Light from Dark Solitons

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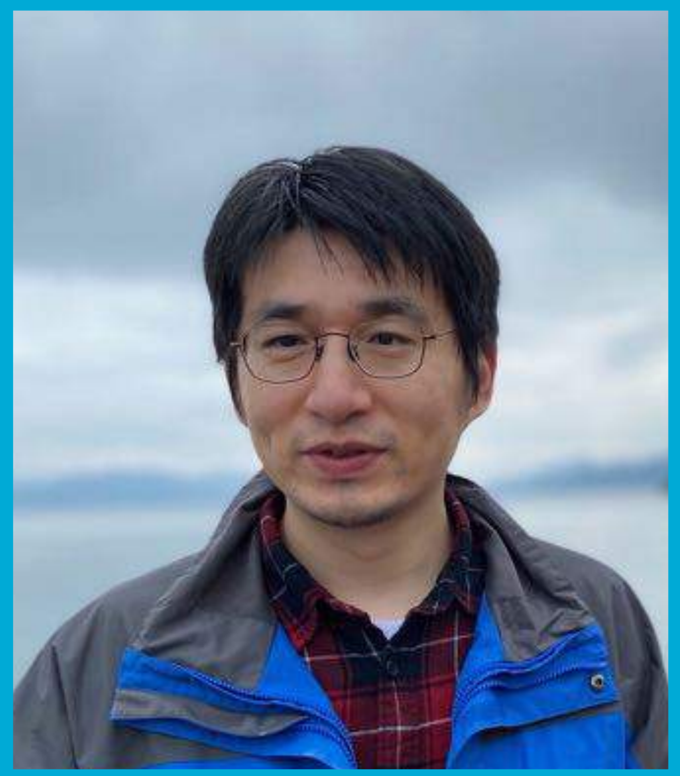
ASPEN CENTER FOR PHYSICS
2021 VIRTUAL WINTER CONFERENCE
A RAINBOW OF DARK SECTORS

based on

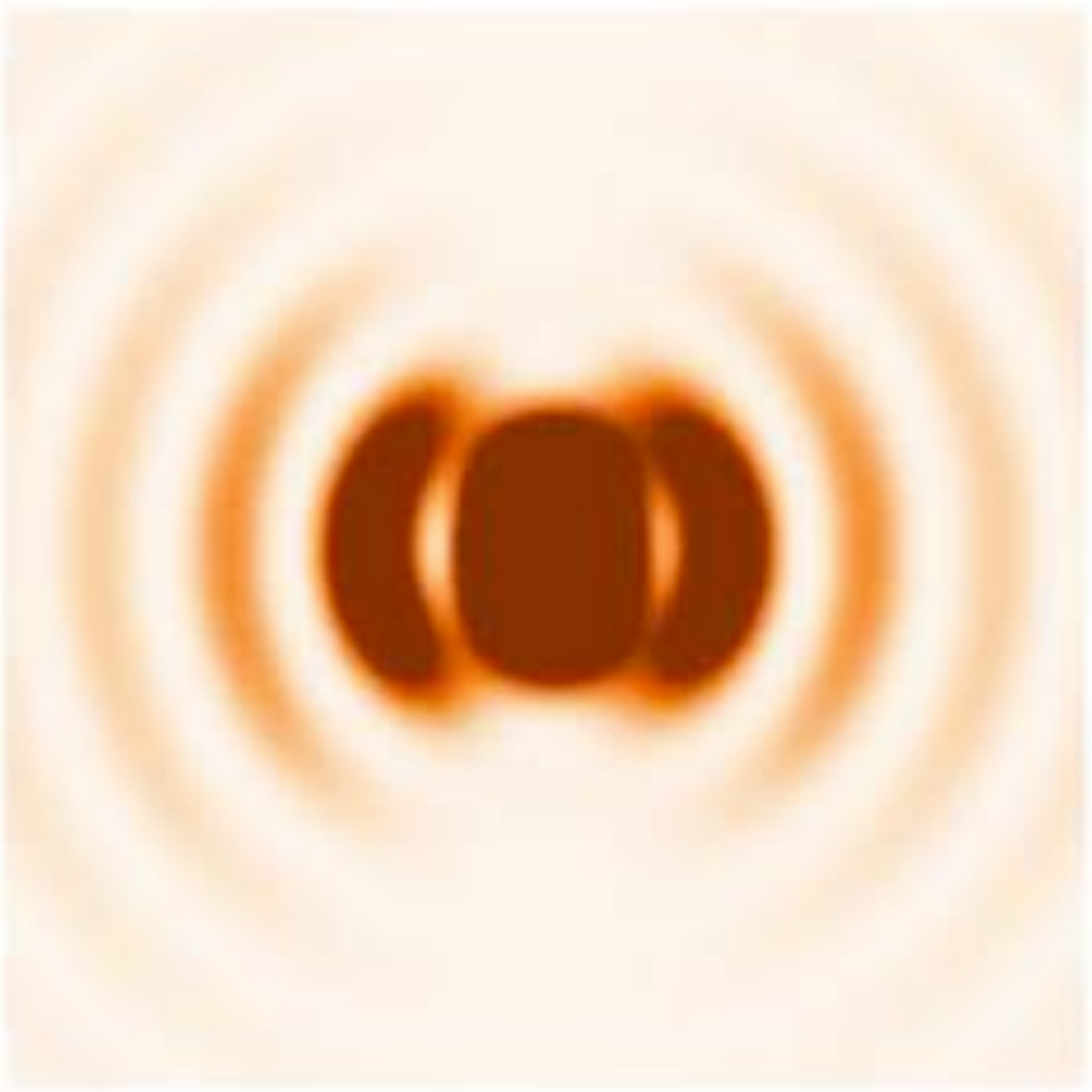
[arXiv: **2103.12082**] with Andrew J. Long, Paul Saffin & Zong-Gang Mou

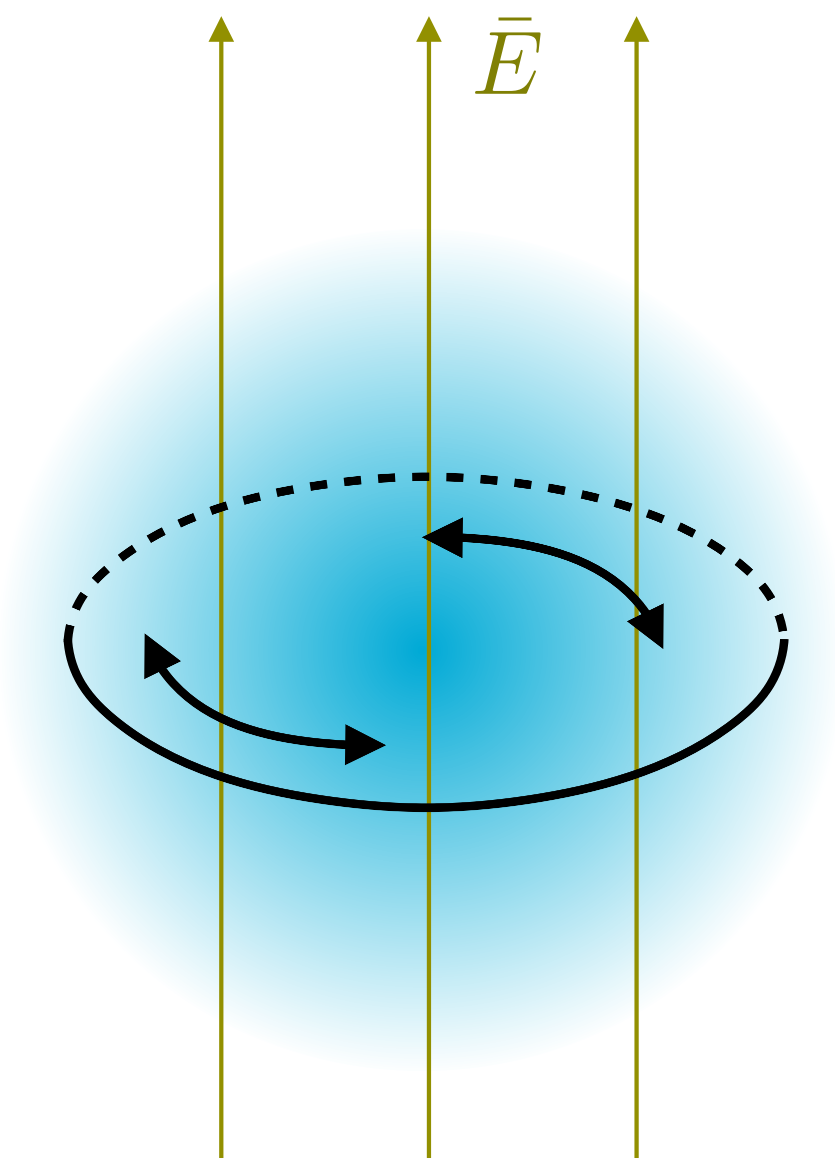


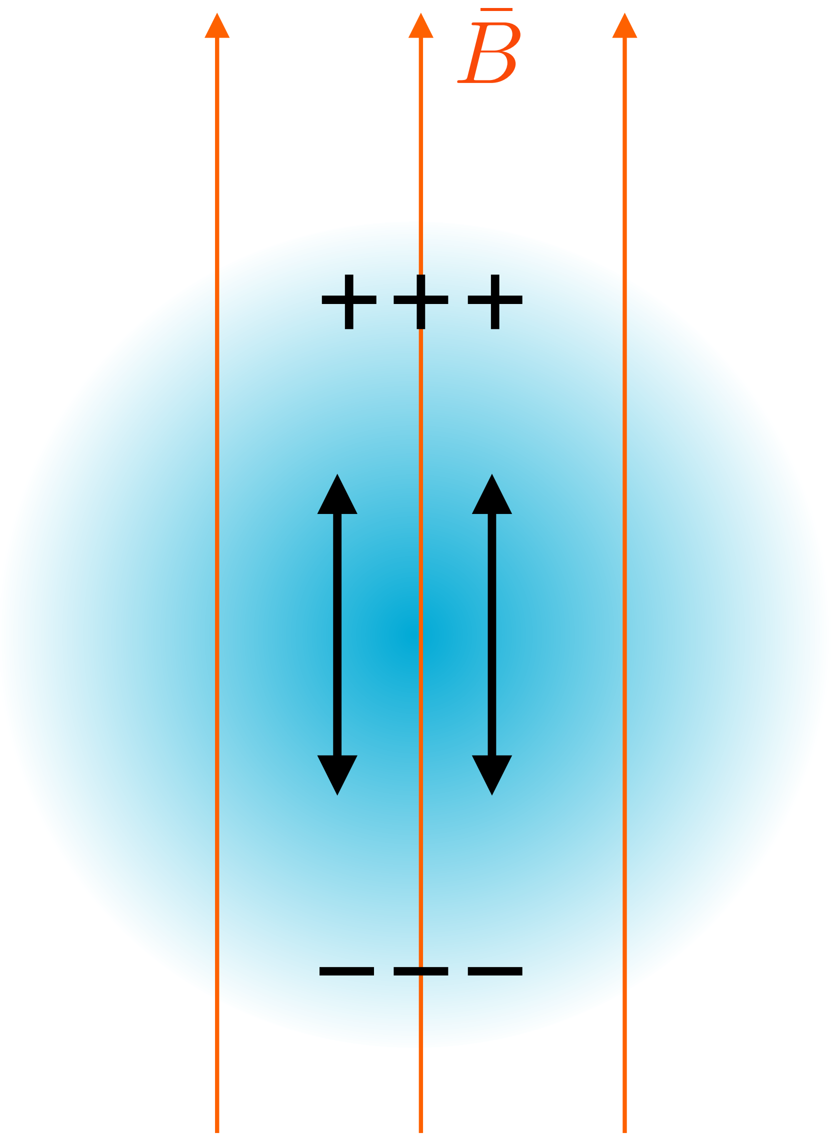
and [arXiv: **2009.11337**] with Zong-Gang Mou

main takeaways

axion stars/oscillons/solitons can radiate energy in electromagnetic fields $g_{a\gamma}\phi\mathbf{E}\cdot\mathbf{B}$





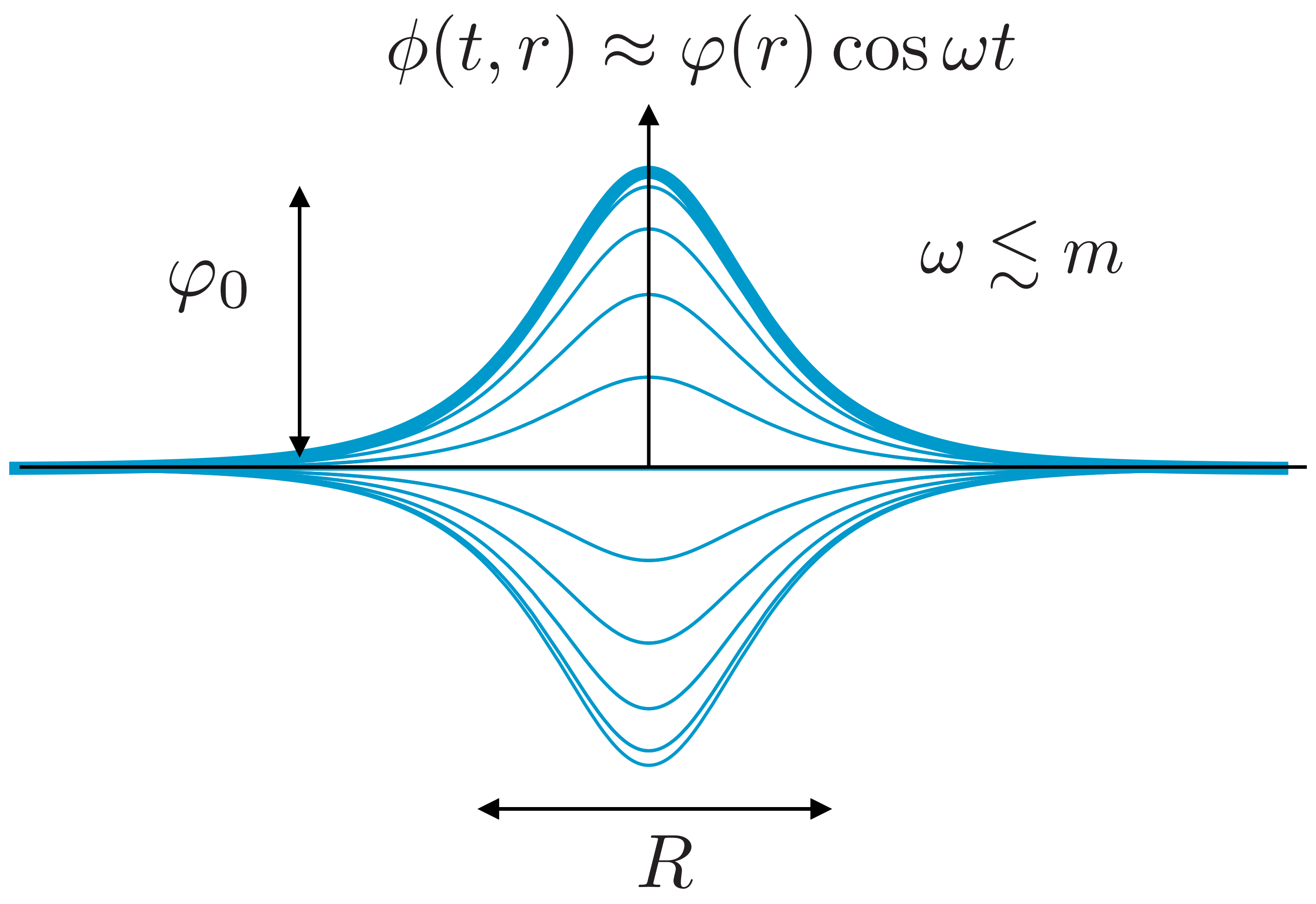


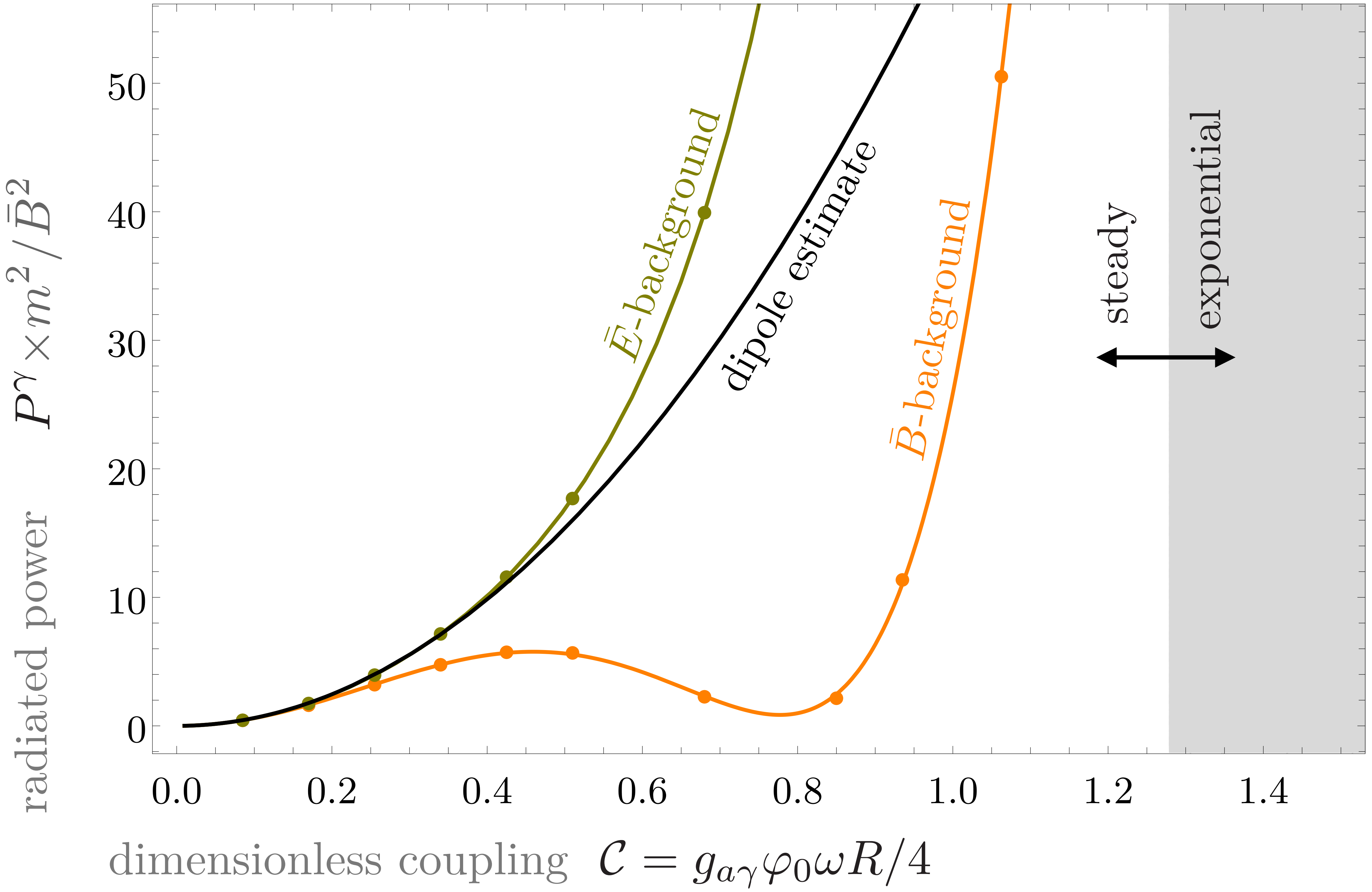
*we have simple analytic results, confirmed by numerical simulations + novel phenomenon which are harder to explain analytically

main takeaways

axion stars/oscillons/solitons can radiate energy in electromagnetic fields $g_{a\gamma}\phi\mathbf{E}\cdot\mathbf{B}$

radiated power depends on axion-photon coupling and characteristics of soliton configuration

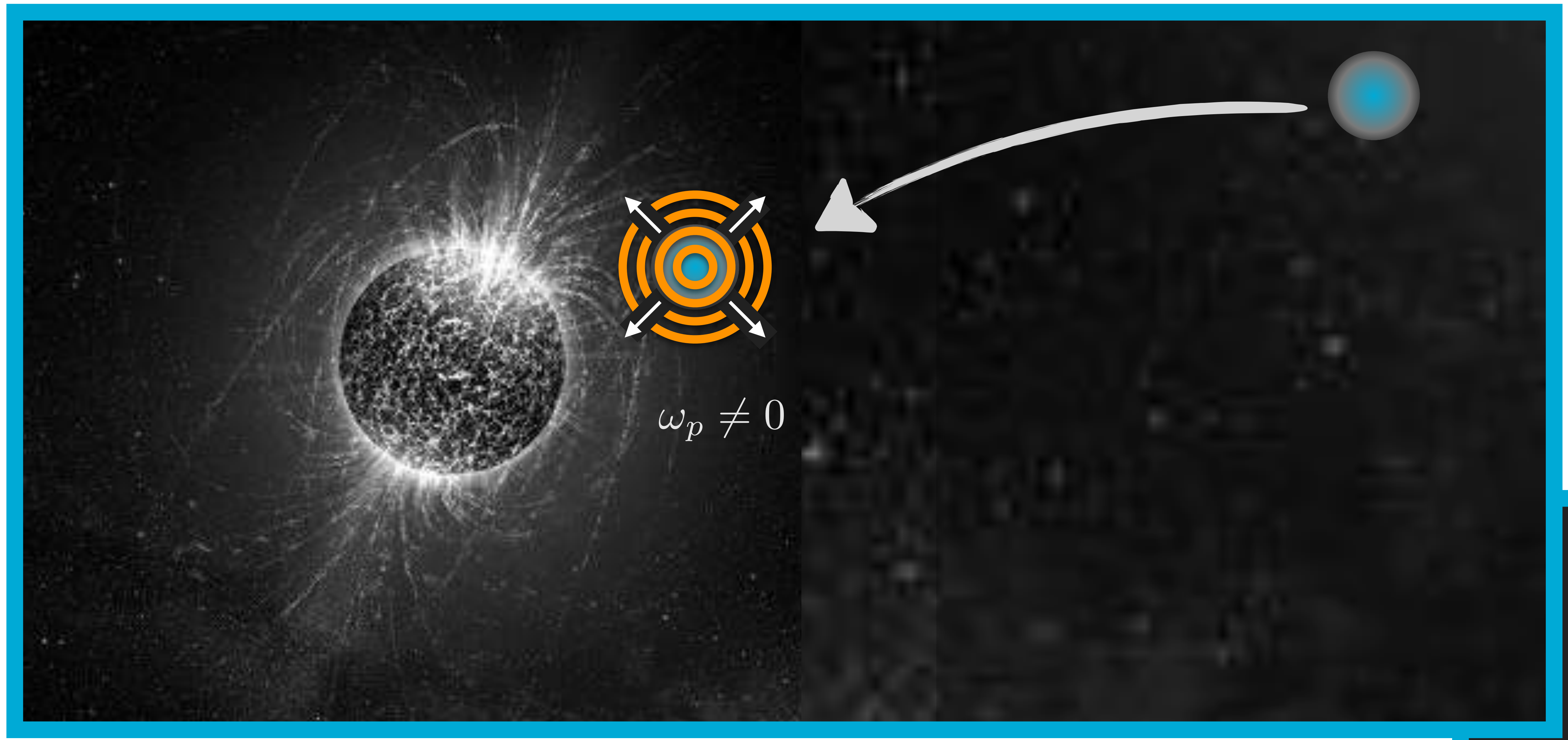




*we have simple analytic results, confirmed by numerical simulations + novel phenomenon which are harder to explain analytically

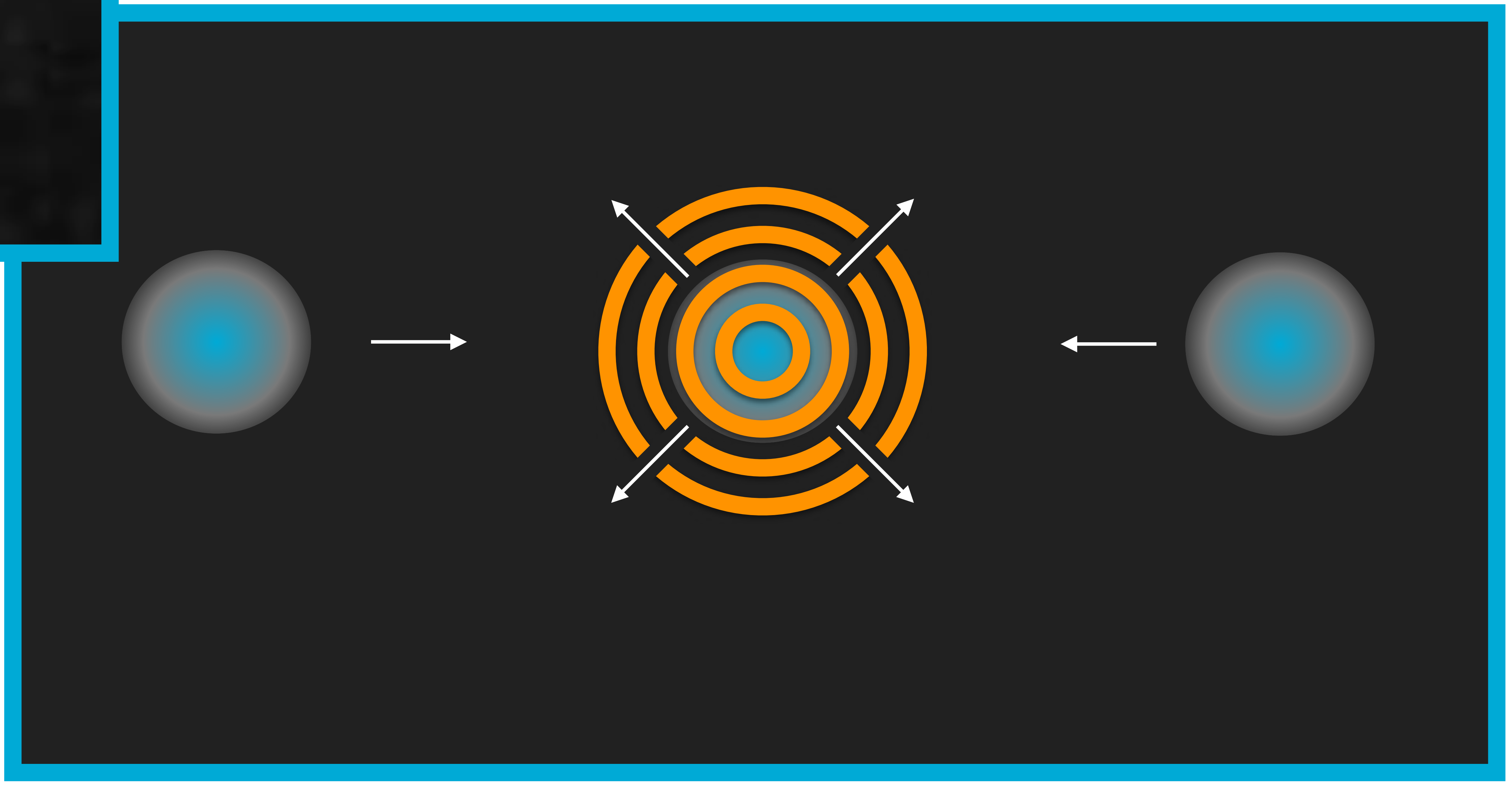
main takeaways

radiation from solitons in external electromagnetic fields (with plasma)



+ early universe effects ?

