Exploring Dark Forces with Multimessenger Studies of Extreme Mass Ratio Inspirals

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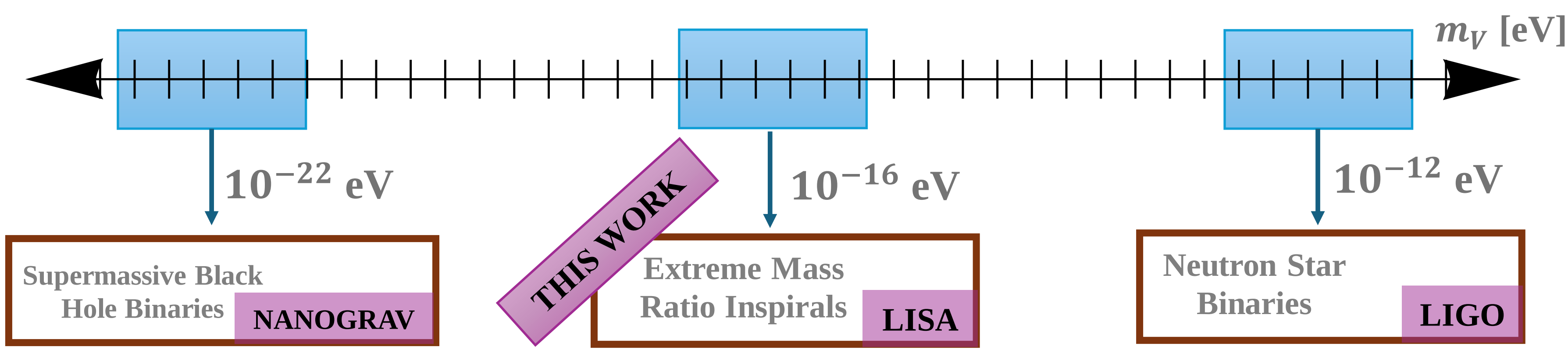
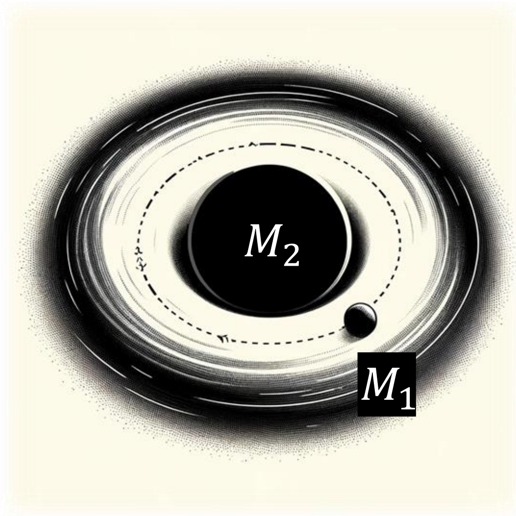


mHz Gravitational Waves.

In-spiral of a compact, stellar-mass object into a massive black hole.



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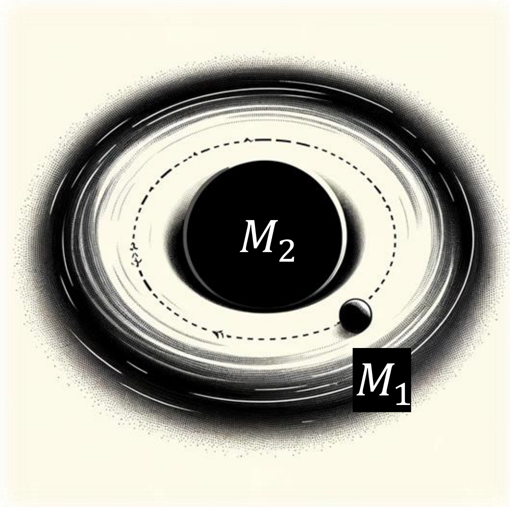

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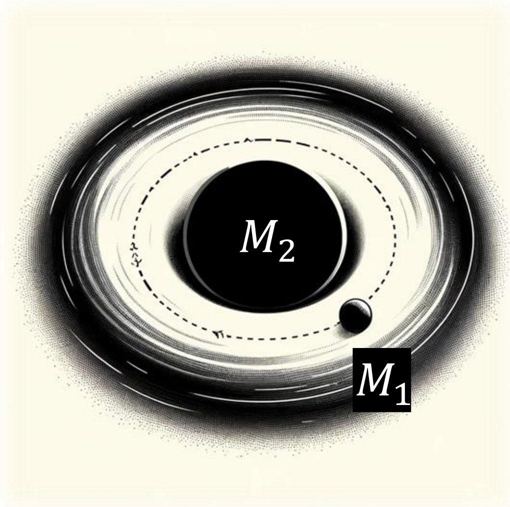

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What is interesting about EMRI?

