Bosenova collapse of axion cloud around a rotating black hole

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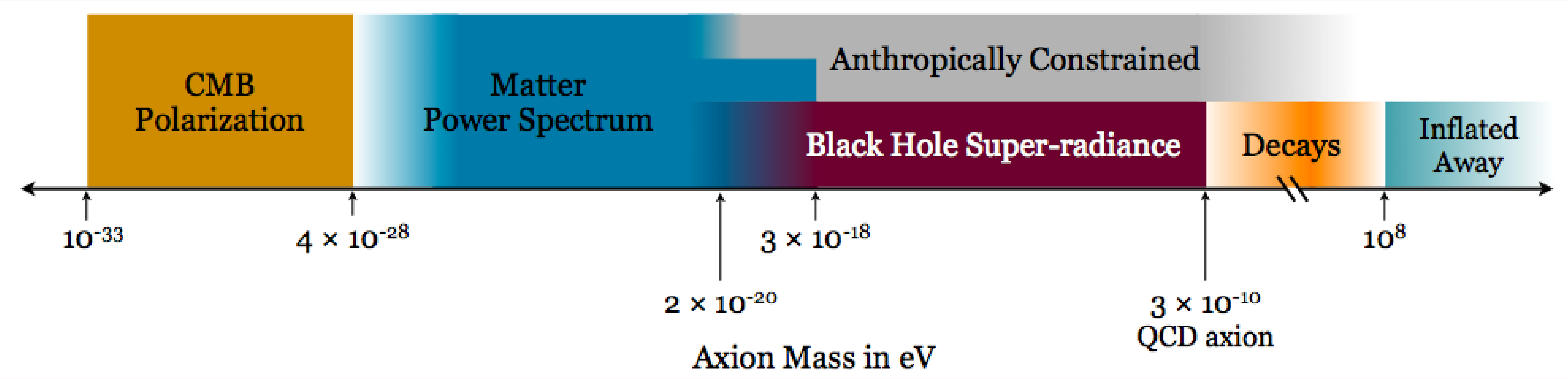
Axions

- Candidates of massive scalar fields. $\nabla^2\Phi - \mu^2\Phi = 0$
  - QCD axion
    - QCD axion was introduced to solve the Strong CP problem.
    - It is one of the candidates of dark matter.
  - String axion

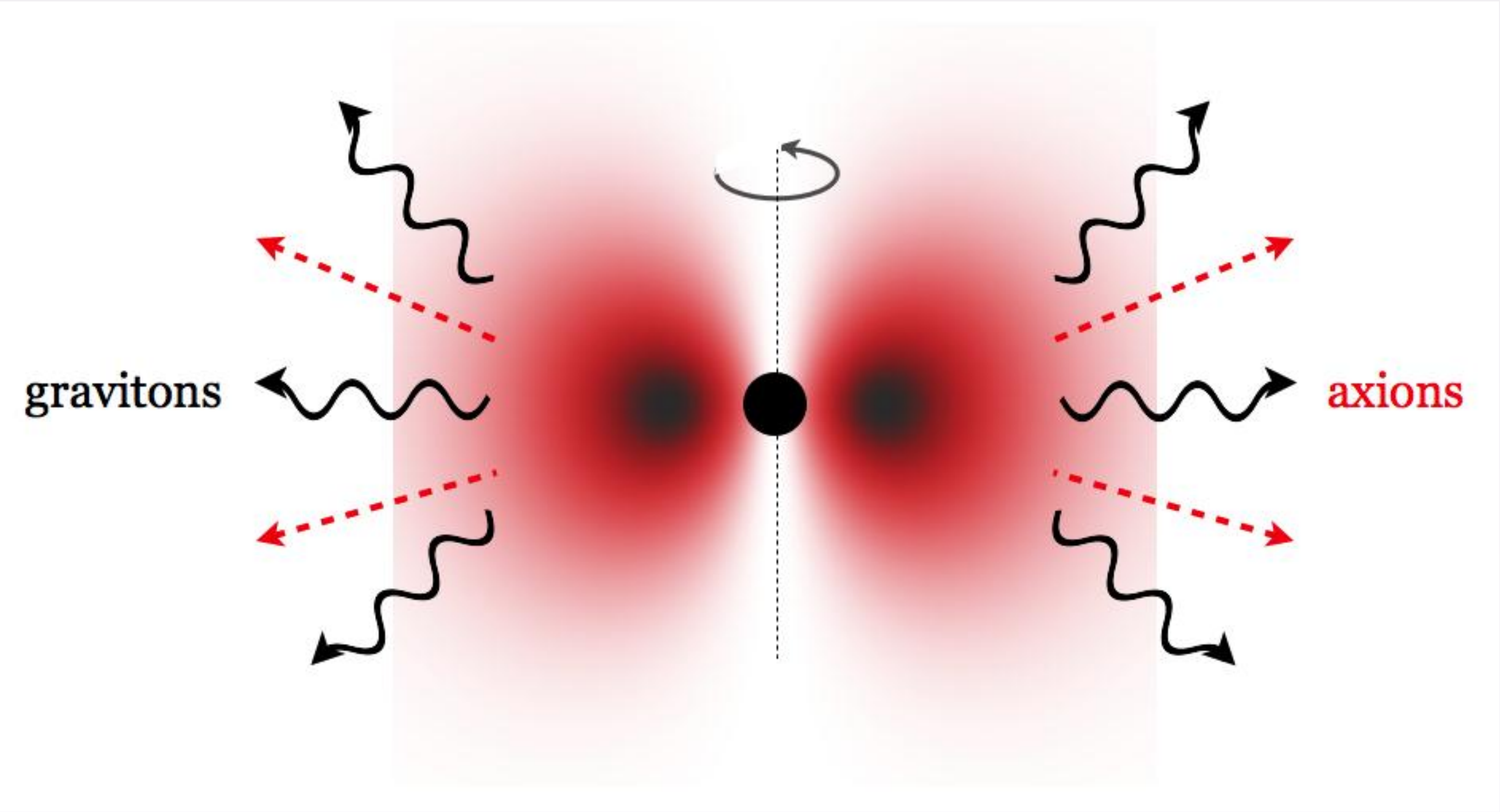
Arvanitaki, Dimopoulos, Dubvosky, Kaloper, March-Russel, PRD81 (2010), 123530.

- String theory predicts the existence of 10-100 axion-like massive scalar fields.
- There are various expected phenomena of string axions.



Axion field around a rotating black hole

- Axion field makes a bound state and causes the superradiant instability

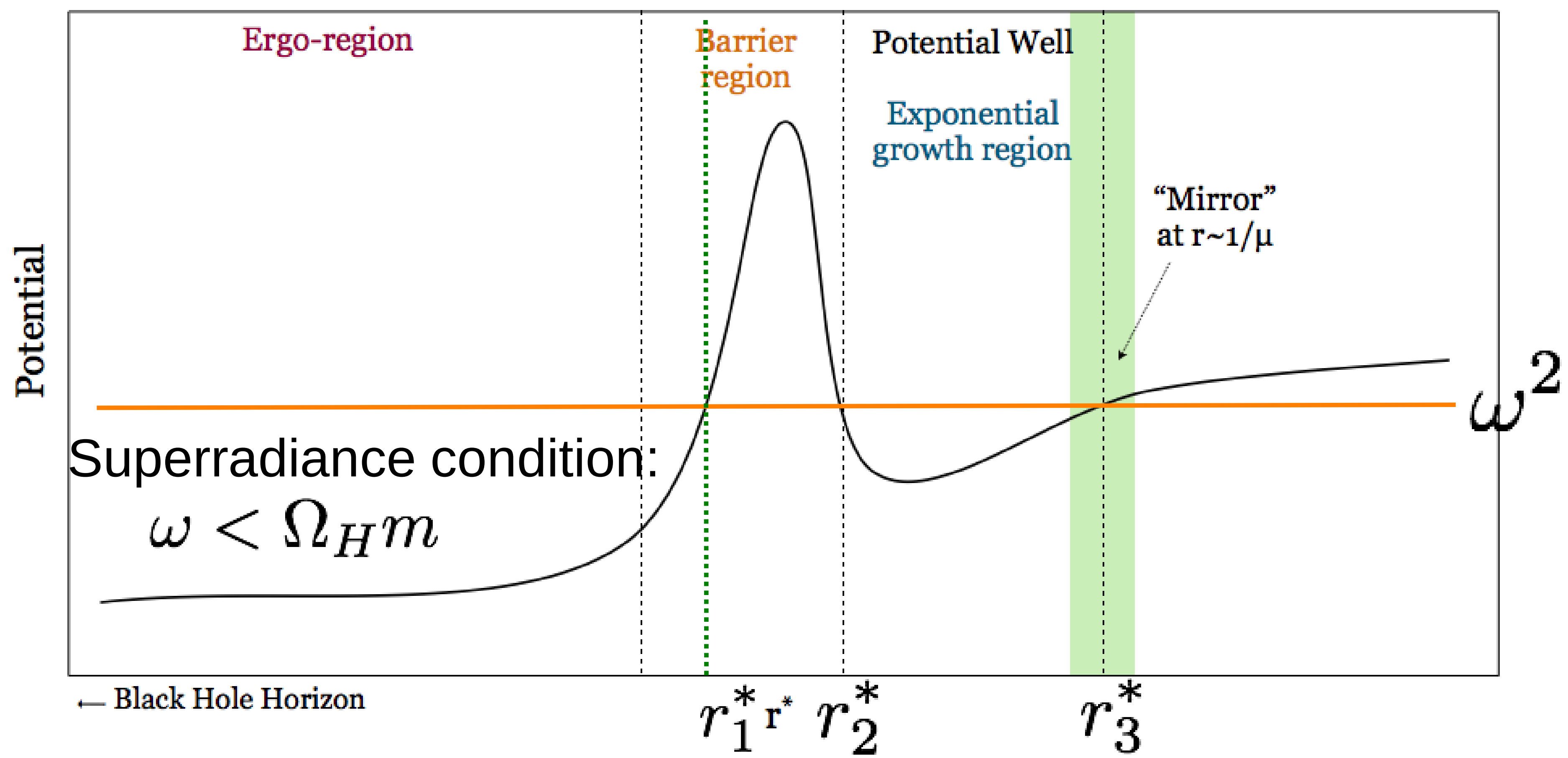


Detweiler, PRD22 (1980), 2323.

