Title: How Lensed Gravitational Waves Can Illuminate Dark Matter

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How Lensed Gravitational Waves Can Illuminate Dark Matter*

Mesut Çalışkan[1,α],

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Perimeter Institute – 25 Nov 2024

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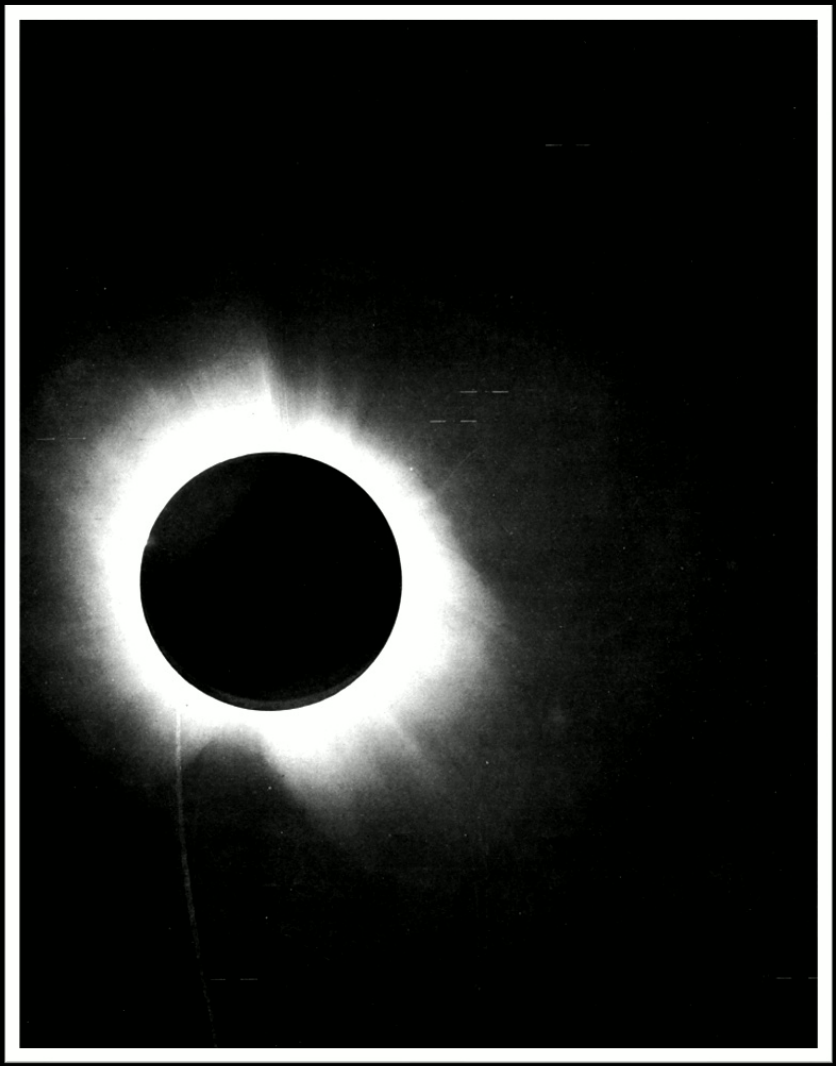
* arXiv: **2201.04619, 2206.02803, 2307.06990**

Dark Matter

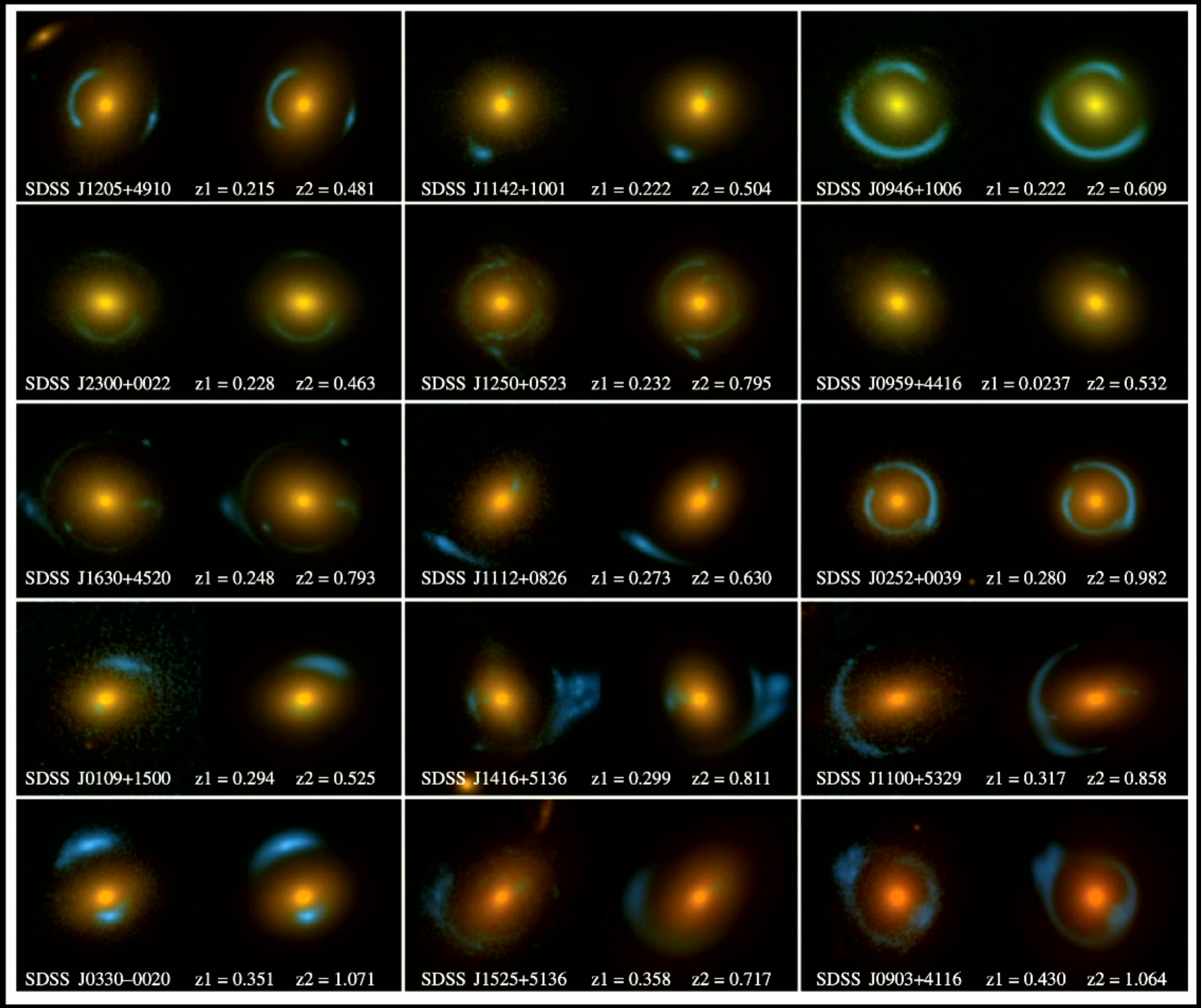
Gravitational Waves

"Do not Bodies act upon Light at a distance, and by their action bend its rays; and is not this action strongest at the least distance?"

Isaac Newton – *Opticks* (1704)



F. W. Dyson, A. S. Eddington, and C. Davidson (1920)



Ellis et al. (2010) & Sloan Lens ACS (SLACS) Survey

Current techniques are limited to probing dark-matter structures heavier than $\sim 10^8\ M_\odot$.

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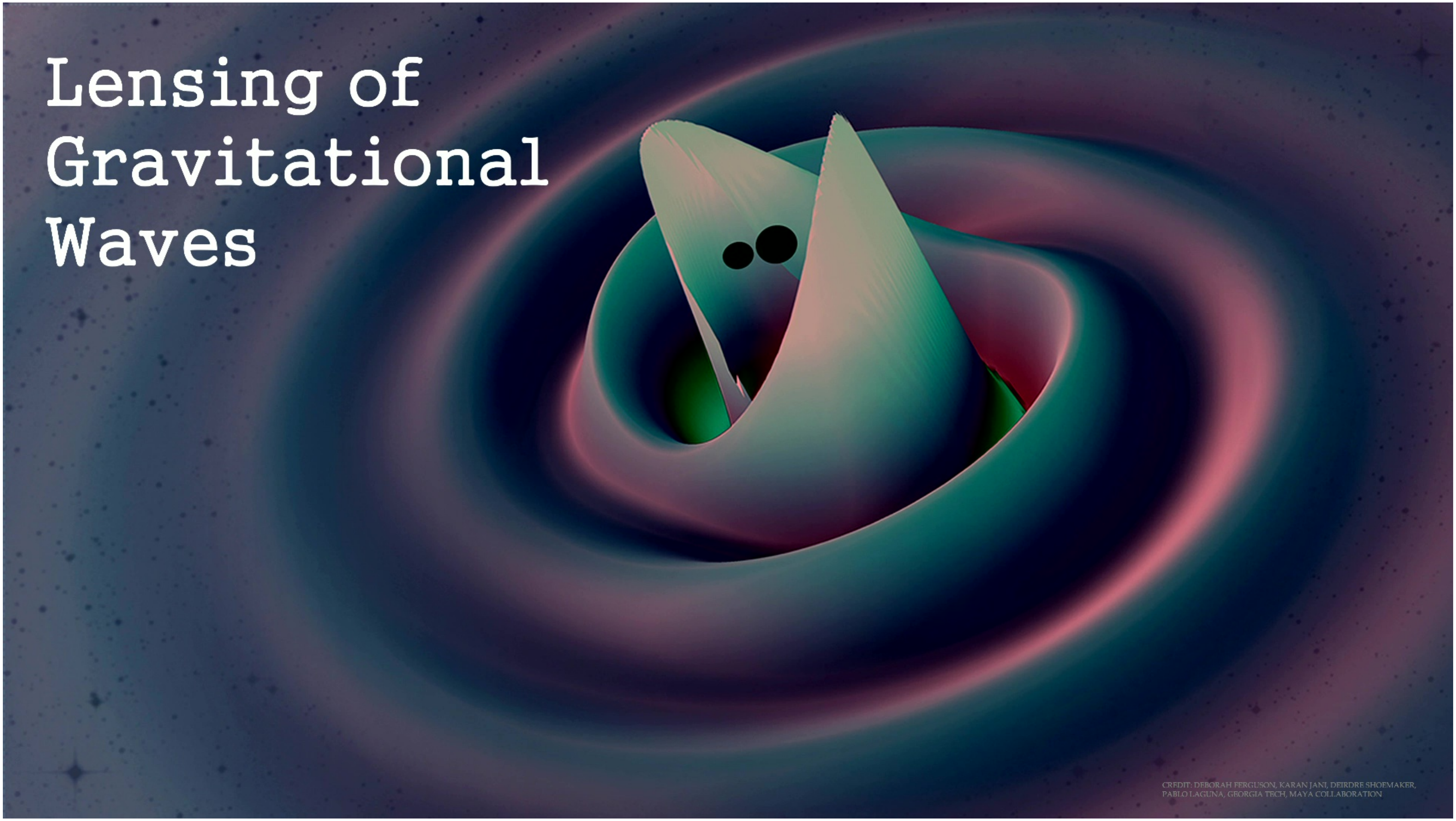
Probing the substructures within DM halos remains challenging because of their faint luminosity and low masses, which lead to much lower detection probabilities.

Testbed for the Nature of Dark Matter


Lensing of Gravitational Waves
CREDIT: DEBORAH FERGUSON, KARAN JANI, DEIRDRE SHOEMAKER, PABLO LAGUNA, GEORGIA TECH, MAYA COLLABORATION

