Gravitational-wave astronomy: Today & tomorrow

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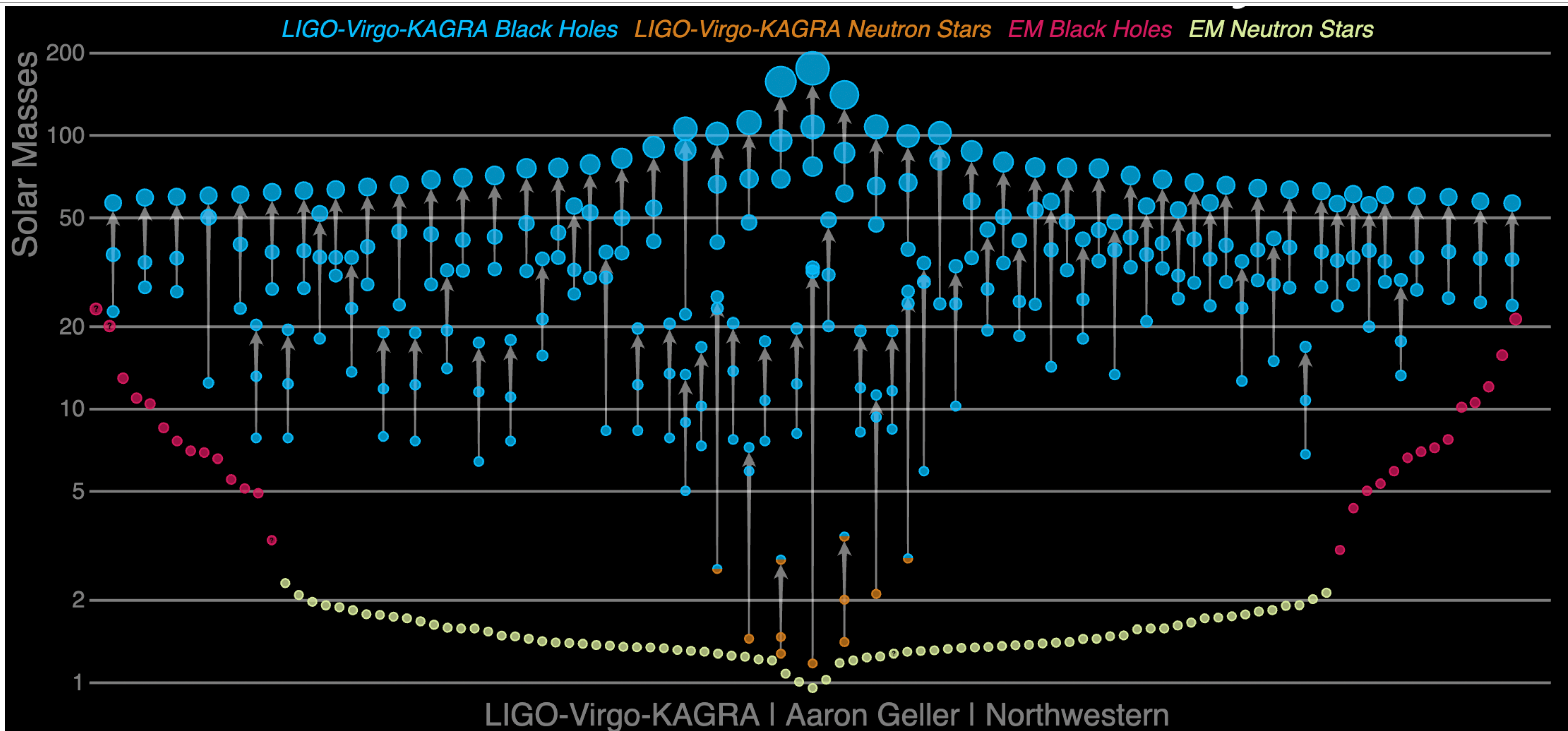
Dark Side of the Universe | Kigali | 14 Jul 2023

GW observations have established a new branch of astronomy



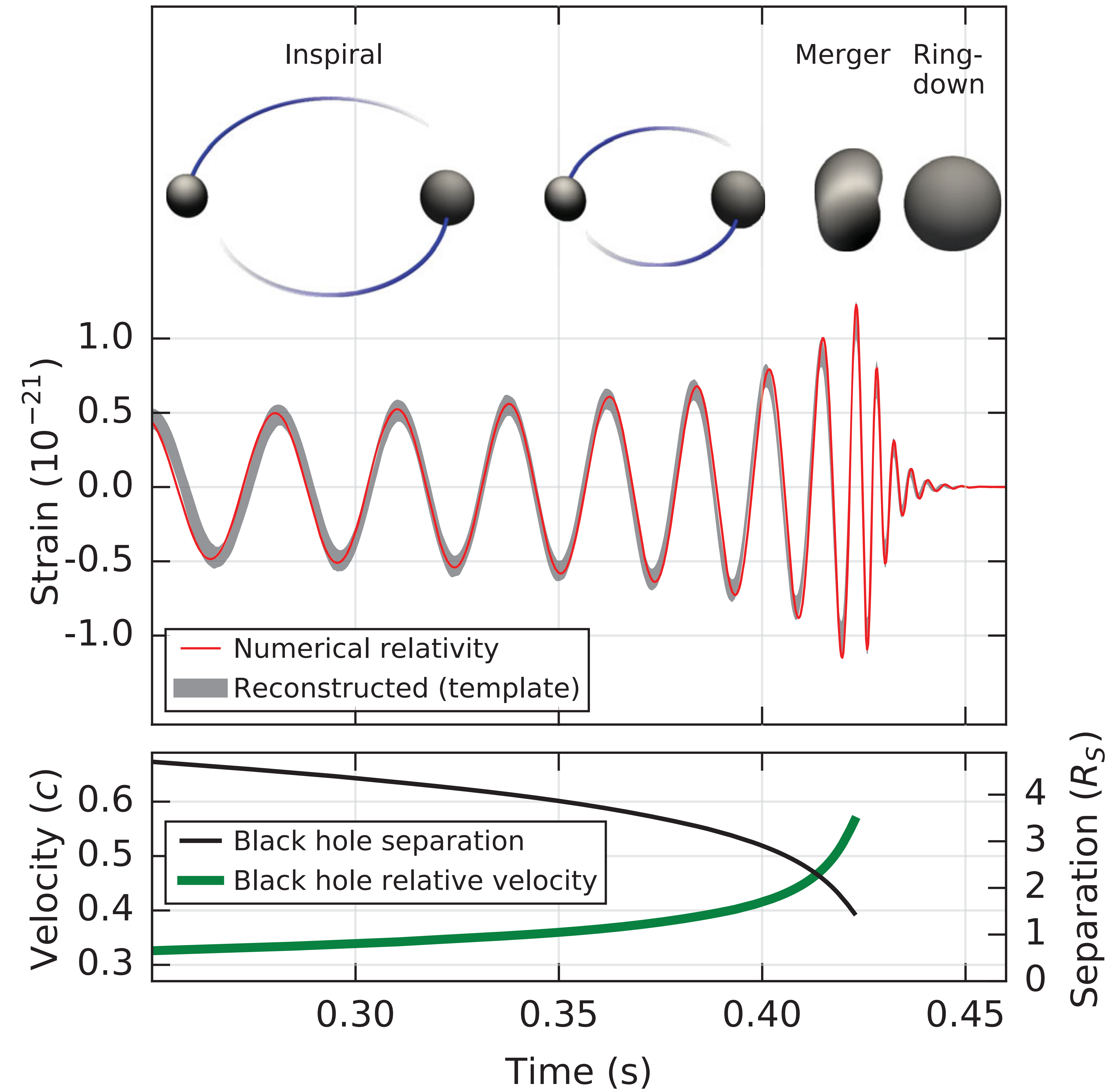
90 CBC detections from the first three observing runs (LVC analysis)
Additional events from independent analyses of the data.

Gravitational-wave astronomy: Observations

- First detections of merging binary BHs and NS-BH binaries.
- First observations of stellar-mass black holes with mass $\gtrsim 30\ M_\odot$.
- Potential evidence of IMBHs (GW190521)
- Multi-messenger observation of a BNS merger (GW170817).
- Additional BNS /NSBH binaries (no EM counterpart).
- Either the heaviest NS or lightest BH ever observed (GW190814).
- Binaries with large mass ratios. Evidence of higher multipoles (GW190814, GW190412).

Gravitational-wave astronomy: Science

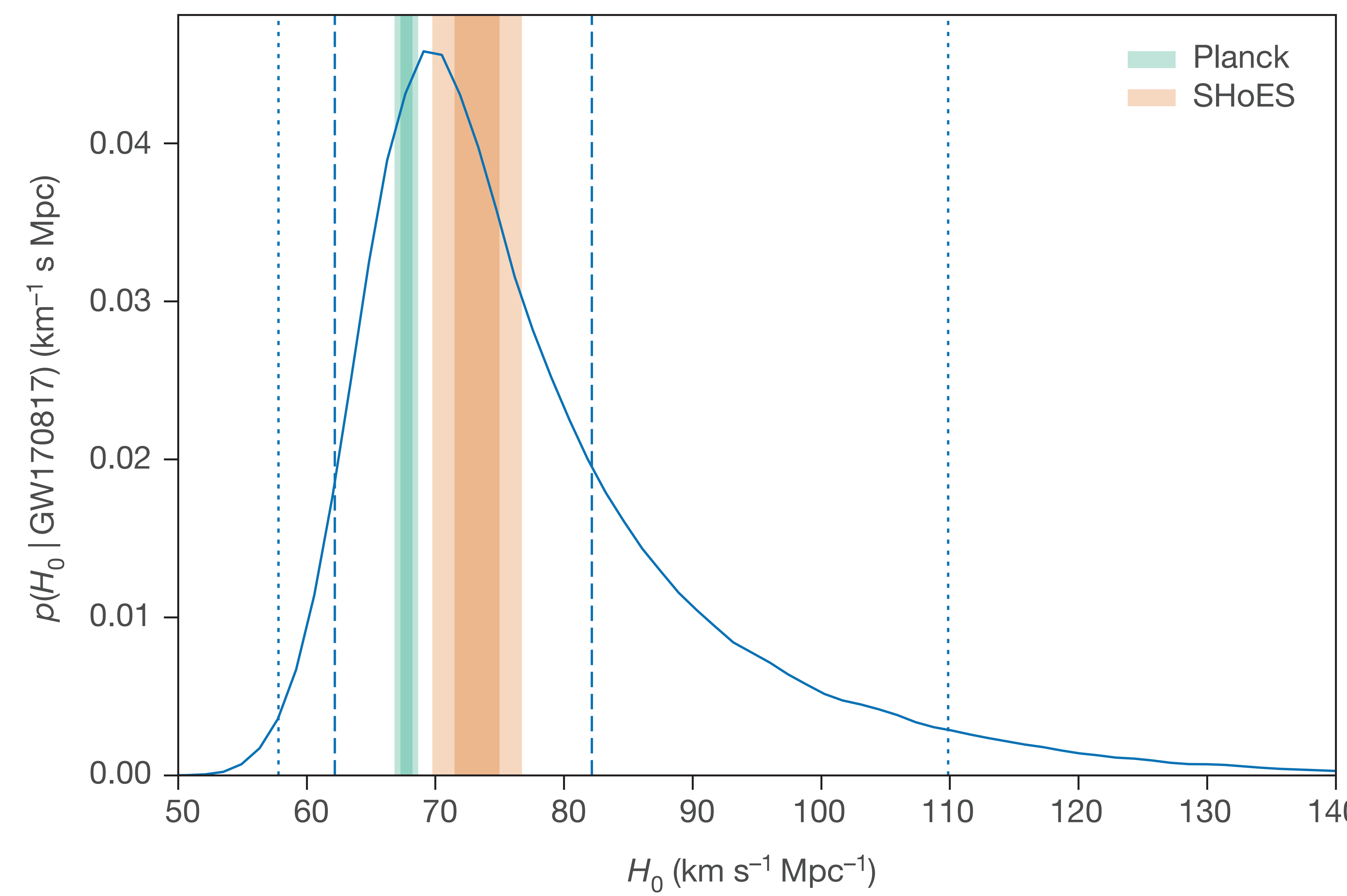
- First tests of GR in the regime of extreme gravity & velocities.
  - **Waveform based tests** Signal consistency, GW generation & propagation, nature of GW polarizations, BH quasi-normal modes, …
  - **Multi-messenger tests** Speed of GWs, Test of the equivalence principle, Lorentz violation, non-compact extra dimensions, …



Gravitational-wave astronomy: Science

- First tests of GR in the regime of extreme gravity & velocities.
- New avenues for cosmography.

