Synergies of deci-Hz gravitational-wave detectors

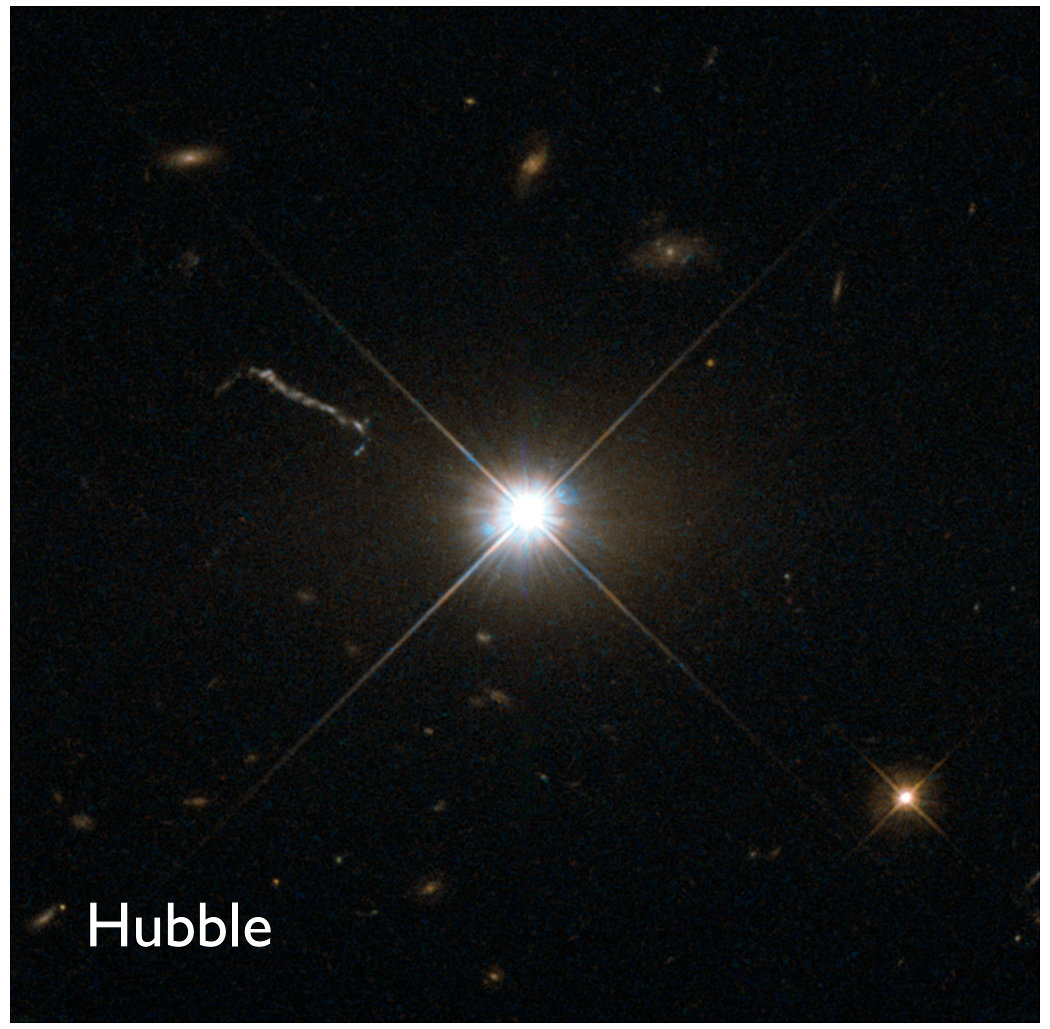
Parameswaran Ajith
International Centre for Theoretical Sciences, Bengaluru

LGWA Meeting | 17 Sep 2025
Polo Didattico di San Benedetto, University of Camerino

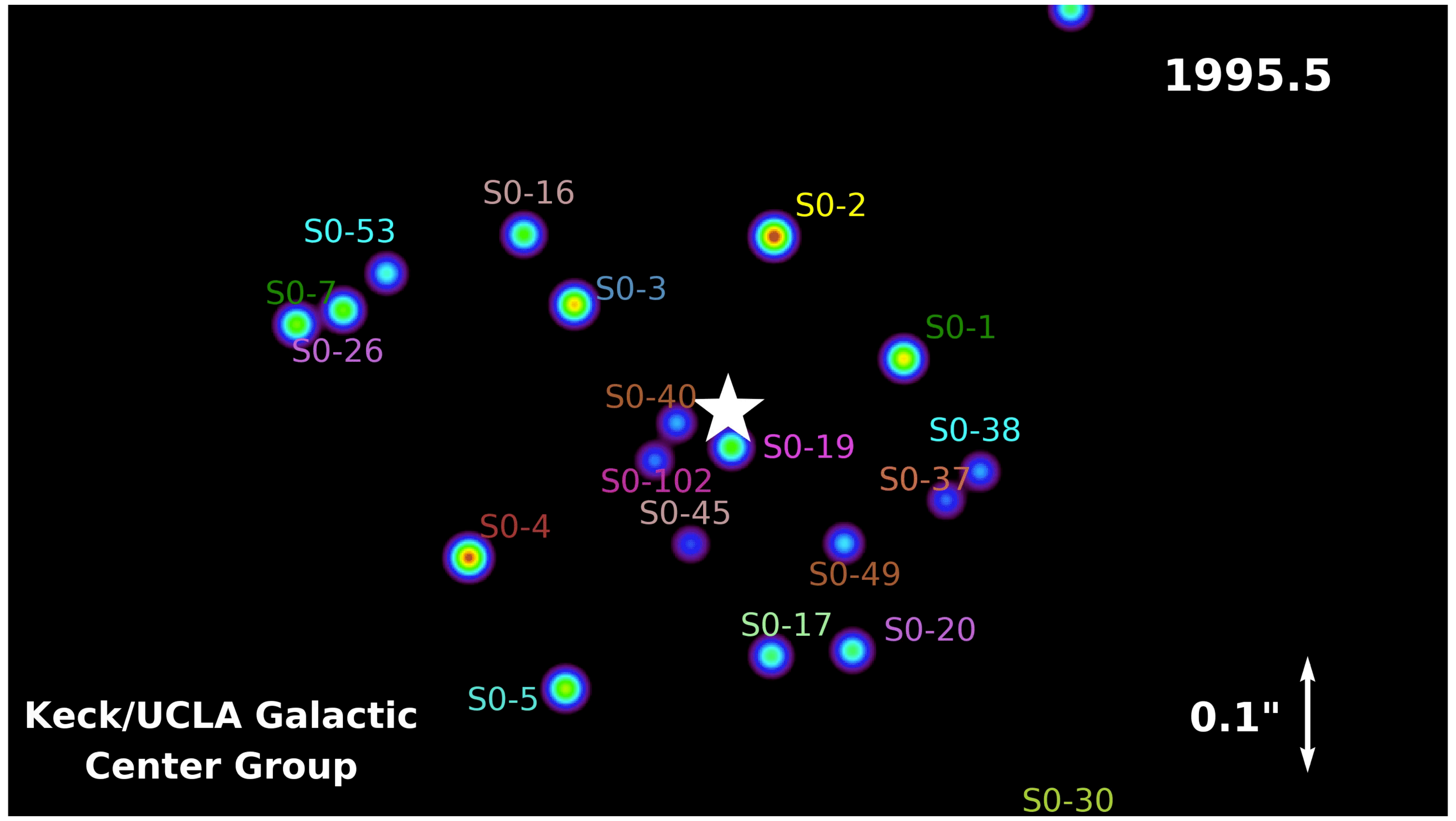
Possible synergies

- Understanding the formation and evolution of SMBHs
- Early warning of ground-based GW detectors
- Source localisation, EM counterparts and cosmography
- Parameter estimation, population inference and tests of GR
- Lensing in wave optics and geometric optics

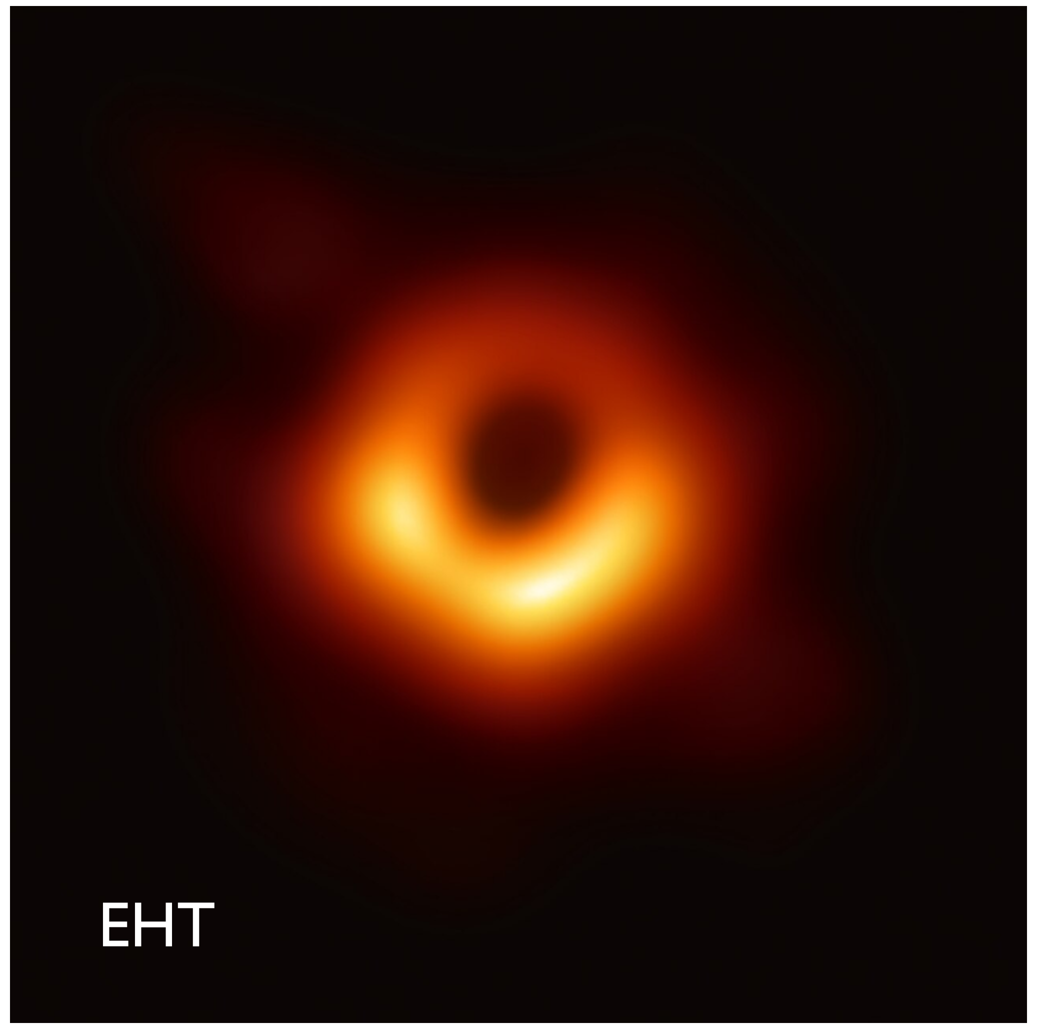
Supermassice black holes



Quasars and AGNs: Powered by gas accretion to SMBHs



Supermassive compact object at the Galactic cener (from stellar orbits)



