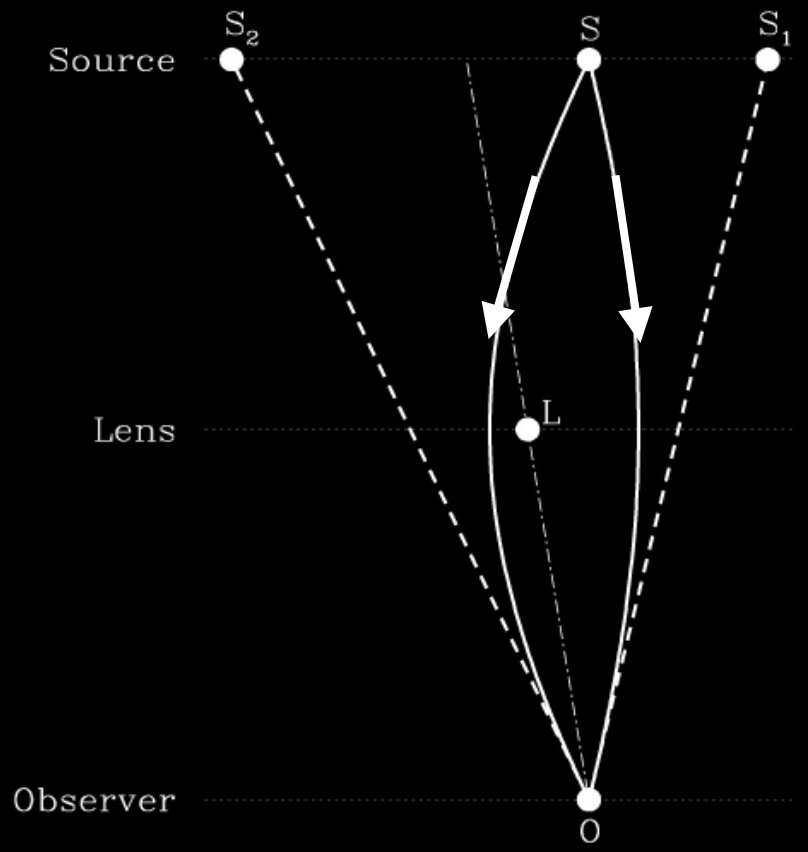
Wave-optics lensing of gravitational waves

3rd Nordic Cosmology Meeting
Tallinn, 24th September 2026

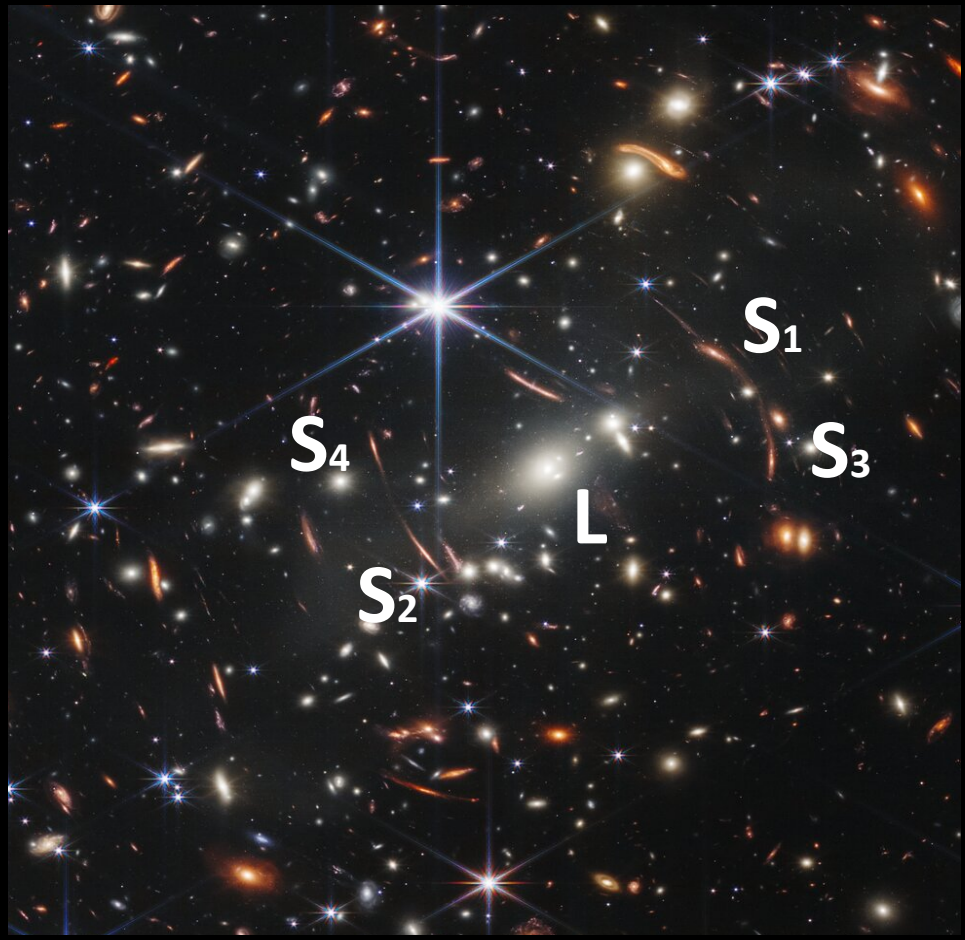
Helena Ubach

KBFI NICPB
ICCUB Institut de Ciències del Cosmos UNIVERSITAT DE BARCELONA
EXCELENCIA MARÍA DE MAEZTU 04/2025-03/2031
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
AGENCIA ESTATAL DE INVESTIGACIÓN
AGAUR Agència de Gestió d'Ajuts Universitaris i de Recerca
Generalitat de Catalunya
Cofinançat per la Unió Europea

Gravitational lensing (historically, of light)

