Probing Fuzzy dark matter with lensed Gravitational waves

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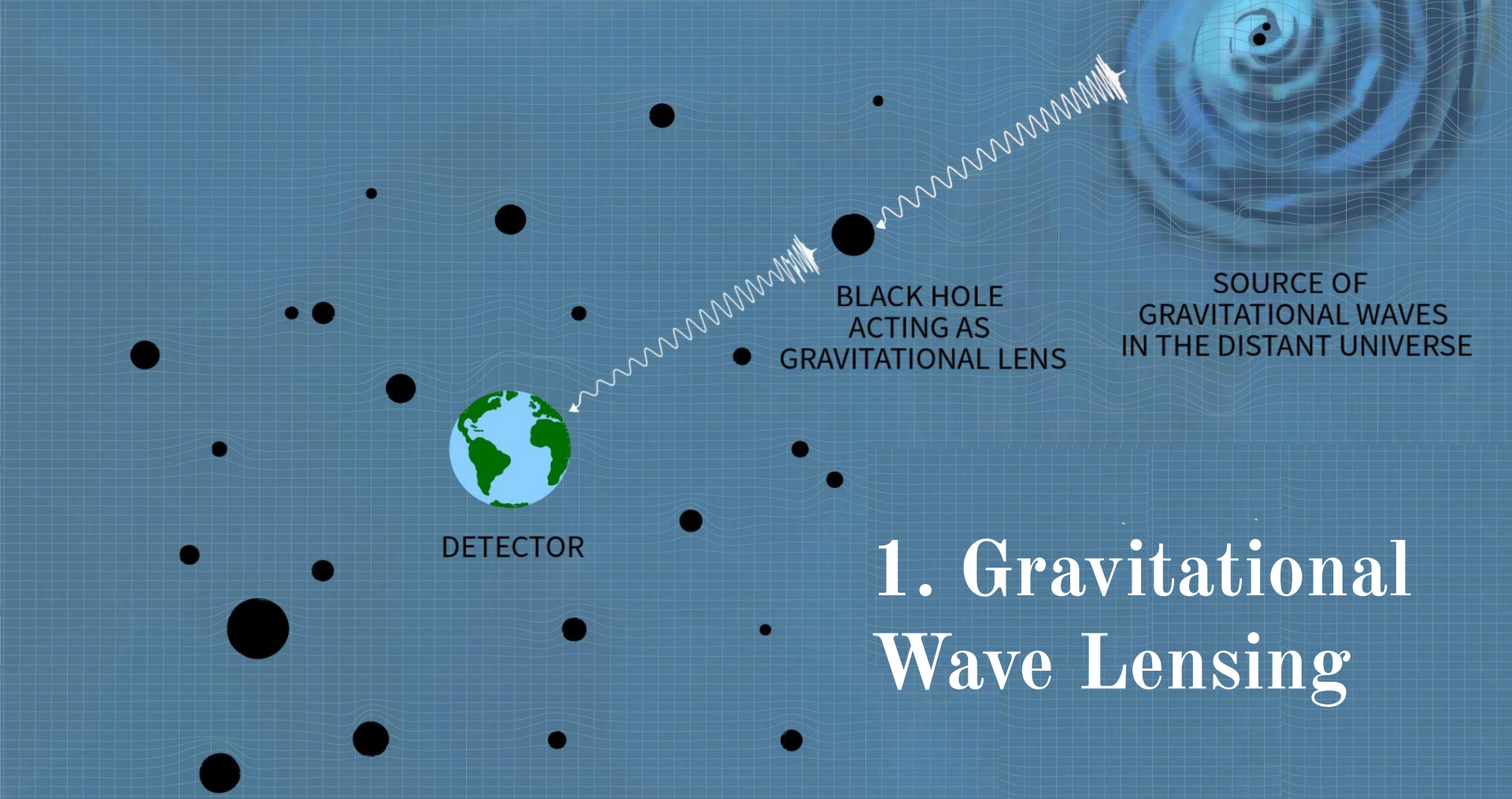
Collaborators : G. Brando, G. Tambalo, M. Zumalacárregui

Cosmology from Home 2023

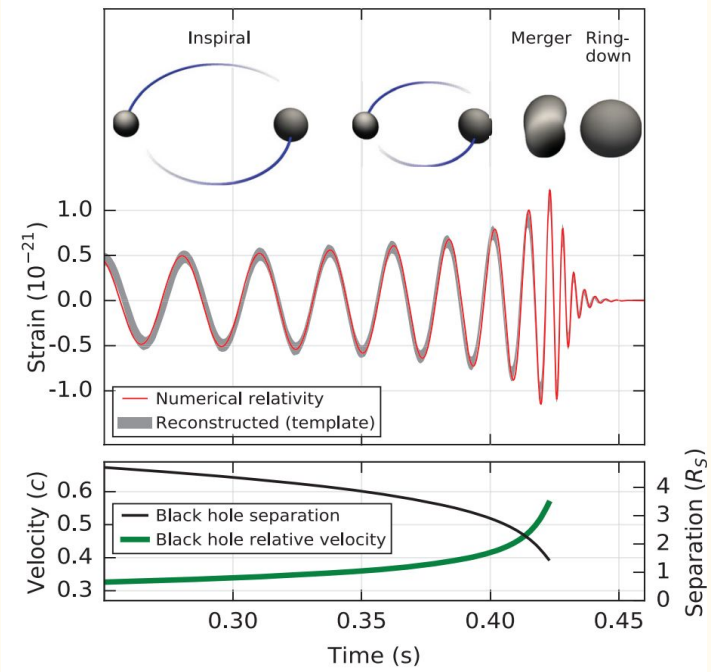
Contents



1. Gravitational Wave Lensing

Image Source: Roshni Samuel / Parameswaran Ajith / ICTS

Gravitational Wave Lensing



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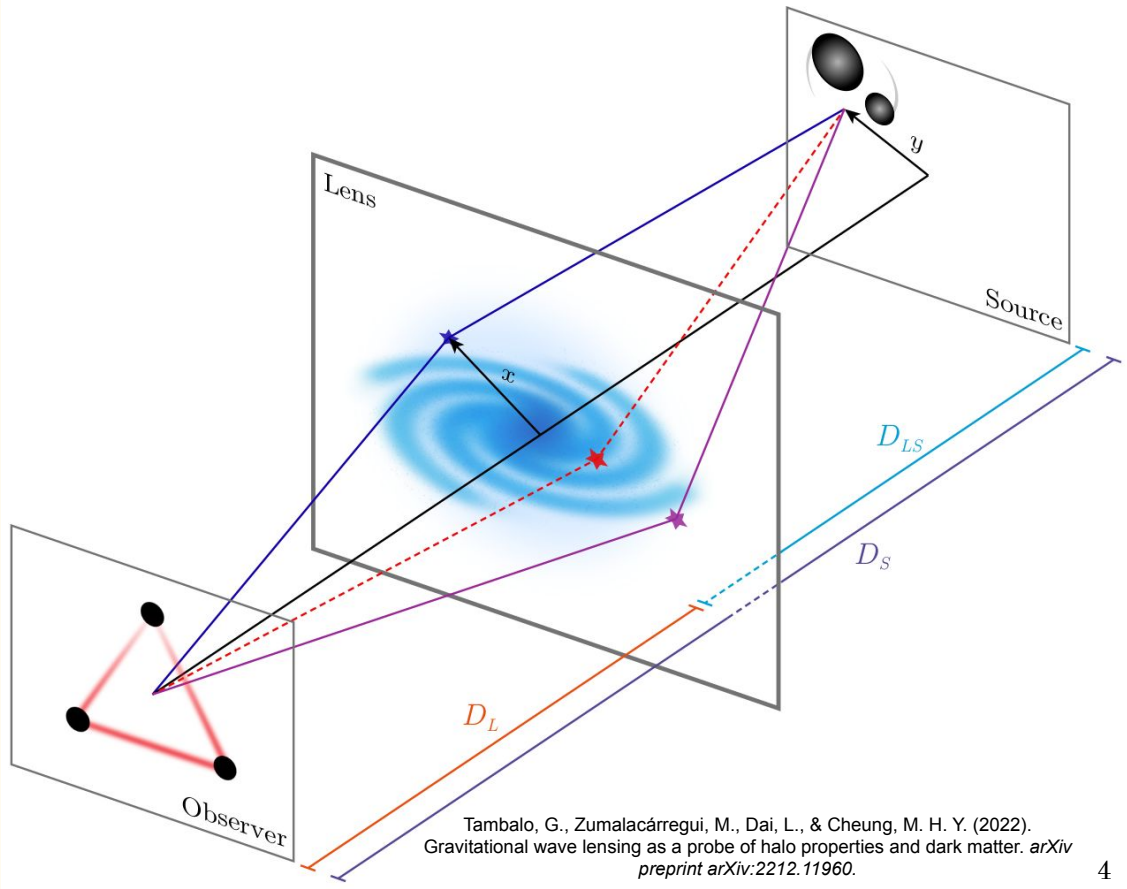

Tambalo, G., Zumalacárregui, M., Dai, L., & Cheung, M. H. Y. (2022). Gravitational wave lensing as a probe of halo properties and dark matter. *arXiv preprint arXiv:2212.11960*.

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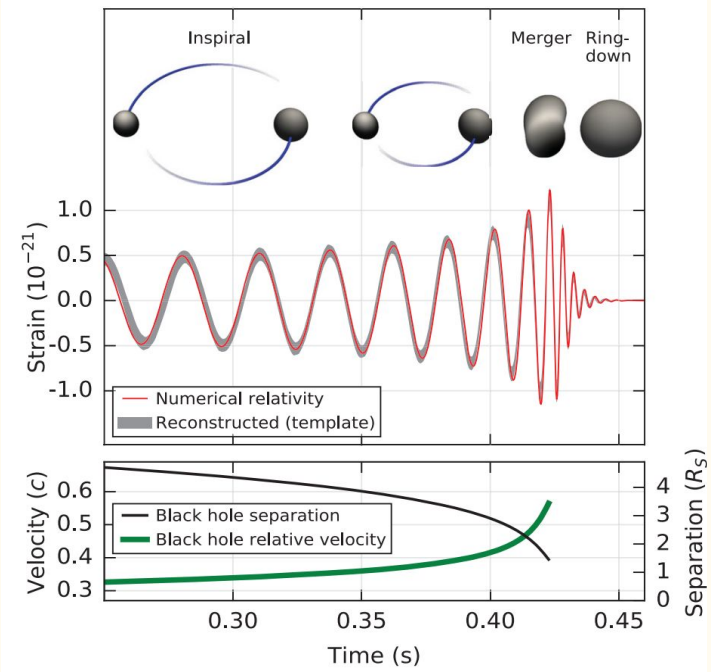

