Title: Tidal heating: a hunt for the horizon

Speakers: Sayak Datta

Series: Strong Gravity

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Abstract: The defining feature of a classical black hole horizon is that it is a "perfect absorber". Any evidence showing otherwise

would indicate a departure from the standard black-hole picture. Due to the presence of the horizon, black holes in binaries exchange

energy with their orbit, which backreacts on the orbit. This is called tidal heating. Tidal heating can be used to test the presence of a horizon.

I will discuss the prospect of tidal heating as a discriminator between black holes and horizonless compact objects, especially supermassive ones, in LISA.

I will also discuss a similar prospect for distinguishing between neutron stars and black holes in the LIGO band.

Tidal heating: a hunt for the horizon

Sayak Datta

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- Inclusion of superfluid nature of matter increases tidal deformability of NS. PRD98,084010(2018), PRD101,064016(2020)
- QNM of Shwarschild BH in $f(R)$ theory breakes isospectrality between Regge-Wheeler and Zerilli mode, unlike GR. Excites massive mode. EPJC80,14(2020)
- Absence of reflection symmetry accross equatorial plane of a stationary axisymmetric body, does not allow equatorial circular orbit.arXiv:2010.12387 [gr-qc]
- Tidal Heating. PRD99,084001(2019), PRD101,044004(2020), PRD102,064040(2020), arXiv:2004.05974[gr-qc], ++

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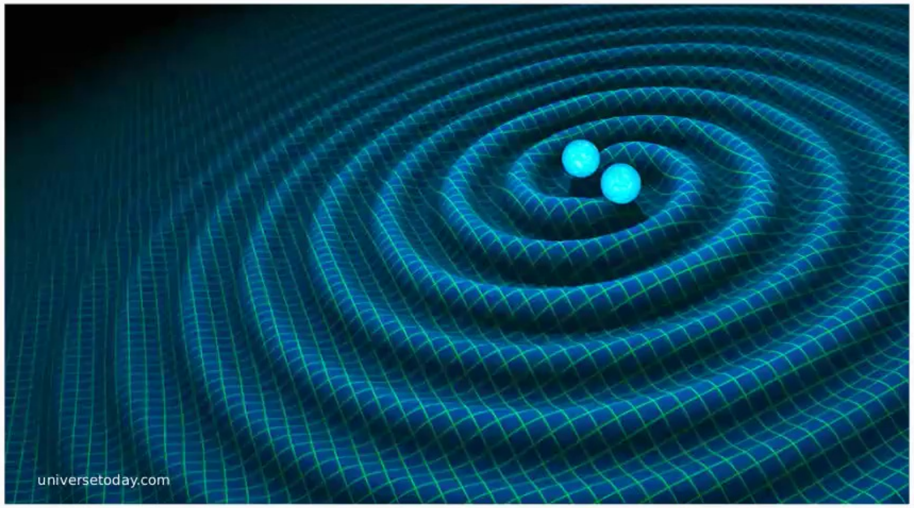
Gravitational Wave

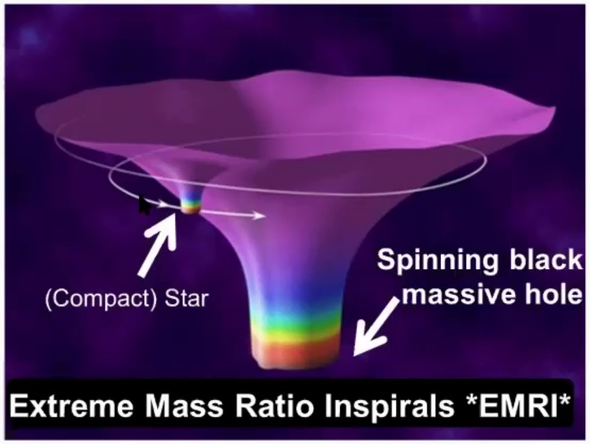
- GWs are the ripples in space time.
- Several sources can emit observable GW.
- We will focus on binary coalescence.



- EMRI and CMRI.

Astrophysical overview: EMRI

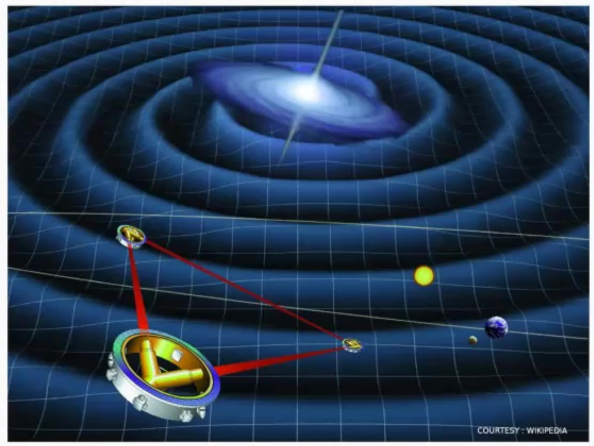
- Center of a galaxy can host SMBH of mass $\sim 10^6 - 10^7 M_\odot$.
- Stellar mass stars, BHs get captured in inspiral around such SMBHs.
- Mass ratio $\leq 10^{-4}$.



Credit: Isoyama

Astrophysical overview: EMRI

- 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 $(10^{-4} - .1)Hz$.



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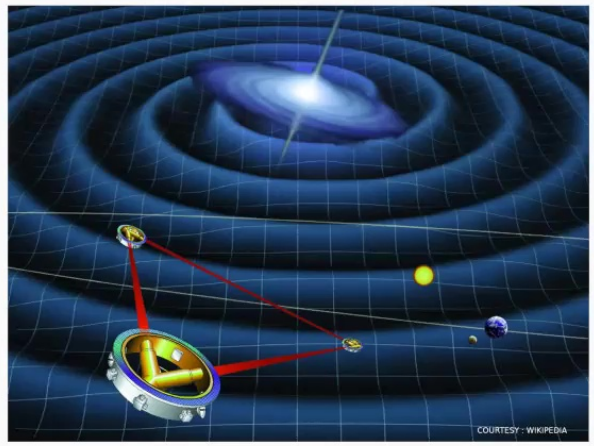
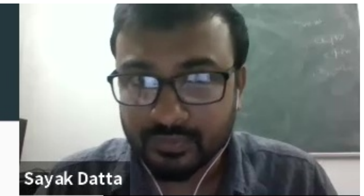


- $\Delta T = \frac{5}{2^{2/3}\pi^{8/3}1024} \frac{c^3}{G\mu} \frac{c^2}{(GM)^{2/3}} (f_1^{-8/3} - f_2^{-8/3})$.
- For $M \sim 10^6 - 10^7 M_\odot$ and $\mu \sim 5 - 50 M_\odot$, $\Delta T \sim$ Months.

Prospects

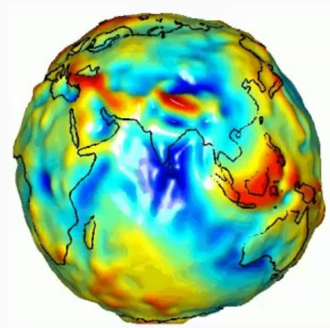


- How to use this opportunity?
- Are they BH of classical GR?
- Not ECO, BS?
- If yes, then how to distinguish from BH?
- How to test the presence(absence) of hair?

