Axion cloud evaporation during inspiral of black hole binaries

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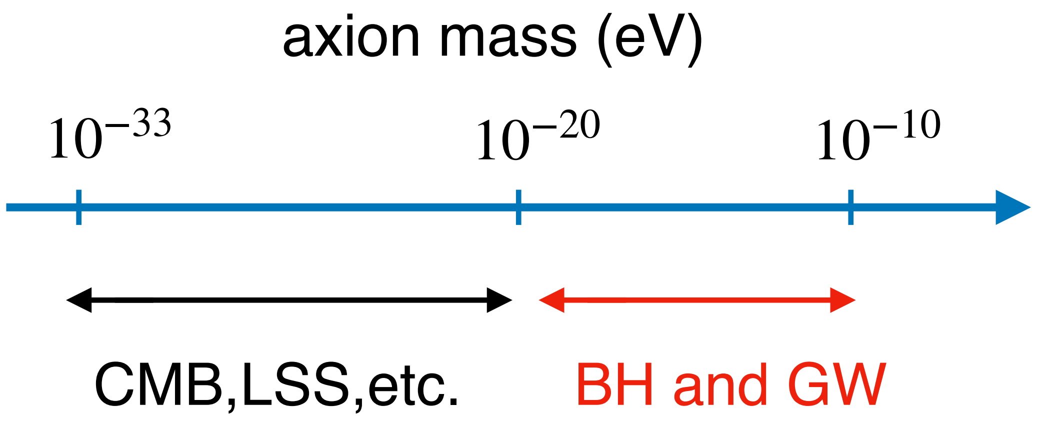
Axion and Black Hole

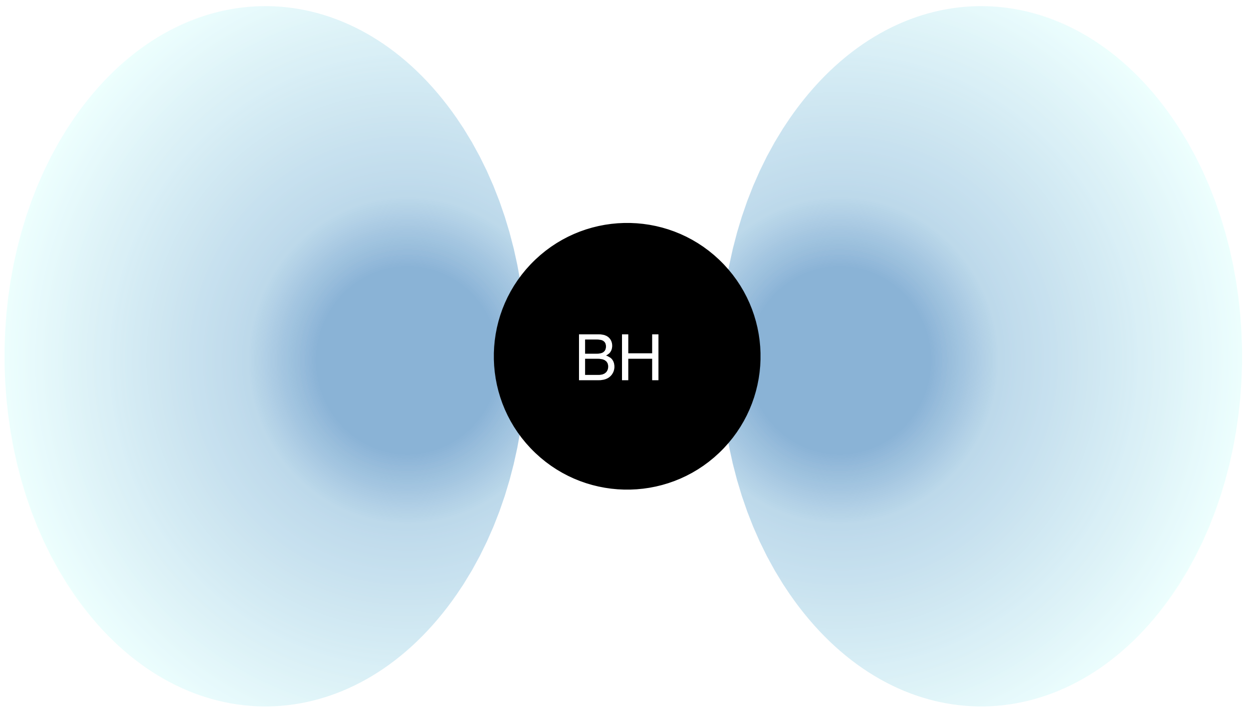
Axion-like particle

- Ultralight scalar field
- QCD axion/ string axion
- Dark matter candidate



BH superradiance

- energy extraction
- gravitationally bounded



Axions can form a cloud around a BH.

