Black hole superradiance:

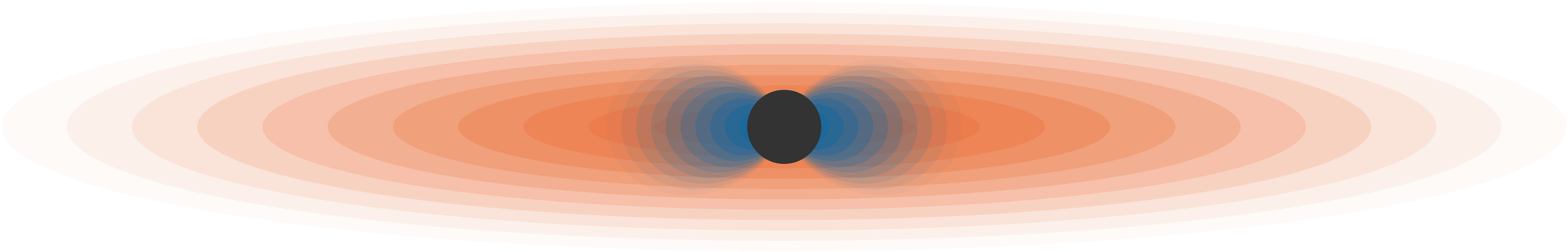
a gateway to new physics

Seoul, May 2025

Daejeon - 26th May 2025

Thomas Spieksma

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



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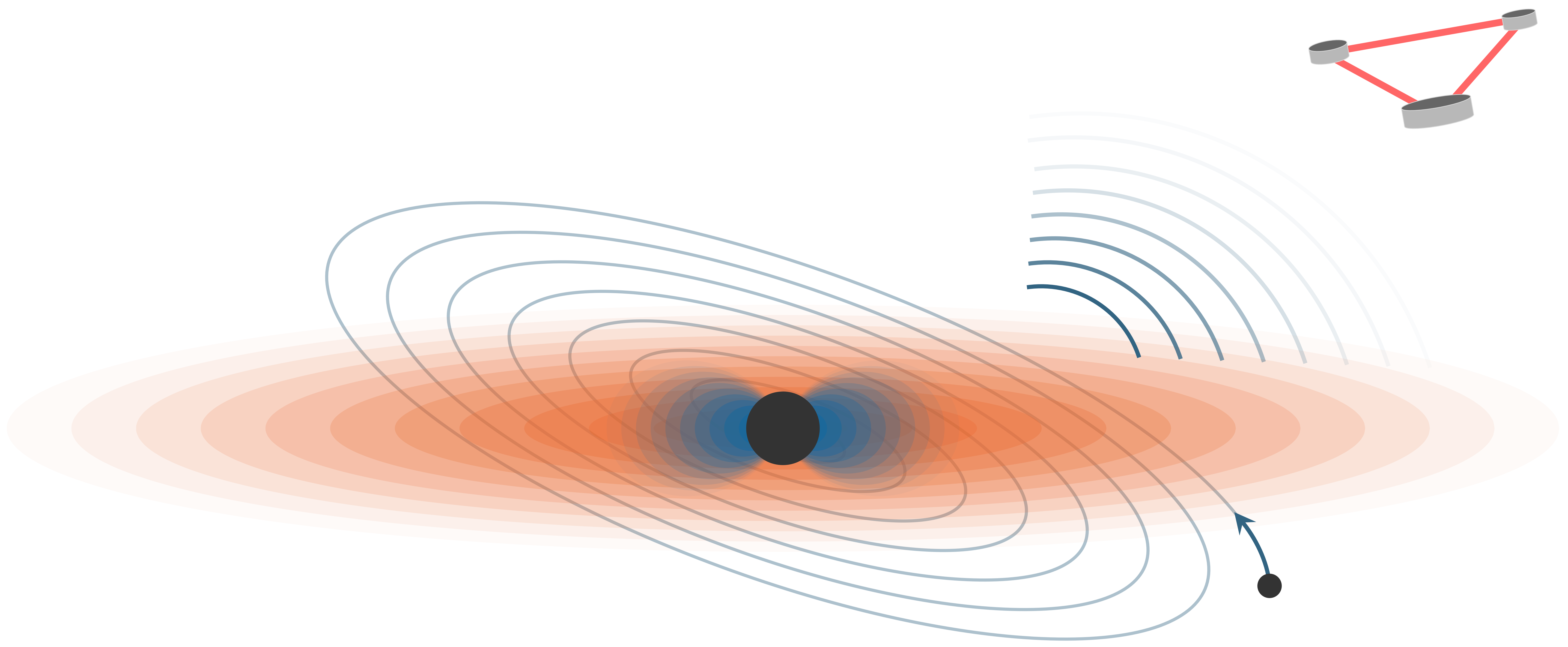

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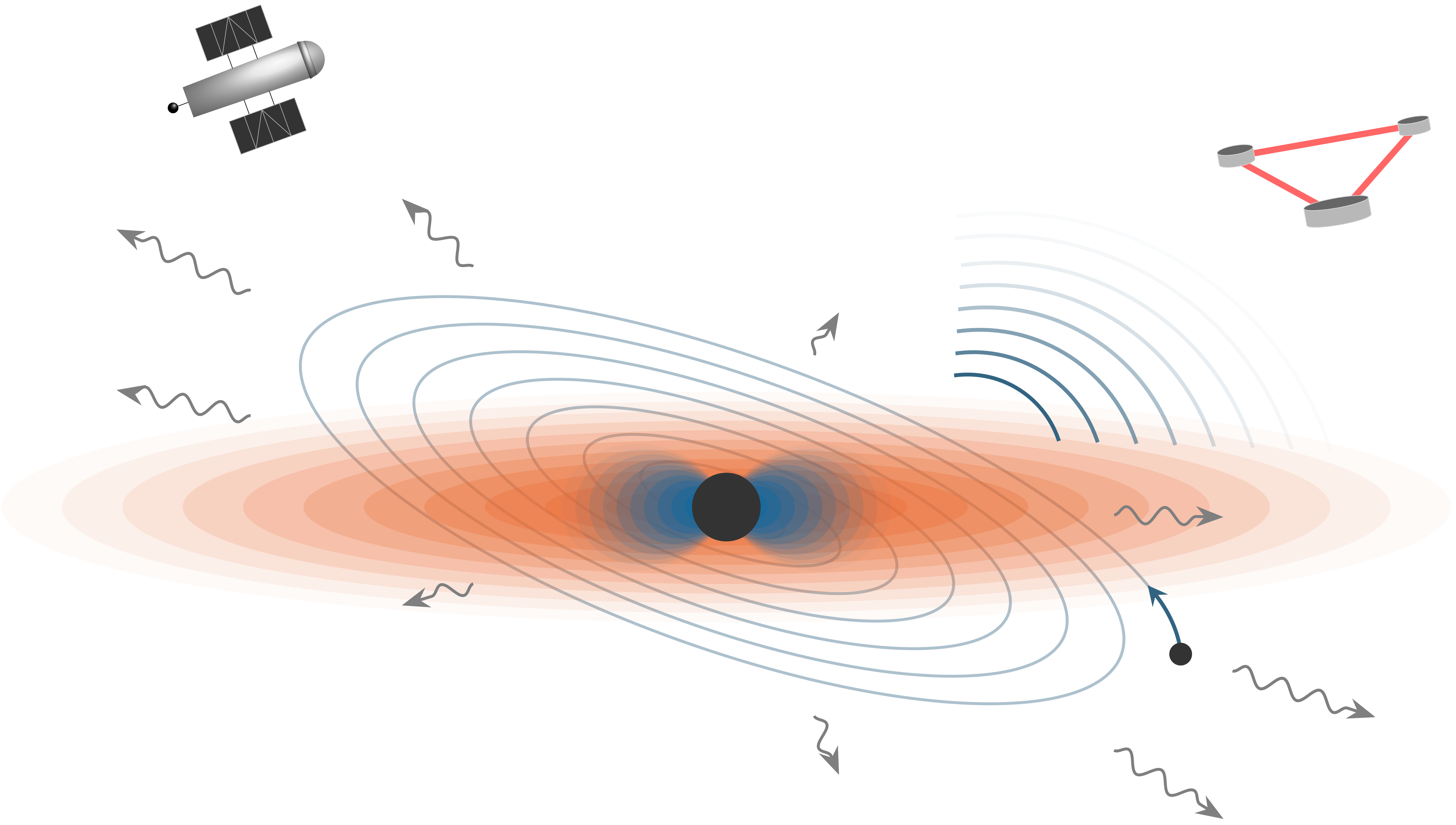


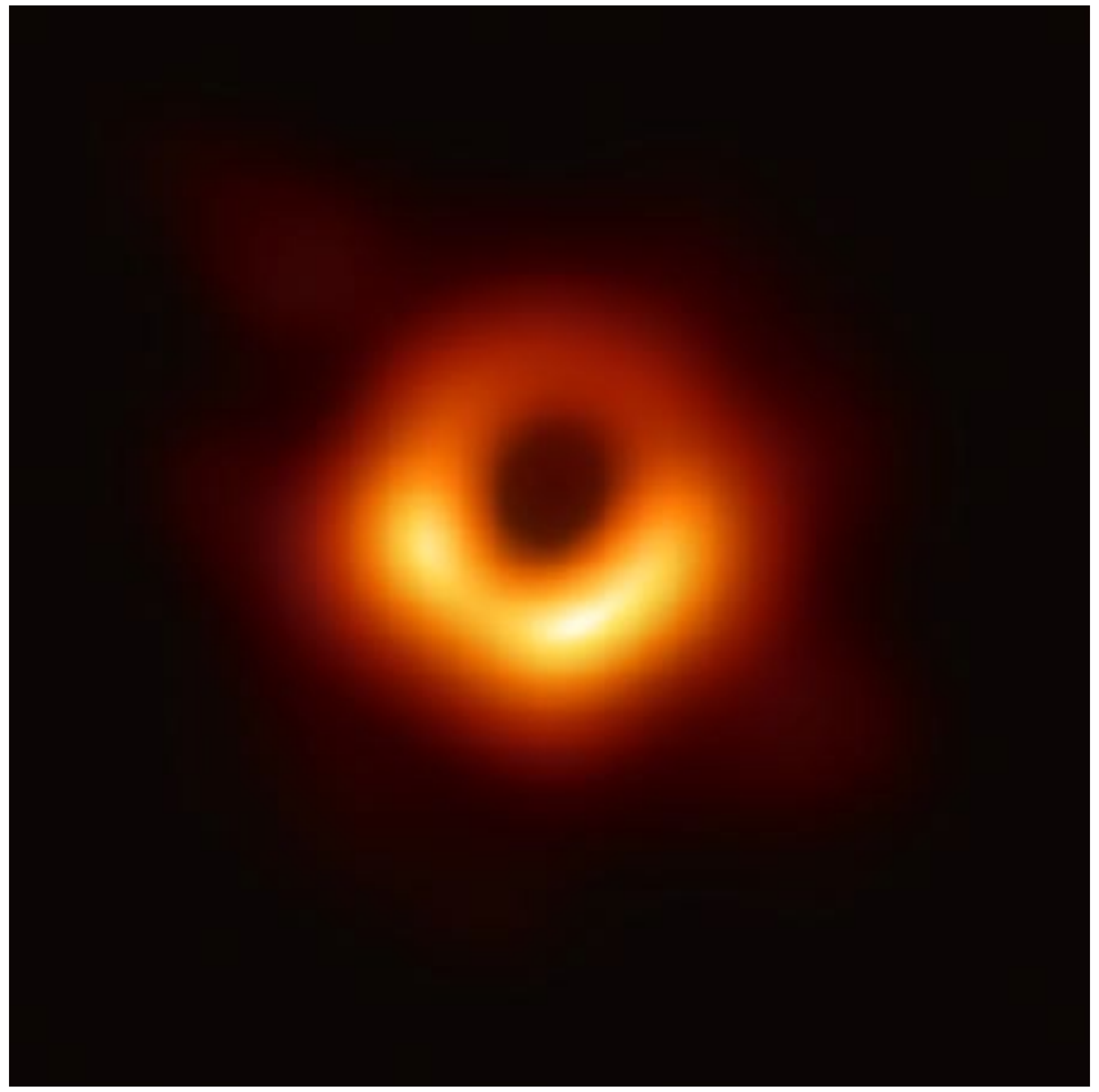
Black hole environments — Taxonomy

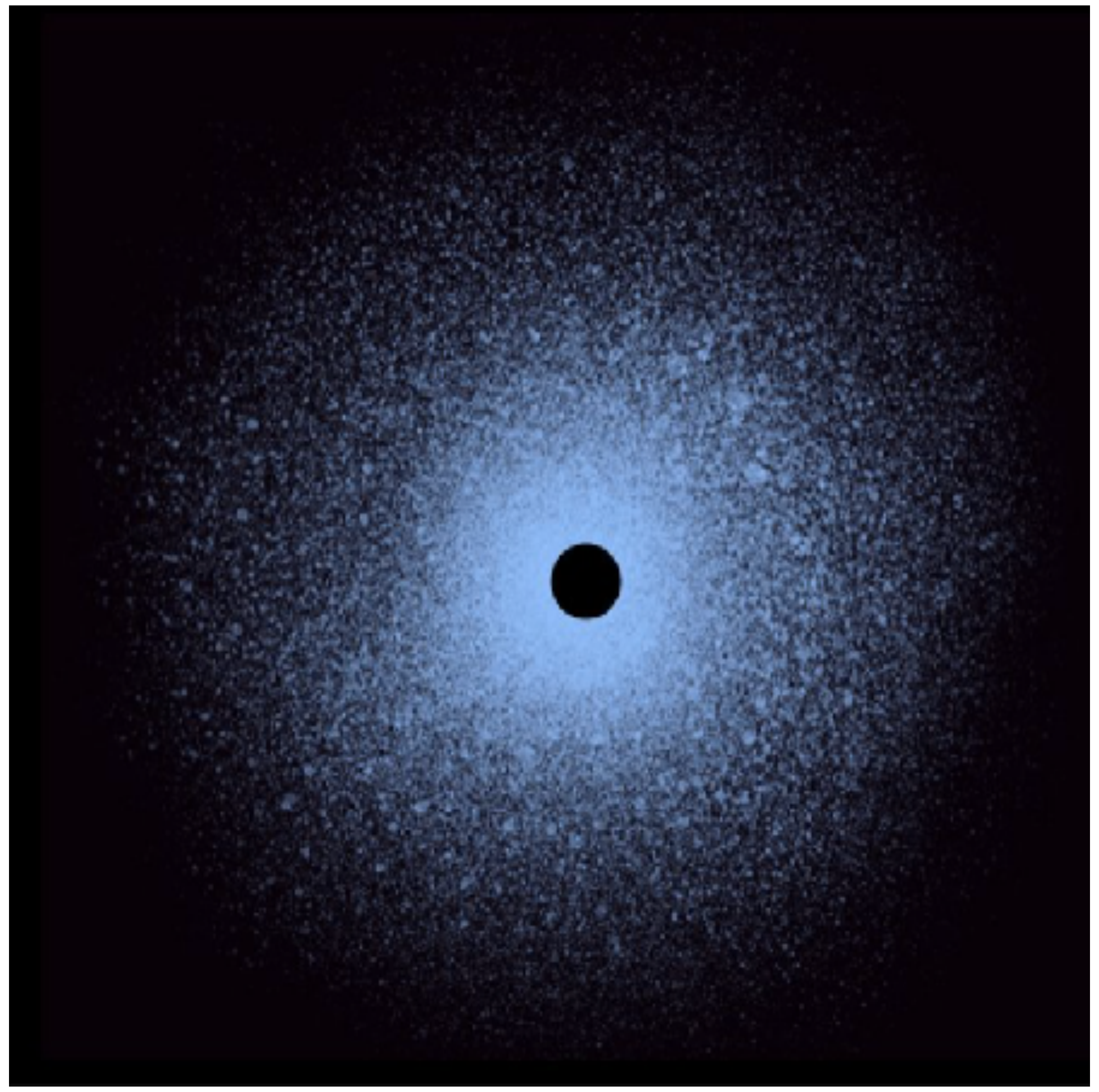
Gaseous

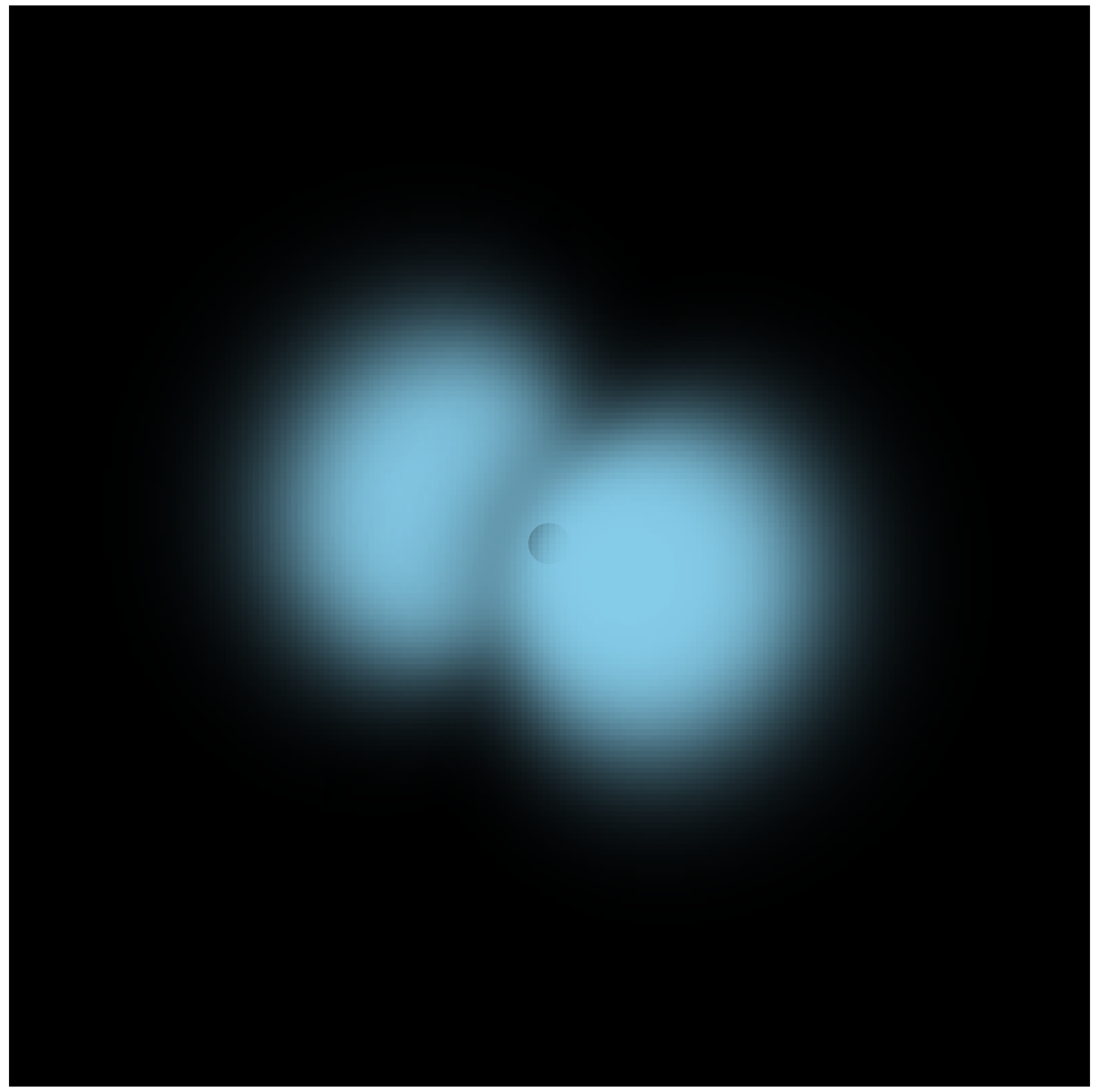
Dark Matter

Classic

Exotic







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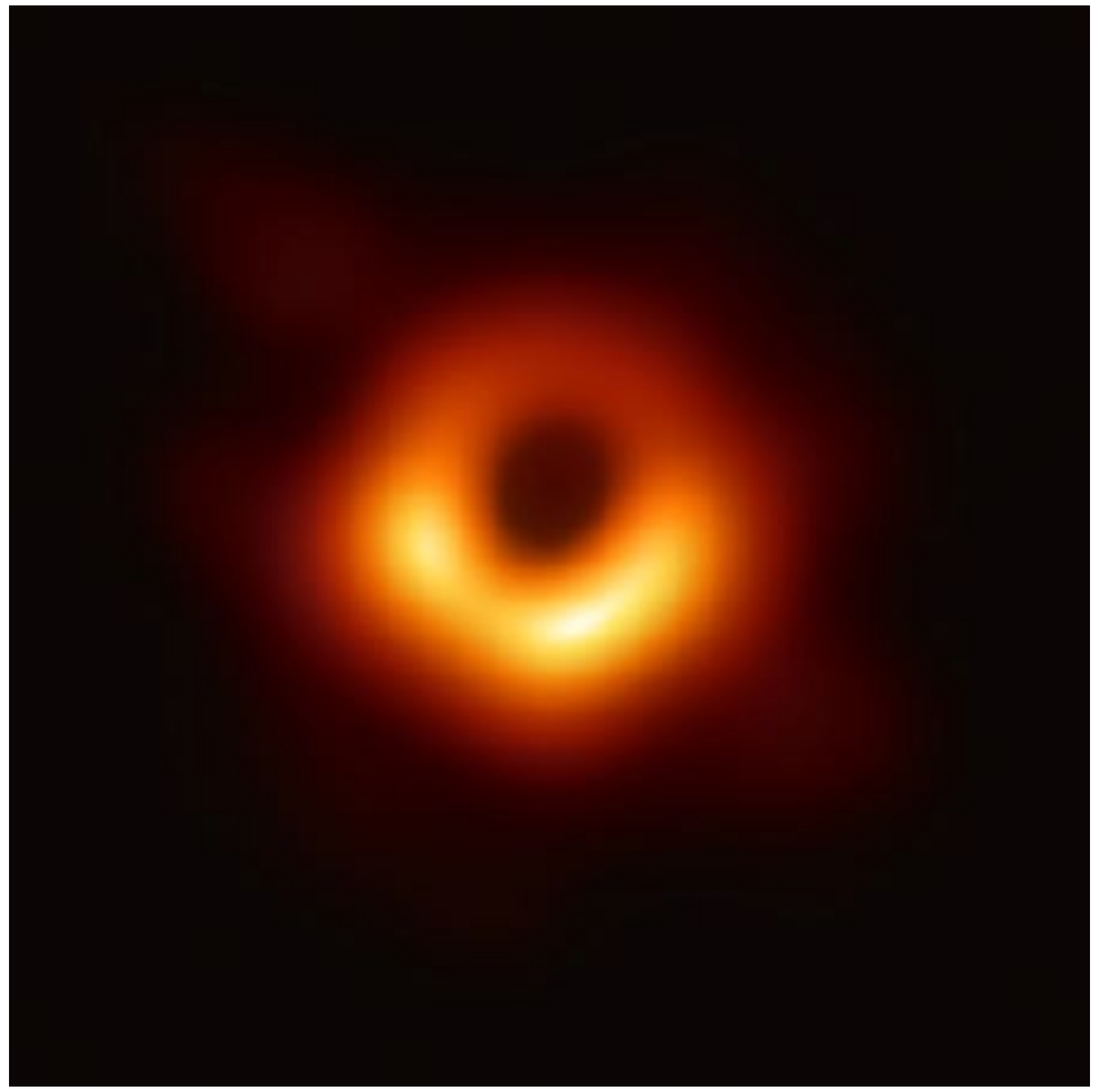
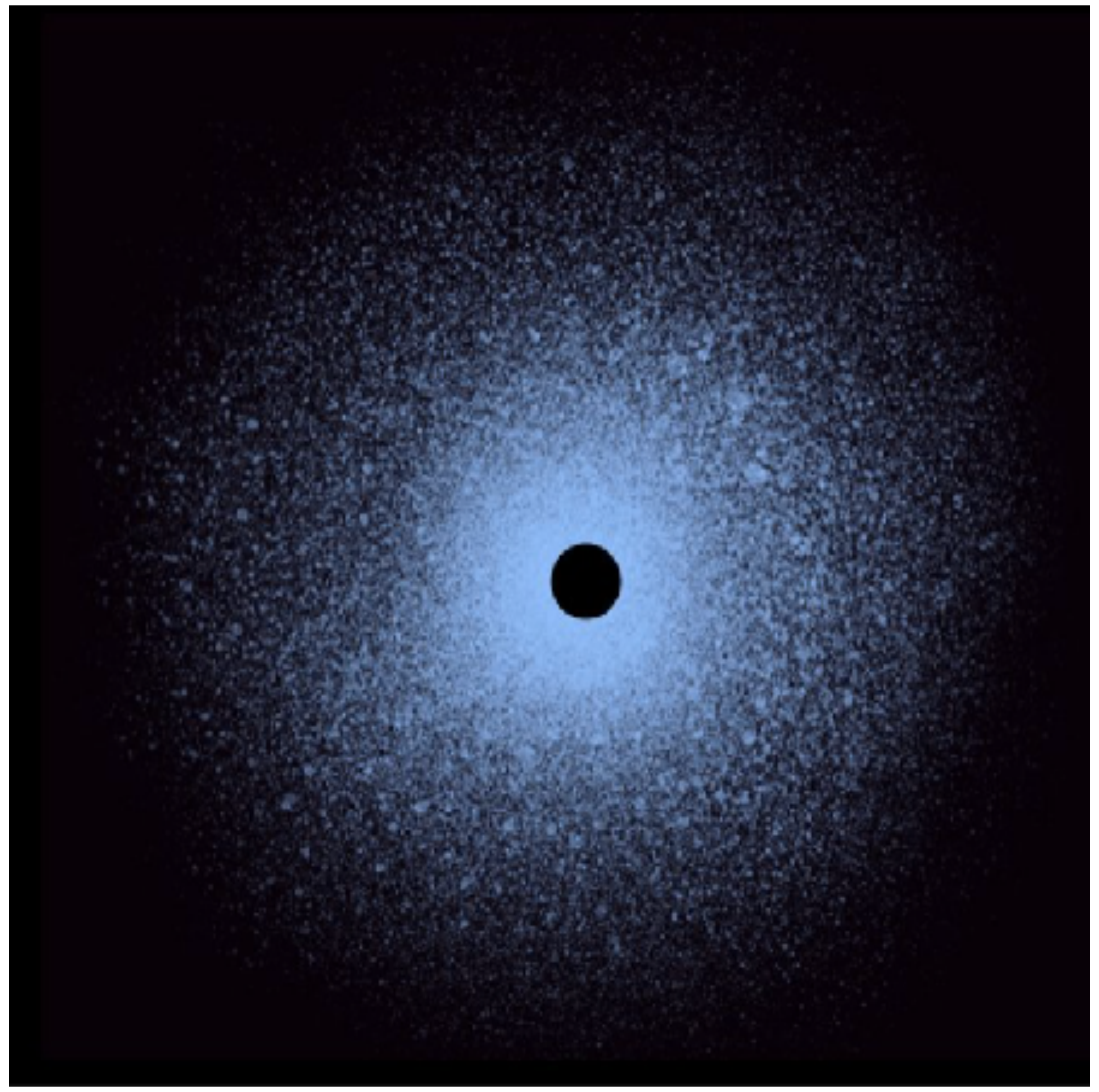
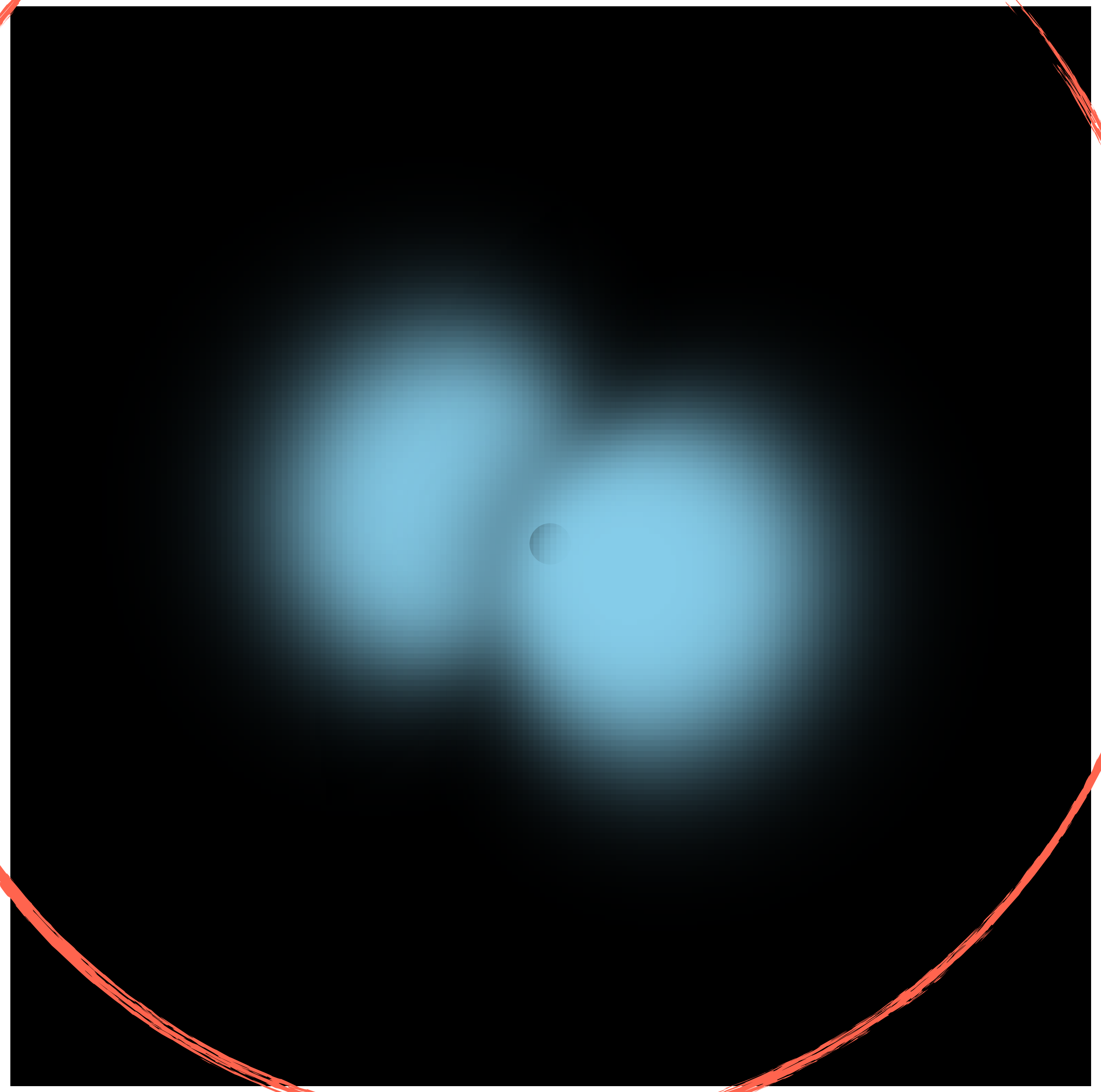
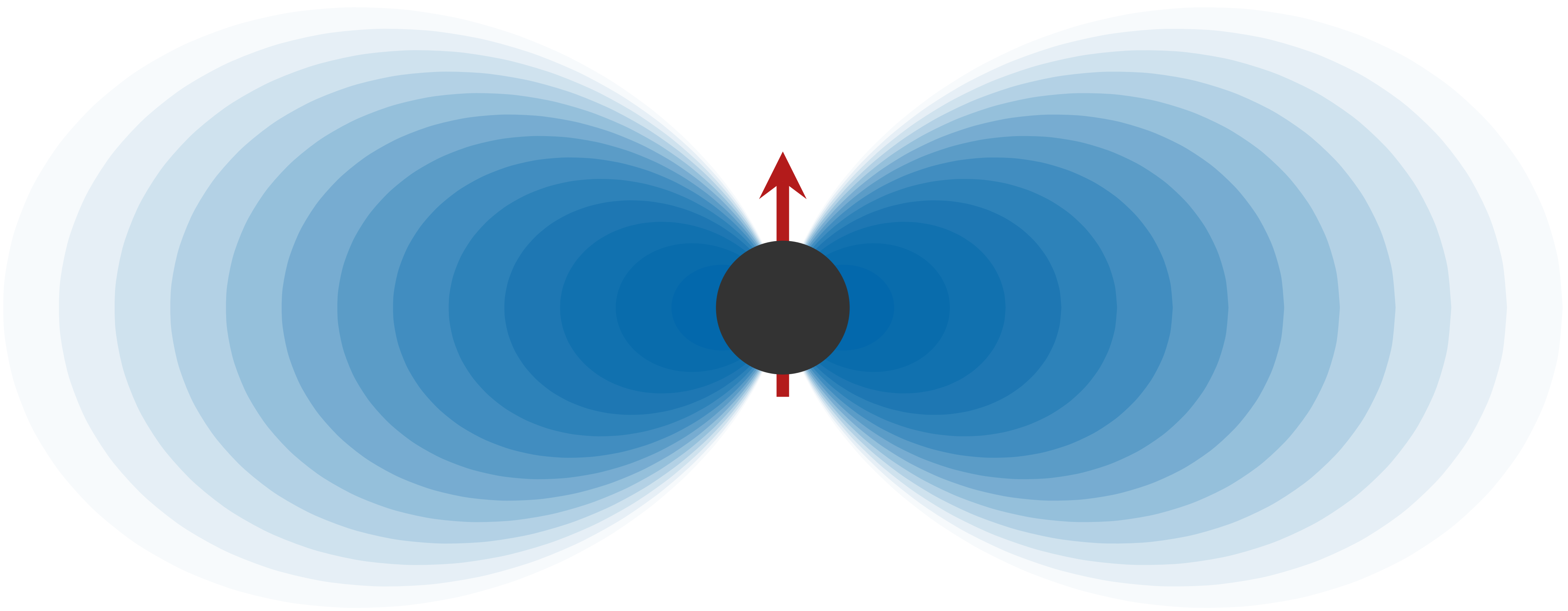






