Center for Theoretical Physics of the Universe

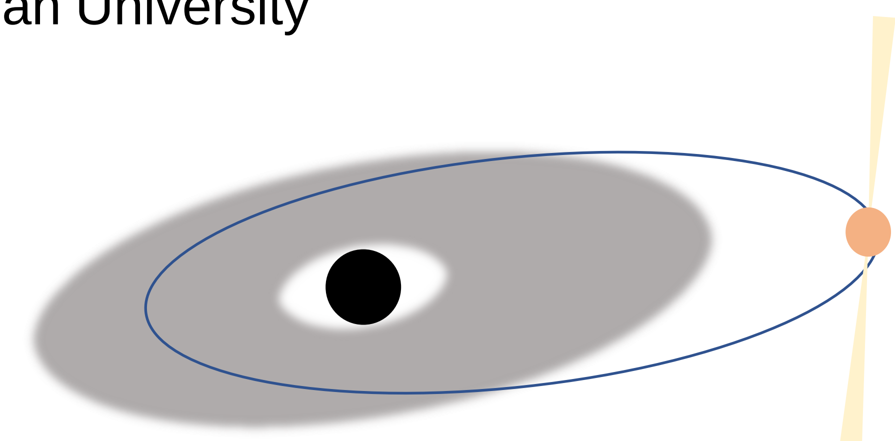
Cosmology, Gravity and Astroparticle Physics

