

Probing Fuzzy dark matter with lensed Gravitational waves

Shashwat Singh

(Shashwat.SINGH@obspm.fr)



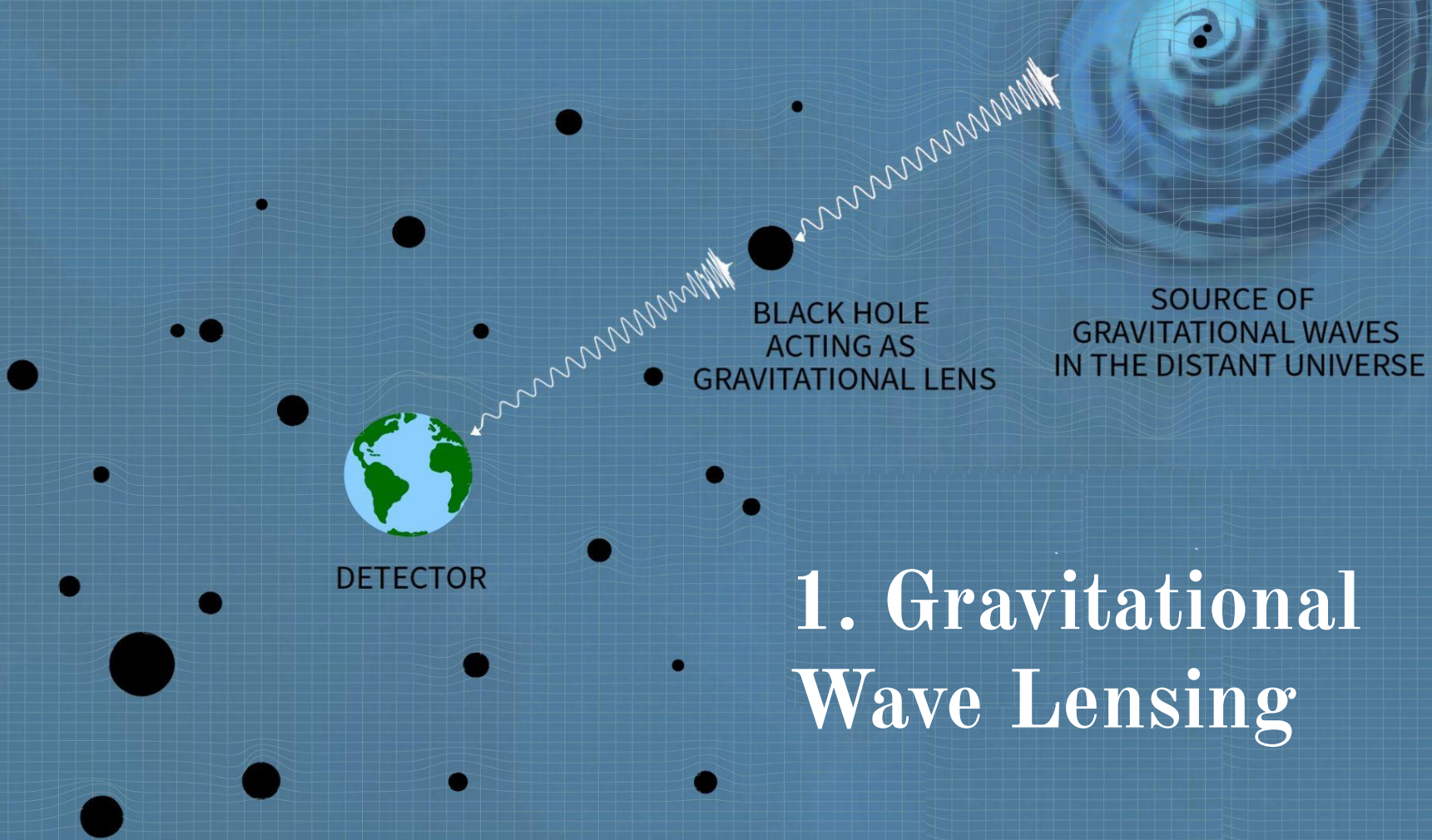
l'Observatoire de Paris – PSL

Collaborators : G. Brando, G. Tambalo, M. Zumalacárregui

Cosmology from Home 2023

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1. Gravitational Wave Lensing
 - New cosmic messenger
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4. Conclusion



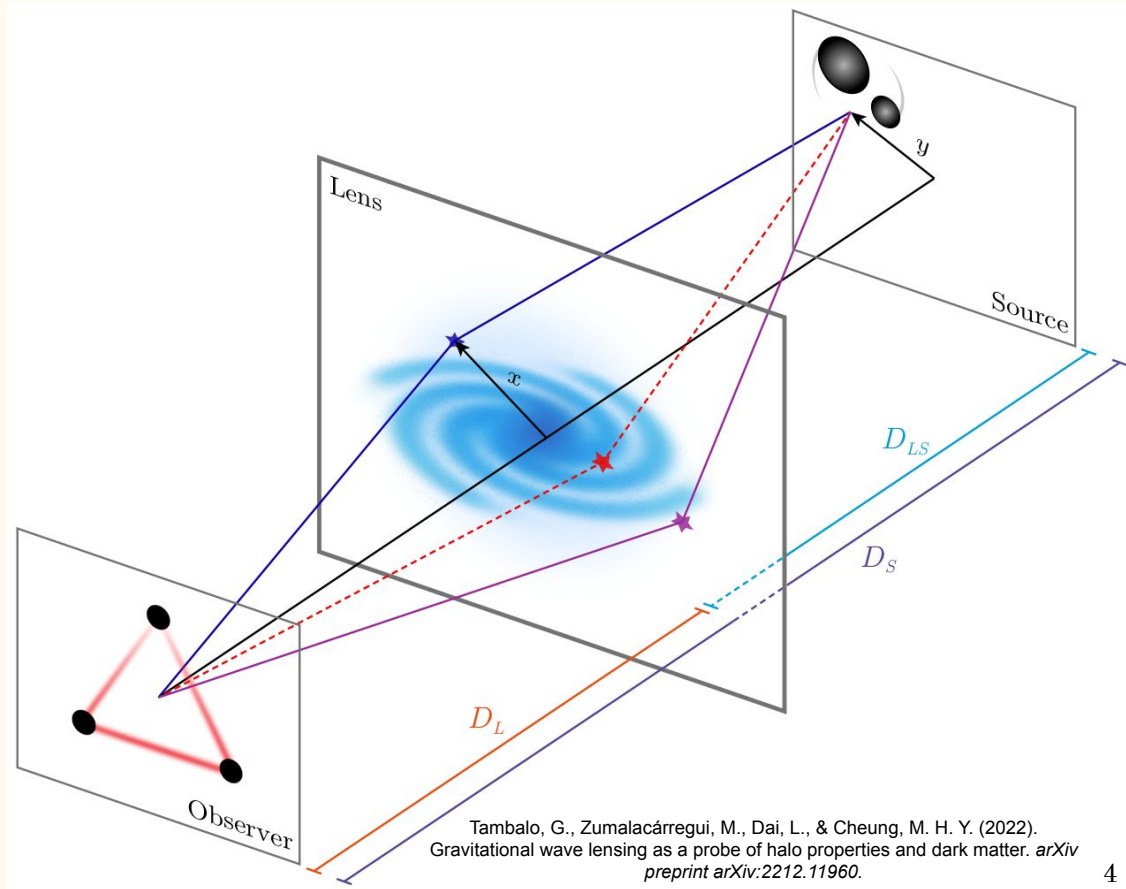
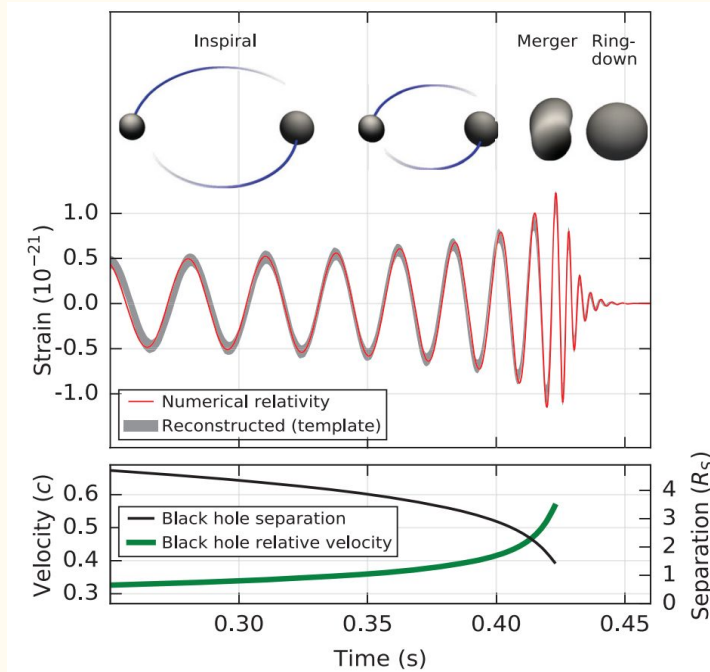
SOURCE OF
GRAVITATIONAL WAVES
IN THE DISTANT UNIVERSE

