Dark photon superradiance: Electrodynamics and multimessenger signals

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Based on 2212.09772, with:

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Motivations

- New vector boson that may or may not be the dark matter,
- Ultra-low energies ($\sim 10^{-12}\ \mathrm{eV}$), macroscopical scales (km),
- Weakly coupled to the Standard Model (electromagnetism).

Outline

- Dark photon superradiance (with kinetic mixing)
- Plasma production
- Electrodynamics
- Electromagnetic emissions and signatures

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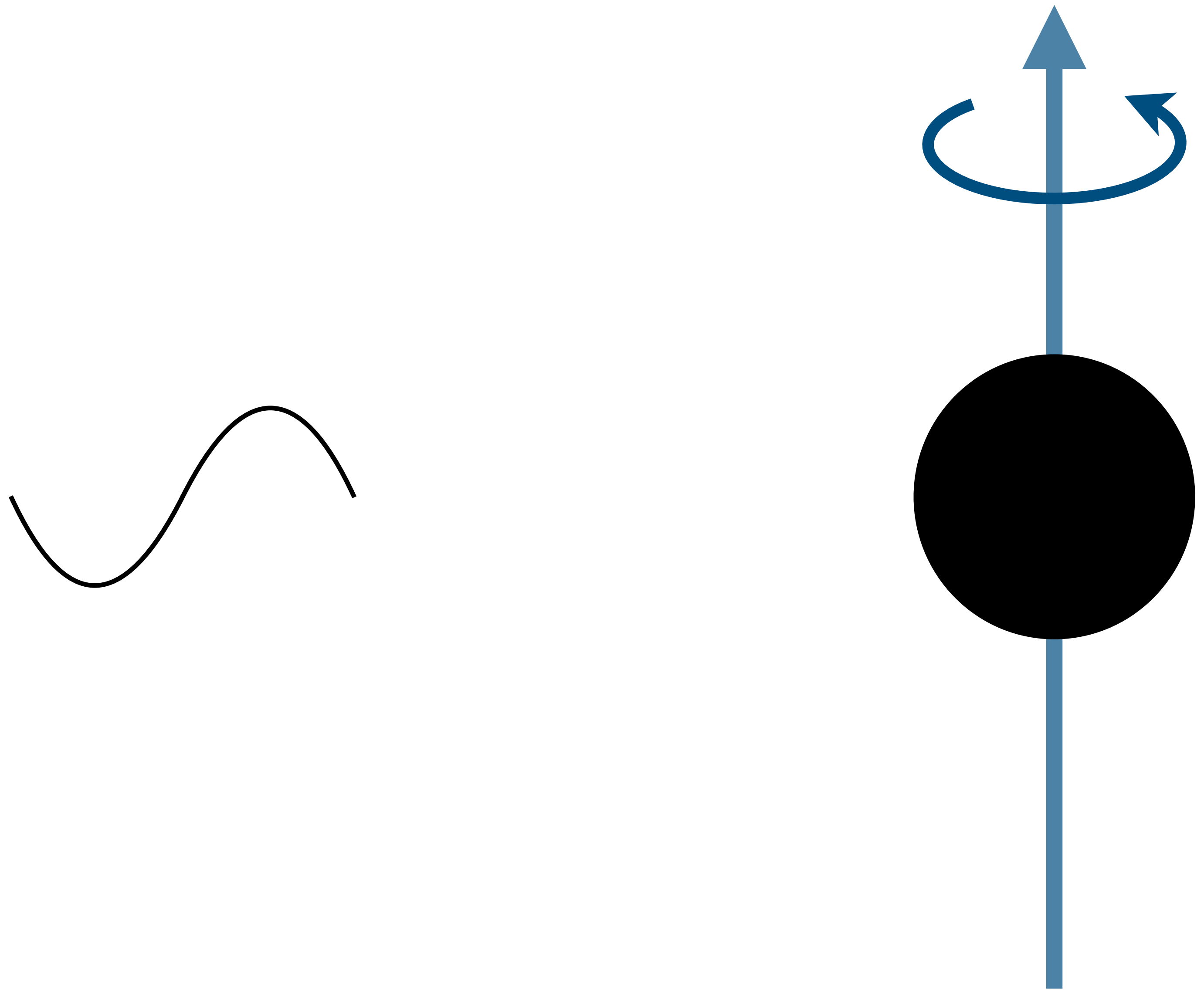
Dark photon superradiance

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}\mu^2 A'^{\mu}A'_{\mu}$$

New massive vector boson

Boson's Compton wavelength $\frac{1}{\mu} \sim GM$ Black hole radius

Spinning back hole



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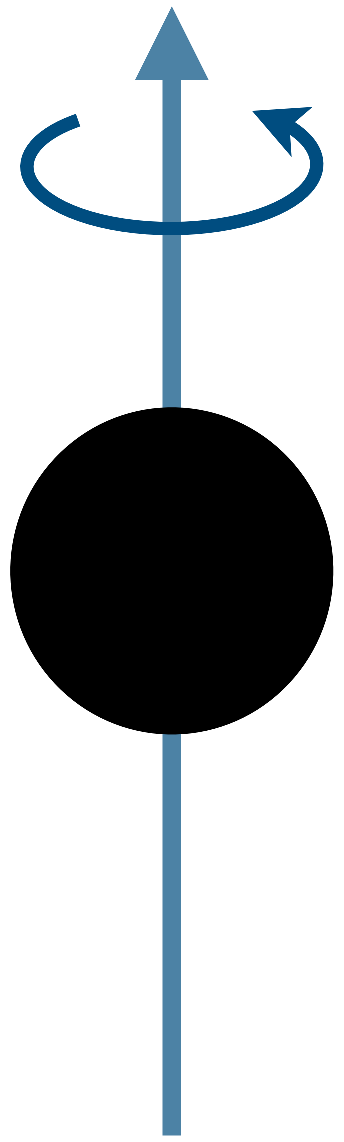

EOM in Kerr spacetime

$$D_\mu F'^{\mu\nu} = \mu^2 A'^{\nu}$$

- Hydrogen-like wave functions

Dark photon superradiance

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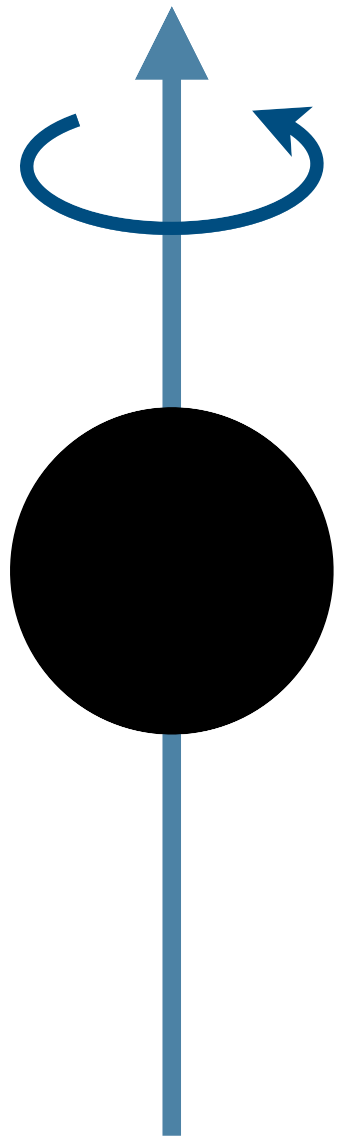

EOM in Kerr spacetime

$$D_\mu F'^{\mu\nu} = \mu^2 A'^{\nu}$$

- Hydrogen-like wave functions
- Energy with imaginary component

If $\frac{\mu}{m} \lesssim \Omega_{\mathrm{H}}$

Orbital angular momentum

Angular velocity of BH horizon

Dark photon superradiance

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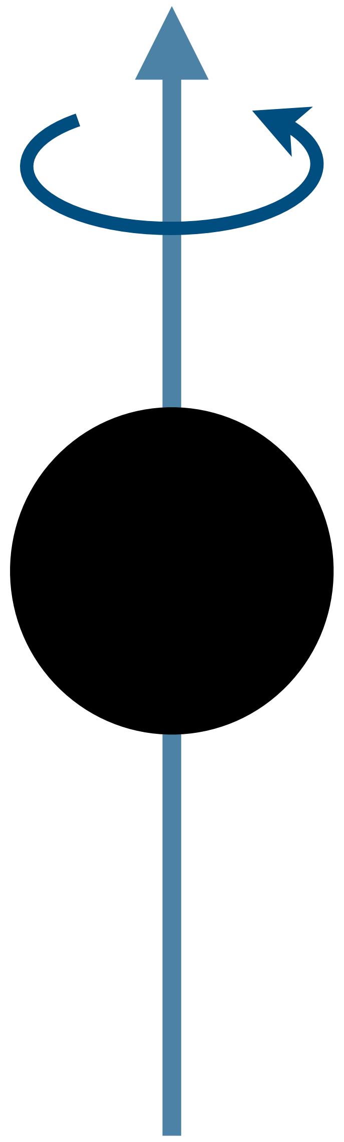


