Axion clouds may survive the perturbative tidal interaction over the early inspiral phase of black hole binaries

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Based on : T. Takahashi & T. Tanaka 2106.08836[gr-qc]

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Introduction

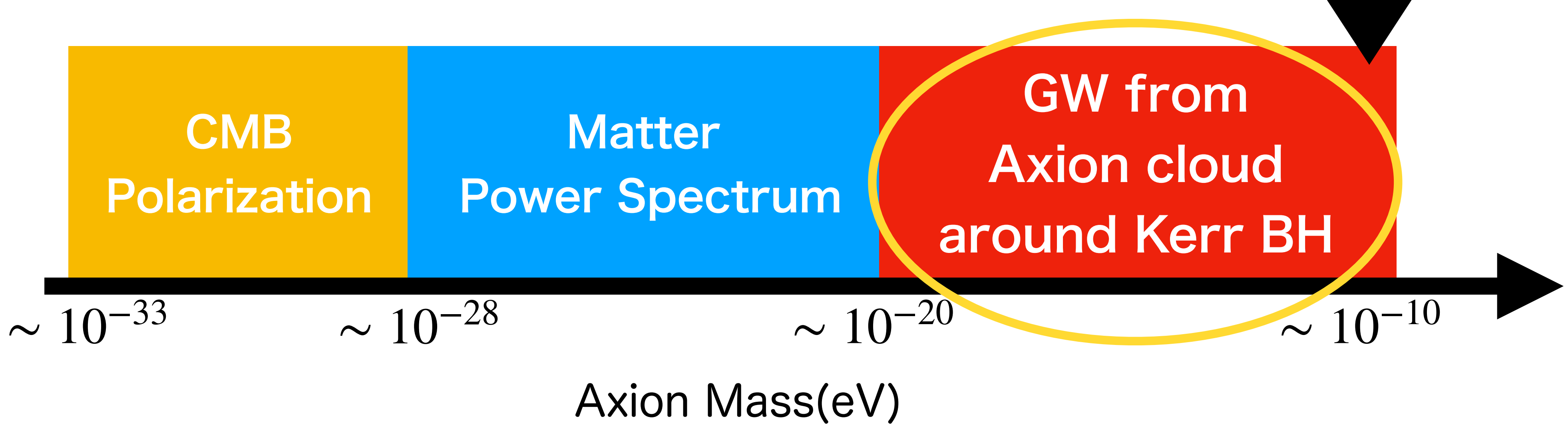
Axion & Astrophysics

The best-motivated extension of the Standard Model

- QCD/String axion
- Dark matter candidate

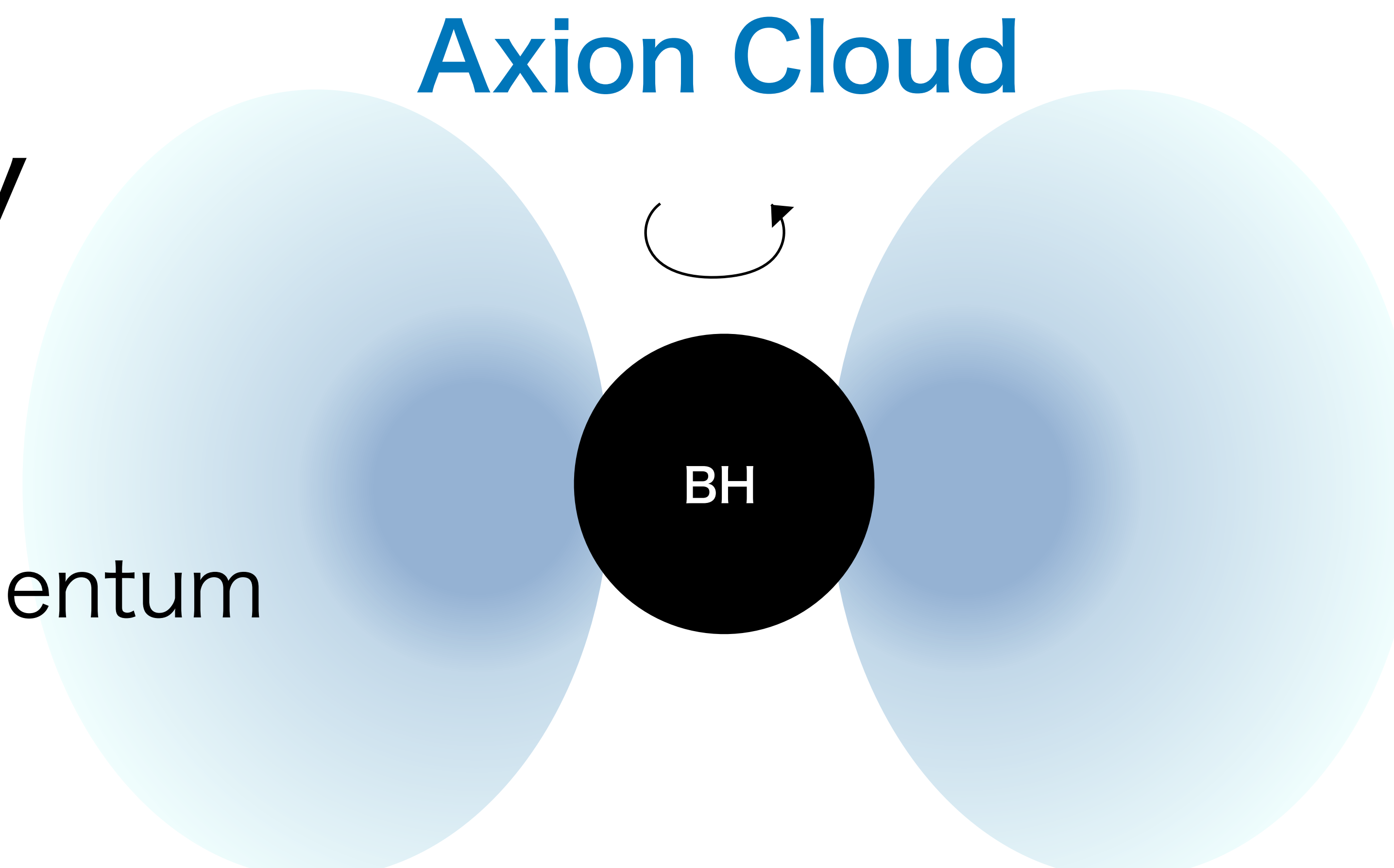
This talk

Cosmic phenomena used in axion exploration by axion mass



(A.Arvanitaki et. al., String Axiverse, arXiv:0905.4720)

