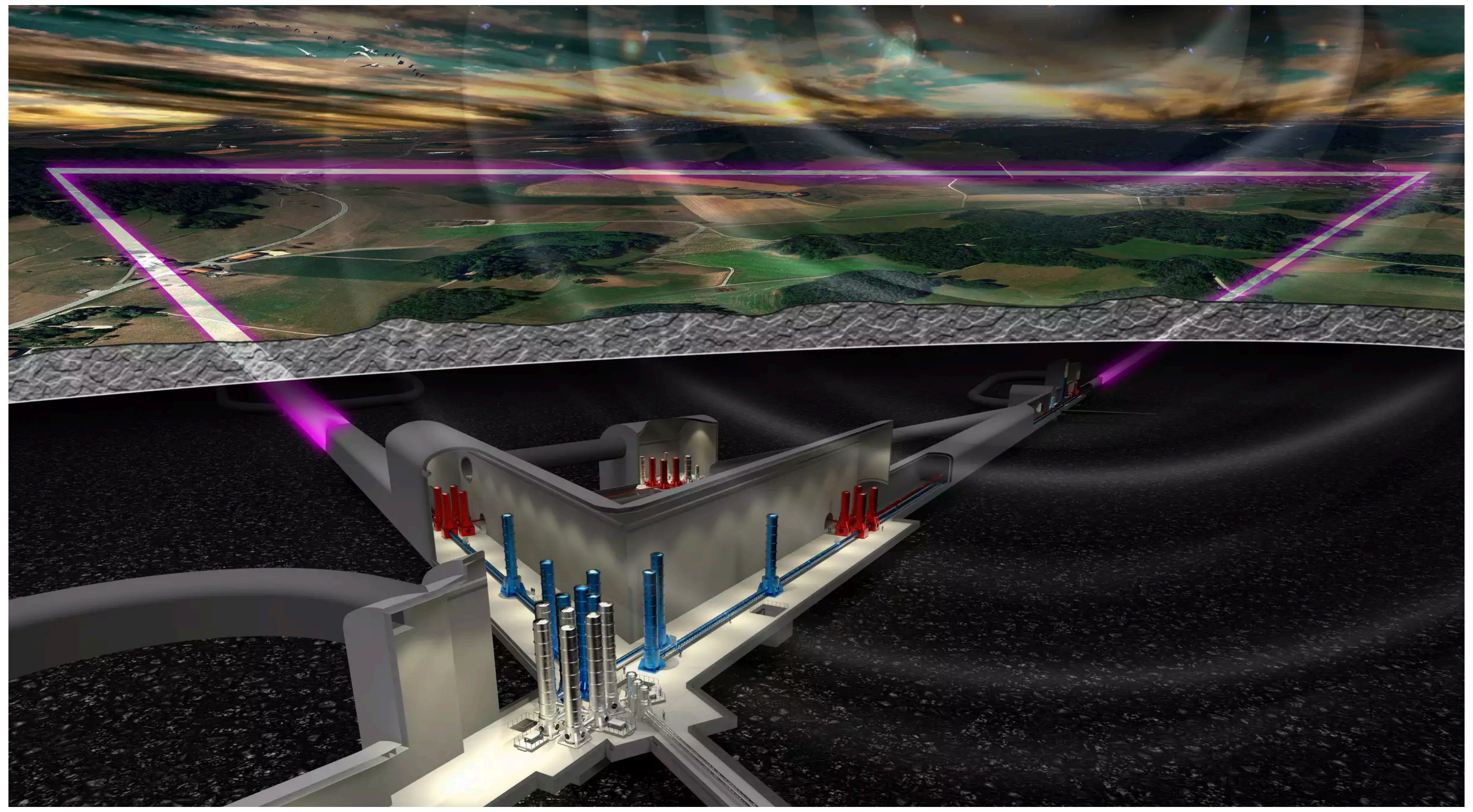
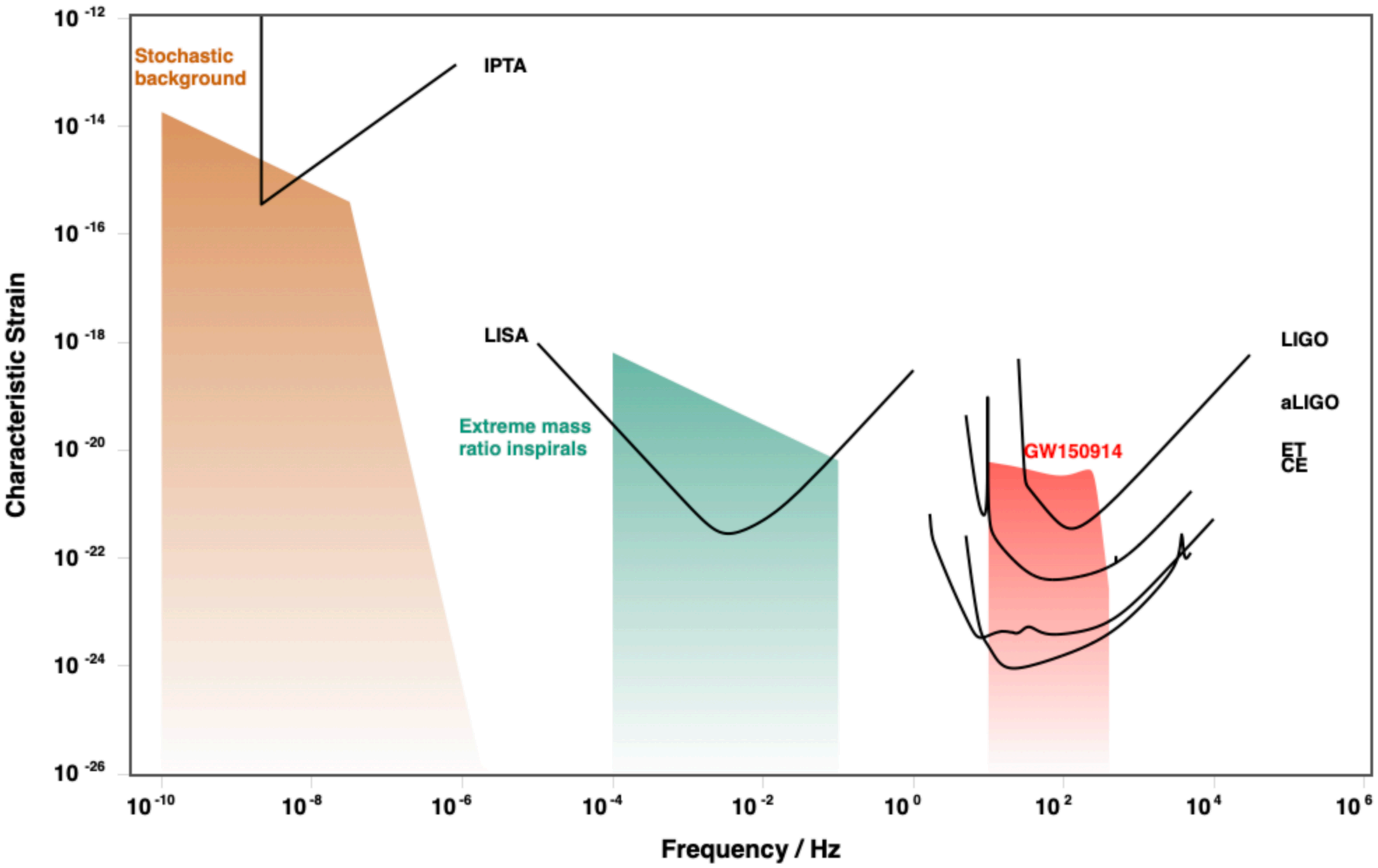
Tidal Heating in eccentric orbits