Mass

Profile

Number Density

Strong Lensing of GWs

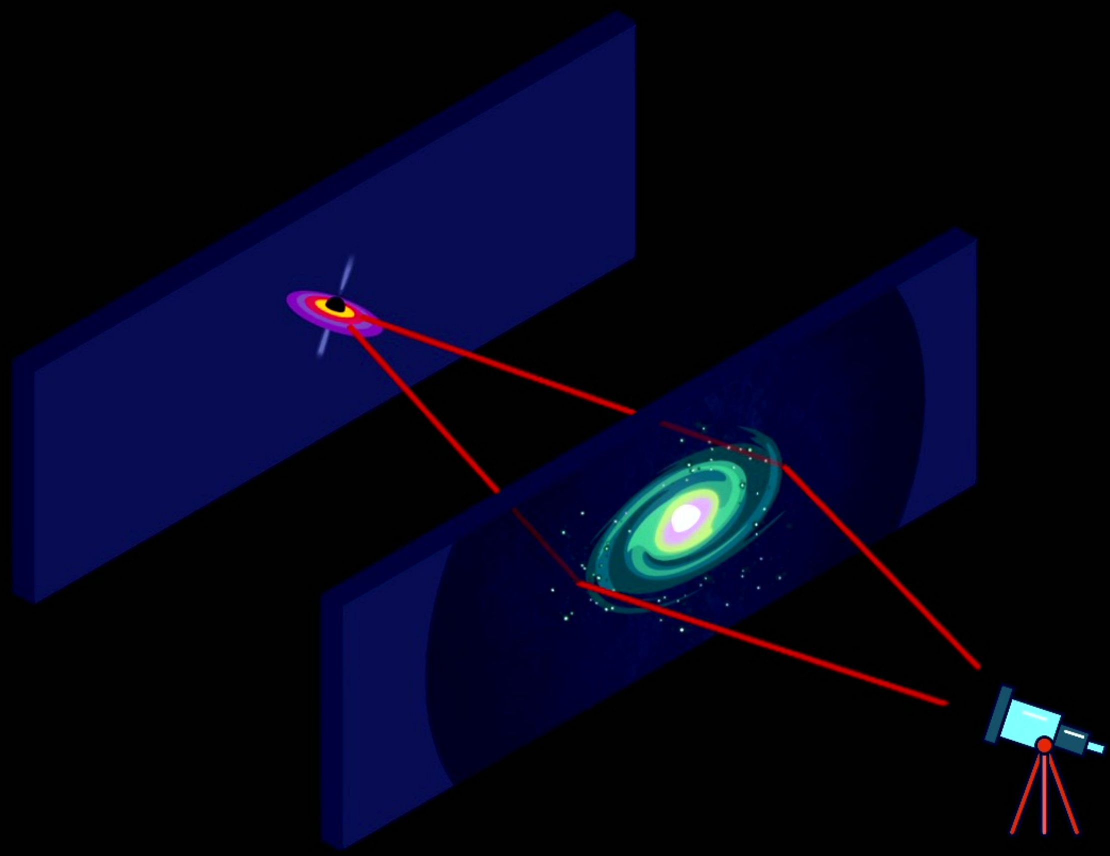


Illustration by Neha Anil Kumar

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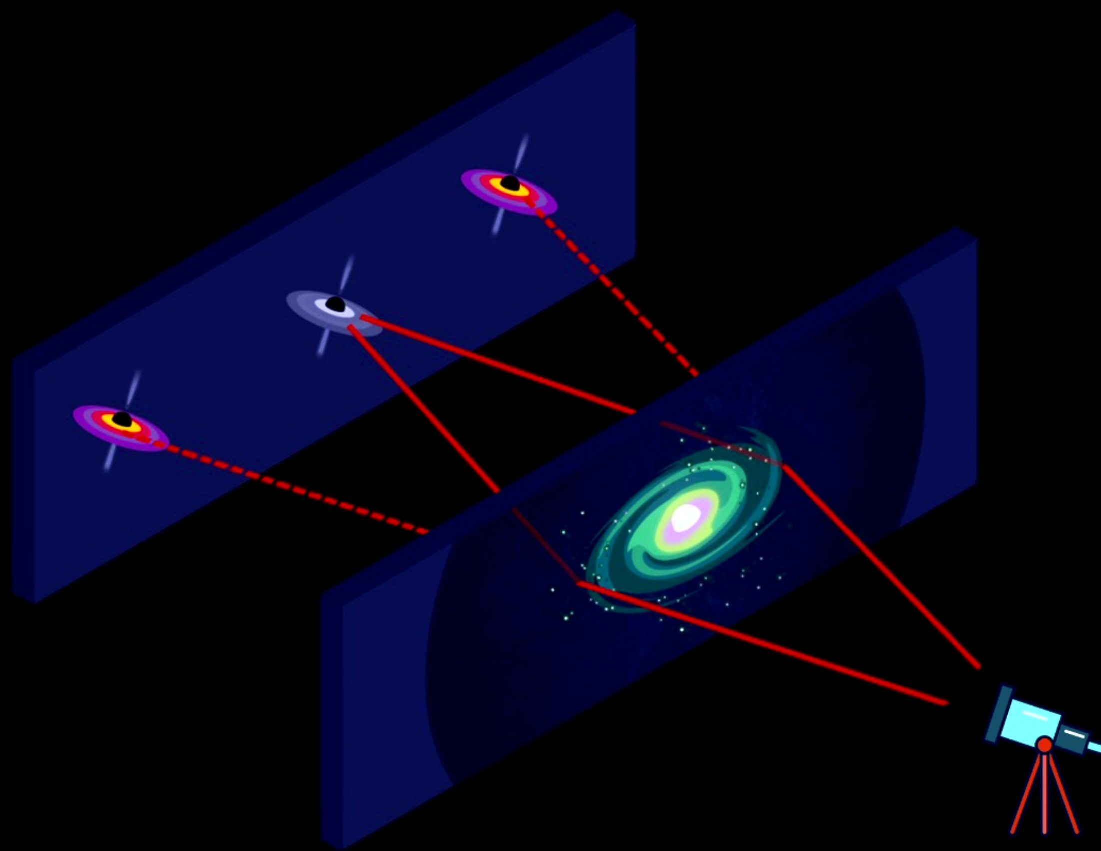
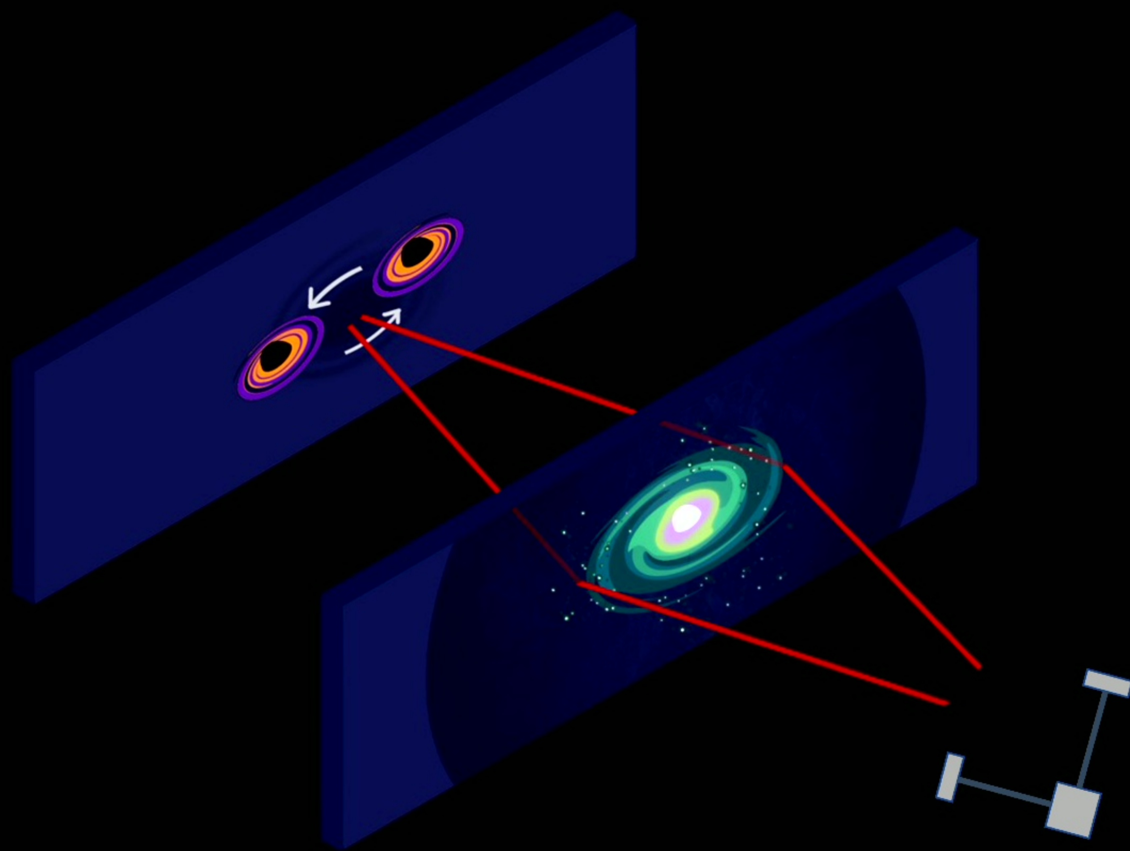


Illustration by Neha Anil Kumar



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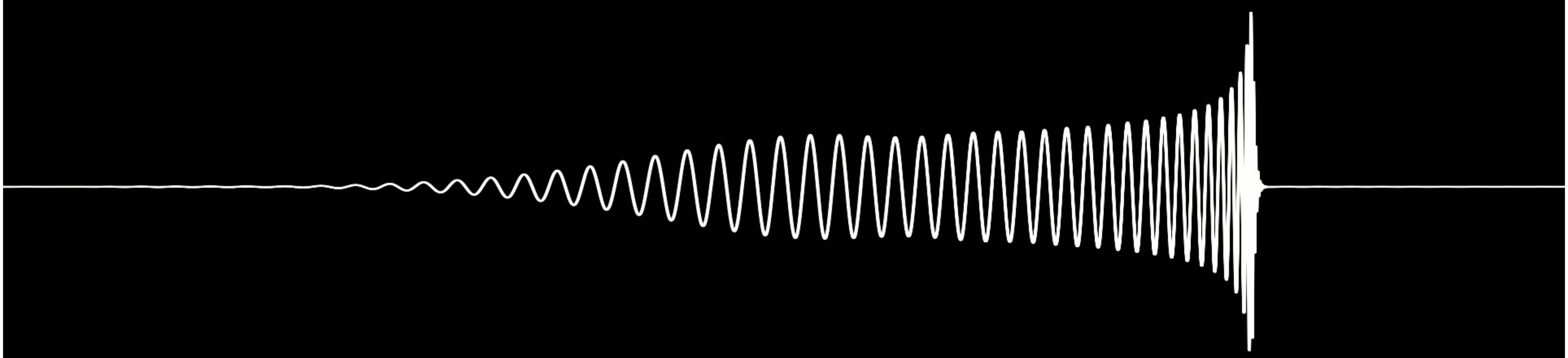
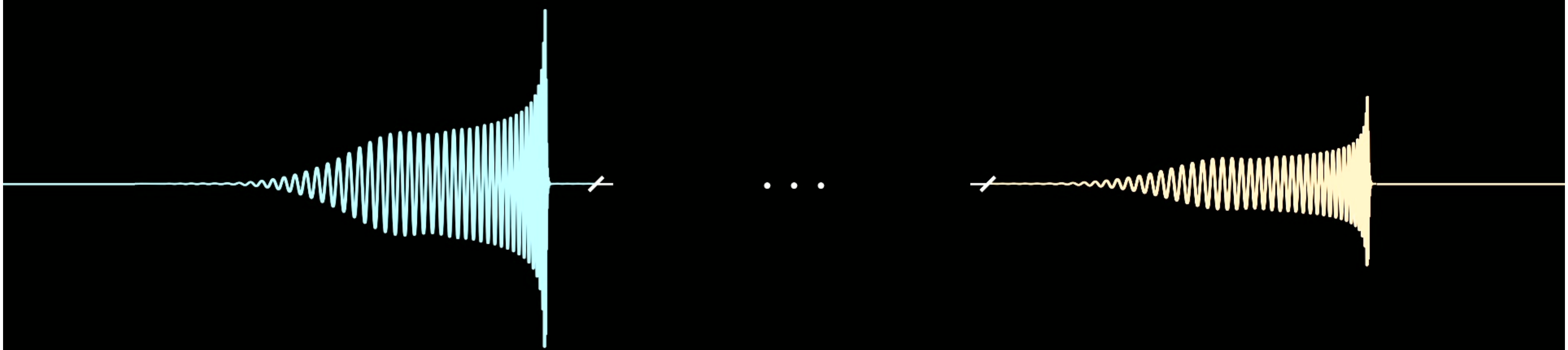
Unlensed Waveform



Strongly Lensed Waveforms



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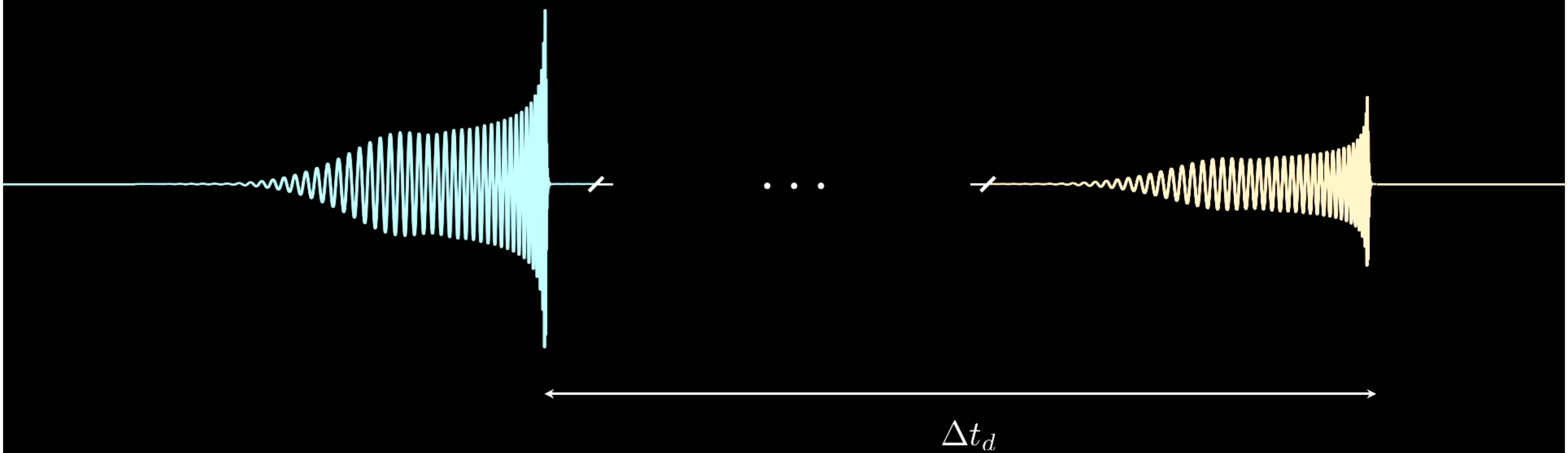
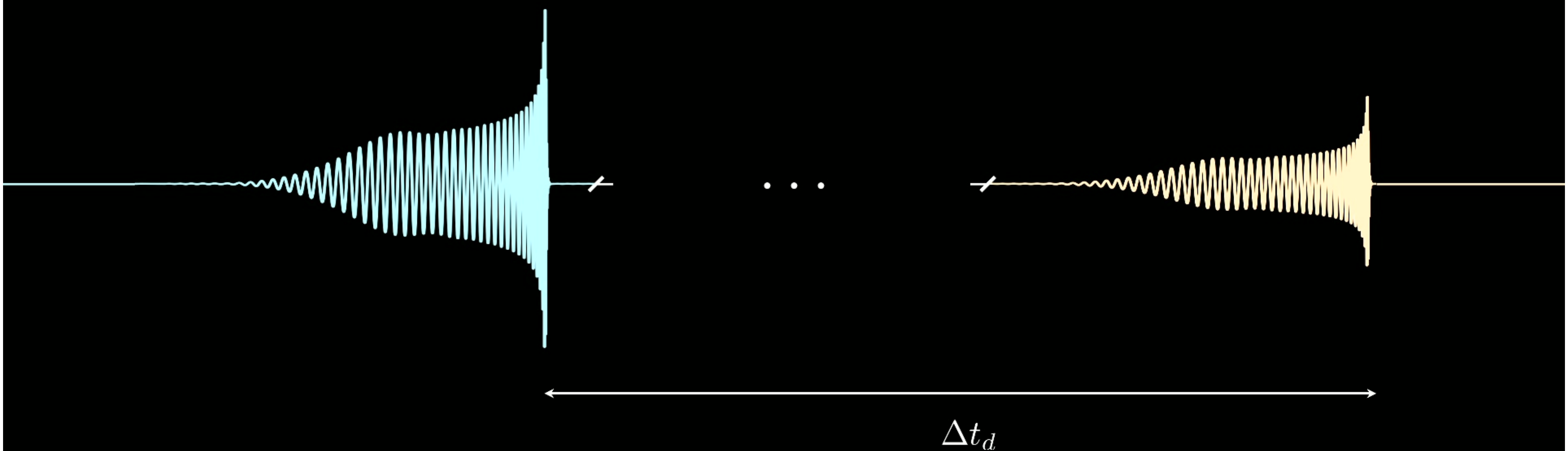
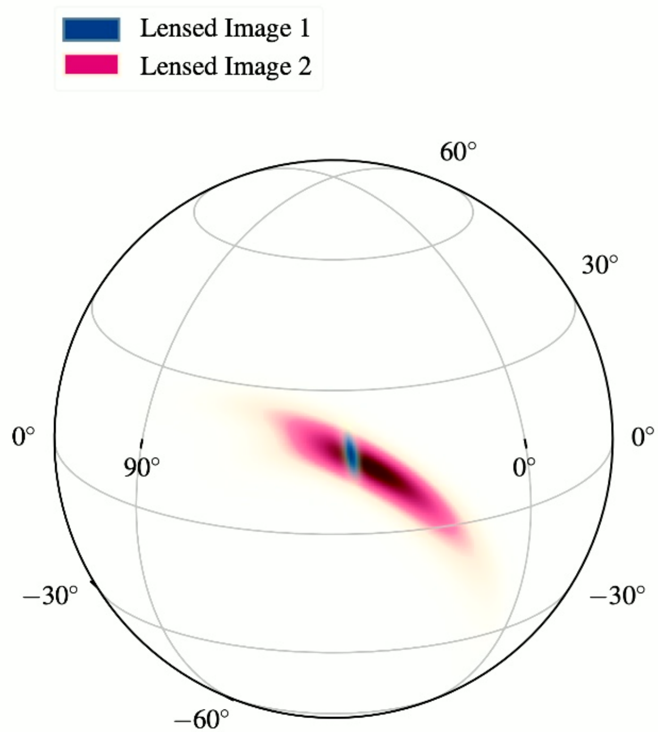
Strongly Lensed Waveforms



Strongly Lensed Waveforms

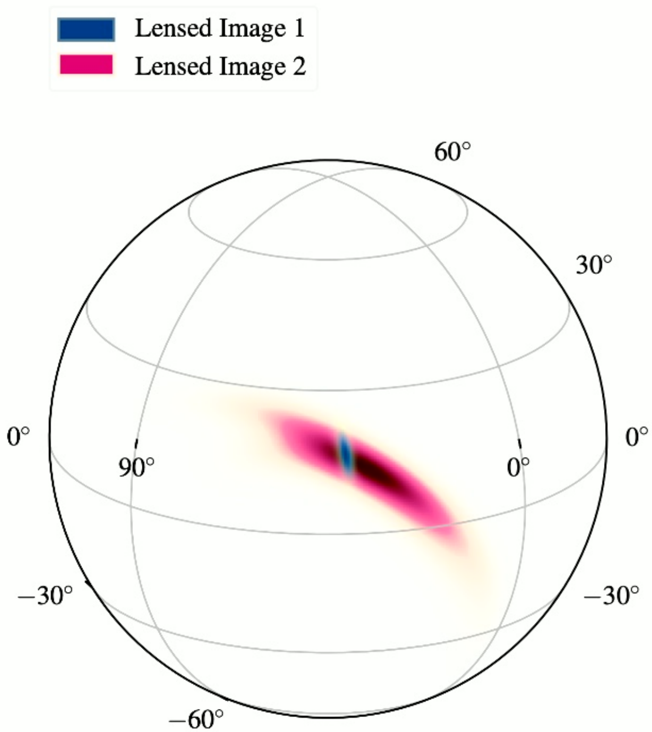


- Candidate: Dai et al. (2020)