Rotating BHs and Axion



Superradiant instability

- This system admits quasi-bound solutions
- Energy and angular momentum extraction from BH

Axion froms a cloud

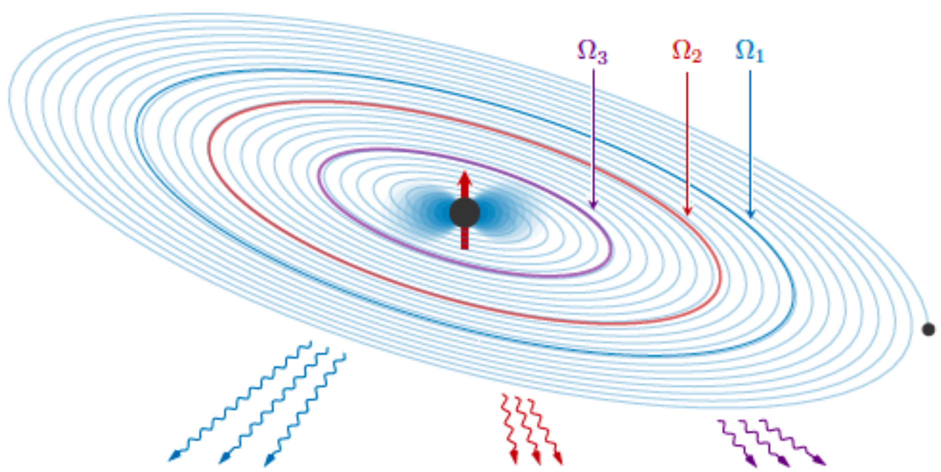
(BH radius M) ~ (Compton wavelength $1/\mu$)

$10^{-20} \sim 10^{-10}$eV

BHs and GWs observation
has the potential of probing axion

Axion Clouds in Binary systems

D.Baumann et al, 1912.04932



- Can we test axion with GW from binary coalescence?

- Does the axion cloud disappear due to binary's tidal interaction?

We made the exhaustive study of cloud depletion in a wide parameter region numerically for equal mass binaries.

Dynamics of the Axion Clouds

Isolated Axion Clouds

$$(g^{\mu\nu}\nabla_\mu\nabla_\nu - \mu^2)\,\phi = 0$$

↓ non-relativistic approx. $M\mu \ll 1$

$$i\frac{\partial}{\partial t}\psi = \left[-\frac{1}{2\mu}\nabla^2 - \frac{M\mu}{r}\right]\psi$$

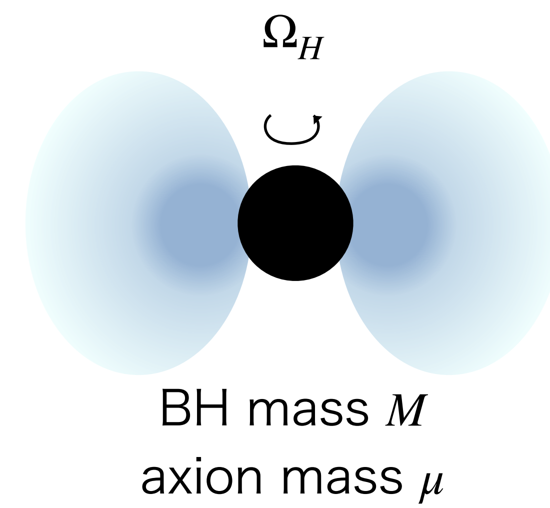
This is formally equivalent
to the hydrogen atom in QM.

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

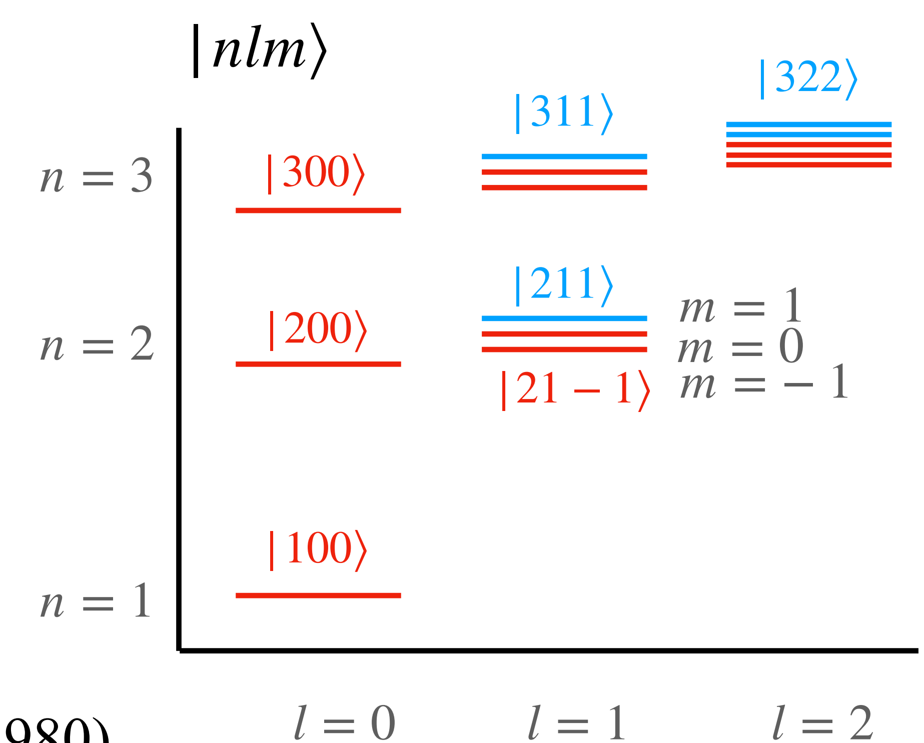
Energy Growth(+)/Decay(-)

$$(\omega_I)_{nlm} \propto (m\Omega_H - \mu)(M\mu)^{4l+5}$$ (S.Detweiler, 1980)

