

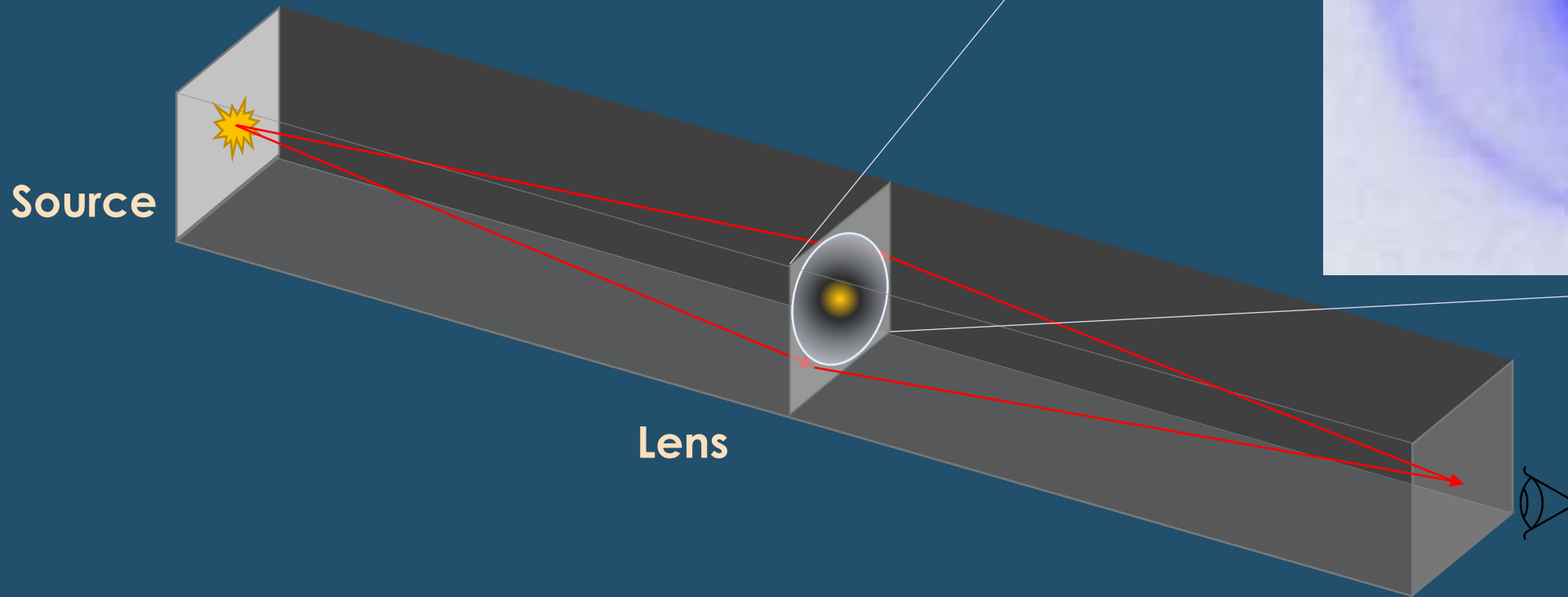
Probing Graviton Mass

Through Strong Lensed Gravitational waves

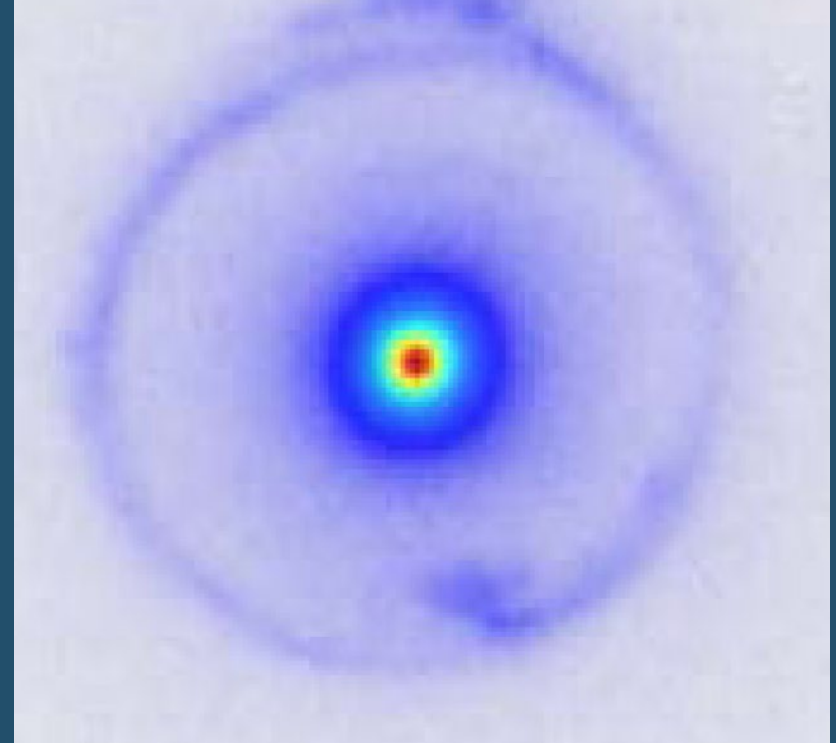
Shuaibo Geng

Collaborators : Sreekanth Harikumar, Marek Biesiada

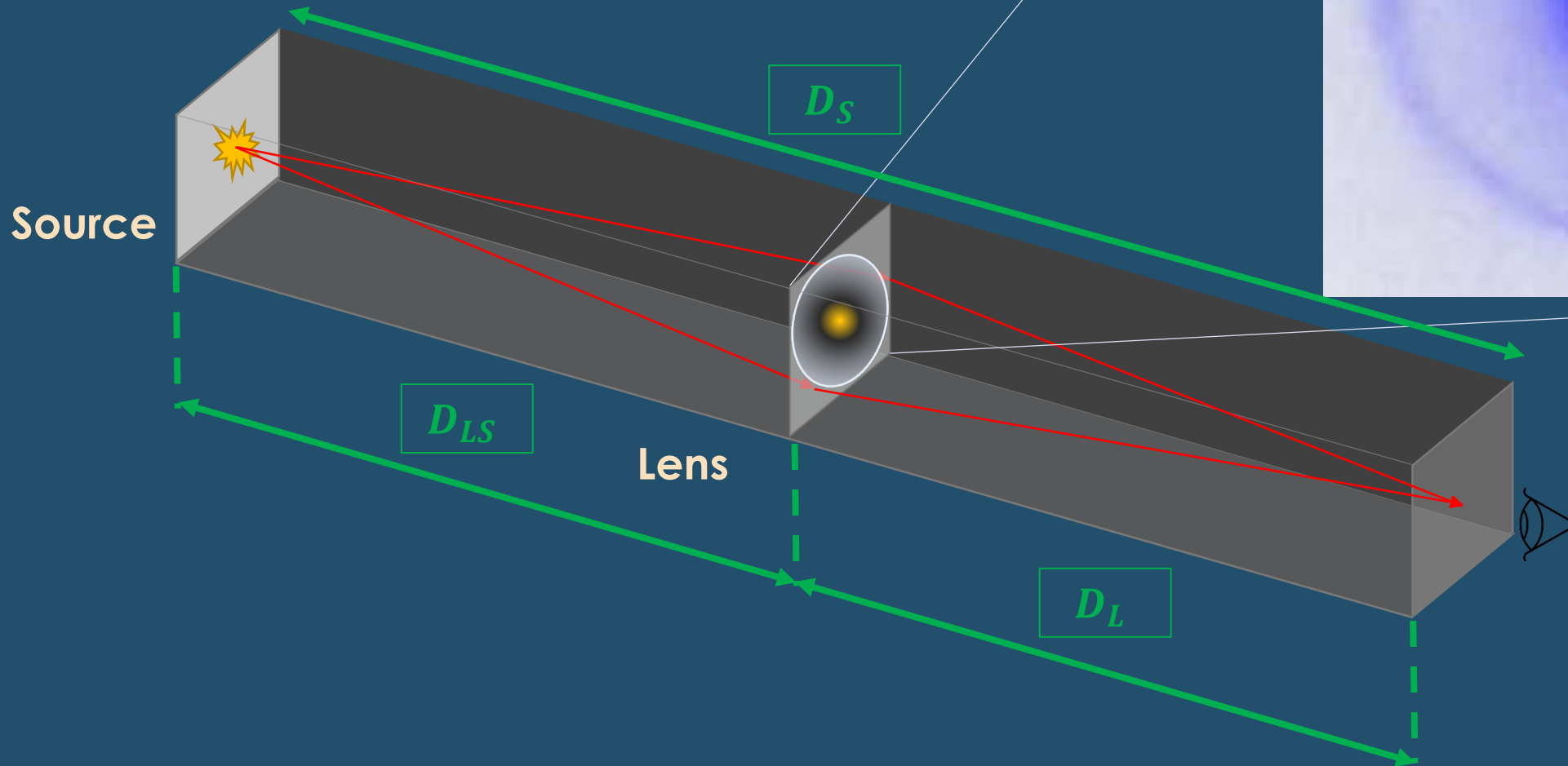
