

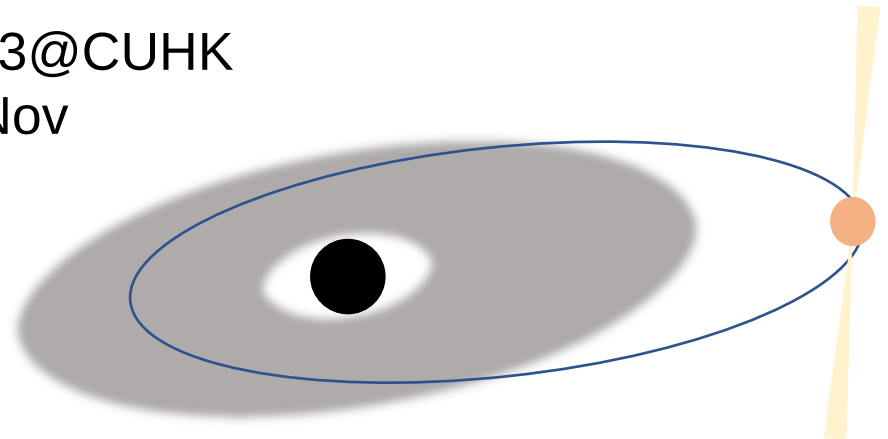
A Dark Matter Probe in Accreting Pulsar-Black Hole Binaries

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Reference: 2304.08824, Ali Akil, Qianhang Ding

