Tidal heating as probe of black hole horizon

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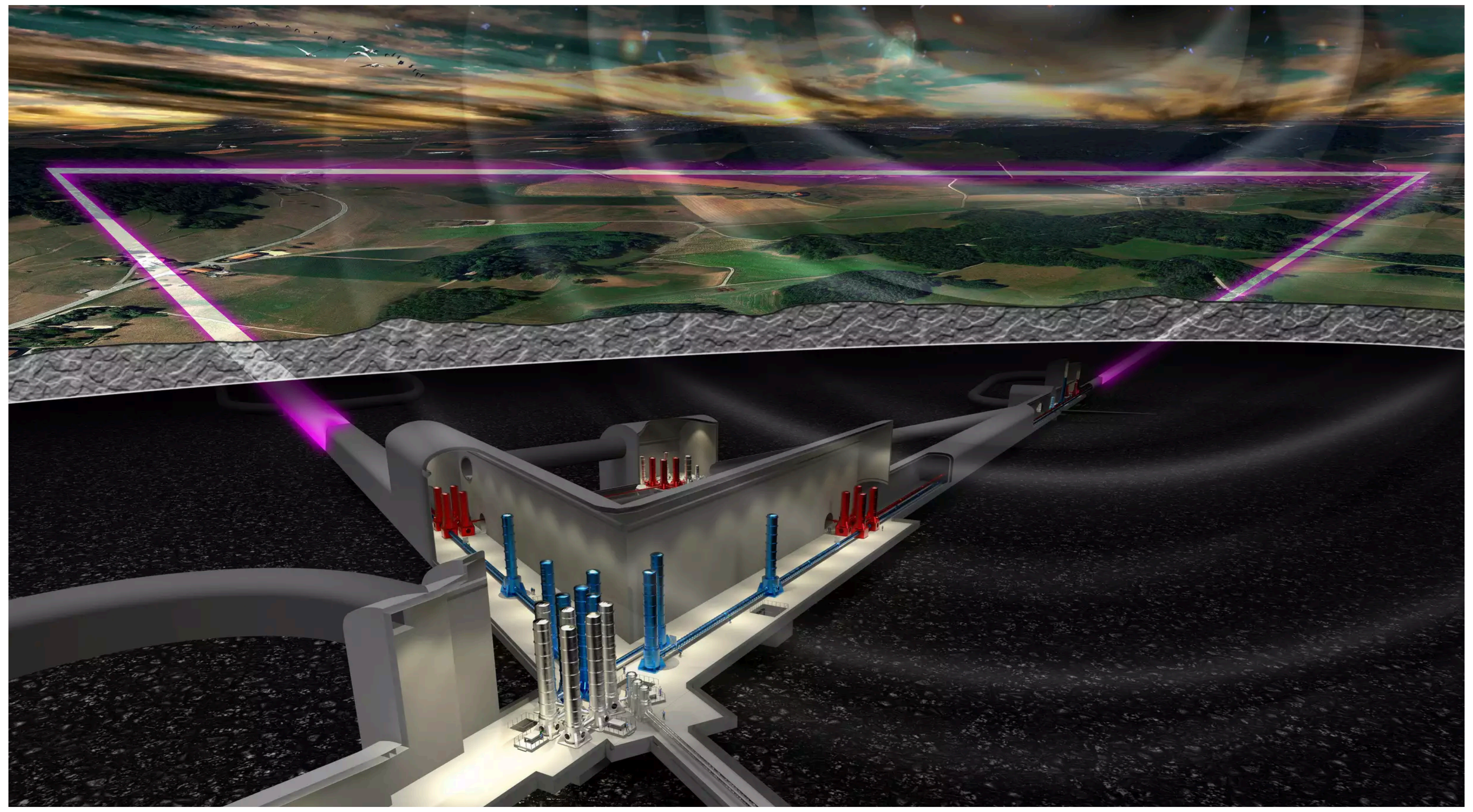
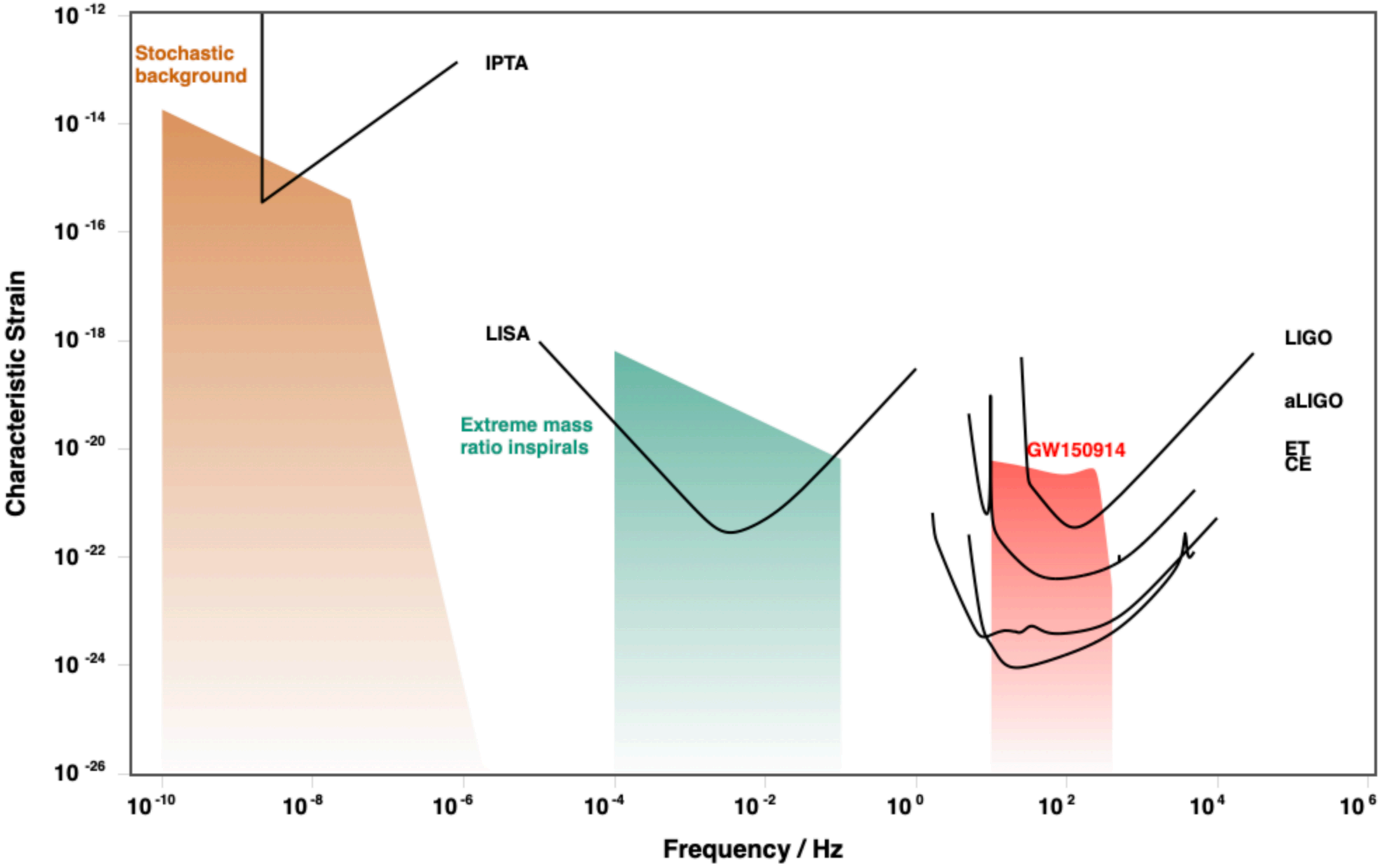
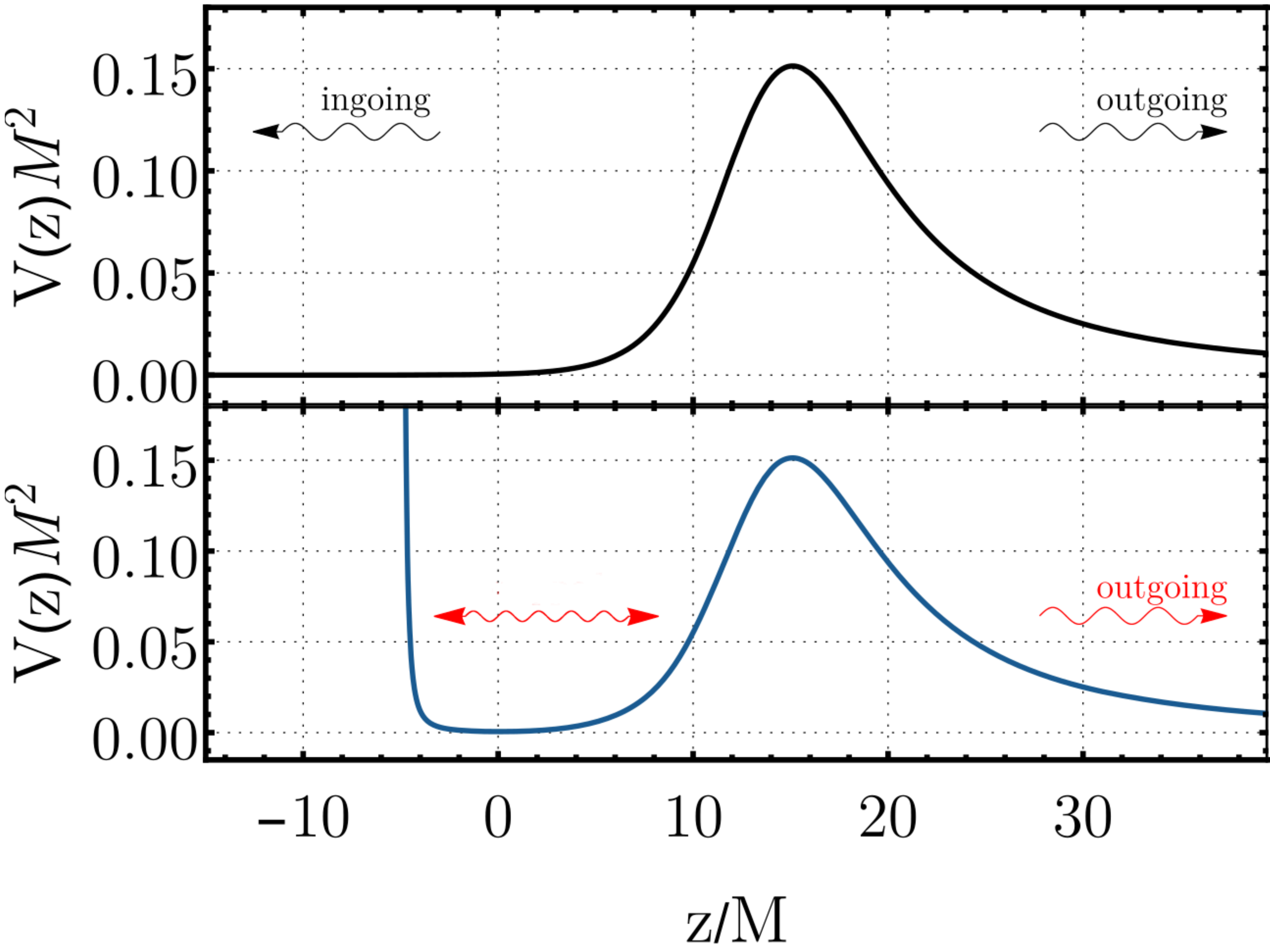
- Current GBDs are being upgraded.
- New detectors Cosmic Explorer, Einstein telescope, and space based LISA is also coming.
- These will be more sensitive detectors.
- This opportunity can be used to test GR.
- Also the nature of the compact objects.
- Exotic compact object (ECO), quantum effects near BH.



