Black Holes as Laboratories for Dark Matter

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Jan 8@APCTP

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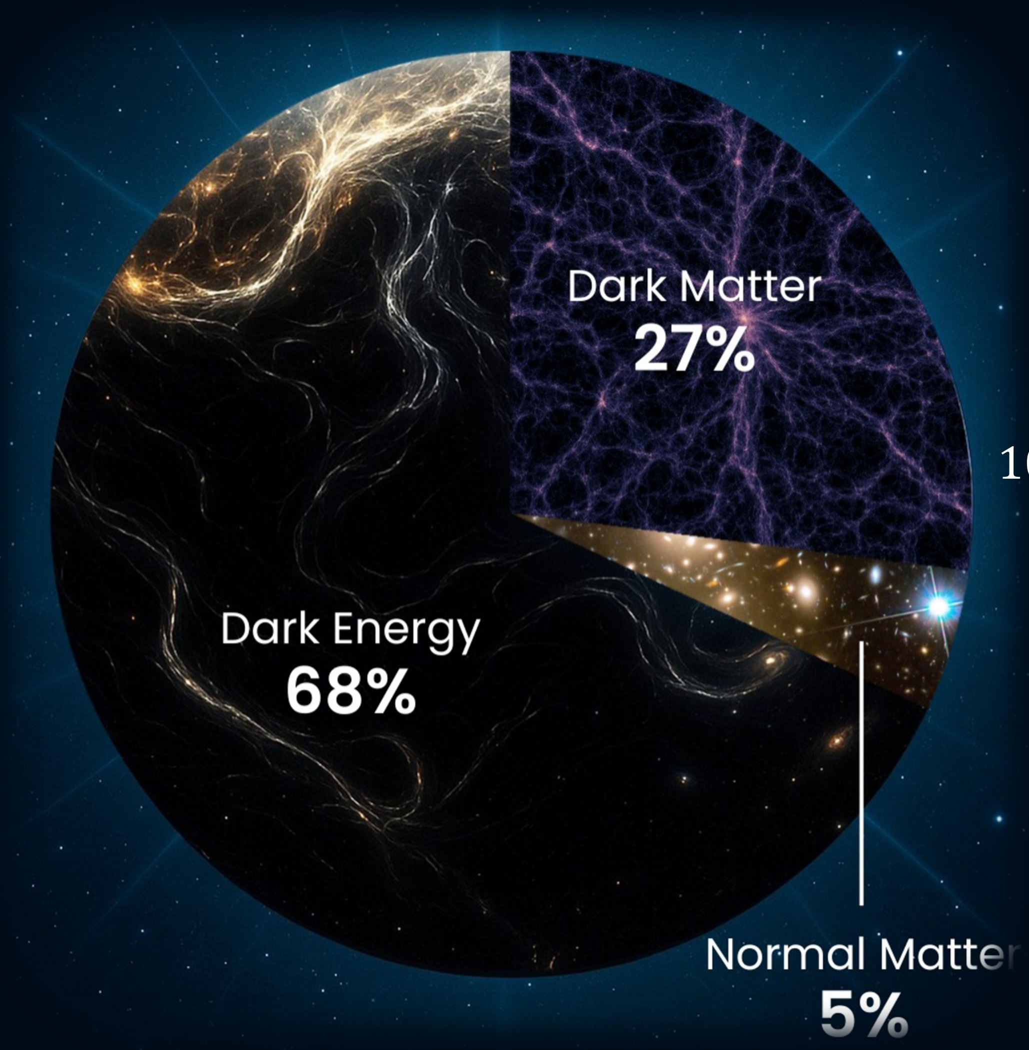
New Perspectives on Cosmology 2026



