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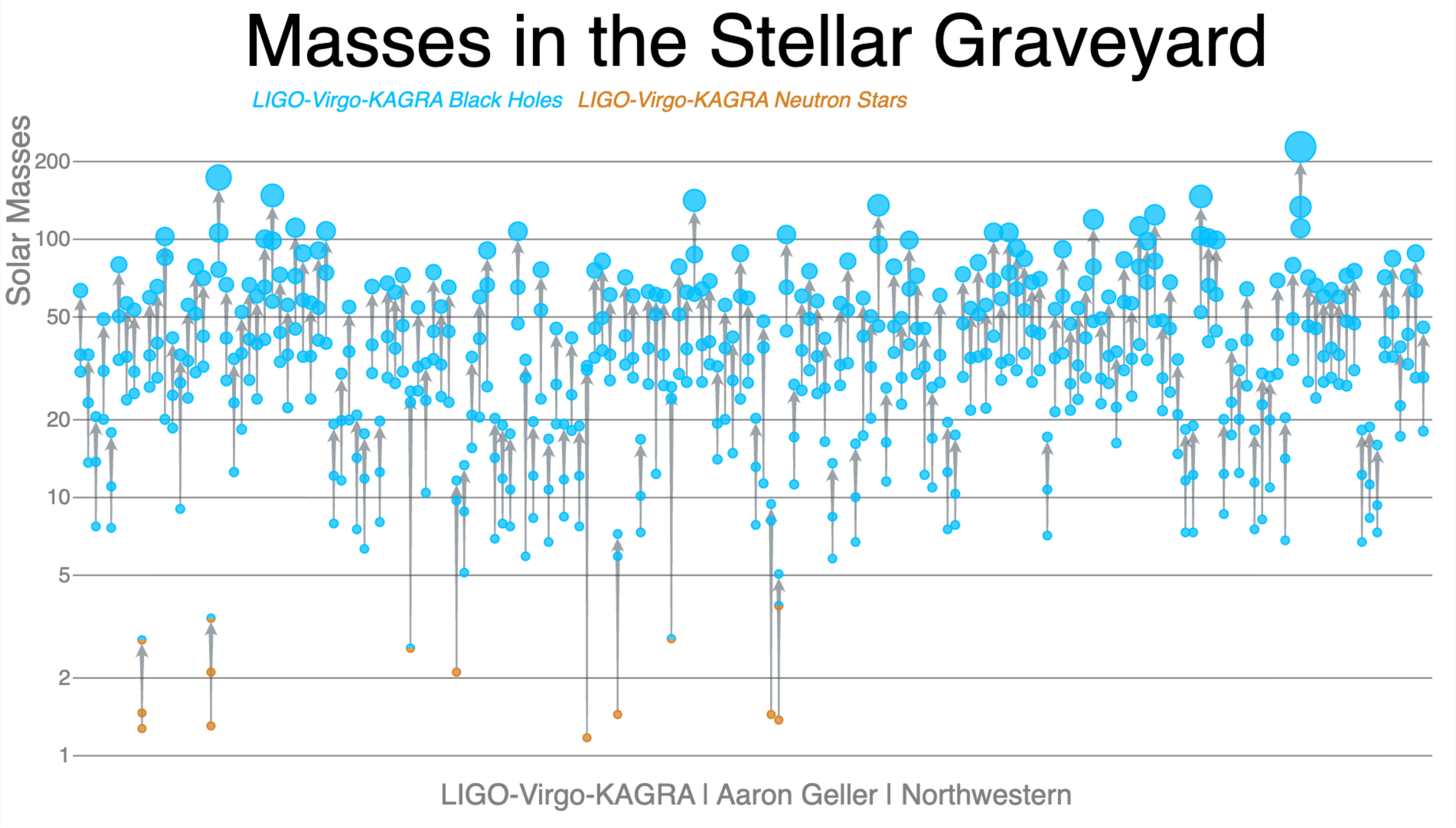
Common Envelope Evolution of Boson Clouds in Black Hole Binaries

张 君

based on arXiv: 2508.18738

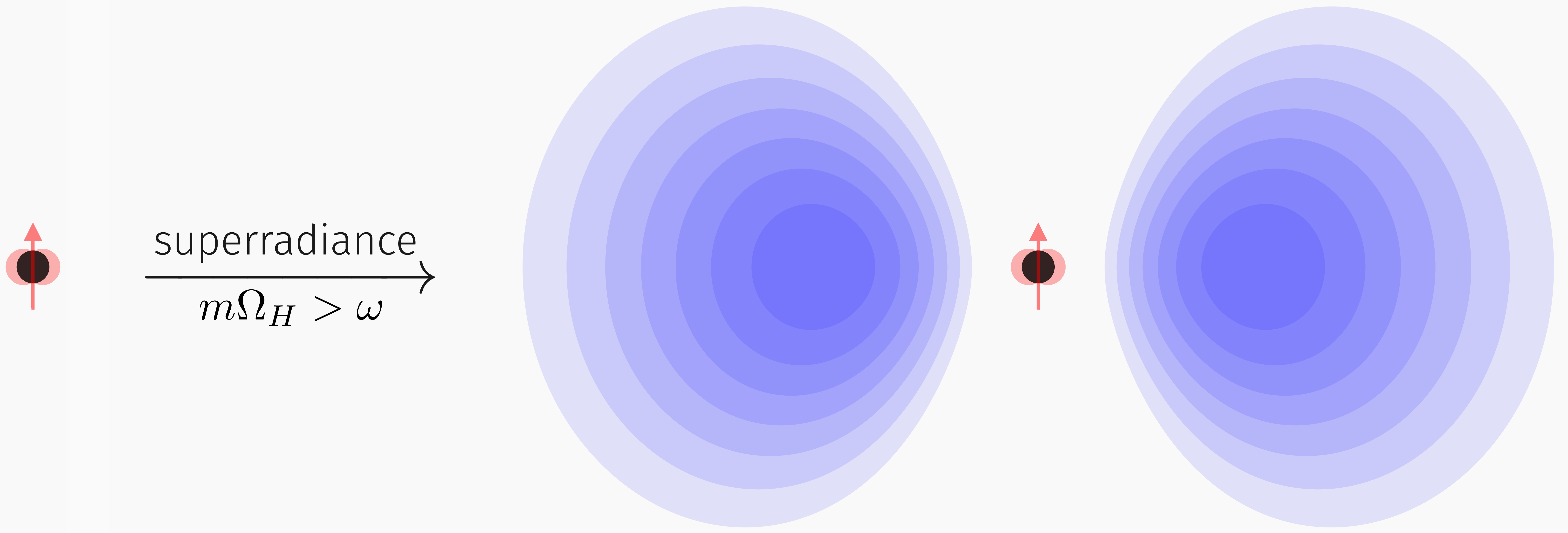
in collaboration with 杨桓 , 郭傲, and 张琪琰

2025 Gravitational Wave Physics Conference



Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Black Hole Superradiance



$$\alpha \equiv \frac{GM\mu}{\hbar c} \simeq 0.1 \left(\frac{M}{10 M_\odot}\right) \left(\frac{\mu}{10^{-12} eV}\right)$$

[Penrose 1969, Press & Teukolsky 1972, Zouros & Eardley 1979, Detweiler 1980]

