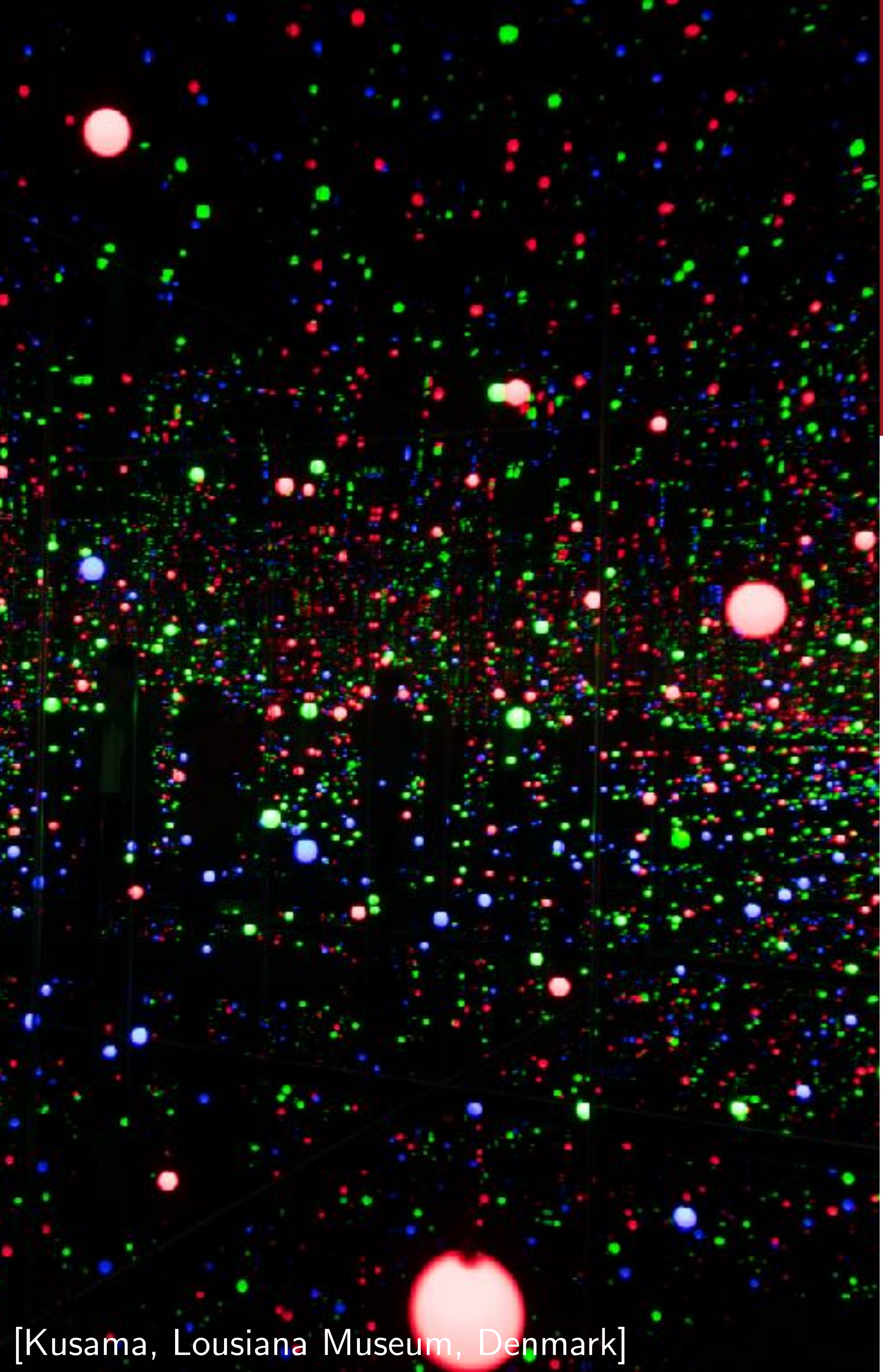
[Kusama, Lousiana Museum, Denmark]

Cosmology with the furthest binary black holes

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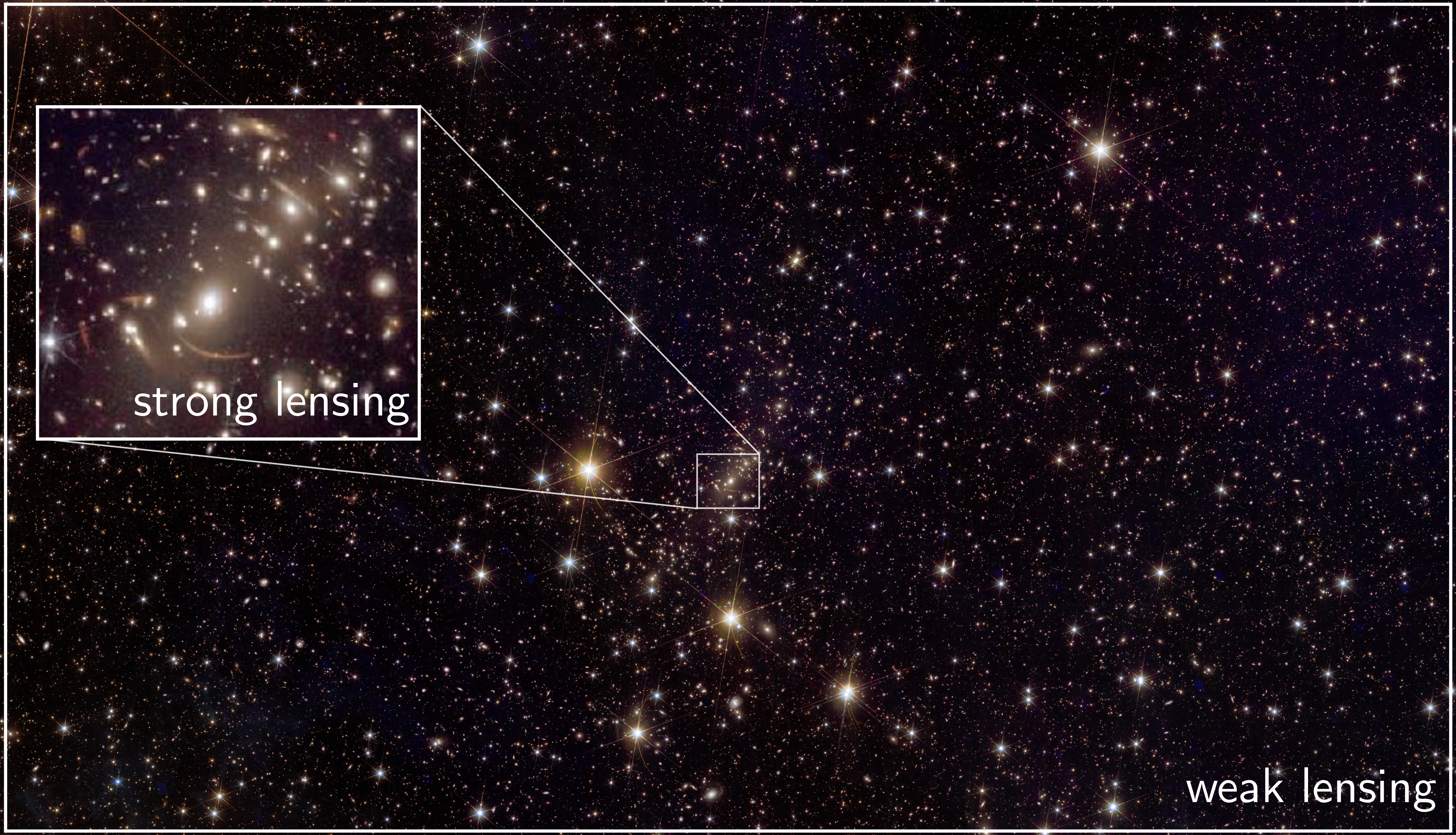
THE CENTER OF GRAVITY

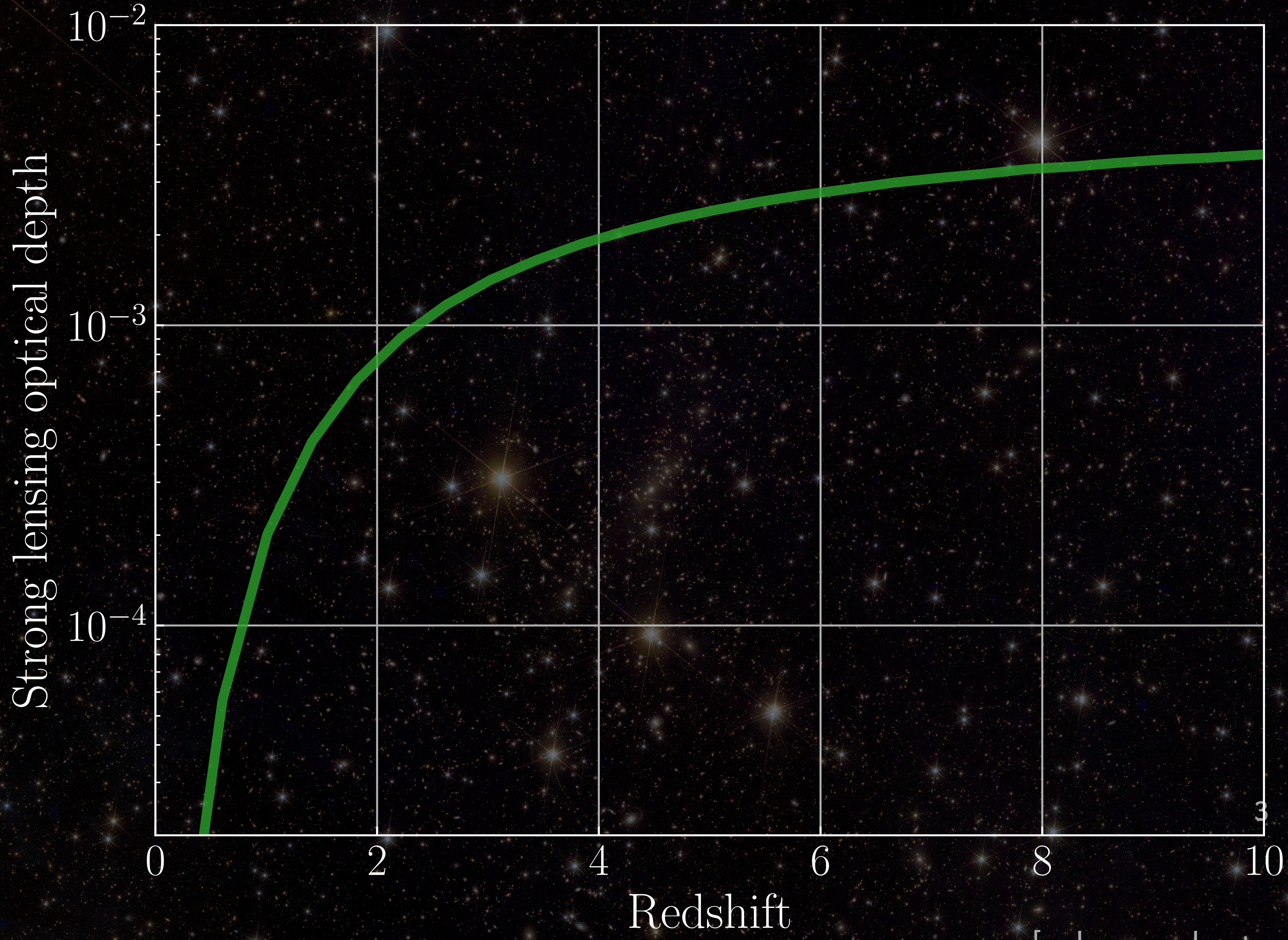
VILLUM FONDEN

The exploration of the *distant Universe* is powered by **gravitational lensing**