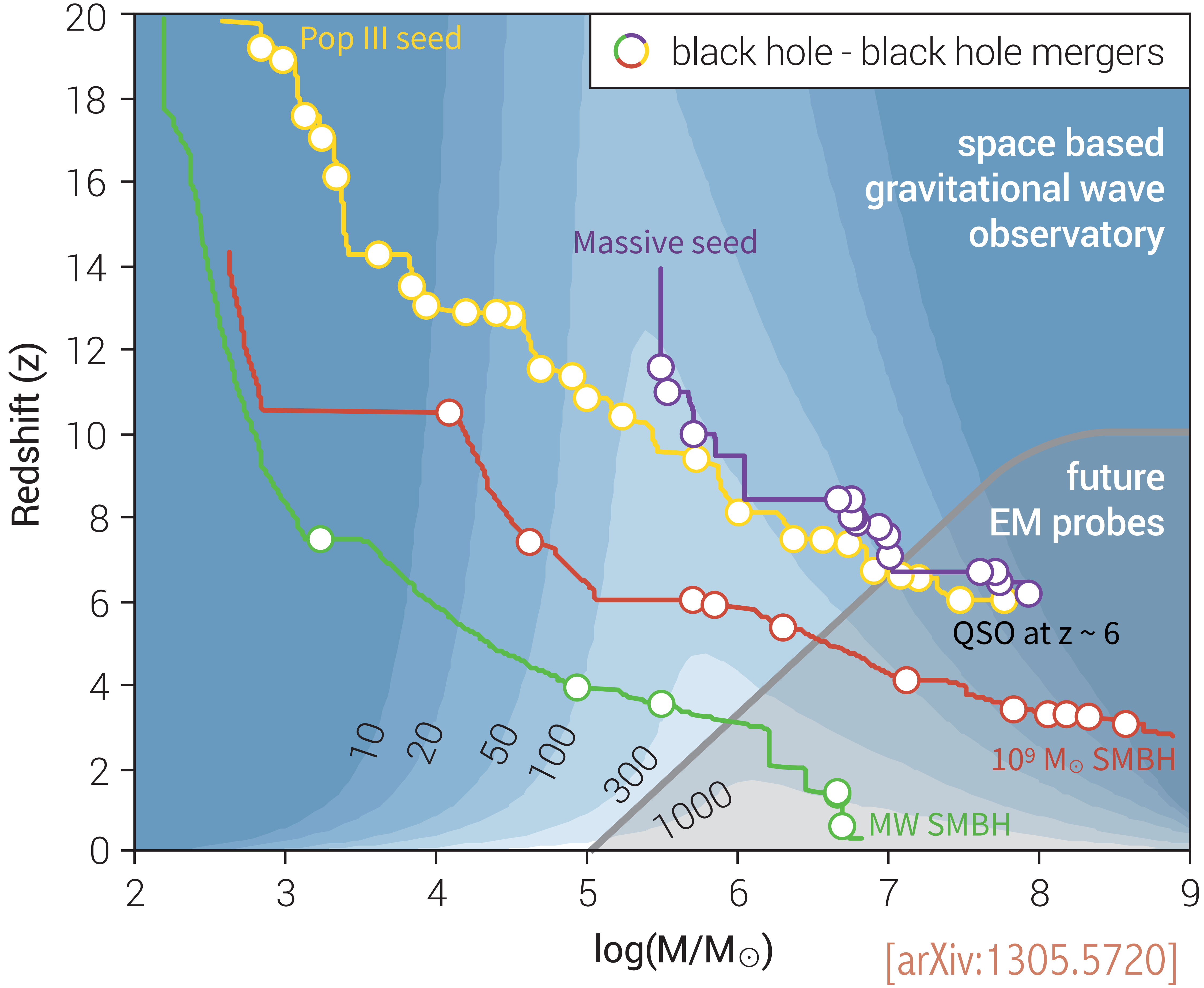
VLBI imaging of the BH shadow

- Distant quasars powered by SMBHs: $\sim 10^7 M_\odot$ at $z \simeq 10$ (UHZ1).
- Lightest massive BH ~ $6800\, M_\odot$ (NGC 205). Heaviest stellar mass BH ~ $225\, M_\odot$ (GW231123). Continuus mass function?

SMBH formation and evolution: Broad paradigm

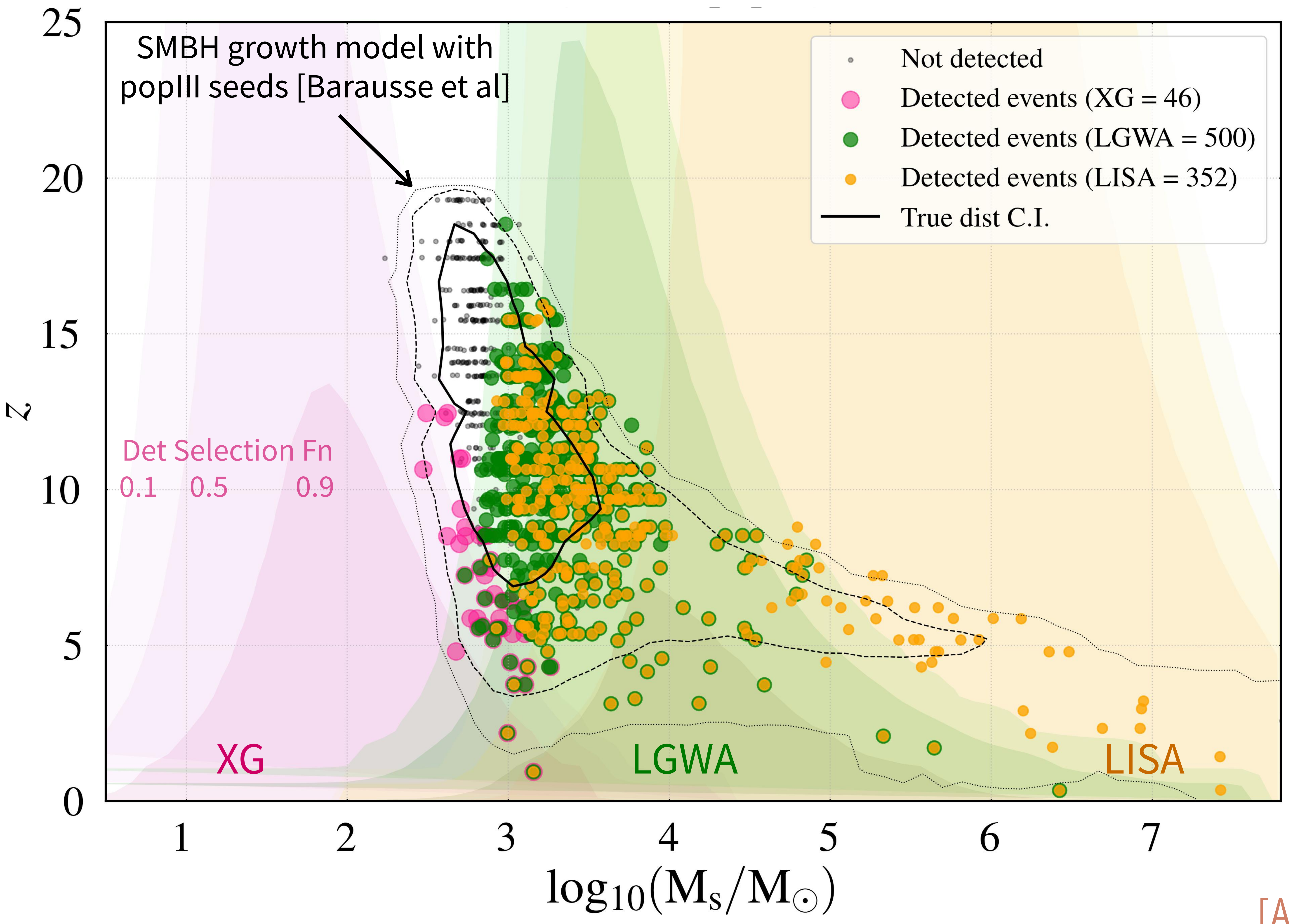
- Seed BHs at high redshifts grow into SMBHs over cosmic time through accretion & mergers.
    - When/how did the first BHs form? Their mass function?
    - Relative contribution of accretion & mergers in the mass growth?
    - Role of SMBHs in galaxy formation?
- Observe BBH mergers in different mass ranges and redshifts.

Possible evolution pathways of typical SMBHs



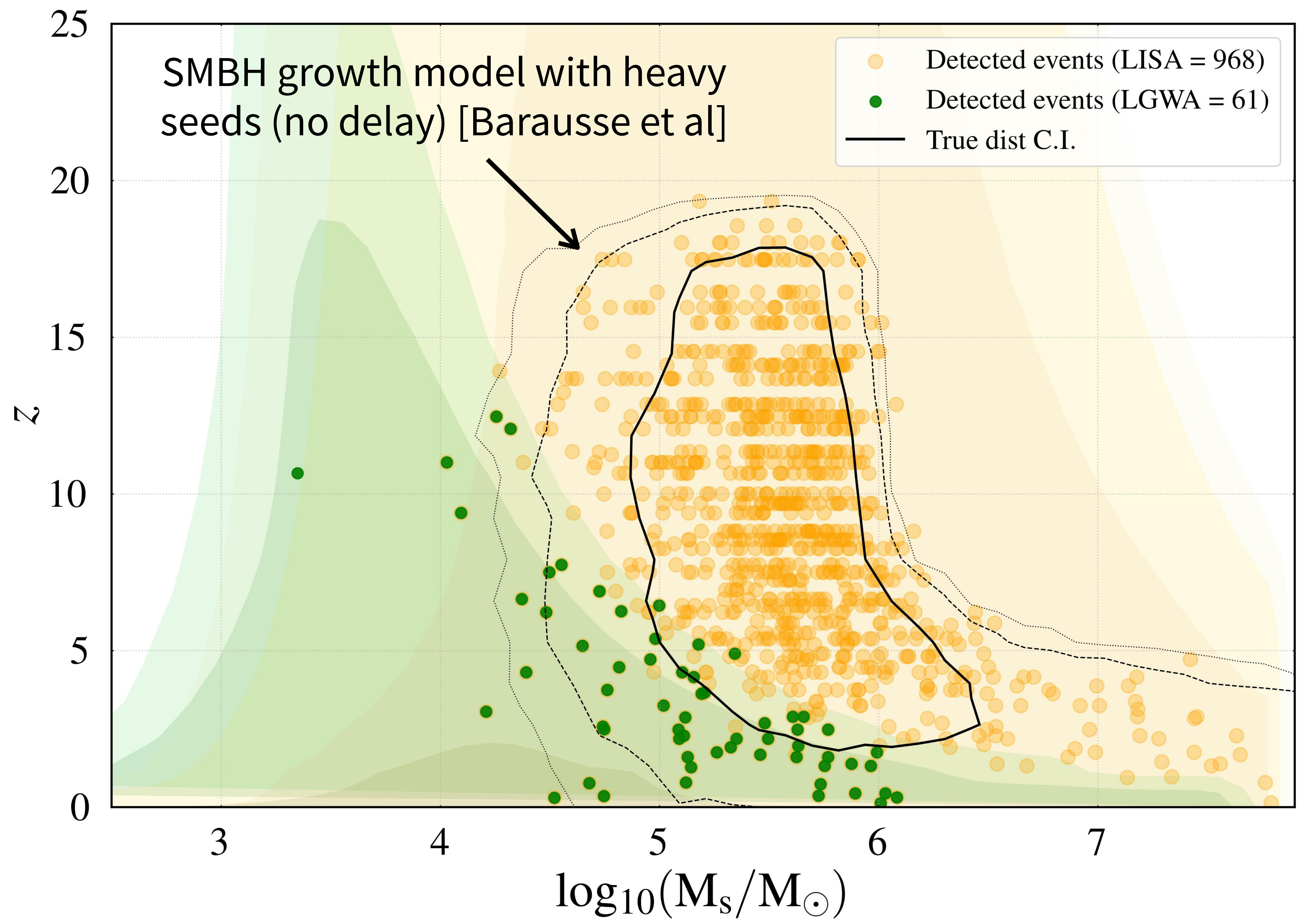
[arXiv:1305.5720]