[Nature 551, 81 (2017)]



Hubble constant estimate from the BNS merger GW170817 and its EM counterparts

Gravitational-wave astronomy: Science

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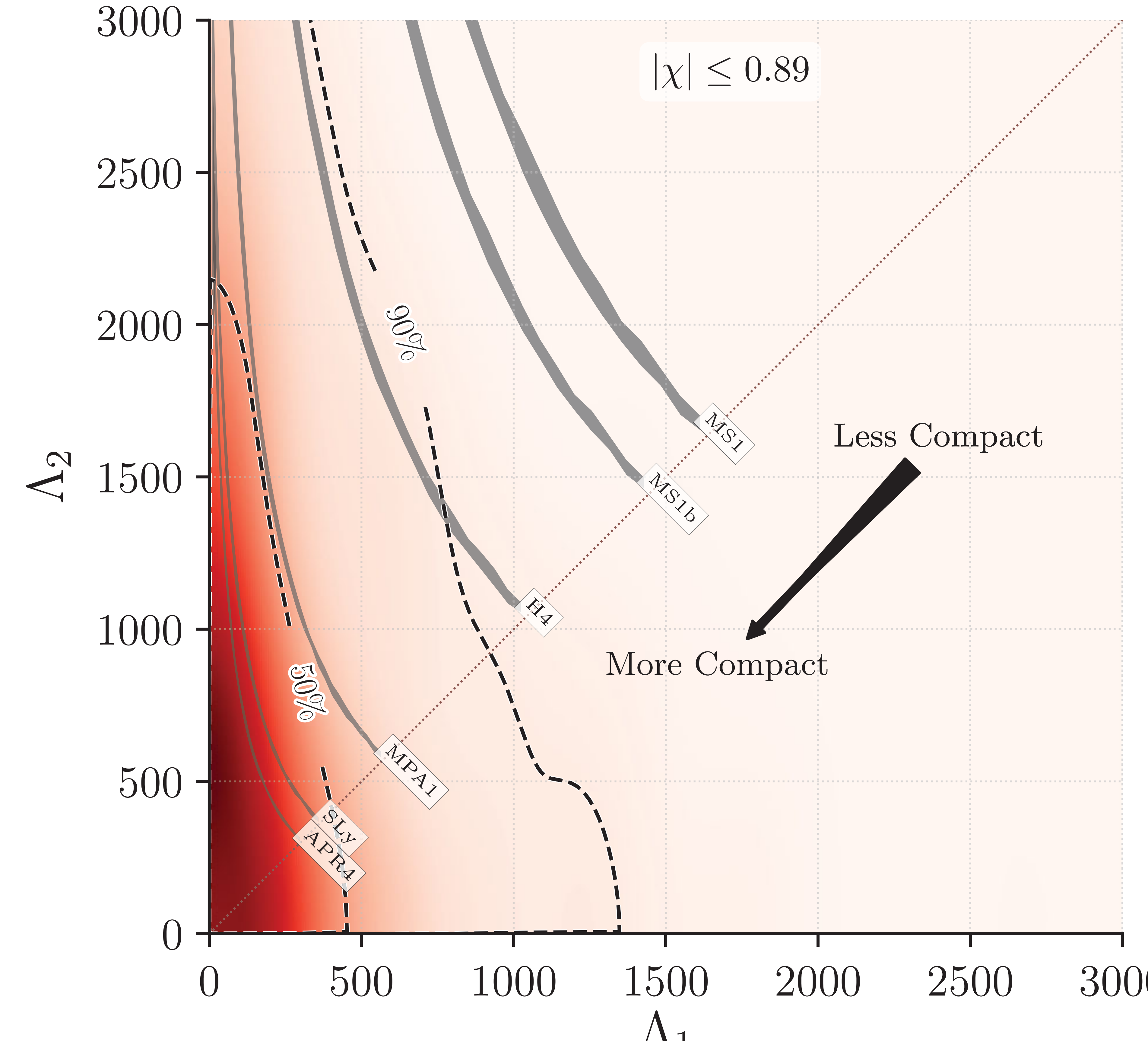
- New avenues for cosmography.
- Constraints on the EoS of dense nuclear matter.

[LVC+, PRL 119, 161101 (2017)]



Constraints on tidal deformability disfavour EoSs that predict less compact stars.

Gravitational-wave astronomy: Science

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- New avenues for cosmography.
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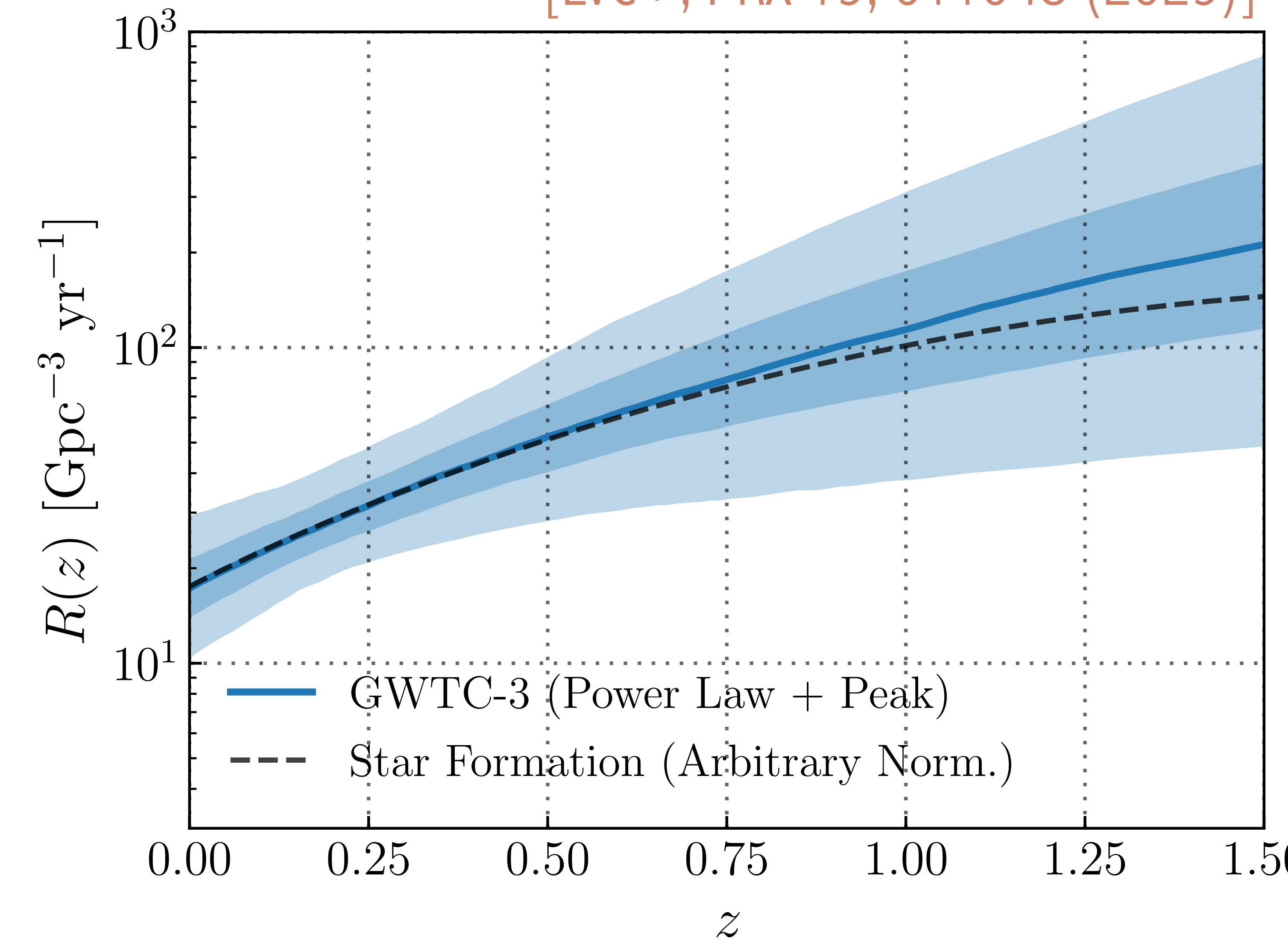
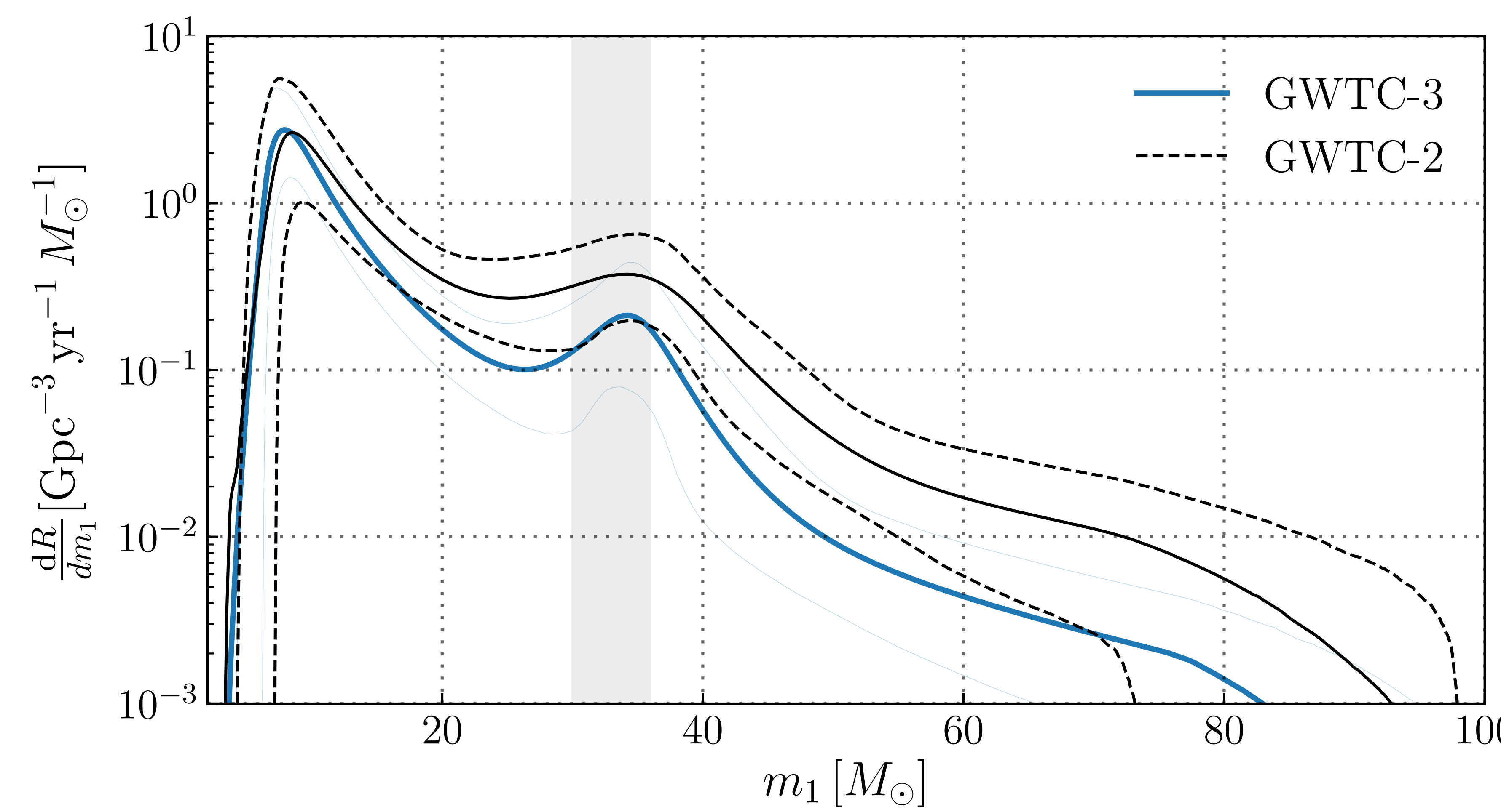
- Binary population inference: merger rates, mass & redshift distribution of CBCs.

[LVC+, PRX 13, 011048 (2023)]