superradiance condition



Energy level

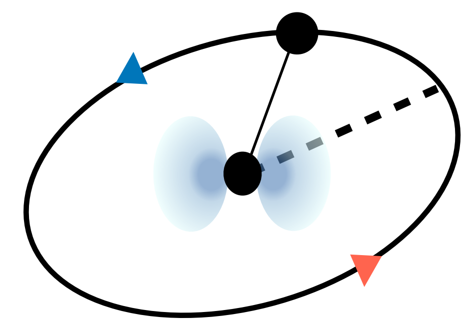


Binary's tidal perturbation

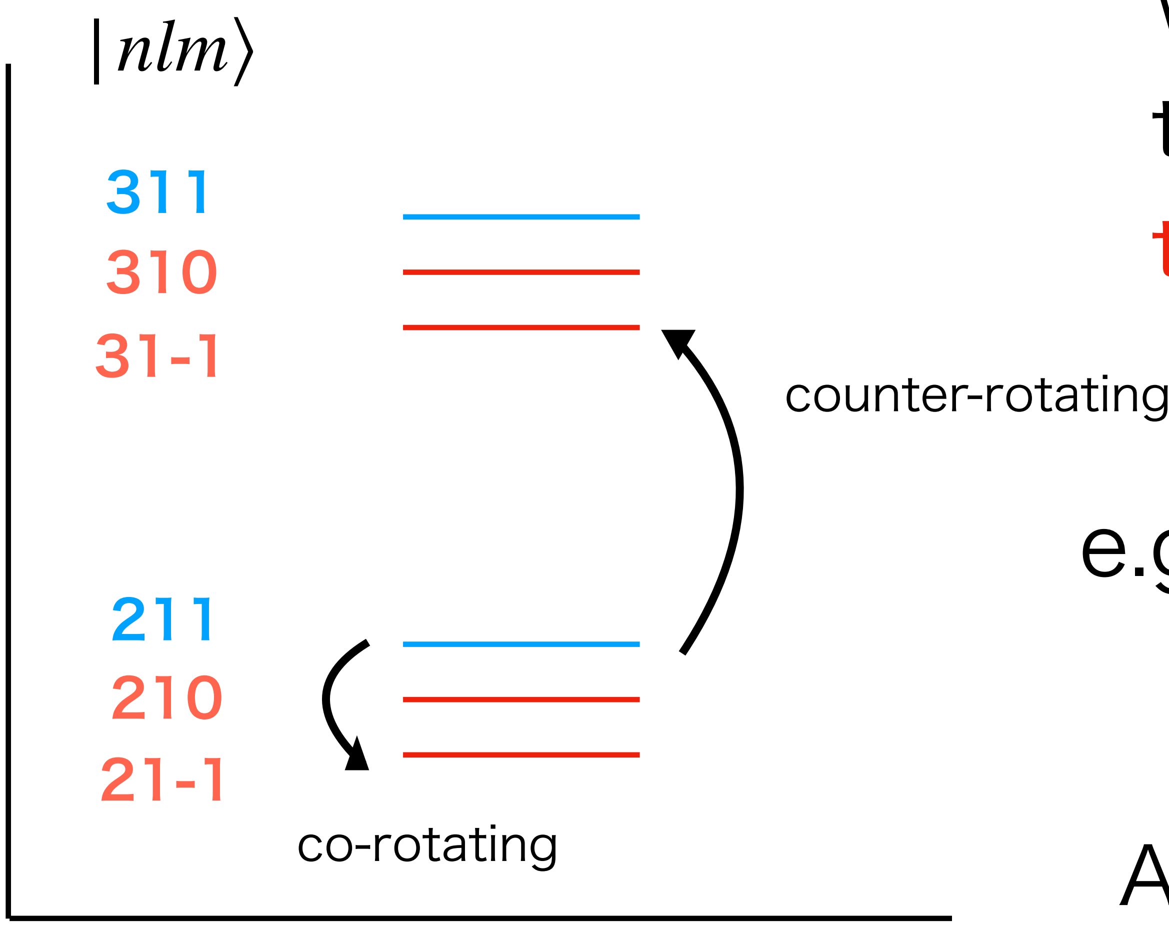
$$i\frac{\partial}{\partial t}\psi = \left[-\frac{1}{2\mu}\nabla^2 - \frac{M\mu}{r} + V_*\right]\psi$$

tidal potential

Orbital freq. Ω



$$H = H_0 + V(t)\ , \quad V(t) = \eta e^{-i\Omega t}$$



When orbital freq. coincides with the energy gap, resonant level transition occurs.

(D.Baumann et al, 1912.04932)

e.g.) co-rot. : $|211\rangle \to |21-1\rangle$

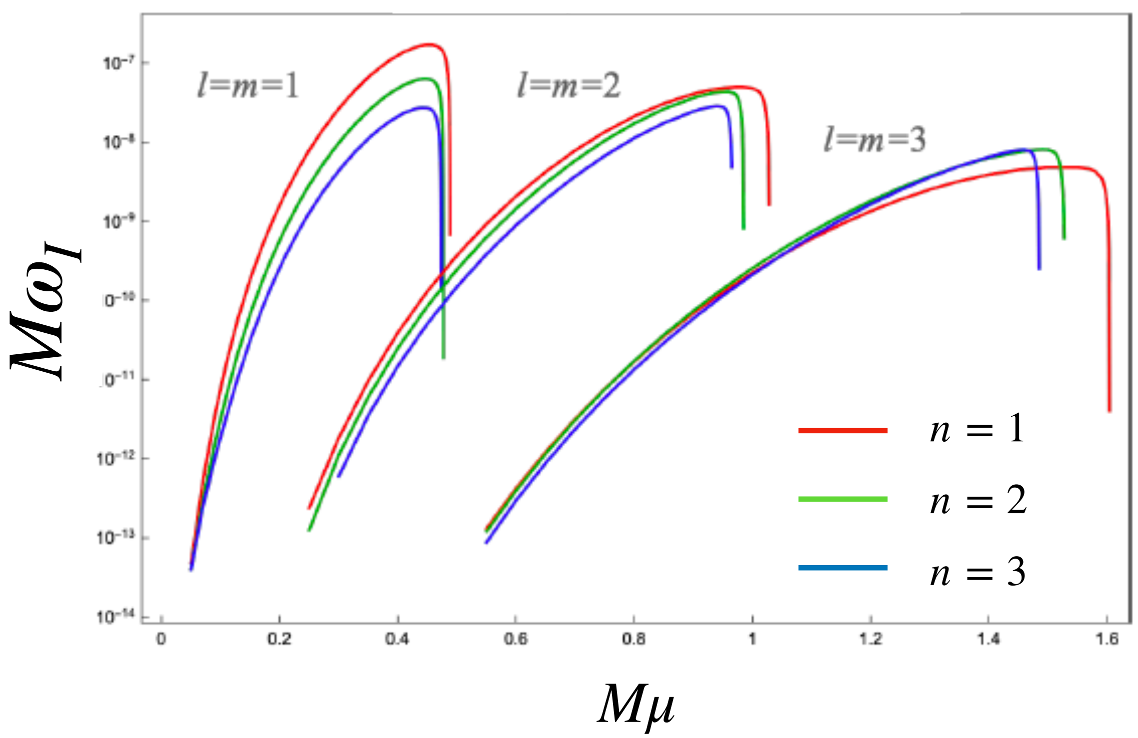
counter-rot. : $|211\rangle \to |31-1\rangle$

Axions in the growing mode are transferred to the decaying mode.