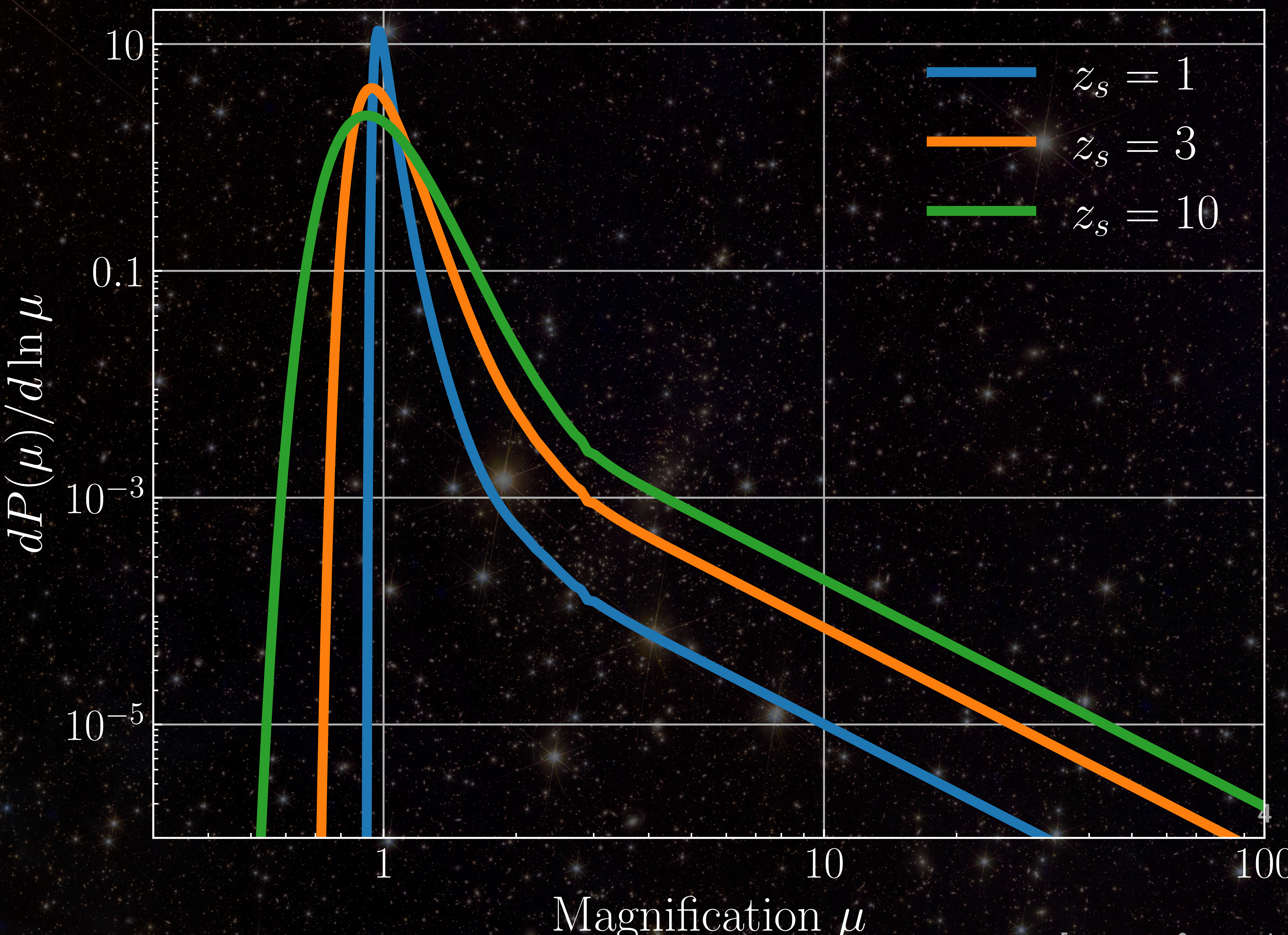
[Euclid's view of Abell 2390]

Gravitational lensing only becomes **more** probable at *higher* redshifts



[galaxy-scale strong lenses]

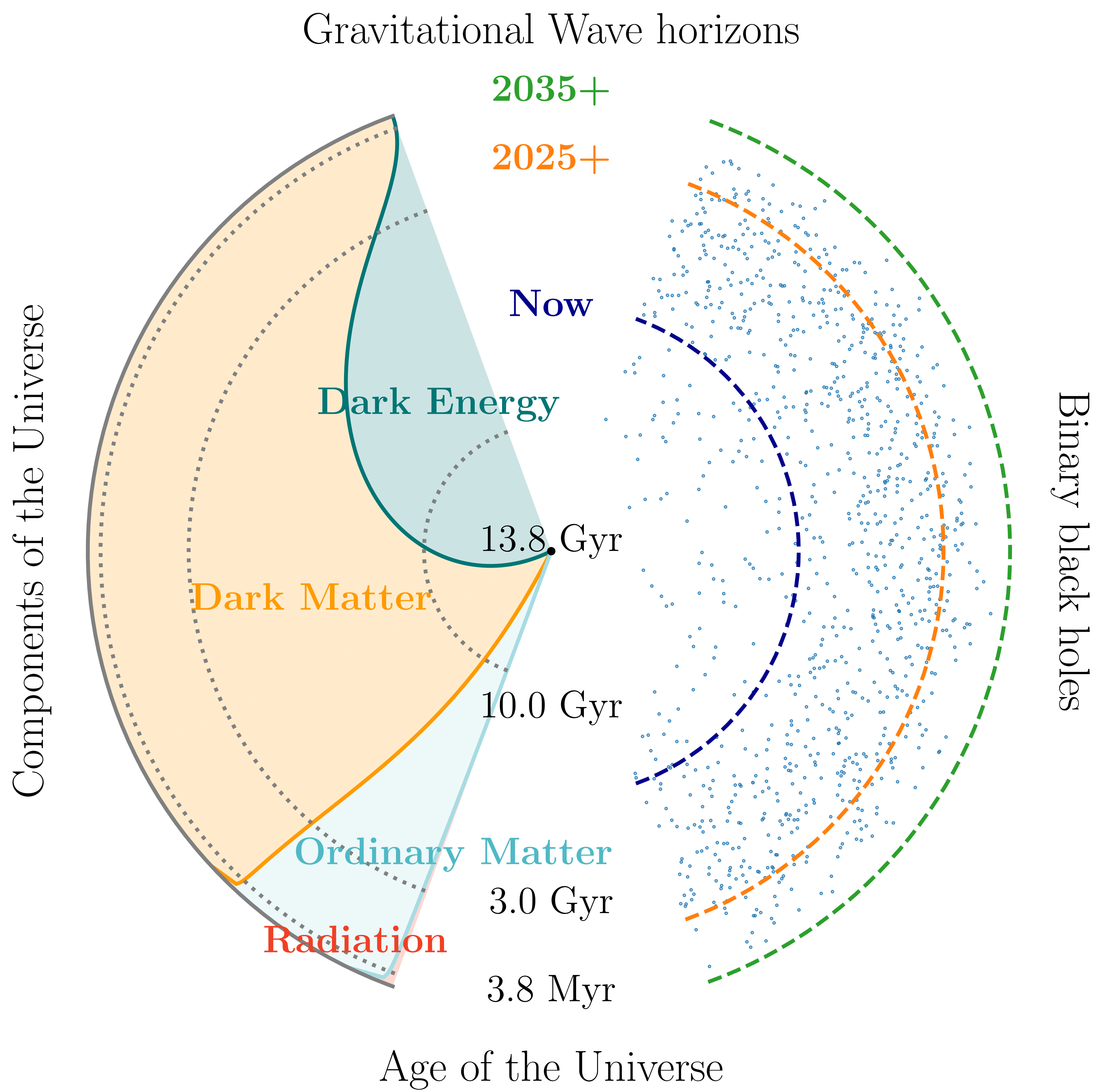
All sources are lensed. A fraction of them with large **magnifications**



[strong & weak lensing]

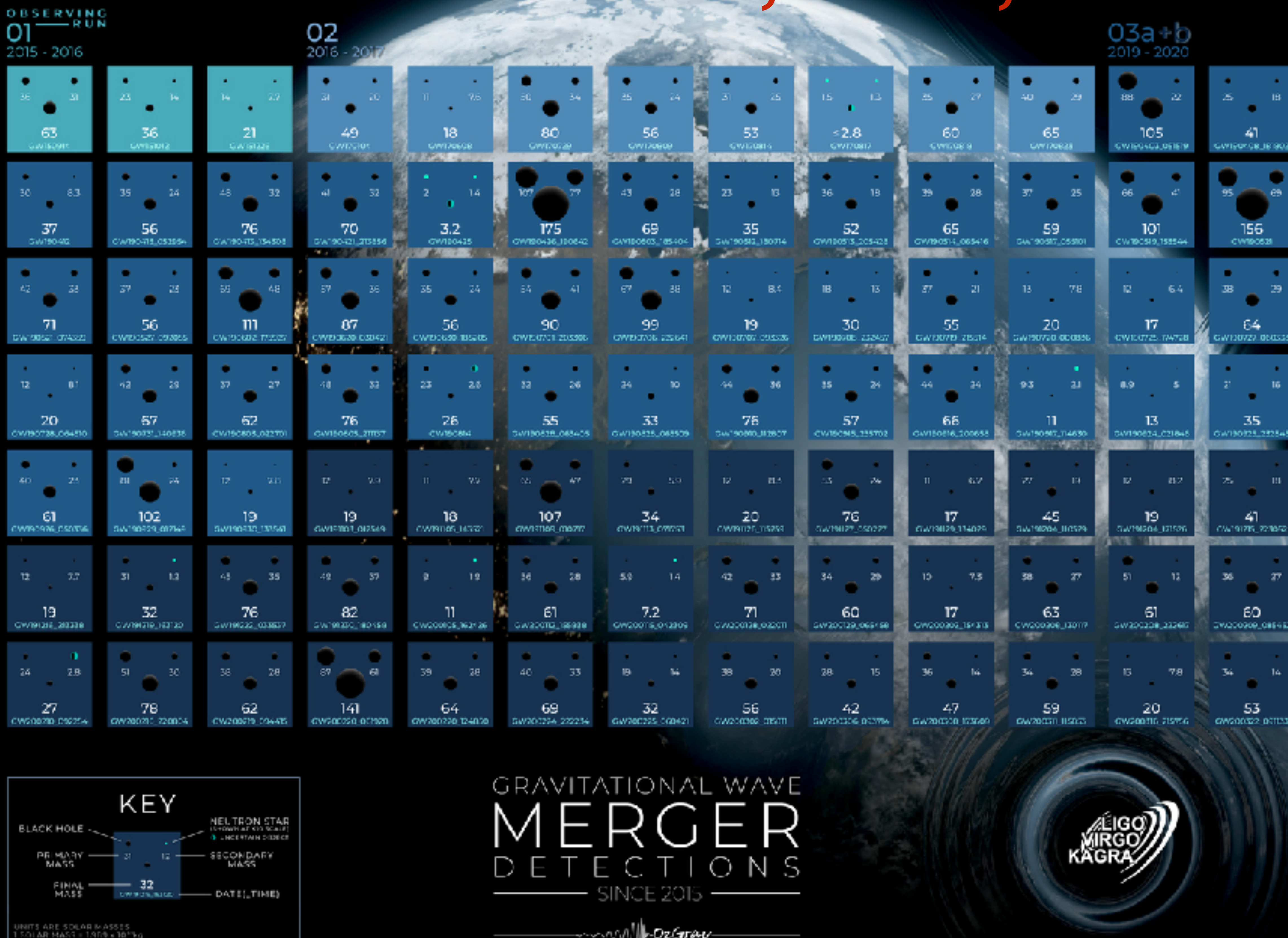
Gravitational waves from compact binary coalescences are *unique* cosmic messengers

- Compact binaries merge at **cosmological** distances
- Signals are **understood** from first principles (solving numerical relativity)
- GWs travel **unaltered** through the Universe, except for gravitational lensing
- GW **wavelengths** are of astrophysical scale


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

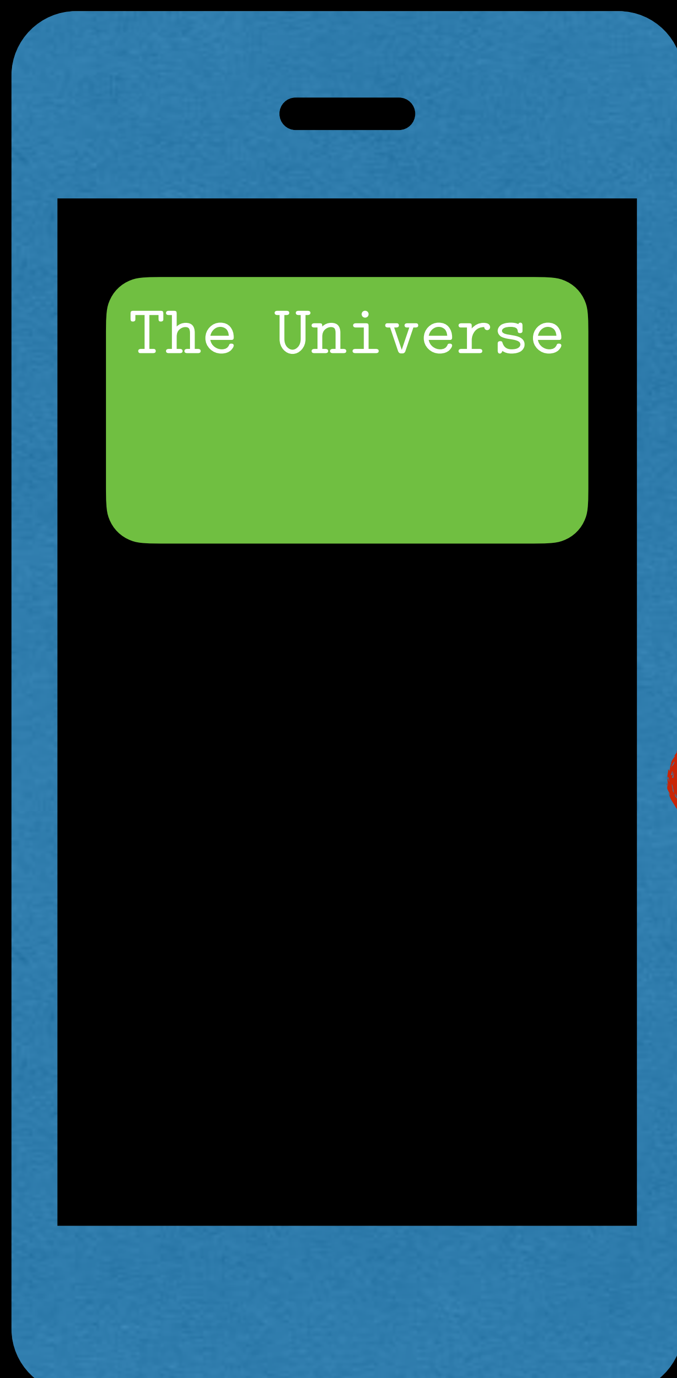
The era of gravitational wave astronomy is **here**!