Dark Matter Candidate

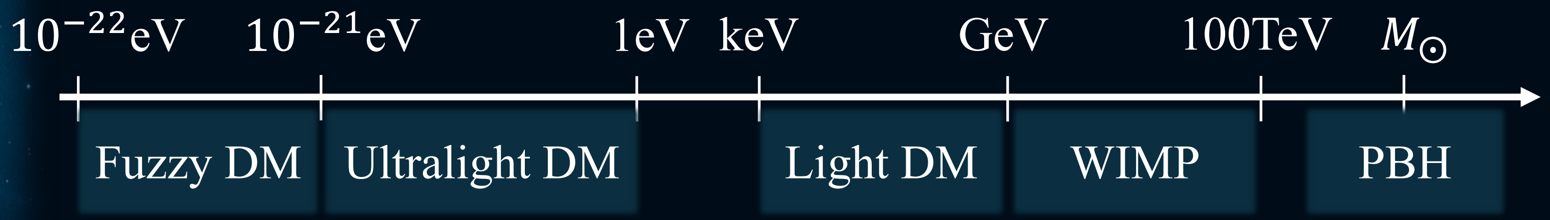


Image Credit: SOU

The Gravitational Monster: Black Hole

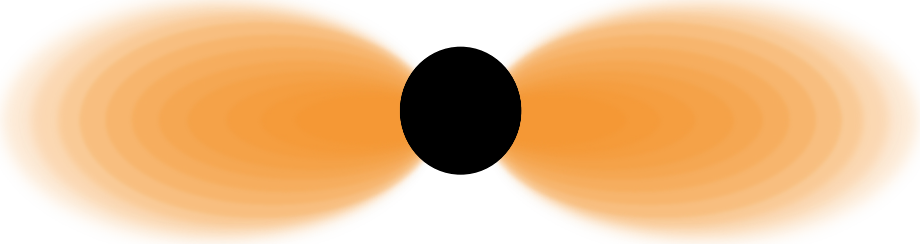
Image Credit: EHT

When dark matter meets black holes

Powered by AI

Black Hole Impacts on DM

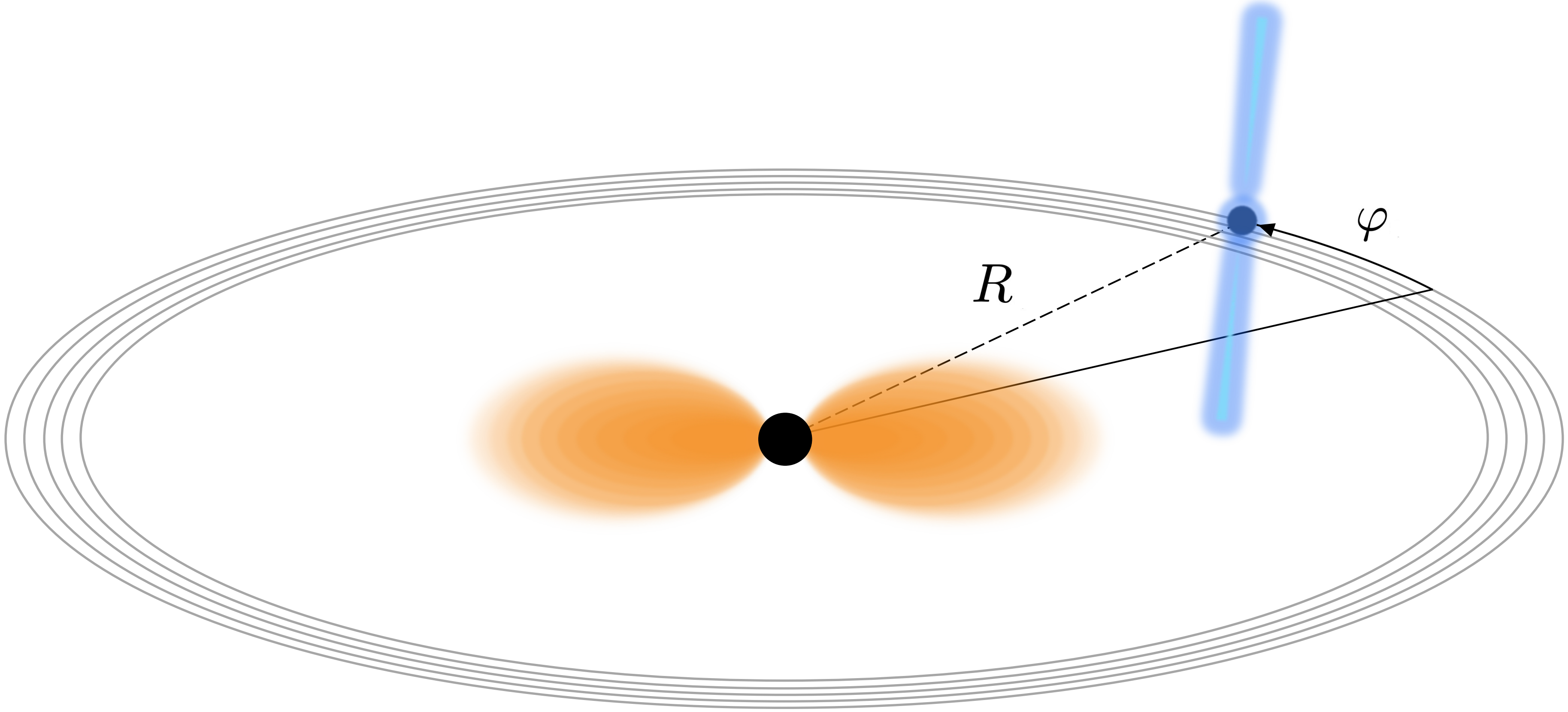
DM Accretion



Superradiance

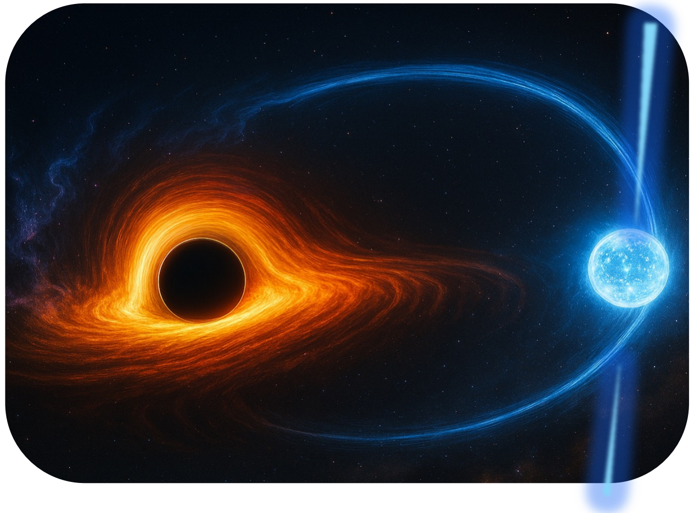
DM Spike

Binary Companion as a DM Probe



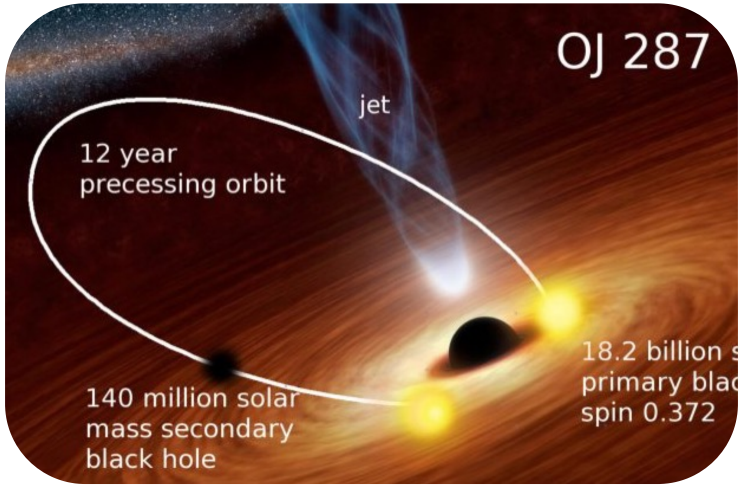
Probe DM in Multi-Messenger Astronomy

Radio Channel



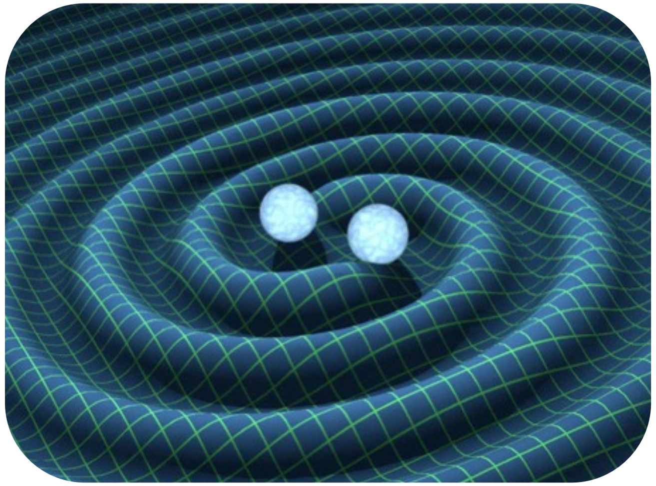
Pulsar-Black Hole Binary

Optical Channel



OJ 287

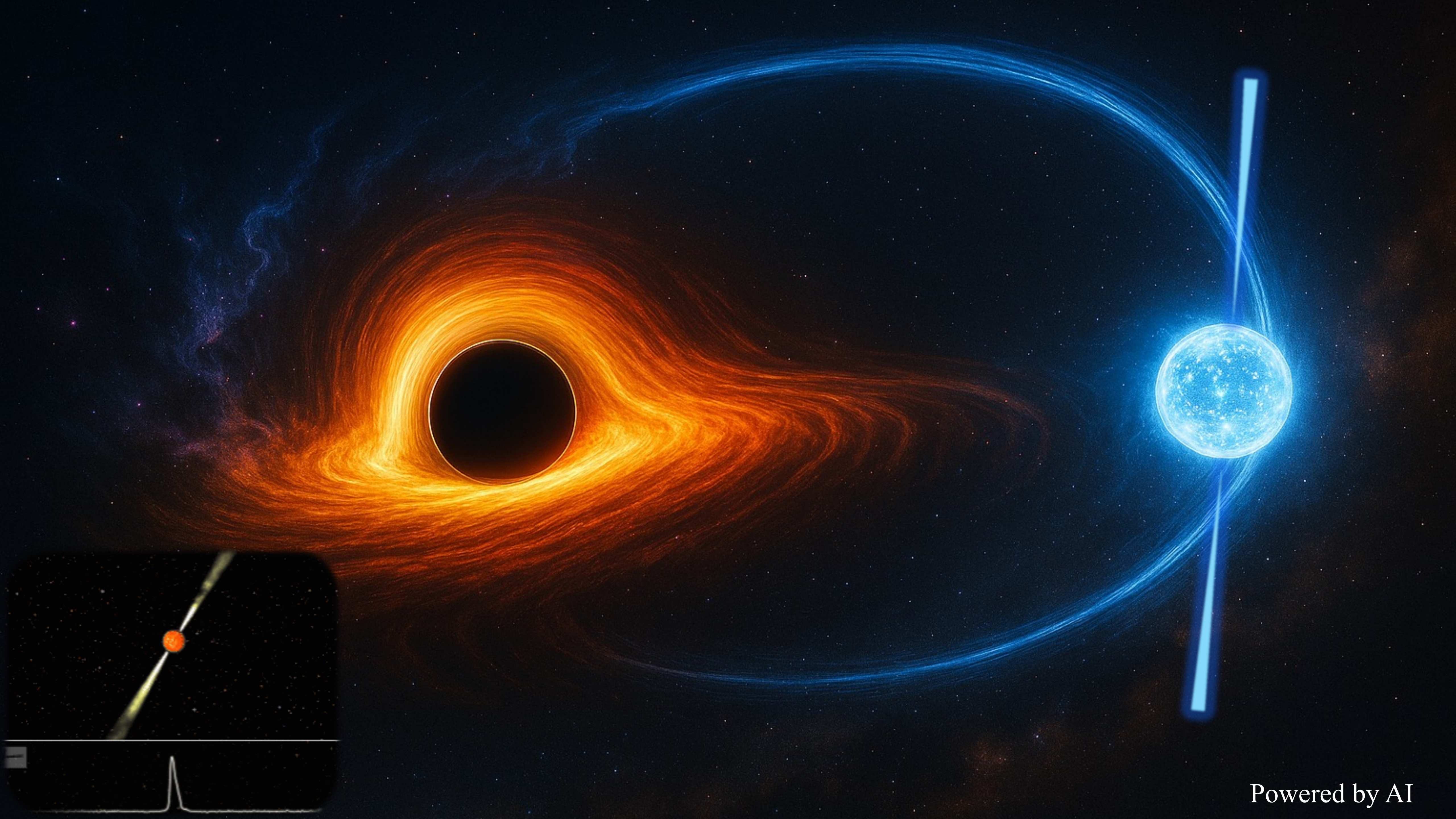
Gravitational Wave Channel



Black Hole Binary

Radio Channel

2304.08824, Ali Akil, QD


Powered by AI

Dark Matter Accretion Rate

Ultralight DM Accretion

$$\frac{\mathrm{d}M_B}{\mathrm{d}t} = \frac{2.5\,M_\odot}{10^{17}\,\mathrm{yr}}\left(\frac{M_B}{100\,M_\odot}\right)^2\left(\frac{\mu}{10^{-22}\,\mathrm{eV}}\right)^6\left(\frac{M_{\mathrm{sol}}}{10^{10}\,M_\odot}\right)^4$$

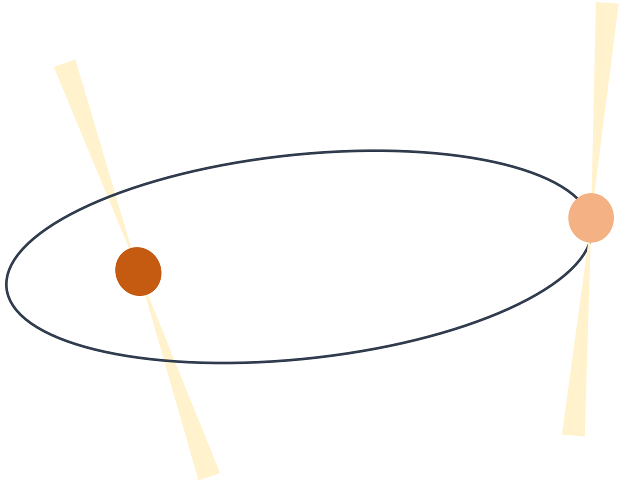
WIMP Accretion

$$\frac{\mathrm{d}M_\mathrm{B}}{\mathrm{d}t} = 4\pi\lambda_B(GM_\mathrm{B})^2\frac{\rho_\infty}{\gamma^{\frac{3}{2}}\,\Theta_\infty^{\frac{3}{2}}c^3} \qquad \Theta = \frac{k_BT}{mc^2} = \frac{c_s^2}{\gamma c^2}$$

PBH Accretion

$$\frac{\mathrm{d}M_\mathrm{B}}{\mathrm{d}t} \simeq \frac{M_\mathrm{PBH}}{t_f} \simeq 27\pi(GM_\mathrm{B})^2\frac{\rho_\mathrm{DM}v}{c^4}$$

Feasibility of DM Detection

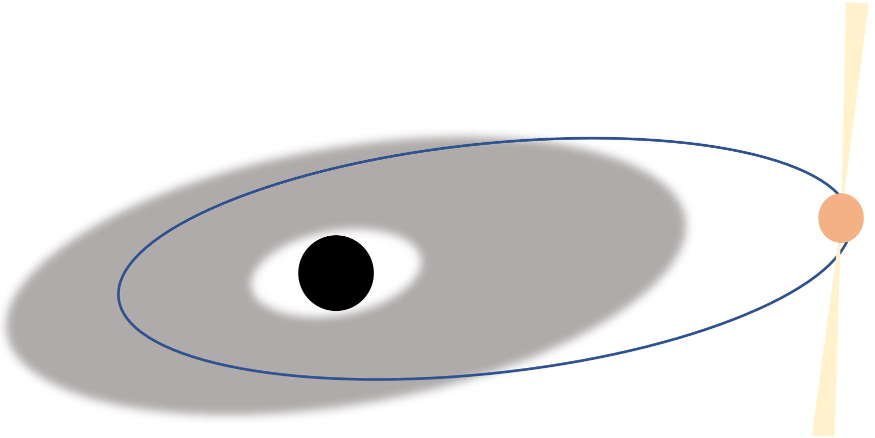


PSR J0737-3039A/B

$$\frac{\Delta m_{\rm PSR}}{m_{\rm PSR}} \sim \mathcal{O}(10^{-13})$$

A detection of pulsar mass change within 16 years observations

Kramer, M., et al. "Strong-field gravity tests with the double pulsar." *Physical Review X* 11.4 (2021): 041050.

