Axion Bosenova and Gravitational Waves

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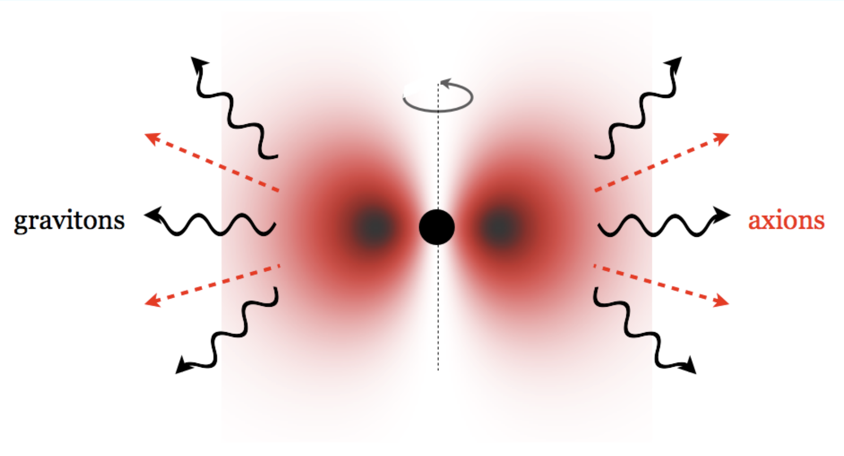
Hideo Kodama
(KEK)



PTP128, 153 (2012); PTEP2014, 043E02 (2014); PTEP2015, 061E01 (2015); arXiv:1505.00714.

Hot Topics in General Relativity and Gravitation
@ Qui Nhon, Vietnam (August 10, 2015)

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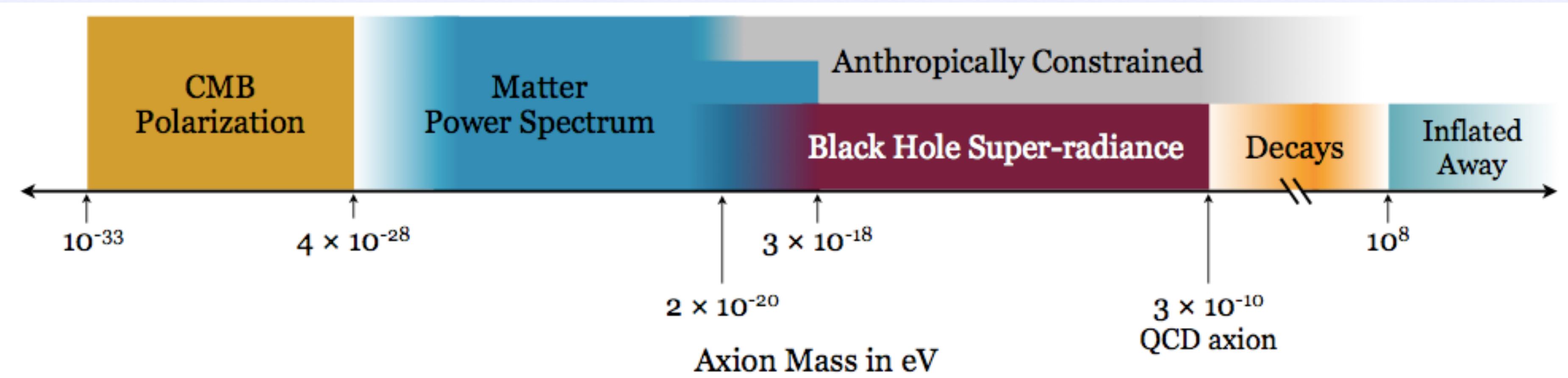
Introduction

AXIVERSE SCENARIO

Arvanitaki, Dimopoulos, Dubvosky, Kaloper, March-Russel,
PRD81 (2010), 123530.

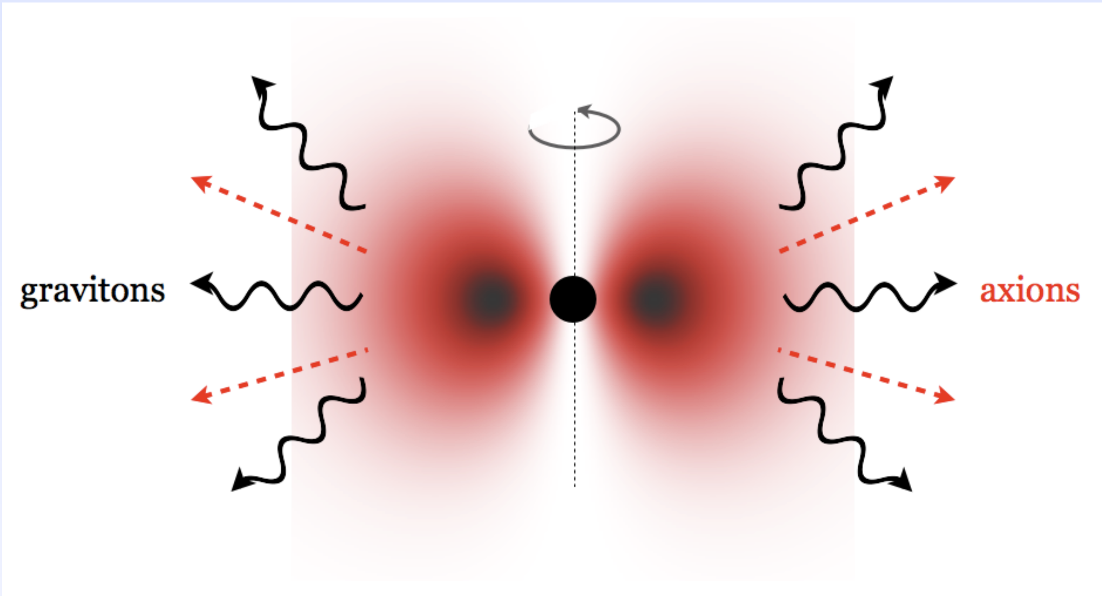
In string theory, many moduli appear when the extra dimensions get compactified.

Some of them (10-100) are expected to behave like scalar fields with very tiny mass, which are called string axions.



If string axion field exists...

- It forms an axion cloud around a rotating astrophysical BH by extracting BH's rotation energy.



- Superradiant instability
- Nonlinear self-interaction
- GW emission

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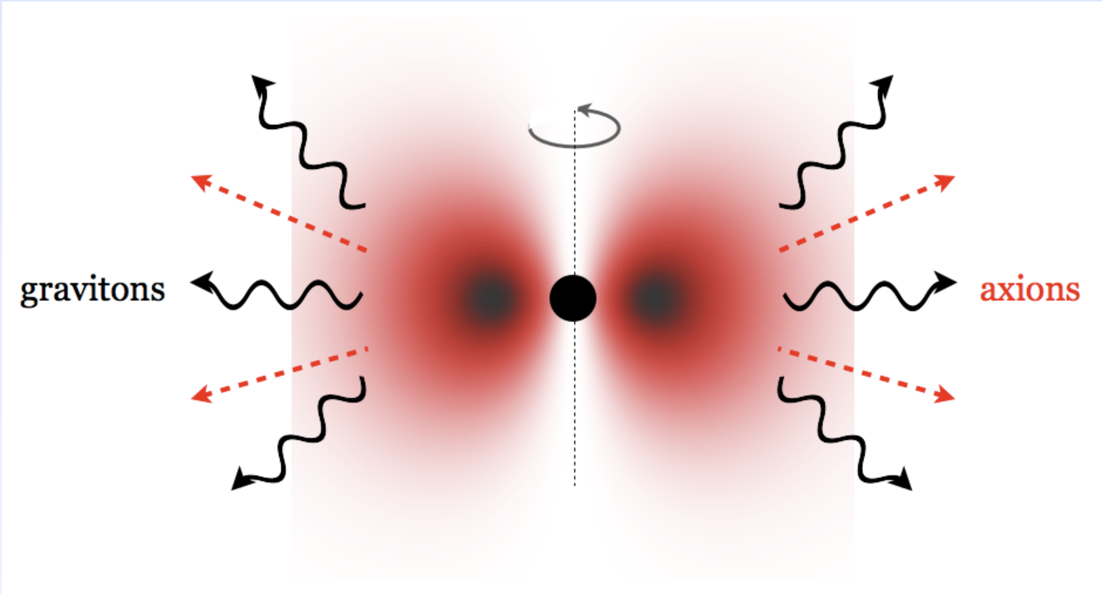

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- GW emission

Superradiant instability

Kerr BH

- Metric

$$ds^2 = -\left(\frac{\Delta - a^2\sin^2\theta}{\Sigma}\right)dt^2 - \frac{2a\sin^2\theta(r^2+a^2-\Delta)}{\Sigma}dtd\phi$$
$$+\left[\frac{(r^2+a^2)^2 - \Delta a^2\sin^2\theta}{\Sigma}\right]\sin^2\theta d\phi^2 + \frac{\Sigma}{\Delta}dr^2 + \Sigma d\theta^2$$

$$\Sigma = r^2 + a^2\cos^2\theta,$$
$$\Delta = r^2 + a^2 - 2Mr.$$

$$J = Ma$$

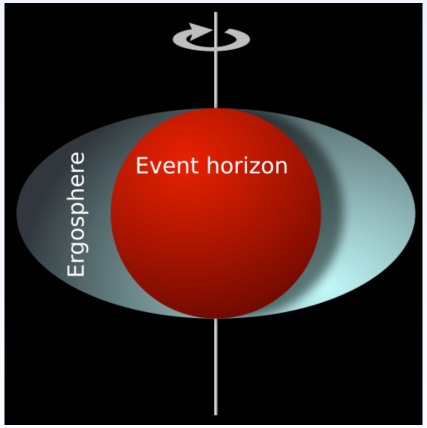
- Ergo region

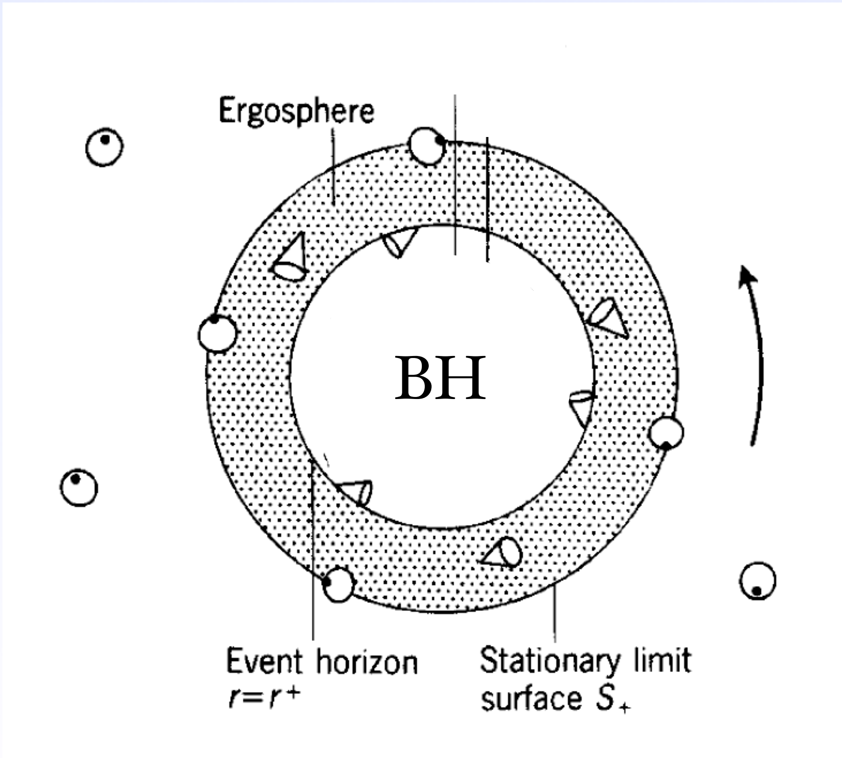
$\xi = \partial_t$ becomes spacelike:

$$\xi_a\xi^a = g_{tt} > 0$$

⇨ $E = -p_a\xi^a$

can be negative





Gravitational Atom

- Massive Klein-Gordon field $\nabla^2\Phi - \mu^2\Phi = 0$

$$\Phi = \mathrm{Re}[e^{-i\omega t}R(r)S(\theta)e^{im\phi}]$$

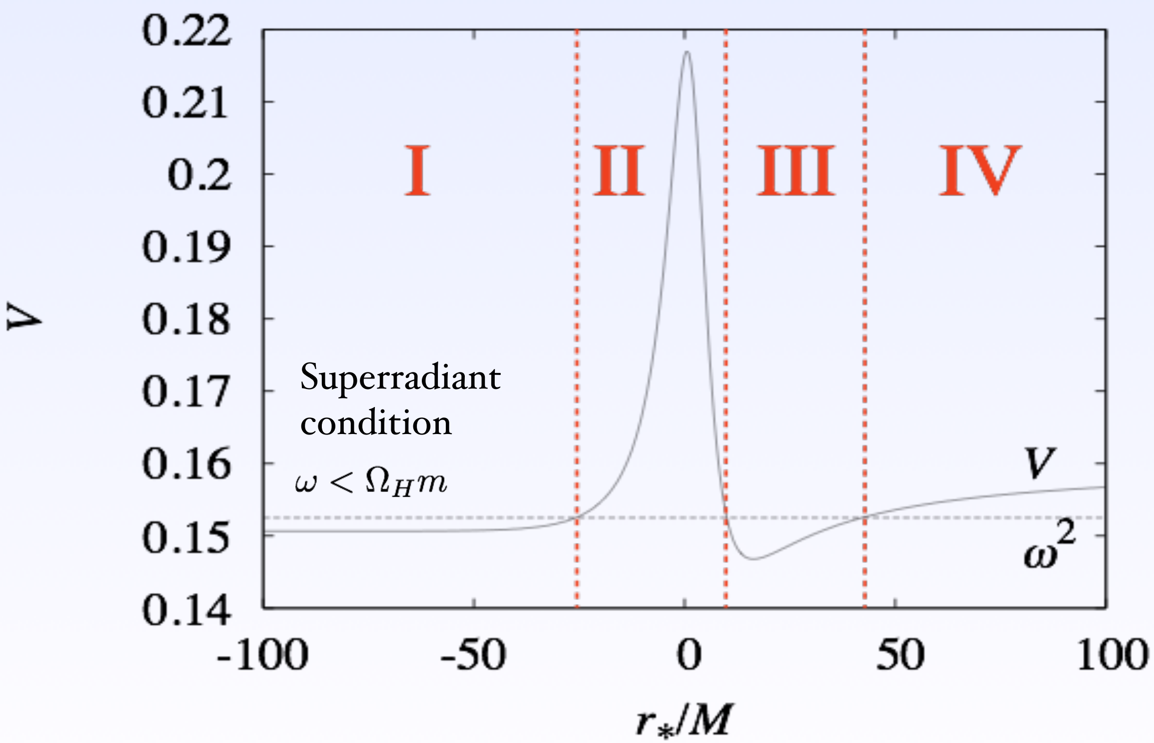
$$R = \frac{u}{\sqrt{r^2 + a^2}}$$

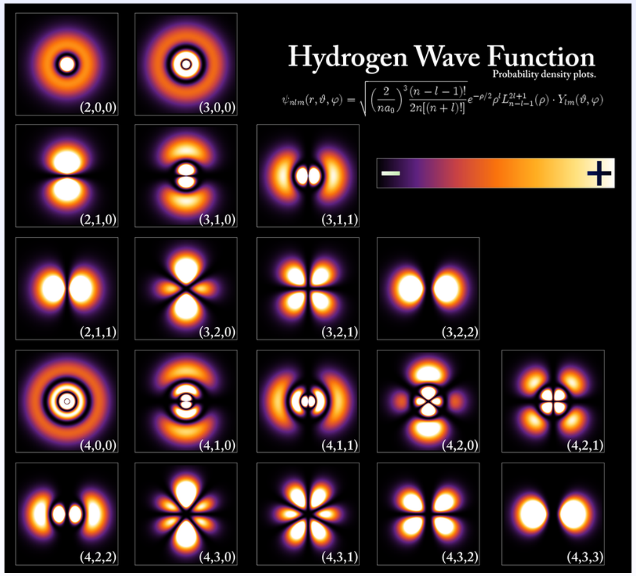
$$\frac{d^2u}{dr_*^2} + \left[\omega^2 - V(\omega)\right]u = 0$$

$$\omega = \omega_R + i\,\omega_I$$ ← Unstable if positive

Quantum numbers:

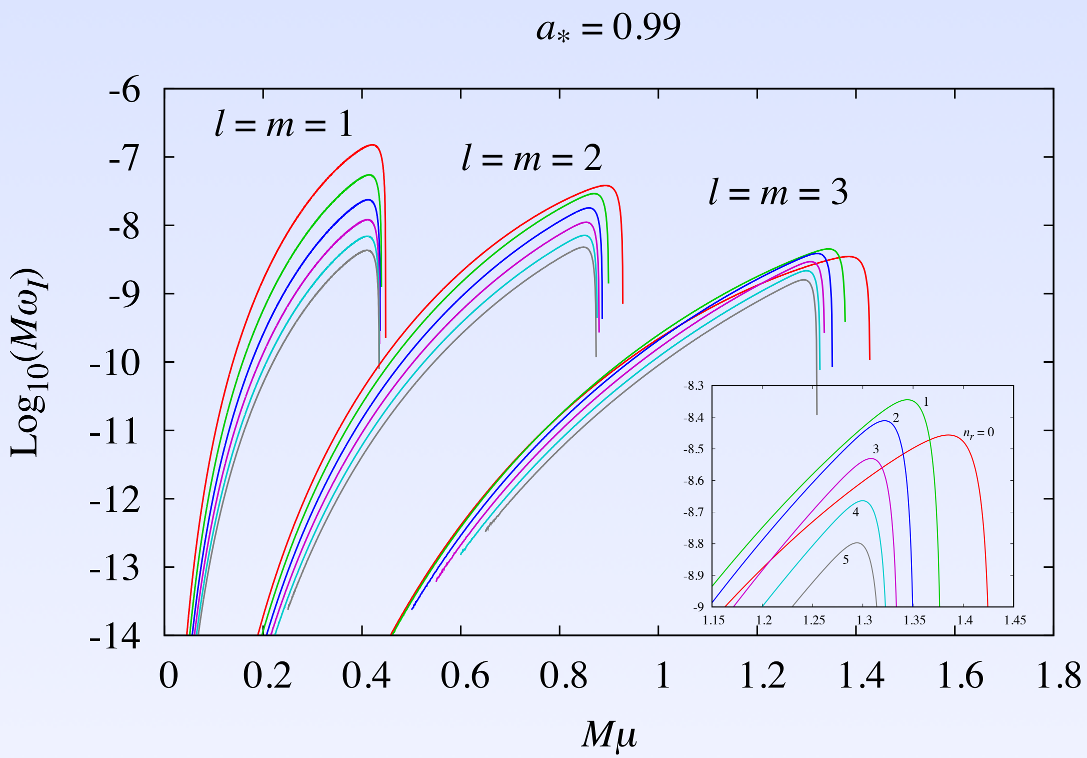
$\ell,\ m,\ n$ (or n_r)





Wave functions & Growth rates

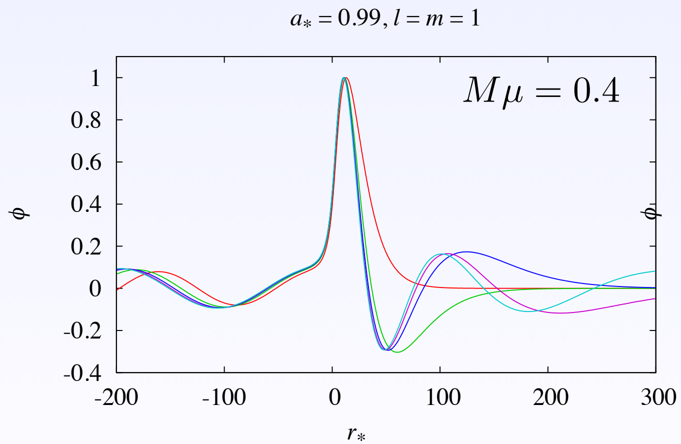
HY and Kodama, arXiv:1505.00714.