Precise Measurement

Long Observation Time

$$\frac{M_1}{M_2} = 10^{-5}$$

We consider a Yukawa force mediated by a particle of mass m_v
Furthermore, we assume that the dark force only acts between two black holes. All other compact objects do not experience it.

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r = separation between the two objects
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In the presence of the dark force, the evolution of orbital frequency is given by

$$\omega^2 = \frac{G(M_1 + M_2)}{r^3}\left[1 + \tilde{\alpha}' e^{-m_V r}(1 + m_V r)\right]$$

$$\tilde{\alpha}' = \frac{\alpha' Q_1 Q_2}{G M_1 M_2}$$

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Rescaling the mass of binary components can imitate the effects of Dark Force. Therefore, it is crucial to measure the mass of binary components without any dark force acting between them.

Other methods, free from dark forces, can determine the mass of SMBH.

1. **Multimessenger Studies with XMRI-EMRI Combinations :**

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3. Studies of Spectroscopic Reverberation Mapping and EMRIs:

$$\frac{\Delta M_{SMBH}}{M_{SMBH}} = 10\%$$

The time evolution of orbital frequency is

$$\frac{d\omega}{dt} = -\frac{32}{5} G\mu\, r^2\, \omega^5 g(\alpha', m_V, r) N^{-1}$$

Relativistic Correction

$$g = -\frac{3 + \alpha' e^{-m_V r}\left(3 + m_V r(3 + m_V r)\right)}{1 + \alpha' e^{-m_V r}\left(1 + m_V r(1 - m_V r)\right)}$$

We assume a 10% uncertainty in the mass measurement of the compact object in this study.

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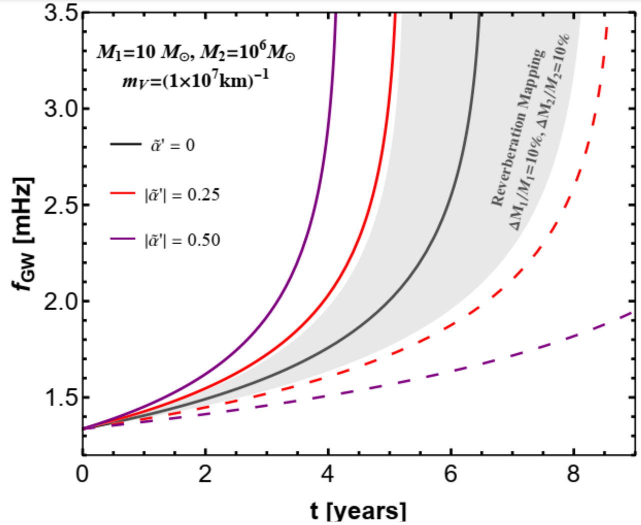
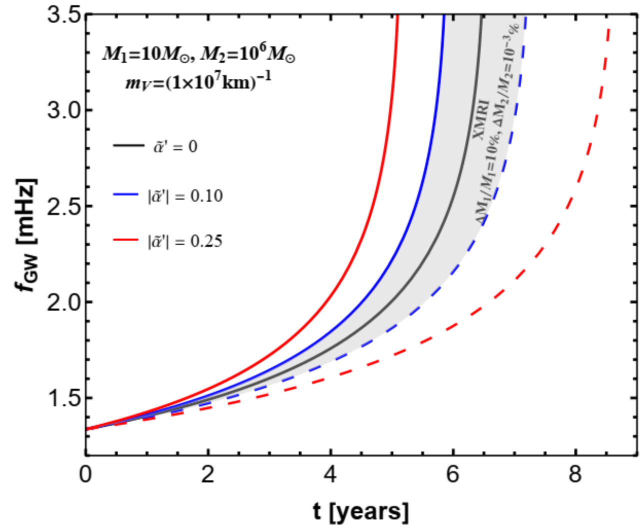
Attractive Dark Force (solid line)

Repulsive Dark Force (dashed line)





The rms amplitude of the gravitational wave emitted for the dominant, m = 2, radiation is

$$h_{o,2} = \frac{3.6 \times 10^{-23}}{r_0/1Gpc}\left(\frac{\mu}{M_\odot}\right)\left(\frac{M}{100M_\odot}\right)^{2/3}\left(\frac{f_2}{100Hz}\right)^{2/3}\mathcal{H}_{o,2}$$