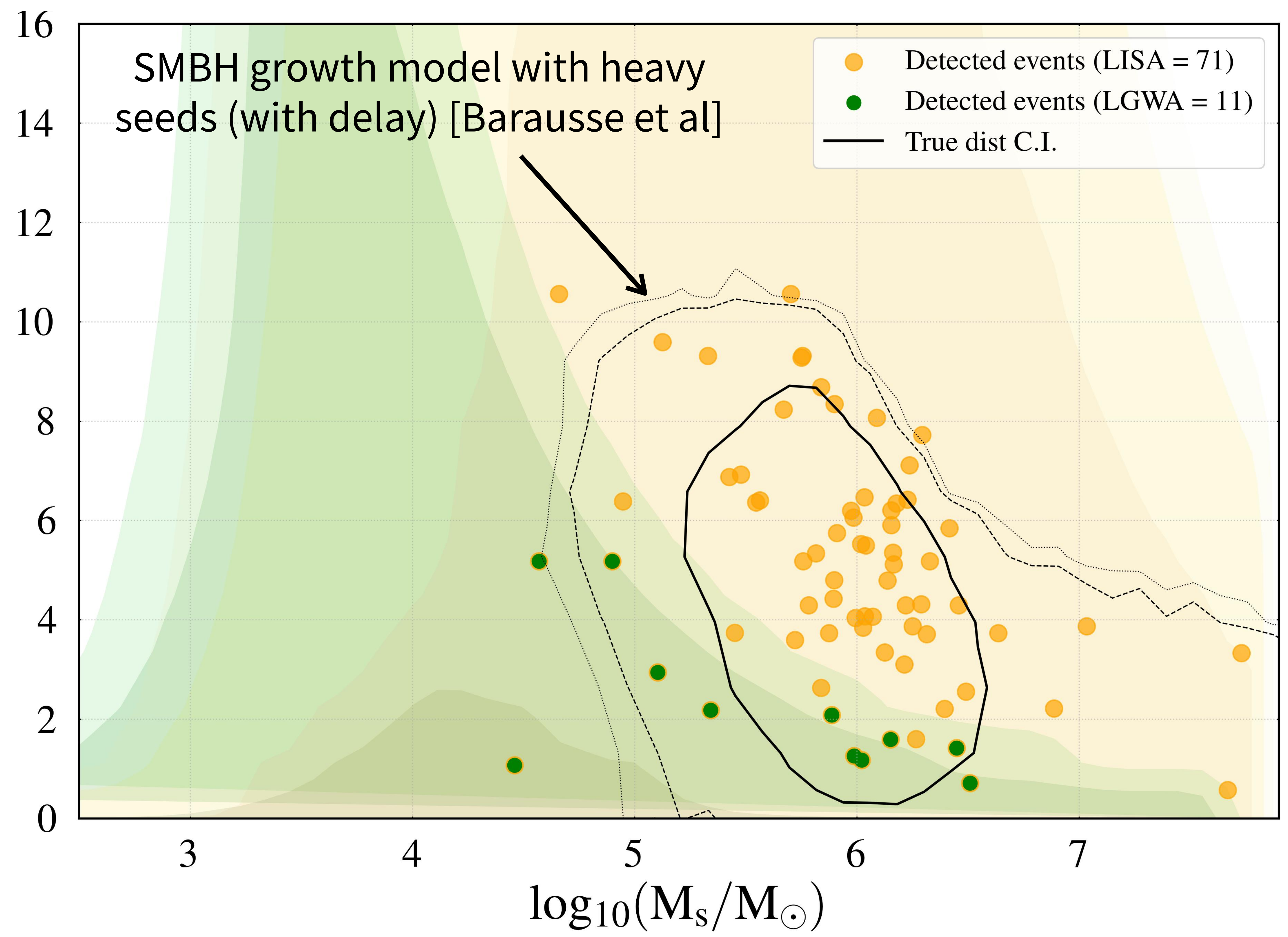
Multi-band observations



[Alorika Kar et al, In prep]

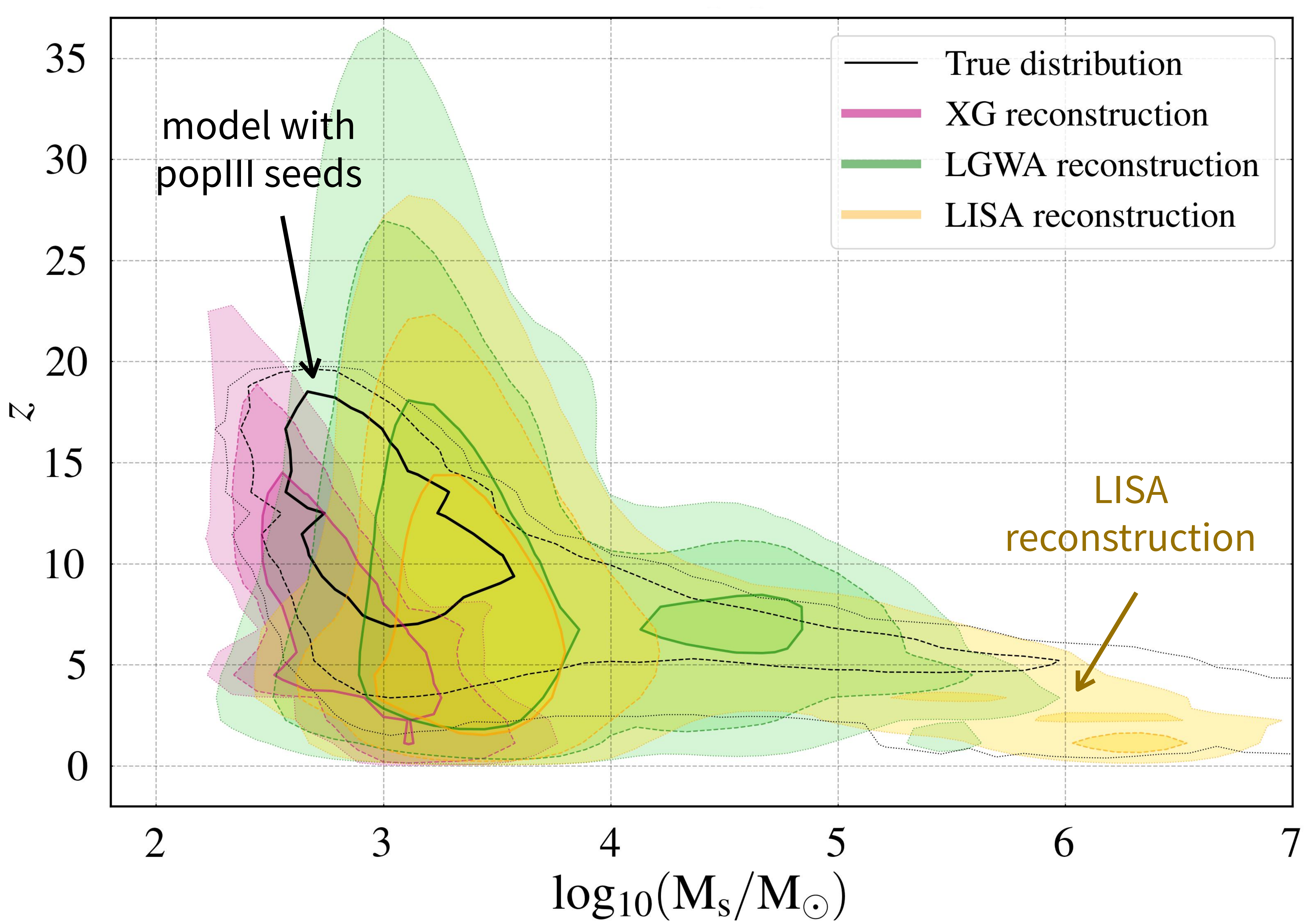
Multi-band observations

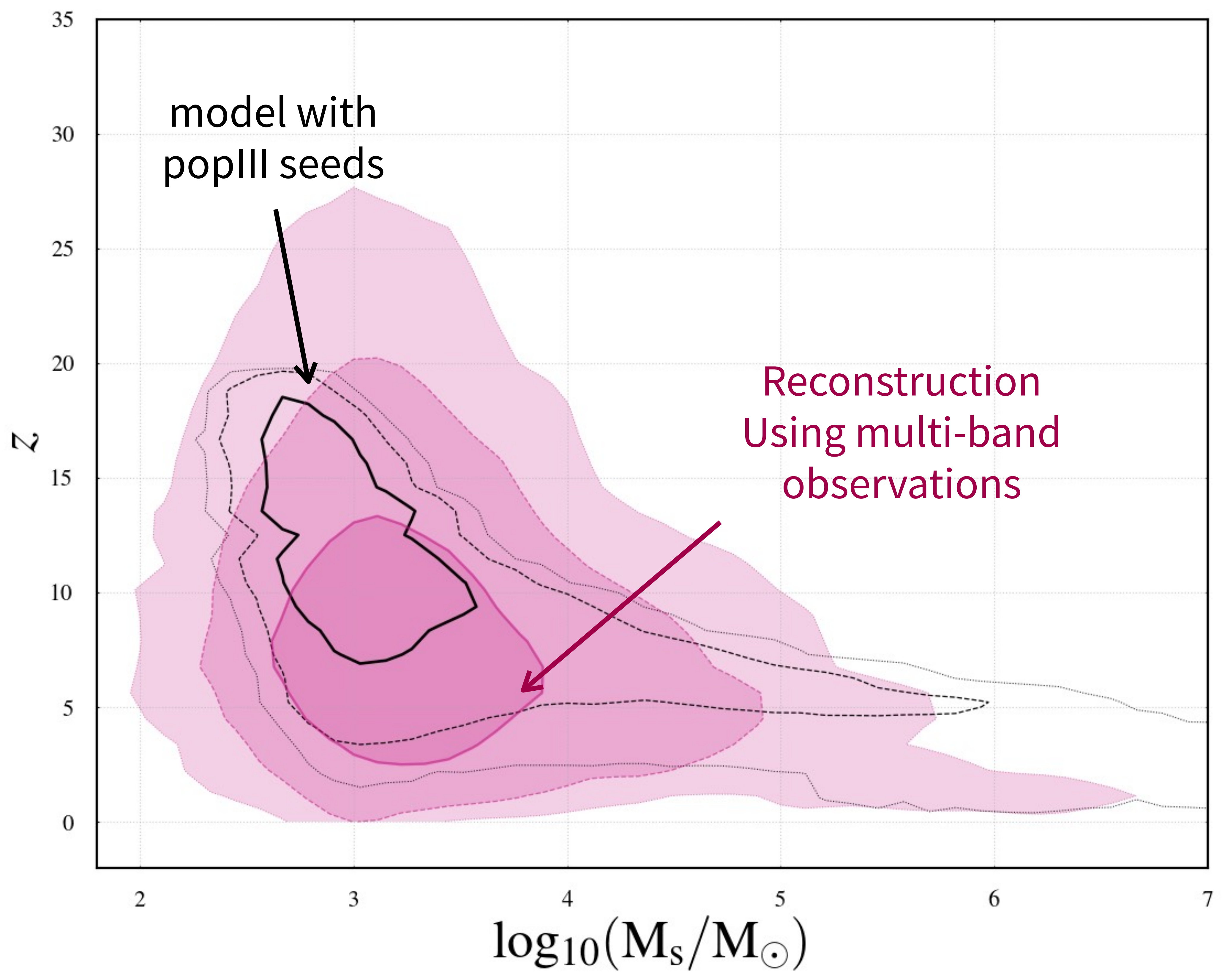




[Alorika Kar et al, In prep]

BH mass function: Non-parametric reconstruction





Using FIGARO code by Rinaldi & Del Pozzo DOI: 10.21105/joss.06589

[Alorika Kar et al, In prep]