Sayak Datta

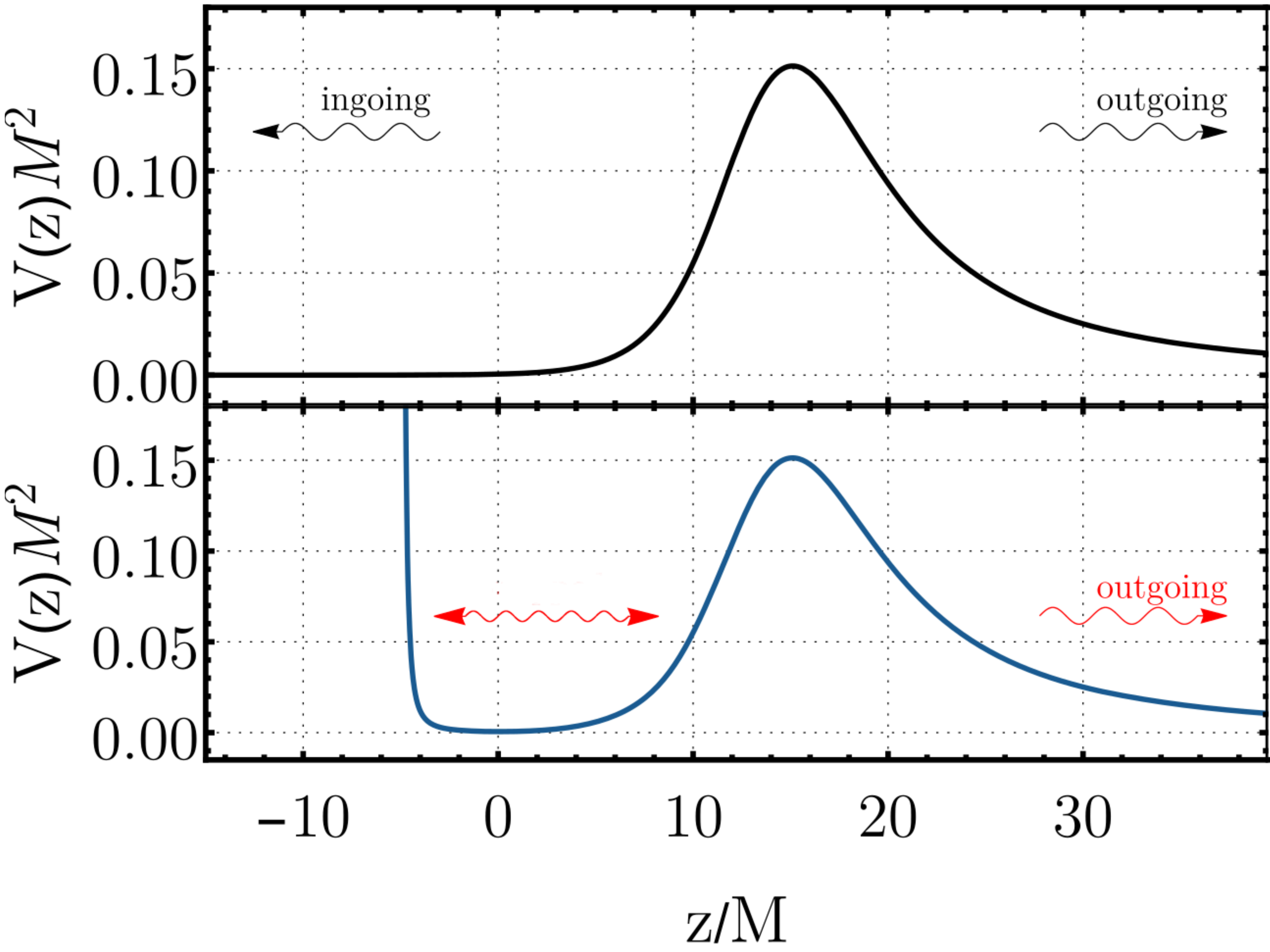
GSSI, L'Aquila

- 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.



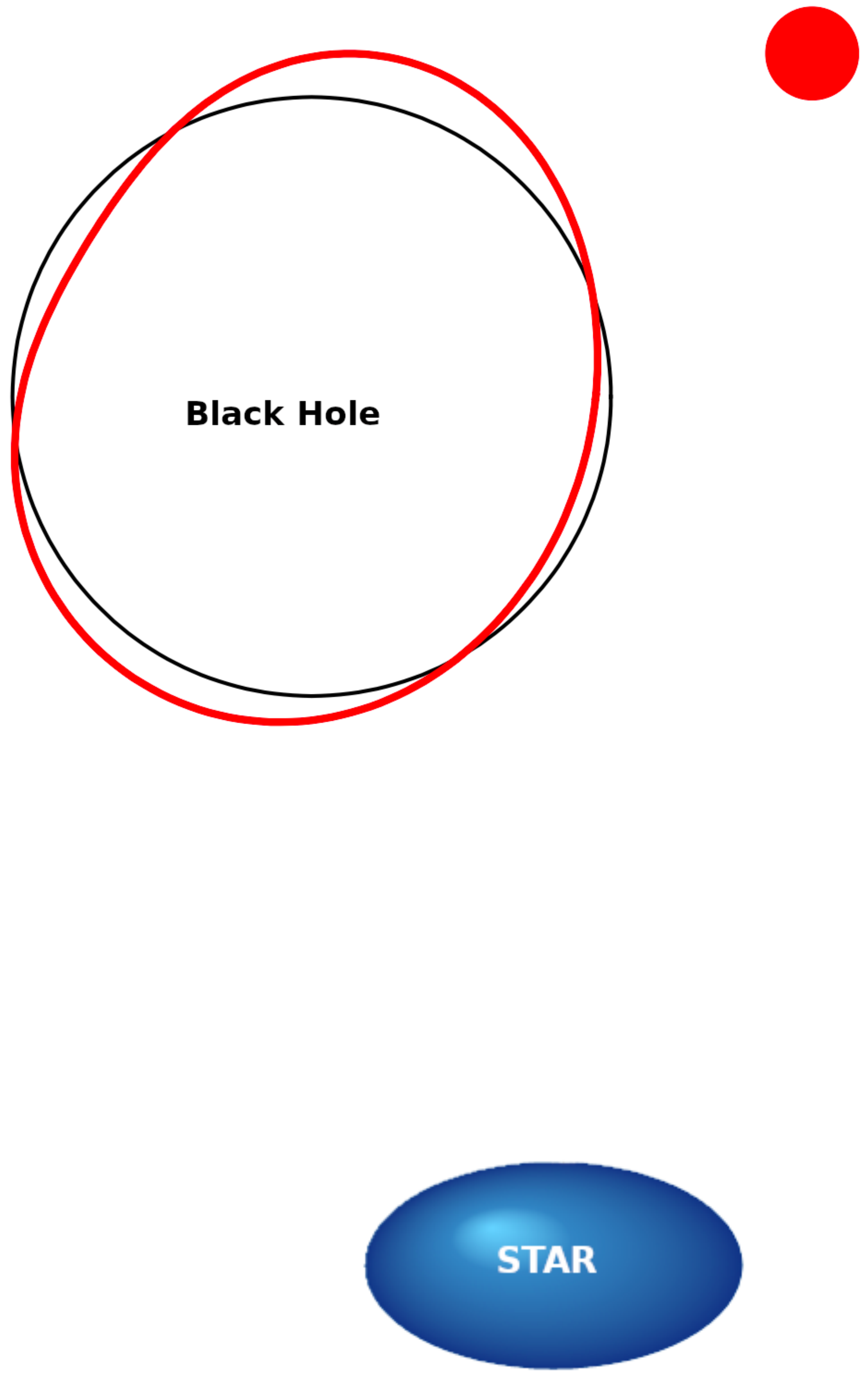


- Classical BH's horizon is perfect absorber due to causality.
- Absence (modification) of this implies imperfect absorption.
- Measuring nonzero reflectivity of compact object surface will be signature of deviation.
- Tidal heating is one such effects.



- 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).



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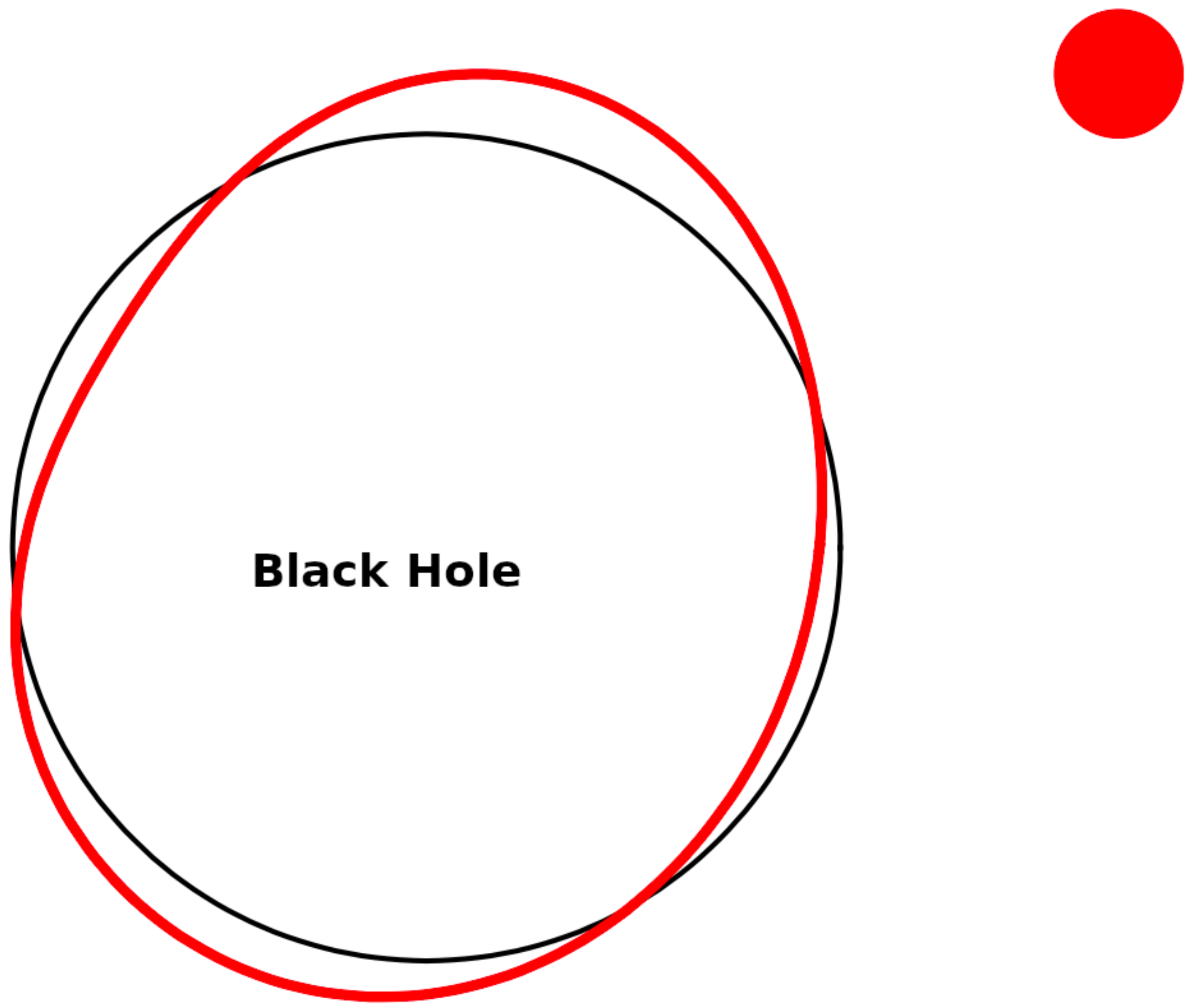
- In stars this absorption comes due to viscous heating in the material.
- In BHs it caused by the change in the BH mass.



