Black hole superradiance:

a gateway to new physics

strong. niels bohr institute

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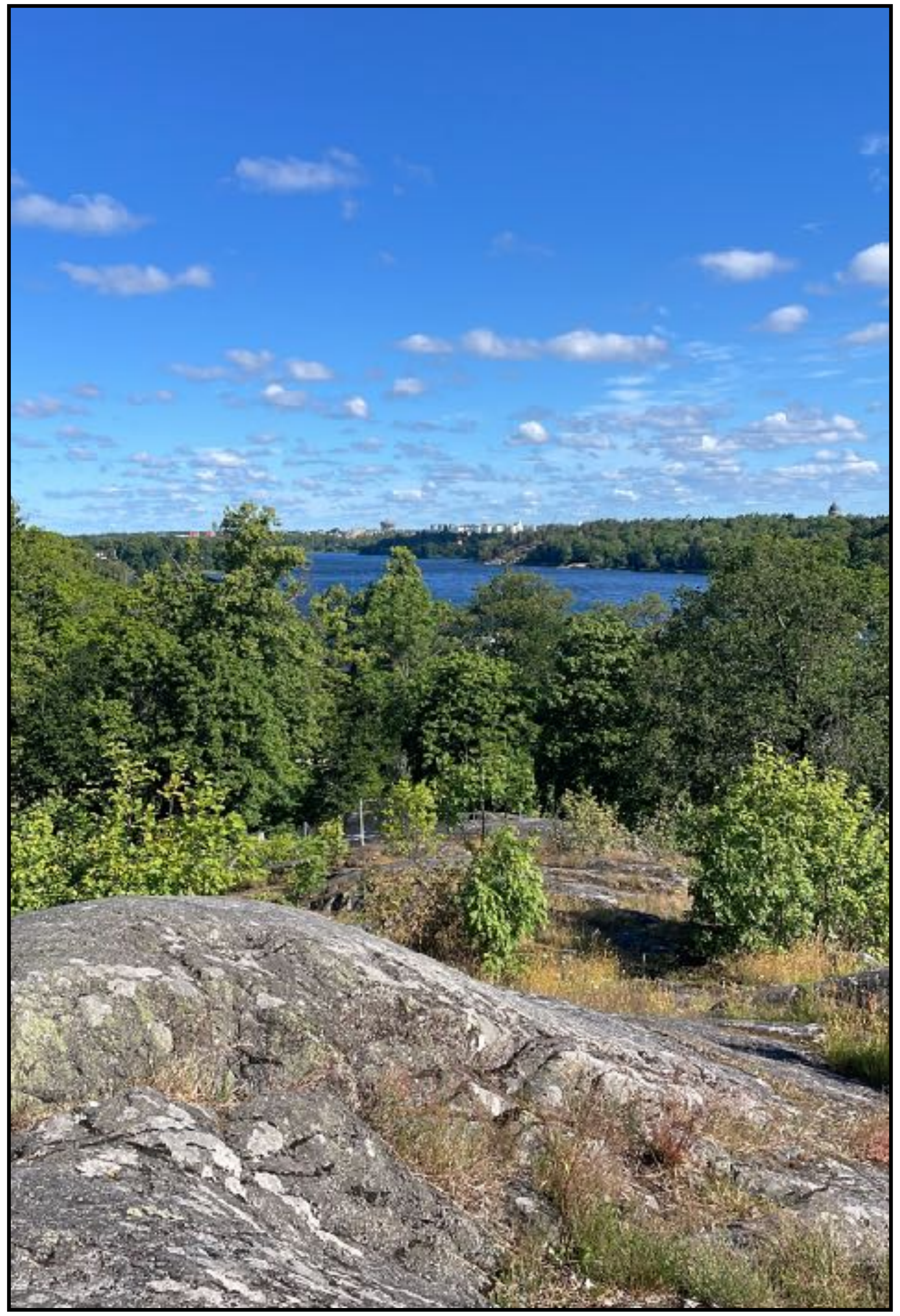
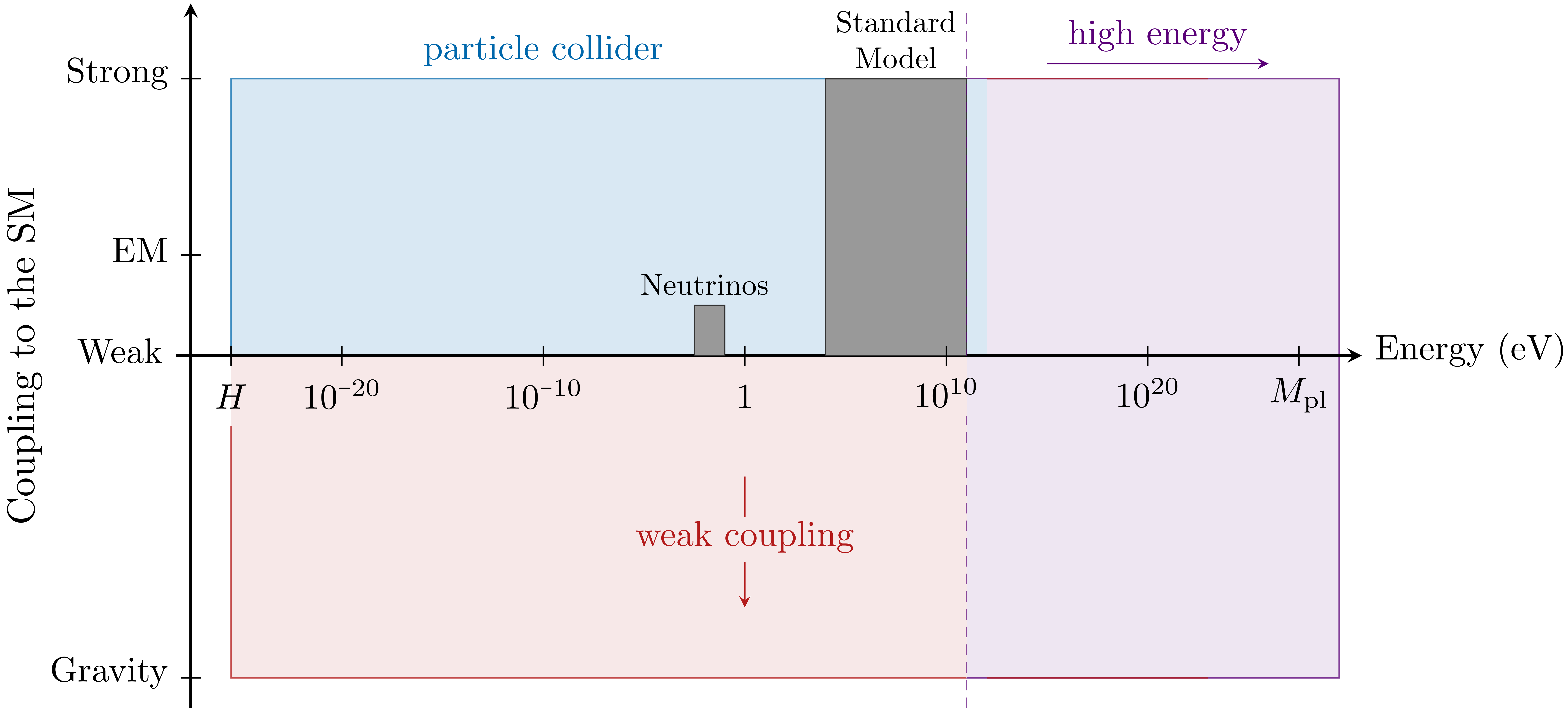


Stockholm, June 2025

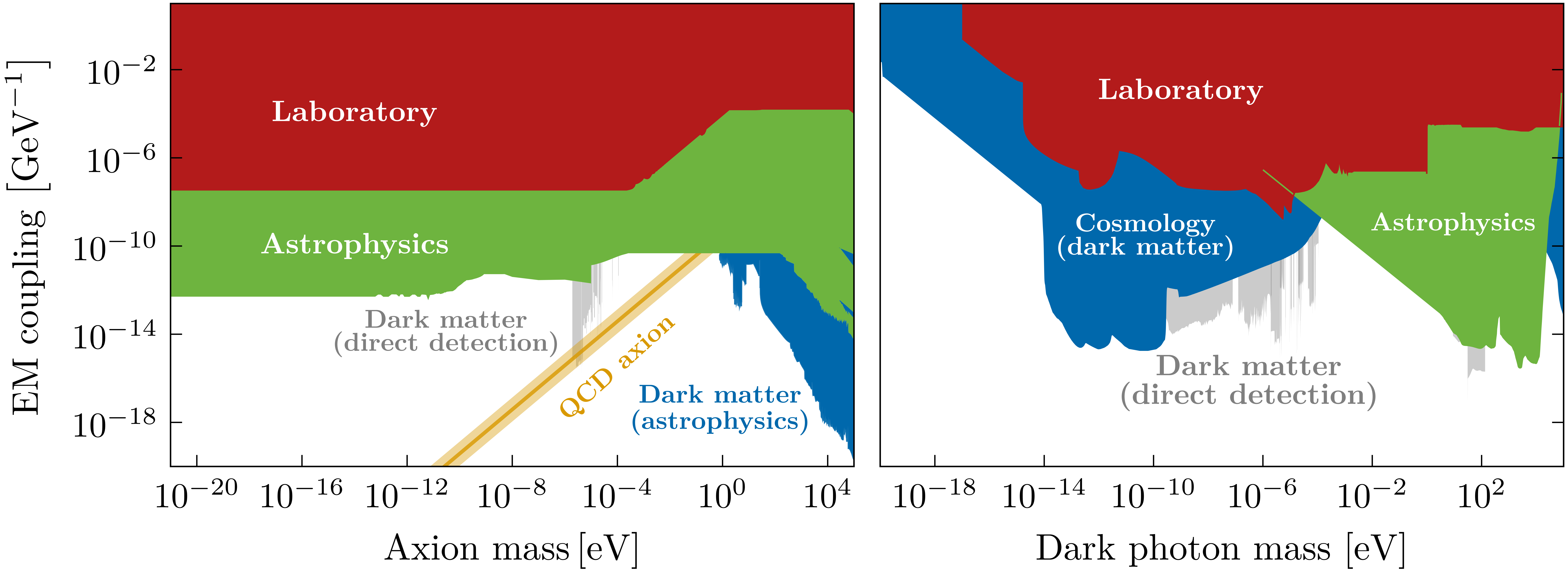
Thomas Spieksma

Exploring the weak-coupling frontier

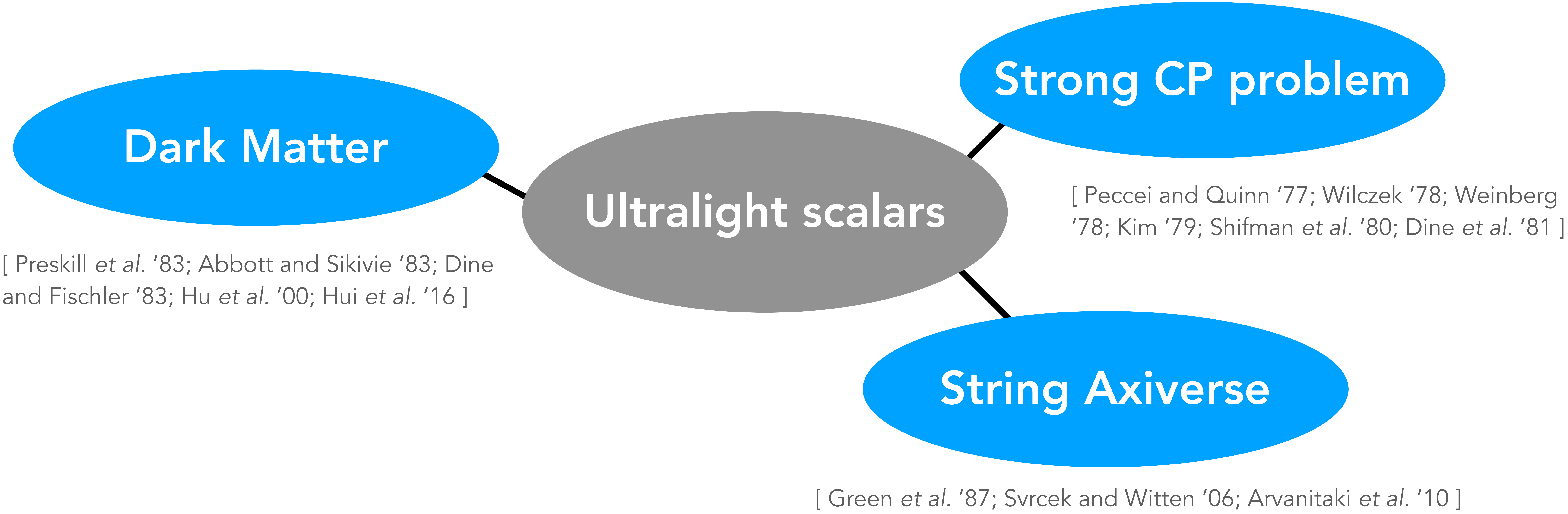


Ultralight particles — Bounds

Ultralight, weak coupling regime is largely unconstrained

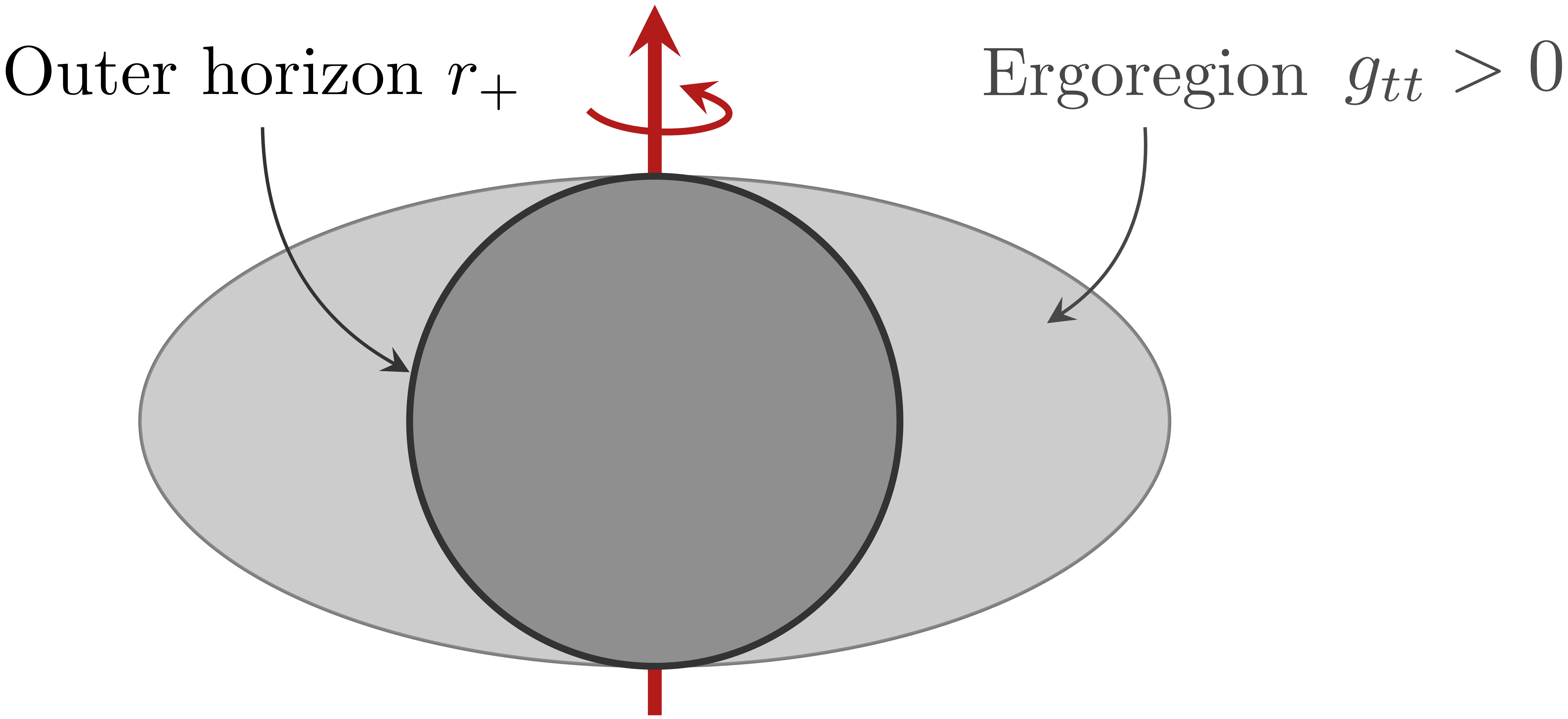


Ultralight particles — Why we care (even if you already do)



How to produce them **abundantly**, and in **high densities**?

Black hole superradiance — Penrose process



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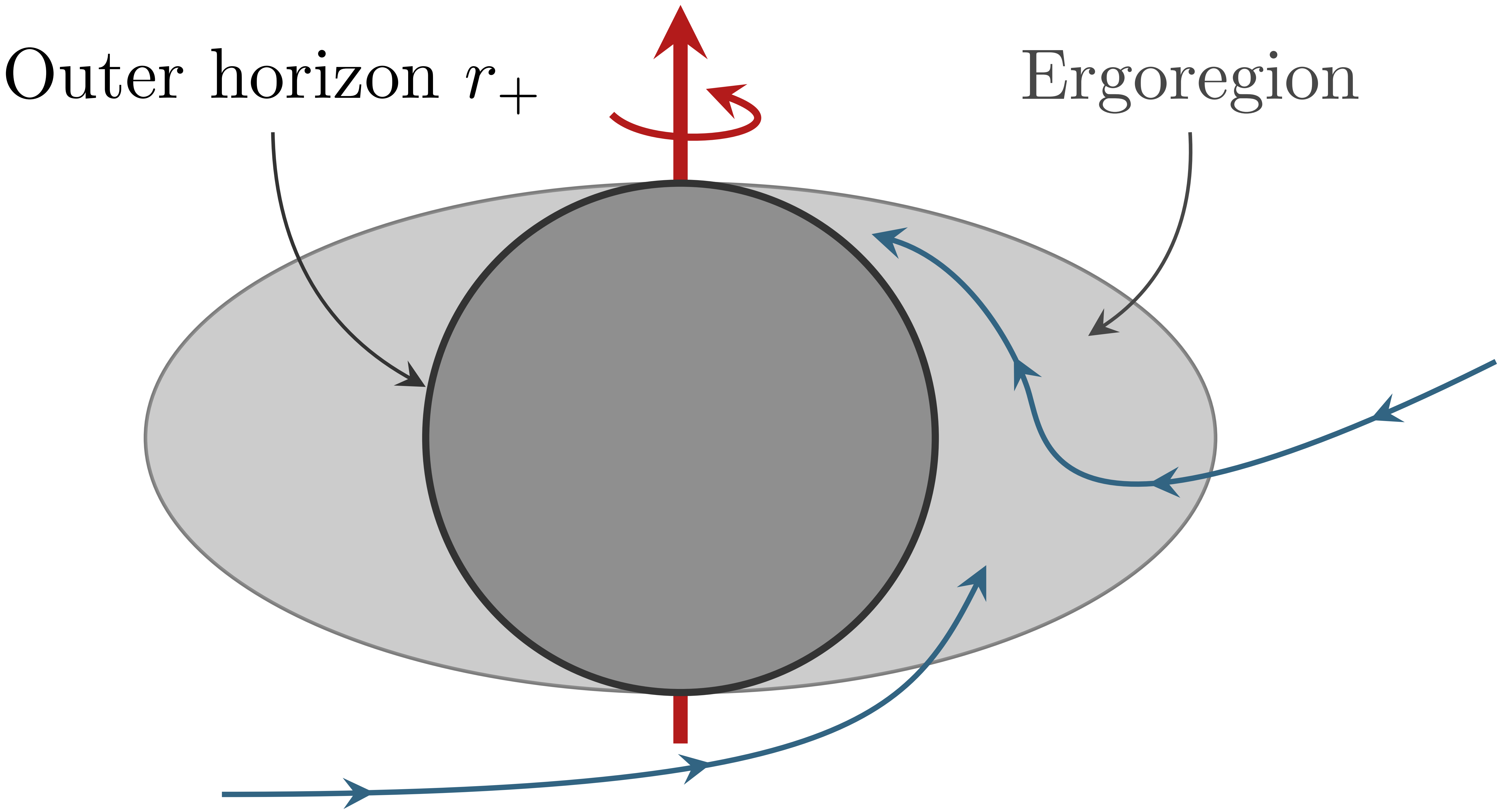

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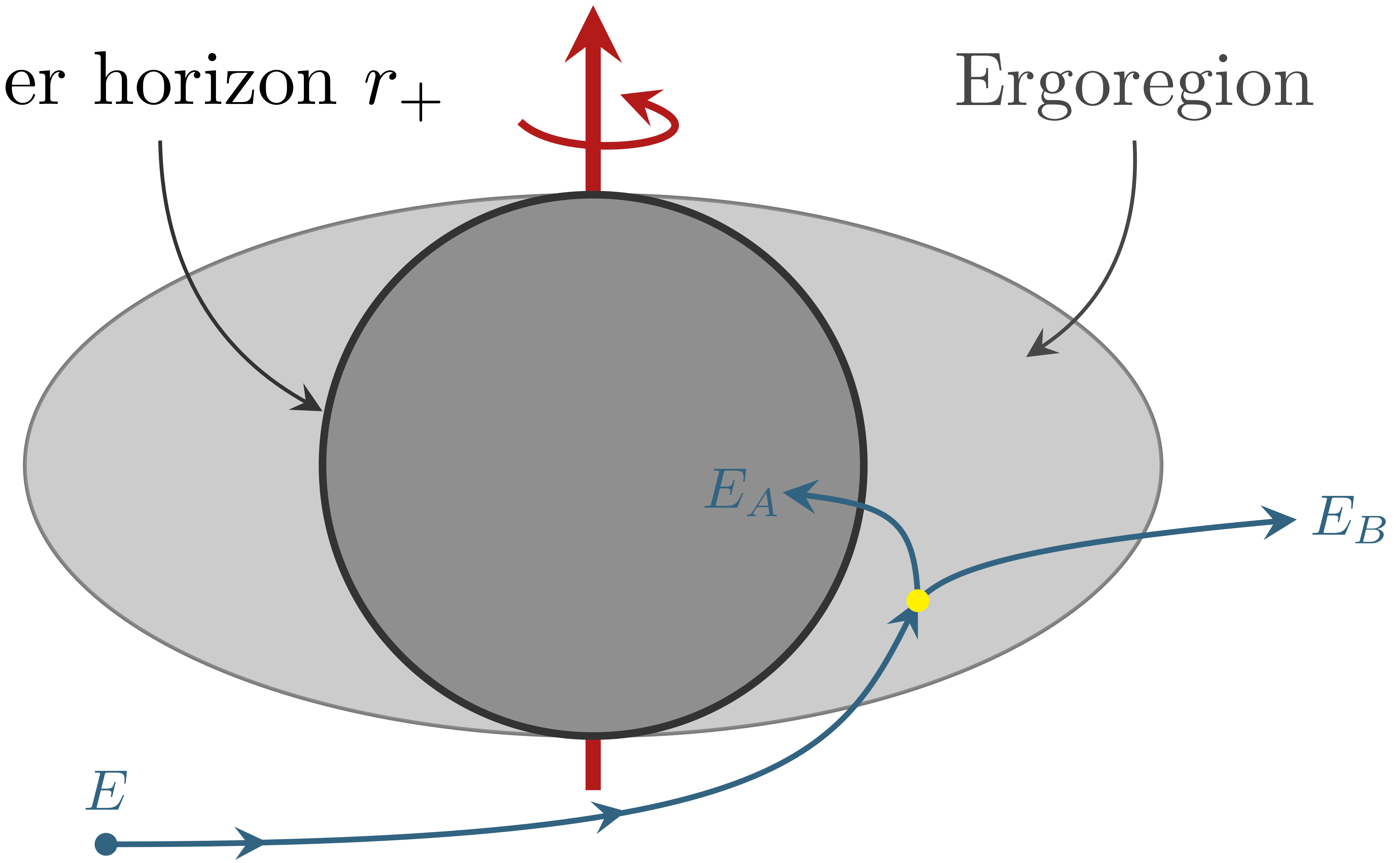
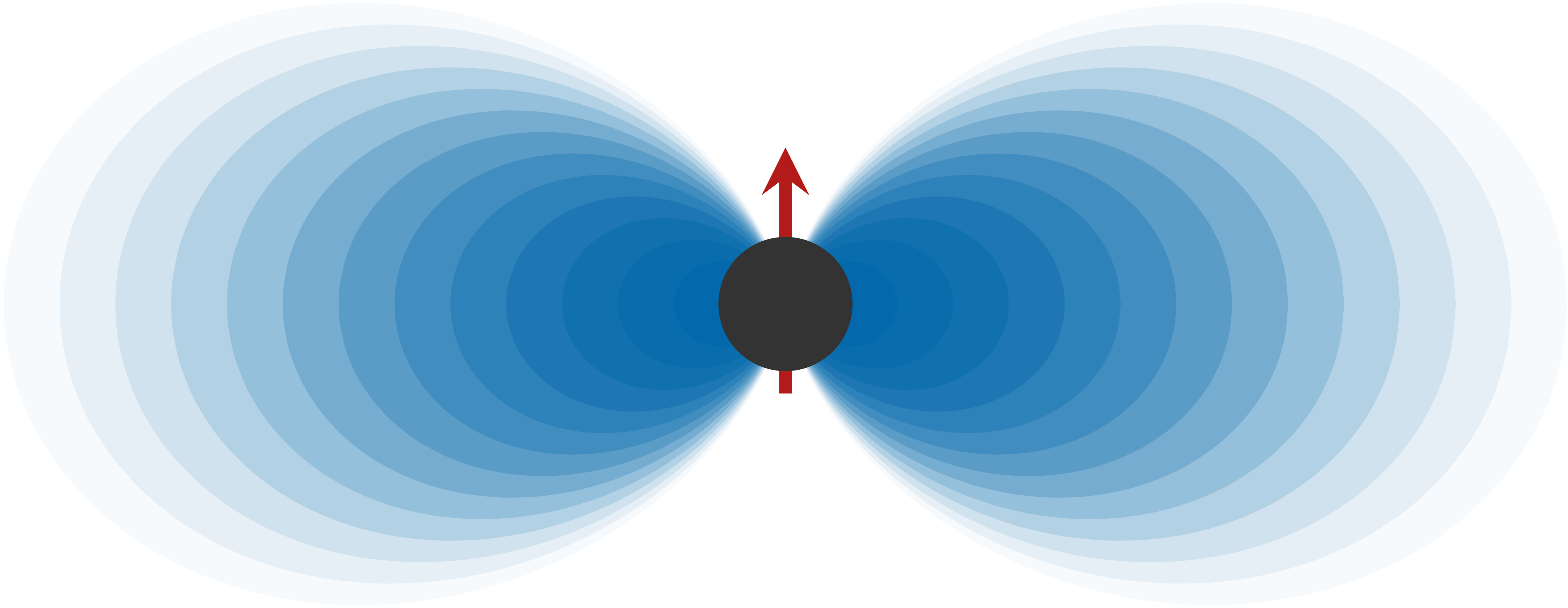


$$E_B = E - E_A > E$$

Black hole superradiance — Gravitational atom

$$\omega < m\Omega$$

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



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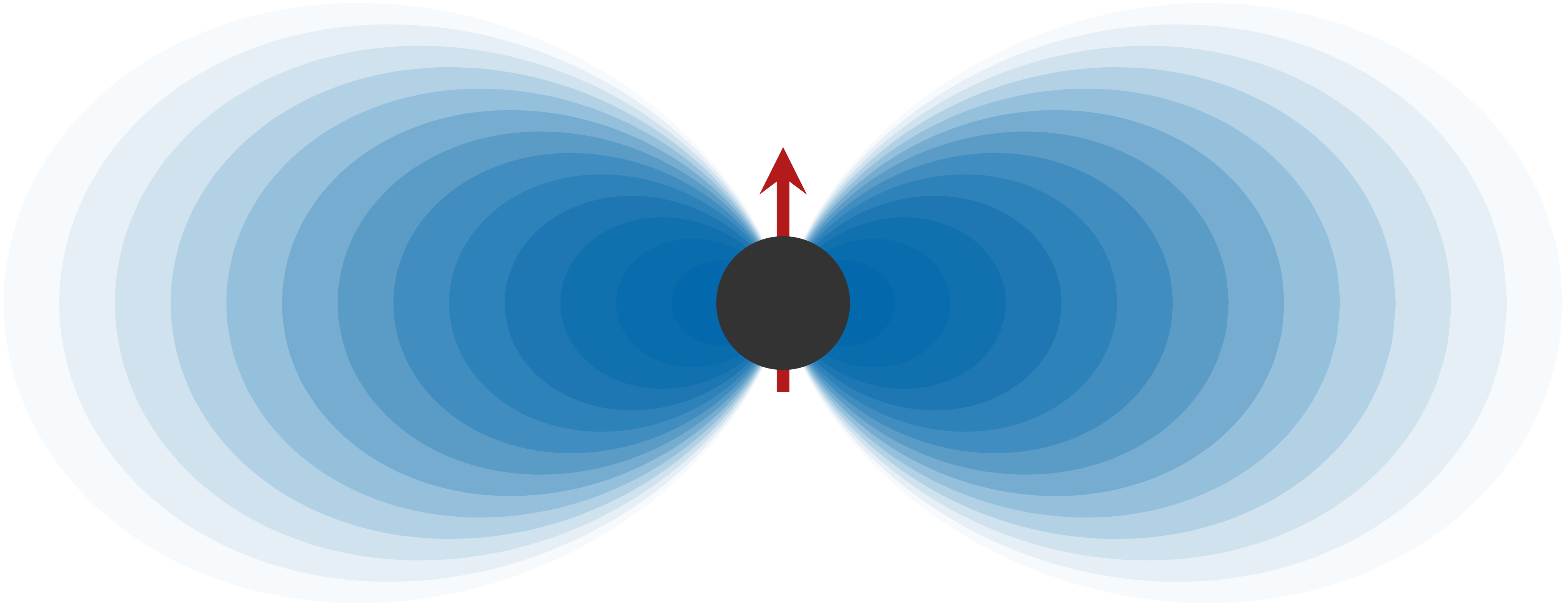


Astrophysical black holes ↔ **Ultralight** bosons

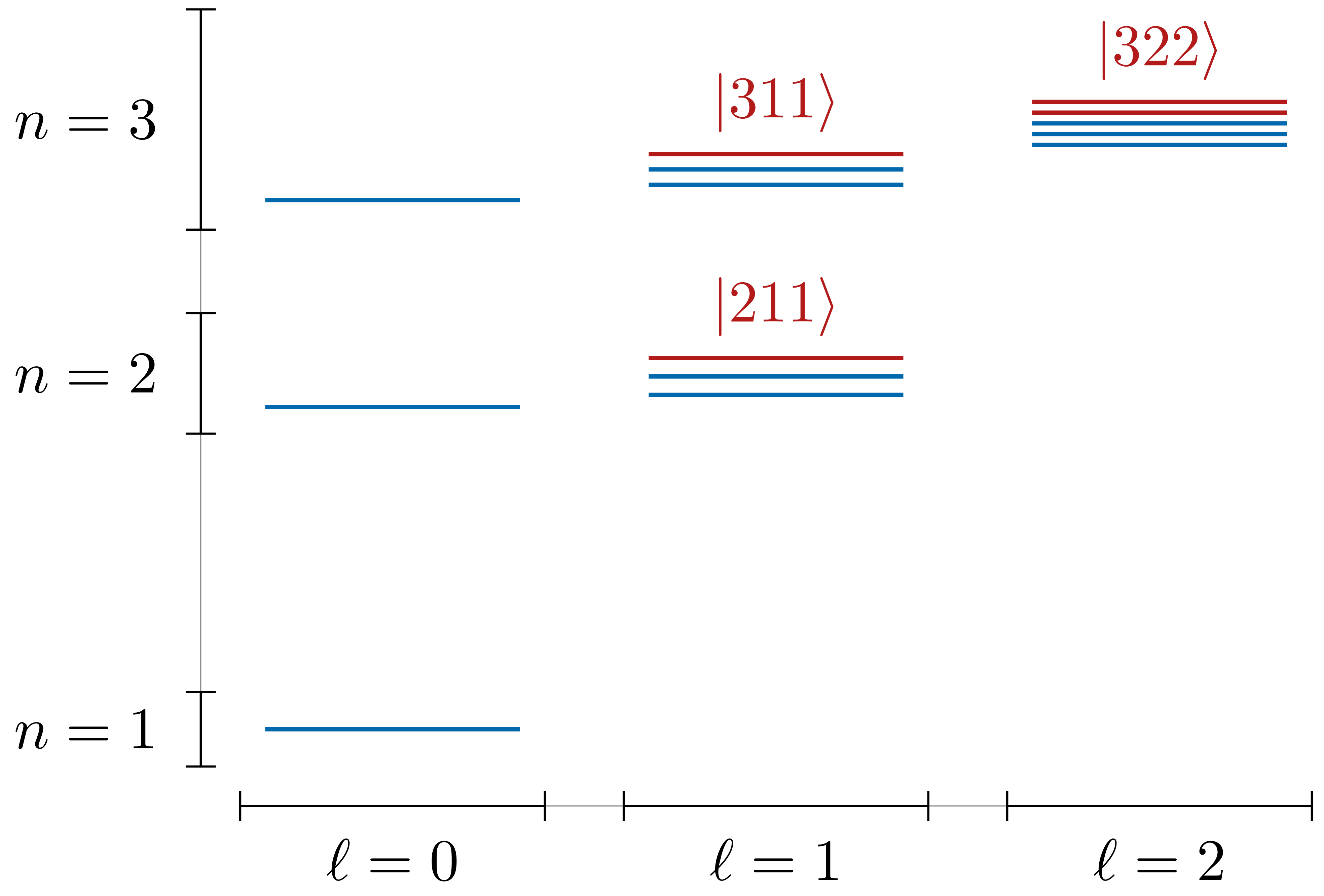
$$M \sim [1 - 10^{10}] M_\odot$$

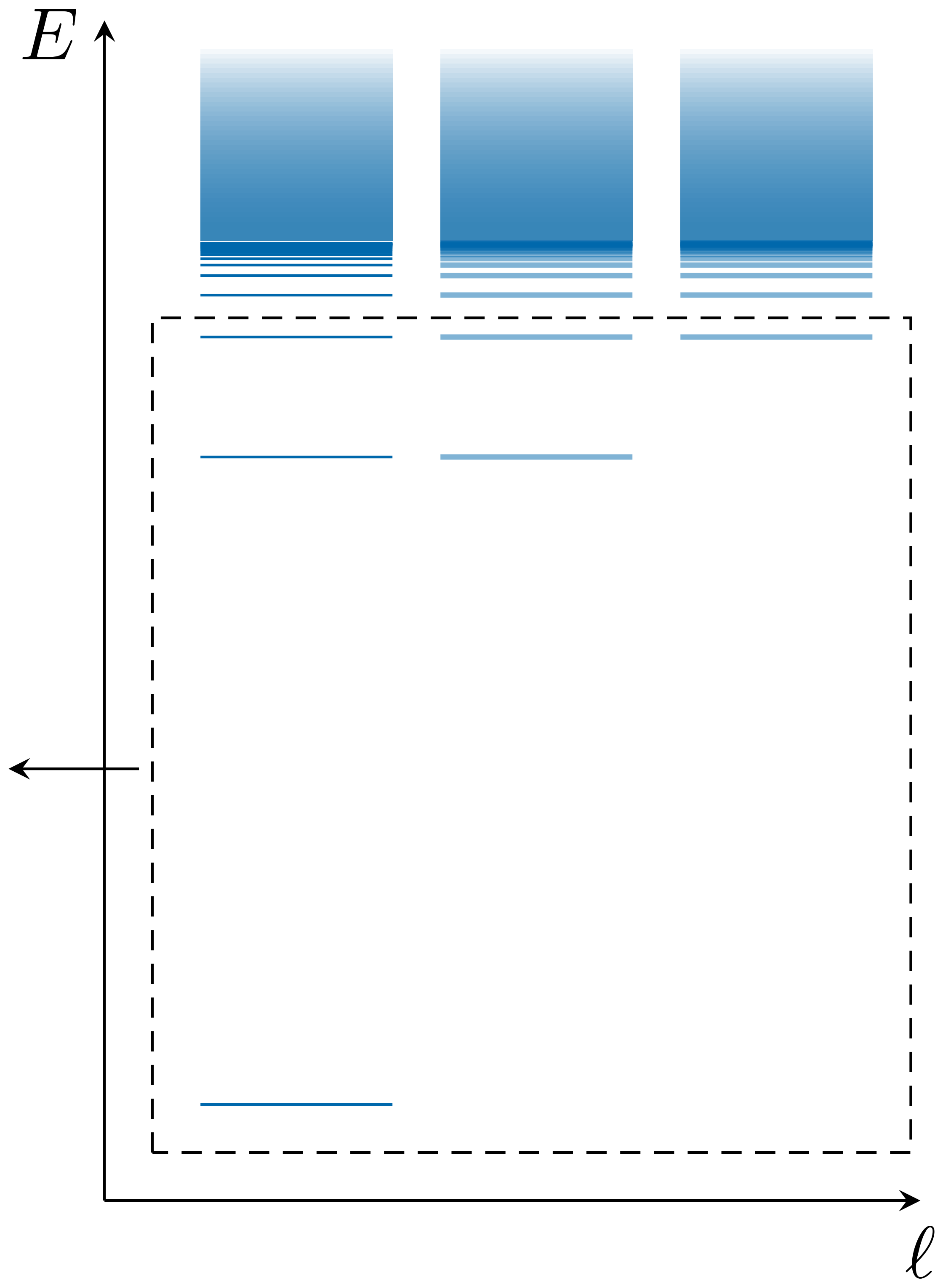
$$\mu \sim [10^{-20} - 10^{-10}]\, {\rm eV}$$