Lensing Structure



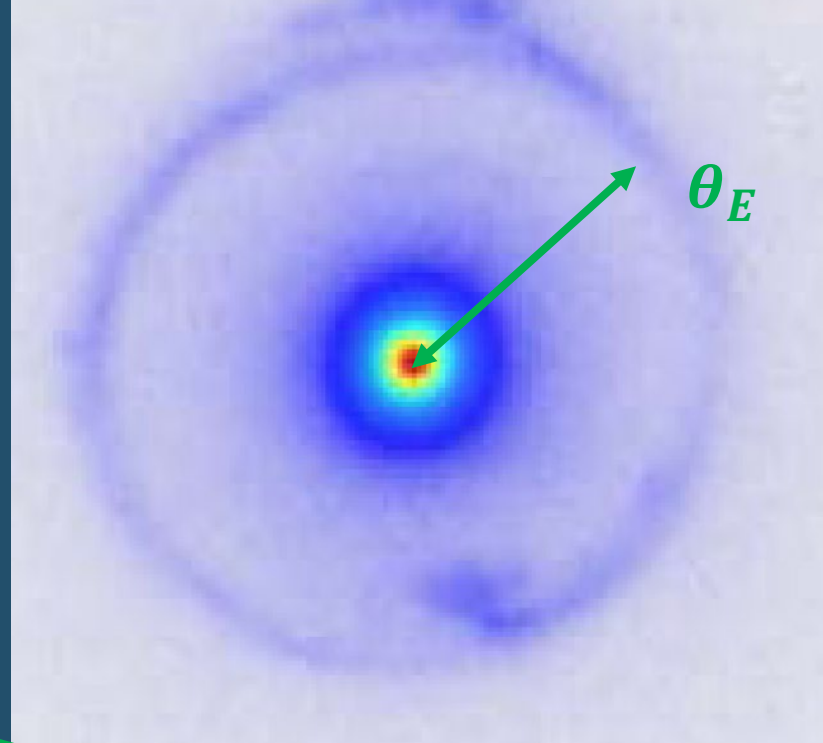
SDSS J1631+1854 (Brownstein et al. 2012)



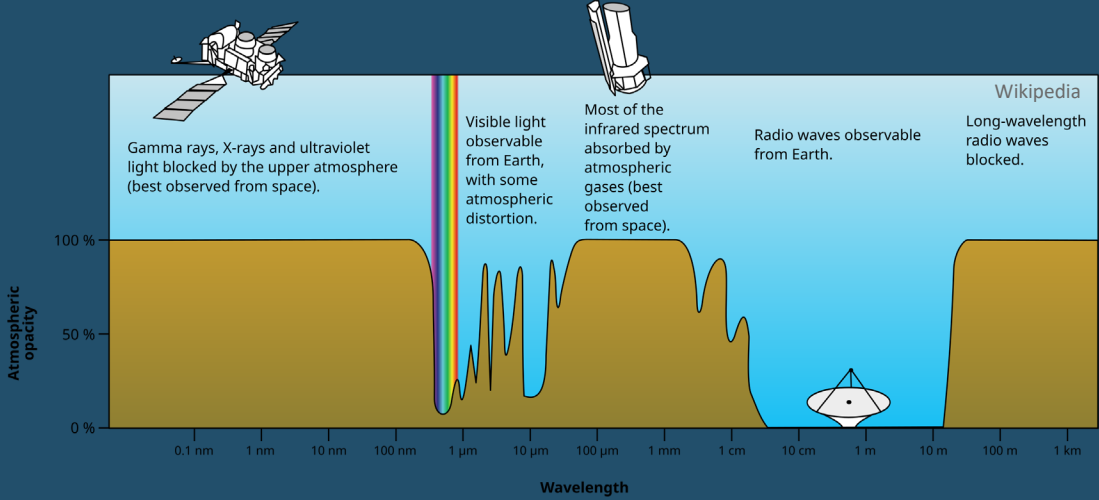
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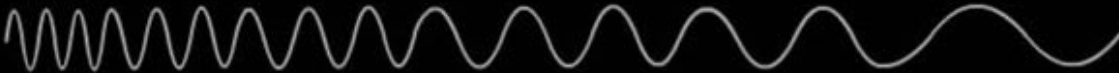
EM+GW spectrum



Space.fm

Energy Increasing

Wavelength Increasing



0.0001 nm 0.01 nm 10 nm 1000 nm 0.01 cm 1 cm 1 m 100 m

Gamma Rays X-Rays Ultra-violet Infrared Radio Waves Radar TV FM AM

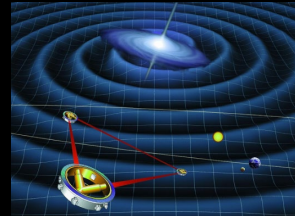
10⁸ m 10¹² m 10¹⁶ m
100 Hz 10⁻² Hz 10⁻⁶ Hz 10⁻¹⁰ Hz