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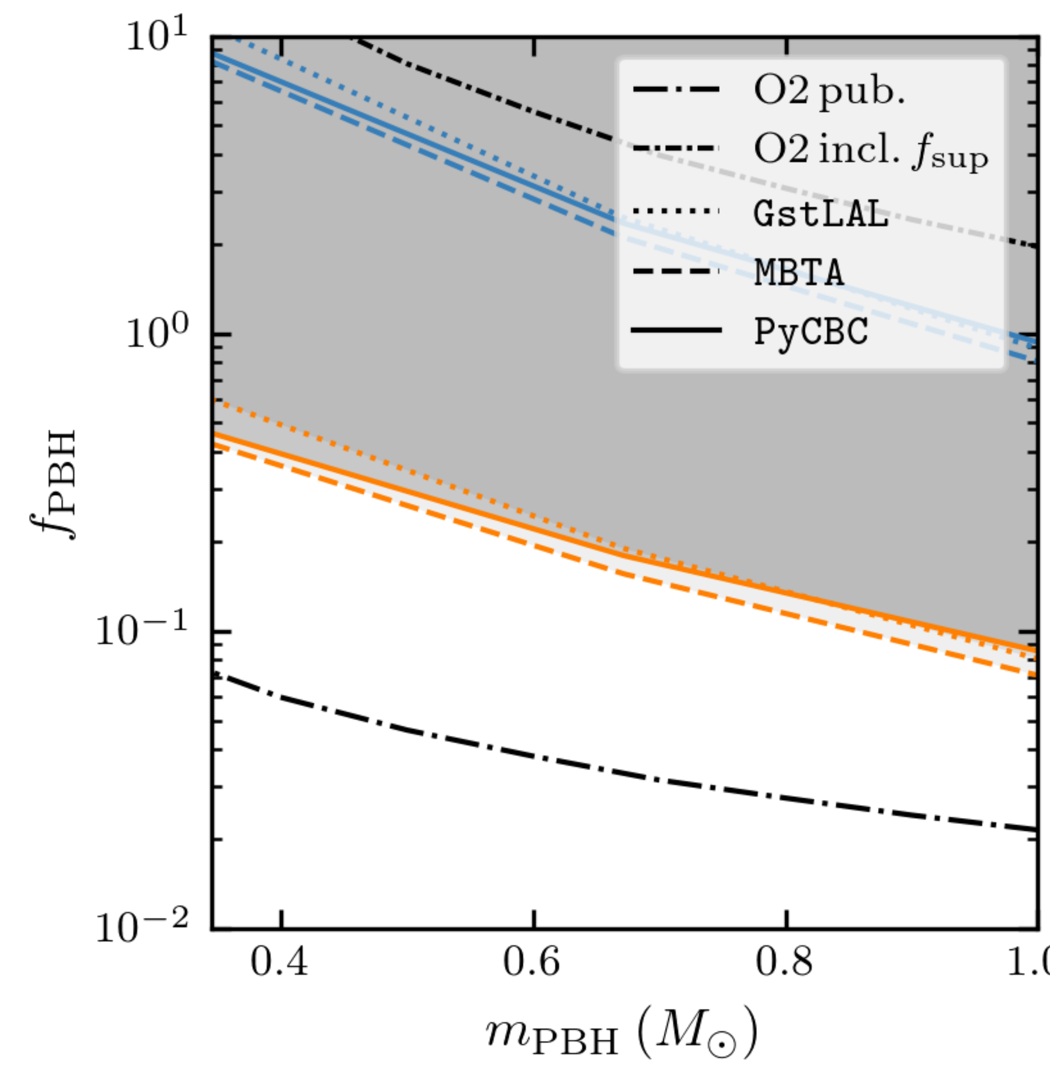
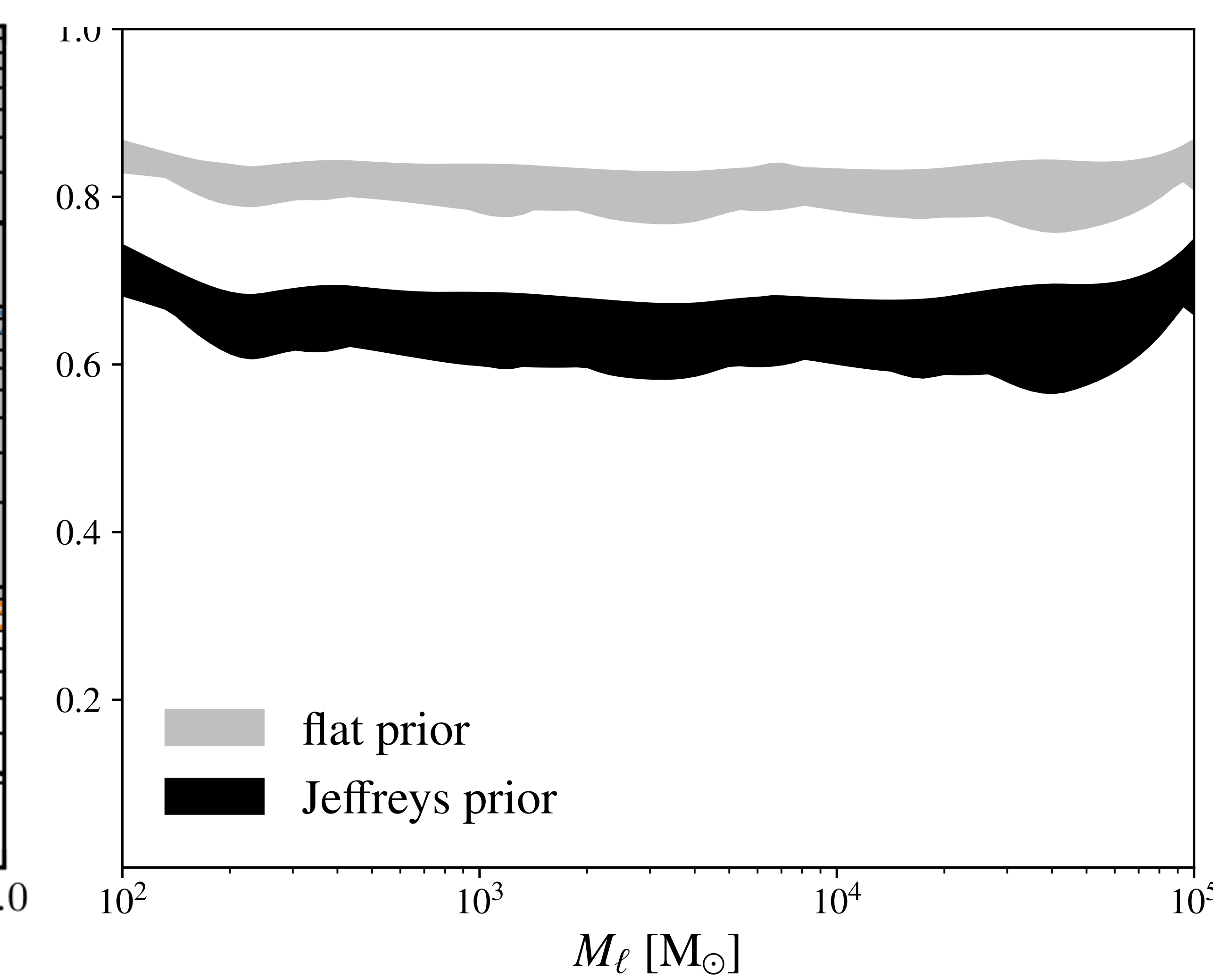
- Binary population inference: merger rates, mass & redshift distribution of CBCs.
- Constraints on primordial BHs.

[LVC+, arXiv:2212.01477]



From the non-observation of sub-solar mass binaries

[LVC+, arXiv:2304.08393]

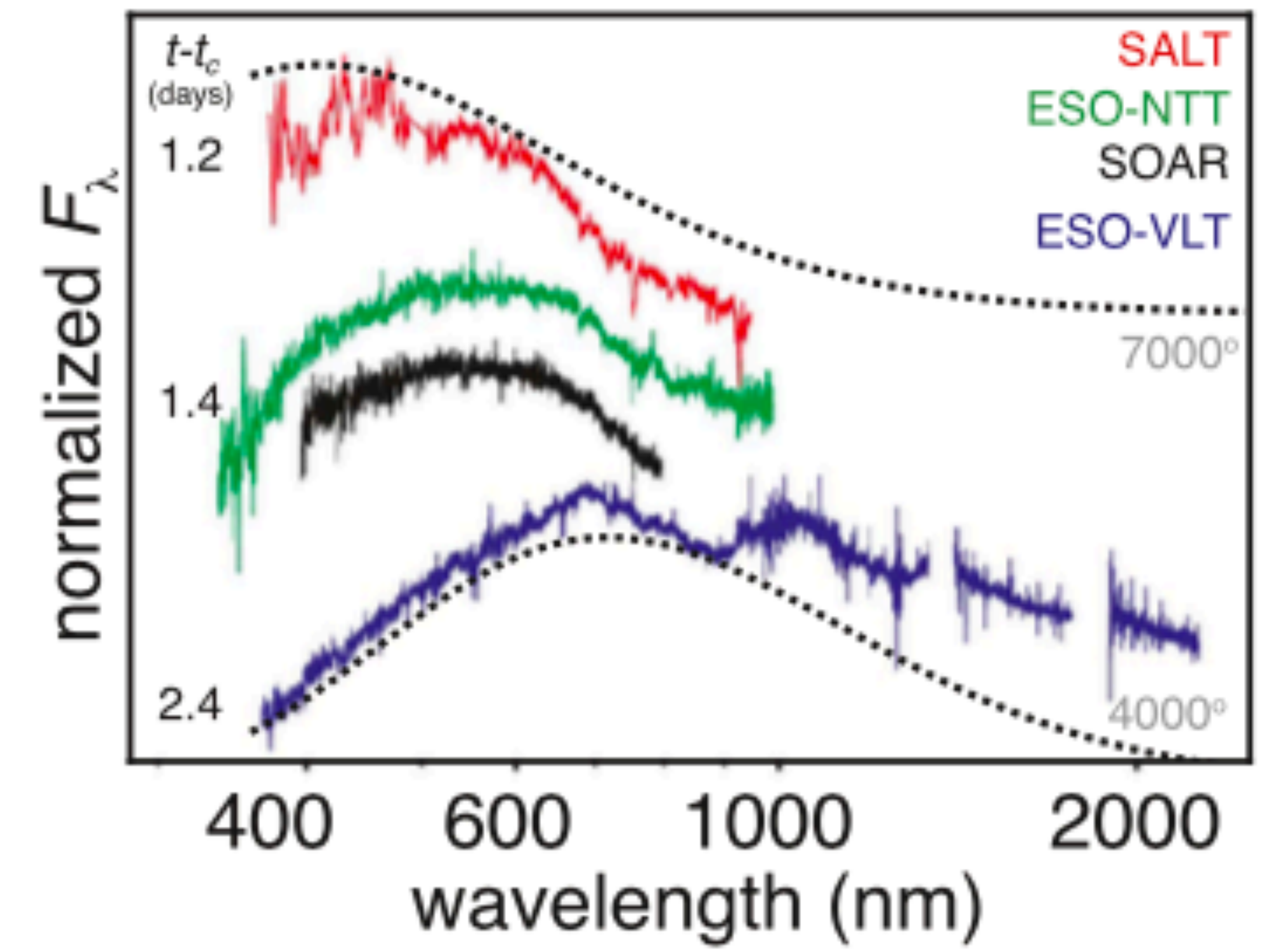


From the non-observation of GW microlensing

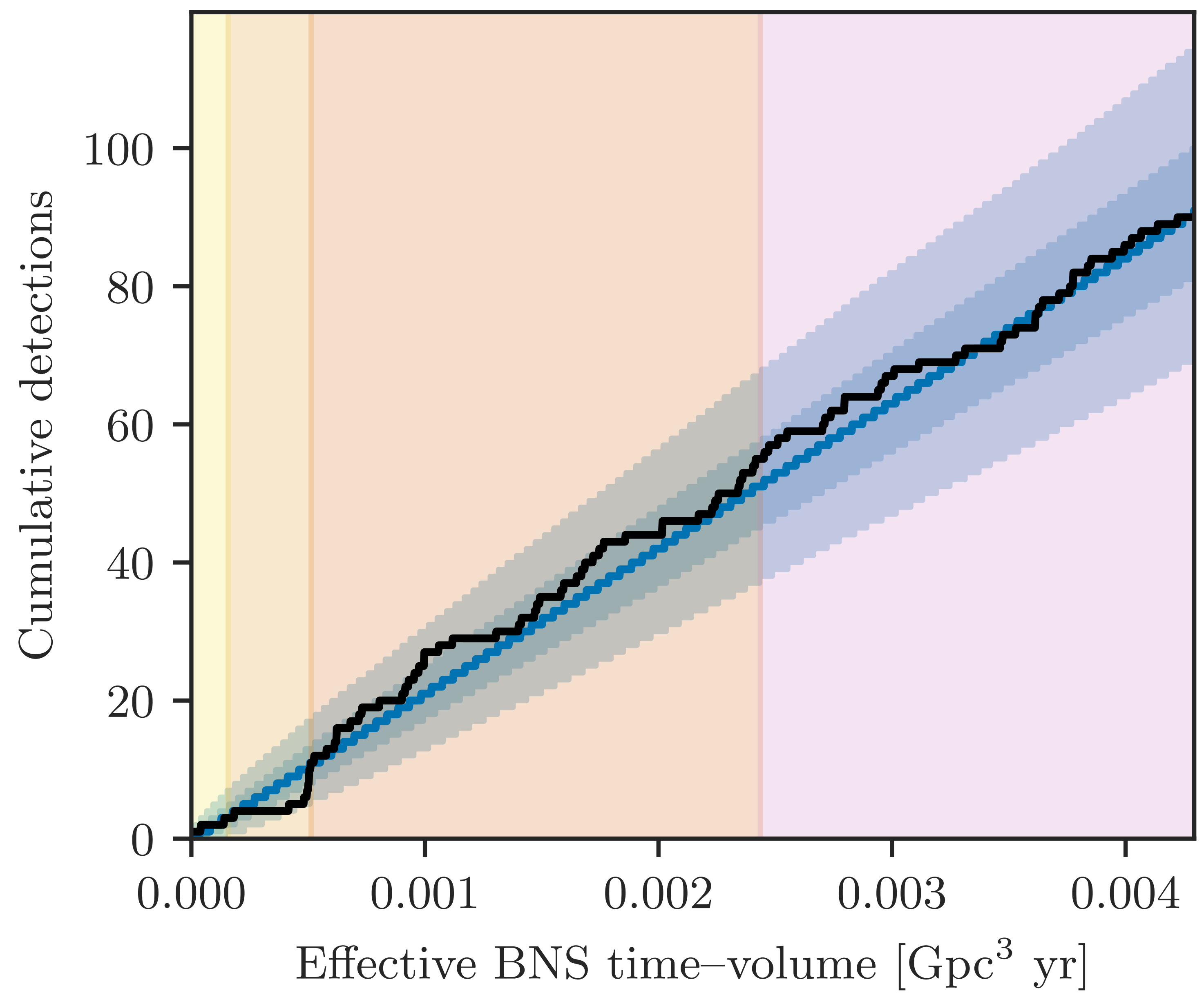
Gravitational-wave astronomy: Science

- First tests of GR in the regime of extreme gravity & velocities.
- New avenues for cosmography.
- Constraints on the EoS of dense nuclear matter.
- Binary population inference: merger rates, mass & redshift distribution of CBCs.
- Constraints on primordial BHs.
- Hints on the origin of heavy elements (from EM counterparts of GW170817).