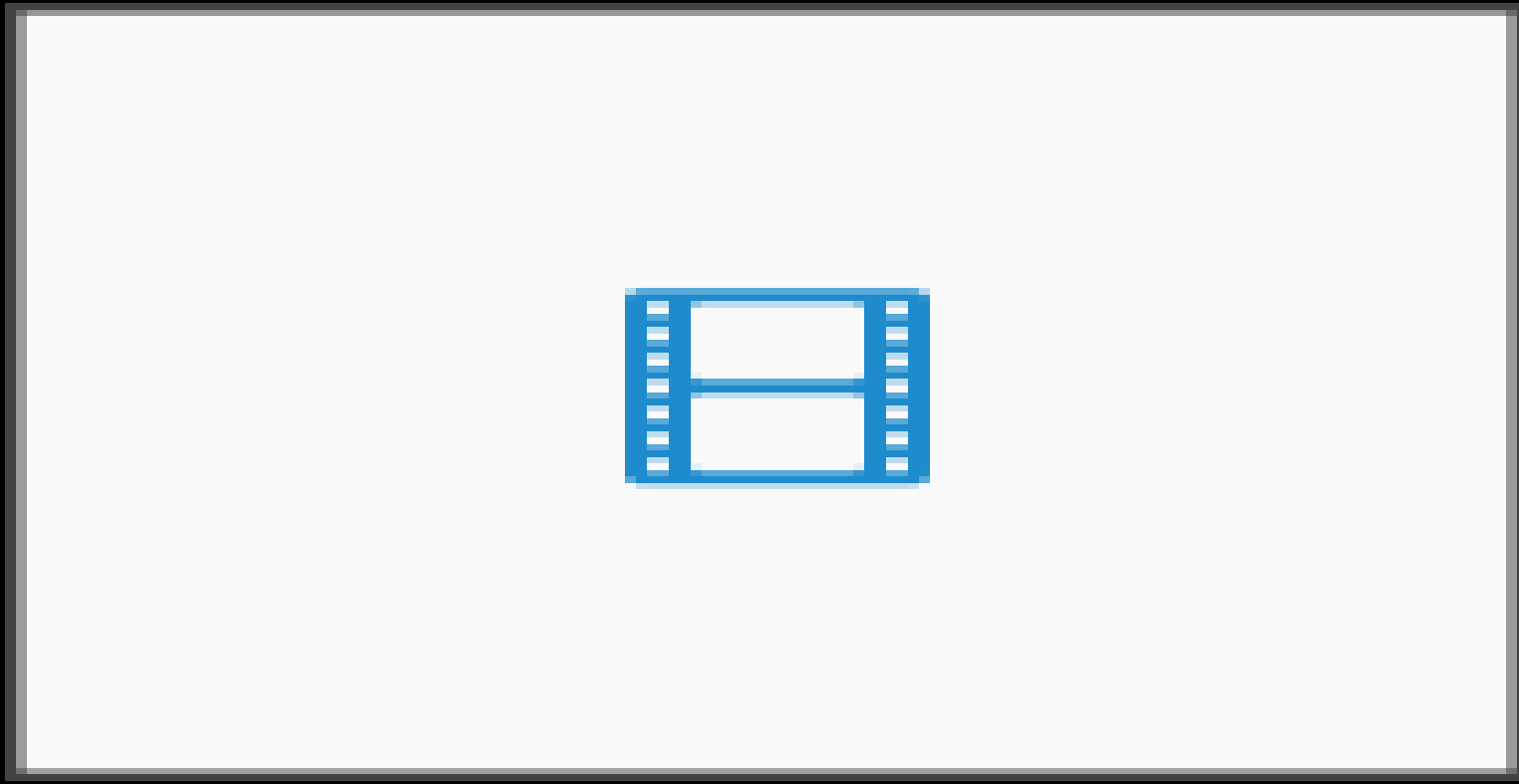


Joachim Wambsganss



Webb Space Telescope (2023)

Gravitational lensing of gravitational waves

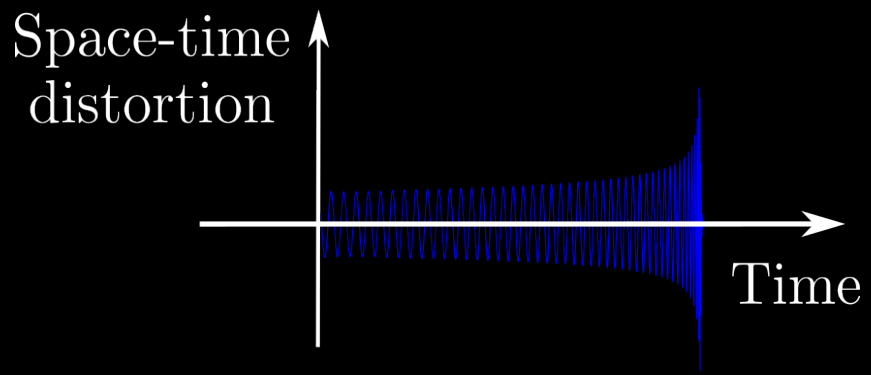


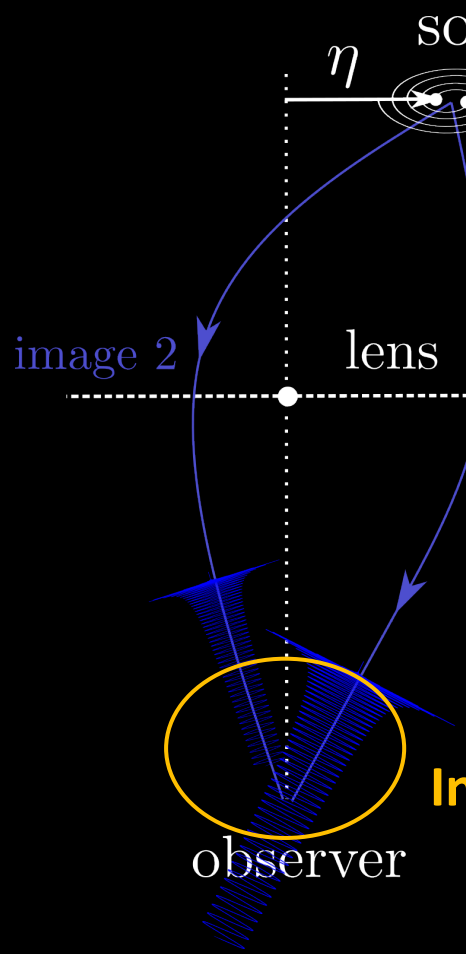
Credit: Hemantakumar Phurailatpam (CUHK, Hong Kong)
https://ler.hemantaph.com/_static/gwlensing_non_rotating.html

