



Black Holes as Laboratories for Dark Matter

Qianhang Ding

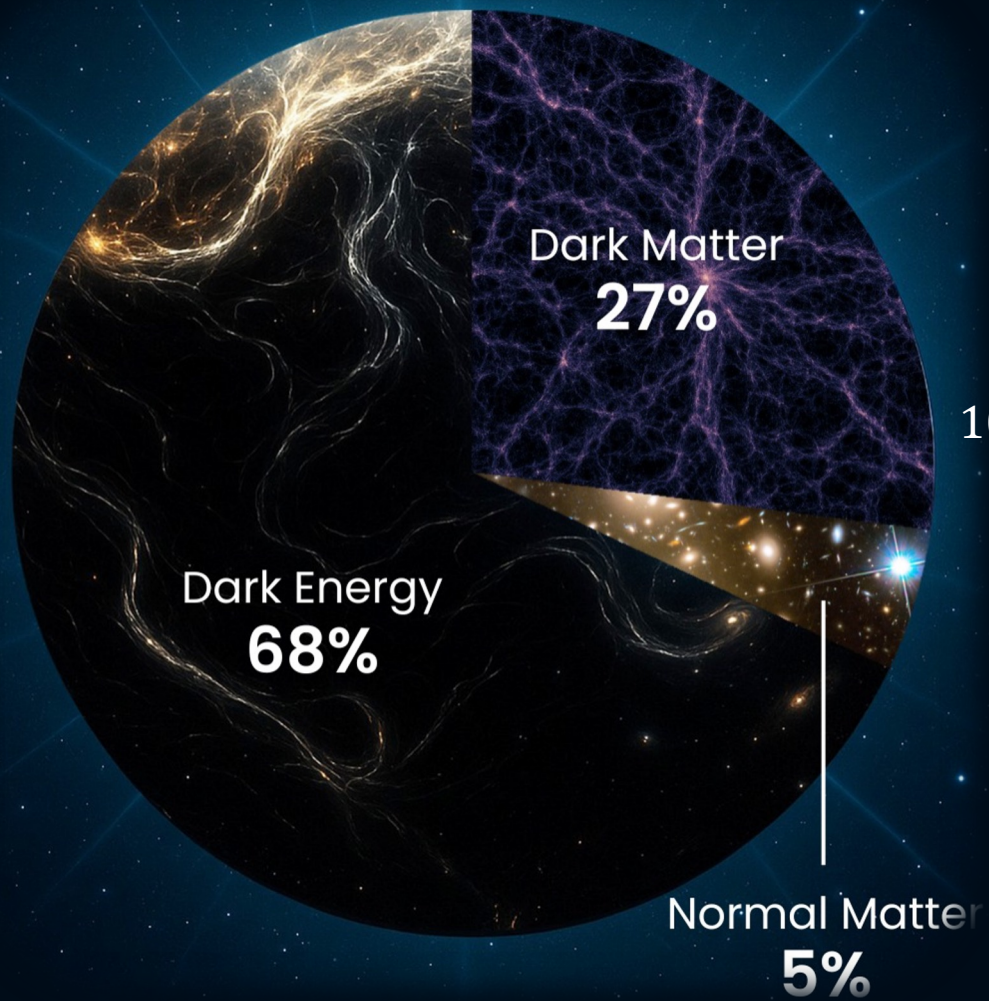
IBS CTPU-CGA

2304.08824, Ali Akil, QD

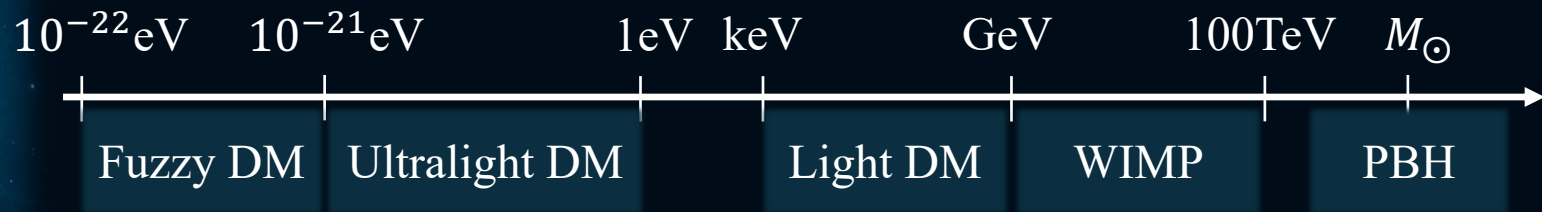
2505.09696, QD, Minxi He, V. Takhistov, Hui-Yu Zhu

2510.27424, QD, Minxi He, Hui-Yu Zhu

Dec 27@ SASGAC 2025



Dark Matter Candidate





The Gravitational Monster: Black Hole

Image Credit: EHT

A black hole with a glowing orange accretion disk and blue/purple nebulae in the background.