BLACK HOLE
ACTING AS
GRAVITATIONAL LENS

DETECTOR

1. Gravitational Wave Lensing

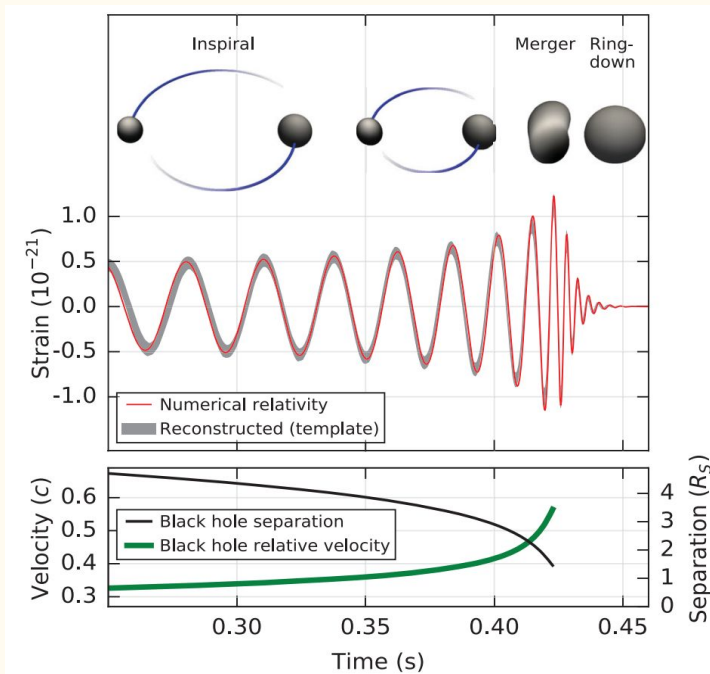
Gravitational Wave Lensing



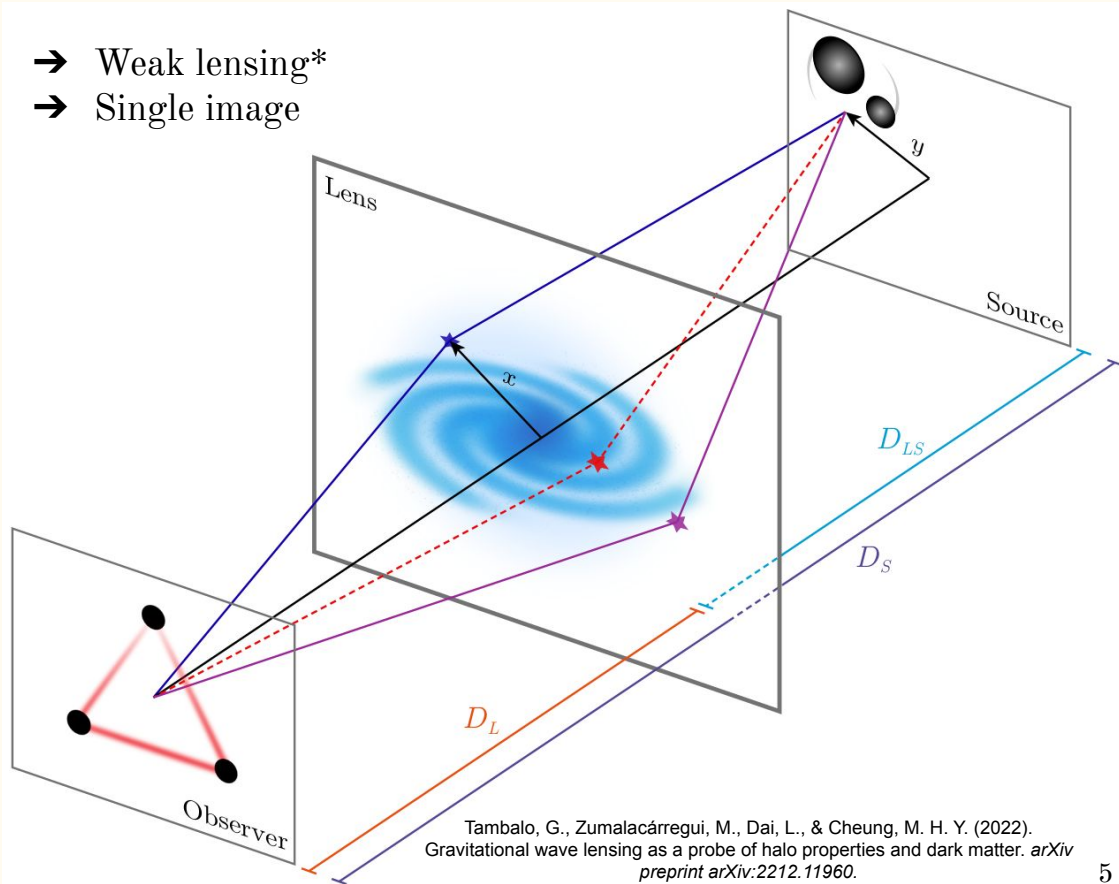
Abbott, B. P., Abbott, R., Abbott, T. D., Abernathy, M. R., Acernese, F., Ackley, K., ... & Cavaliere, R. (2016). Observation of gravitational waves from a binary black hole merger. *Physical review letters*, 116(6), 061102.

Tambalo, G., Zumalacárregui, M., Dai, L., & Cheung, M. H. Y. (2022). Gravitational wave lensing as a probe of halo properties and dark matter. *arXiv preprint arXiv:2212.11960*.

Gravitational Wave Lensing



- Weak lensing*
- Single image



Abbott, B. P., Abbott, R., Abbott, T. D., Abernathy, M. R., Acernese, F., Ackley, K., ... & Cavalieri, R. (2016). Observation of gravitational waves from a binary black hole merger. *Physical review letters*, 116(6), 061102.

* Çalıřkan, M., Ji, L., Cotesta, R., Berti, E., Kamionkowski, M., & Marsat, S. (2023). Observability of lensing of gravitational waves from massive black hole binaries with LISA. *Physical Review D*, 107(4), 043029.

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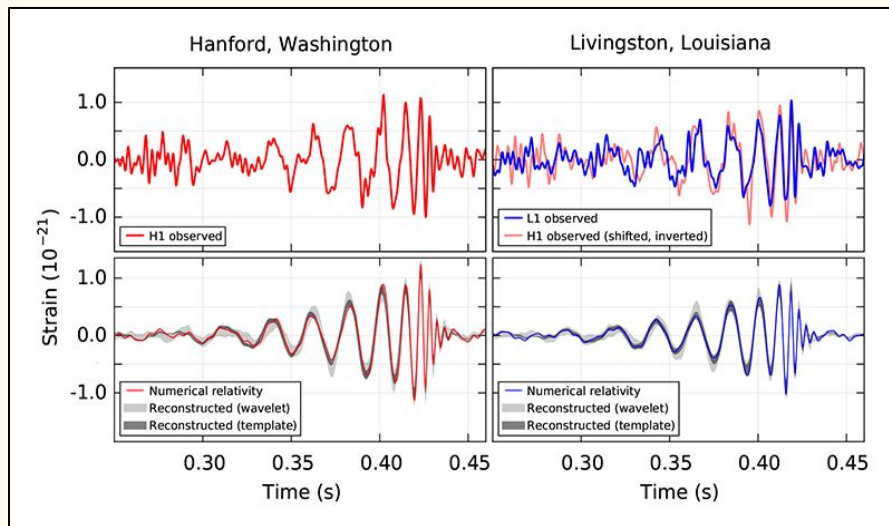
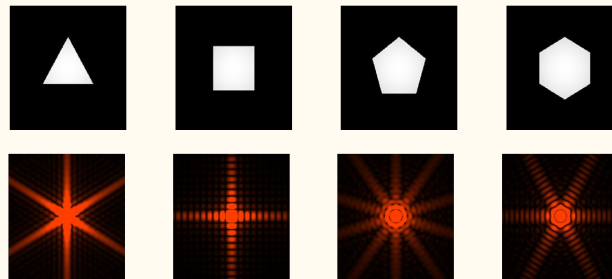
Gravitational Wave Lensing – New cosmic messenger

Longer
wavelength

Coherence
of waves

Weakly
coupled

accuracy of
modeling



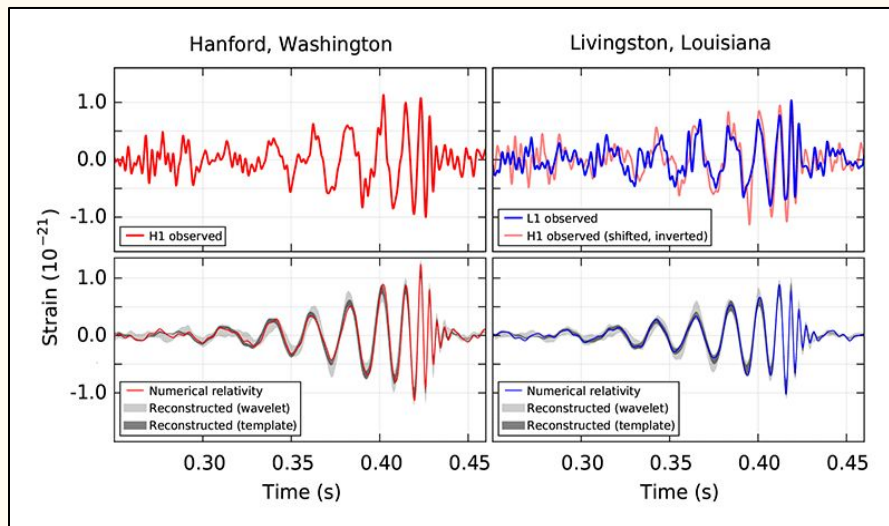
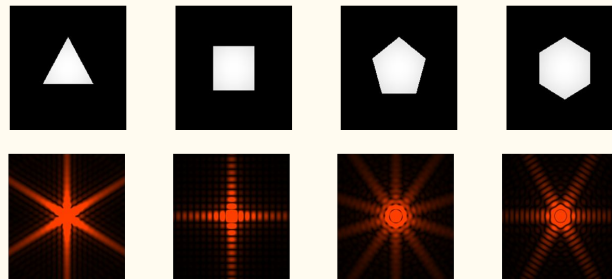
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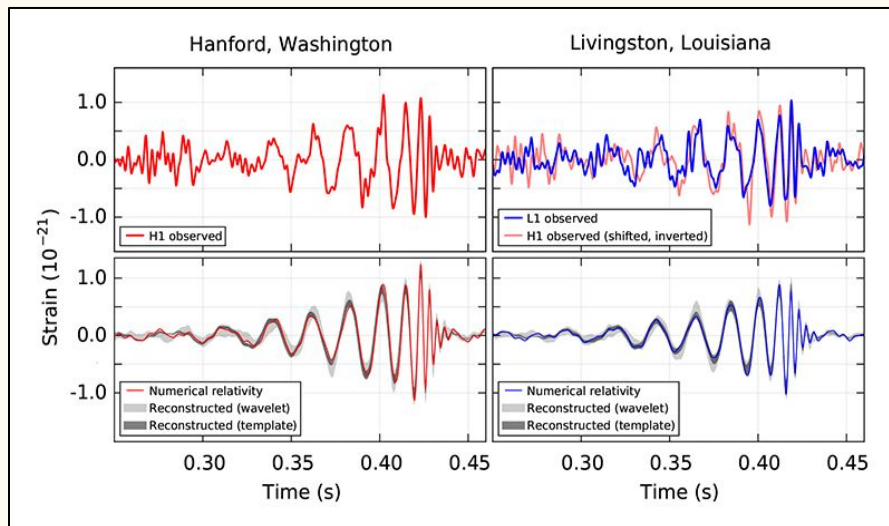
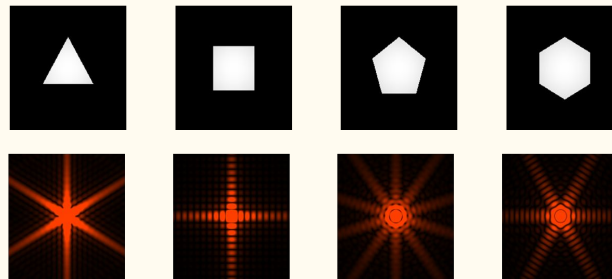
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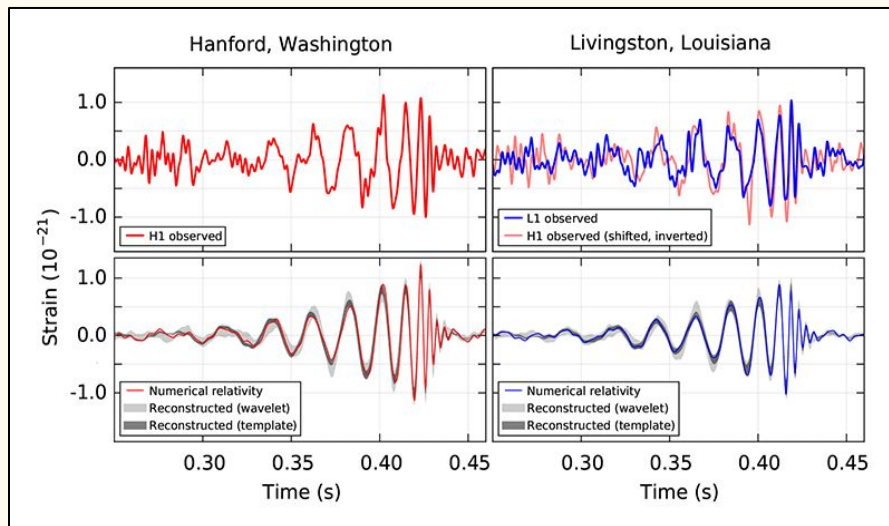
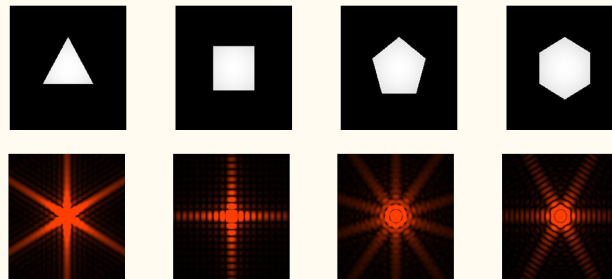
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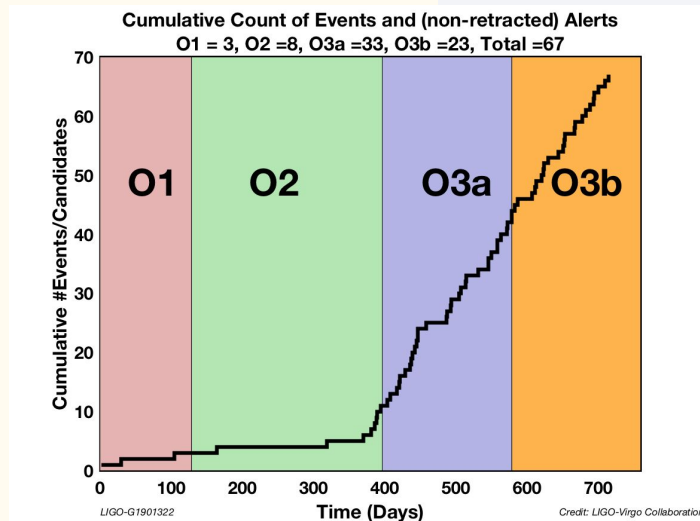
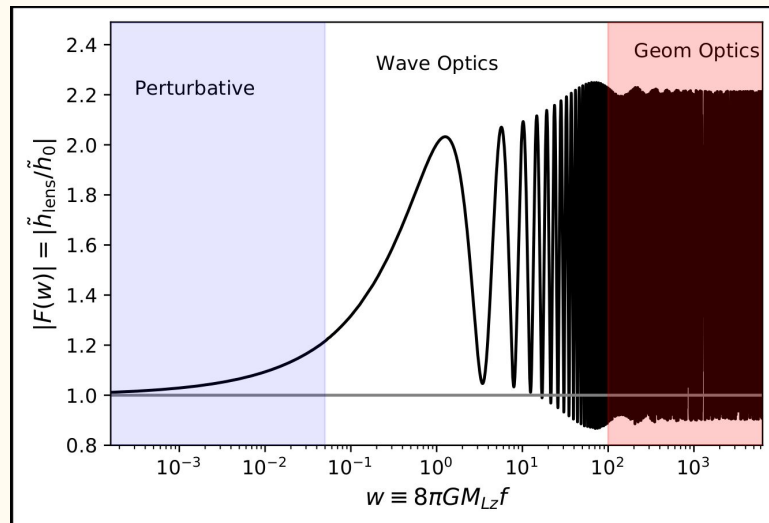