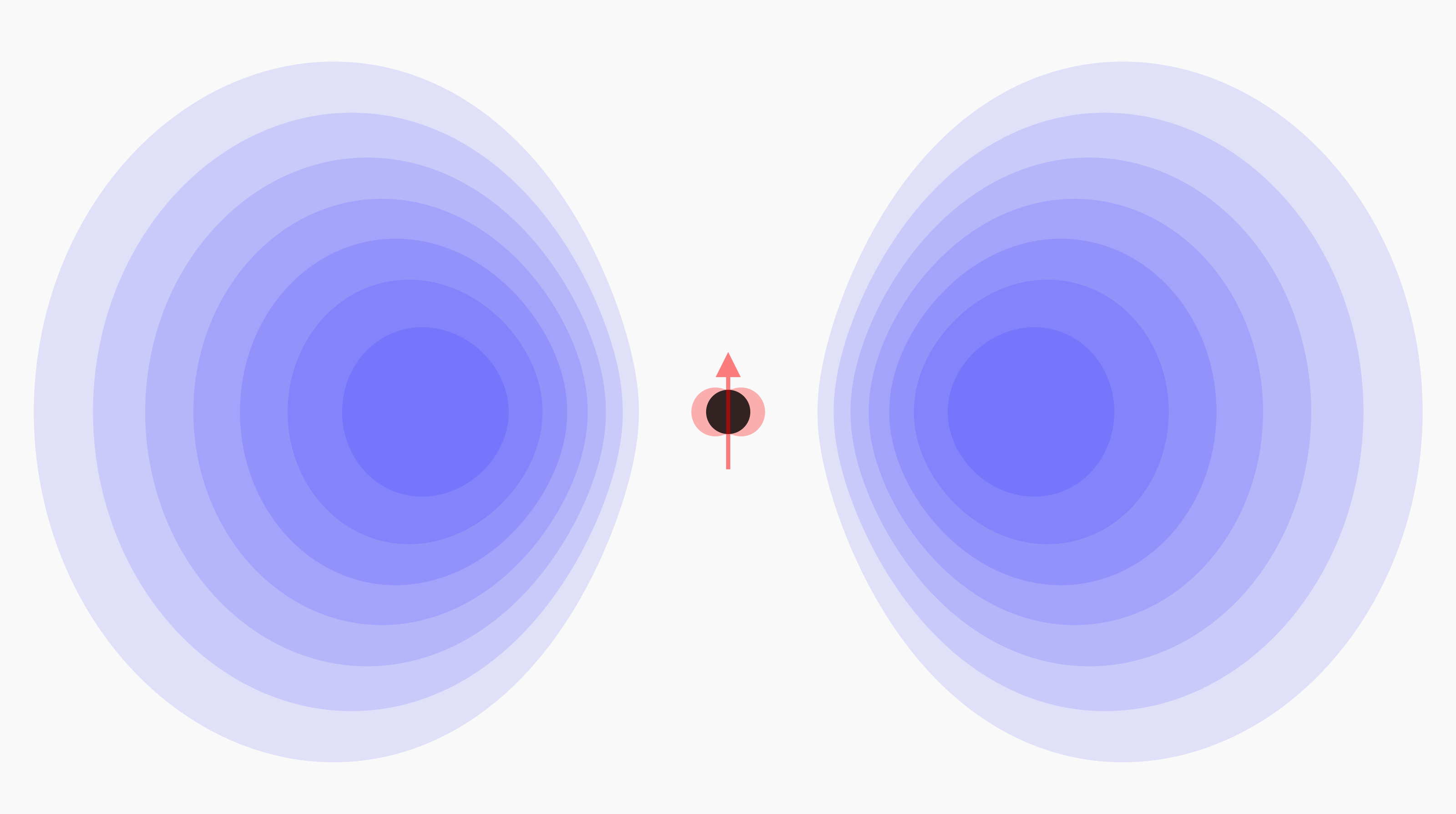
Black Hole Superradiance

- cloud size $r_B \sim GM/\alpha^2$
- cloud mass $M_c \sim \alpha M$
- Hydrogen atom-like spectrum

$$\left(g^{ab}\nabla_a\nabla_b - \mu^2\right)\Psi(t,\mathbf{r}) = 0$$

$$\Psi = \frac{1}{\sqrt{2\mu}}\left(\psi e^{-i\mu t} + \psi^* e^{i\mu t}\right)$$

$$i\partial_t\,\psi = H\psi \qquad H = -\frac{\nabla^2}{2\mu} + \frac{\alpha}{r} + \mathcal{O}(\alpha^2)$$