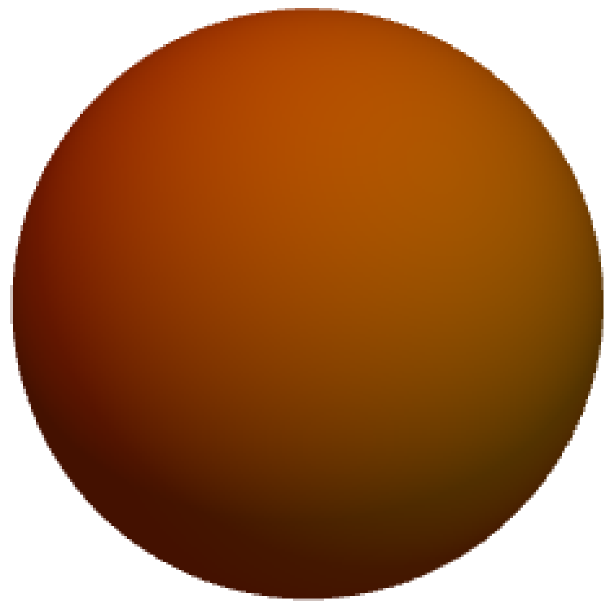


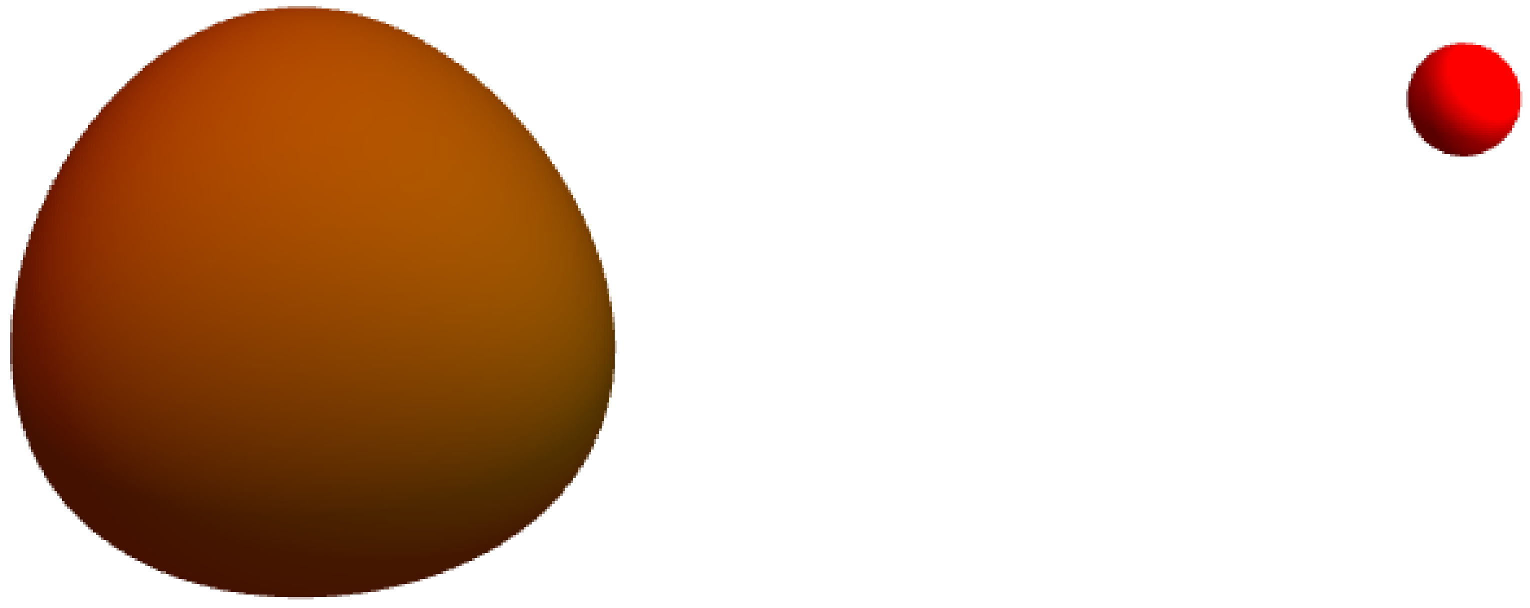
- Classical BH's horizon is perfect absorber due to causality.
- Absence (modification) of this implies imperfect absorption.
- Measuring nonzero reflectivity of compact object surface will be signature of deviation.
- Tidal heating is one such effects.



- Living Rev.Rel. 22 (2019) 1, 4

- Components in a binary feel each others’ tidal fields (strongly in the late inspiral).
- If the bodies are(at least partially) absorbing, these backreact on the orbit, exchanging energy and angular momentum with the orbit.
- This effect is called tidal heating J. B. Hartle, PRD8, 1010 (1973), S. A. Hughes, PRD64,064004 (2001).
- In stars this absorption comes due to viscous heating in the material.
- In BHs it caused by the increase in the BH mass.

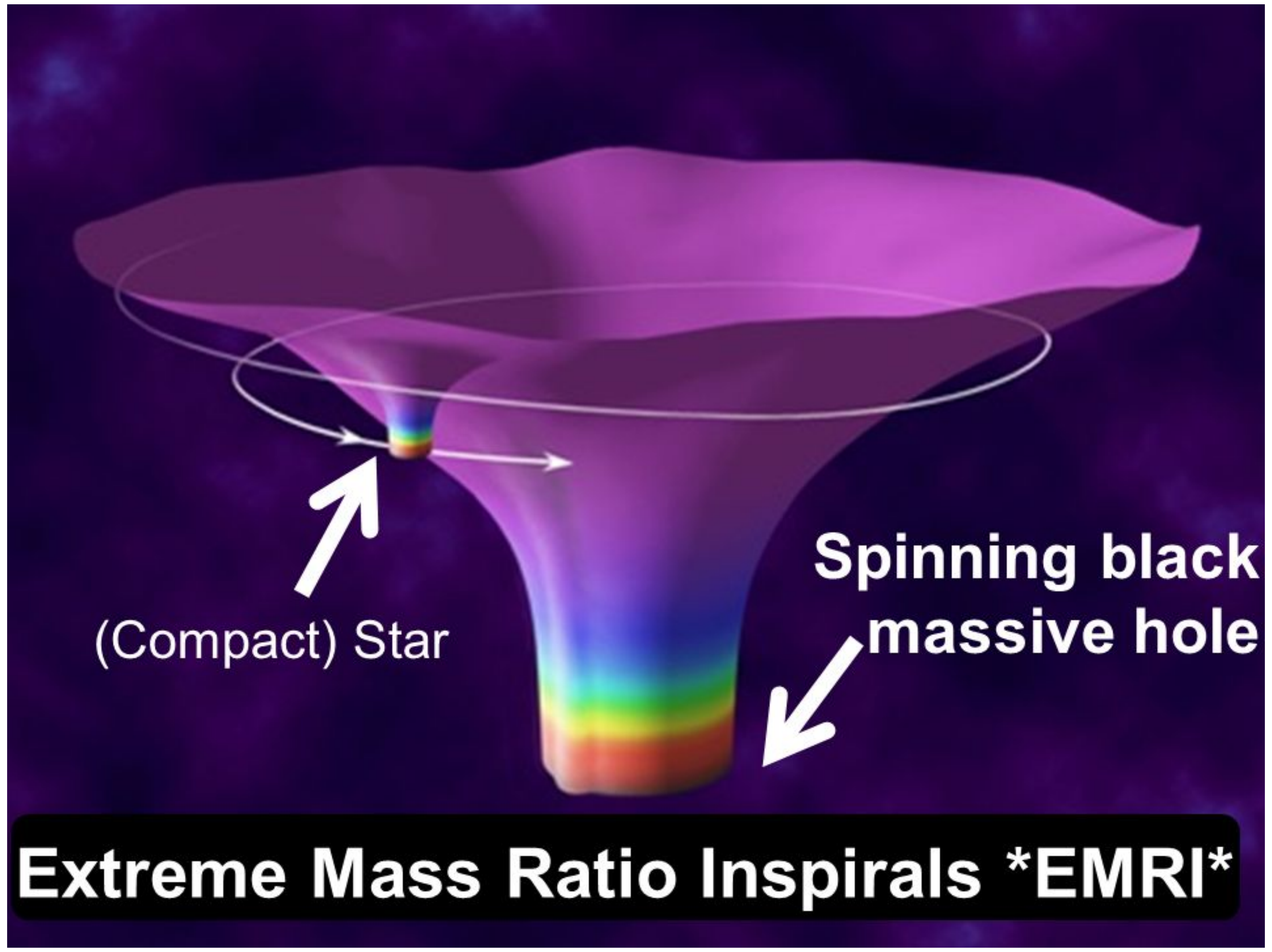


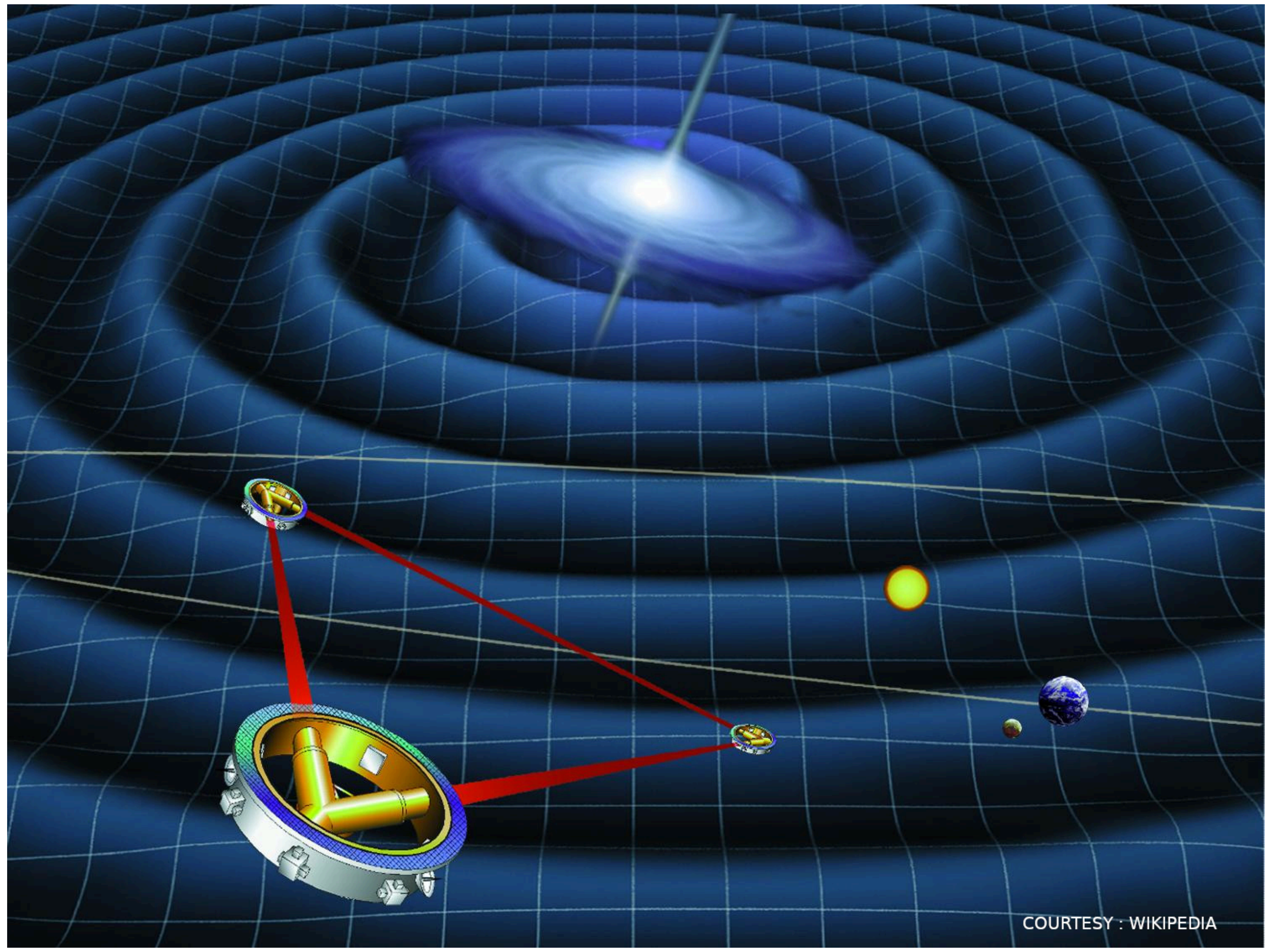


- Expression for TH of a star and BH can be brought into same footing with viscosity coefficient ($\nu_{BH} \sim M$). K. Glampedakis+ PRD89,024007(2014)
- For NS, $$\nu_{NS} = 10^4 (\frac{\rho}{10^{14} gmcm^{-3}})^{\frac{5}{4}} (\frac{10^8 K}{T})^2 cm^2 s^{-1}$$
- $$\nu_{BH} = 8.6 \times 10^{14} (\frac{M}{M_\odot}) cm^2 s^{-1}$$
- Even for $M_{BH} \sim M_{NS}$, $\nu_{NS} \ll \nu_{BH}$, resulting in ignorable TH compared to BH.
- Distinguish BH and NS in this range can change NS mass upperbound and BH mass lower bound. SD, Phukon, Bose PRD 104 (2021) 8, 084006