Image: <https://www.ligo.caltech.edu/news/ligo20200326>

Oscillations in amplification factor

$$F(\omega) \equiv \frac{\tilde{h}}{\tilde{h}_0}$$

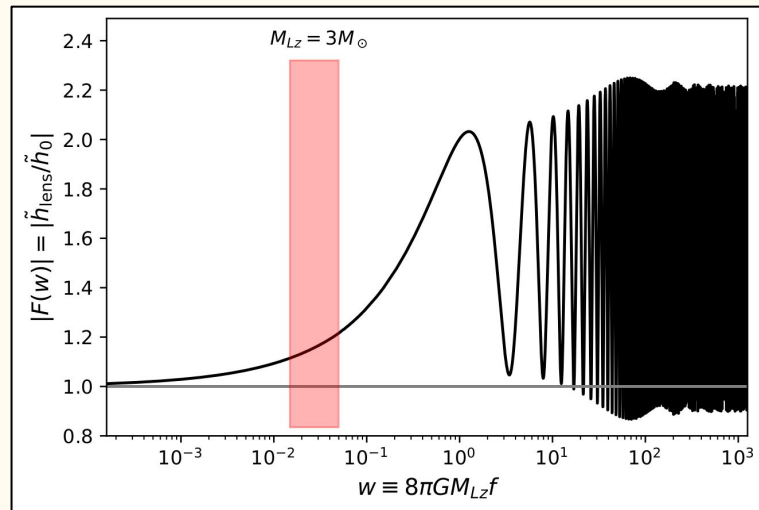
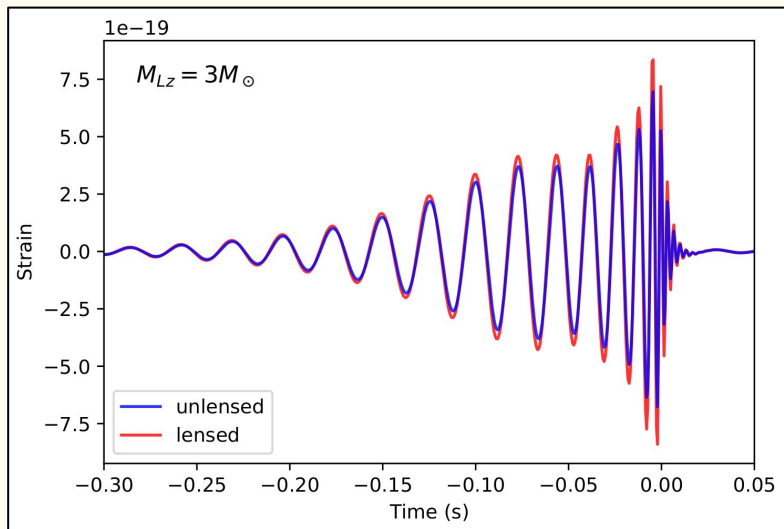
$$\omega \equiv 8\pi GM_{Lz}f \sim \left(\frac{M_{Lz}}{10^4 M_\odot}\right) \left(\frac{f}{\text{Hz}}\right)$$



Oscillations in amplification factor

$$F(\omega) \equiv \frac{\tilde{h}}{\tilde{h}_0}$$

$$\omega \equiv 8\pi GM_{Lz}f \sim \left(\frac{M_{Lz}}{10^4 M_\odot}\right) \left(\frac{f}{\text{Hz}}\right)$$



Perturbative regime

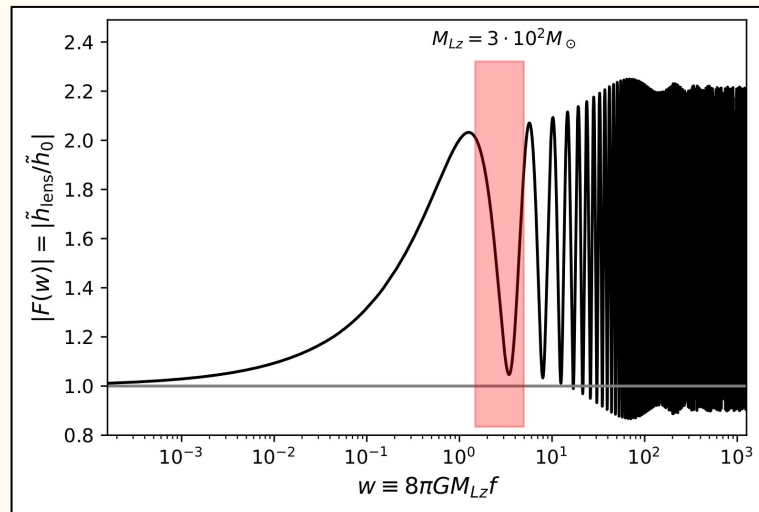
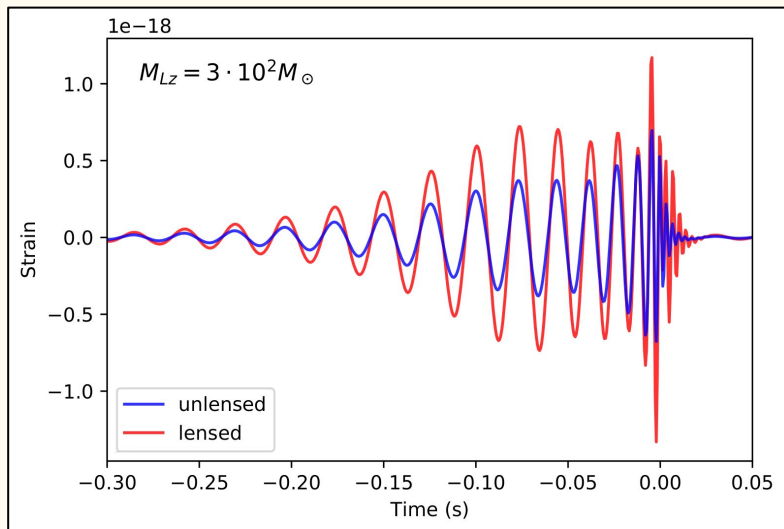
$$\omega \ll 1$$

$$F(\omega) \sim 1 + A\omega^\alpha$$

Oscillations in amplification factor

$$F(\omega) \equiv \frac{\tilde{h}}{\tilde{h}_0}$$

$$\omega \equiv 8\pi GM_{Lz}f \sim \left(\frac{M_{Lz}}{10^4 M_\odot}\right) \left(\frac{f}{\text{Hz}}\right)$$



