
[Pompei]

Cosmology with binary black holes

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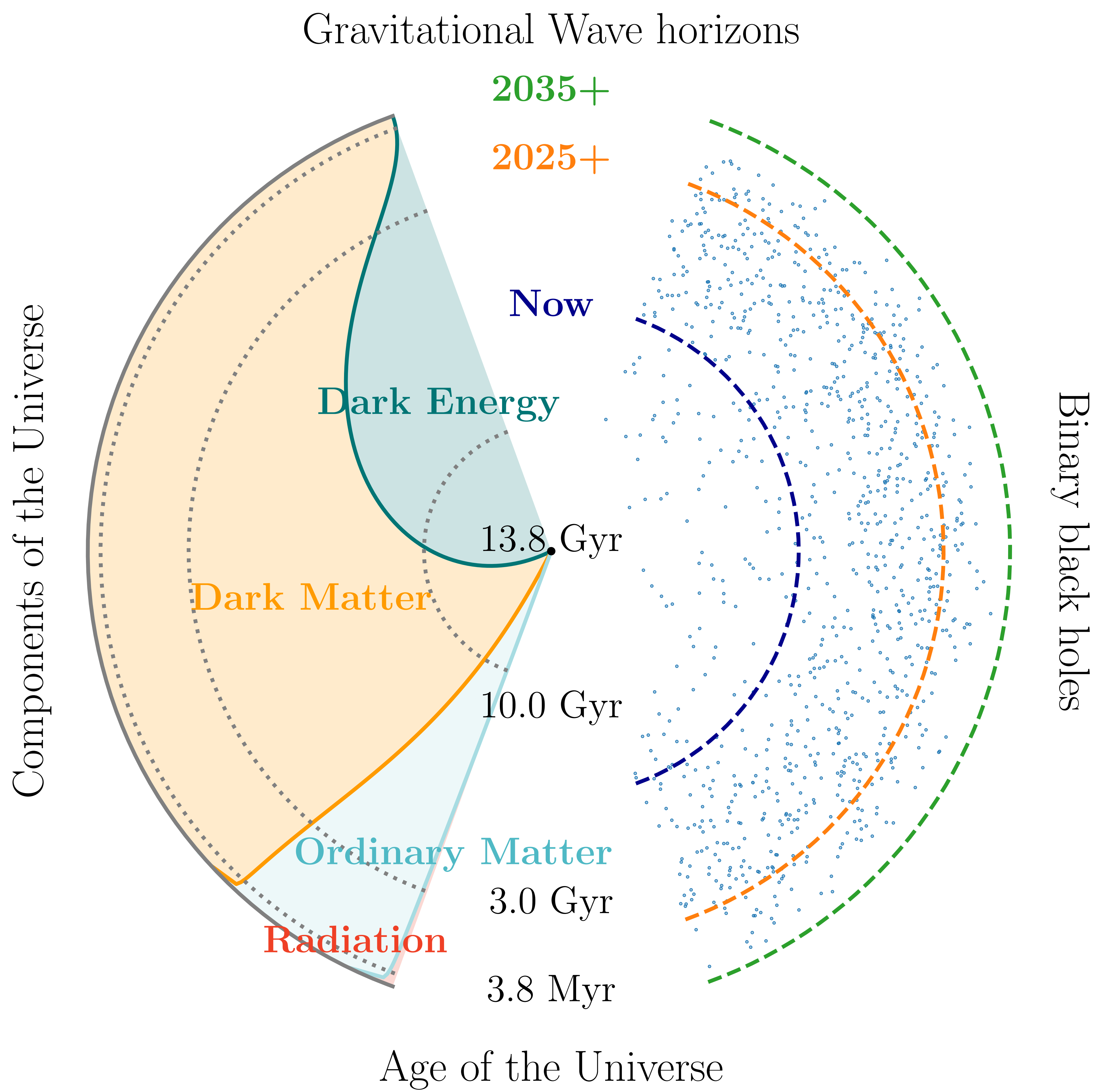
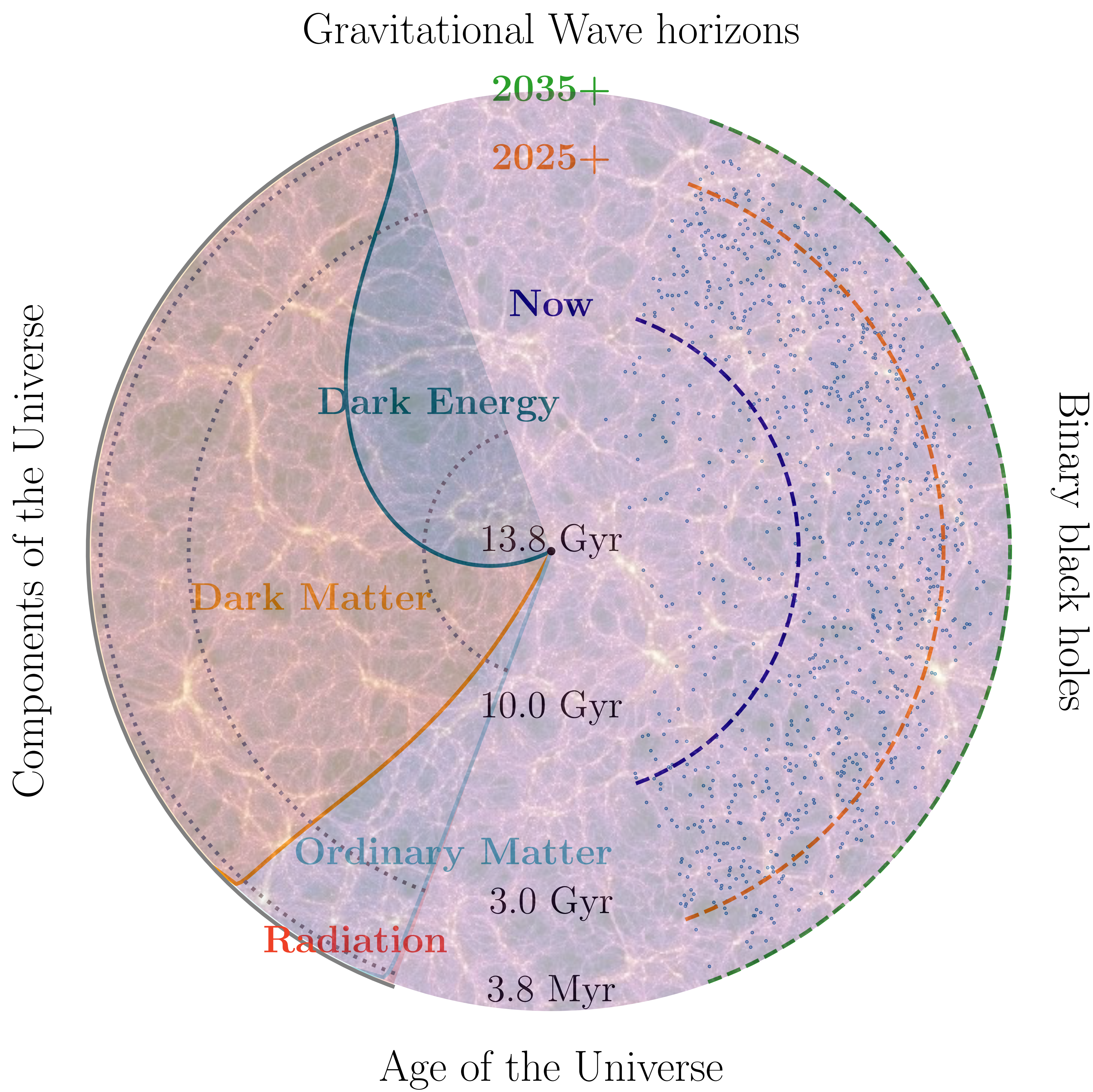
KØBENHAVNS UNIVERSITET


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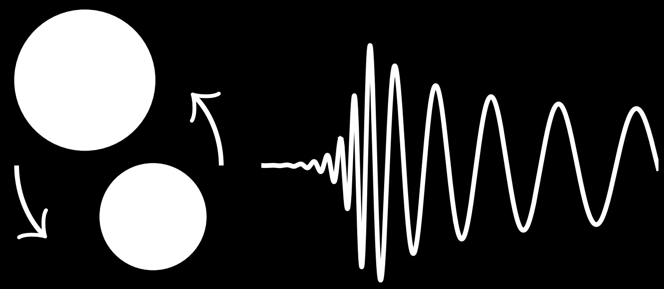
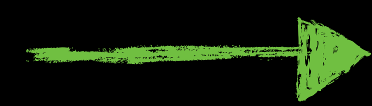
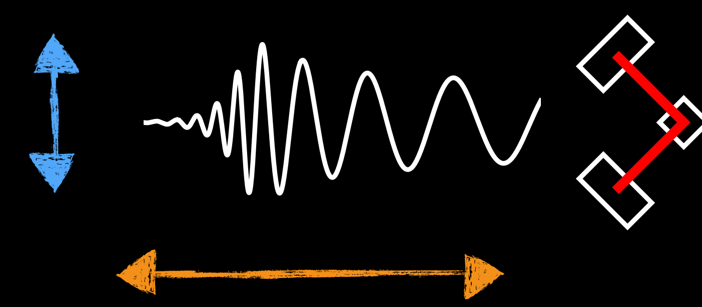
GWs are standard sirens

[well understood selection effects]







[cosmo propagation]

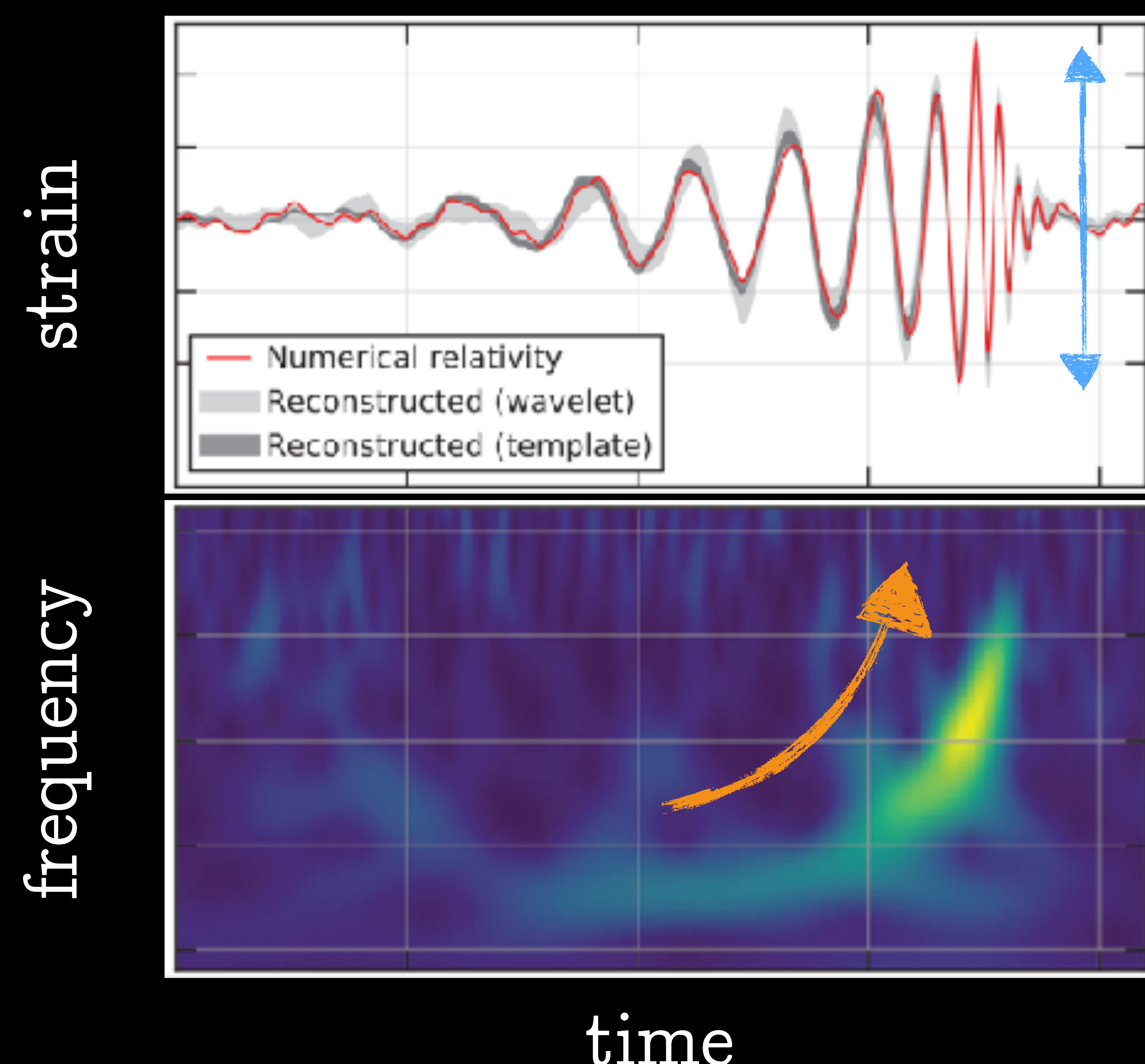
[GR predicts waveform]