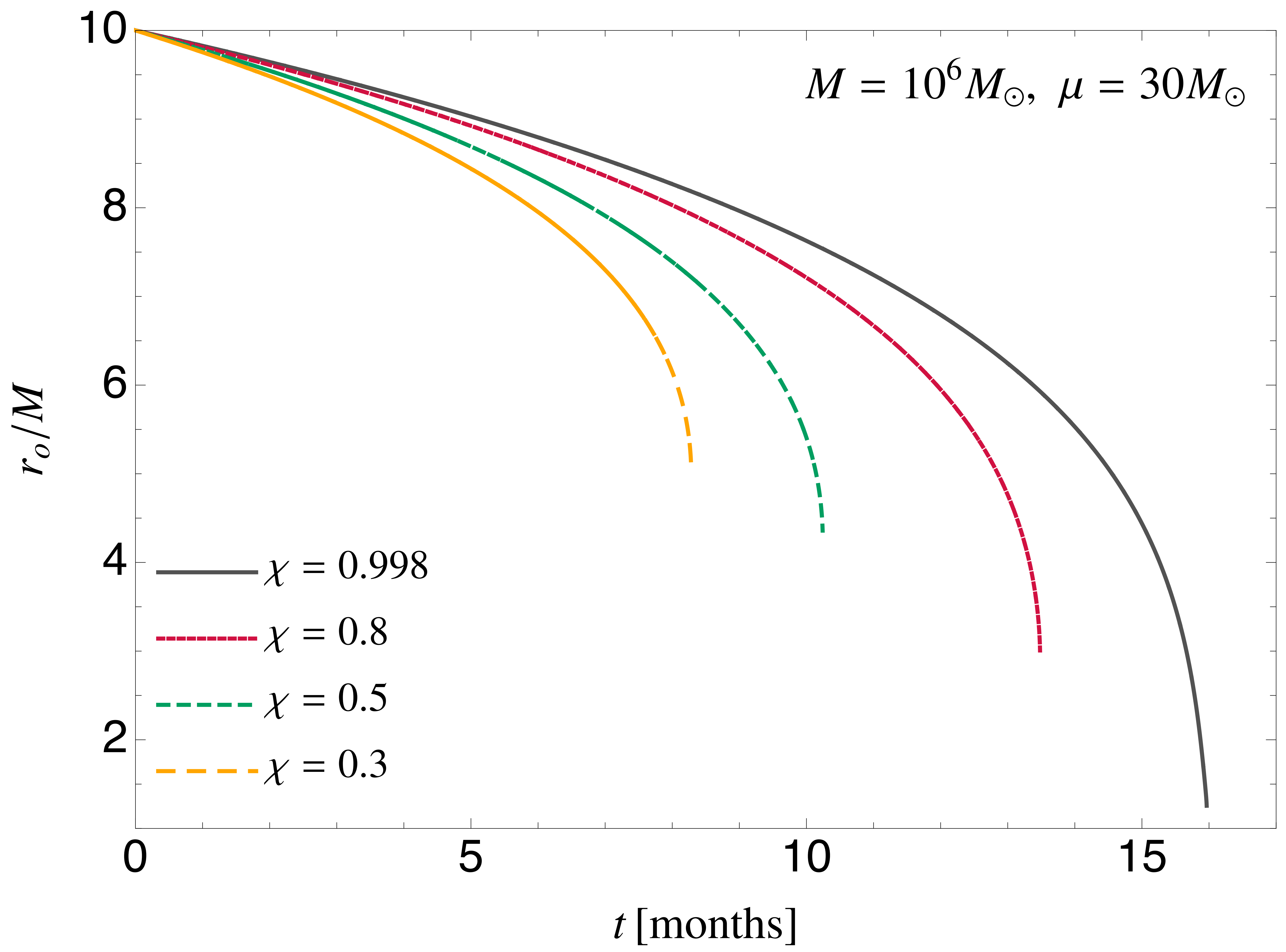
TH in EMRI

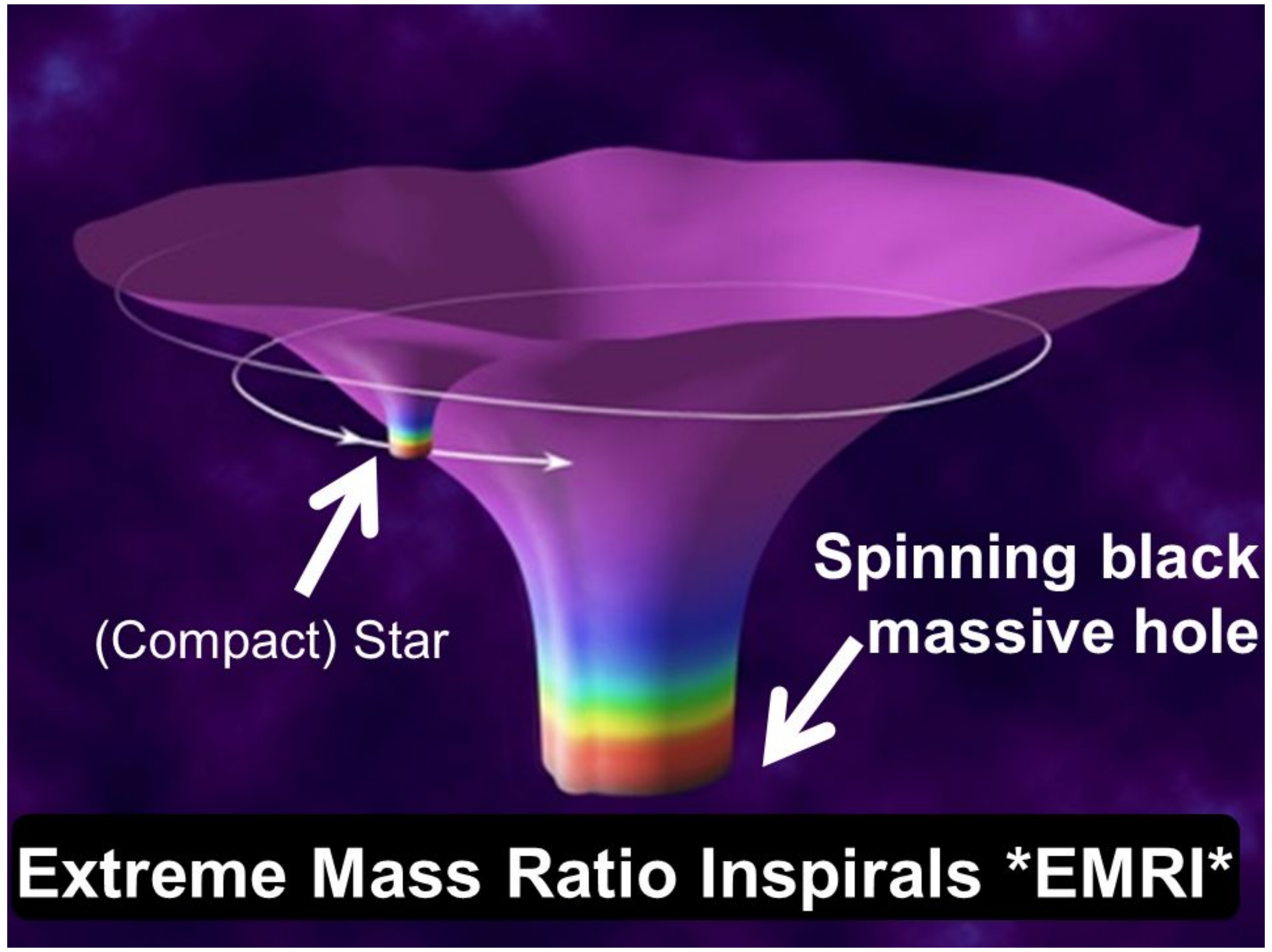
- Center of a galaxy can host SMBH of mass $M \sim 10^6 - 10^7 M_\odot$.
- Stellar mass stars, BHs get captured in inspiral around such SMBHs.
- Mass ratio $\leq 10^{-4}$.
- Frequency of EMRI $\frac{c^3}{50MG} \leq f \leq \frac{c^3}{MG}$.
- For $M \sim 10^6 M_\odot$, $.004Hz \leq f \leq .2Hz$.
- Perfect for LISA$(10^{-4} - .1)Hz$





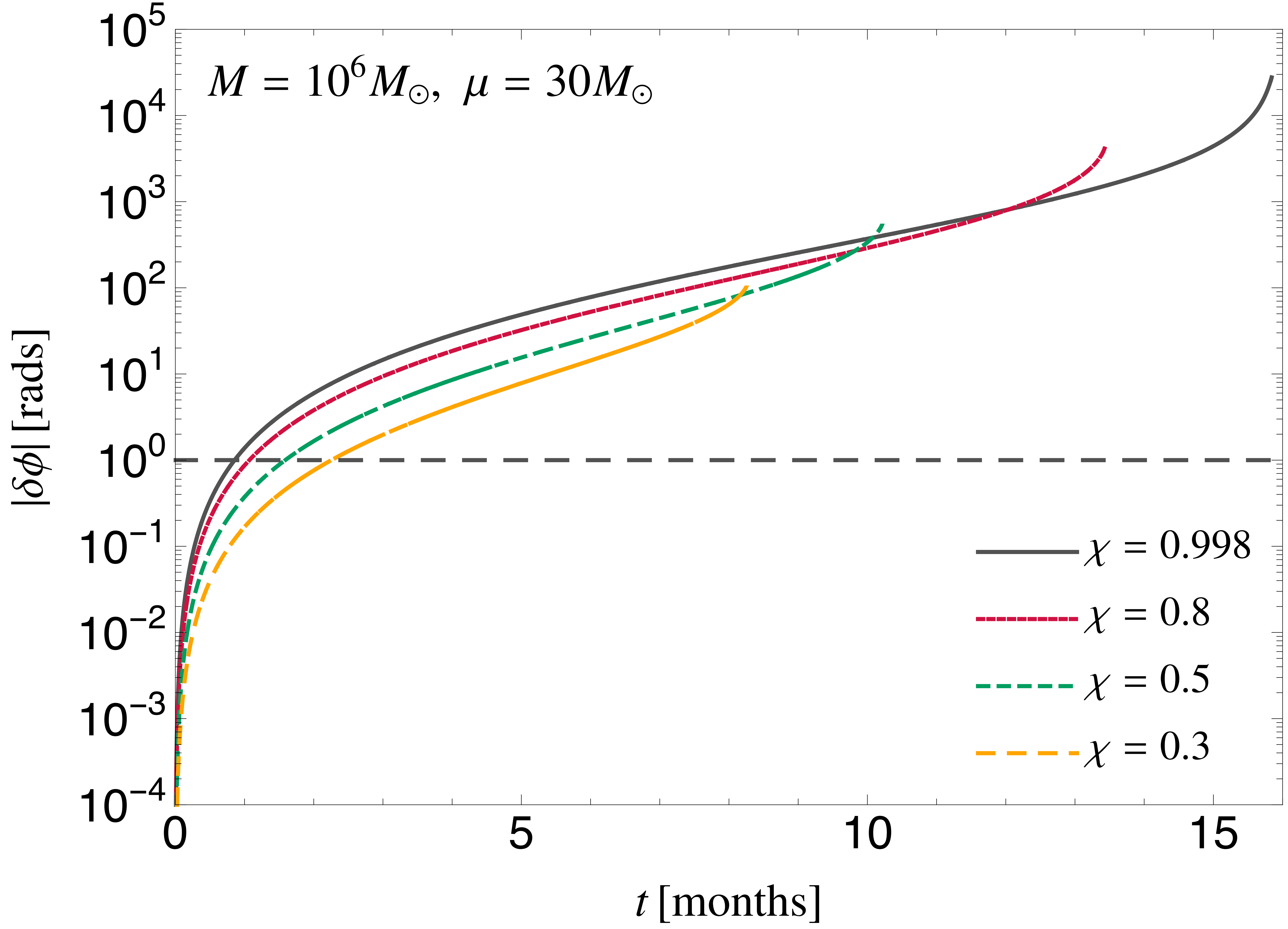
- We will focus on EMRI first, where a stellar mass $\sim 10 - 100 M_\odot$ Inspirals around SMBH of $\sim 10^5 - 10^7 M_\odot$, observable in LISA.
- Hence we calculate perturbation around BH by a small particle.