Gravitational lensing of gravitational waves (GWs)

Source of gravitational waves:
merger of two compact objects
(neutron stars, black holes...)







$$\vec{y} = \vec{\eta}\sqrt{\frac{d_{\rm L}}{2R_{\rm S}d_{\rm S}d_{\rm LS}}}$$

Source position $\vec{y}$

Mass of the lens $M_{\rm Lens}$

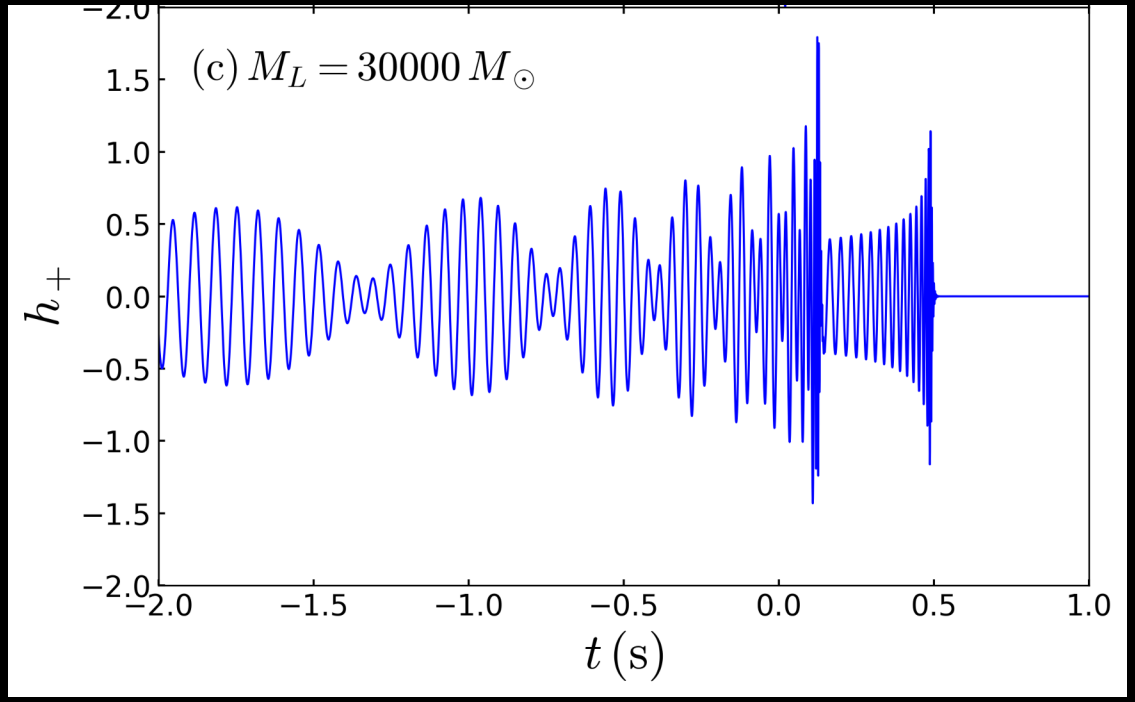
Frequency of GWs

Interference

Nakamura (1999)
Takahashi & Nakamura (2003),
[...]
Urrutia & Vaskonen (2021),
Bulashenko & Ubach (2022), ...

Lensing of gravitational waves not confidently detected yet
[But see GW231123 event, arXiv:2507.08219]

Interfering gravitational waves (+sonification)

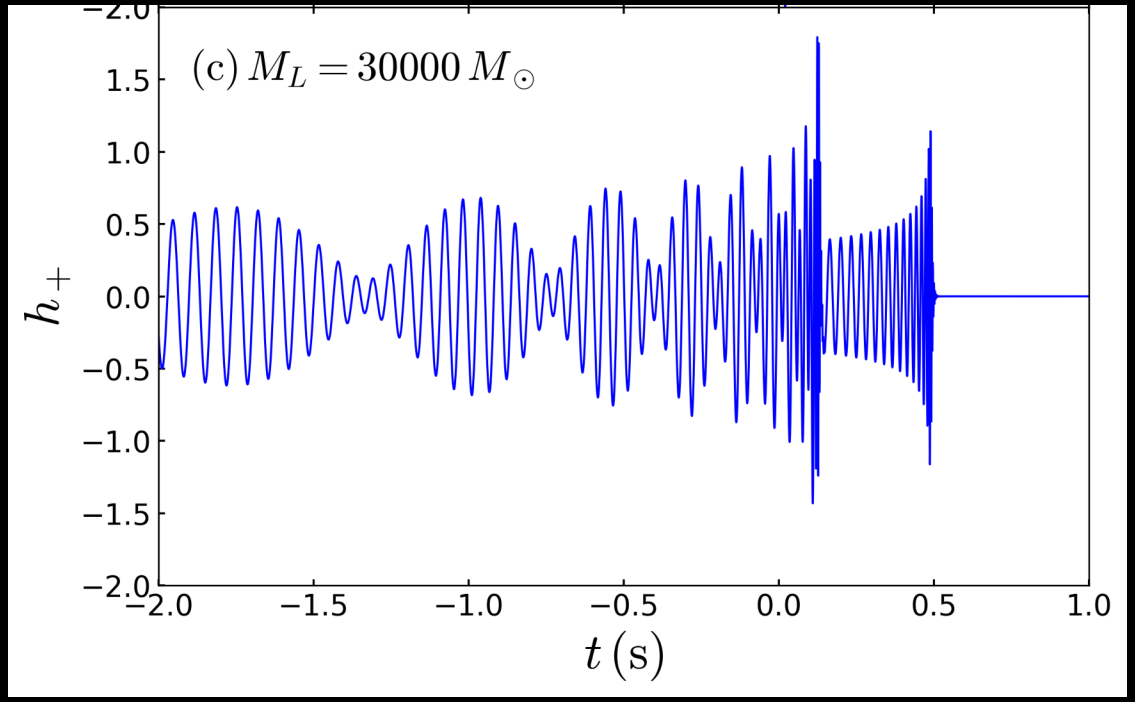


Ubach & Espuny, arXiv:2407.09588 (2024)