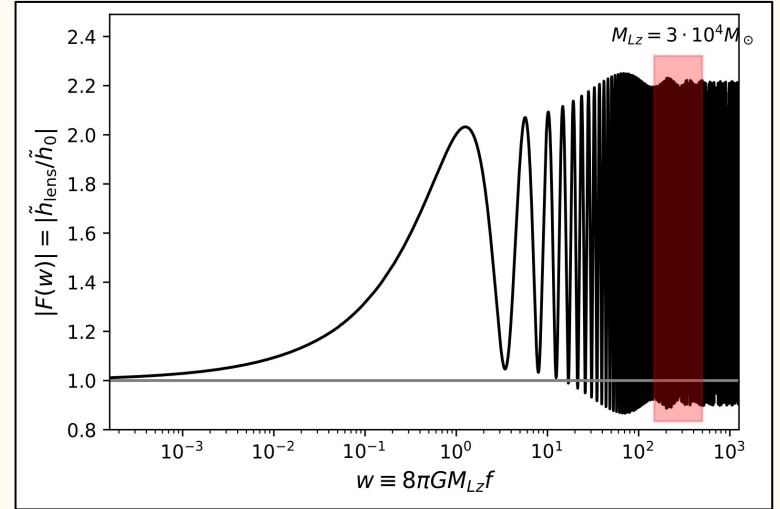
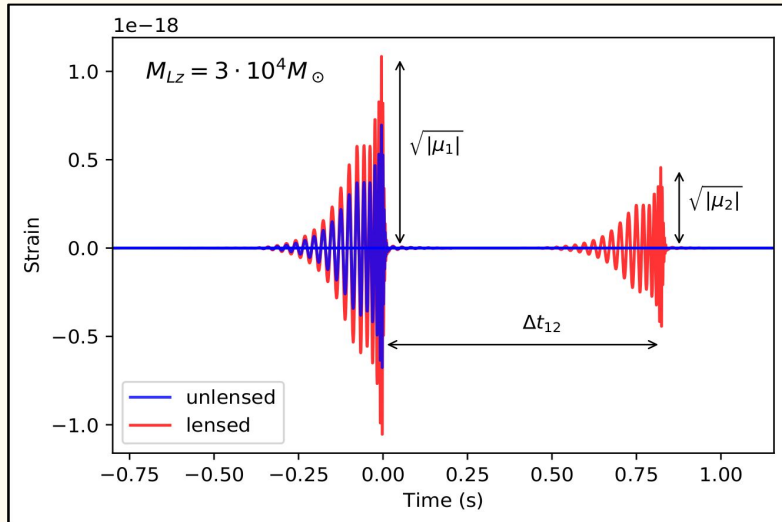
Wave Optics (WO) regime

$$F(\omega) = \frac{\omega}{2\pi i} \int d^2x e^{i\omega\phi(x,y)}$$

Oscillations in amplification factor

$$F(\omega) \equiv \frac{\tilde{h}}{\tilde{h}_0}$$

$$\omega \equiv 8\pi G M_{Lz} f \sim \left(\frac{M_{Lz}}{10^4 M_\odot} \right) \left(\frac{f}{\text{Hz}} \right)$$



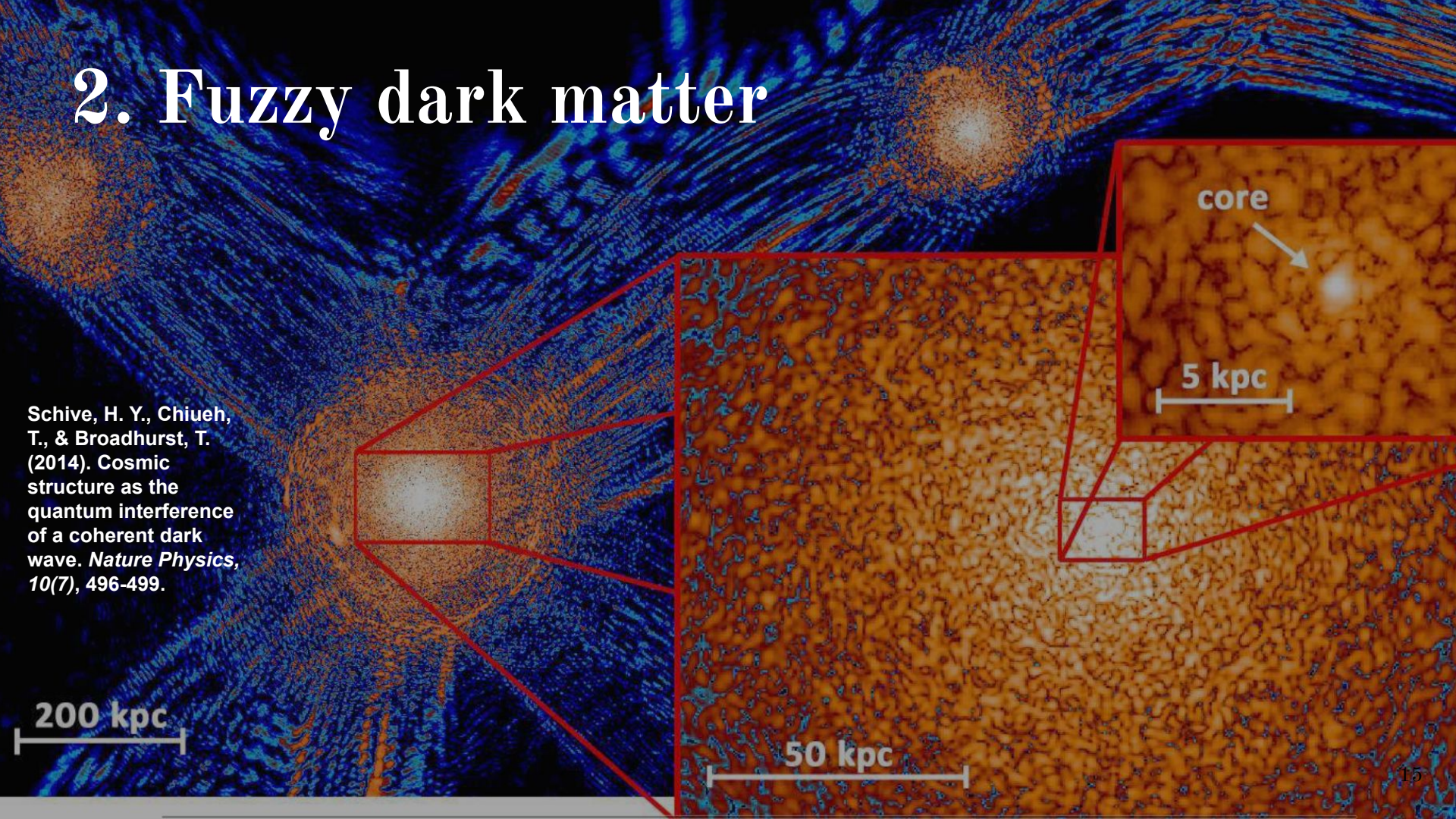
Geometric optics (GO) regime

$$\omega \gg 1$$

$$F(\omega) = \sum_J |\mu_J|^{1/2} e^{i\omega\phi_J - i\pi n_J}$$

2. Fuzzy dark matter

Schive, H. Y., Chiueh, T., & Broadhurst, T. (2014). Cosmic structure as the quantum interference of a coherent dark wave. *Nature Physics*, 10(7), 496-499.



