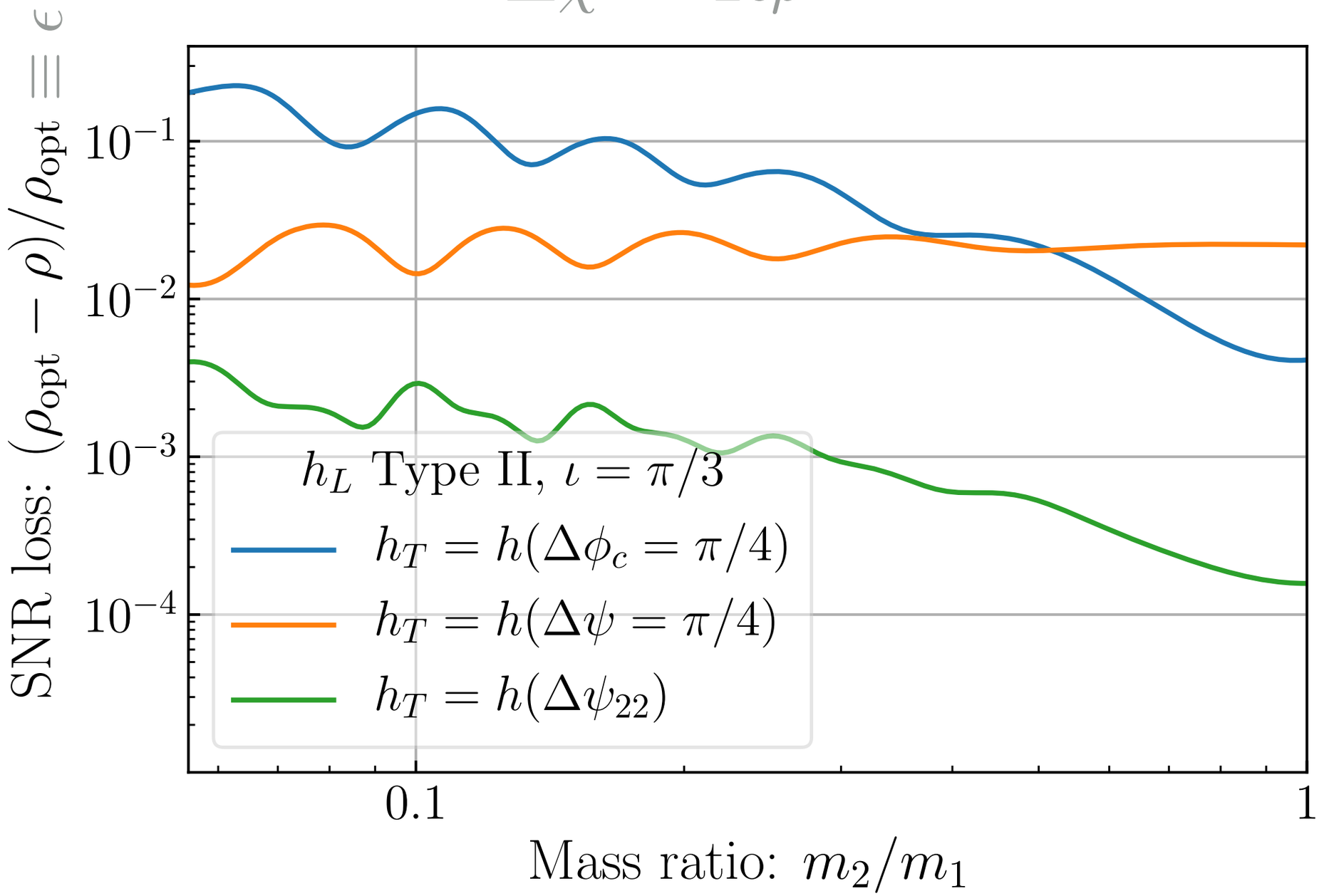
$$n_j = 0,\, 1/2,\, 1$$

- 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)

type II image: Effect on parameter estimation

$$\Delta\chi^2 \sim 2\epsilon\rho^2$$



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

Implications for next-generation detectors: Wang et al.'21, Janquart et al.'21, Vijaykumar et al'22

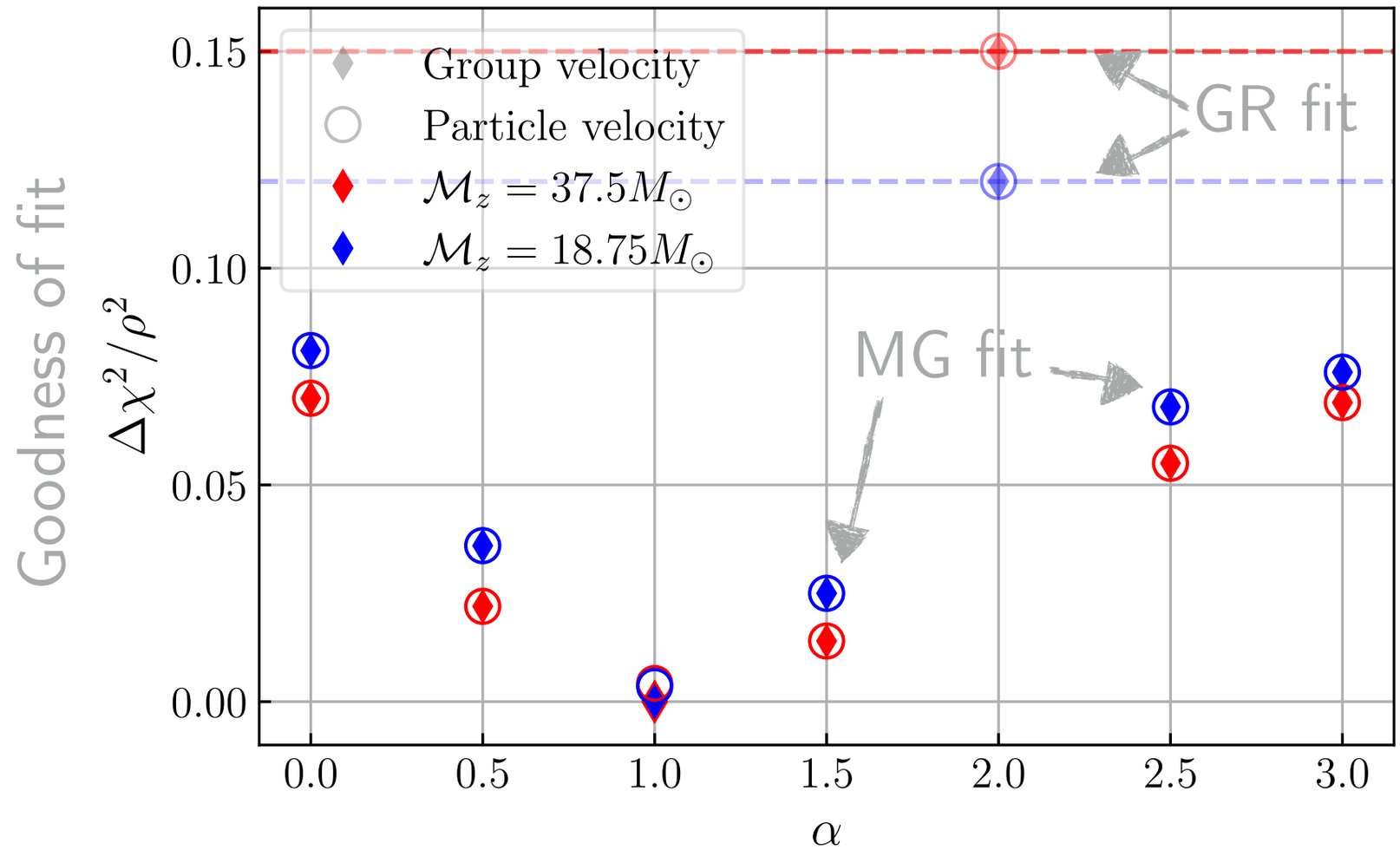
Note: degeneracies with modified gravity

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

- Modified GW propagation: $h_{\rm mg} \sim h_{\rm gr}\, e^{-i\int \Delta\omega \mathrm{d}z/H(z)} \equiv h_{\rm gr} e^{i\Delta\Psi}$

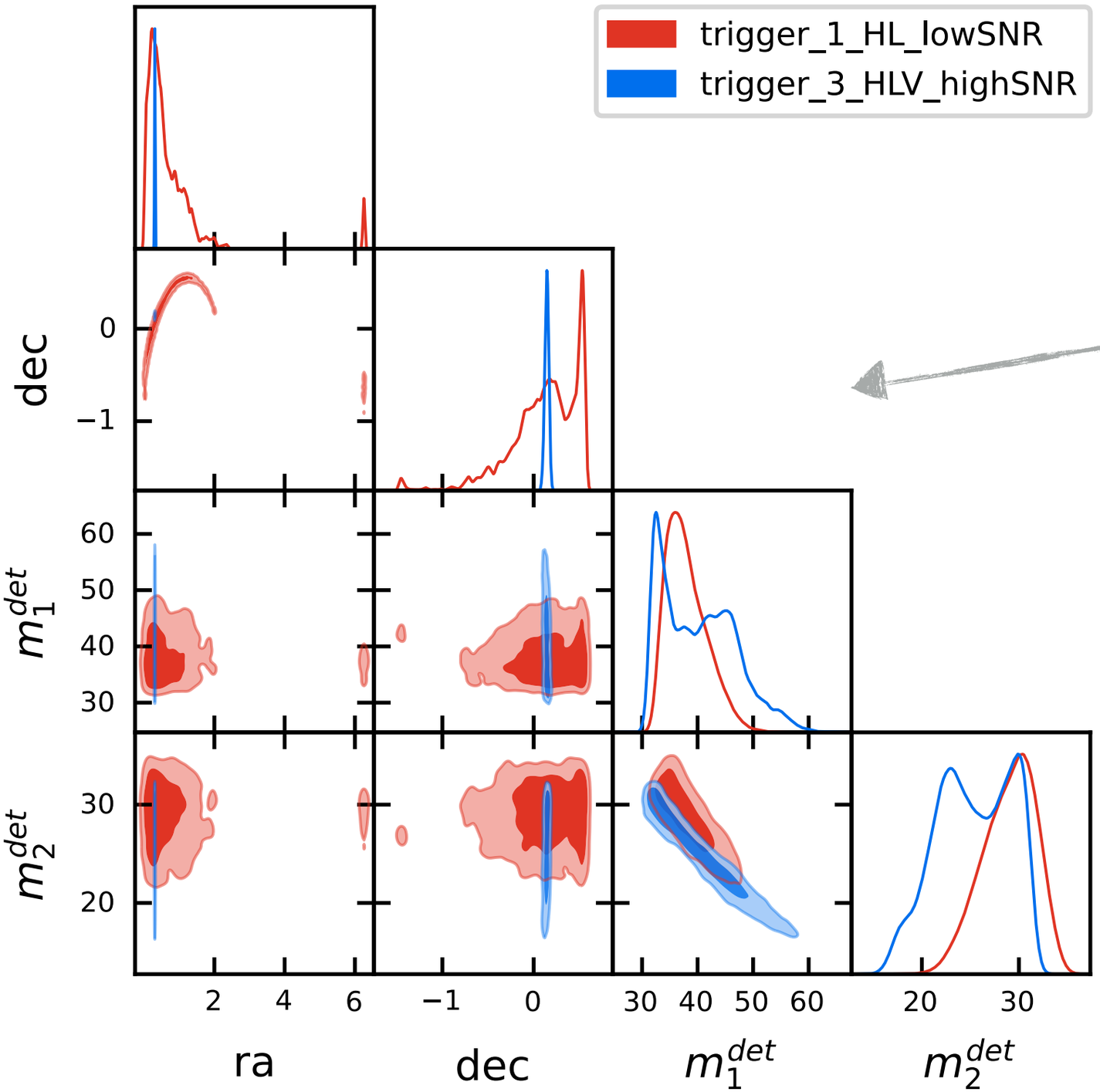
$$\omega^2 = c^2k^2 + \mathbb{A}(ck)^\alpha$$