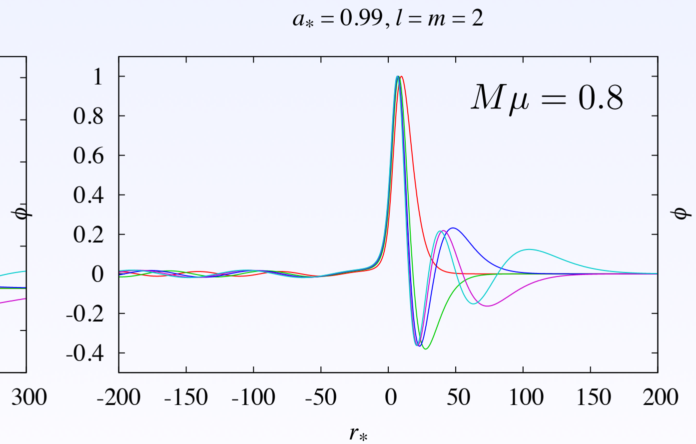


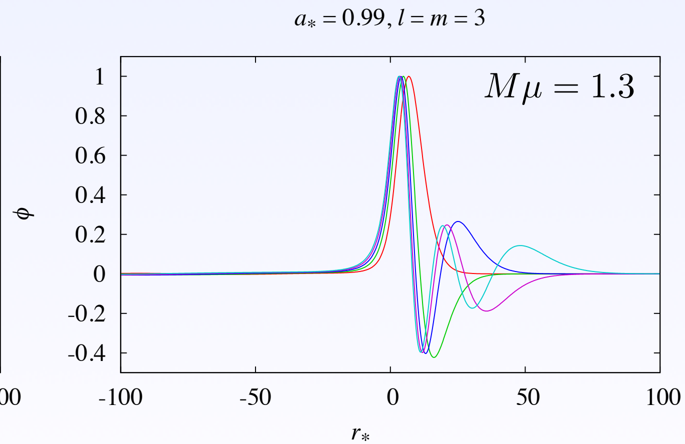
Time scale:

$$\omega_I M \sim 10^{-7} \quad \Rightarrow \quad \sim 1 \text{ min.}$$

$$M = M_\odot$$



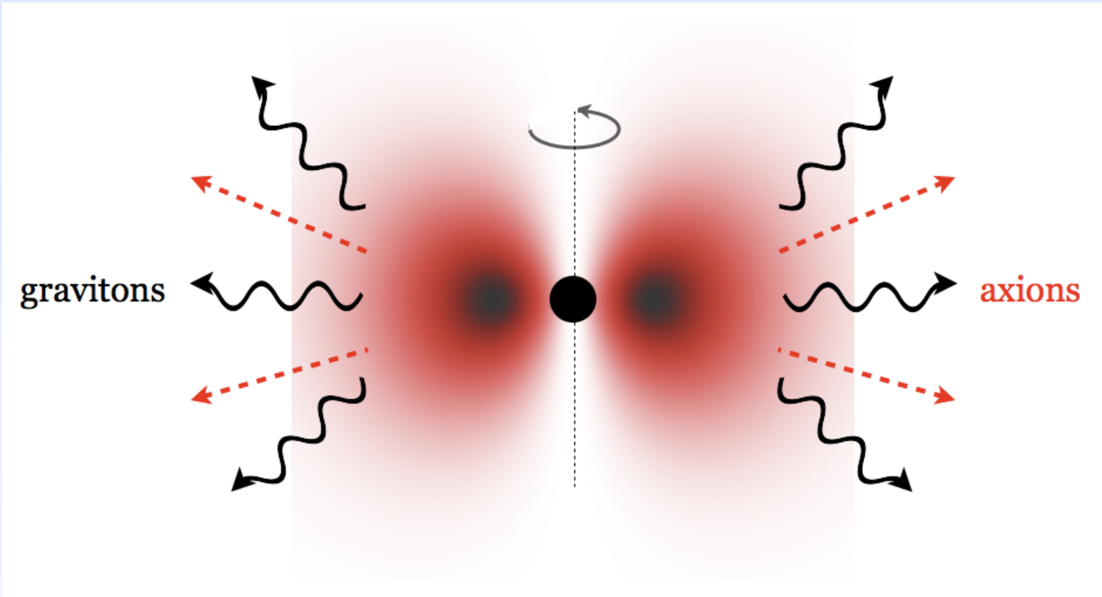




Axion Bosenova

If string axion field exists...

- It forms an axion cloud around a rotating astrophysical BH by extracting BH's rotation energy.



- Superradiant instability
- Nonlinear self-interaction
- GW emission

Nonlinear Self-Interaction

- $V = f_a^2 \mu^2 [1 - \cos(\Phi / f_a)]$

$$\Rightarrow \boxed{\nabla^2 \varphi - \mu^2 \sin \varphi = 0} \qquad \varphi \equiv \frac{\Phi}{f_a}$$

Simulation

- Sine-Gordon field in the Kerr background

$$\nabla^2 \varphi - \mu^2 \sin \varphi = 0$$

- Codes:
  - 3D code (r, θ, ϕ) HY and Kodama, PTP128, 153 (2012)

    Use rotating coordinates to avoid numerical instability

  - Pseudo spectral code

$$\varphi = \sum_{\ell, m} a_{\ell m}(t, r_*) Y_{\ell m}(\theta, \phi)$$

Simulations performed up to now

Simulations	a_*	$M\mu$	(ℓ, m)	Bosenova?
(1a)	0.99	0.4	$(1, 1)$	Yes
(1b)	0.99	0.3	$(1, 1)$	Yes
(1c)	0.99	0.4	$(1, 1) + (2, 2)$	Yes
(2)	0.99	0.8	$(2, 2)$	No

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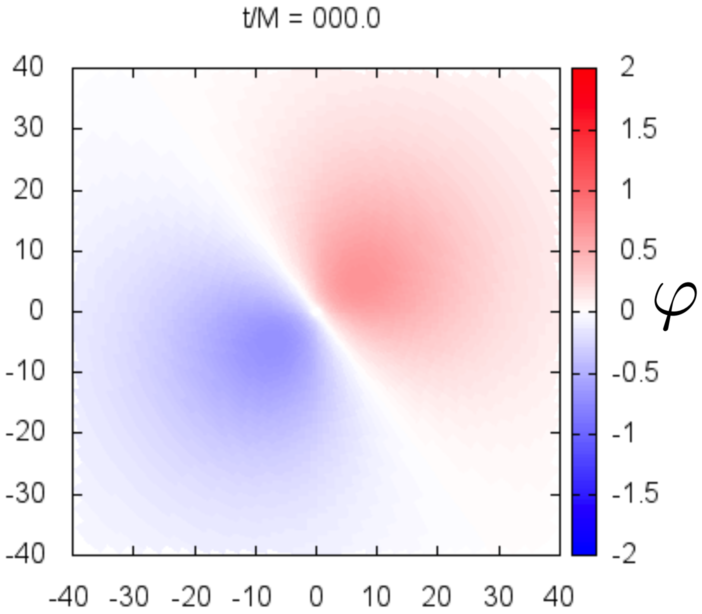
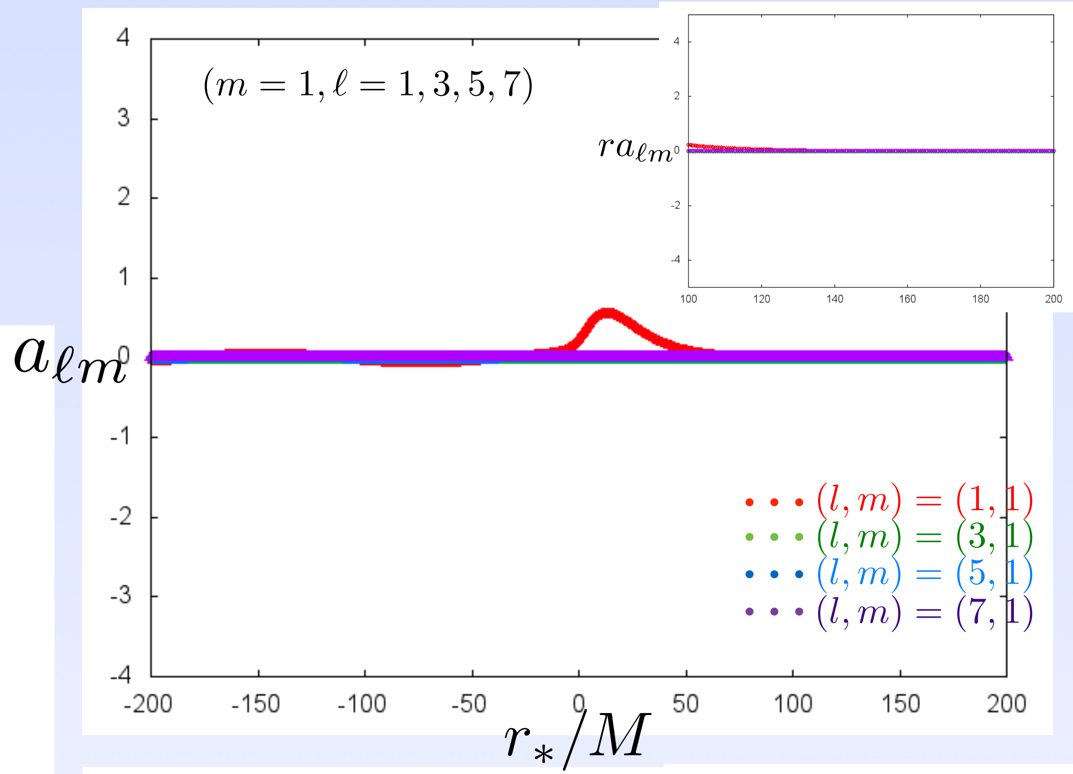
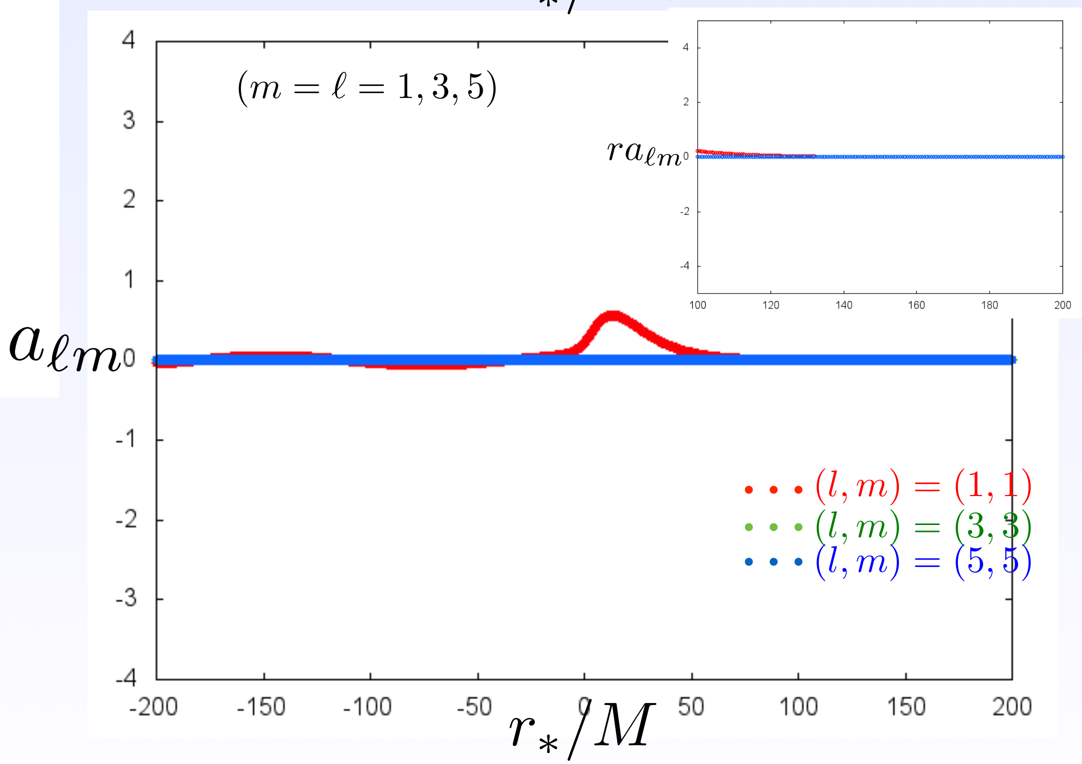
Time evolution: case (1a)