EOM in Kerr spacetime

$$D_\mu F'^{\mu\nu} = \mu^2 A'^{\nu}$$

- Hydrogen-like wave functions
- Energy with imaginary component

If $\frac{\mu}{m} \lesssim \Omega_{\mathrm{H}}$ the superradiance instability occurs

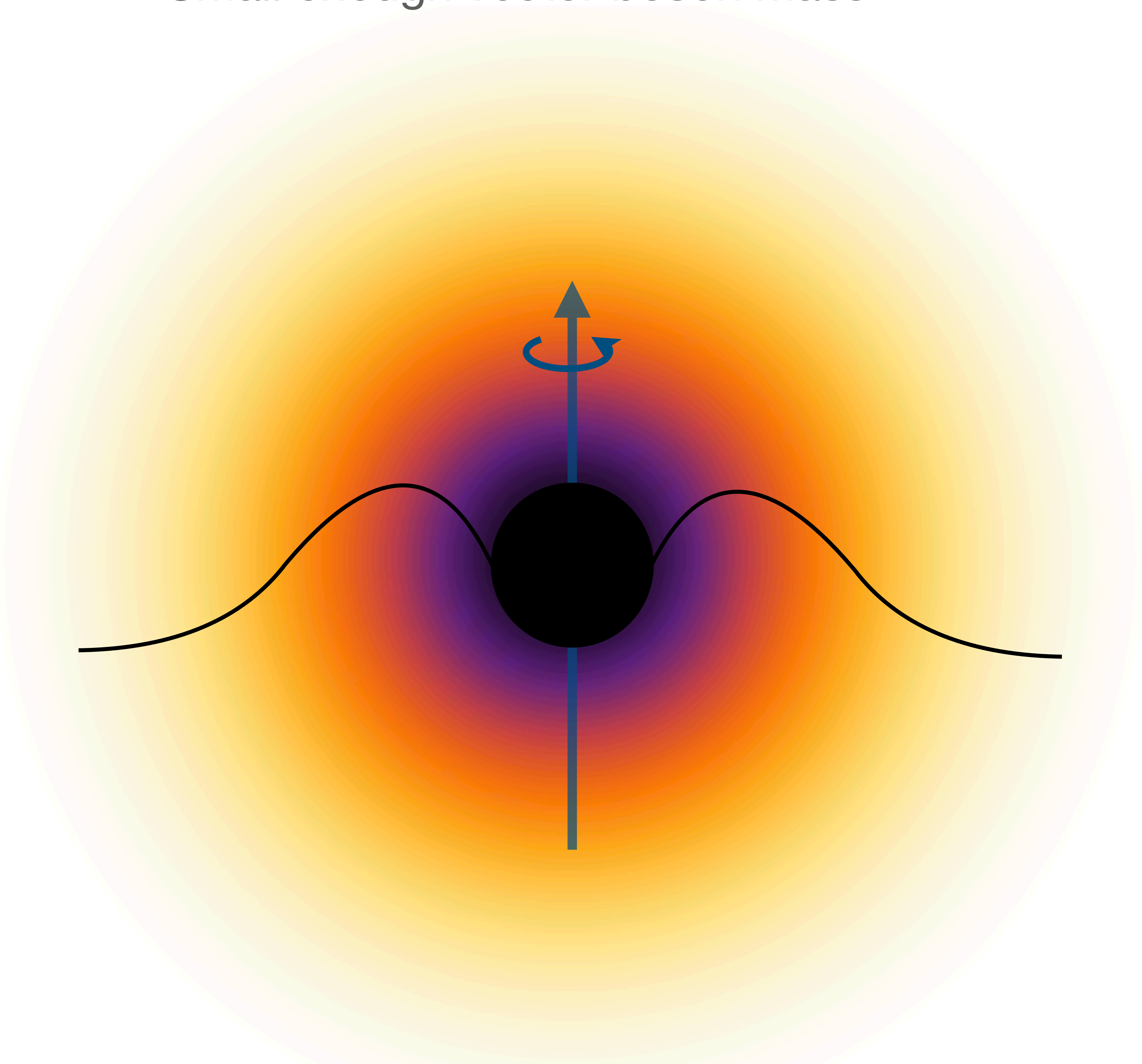
Orbital angular momentum

Angular velocity of BH horizon

Exponential growth of the occupation number

Dark photon superradiance

- For large enough BH spin
- Small enough vector boson mass



Gravitational coupling: $\alpha \equiv \mu G M$

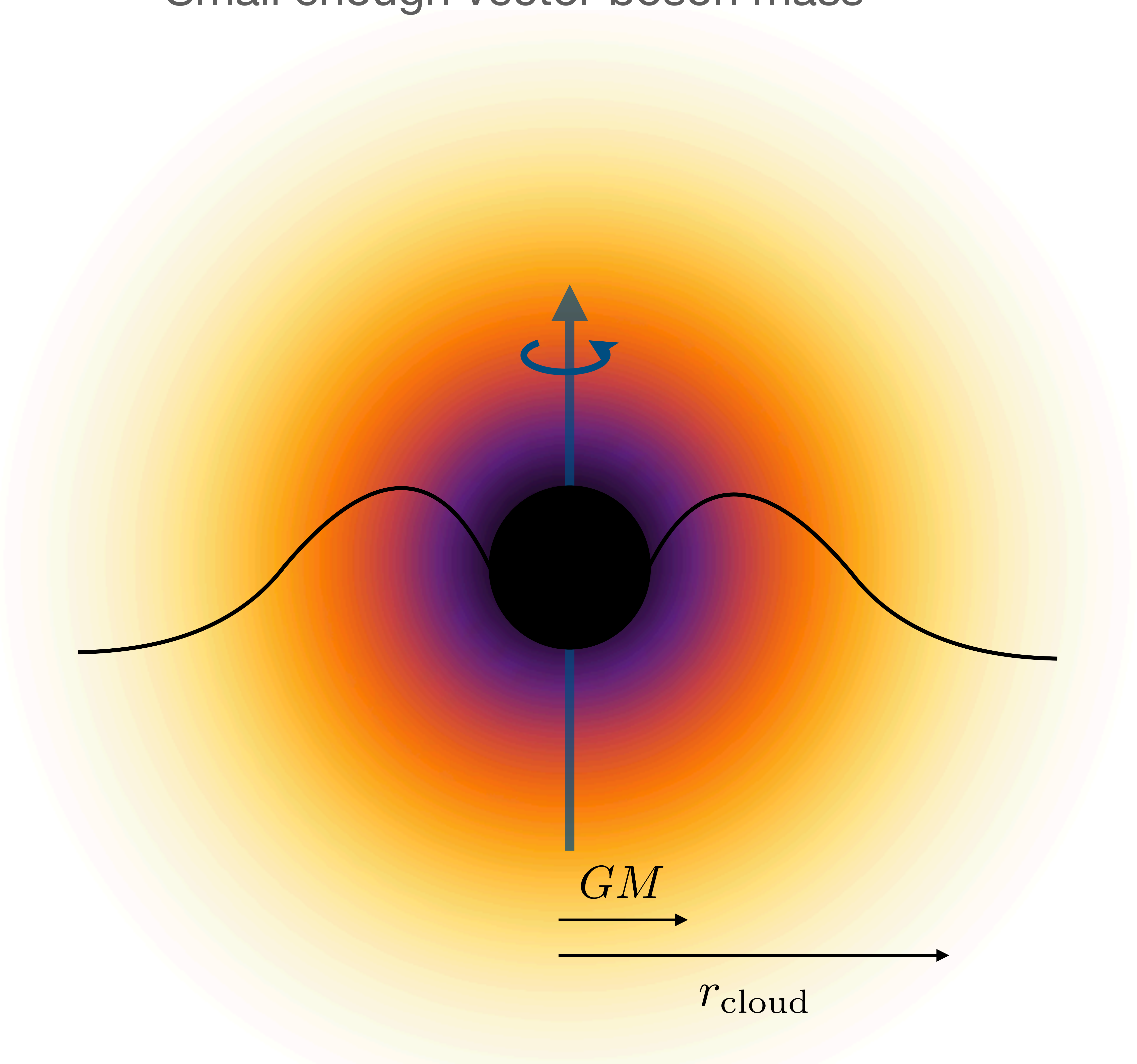
For maximally spinning BH, superradiance occurs for:

$$\frac{\alpha}{m} \lesssim 0.5$$

The boson cloud extracts energy and angular momentum from the BH.

