Gravitational lensing of gravitational waves: A new tool for cosmology

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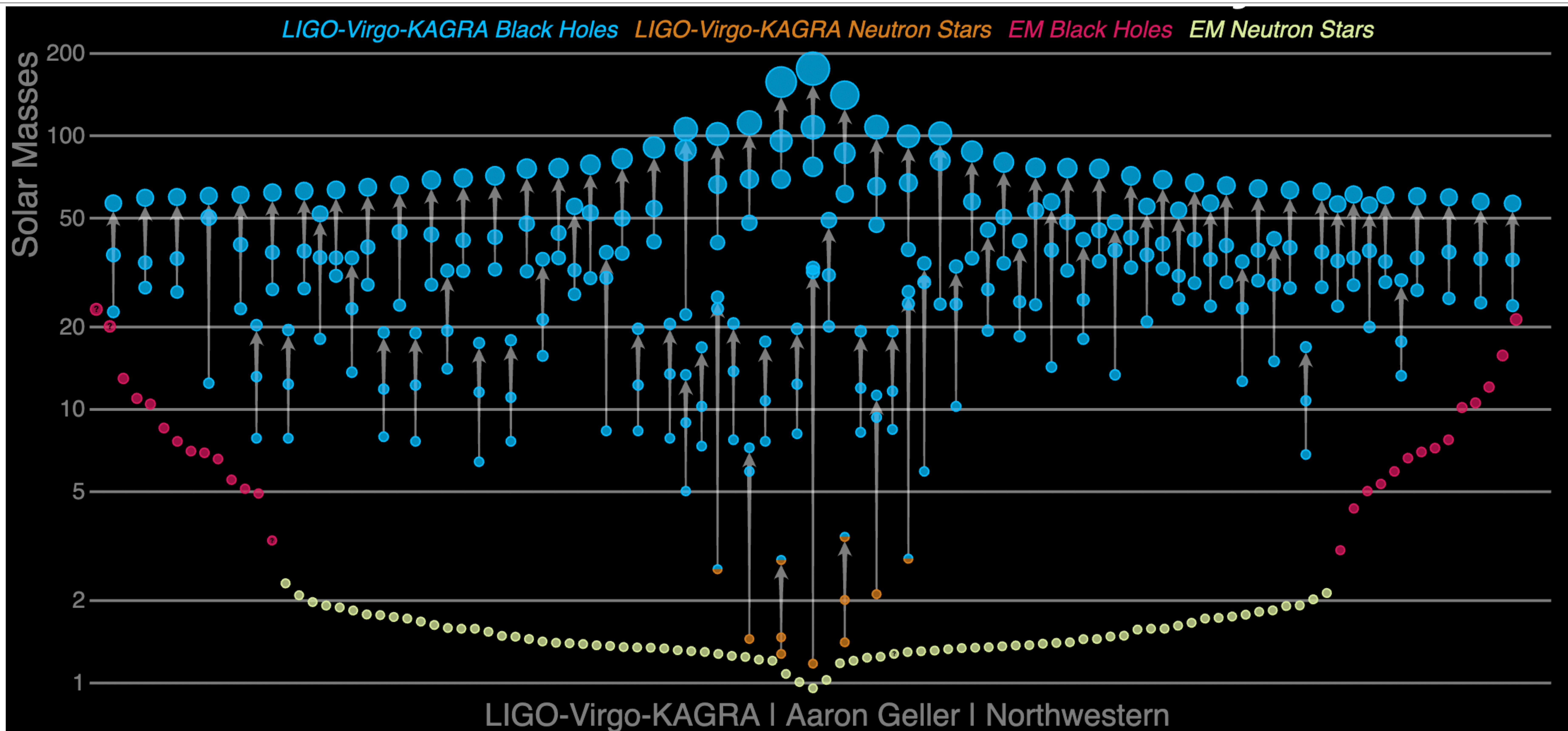
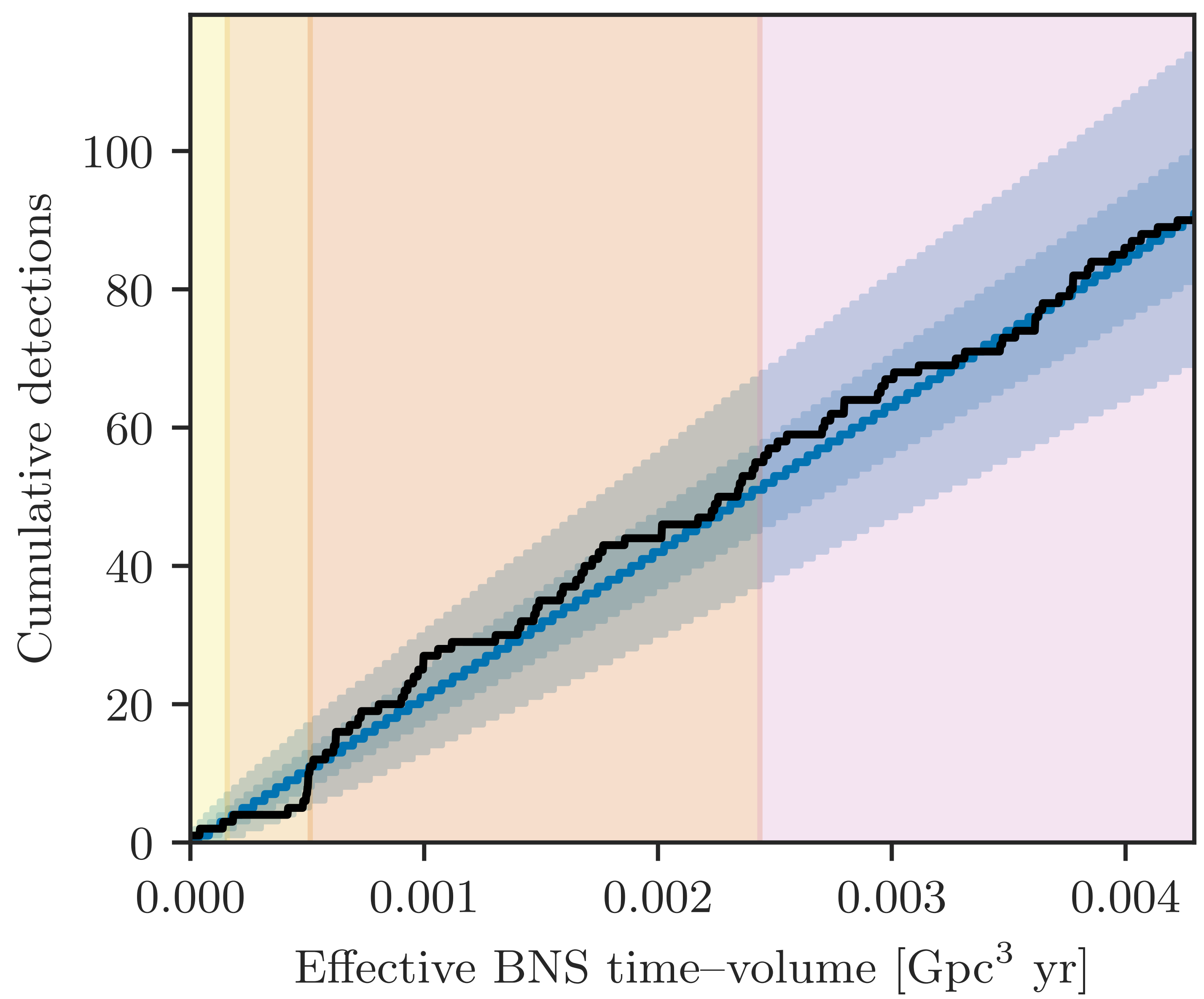
GW observations have established a new branch of astronomy



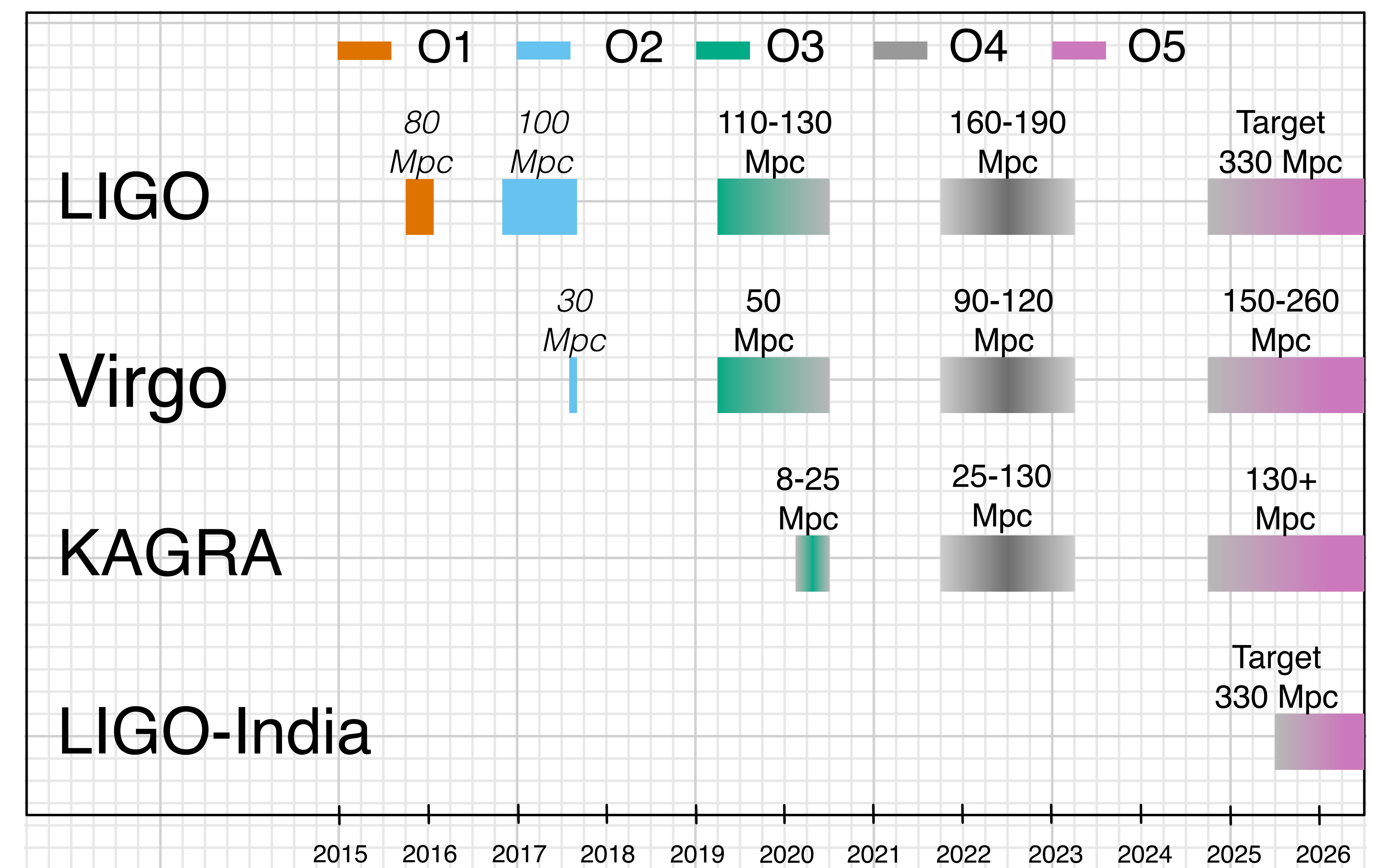
Around100 CBC detections from the first three observing runs

Over 200 Significant Detection Candidates from the ongoing fourth observing run

Gravitational astronomy has only begun



[arXiv:2111.03606]