~100 events: BBH, BNS, NSBH



We are taking data!

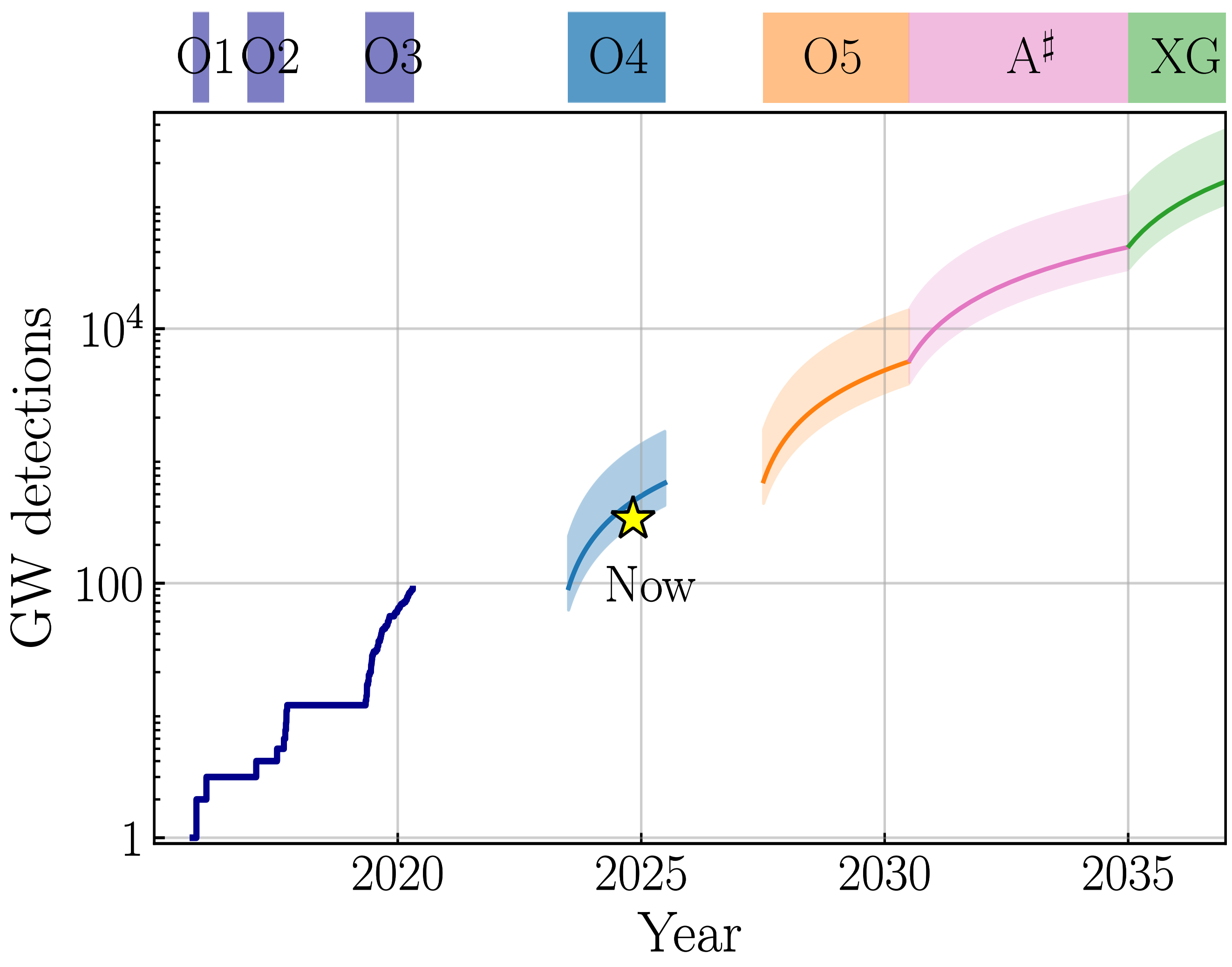
https://gracedb.ligo.org/superevents/public/O4/#

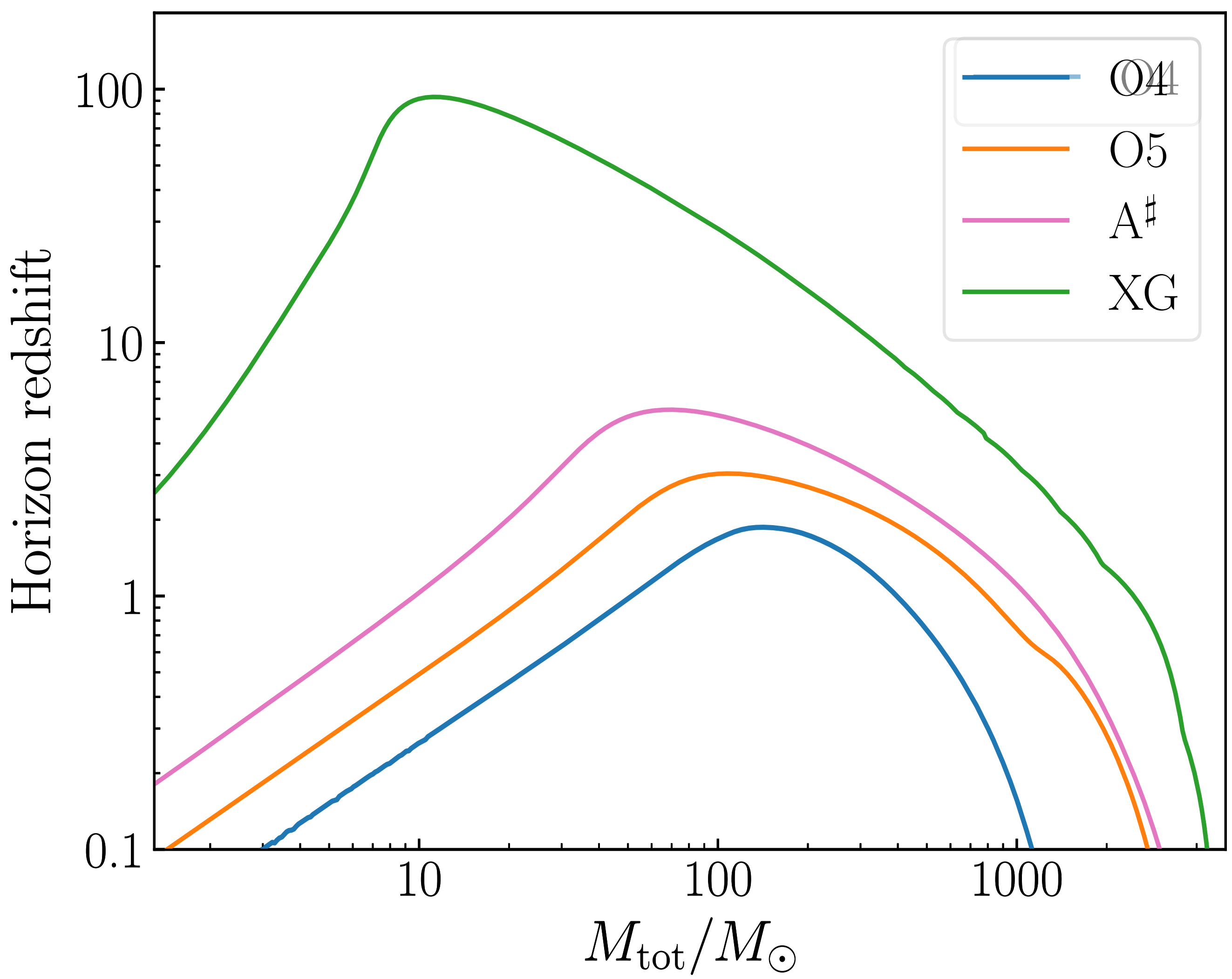


Check arXiv this summer!

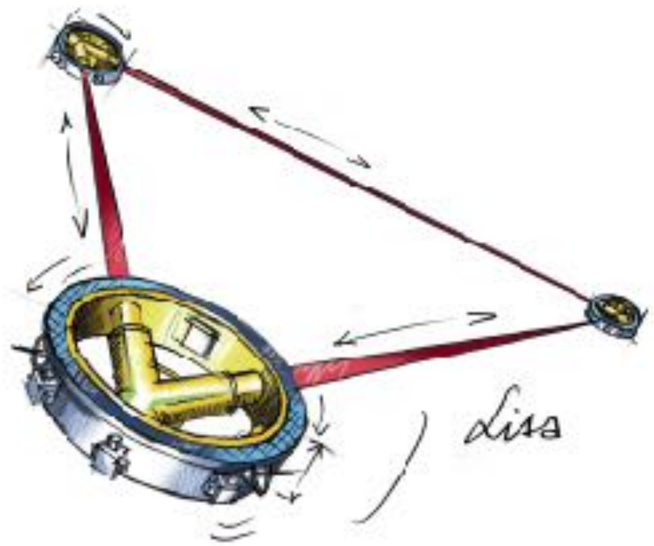
+200 candidates

The **future**: “big data” & distant Universe

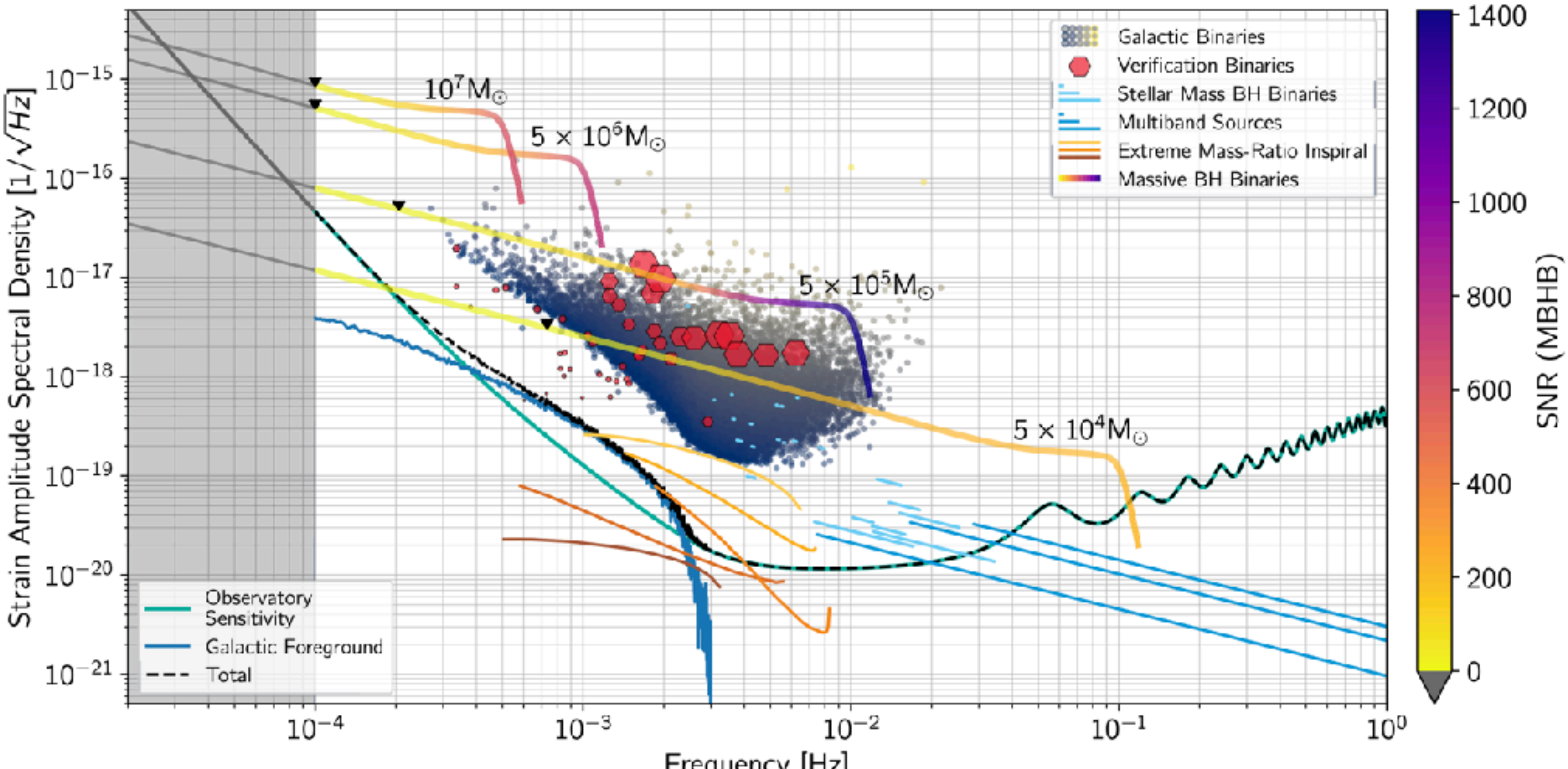




[Chen, **Ezquiaga** & Gupta (CQG’24)]