Is there any chance the Cloud won’t disappear？

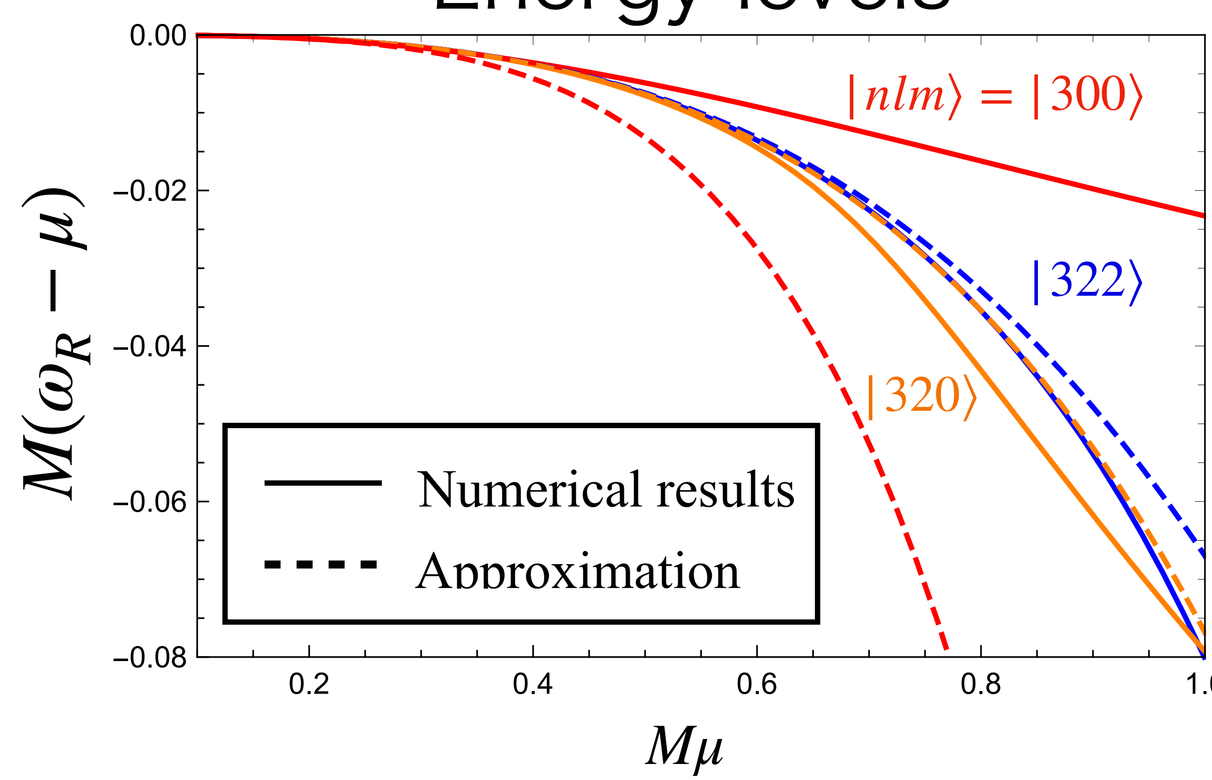
- We are interested in the case $M\mu \gtrsim 0.1$.
- Resonance freq. is determined by the energy gap.
- We need to calculate the eigenfrequencies numerically.

Growth rate



higher-l mode

Energy levels



non-trivial transition

Parameter : coupling and BH spin $(M\mu, a/M)$

Story

① Transition destination

Initially, axions occupy the fastest growing mode.

$$|n_0 l_0 m_0\rangle \rightarrow |?>$$

↑

- quadruplolar tidal perturbation V_*
- Selection rules

e.g.) non-rela approxi.

co-rot. : $|211\rangle \rightarrow |21-1\rangle$

$|322\rangle \rightarrow |320\rangle$

② How much fraction of the cloud will disappear

If transition is adiabatic, all axions are transferred to another mode.

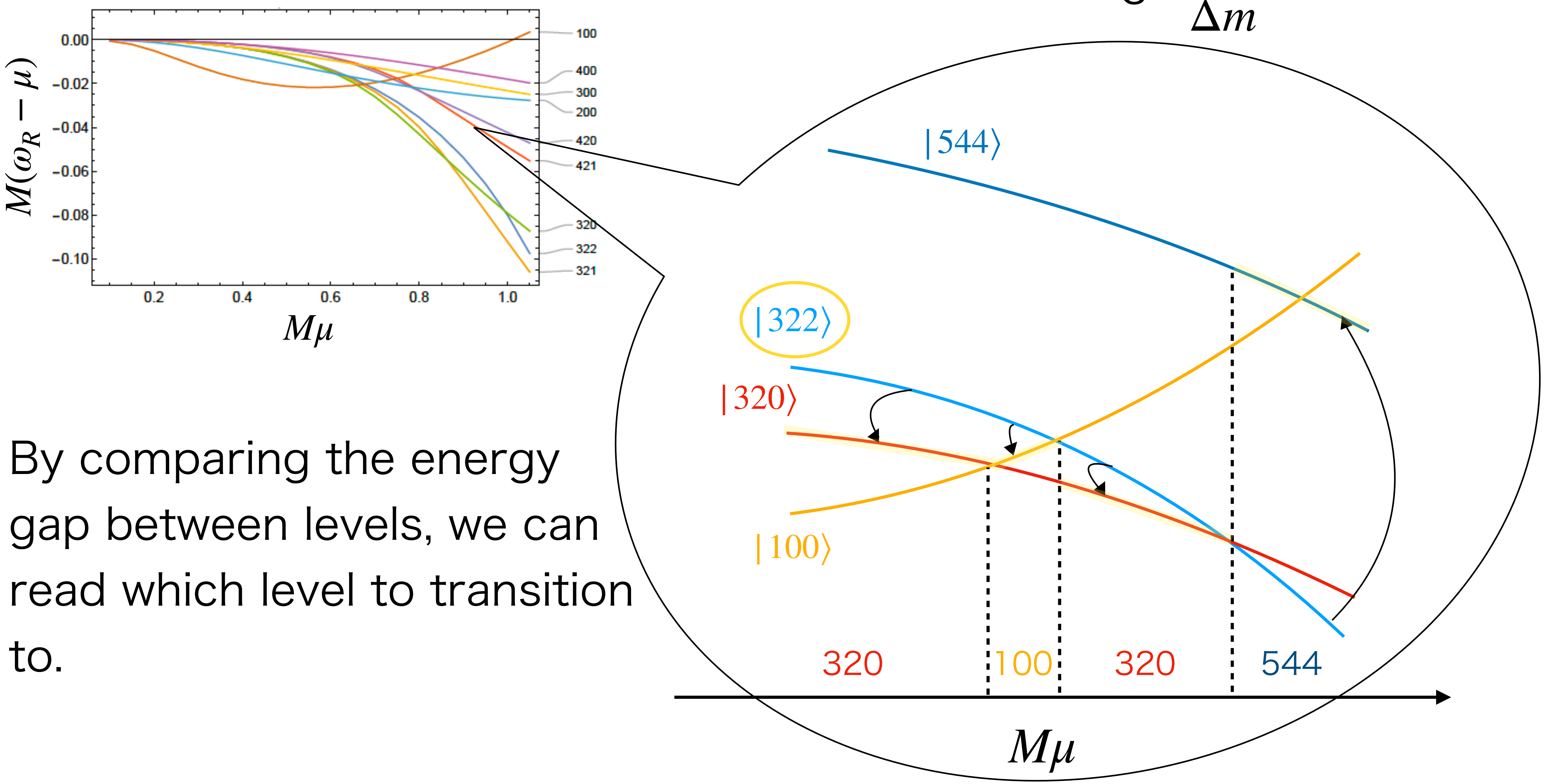
$$M_{cl} \simeq M_0 \exp\left(\underline{\omega_I}\ \underline{t_m}\right)$$