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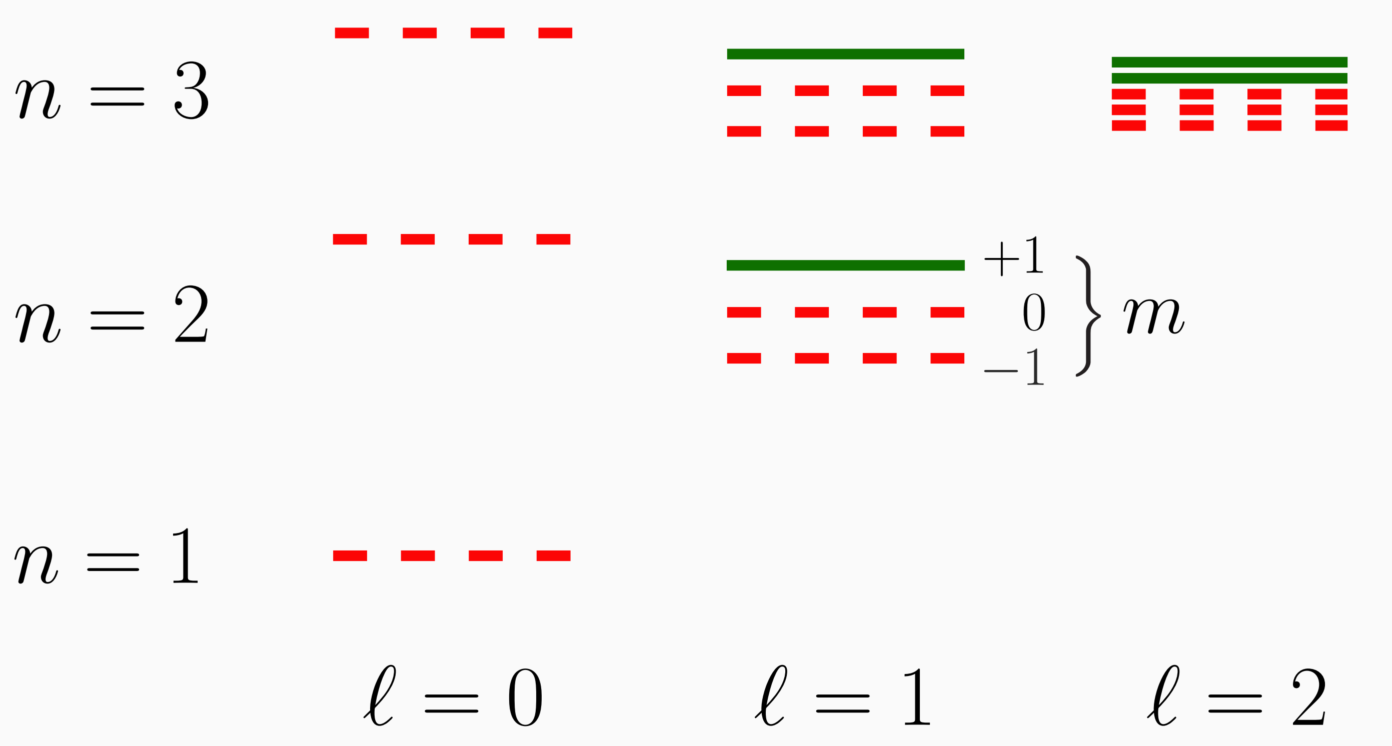
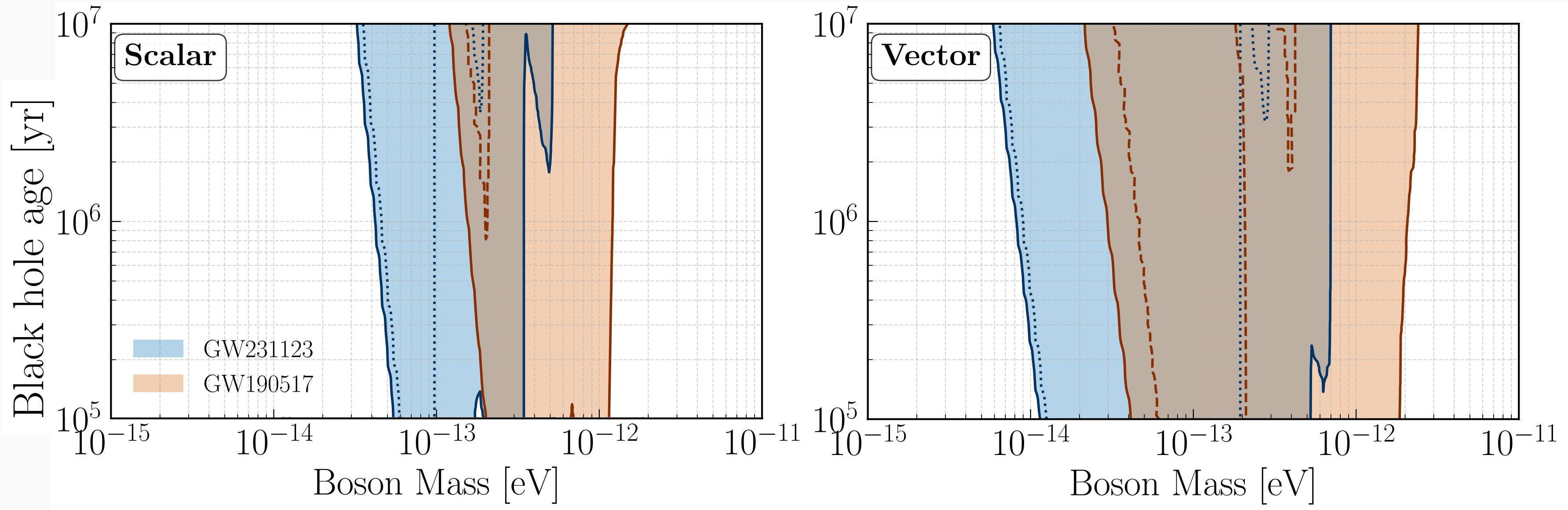
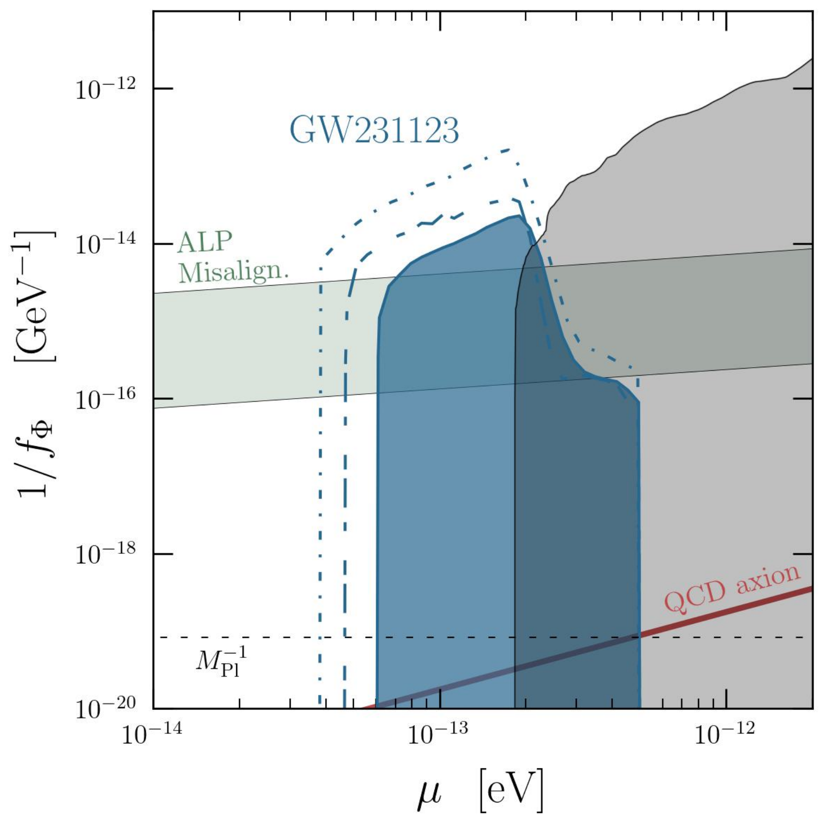