- CQG28,175006 (2011)

- Tanja Hinderer

- 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, $$\nu_{NS} = 10^4\left(\frac{\rho}{10^{14} gmcm^{-3}}\right)^{\frac{5}{4}}\left(\frac{10^8 K}{T}\right)^2 cm^2 s^{-1}$$
- $$\nu_{BH} = 8.6 \times 10^{14}\left(\frac{M}{M_\odot}\right) cm^2 s^{-1}$$
- Even for $M_{BH} \sim M_{NS}$, $\nu_{NS} \ll \nu_{BH}$, resulting in ignorable TH compared to BH.

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- 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, Phukong, Bose, PRD104(2021) 084006

TH in eccentric orbits

- TH depends on the tidal environment, $\mathscr{E}_{ab}(r, \dot{r}, \phi, \dot{\phi})$ and $\mathscr{B}_{ab}(r, \dot{r}, \phi, \dot{\phi})$. Taylor+ PRD 78, 084016 (2008)
- $\dot{m} = \dot{m}(\bar{\mathscr{E}}_{ab}, \bar{\mathscr{B}}_{ab})$ and similarly $\dot{J}$. Taylor+ PRD 78, 084016 (2008) , Poisson, PRD70, 084044 (2004)
- Upon averaging over the orbit,
  $\langle \dot{m} \rangle = \dot{m}_{circ}\mathscr{M}(e_t)$, $\langle \dot{m} \rangle_\chi = \dot{m}_{circ,\chi}\mathscr{M}_\chi(e_t)$, $\langle \dot{J} \rangle_\chi = \dot{J}_{circ,\chi}\mathscr{J}_\chi(e_t)$
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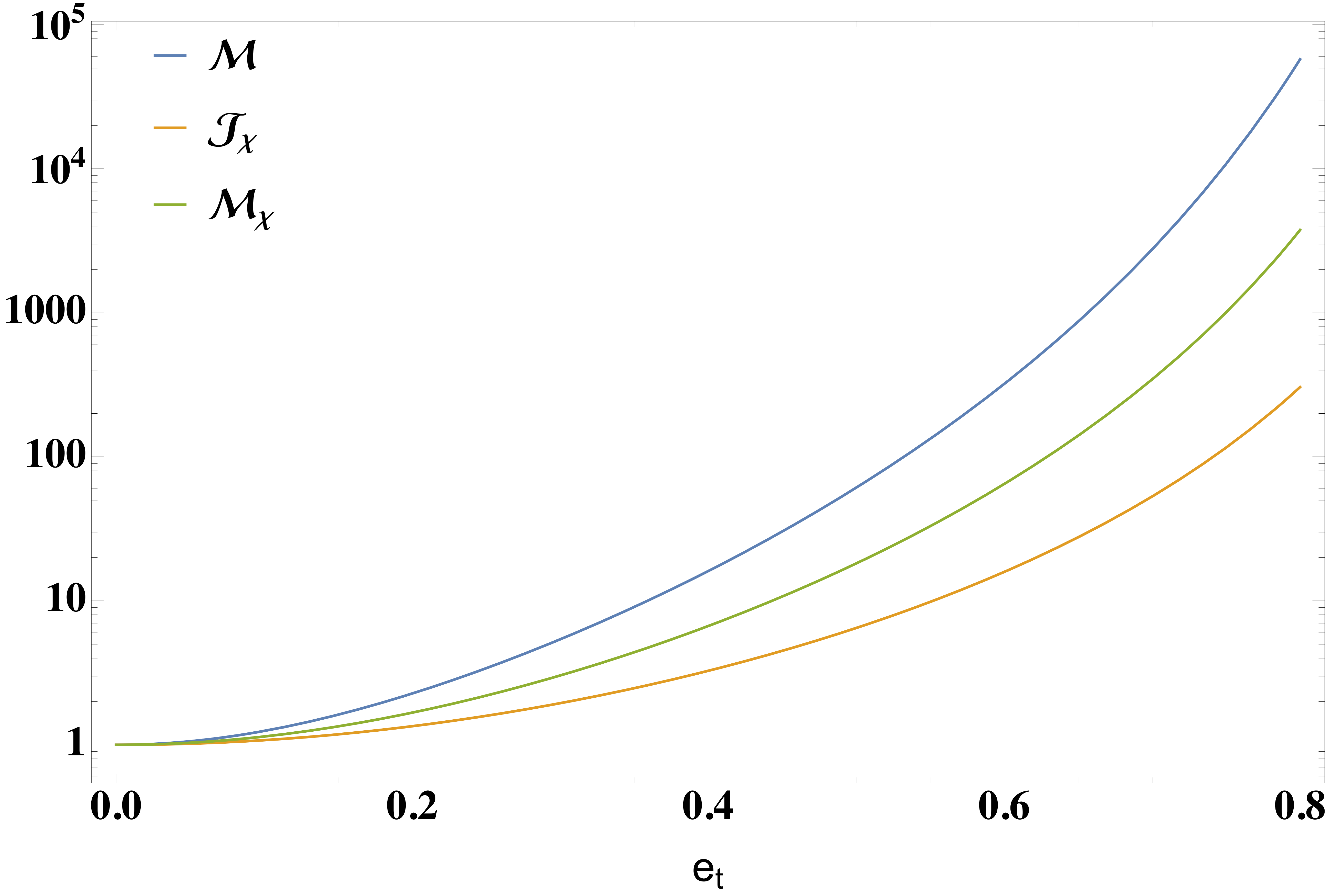
SD, EPJC (2024), Munna+ 2306.12481

- $$\langle \dot{J}_1 \rangle = -\frac{8m_1^5 m_2^2 \xi^4 \chi\left(3\chi^2+1\right)}{5M^6}\frac{\left(3e_t^4+24e_t^2+8\right)}{8\left(1-e_t^2\right)^{9/2}}$$
- $$\langle \dot{m}_1 \rangle = -\frac{8\epsilon m_1^5 m_2^2 \xi^5 \chi\left(3\chi^2+1\right)}{5M^7}\frac{\left(5e_t^6+90e_t^4+120e_t^2+16\right)}{16\left(e_t^2-1\right)^6}$$



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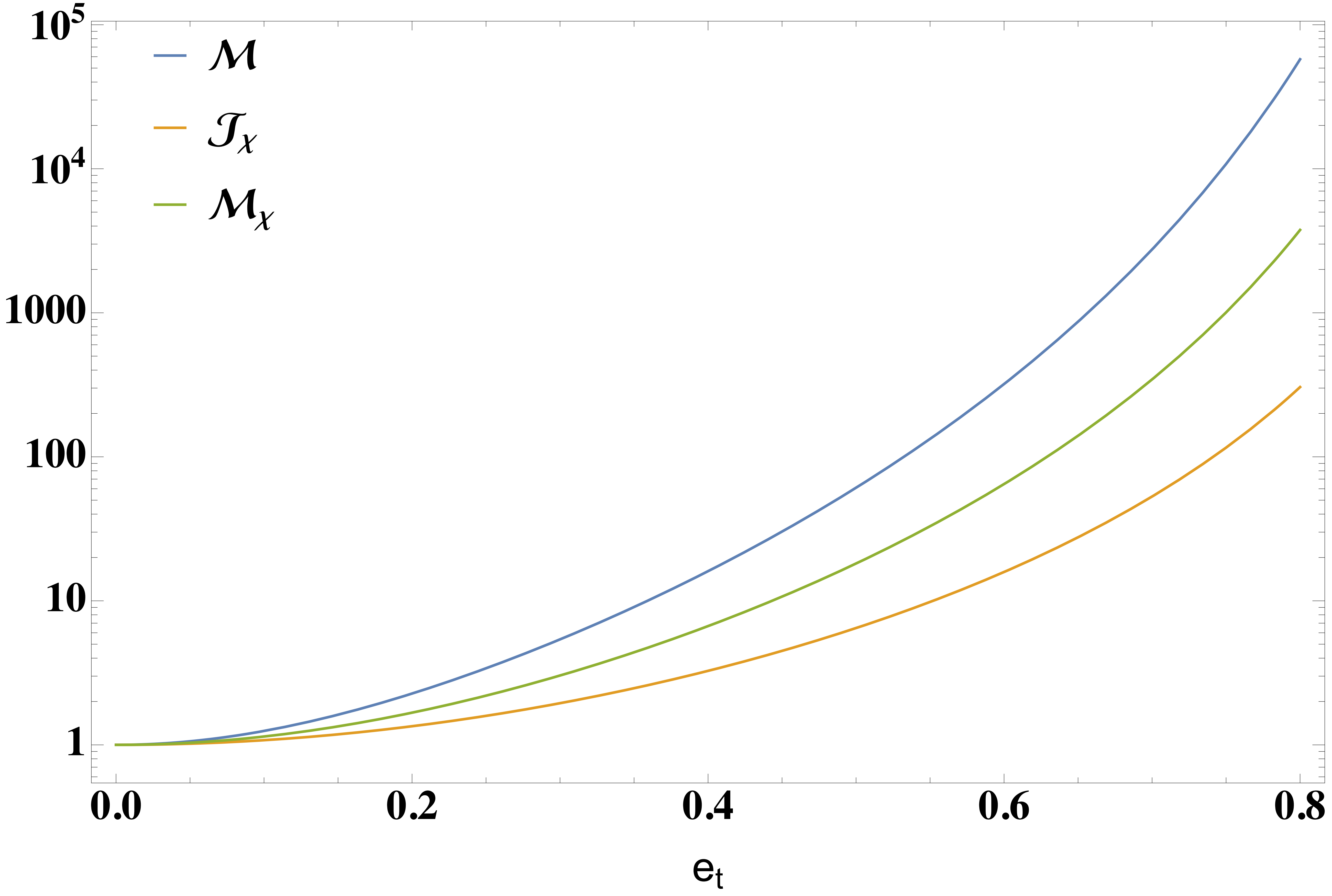