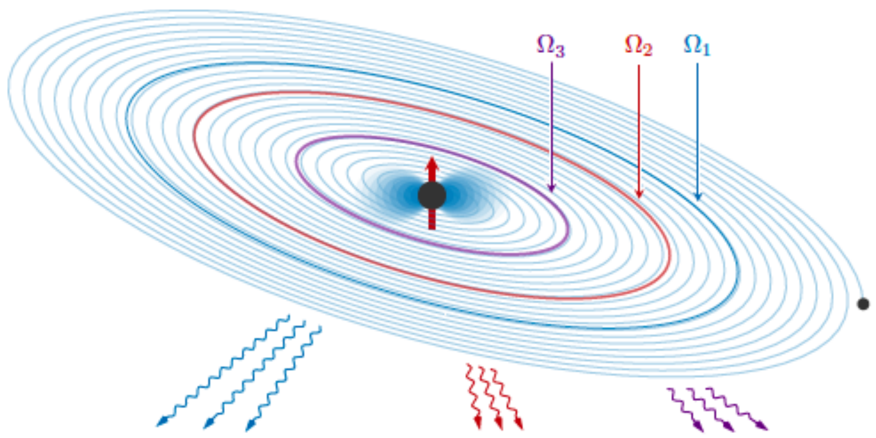
Observation

① Gravitational Wave

modulation of waveform

PN parameter, QNM, etc.

D.Baumann et al., 2020

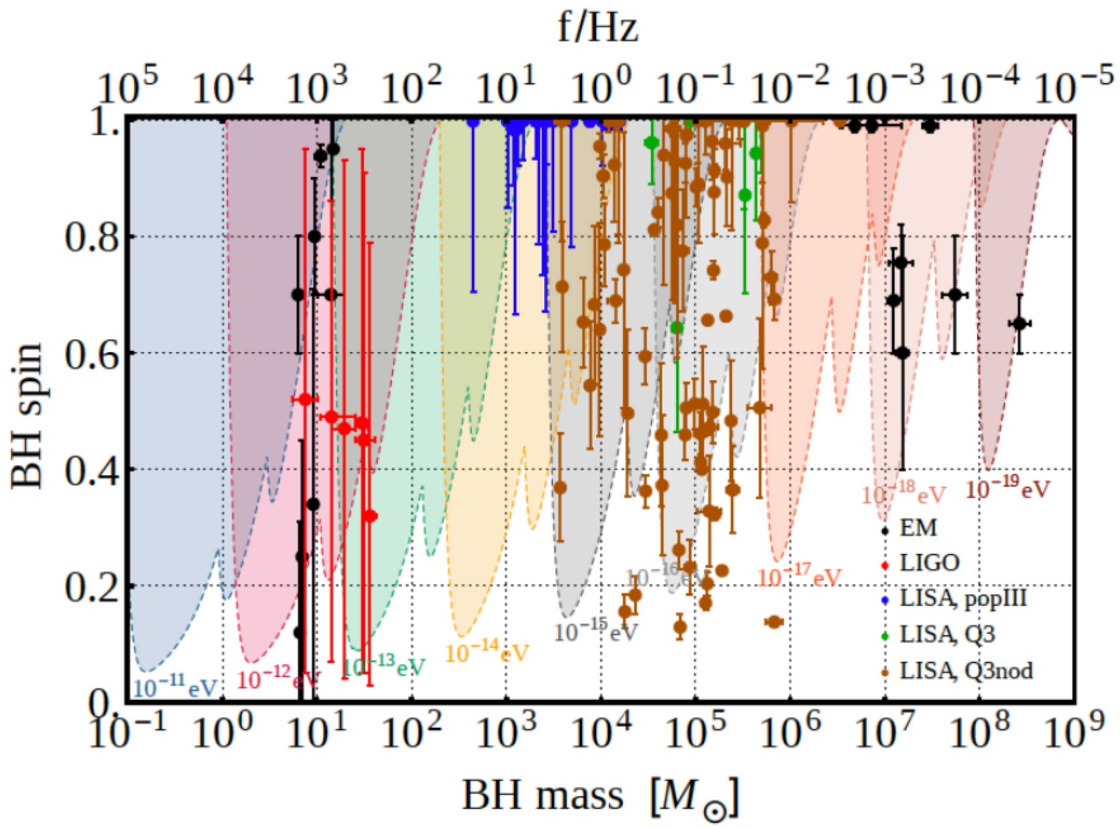


② BH parameter

“forbidden region”