Observational Signatures of BH Superradiance

■ Black hole spindown

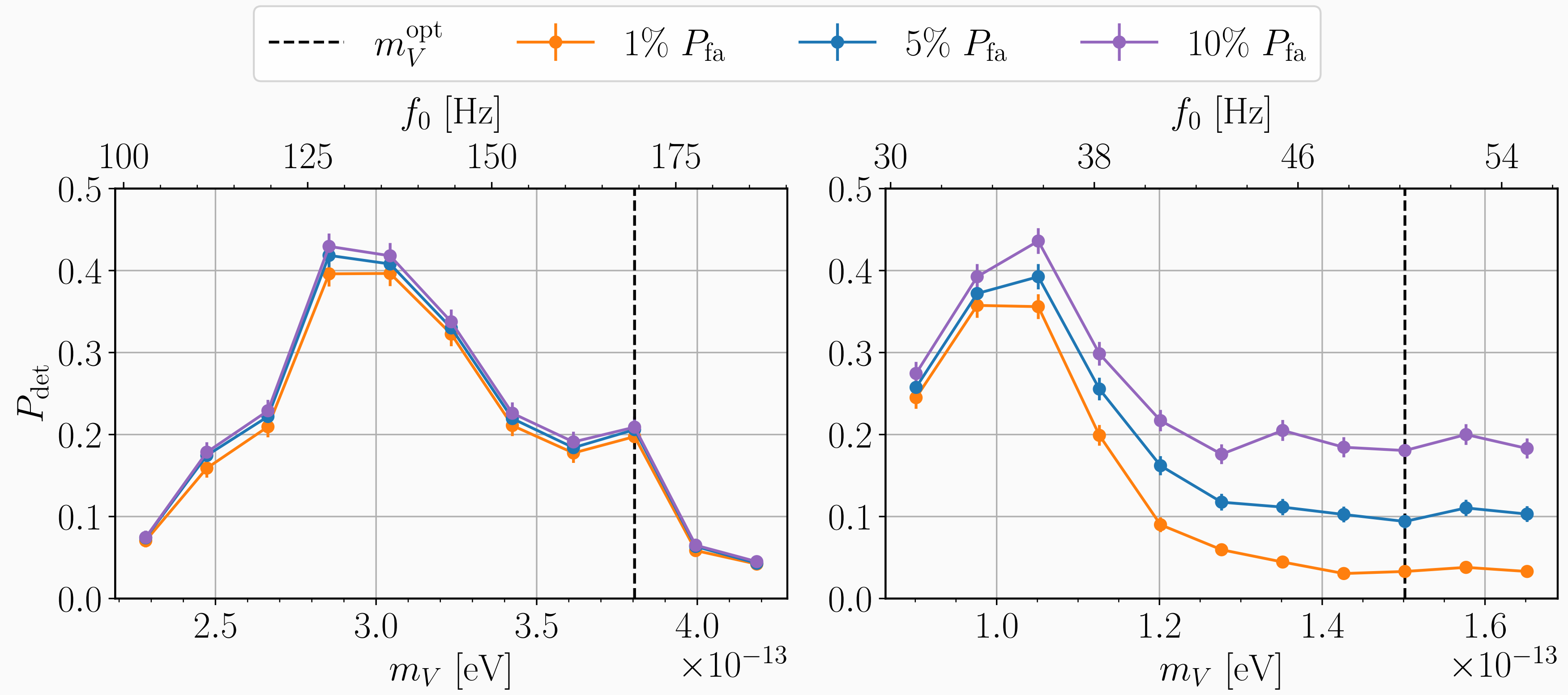


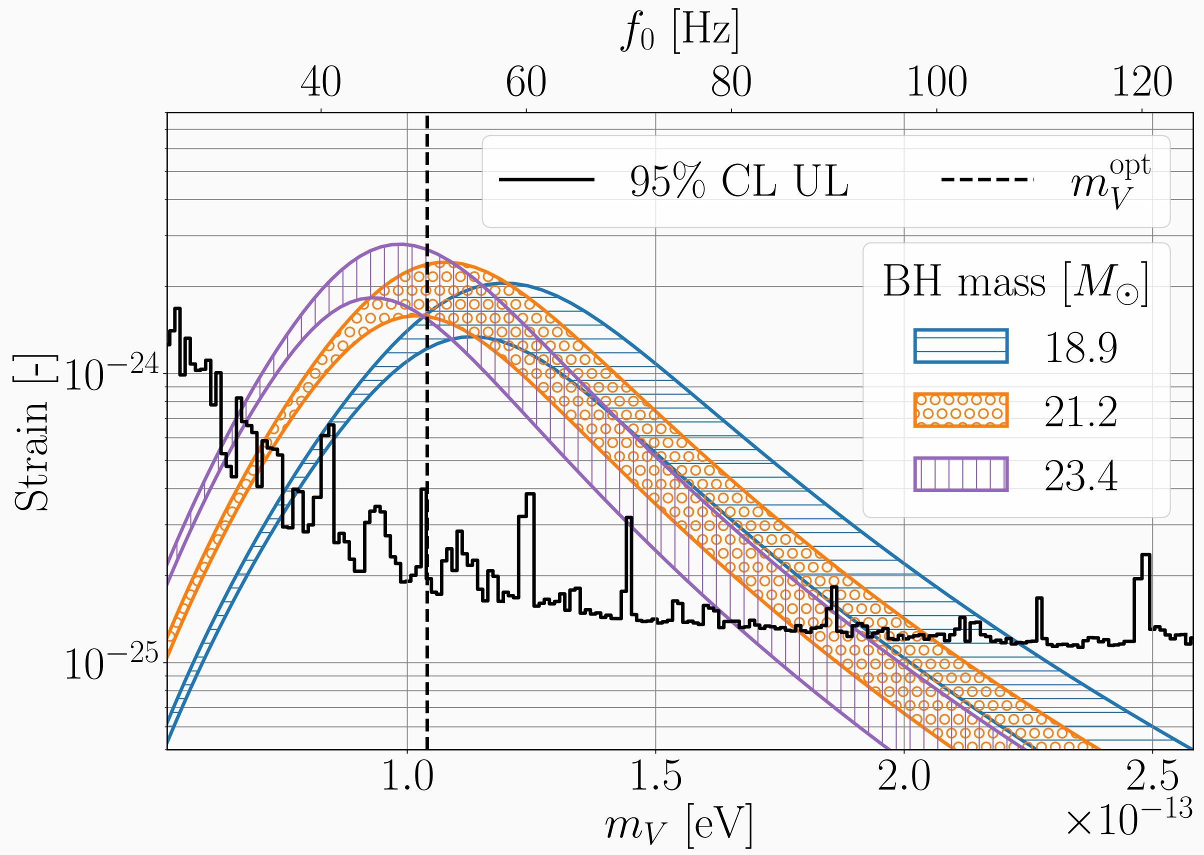
[East et al., arXiv:2507.20979]



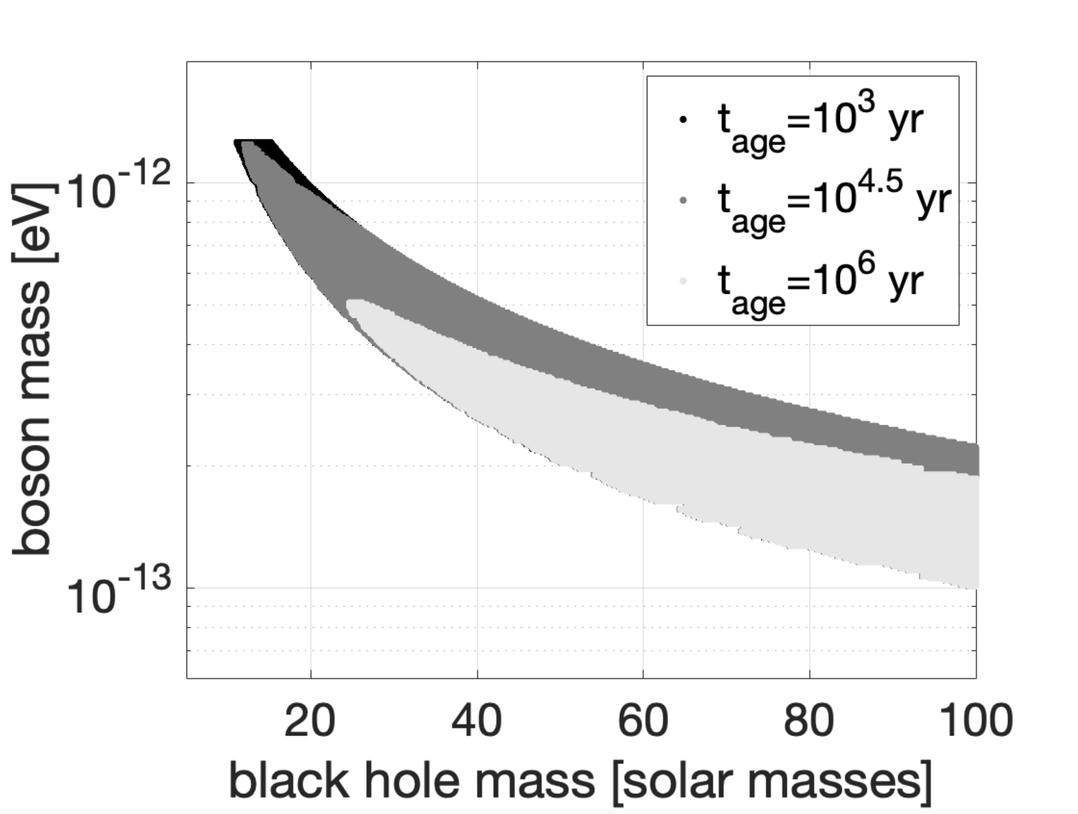
[Caputo et al., arXiv:2507.21788]