Zouros and Eardley, Ann. Phys. 118 (1979), 139.

Bound state

Zouros and Eardley, Ann. Phys. 118 (1979), 139.



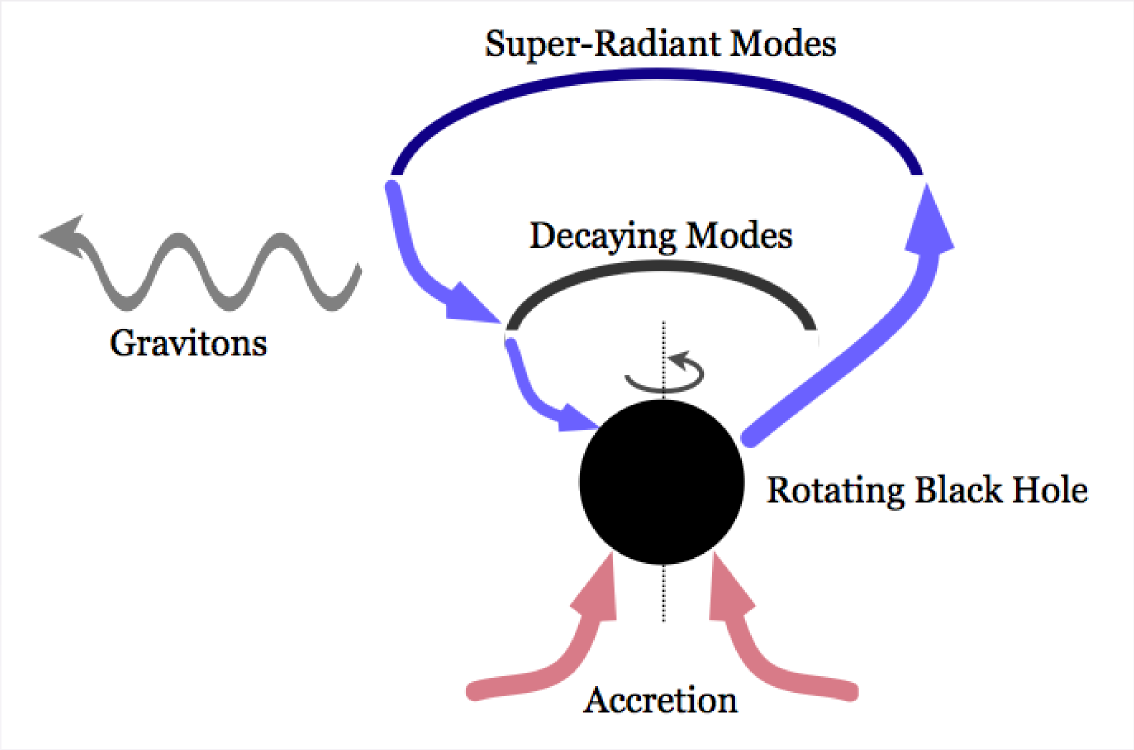
Superradiance condition:

$$\omega < \Omega_H m$$

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

$$R = \frac{u}{\sqrt{r^2 + a^2}} \quad \Rightarrow \quad \frac{d^2 u}{dr_*^2} + \left[\omega^2 - V(\omega)\right] u = 0$$

BH-axion system



Arvanitaki and Dubovsky, PRD83 (2011), 044026.

- Superradiant instability
  - Emission of gravitational waves
  - Pair annihilation of axions
- Effects of nonlinear self-interaction
  - Bosenova
  - Mode mixing

Nonlinear effect

- QCD axion

break

U(1)PQ symmetry → Z(N) discrete symmetry

$V(\Phi)$ becomes periodic. $\Delta\Phi = 2\pi v_a/N = 2\pi f_a$

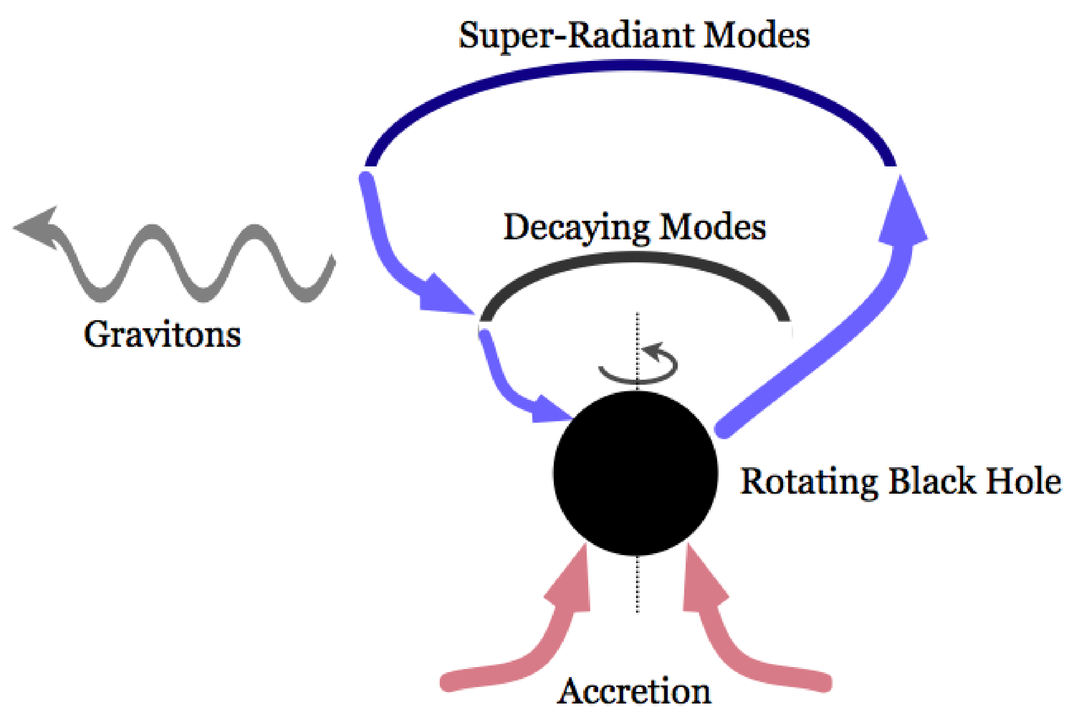
$$V = f_a^2 \mu^2 [1 - \cos(\Phi/f_a)]$$

$$\Rightarrow \quad \boxed{\nabla^2 \Phi - \mu^2 f_a \sin\left(\frac{\Phi}{f_a}\right) = 0}$$

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

- The similar statement holds also for string axions.

BH-axion system



Arvanitaki and Dubovsky, PRD83 (2011), 044026.

