A premier on gravitational wave lensing

[O'Keeffe, 1965]

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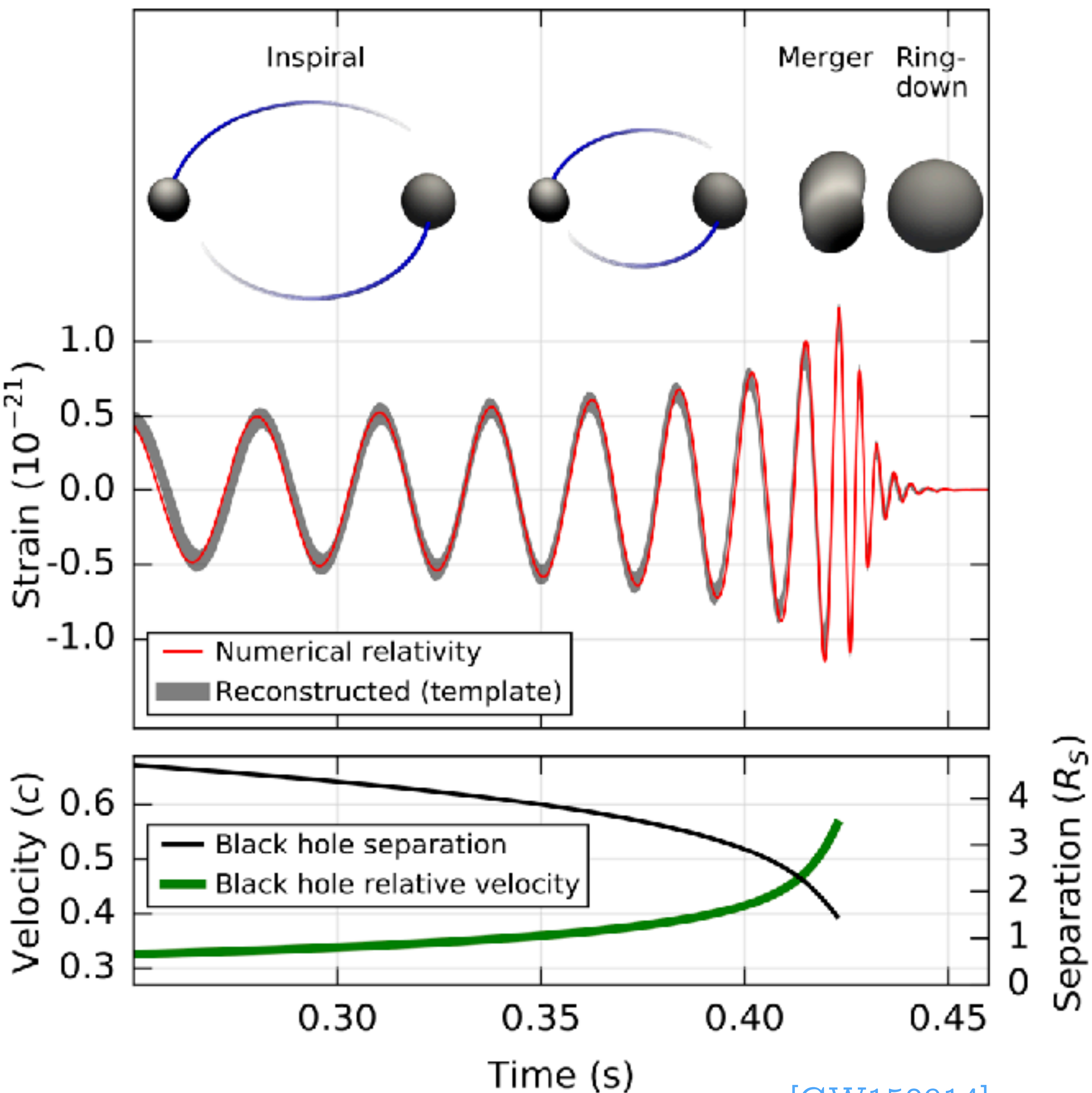
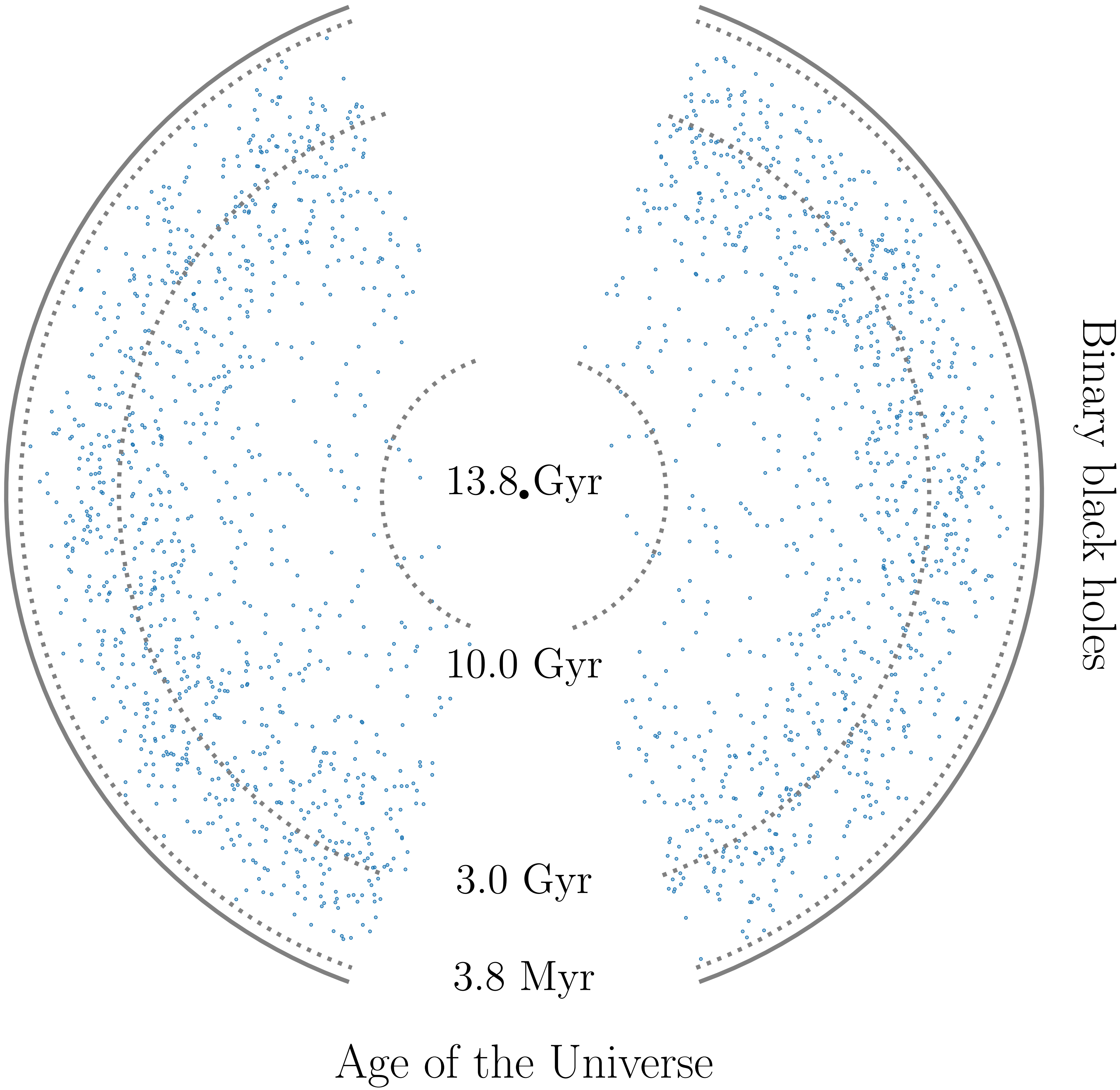
ezquiaga.github.io

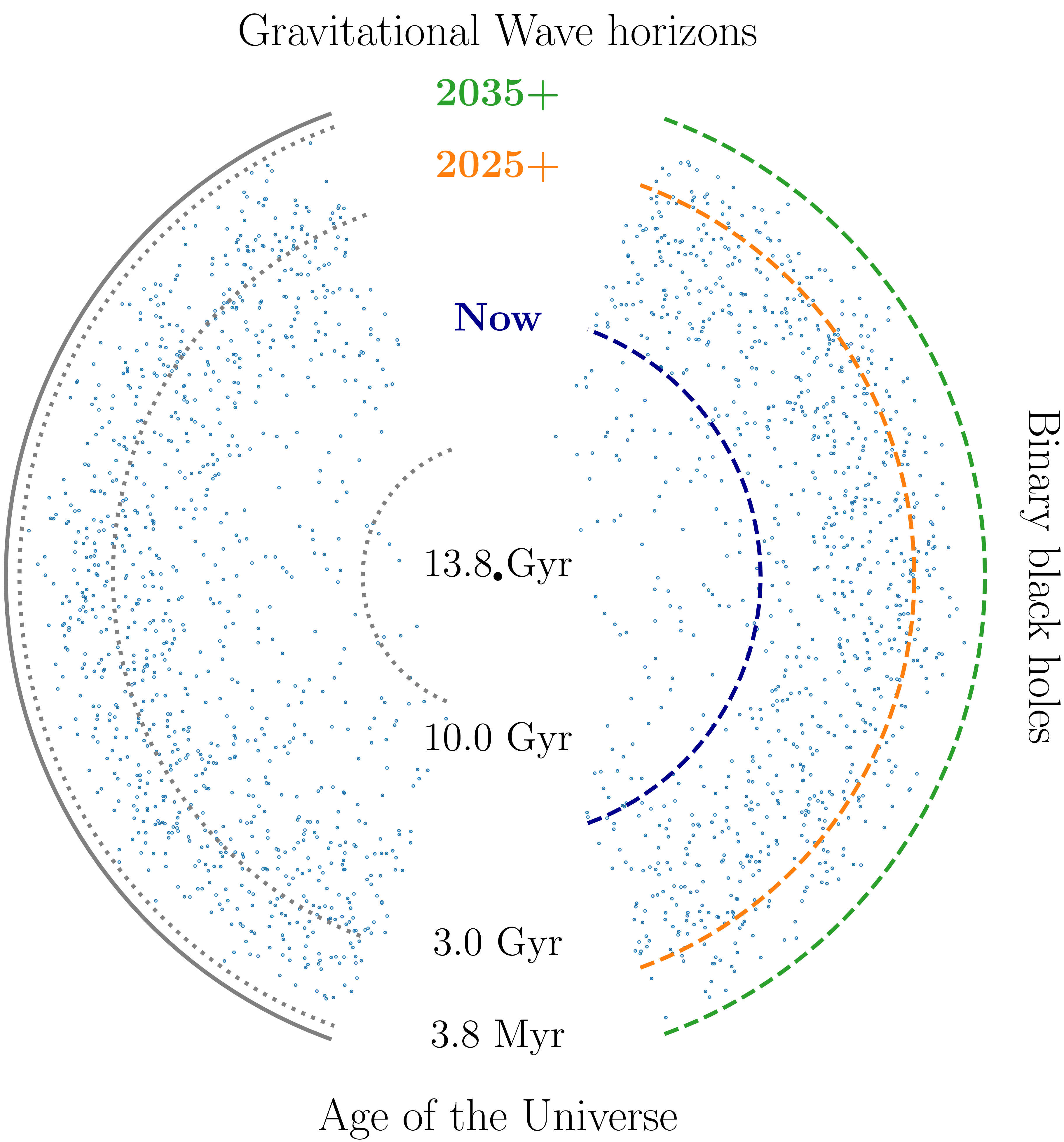
VILLUM FONDEN

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]