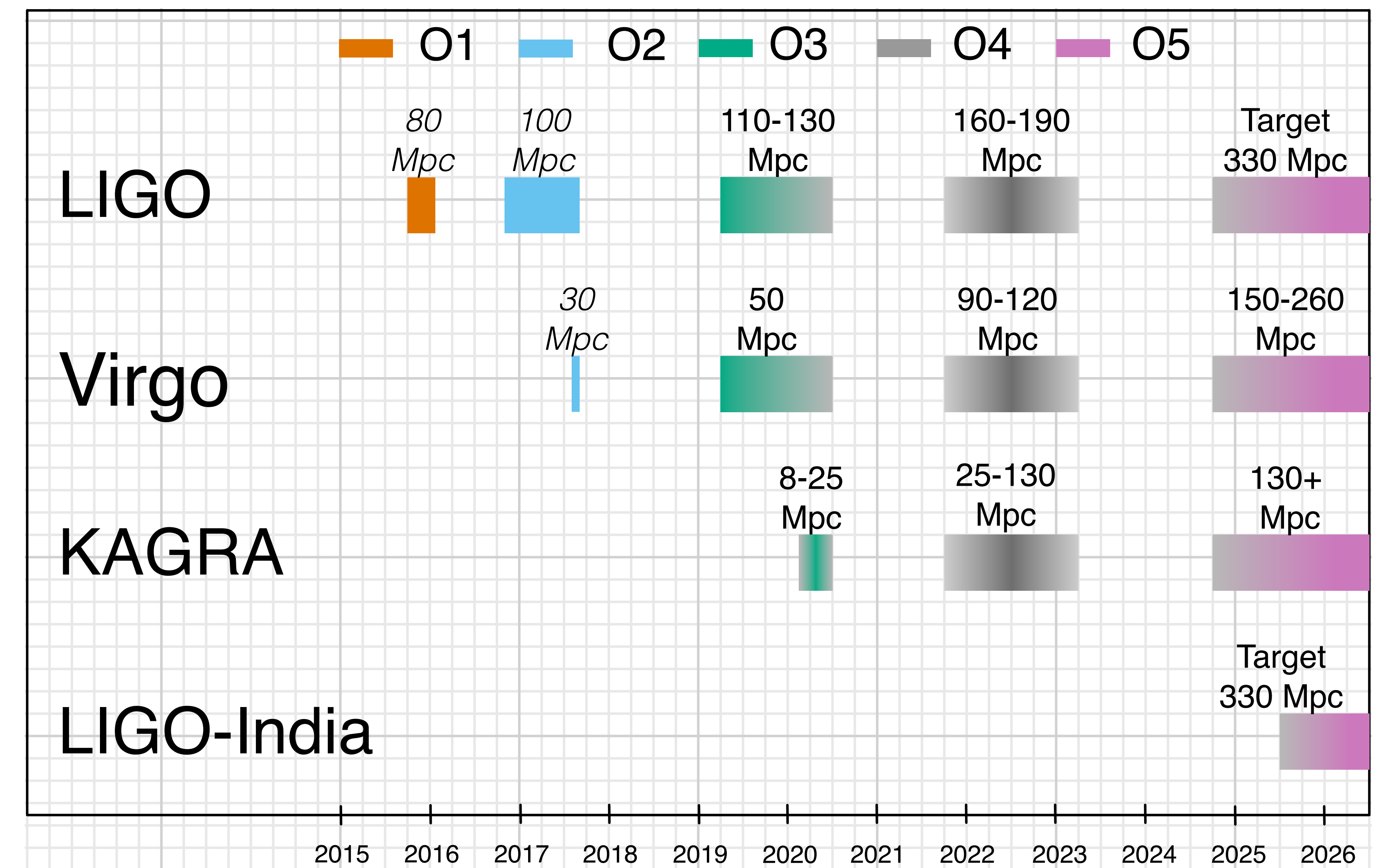
[ApJ 848:L12, 59 (2017)]



Gravitational astronomy has only begun



[arXiv:2111.03606]



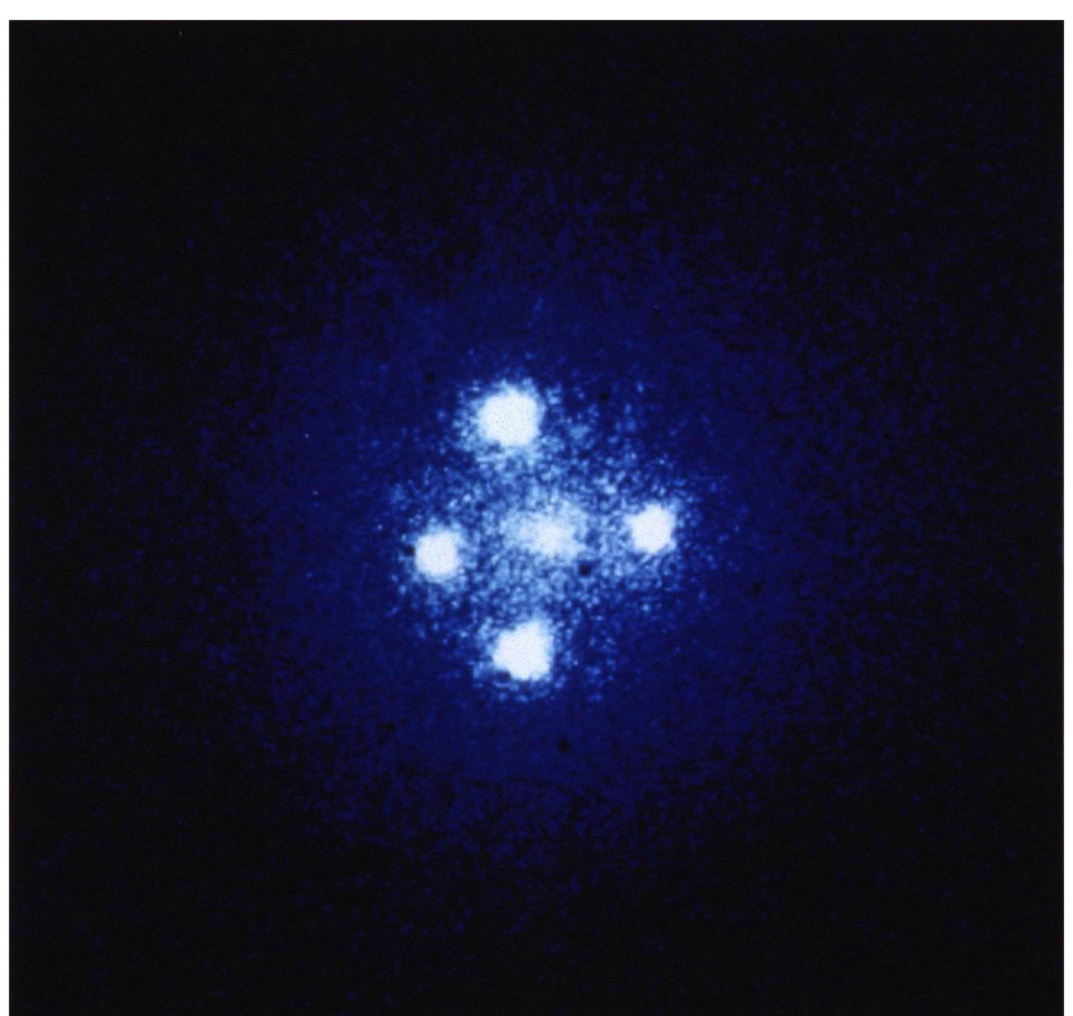
[Living Rev. Rel. 19 (2016) 1]

Note: Timelines have slipped

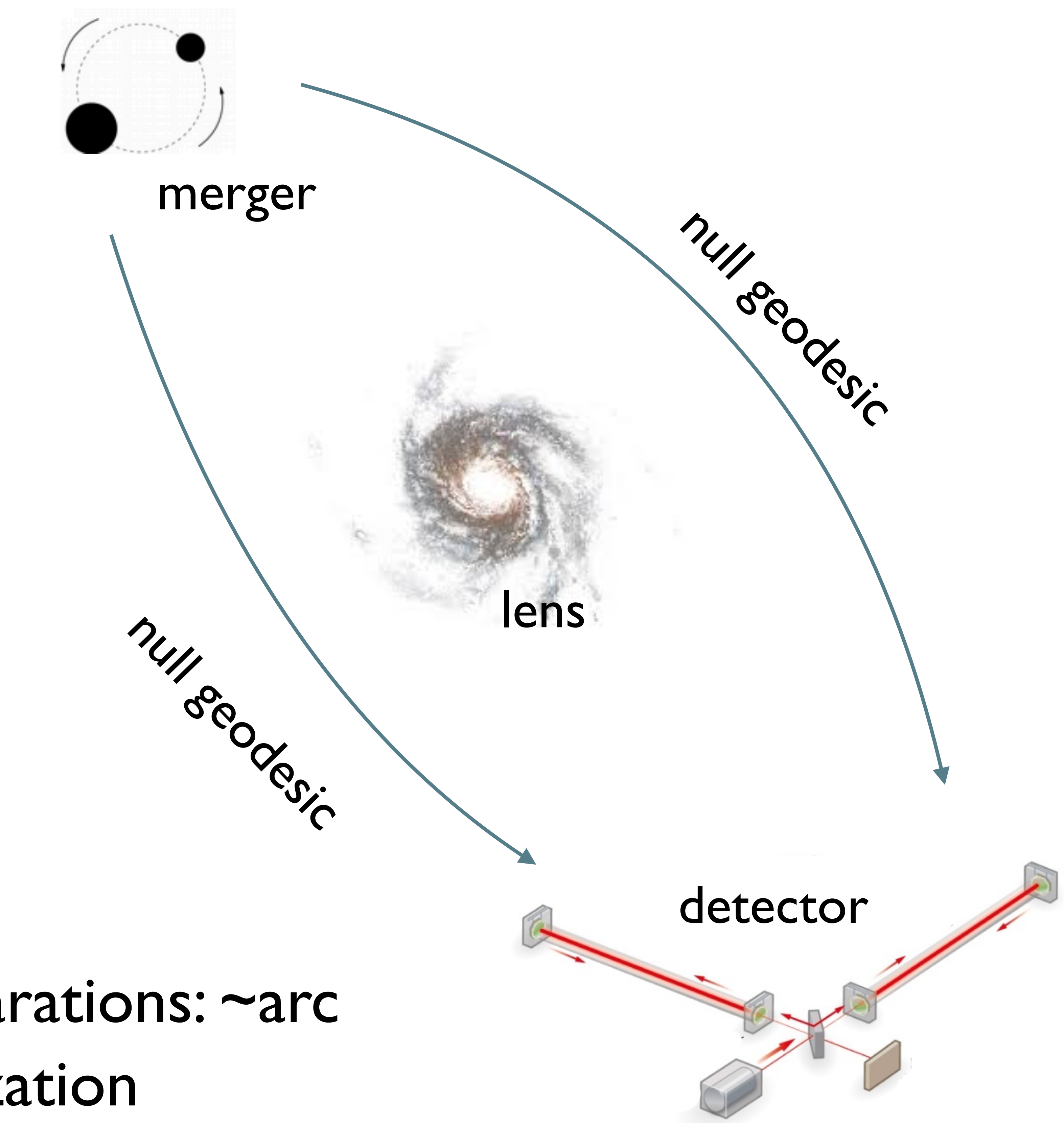
- LIGO & Virgo will continue to improve their sensitivities. KAGRA and LIGO-India expected to join in the next few years. 1000s of GW detections anticipated.
- Plans & proposals to host upgraded detectors in the existing facilities (A#, Voyager, ...).
  - **New phenomena** Detection of SGWB, spinning neutron stars and galactic SNe, **lensing of GWs**.

Gravitational lensing of gravitational waves

- Small fraction (~0.1-0.5%) of detectable BBH mergers could be strongly lensed by intervening galaxies/clusters $\Longrightarrow$ multiple images, separated by hours to months.



