Self-lensing signatures to constrain the environment of binary mergers

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From which astrophysical environments can gravitational waves come? [I]

Gravitational waves (GWs) are produced in mergers of compact binary objects, such as black holes (BHs). Stellar-mass BH binaries can be formed in dense environments. However, the origin of observed gravitational-wave events remains elusive.
Can we use gravitational lensing by an object in the same environment (self-lensing) to distinguish the origin of a GW signal?

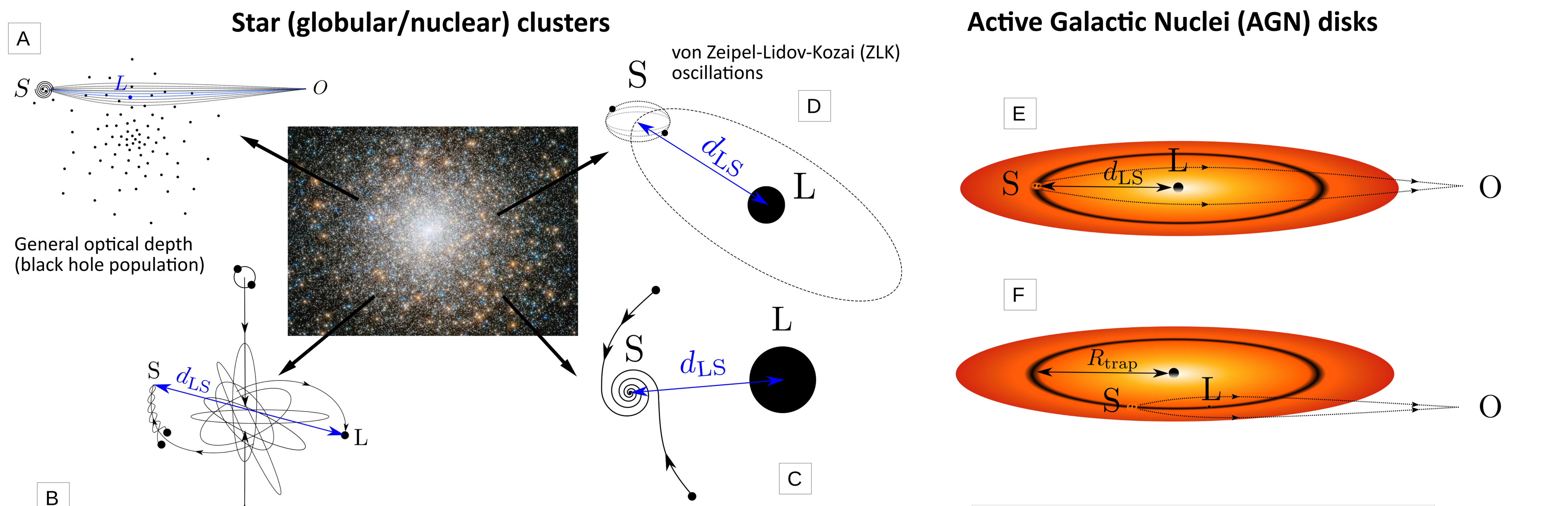


Fig.1. Astrophysical environments where we consider self-lensing. Different scenarios are labelled A-F.

Probability of self-lensing [II]

To determine how often is self-lensing expected to be seen in detections, we quantify the probability in the different astrophysical environments labelled in Fig.1.

Probability $\simeq$ optical depth τ

$$\tau \propto \frac{v_{\rm orbit}^2}{c^2}\, y_{\max}^2 \propto \frac{R_{\rm L}}{d_{\rm LS}}\, y_{\max}^2 \qquad R_{\rm L} = \frac{2Gm_{\rm L}}{c^2}$$

$$\tau \propto \frac{\sigma^2}{c^2}\, y_{\max}^2$$

Given by detectability criteria

The detectability of the lensing effect is quantified by $y_{\max}$, the maximum displacement of the source position with respect to perfect alignment, which we will determine in [III].