[Zel'Dovich '72; Starobinsky '73; Dolan '07; Arvanitaki *et al.* '09]

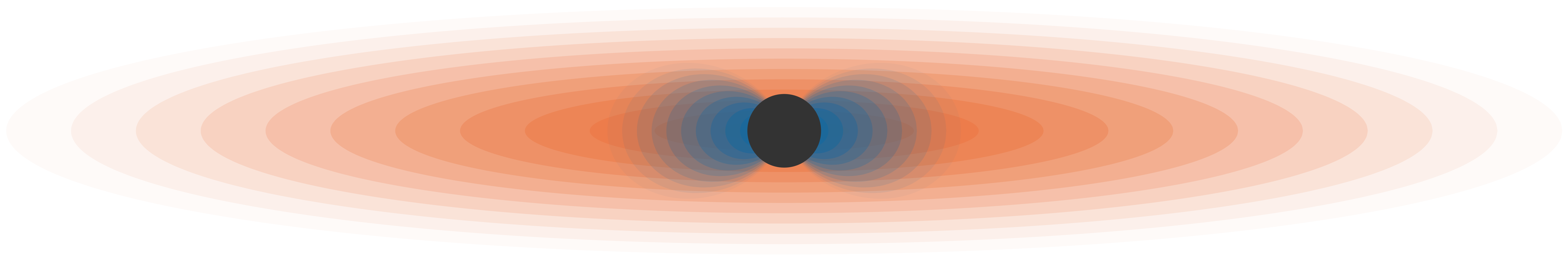
Black hole superradiance — Spectrum

$$(\Box - \mu^2)\Phi = 0 \quad \Longrightarrow \quad i\frac{\mathrm{d}\psi}{\mathrm{d}t} \approx \left(-\frac{1}{2\mu}\nabla^2 - \frac{\alpha}{r} + \dots\right)\psi$$





Searching for **axions** in regions of **strong gravity**



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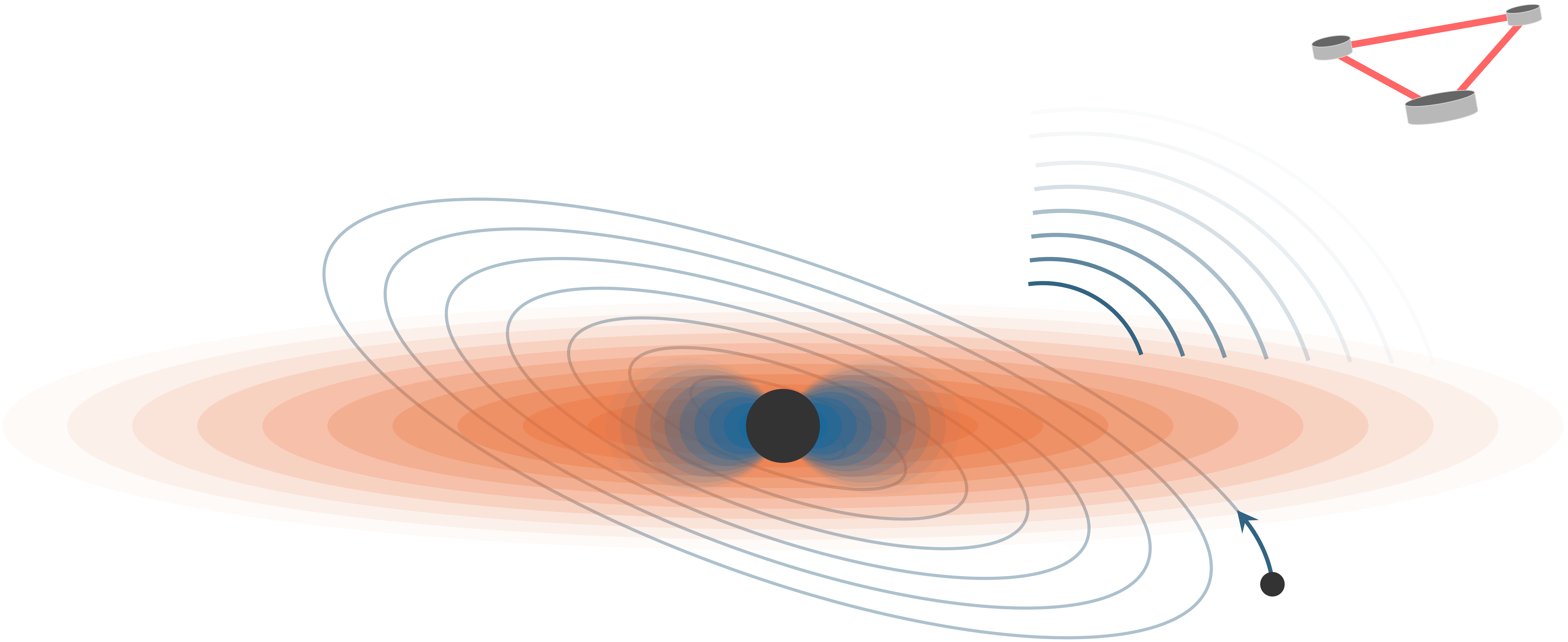

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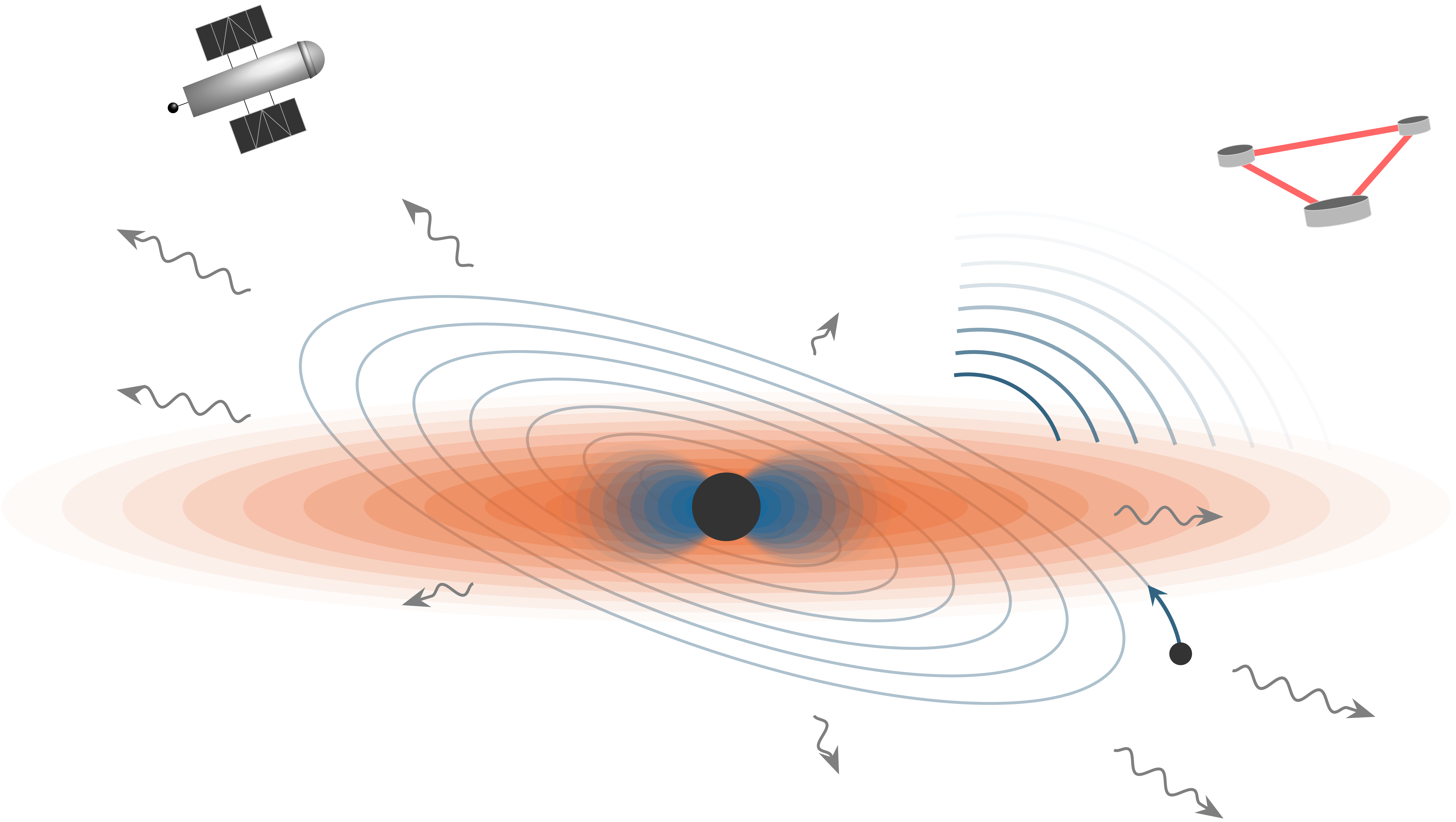
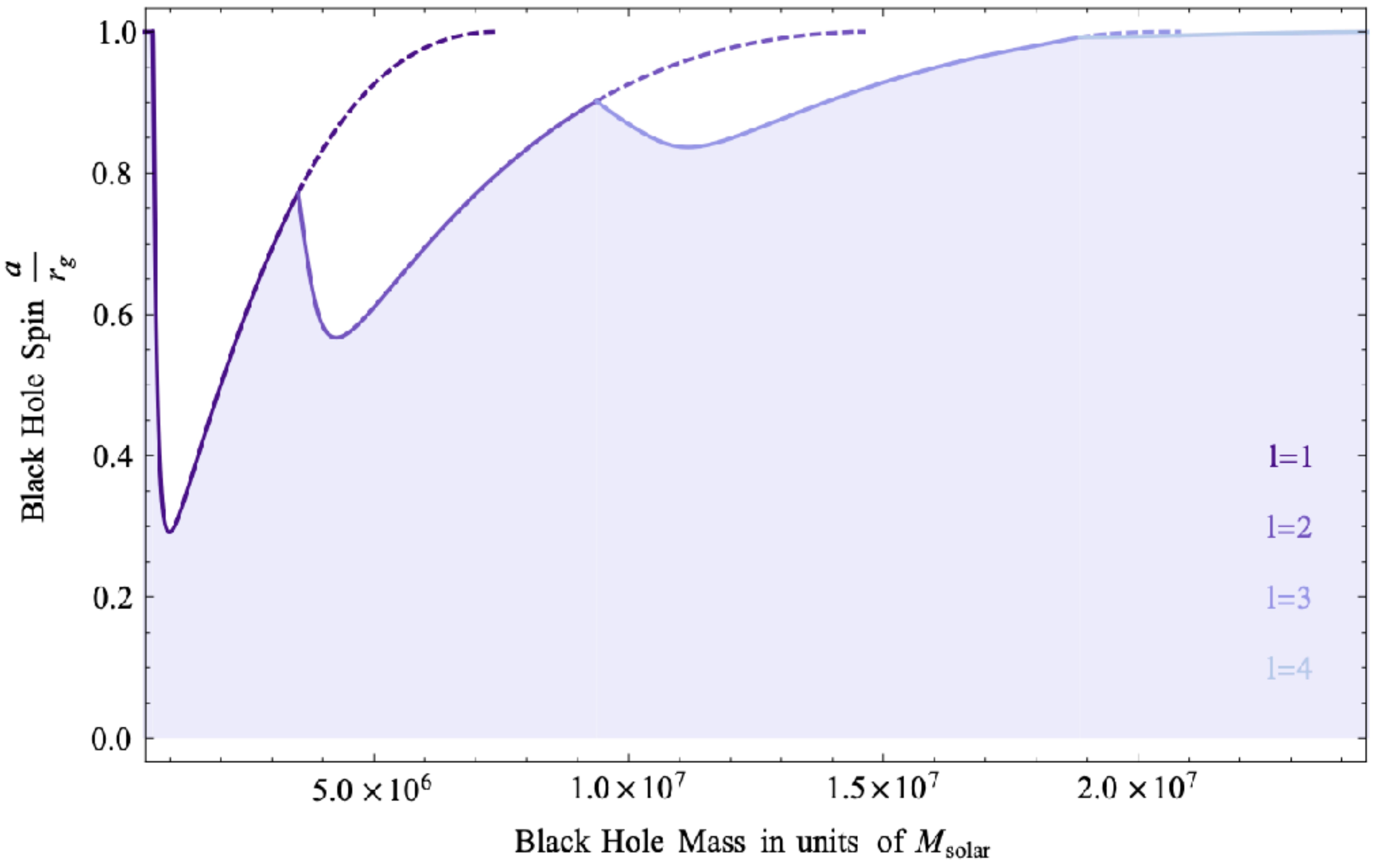


Gravitational atoms — Probes

BH spin-down leads to ***gaps*** in the BH mass-spin diagram



 [Arvanitaki *et al.* '11]

Gravitational atoms — Probes

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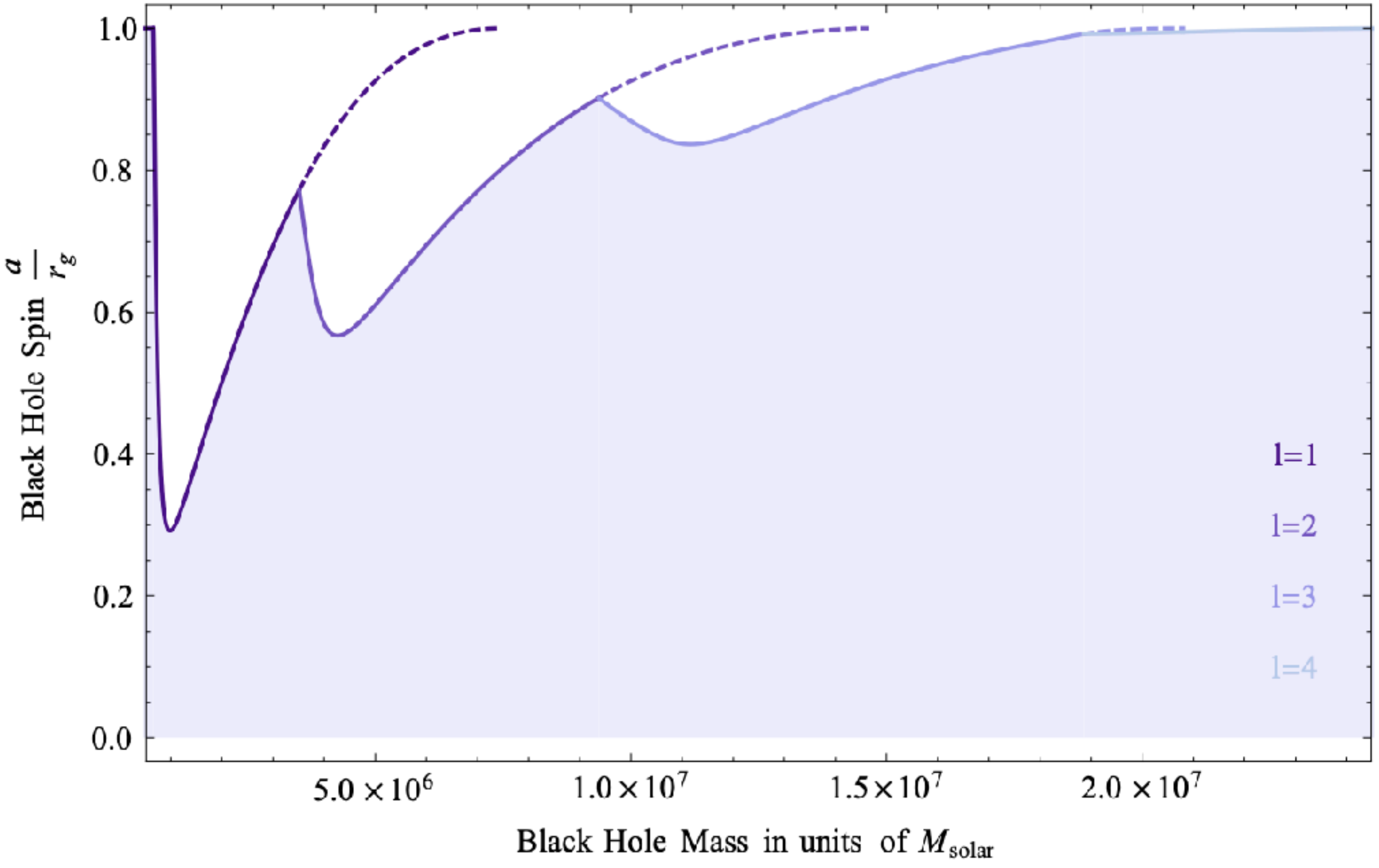


Tentative bounds in the range:

$$\mu \sim [10^{-13} - 10^{-11}]\,\mathrm{eV}$$

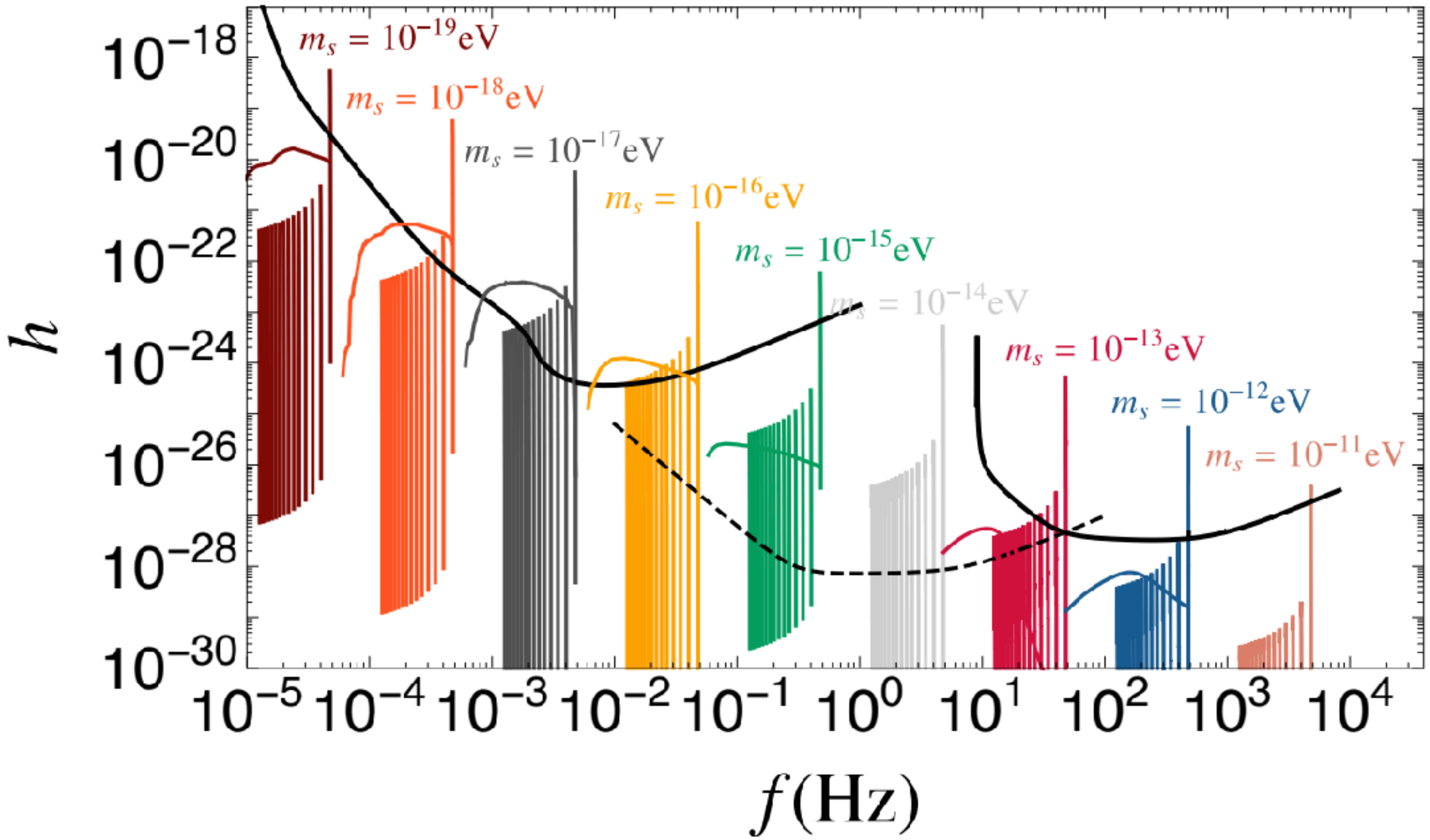
Next-generation gravitational wave detectors can extend this range

Gravitational atoms — Probes

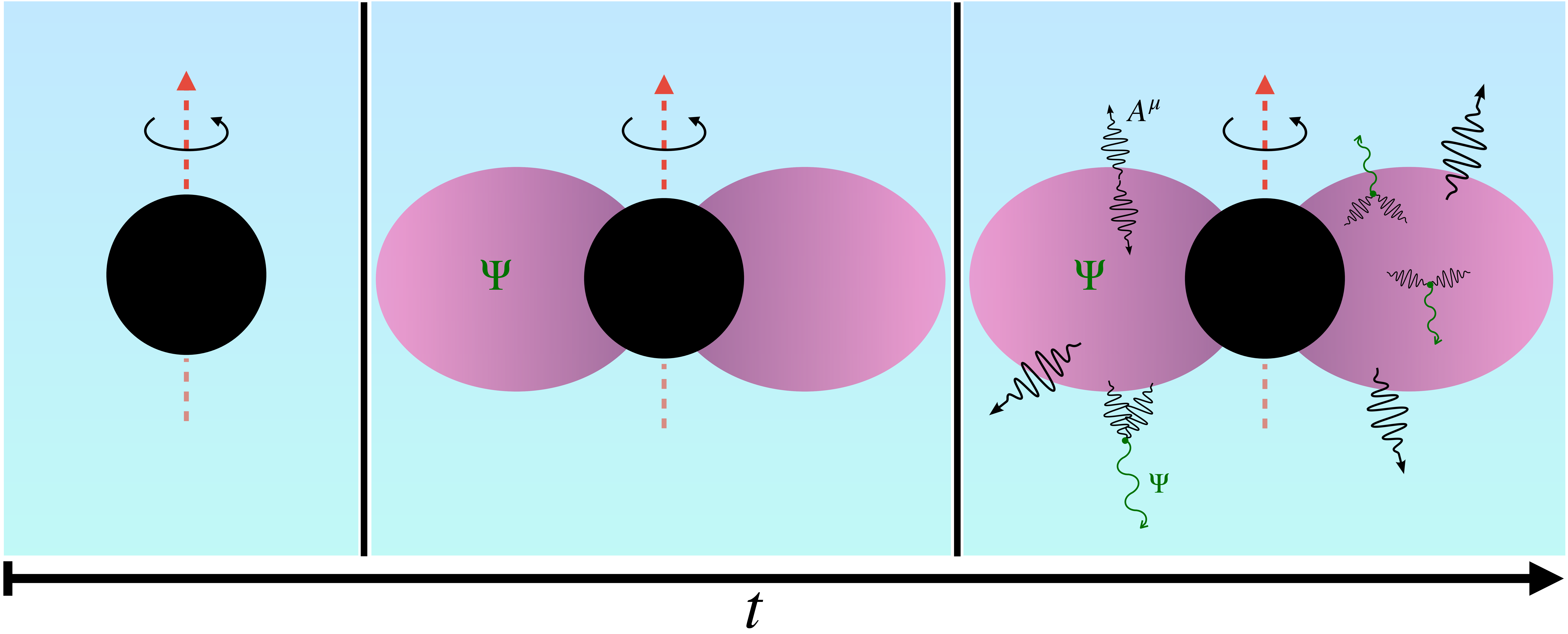
Boson clouds emit **monochromatic** gravitational waves

$$\chi_i = 0.9$$
$$z \in (0.001, 3.001)$$

$$f_{\rm GW} \simeq 483\,{\rm Hz}\left(\frac{\mu}{10^{-12}\,{\rm eV}}\right)$$



Axionic couplings — Overview



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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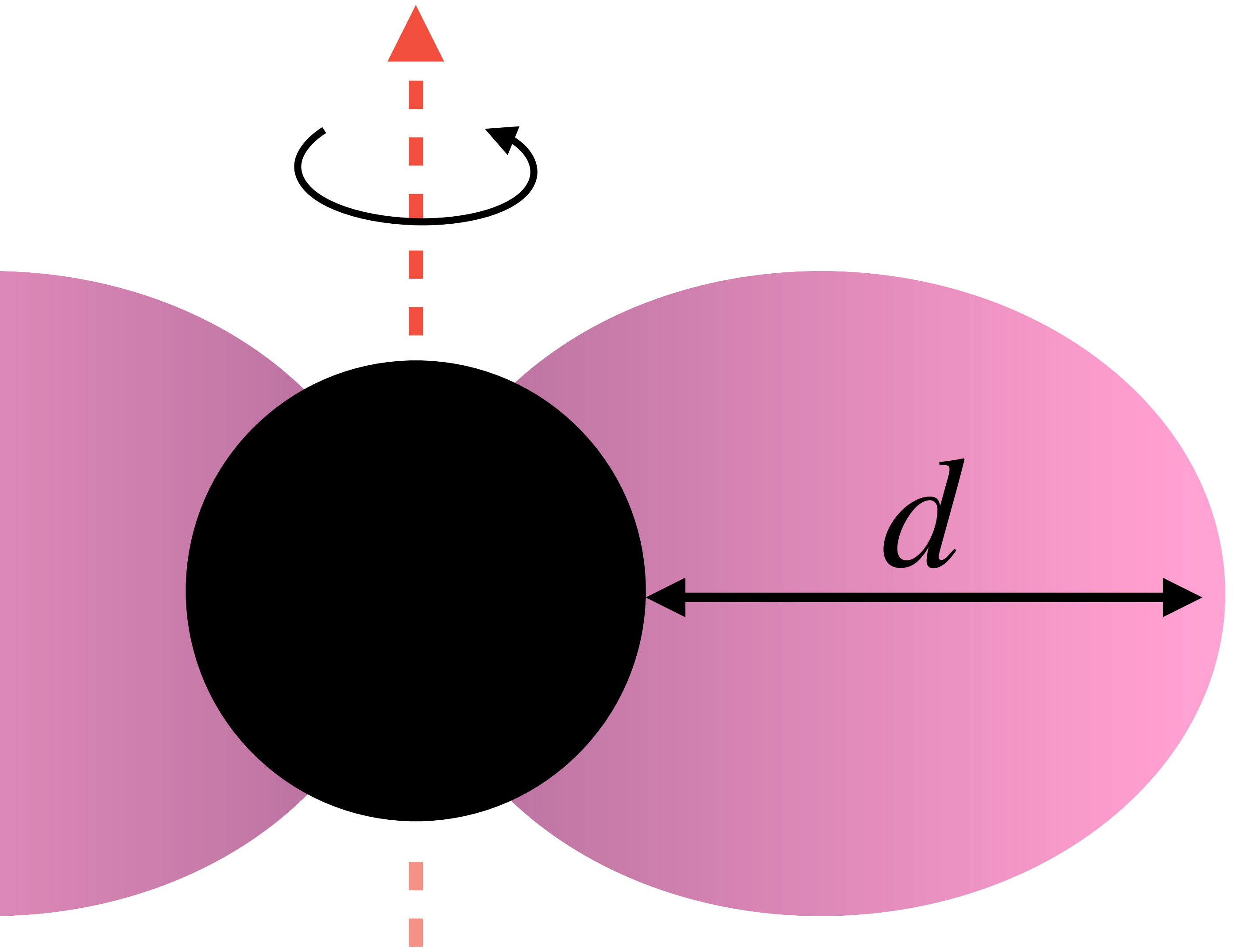


- In the ***subcritical*** regime, photons **leave** the system before the instability ensues

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

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

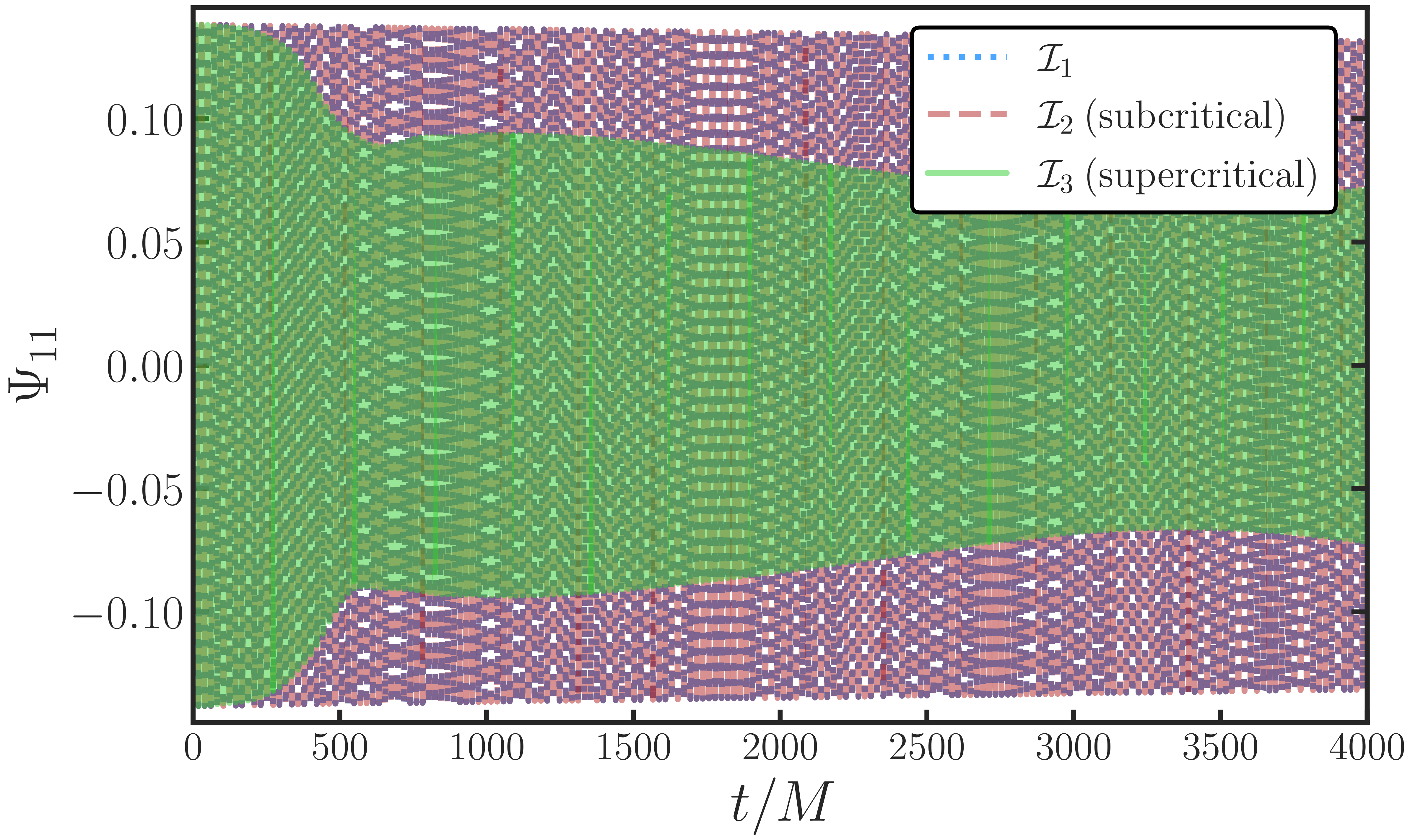
$$\frac{1}{d} \lesssim \mu k_{\rm a} \Psi_0$$