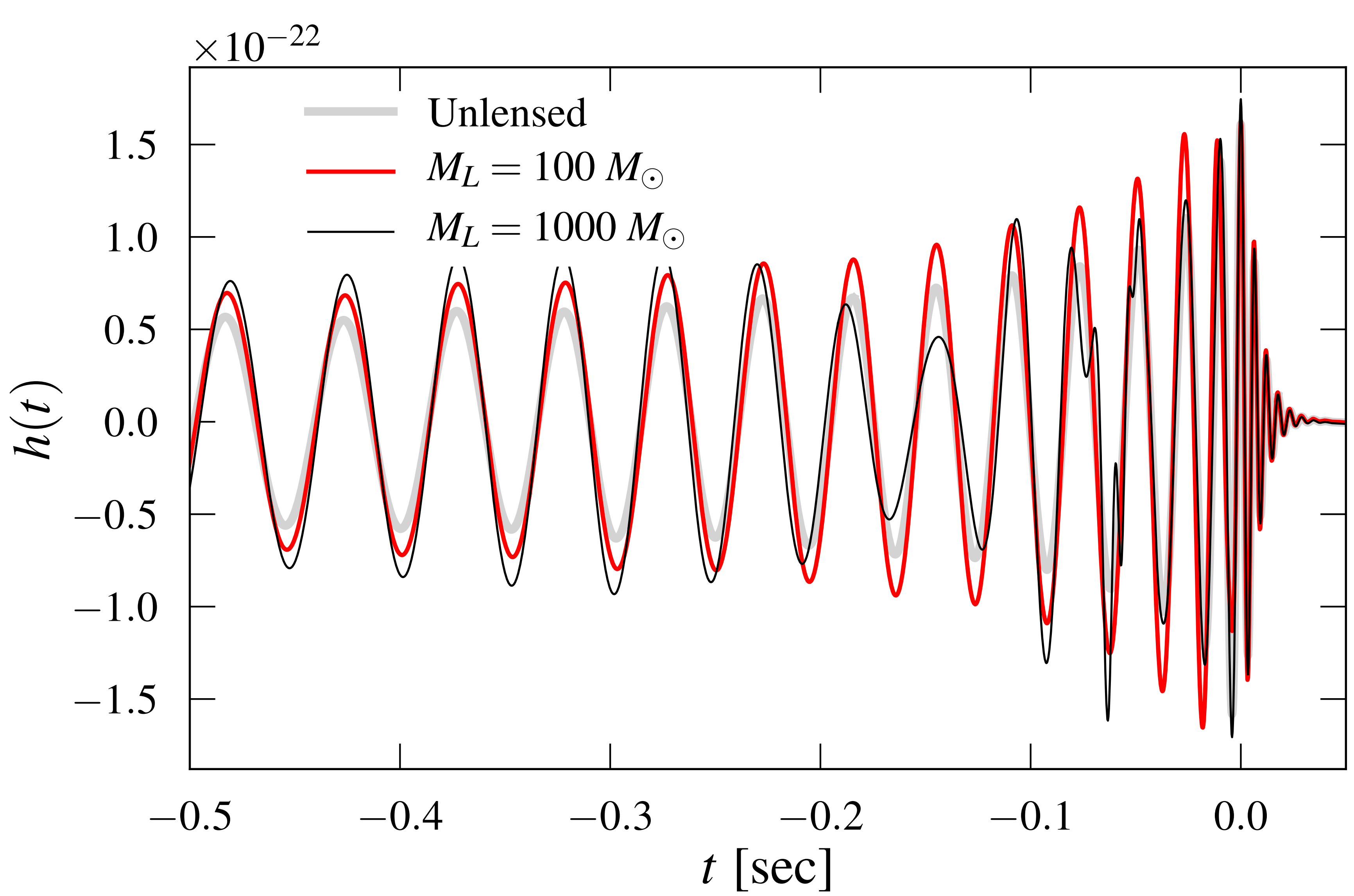
A lensed quasar

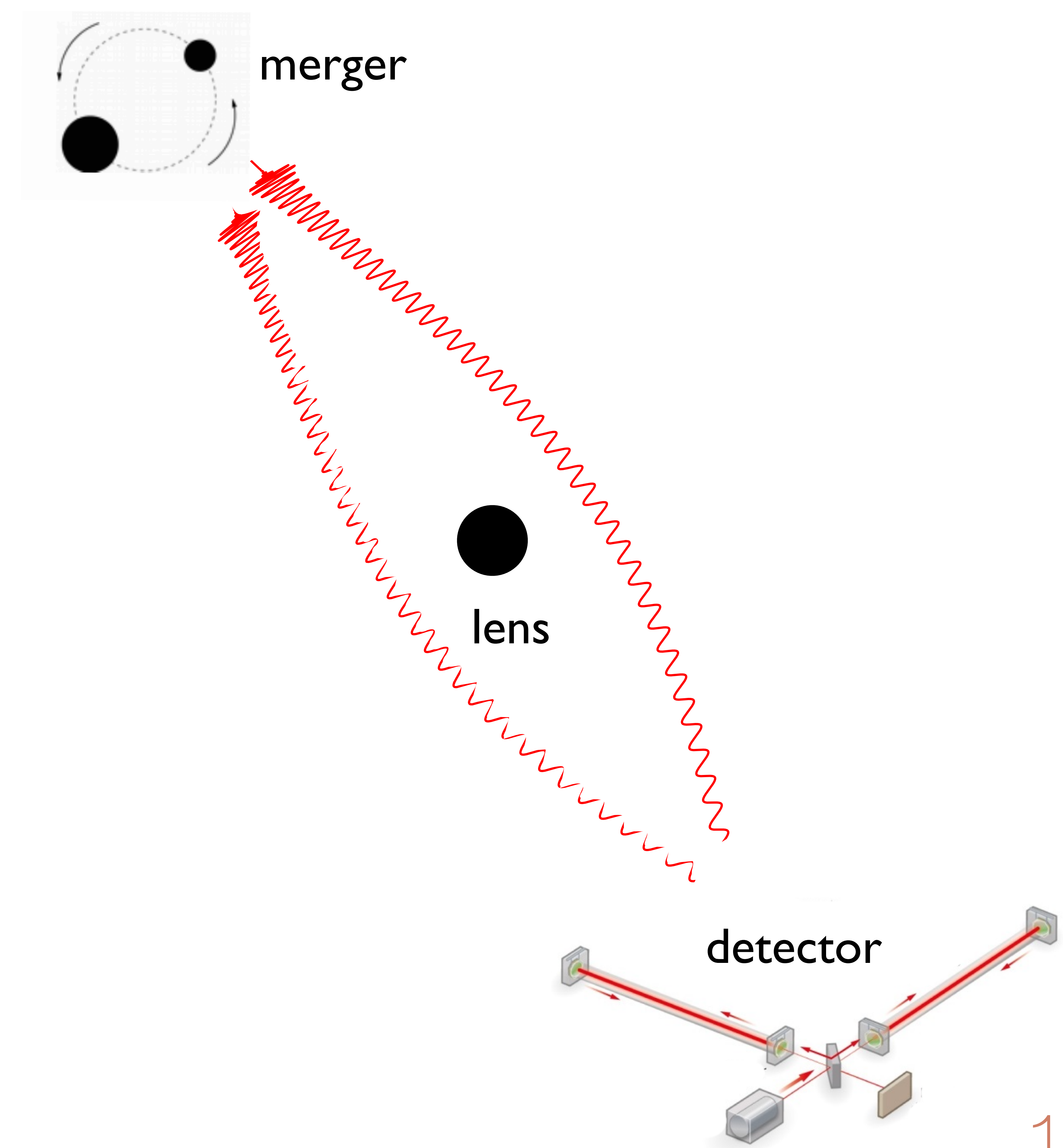


Typical mage separations: ~arc sec $\ll$ GW localization

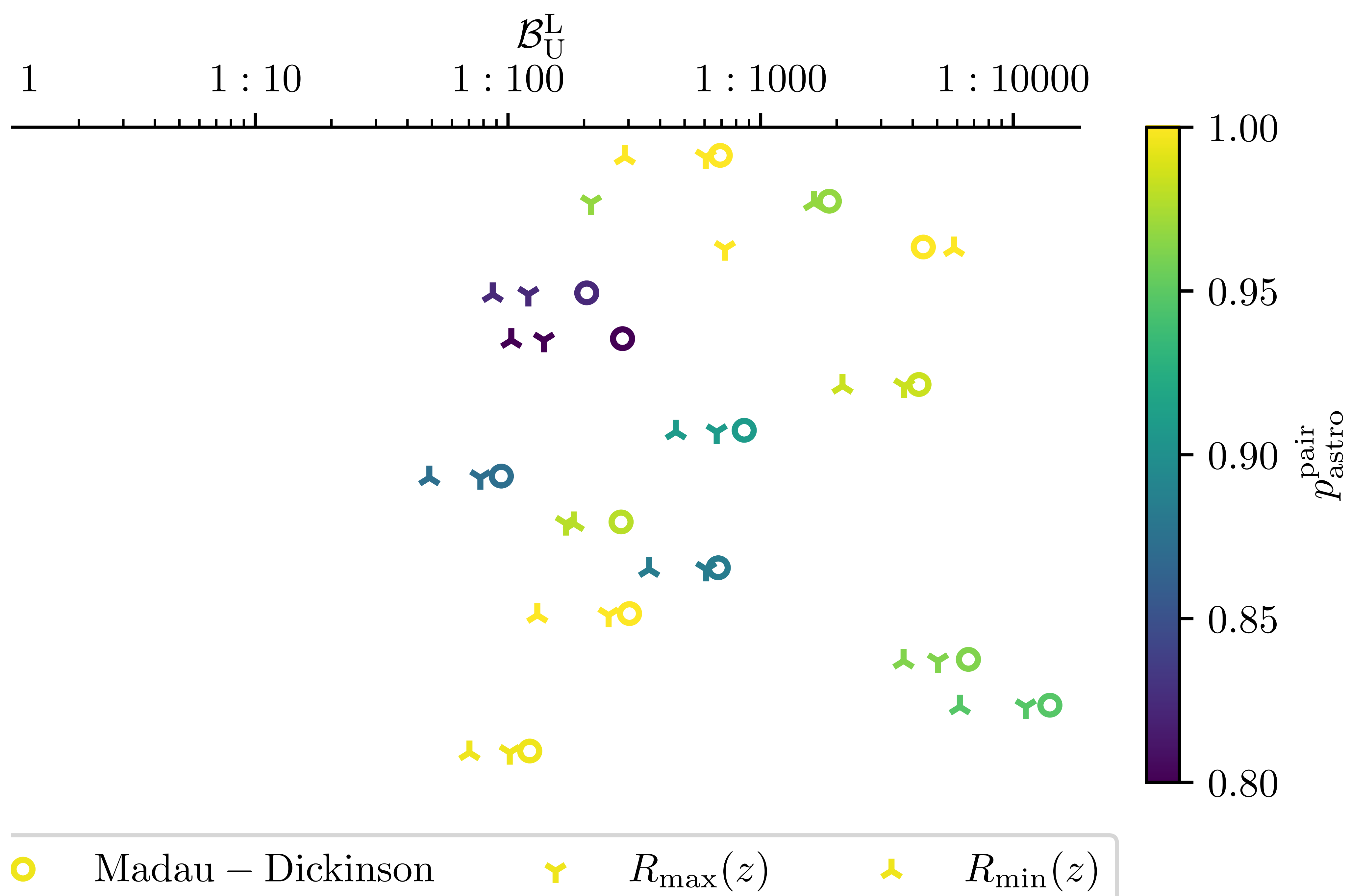
Wave optics effects in the lensing of GWs

- When the gravitational radius of the lens ~ GW wavelength $\Longrightarrow$ wave optics (microlensing).