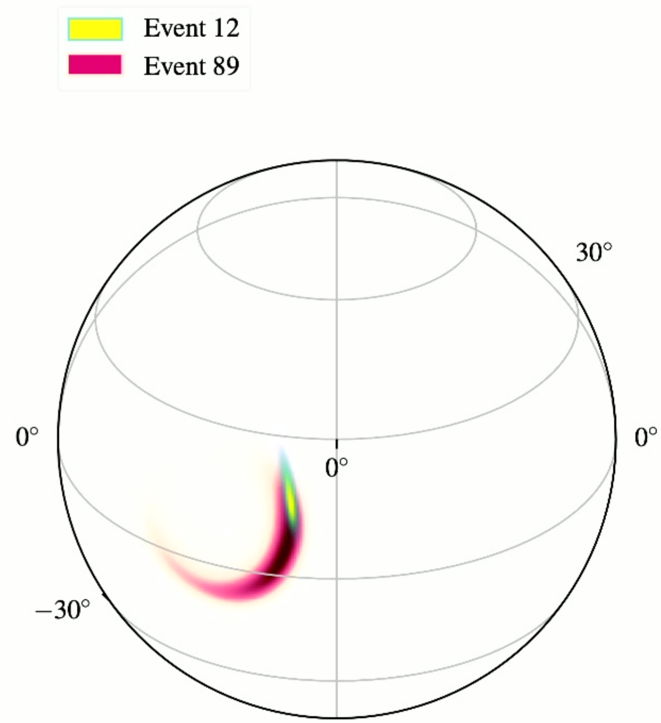


(a) lensed

[2] **Çalışkan** et al. (2022)



(a) lensed



(b) not lensed

[2] **Çalışkan** et al. (2022)

False Alarm Probability

$$\sim \frac{1}{10^4}$$

[2] **Çalışkan** et al. (2022)

Strong Lensing Rate?

$$\sim \frac{1}{10^3}$$

Li et al. (2018)

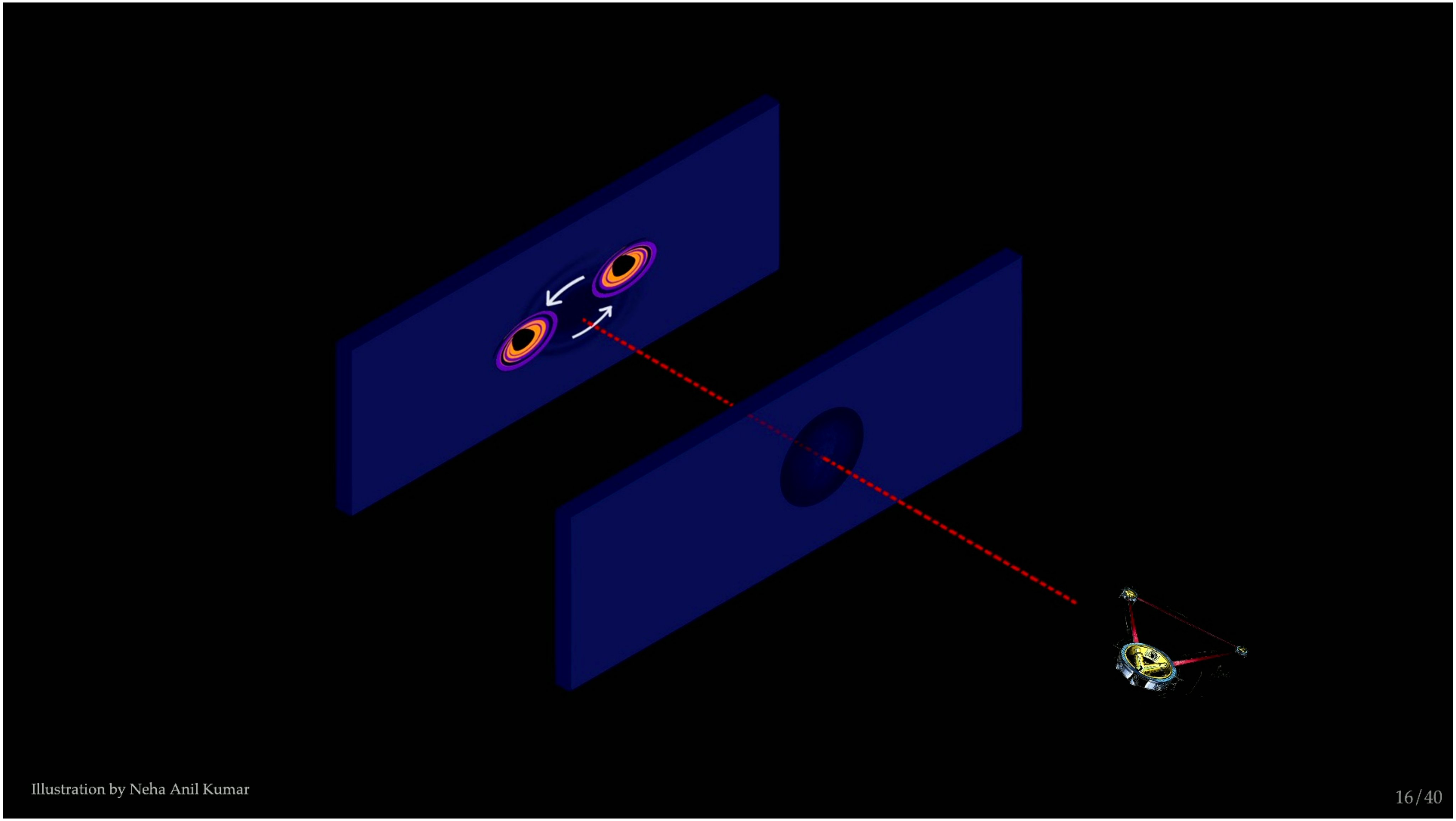
$$N_{\text{lensed}} \propto N_{\text{events}}$$

[2] **Çalışkan** et al. (2022)

$$N_{\text{lensed}} \propto N_{\text{events}}$$
$$N_{\text{false alarms}} \propto N_{\text{events}}^2$$

[2] **Çalışkan** et al. (2022)

What if the lens is smaller?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Wave-Optics Effects

Wave-Optics Effects

$$M_L \lesssim 10^5\, M_\odot \left(\frac{f}{\mathrm{Hz}}\right)^{-1}$$

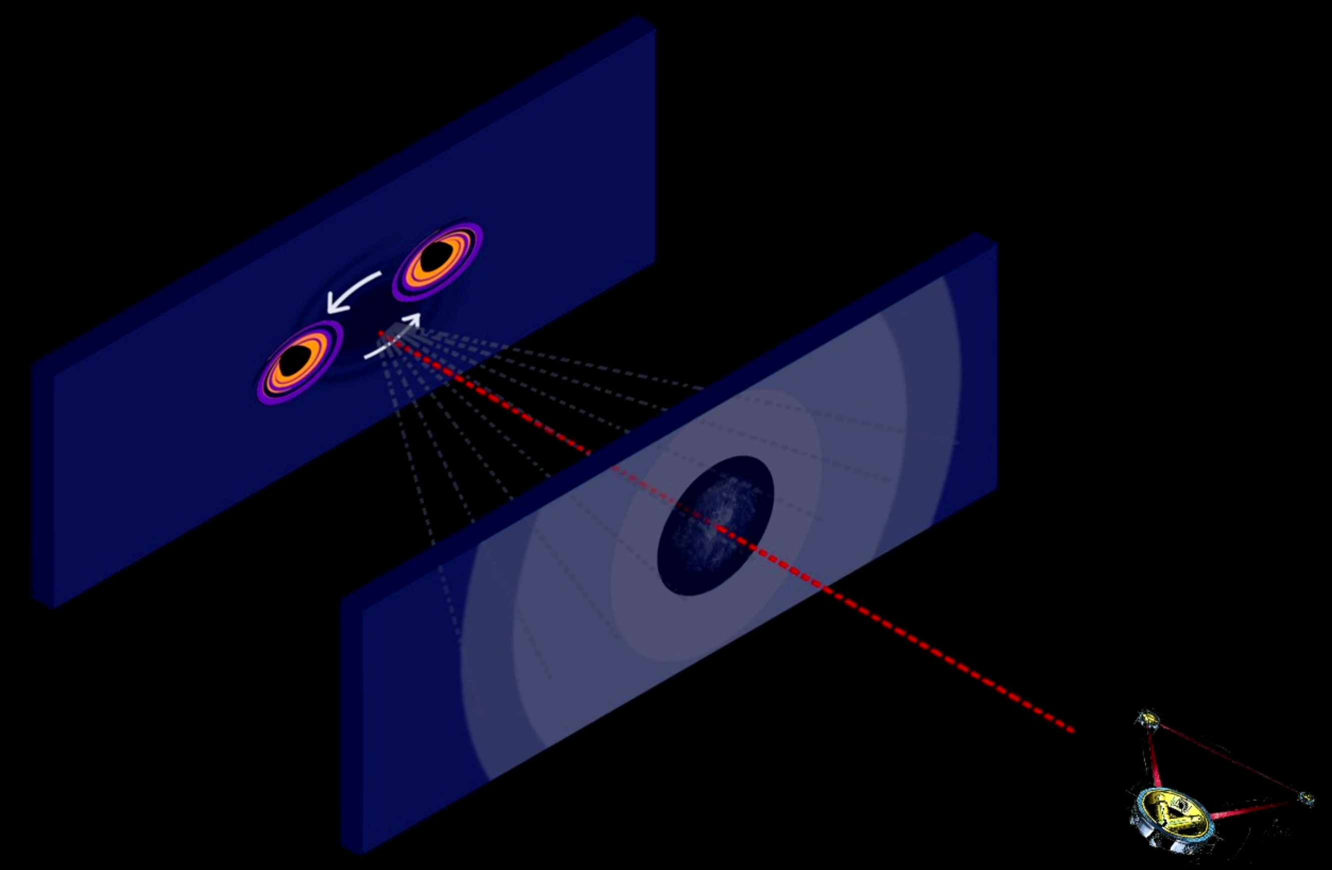

Illustration by Neha Anil Kumar

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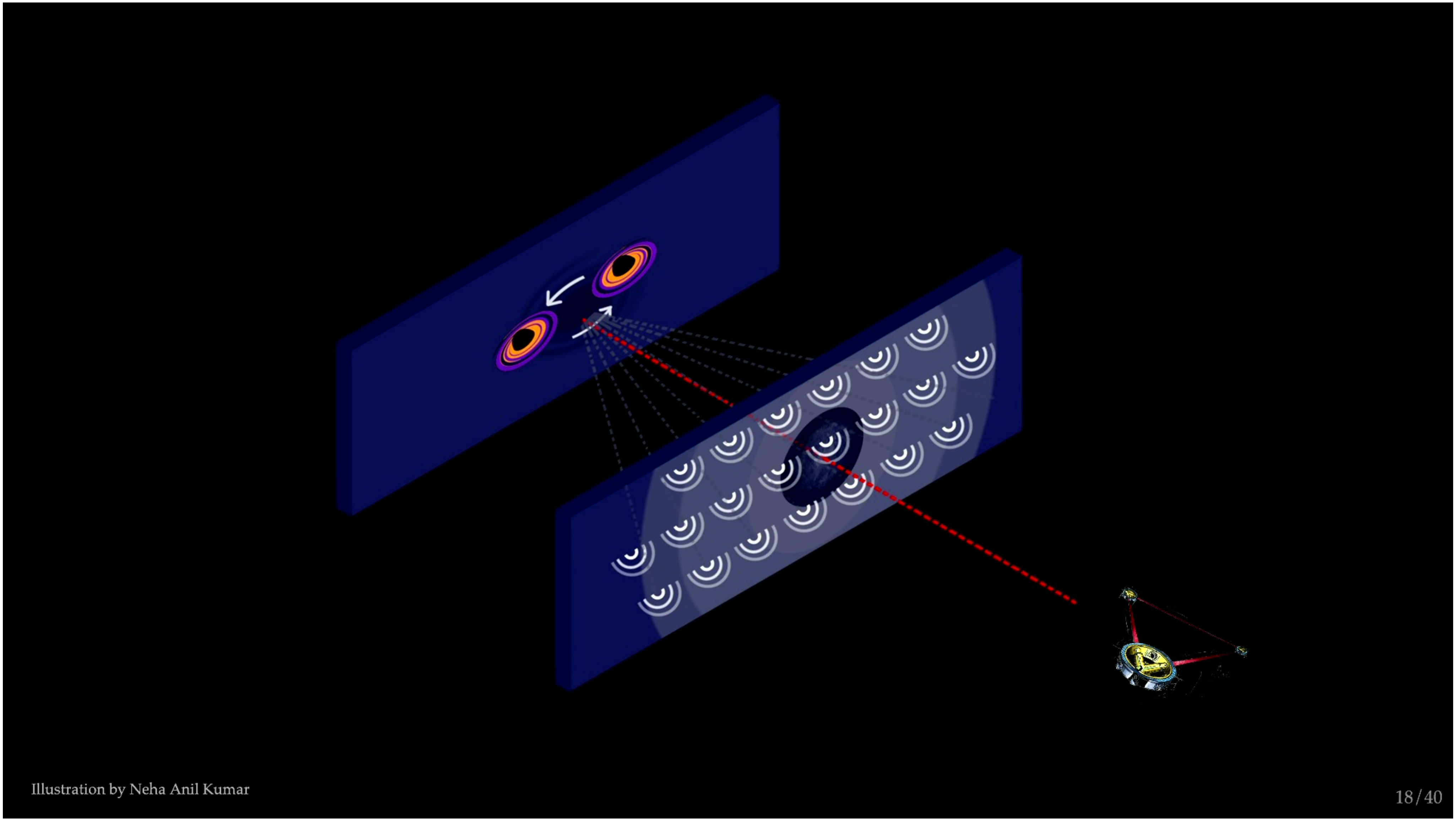
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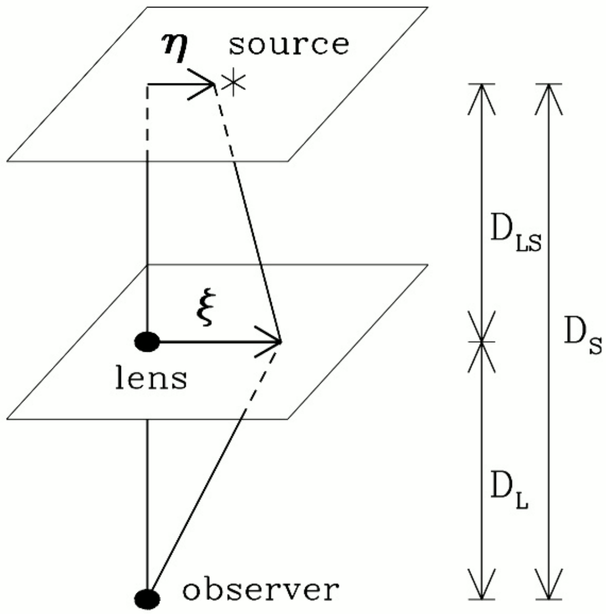
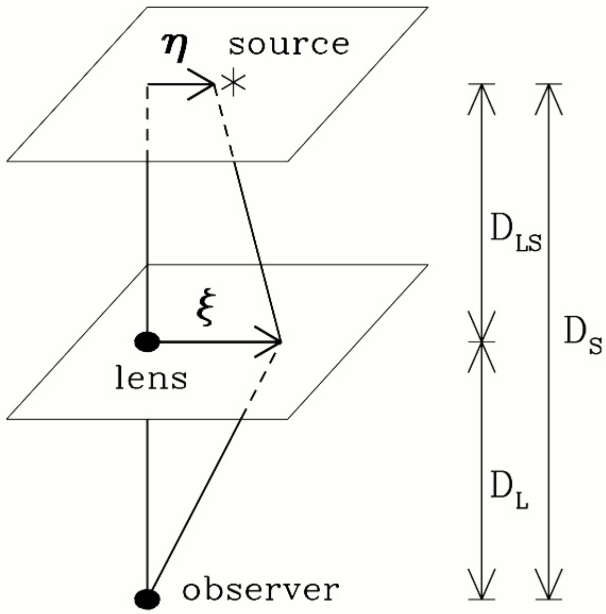


$$\boldsymbol{x} \equiv \frac{\boldsymbol{\xi}}{\xi_0} \quad \text{and} \quad \boldsymbol{y} \equiv \boldsymbol{\eta}\frac{D_\mathrm{L}}{\xi_0 D_\mathrm{S}}$$