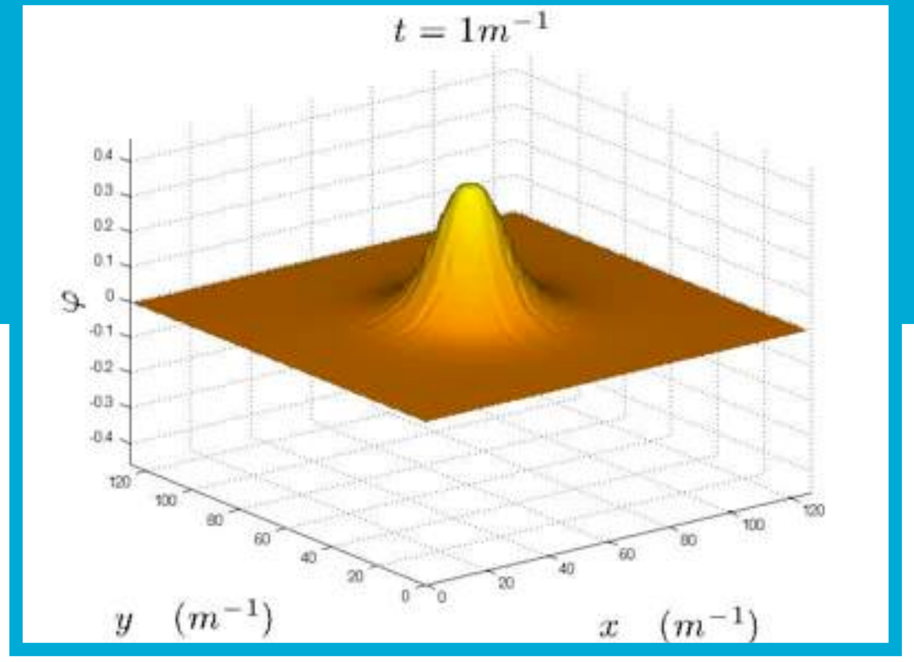
radiation from collisions of solitons

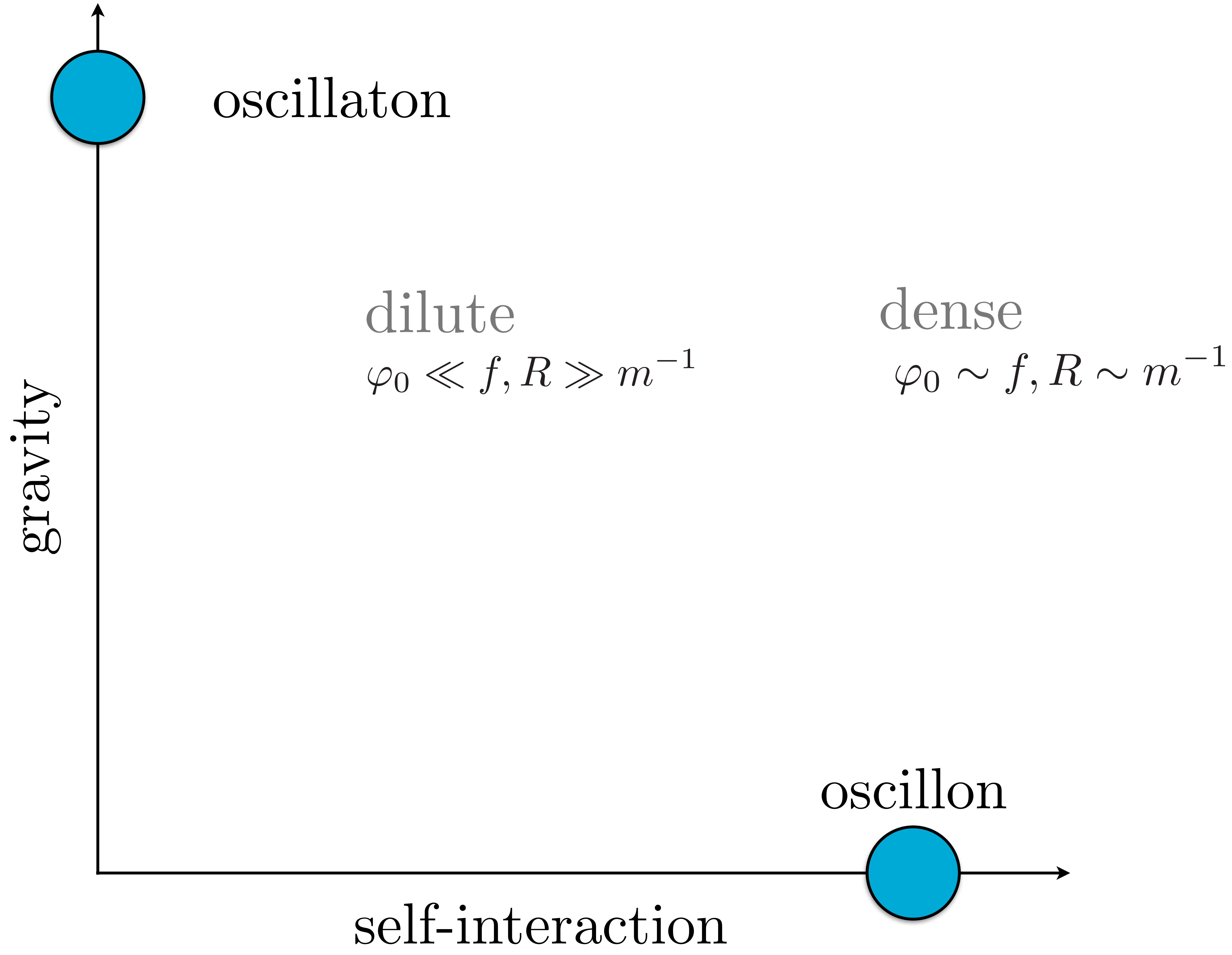


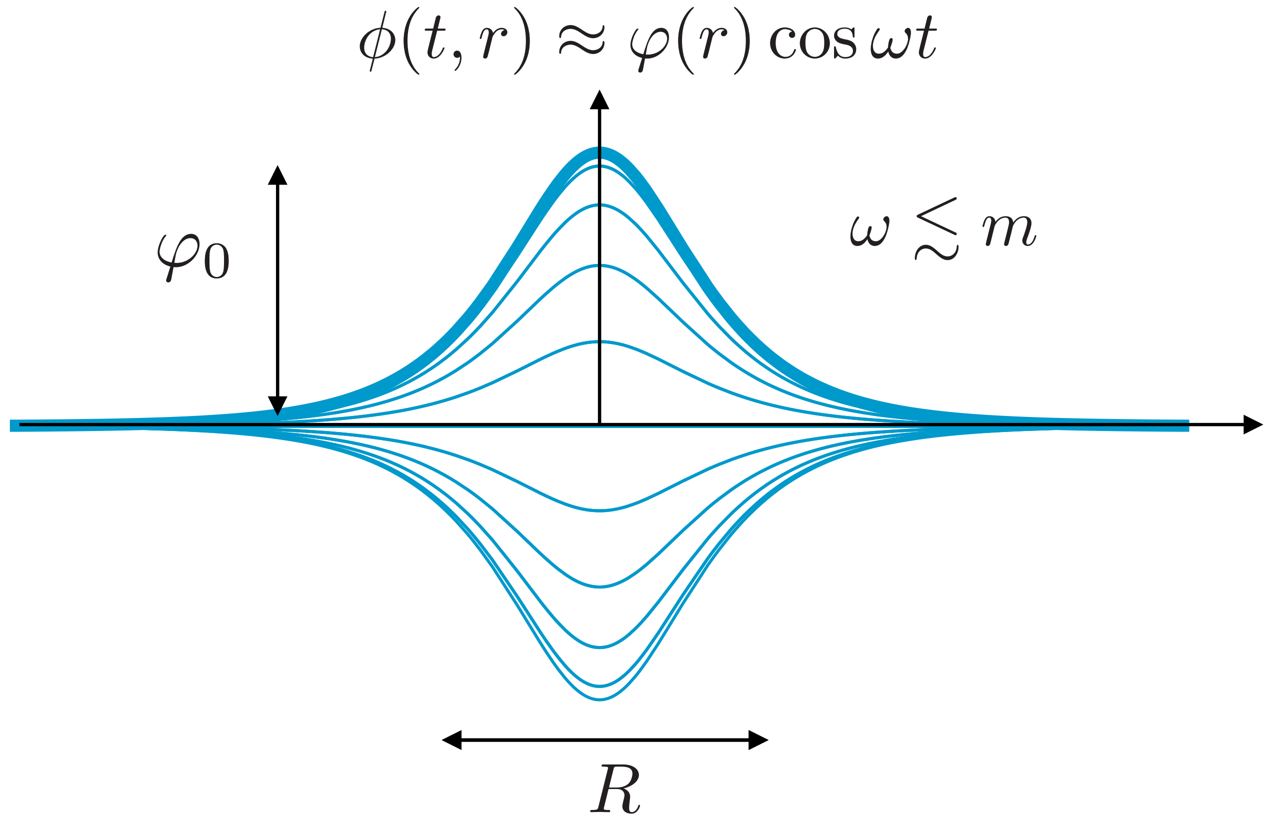
+ Fast Radio Bursts ?

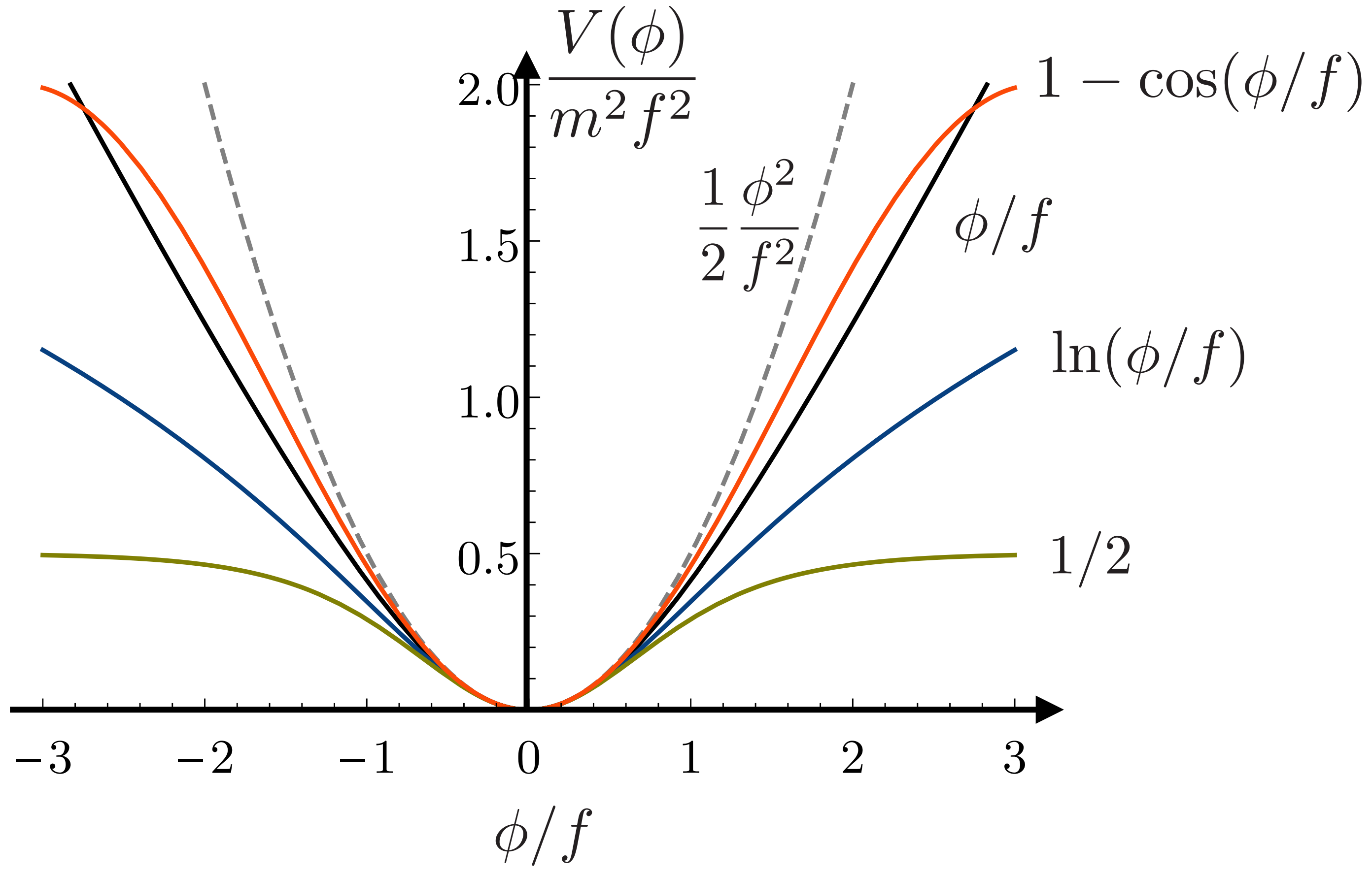
solitons : oscillons, axion stars …

spatially localized, coherently oscillating, long-lived





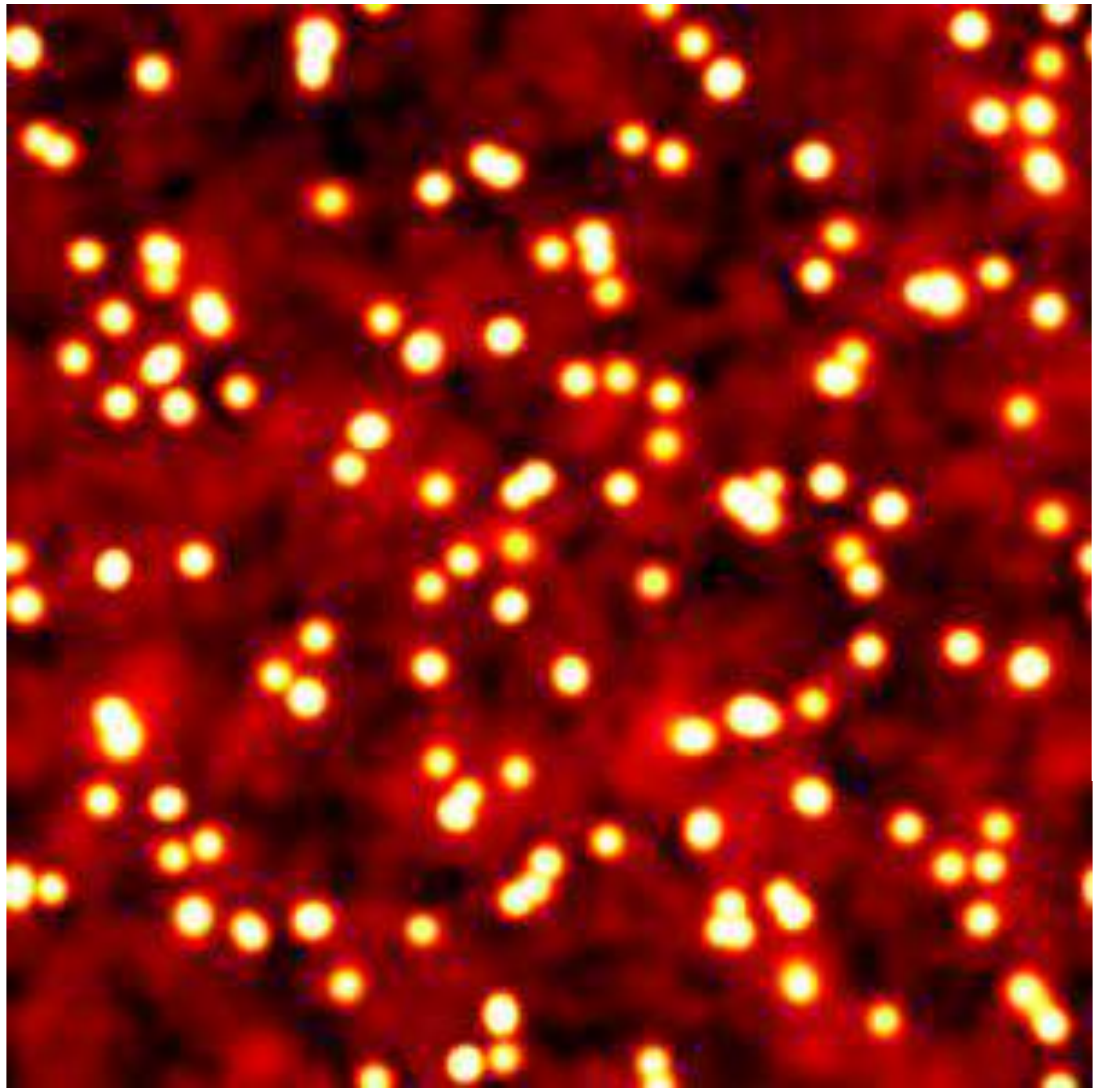




*ask me about lifetime concerns, see Zhang et. al (2020a, b)

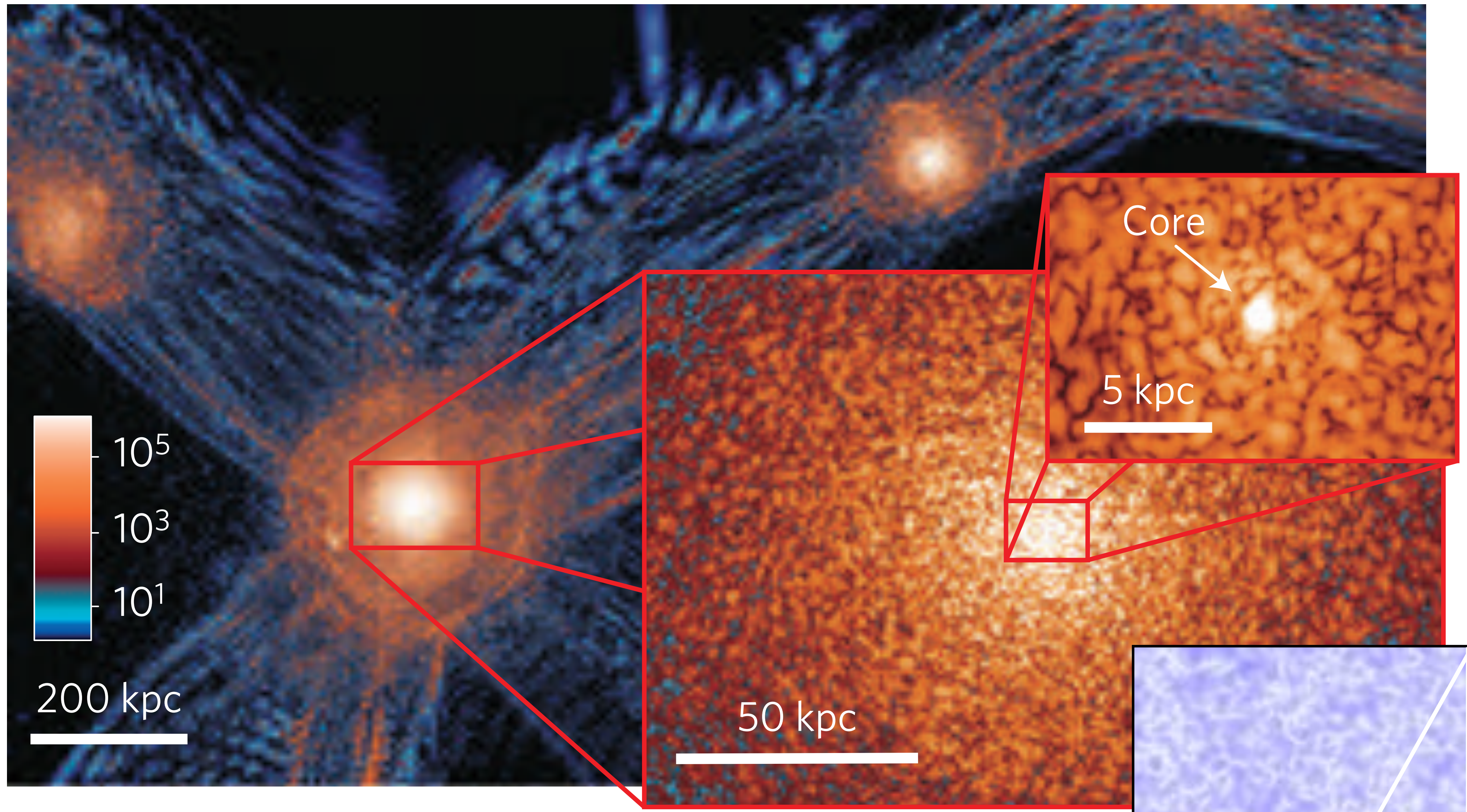
soliton formation mechanisms

self-interaction instability + gravity



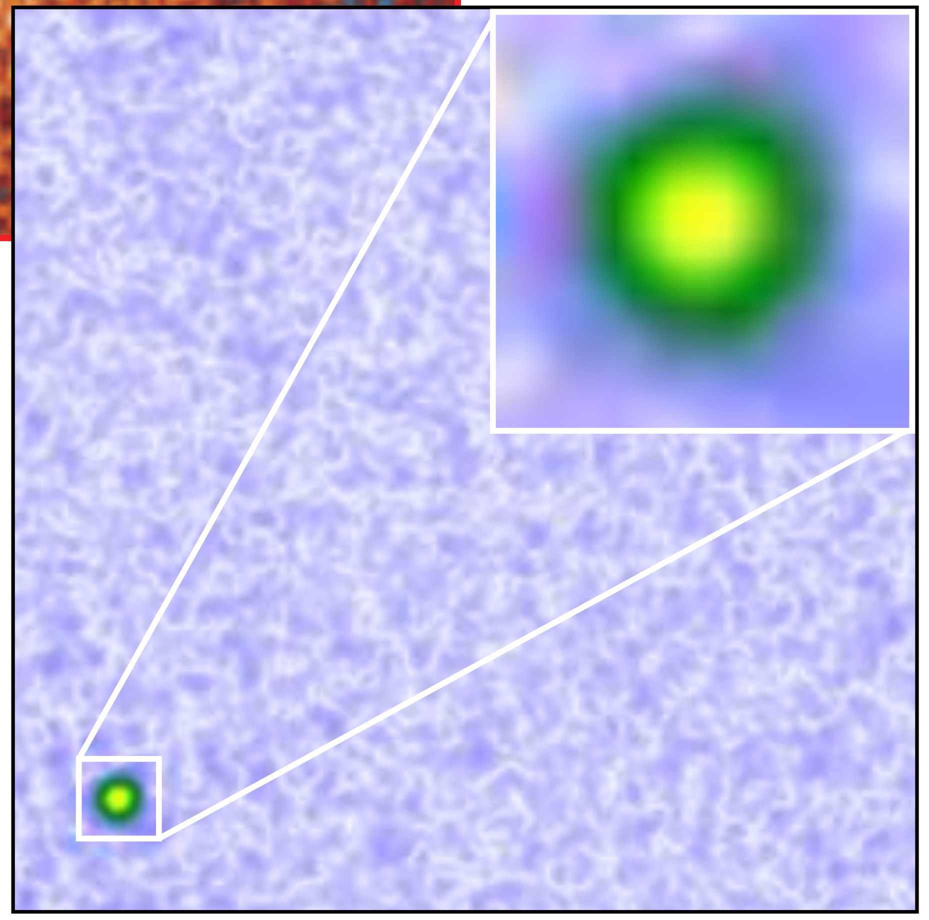
MA & Mocz (2019)

gravitational instability + kinetic nucleation



Schive et. al (2015)

Levkov et. al (2018)

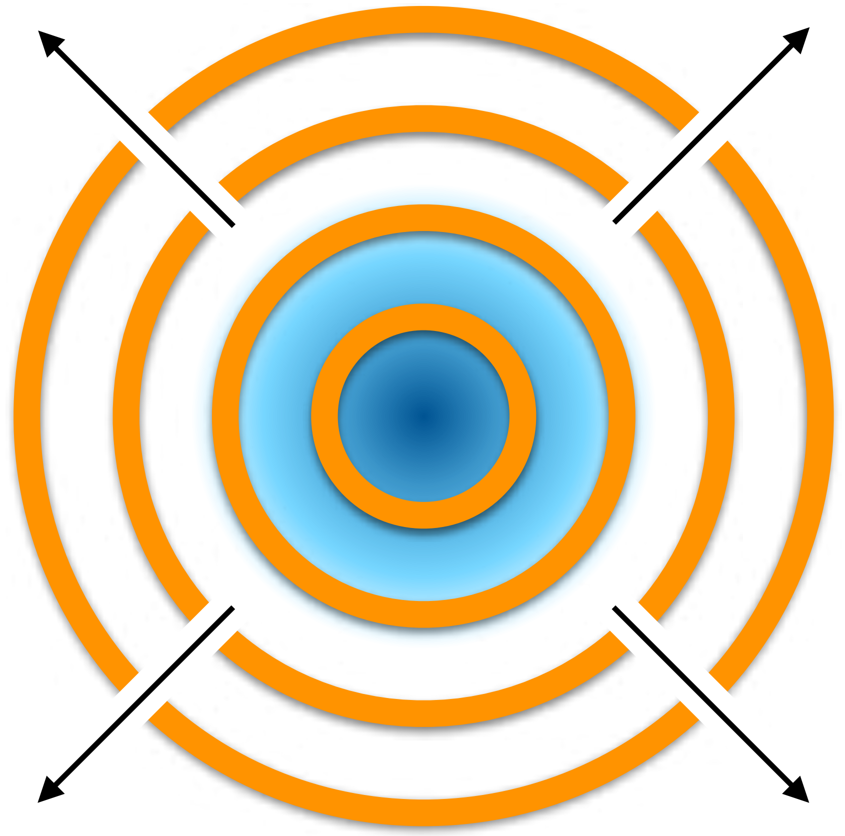


also phase transitions, nucleation around BHs, etc.