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  - Emission of gravitational waves
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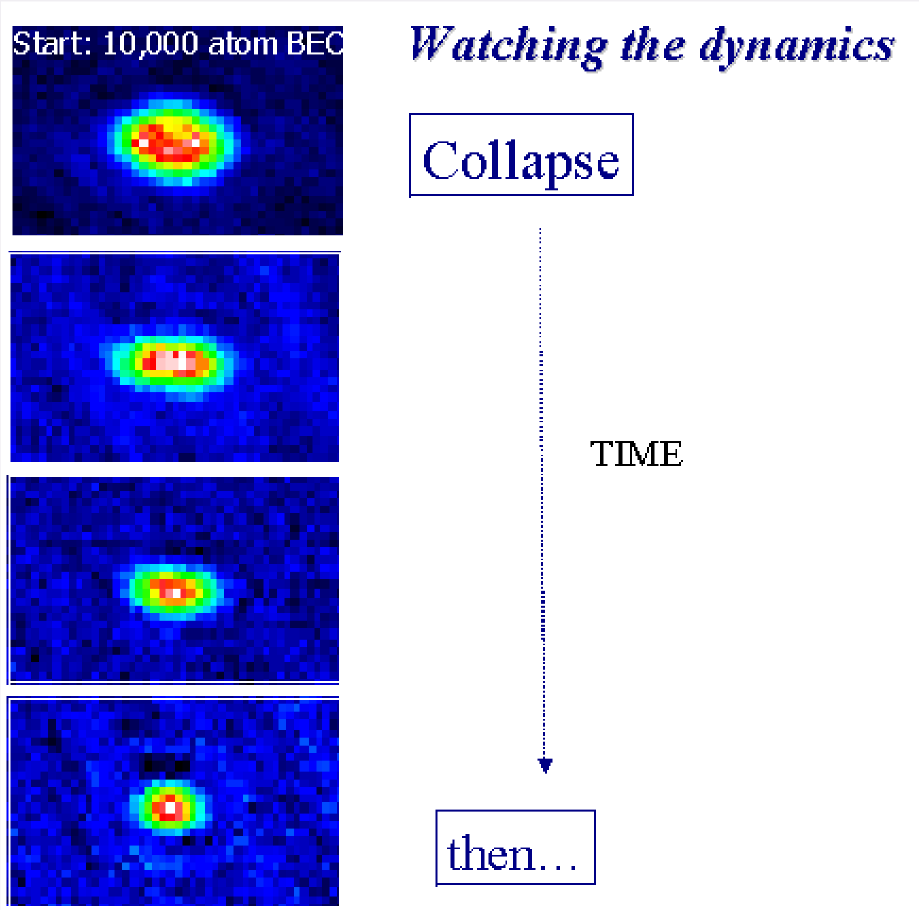
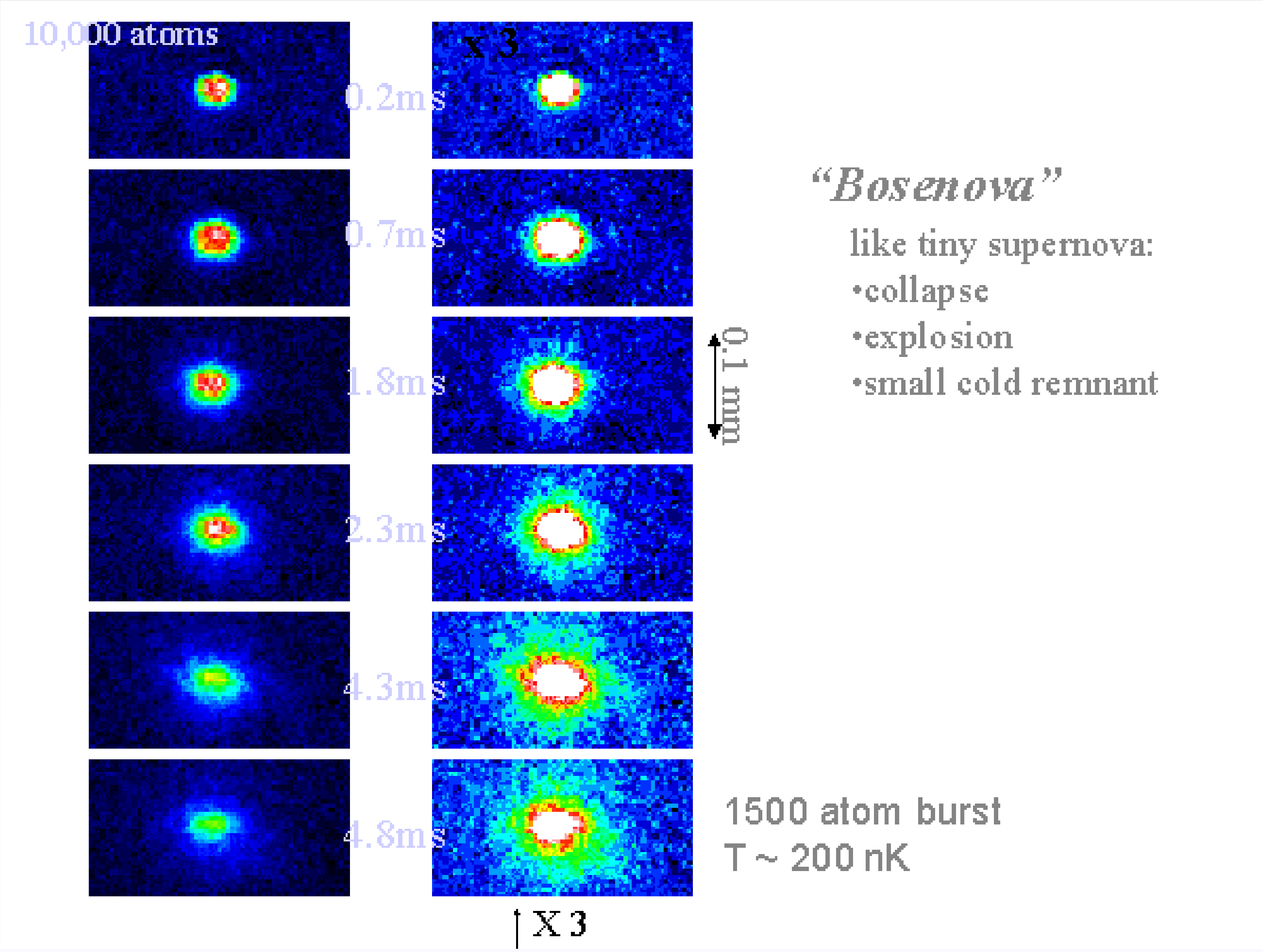
Bosenova in condensed matter physics

http://spot.colorado.edu/~cwieman/Bosenova.html





BEC state of Rb85（interaction can be controled）

Switch from repulsive interaction to attractive interaction

Wieman et al., Nature 412 (2001), 295

What we would like to do

- We would like to study the phenomena caused by axion cloud generated by the superraciant instability around a rotating black hole.

- In particular, we study numerically whether “Bosenova” happens when the nonlinear interaction becomes important.

- We adopt the background spacetime as the Kerr spacetime, and solve the axion field as a test field.

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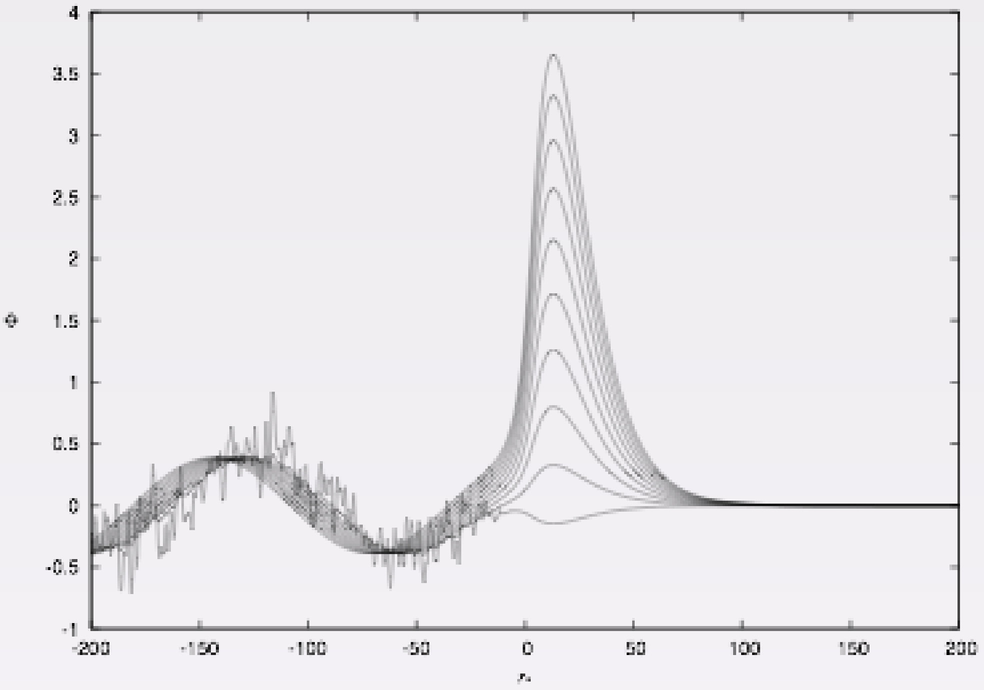
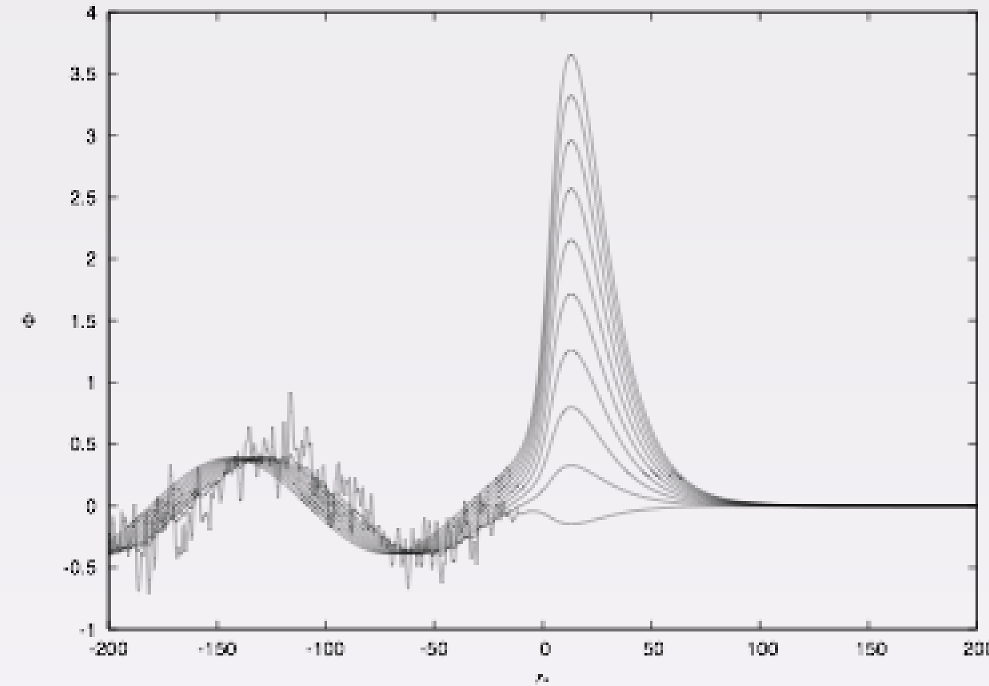
First difficulty

- Stable simulation cannot be realized in Boyer-Lindquist coordinates.