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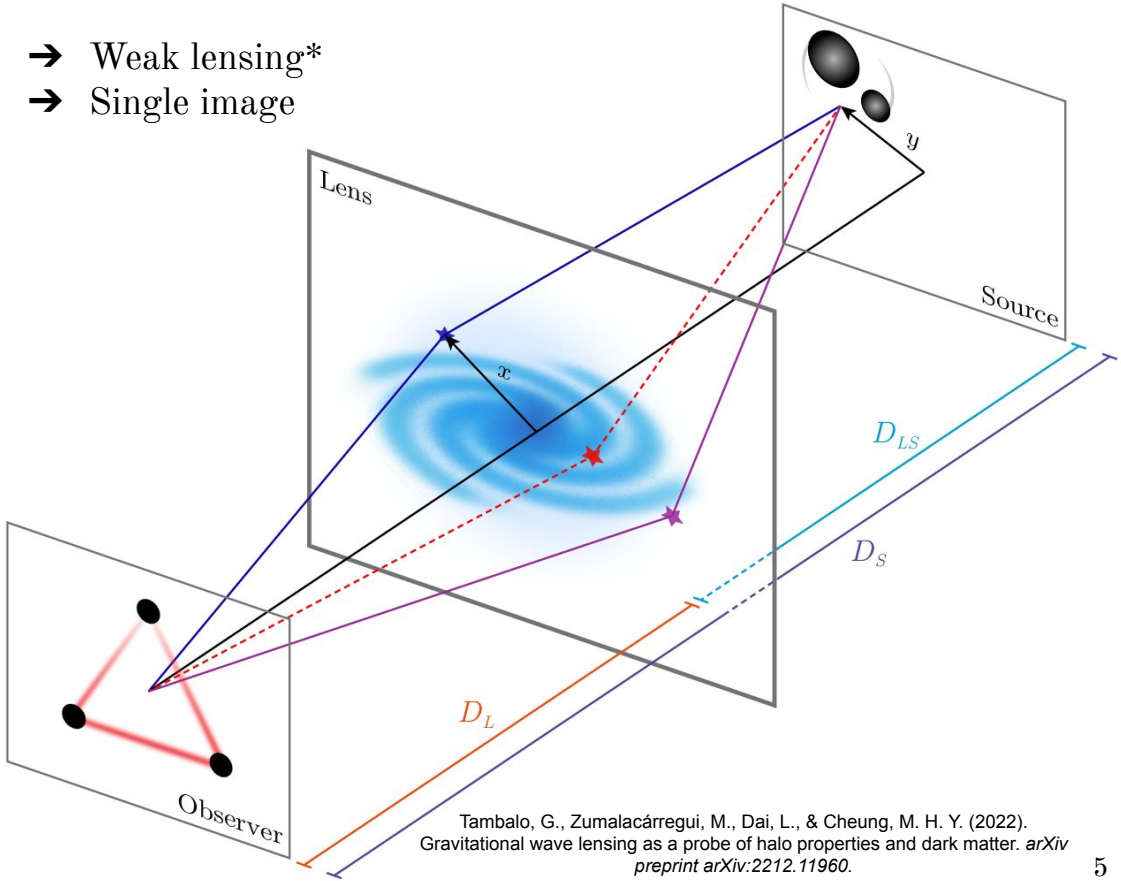
* Çalışkan, M., Ji, L., Cotesta, R., Berti, E., Kamionkowski, M., & Marsat, S. (2023). Observability of lensing of gravitational waves from massive black hole binaries with LISA. *Physical Review D, 107(4)*, 043029.

- ➔ Weak lensing*
- ➔ Single image



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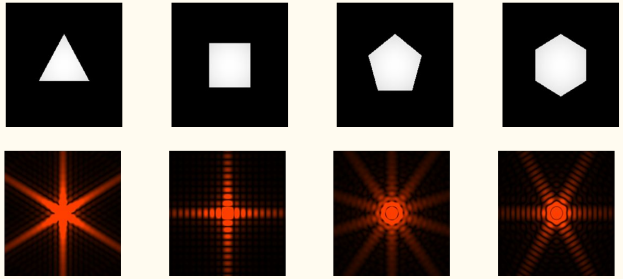
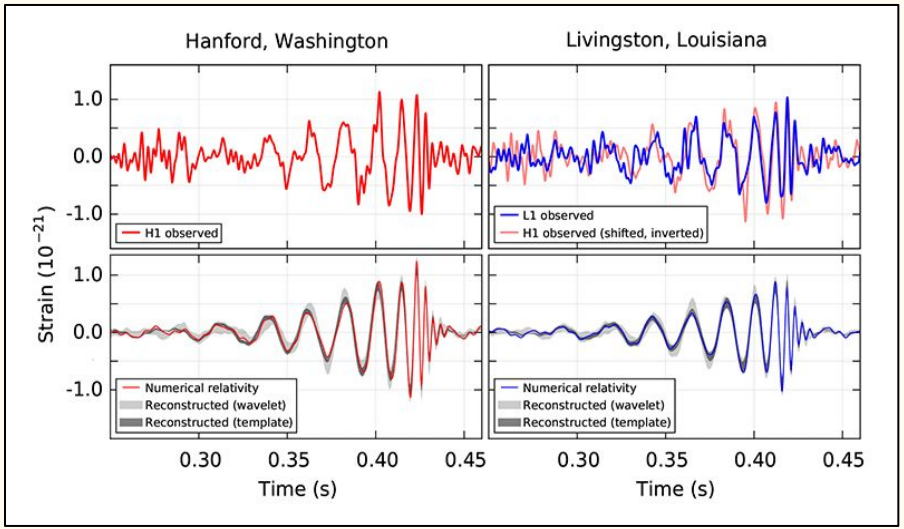
Gravitational Wave Lensing – New cosmic messenger

- Longer wavelength
- Coherence of waves
- Weakly coupled
- accuracy of modeling





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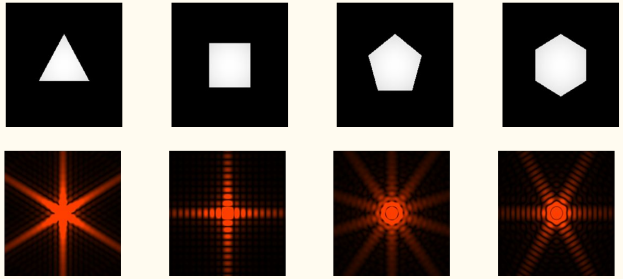

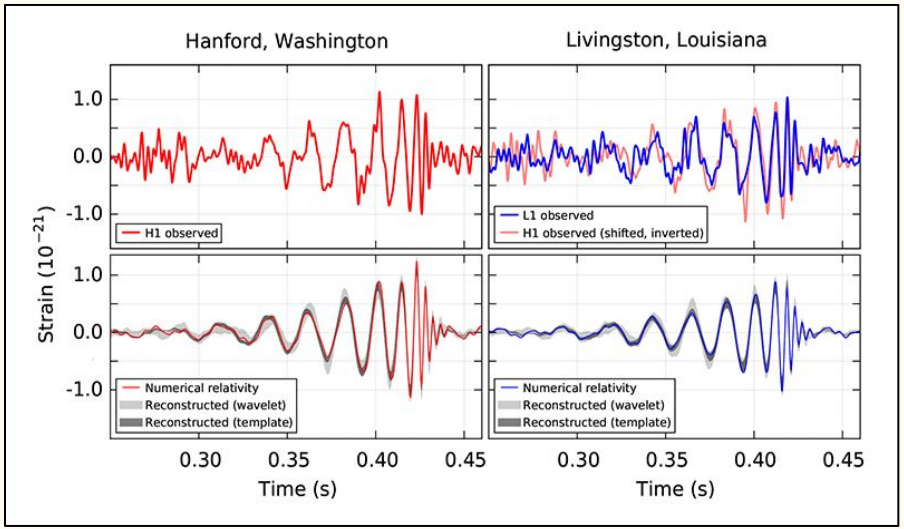

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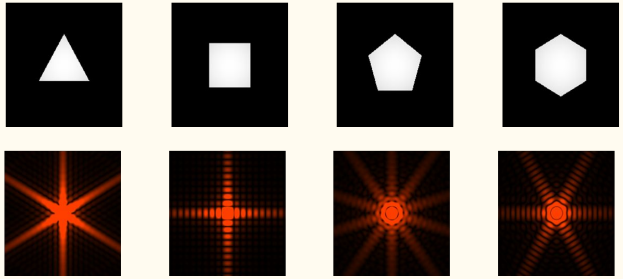

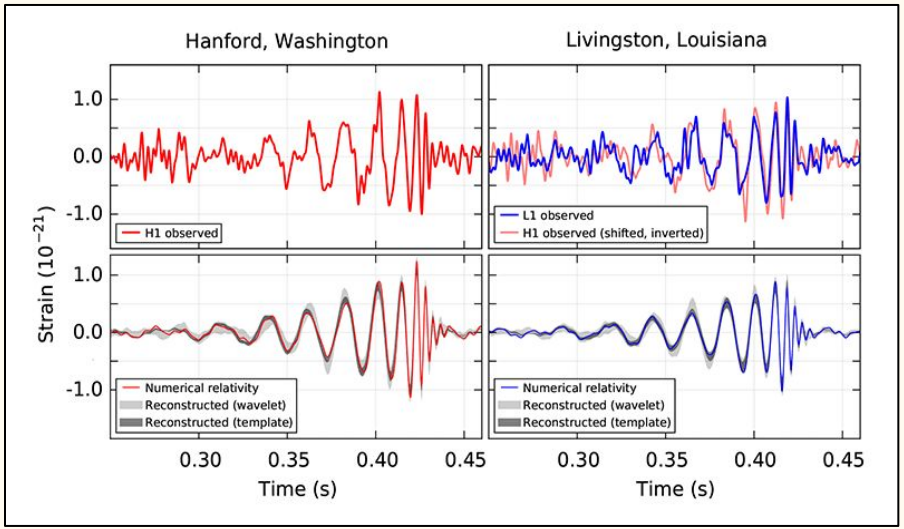

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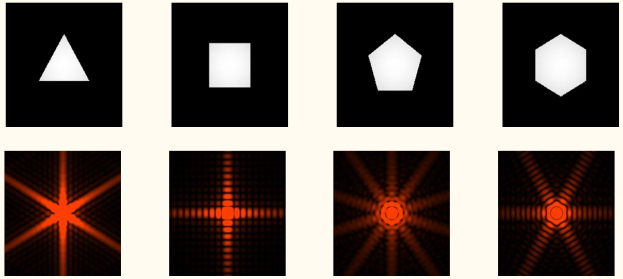