CosPA 2023@CUHK
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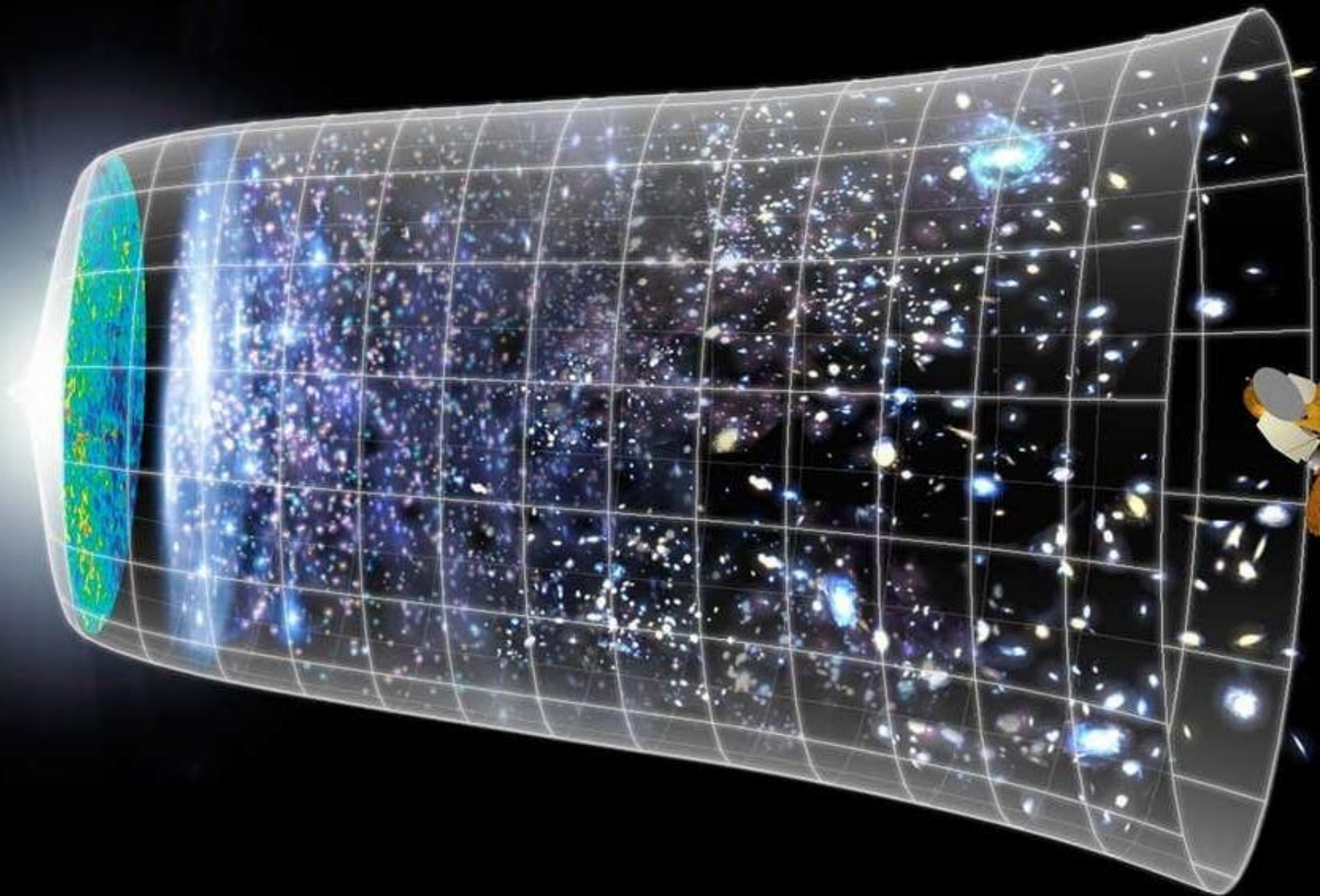
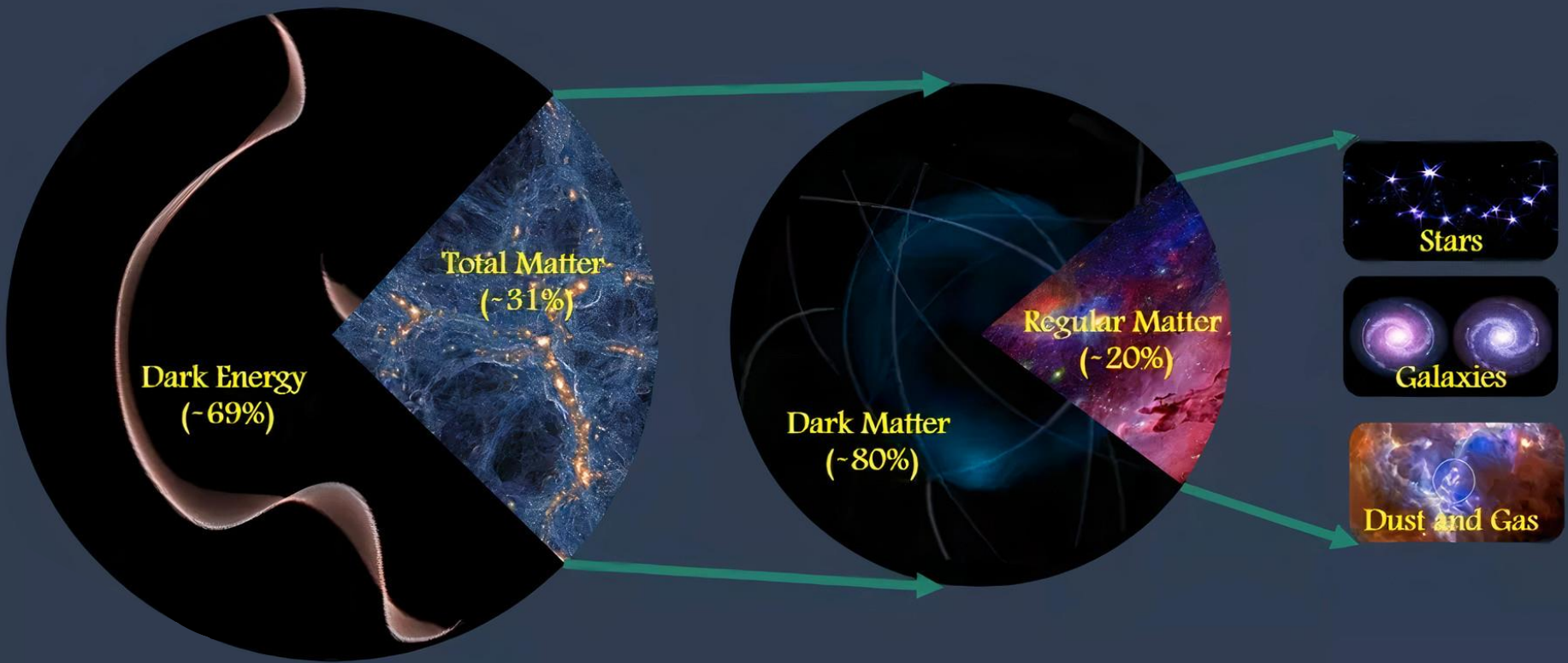
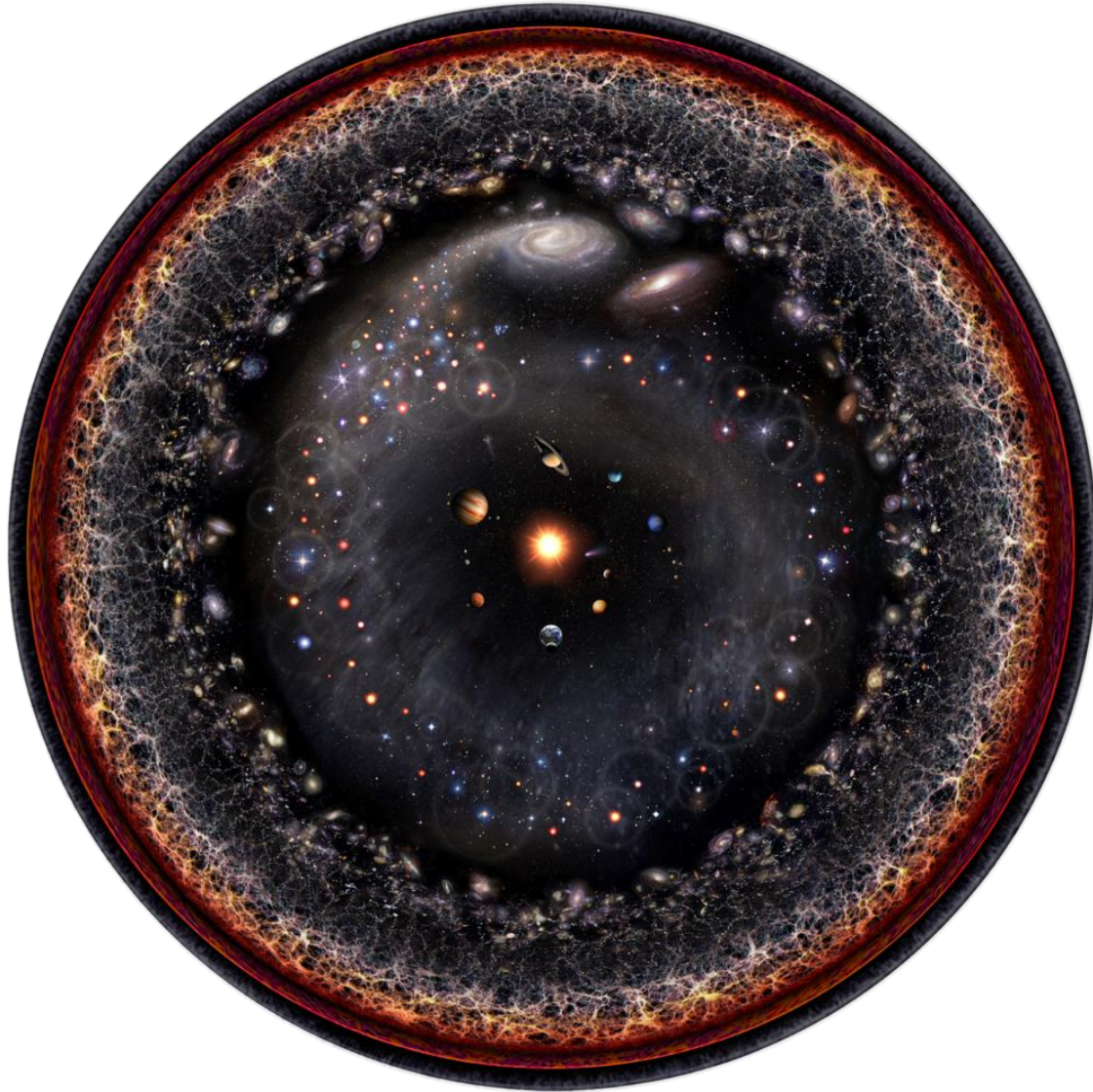