Decay width　Time to merger

Transition destination

Example) $a/M = 0.998$, $l = m = 2$ is the fastest

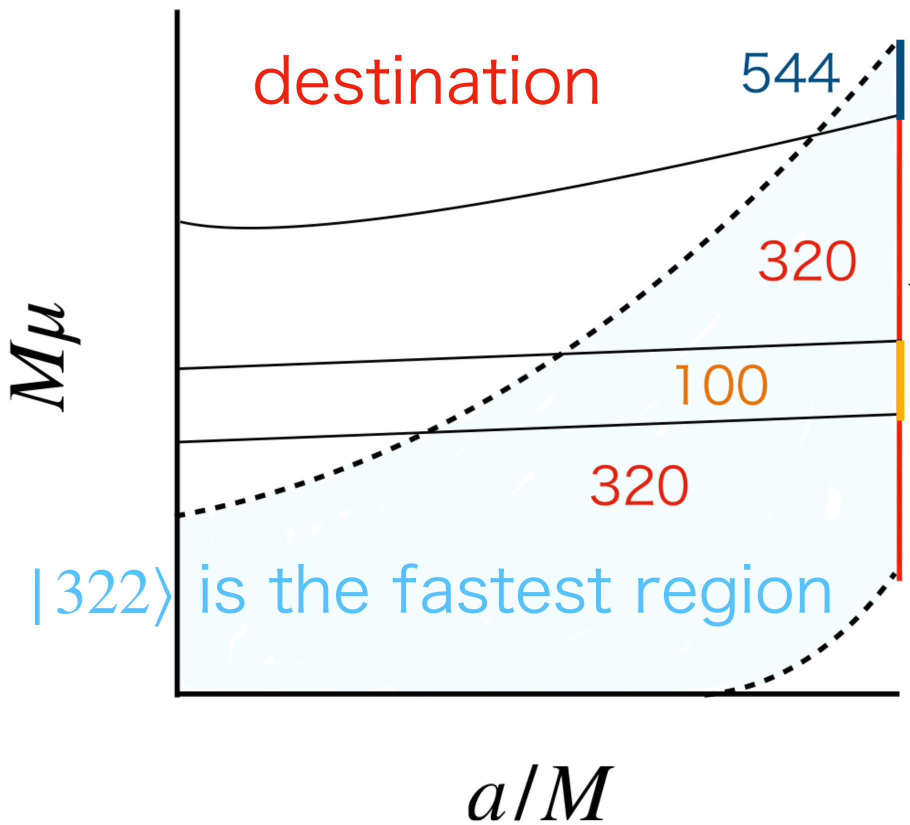
for co-rotating $\dfrac{\Delta E}{\Delta m} > 0$