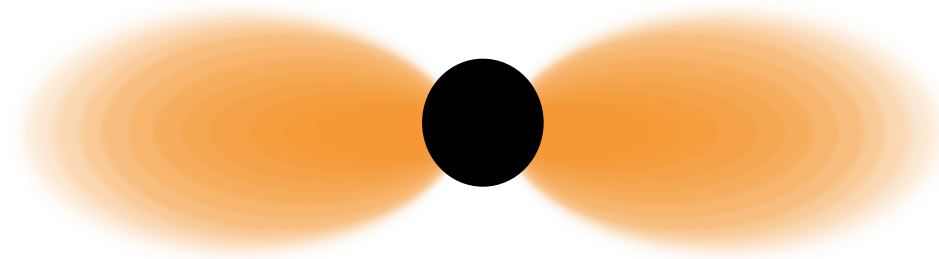
When dark matter meets black holes

Powered by AI

Black Hole Impacts on DM



DM Accretion

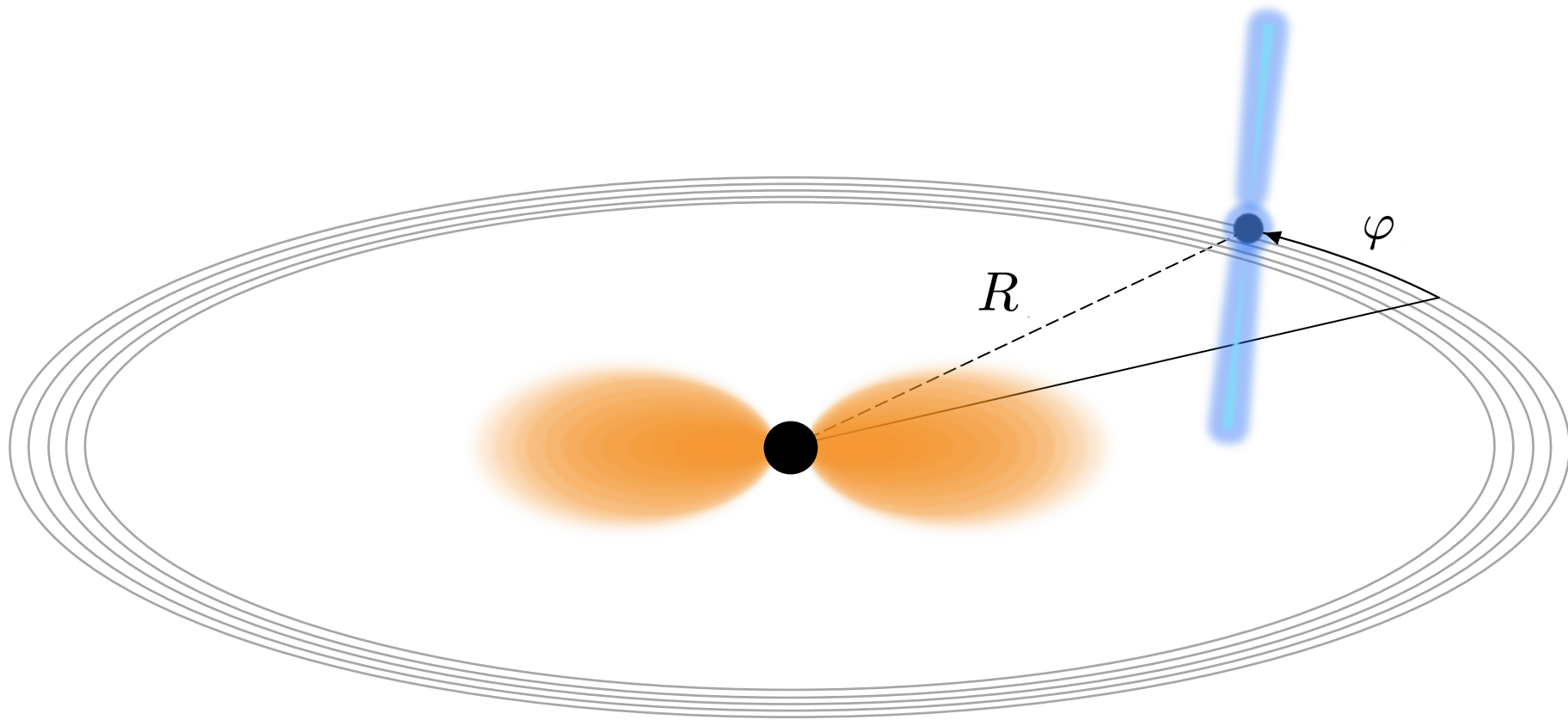


Superradiance



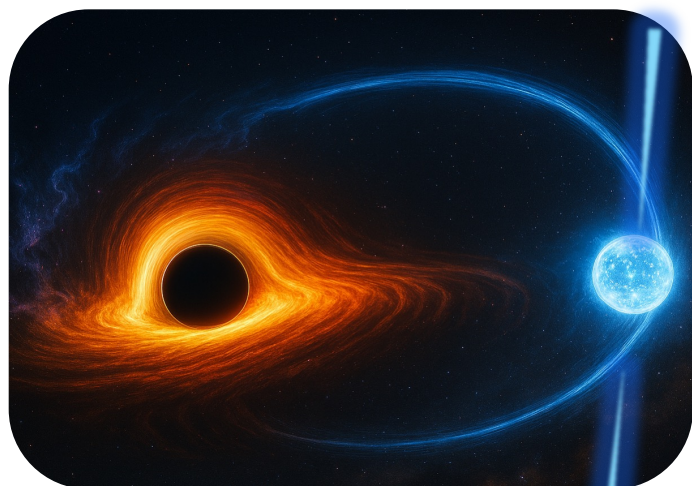
DM Spike

Binary Companion as a DM Probe



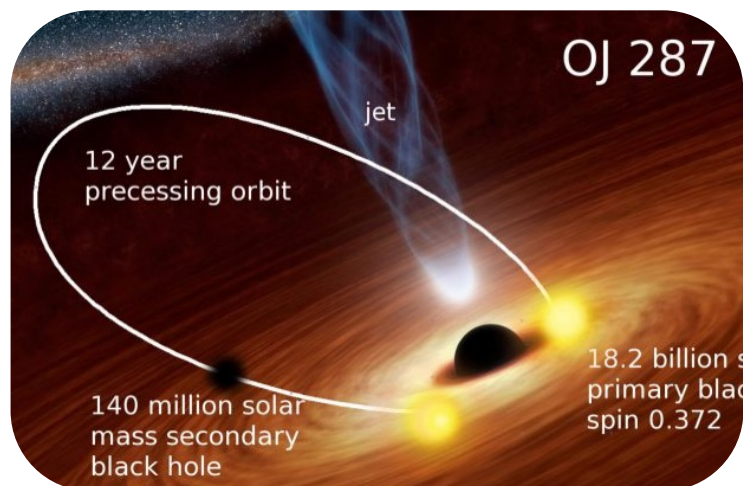
Probe DM in Multi-Messenger Astronomy

Radio Channel



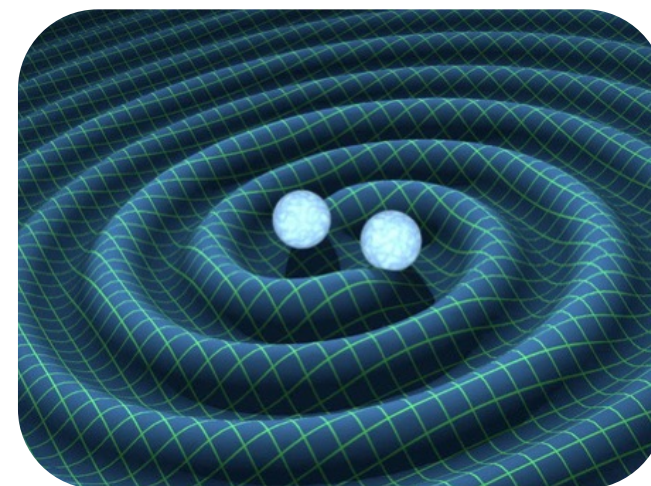
Pulsar-Black Hole Binary

Optical Channel



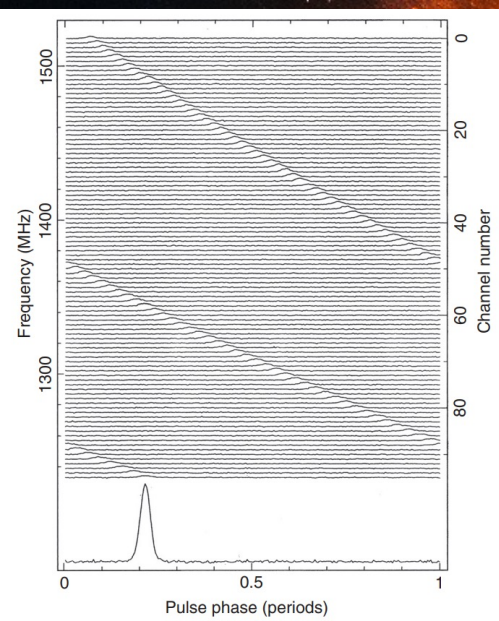
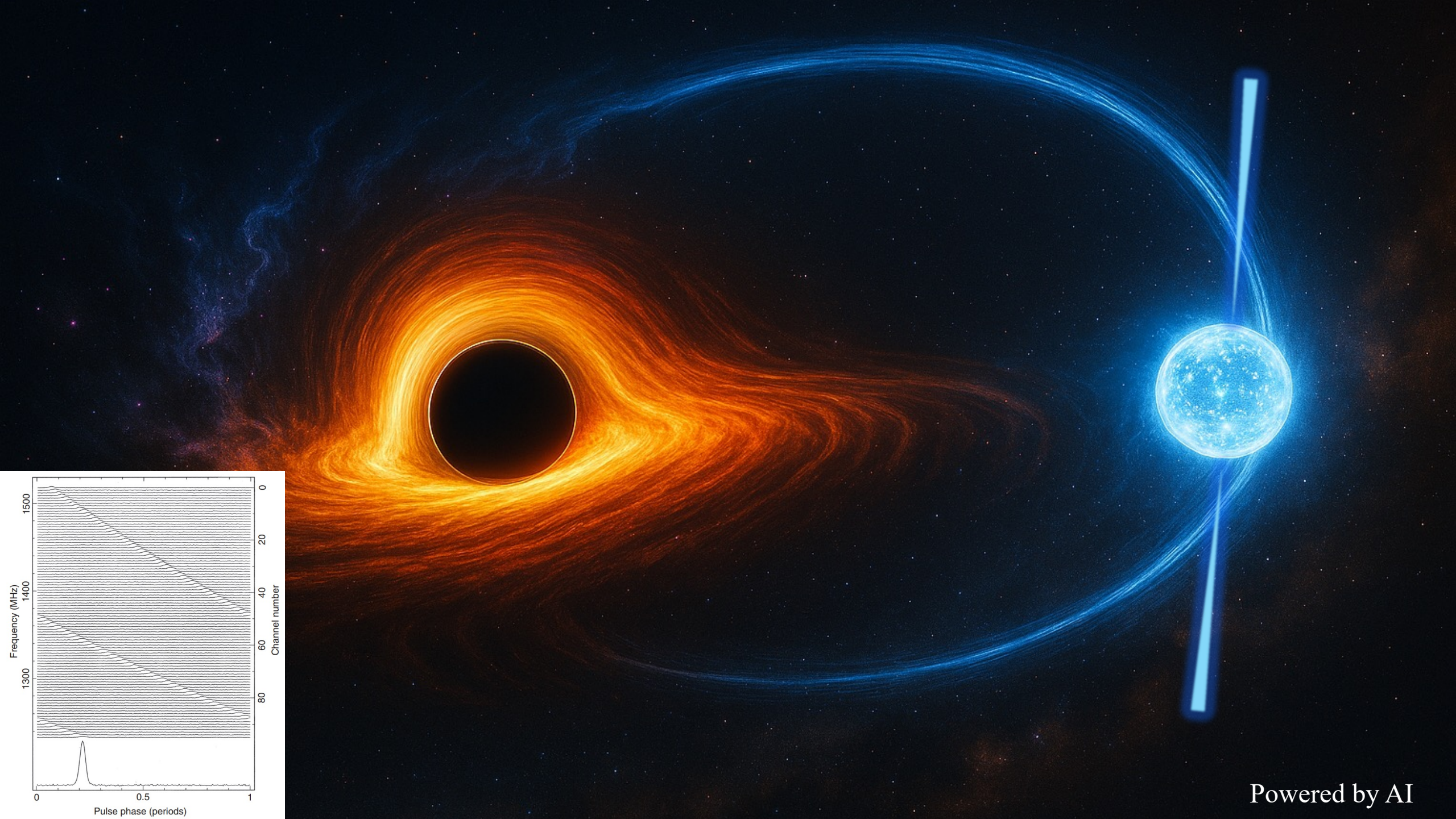
OJ 287

Gravitational Wave Channel



Black Hole Binary

Radio Channel



Powered by AI

Dark Matter Accretion Rate

Ultralight DM Accretion

$$\frac{dM_B}{dt} = \frac{2.5 M_\odot}{10^{17} \text{ yr}} \left(\frac{M_B}{100 M_\odot} \right)^2 \left(\frac{\mu}{10^{-22} \text{ eV}} \right)^6 \left(\frac{M_{\text{sol}}}{10^{10} M_\odot} \right)^4$$