$$F^H \propto \Omega(\Omega - \Omega_H)$$

$$\Omega \sim v^3$$

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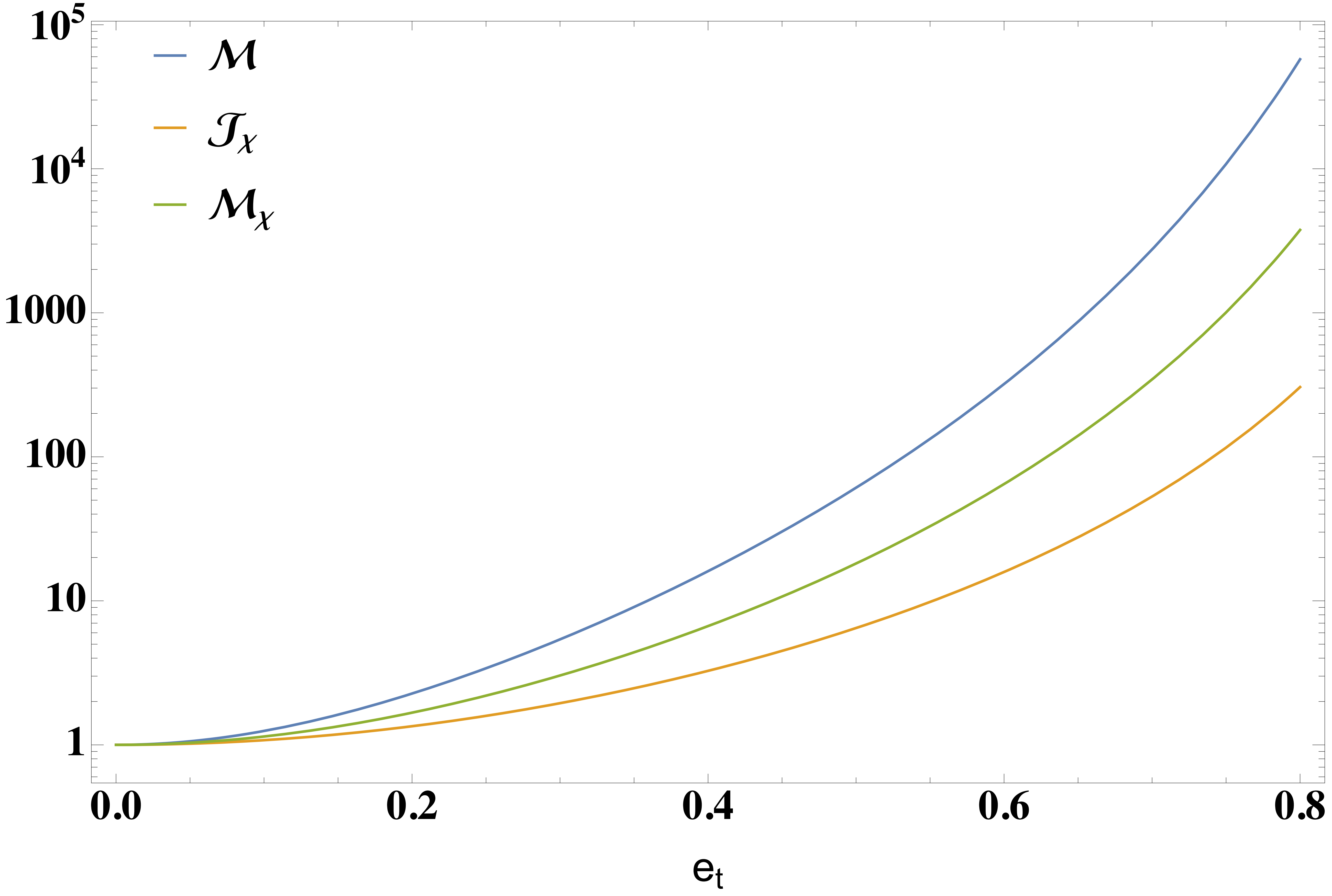


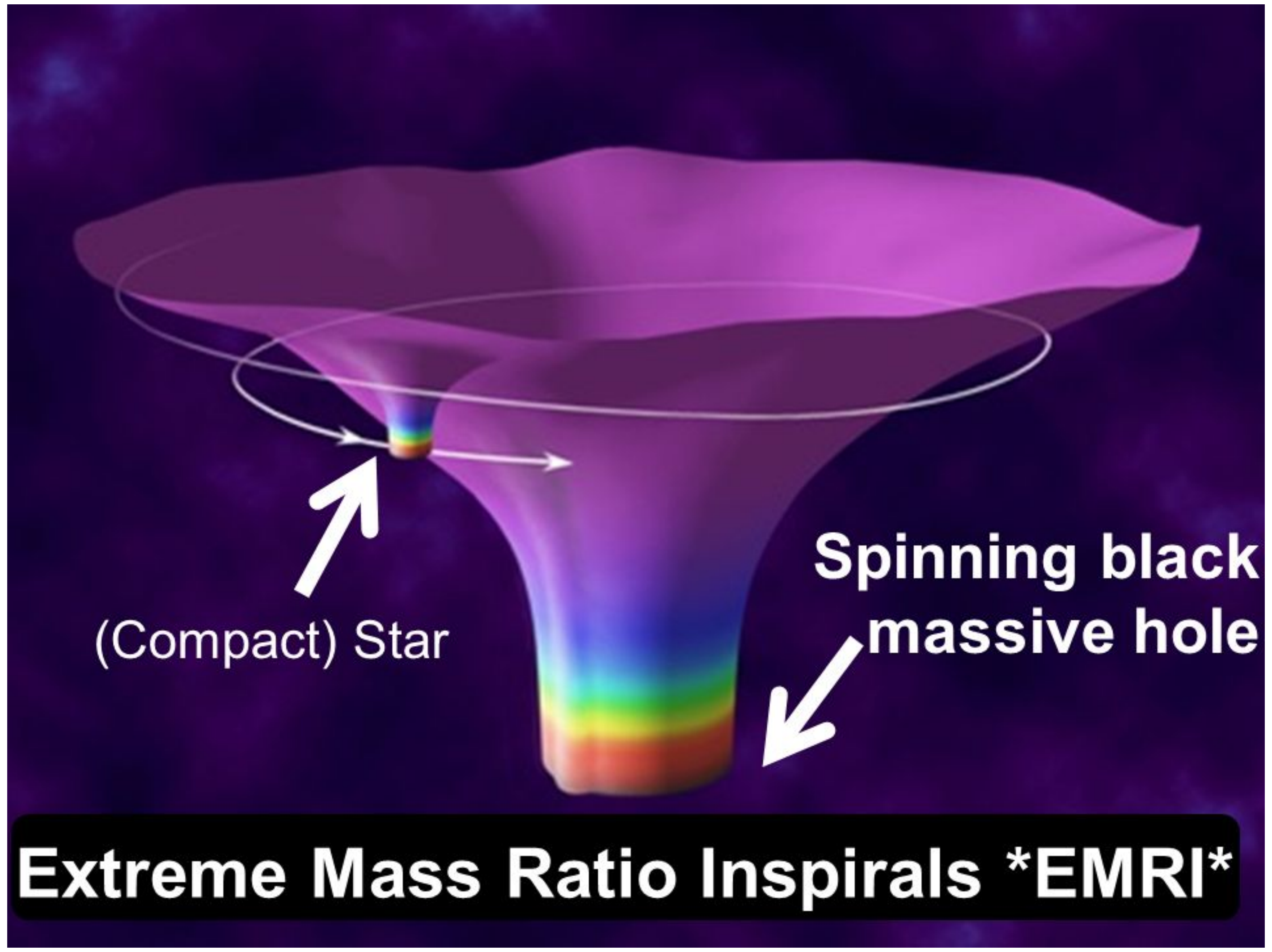
$$F^H \propto \Omega(\Omega - \Omega_H)$$

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

$$\Omega \sim v^3$$

Strength in EMRI

- We will focus on EMRI, 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 Kerr BH by a small particle.