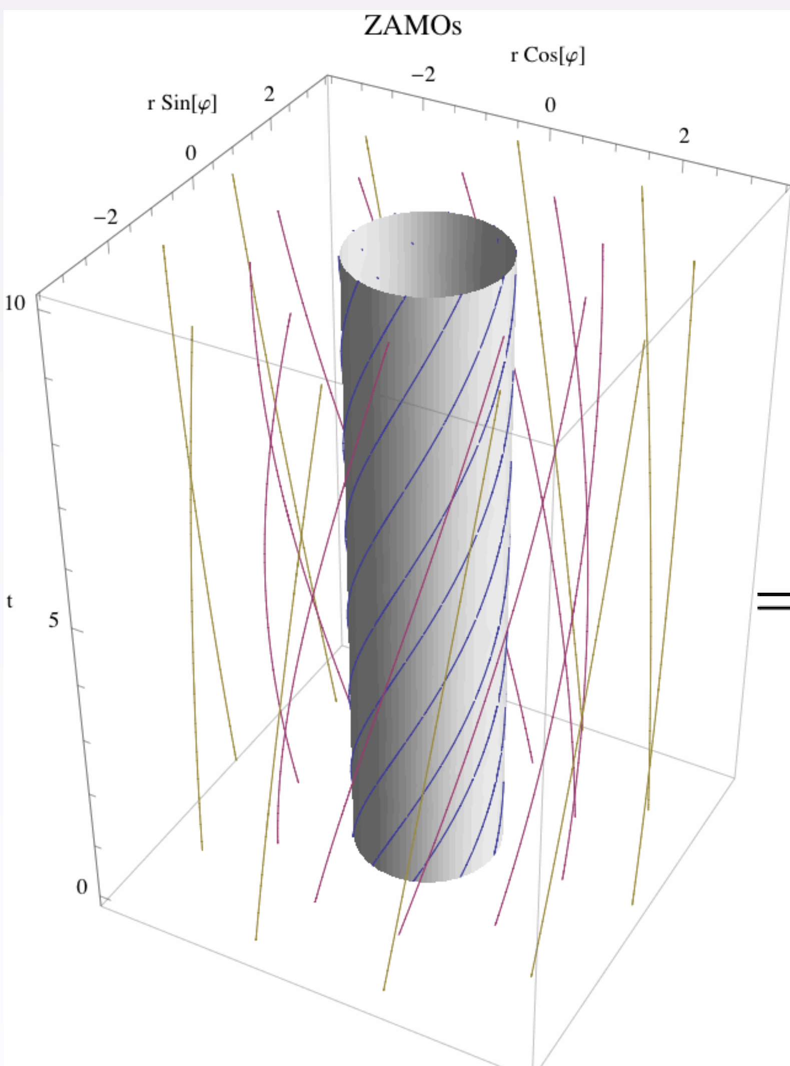


First difficulty



- Stable simulation cannot be realized in Boyer-Lindquist coordinates.

We use ZAMO coordinates.



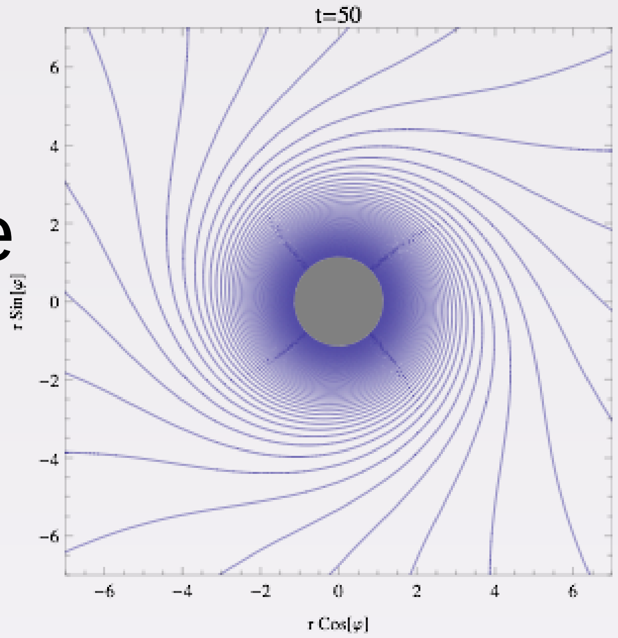
$$\Omega = \frac{d\phi}{dt} = \frac{u^\phi}{u^t} = -\frac{g_{t\phi}}{g_{\phi\phi}}$$

$$= \frac{2Mar}{(r^2+a^2)^2 - \Delta a^2 \sin^2\theta}$$

$$\tilde{t} = t,$$
$$\tilde{\phi} = \phi - \Omega(r,\theta)t,$$
$$\tilde{r} = r,$$
$$\tilde{\theta} = \theta,$$

Second difficulty

- ZAMO coordinates becomes more and more distorted in the time evolution



Second difficulty

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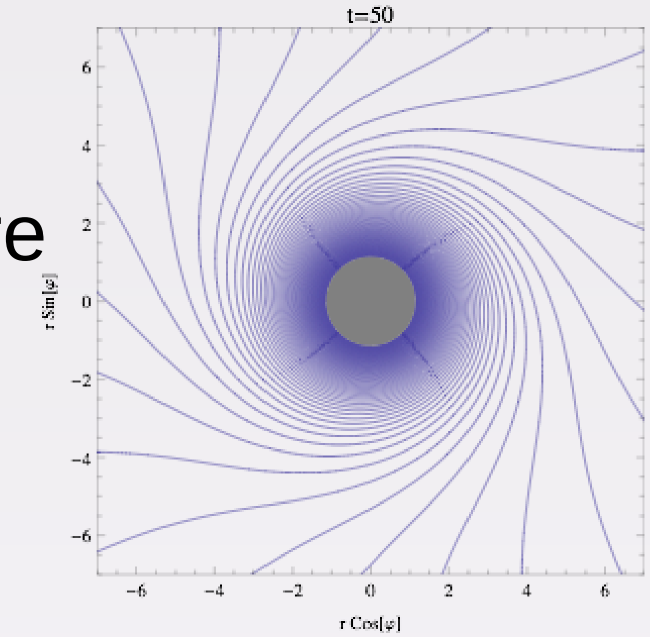
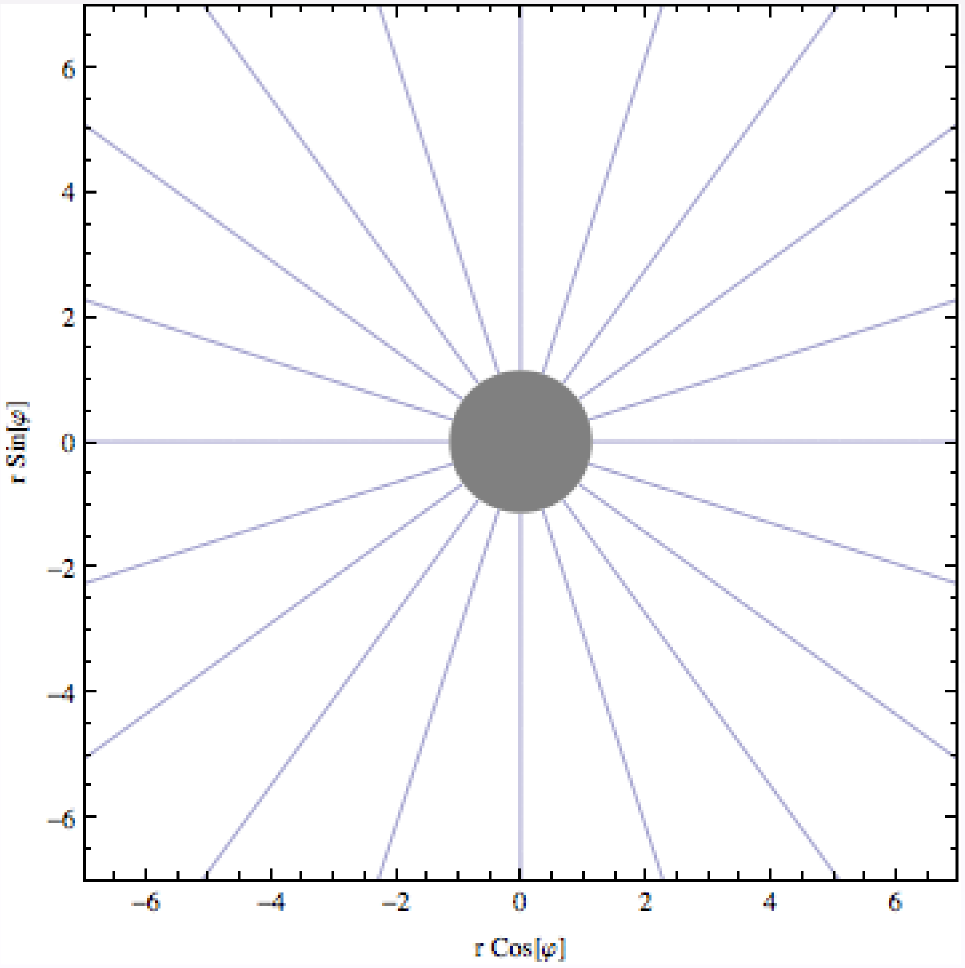


➢ We "pull back" the coordinates

$$nT_P \leq t \leq (n+1)T_P :$$

$$\begin{aligned} t^{(n)} &= t, \\ \phi^{(n)} &= \phi - \Omega(r,\theta)(t - nT_P), \\ r^{(n)} &= r, \\ \theta^{(n)} &= \theta. \end{aligned}$$

