Constraining the environment of compact binary mergers with self-lensing signatures

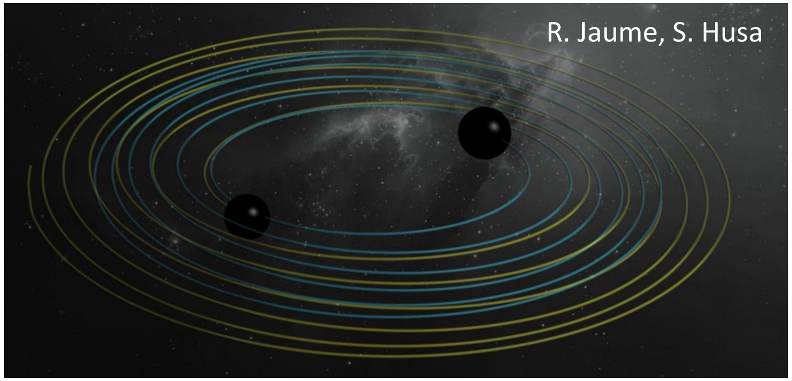
5th Meeting on Gravitational Wave Science in Scandinavia
Niels Bohr Institute, 15th May 2025

Helena Ubach, Mark Gieles, Jordi Miralda-Escudé
arXiv:2505.04794

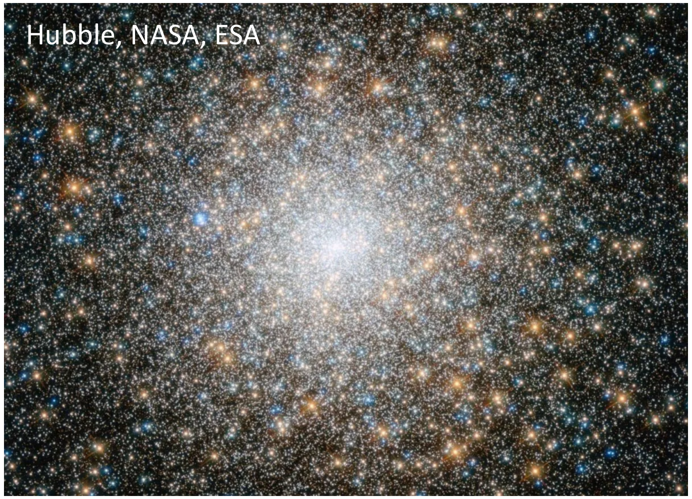
Institute of Cosmos Sciences (ICCUB), University of Barcelona
helenaubach@icc.ub.edu

Motivation

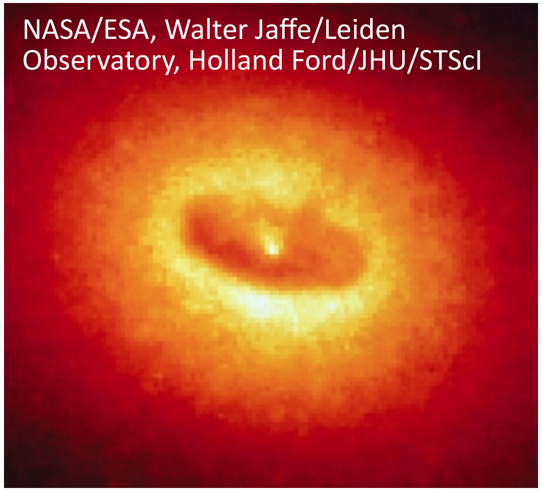
Gravitational waves from different environments:



Isolated binaries, «in the field»



