Continuous gravitational waves from self-interacting axion condensate

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Work in progress with
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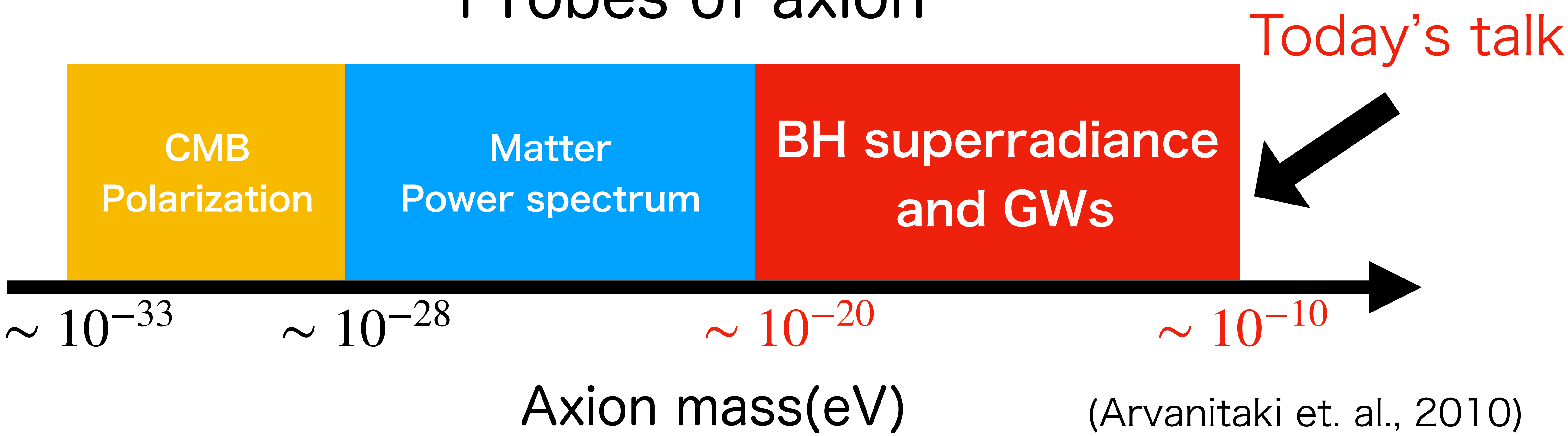
Introduction

- Axions are attracting many interests!
  - A solution to strong CP problem
  - Derived from the string theory
  - Candidate of dark matter
  - **Can be observed by cosmological/astrophysical phenomena**

Probes of axion



(Arvanitaki et. al., 2010)

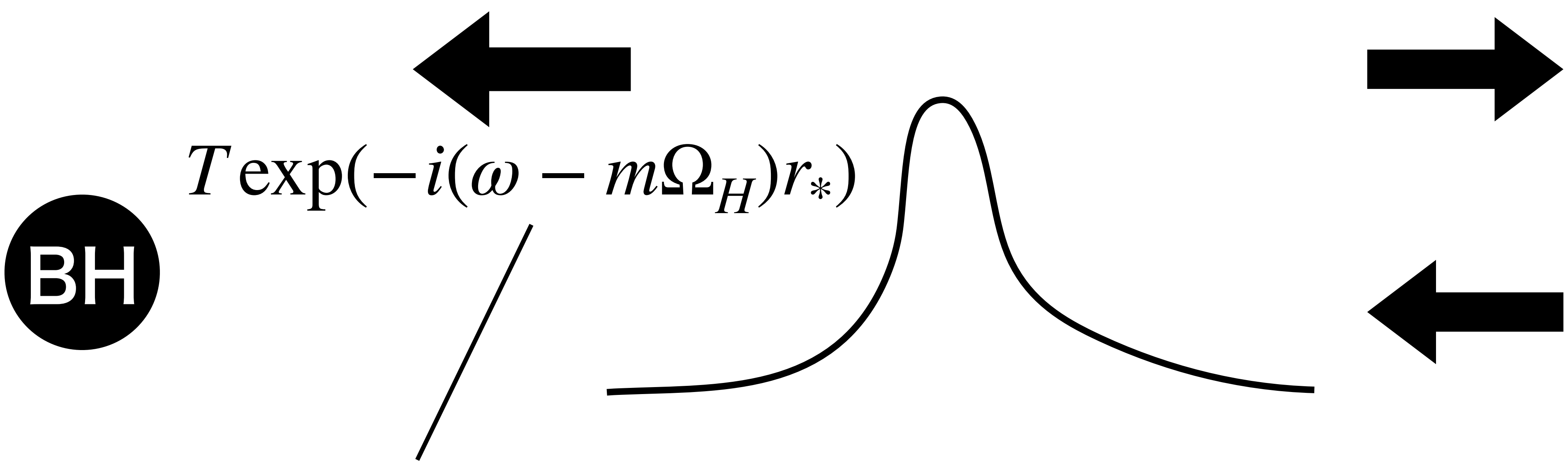
$$GM_{\odot} \sim \frac{1}{10^{-10}\mathrm{eV}}$$

Superradiant instability

(Press&Teukolsky,1972,⋯⋯)

Superradiance

Energy and angular momentum extraction from black hole via wave



$R \exp(+i\omega r_*)$

$T \exp(-i(\omega - m\Omega_H)r_*)$

$\exp(-i\omega r_*)$

Wave number changes due to black hole spin

Particle number conservation,

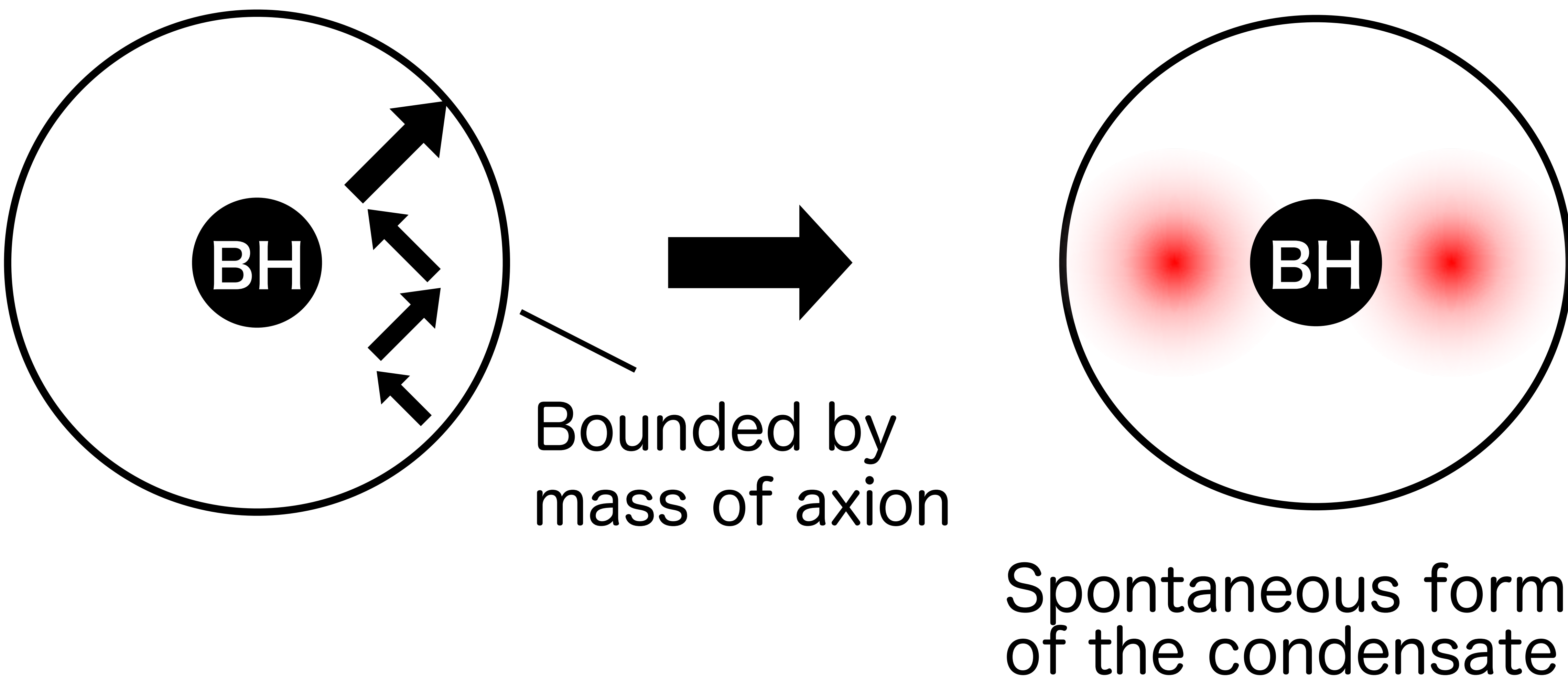
$$|R|^2 = 1 - \frac{\omega - m\Omega_H}{\omega}|T|^2$$