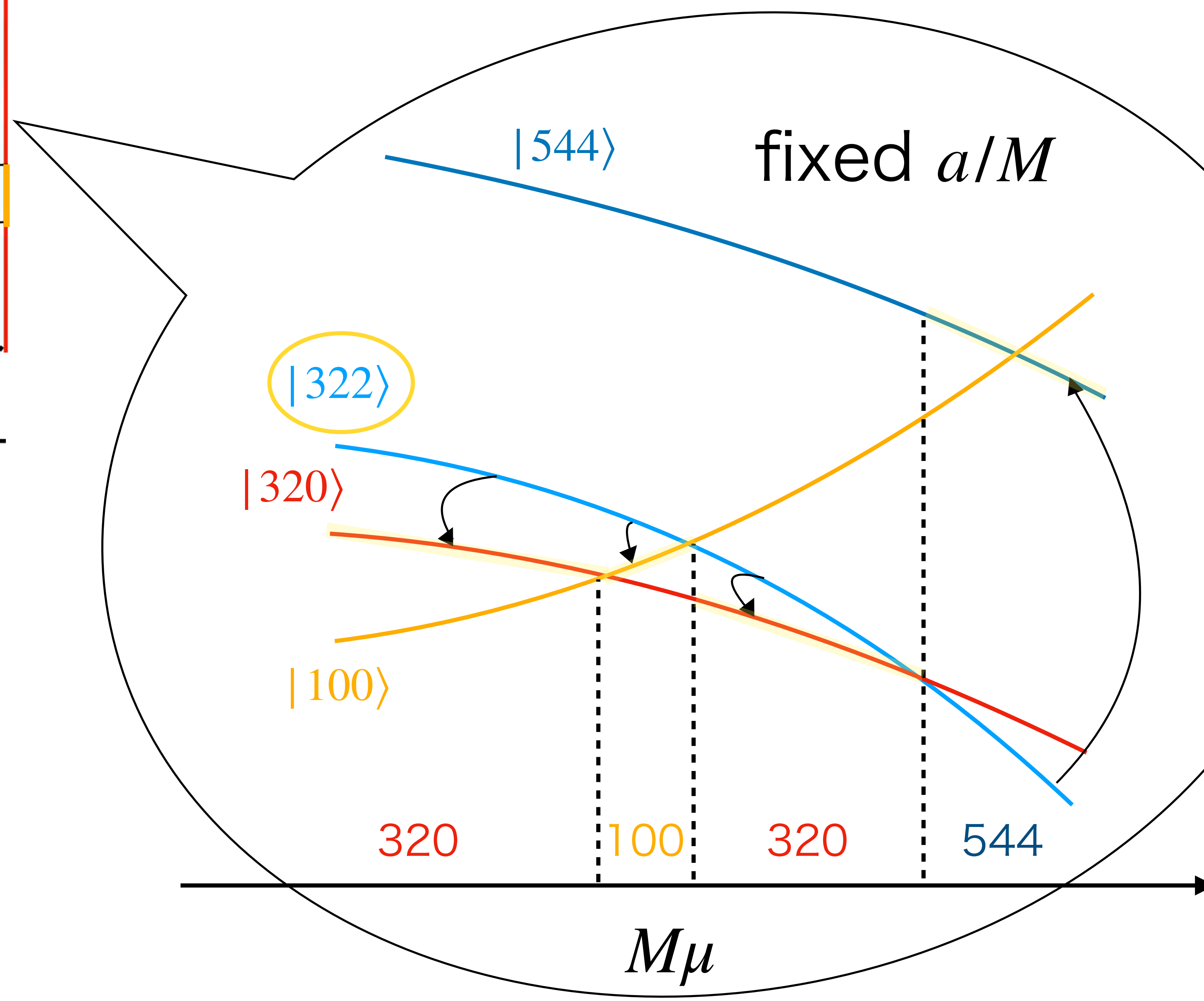
By comparing the energy gap between levels, we can read which level to transition to.

Transition destination

Parameter $(M\mu, a/M)$ plane



Transition destination changes where level crossing occur.