$$d_L(z)$$

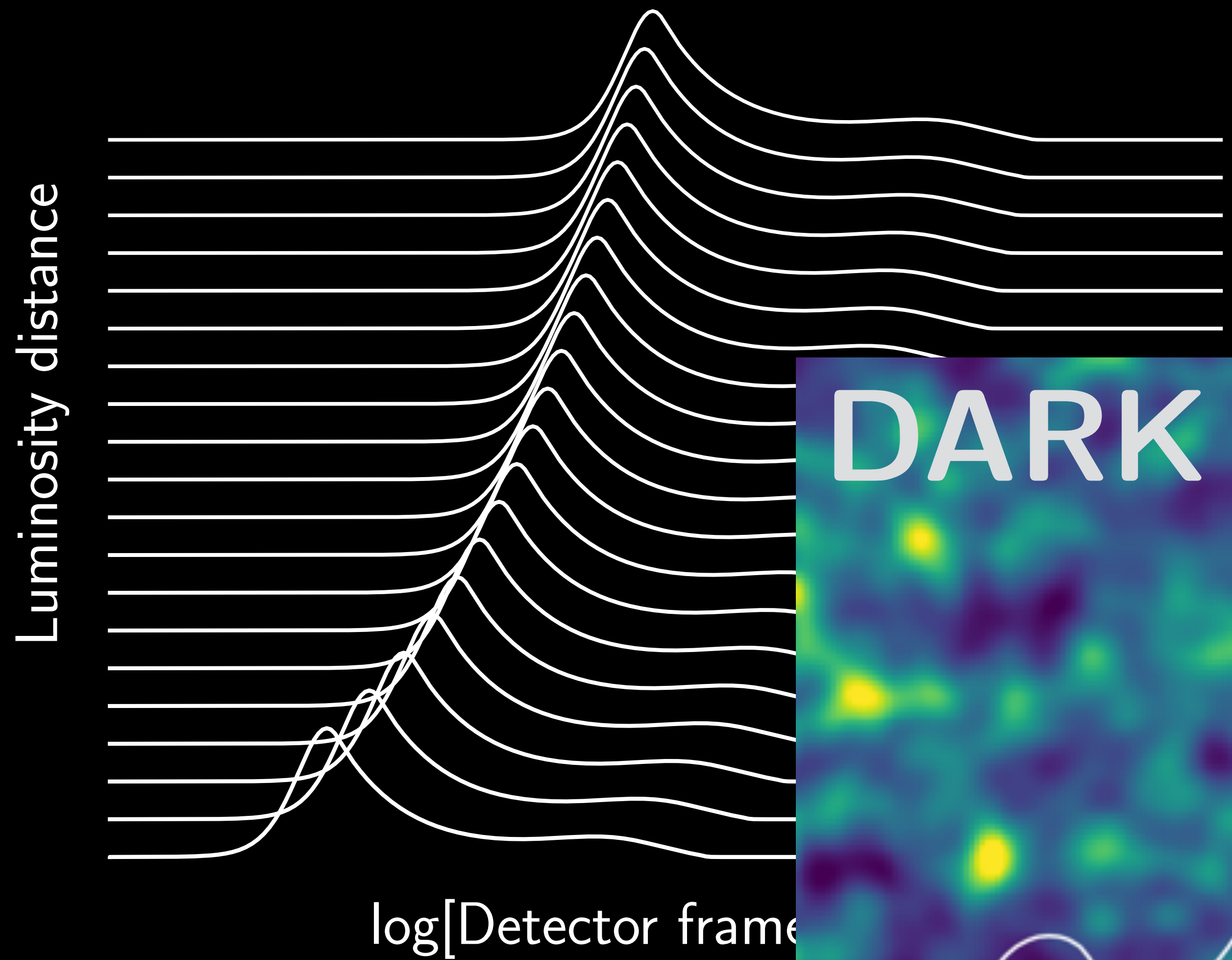
[GW Hubble diagram]

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

[Interplay with astrophysics]



SPECTRAL SIRENS



Love sirens

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Cosmography with next-generation gravitational wave detectors

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CrossMark

Abstract

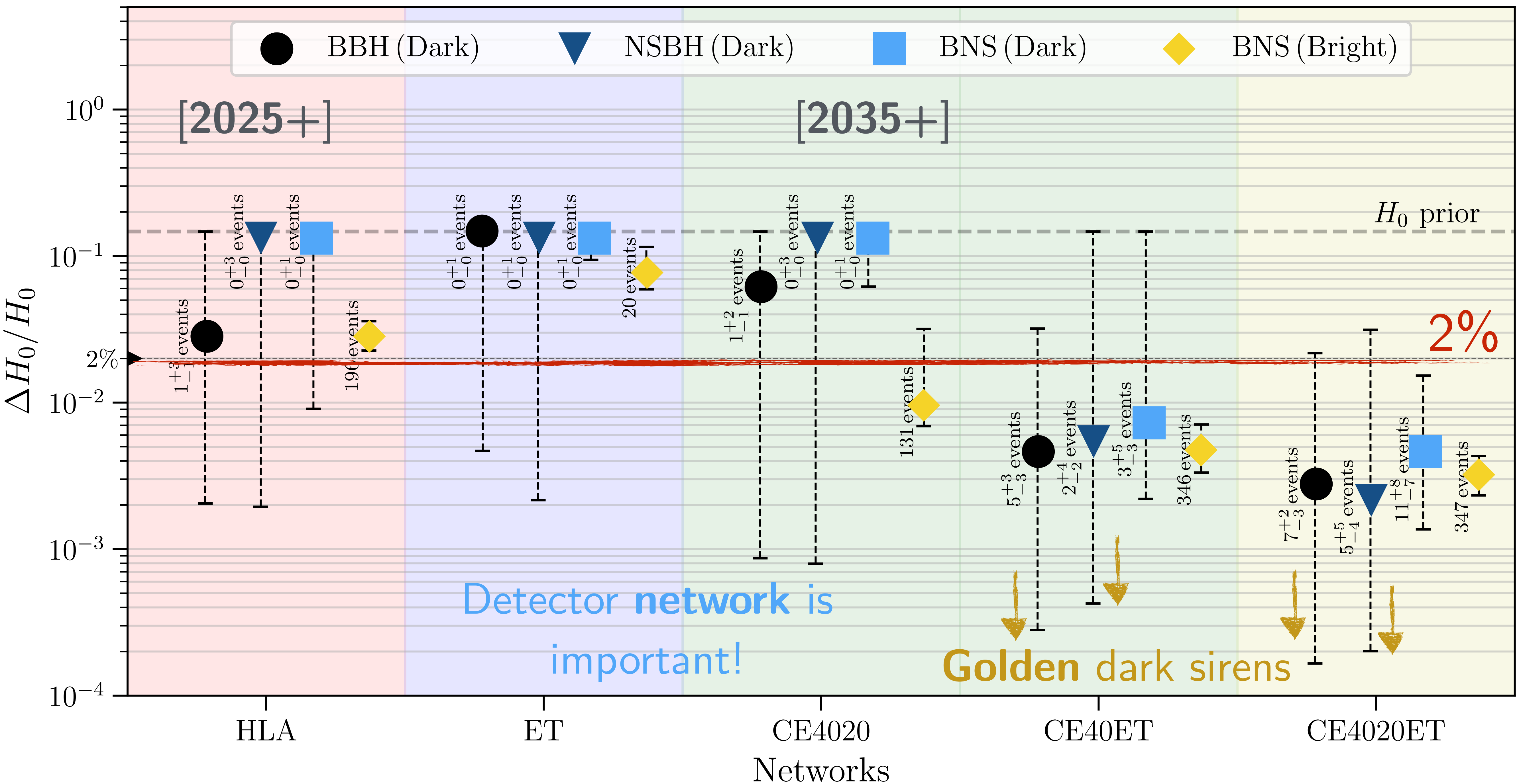
Advancements in cosmology through next-generation (XG) ground-based gravitational wave (GW) observatories will bring in a paradigm shift. We explore the pivotal role that GW standard sirens will play in inferring cosmological parameters with XG observatories, not only achieving exquisite precision but also opening up unprecedented redshifts. We examine the merits and the systematic biases involved in GW standard sirens utilizing binary black holes, binary neutron stars, and neutron star-black hole mergers. Further, we estimate the precision of bright sirens, golden dark sirens, and spectral sirens for these binary coalescences and compare the abilities of various XG observatories ($A^\sharp$, cosmic explorer, Einstein telescope, and their possible networks). When combining different sirens, we find sub-percent precision over more than 10 billion years of cosmic evolution for the Hubble expansion rate $H(z)$. This work presents a broad view of opportunities to precisely measure the cosmic expansion rate, decipher the elusive dark energy and dark matter, and potentially discover new physics in the uncharted Universe with XG GW detectors.

Keywords: gravitational wave, standard siren, cosmology

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

H_0 (also) with dark sirens

H: Hanford (US)
L: Livingston (US)
A: Aundha (India)
ET: Einstein Telescope (EU)
CE: Cosmic Explorer (US)

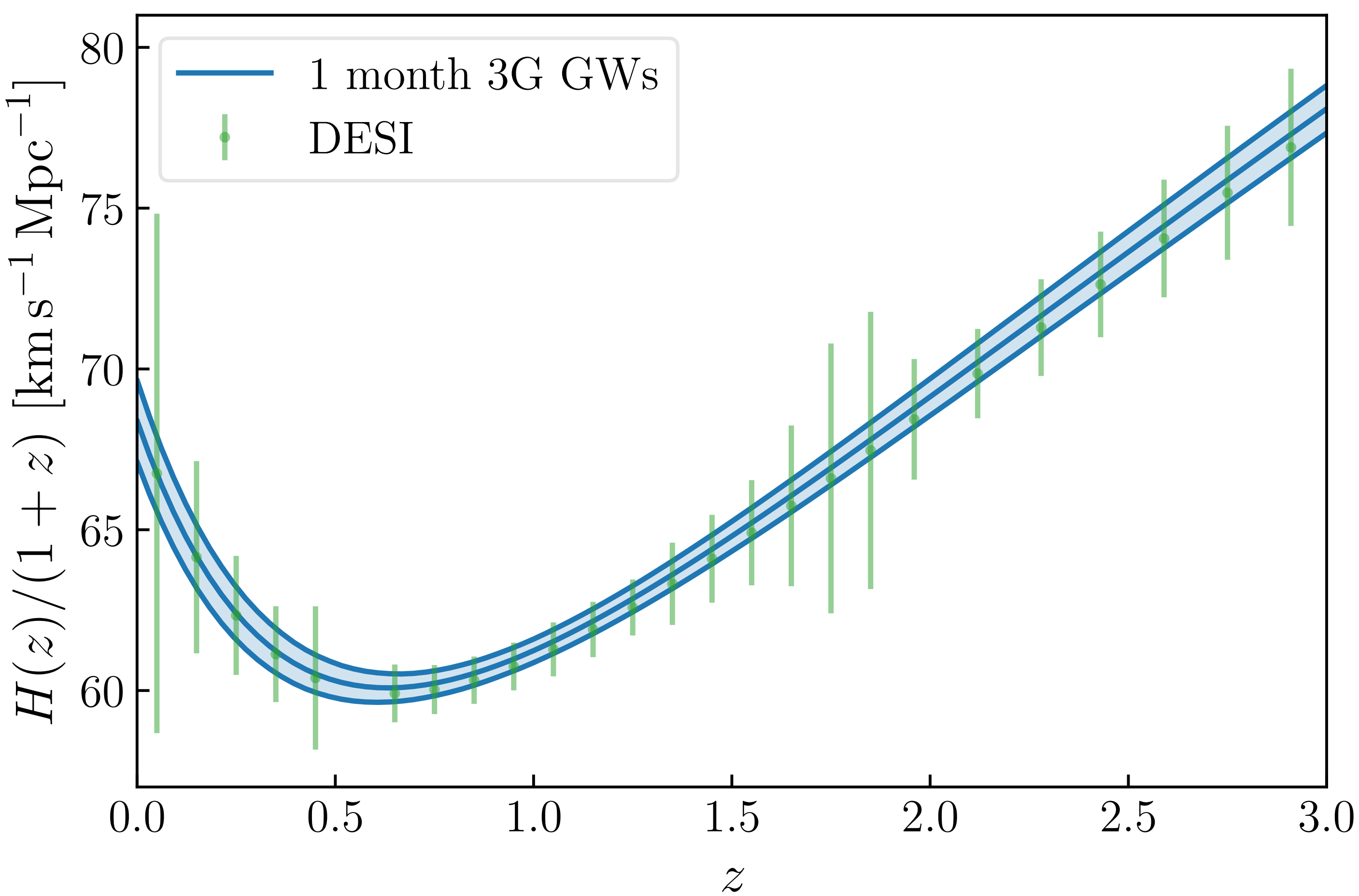


[Chen, **Ezquiaga** & Gupta (CQG'24)]