If $\omega < m\Omega_H$, $|R|^2 > 1$

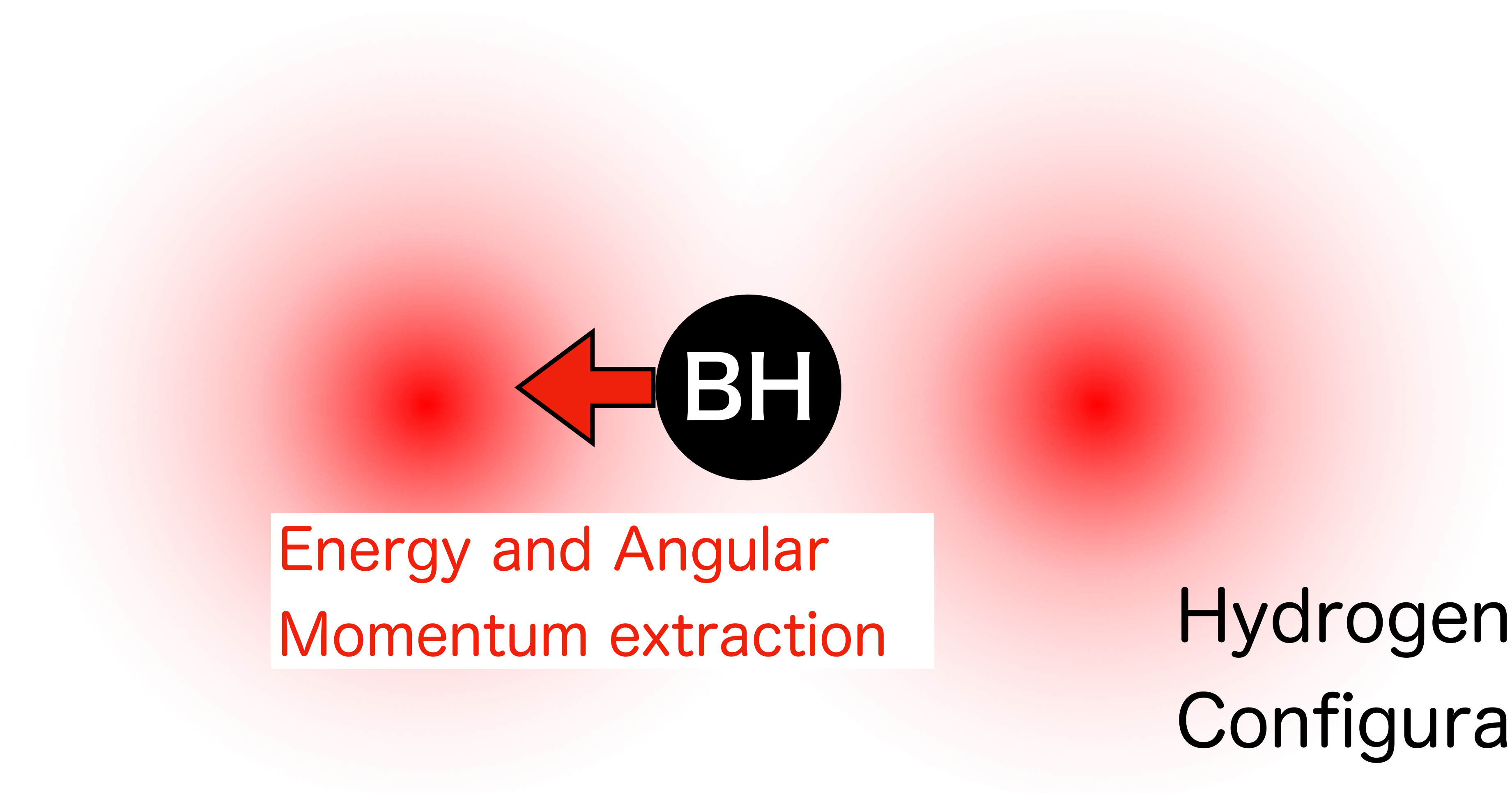
Superradiant instability

(Press&Teukolsky,1972,……)

Instability due to multiple occurence of superradiance



Axion cloud



Hydrogen atom-like Configuration

$$\phi = R_{lm\omega}(r) S_{lm\omega}(\theta) e^{-i(\omega t - m\varphi)} + \mathrm{c.c.}$$

$$\omega = \omega_R + i\omega_I \qquad \tau = \omega_I^{-1} \sim 1\mathrm{min} \ (\mu M \sim 0.42, M \sim M_\odot)$$

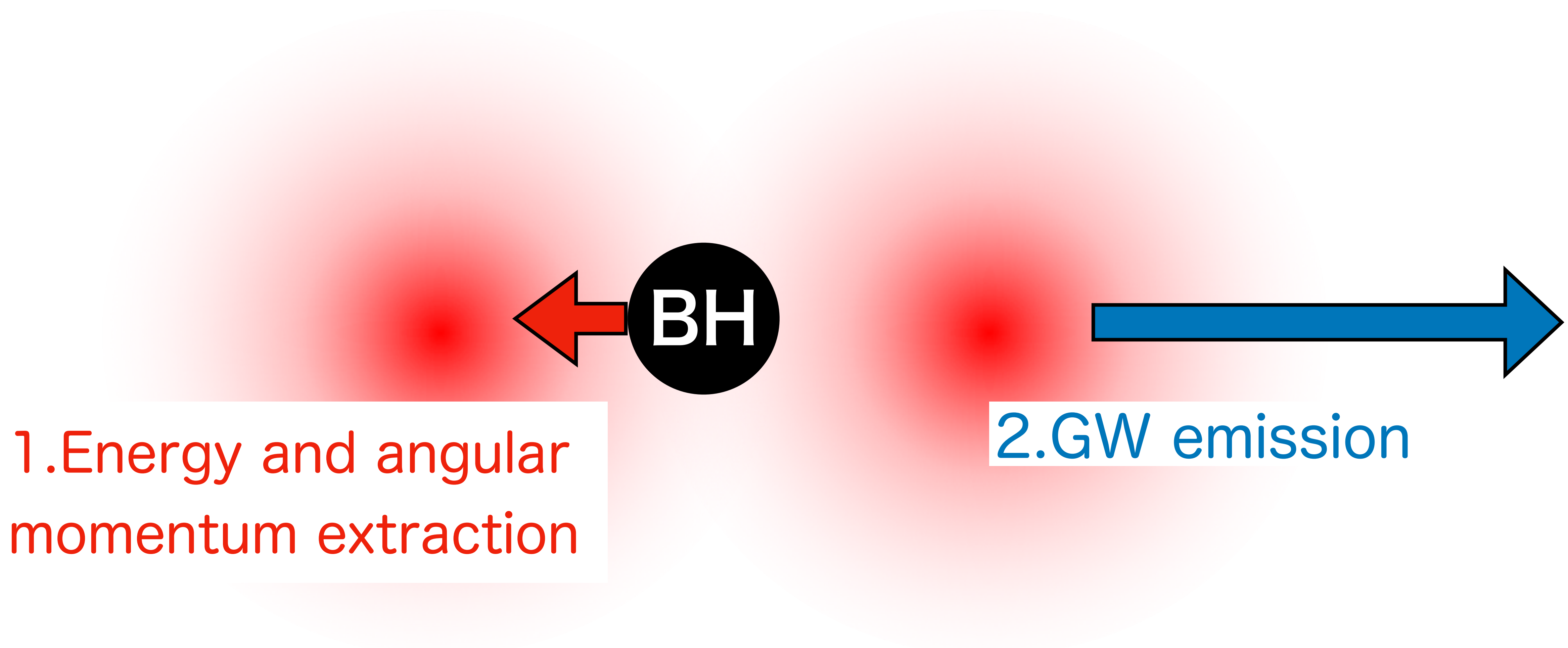
$$\underline{\omega_I > 0}, \ \underline{\omega_R \sim \mu \gg \omega_I}, \ \underline{\omega_R - m\Omega_H < 0}$$

Instability

Adiabatic growth

Supperradiance condition

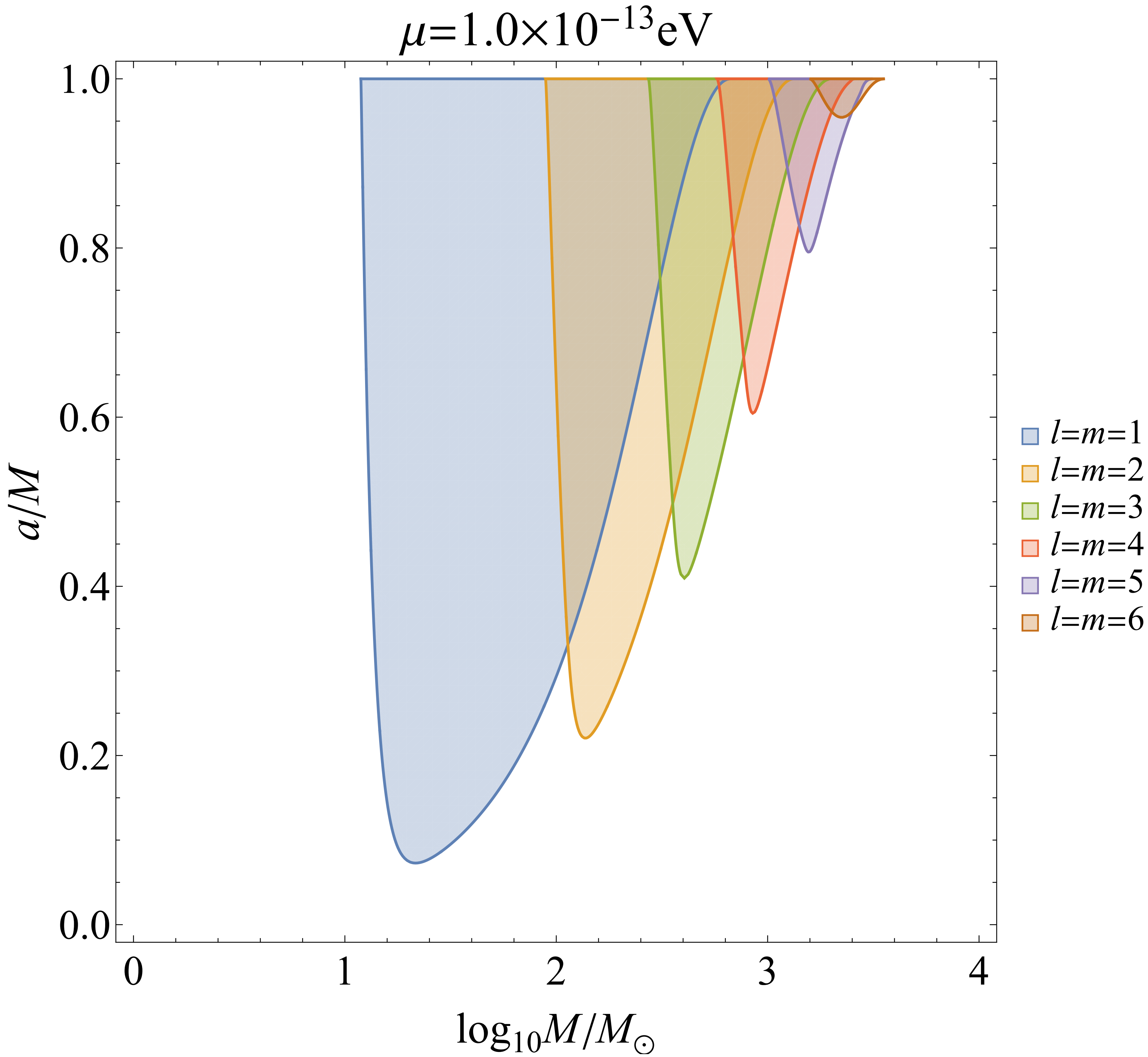
Observable effects



- 1. Implies no highly spinning BH exists
- Direct detection of 2. would be strong evidence of the axion (Frequency $\sim 10^2\mathrm{kHz}(M_\odot/M)$, $1\mathrm{kHz}(M_\odot/M)$)