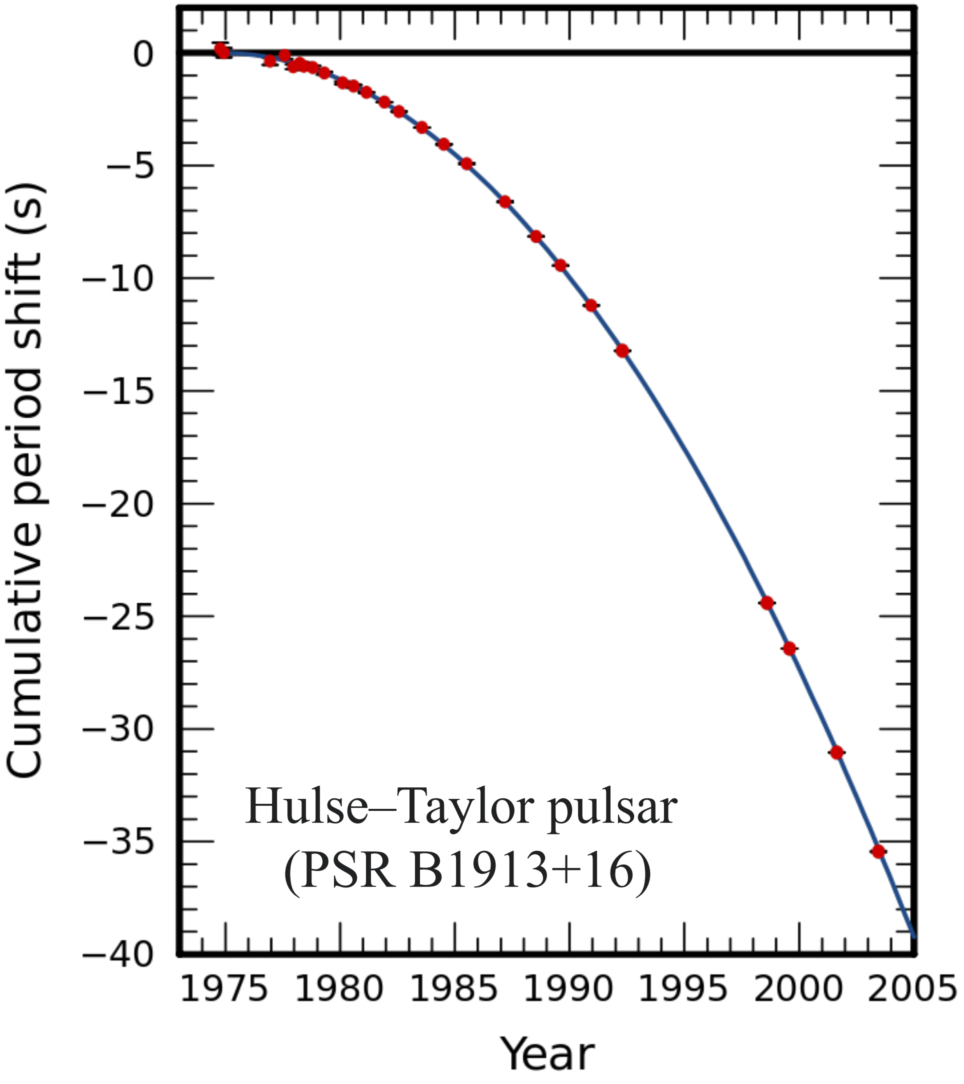


Pulsar-Black Hole Binary

$$\frac{\Delta M_B}{M_B} \sim \mathcal{O}(10^{-12})$$

The relative BH mass change within 10 years, if $M_B = 10 M_\odot$ and $\Theta = 10^{-10}$ or $m_{ul} = 10^{-20}$ eV

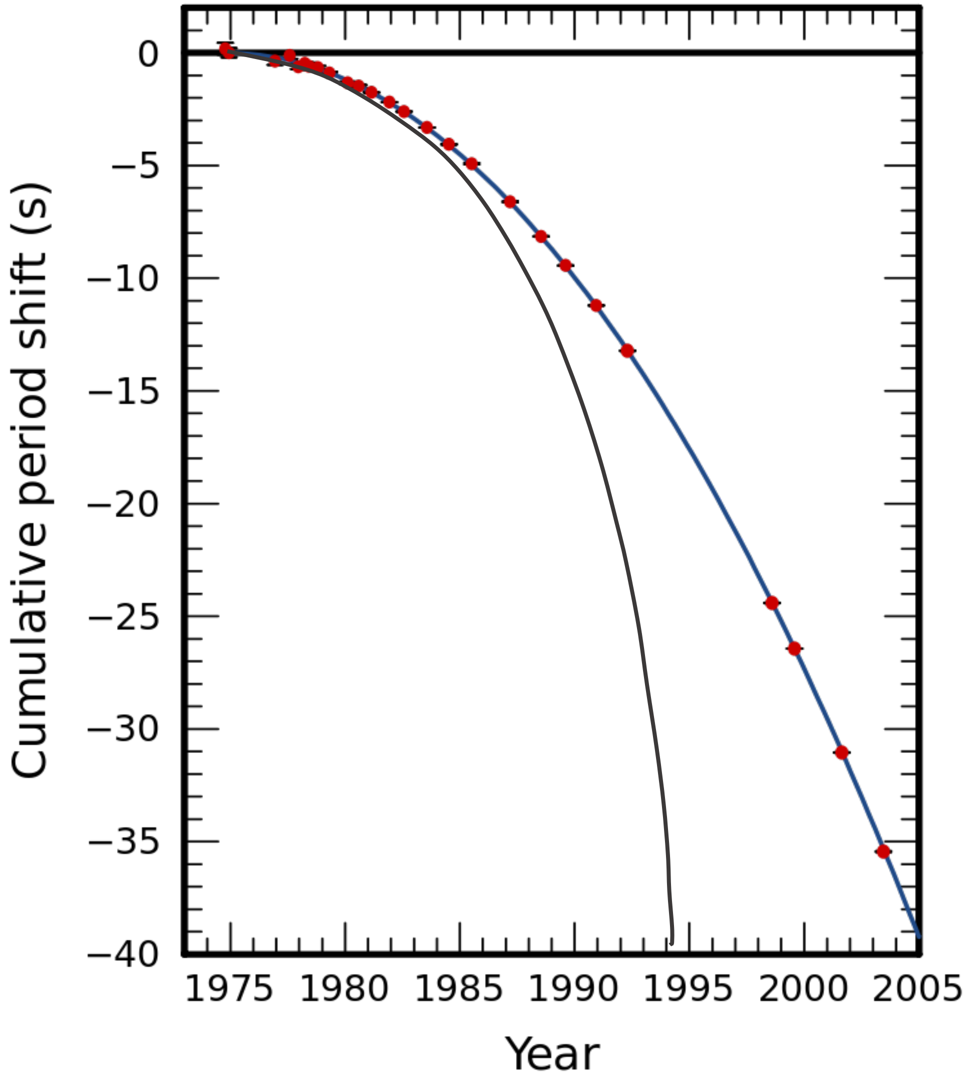
Orbital Phase Delay



$$\Delta\phi(t) = 2\pi \int_0^t f_{\rm GR}(\tau)d\tau - 2\pi \int_0^t f_{\rm Newton}(\tau)d\tau$$

$$\sigma_{\Delta\phi} = \frac{2\pi}{\sqrt{t/1\,\mathrm{day}}}\frac{P}{t_{\rm obs}}$$

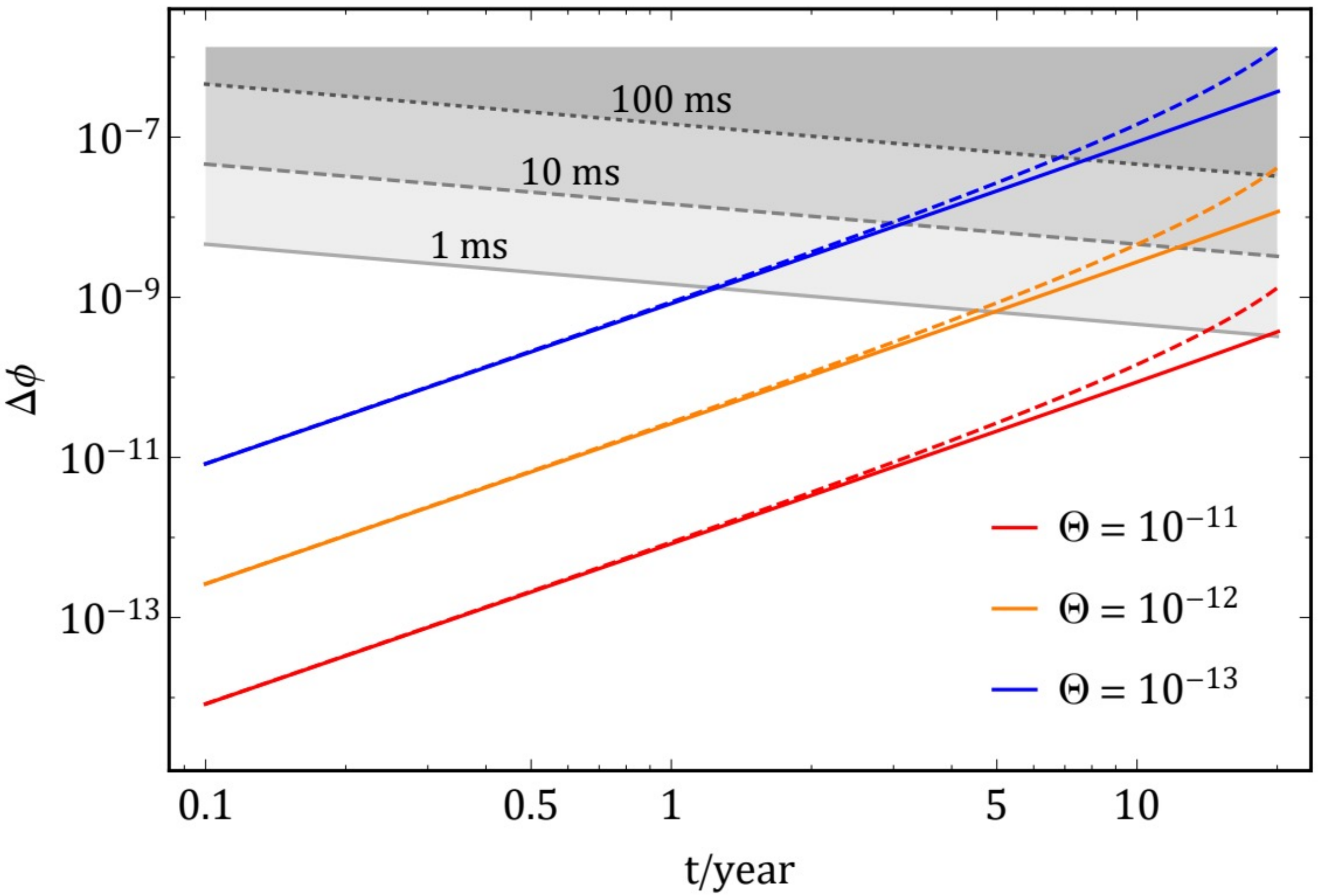
Orbital Phase Delay



$$\Delta\phi(t) = 2\pi \int_0^t f(\tau)d\tau - 2\pi \int_0^t f_{\mathrm{GR}}(\tau)d\tau$$

$$\sigma_{\Delta\phi} = \frac{2\pi}{\sqrt{t/1\,\mathrm{day}}}\frac{P}{t_{\mathrm{obs}}}$$