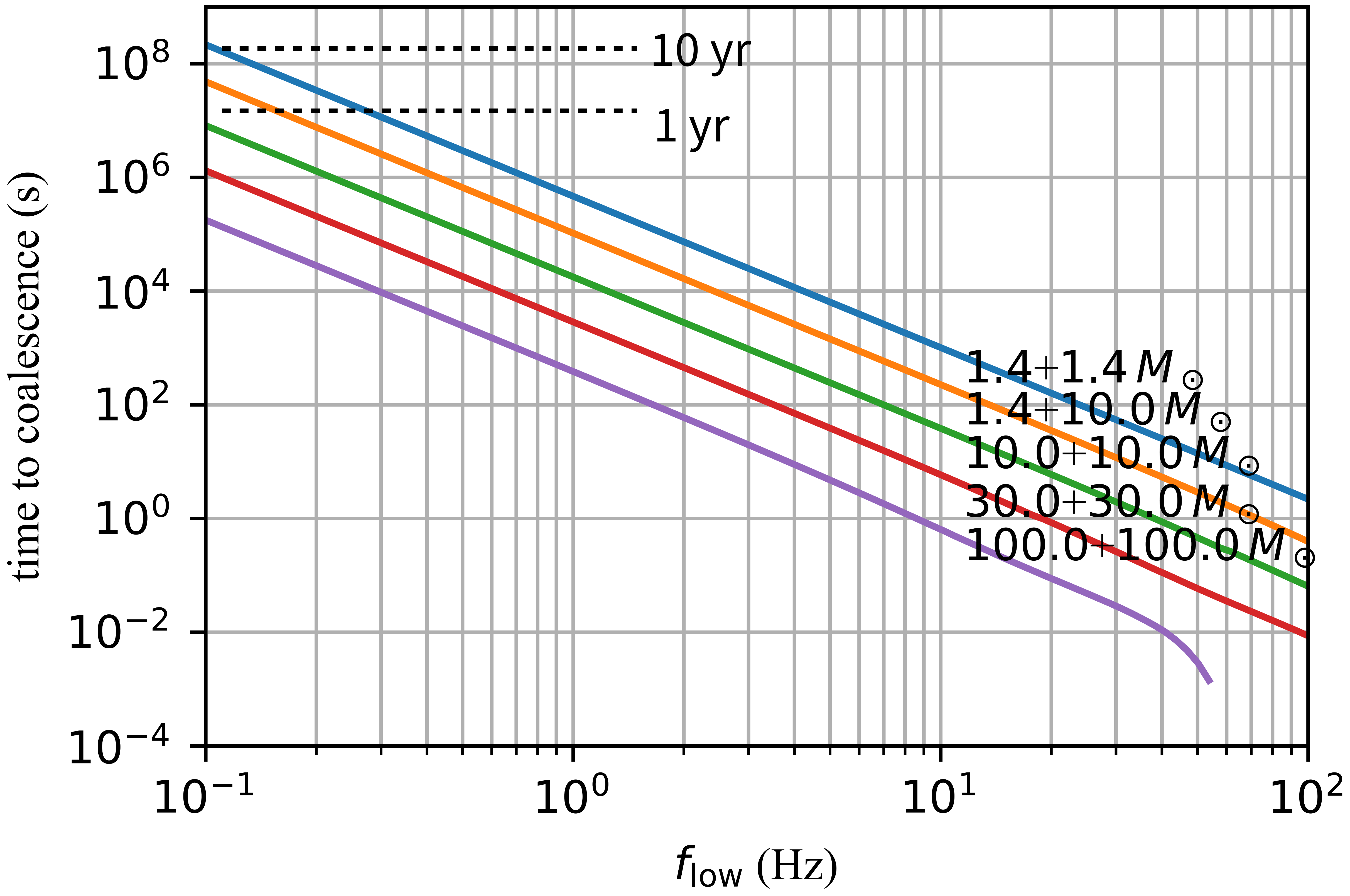
Early warning for ground-based detectors

- The in-band time of a CBC steeply increases with low-frequency sensitivity.

$$t_{\rm m}(f) = 5.4 \left(\frac{\mathcal{M}_c}{1.2\,M_\odot}\right)^{-5/3} \left(\frac{f}{1\,{\rm Hz}}\right)^{-8/3} \ {\rm days}$$

- LISA early warning might be possible only for a very small fraction of CBCs. Deci-Hz is much more promising.

[Adhikari et al CQG 36 (2019) 245010]



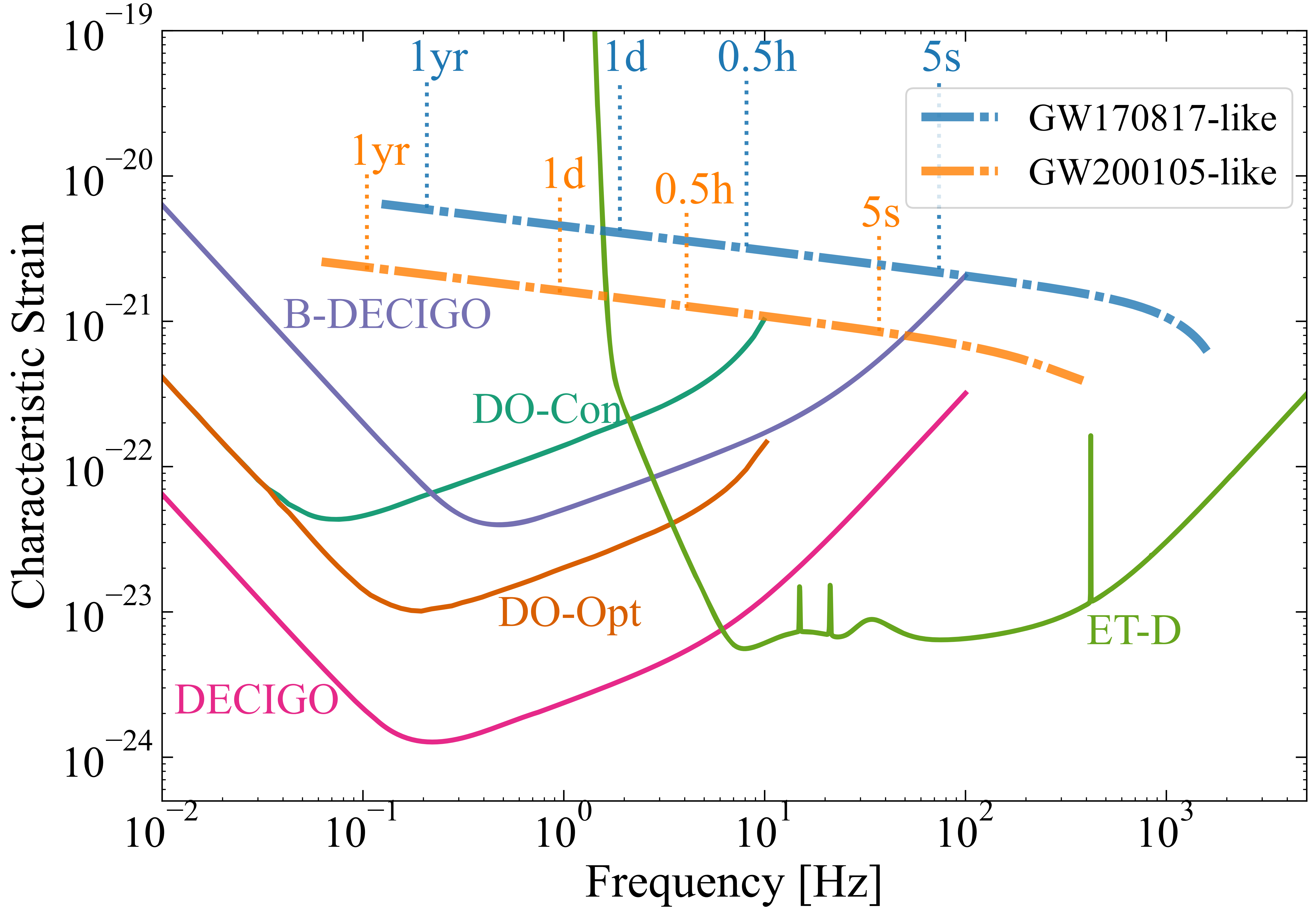
Early warning for ground-based detectors

- The in-band time of a CBC steeply increases with low-frequency sensitivity.

$$\tau(f) = \frac{5}{256} \frac{c^5}{(G\mathcal{M}_c)^{5/3}} (\pi f)^{-8/3}.$$

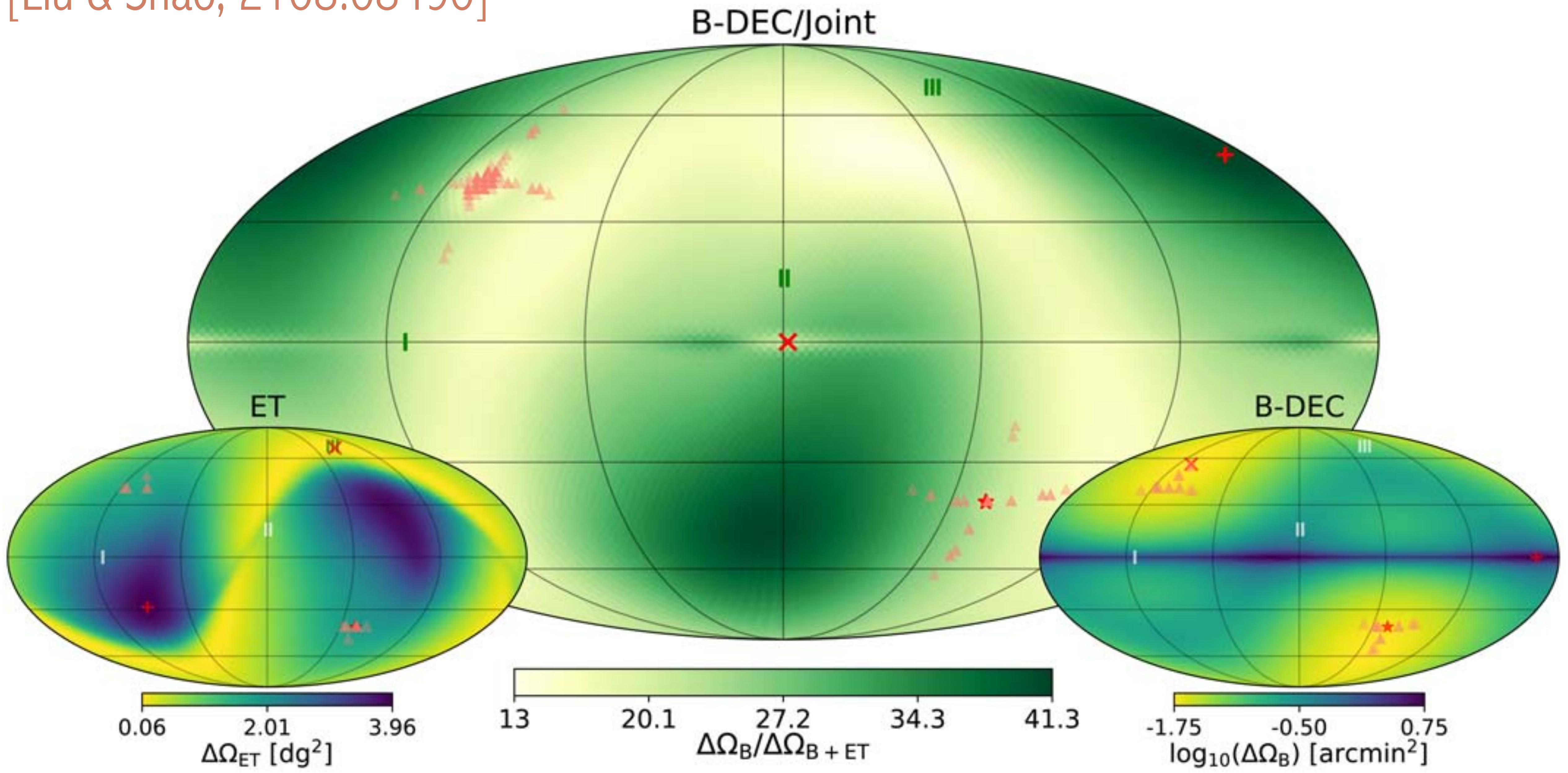
- LISA early warning might be possible only for small number of CBCs [Sesana, PRL 2016]. Deci-Hz is much more promising.