A Dark Matter Probe in Accreting Pulsar-Black Hole Binaries

Qianhang Ding 丁乾航
IBS CTPU-CGA

Based on 2304.08824, Ali Akil, Qianhang Ding

June 20@Jinan University



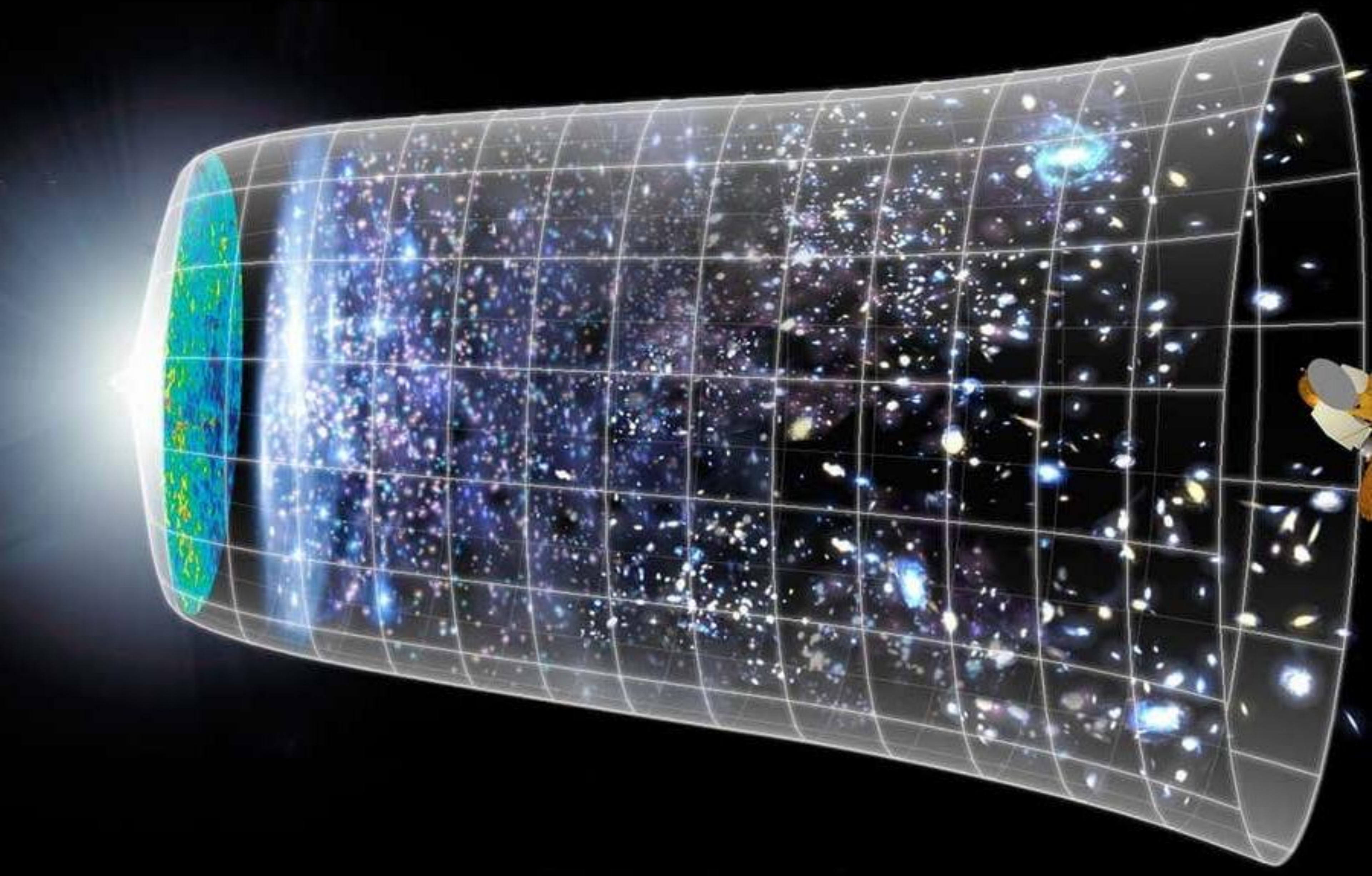


Image Credit: NASA

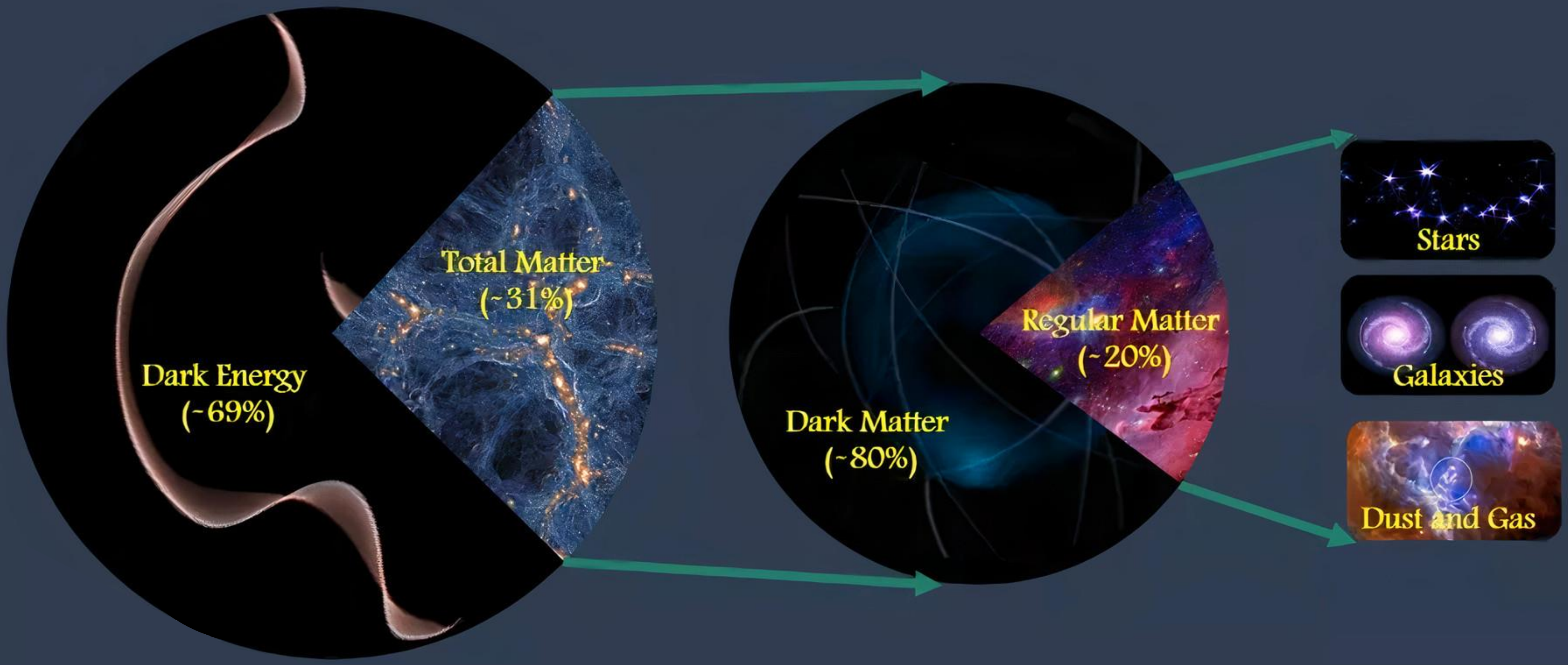


Image Credit: UCR/Mohamed Abdullah

CDM Problems

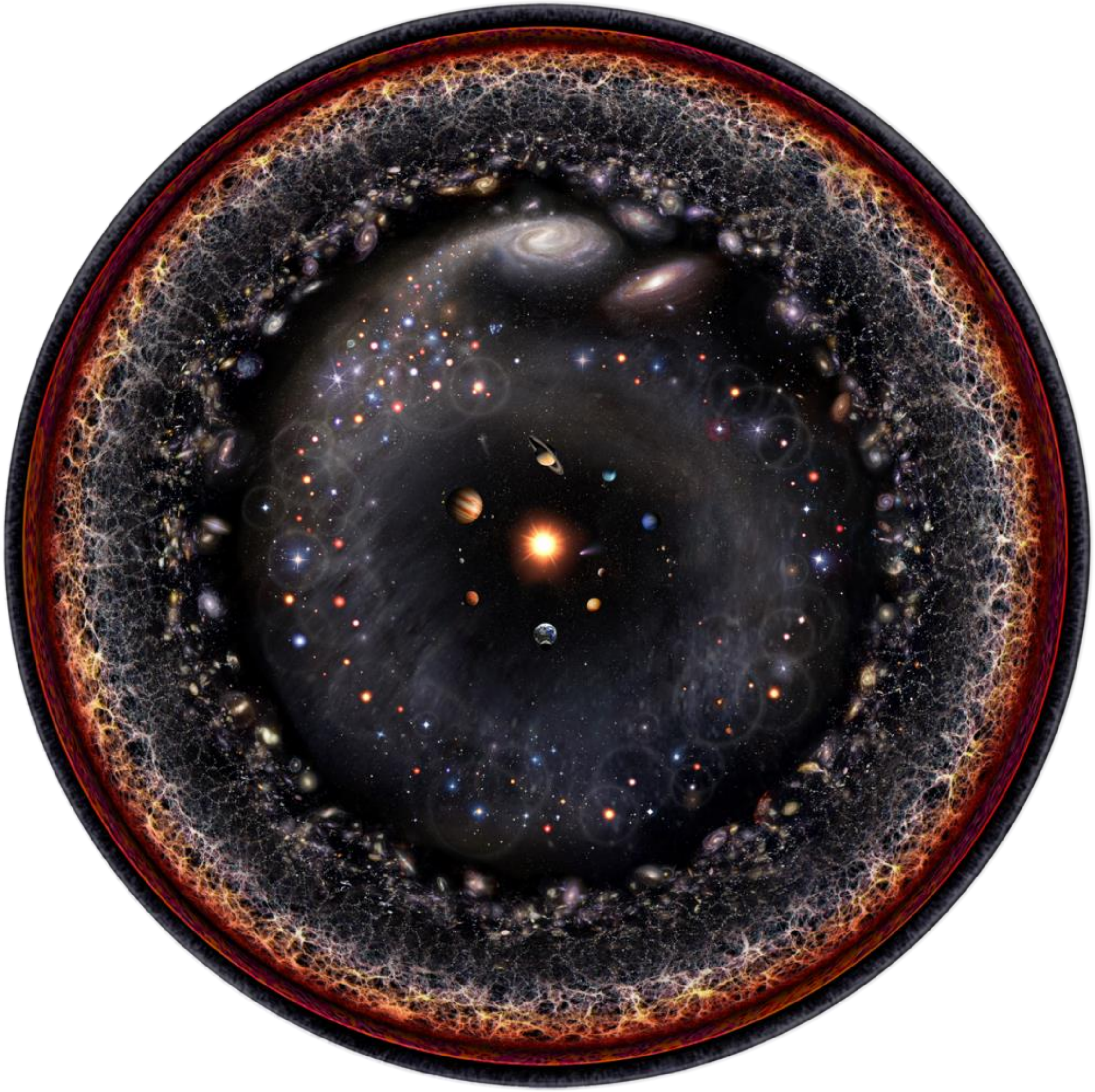
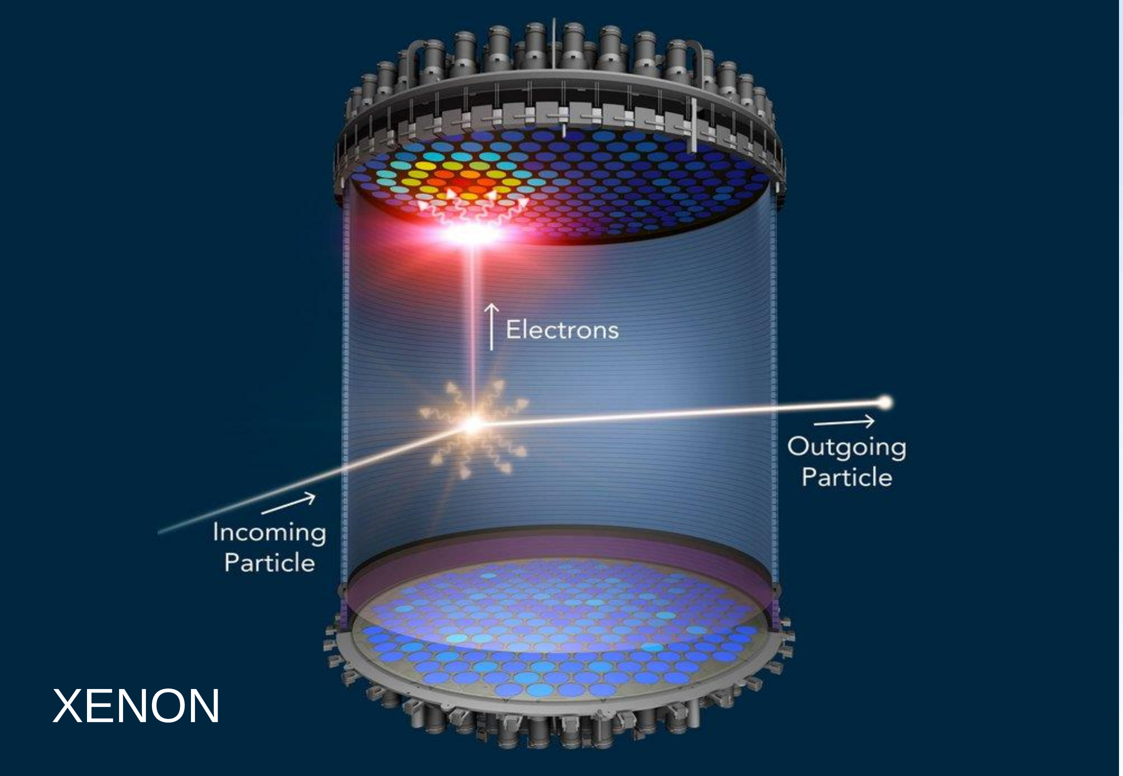
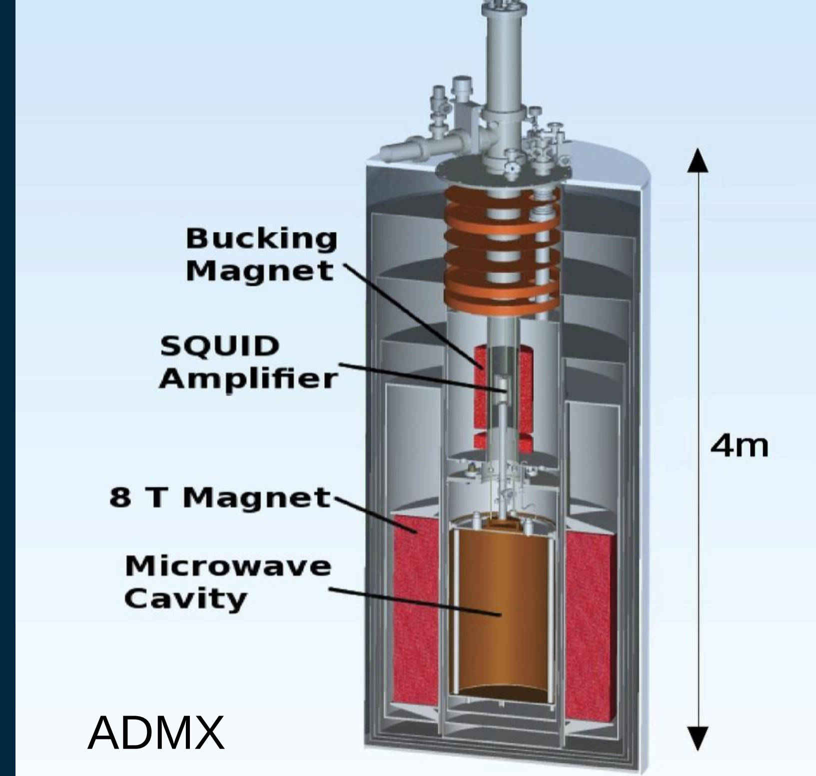


Image Credit: Pablo Carlos Budassi

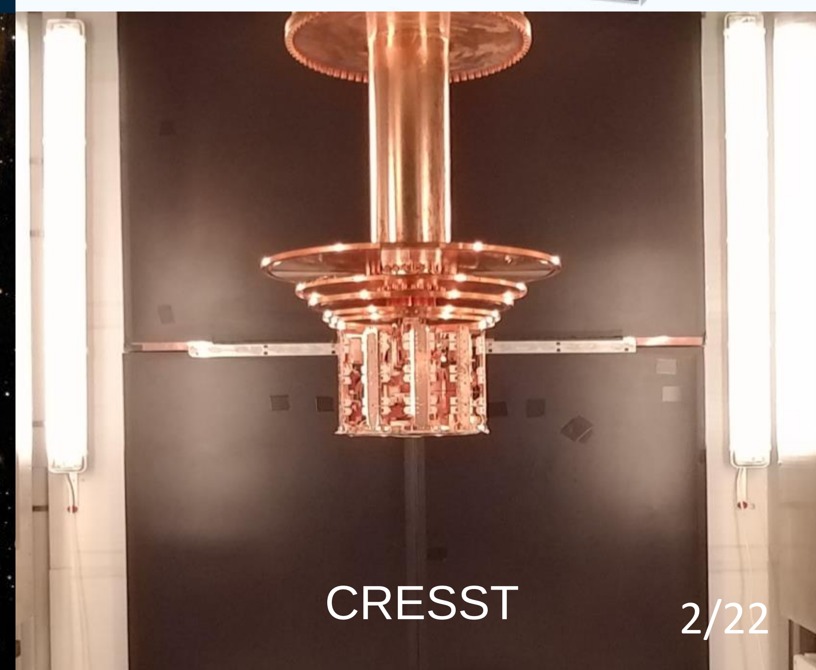
Cold DM at Small Scales:

- Core-Cusp Problem
- Missing Satellites Problem
- Too Big To Fail Problem (TBTF)


Electrons
Outgoing Particle
Incoming Particle
XENON


Bucking Magnet
SQUID Amplifier
8 T Magnet
Microwave Cavity
4m
ADMX

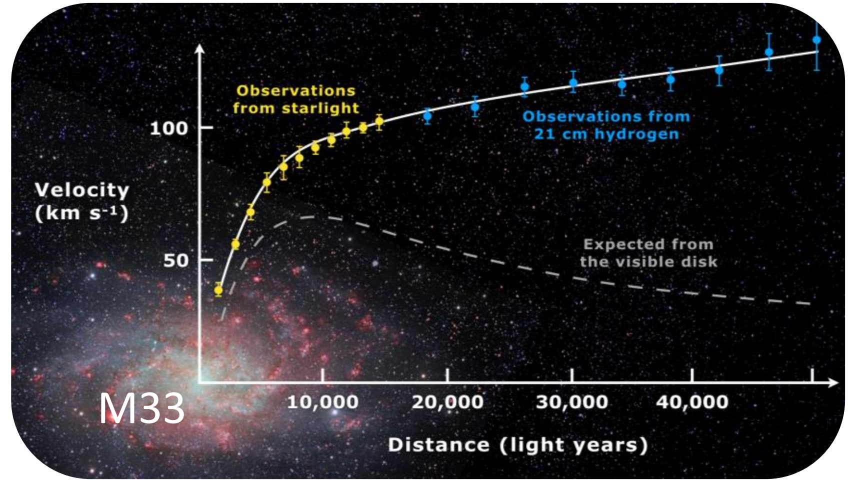

DAMPE(悟空)


CRESST

How to study the nature of DM in different DM models?