Image Credit: NASA



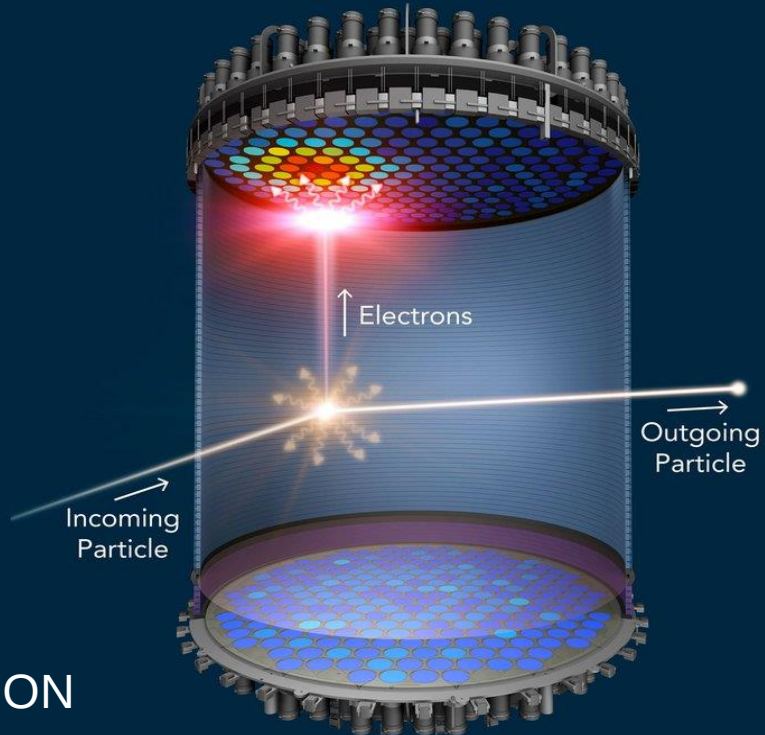
CDM Problems



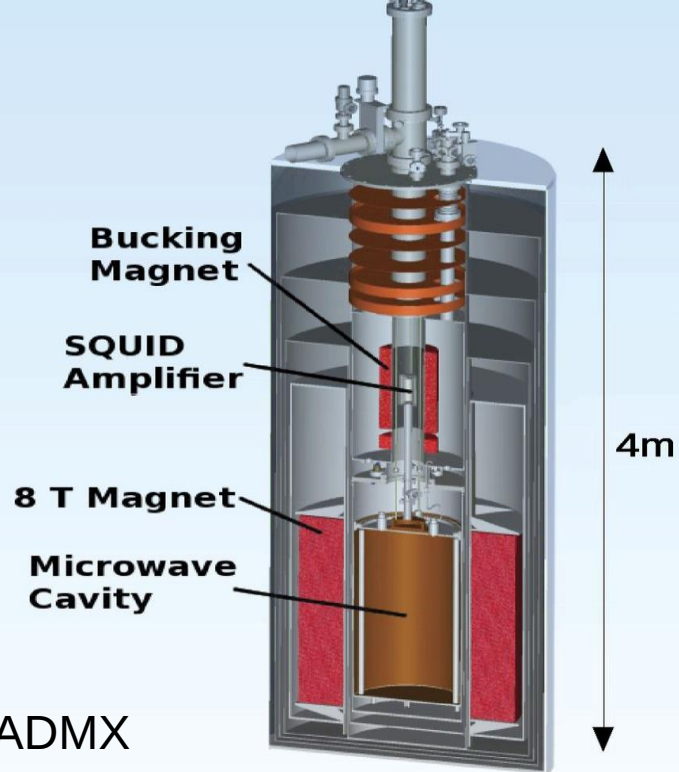
Cold DM at Small Scales:

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

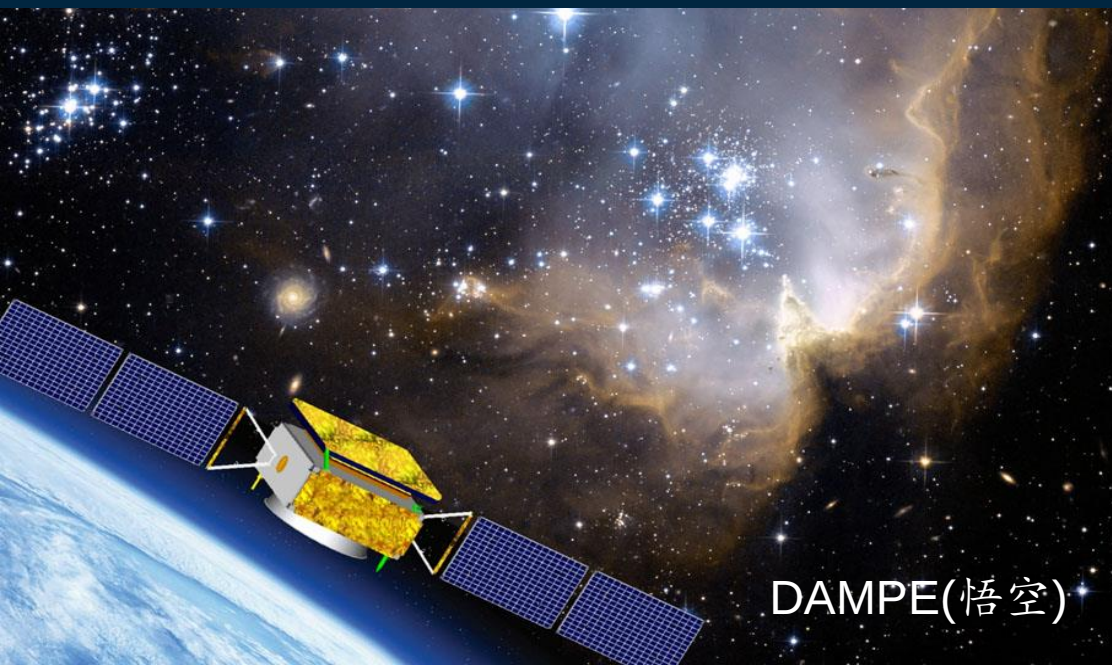
XENON



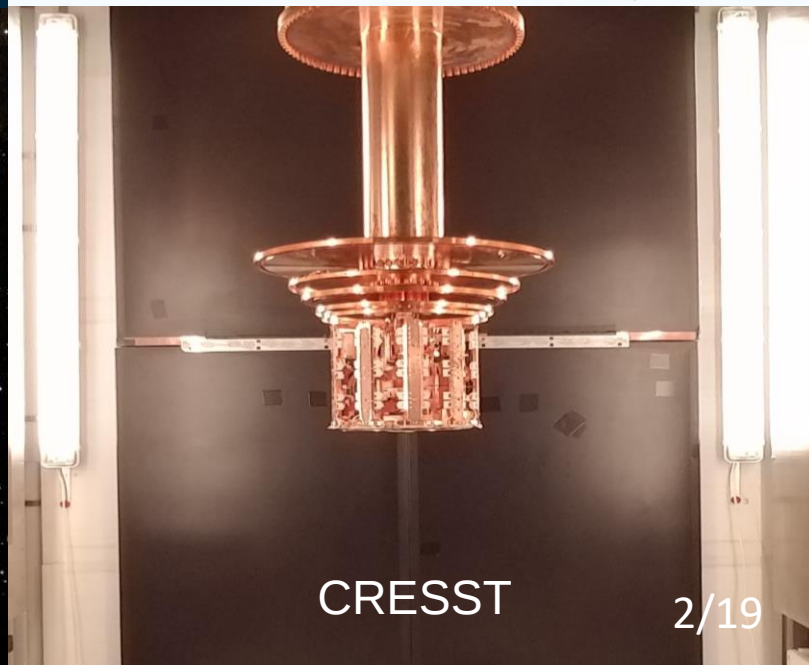
ADMX



DAMPE(悟空)