In collaboration with Jordi Espuny:
https://zoom3.net/sonificacions/

*Geometric Optics
*Point mass lens model

Interfering gravitational waves (+sonification)

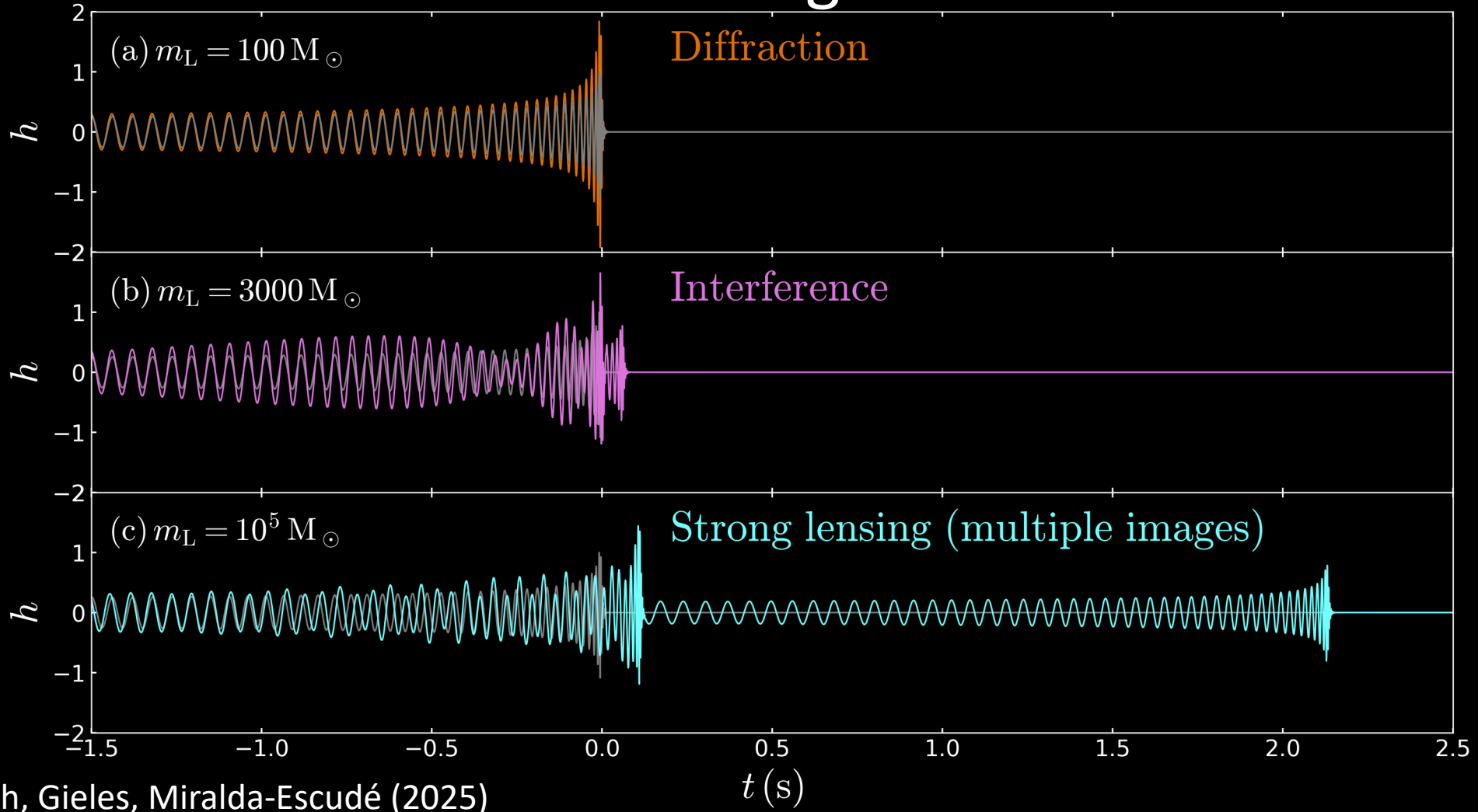


Ubach & Espuny, arXiv:2407.09588 (2024)

In collaboration with Jordi Espuny:
https://zoom3.net/sonificacions/

*Geometric Optics
*Point mass lens model

How does lensing look like?



Ubach, Gieles, Miralda-Escudé (2025)