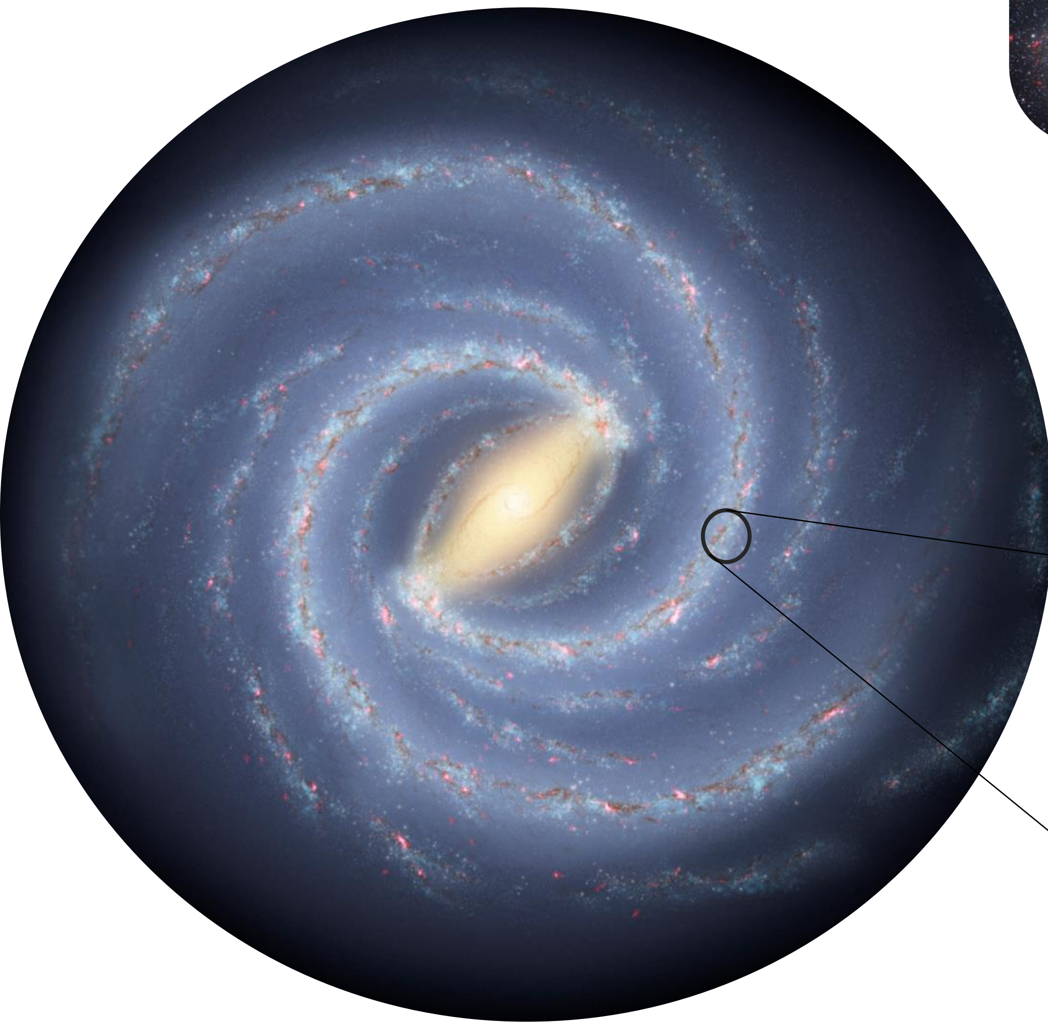
a cumulative gravitational effect in strong gravity field

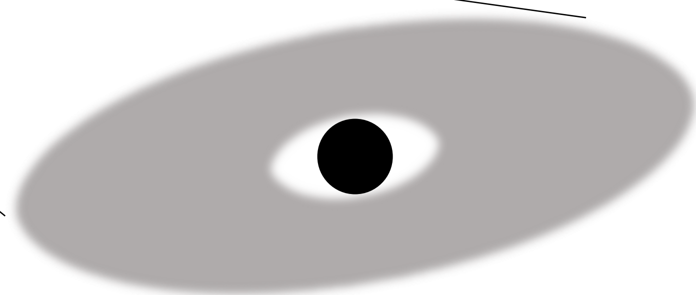
DM Accretion in BH



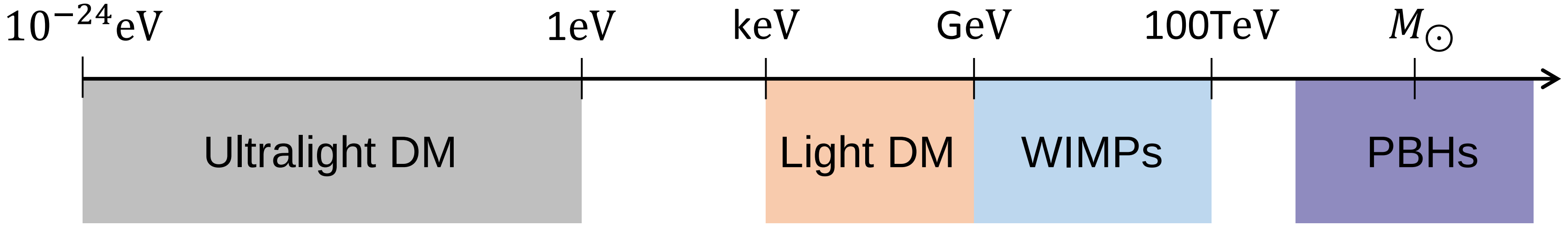
Navarro–Frenk–White (NFW) profile

$$\rho(r) = \frac{\rho_0}{\frac{r}{R}\left(1+\frac{r}{R}\right)^2}$$





DM Models



$10^{-24}\mathrm{eV}$
$1\mathrm{eV}$
keV
GeV
$100\mathrm{TeV}$
$M_{\odot}$
Ultralight DM
Light DM
WIMPs
PBHs

WIMPs Accretion

We use the Bondi formula to describe the accretion of a DM gas with a dimensionless temperature Θ

Bondi formula
$$\frac{dM_B}{dt} = 4\pi\lambda_B (GM_B)^2 \frac{\rho_{DM}}{\gamma^{3/2}\Theta^{3/2}c^3}$$
$$\Theta = \frac{k_B T}{mc^2} = \frac{c_s^2}{\gamma c^2}$$

The DM sound speed is bounded by Jeans length of the Milky Way as $c_s < 10^{-4}c$, which gives an upper bound of Θ

$$\Theta < \mathcal{O}(10^{-8})$$

P. P. Avelino, V. M. C. Ferreira, “Constraints on the dark matter sound speed from galactic scales: the cases of the Modified and Extended Chaplygin Gas.” Phys.Rev.D 91:083508, 2015

Ultralight DM Accretion

A non-rotating BH travel with velocity v in a uniform distributed scaler field with mass m_{ul} and density ρ_{DM} has accretion rate

$$\frac{dM_B}{dt} = \frac{32\pi^2 (GM_B)^3 m_{ul}\rho_{DM}}{\hbar c^3 v[1 - \exp(-\xi)]} \qquad \xi = \frac{2\pi G M_B m_{ul}}{\hbar v}$$

Unruh, W. G. . "Absorption cross section of small black holes." Physical Review D 14.12(1976):3251-3259.

Apply this accretion rate at the center soliton of the Milky Way with a soliton mass $10^9 M_\odot$

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

PBHs Accretion

The accretion of PBHs into BH can be estimated by its mean free path l_f and mean free time t_f

$$l_f = \frac{1}{\sigma n} = \frac{1}{27\pi}\left(\frac{c^2}{GM_B}\right)^2 \frac{M_{PBH}}{\rho_{DM}} \quad \sigma = 27\pi\left(\frac{GM_B}{c^2}\right)^2 \quad n = \frac{\rho_{DM}}{M_{PBH}}$$

$$t_f = \frac{l_f}{v}$$

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

How to probe such a small mass increment?

How to probe such a small mass increment?