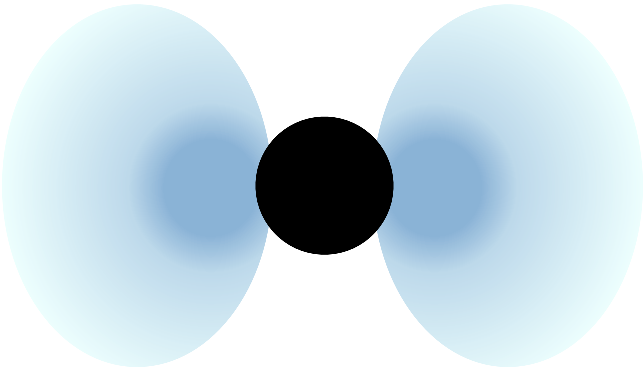
in mass and spin

distribution of BHs



R.Brito et al., 2017

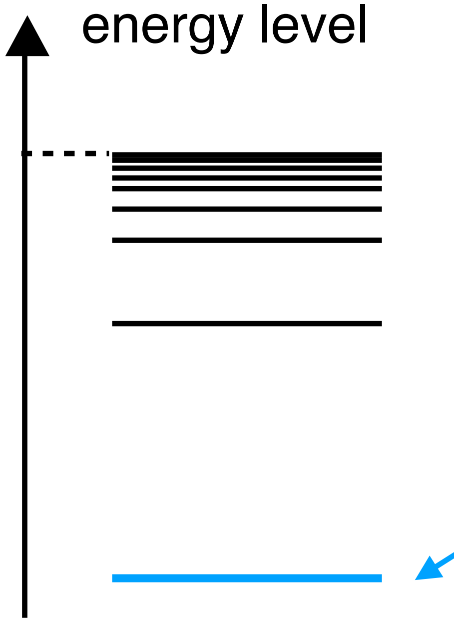
Axion Clouds in Binary Systems



Hydrogen atom-like structure

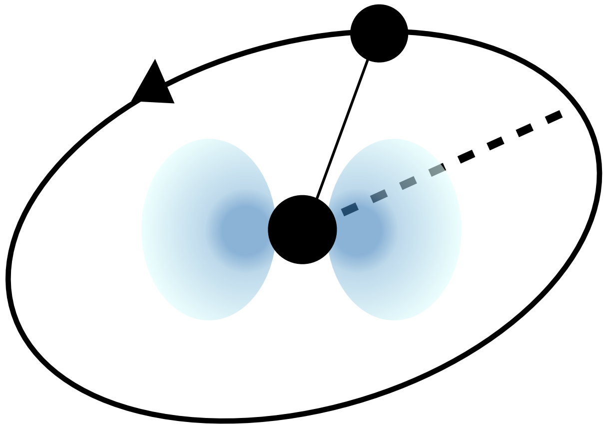
bound state

$$\psi_{nlm} = e^{-i(\omega_{nlm}-\mu)t} R_{nl}(r) Y_{lm}(\theta,\varphi)$$



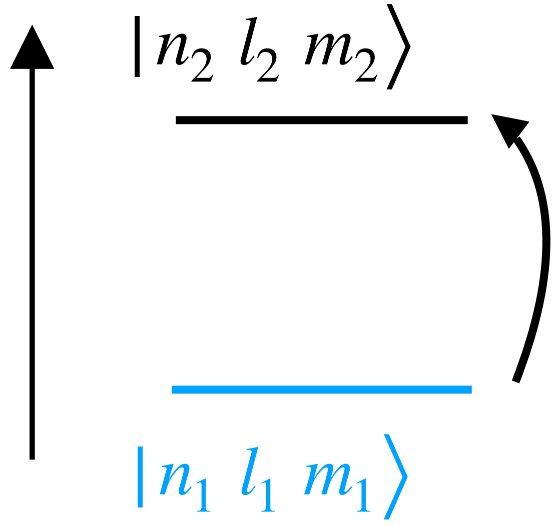
$$\omega_{nlm} = (\omega_R)_{nlm} + i(\omega_I)_{nlm}$$

Axions initially occupy the fastest growing mode.



Tidal interaction

= oscillating external field



$|n_2\ l_2\ m_2\rangle$

$|n_1\ l_1\ m_1\rangle$

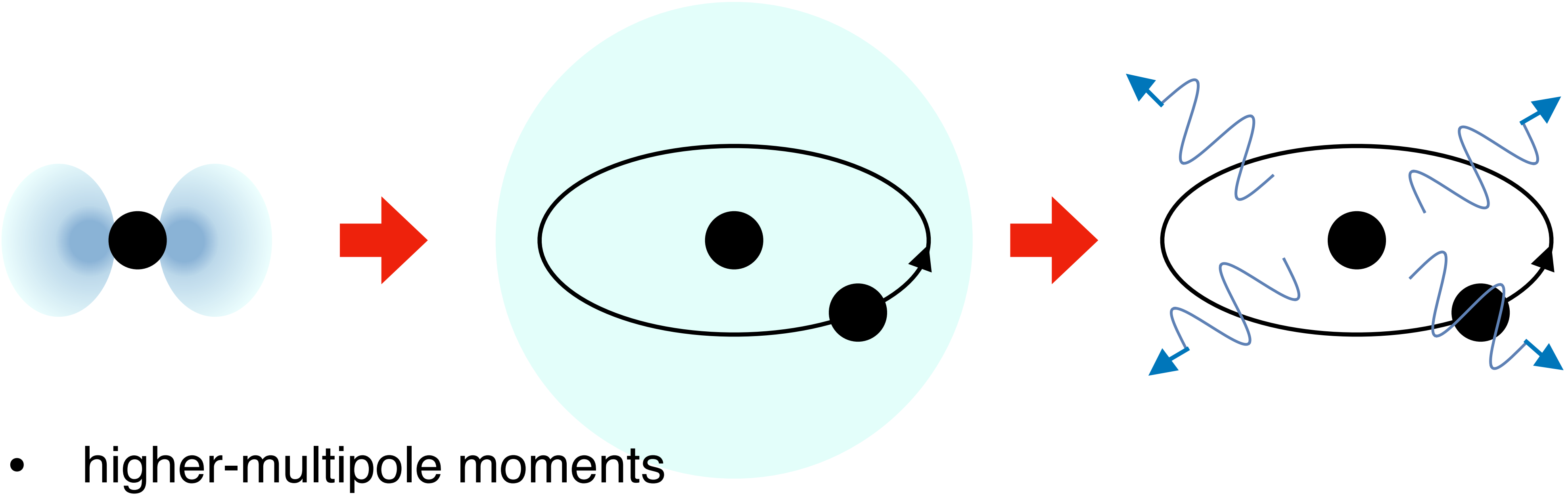
$$\boxed{\Delta E = \Delta m \Omega}$$

Resonant level transition

Motivation and Overview

- The tidal interaction from the companion in a binary greatly affects the evolution of the cloud.
- How does the level transition affect the observational signature?