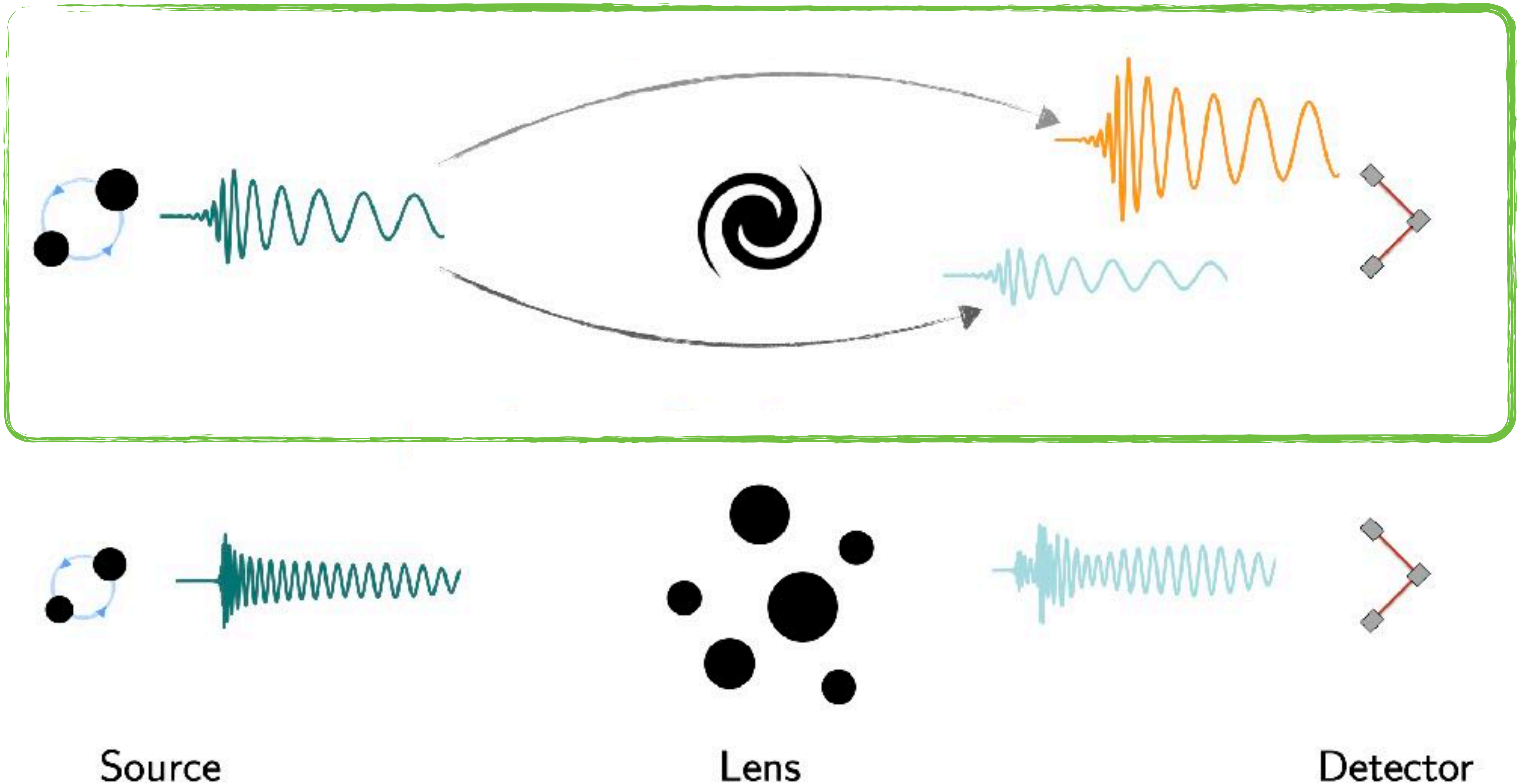

13.8 Gyr
10.0 Gyr
3.0 Gyr
3.8 Myr
Binary black holes
Age of the Universe


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

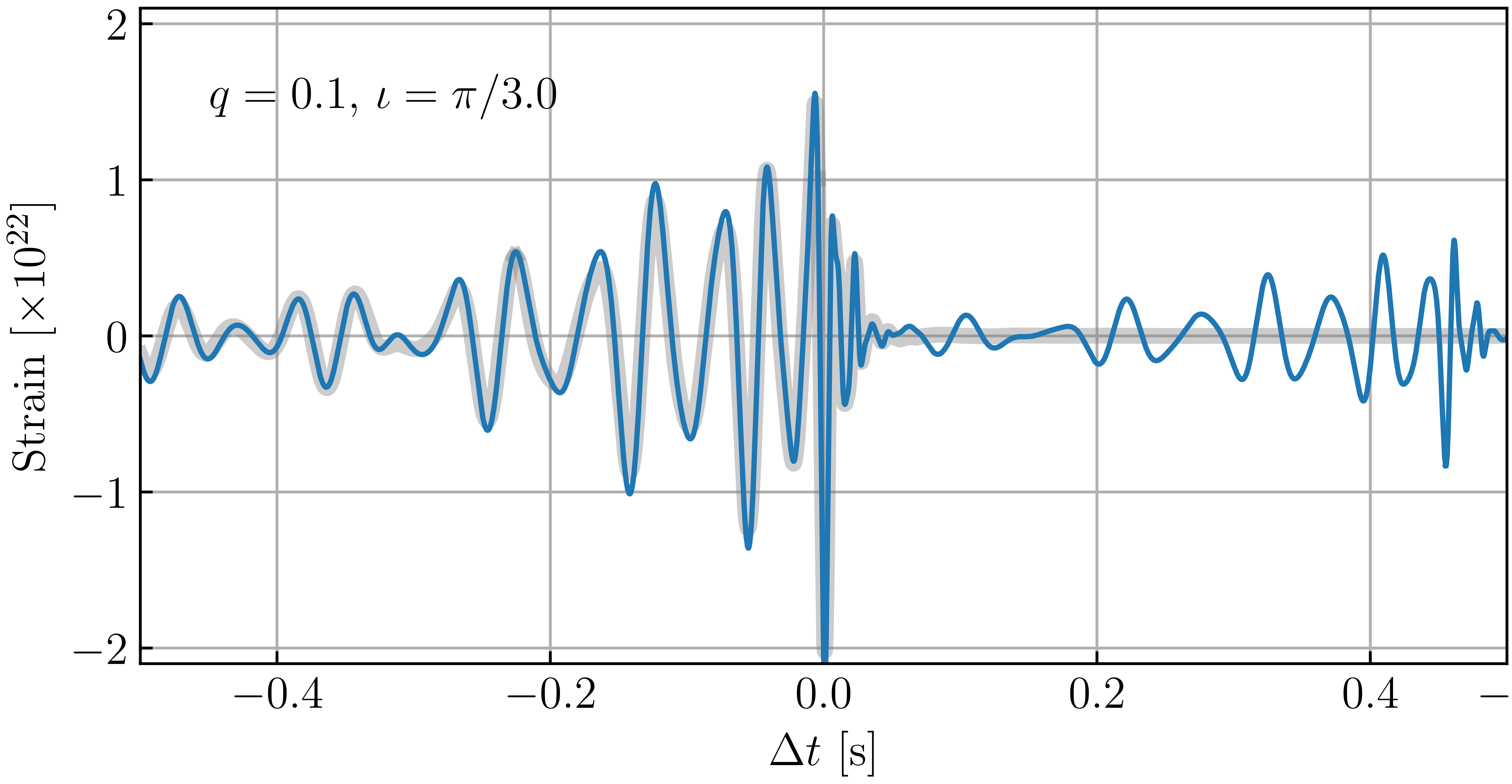
Gravitational waves

- **Signals from first principles:** *general relativity* predicts the waveform of a compact binary coalescence
- **Well understood selection effects:** signals can be injected in real noise
- **Powerful population studies:** all sky coverage up to cosmological distances, not affected by medium
- **Wavelengths of astrophysical scale:** frequency from the orbital motion

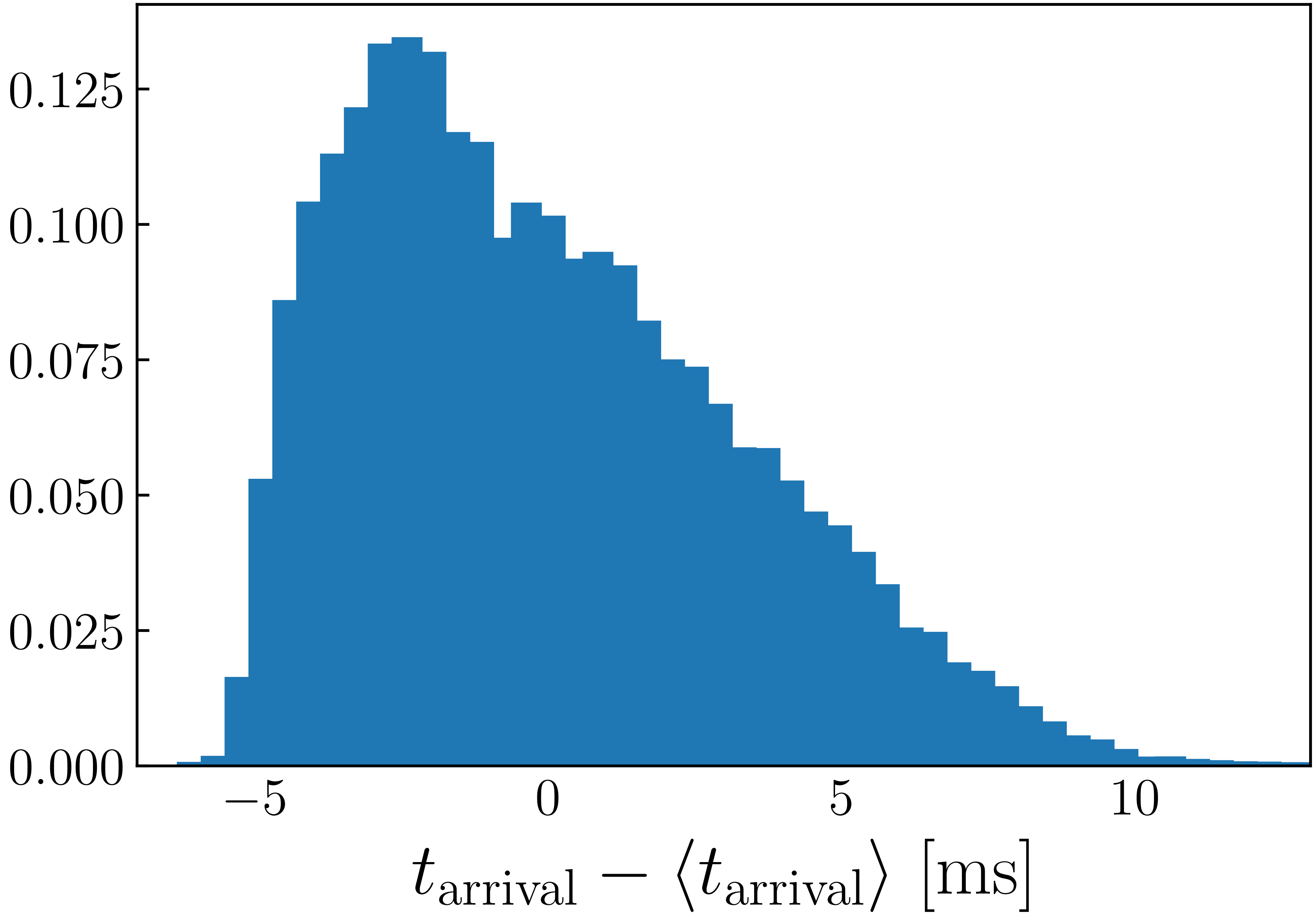
What lensing?



Repeated signals

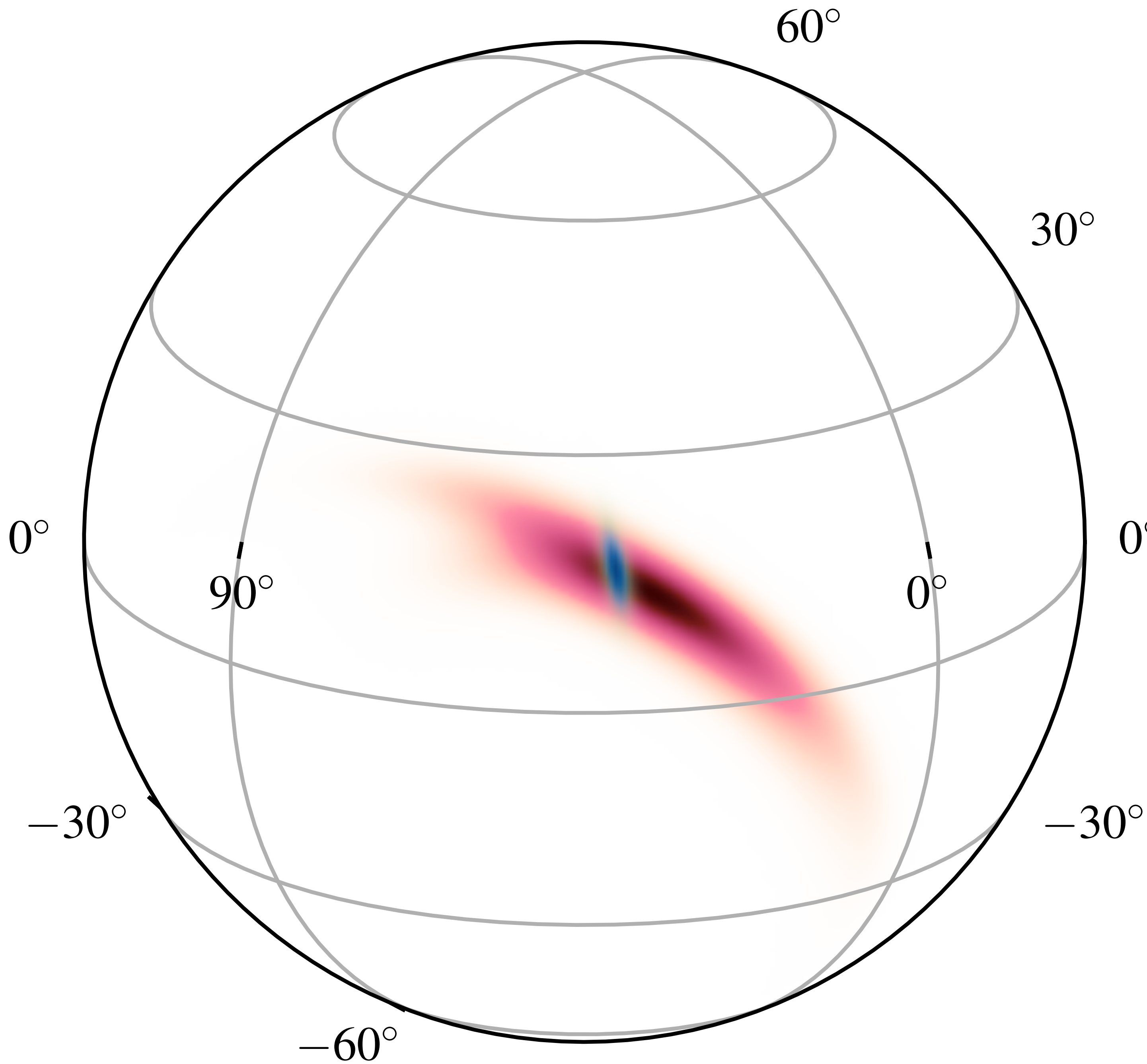


Precise timing



Poor sky localization

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



Gravitational lensing of gravitational waves

- Repeated signals
- Precise timing
- Poor sky localization
- Coherent detection of waveform