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

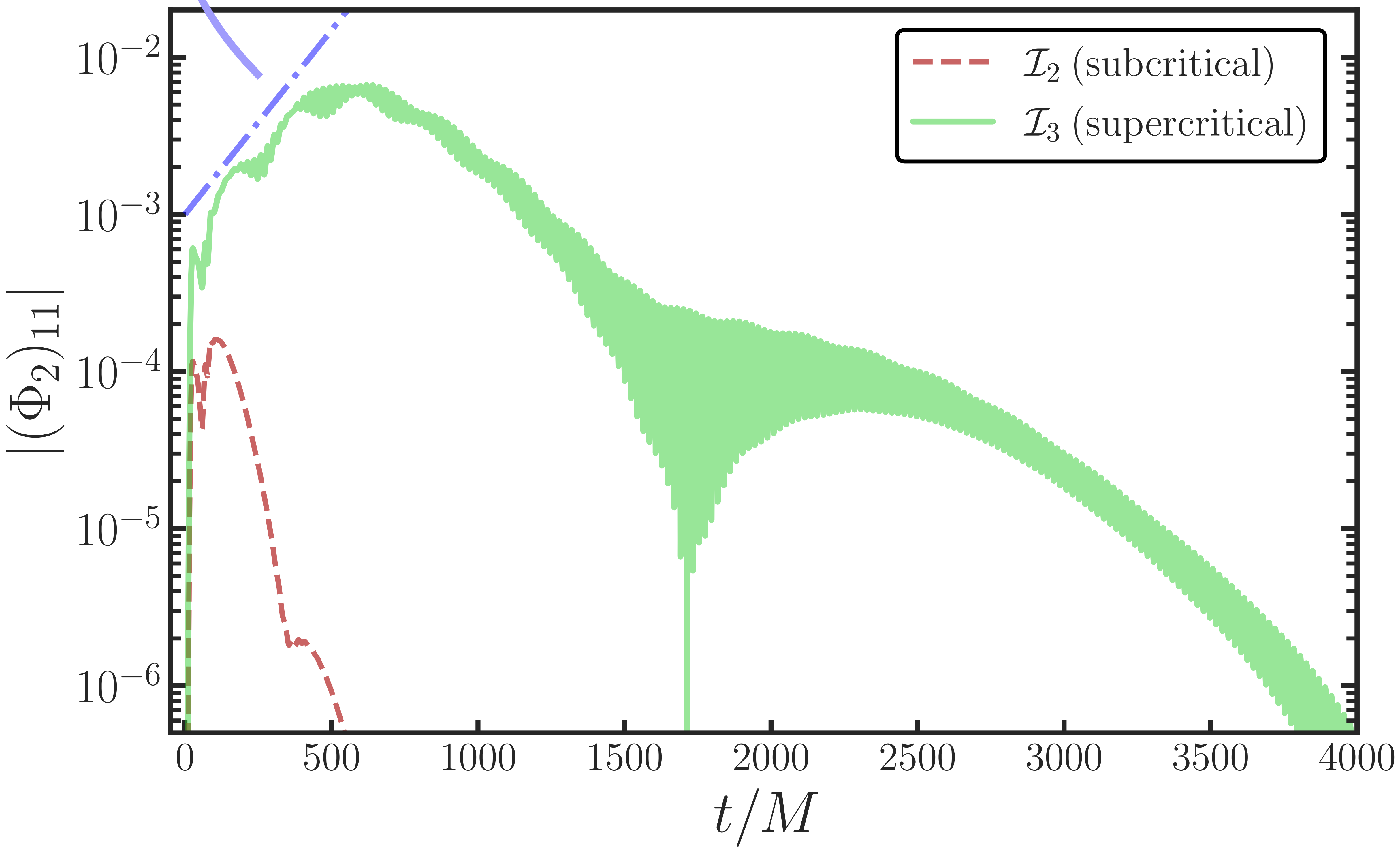
Axionic couplings — Boson clouds

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

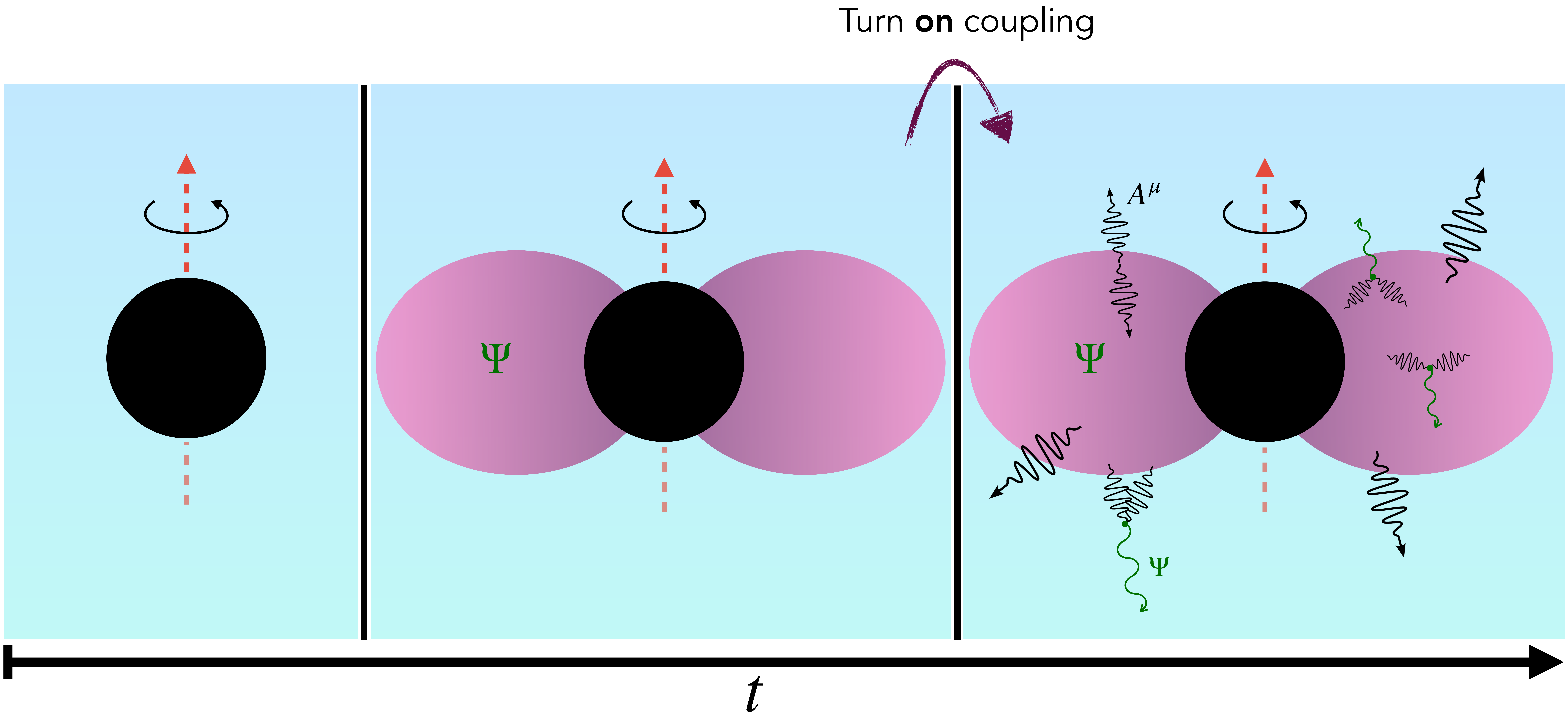
Axion field



EM field

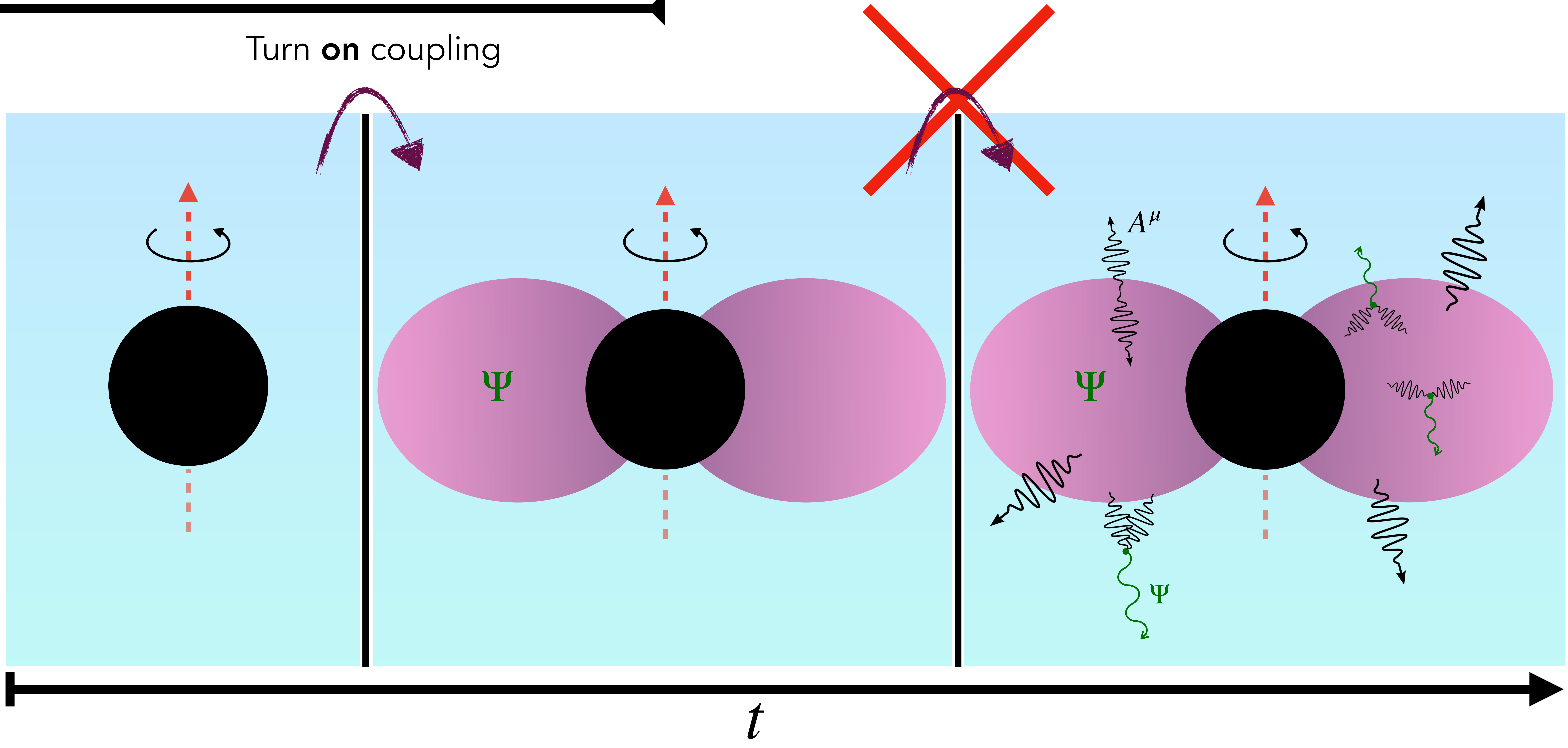


Axionic couplings — Overview



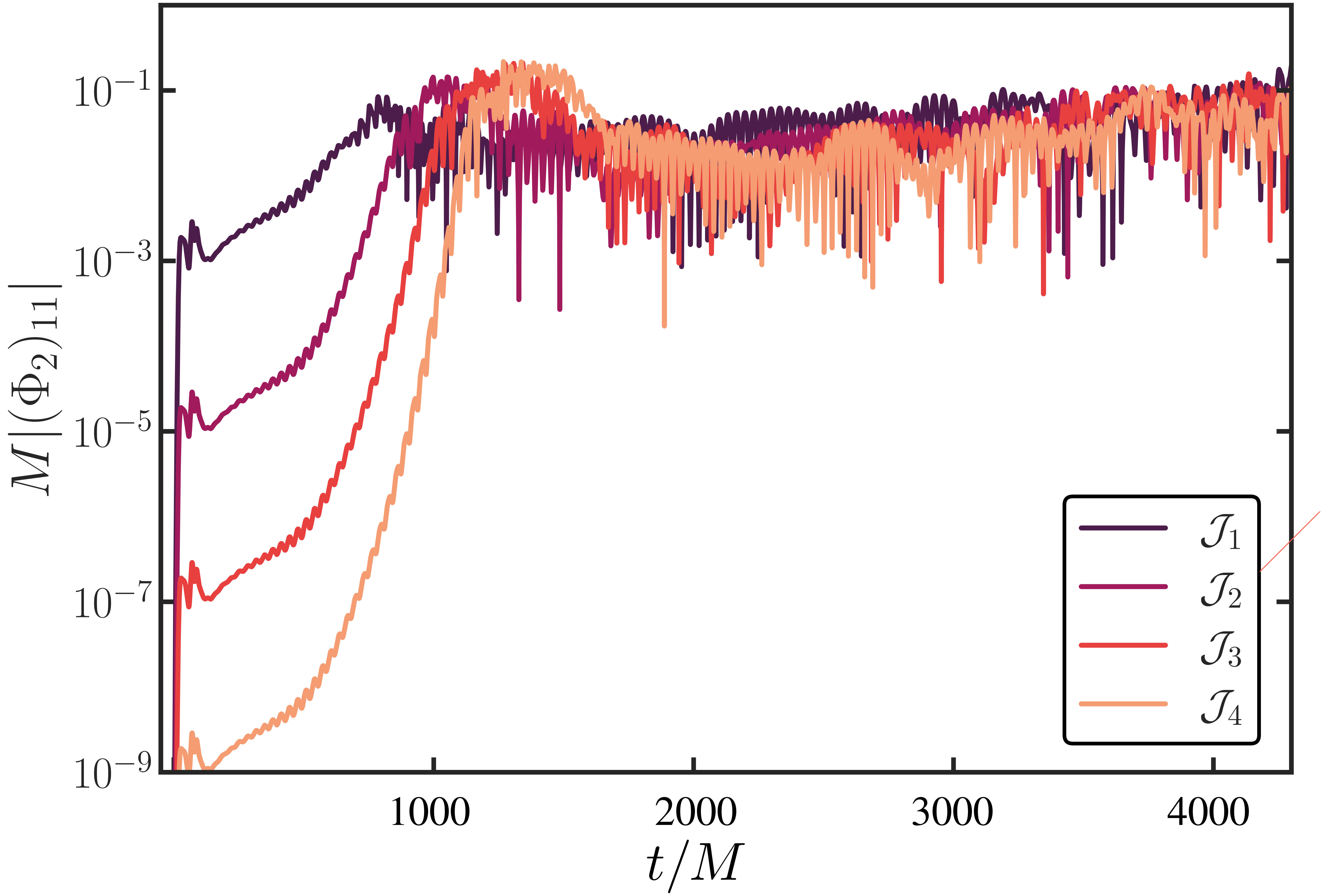
Axionic couplings — Overview

Turn **on** coupling



Axionic couplings — Superradiance

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

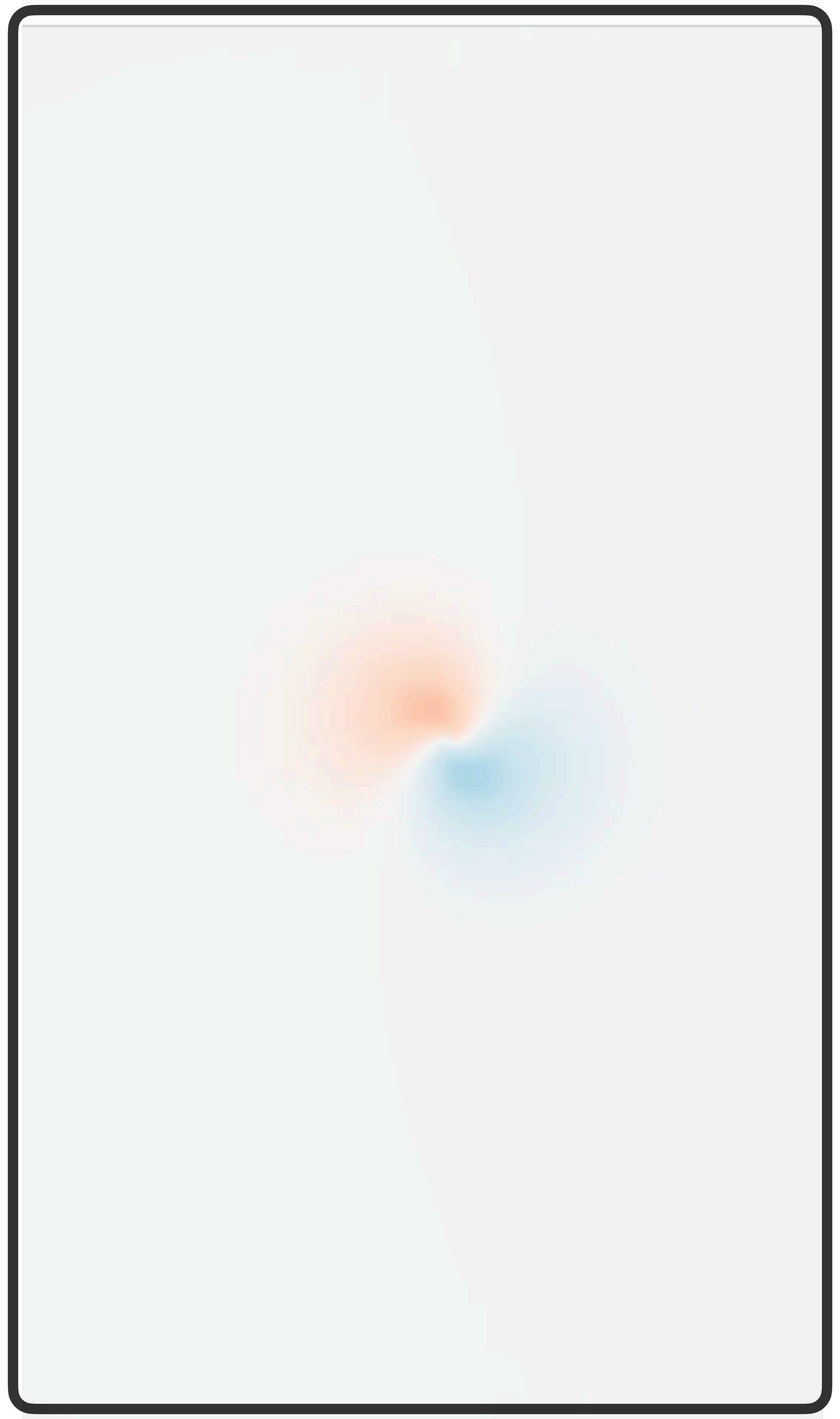


- Varying initial EM perturbation

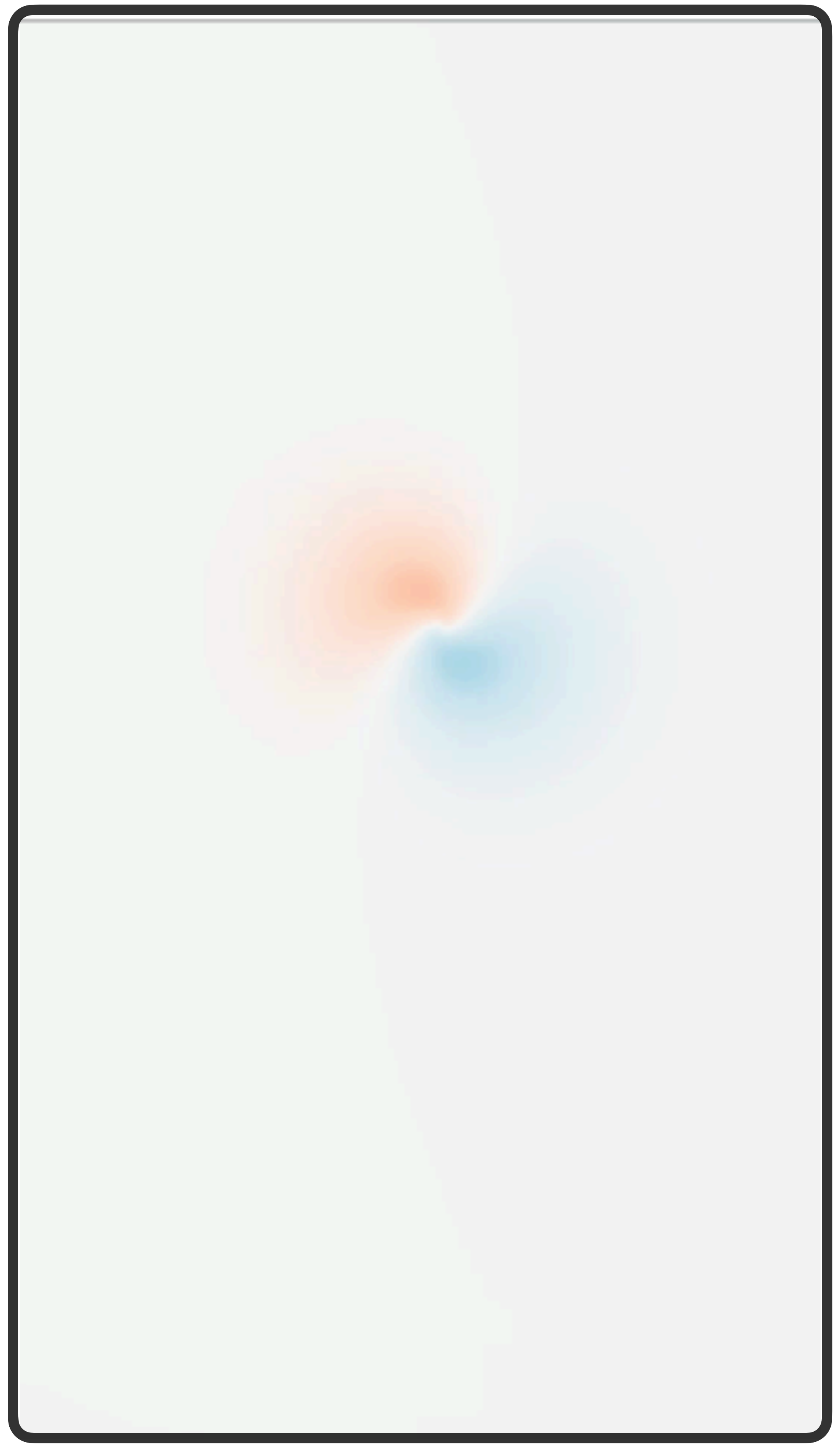
Axionic couplings — Summary

No SR growth

Subcritical



Including SR growth



Observational signatures — EM emission

Saturation phase: $\Gamma_{\rm SR} \simeq \Gamma_{\rm PI}$

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

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✦ High luminosity

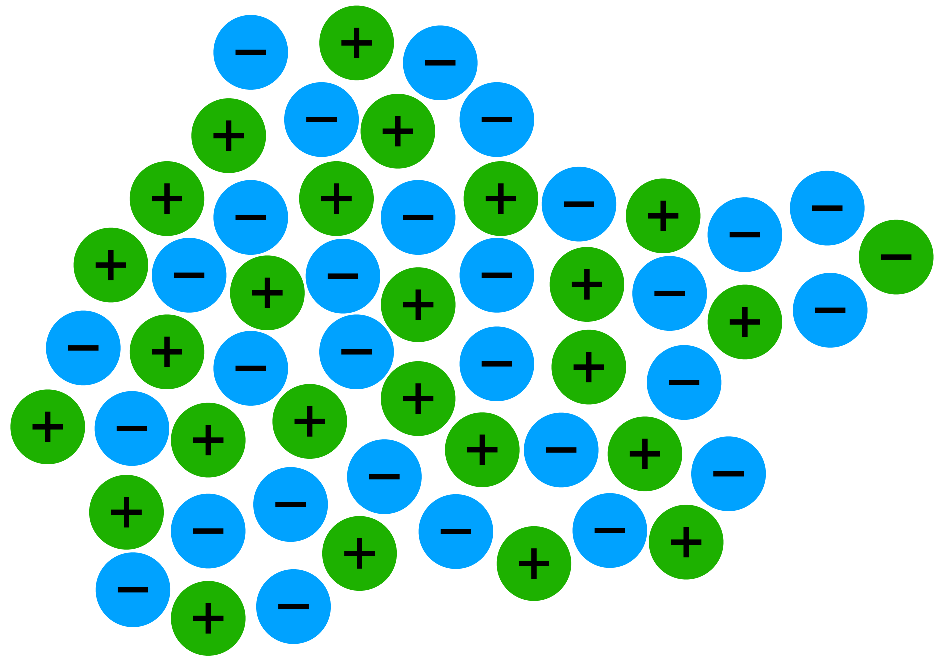
✦ (Nearly) Constant

✦ Monochromatic

But **detectable**...?

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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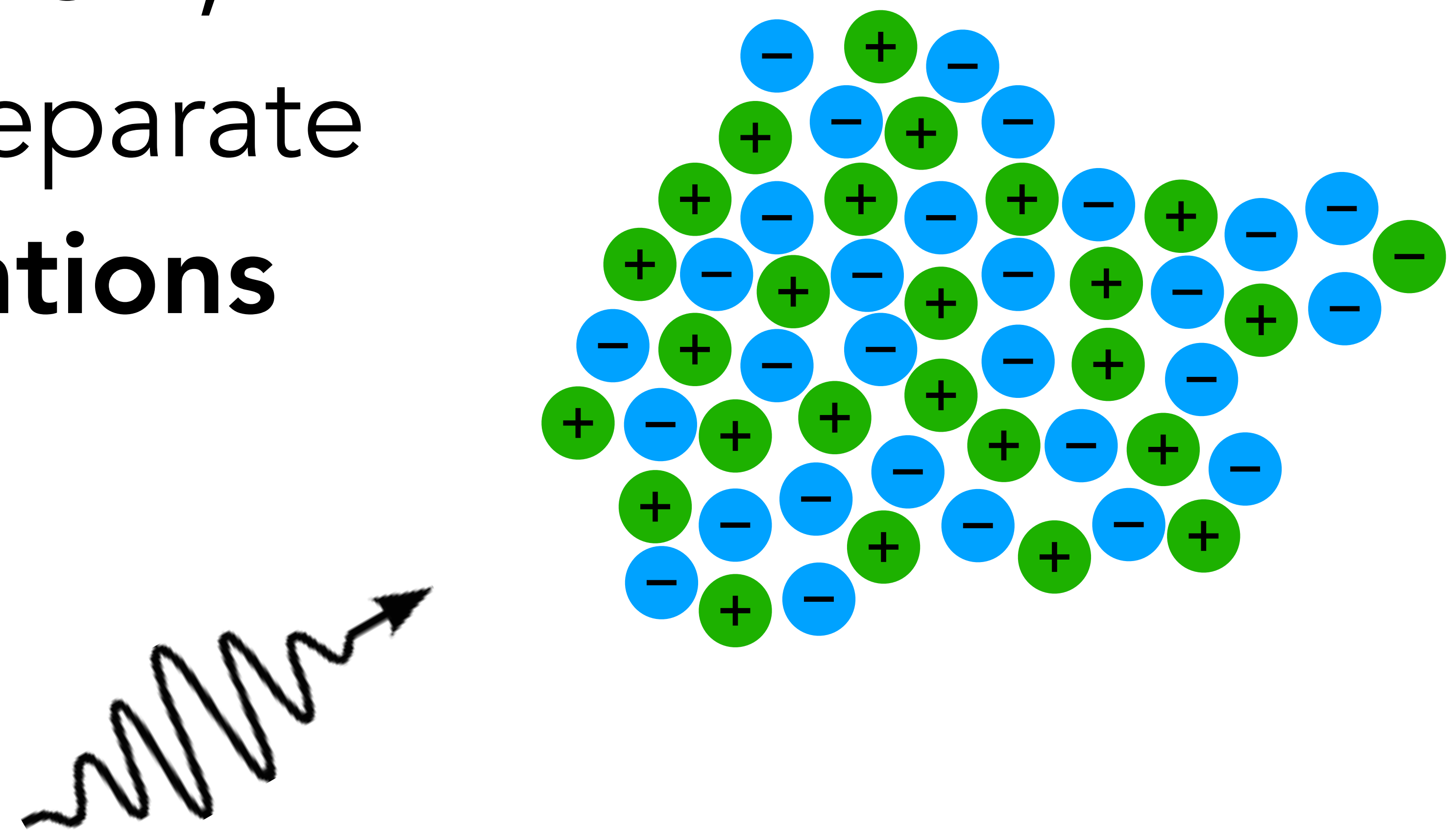


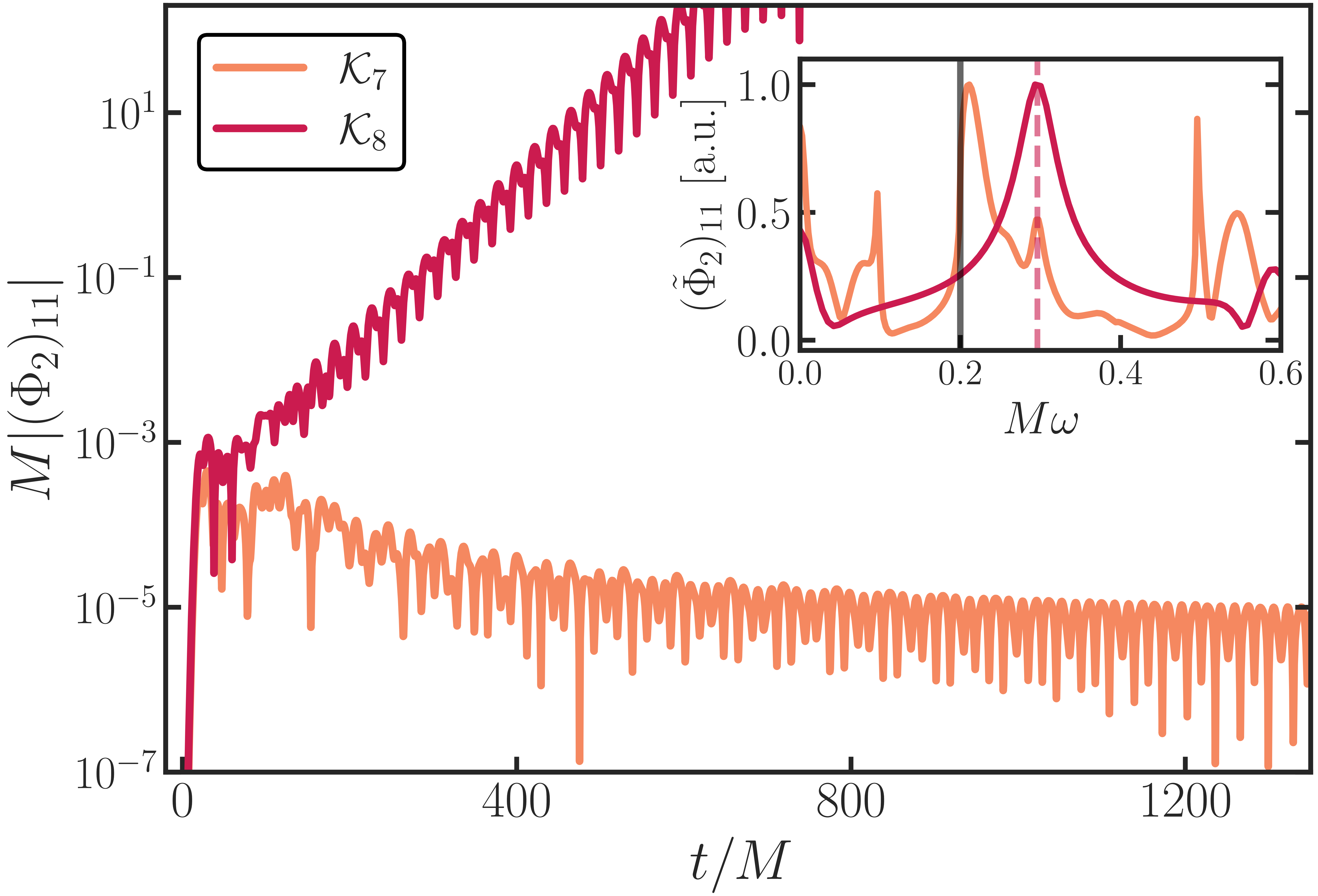
If **plasma** is perturbed by an EM wave, electrons are displaced and start **oscillating** with the **plasma frequency**:

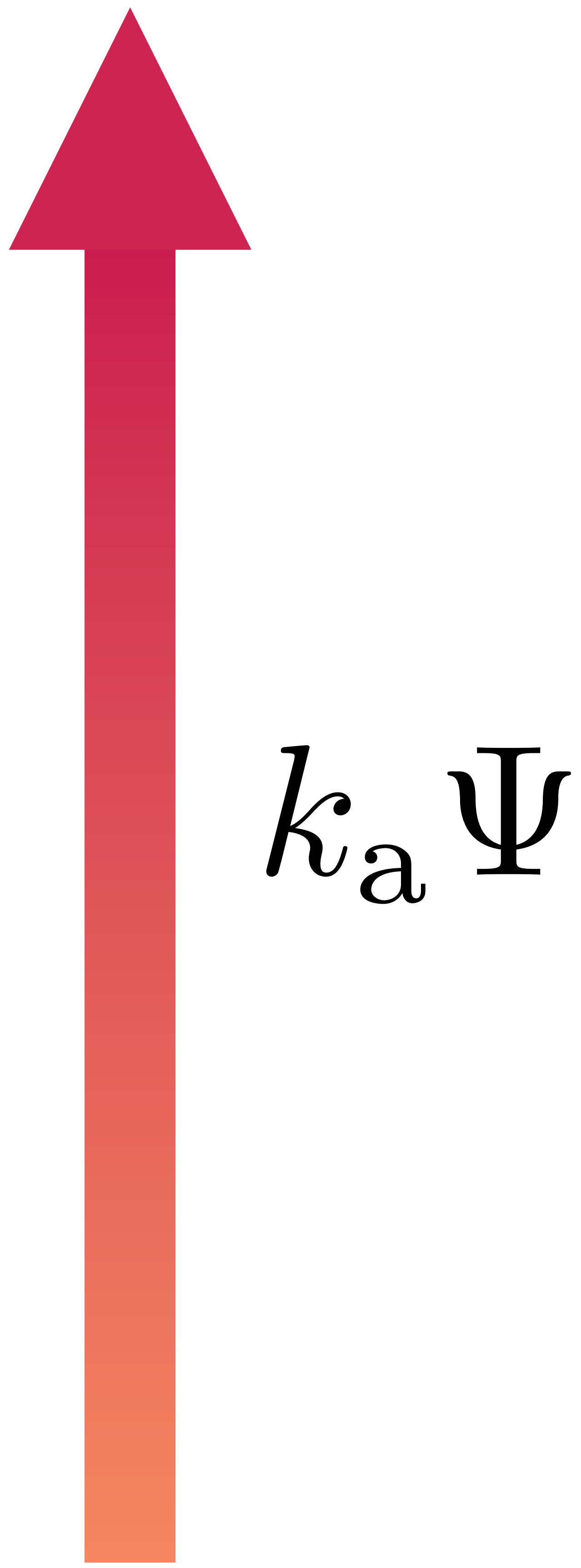
$$\omega_{\rm p} = \sqrt{\frac{n_e q_e^2}{m_e}} \approx 10^{-12} \sqrt{\frac{n_e}{10^{-3}{\rm cm}^{-3}}}\,{\rm eV}$$

Axionic couplings — Higher bands

$\mu M = 0.3$

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

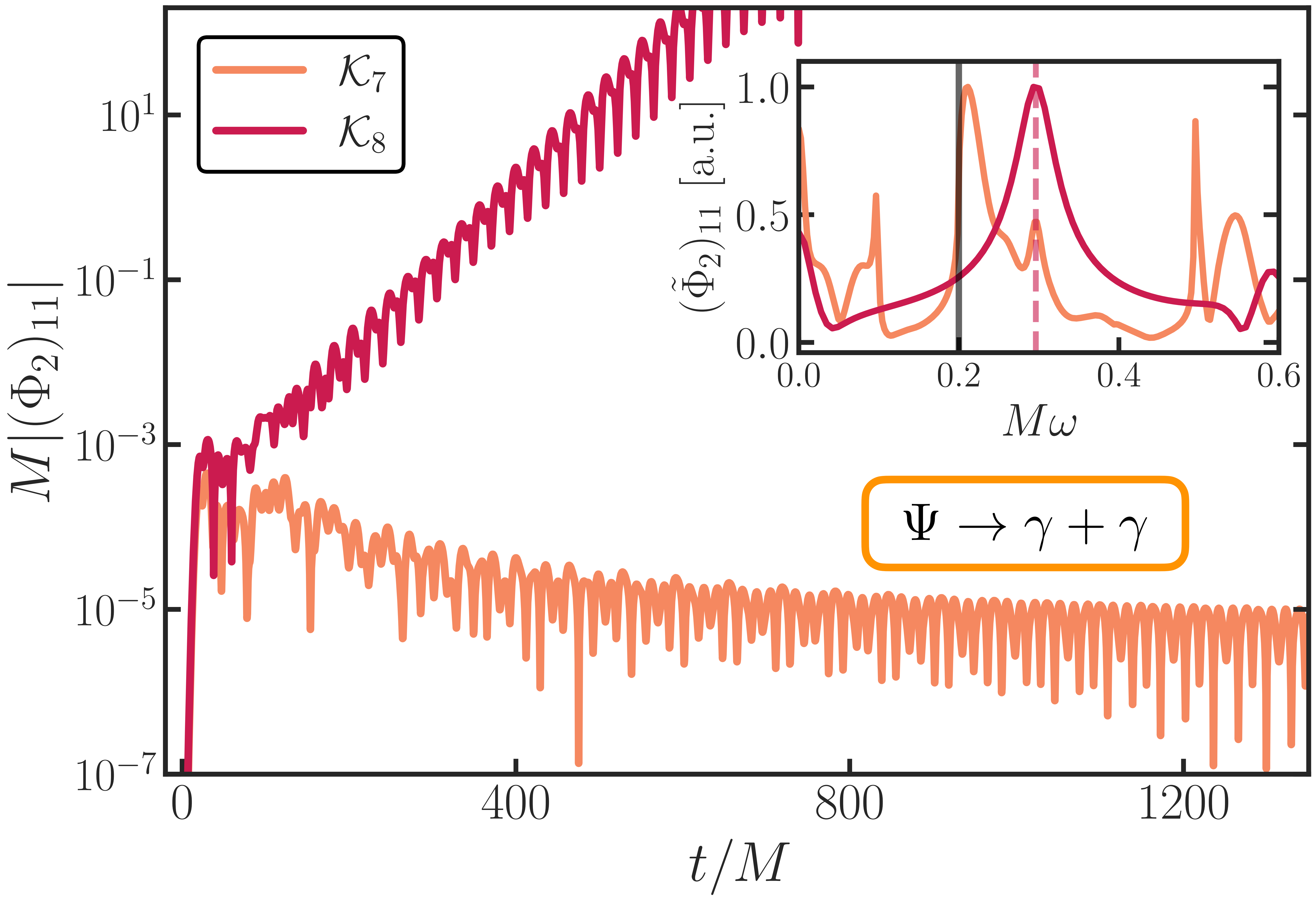




 [Spieksma *et al.* '23]

Axionic couplings — Higher bands

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

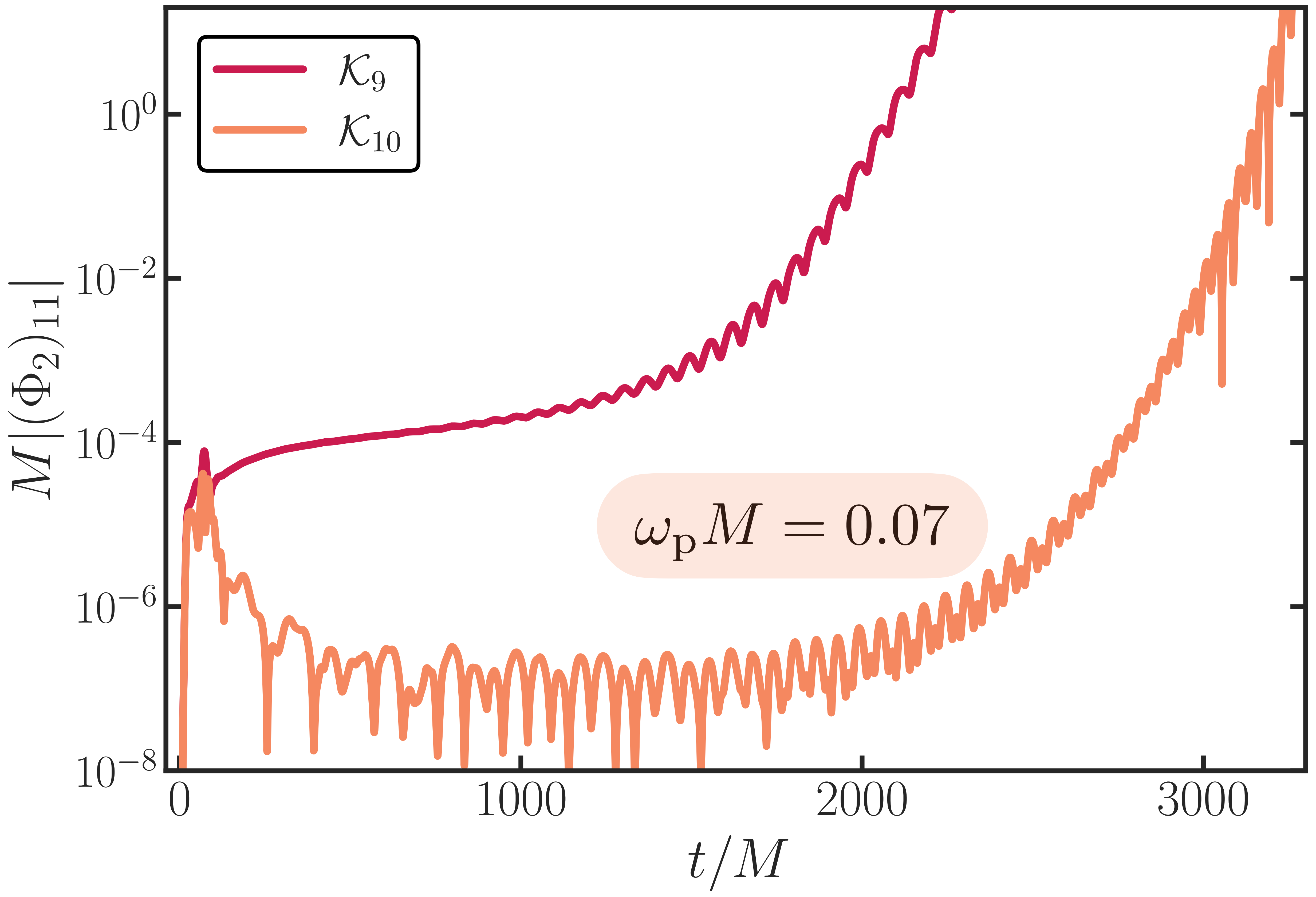


$\Psi \to \gamma + \gamma$

$k_{\rm a}\Psi$

Superradiance to the **rescue**!