■ GW emitted by superradiant clouds





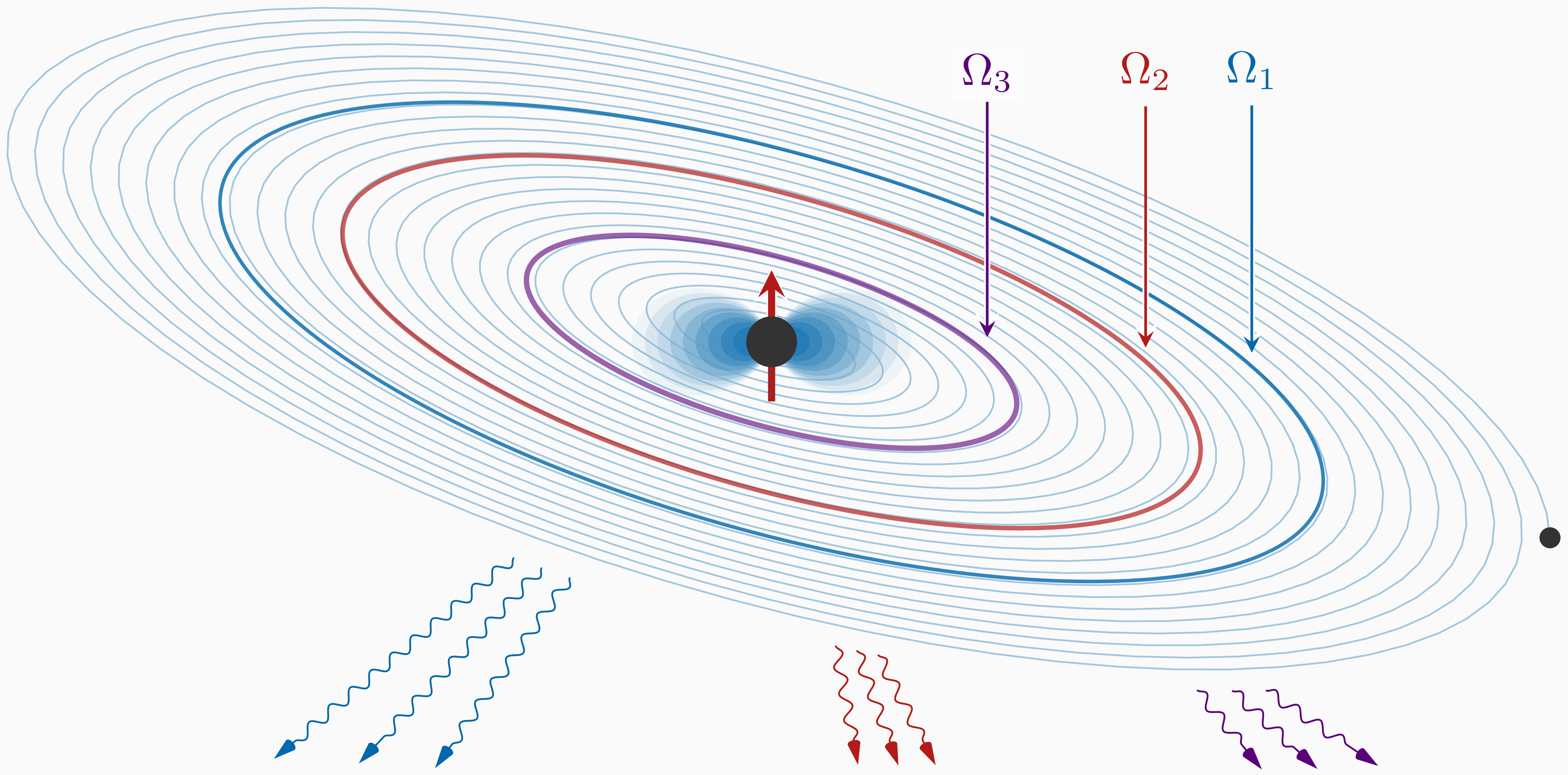
[LVK, arXiv:2509.07352]



[LVK, PRD (2022)]

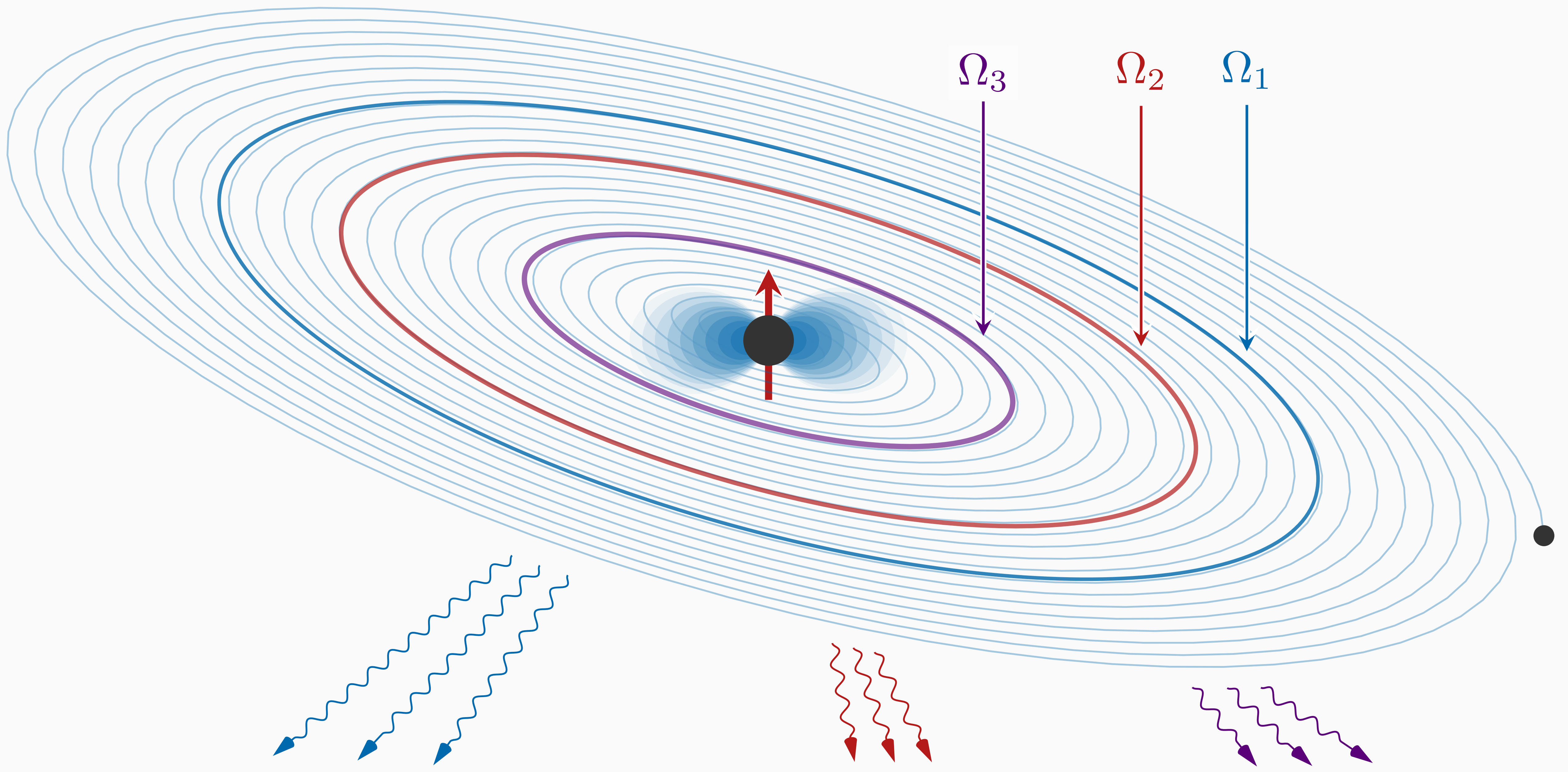
Observational Signatures of BH Superradiance