Impact Parameter

[1] Takahashi and Nakamura (2003)

Propagation of GWs Around a Lens and Wave Optics Effects



$$\boldsymbol{x} \equiv \frac{\boldsymbol{\xi}}{\xi_0} \quad \text{and} \quad \boldsymbol{y} \equiv \boldsymbol{\eta}\frac{D_L}{\xi_0 D_S}$$

Impact Parameter

Einstein Radius

- $F(f, \boldsymbol{y}) = \frac{D_S(1+z_L)\xi_0^2}{D_L D_{LS}} \frac{f}{i} \int d^2\boldsymbol{x} \exp[2\pi i f t_d(\boldsymbol{x}, \boldsymbol{y})]$
- $t_d(\boldsymbol{x}, \boldsymbol{y}) = \frac{D_S \xi_0^2}{D_L D_{LS}}(1+z_L)\left[\frac{1}{2}|\boldsymbol{x}-\boldsymbol{y}|^2 - \psi(\boldsymbol{x}) + \phi(\boldsymbol{y})\right]$
- $w = 8\pi M_{Lz} f$

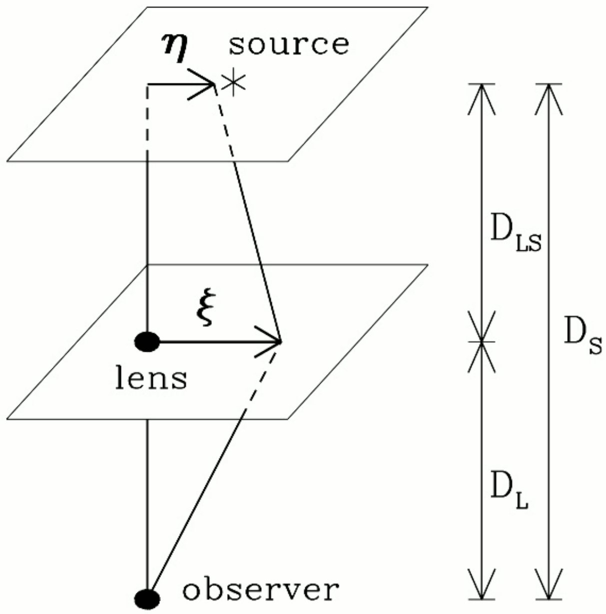
Deflection Potential

(Based on the Matter Distribution of the Lens)

Lensed Waveform in the Frequency Domain: $\tilde{h}^L(f; w, y) = F(w, y)\tilde{h}(f)$

[1] Takahashi and Nakamura (2003)

Propagation of GWs Around a Lens and Wave Optics Effects



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Lensed Waveform in the Frequency Domain: $\tilde{h}^L(f; w, y) = F(w, y)\tilde{h}(f)$

Geometrical optics limit: frequency-independent magnification, time delay, and phase shift

Wave optics effects: frequency-dependent modulations in the amplitude and phase of the waveform (directly dependent on the profile and mass of the lens)

[1] Takahashi and Nakamura (2003)

Lensing of Gravitational Waves

- The wavelength of GWs can be comparable to the size of the lenses, leading to ***frequency-dependent* modulations in the waveform phase and amplitude** due to wave-optics (WO) effects.

- At least in principle, this allows for the possibility of **infer the lens properties** (such as mass and profile) from a single GW observation.

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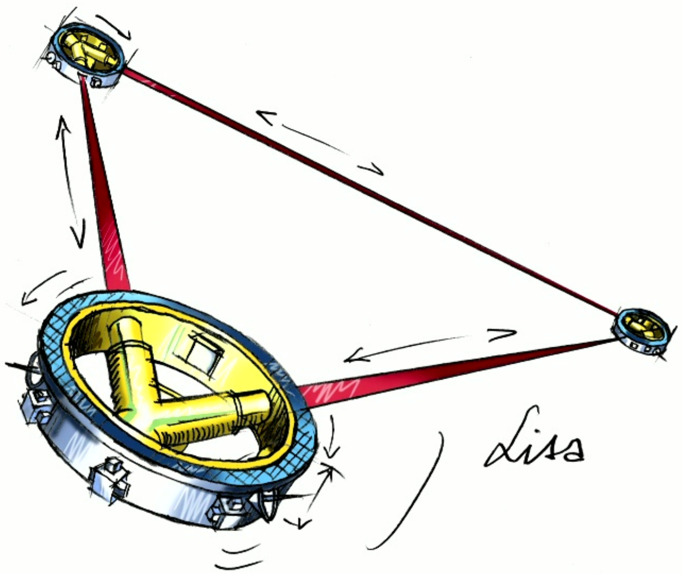
[1] Takahashi and Nakamura (2003)
[3] **Çalışkan** et al. (2023a)
[4] **Çalışkan**, Anil Kumar, et al. (2023b)
[5] Tambalo et al. (2022)
[6] Fairbairn et al. (2022)
[7] Savastano et al. (2023)
[8] Ji and Dai (2024)
[9] Leung et al. (2023)
[10] Dai et al. (2018)

Also:
[11] Feldbrugge, Pen, and Turok (2023)
[12] Feldbrugge and Turok (2020)
[13] Jow and Pen (2022)
[11] Jow and Pen (2024)
[12] Villarrubia-Rojo et al. (2024)



Laser Interferometer Space Antenna (LISA)

- LISA will be the first dedicated space-based gravitational-wave observatory.
- LISA will detect gravitational waves (GWs) emitted by massive black hole binaries (MBHBs) in the low-frequency (~mHz) band.
- These MBHBs ($M_{\mathrm{Total}} \approx 10^4 - 10^8\, M_\odot$) will have high SNRs and large redshifts.
- Low-mass lenses, such as dark-matter (DM) subhalos, have sizes comparable to the wavelength of these GWs.

As such, MBHBs are excellent candidates for observing WO effects.

[Credit:] ESA-C. Vijoux

Neha Anil Kumar

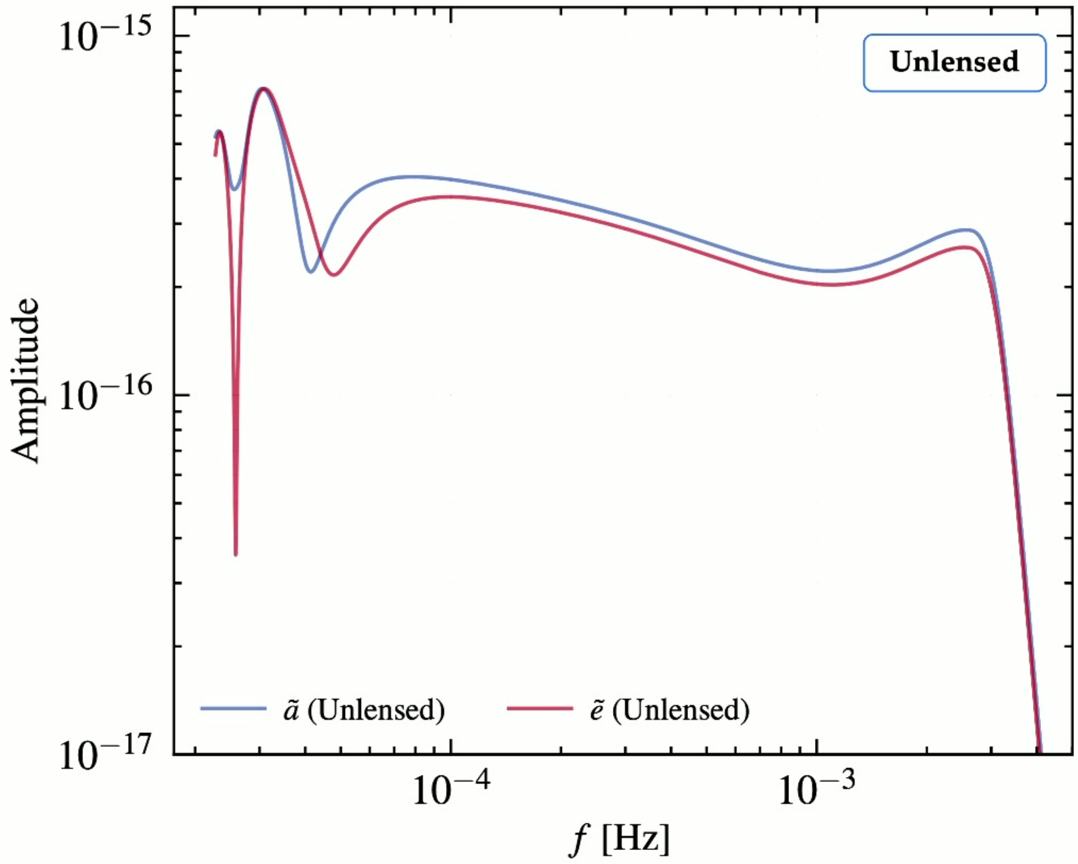
Johns Hopkins University

Lingyuan Ji

Berkeley / Now @ Citadel

Lensed and Unlensed Waveforms

$$\tilde{h}^L(f; w, y) = F(w, y)\tilde{h}(f)$$



[3] **Çalışkan** et al. (2023a)

Lensed and Unlensed Waveforms

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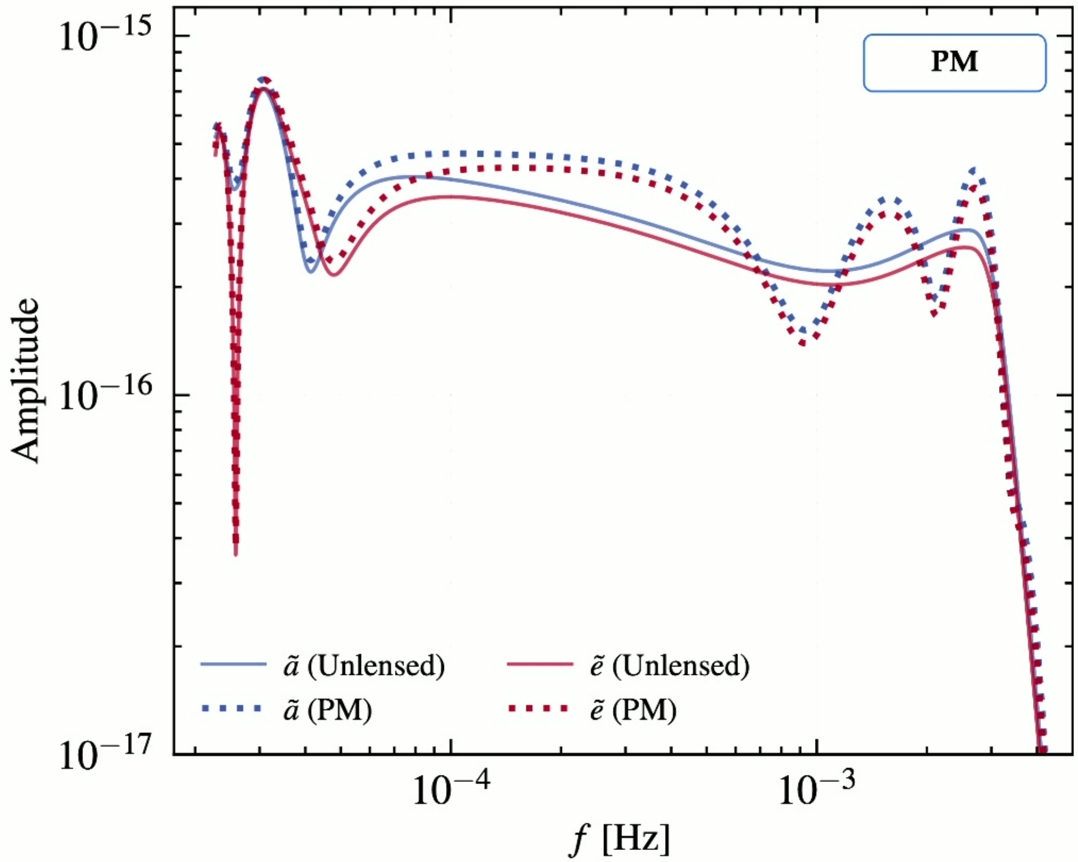

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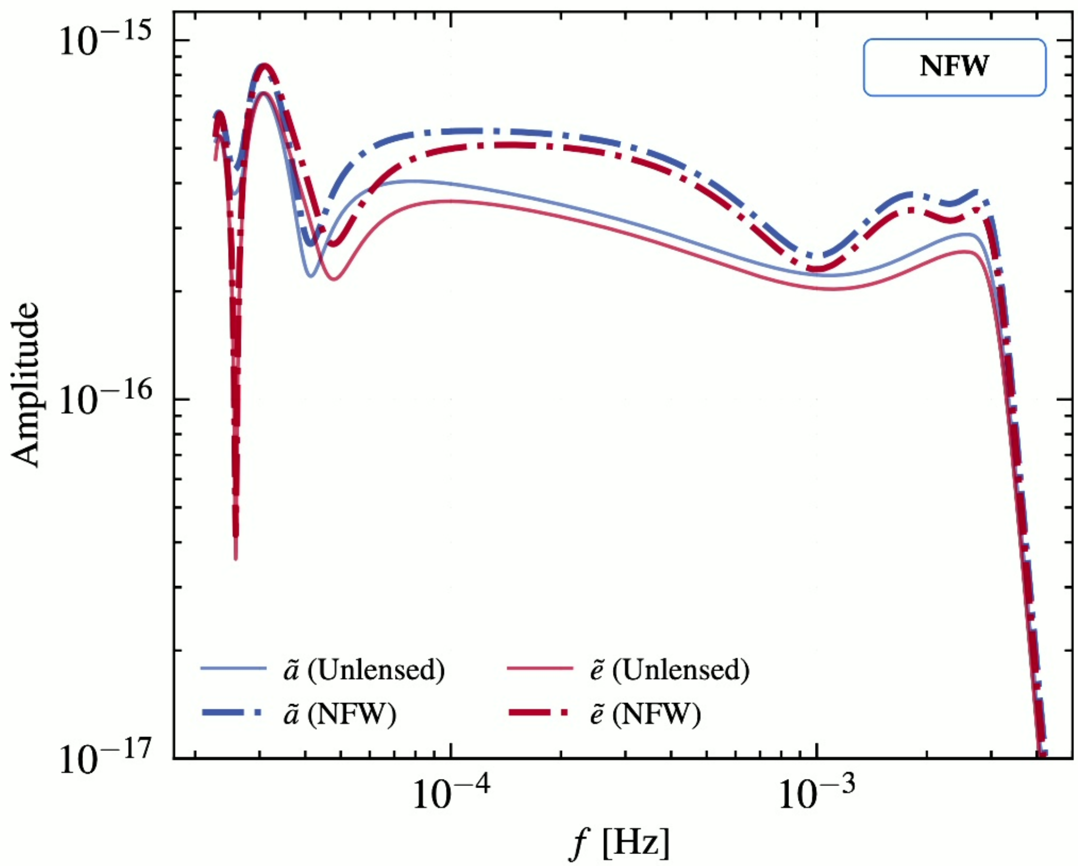
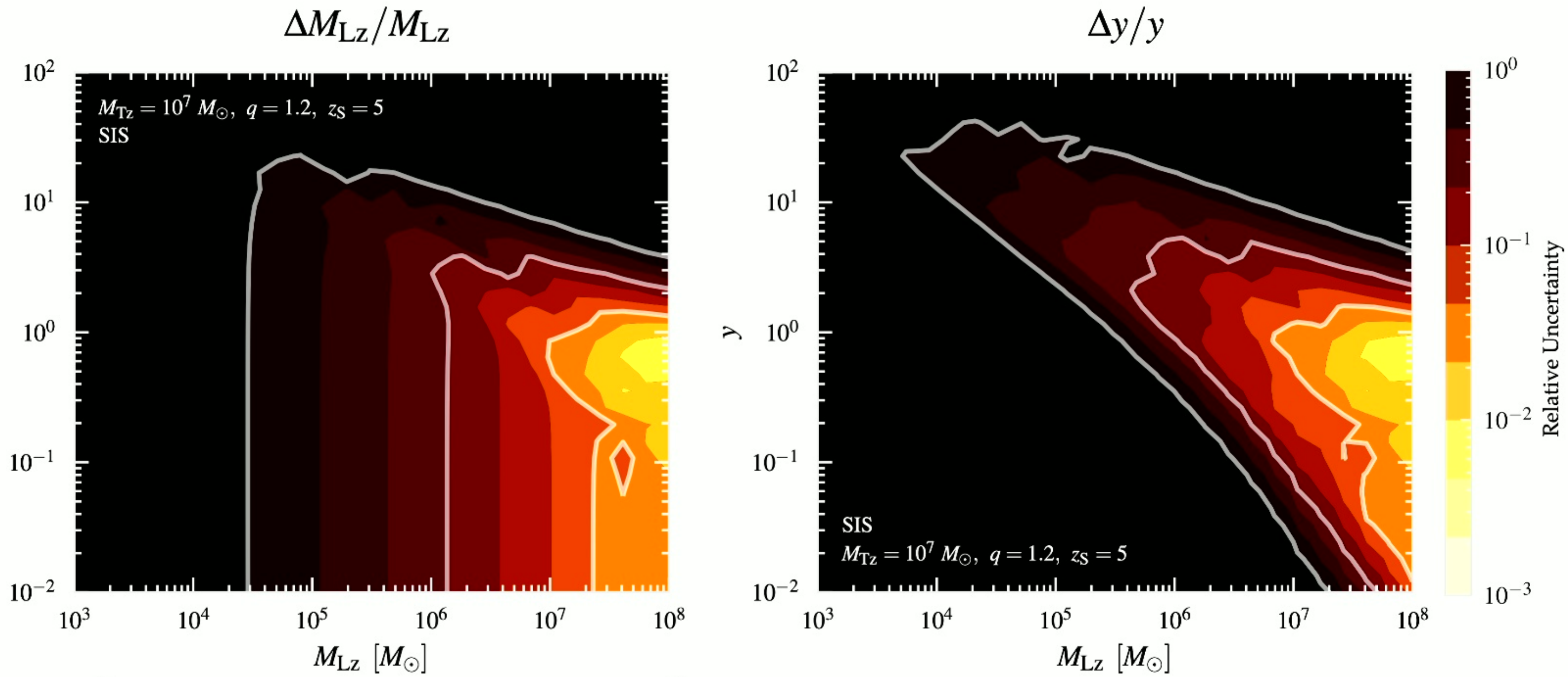