Prospects

- EMRIs are probe of BH space-time with small particle.
- Measurment analogous to geodesy(measurement of gravitational field with orbit) will bring important information.
- In Newtonian case,

$$\nabla^2 \Phi = 4\pi G \rho. \tag{1}$$



Credit: GRACE

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$$\Phi = -\frac{GM}{r} + \sum_{\ell} \sum_{m} M_{\ell m} Y_{\ell m}(\theta, \phi) \tag{2}$$

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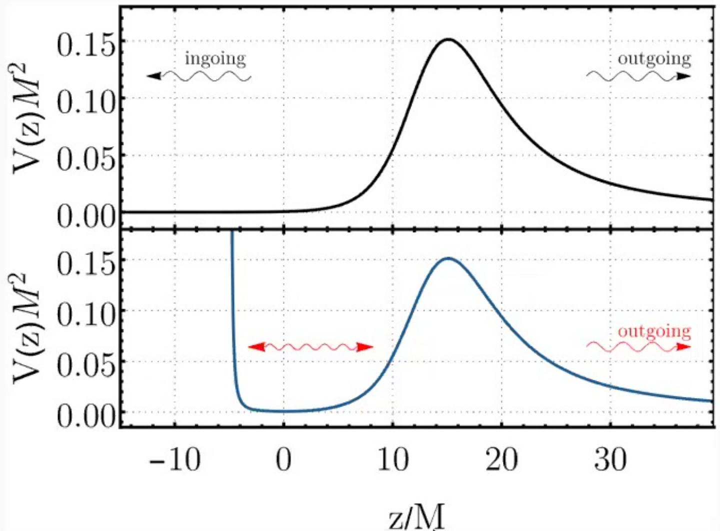
Tidal heating

- Classicaly black hole (BH) horizons (apparent) are perfect absorbers.
- Absence (modification) of horizon implies imperfect absorption.
- Measuring some amount of reflectivity near a dark compact object would be a smoking gun of departures from the classical BH picture.



Credit: Vitor Cardoso

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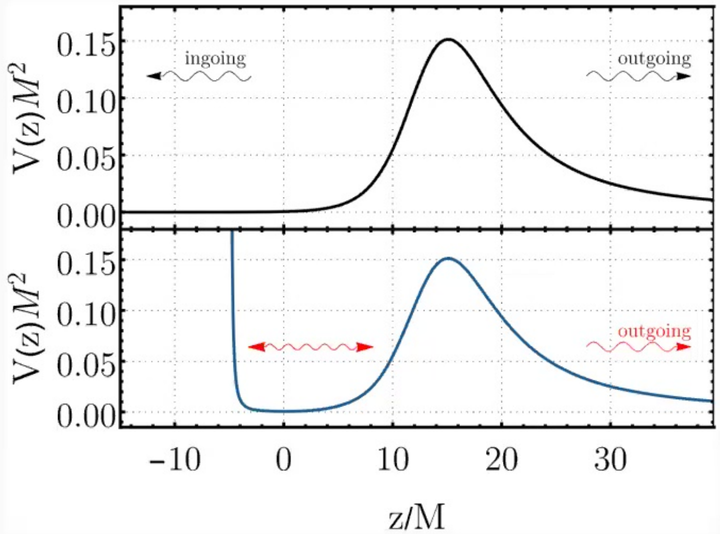
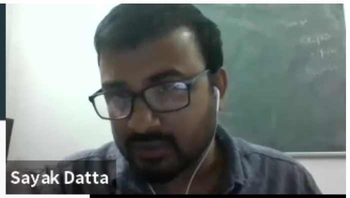


Credit: Vitor Cardoso

- ECO, Quantum BH? Abedi+ Universe43,6(3)2020



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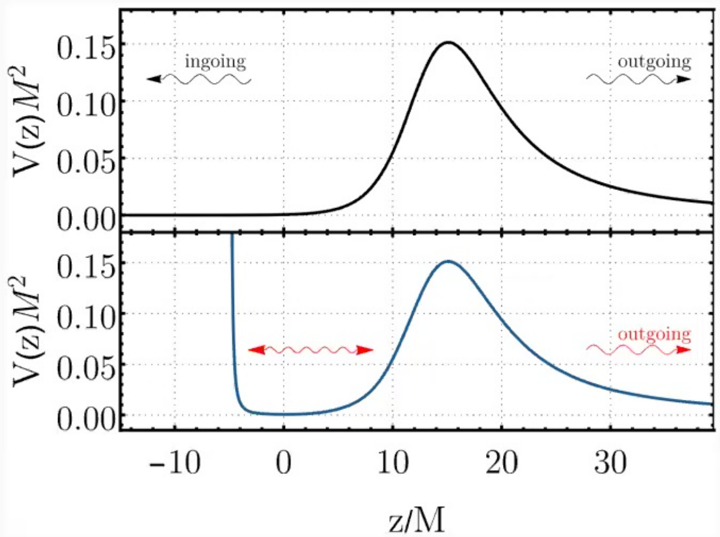
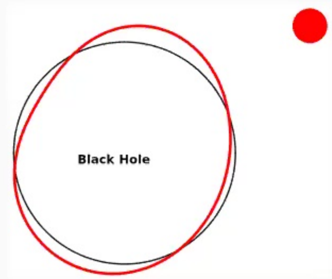


Credit: Vitor Cardoso

- ECO, Quantum BH? Abedi+ Universe43,6(3)2020
- This can be done using Tidal heating.

Tidal heating

- Components in a binary feel each others' tidal fields (strongly in the late inspiral).



Credit: CQG28,175006(2011)

Credit: Tanja Hinderer

- 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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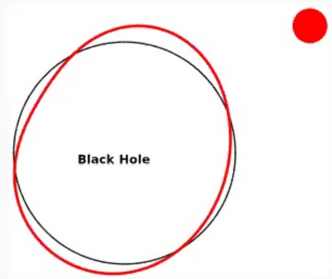

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- We study importance and implication of it in EMRI and CMRI.

Tidal heating

- 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.
- Theory suggests single-star evolution can't produce BH of $3 - 5 M_\odot$, referred to as the lower mass gap. (Bailyn+ APJ499,367(1998), Samsing+ arXiv:2006.09744, Essick+ APJ904,80(2020))
- Distinguish BH and NS in this range can change NS mass upperbound and BH mass lower bound.

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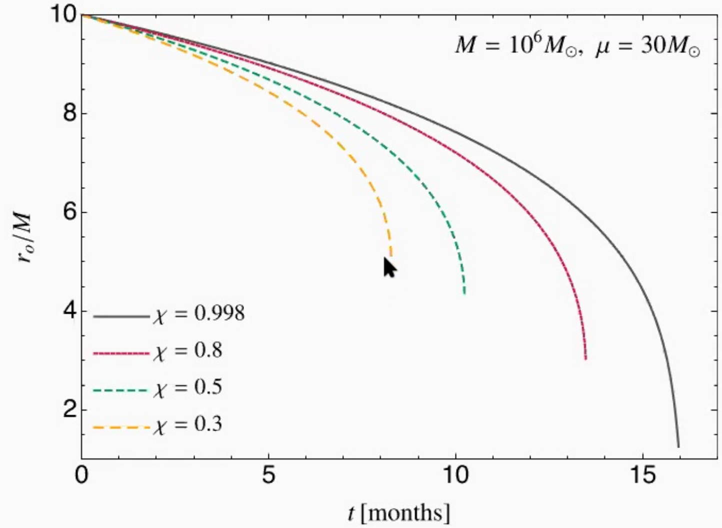
Construction

- We will focus on SMBH first.
- For the first project we calculate perturbation around Kerr 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.