Overview



disrupted

evaporation

- higher-multipole moments
- backreaction

- axion emission

EoM and Tidal Interaction

EoM for axions around BHs

- non-relativistic approx. for axions
- leading order in $1/r$

$$i\frac{\partial}{\partial t}\psi = \left(-\frac{1}{2\mu}\nabla^2 - \frac{\alpha}{r}\right)\psi$$

$$\boxed{\alpha = M\mu}$$

BH mass M ,
axion mass μ

This is good approx. for $\alpha \ll 1$.

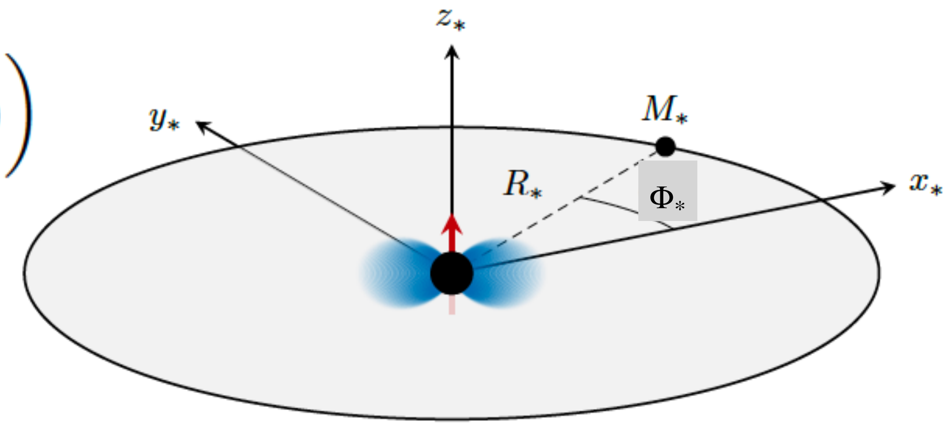
Tidal potential from the companion

- multi-pole expansion

$$V_*(t) = \sum_{l_*\geq 2}\sum_{|m_*|\leq l_*} \mathcal{E}_{l_* m_*} e^{-i m_* \Phi_*}\left(\frac{r^{l_*}}{R_*^{l_*+1}}\,\theta(R_*-r) + \frac{R_*^{l_*}}{r^{l_*}}\,\theta(r-R_*)\right)$$

$$i\frac{\partial}{\partial t}\psi = \left(-\frac{1}{2\mu}\nabla^2 - \frac{\alpha}{r} + \boxed{V_*(t)}\right)\psi$$

D.Baumann et al., 2021



Level Transition

D.Baumann et al., 2020

- two level system $\psi = c_1(t)\varphi_1 + c_2(t)\varphi_2$
- linear orbital evolution around the resonance $\frac{\mathrm{d}\Omega}{\mathrm{d}t} = \gamma$
- mixing term $\langle \varphi_1 | V_*(t) | \varphi_2 \rangle = \eta \, e^{-i m_* \Phi_*(t)}$