Cold dark matter: Issues on small scales

Core cusp
problem

Too big to
fail

Number
density of
halos

Earliest
structure
 $z \sim 50$

Cold dark matter: Issues on small scales

Core cusp
problem

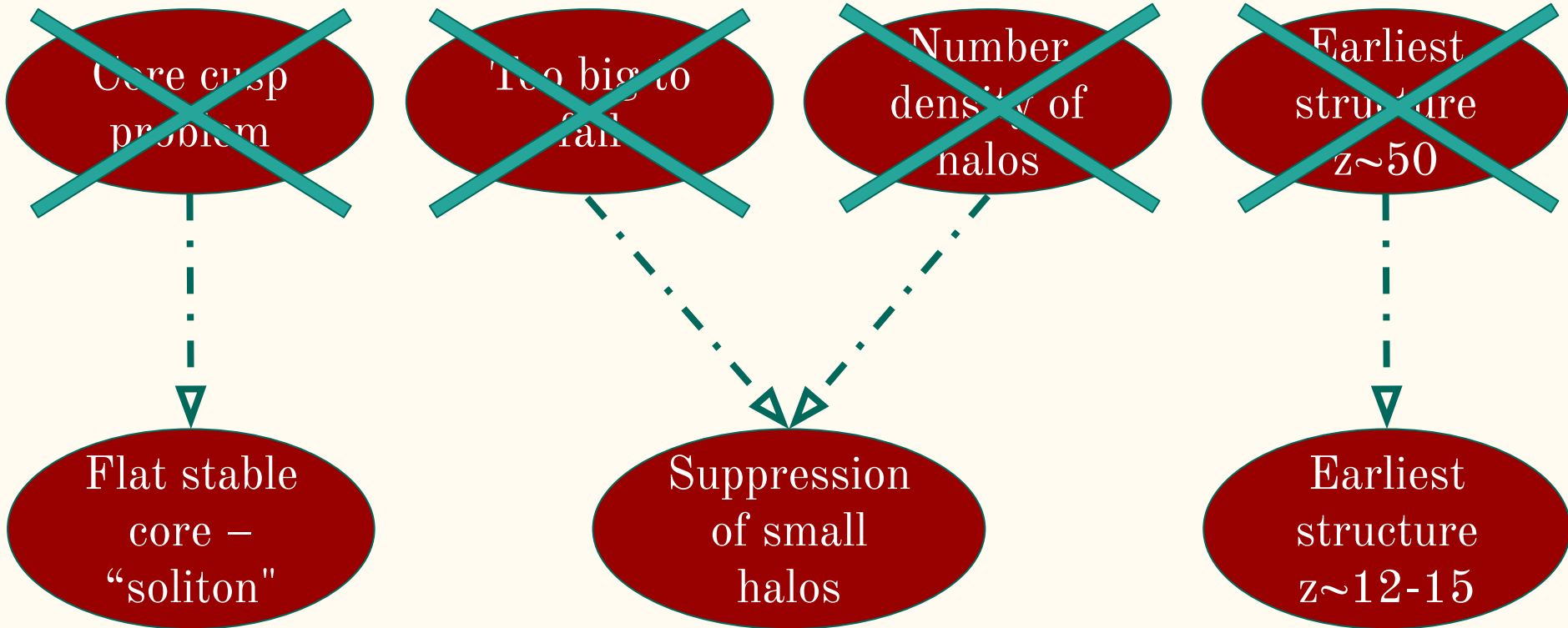
Too big to
fail

Number
density of
halos

Earliest
structure
 $z \sim 50$

very light bosons $m_\phi \sim 10^{-22} - 10^{-23} \text{ eV}$

Cold dark matter: Issues on small scales



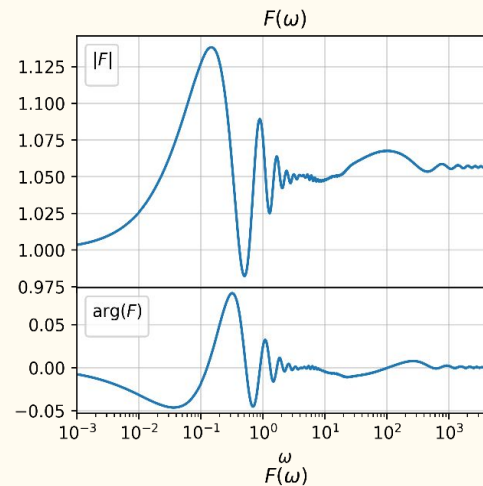
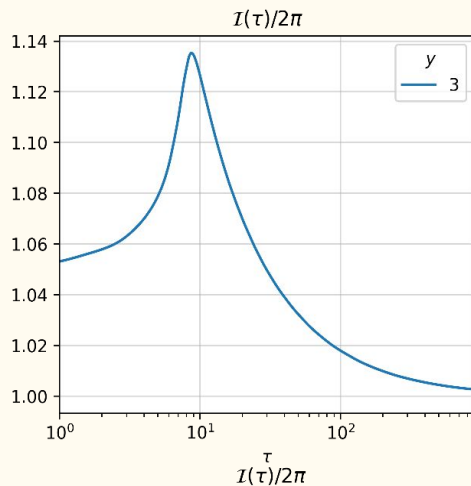
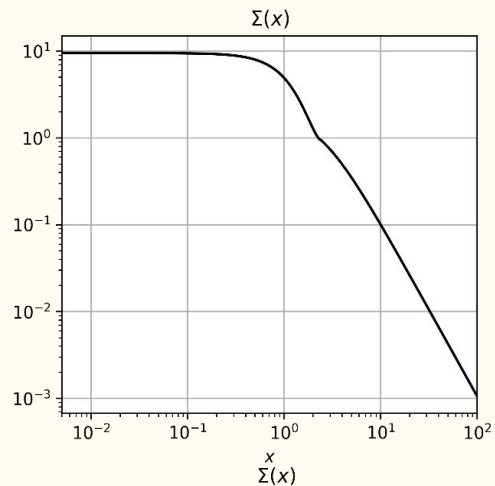
3. Lensing Features

The image displays a vast field of galaxies and stars. In the center-right, a prominent feature is a bright yellow star surrounded by a glowing blue ring, known as an Einstein ring. This is a result of gravitational lensing. The background is filled with various types of galaxies, including spirals and ellipticals, and many individual stars of different colors and sizes. The overall scene is set against a dark, black cosmic background.

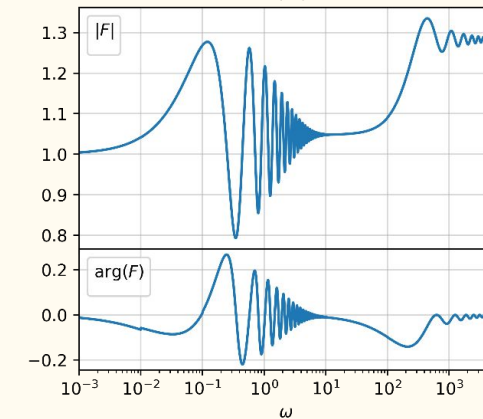
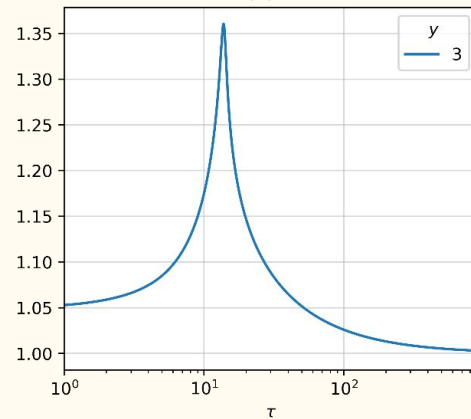
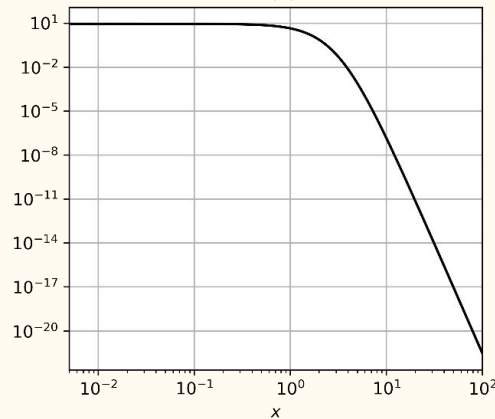
Einstein Rings of LRG 3-757 taken with the Hubble
Space Telescope's Wide Field Camera 3.
Image : <https://apod.nasa.gov/apod/ap111221.html>

Lensing Features

FDM

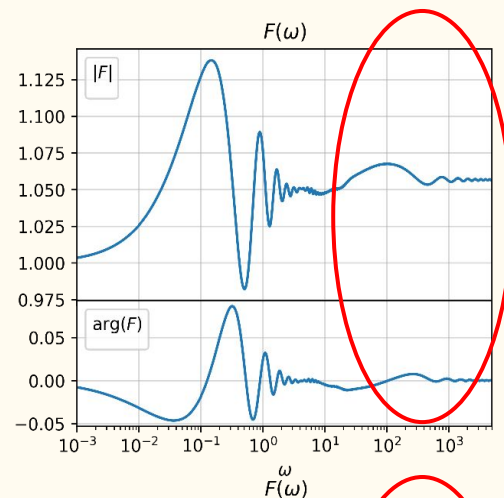
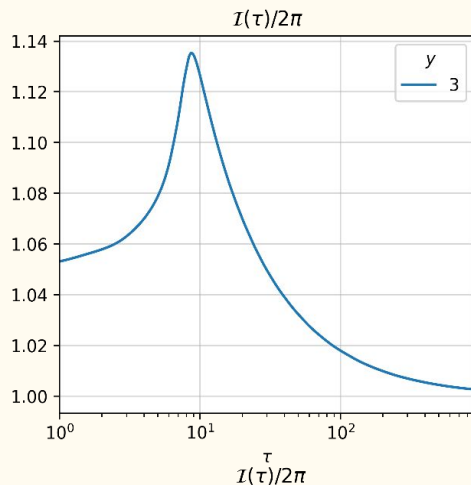
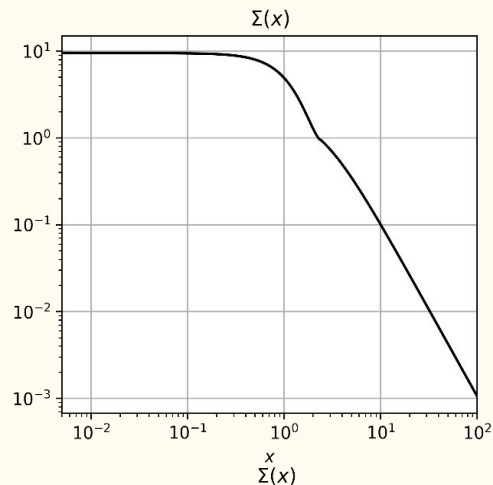


SC

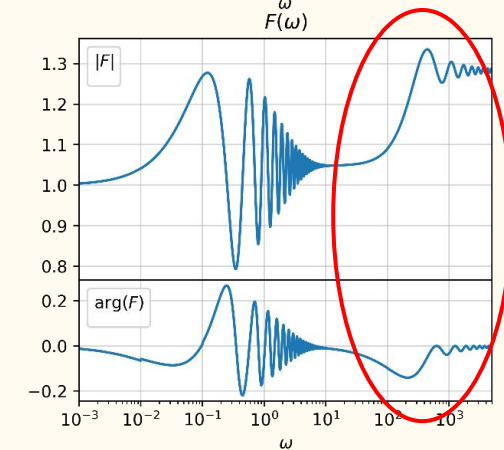
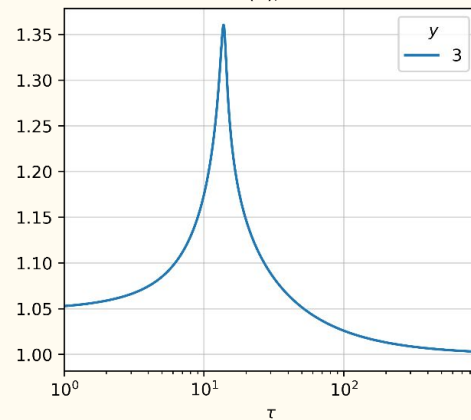
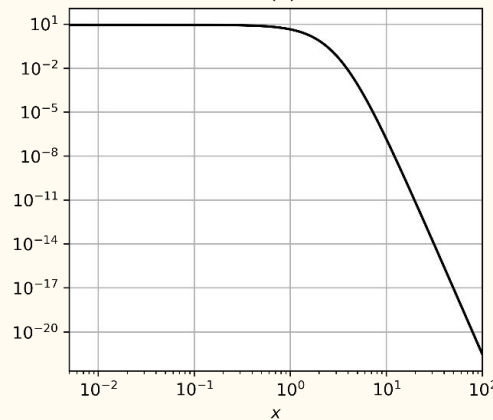


Lensing Features

FDM

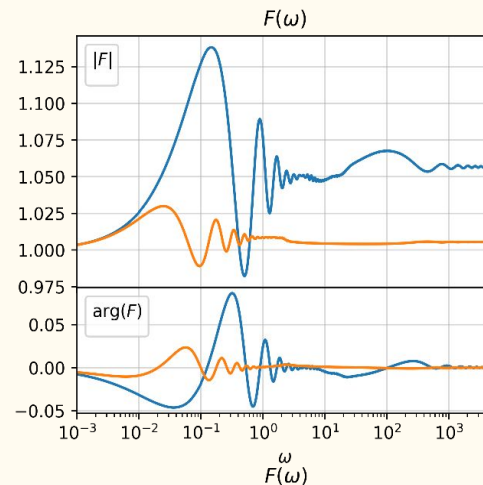
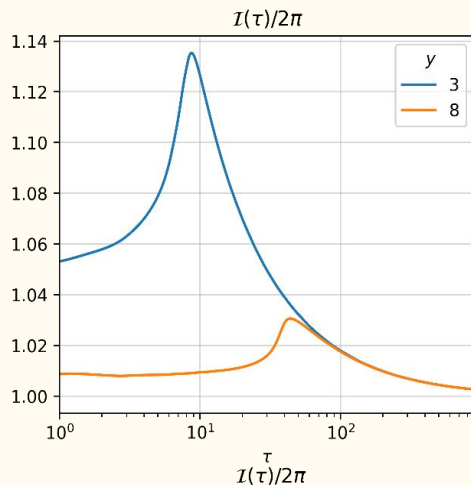
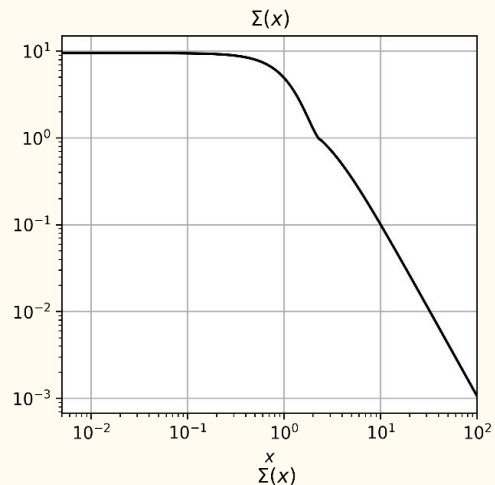