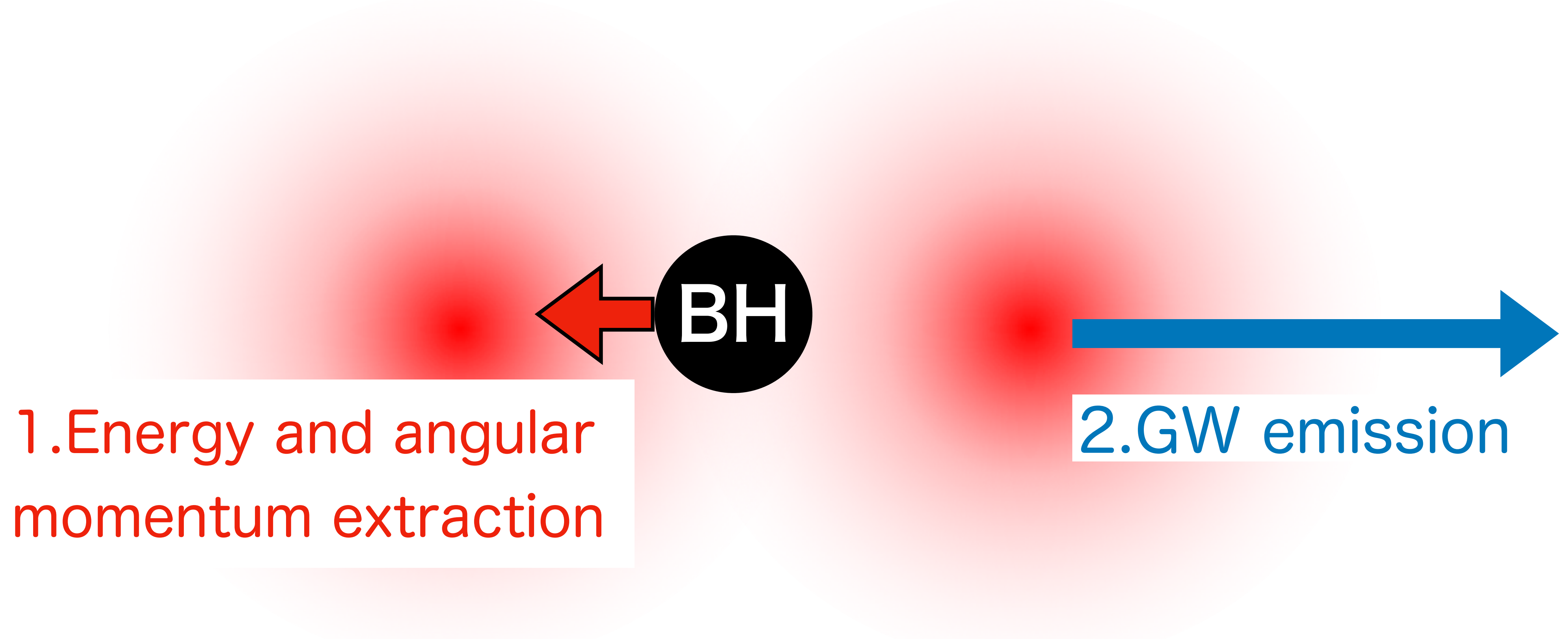
Observable effects

- 1. Implies no highly spinning BH exist



Exclusion region on spin v.s. mass plot due to axion without self-interaction

Observable effects



To give a precise constraint on axion from observation, a precise understanding of the evolution is necessary.

Important effects

- Self-interaction→Saturate the growth
- Tidal effect from the companion(Takahashi-kun's talk)
- Spin-up due to the accretion

Self-interaction

$$S = F_a^2 \int d^4x \sqrt{-g} \left[-\frac{1}{2}(\partial_\mu \phi)^2 - \mu^2 \left(1 - \cos\phi\right) \right]$$

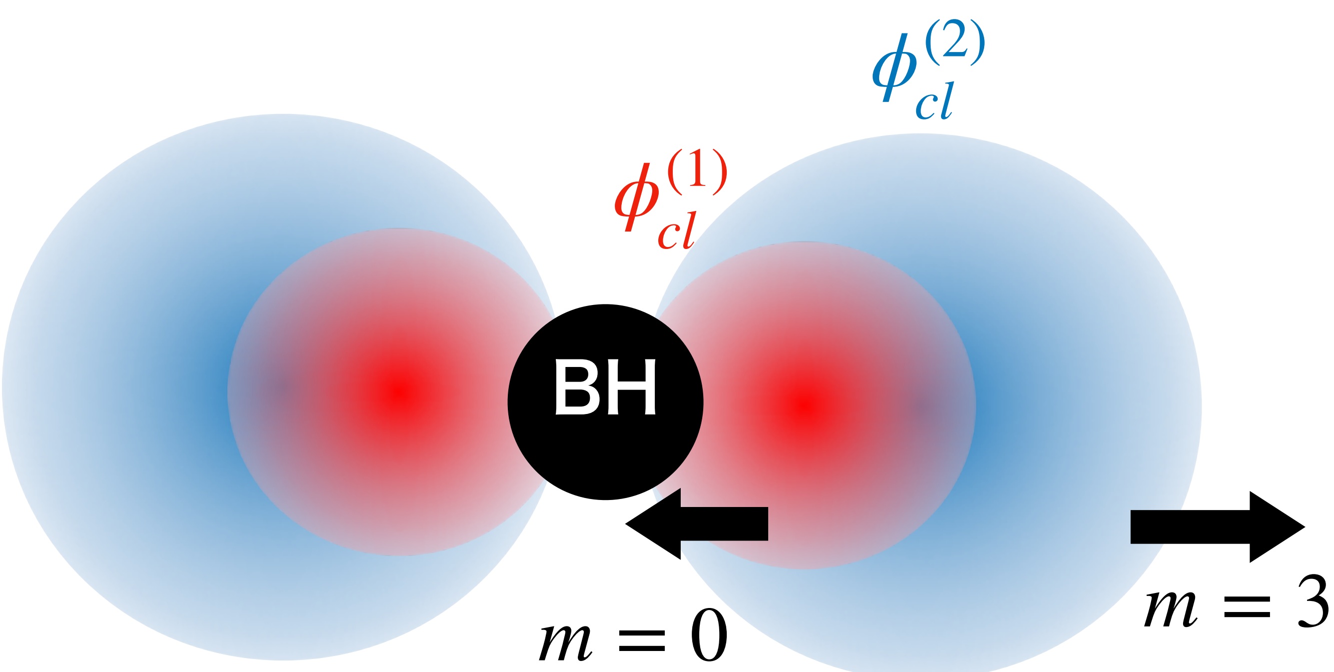
$$\sim \frac{1}{2}\mu^2\phi^2 - \frac{1}{4!}\mu^2\phi^4 + \cdots$$

g:Kerr metric ϕ:Axion μ:mass F_a:decay constant

When condensate becomes dense,
self-interaction induces an efficient dissipation channel.

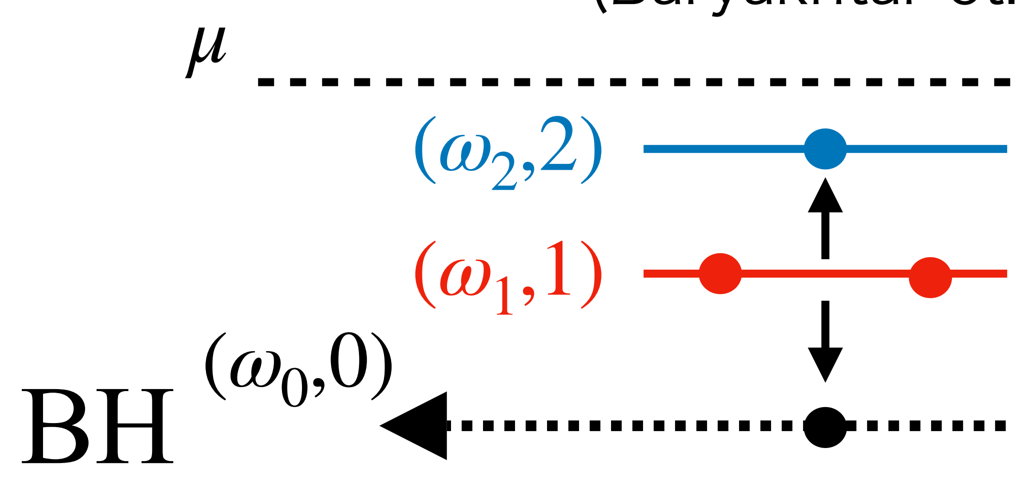
Dissipation by mode coupling

(Baryakhtar et. al. 2020)



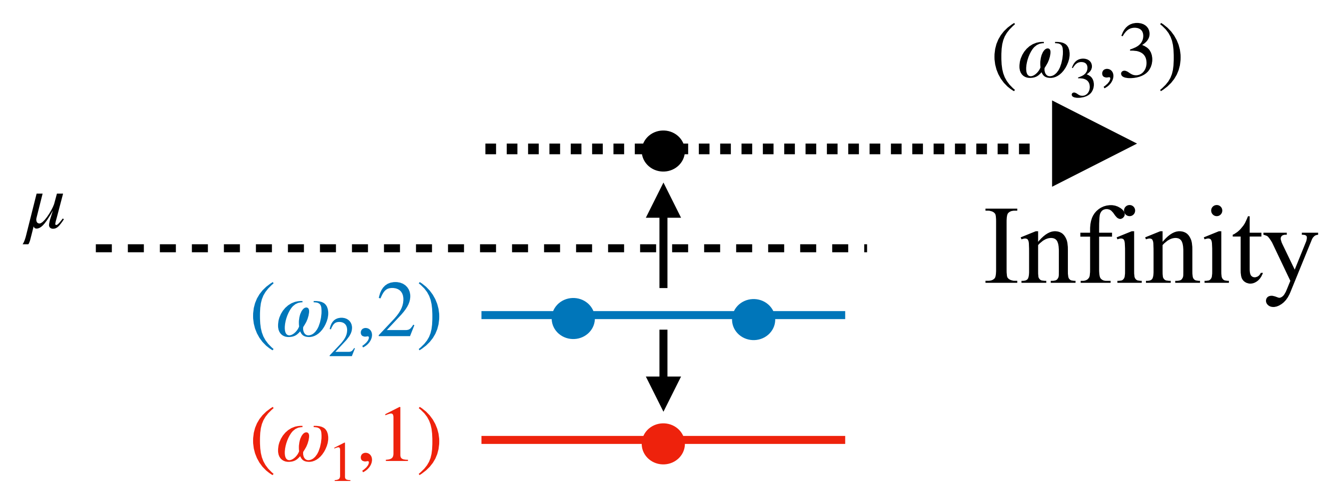
$\phi_{cl}^{(1)} : l = m = 1, \omega_R^{(1)} < \mu$

$\phi_{cl}^{(2)} : l = m = 2, \omega_R^{(1)} < \omega_R^{(2)} < \mu$



$l = m = 1$ transit to $l = m = 2$.

$m = 0$ mode dissipates energy to black hole.