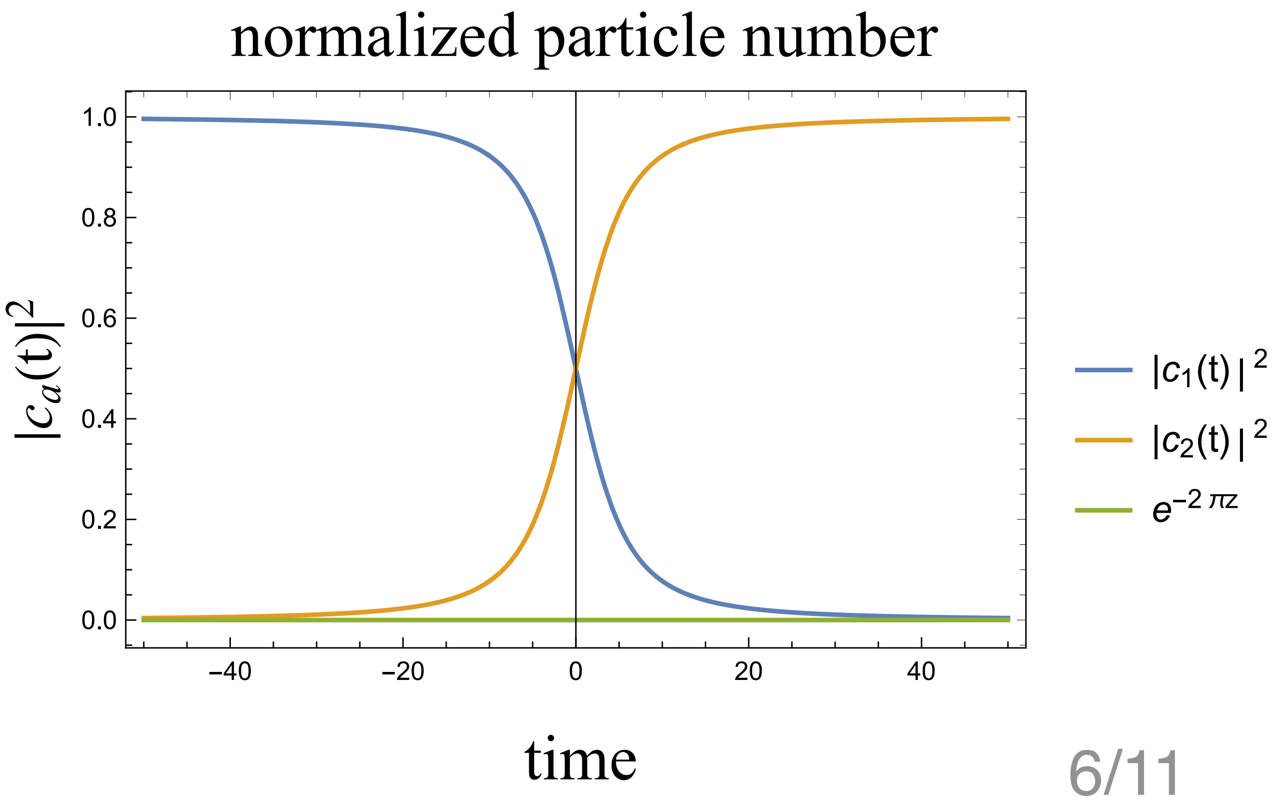
EoM for two states

(in dimensionless unit)

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} c_1 \\ c_2 \end{pmatrix} = \begin{pmatrix} t & \sqrt{z} \\ \sqrt{z} & -t \end{pmatrix}\begin{pmatrix} c_1 \\ c_2 \end{pmatrix}$$

adaibaticity of the transition:

$$z \equiv \eta^2/\gamma$$


normalized particle number

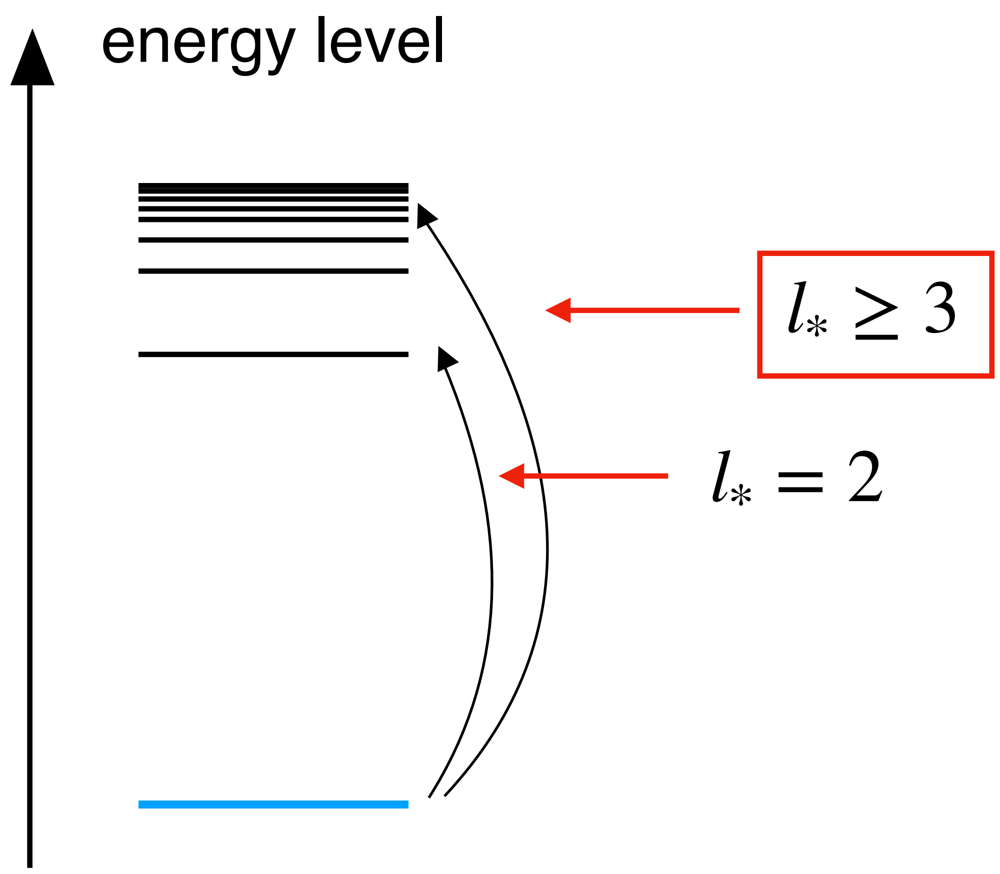
Higher-Multipole Moments

- multipole expansion

$$V_*(t) = \sum_{l_* \geq 2} \sum_{|m_*| \leq l_*} \mathcal{E}_{l_* m_*} e^{-i m_* \Phi_*} \left(\frac{r^{l_*}}{R_*^{l_*+1}} \theta(R_* - r) + \frac{R_*^{l_*}}{r^{l_*}} \theta(r - R_*) \right)$$

In the previous works, the leading $l_* = 2$ has been focused.