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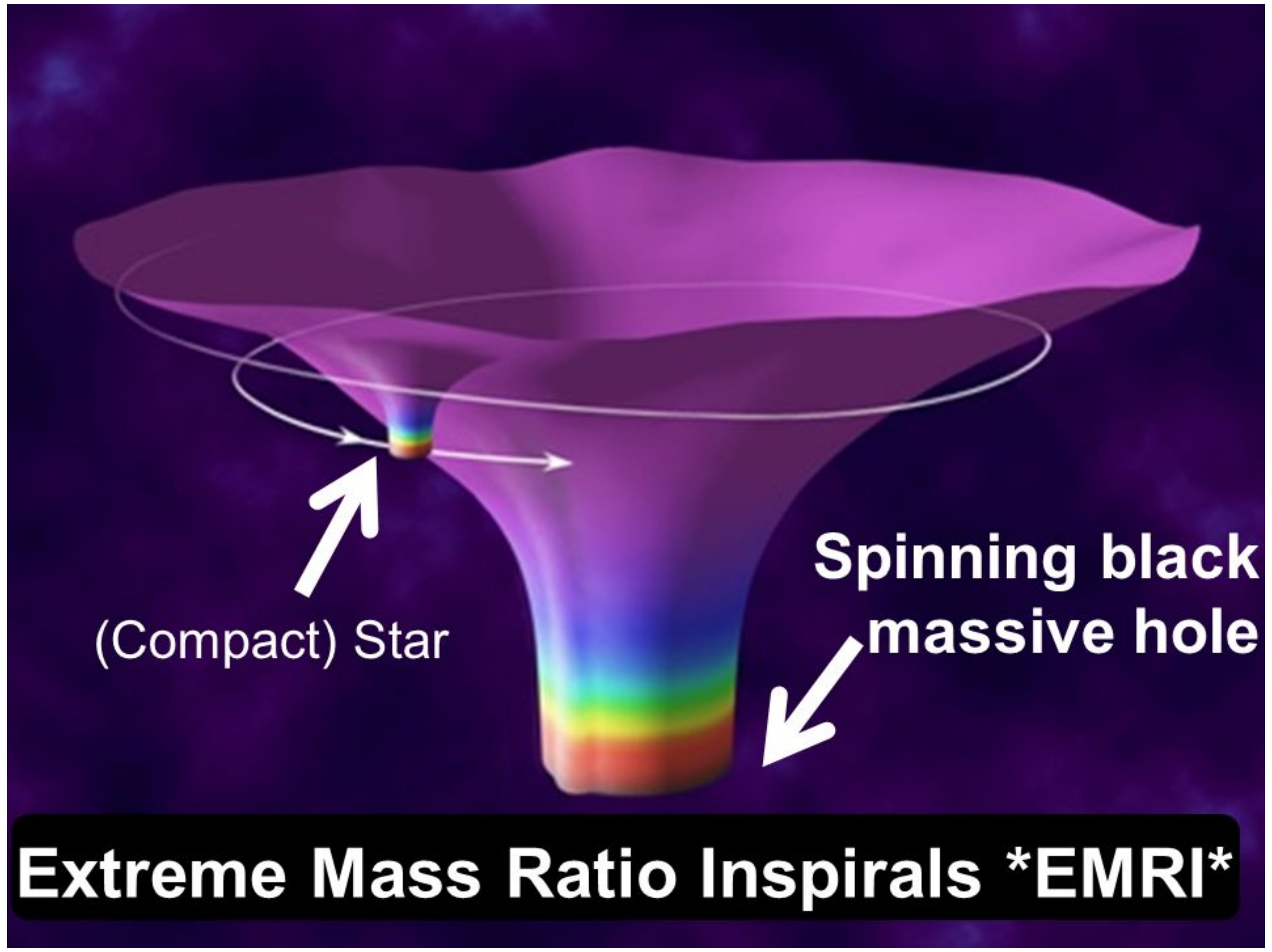
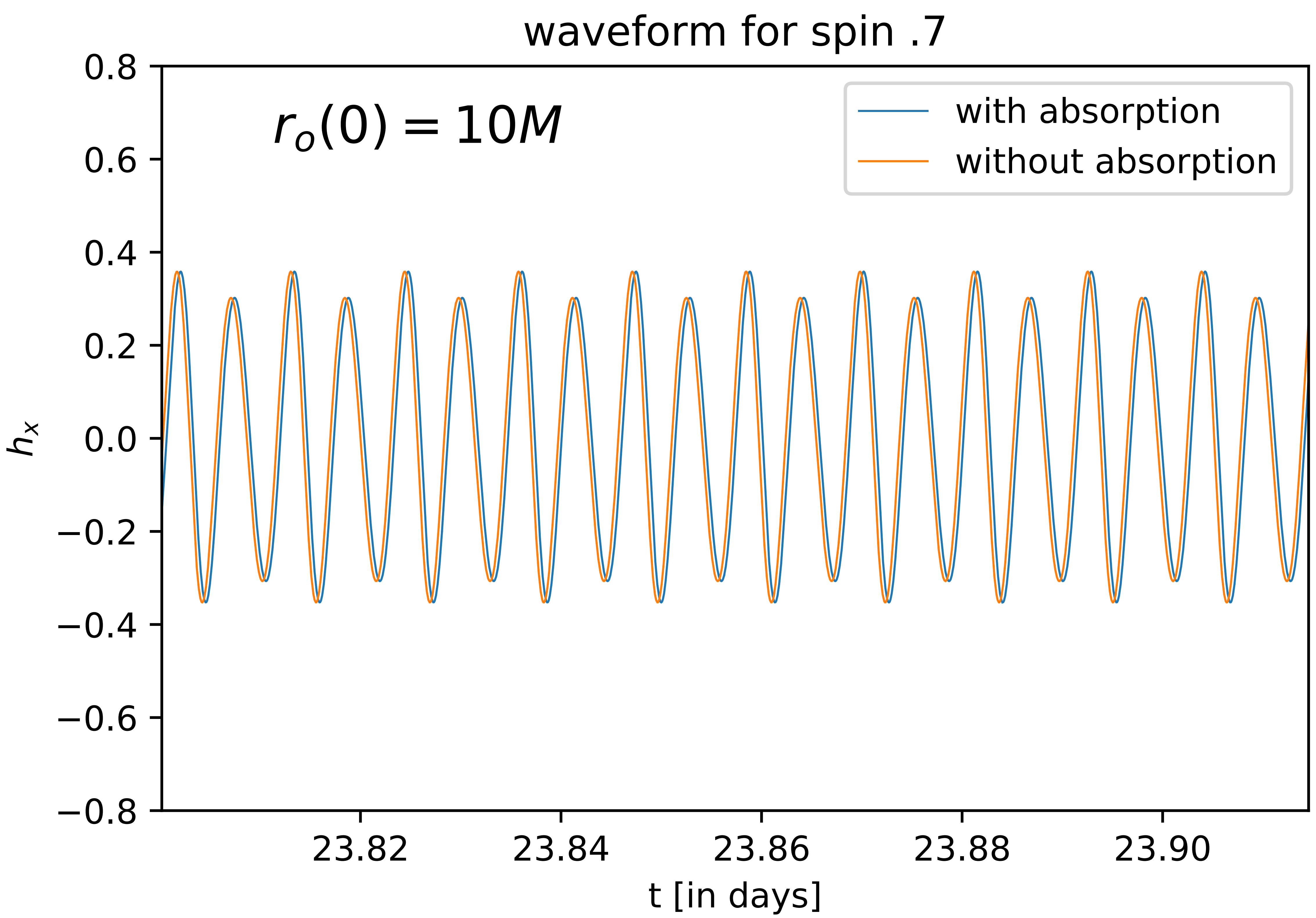
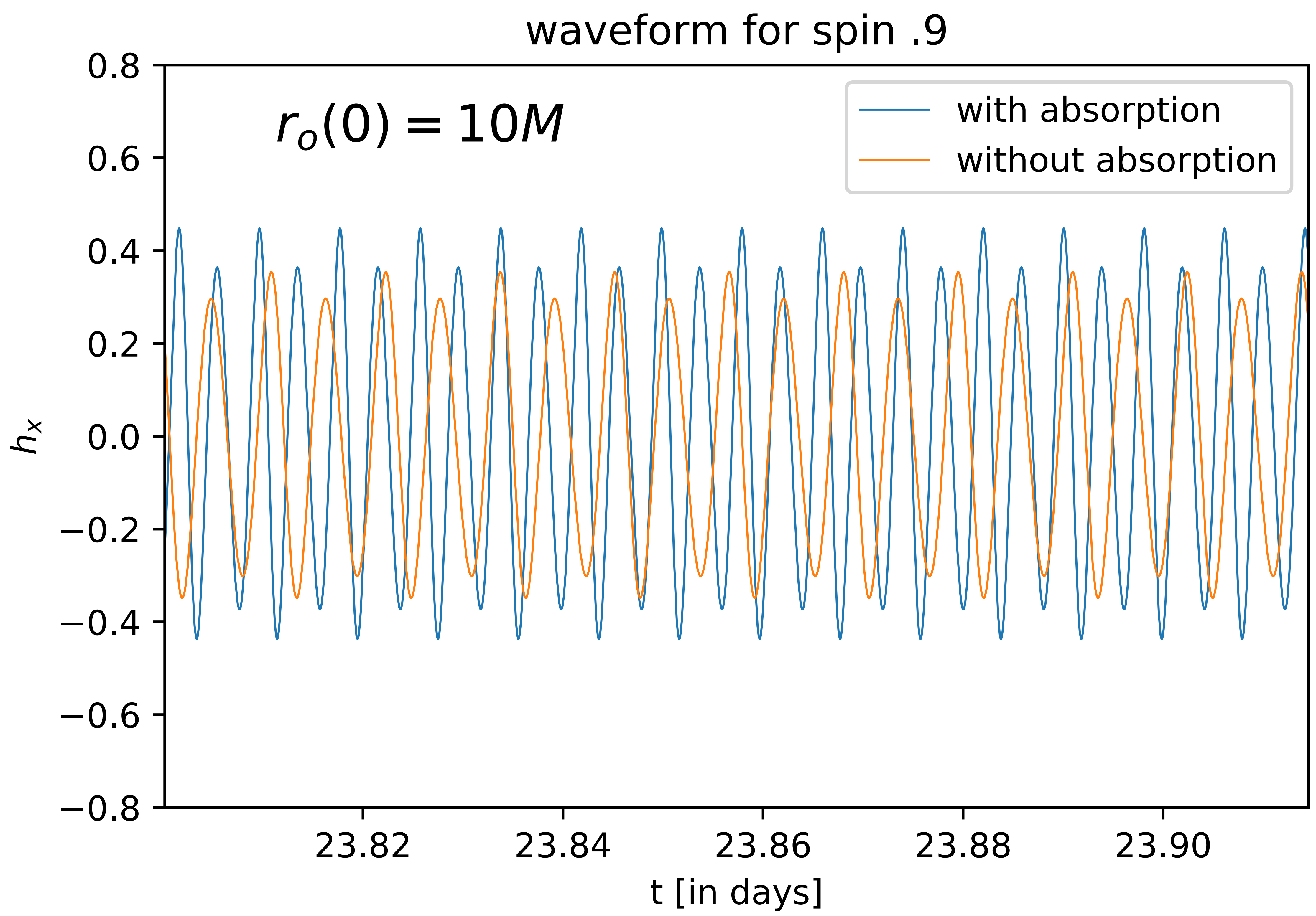