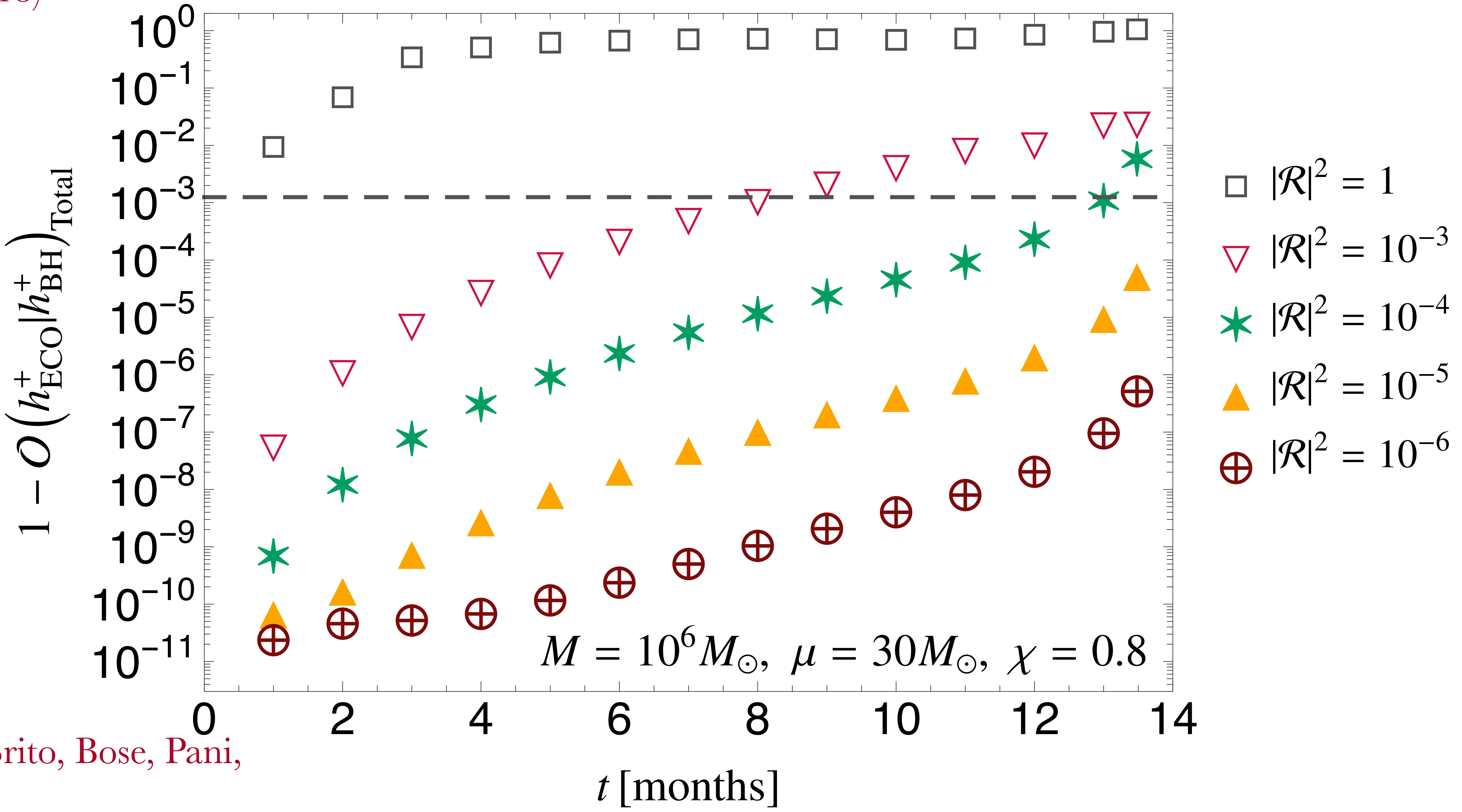
- ψ_4 is the perturbation quantity satisfying Teukolsky equation.
- From ψ_4 GW waveform, energy fluxes at infinity and also the flux at horizon can be calculated.

- Circular orbit



- PRD.101.044004 SD, Brito, Bose, Pani, Hughes.

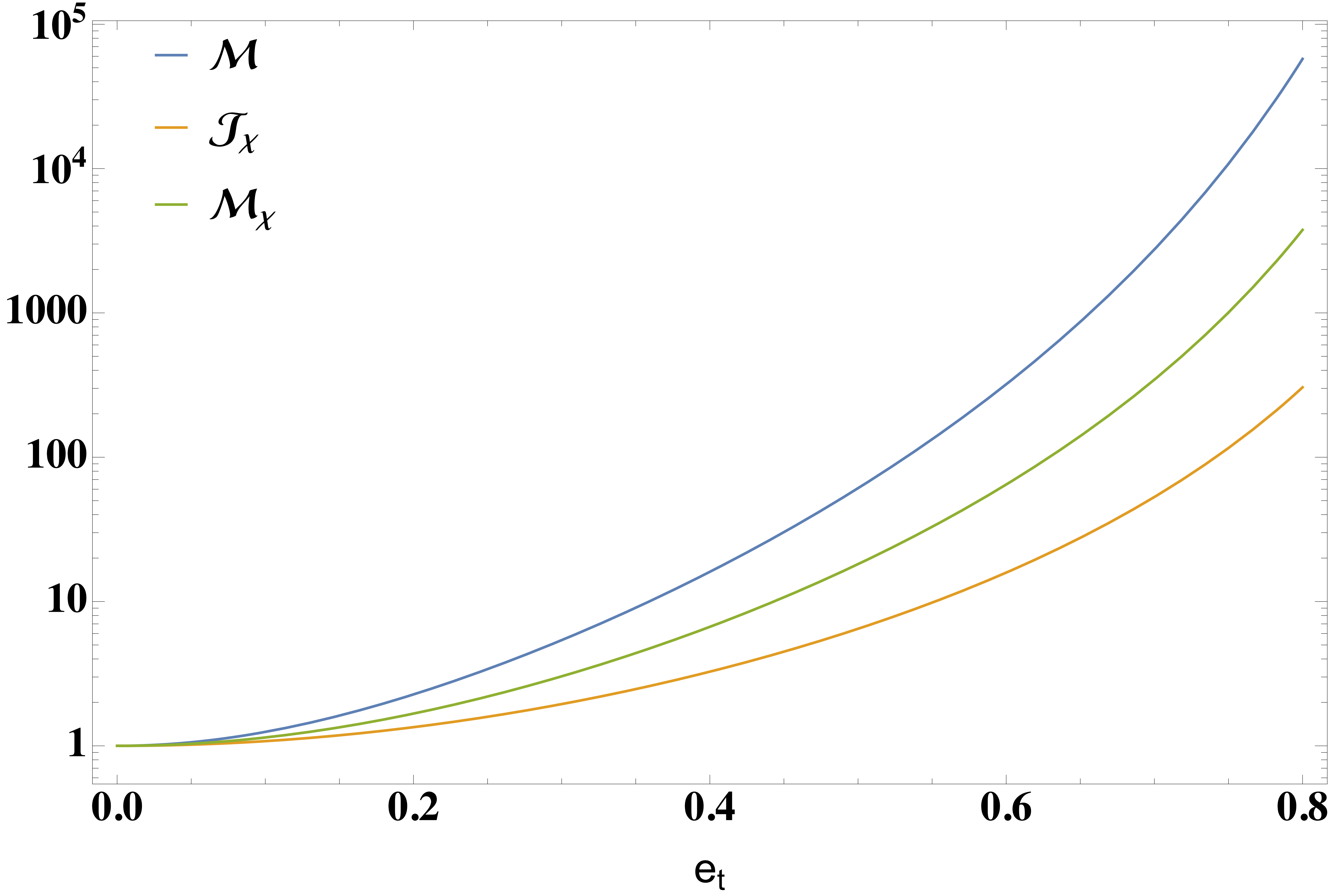
- For ECO, (SD, PRD.102.064040)
- Circular orbit
- $\dot{E}_{\rm ECO} = (1 - |\mathscr{R}|^2)\dot{E}_H + \mathcal{O}(\epsilon)$
- $\mathscr{R}$ is reflectivity of the ECO (QBH). SD, S. Bose, PRD99,084001 (2019), Maselli+, PRL120,081101(2018)



- PRD.101.044004 SD, Brito, Bose, Pani, Hughes

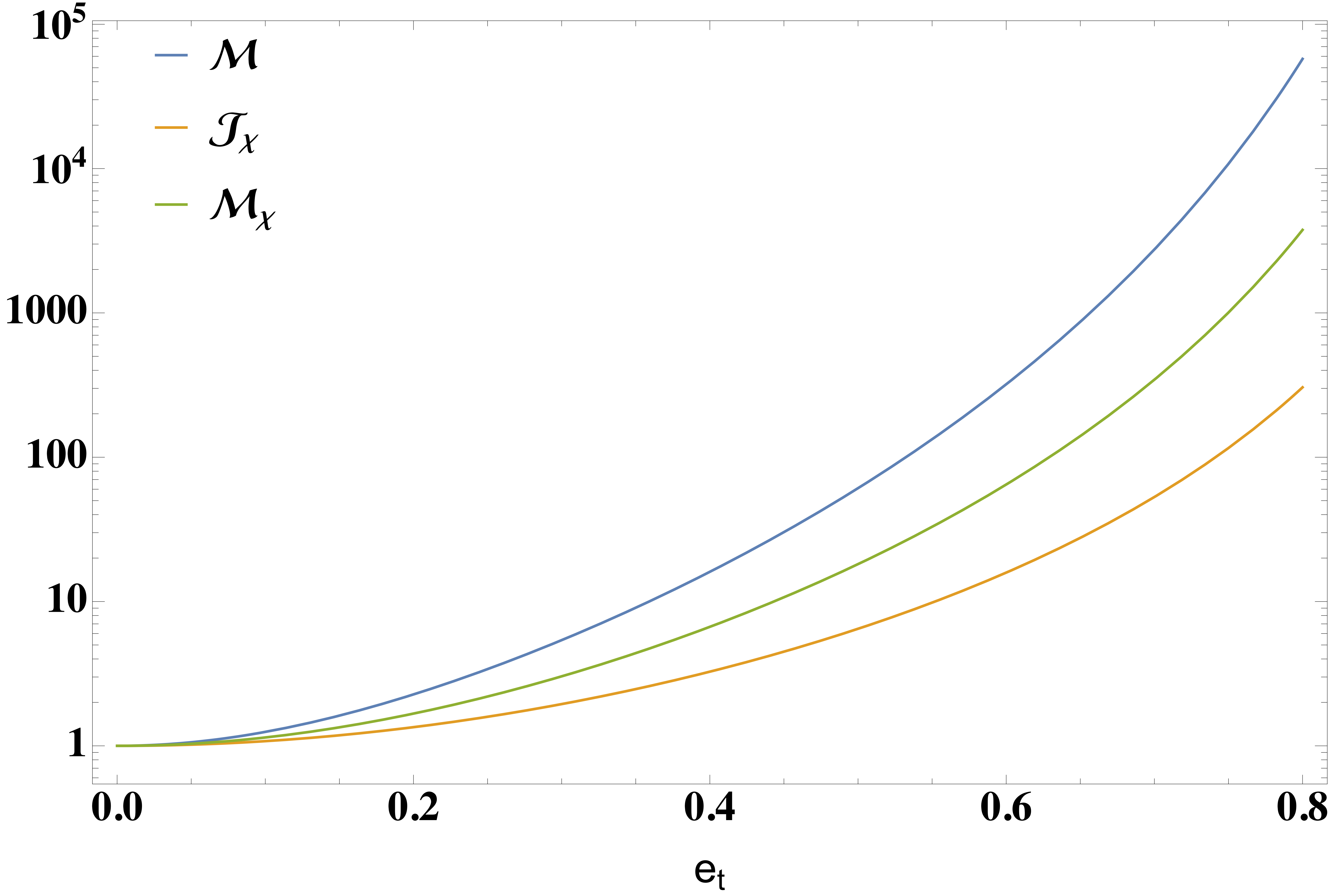
TH in eccentric orbits

- $\langle \dot{m} \rangle = \dot{m}_{circ} \mathscr{M}(e_t)$, $\langle \dot{m} \rangle_\chi = \dot{m}_{circ,\chi} \mathscr{M}_\chi(e_t)$, $\langle \dot{J} \rangle_\chi = \dot{J}_{circ,\chi} \mathscr{J}_\chi(e_t)$ SD, EPJC (2024)



- $\langle \dot{m} \rangle = \dot{m}_{circ} \mathscr{M}(e_t)$, $\langle \dot{m} \rangle_\chi = \dot{m}_{circ,\chi} \mathscr{M}_\chi(e_t)$, $\langle \dot{J} \rangle_\chi = \dot{J}_{circ,\chi} \mathscr{J}_\chi(e_t)$

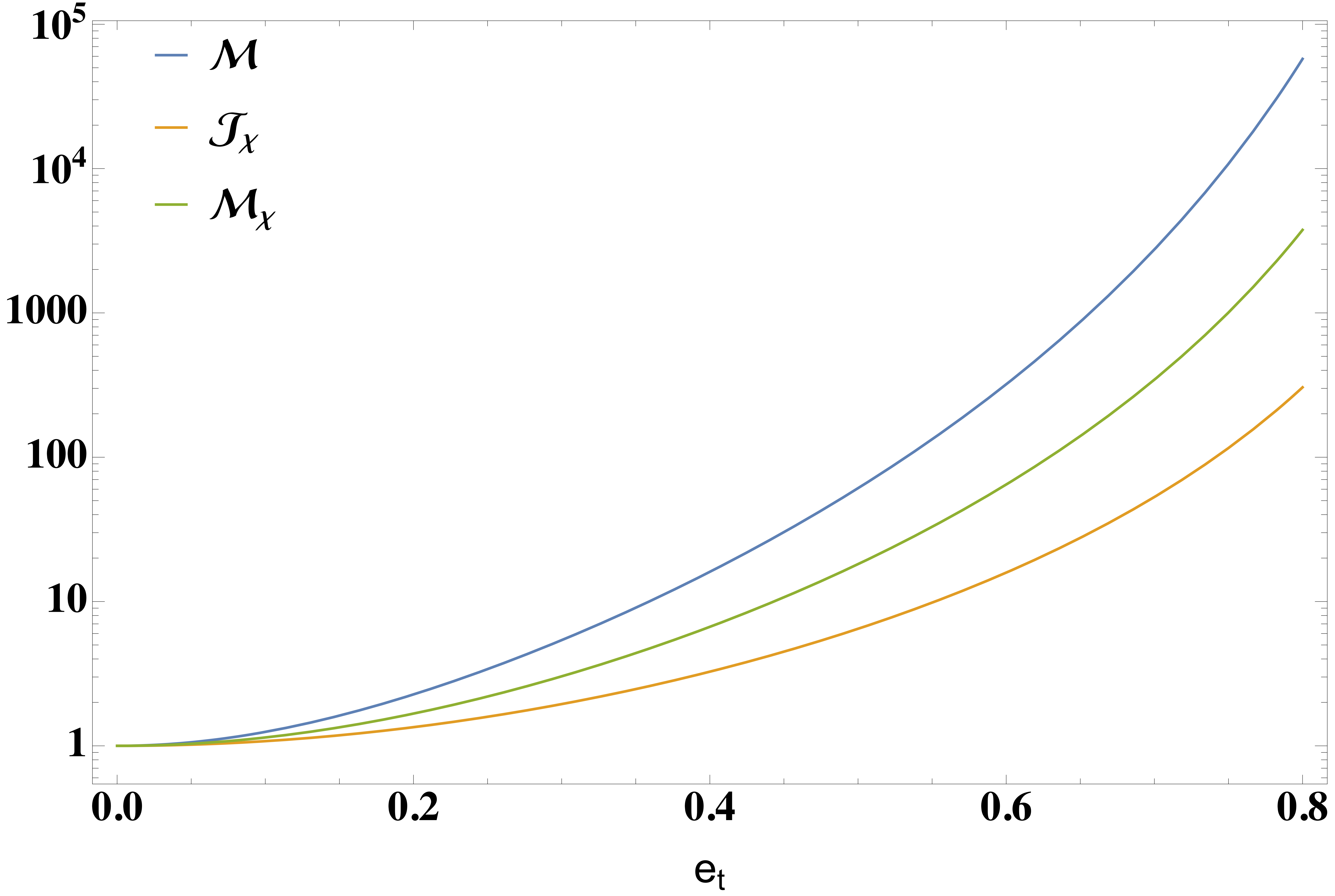
SD, EPJC (2024)