Strong lensing

$$\boxed{\Delta t_d \cdot \omega \gg 1}$$

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

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

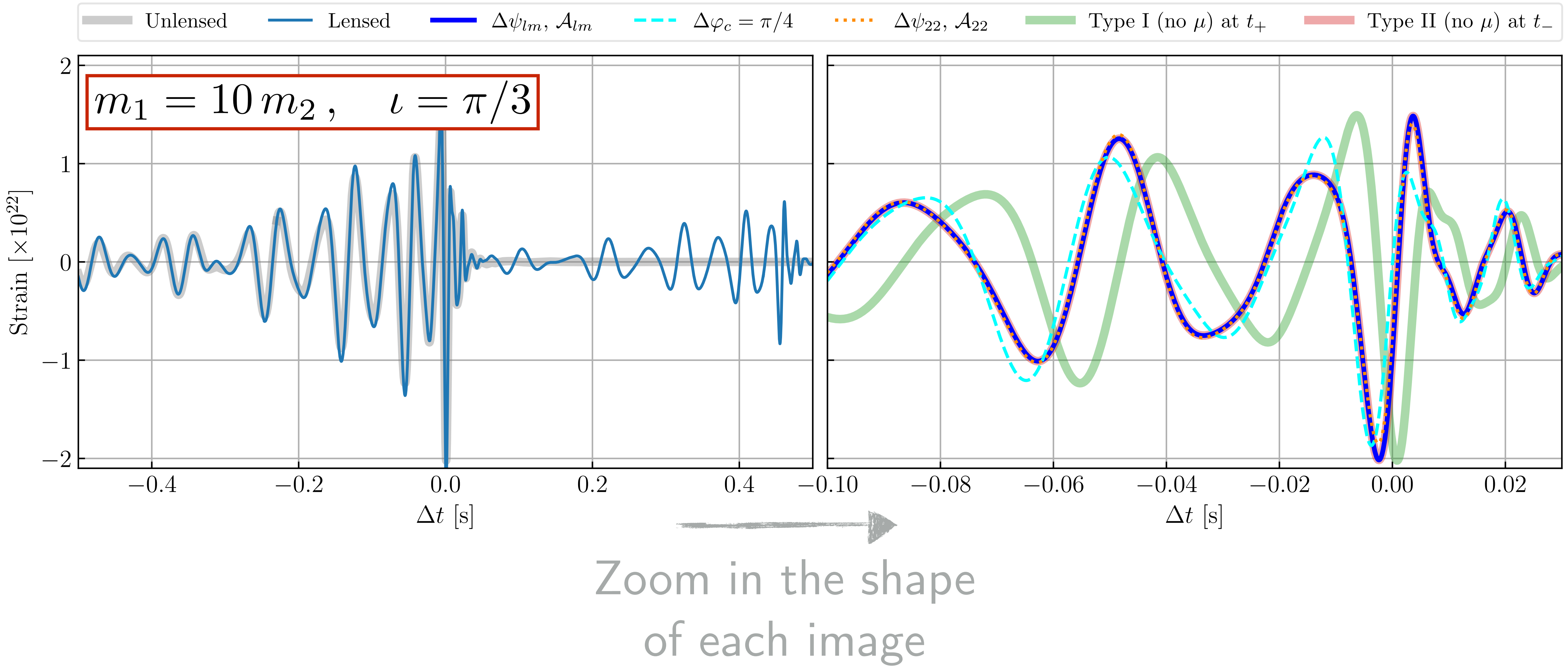
Magnification
Time delay
Phase shift

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

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

Waveform distortions in **type II** images

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



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

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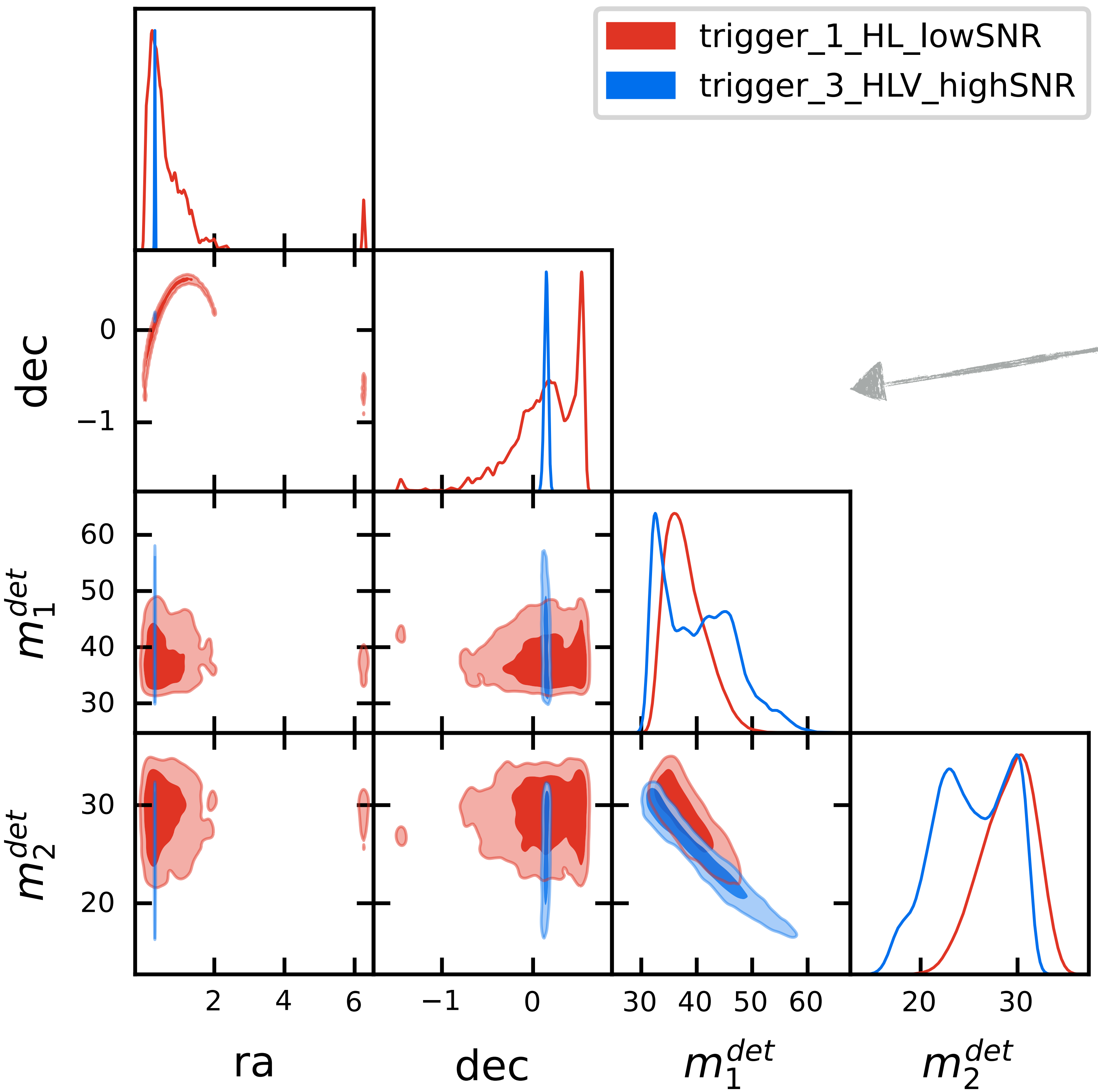
$$n_j = 0,\ 1/2,\ 1$$

- 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)

Searching for strongly lensed GWs



Look for events with similar properties: masses, sky positions, spins...

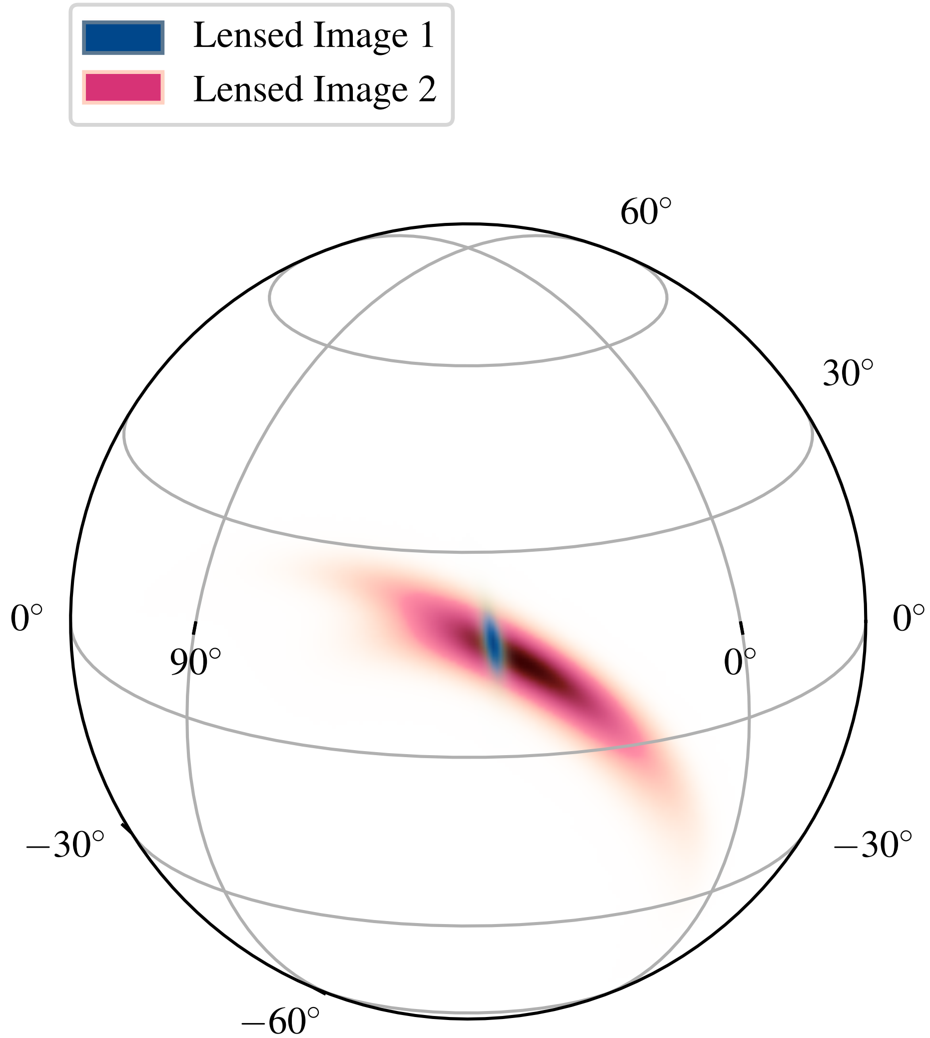
+

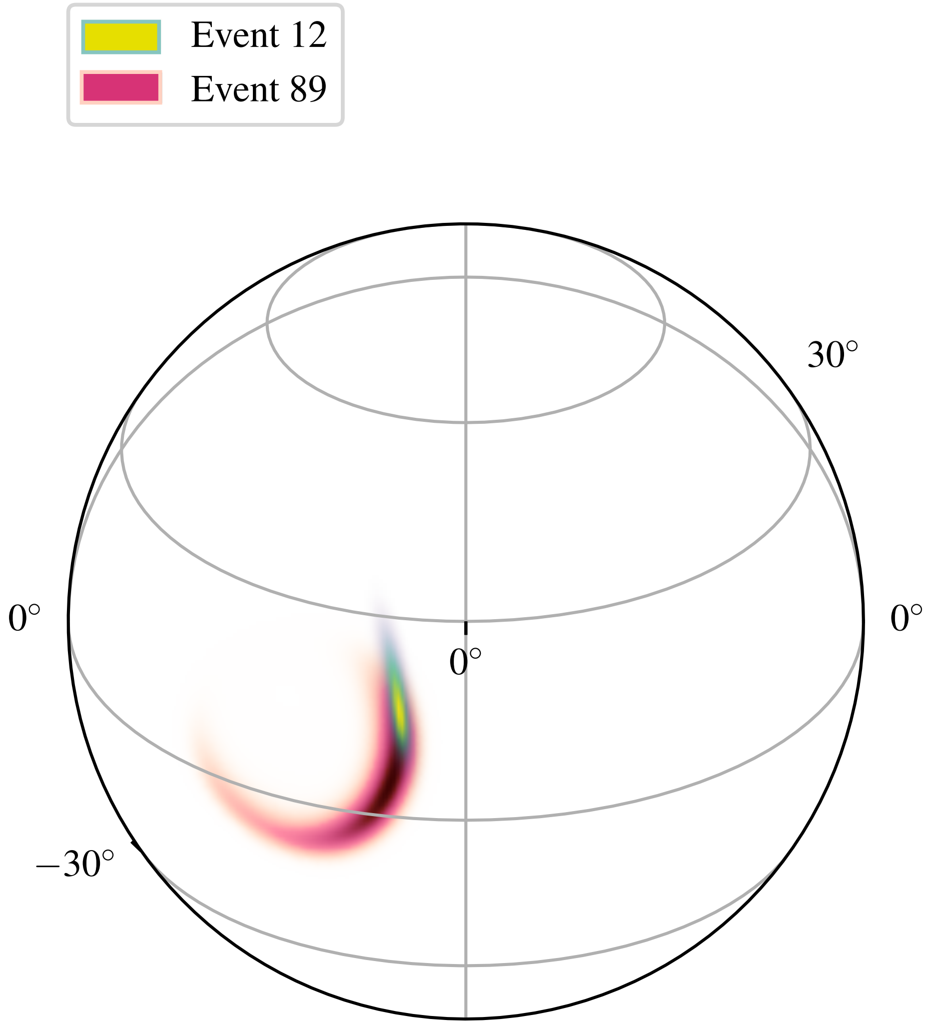
Joint parameter estimation

Lensing or luck?

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

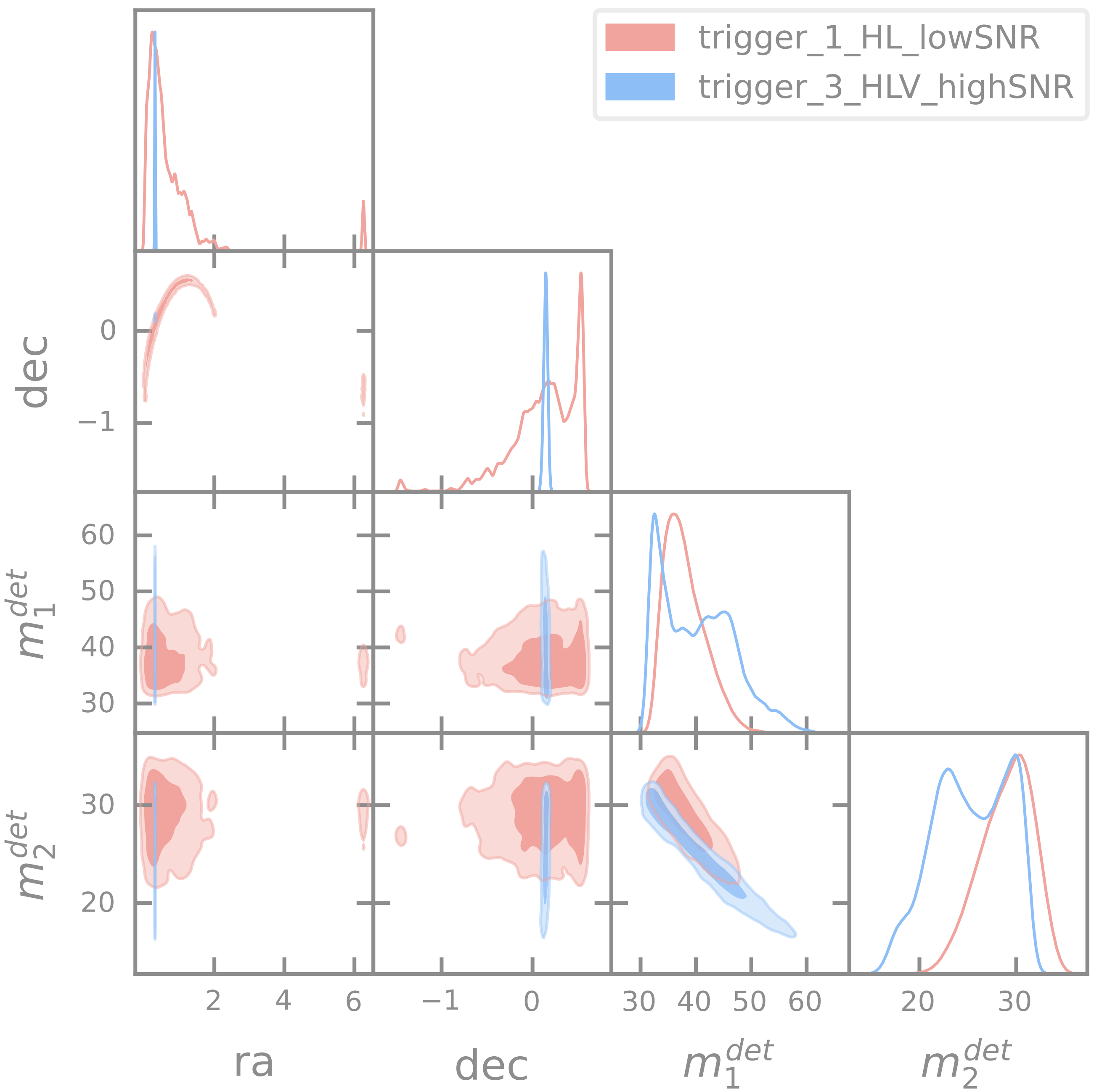
Mesut Çalışkan (JHU)