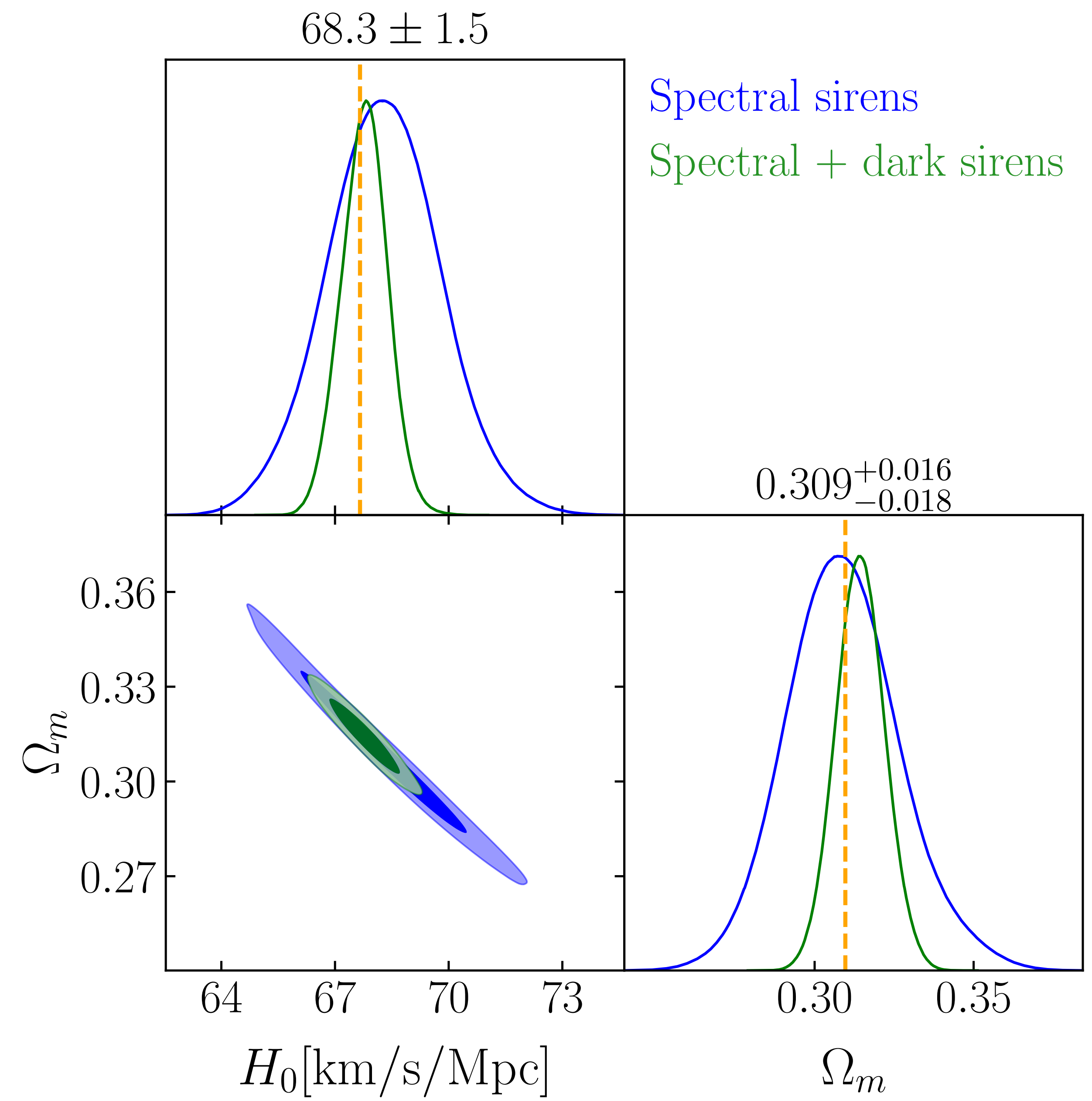
Expansion rate at high redshift *H(z)*

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

Spectral sirens are competitive with cosmic surveys



[**Ezquiaga** & Holz (PRL'22)]



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

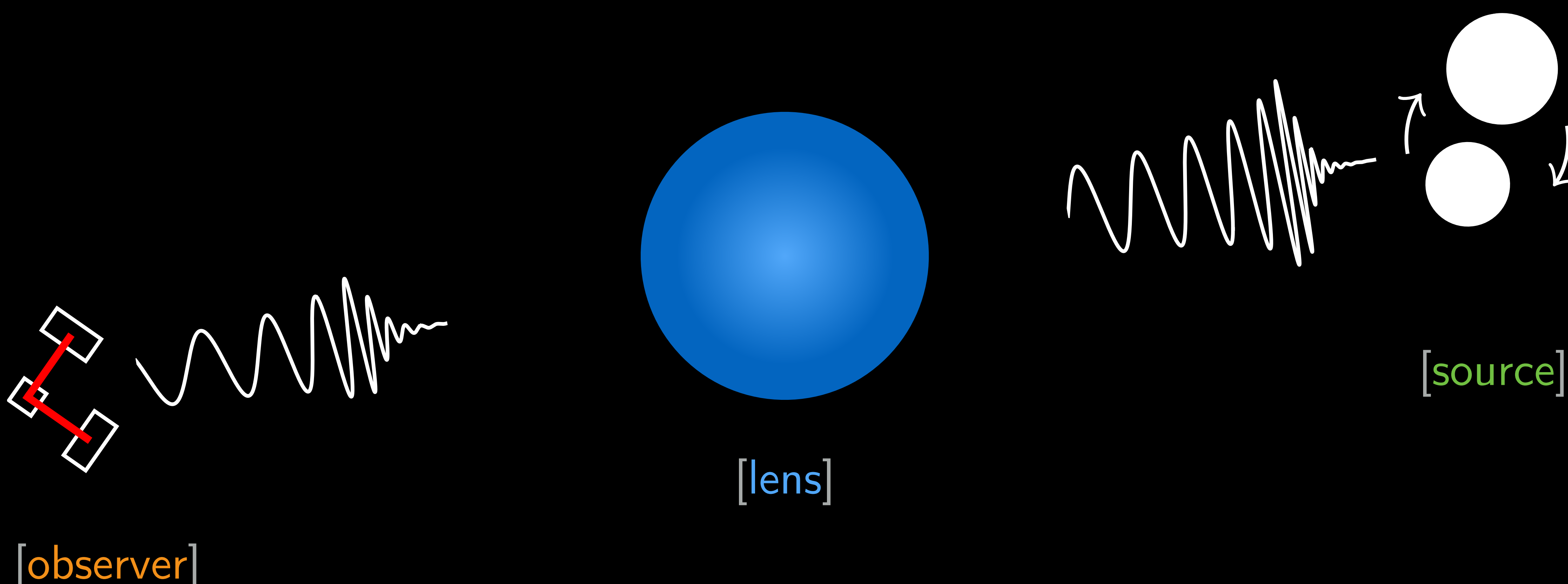
[https://ezquiaga.github.io/lectures/Lecture_Notes.pdf]

Gravitational lensing

- Solve GW propagation on a curved background

$$\Box\bar{h}_{\mu\nu} + 2\bar{R}_{\alpha\mu\beta\nu}\bar{h}^{\alpha\beta} = 0$$

- We want to make a mapping between the source and the observer through the lens



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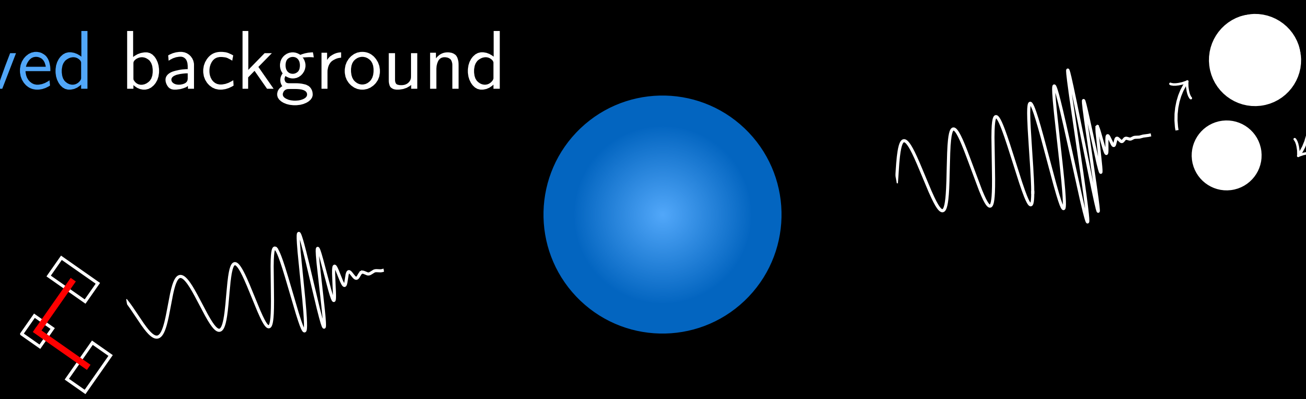


- Within *weak-gravity* & *thin lens* approximations, in *Fourier* space:

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

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

[Dimensionless variables] $\vec{x} \equiv \vec{\theta}/\theta_* \,, \quad \vec{y} \equiv \vec{\theta}_S/\theta_* \,, \quad w \equiv \tau_D \theta_*^2 \omega$

$$T_d \equiv t_d/\tau_D \theta_*^2 \qquad \tau_D \equiv (1+z_L) D_L D_S / c D_{LS}$$

Stationary Phase Approximation

- Solve integral in the limit of highly oscillatory integrand

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

- Stationary points define the images:

$$\left.\frac{\partial t_d}{\partial \theta_a}\right|_{\vec{\theta}=\vec{\theta}_j} = 0$$

$$T_d(\vec{\theta}) \approx T_d(\vec{\theta}_j) + \frac{1}{2}\sum_{(a,b)=1}^{2} \delta\theta_a \delta\theta_b \frac{\partial^2 T_d(\vec{\theta}_j)}{\partial\theta_a\partial\theta_b} + \cdots$$

- Hessian matrix determines magnifications

$$\mu(\theta_j) = 1/\det(T_{ab}(\theta_j))$$

$$T_{ab} \equiv \tau_D^{-1}\partial^2 t_d/\partial\theta_a\partial\theta_b$$

Strong lensing

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

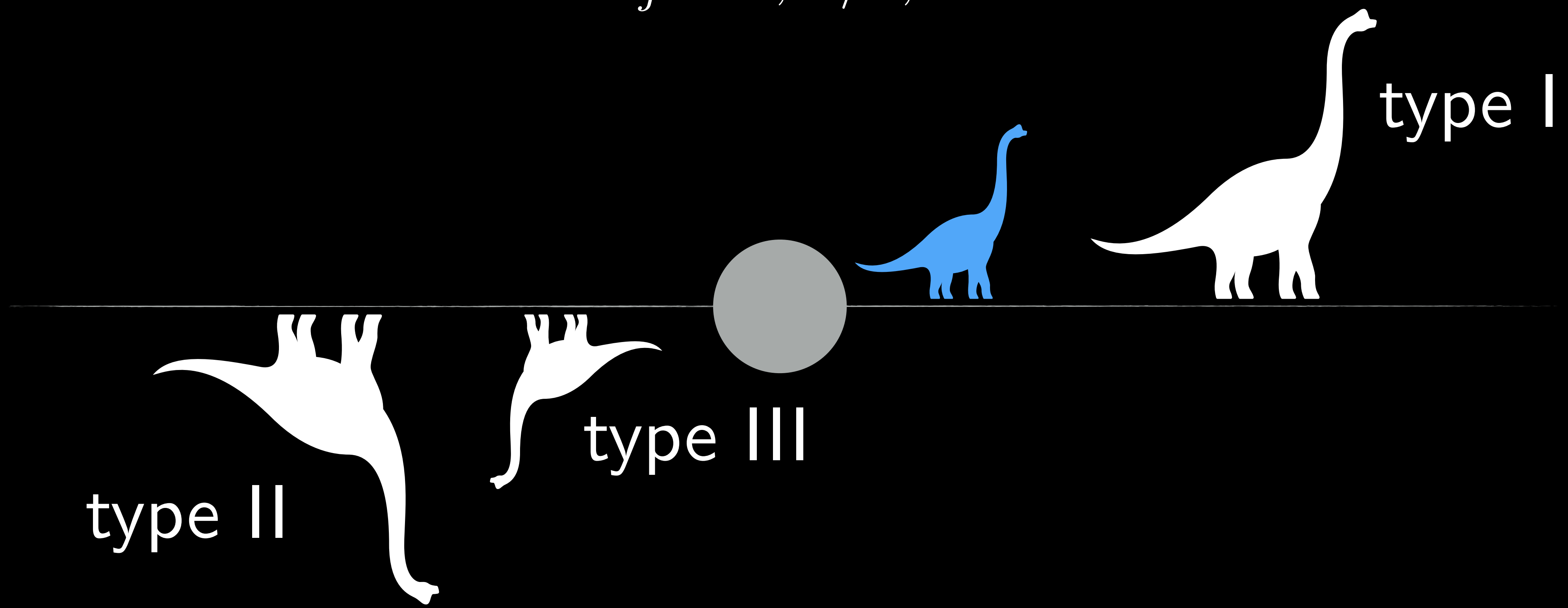
$$h_L(\omega) = F(\omega, \theta_S) \cdot h(\omega)$$