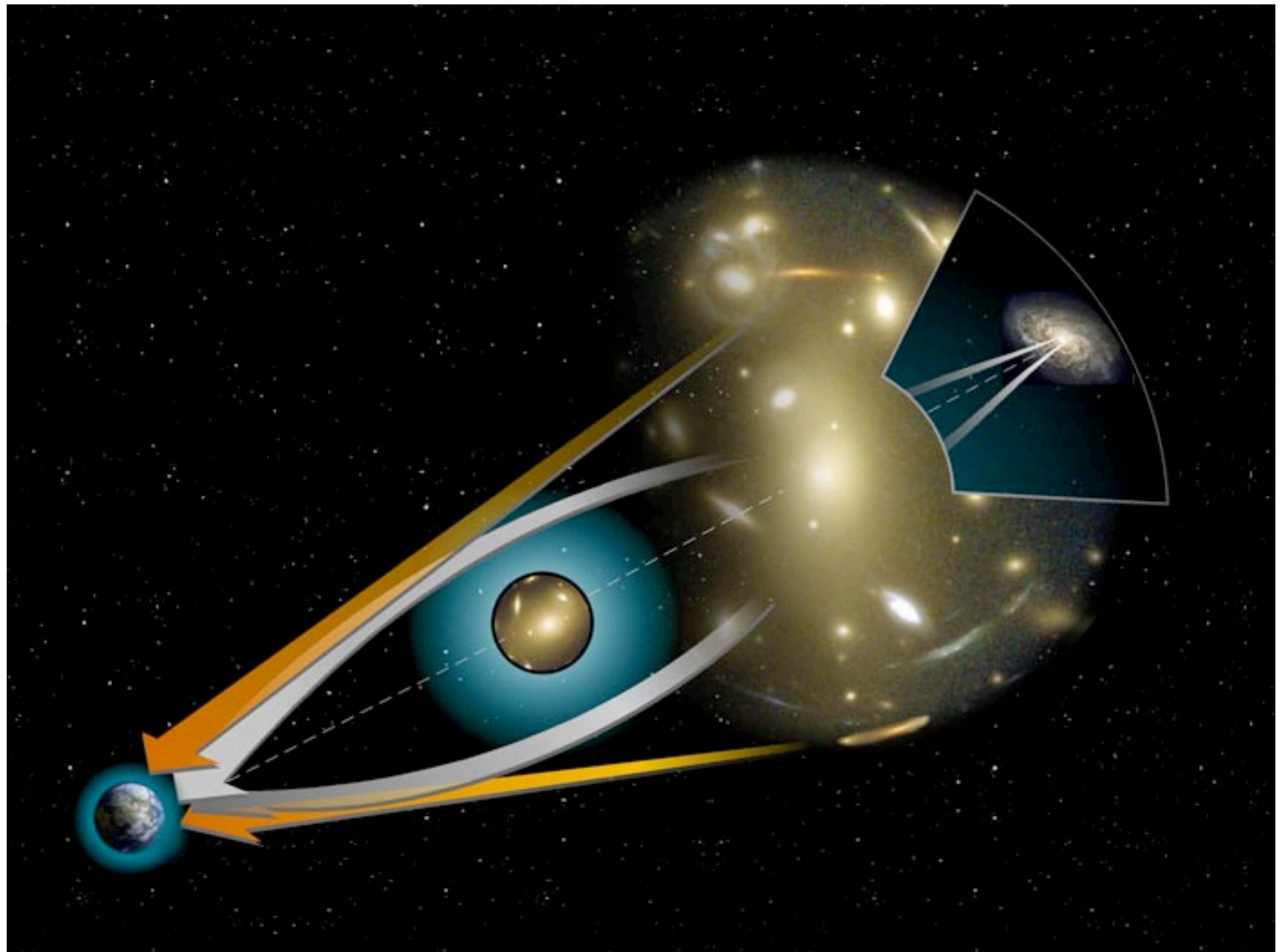


[Living Rev. Rel. 19 (2016)]

Note: Timelines have slipped

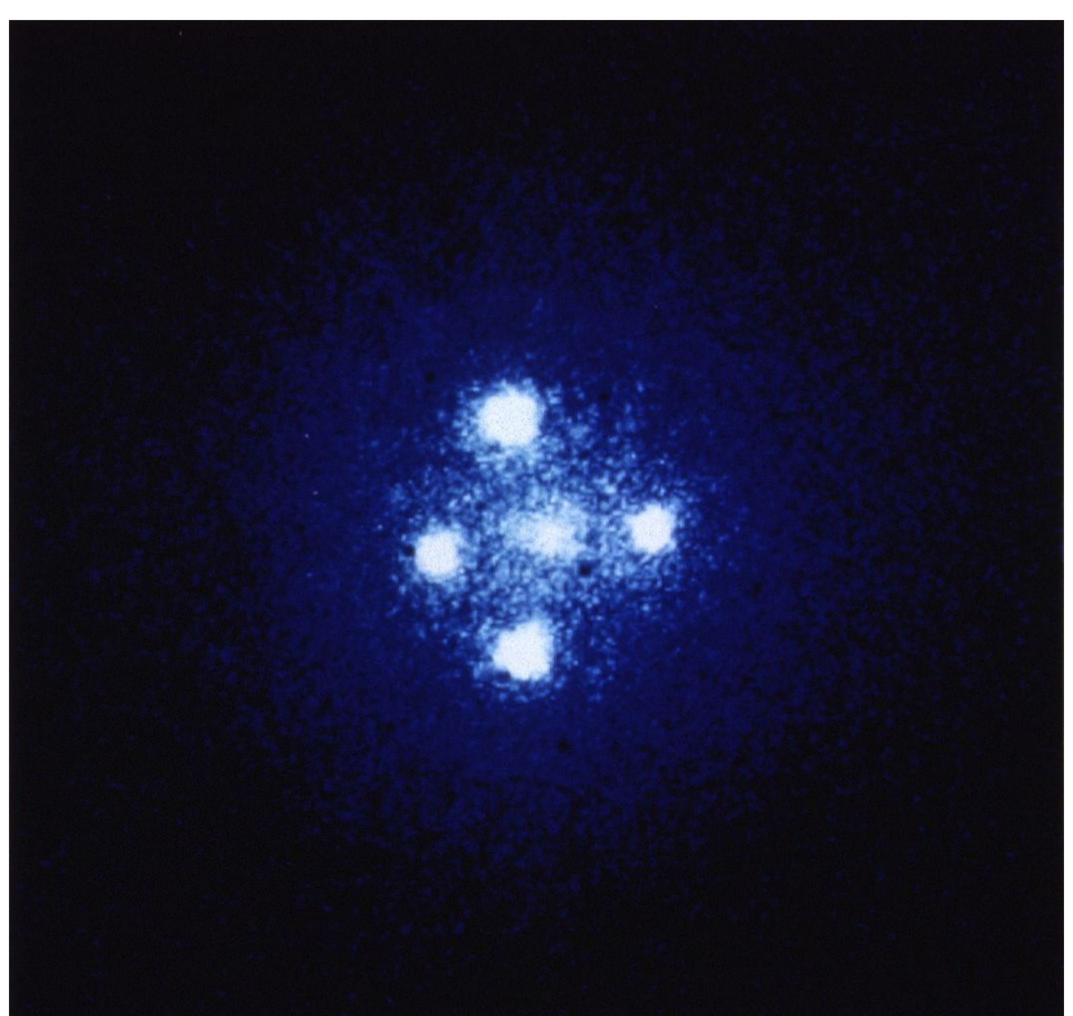
- LIGO, Virgo & KAGRA will continue to improve their sensitivities. LIGO-India expected to join in the next few years. 1000s of GW detections anticipated.
- Plans & proposals to host upgraded detectors in the existing facilities (A#, Voyager, ...).
- Ongoing proposals to build the next generation (XG)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