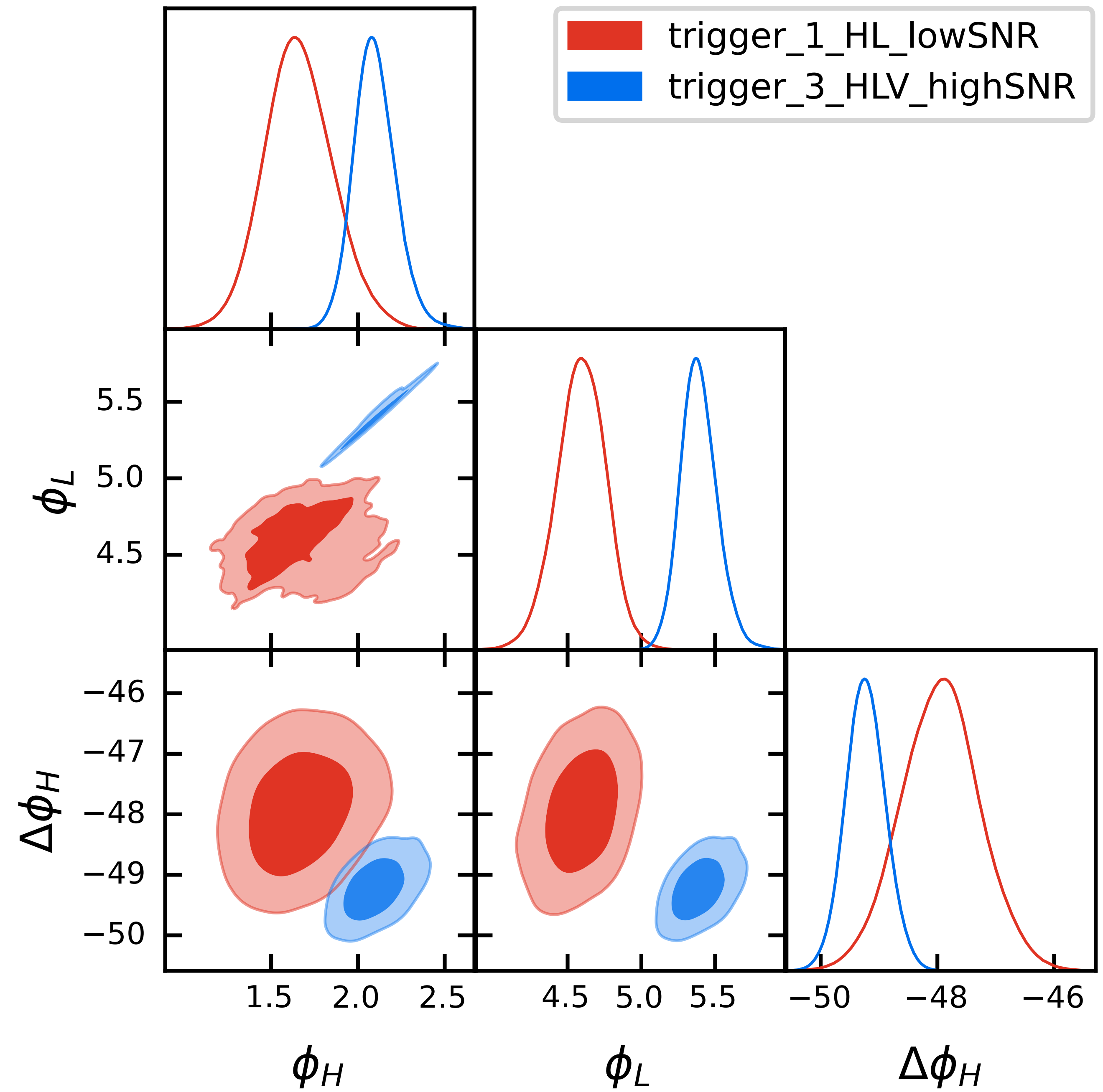




Çalışkan, **Ezquiaga**, Hannuksela and Holz; *Lensing or luck* (PRD, arXiv 2201.04619)

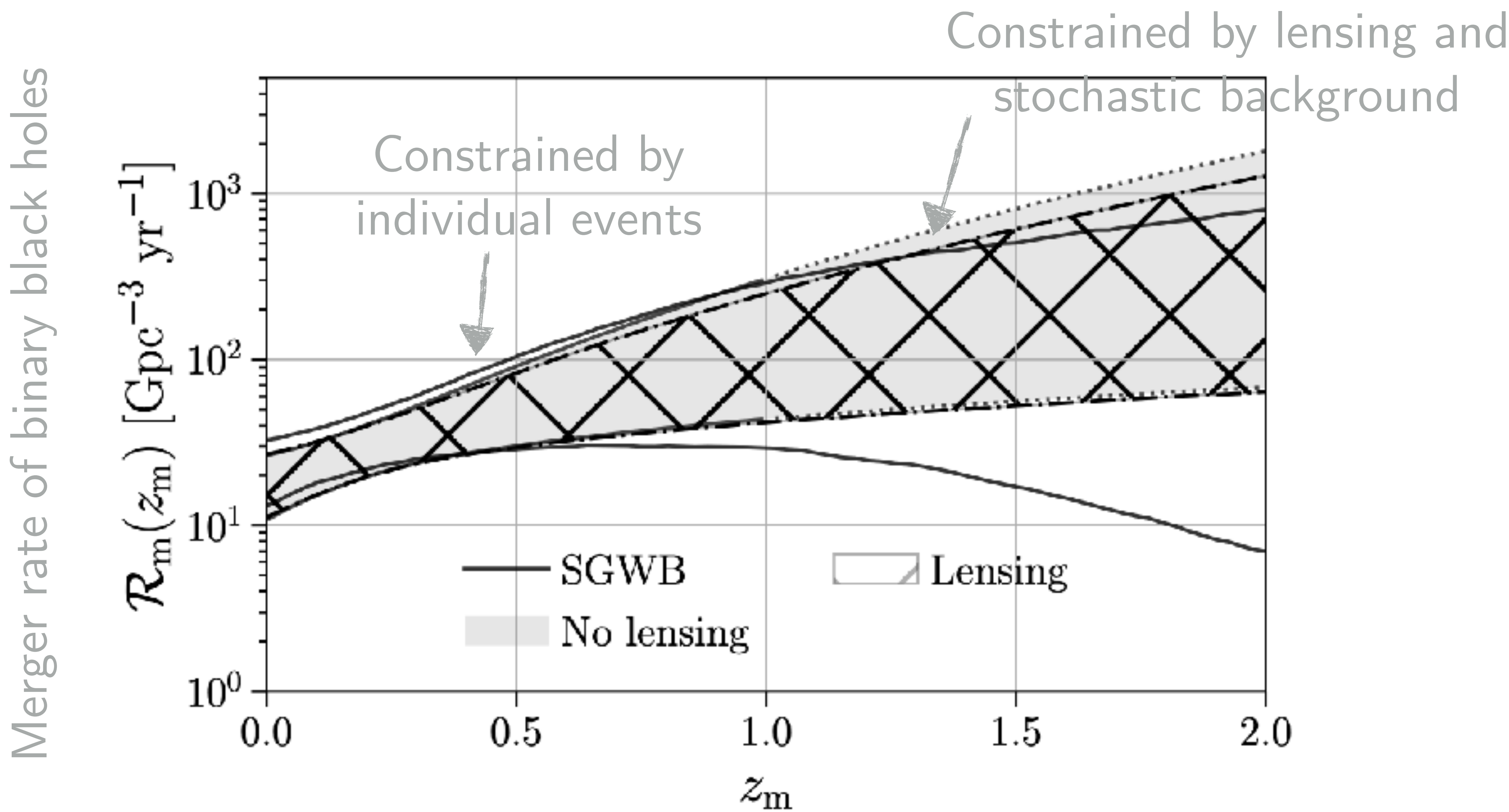
Fight false alarms: **phase consistency**





Ezquiaga, Hu and Lo; *to appear*

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



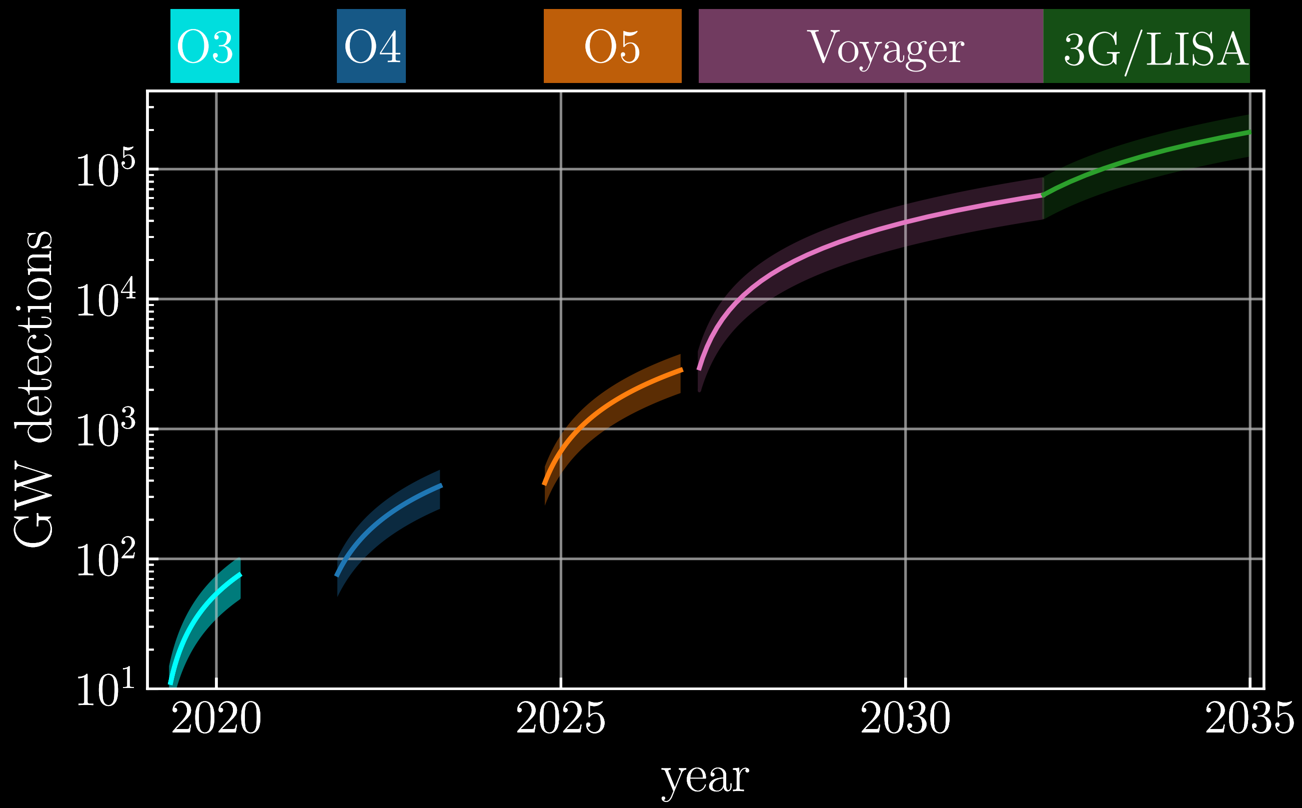
LVC (incl. **Ezquiaga**); *Search GW lensing O3a* (ApJ, arXiv 2105.06384, *science summary*)
LVK (incl. **Ezquiaga**); *Search GW lensing full O3* (arXiv 2304.08393, *science summary*)