also work by D. Croon, C. Prescod-Weinstein

why EM radiation from solitons ?

solitons with coherence & large (non-redshifting) central amplitudes — can significantly change expectations of axion-photon conversion



electromagnetic radiation from solitons

$g_{a\gamma}\phi\mathbf{E}\cdot\mathbf{B}$

$$\ddot{\boldsymbol{E}} - \boldsymbol{\nabla}^2\boldsymbol{E} = -\boldsymbol{\nabla}\rho - \dot{\boldsymbol{J}}$$

$$\ddot{\boldsymbol{B}} - \boldsymbol{\nabla}^2\boldsymbol{B} = \boldsymbol{\nabla}\times\boldsymbol{J}$$

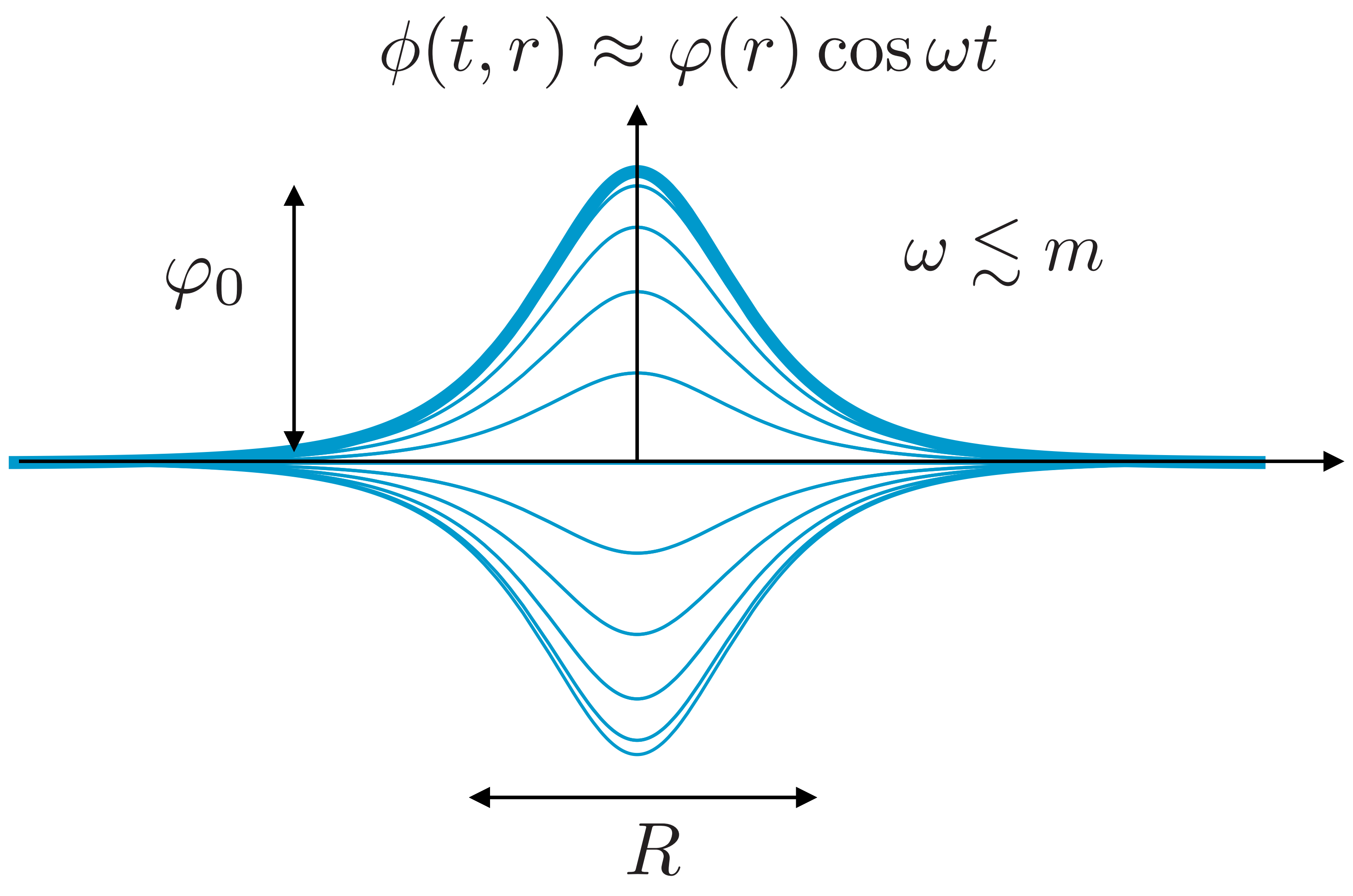
effective charge

$$\rho = -g_{a\gamma}\nabla\phi\cdot\boldsymbol{B}$$

current densities

$$\boldsymbol{J} = g_{a\gamma}\left(\dot{\phi}\boldsymbol{B} + \nabla\phi\times\boldsymbol{E}\right)$$

electromagnetic radiation from solitons



$$\ddot{\boldsymbol{E}} - \boldsymbol{\nabla}^2 \boldsymbol{E} = -\boldsymbol{\nabla}\rho - \dot{\boldsymbol{J}}$$

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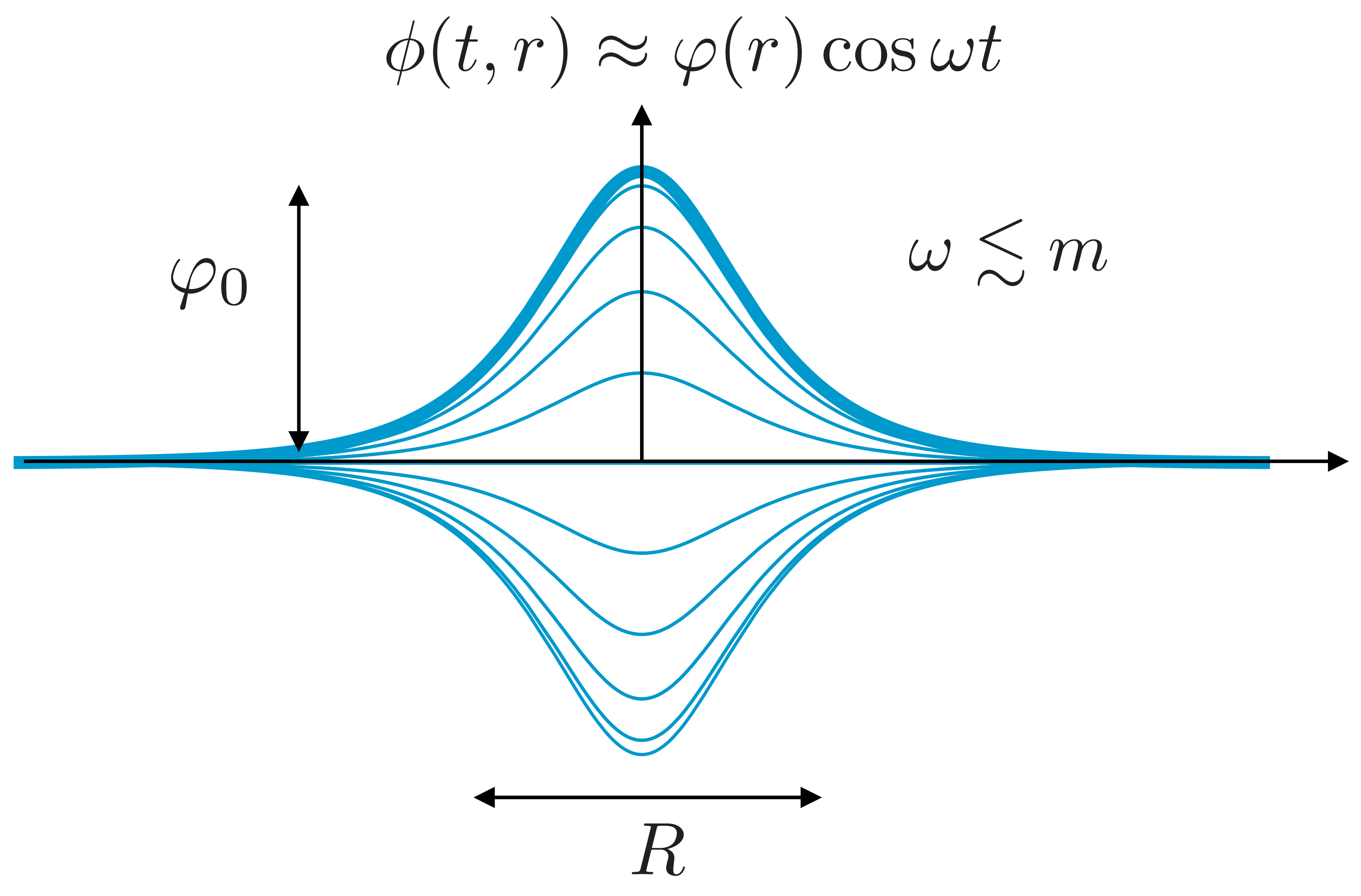

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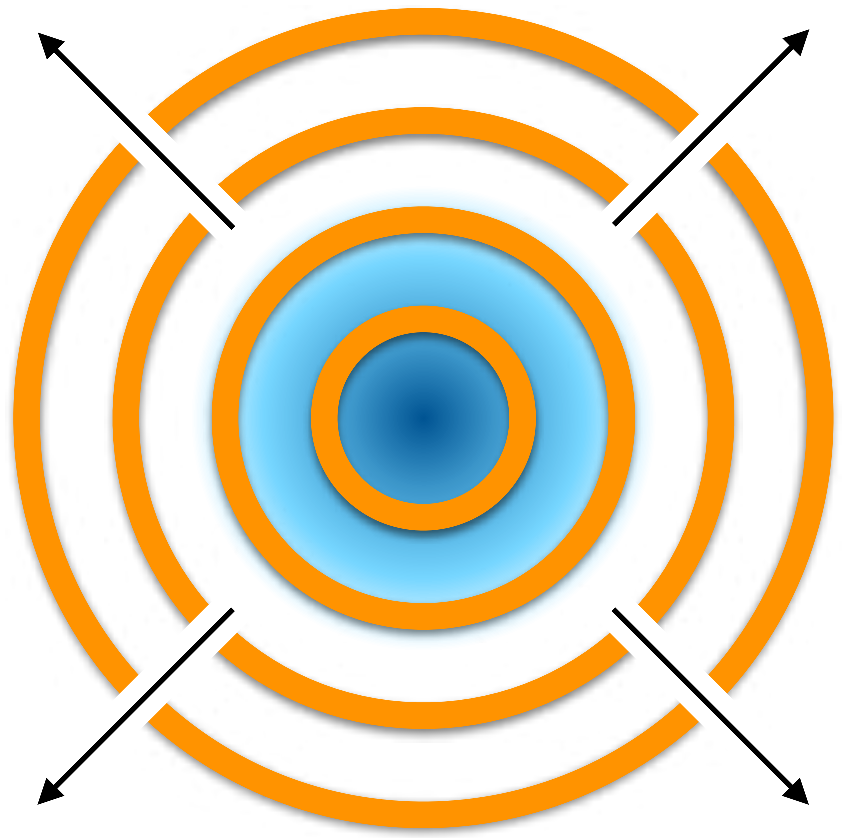
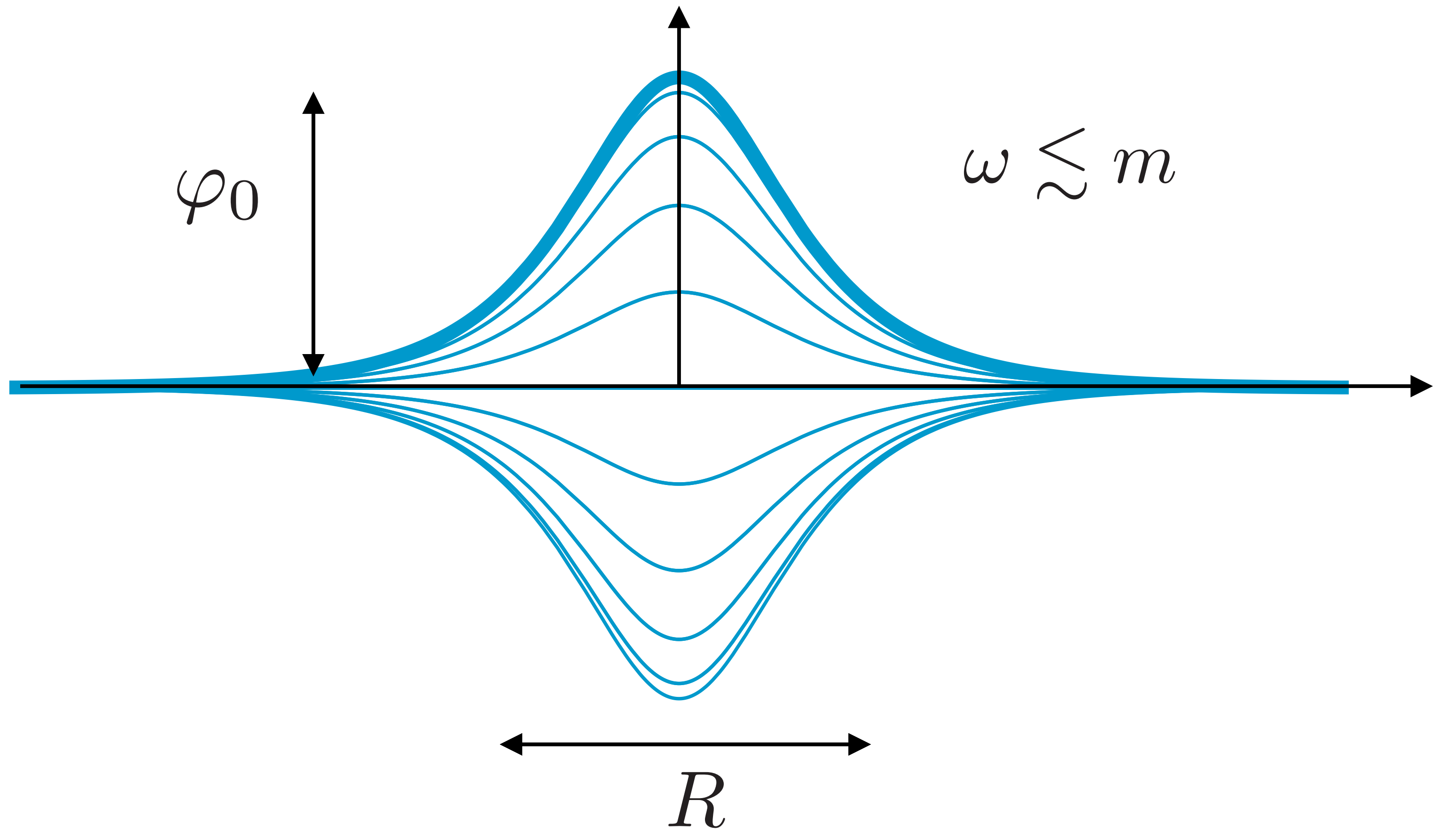


electromagnetic radiation from solitons

$$\phi(t,r) \approx \varphi(r)\cos\omega t$$



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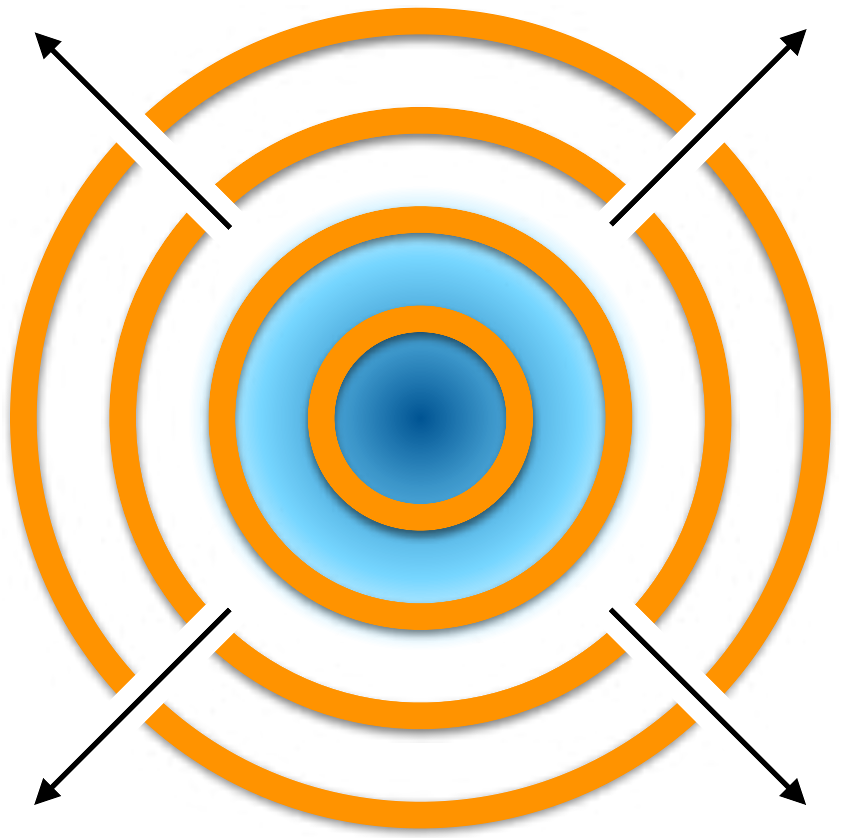
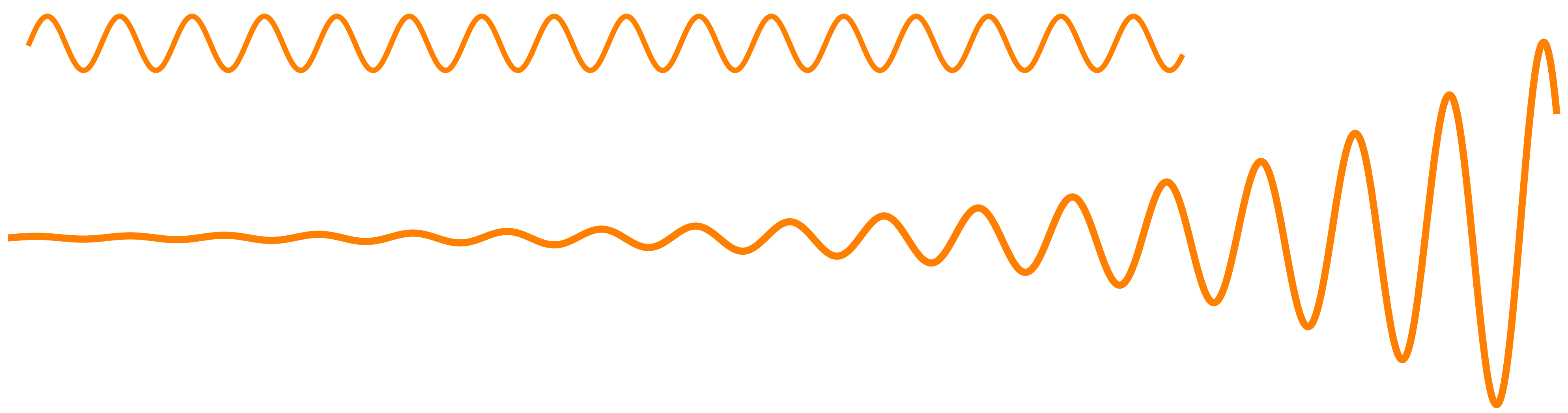


axion field oscillations = periodic coefficients — Floquet theory applies:

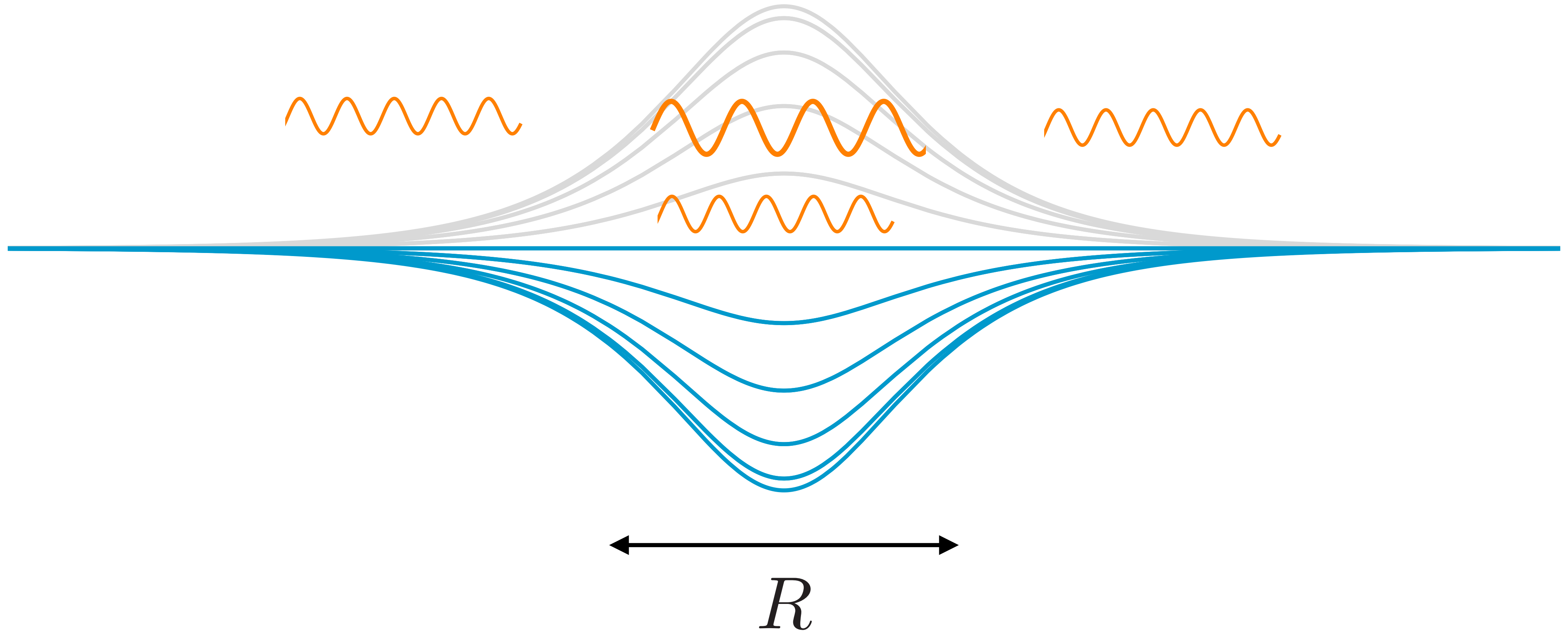
$\boldsymbol{E},\boldsymbol{B}$

1. steady solutions
2. exponentially growing



EM radiation from solitons: steady vs. explosive

$$\mathcal{C} \equiv \frac{\text{escape time-scale}}{\text{Bose-enhancement time-scale}}$$