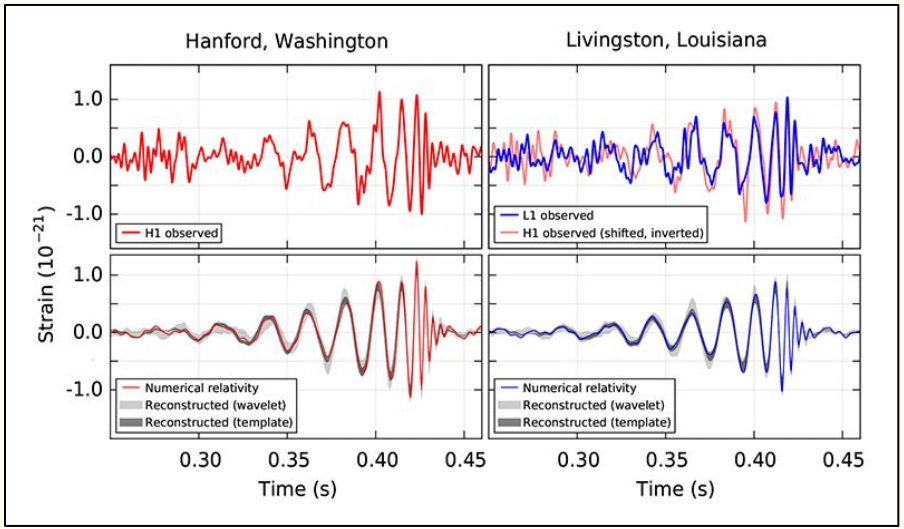

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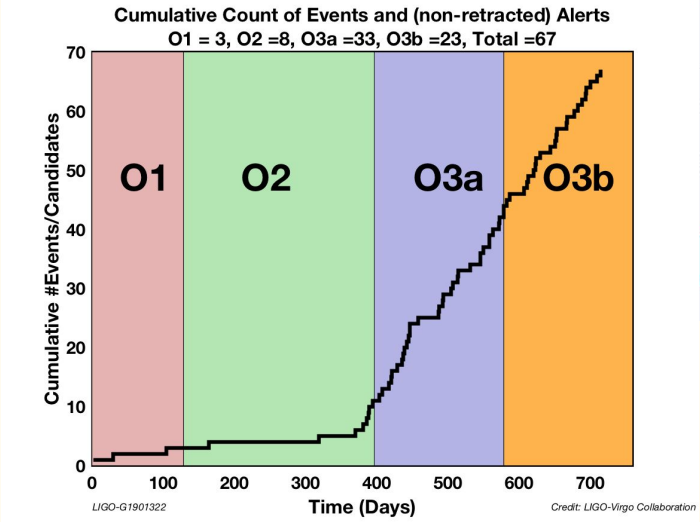


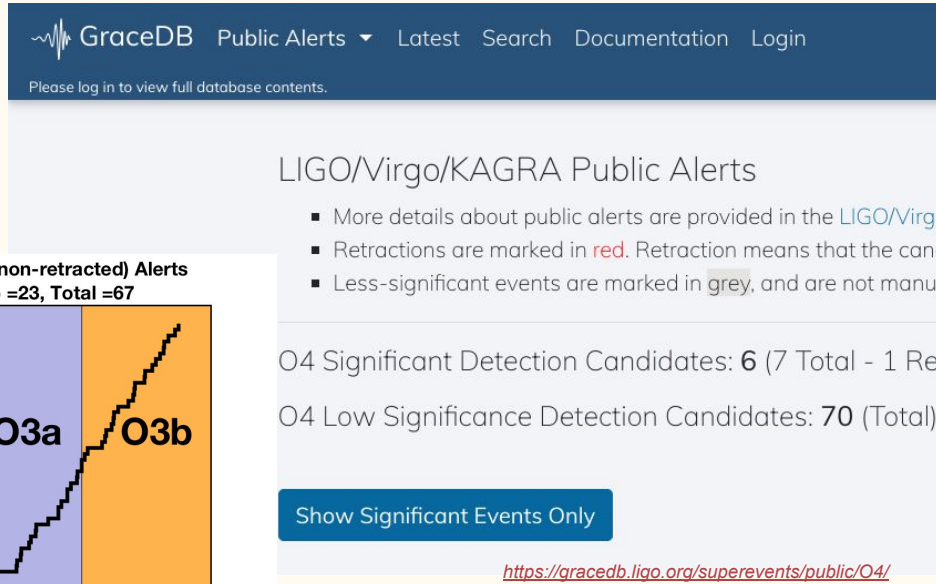
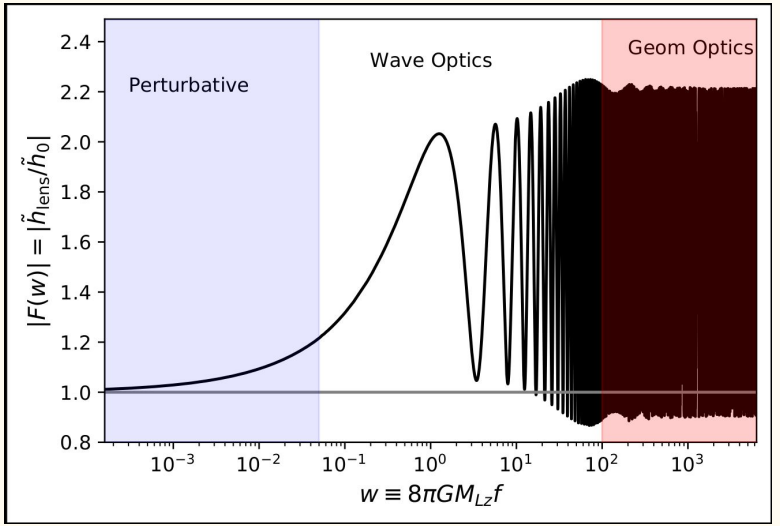


Image: https://www.ligo.caltech.edu/news/ligo20200326

Oscillations in amplification factor

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

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



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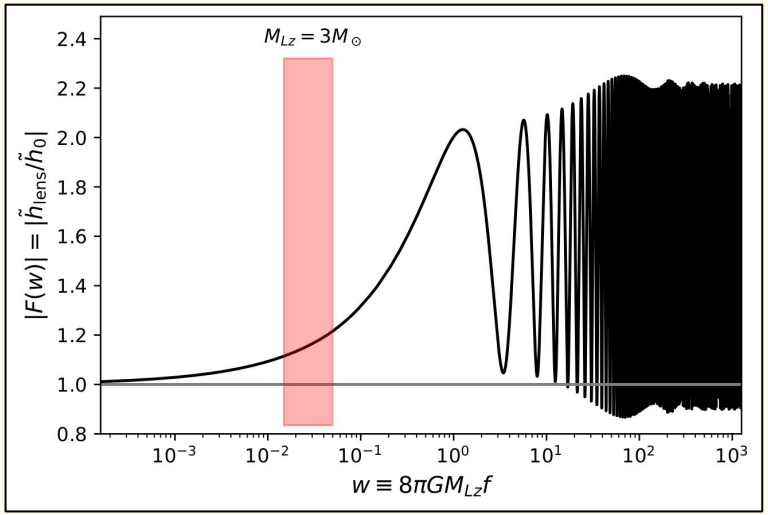
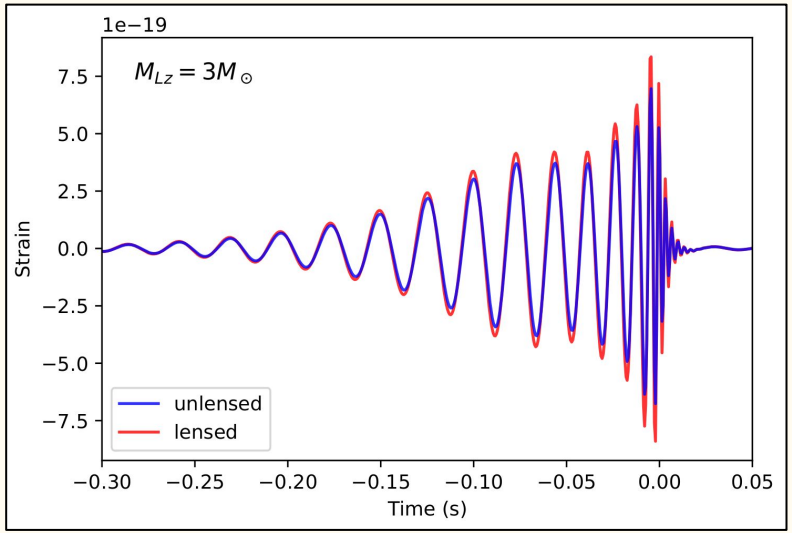