Superradiance

$$\frac{r_{\mathrm{g}}}{\lambda_{\mathrm{c}}} = \mu M \sim \mathcal{O}(0.01) - \mathcal{O}(1)$$



Superradiance

Astrophysical black holes

$$M \sim [1 - 10^{10}]M_\odot$$

Ultralight bosons

$$\mu \sim [10^{-20} - 10^{-10}]\,\mathrm{eV}$$

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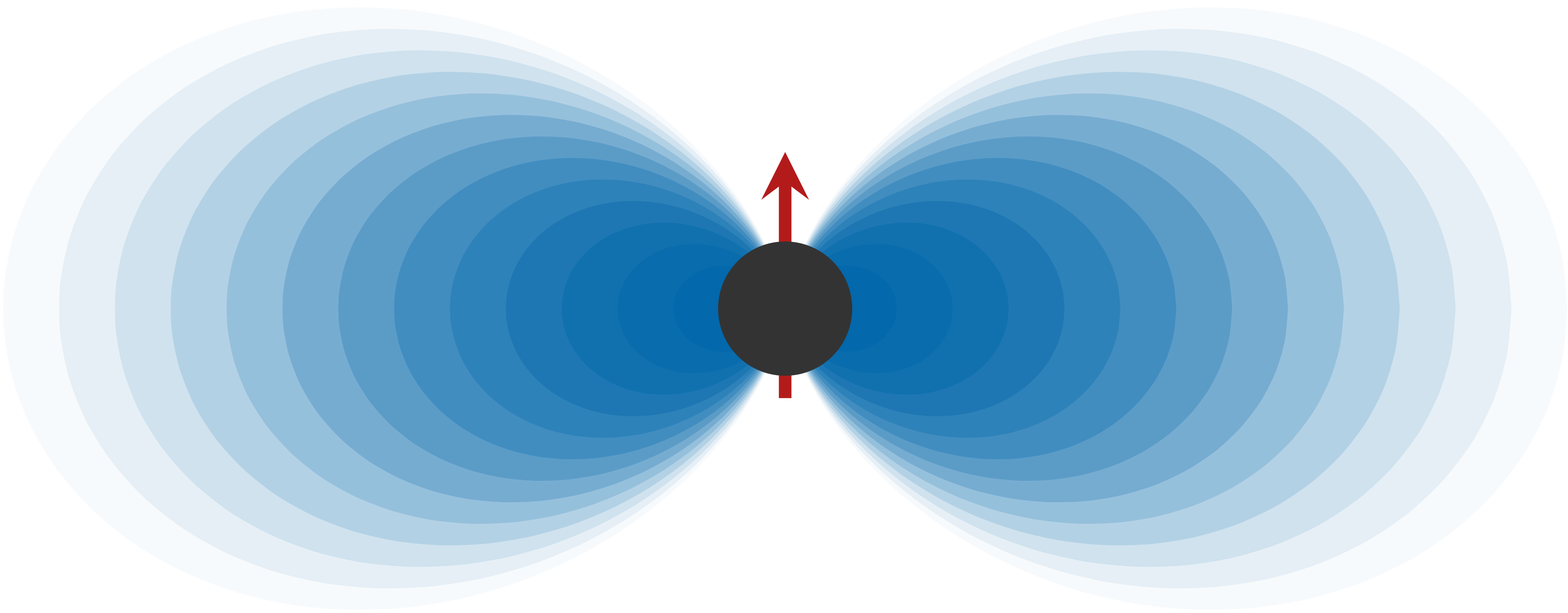
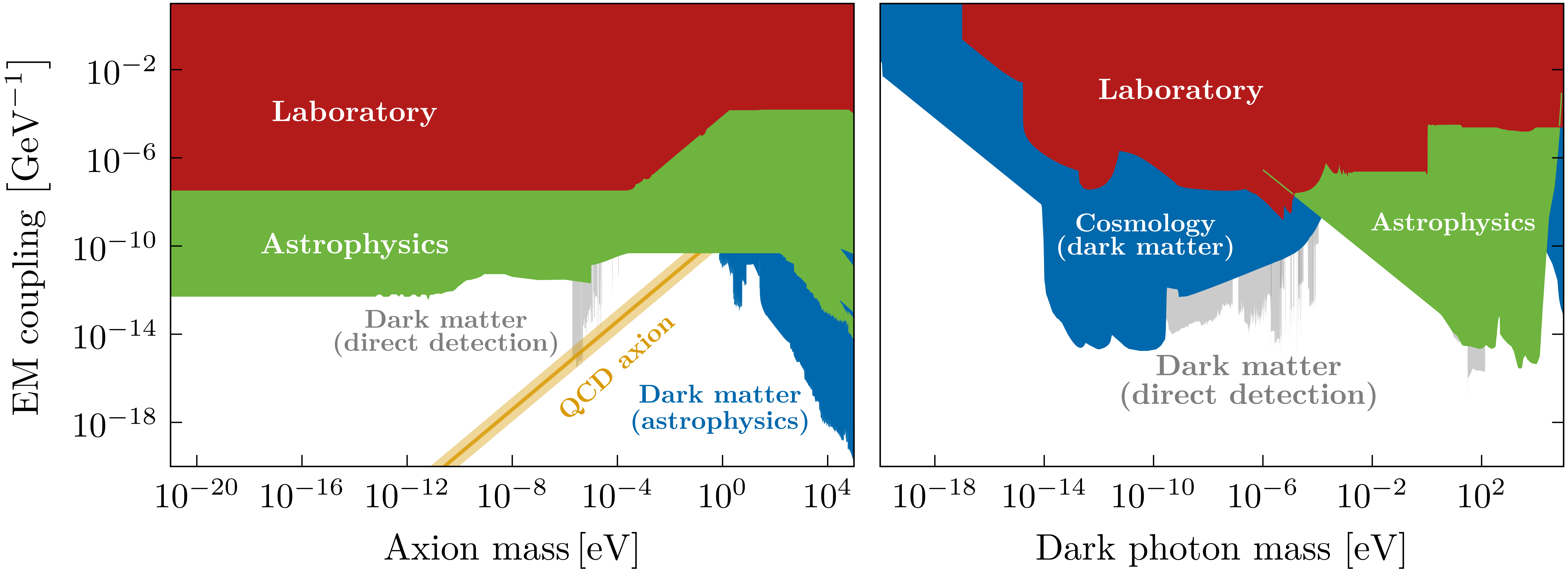


Ultralight particles

Ultralight, weak coupling regime is largely unconstrained



Axionic couplings — Levels of complexity

- **Axionic** couplings to the **Maxwell sector:**

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

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Flat space and homogenous axion condensate

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$y = \alpha_i \exp(-i\omega t)$

Flat space and homogenous axion condensate

- **Mathieu** equation: $\boxed{\partial_T^2 y + \left(\omega^2/\mu^2 + 2k_{\mathrm{a}} \Psi_0 \omega/\mu \cos T\right) y = 0}$

[Hertzberg & Schappacasse '19; Boskovic *et al.* '19; Ikeda *et al.* '19]

Axionic couplings — Mathieu equation

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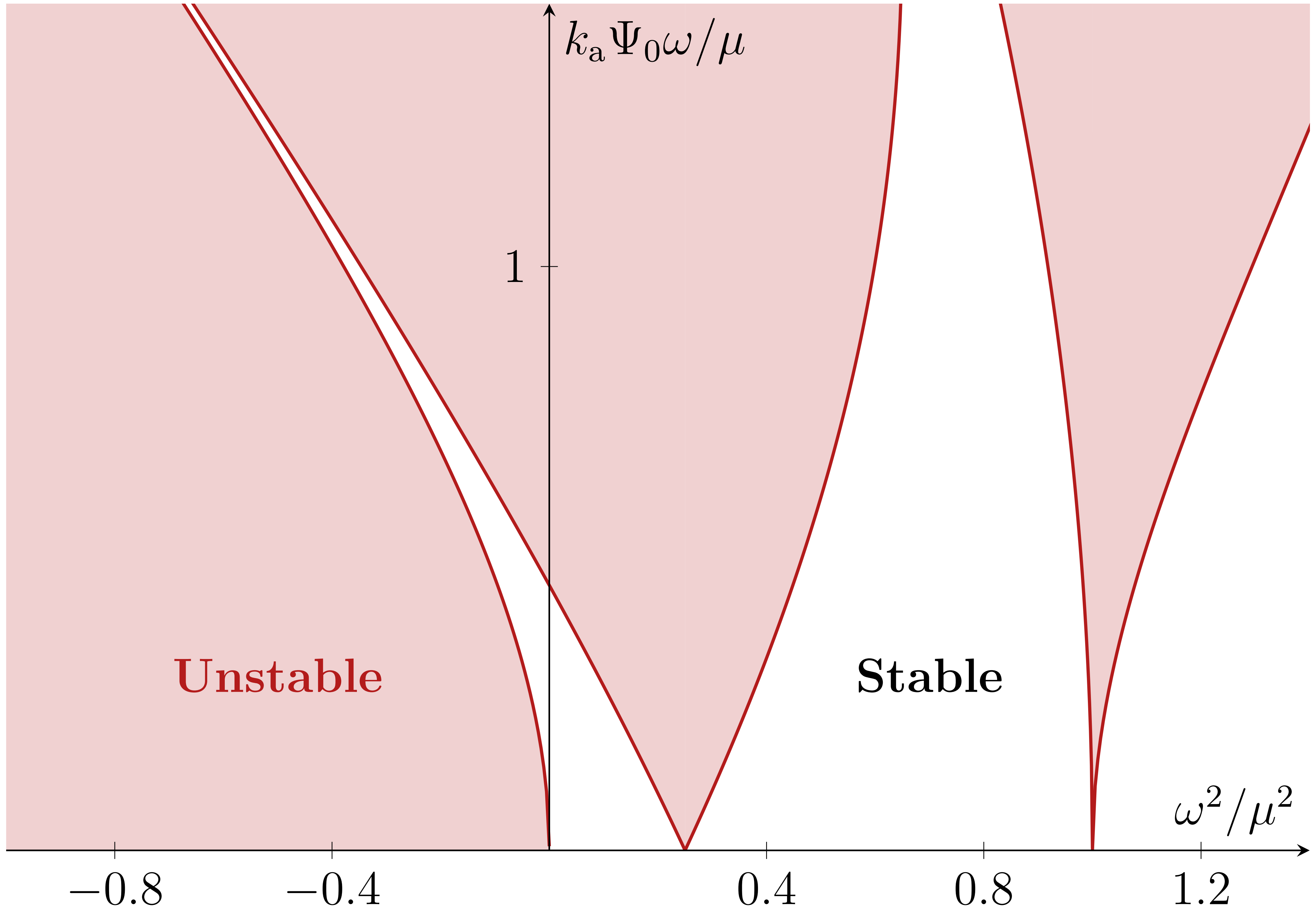
Parametric instabilities:

$$\omega_* = \mu/2, \mu, 3\mu/2, \ldots$$

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

Ince-Strutt diagram



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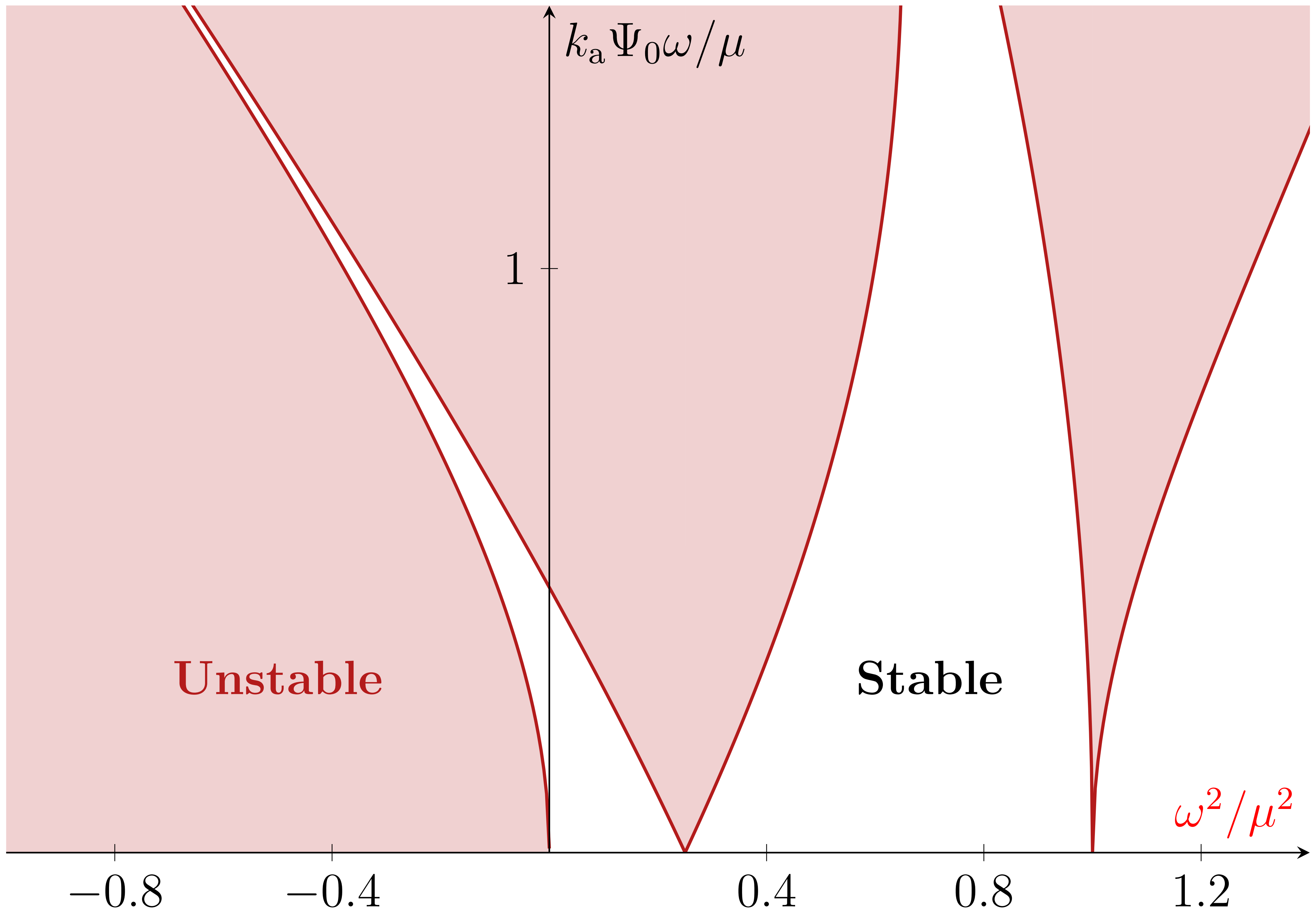

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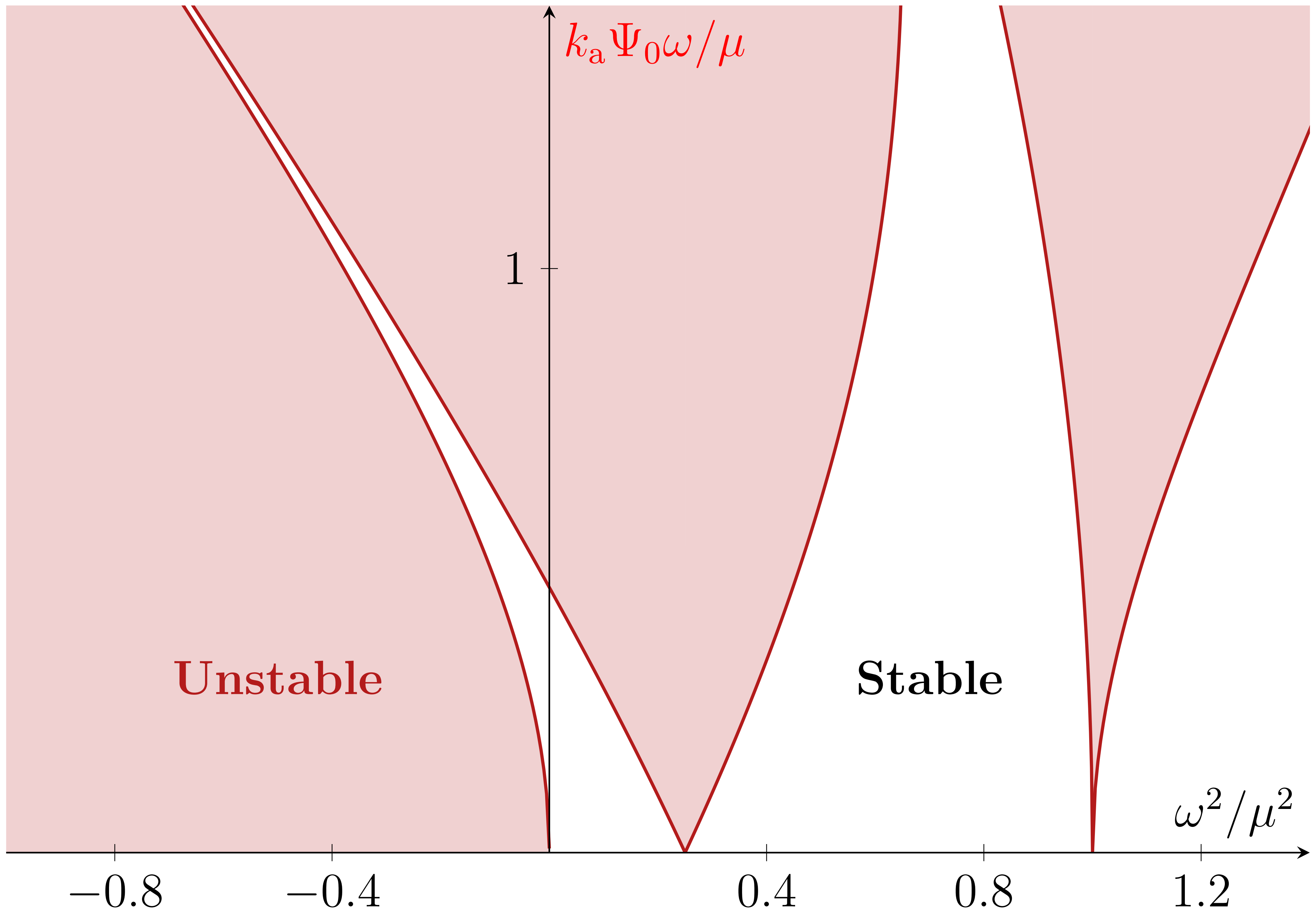
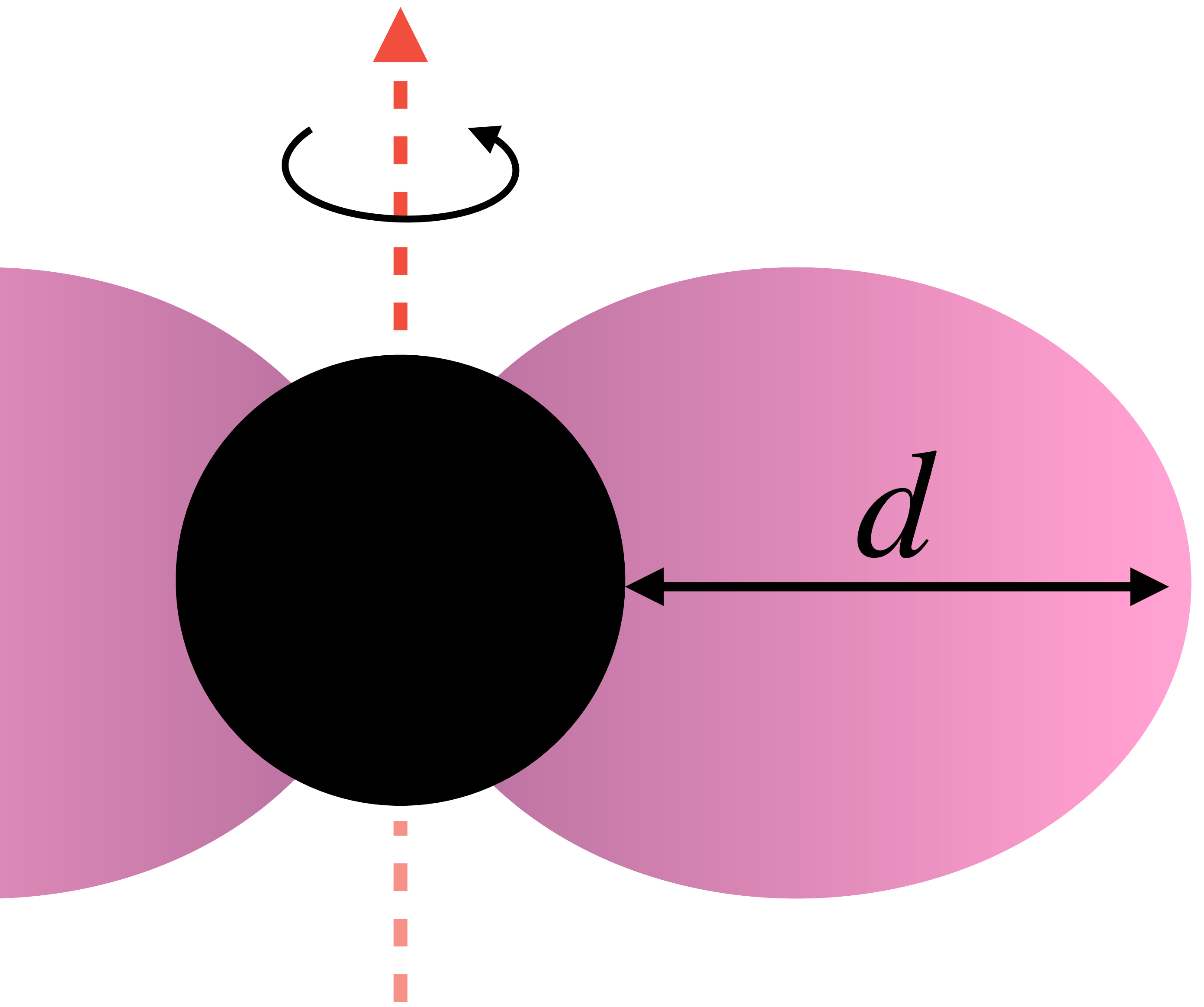


[Hertzberg & Schappacasse '19; Boskovic *et al.* '19; Ikeda *et al.* '19]