- Dynamical signatures of superradiant cloud in black hole binaries



Observational Signatures of BH Superradiance

- **Dynamical signatures of superradiant cloud in black hole binaries**



$$H = \underline{-\frac{1}{2\mu}\nabla^2 - \frac{GM_1\mu}{|\mathbf{r}-\mathbf{r}_1|}} - \frac{GM_2\mu}{|\mathbf{r}-\mathbf{r}_2|}$$

Observational Signatures of BH Superradiance

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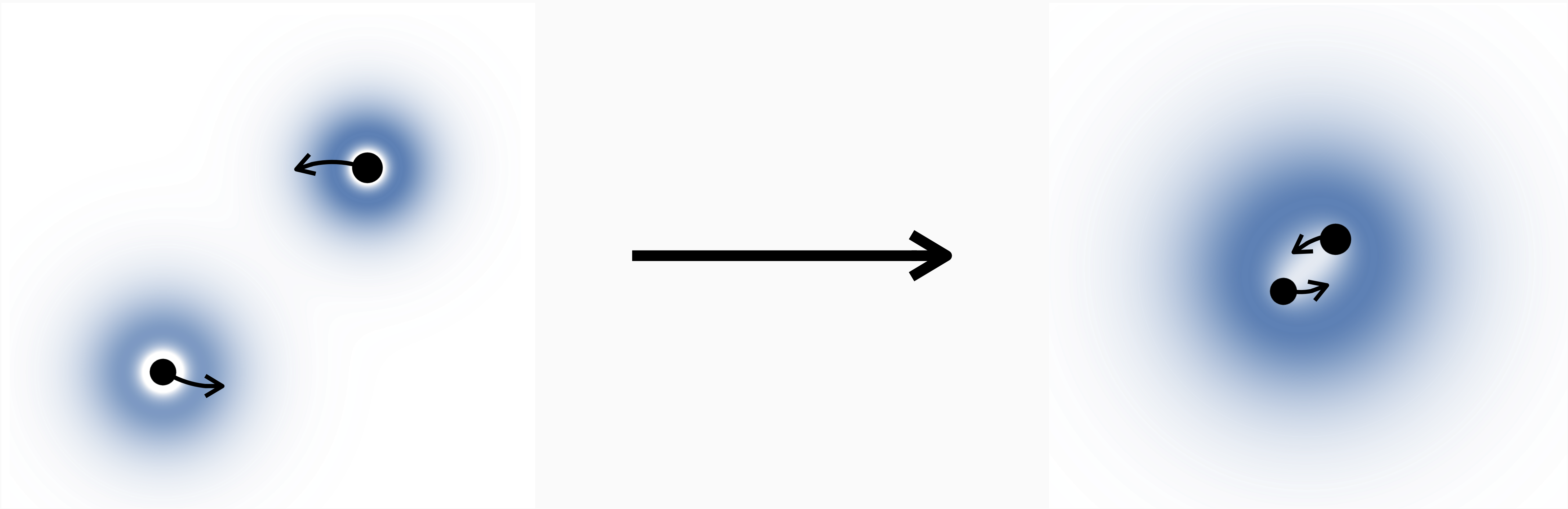

[Guo, Zhang, Yang & **JZ**, arXiv: 2508.18738]

Observational Signatures of BH Superradiance

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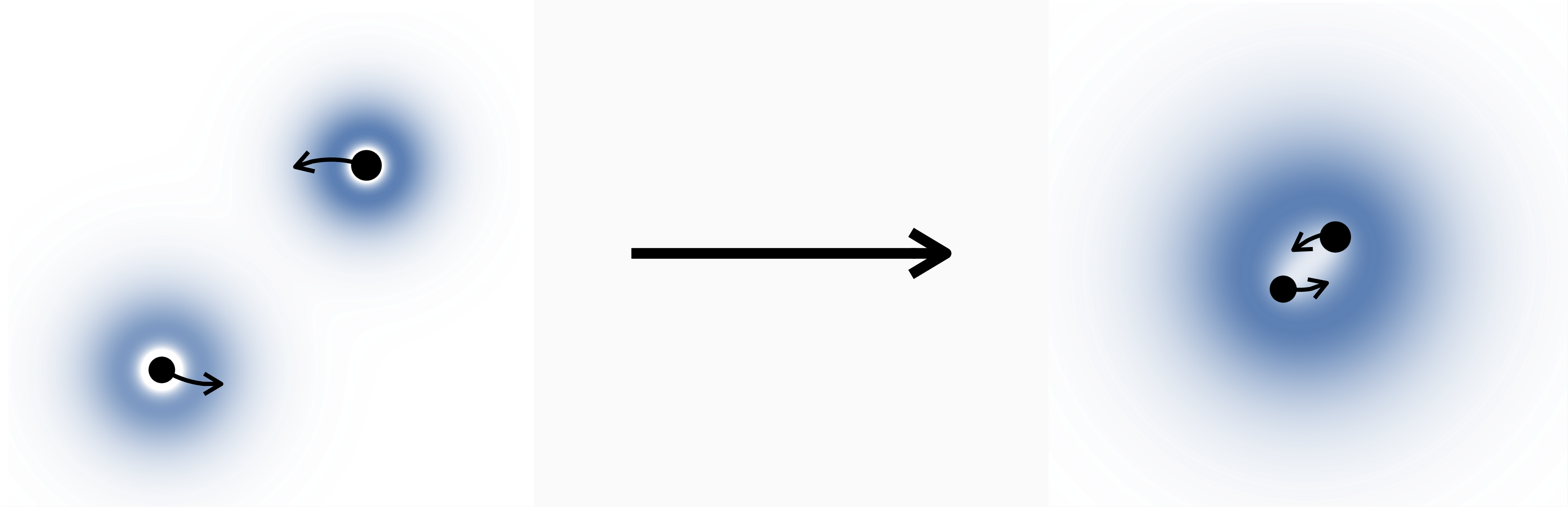


$$H = \underline{-\frac{1}{2\mu}\nabla^2 - \frac{GM_1\mu}{|\mathbf{r}-\mathbf{r}_1|}} - \frac{GM_2\mu}{|\mathbf{r}-\mathbf{r}_2|} \longrightarrow H = \underbrace{-\frac{1}{2\mu}\bar{\nabla}^2 - \frac{GM_1\mu}{|\bar{\mathbf{r}}-\bar{\mathbf{r}}_1|} - \frac{GM_2\mu}{|\bar{\mathbf{r}}-\bar{\mathbf{r}}_2|}}_{H_0} + i\Omega\,\partial_{\bar{\phi}}$$