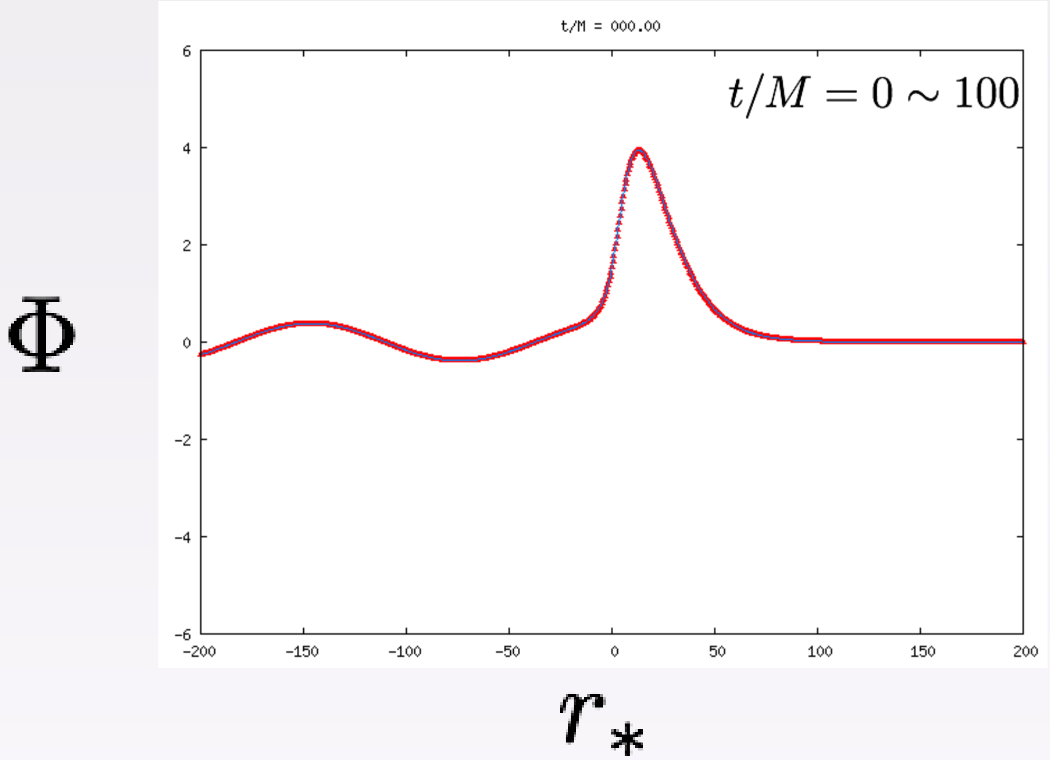


Our 3D code

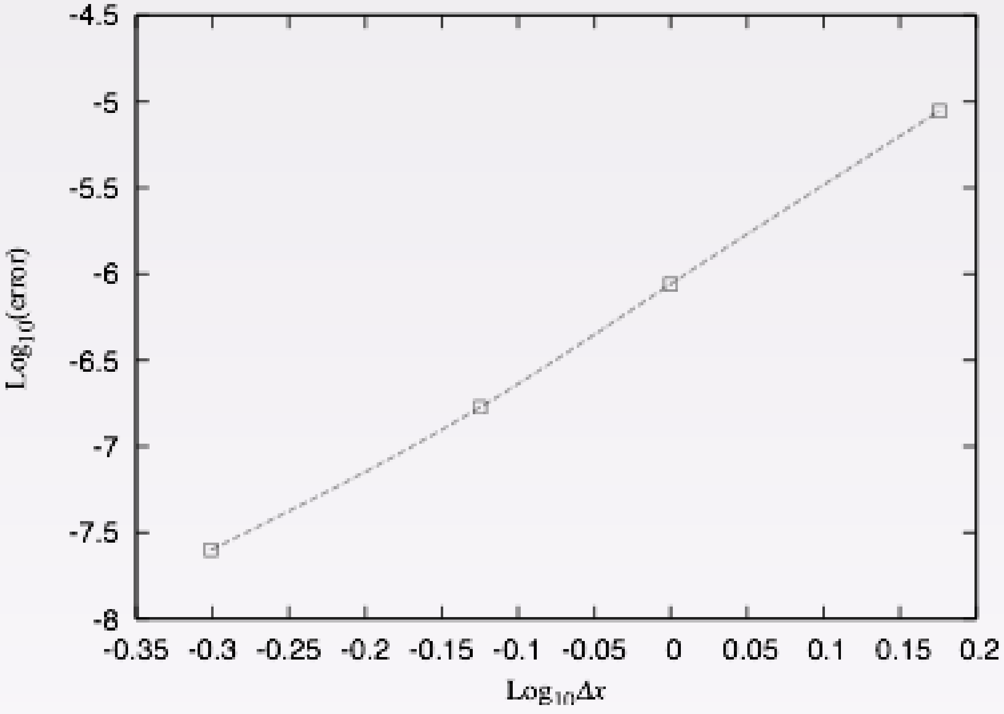
- Space direction：6th-order finite discretization
- Time direction：4th-order Runge-Kutta
- Grid size: $\Delta r_* = 0.5 \quad (M = 1)$
  $\Delta\theta = \Delta\phi = \pi/30$
- Courant number: $C = \dfrac{\Delta t}{\Delta r_*} = \dfrac{1}{20}$
- Pure ingoing BC at the inner boundary,
  Fixed BC at the outer boundary
- Pullback: 7th-order Lagrange interpolation

Code check

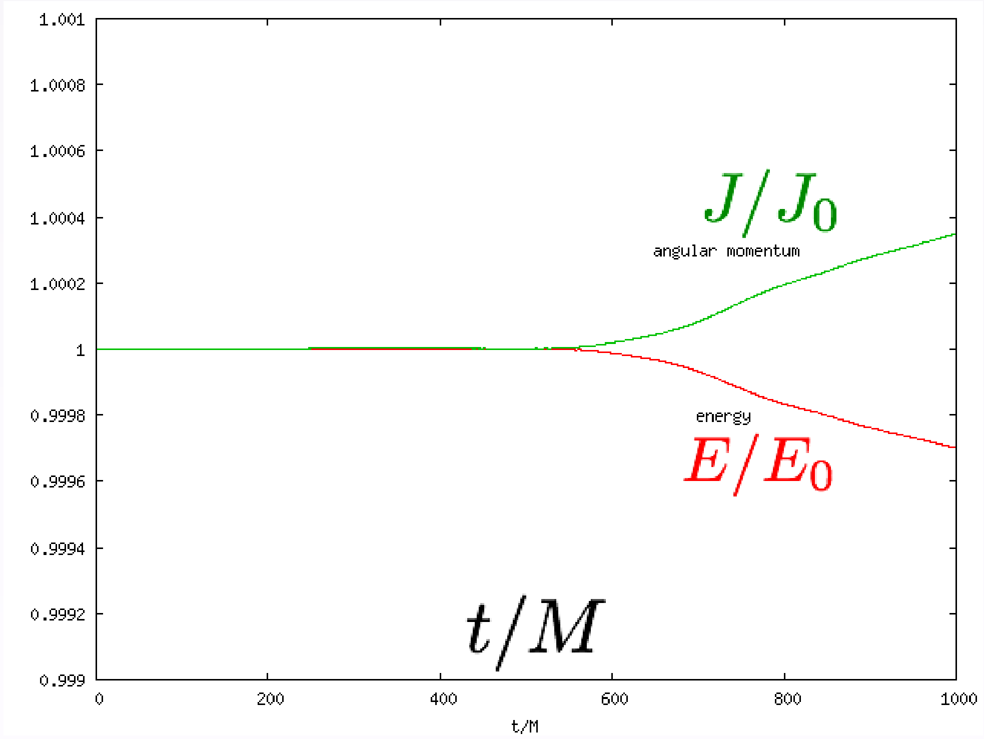
- Comparison with semianalytic solution in the Klein-Gordon case