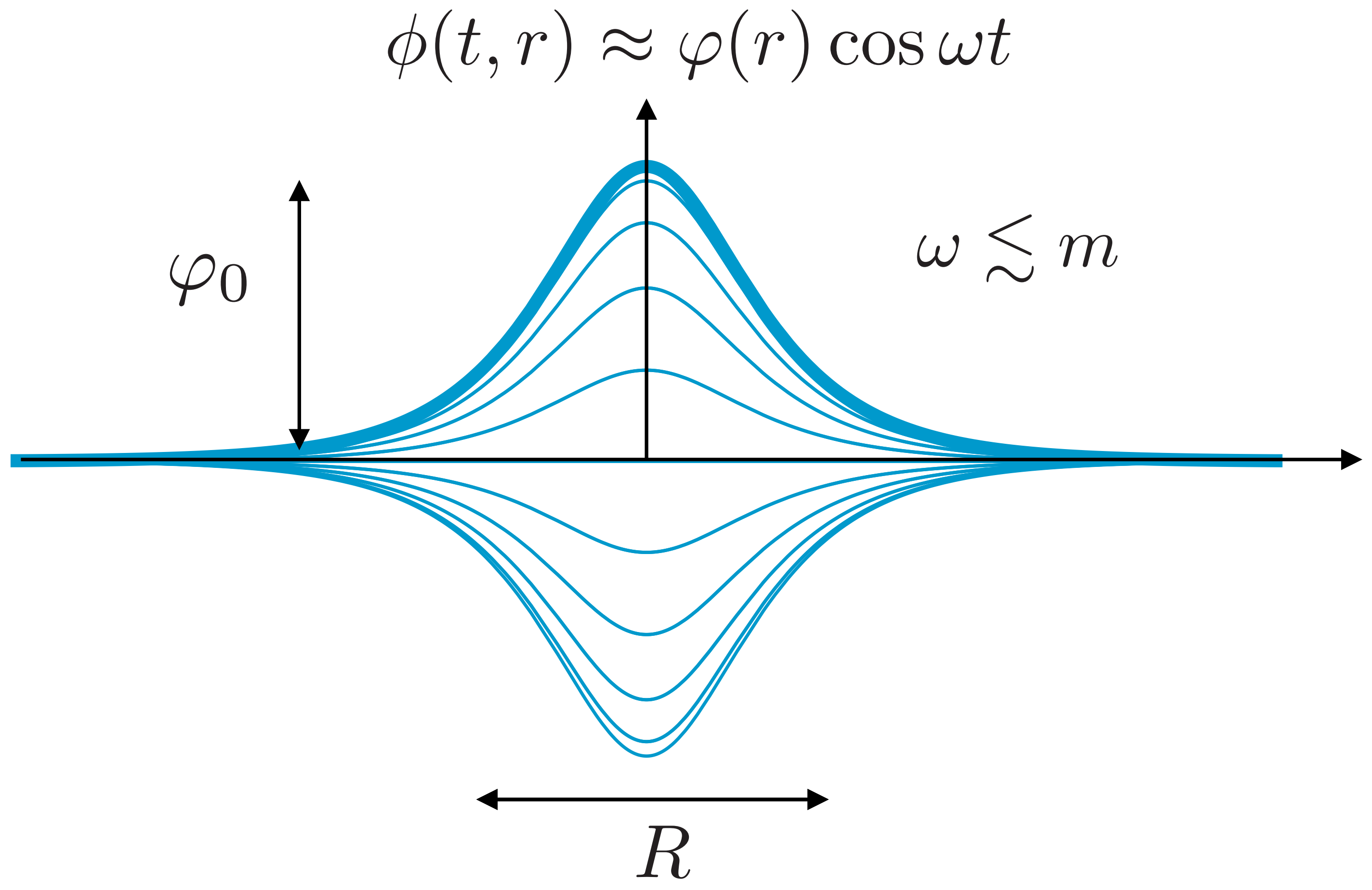
EM radiation from solitons: steady vs. explosive

$$\mathcal{C} \equiv \frac{\text{escape time-scale}}{\text{Bose-enhancement time-scale}}$$

$$\equiv \frac{R}{\mu_{\rm hom}^{-1}} \approx \frac{1}{4} g_{a\gamma}\varphi_0 \omega R$$

numerator and denominator are calculable "by hand"

depends on axion-photon coupling and soliton parameters



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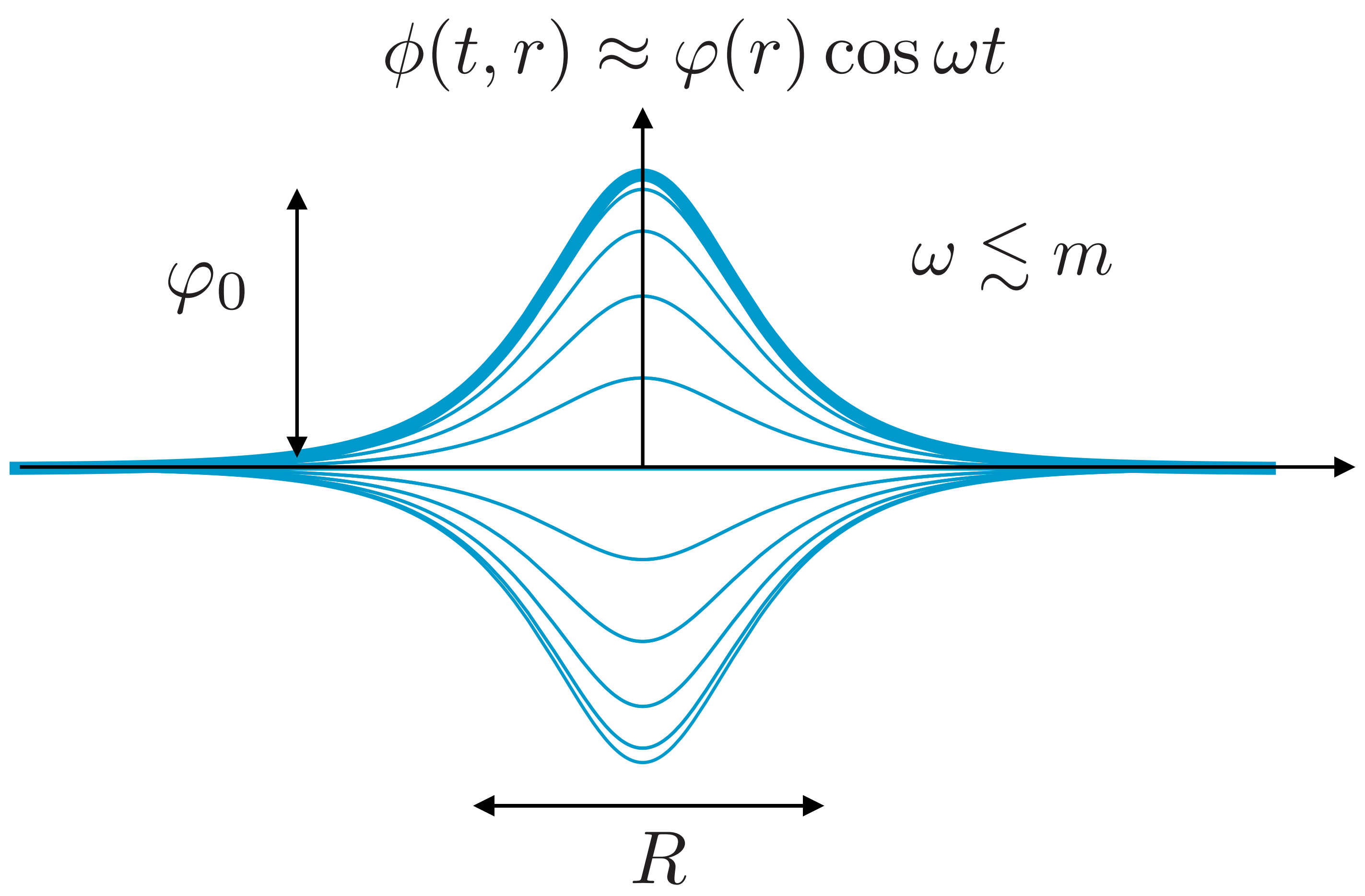
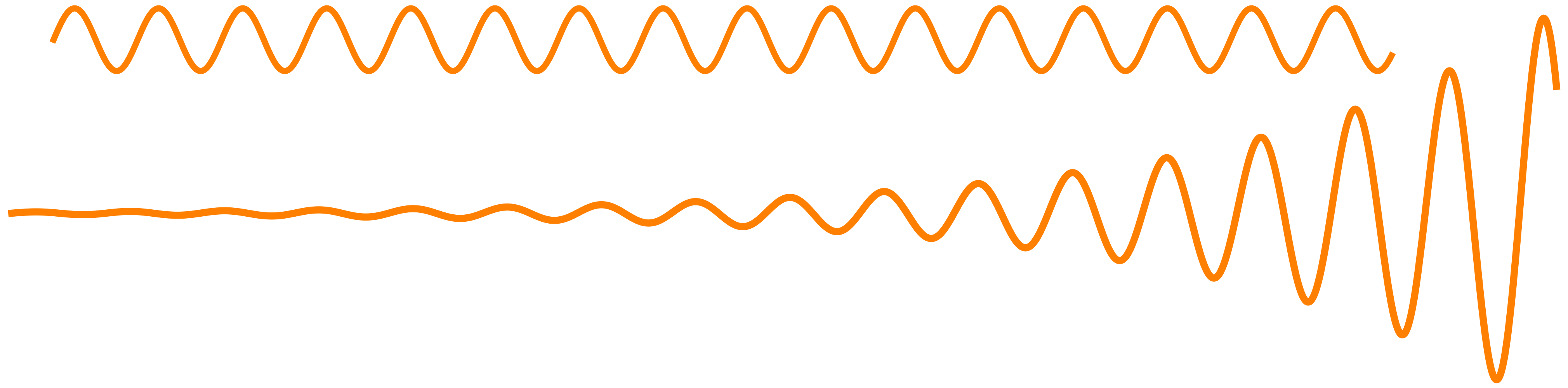


numerator and denominator are calculable “by hand”

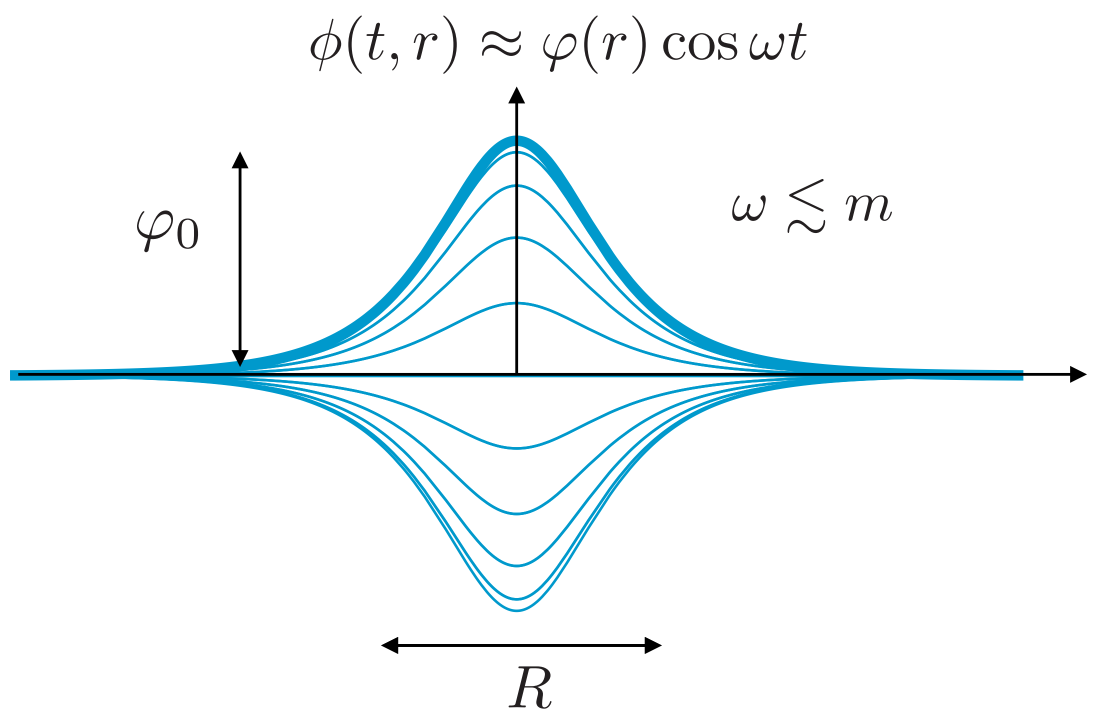
depends on axion-photon coupling and soliton parameters

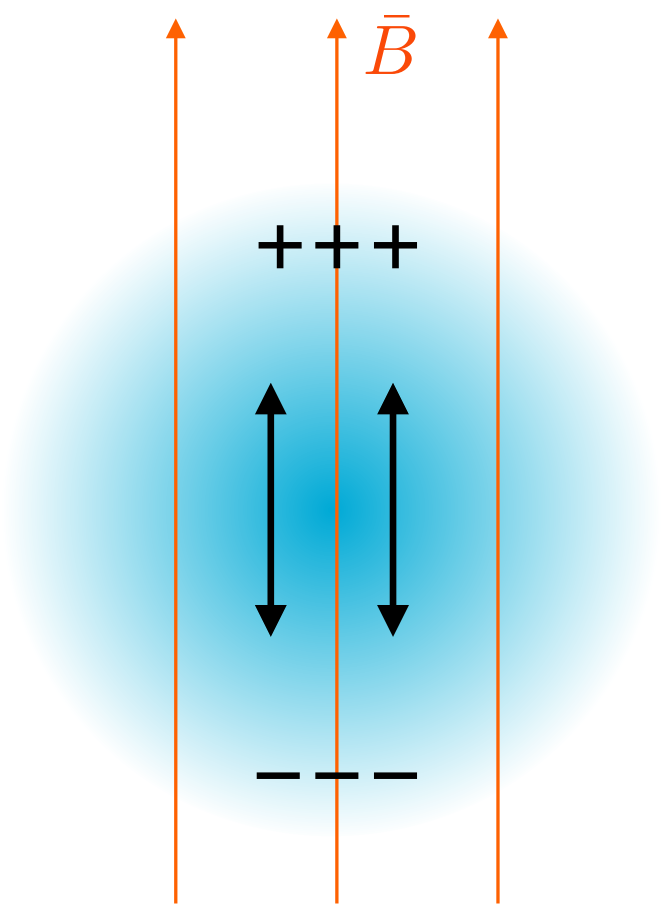
$\mathcal{C} \ll 1 \longrightarrow$

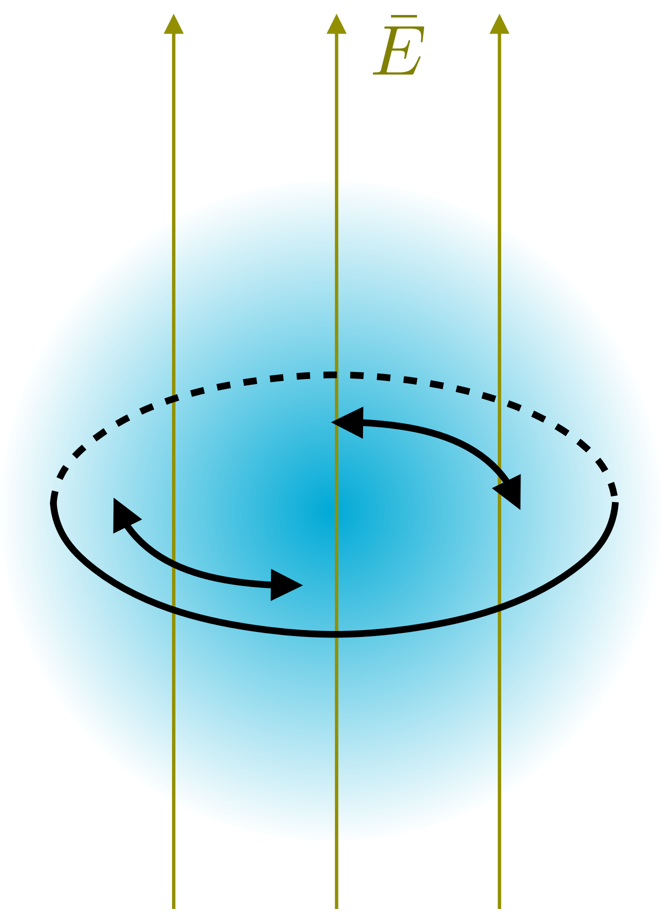
$\mathcal{C} \gtrsim 1 \longrightarrow$



EM radiation from solitons: perturbative calculation







$$\rho = -g_{a\gamma}\nabla\phi \cdot \bar{\boldsymbol{B}}$$

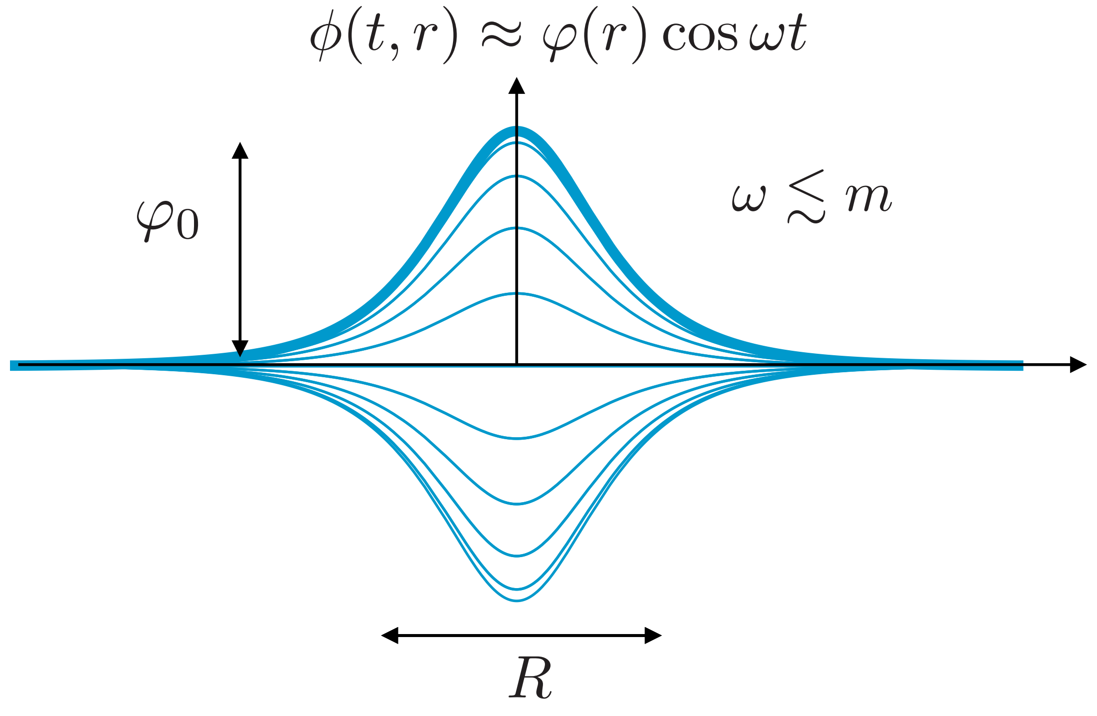
$$\boldsymbol{J} = g_{a\gamma}\left(\dot{\phi}\bar{\boldsymbol{B}} + \nabla\phi \times \bar{\boldsymbol{E}}\right)$$

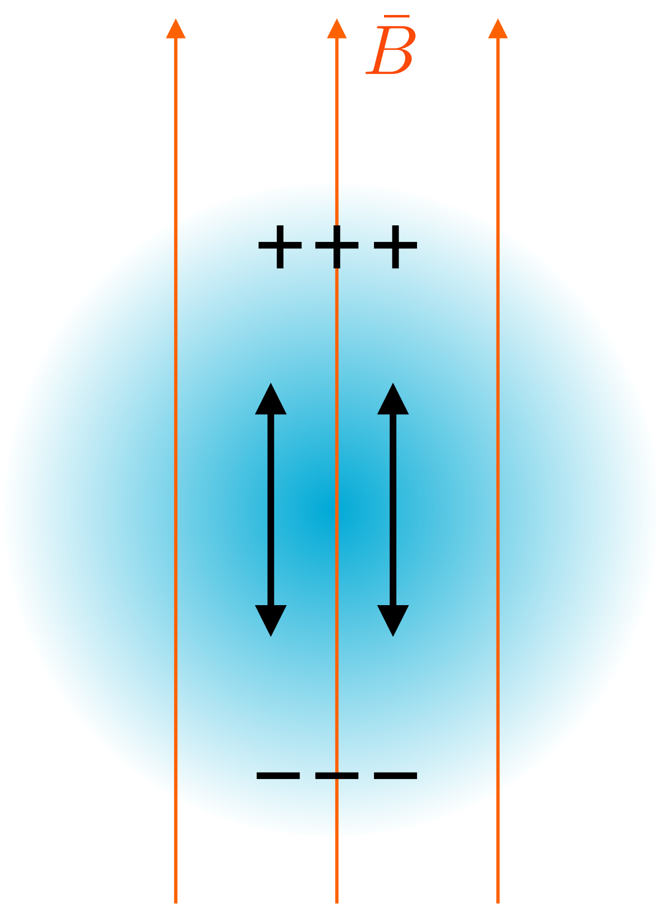
$\mathcal{C} \sim g_{a\gamma}\varphi_0\omega R \ll 1$

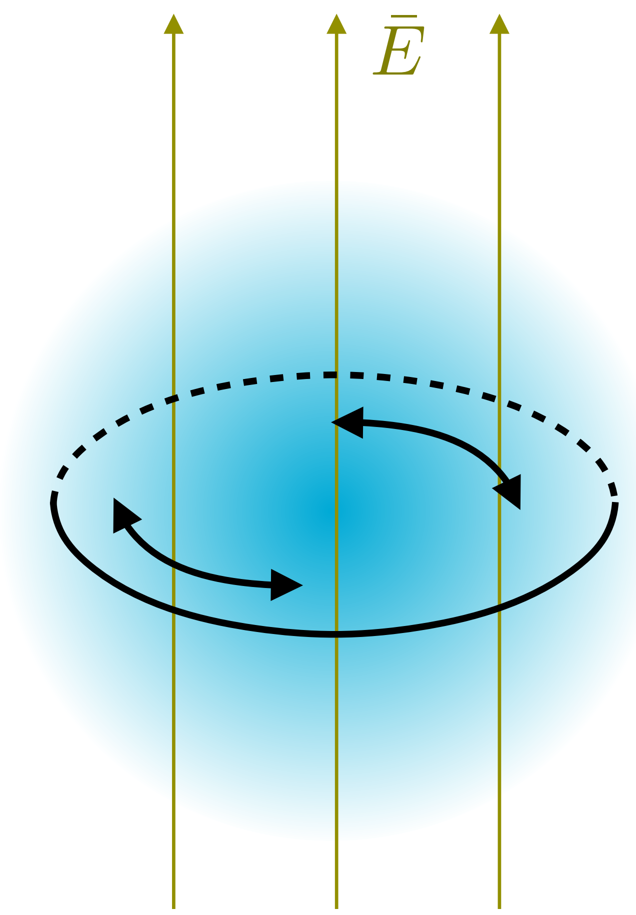
bounded periodic solutions

leading order in $g_{a\gamma}\varphi_0$ only

EM radiation from solitons: dipole radiation







$\mathcal{C} \sim g_{a\gamma}\varphi_0\omega R \ll 1$

bounded periodic solutions

$$\rho = -g_{a\gamma}\nabla\phi\cdot\bar{\boldsymbol{B}} \qquad \boldsymbol{J} = g_{a\gamma}\left(\dot{\phi}\bar{\boldsymbol{B}} + \nabla\phi\times\bar{\boldsymbol{E}}\right)$$

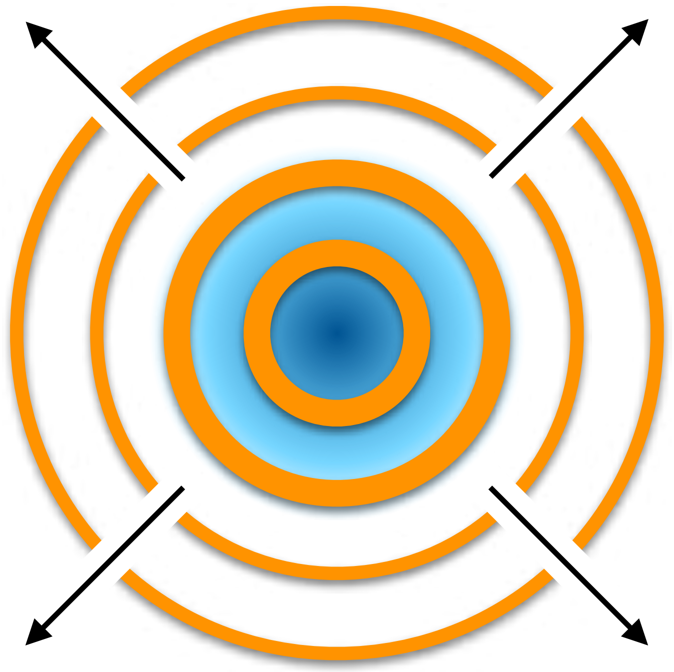
leading order in $g_{a\gamma}\varphi_0$ only

$$\frac{dP^{\gamma}_{(2)}}{d\Omega} = \frac{g_{a\gamma}^2\omega^4\tilde{\varphi}^2(\omega)}{32\pi^2}\left[\left(\hat{\boldsymbol{x}}\times\bar{\boldsymbol{B}}\right)^2 + \left(\hat{\boldsymbol{x}}\times\bar{\boldsymbol{E}}\right)^2 - 2\hat{\boldsymbol{x}}\cdot\left(\bar{\boldsymbol{E}}\times\bar{\boldsymbol{B}}\right)\right]\left(1+\cos\left(2\omega t - 2\omega|\boldsymbol{x}|\right)\right)$$

dipole radiation

EM radiation & soliton profile

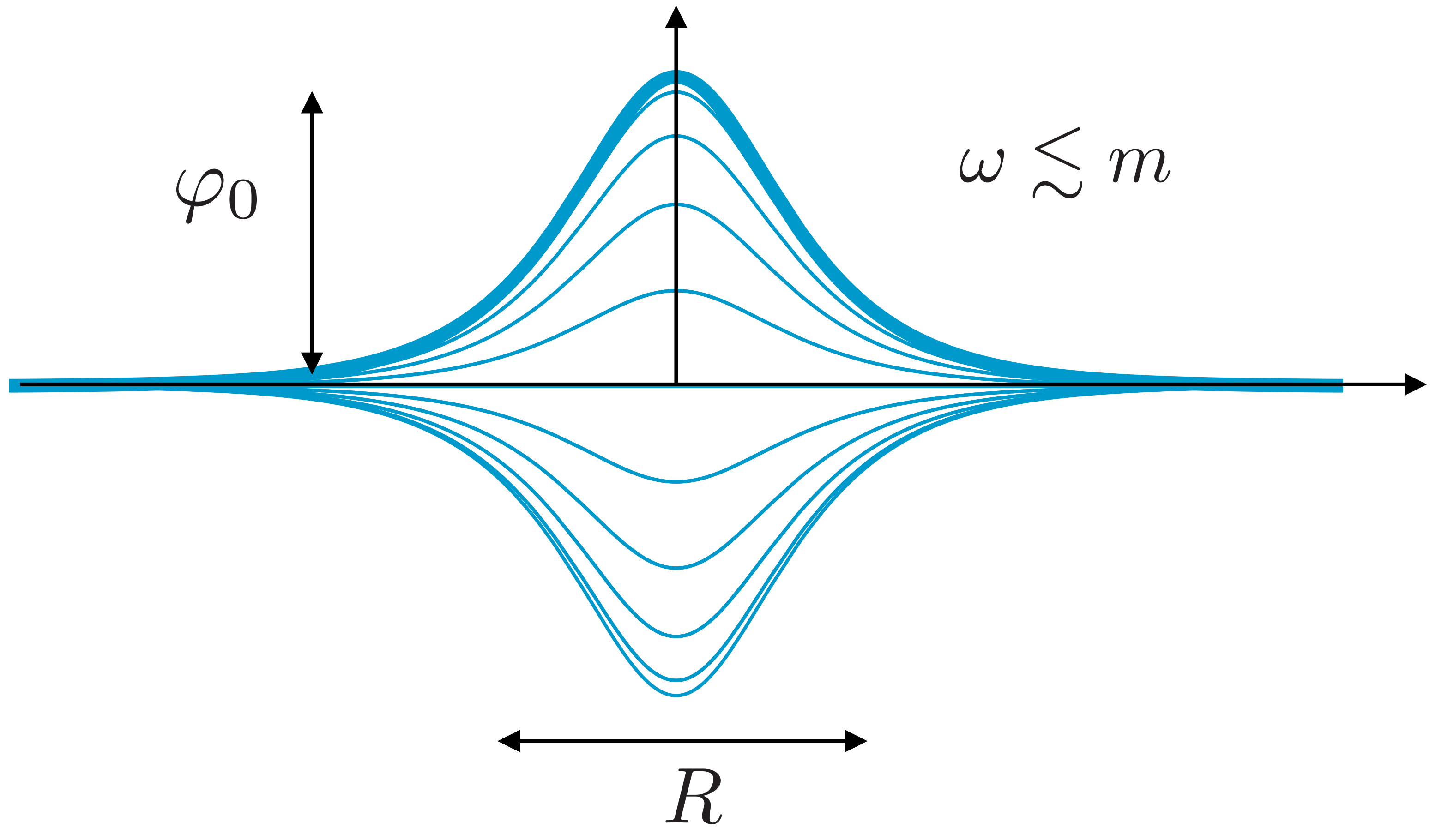
leading order in $g_{a\gamma}\varphi_0$ only



$$\left\langle \frac{dP^{\gamma}_{(2)}}{d\Omega} \right\rangle_t = \frac{g^2_{a\gamma}\omega^4 \tilde{\varphi}^2(\omega)}{32\pi^2} \bar{\boldsymbol{B}}^2 \sin^2\theta$$

spatial Fourier transform of soliton profile at radiating frequency wavenumber

$$\phi(t,r) \approx \varphi(r)\cos\omega t$$



EM radiation & soliton profile

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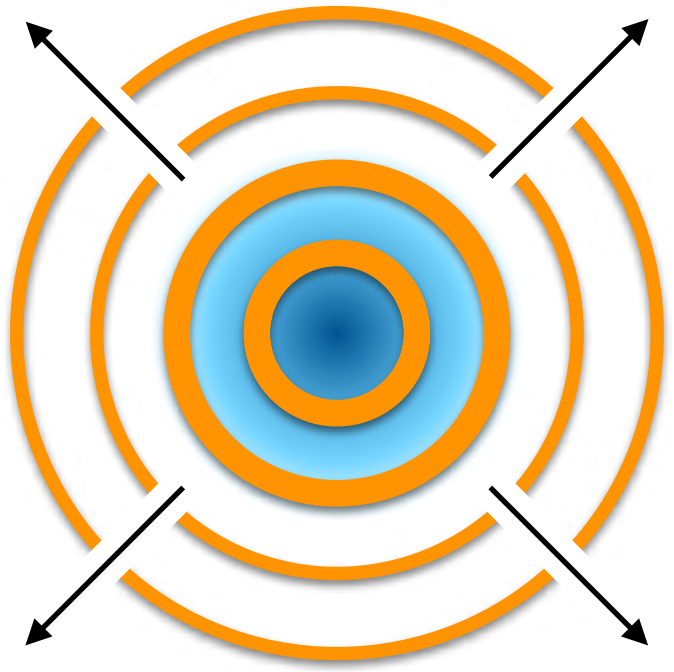