Binaries in **star clusters**

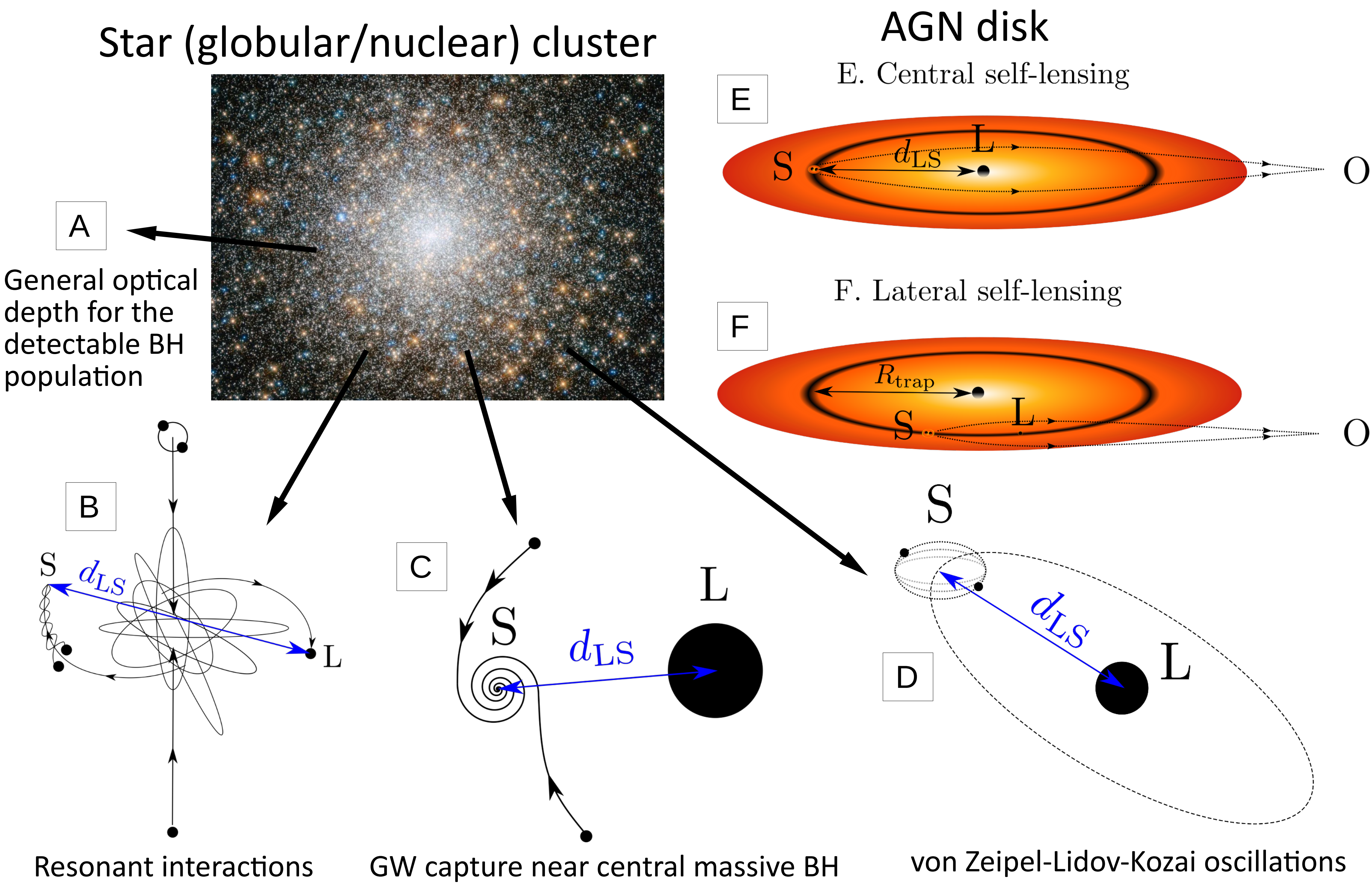


Binaries in **AGN disks**

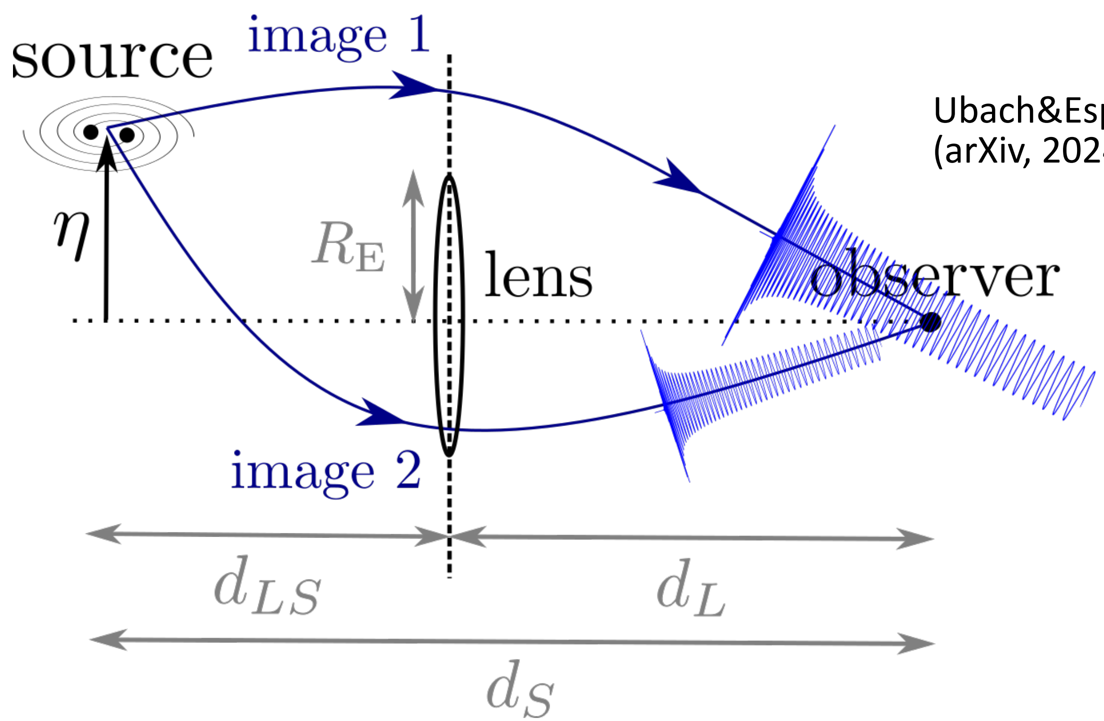
How to distinguish the environment of GW sources?

Spins, eccentricity, Doppler shifts... + <u>self-lensing</u>

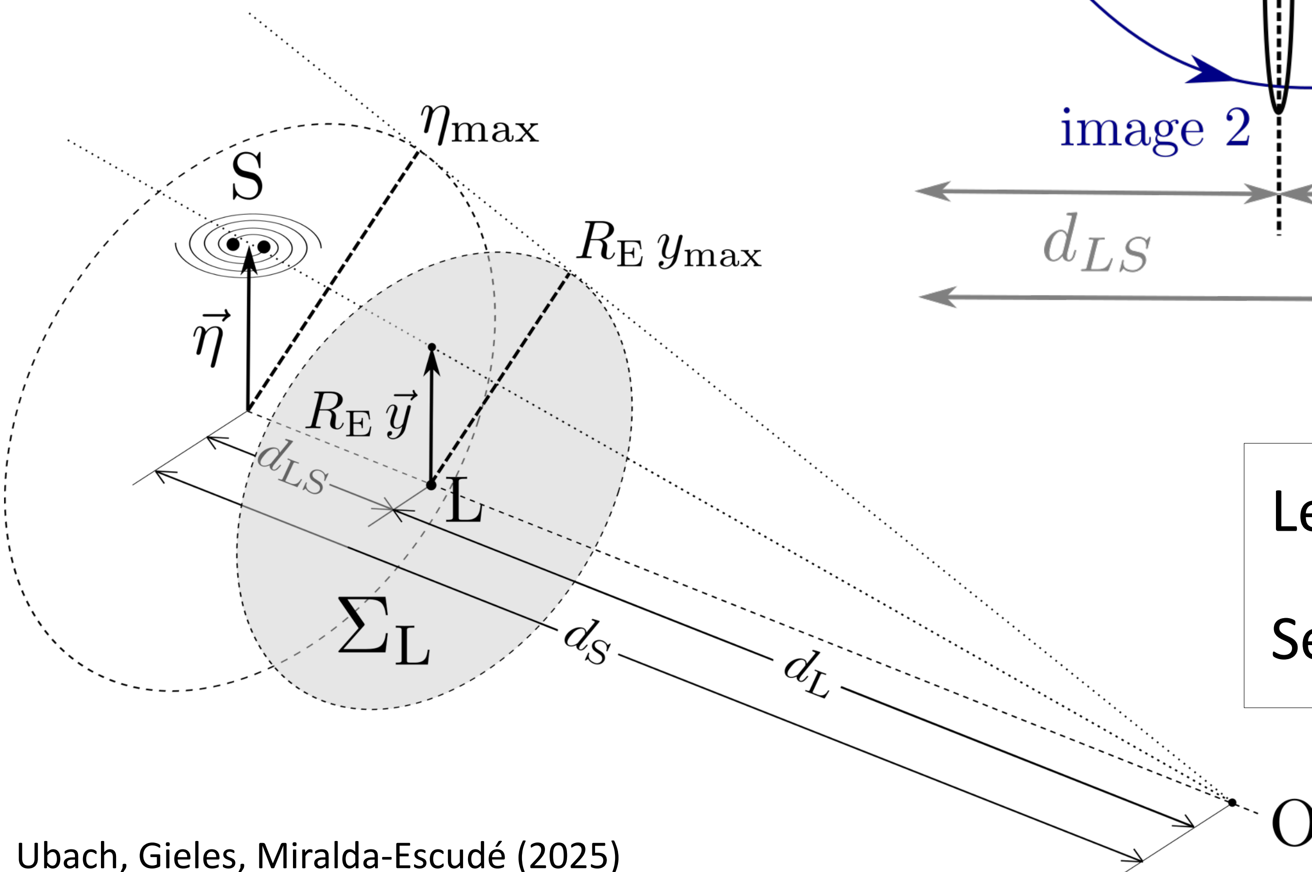
Environments and scenarios



Gravitational lensing



Ubach&Espuny (arXiv, 2024)



Lens model: point mass

Self-lensing: $d_{LS} \ll d_L,\, d_S$

Ubach, Gieles, Miralda-Escudé (2025)
https://arxiv.org/abs/2505.04794

Probability of self-lensing

- Probability $\simeq$ optical depth τ

$$\tau \propto \frac{\sigma^2}{c^2}$$

population of lenses, optical lensing

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

one lens, e.g. Gould (1995)

→ low value: self-lensing usually neglected

Nevertheless,

- very dense (relativistic) environments, $\sigma \uparrow$
- # detections ↑↑ (next generation detectors)

→ low probability $\neq$ impossible

Detectability

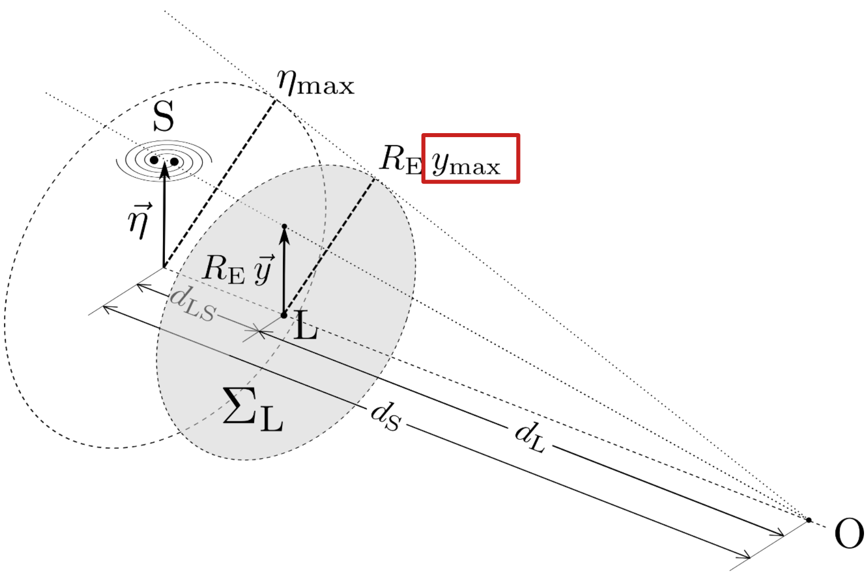
Probability of **detectable lensing**

Detectability:

- Distortion (diffraction, interference)
- Multiple images

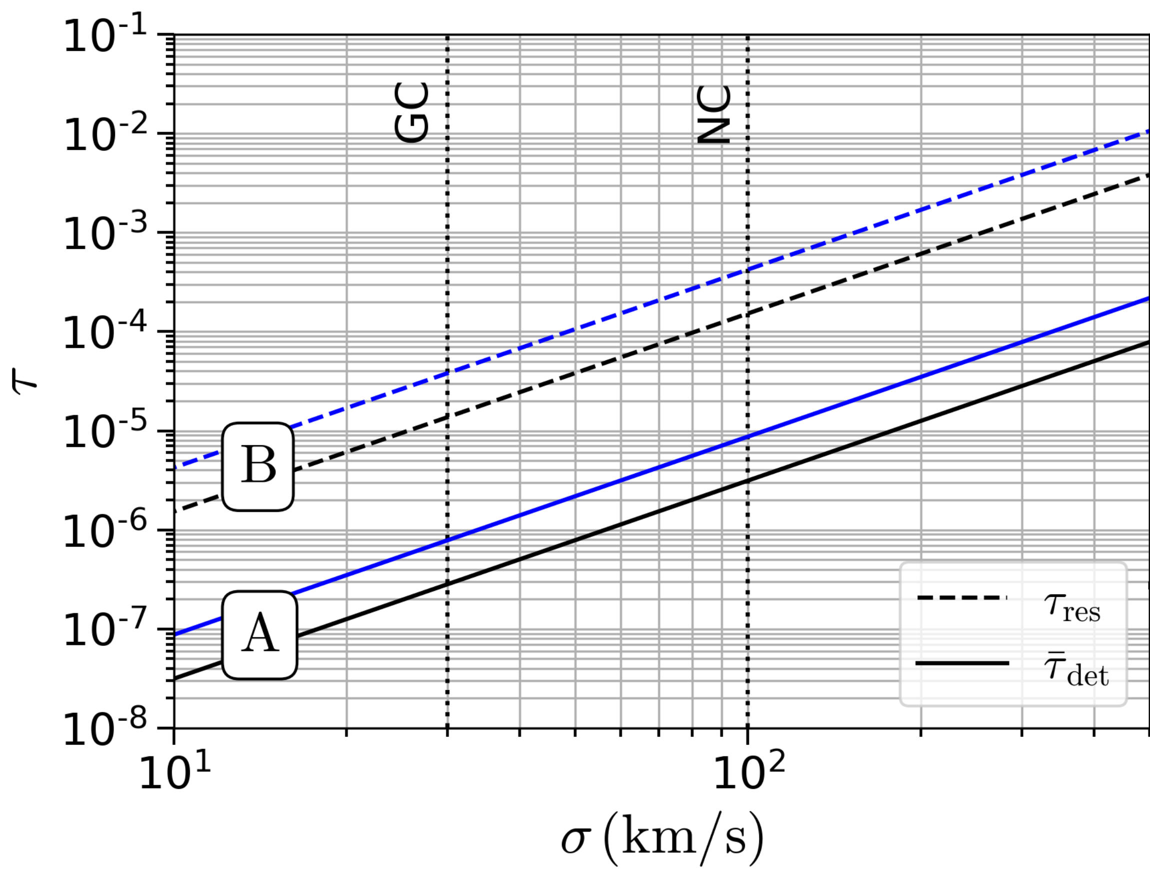
$$\tau \propto \frac{\sigma^2}{c^2} y_{\max}^2 \qquad \tau \propto \frac{v_{\rm orbit}^2}{c^2} y_{\max}^2 \propto \frac{R_{\rm L}}{d_{\rm LS}} y_{\max}^2$$

+ considering just detectable lens population



Probability of self-lensing

- Probability of self-lensing (population): $\tau \propto \dfrac{\sigma^2}{c^2}\, y_{\max}^2$



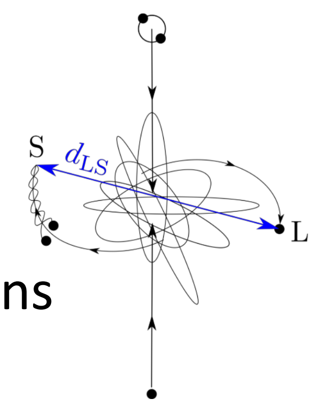
$y_{\max} \uparrow$ when SNR $\uparrow$

$y_{\max} = 2.5$

$y_{\max} = 1.5$

B

Resonant interactions



A

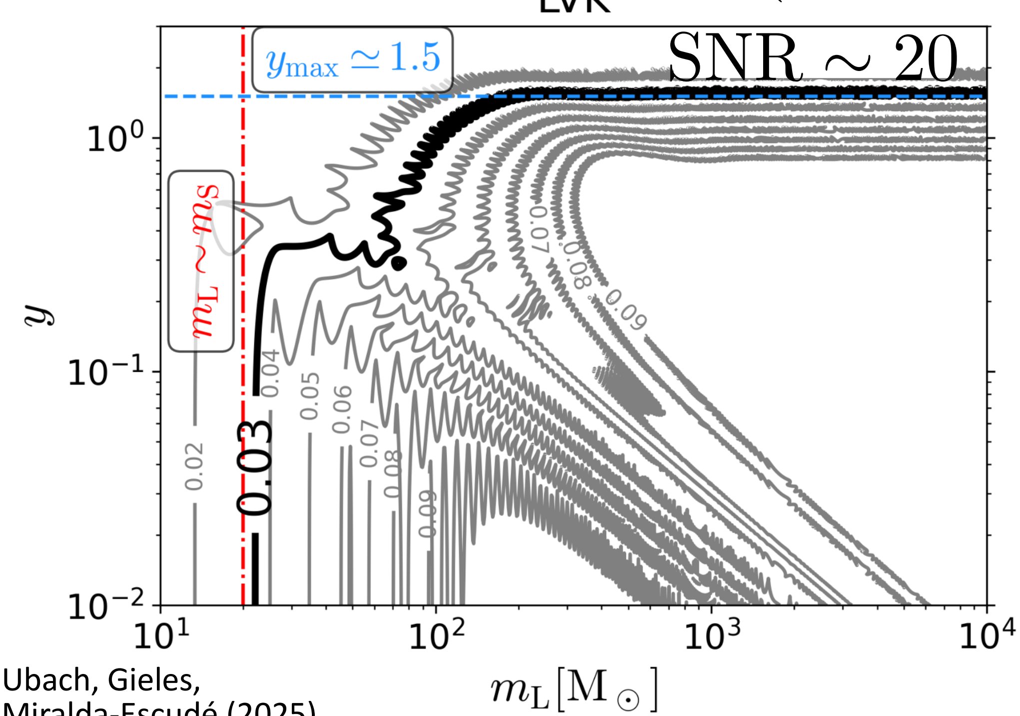
General optical depth for the detectable BH population

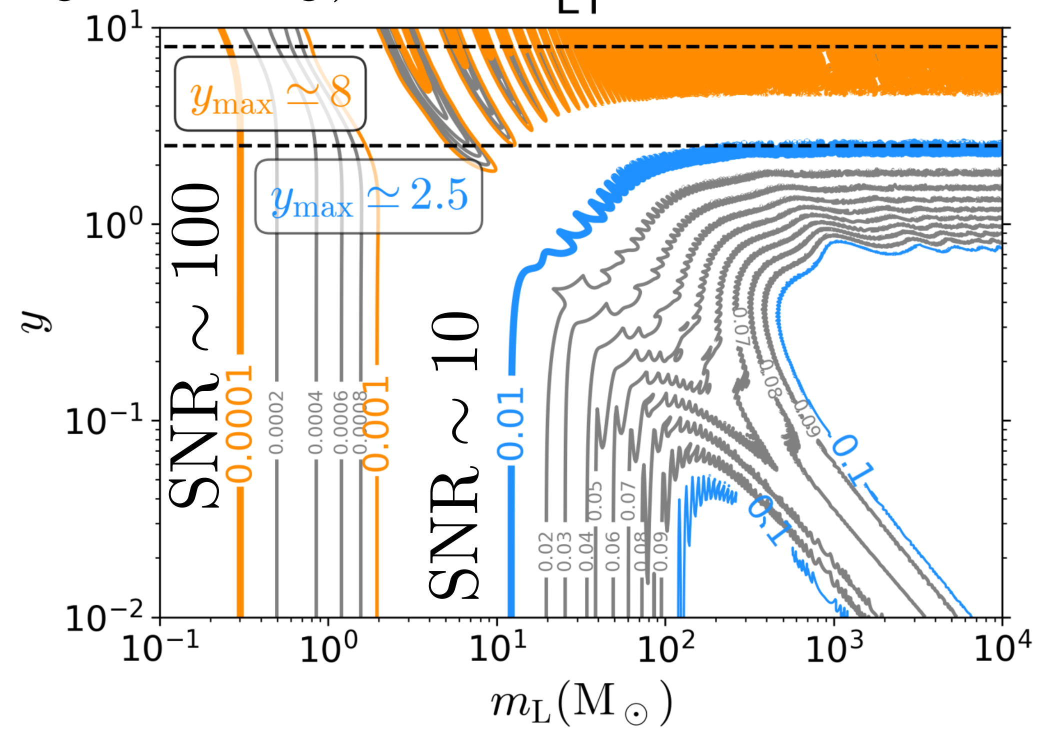
Ubach, Gieles, Miralda-Escudé (2025)
https://arxiv.org/abs/2505.04794

Detectability

- Distortion on single waveform (diffraction, interference)

$$(m_{\rm S} = 10\,M_\odot + 10\,M_\odot)$$





Ubach, Gieles, Miralda-Escudé (2025)
https://arxiv.org/abs/2505.04794

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

Lindblom+(2008), Cornish+ (2011) Gao+ (2022), Tambalo+(2023), Savastano+(2023)