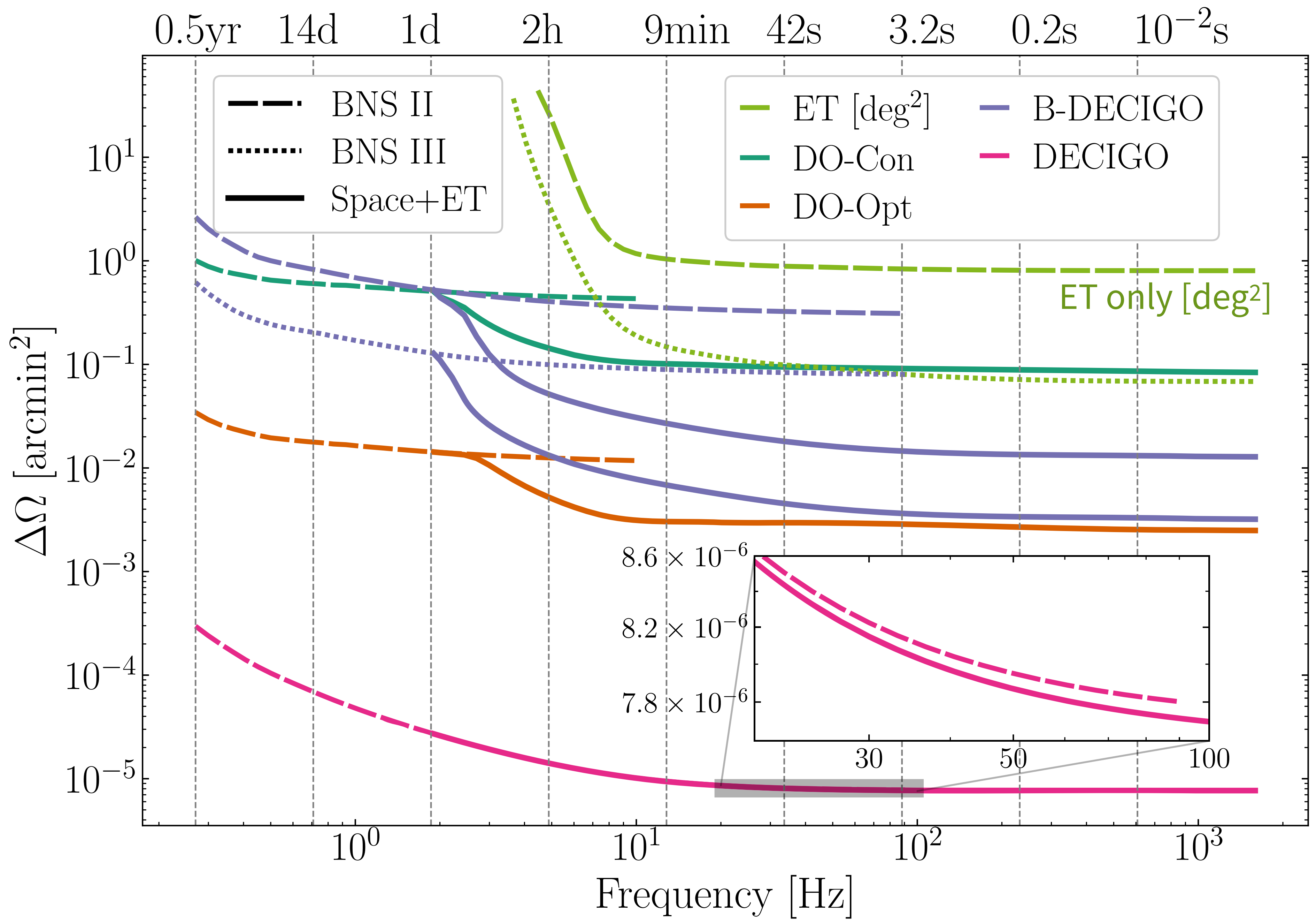
[Liu & Shao, 2108.08490]



Sky localisation of BNS mergers

[Liu & Shao, 2108.08490]

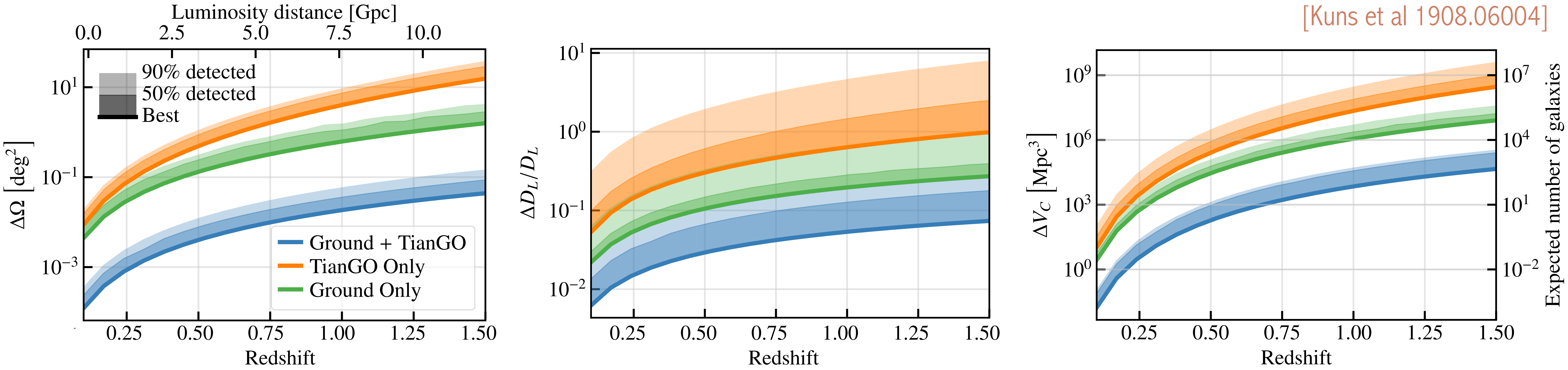




- Low-frequency detectors ⇛ better early warning.
- High-frequency detectors ⇛ better timing resolution ⇛ better angular resolution.
- Multi-band observations ⇛ progressive reduction in localisation error as the binary chirps in.

Cosmography using multi-band observations

[Kuns et al 1908.06004]



- Significant improvment in sky localisation & distance estimation using multi-banding ⇛ identification of the host galaxy of the merger ⇛ GW cosmography.

Improved parameter estimation using multibanding

Dimensionless velocity
(PN parameter)

GW phase

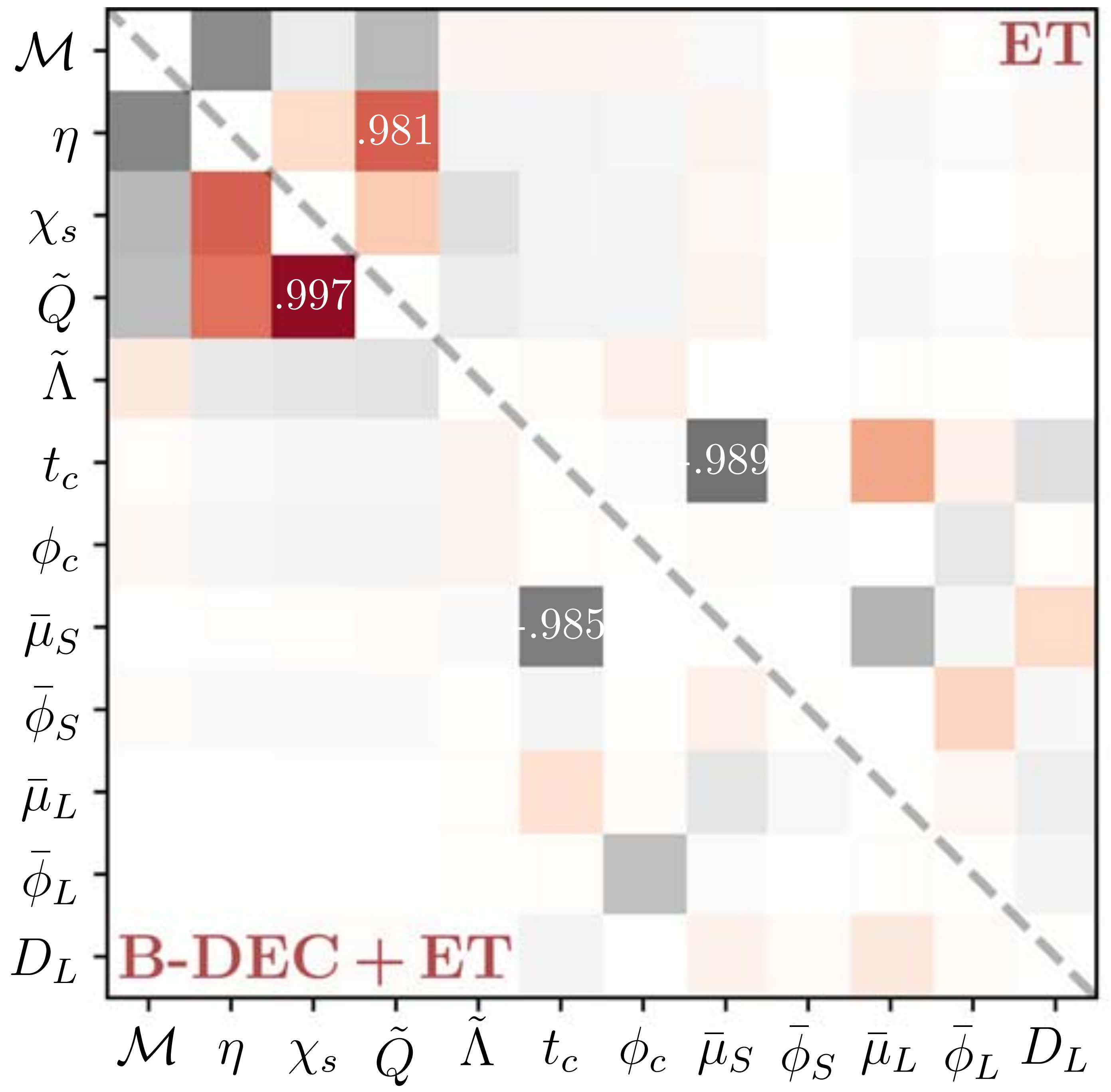
$$\Phi(f) = 2\pi f t_c - \phi_c + \frac{3}{128\eta v^5}\left[\sum_{k=0}^{K}\phi_k v^k + \sum_{kl=0}^{K}\phi_{kl} v^{kl}\ln v\right]$$

PN coefficients

(Contain various physical effect of the source at diff PN orders)

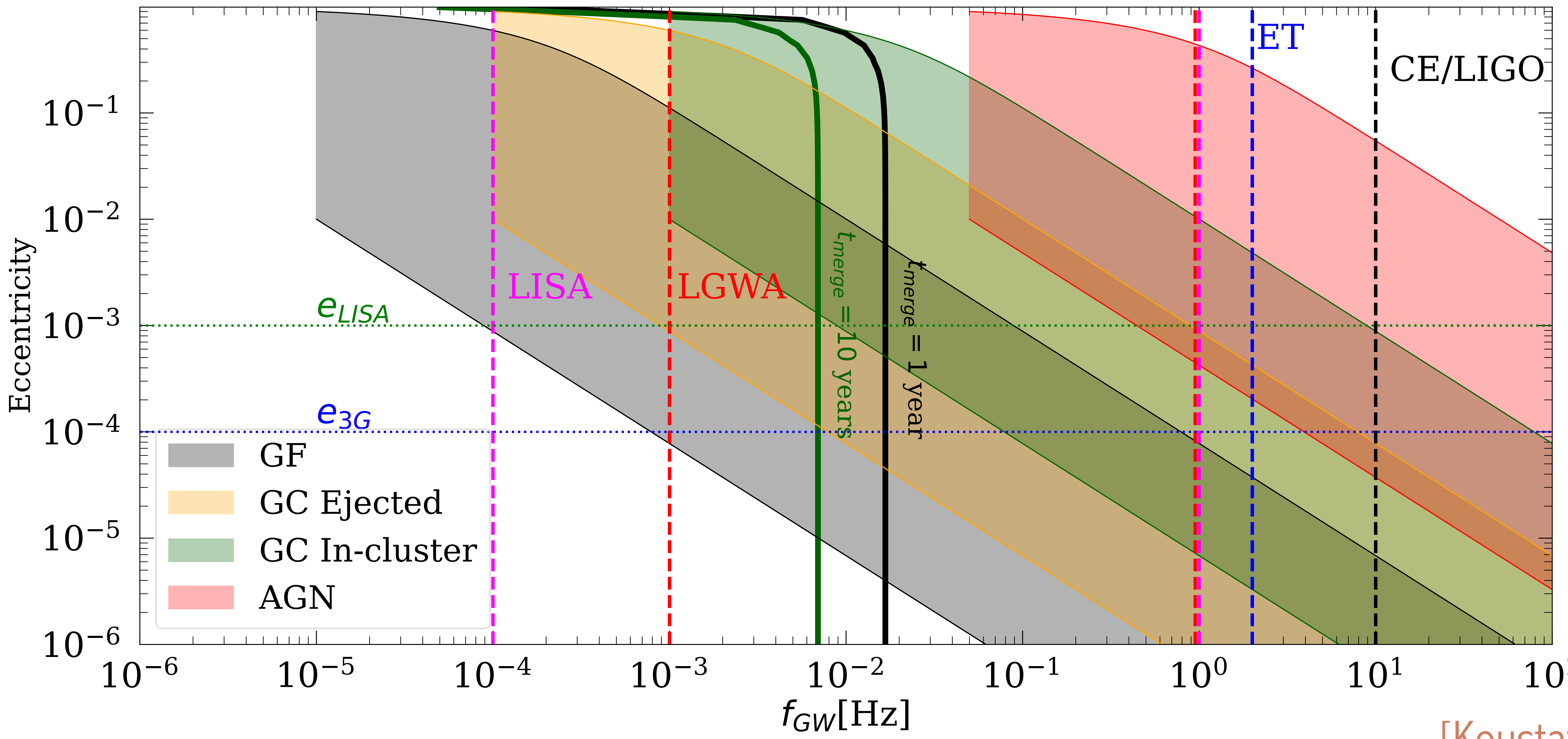
- 0PN: Chirp mass
- 1PN: Chirp mass , Mass ratio
- 1.5PN: Chirp mass , Mass ratio, Spins
- 2PN: Chirp mass , Mass ratio, Spins , Spin-deformation
- Enviromental effects at “— PN” orders.