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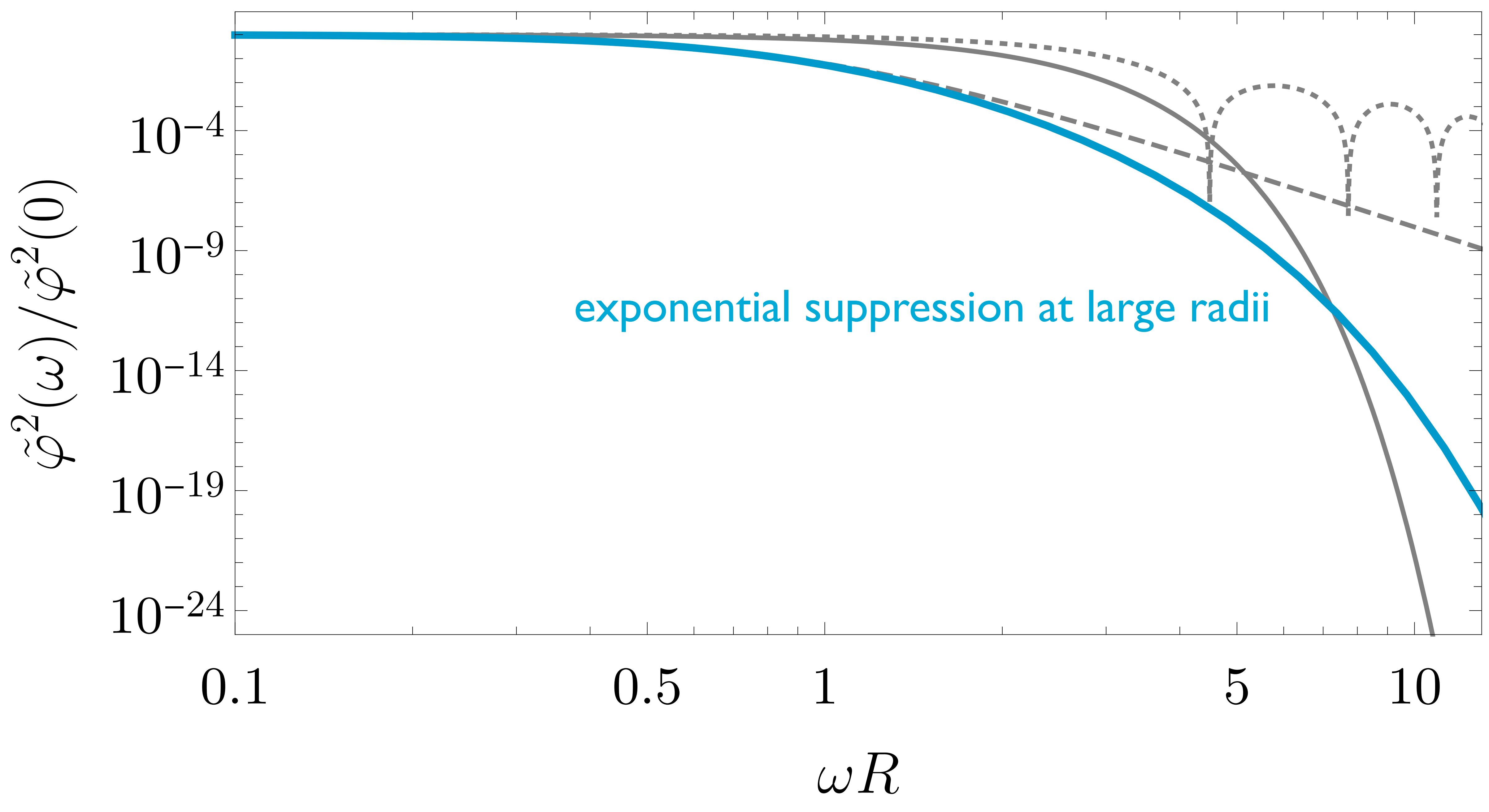
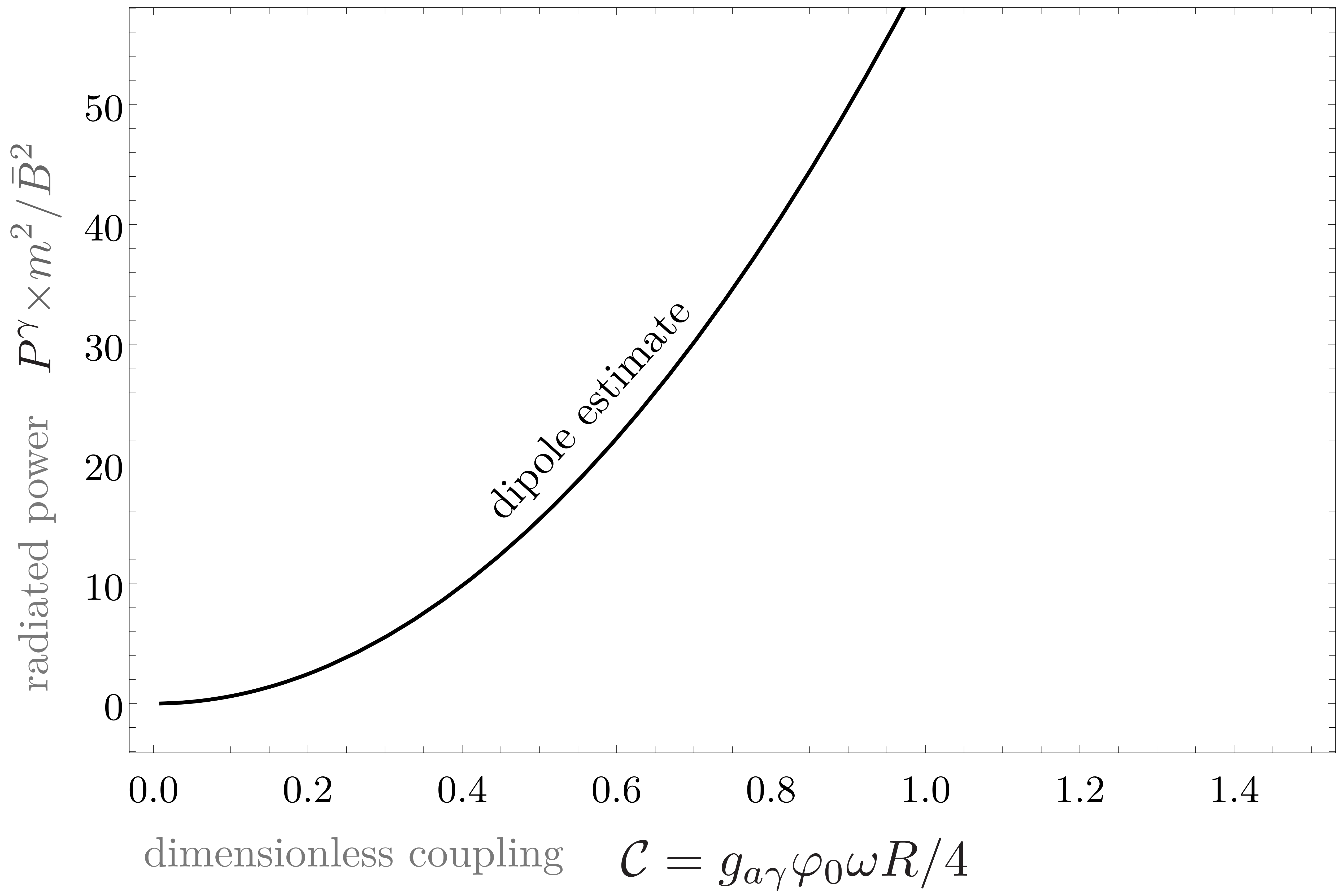


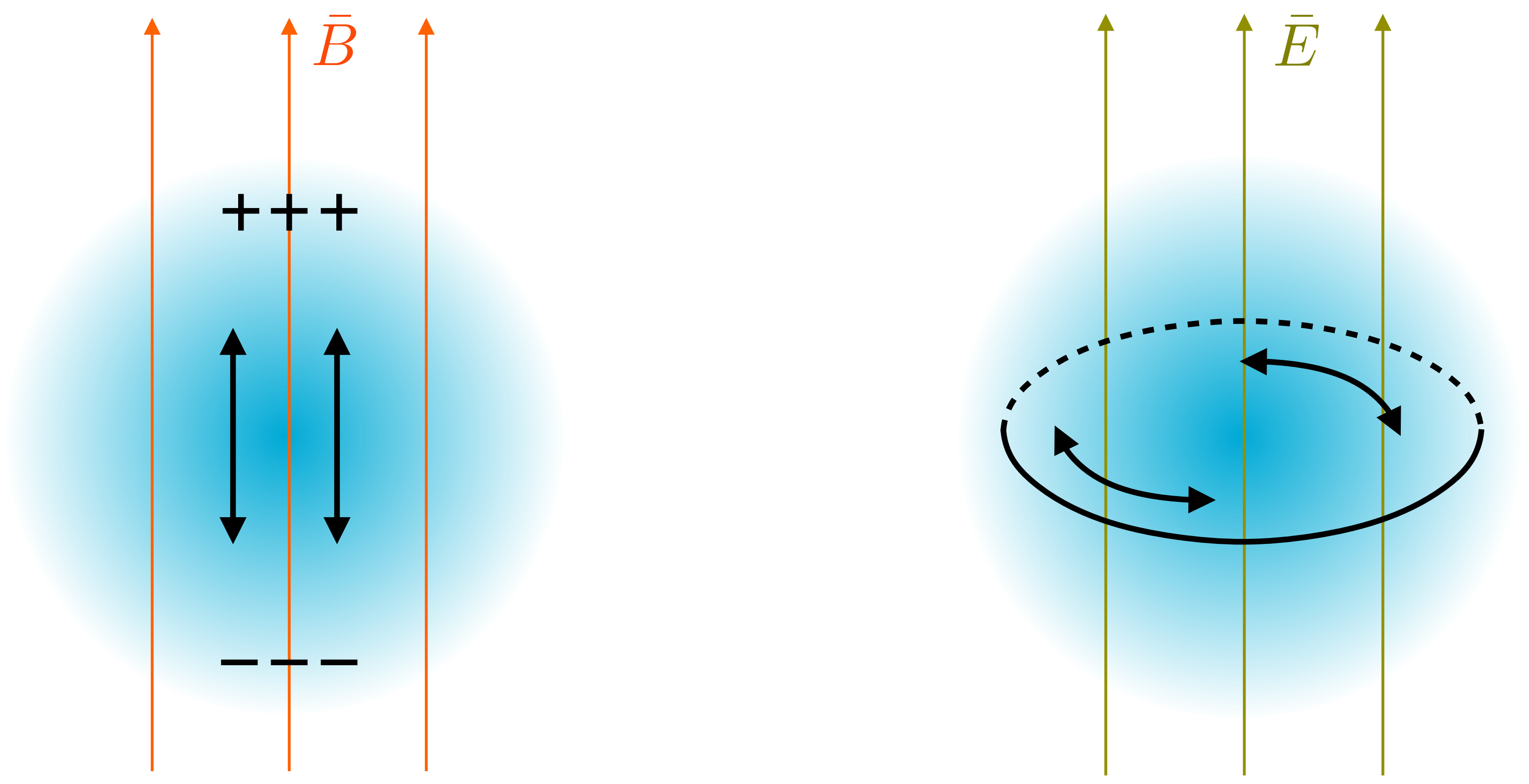
1. use correct physical profile
2. focus on dense, small radius solitons

EM radiation at moderate coupling

higher order in $g_{a\gamma}\varphi_0$

$\mathcal{C} \sim g_{a\gamma}\varphi_0\omega R \lesssim 1$



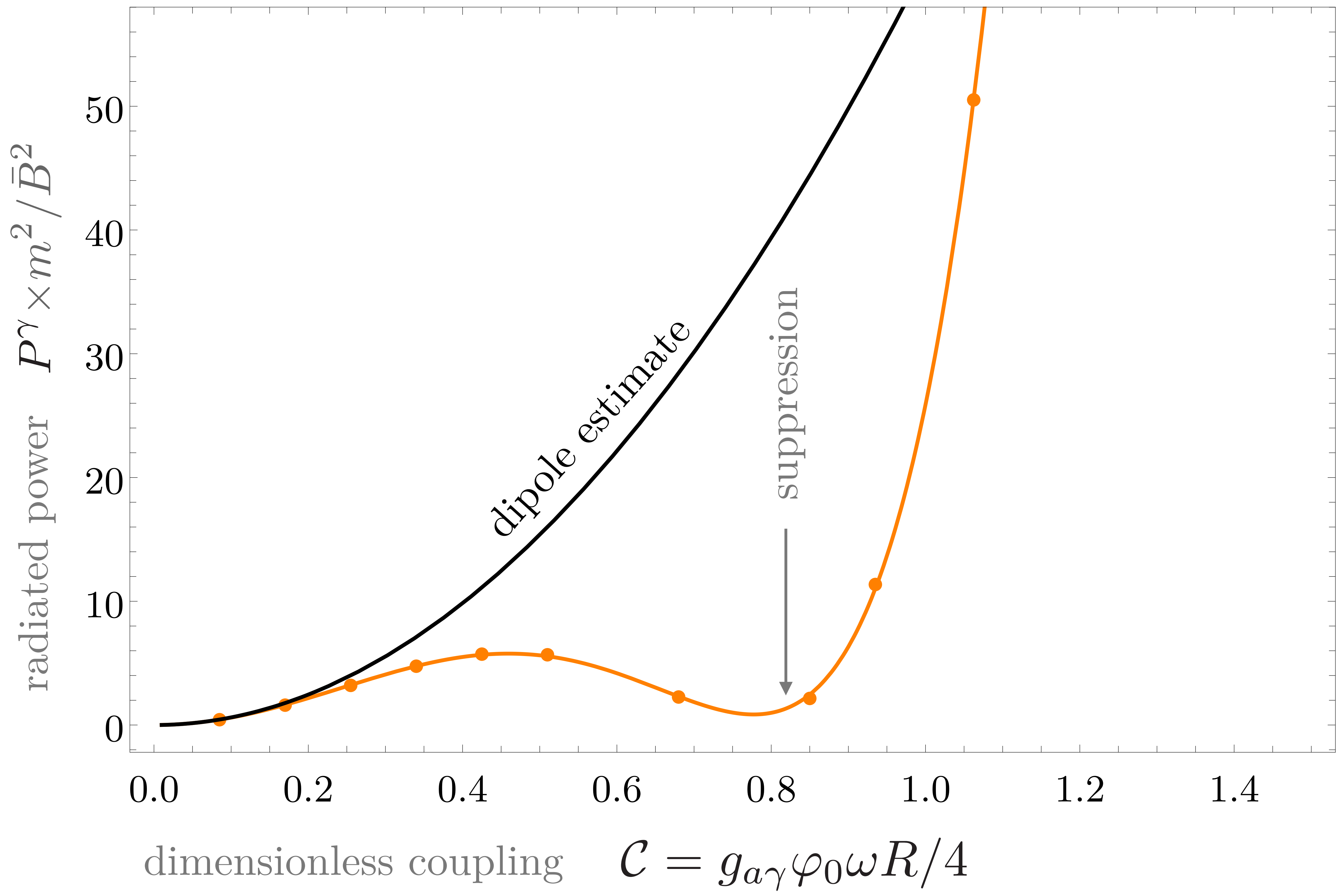


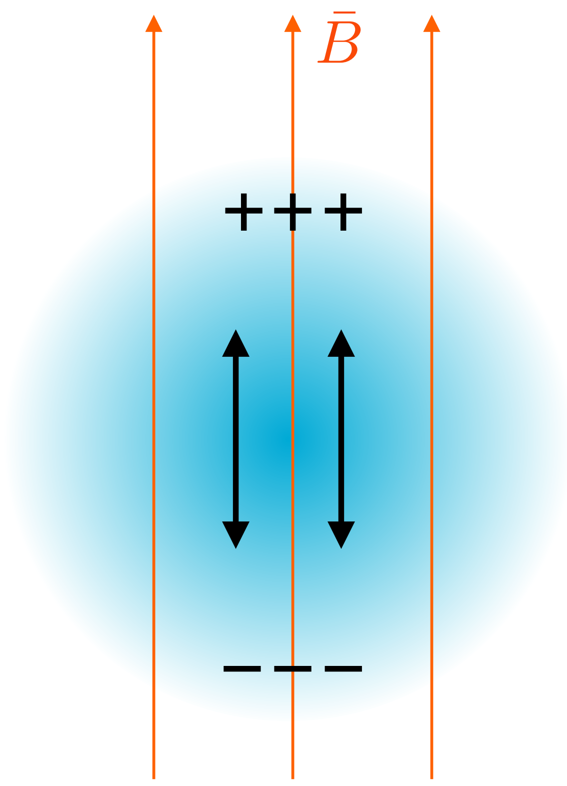
*keep soliton fixed, change axion-photon coupling

EM radiation at moderate coupling

higher order in $g_{a\gamma}\varphi_0$

$\mathcal{C} \sim g_{a\gamma}\varphi_0\omega R \lesssim 1$





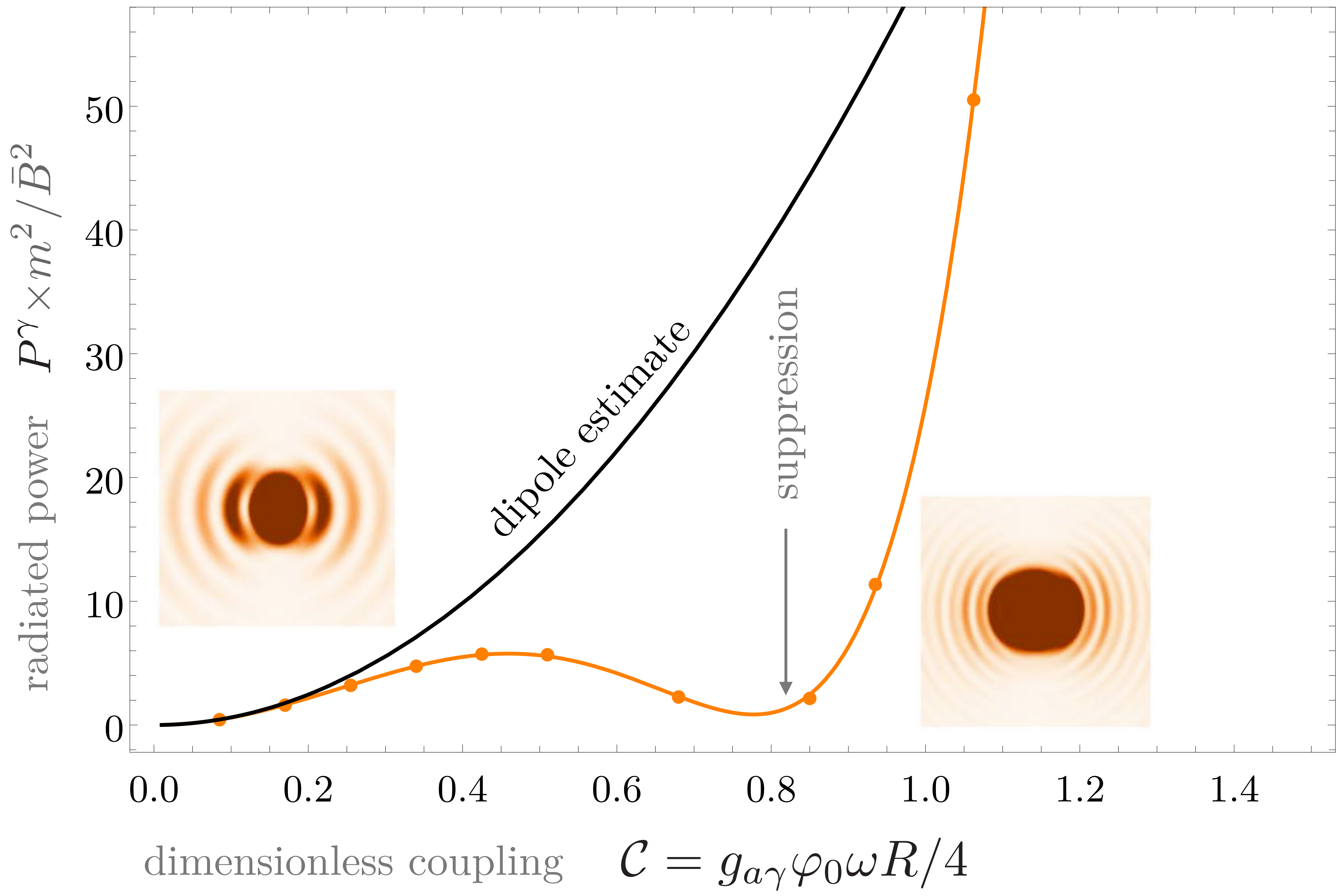
- dipole est. works well for small coupling (as expected)
  - suppression for B background at intermediate coupling !