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

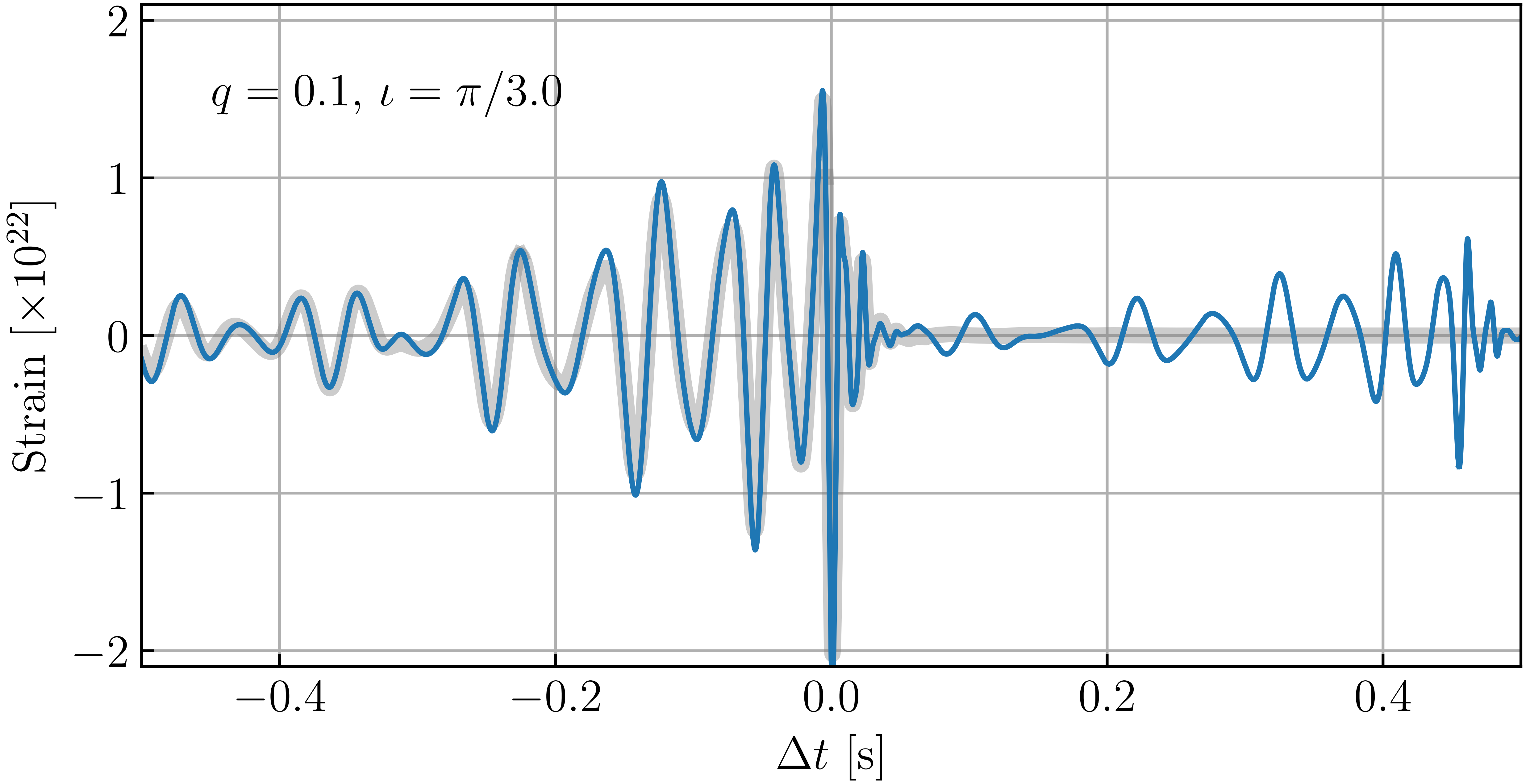
Magnification
Time delay
Phase shift

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

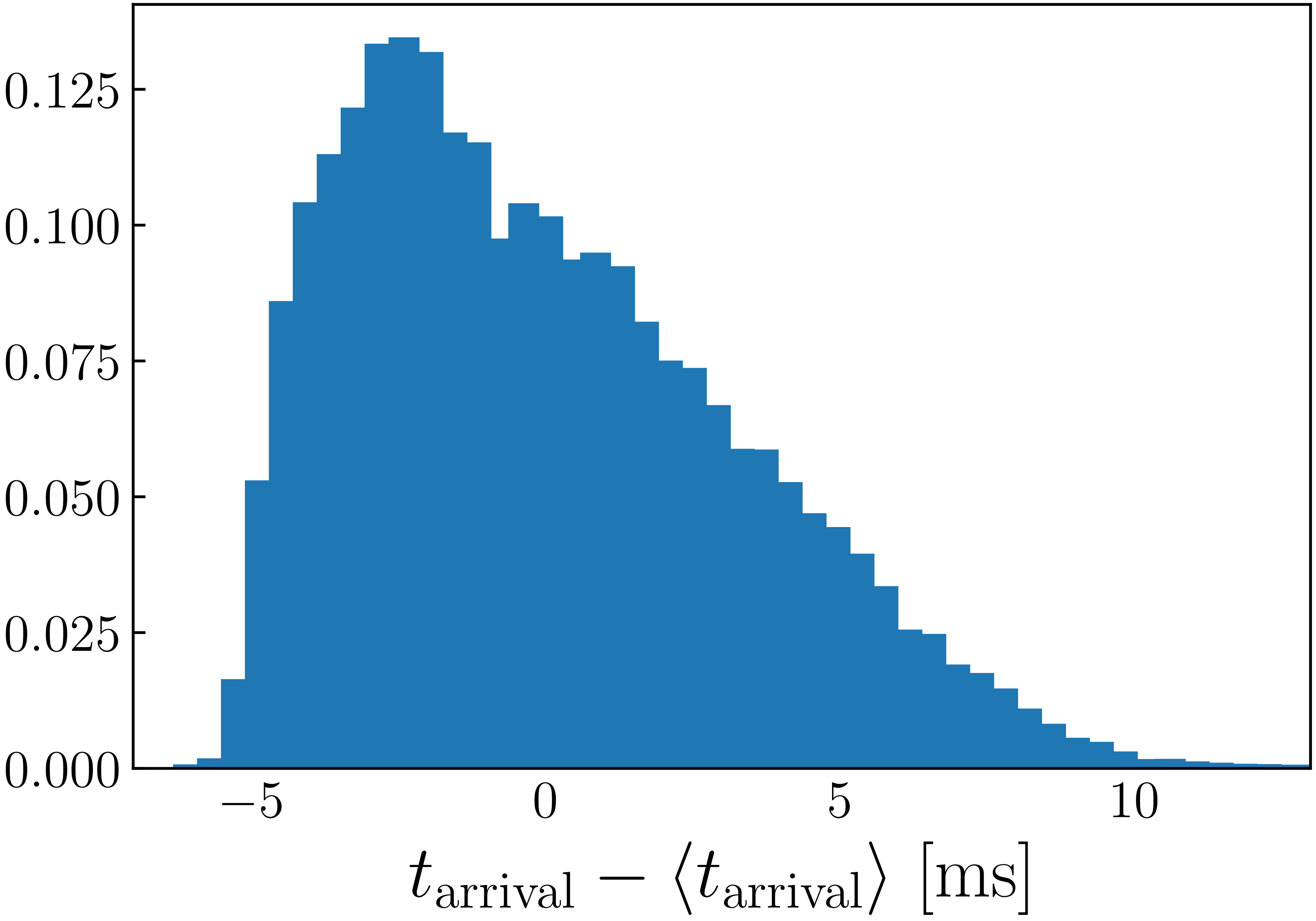
$$n_j = 0,\ 1/2,\ 1$$



Repeated, coherent signals

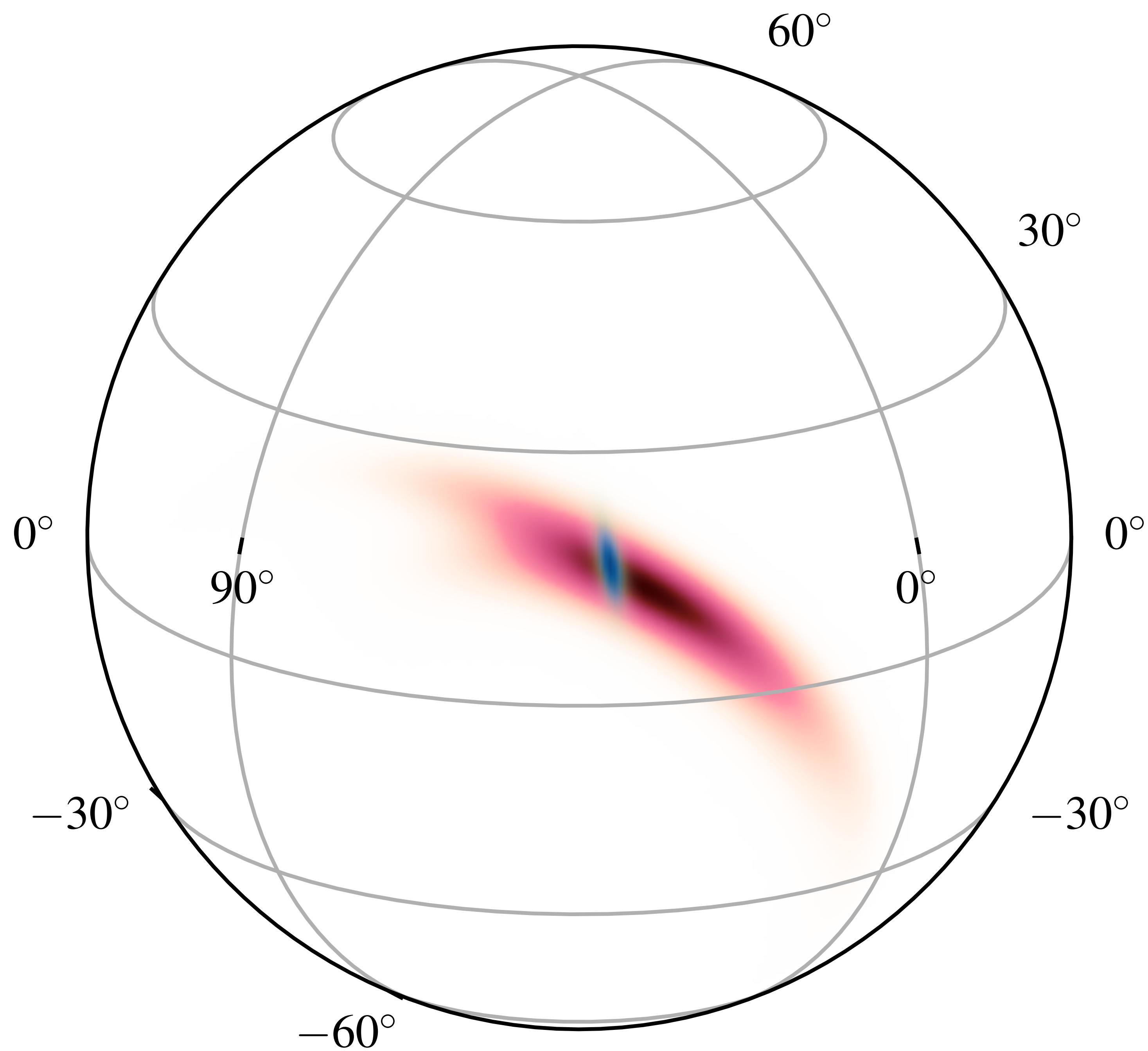


Precise timing



Poor sky localization

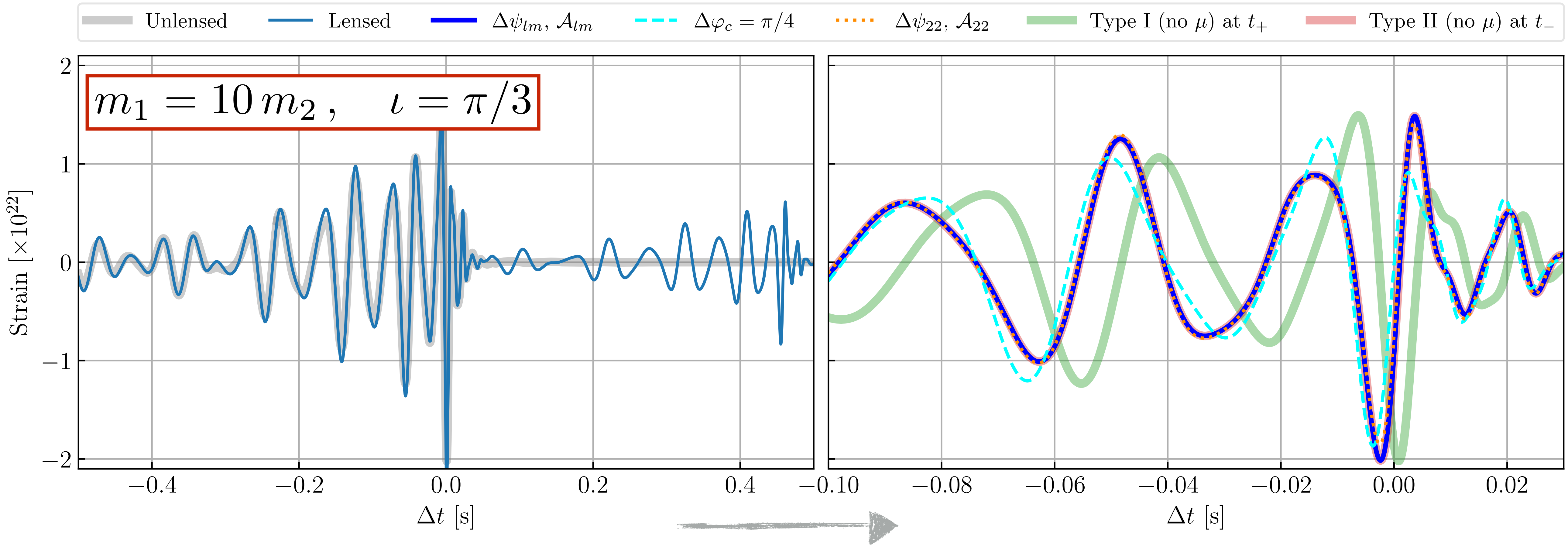
$$\theta_E \sim 1'' \sqrt{\frac{M}{10^{12} M_\odot}} \sqrt{\frac{1\mathrm{Gpc}}{D}}$$



[cf. Wayne's talk!]