Here
r_0 is the distance from EMRI.
$\mathcal{H}_{o,2}$ is the relativistic correction to the amplitude

$$h_{c,2} \stackrel{\text{def}}{=} h_{o,2}\sqrt{\frac{2{f_2}^2}{\dot{f}_2}}$$

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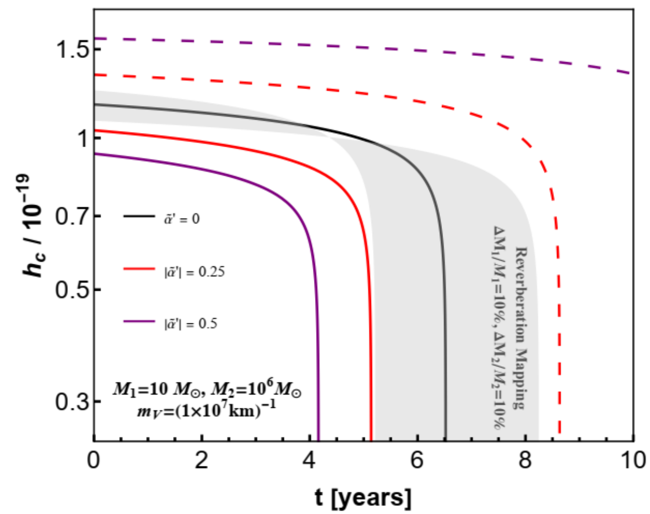
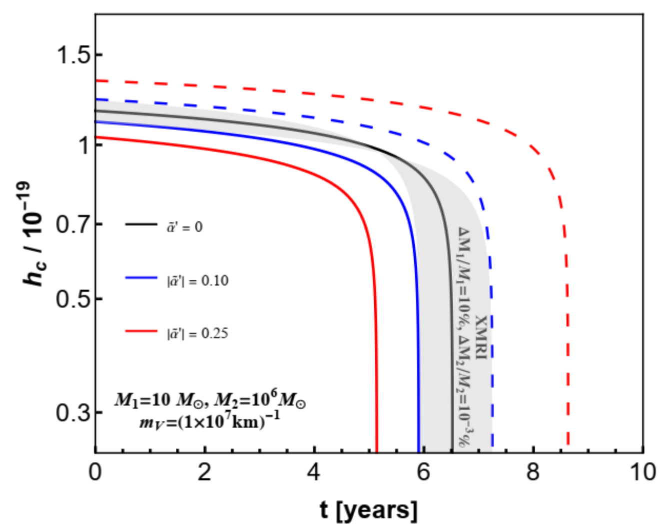


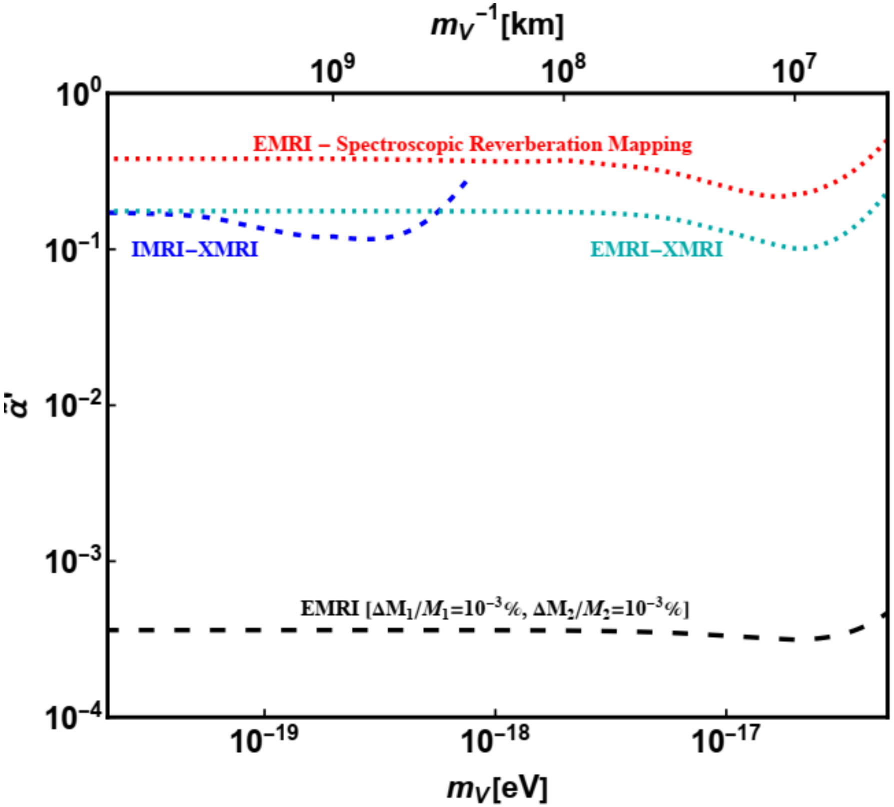


LIKELIHOOD ANALYSIS

$$\Lambda(s|\tilde{\alpha}') = \mathcal{K}\exp[(h_{\tilde{\alpha}'}|s) - \frac{1}{2}(h_{\tilde{\alpha}'}|h_{\tilde{\alpha}'}) - \frac{1}{2}(s|s)]$$

$$(h_{\tilde{\alpha}'}|s) = \mathrm{Re}\int_{f_{\min}}^{f_{\max}} df_{\mathrm{GW}} \frac{h_{c,\tilde{\alpha}'}(f_{\mathrm{GW}}) s_c(f_{\mathrm{GW}})}{f_{\mathrm{GW}}^2 S_n(f_{\mathrm{GW}})}$$