[3] **Çalışkan** et al. (2023a)

Measurability of the Lens Parameters

Measurability of Lens Mass ($M_{\rm Lz}$)

Measurability of Alignment (y)



Varying Alignments

Varying Dark Matter Halo (Lens) Masses

[3] **Çalışkan**, et al. (2023a)
[4] **Çalışkan**, Anil Kumar, et al. (2023b)

Lensed and Unlensed Waveforms

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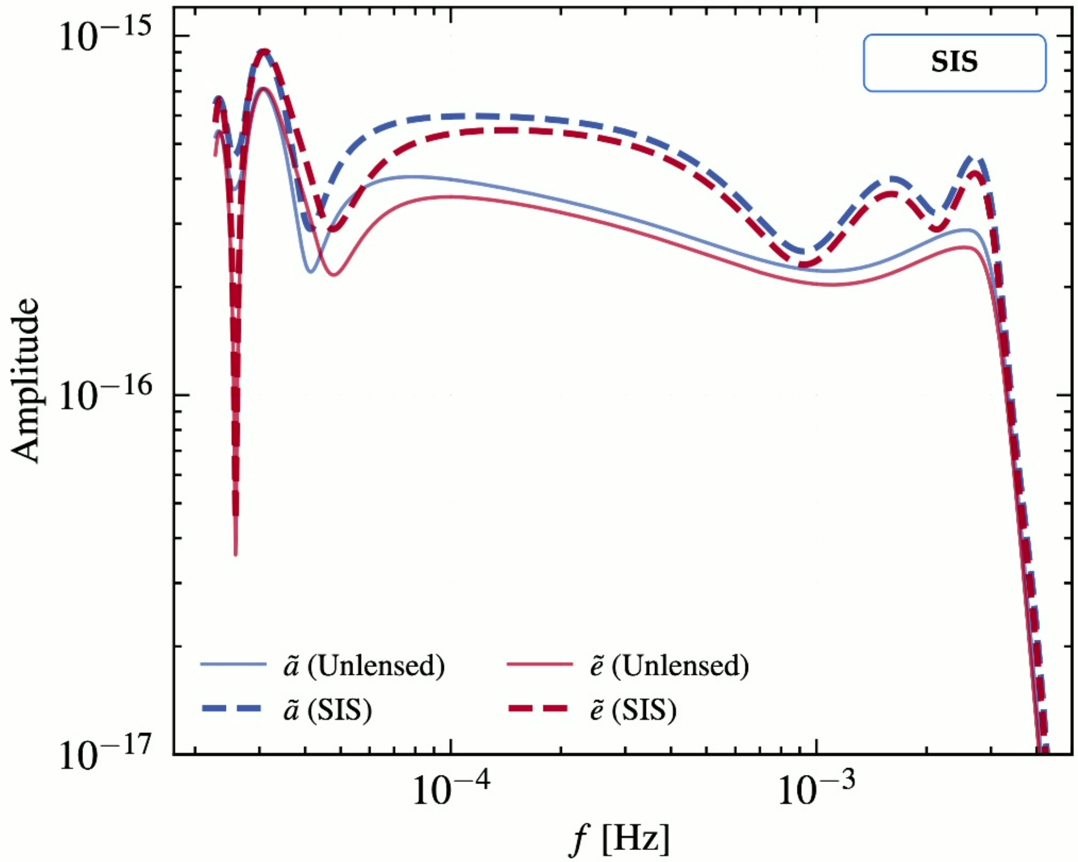


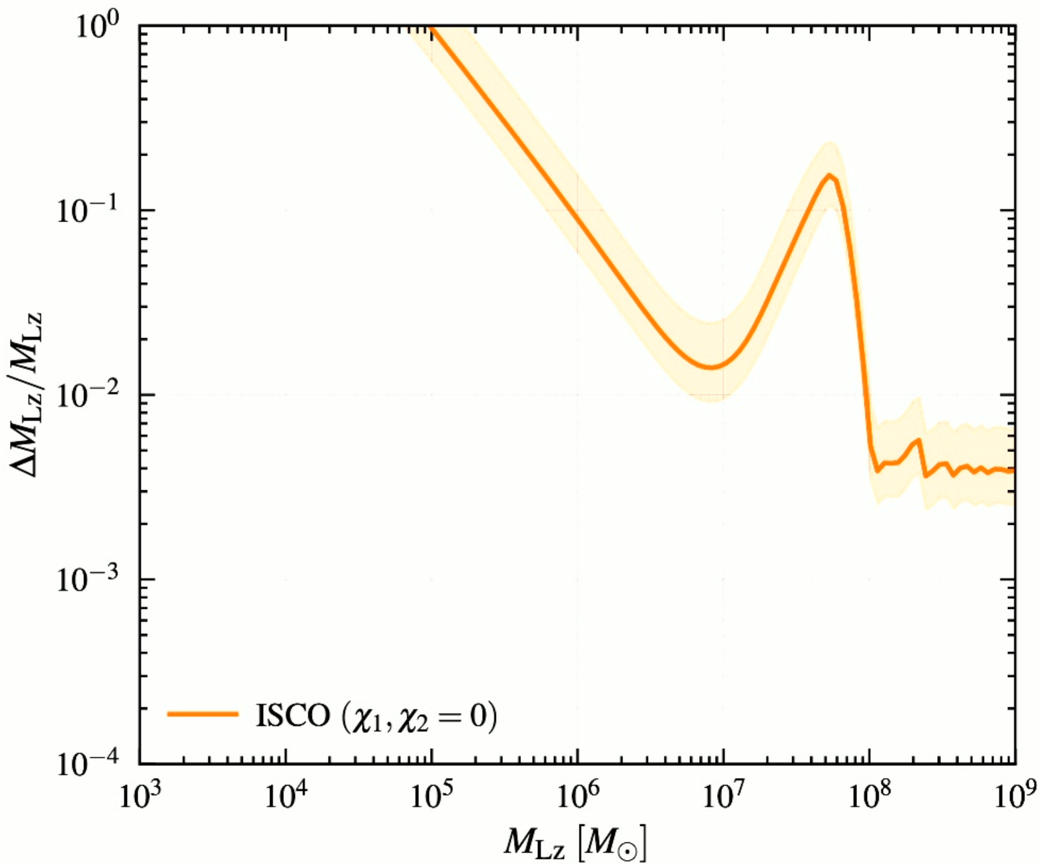
[3] **Çalışkan** et al. (2023a)

What Did We (the Field) Miss Before?

Inspiral-Only

- $M_{\mathrm{Tz}} = 2 \times 10^6\, M_\odot$
- $q = 1$
- $z_{\mathrm{S}} = 1$
- $\chi_1 = \chi_2 = 0$

- PM Lens
- $y = 0.1$



[3] **Çalışkan** et al. (2023a)

Merger!

- $M_{\mathrm{Tz}} = 2 \times 10^6\, M_\odot$
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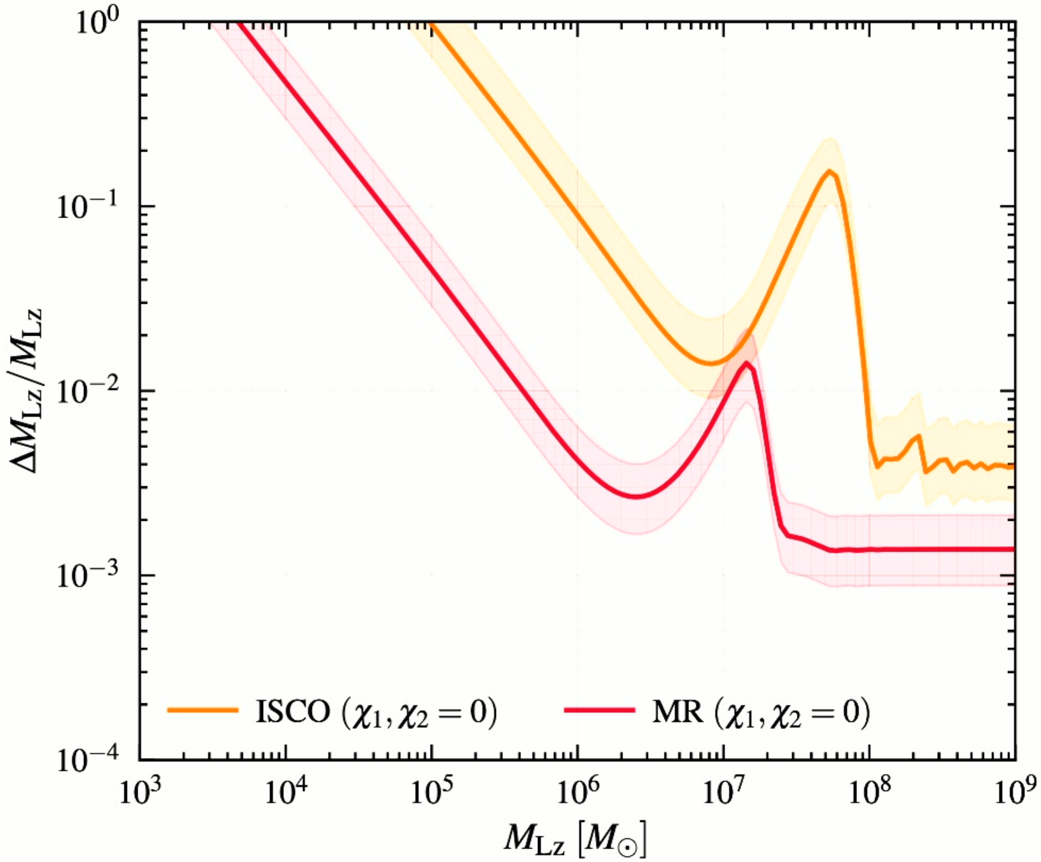
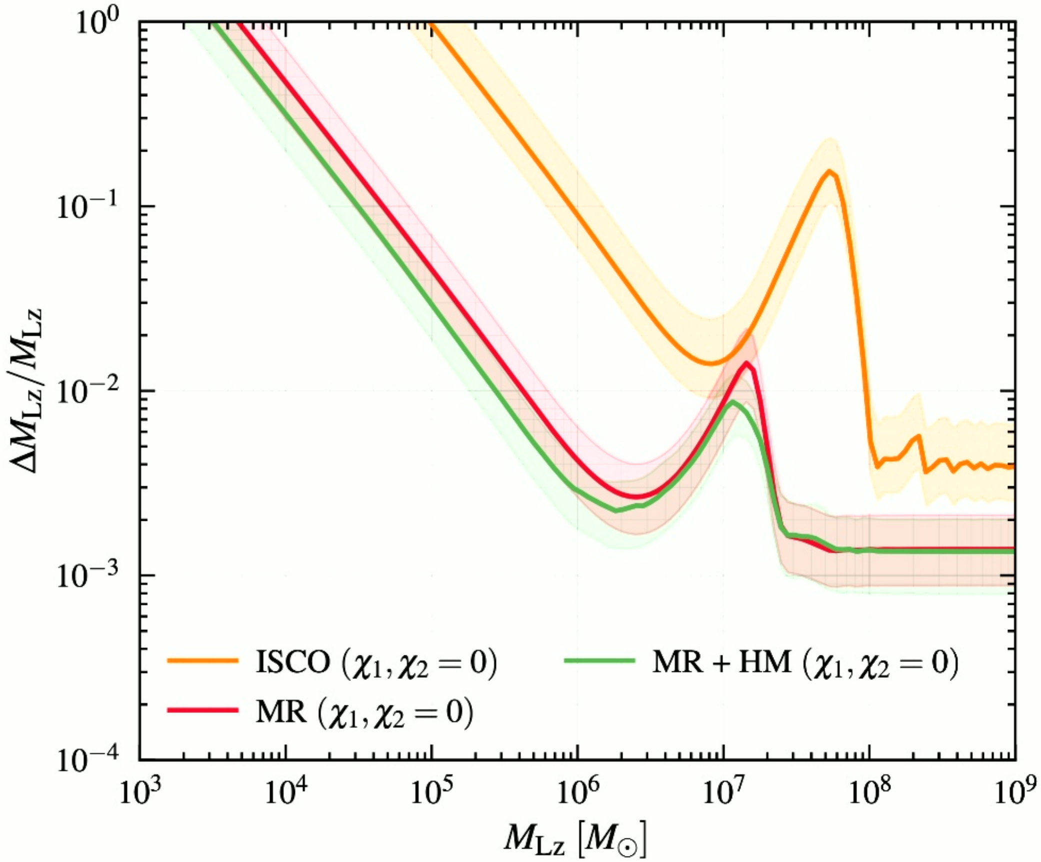


[3] **Çalışkan** et al. (2023a)

Higher-Order Modes?