LISA's perspective



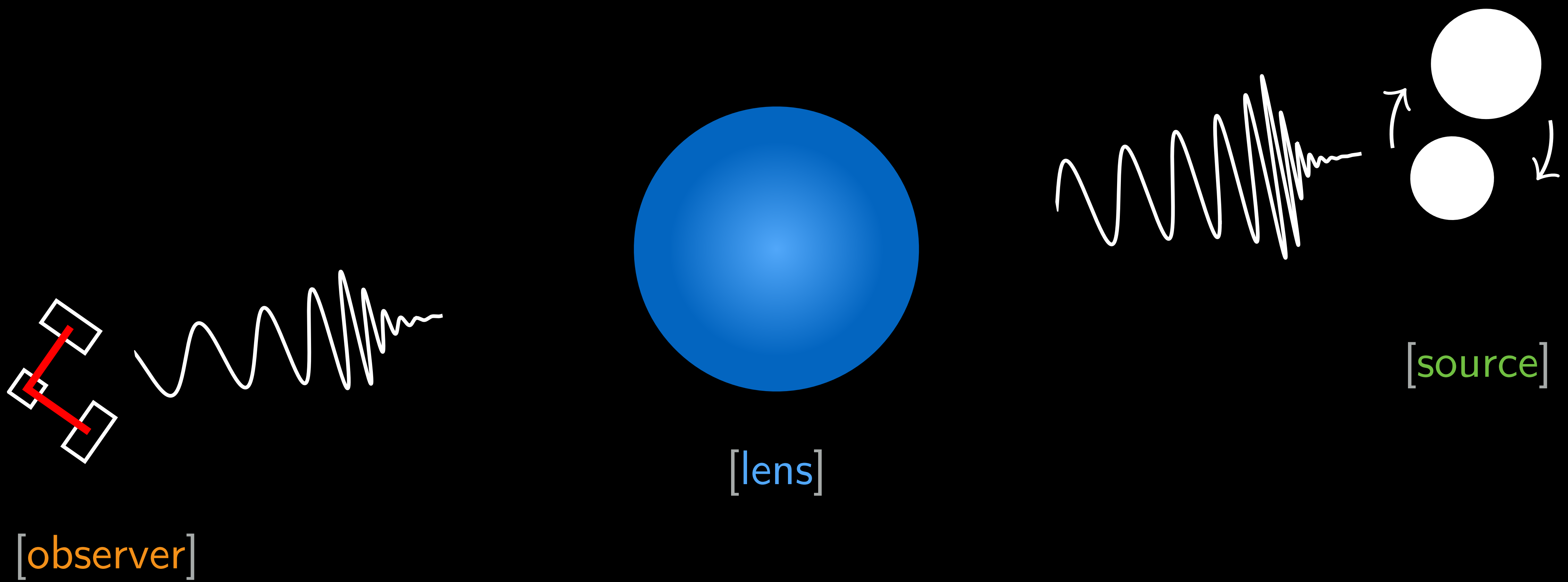
[LISA red book]

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

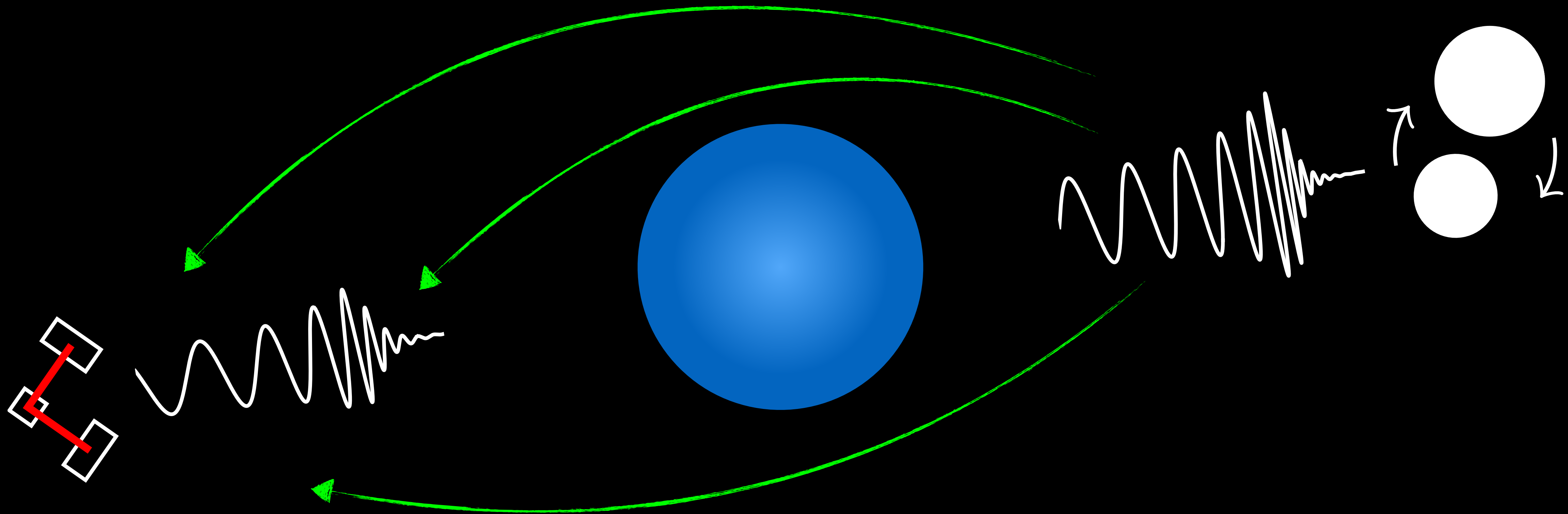


Gravitational lensing

- In *weak-gravity* and *thin lens* approximation, solve in *Fourier* space:

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

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



Multiple chirps

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

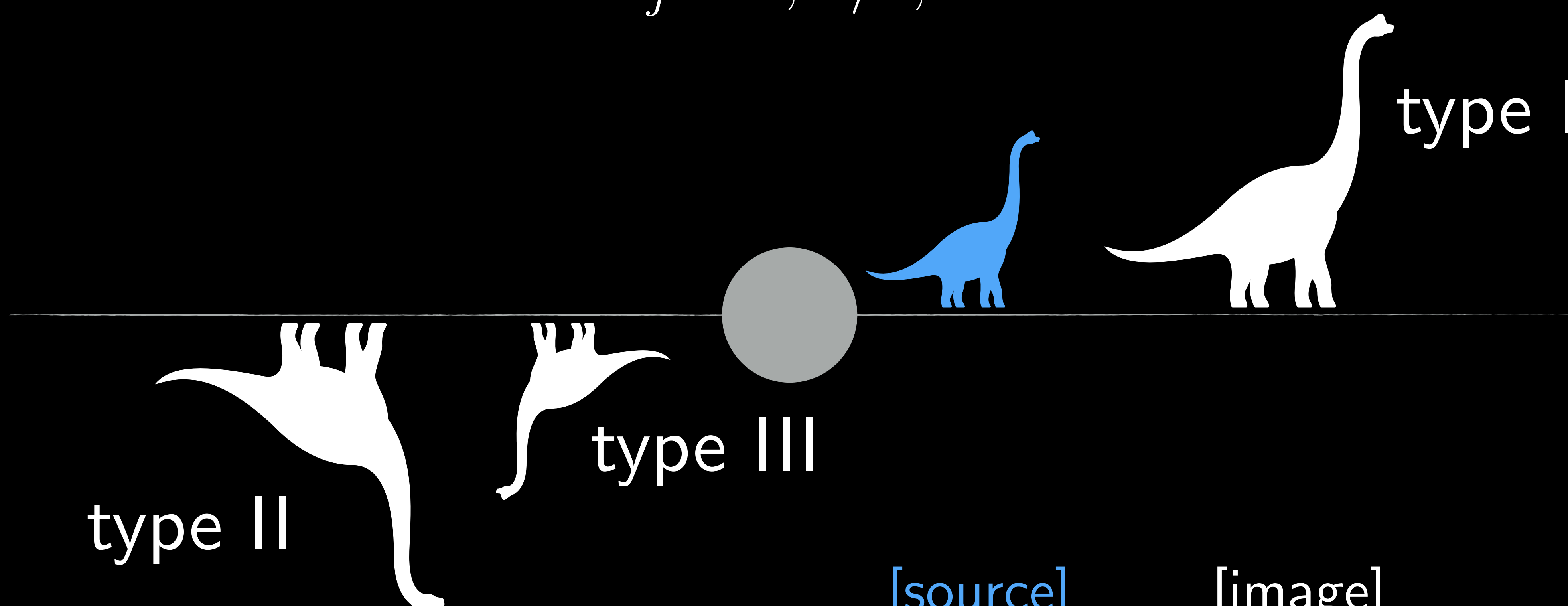
$$h_L(\omega) = F(\omega, \theta_S) \cdot h(\omega)$$

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

Magnification
Time delay
Phase shift

- Lensed signals acquire a different phase shift

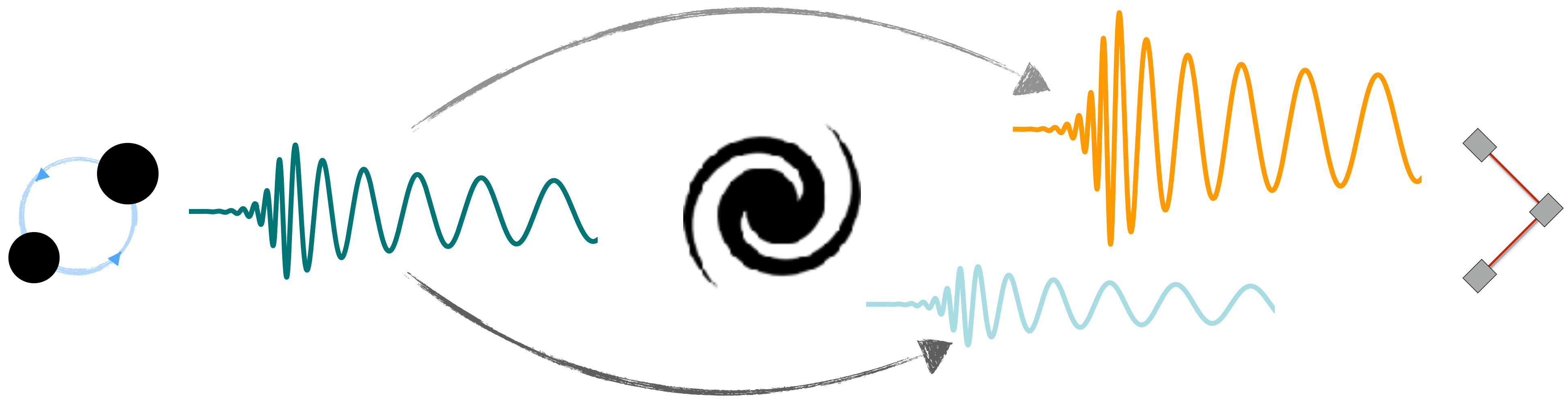
$$n_j = 0,\ 1/2,\ 1$$



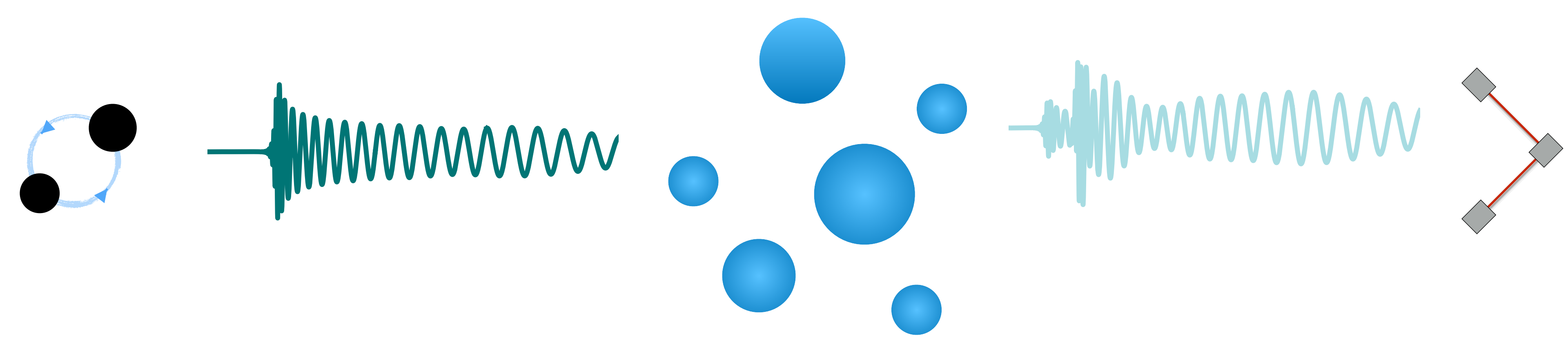
[source] [image]