Waveform distortions in **type II** images

- Lensing imprints *small* but *characteristic* modifications in the signals that cannot be mapped to other astrophysical parameters



Zoom in the shape of each image

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

Wave optics

$\Delta t_d \cdot \omega$

- Time delay scales with the lens mass

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

[point mass lens]

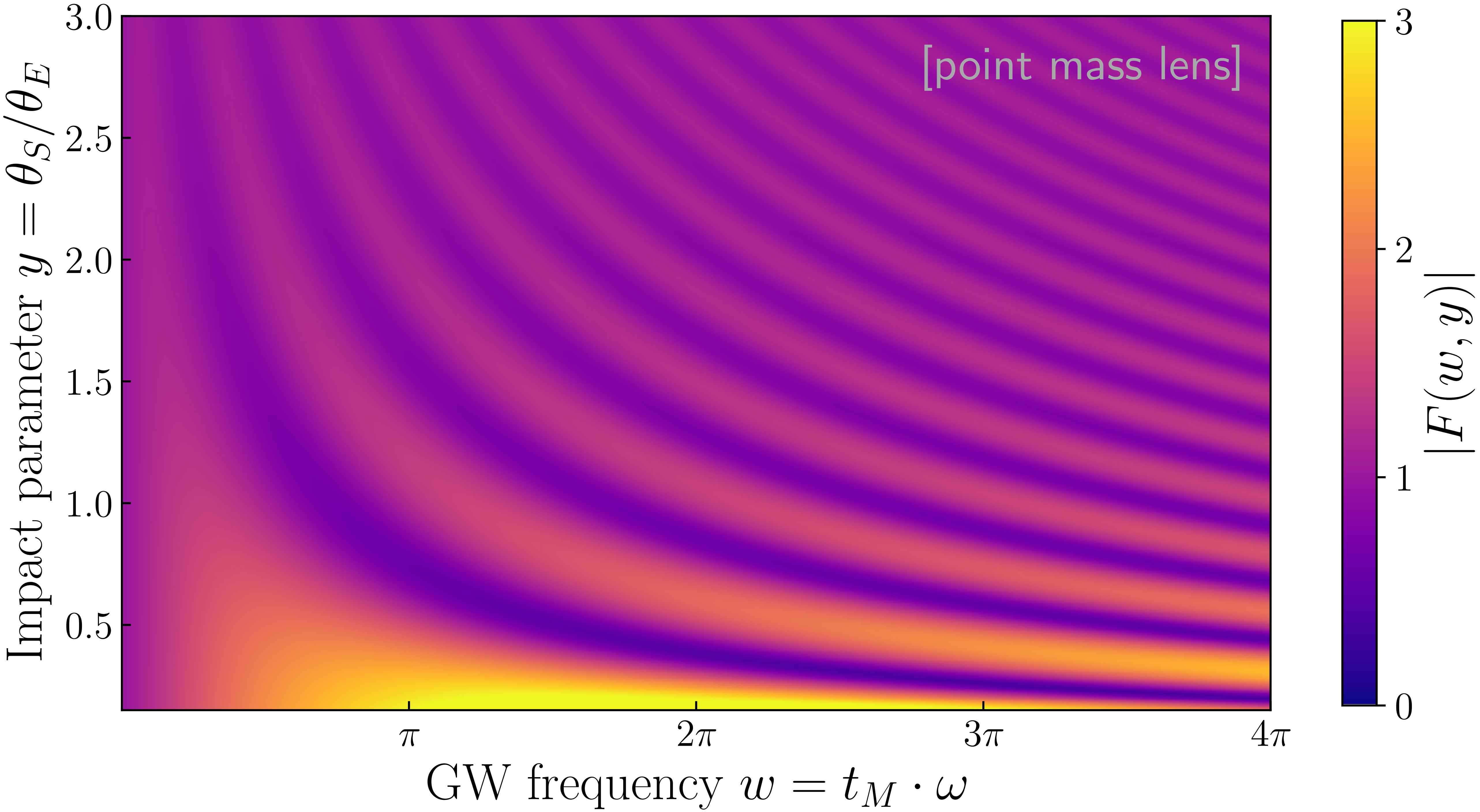
- GW frequency scales with binary mass *(has astrophysical size!)*

$$f \sim \frac{1}{2\pi} \frac{1}{2t_{\rm Sch}} \sim 800\text{Hz} \left(\frac{10 M_\odot}{M} \right)$$

- Wave optics regime: $\Delta t_d \cdot \omega \sim 1$

- Low-frequency limit has small lensing $\omega \to 0 \quad \Rightarrow \quad F \to 1$

Wave optics: **point lens**



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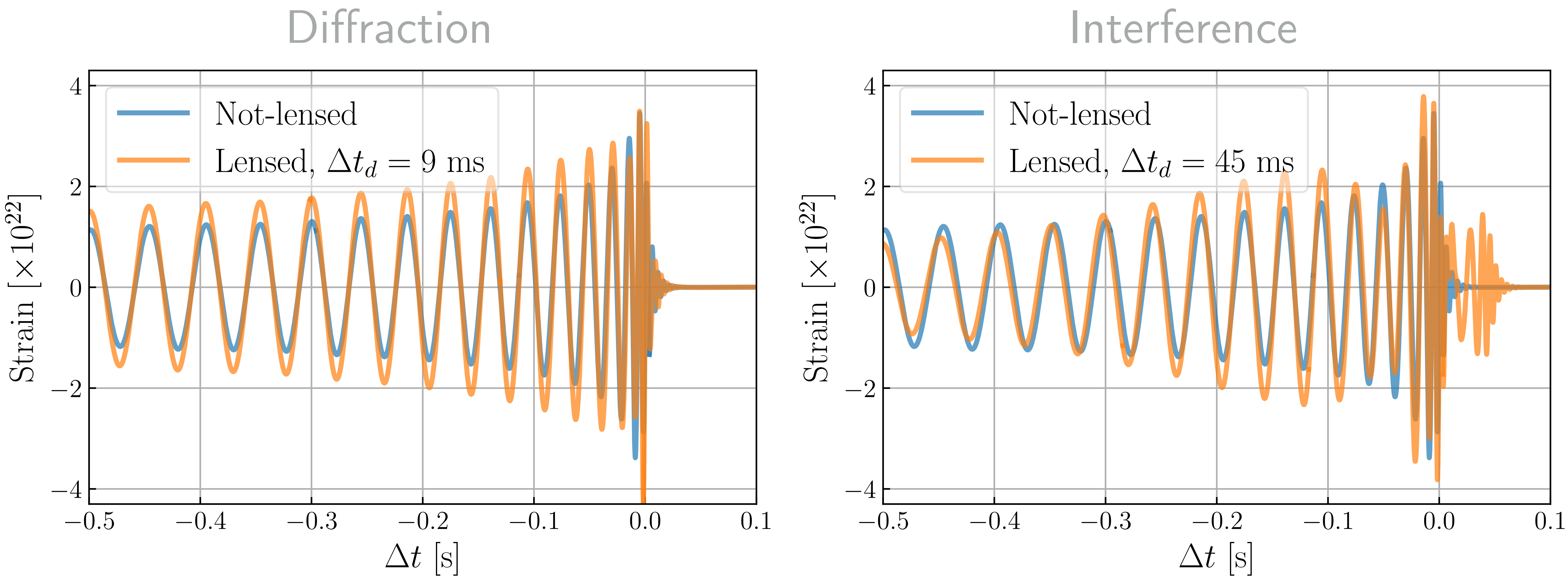


Many recent works: probing compact objects (Dai et al.'18, Diego'19, Tambalo et al.'22, ...), strong lensing + microlensing (Seo et al.'21, Mena et al.'22, ...), breaking mass-sheet degeneracy (Cremonese, Ezquiaga, Salzano'21), solving diffraction integral (Feldbrugge&Turok'20, Tambalo et al.'22) ...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

New **public** codes: https://github.com/miguelzuma/GLoW_public

Caustics

- For point sources, there are singular points in the lens mapping

$$\det\left(\frac{\partial^2 T_d(\theta_j)}{\partial\theta_a\partial\theta_b}\right) \to 0 \quad \Rightarrow \mu(\theta_j) \to \infty$$

- Caustics exhibit *universal* behaviors (described by catastrophe theory)

$$\mu_\pm \sim 1/\sqrt{\Delta\theta_{\rm S}} \sim \Delta t^{-1/3}$$

- SPA is broken when approaching to a caustic
- Maximum magnification set by diffraction

Observational Signatures of Highly Magnified Gravitational Waves from Compact Binary Coalescence

Rico K. L. Lo,* Luka Vujeva, Jose María Ezquiaga, and Juno C. L. Chan
Niels Bohr International Academy, Niels Bohr Institute,
Blegdamsvej 17, DK-2100 Copenhagen, Denmark
(Dated: July 26, 2024)

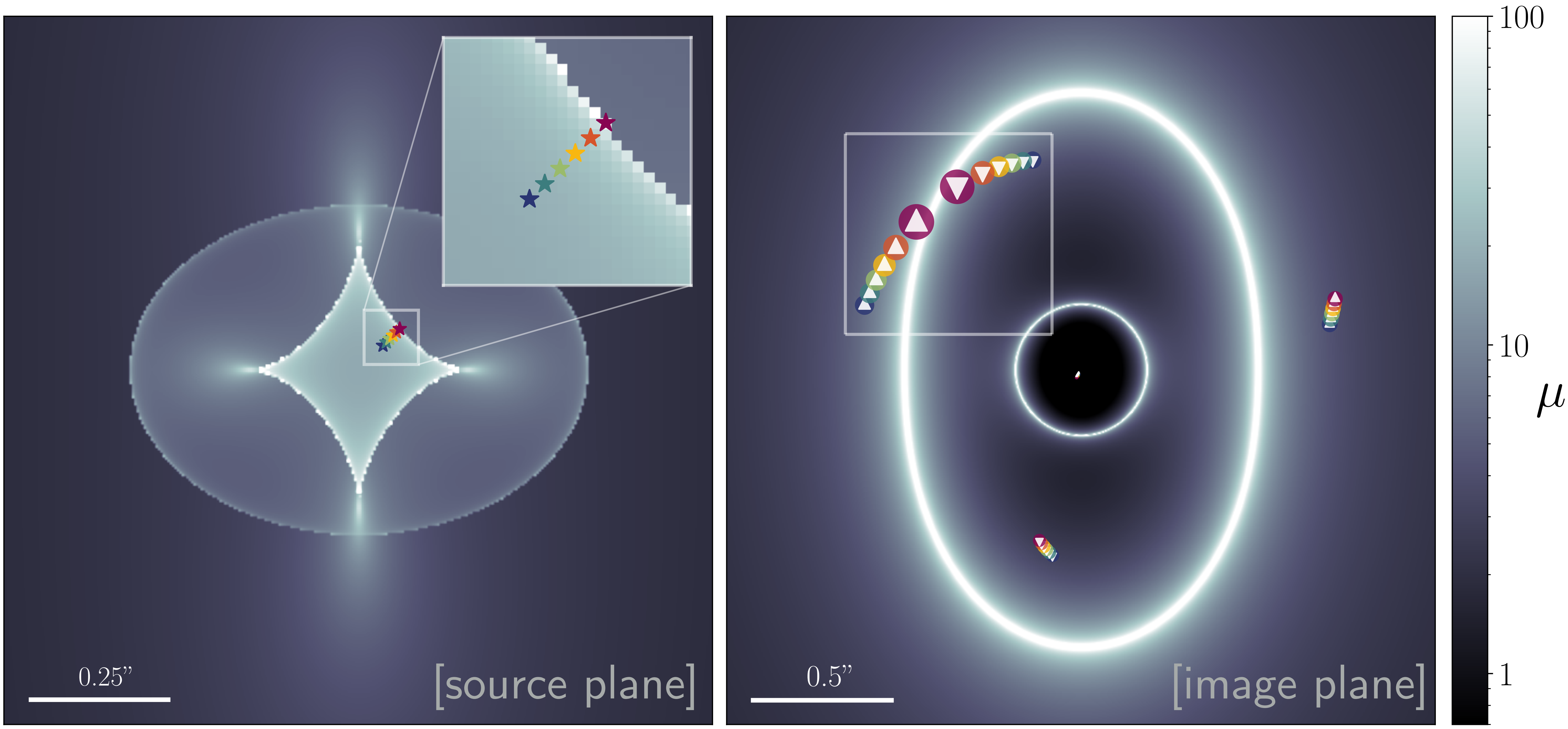
Gravitational lensing has empowered telescopes to discover astronomical objects that are otherwise out of reach without being highly magnified by foreground structures. While we expect gravitational waves (GWs) from compact binary coalescences to also experience lensing, the phenomenology of highly magnified GWs has not been fully exploited. In this letter, we fill this gap and explore the observational signatures of these highly magnified GWs. We find that these signatures are robust against modeling details and can be used as smoking-gun evidence to confirm the detection of lensing of GWs without any electromagnetic observation. Additionally, diffraction becomes important in some cases, which limits the maximum possible magnification and gives waveform signatures of lensing that can only be observed by GW detectors. Even with current-generation observatories, we are already sensitive to these highly magnified GWs and can use them to probe the high-redshift Universe beyond the usual horizon.