We need a high-precision detector around BH

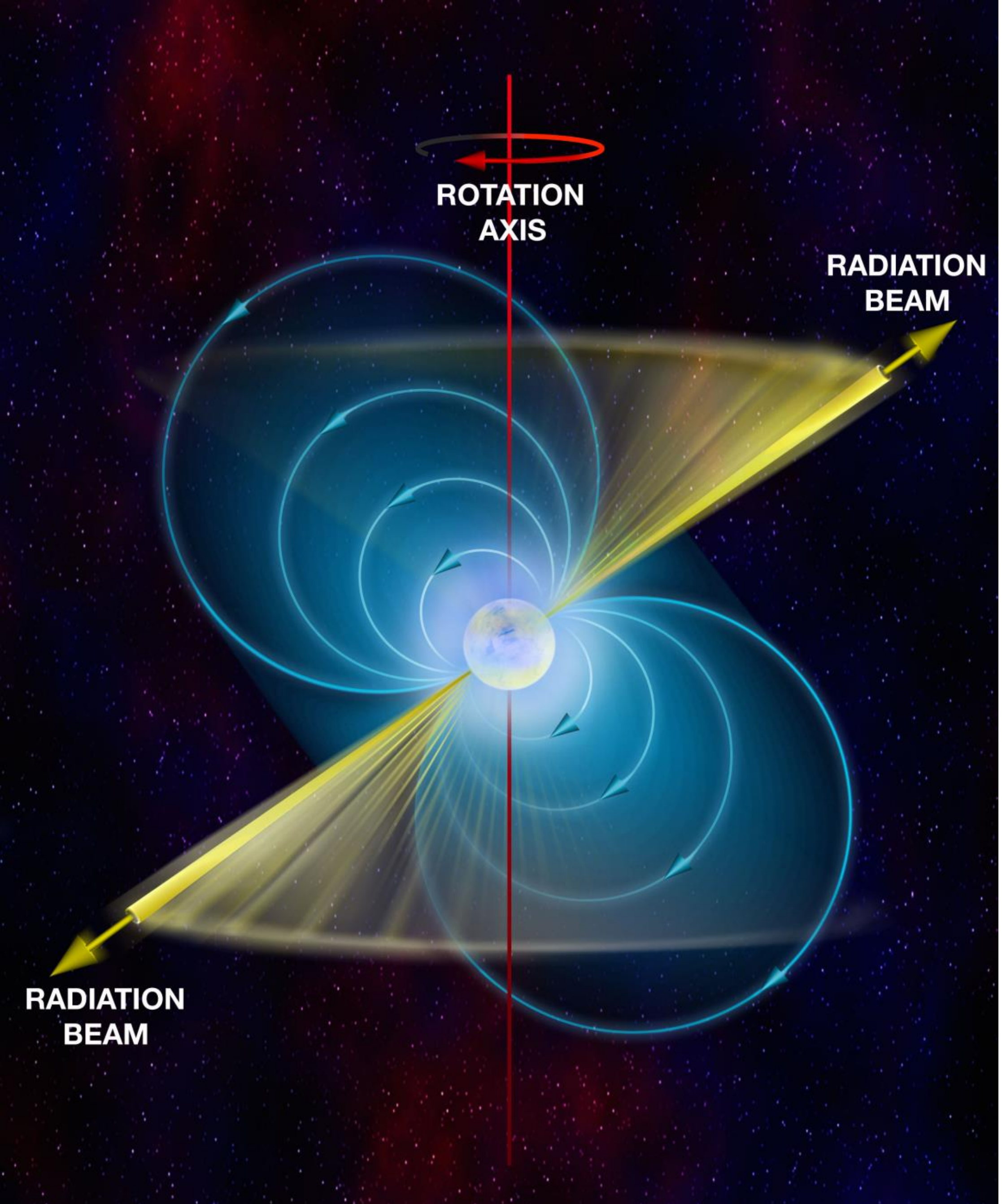


Image Credit: NRAO

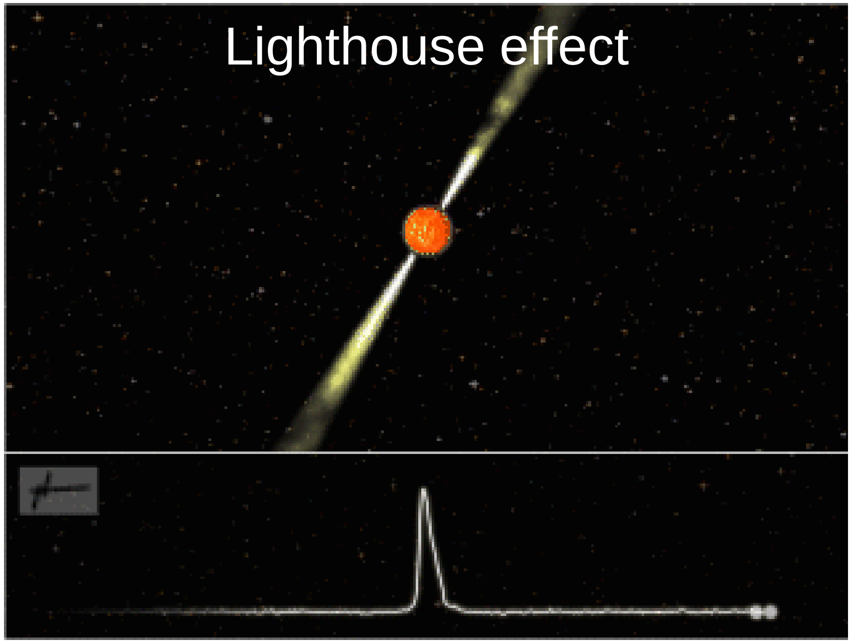
Pulsar is a highly magnetized rotating neutron star that emits beams of electromagnetic radiation out of its magnetic poles.

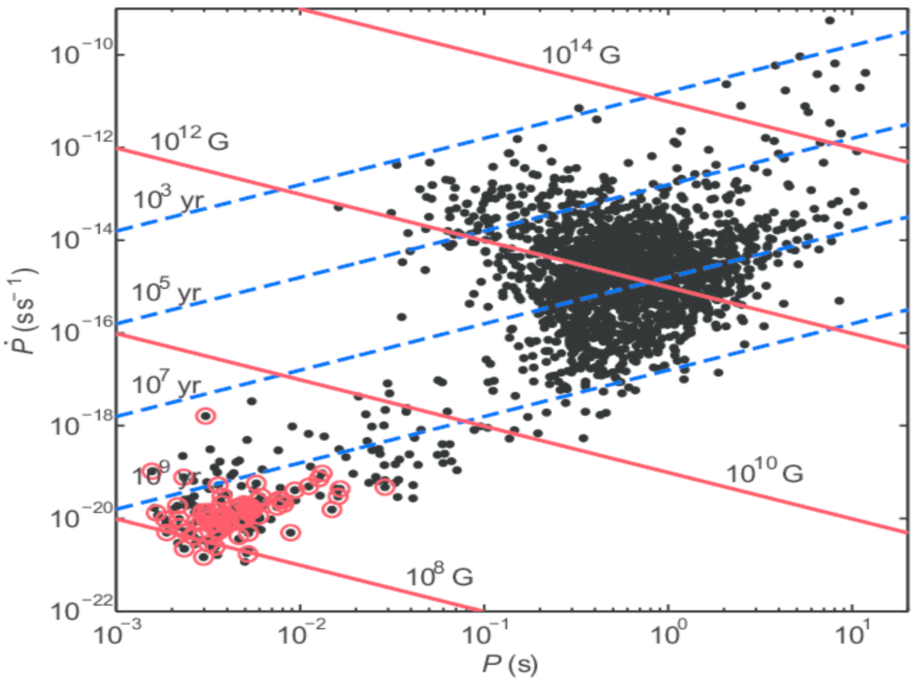
Pulsar is produced from the supernova explosion of dying star.