$$\langle \dot{m} \rangle \propto \sim \Omega(\Omega_H - \Omega)$$

$$\Omega \sim v^3$$

- $\langle \dot{m} \rangle = \dot{m}_{circ}\mathscr{M}(e_t)$, $\langle \dot{m} \rangle_\chi = \dot{m}_{circ,\chi}\mathscr{M}_\chi(e_t)$, $\langle \dot{J} \rangle_\chi = \dot{J}_{circ,\chi}\mathscr{J}_\chi(e_t)$ SD, EPJC (2024)

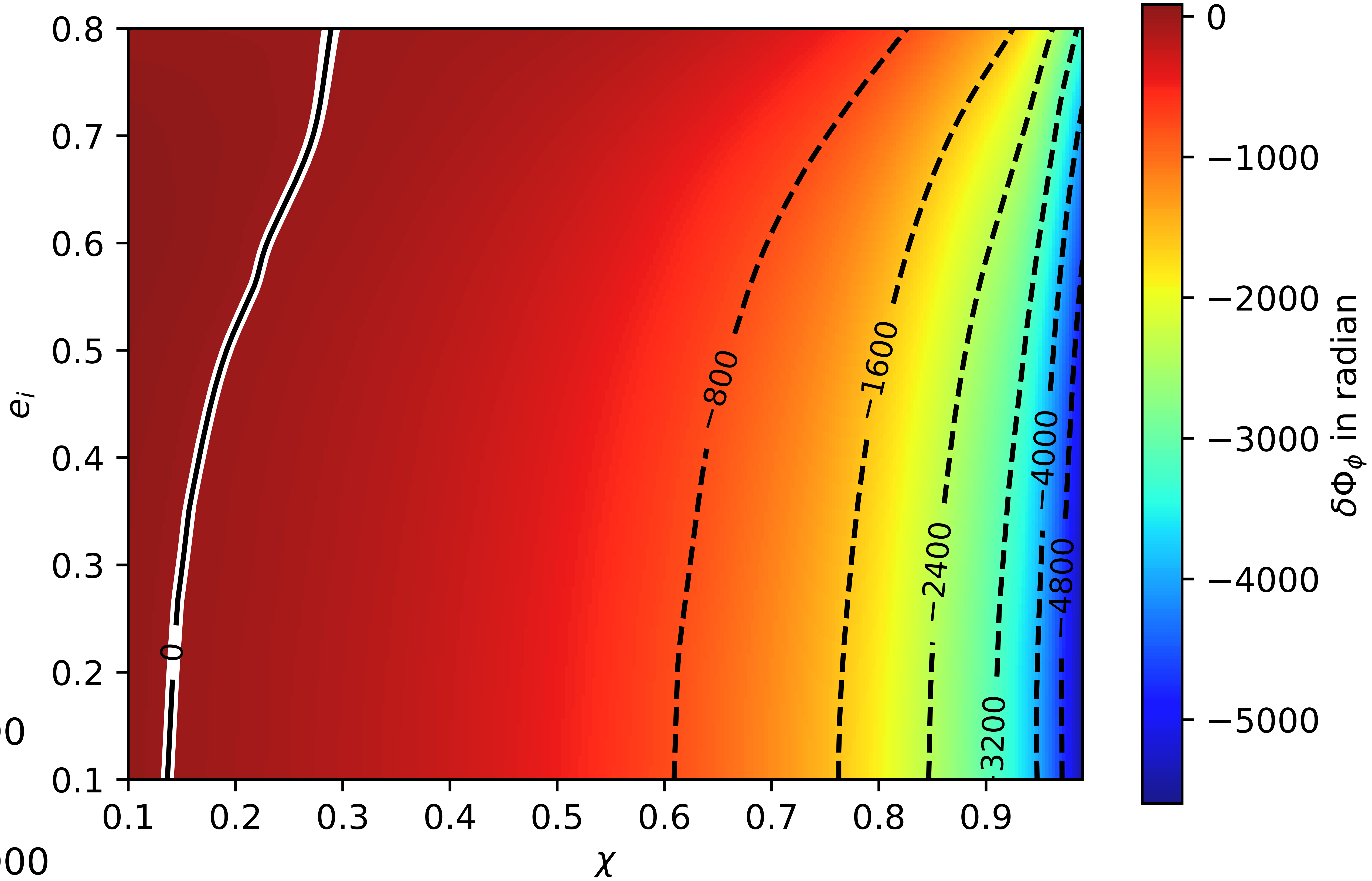


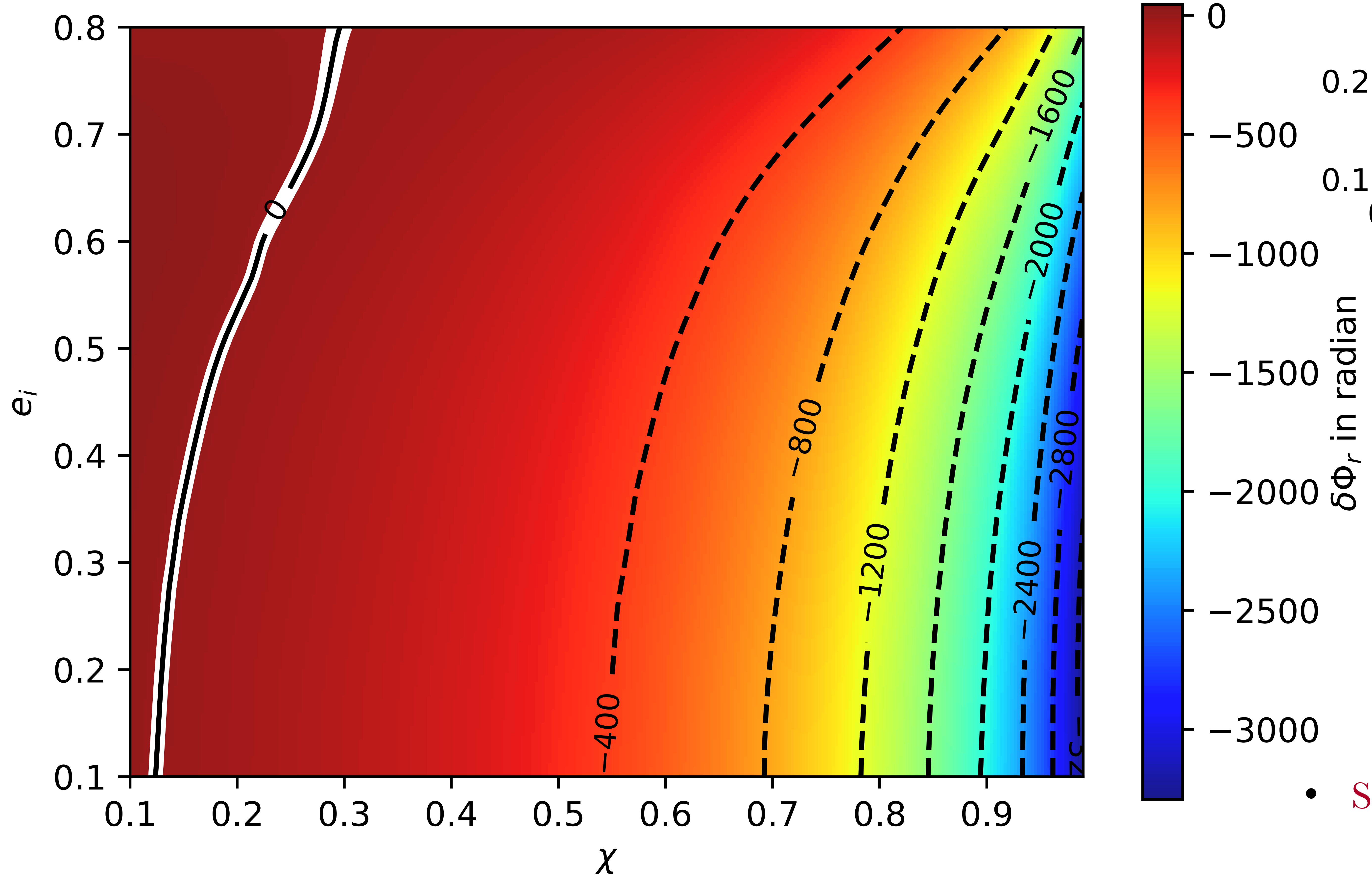
$$\langle \dot{m} \rangle \propto \sim \Omega(\Omega_H - \Omega)$$

