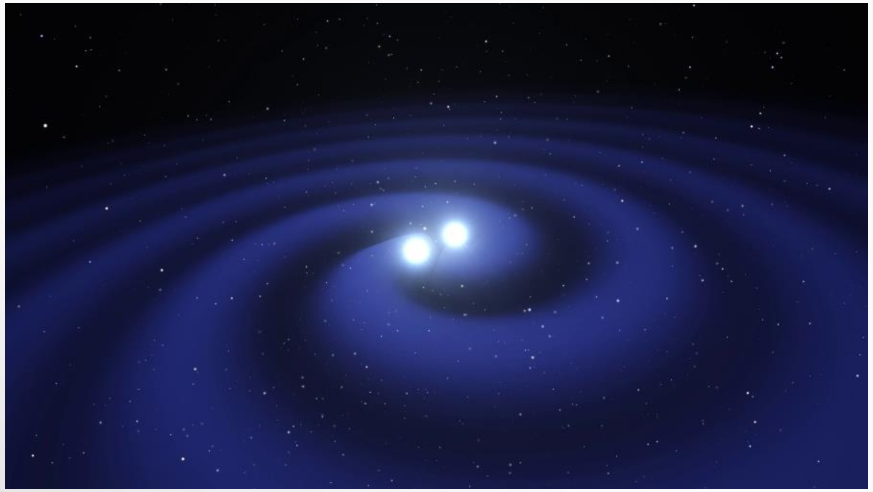
DARK MEDIATOR SPECTROSCOPY WITH BINARY INSPIRALS



Credits: European Space Agency

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OUTLINE

Gravitational Waves from Extreme Mass Ratio Inspirals (EMRIs).

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Fifth force effects in EMRI evolution.

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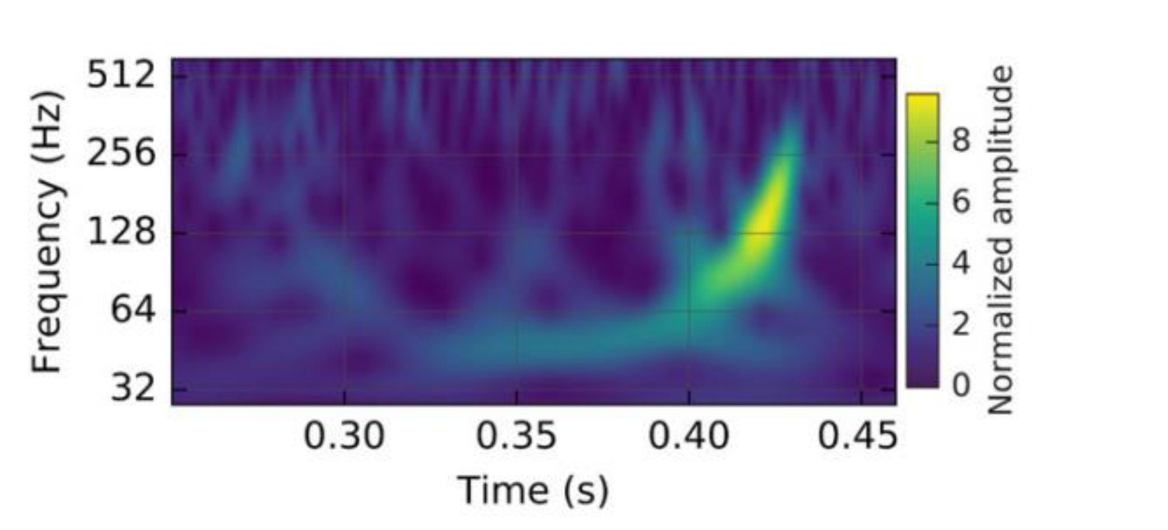
Effect of Dipole Radiation on EMRI.

INTRODUCTION

The first observed gravitational wave (GW) signal, GW150914, was emitted by the inspiral and merger of two black holes.

LIGO has detected several gravitational waves from equal mass binary mergers since then.