Perturbative regime

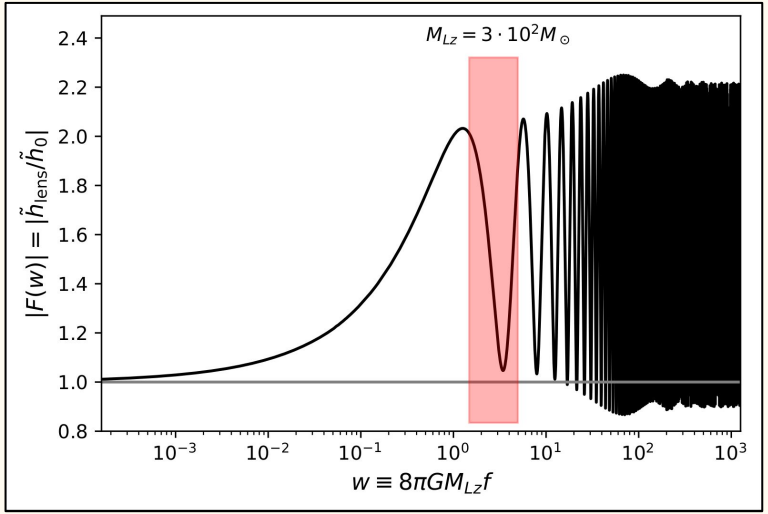
$$\omega << 1$$

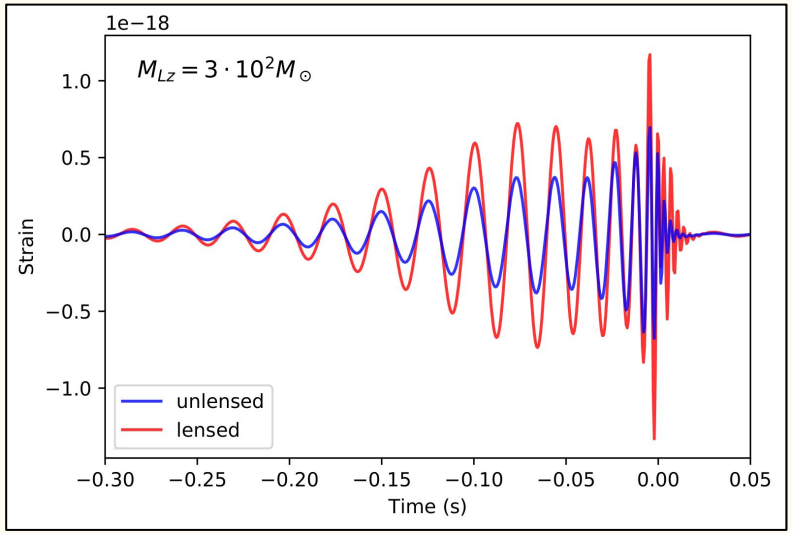
$$F(\omega) \sim 1 + A\omega^{\alpha}$$

Oscillations in amplification factor

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

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





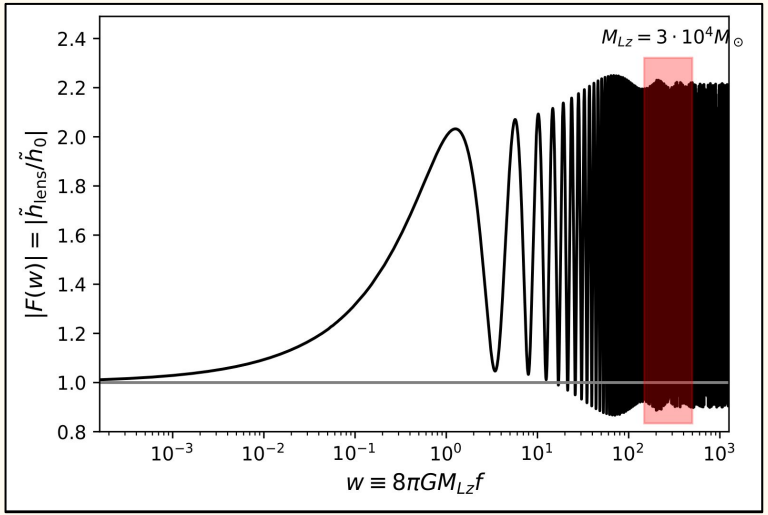
Wave Optics (WO) regime

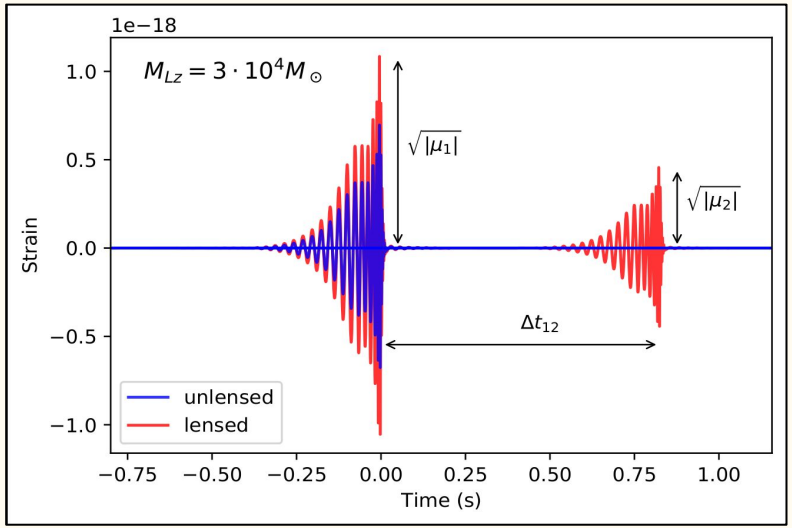
$$F(\omega) = \frac{\omega}{2\pi i} \int d^2x e^{i\omega\phi(x,y)}$$

Oscillations in amplification factor

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

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



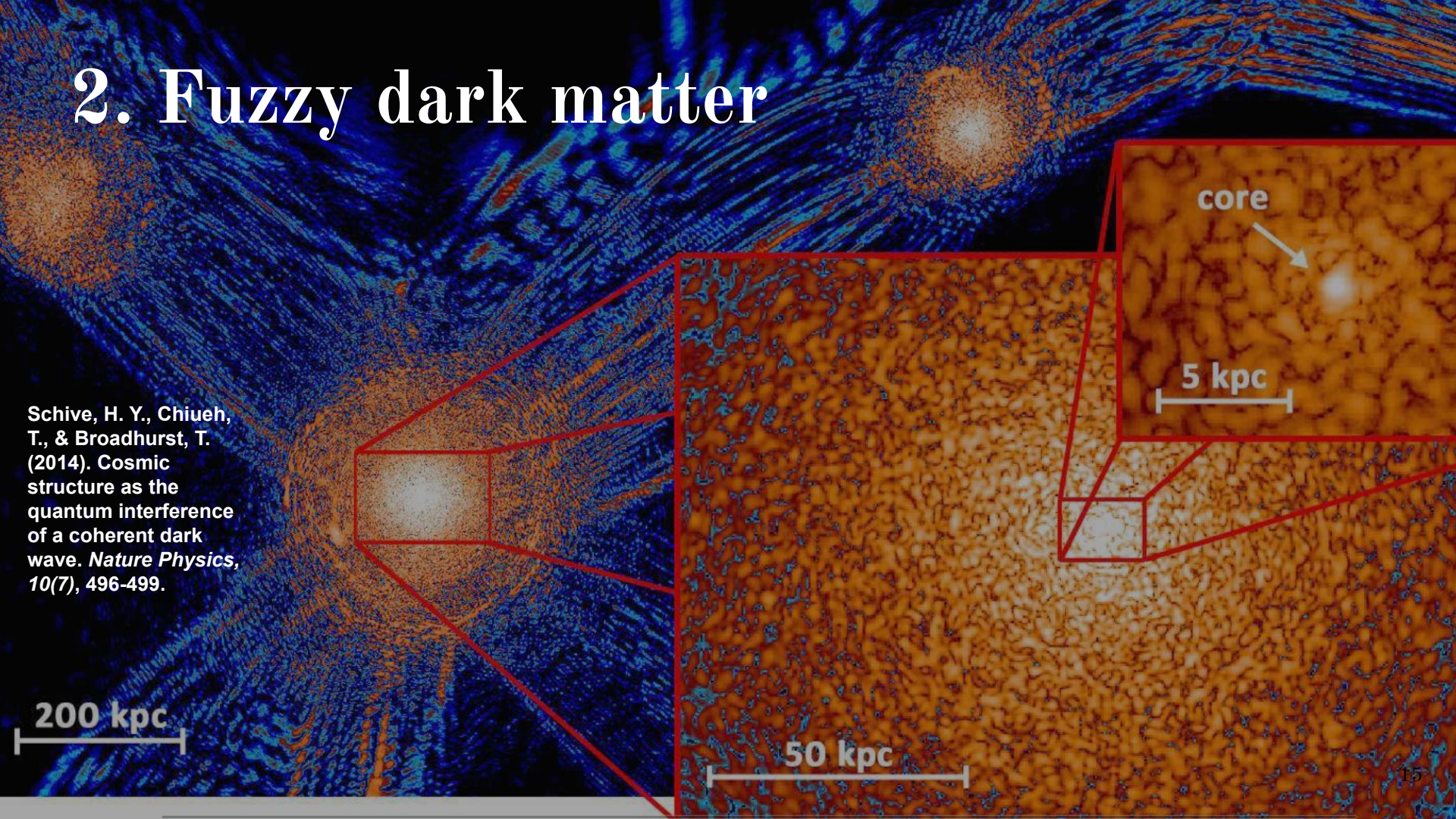


Geometric optics (GO) regime

$$\omega >> 1$$

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

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~50

Cold dark matter: Issues on small scales

Core cusp problem

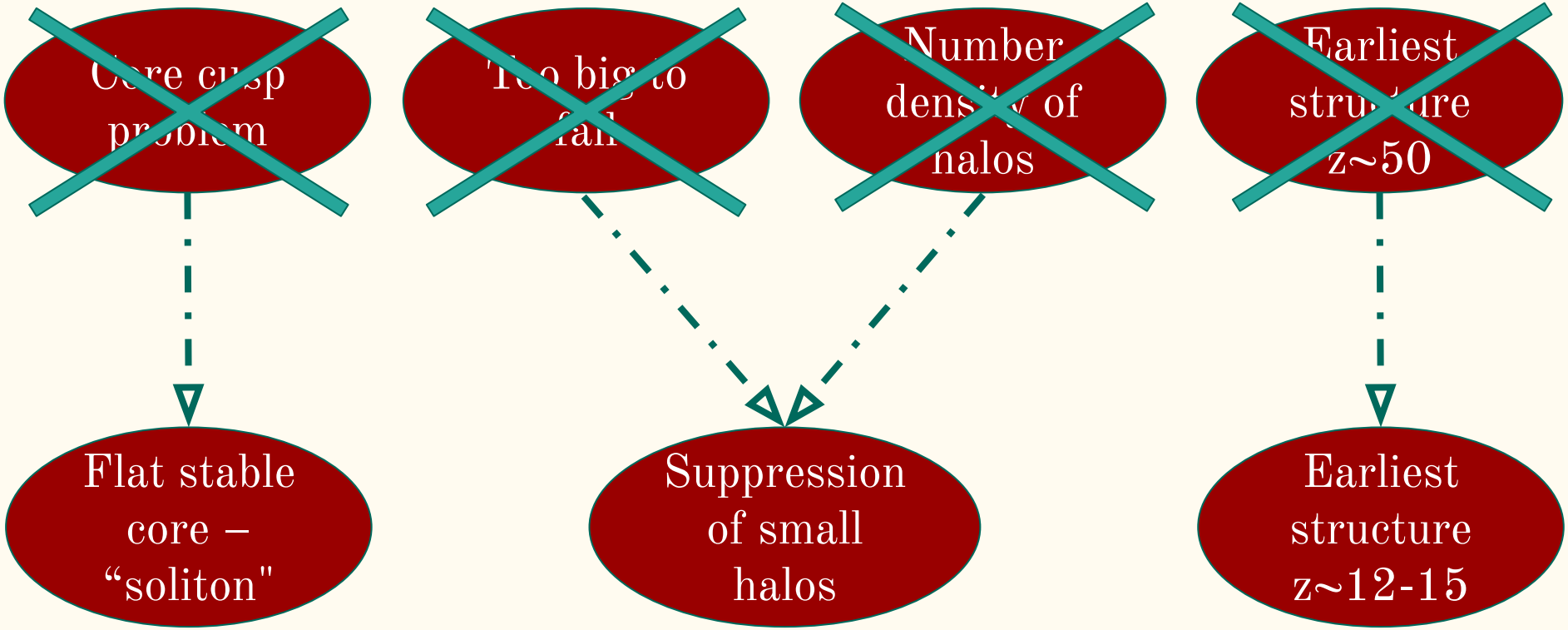
Too big to fail

Number density of halos

Earliest structure z~50

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

Cold dark matter: Issues on small scales

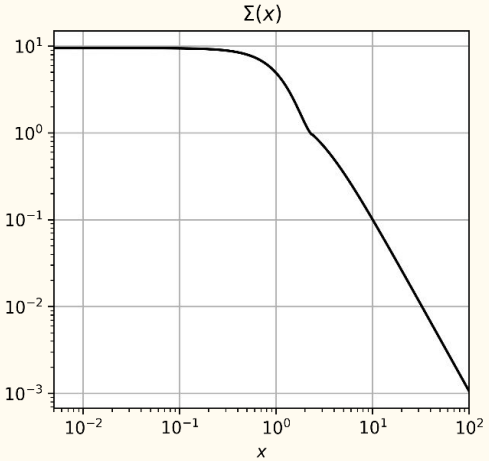


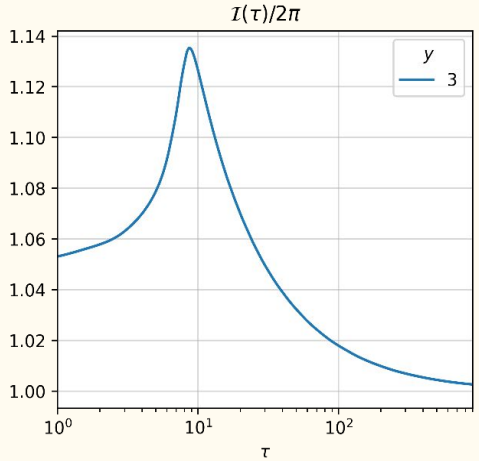
3. Lensing Features

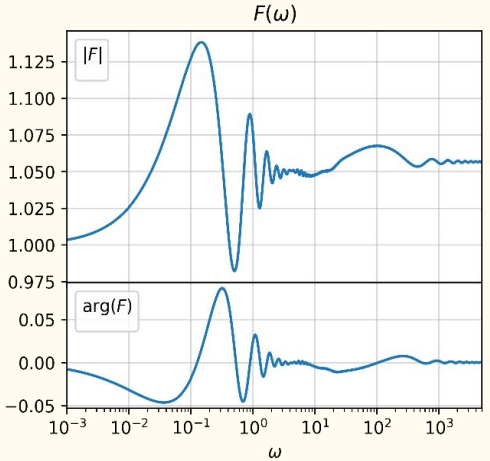
Einstein Rings of LRG 3-757 taken with the Hubble Space Telescope's Wide Field Camera 3.
Image : https://apod.nasa.gov/apod/ap111221.html