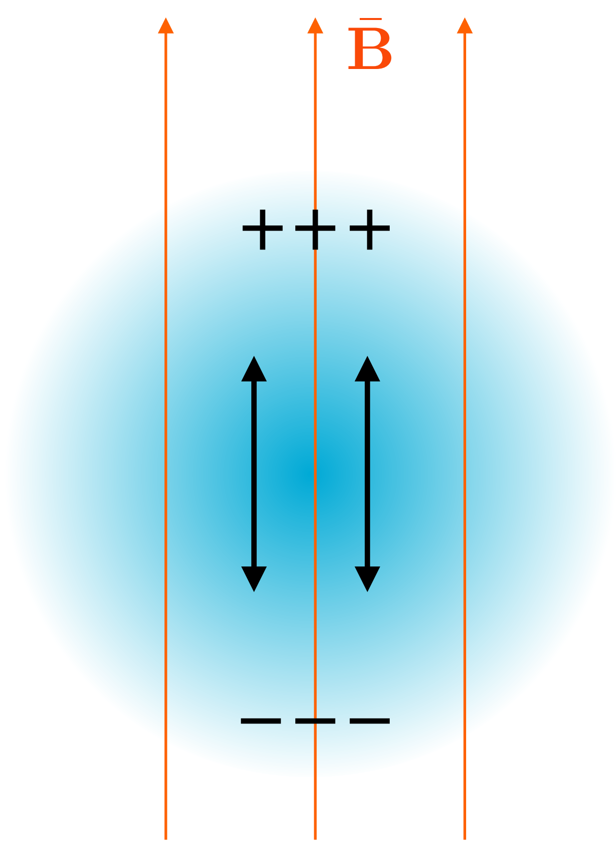
*keep soliton fixed, change axion-photon coupling

EM radiation at moderate coupling

higher order in $g_{a\gamma}\varphi_0$

$\mathcal{C} \sim g_{a\gamma}\varphi_0 \omega R \lesssim 1$





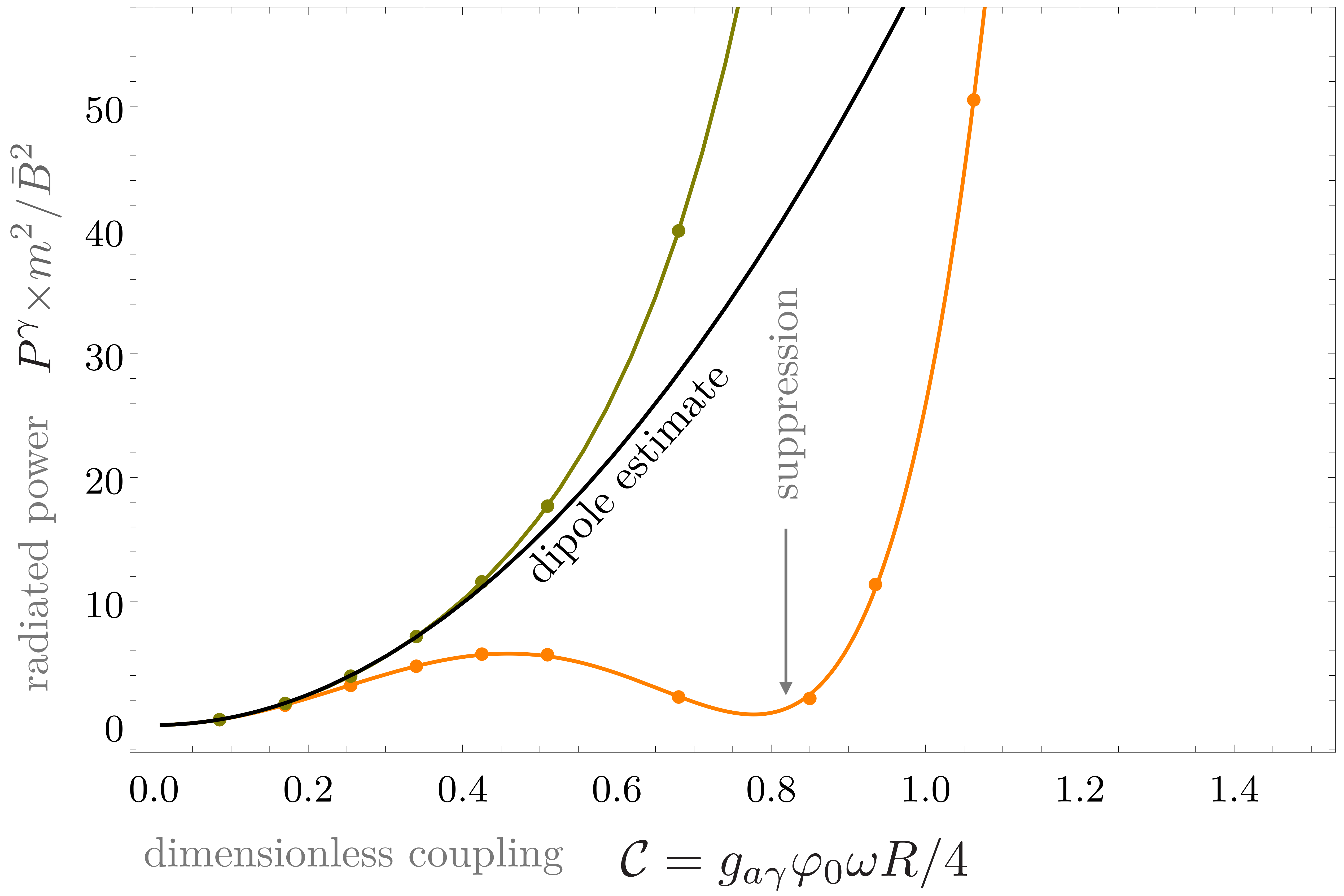
- dipole est. works well for small coupling (as expected)
  - suppression for B background at intermediate coupling !
  - change in dominant frequency of radiation

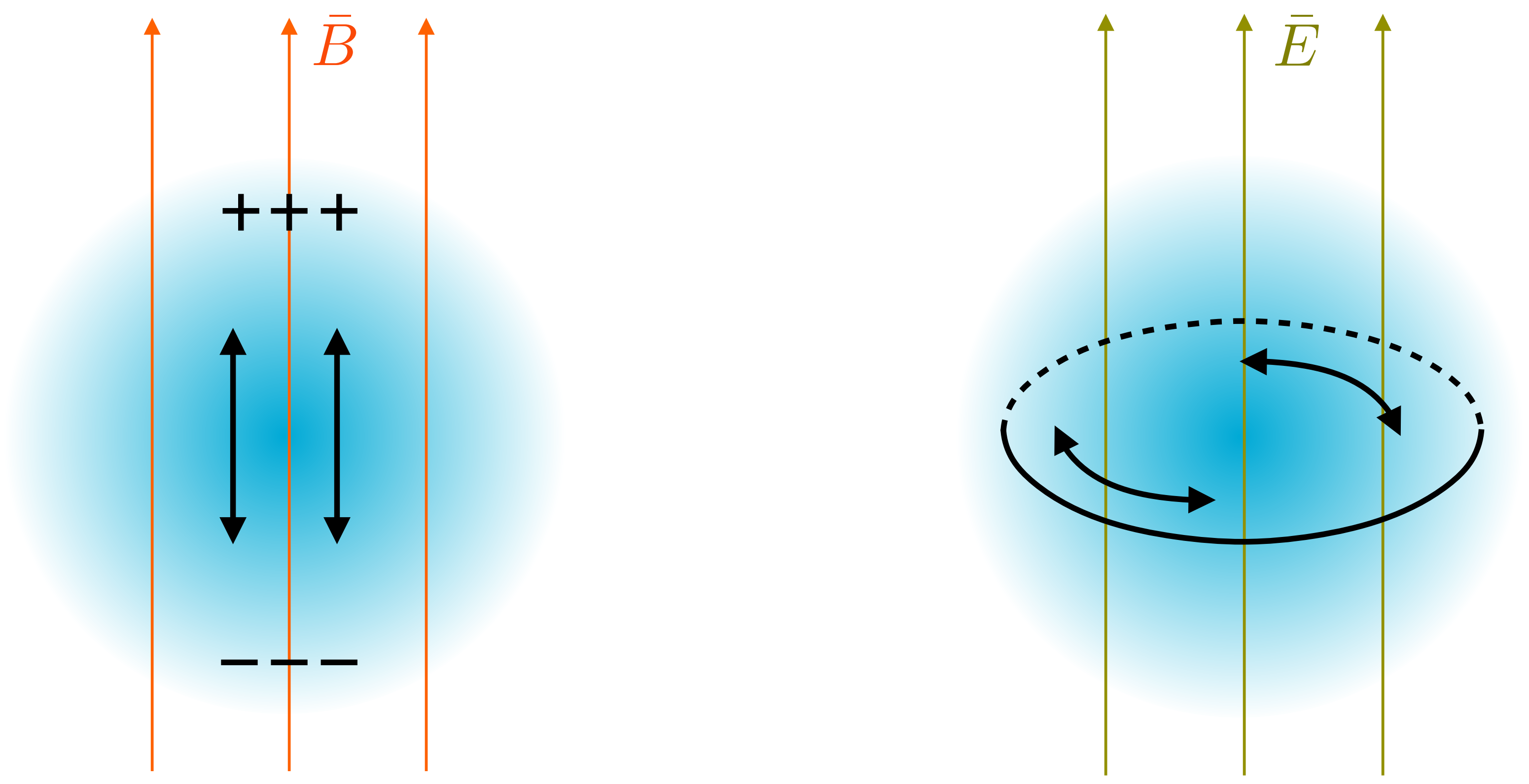
*keep soliton fixed, change axion-photon coupling

steady EM radiation at moderate coupling

higher order in $g_{a\gamma}\varphi_0$

$$\mathcal{C} \sim g_{a\gamma}\varphi_0\omega R \lesssim 1$$



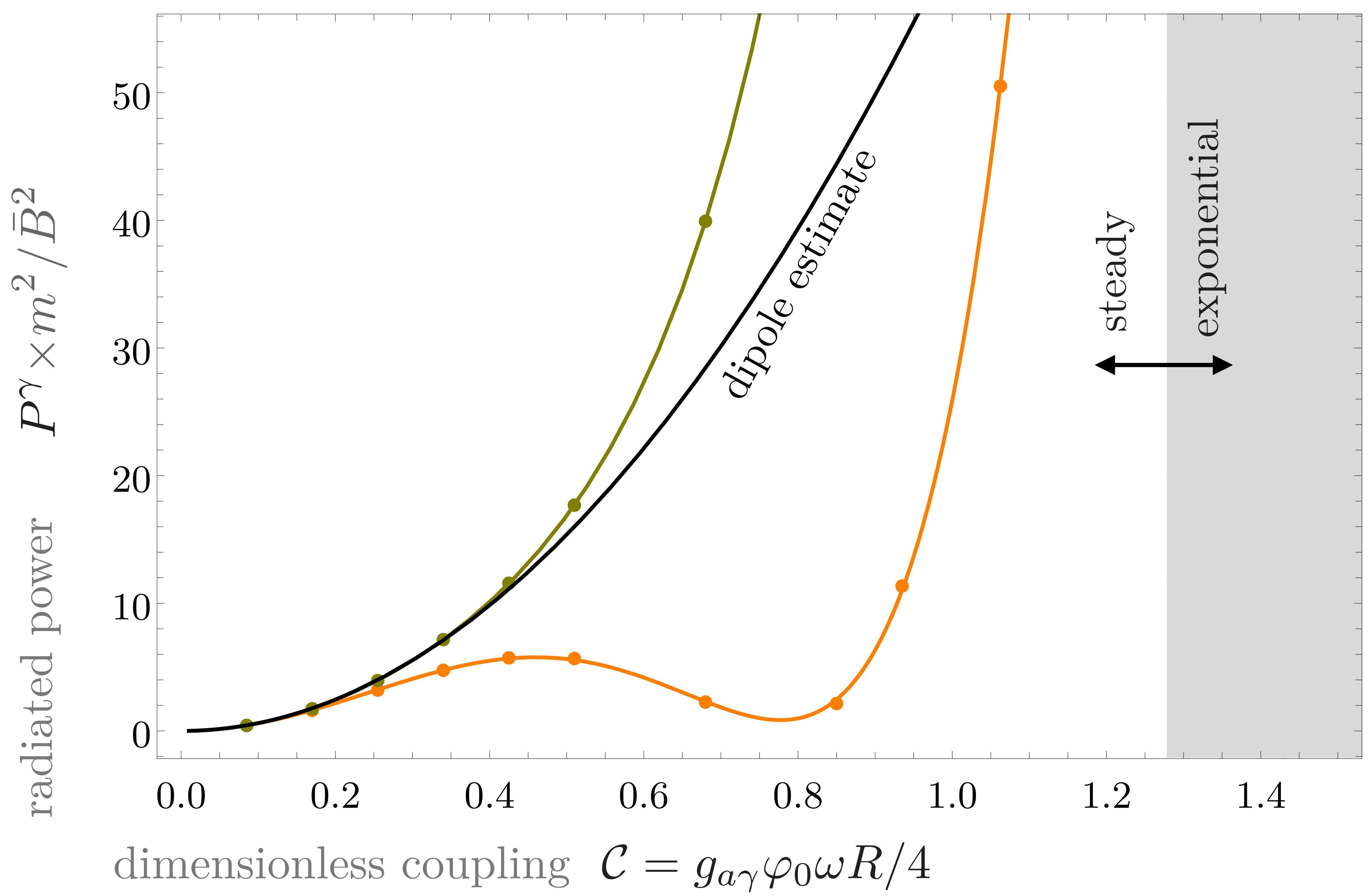


- dipole est. works well for small coupling (as expected)
  - suppression for B background at intermediate coupling !
  - difference between E and B begins to show

*keep soliton fixed, change axion-photon coupling

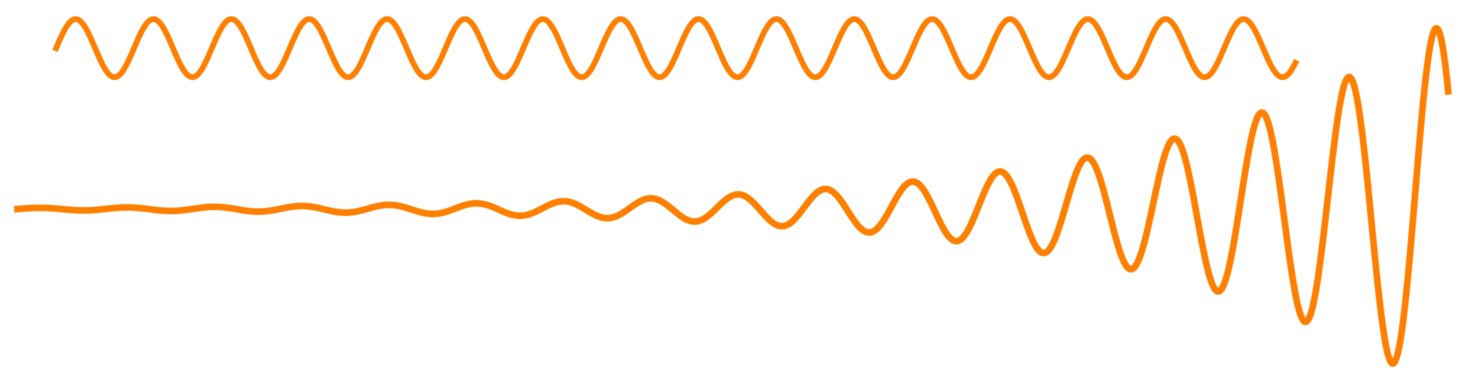
explosive radiation

non perturbative $g_{a\gamma}\varphi_0$



$\mathcal{C} \ll 1 \longrightarrow$

$\mathcal{C} \gtrsim 1 \longrightarrow$

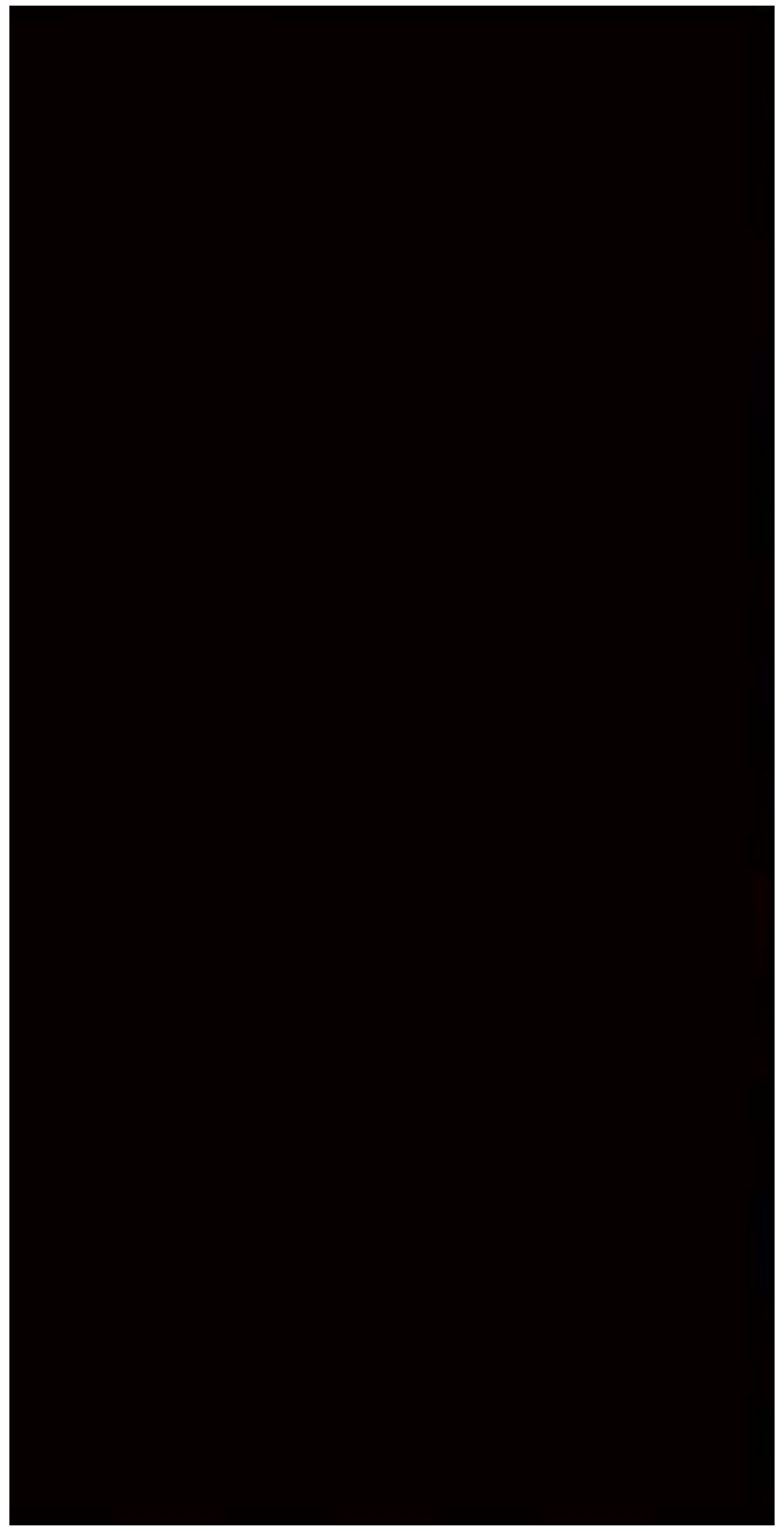


- parametric resonance does not even require background EM fields, quantum fluctuations are enough
- can be efficient for works for dilute and dense cases [see Hertzberg & Schiappacasse (2018), MA & Mou (2020)]

*keep soliton fixed, change axion-photon coupling

explosive production from soliton mergers

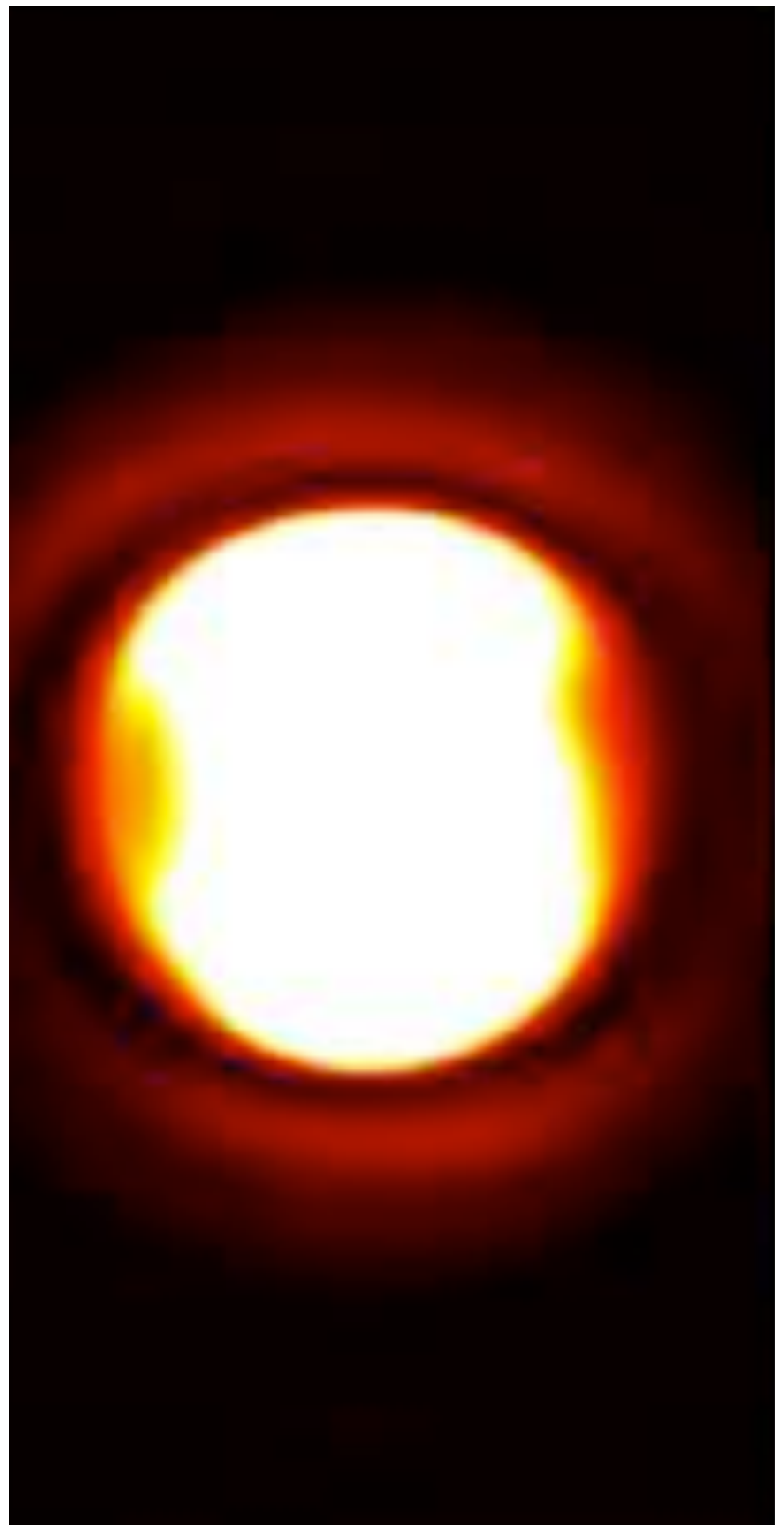
- no emission before merger $\mathcal{C} \lesssim 1$
- explosive after merger $\mathcal{C} \gtrsim 1$
- a threshold & resonant effect



explosive photon production from soliton mergers

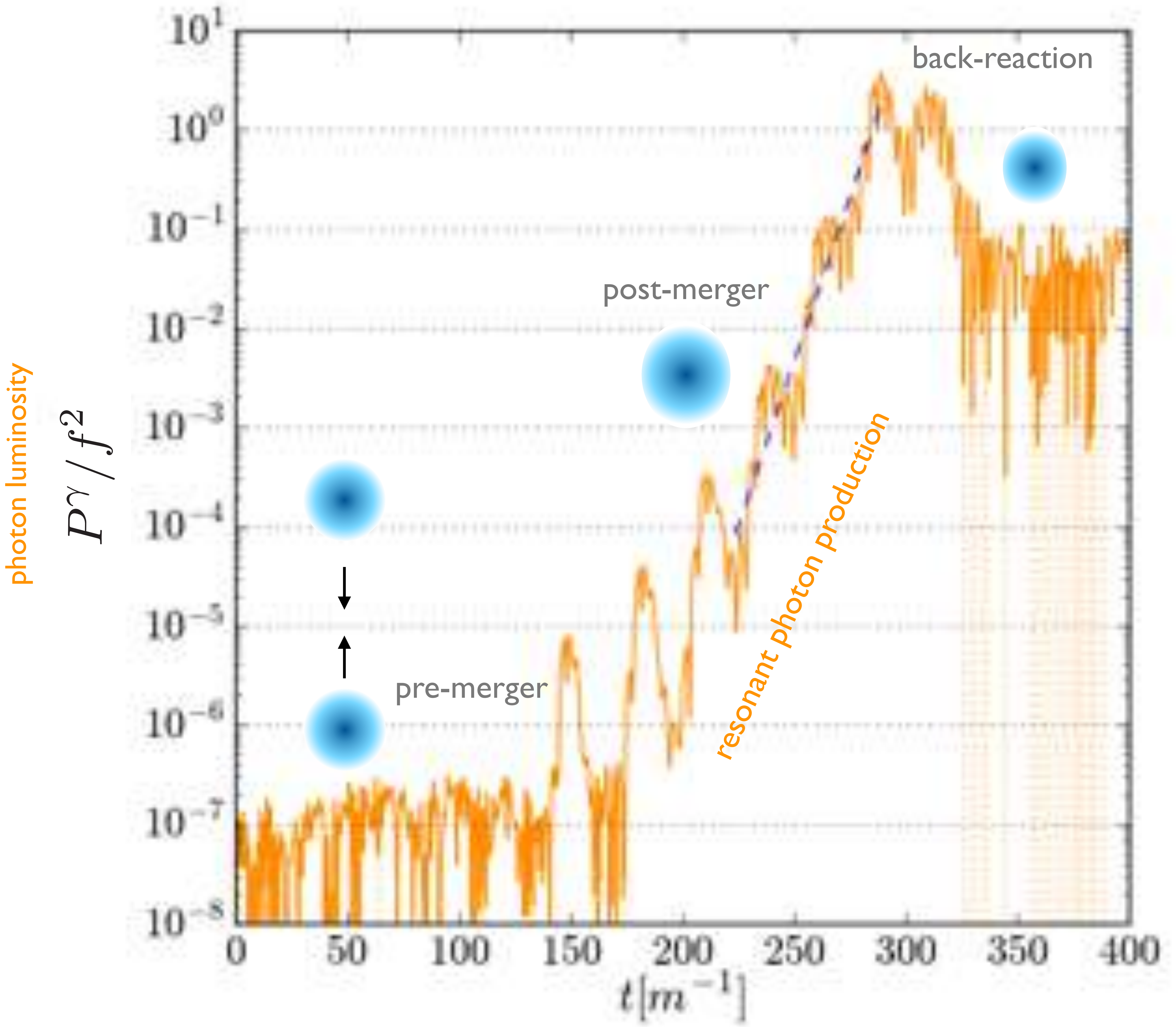
~30% of total energy goes into axion waves