Gravitational lensing

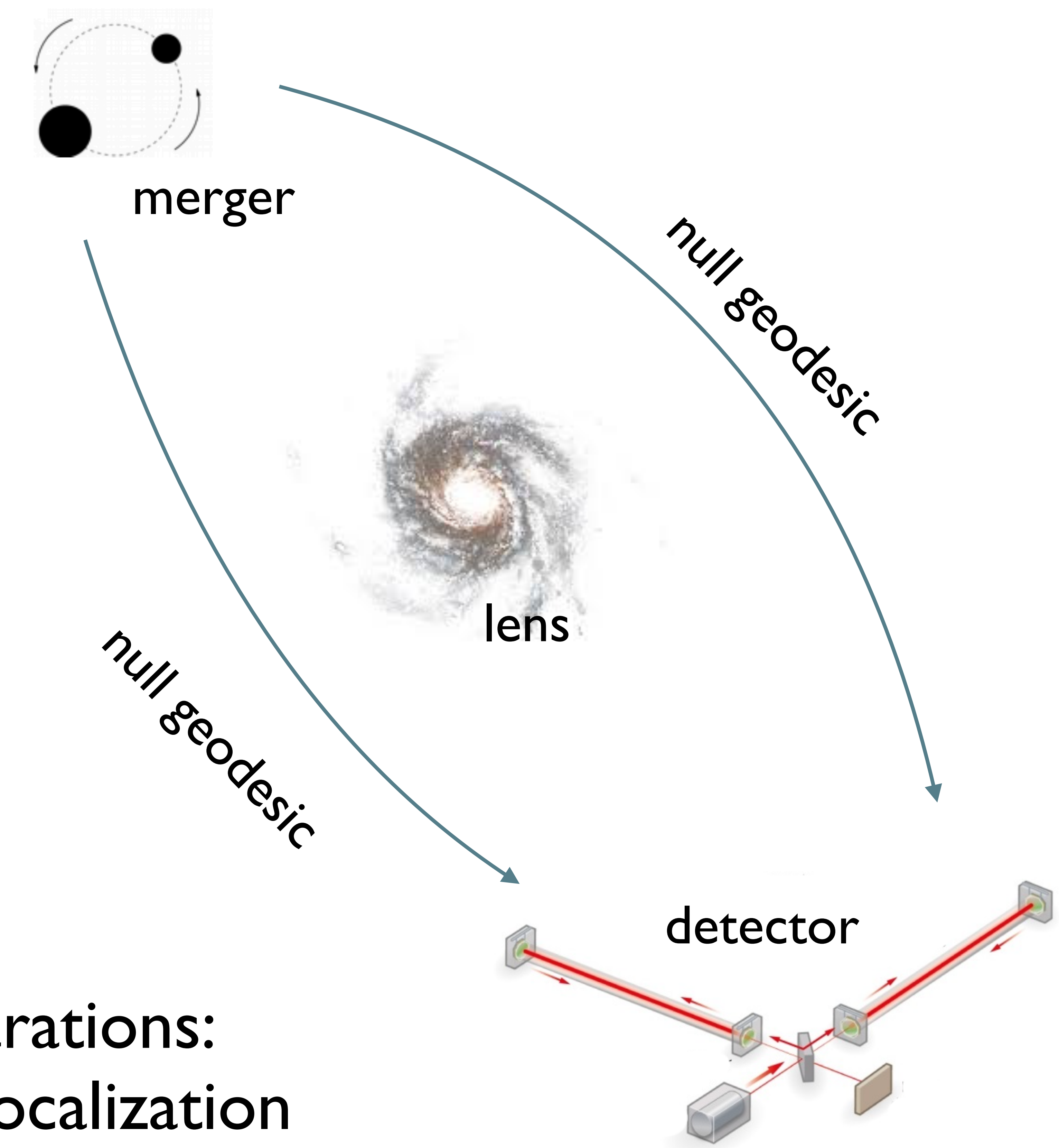


Strong gravitational lensing of GWs

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

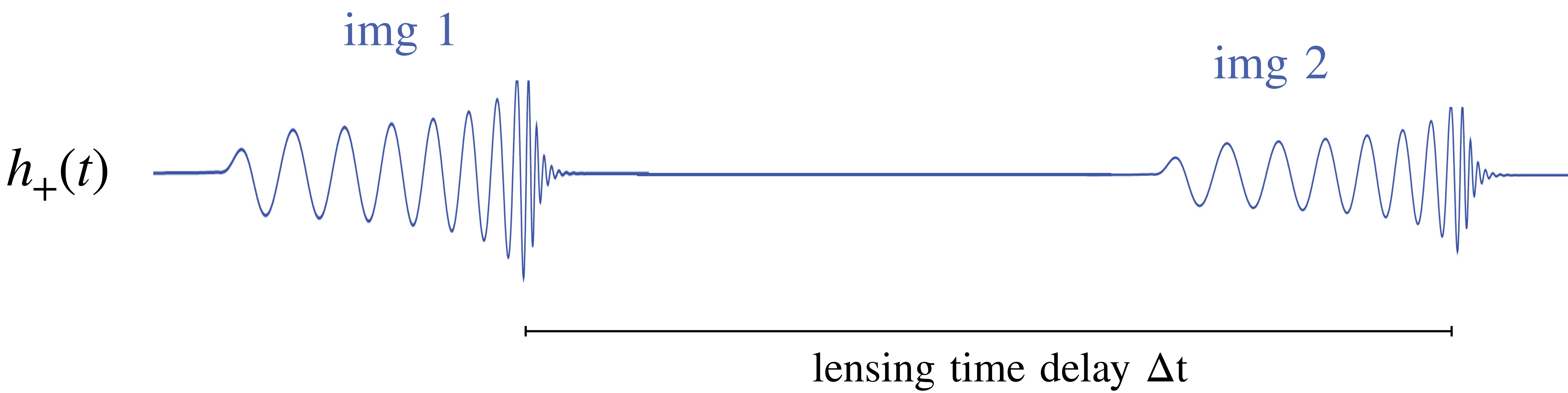


A lensed quasar



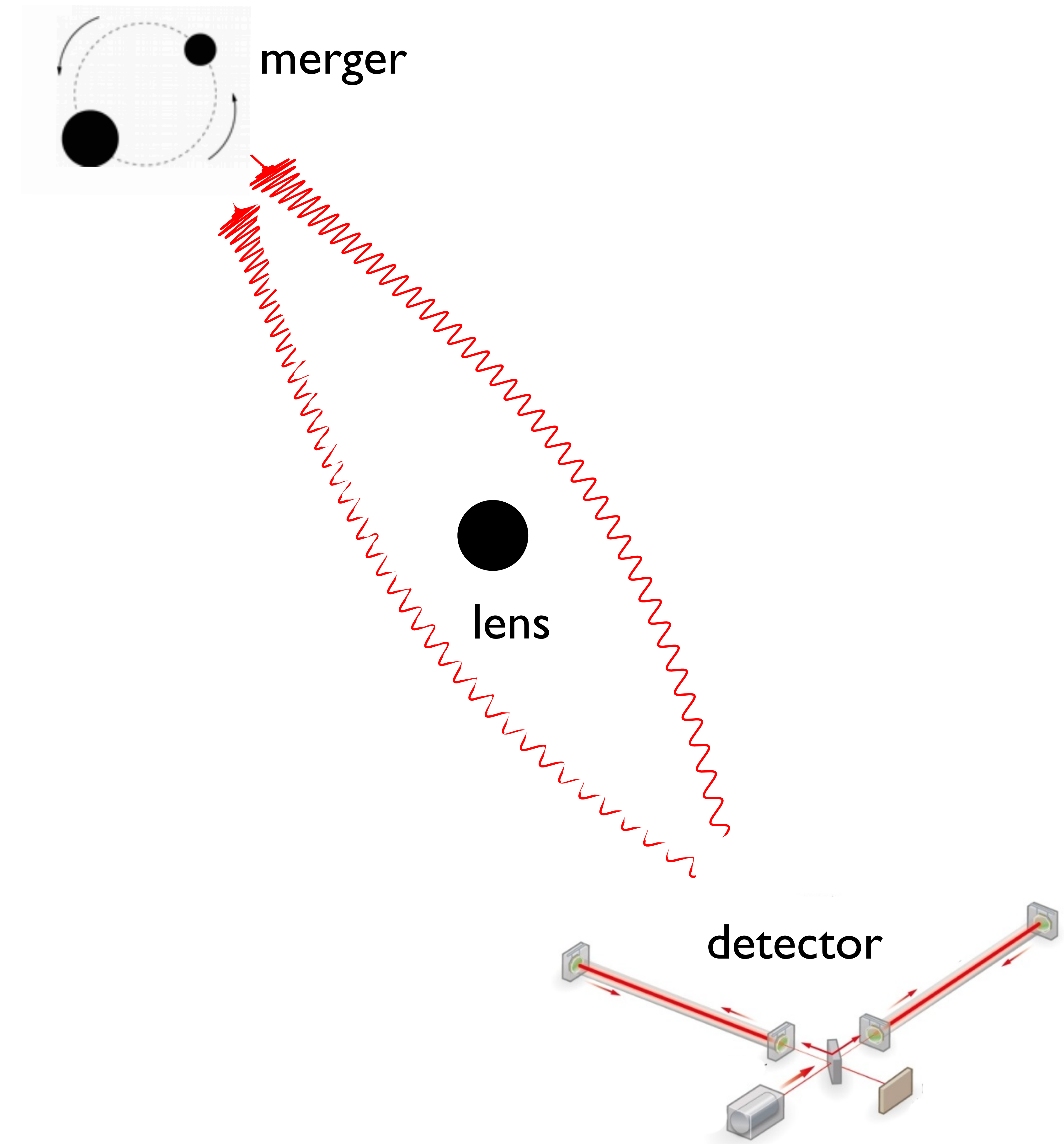
Typical mage separations:
~arc sec ≪ GW localization

Strong gravitational lensing of GWs



Wave optics effects in the lensing of GWs

- When the gravitational radius of the lens ~ GW wavelength, interesting wave optics phenomena happens.
    - Unique opportunity to observe this in GWs, because of the long wavelength (~10^2-10^3 km)

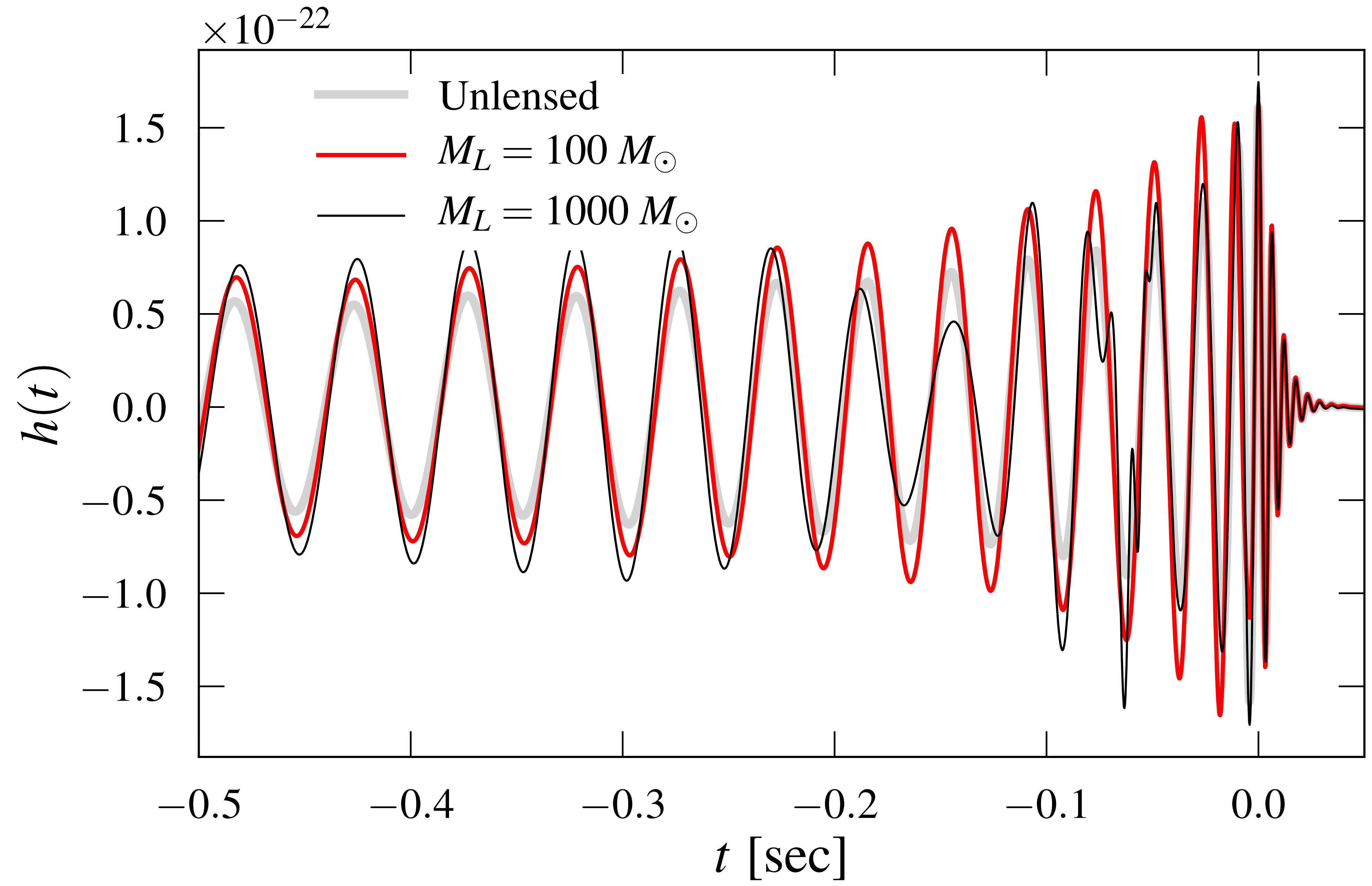


Wave optics effects in the lensing of GWs

- Lensing-induced deformations in the GW signal can be identified.

$$h_{\rm L}(f;\,\boldsymbol{\lambda},\,M_{\rm L}^z,\,y) = h(f;\,\boldsymbol{\lambda})\,F(f;\,M_{\rm L}^z,\,y)$$

Lensed waveform (Fourier transform) — Original waveform — Frequency-dependent magnification



Searches for lensed GWs

Geomtric optics regime

Compute the likelihood ratio between the 'lensed' and 'unlensed' hypotheses from a pair of GW events.

$$\mathcal{B}^L_U = \frac{P(d_1, d_2 \mid \mathcal{H}_L)}{P(d_1, d_2 \mid \mathcal{H}_U)}$$

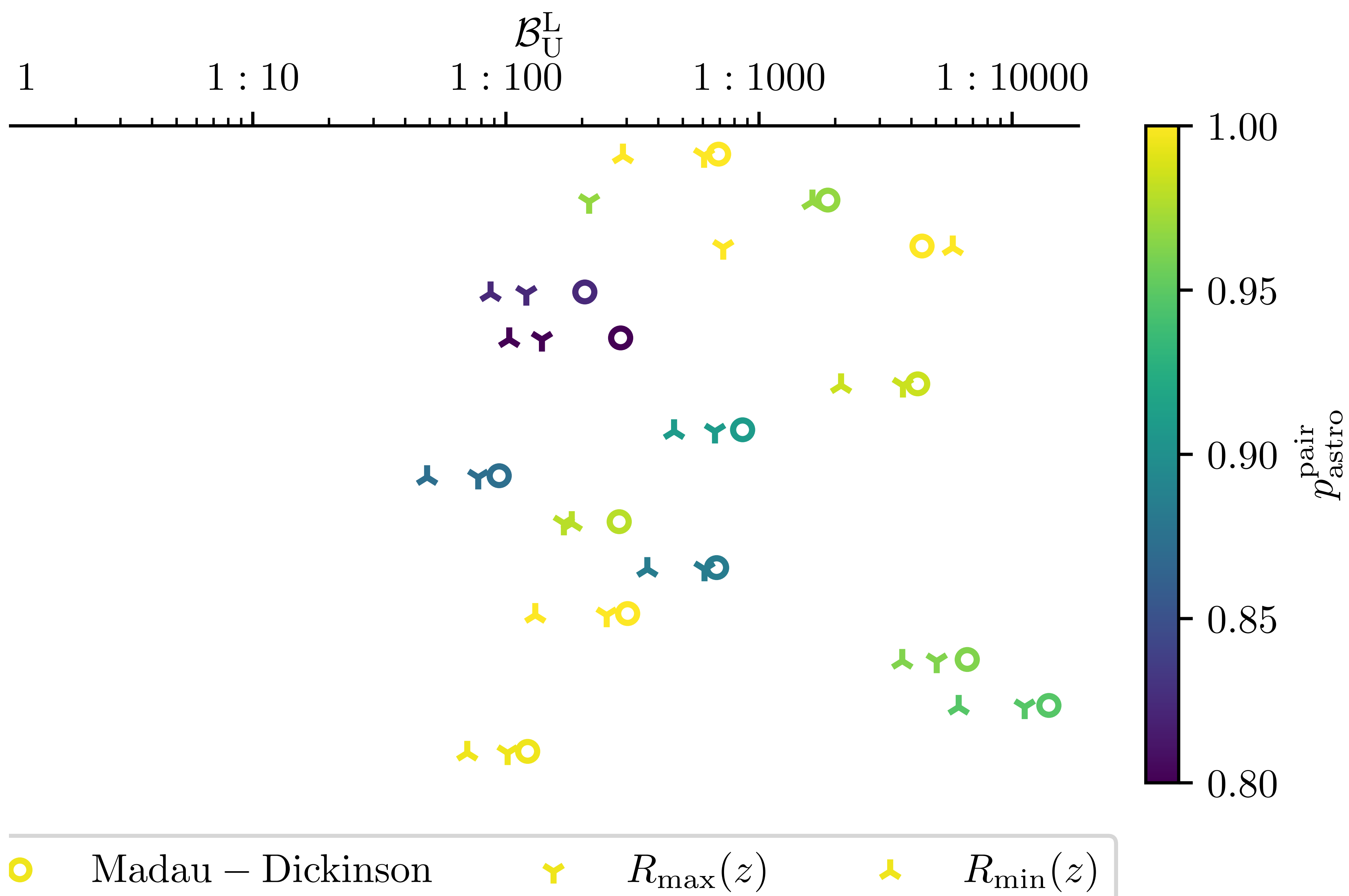
Wave optics regime

Compute the likelihood ratio between the 'microlensed' and 'unlensed' hypotheses from one GW event