Dark photon superradiance

- For large enough BH spin
- Small enough vector boson mass



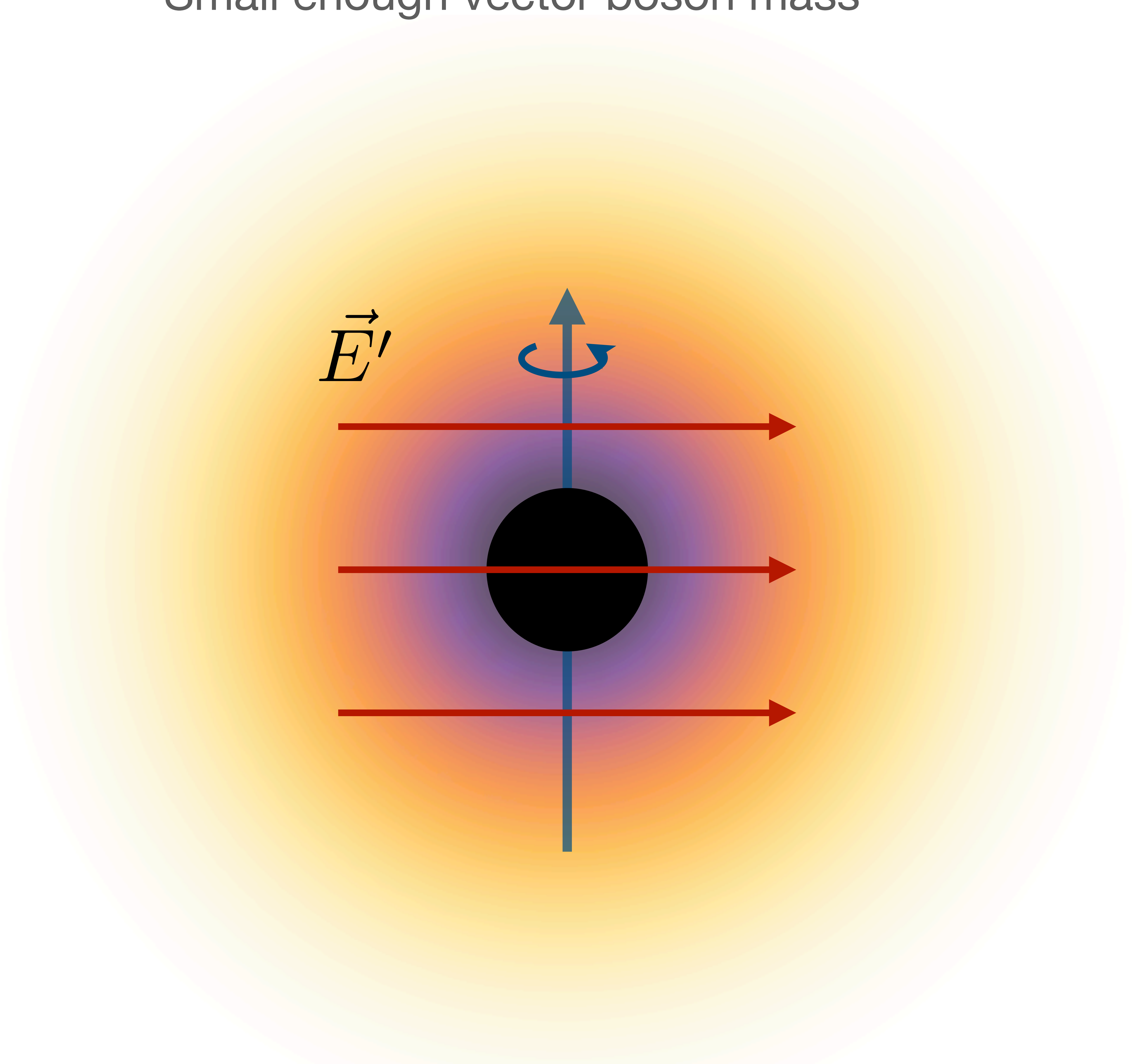
Gravitational coupling: $\alpha \equiv \mu G M$

Lowest energy level (n=0, l=0, m=1)
of the "gravitational atom":

$$r_{\text{cloud}} \sim \frac{1}{\alpha\mu} = \frac{GM}{\alpha^2} \gg GM$$

Dark photon superradiance

- For large enough BH spin
- Small enough vector boson mass



Gravitational coupling: $\alpha \equiv \mu G M$

Large, rotating dark electric field

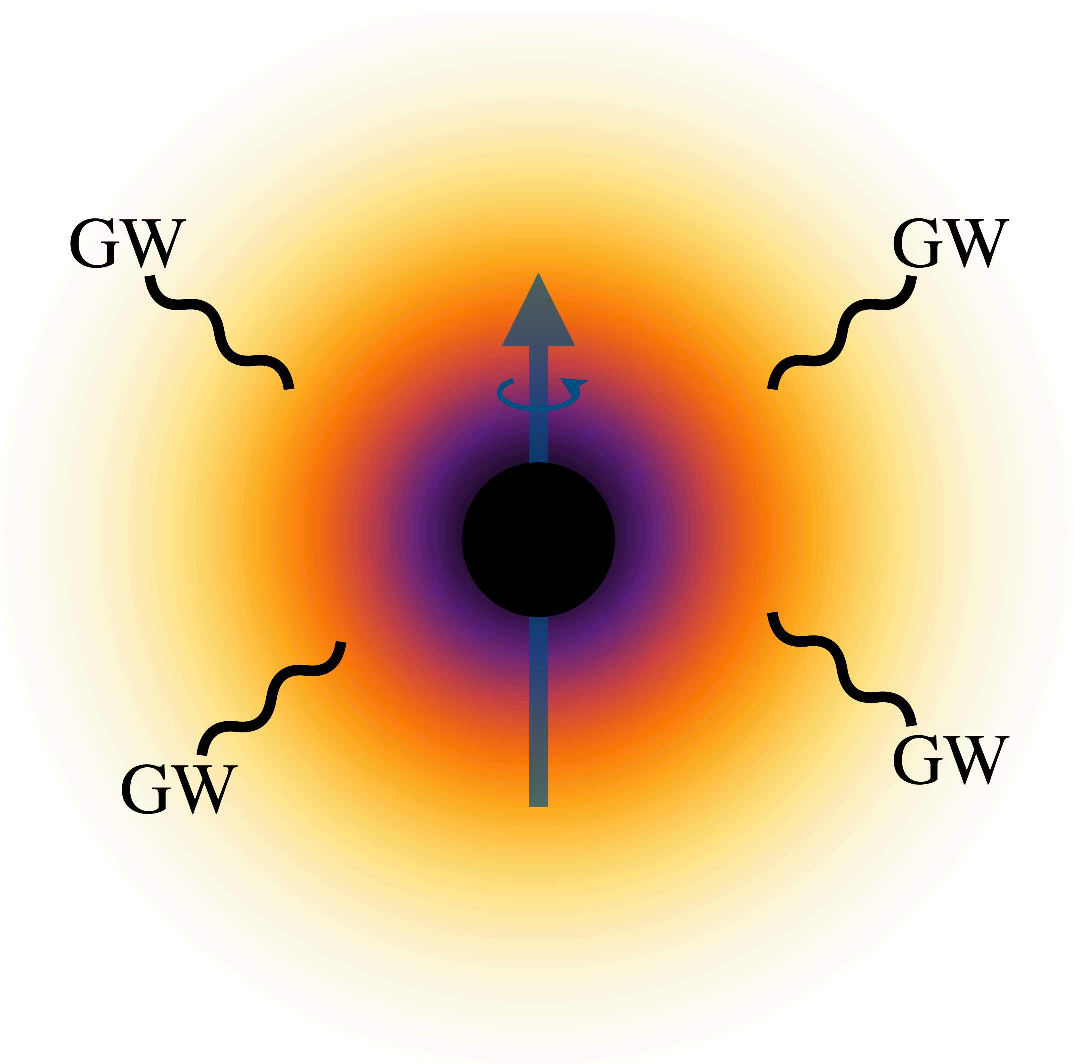
$$|\vec{E}'| \sim \alpha^{5/2} \mu M_{\mathrm{pl}}$$

$$|\vec{B}'| \sim \alpha |\vec{E}'| \ll |\vec{E}'|$$

The rotational frequency is given by the boson's energy $\omega \simeq \mu$

Black hole superradiance

Y. B. Zeldovich, 1971



Can be used to probe ultralight bosons (axion, dark photon, etc.)