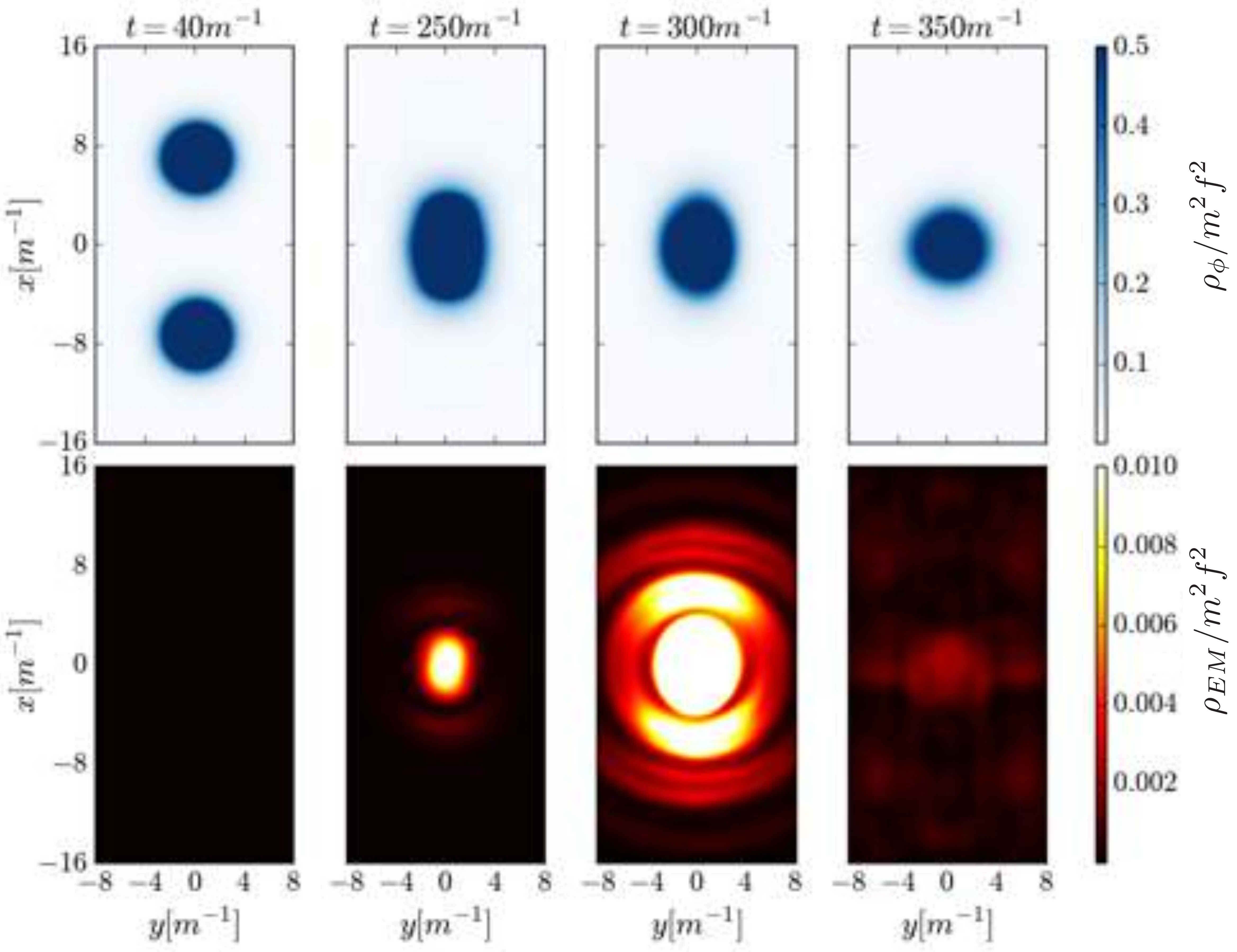
~20% of remaining goes into EM radiation



$$E_\gamma \sim 0.1 \times M_{\rm osc} c^2 \;\sim 10^{35} \left(\frac{f}{10^{10}\,\mathrm{GeV}}\right)^2 \left(\frac{10^{-5}\mathrm{eV}}{m}\right) \mathrm{GeV}$$

explosive, self-regulating photon production from mergers

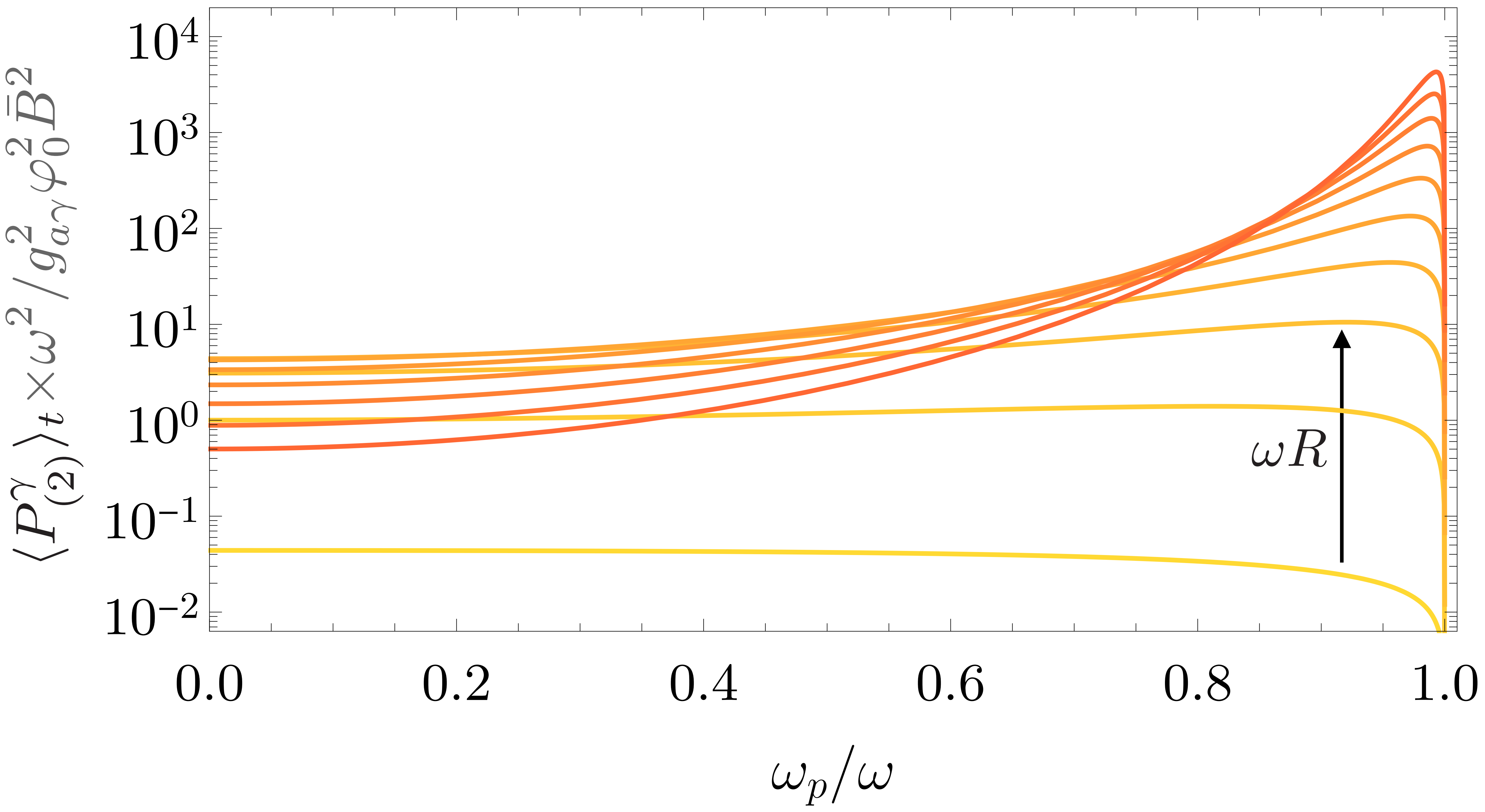




*after backreaction shuts of resonance, the luminosity falls to small values — at late times the apparent moderate value it due to a periodic box

solitons falling on to compact stars — plasma effects ?

solitons falling on to compact stars — resonant conversion!



$$\langle P^\gamma_{(2)} \rangle_t = \frac{g^2_{a\gamma}\omega^4}{12\pi} \frac{\kappa}{\omega} \tilde{\varphi}^2(\kappa) \left(\bar{\boldsymbol{B}}^2 + \bar{\boldsymbol{E}}^2\right)$$

where $\quad \kappa \equiv \sqrt{\omega^2 - \omega_p^2}$

$\omega_p \approx \sqrt{4\pi\alpha n_e/m_e}$ plasma frequency

*This resonance is NOT parametric resonance discussed earlier

Observational estimates

$$S \simeq (2\times 10^7\ \mu\mathrm{Jy})\left(\frac{d_\star}{100\ \mathrm{pc}}\right)^{-2}\left(\frac{m}{10^{-5}\ \mathrm{eV}}\right)^{-3}\left(\frac{g_{a\gamma}}{0.66\times 10^{-10}\ \mathrm{GeV}^{-1}}\right)^{2}$$
$$\times\left(\frac{f}{10^{10}\ \mathrm{GeV}}\right)^{-2}\left(\frac{\bar{\boldsymbol{B}}}{10^{10}\ \mathrm{G}}\right)^{2}\mathcal{F}(\omega R, \omega_p/\omega)\ ,$$

$$\mathcal{F}(\omega R,\omega_p/\omega) \approx \begin{cases} (\pi\omega R)^4 e^{-\pi\omega R}, & \text{for } \omega_p \approx 0 \\ \frac{1}{16}(\pi\omega R)^6\sqrt{1-\omega_p^2/\omega^2}, & \text{for } \omega_p \approx \omega \end{cases}$$

* does *not* include large coupling regime.

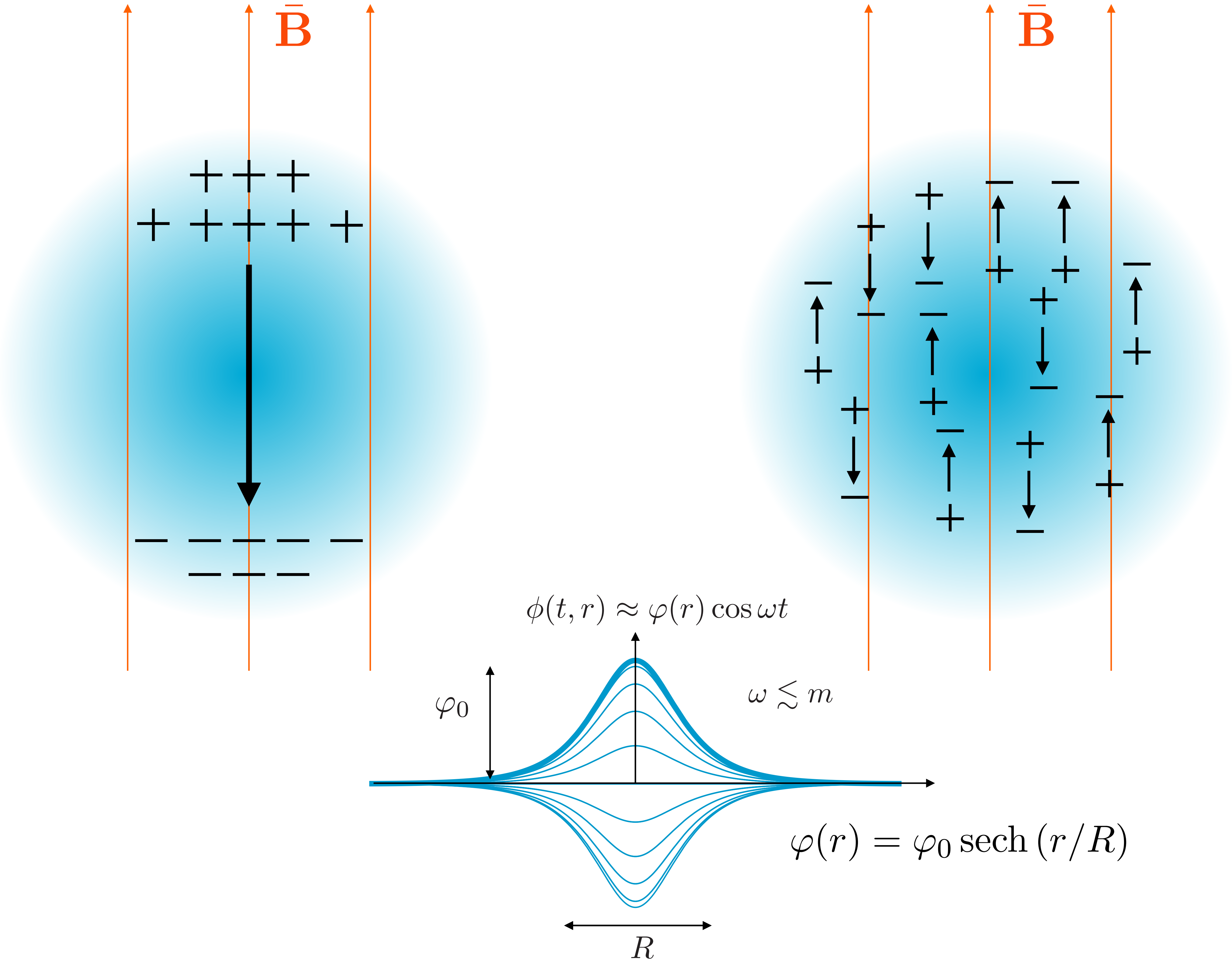
*Conservative axion star - compact star interaction rate, there is freedom to change these numbers by orders of magnitude

$$\Gamma \simeq (4\times 10^{-5}\ \mathrm{hr}^{-1})\left(\frac{M_\star}{1\ M_\odot}\right)\left(\frac{R_\star}{0.01\ R_\odot}\right)\left(\frac{\rho_{\mathrm{as}}}{0.3\ \mathrm{GeV/cm^3}}\right)\left(\frac{M_{\mathrm{sol}}}{10^9\ \mathrm{kg}}\right)^{-1}\left(\frac{v_{\mathrm{rel}}}{10^{-3}}\right)^{-1}$$

what is the relevance of the soliton? — interference effects

soliton — 1 dipole

N incoherent dipoles

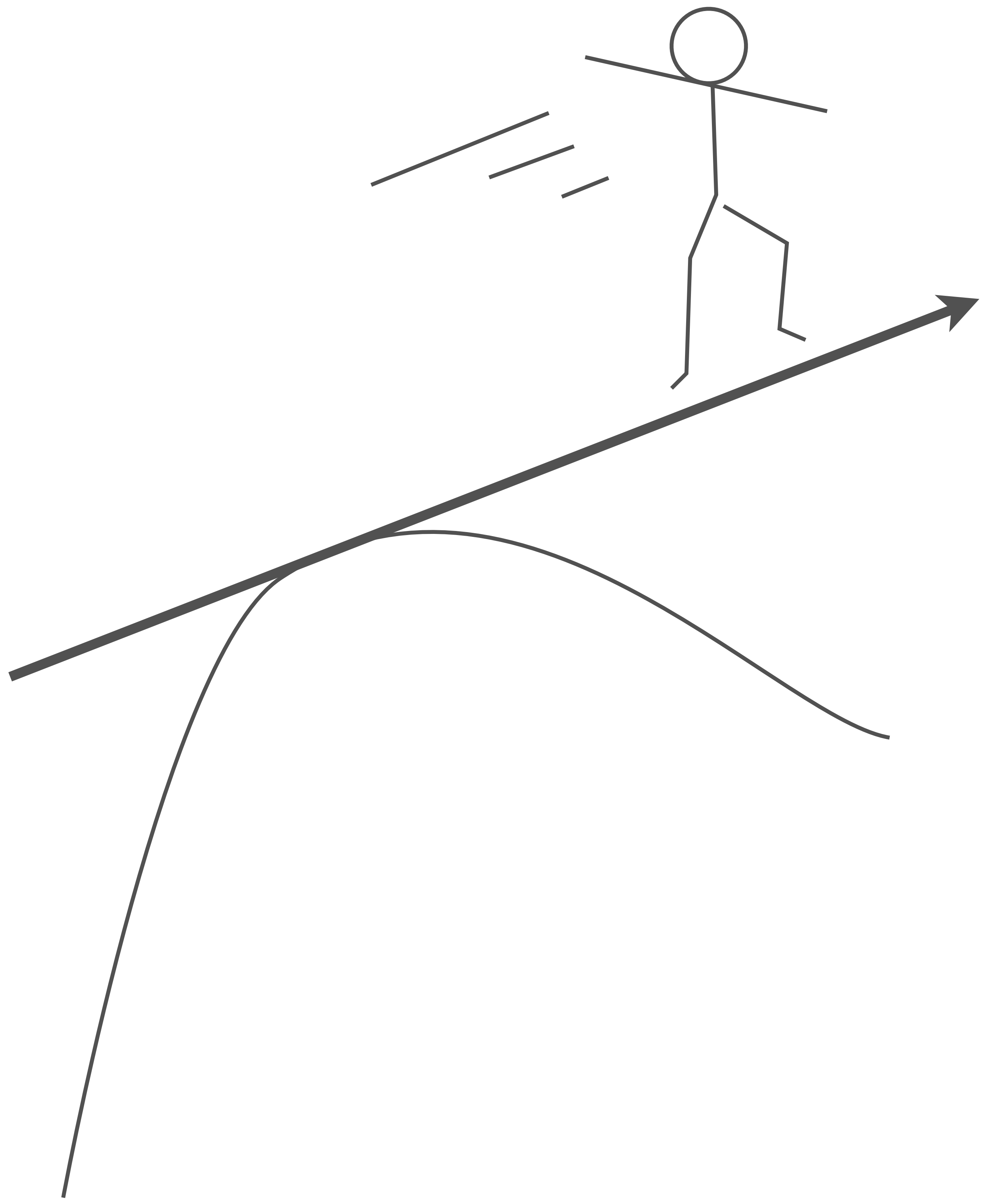


ratio of radiated power

$$\frac{N \text{ incoherent dipoles}}{\text{coherent soliton}} \sim \frac{e^{\pi\omega R}}{N}$$

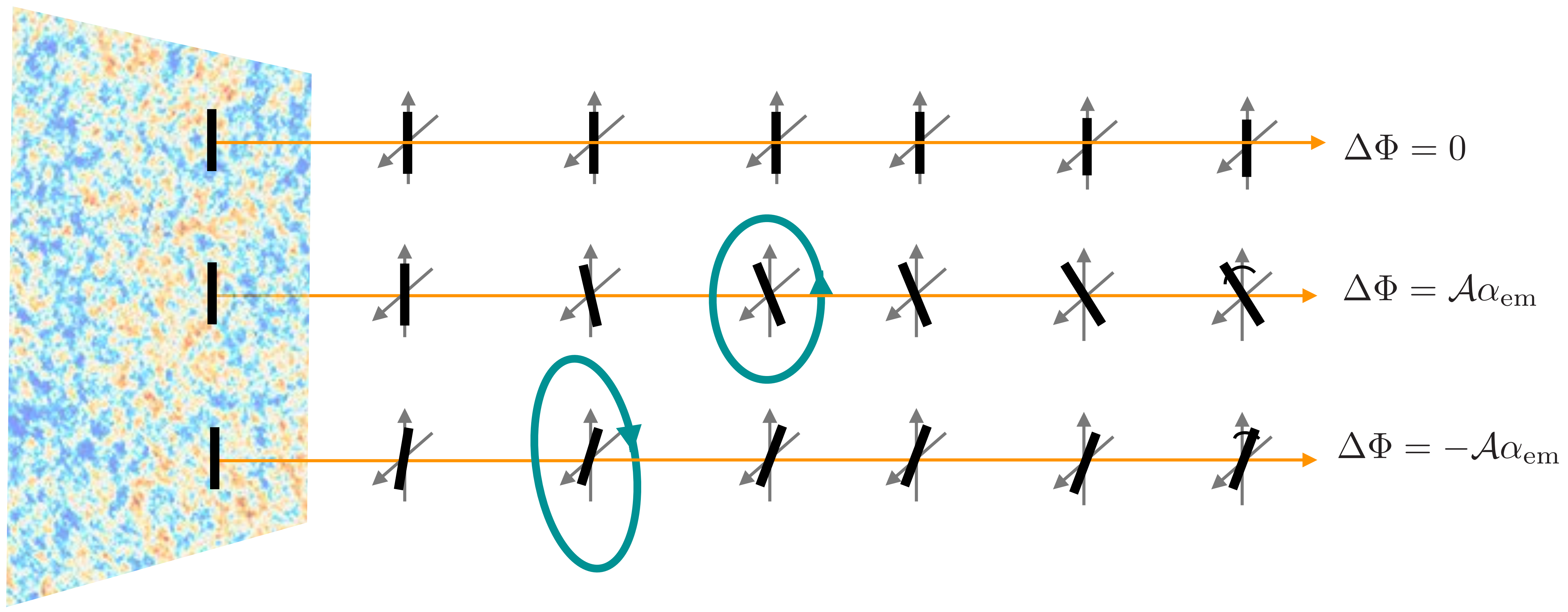
lose power by sub-dividing *too* much

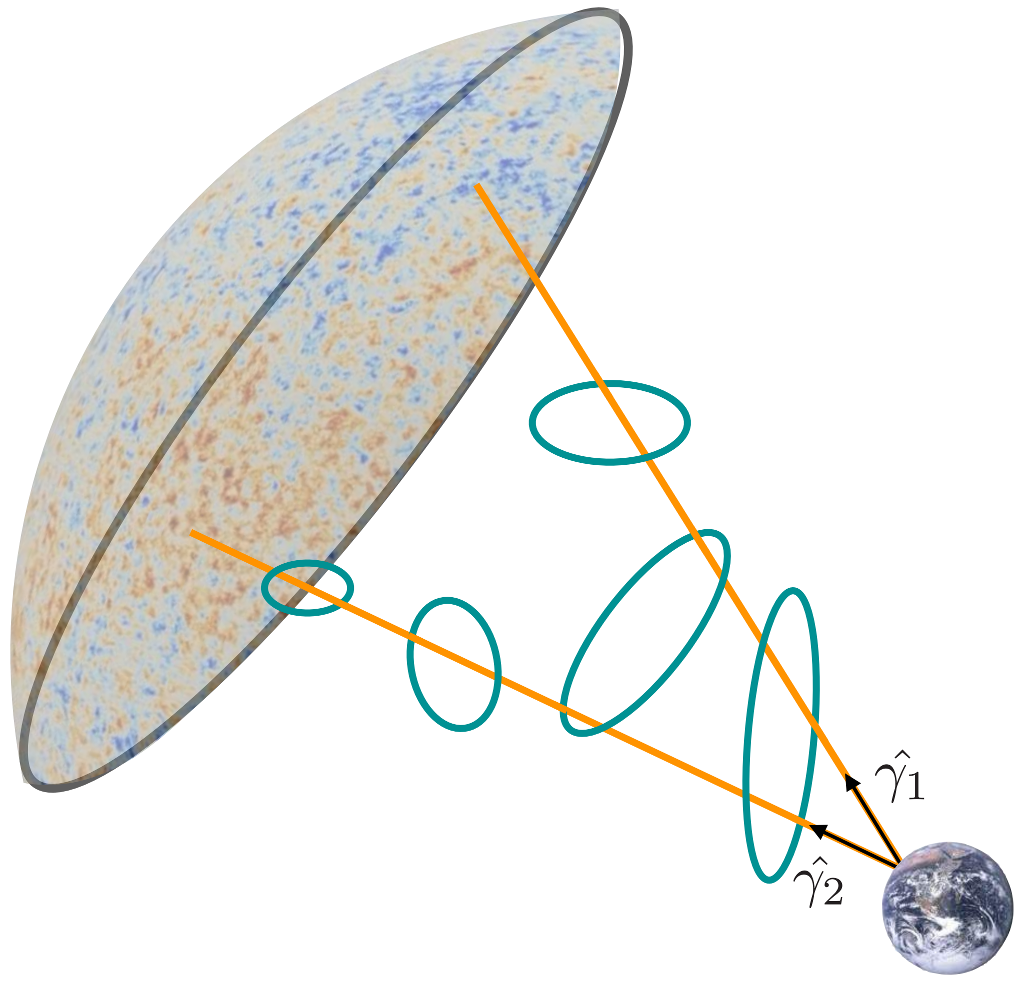
tangential digression (advertisement)