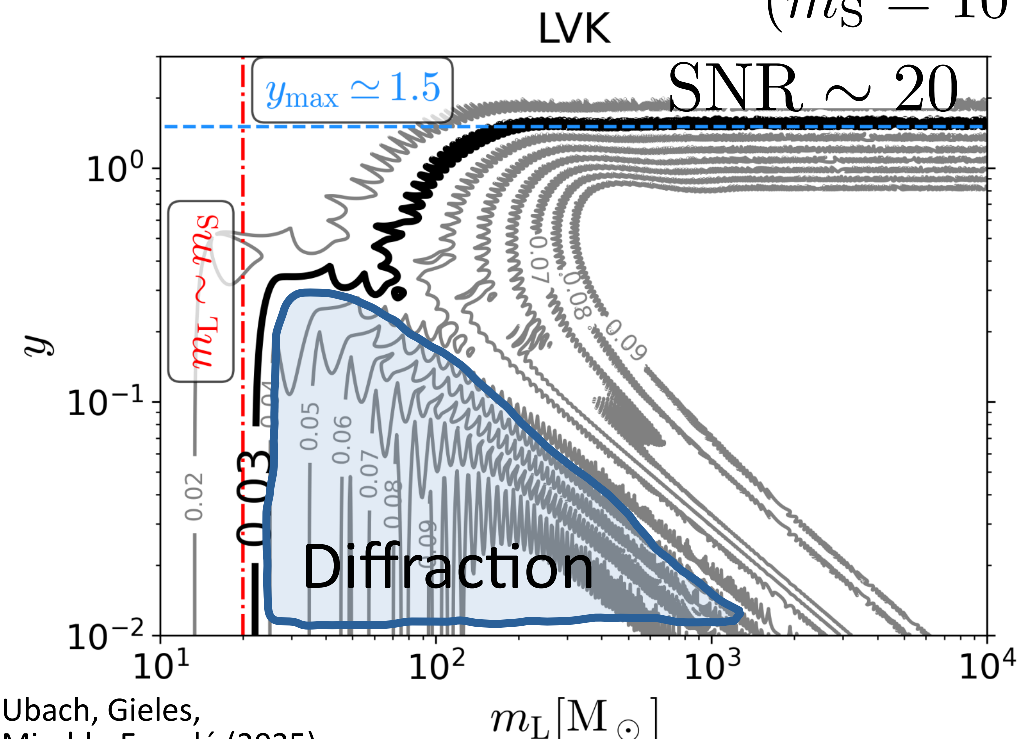
$$\begin{cases} m_{\rm L} \gtrsim m_{\rm S} \\ y < y_{\rm max} \simeq 1.5 \end{cases}$$

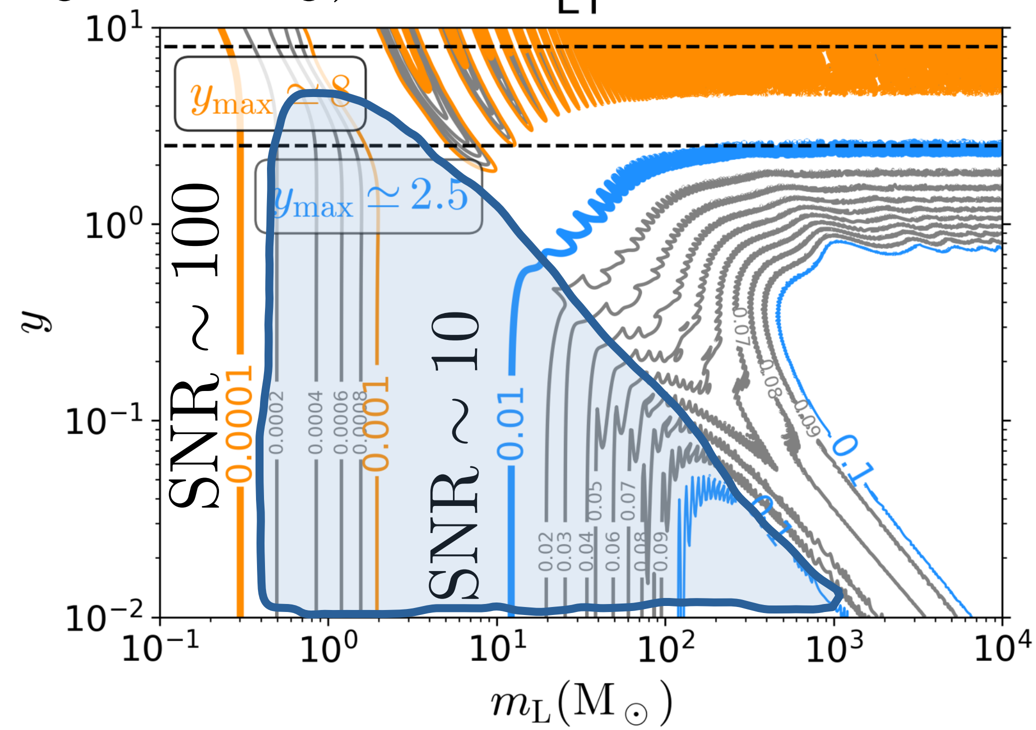
$$y < y_{\rm max} \simeq 2.5$$

Detectability

- Distortion on single waveform (diffraction, interference)

$$(m_{\rm S} = 10\,M_\odot + 10\,M_\odot)$$





Ubach, Gieles, Miralda-Escudé (2025)
https://arxiv.org/abs/2505.04794

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

Lindblom+(2008), Cornish+ (2011) Gao+ (2022), Tambalo+(2023), Savastano+(2023)

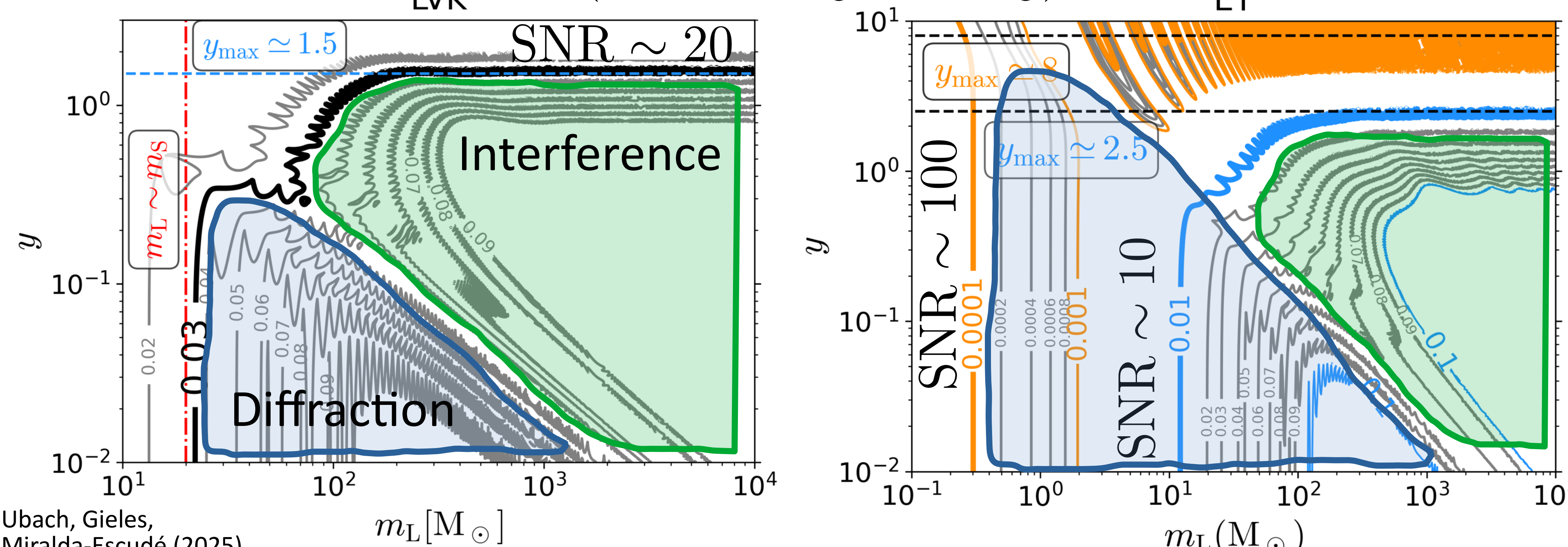
$$\begin{cases} m_{\rm L} \gtrsim m_{\rm S} \\ y < y_{\rm max} \simeq 1.5 \end{cases}$$

$$y < y_{\rm max} \simeq 2.5$$

Detectability

- Distortion on single waveform (diffraction, interference)