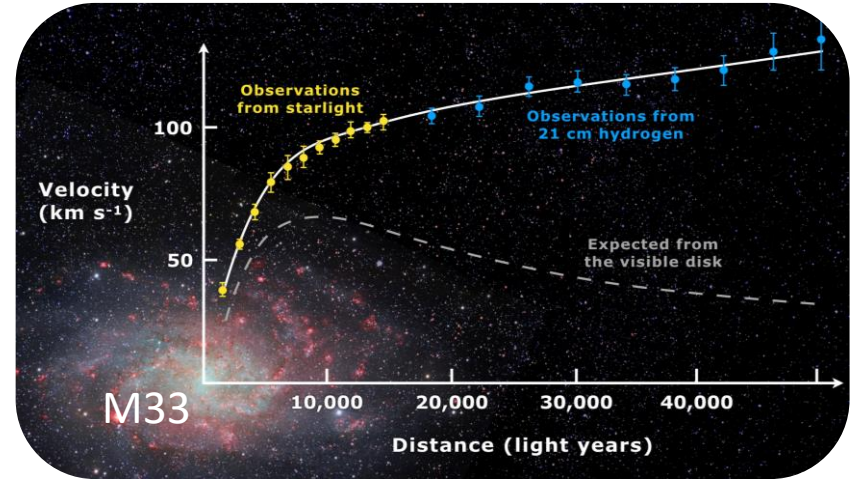
CRESST



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

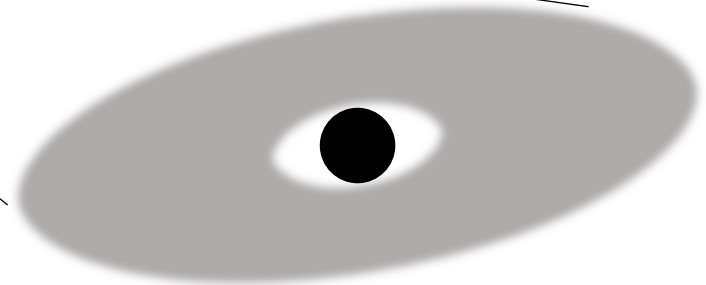
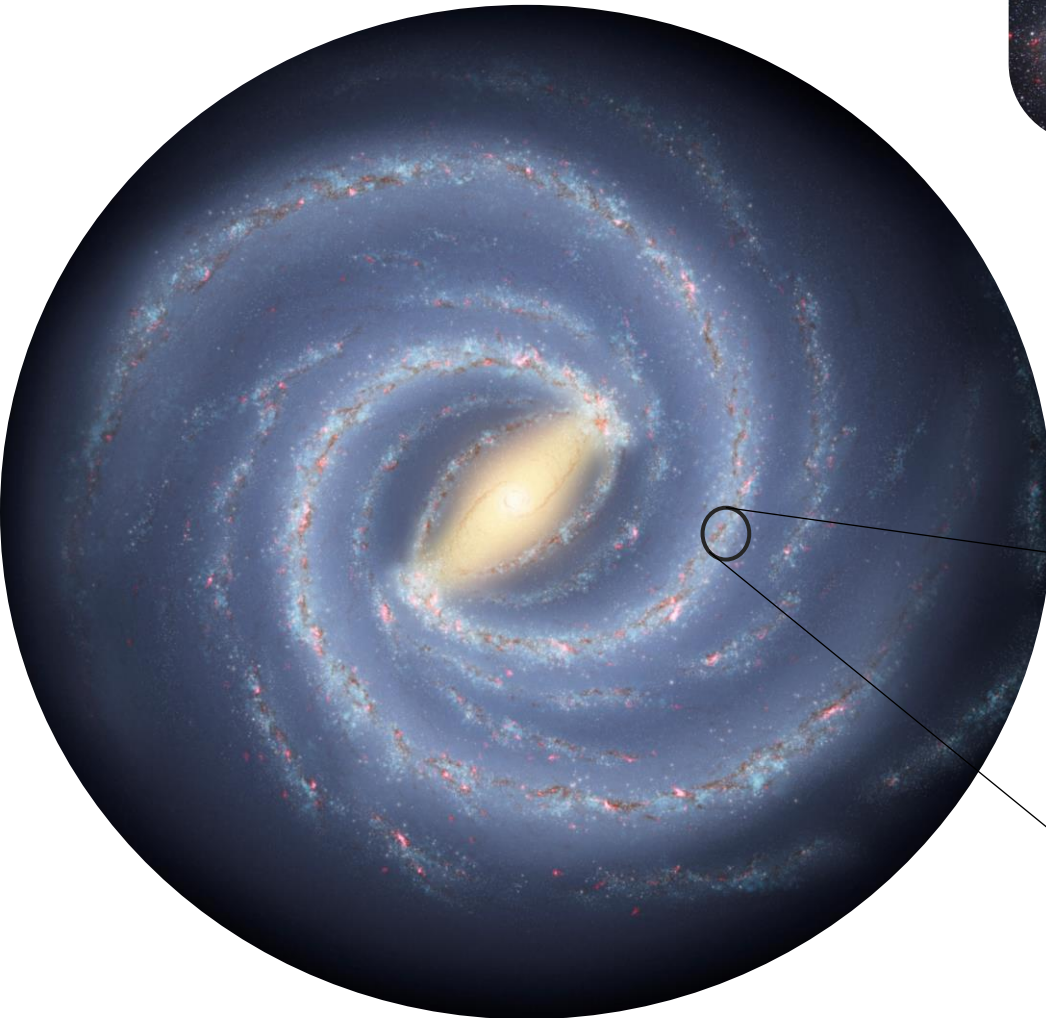
a cumulative gravitational effect in strong gravity field

DM Accretion in BH

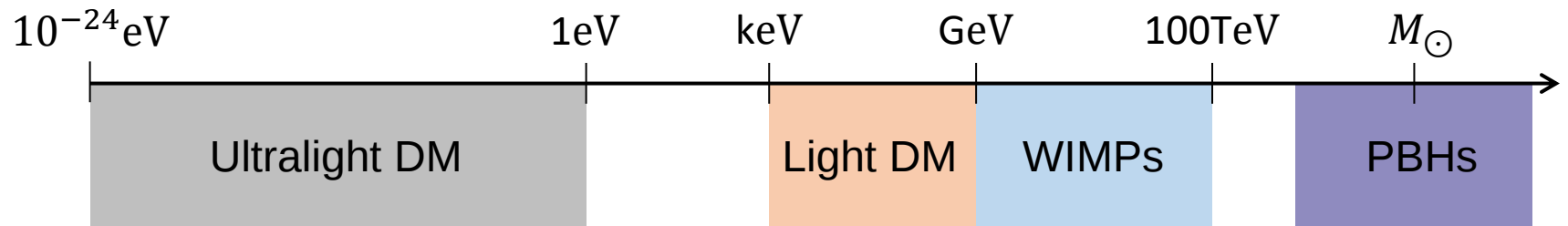


Navarro–Frenk–White (NFW) profile

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



DM Models



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

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

Ultralight DM Accretion

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

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

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 $10^9 M_\odot$

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

PBHs Accretion

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

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

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

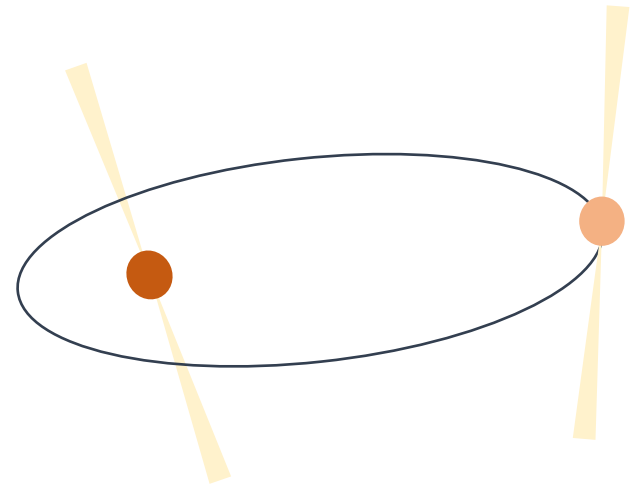
$$\frac{dM_B}{dt} \simeq \frac{M_{PBH}}{t_f} = 27\pi (GM_B)^2 \frac{\rho_{DM} v}{c^4}$$