- We solve BHP equation.
- Energy fluxes at infinity and the horizon can be calculated from the perturbation GW waveform.
- $\dot{E} = \dot{E}_{\infty} + \dot{E}_H$
- $\dot{E}_{\mathrm{TH}} = (1 - |\mathscr{R}|^2)\dot{E}_H, \ \ \dot{J}_{\mathrm{TH}} = (1 - |\mathscr{R}|^2)\dot{J}_H$

- $M = 10^6 M_{\odot}, M = 30000\mu$



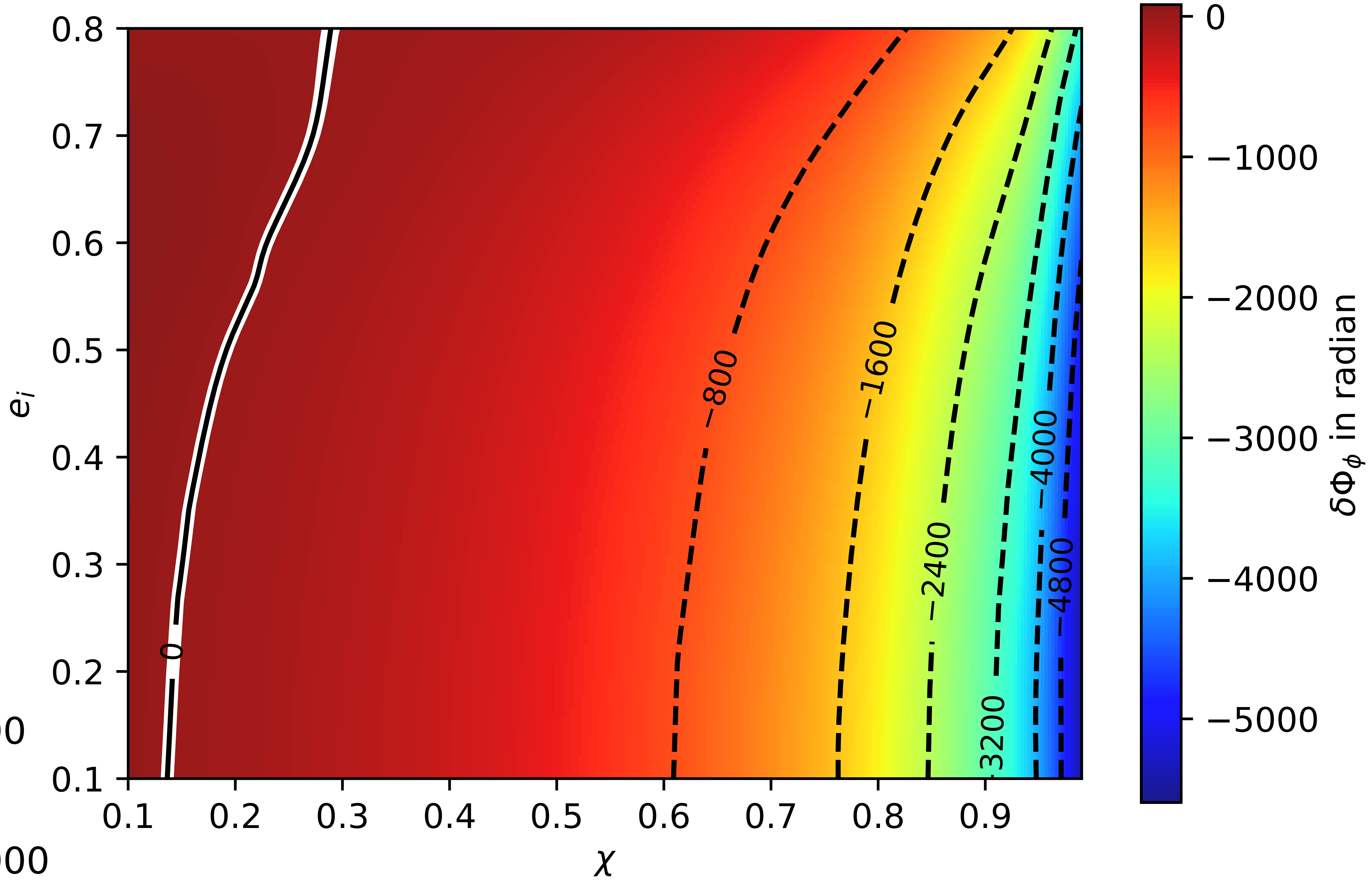


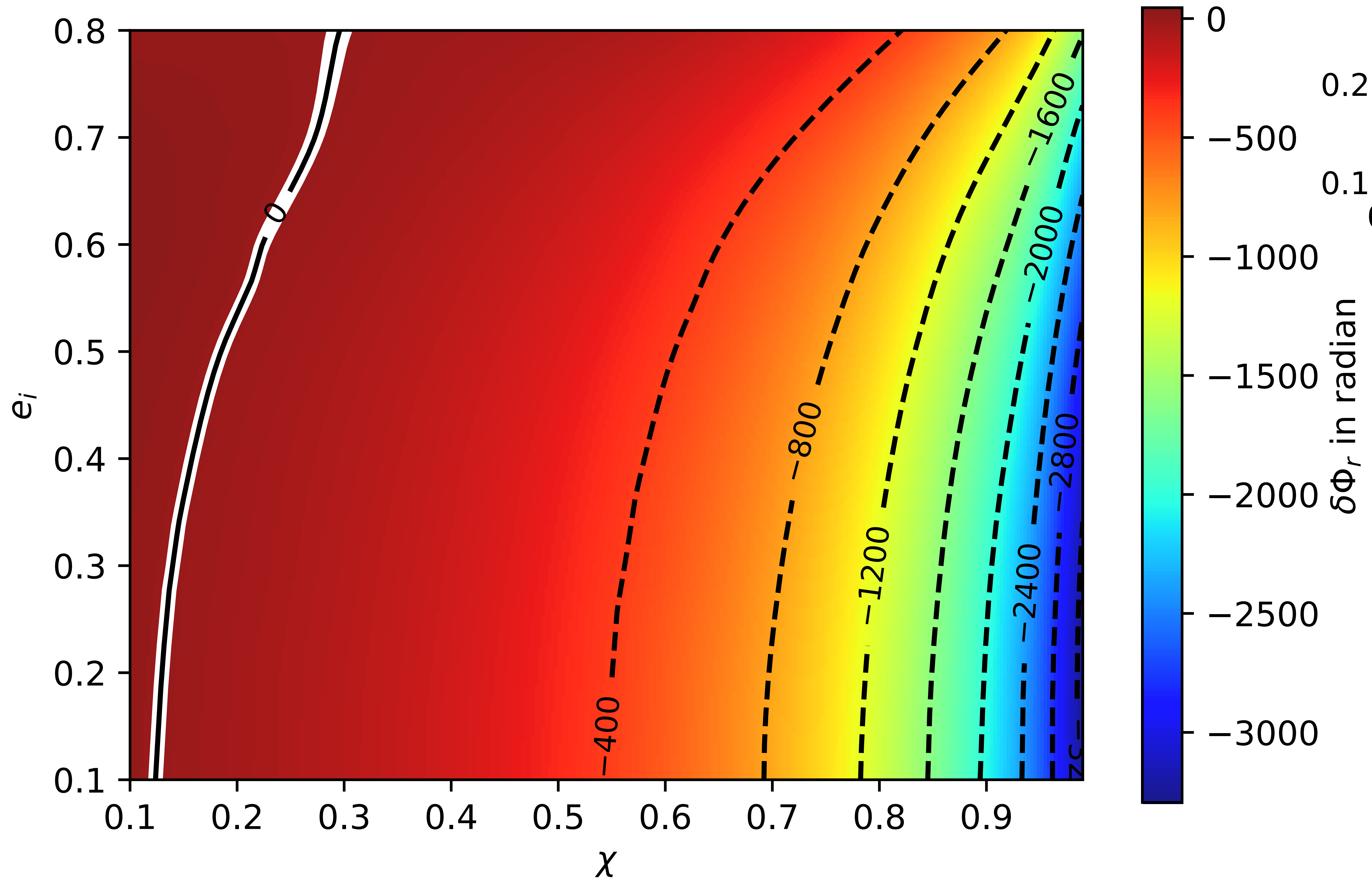
- Inspiral of binary is driven by energy loss at infinity and at horizon.
- Switching off energy exchange due to heating modifies inspiral rate, resulting in change in GW.
- Calculate GW with and without TH and calculate dephasing PRD.101.044004 SD, Brito, Bose, Pani, Hughes.