$$\Delta\Psi(f) = -\frac{\mathbb{A}}{2} D_\alpha (2\pi f_s)^{1-\alpha}$$



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

Searching for strongly lensed GWs



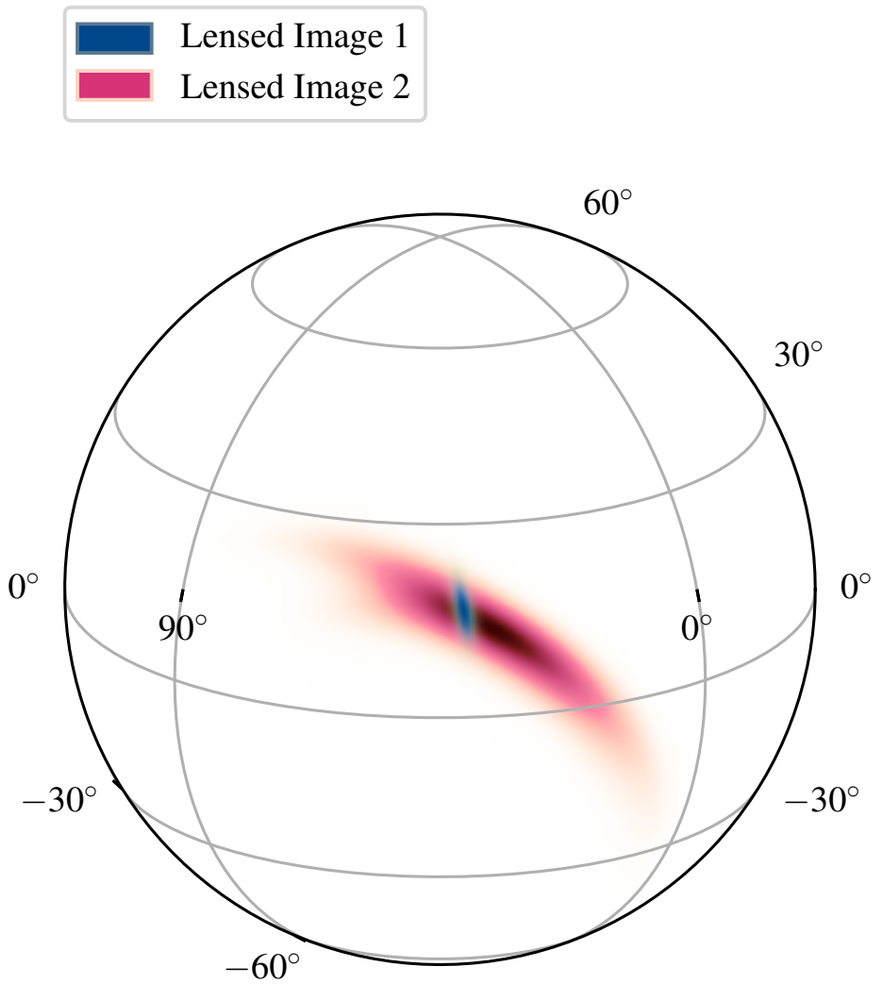
Look for overlaps in the (detector frame) masses, sky positions and spins

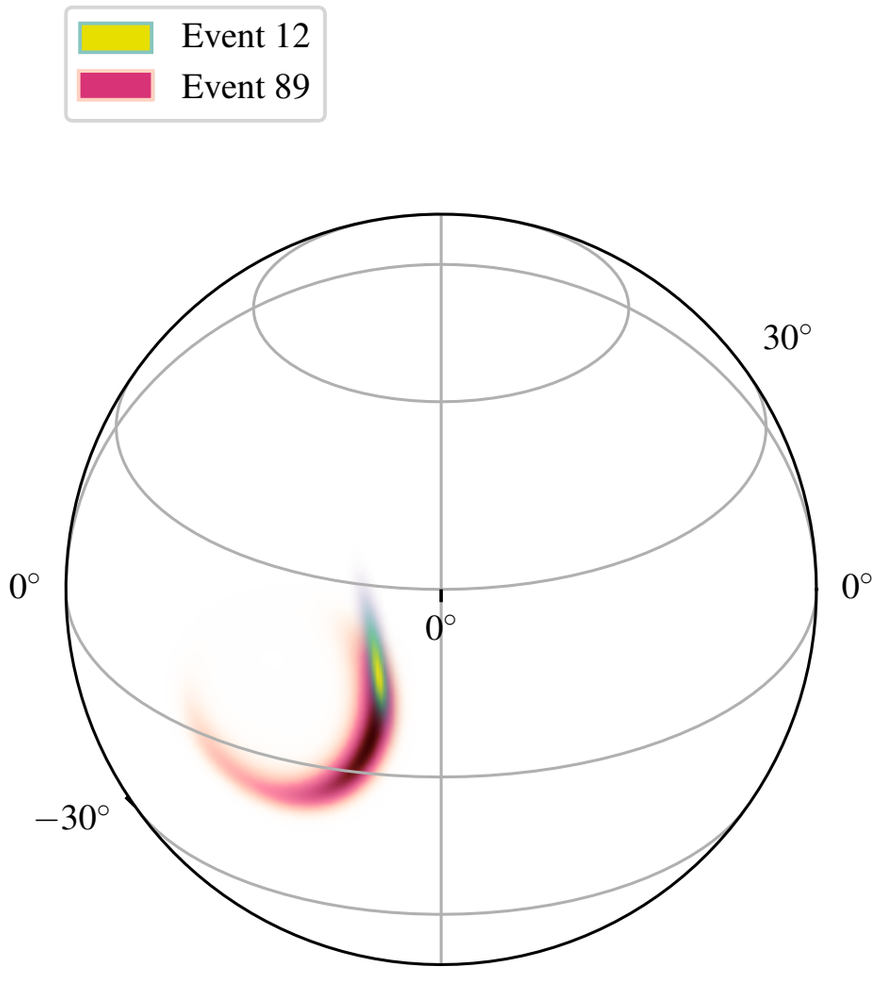
+

Joint parameter estimation

Lensing or luck?

$$N_{\text{false alarm}} \sim N^2$$

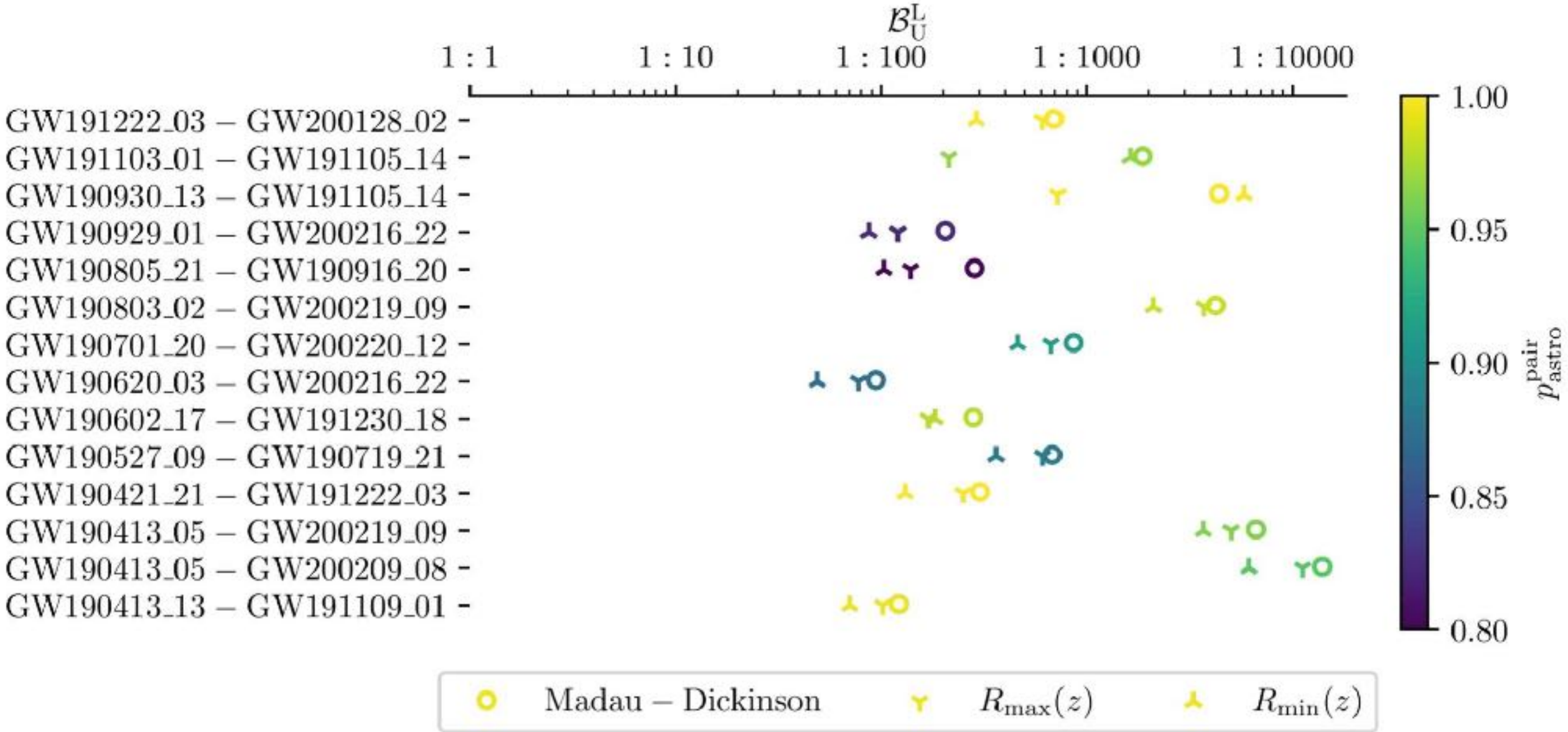




Mesut Çalışkan (UChicago/JHU)

Çalışkan, **Ezquiaga**, Hannuksela and Holz; *Lensing or luck* (PRD, arXiv 2201.04619)

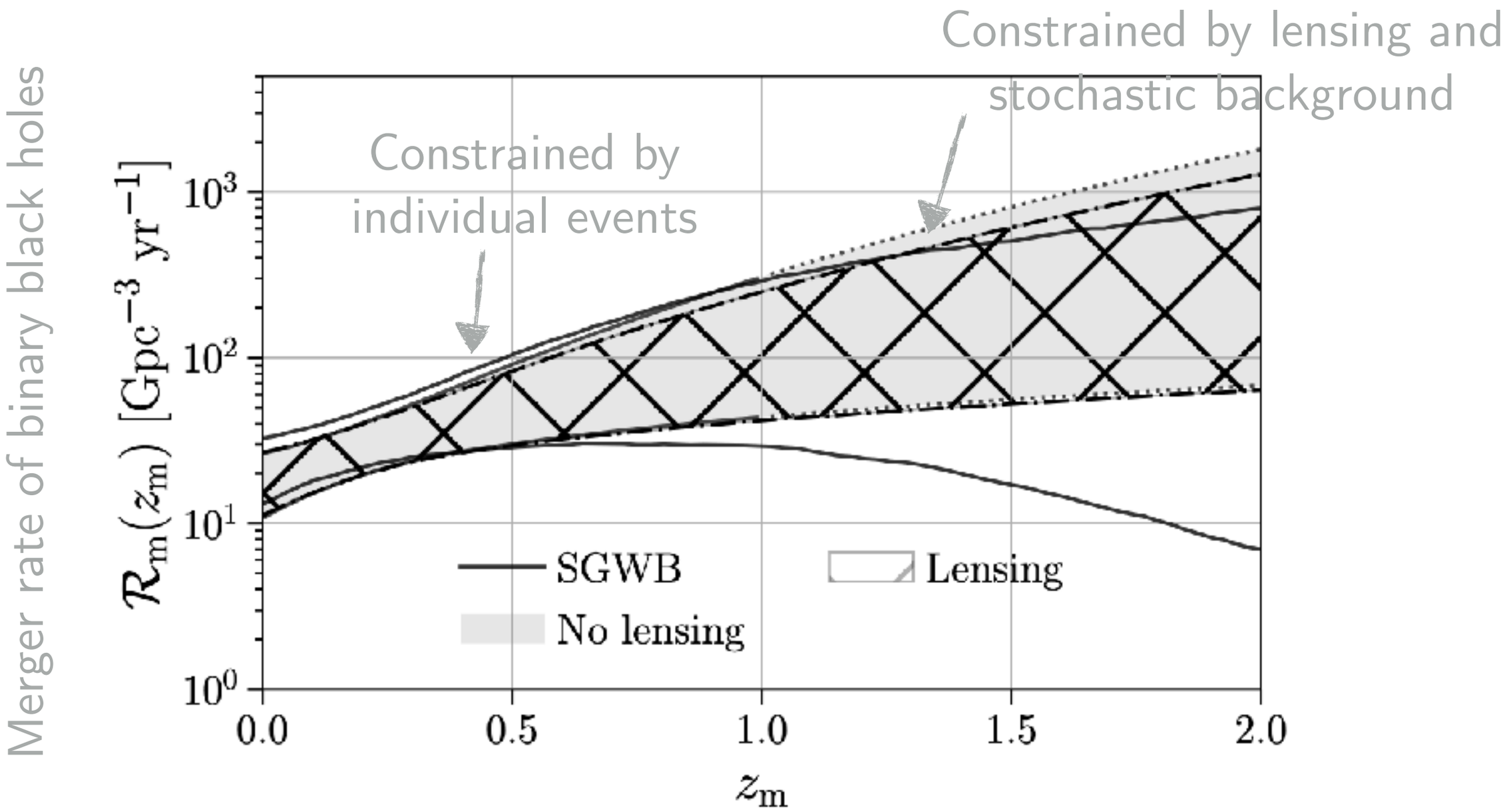
LVK: no evidence of strong lensing so far...