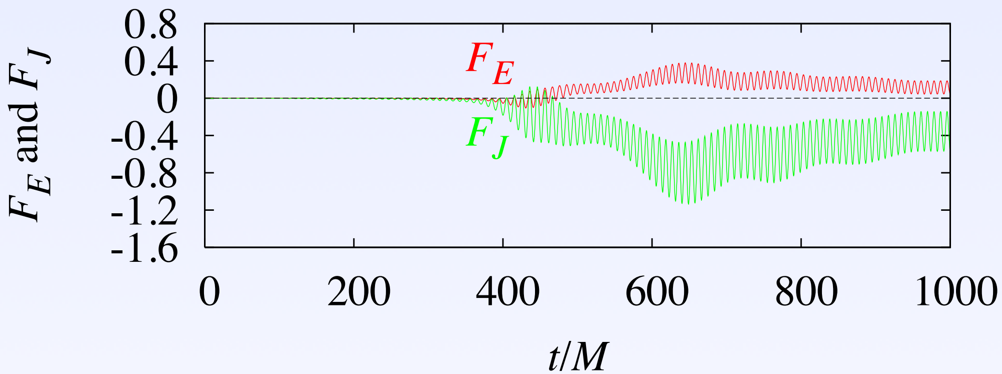


Summary of the simulation (1a)

- $\varphi_{\rm peak} \lesssim 0.6$ ⇨ Nothing happens.

- $\varphi_{\rm peak} \gtrsim 0.7$ ⇨ Bosenova collapse.

- The bosenova collapse is characterized by the infall of positive energy due to mode excitation.

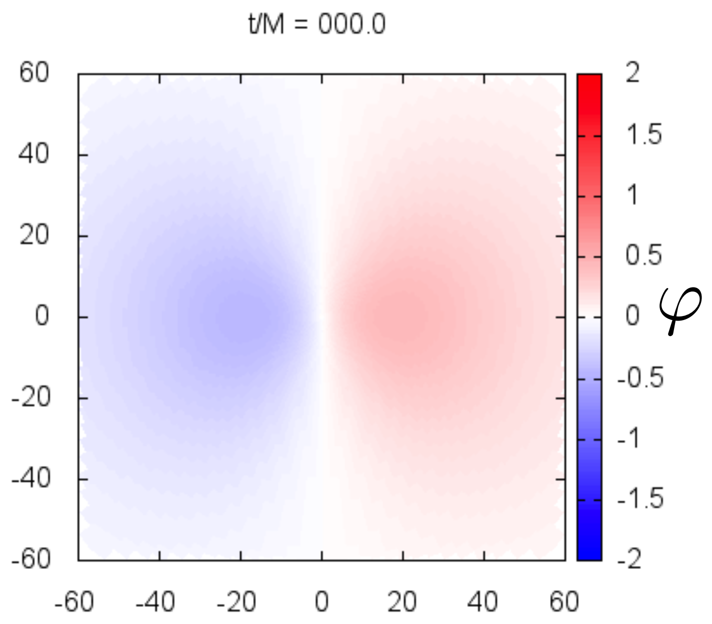


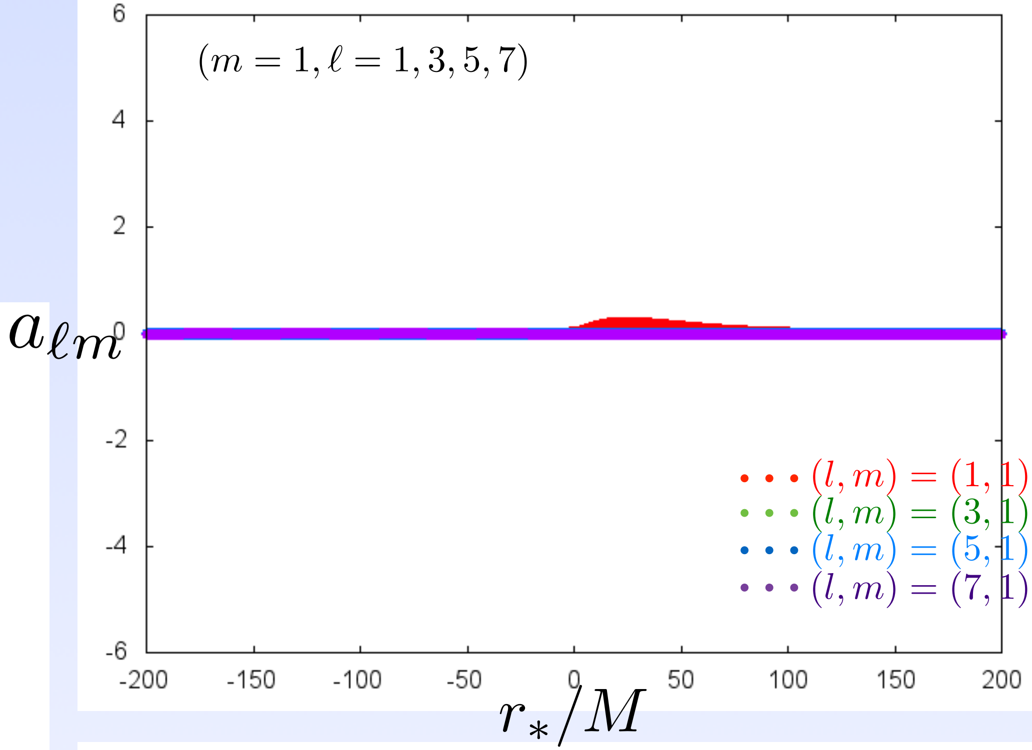
  - m = -1 mode: Terminates the bosenova, About 5% of energy falls into the BH.
  - higher (l,m) modes: Carry about 20% energy to the distant place.

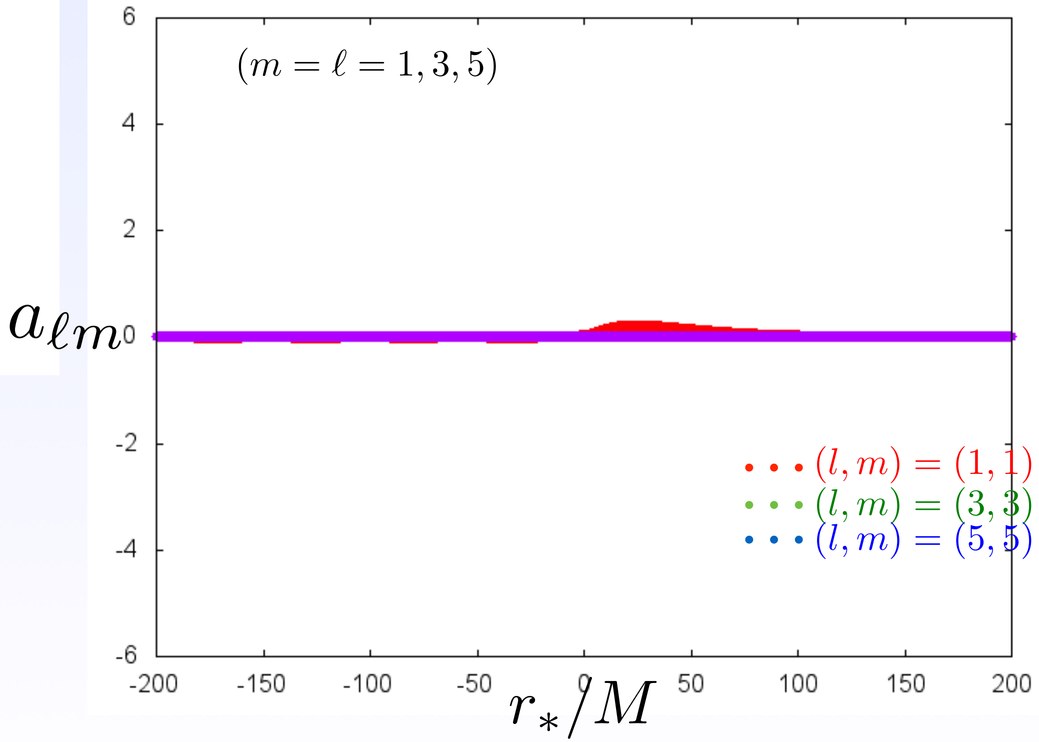
Simulations performed up to now

Simulations	a_*	$M\mu$	(ℓ, m)	Bosenova?
(1a)	0.99	0.4	$(1, 1)$	Yes
(1b)	0.99	0.3	$(1, 1)$	Yes
(1c)	0.99	0.4	$(1, 1) + (2, 2)$	Yes
(2)	0.99	0.8	$(2, 2)$	No

Time evolution: case (1b)

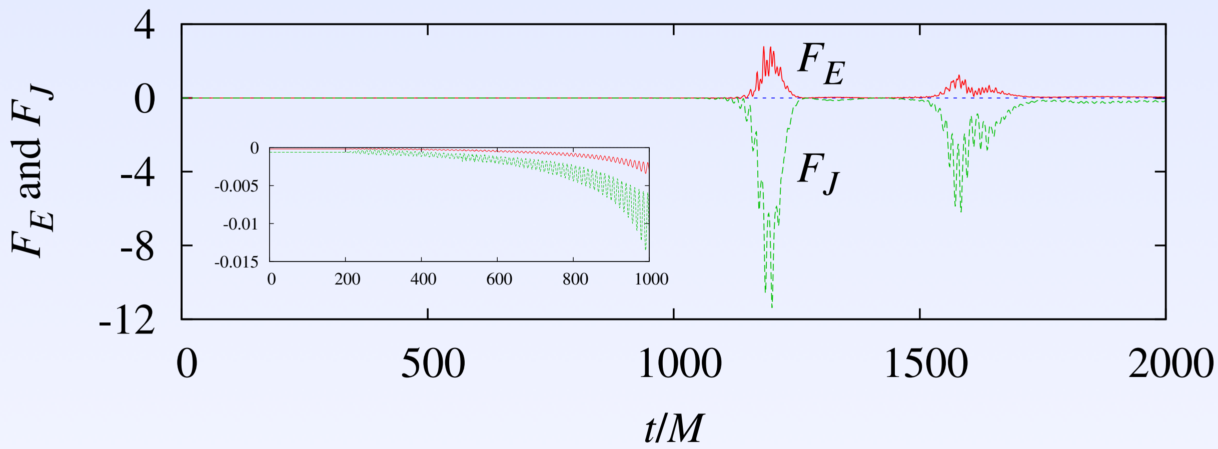






Summary of the simulation (1b)

- $\varphi_{\rm peak} \lesssim 0.4$ ➩ Nothing happens.
- $\varphi_{\rm peak} \lesssim 0.45$ ➩ Bosenova collapse.