Lensing Features

FDM







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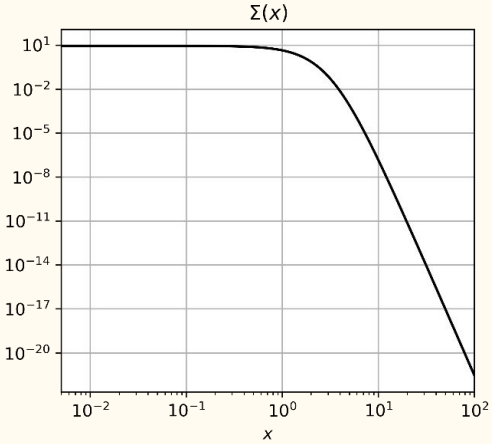

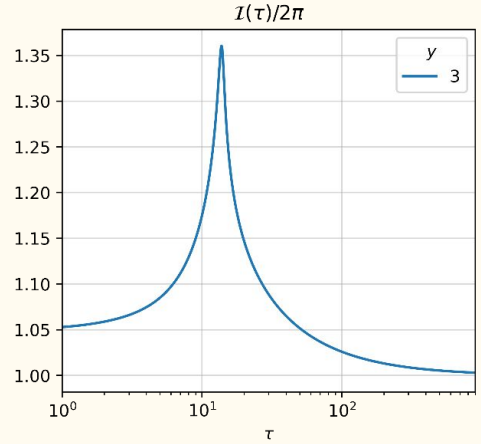

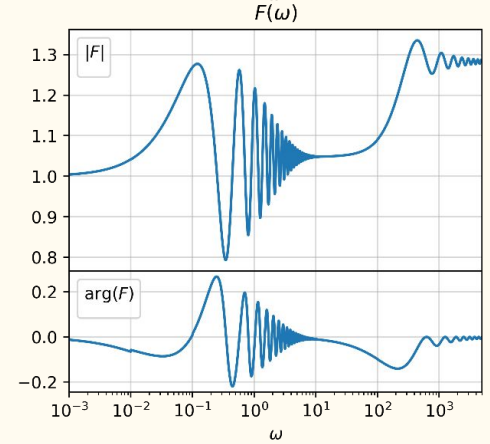

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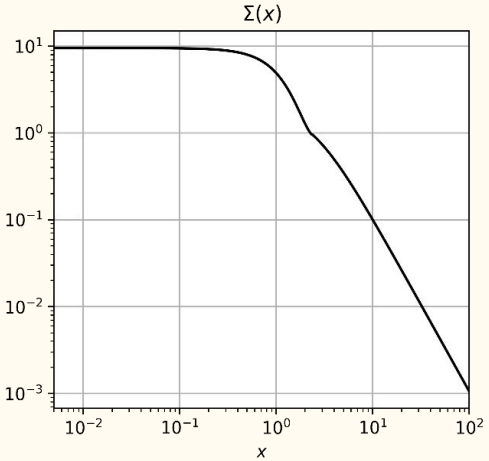

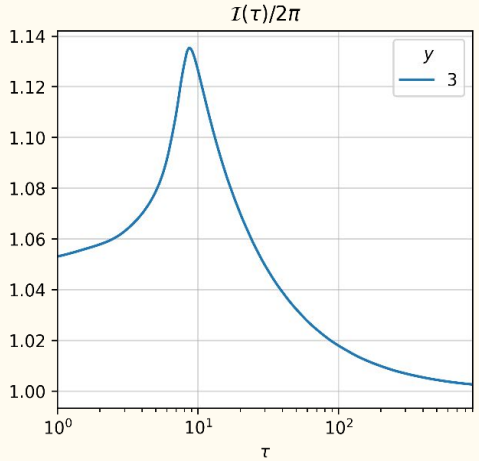

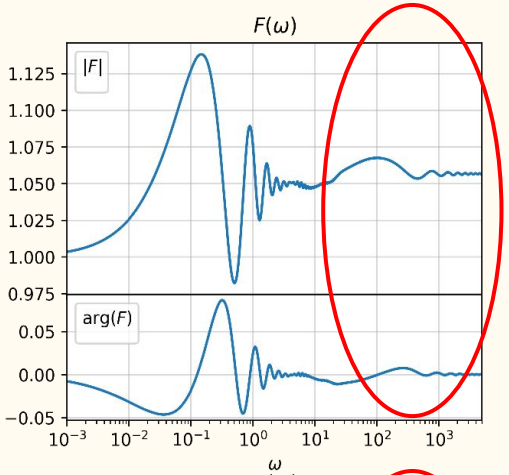

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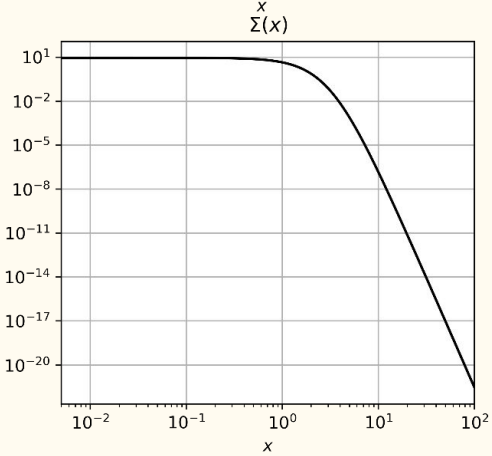

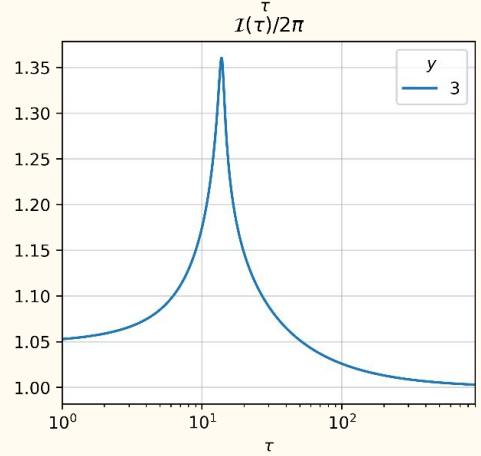

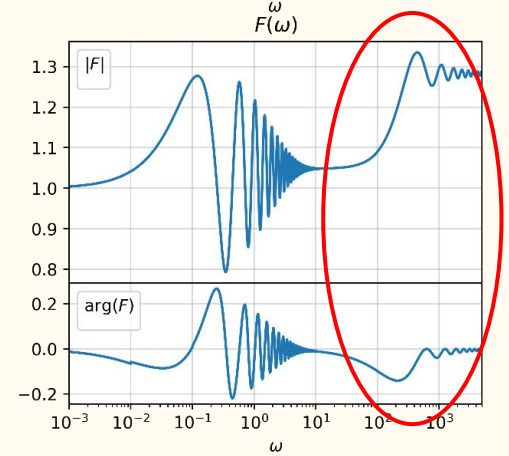

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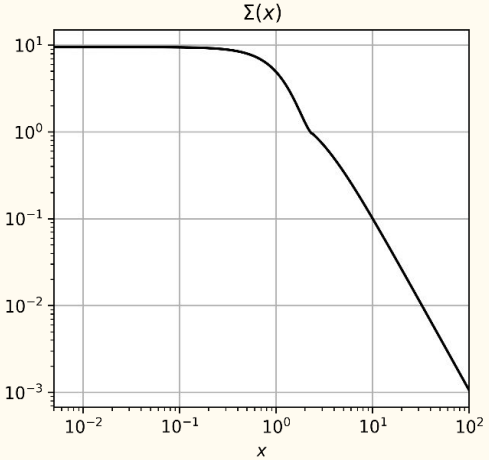

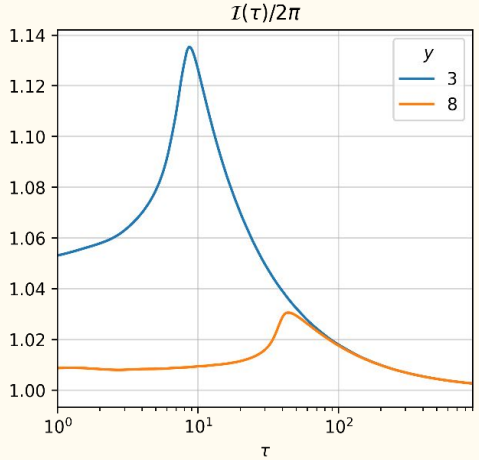

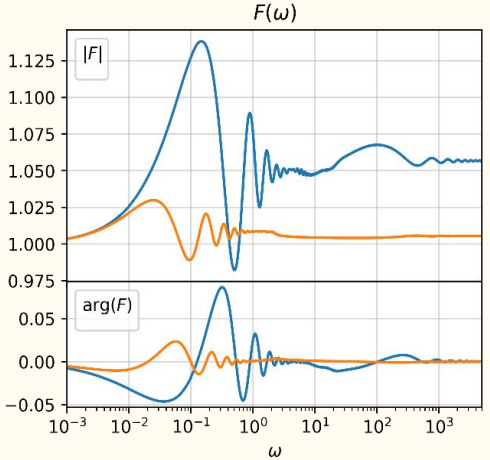

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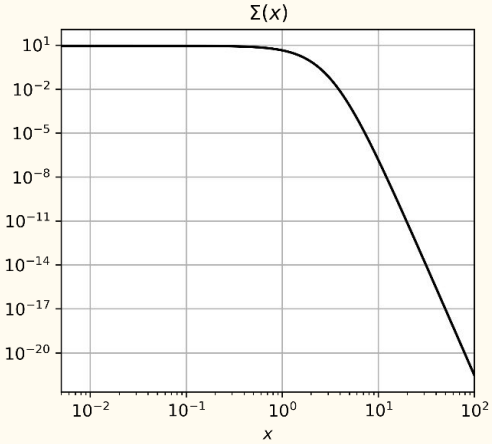