0905.4720, *String Axiverse*
A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, J. March-Russell

1004.3558, *Exploring the String Axiverse with Precision Black Hole Physics*
A. Arvanitaki, S. Dubovsky

1411.2263, *Discovering the QCD Axion with Black Holes and Gravitational Waves*
A. Arvanitaki, M. Baryakhtar, X. Huang

1704.04791, *Superradiant Instability and Backreaction of Massive Vector Fields around Kerr Black Holes*
W. E. East, F. Pretorius

1801.01420, *Constraining the mass of dark photons and axion-like particles through black-hole superradiance*
V. Cardoso, O. J. C. Dias, G. S. Hartnett, M. Middleton, P. Pani, J. E. Santos

....

- Spin distribution of BH population.
- Continuous gravitational wave emissions (on going searches by Ligo-Virgo-Kagra).

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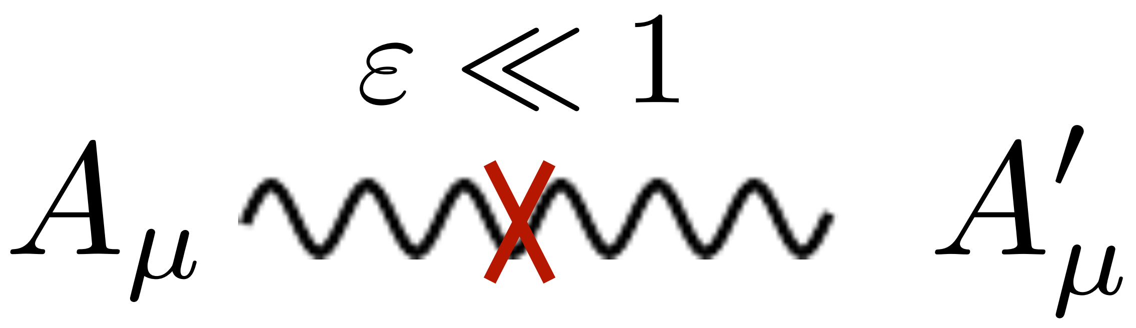
Dark photon kinetic mixing

Standard Model photon

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}\mu^2 A'^{\mu}A'_{\mu} - \boxed{\frac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu}}$$



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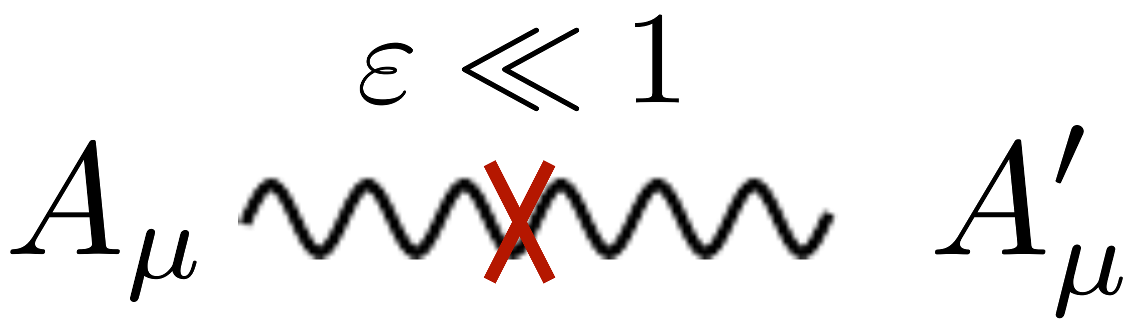


$$\Big\downarrow \quad A_\mu \to A_\mu + \varepsilon A'_\mu$$

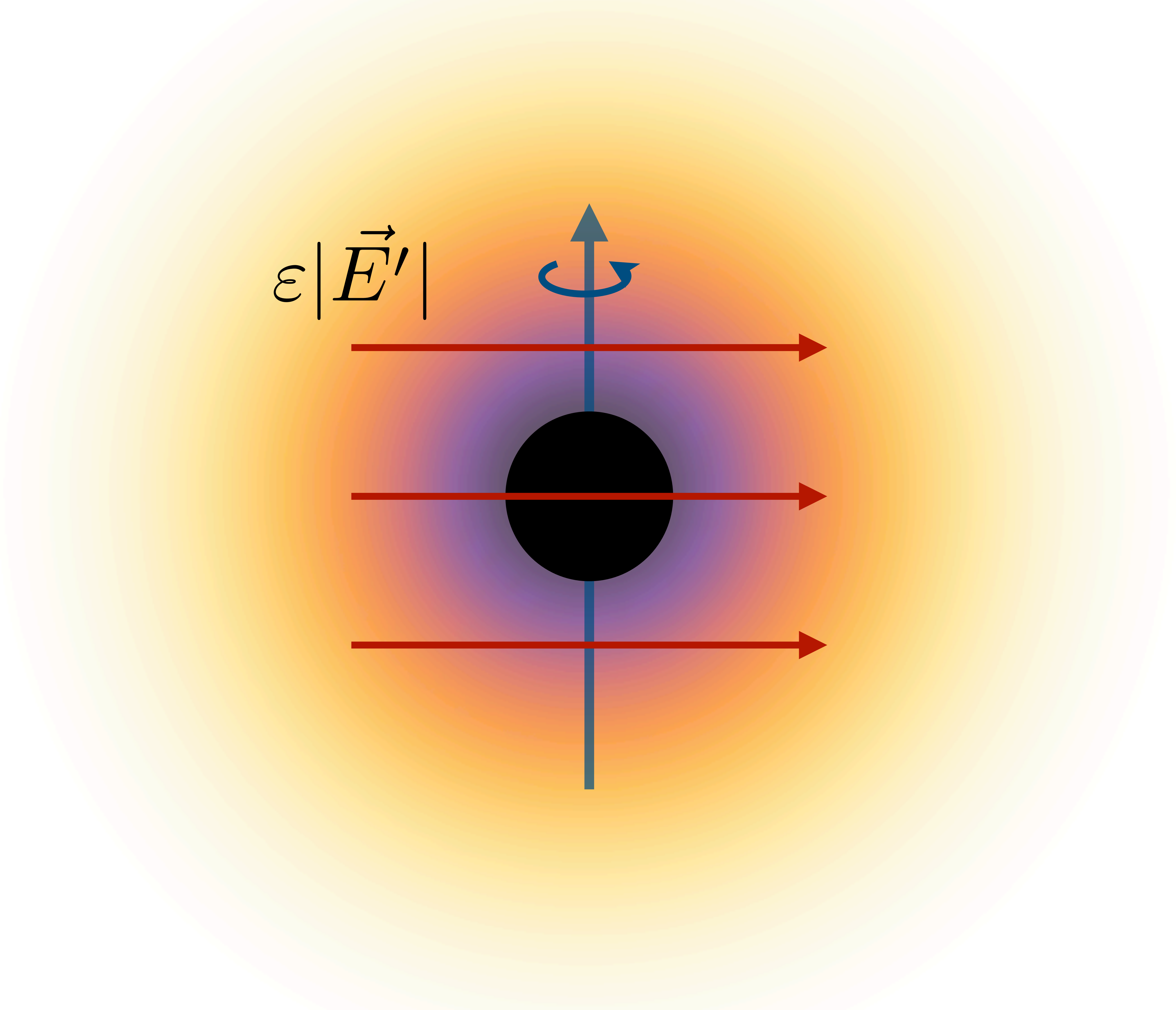
$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}\mu^2 A'^{\mu}A'_{\mu} + \boxed{J^{\mu}_{\mathrm{EM}}(A_\mu + \varepsilon A'_\mu)}$$