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

e_i
χ
Δt in hour
$\Delta t\,/\,t$ in %
0
−15
−30
−45
−75
90
−105
−120
0.25
0.00
−0.25
−0.75
−1.00
8
16
24
32
40
48
56
64
72
0.08
0.16
0.24
0.32
0.40
0.48
0.56

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

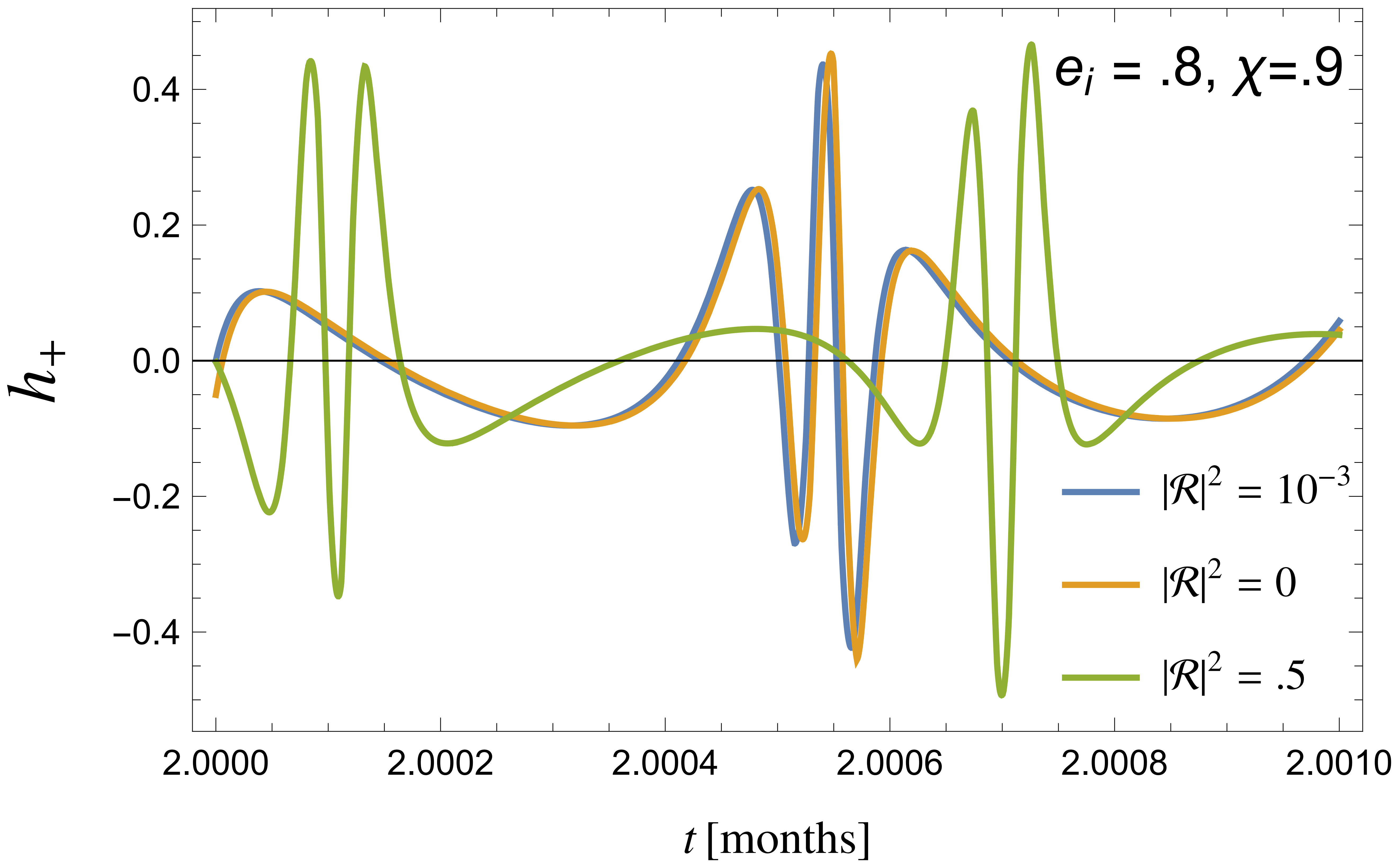


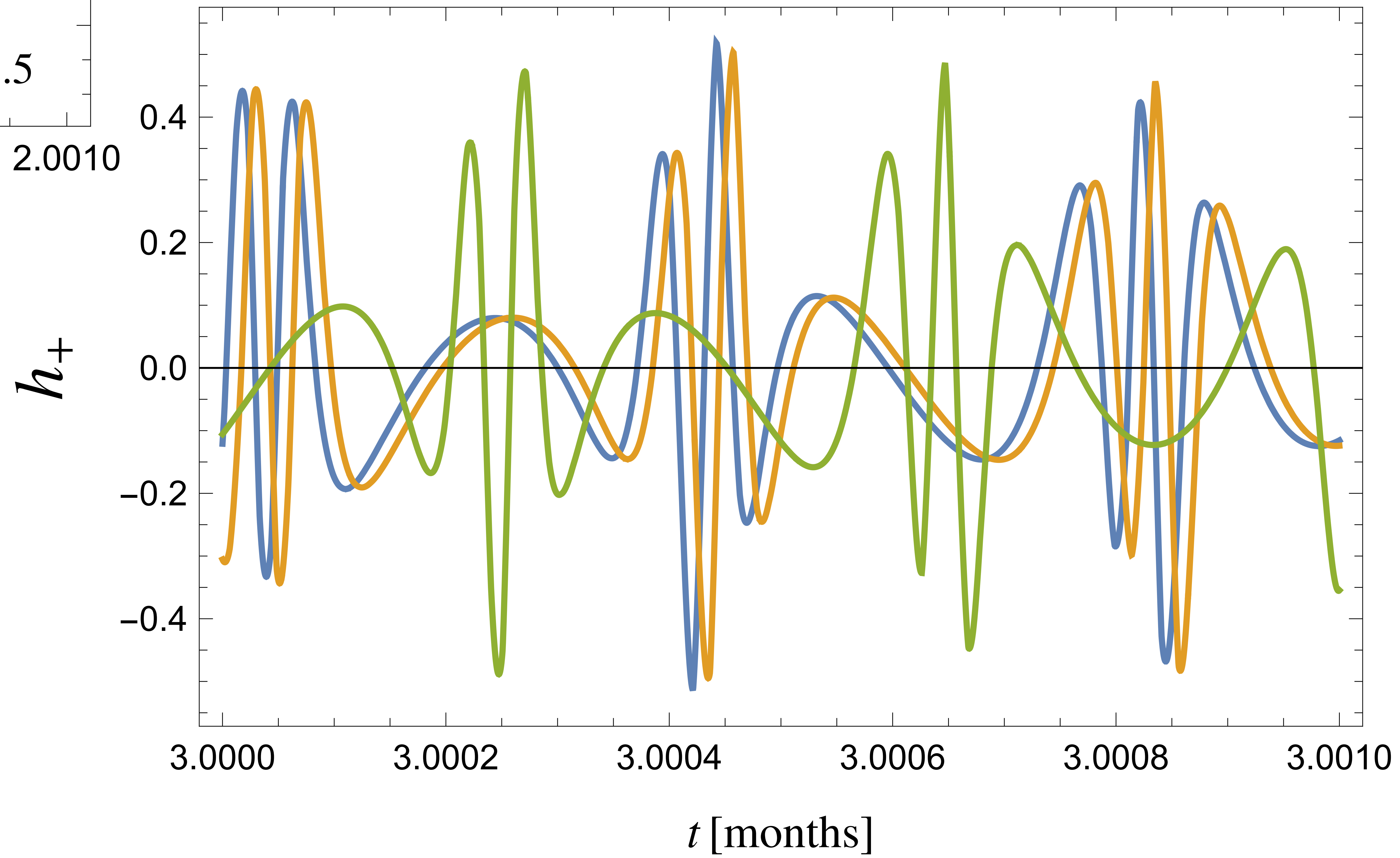


0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
e_i
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
χ
−200
−300
−400
−500
−600
−700
−800
−900
−1000
−1100
$\delta\Phi_\phi$ in radian
120
180
240
300
360
420
480
540
600
660
100
200
300
400
500
600
$\delta\Phi_r$ in radian