$\mu M = 0.1$



Axionic couplings — Plasma and superradiance

Superradiance to the **rescue**!

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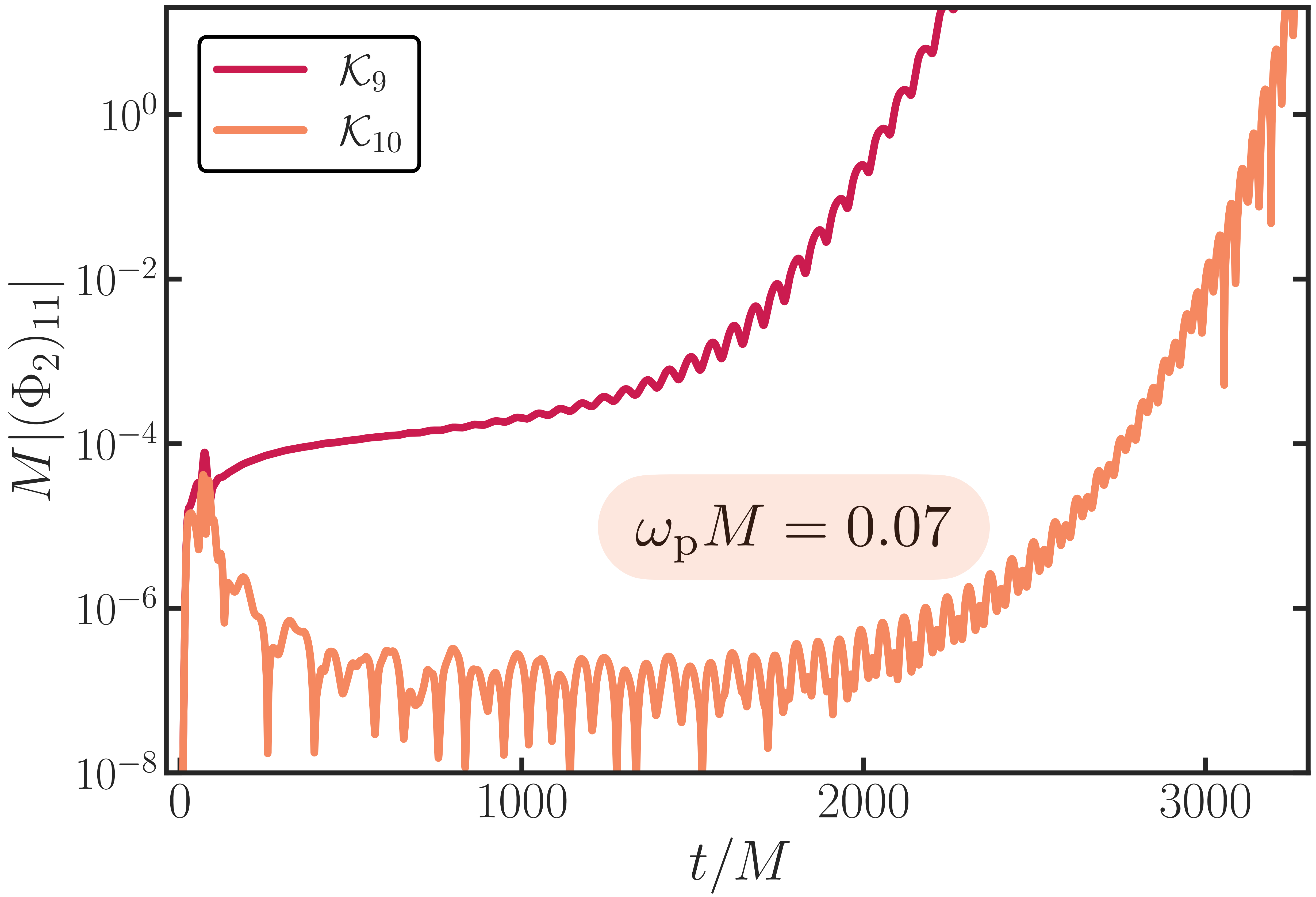

$$\frac{10^{-13}\ \mathrm{GeV}^{-1}}{k_a} \lesssim 8 \times 10^5 \left(\frac{10^{-3}\ \mathrm{cm}^{-3}}{n_e}\right) \left(\frac{M_c/M}{0.1}\right)^{1/2} \times \left(\frac{1 M_\odot}{M}\right)^2 \left(\frac{\mu M}{0.2}\right)^4$$

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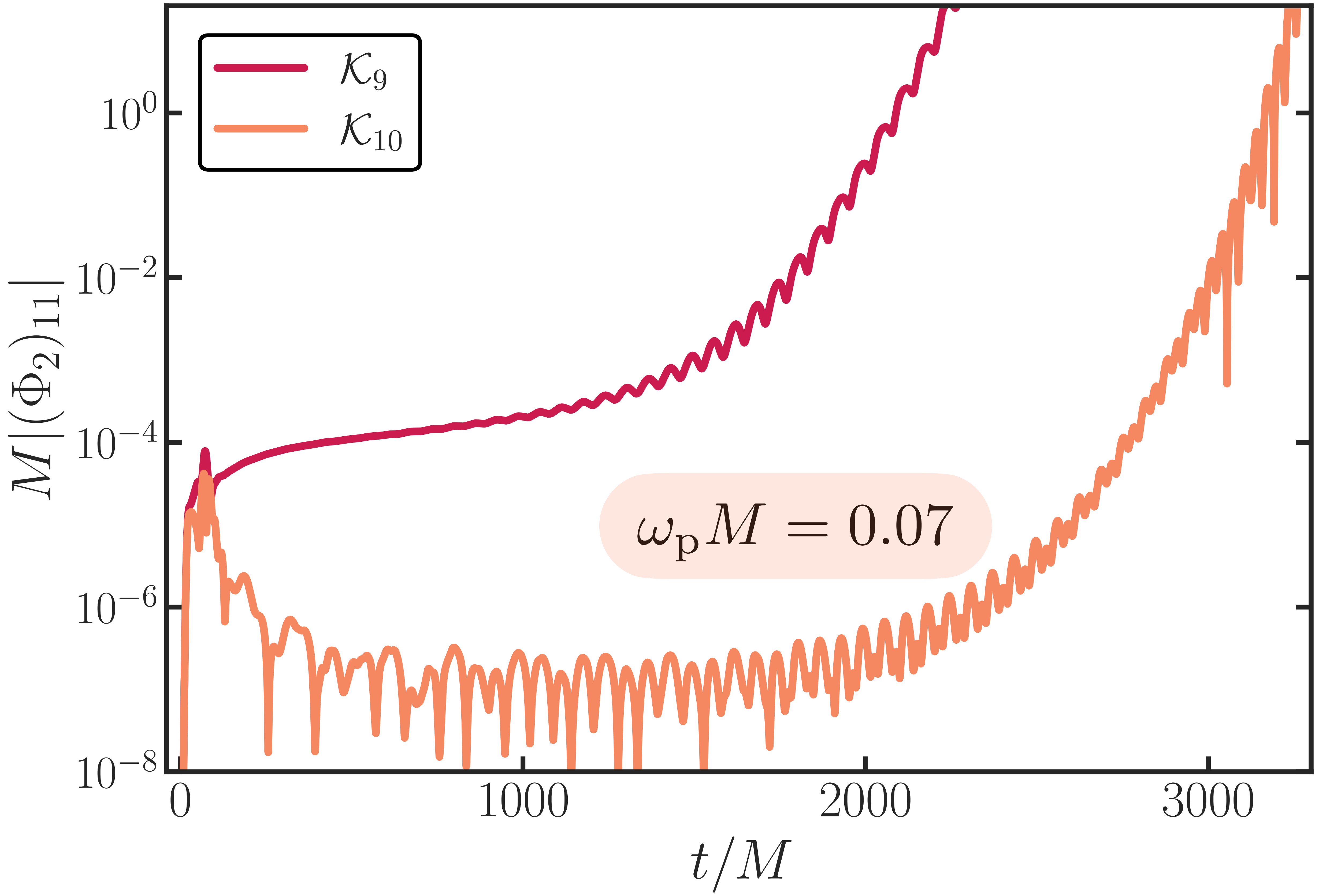

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Instabilities triggered for plasmas way denser than the **interstellar medium**!

Conclusions — Part I

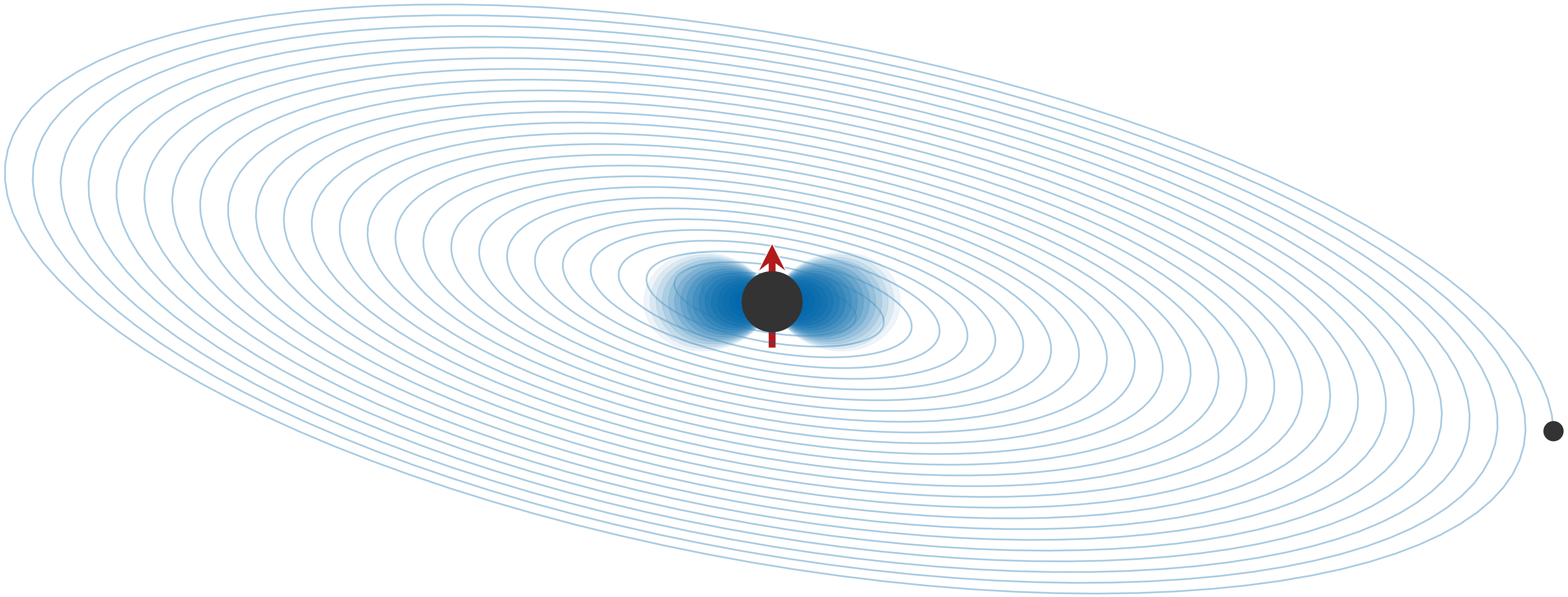
Superradiance offers a way to explore the ultralight, **weak-coupling** regime of particle physics

- ✦ 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**

↓

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

Boson clouds in black hole binaries



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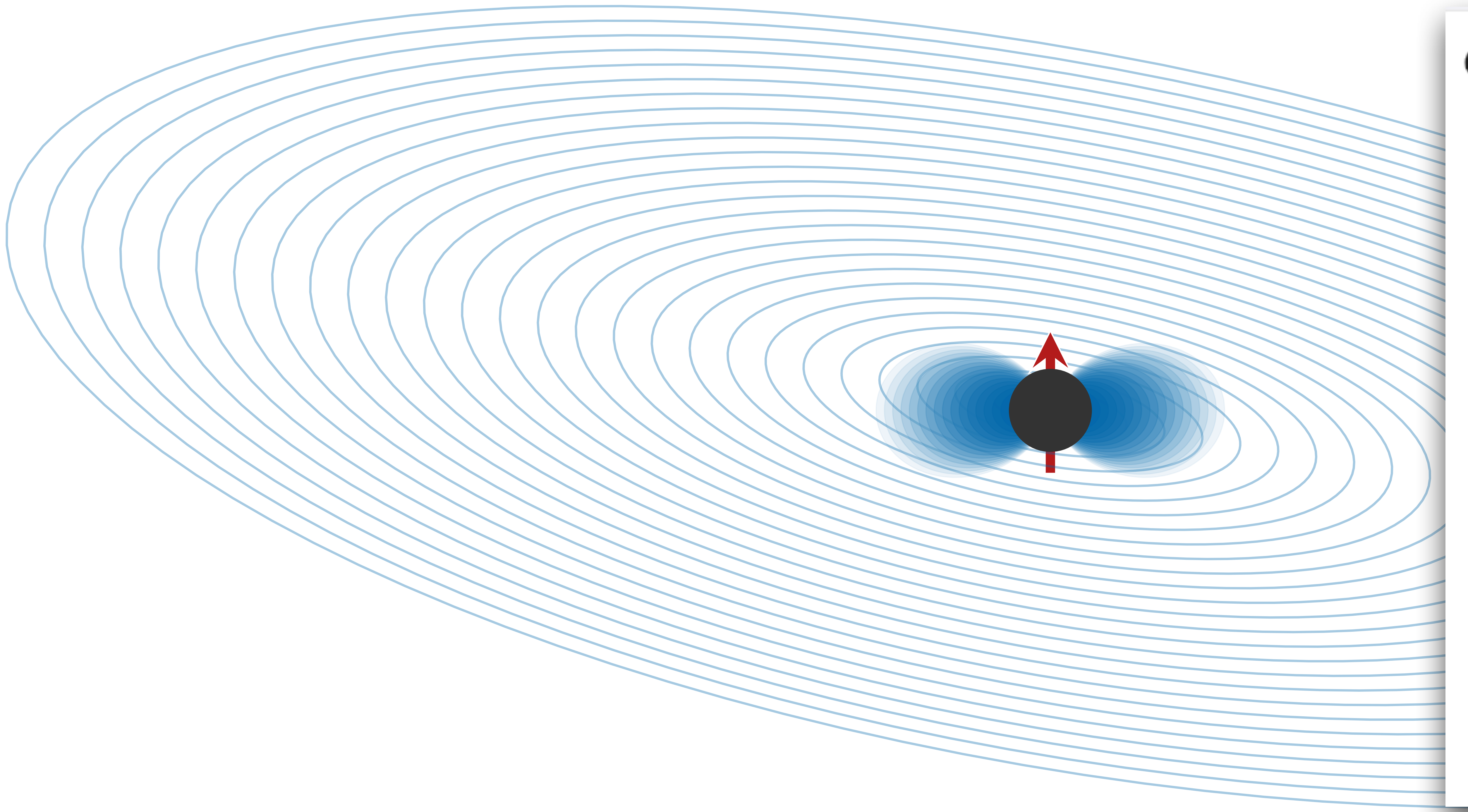
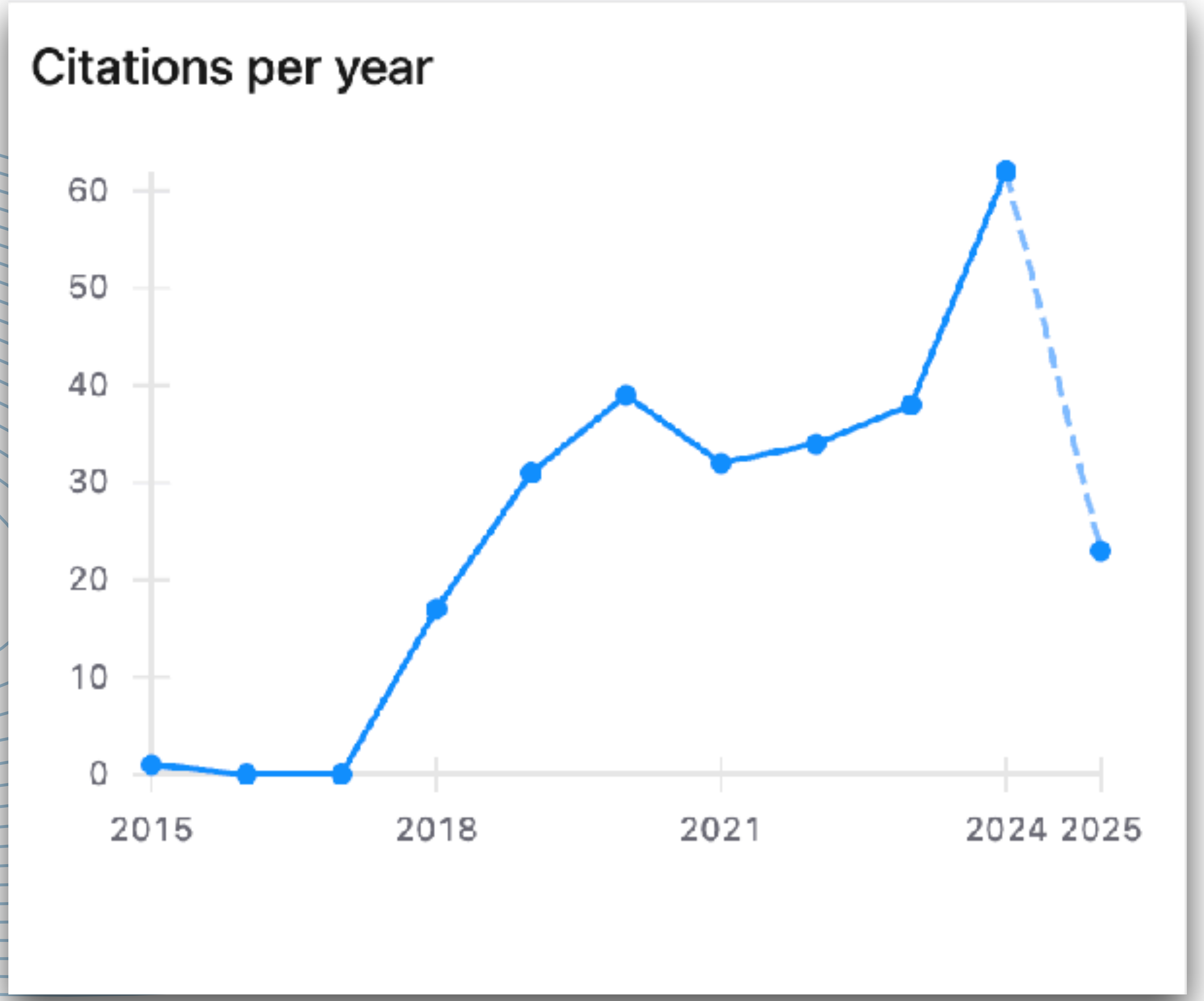
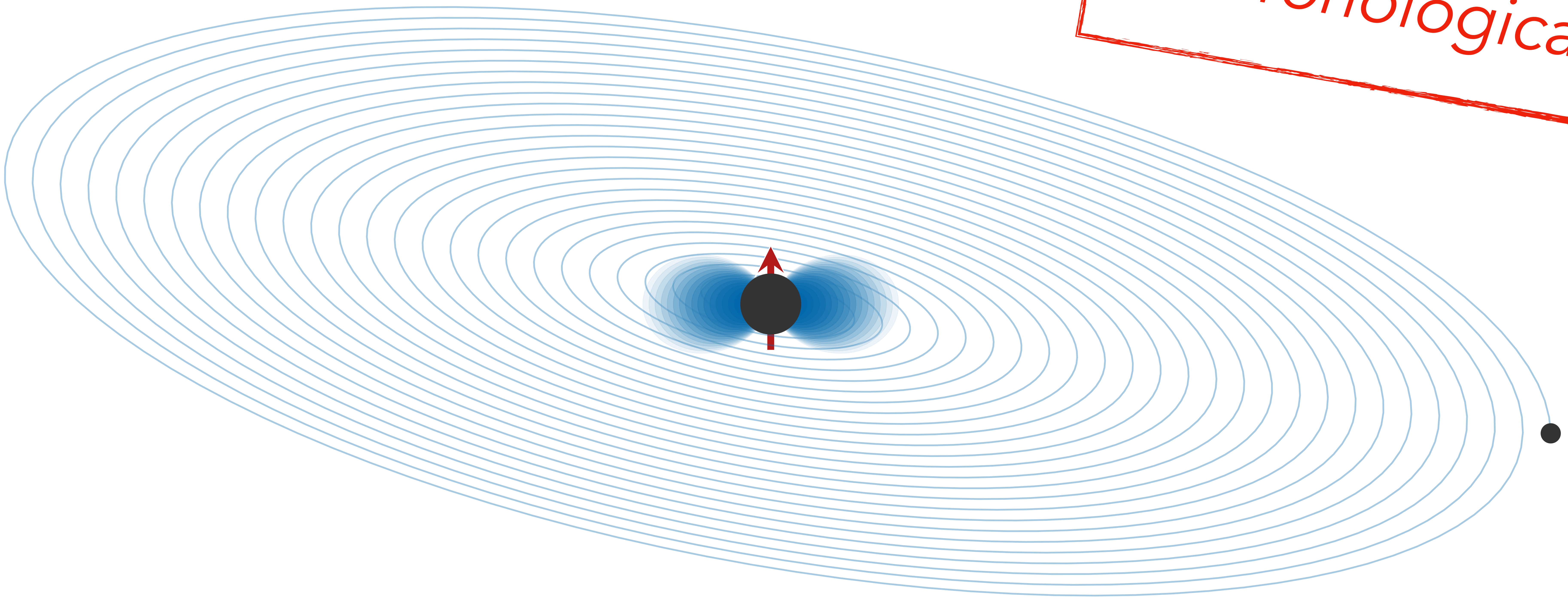




 [Baumann *et al.* ’18]

Boson clouds in black hole binaries

A chronological story



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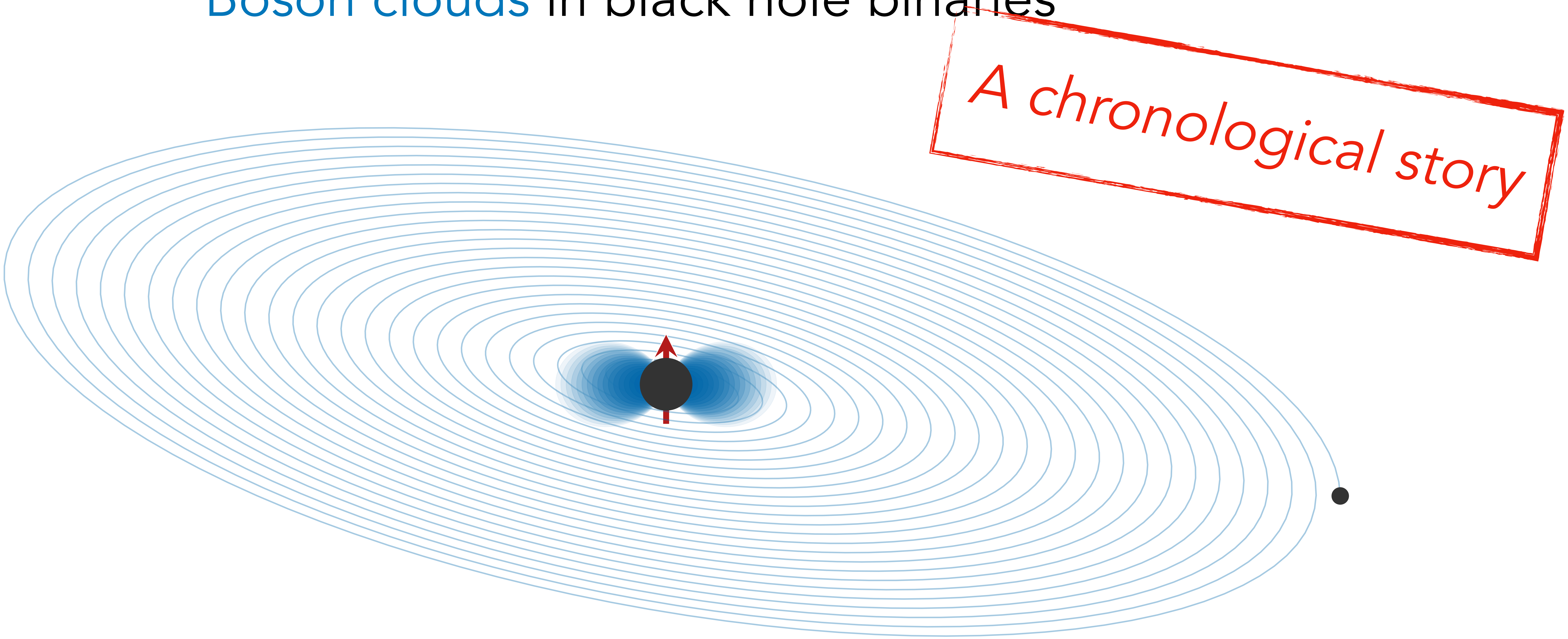
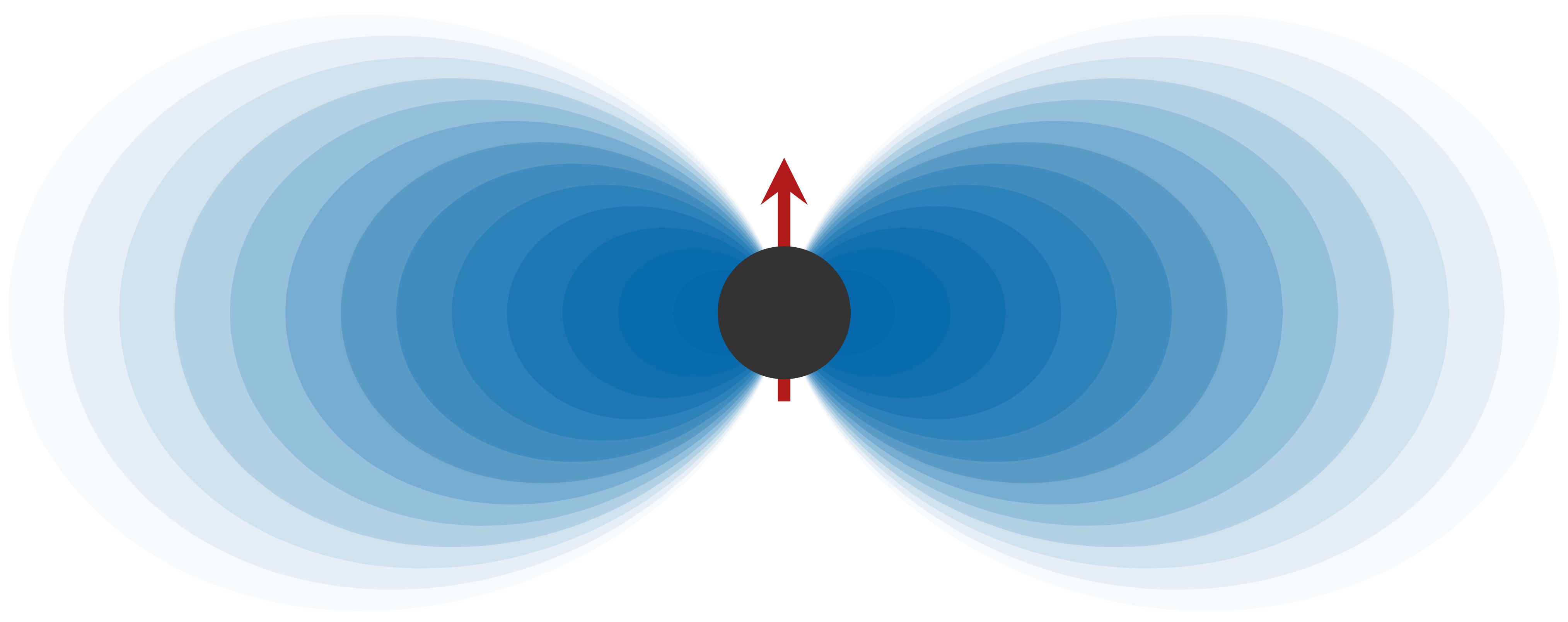
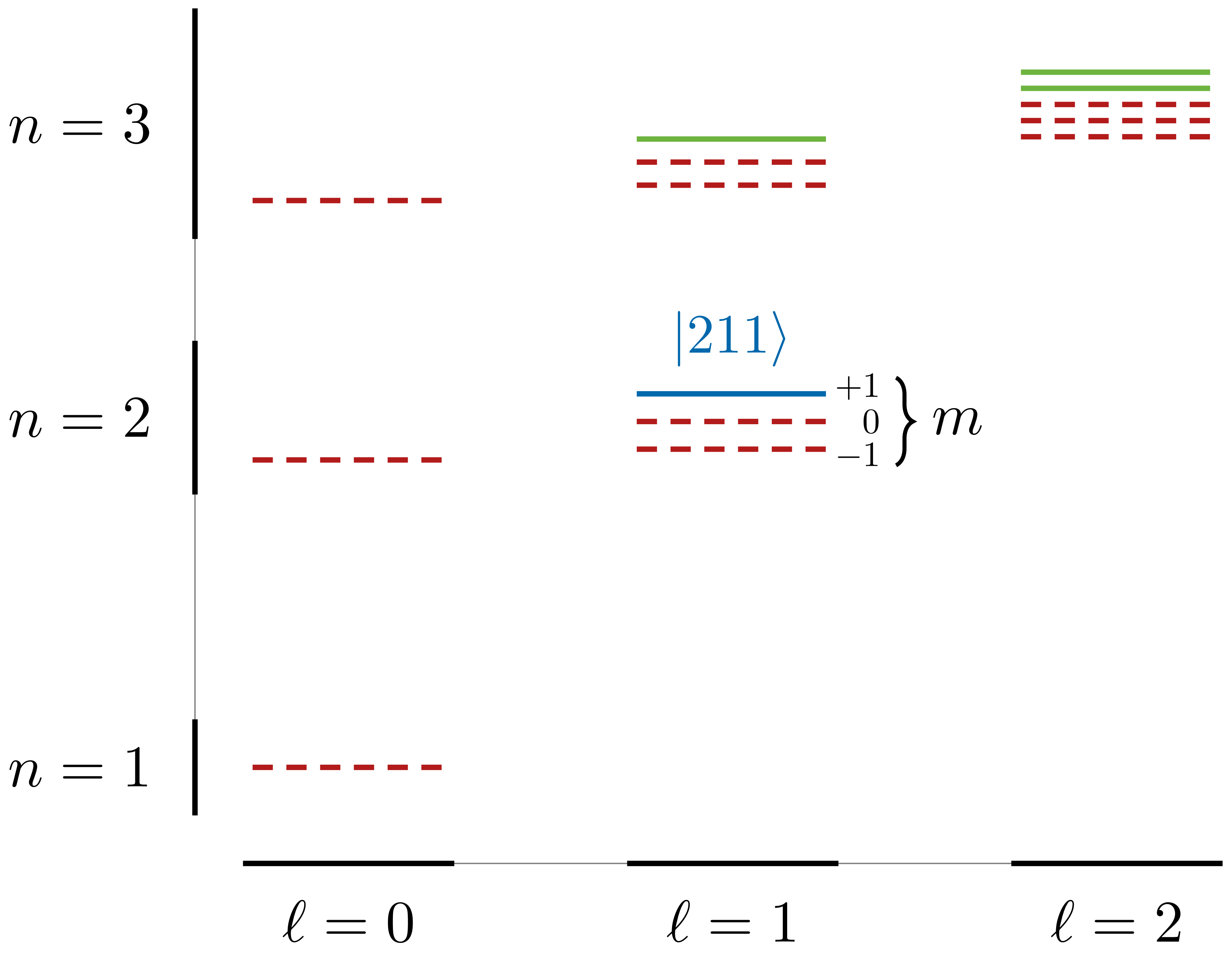


- Is the cloud there when the binary becomes **detectable**?
- What is the state of the cloud?
- What is the binary's configuration?