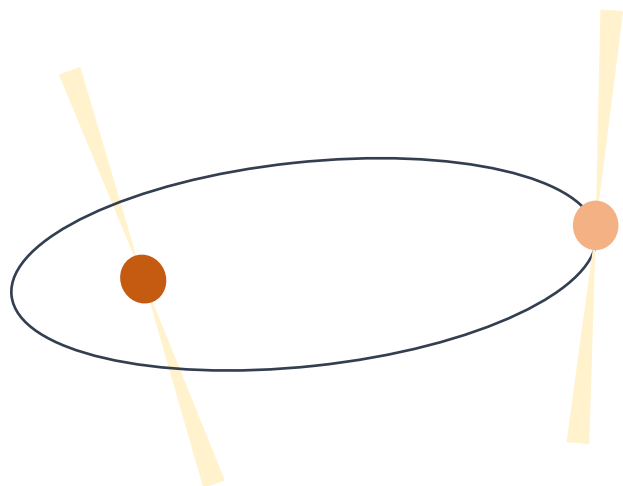
WIMP Accretion

$$\frac{dM_B}{dt} = 4\pi\lambda_B(GM_B)^2 \frac{\rho_\infty}{\gamma^{\frac{3}{2}} \Theta_\infty^{\frac{3}{2}} c^3} \quad \Theta = \frac{k_B T}{mc^2} = \frac{c_s^2}{\gamma c^2}$$

PBH Accretion

$$\frac{dM_B}{dt} \simeq \frac{M_{\text{PBH}}}{t_f} \simeq 27\pi(GM_B)^2 \frac{\rho_{\text{DM}} v}{c^4}$$

Feasibility of DM Detection

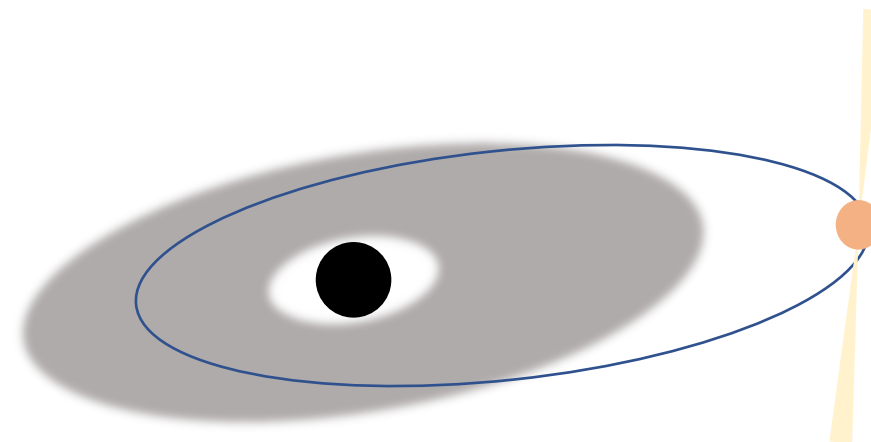


PSR J0737-3039A/B

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

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.