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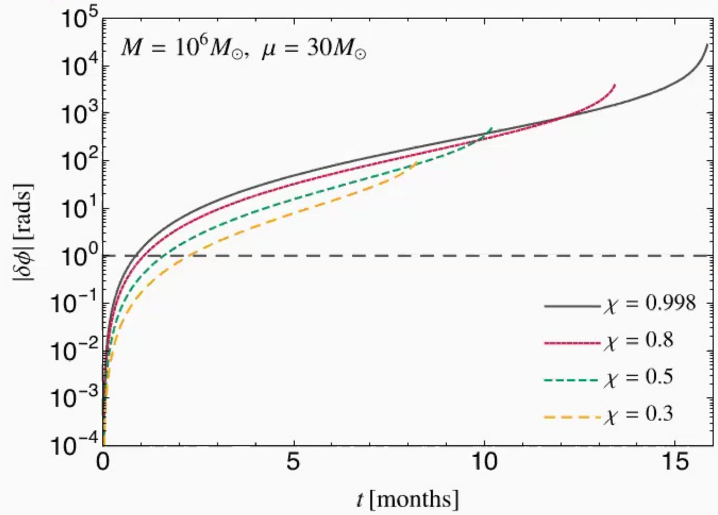
Importance of heating

- 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.
- Gremlin code available in the Black Hole Perturbation Toolkit is used.
- Calculate GW with and without TH and calculate dephasing (PRD.101.044004 SD, Richard Brito, Sukanta Bose, Paolo Pani, Scott A. Hughes).



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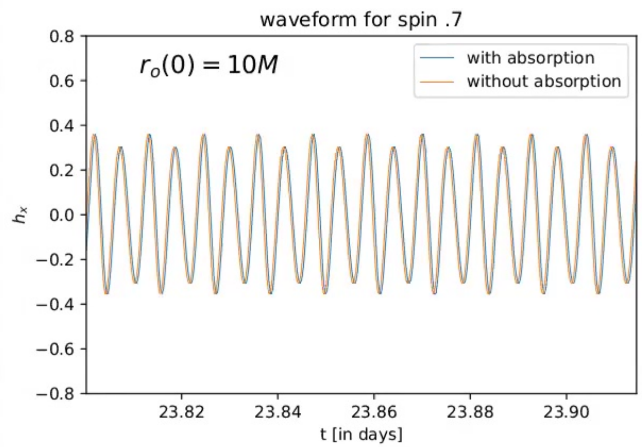
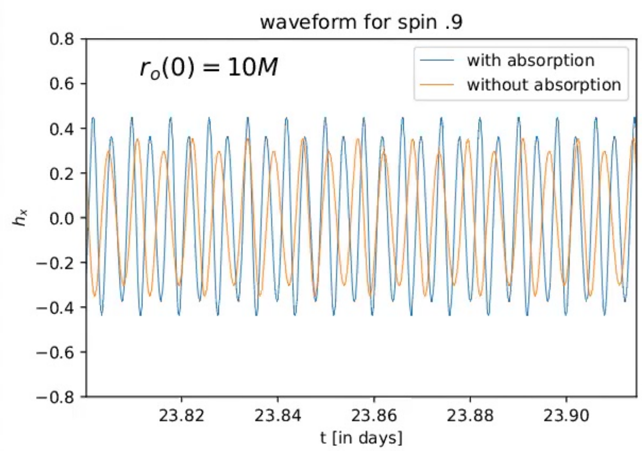
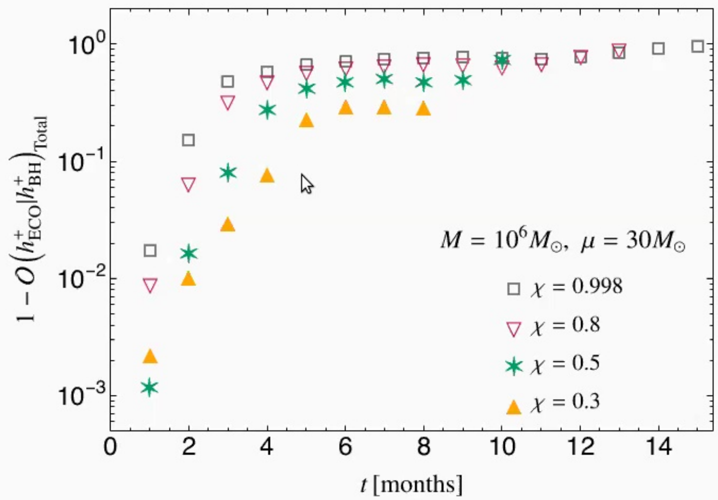
Importance of heating

- What about the waveform?





Importance of heating



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Usefulness of heating

Usefulness of heating

- For ECO, (SD, PRD.102.064040)

$$\dot{E}_{\mathrm{ECO}} = (1 - |\mathcal{R}|^2)\dot{E}_H + \mathcal{O}(\epsilon)\,, \tag{3}$$

- $\mathcal{R}$ is reflectivity of the ECO (QBH).
- position of the reflective surface $r_s = r_H(1+\epsilon)$.
- Measuring $|\mathcal{R}|^2$ tests "Blackness" of the hole and ϵ tests the horizon position. (SD, S. Bose, PRD99,084001 (2019), (Maselli+, PRL120,081101(2018))

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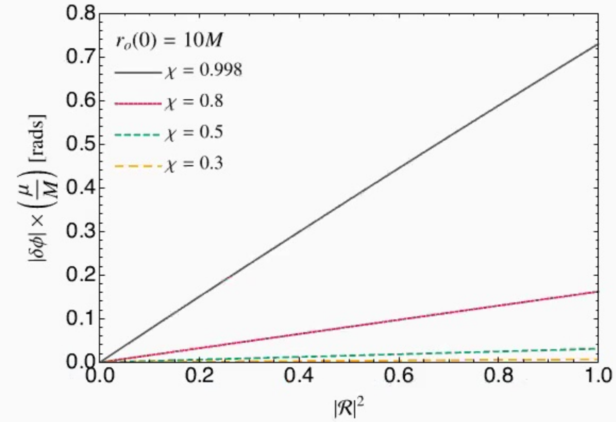
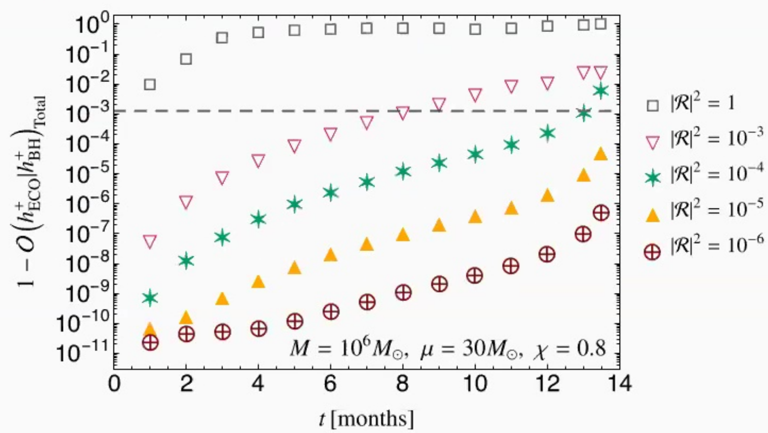
Usefulness of heating





(PRD.101.044004 SD, Richard Brito, Sukanta Bose, Paolo Pani, Scott A. Hughes)

Entrance of the Horizon parameter

- This is a 2.5 pn correction. So, the flux has an extra contribution $(\frac{dE}{dt}\big|_H)$.

$$-\frac{dE}{dt} = -\frac{dE}{dt}\bigg|_{NoTH} - \frac{dE}{dt}\bigg|_{TH}.$$

- To track these terms we multiply these contributions by H.
- So, now we have

$$-\frac{dE}{dt} = -\frac{dE}{dt}\bigg|_{NoTH} - H\frac{dE}{dt}\bigg|_{TH}.$$

- $$H = 1 - |\mathcal{R}|^2$$
- Now if $H = 1$ then these terms will contribute in the phase, implying the presence of horizon.
- Now if $H = 0$ then these terms will not contribute in the phase, implying the absence of the horizon.
- We name it Horizon parameter.

