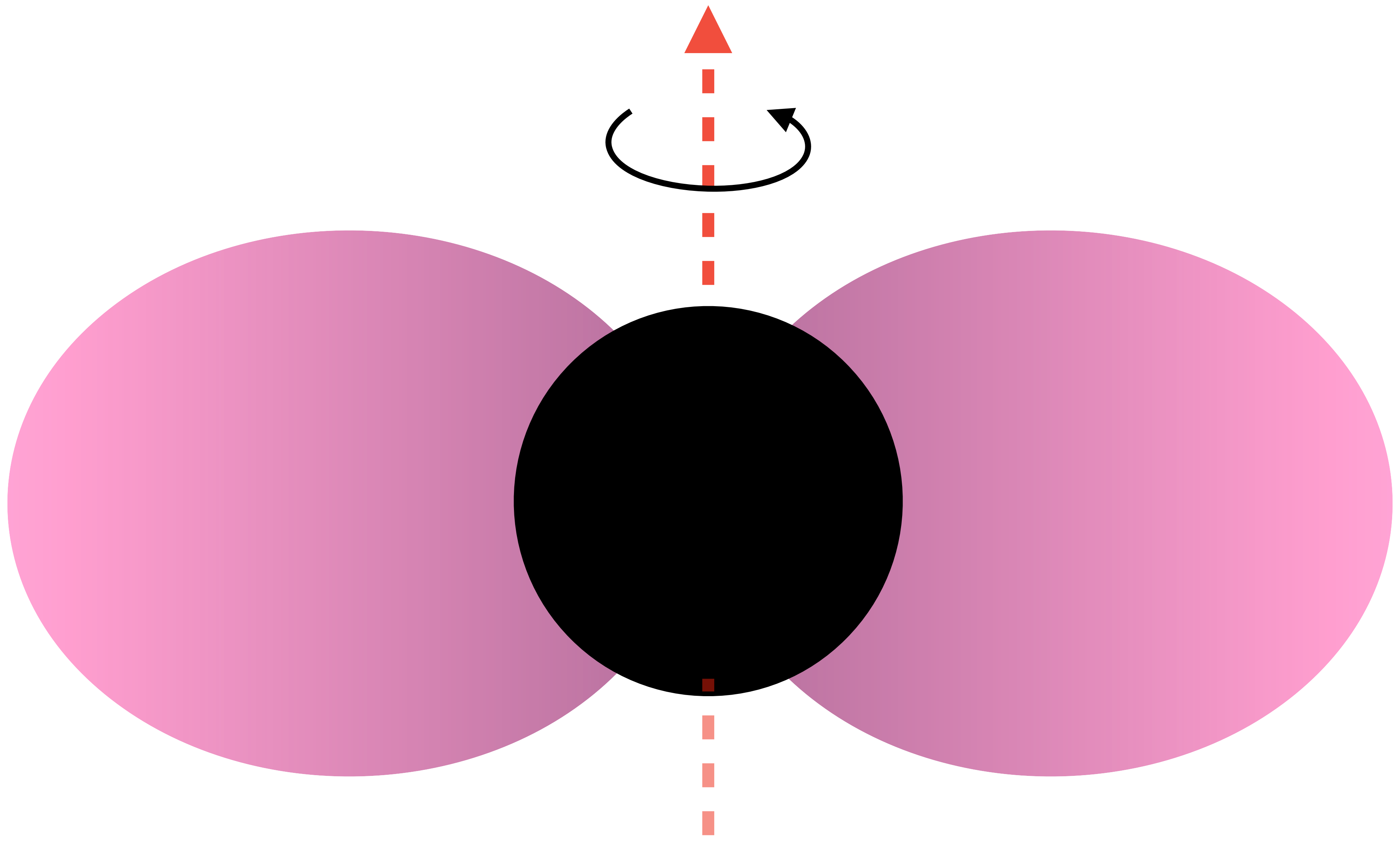
strong.
niels bohr
institute

KØBENHAVNS UNIVERSITET

Superradiance:

Axionic Couplings and Plasma Effects



In collaboration with:

E. Cannizzaro, T. Ikeda,
V. Cardoso & Y. Chen

Thomas Spieksma

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arXiv: 2306.16647

VILLUM FONDEN

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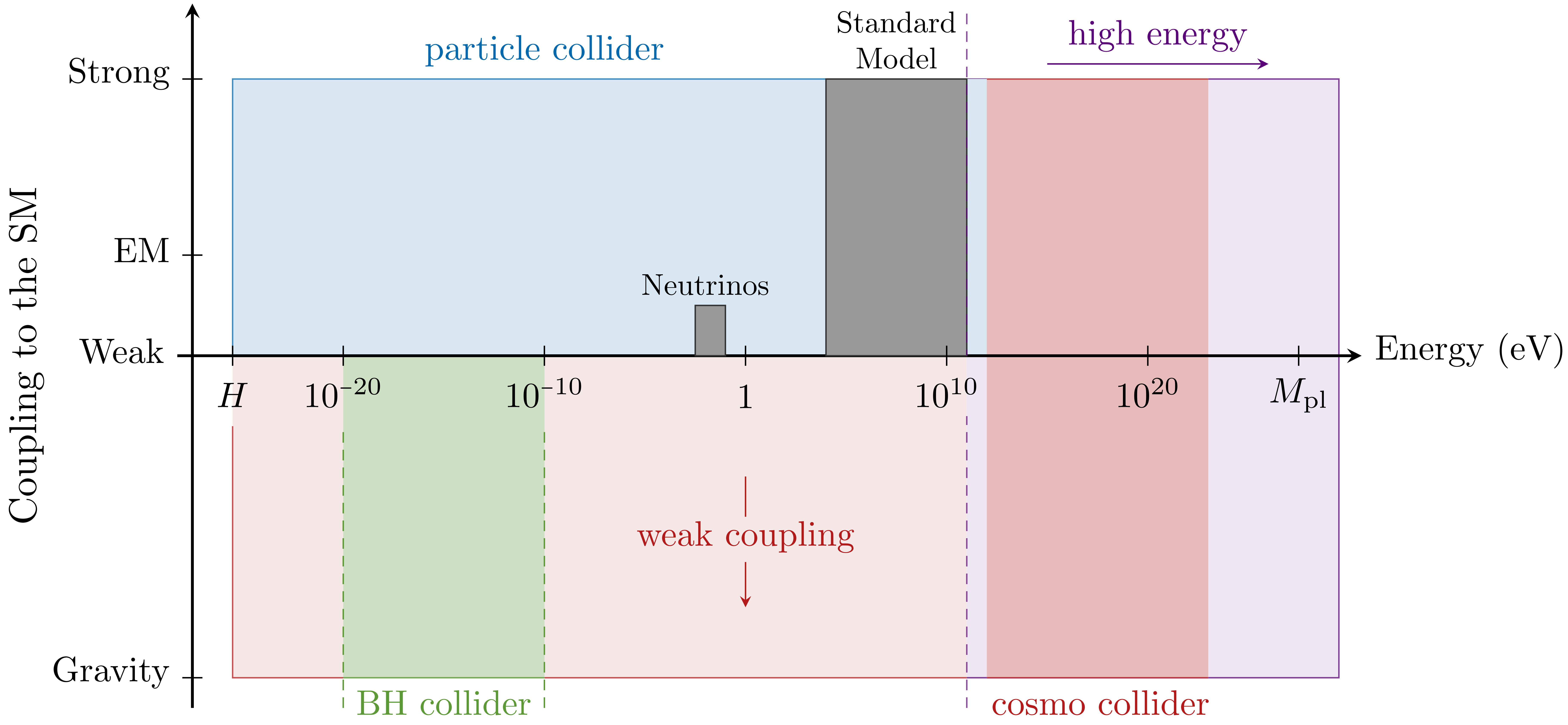
Motivation



Searching for **new physics** in regions of **strong gravity**

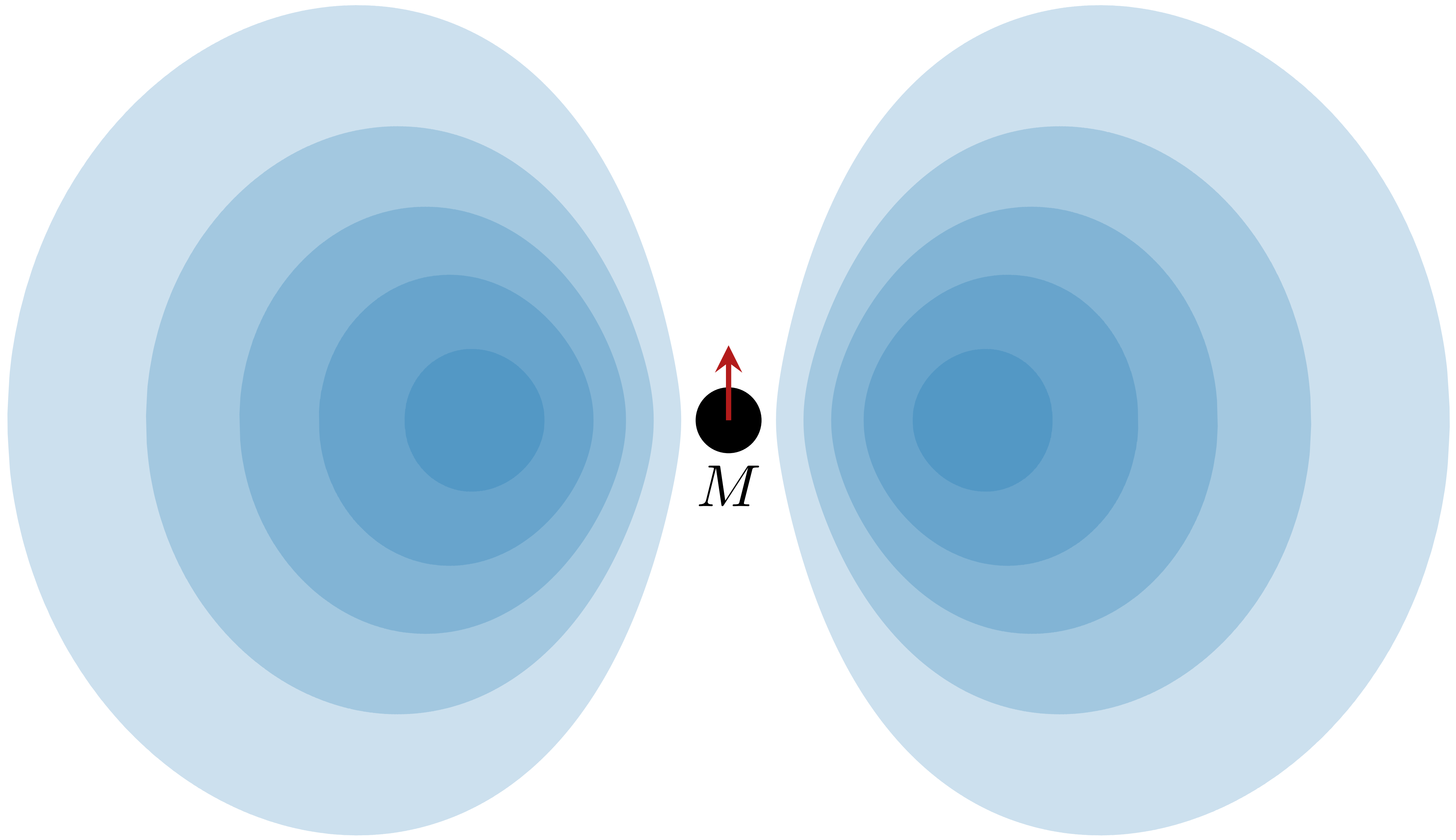
Black Hole Superradiance

$$\left(\Box - \mu^2\right)\Psi = 0$$

$$\downarrow$$

$$i\frac{\mathrm{d}\psi}{\mathrm{d}t} \approx \left(-\frac{1}{2\mu}\nabla^2 - \frac{\mu M}{r} + \cdots\right)\psi$$

"Gravitational Atom"



[Zeldovich '72], [Starobinsky '73], [Dolan '07], [Brito et al. '15]

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$$\frac{r_g}{\lambda_c} = \boxed{\mu M} \sim \mathcal{O}(0.01) - \mathcal{O}(1)$$

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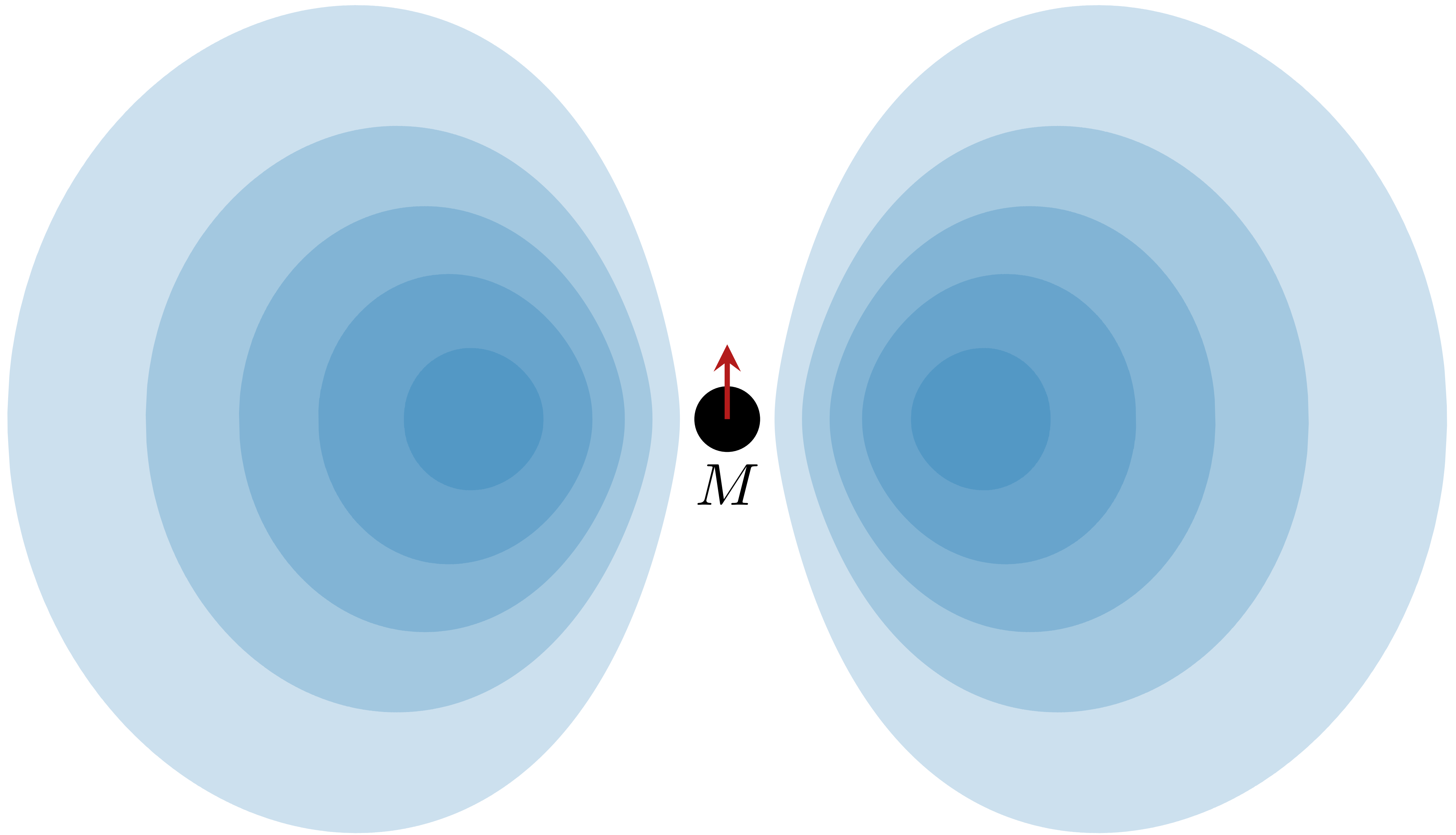