Binary inspirals can serve as probes of dark mediators, under the assumption that the spiraling objects accumulate dark charge



Time-frequency plot of GW150914 signal.
Credits: LIGO and VIRGO collaborations

Extreme Mass Ratio Inspirals (EMRI)

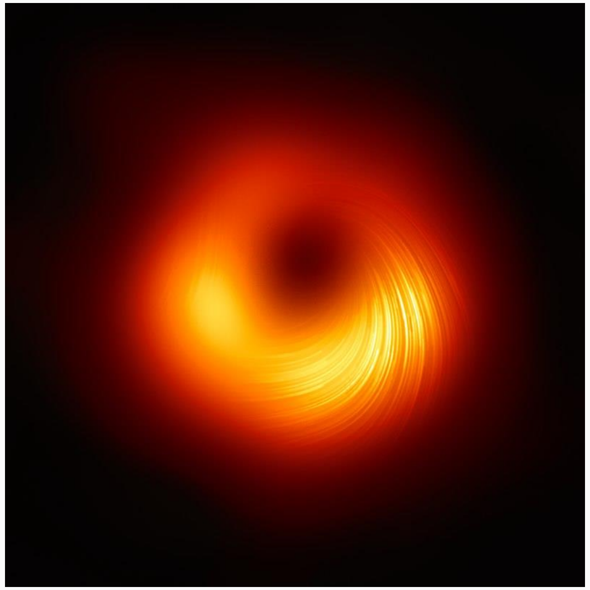
In-spiral of a compact, stellar-mass object into a massive black hole.

Precise Measurement

Few EMRIs per year should be detectable by LISA every year.

Long Observation Time

Significant scientific payoffs will result from LISA's observations of gravitational waves from such inspirals.



A view of M87* black hole in polarised light Event Horizon Telescope

Basic Physics of Mergers

ENERGY RADIATED VIA GRAVITATIONAL WAVES

$$\frac{dE_{GW}}{dt} = \frac{32}{5}\frac{G}{c^5}\mu^2 r^4 \omega^6$$

THIS ENERGY LOSS DRAINS THE ORBITAL ENERGY $E_{orb} = -\frac{G\,M\mu}{2\,r}$.

$$\frac{dE_{orb}}{dt} = -\frac{dE_{GW}}{dt}$$

$$\frac{G\,M\mu}{2\,r^2}\dot{r} = -\frac{32}{5}\frac{G}{c^5}\mu^2 r^4 \omega^6$$

From Kepler's third law, we have $r^3 = \frac{G\,M}{\omega^2}$.

Consequently, the system's evolution as an inspiral is given by

$$\dot{\omega}^3 = \left(\frac{96}{5}\right)^3 \frac{\omega^{11}}{c^{15}} G^5 \mu^3 M^2$$

DARK FORCE

Consider a Yukawa force mediated by a particle of mass m_φ

$$F_{DARK} = \frac{\alpha' Q_1 Q_2}{\Delta^2} e^{-m_\varphi \Delta}(1 + m_\varphi \Delta)$$