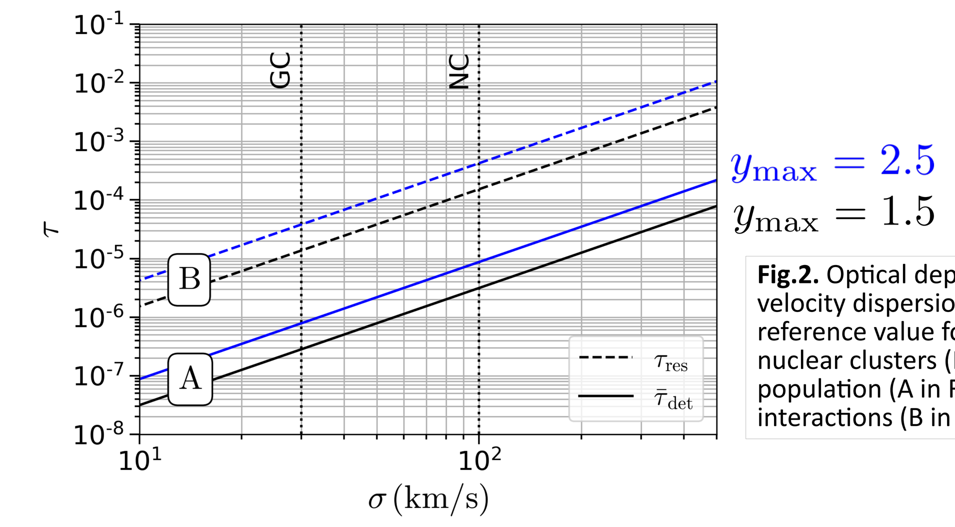


Fig.2. Optical depth as a function of the velocity dispersion of an environment, with a reference value for globular clusters (GC) and nuclear clusters (NC). For the general BH population (A in Fig.1.) and for resonant interactions (B in Fig.1.).

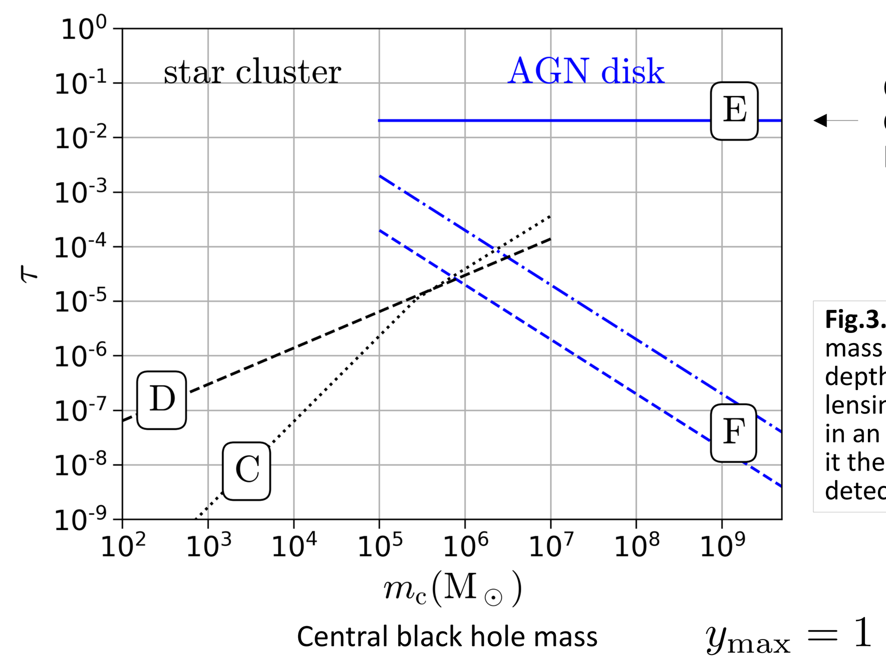


Fig.3. Optical depth as a function of the mass of the central BH. The optical depth is largest for the case of self-lensing by the supermassive BH (SMBH) in an AGN disk (E in Fig.1.), which makes it the most probable scenario to be detected.

Detectability of self-lensing on gravitational wave events [III]

Even when gravitational lensing is imprinted on a signal [IV], the effect needs to be significant enough to be detectable.

(a) Distorted waveform (diffraction, interference)

For a single distorted signal, we quantify the mismatch between a lensed and an unlensed template and the detectability given a signal-to-noise ratio (SNR).

