A Dark Matter Probe in Accreting Pulsar-Black Hole Binaries

Ali Akil [1 2], Qianhang Ding [2]
[1] Department of Physics, Southern University of Science and Technology, Shenzhen, China
[2] Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

Introduction

The accretion of dark matter (DM) into astrophysical black holes slowly increases their mass. The rate of this mass accretion depends on the DM model and the model parameters. If this mass accretion effect can be measured accurately enough, it is possible to rule out some DM models, and, with the sufficient technology and the help of other DM constraints, possibly confirm one model. We propose a DM probe based on accreting pulsar-black hole binaries, which provide a high-precision measurement on binary orbital phase shifts induced by DM accretion into black holes, and can help rule out DM models and study the nature of DM.

Dark Matter Accretion in Black Hole

WIMPs: The accretion of Weakly Interacting Massive Particles (WIMPs) by BHs is captured by the well-known Bondi accretion formula.

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

ULDM: The accretion rate of the ultralight DM is derived from the Klein-Gordon equation on a non-rotating BH background, which is

$$\frac{\mathrm{d}M_\mathrm{B}}{\mathrm{d}t} = \frac{32\pi^2 (GM_\mathrm{B})^3 m_\mathrm{ul}\rho_\mathrm{DM}}{\hbar c^3 v[1-\exp(-\xi)]}$$

In the central region of the galaxy, the accretion follows

$$\frac{\mathrm{d}M_\mathrm{B}}{\mathrm{d}t} = \frac{2.5\,M_\odot}{10^{17}\,\mathrm{yr}} \left(\frac{M_\mathrm{B}}{\tilde{M}_\mathrm{B}}\right)^2 \left(\frac{m_\mathrm{ul}}{\tilde{m}_\mathrm{ul}}\right)^6 \left(\frac{M_\mathrm{sol}}{\tilde{M}_\mathrm{sol}}\right)^4$$

PBHs: The accretion of a Primordial Black Hole (PBH) in an astrophysical BH can be estimated by the mean free path of astrophysical BH and its moving velocity.

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

Accreting Pulsar-Black Hole Binaries

Pulsar-Black Hole Binaries: The PSR-BH binary system is the holy grail in radio astronomy, since the stable pulse signals emitted from pulsar can provide high precision measurements on the strong gravity field around the BH.

Orbital Phase Shift: The Time-of-Arrival from PSR-BH binary system can tell us the evolution of binary orbital phase in the general relativistic background.

$$\phi(t) = \int_0^t f_\mathrm{GR}(\tau)d\tau$$

When DM is accreted into BH, it would change the orbital frequency of the binary and further affect the binary orbital phase, which causes an orbital phase shift.

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

If this orbital phase shift can be detected, it should larger than the measurement uncertainty of orbital phase shift.

$$|\Delta\phi(t)| > \sigma_{\Delta\phi}(t)\ ,\ \sigma_{\Delta\phi} = \frac{1}{\sqrt{t/1\,\mathrm{day}}}\frac{P}{t_\mathrm{obs}}$$

Orbital Evolution: The DM accretion into BH would effectively change the gravitational wave emission and gravitational potential of the binary, which influences orbital evolution and induces an orbital phase shift. The orbital frequency evolution in DM accretion scenario is

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{1}{4\pi}\frac{a^{-5/2}G^{1/2}}{(m_\mathrm{p}+M_\mathrm{B})^{1/2}}\left(a\frac{\mathrm{d}M_\mathrm{B}}{\mathrm{d}t} - 3(m_\mathrm{p}+M_\mathrm{B})\frac{\mathrm{d}a}{\mathrm{d}t}\right)$$

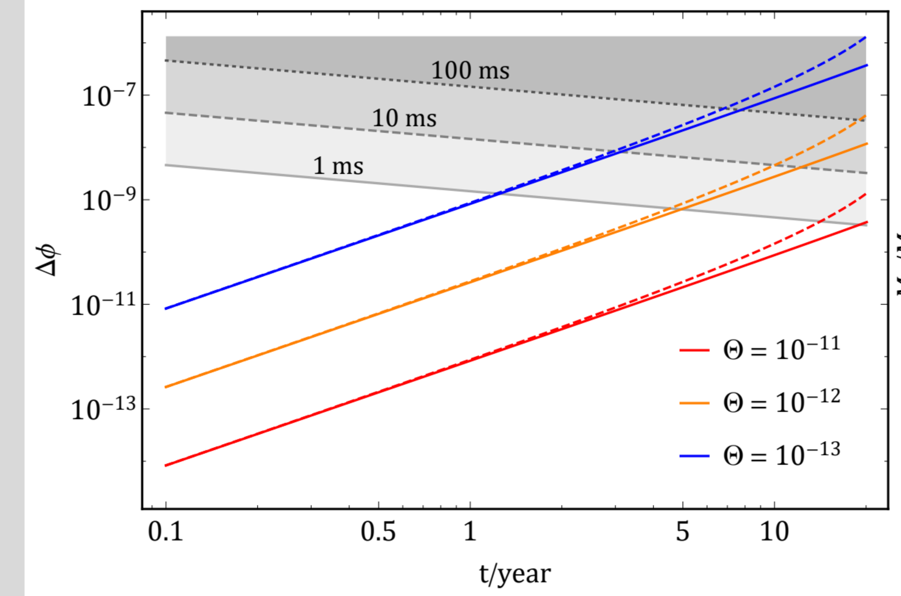
While the orbital frequency evolution in general relativistic background follows