- Convergence



- Conserved quantities



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- Summary

Numerical simulation

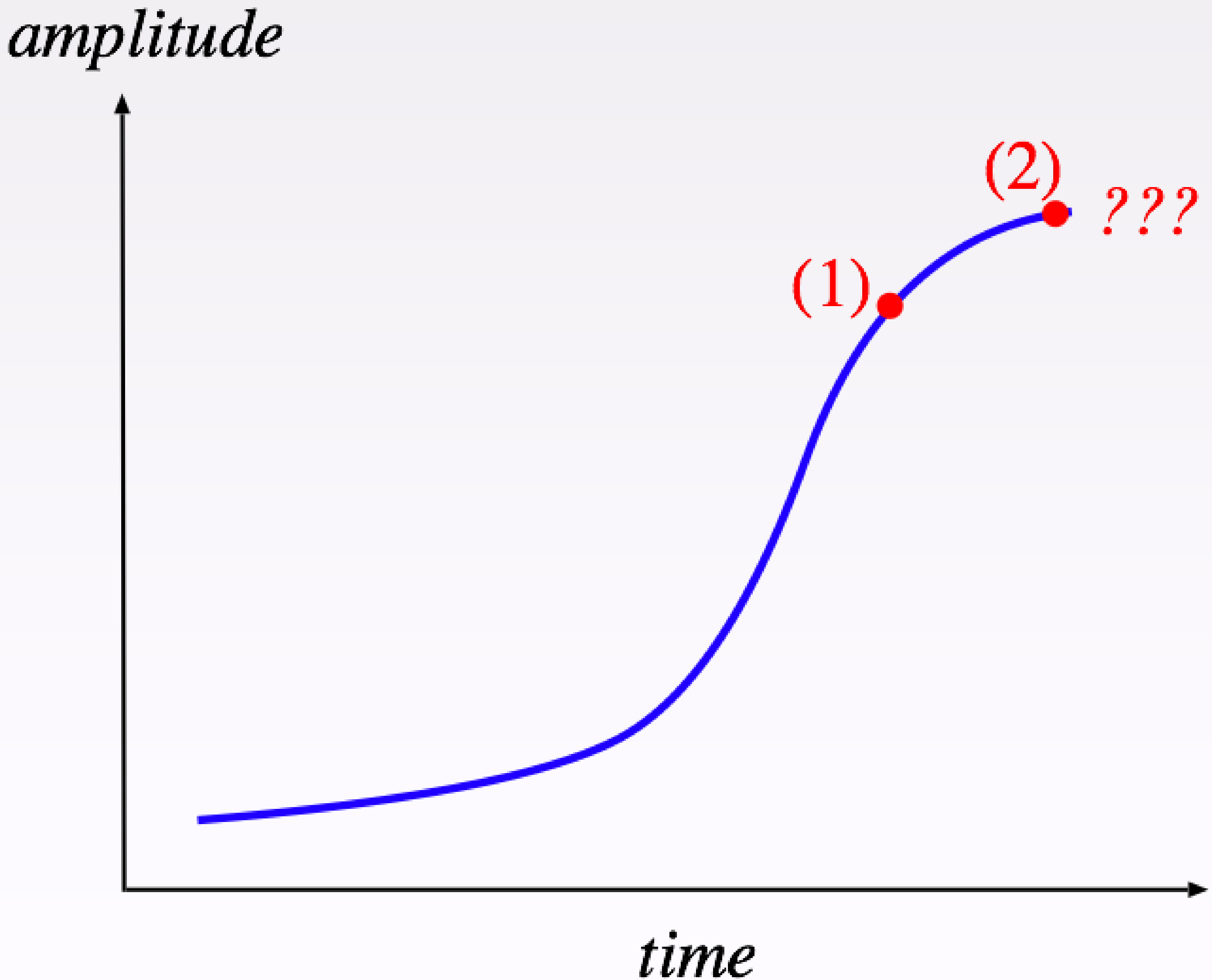
- Sine-Gordon equation

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

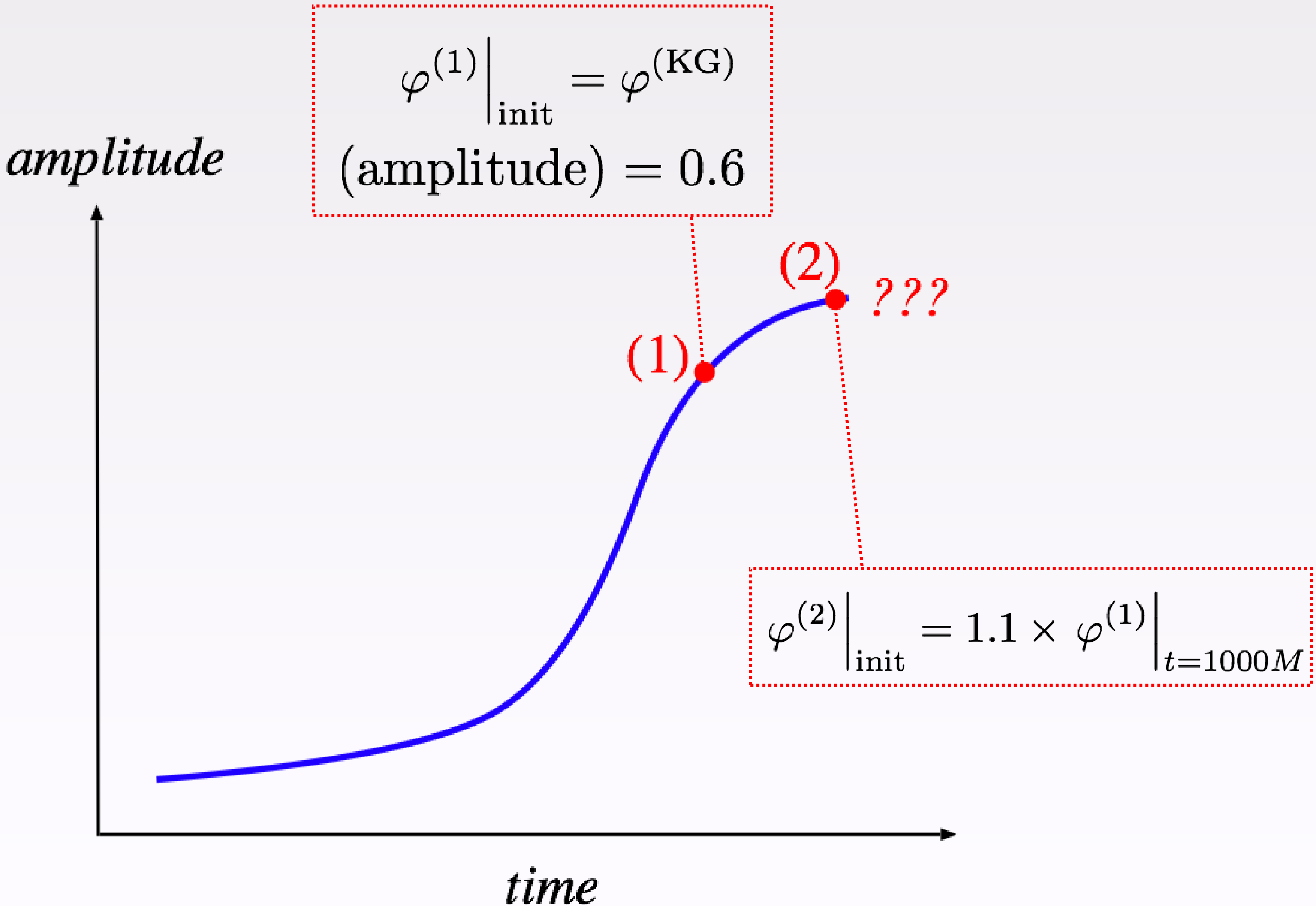
- Setup $a/M = 0.99, \quad M\mu = 0.4$

- We choose the state of axion cloud that has grown by superradiant instability of $l = m = 1$ mode.

Expected evolution



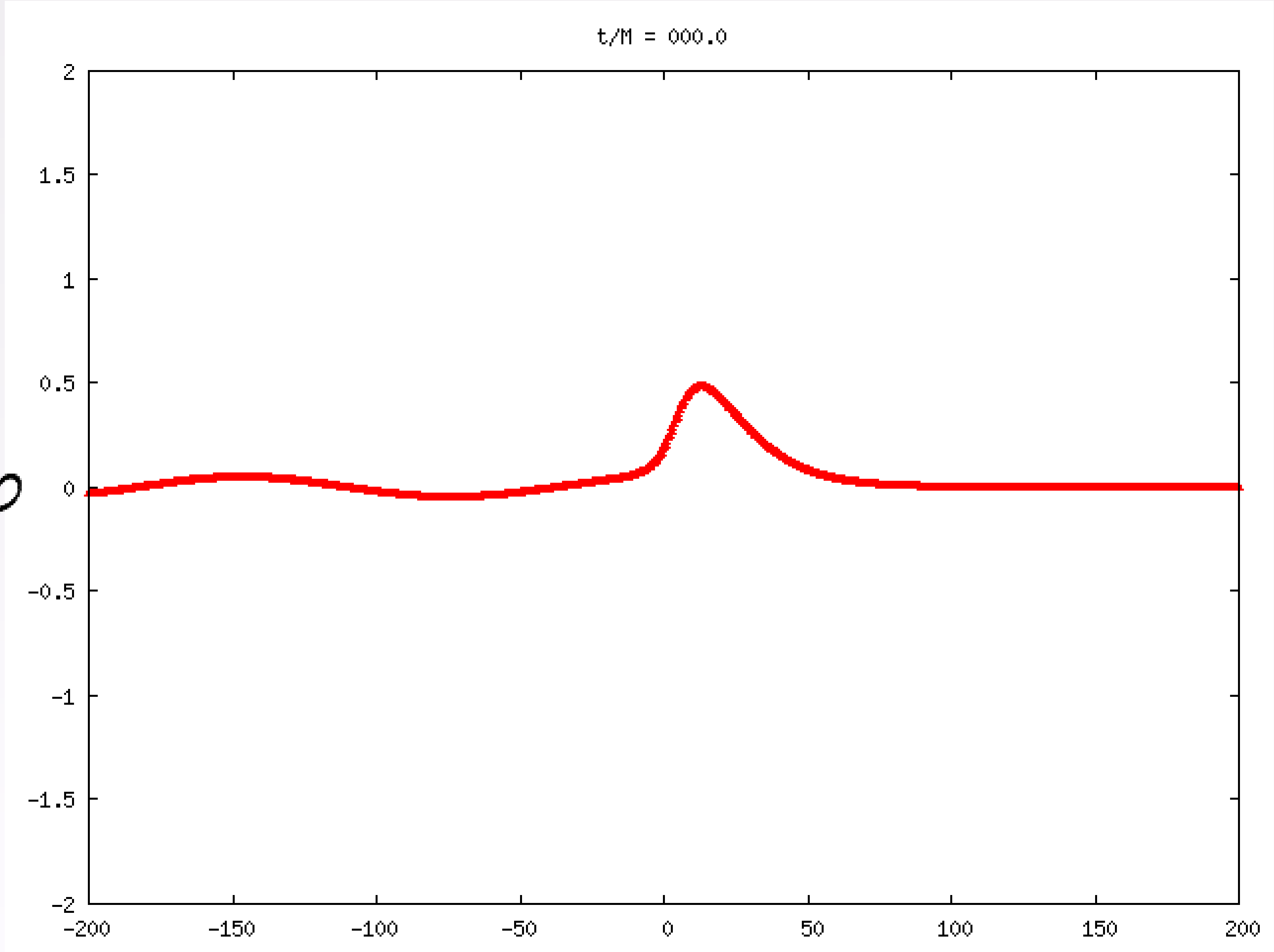
Expected evolution



Simulation (1)