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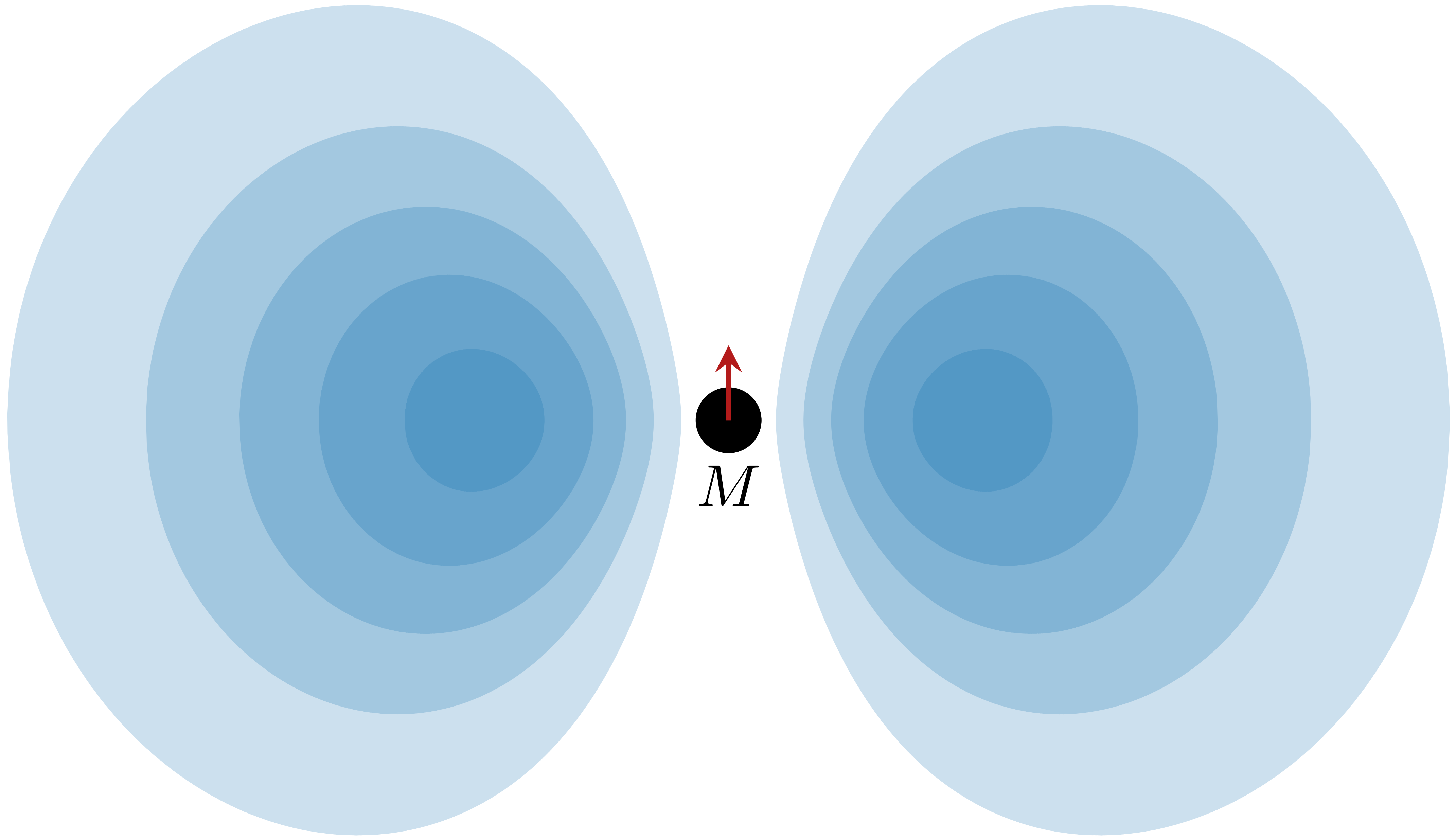


Axionic couplings to the **Maxwell sector:**

$$\mathcal{L} \supset k_{\mathrm{a}}\Psi\, {}^*F^{\mu\nu}F_{\mu\nu}$$

[Zeldovich '72], [Starobinsky '73], [Dolan '07], [Brito et al. '15]

Approach - Japanese Sake

Junmai - Full Bodied

Numerical Relativity

Honjozo - Fresh & Light

Analytic Estimates

Axionic couplings - no SR

Maxwell equations:

$$\nabla^\nu F_{\mu\nu} = -2k_{\rm a}\tilde{F}_{\mu\nu}\nabla^\nu\Psi$$

Flat space + Homogeneous axion condensate →

Mathieu equation:

$$\partial_T^2 y + \left(\omega^2/\mu^2 + 2k_{\rm a}\Psi_0\omega/\mu\cos T\right) y = 0$$

▼

Parametric instabilities:

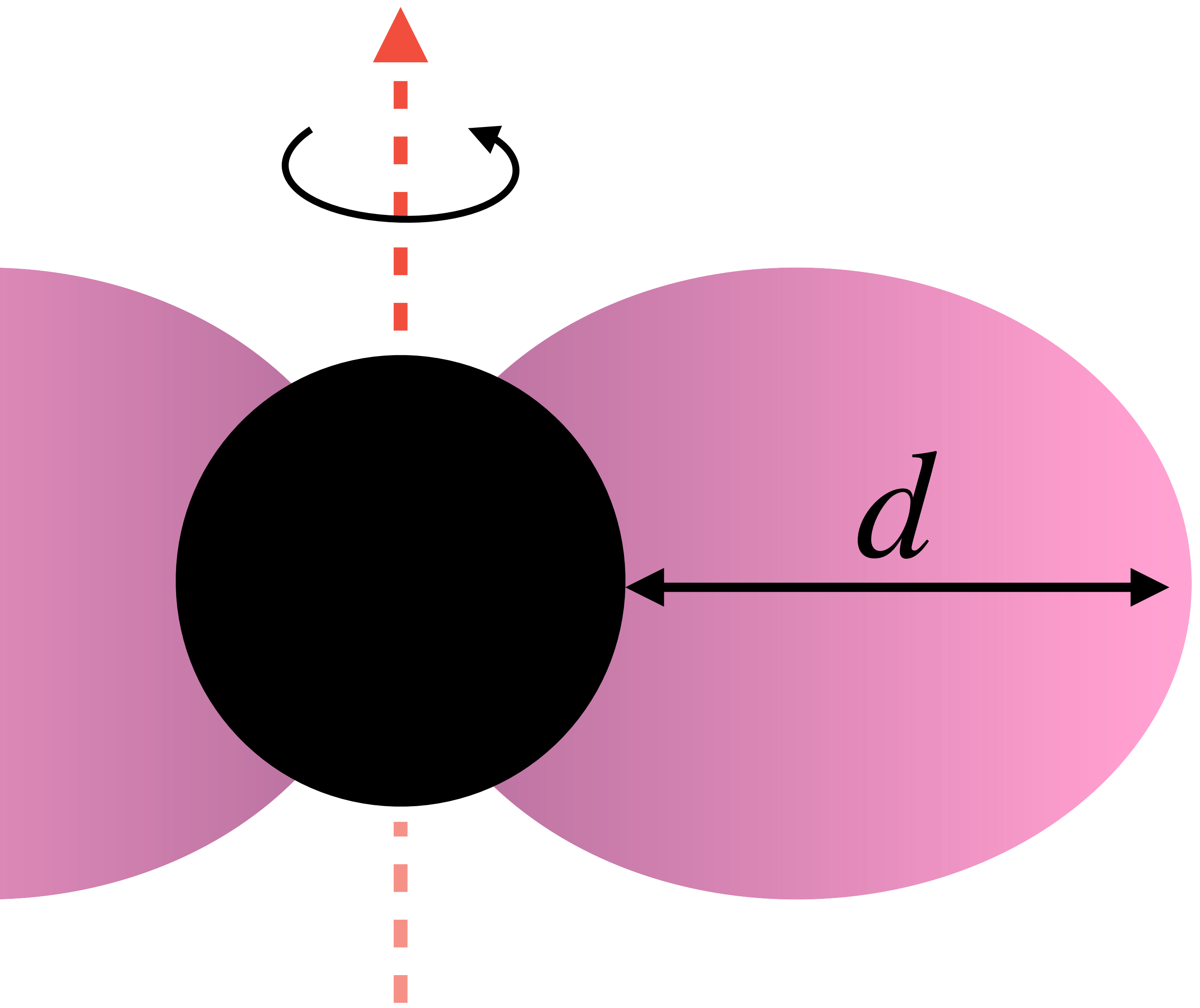
$$\lambda_* = \frac{1}{2}\omega_* k_{\rm a}\Psi_0$$

$$\omega_* = \{\mu/2,\ \mu,\ 3\mu/2,\ \cdots\}$$

[Hertzberg, Schappacasse '19], [Boskovic et al. '19], [Ikeda et al. '19]

Axionic couplings - no SR

Compared to the previous case, there are now **finite-size** effects related to the time needed for photons to leave the cloud



Depending on μM and $k_{\rm a}\Psi_0$, there exist **two** regimes

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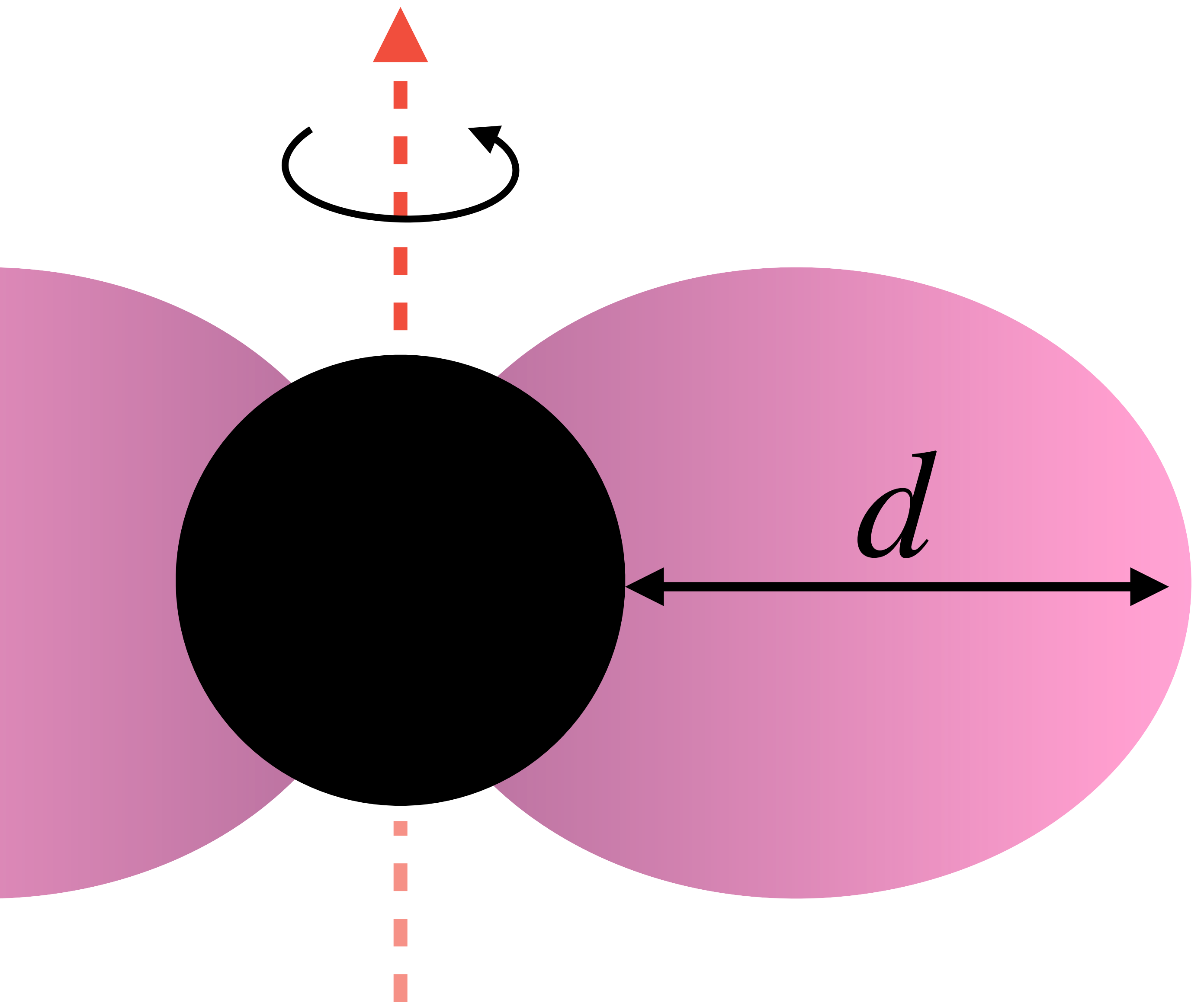


Depending on μM and $k_a \Psi_0$, there exist **two** regimes

In the *subcritical* regime, photons **leave** the system before the instability ensues