Orbital Phase Delay



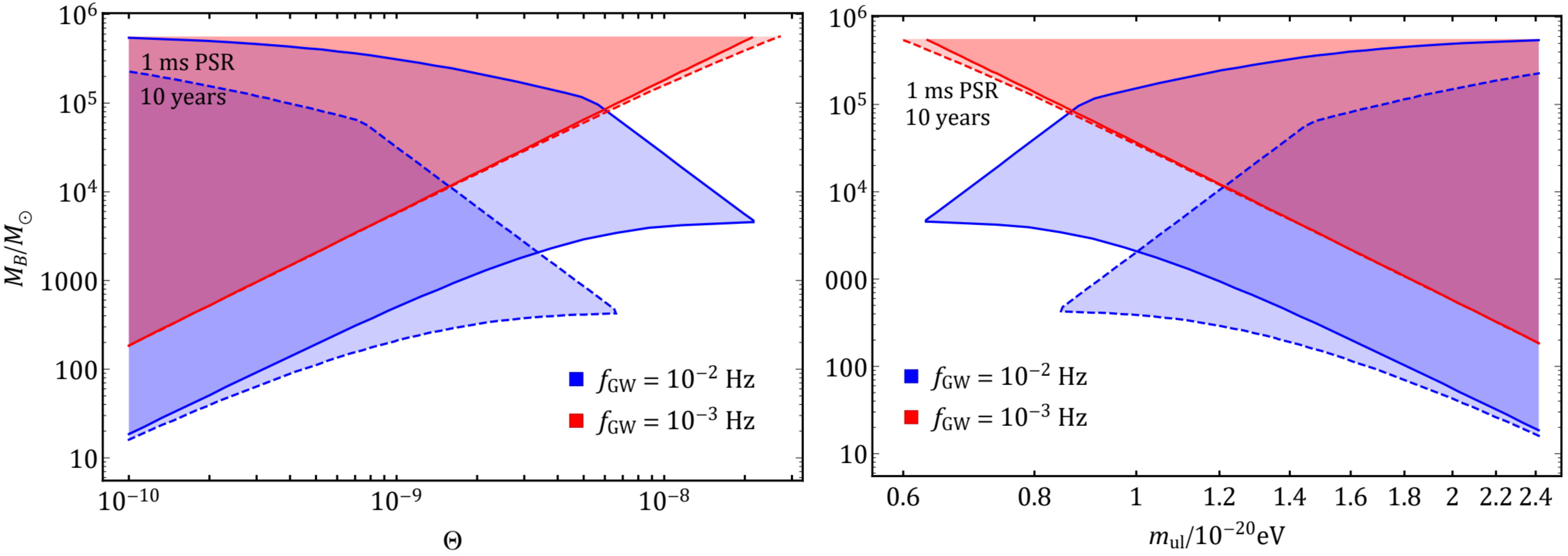
$$P = \frac{G}{5c^5}\left(\frac{\mathrm{d}^3Q_{ij}}{\mathrm{d}t^3}\frac{\mathrm{d}^3Q_{ij}}{\mathrm{d}t^3} - \frac{1}{3}\frac{\mathrm{d}^3Q_{ii}}{\mathrm{d}t^3}\frac{\mathrm{d}^3Q_{jj}}{\mathrm{d}t^3}\right)$$

$$\frac{\mathrm{d}E_p}{\mathrm{d}t} = -\frac{Gm_\mathrm{p}}{a}\frac{\mathrm{d}M_\mathrm{B}}{\mathrm{d}t}$$

$$\Delta\phi(t) = 2\pi\int_0^t f(\tau)d\tau - 2\pi\int_0^t f_\mathrm{GR}(\tau)d\tau$$

$$\sigma_{\Delta\phi} = \frac{2\pi}{\sqrt{t/1\,\mathrm{day}}}\frac{P}{t_\mathrm{obs}}$$

Dark Matter Constraint



Null-Detections prefer weaker accretion DM models, such as PBHs

Optical Channel

2505.09696, QD, Minxi He, Volodymyr Takhistov, Hui-Yu Zhu

OJ 287

$M_{\rm BH} = 1.8\times10^{10} M_\odot$ $\quad T = 12.067\ yr$

$m_{\rm BH} = 1.5\times10^{8} M_\odot$ $\quad \dot{T} = -0.00099$

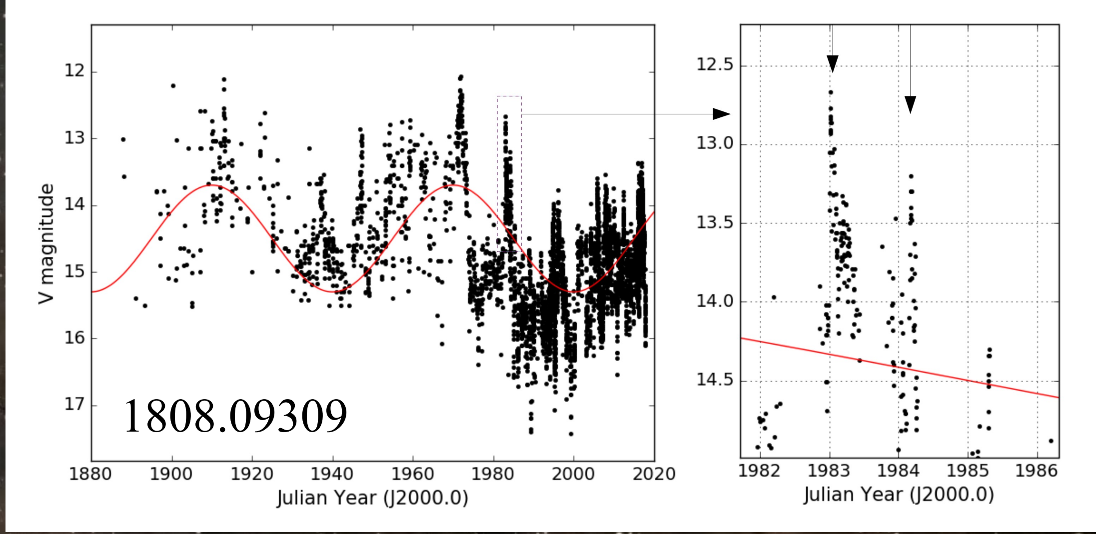
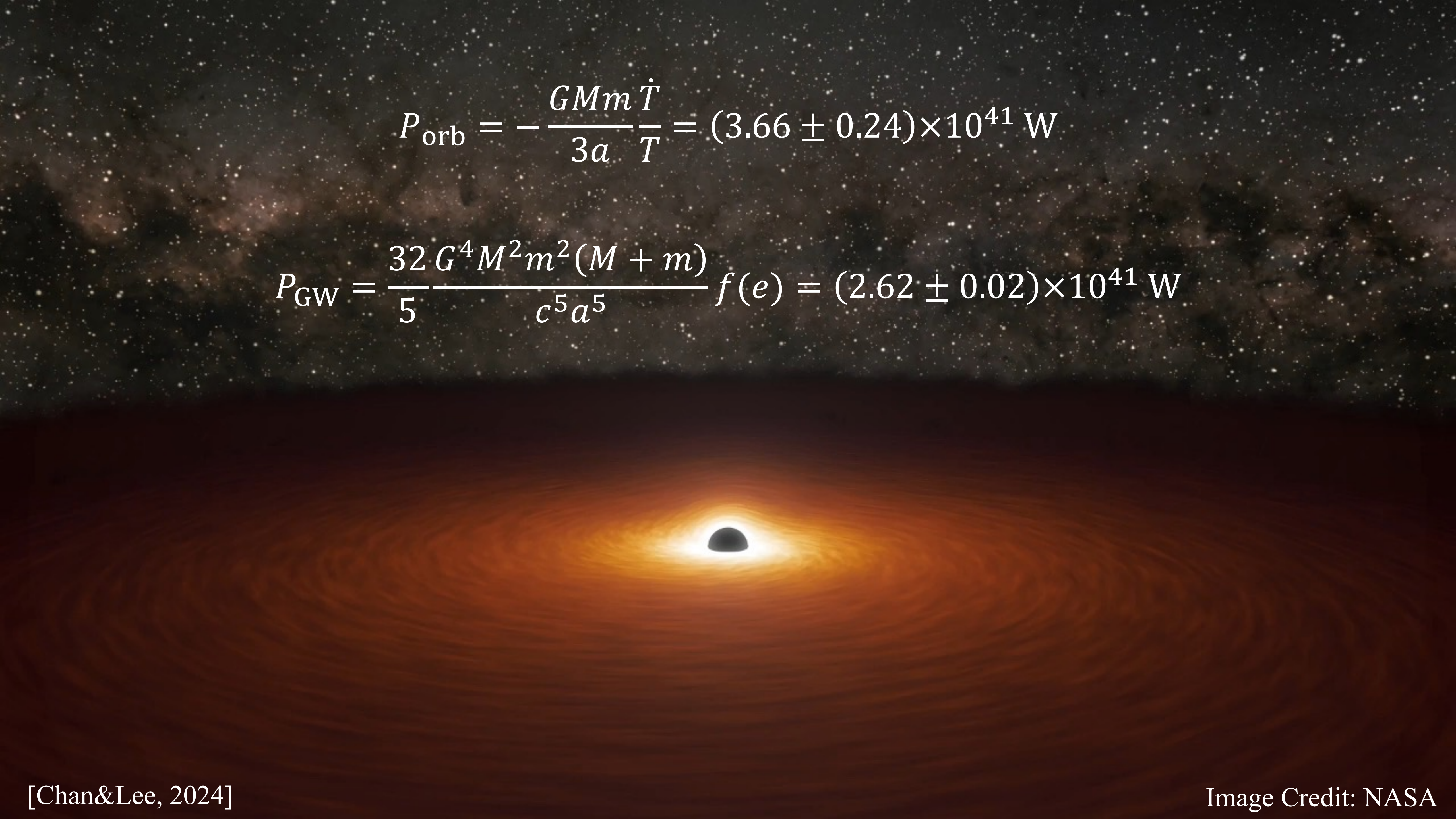