Axionic couplings — Boson clouds

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



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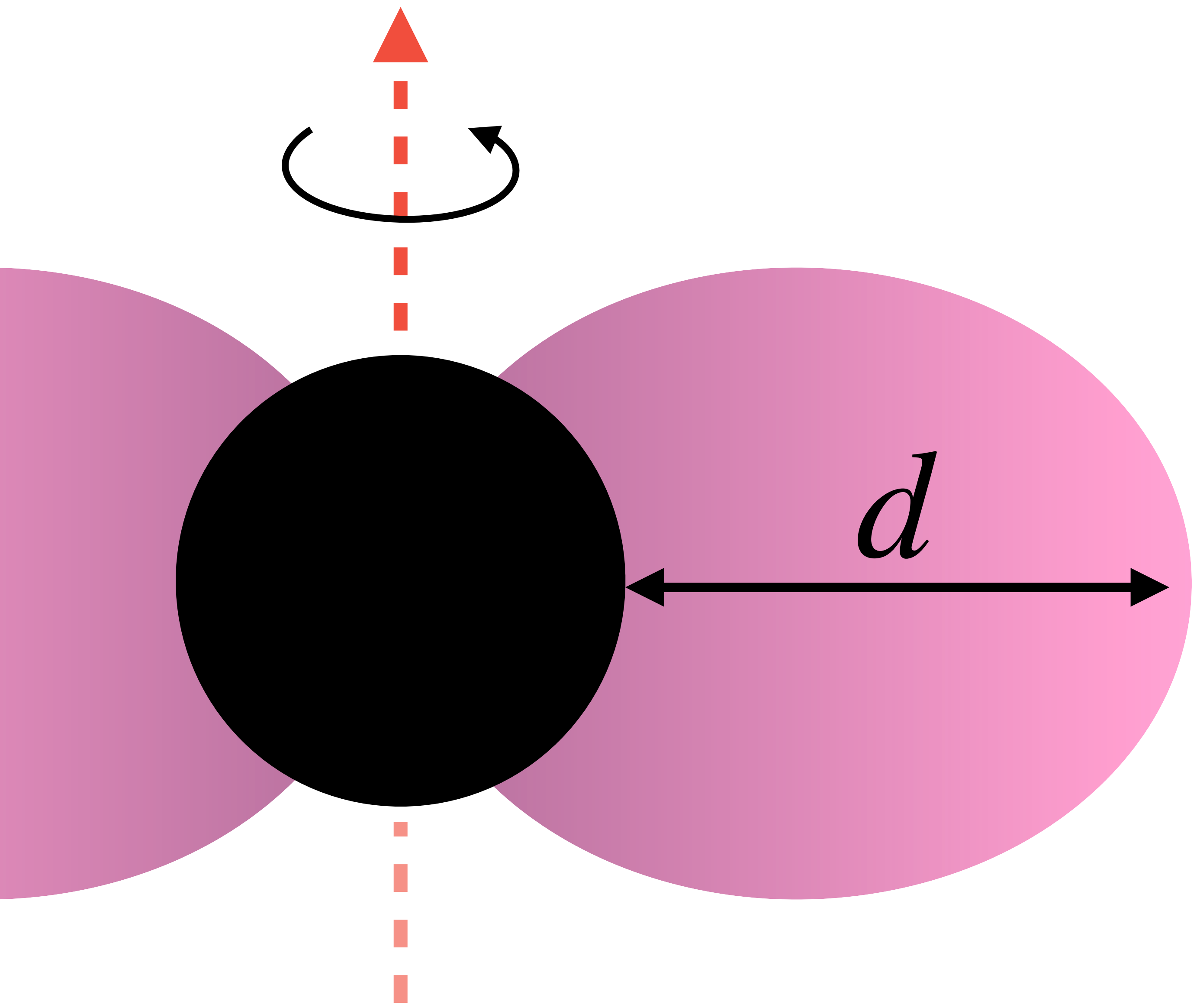


Depending on μM and $k_{\mathrm{a}}\Psi_0$, there exist **two** regimes:

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

$$\lambda_{\mathrm{esc}} \sim \frac{1}{d} > \mu k_{\mathrm{a}} \Psi_0 \sim \lambda_*$$

- In the ***supercritical*** regime, photons **build up** inside the cloud, triggering an **exponential growth**

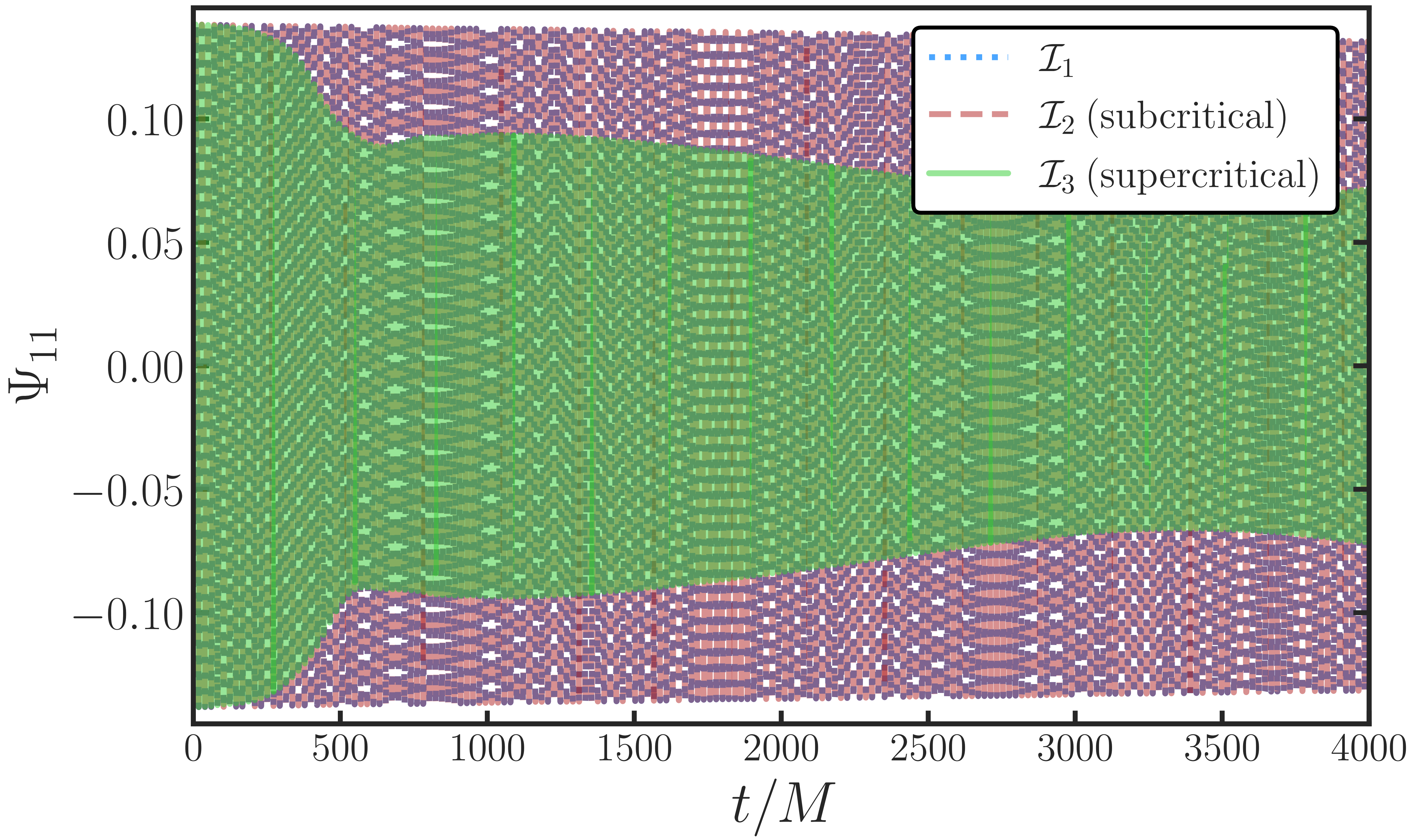
$$\frac{1}{d} \lesssim \mu k_{\mathrm{a}} \Psi_0$$

 [Rosa & Kephart '18; Boskovic *et al.* '19; Ikeda *et al.* '19]

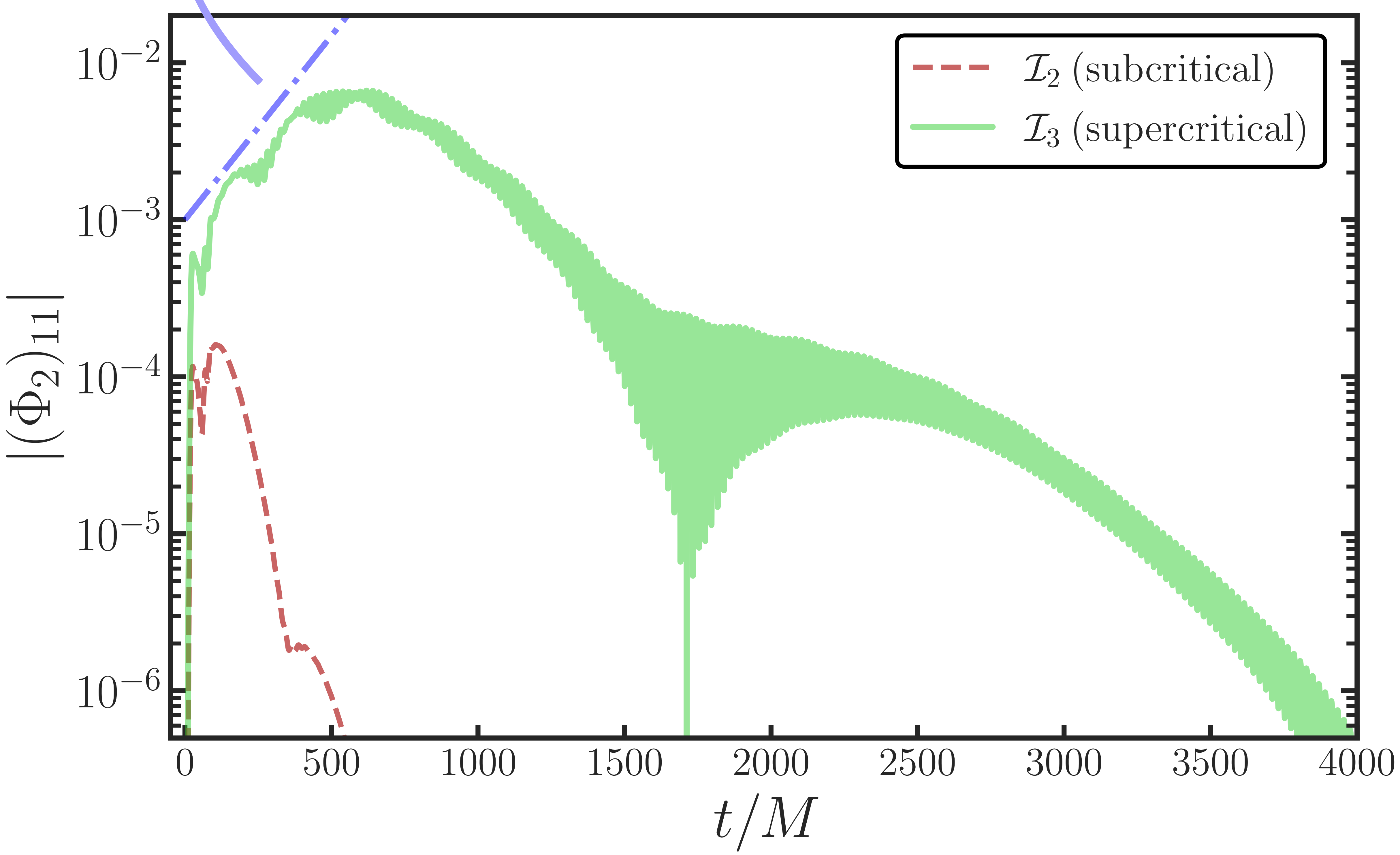
Axionic couplings — Boson clouds

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

Axion field

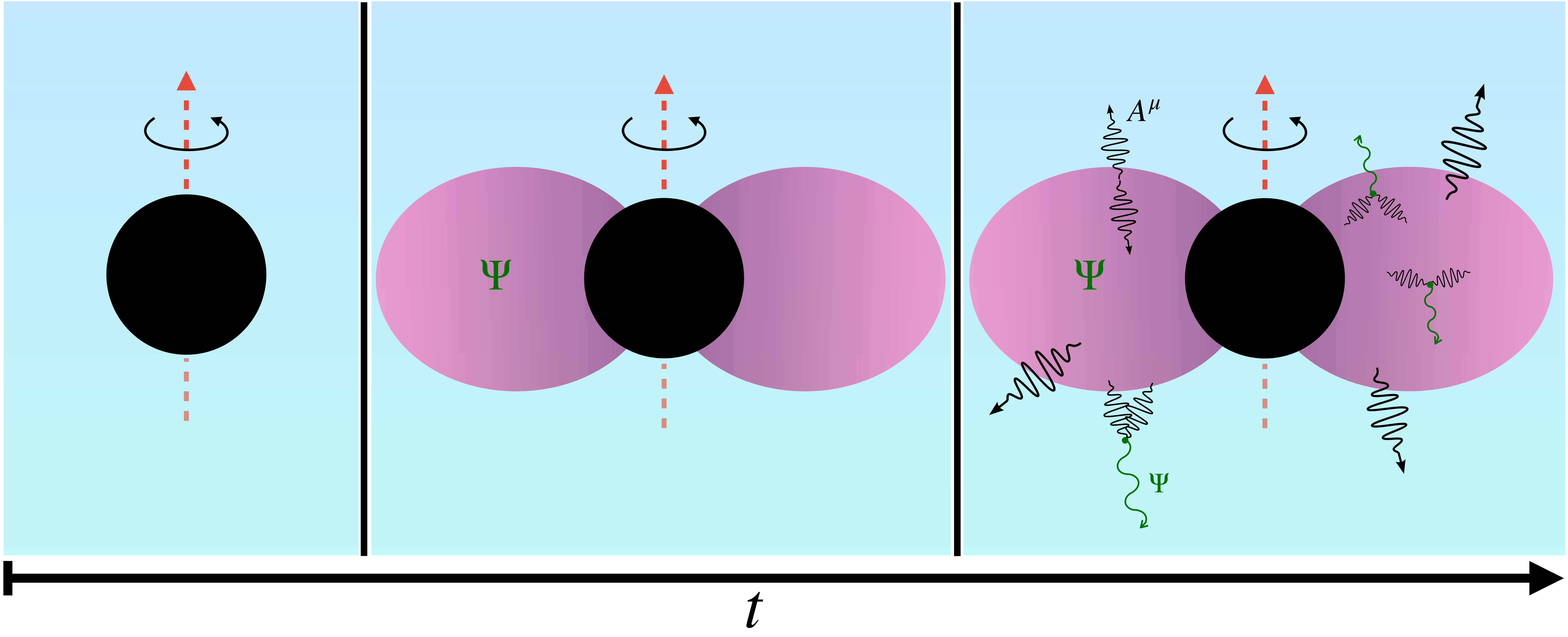


EM field



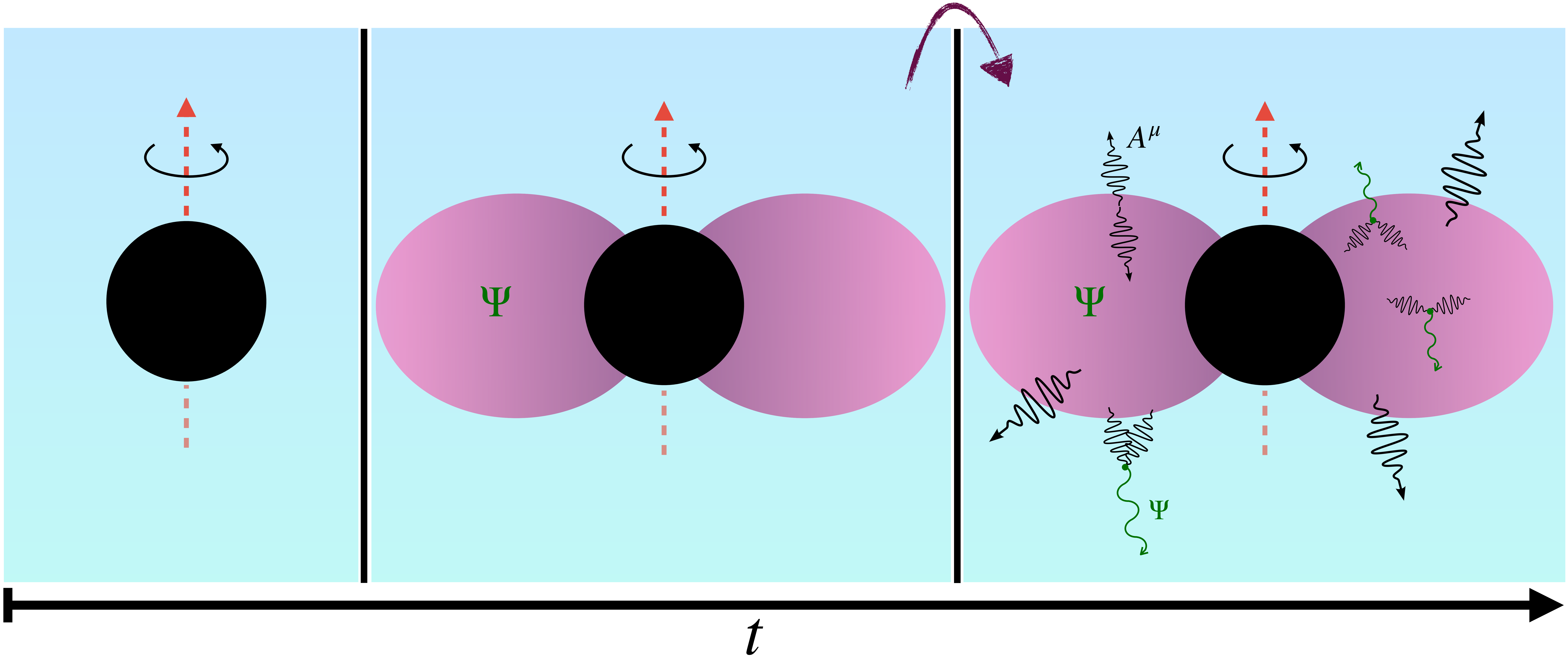
[Spieksma *et al.* ’23]

Axionic couplings — Overview



Axionic couplings — Overview

Turn **on** coupling



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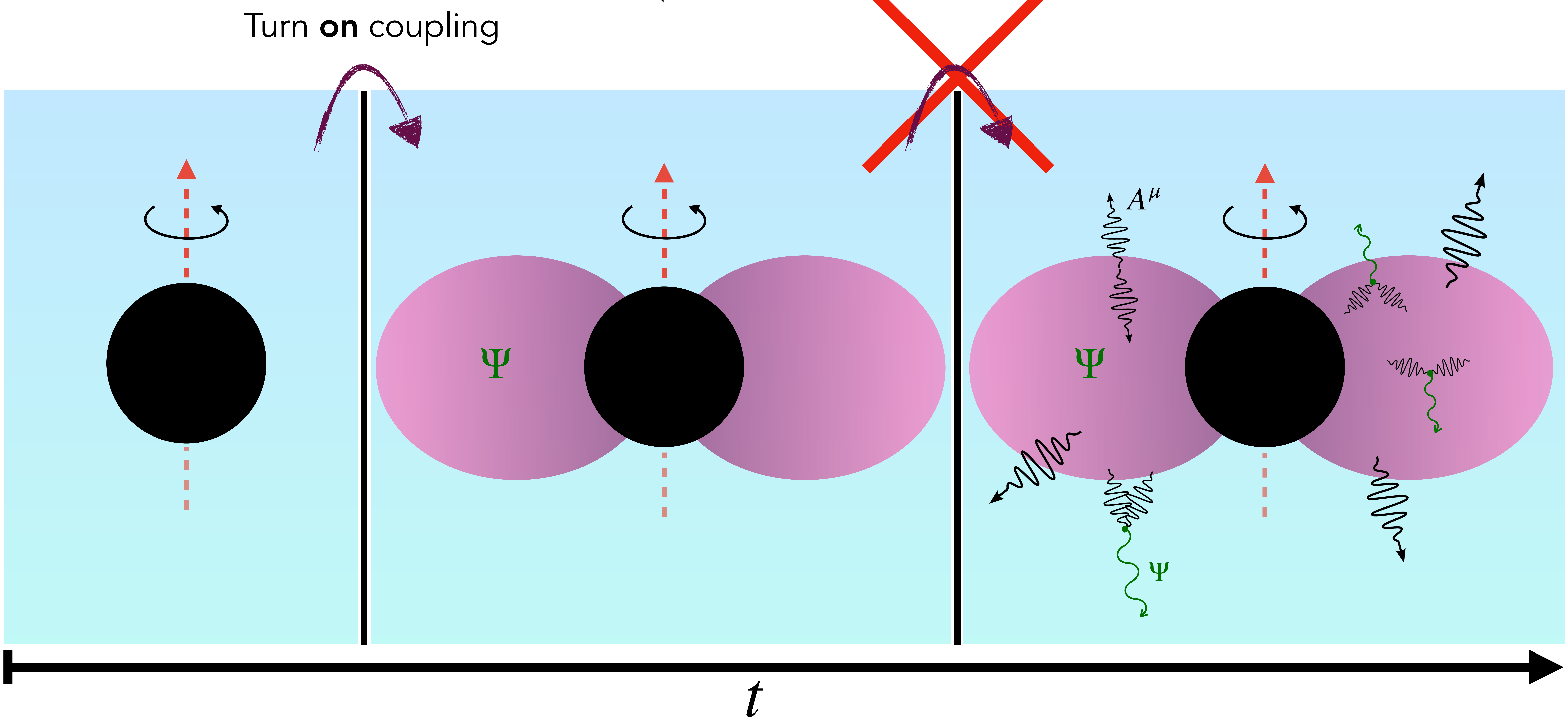
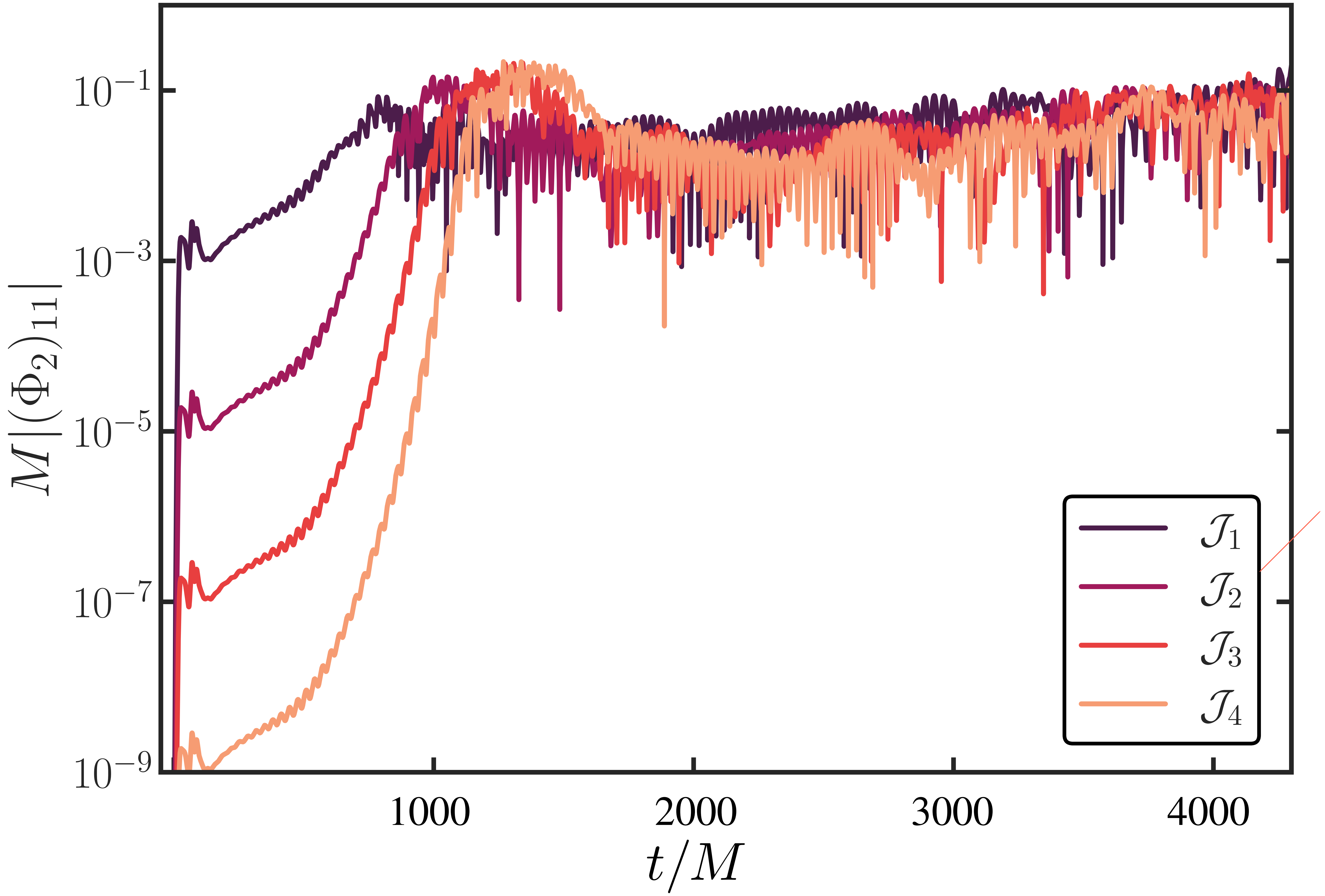


Axionic couplings — Superradiance

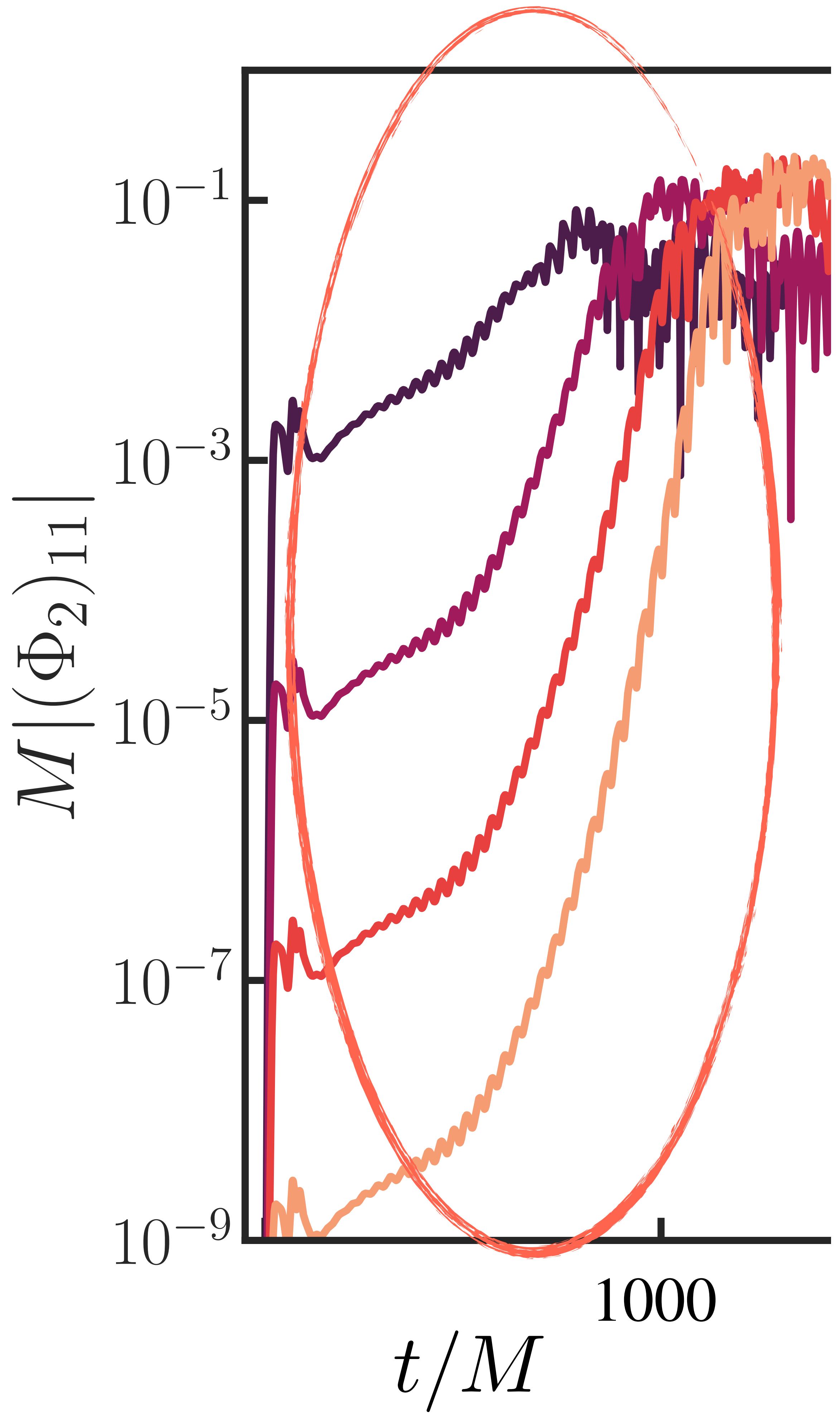
Energy outflow from EM radiation and axion production balance ⟶ **Saturation phase**