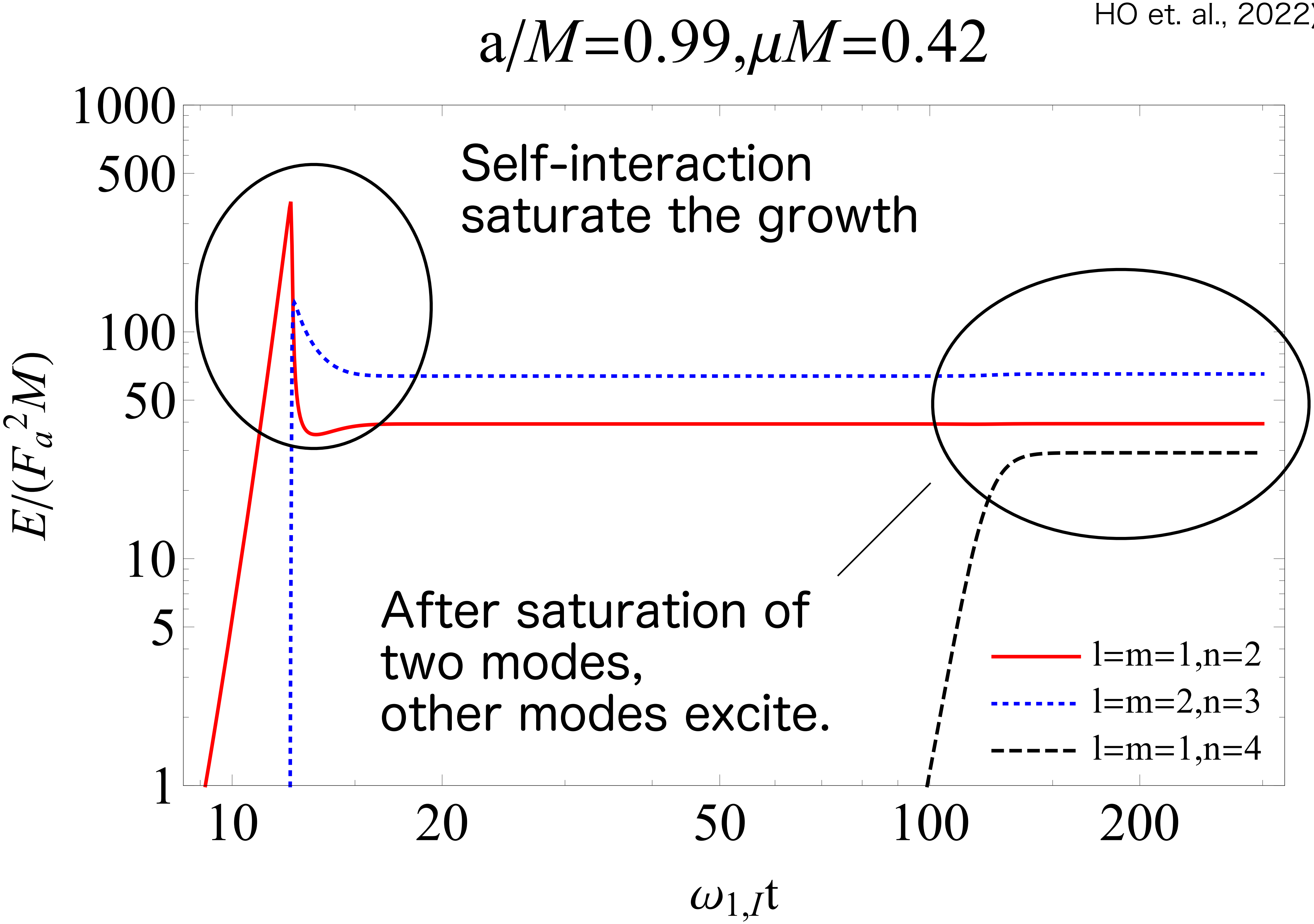


$l = m = 2$ transit to $l = m = 1$.

$m = 3$ mode dissipates energy to infinity.

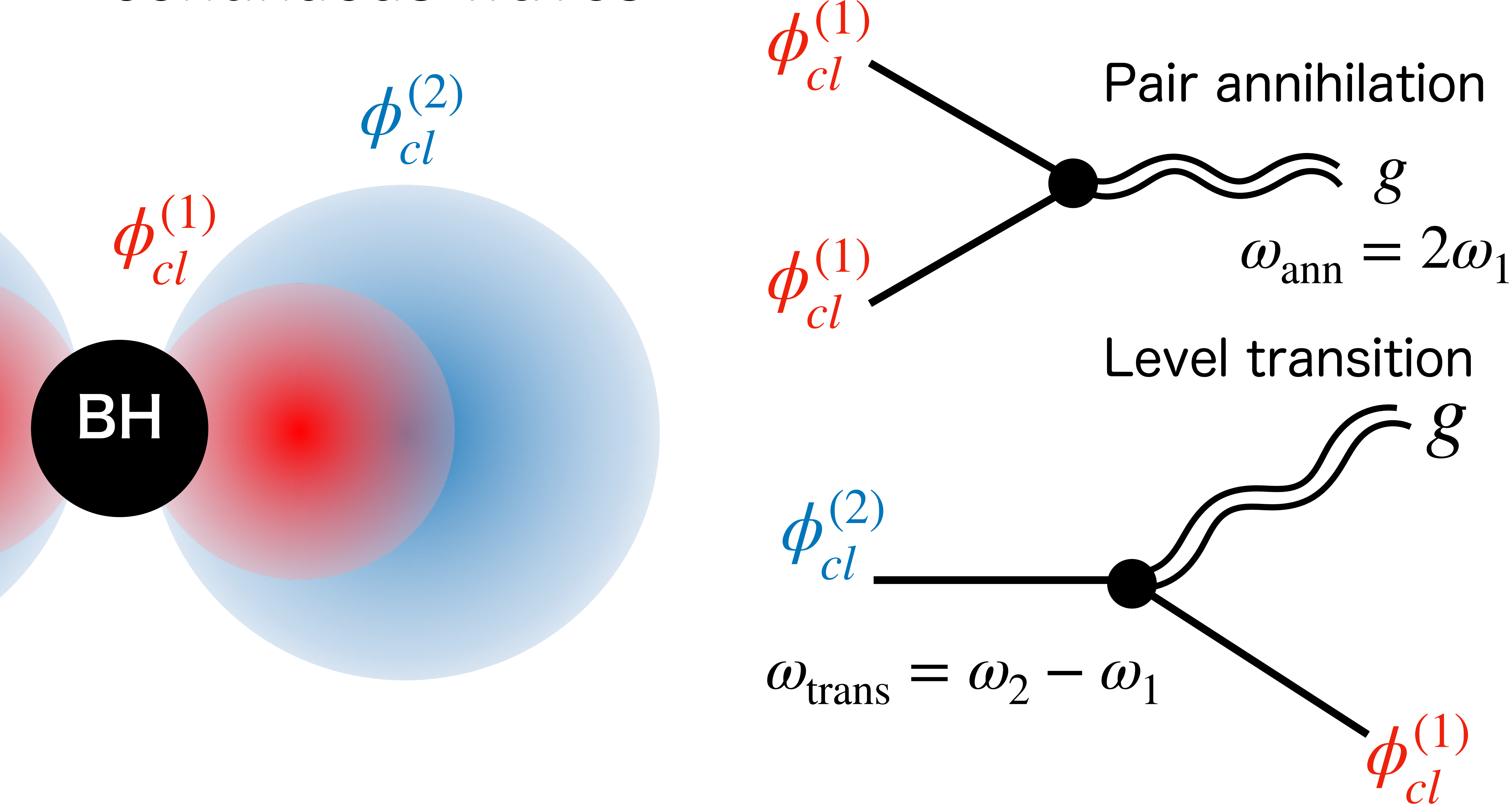
Evolution including self-interaction

(Baryakhtar et. al. 2020,
HO et. al., 2022)



Gravitational waves

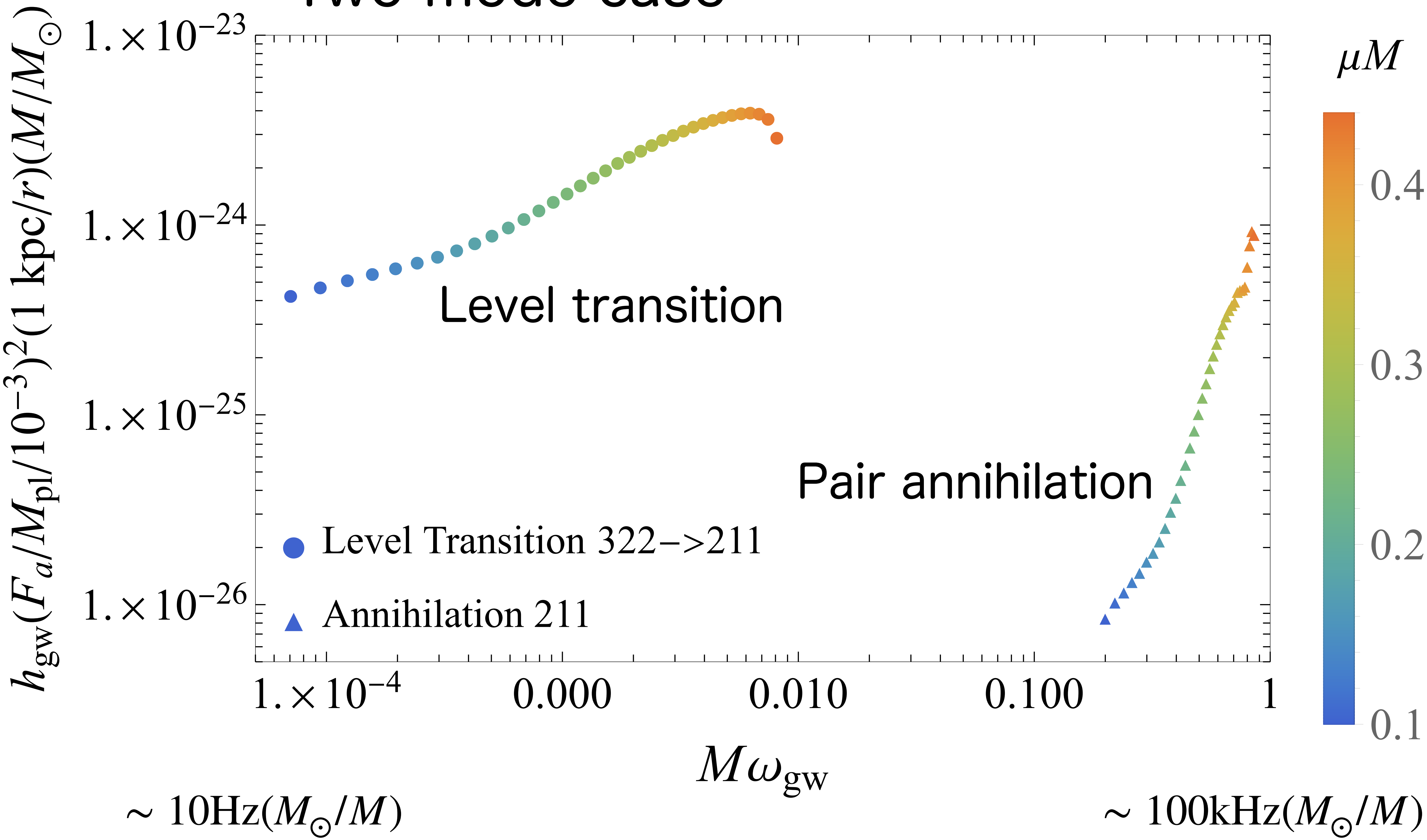
Saturated configuration emits continuous waves