Modelling

- BHs are expected to be Kerr-like.
- Kerr BH has multipole of the form,

$$M_\ell + iS_\ell = M(ia)^\ell \tag{4}$$

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$$M_{2\ell+1} = S_{2\ell} = 0 \tag{5}$$

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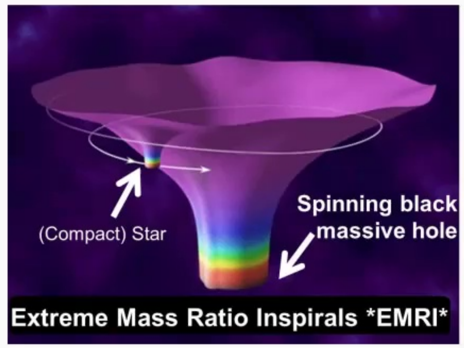
Modelling

- We construct waveform of EMRI in circular equatorial orbit.



- We model multipole moments of central object as $M_\ell + iS_\ell = \alpha_\ell M(ia)^\ell$ and treat α_ℓ as independent parameter. Check Krishnendu+ PRL119,091101(2017) too.

Modelling

- GW,

$$h = Ae^{i\psi} \tag{6}$$

- In adiabatic limit $(\frac{\dot{f}}{f^2}) \ll 1$ (Tichy+ PRD 61, 104015(2000))

$$\psi(f) =\sim \int_{v_i}^{v} d\bar{v}(v^3 - \bar{v}^3)\frac{E'(\bar{v})}{-dE/dt}, \tag{7}$$

$v = (\pi M f)^{1/3}$ and $f = 2\Omega$.

- Flux depends on physical parameters,

$$-\frac{dE}{dt}\Big|_{I_{ij}} = \frac{32}{5} m^2 r^4 \Omega^6. \tag{8}$$

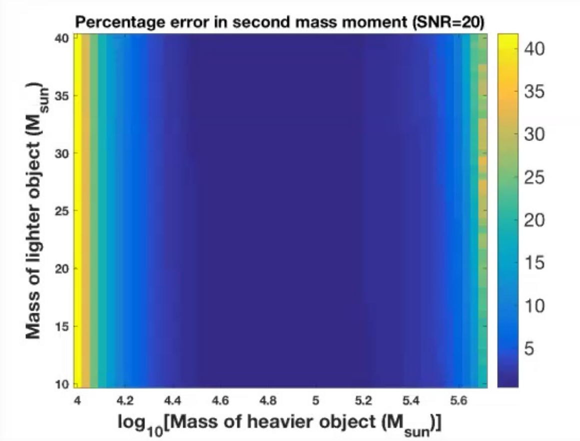
- $$r = M v^{-2}\Big(1 + \sum_{\ell=2,4,\ldots} \sim M_\ell v^{2\ell} - \sum_{\ell=1,3,\ldots} \sim S_\ell v^{2\ell+1}\Big) \tag{9}$$

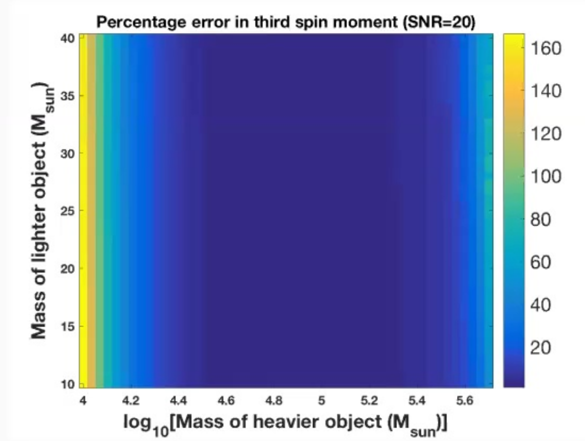
(Ryan, PRD 52, 5707(1995))

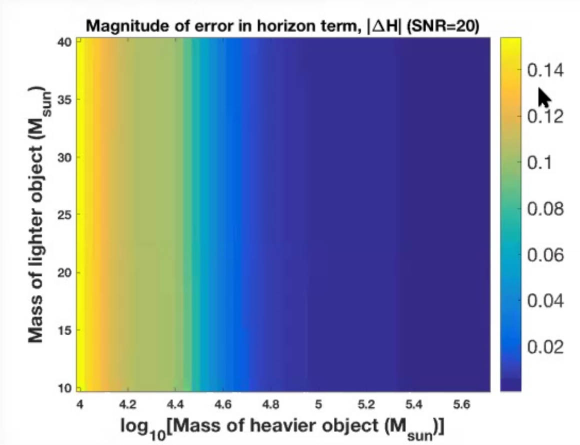
Estimates

- We do a Fisher analysis with some injected values of the model parameters ($H, \alpha_\ell, a, \Lambda$ etc).
- Then adding the LISA noise curve we try to estimate the values for SNR 20 (SD, S. Bose, PRD99,084001 (2019)).

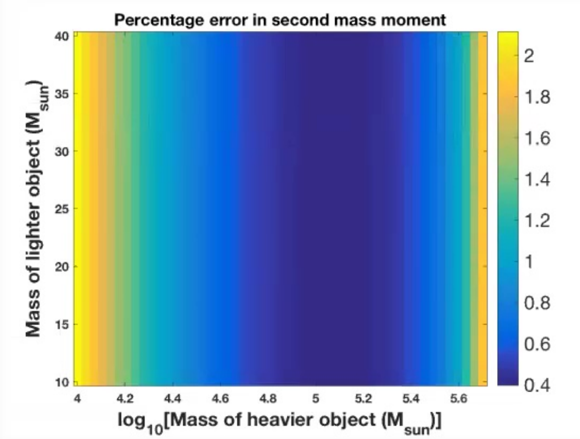
Estimates (BH case)

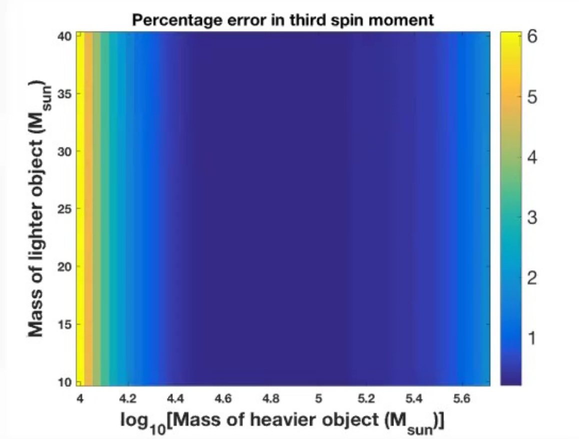






Estimates (BS case)