- The bosenova for smaller $M\mu$ is more violent in the sense that more amount of higher (l, m) modes are excited.
- The bosenova for smaller $M\mu$ happens with a smaller peak value but with a larger energy amount.

Simulations performed up to now

Simulations	a_*	$M\mu$	(ℓ, m)	Bosenova?
(1a)	0.99	0.4	$(1, 1)$	Yes
(1b)	0.99	0.3	$(1, 1)$	Yes
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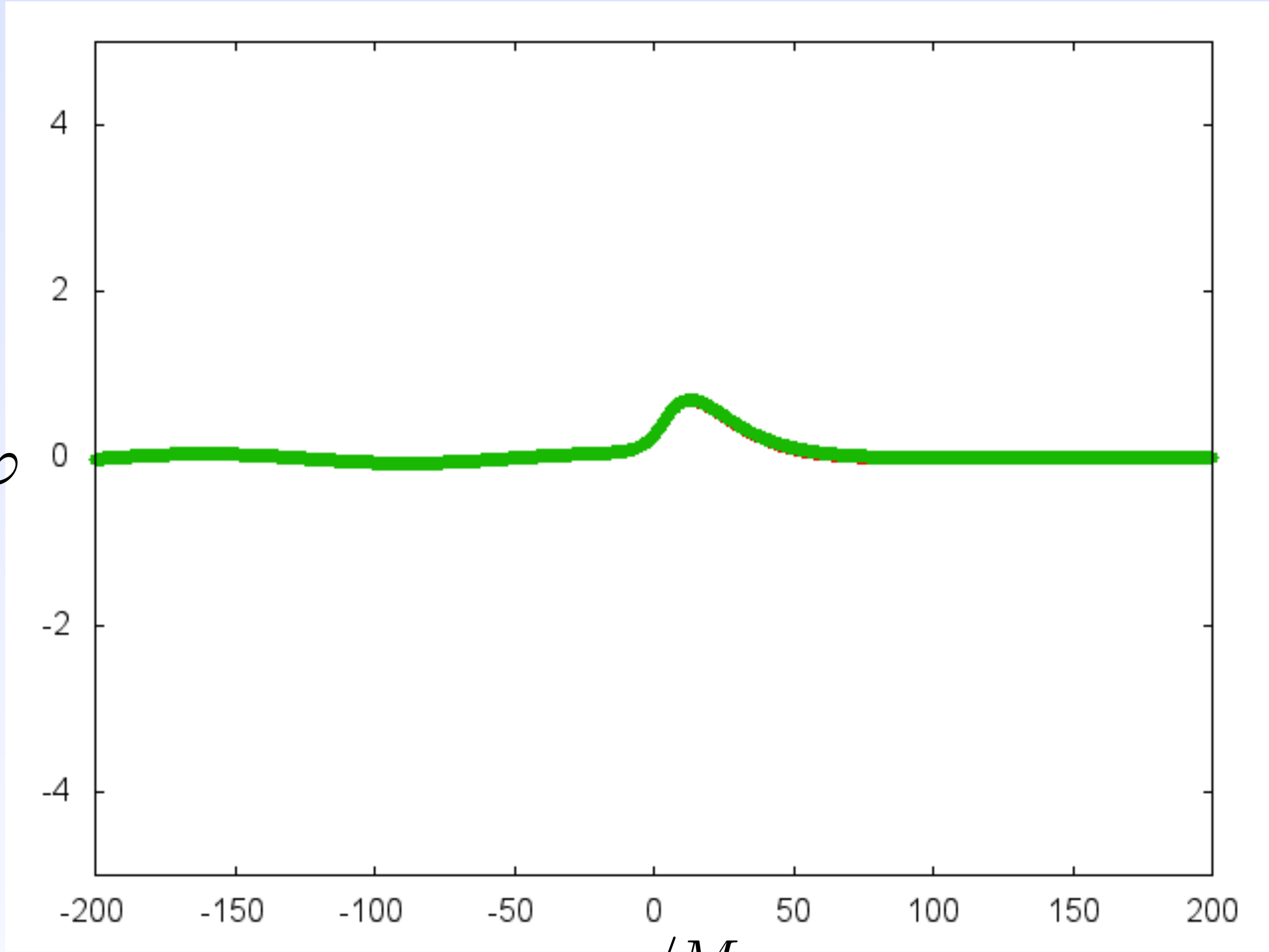
Time evolution: cases (Ia) and (Ic)



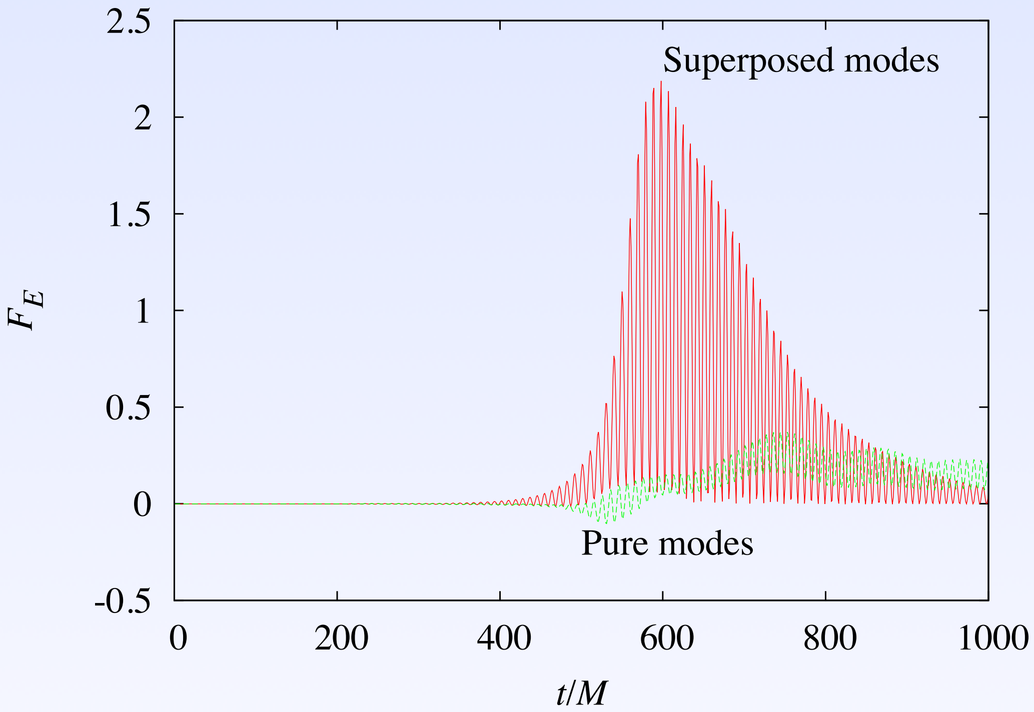
φ

r_*/M

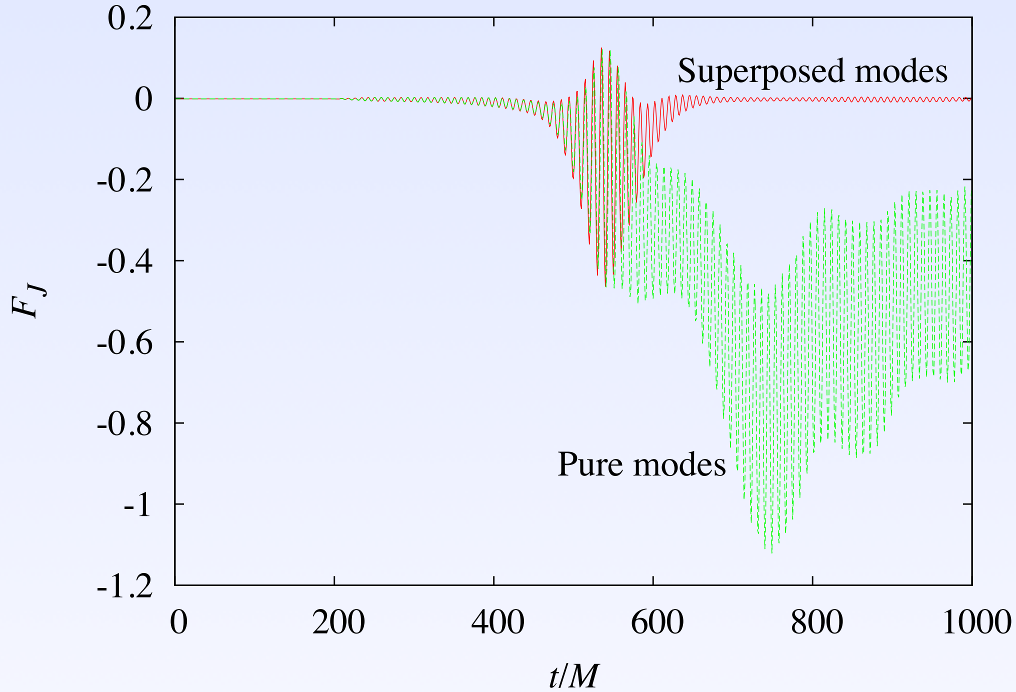
$\cdots (1,1)$

$\cdots (1,1) + (2,2)$

Energy flux to the horizon



Angular momentum flux to the horizon



Summary of the simulation (1c)

- Adding a small amount of the l=m=2 mode to the l=m=1 axion cloud causes fairly large change of scalar field dynamics.

- This is because the l=m=2 mode grows analogously to the resonance in the forced oscillation.

- Axion cloud shows very rich dynamical phenomena that highly depend on the initial setup.

- A detailed prediction of the scalar field dynamics would be very difficult.