Gravitational waves

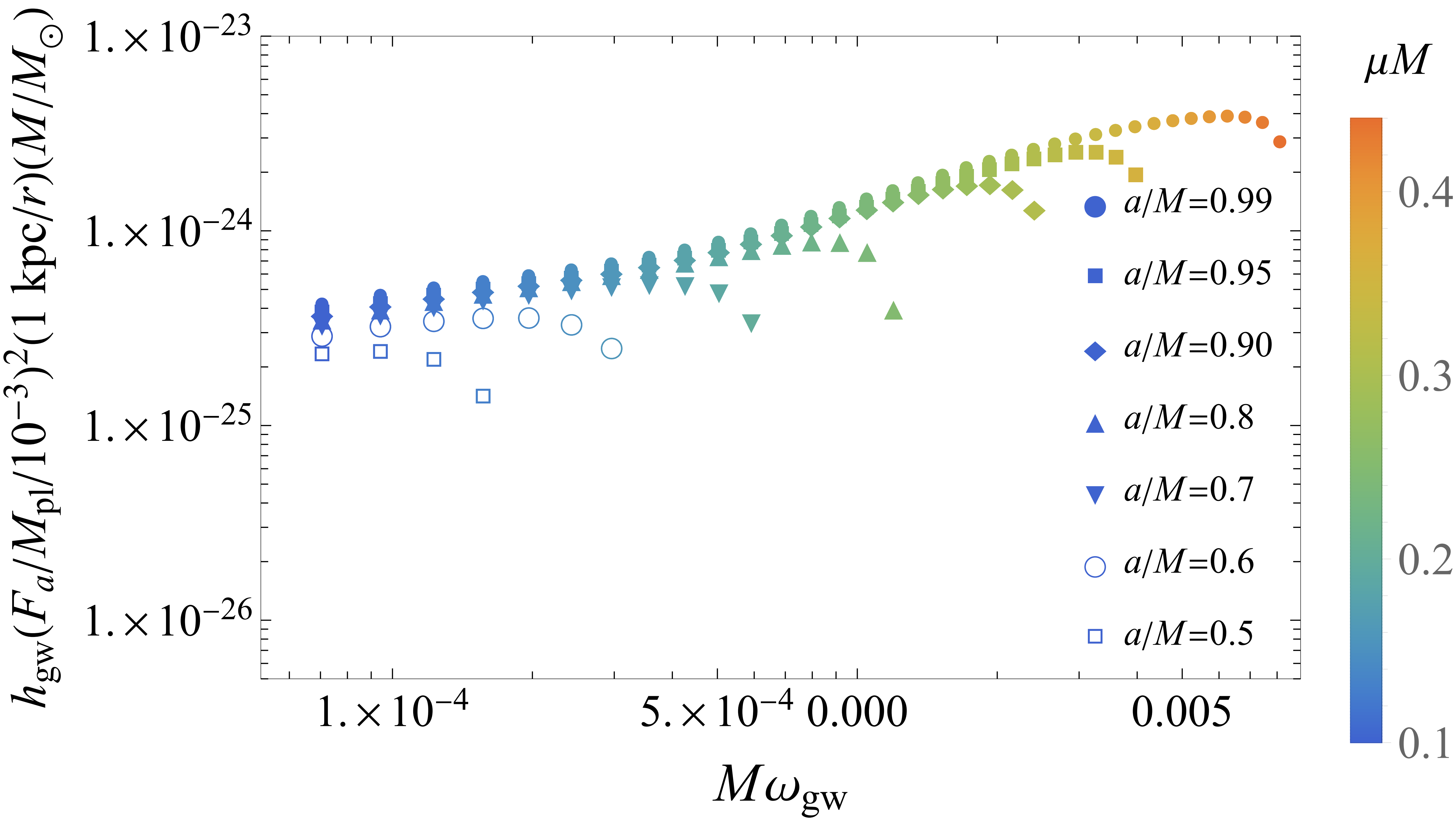
(Work in Progress)

Two mode case



Gravitational waves

(Work in Progress)



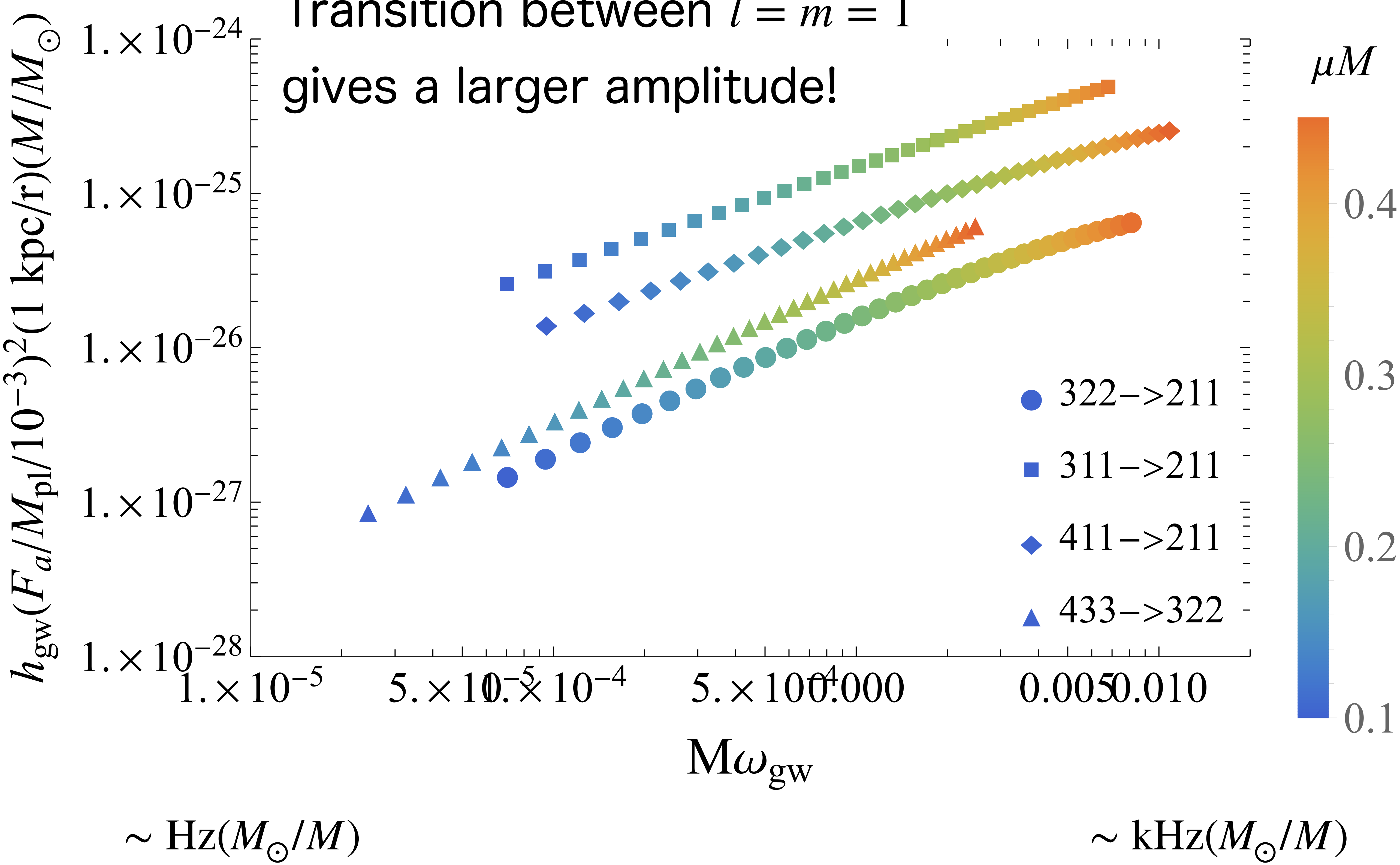
$\sim 10{\rm Hz}(M_\odot/M)$

$\sim {\rm kHz}(M_\odot/M)$

More Level transition

(Work in Progress)

Transition between $l = m = 1$ gives a larger amplitude!



Spin-down

(Work in Progress)

Excitation of other modes is slow.

We must include the spin-down of the black hole.

Evolution equations(two mode)

$m = 0$ mode $\quad$ $m = 3$ mode

$$\frac{dM_1}{dt} = 2\omega_{1,I} M_1 - \frac{2\omega_{1,R}}{\omega_{0,R}} \frac{F_0}{M^3} M_1^2 M_2 + \frac{\omega_{1,R}}{\omega_{3,R}} \frac{F_3}{M^3} M_1 M_2^2 \ ,$$

$$\frac{dM_2}{dt} = 2\omega_{2,I} M_2 + \frac{\omega_{2,R}}{\omega_{0,R}} \frac{F_0}{M^3} M_1^2 M_2 - \frac{2\omega_{2,R}}{\omega_{3,R}} \frac{F_3}{M^3} M_1 M_2^2 \ ,$$

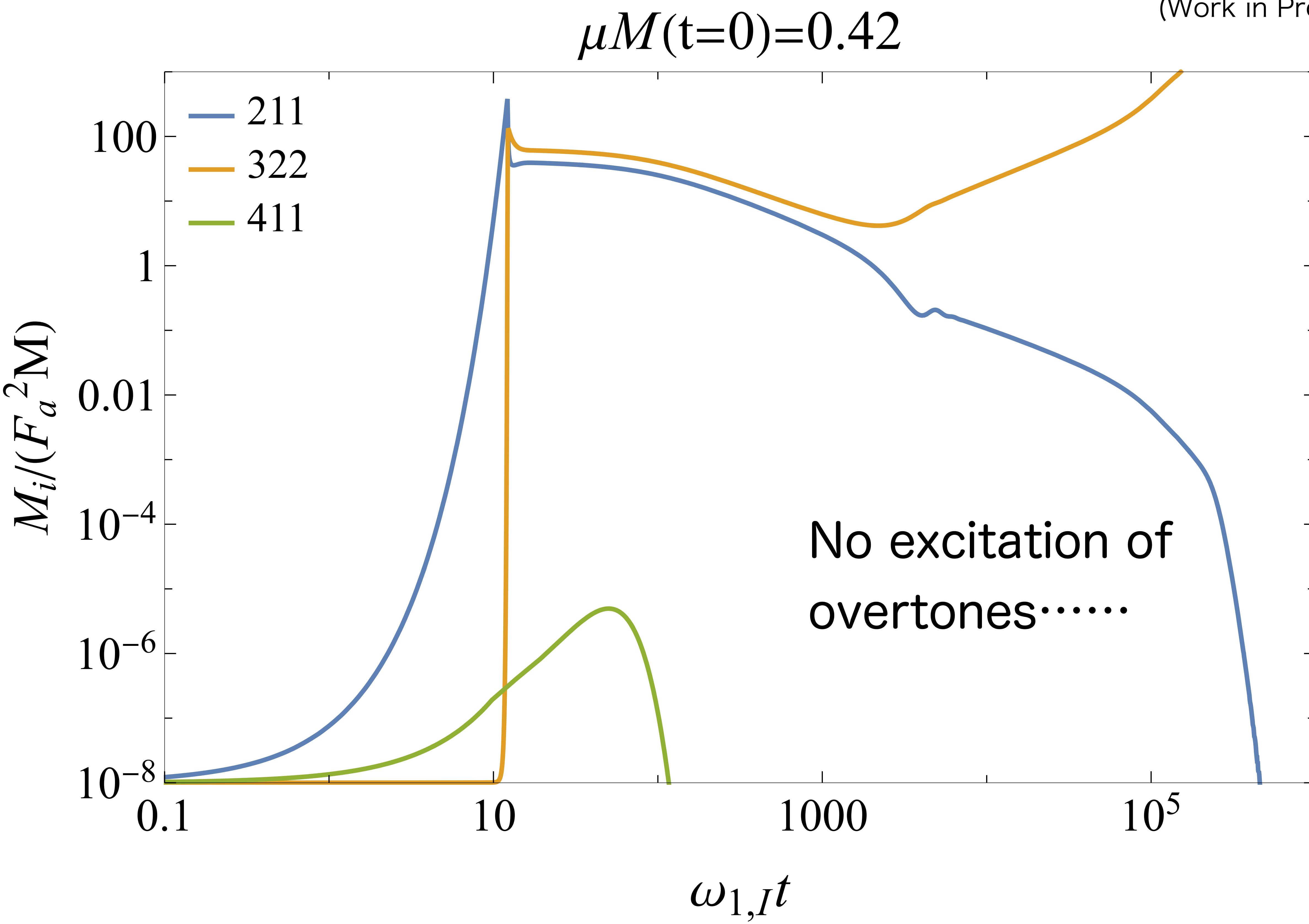
$$\frac{dM}{dt} = -F_a^2 \left(2\omega_{1,I} M_1 + 2\omega_{2,I} M_2 - \frac{F_0}{M^3} M_1^2 M_2 \right) \ ,$$

$$\frac{dJ}{dt} = -F_a^2 \left(2\omega_{1,I} \frac{1}{\omega_{1,R}} M_1 + 2\omega_{2,I} \frac{2}{\omega_{2,R}} M_2 \right) \ ,$$