Detectability

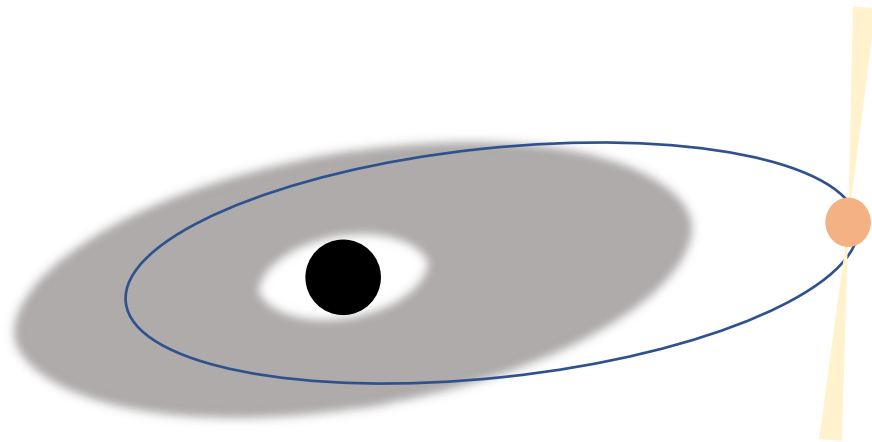
$$\frac{\Delta m}{m} \sim \mathcal{O}(10^{-13})$$

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



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

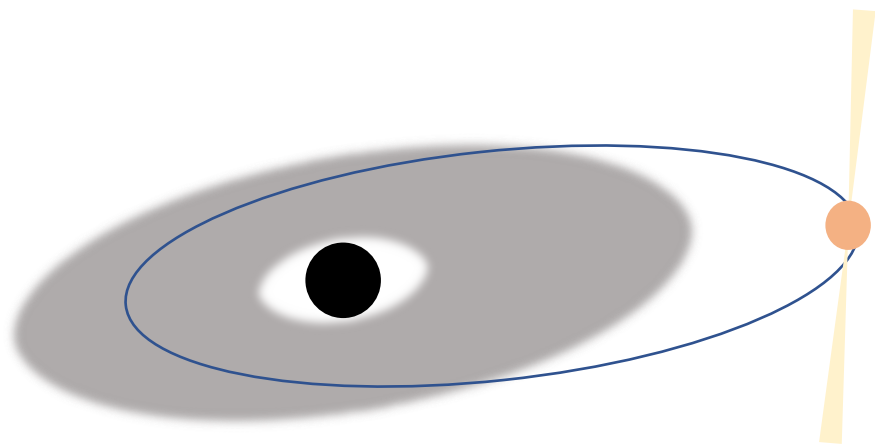
The relative BH mass change within 10 years, if $M_B = 10M_\odot$ and $\Theta = 10^{-10}$ or $m_{ul} = 10^{-20}$ eV

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.



