Interfering gravitational waves

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Wave effects on gravitational waves have a universal signature. Low mass lenses are potentially detectable.

When are wave effects important?

Gravitational wavefronts are deflected as they pass through a potential. Most lensing contribution comes from around the stationary points of the time delay function

$$\tau = \frac{1}{2}|\vec{x}-\vec{y}|^2 - \psi,$$

corresponding to the position of the Geometrical Optics (GO) images.

However, **for low** f, M_L **or** y^*, the images are still not completely defined:

- Diffraction appears
- Interference oscillations appear due to interference of the emerging images

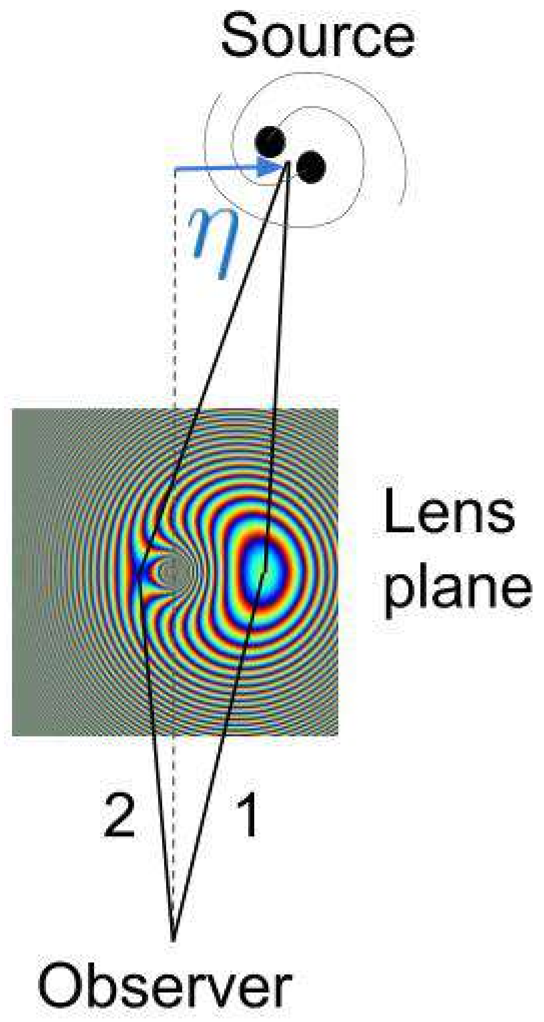


Fig. 1: Interference in the point mass lens model. The phase at the lens plane has two stationary points [1].

What do interference oscillations tell us?

Boundary between Diffraction/Amplification and GO oscillations: $\lambda \lesssim 8R_S y$ *