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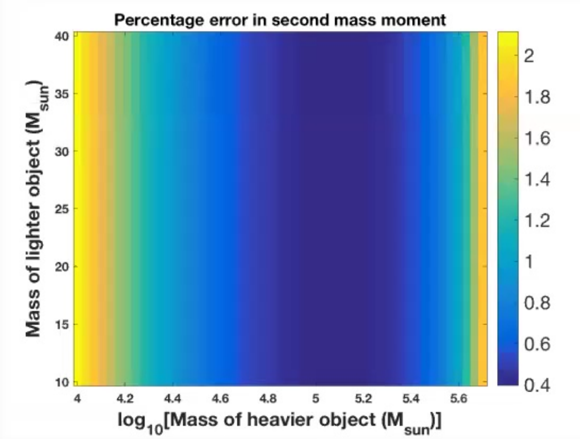
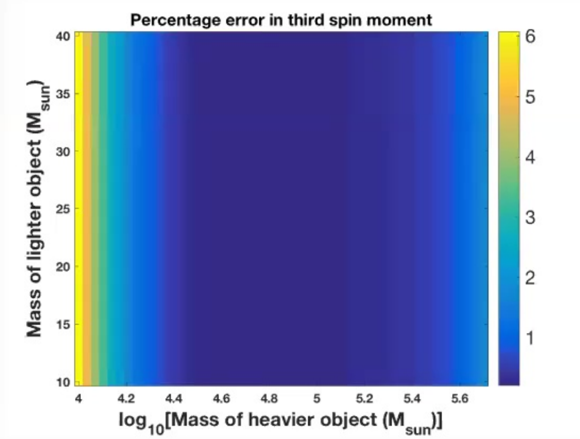
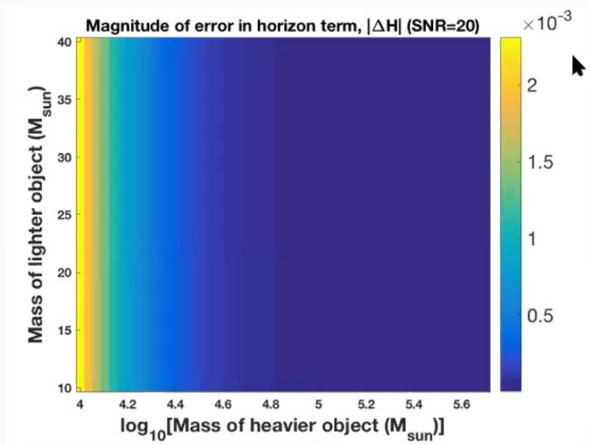






What does it mean?

- TH is a strong effect.
- It can add thousands of cycles in the phase of GW from EMRI.
- α_4 and α_5 which represents M_4 and S_5 will have huge error if estimated.
- We we will be able to measure H better than $1 \pm .5$ for BBH.
- For BSBH case H will be measured better than $0 \pm .04$.
- So, $H = 1$ and $H = 0$ case are distinguishable.
- Presence or absence of horizon is testable.
- α_2 and α_3 are measurable as $1 \pm .4$ and $1 \pm .8$ for BBH case and as $34 \pm .68$ and 47 ± 2.82 for BSBH case.
- Therefore, testing presence of hair and distinguishing between different sources will be possible.

What about Surface position?

- What if the position is at $r_s = r_+(1+\epsilon)$?
- Outside it the metric is like Kerr BH.
- Area can be expanded in ϵ,

$$A = \sum_{i=0}^{\infty} \epsilon^i A^{(i)}, \tag{10}$$

- For BH

$$\delta A = \partial_M A \delta M + \partial_a A \delta a \tag{11}$$

- Now,

$$\partial_M A = \sum_{i=0}^{\infty} \epsilon^i \partial_M A^{(i)}, \tag{12}$$

$$\partial_a A = \sum_{i=0}^{\infty} \epsilon^i \partial_a A^{(i)}, \tag{13}$$

What about Surface position?

- For BH,

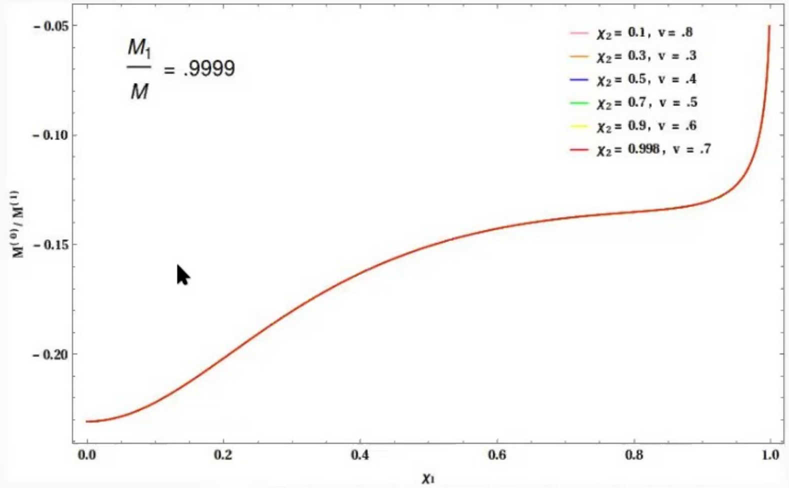
$$\frac{dA}{dt} \propto |\psi_0|^2|_{r=r_+} \tag{14}$$

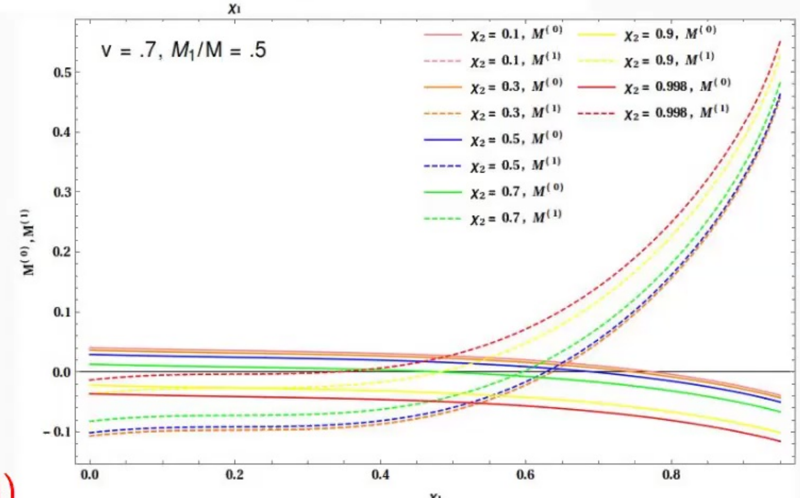
- Knowledge of $|\psi_0| \to$ knowledge of $\delta A \to$ knowledge of δM.
- Since, ϵ is small and object is "almost Kerr", we assume

$$\frac{dA}{dt} \propto |g_s|^{1/2}|\psi_0|^2|_{r=r_s} \tag{15}$$

- For BH, $\psi_0|_{r_+} \sim e^{-i\omega t}e^{-ikr_*}$
- Now, $\psi_0|_{r_s} \sim e^{-i\omega t}(\mathcal{T}e^{-ikr_*} + \mathcal{R}e^{ikr_*})$
- Using this, $\frac{dM}{dt} \propto \mathcal{T}^2 \sum_{i=0}^{1} \mathcal{M}^{(i)}\epsilon^i$
- Hence, $\mathcal{T}^2 \sim H \sim 1 - \mathcal{R}^2$
- $\mathcal{M}^{(0)}$ is BH part, $\mathcal{M}^{(1)}$ is the "new" part.

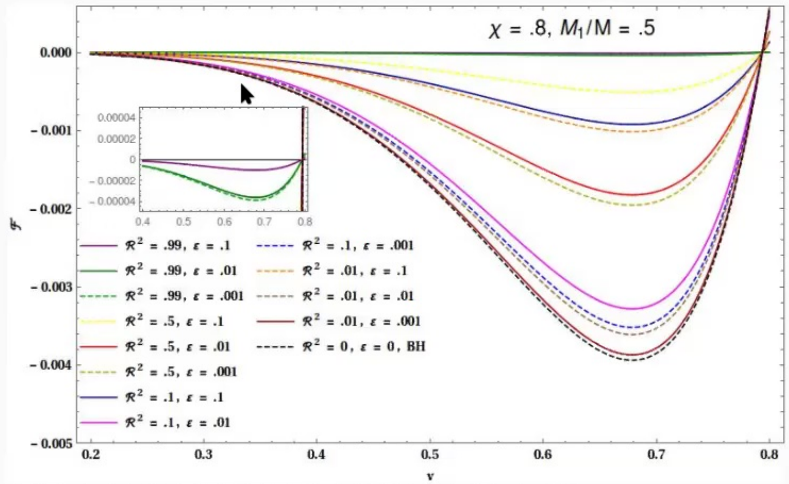
What about Surface position?