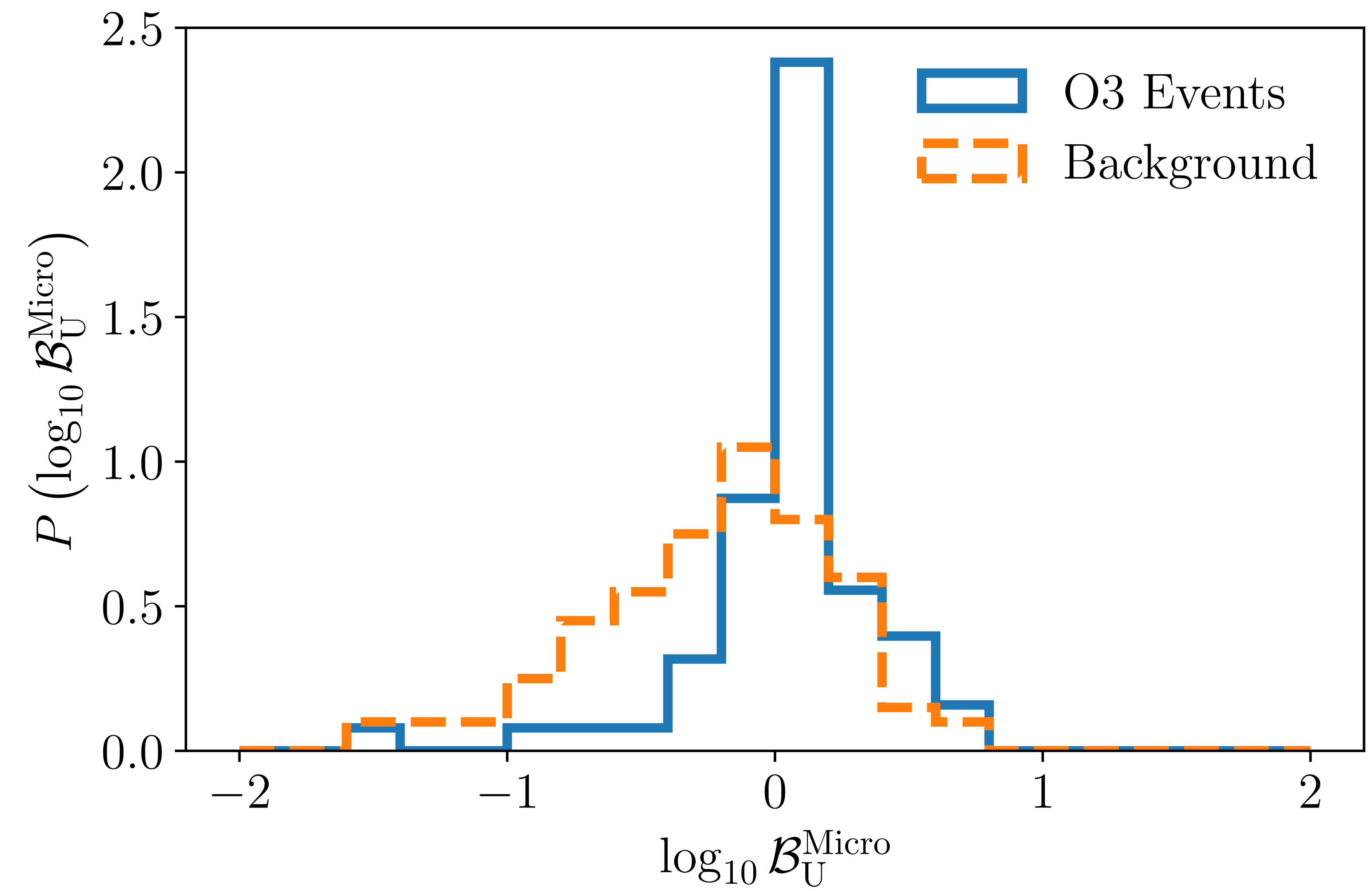


No evidence of lensing so far



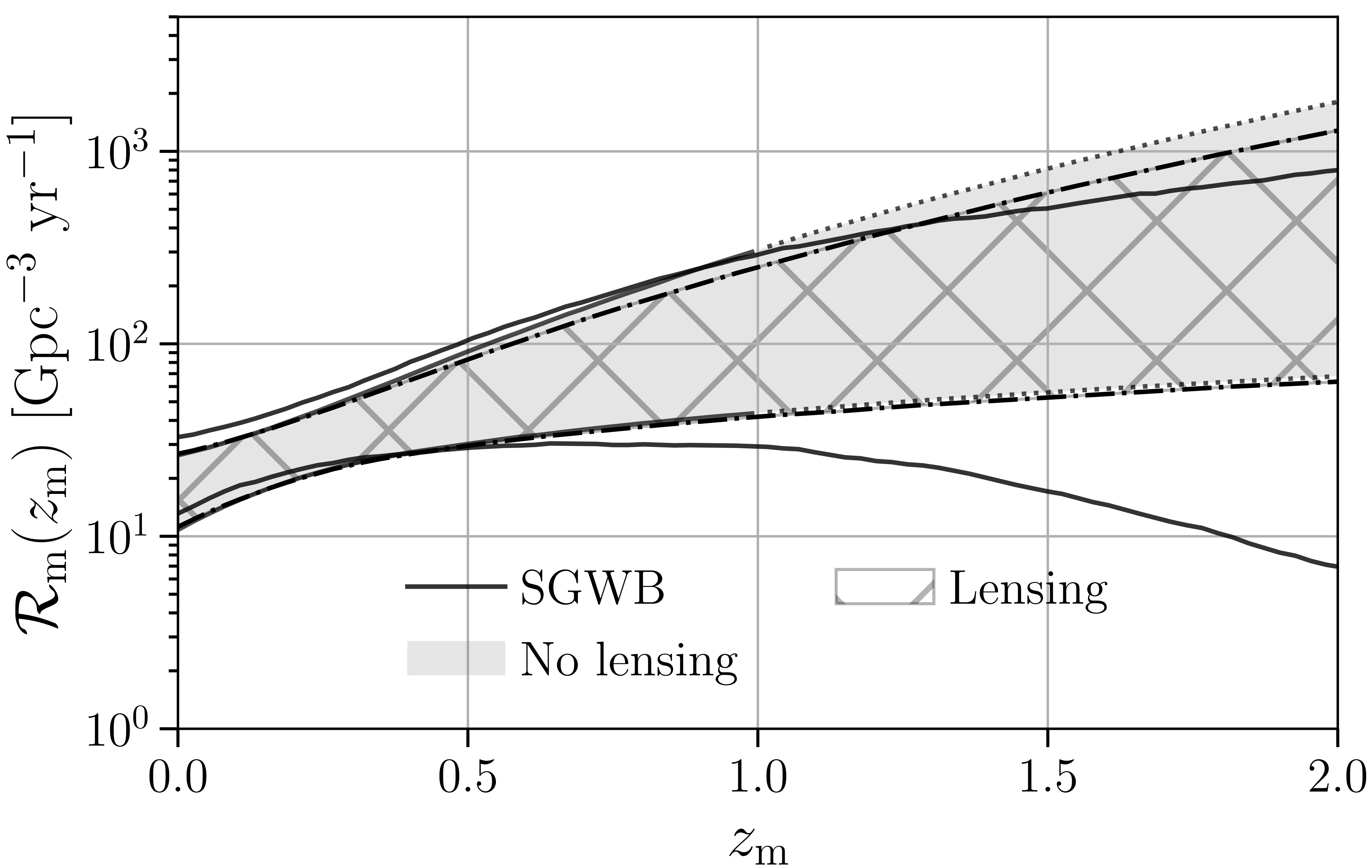
Lensed vs Unlensed Bayes factor from the most significant event pairs.

[LVC+, arXiv:2304.08393]

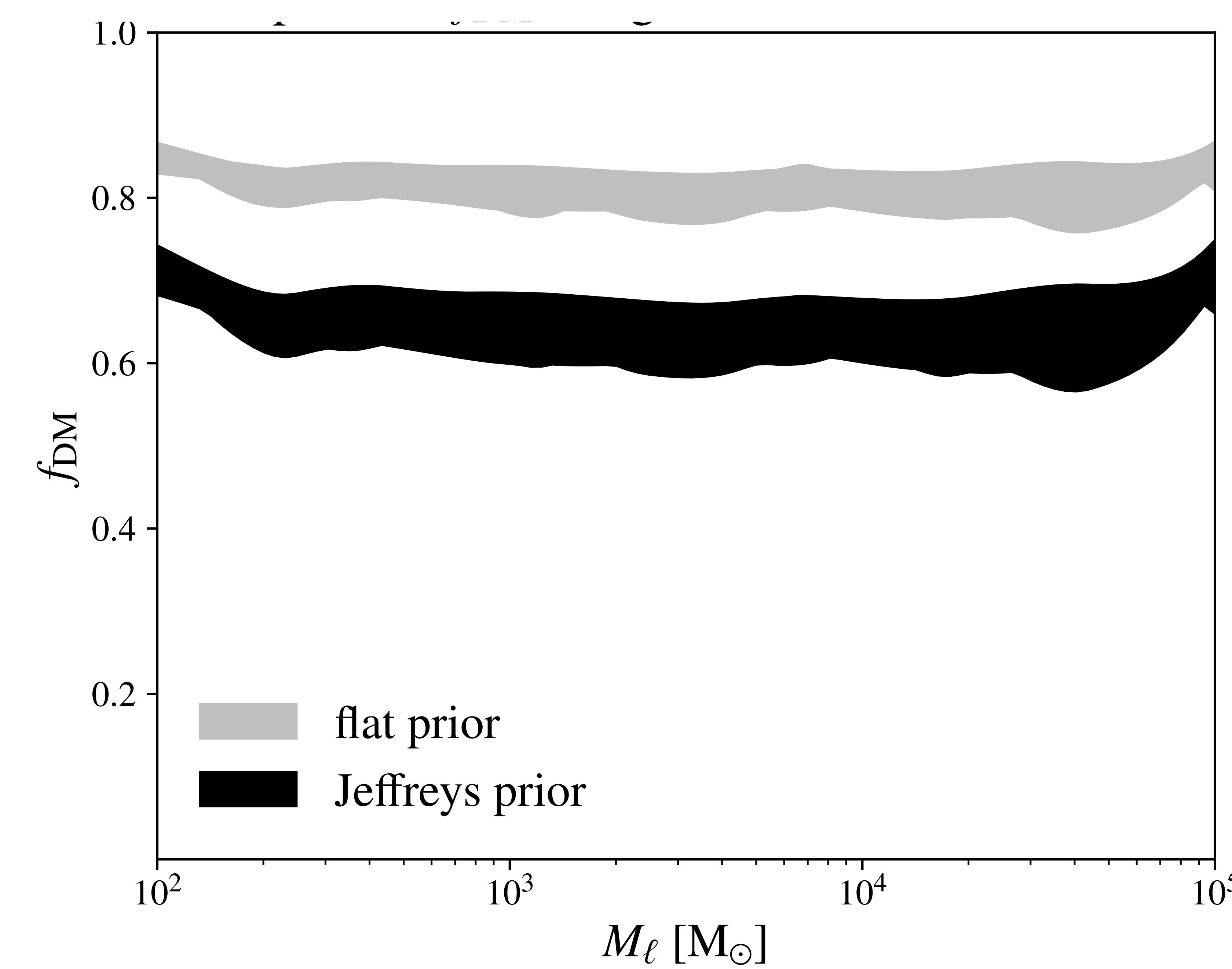


Distribution of microlensing Bayes factors from all events

Constraints from the non-observation of lensing



High-redshift merger rate

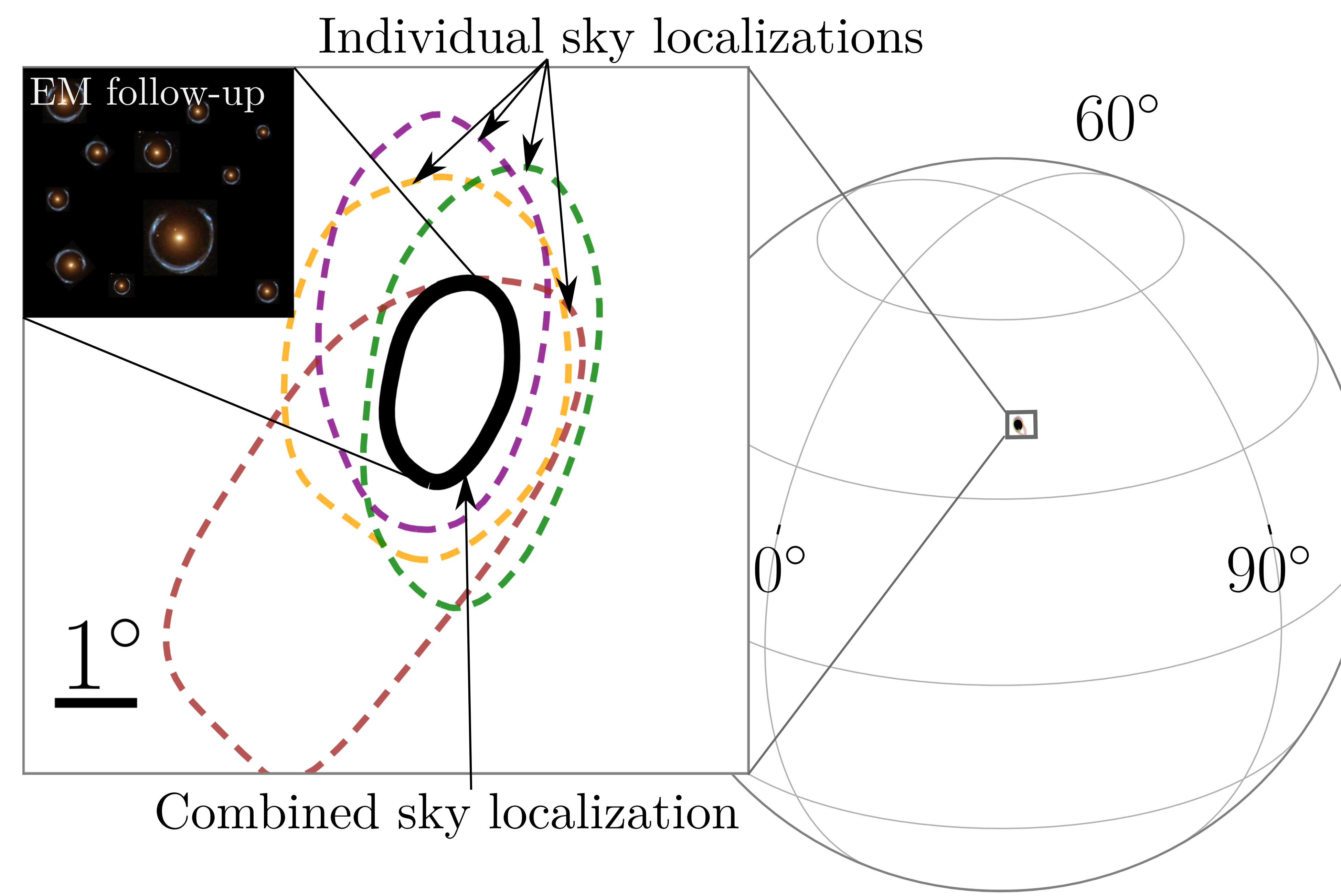


Primordial BHs as dark matter

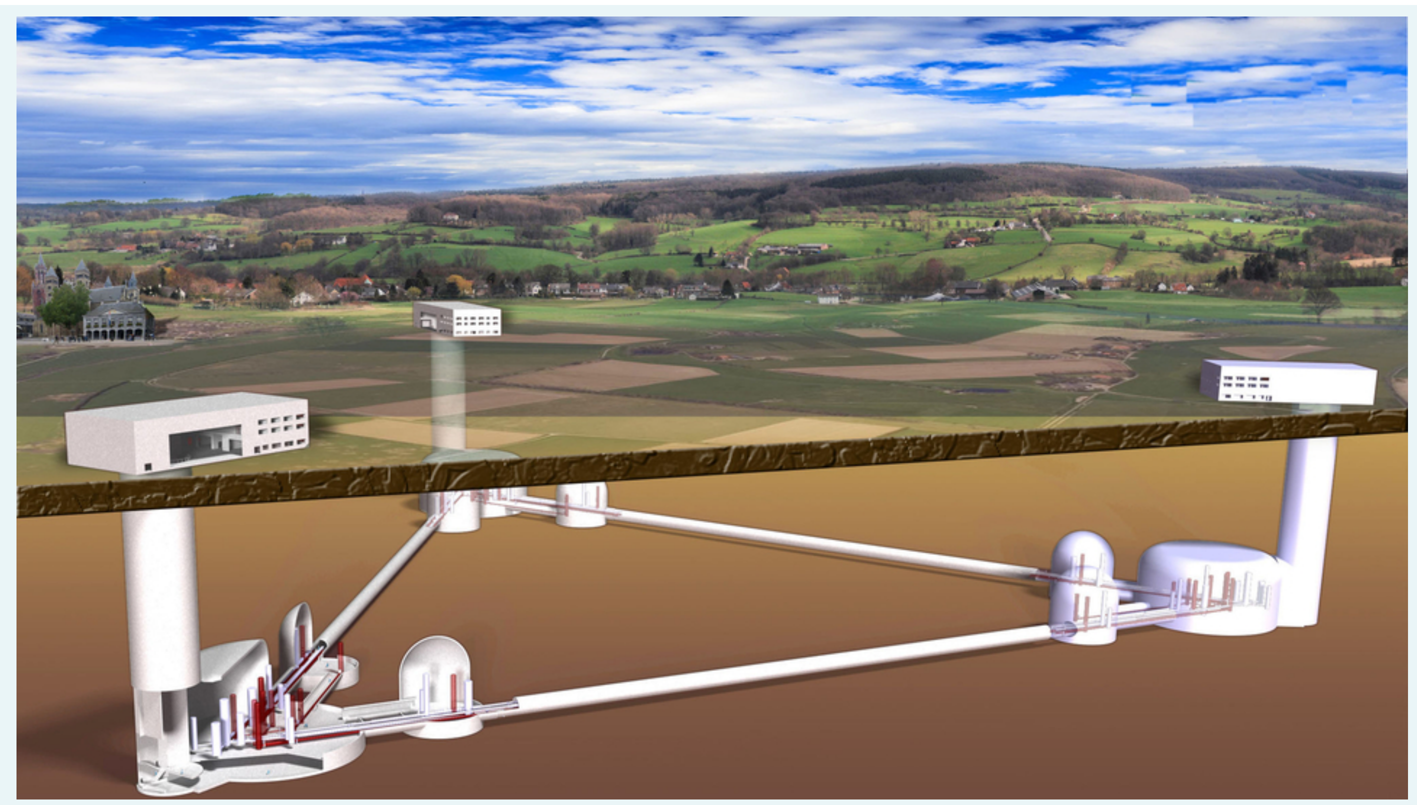
What can we learn from GW lensing?