Depends on y^* **as well**

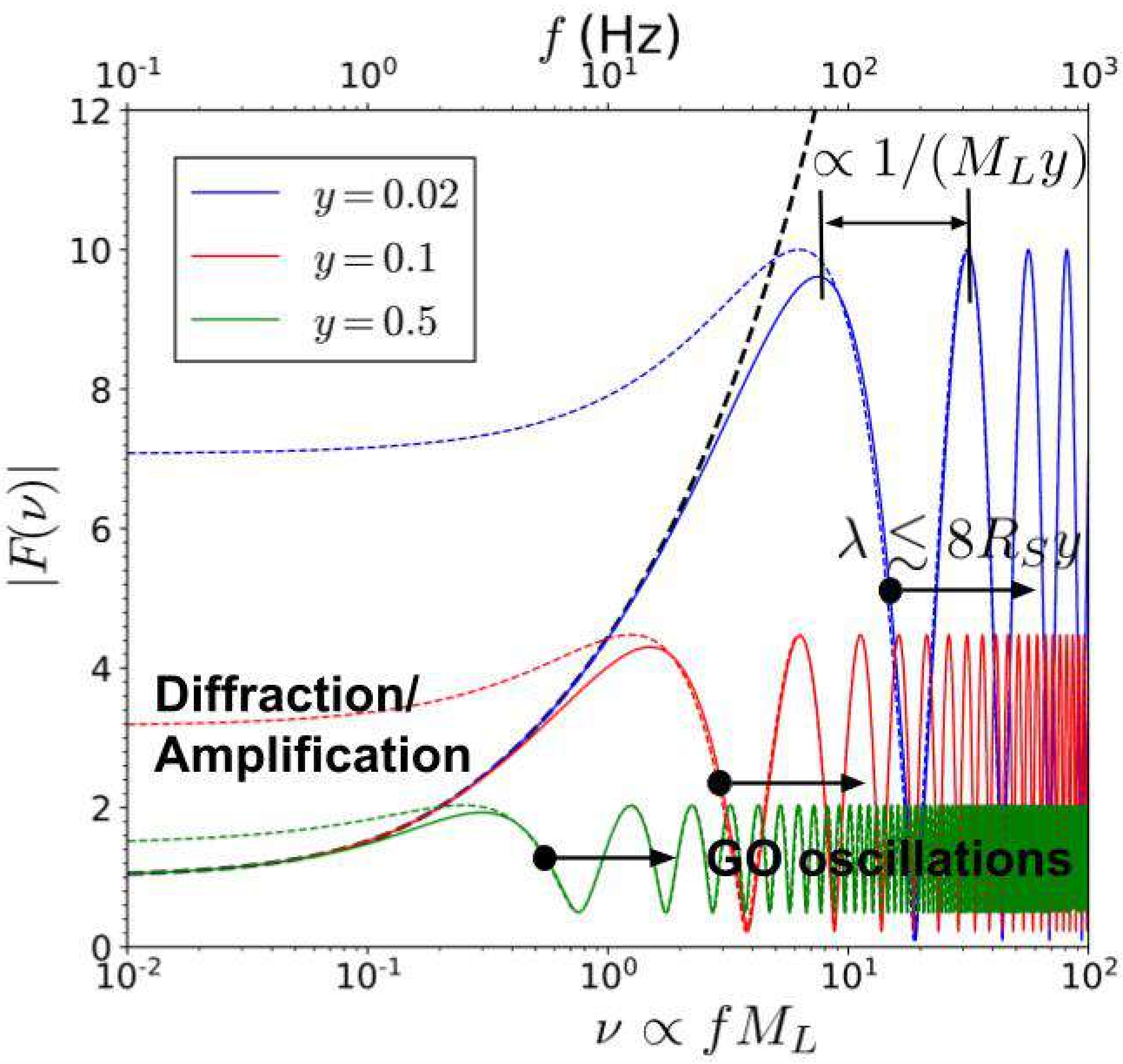


Fig. 2: Interference pattern: transmission factor F for different values of y [1]

$$F = -i\nu \iint e^{2\pi i \nu \tau(\mathbf{x},\mathbf{y})}\, d^2\mathbf{x}$$

Lensing of gravitational waves from compact binaries:

$$\frac{M_L}{M_S} \sim \frac{1}{y} \;^*$$

What do wave effects look like?

Wave effects are seen as oscillations due to interference:

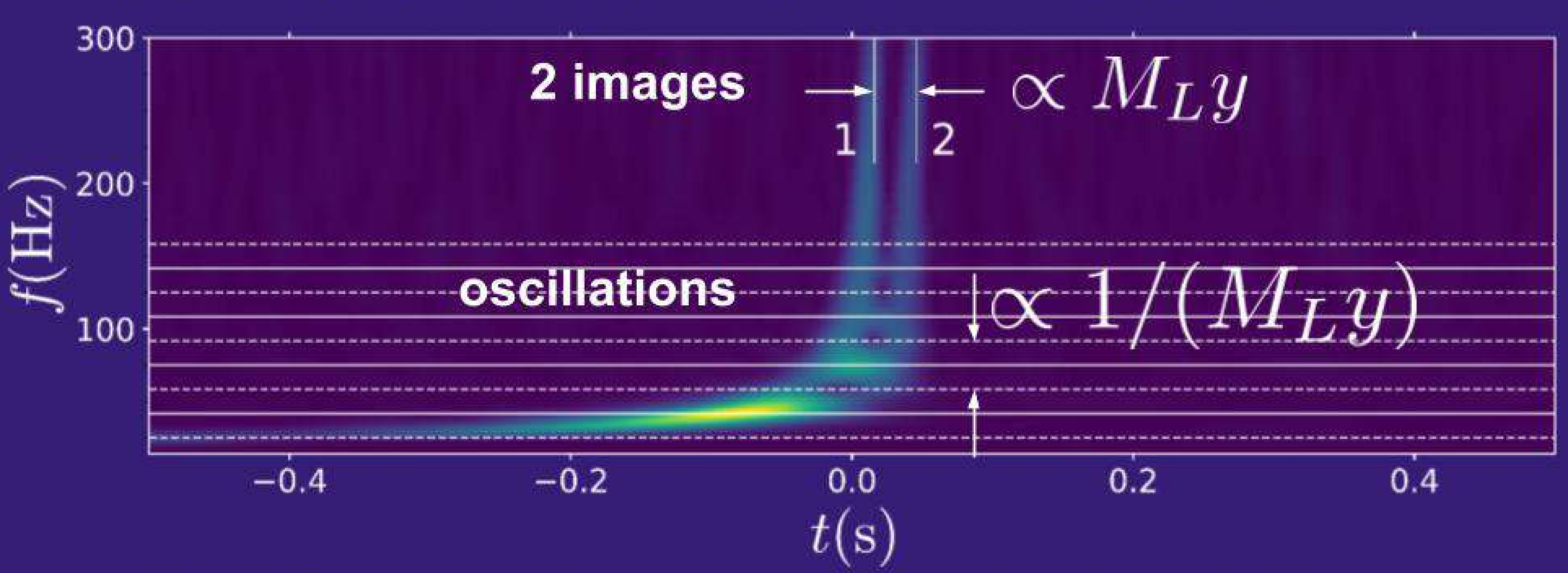


Fig. 3: Spectrogram of a microlensed gravitational wave. Both the oscillations and the images (1,2) appear [2]. $y = 0.25\,, M_L = 3000\,M_\odot$

M_L and y^* can be extracted from the oscillations [1,2]:

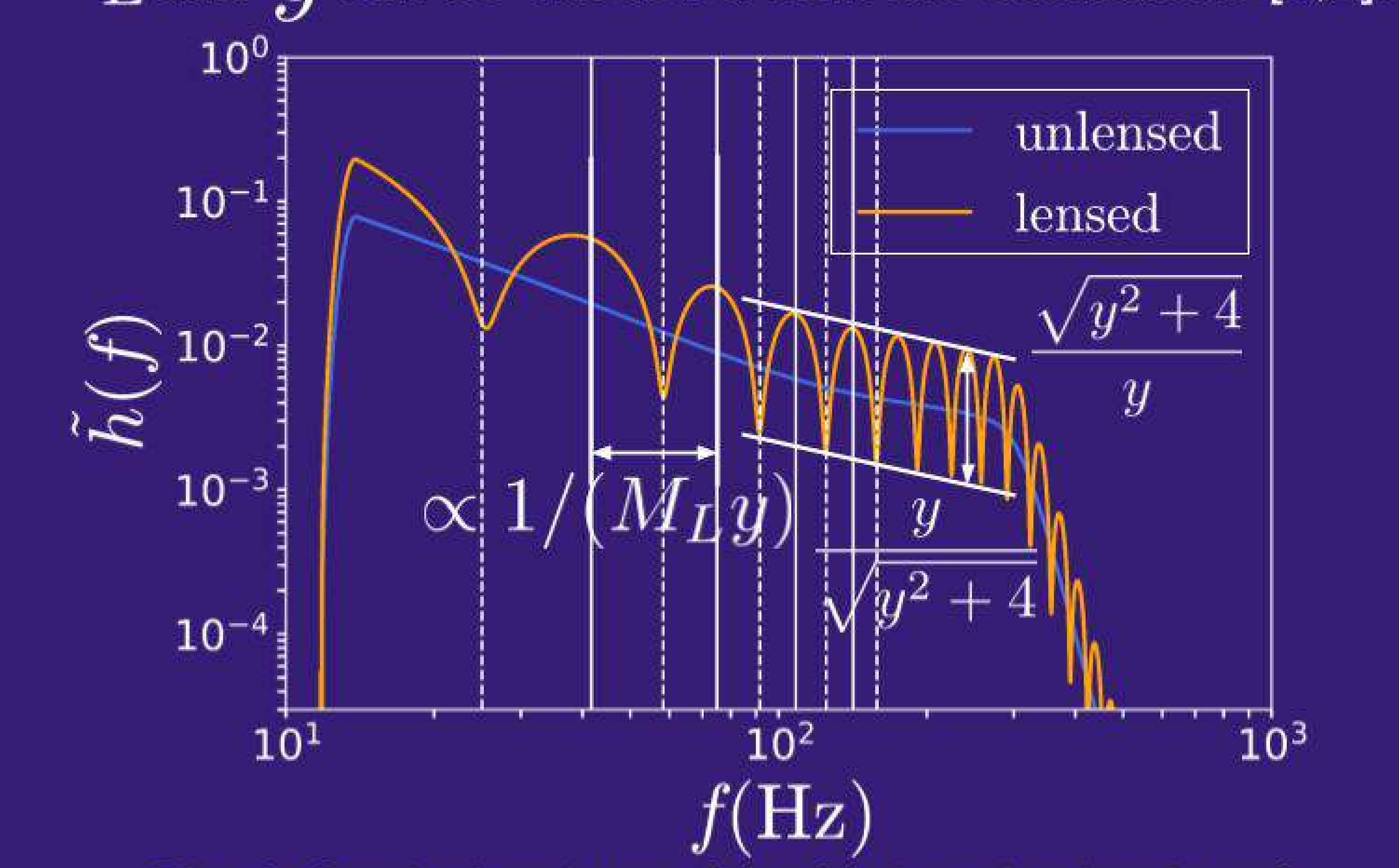
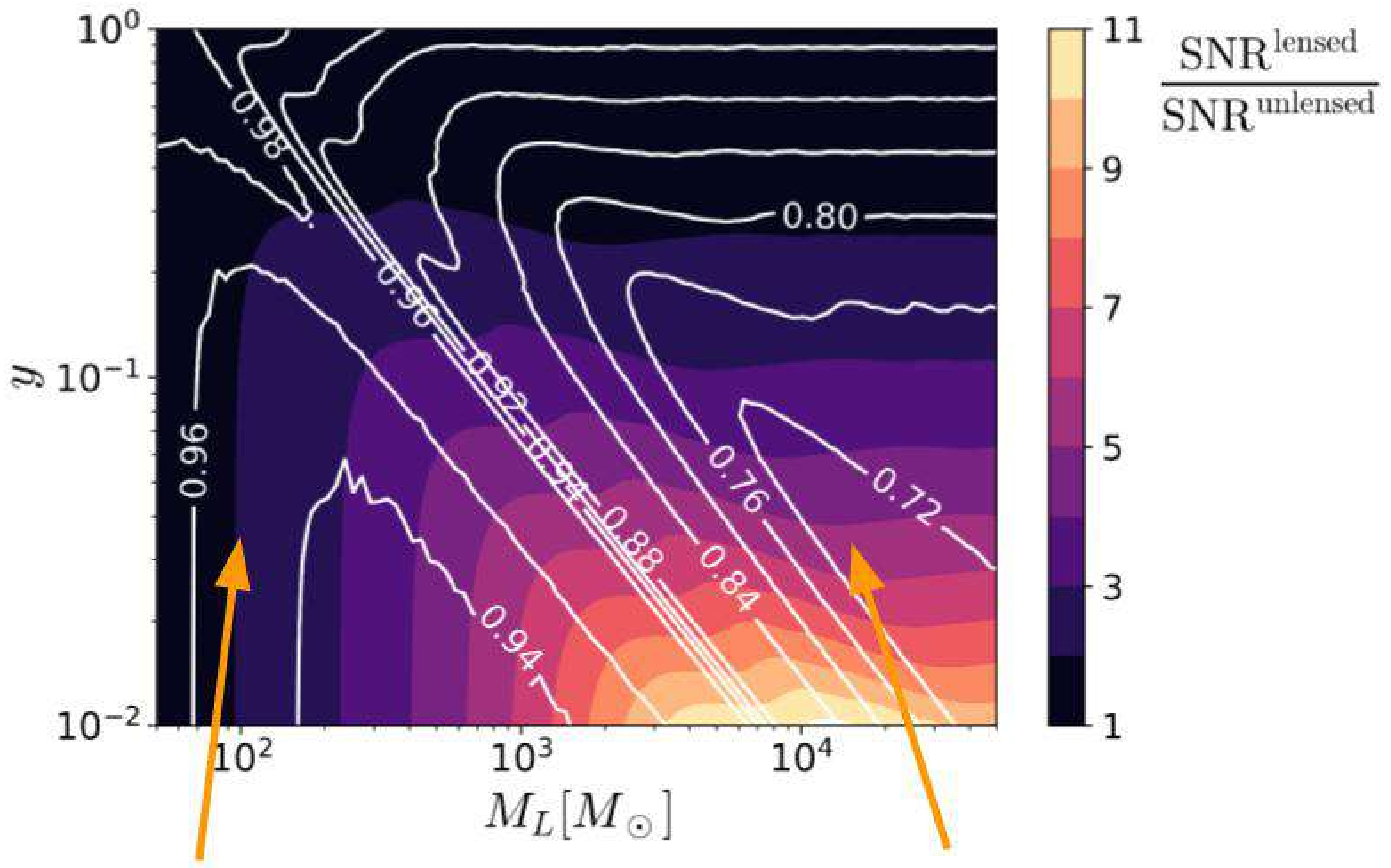