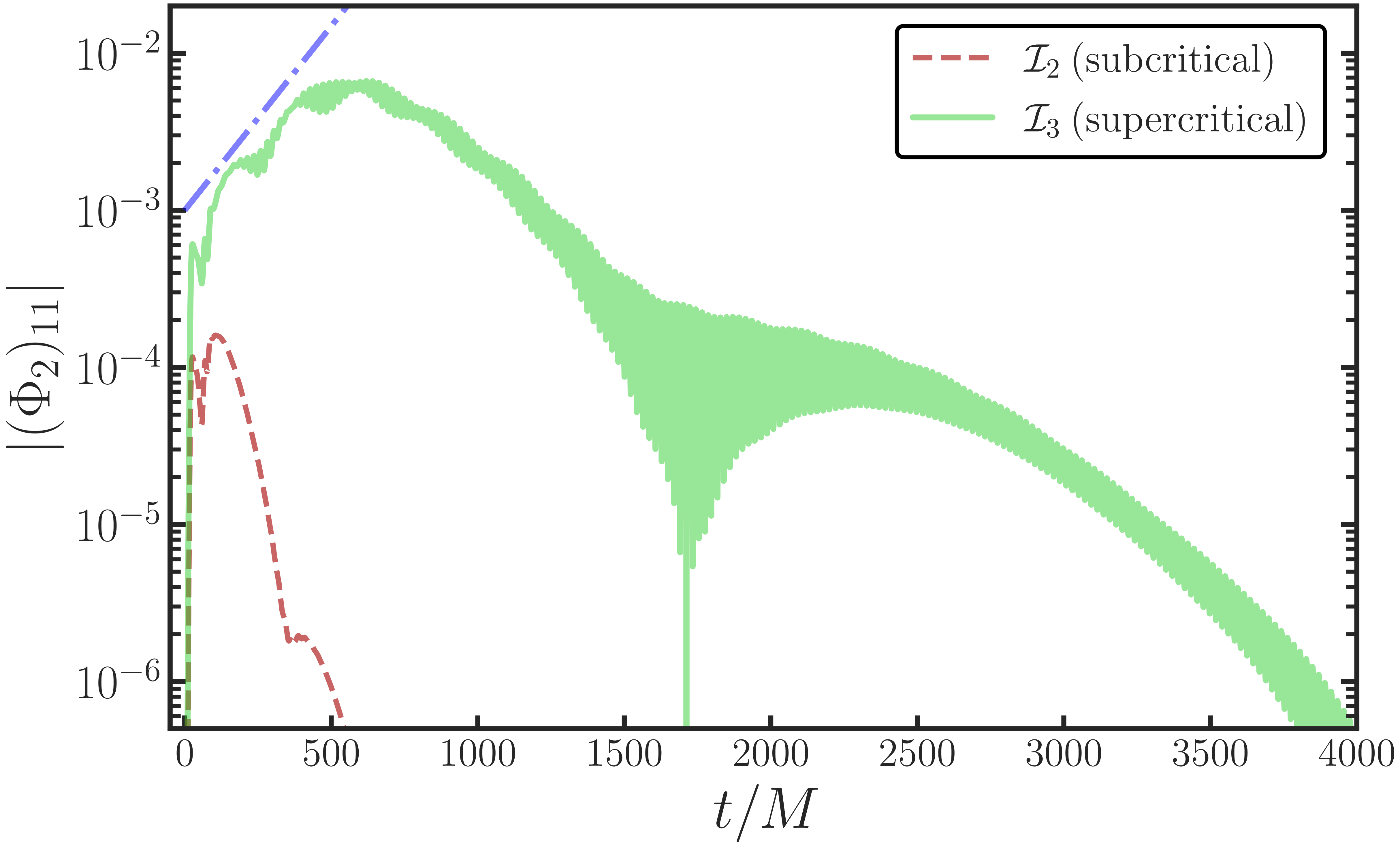
$$\lambda_{\rm esc} \sim \frac{1}{d} > \mu k_a \Psi_0 \sim \lambda_*$$

Conversely, in the *supercritical* regime, a **large quantity** of photons is built up inside the cloud, triggering an **exponential growth**

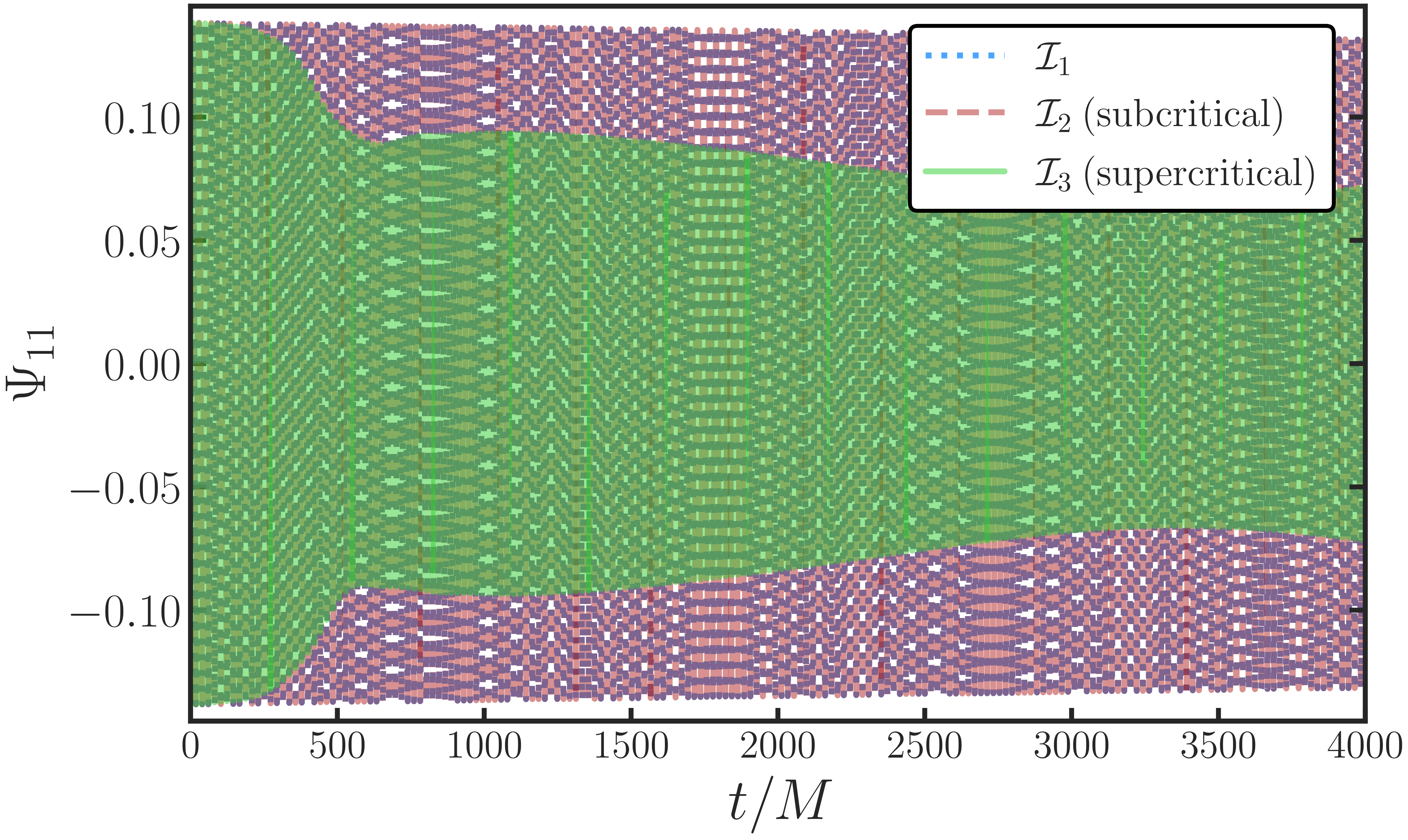
[Rosa, Kephart '18], [Boskovic et al. '19], [Ikeda et al. '19]

Axionic couplings - no SR

EM **field**

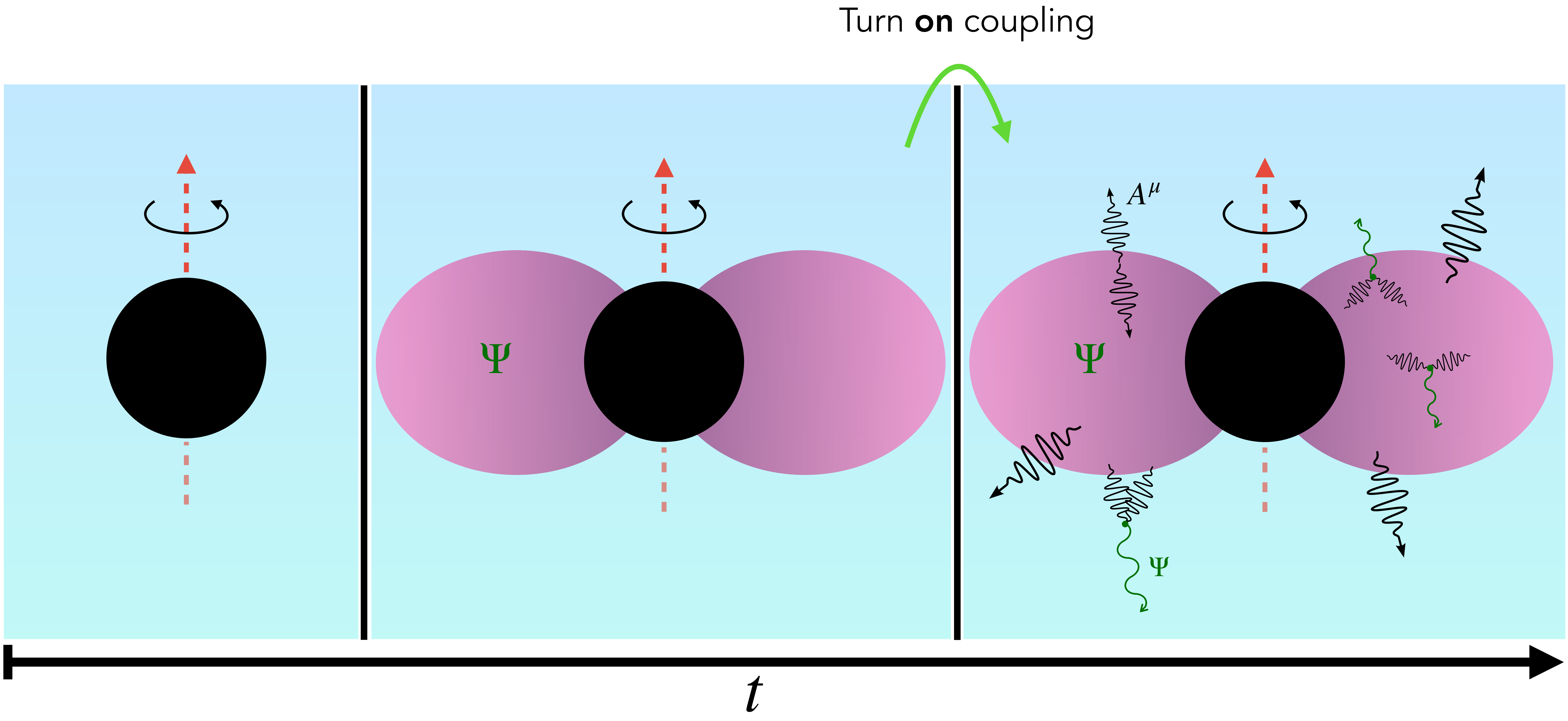


Axion **field**

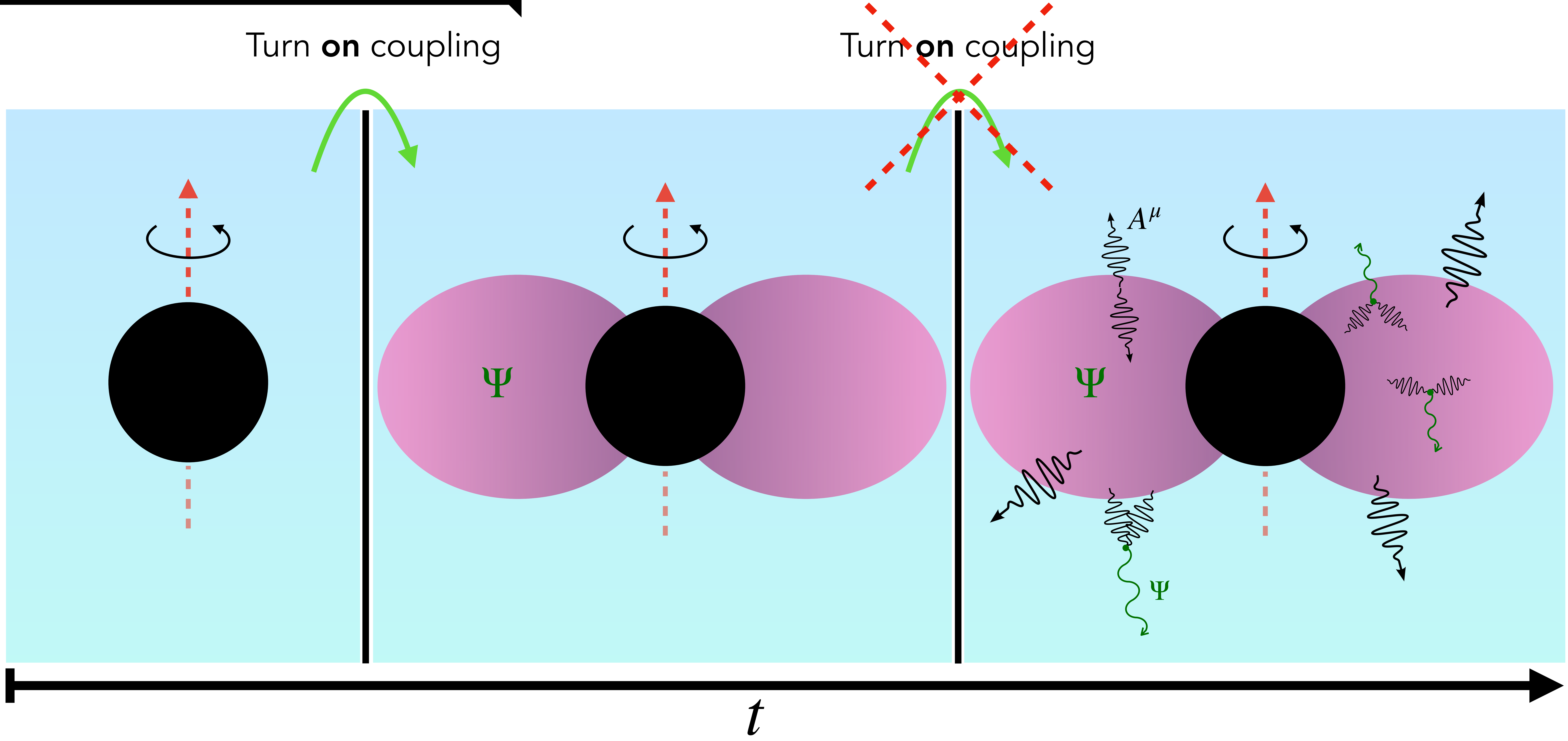


[Spieksma et al. '23]