- Varying initial EM perturbation

Axionic couplings — Superradiance

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



The **Mathieu** equation again!

$$\partial_T^2 y + \frac{1}{\mu^2}\left(p_z^2 + 2p_z e^{CT/\mu}\Psi_0 k_{\rm a}(C\cos T - \mu\sin T)\right) y = 0$$

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

Observational signatures — EM emission

Saturation phase: $\Gamma_{\rm SR} \simeq \Gamma_{\rm PI}$ $\longrightarrow$ $A_\gamma \propto \sqrt{C}$

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

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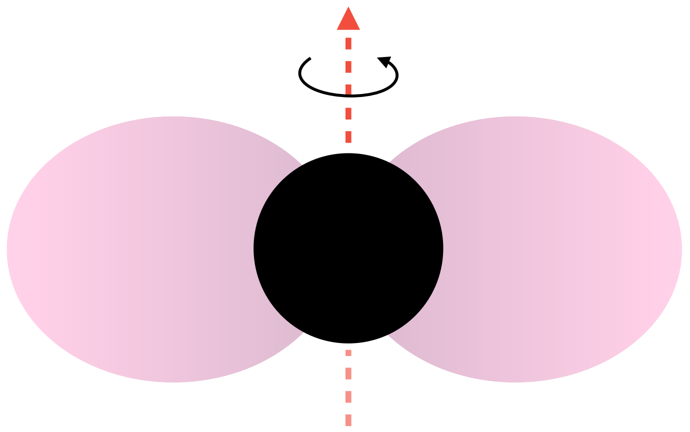
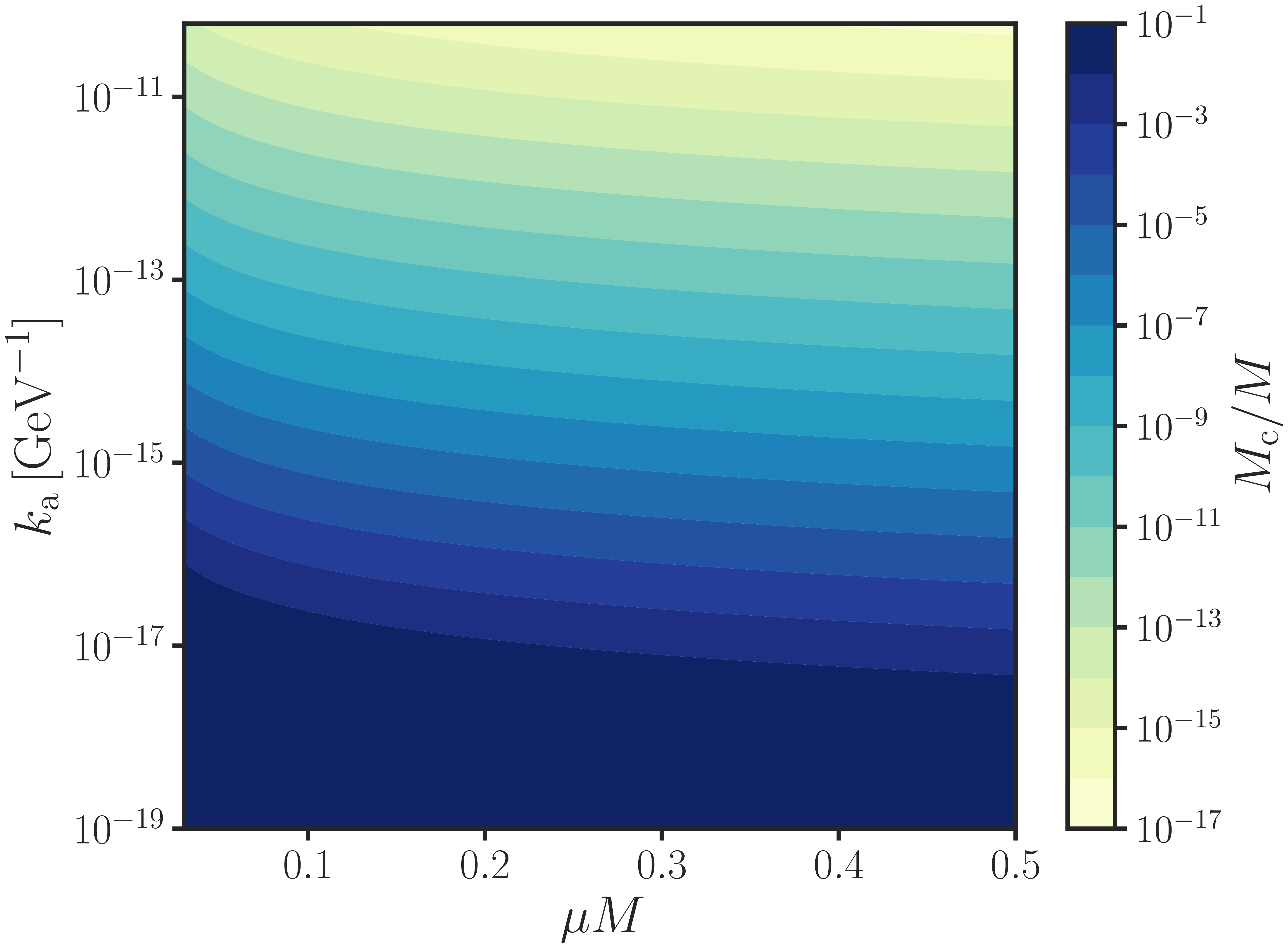
- ✦ High luminosity
- ✦ (Nearly) Constant
- ✦ Monochromatic
- ✦ Multi-messenger signal

Observational signatures — The cloud





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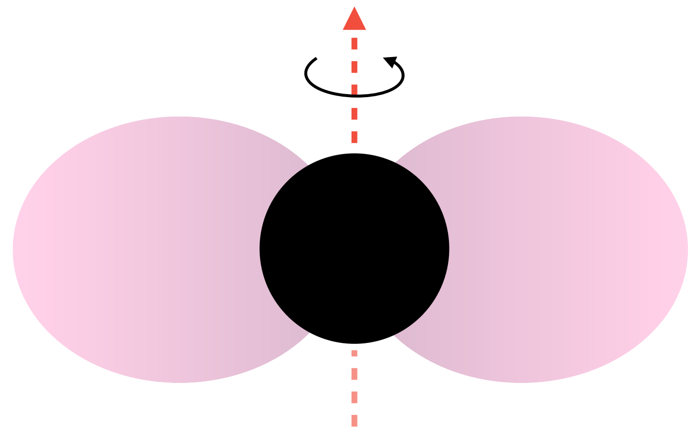

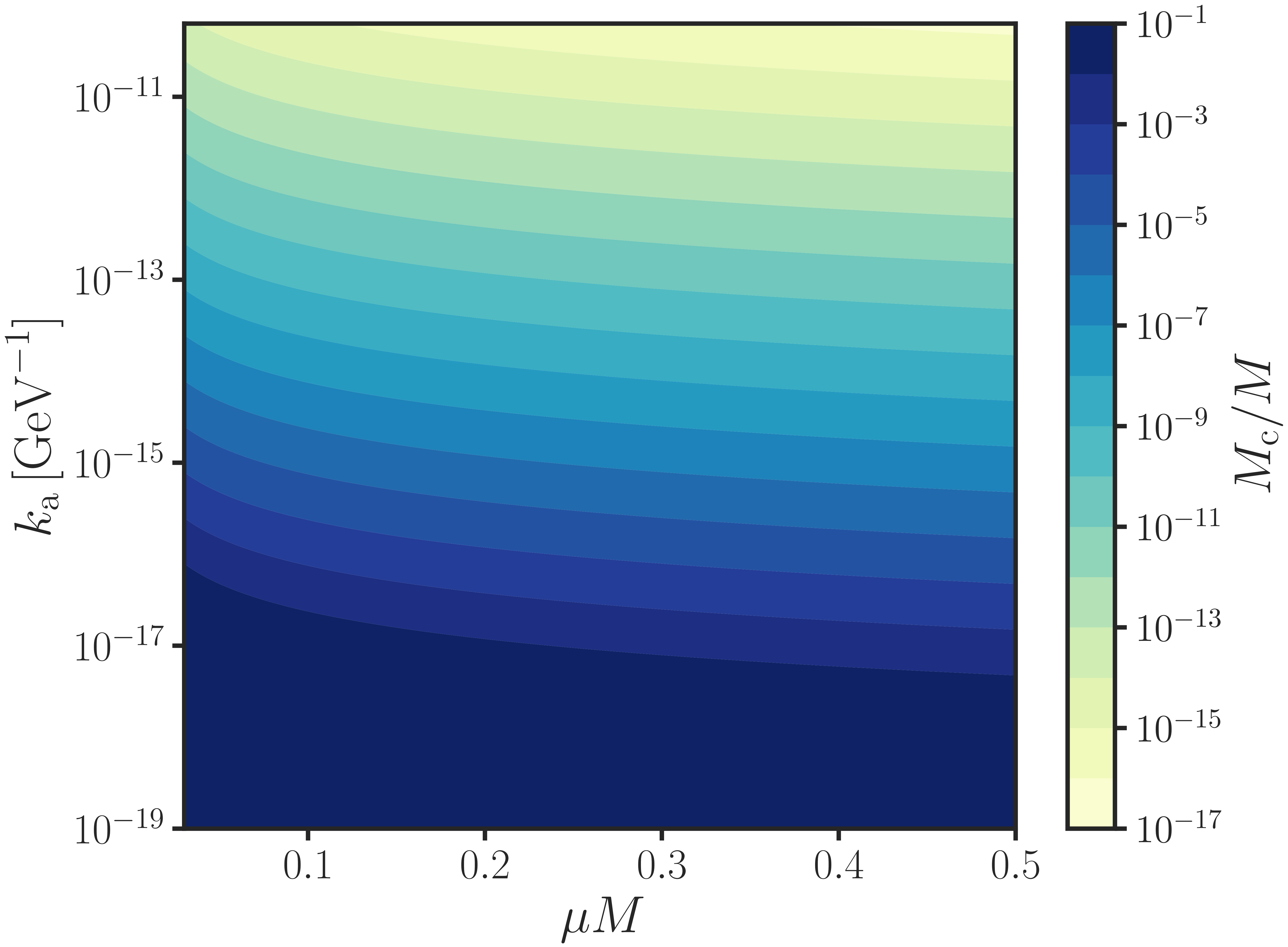

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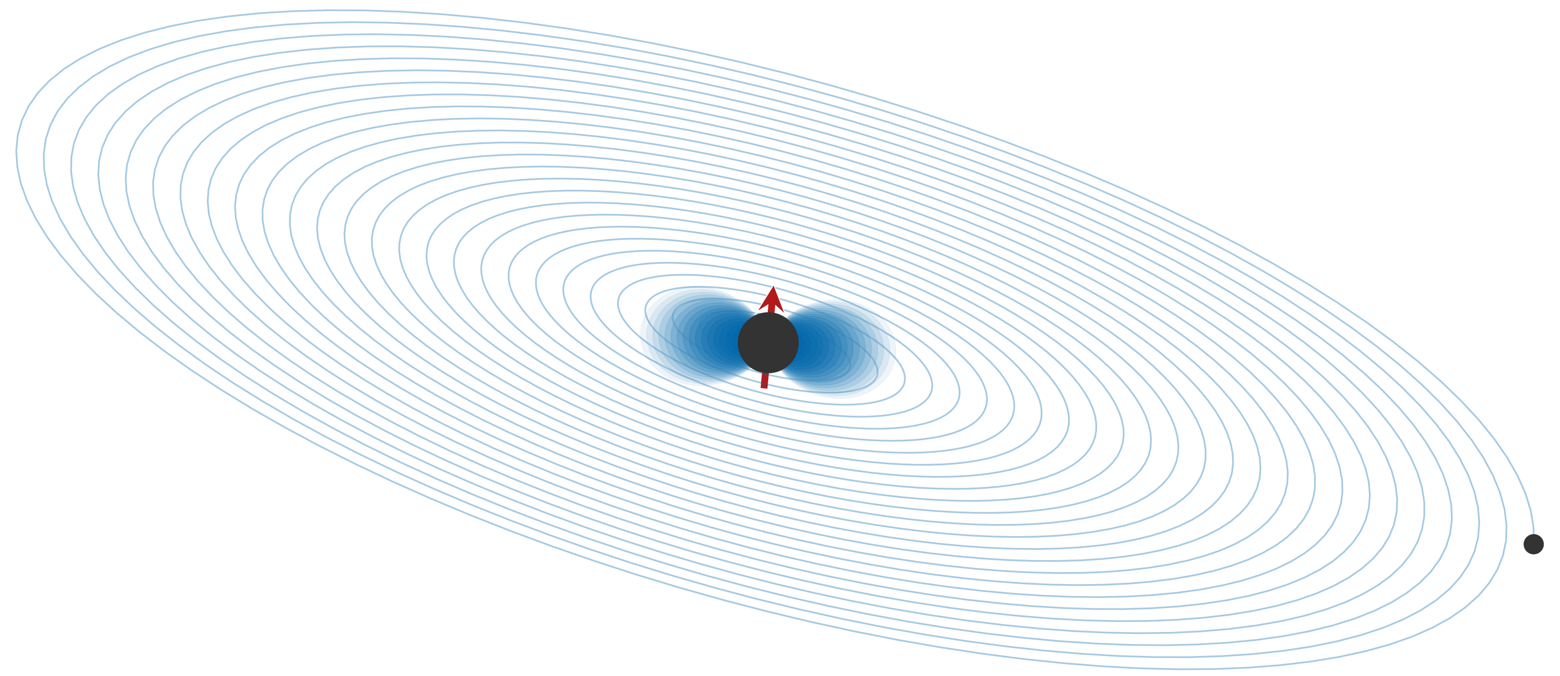

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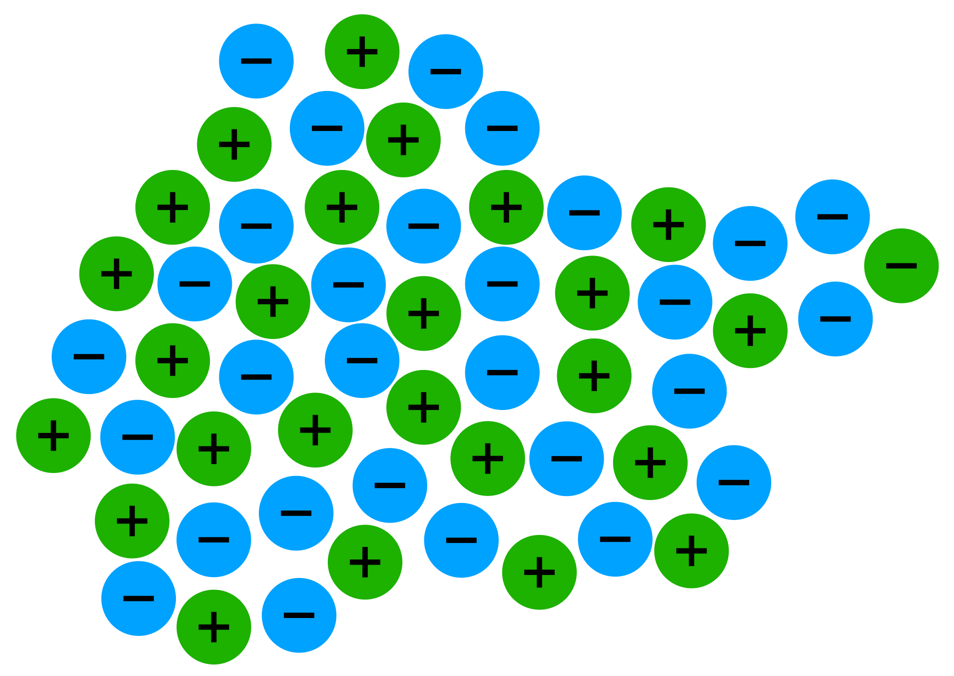
Axionic couplings — Plasma effects

Consider a plasma in the **two-fluid formalism**, where **electrons** and **ions** are treated as separate fluids, coupled through the **Maxwell equations**



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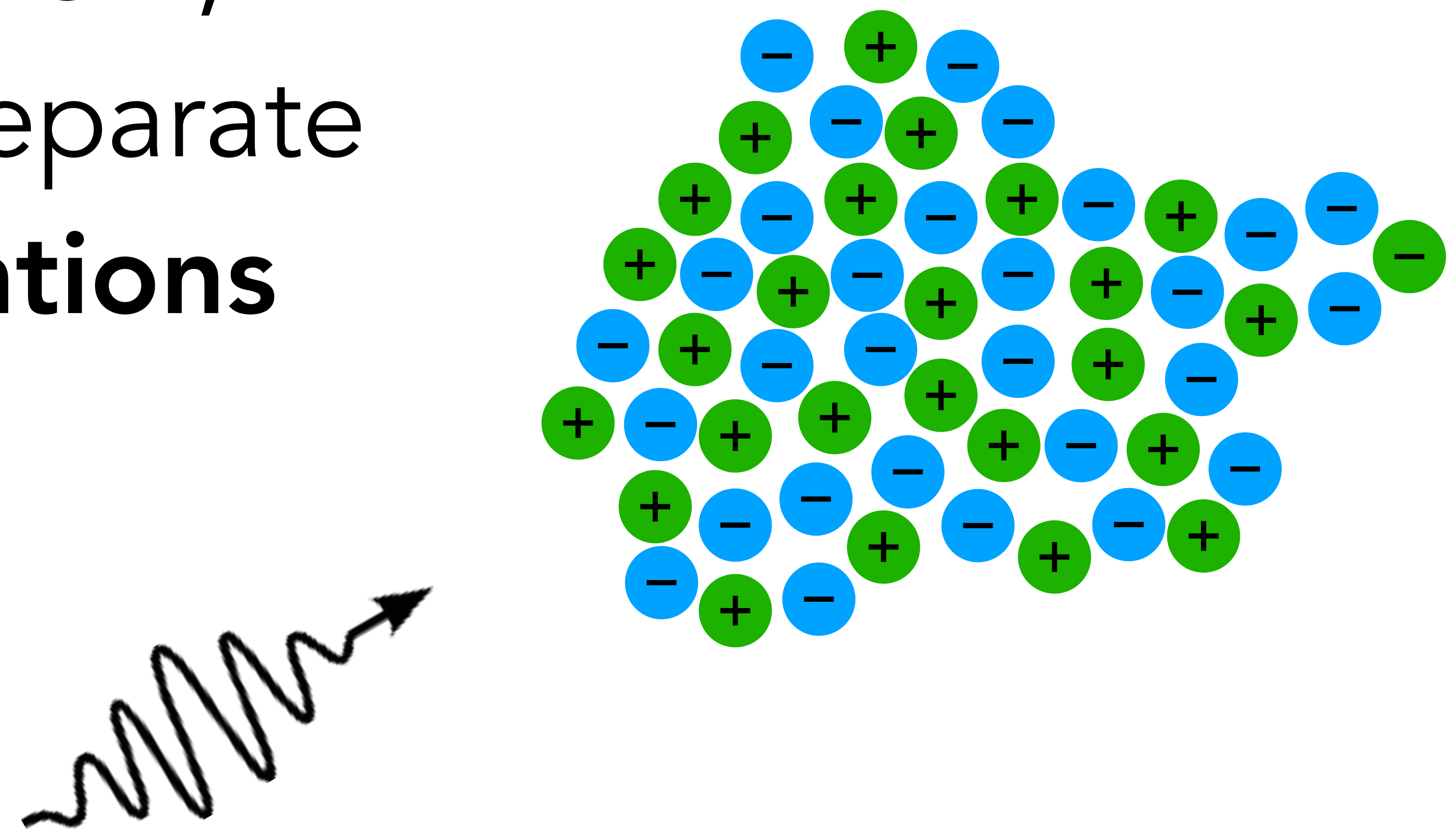
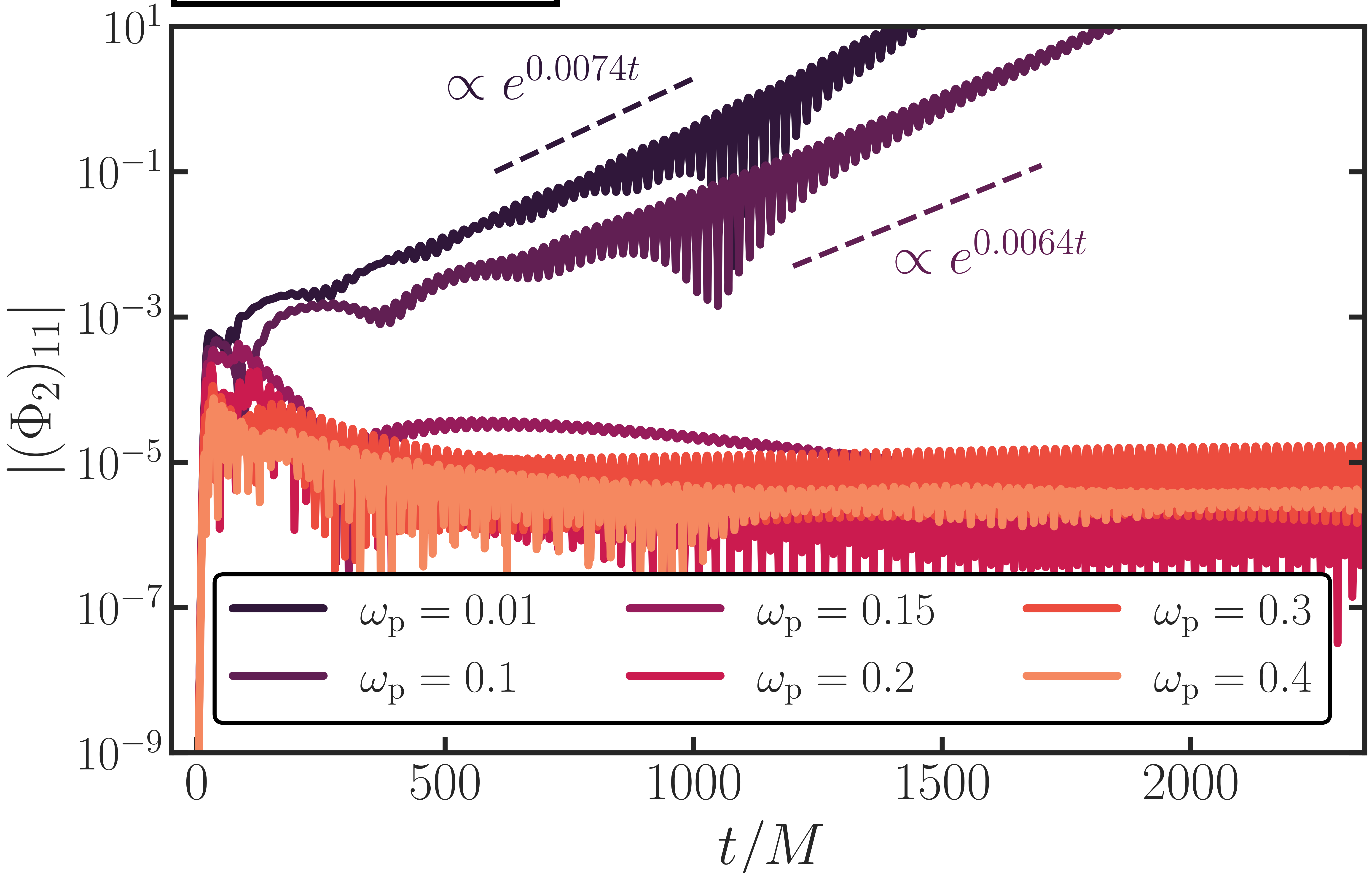


If **plasma** is perturbed by an EM wave, electrons are displaced and start **oscillating** with the **plasma frequency**:

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

Axionic couplings — Plasma effects

$\boxed{\mu M = 0.3}$



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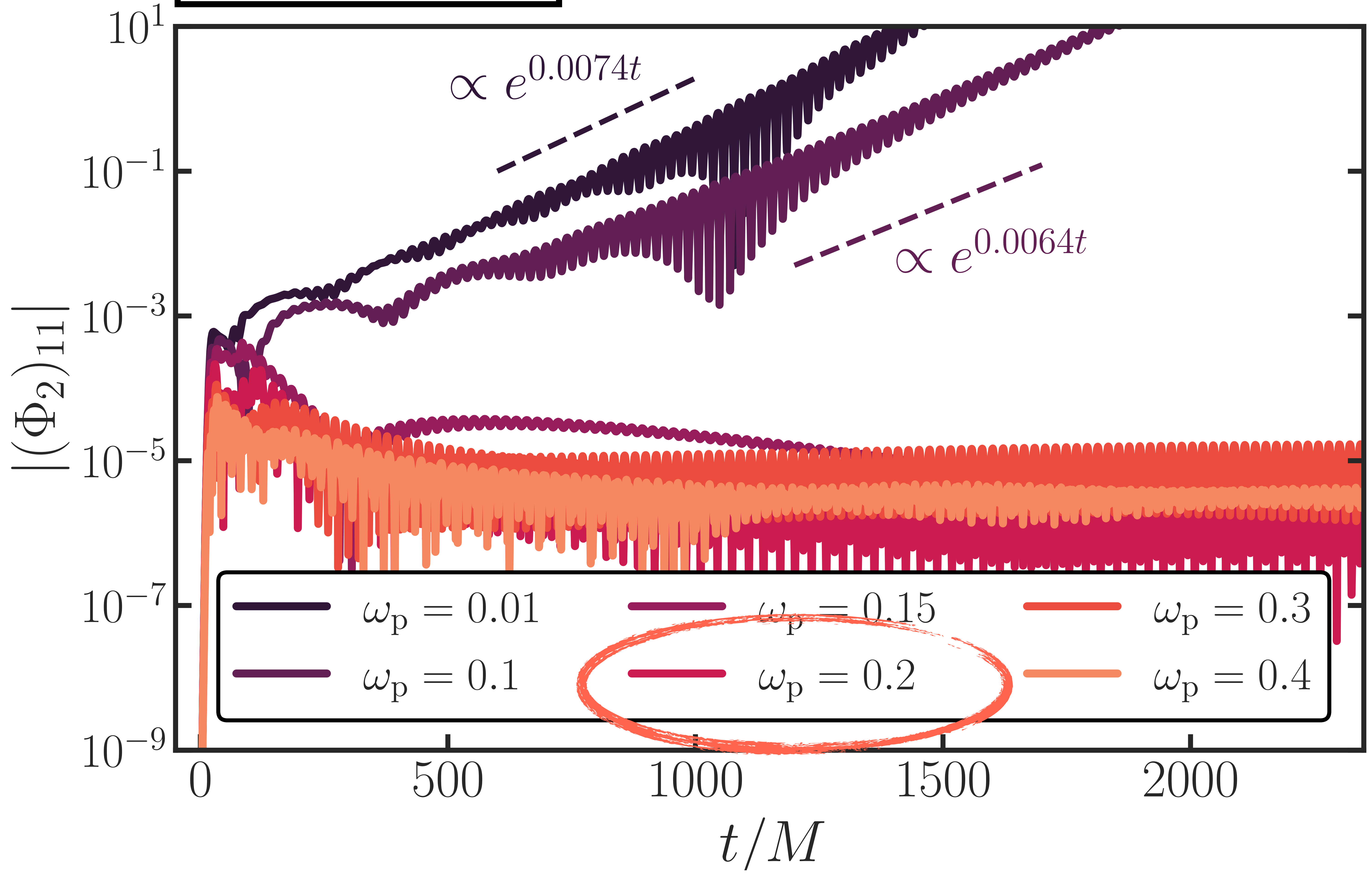