$$\mathcal{B}^{\mu L}_U = \frac{P(d|\mathcal{H}_{\mu L})}{P(d|\mathcal{H}_U)}$$

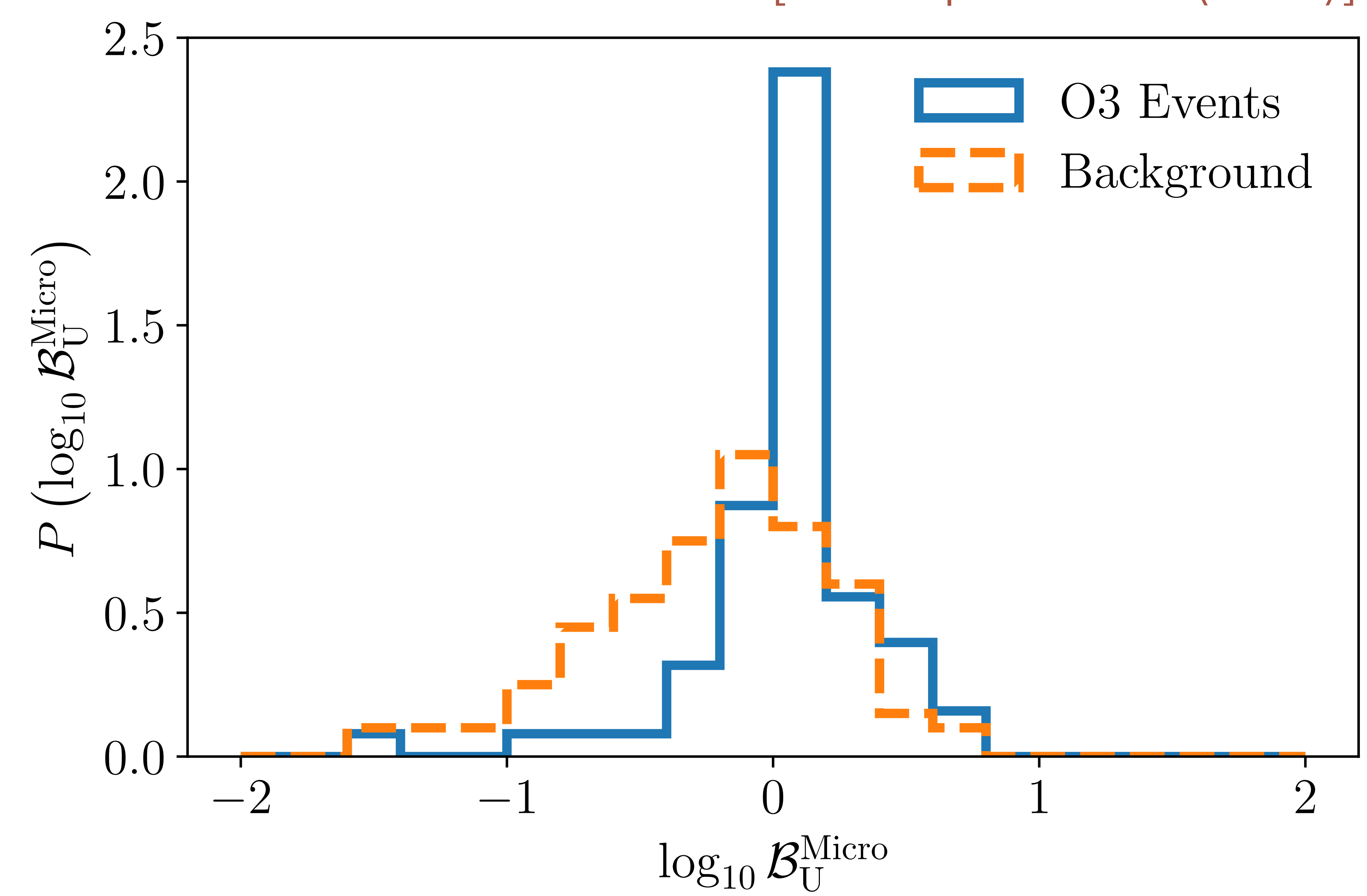
Searches for lensed GWs

Geomtric optics regime



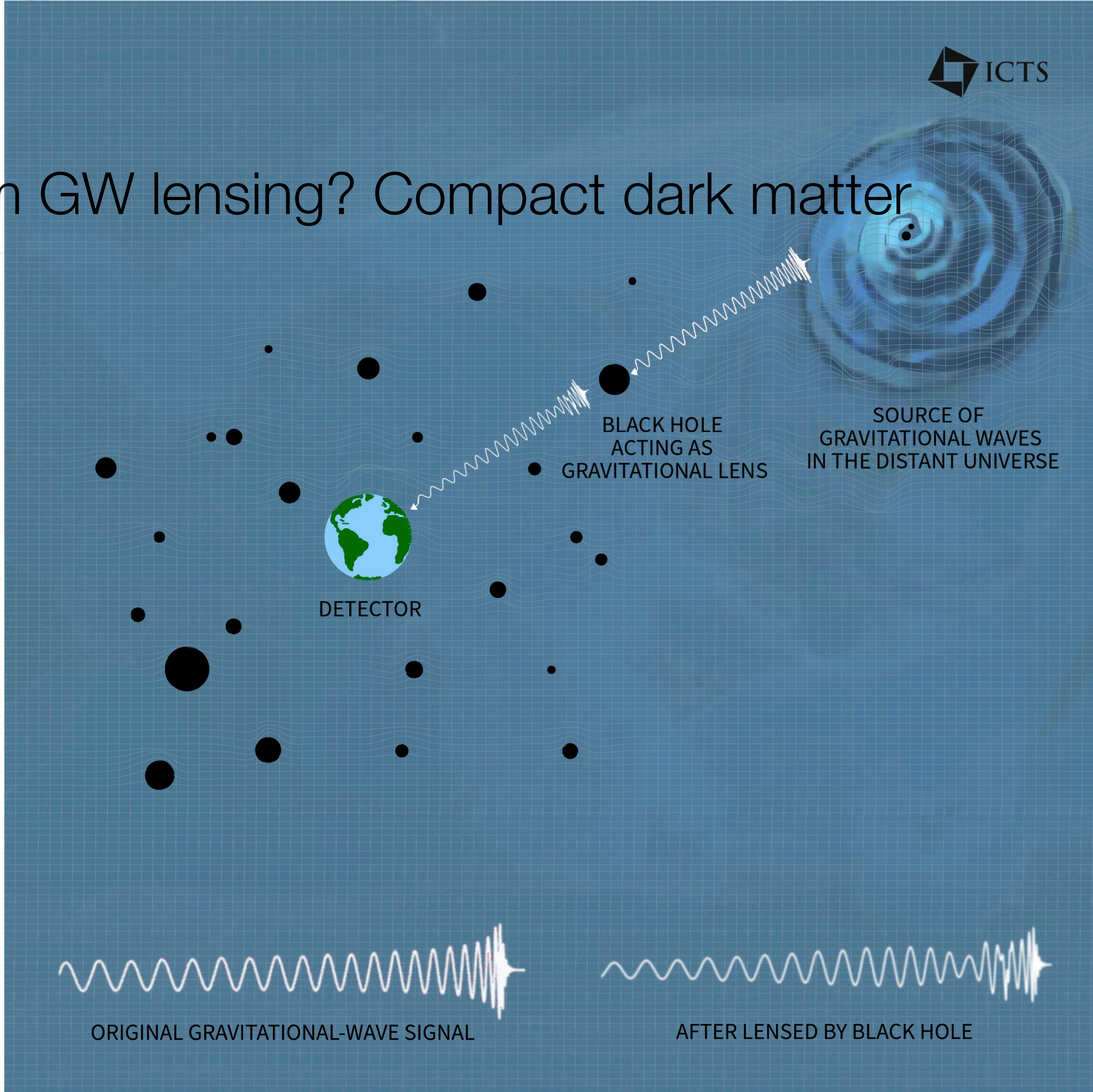
Wave optics regime

[LVK+ ApJ 970 191 (2024)]



No evidence of strong lensing or microlensing in the data so far.

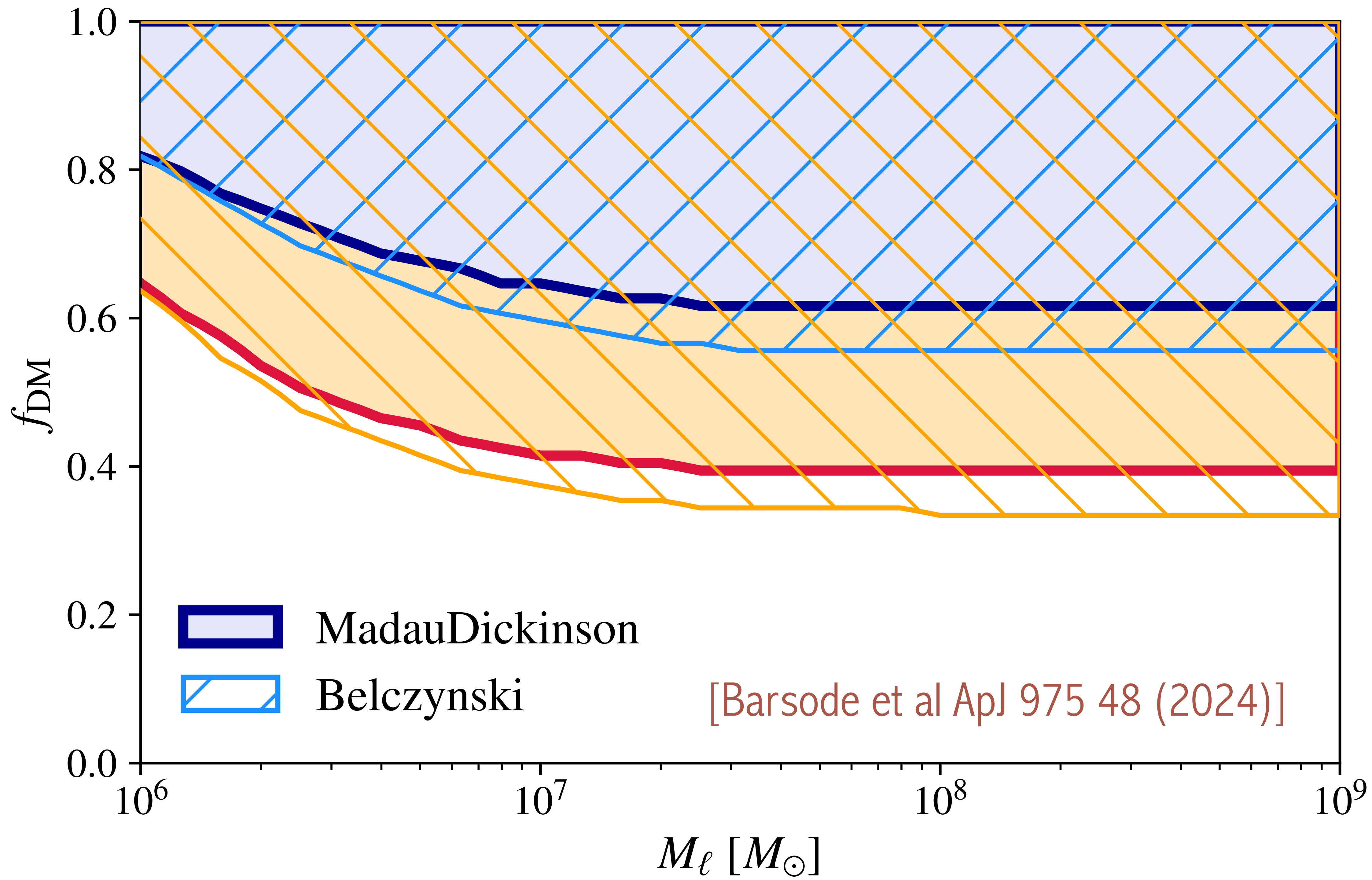
What can we learn from GW lensing? Compact dark matter