- Axion field on equatorial plane $(\phi = 0)$

φ



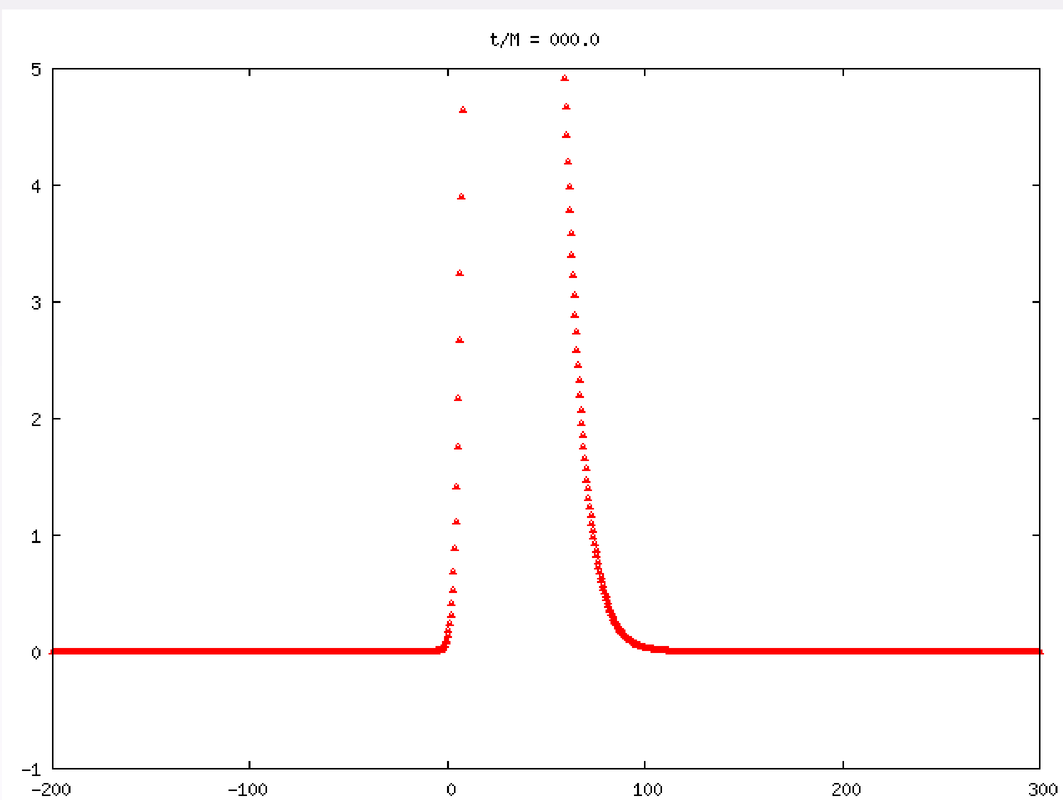
$$-200 \leq r_*/M \leq 200$$

Simulation (1)

- Energy density with respect to the tortoise coordinate

$$t/M = 0$$

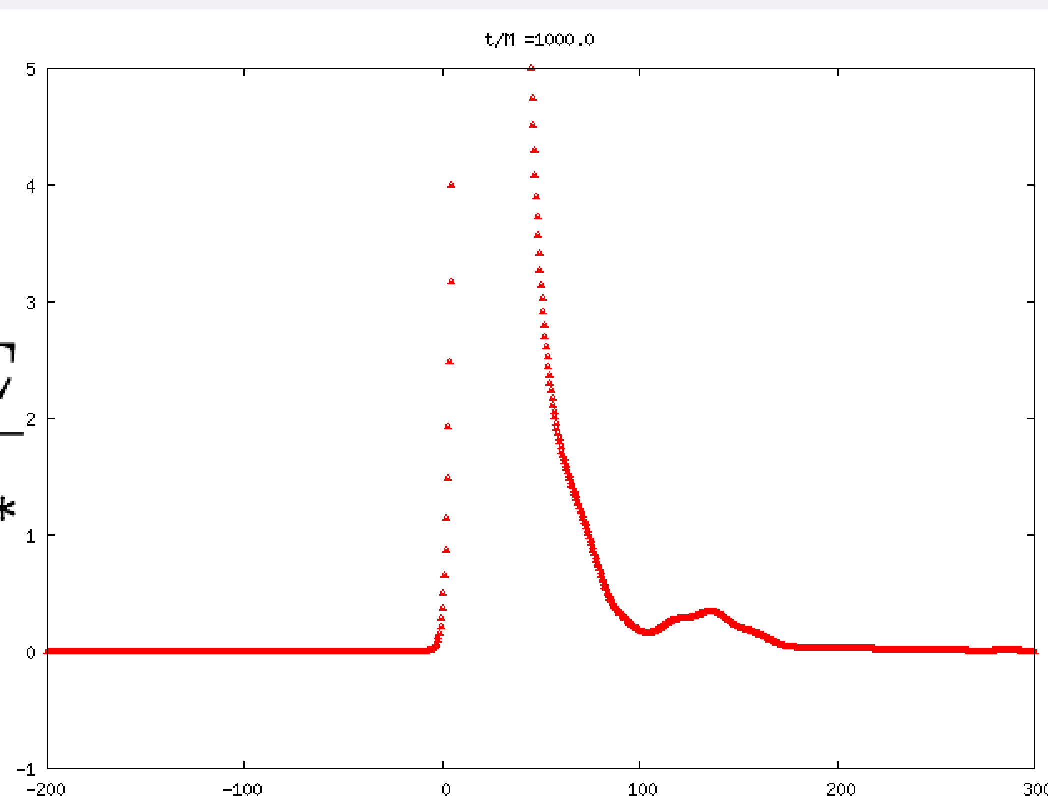
$$\frac{dE}{dr_*}$$



$$-200 \leq r_*/M \leq 300$$

$$t/M = 1000$$

$$\frac{dE}{dr_*}$$



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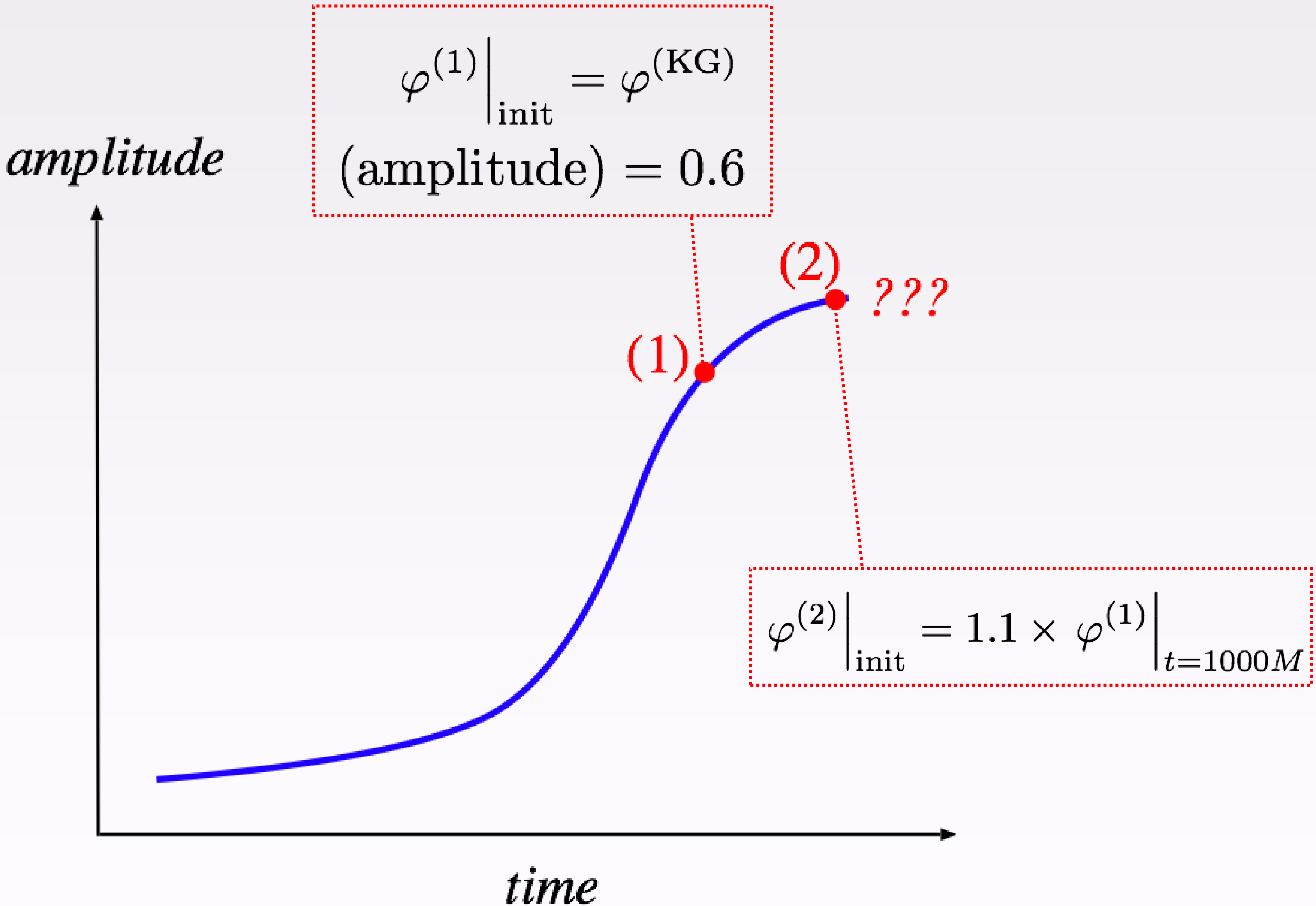
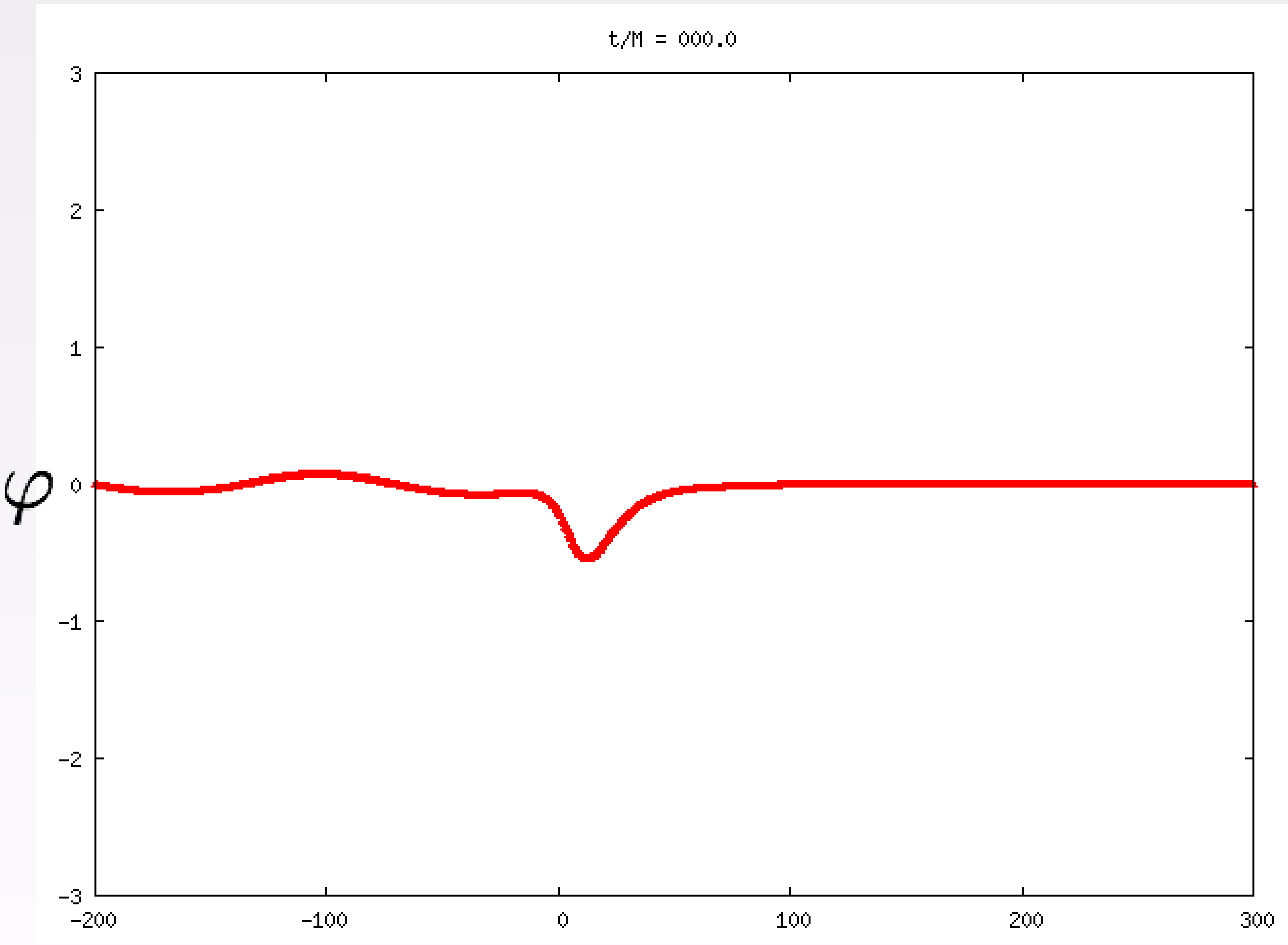