Rico Lo

Luka Vujeva

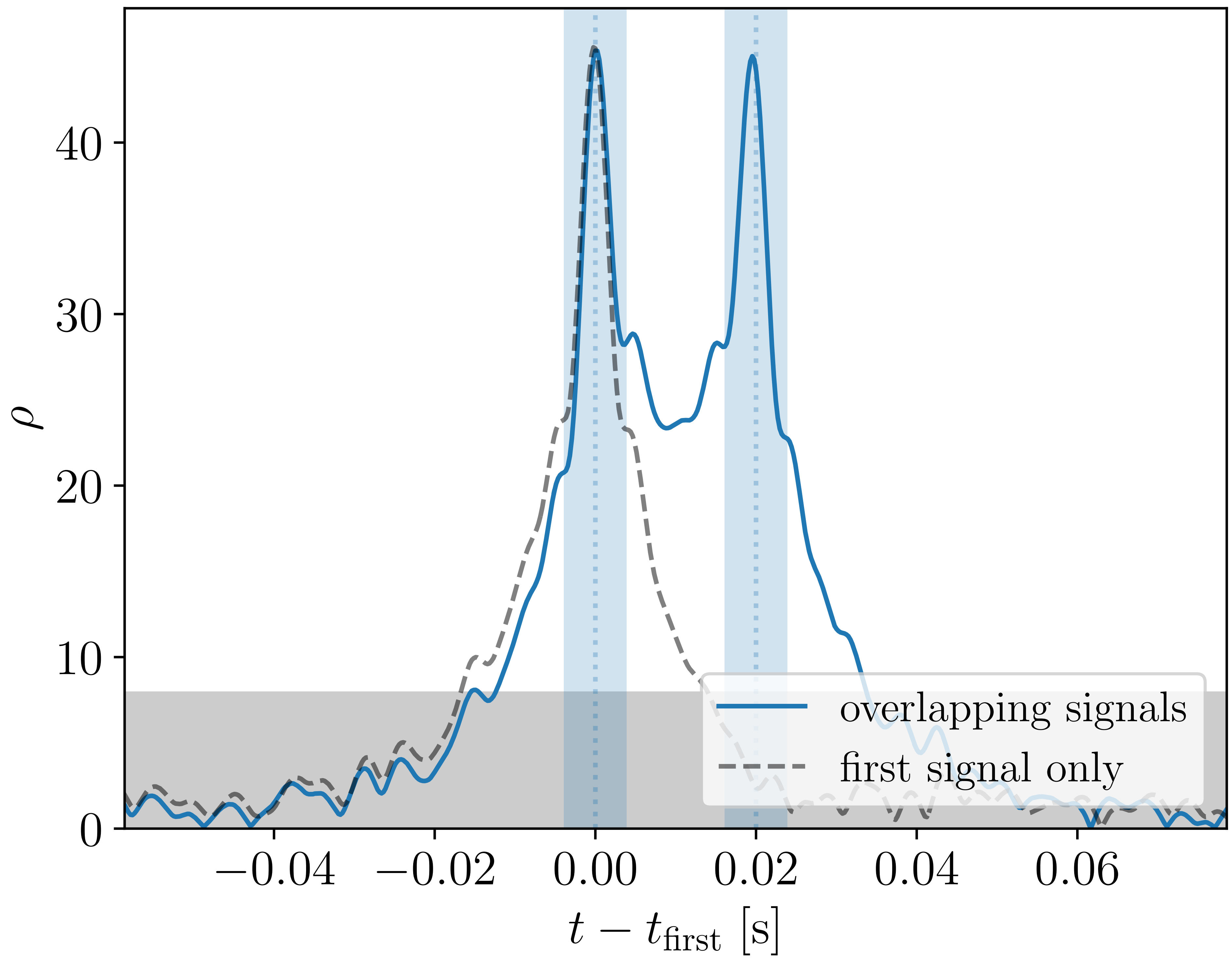
[Lo, Vujeva, **Ezquiaga**, Chan, arXiv 2407.17547]

Fold caustics around galaxies

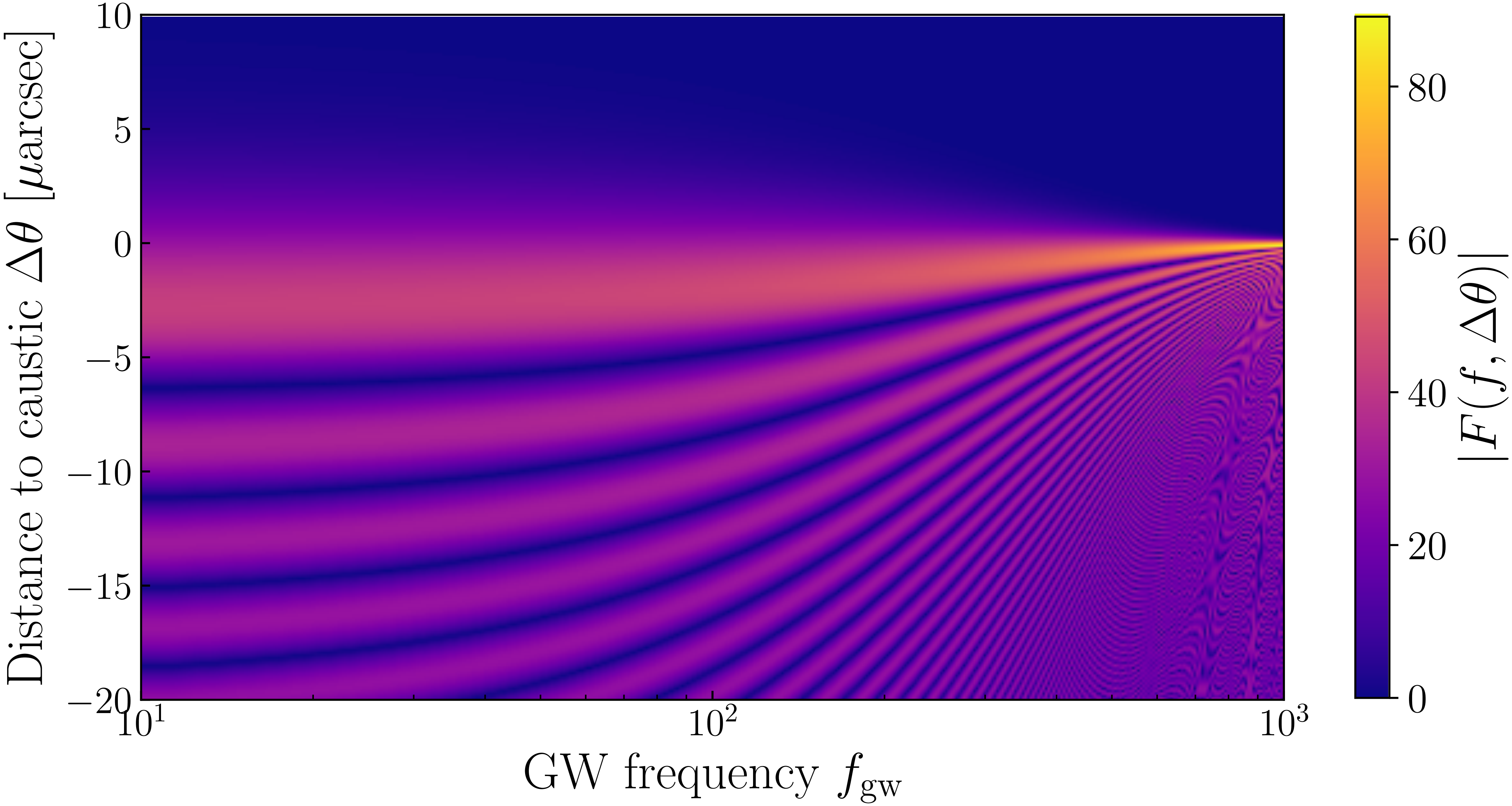


[galaxy lens with a cored singular isothermal ellipsoid density profile]