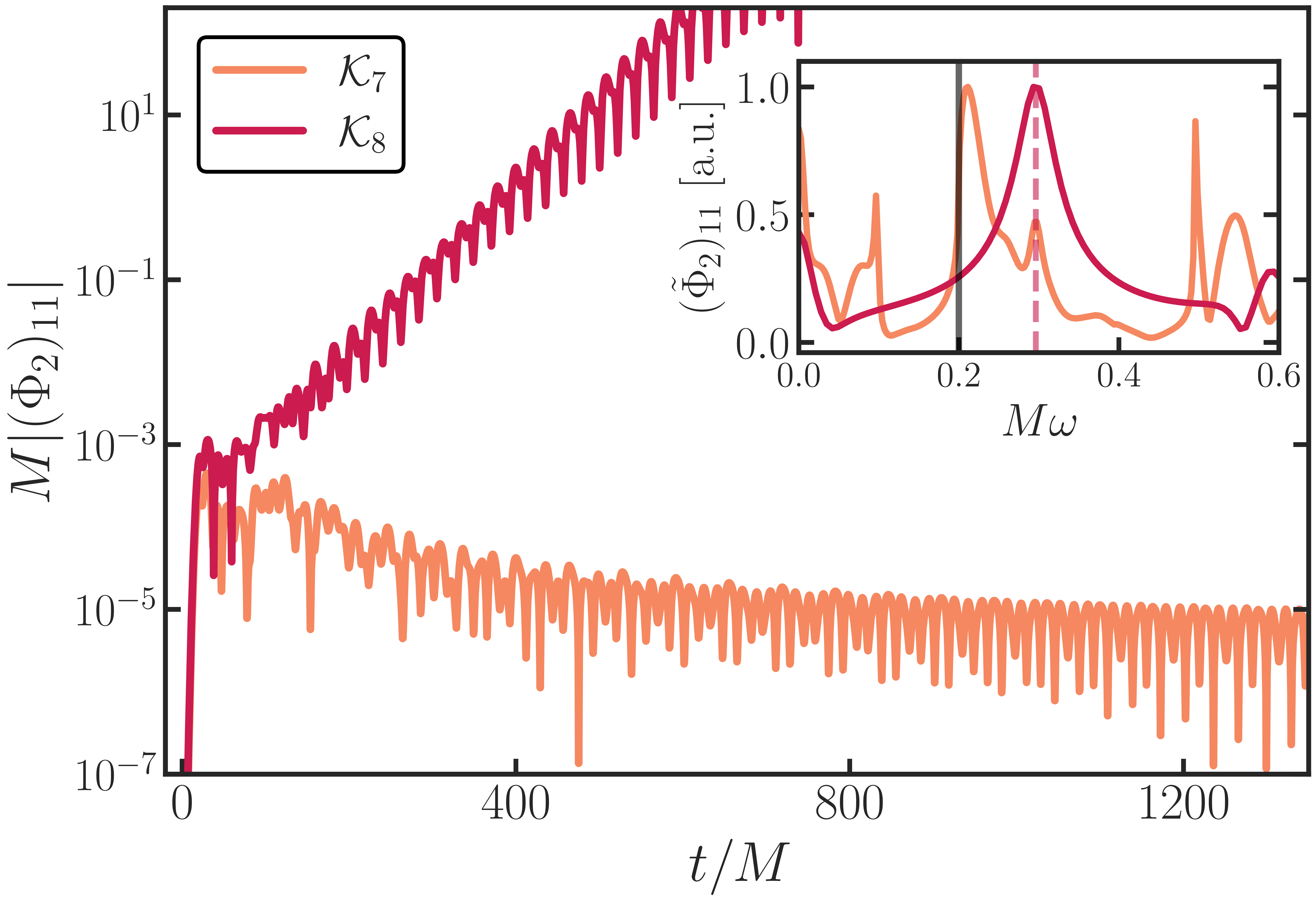
A burst is highly **suppressed** when

$$\omega_p > \mu/2$$

Axionic couplings — Higher bands

$\mu M = 0.3$

$\omega_{\rm p} M = 0.2$



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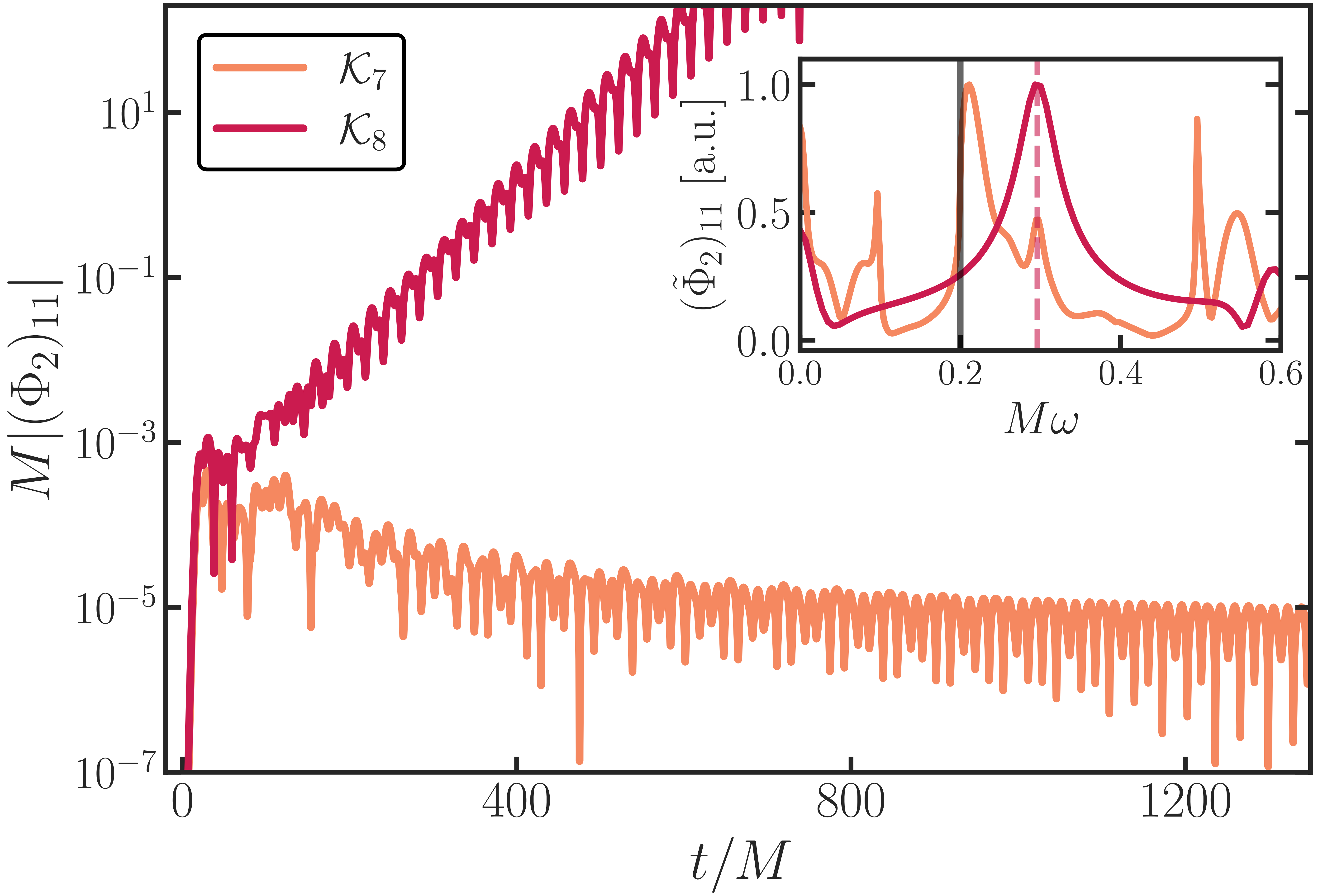

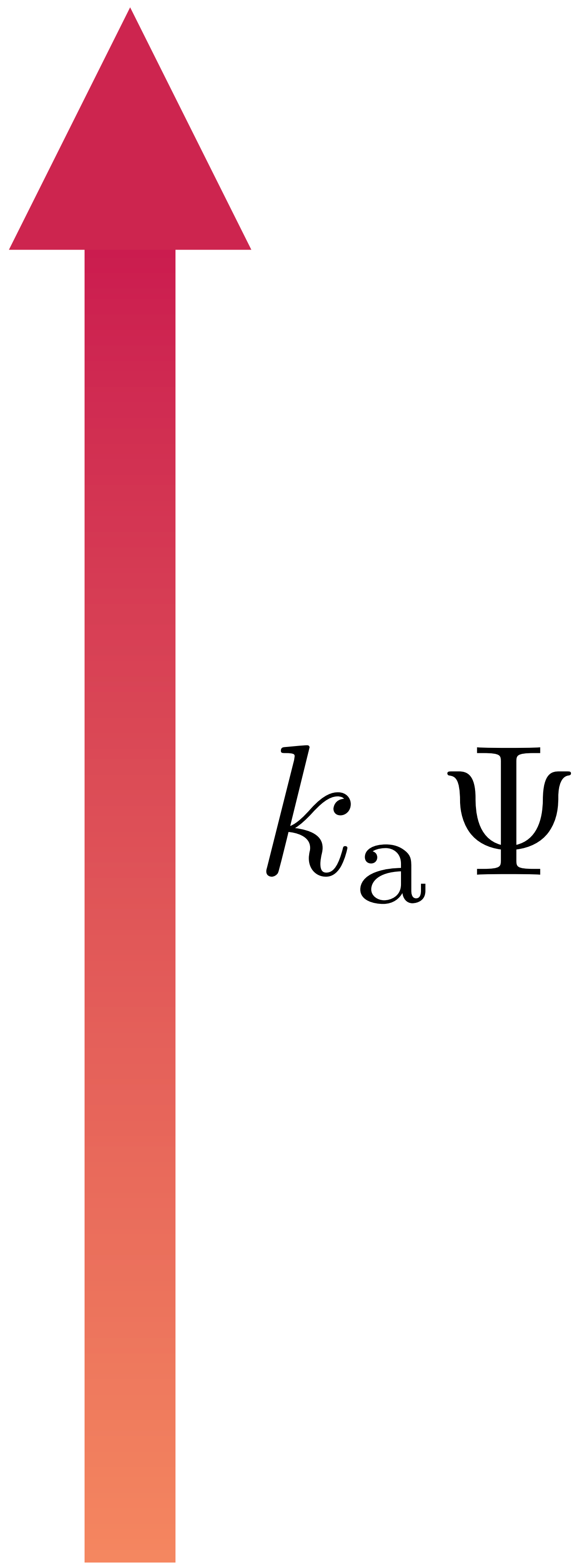

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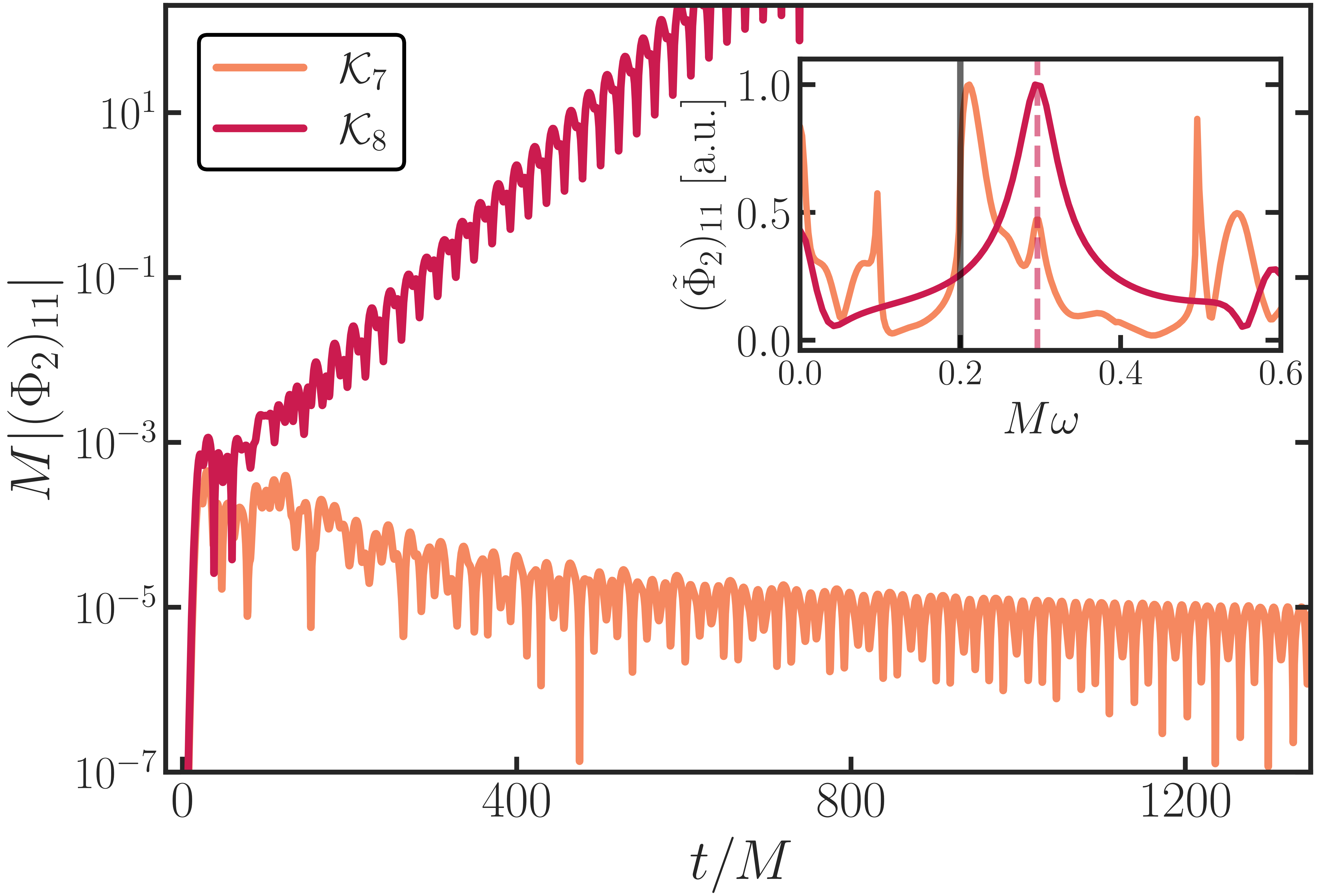

The **Mathieu** equation again!

$$\partial_T^2 y + \frac{1}{\mu}\left(p_z^2 + \omega_{\rm p}^2 - 2\mu p_z \Psi_0 k_{\rm a} \sin T\right) y = 0$$

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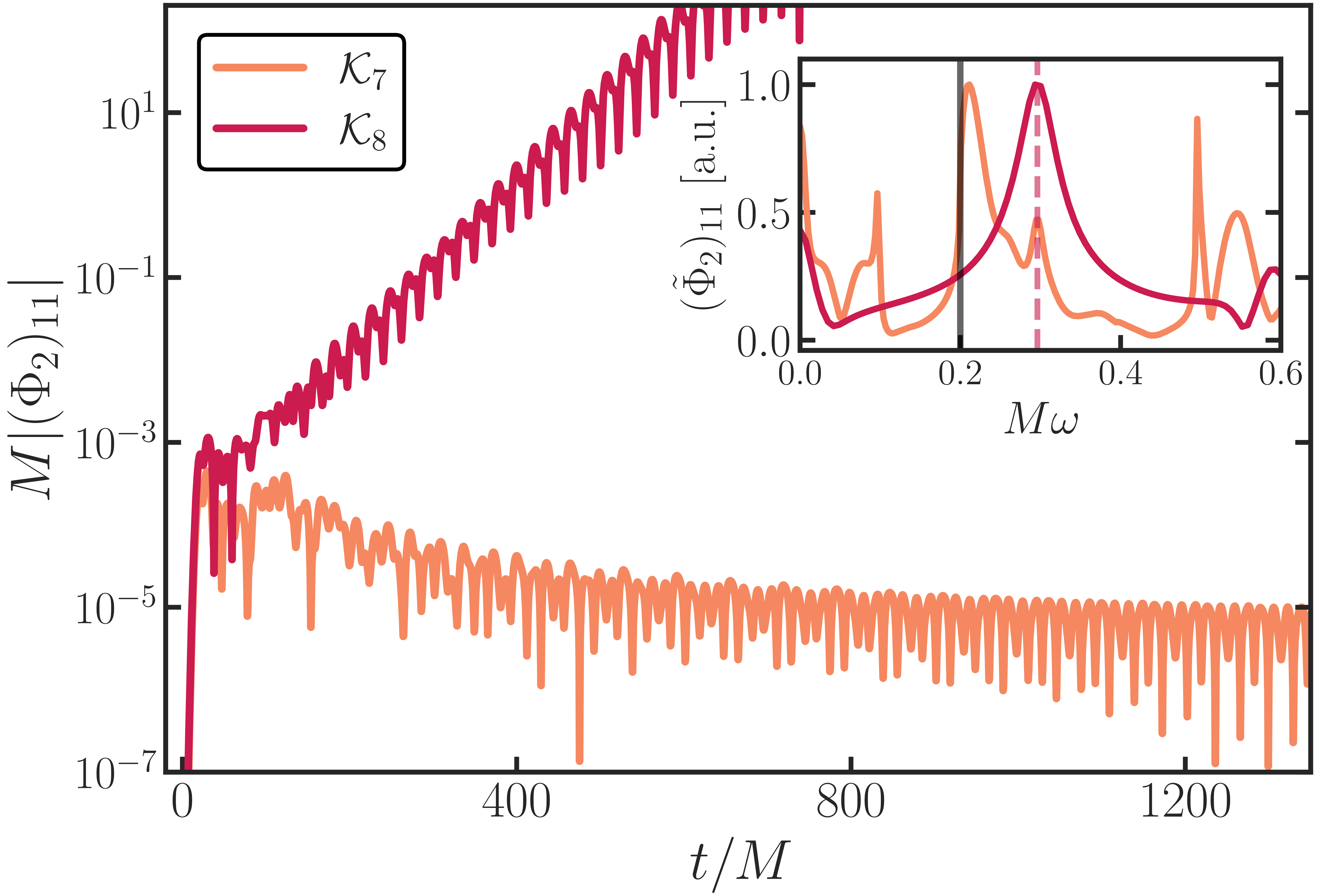

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$$p_z^2 + \omega_{\rm p}^2 = n^2 \frac{\mu^2}{4}\,, \text{with} \quad n \in \mathbb{N}$$

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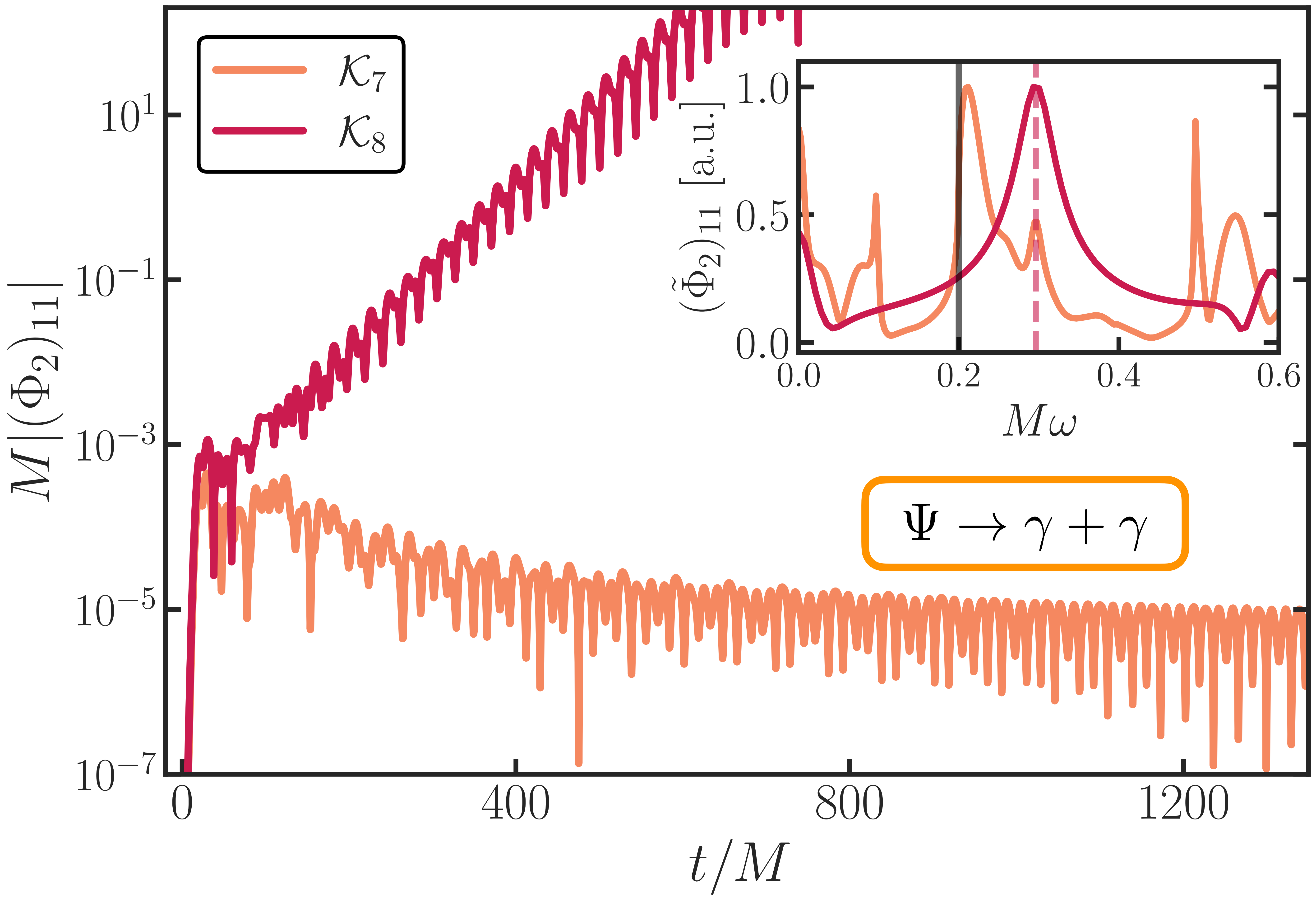
$$\boxed{\Psi + \Psi \to \gamma + \gamma}$$



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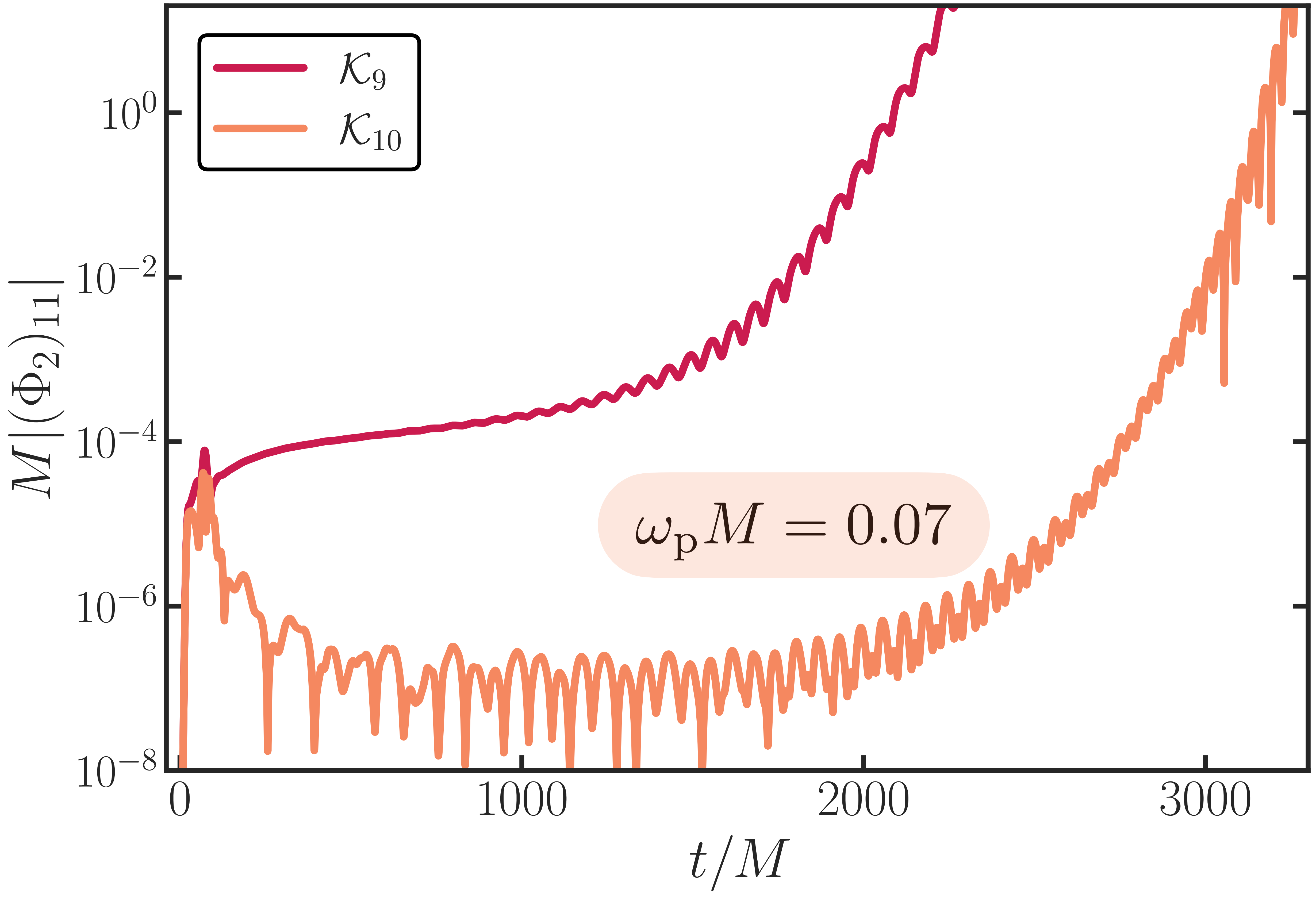
Superradiance to the **rescue**!

$$\boxed{\mu M = 0.1}$$



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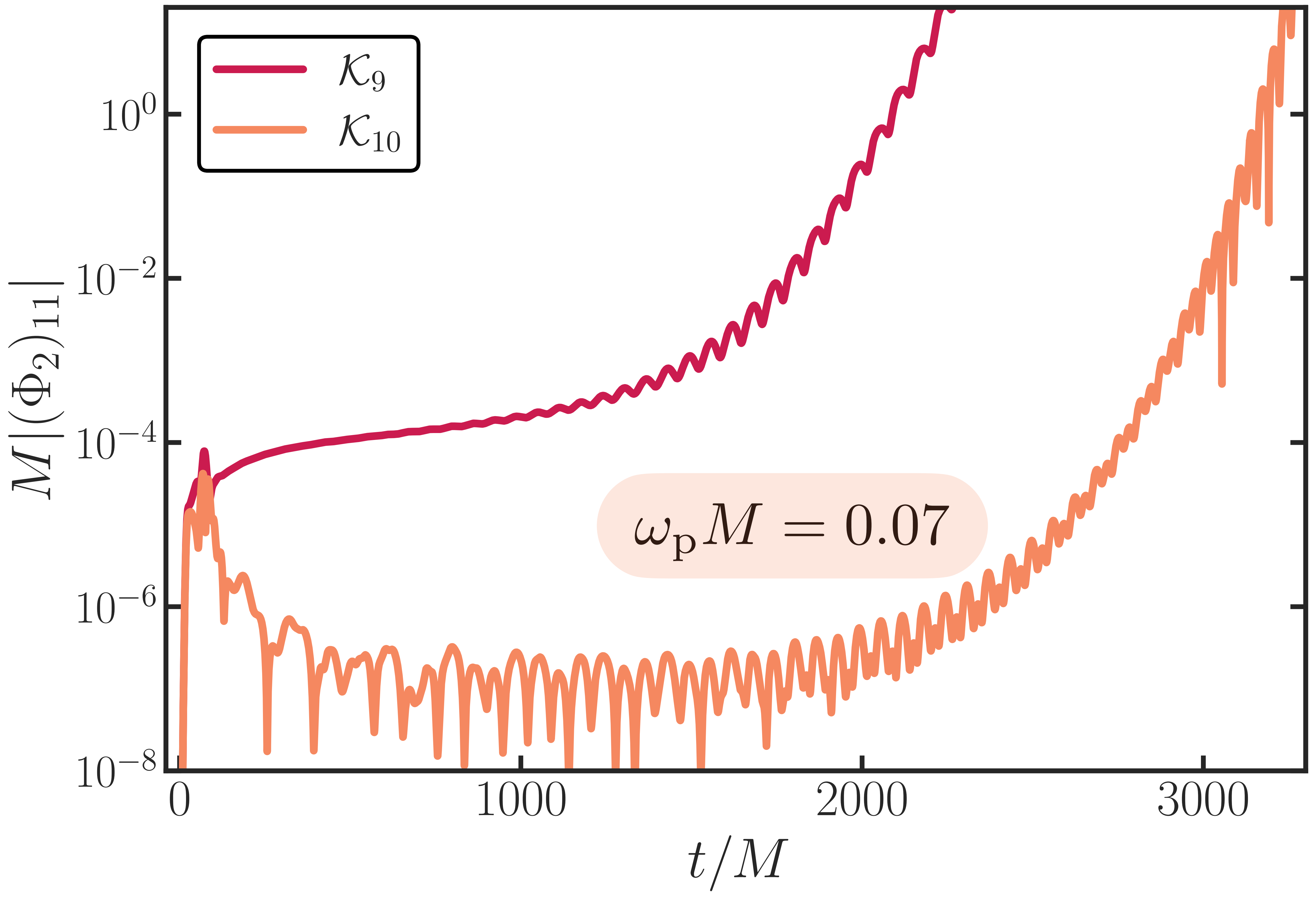

$$\partial_T^2 y + \frac{1}{\mu}\left(p_z^2 + \cancel{\omega_{\mathrm{p}}^2} - 2\mu p_z \Psi_0 k_{\mathrm{a}} \sin T\right) y = 0$$