Simulation (2)

- Axion field on equatorial plane $(\phi = 0)$



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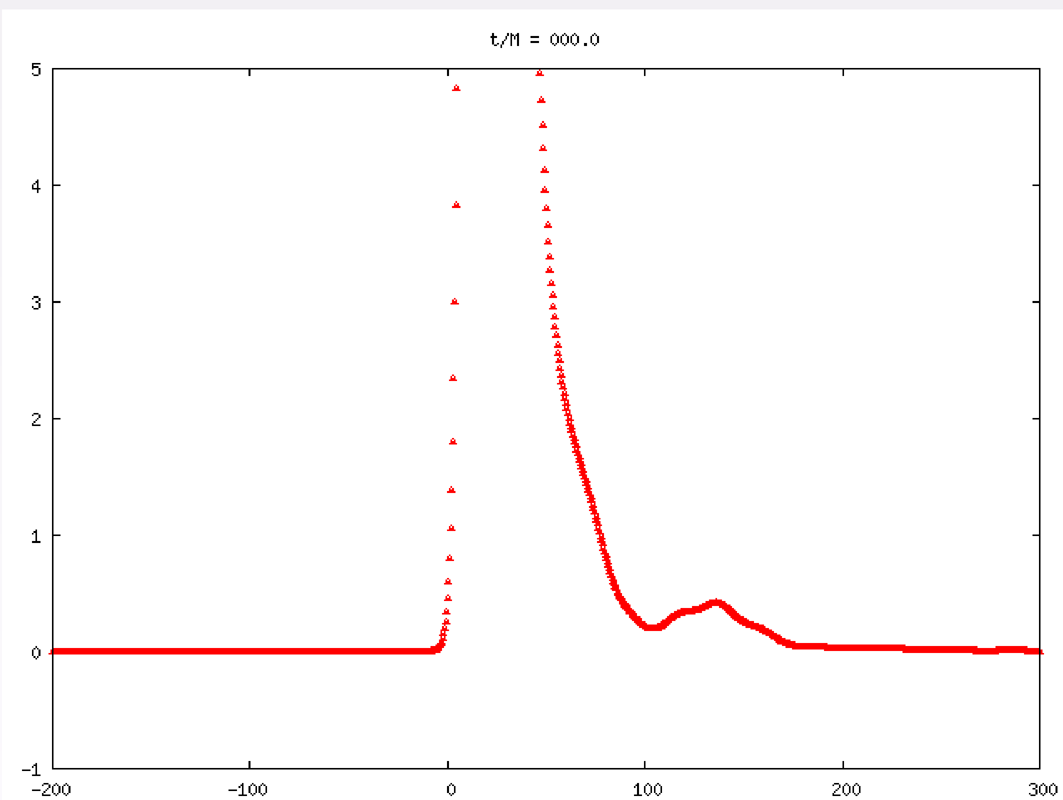

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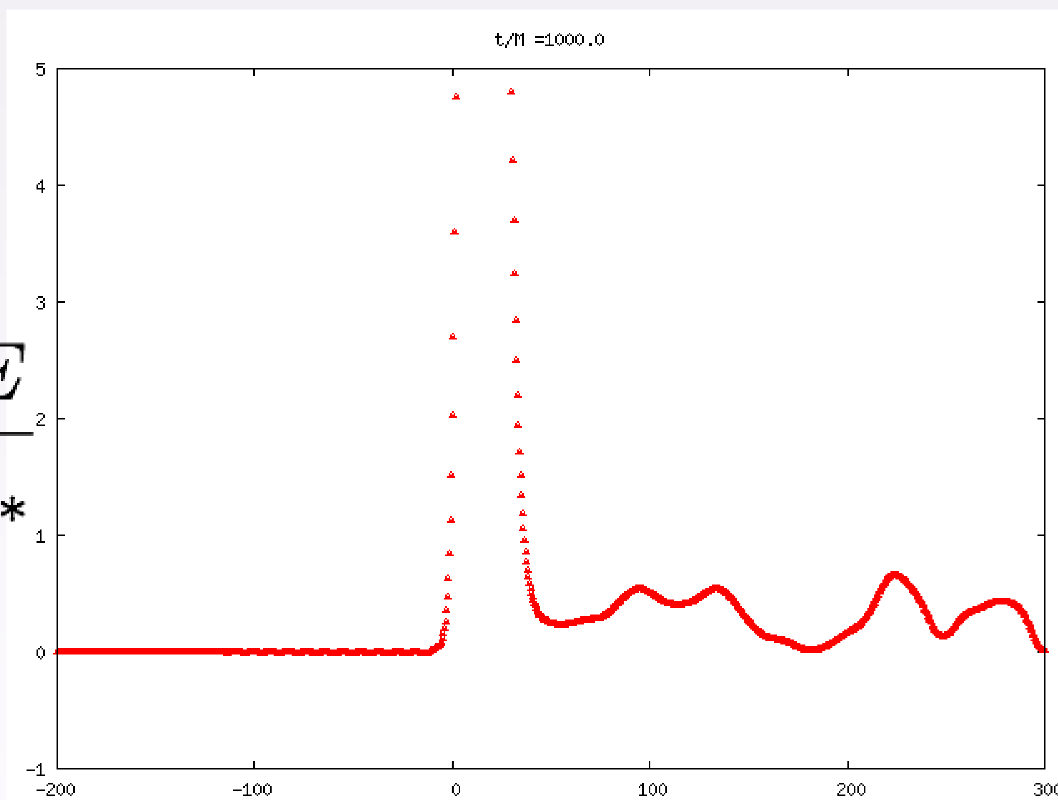

$$-200 \le r_*/M \le 300$$

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Summary

- We developed a reliable code and numerically studied the behaviour of axion field around a rotating black hole.

- When the nonlinear self-interaction becomes relevant, the “bosenova collapse” can be seen, but not very violent.

- The final state of superradiant instability would be a quasi-stationary state.

Issues for future

- Calculation of the gravitational waves emitted in bosenova.

- The case where axions couple to magnetic fields.