$$(m_{\rm S} = 10\,M_\odot + 10\,M_\odot)$$



Ubach, Gieles, Miralda-Escudé (2025)
https://arxiv.org/abs/2505.04794

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

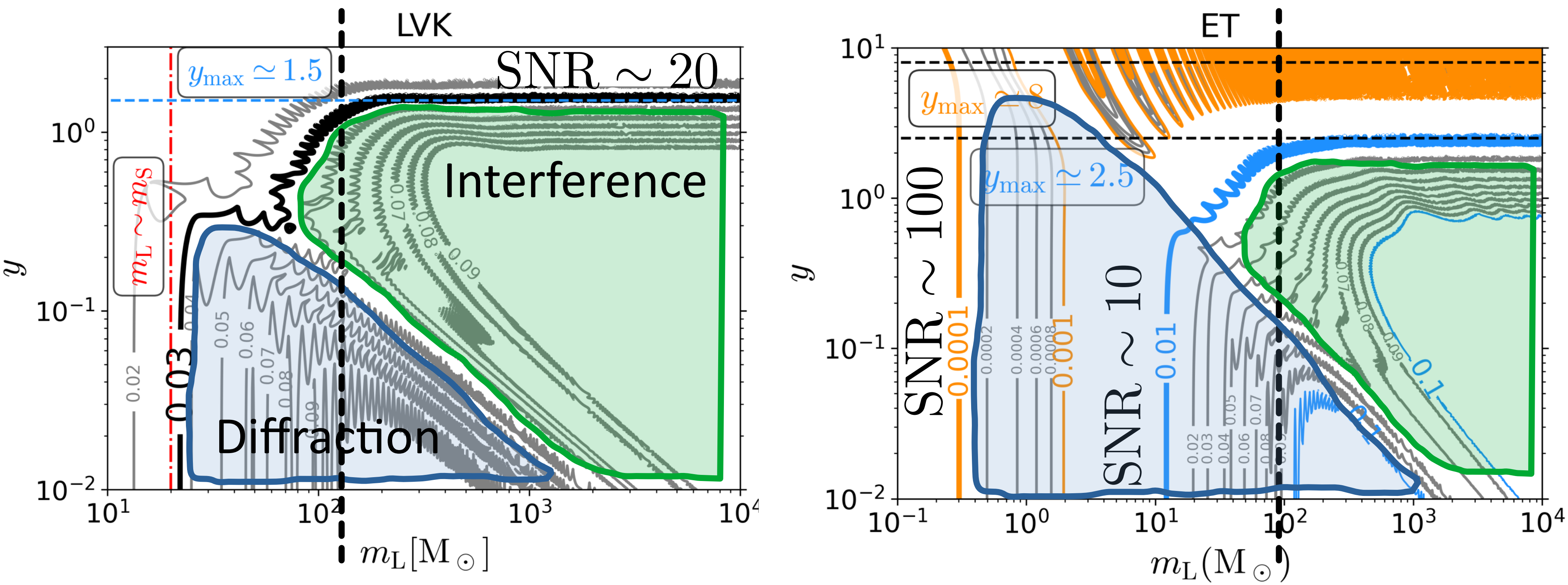
Lindblom+(2008), Cornish+ (2011) Gao+ (2022), Tambalo+(2023), Savastano+(2023)

$$\begin{cases} m_{\rm L} \gtrsim m_{\rm S} \\ y < y_{\rm max} \simeq 1.5 \end{cases}$$

$$y < y_{\rm max} \simeq 2.5$$

Detectability

Stellar-mass BH lenses: mostly undetectable, $m_{\mathrm{L}} \sim m_{\mathrm{S}}$,

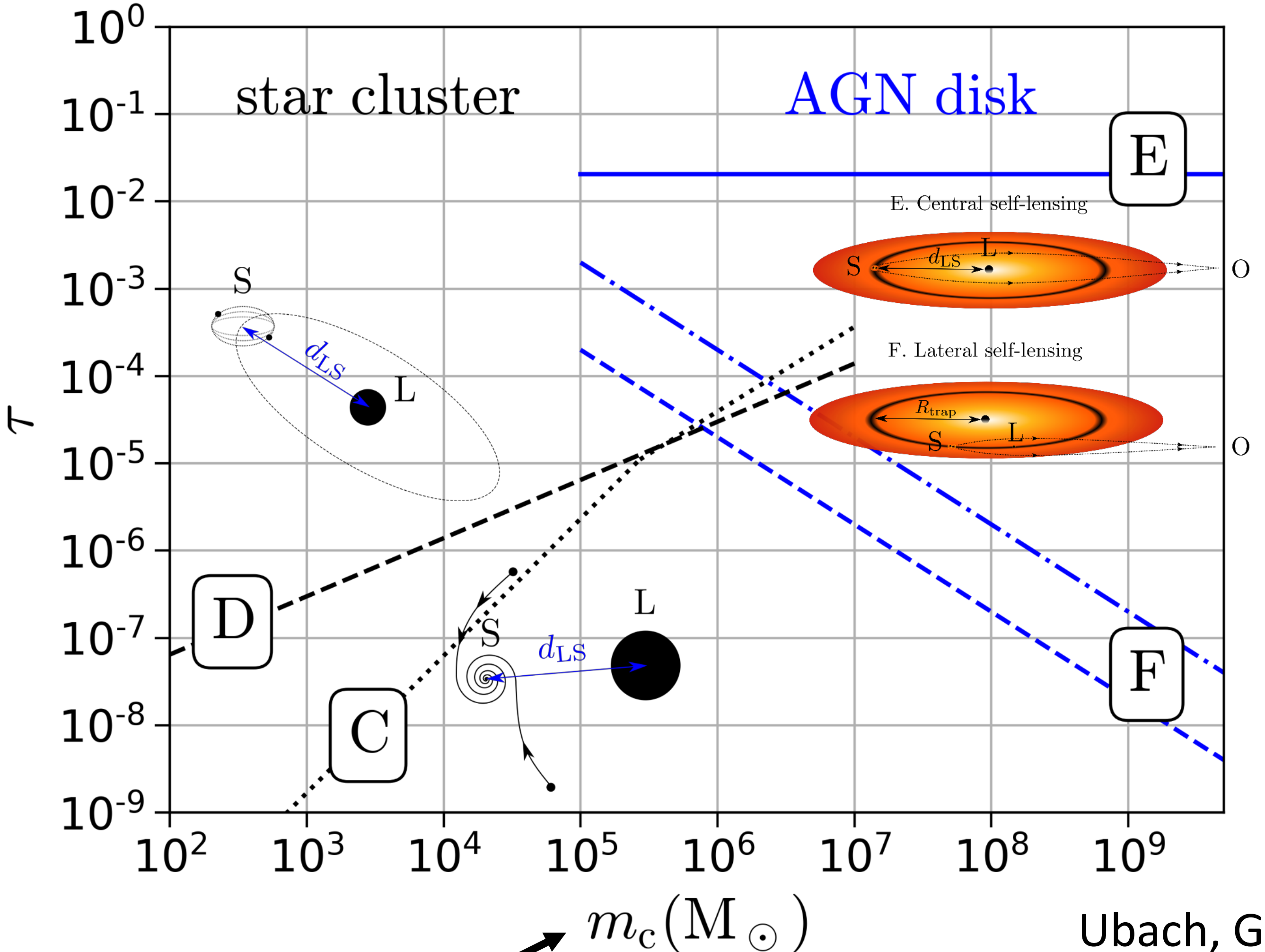


$m_{\mathrm{L}} < 10^2\, M_\odot$ $m_{\mathrm{L}} < 10^2\, M_\odot$

→ To have **detectable** imprint (interference pattern / multiple images), we need a **massive BH** in the star cluster (IMBH/SMBH)

Probability of self-lensing

- Probability of self-lensing (one lens): $\tau \propto \frac{v_{\rm orbit}^2}{c^2} \propto \frac{R_{\rm L}}{d_{\rm LS}}$



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

$$y_{\rm max} = 1$$

Ubach, Gieles, Miralda-Escudé (2025)
https://arxiv.org/abs/2505.04794

Detectability

- Multiple images (strong lensing), $m_{\mathrm{L}} \gtrsim 10^3\,\mathrm{M}_\odot$