▼

$$k_{\mathrm{a}}\Psi_0 \geq \frac{\omega_{\mathrm{p}}^2 + p_z^2}{2\mu p_z} \approx \frac{\omega_{\mathrm{p}}^2}{\mu^2}$$

Axionic couplings — Plasma and superradiance

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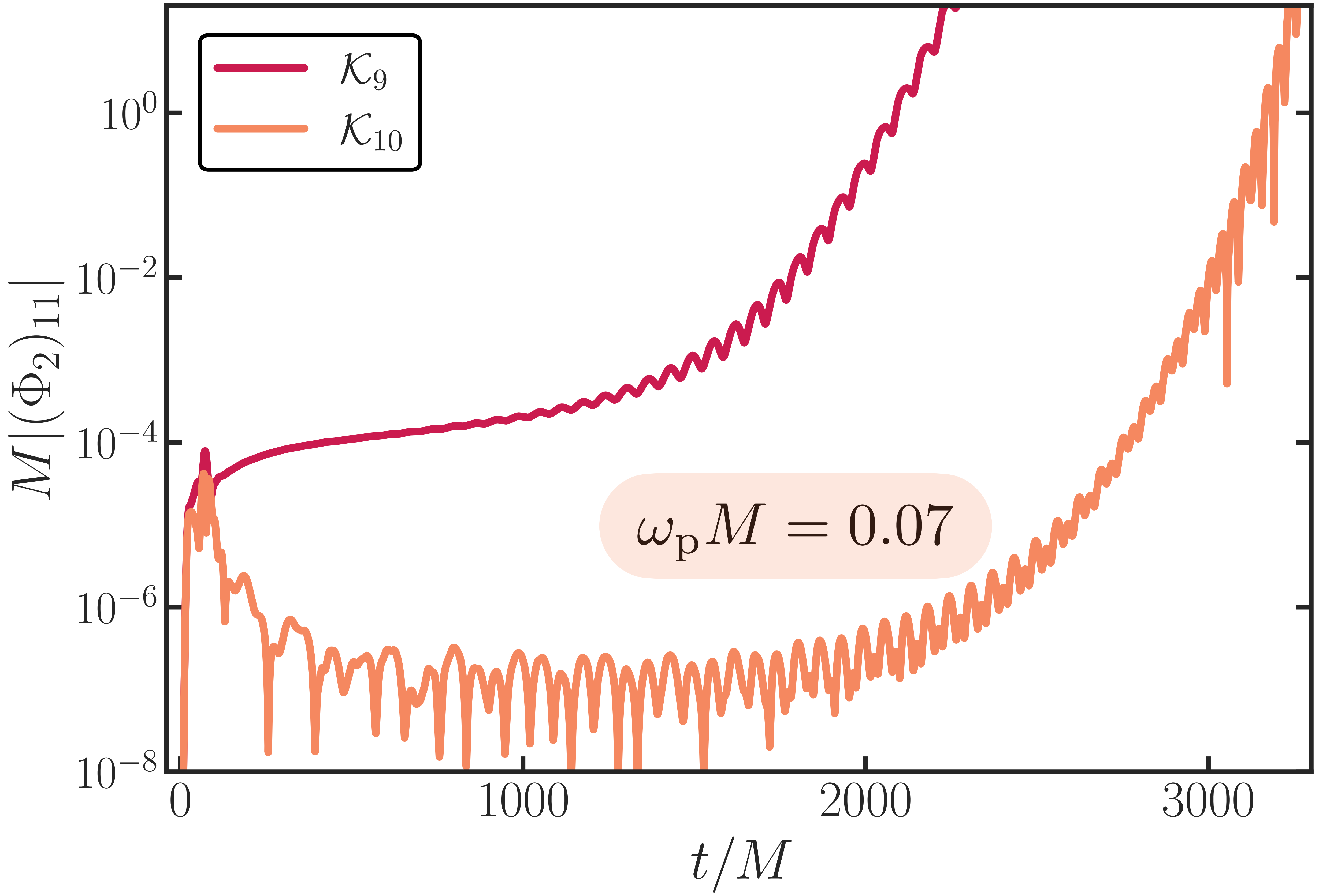
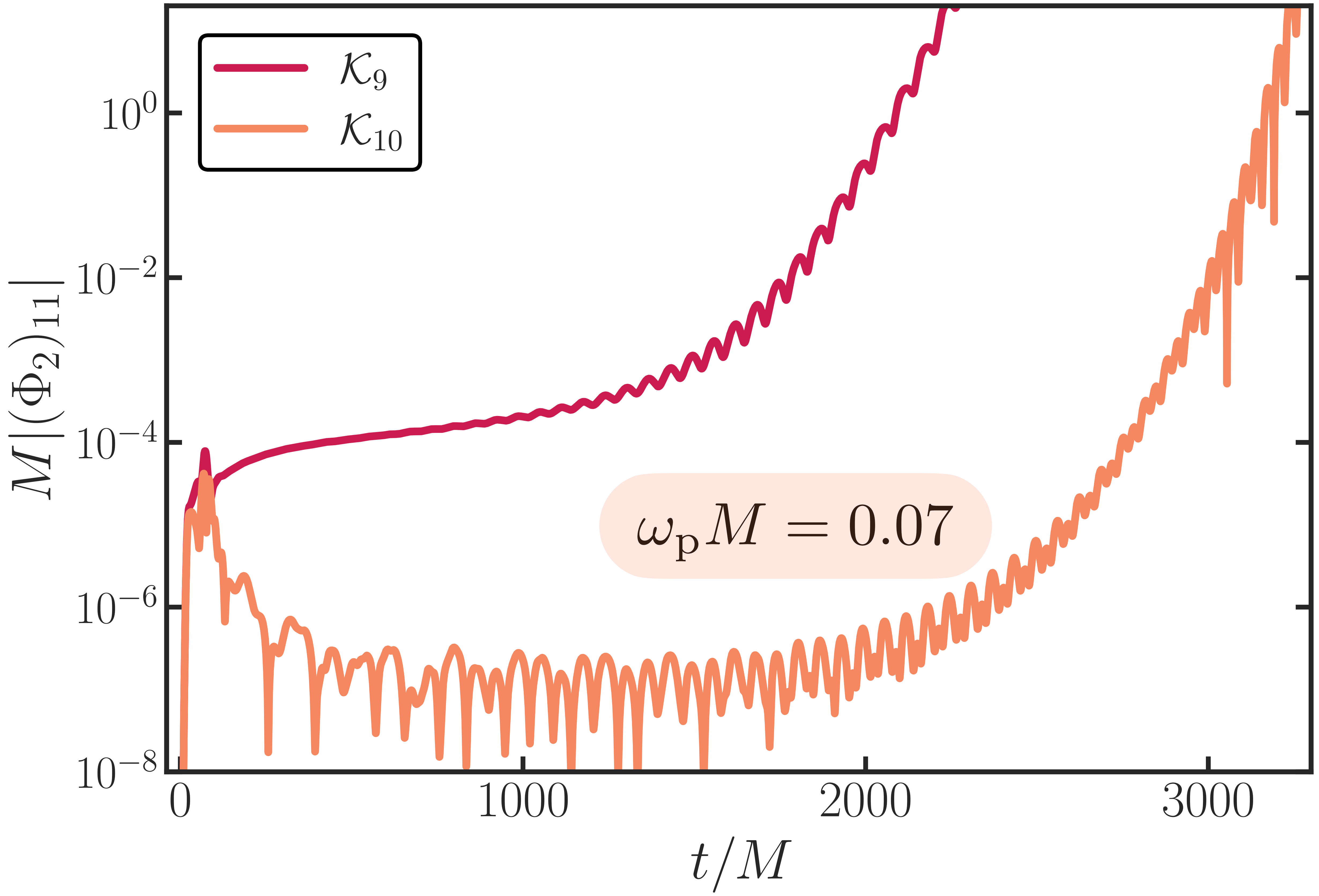


$$\frac{10^{-13}\ \mathrm{GeV}^{-1}}{k_\mathrm{a}} \lesssim 8\times 10^5 \left(\frac{10^{-3}\ \mathrm{cm}^{-3}}{n_\mathrm{e}}\right)\left(\frac{M_\mathrm{c}/M}{0.1}\right)^{1/2} \times \left(\frac{1M_\odot}{M}\right)^2 \left(\frac{\mu M}{0.2}\right)^4$$

Superradiance to the **rescue**!

$$\boxed{\mu M = 0.1}$$



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

Instabilities triggered for plasmas way denser than the **interstellar medium**!

Conclusions

Superradiance offers a way to explore the ultralight, **weak-coupling** regime of particle physics

- ✦ Consistent evolution of the coupled cloud-Maxwell system reveals a **monochromatic**, **powerful** flux of light
- ✦ Consideration of astrophysical plasma is important, as it may **stop** the signal from **propagating**

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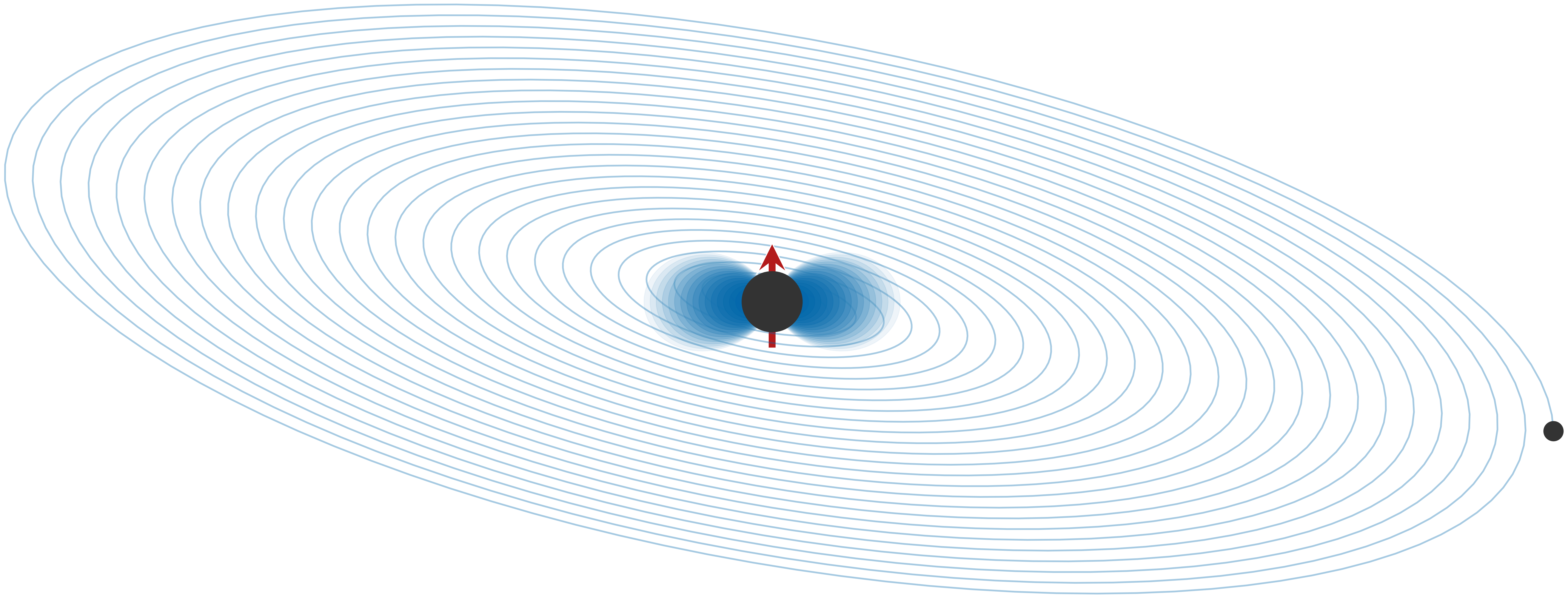
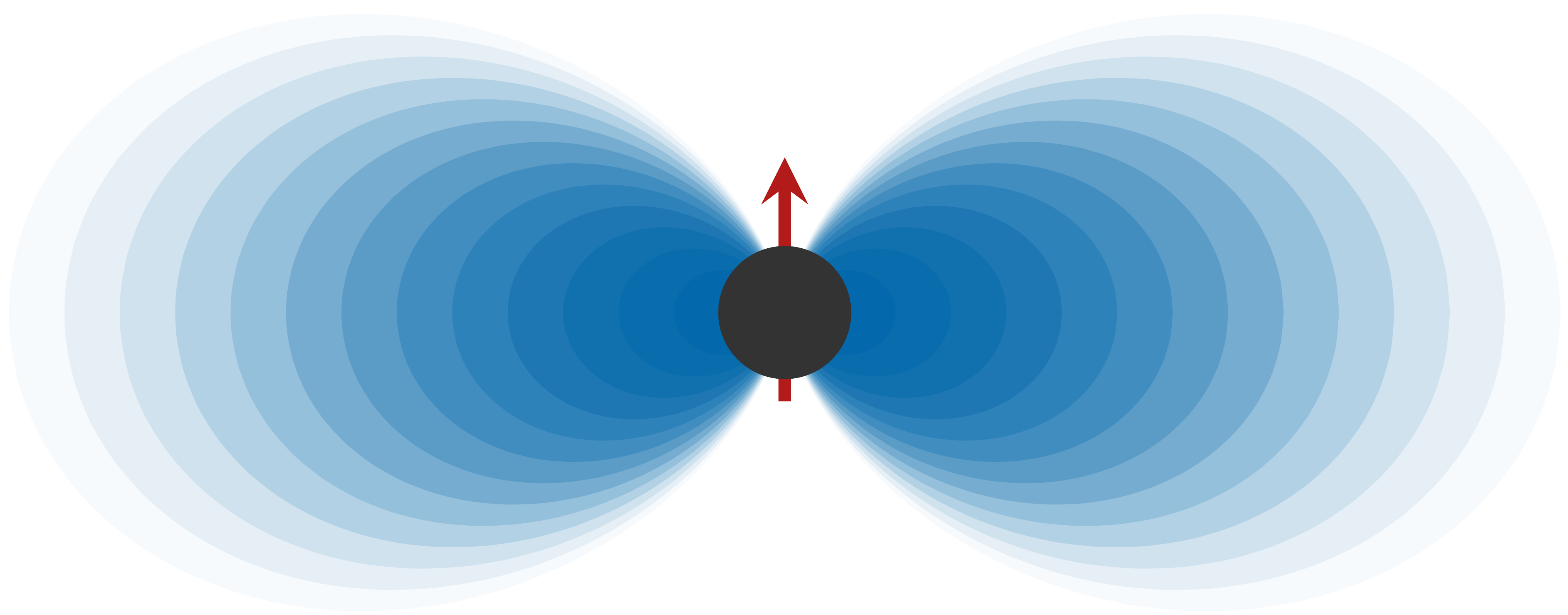
↓

Further analysis should focus on **geometric structure** and **nonlinear effects** of the plasma

Boson clouds in black hole binaries



Boson clouds in binaries



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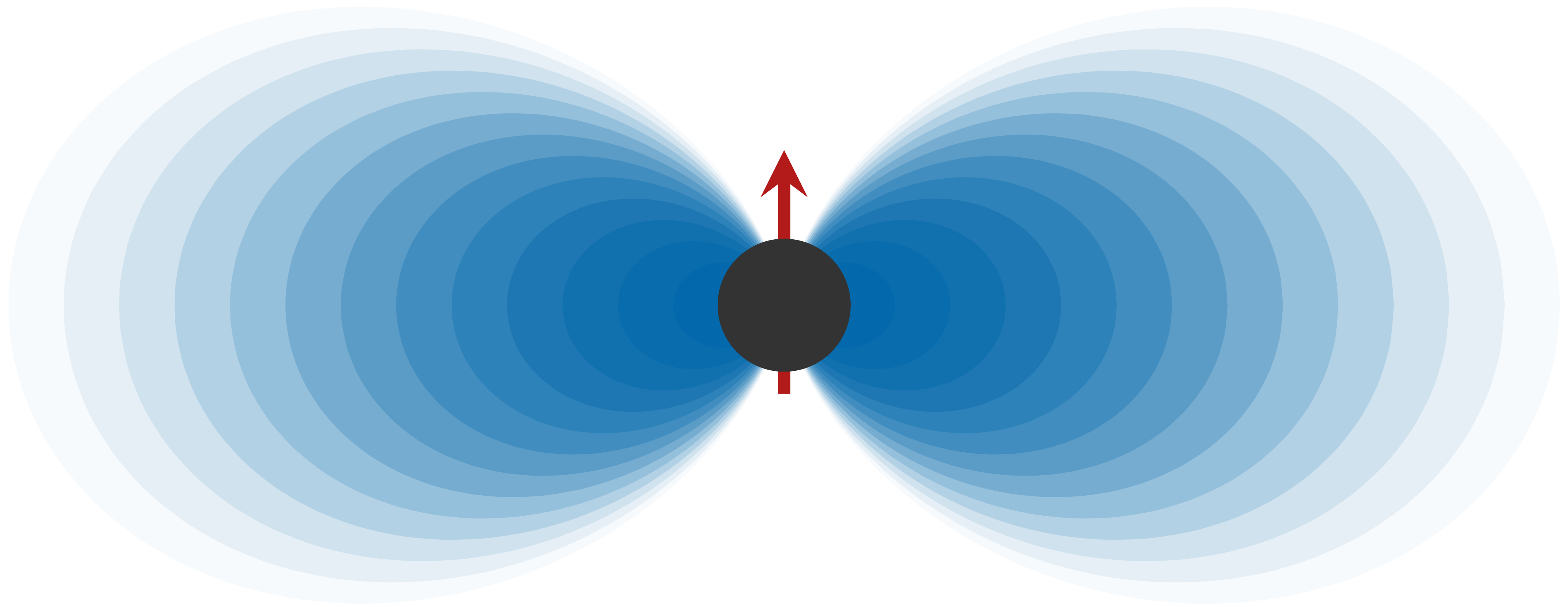