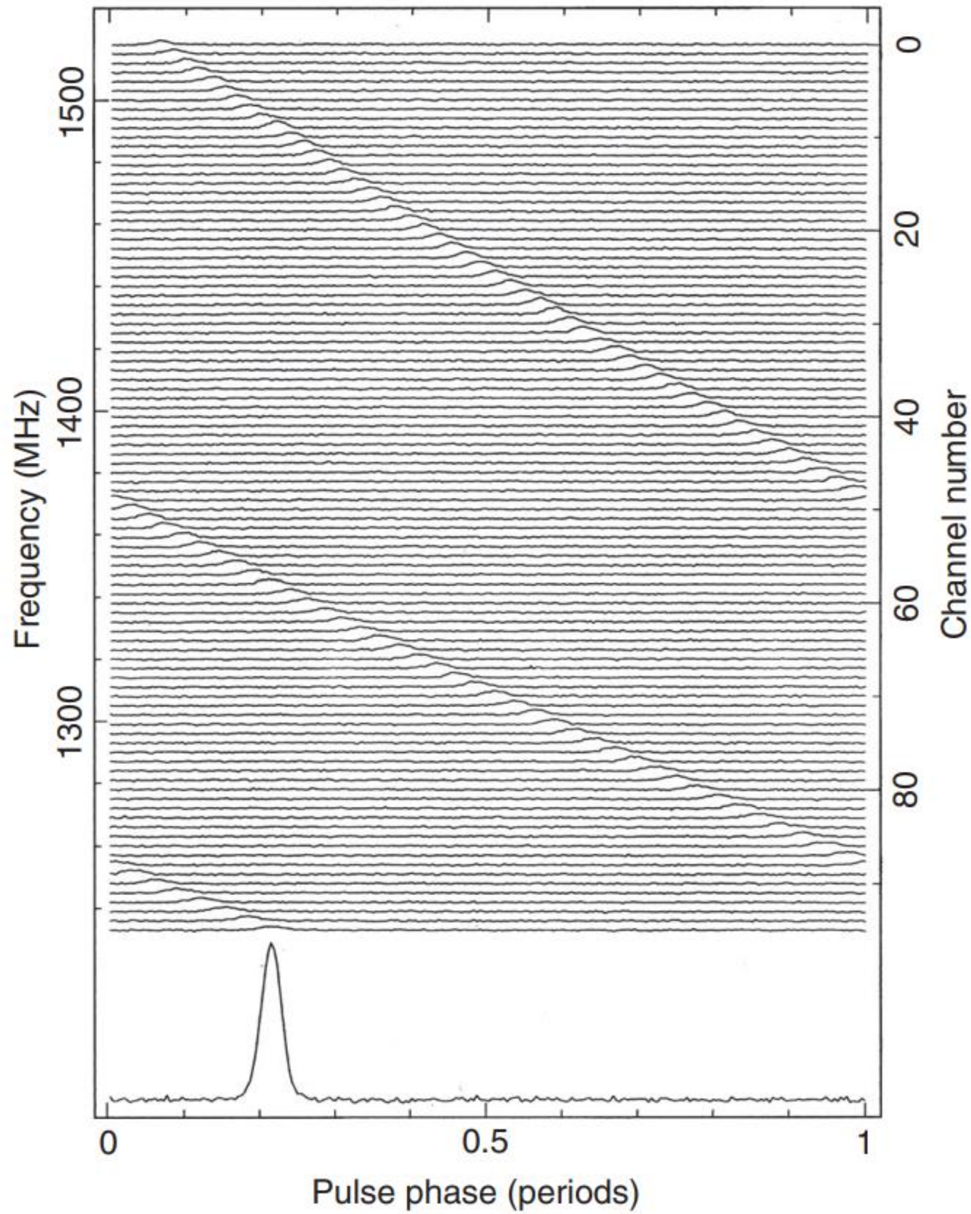
Mass: ~1.46 Solar Mass

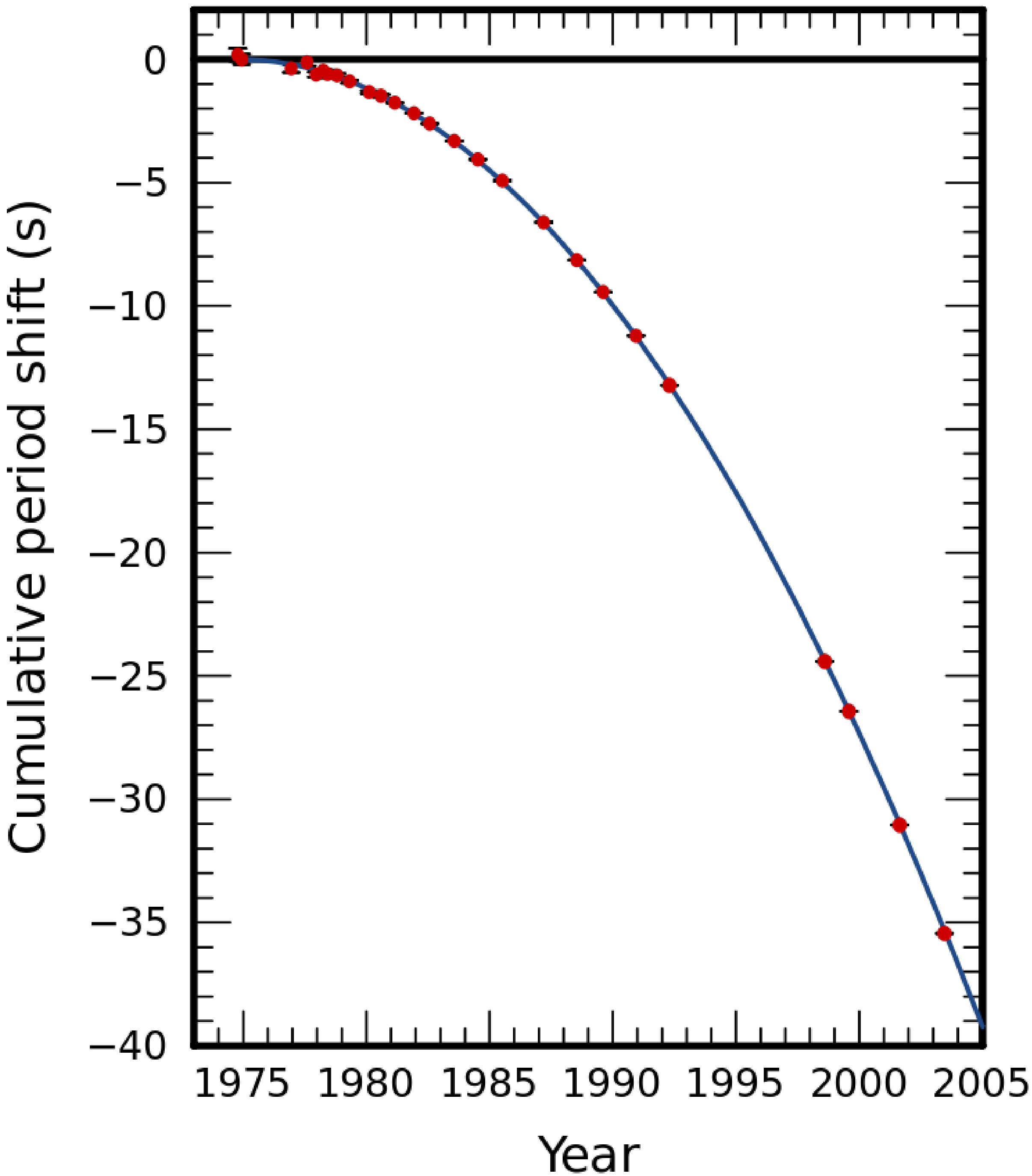
Radius: 10~15 km

Period: Millisecond to Second

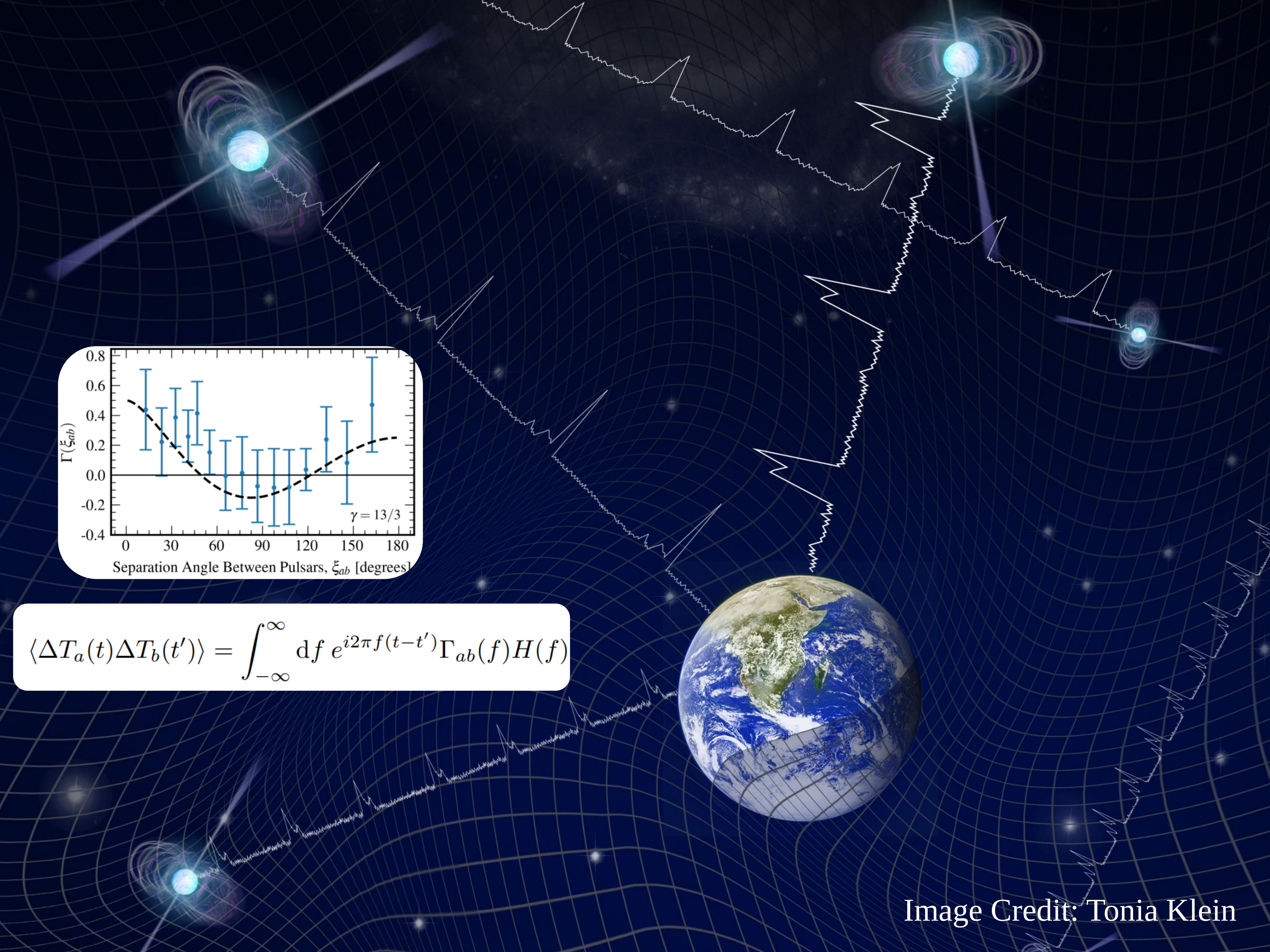

Lighthouse effect


10^{14} G
10^{12} G
10^{10} G
10^{8} G
10^{3} yr
10^{5} yr
10^{7} yr
10^{9} yr
$\dot{P}\,(\mathrm{s\,s^{-1}})$
P (s)
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}


Frequency (MHz)
1500
1400
1300
Channel number
0
20
40
60
80
Pulse phase (periods)
0
0.5
1



Hulse–Taylor pulsar
(PSR B1913+16)



$$\langle \Delta T_a(t) \Delta T_b(t') \rangle = \int_{-\infty}^{\infty} \mathrm{d}f \, e^{i2\pi f(t-t')} \Gamma_{ab}(f) H(f)$$

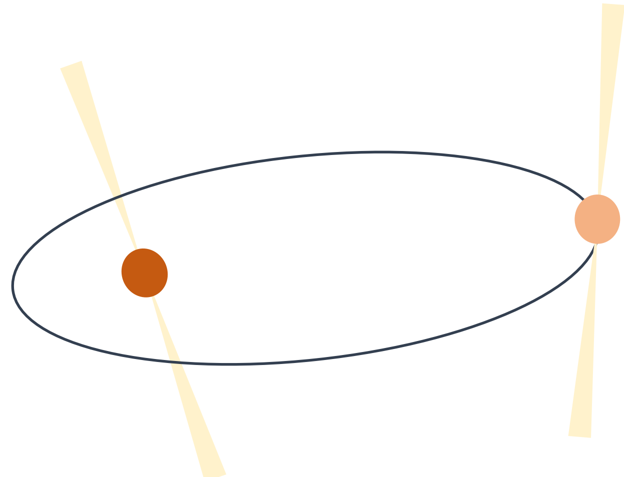
Image Credit: Tonia Klein

Detectability

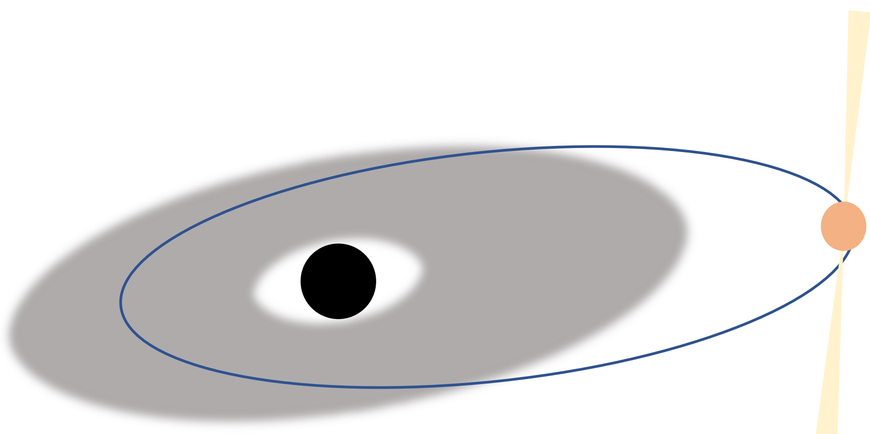
$$\frac{\Delta m}{m} \sim \mathcal{O}(10^{-13})$$

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.