LVC (incl. **Ezquiaga**); *Search GW lensing O3a* (ApJ, arXiv 2105.06384, *science summary*)

LVK (incl. **Ezquiaga**); *Search GW lensing full O3* (arXiv 2304.08393, *science summary*)

LVK: no evidence of strong lensing so far...



LVC (incl. **Ezquiaga**); *Search GW lensing O3a* (ApJ, arXiv 2105.06384, *science summary*)

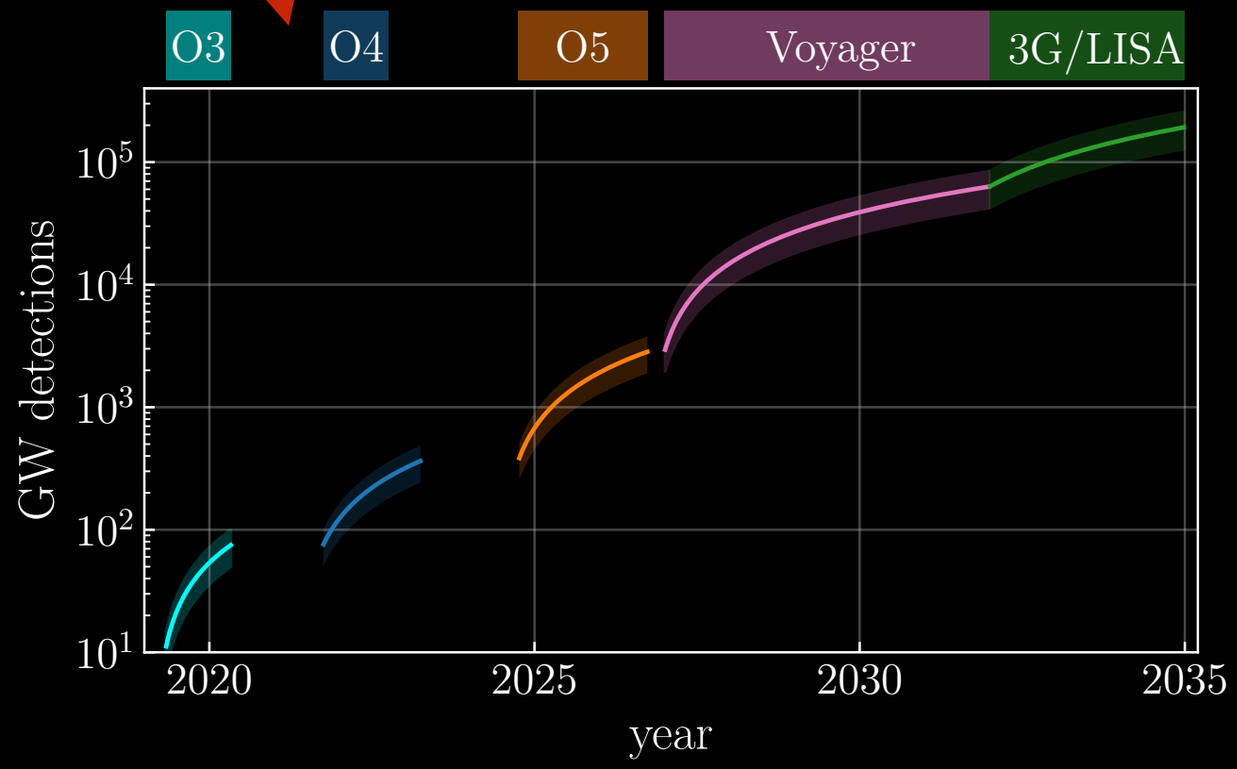
LVK (incl. **Ezquiaga**); *Search GW lensing full O3* (arXiv 2304.08393, *science summary*)

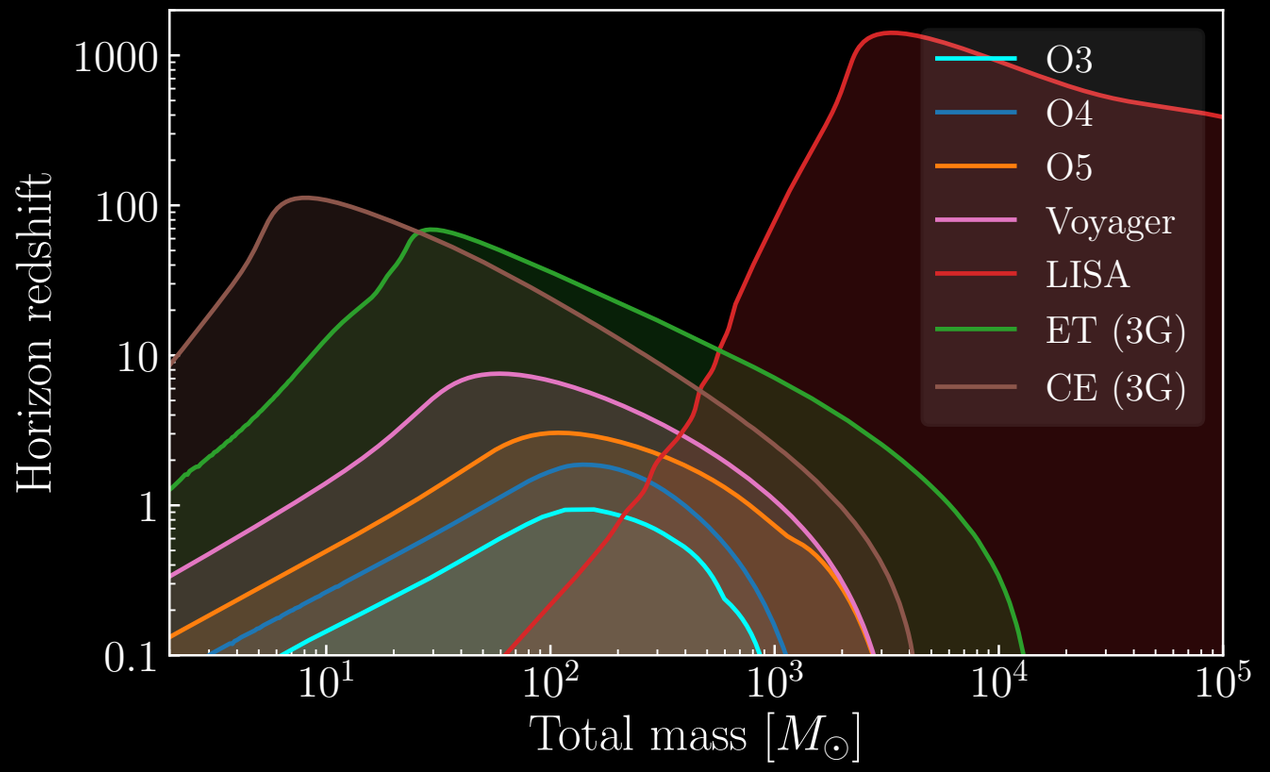
Looking ahead

Now

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

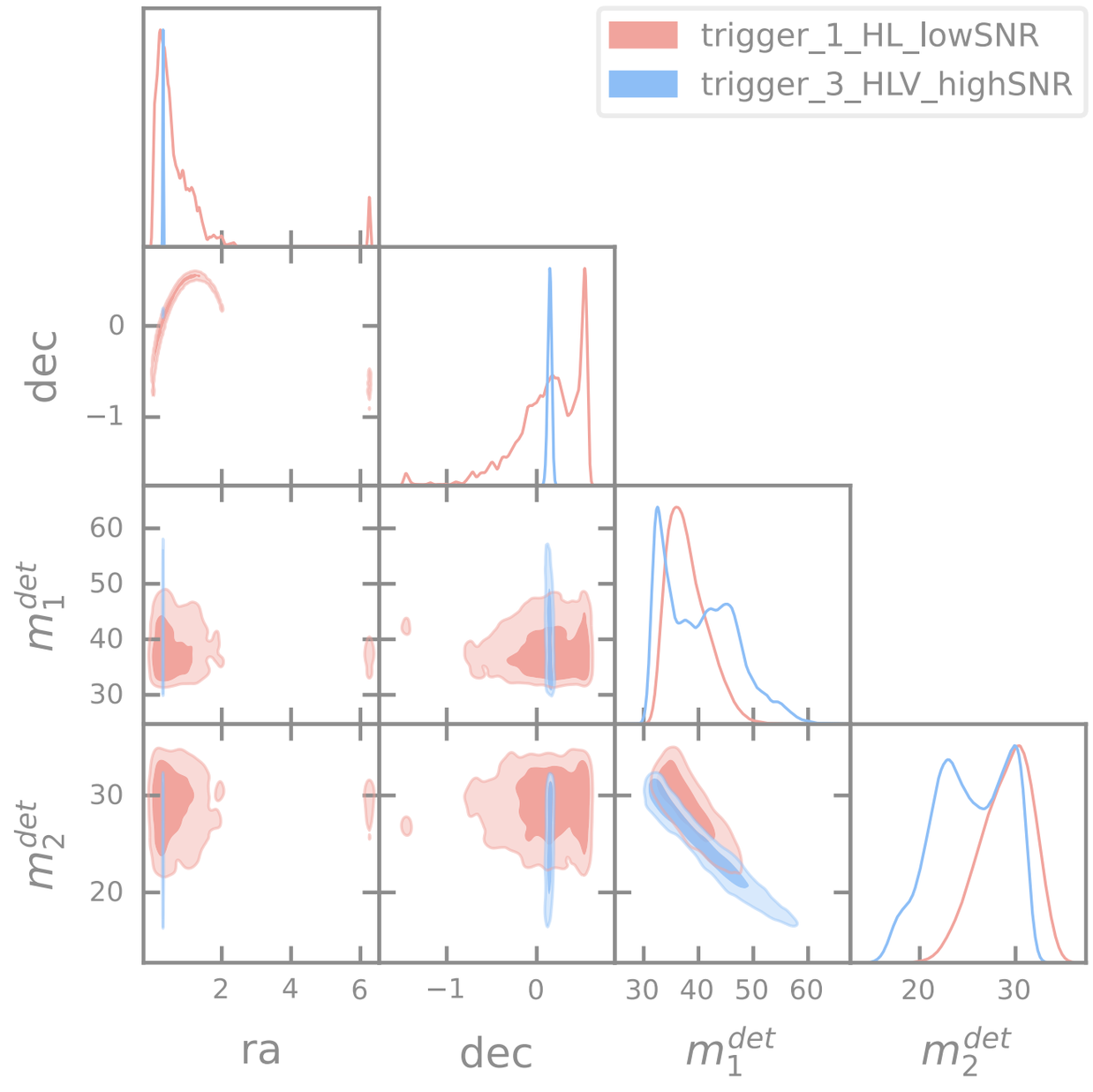
***3G**: next generation ground-based GW detectors*

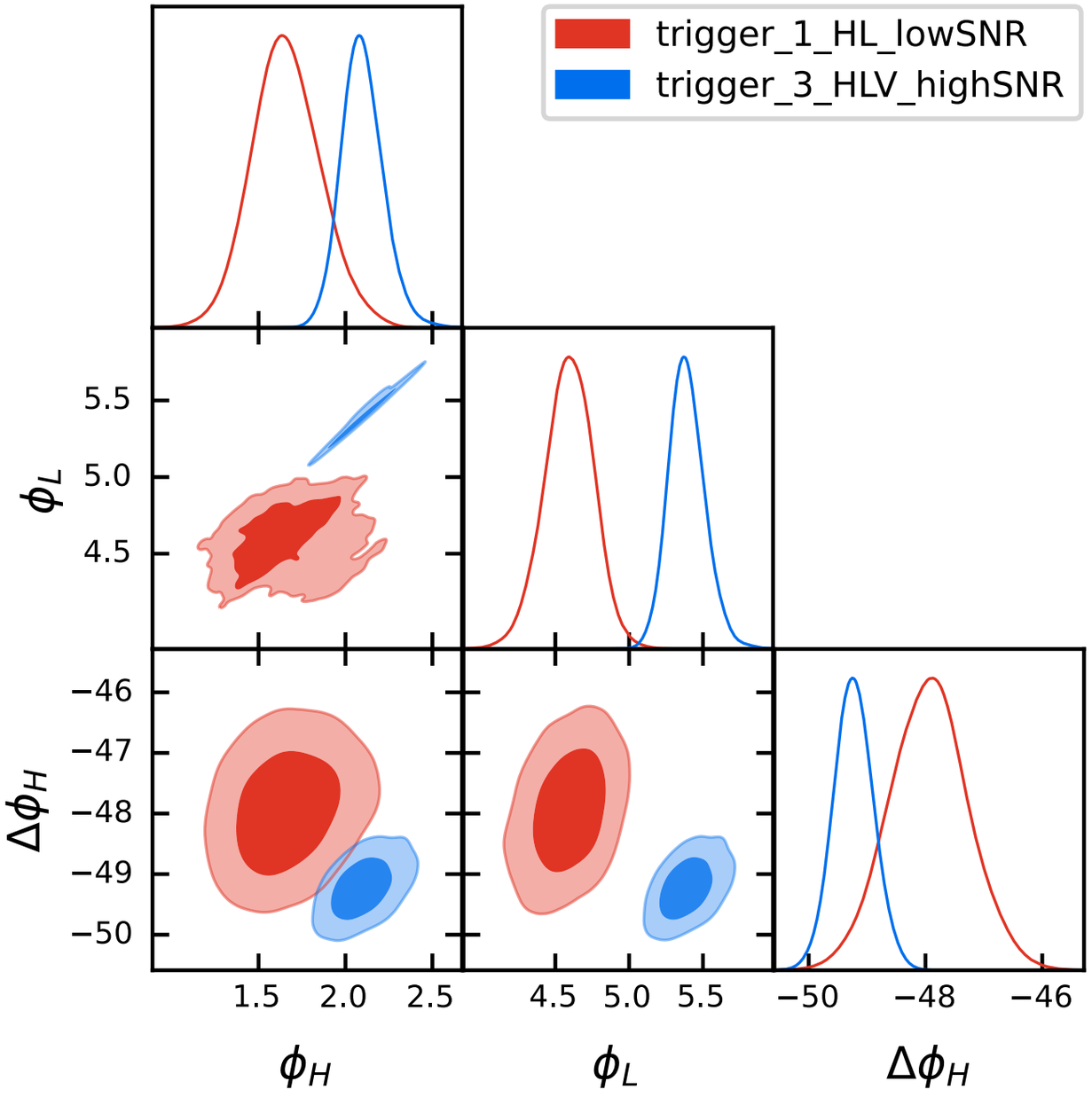




Approx. ***100*** events typically at $z < 0.6$ → ***1000s / year*** with some $z > 1$ → ***100,000s / year*** with most $z > 1$