Boson clouds in binaries — Spectrum





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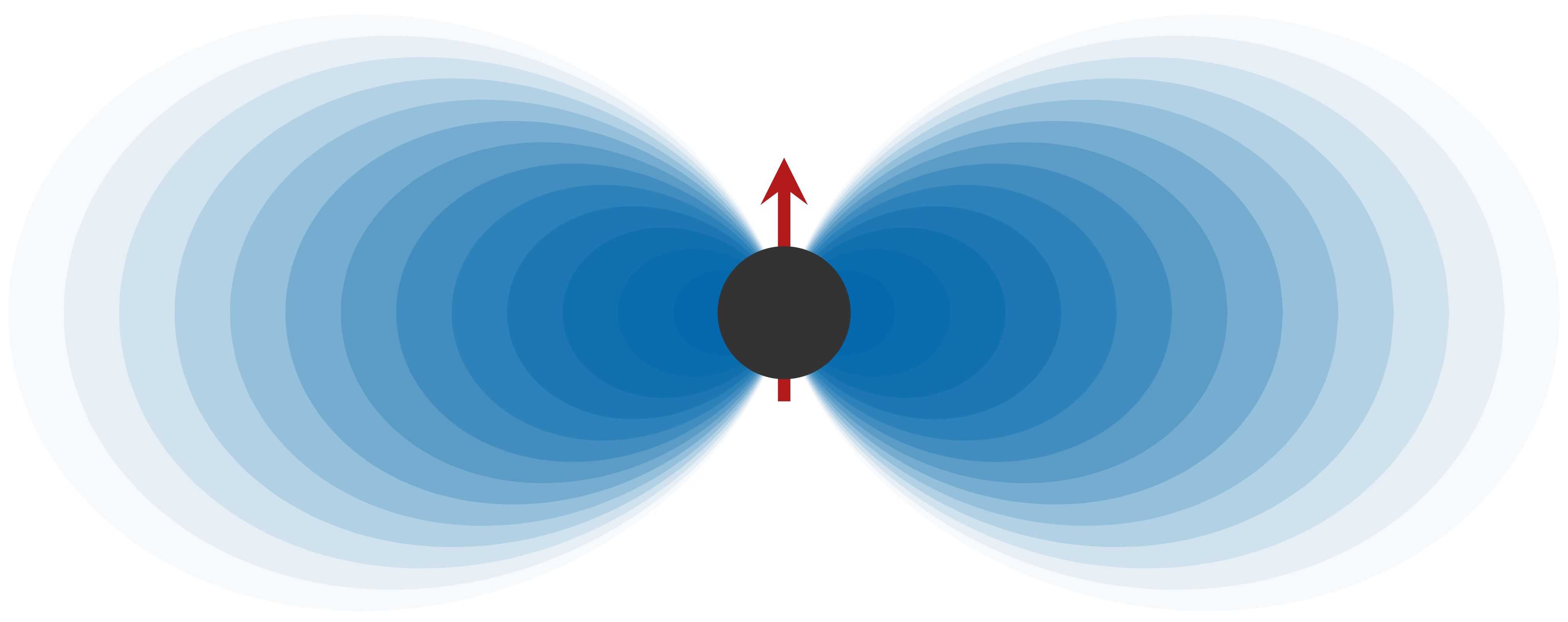
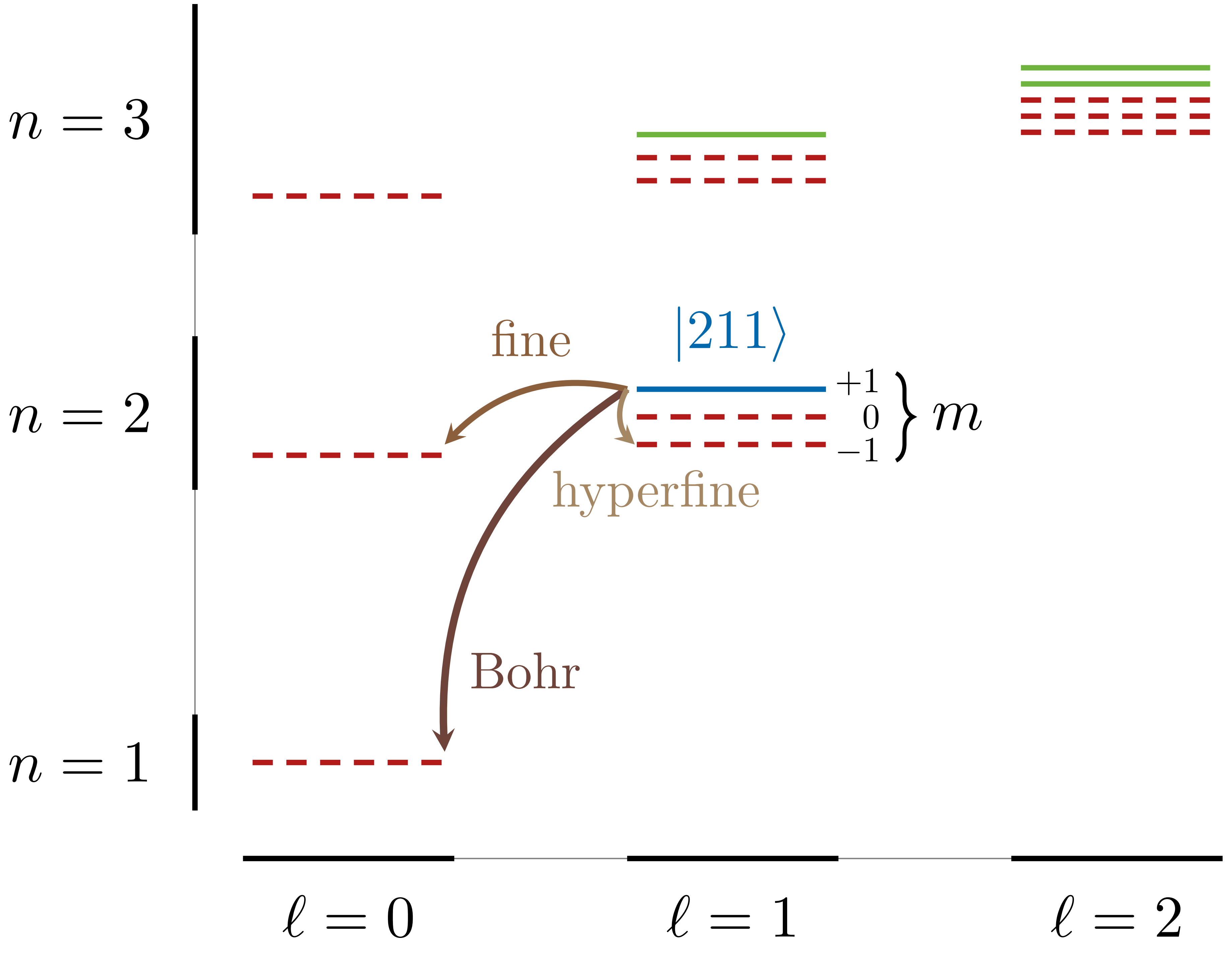
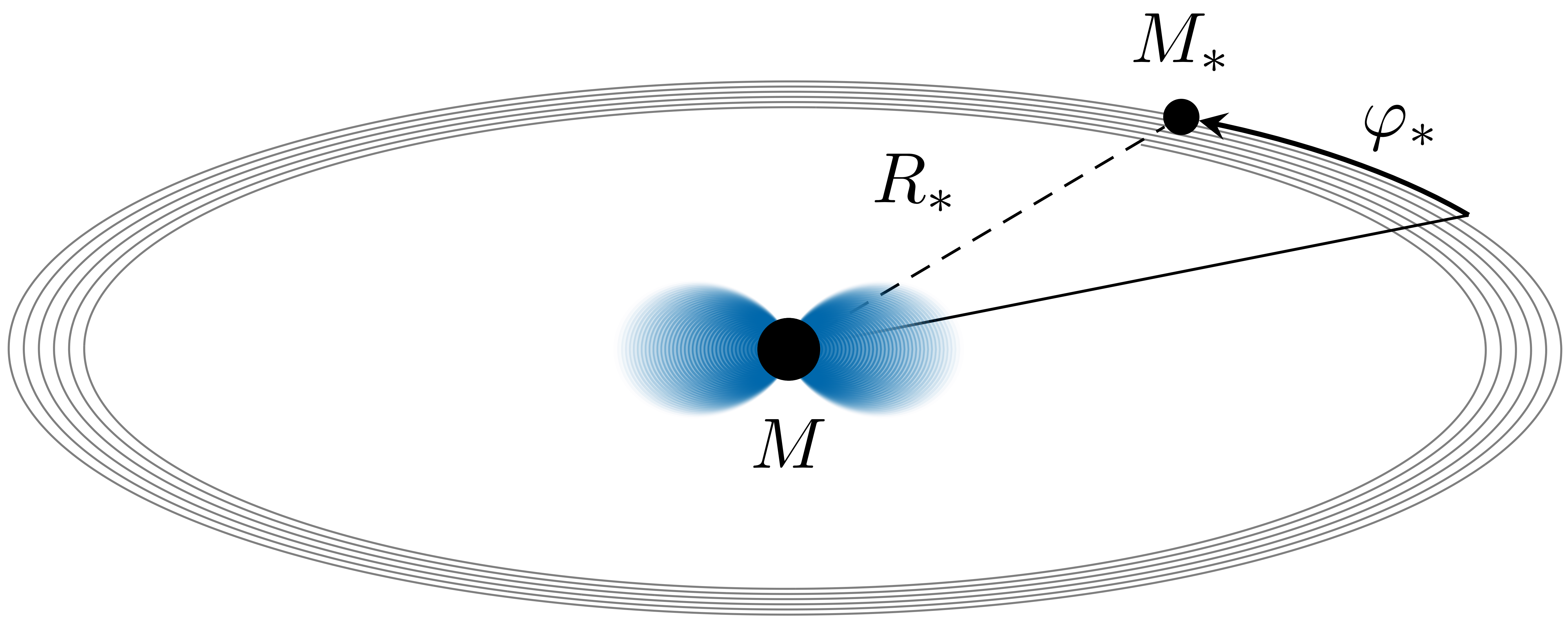




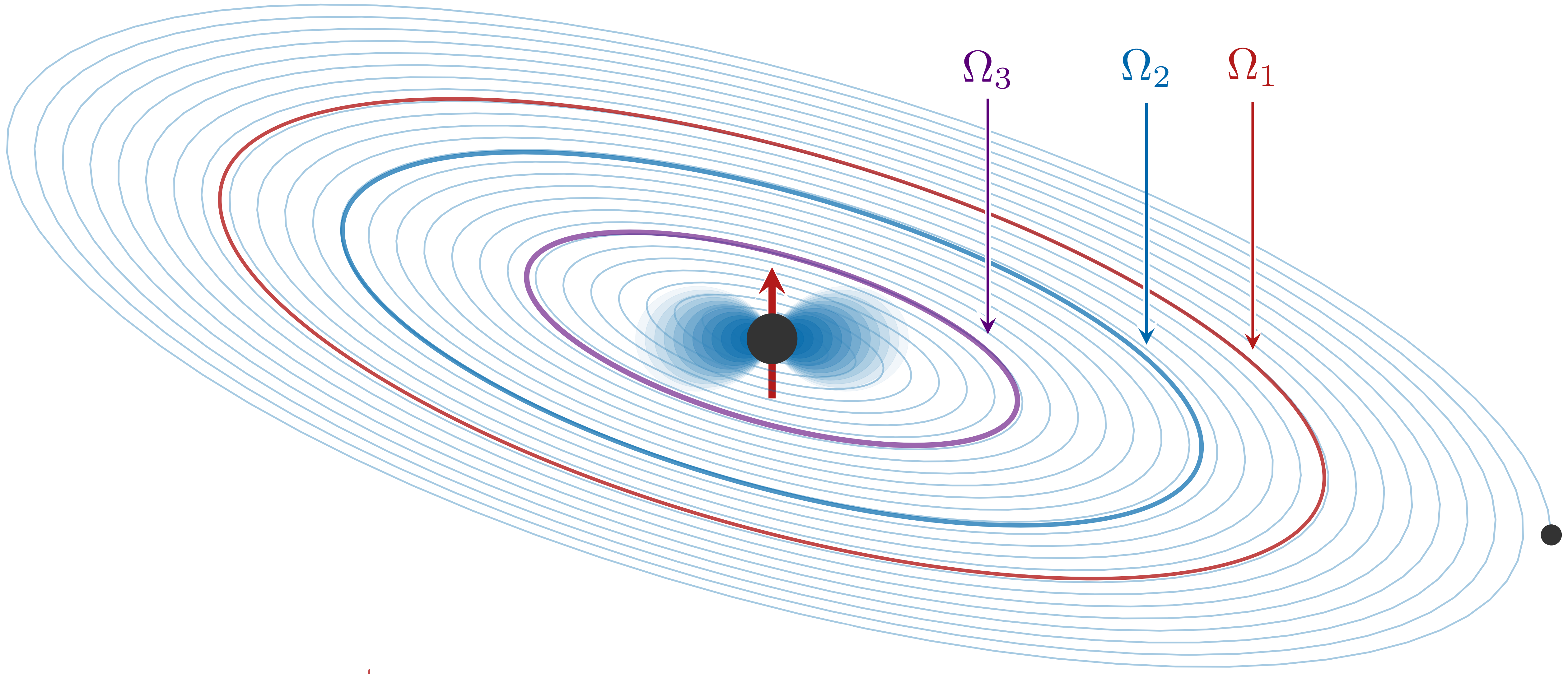
Newtonian perturbation with slowly increasing frequency



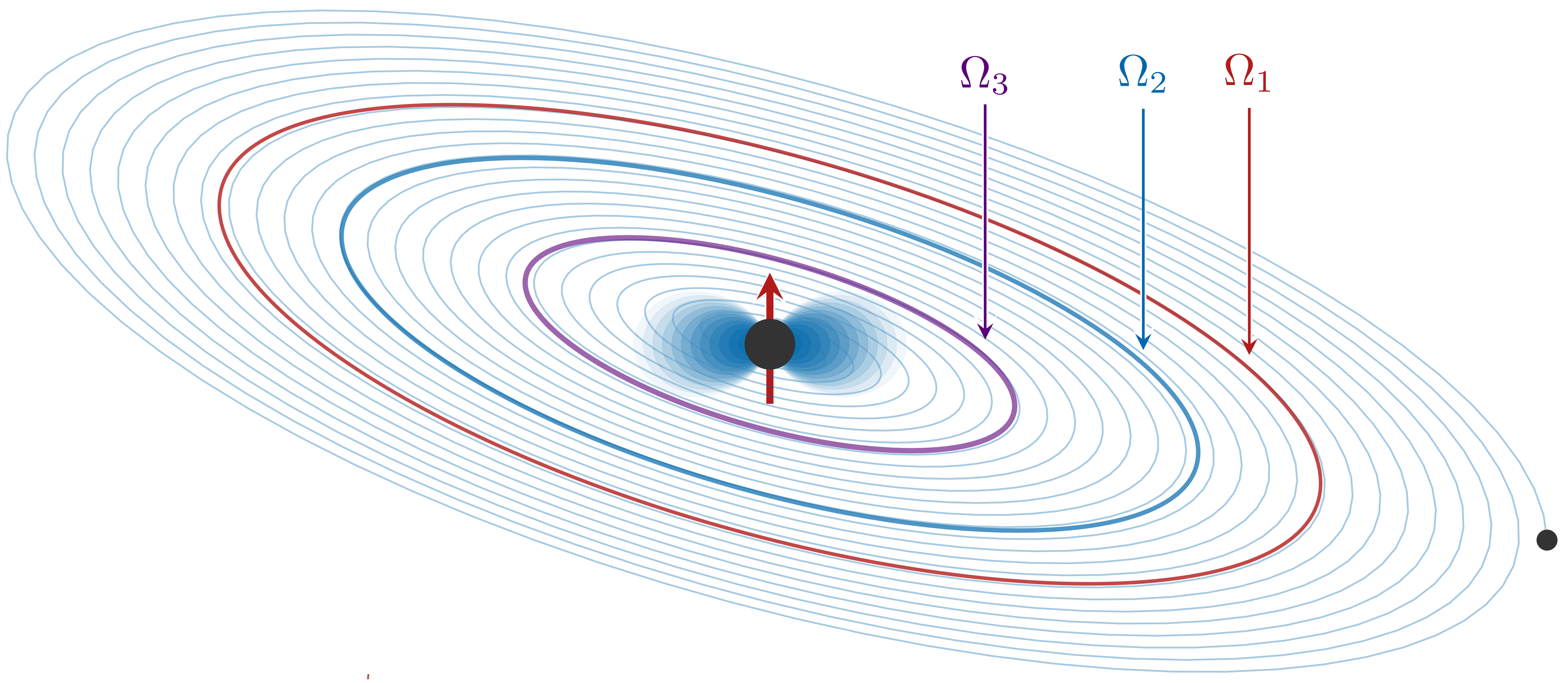
$$i\frac{\mathrm{d}\psi}{\mathrm{d}t} = \left(-\frac{1}{2\mu}\nabla^2 - \frac{\alpha}{r} + V_*(R_*, \varphi_*)\right)\psi$$

Boson clouds in binaries — Resonances

$$\langle a|V_*(t)|b\rangle = \sum_g \eta^{(g)} e^{-ig\Omega t}$$

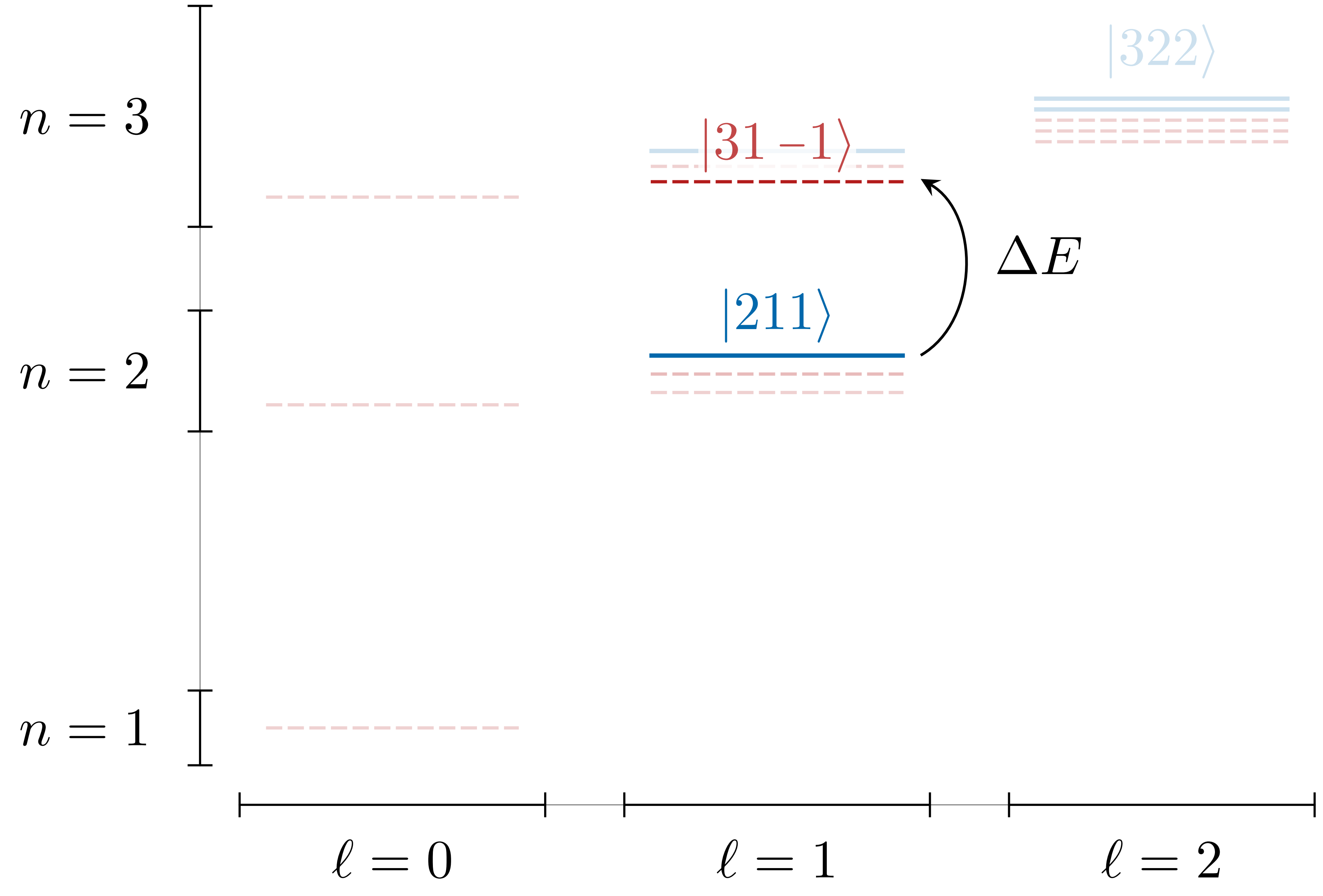


Boson clouds in binaries — Resonances



$$\langle a|V_*(t)|b\rangle = \sum_g \eta^{(g)} e^{-ig\Omega t}$$

$$\Omega_r = \left|\frac{\Delta E}{\Delta m}\right|$$



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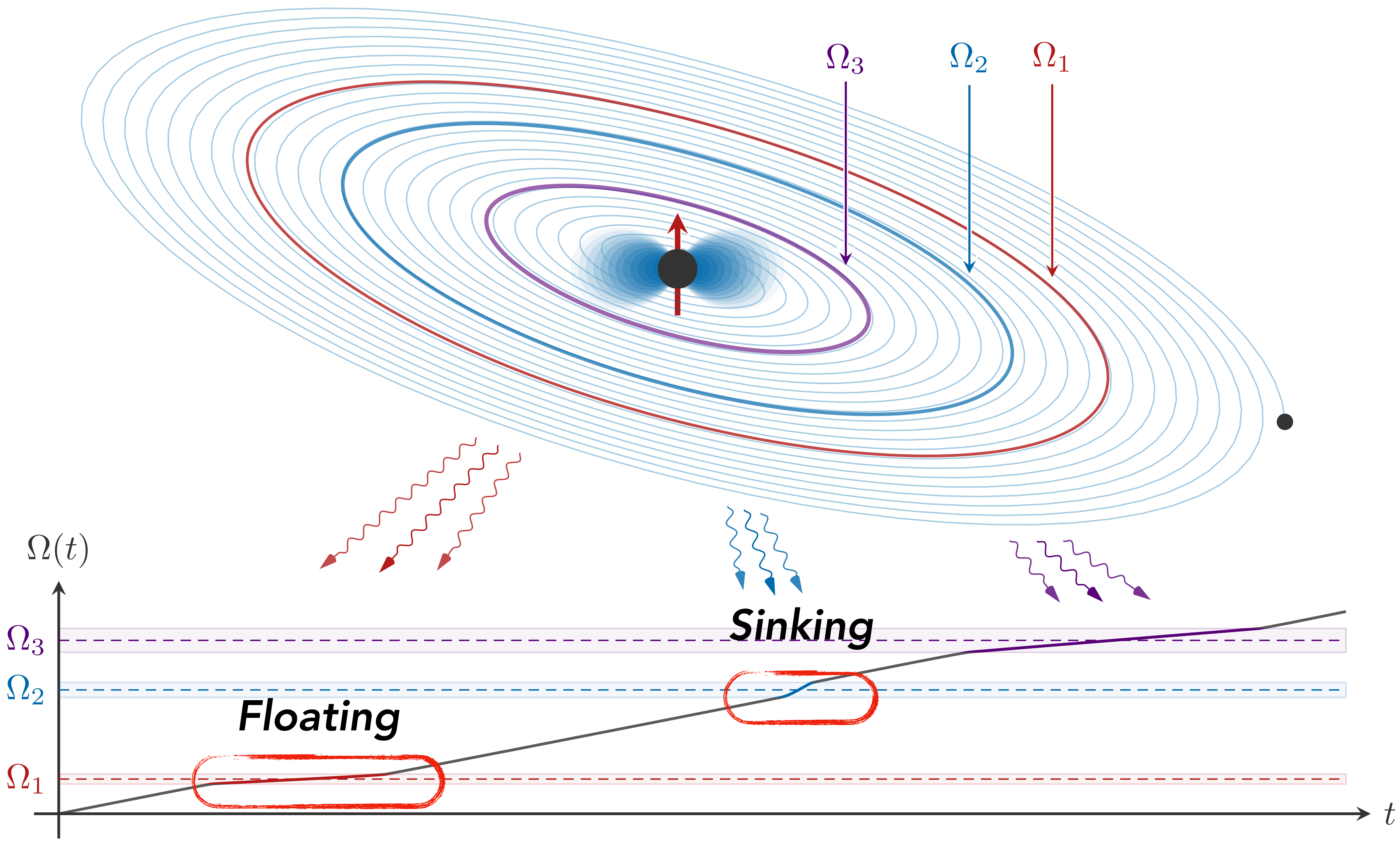

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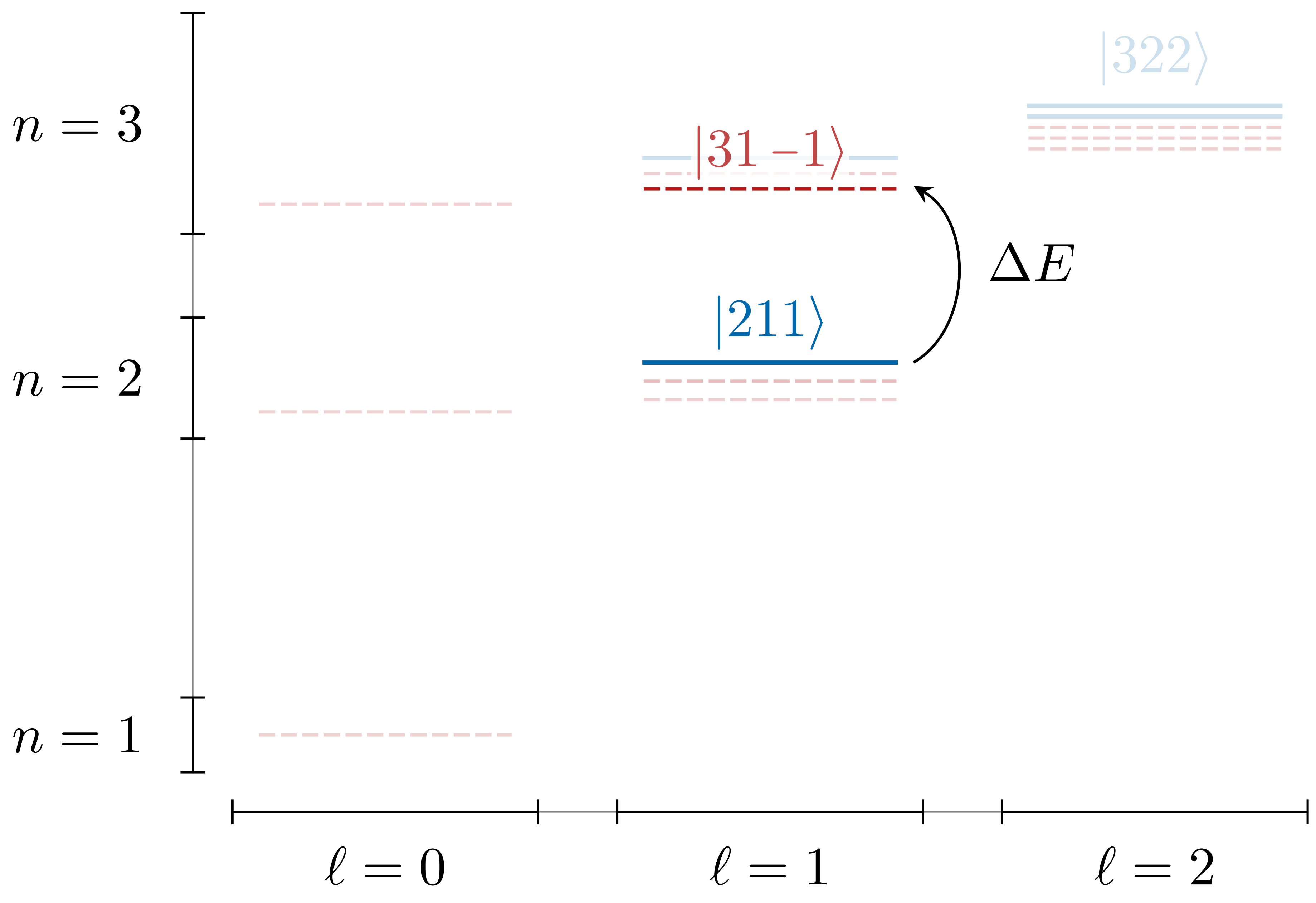
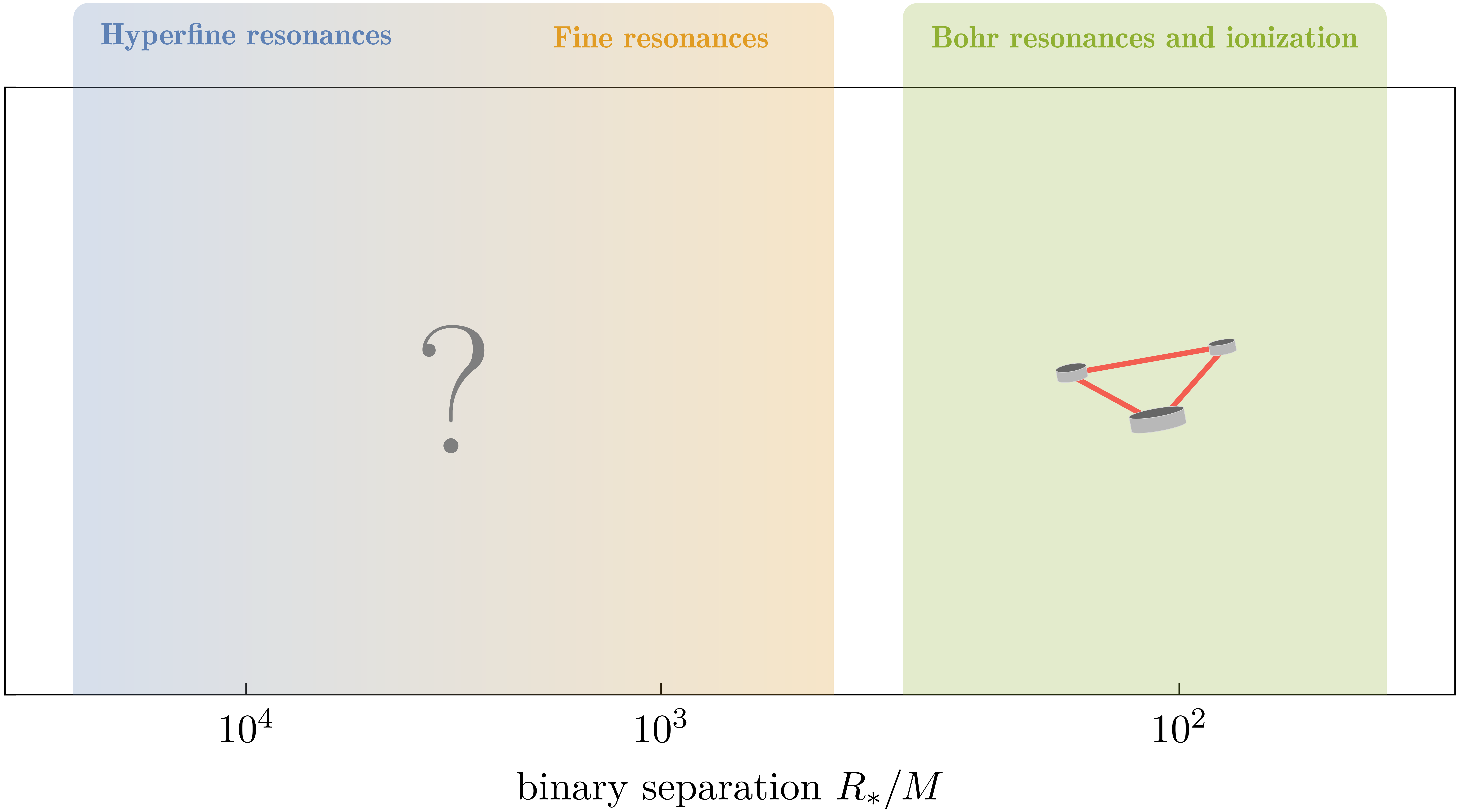
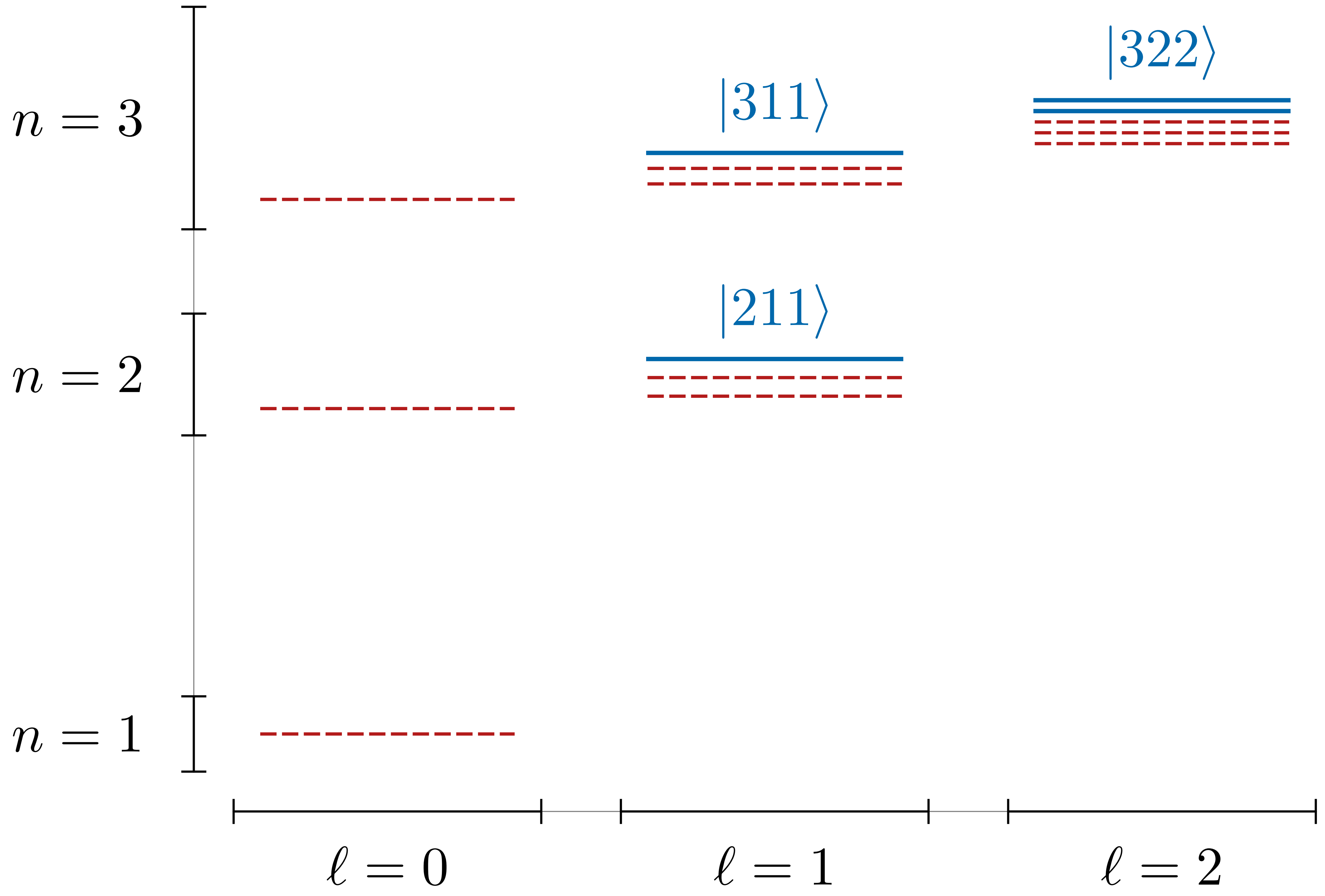


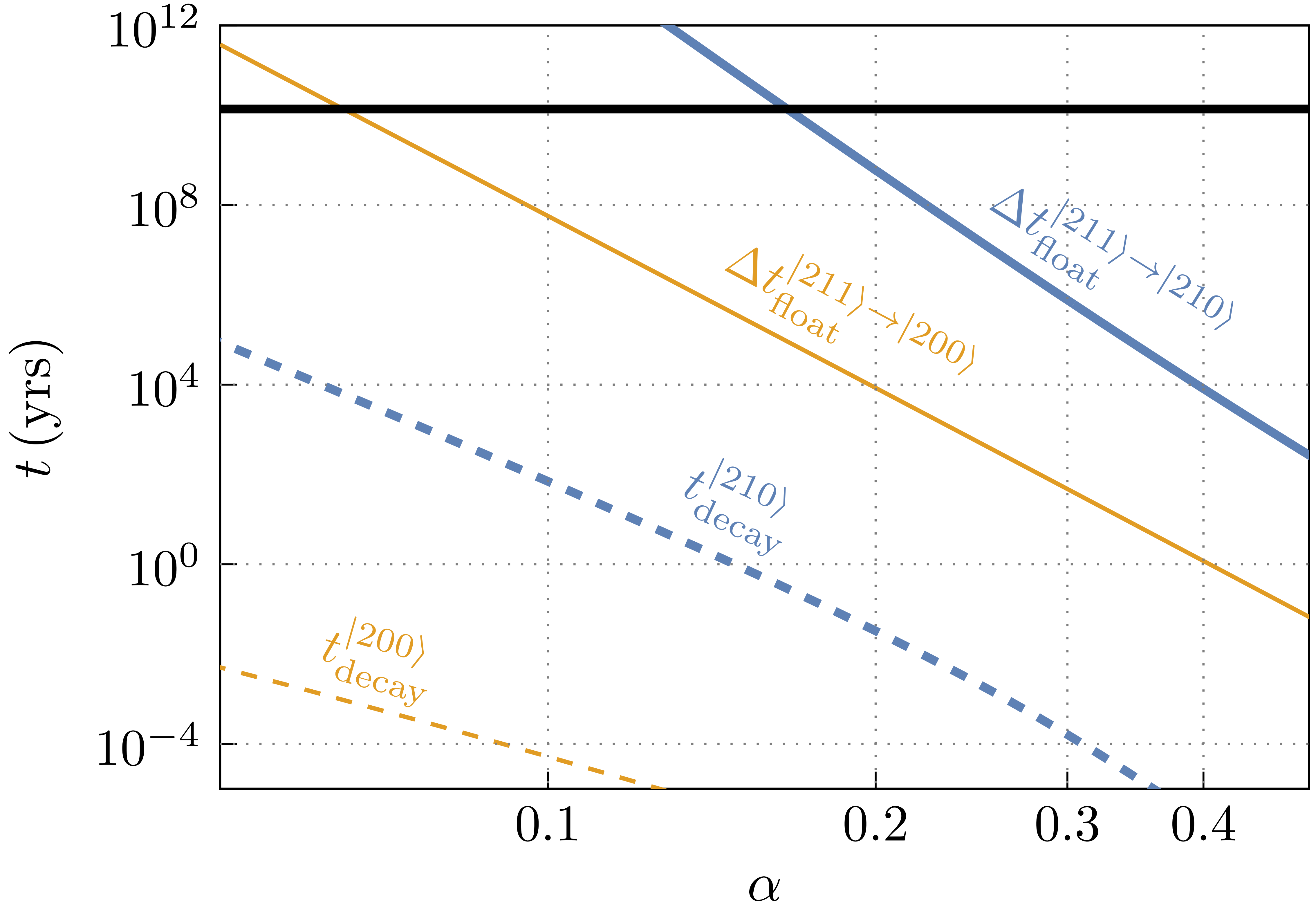
Boson clouds in binaries — A **resonant** history