Image Credit: NASA

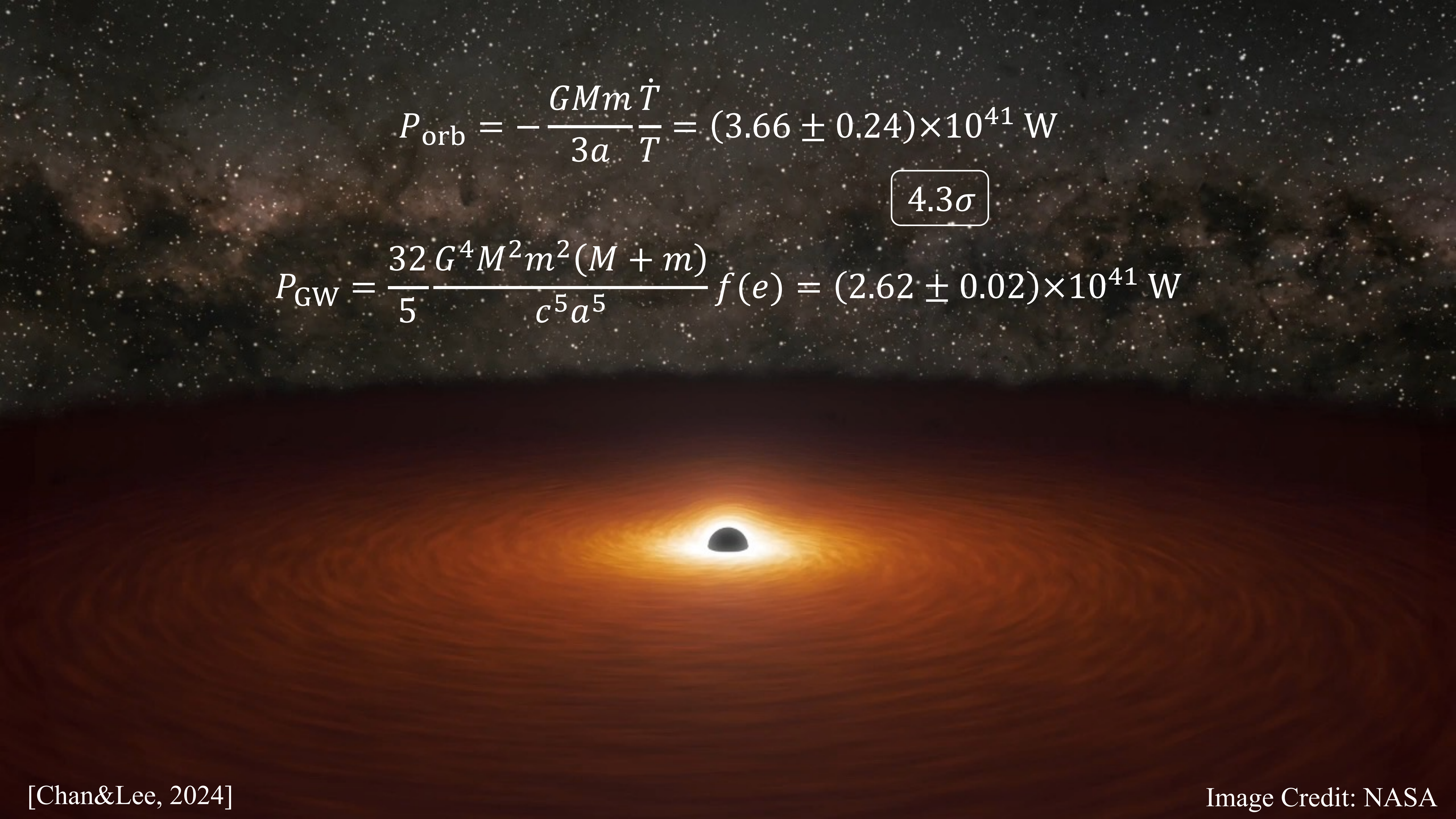


$$P_{\mathrm{orb}} = -\frac{GMm}{3a}\frac{\dot{T}}{T} = (3.66 \pm 0.24)\times 10^{41}\ \mathrm{W}$$

$$P_{\mathrm{GW}} = \frac{32}{5}\frac{G^4M^2m^2(M+m)}{c^5a^5}f(e) = (2.62 \pm 0.02)\times 10^{41}\ \mathrm{W}$$

[Chan&Lee, 2024]

Image Credit: NASA



$$P_{\mathrm{orb}} = -\frac{GMm}{3a}\frac{\dot{T}}{T} = (3.66 \pm 0.24)\times 10^{41}\ \mathrm{W}$$

4.3σ

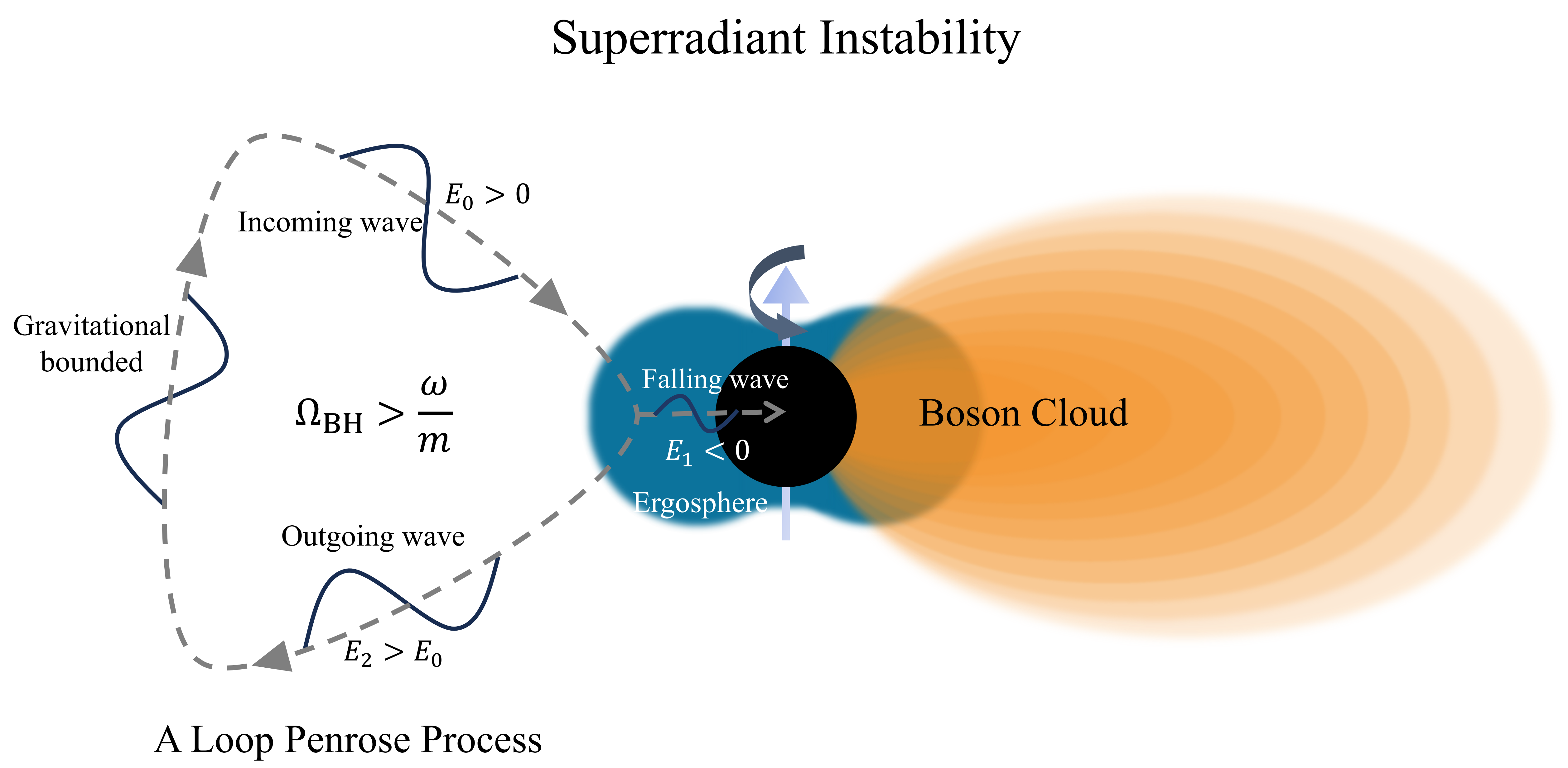
$$P_{\mathrm{GW}} = \frac{32}{5}\frac{G^4 M^2 m^2 (M+m)}{c^5 a^5} f(e) = (2.62 \pm 0.02)\times 10^{41}\ \mathrm{W}$$

[Chan&Lee, 2024]