Fight false alarms: **phase consistency**



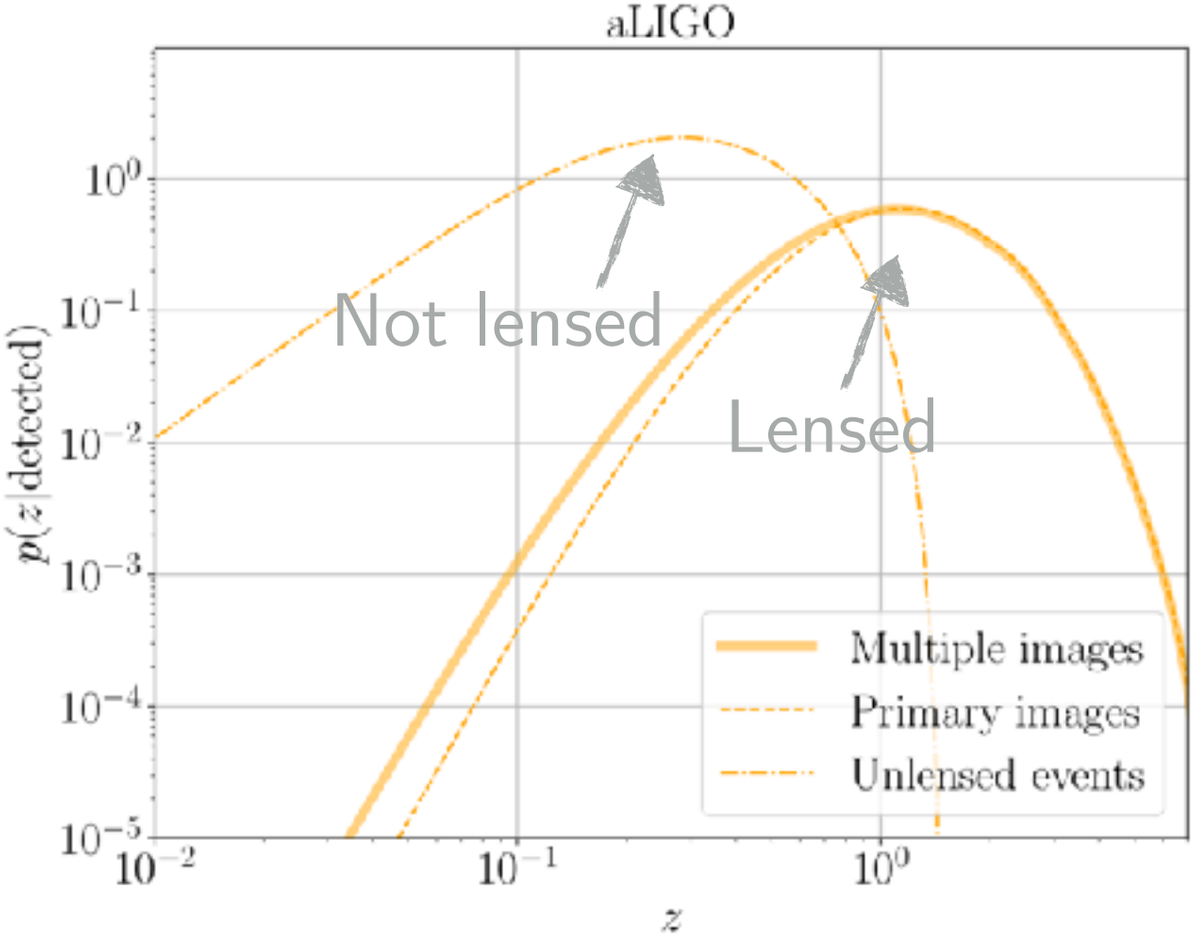


Ezquiaga, Hu and Lo; *in preparation*

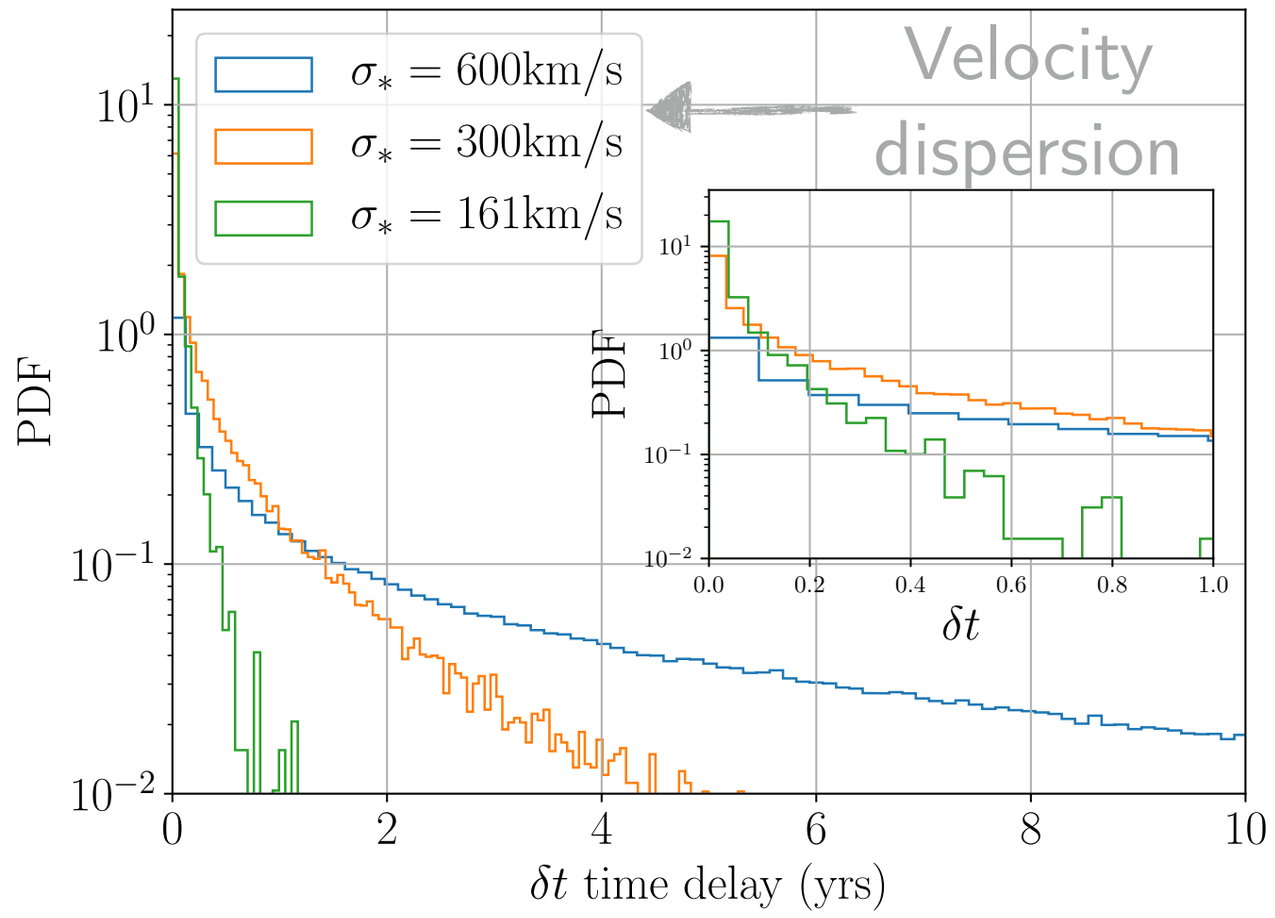
Probing source and lens populations

Fei Xu
(UChicago)

Detected populations

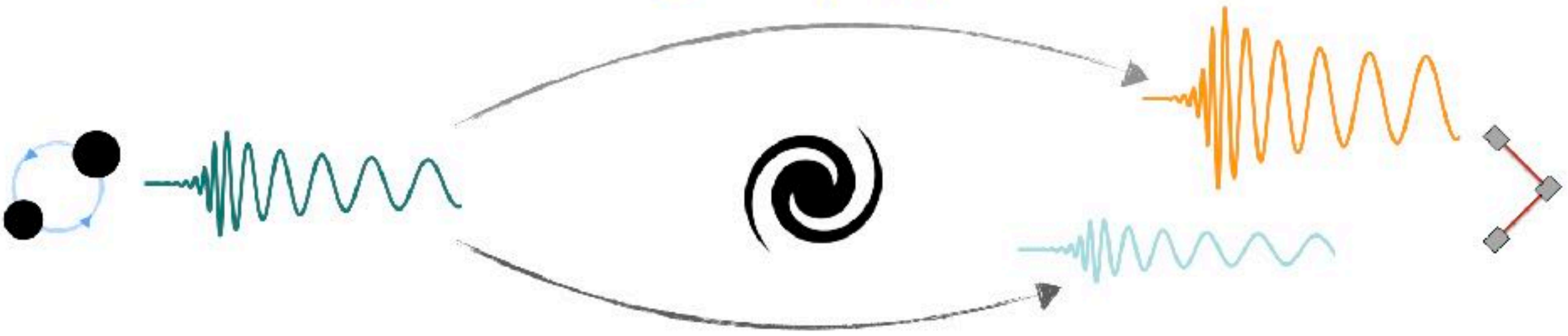


Time delay distributions

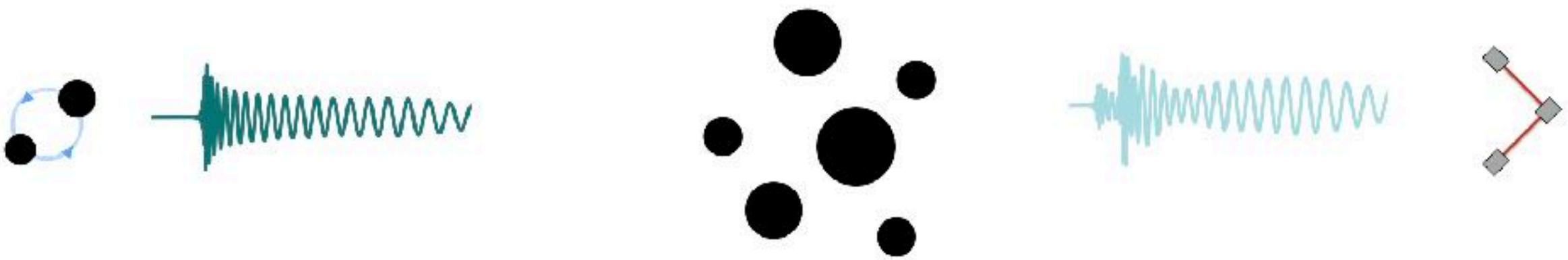


Xu, **Ezquiaga** and Holz; *Strong lensing probes compact and galaxy pop* (ApJ, arXiv 2105.14390)