We fix to $F_a = 10^{-3} M_{pl}$.

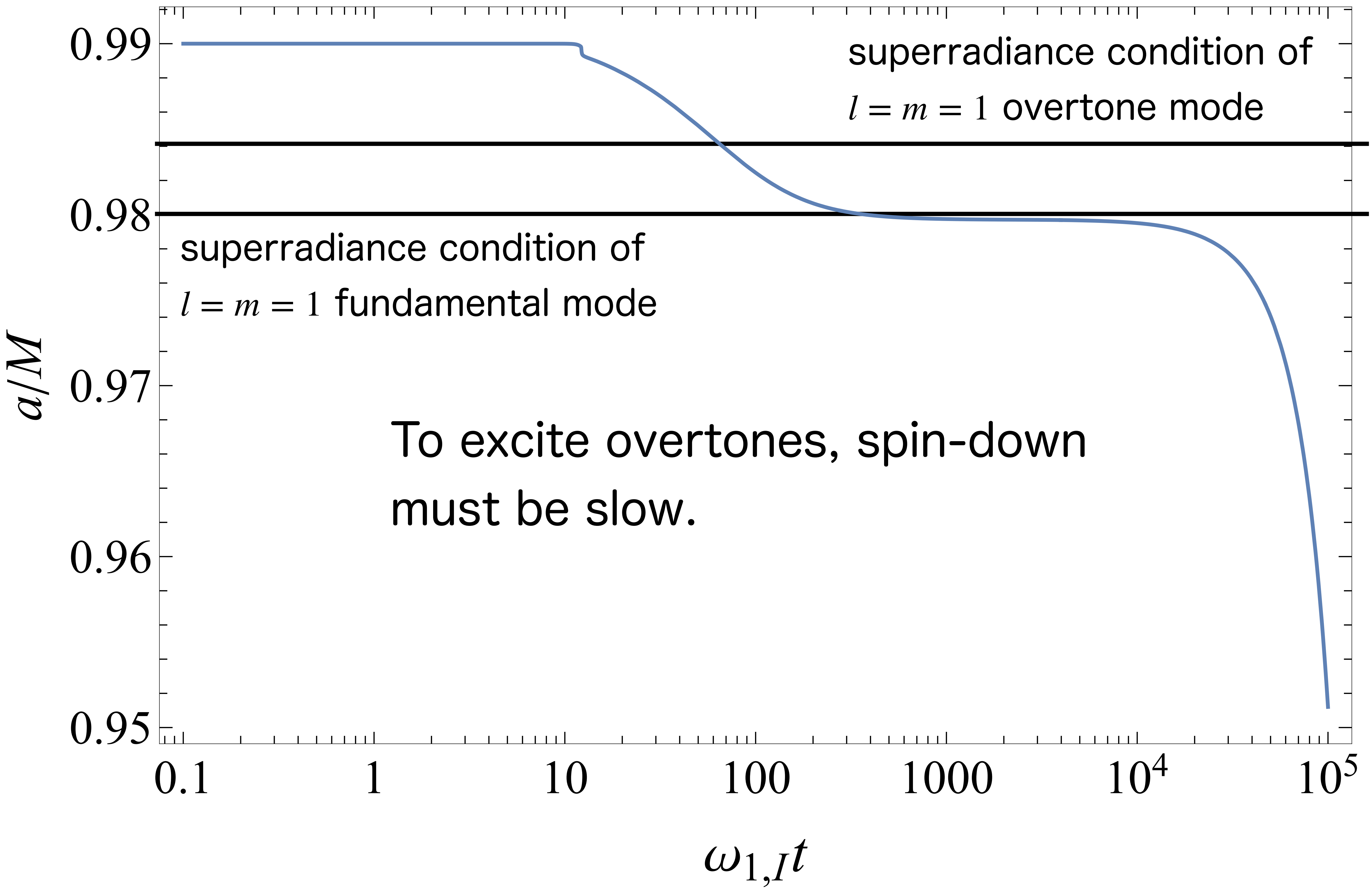
Spin-down

(Work in Progress)



Spin-down

(Work in Progress)



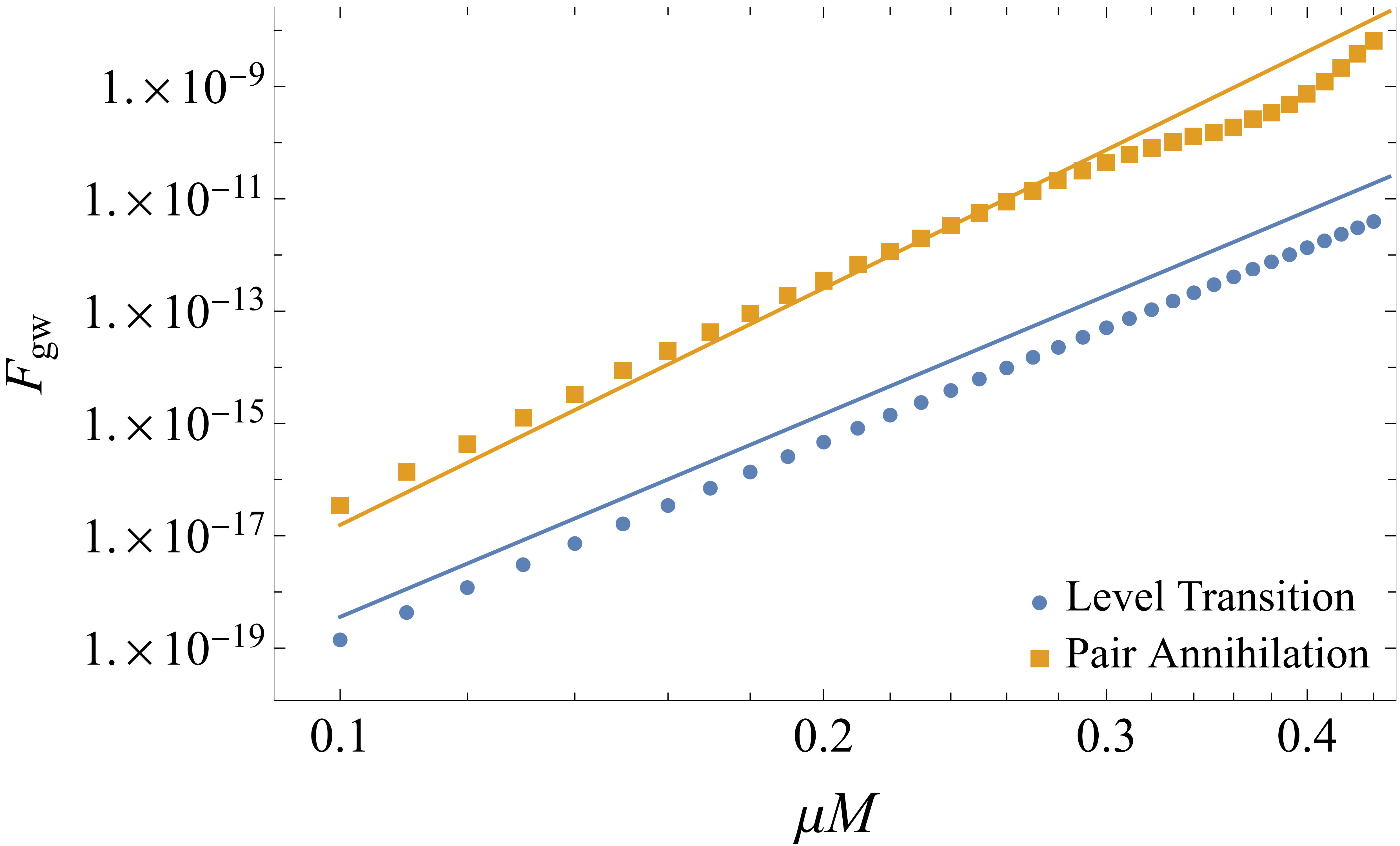
Summary

- We want to calculate the observable signature of the axion, especially gravitational waves.
- Extending the previous works, we numerically calculate the gravitational wave amplitude and the time evolution of the condensate including the evolution of the black hole for various parameters.
- Axion condensate emits continuous gravitational waves in different frequencies.
- Gravitational wave amplitude is suppressed by $(F_a/M_{pl})^2$.
- Spin-down of black hole terminates excitation of overtones.