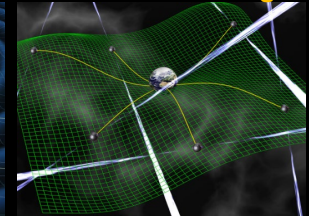
Terrestrial Interferometers



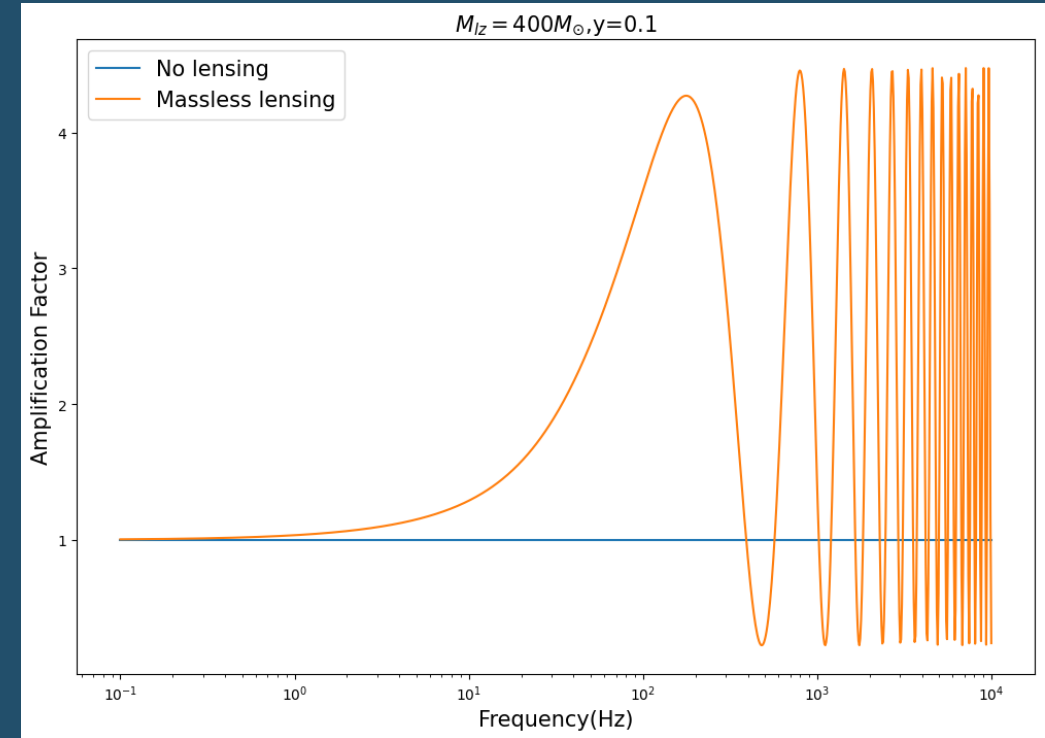
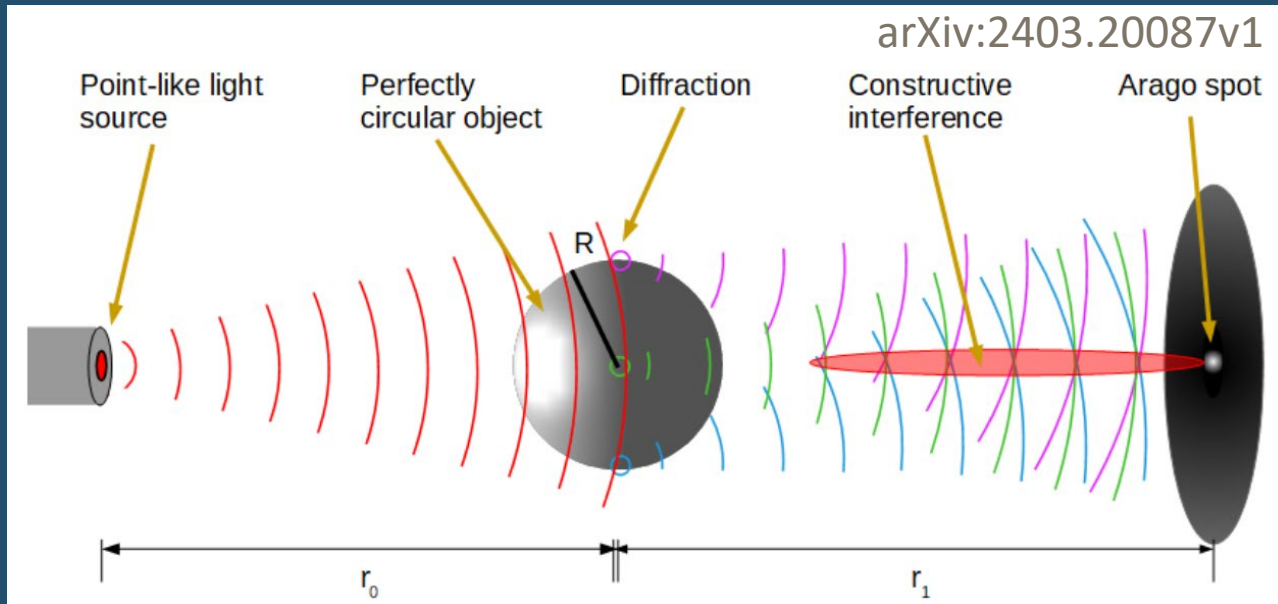
Space-based Interferometers