Gravitational lensing - gravitational wave spectrum

Repeated chirps due to strong lensing

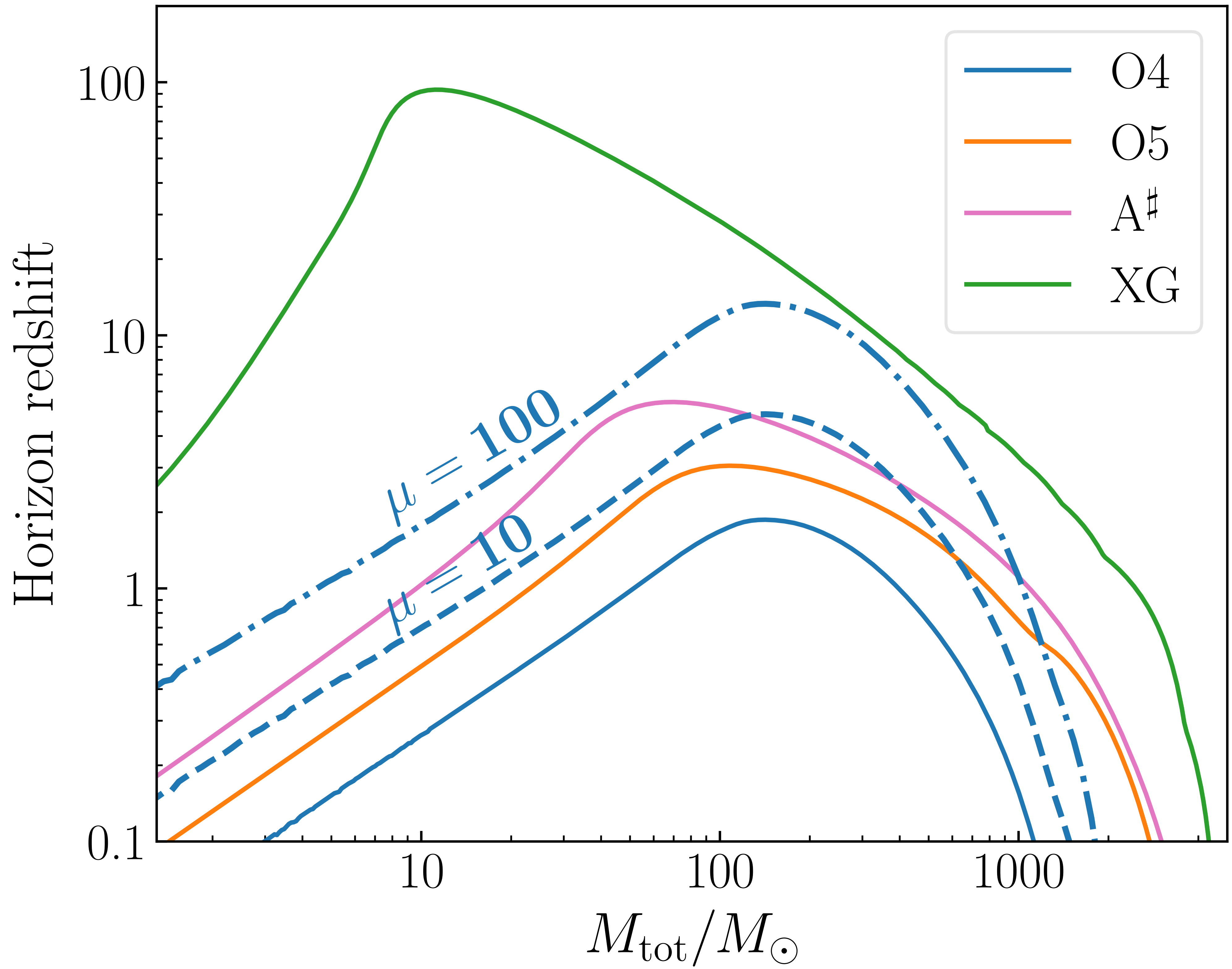


Waveform *distortions* by substructures



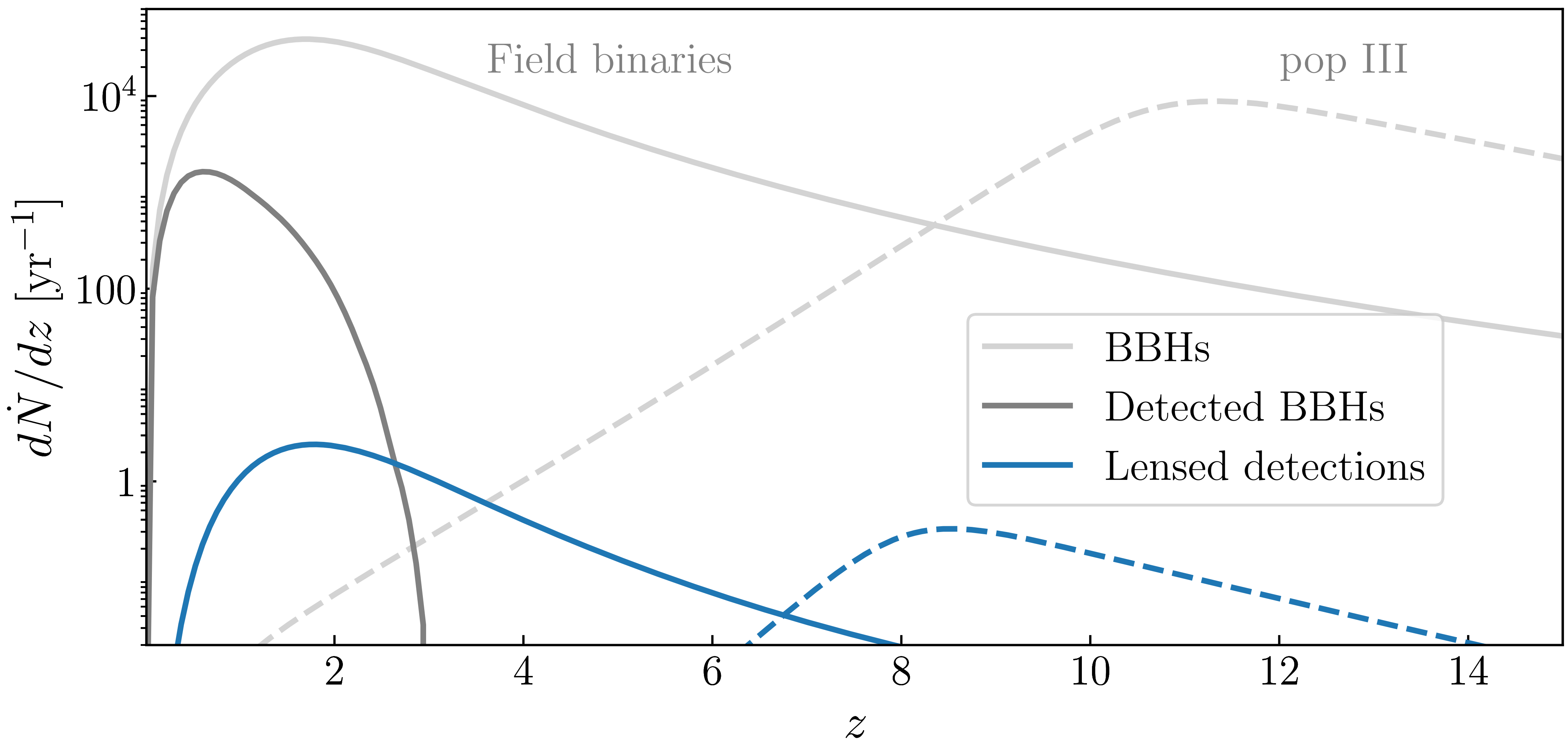
Source Lens Detector

Gravitational wave lensing:
expanding *horizons*



Gravitational wave lensing:
expanding *horizons* to detect new populations

E.g. two (toy) populations of black holes

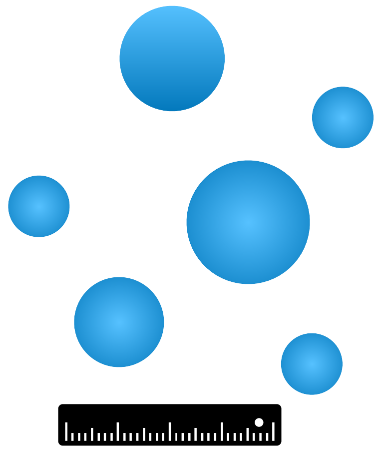


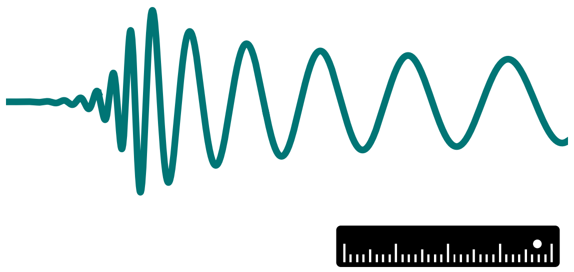
"field": ∼100,000 /yr; 100 lensed/yr;
[O5] 1500 det./yr, 5 lens det./yr

"pop-III": ∼35,000 /yr; 150 lensed/yr
[O5] 0 det./yr, 1 lens. det./yr

Gravitational wave lensing:

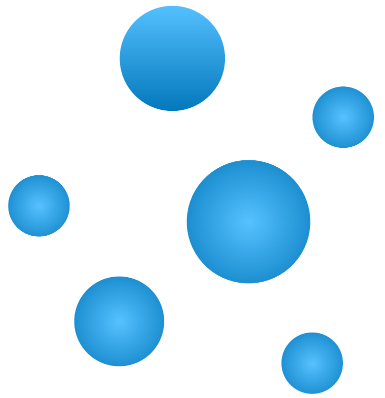
probing *dark matter* structures





$$\lambda_{\rm gw} \sim 10^3 {\rm km} \left(\frac{M_{\rm bbh}}{10 M_\odot} \right)$$