- $M_{\mathrm{Tz}} = 2 \times 10^6\, M_\odot$
- $q = 1$
- $z_{\mathrm{S}} = 1$
- $\chi_1 = \chi_2 = 0$

- PM Lens
- $y = 0.1$



[3] **Çalışkan** et al. (2023a)

We Need Faster Solutions

Singular Isothermal Sphere (SIS) Lens

- $$F(\underbrace{w}_{w=8\pi M_{\mathrm{Lz}}f}, y) = \frac{w}{i}\exp\left\{iw\left[\frac{y^2}{2} + \underbrace{\phi(y)}_{y+\frac{1}{2}}\right]\right\}\int_0^\infty x\mathrm{d}x\ \exp\left\{iw\left[\frac{x^2}{2} - \underbrace{\psi(x)}_{x}\right]\right\} J_0(wxy)$$

[3] **Çalışkan** et al. (2023a)

Singular Isothermal Sphere (SIS) Lens

- $$F(\underbrace{w}_{w=8\pi M_{\mathrm{Lz}}f}, y) = \frac{w}{i}\exp\left\{iw\left[\frac{y^2}{2} + \underbrace{\phi(y)}_{y+\frac{1}{2}}\right]\right\}\int_0^\infty x\mathrm{d}x\,\exp\left\{iw\left[\frac{x^2}{2} - \underbrace{\psi(x)}_{x}\right]\right\}J_0(wxy)$$
  - Taylor expansion of the exponential factor $\exp[-iw\psi(x)]$
  - $$I_n(w,y) \equiv \int_0^\infty x^n e^{iwx^2/2} J_0(wxy)\,x\mathrm{d}x \;= \frac{1}{2}\left(\frac{2i}{w}\right)^N \Gamma(N)\,{}_1F_1\left(\underbrace{N}_{N\equiv(n+2)/2}, 1; -i\frac{wy^2}{2}\right)$$

[3] **Çalışkan** et al. (2023a)

Singular Isothermal Sphere (SIS) Lens

- $$F(w,y) = \frac{w}{i}\exp\left\{iw\left[\frac{y^2}{2}+\phi(y)\right]\right\}\sum_{n=0}^{\infty}\Psi_n(w)I_n(w,y)$$

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  - $$\Psi(w,x) \equiv e^{-iw\psi(x)} = \sum_{n=0}^{\infty}\Psi_n(w)x^n$$

$$\Psi_n(w) = (-iw)^n/n!$$

[3] **Çalışkan** et al. (2023a)

[14] Matsunaga and Yamamoto (2006)

PM Lens

SIS Lens

- $F(w,y) = \exp\left\{\frac{\pi w}{4} + i\frac{w}{2}\left[\ln\frac{w}{2} - 2\phi(y)\right]\right\}\Gamma\left(1-\frac{w}{2}i\right){}_1F_1\left(\frac{w}{2}i, 1; \frac{wy^2}{2}i\right)$
- $F(w,y) = \frac{w}{i}\exp\left\{iw\left[\frac{y^2}{2} + \phi(y)\right]\right\}\sum_{n=0}^{\infty}\Psi_n(w)I_n(w,y)$

- $\Gamma(z) = \left\{z\, e^{cz}\prod_{r=1}^{\infty}\left[\left(1+\frac{z}{r}\right)e^{-z/r}\right]\right\}^{-1}$
- $\Gamma'(z) = \Gamma(z)\ \Psi(z)$

$$\frac{\partial\Gamma\left(1-\frac{w}{2}i\right)}{\partial w} = -\frac{1}{2}i\ \Gamma\left(1-\frac{w}{2}i\right)\ \Psi\left(1-\frac{w}{2}i\right)$$

- ${}_1F_1(a,b;z) = 1 + \frac{a}{b}\frac{z}{1!} + \frac{a(a+1)}{b(b+1)}\frac{z^2}{2!} + \ldots$

$$\frac{\partial\,{}_1F_1(a,b;z)}{\partial z} = \frac{a}{b}\,{}_1F_1(a+1,b+1;z)$$

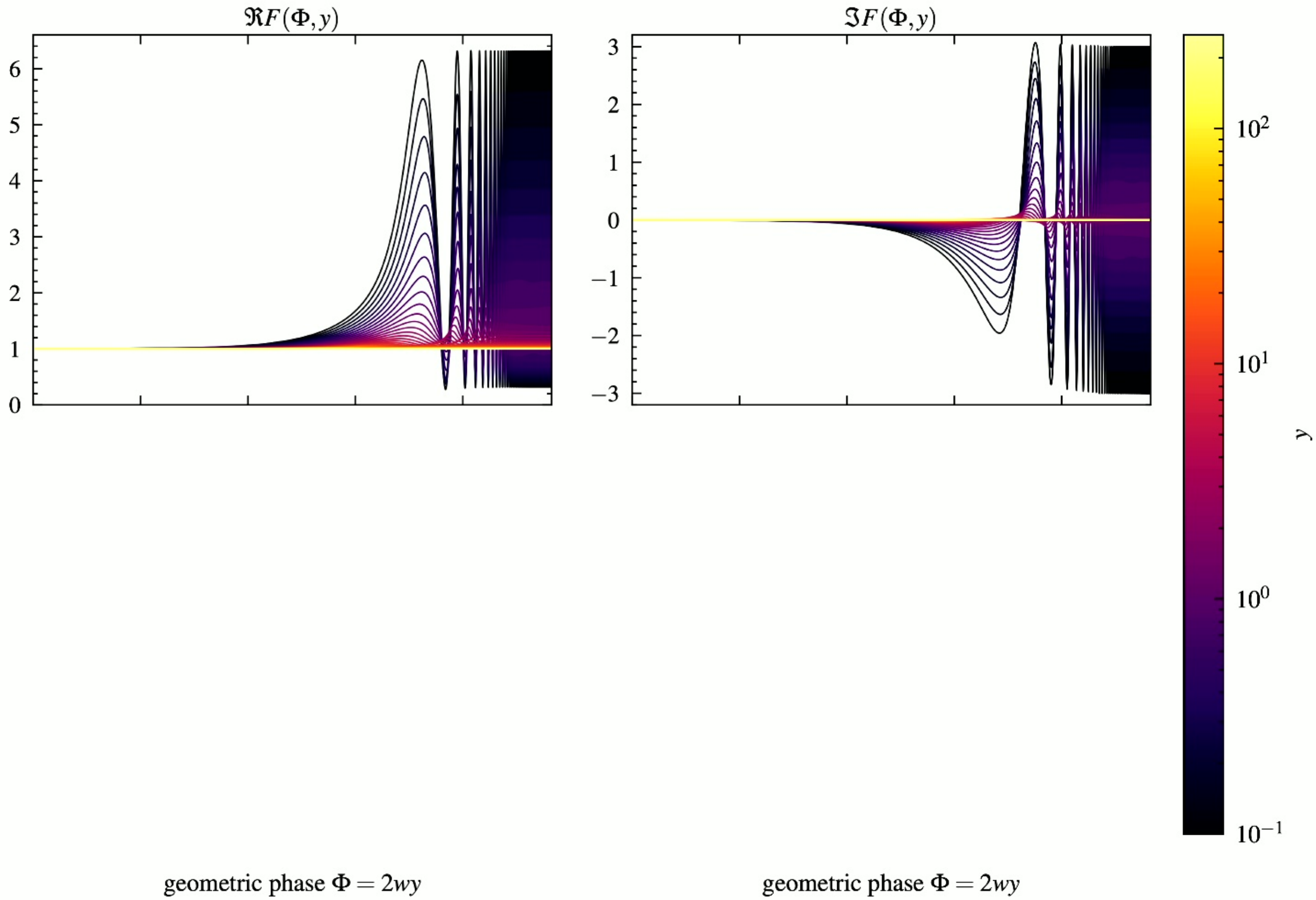
$$\frac{\partial\,{}_1F_1(a,b;z)}{\partial a} = \sum_{k=0}^{\infty}\frac{(a)_k\Psi(a+k)z^k}{k!(b)_k} - \Psi(a)\,{}_1F_1(a,b;z)$$

- $$\begin{aligned}\frac{\partial\,{}_1F_1(a,b;z)}{\partial w} &= \frac{\partial\,{}_1F_1(a,b;z)}{\partial a}\cdot\frac{\partial a}{\partial w} + \frac{\partial\,{}_1F_1(a,b;z)}{\partial z}\cdot\frac{\partial z}{\partial w}\\ &= \frac{i}{2}\cdot\frac{\partial\,{}_1F_1(a,b;z)}{\partial a} + \frac{y^2}{2}i\cdot\frac{\partial\,{}_1F_1(a,b;z)}{\partial z}\\ &= \frac{i}{2}\sum_{k=0}^{\infty}\frac{(i\frac{w}{2})_k\Psi(i\frac{w}{2}+k)z^k}{k!(1)_k} - \Psi\left(i\frac{w}{2}\right)\ {}_1F_1\left(i\frac{w}{2},1;i\frac{wy^2}{2}\right) - \frac{wy^2}{4}\ {}_1F_1\left(i\frac{w}{2}+1,2;i\frac{wy^2}{2}\right)\end{aligned}$$

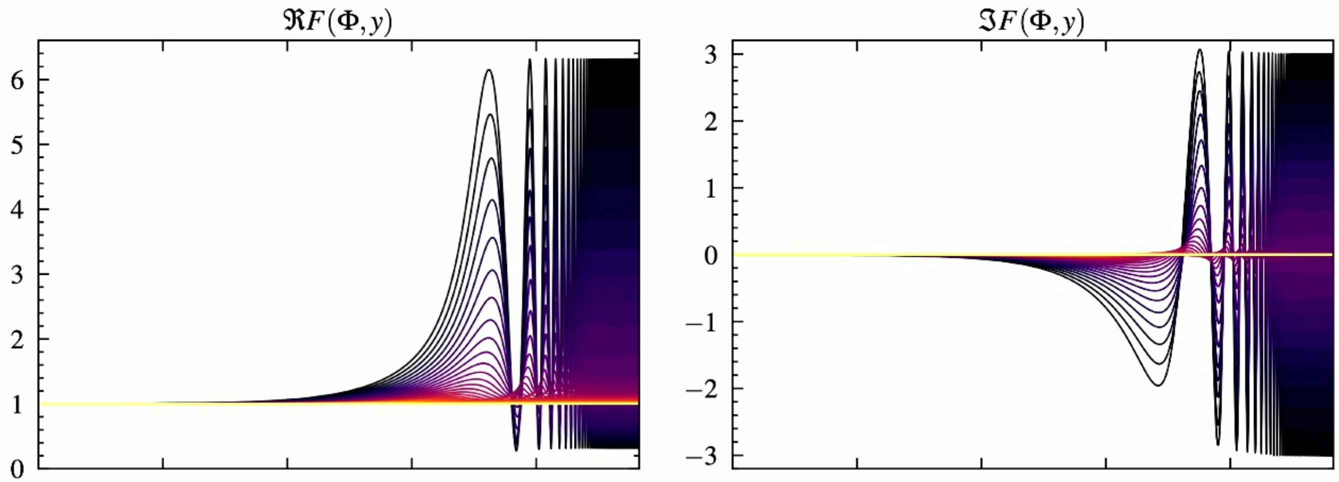
- $\frac{\partial\,{}_1F_1(a,b;z)}{\partial y} = -\frac{w^2y}{2}\ {}_1F_1\left(\frac{w}{2}i+1,2;\frac{wy^2}{2}i\right)$

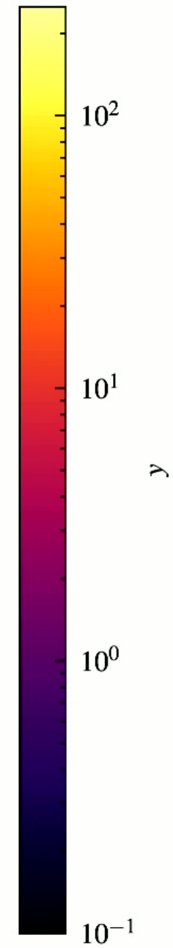
- $\frac{\partial\Psi_n(w)}{\partial w} = \frac{(-i)^n}{(n-1)!}w^{n-1}$
- $\frac{\partial I_n(w,y)}{\partial w} = \frac{N}{2}\left(\frac{2i}{w}\right)^N\Gamma(N)\left[\left(-i\frac{y^2}{2}\right)\ {}_1F_1\left(N+1,2;-i\frac{wy^2}{2}\right) - \frac{1}{w}\ {}_1F_1\left(N,1;-i\frac{wy^2}{2}\right)\right]$
- $\frac{\partial I_n(w,y)}{\partial y} = -iN\frac{wy}{2}\left(\frac{2i}{w}\right)^N\Gamma(N)\ {}_1F_1\left(N+1,2;-i\frac{wy^2}{2}\right)$
- $\frac{\partial F(w,y)}{\partial w} = \frac{\partial E(w,y)}{\partial w}\sum_{n=0}^{\infty}\Psi_n(w)I_n(w,y) + E(w,y)\sum_{n=0}^{\infty}\left[\frac{\partial\Psi_n(w)}{\partial w}I_n(w,y) + \Psi_n(w)\frac{\partial I_n(w,y)}{\partial w}\right]$
- $\frac{\partial F(w,y)}{\partial y} = \frac{\partial E(w,y)}{\partial y}\sum_{n=0}^{\infty}\Psi_n(w)I_n(w,y) + E(w,y)\sum_{n=0}^{\infty}\Psi_n(w)\frac{\partial I_n(w,y)}{\partial y}$

[3] **Çalışkan** et al. (2023a)



[4] **Çalışkan**, Anil Kumar, et al. (2023b)