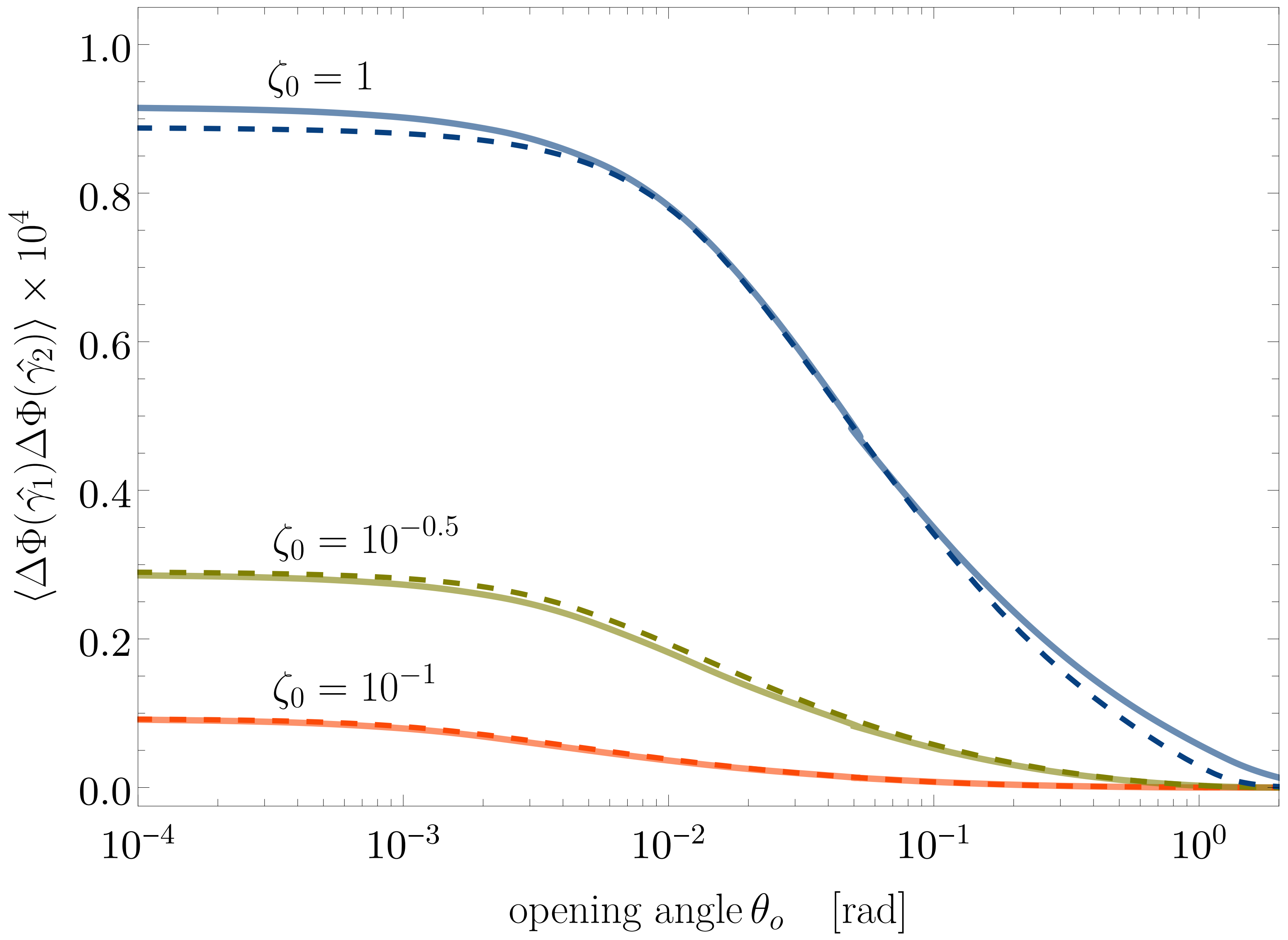


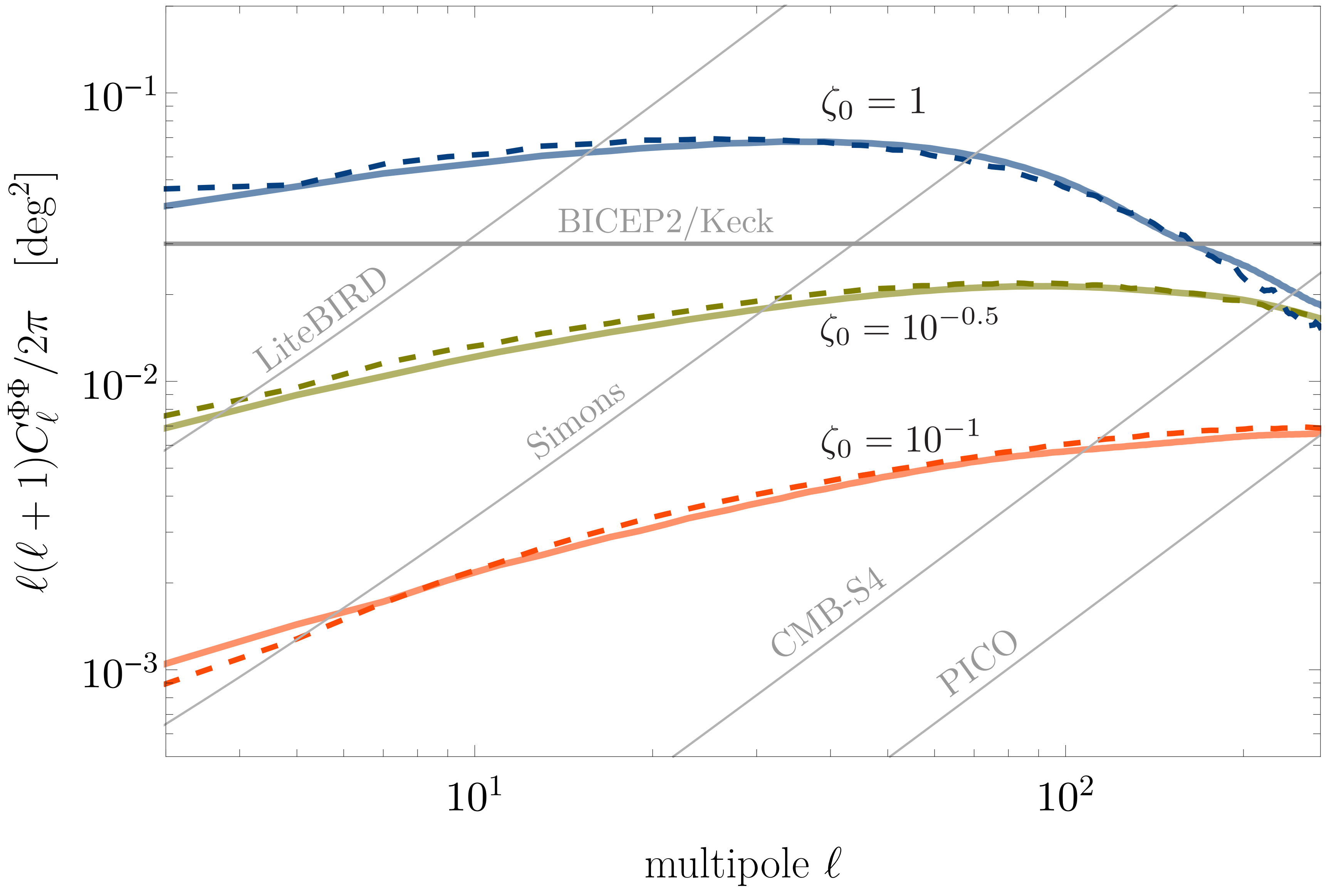
[arXiv:2103.10962] with Andrew Long and **Mudit Jain**

CMB birefringence from ultralight-axion string networks

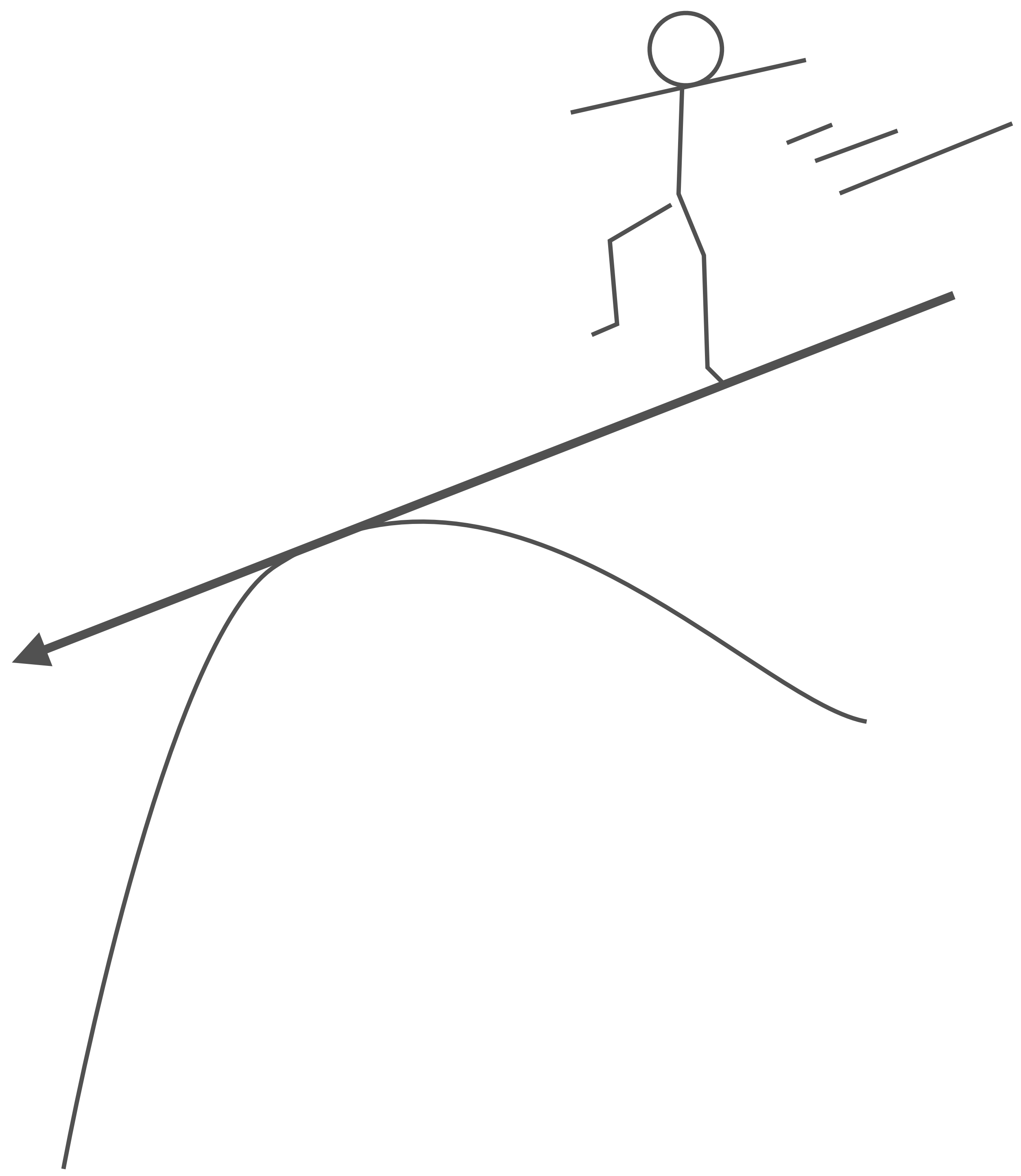




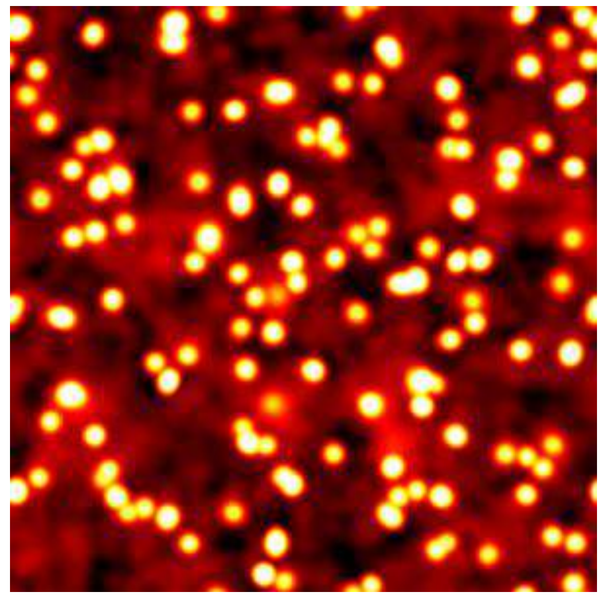


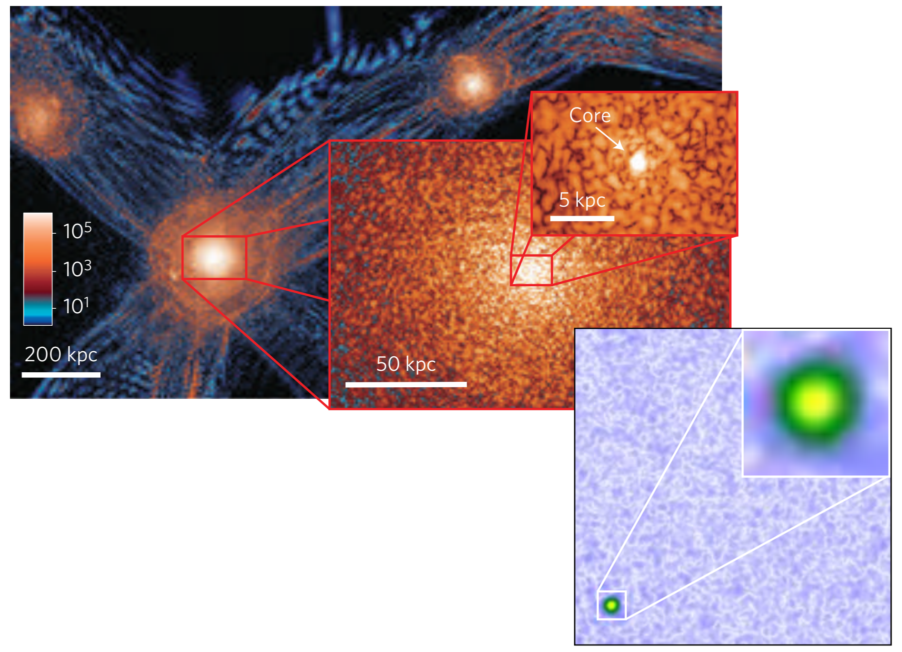


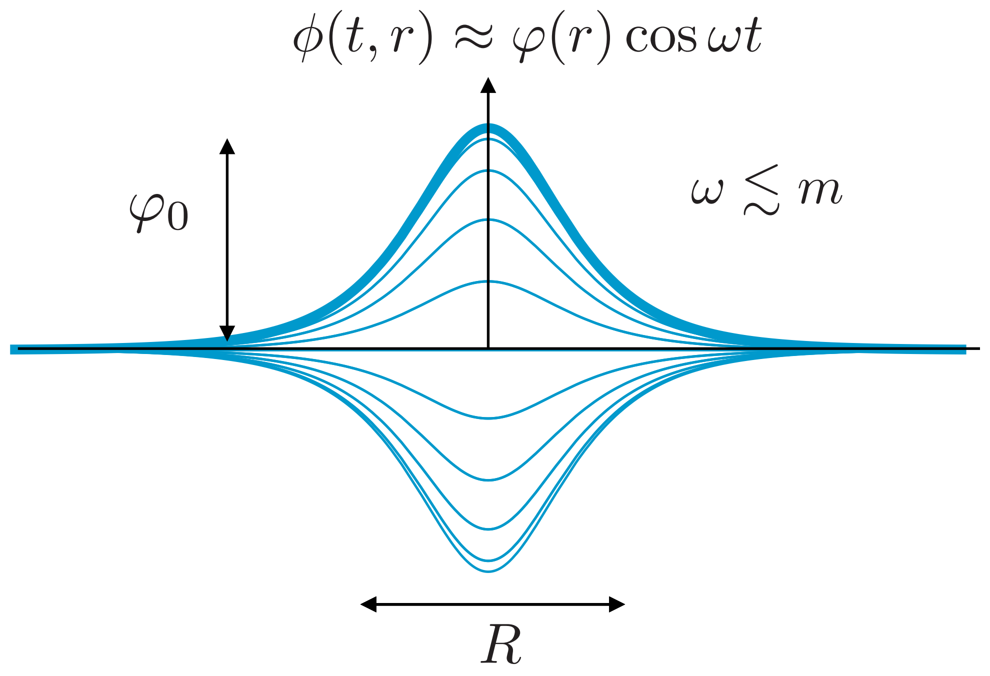
end tangential digression

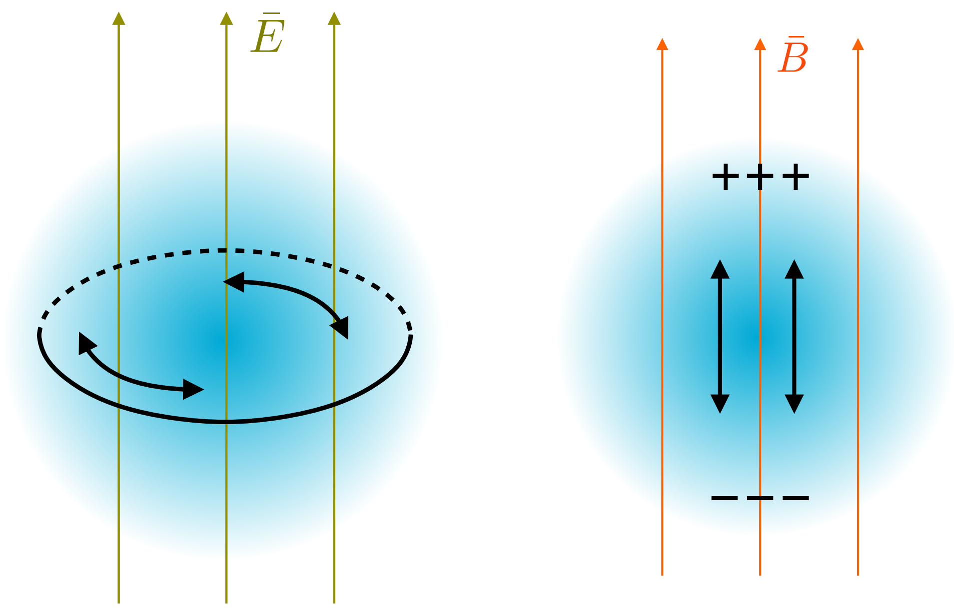


light from dark solitons : summary

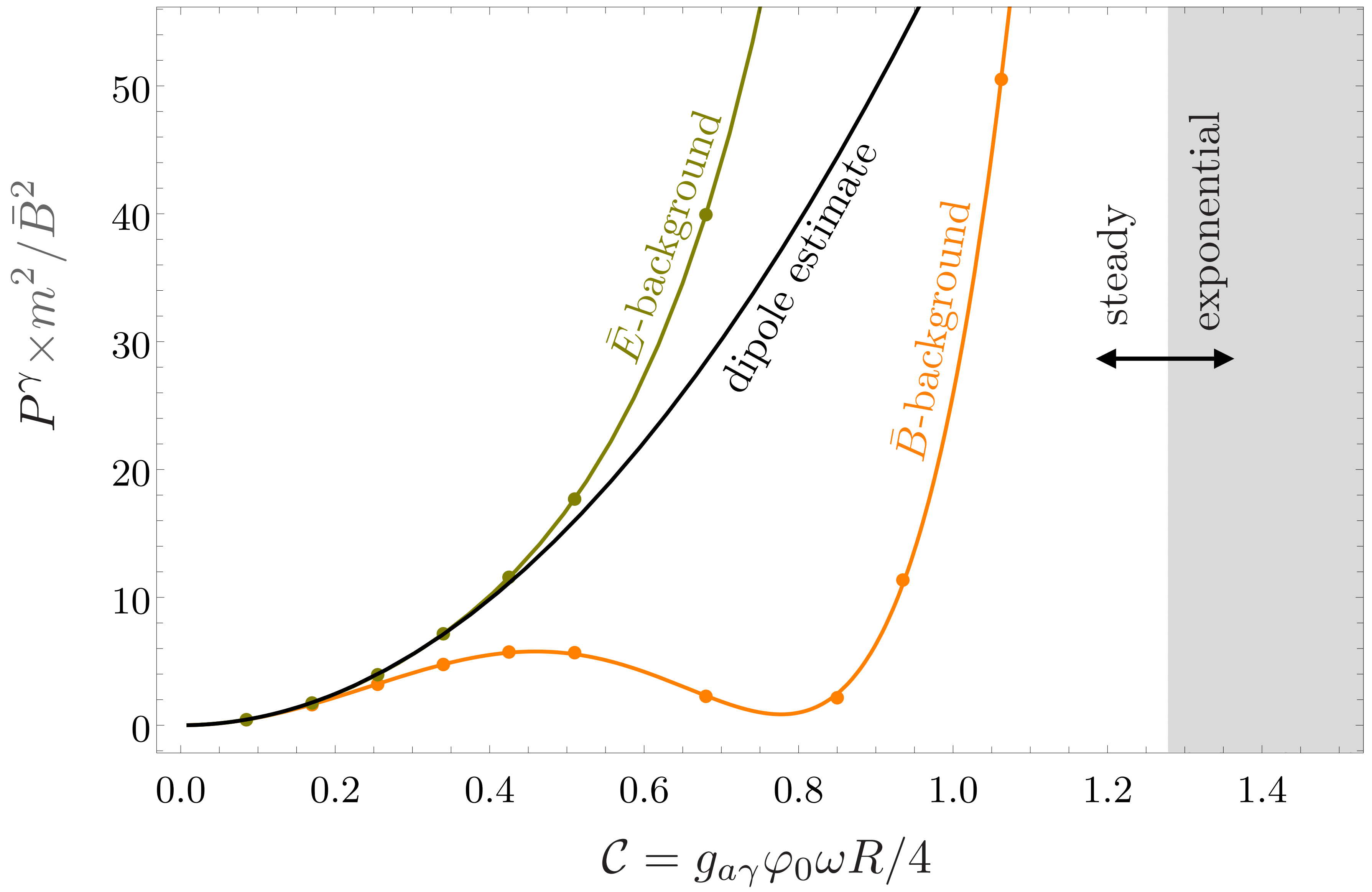


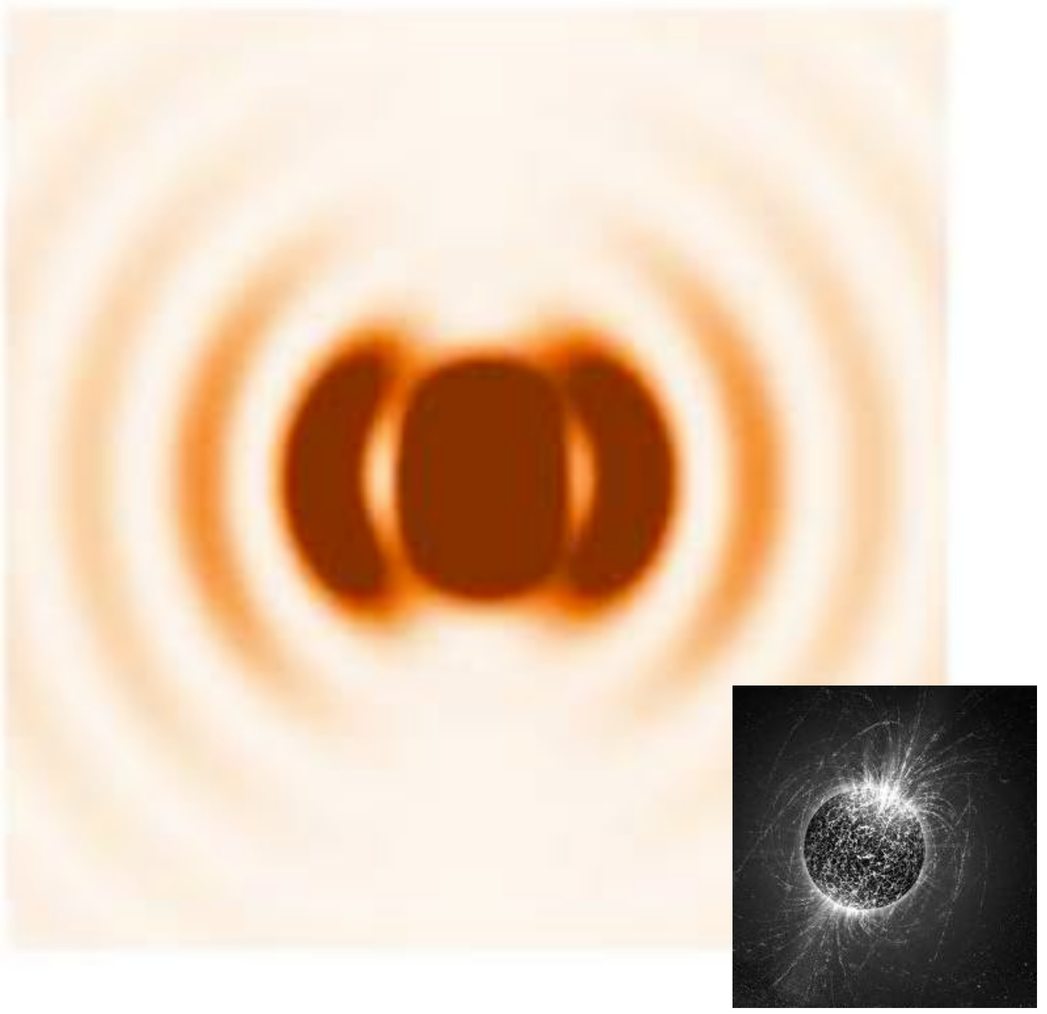


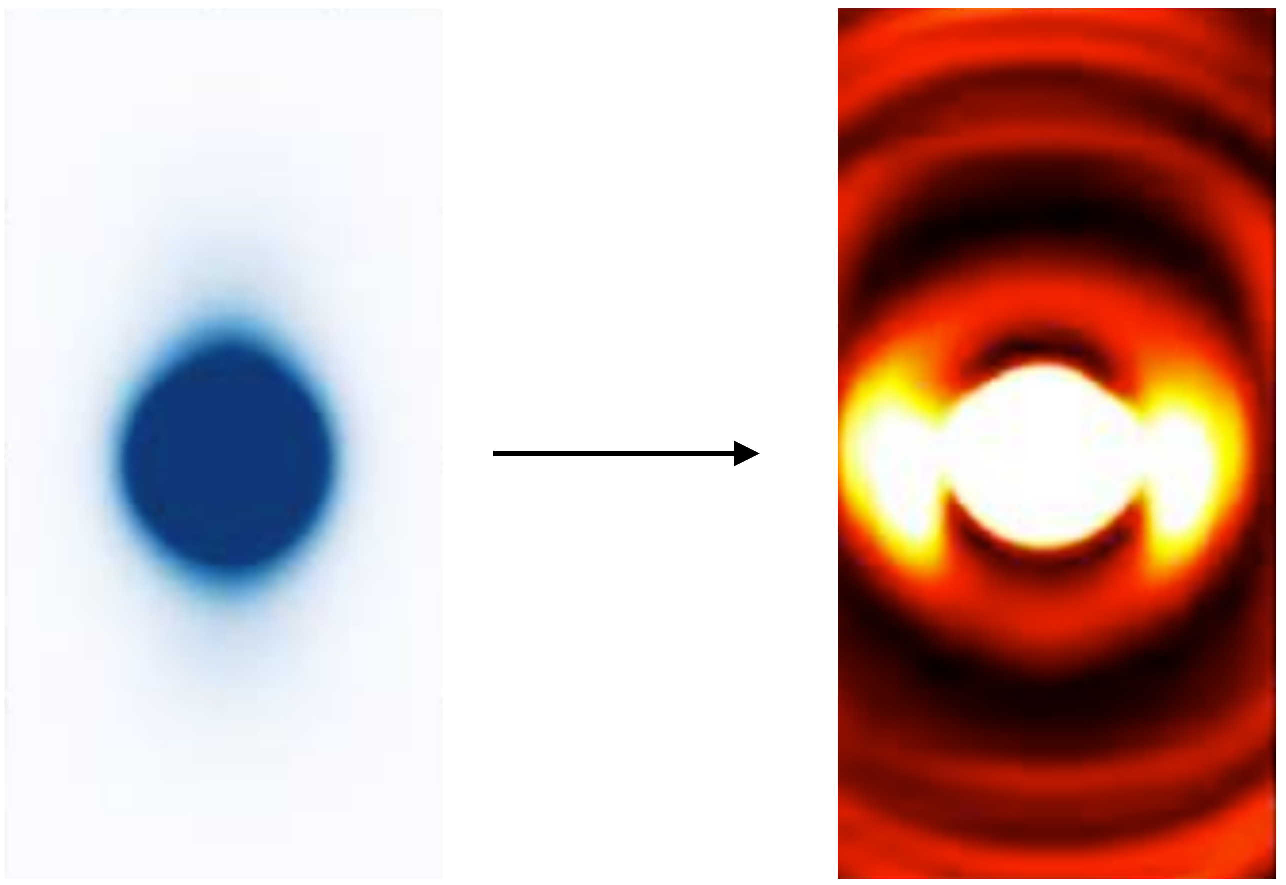




$g_{a\gamma}\phi\mathbf{E}\cdot\mathbf{B}$ perturbative & non-perturbative effects included







[arXiv: 2103.12082]

[arXiv: 2009.11337]