[Tomaselli, Spieksma, Bertone '24]

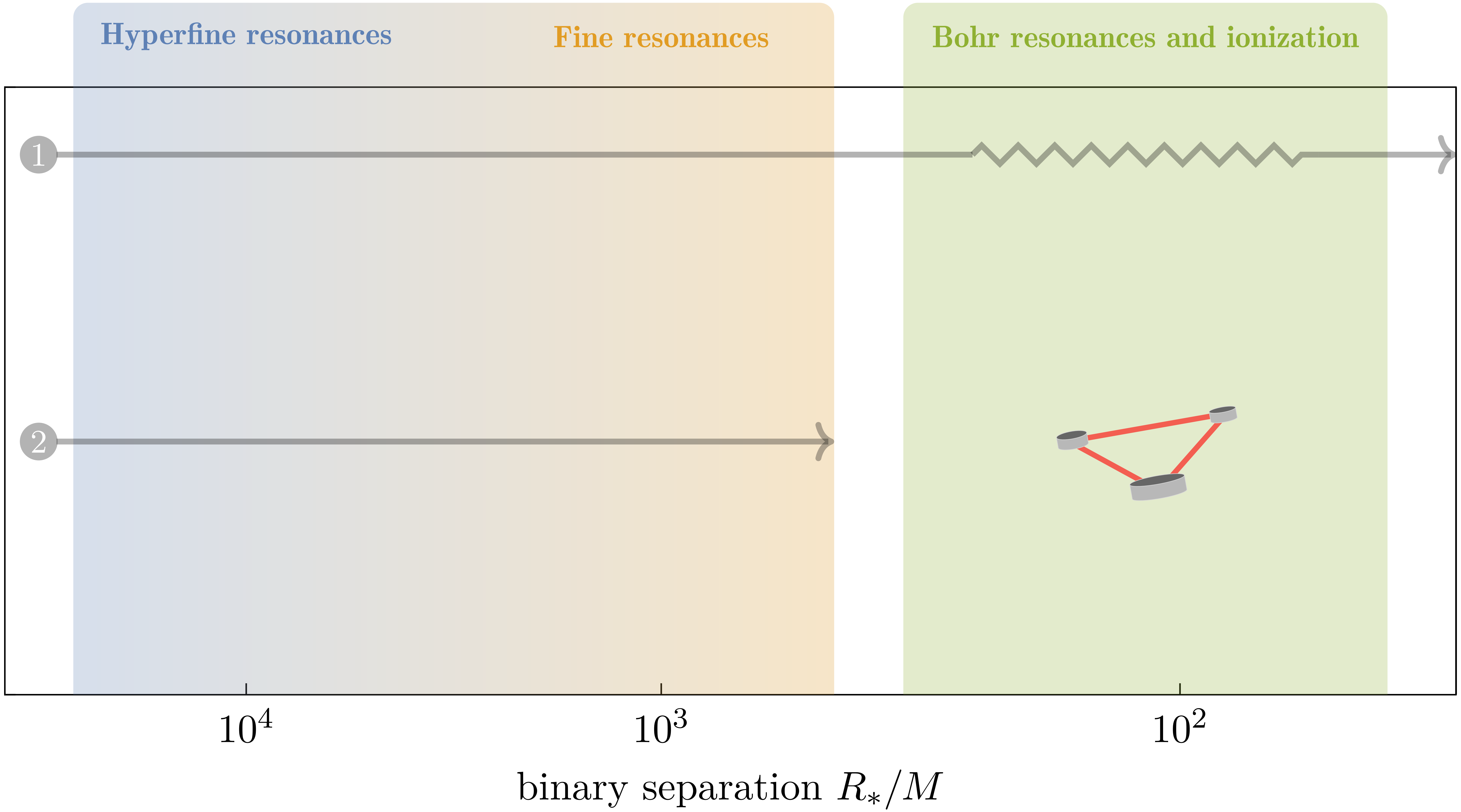
Boson clouds in binaries — Timescales





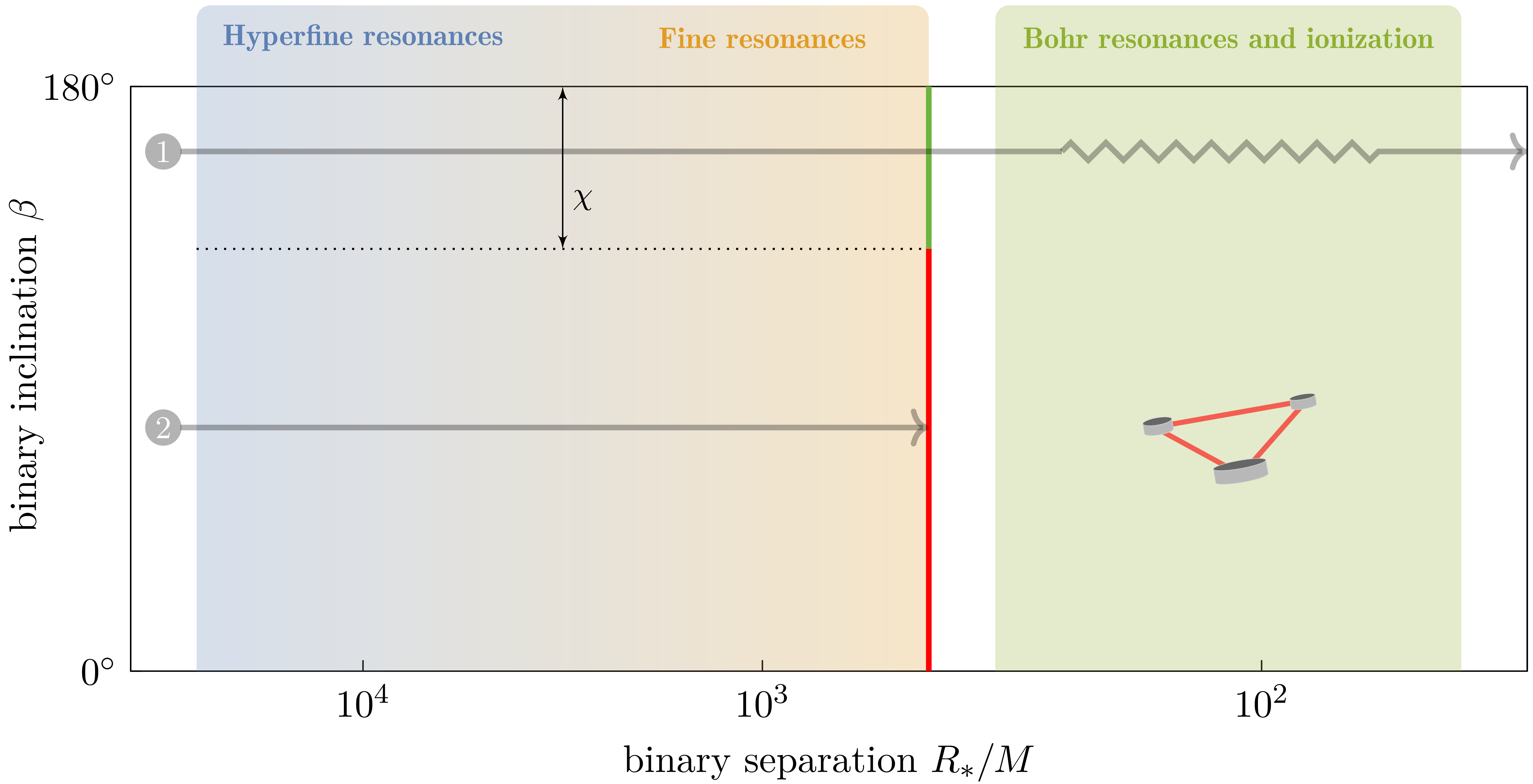
$\Delta t_{\rm float} \gg t_{\rm decay}$ → Cloud ***survives*** or ***dies***

Boson clouds in binaries — A **resonant** history



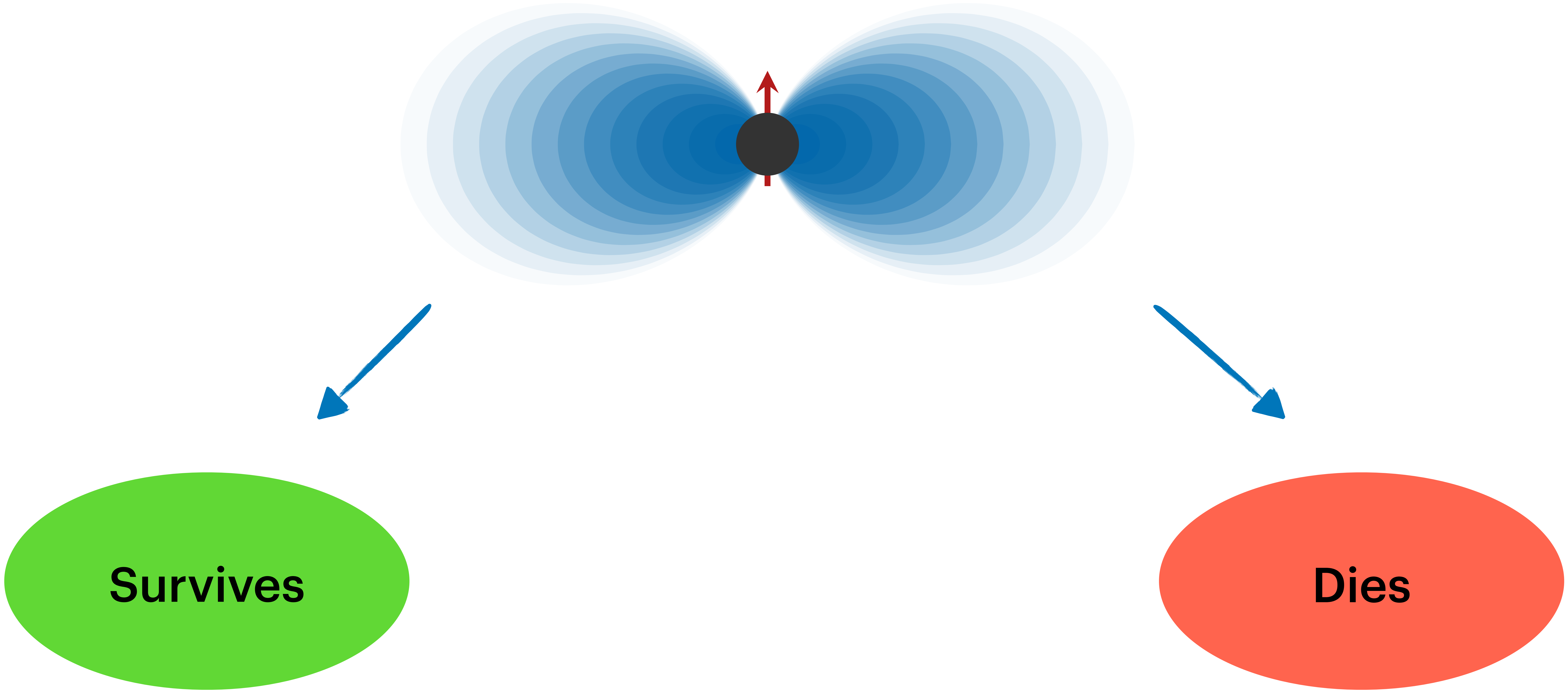
 [Tomaselli, Spieksma, Bertone '24]

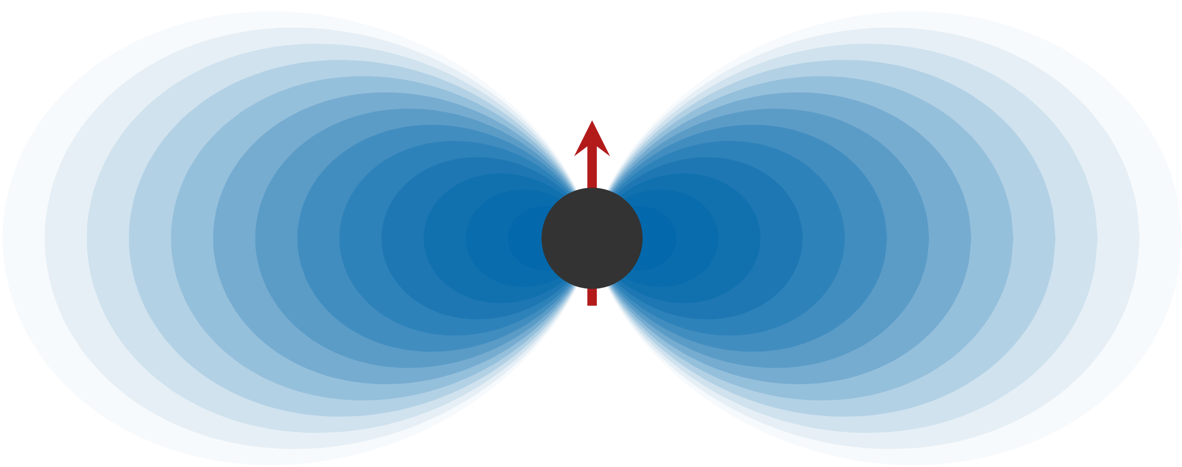
The resonant history

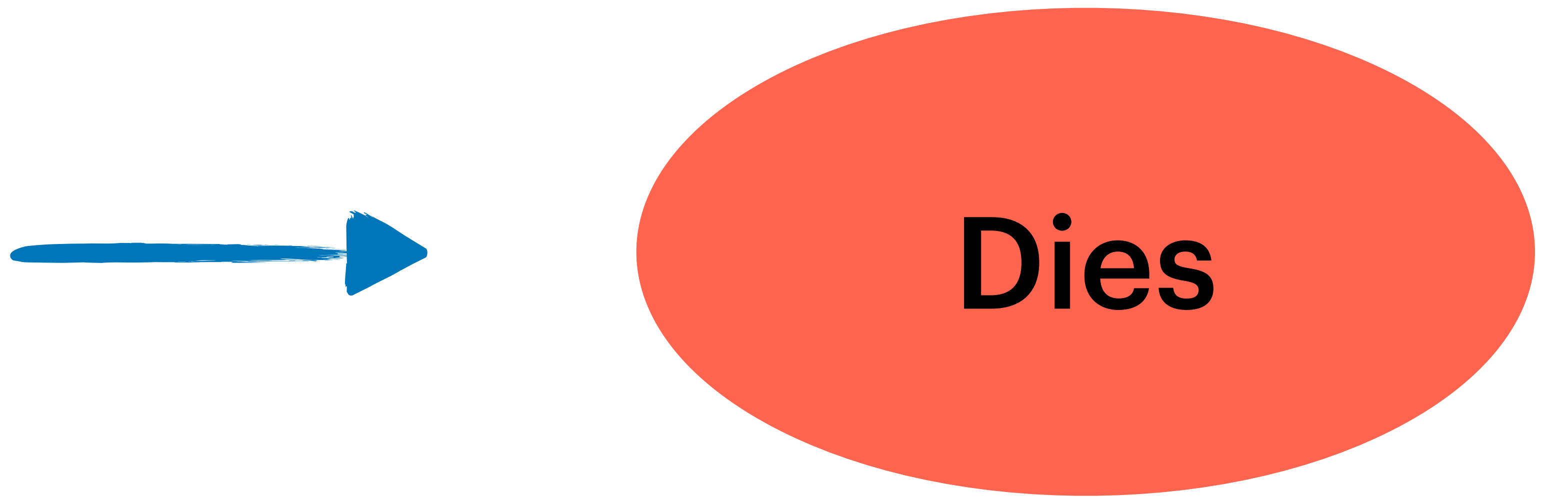


 [Tomaselli, Spieksma, Bertone ’24]

Two outcomes



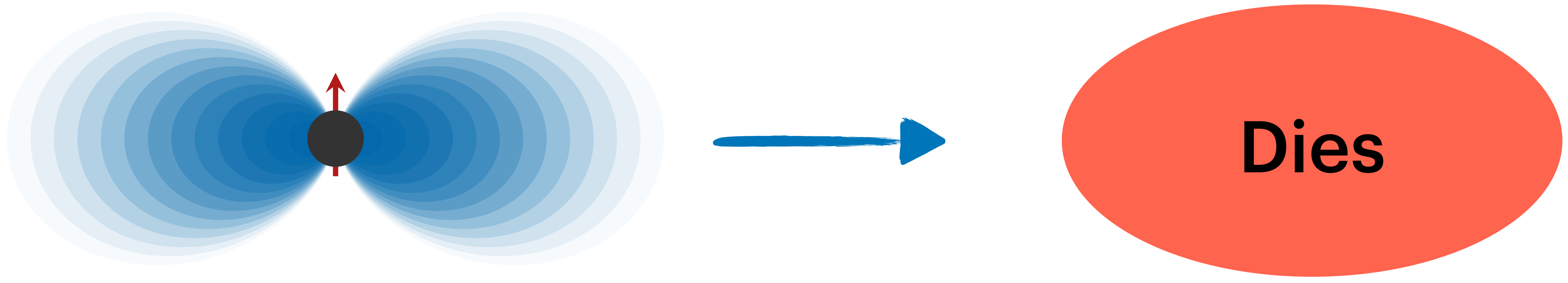




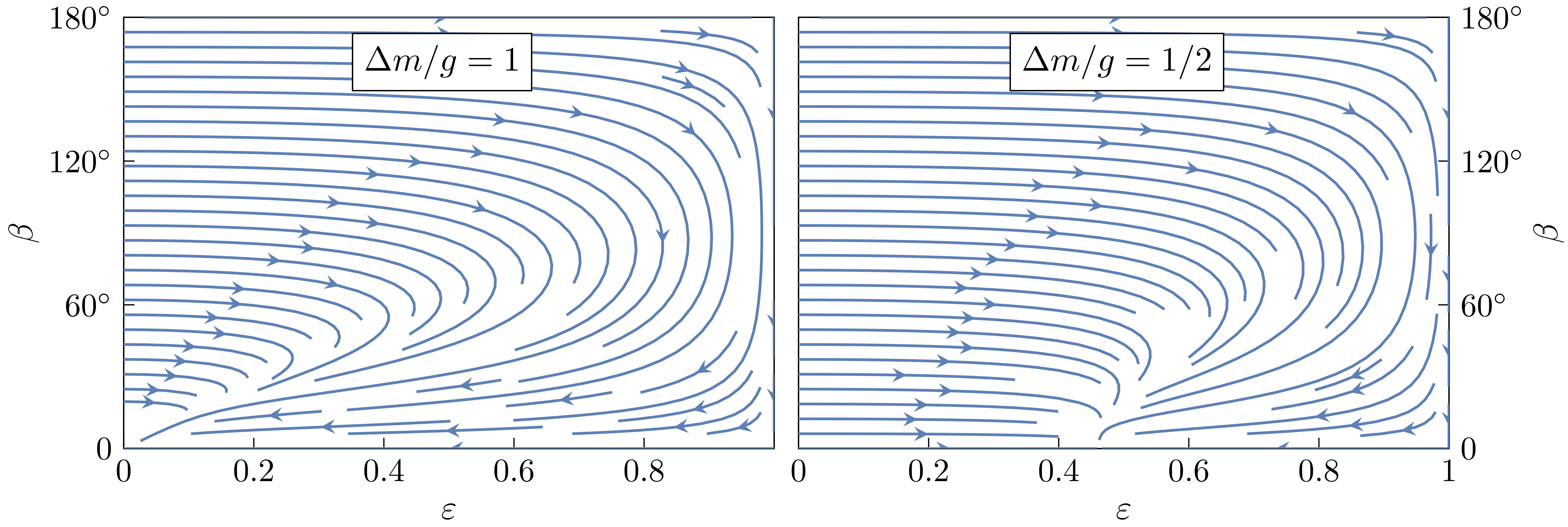
Indirect observational signatures through the impact on **binary parameters**

[Tomaselli, Spieksma, Bertone ’24; Boskovic *et al.* ’24]

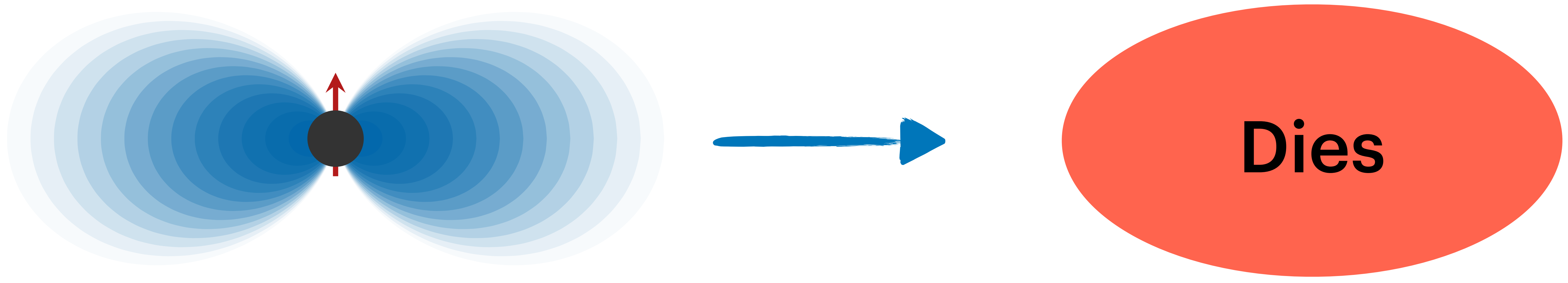
Indirect signatures



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



Indirect signatures



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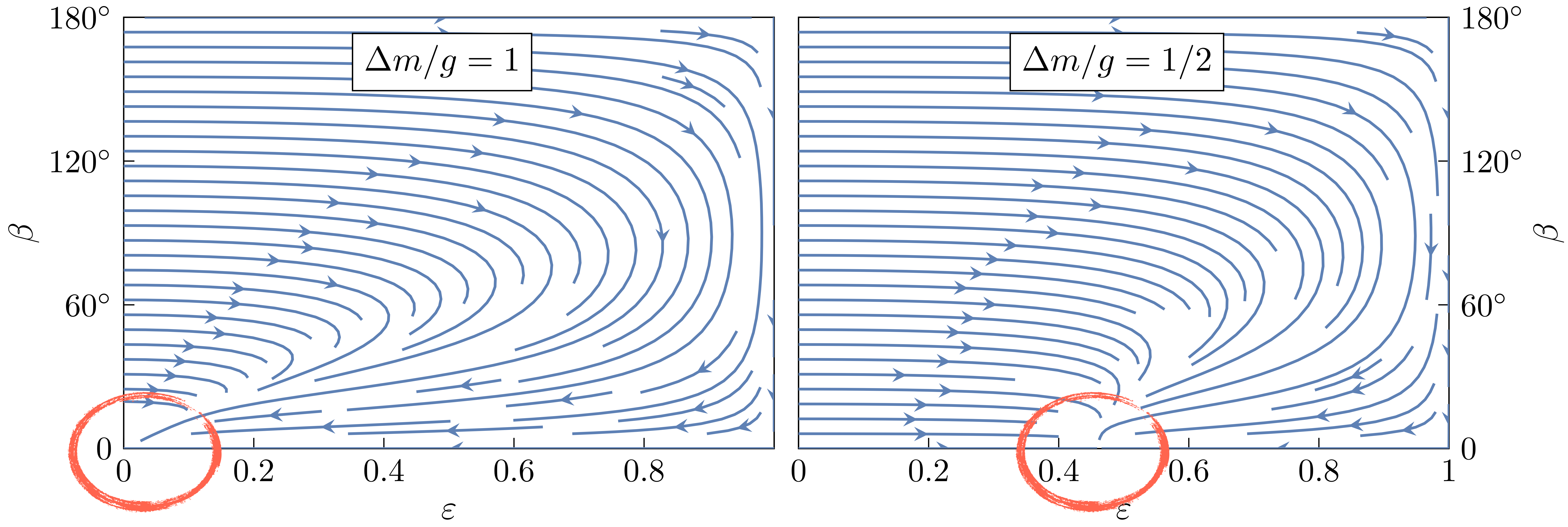
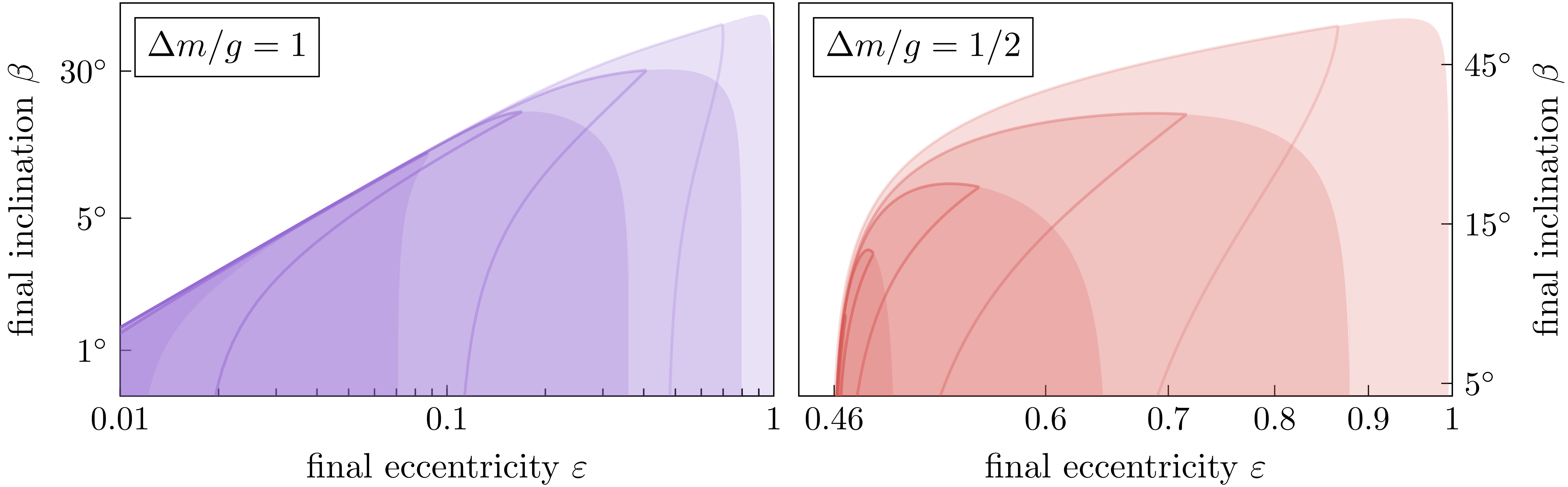


Fixed points:

- Inclination always goes to **zero**
- Eccentricity goes to (potentially) **nonzero point** $\varepsilon \approx 0, 0.46, 0.58, 0.65, \cdots$

Cloud's legacy

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



[Tomaselli, Spieksma, Bertone '24]

Cloud's legacy

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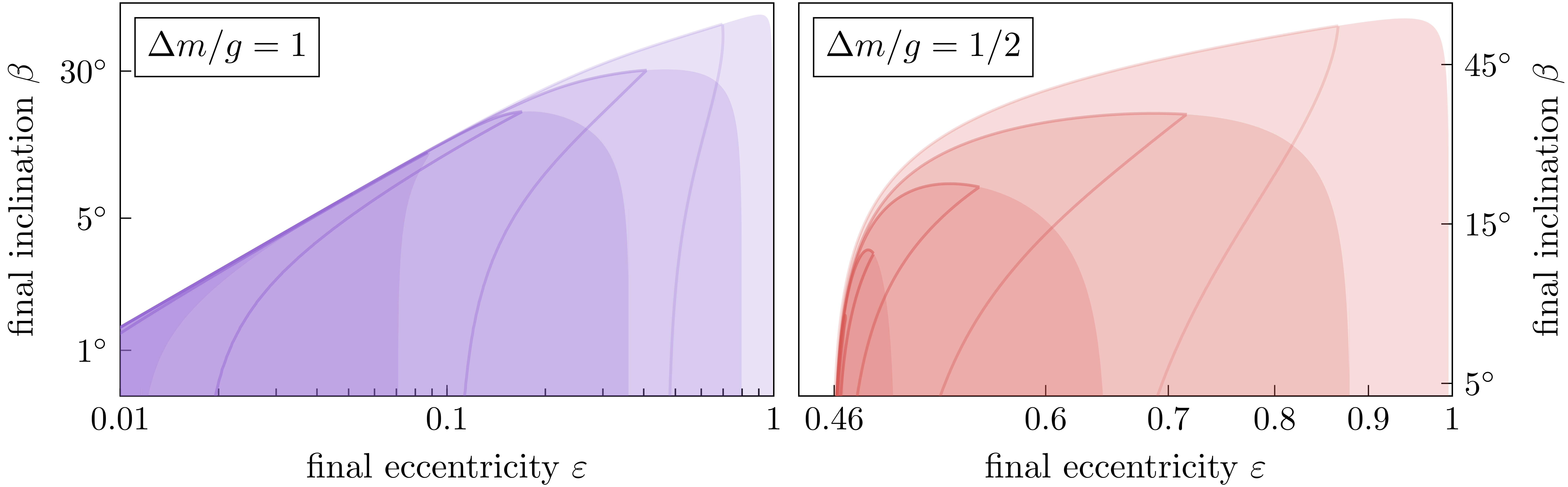
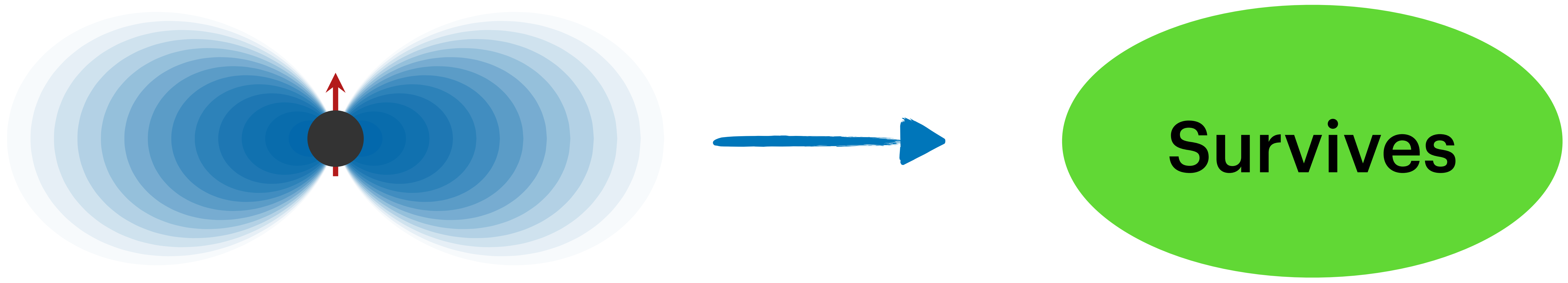


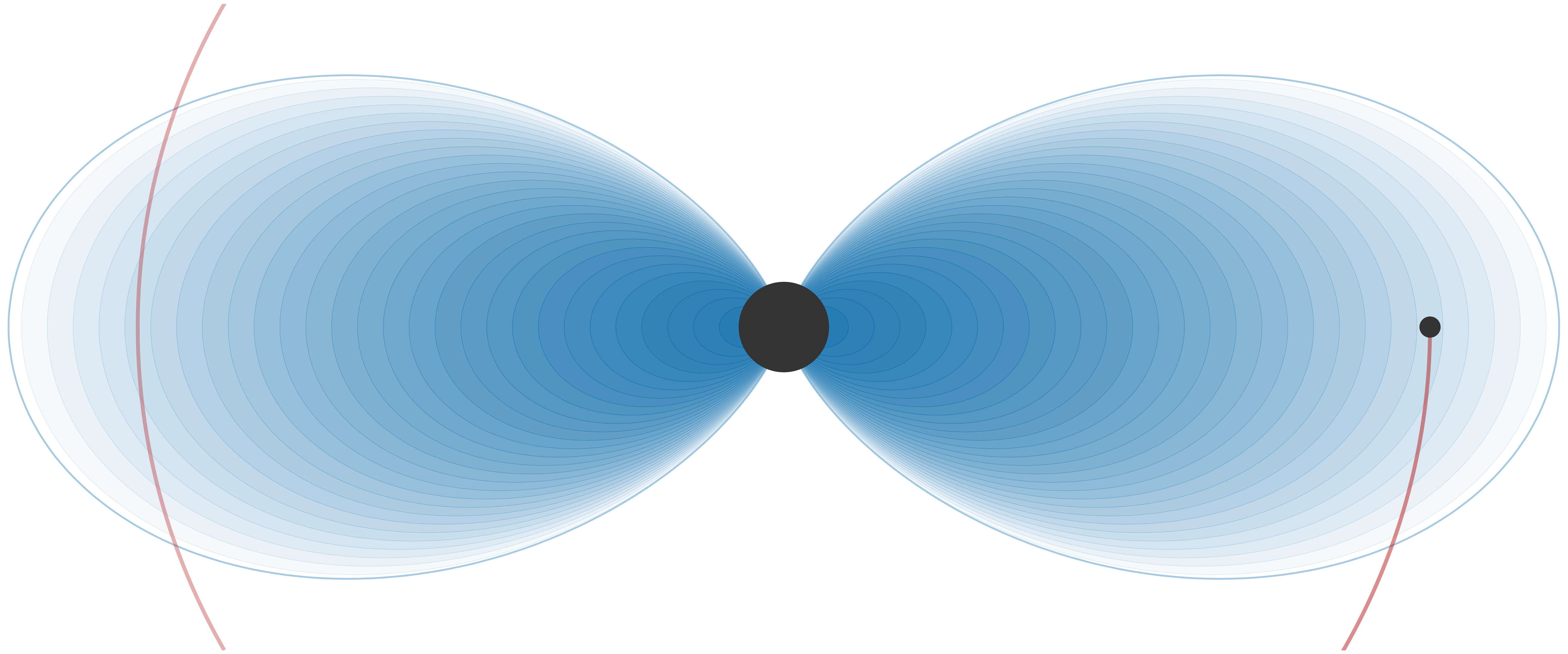
Statistical analysis of large number of BH binaries could unveil existence boson clouds!