	EMRI-SRM	EMRI-XMRI	IMRI-XMRI
M_1	$10\ M_\odot$	$10\ M_\odot$	$10^4\ M_\odot$
M_2	$10^6\ M_\odot$	$10^6\ M_\odot$	$10^8\ M_\odot$
$\frac{\Delta M_1}{M_1}$	10 %	10 %	10 %
$\frac{\Delta M_2}{M_2}$	10 %	10^{-3} %	10^{-3} %



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An independent mass measurement of the central SMBH breaks the degeneracy of the effect of the dark force with a simple rescaling of the binary component masses.

THANK YOU

Consider a millicharged DM fermion interacting by the exchange of a vector mediator

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V V_\mu V^\mu + \bar{\chi}(i\gamma_\mu D^\mu - m_\chi)\chi \ .$$

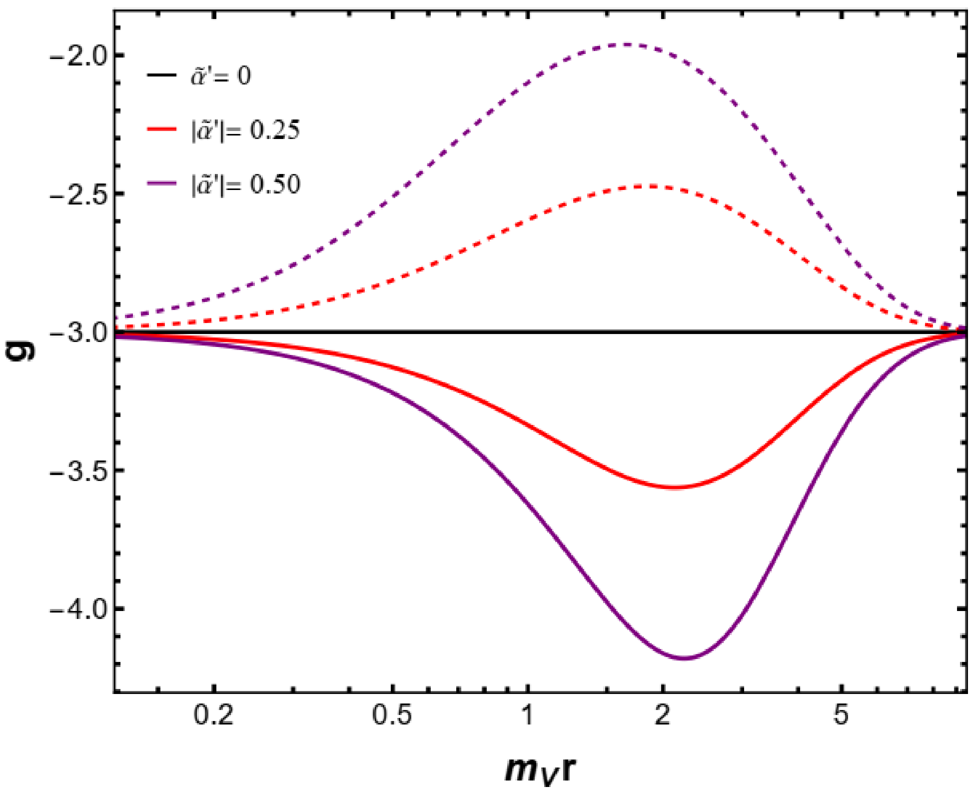
$Q \sim M$ → $Q_2 = N_2 q_\chi$

$m_\chi \sim m_p, \quad \text{and} \quad q_\chi \sim 10^{-18}\, e$

Assuming that the SMBH is in an environment with density *ρ* of oppositely charged dark fermions moving with velocity *v*

$$\tau_{\rm discharge} \sim \left(\frac{v}{220\,{\rm km/s}}\right)^3 \left(\frac{0.4\,{\rm GeV/cm^3}}{\rho}\right)\left(\frac{10M_\odot}{M_2}\right)\left(\frac{m_\chi}{m_p}\right)\left(\frac{e}{q_\chi}\right)\ {\rm yr}$$

BACKUP SLIDE: MORE RESULTS



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