Detectable for $\text{Mismatch} \times \text{SNR}^2 > \ln B \sim (1-10)$

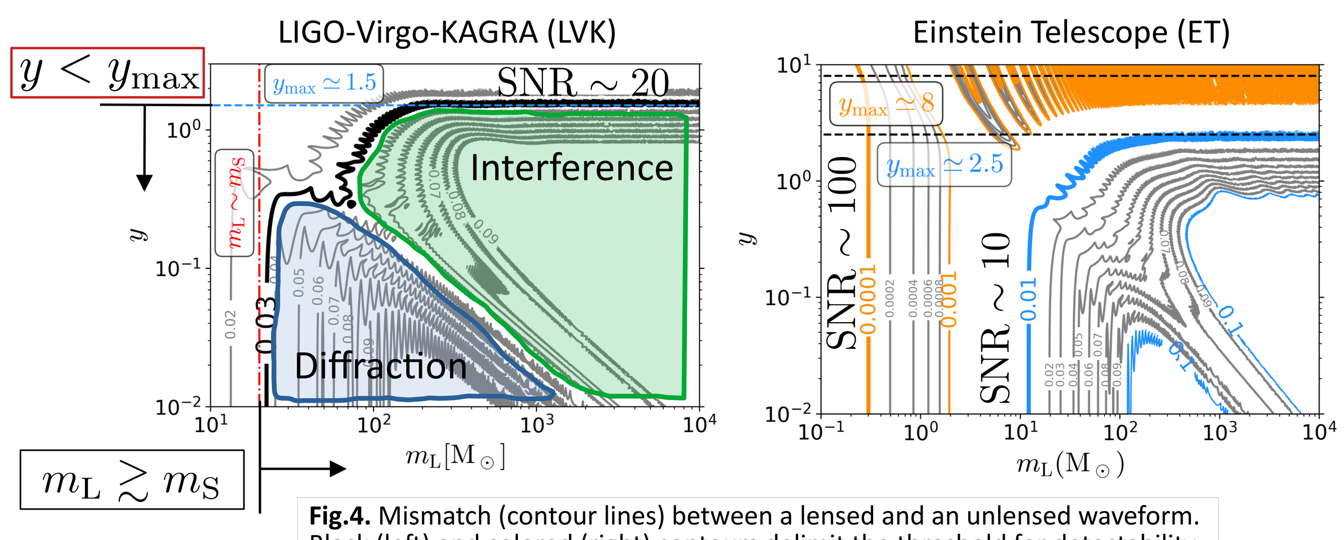


Fig.4. Mismatch (contour lines) between a lensed and an unlensed waveform. Black (left) and colored (right) contours delimit the threshold for detectability.

(b) Separate images (strong lensing)

For separate images, which will appear as separate signals, both need to be above the noise.

$\text{SNR} > 8$ **for both images**

$$\left(\frac{\mu_+}{\mu_-}\right) = \left(\frac{\text{SNR}^+_{\rm lensed}}{\text{SNR}^-_{\rm lensed}}\right)^2 \rightarrow y_{\max}$$

For LVK, $(\text{SNR}^+_{\rm L})^{\max} = 50$, $y_{\max} \simeq 2.$
For ET, $(\text{SNR}^+_{\rm L})^{\max} = 1000$ $y_{\max} \simeq 10.$