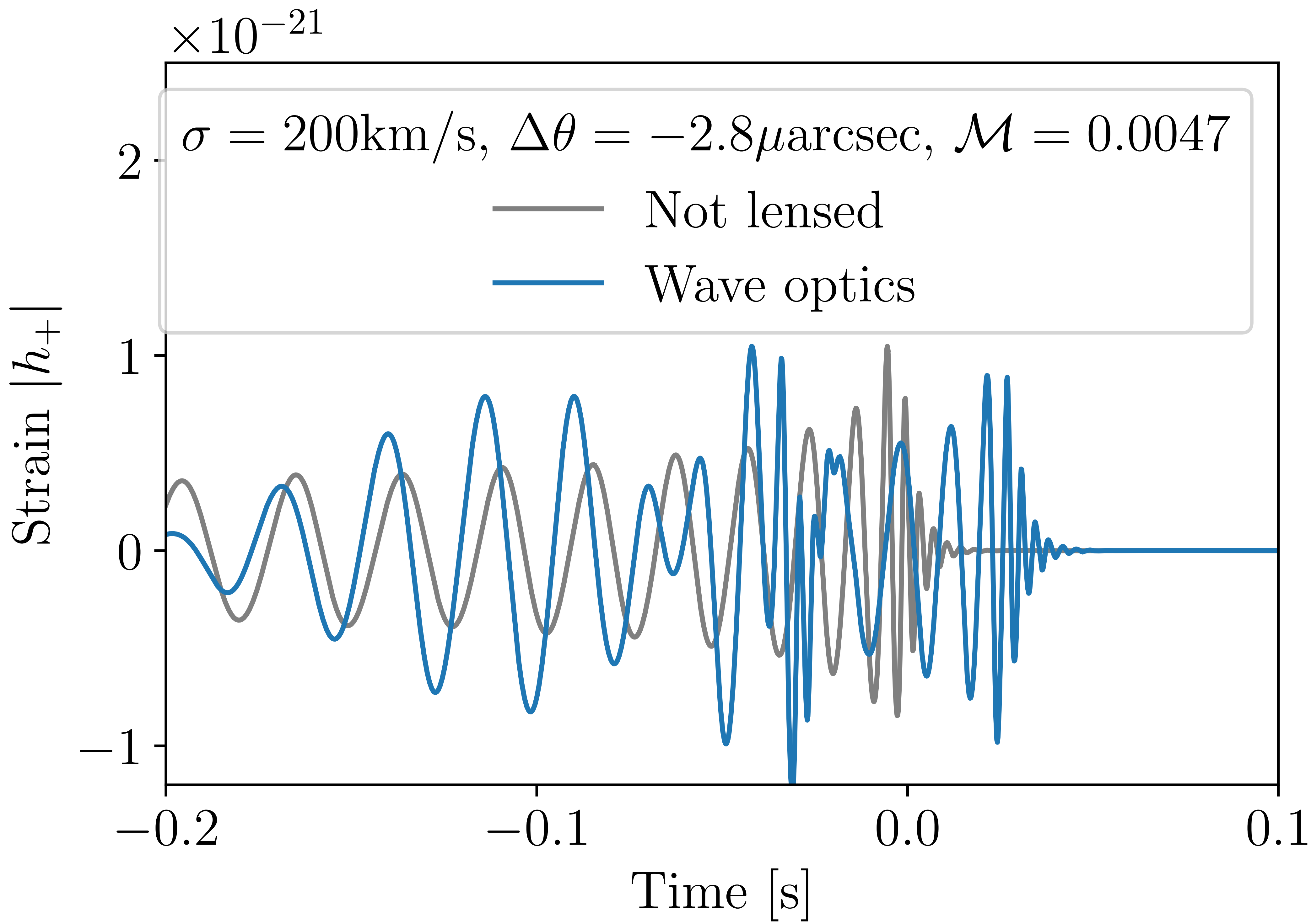
Overlapping signals



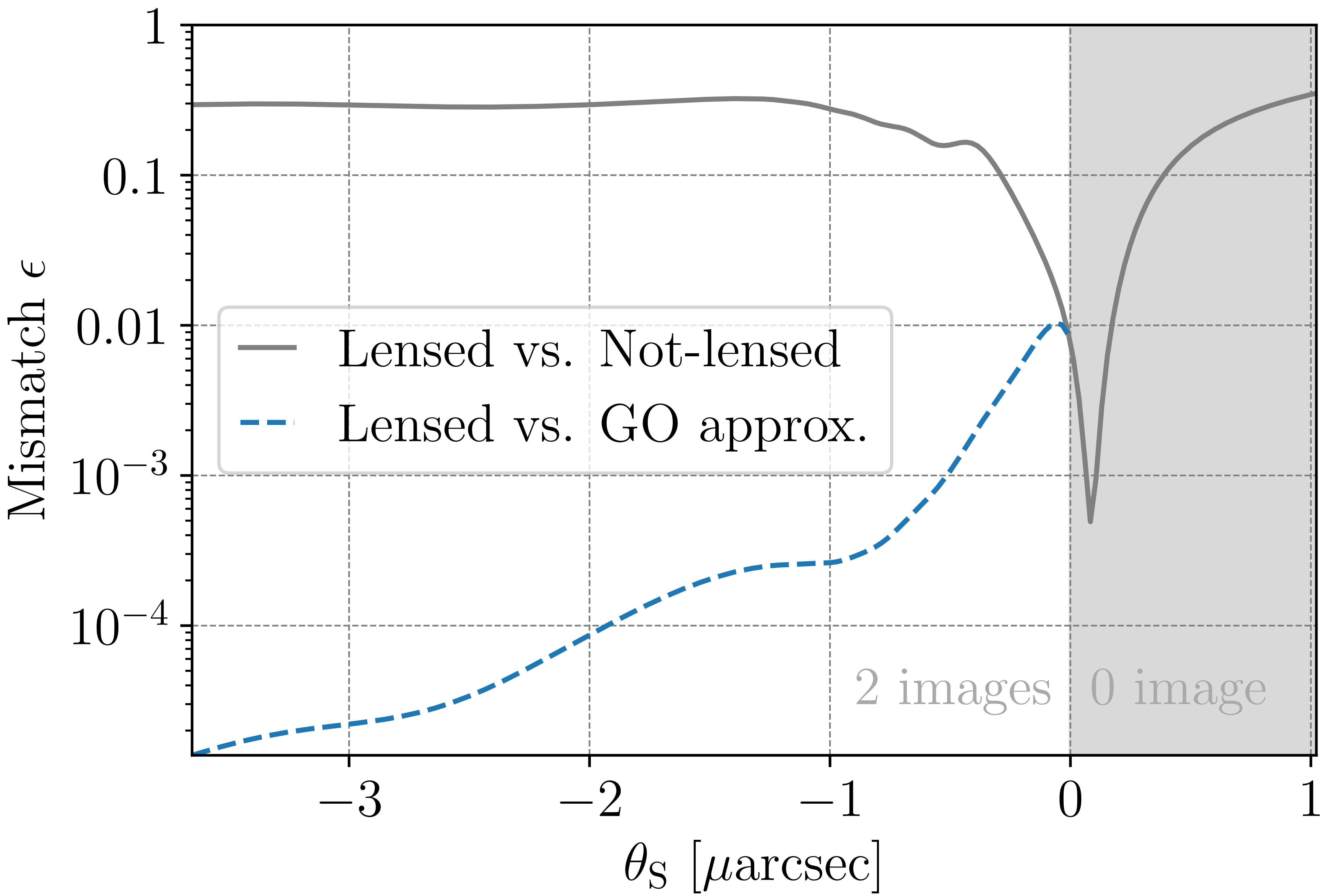
Diffraction around fold caustics



Waveform distortions

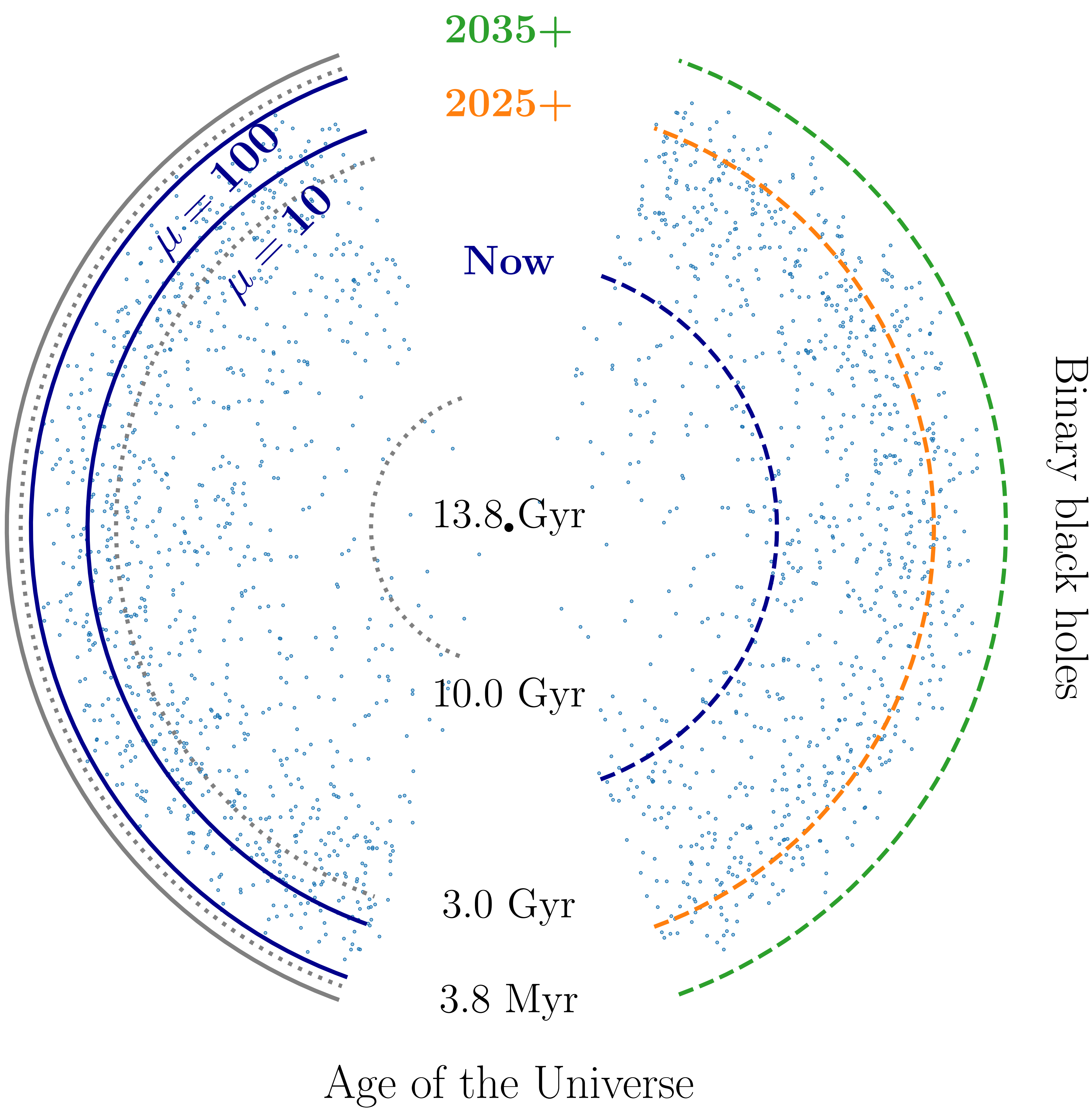


Observing GW diffraction



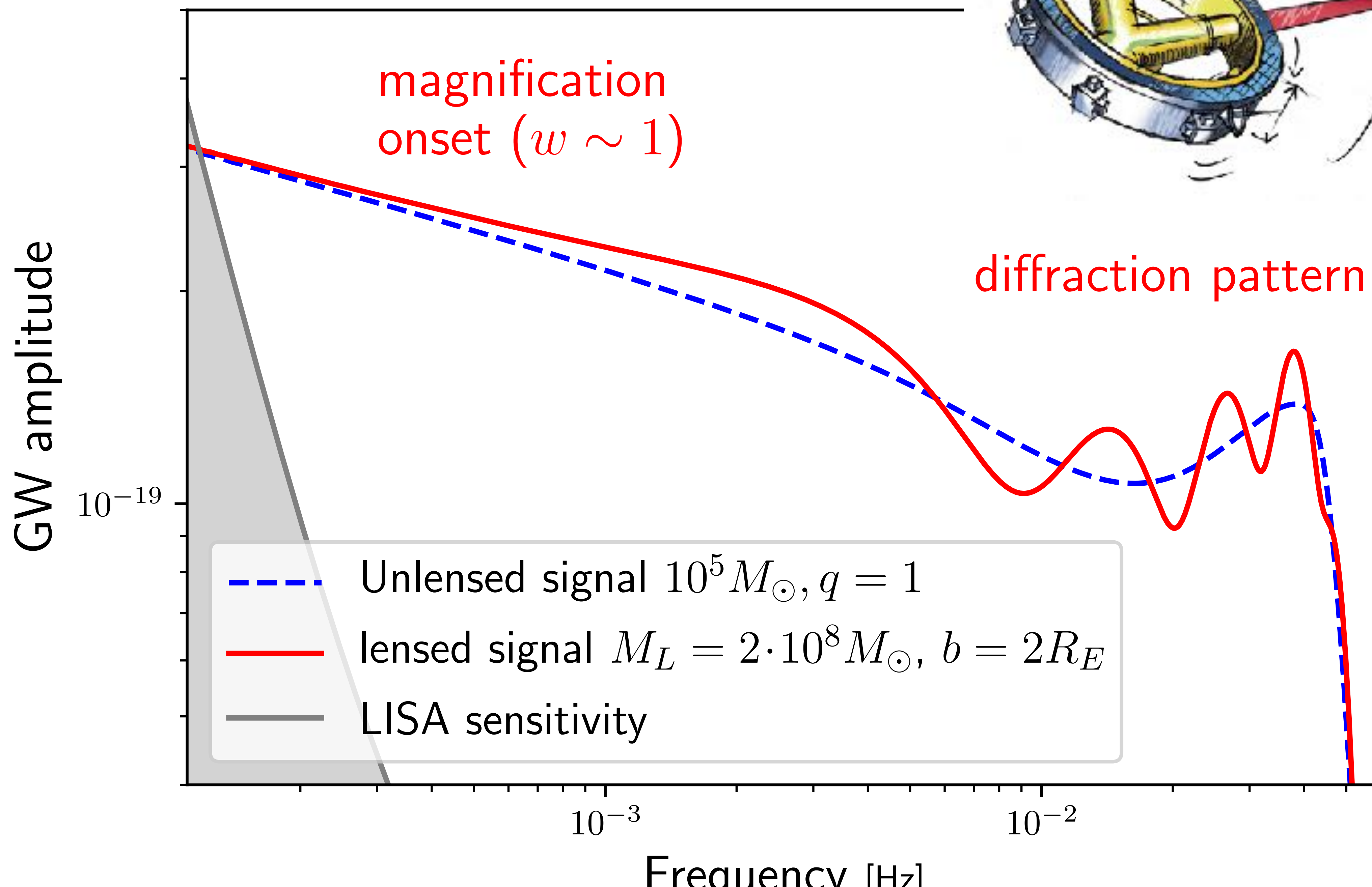
Gravitational Wave horizons

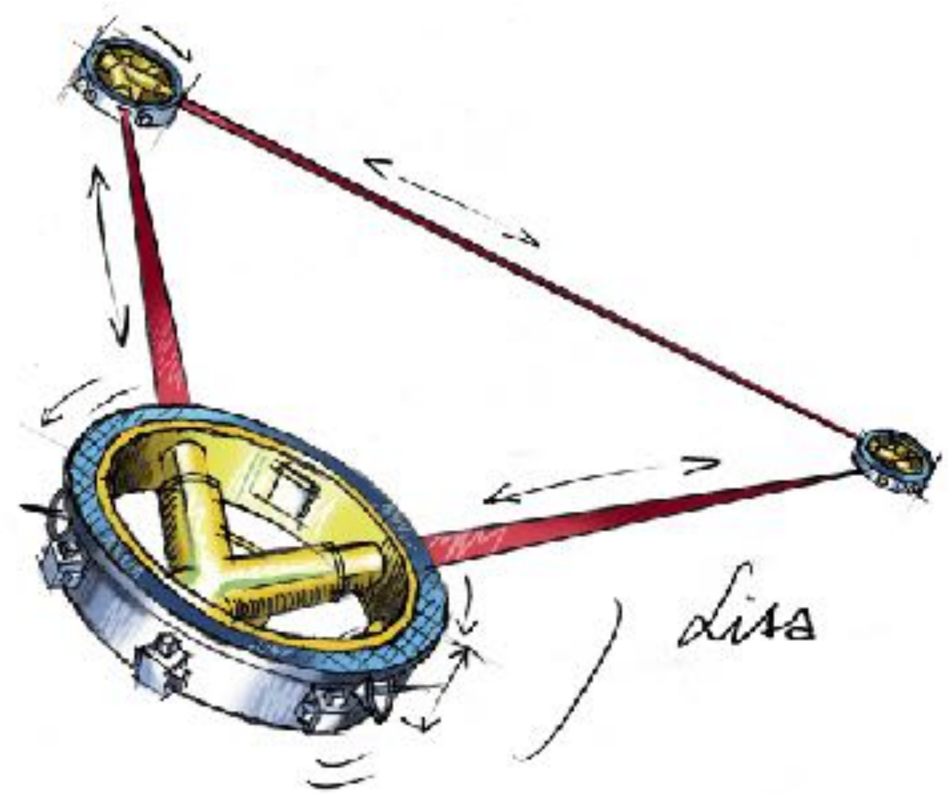
[a shortcut to next-generation detectors]