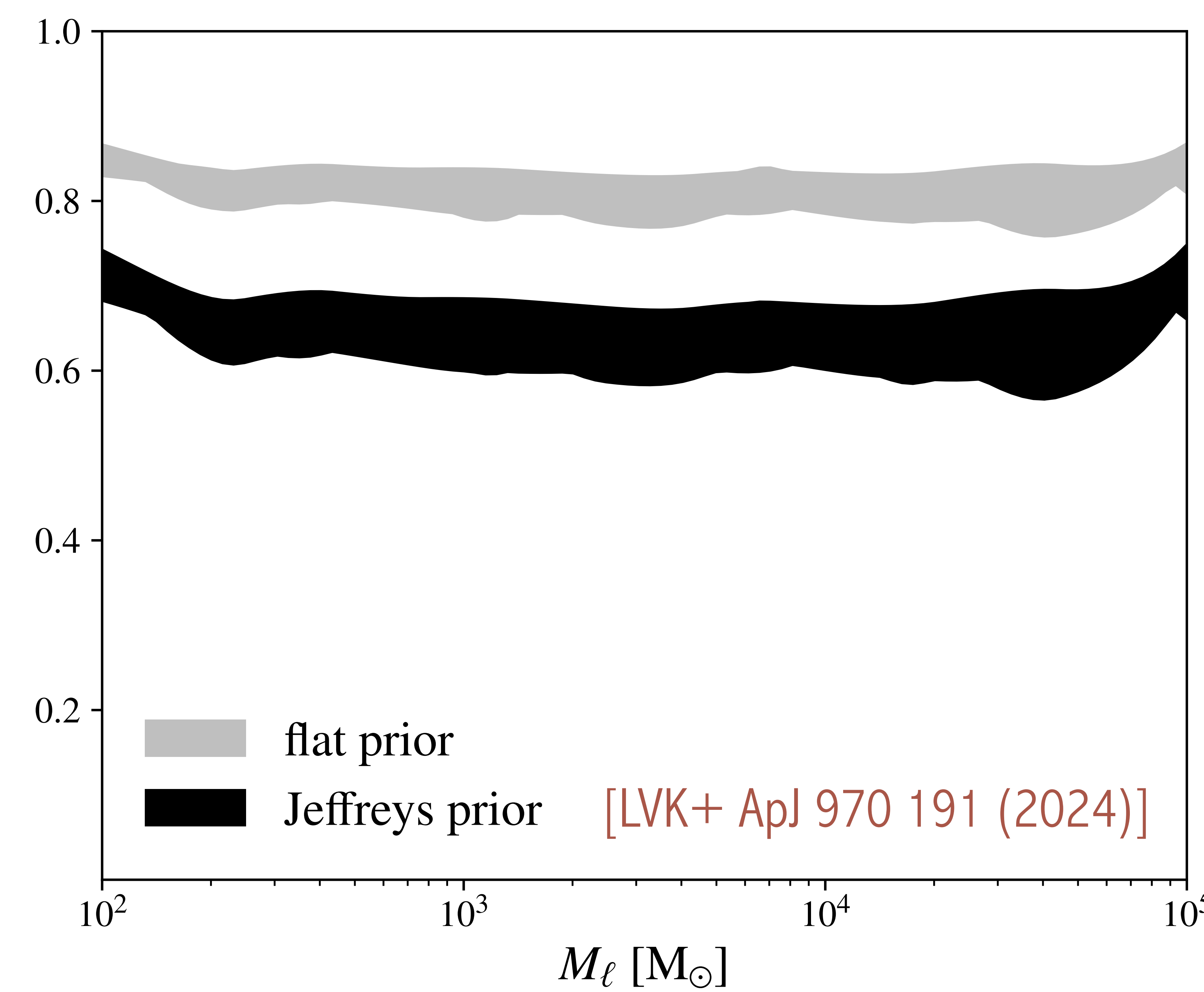
[Roshni Samuel / P. Ajith / ICTS]

Constraints on primordial BHs being dark matter

Geomtric optics regime

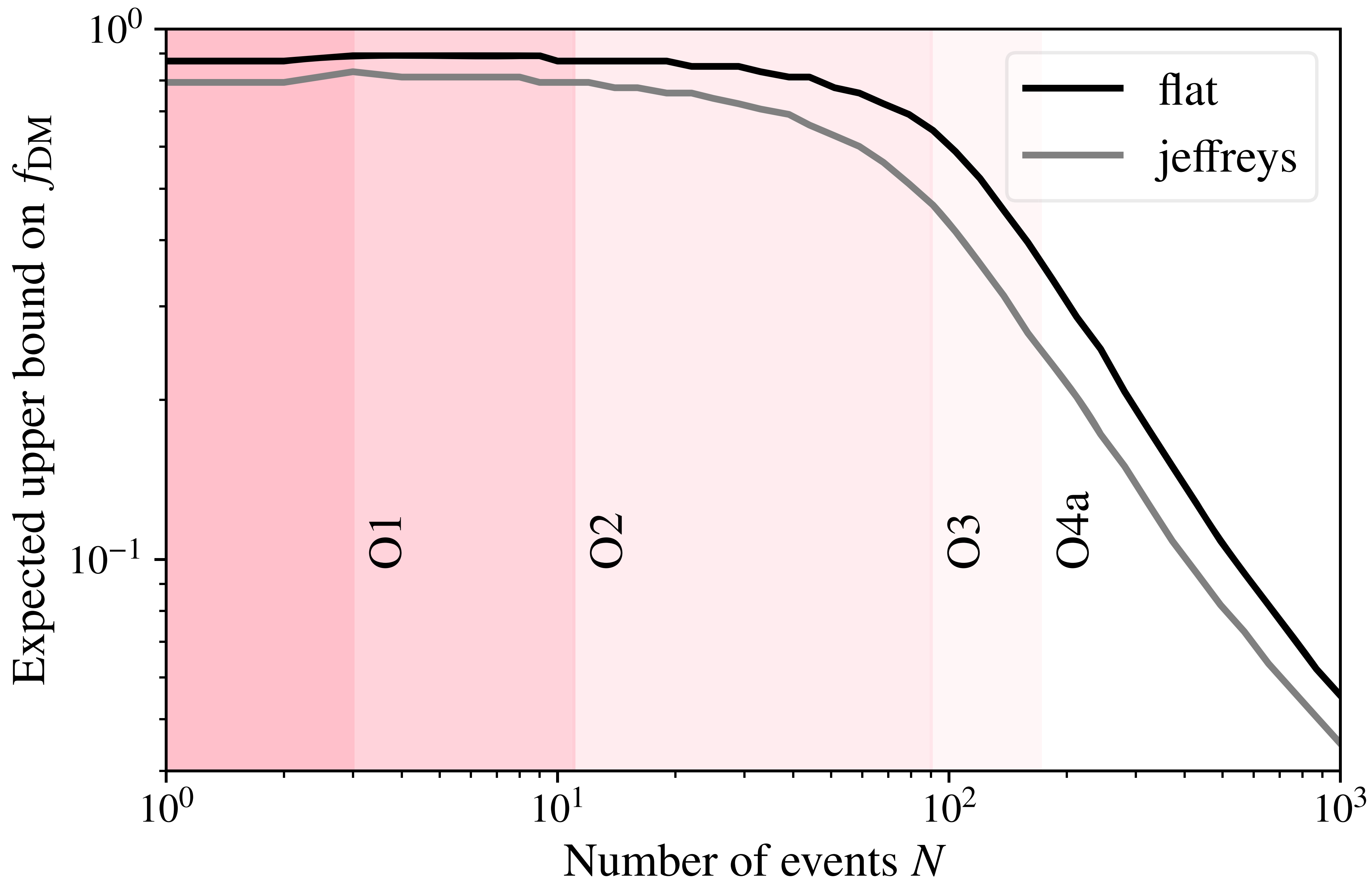


Wave optics regime



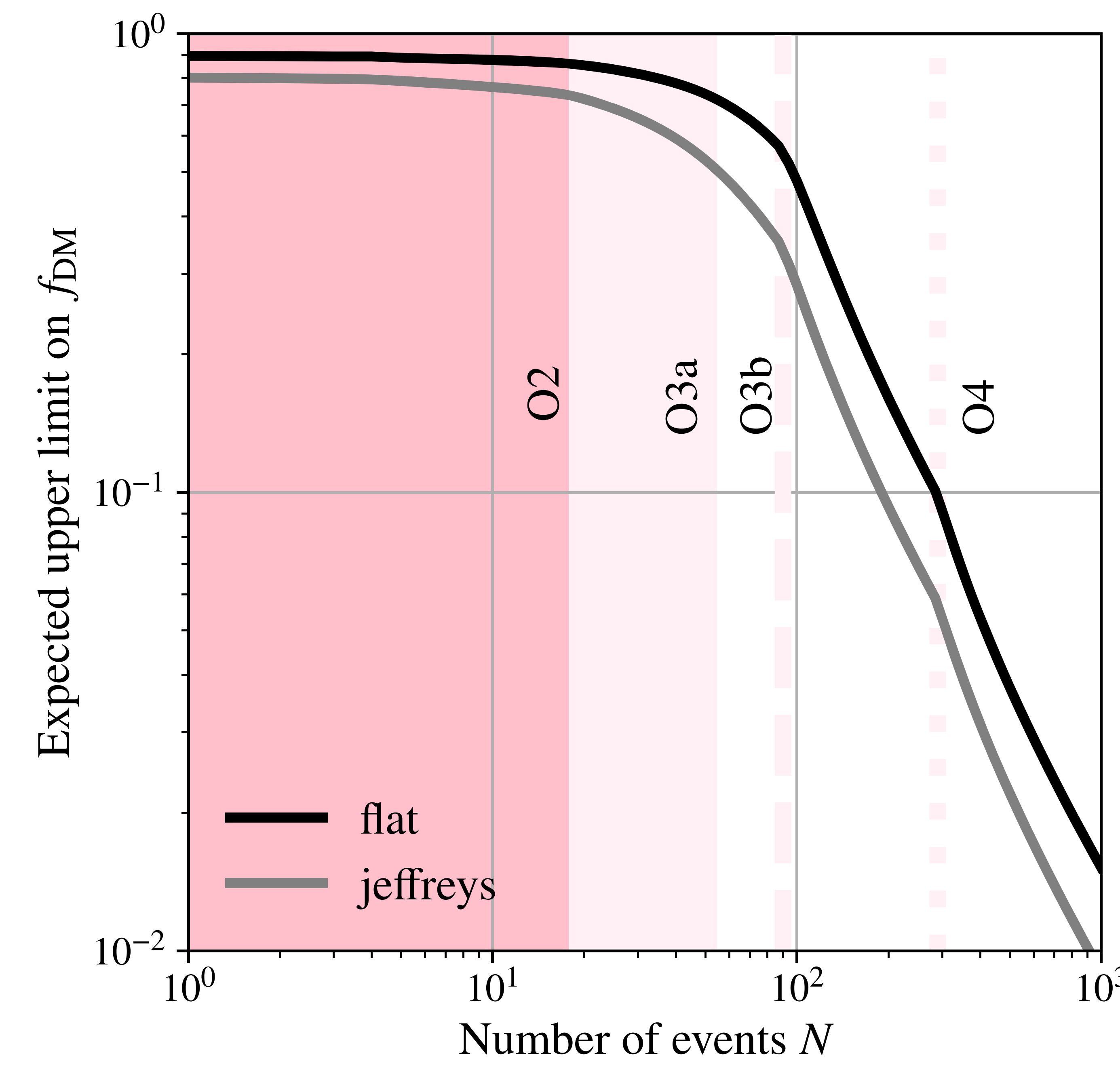
Constraints on primordial BHs being dark matter

Geomtric optics regime



[Barsode et al ApJ 975 48 (2024)]