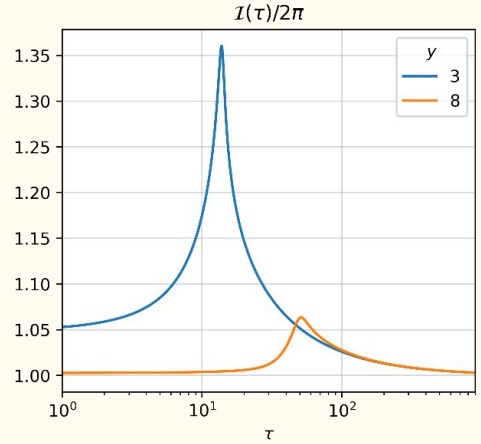

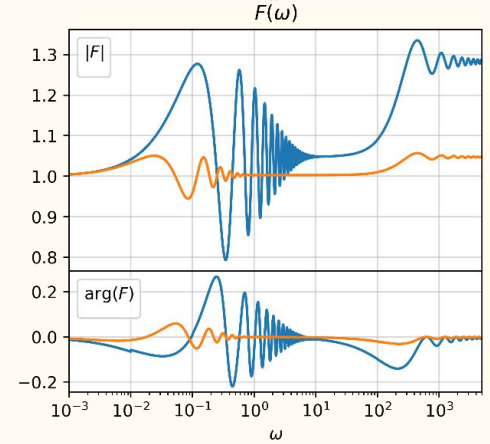

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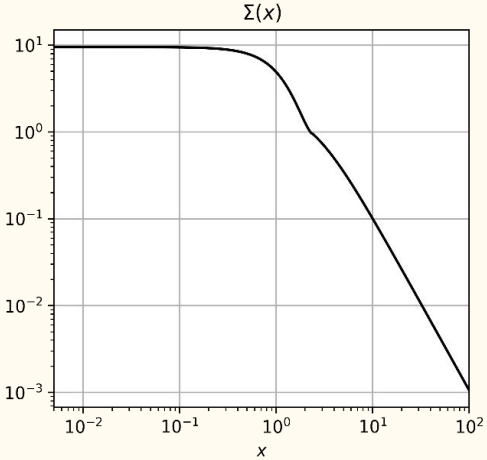

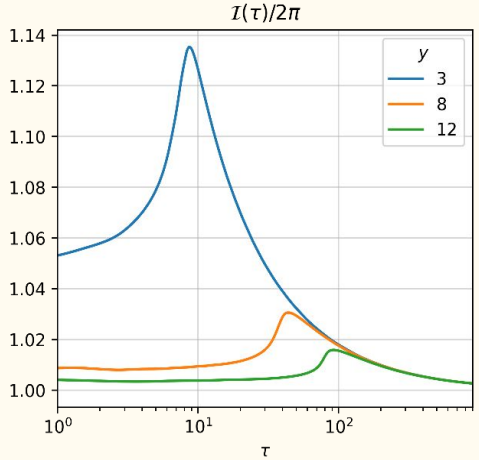

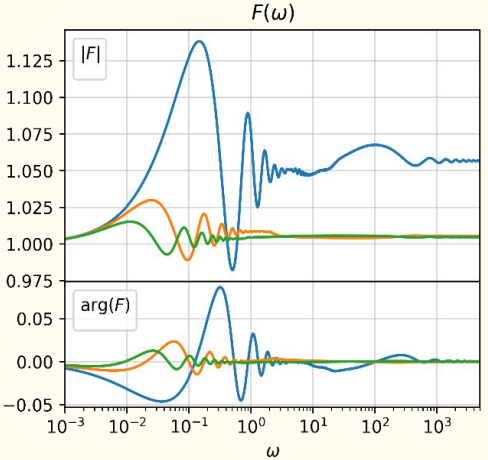

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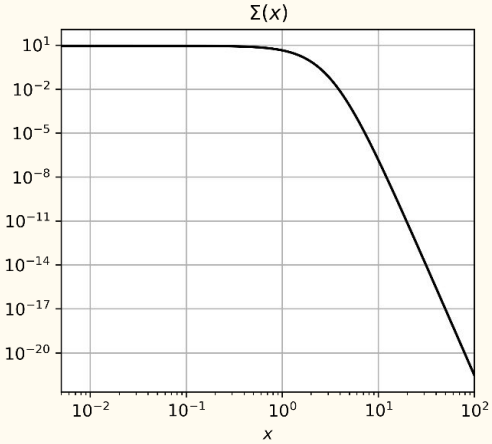

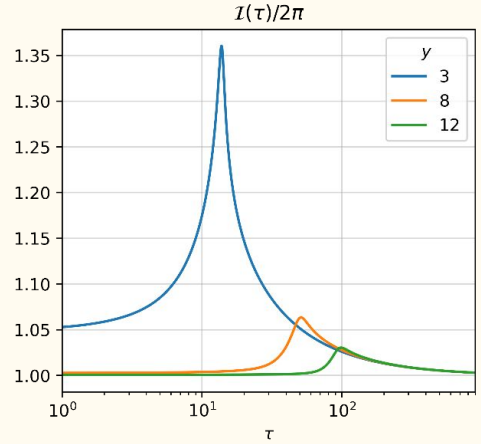

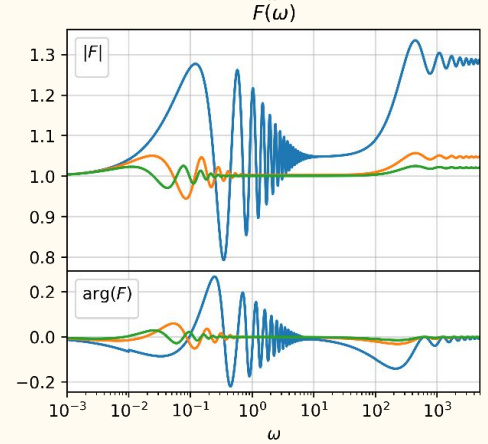

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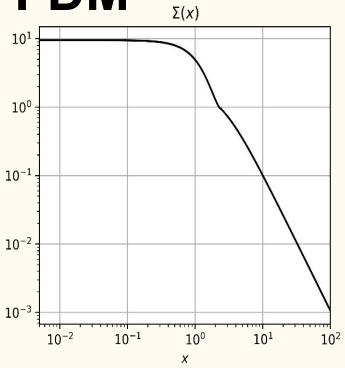
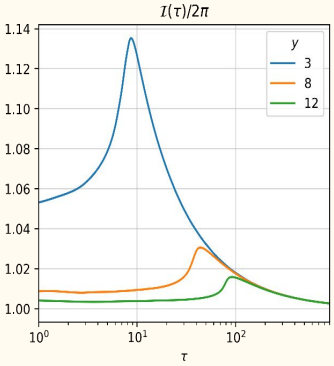
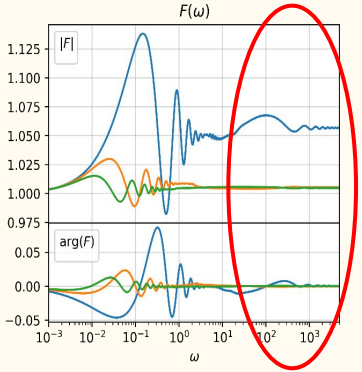
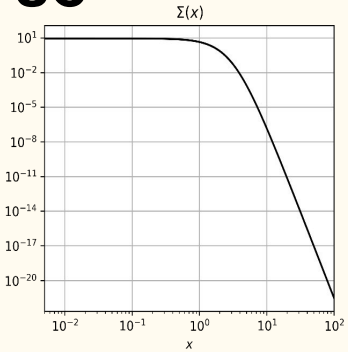
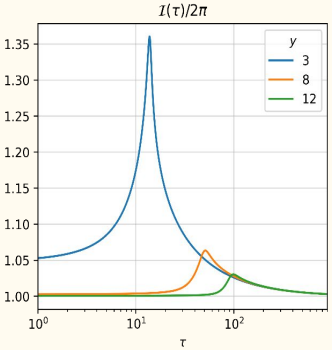