But, higher multipole moments work earlier during the inspiral phase.



resonance frequency

$$\Omega_0 = \frac{\Delta E}{\Delta m}$$

conservation of angular momentum

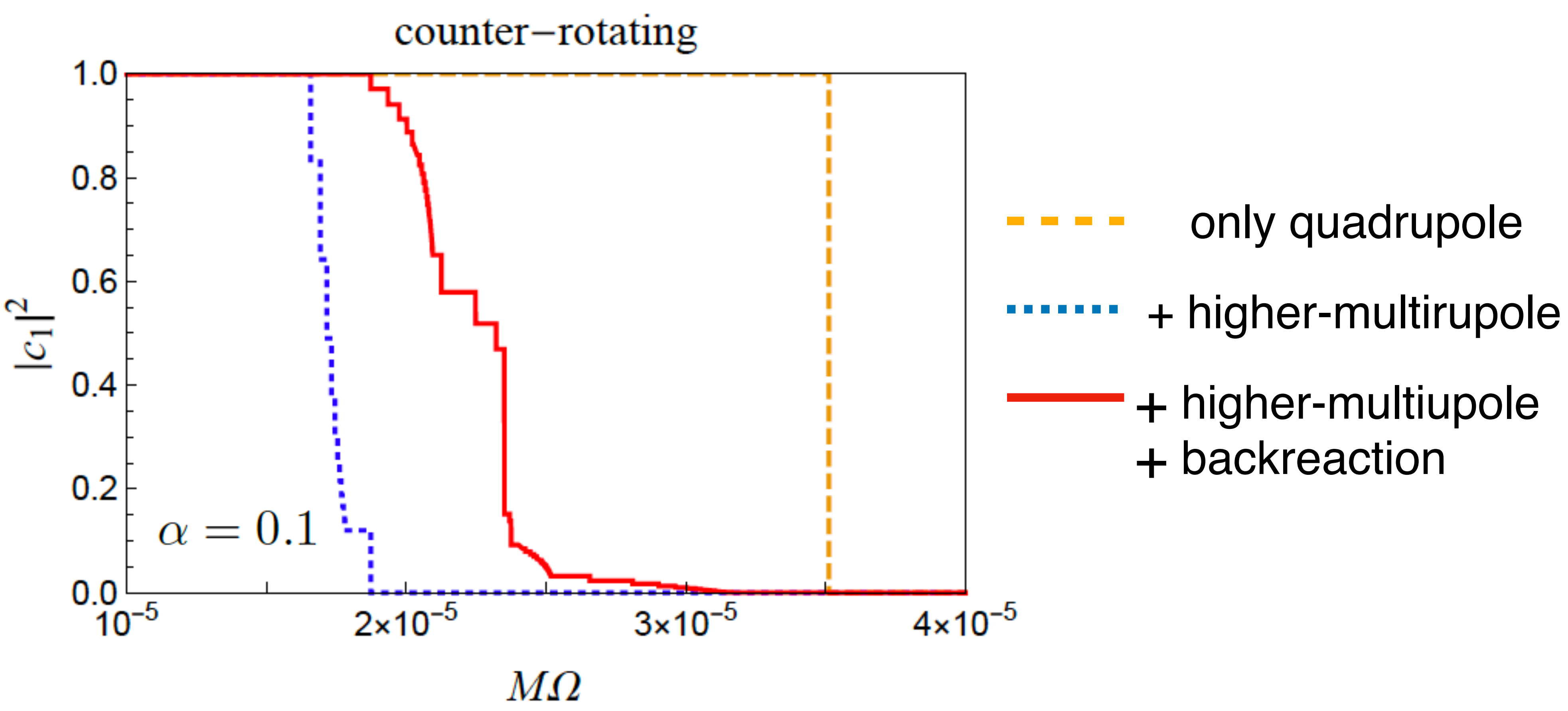
$$\Delta m = m_* \leq l_*$$

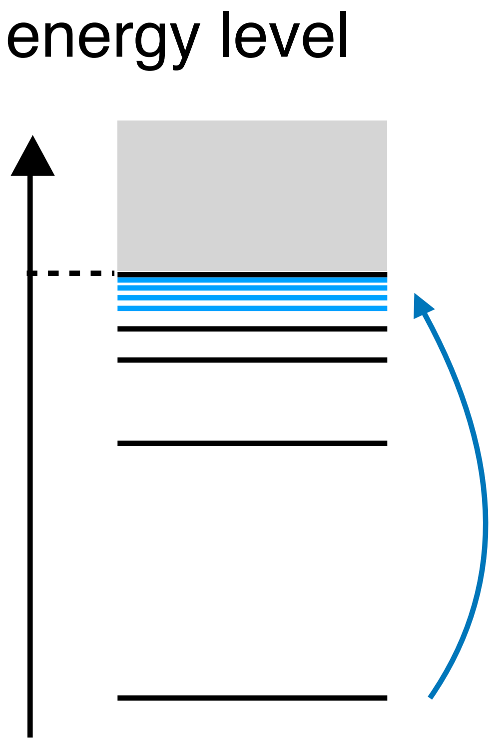
large l_* ➞ small Ω_0

Time Evolution during Inspiral

Backreaction to the orbital motion

- We derived the formula for the transition rate in the strongly non-linear regime.
- The results do not depend on the direction of the orbital motion for almost equal mass binaries.