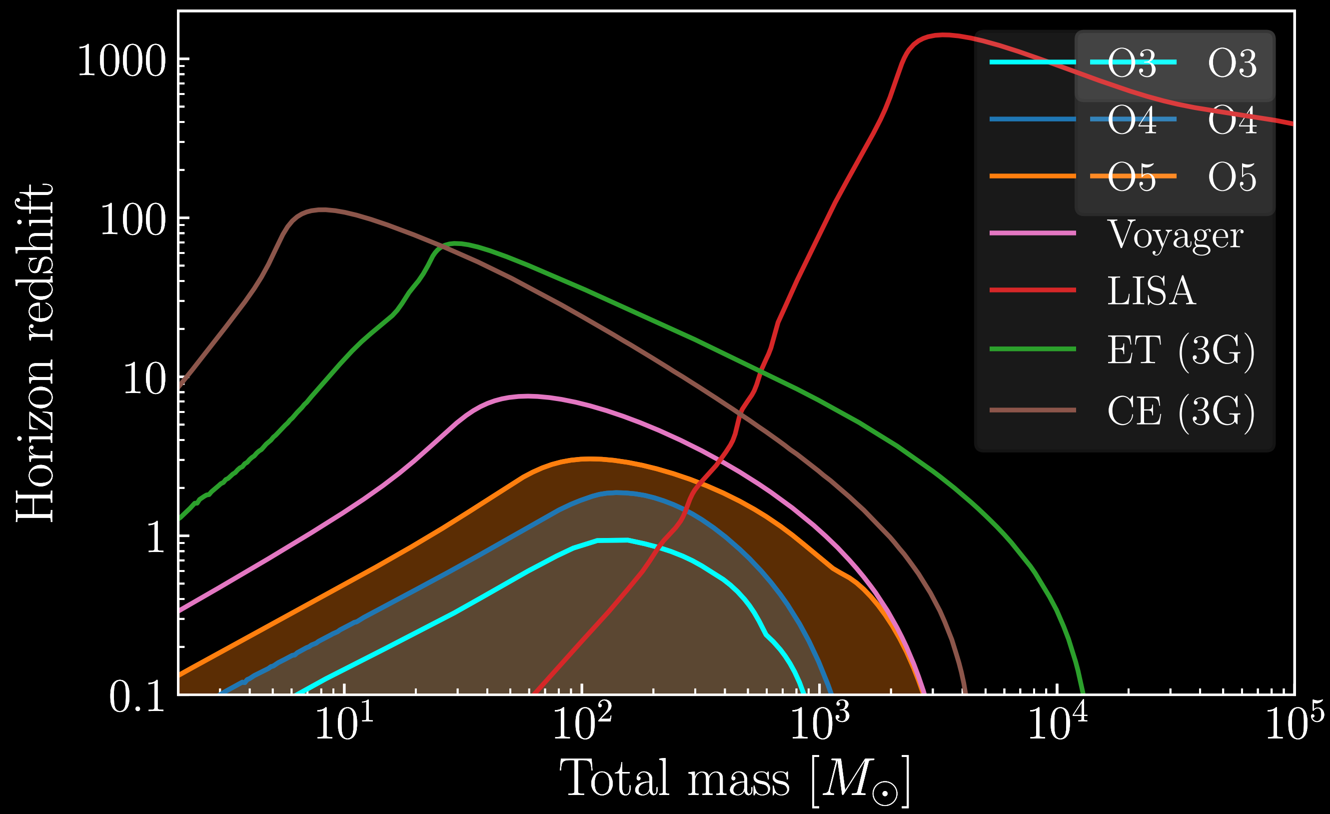
Looking ahead

Now

2G: current generation ground-based GW detectors

3G: next generation ground-based GW detectors



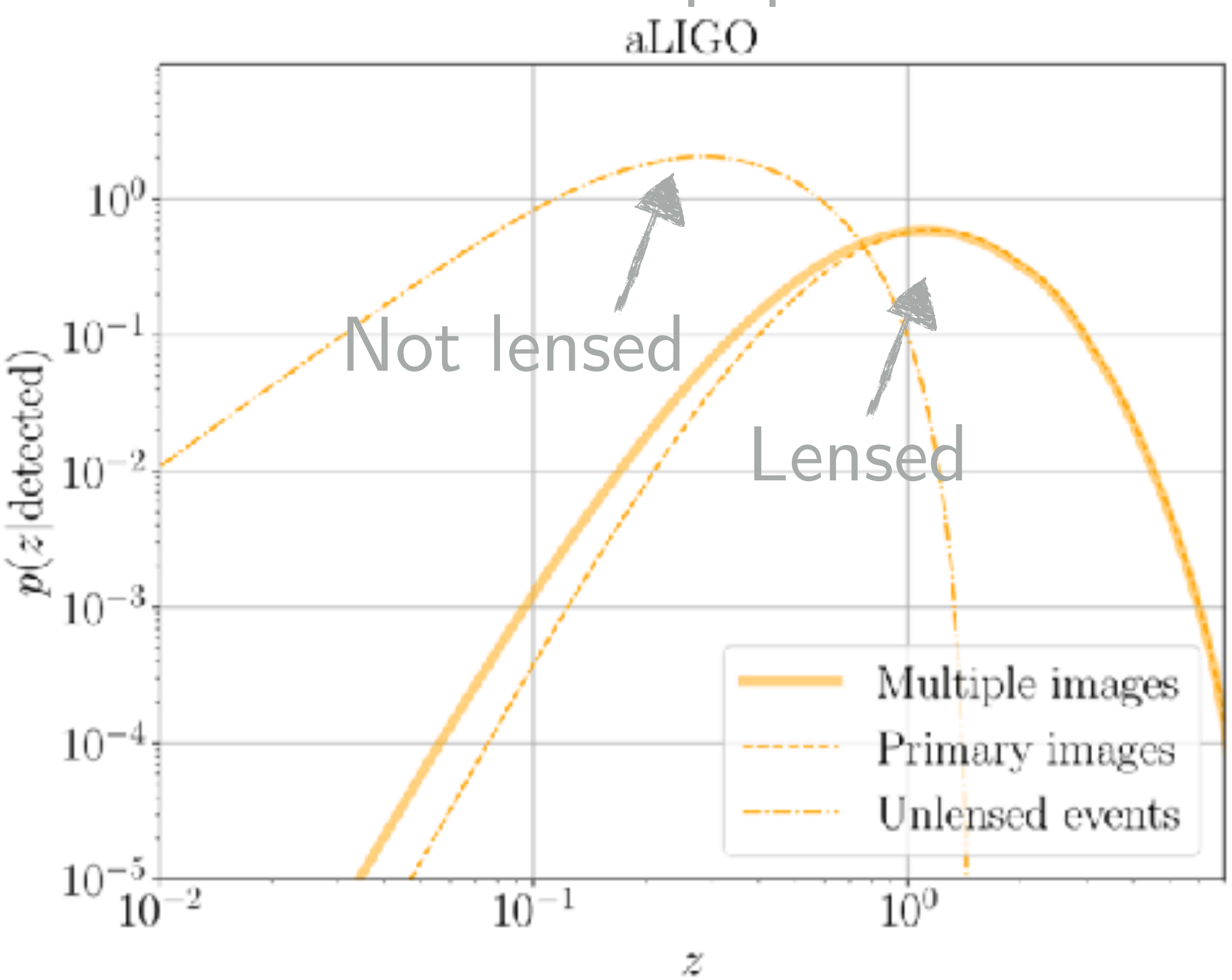


Approx. ***100*** events typically at z < 0.6 → ***1000s / year*** with some z > 1 → ***100,000s / year*** with most z > 1

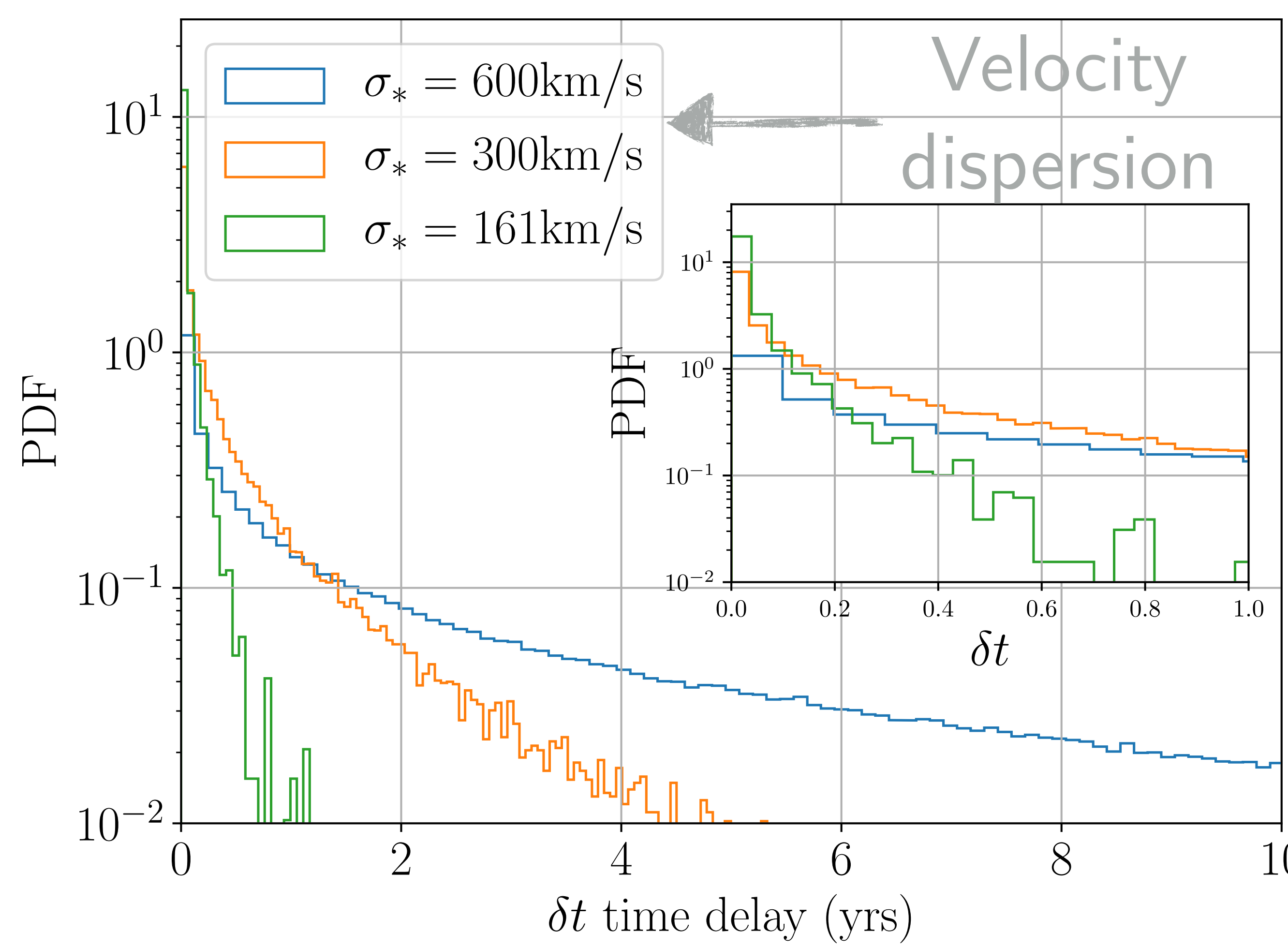
Probing source and lens populations

Fei Xu
(UChicago)