$$\rightarrow \Omega(\mathscr{M}_\chi \Omega_H - \mathscr{M}\Omega)$$

$$\Omega \sim v^3$$

- $\delta\Phi_{m,n} = m\delta\Phi_\phi + n\delta\Phi_r$

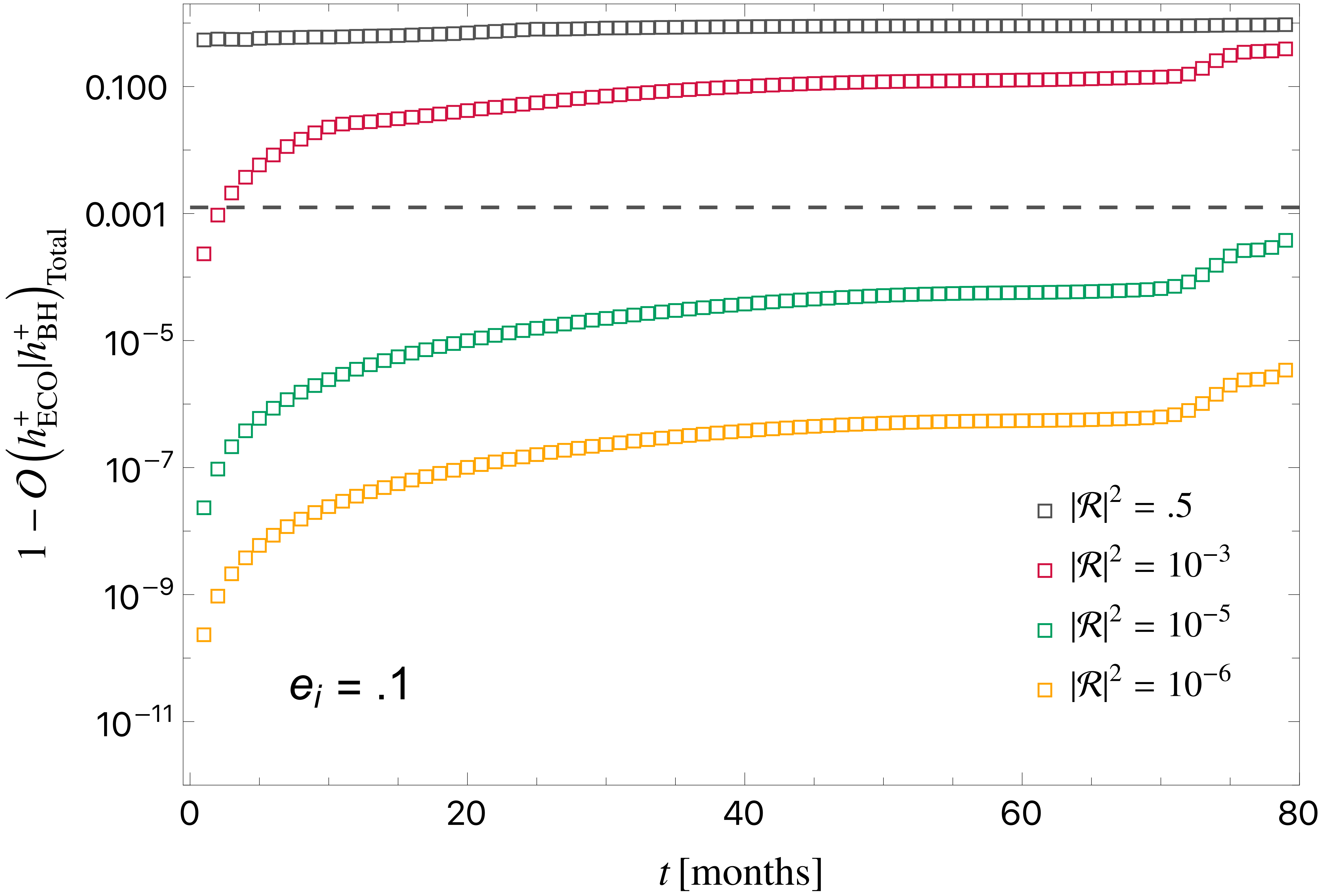


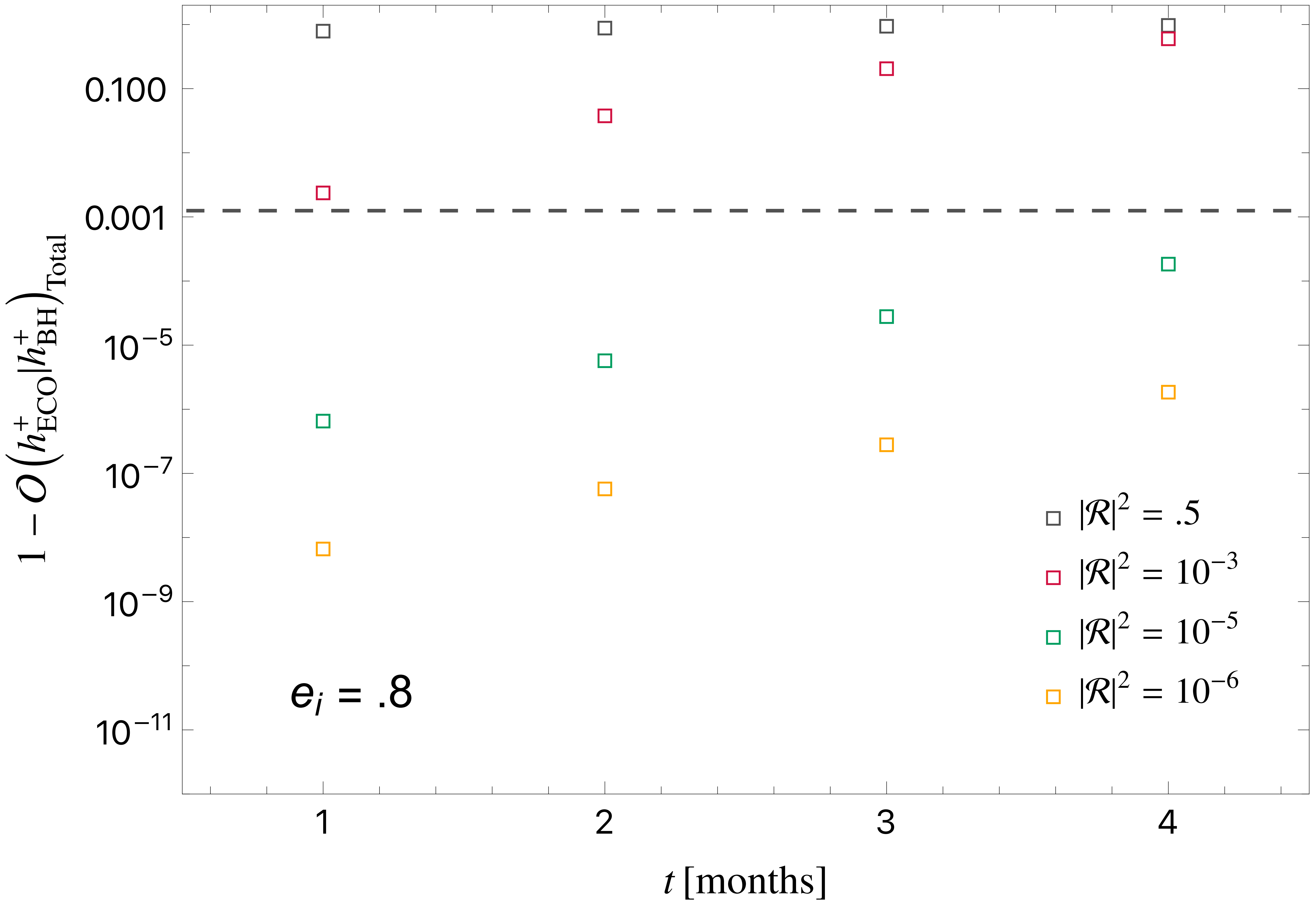


- Numerical evolution of eccentric EMRI

- SD, Brito, Hughes, Klinger, Pani, PRD110(2024) , 024048

- Prograde, $\chi = .9$
- Eccentric orbit

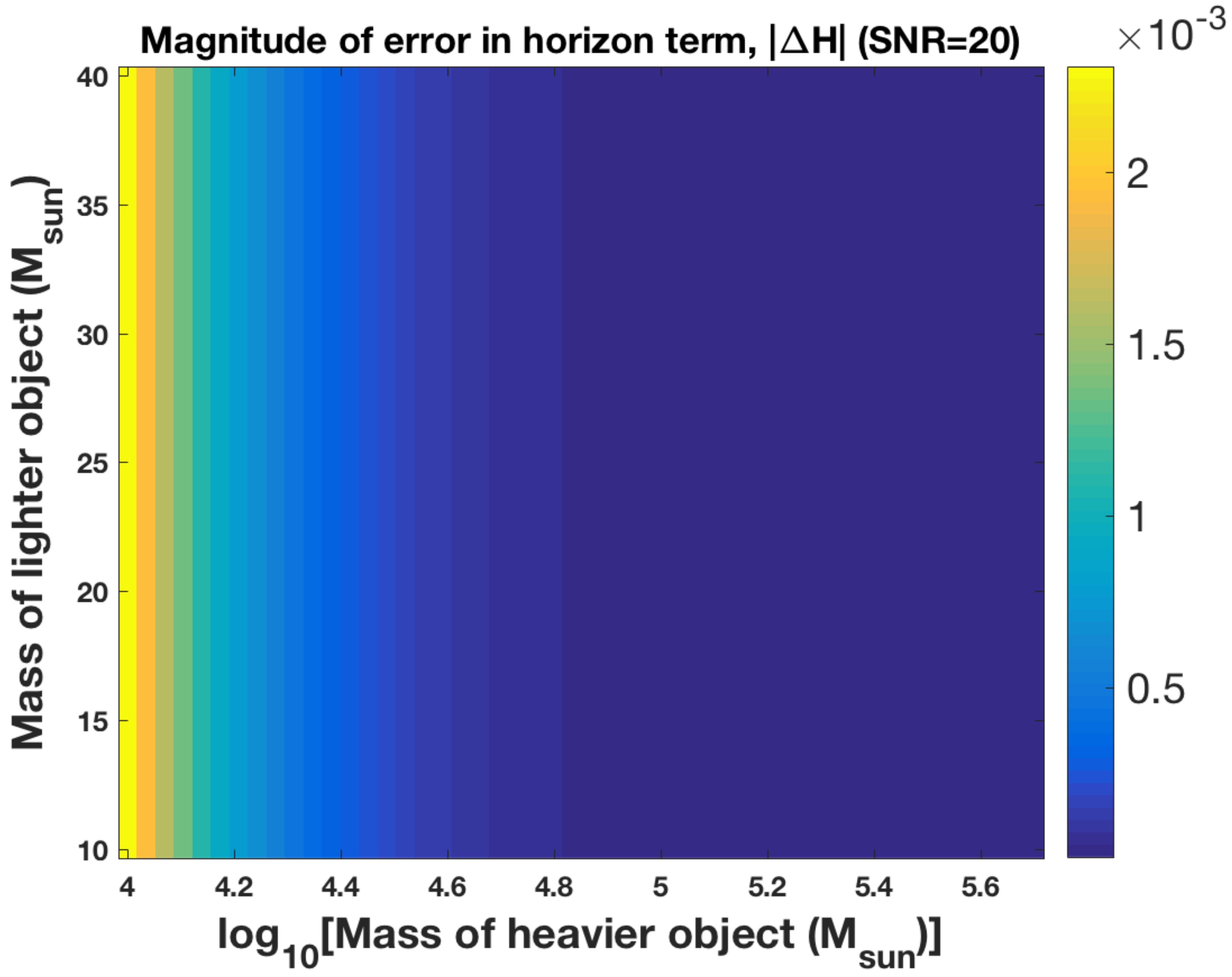




- $\dot{E}_{\rm ECO} = (1 - |\mathscr{R}|^2)\dot{E}_H + \mathcal{O}(\epsilon)$
- Image is the accumulated mismatch between waveforms with $|\mathscr{R}|^2 \neq 0$ and BH with time.

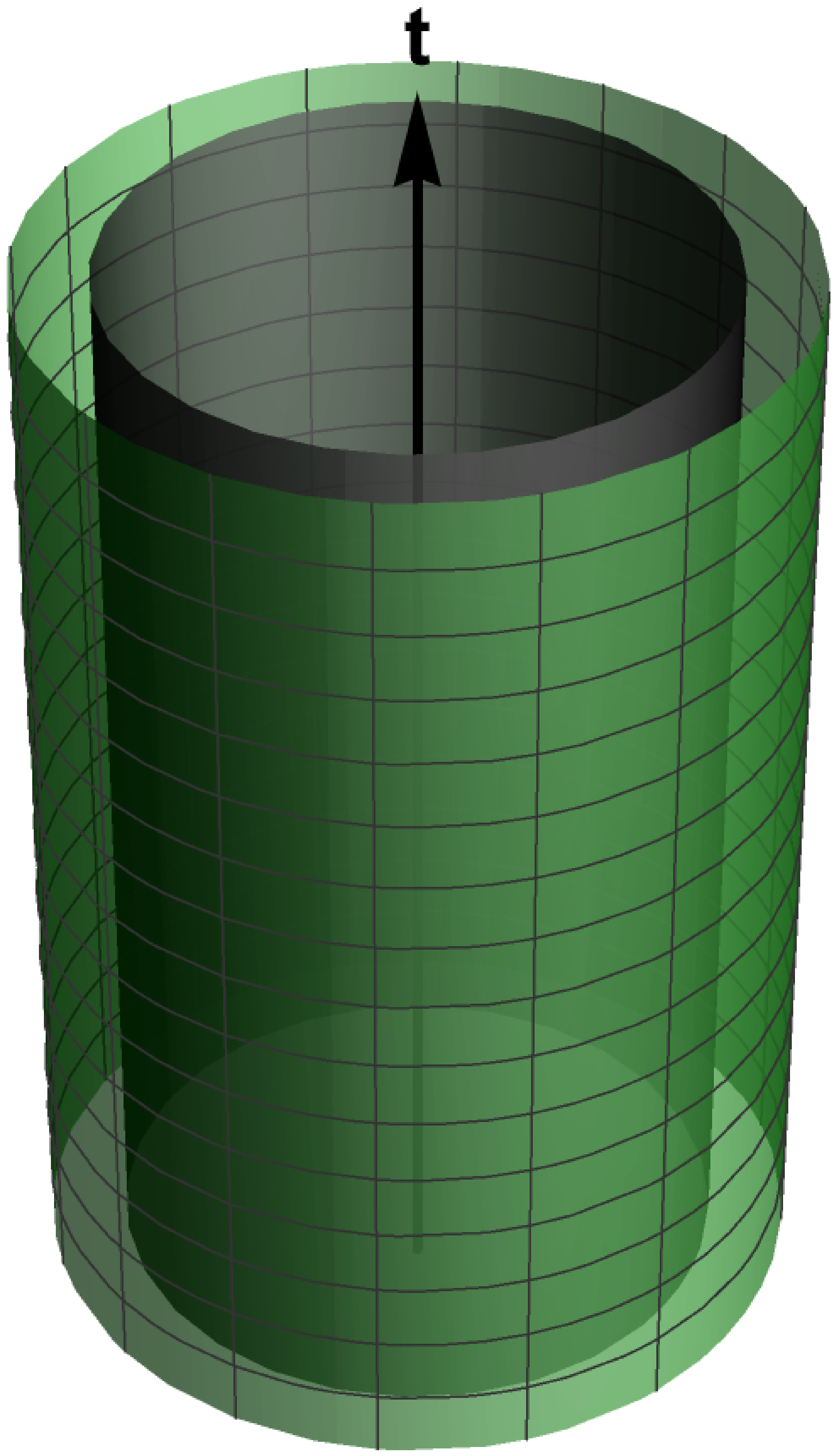
- $-\dot{E} = -\dot{E}|_{NoTH} - H\,\dot{E}|_{TH}$. SD, S. Bose, PRD99,084001 (2019)
- $H = 1 - |\mathscr{R}|^2$
- $H = 1$ implies these terms will contribute in the phase, implying the presence of horizon.
- $H = 0$ implies these terms will not contribute in the phase, implying the absence of the horizon.
- We name it Horizon parameter.