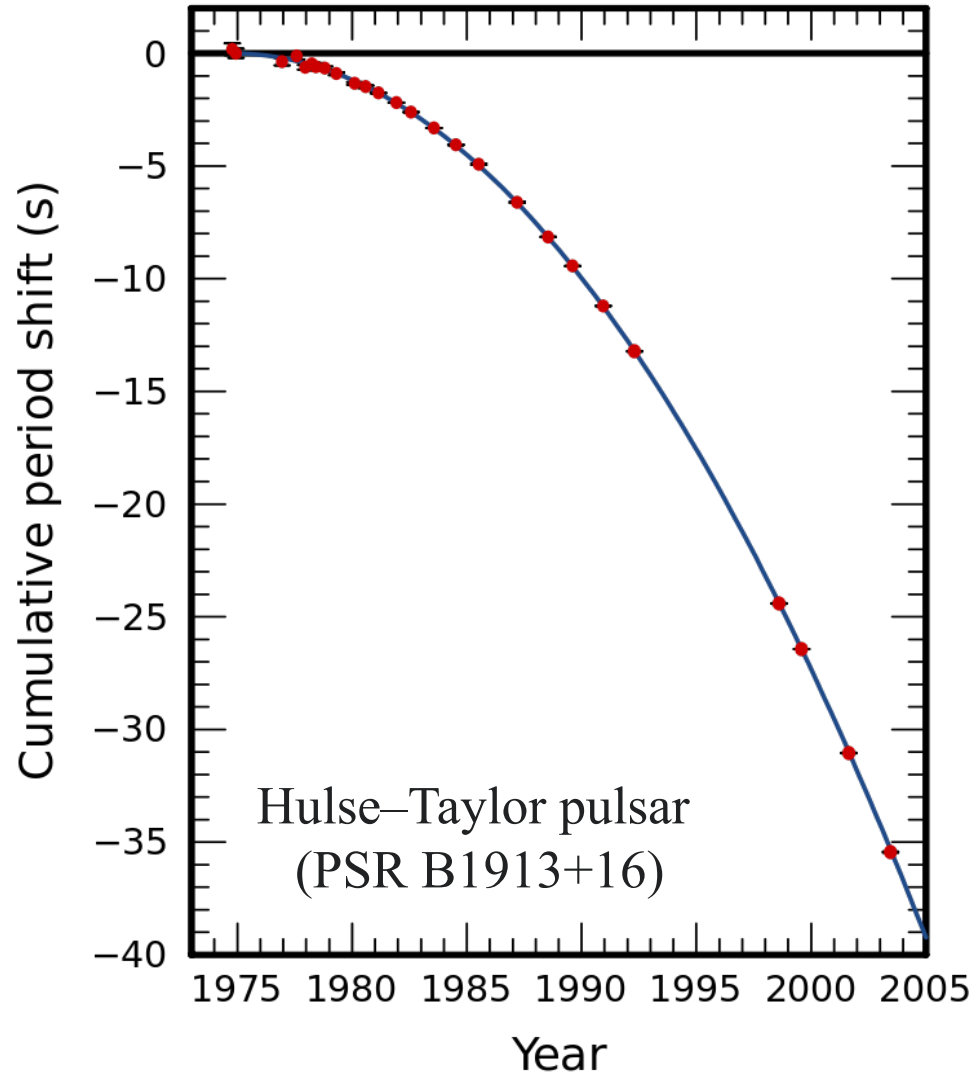


Pulsar-Black Hole Binary

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

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

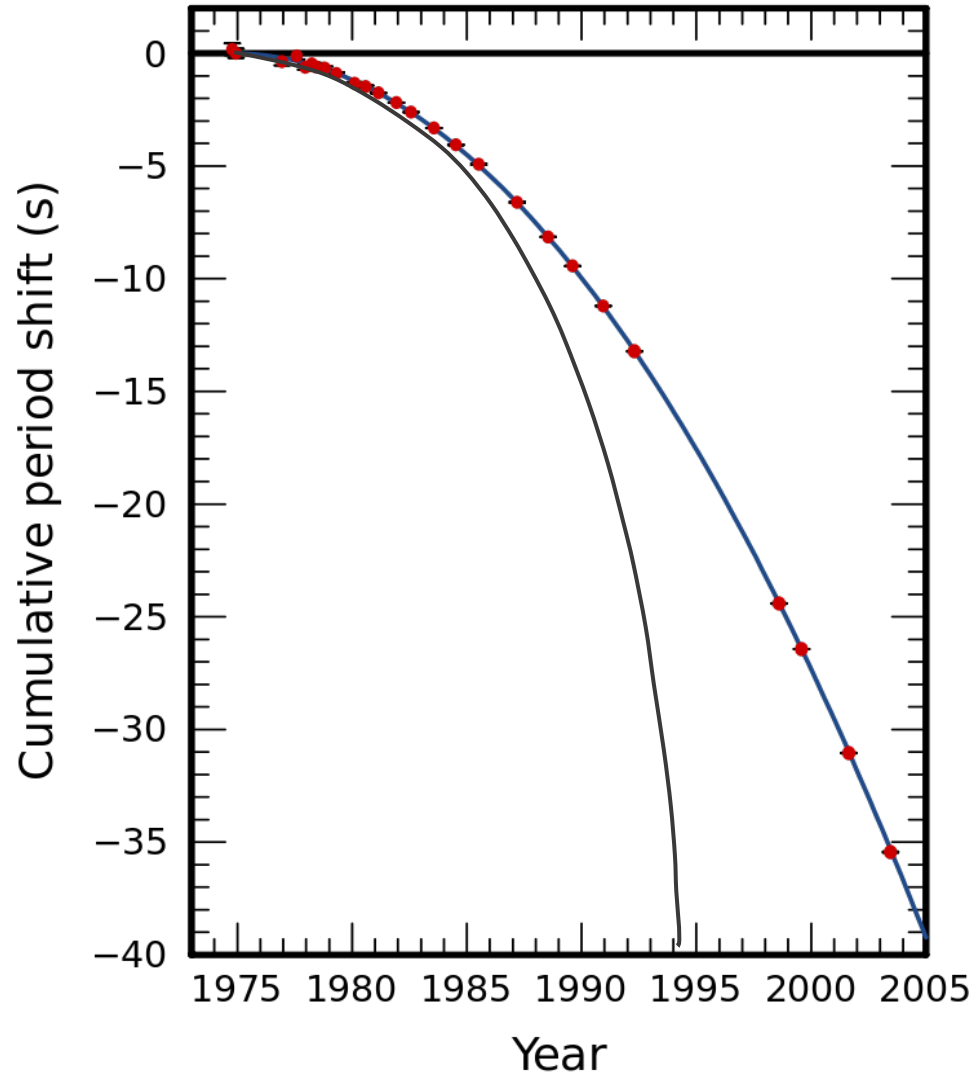
Orbital Phase Delay



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

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

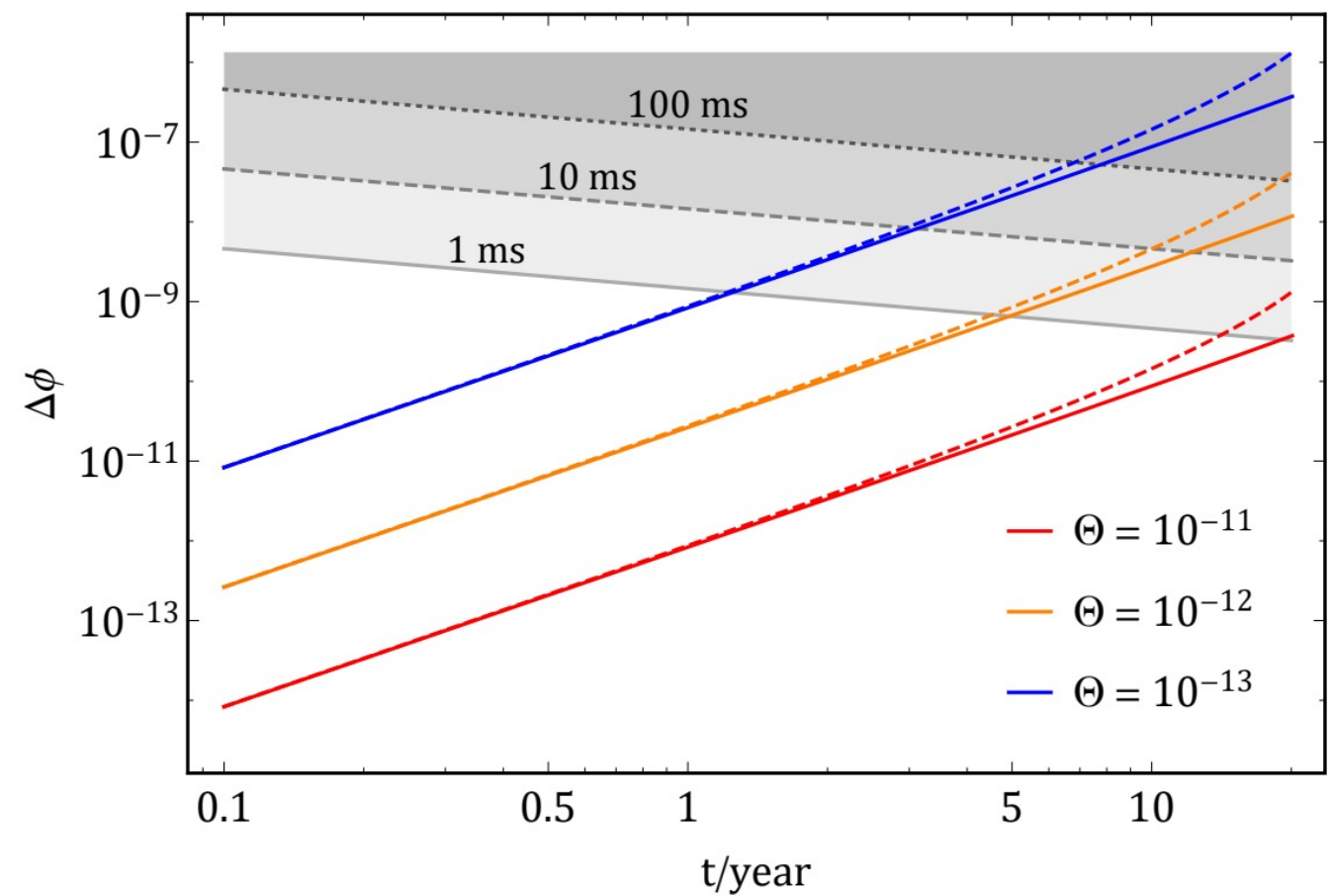
Orbital Phase Delay



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

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

Orbital Phase Delay



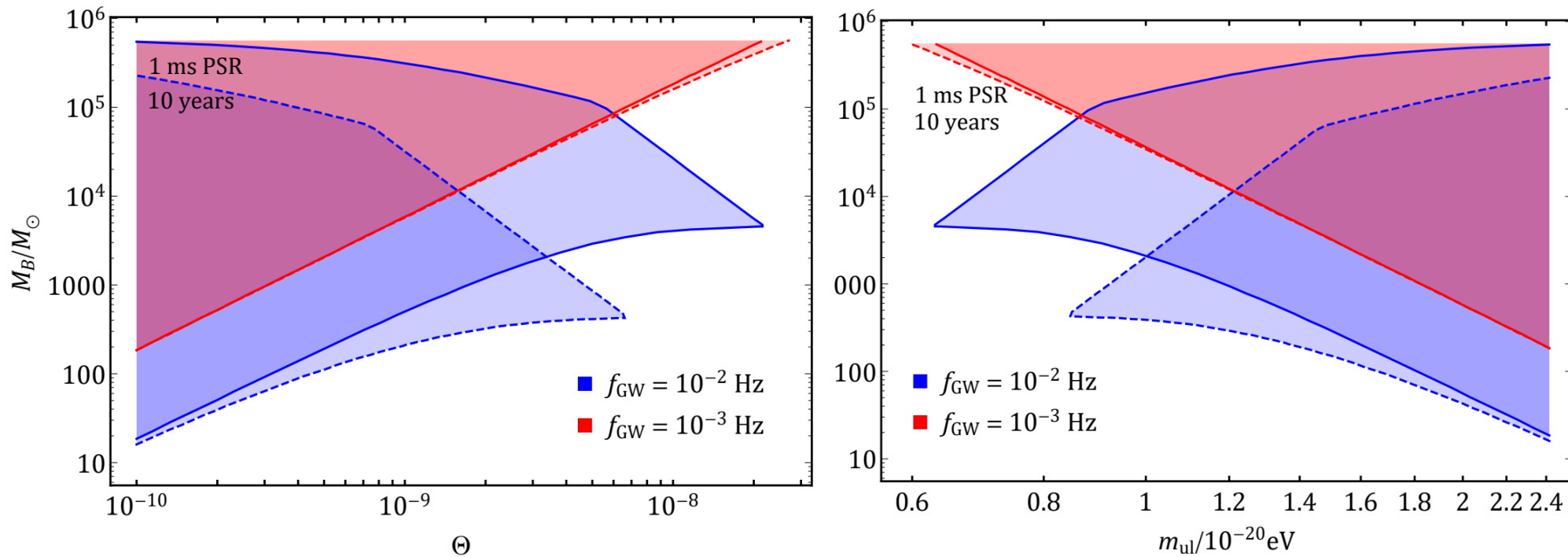
$$P = \frac{G}{5c^5} \left(\frac{d^3 Q_{ij}}{dt^3} \frac{d^3 Q_{ij}}{dt^3} - \frac{1}{3} \frac{d^3 Q_{ii}}{dt^3} \frac{d^3 Q_{jj}}{dt^3} \right)$$