Strong lensing by galaxies

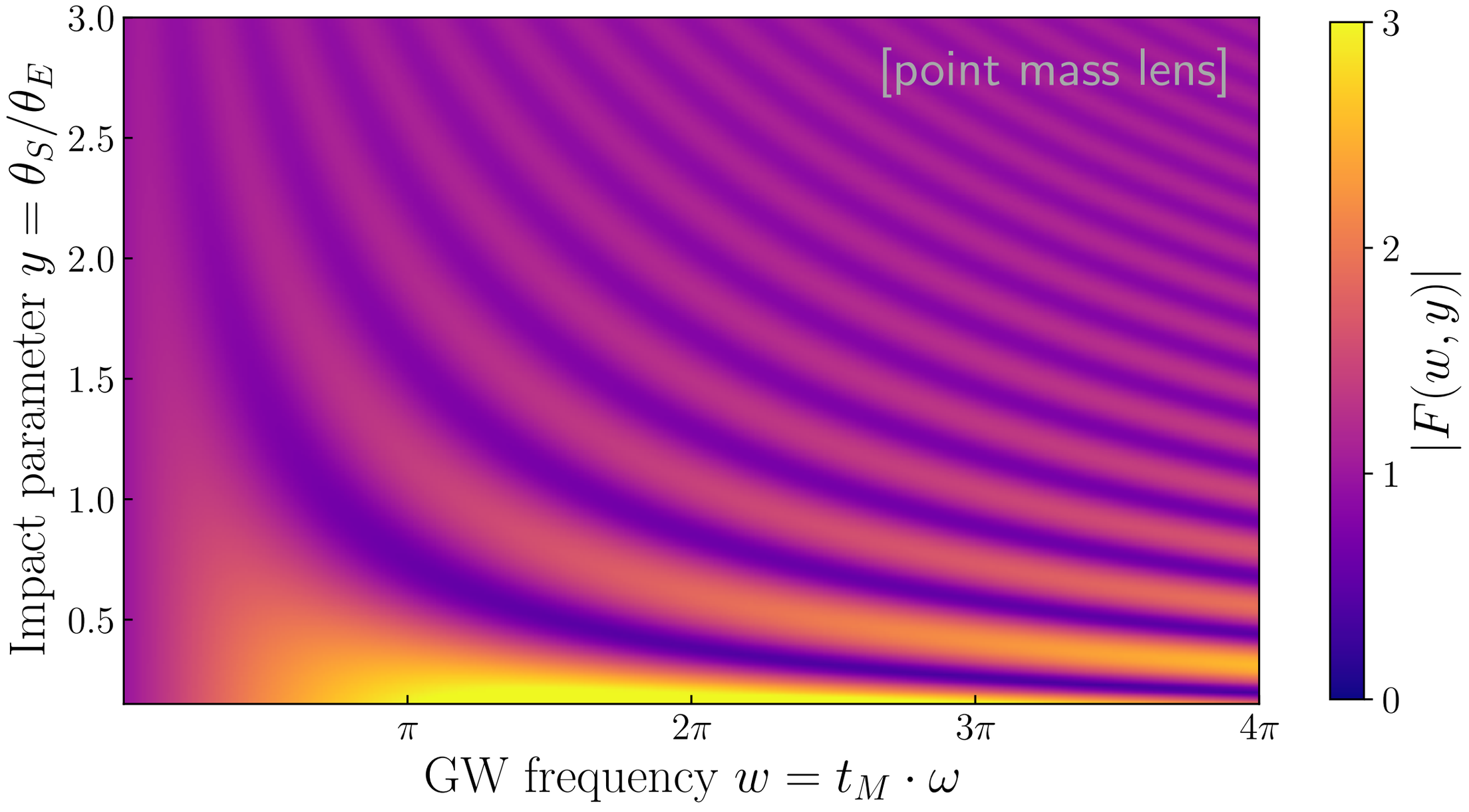


Interference effects by compact lenses



Wave effects:

$$F(w, \vec{y}) = \frac{w}{2\pi i} \int \mathrm{d}^2 x \exp\left[iwT(\vec{x}, \vec{y})\right]$$

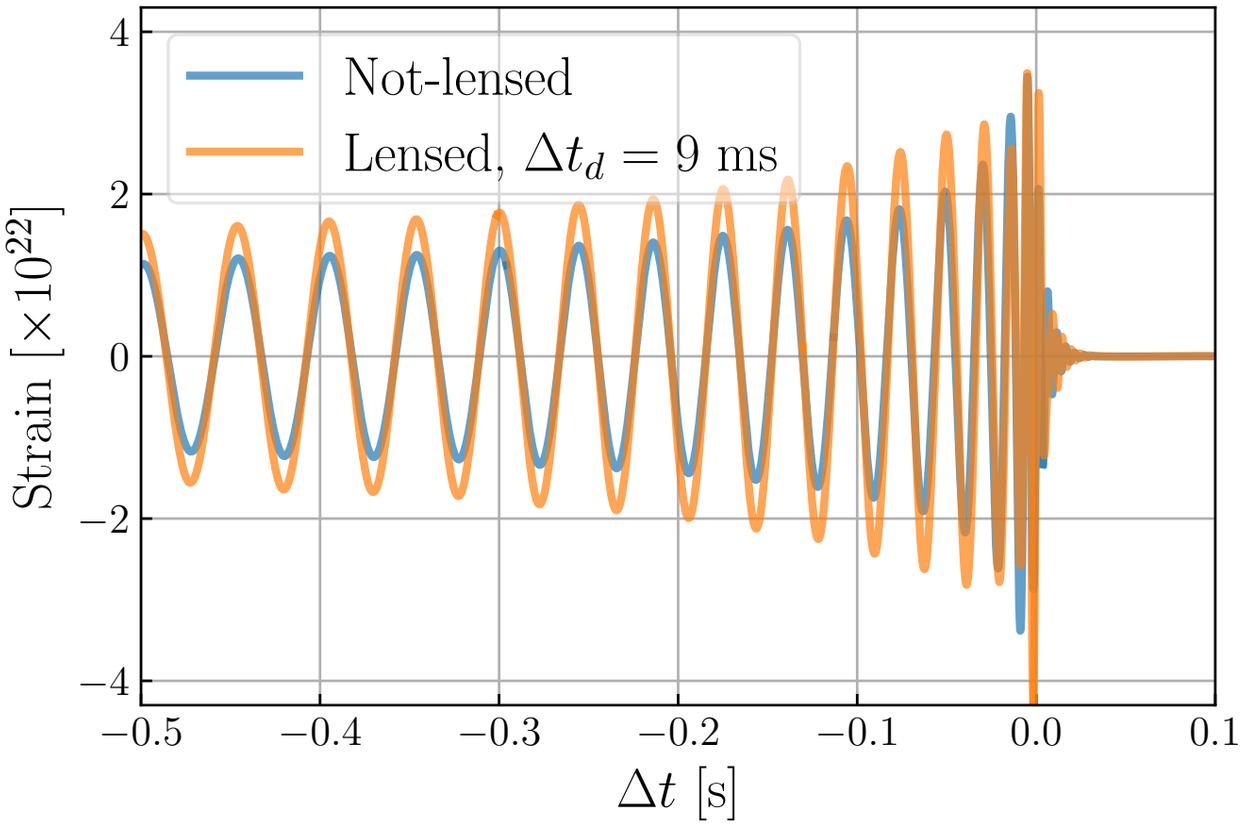


[point mass lens]

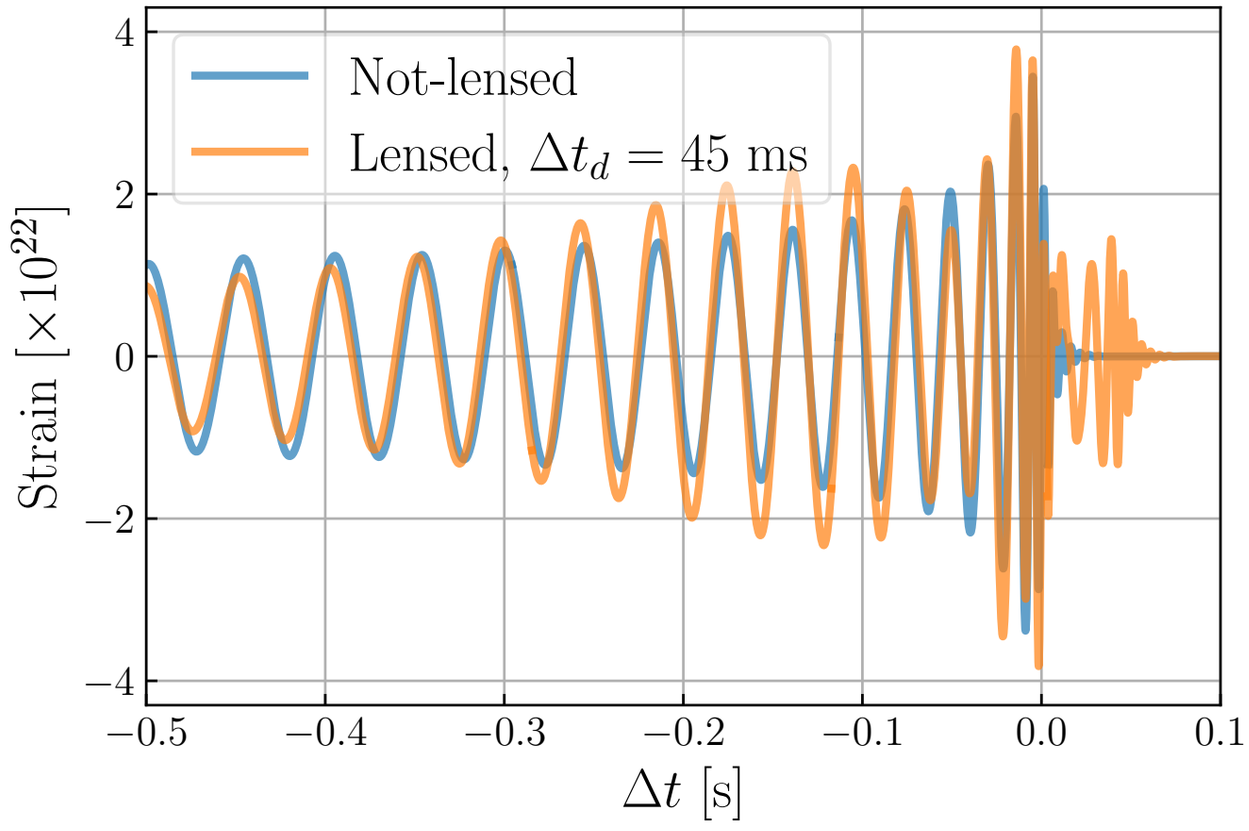
Wave effects:

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

Diffraction

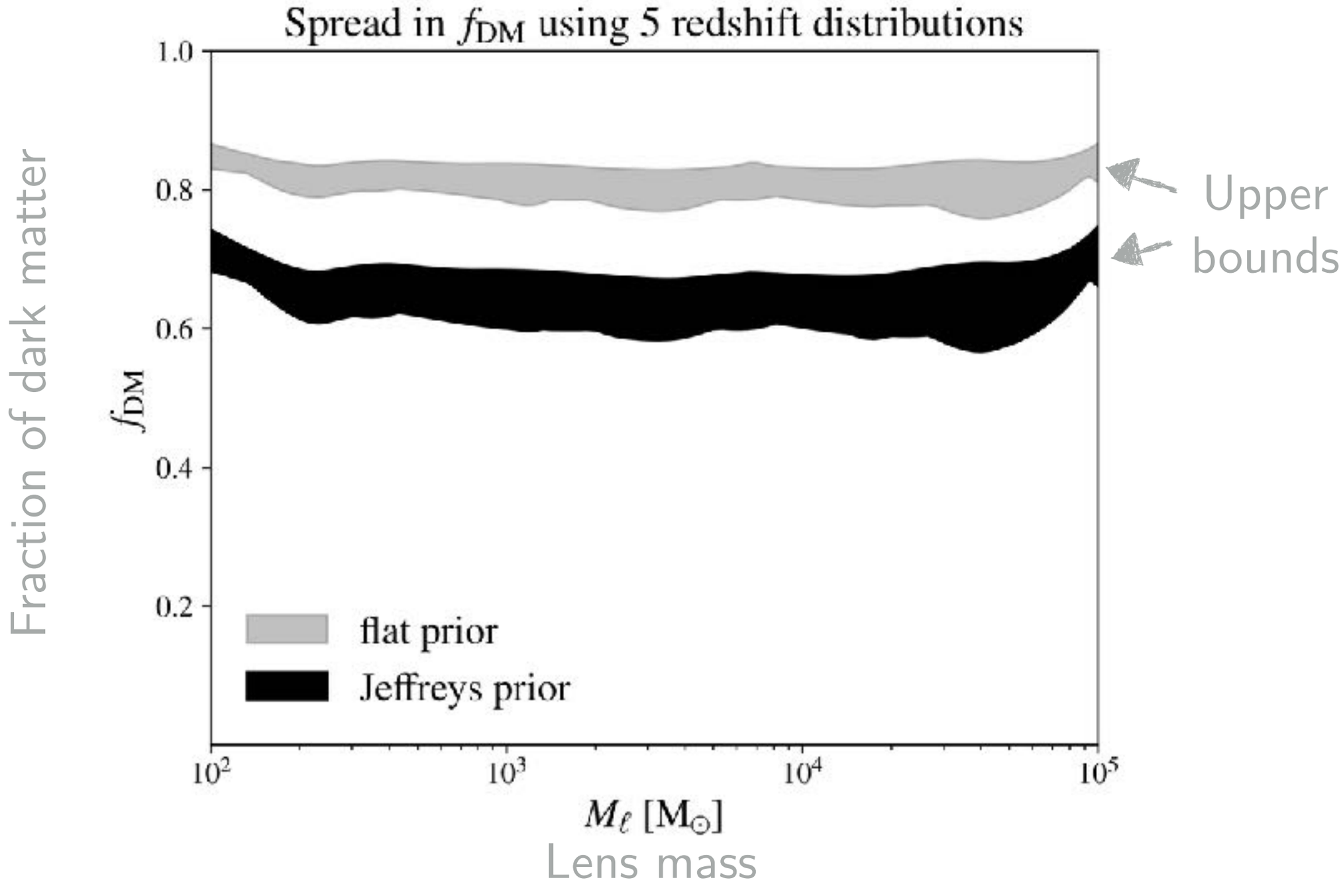


Interference



Probing compact objects (Dai et al.'18, Diego'19, Tambalo et al.'22, ...), strong lensing + microlensing (Seo et al.'21, Mena et al.'22, ...), breaking mass-sheet degeneracy (Cremonese, Ezquiaga, Salzano'21), solving diffraction integral (Feldbrugge&Turok'20, Tambalo et al.'22)