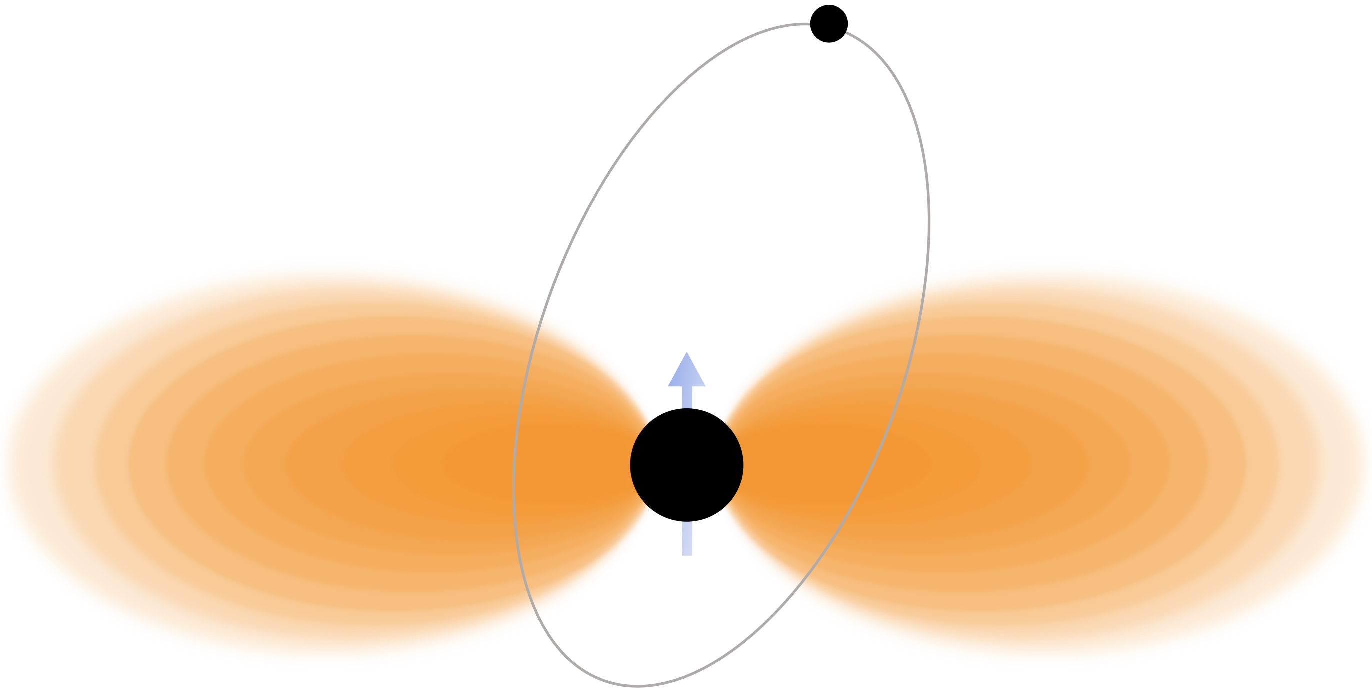
Image Credit: NASA

$$P_{\mathrm{orb}} = P_{\mathrm{GW}} + P_{\mathrm{DF}}$$

Image Credit: NASA


Superradiant Instability
$E_0 > 0$
Incoming wave
Gravitational bounded
$\Omega_{BH} > \frac{\omega}{m}$
Falling wave
$E_1 < 0$
Ergosphere
Boson Cloud
Outgoing wave
$E_2 > E_0$
A Loop Penrose Process

Dynamical Friction Power



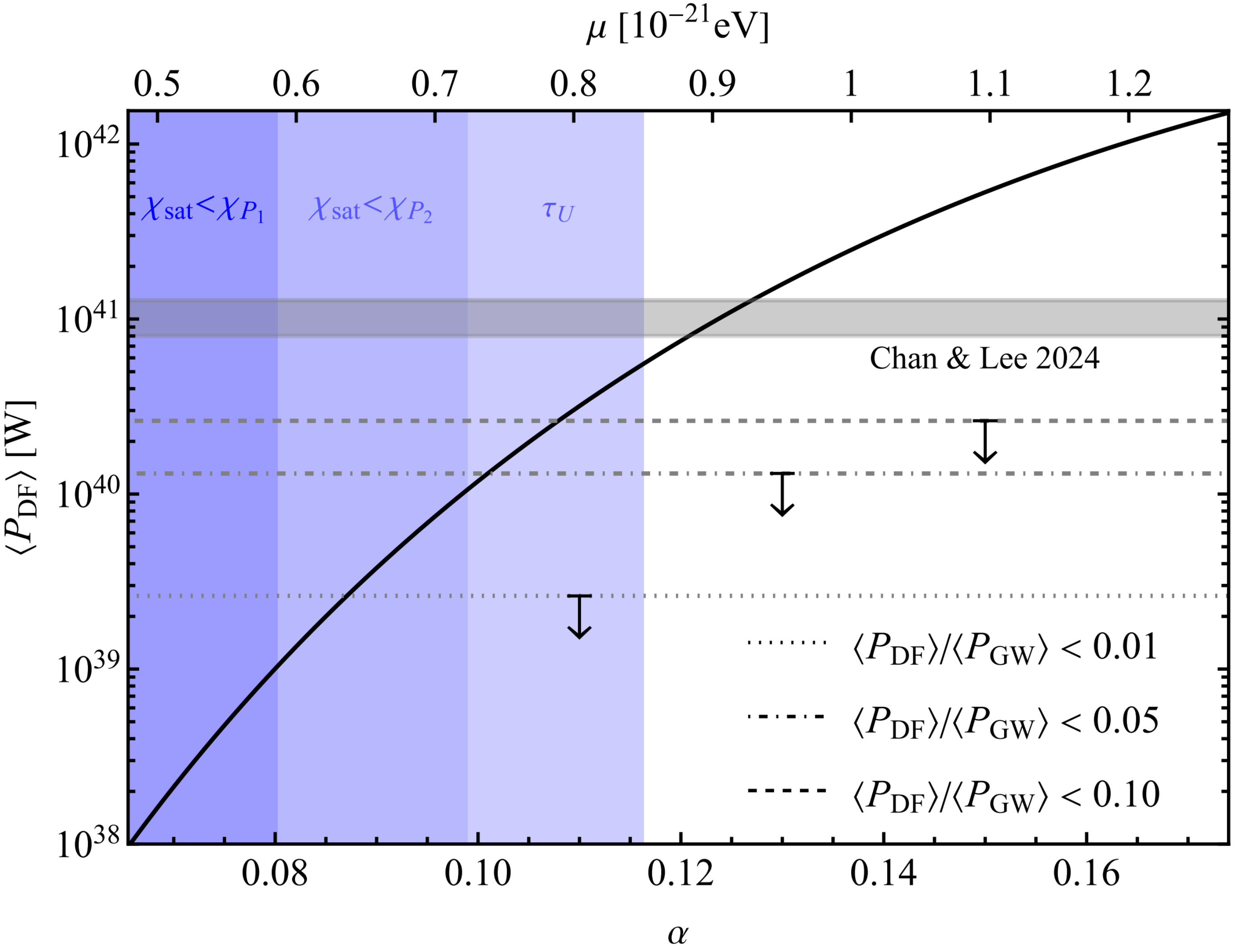
$$P_{\mathrm{DF}} = \frac{4\pi q^2 M_{\mathrm{BH}}^2}{v} \rho_{nlm}(x_*, \theta_*) C_\Lambda$$

$$\rho_{211}(x, \theta) = \frac{\beta}{64\pi} \frac{M_{\mathrm{BH}}}{r_0^3} x^2 e^{-x} \sin^2\theta$$

$$R_*(\varphi_*) = \frac{a(1-e^2)}{1 + e\cos(1-\zeta)\varphi_*}$$

$$\langle P_{\mathrm{DF}} \rangle = \frac{1}{T} \int_0^{2\pi} P_{\mathrm{DF}}(R_*(\varphi_*), \theta_*(\varphi_*, \iota)) \frac{\mathrm{d}t}{\mathrm{d}\varphi_*} \mathrm{d}\varphi_*$$