$$\frac{dE_p}{dt} = - \frac{Gm_p}{a} \frac{dM_B}{dt}$$

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

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

Dark Matter Constraint



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

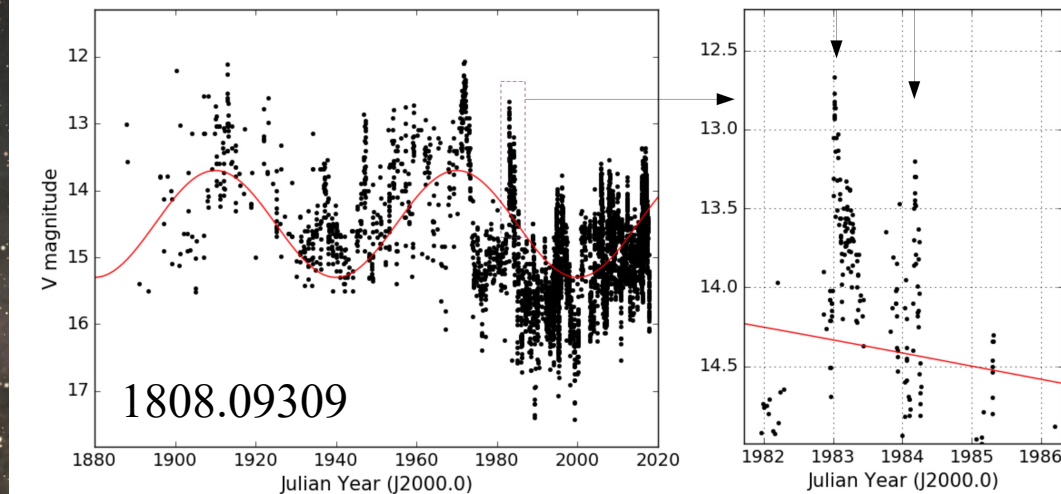
Optical Channel

$$M_{\text{BH}} = 1.8 \times 10^{10} M_{\odot}$$

$$T = 12.067 \text{ yr}$$

$$m_{\text{BH}} = 1.5 \times 10^8 M_{\odot}$$

$$\dot{T} = -0.00099$$

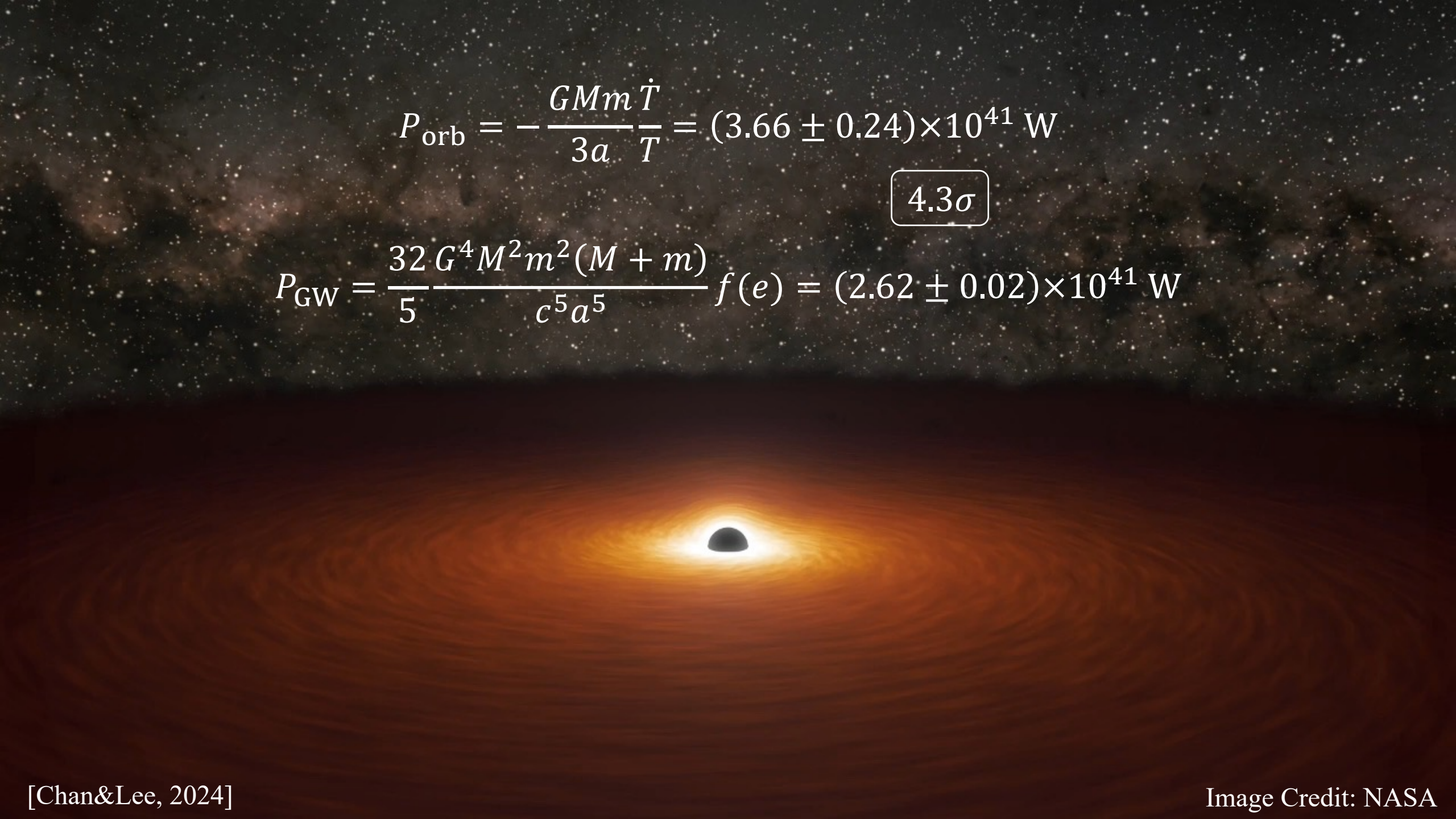


OJ 287

Image Credit: NASA

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

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



The background of the slide features a central black hole with glowing accretion disks and concentric ripples representing gravitational waves. The upper portion of the image shows a dark, star-filled sky with a faint, glowing nebula or galaxy structure.