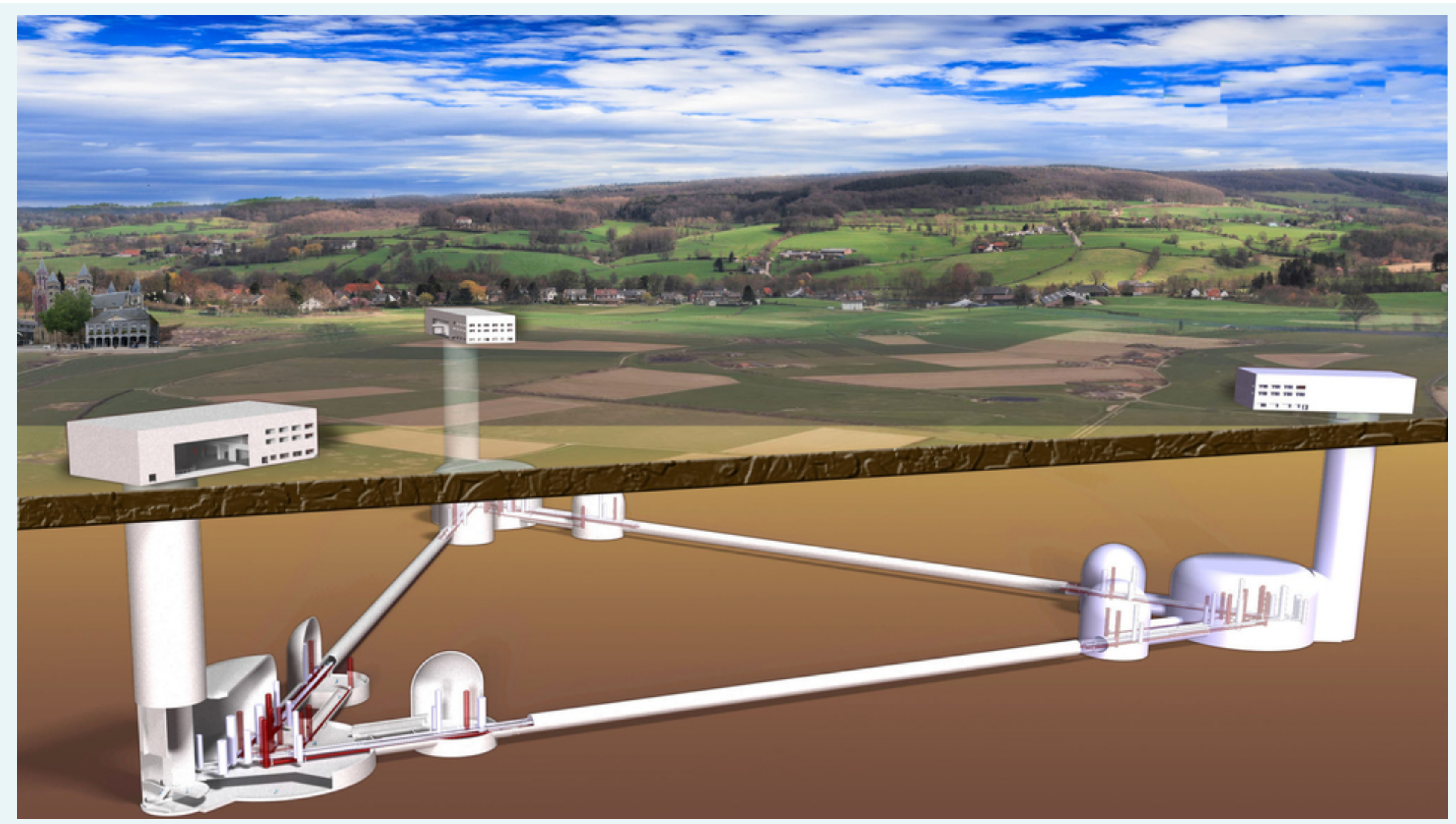
Wave optics regime

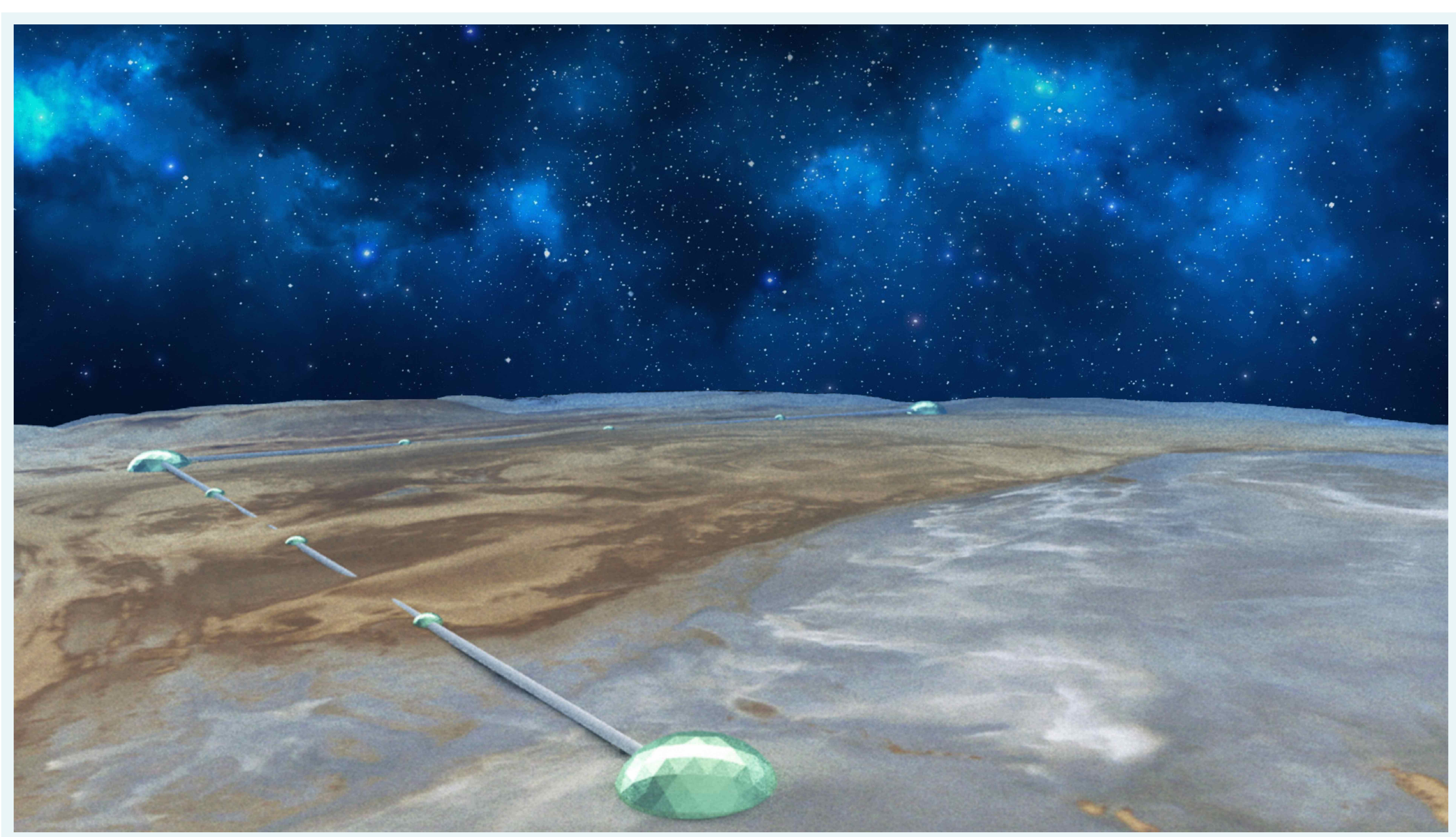


[Basak et al ApJ Lett 926, L28 (2022)]

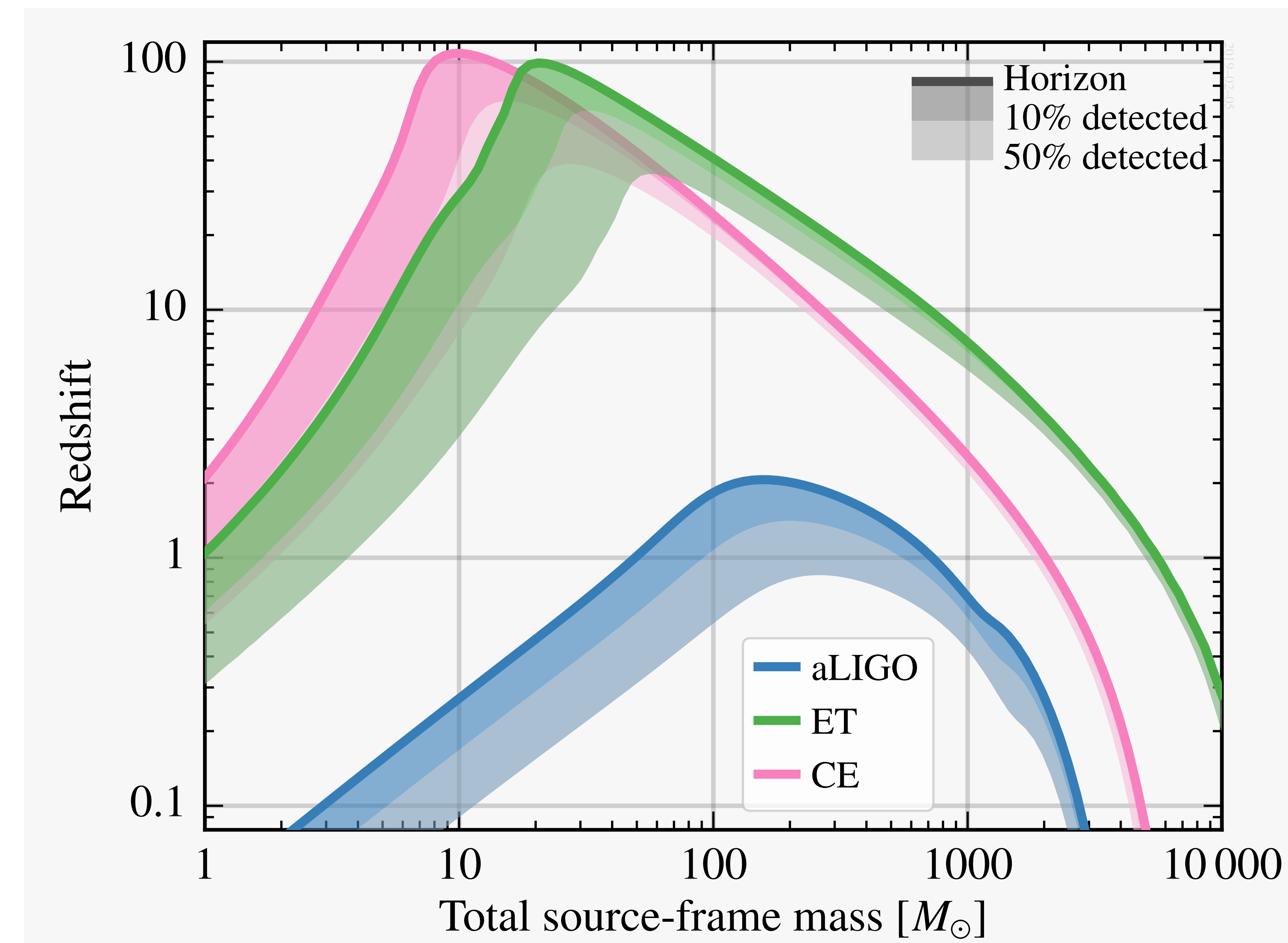
Constraints will get significantly better in the near future (*Caveats)

Next generation ground-based GW 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]

Cosmology using strongly lensed GWs

- XG detectors are expected to detect ~10^7 mergers. ~10^4 would be strongly lensed.
- Detected number of lensed signals & their time delay distribution contain imprints of cosmological parameters and the nature of dark matter particle.
- Cosmography in the intermediate redshift regime ($z \sim 2 - 10$) between SNe and CMB. A new probe of particle dark matter.

Expected number of lensed GWs

Merger rate

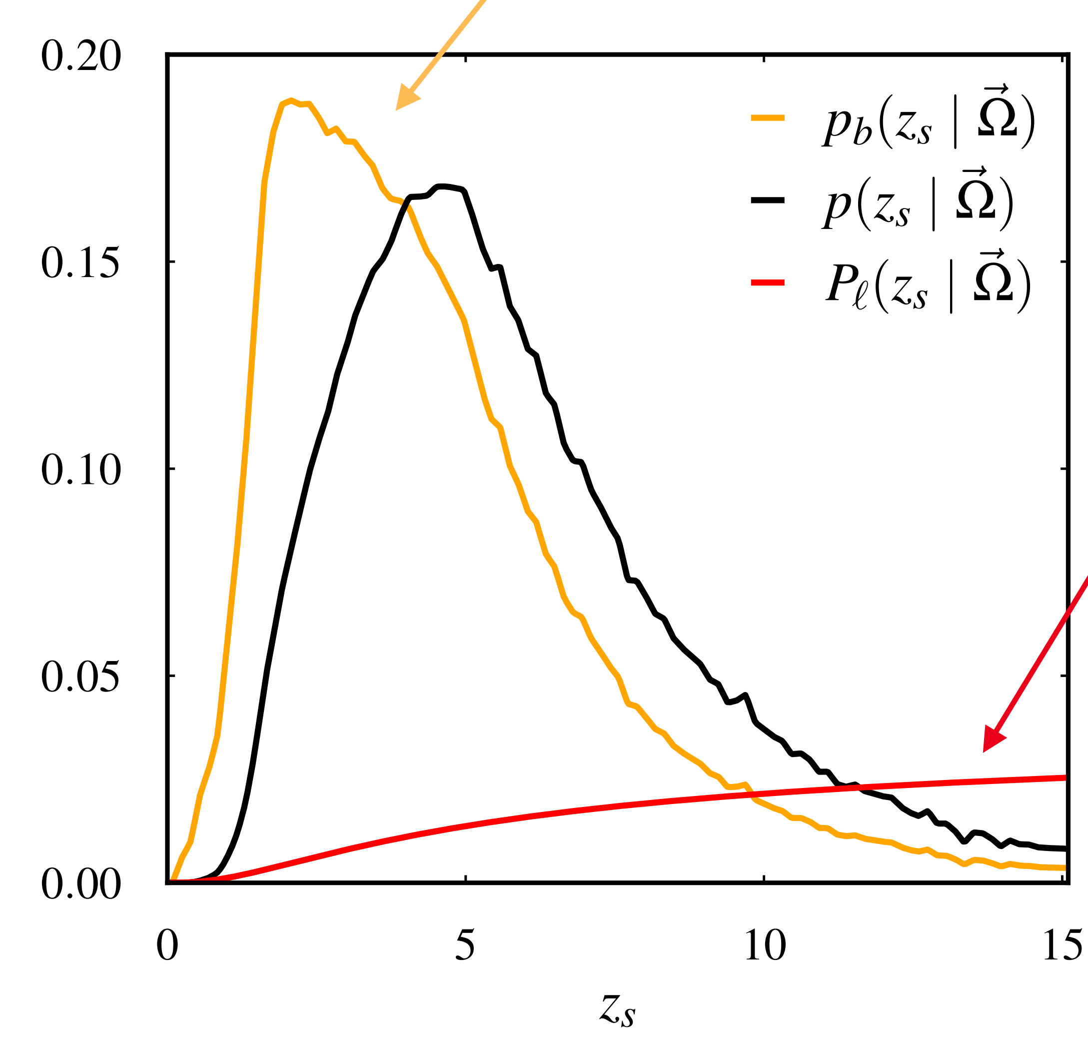
Cosmological parameters

$$\Lambda(\vec{\Omega}, T_{\rm obs}) = \mathcal{S}(T_{\rm obs}) \times R \int_0^{z_s^{\rm max}(\vec{\Omega})} p_b(z_s|\vec{\Omega})\, P_\ell(z_s|\vec{\Omega})\, dz_s$$