OJ 287 Constraint on Ultralight Boson



Dissipative Energy from Boson Cloud

$$P_{\rm orb} = P_{\rm GW} + P_{\rm DF}$$

$$\mu = (8.8\text{–}9.3) \times 10^{-22}\,{\rm eV}$$

A Null Detection Result

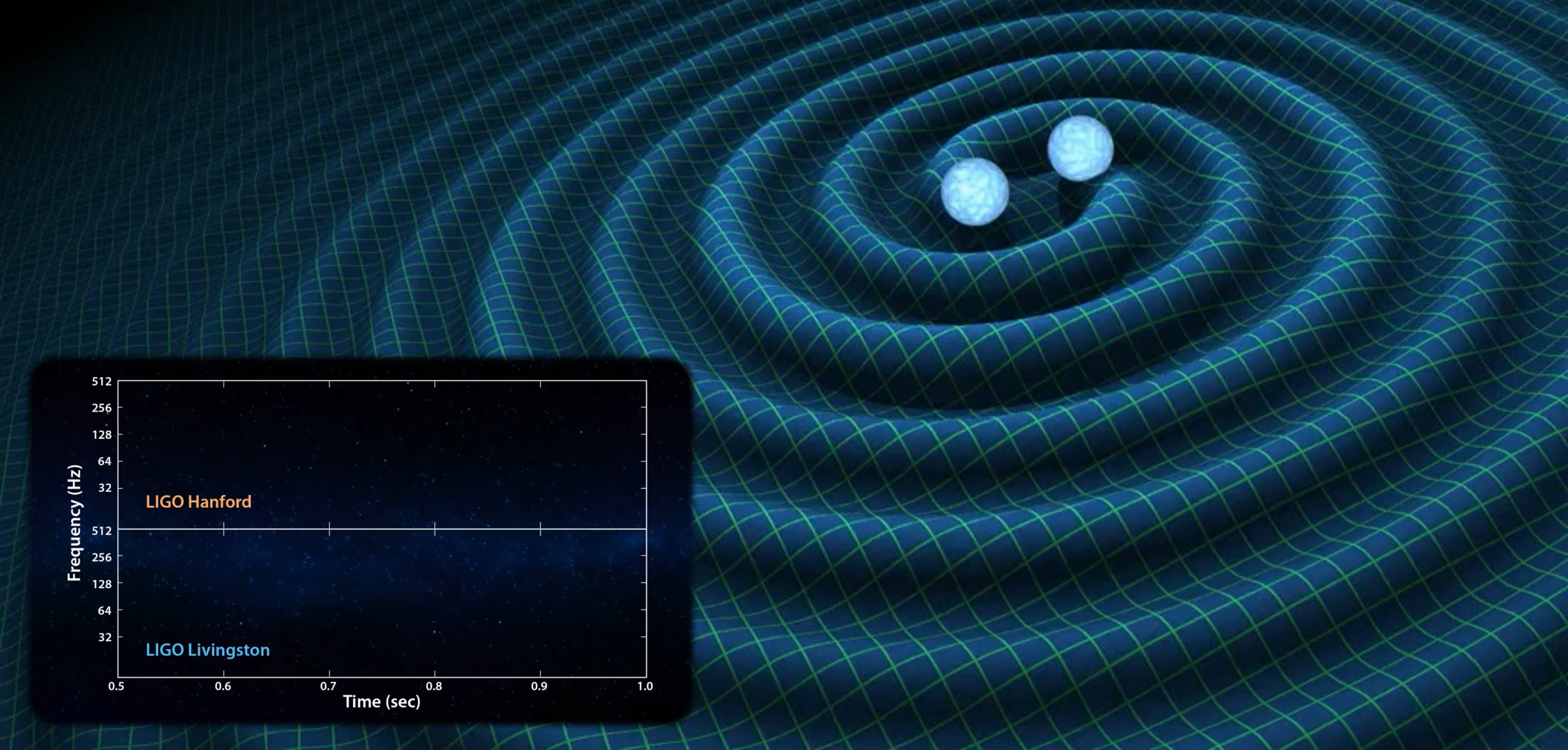
$$\frac{P_{\rm DF}}{P_{\rm GW}} < 1\%$$

$$\mu \notin (8.5 - 22) \times 10^{-22}\,{\rm eV}$$

Gravitational Wave Channel

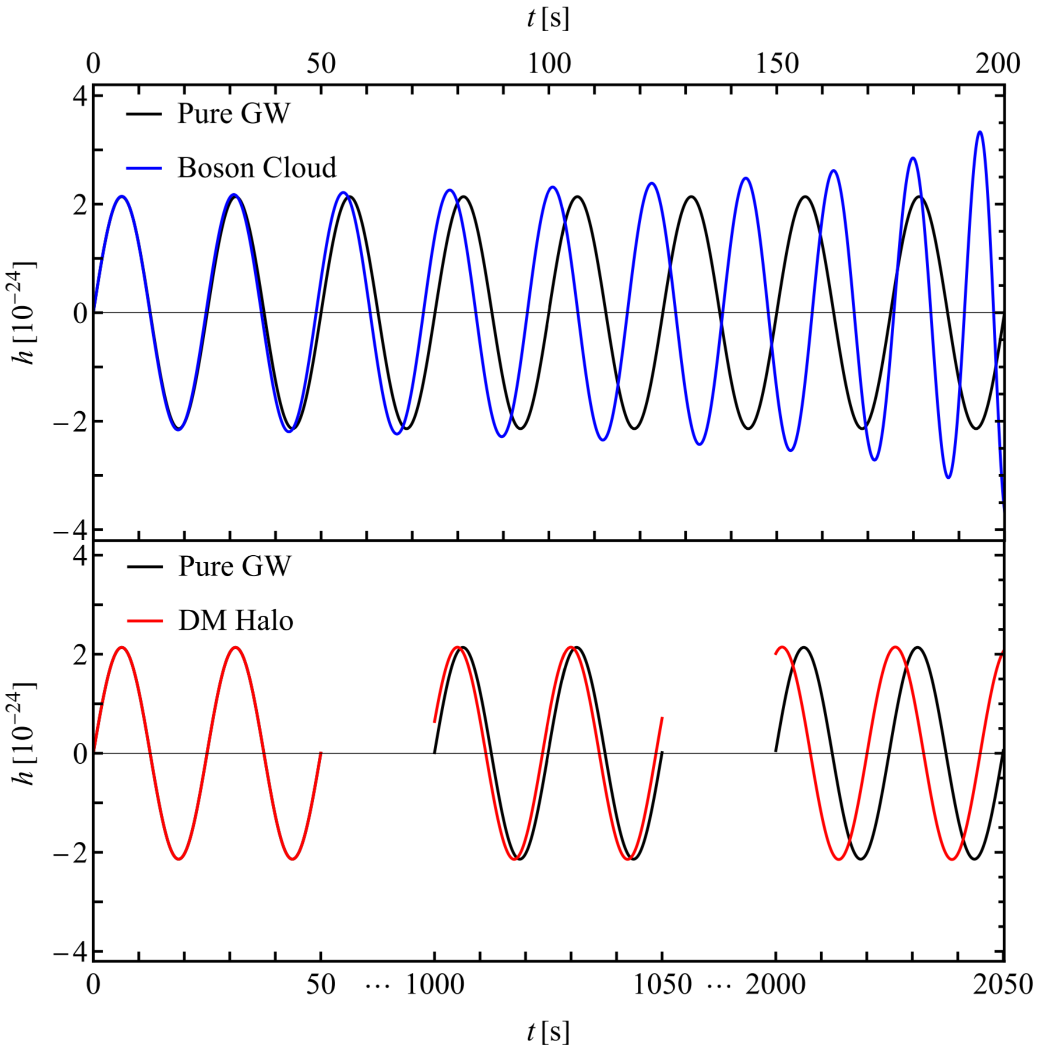
2510.27424, QD, Minxi He, Hui-Yu Zhu

GW150914



512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

Dark Dense Environment Impacts on GWs



$$\frac{\mathrm{d}f_s}{\mathrm{d}t_s} = -\frac{3}{(\pi G)^{2/3}} \frac{f_s^{1/3}}{\mathcal{M}_c^{5/3}} (P_{\mathrm{GW}} + P_{\mathrm{DF}})$$

$$P_{\mathrm{DF}} = -4\pi \frac{G^2 M_*^2}{v} \rho_D C_\Lambda$$

A Novel DM Probe in GWs

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{96}{5}\frac{[G\mathcal{M}_c(1+z)]^{5/3}\pi^{8/3}f^{11/3}}{c^5} + \frac{3f^{1/3}}{(\pi G)^{2/3}[\mathcal{M}_c(1+z)]^{5/3}}|P_{\mathrm{DF}}|$$

$$h = \frac{4\pi^{2/3}}{d_L(z)}\frac{[G\mathcal{M}_c(1+z)]^{5/3}}{c^4}f^{2/3}$$

$$g(t) \equiv \frac{1}{hf^3}\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{24}{5}\frac{d_L(z)\pi^2}{c} + \frac{12G}{c^4 d_L(z)}\frac{|P_{\mathrm{DF}}|}{h^2 f^2}$$

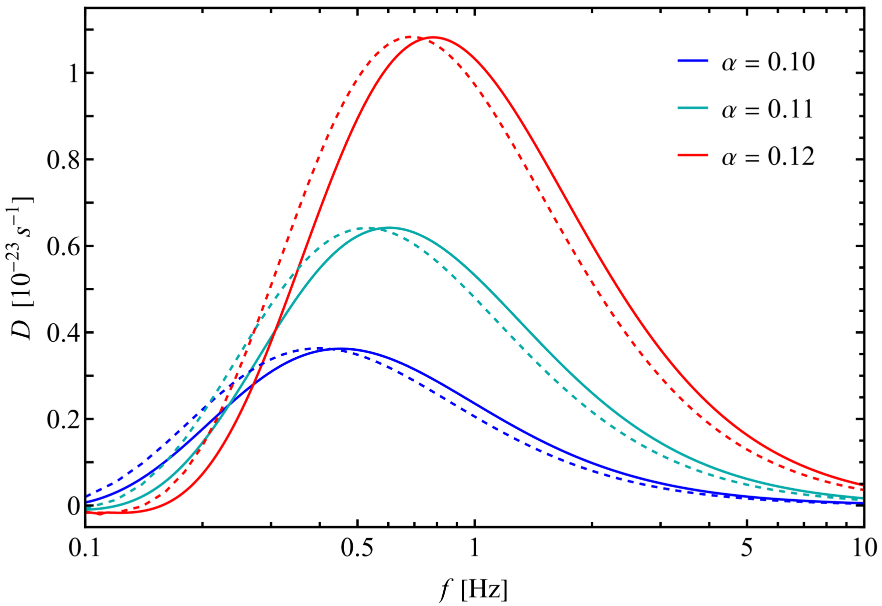
$$\frac{\mathrm{d}g}{\mathrm{d}t} = \frac{12G}{c^4 d_L(z)}\frac{|P_{\mathrm{DF}}|}{h^2 f^3}\frac{\mathrm{d}f}{\mathrm{d}t}\left(\frac{\mathrm{d}\ln\rho}{\mathrm{d}\ln f} + \frac{\mathrm{d}\ln C_\Lambda}{\mathrm{d}\ln f} - \frac{11}{3}\right)$$

$$D \equiv -h^2 f^3\frac{\mathrm{d}g/\mathrm{d}t}{\mathrm{d}f/\mathrm{d}t} = \frac{\mathrm{d}h}{\mathrm{d}t} + 3\frac{h}{f}\frac{\mathrm{d}f}{\mathrm{d}t} - \frac{h}{\mathrm{d}f/\mathrm{d}t}\frac{\mathrm{d}^2 f}{\mathrm{d}t^2}$$

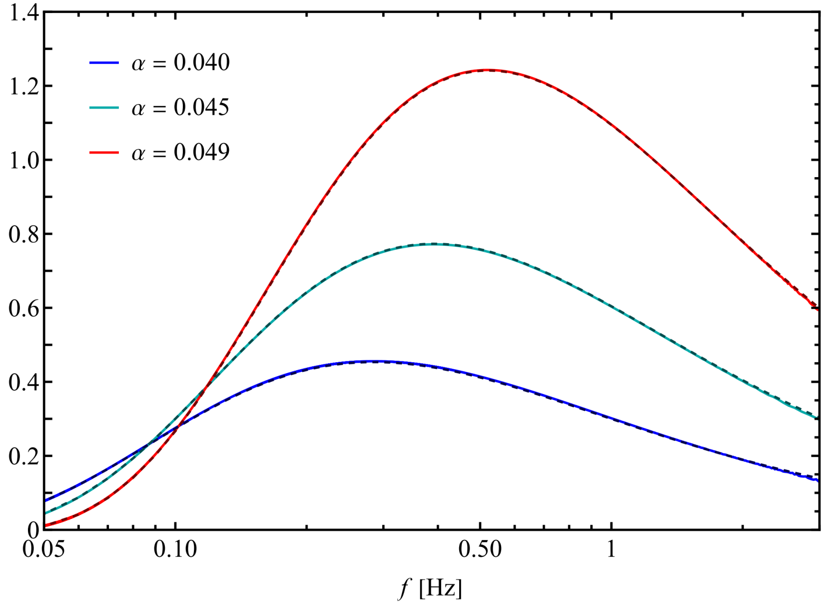
$$= \frac{12G}{c^4 d_L(z)}|P_{\mathrm{DF}}|\left(\frac{11}{3} - \frac{\mathrm{d}\ln\rho}{\mathrm{d}\ln f} - \frac{\mathrm{d}\ln C_\Lambda}{\mathrm{d}\ln f}\right)$$