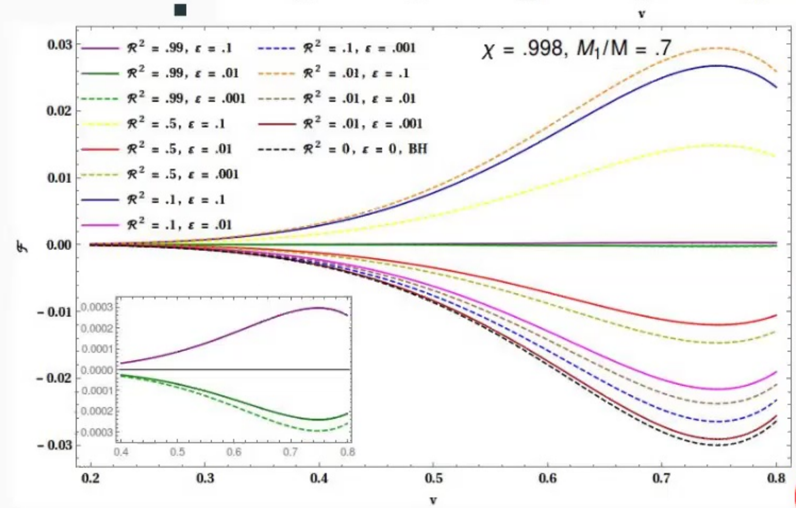




(SD, PRD.102.064040)

What about Surface position?





(SD, PRD.102.064040)

What about Surface position?

- $|\mathcal{M}^{(0)}| \sim |\mathcal{M}^{(1)}|$
- The contribution in flux ,

$$\frac{dM}{dt} \propto (\mathcal{M}^{(0)} - |\mathcal{R}|^2\mathcal{M}^{(0)} + \mathcal{M}^{(1)}\epsilon - |\mathcal{R}|^2\mathcal{M}^{(1)}\epsilon) \qquad (16)$$

.

- Since, $|\mathcal{R}|^2 \sim 10^{-5}$ is observable, then it may be $\epsilon \sim 10^{-5}$ can add "sufficient" imprint too.
- $\mathcal{O}(\epsilon^2)$ has terms like $|\mathcal{T}||\mathcal{R}|cos(\phi_{\mathcal{R}} - \phi_{\mathcal{T}} - \bar{\alpha}(\chi, M)log(\epsilon))$. (UPCOMING: Sumanta Chakraborty, SD, Subhadip Sau, Sukanta Bose)
- $\mathcal{T} = |\mathcal{T}|e^{i\phi_{\mathcal{T}}}$ and $\mathcal{R} = |\mathcal{R}|e^{i\phi_{\mathcal{R}}}$

What about CMRI?

- $M_1 \sim M_2$
- For EMRI TH of the small body is comparatively ignorable.
- In CMRI they are not.
- For near equal mass binary there will be H_1 and H_2 for the two components.
- For observation they are degenarate parameters.
-

$$\begin{aligned}\Psi_{TH} \propto \Big[&\sim v^5 (f(H_1, m_1, \chi_1) + f(H_2, m_2, \chi_2)) \\ &+ \sim v^7 (f(H_1, m_1, \chi_1) + f(H_2, m_2, \chi_2)) \\ &+ \sim v^8 (g(H_1, m_1, \chi_1) + g(H_2, m_2, \chi_2)) \Big] \end{aligned} \tag{17}$$

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H_{eff5} and H_{eff8}

- Effective parameters are needed.
- Due to degeneracy we define,

$$H_{eff5} = \sum_{i=1}^{2} H_i \left(\frac{m_i}{m}\right)^3 \left(\hat{L}.\hat{S}_i\right) \chi_i \left(3\chi_i^2 + 1\right) , \tag{18a}$$

$$H_{eff8} = 4\pi H_{eff5} + \sum_{i=1}^{2} H_i \left(\frac{m_i}{m}\right)^4 \left(3\chi_i^2 + 1\right) \left(\sqrt{1 - \chi_i^2} + 1\right)$$

(SD, Khunsang Phukon, Sukanta Bose)

- Phase due to TH becomes,

$$\Psi_{TH} = -\frac{3}{128\nu}\left(\frac{1}{v}\right)^5 \left[\frac{10}{9} v^5 H_{eff5} \left(3\log(v) + 1\right) + \frac{5}{168} v^7 H_{eff5} \left(952\nu + 995\right) + \frac{5}{9} v^8 \left(4H_{eff8} - H_{eff5}\psi_{SO}\right)\left(3\log(v) - 1\right)\right] . \tag{19}$$

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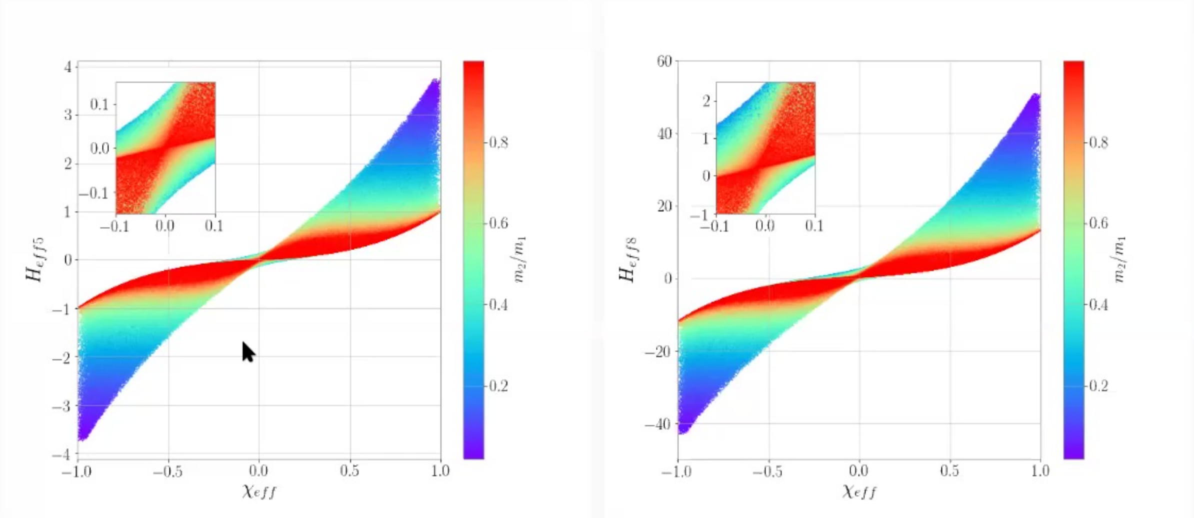
H_{eff5} and H_{eff8}



- (arXiv:2004.05974 SD, Khunsang Phukon, Sukanta Bose)