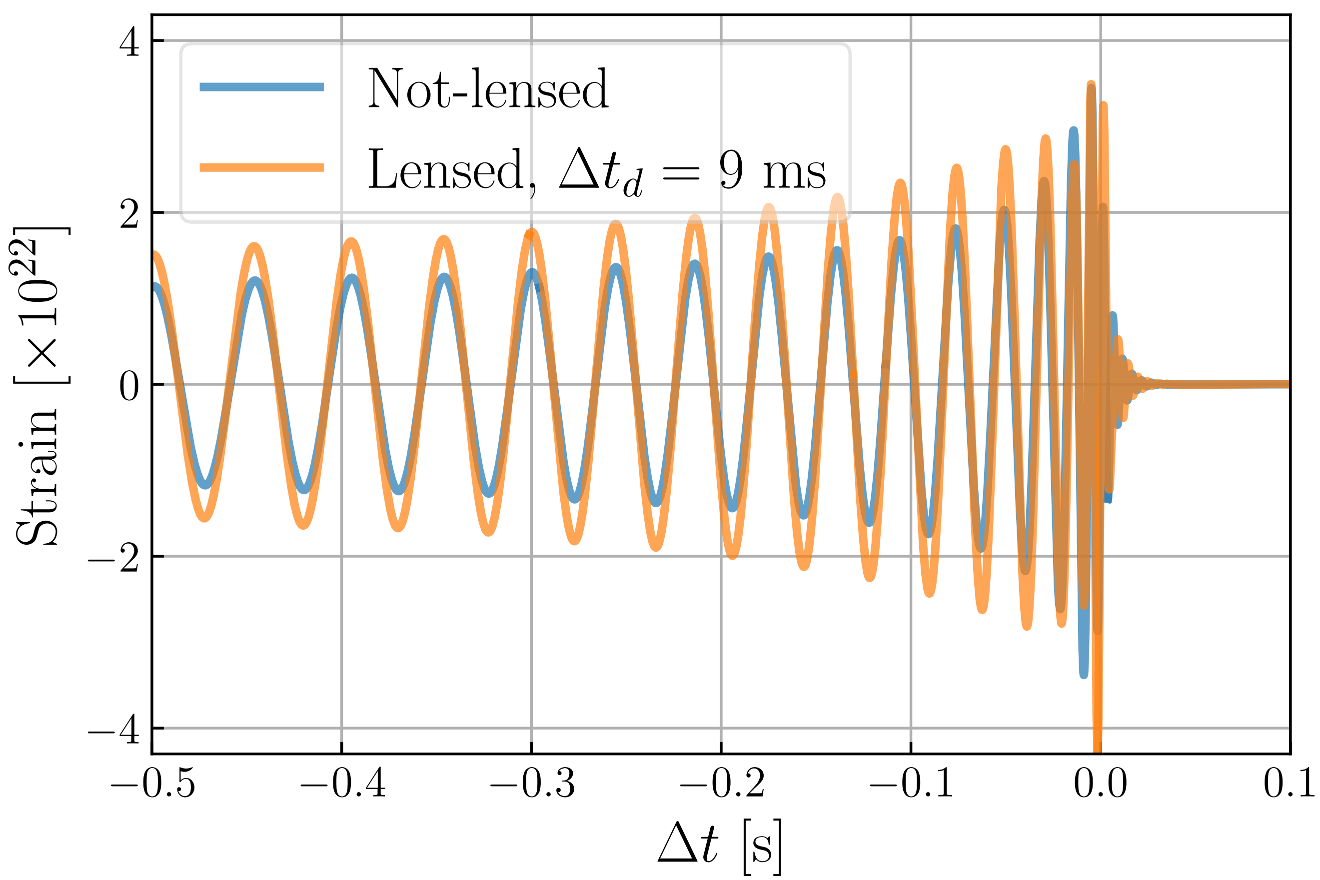
Gravitational wave lensing:
probing *dark matter* structures



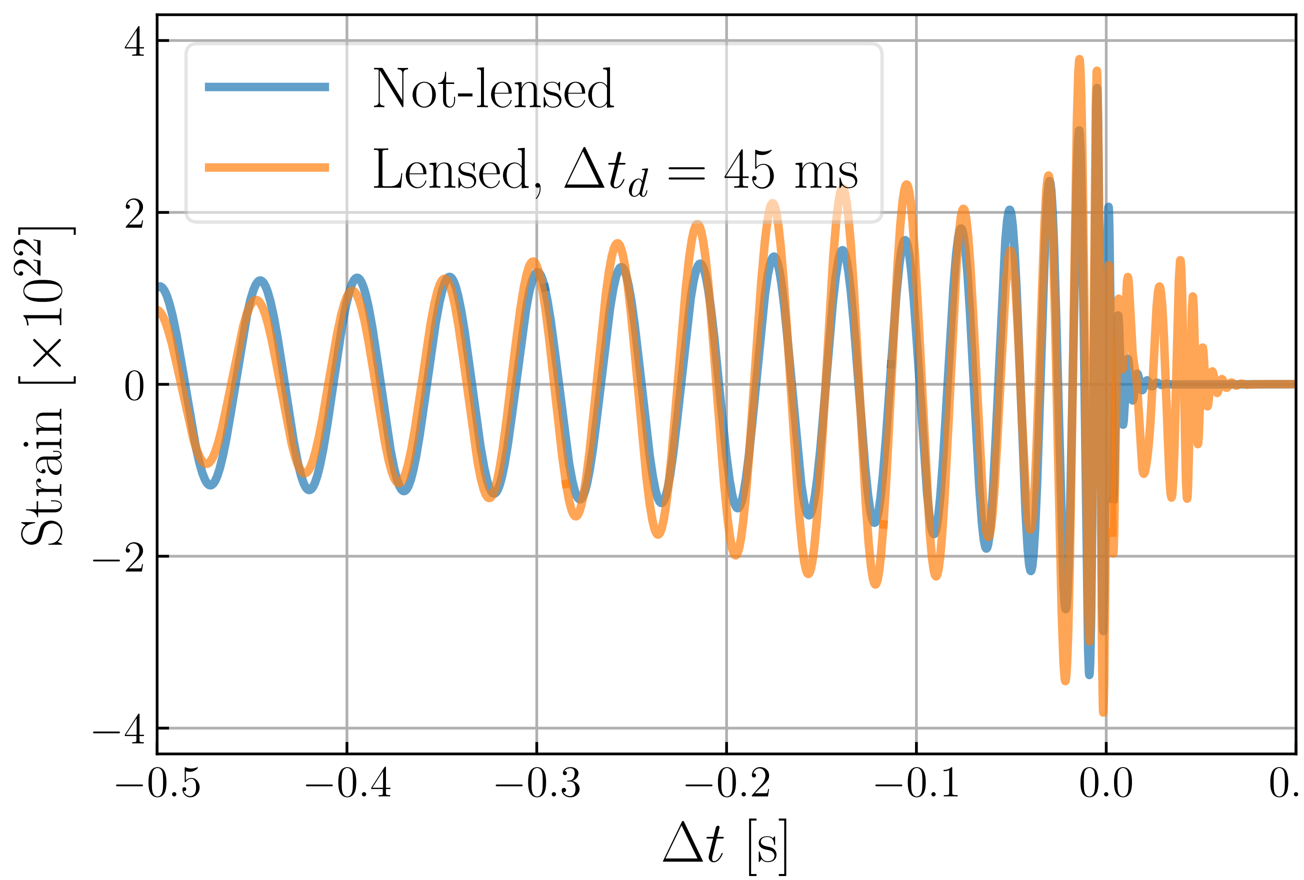
E.g. compact (point) lenses: *PBHs*, *IMBHs*

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

Diffraction

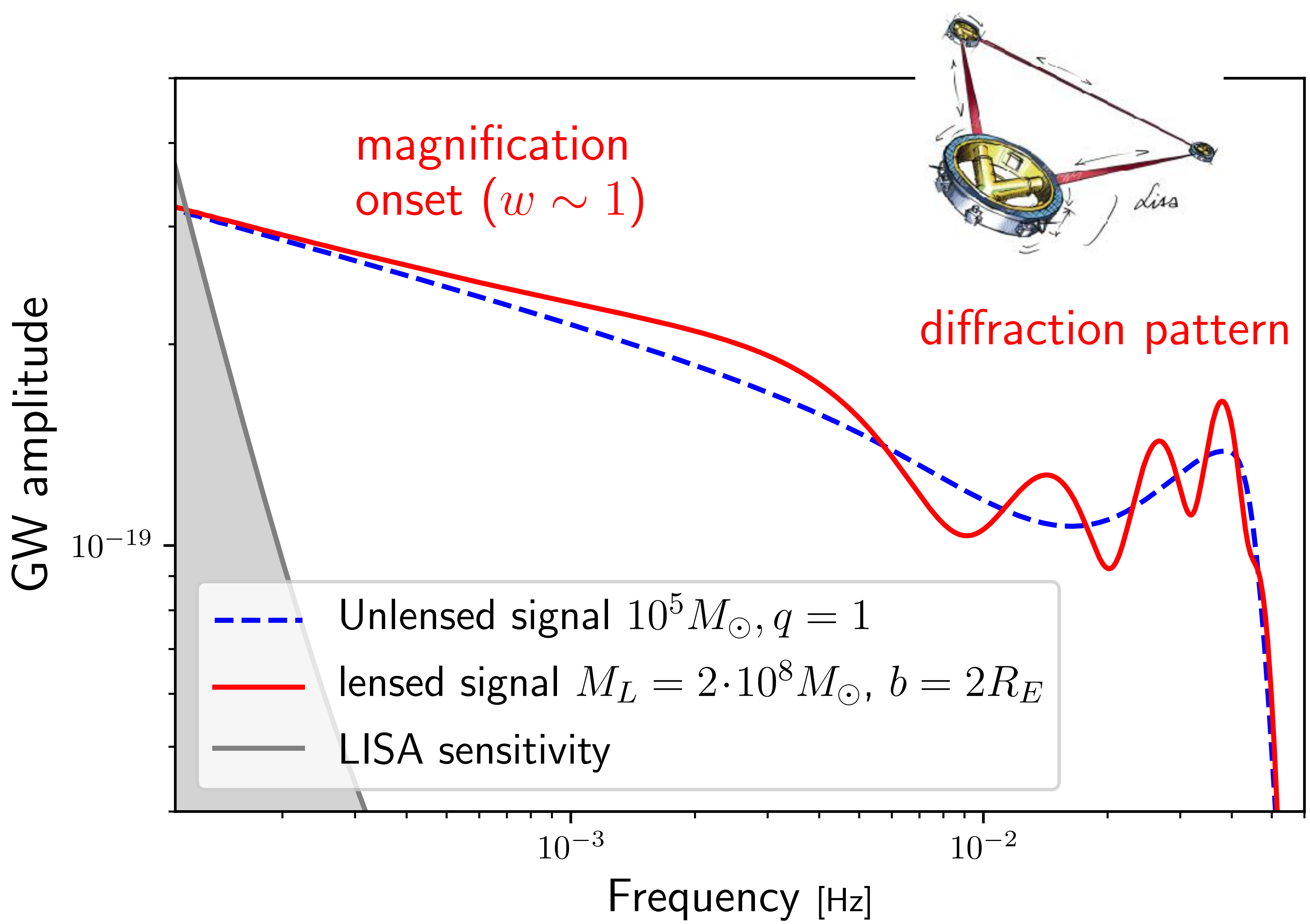


Interference



Gravitational wave lensing:
probing *dark matter* structures

E.g. subhalos are comparable to *supermassive* binary black hole coalescences. *LISA* signals could distorted by lensing!



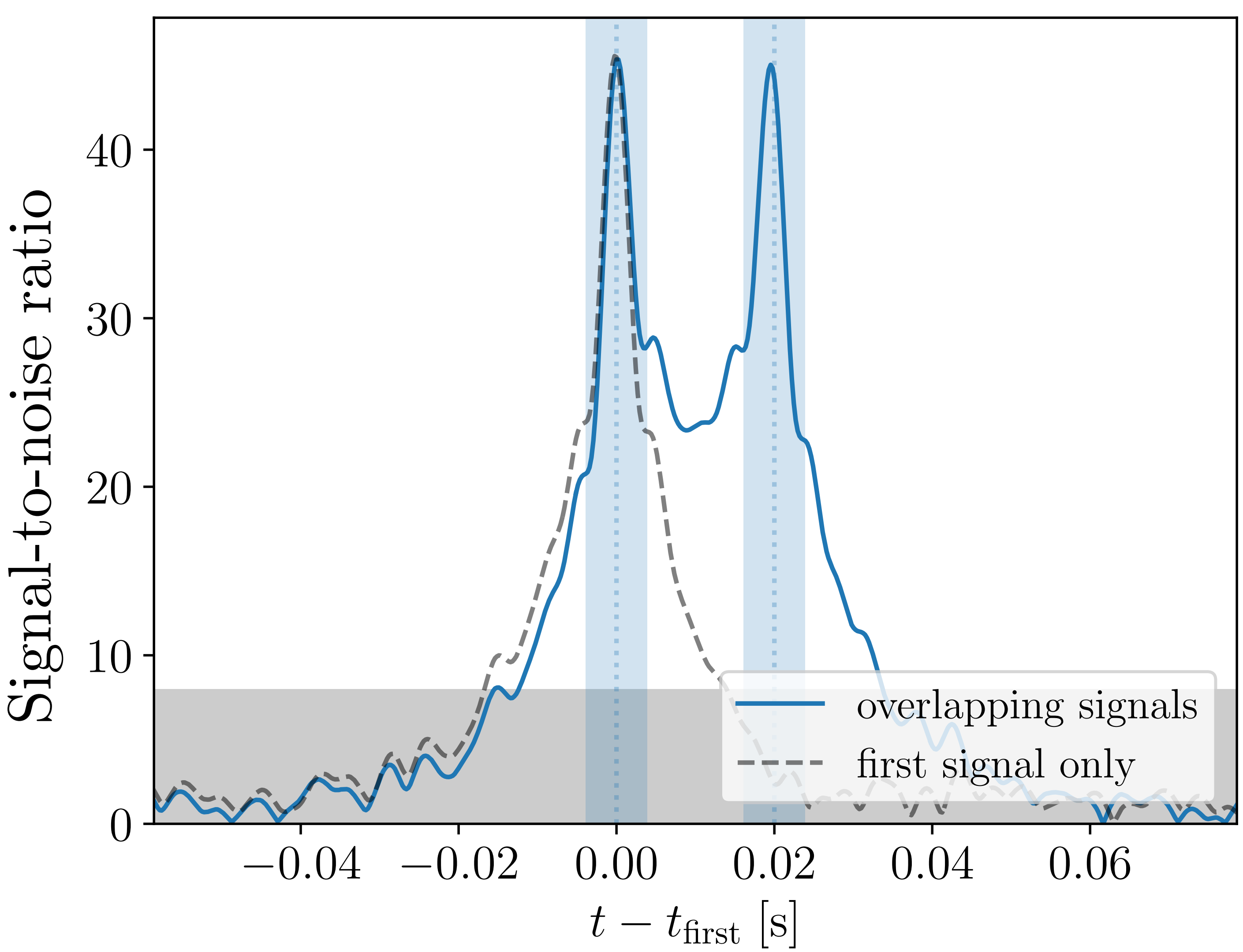
[Çalışkan *et al.*; PRD'23]
[Brando *et al.*; PRD'25]