Axionic couplings - no SR

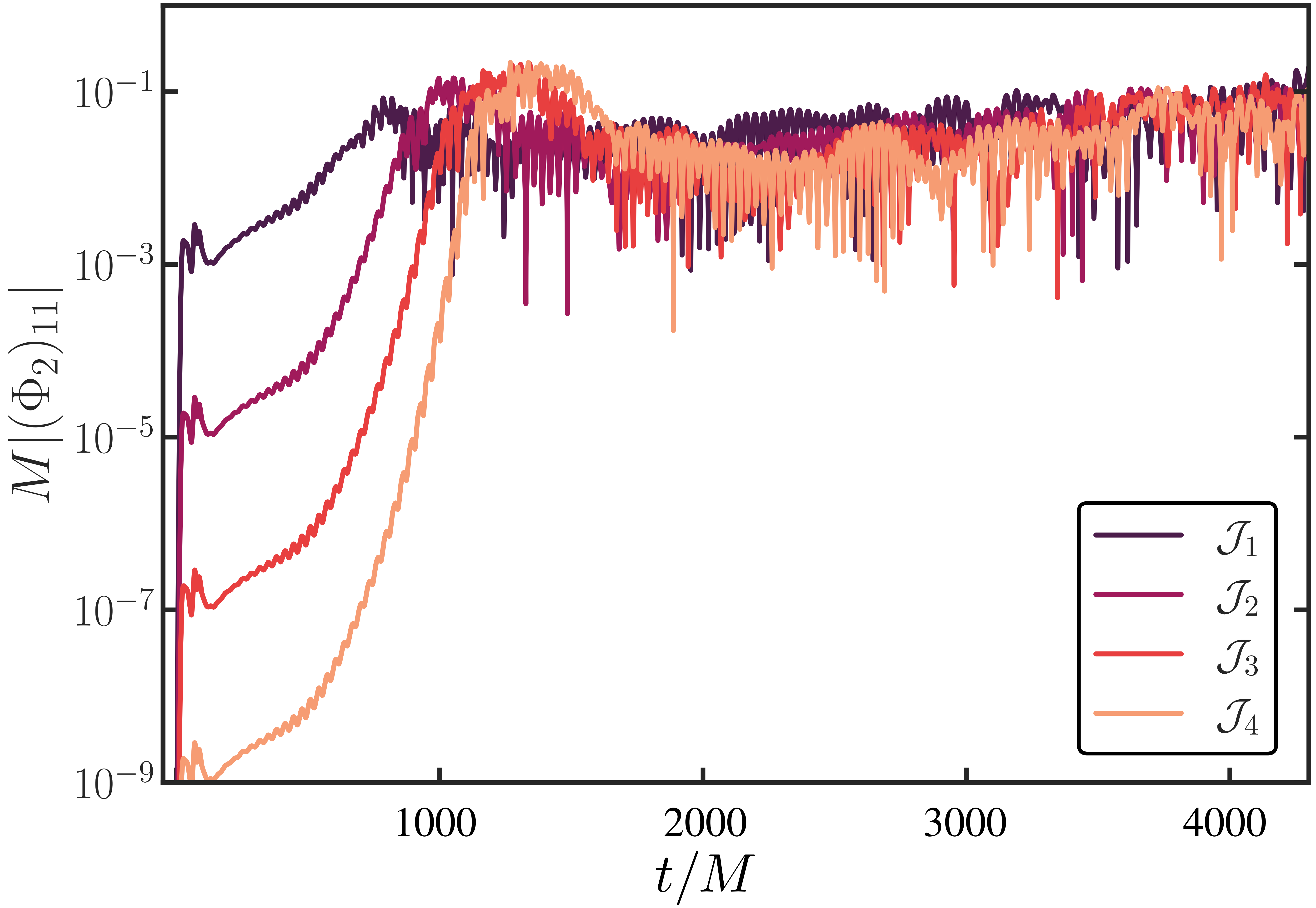


Axionic couplings - no SR



Axionic couplings - with SR

Energy outflow from EM radiation and axion production balance → **Saturation phase**



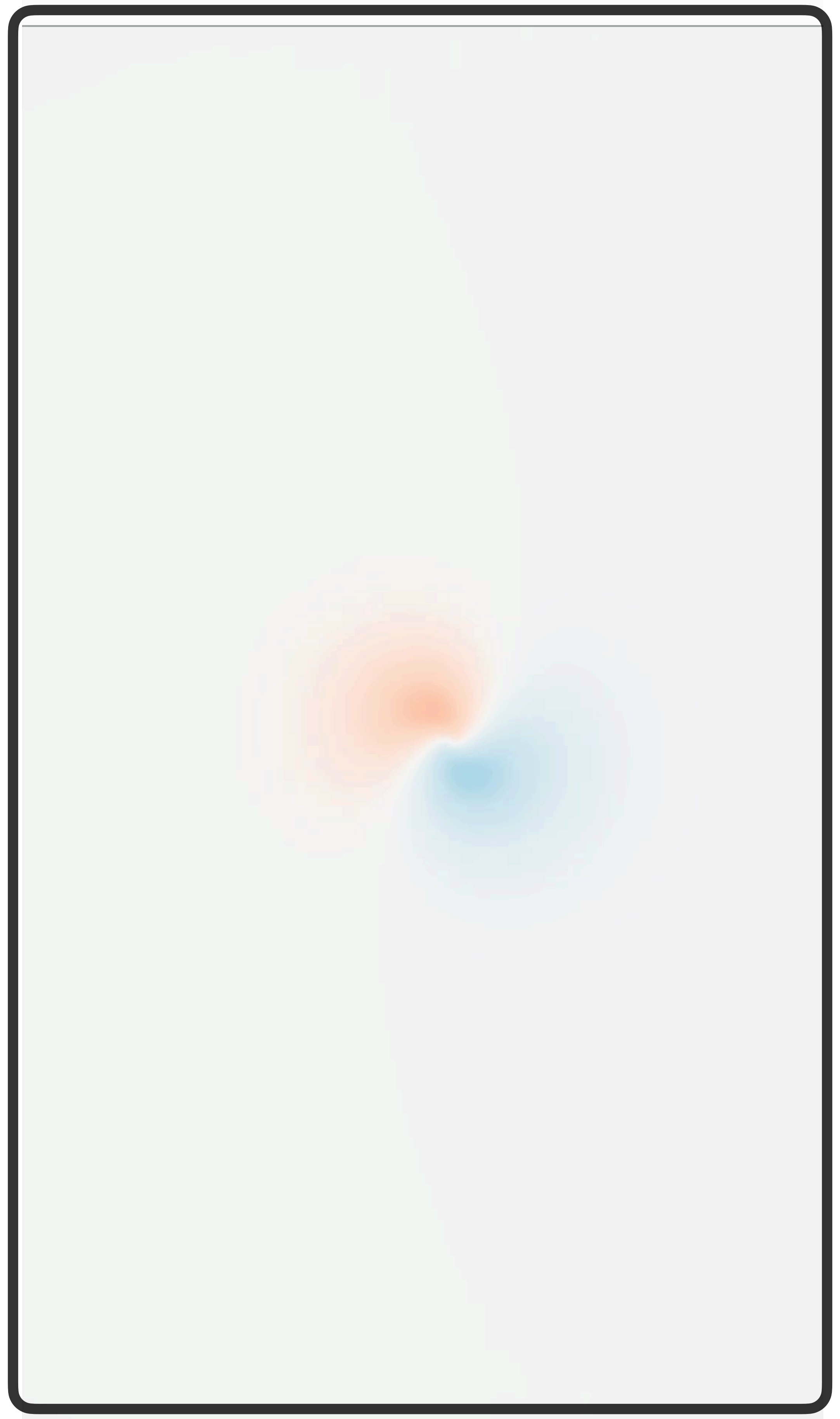
$$\lambda_{\rm SM} = \frac{\mu}{2} k_{\rm a} \Psi_0 e^{Ct/2}$$

→ Varying initial EM perturbation

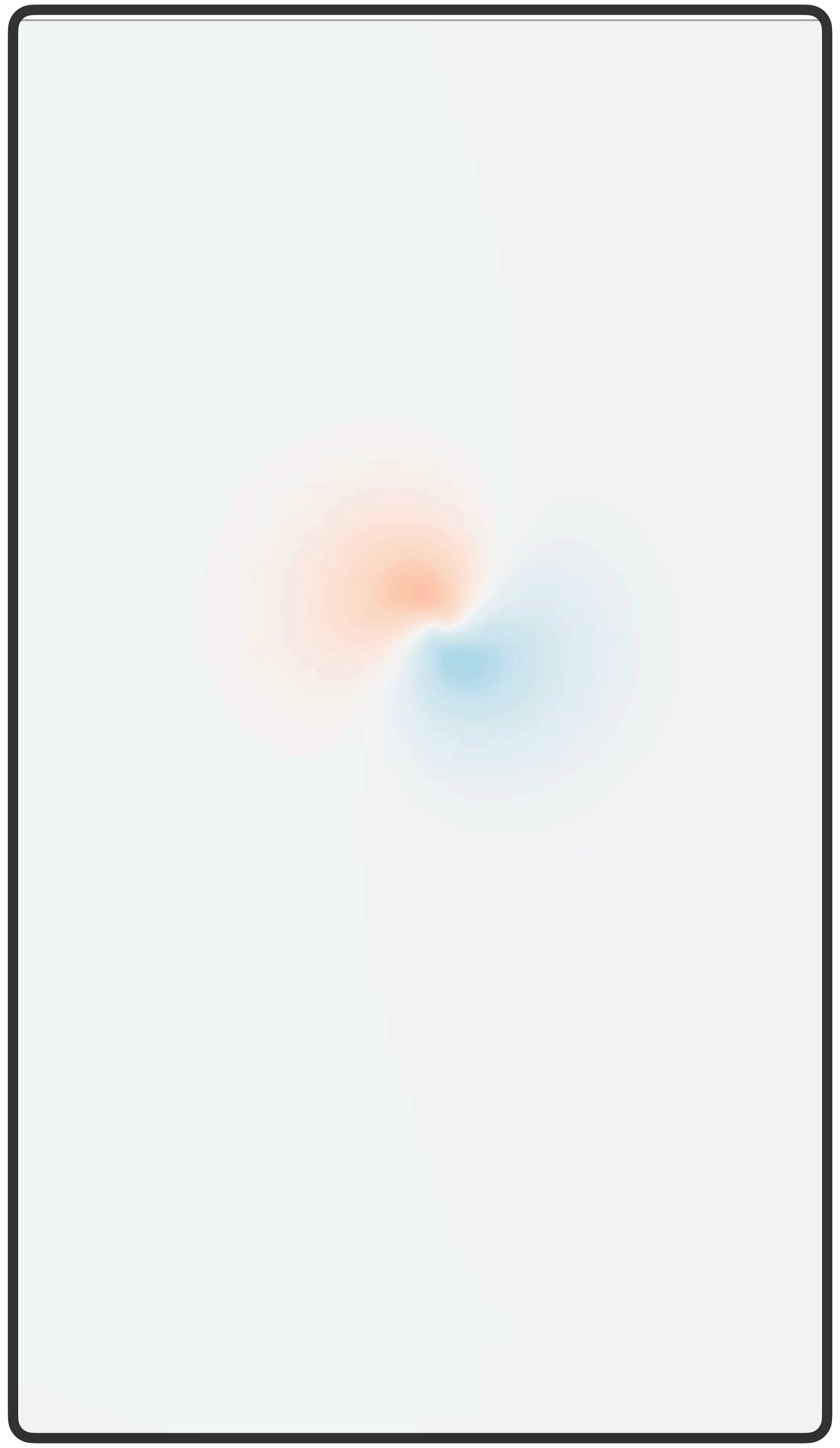
[Spieksma et al. '23]

Axionic couplings - summary

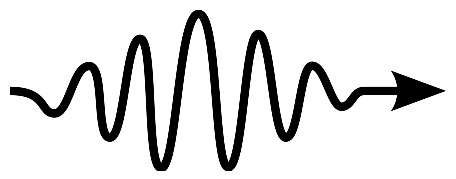
No SR growth
Subcritical



Including SR growth



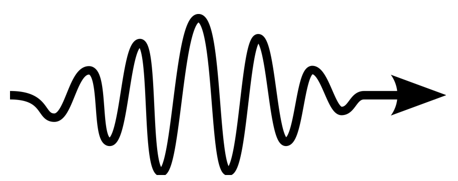
Observational signatures



$$\frac{\mathrm{d}E}{\mathrm{d}t} \approx 8.1 \times 10^{40} \left(\frac{a_{\mathrm{J}}/M}{1}\right) \left(\frac{\mu M}{0.2}\right)^7 \left(\frac{10^{-13}\mathrm{GeV}^{-1}}{k_{\mathrm{a}}}\right)^2 \mathrm{erg/s}$$