Coupling to SM charged particles $\propto e\varepsilon$

Dark photon kinetic mixing

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}\mu^2 A'^{\mu}A'_{\mu} + J^{\mu}_{\rm EM}(A_\mu + \varepsilon A'_\mu)$$

Coupling to SM charged particles: $e\varepsilon$



Large, rotating electric field

$$|\vec{E}| = \varepsilon|\vec{E}'| \sim \varepsilon\alpha^{5/2}\mu M_{\rm pl}$$

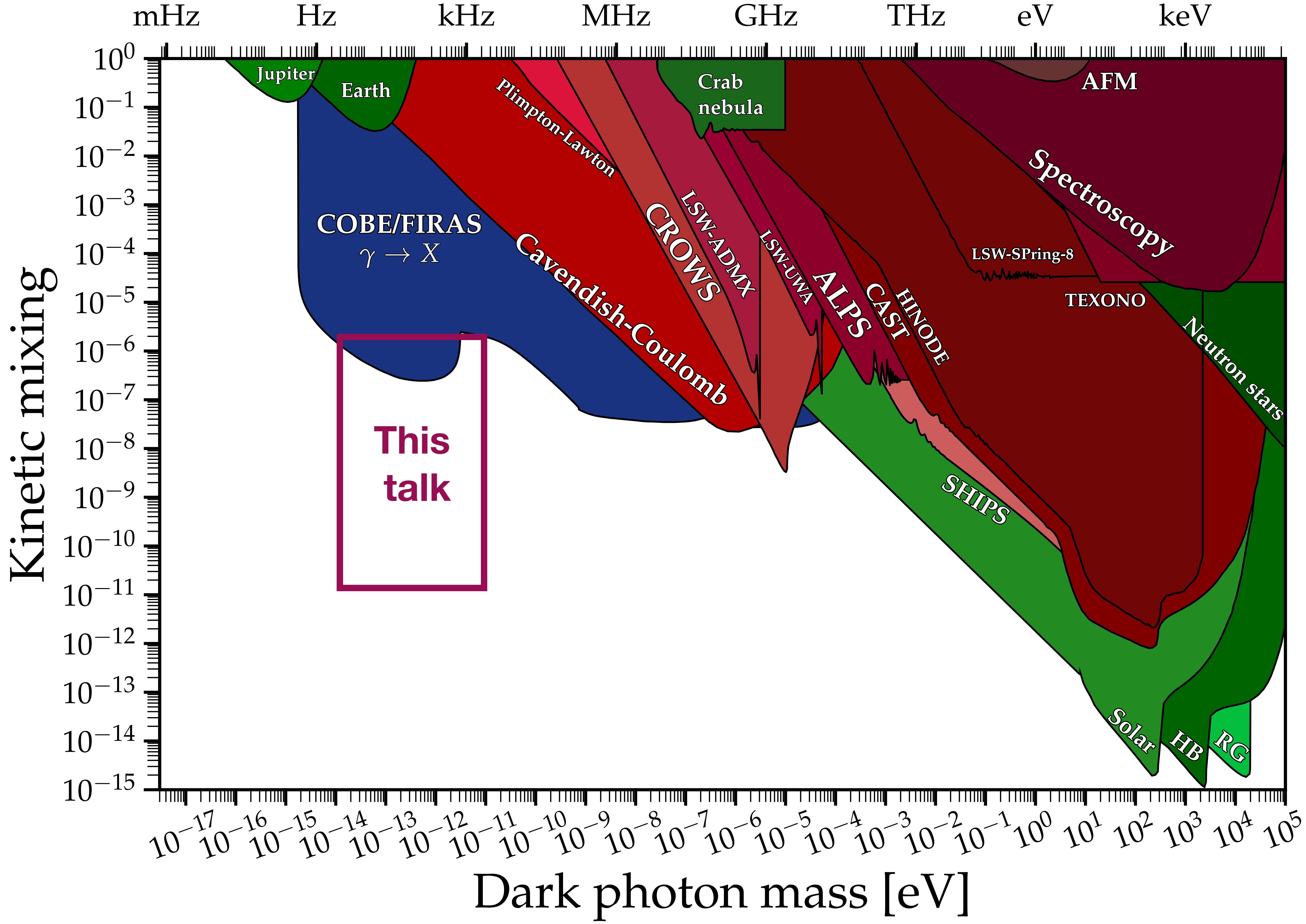
$$|\vec{E}| \sim 10^{13}\ {\rm V/m}\left(\frac{\varepsilon}{10^{-7}}\right)\left(\frac{\alpha}{0.1}\right)^{5/2}\left(\frac{\mu}{10^{-12}\,{\rm eV}}\right)$$

Dark photon parameter space

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}\mu^2 A'^{\mu}A'_{\mu} + J^{\mu}_{\mathrm{EM}}(A_\mu + \varepsilon A'_\mu)$$

Coupling to SM charged particles: $e\varepsilon$

Dark photons that are NOT the dark matter.



From 2105.04565, *Dark photon limits: a handbook*
A. Caputo, A. J. Millar, C. A. J. O'Hare, E. Vitagliano

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- Electrodynamics
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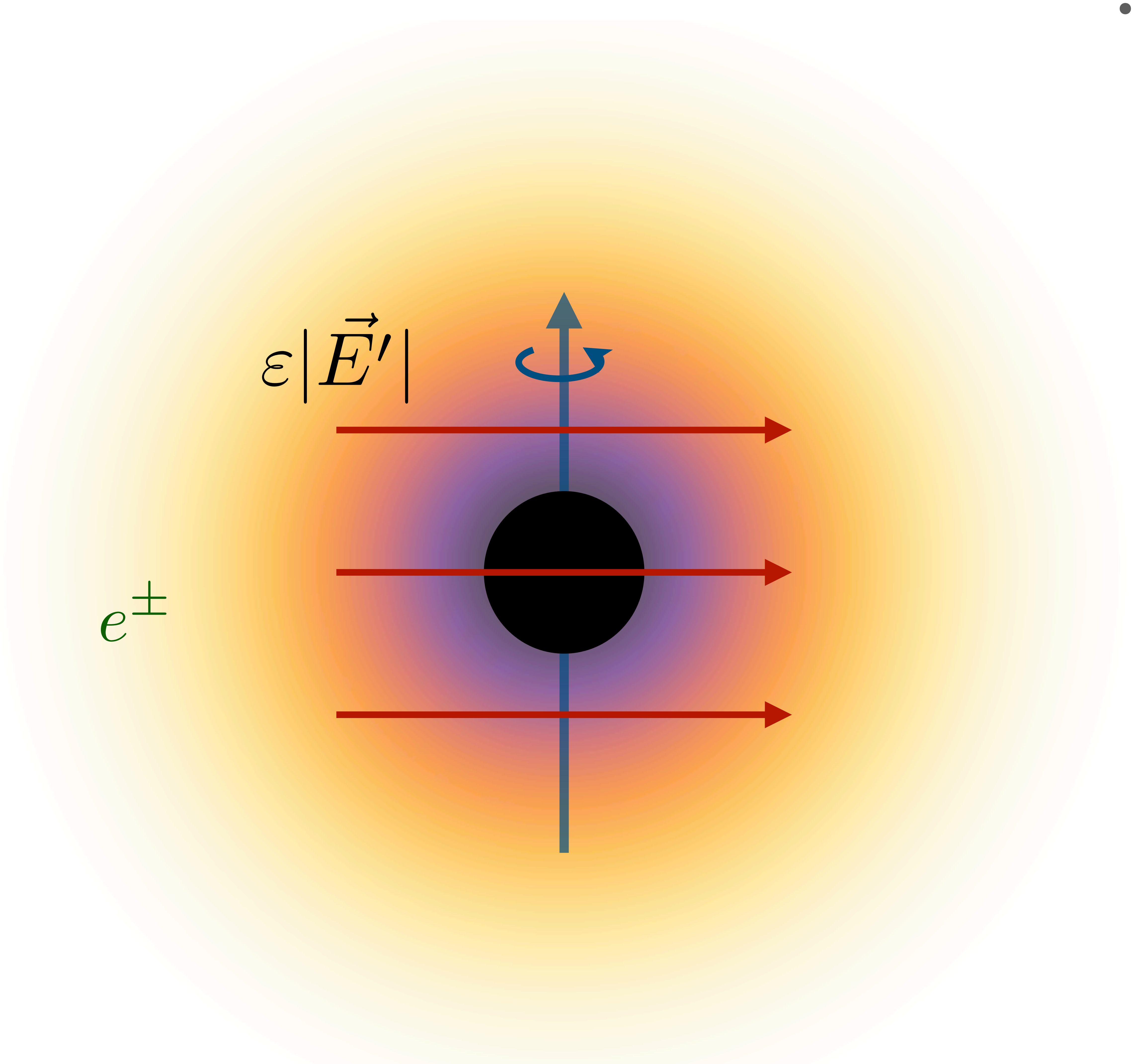
Plasma production