Detected populations

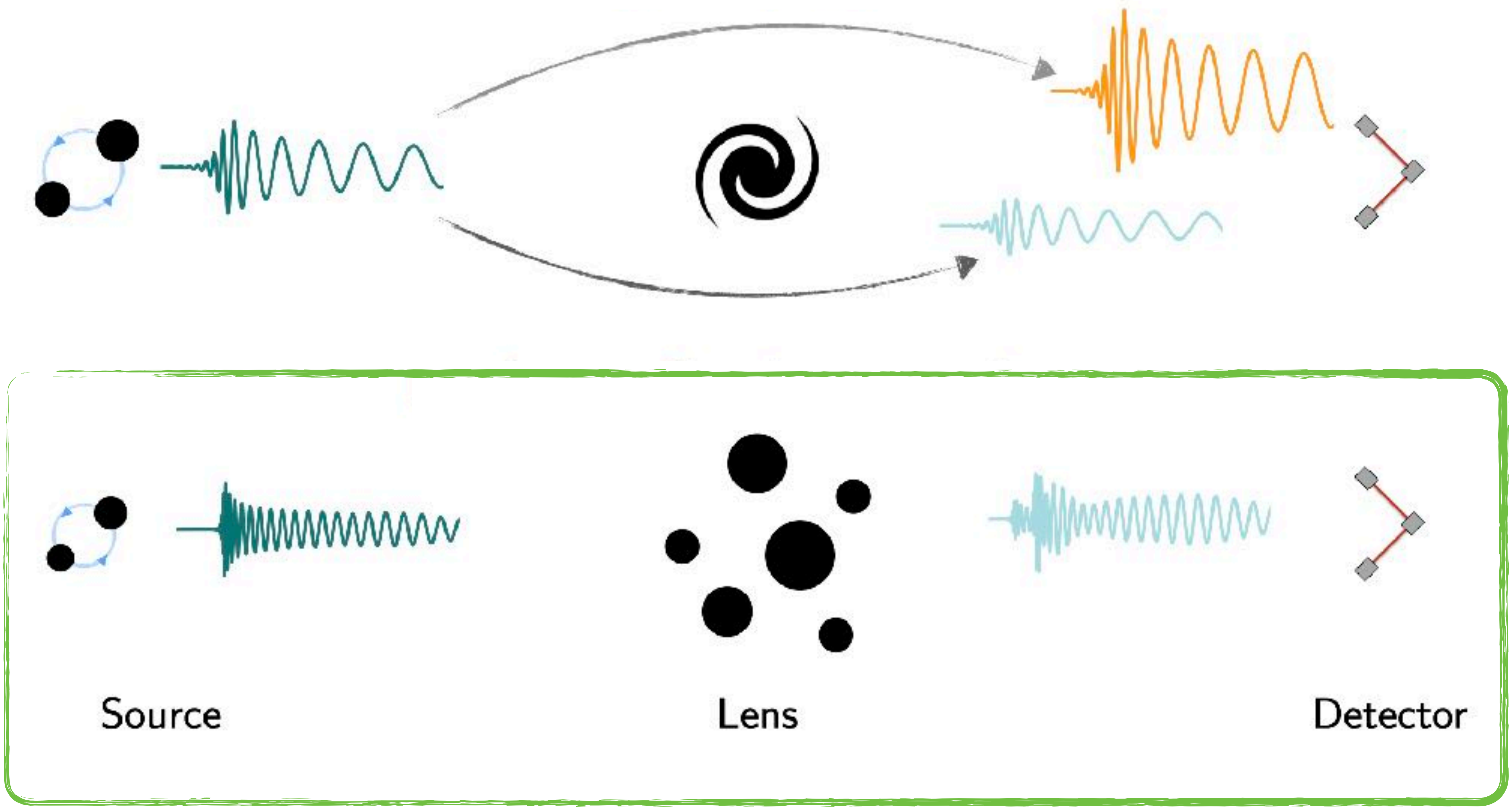


Time delay distributions



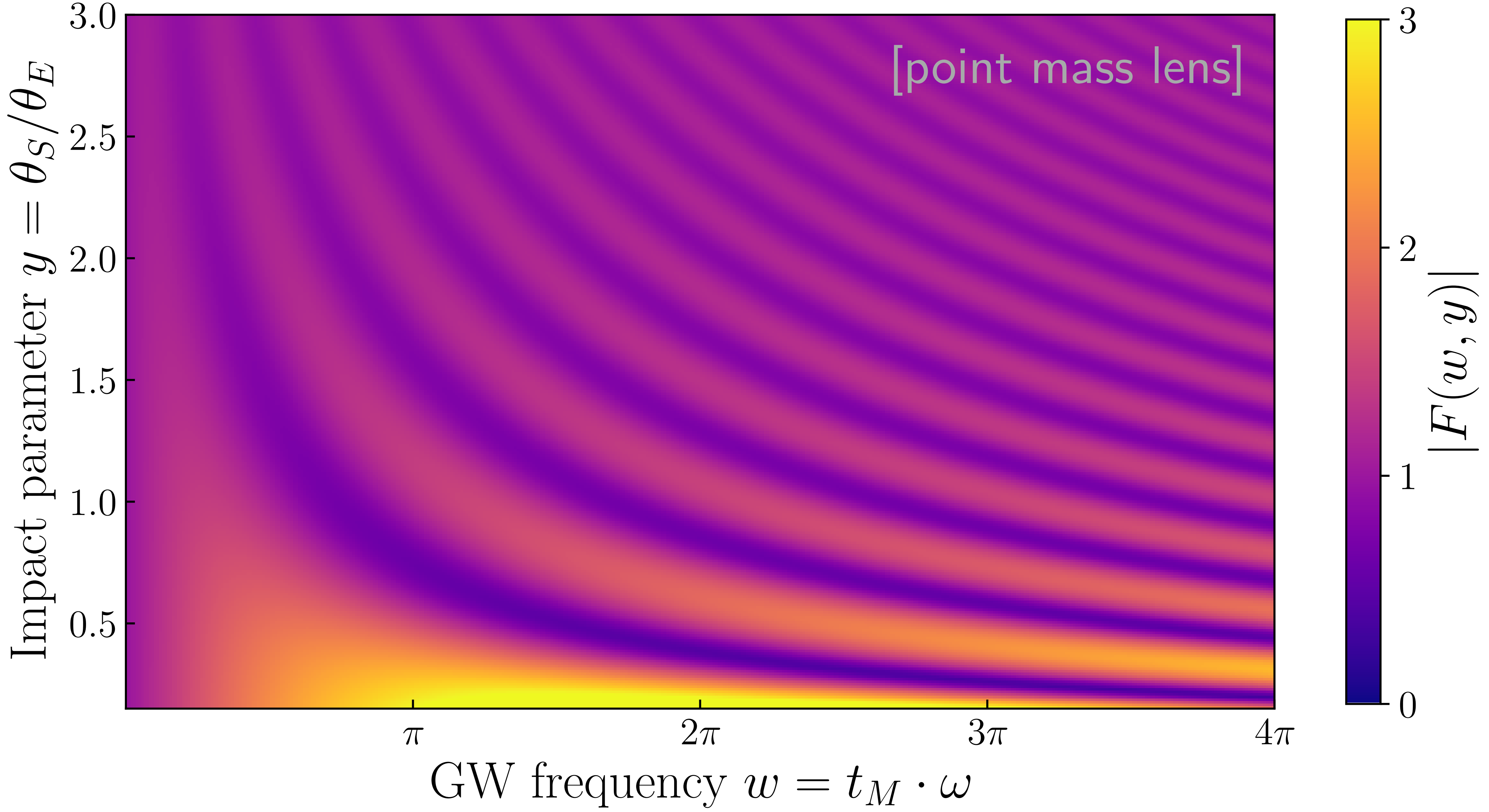
<u>*Xu*</u>, **Ezquiaga** and Holz; *Strong lensing probes compact and galaxy pop* (ApJ, arXiv 2105.14390)

What lensing?



Wave effects:

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

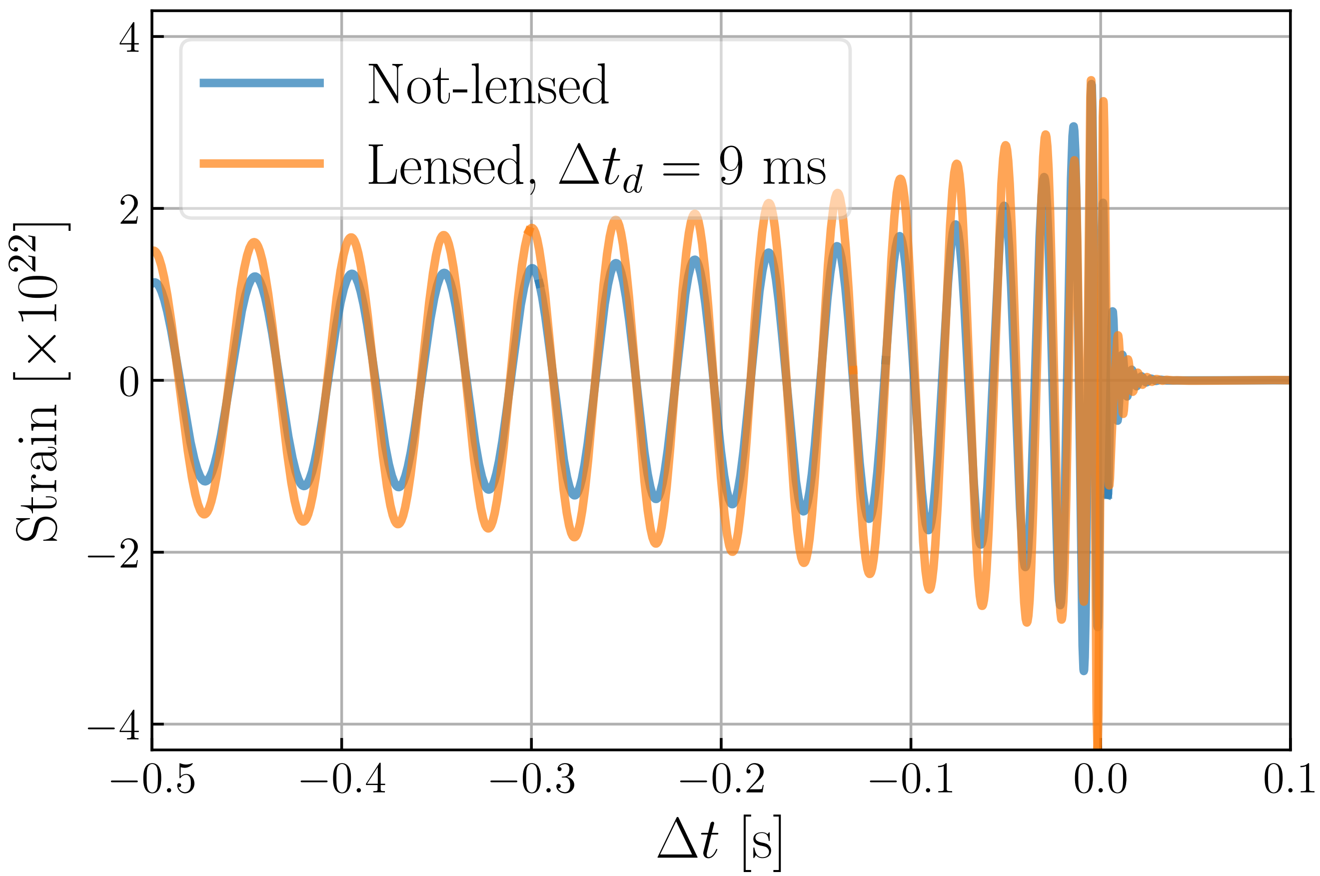


[point mass lens]

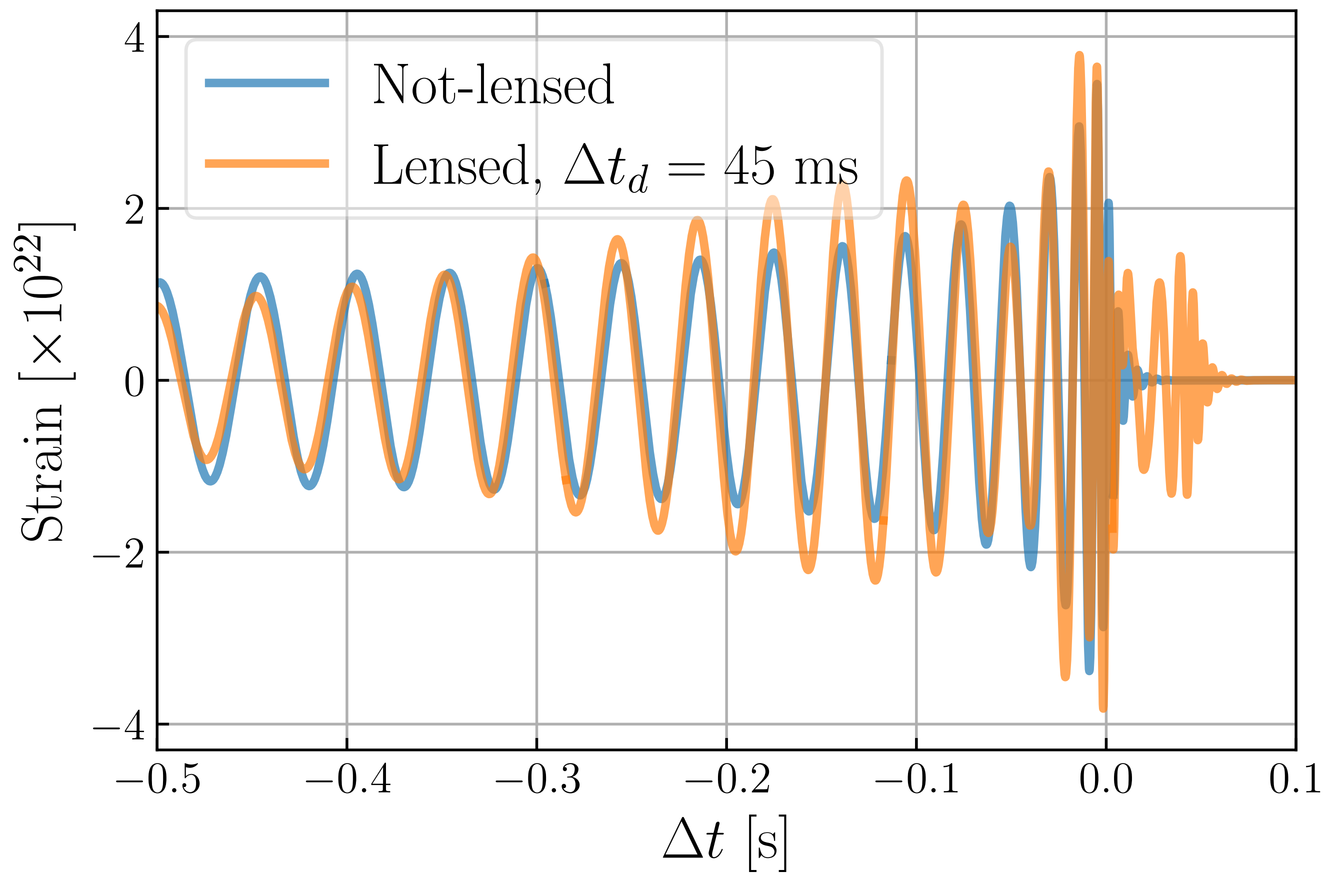
Wave effects:

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

Diffraction

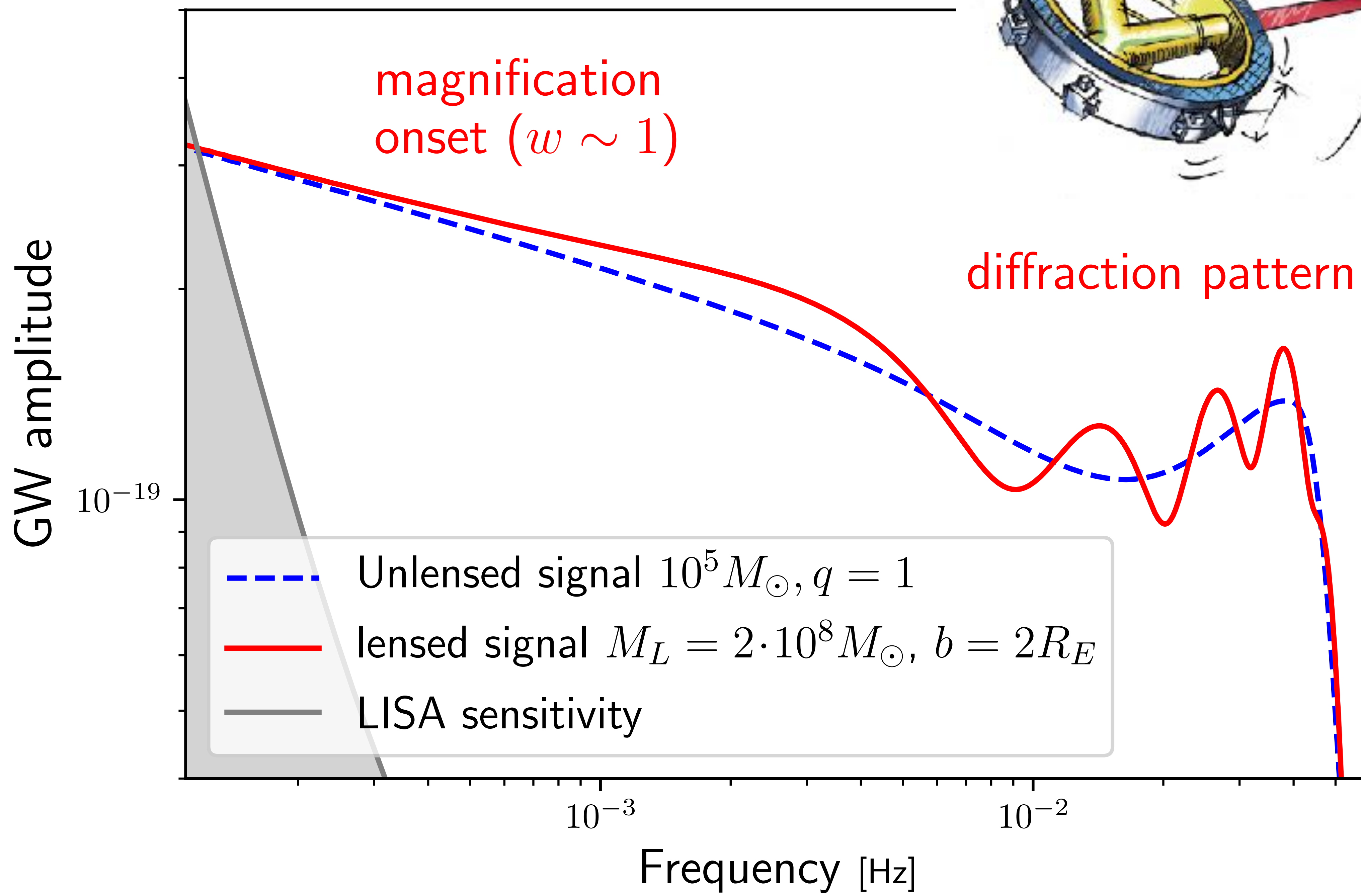


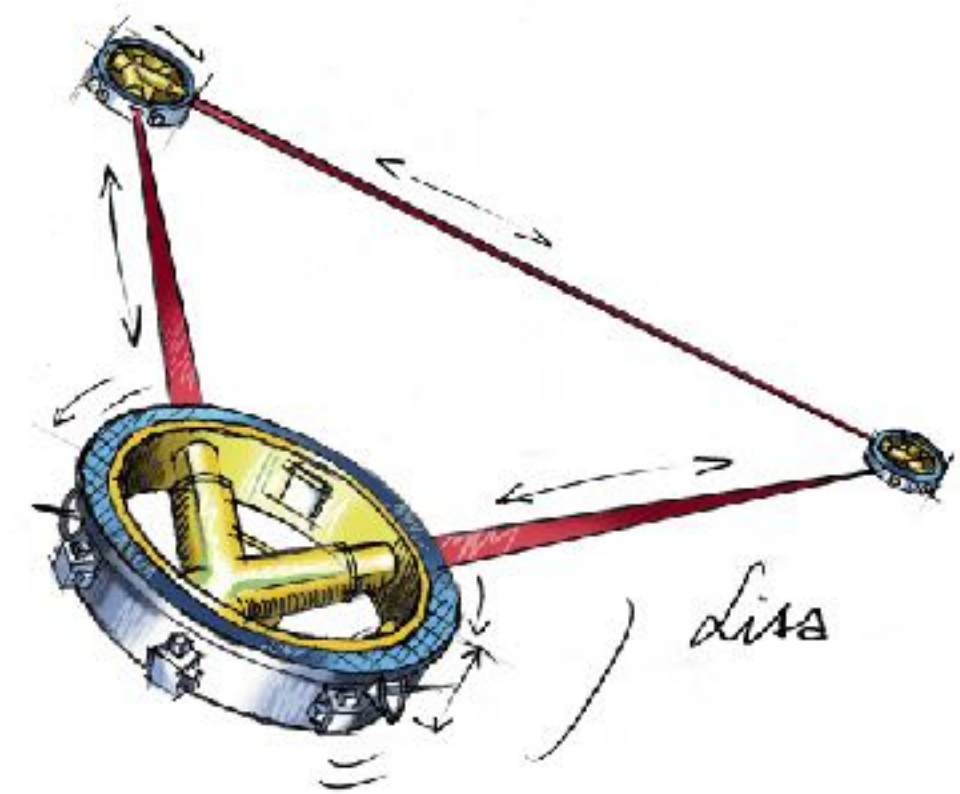
Interference



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)