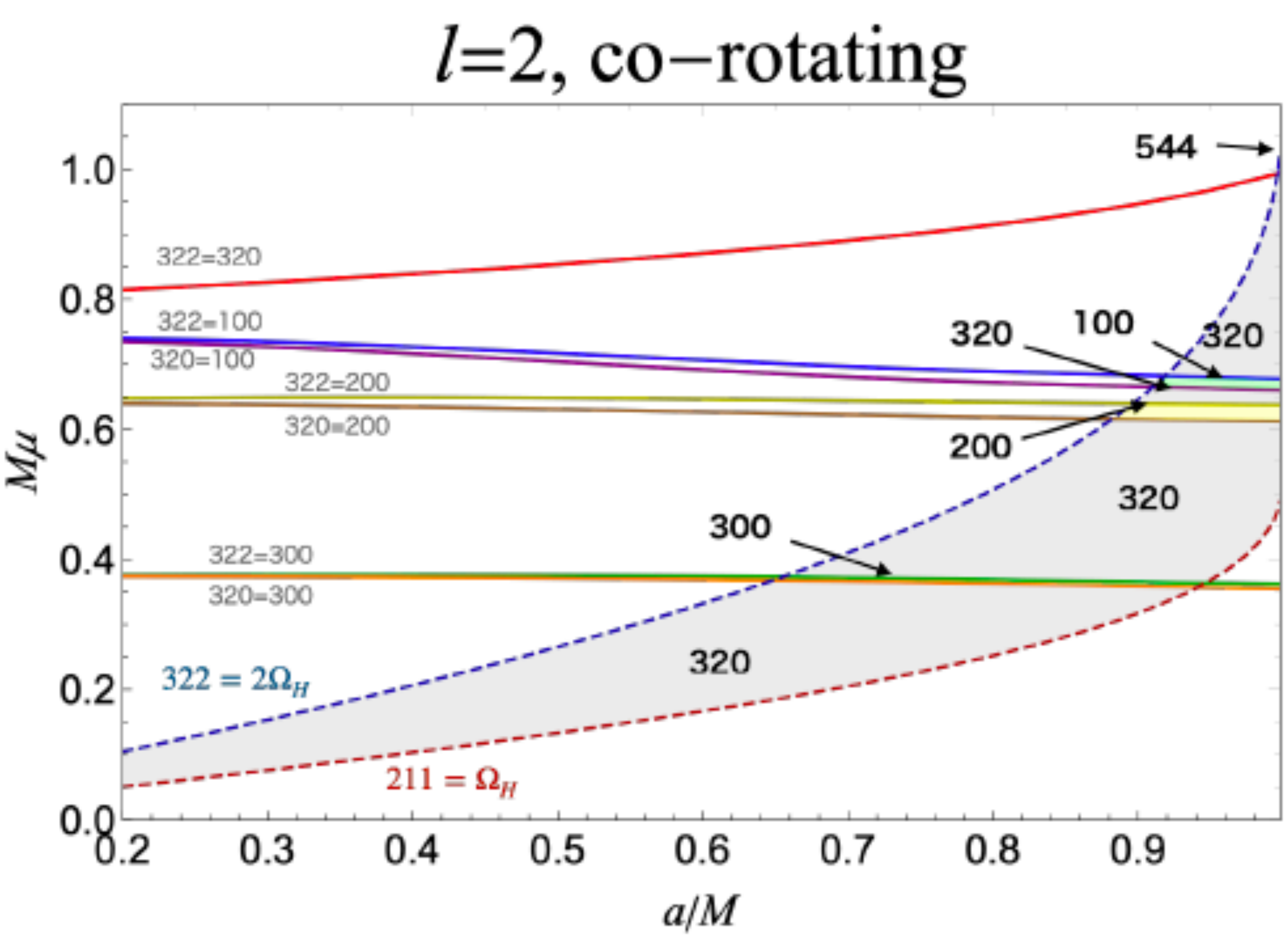
Transition Map

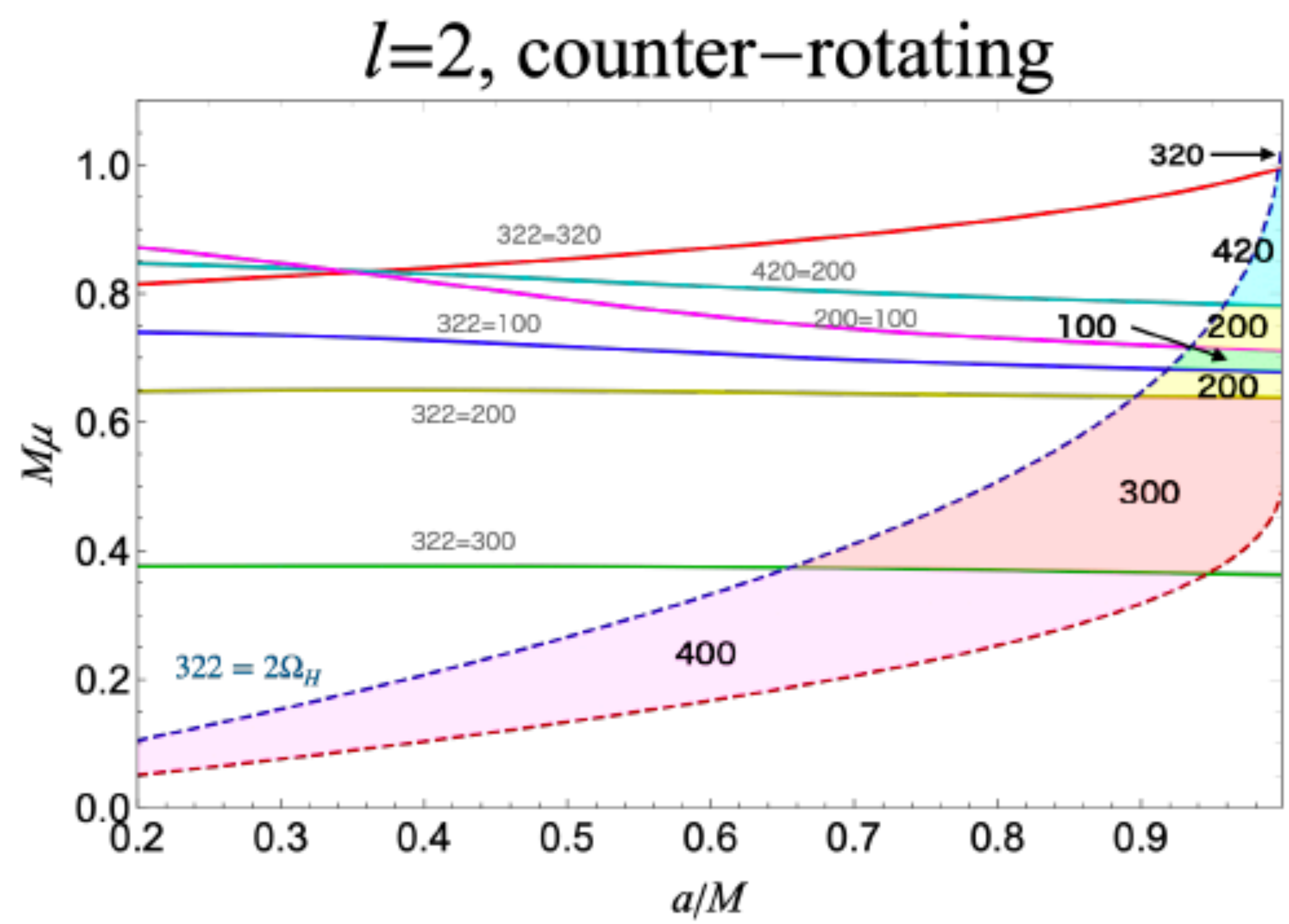
$l = 1$

Transition destinations are the same the non-rela approx.

i.e. co-rot. $|211\rangle \to |21-1\rangle$, conter-rot. $|211\rangle \to |31-1\rangle$