Simulations performed up to now

Simulations	a_*	$M\mu$	(ℓ, m)	Bosenova?
(1a)	0.99	0.4	$(1, 1)$	Yes
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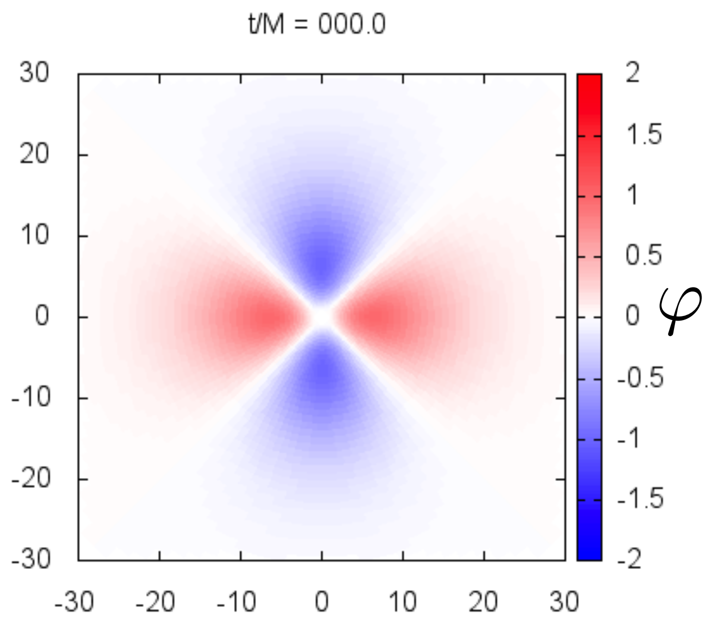
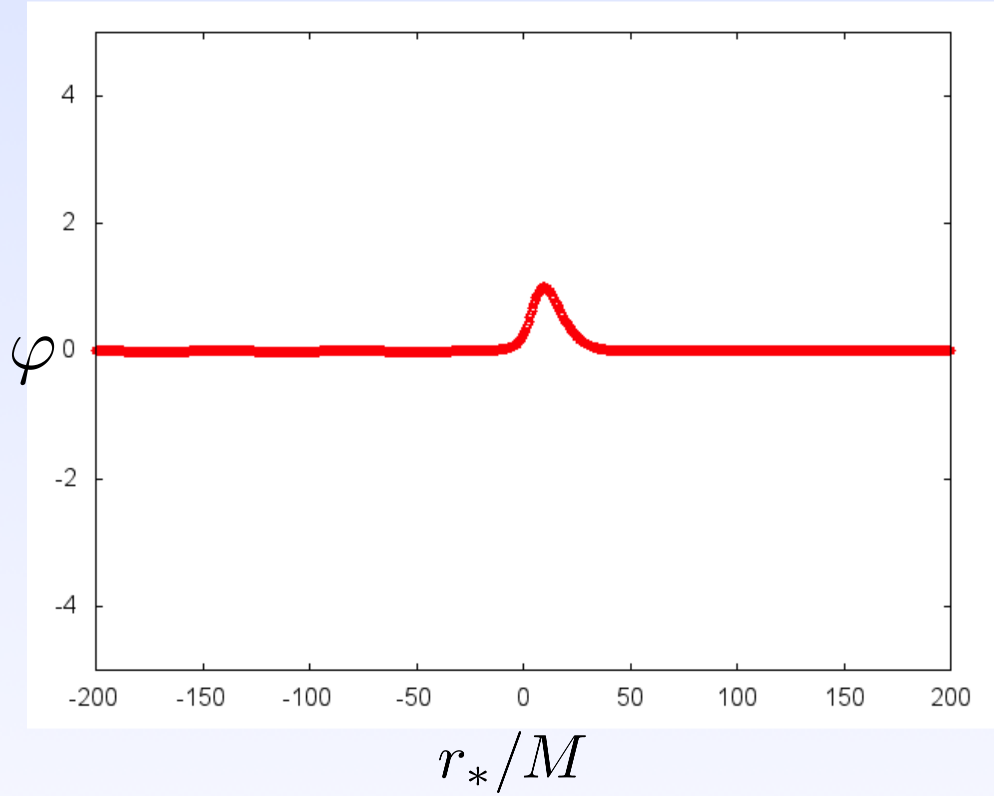
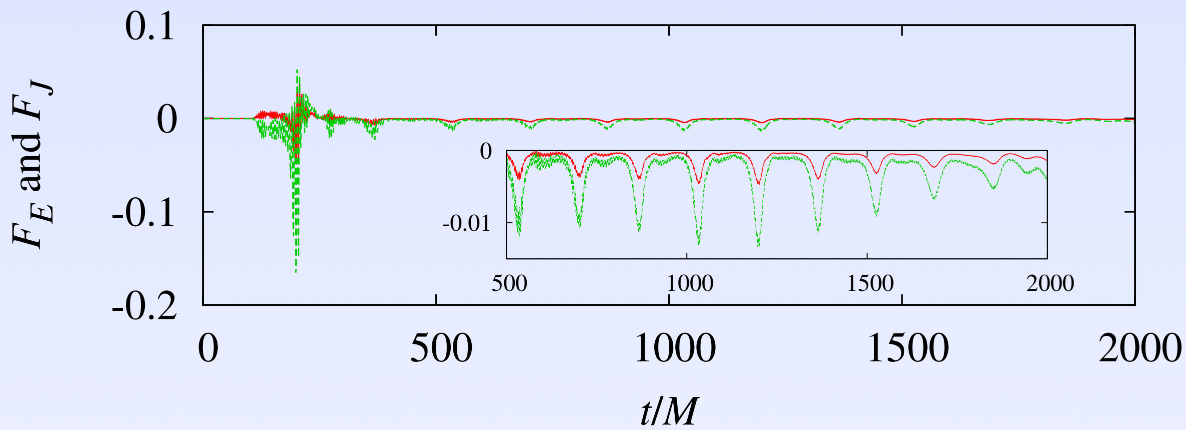
Time evolution: case (2)



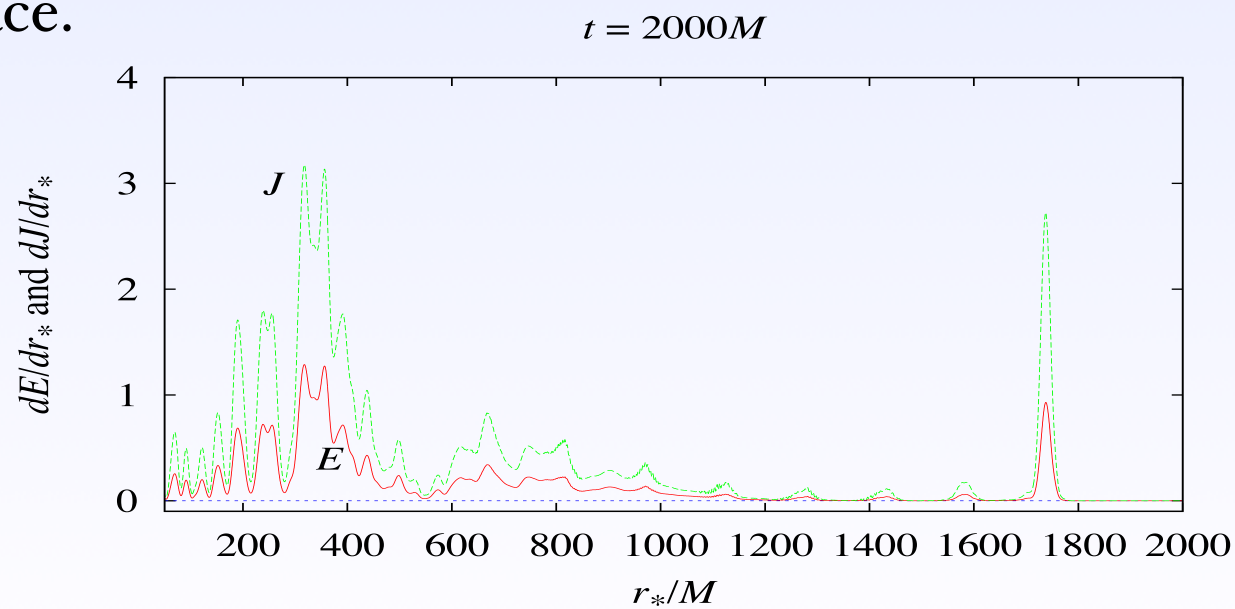


Result of simulation (2)

- The energy and angular momentum continue to be extracted.



- Energy and angular momentum continues to be emitted to the distant place.



Summary of the simulation (2)

- If the axion cloud is in the l=m=2 mode, a bosenova does not happen.

- The energy extraction from the BH continues, while outgoing flow is formed.

- Axion cloud in the l=m=2 mode is more like a scalar breather.

Simulations performed up to now

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GW emission

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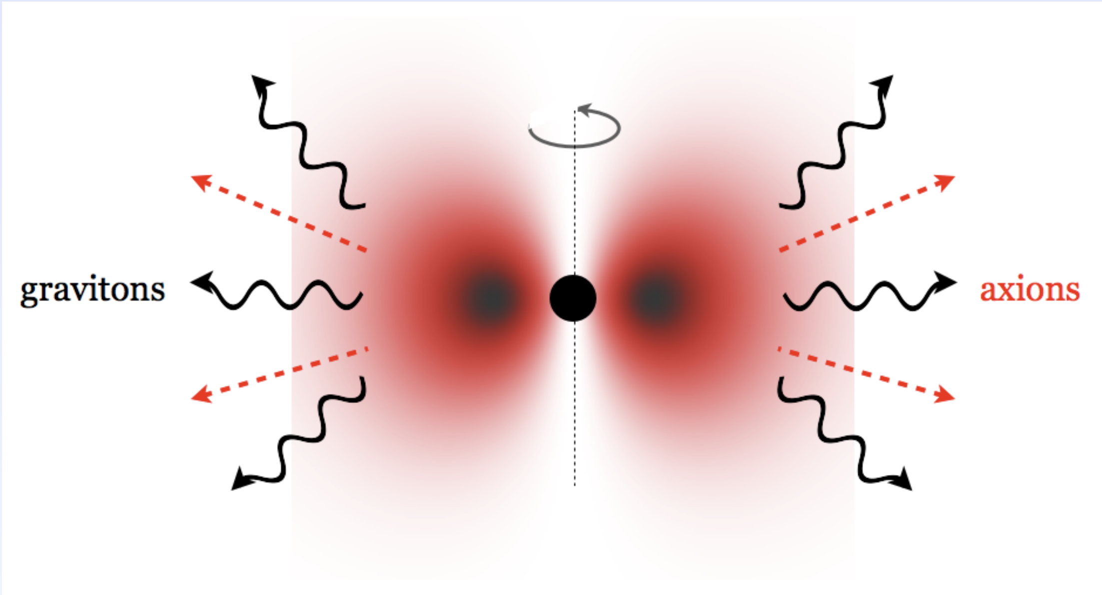

- Superradiant instability
- Nonlinear self-interaction
- GW emission

Simulating GWs from bosenova

- Calculate scalar behavior in a test-field approximation in Kerr background;

$$\nabla^2 \varphi - \mu^2 \sin\varphi = 0$$

- Calculate $T_{\mu\nu}$ of the scalar field;

- Calculate GWs sourced by $T_{\mu\nu}$ by solving Teukolsky equation in time domain.

$$\left[\frac{(r^2+a^2)^2}{\Delta} - a^2\sin^2\theta\right]\frac{\partial^2\psi}{\partial t^2} + \frac{4Mar}{\Delta}\frac{\partial^2\psi}{\partial t\partial\phi} + \left[\frac{a^2}{\Delta} - \frac{1}{\sin^2\theta}\right]\frac{\partial^2\psi}{\partial\phi^2}$$

$$-\Delta^{-s}\frac{\partial}{\partial r}\left(\Delta^{s+1}\frac{d\psi}{dr}\right) - \frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial\psi}{\partial\theta}\right) - 2s\left[\frac{a(r-M)}{\Delta} + \frac{i\cos\theta}{\sin^2\theta}\right]\frac{\partial\psi}{\partial\phi}$$

$$-2s\left[\frac{M(r^2-a^2)}{\Delta} - r - ia\cos\theta\right]\frac{\partial\psi}{\partial t} + (s^2\cot^2\theta - s)\psi = 4\pi\Sigma T$$

Because this work is ongoing, we show the results only for the case of Schwarzschild BH

Simulations

- Setup

HY and Kodama, arXiv:1505.00714.