Summary of the characteristic signatures

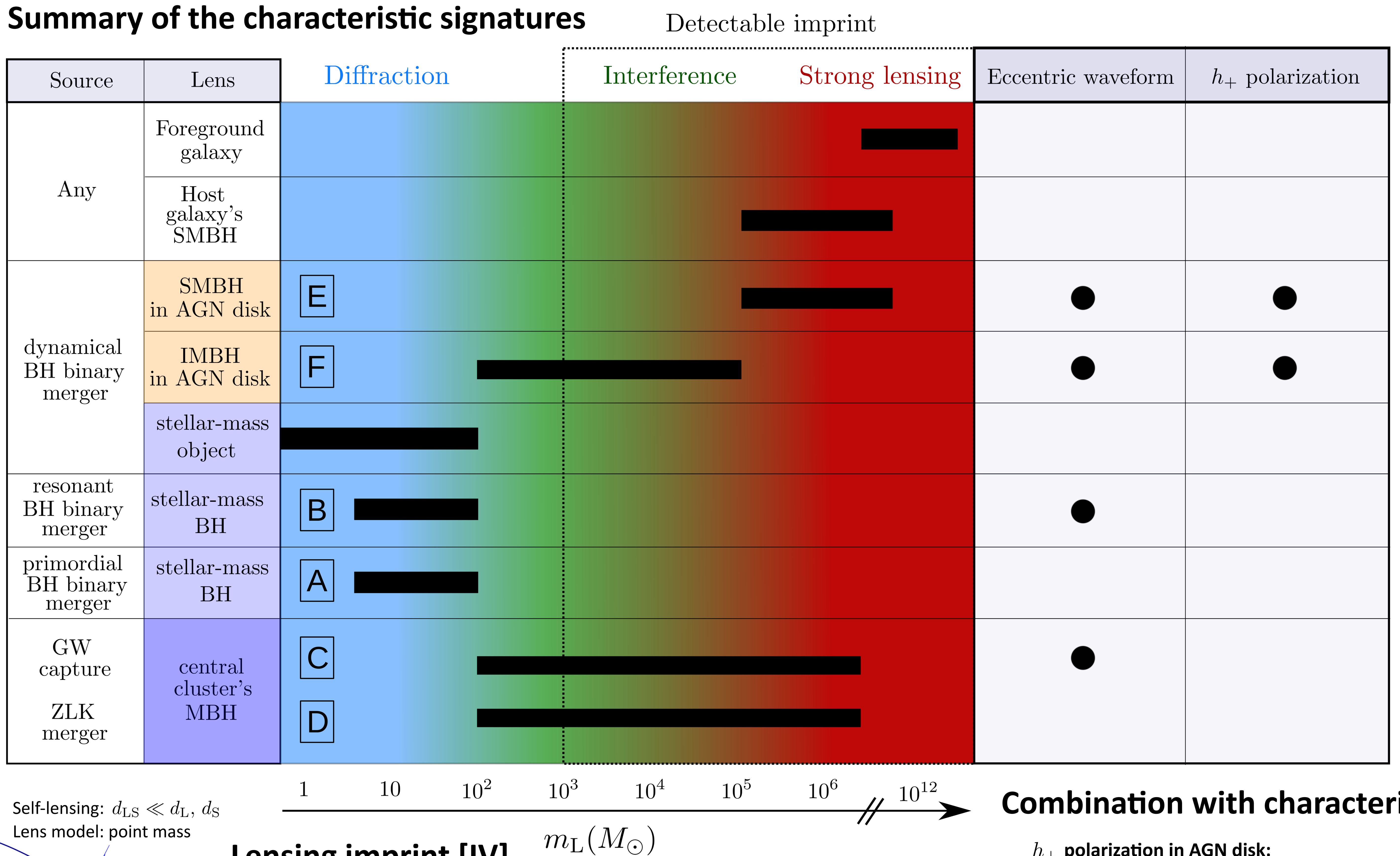
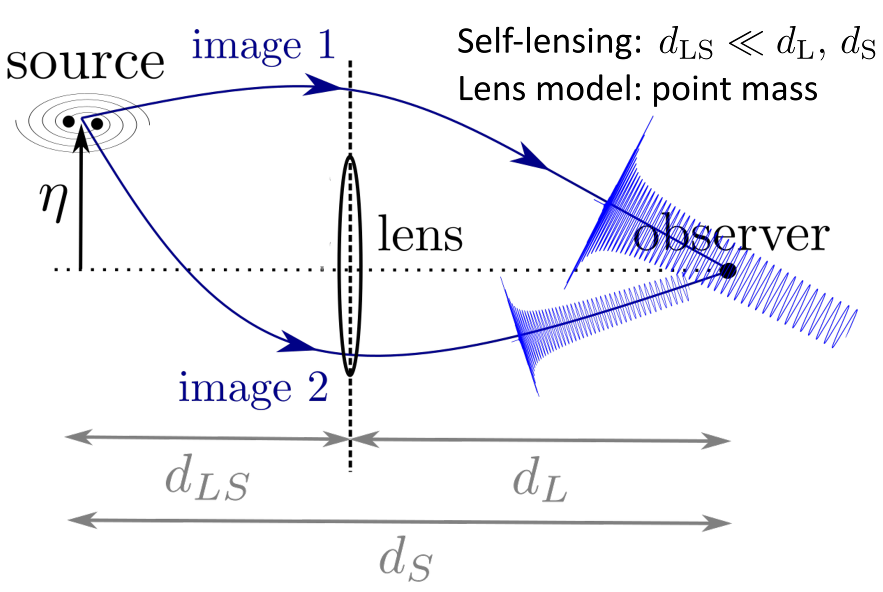


Fig.5. Summary of the characteristic signatures we may see in a GW signal, including lensing imprints, eccentricity in the waveform and a preferential polarization. As we can see, every scenario has different combinations, which potentially enables us to distinguish some of them.

Lensing imprint [IV]



τ	Lensing optical depth
σ	Velocity dispersion of the environment
d_{LS}	Distance between the lens and the source
y	Position of the source with respect to the lens
m_L, m_S	Mass of the lens and the source (total mass)
h	Strain of the gravitational wave signal
μ_+, μ_-	Lensing magnification of images 1 and 2
B	Bayes factor between lensed and unlensed hypotheses
c	Speed of light in vacuum
G	Gravitational constant