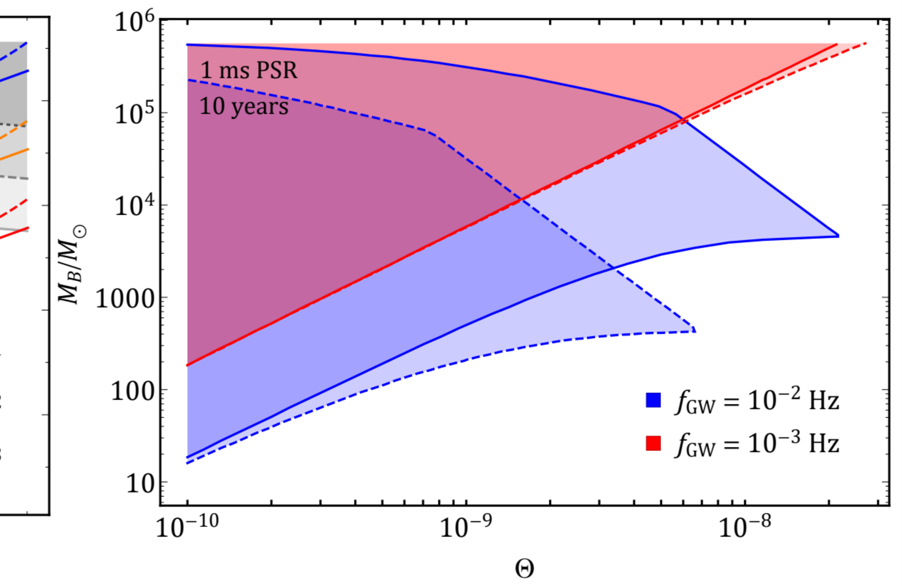
$$\frac{\mathrm{d}f_\mathrm{GR}}{\mathrm{d}t} = -\frac{3}{4\pi}\frac{G^{1/2}(m_\mathrm{p}+M_\mathrm{B})^{1/2}}{a_\mathrm{GR}^{5/2}}\frac{\mathrm{d}a_\mathrm{GR}}{\mathrm{d}t}$$

Then the numerical solution of orbital frequency would produce a detectable orbital phase shift.

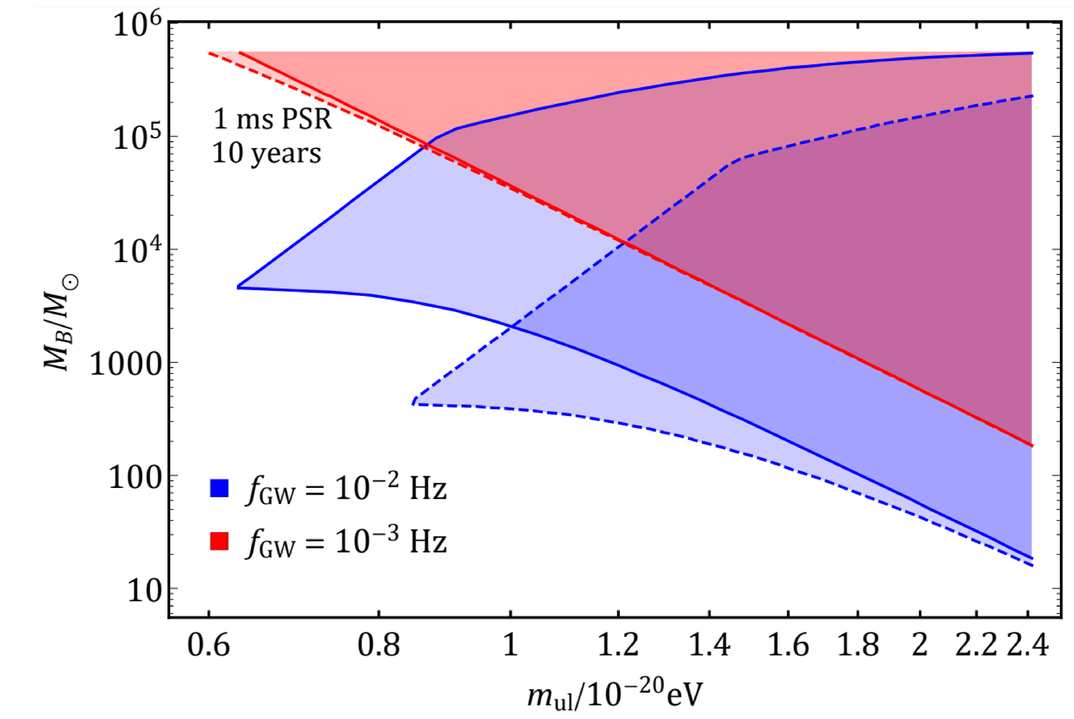
DM Accretion in PSR-BH Binaries

WIMPs: From the accretion rate of WIMPs in BH, we can obtain the evolution of orbital phase shift with different WIMPs parameters, and detectable parameter regions in PSR-BH binaries





ULDM: From the accretion rate of ULDM in BH, we can obtain detectable parameter regions in PSR-BH binaries



PBHs: The accretion rate of PBHs in BH is extremely small compared with WIMPs, which can be estimated as,

$$\frac{\dot{M}_\mathrm{B}^\mathrm{P}}{\dot{M}_\mathrm{B}^\mathrm{W}} \simeq \frac{27}{4}\frac{v}{c}\Theta^{3/2}$$

For a WIMPs with $\Theta \sim 10^{-10}$, and relative velocity is around 200 km/s, the above value is $\dot{M}_\mathrm{B}^\mathrm{P}/\dot{M}_\mathrm{B}^\mathrm{W} \sim \mathcal{O}(10^{-17})$. This value is extremely small and can hardly detected in PSR-BH binaries. Therefore, a null detection result may indicate a possibility of PBHs as DM.

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qdingab@connect.ust.hk