  - Schwarzschild black hole
  - $M\mu = 0.3$
  - Initial condition: Quasi-bound state of Klein-Gordon field in the mode l = m = 1, nr=0
  - (1) Klein-Gordon case
  - (2) Mildly nonlinear case
  - (3) Strongly nonlinear case

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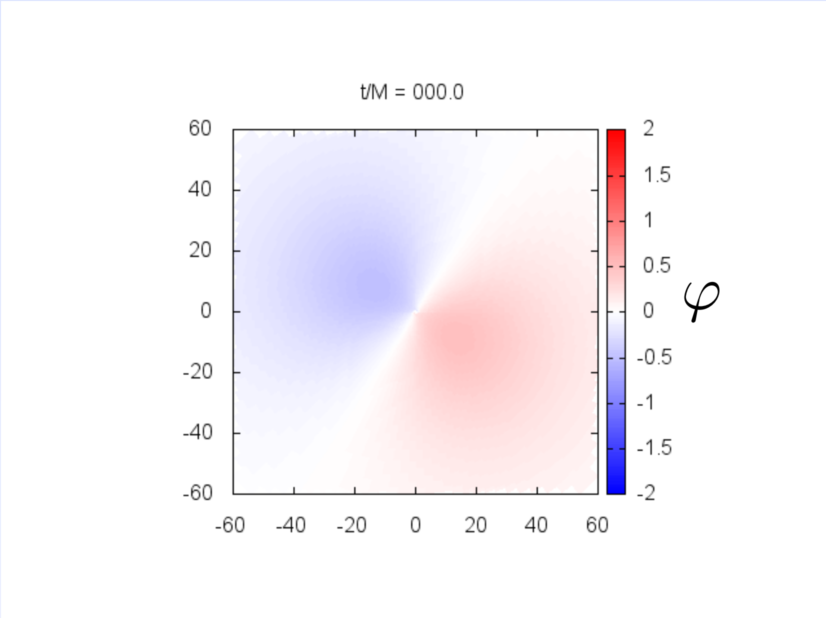
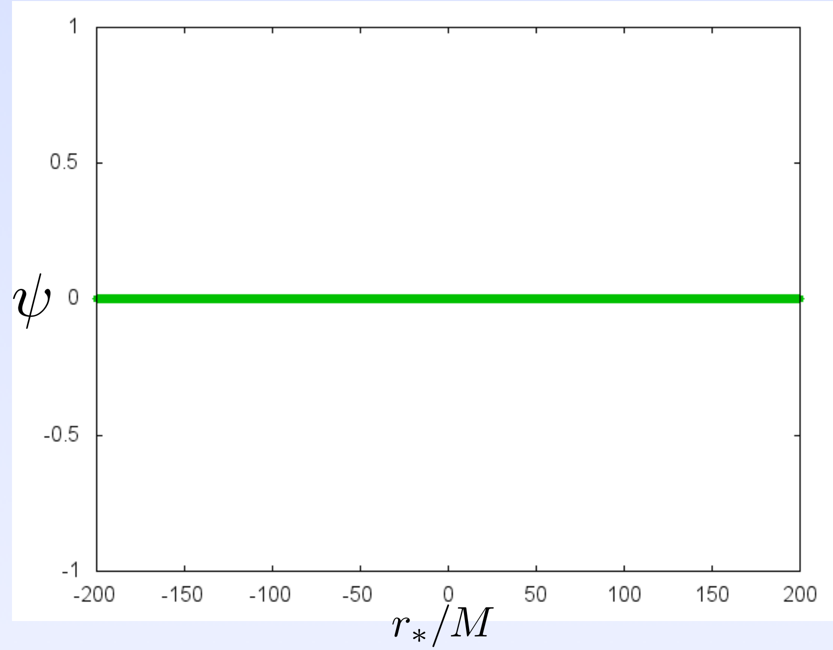
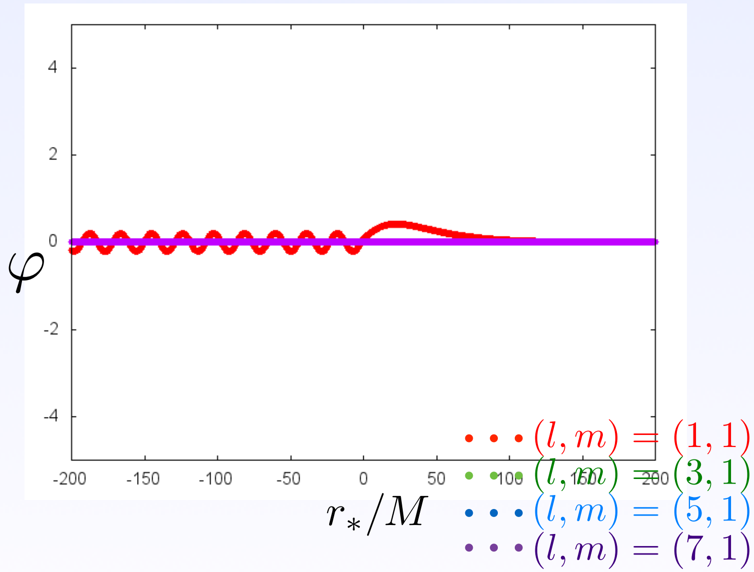
GWs from “Bosenova” in the Schwarzschild case