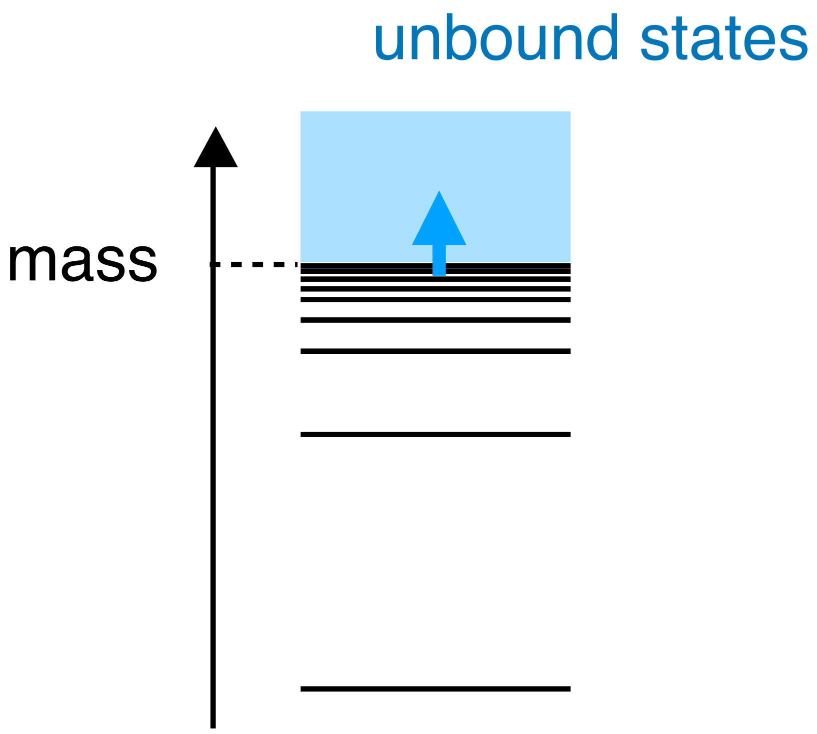




Axions are first transferred to the higher levels. (disruption)

Axion Emission

Axions transferred to higher levels can be further excited to unbound states by tidal interaction.



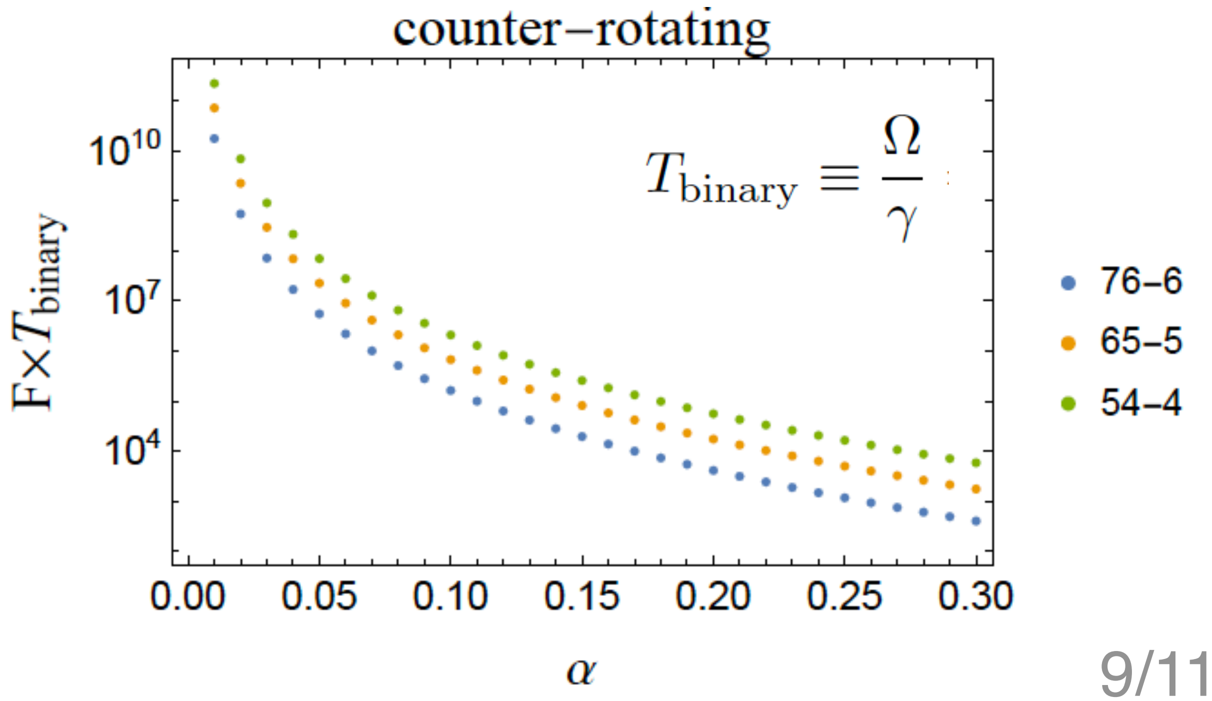
Eq. $$\left(i\partial_t + \frac{1}{2\mu}\nabla^2 + \frac{\alpha}{r}\right)\psi^r = V_* \psi^b$$