Here,

α' = Coupling Constant of the Dark Force

m_φ = mass of the dark force mediator

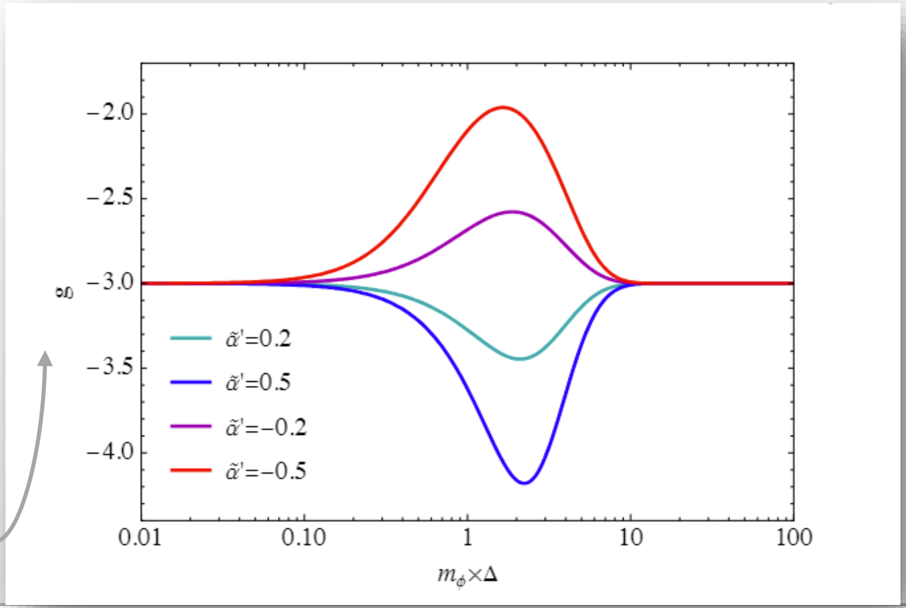
Δ = separation between the two objects

Q_i = dark charge on i^{th} object.

In presence of fifth force, evolution of orbital frequency is given by

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

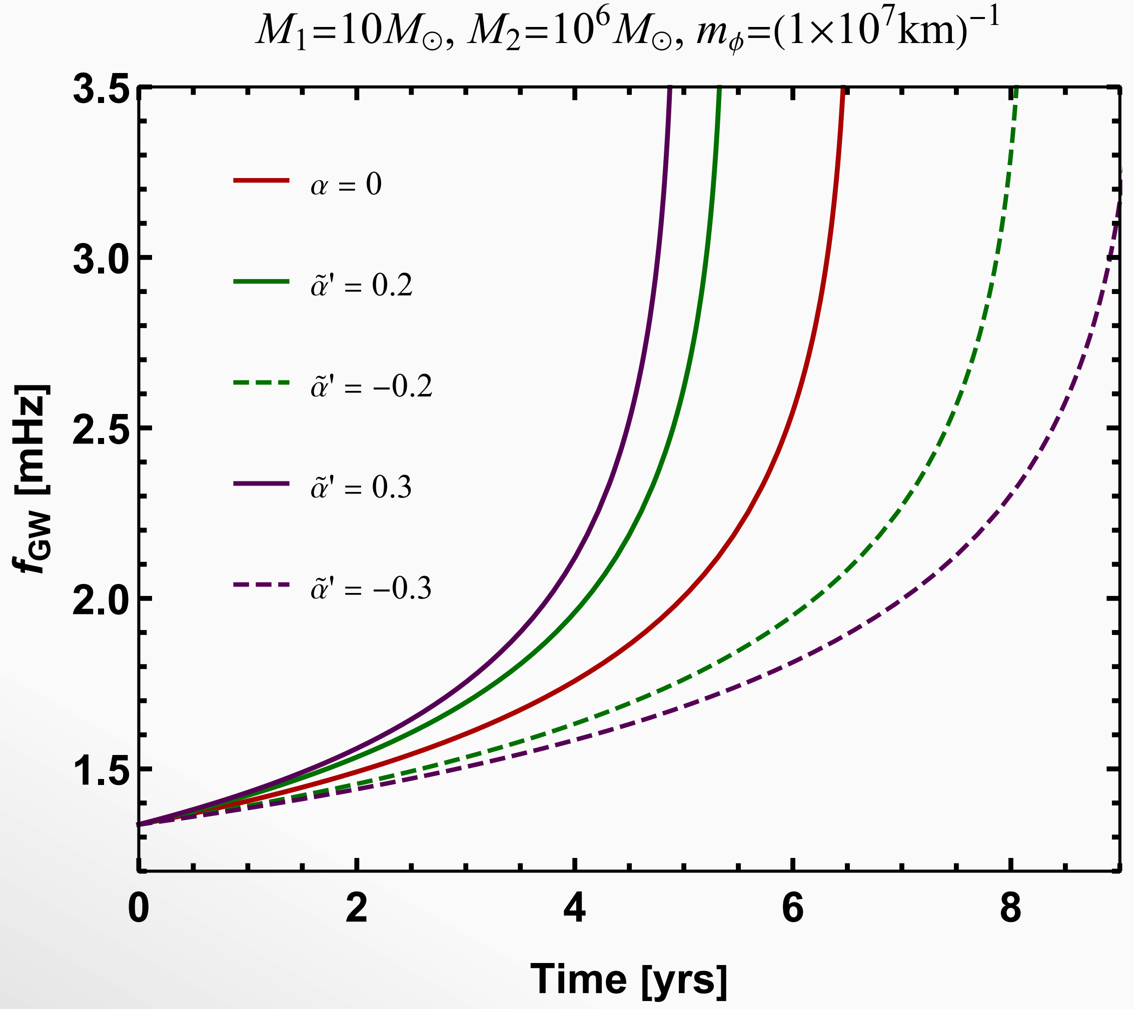
$$\tilde{\alpha}' = \frac{\alpha' Q_1 Q_2}{G M_1 M_2}$$