Effective observation time

Redshift distribution of BBH mergers

Lensing probability



Distribution of the time delay between lensed images

Lens parameters and source position

$$\vec{\lambda} \equiv \{y, \sigma, z_\ell, z_s\}$$

$$p\left(\Delta t \mid \vec{\Omega}\right) = \int p\left(\Delta t \mid \vec{\lambda}, \vec{\Omega}\right) \quad p(\vec{\lambda} \mid \vec{\Omega}) \ \ d\vec{\lambda}$$

Time delay, given the source and lens parameters and cosmology

Distribution of lenses and sources, given the cosmology

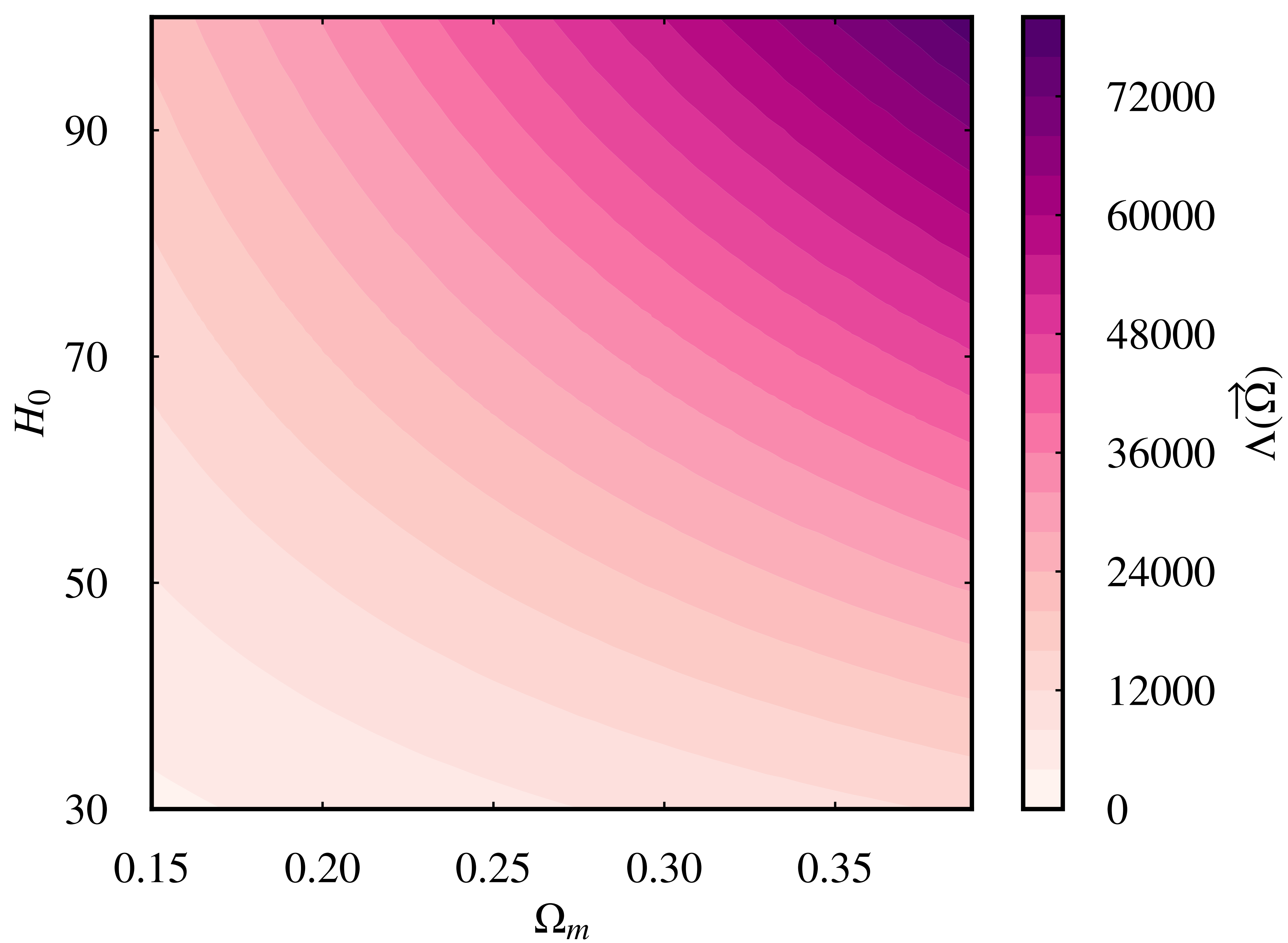
$$\Delta t(z_\ell, \sigma, z_s, y, \overrightarrow{\Omega}) = \frac{32\pi^2 \ y}{c} \ \frac{(1+z_\ell)\, D_\ell D_{\ell s}}{D_s} \ \left(\frac{\sigma}{c}\right)^4$$

(Currently assume SIS lens)

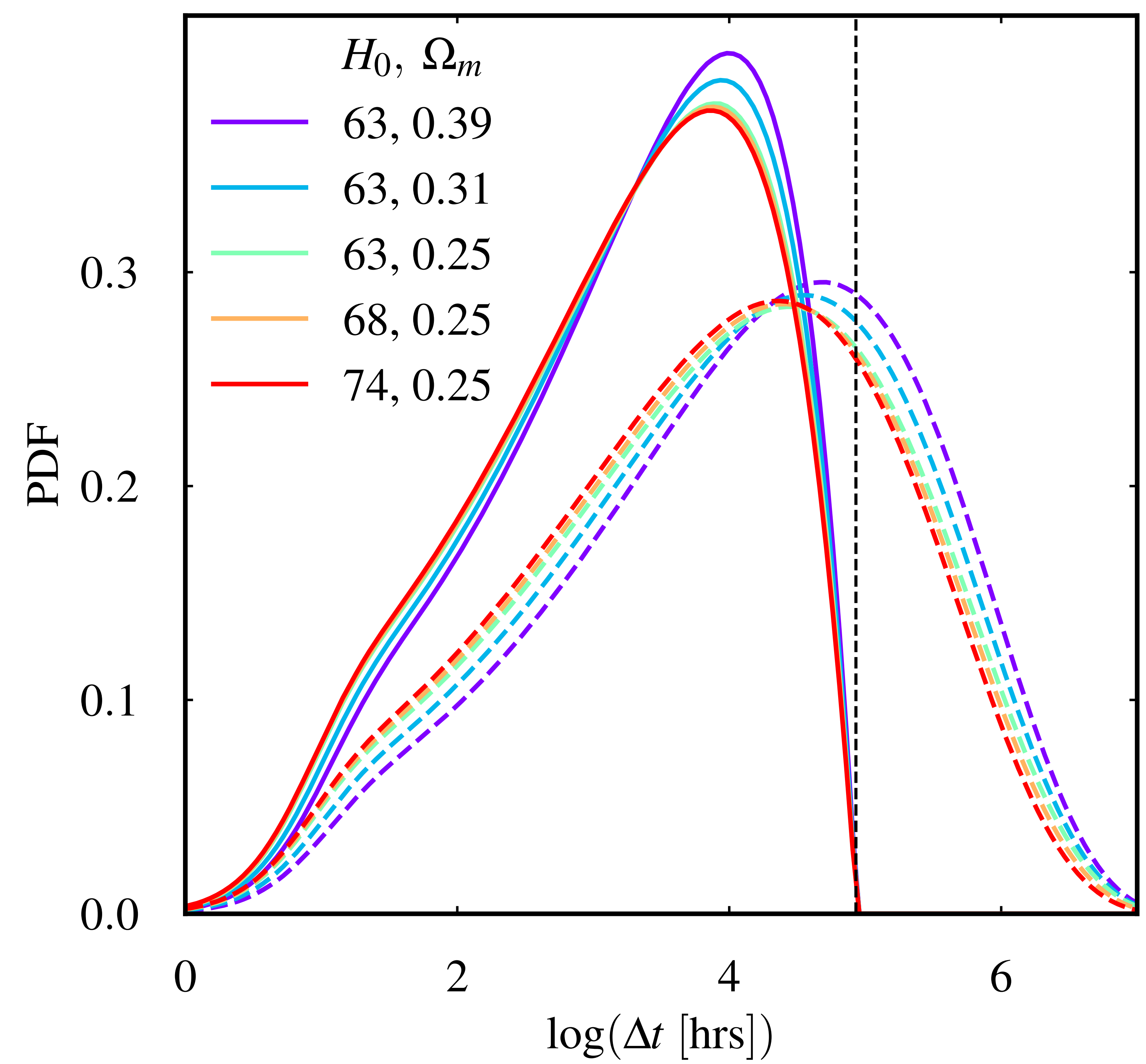
Imprint of cosmological parameters

[Jana et al PRL 130, 261401 (2023)]

Expected number of lensed events (10 yrs)



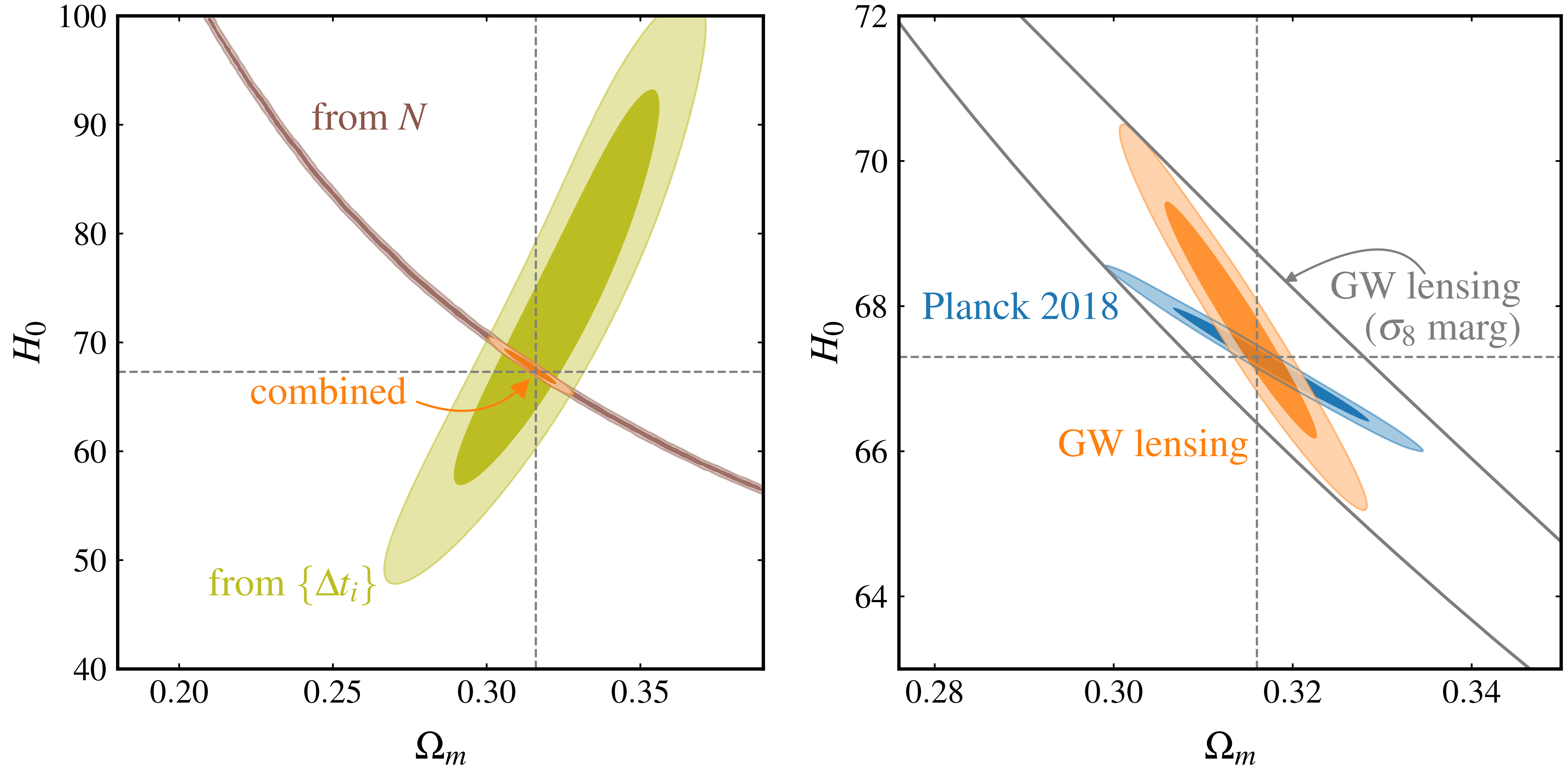
Lensing time delay distribution



Assuming flat LCDM model

Expected constraints on cosmological parameters

[Jana et al PRL 130, 261401 (2023)]