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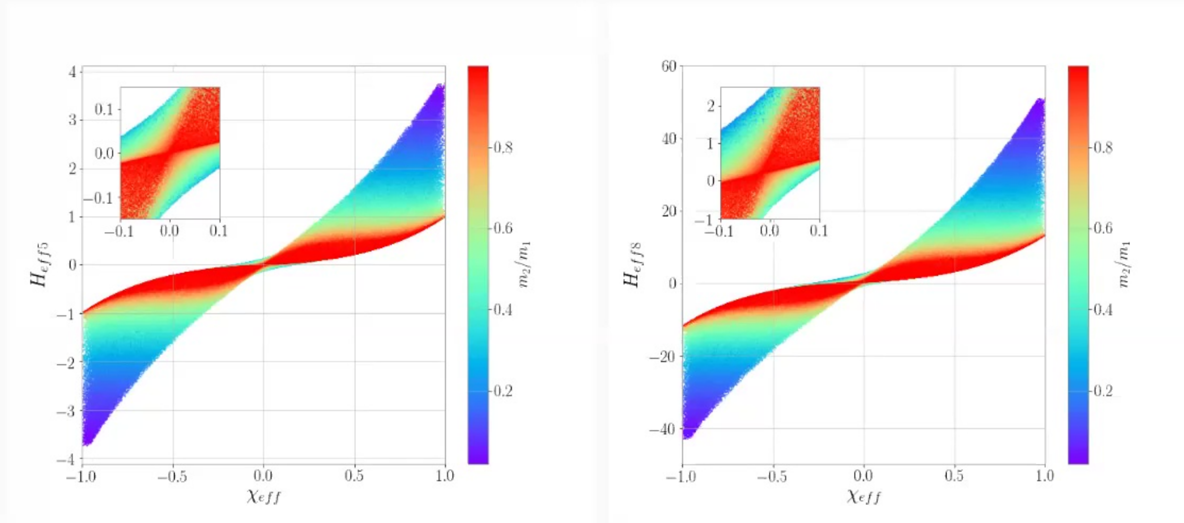
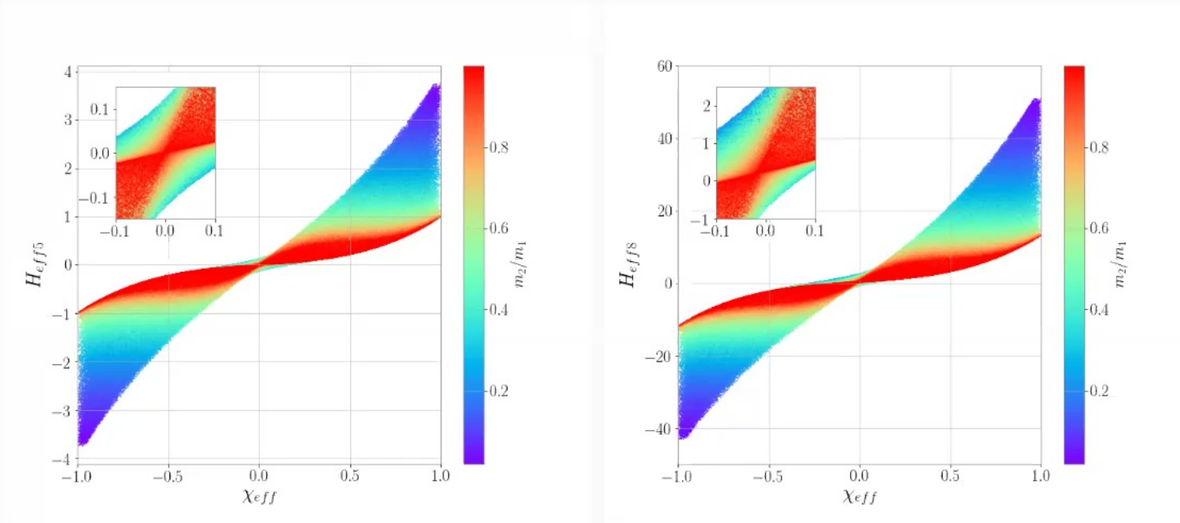
H_{eff5} and H_{eff8}



- (arXiv:2004.05974 SD, Khunsang Phukon, Sukanta Bose)
- For non-spinning case $H_{eff5} = 0$ but $H_{eff8} \neq 0$

$H_{eff\,5}$ and $H_{eff\,8}$



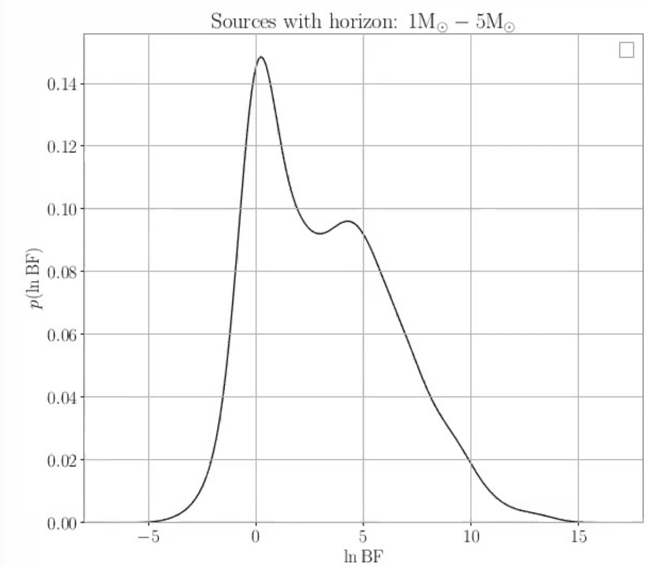
- (arXiv:2004.05974 SD, Khunsang Phukon, Sukanta Bose)
- For non-spinning case $H_{eff\,5} = 0$ but $H_{eff\,8} \neq 0$
- So, in low spin case $H_{eff\,8}$ is the discriminator of horizon.

Bayesian evidence

- Using H_{eff5} and H_{eff8} we can construct Bayesian model selection for presence of horizon.
- We choose TaylorF2 as waveform for absence of horizon.
- TaylorF2 + TH =HTF2 (Heated TaylorF2) for presence of horizon.
- After injecting a particular kind of waveform we can test the evidence of both TF2 and HTF2 using B_F.

Bayesian evidence

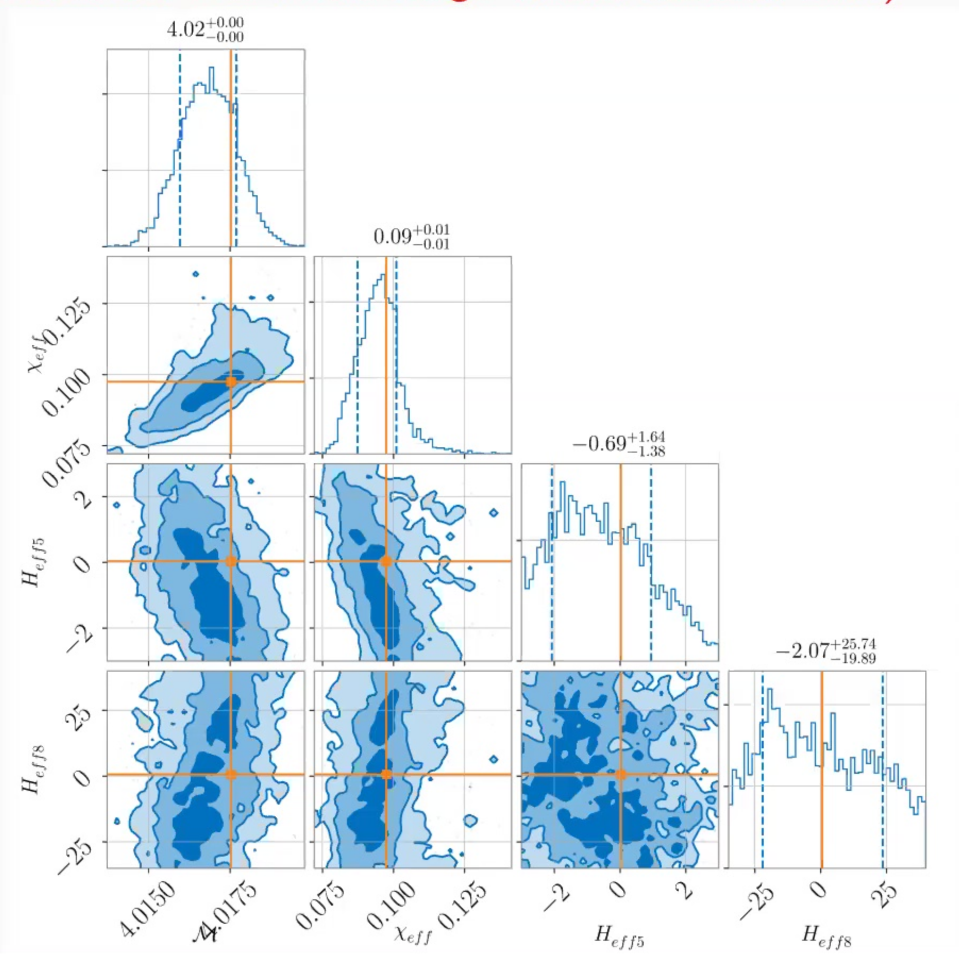
- For $50 - 250MPc$ and $1 - 5M_{\odot}$ binaries with advance LIGO, (SD, Khunsang Phukon, Sukanta Bose)