The time evolution of orbital frequency is

$$\frac{d\omega}{dt} = -\frac{32}{5} G\mu\Delta^2\omega^5 g(\alpha', m_\varphi, \Delta)$$

$$g = -\frac{3 + \alpha' e^{-m_\varphi \Delta}\left(3 + m_\varphi \Delta(3 + m_\varphi \Delta)\right)}{1 + \alpha' e^{-m_\varphi \Delta}\left(1 + m_\varphi \Delta(1 - m_\varphi \Delta)\right)}$$



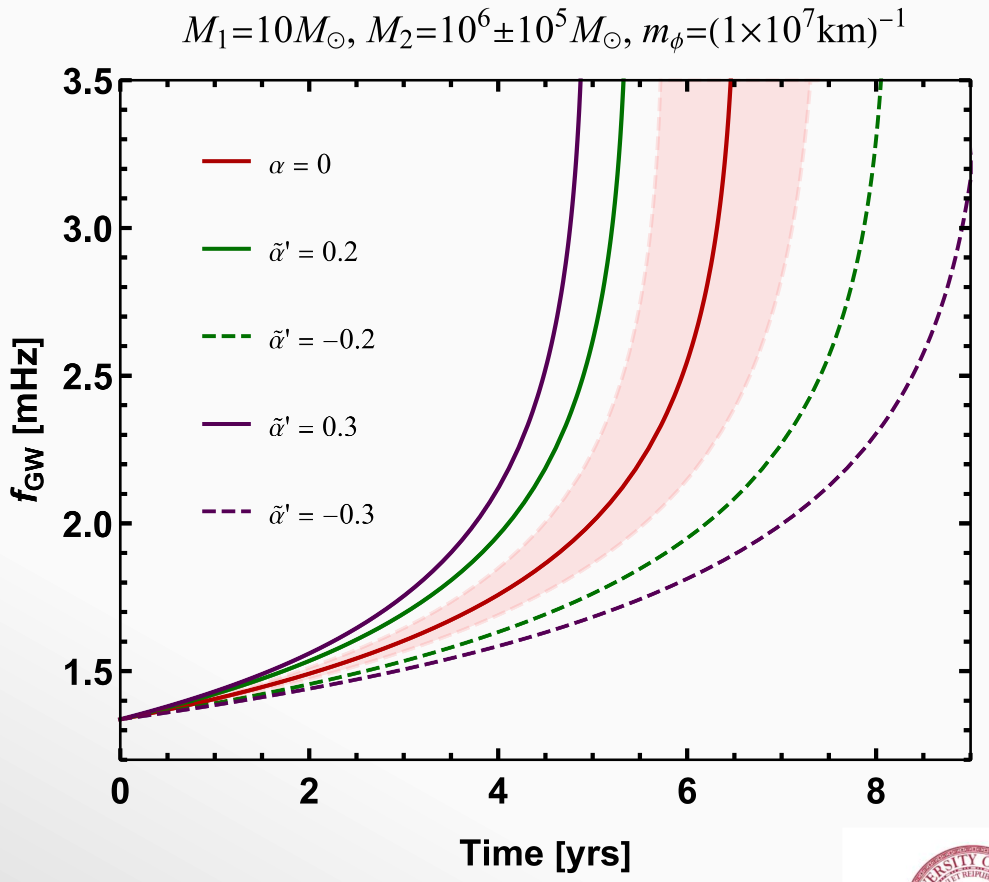
DISTINCTION FROM PURE GRAVITY

The effect of the fifth force can be mimicked.by re-scaling both masses of the inspiral system.