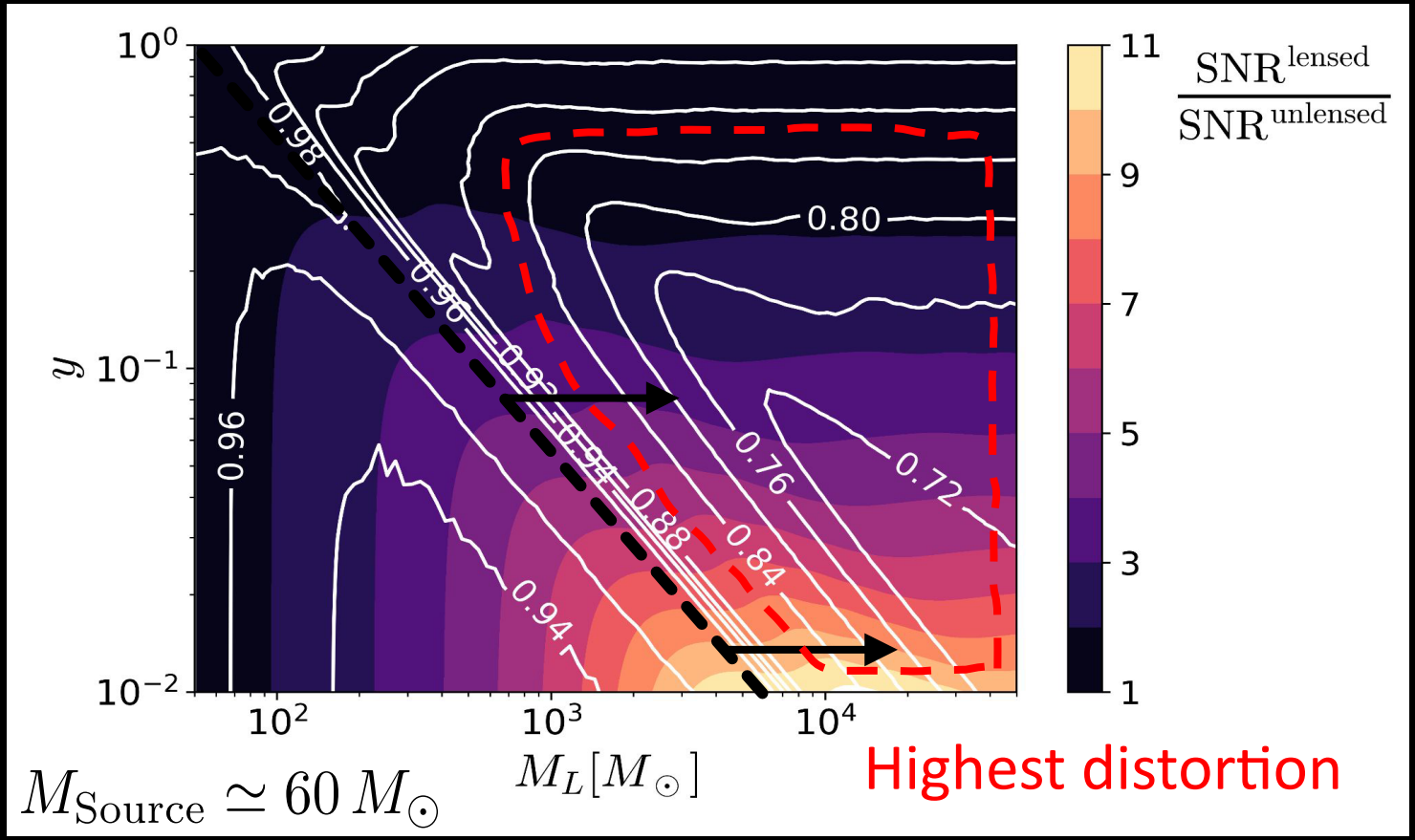
What can lensing of GWs be used for?

GWs are not distorted, dispersed or absorbed, except for lensing

To see invisible objects:
- Dense environments, opaque to light
  → distinguish formation environment of GW sources
- intermediate-mass regime $M_{\rm Lens} \sim (10^2 - 10^7)\, M_\odot$,
  challenging to light
  → probe intermediate-mass black holes, dark matter subhalos...

To see much further than what instruments allow
  → evolution across cosmic time of
    - GW sources
    - lenses: e.g. intermediate-mass & supermassive black holes

Detectability of lensing distortions: Distortion from the unlensed signal («match»)



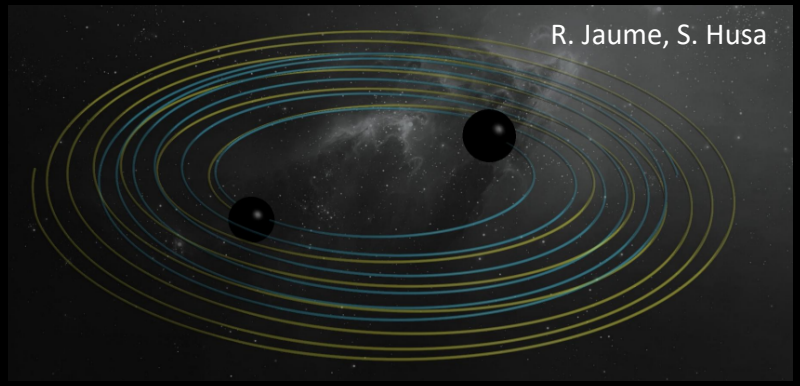
$$\frac{M_{\mathrm{Lens}}}{M_{\mathrm{Source}}} \gtrsim \frac{1}{y}$$

Bondarescu, Ubach, Bulashenko, Lundgren (2023)
See also Mishra+(2024)

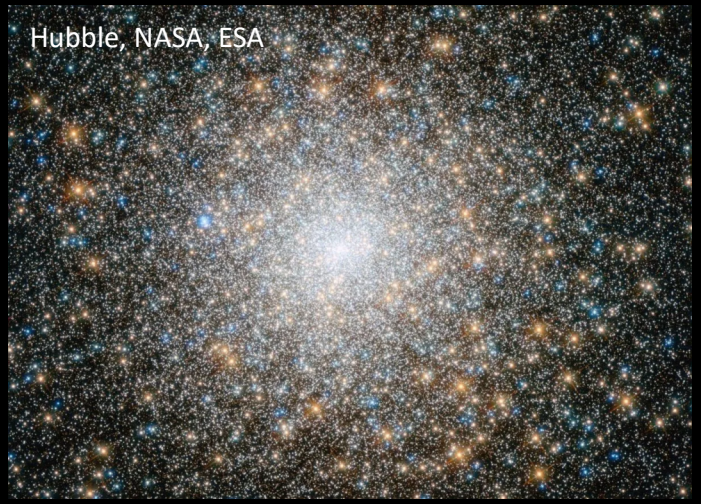
*However, see Chan+(2025)
→ detectability might decrease in wave-optics region

Self-lensing

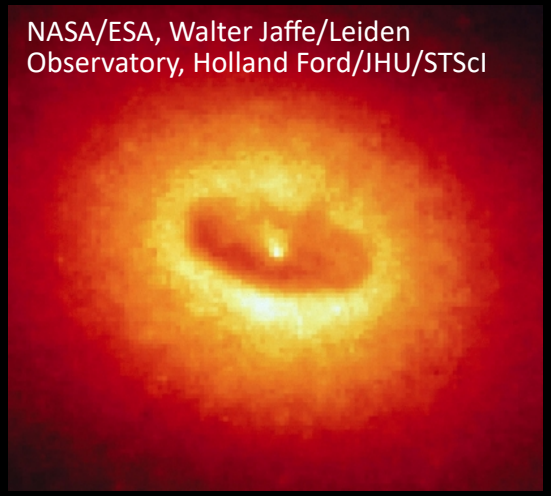
Gravitational waves from different astrophysical environments:



Isolated binaries, «in the field»