[Liu & Shao, 2108.08490]



- Observations in different freq bands can measure different PN coefficients more accurately ⇛ reduced correlations ⇛ better measurement of source parameters.

Eccentricity, probing BBH formation challels



[Koustav Maity et al, In Prep]

- Orbital eccentricity decays quickly due to radiation reaction. Low-frequency measurements will allow us to catch the stage when the eccentricity is measurable.

Tests of GR using multi-band observations

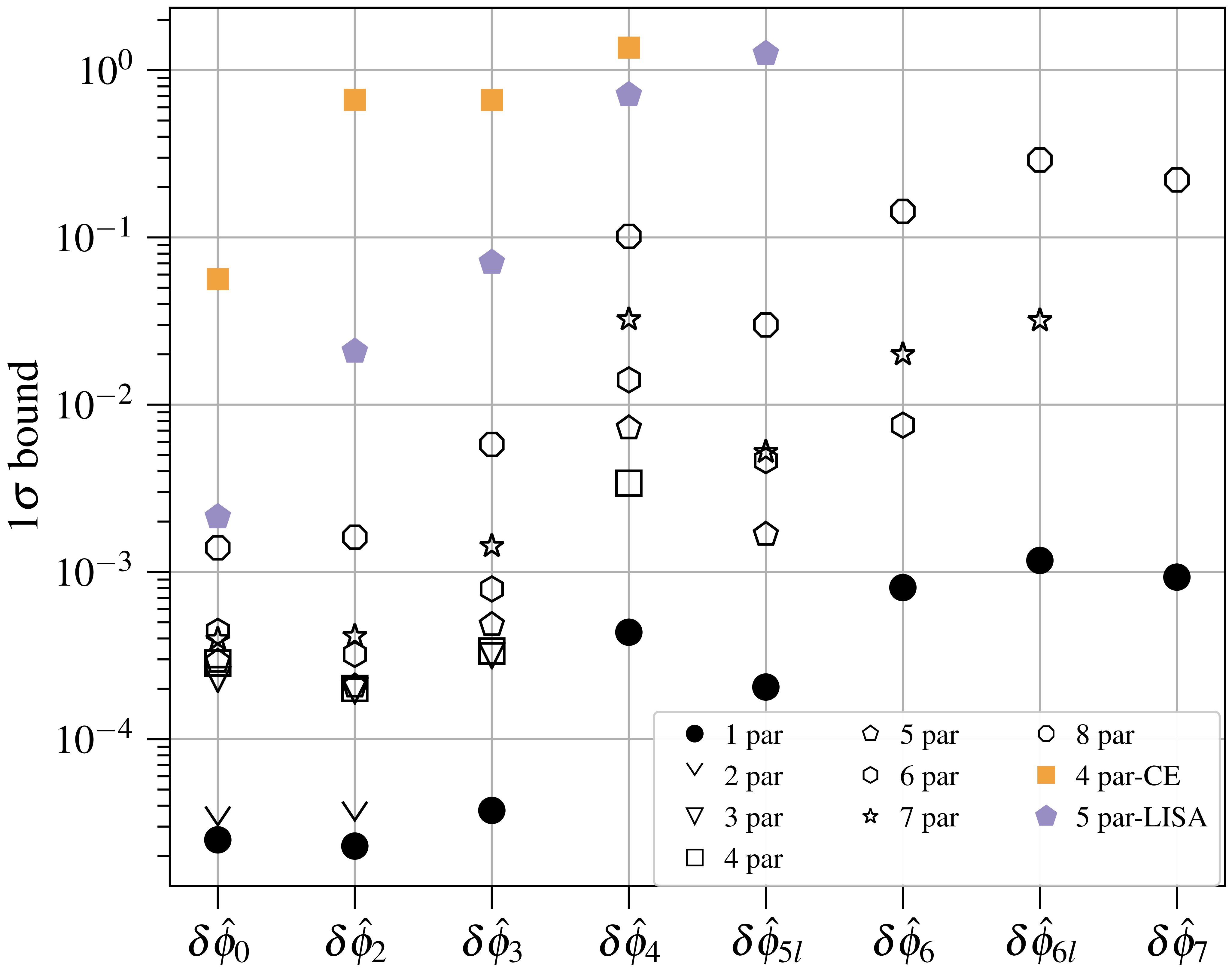
GW phase

Dimensionless velocity
(PN parameter)

$$\Phi(f) = 2\pi f t_c - \phi_c + \frac{3}{128\eta v^5}\left[\sum_{k=0}^{K} \phi_k v^k + \sum_{kl=0}^{K} \phi_{kl} v^{kl} \ln v\right]$$

PN coefficients
(Different from GR in other theories)

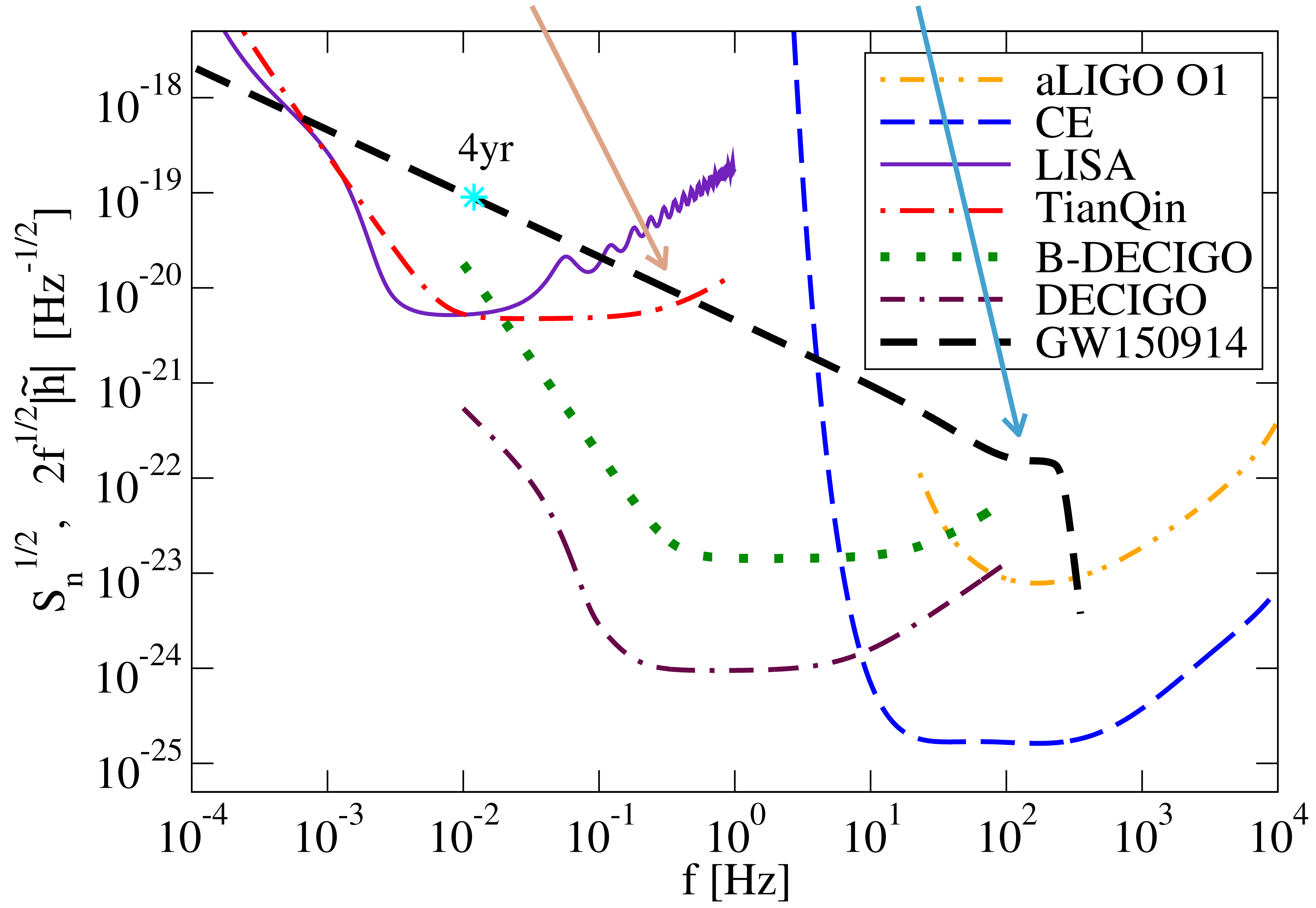
Expected bounds on deviations from PN params in GR



[Gupta et al PRL 125, 201101 (2020)]

Tests of GR using multi-band observations

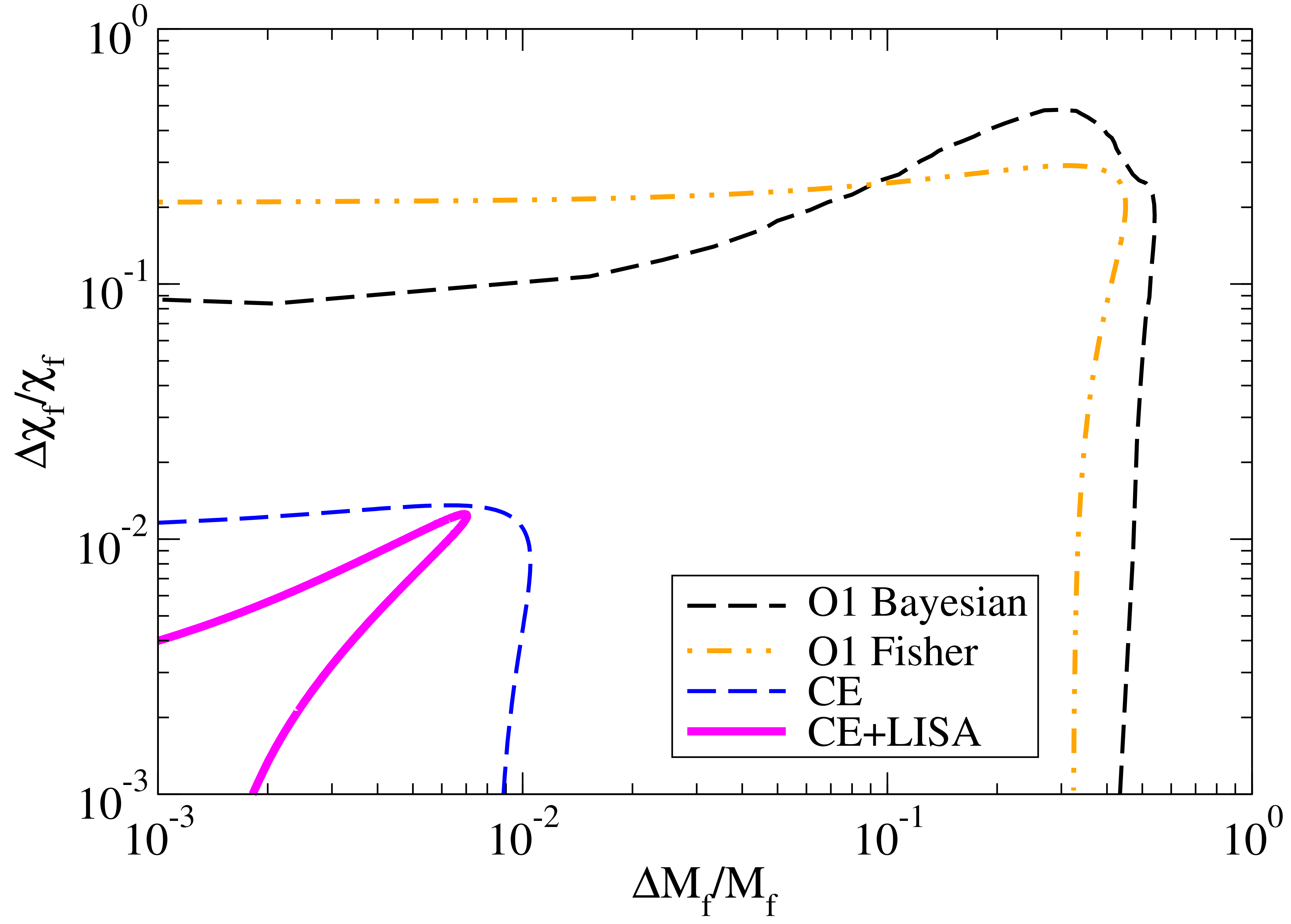
Estimate the mass and spin of the remnant BH from the inspiral and the QNM ring down.