Radio pulsar timing arrays



Wave optics effect



**Amplification
Factor**

$$F(\omega) = \frac{h^L}{h}$$

$$= \frac{w}{2\pi i} \iint_{\Sigma} e^{i\omega T(\vec{x}, \vec{y})} dx^2$$

$$T(\vec{x}, \vec{y}) = \left[\frac{(\vec{x} - \vec{y})^2}{2} - \psi(\vec{x}) + \phi_m(\vec{y}) \right],$$

$$\omega = 2\pi f \frac{1 + z_l}{c} \frac{D_L D_S}{D_{LS}} \theta_{\text{Ein}}^2$$

Probe graviton mass

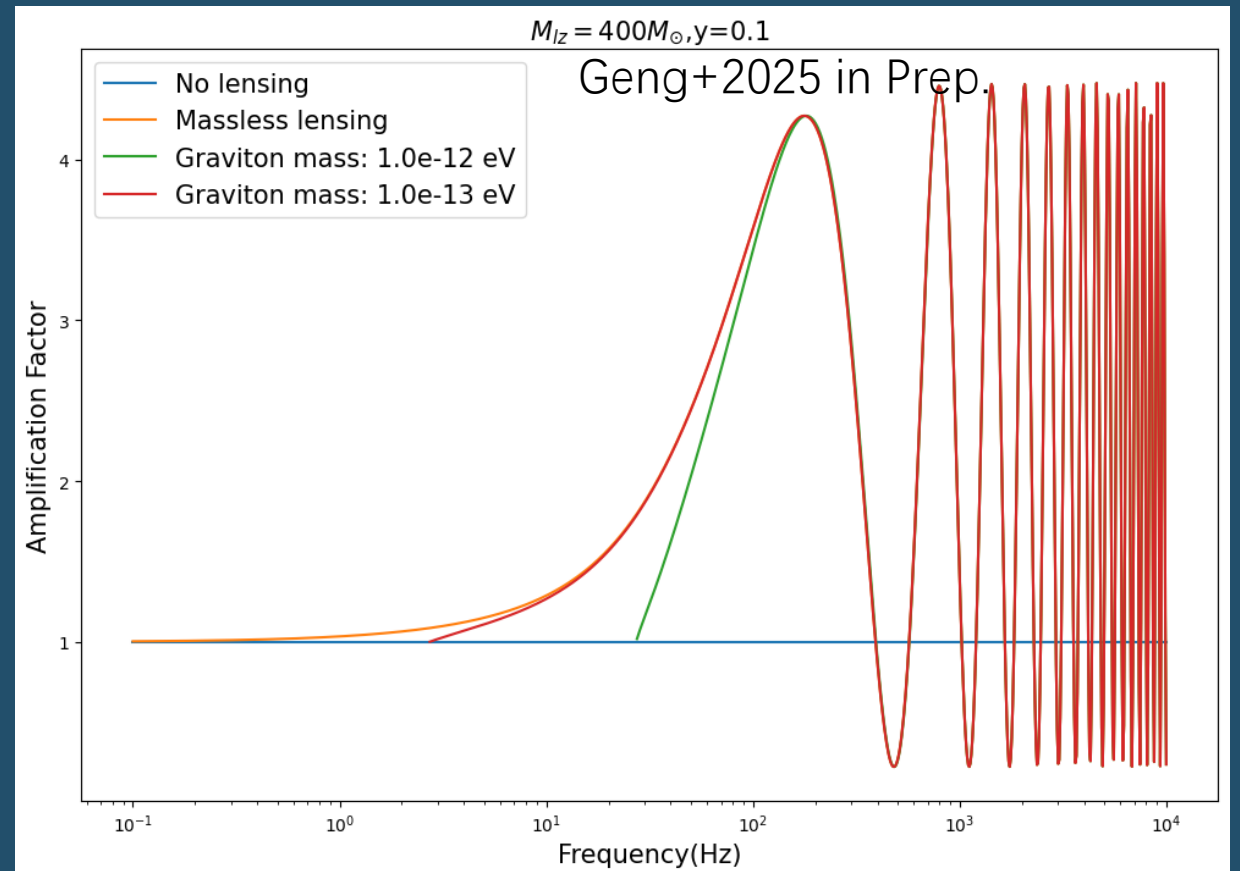
Do gravitational waves propagate at the speed of light?
What if the graviton has mass?