Binaries in **star clusters**

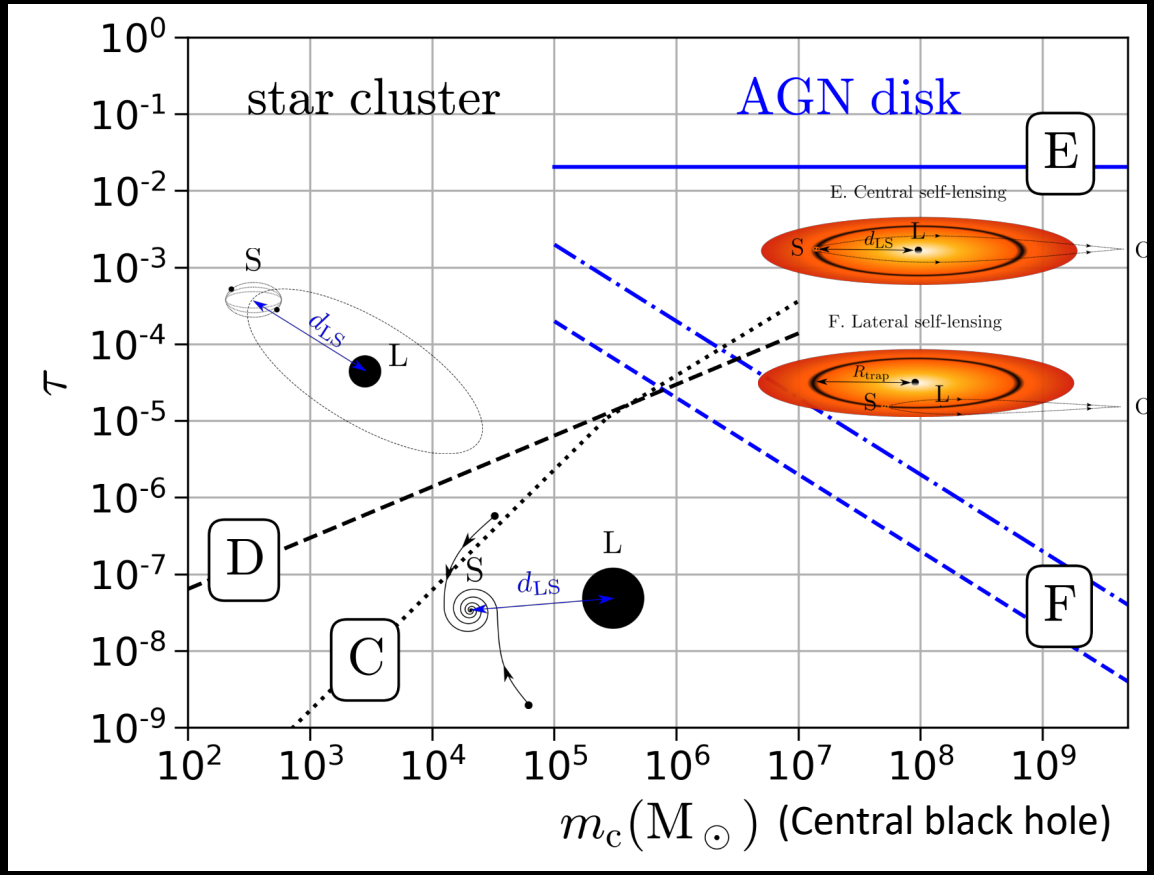


Binaries in **AGN disks**

How to distinguish the environment of GW sources?

Spins, eccentricity, Doppler/phase shifts..., self-lensing

Probability of self-lensing



C: GW capture
D: Lidov-Kozai
E: Central lens
F: Lateral lens

← Coincident with Gondán&Kocsis (2022), Leong et al. (2024)

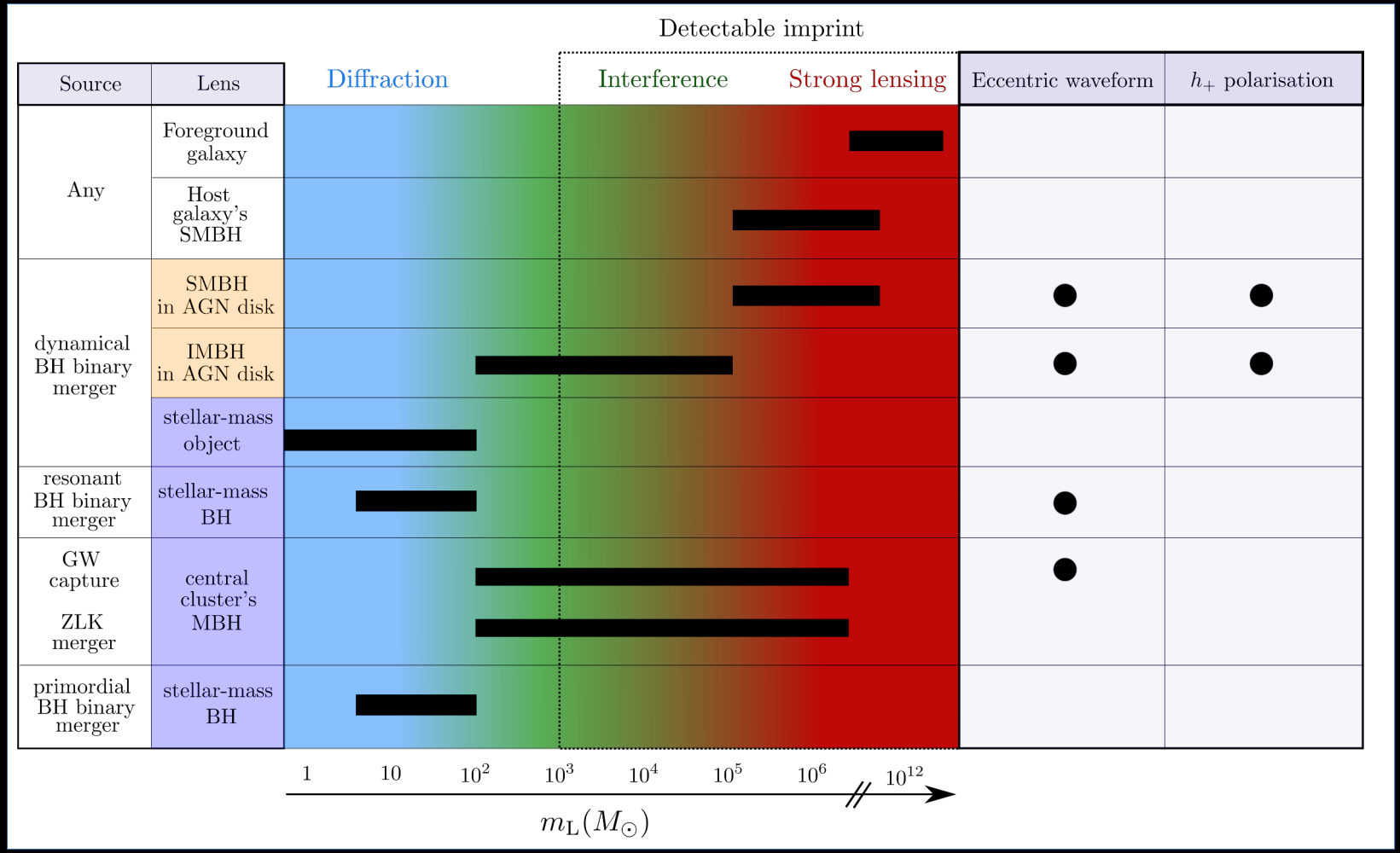
Self-lensing probability by central BH:

$$\tau \propto \frac{v_{\rm orbit}^2}{c^2} \propto \frac{M_{\rm Lens}}{d_{\rm LS}}$$

Higher probability when source (binary) is closer to lens (central massive black hole), $\boxed{d_{\rm LS} \downarrow}$

Ubach, Gieles, Miralda-Escudé (2025)

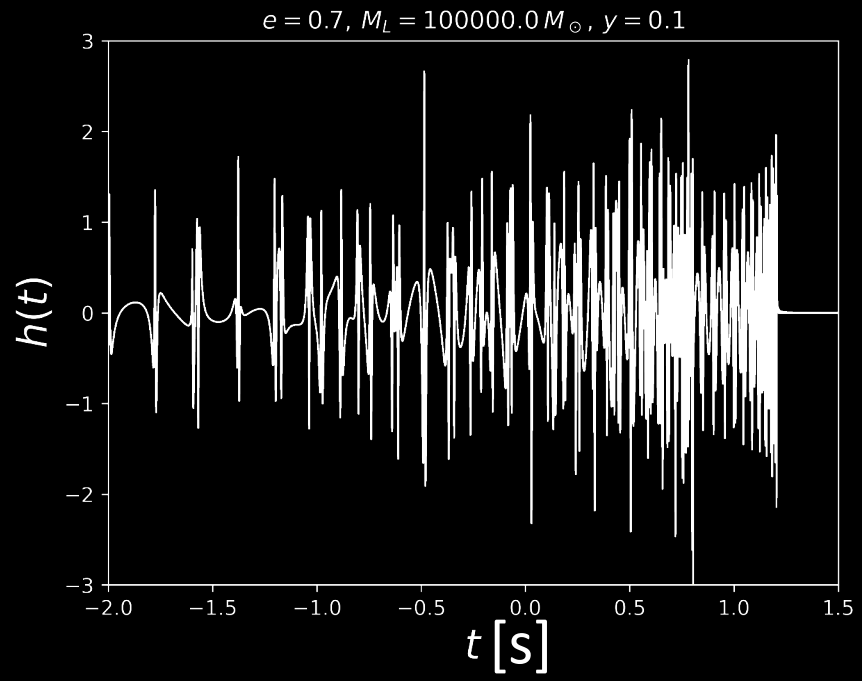
Signatures to distinguish between astrophysical environments



Ubach, Gieles, Miralda-Escudé (2025)

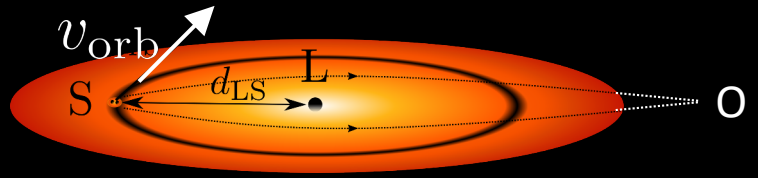
Signatures to distinguish self-lensing from foreground lensing?

Eccentric + lensed?
(e.g. high eccentricity
in AGN disks)