PSR J0737-3039A/B



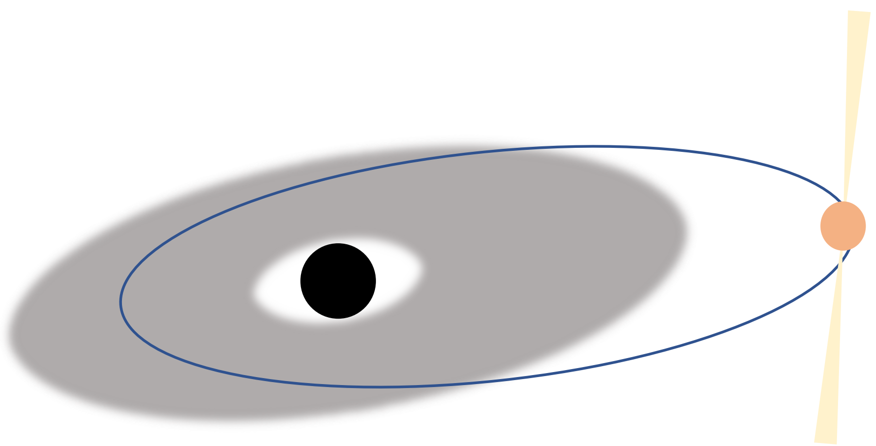
$$\frac{\Delta M_B}{M_B} \sim \mathcal{O}(10^{-12})$$

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

Detectability

The number of estimated PSR-BH binaries in the Milky Way is around $\mathcal{O}(10) - \mathcal{O}(1000)$.

[1] Shao, Y. , and L. Xiang-Dong . "Black hole/pulsar binaries in the Galaxy." Monthly Notices of the Royal Astronomical Society: Letters 1(2018):1.
[2] Chattopadhyay, D. , et al. "Modelling Neutron Star-Black Hole Binaries: Future Pulsar Surveys and Gravitational Wave Detectors.", 10.1093/mnras/stab973. 2020.



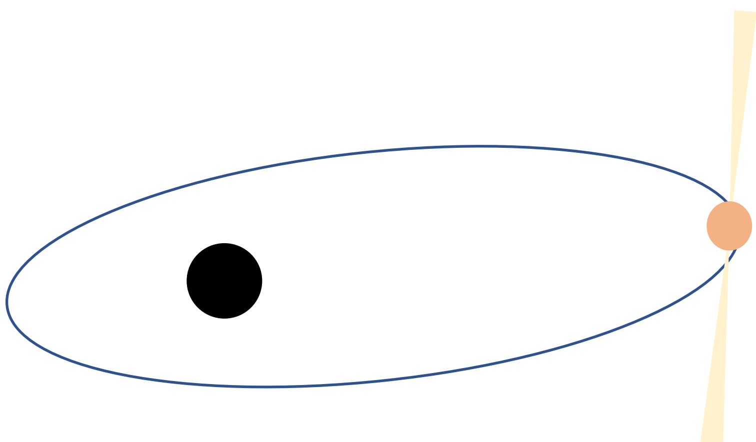
PSR-BH Binary

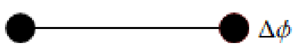
By measuring the Time-of-Arrival of the pulse from pulsar, we can obtain the orbital phase evolution in PSR-BH binaries. A new phenomena could provide an orbital phase shift

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

If the measured orbital phase shift is larger than measured uncertainty, such a new phenomena is detected

$$\Delta\phi(t) > \sigma_{\Delta\phi}(t) = \frac{2\pi}{\sqrt{t\ \mathrm{days}}}\frac{P}{t_{\mathrm{obs}}}$$





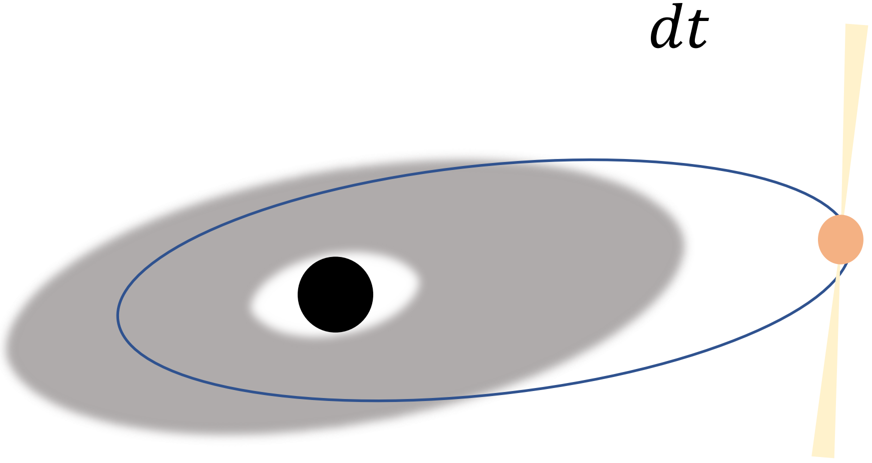
Accreting PSR-BH Binary

The accretion of DM would affect the GW radiation and gravitational potential energy

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

$$\frac{dL_i}{dt} = \frac{2G}{5c^2}\epsilon_{ijk}\frac{d^2Q_{mj}}{dt^2}\frac{d^3Q_{mk}}{dt^3} \qquad Q_{ij} = \sum_\alpha m_\alpha x_{\alpha i} x_{\alpha j}$$

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



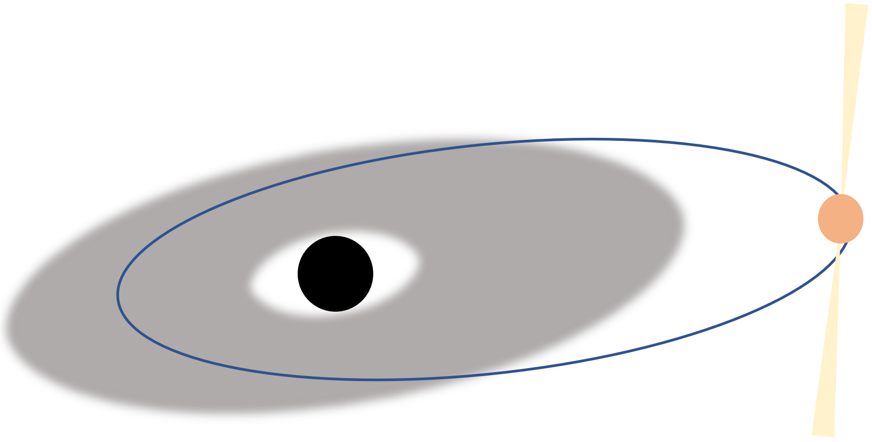
Accreting PSR-BH Binary

The orbital evolution of accreting PSR-BH binary is

$$\frac{dE}{dt} = -P_{acc} + \frac{dE_p}{dt} \qquad \frac{dL}{dt} = \frac{dL_{acc}}{dt}$$

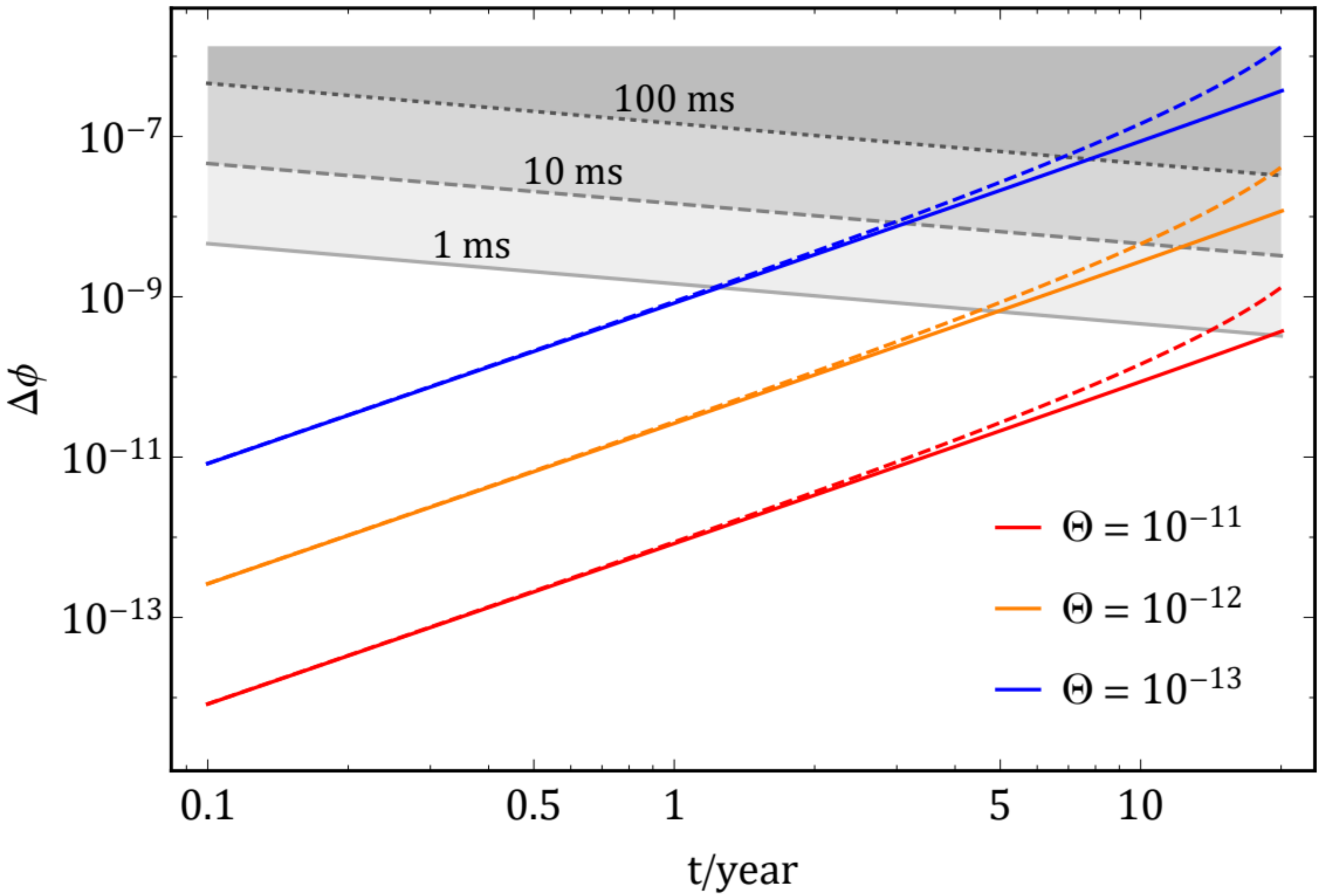
$$\frac{df}{dt} = \frac{1}{4\pi}\frac{a^{-5/2}G^{1/2}}{(m_p + M_B)^{1/2}}\left(a\frac{dM_B}{dt} - 3(m_p + M_B)\frac{da}{dt}\right)$$

$$\frac{df_{GR}}{dt} = -\frac{3}{4\pi}\frac{G^{1/2}(m_p + M_B)^{1/2}}{a_{GR}^{5/2}}\frac{da_{GR}}{dt}$$