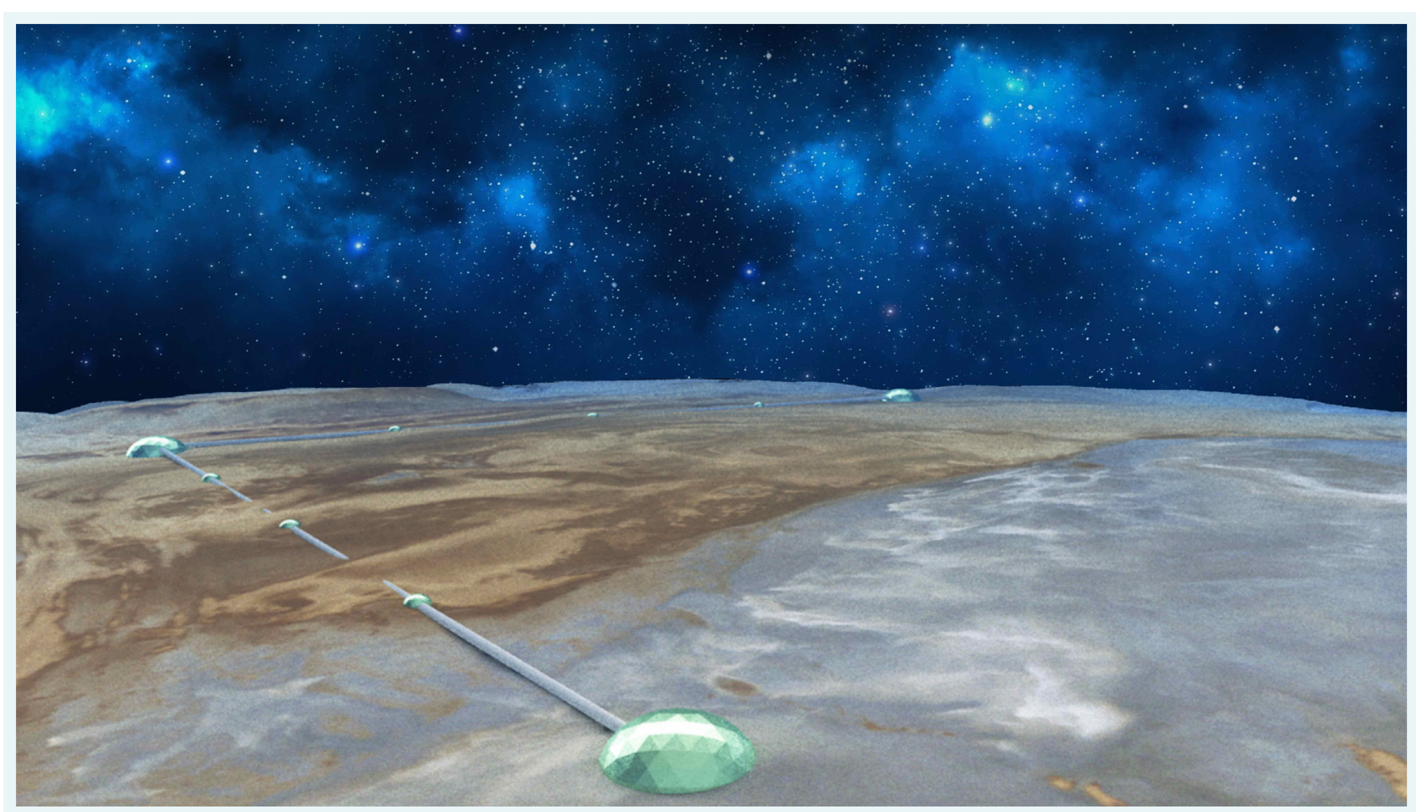
- First detection of strong lensing expected soon.
- Precise localization of mergers from lensed images from the observed time delay and magnification ratio. [Hannuksela et al 2020]
- Early warning of EM precursors: Predict the arrival of the next image. [Magare et al, 2023]
- Better ability to constrain the polarization modes. Are they consistent with GR? [Goyal et al, 2021)]

[Hannuksela et al 2020]

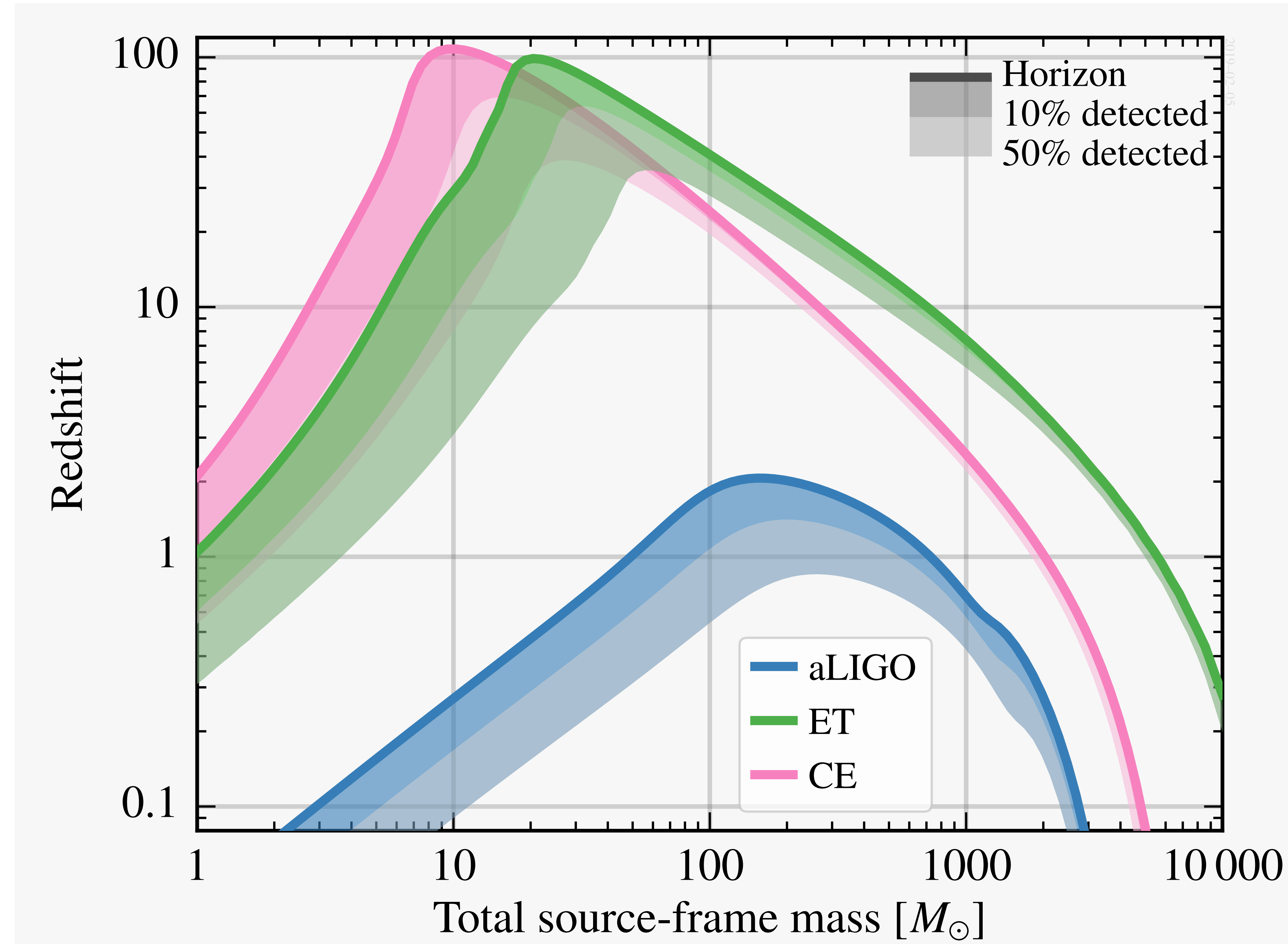


Going deeper: Next generation ground-based detectors





Artists conception of the Einstein Telescope (top) and Cosmic Explorer (bottom)



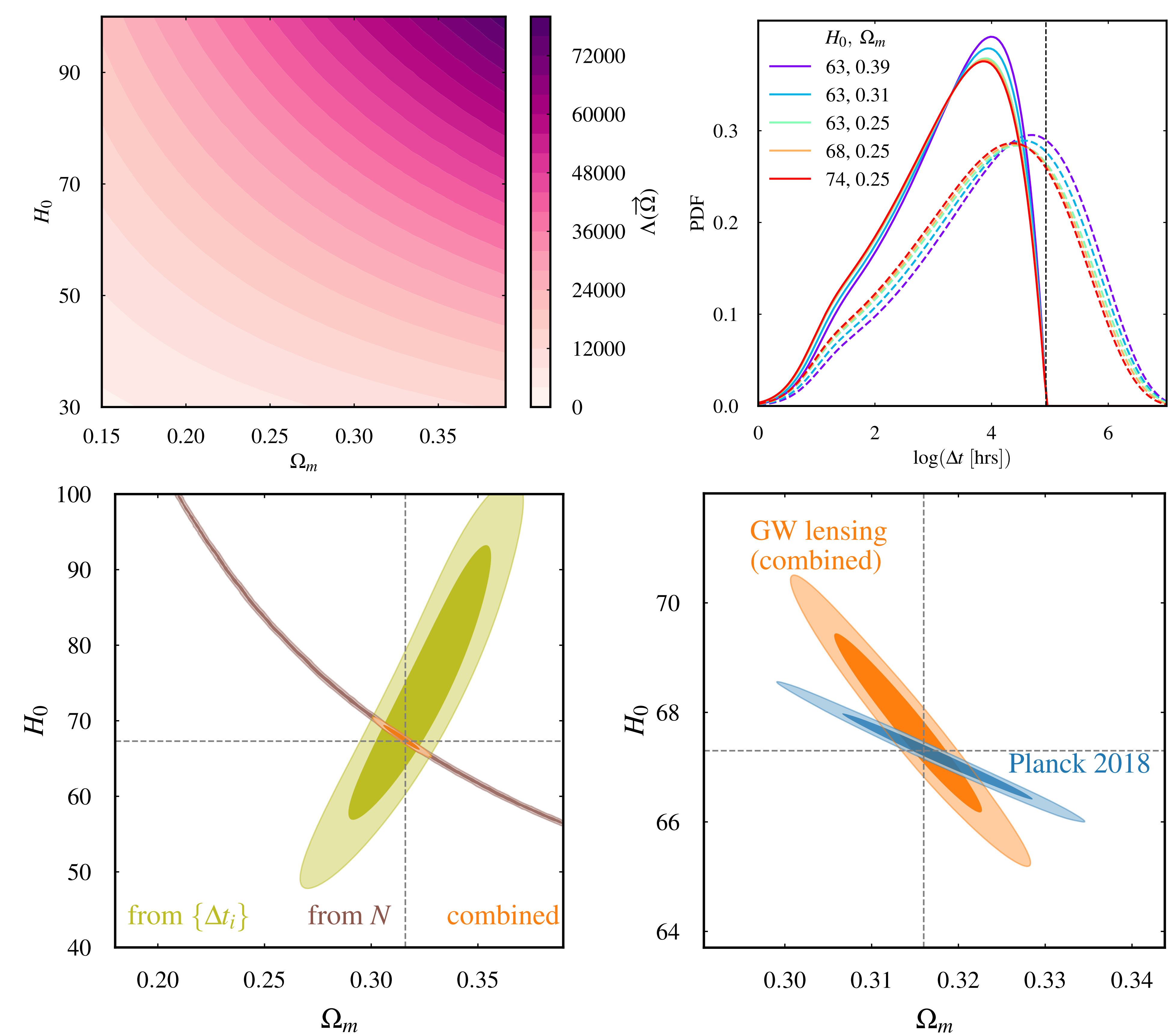
Expected horizon distance

[The Next Generation Global Gravitational Wave Observatory:The Science Book arXiv:2111.06990]

GW lensing cosmography

[S. Jana et al, PRL 2023]

- 3G detectors are expected to detect ~10^6 mergers. ~10^4 would be strongly lensed.
- Detected number of lensed signals & their time delay distribution contain imprints of cosmological parameters — a new probe of cosmology.