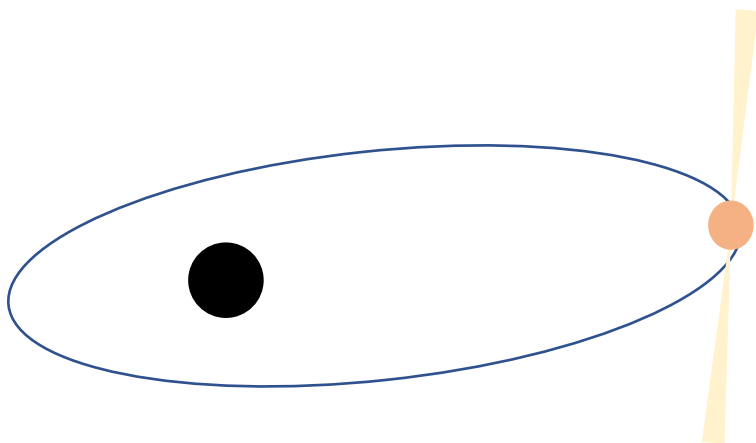
PSR-BH Binary

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

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



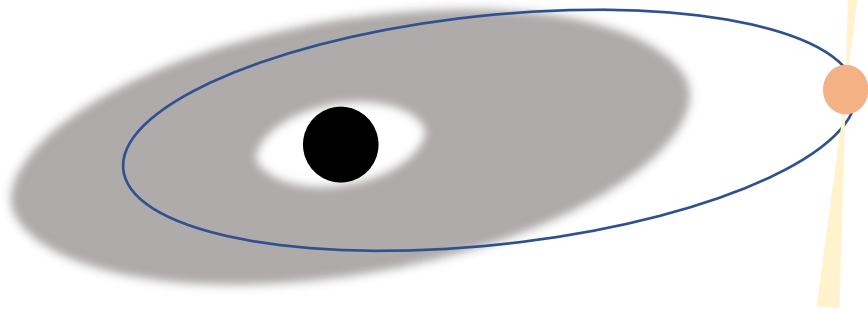
Accreting PSR-BH Binary

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

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

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

$$\frac{dE_p}{dt} = - \frac{G m_p}{a} \frac{dM_B}{dt}$$



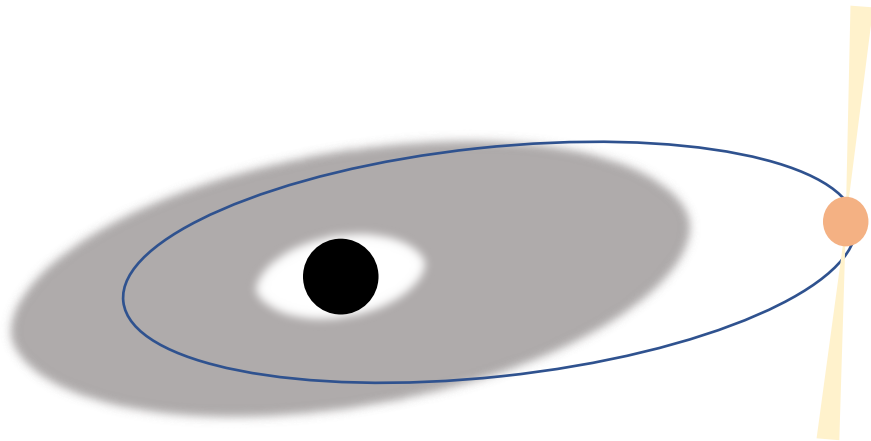
Accreting PSR-BH Binary

The orbital evolution of accreting PSR-BH binary is

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

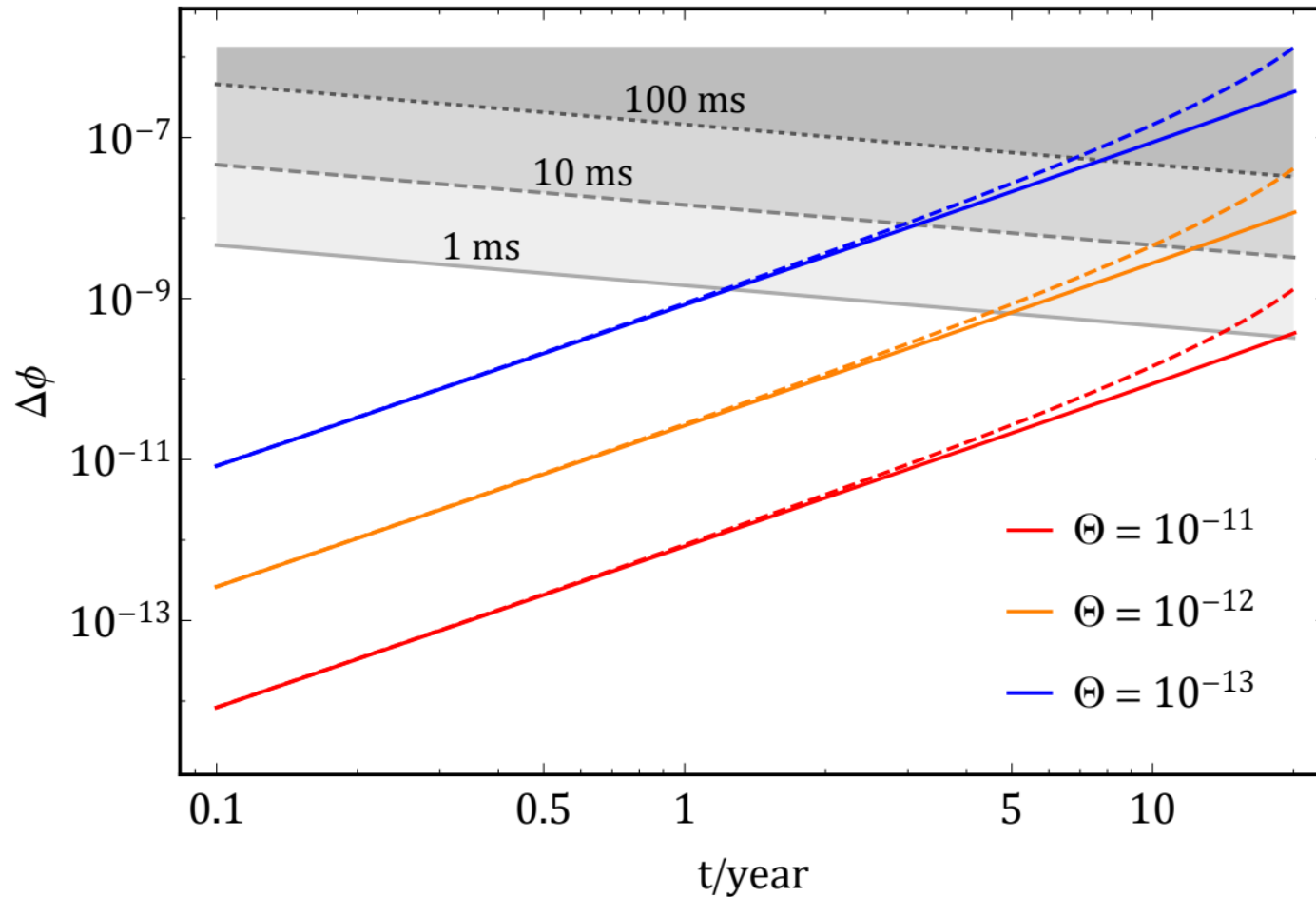
$$\frac{df}{dt} = \frac{1}{4\pi} \frac{a^{-5/2} G^{1/2}}{(m_p + M_B)^{1/2}} \left(a \frac{dM_B}{dt} - 3(m_p + M_B) \frac{da}{dt} \right)$$