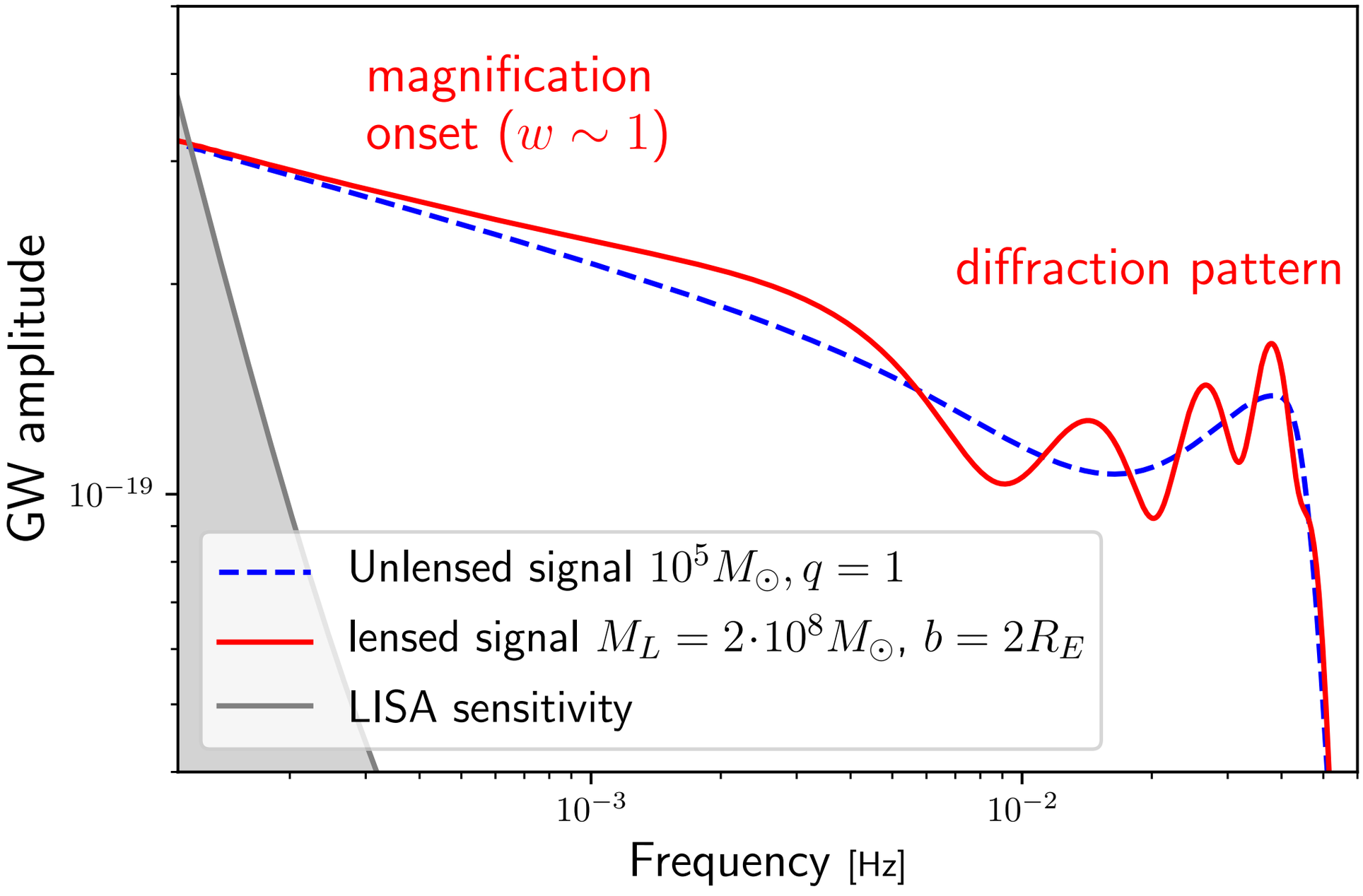
LVK: no evidence of wave effects so far...



LVC (incl. **Ezquiaga**); *Search GW lensing O3a* (ApJ, arXiv 2105.06384, *science summary*)

LVK (incl. **Ezquiaga**); *Search GW lensing full O3* (arXiv 2304.08393, *science summary*)

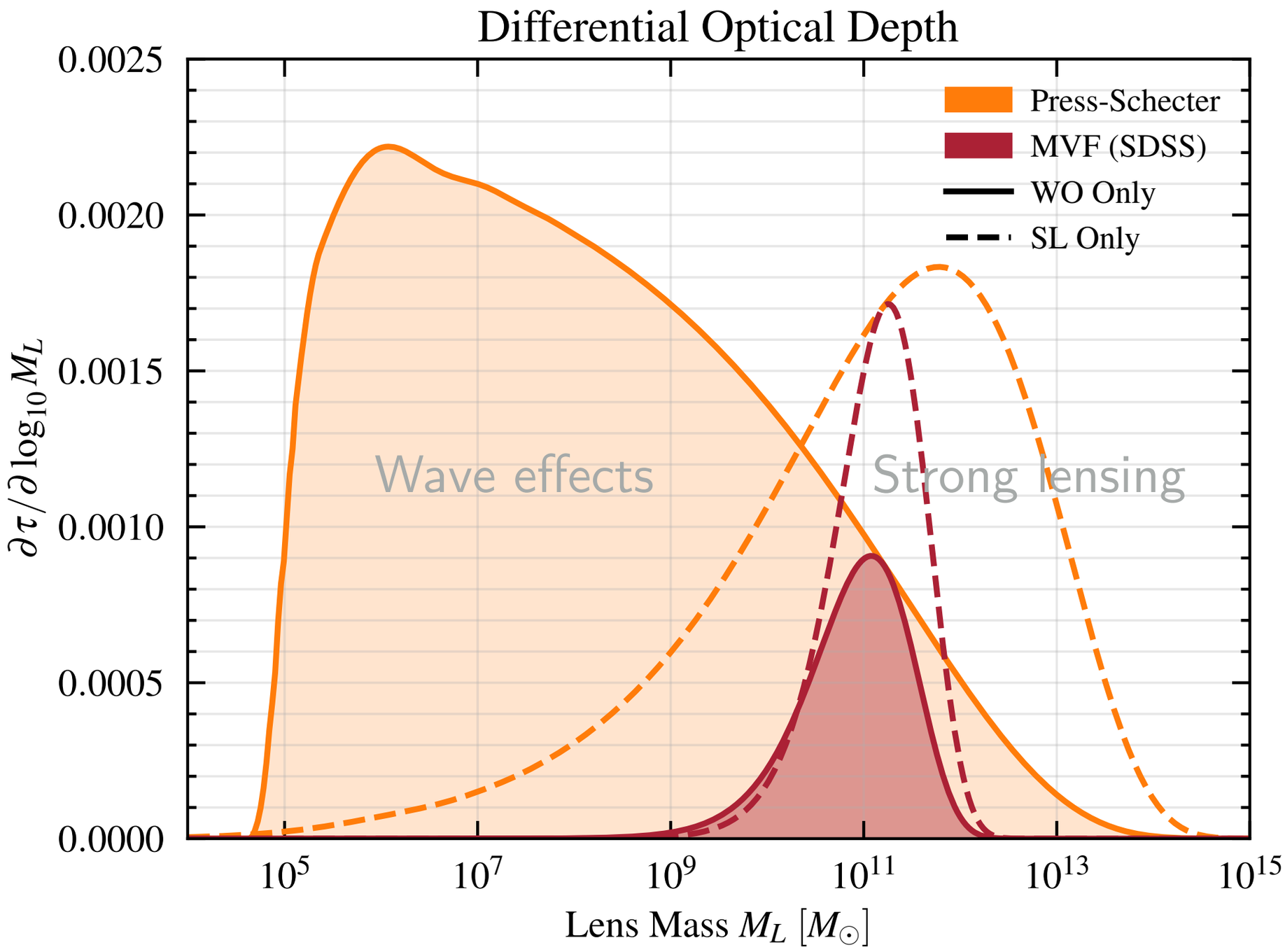
Wave effects: **LISA**



LISA Cosmo WG white paper (arXiv 2204.05434) and references therein

Probing dark matter sub-halos

Mesut Çalışkan (JHU)