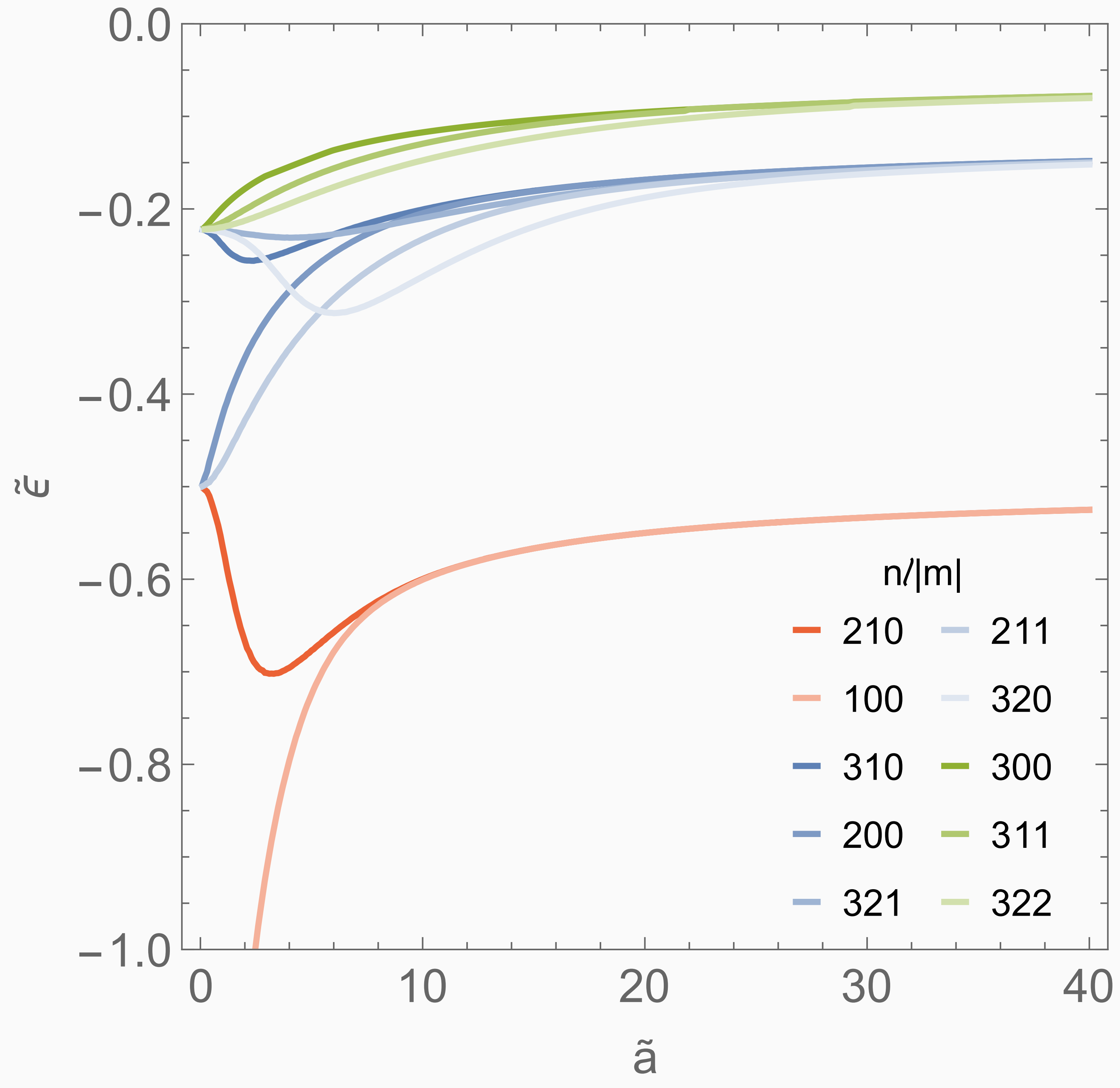
[Guo, Zhang, Yang & **JZ**, arXiv: 2508.18738]

Common Envelope Evolution of Clouds in BHBs

$$i\partial_t \bar{\Psi} = \left(H_0 + i\Omega\partial_{\bar{\phi}}\right) \bar{\Psi} \qquad \bar{\Psi}\left(t, \bar{\mathbf{r}}\right) = \sum_i c_i(t)\, \bar{\psi}_i\left(\bar{\mathbf{r}}\right) e^{-i\epsilon_i t}$$

- **Adiabatic evolution in circular orbits**

$$i\dot{c}_i = \sum_j \eta_{ij}\, e^{i\epsilon_{ij} t}\, c_j \qquad \eta_{ij} = i\Omega\langle\bar{\psi}_i|\partial_{\bar{\phi}}|\bar{\psi}_j\rangle$$



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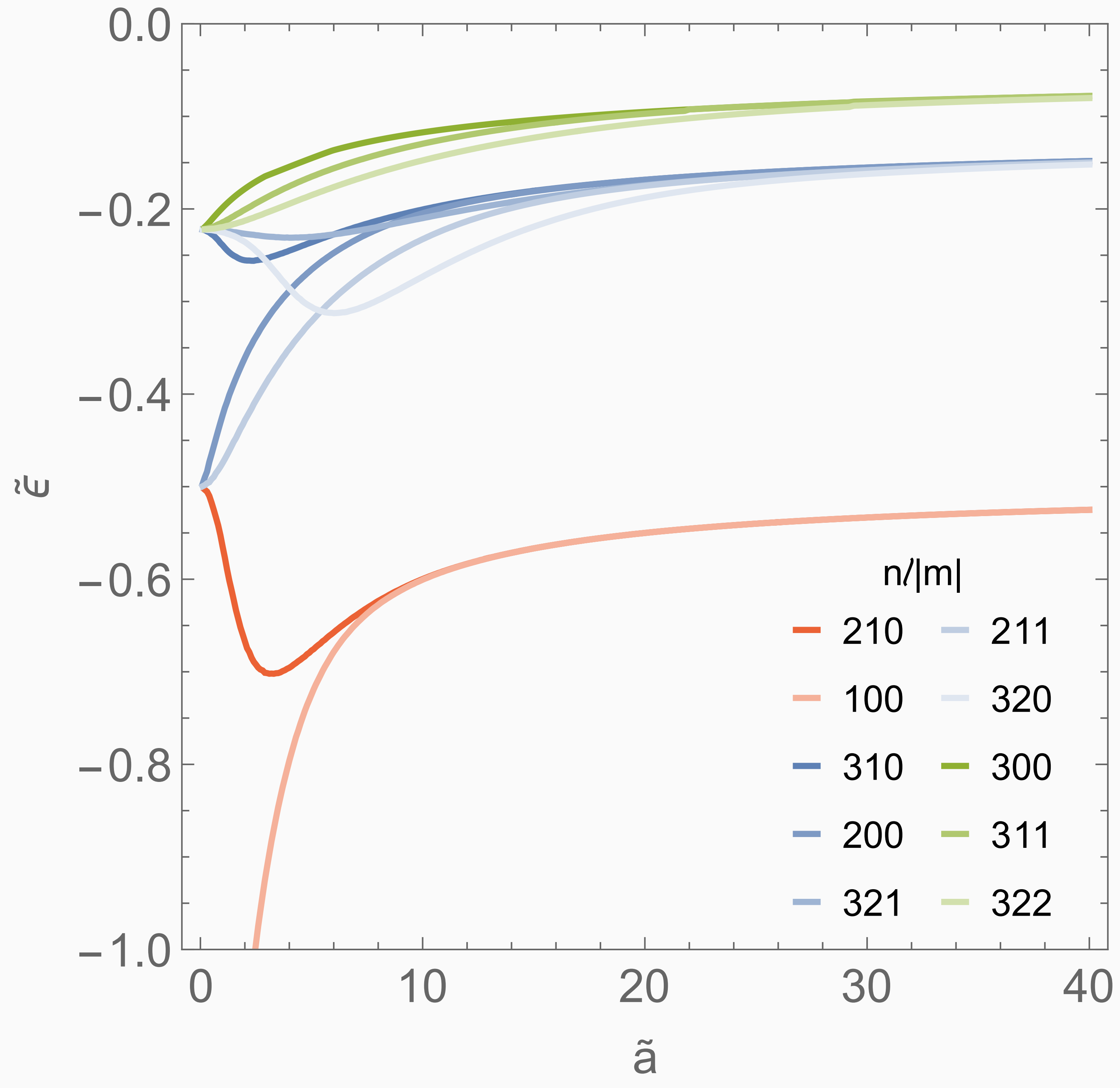
- **Initial condition** $q = 1$

$$|\bar{\mathbf{r}}_1 - \bar{\mathbf{r}}_2| \to \infty$$

$$\varphi_{1,211} + \varphi_{2,211} = \frac{e^{-i\Omega_0 t}}{\sqrt{2}}\left(\bar{\psi}_{211} - \bar{\psi}_{21-1} + \bar{\psi}_{310} - \bar{\psi}_{430}\right)$$