Can lead to constraints on Hawking's area theorem, energy loss into non-GR/environmental effects.

Expected bounds on the IMR consistency

Detector	90% area
TianQin+CE	4.9×10^{-5}
LISA+CE	5.1×10^{-5}

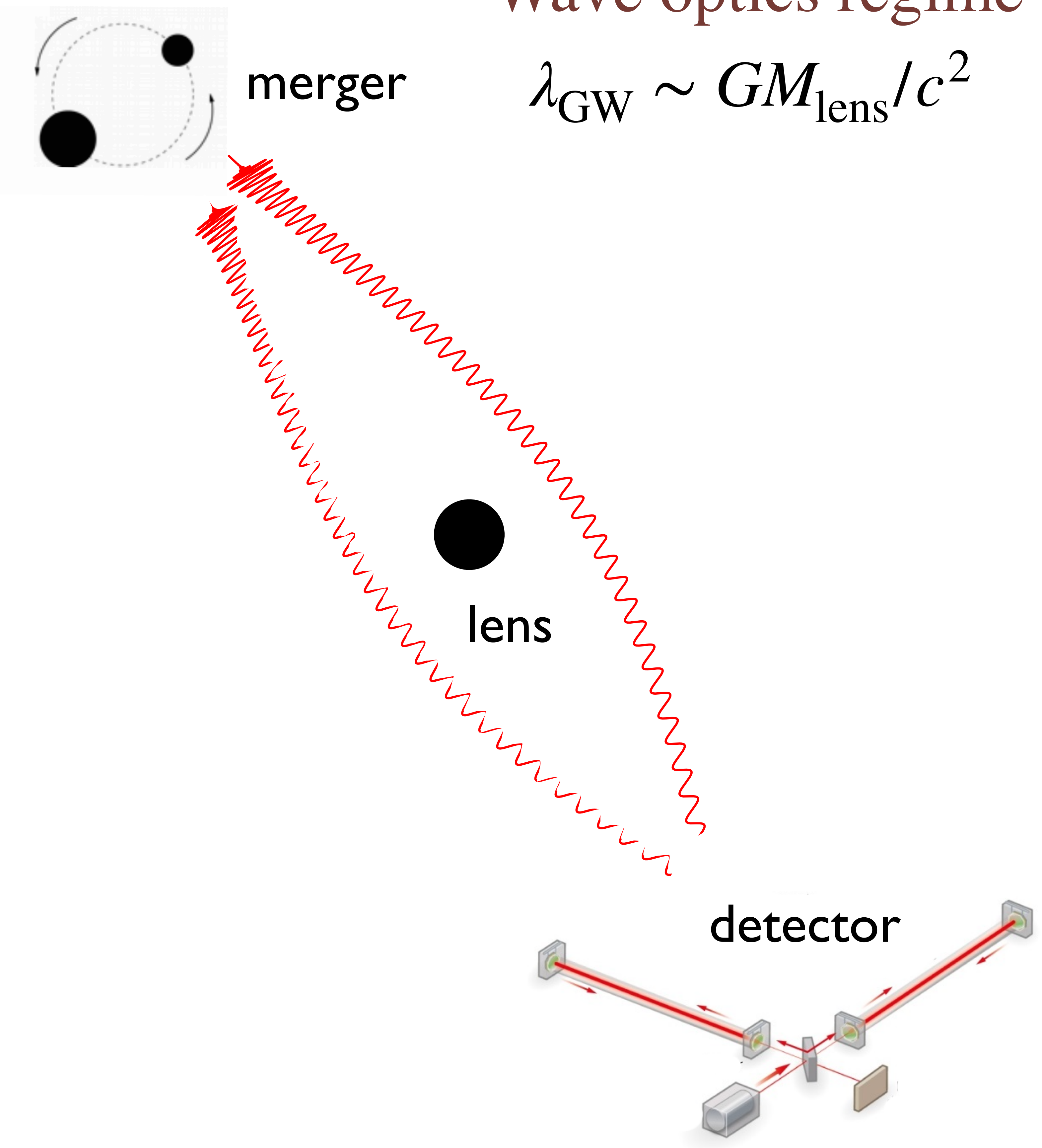


[Carson & Yagi, 1905.13155]

Gravitational lensing of GWs

Wave optics regime

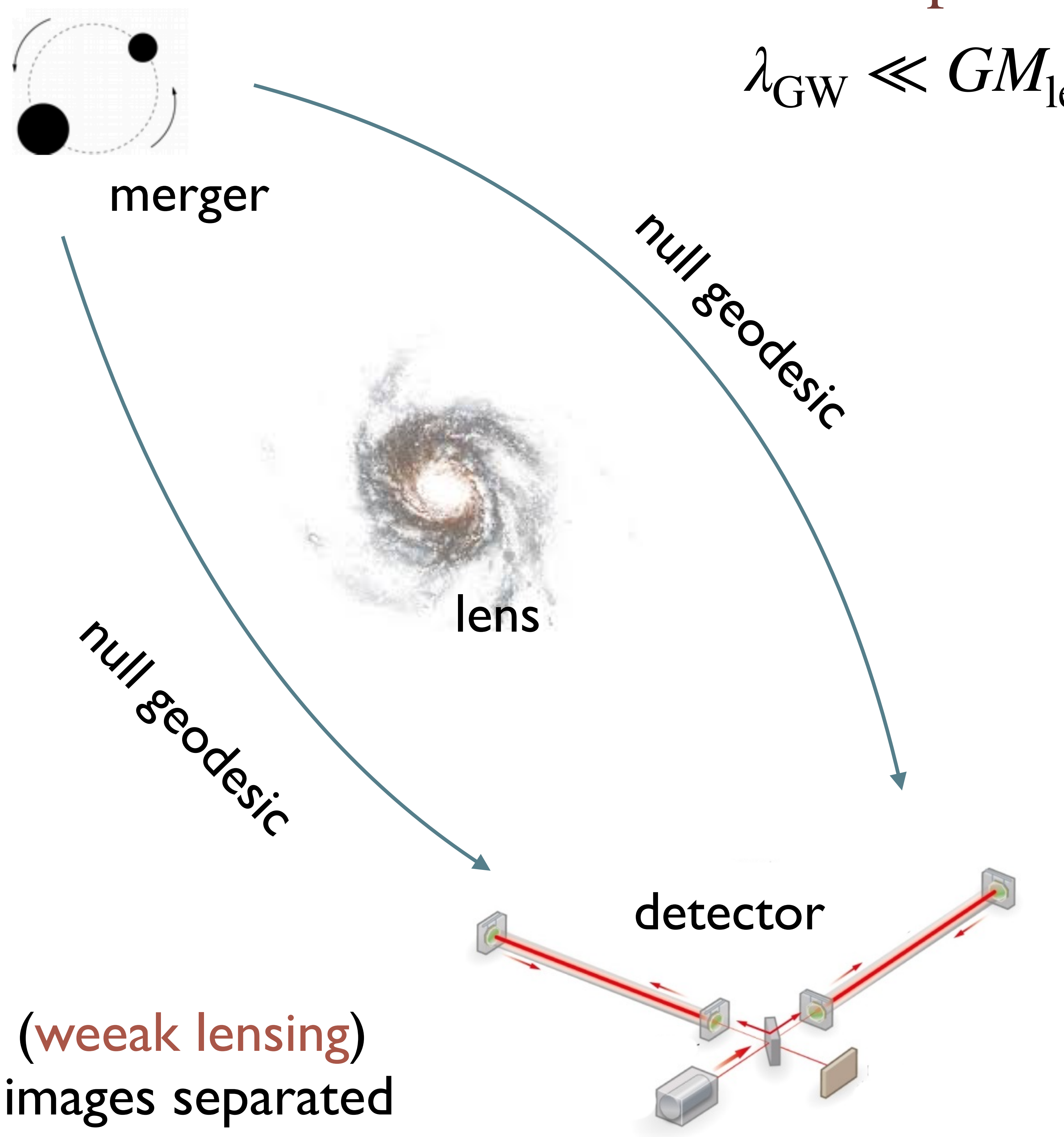
$\lambda_{\rm GW} \sim GM_{\rm lens}/c^2$



Single diffracted image (microlensing).
Waveforms distorted.

Geomtric optics regime

$\lambda_{\rm GW} \ll GM_{\rm lens}/c^2$



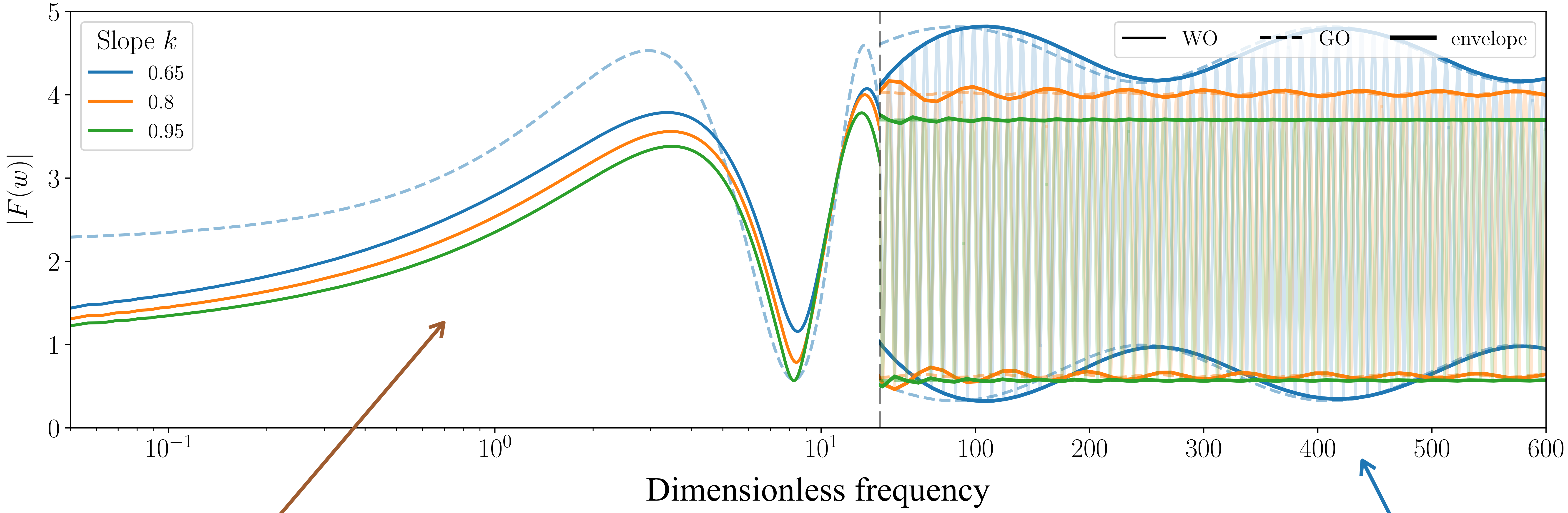
Single image (weeak lensing)
or multiplie images separated
by a time delay (strong lensing).