- Electron/positron highly accelerated in the electric field $\gamma_e \sim 10^{12}$
- Trajectory bends as the electric field rotates



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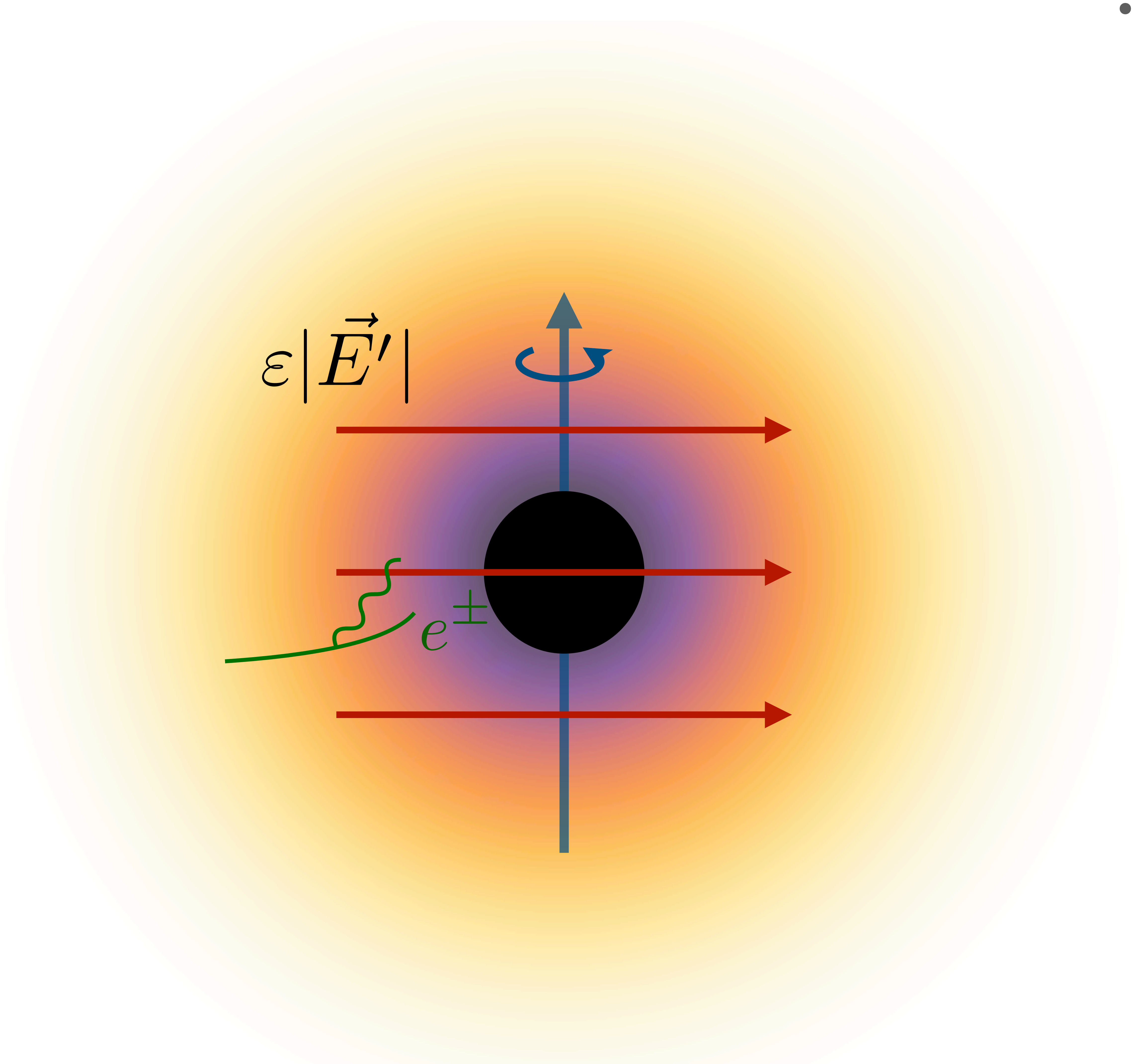

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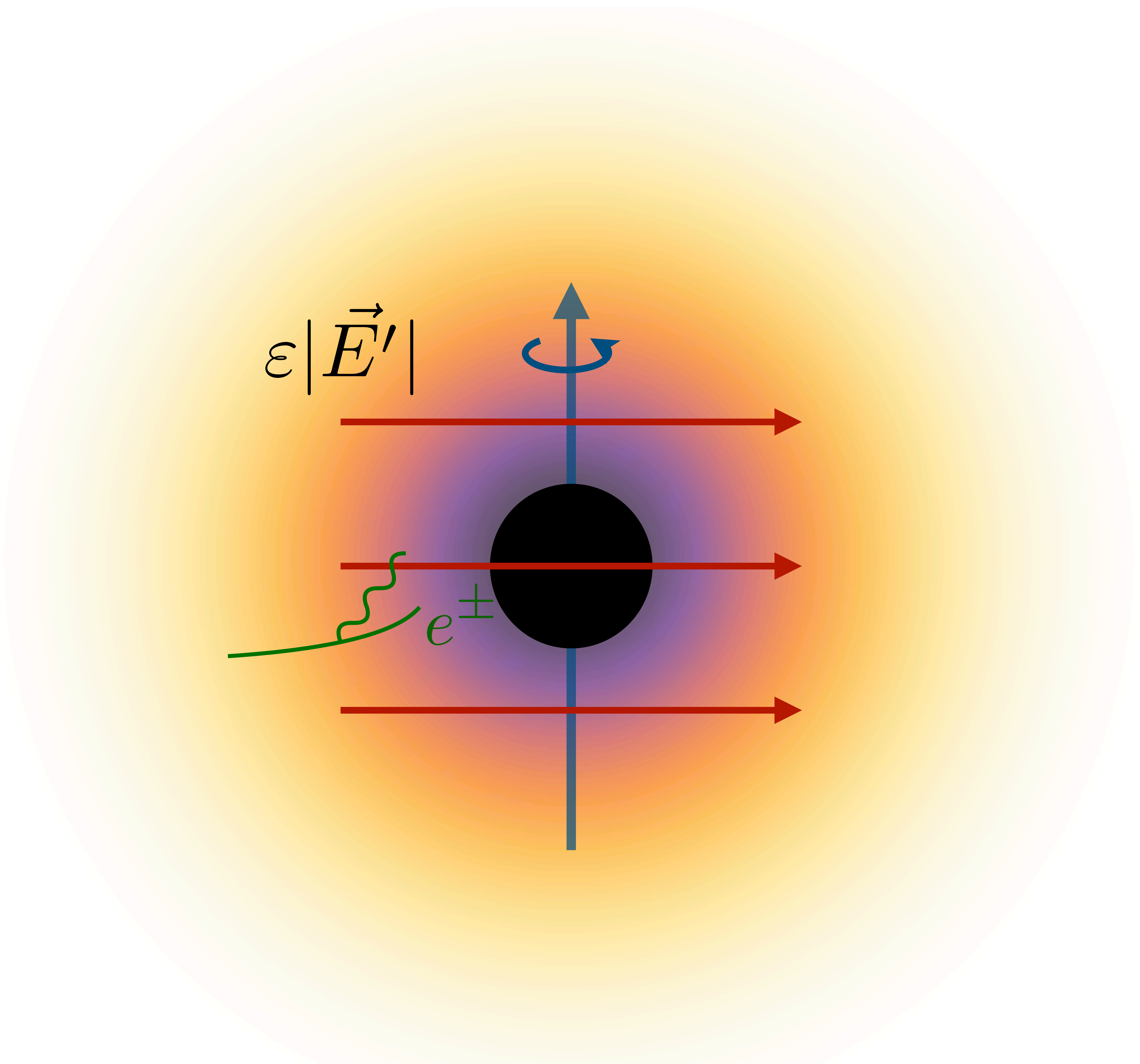
↓