However, the mass of supermassive black holes can be measured well by other means, up to some uncertainty. We assume a 10% uncertainty in SMBH mass measurement in this study.

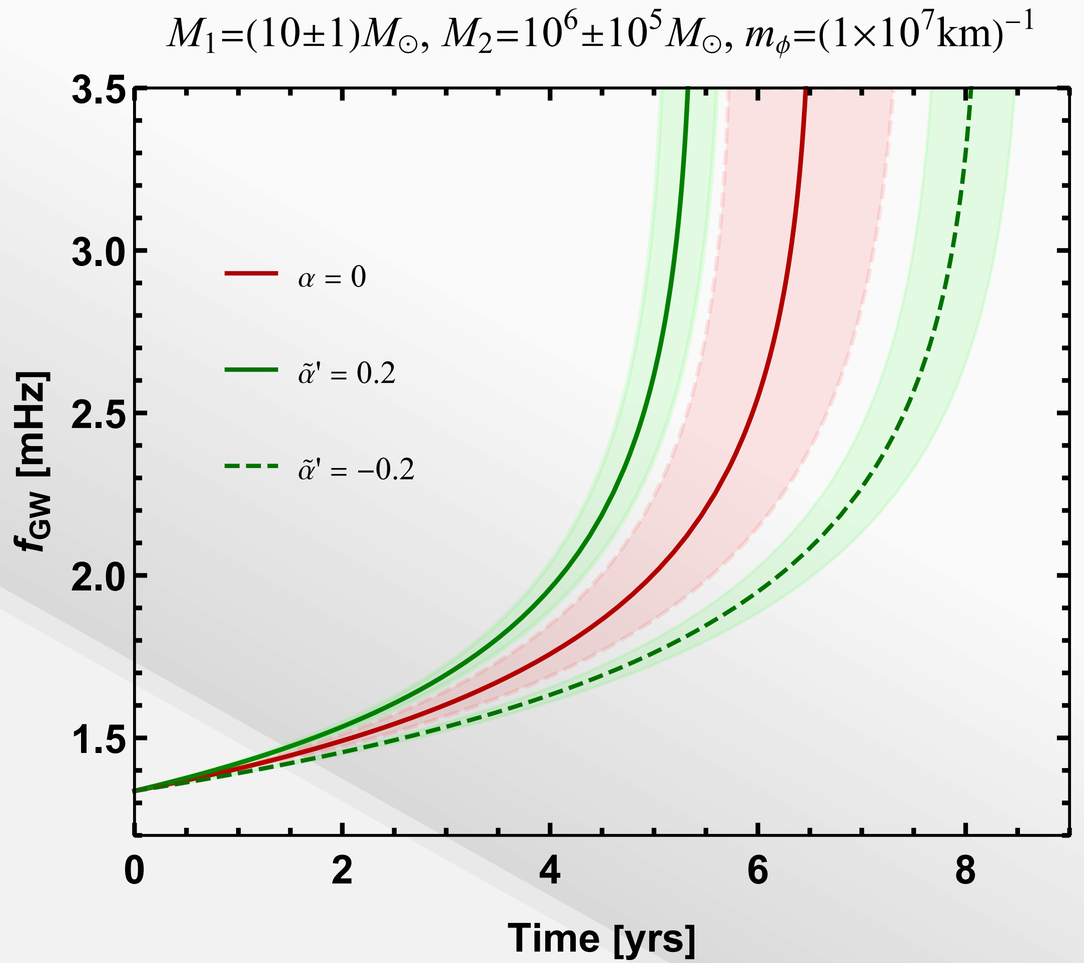
$$M_{uncertain} = 10\%$$

$$\Delta^3 = \frac{G(M \pm 0.1M)}{\omega^2}\left[1 + \tilde{\alpha}' e^{-m_\varphi \Delta}(1 + m_\varphi \Delta)\right]$$