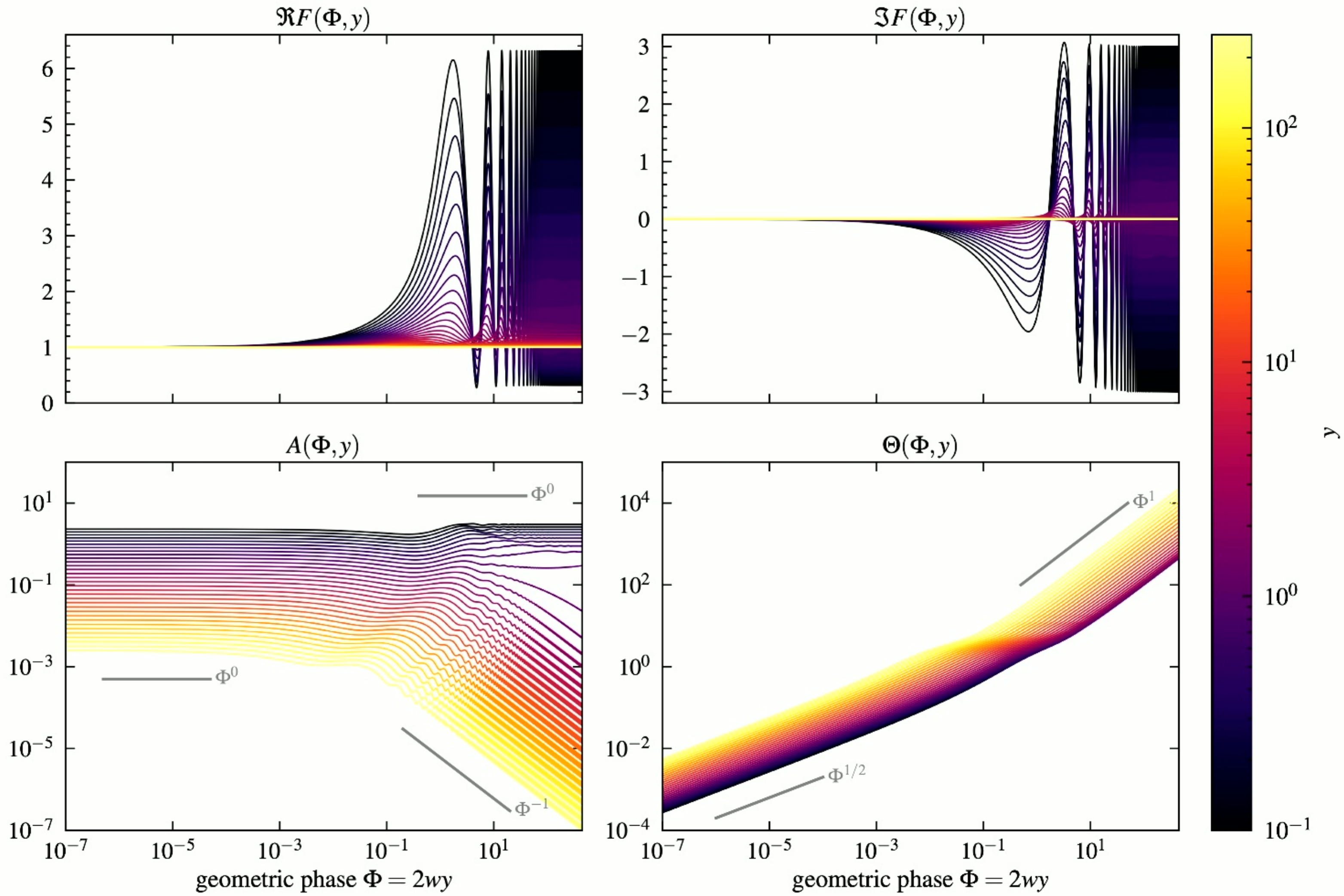




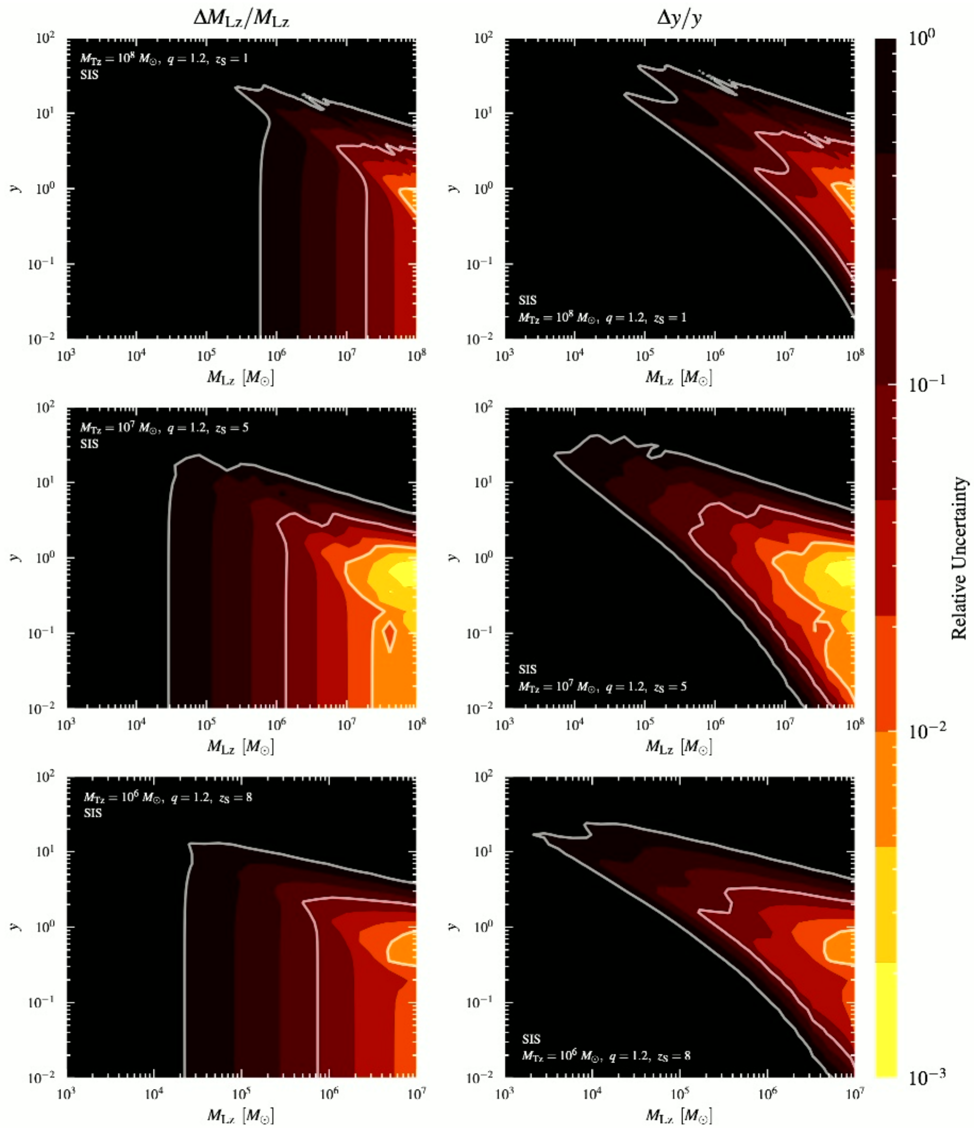
$$O(w, y) \equiv F(w, y) - |\mu_+(y)|^{1/2}$$

geometric phase $\Phi = 2wy$ geometric phase $\Phi = 2wy$

[4] **Çalışkan**, Anil Kumar, et al. (2023b)



[4] **Çalışkan**, Anil Kumar, et al. (2023b)



[3] **Çalışkan**, et al. (2023a)
[4] **Çalışkan**, Anil Kumar, et al. (2023b)

Optical Depth and Detection Probability

Optical Depth and Probability

Set of Source Parameters

Halo Virial Mass

$$\tau(\boldsymbol{\theta}^{\mathrm{S}} = \{z_{\mathrm{S}}, \dots\}) = \int_0^{z_{\mathrm{S}}} \mathrm{d}z_{\mathrm{L}} \int_{M_{\mathrm{L}}^{\mathrm{min}}}^{M_{\mathrm{L}}^{\mathrm{max}}} \mathrm{d}M_{\mathrm{L}} \, \frac{4\pi M_{\mathrm{L}} D_{\mathrm{LS}}}{D_{\mathrm{L}} D_{\mathrm{S}}} \, y_{\mathrm{cr}}^2(M_{\mathrm{L}}|\boldsymbol{\theta}^{\mathrm{S}}) \, n\,[M_{200}, z_{\mathrm{L}}, z_{\mathrm{S}}] \, \chi^2(z_{\mathrm{L}}) \frac{\mathrm{d}\chi(z_{\mathrm{L}})}{\mathrm{d}z_{\mathrm{L}}} \frac{\mathrm{d}M_{200}}{\mathrm{d}M_{\mathrm{L}}}$$

Source Redshift

Lens Redshift

Lens Mass

Critical Impact Parameter

Comoving Number Density of Halos

Comoving Distance

$$P = 1 - e^{-\tau(\boldsymbol{\theta}^{\mathrm{S}} = \{z_{\mathrm{S}}, \dots\})}$$

[4] **Çalışkan**, Anil Kumar, et al. (2023b)
[2] Schneider et al. (1992)

Optical Depth and Probability

Set of Source Parameters

Halo Virial Mass

$$\tau(\boldsymbol{\theta}^{\rm S} = \{z_{\rm S}, \dots\}) = \int_0^{z_{\rm S}} {\rm d}z_{\rm L} \int_{M_{\rm L}^{\rm min}}^{M_{\rm L}^{\rm max}} {\rm d}M_{\rm L}\, \frac{4\pi M_{\rm L} D_{\rm LS}}{D_{\rm L} D_{\rm S}} \left(y_{\rm cr}^2(M_{\rm L}|\boldsymbol{\theta}^{\rm S}) \right) n\left[M_{200}, z_{\rm L}, z_{\rm S}\right] \chi^2(z_{\rm L}) \frac{{\rm d}\chi(z_{\rm L})}{{\rm d}z_{\rm L}} \frac{{\rm d}M_{200}}{{\rm d}M_{\rm L}}$$

Source Redshift

Lens Redshift

Lens Mass

Critical Impact Parameter

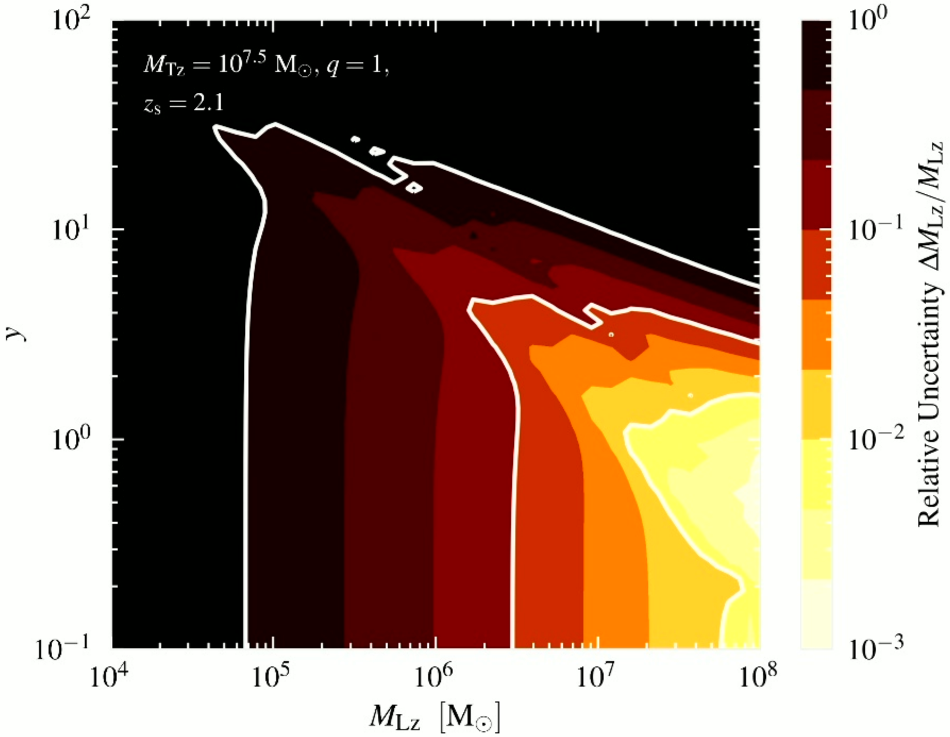
Comoving Number Density of Halos

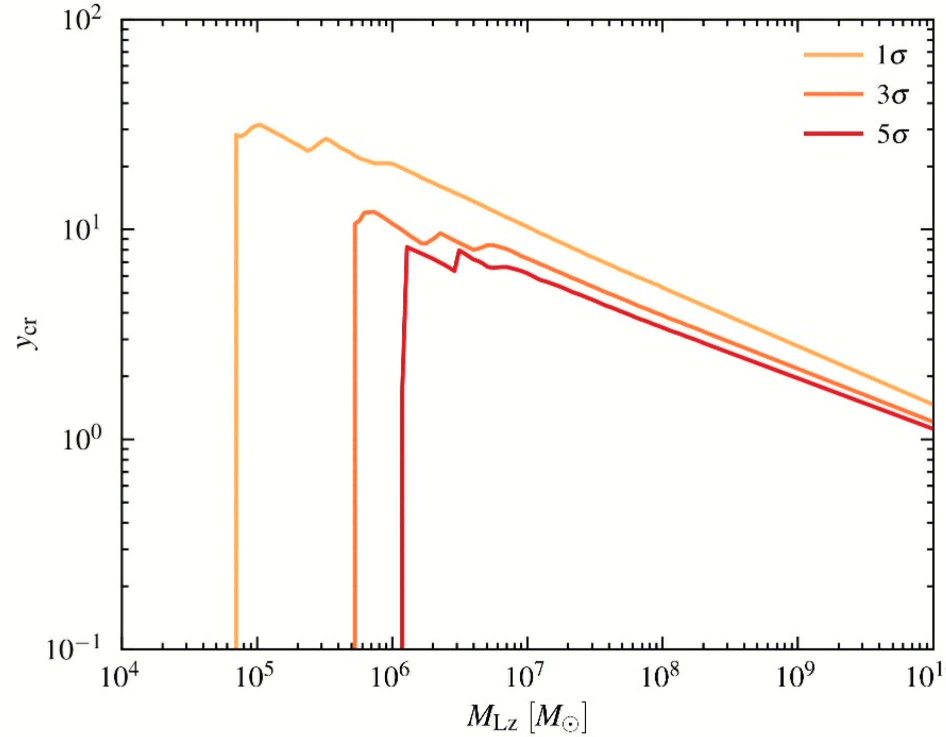
Comoving Distance

Strong Lensing: $y_{\rm cr}^{\rm SL} = 1$

Wave-Optics: $y_{\rm cr}^{\rm WO} \in [10, 100]$

[4] **Çalışkan**, Anil Kumar, et al. (2023b)
[2] Schneider et al. (1992)

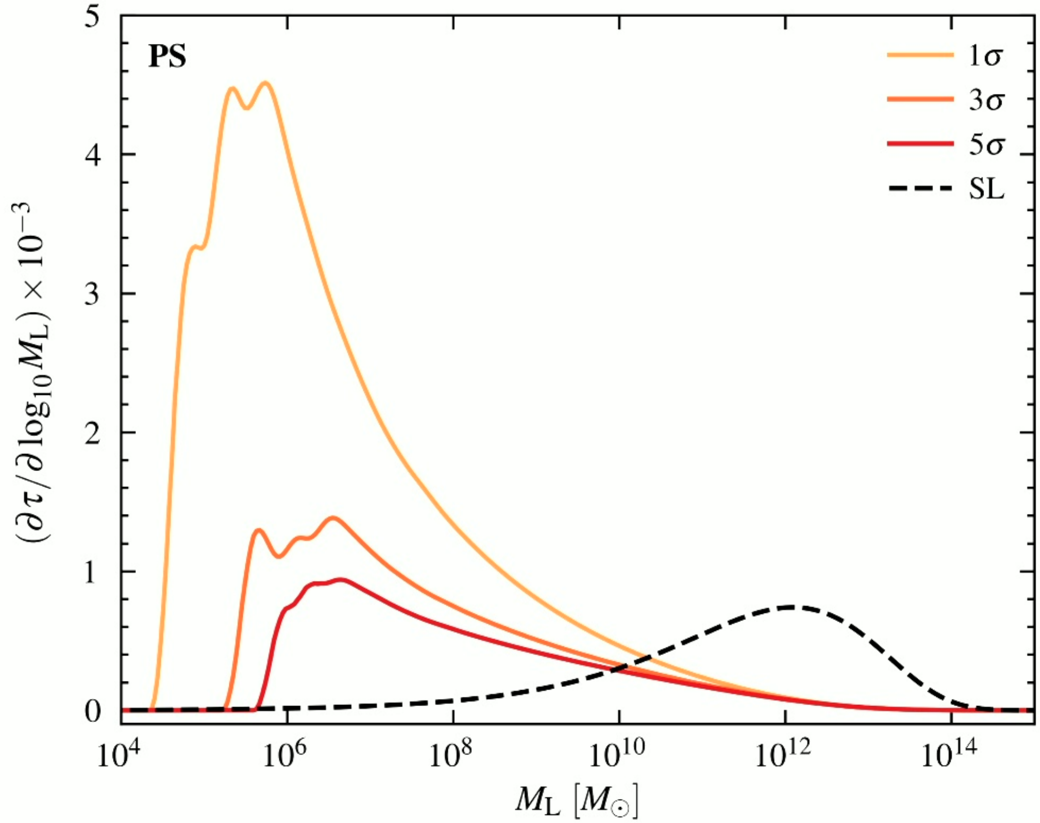




[3] **Çalışkan**, et al. (2023a)
[4] **Çalışkan**, Anil Kumar, et al. (2023b)

Differential Optical Depth (Probability)

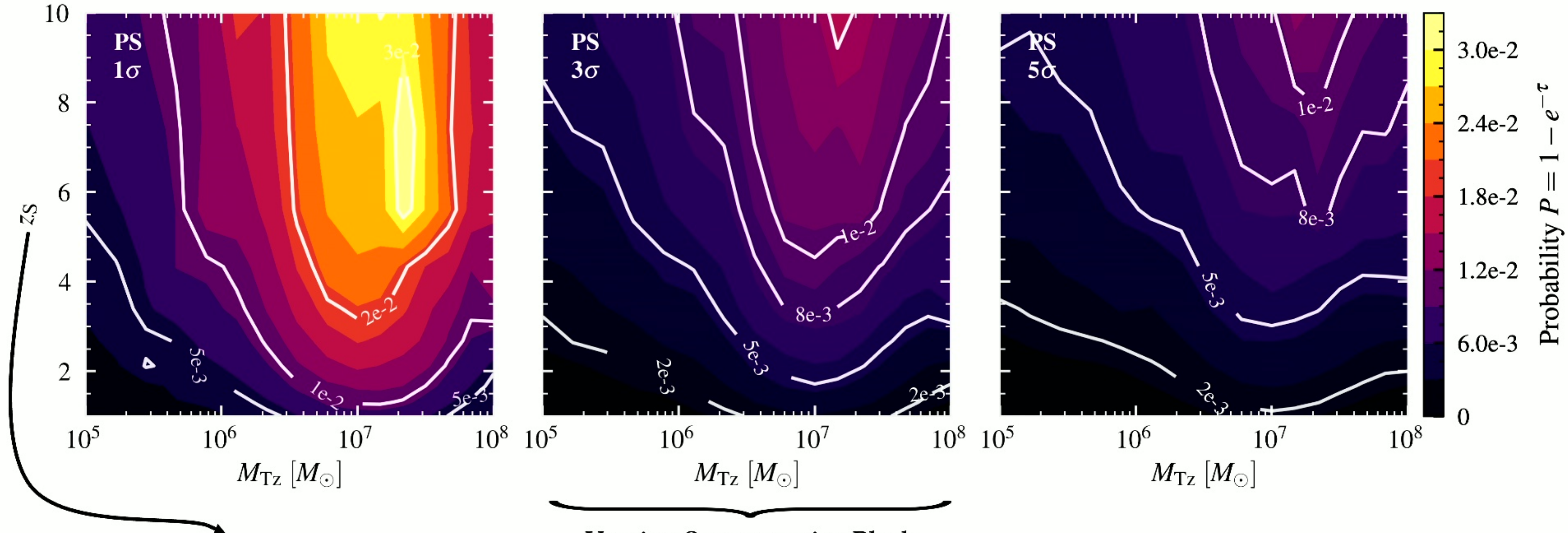
Differential Probability



Lens Mass

[3] **Çalışkan**, et al. (2023a)
[4] **Çalışkan**, Anil Kumar, et al. (2023b)