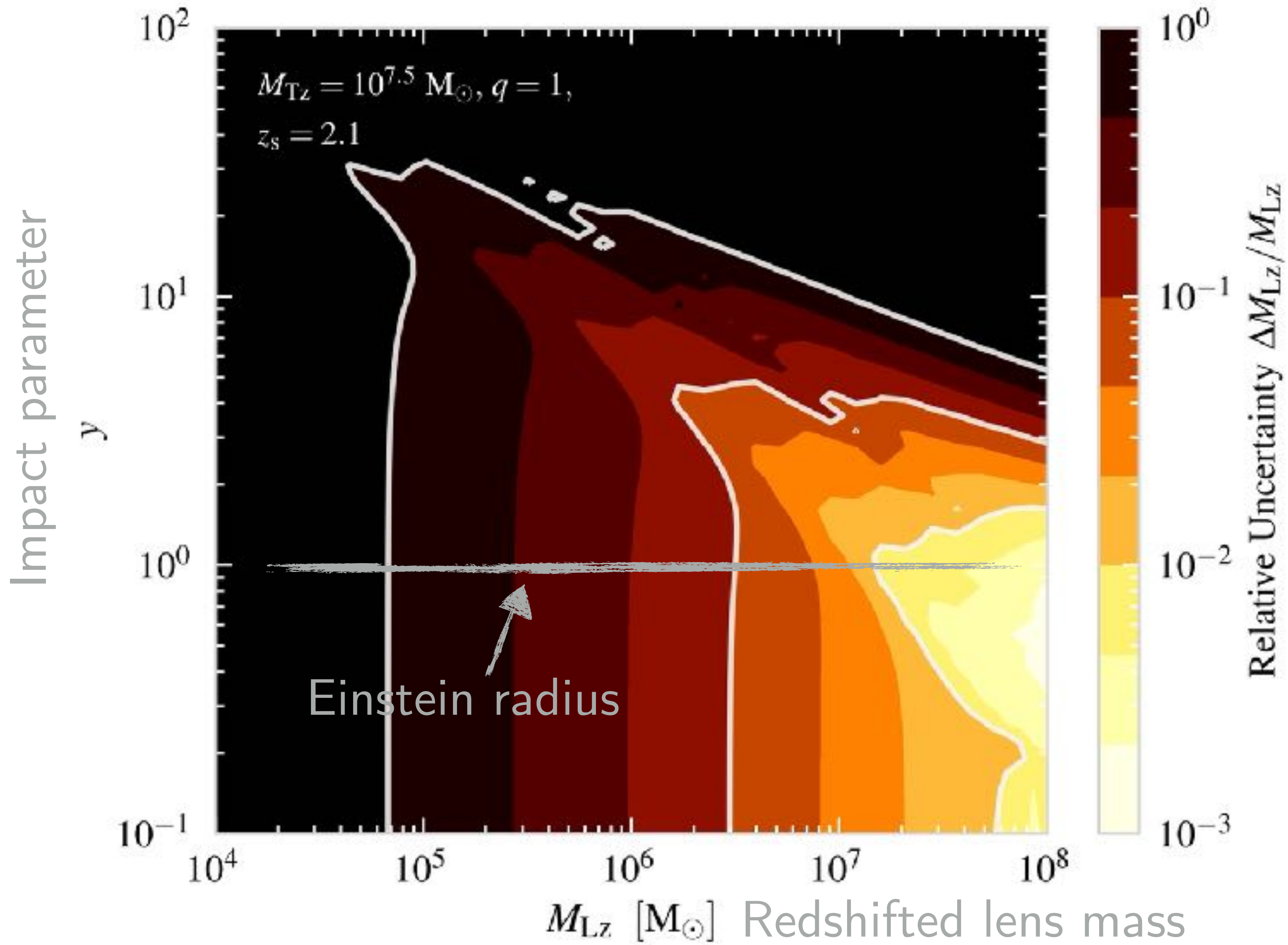
Wave effects: **LISA**





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

Increased optical depth

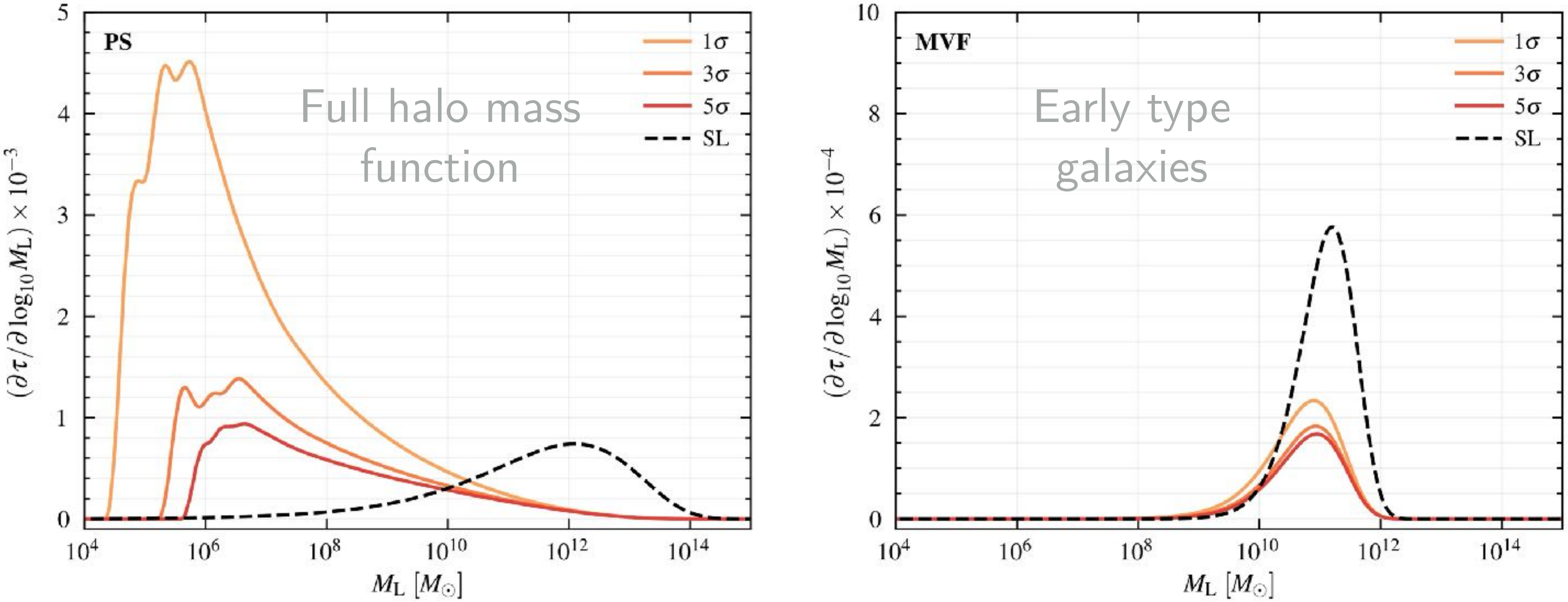


Çalışkan et al. (incl. **Ezquiaga**); (arXiv 2307.06990)

Probing dark matter sub-halos

Mesut Çalışkan (JHU)

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



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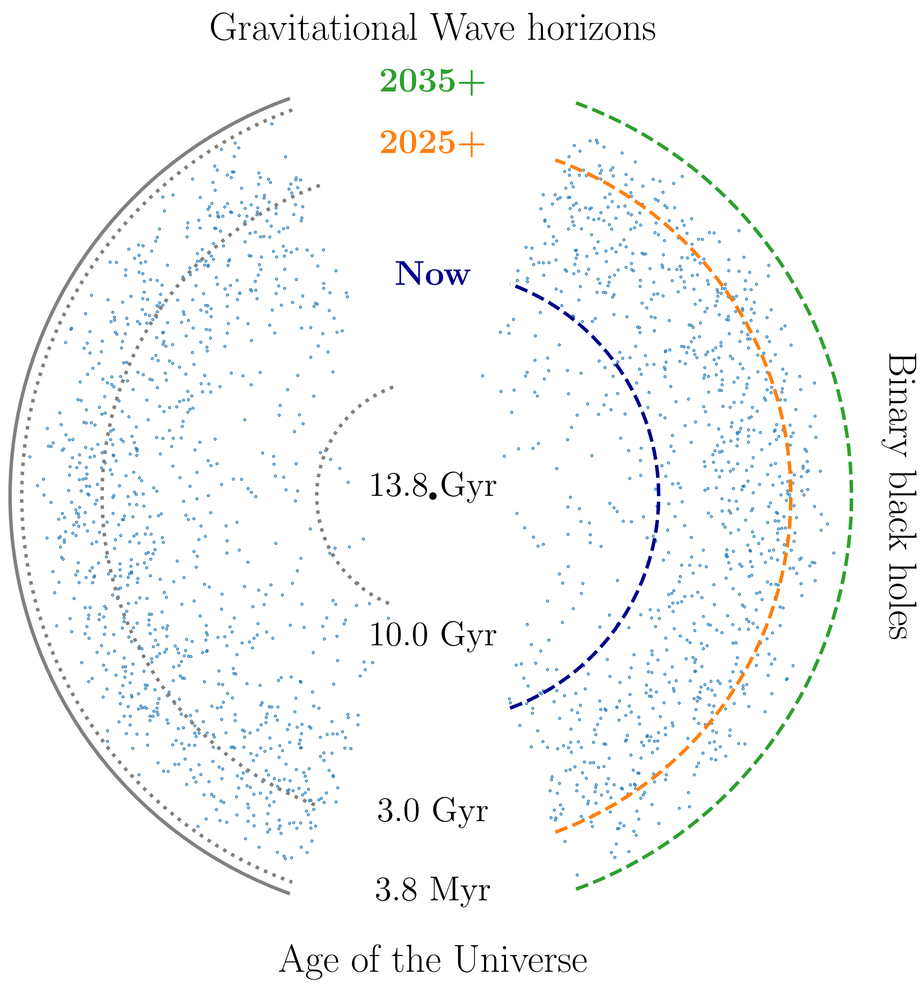
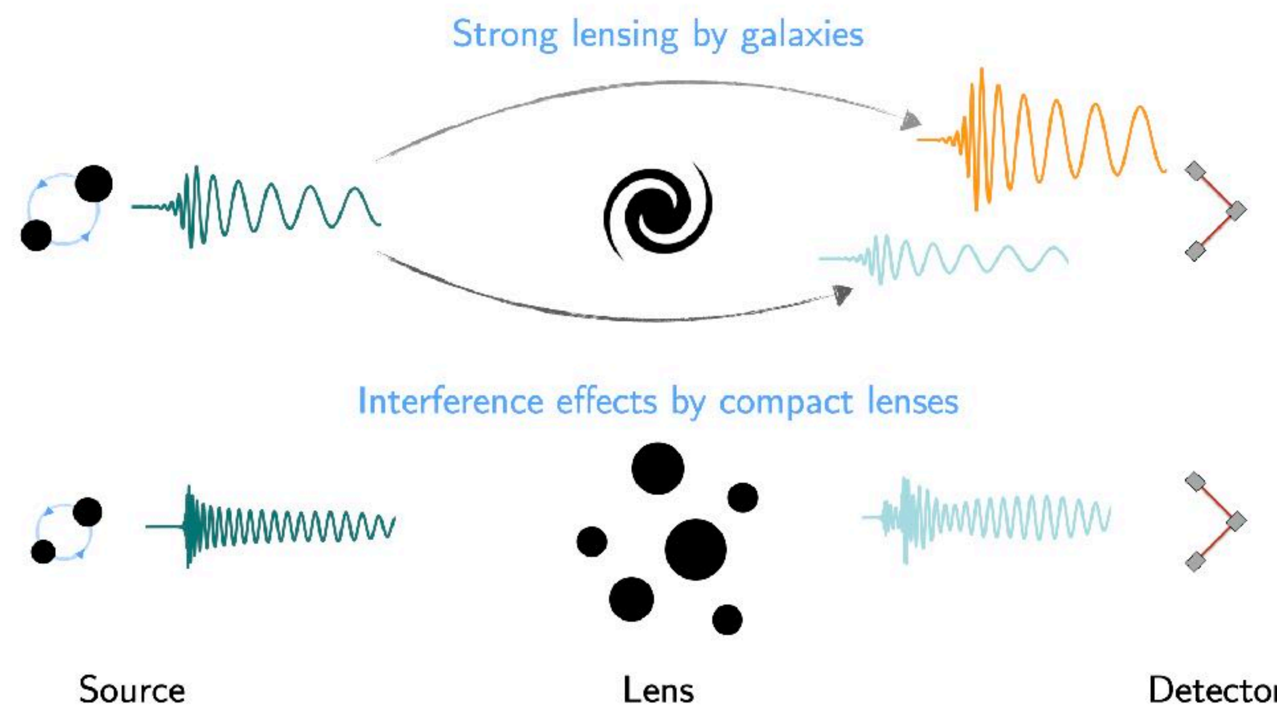
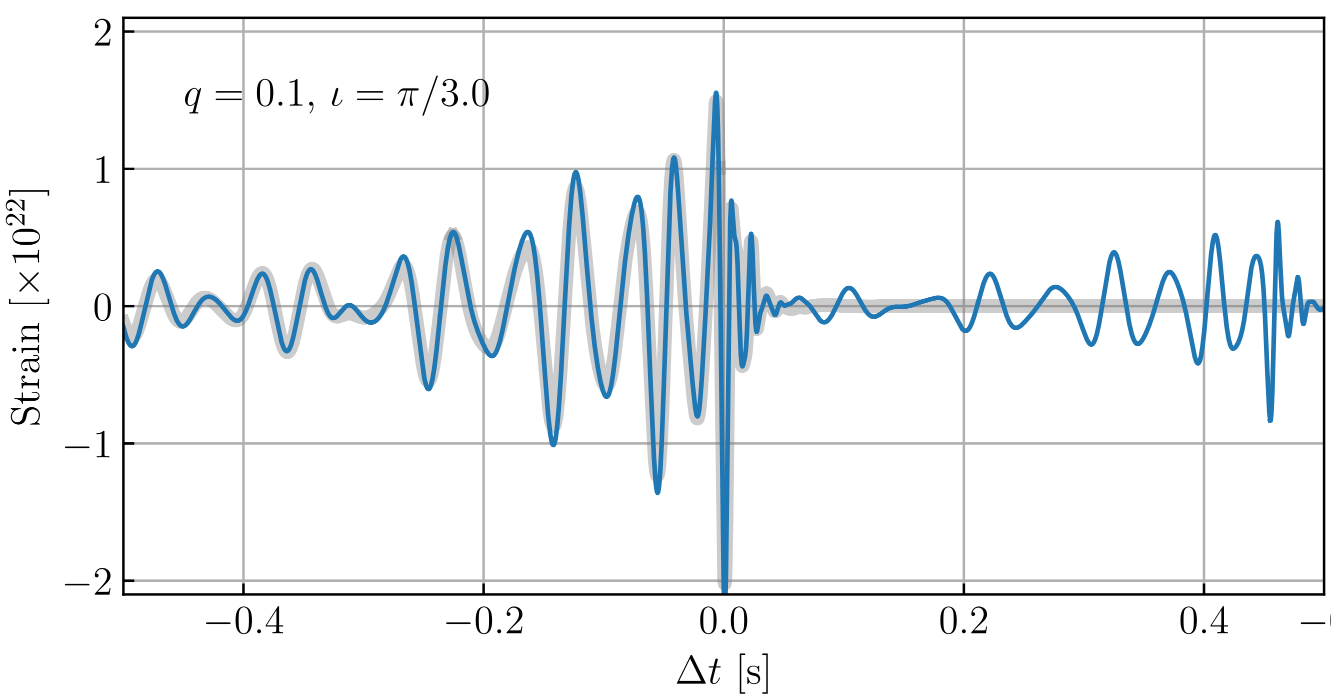
Synergies