Synchrotron emission of high energy photons

$$\omega_{\text{syn}} \simeq \gamma_e^3 \mu \gg m_e$$

Plasma production



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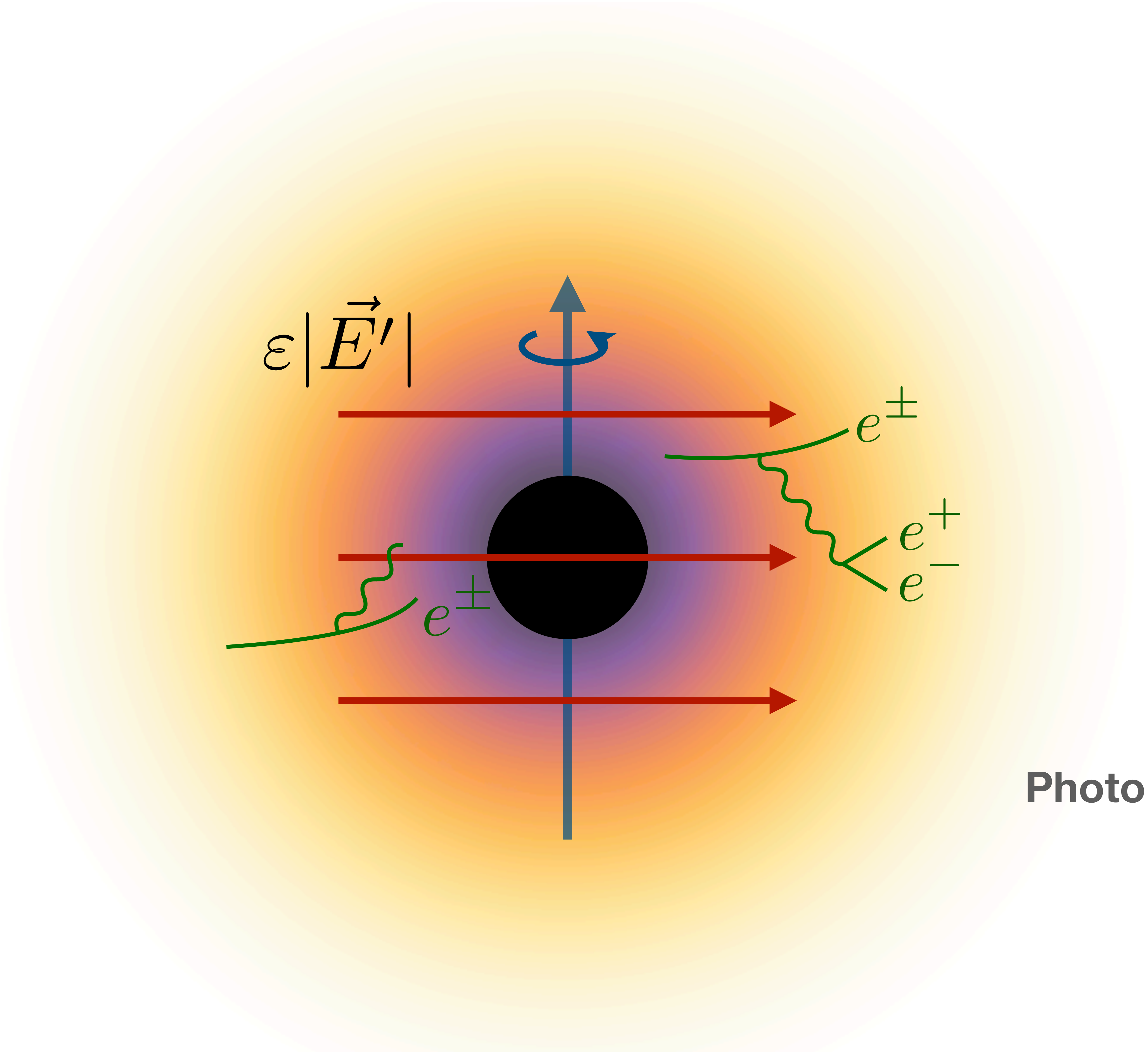
Schwinger pair production: $$\Gamma_{e^\pm} \propto \exp\left(-\frac{\pi m_e^2}{e|\vec{E}|}\right)$$

$$|\vec{E}| \gtrsim 10^{18}\ \mathrm{V/m}$$

Plasma production



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Photon-assisted Schwinger pair production: $\Gamma_{e^\pm} \propto \exp\left(-\frac{2m_e^2}{e|\vec{E}|}\frac{2m_e}{\omega_{\rm syn}}\right)$

Plasma production

Photon-assisted Schwinger pair production: $\Gamma_{e^\pm} = \frac{\alpha_{\rm EM}}{2\pi}\frac{e\varepsilon|\vec{E}'|}{m_e}\exp\left(-\frac{4m_e^6\mu^2}{(e\varepsilon|\vec{E}'|)^4}\right)$

Size of the superradiance cloud: $r_{\rm cloud} = \frac{1}{\alpha\mu}$

Plasma production

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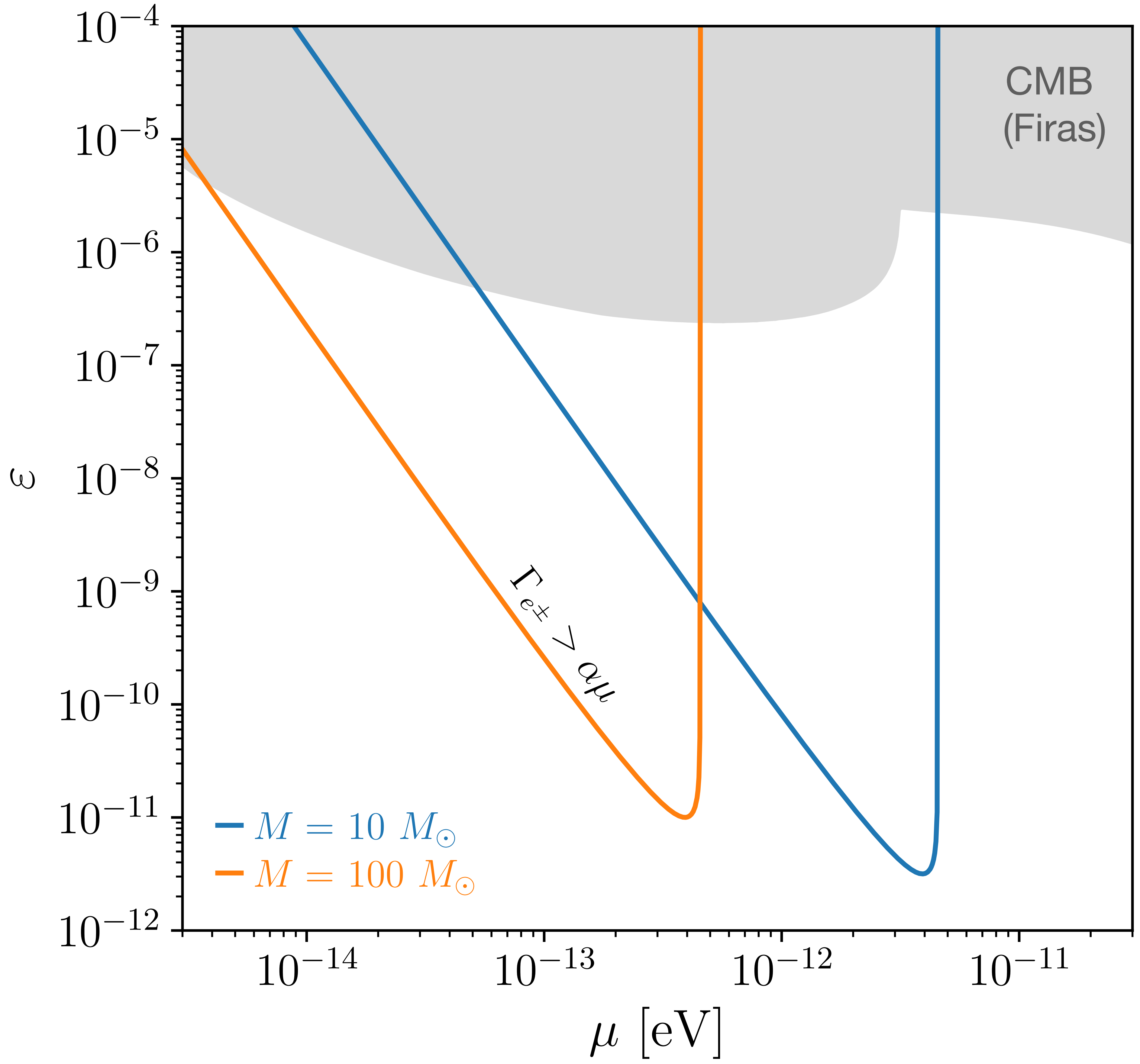
Efficient pair production if