- Sufficient contribution in dephasing does not immediately imply that it is measurable.
- Measurability can be addressed with Fisher matrix analysis. In this way the error in a particular parameter can be forecasted.
- In the figure possible error in H when $H = 0$ in EMRI is shown.
  SD, S. Bose, PRD99,084001 (2019)



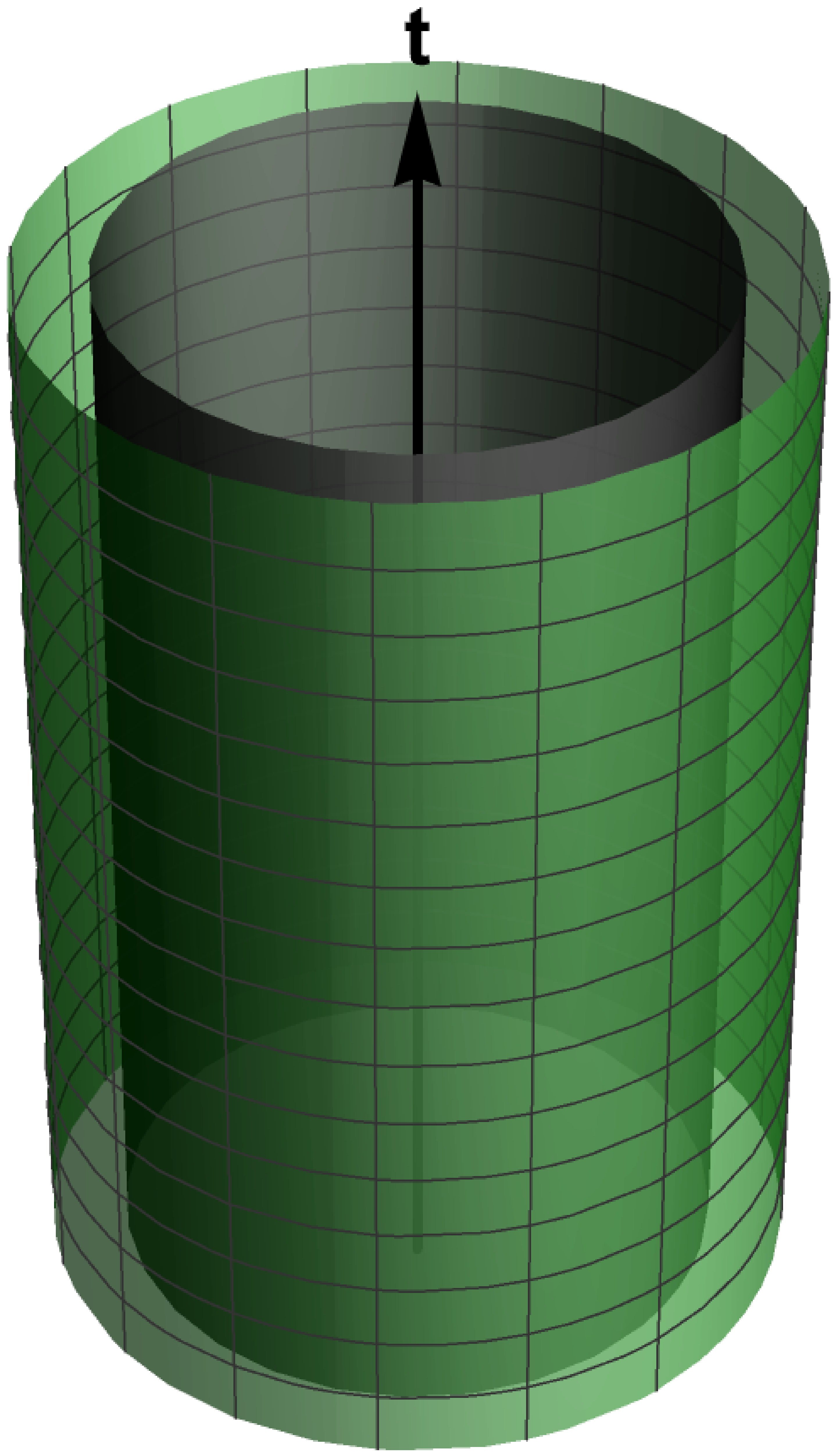
Effect of surface position

- What if the position is at $r_s = r_H(1+\epsilon)$?
- Outside it the metric is like Kerr BH.
- Using this, $\frac{dM}{dt} \propto \mathcal{T}^2 \sum_{i=0}^{1} \mathcal{M}^{(i)} \epsilon^i$. Hence, $\mathcal{T}^2 \sim H \sim 1 - \mathcal{R}^2$ SD, PRD.102.064040

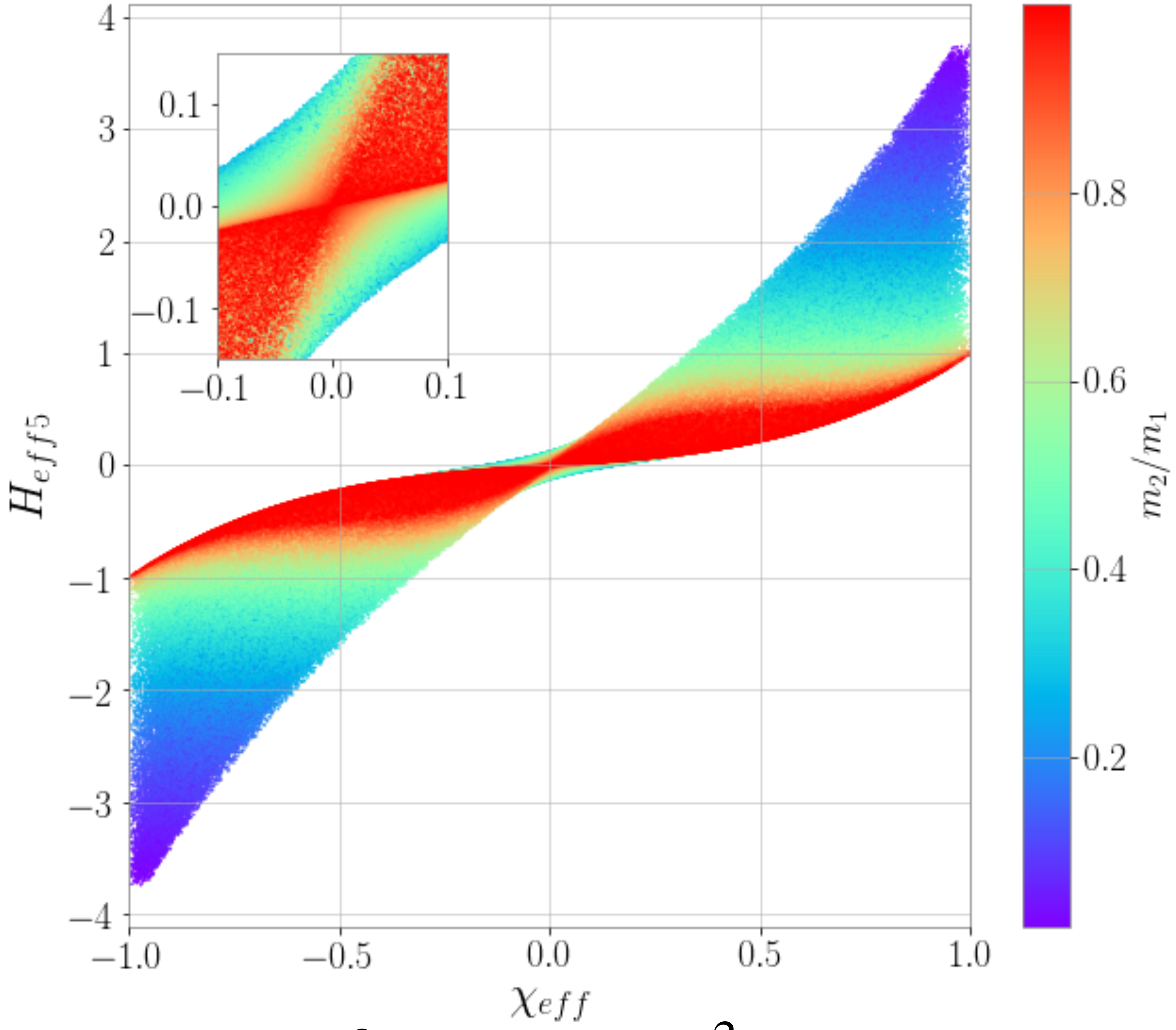


- TH flux can have significant modification, depending on ϵ value.
- Superradiance can occur which should be absent for BH. SD, PRD 102.064040

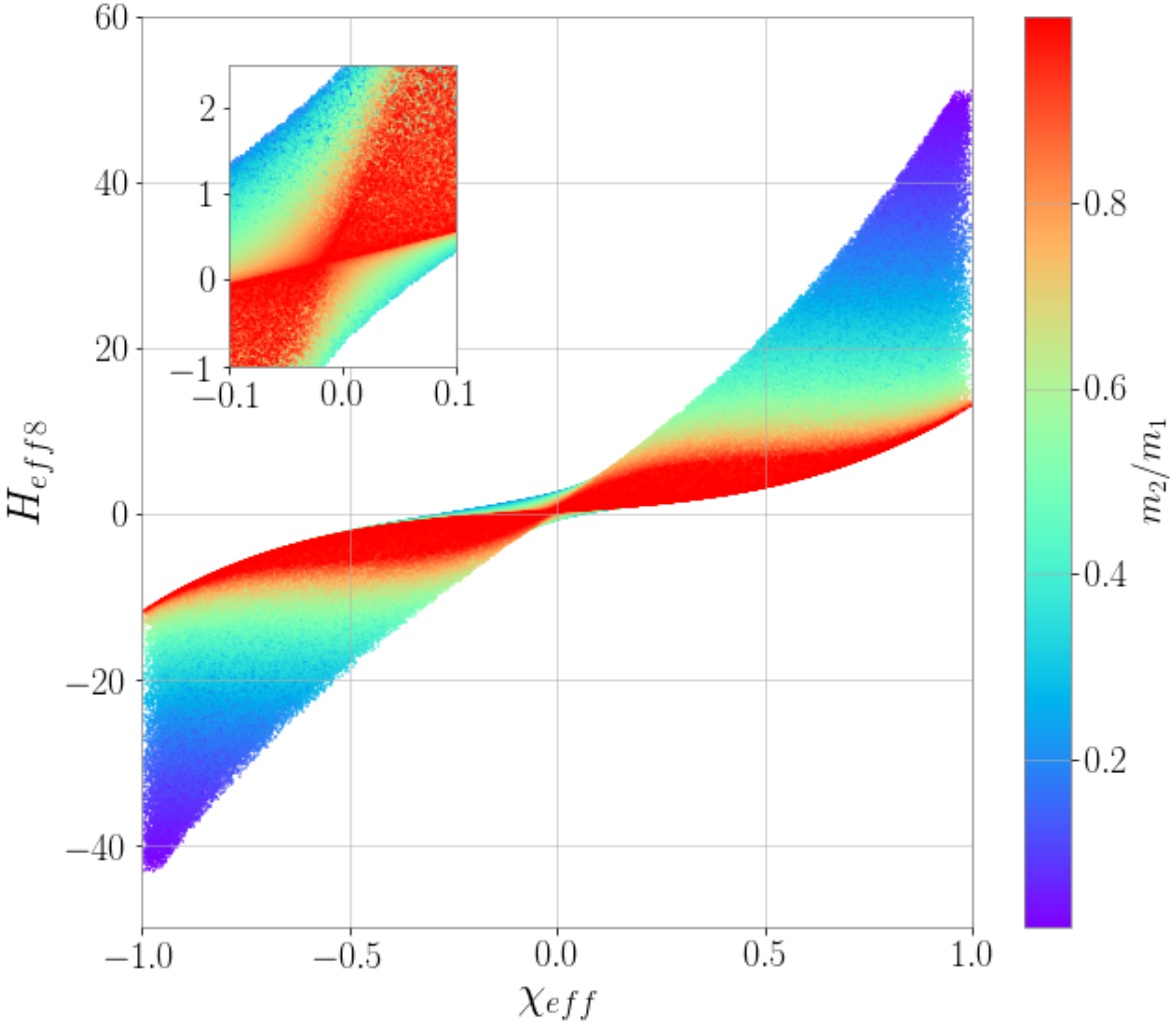
- What if the position is at $r_s = r_H(1+\epsilon)$?
- Outside it the metric is like Kerr BH.
- Using this, $\frac{dM}{dt} \propto \mathcal{T}^2 \sum_{i=0}^{1} \mathcal{M}^{(i)} \epsilon^i$. Hence, $\mathcal{T}^2 \sim H \sim 1 - \mathcal{R}^2$ SD, PRD.102.064040
- Then $\epsilon \sim 10^{-5}$ can add "sufficient" imprint in EMRI.