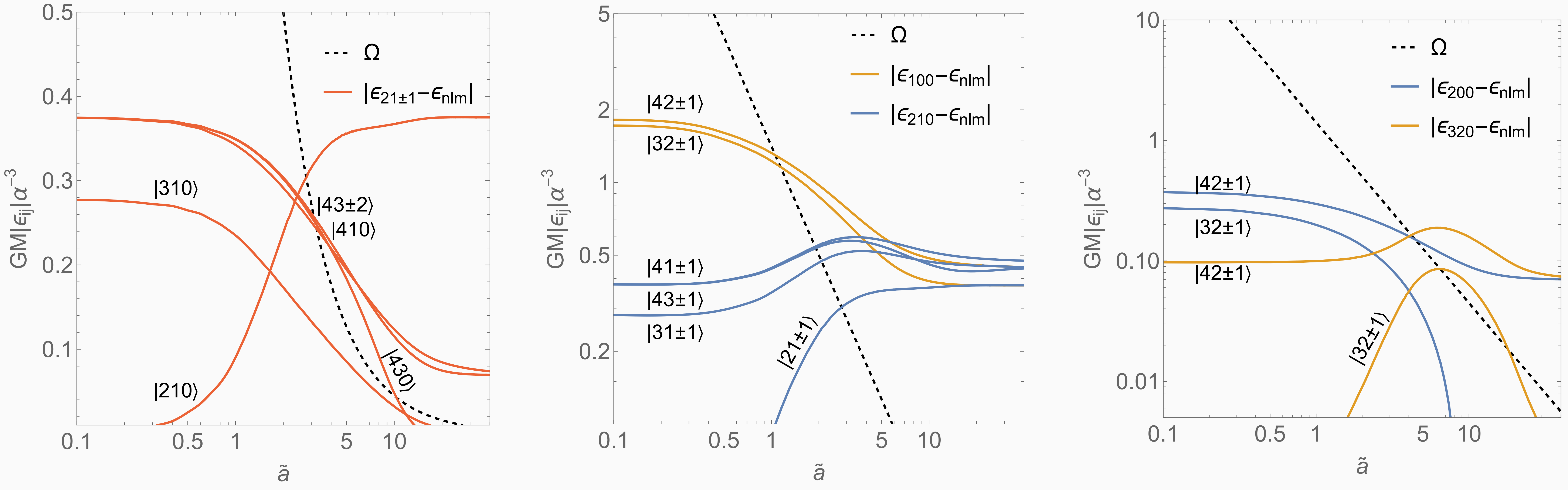


[Guo, Zhang, Yang & **JZ**, arXiv: 2508.18738]

Common Envelope Evolution of Clouds in BHBs

- **Resonant transitions in eccentric orbits**

$$i\dot{c}_i = \sum_j \left[\eta_{ij} e^{i\epsilon_{ij}t} + \eta'_{ij}\left(e^{i\epsilon_{ij}t+\bar{\Omega}t} + e^{i\epsilon_{ij}t-\bar{\Omega}t}\right)\right] c_j$$

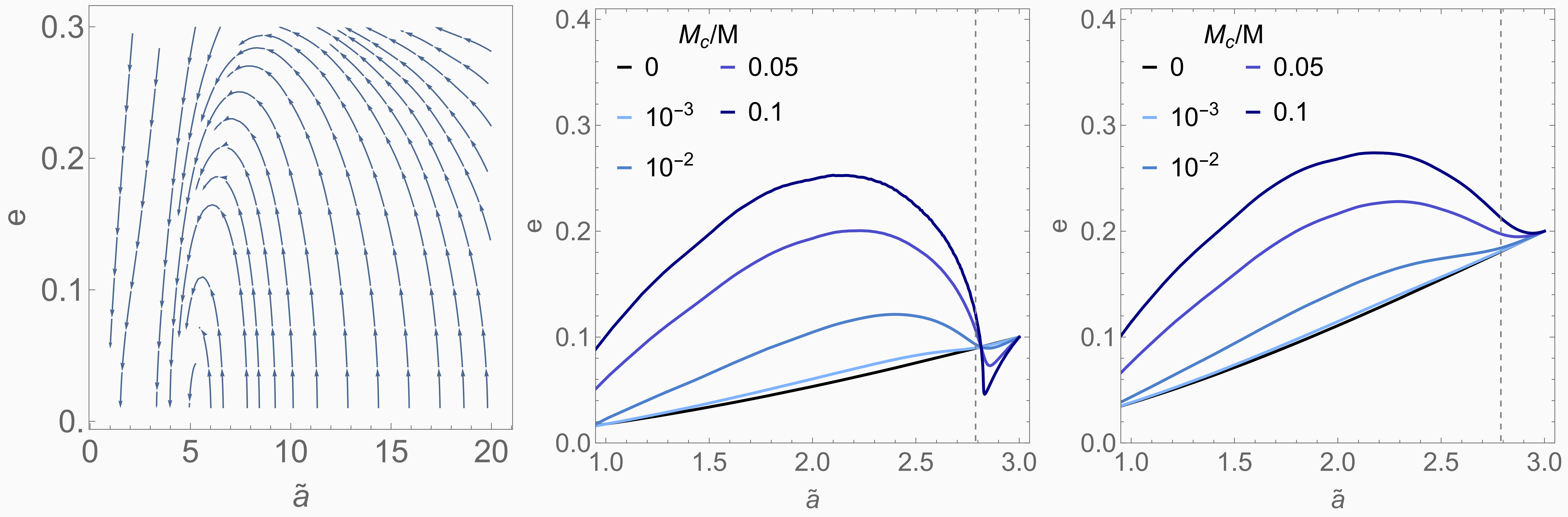


[Guo, Zhang, Yang & **JZ**, arXiv: 2508.18738]

Common Envelope Evolution of Clouds in BHBs

- **Dynamical signatures in orbital evolution**

$$E_{\rm c} = M_{\rm c}\alpha^2 \left[\sum_i |c_i|^2 \tilde{\epsilon}_i + (1+q)^{1/2}\tilde{a}^{-3/2}\sum_{i,j} c_i^* c_j \tilde{\eta}_{ij}\right] \qquad J_{\rm c} = -\frac{GMM_c}{\alpha}\sum_{i,j} c_i^* c_j \tilde{\eta}_{ji}$$



$$e \sim \mathcal{O}(0.1) \times \left(\frac{\alpha}{0.1}\right)^3 \left(\frac{5M_\odot}{M}\right) \quad \text{at} \quad f_{\rm GW} \sim 20\text{Hz}$$

[Guo, Zhang, Yang & **JZ**, arXiv: 2508.18738]

Summary

- Dynamical signatures of clouds provide an independent way of probing ultralight bosons.
- We propose a framework to investigate the evolution of clouds in the late inspiral stage of comparable mass ratio binaries.
- We find that the eccentricity of the orbit could be enhanced in the late inspiral by the clouds.
- This framework can be used in modeling GWs from black hole binaries in the presence of clouds.

Thank you !