- High luminosity
- Monochromatic
- (Nearly) Constant
- Multimessenger signal

Observational signatures



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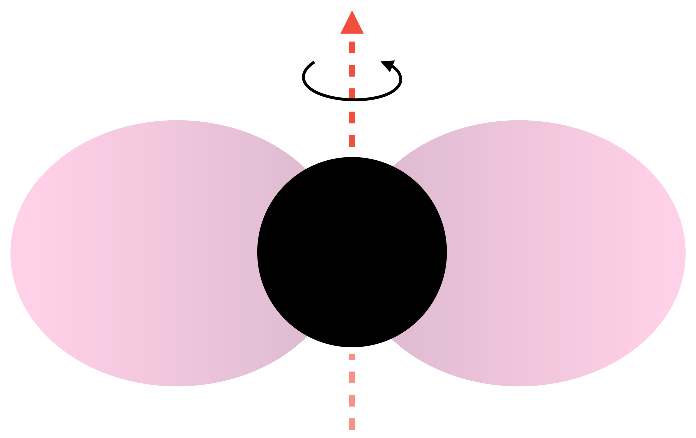
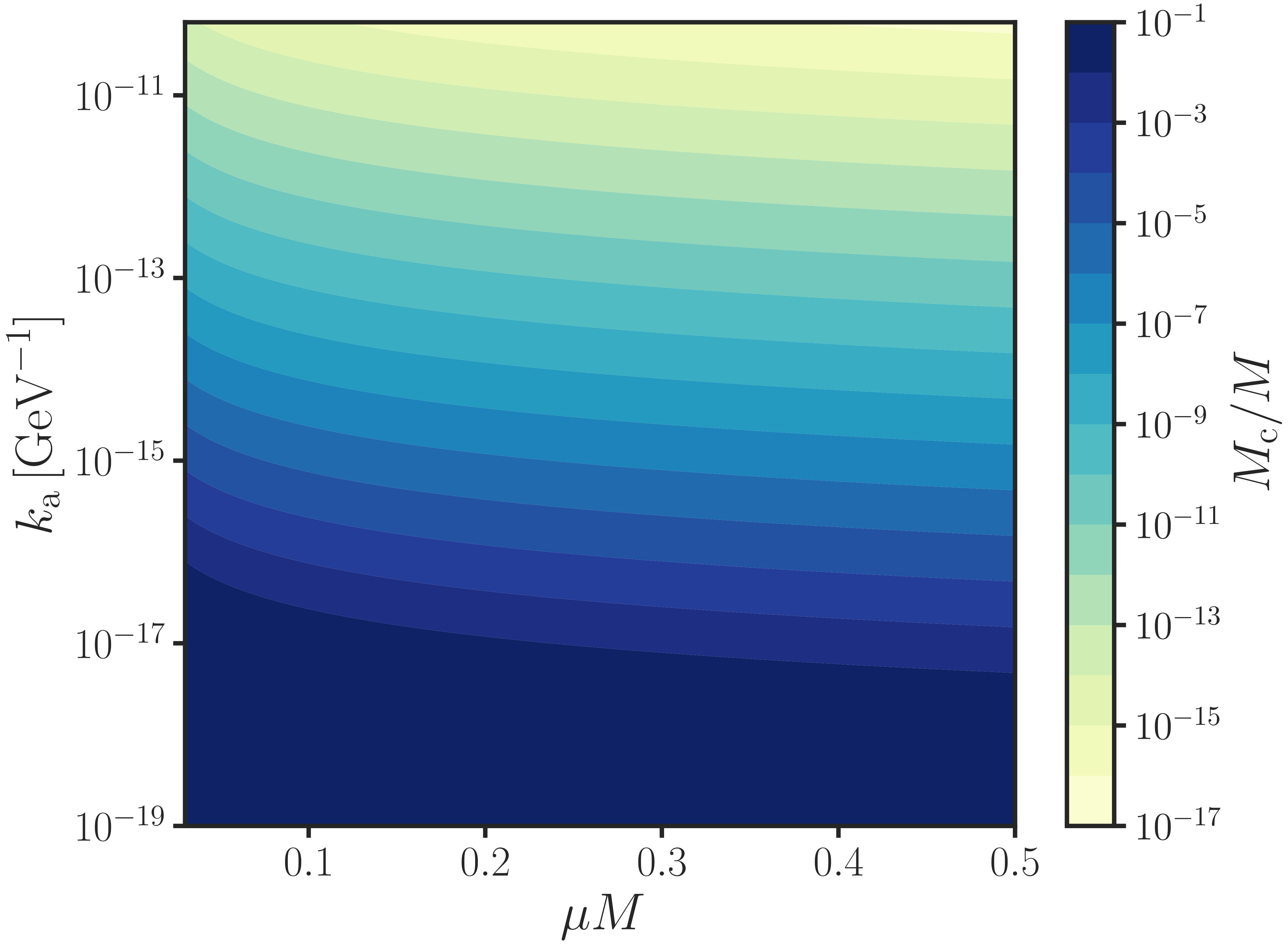
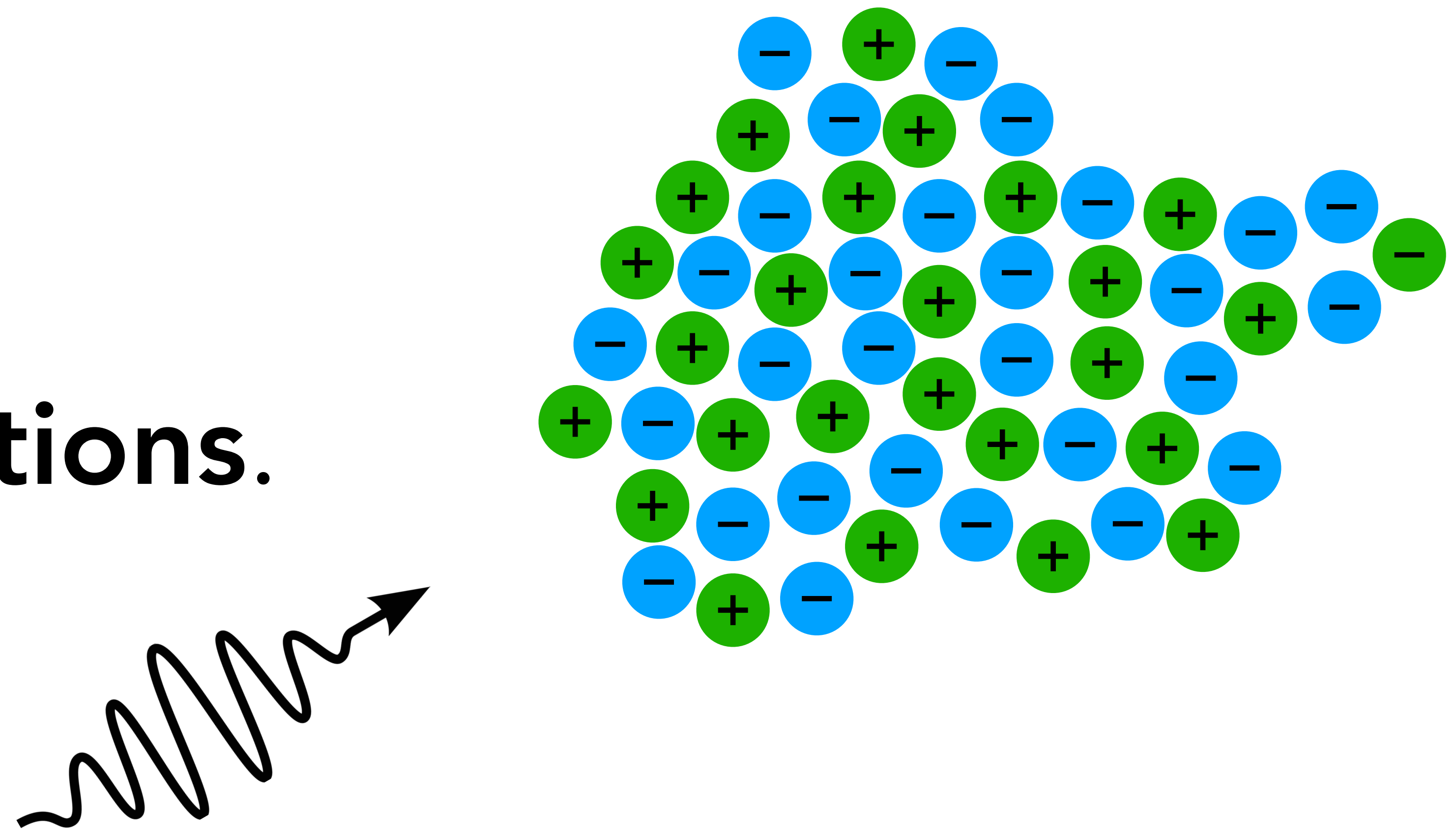




[Spieksma et al. '23]

Plasma effects

We adopt a **two-fluid formalism**, where **electrons** and **ions** are treated as separate fluids, coupled through the **Maxwell equations**.



If a **plasma** is perturbed by an **EM wave**, electrons are displaced and start **oscillating** with the **plasma frequency**

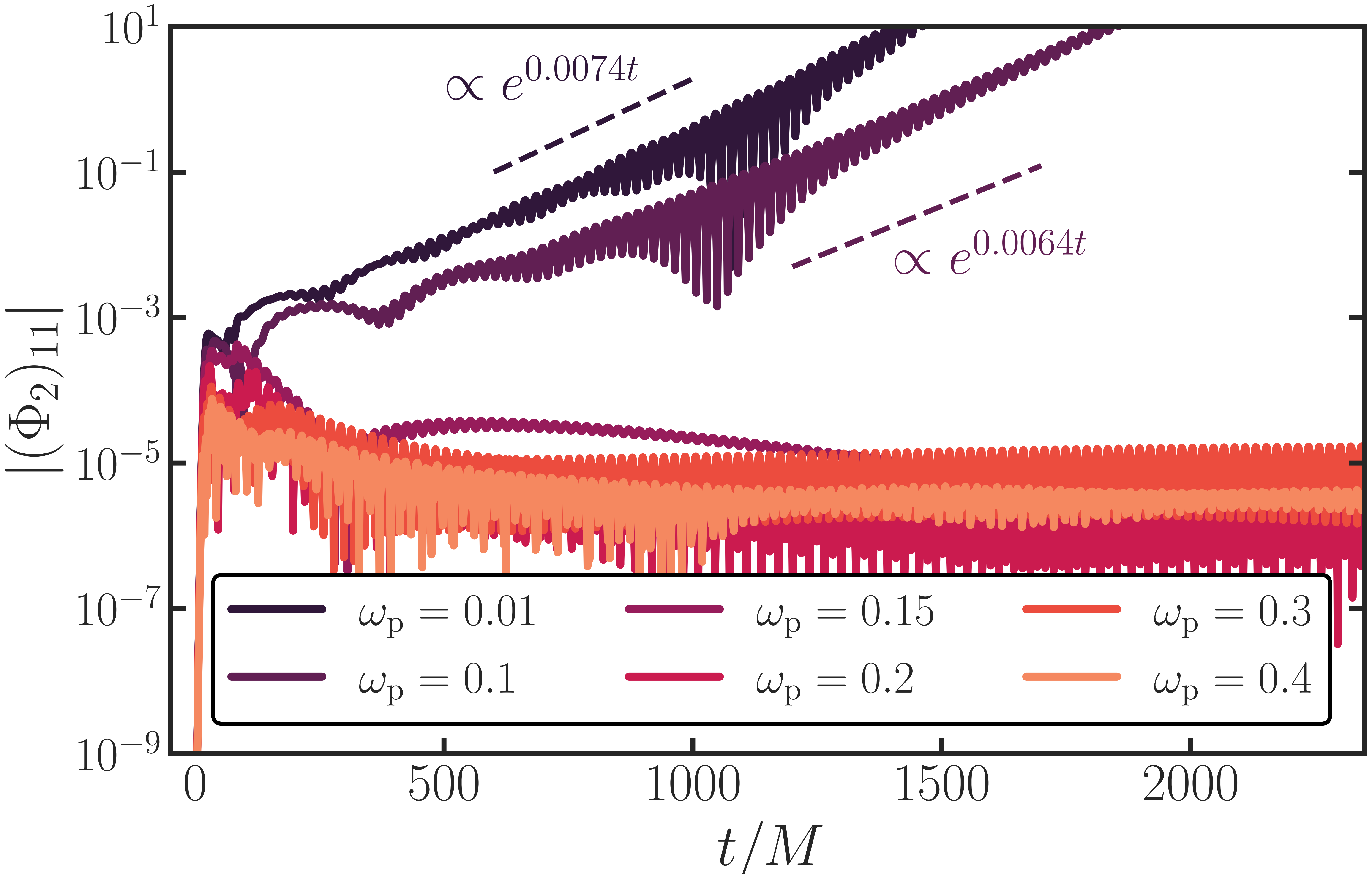
$$\omega_{\rm p} = \sqrt{\frac{n_e q_e^2}{m_e}} \approx 10^{-12}\sqrt{\frac{n_e}{10^{-3}{\rm cm}^{-3}}}\,{\rm eV}$$

Plasma effects

A burst is highly **suppressed** when

$$\omega_{\rm p} > \mu/2$$

$\mu M = 0.3$



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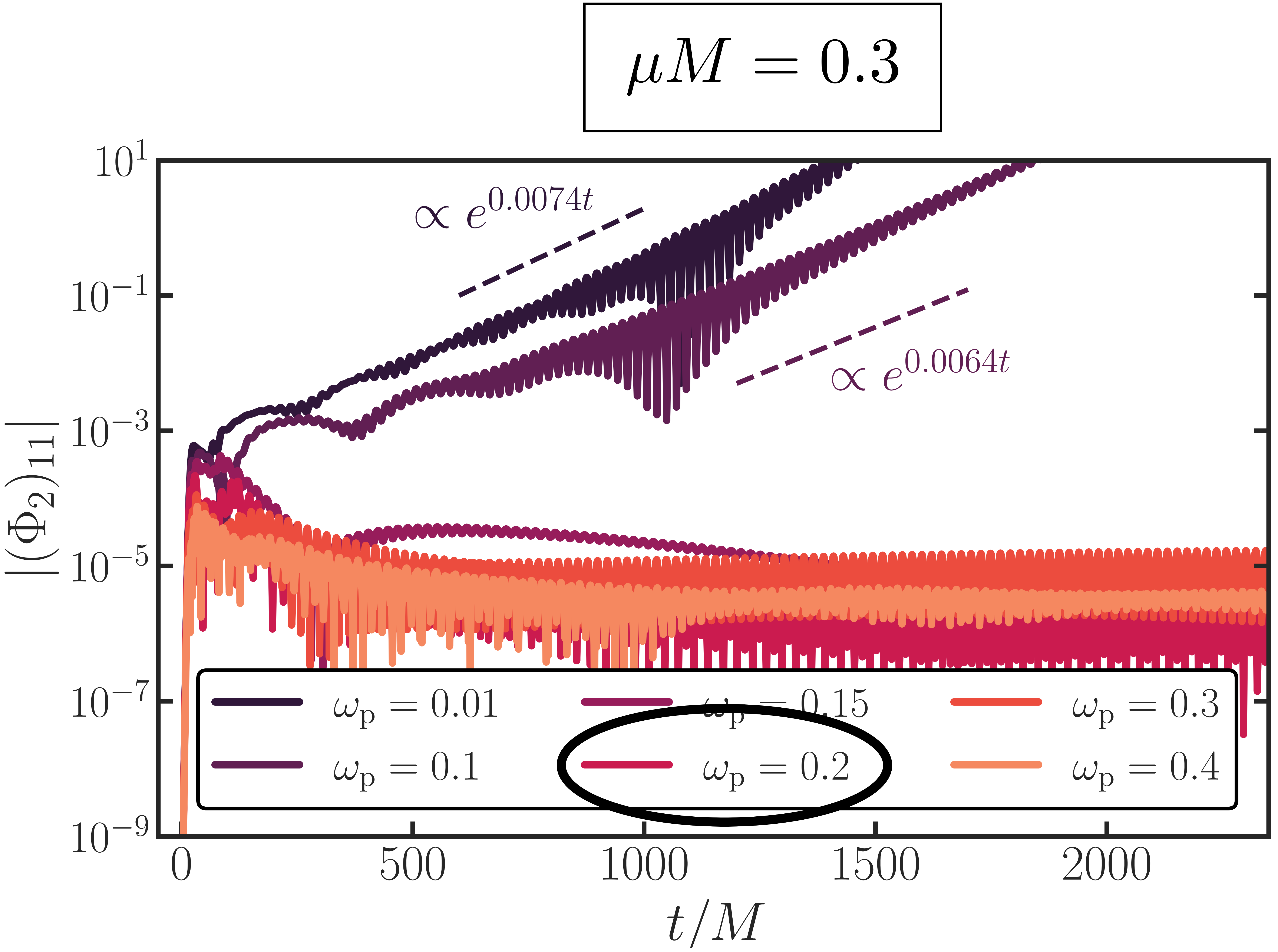
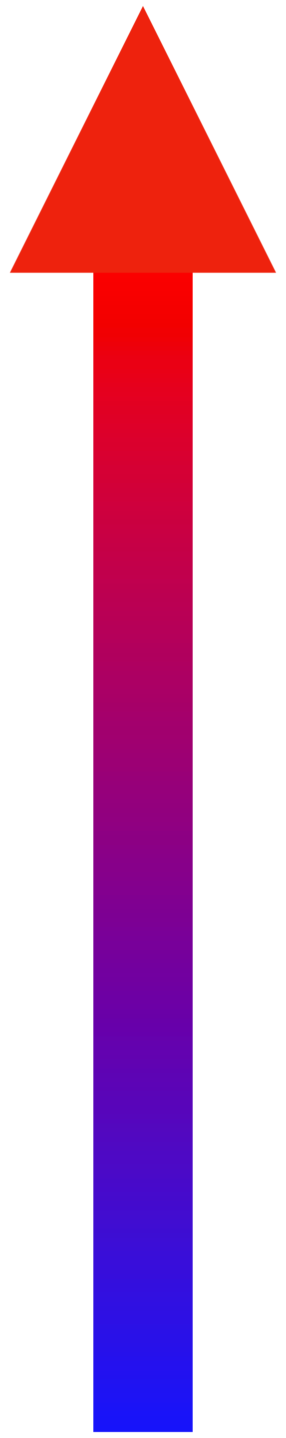
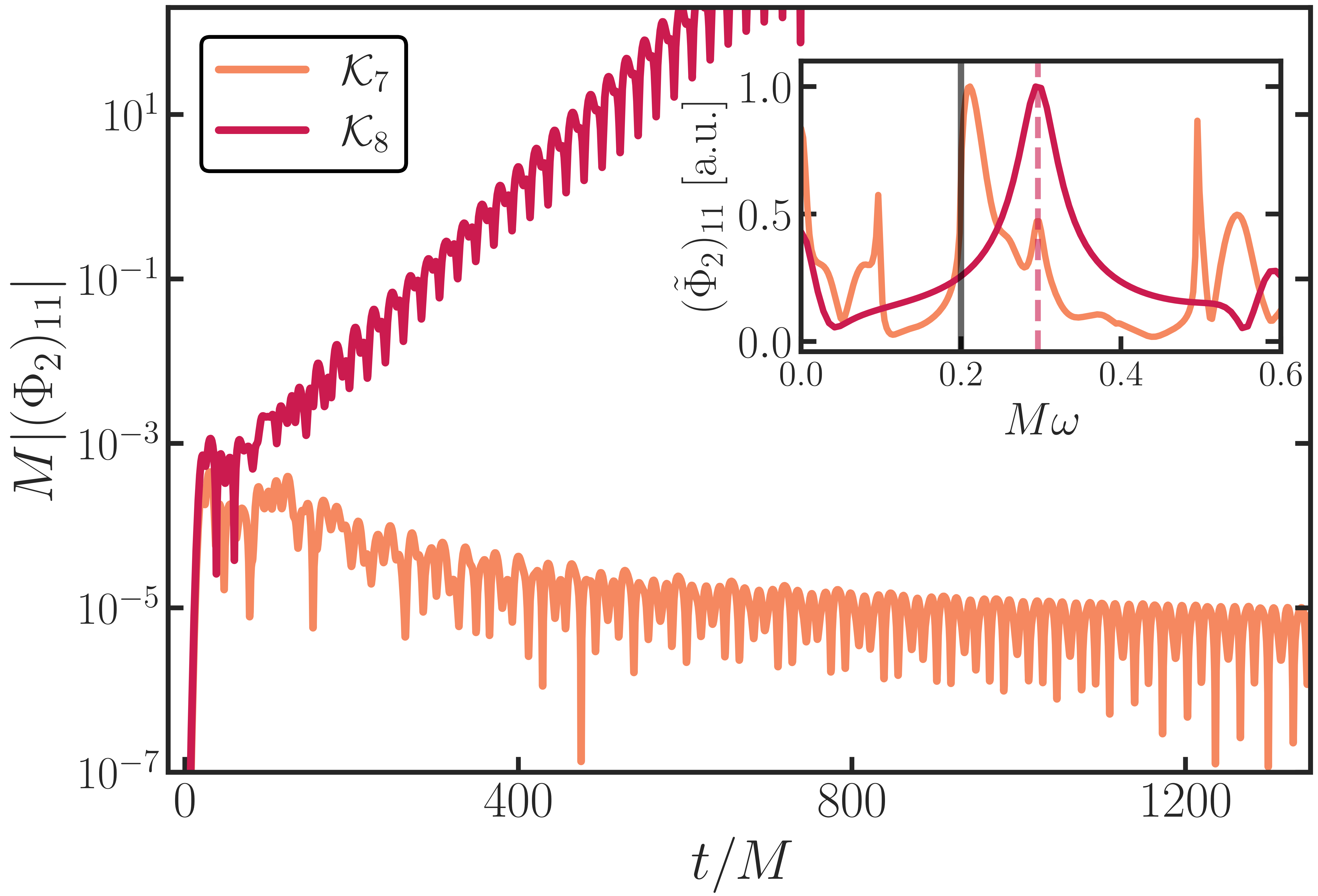