$\mathrm{SNR} > 8$ for both images

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

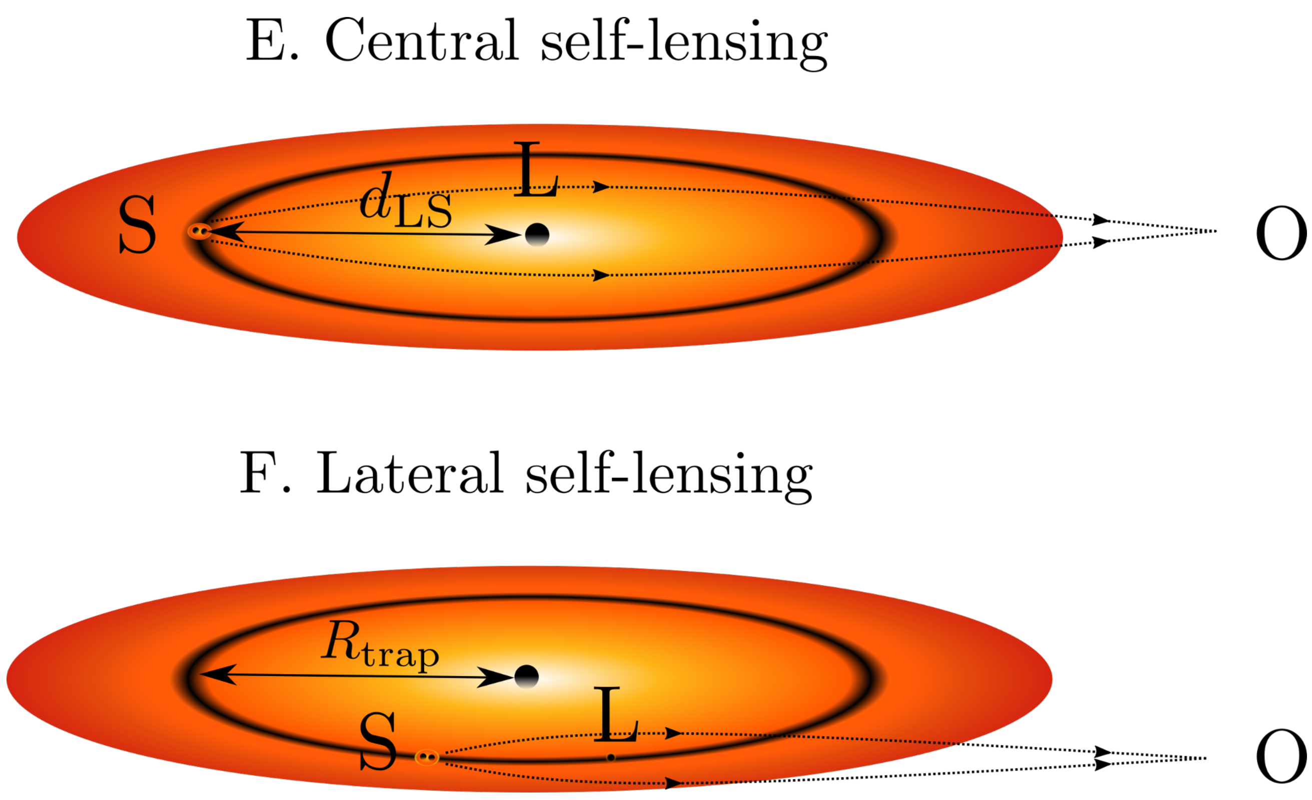
$$\text{For LVK, } (\mathrm{SNR}^+_{\mathrm{L}})^{\mathrm{max}} = 50,\ y_{\mathrm{max}} \simeq 2.$$
$$\text{For ET, } (\mathrm{SNR}^+_{\mathrm{L}})^{\mathrm{max}} = 1000,\ y_{\mathrm{max}} \simeq 10.$$

Signatures from environments

Detectable imprint: **interference pattern, multiple images**
→ central massive BH

- *How do we know if star cluster or AGN disk?*

AGN disk has characteristic signature: h_+ **polarization**



Geometry:
edge-on disk
+ edge-on binary
(aligned with disk)

→ we receive
h_+ polarisation

Ubach, Gieles, Miralda-Escudé (2025)
https://arxiv.org/abs/2505.04794

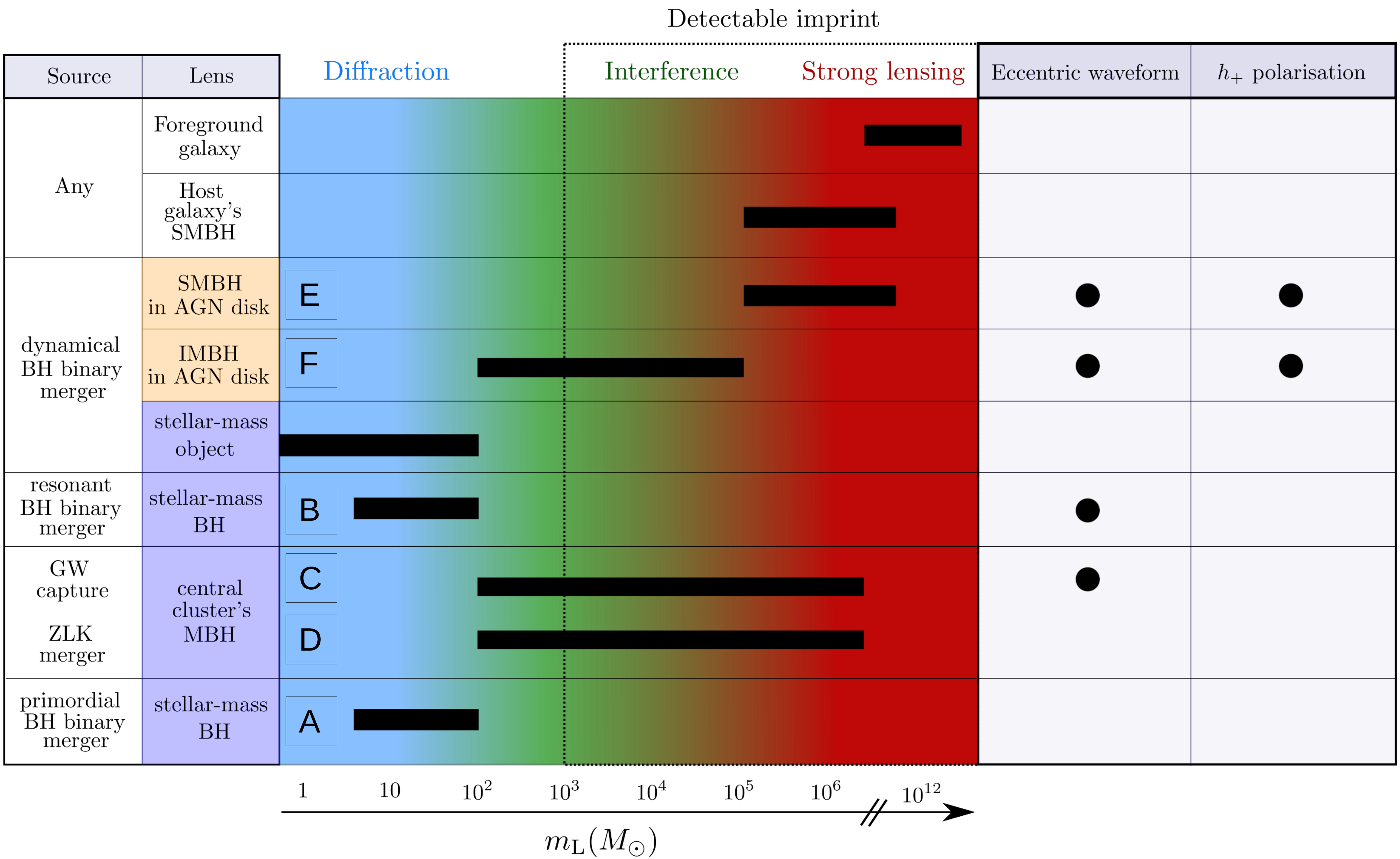
Conclusions

- **Stellar-mass** BH **lenses** are both unlikely and mostly **undetectable** (diffraction)

- AGN disk self-lensing has **highest probability** ($\tau \simeq 2 \times 10^{-2}$)
  + **detectable lensing** imprint
  + characteristic feature: h_+ **polarization**