 [Tomaselli, Spieksma, Bertone '24]

Direct signatures



Direct observational signatures through **dynamical effects**…



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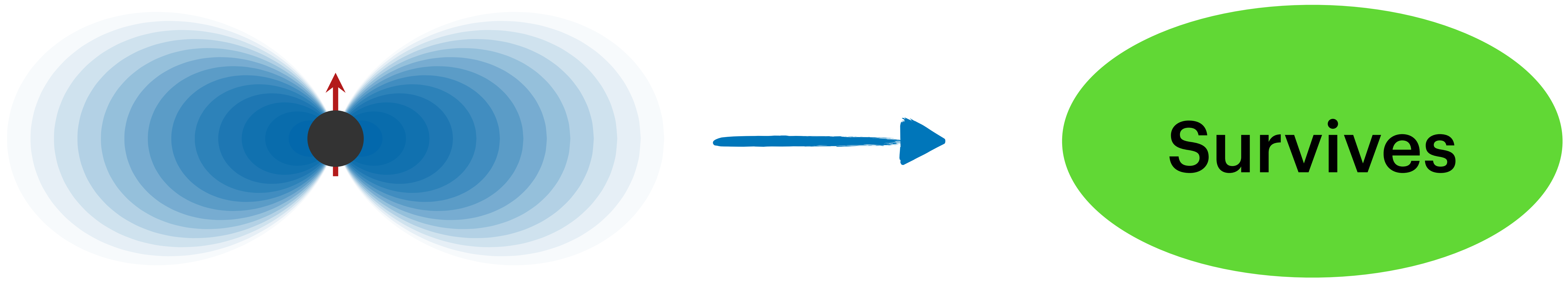
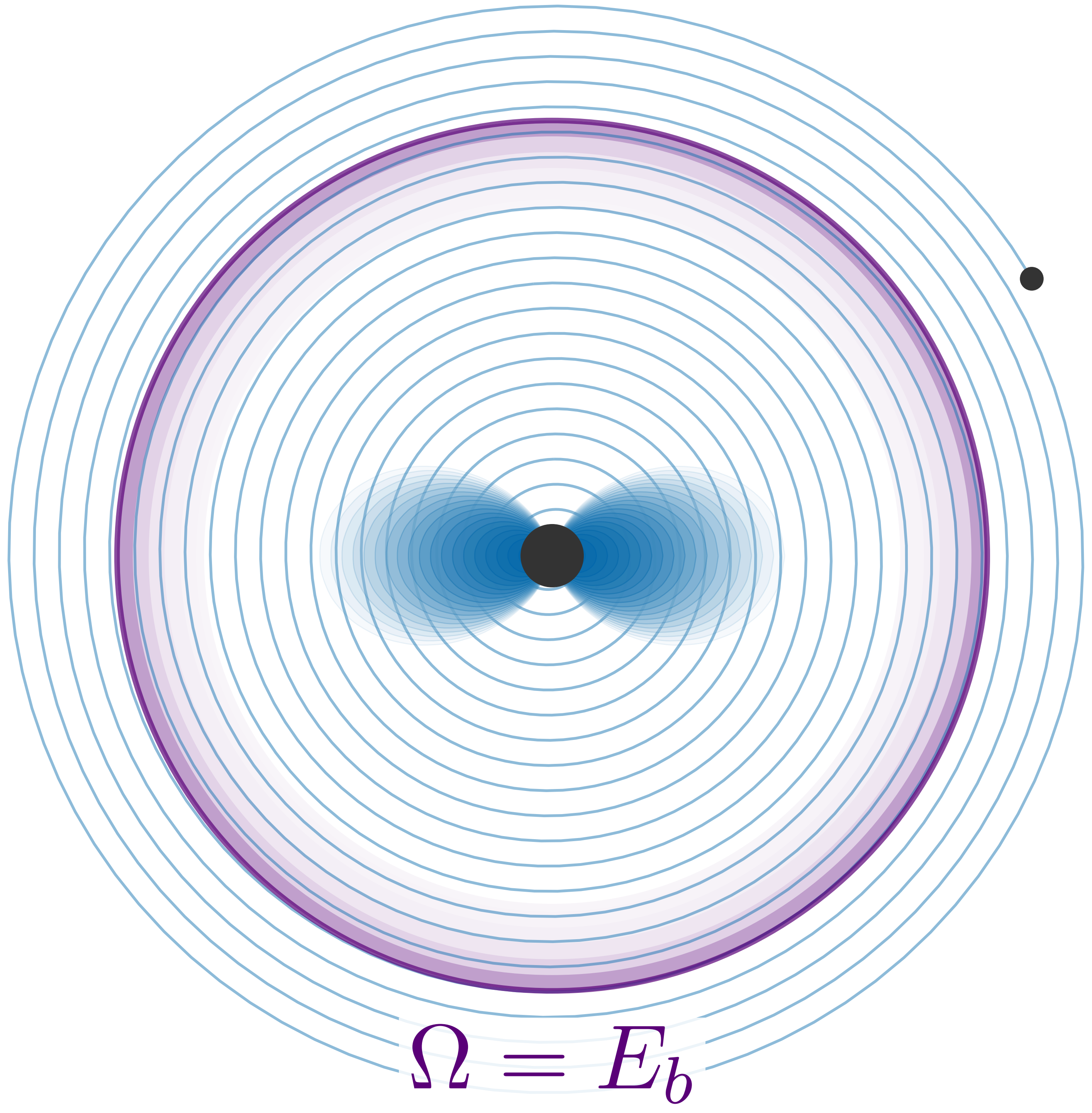
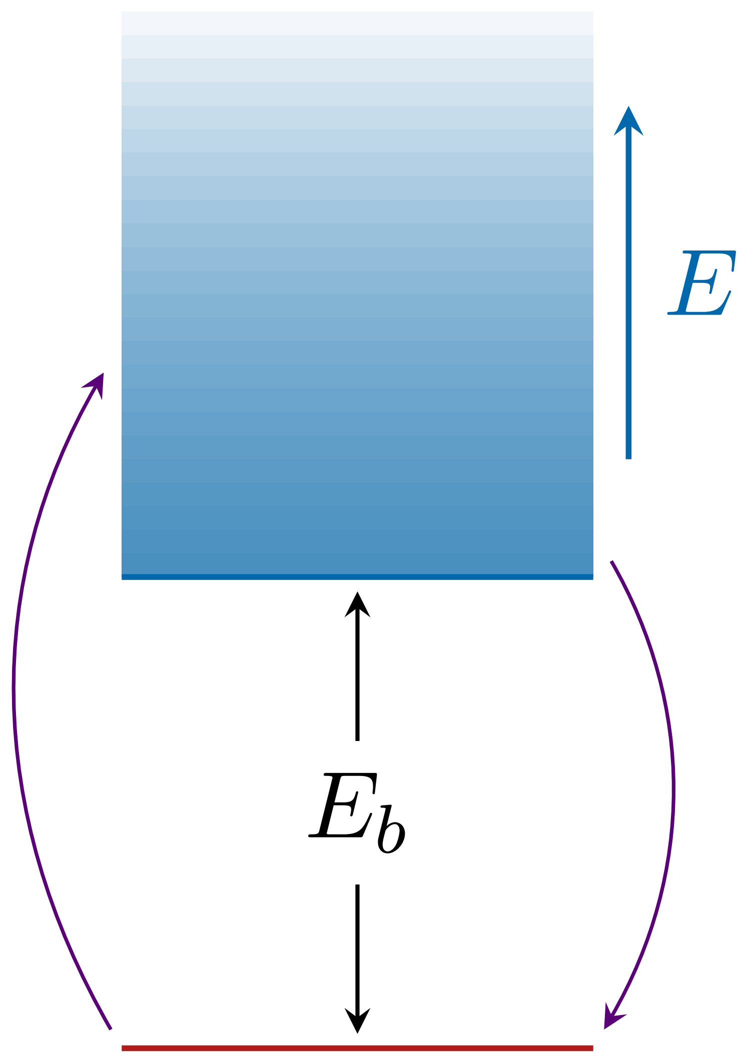


Orbital frequency above a **threshold,** transitions to **unbound states** are excited





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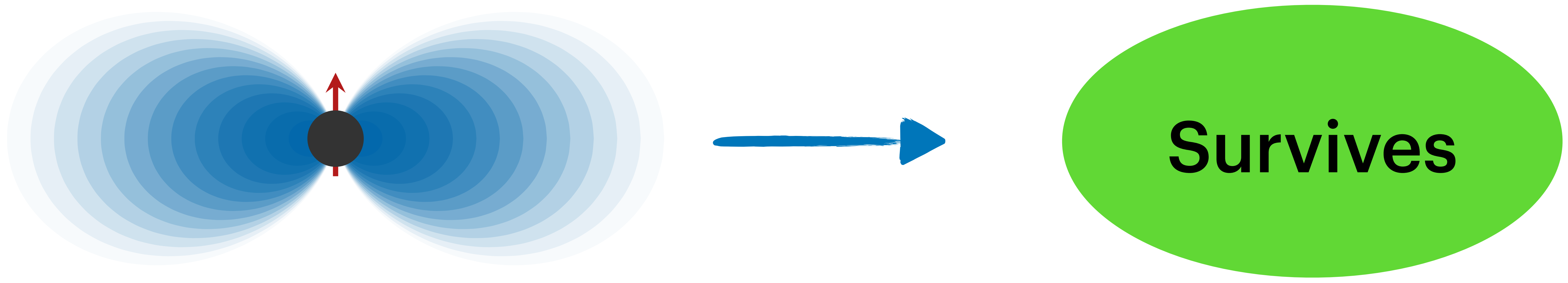

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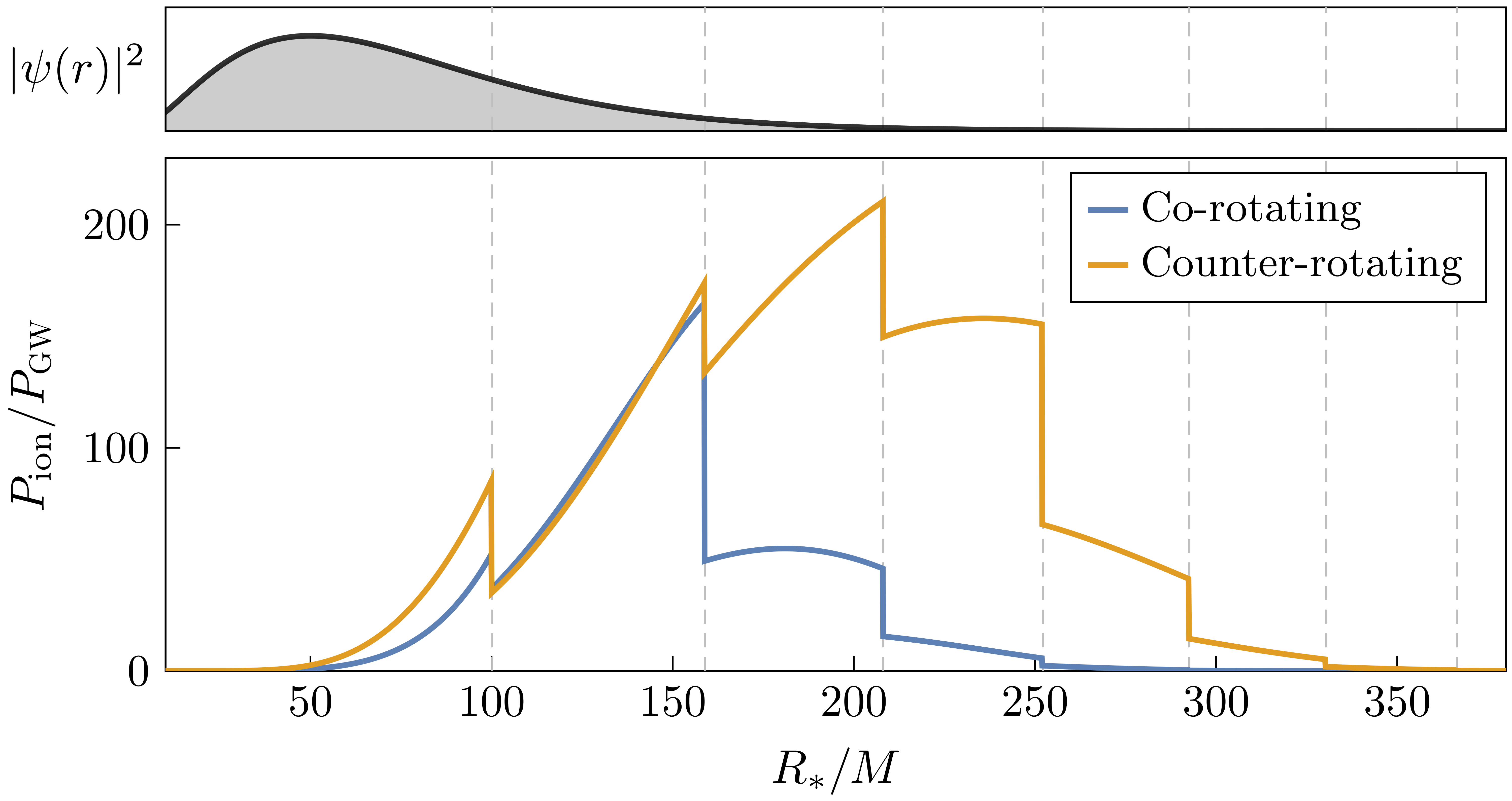
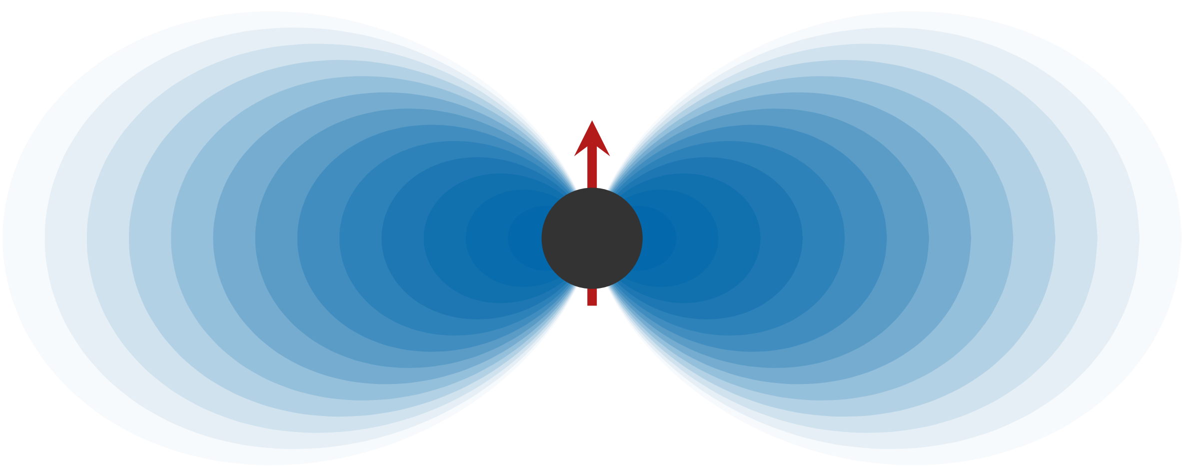


$$|211\rangle$$
$$q = 10^{-3}$$
$$\alpha = 0.2$$
$$M_{\rm c}/M = 0.01$$

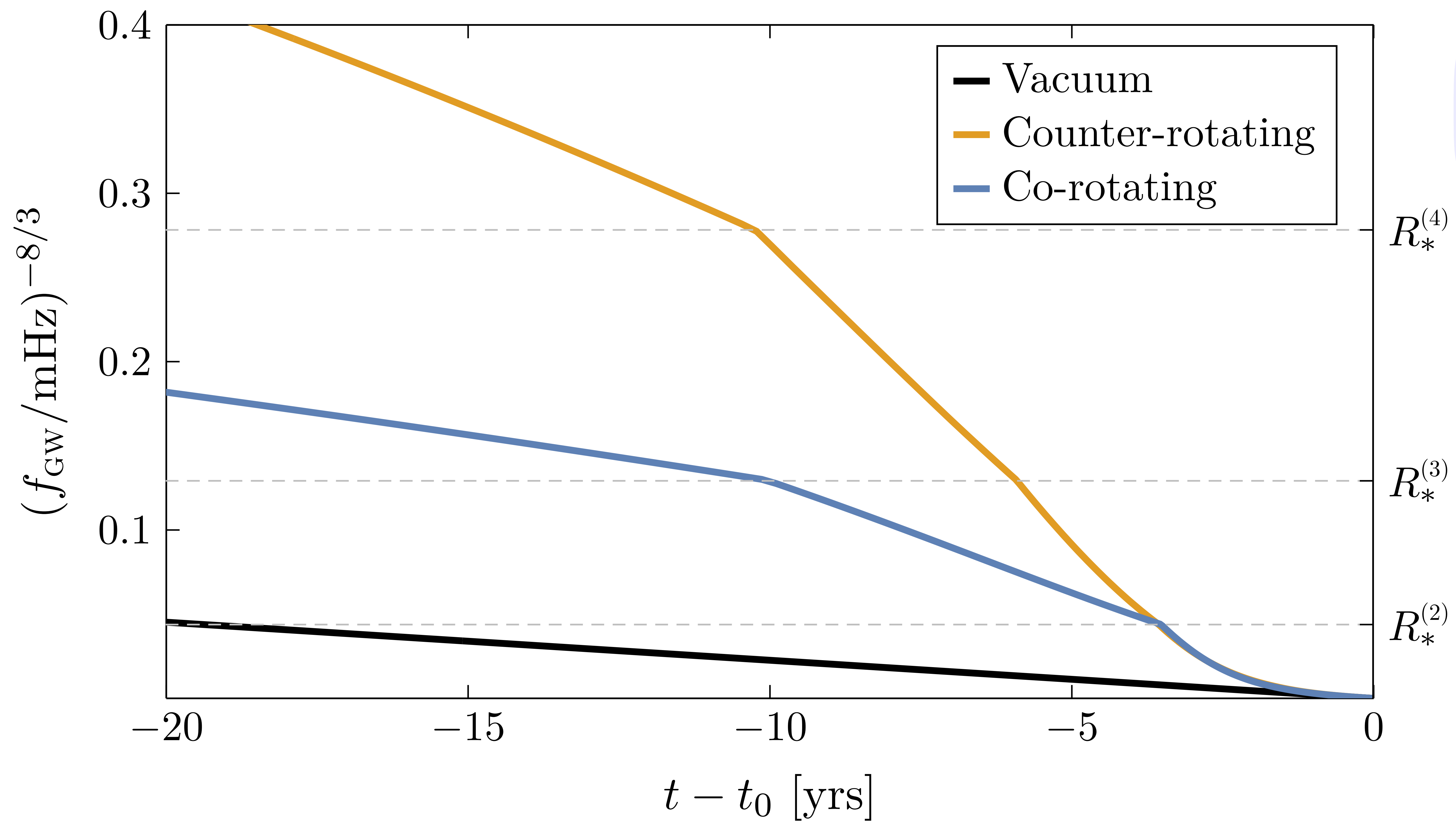
[Baumann *et al.* ’22]

Direct signatures



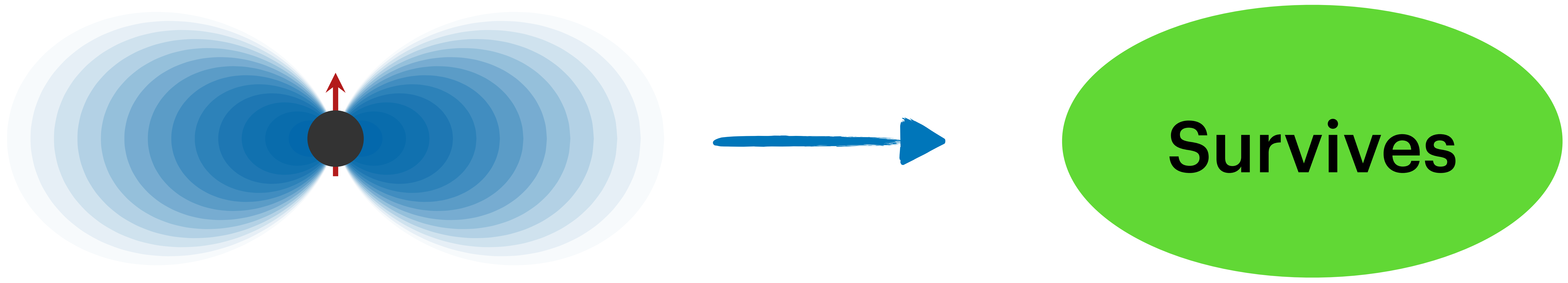
Survives

Direct observational signatures through **dynamical effects**…



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

Direct signatures



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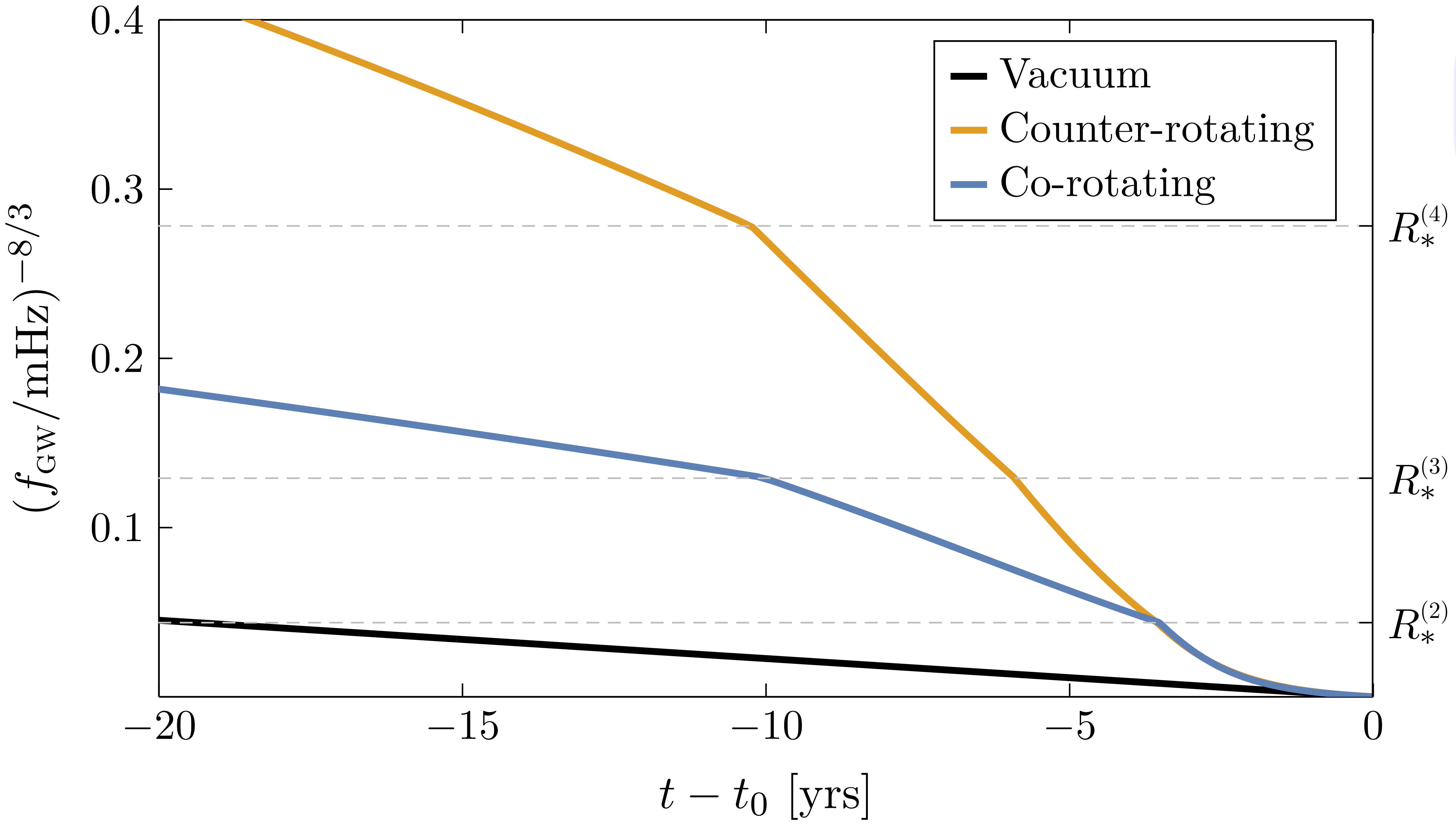

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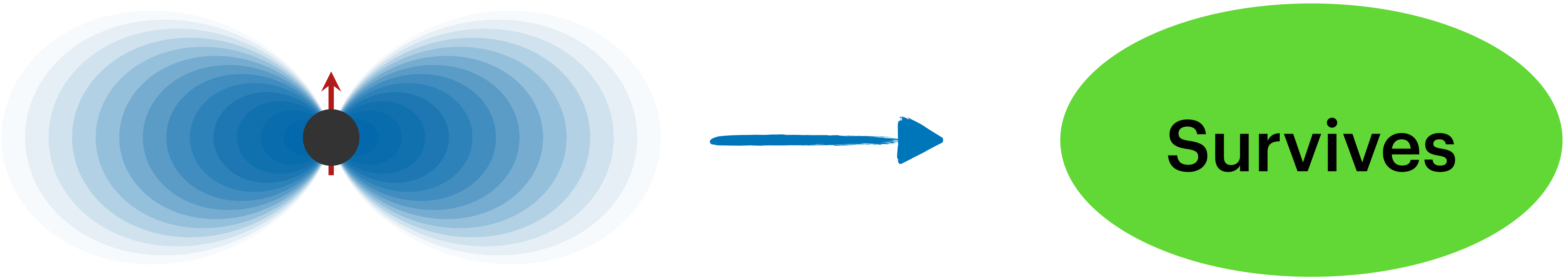
What do resonances teach us?

- 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]

Conclusions — Part II

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.

Boson clouds in binaries — ***Relativistic*** regime

Expand the metric and the field in both the mass ratio *and* the energy densities

$$\mathbf{g}_{\mu\nu} = g_{\mu\nu} + \epsilon^n h_{\mu\nu}^{(n,0)} + q h_{\mu\nu}^{(0,1)} + \epsilon^n q h_{\mu\nu}^{(n,1)} + \epsilon^n q^2 h_{\mu\nu}^{(n,2)} + q^2 h_{\mu\nu}^{(0,2)} + \cdots \,,$$

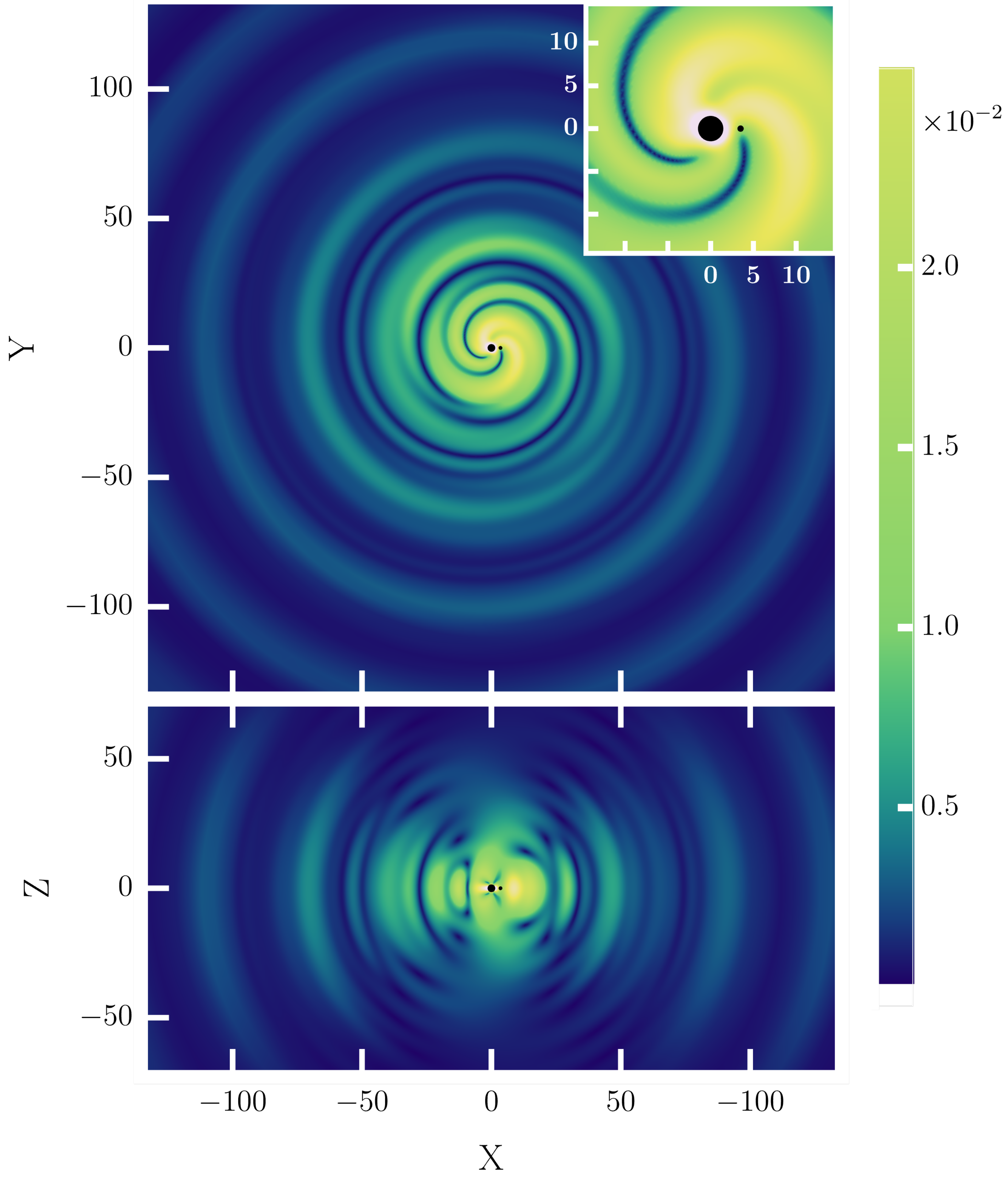
$$\boldsymbol{\Psi} = \epsilon\psi^{(1,0)} + \epsilon q \psi^{(1,1)} + \epsilon q^2 \psi^{(1,2)} + \cdots$$

↓

$$\left(\Box - \mu^2\right) \phi^{(1,1)} = h^{\mu\nu}_{(0,1)} \nabla_\mu \nabla_\nu \phi^{(1,0)}$$

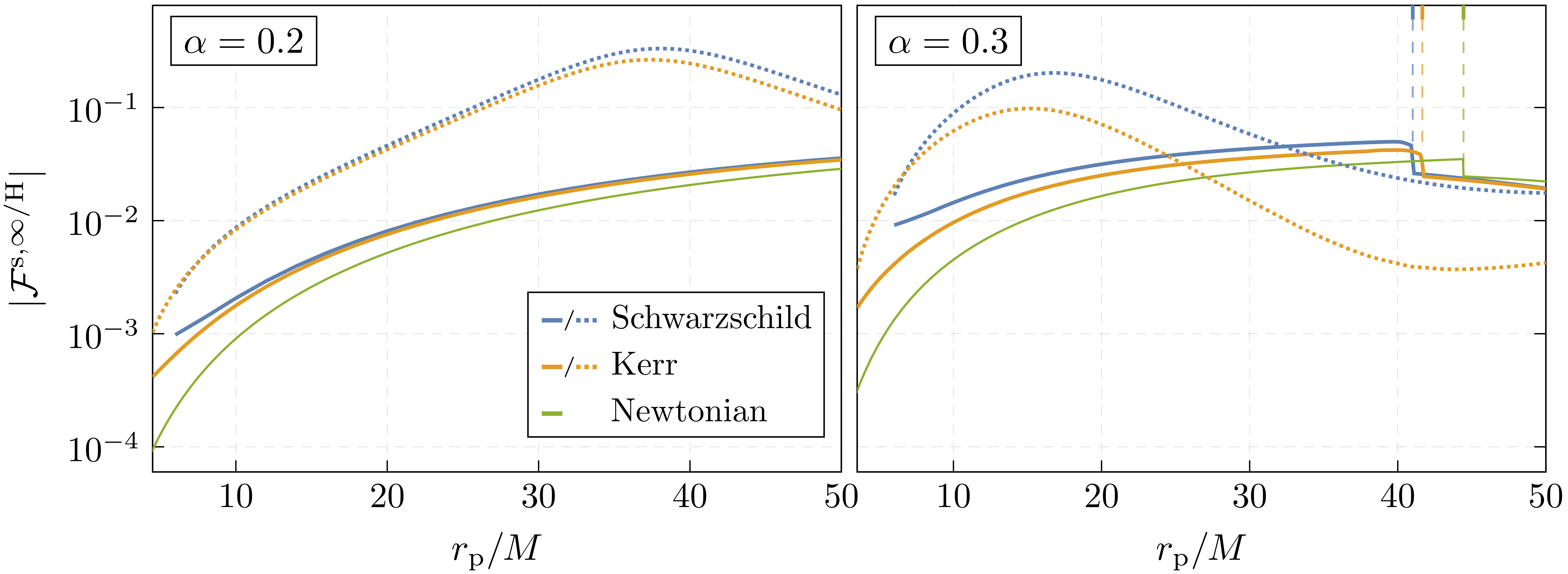
[Brito and Shah ’23; Duque *et al.* ’23; Dyson, Spieksma *et al.* ’25]

Boson clouds in binaries — ***Relativistic*** regime

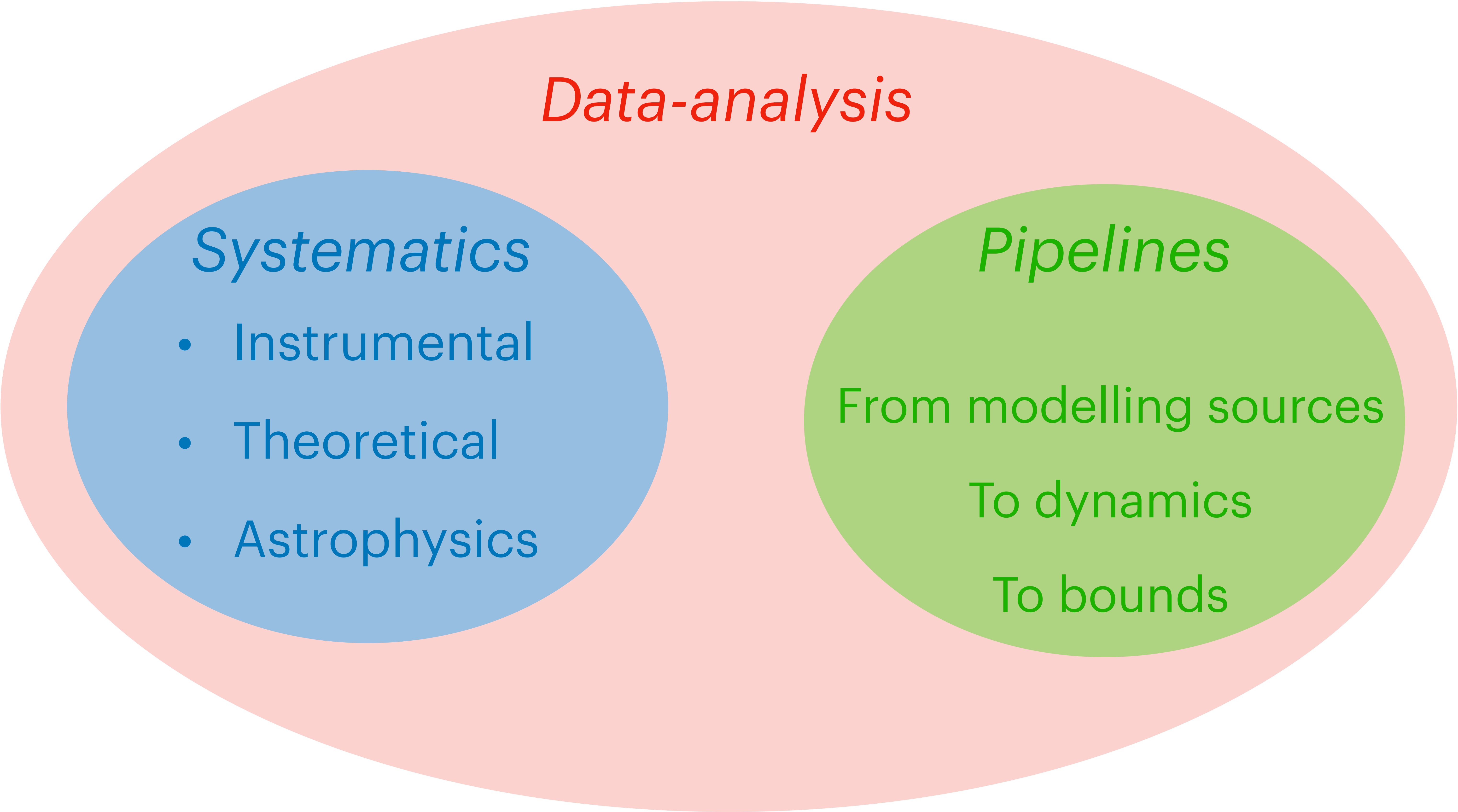


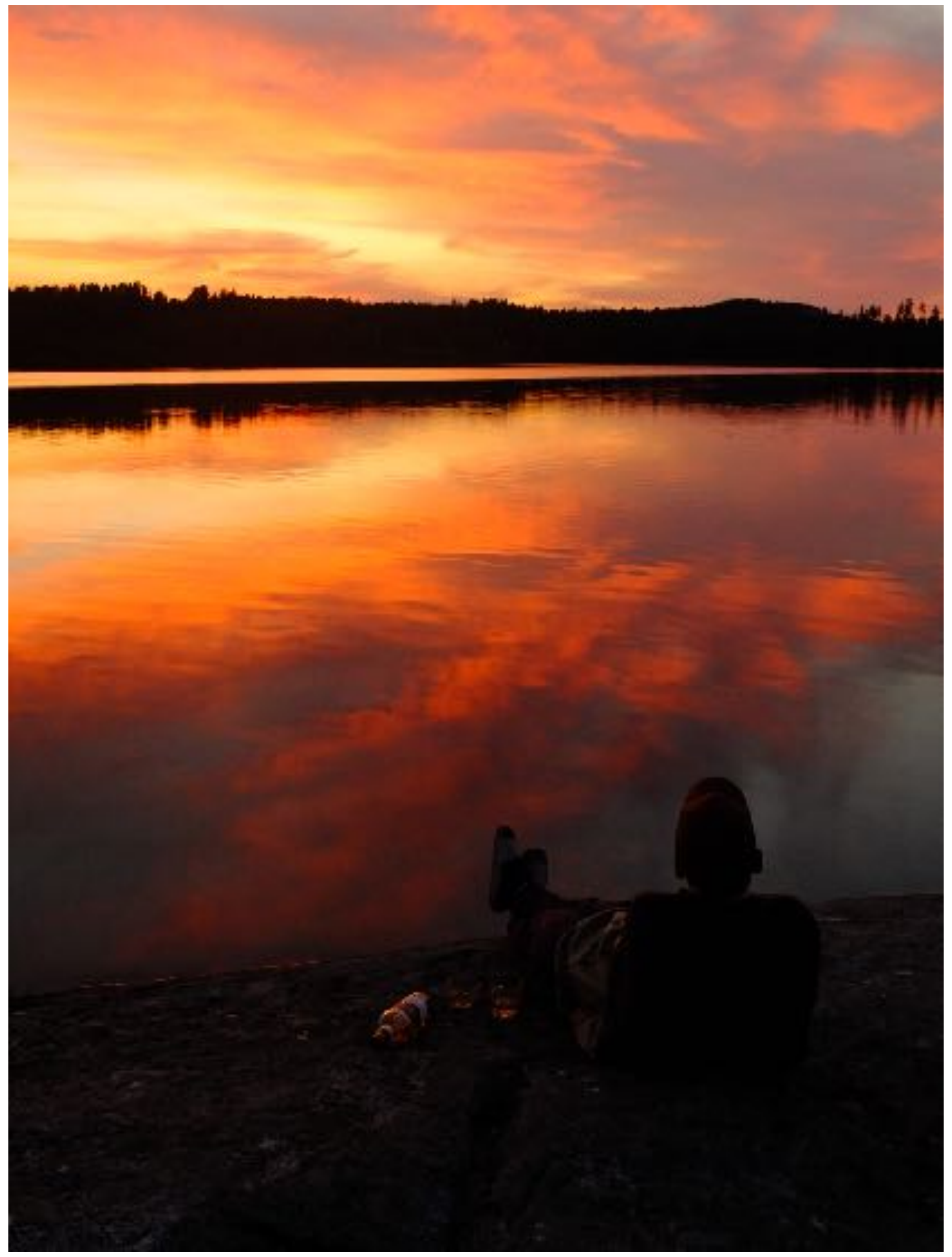
[Dyson, Spieksma *et al.* ’25]