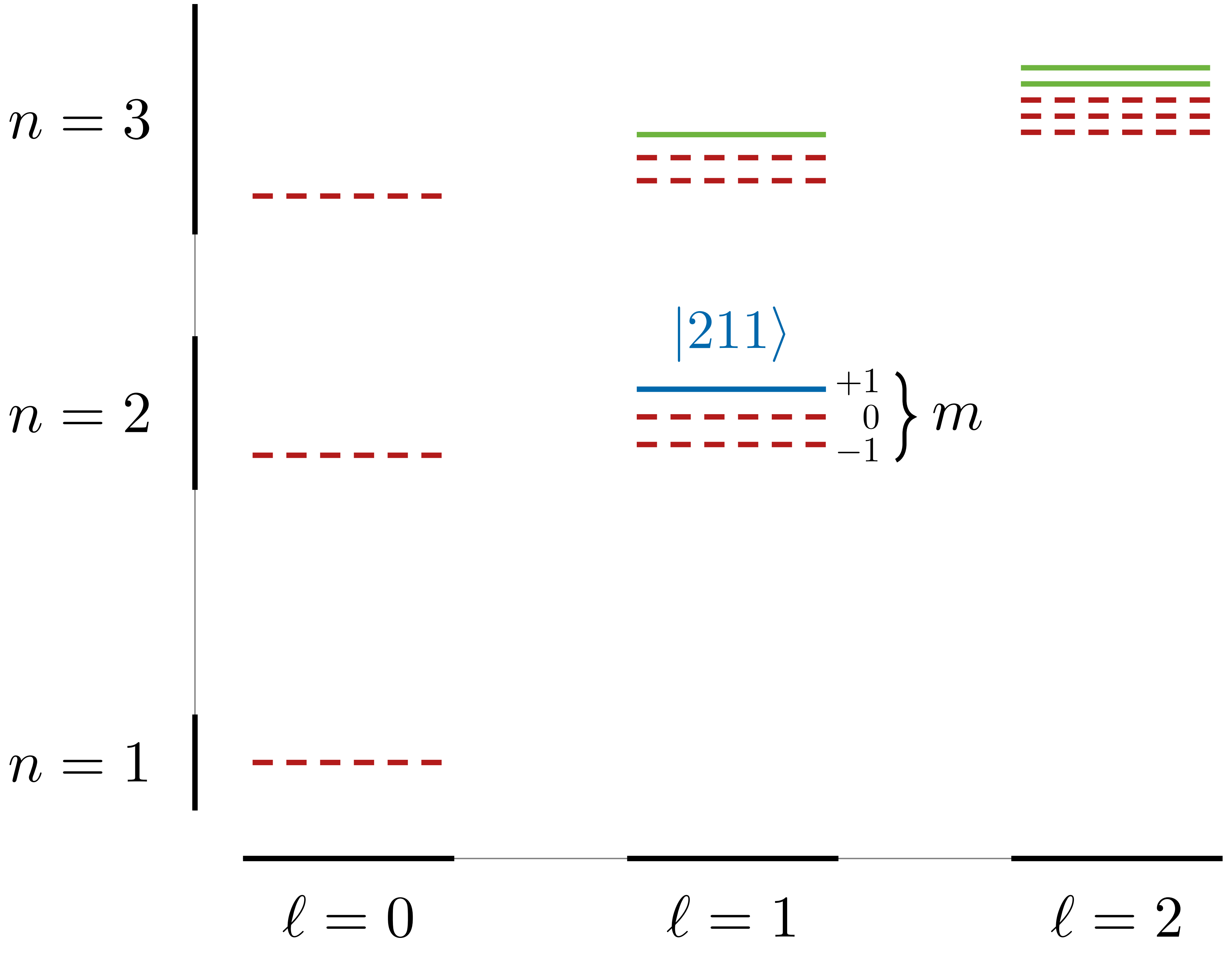

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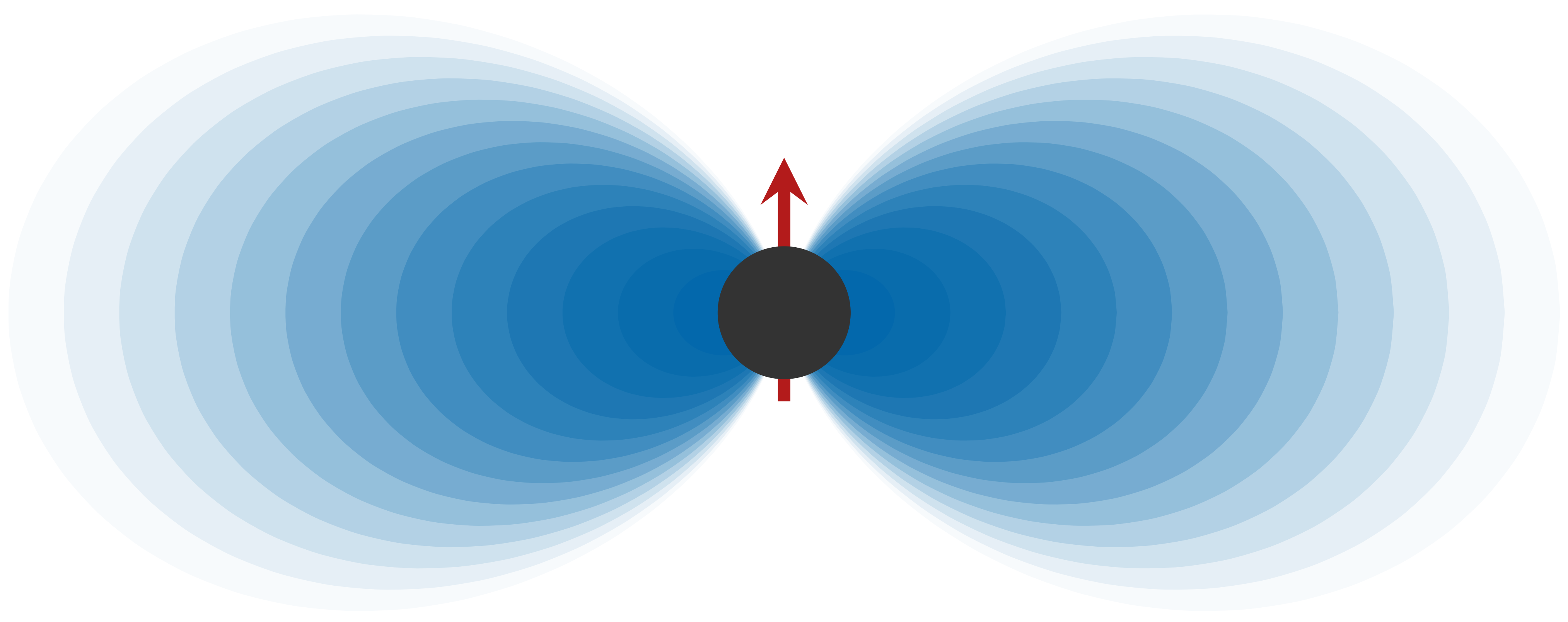
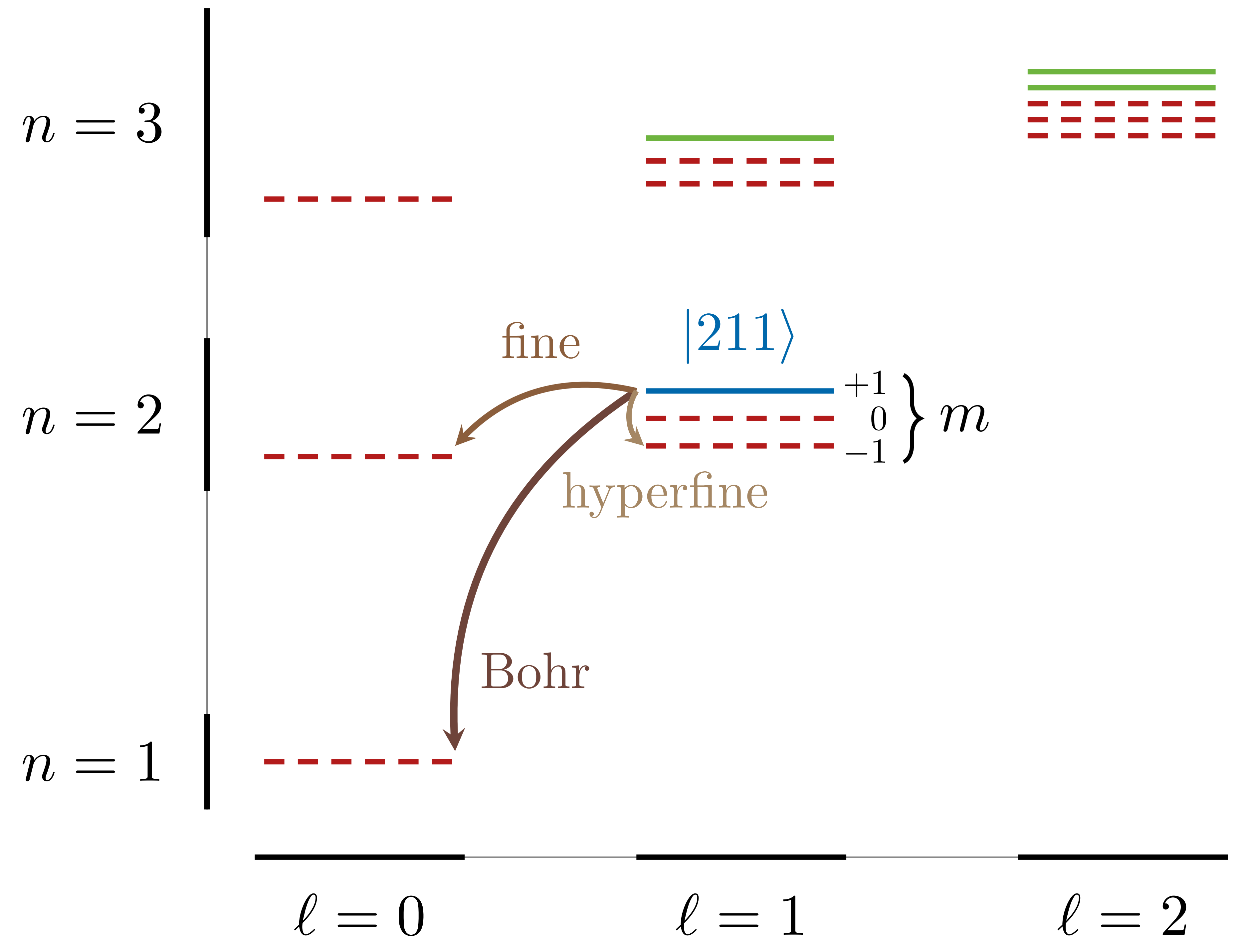
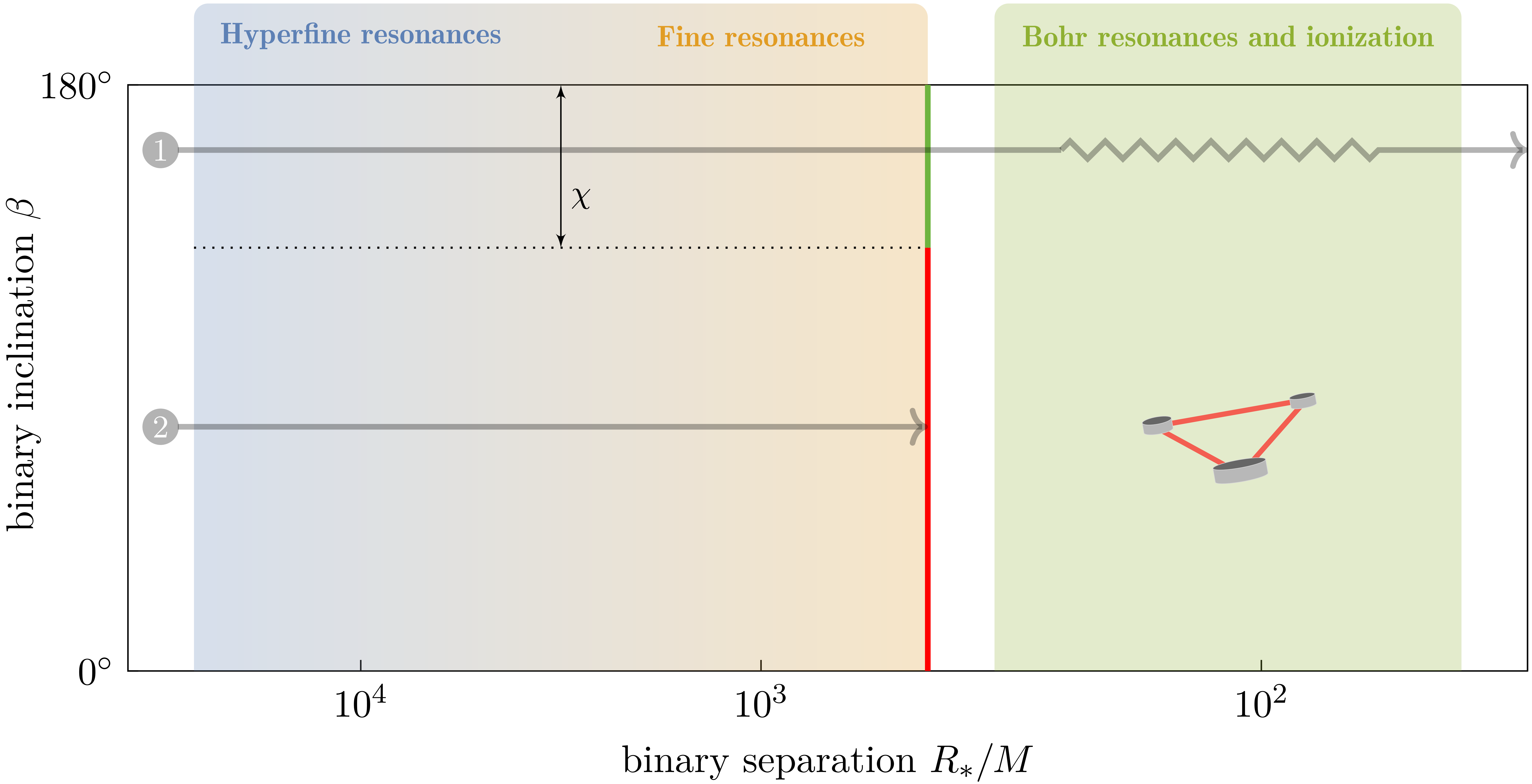
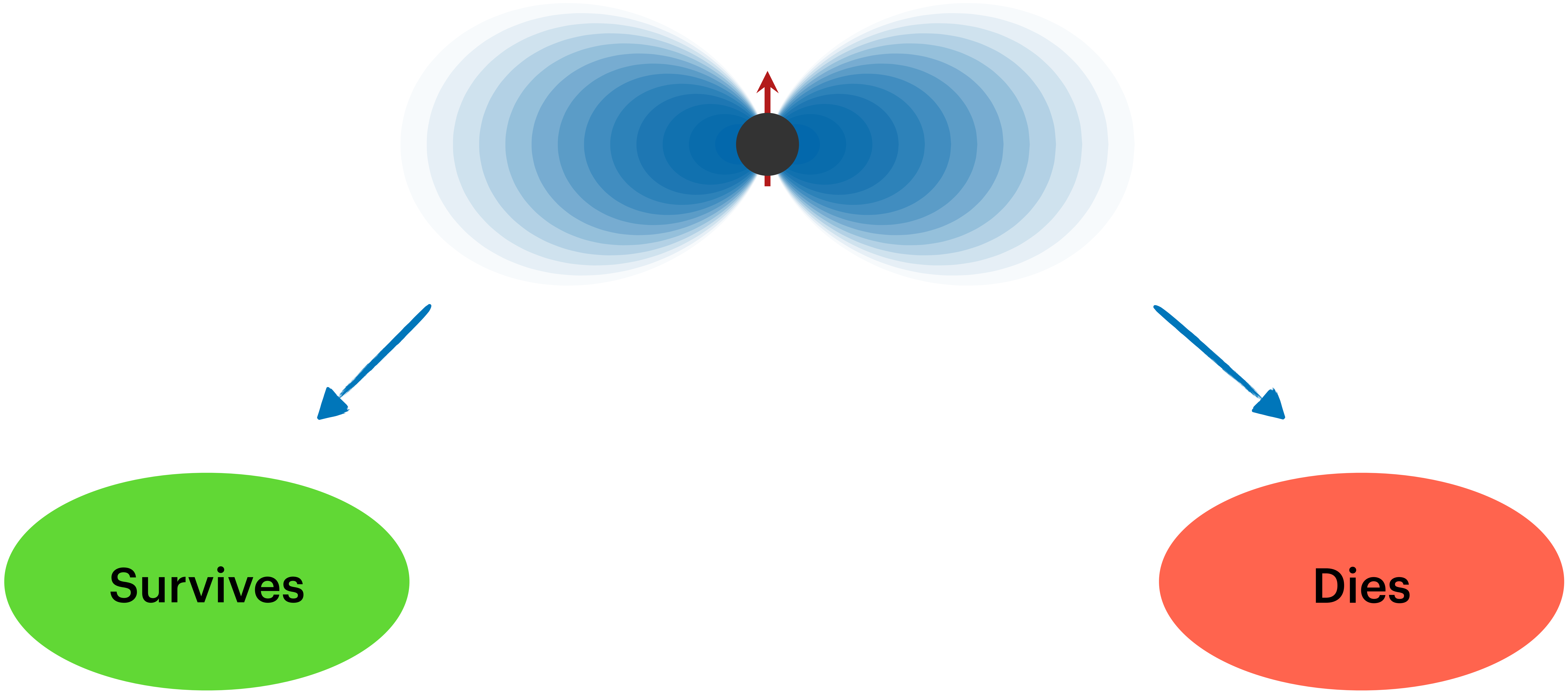




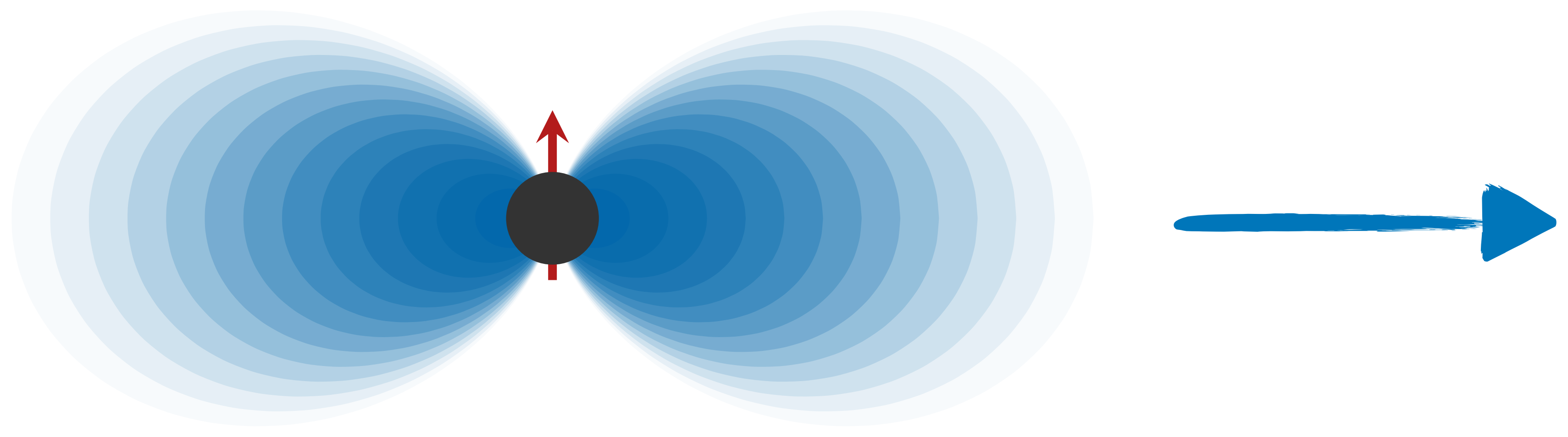
The resonant history



Two outcomes

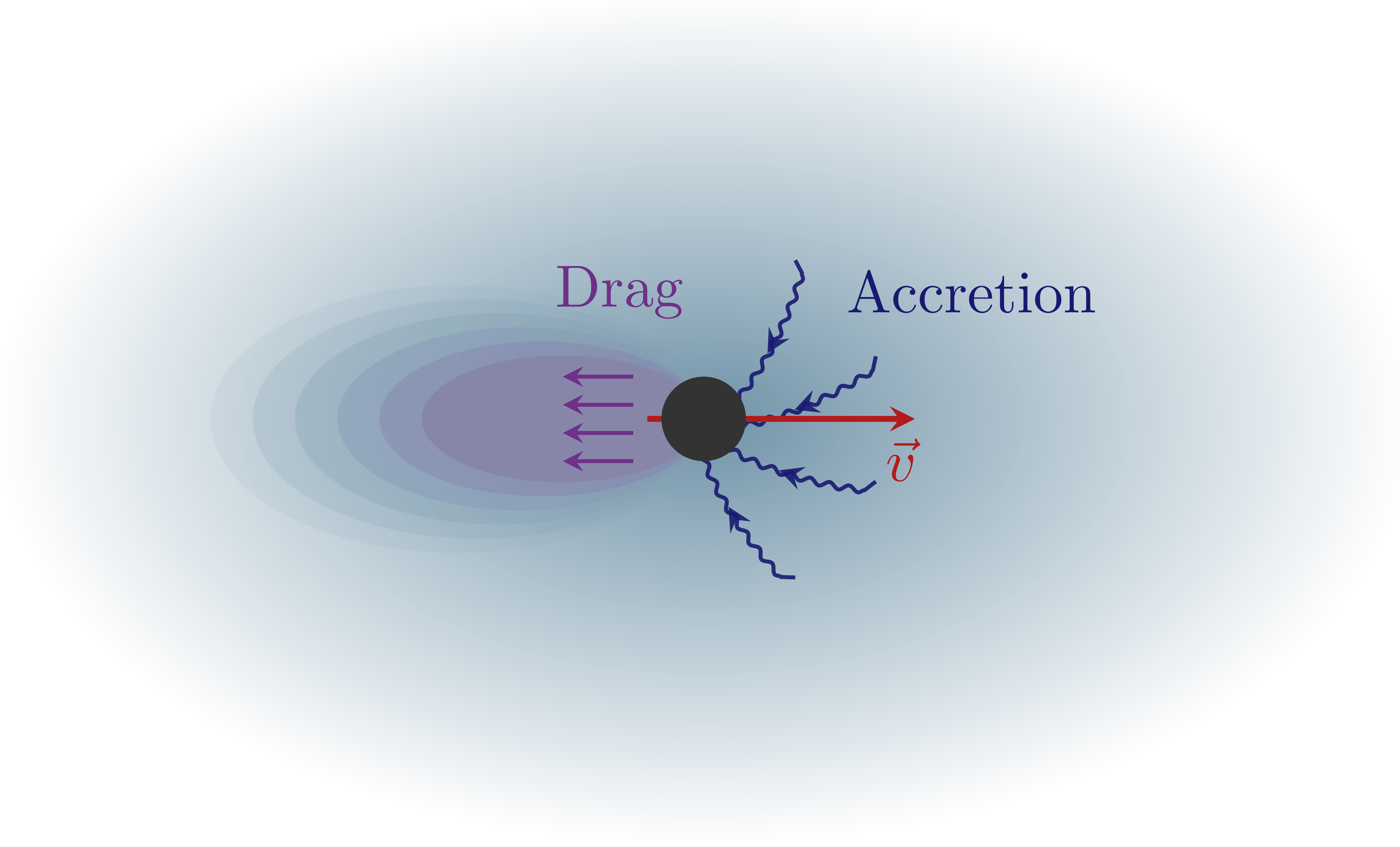


Direct signatures



Survives

Direct observational signatures through **dynamical effects**...



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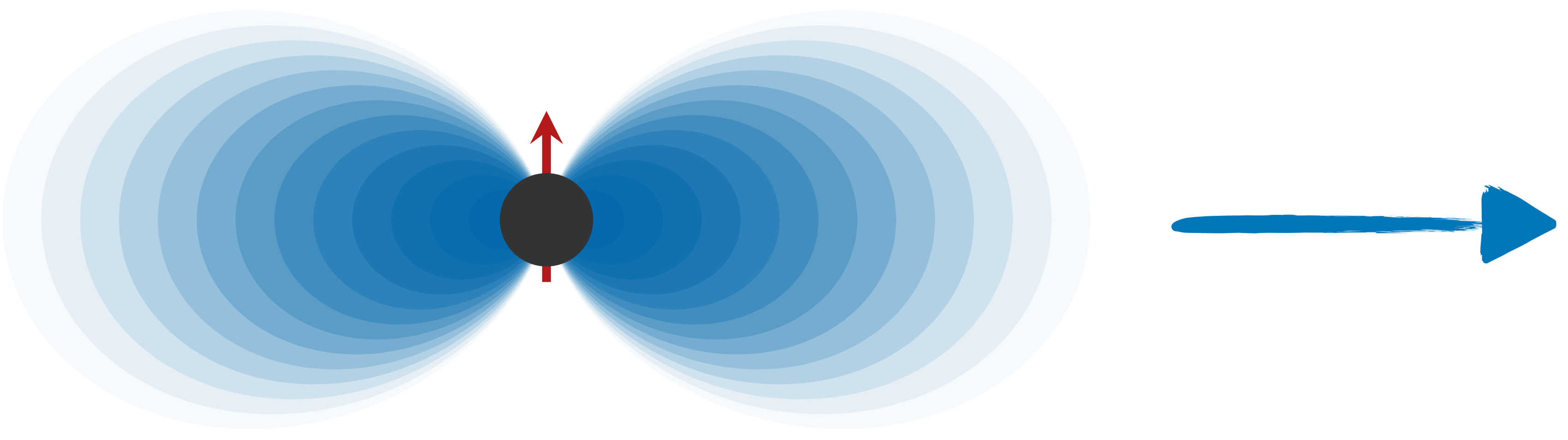

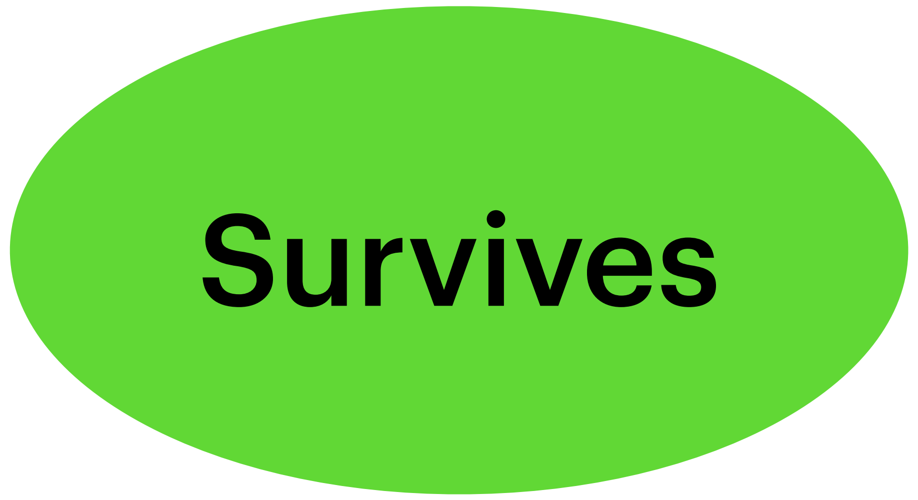

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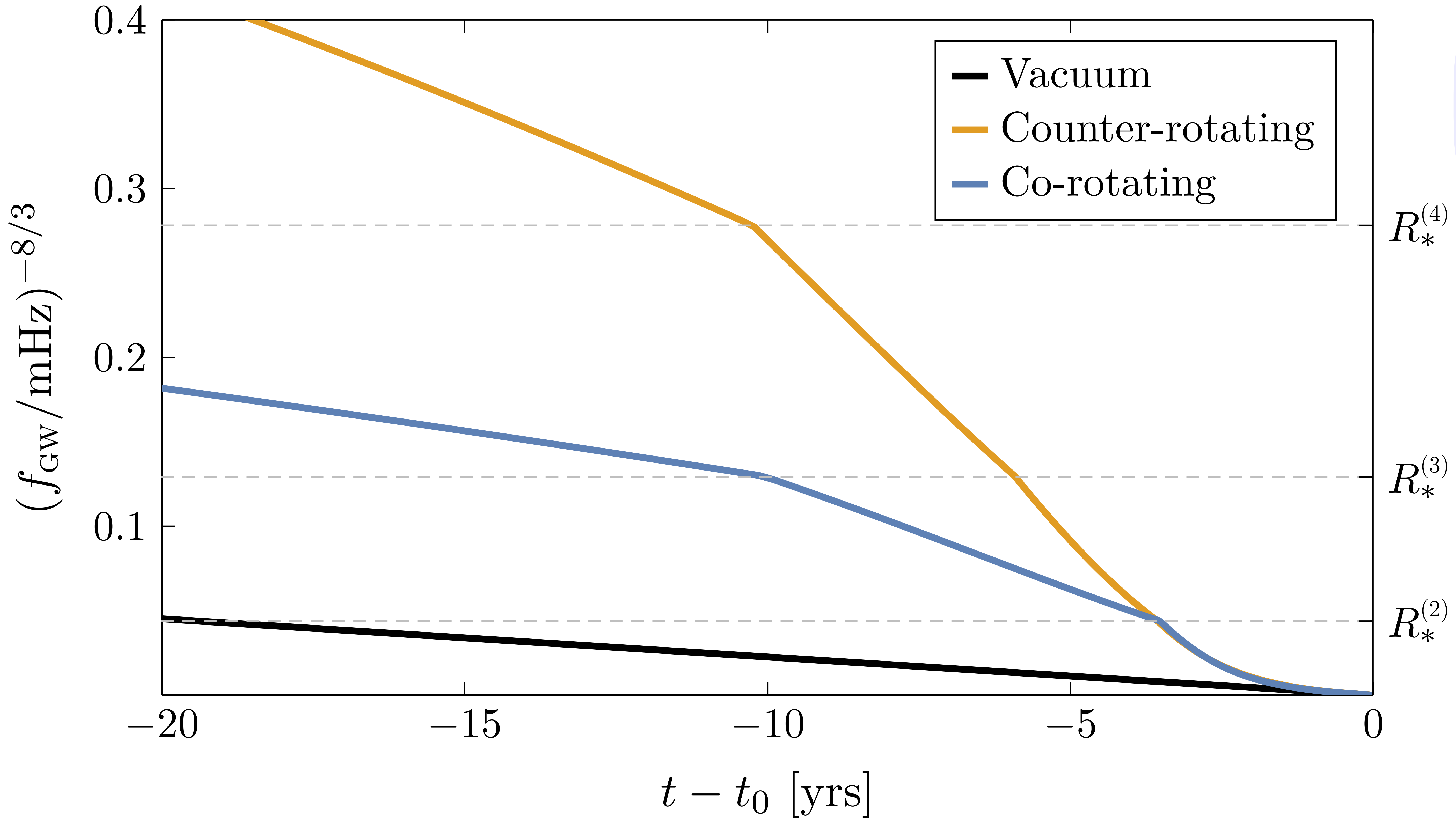
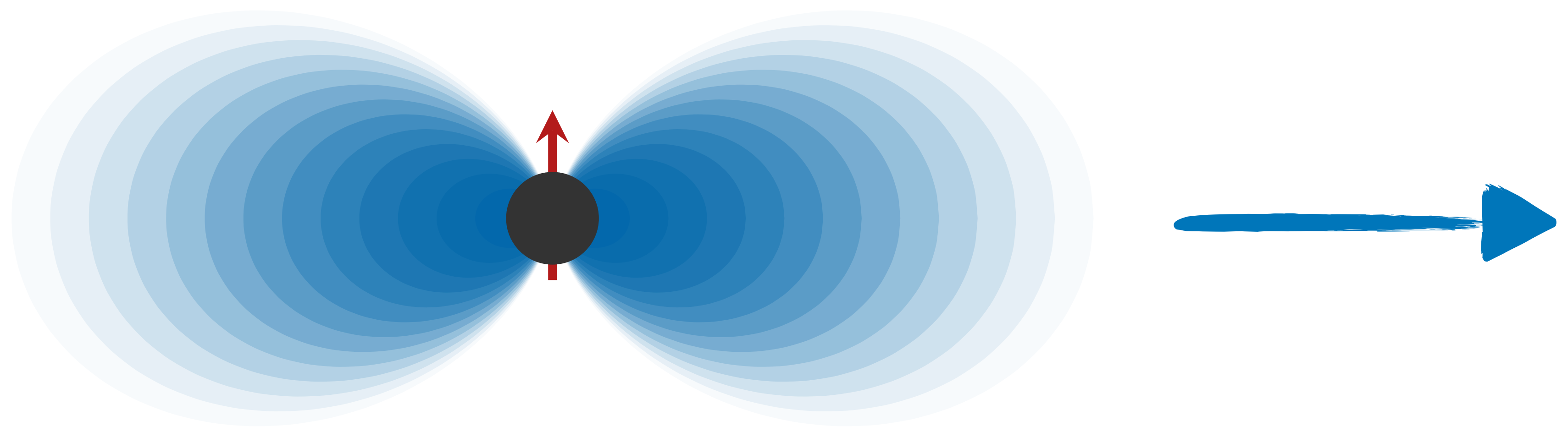


$$f_{\mathrm{GW}}^{(g)} = \frac{6.45\mathrm{mHz}}{g}\left(\frac{10^4 M_\odot}{M}\right)\left(\frac{\alpha}{0.2}\right)^3\left(\frac{2}{n}\right)$$

 [Baumann *et al.* ’22]

Direct signatures



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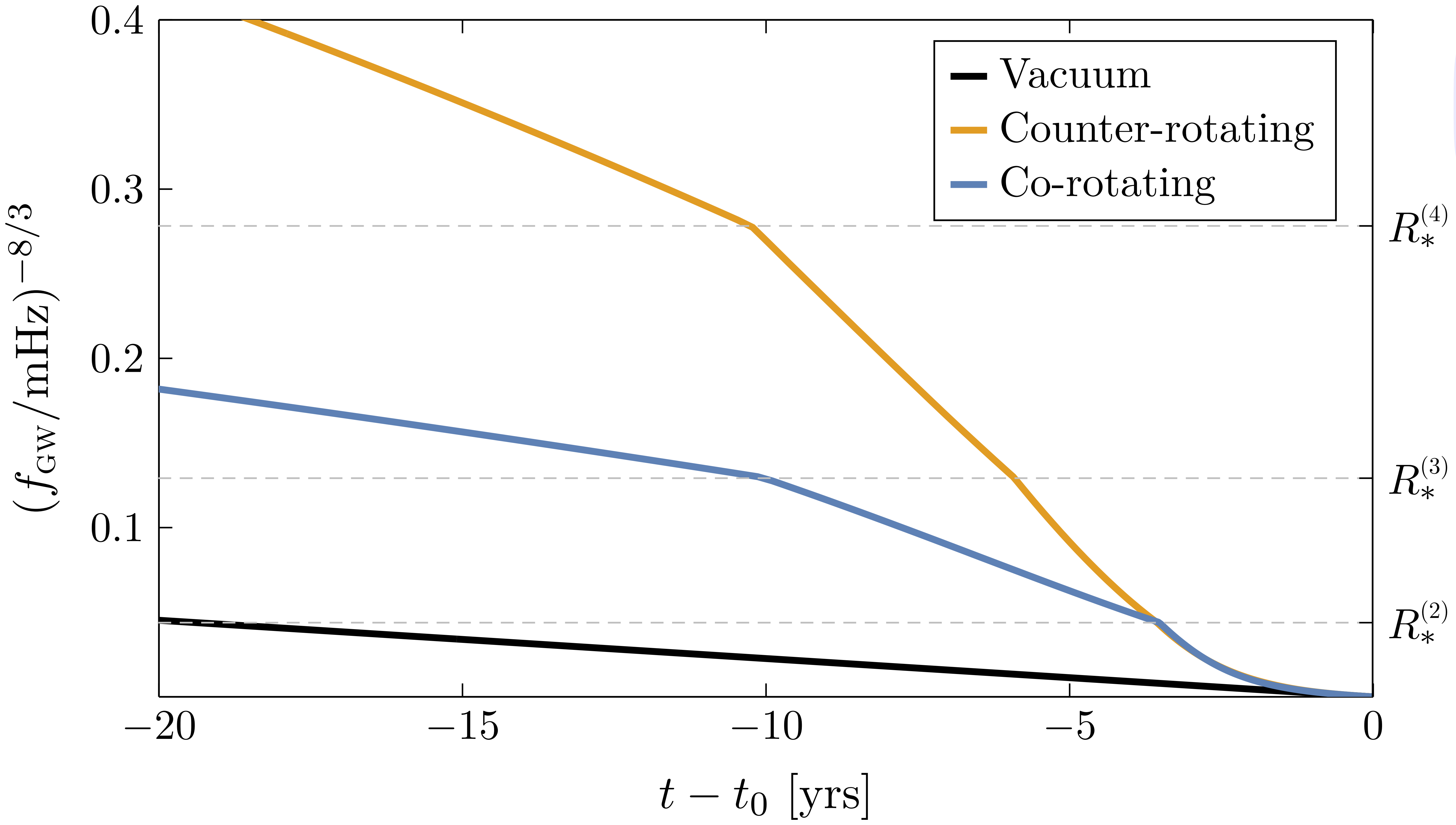
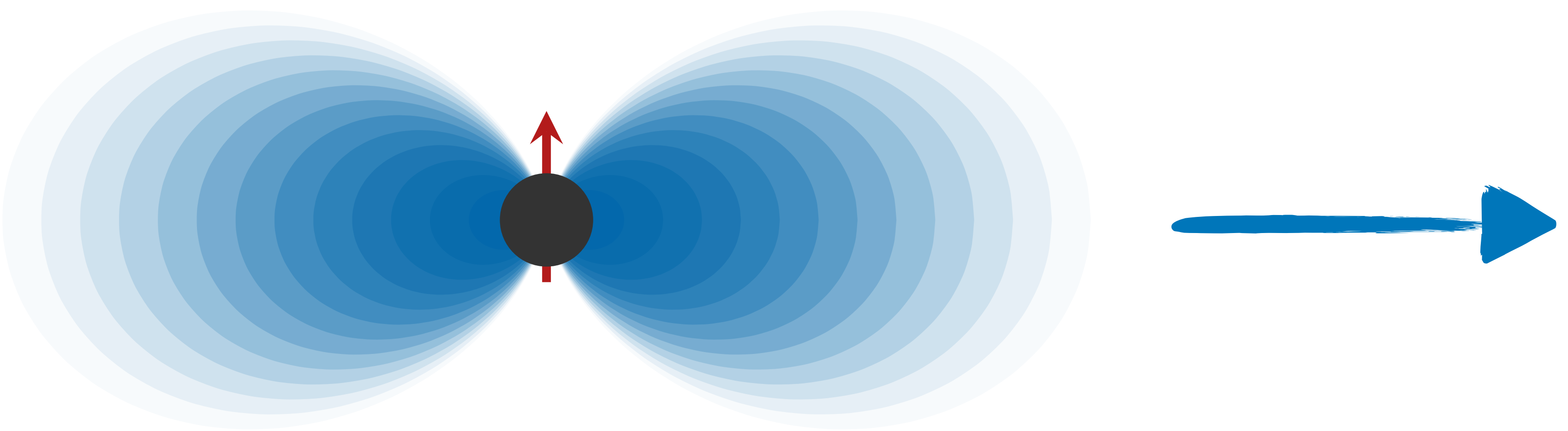


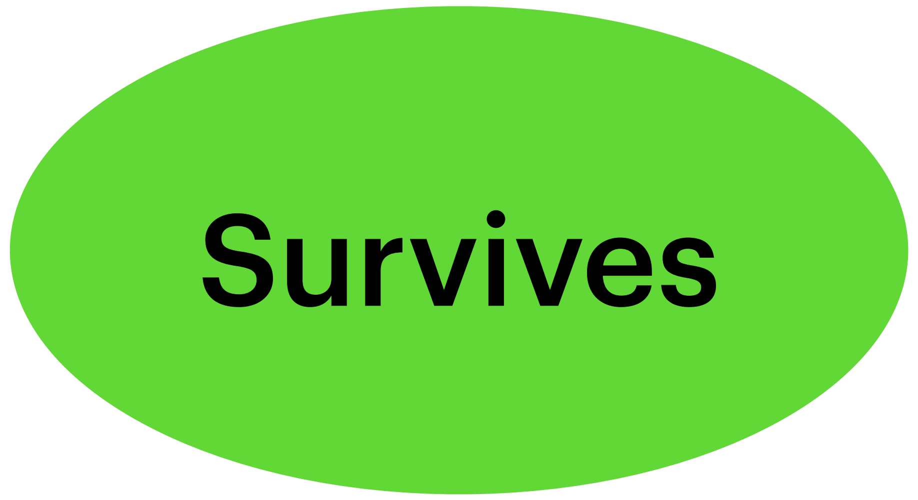
$$f_{\mathrm{GW}}^{(g)} = \frac{6.45\mathrm{mHz}}{g}\left(\frac{10^4 M_\odot}{M}\right)\left(\frac{\alpha}{0.2}\right)^3\left(\frac{2}{n}\right)$$

What do resonances teach us?