Fig. 4: Gravitational waveform for the microlensing of LIGO-Virgo-KAGRA compact binary mergers [2].

Are wave effects detectable?



Diffraction/Amplification: harder to distinguish

GO oscillations: Potentially **detectable**

Fig. 5: *White contours*: match between the lensed and the unlensed waveforms. *Color density*: increase in Signal-to-Noise Ratio (SNR) [2]

What would we see if there was an electromagnetic counterpart?

$M_L \sim 10^2 - 10^5 M_\odot$ to have wave effects in LIGO-Virgo-KAGRA gravitational waves

Microlensing of light: $\theta_E \sim (0.03-1)\,\mathrm{mas}\sqrt{\frac{d_S}{d_L d_{LS}}\mathrm{Gpc}}$

→ unresolved/ too faint electromagnetic images

*

- M_L mass of the lens
- f gravitational wave frequency $\propto 1/\lambda$
- λ wavelength
- y source position
- $\vec{y} = \vec{\eta}\sqrt{\frac{d_L}{2R_S d_S d_{LS}}}$
- $R_S = \frac{2GM_L}{c^2}$ Schwarzschild radius of the lens
- M_S mass of the source $\propto 1/f$
- θ_E Einstein angle
- $\theta_S = y\,\theta_E$ angular source position

References

[1] Bulashenko & **Ubach**
JCAP (2022)
arXiv:2112.10773

[2] Bondarescu, **Ubach**, Bulashenko, Lundgren
PRD (2023)
arXiv:2211.13604