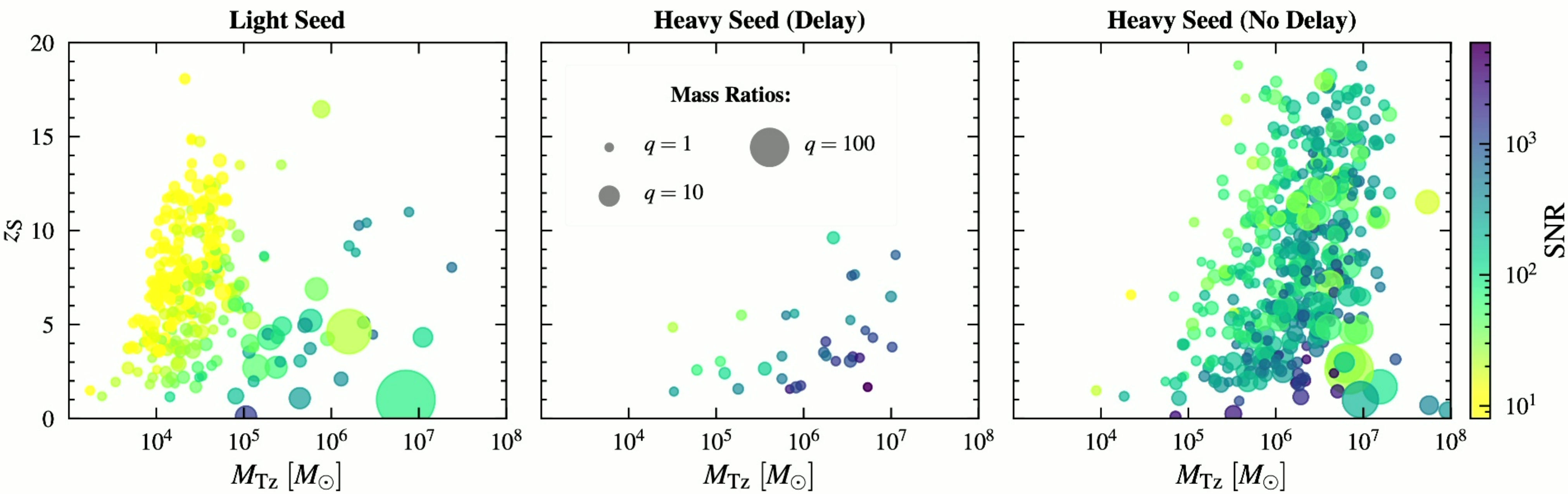
Detection Probability (Source Model Agnostic)



Redshift of Supermassive Black Holes (Measure of Distance)

Varying Supermassive Black Hole Masses

[4] **Çalışkan**, Anil Kumar, et al. (2023b)



[4] **Çalışkan**, Anil Kumar, et al. (2023b)
[11] Barausse (2012)
[12] Klein, Barausse, et al. (2016)

Total Number of Binaries in the Population

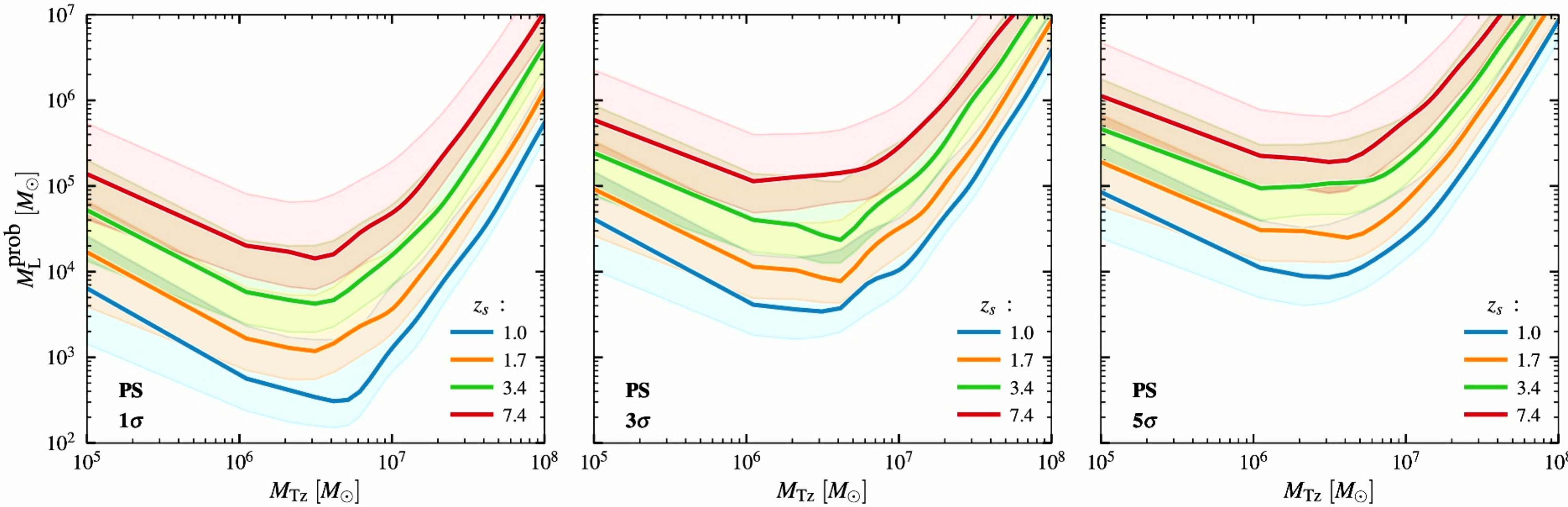
Expected Number of Lensed Binaries with WO Effects (for Varying Detection Thresholds)

Resulting Lensing Rate

Source Population	Lens Population	N_{detect}	$N^{1\sigma}_{\mathrm{lensed}}$	$N^{3\sigma}_{\mathrm{lensed}}$	$N^{5\sigma}_{\mathrm{lensed}}$	Lensing Rate $\{1\sigma, 3\sigma, 5\sigma\}$ [%]
Heavy Seed (No Delay)	PS	474	**7.96**	**4.13**	**3.24**	$\{1.68,\ 0.87,\ 0.68\}$
Heavy Seed (No Delay)	MVF	474	0.42	0.36	0.35	$\{0.09,\ 0.07,\ 0.07\}$
Heavy Seed (Delay)	PS	32	0.47	0.21	0.15	$\{1.47,\ 0.65,\ 0.47\}$
Heavy Seed (Delay)	MVF	32	0.01	0.009	0.008	$\{0.03,\ 0.03,\ 0.03\}$
Light Seed	PS	282	**1.51**	0.57	0.37	$\{0.53,\ 0.20,\ 0.13\}$
Light Seed	MVF	282	0.02	0.01	0.01	$\{0.007,\ 0.004,\ 0.004\}$

[4] **Çalışkan**, Anil Kumar, et al. (2023b)

Detectable Halo Mass Range



[4] **Çalışkan**, Anil Kumar, et al. (2023b)

LIMITATIONS

Navarro–Frenk–White?

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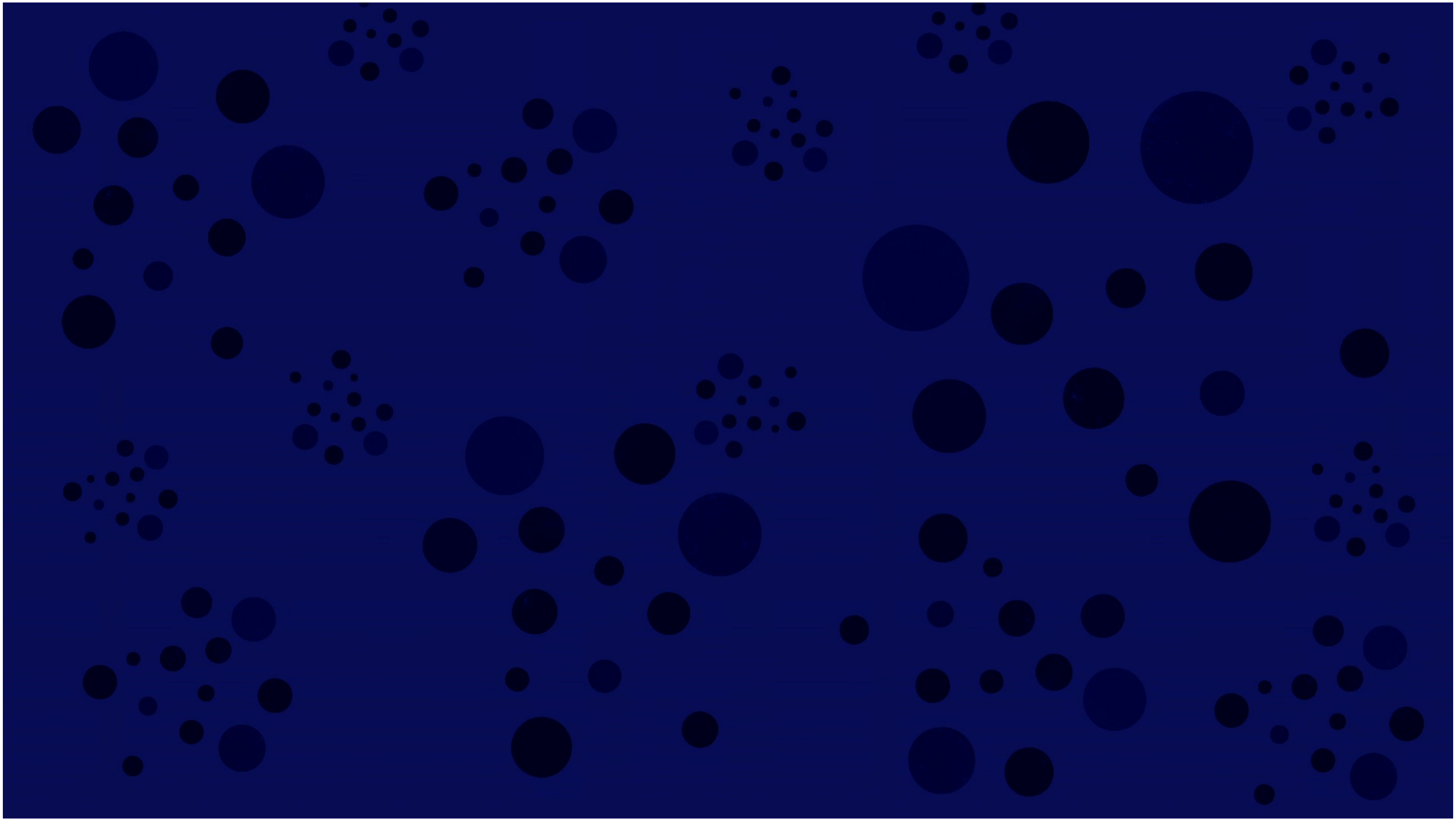
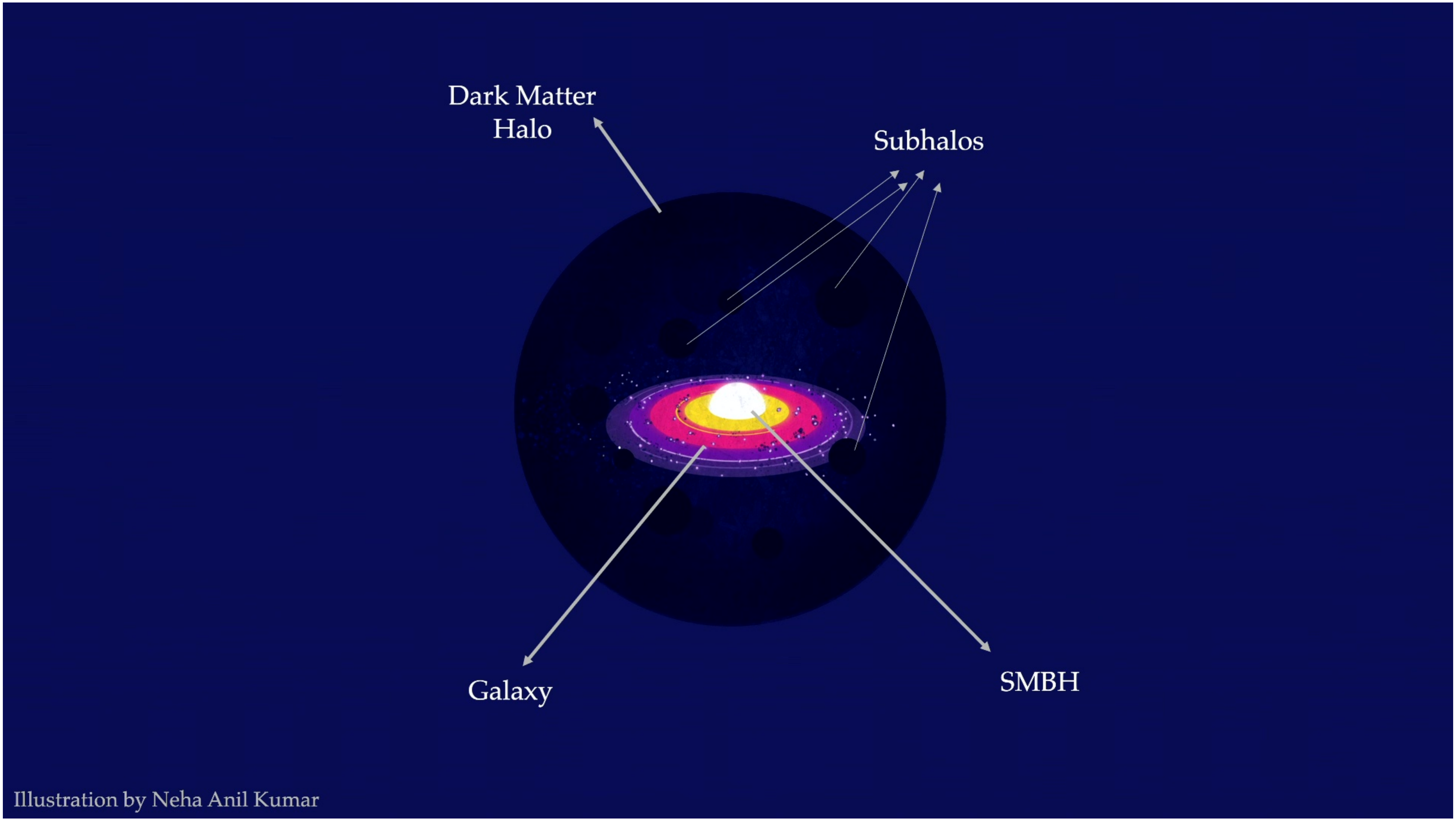
$$P_{\mathrm{NFW}} \lesssim \mathcal{O}(10^{-1}) P_{\mathrm{SIS}}$$

Brando et al. (2024)




Dark Matter
Halo
Subhalos
Galaxy
SMBH
Illustration by Neha Anil Kumar

Differing Profiles?

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How Lensed Gravitational Waves Can Illuminate Dark Matter*

Mesut Çalışkan[1,α],

Neha Anil Kumar, Lingyuan Ji, Marc Kamionkowski, Emanuele Berti et al.

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Perimeter Institute – 25 Nov 2024

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* arXiv: **2201.04619, 2206.02803, 2307.06990**