Flux $$F = \int d\theta \sin\theta d\varphi \frac{r^2}{2\mu i}\left(\psi^{r*}\partial_r\psi^r - \psi^r\partial_r\psi^{r*}\right)$$

Comparison with timescale of the binary evolution

↓

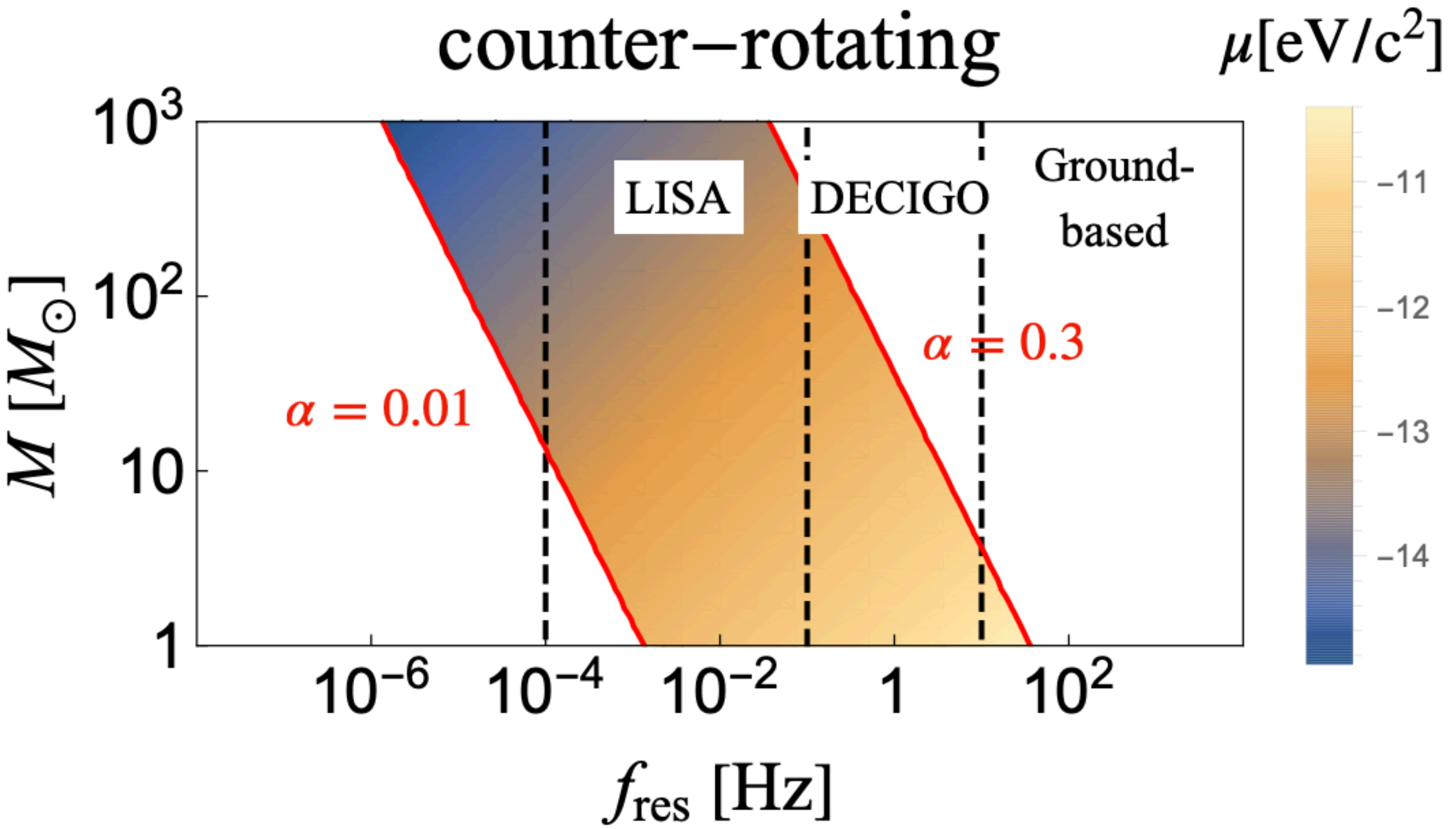
The number flux is large enough for the cloud to evaporate.



Implications for Observations

① Gravitational Wave

$f_{\mathrm{res}} \simeq$ GW frequency of the binary at which clouds evaporate



② BH parameter

Our results imply that the current constraint on axion mass from the mass and the spin of BHs will not be altered.

Summary and Ongoing Work

The dynamics of the axion cloud in a binary systems

- **Higher-multipole moments**

  axions are first transferred to higher levels

- **Backreaction**

  independent of the direction of the orbital motion

- **Axion emssion**

  axions are radiated away, eventually

- Extreme mass ratio inspiral
- Observational signature