Boson clouds in binaries — ***Relativistic*** regime



Outlook — Looking ahead





In the middle of nowhere, Sweden, July 2024

Complicated task… But **unique** channel into the **ultralight** and **weak coupling** regime of particle physics

Additional slides

Ultralight particles — Self-Interactions

- **Gravitational** interactions are all that is necessary for superradiance.
- However, many beyond-the-Standard-Model candidates (including the QCD axion) have other interactions, e.g.,

Self-interactions: $\lambda \sim \mu^2/f_a^2 \simeq 10^{-74} \left(\frac{\mu}{10^{-12}\,\mathrm{eV}}\right)^2 \left(\frac{10^{16}\,\mathrm{GeV}}{f_a}\right)^2$

Ultralight particles — Self-Inte

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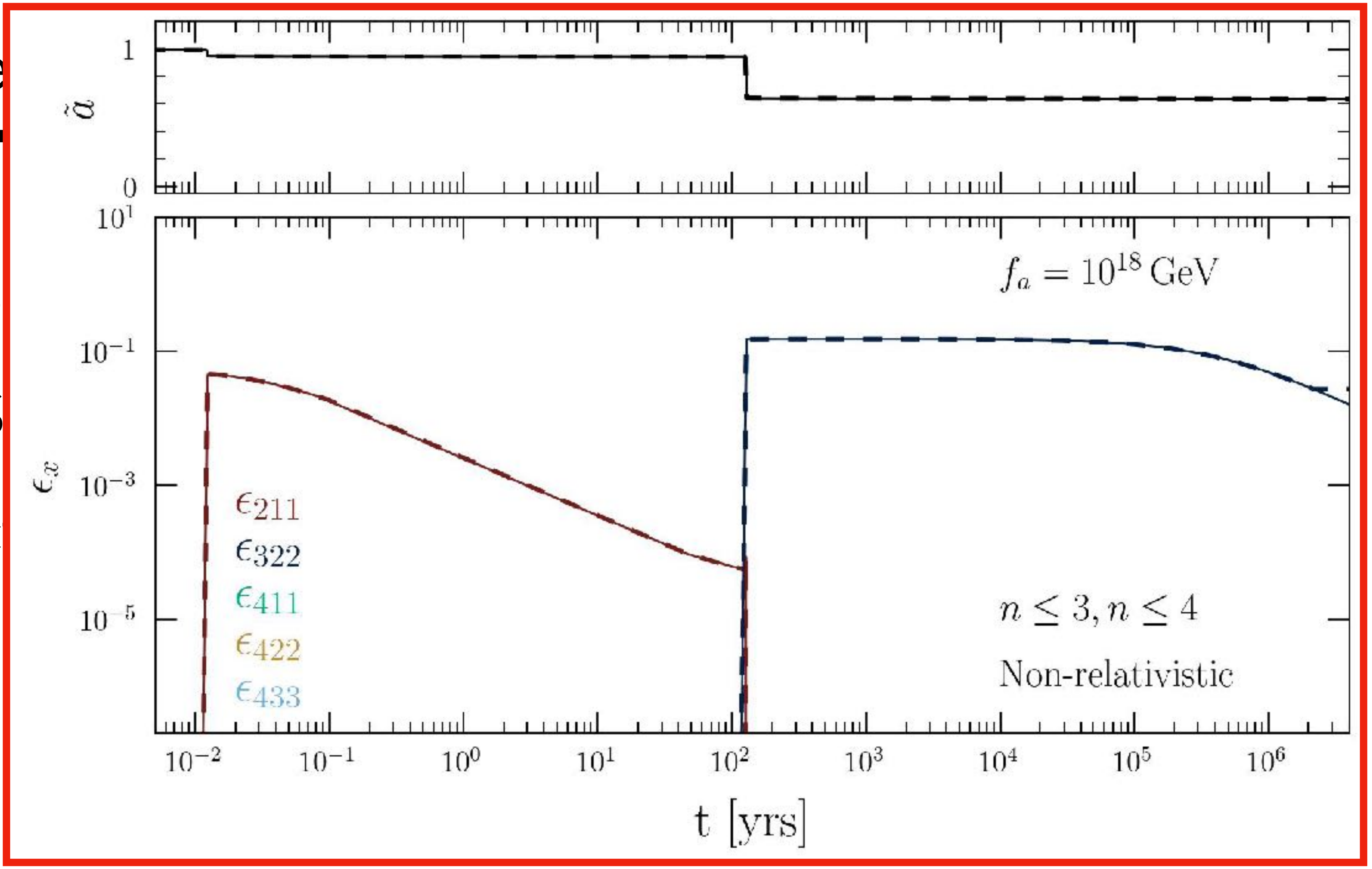

Self-interactions: $$\lambda \sim \mu^2/f_{\mathrm{a}}^2 \simeq 10^{-74} \left(\frac{\mu}{10^{-12}\,\mathrm{eV}}\right)^2 \left(\frac{10^{16}\,\mathrm{GeV}}{f_{\mathrm{a}}}\right)^2$$

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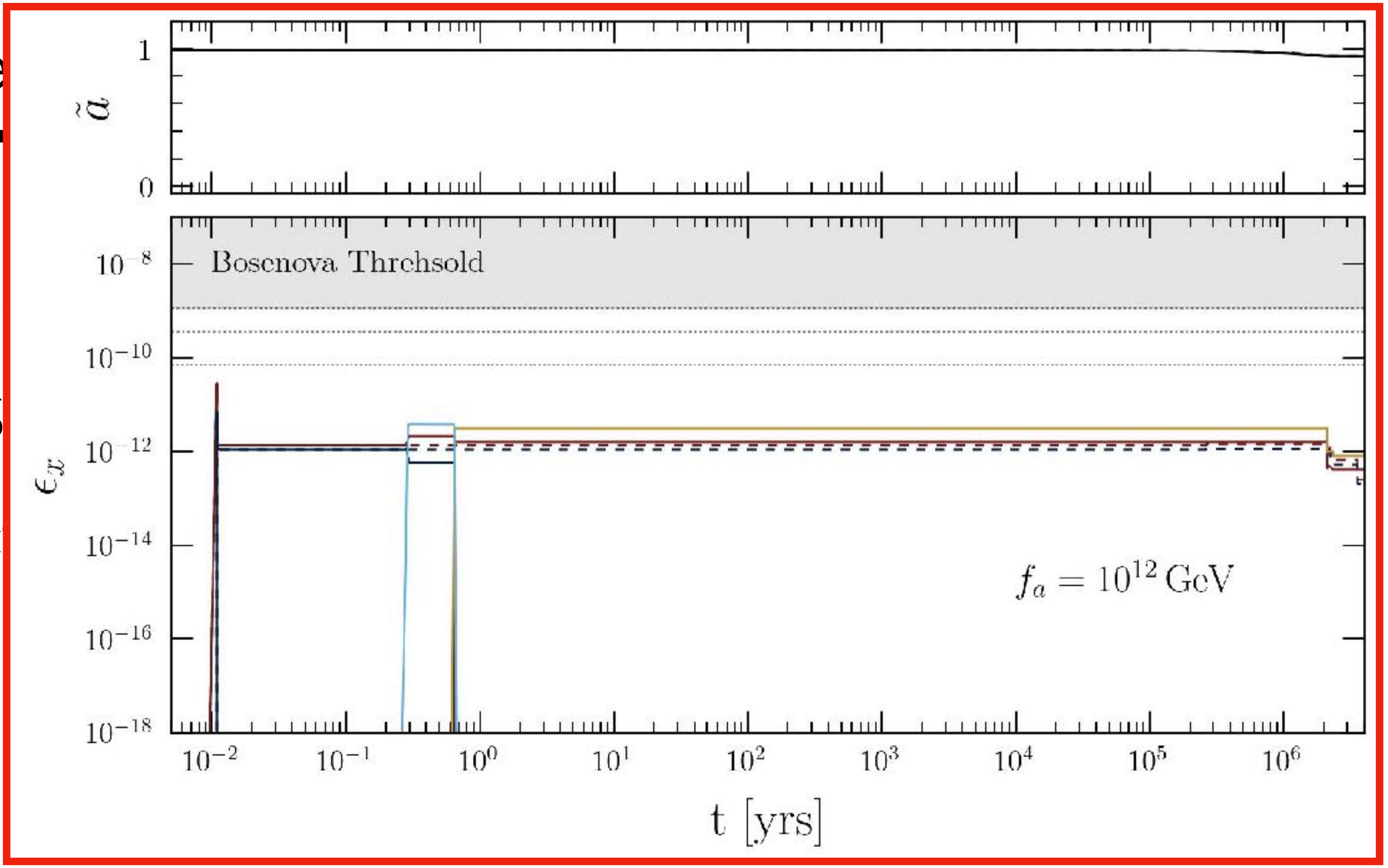

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Initial data

Constraint equations:

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

Scalar field (bound state constructed through Leaver):

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

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):

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

[Spieksma *et al.* ’23]

Artificial superradiance

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

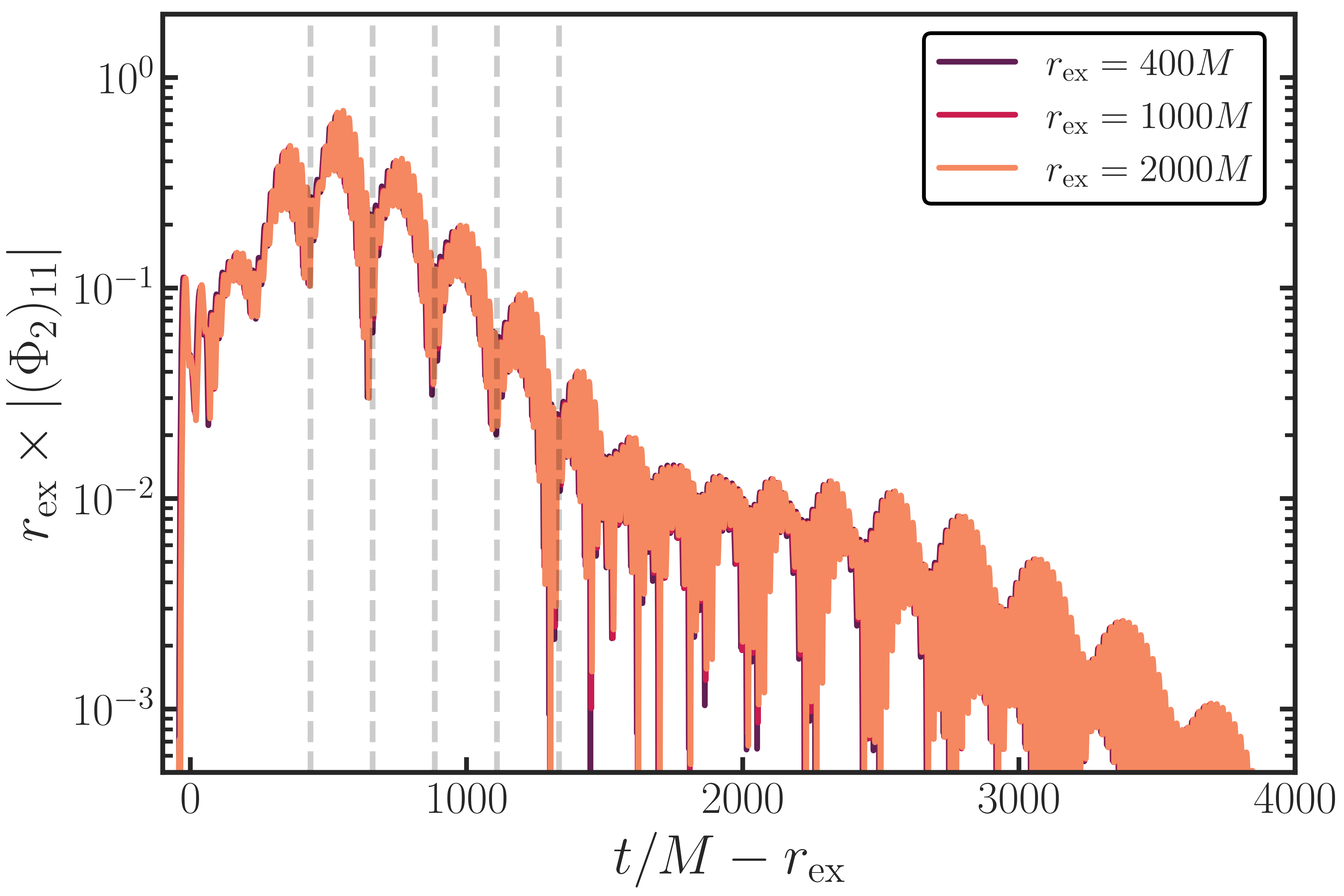
$$\downarrow$$

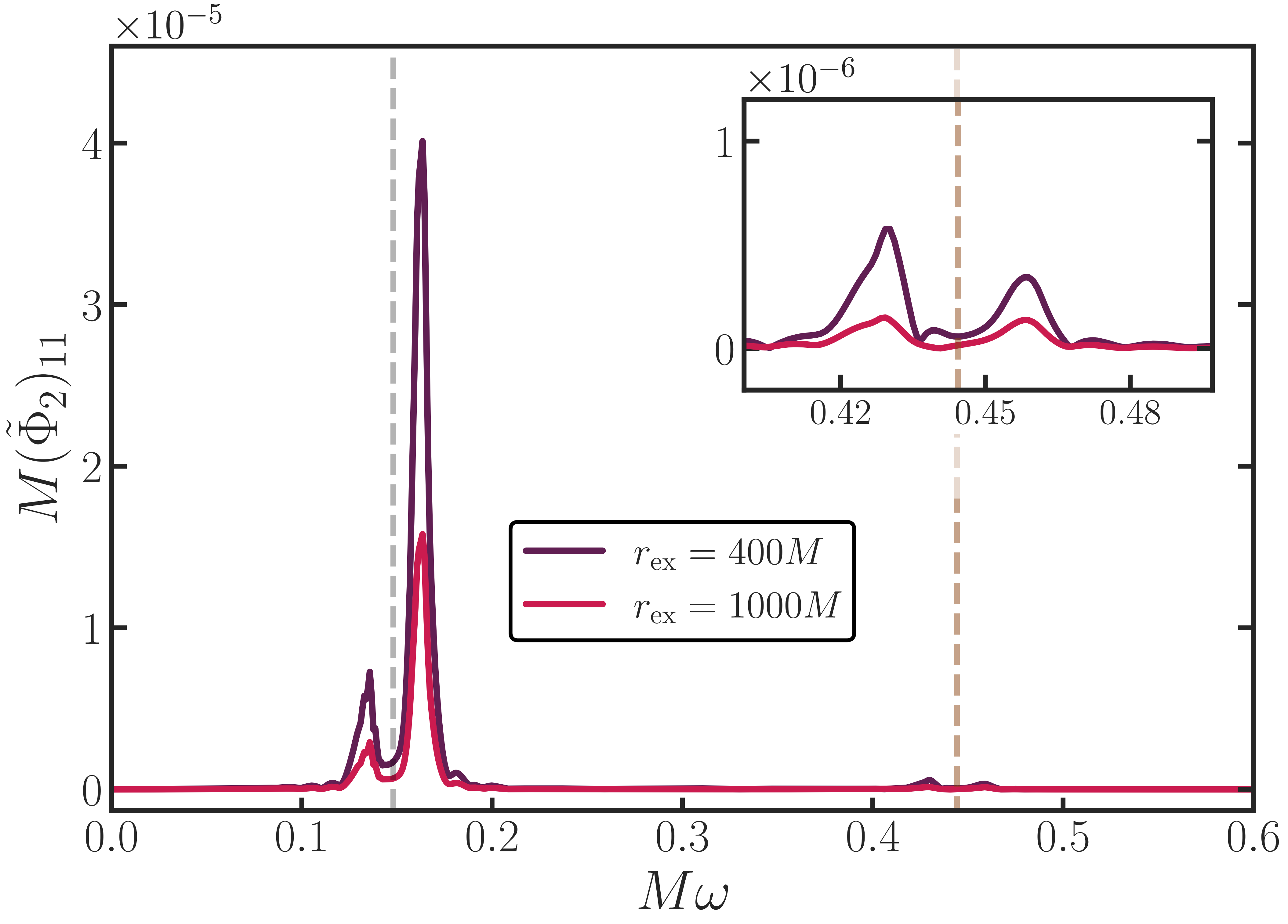
$$t_{\rm instability} \sim 1/C$$

[Spieksma *et al.* '23]

Axionic couplings — no SR — large radii

EM field

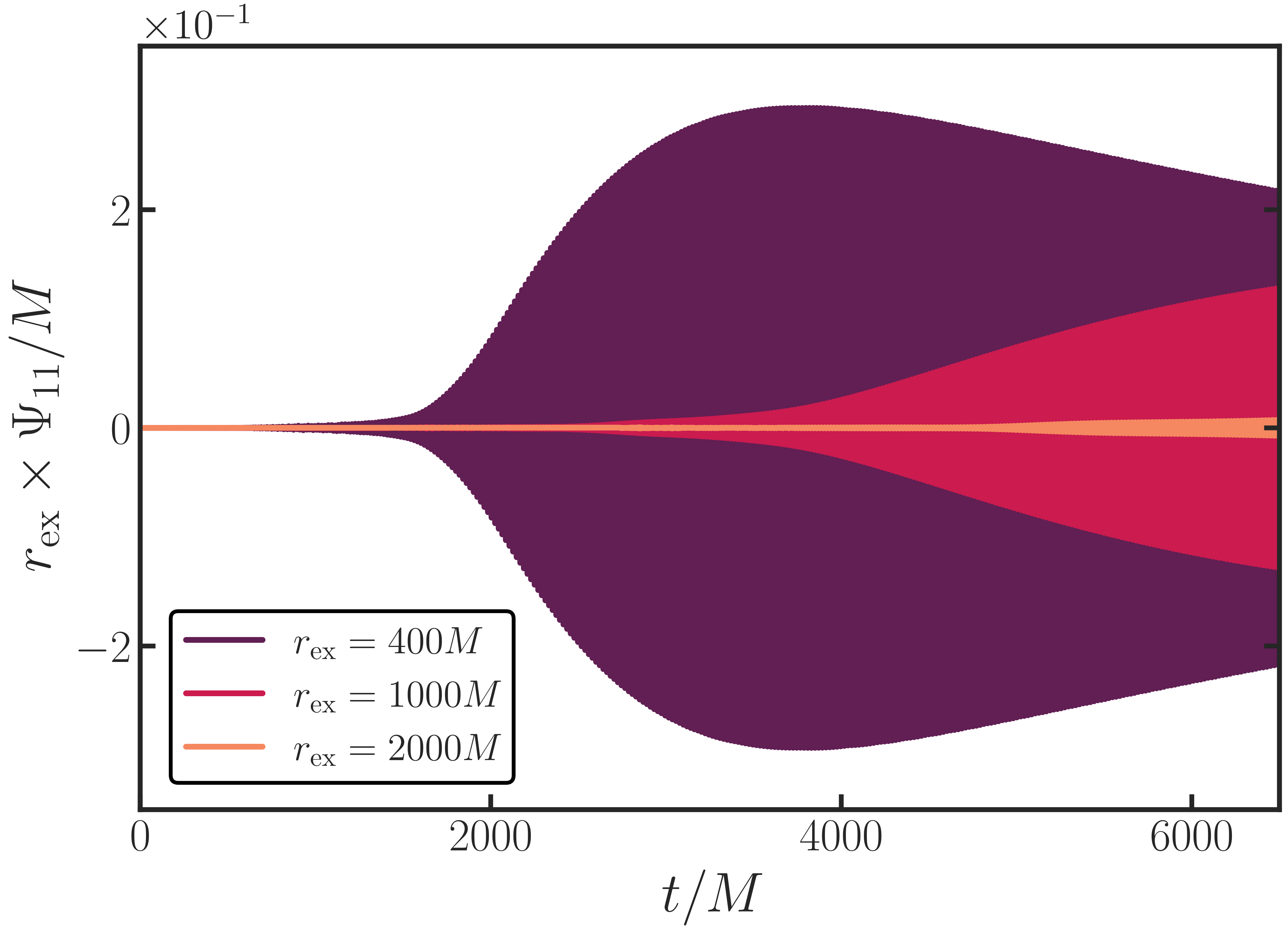


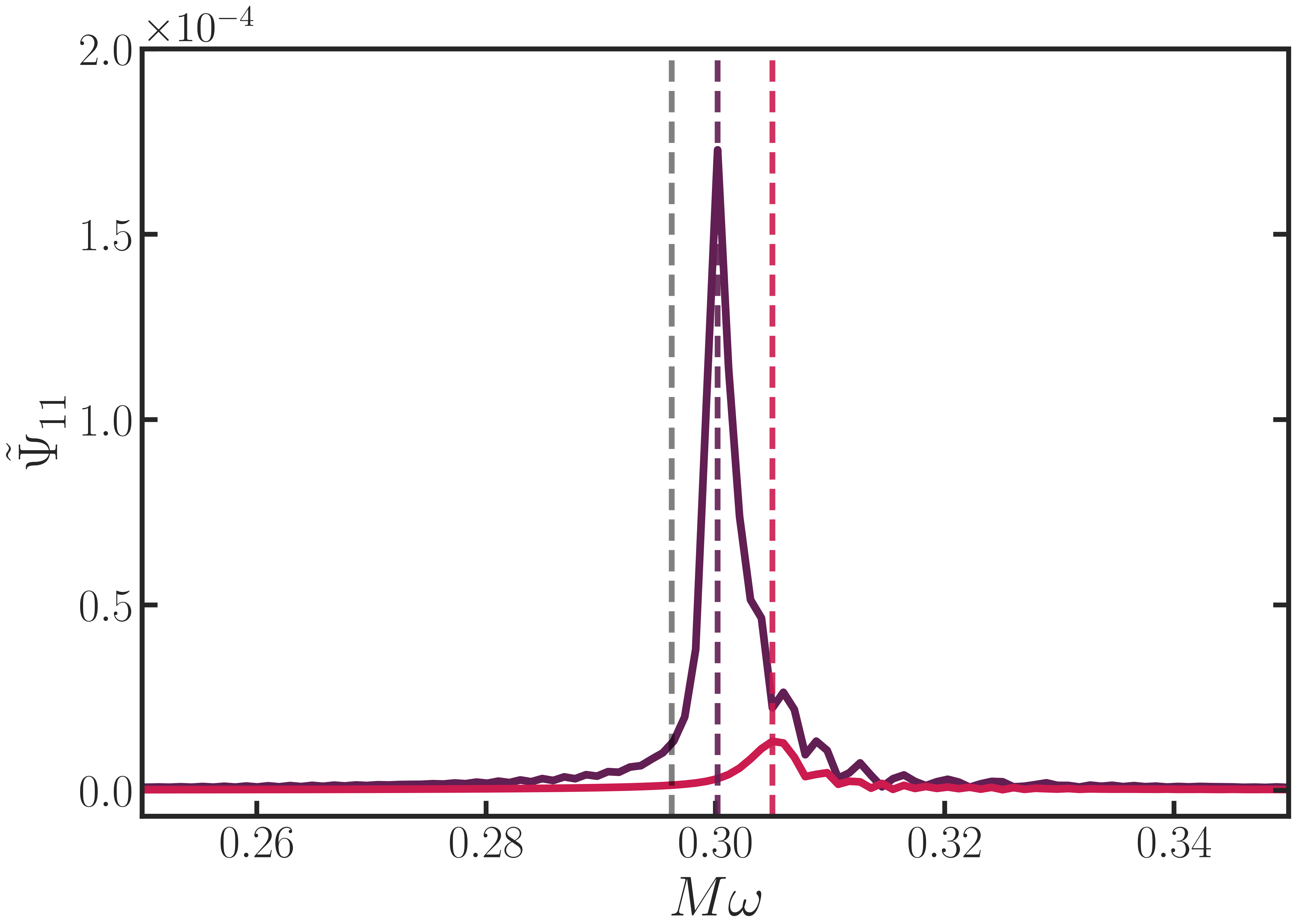


[Spieksma *et al.* ’23]

Axionic couplings — no SR — axion emission

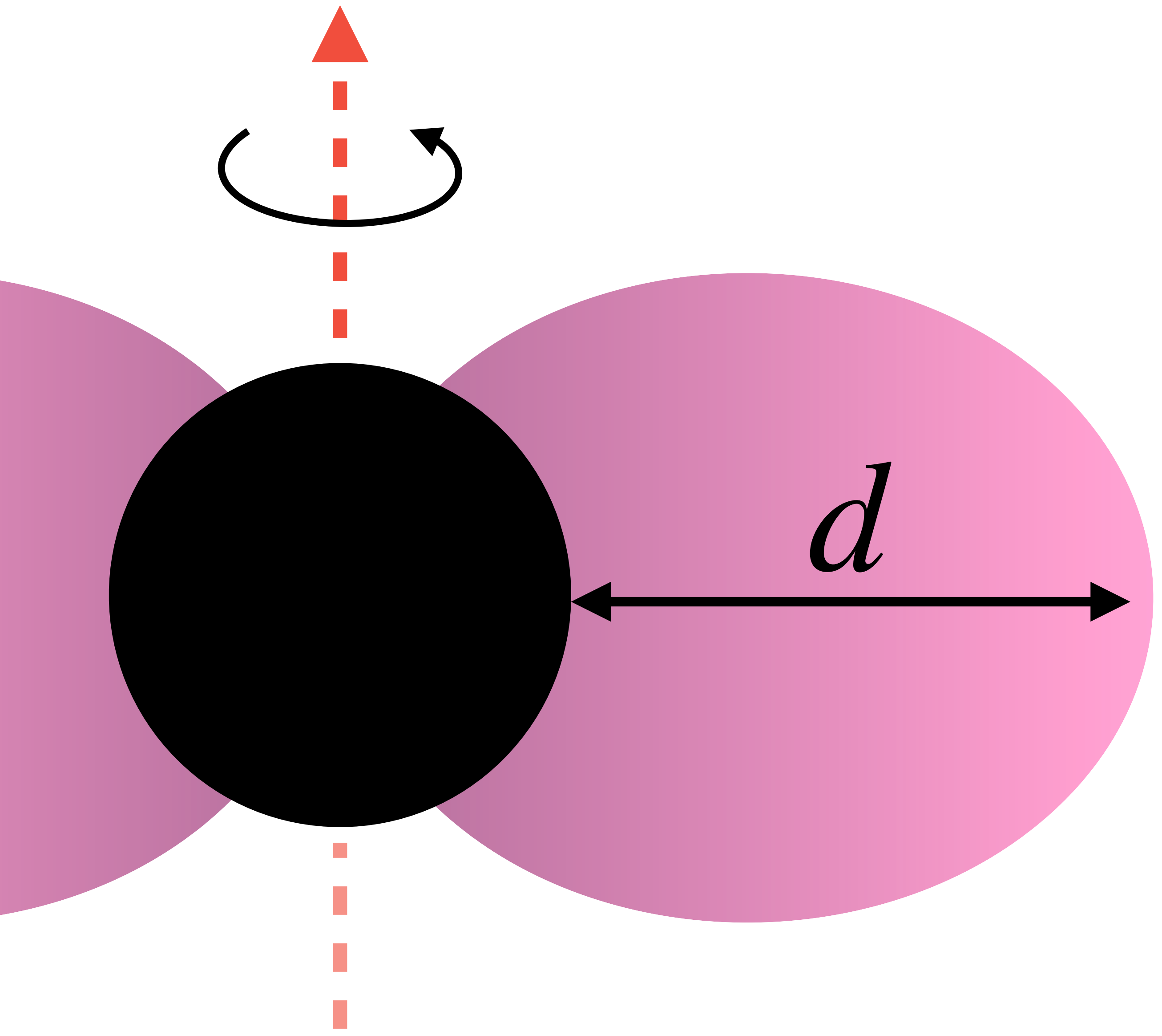
Axion field





[Spieksma *et al.* '23]

Axionic couplings - with SR



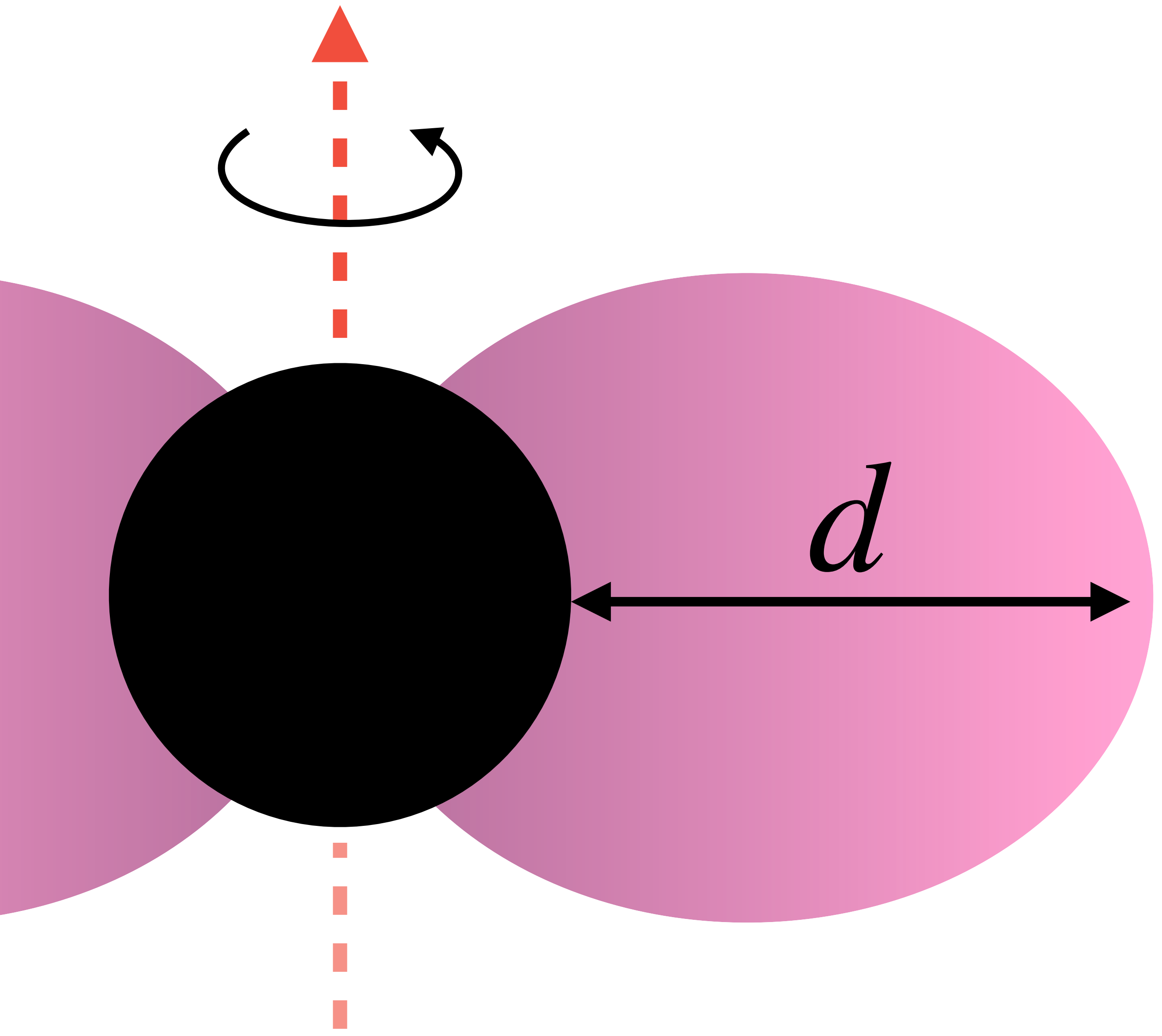
During saturation

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

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

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

Axionic couplings - with SR



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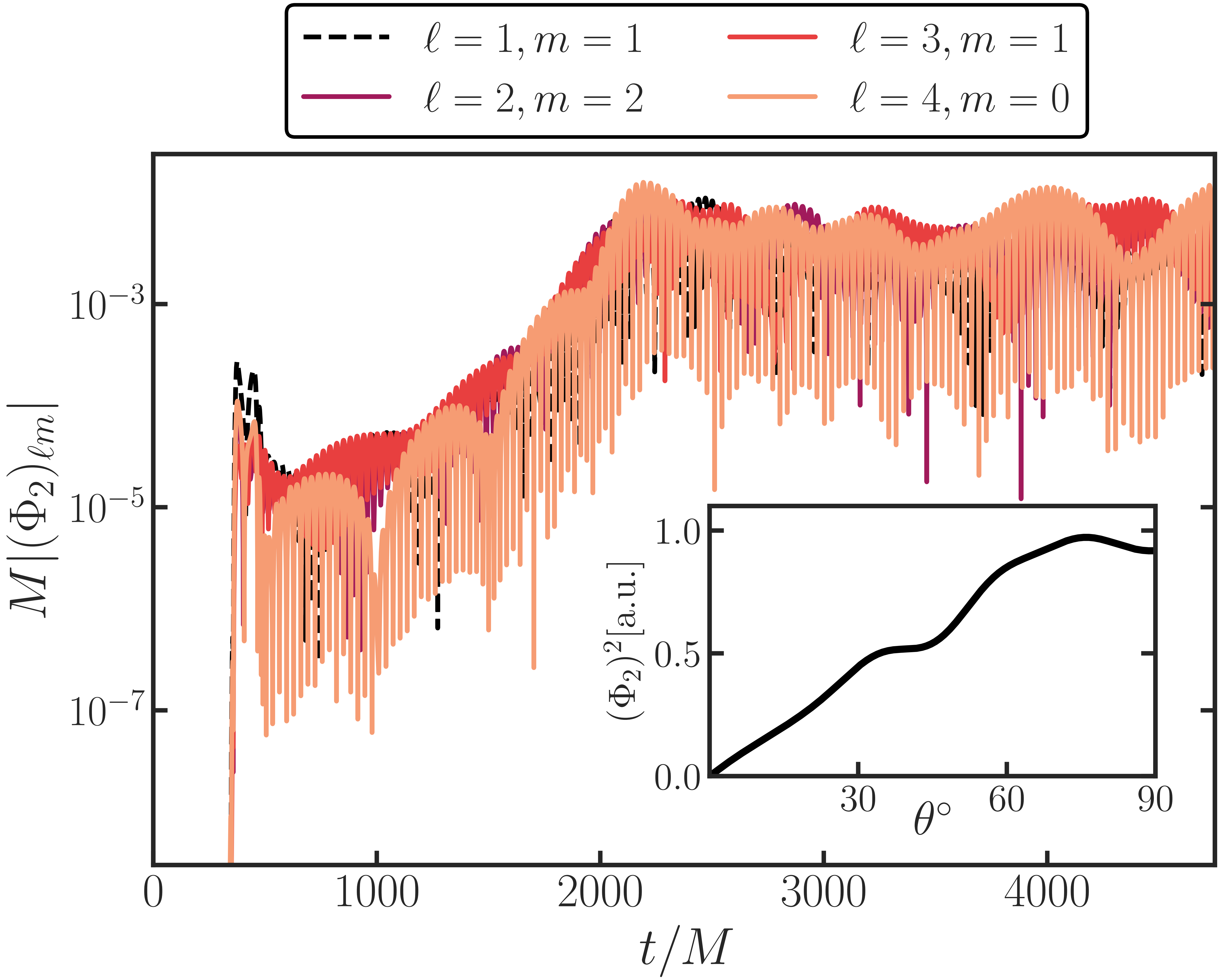
Saturation value of the axion field **does not** depend on (artificial) **SR growth rate**!

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

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

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

Observational signatures



[Spieksma *et al.* ’23]