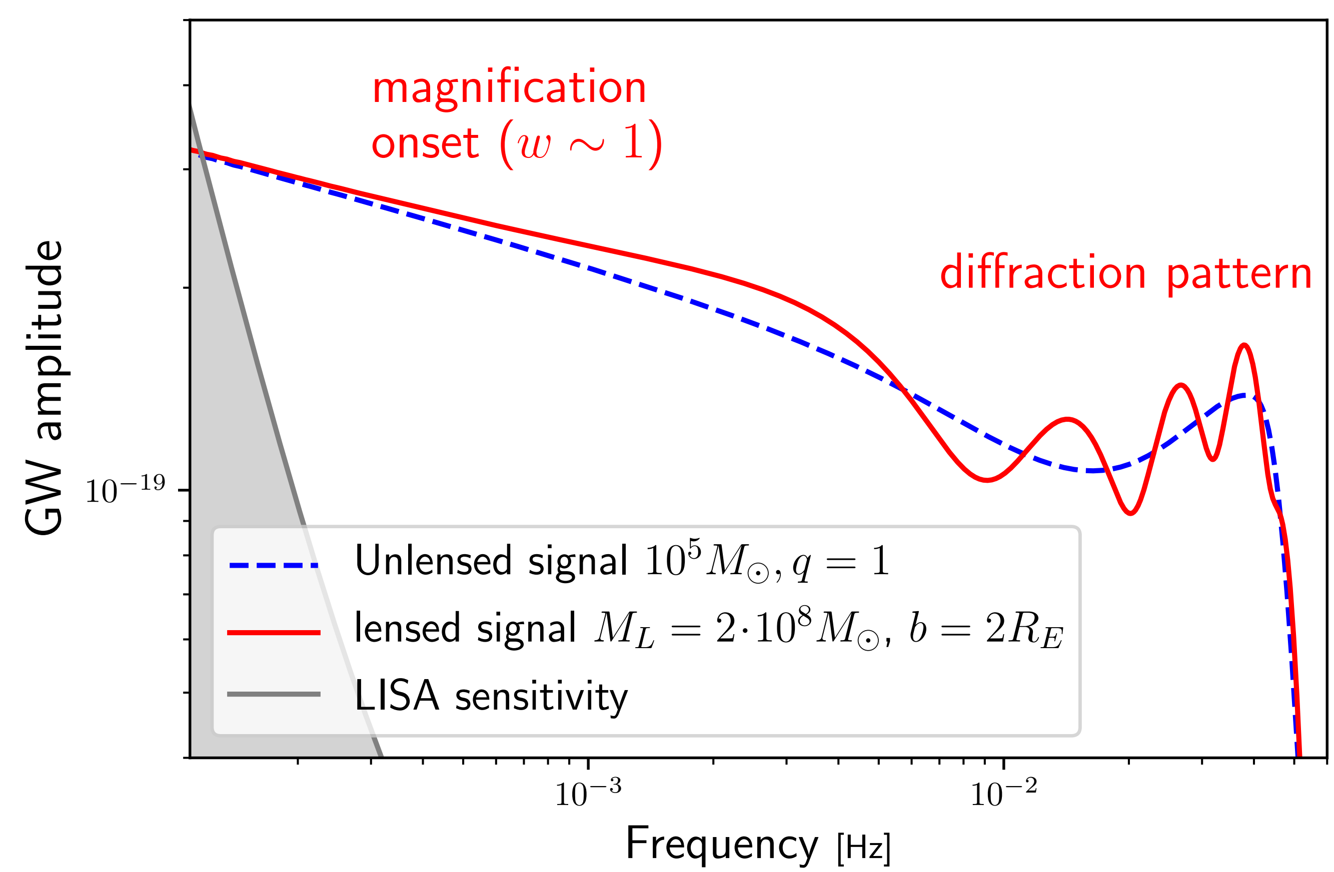
- **Cross correlate with strong lensing catalogs** (I'd love to know where to find them and how to use them!)
- **Targeted follow-ups** for promising candidates
- **Joint lensing inference** to improve cosmology/gravity tests
- **Constraints on optical depth** combining different probes







Multiple images, type II distortion, expected soon!



Wave effects, PBH, sub-halos

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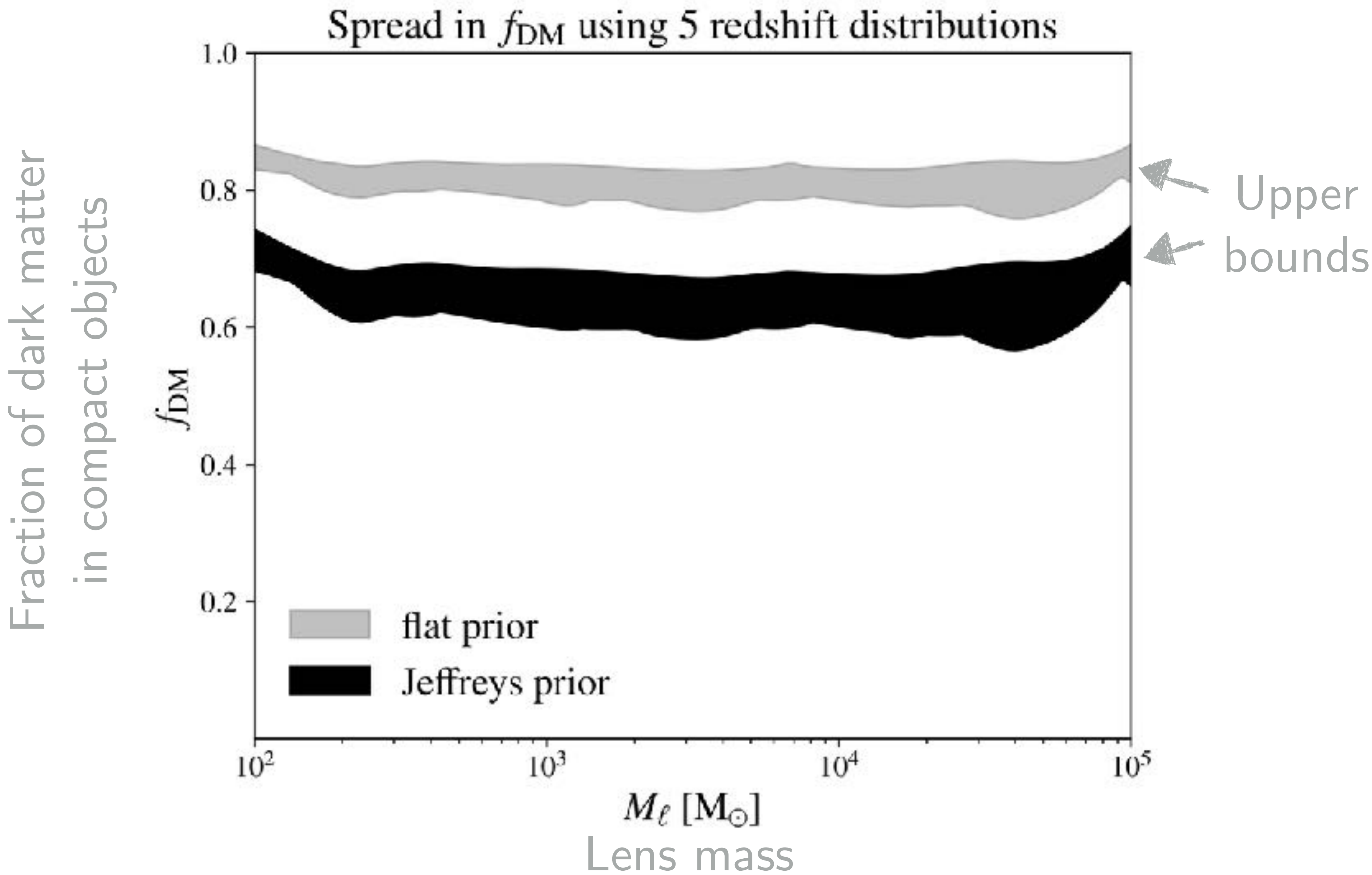
ezquiaga.github.io/joinus

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



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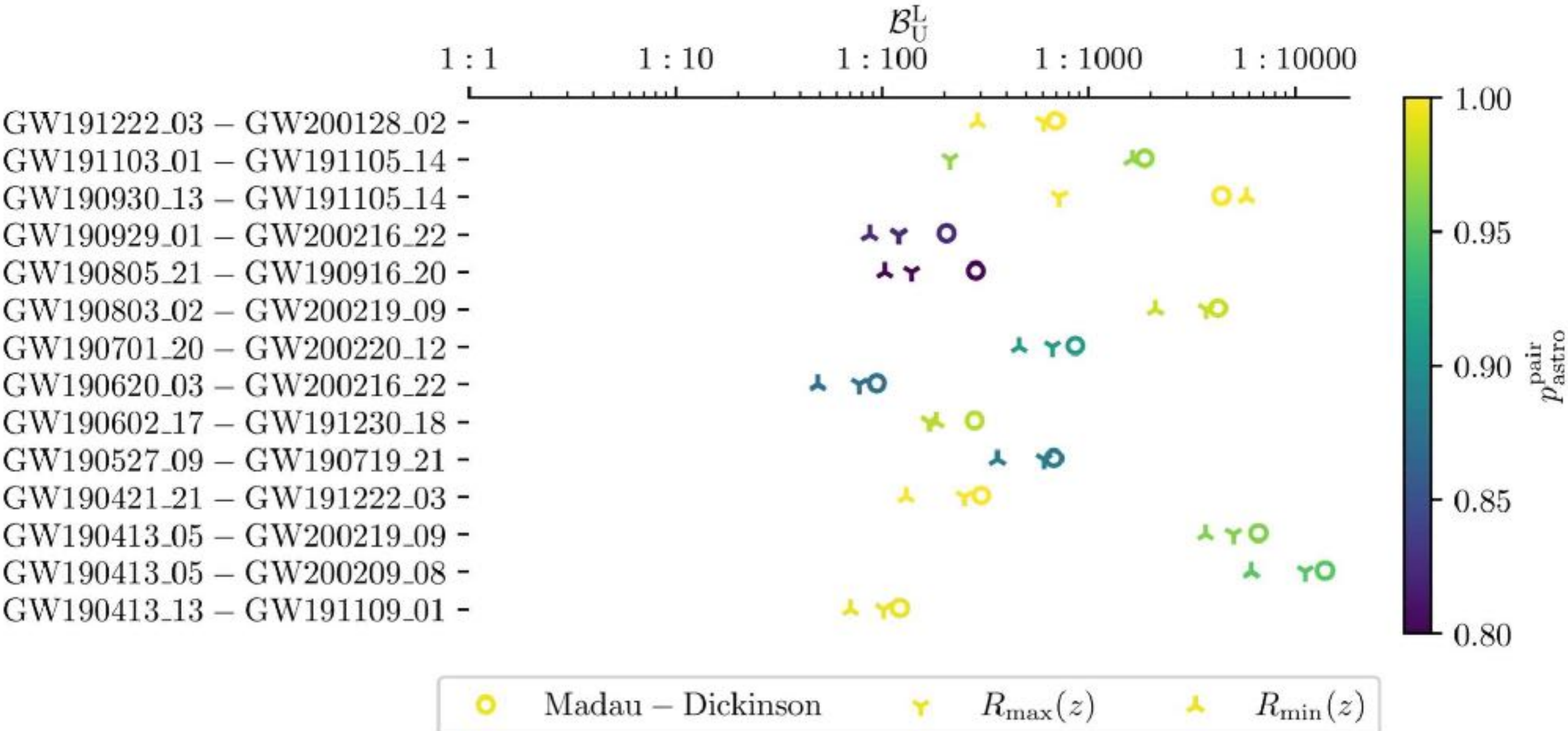

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