Back up

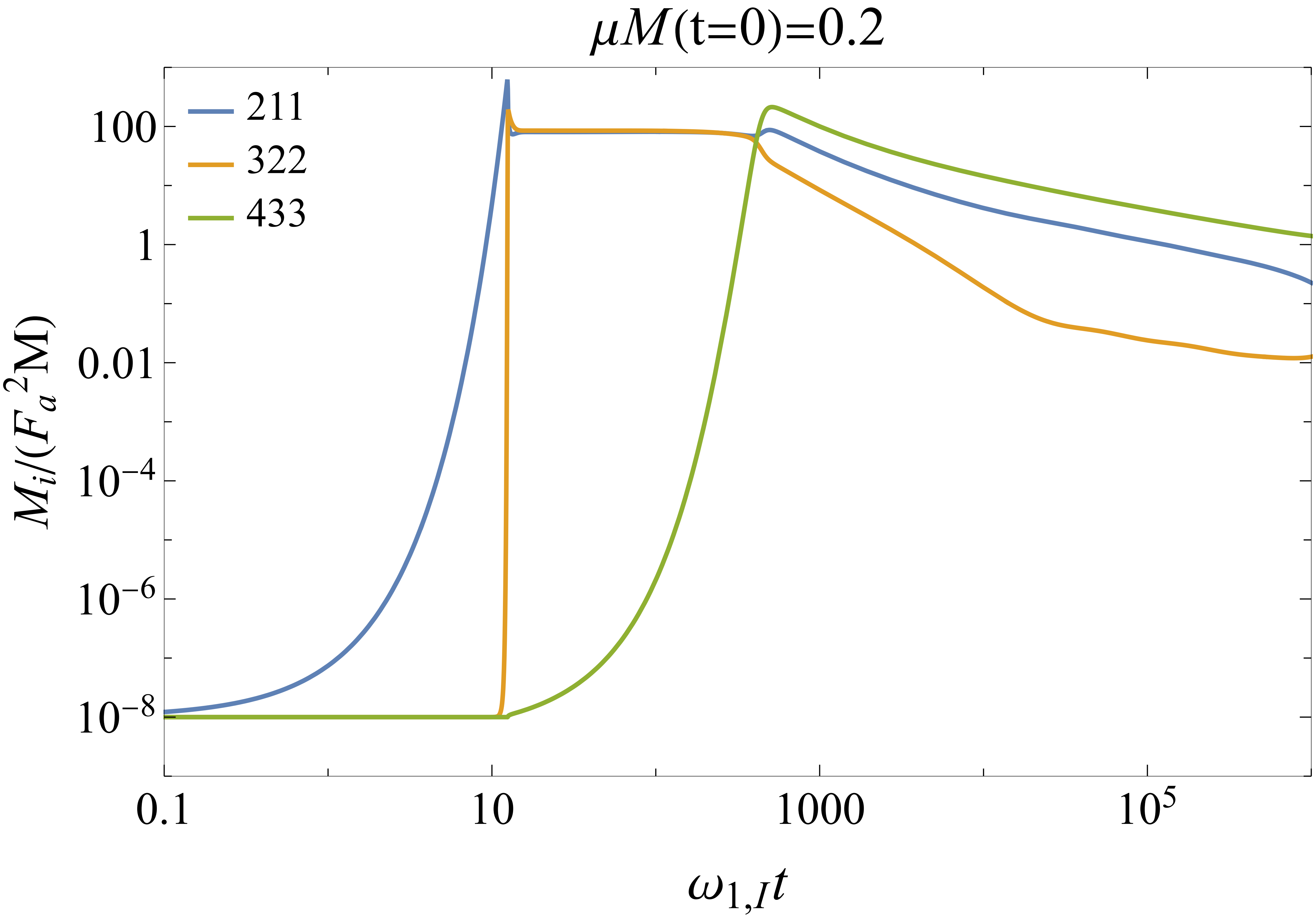
Gravitational wave energy flux

(Work in Progress)



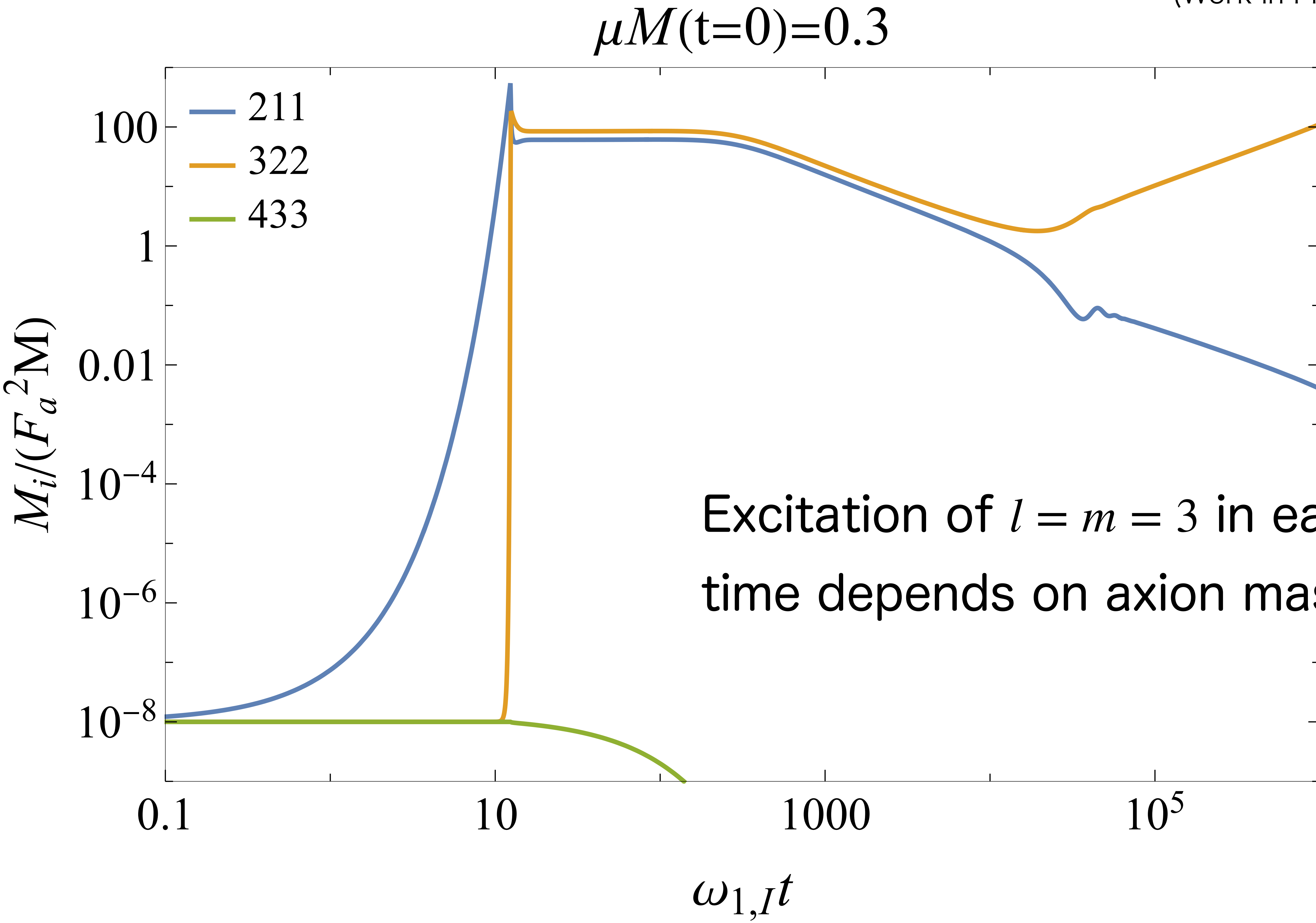
$l = m = 3$ modes

(Work in Progress)



$l = m = 3$ modes

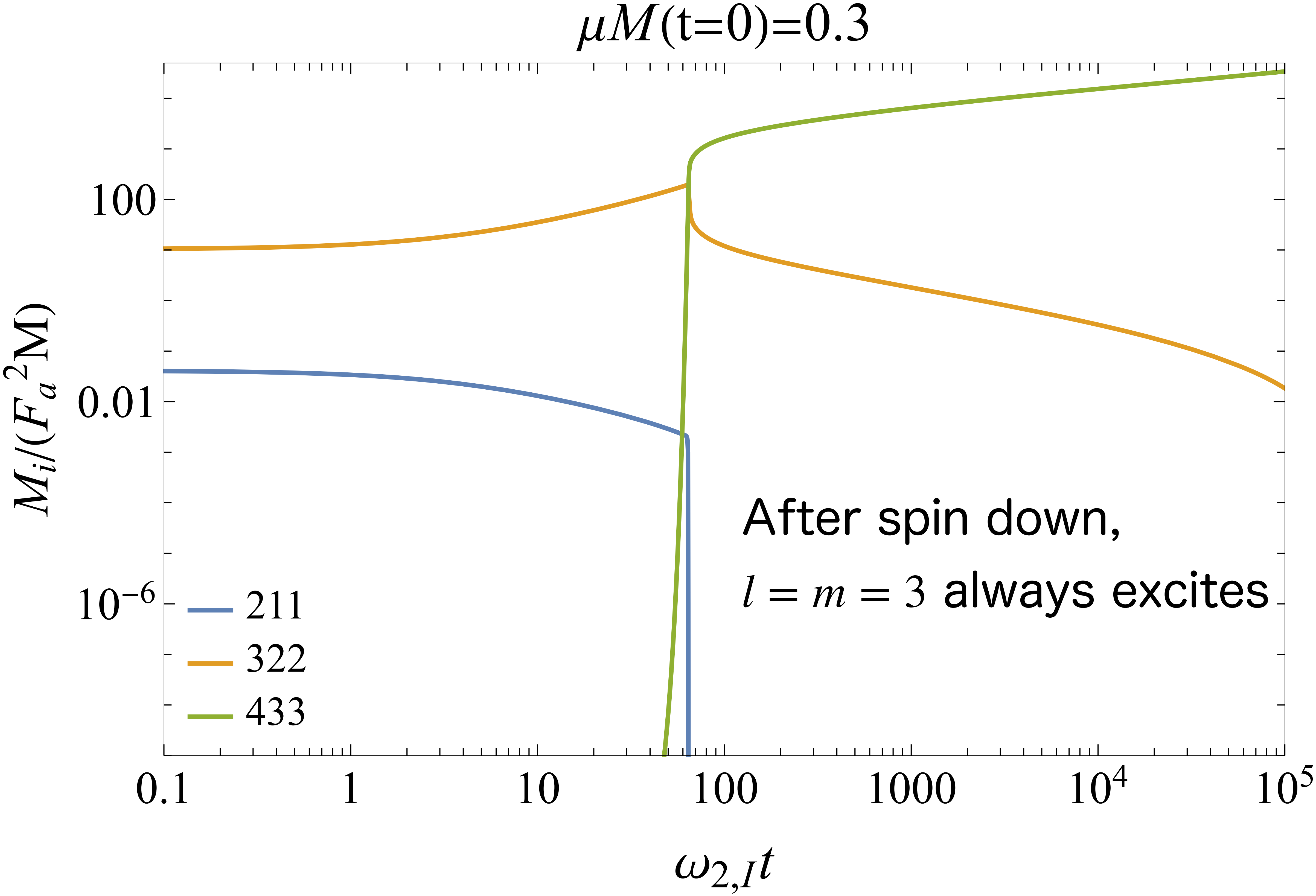
(Work in Progress)