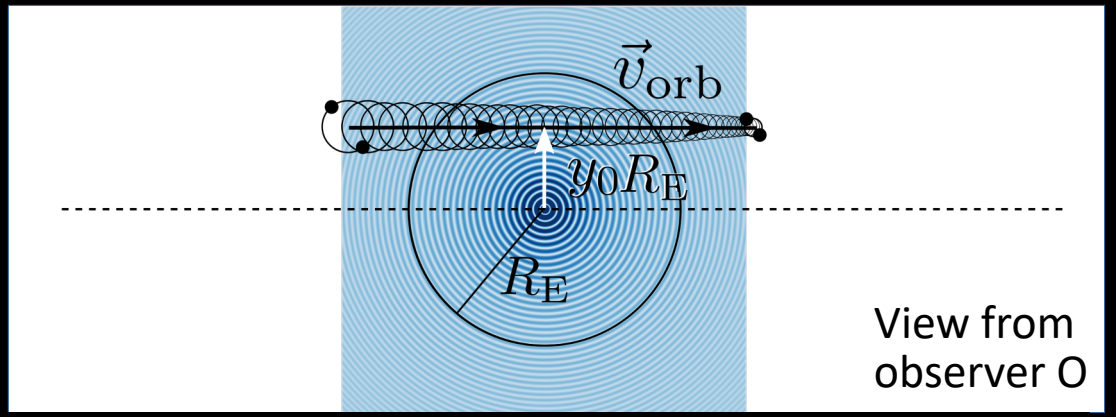


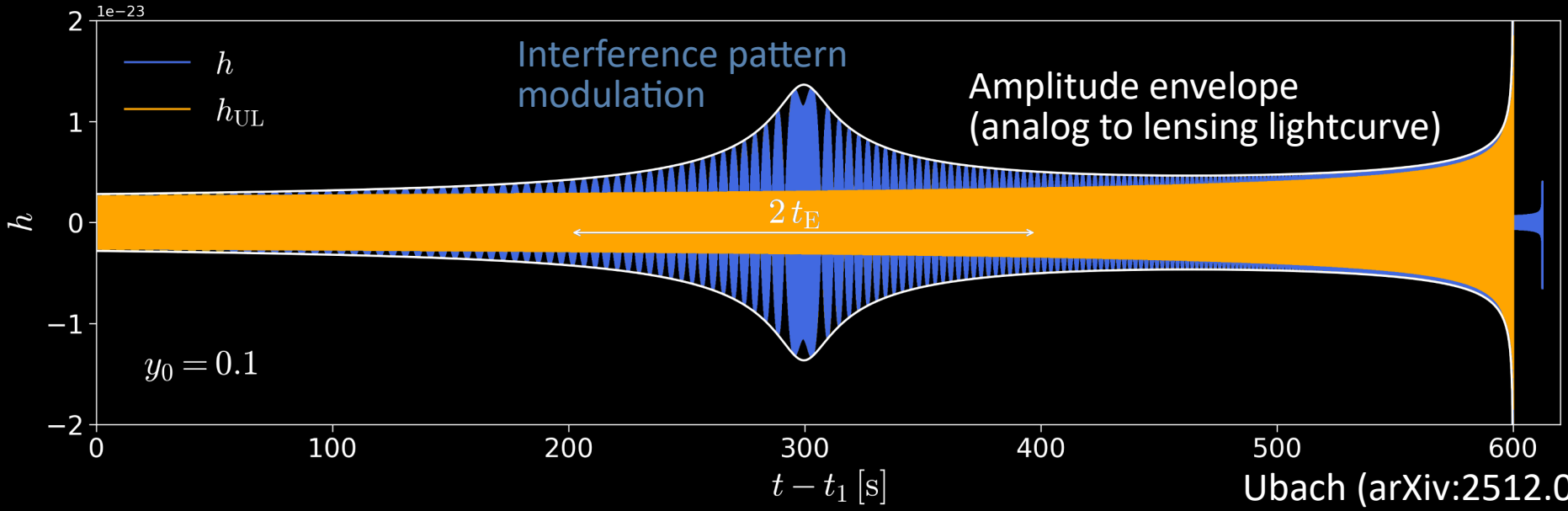
Unique self-lensing signatures?
Exploring the moving source

Self-lensing of a (fast) moving source



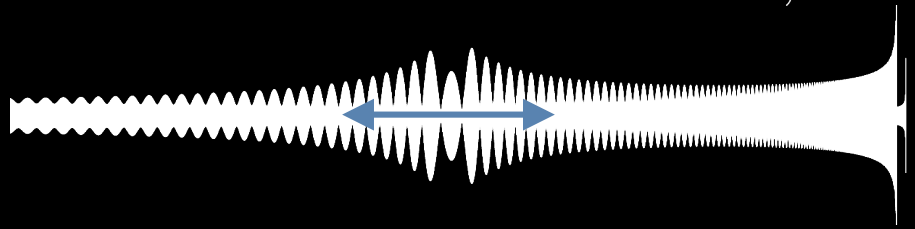
Fast moving source (e.g. binary orbiting close to massive BH)





Ubach (arXiv:2512.08898)

Constraints on $d_{\rm LS}$ and $M_{{\rm MBH},z}$

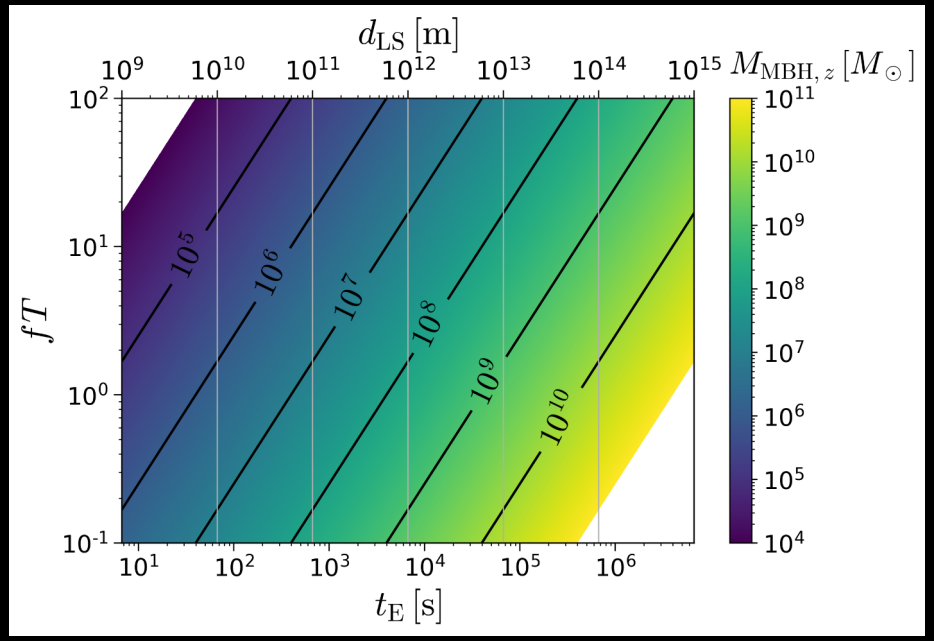


- $d_{\rm LS}$ from measuring $t_{\rm E}$:

$$d_{\rm LS} = c t_{\rm E}/2$$

- $M_{{\rm MBH},z}$ from additionally measuring T from modulations and f:

$$M_{{\rm MBH},z} \simeq 2.5 \times 10^6\, M_\odot\, (t_{\rm E}/[100\,{\rm s}])\, (f\,T)^{-1}$$



Ubach (arXiv:2512.08898)

Future

In next generation GW detectors (Einstein Telescope, Cosmic Explorer), $\sim 10^6$ events per year, compensating small self-lensing probabilities

Many overlapping signals: need to consider moving source signature

Self-lensing signature on the moving source can provide constraints on formation of merging binaries