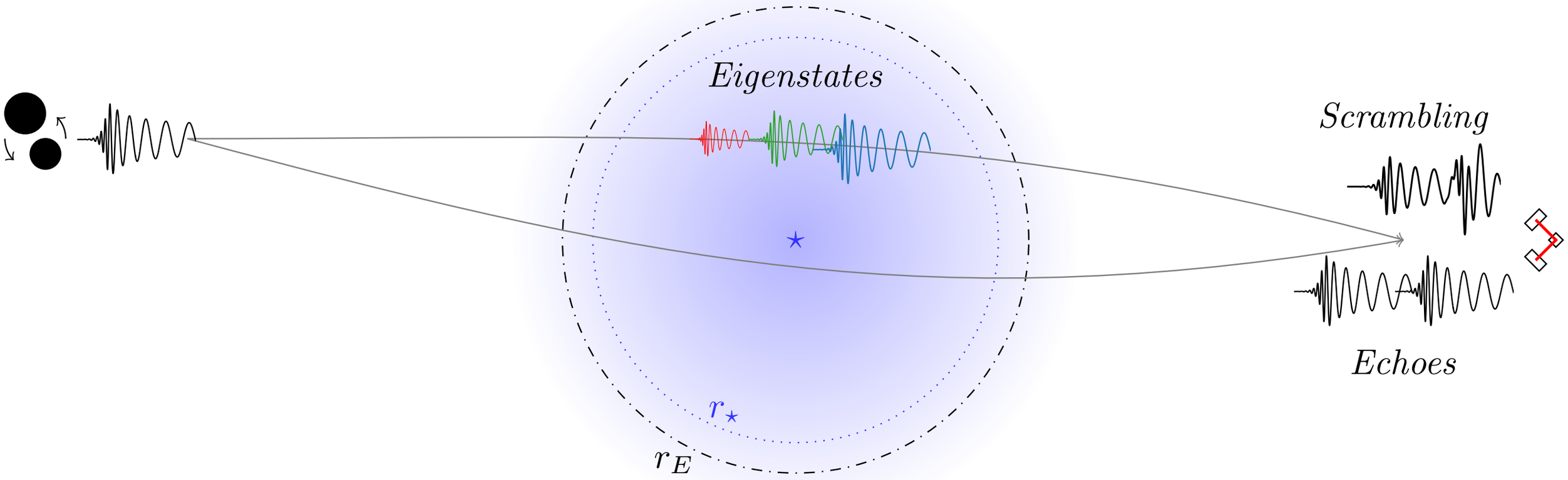


Çalışkan et al. (incl. **Ezquiaga**); *in preparation*

Gravitational lensing beyond general relativity

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

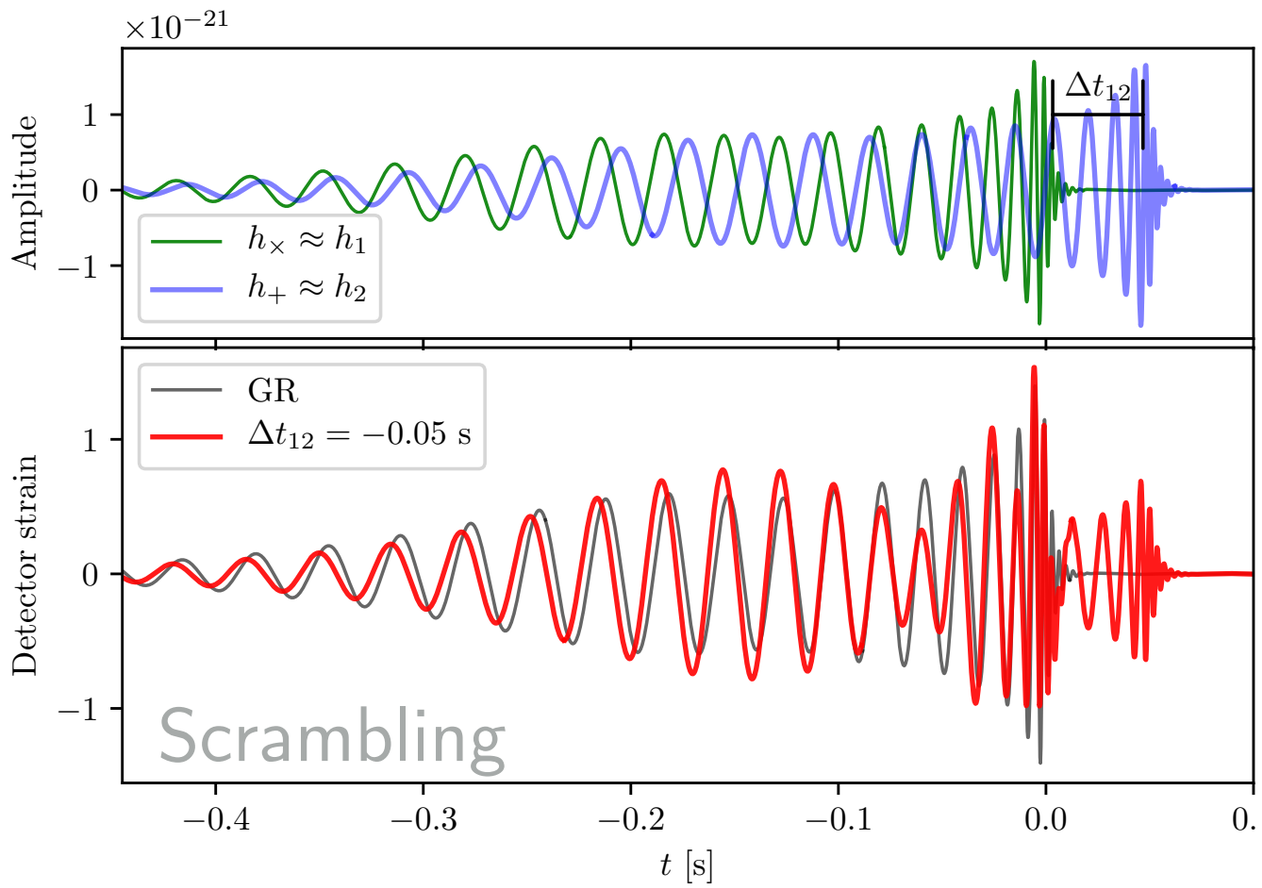
Ezquiaga & Zumalacárregui; *GW lensing beyond GR* (PRD, arXiv 2009.12187)

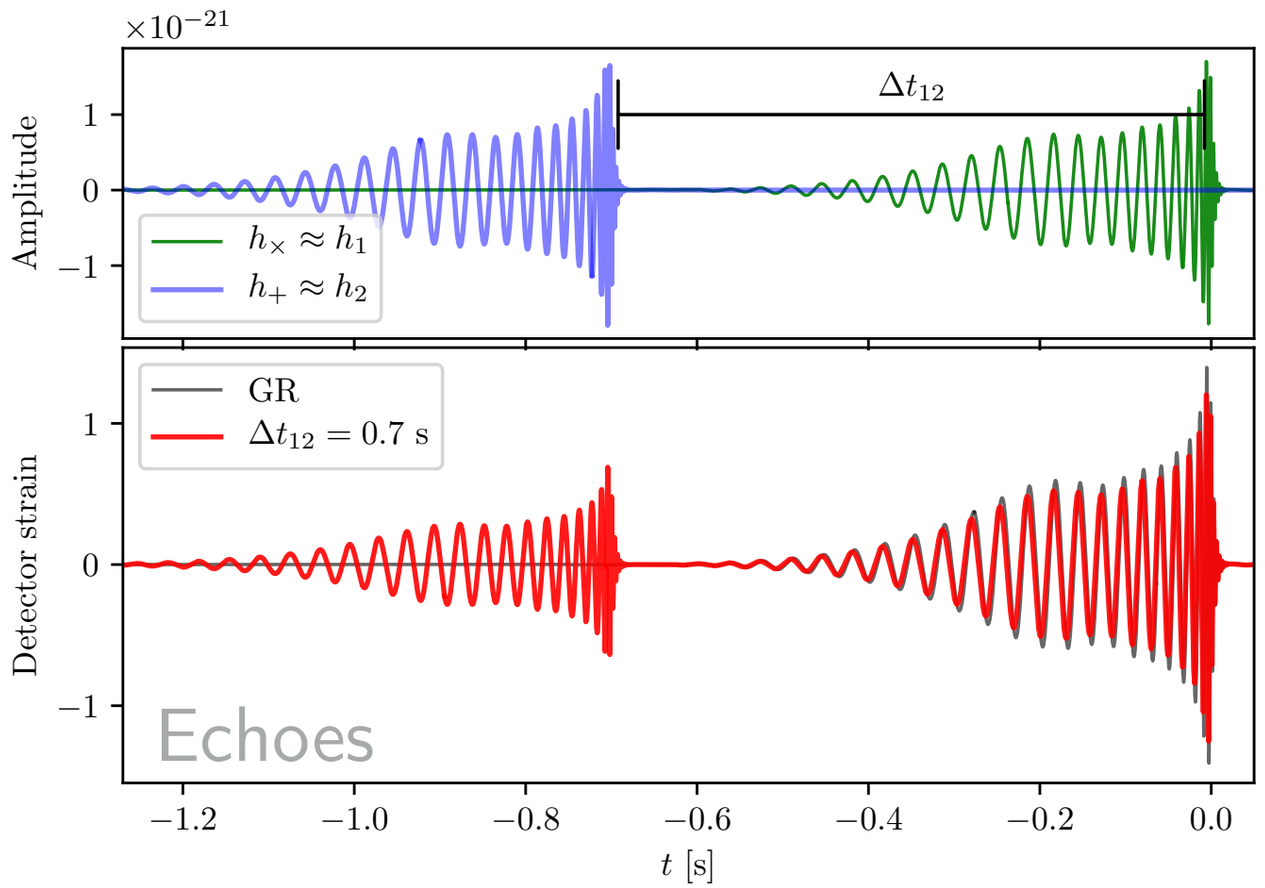
GW lensing beyond GR

Modified effective metric for each eigenstate and polarization mixing

Time delays

Birefringence



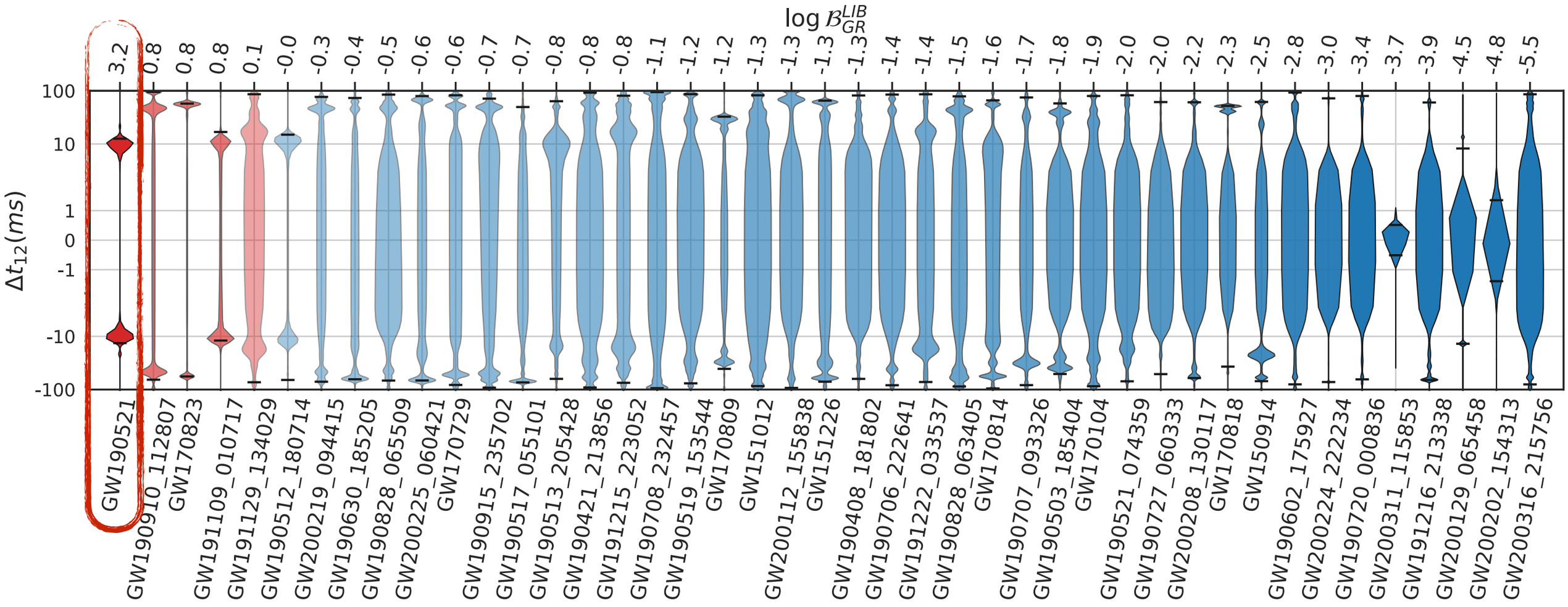


- No need of EM counterpart! Extend cosmological test GW propagation!

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

Probing lens-induced birrefringence (LIB)

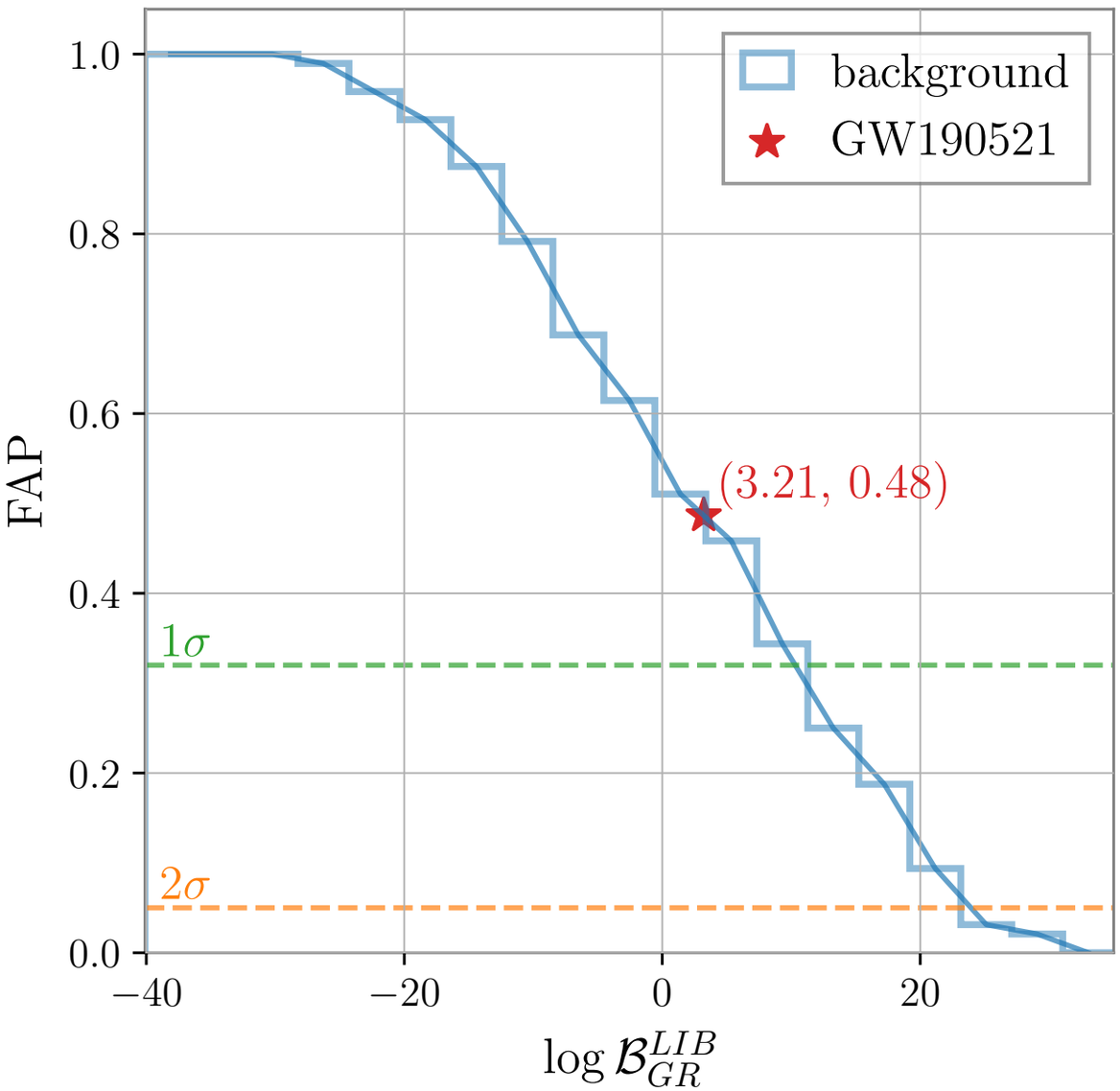
Srashti Goyal
(ICTS)