$l = 2$





Cloud depletion

$$M_{cl} \simeq M_0 \exp\left(\omega_I\ t_m\right)$$

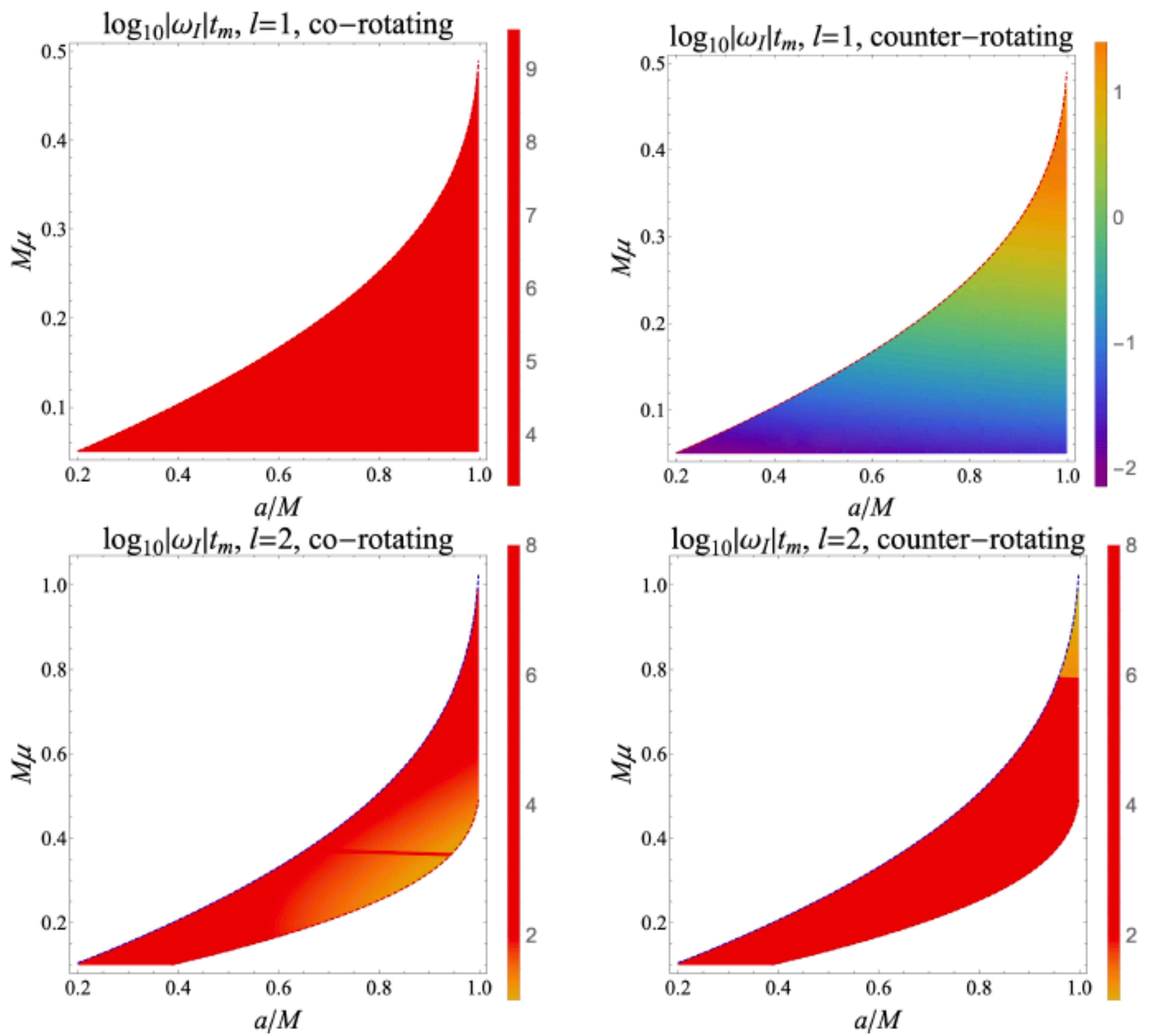
Decay width

Time to merger

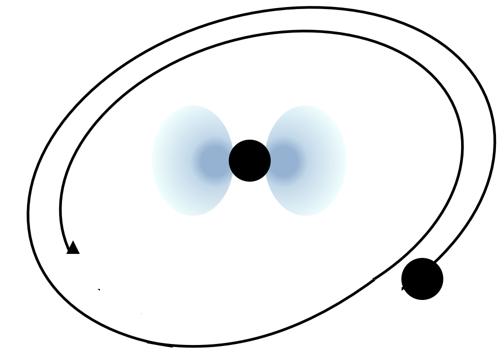
$|\omega_I|\, t_m \gg 1$

→ disappear

axions in $l \geq 2$ mode can be transferred to smaller l mode.



Summary



We studied the axion cloud depletion due to binary's tidal interaction in a wide parameter region including the cloud is in the relativistic regime.

assuming
- only leading quadrupolar tidal perturbation is at work
- transition is adiabatic

This is the first step!

Ongoing work

- Effect of higher multipole moment of tidal potential
- Study this system in more detail

Backup

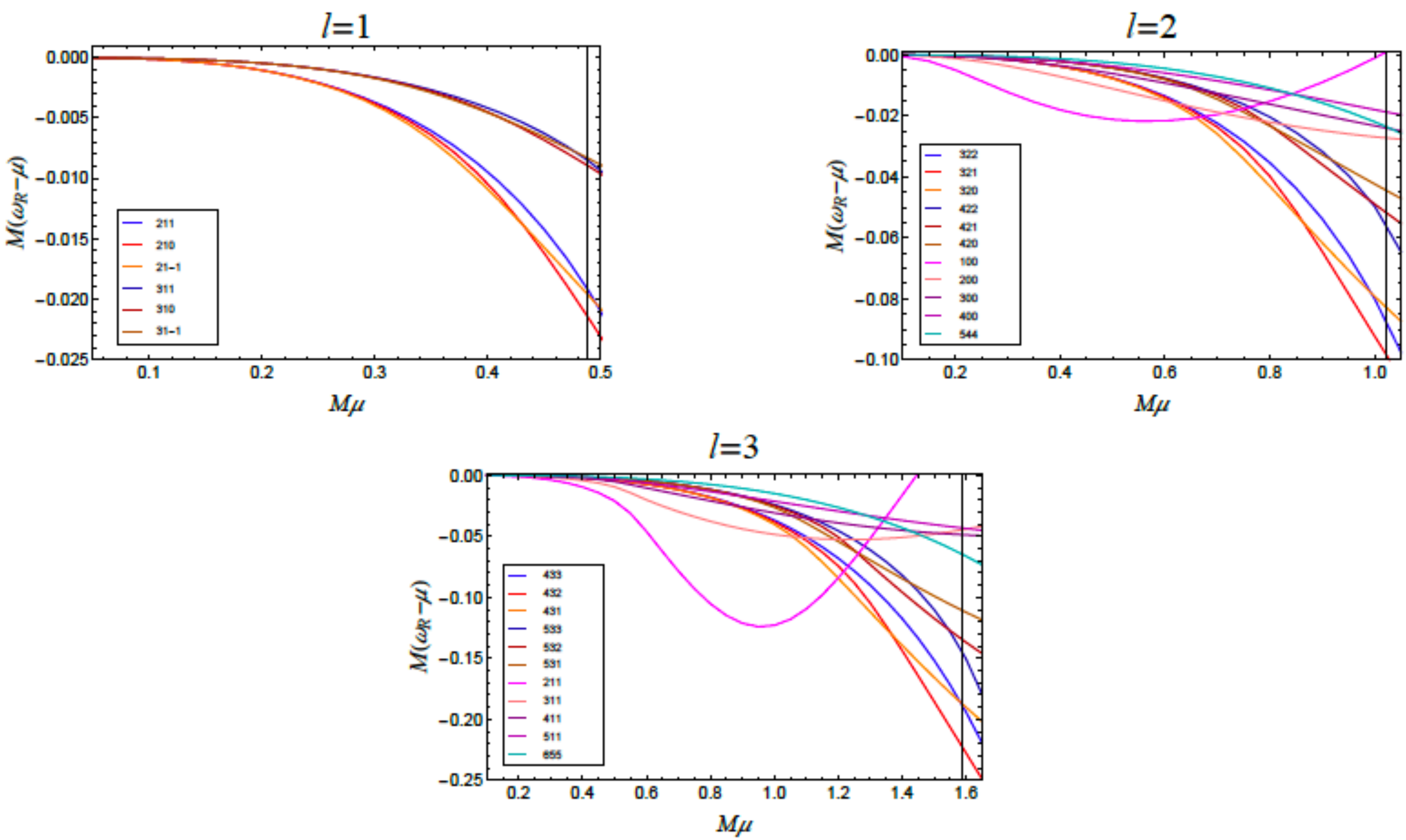


Figure 1. Energy spectra of bound states with $l = 1, 2$ and 3 relevant in discussing the transitions for a/M=0.998. Here, the vertical lines in the respective panels show the range of $M\mu$ beyond which $|nlm\rangle = |211\rangle\,, |322\rangle\,, |433\rangle$ are not the fastest growing modes of interest.