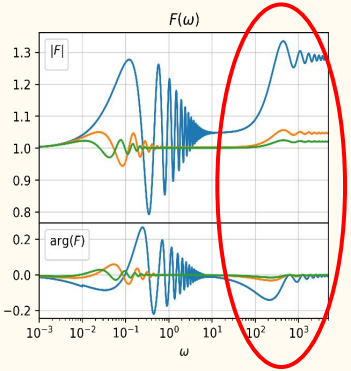




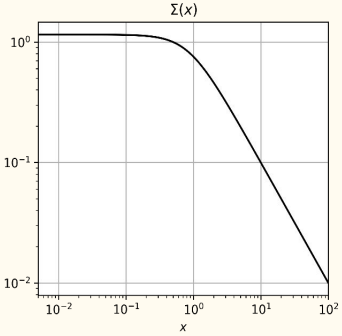
SC

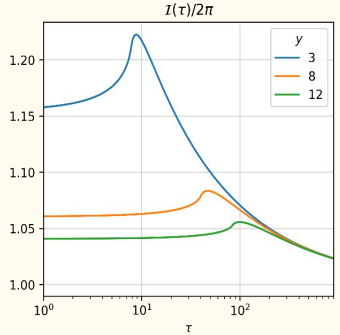


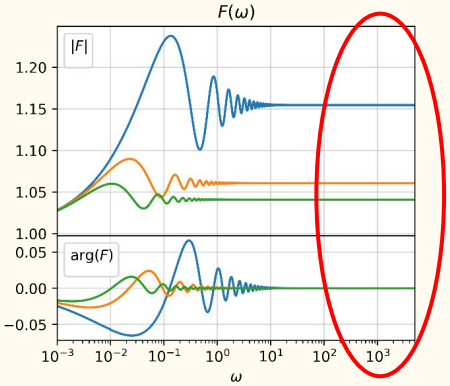




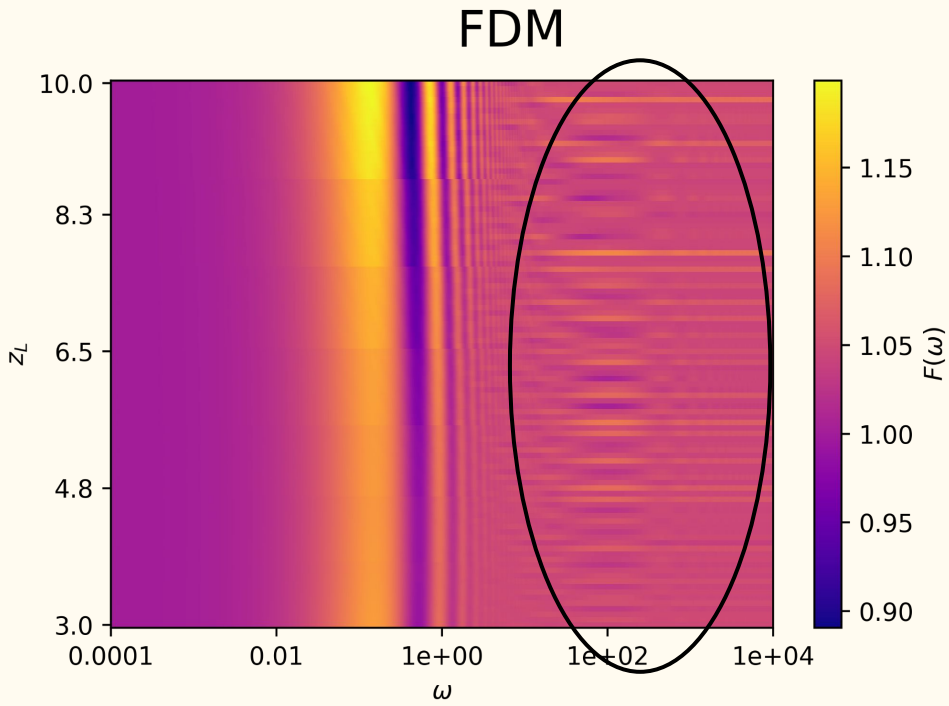
CIS

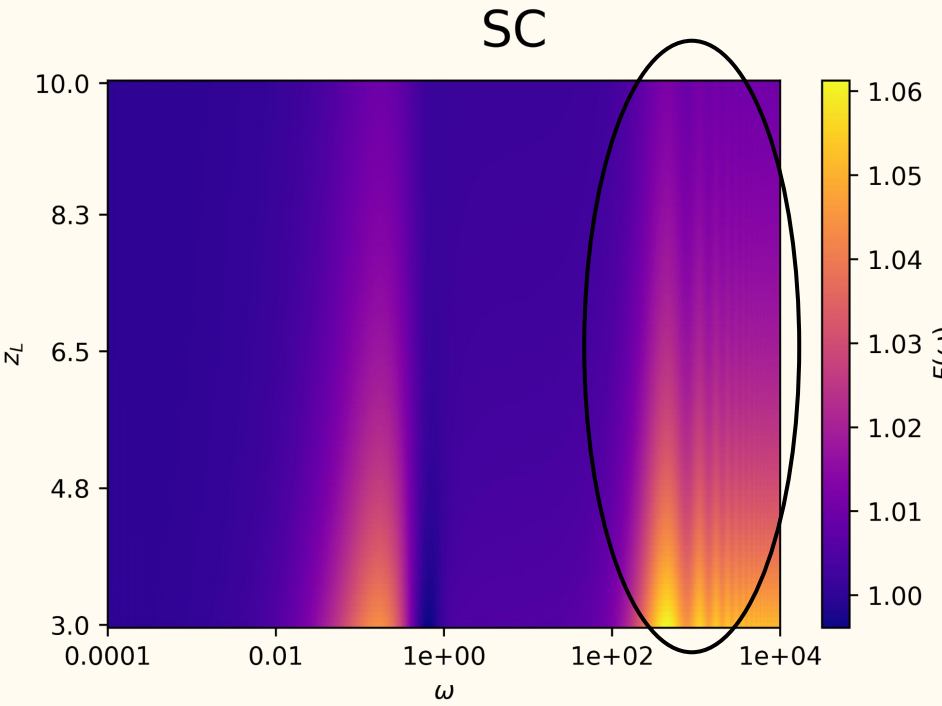






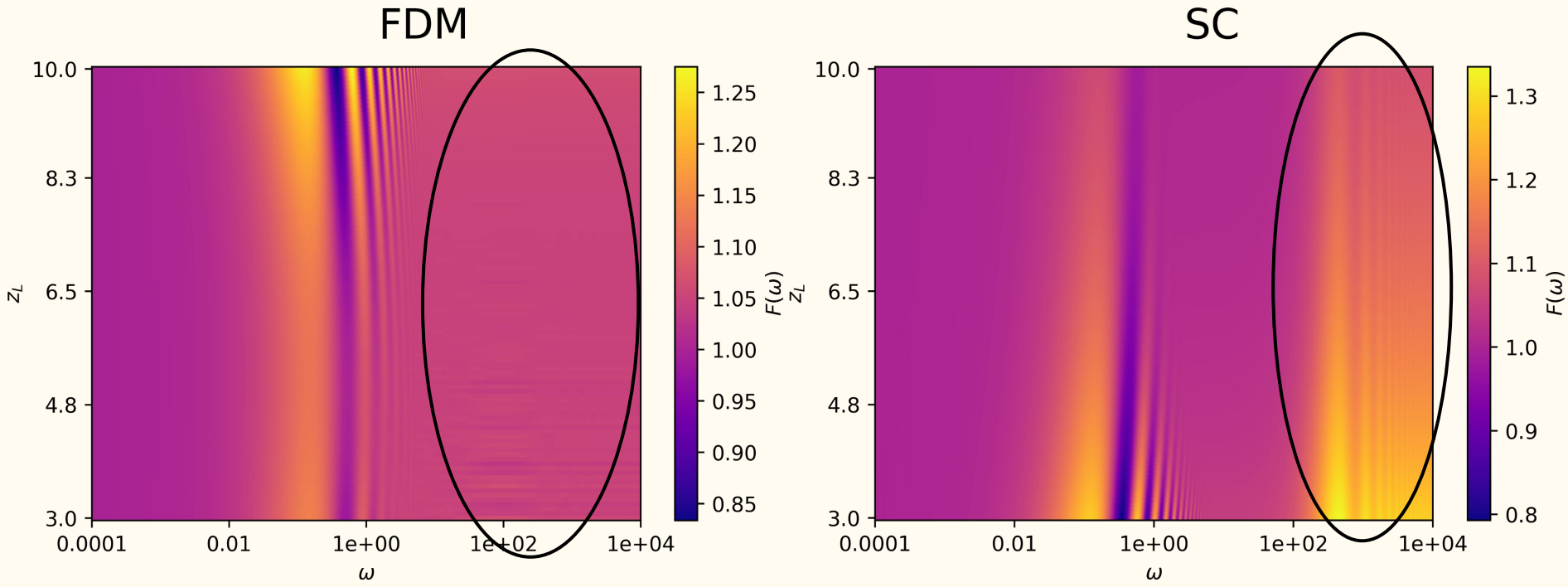
Lensing Features





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

Lensing Features



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

Lensing Features

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

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

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

Lensing Features

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

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

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

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

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

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

$M_L = 10^8 M_\odot$

$M_L = 10^9 M_\odot$

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

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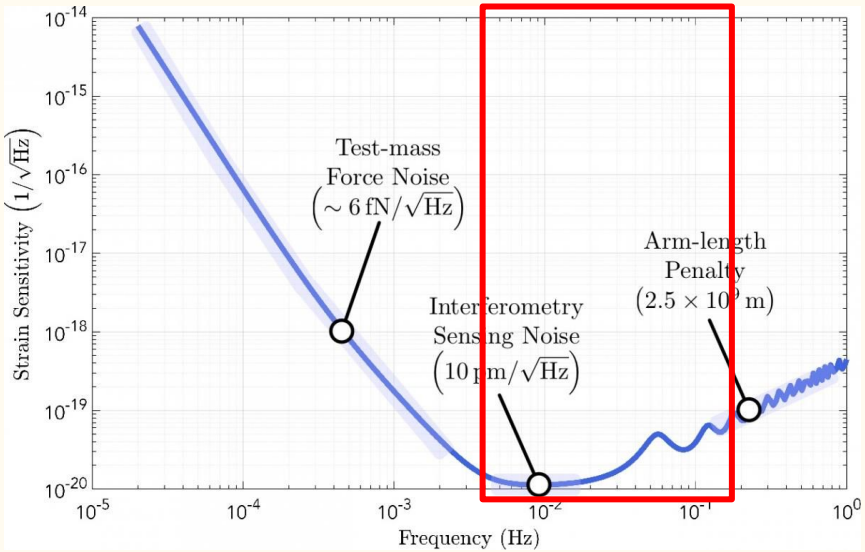
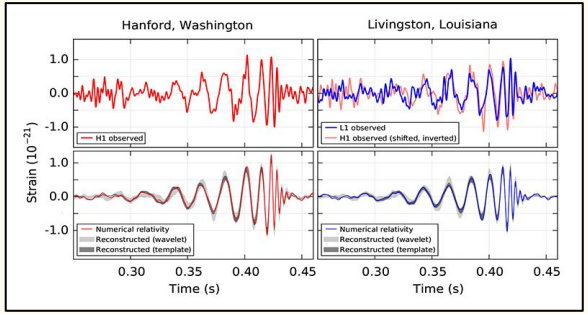


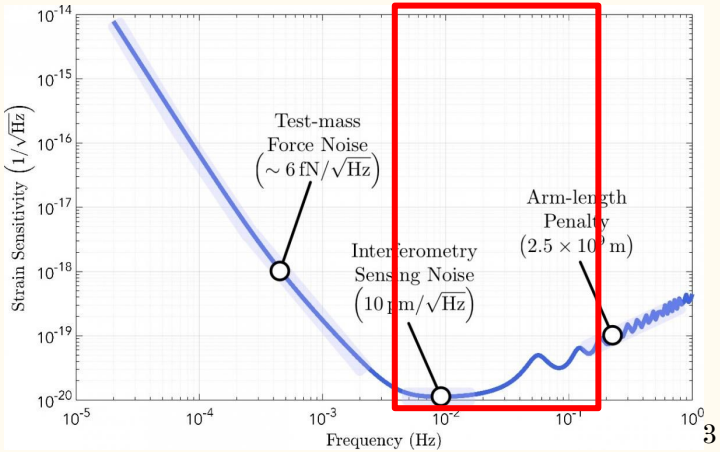
LISA sensitivity :
0.1 mHz to 1 Hz

https://www.elisascience.org/multimedia/image/lisa-sensitivity

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 †

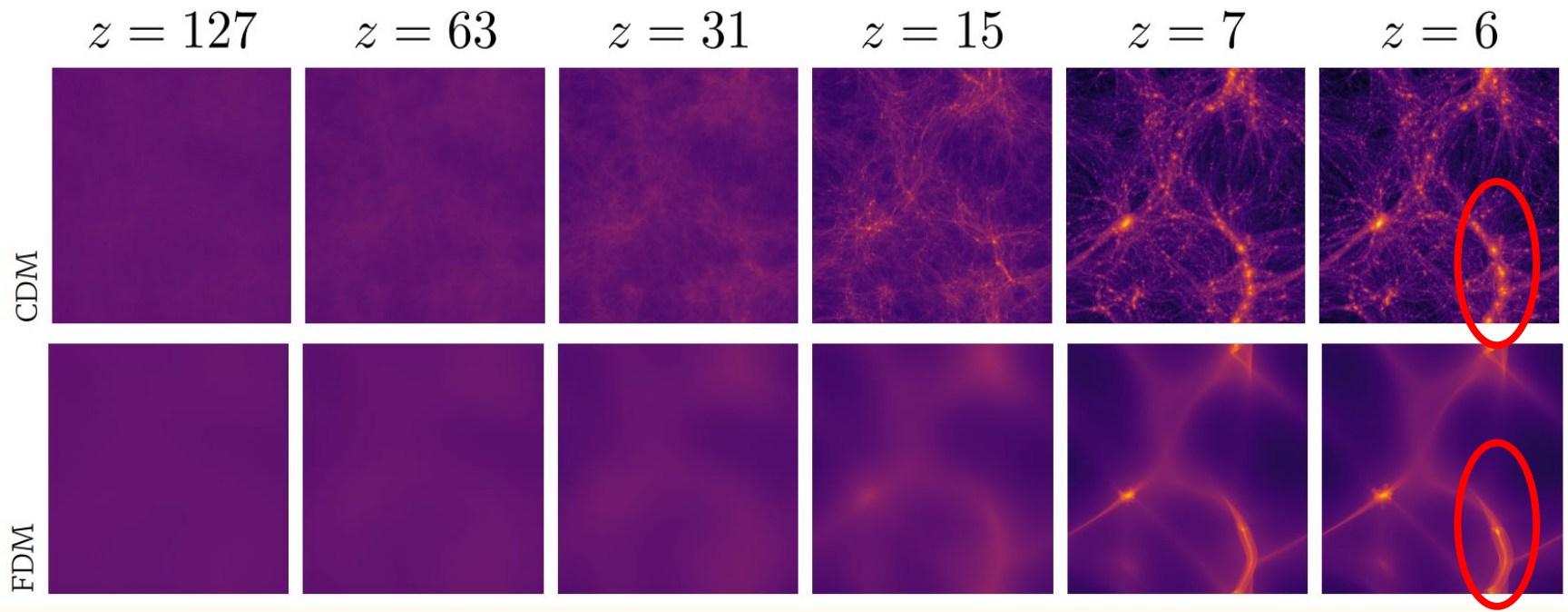


* https://arxiv.org/abs/2306.05282
† https://arxiv.org/abs/2212.11960

Thanks !!