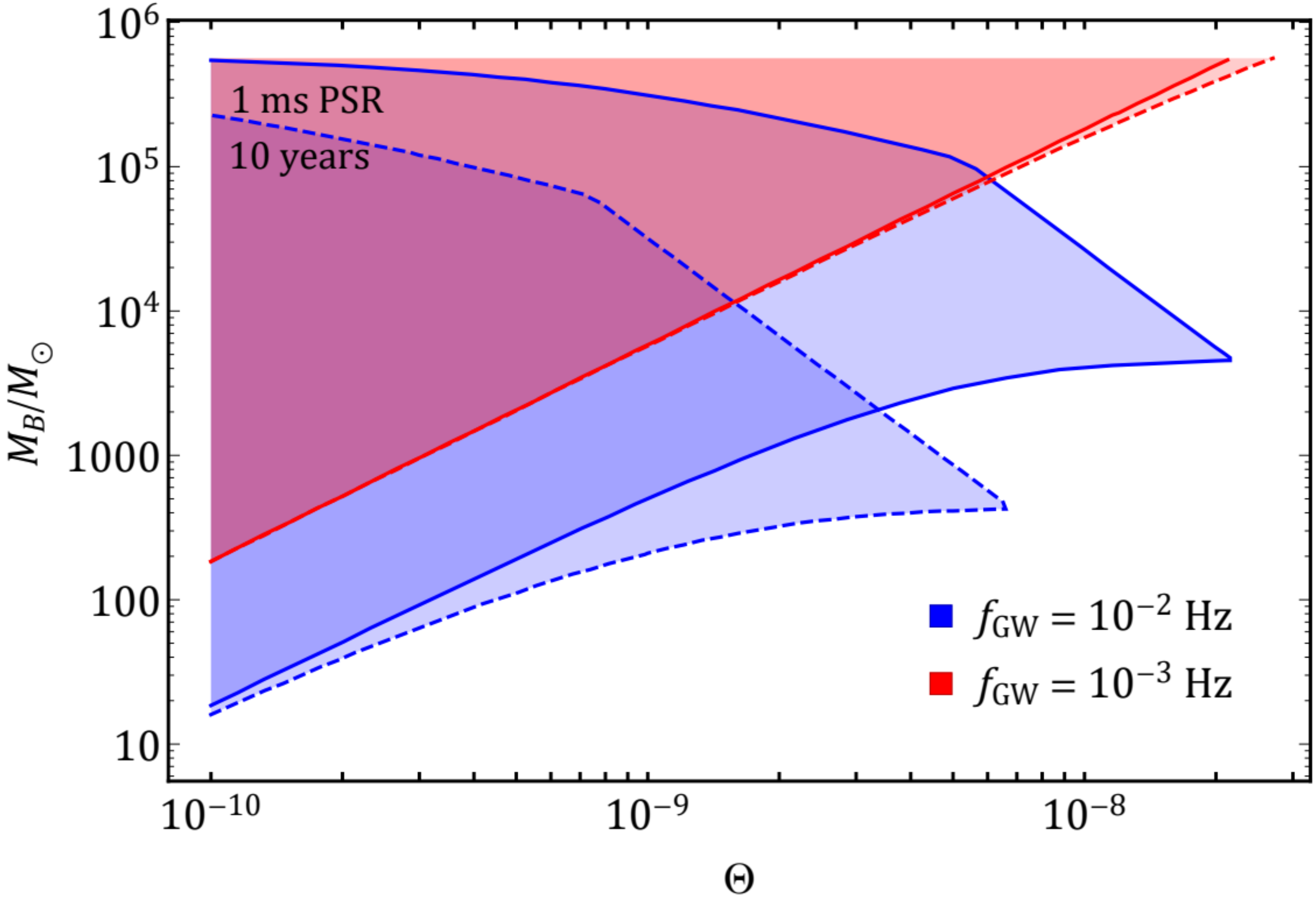
WIMPs Accretion

$$\frac{dM_B}{dt} = 4\pi\lambda_B (GM_B)^2 \frac{\rho_{DM}}{\gamma^{3/2}\Theta^{3/2}c^3}$$



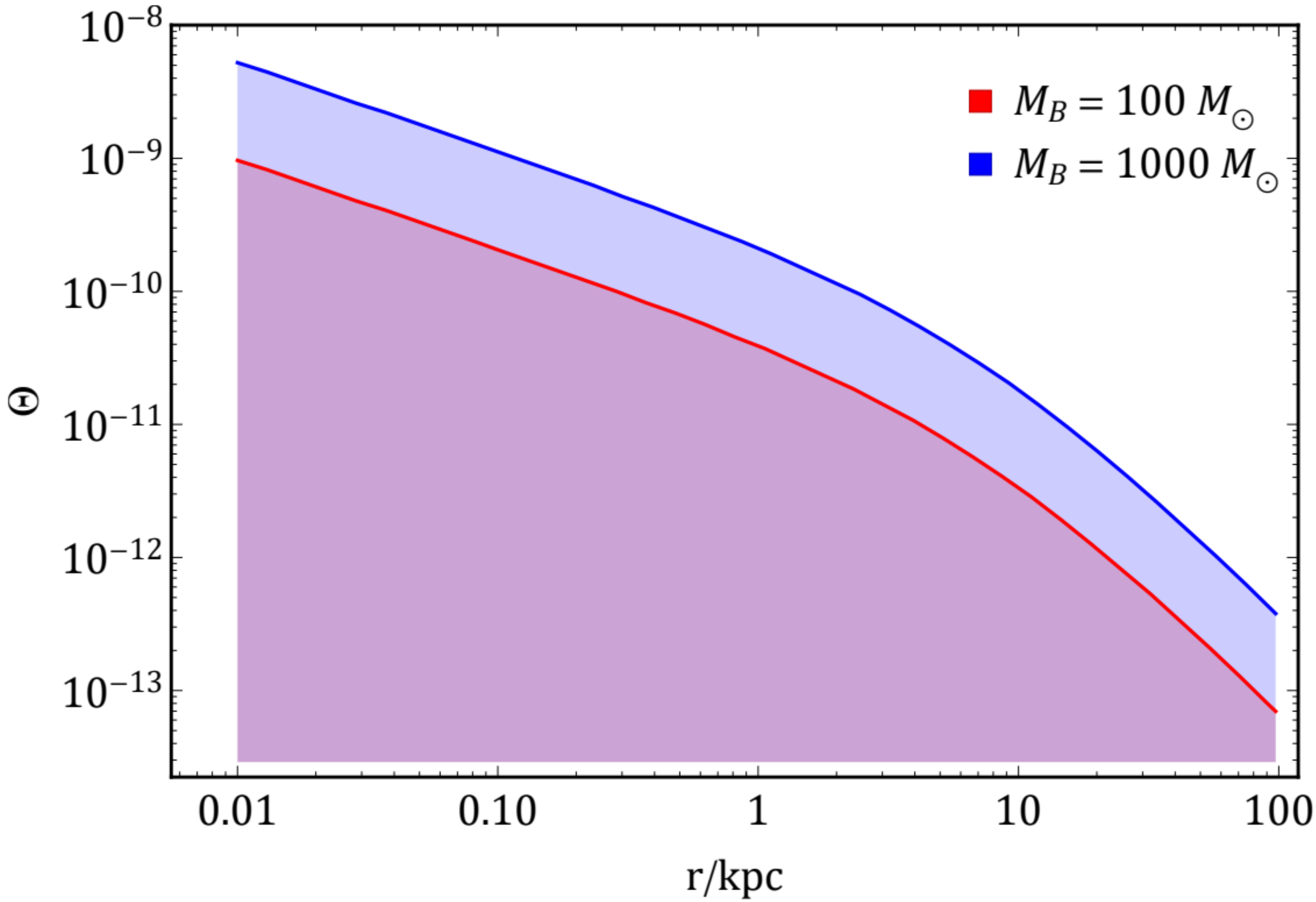
WIMPs Accretion

$$\frac{dM_B}{dt} = 4\pi\lambda_B (GM_B)^2 \frac{\rho_{DM}}{\gamma^{3/2}\Theta^{3/2}c^3}$$