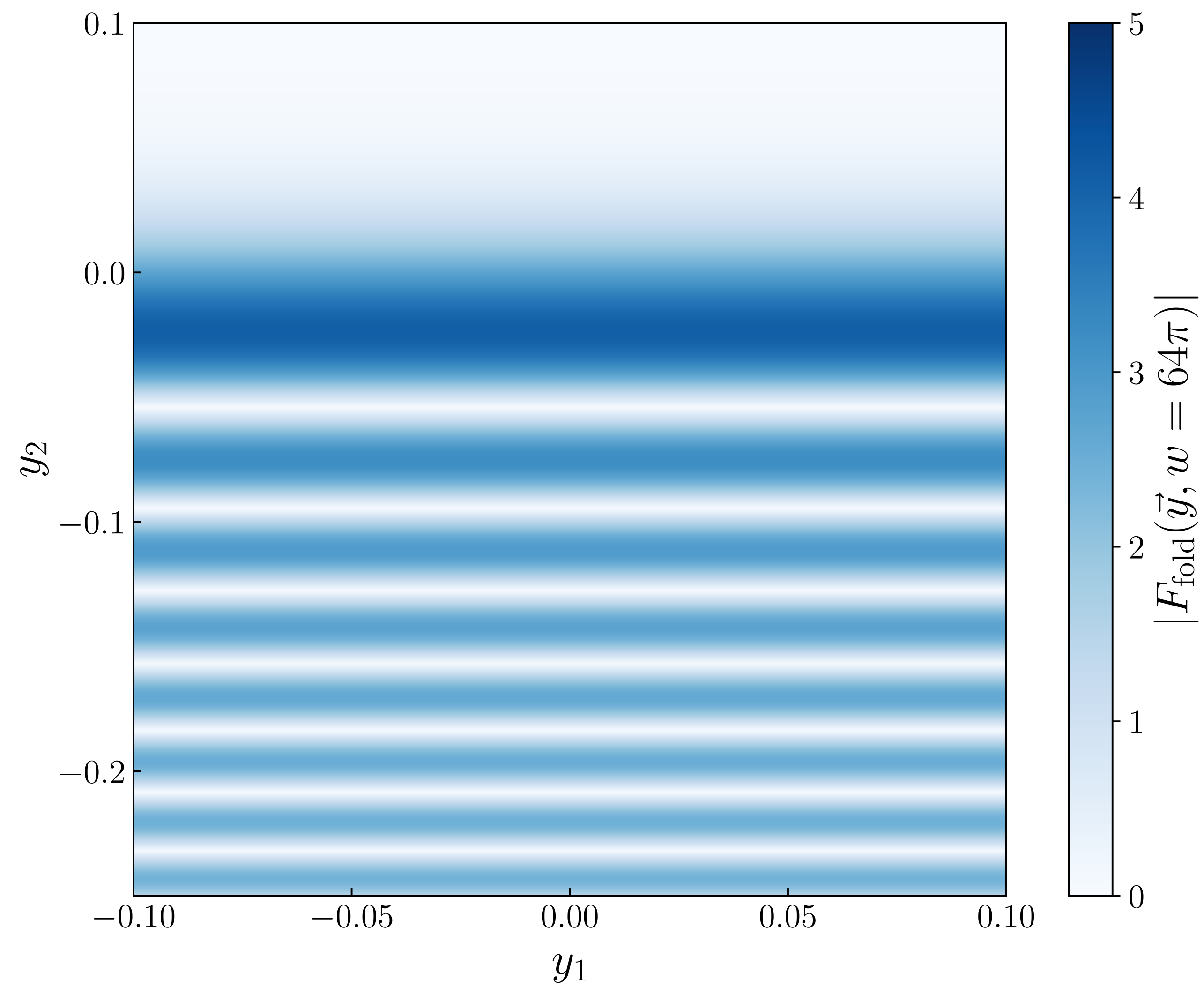
[LISA Cosmo white paper]

Gravitational wave lensing:

Highly magnified, overlapping signals near caustics

E.g. interference and diffraction near fold caustic



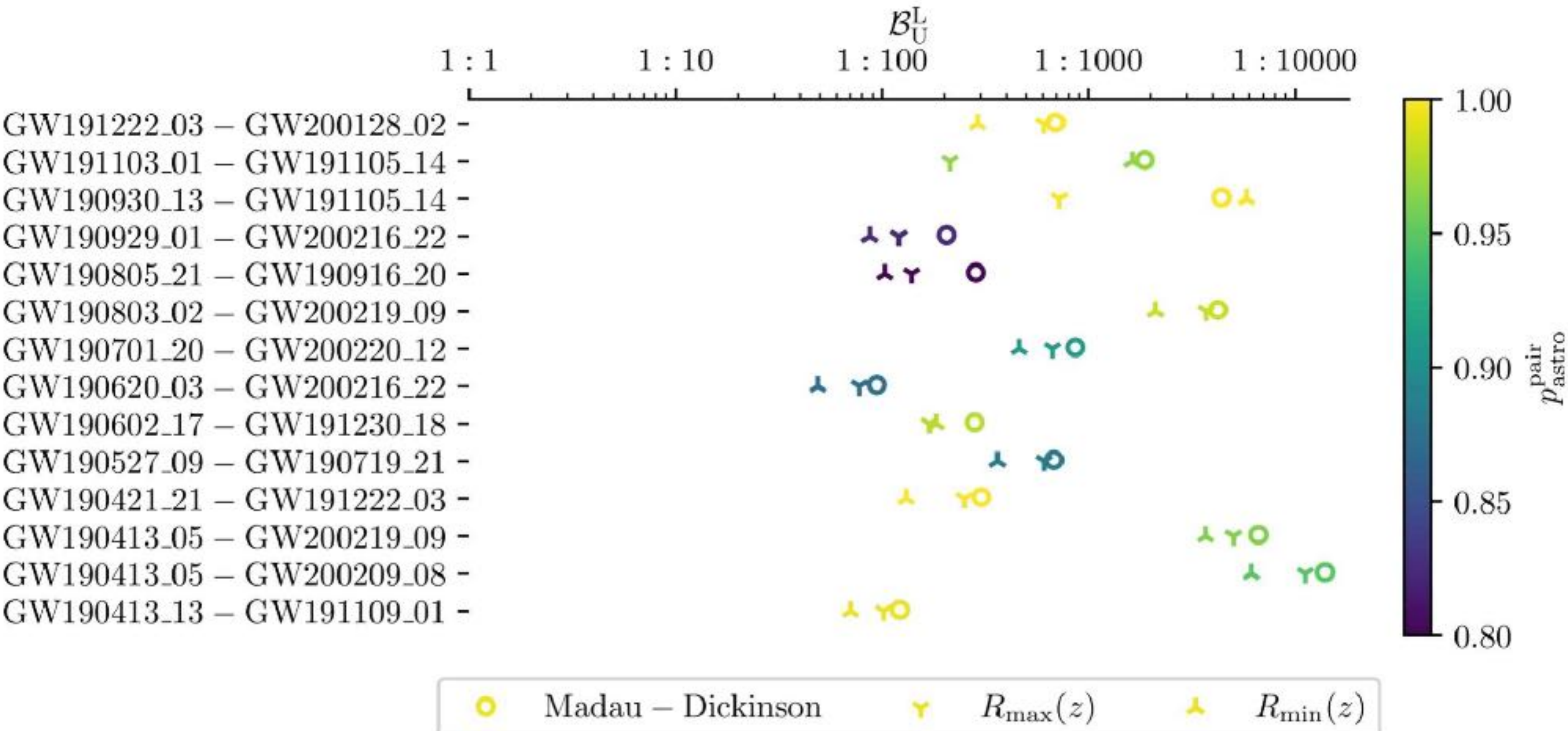


[Lo, Vujeva, **Ezquiaga**, Chan; PRL'25]

[**Ezquiaga**, Lo, Vujeva; 2025]

Lensing searches: GWTC-3

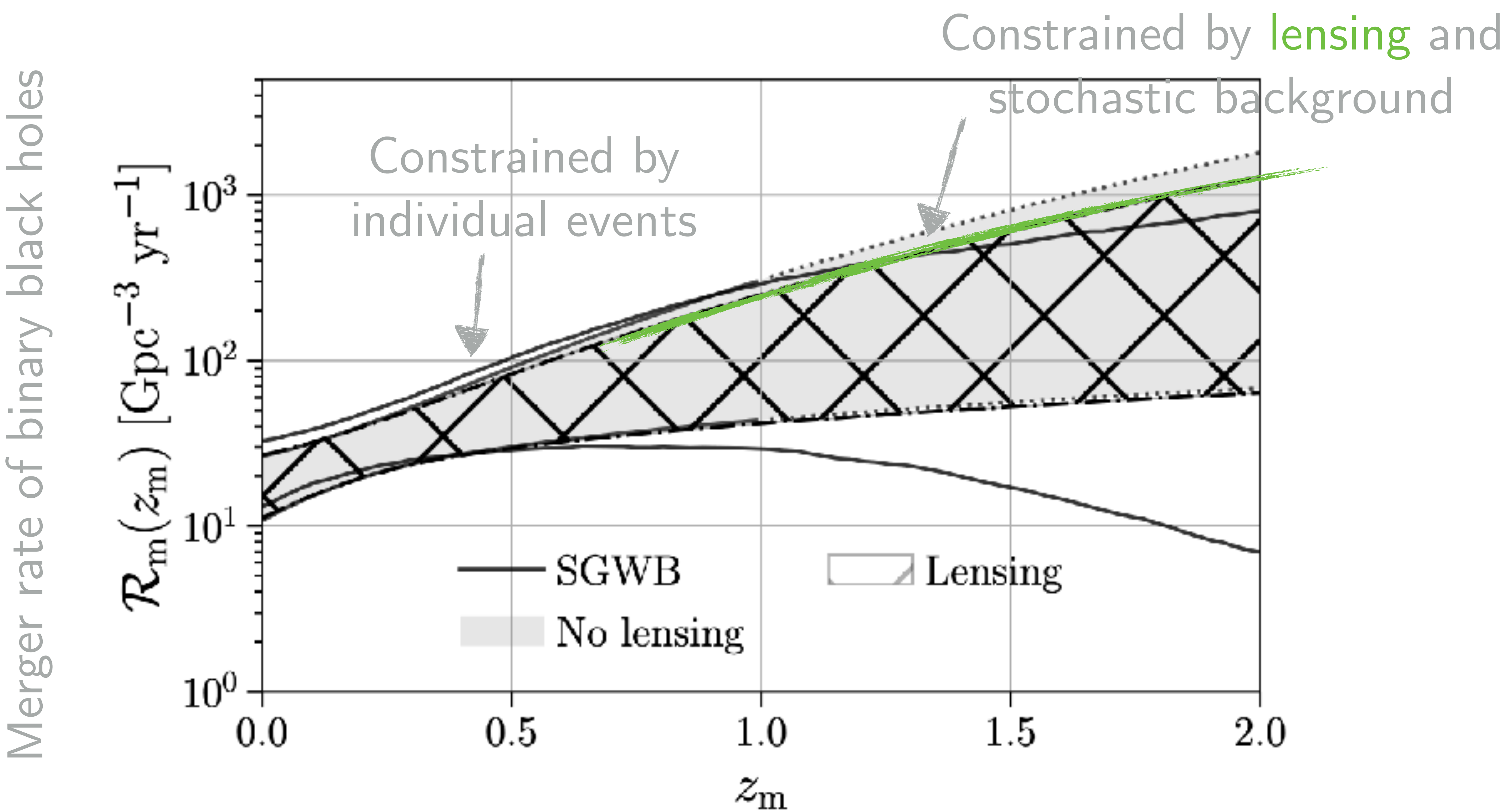
- No evidence of *repeated chirps* in the data
- No evidence of *distorted lensed* waveforms in the data