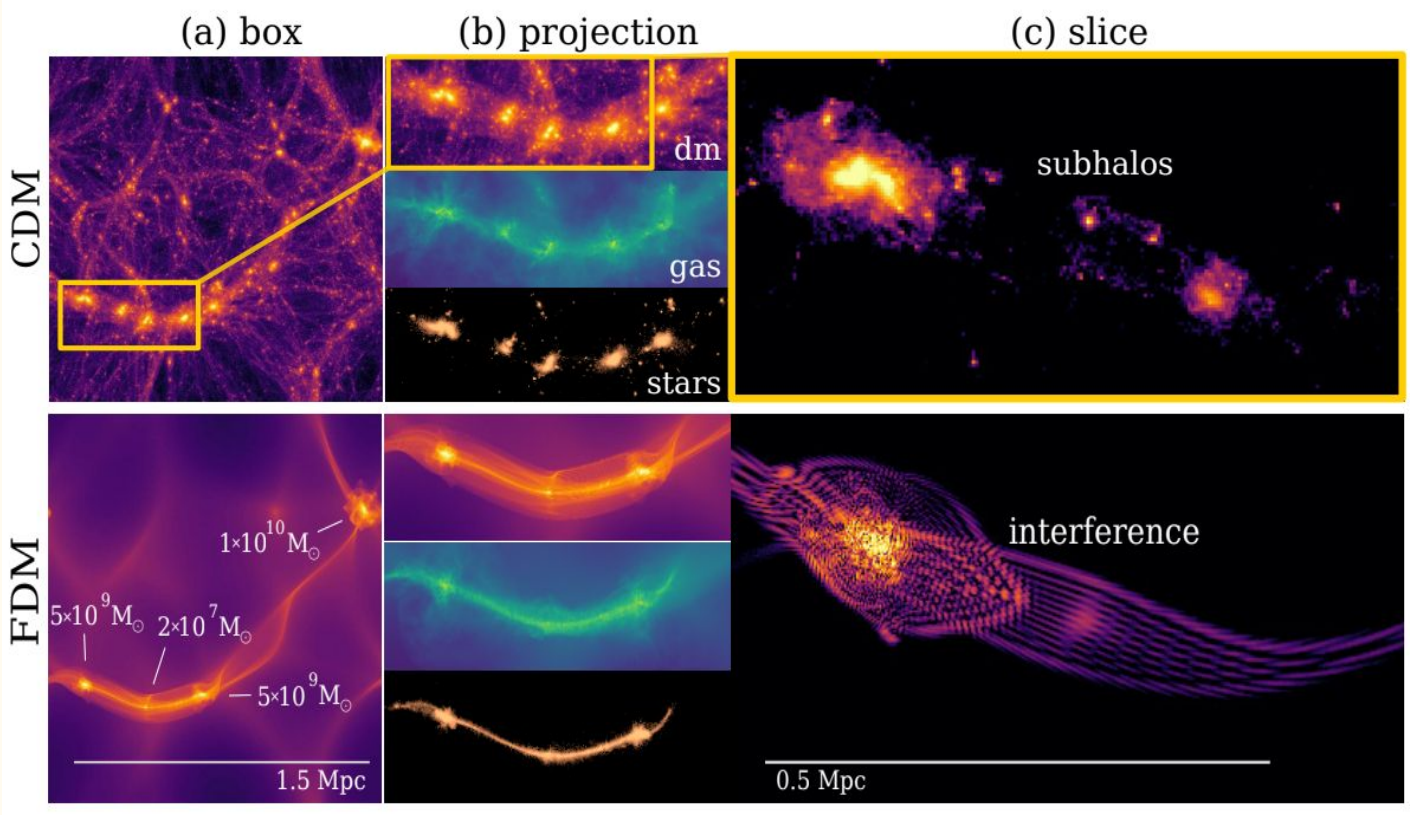
Extra Slides ..

A view of fuzzy Universe



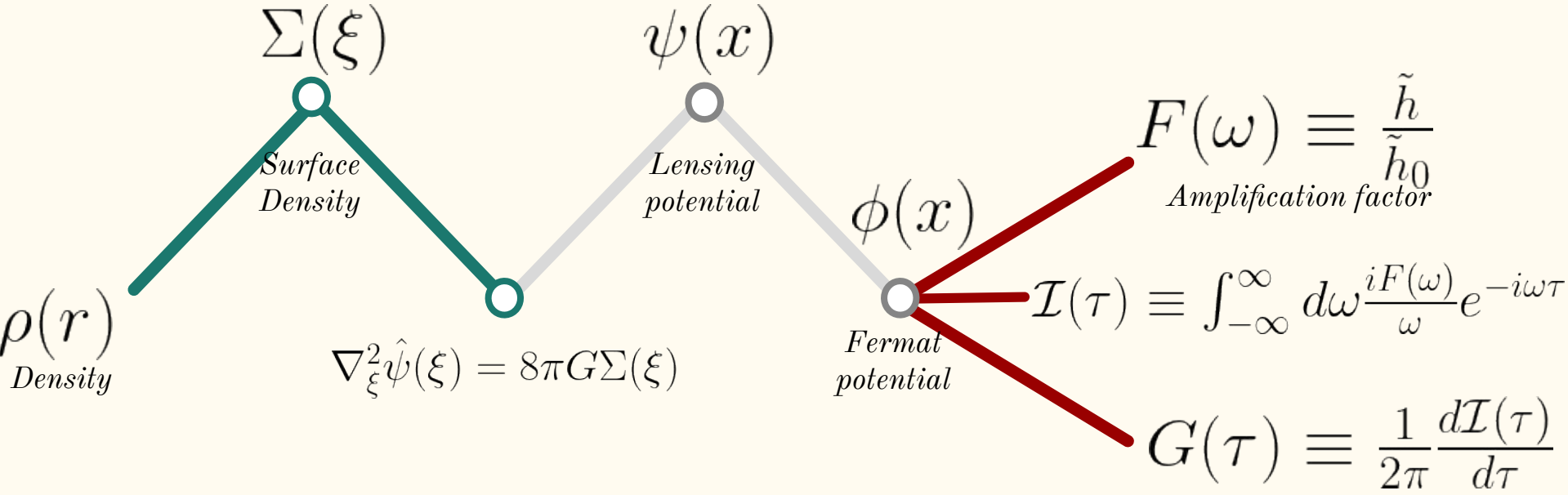
Pmócz, A. (2019). Fuzzy dark matter: overview. Retrieved from https://indico.neic.no/event/101/contributions/366/attachments/154/245/pmocz_2019_09_30_reykjavic.pdf

A view of fuzzy Universe

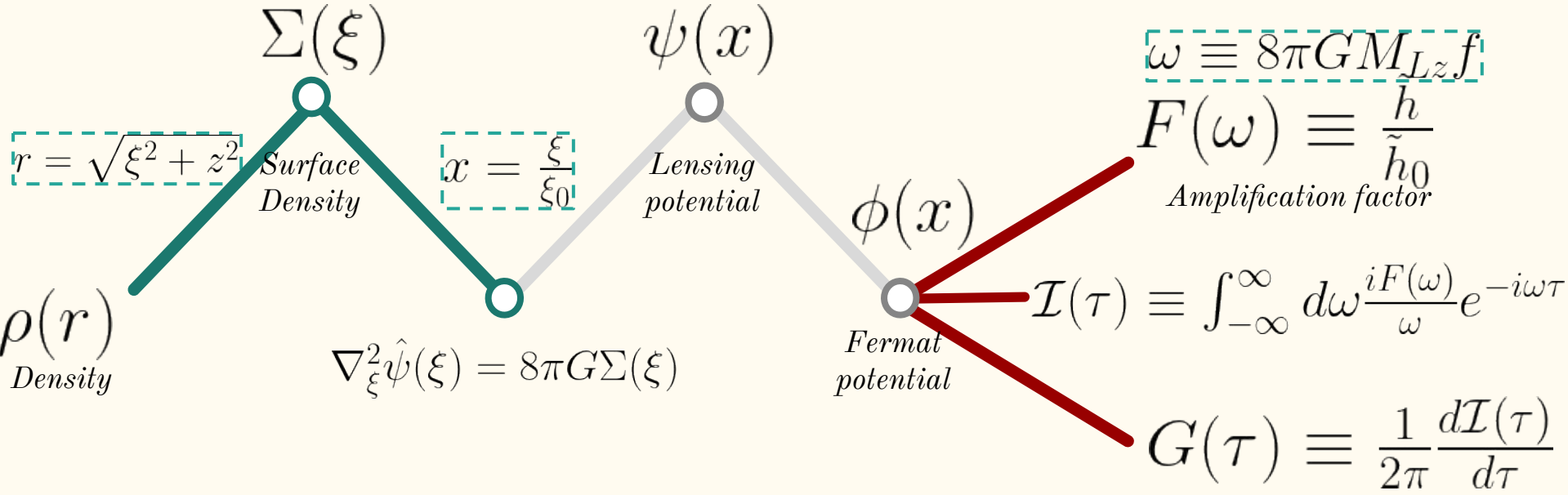


Pmócz, A. (2019). Fuzzy dark matter: overview. Retrieved from https://indico.neic.no/event/101/contributions/366/attachments/154/245/pmocz_2019_09_30_reykjavic.pdf

Gravitational Wave Lensing – Theory



Gravitational Wave Lensing – Theory



$$M_{Lz} \equiv \frac{\xi_0^2}{4G d_{\mathtt{eff}}}$$