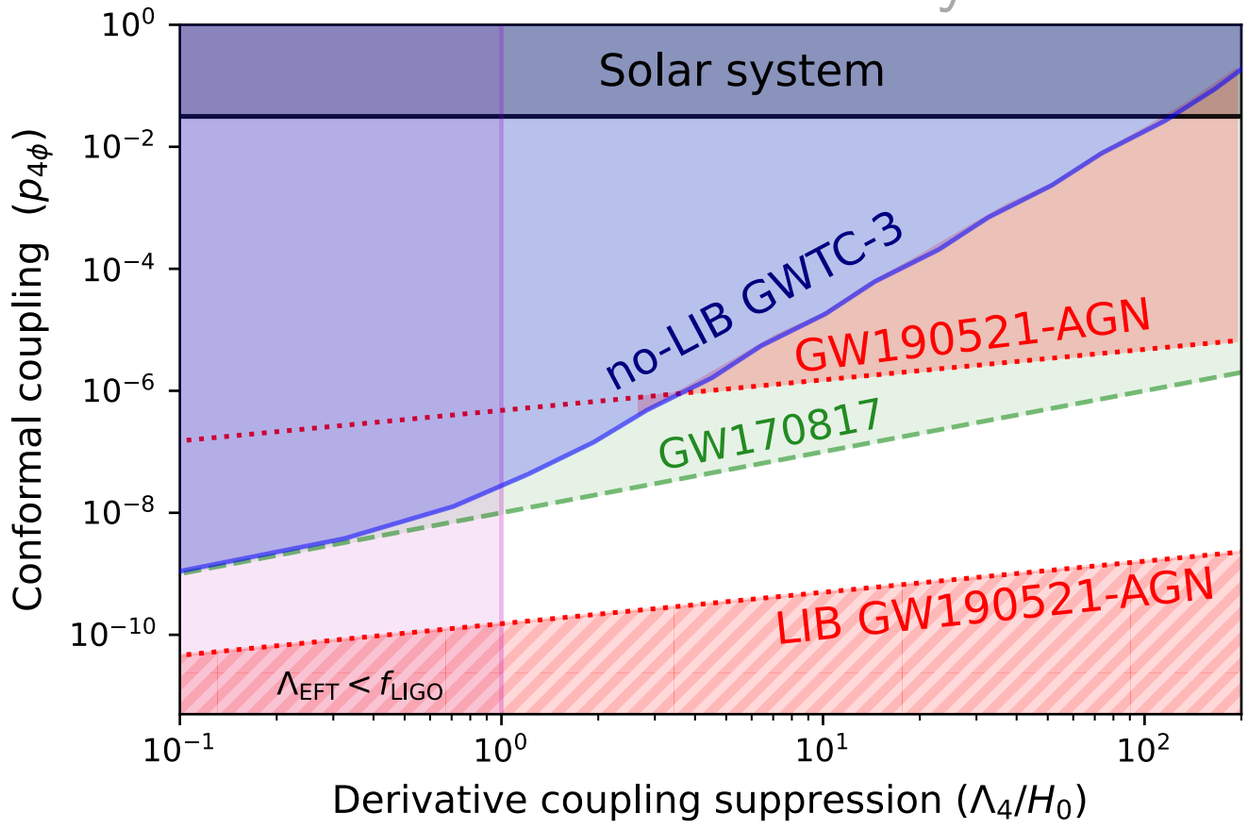
Goyal, *Vijaykumar*, **Ezquiaga** and Zumalacárregui; (arXiv 2301.04826)

Probing lens-induced birrefringence (LIB)

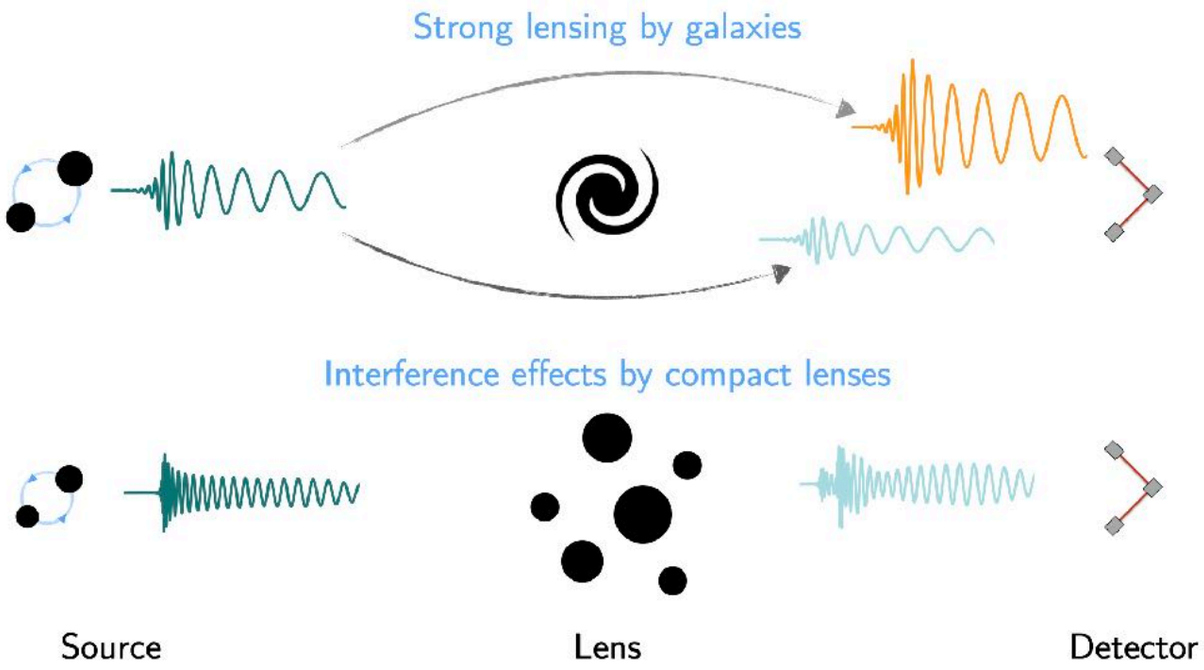
Srashti Goyal
(ICTS)

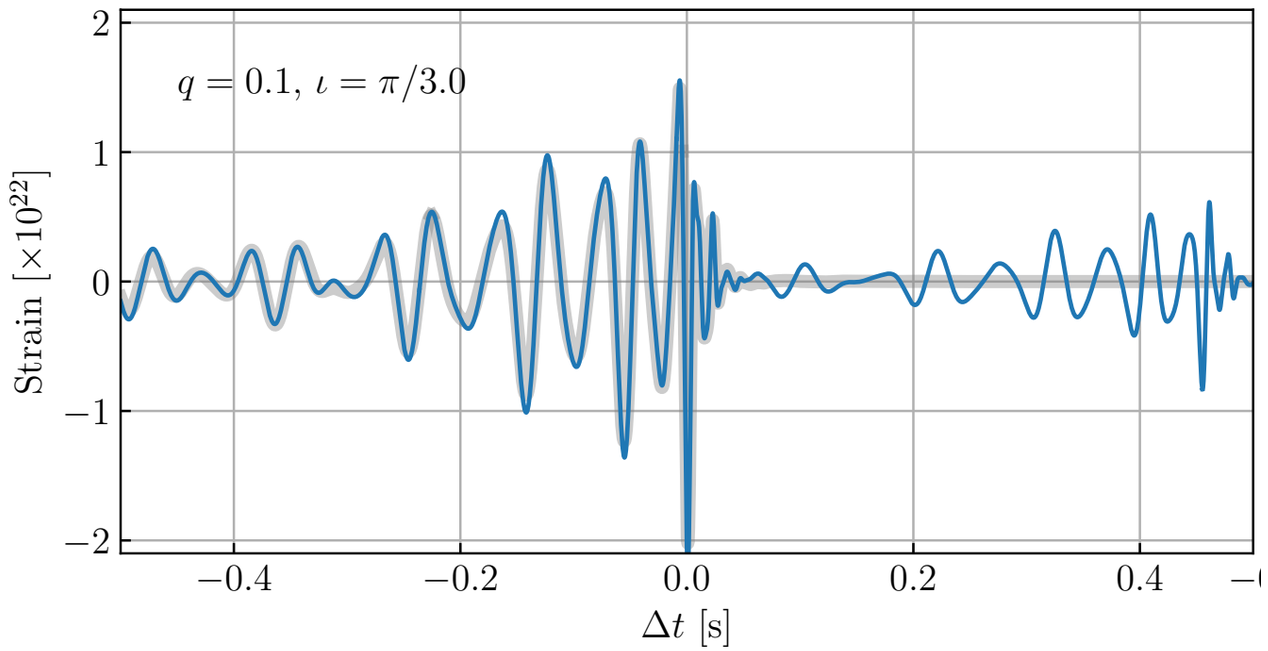


Constraints on (quartic) Horndeski theory

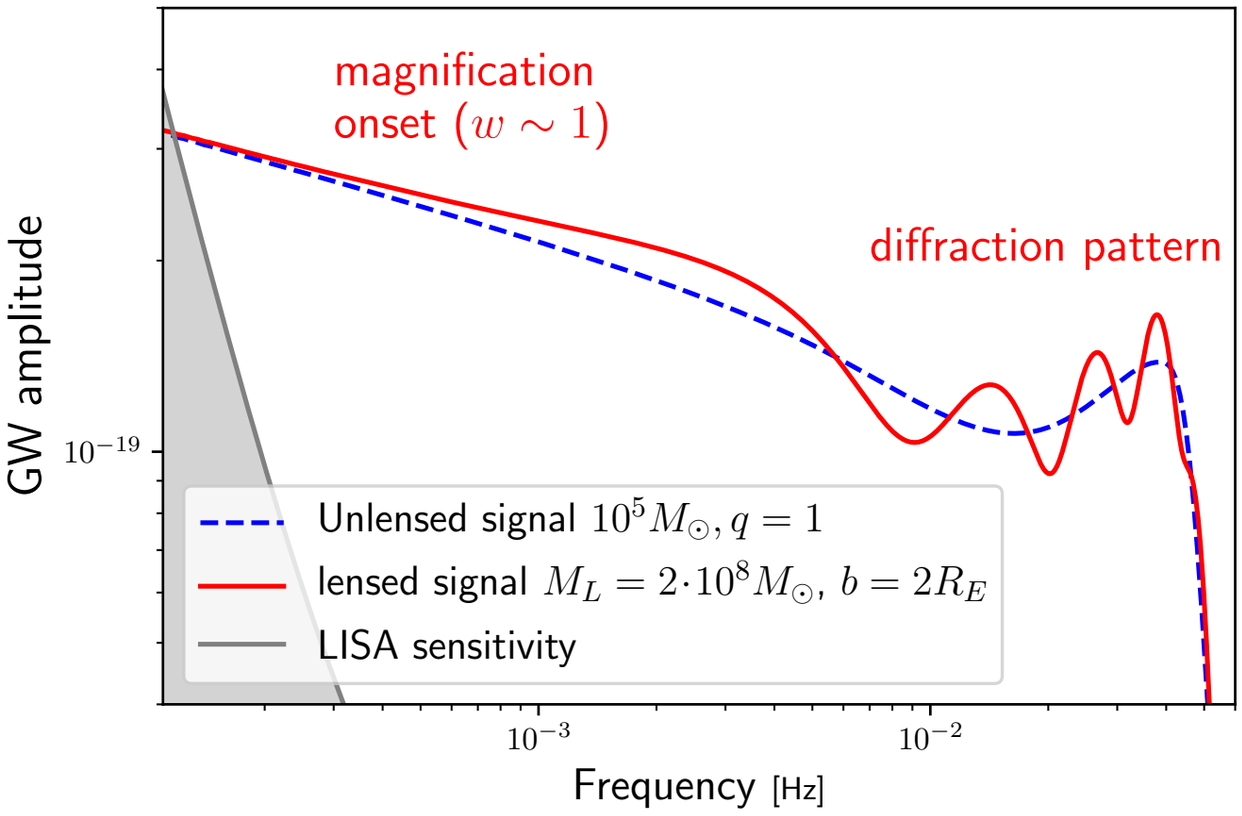


Goyal, *Vijaykumar*, **Ezquiaga** and Zumalacárregui; (arXiv 2301.04826)





Multiple images, type II distortion, expected soon!



Wave effects, PBH, sub-halos

Lensing beyond general relativity

Medfinansieret af Den Europæiske
Unions Connecting Europe-faciliteI

Join us!

VILLUM FONDEN

ezquiaga.github.io/joinus