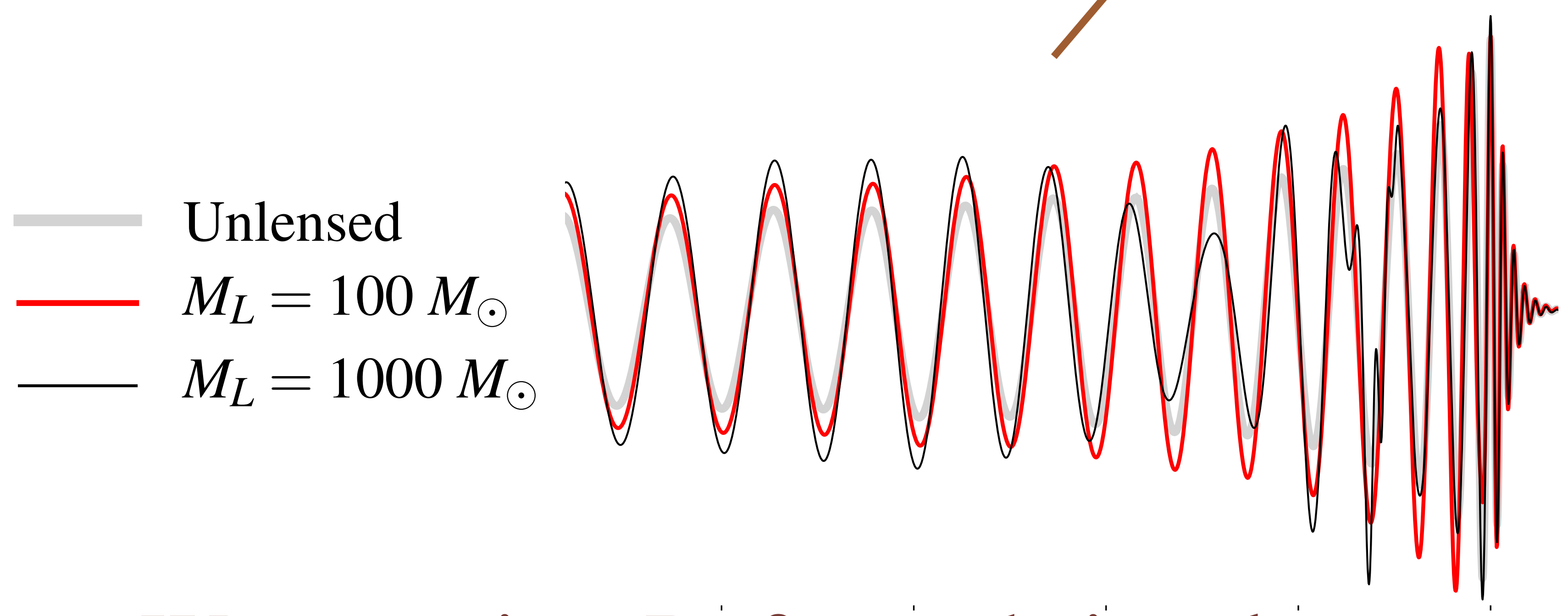
Waveforms unaffected, except for a magnification.

Transition from wave optics to geometric optics

[Tambalo et al 2212.11960]

Frequency dependent magnification



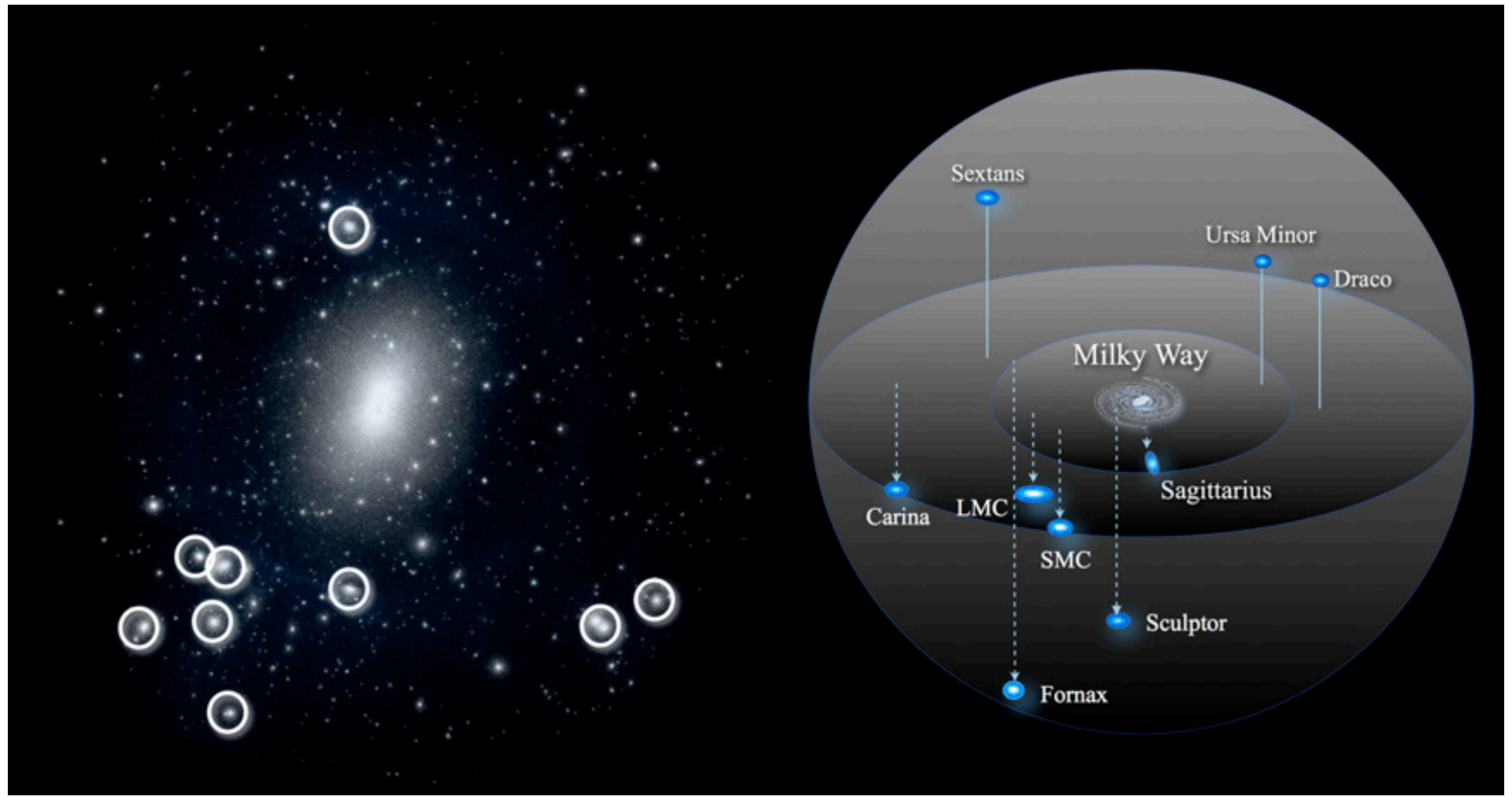


Wave optics: Deformed signals

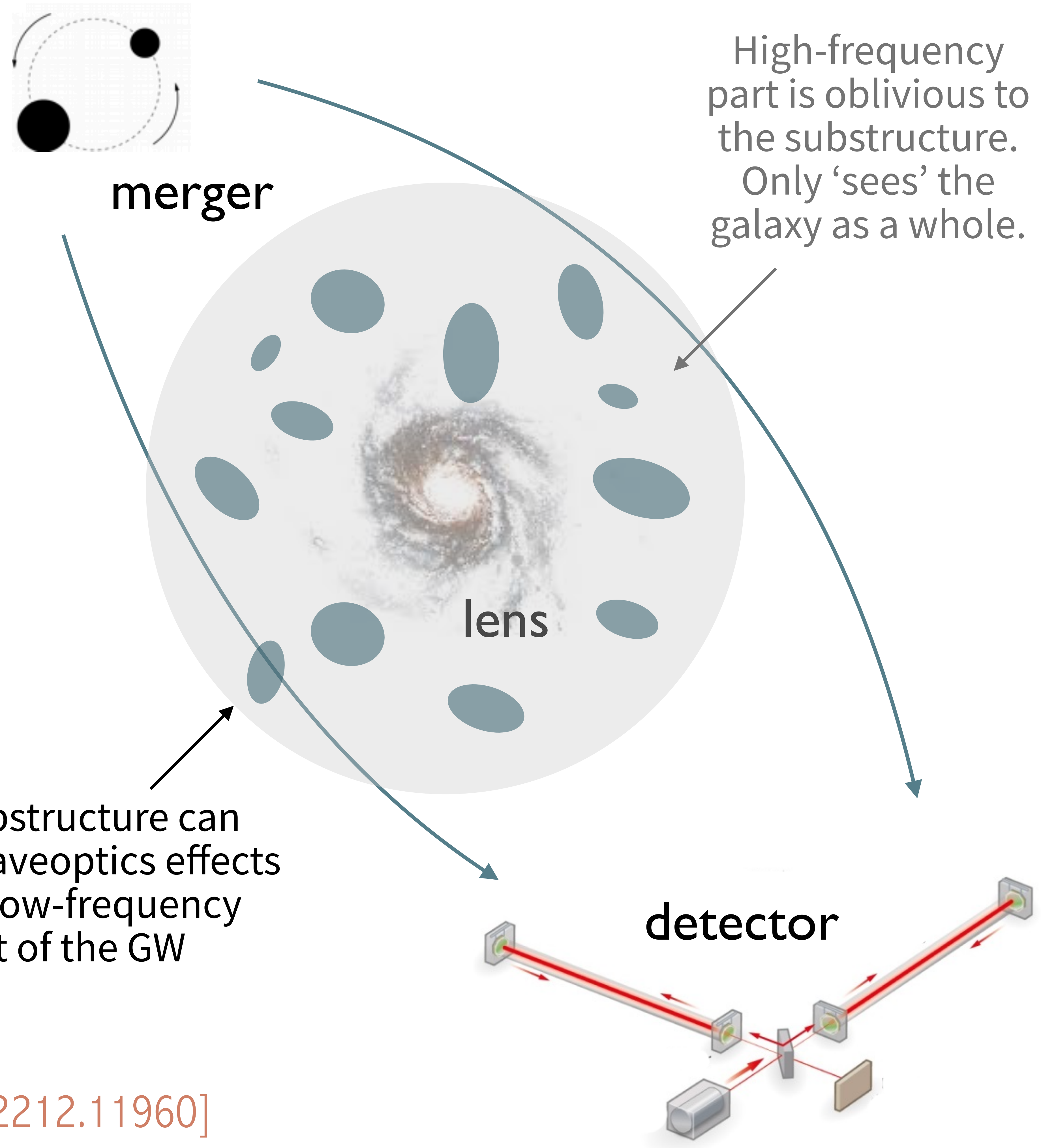
Geometric optics: Multiple signal copies

Probing halo substructure: nature of DM

[Weinberg et al, PNAS, 2015]



CDM simulations predict a larger number of sub-halos than observed in Milky Way. *Could* suggest a problem with CDM



[Related work: Tambalo et al 2212.11960]

Summary

- Deci-Hz GW observations have great synergies with observations in other frequency bands. Exmaples include:
  - Understanding the formation and evolution of SMBHs
  - Early warning of ground-based GW detectors
  - Source localisation, identification of EM counterparts $\Longrightarrow$ cosmography
  - Parameter estimation, population inference and tests of GR
  - Lensing in wave optics and geometric optics $\Longrightarrow$ cosmology and dark matter.