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



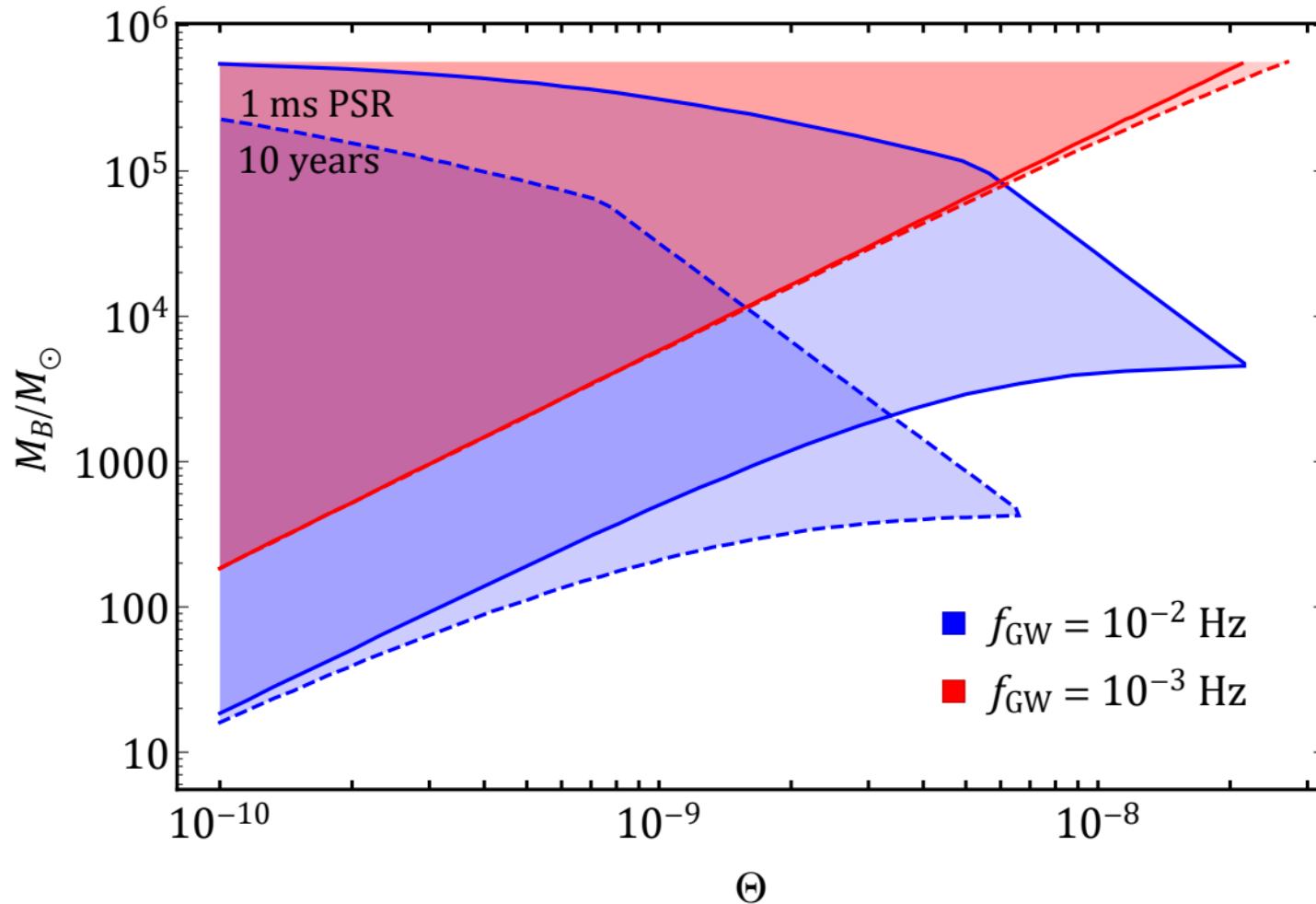
WIMPs Accretion

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



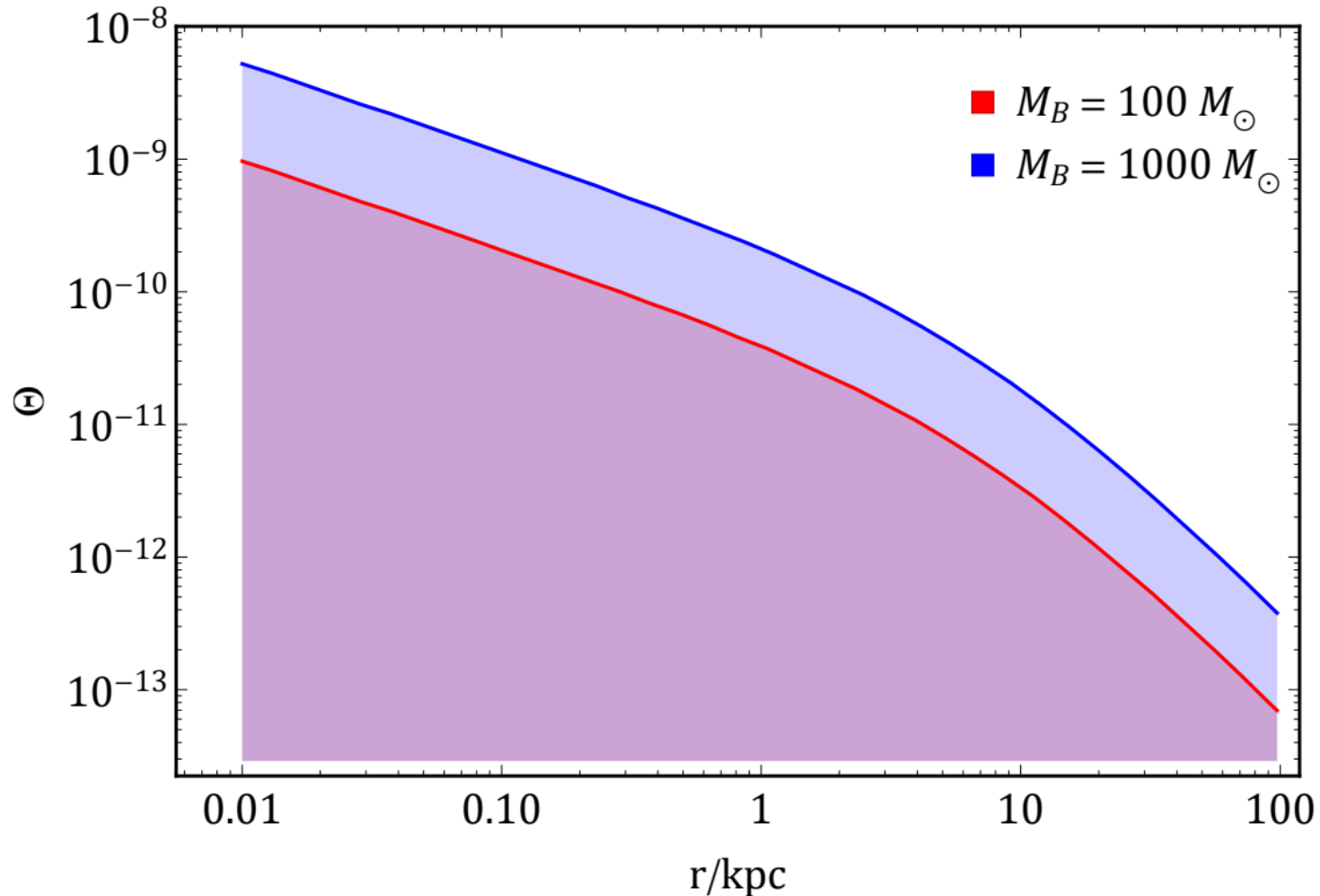
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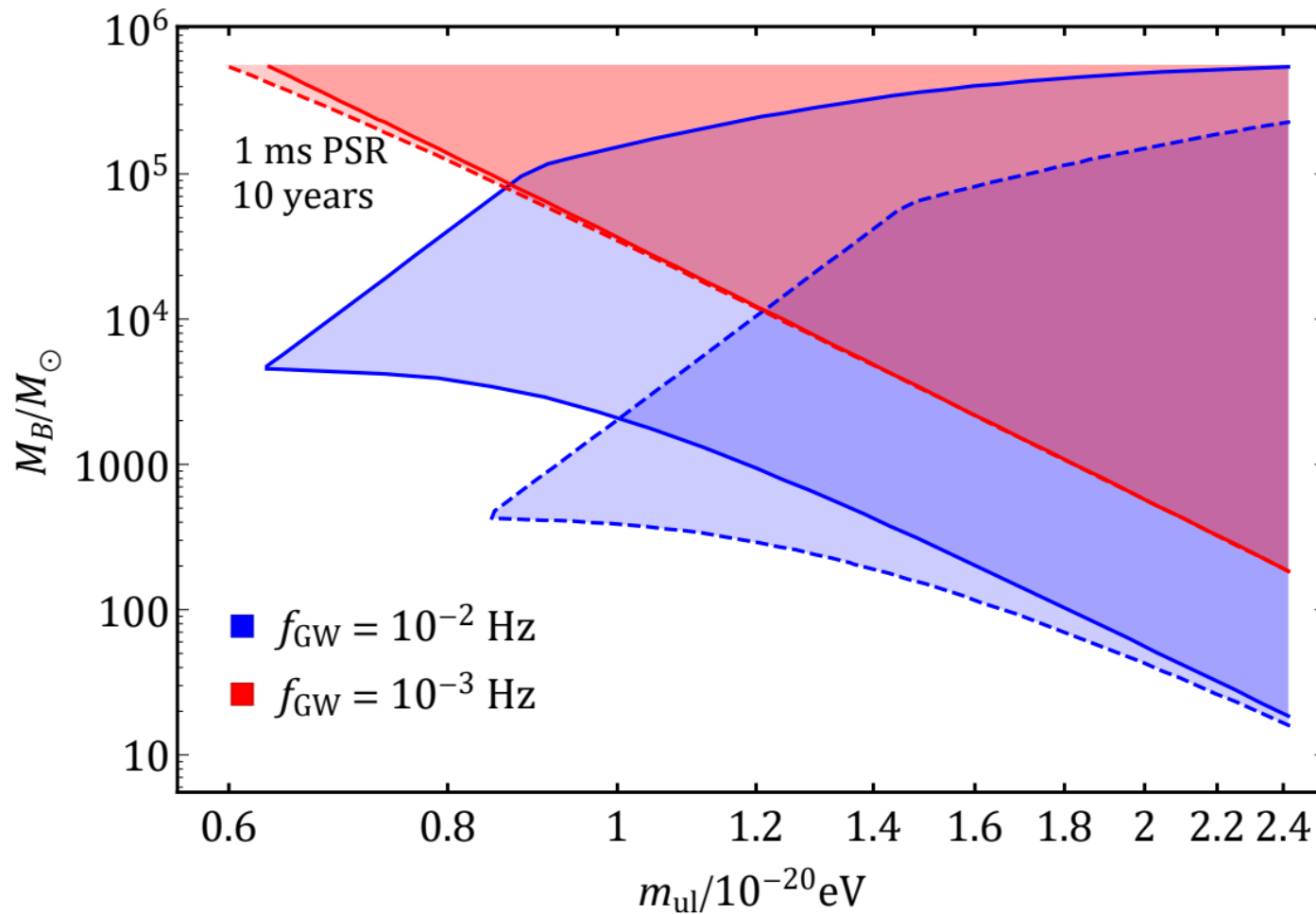
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Ultralight DM Accretion