$D-f$ Diagram in GWs

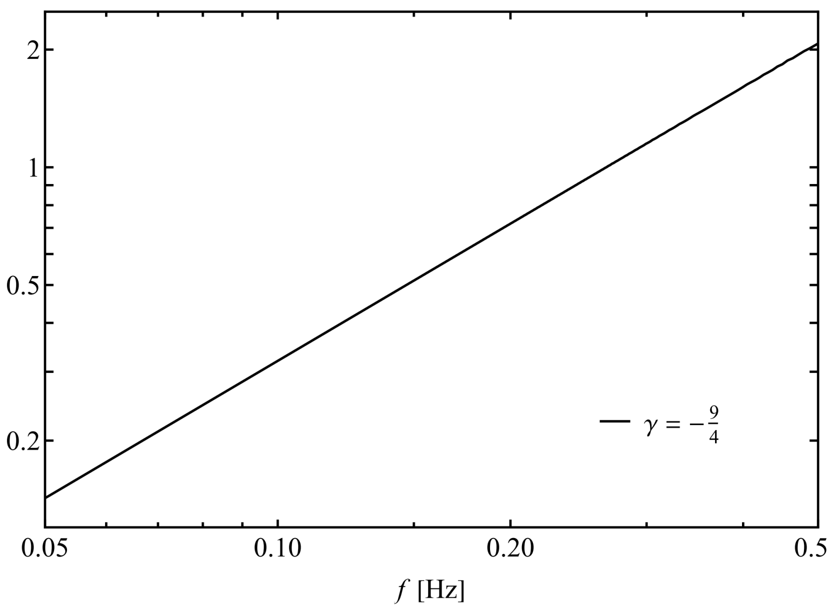
Superradiant Boson Cloud



Soliton



DM Spike

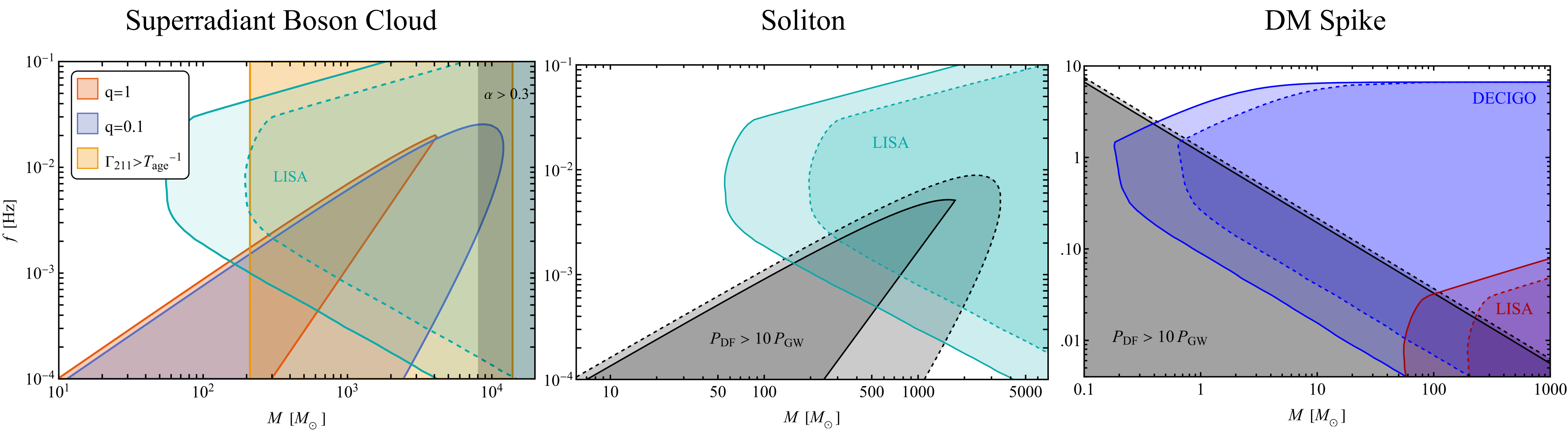


$$D = \frac{8G}{c^4 d_L(z)}|P_{\rm DF}|\left(\frac{15}{2} - \left(\frac{f_0}{f}\right)^{\frac{2}{3}} - \frac{3}{2}\frac{{\rm d}\ln C_\Lambda}{{\rm d}\ln f}\right)$$
$$\propto \left(\frac{f_0}{f}\right)^{\frac{5}{3}} e^{-\left(\frac{f_0}{f}\right)^{\frac{2}{3}}}\left(\frac{15}{2} - \left(\frac{f_0}{f}\right)^{\frac{2}{3}} - \frac{3}{2}\frac{{\rm d}\ln C_\Lambda}{{\rm d}\ln f}\right) C_\Lambda$$

$$D = \frac{8G}{c^4 d_L(z)}|P_{\rm DF}|\left(\frac{11}{2} - 2\left(\frac{f_0}{f}\right)^{\frac{2}{3}} - \frac{3}{2}\frac{{\rm d}\ln C_\Lambda}{{\rm d}\ln f}\right)$$
$$\propto \left(\frac{f_0}{f}\right)^{\frac{1}{3}} e^{-2\left(\frac{f_0}{f}\right)^{\frac{2}{3}}}\left(\frac{11}{2} - 2\left(\frac{f_0}{f}\right)^{\frac{2}{3}} - \frac{3}{2}\frac{{\rm d}\ln C_\Lambda}{{\rm d}\ln f}\right) C_\Lambda$$

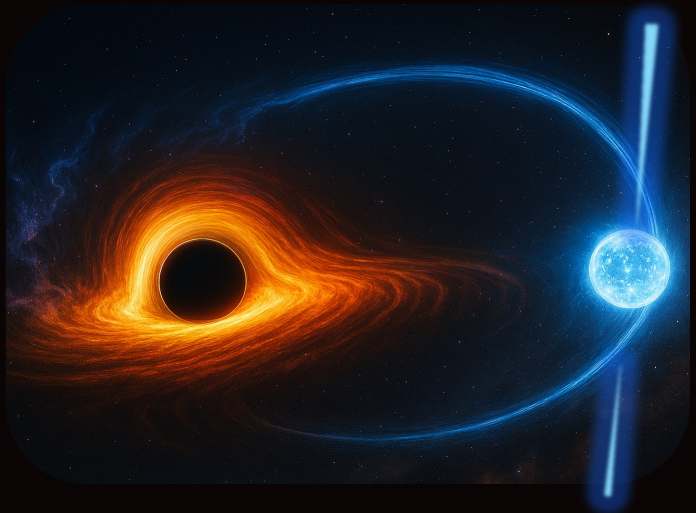
$$D = \frac{8G}{c^4 d_L(z)}|P_{\rm DF}|\left(\gamma + \frac{11}{2}\right)$$
$$\propto f^{-\frac{2}{3}\left(\gamma+\frac{1}{2}\right)}\left(\gamma + \frac{11}{2}\right) .$$

Detectability of Dark Dense Environments

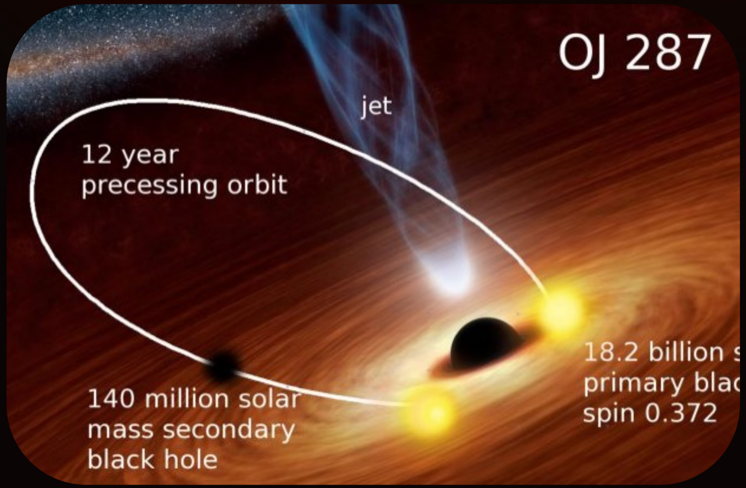


Detectability: $P_{\rm DF} > 10\, P_{\rm GW}$ SNR > 8

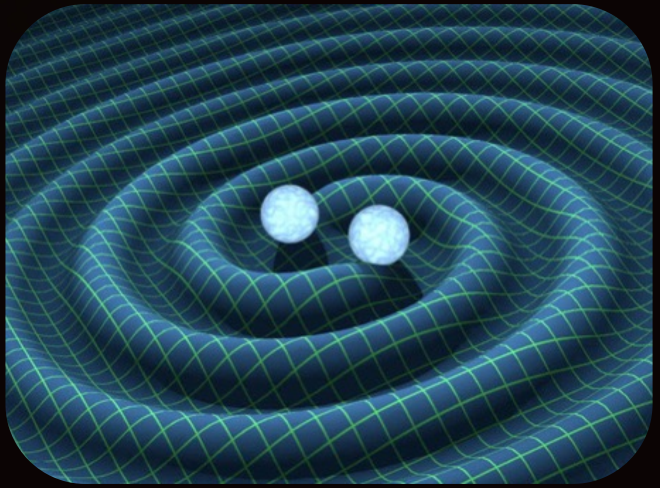
Radio Channel



Optical Channel

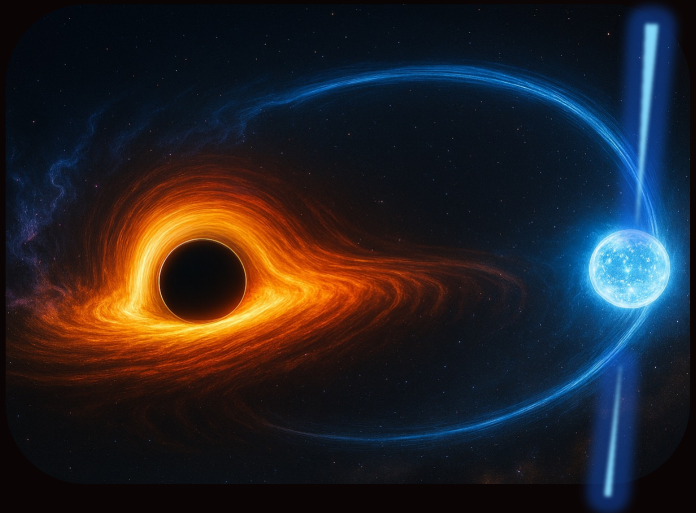


Gravitational Wave Channel

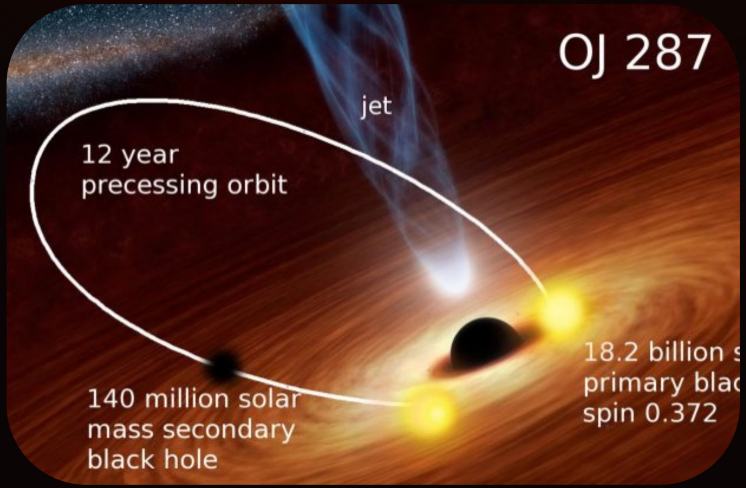


Thank you!

Radio Channel



Optical Channel



Gravitational Wave Channel