A population study of compact objects near SMBH estimates an uncertainty of 5% in the mass of spiraling objects.

$$\frac{d\omega}{dt} = -\frac{32}{5} G(\mu + 0.1\mu)\Delta^2\omega^5 g(\alpha', m_\varphi, \Delta)$$



STRAIN

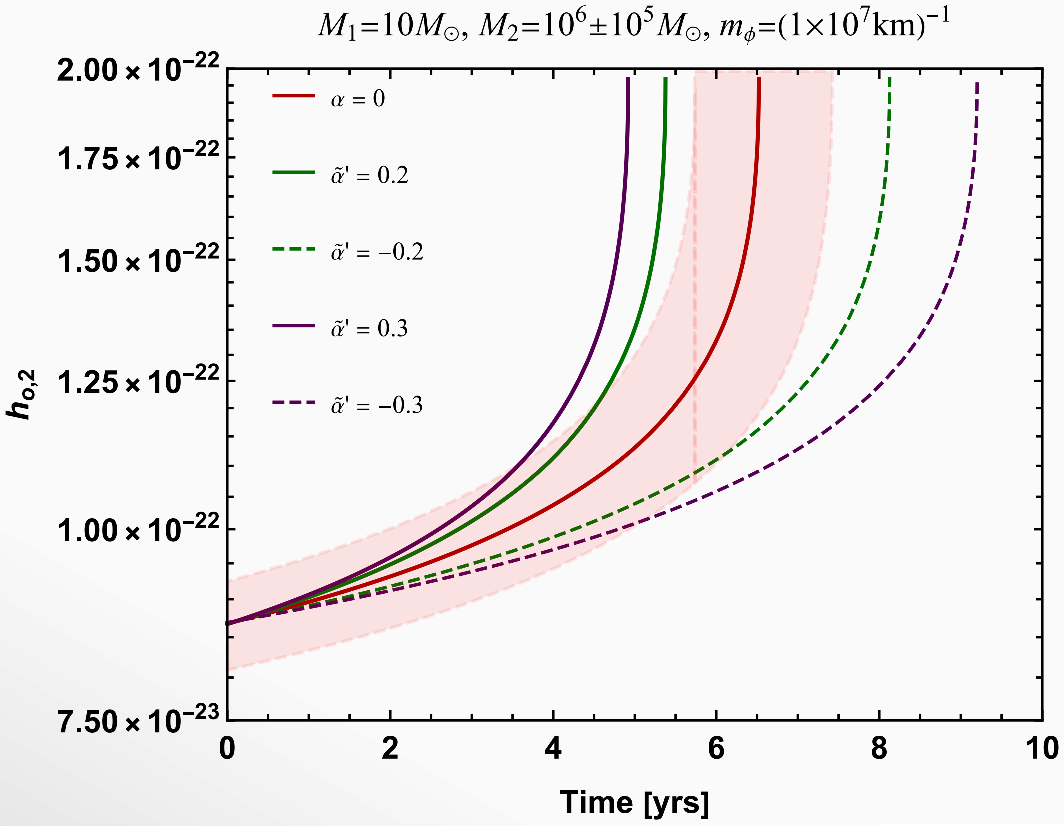
The rms amplitude of the gravitational wave emitted for the dominant, m = 2, radiation is