*stellar mass binary black holes

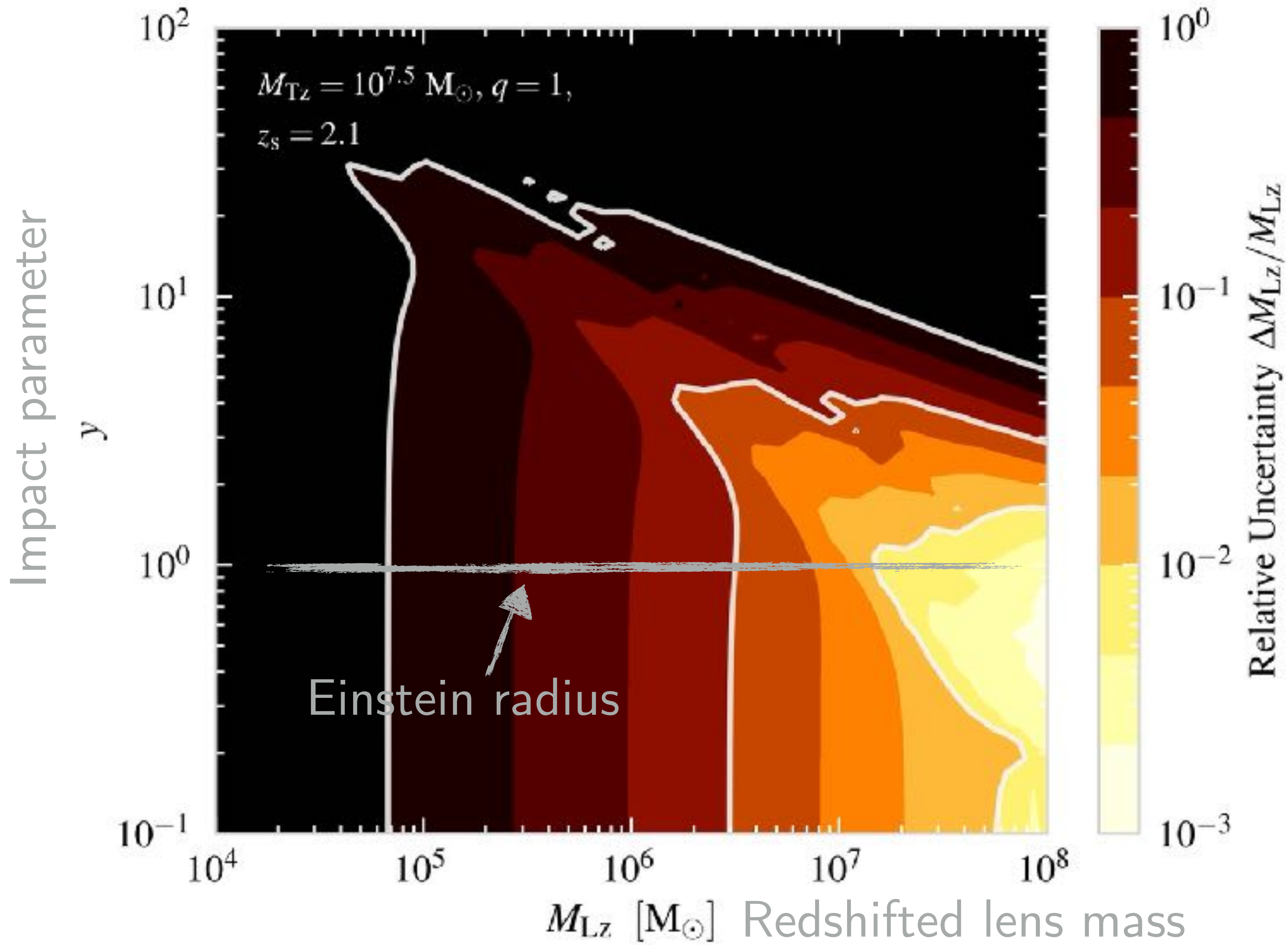
Wave effects: **LISA**





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

Increased optical depth in wave optics

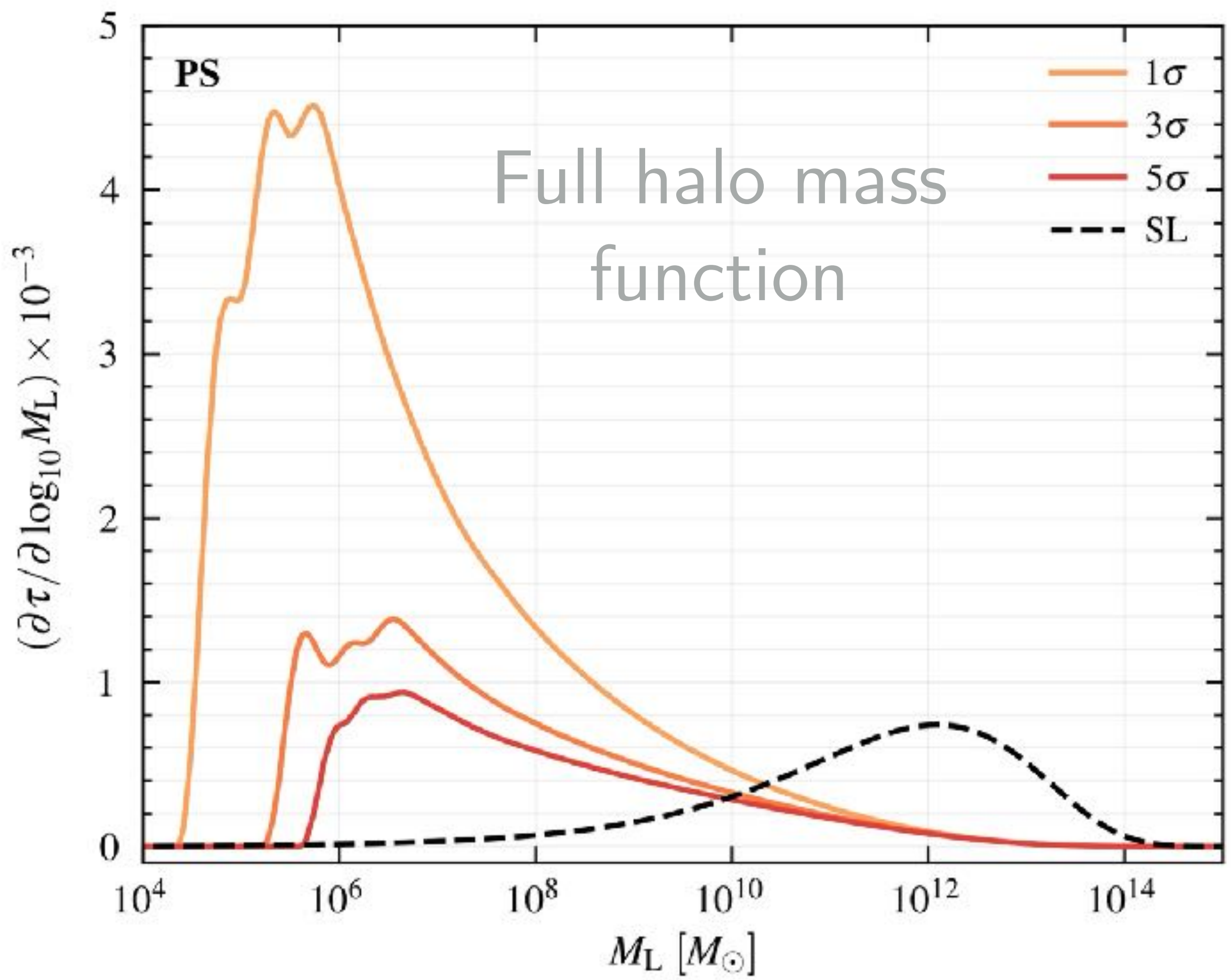


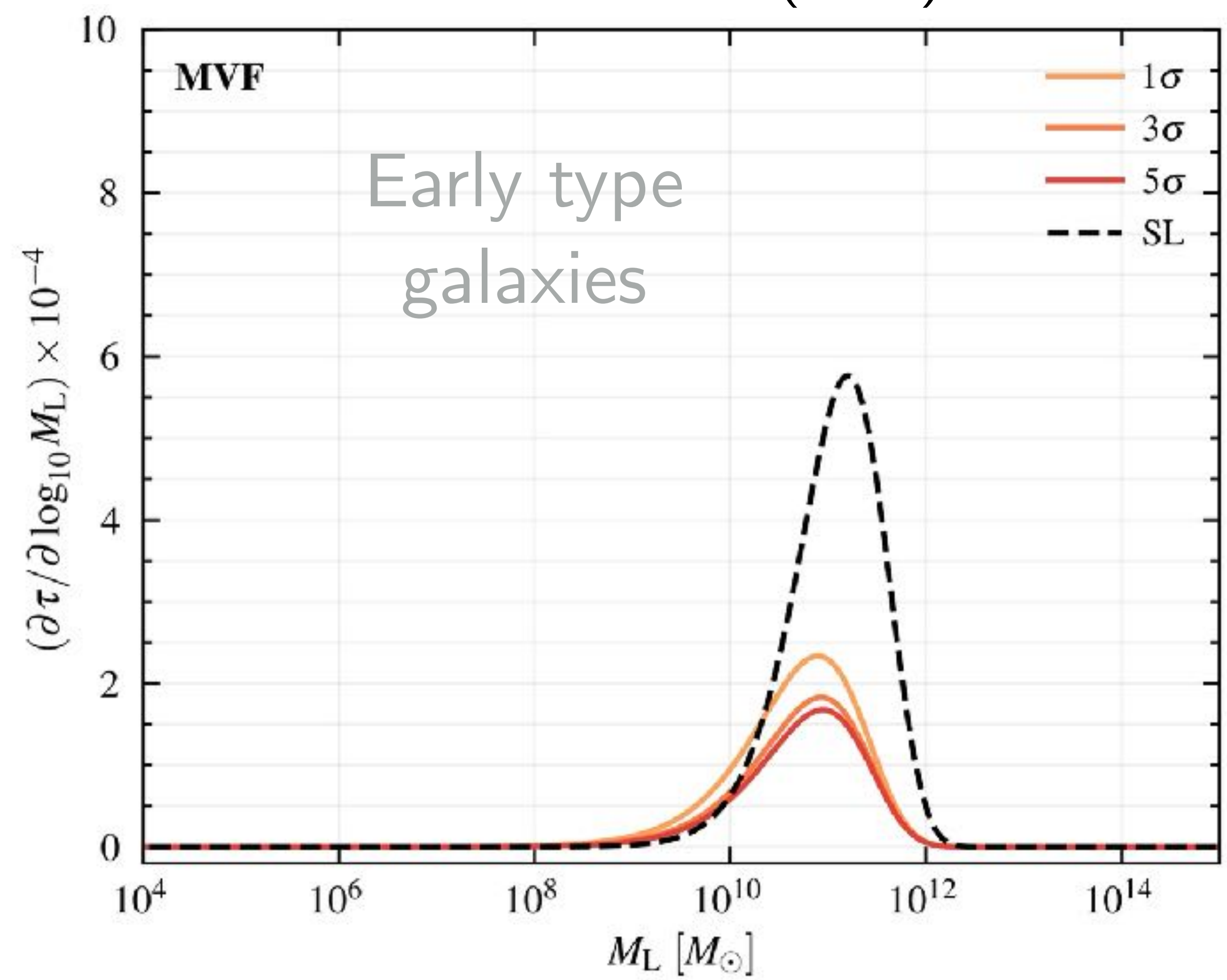
Çalışkan *et al.* (incl. **Ezquiaga**) (PRD, arXiv 2307.06990)

Probing low-mass dark matter halos

Mesut Çalışkan (JHU)

- Probability of wave optics lensing: few percent and larger than strong lensing





Çalışkan *et al.* (incl. **Ezquiaga**) (PRD, arXiv 2307.06990)

Conclusions

Binary black holes are precious cosmological probes:

1. H_0 (also) with **dark sirens**
2. Expansion rate at high redshift $H(z)$ with **spectral sirens**
3. Probing inhomogeneous Universe via **lensing**
4. Highly magnified GWs have **unique** observational signature
5. Probing low-mass halos with **LISA** binaries

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