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

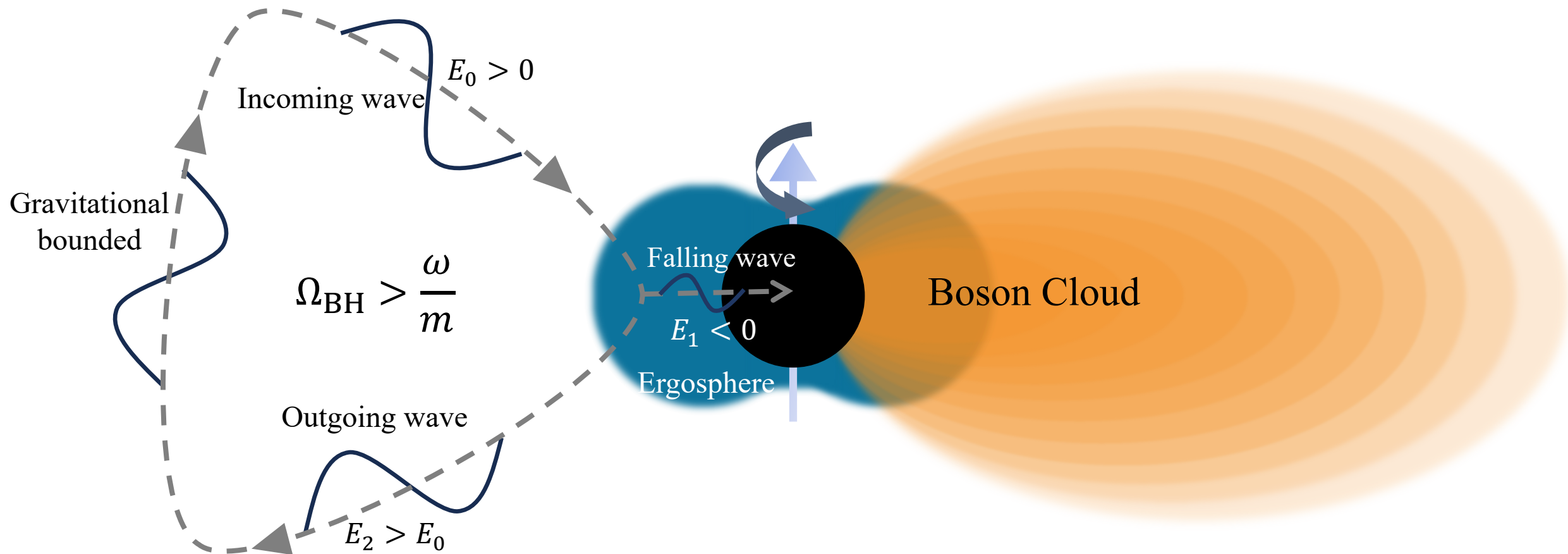
4.3σ

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

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

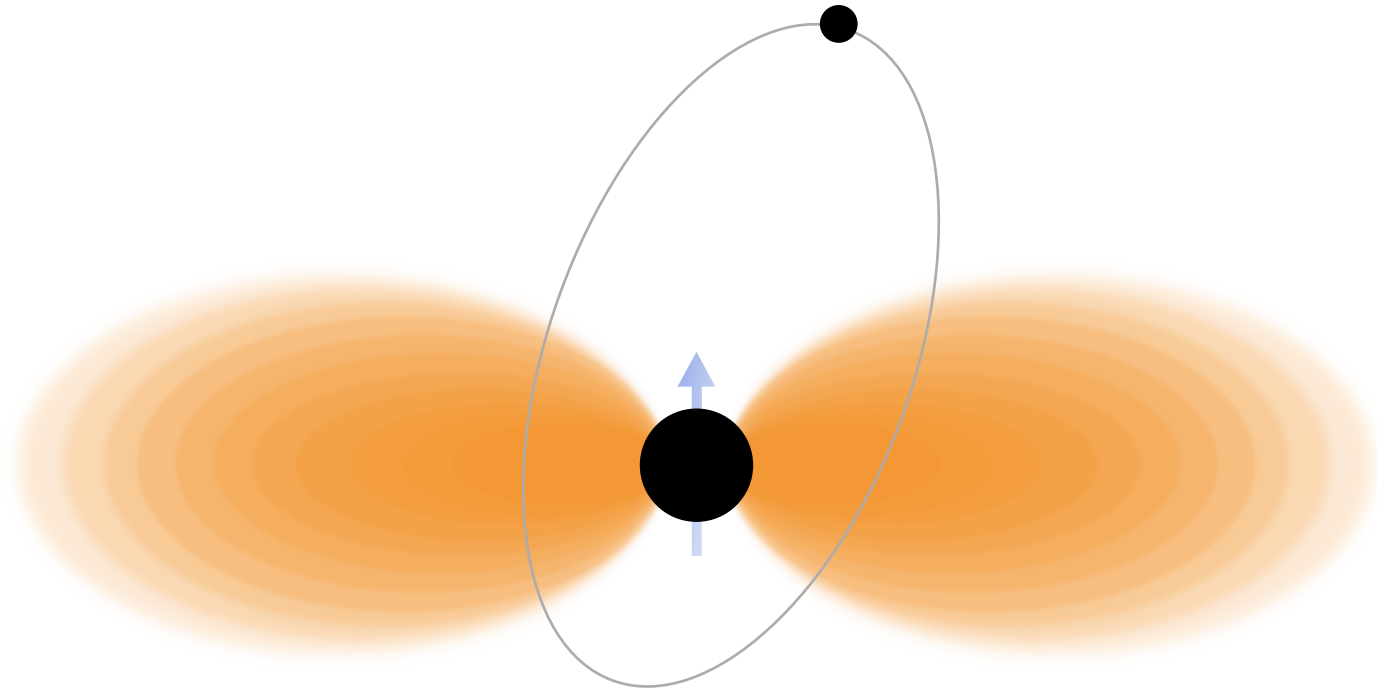


Superradiant Instability



A Loop Penrose Process

Dynamical Friction Power



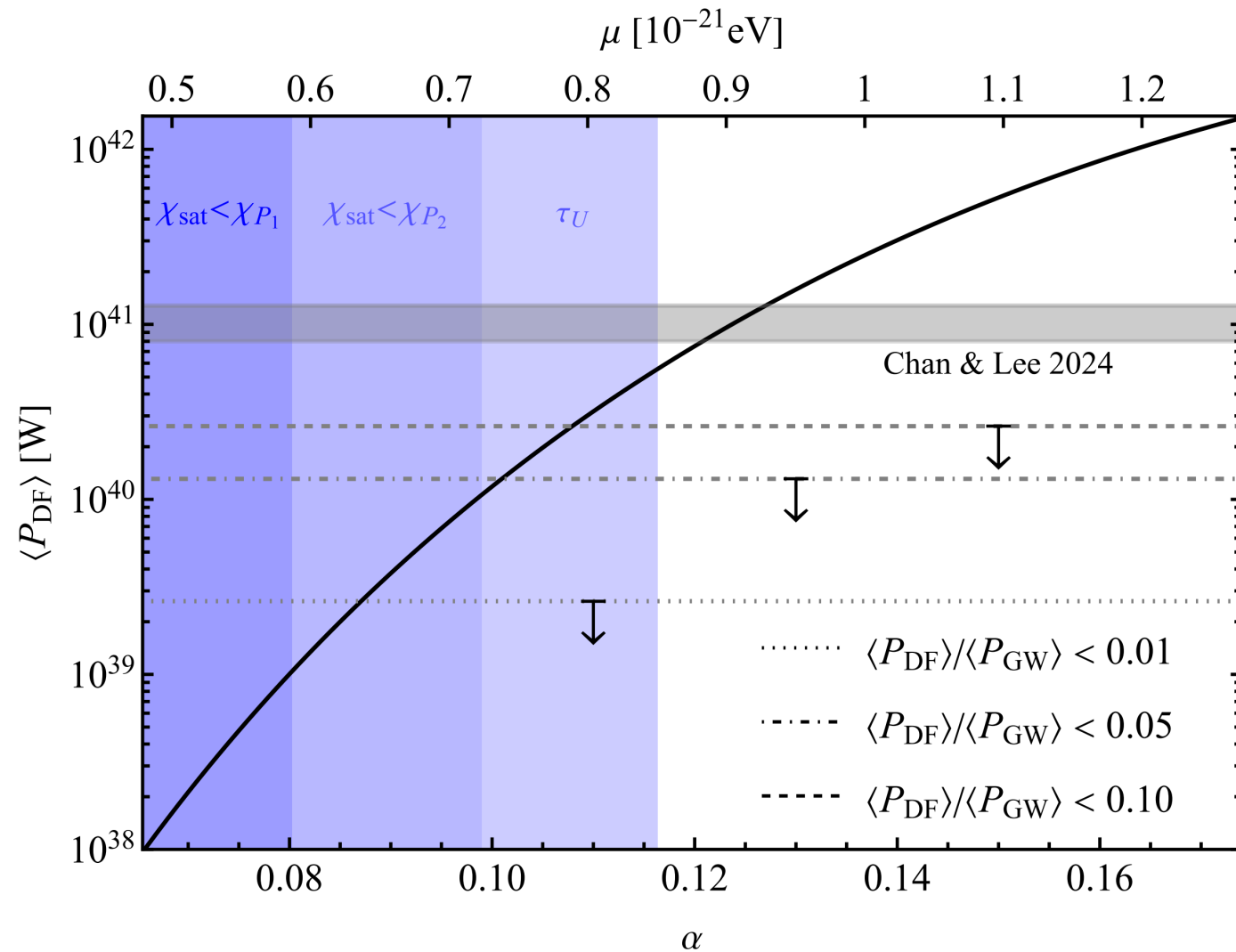
$$P_{\text{DF}} = \frac{4\pi q^2 M_{\text{BH}}^2}{v} \rho_{nlm}(x_*, \theta_*) C_{\Lambda}$$

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

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

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

OJ 287 Constraint on Ultralight Boson



Dissipative Energy from Boson Cloud

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

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

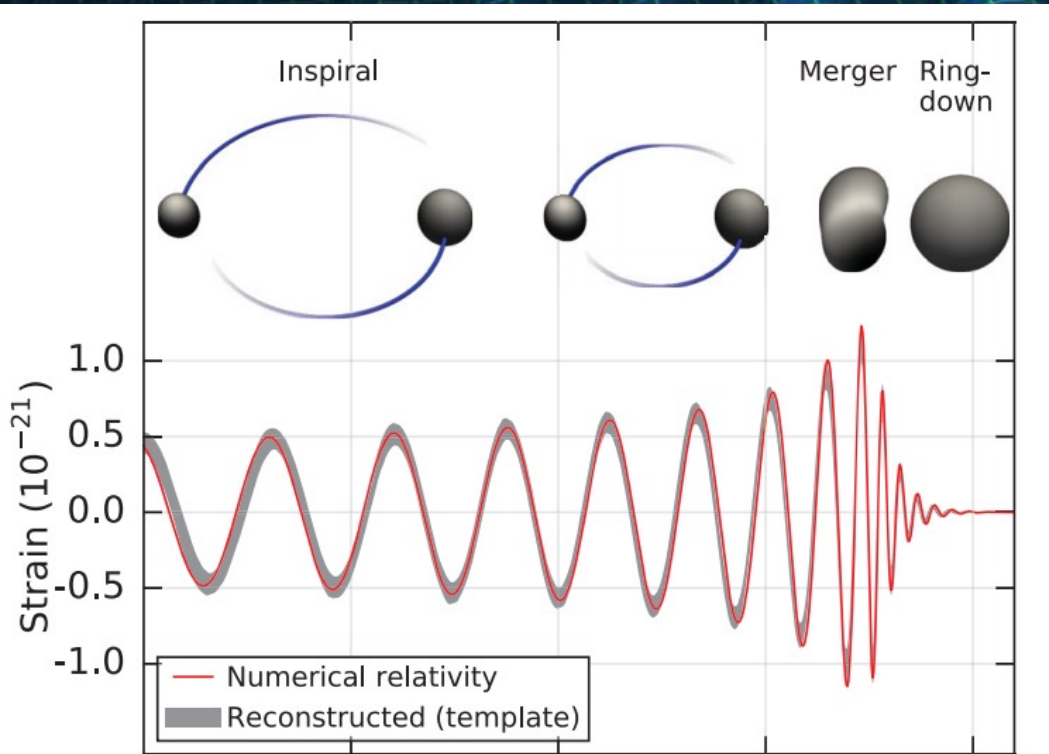
A Null Detection Result

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

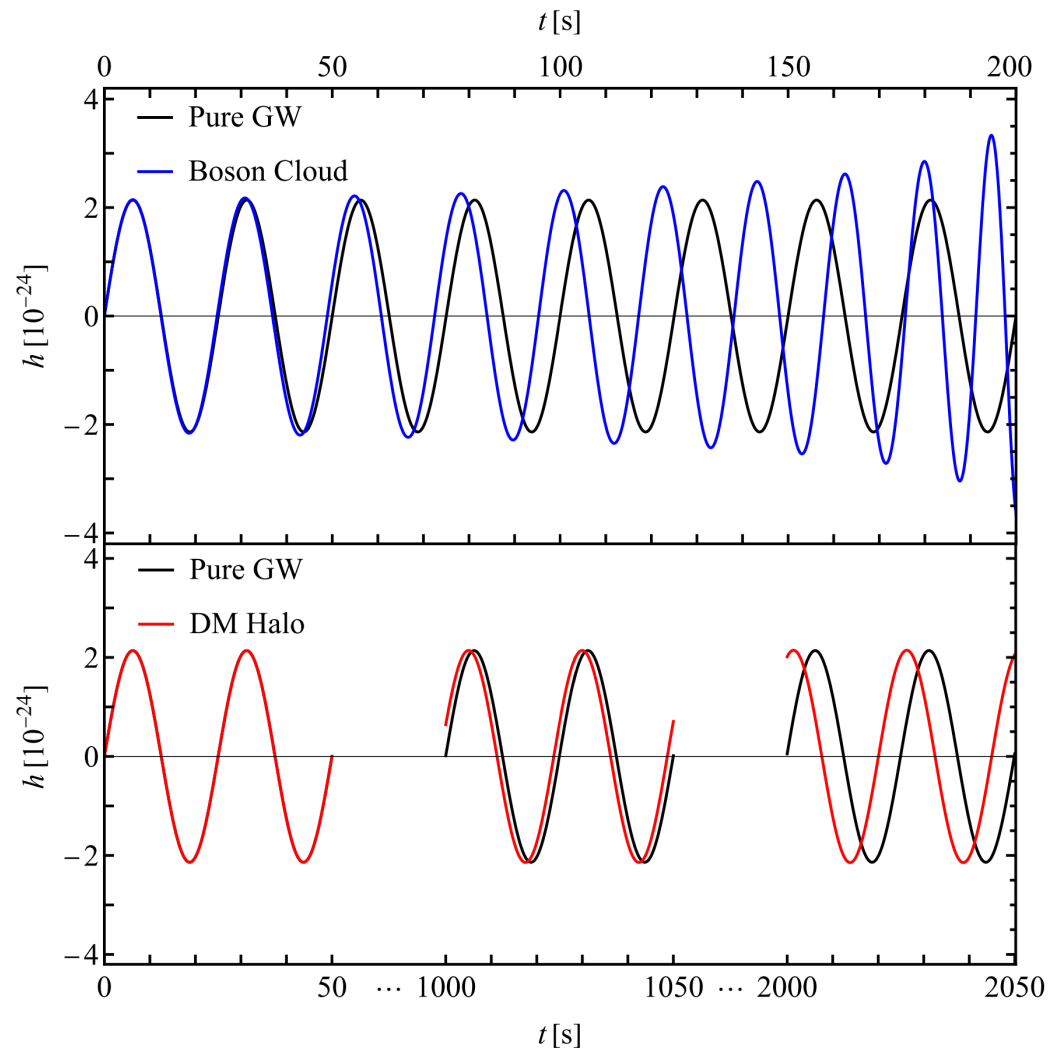
$$\mu \notin (8.5 - 22) \times 10^{-22} \text{ eV}$$