$$m^2 c^4 = \hbar^2 \omega^2 - \hbar^2 k^2 c^2$$
$$k^2 = \frac{\omega^2}{c^2} - \frac{m^2 c^2}{\hbar^2} = \left(1 - \frac{m^2 c^4}{\hbar^2 \omega^2}\right) \frac{\omega^2}{c^2}$$

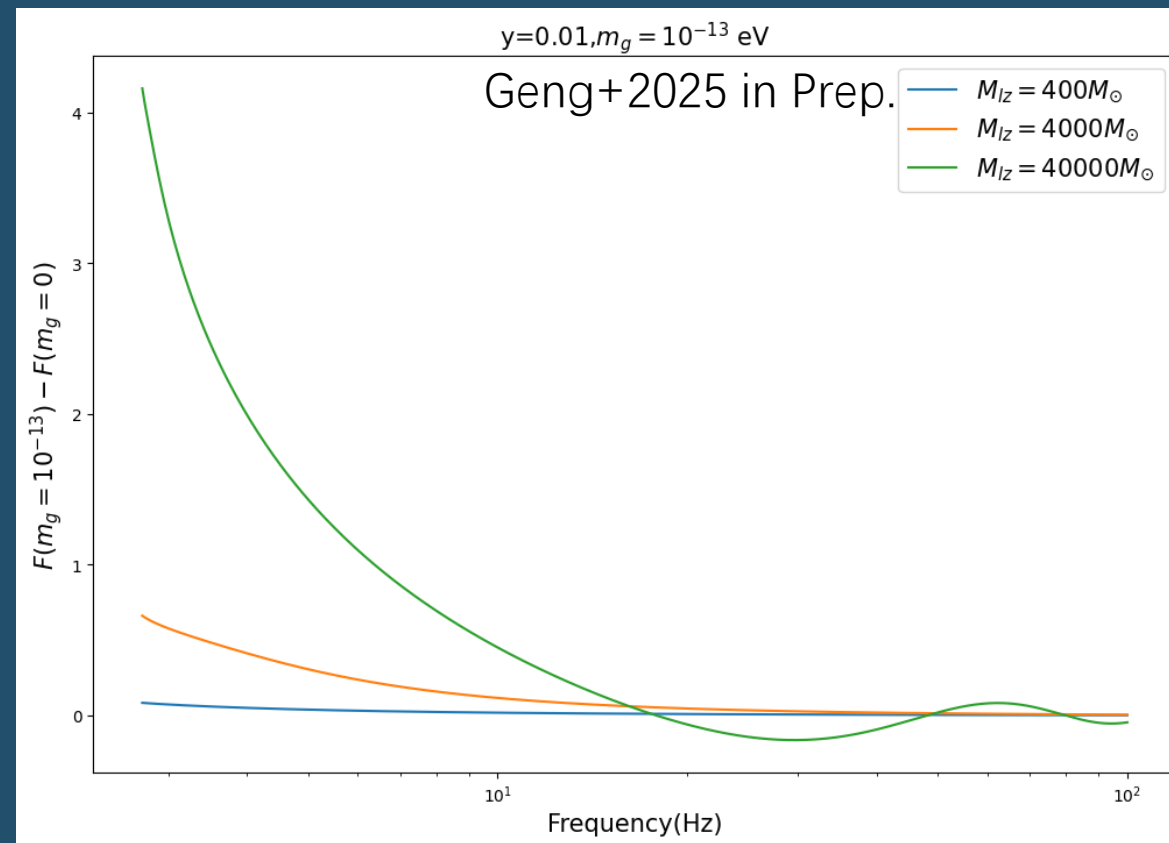
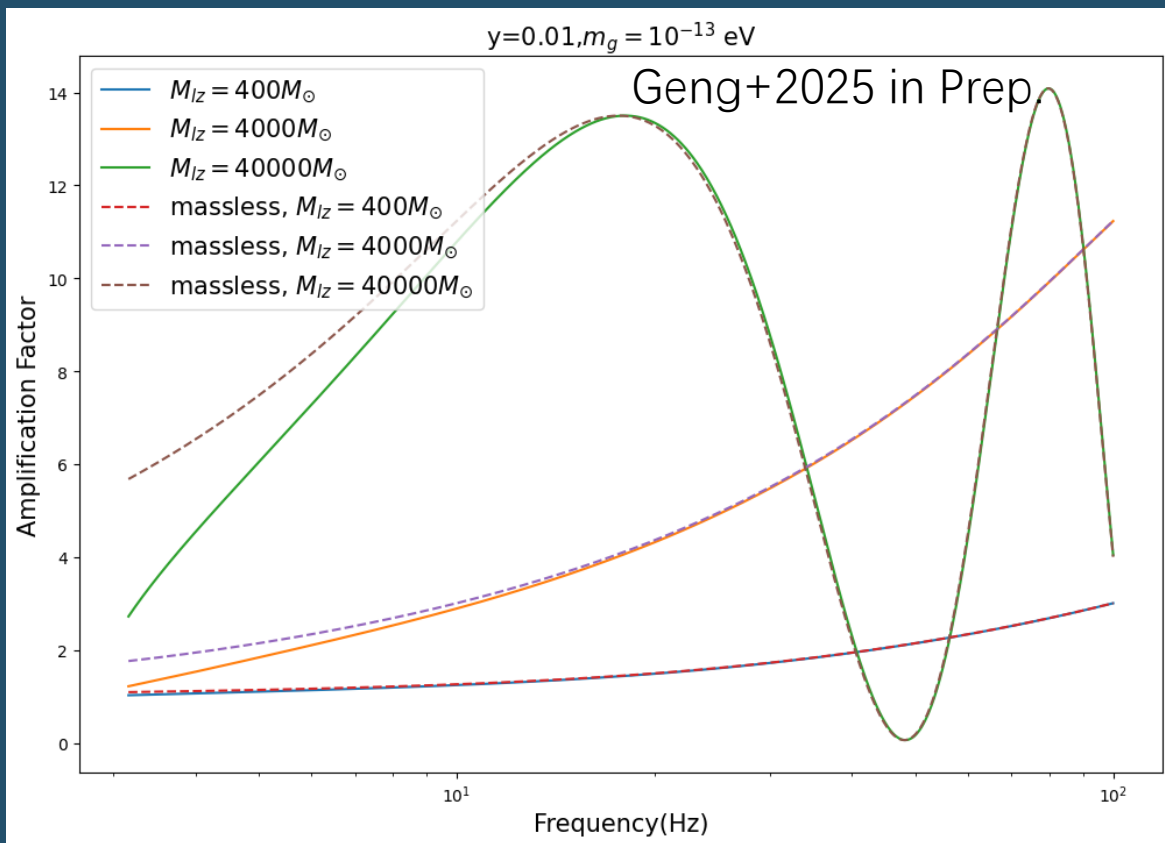
$$|k| \simeq \left(1 - \frac{m^2 c^4}{2\hbar^2 \omega^2}\right) \frac{\omega}{c} = \frac{\omega}{c} - \frac{m^2 c^4}{2c\hbar^2 \omega}$$