Plasma effects

$\mu M = 0.3$

$k_{\rm a}\Psi$





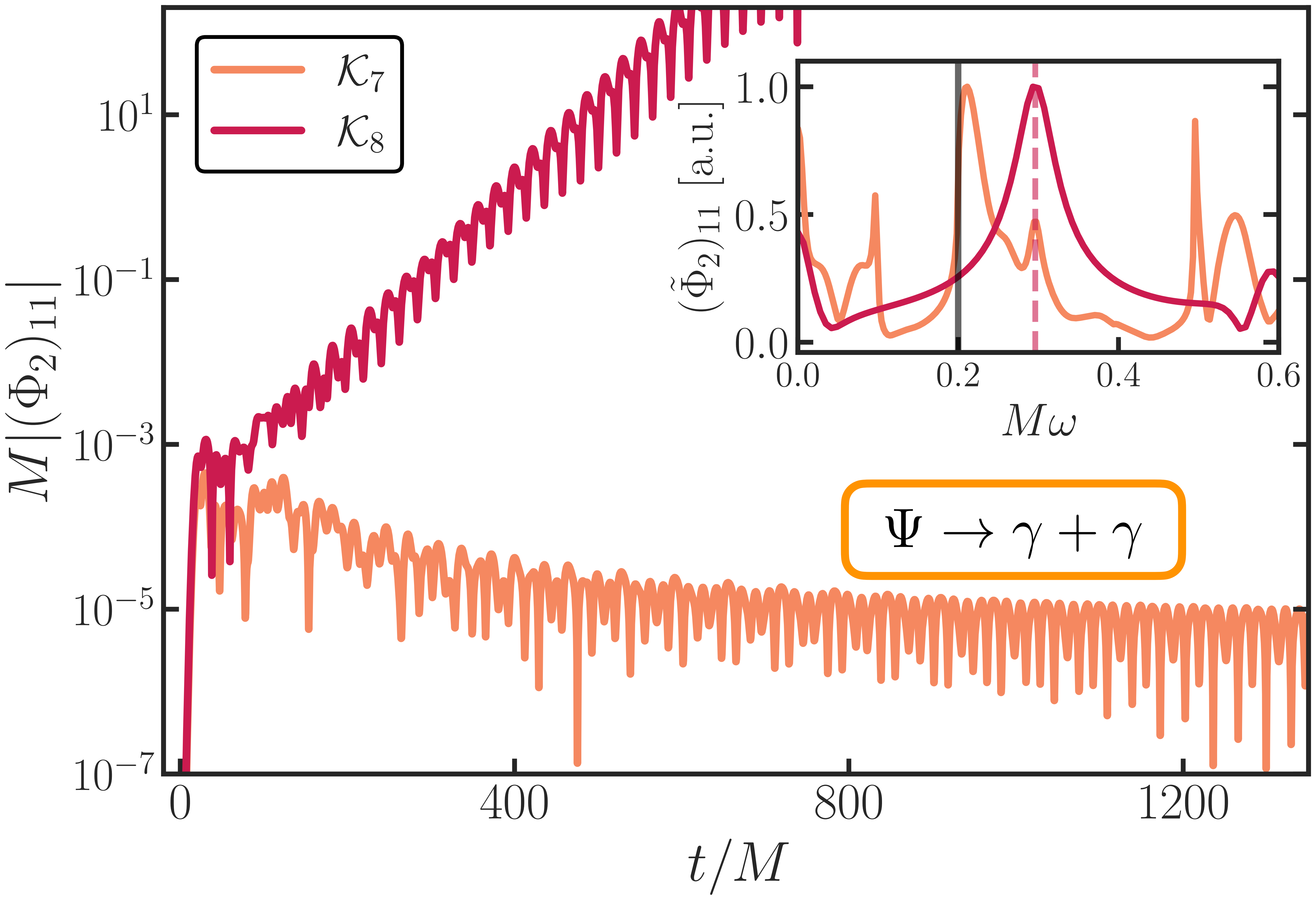
[Spieksma et al. '23]

Plasma effects

$k_{\rm a}\Psi$

$\mu M = 0.3$

$\Psi + \Psi \to \gamma + \gamma$

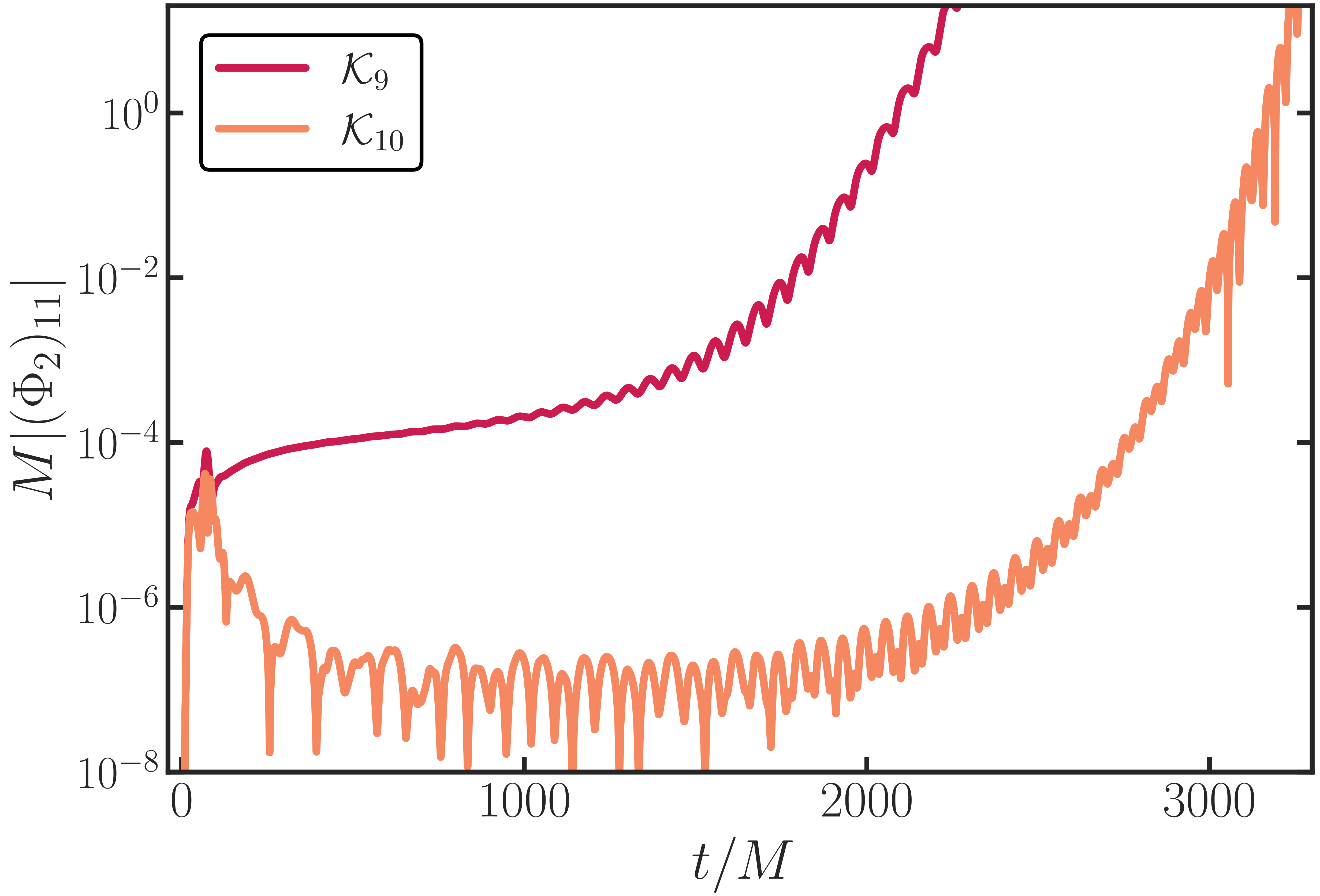


$\Psi \to \gamma + \gamma$

[Spieksma et al. '23]

Plasma effects

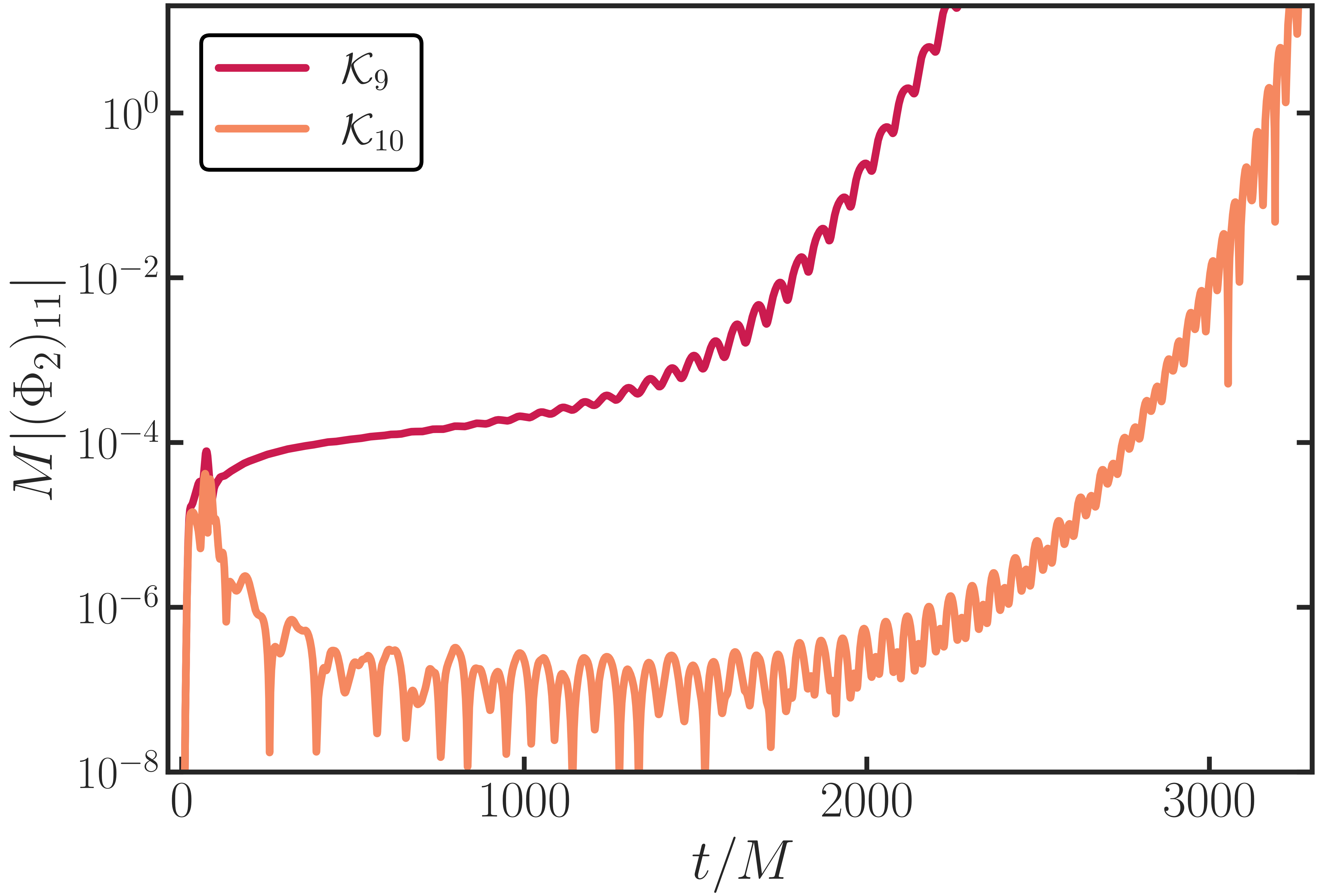
Superradiance to the **rescue**!



[Spieksma et al. '23]

Plasma effects

Superradiance to the **rescue**!