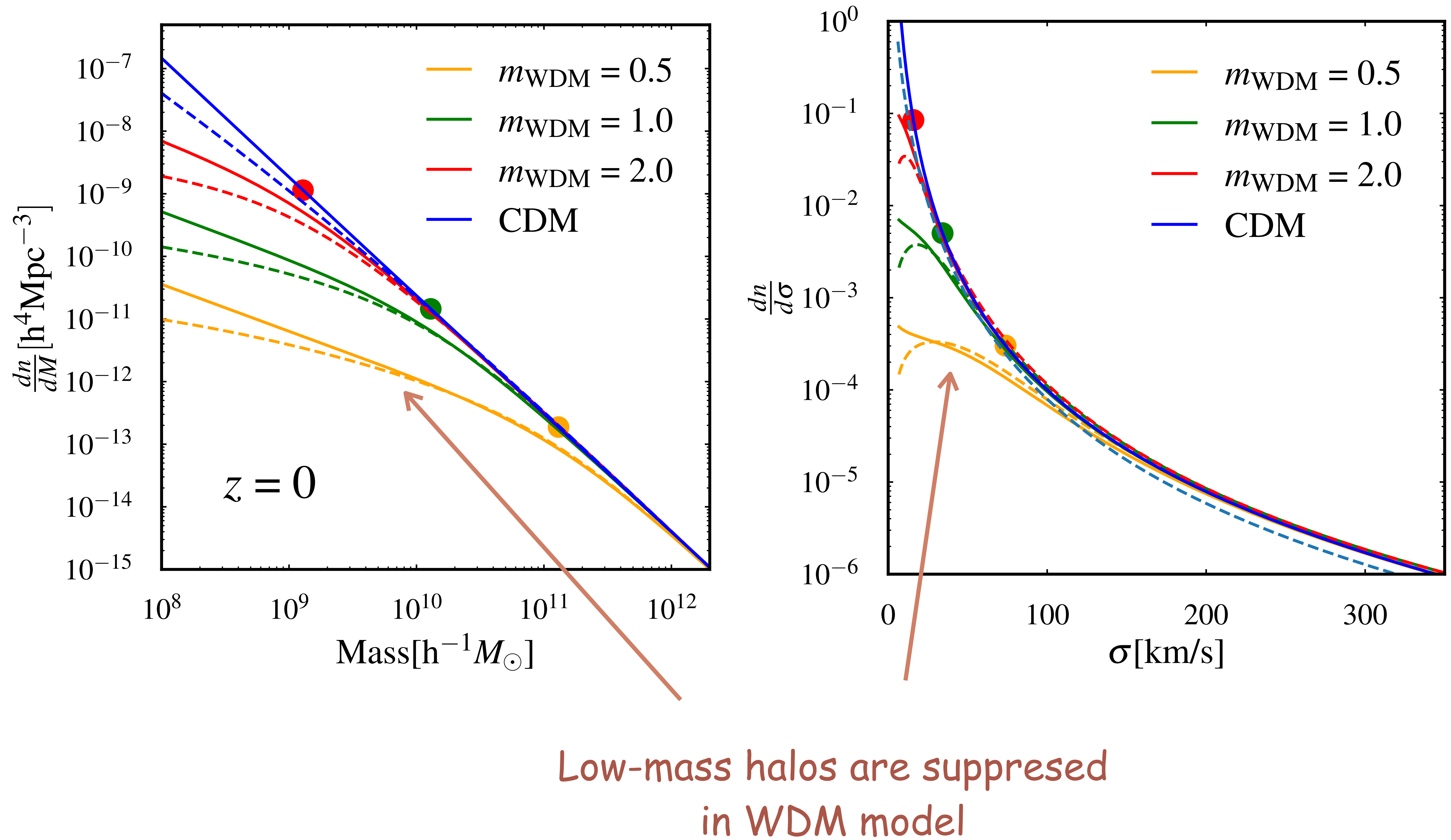


- Assuming 10 yrs of observation using XG detectors and merger rate $R = 5 \times 10^5\ \mathrm{yr}^{-1}$

GW lensing as a probe of dark matter

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

[Jana et al PRL in press, arXiv:2408.05290]



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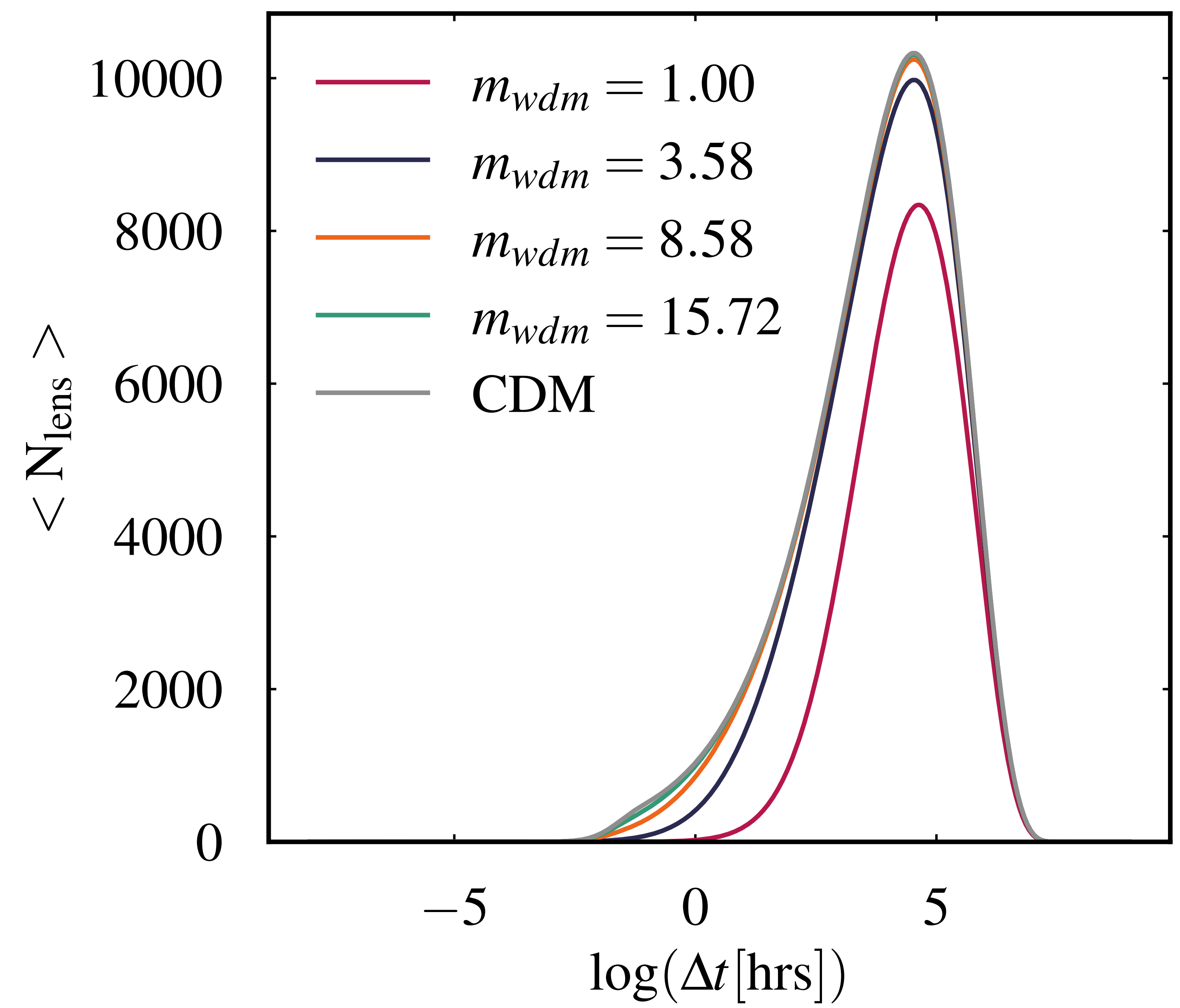

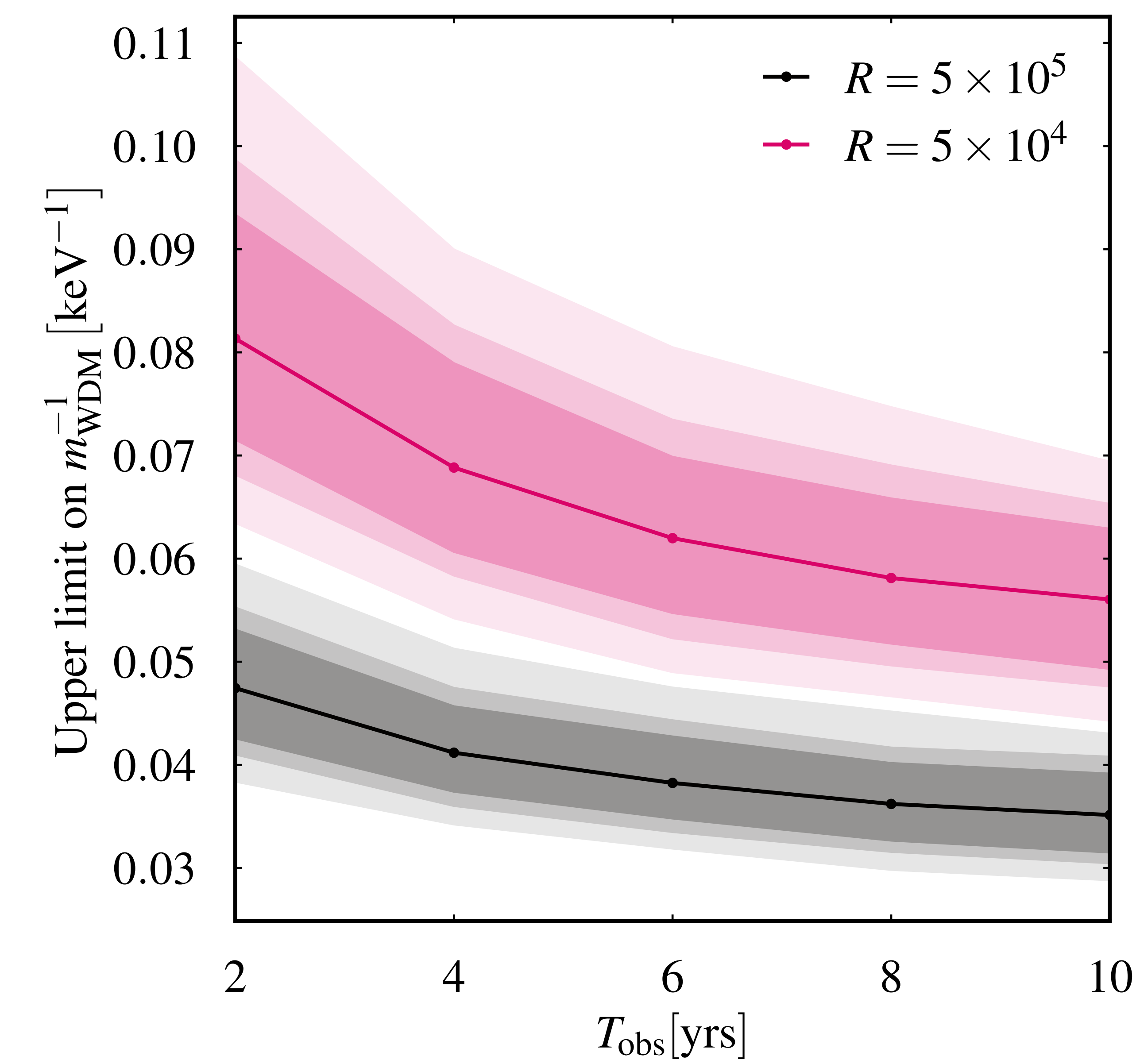

Expected constraints from 10 yr obs of 3G detectors

Summary

- The first observation of gravitationally lensed GWs should happen int the next few years. Most likely lenses are galaxies and clusters.
- Next generation GW detectors will observe tens of thousands of strongly lensed GWs. Their exact number and the time delay distribution will depend on a combination of the properties of the sources, lenses and cosmology.
- This will enable interesting probes of cosmology (expansion rate, nature of dark matter, etc).
- Probing the intermediate redshift regime ($z \sim 2$ — 10) that is not well probed by other observations.

Challenges

- Accurate identification of strongly lensed GW events (or, modeling the contamination accurately).
- Uncertainties in measuring the source population properties (likely to be negligible in XG). Selection effects.
- Accurate modeling of the lens population. Need input from cosmological simulations and EM lensing observations.

Some ongoing work [Jana et al CQG 41 245010 (2024), Jana et al (In Prep), K. Maity et al (In Prep)]