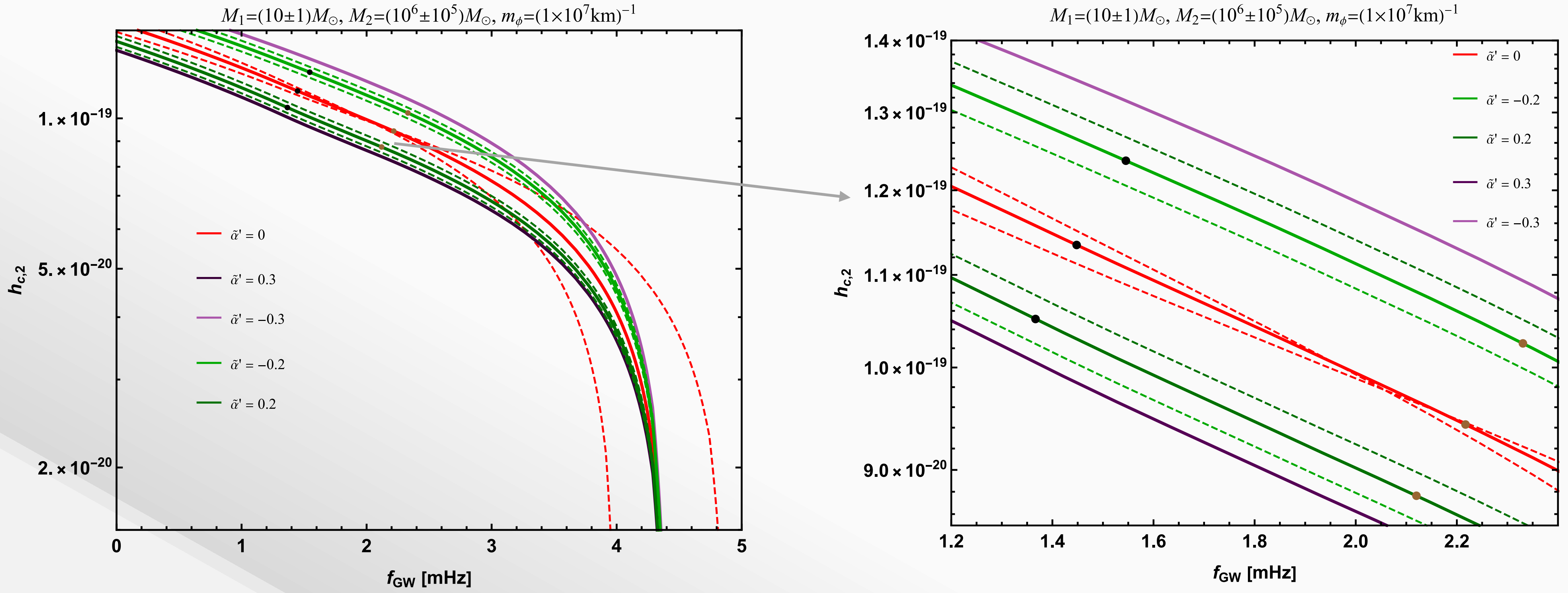
$$h_{o,2} = \frac{3.6 \times 10^{-23}}{r_0/1Gpc}\left(\frac{\mu}{M_\odot}\right)\left(\frac{M}{100M_\odot}\right)^{2/3}\left(\frac{f_2}{100Hz}\right)^{2/3}\mathcal{H}_{o,2}$$

Here

r_0 is the distance from EMRI.

$\mathcal{H}_{o,2}$ is the relativistic correction to the amplitude





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

Is the characteristic amplitude for the waves

DIPOLE RADIATION

The radiation of ultra-light mediator particles may also contribute to the energy loss during the inspiral.

The power radiated by vector mediators is

$$\frac{dE_{dipole}}{dt} = \frac{2}{3}\alpha' \mu^2 \gamma^2 \omega^4 \Delta^2 \times Re\left[\sqrt{1-\left(\frac{m_{med}}{\omega}\right)^2}\left[1+\frac{1}{2}\left(\frac{m_{med}}{\omega}\right)^2\right]\right]$$

Here

$$\gamma = \frac{Q_1}{M_1} - \frac{Q_2}{M_2}$$

Thus, dipole radiation is only possible if the two objects have different dark charge-over-mass ratio.