[LVK lensing GWTC-2] [LVK lensing GWTC-3]

Lensing searches: GWTC-3

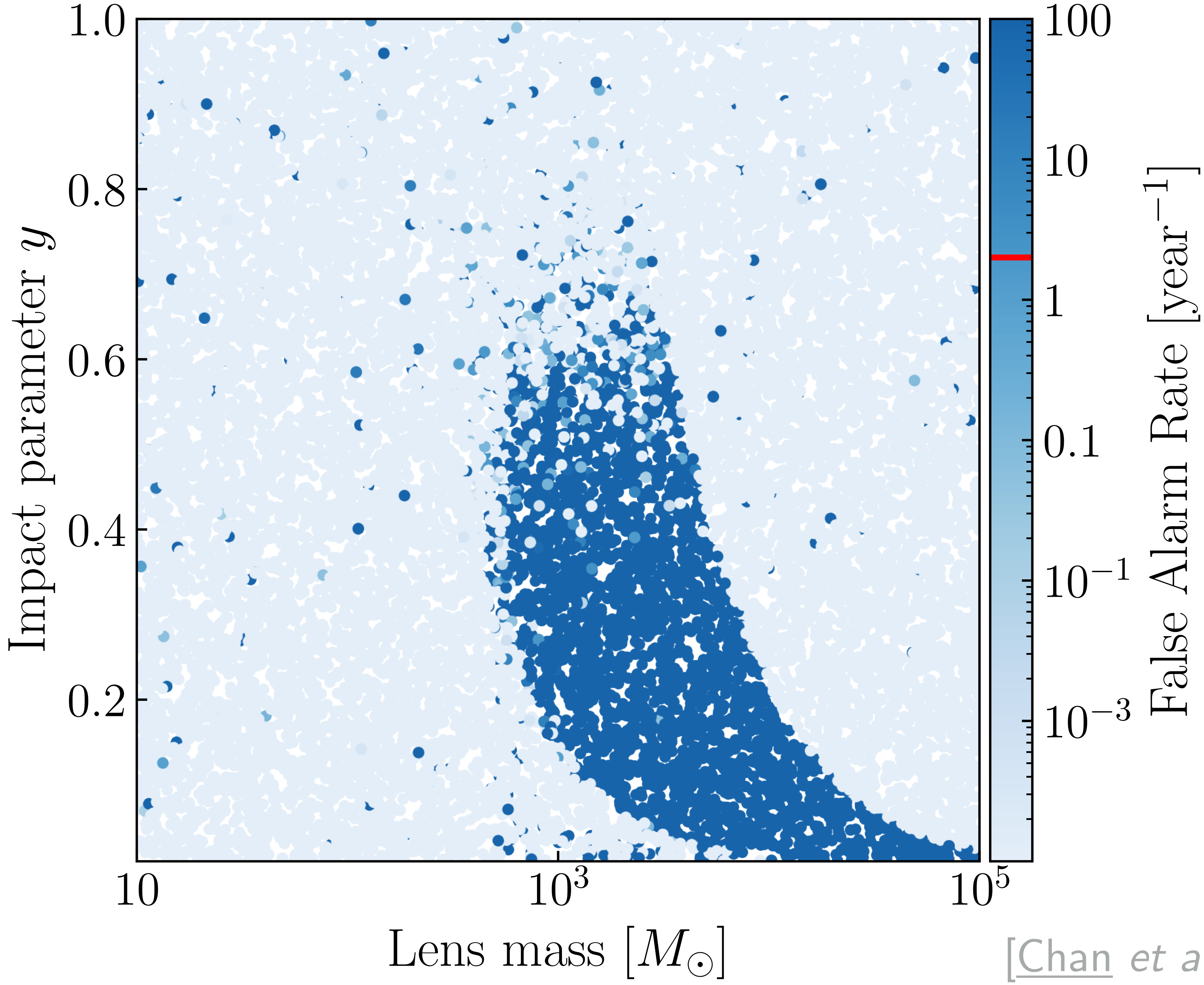
- *Upper bound* on binary black hole merger rate



[LVK lensing GWTC-2] [LVK lensing GWTC-3]

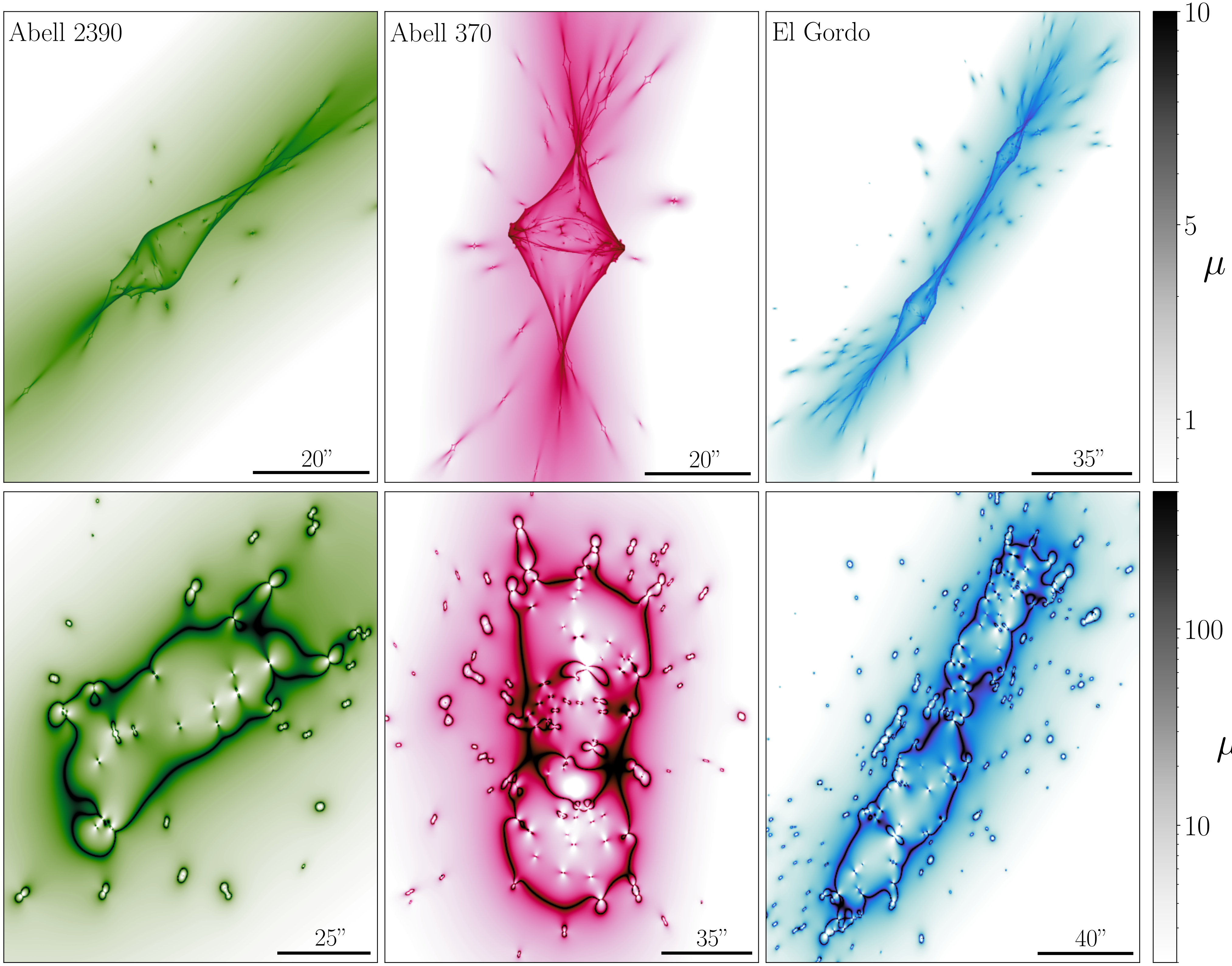
Searching for lensed GWs

- Distorted waveforms could be *missed* by current searches!



[Chan *et al.*; PRD'25]

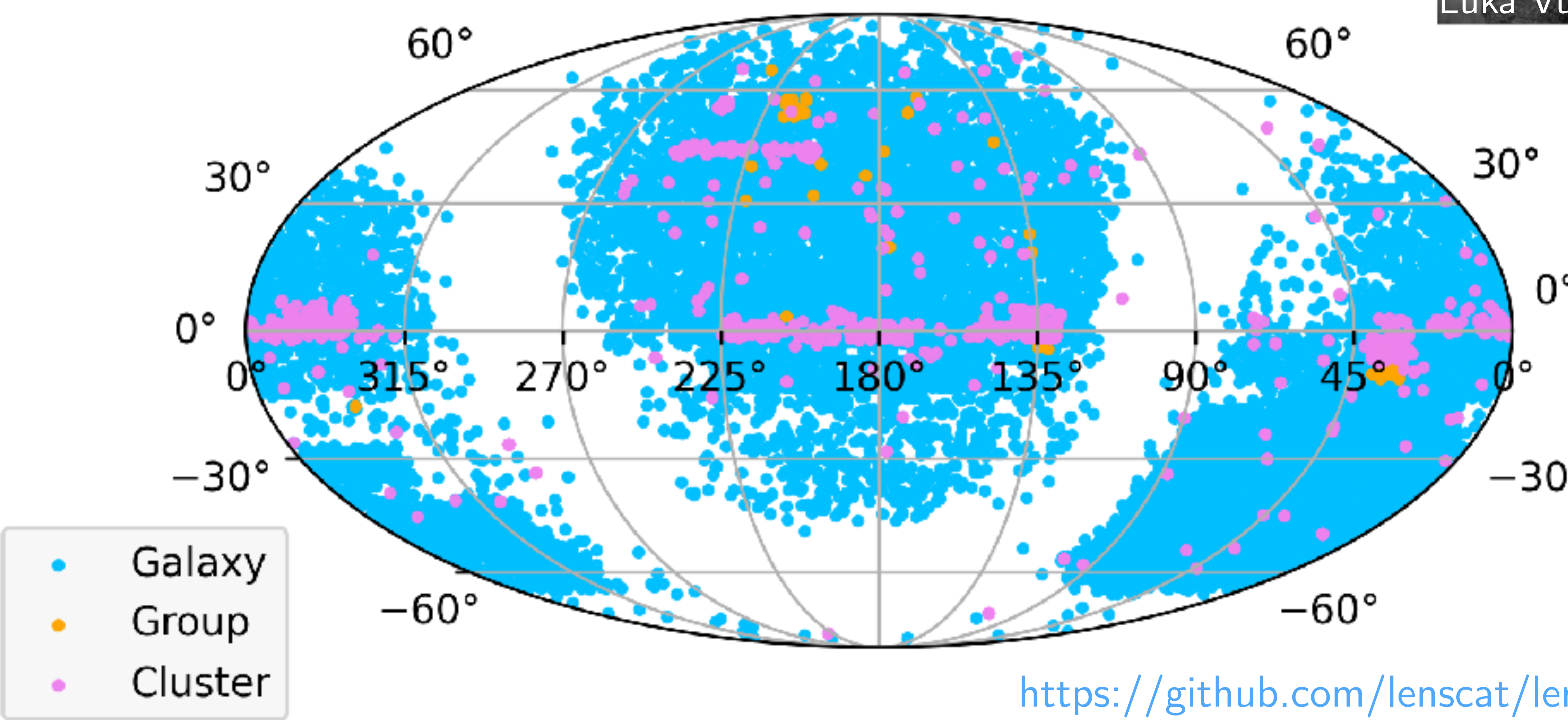
Substructures - clusters



[Vujeva, **Ezquiaga**, Lo, Chan; 2025]

Multi-messenger lensing

- Cross match GWs with *lens catalogs*
- Identify host galaxy (*sky localization!*)
- Watchlist for efficient lenses



https://github.com/lenscat/lenscat

Conclusions

Looking forward for your questions!

Gravitational waves are precious cosmological probes:

- Well understood signals from general relativity
- Travel unaltered except for *gravitational lensing*

- Probing origin of the observed black holes and dark matter substructures via lensing

- Future of gravitational wave astronomy is exciting!

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Join us!

ezquiaga.github.io/joinus