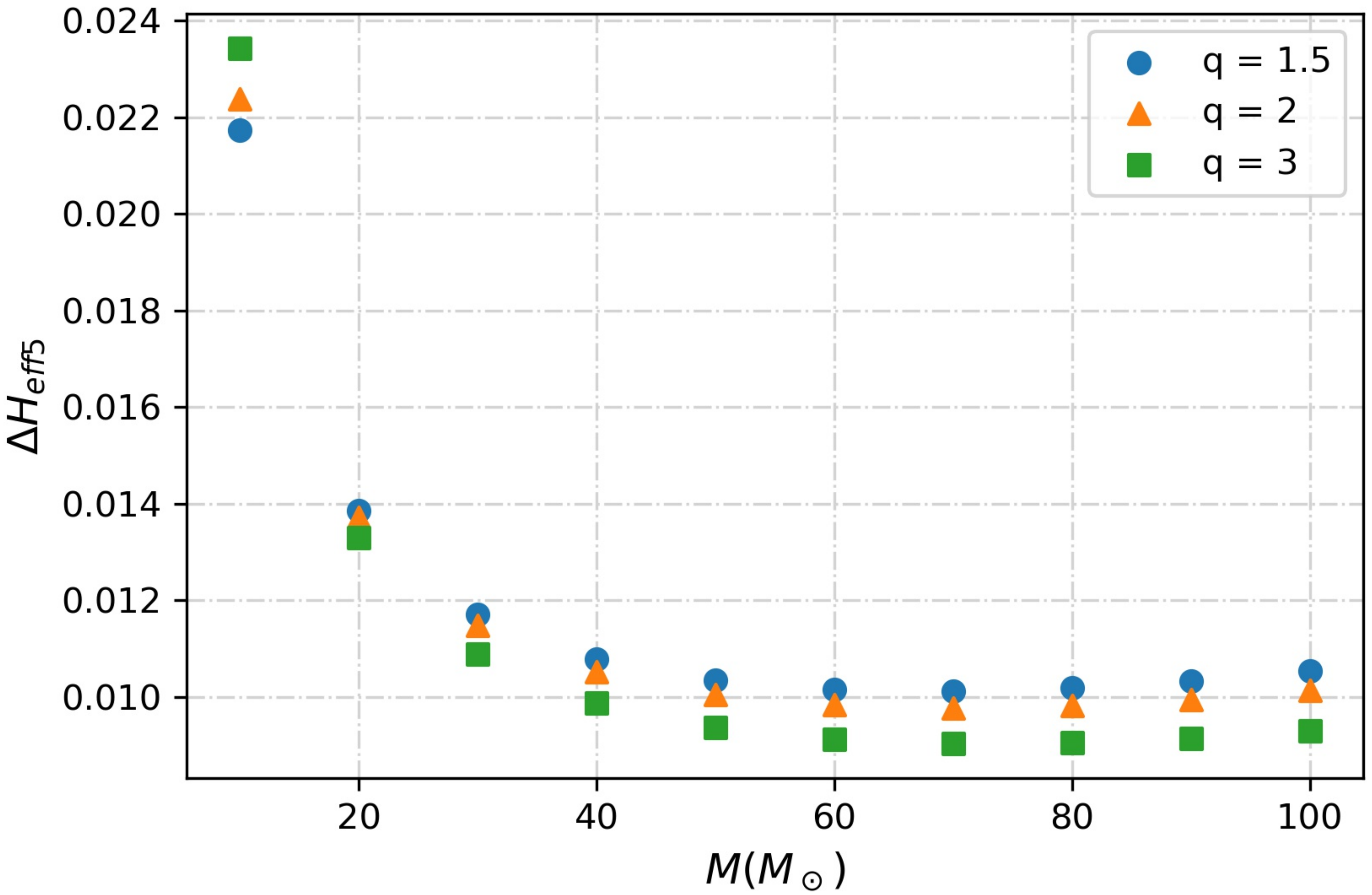
TH in CMRI

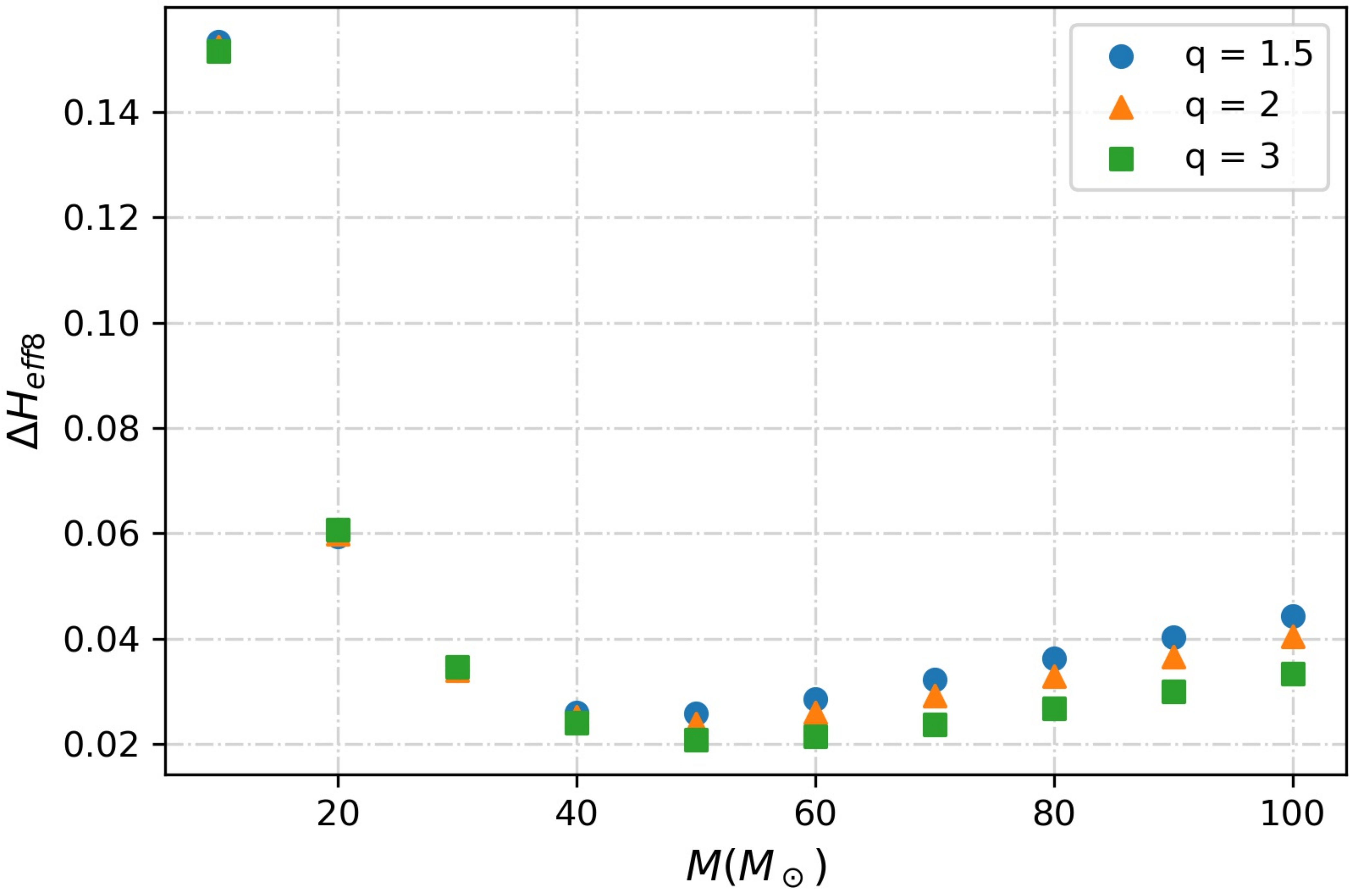


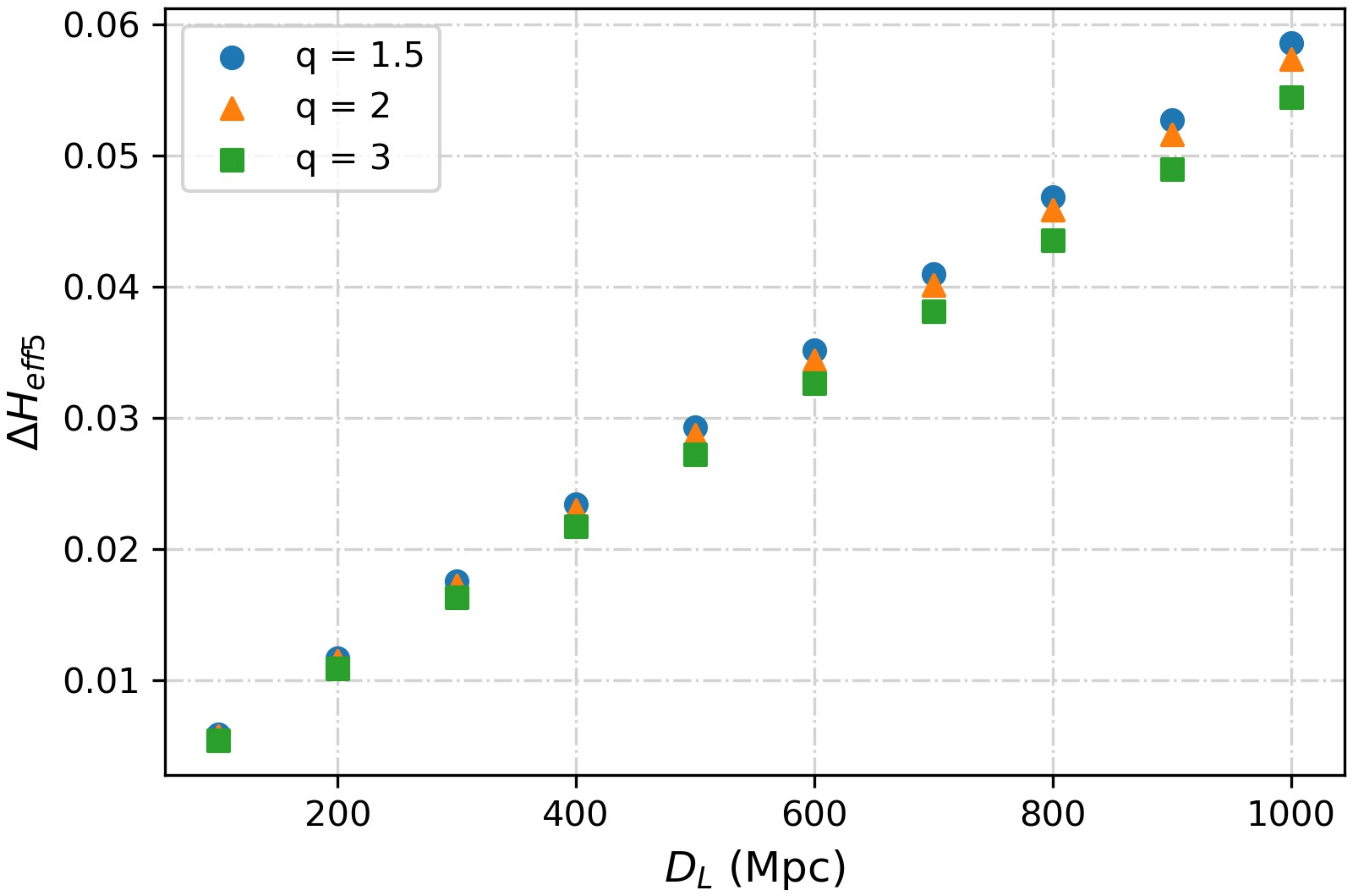
- Near equal mass binaries need H_1 and H_2 for the two components. SD, Phukon, Bose PRD 104 (2021) 8, 084006.
- They are degenarate parameters. $\Psi_{TH} \propto \sim \log(v)(f(H_1, m_1, \chi_1) + f(H_2, m_2, \chi_2)) + \ldots$



- $H_{eff5} = \sum_{i=1}^{2} H_i \left(\frac{m_i}{m}\right)^3 \left(\hat{L}\,.\,\hat{S}_i\right) \chi_i \left(3\chi_i^2 + 1\right)$
- $H_{eff8} = 4\pi H_{eff5} + \sum_{i=1}^{2} H_i \left(\frac{m_i}{m}\right)^4 (3\chi_i^2 + 1)\left(\sqrt{1-\chi_i^2} + 1\right)$
- $\Psi_{TH} \propto \sim H_{eff5} \log(v) + \sim v^3 H_{eff8} \log(v)$.







- In ET and CE they are well measured.
- Figures are for distance 200 MPc. Mukherjee, SD, Tiwari, Phukon, Bose, PRD 106 (2022) 10, 104032.

Post-ISCO: nonspinning

(a) (b) (c)

- Mukherjee, SD, Bose, Phukon, arXiv:2506.22363[gr-qc].

Take Home

- In EMRI TH can lead to significant dephasing, resulting in constraining $|\mathscr{R}|^2 \sim 10^{-5}$.
- $\epsilon \sim 10^{-5}$ can have observable impact.
- Fisher analysis with H suggests similar conclusion.
- With H_{eff5} and H_{eff8} even in CMRI there is the possibility to test BH-ness.
- Better in ET-CE.
- Post-ISCO the effect strengthens rapidly.

- Taracchini+ PRD 88 (2013) 044001