$$g(\omega, \mathbf{r}) = h(\omega, \mathbf{r}) e^{-iar/\omega}$$

$$a = \frac{m_g^2 c^4}{2\hbar^2 (1+z)}$$

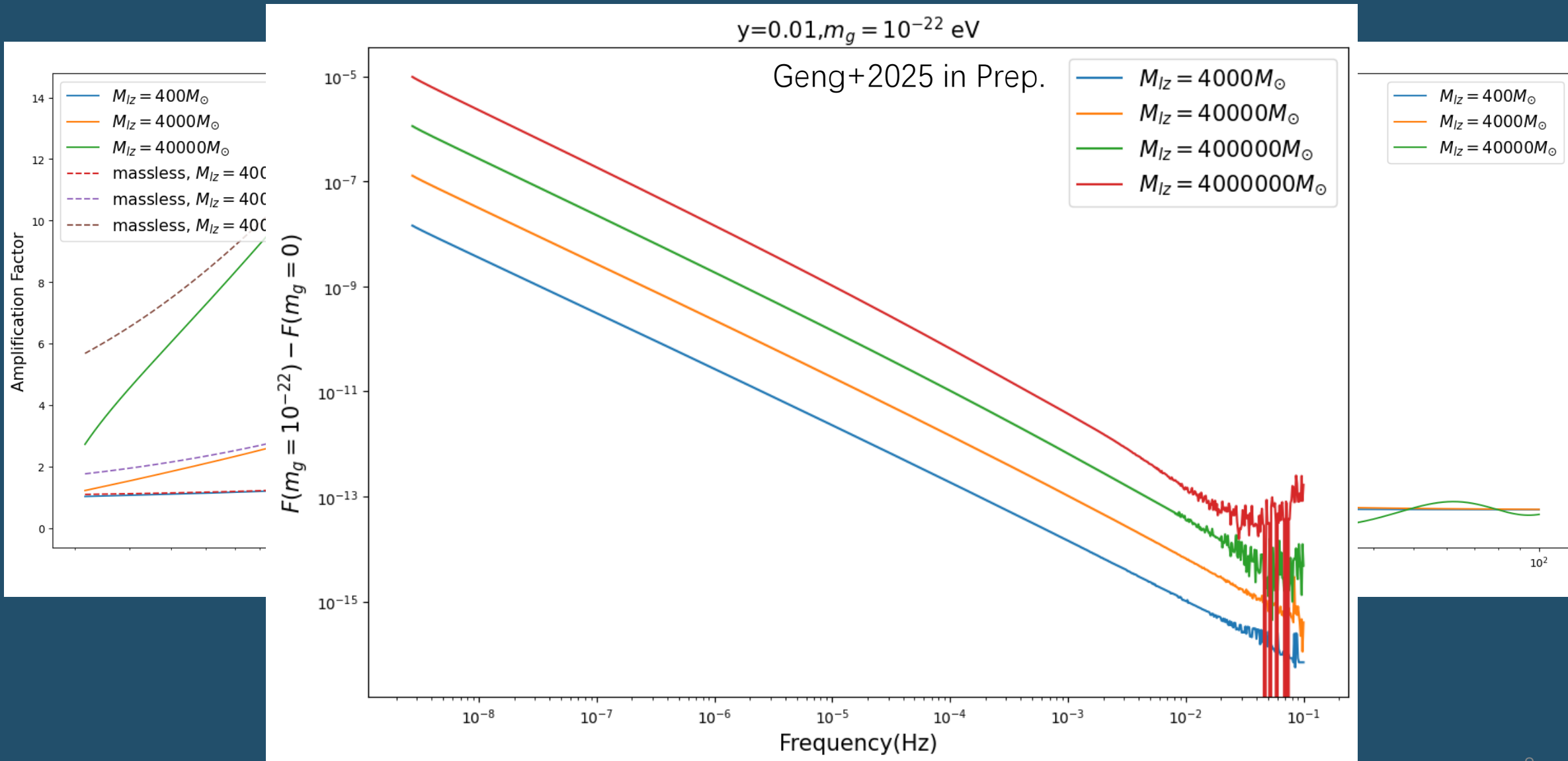


Lensed massive GW



$$M_{l_z} = (1 + z)M_{lens}$$

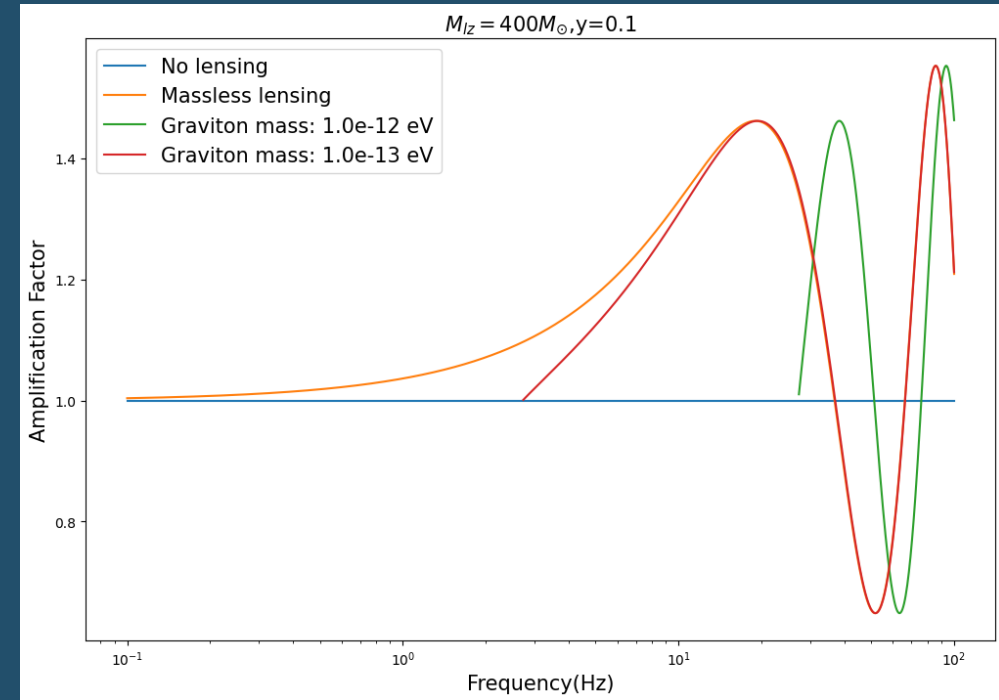
Lensed massive GW



Take-home message

Take-home message

- **Massive lensing:**
Oscillation + Strain difference
- **Why lensing?**
No lensing, no strain difference
- **How to detect lower mass graviton?**
Lower frequency source
More massive lens
More sensitive detector



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