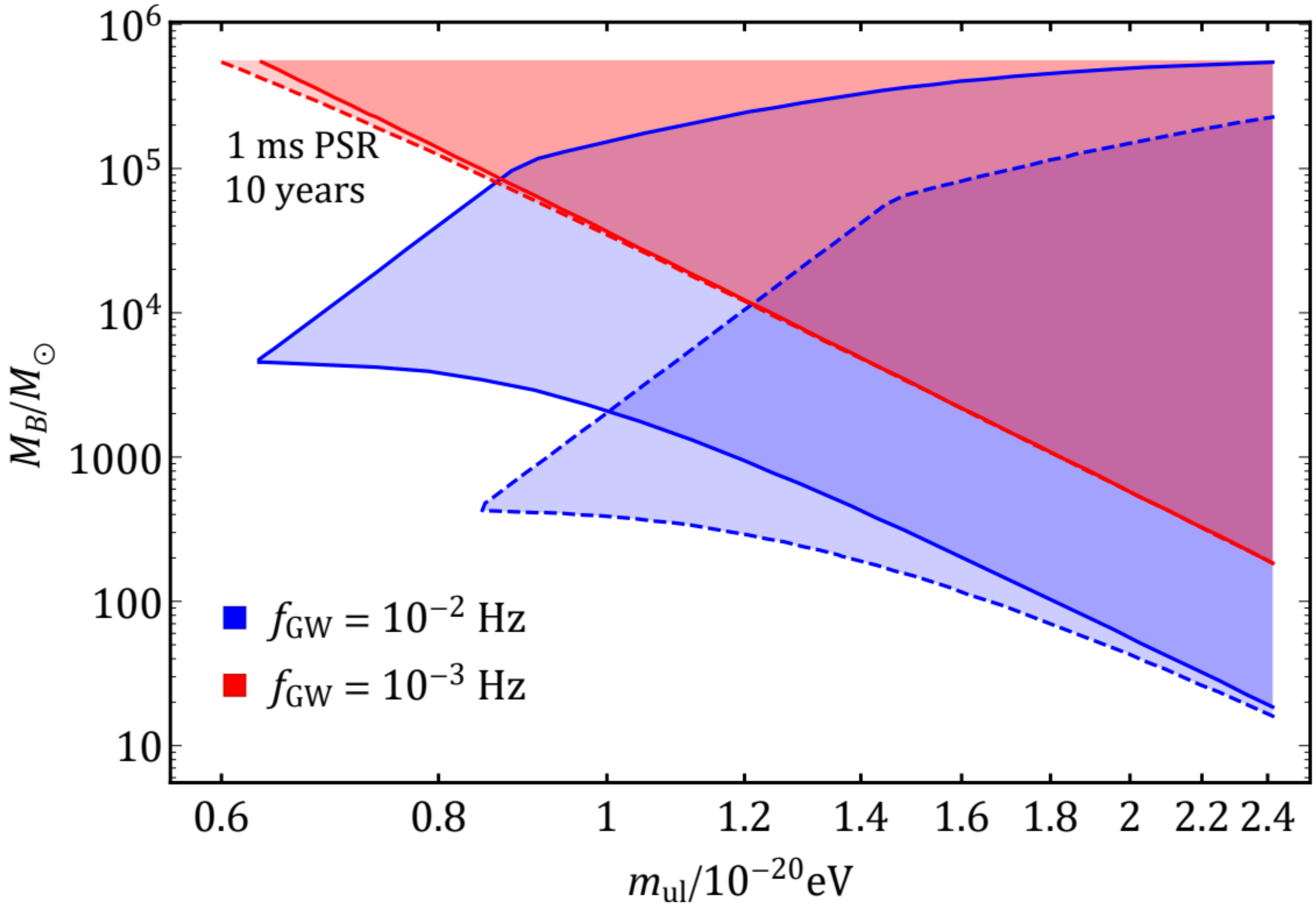
WIMPs Accretion

$$\frac{dM_B}{dt} = 4\pi\lambda_B (GM_B)^2 \frac{\rho_{DM}}{\gamma^{3/2}\Theta^{3/2}c^3}$$



Ultralight DM Accretion

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



PBHs Accretion

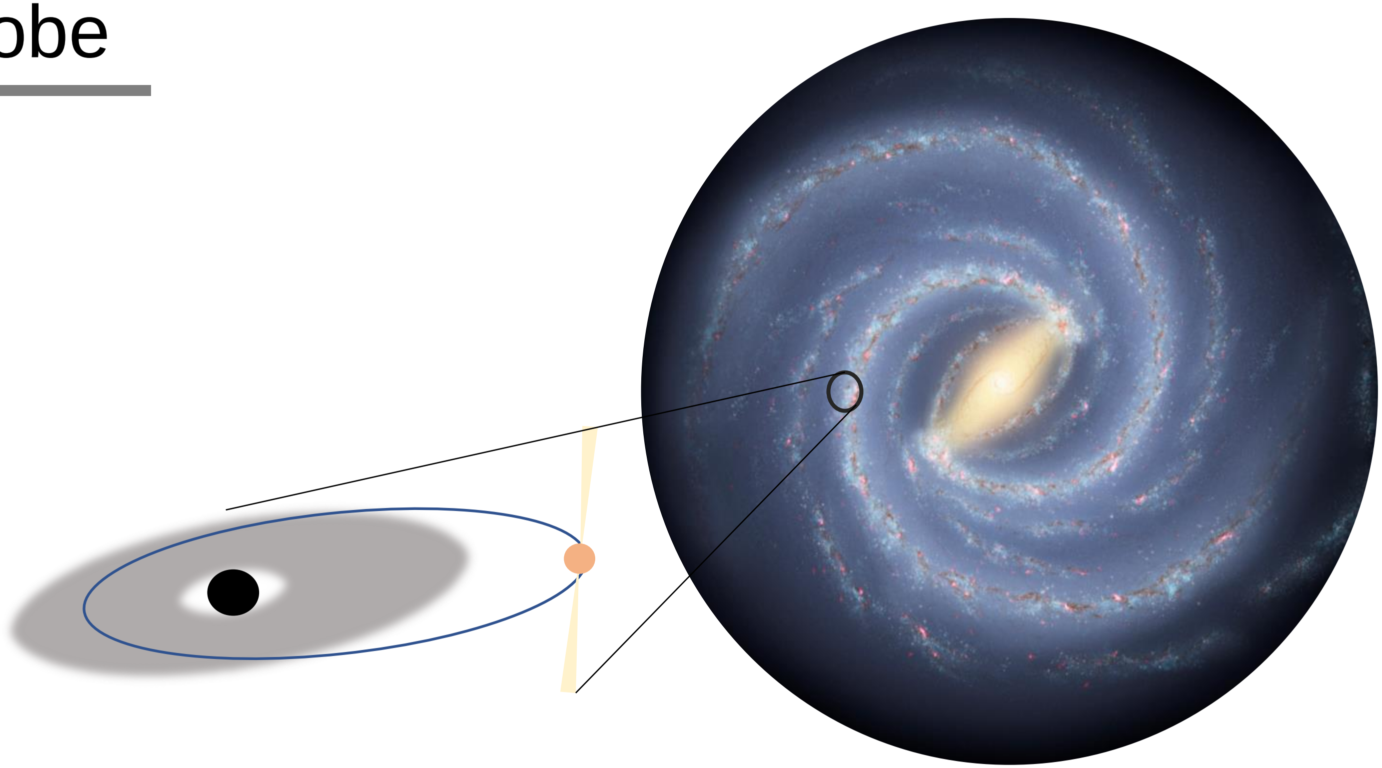
$$\frac{dM_B}{dt} \simeq \frac{M_{PBH}}{t_f} = 27\pi(GM_B)^2\frac{\rho_{DM}v}{c^4}$$

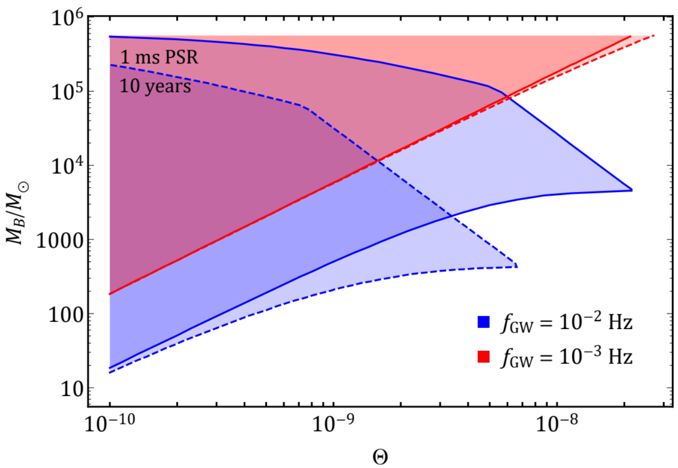
$$\frac{\dot{M}_P}{\dot{M}_W} \simeq \frac{27}{4}\frac{v}{c}\Theta^{\frac{3}{2}} \sim \mathcal{O}(10^{-17}) \qquad \Theta \sim \mathcal{O}(10^{-10})$$

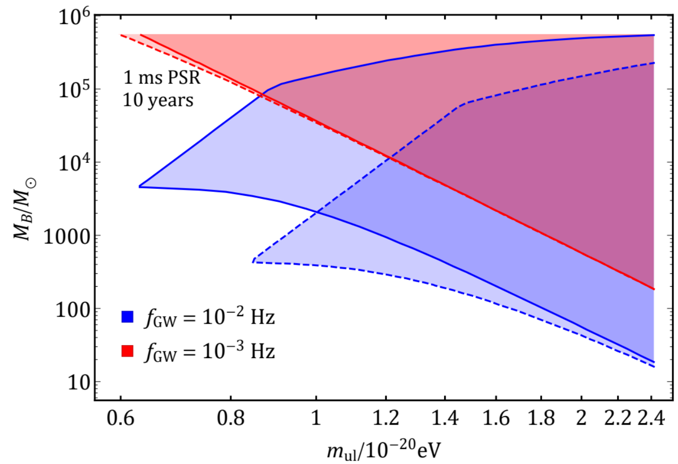
$$\frac{dM_B}{dt} = M_{PBH}\sum_{n=1}^{\infty}\delta(t - nt_f)$$

$$t_f = \frac{1}{27\pi v}\left(\frac{c^2}{GM_B}\right)^2\frac{M_{PBH}}{\rho_{DM}} \sim \mathcal{O}(10^{26})\text{ years}$$

A DM Probe







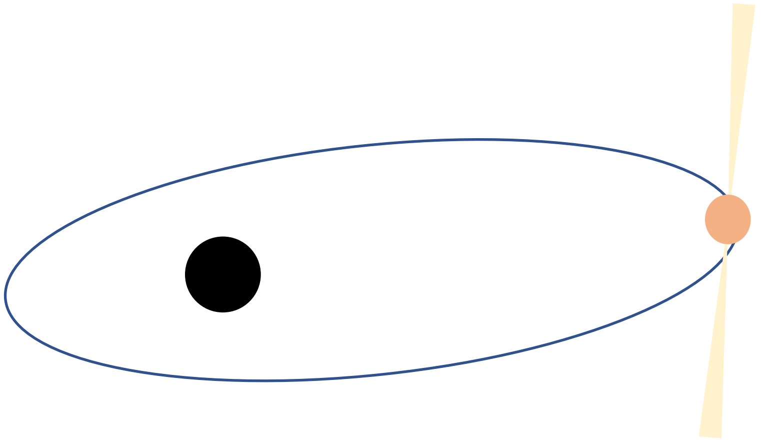
Null-Detections prefer weaker accretion DM models, such as PBHs

Outlook

- Superradiance around a Kerr black hole, the mass loss can be up to 10% (2307.05181)

- Study the complex matter surrounding background in the center of the galaxy

- The Hawking radiation induced by small mass primordial black holes




ibs
기초과학연구원
Institute for Basic Science
Thank you and welcome to visit IBS!