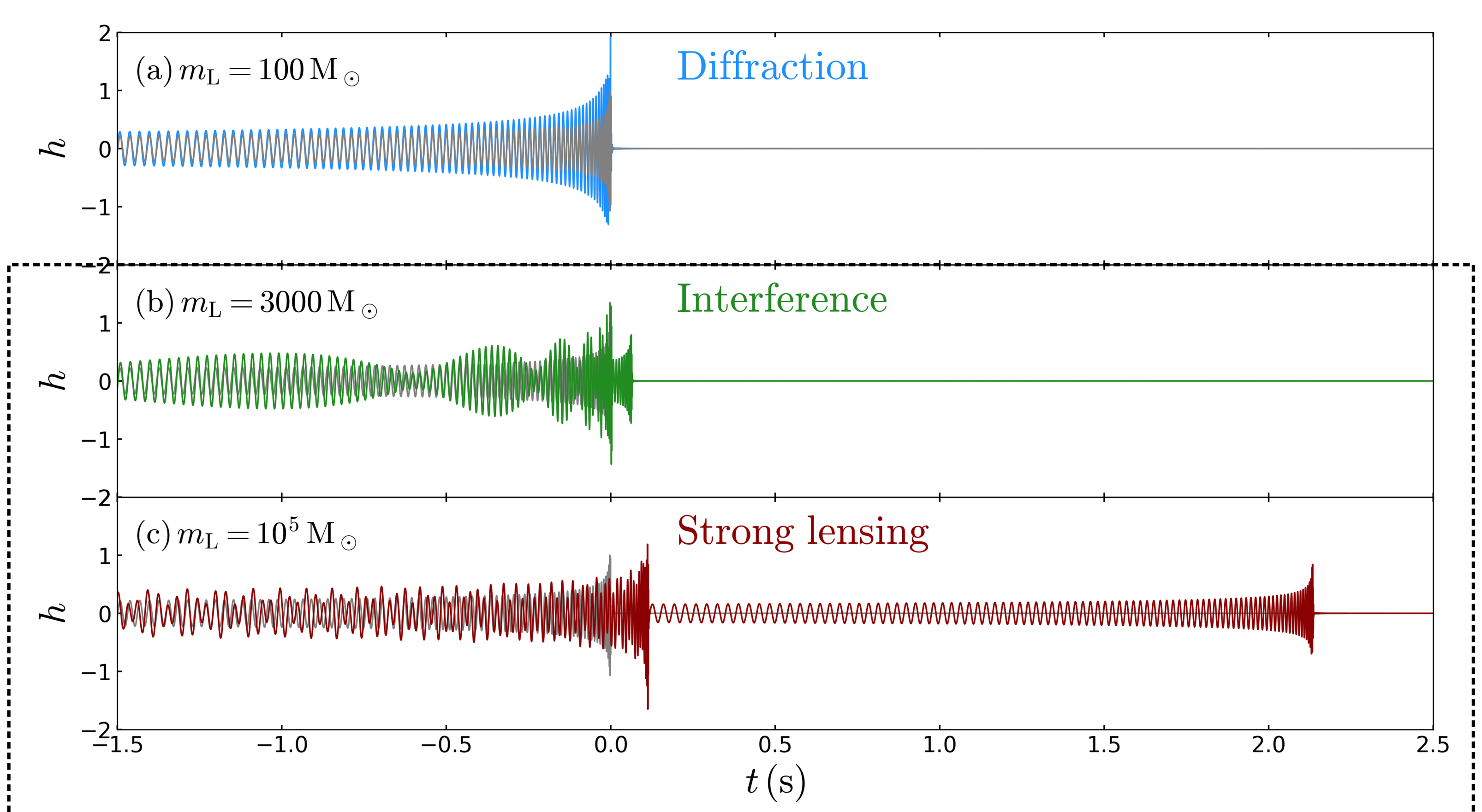


Fig.6. Strain (waveform) of the lensed gravitational wave signal as a function of time. The lensing imprint is different for different lens masses m_L. Here we take a fixed $y = 0.25$.

Combination with characteristic signatures

h_+ polarization in AGN disk:
due to the alignment of the binary orbital plane with the AGN disk, and the limitation of observing self-lensing only in edge-on disks

Eccentric signals:
- AGN disks: high eccentricity is expected
- Star clusters:
  - Most gravitational-wave captures are eccentric, while only a fraction of ZLK mergers are eccentric (detectable lensing cases)
  - Resonant interactions are expected to be eccentric (undetectable lensing case)

Conclusions

- **Self-lensing by a stellar-mass** BH is both unlikely and mostly **undetectable** (diffraction)
- **AGN disk** self-lensing has the **highest probability** ($\tau \simeq 2 \times 10^{-2}$)
  + **detectable lensing** imprint
  + characteristic feature: **h_+ polarization**
  → could be distinguished from galaxy lensing and star cluster self-lensing
- Combining self-lensing with polarization and eccentricity can help us constrain the astrophysical environment of an individual GW event.