Mathieu equation predicts when an **instability** occurs:

$$\frac{10^{-13}\ \mathrm{GeV}^{-1}}{k_\mathrm{a}} \lesssim 8\times 10^5 \left(\frac{10^{-3}\ \mathrm{cm}^{-3}}{n_\mathrm{e}}\right)\left(\frac{M_\mathrm{c}/M}{0.1}\right)^{1/2} \times \left(\frac{1M_\odot}{M}\right)^2\left(\frac{\mu M}{0.2}\right)^4$$

Instabilities still triggered for plasmic environments way denser than interstellar medium!

Conclusions

- A **growing** SR cloud that is coupled to the **EM field** gives rise to a **constant EM flux**
- This could lead to a potentially detectable **EM signal,** while influencing **the mass of the cloud**
- Even in the presence of **plasma**, these bursts can be **initiated** and **propagated**

Conclusions & Outlook

- A **growing** SR cloud that is coupled to the **EM field** gives rise to a **constant EM flux**
- This could lead to a potentially detectable **EM signal,** while influencing **the mass of the cloud**
- Even in the presence of **plasma**, these bursts can be **initiated** and **propagated**

- The geometry of realistic plasmic environments
- Non-linear dynamics of axion-photon-plasma system

Additional slides

Initial data

Constraint equations:

$$D_i B^i = 0\,,$$
$$D_i E^i = \rho - 2k_{\rm a} B_i D^i \Psi\,,$$
$$(n^\mu + \mathcal{U}^\mu)\nabla_\mu \Gamma_{\rm e} = \Gamma_{\rm e}\mathcal{U}^i\mathcal{U}^j K_{ij} - \Gamma_{\rm e}\mathcal{U}^i a_i - \frac{q_{\rm e}}{m_{\rm e}} E^i \mathcal{U}_i$$

Scalar field (bound state constructed through Leaver):

$$\Psi_{\ell m} = e^{-i\omega t_{\rm BL}} S_{\ell m}\left(\theta_{\rm BL}\right) R_{\ell m}\left(r_{\rm BL}\right)$$

EM field (Gaussian):

$$E^r = E^\theta = \mathcal{A}_i = 0\,,$$
$$E^\varphi = E_0 e^{-\left(\frac{r-r_0}{\sigma}\right)^2} M$$

Plasma (assume quasi-neutrality):

$$\rho = -n_\mu (e n_{\rm e} u^\mu_{\rm e} - Z e n_{\rm ion} u^\mu_{\rm ion}) = e n_{\rm e} - Z e n_{\rm ion} = 0$$

[Spieksma et al. '23]

Artificial SR

$$\left(\nabla^{\mu}\nabla_{\mu} - \mu^2\right)\Psi = \boxed{C\frac{\partial \Psi}{\partial t}} + \frac{k_{\rm a}}{2}\,{}^{*}F^{\mu\nu}F_{\mu\nu}$$

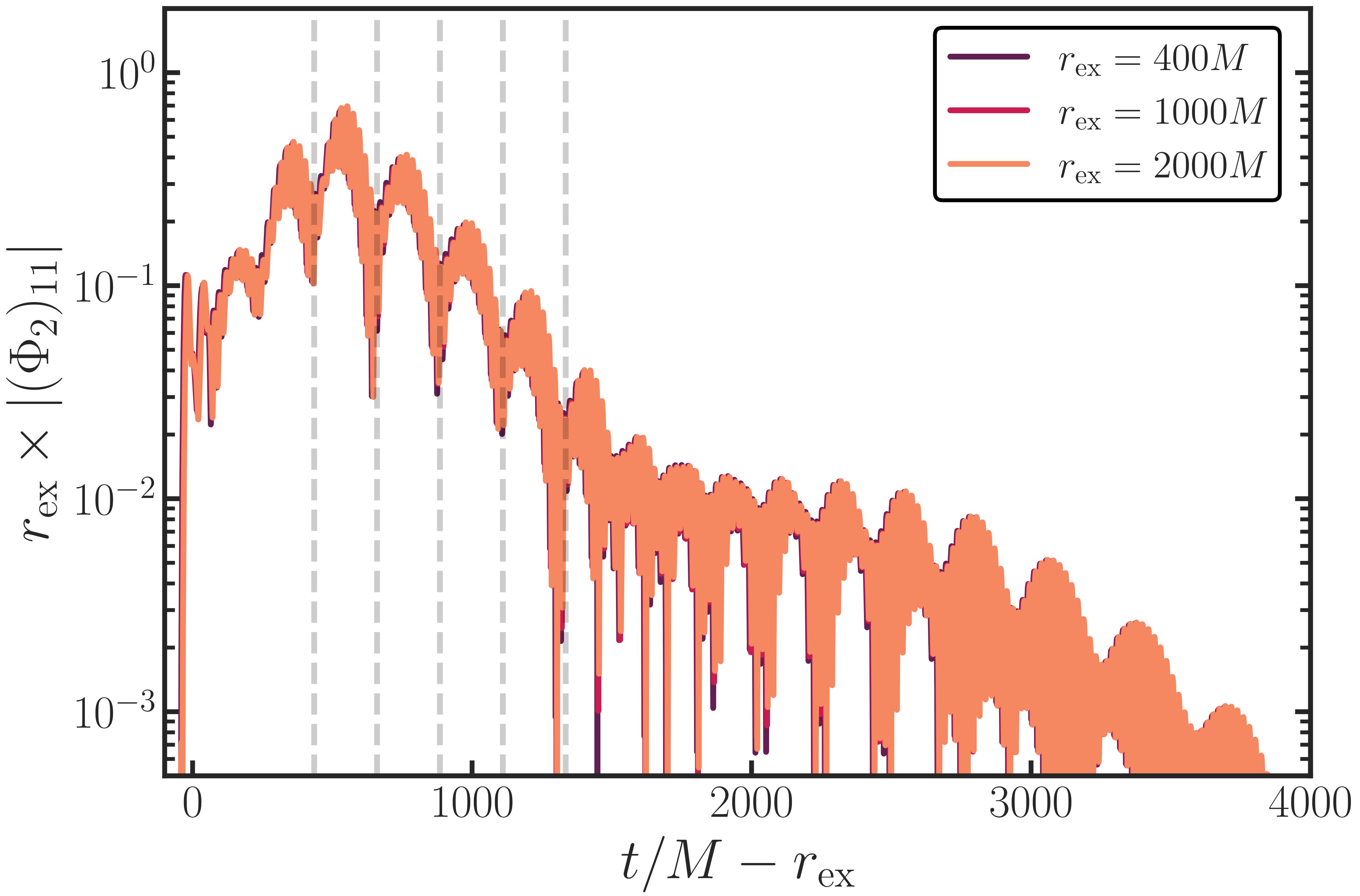
$$\Downarrow$$

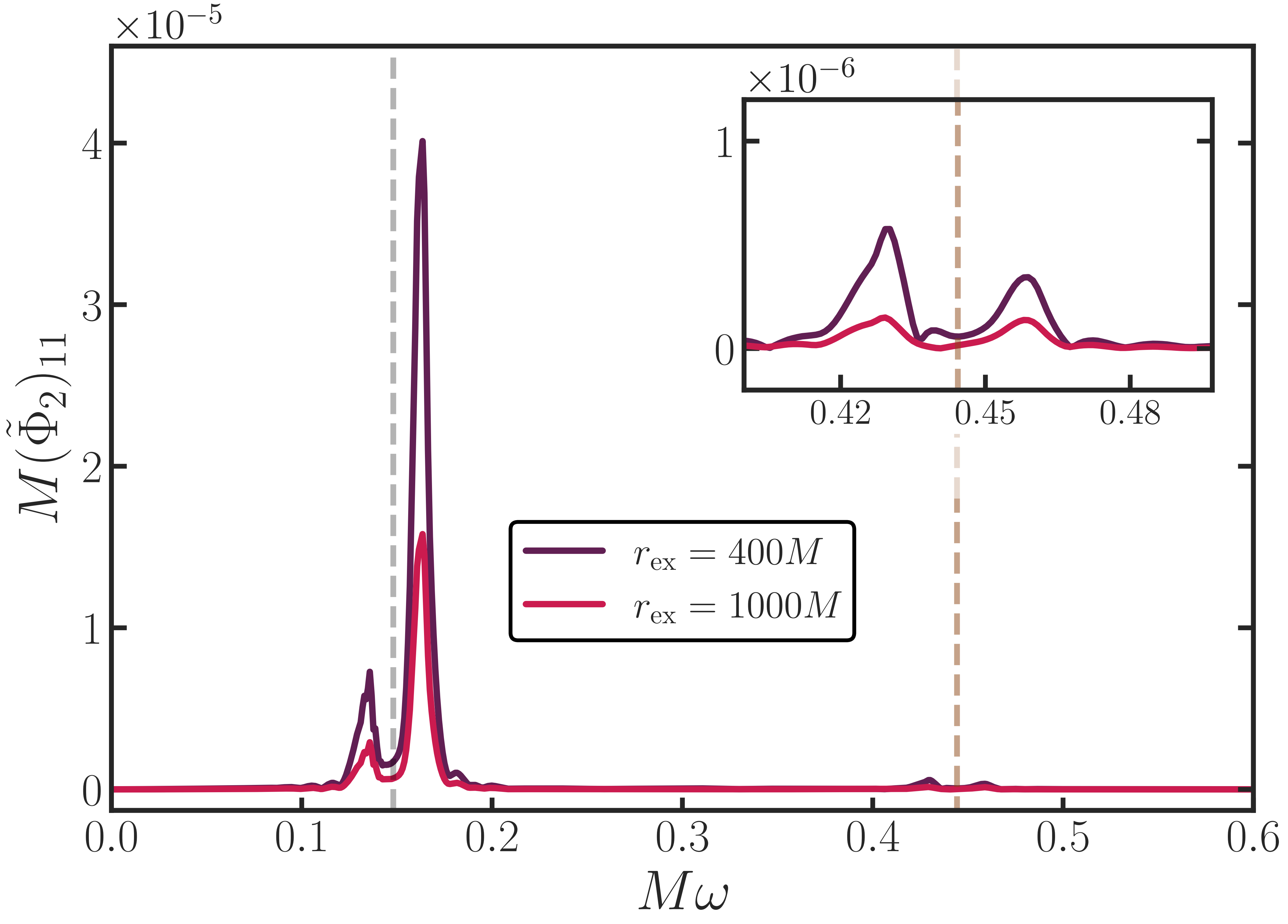
$$t_{\rm instability} \sim 1/C$$

[Spieksma et al. '23]