Gravitational Wave Channel

GW150914



Dark Dense Environment Impacts on GWs



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

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

A Novel DM Probe in GWs

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

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

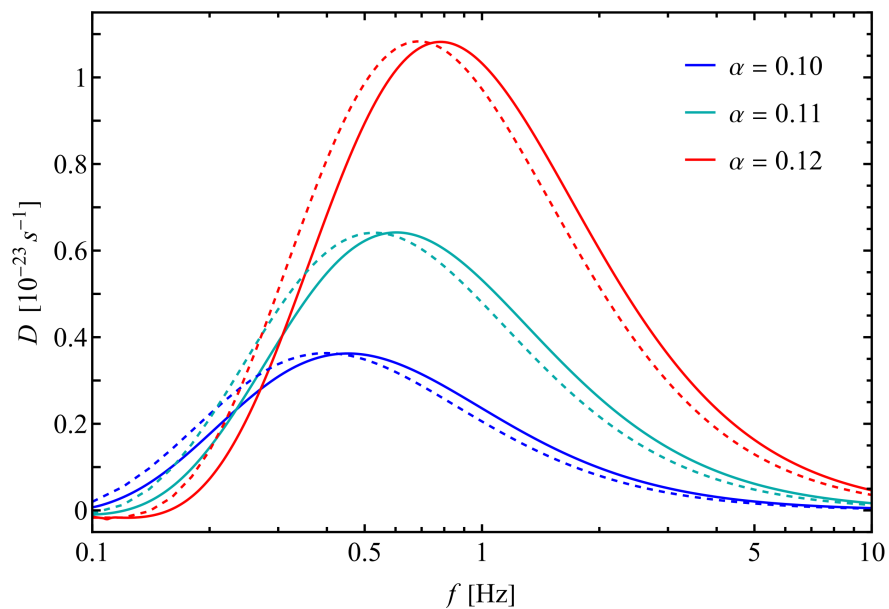
$$g(t) \equiv \frac{1}{hf^3} \frac{df}{dt} = \frac{24}{5} \frac{d_L(z)\pi^2}{c} + \frac{12G}{c^4 d_L(z)} \frac{|P_{\text{DF}}|}{h^2 f^2}$$

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

$$\begin{aligned} D &\equiv -h^2 f^3 \frac{dg/dt}{df/dt} = \frac{dh}{dt} + 3 \frac{h}{f} \frac{df}{dt} - \frac{h}{df/dt} \frac{d^2 f}{dt^2} \\ &= \frac{12G}{c^4 d_L(z)} |P_{\text{DF}}| \left(\frac{11}{3} - \frac{d \ln \rho}{d \ln f} - \frac{d \ln C_\Lambda}{d \ln f} \right) \end{aligned}$$

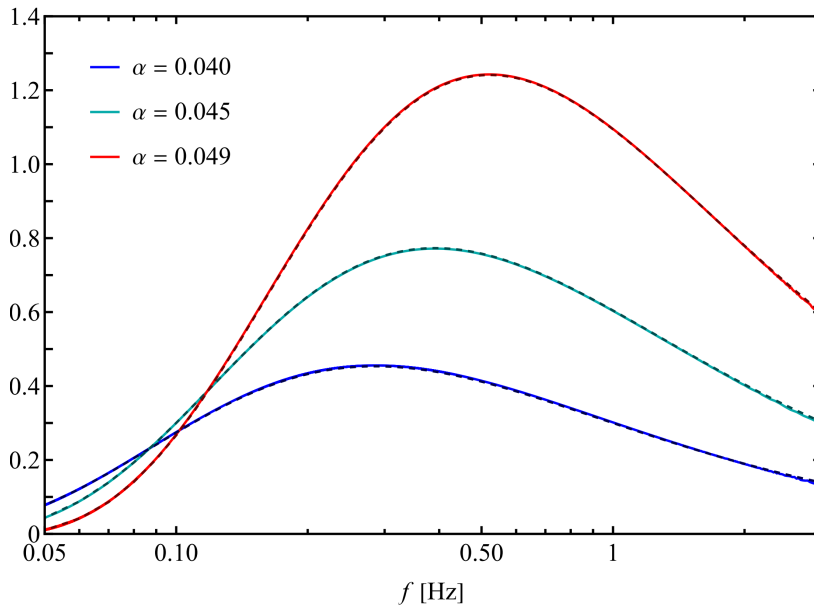
$D - f$ Diagram in GWs

Superradiant Boson Cloud



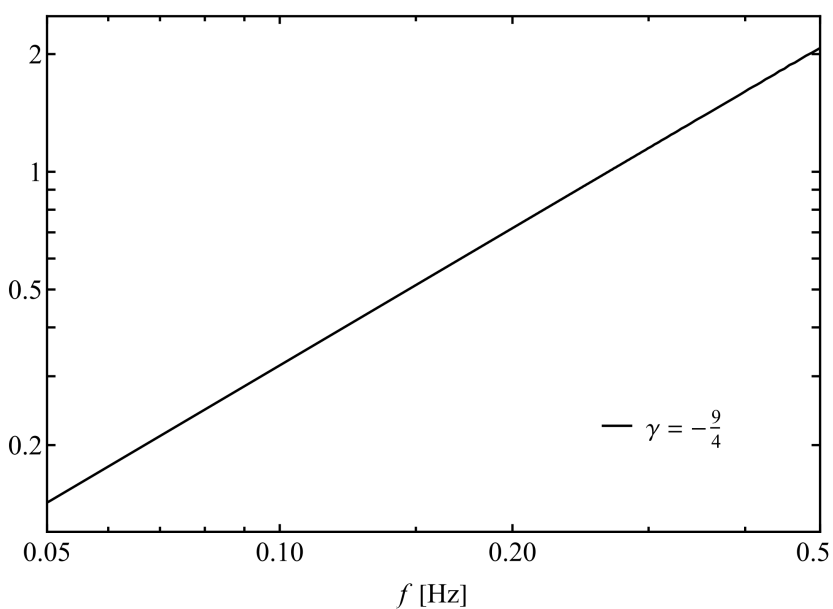
$$D = \frac{8G}{c^4 d_L(z)} |P_{\text{DF}}| \left(\frac{15}{2} - \left(\frac{f_0}{f} \right)^{\frac{2}{3}} - \frac{3}{2} \frac{d \ln C_\Lambda}{d \ln f} \right) \\ \propto \left(\frac{f_0}{f} \right)^{\frac{5}{3}} e^{-\left(\frac{f_0}{f} \right)^{\frac{2}{3}}} \left(\frac{15}{2} - \left(\frac{f_0}{f}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