Expected constraints from 10 yr observations observation of 3G detectors (conservative assumptions on merger rates)

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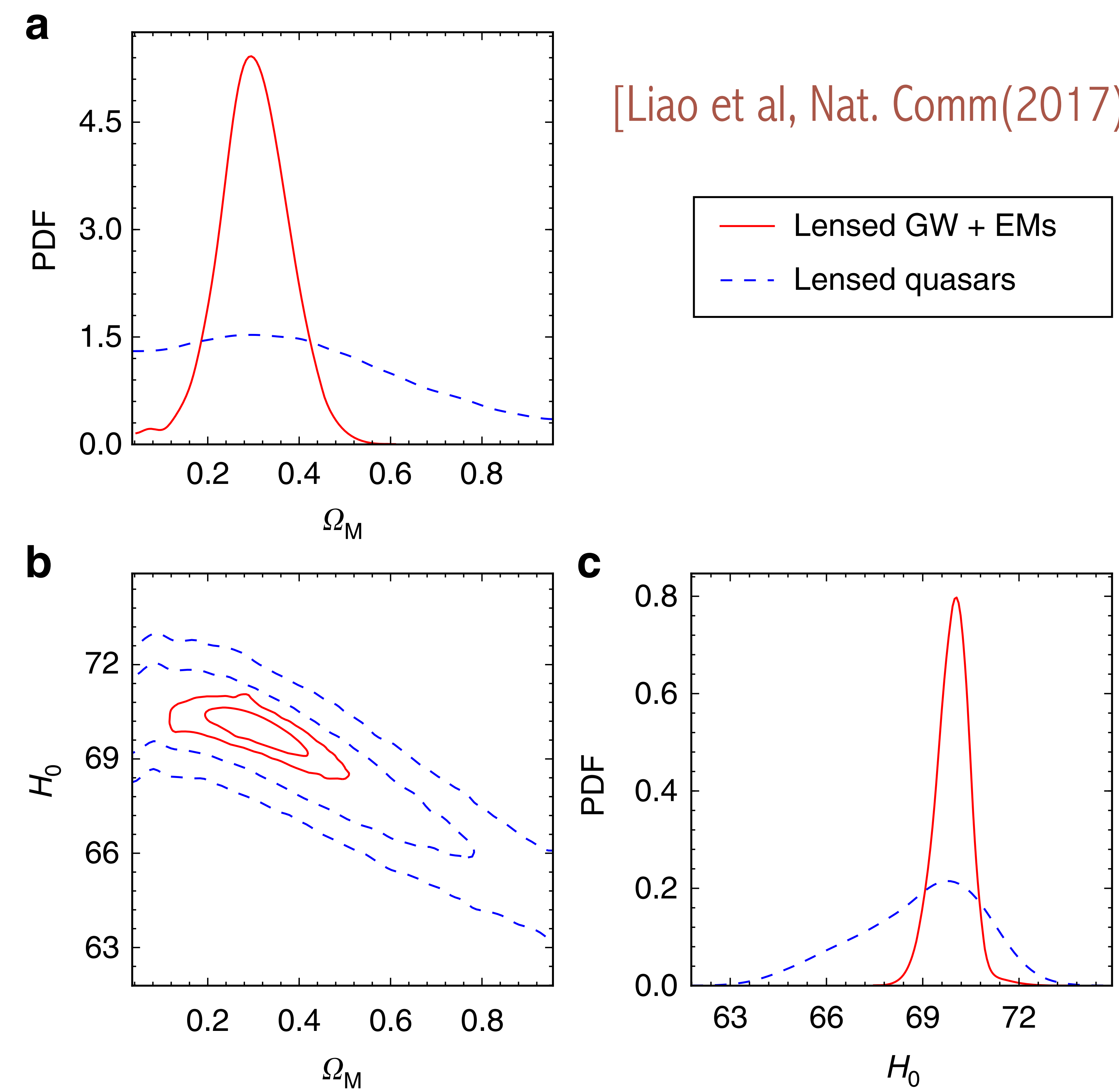


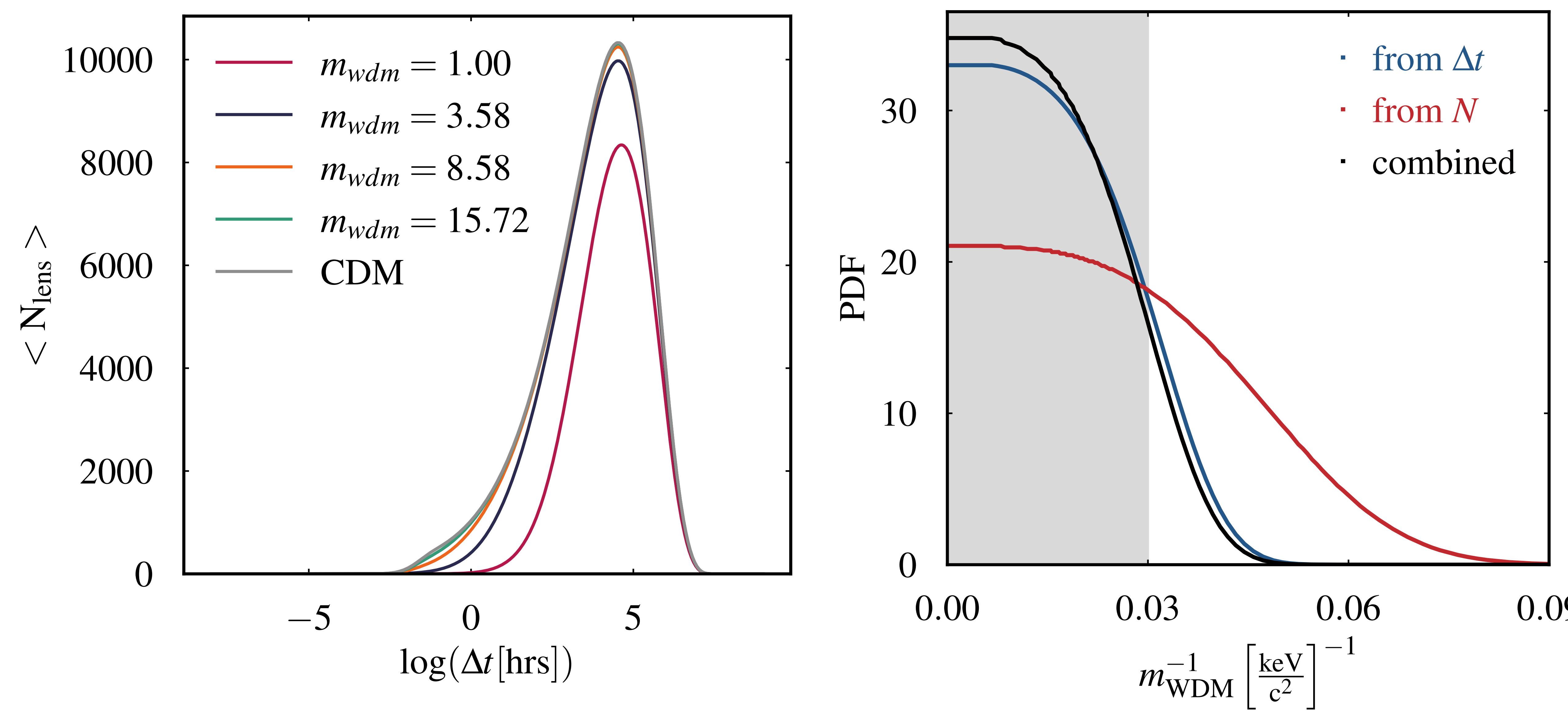
[Liao et al, Nat. Comm(2017)]

Expected constraints on cosmological parameters using ~100 GW-EM detections

Probing the nature of dark matter using GW lensing

- Warm dark matter would affect the abundance of low-mass halos $\Longrightarrow$ imprint on the distribution of time delays and lensing fraction.

[S. Jana et al, In preparation]



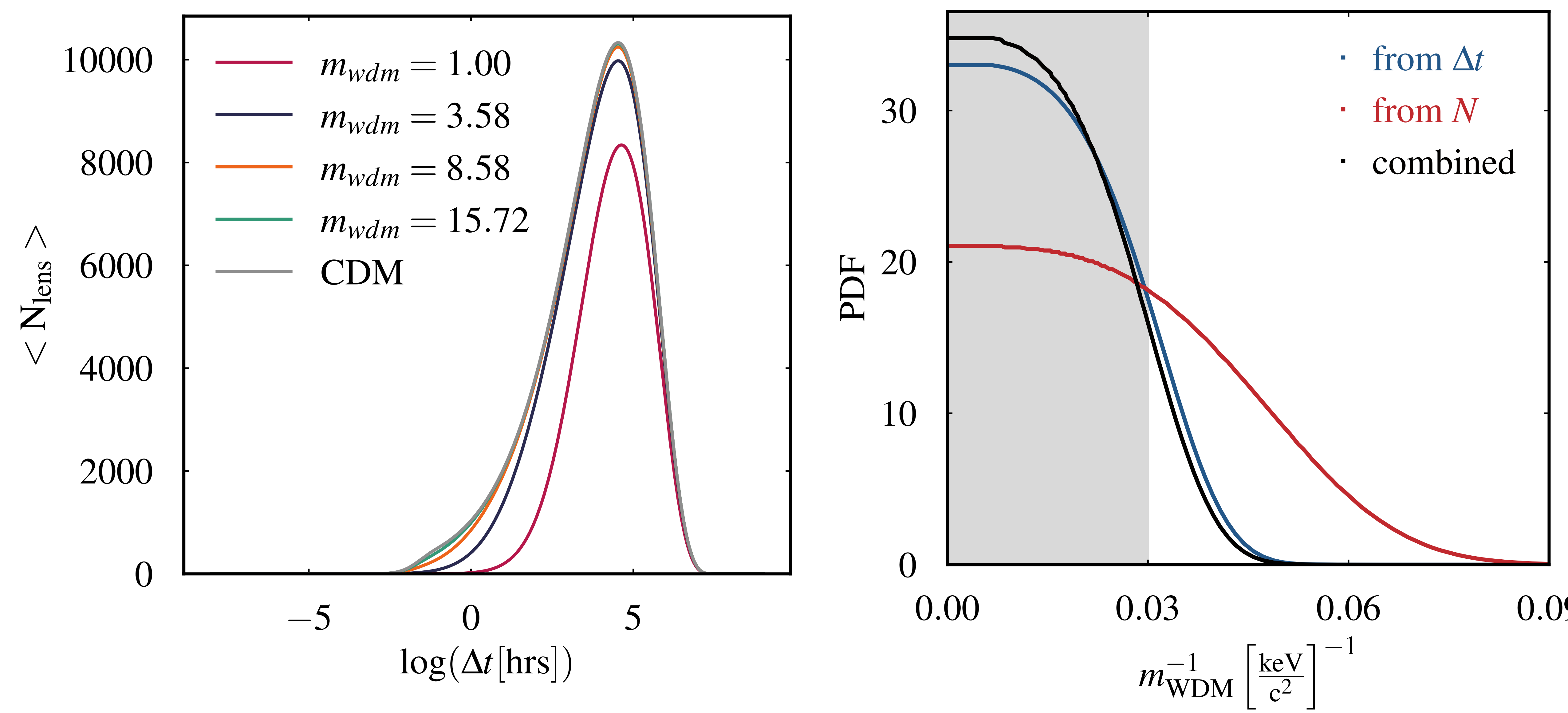
Expected constraints from 10 yr observations observation of 3G detectors (conservative assumptions on merger rates)

[Simona Vegetti's talk on Tuesday]

Probing the nature of dark matter using GW lensing

- Warm dark matter would affect the abundance of low-mass halos $\implies$ imprint on the distribution of time delays and lensing fraction.
    - Also: Probe sub-structure of DM halos from individual, well resolved lensed events $\implies$ potential probes of self-interacting / ultra-light / fuzzy DM [Tambalo et al, 2022,]

[S. Jana et al, In preparation]



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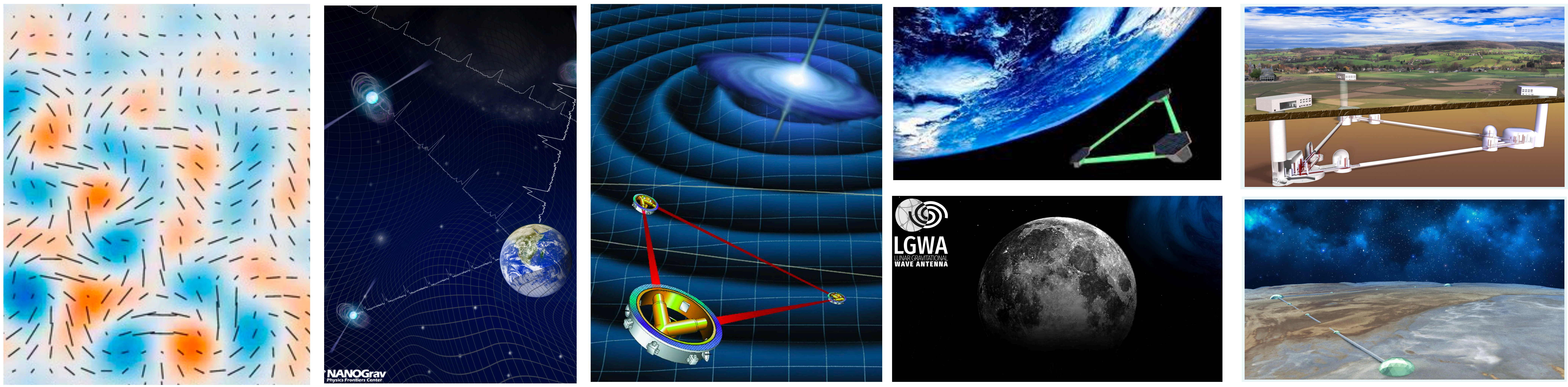
Future: Going deeper and wider



Frequency	10^{-16} Hz	$10^{-9} - 10^{-6}$ Hz	$10^{-5} - 10^{-1}$ Hz	$10^{-1} - 1$ Hz	$1 - 10^{4}$ Hz
Wavelength	10^{21} km	$10^{14} - 10^{11}$ km	$10^{10} - 10^{6}$ km	$10^{6} - 10^{5}$ km	$10^{5} - 10$ km
Detection	CMB Polarization	Pulsar timing	eLISA/NGO	BBO/DECIGO	LIGO/Virgo/KAGRA/ET