Axionic couplings - no SR - large radii

EM field

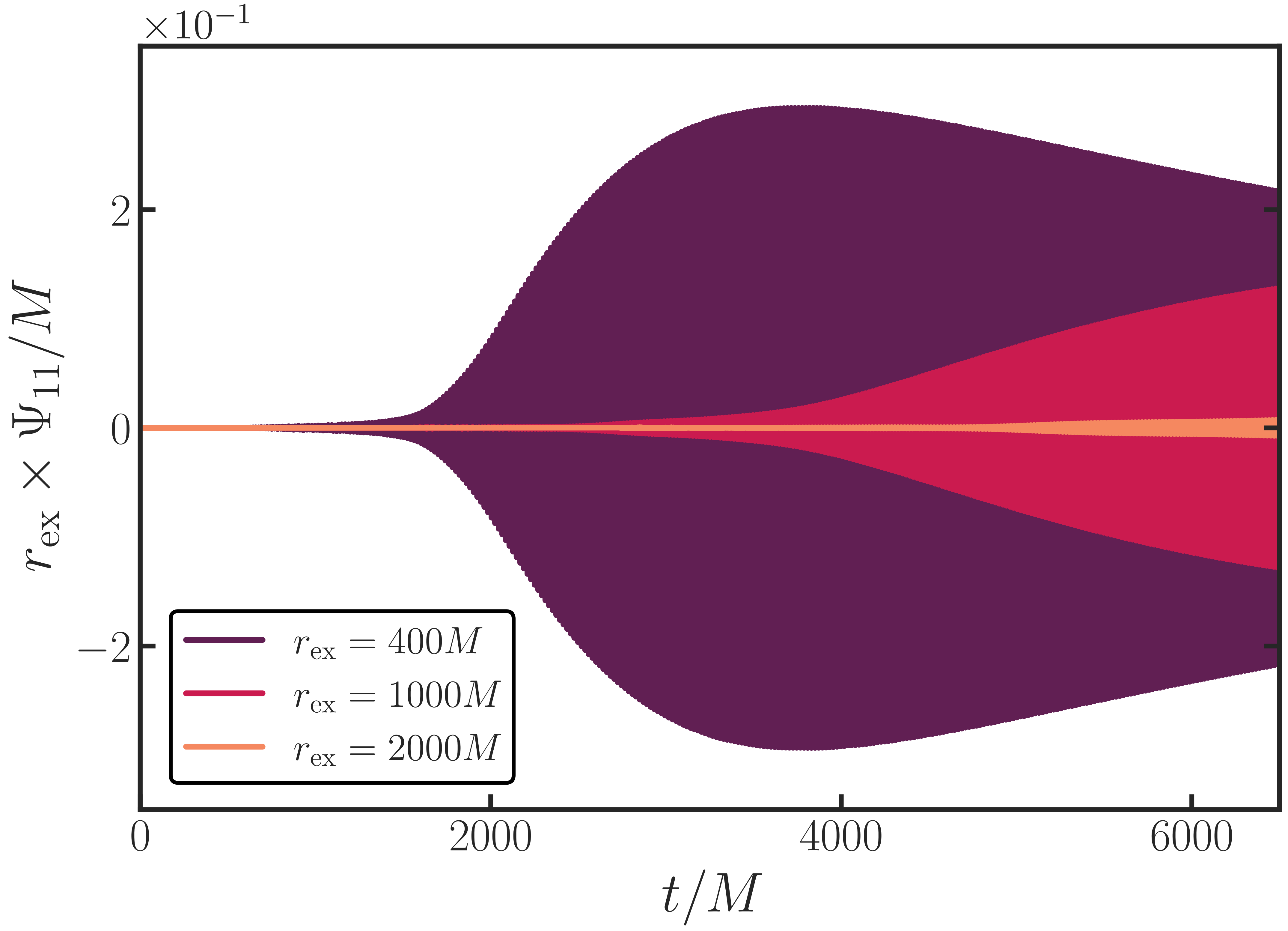


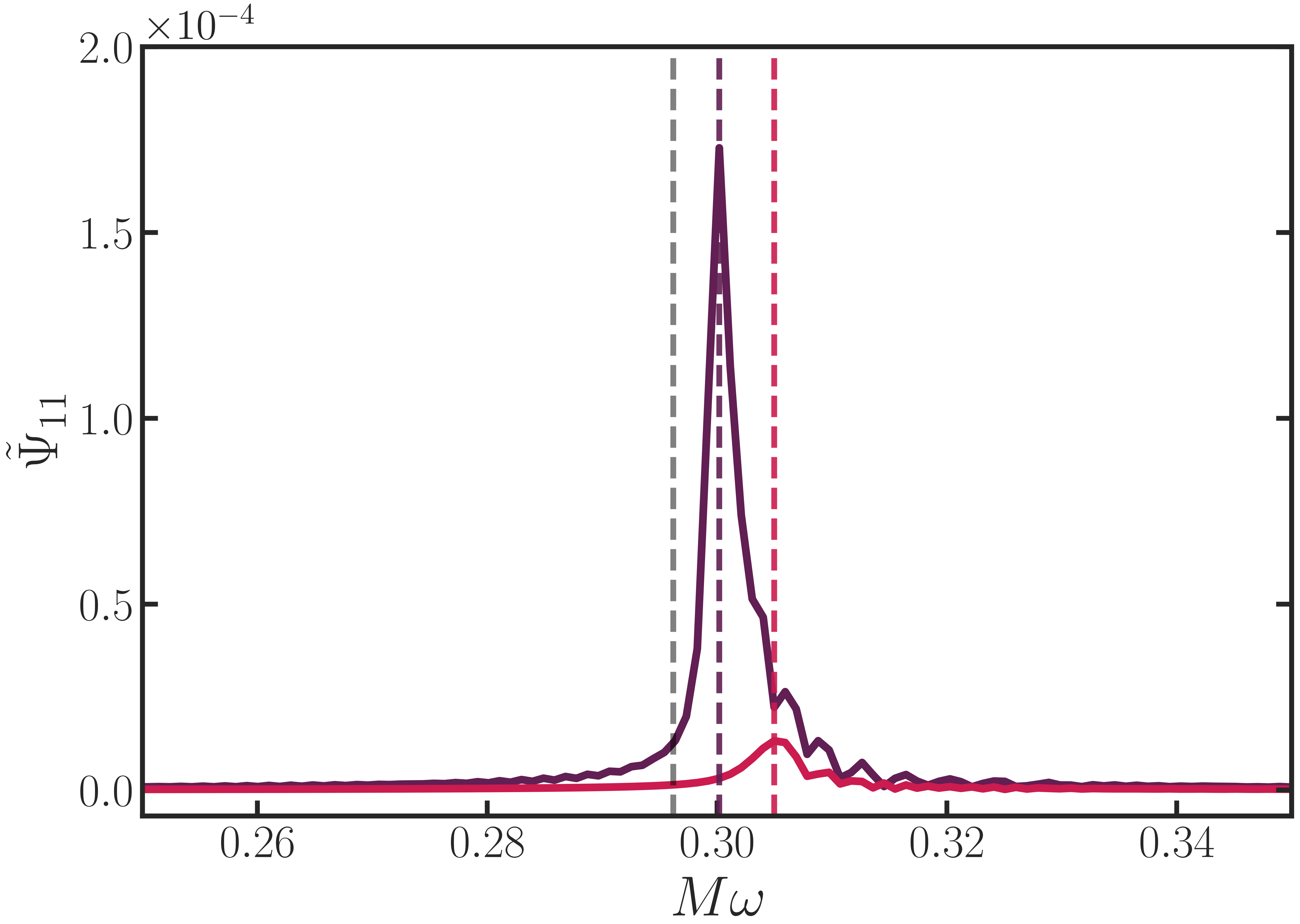


[Spieksma et al. '23]

Axionic couplings - no SR - axion emission

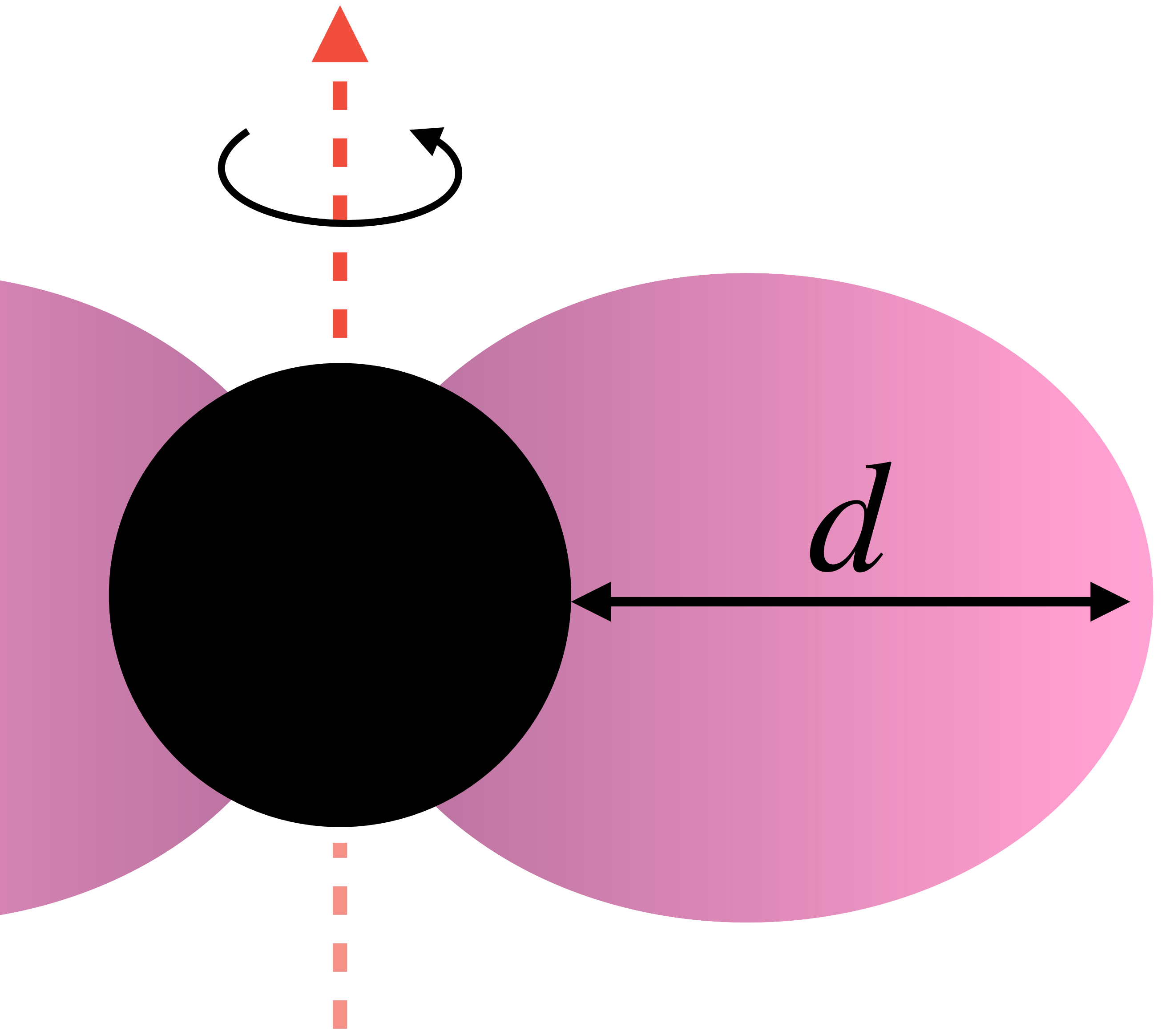
Axion field





[Spieksma et al. '23]

Axionic couplings - with SR



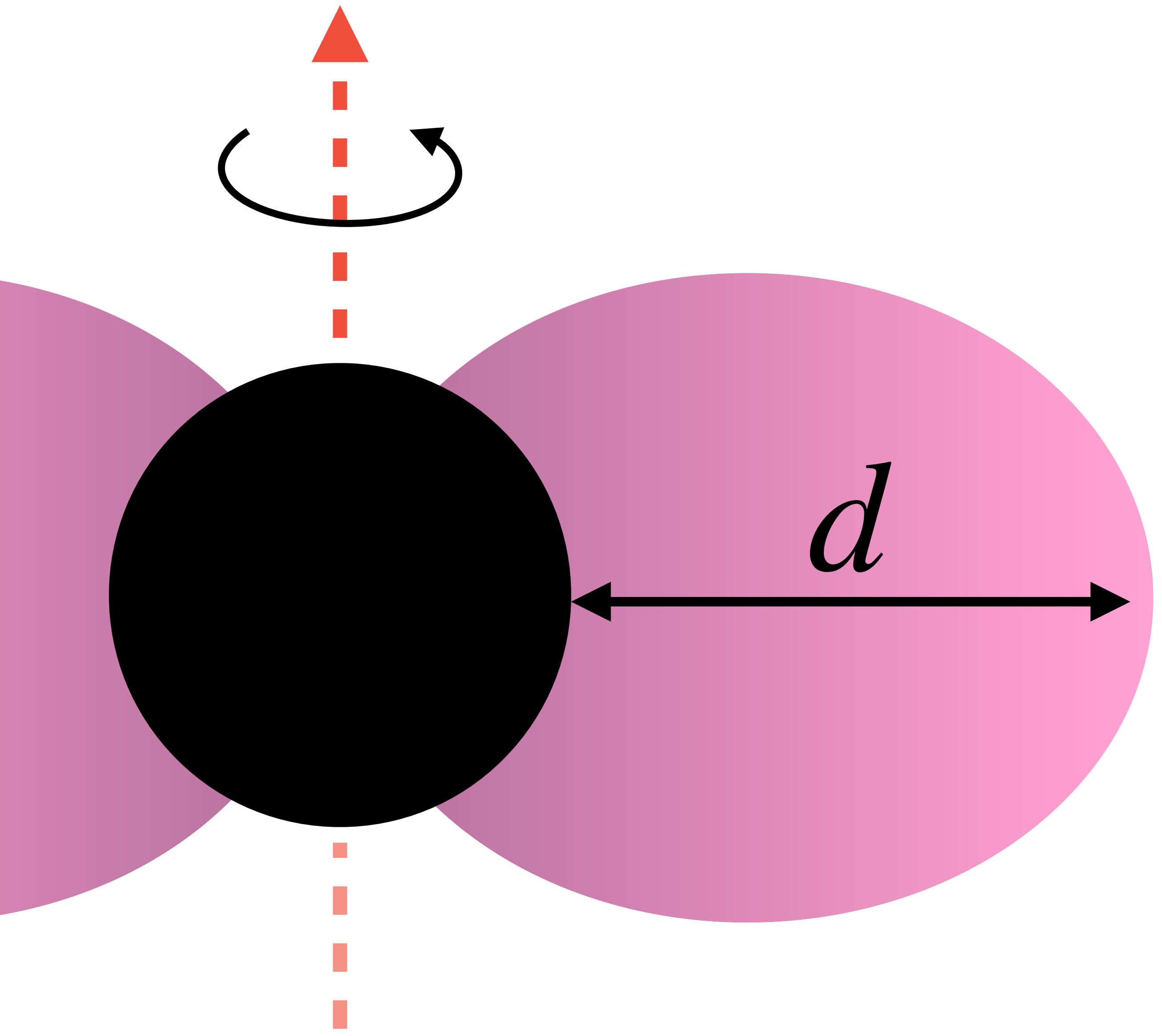
During saturation

$$\lambda_{\rm esc} \sim \frac{1}{d} \approx \frac{\mu k_a \Psi_{\rm sat}}{2} \sim \lambda_*$$

$$k_{\rm a} \Psi_{\rm sat} \approx \frac{\mu M}{\sqrt{3}}$$

Saturation value of the axion field **does not** depend on (artificial) **SR growth rate**!

Axionic couplings - with SR



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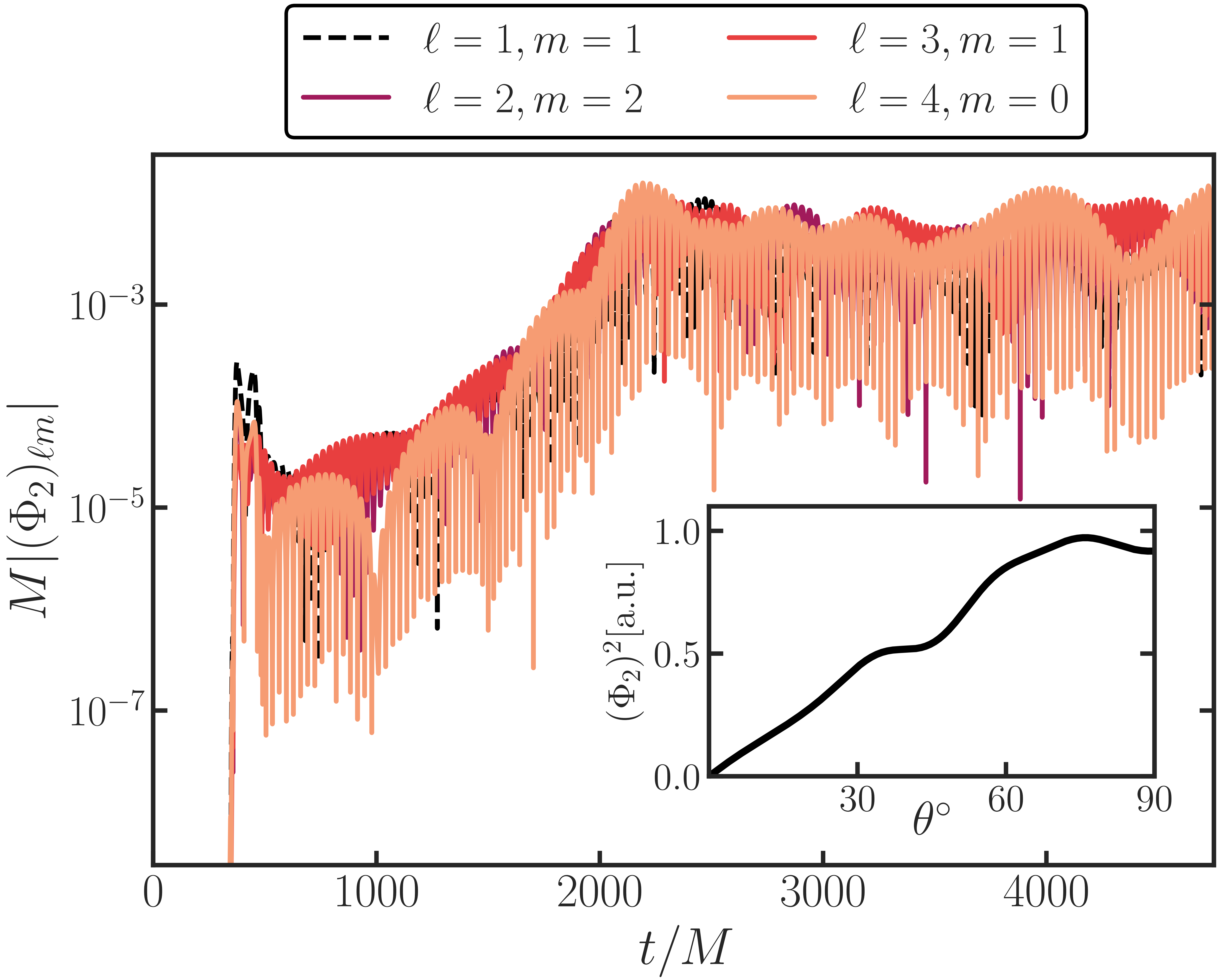
Saturation value of the axion field **does not** depend on (artificial) **SR growth rate**!

$$\Gamma_{\rm SR} \sim \Gamma_{\rm PI}$$

$$\frac{A_\gamma^2}{\Psi_{\rm sat}^2} \approx \frac{4C}{\pi \mu k_a \Psi_{\rm sat}} \approx \frac{2C}{\pi \lambda_{\rm esc}}$$

Amplitude **EM field** depends on $\sqrt{C}$

Observational signatures



[Spieksma et al. '23]