The rate of change of orbital frequency is

$$\frac{d\omega}{dt} = \frac{96}{5}(GM_c)^{\frac{5}{3}}\omega^{\frac{11}{3}} + \frac{1}{2}G(M_1+M_2)\beta'\omega^3 \times \mathrm{Re}\left[\sqrt{1-\left(\frac{m_{med}}{\omega}\right)^2}\left[1+\frac{1}{2}\left(\frac{m_{med}}{\omega}\right)^2\right]\right]$$

$$\beta' = \frac{4\alpha'\gamma^2 M_1 M_2}{G(M_1+M_2)^2}$$

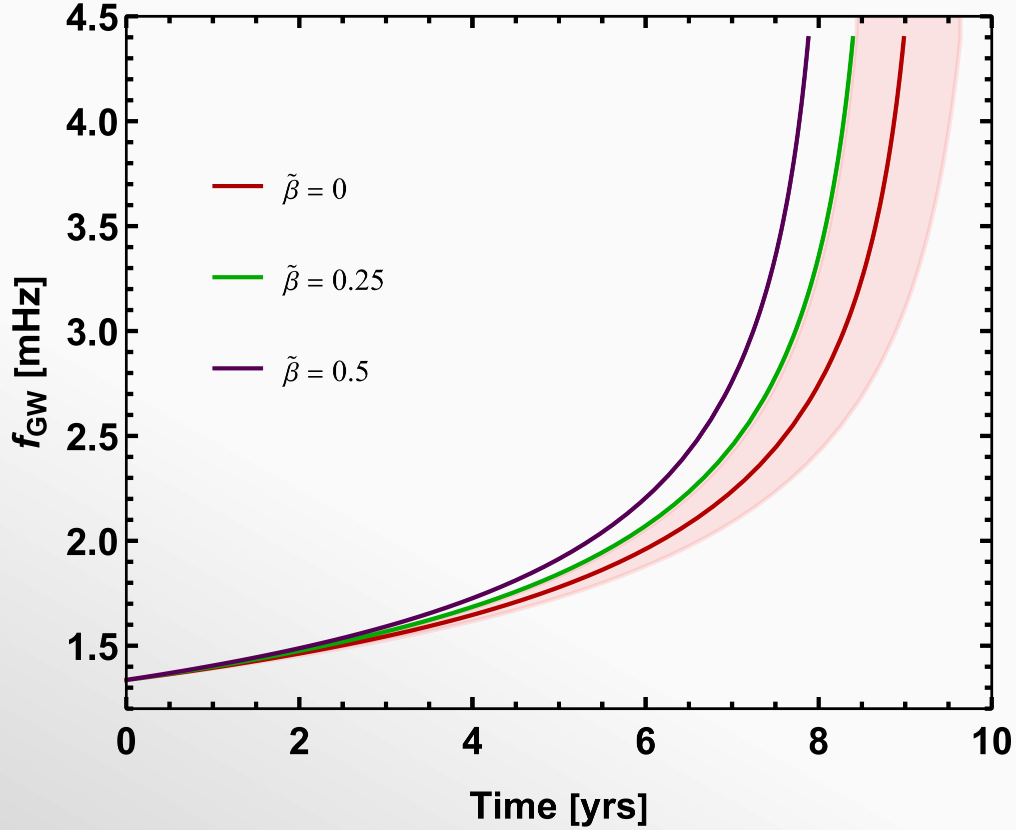
$$\beta' = \tilde{\beta}\frac{M_1}{M_2}$$

$\tilde{\beta}$ parameterizes the magnitude of the radiation effect relative to gravity

The dipole radiation of EMRI is suppressed by the mass ratio

$$\beta' \propto \frac{M_1}{M_2} \sim 10^{-5}$$

M_1=10$M_\odot$, M_2=$10^6 M_\odot$, m_ϕ=10^{-18}eV



CONCLUSION

EMRI system can be used for mediator spectroscopy measurement.

EMRI is sensitive to range of mediator masses. The best sensitivity arises for mediator mass which is comparable to the separation of the EMRI.

EMRI breaks the degeneracy of chirp mass of the binary system, which usually limits the application of equal-mass inspiral systems to detect long range dark force.

Dipole radiation can be an effective energy loss mechanism for an EMRI system if only one of the objects is charged.

THANK YOU