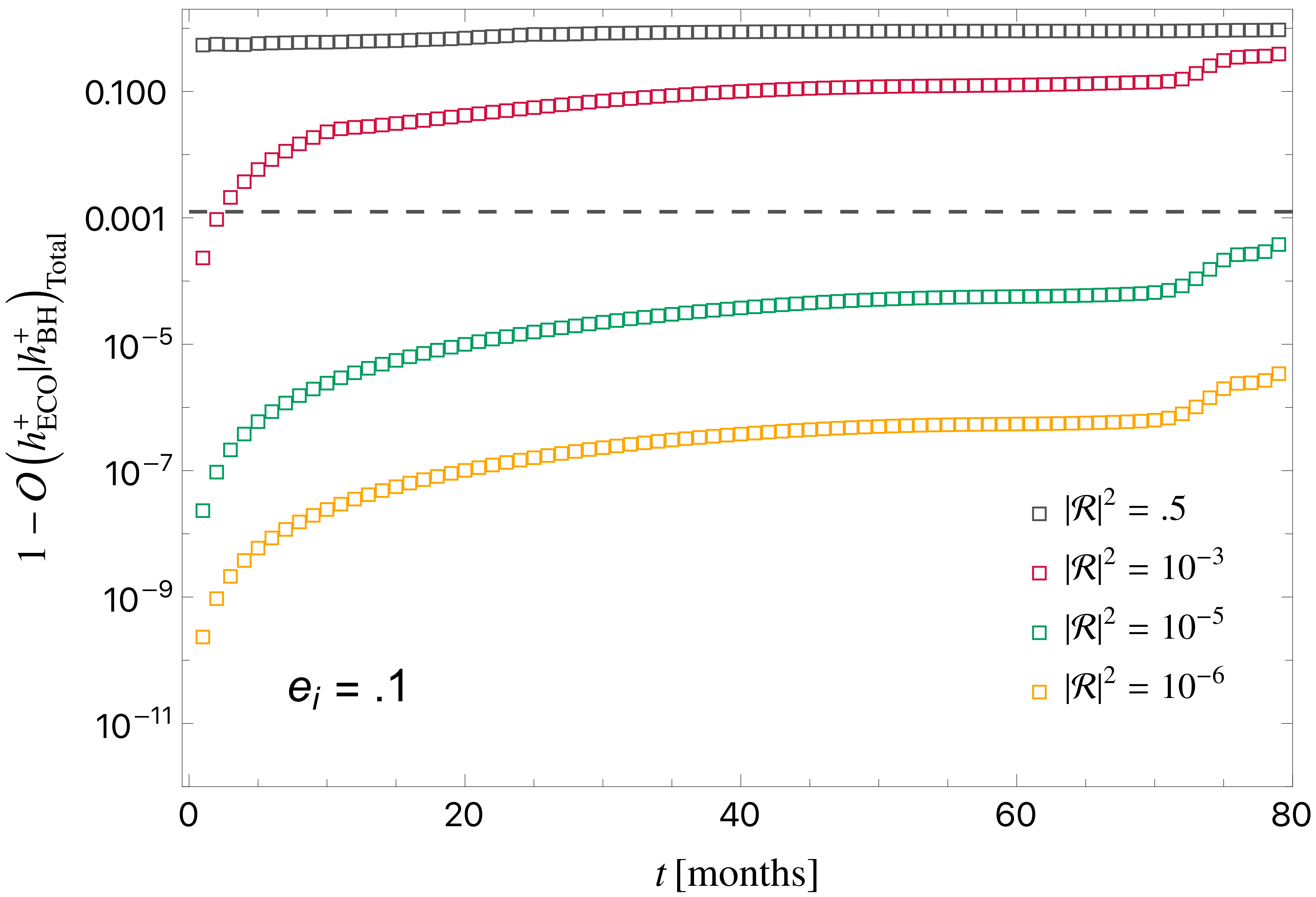
Usefulness of TH

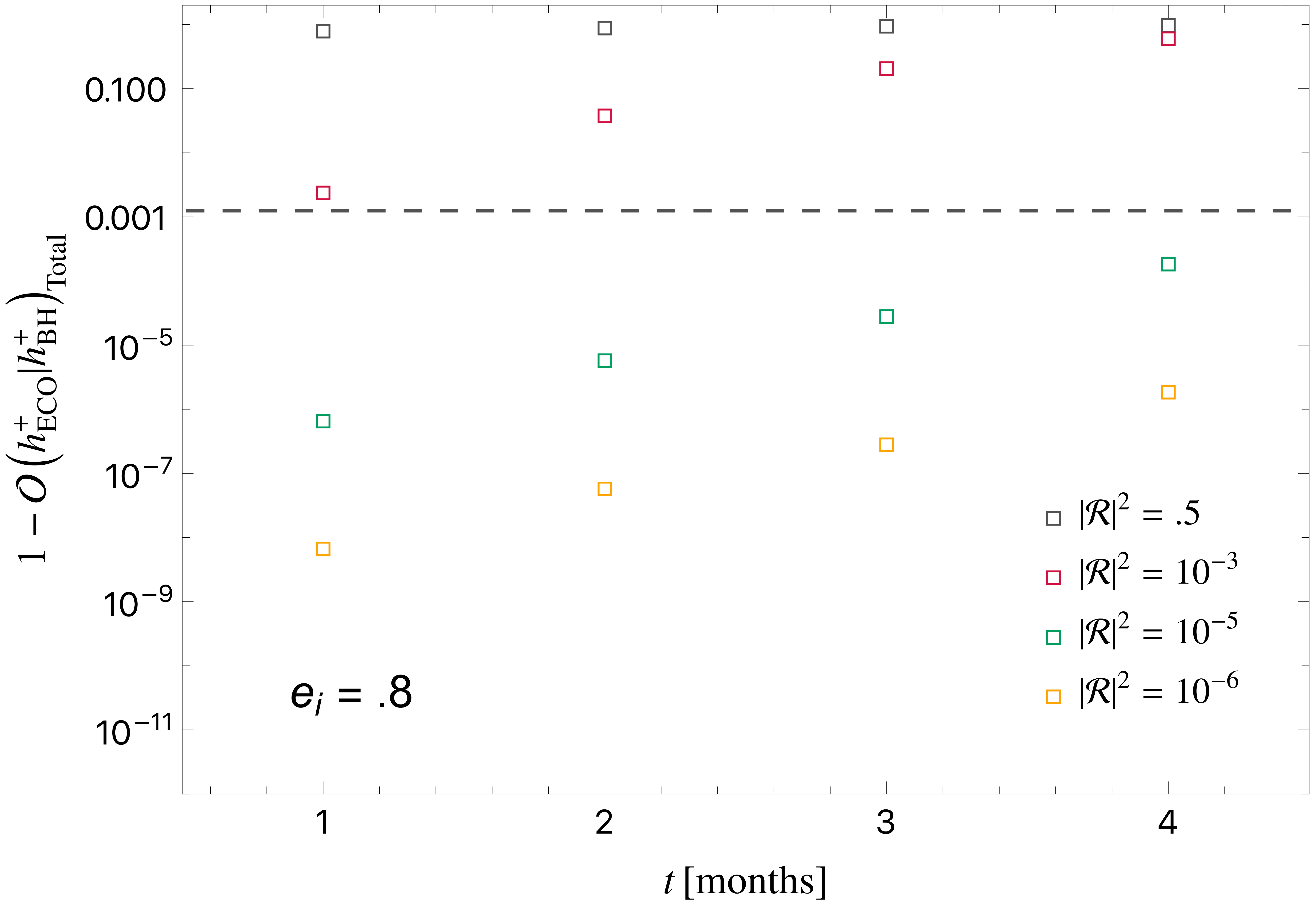
- $\dot{E}_{\mathrm{ECO}} = (1 - |\mathscr{R}|^2)\dot{E}_H + \mathcal{O}(\epsilon)$ SD, PRD.102.064040 , Maggio+ PRD104 (2021) 10, 104026
- $\mathscr{R}$ is the reflectivity of the ECO (QBH).
- position of the reflective surface $r_s = r_H(1 + \epsilon)$.
- Measuring $|\mathscr{R}|^2$ tests the "Blackness" of the hole and ϵ tests the "horizon" position. SD, S. Bose, PRD99,084001 (2019), Maselli+, PRL120,081101(2018)





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





- Image is the accumulated mismatch between waveforms with $|\mathscr{R}|^2 \neq 0$ and BH. with time.

$1-\mathcal{O}\left(h^+_{\rm ECO}|h^+_{\rm BH}\right)_{\rm Total}$
t [months]
$e_i = .5$
$|\mathcal{R}|^2 = .5$
$|\mathcal{R}|^2 = 10^{-3}$
$|\mathcal{R}|^2 = 10^{-5}$
$|\mathcal{R}|^2 = 10^{-6}$
$1-\mathcal{O}\left(h^+_{\rm ECO}|h^+_{\rm BH}\right)_{\rm Total}$
t [months]
$e_i = .1$
$|\mathcal{R}|^2 = .5$
$|\mathcal{R}|^2 = 10^{-3}$
$|\mathcal{R}|^2 = 10^{-5}$
$|\mathcal{R}|^2 = 10^{-6}$

Take Home

- TH in eccentric case computed analytically.
- Enhancement is different for spinning and non spinning.
- In EMRI, final orbital quantities can change due to modified TH, implying changed inspiral.
- TH induces large dephasing.
- In EMRI TH can lead to significant dephasing, resulting in constraining $|\mathscr{R}|^2 \sim 10^{-5} - 10^{-6}$.