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PBHs Accretion

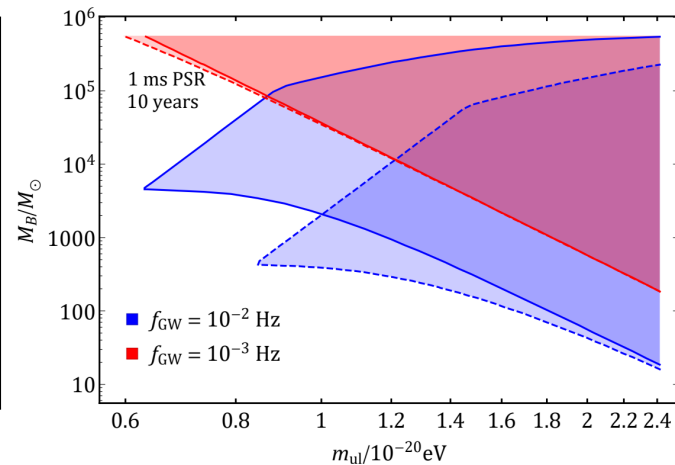
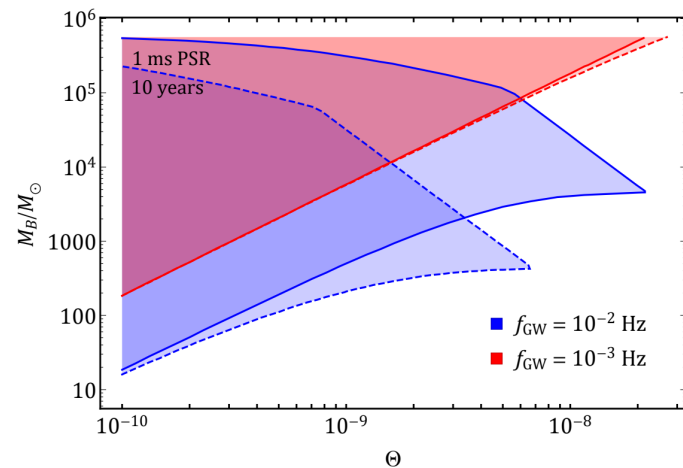
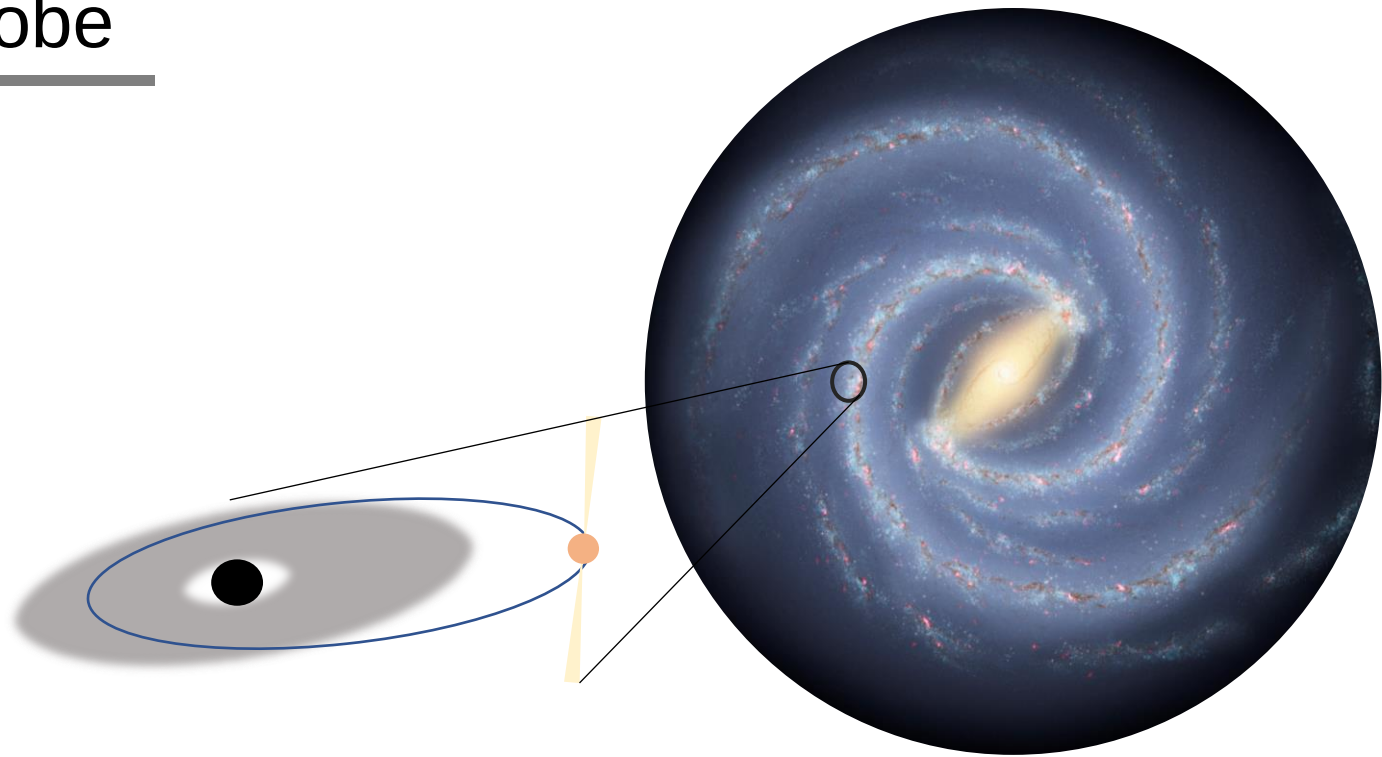
$$\frac{dM_B}{dt} \simeq \frac{M_{PBH}}{t_f} = 27\pi(GM_B)^2 \frac{\rho_{DM} v}{c^4}$$

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

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

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

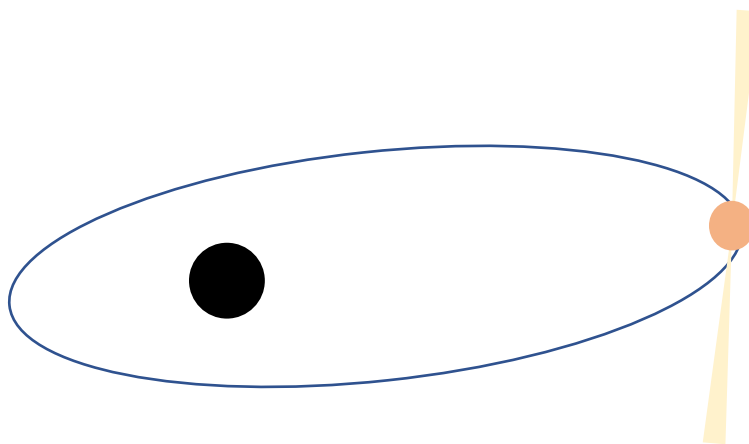
A DM Probe



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



Thank you !