Soliton



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

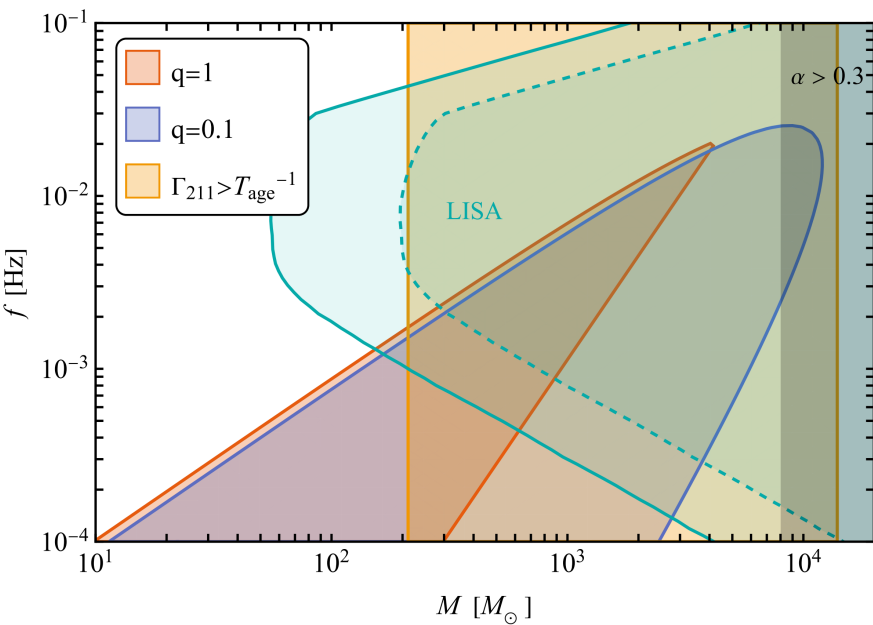
DM Spike



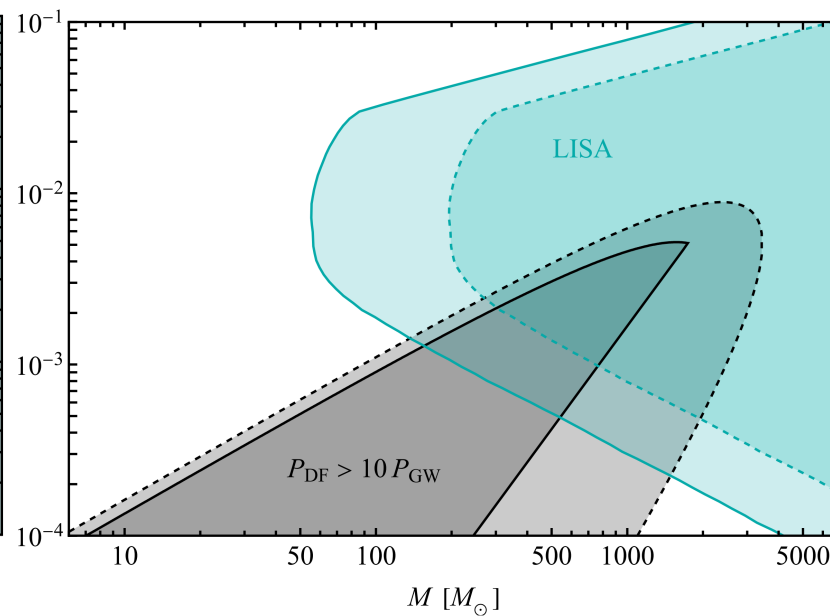
$$D = \frac{8G}{c^4 d_L(z)} |P_{\text{DF}}| \left(\gamma + \frac{11}{2} \right) \\ \propto f^{-\frac{2}{3}(\gamma + \frac{1}{2})} \left(\gamma + \frac{11}{2} \right) .$$

Detectability of Dark Dense Environments

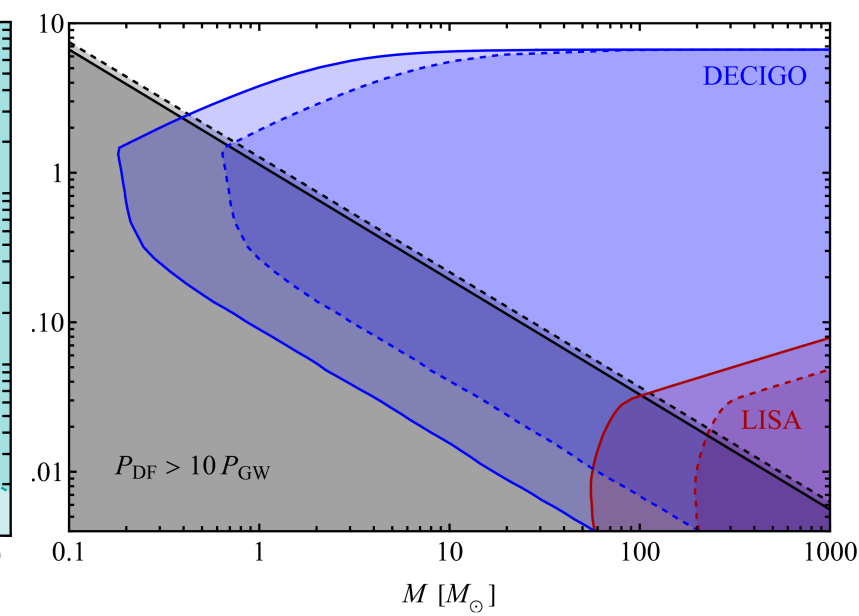
Superradiant Boson Cloud



Soliton



DM Spike



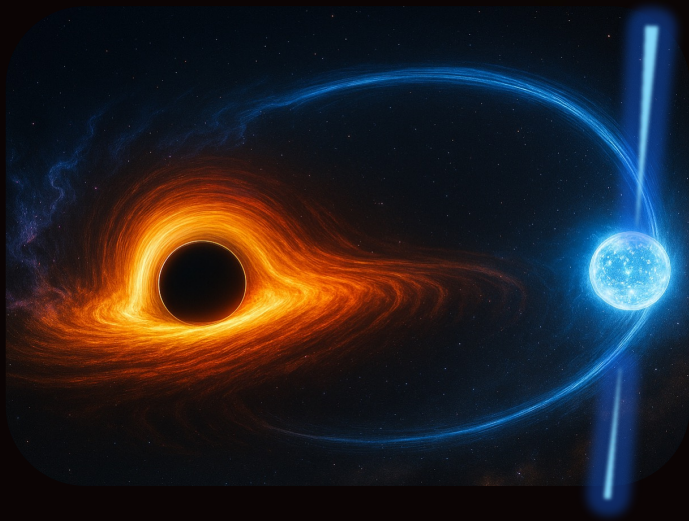
Detectability:

$$P_{\text{DF}} > 10 P_{\text{GW}}$$

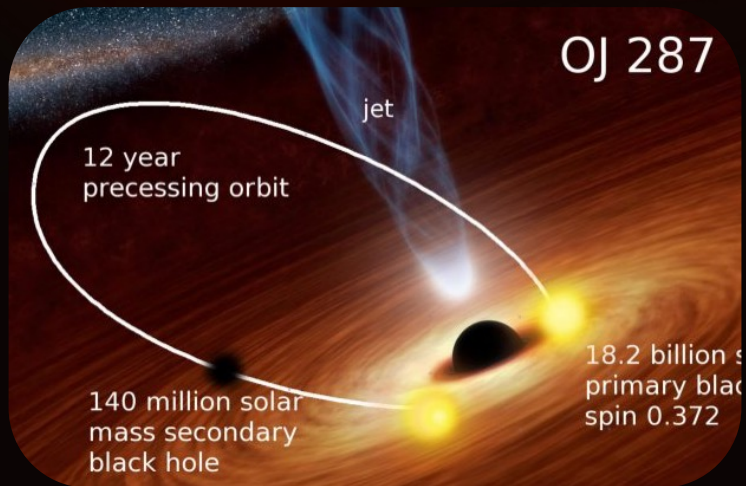
$$\text{SNR} > 8$$



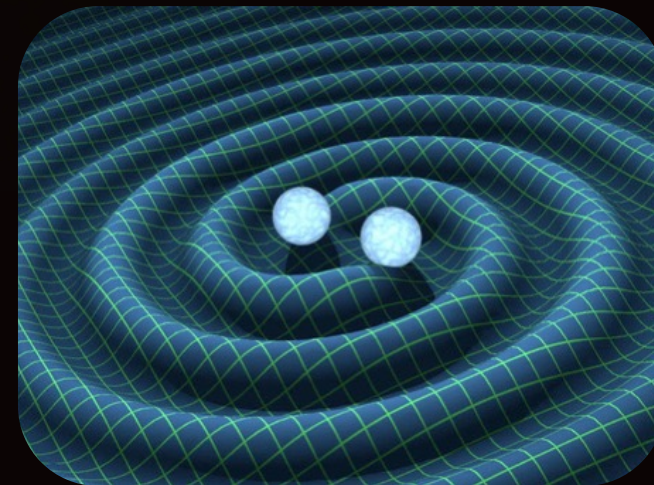
Radio Channel



Optical Channel

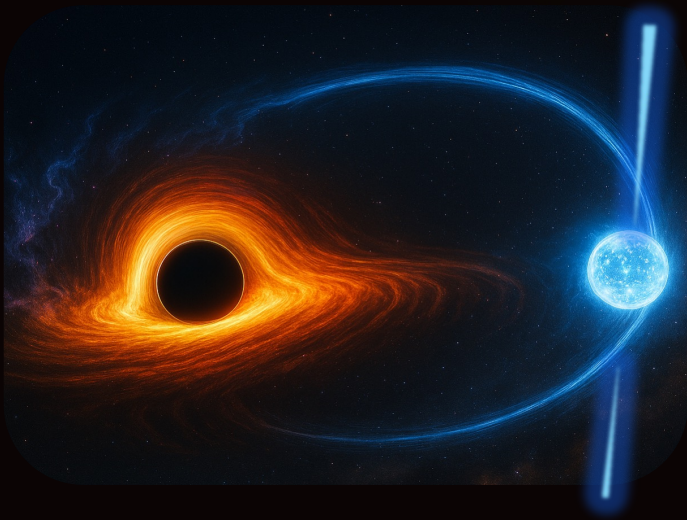


Gravitational Wave Channel

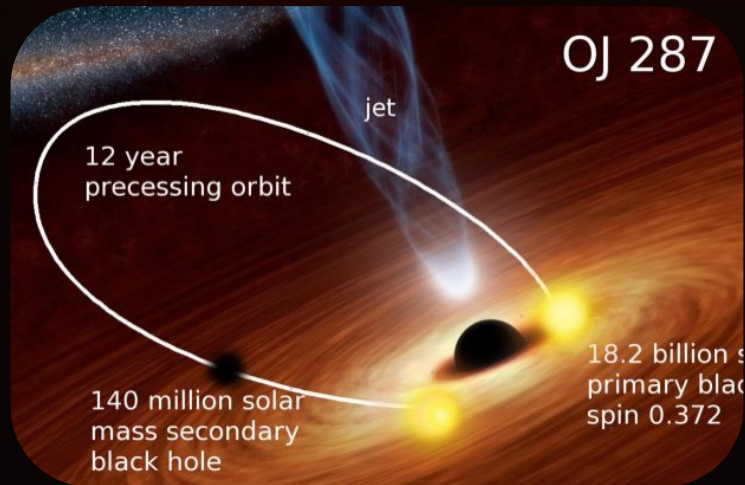


Thank you!

Radio Channel



Optical Channel



Gravitational Wave Channel