- ✦ Initial state of the cloud **remains the same**
- ✦ Near-**counter rotating**

Direct signatures





… but also **sinking resonances**!

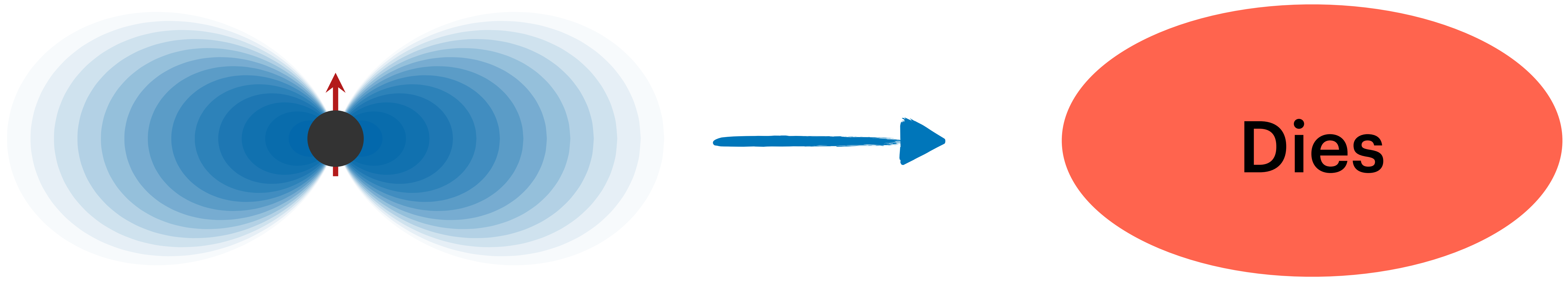
$$f_{\rm GW}^{\rm res} = \frac{26{\rm mHz}}{g}\left(\frac{10^4 M_\odot}{M}\right)\left(\frac{\alpha}{0.2}\right)^3\left(\frac{1}{n_a^2}-\frac{1}{n_b^2}\right)$$

$$\Delta f_{\rm GW} = \frac{0.61{\rm mHz}}{\Delta m^{1/3}}\left(\frac{10^4 M_\odot}{M}\right)\left(\frac{M_{\rm c}/M}{0.01}\right)\left(\frac{10^{-3}}{q}\right)\left(\frac{\alpha}{0.2}\right)^3\left(\frac{1}{n_a^2}-\frac{1}{n_b^2}\right)^{4/3}\left(\frac{|c_b|^2}{10^{-3}}\right)$$

Directly probing the **microscopic properties** of the cloud

 [Baumann *et al.* '19; Tomaselli, Spieksma, Bertone '24]

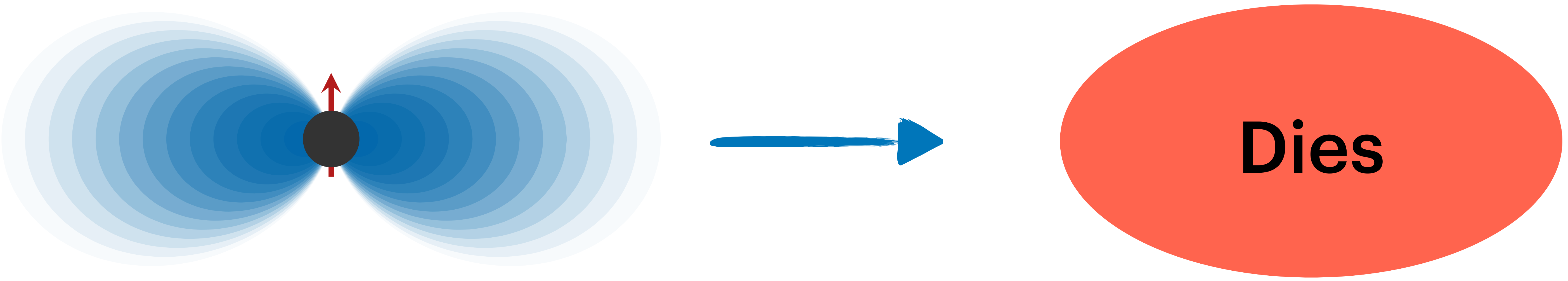
Indirect signatures



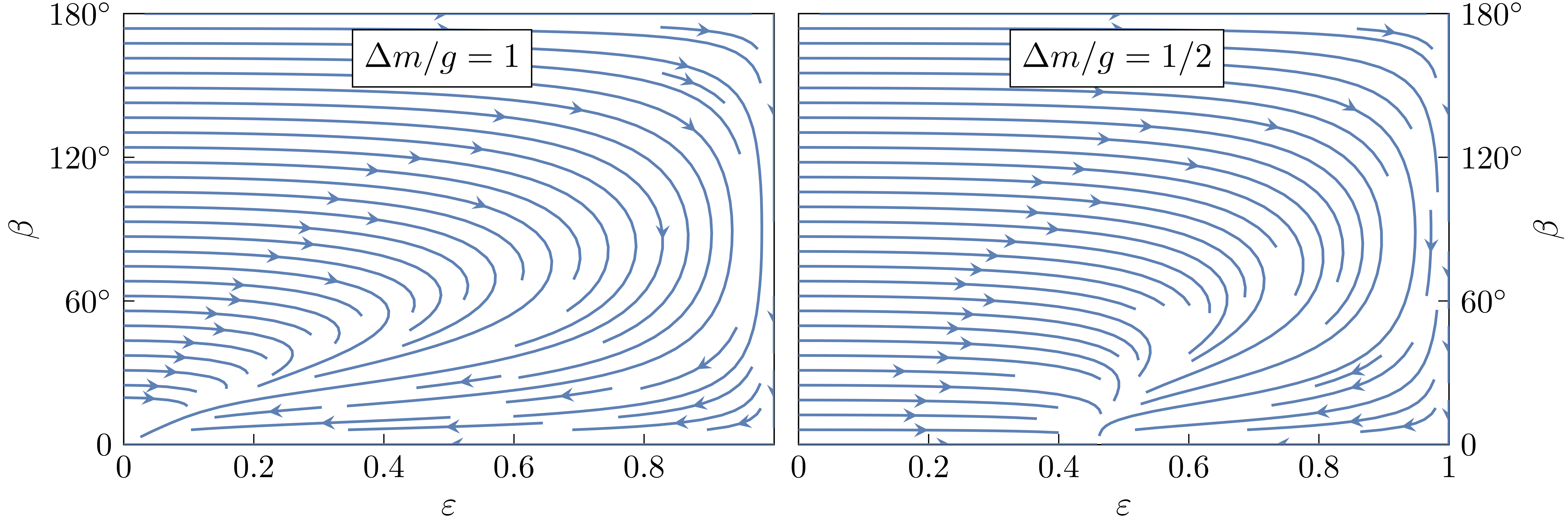
Indirect observational signatures through the impact on **binary parameters**

 [Tomaselli, Spieksma, Bertone '24]

Indirect signatures



Evolution of the **eccentricity** and **inclination** during a float:



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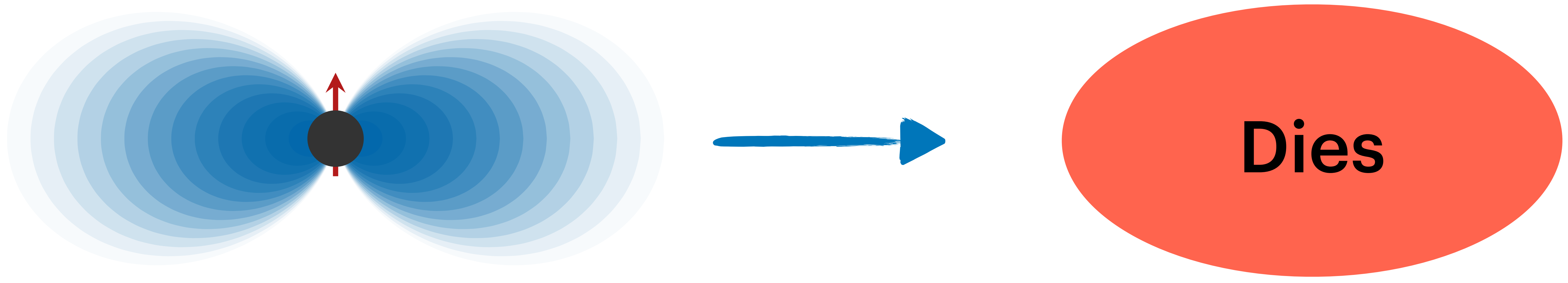

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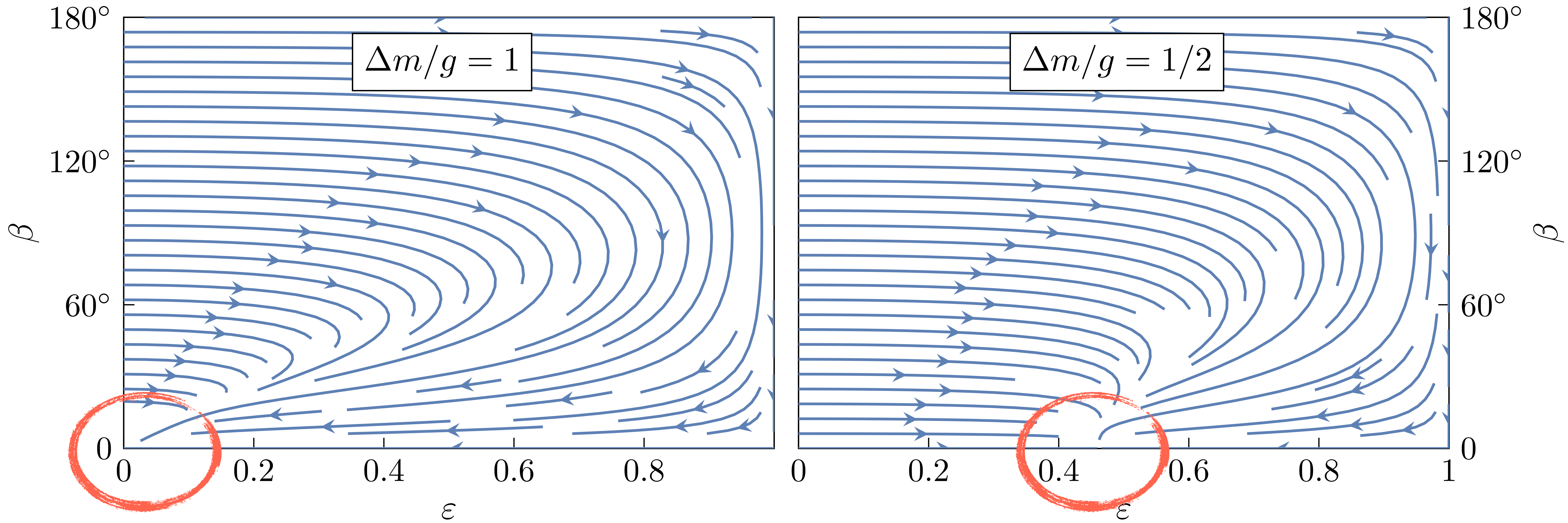
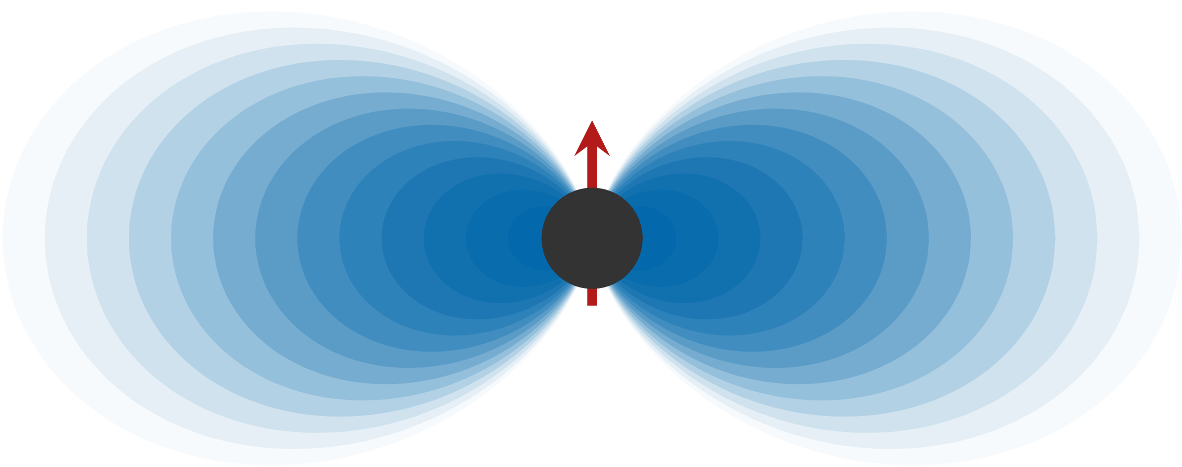


Fixed points:

✦ Inclination always goes to **zero**

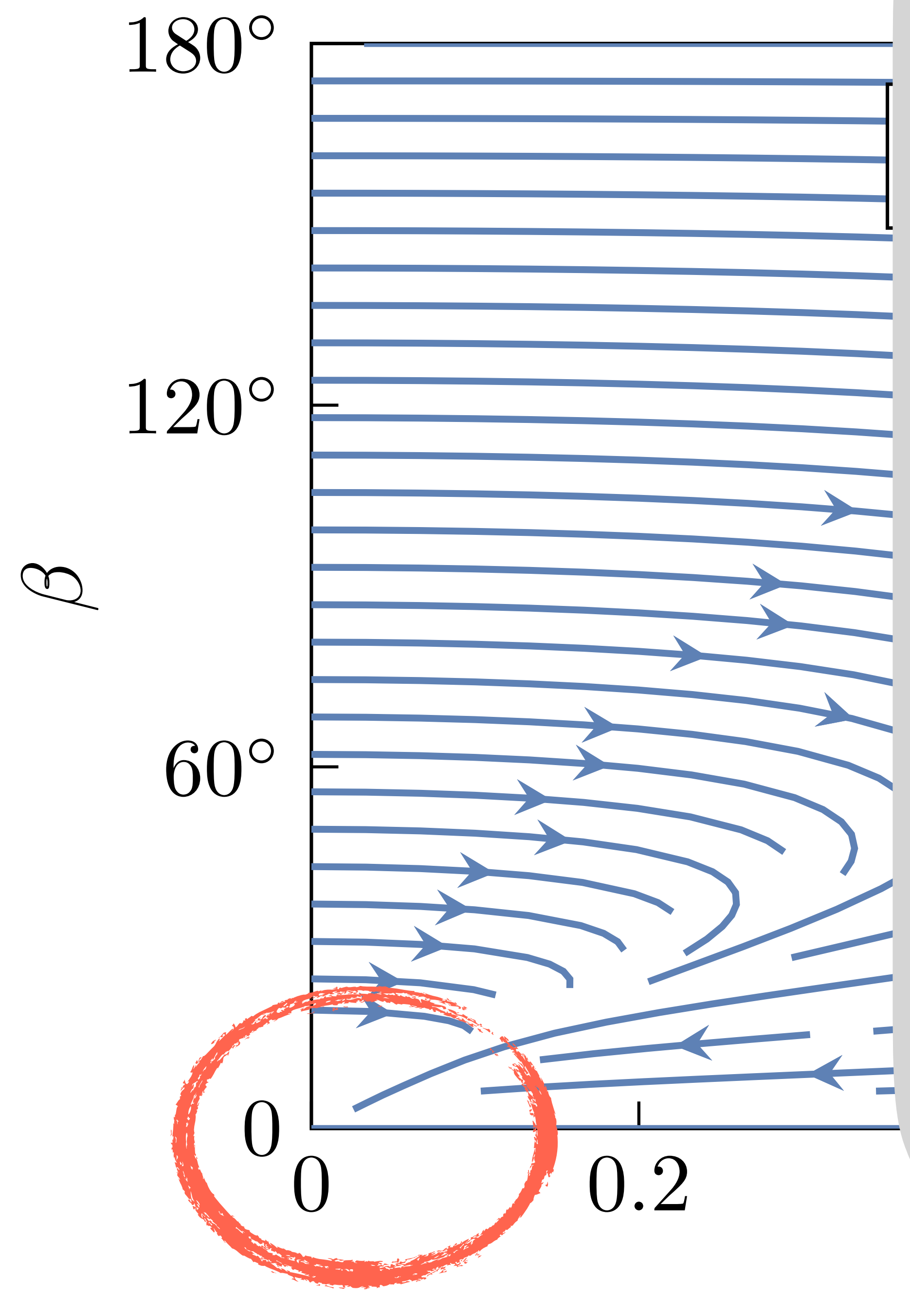
✦ Eccentricity goes to (potentially) **nonzero point** $\varepsilon \approx 0, 0.46, 0.58, 0.65, \cdots$

Indirect signatures



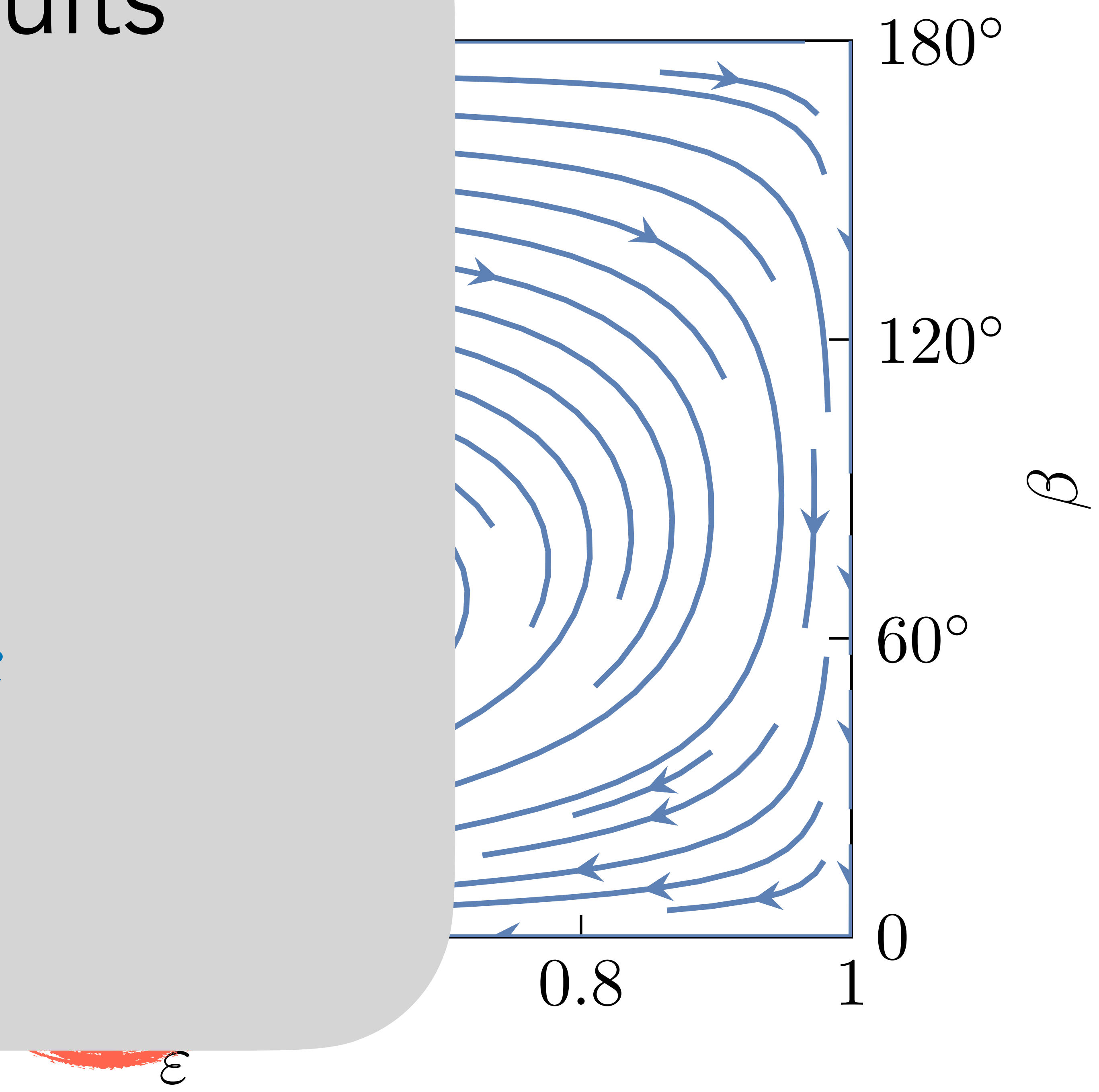
Dies

Evolution during a float:



Interesting overlap with results from **circumbinary disks**

[Zrake *et al.* '21;
D'Orazio & Duffell '21;
Siwek, Weinberger, Hernquist '23;
Tiede & D'Orazio '23]



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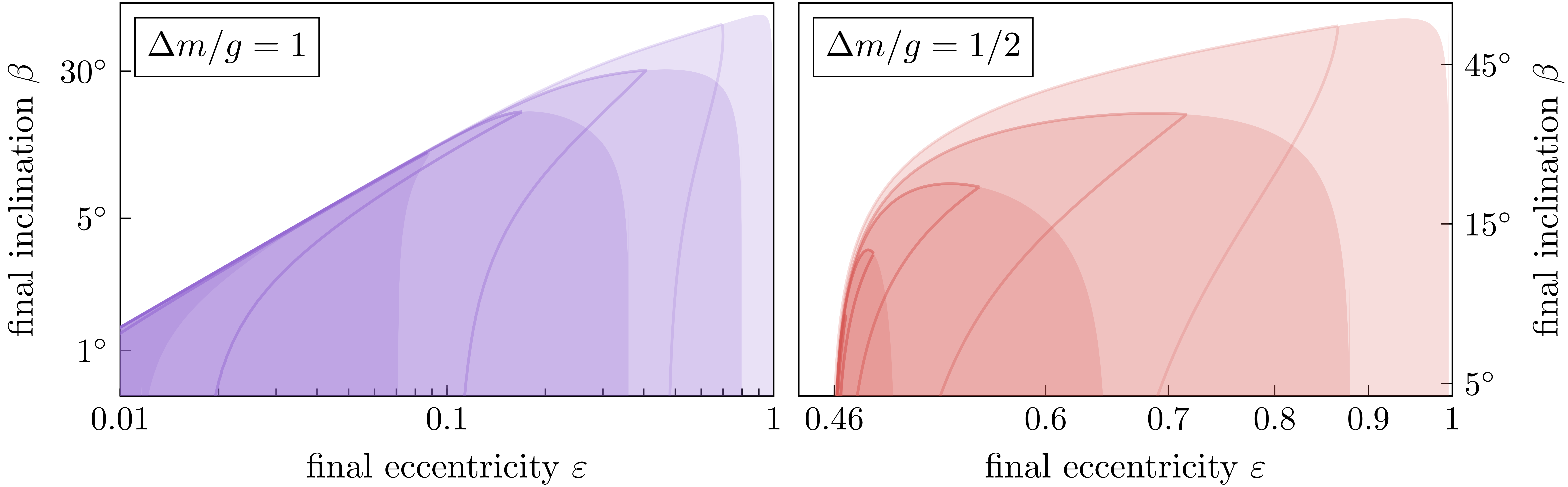
Cloud's legacy

Final values of binary parameters determined by: $D \propto M_c q^{-1} \alpha \tilde{a}$



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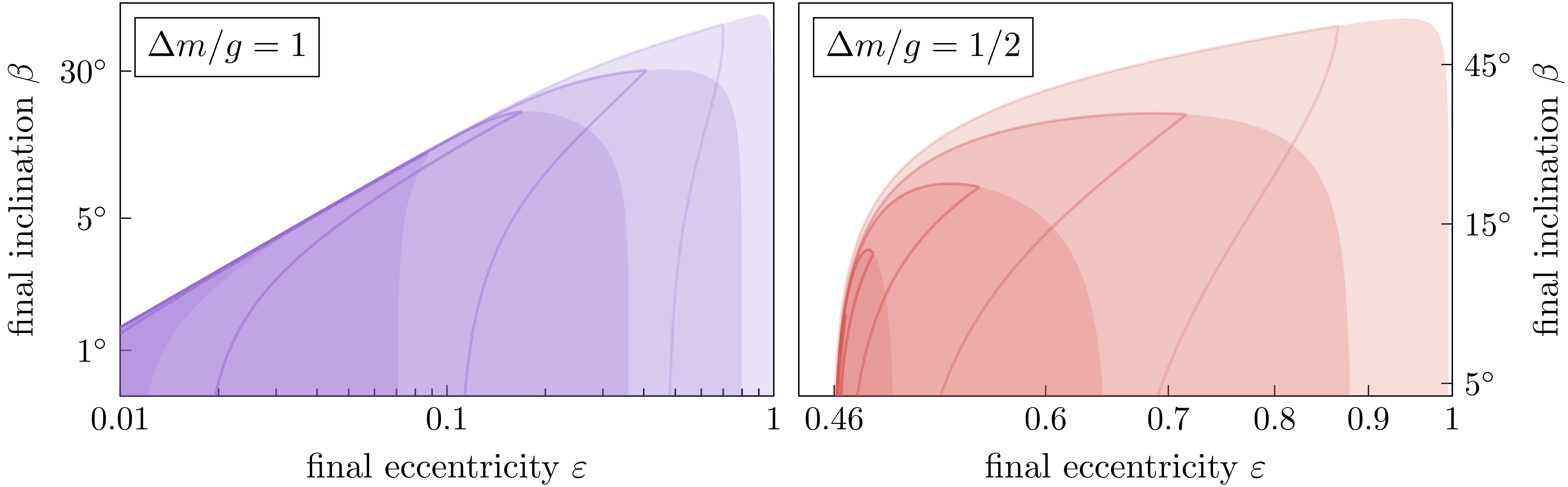

Statistical analysis of large number of BH binaries could unveil existence boson clouds!

Conclusions

Observational signatures in any scenario

The cloud **survives**, becoming **directly** observable in the sensitivity band of future detectors

The cloud **dies**, becoming **indirectly** observable through the binary parameters.