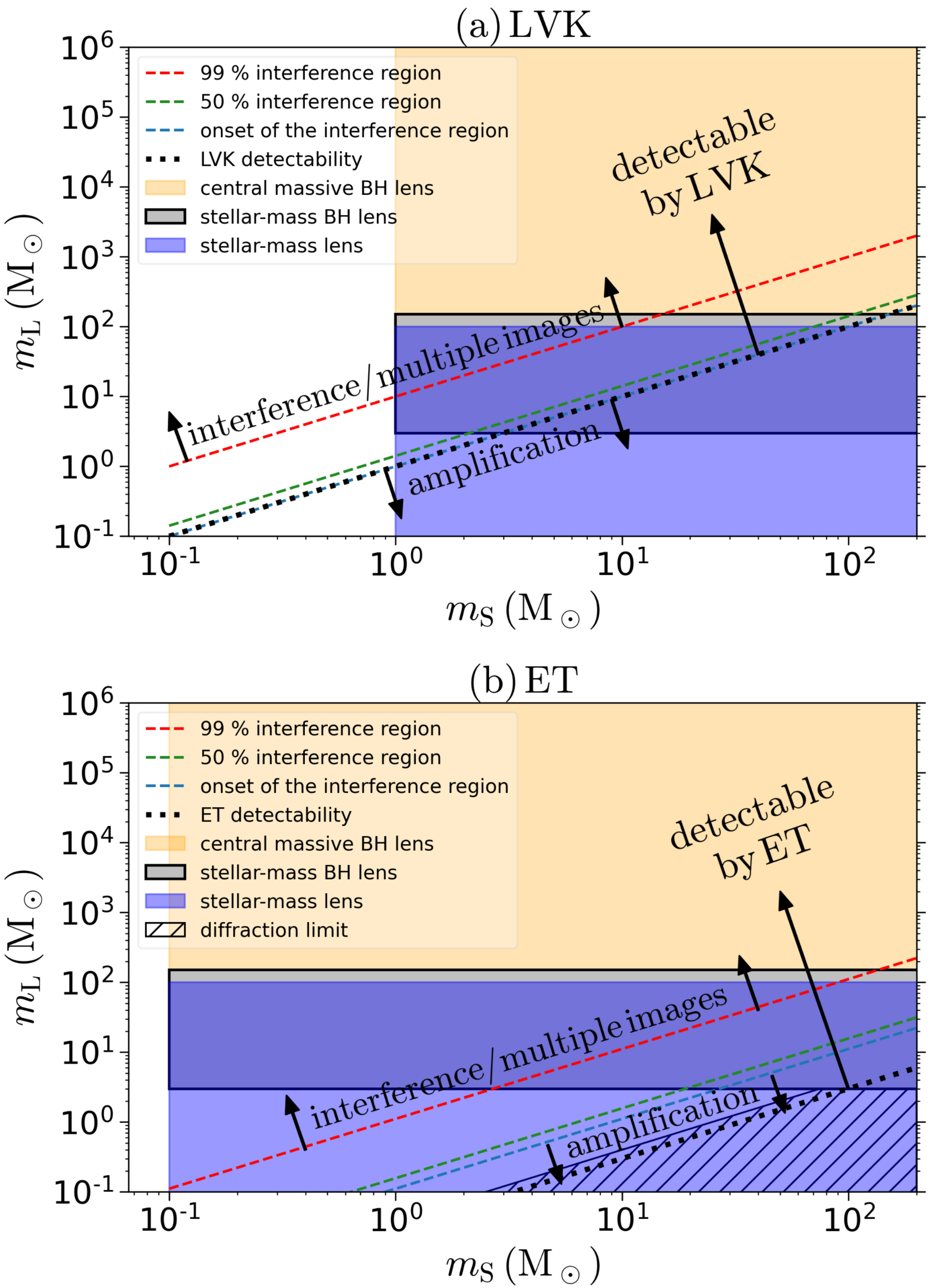
→ could be distinguished from galaxy lensing, star cluster self-lensing

- Combining self-lensing with polarization and eccentricity can help constrain the astrophysical environment



Detectable imprint
Source
Lens
Diffraction
Interference
Strong lensing
Eccentric waveform
h_+ polarisation
Any
Foreground galaxy
Host galaxy's SMBH
dynamical BH binary merger
SMBH in AGN disk
E
IMBH in AGN disk
F
stellar-mass object
resonant BH binary merger
stellar-mass BH
B
GW capture
ZLK merger
central cluster's MBH
C
D
primordial BH binary merger
stellar-mass BH
A
1
10
10^2
10^3
10^4
10^5
10^6
10^{12}
$m_{\rm L}(M_\odot)$

Backup slides



(a) LVK
99 % interference region
50 % interference region
onset of the interference region
LVK detectability
central massive BH lens
stellar-mass BH lens
stellar-mass lens
detectable by LVK
interference / multiple images
amplification
m_L ($M_\odot$)
m_S ($M_\odot$)
(b) ET
99 % interference region
50 % interference region
onset of the interference region
ET detectability
central massive BH lens
stellar-mass BH lens
stellar-mass lens
diffraction limit
detectable by ET
interference / multiple images
amplification
m_L ($M_\odot$)
m_S ($M_\odot$)

Geometrical optics (GO) validity

GO approximation validity: $\nu \gtrsim \nu_G = \frac{1}{4y}$

$R_S = \frac{2GM}{c^2}$

Before:

$$\nu \gg 1$$

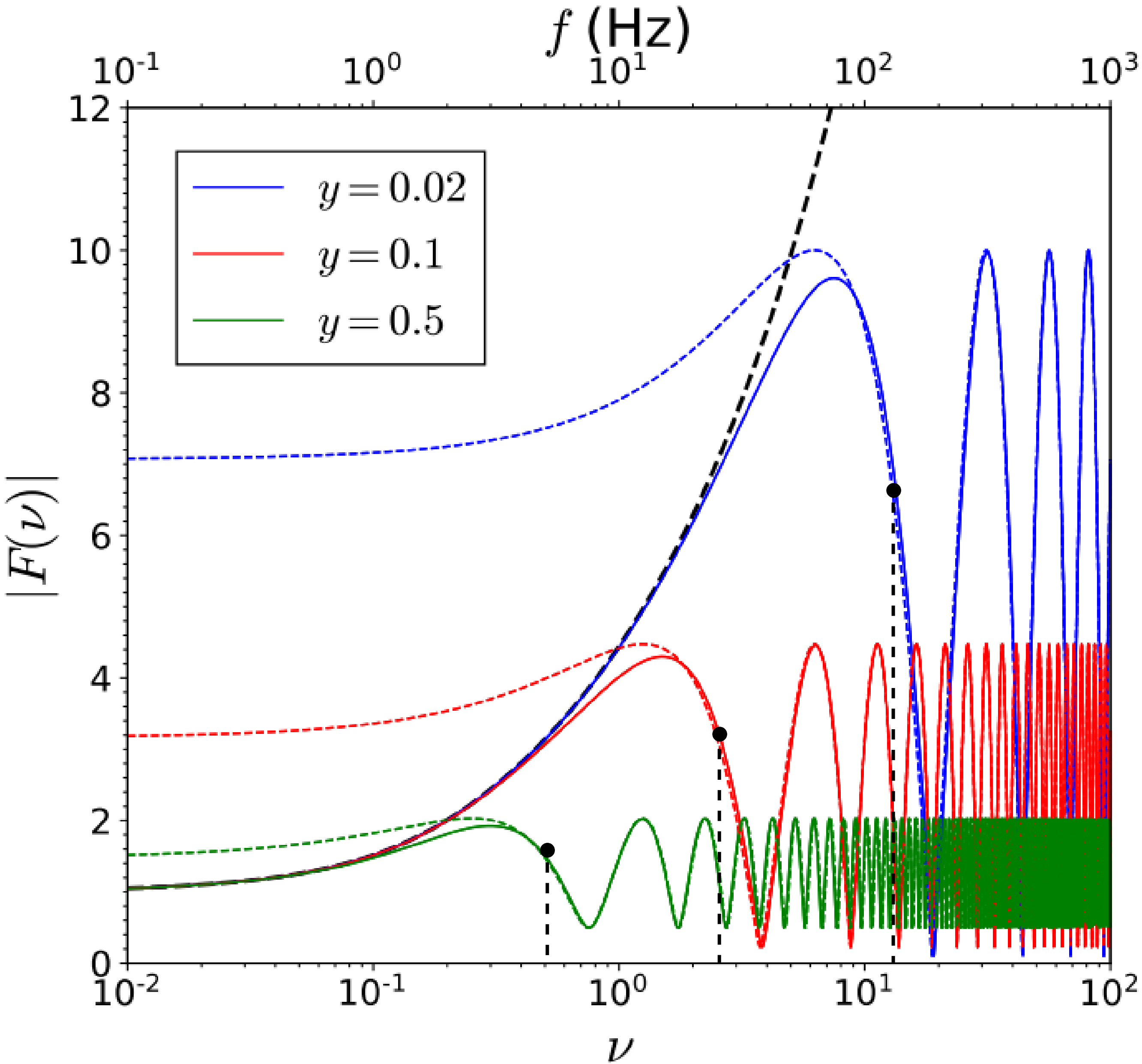
$$\Downarrow$$

$$\lambda \ll R_\mathrm{S}$$

$$\lambda \lesssim 8R_\mathrm{S}y$$

- Less restrictive condition
- Depends also on y

Bulashenko and Ubach (2022)