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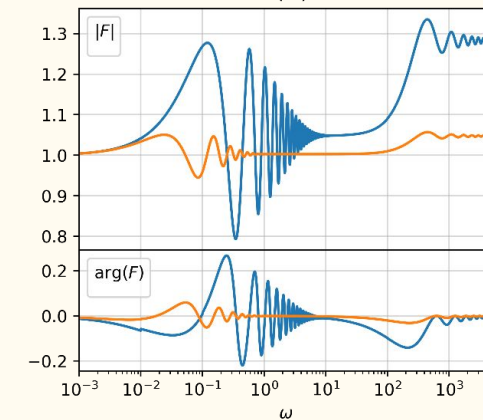
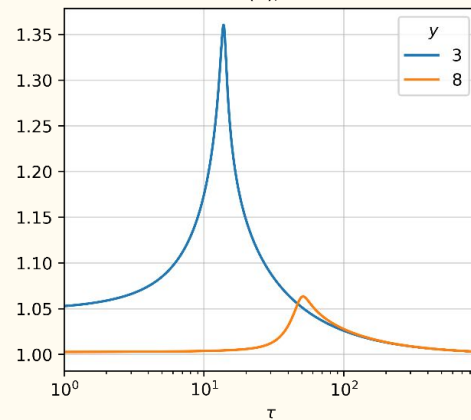
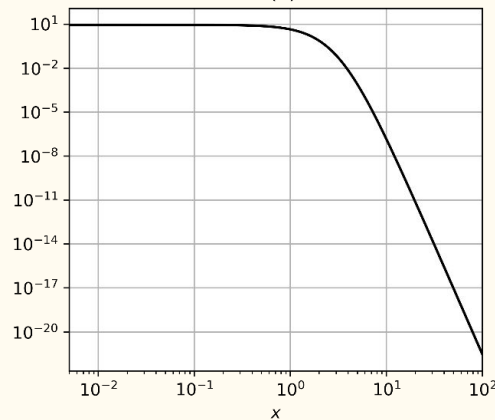


Lensing Features

FDM

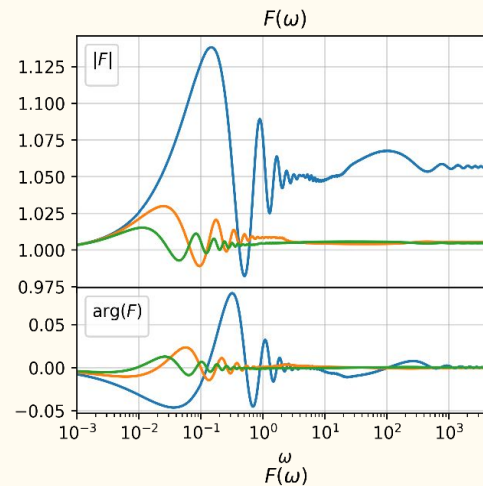
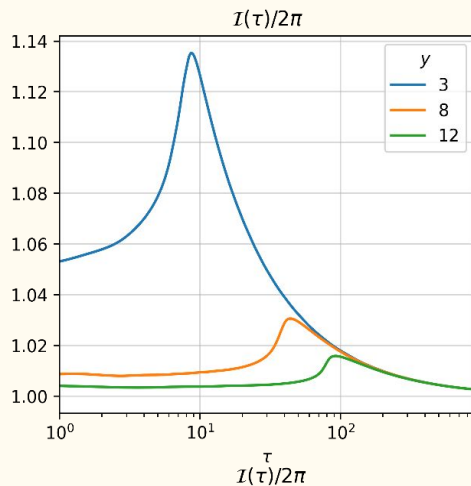
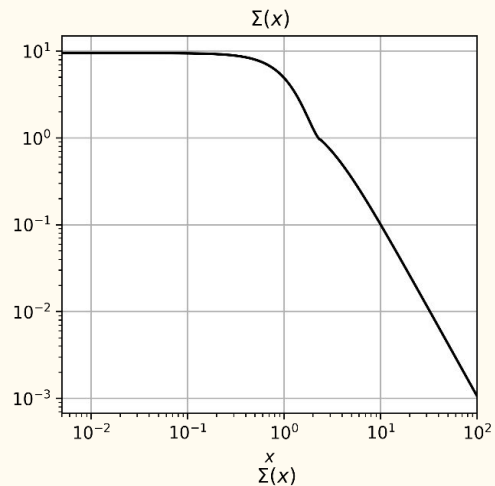


SC

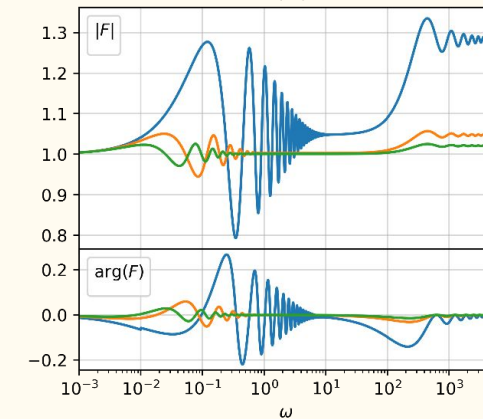
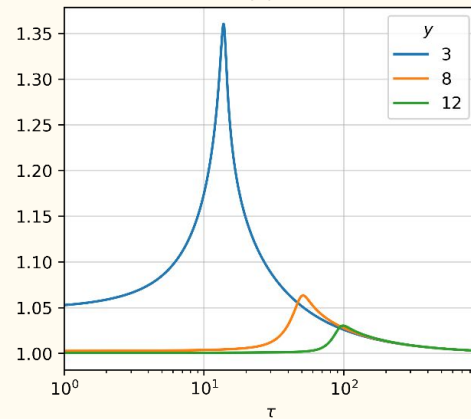
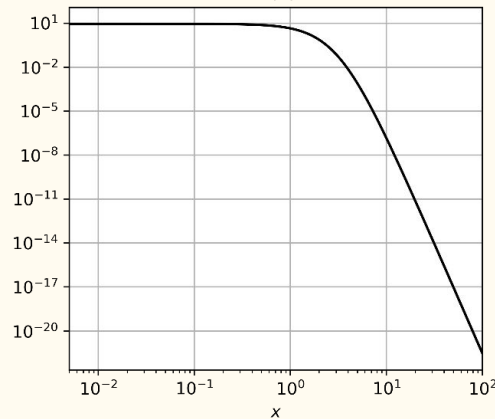


Lensing Features

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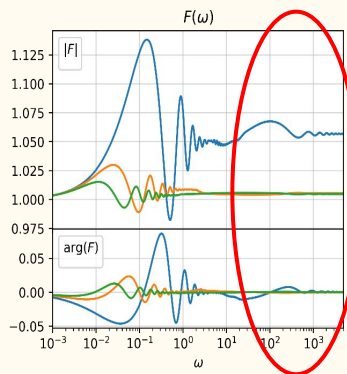
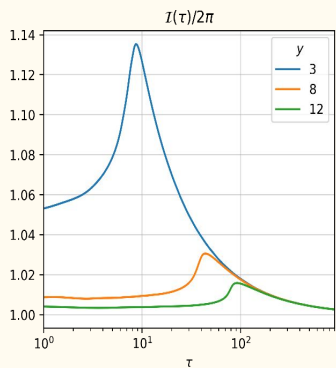
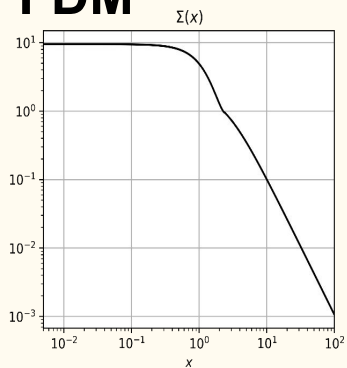


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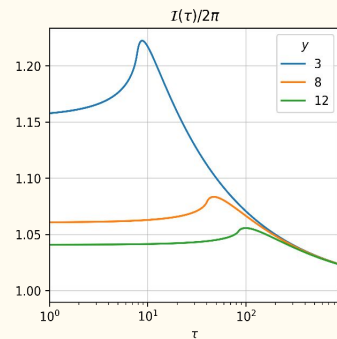
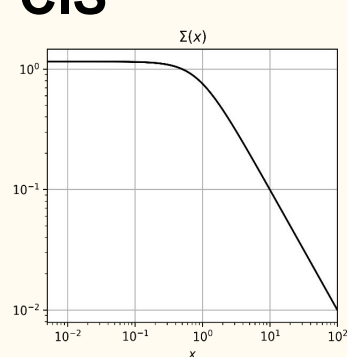