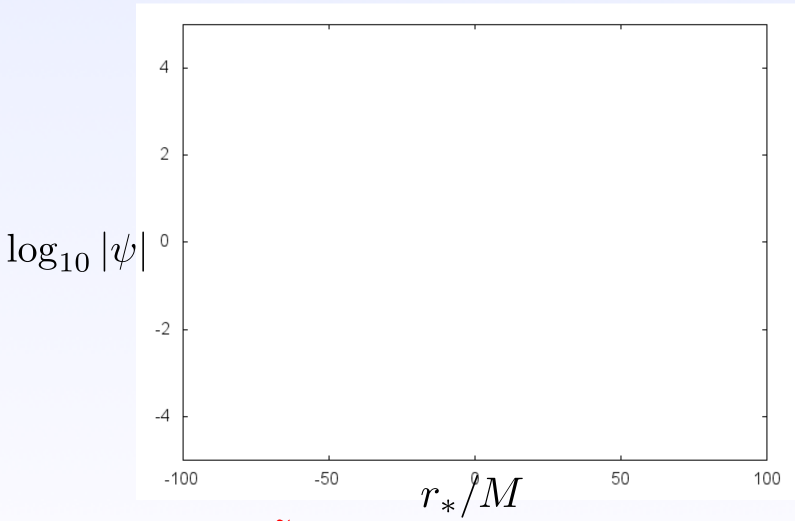
Scalar field



Gravitational waves





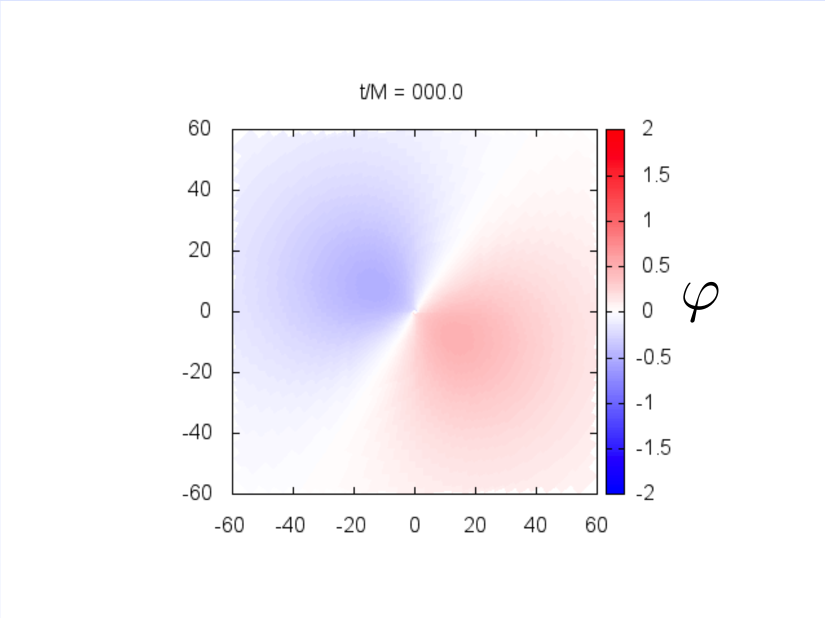


$(\tilde{\ell}, \tilde{m}) = (2, 2)$, real part

$(\tilde{\ell}, \tilde{m}) = (2, 2)$, imaginary part

GWs from “Bosenova” in the Schwarzschild case

Scalar field



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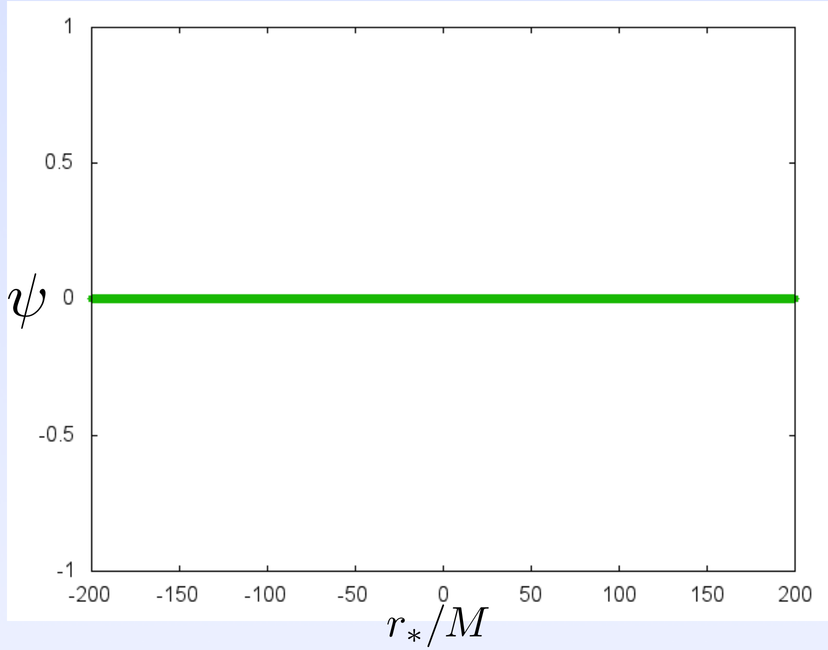
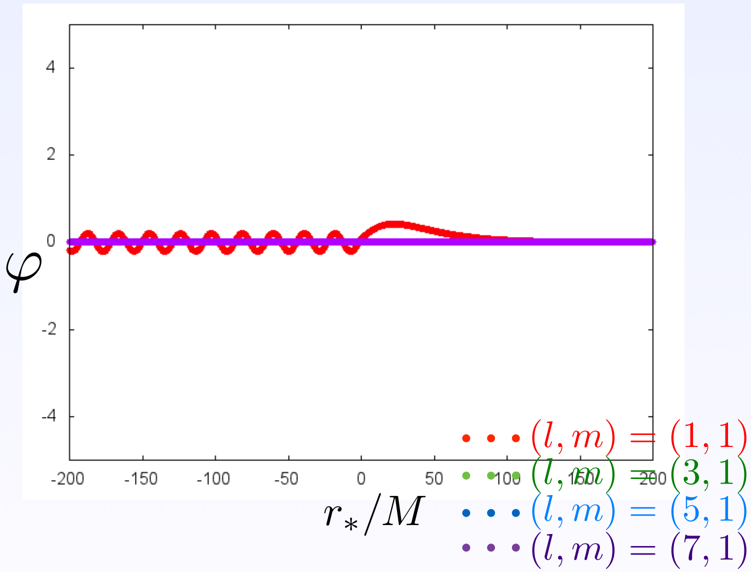
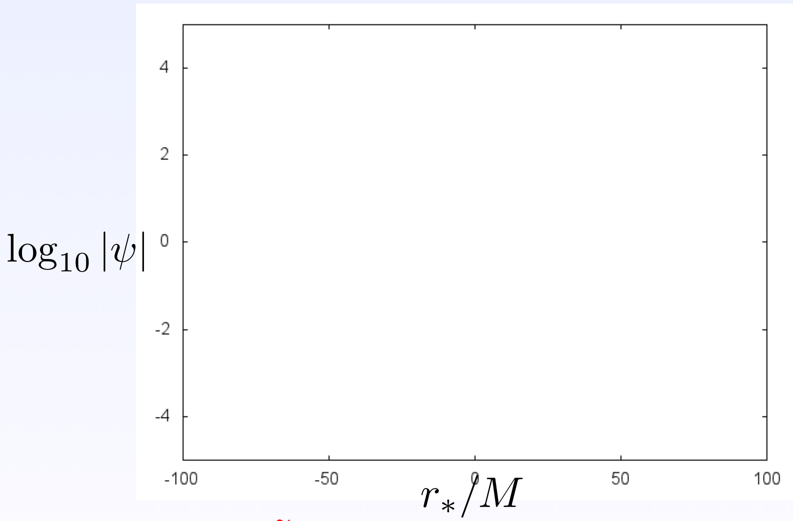


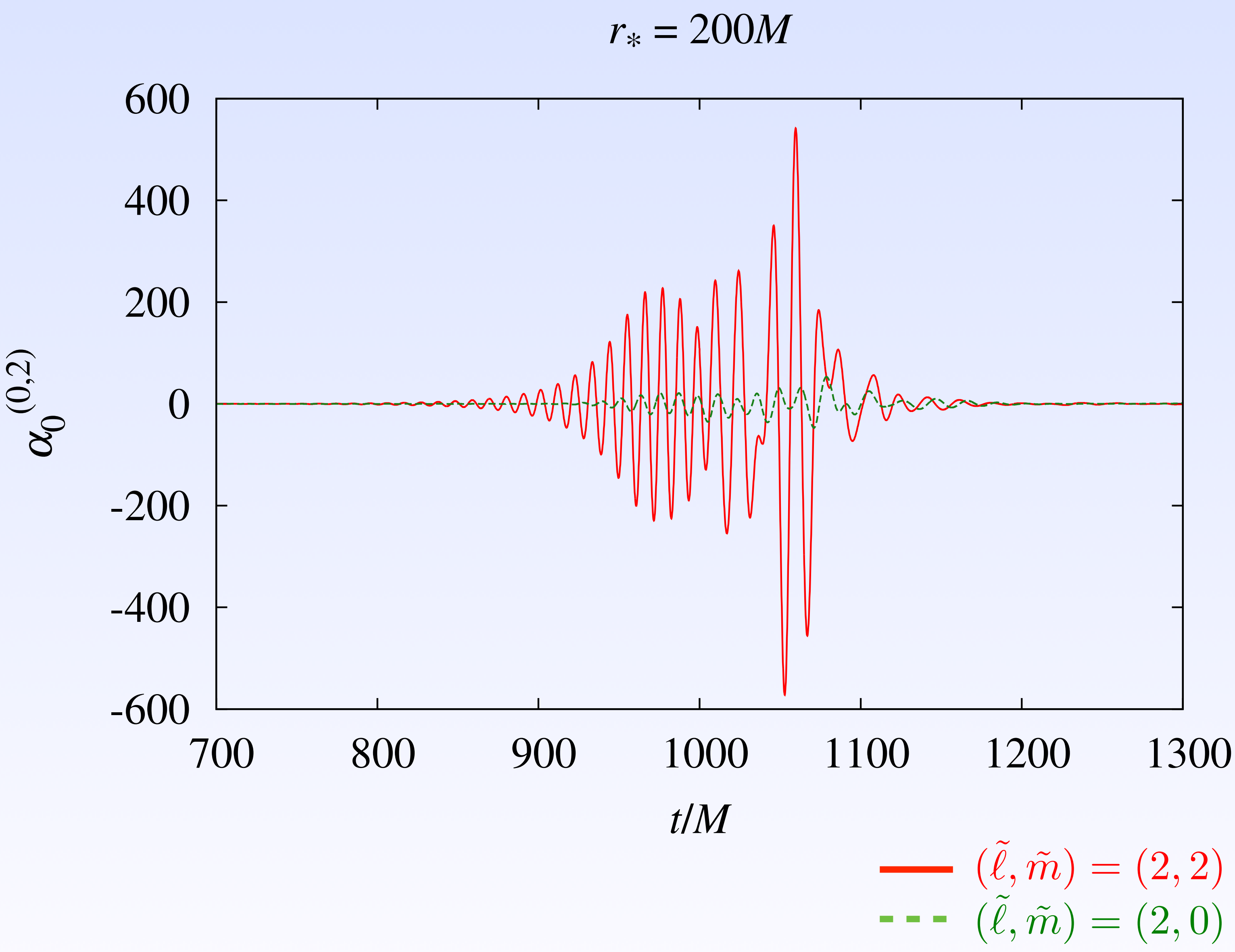




$\cdots (\tilde{\ell}, \tilde{m}) = (2,2)$, real part

$\cdots (\tilde{\ell}, \tilde{m}) = (2,2)$, imaginary part

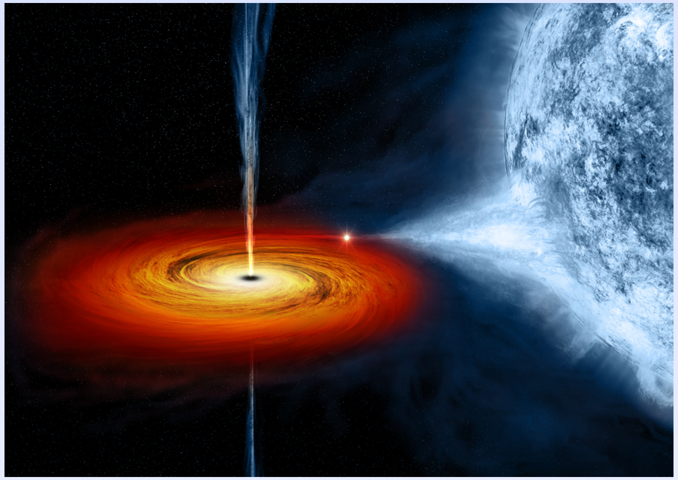
Gravitational Waveform



Possible constraints

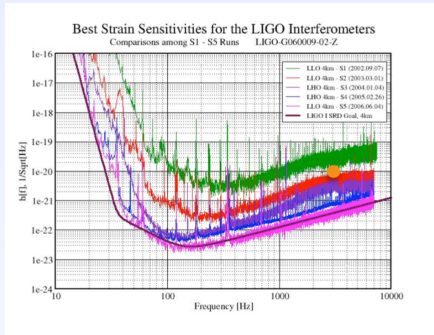
Possible constraints from Cygnus X-1

- $M \approx 15 M_\odot$
- $a_* \gtrsim 0.983$
- $d \approx 1.86$ kpc



McClintock, et al., arXiv:1106.3688-3690{astro-ph}

In the case of $\mu = 2.4 \times 10^{-12}\text{eV} \quad (M\mu = 0.3)$



- Constraint from GW observation ⇨ $f_a \lesssim 10^{15}$ GeV

- Constraint from BH parameter evolution ⇨ $\Delta a_* \ll 1$

⇨ $f_a \lesssim 10^{11}$ GeV (PRELIMINARY)

Summary

Summary

- Axion Bosenova
  - We developed reliable codes and numerically studied the behavior of axion field around a rotating black hole.
  - The bosenova collapse happens as a result of superradiant instability for axion cloud in the l=m=1 mode, while it does not happen for the l=m=2 mode.
  - The bosenova show rich phenomena that depend on setups.
- GWs
  - Burst-type GWs are emitted during the bosenova.
  - Such bursts are expected to be emitted intermittently, and the BH-axion system can be regarded as a gravitational wave geyser.
- If we take account of BH parameter evolution, it may be difficult to detect GWs from BH-axion system.

Thank you!