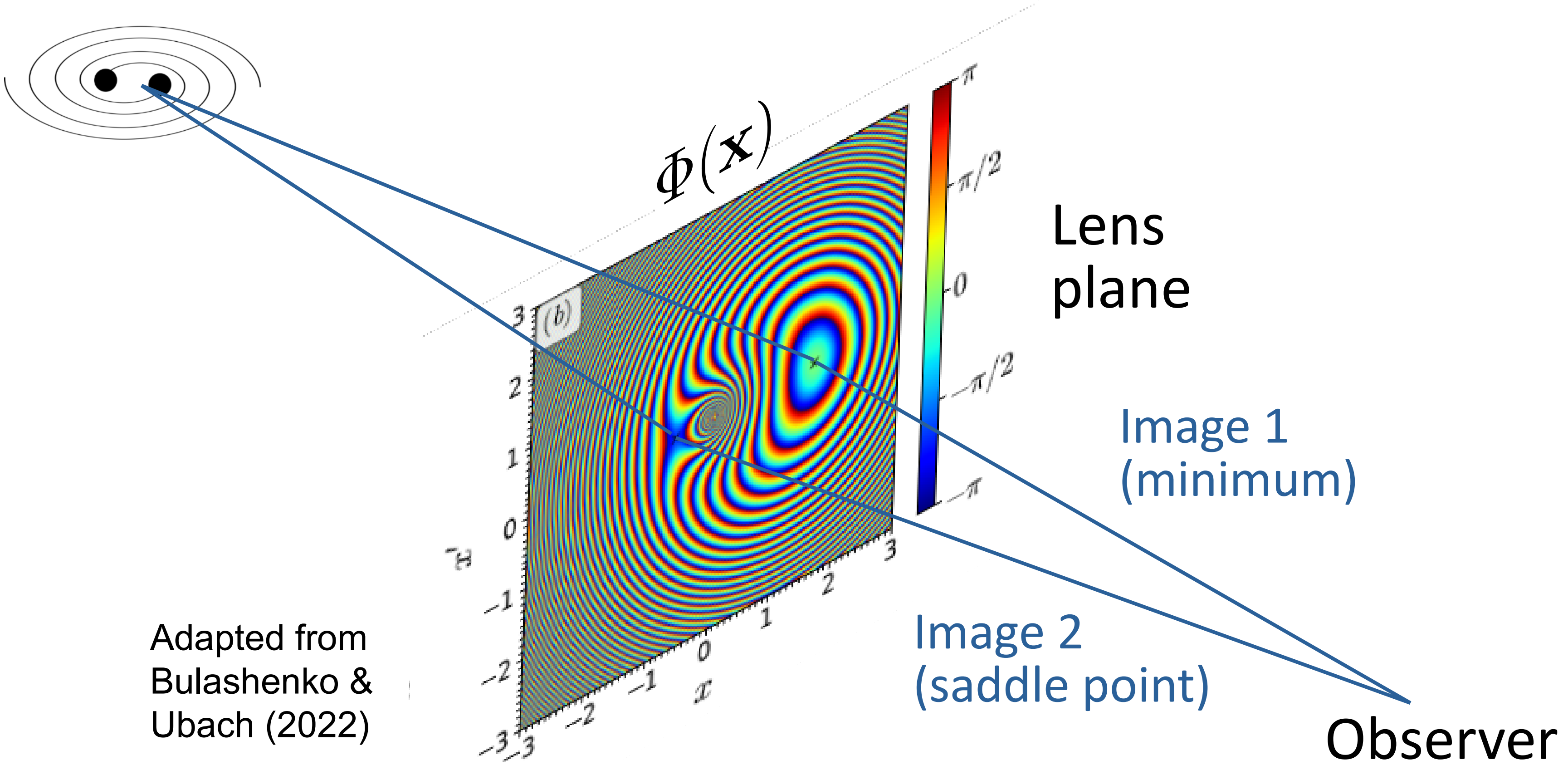
GO approximation valid:

$$\nu \gtrsim \nu_G$$

- $$\nu_G = \frac{1}{4y}$$

Bulashenko and Ubach (2022)

Wave effects

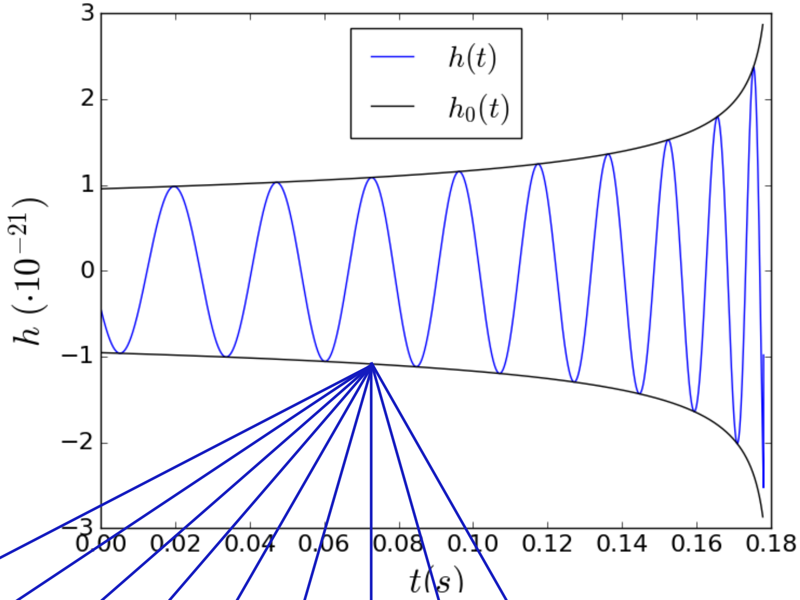


$$\nu = 4$$

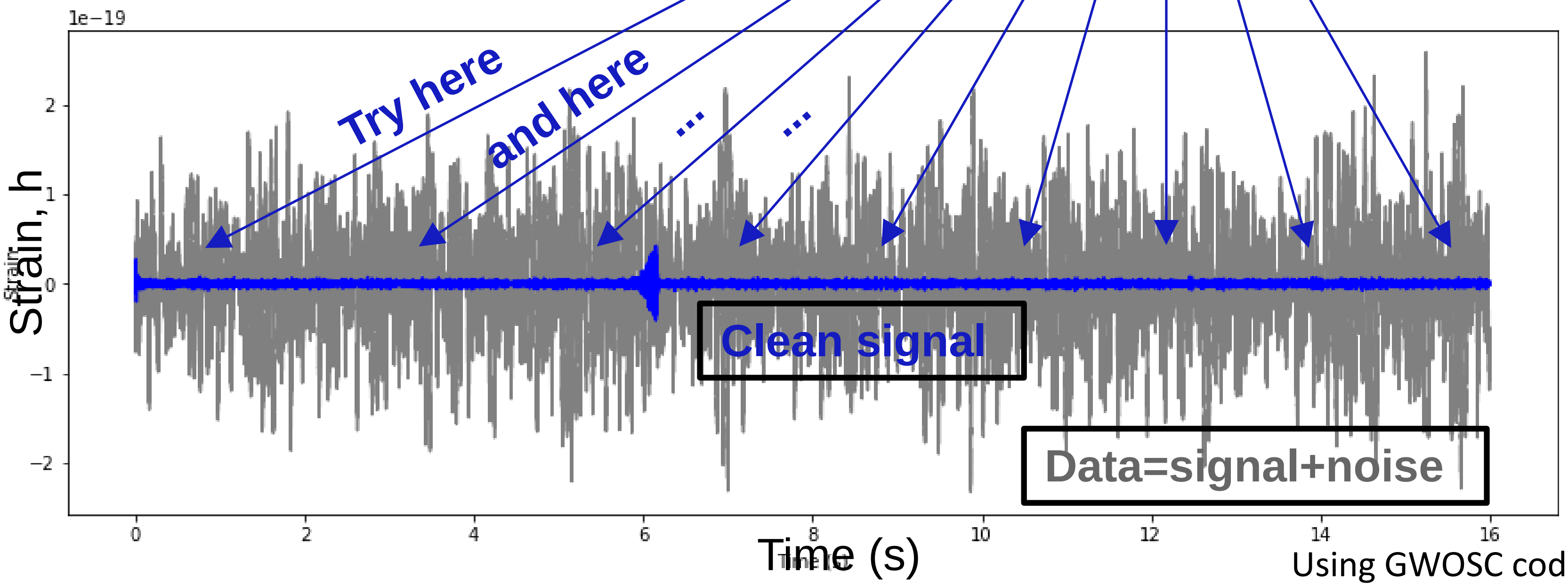
Point mass lens model

Detection: matched filtering

Template:



Recovery of an injected signal
(mock example)



Using GWOSC code