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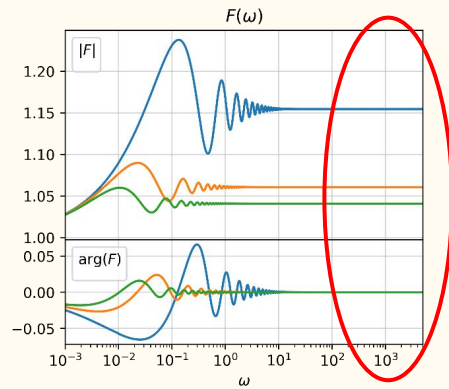
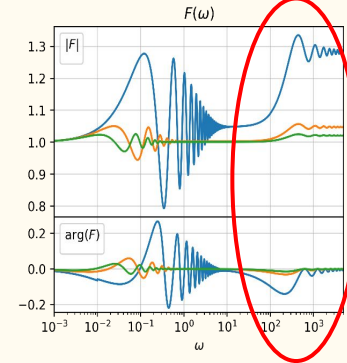
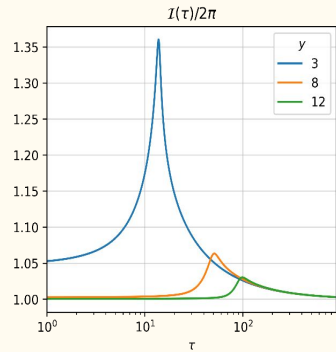
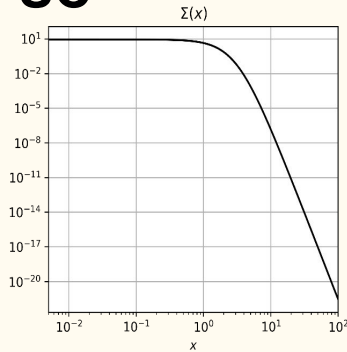
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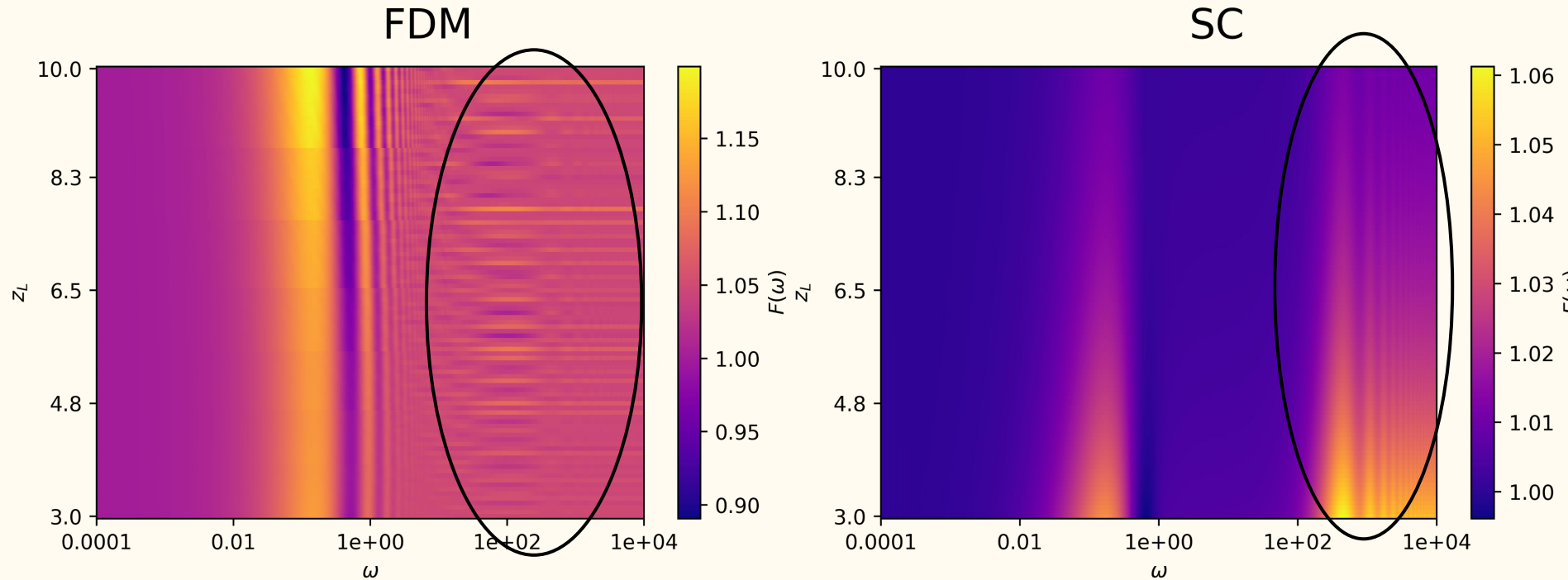
CIS



SC

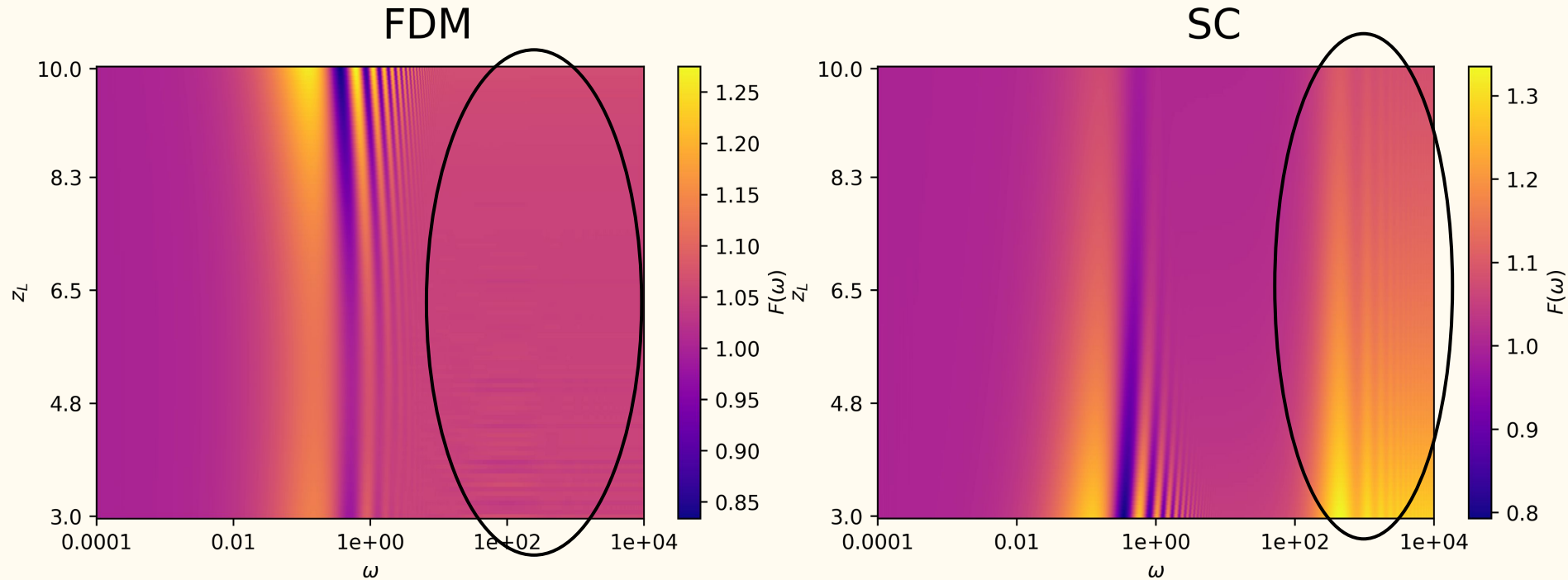


Lensing Features



$$M_L = 10^8 M_\odot$$

Lensing Features



$$M_L = 10^9 M_\odot$$

Lensing Features

$$\omega \equiv 8\pi G M_{Lz} f \sim \left(\frac{M_{Lz}}{10^4 M_\odot} \right) \left(\frac{f}{\text{Hz}} \right)$$

$$M_L = 10^8 M_\odot$$

$$M_L = 10^9 M_\odot$$

Lensing Features

$$\omega \equiv 8\pi G M_{Lz} f \sim \left(\frac{M_{Lz}}{10^4 M_\odot} \right) \left(\frac{f}{\text{Hz}} \right)$$

$$M_L = 10^8 M_\odot$$

$$M_L = 10^9 M_\odot$$

$$\omega \sim 10^{3-4}$$

Lensing Features

$$\omega \equiv 8\pi G M_{Lz} f \sim \left(\frac{M_{Lz}}{10^4 M_\odot} \right) \left(\frac{f}{Hz} \right)$$

$$M_L = 10^8 M_\odot$$

$$M_L = 10^9 M_\odot$$

$$\omega \sim 10^{3-4}$$

$$f \sim 0.1 - 1 Hz$$

$$f \sim 0.01 - 0.1 Hz$$

Lensing Features

$$\omega \equiv 8\pi G M_{Lz} f \sim \left(\frac{M_{Lz}}{10^4 M_{\odot}} \right) \left(\frac{f}{\text{Hz}} \right)$$

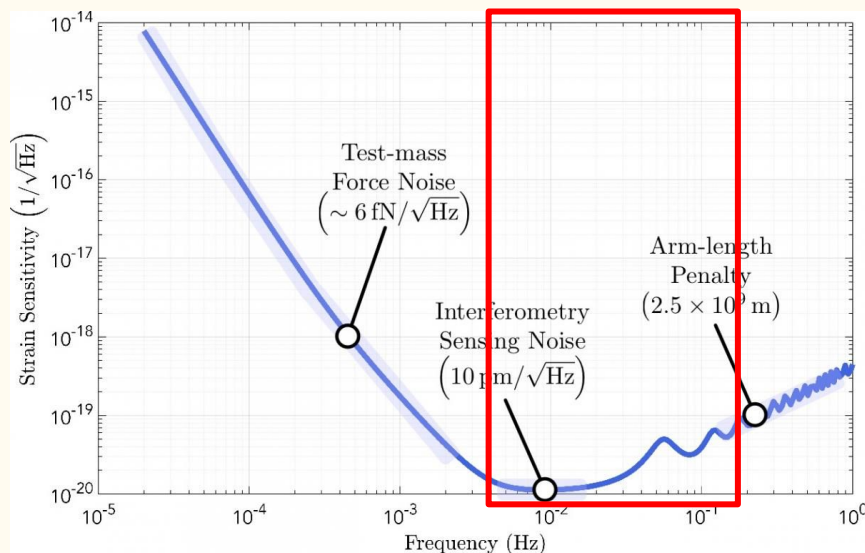
$$M_L = 10^8 M_{\odot}$$

$$M_L = 10^9 M_{\odot}$$

$$\omega \sim 10^{3-4}$$

$$f \sim 0.1 - 1 \text{ Hz}$$

$$f \sim 0.01 - 0.1 \text{ Hz}$$



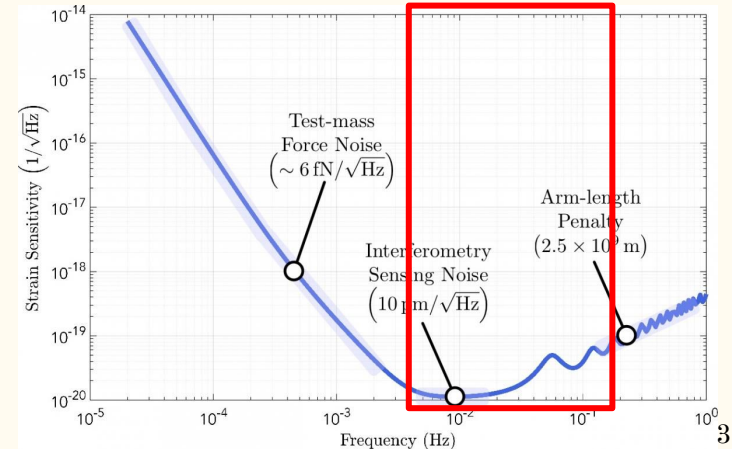
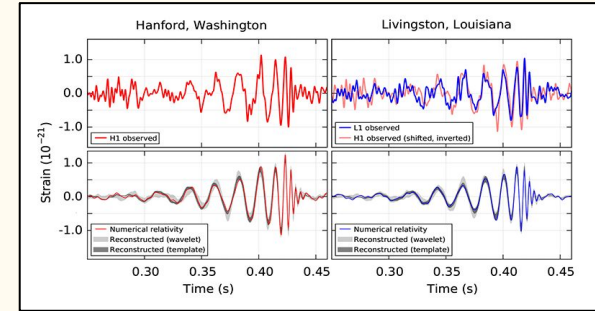
LISA sensitivity :
0.1 mHz to 1 Hz