Excitation of $l = m = 3$ in early time depends on axion mass

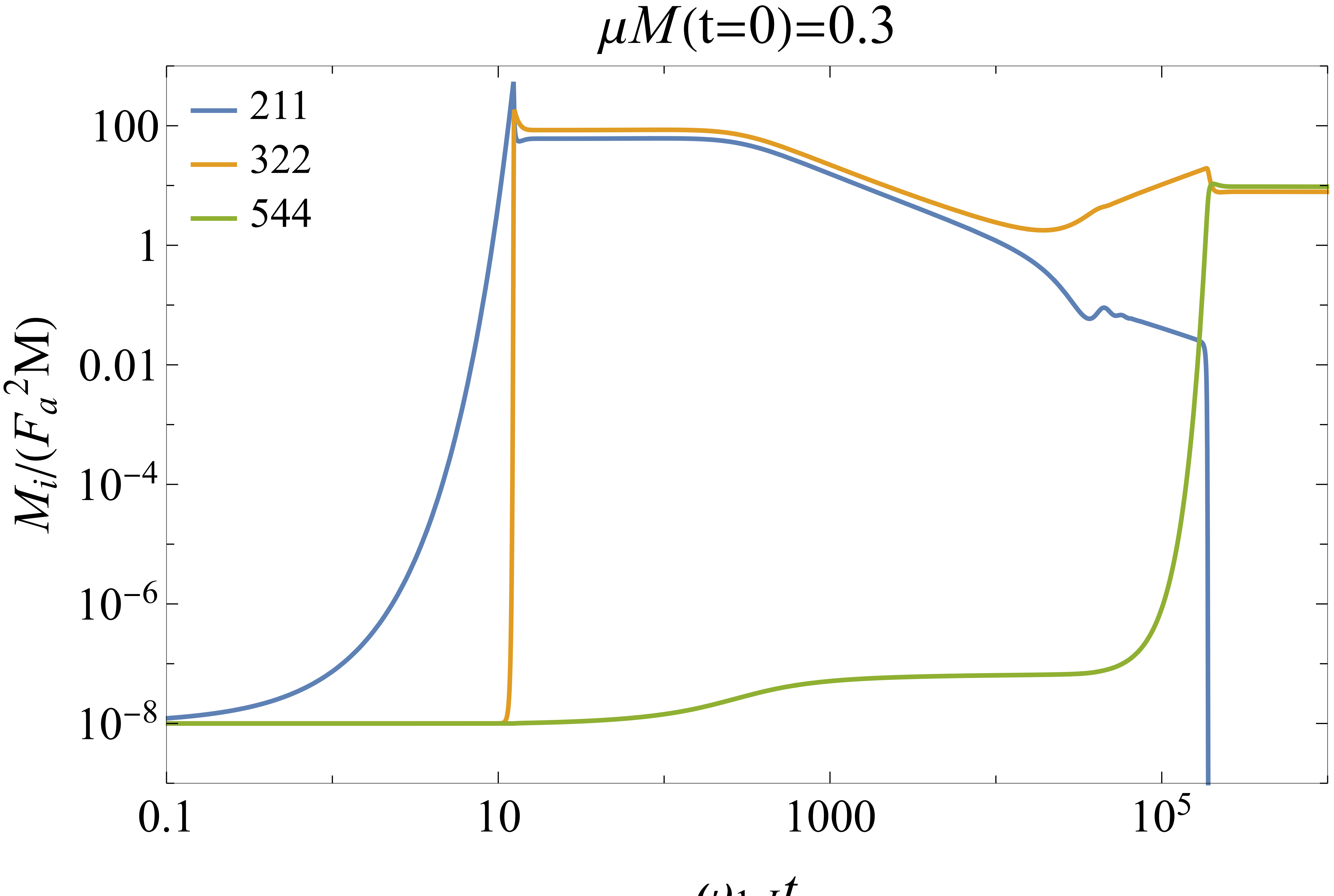
$l = m = 3$ modes

(Work in Progress)



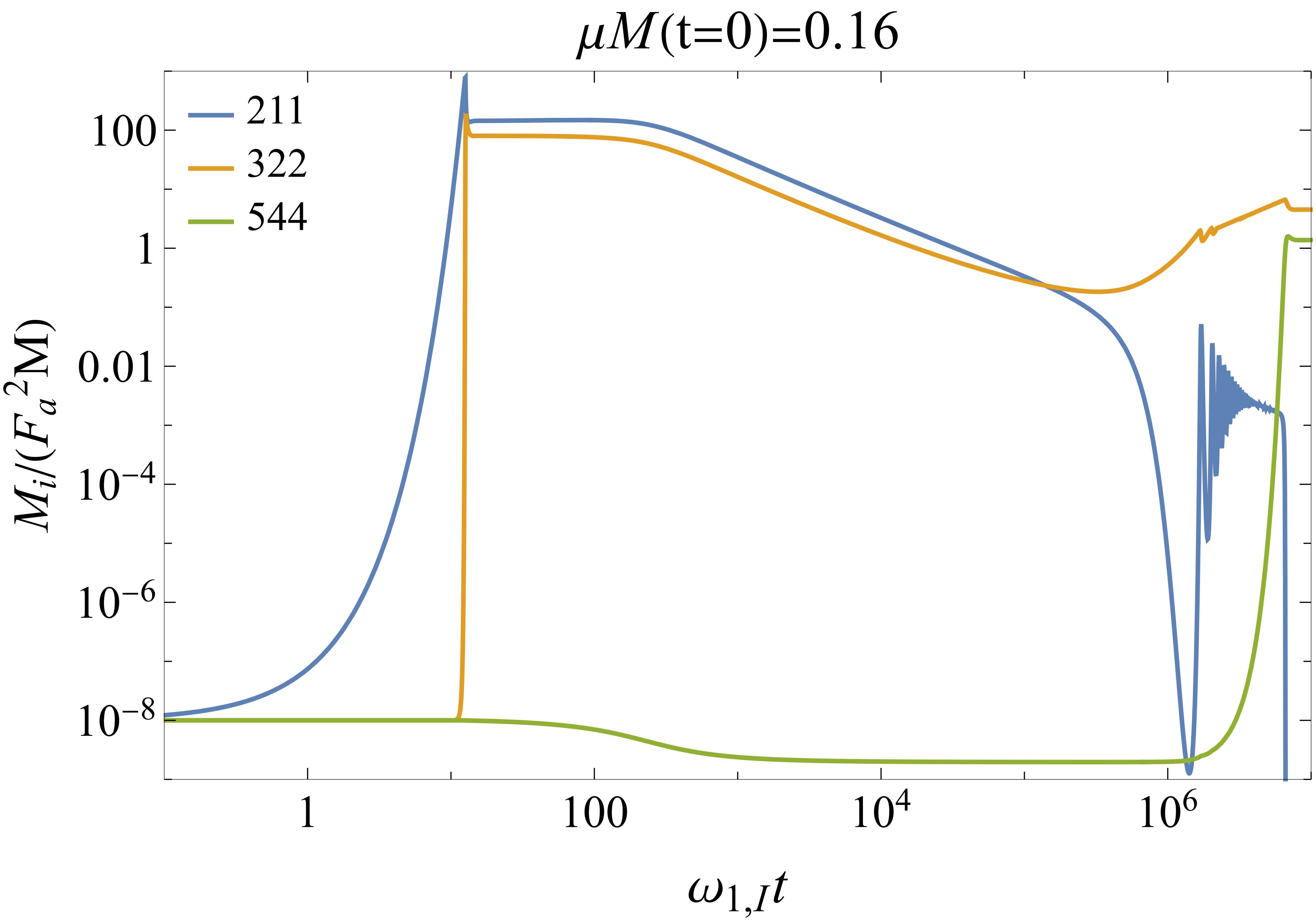
$l = m = 4$ modes

(Work in Progress)



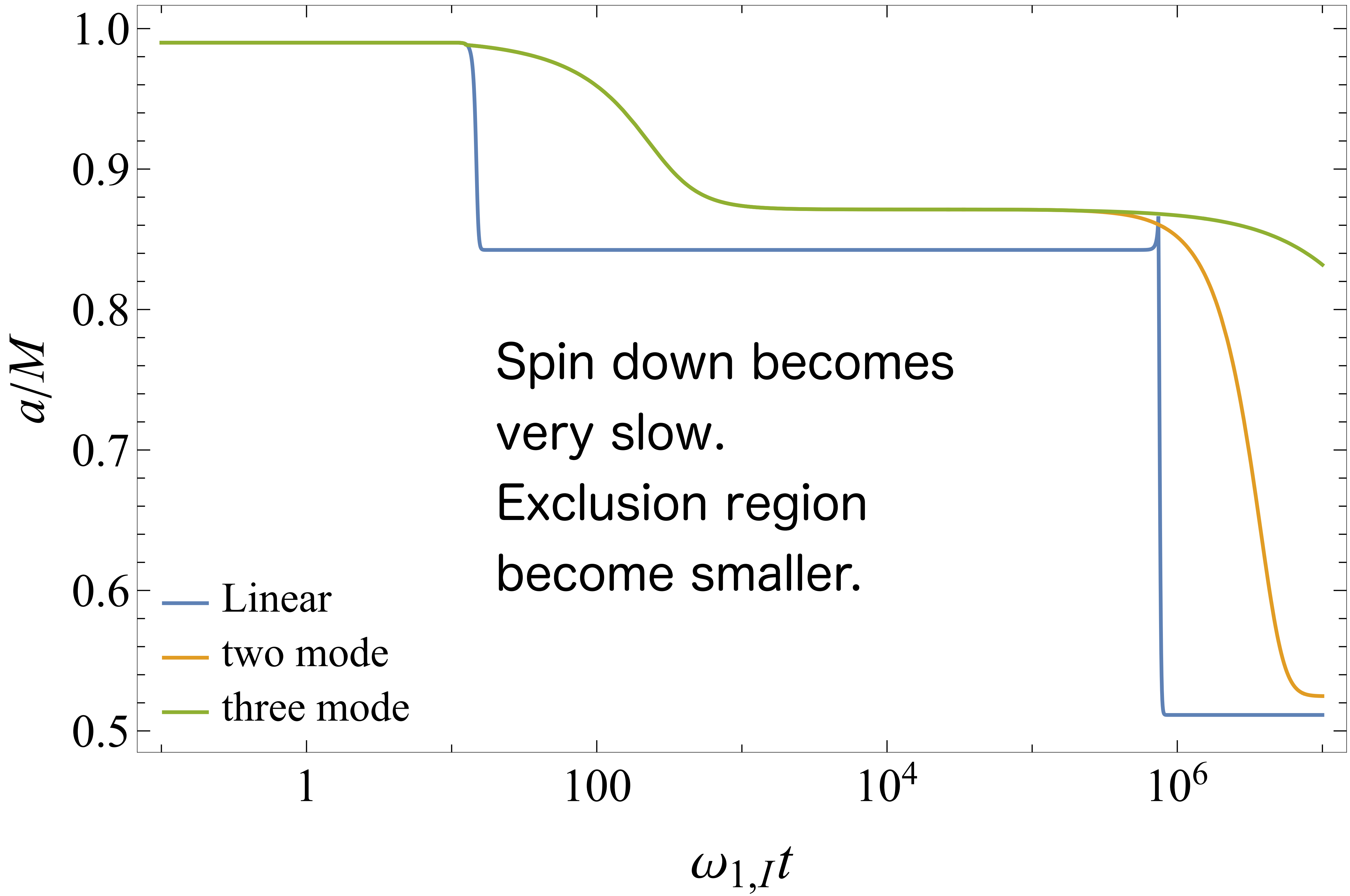
$l = m = 4$ modes

(Work in Progress)



$l = m = 4$ modes

(Work in Progress)



Spin down becomes very slow.
Exclusion region become smaller.