- duration is 16s and ISCO is cutoff.

Bayesian evidence

- (arXiv:2004.05974 SD, Khunsang Phukon, Sukanta Bose)



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Projects for the future!!

- Model TH properly.
- Include TH in BBH.
- Model BHNS with TH.
- Are BNS waveforms "right"? Sytematics?
- New phenom models with TH.
- Effect of reflectivity on merger phase. NR?

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Area quantization

What if BH area is quantized?

- There are proposals of BH area quantization (Bekenstein and Mukhanov PLB360,7(1995), Agullo+ PRL100,211301(2008)).

$$A_N = \alpha \ell_{Planck}^2 N, \quad \ell_{Planck} = \sqrt{\hbar G/c^3} = 1.6 \times 10^{-35}\mathrm{m} \tag{20}$$

- Since Area, mass and spin is related in Kerr metric, area quantization leads to discrete mass (Agullo+ PRL.126.041302(2021)).
- If mass is increasing then it will increase discretely and infalling energy should respect it by having quanta $= \hbar\omega_n$.
-

$$\omega_n = \frac{\kappa\alpha}{8\pi} n + 2\Omega_H \tag{21}$$

- Hawking radiation gives, the line width Γ.
- Has been studied in the context of postmerger (Cardoso JCAP08(2019), Laghi+ arXiv:2011.03816)

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- In inspiral this implies $H \to H(\omega)$.

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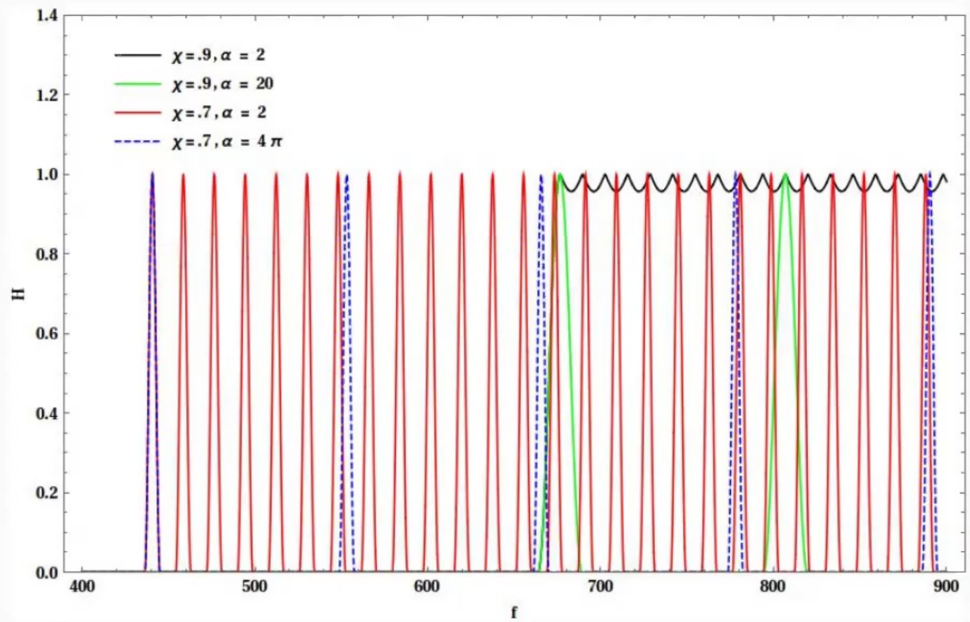
What if BH area is quantized?

- For this phenomena to be present in inspiral $f_0 < f_{Contact}$.
- To measure α, $f_1 < f_{Contact}$.



- Presence of TH below $f < f_0$ rules out area quantization.

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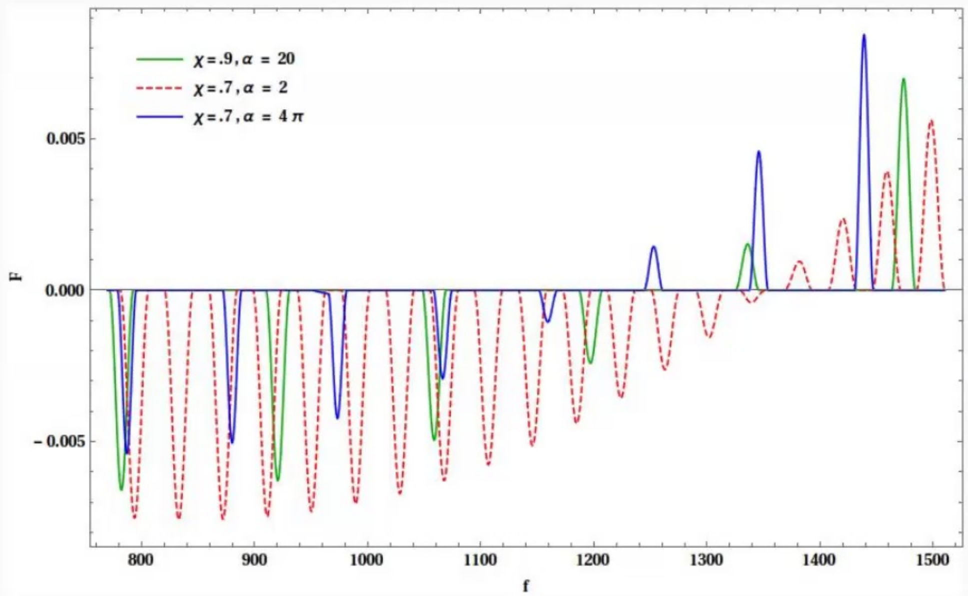
What if BH area is quantized?



- With this we can measure α.
- By treating Γ as independent parameter, we can probably probe Hawking radiation.

Take home

- TH is very strong in EMRI.
- It can add hundreds of cycles in the GW.
- Using H presence of horizon can be tested.
- In EMRI even $|\mathcal{R}|^2 \sim 10^{-5}$ can have observable effect.
- α_ℓ measurement can test presence of hair.
- ϵ can leave observable imprint, but degenarate with H
- In CMRI due to degenaracy we need H_{eff5} and H_{eff8}.
- Using Bayes factor absence of TH can be distinguished.
- With proper modeling it might be possible to probe area quantization and Hawking radiation.

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THANK YOU!