Conclusion

- GWs complement EM lensing
 - ◆ ability to probe lens features
- Fast and accurate method to evaluate lensing features*
- Features of FDM detectable
 - ◆ within the sensitivity of LISA
- Next steps
 - ◆ interference pattern
 - ◆ probing lens parameters[†]

* <https://arxiv.org/abs/2306.05282>

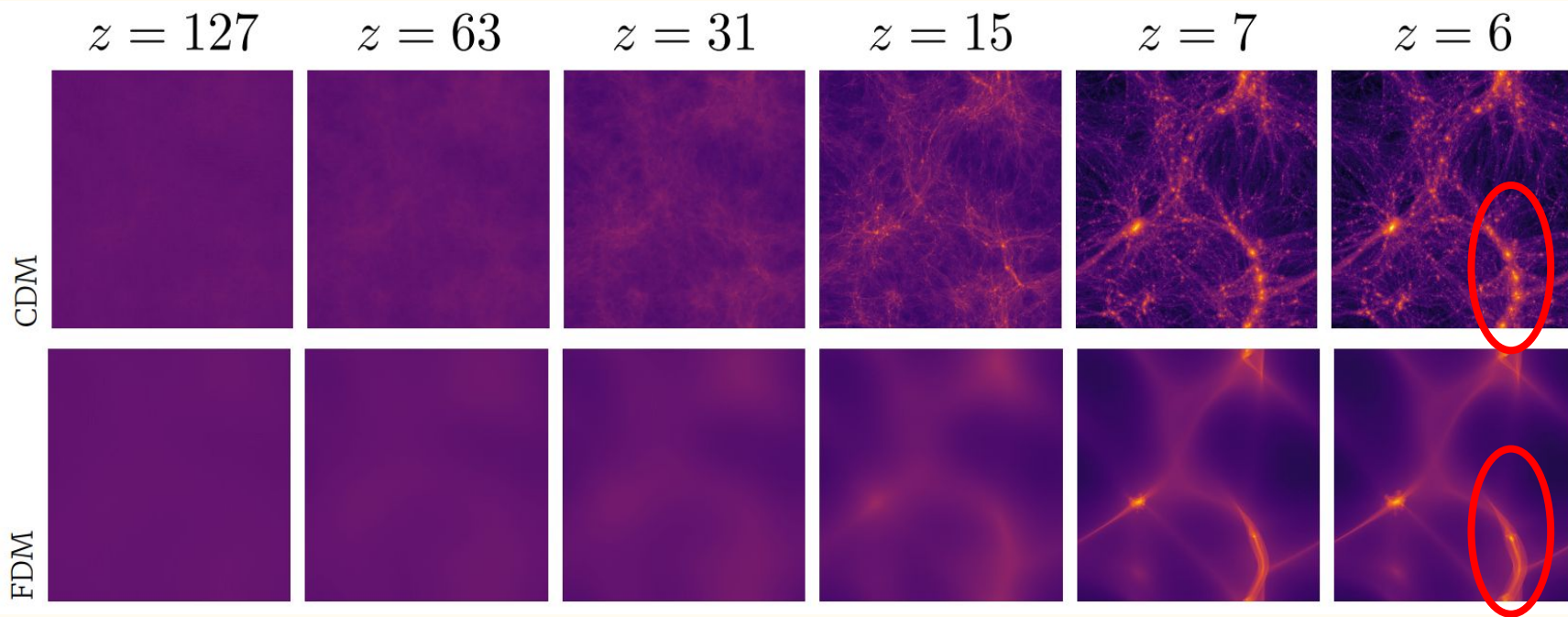
† <https://arxiv.org/abs/2212.11960>



Thanks !!

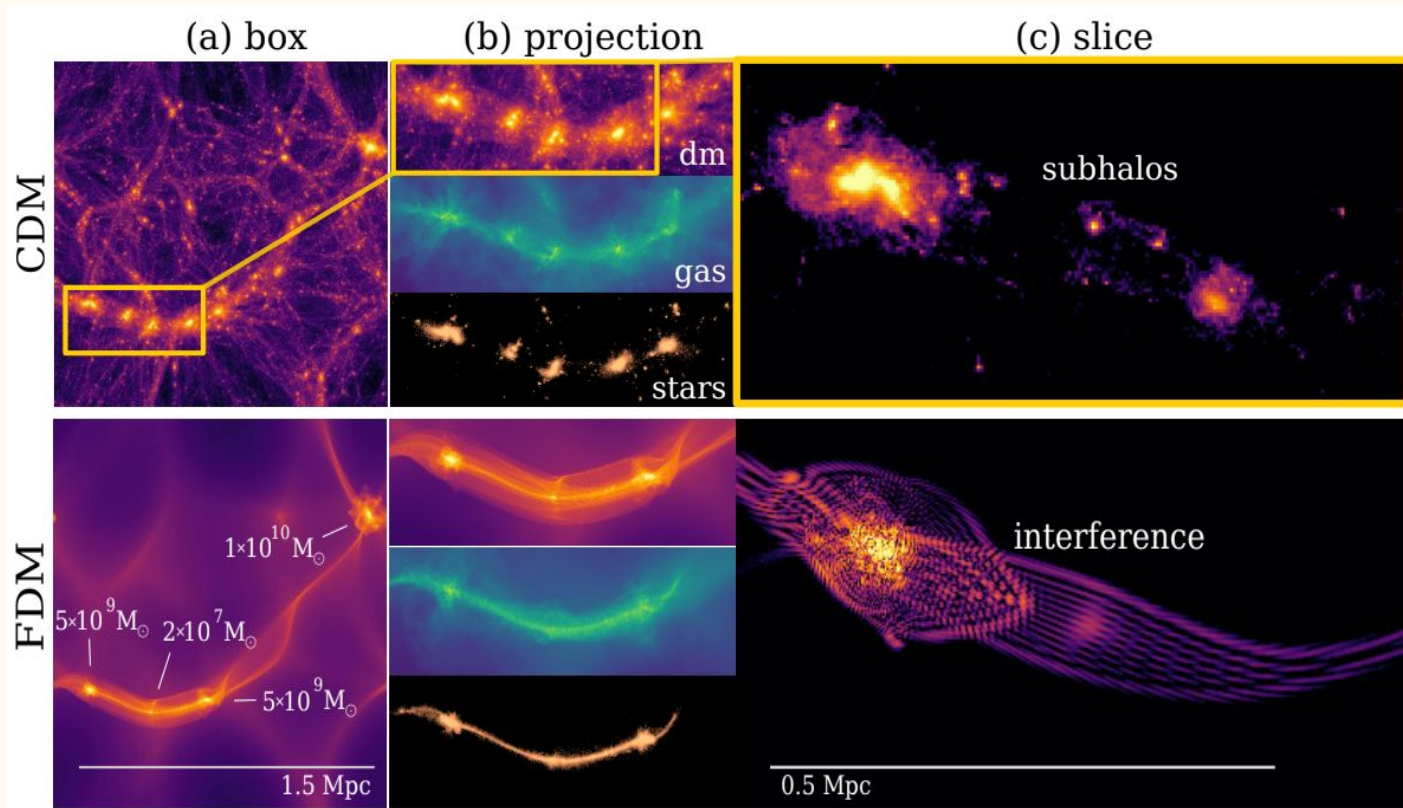
Extra Slides ..

A view of fuzzy Universe

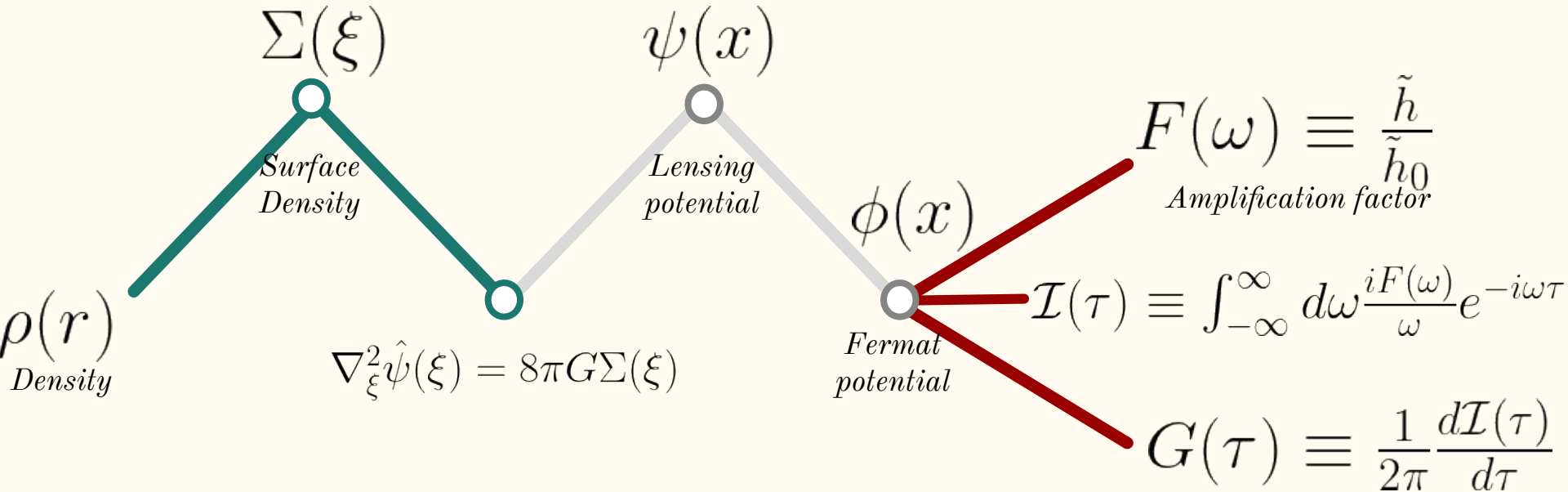


Pmócz, A. (2019). Fuzzy dark matter: overview. Retrieved from https://indico.neic.no/event/101/contributions/366/attachments/154/245/pmocz_2019_09_30_reykjavic.pdf

A view of fuzzy Universe



Gravitational Wave Lensing – Theory



Gravitational Wave Lensing – Theory