$$\Gamma_{e^\pm} \gg \alpha\mu$$

$$(\alpha \equiv \mu G M)$$



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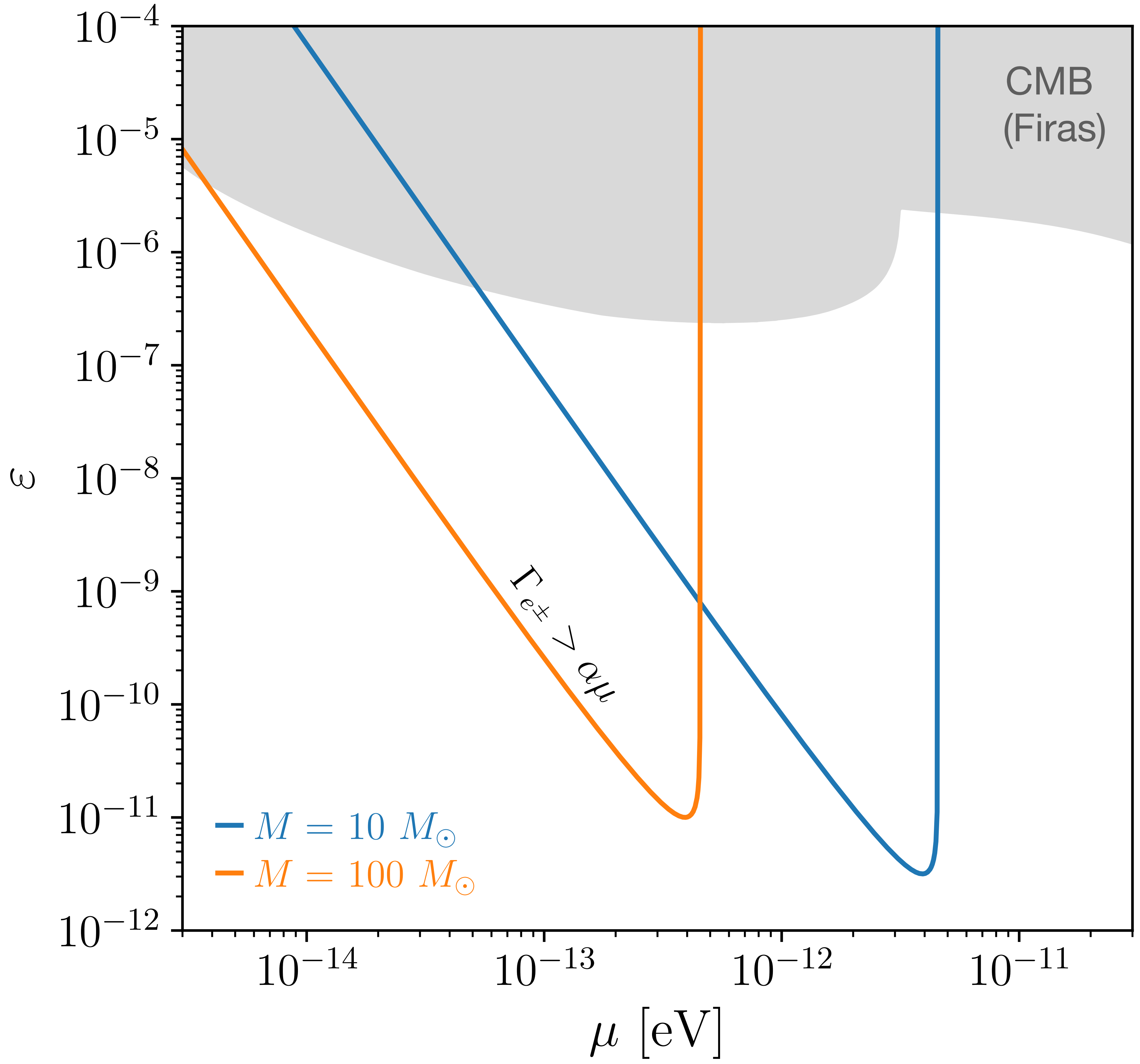
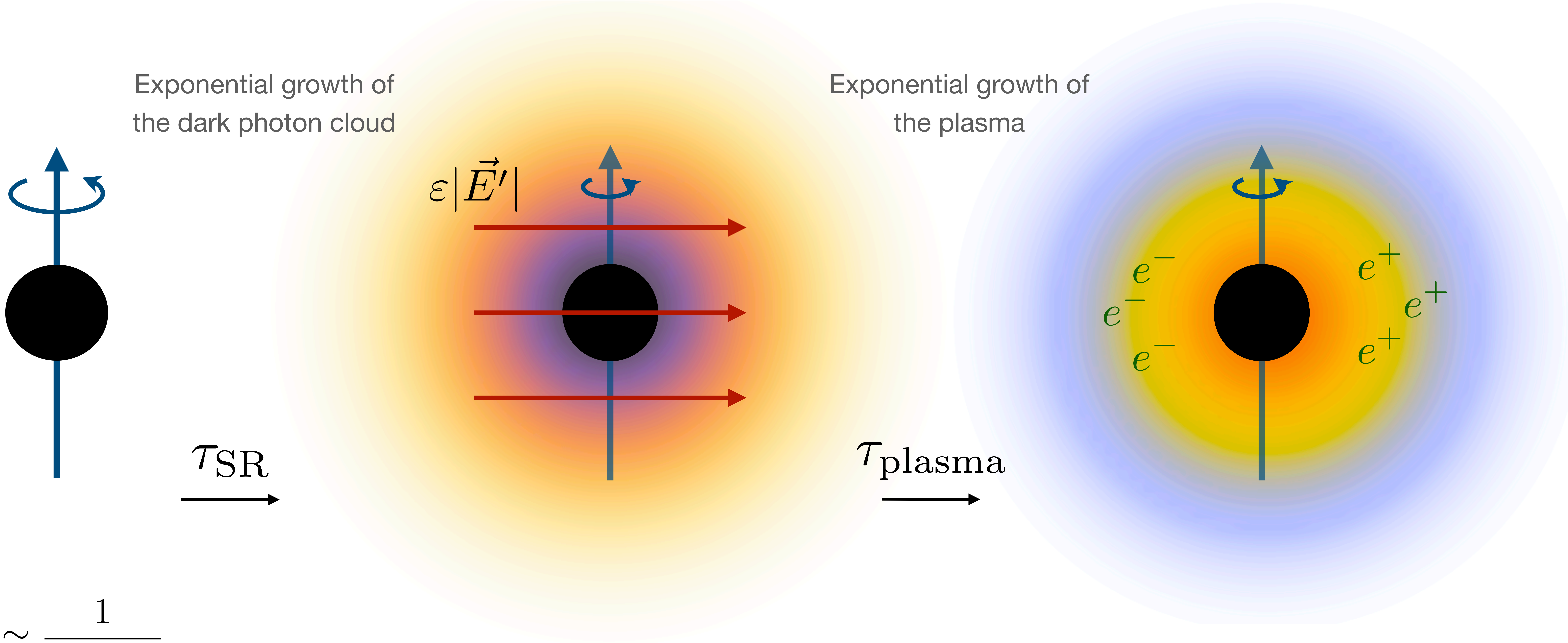


→ Cascade production of charged particles until the electric field is screened

$$e n_e \simeq \varepsilon \nabla \cdot \vec{E}'$$

Important timescales



Exponential growth of the dark photon cloud

$\xrightarrow{\tau_{\rm SR}}$

Exponential growth of the plasma

$\xrightarrow{\tau_{\rm plasma}}$

$$\tau_{\rm SR} \simeq \frac{1}{4a_* \alpha^6 \mu}$$

$$\tau_{\rm plasma} \simeq \frac{1}{\Gamma_{e^\pm}}$$

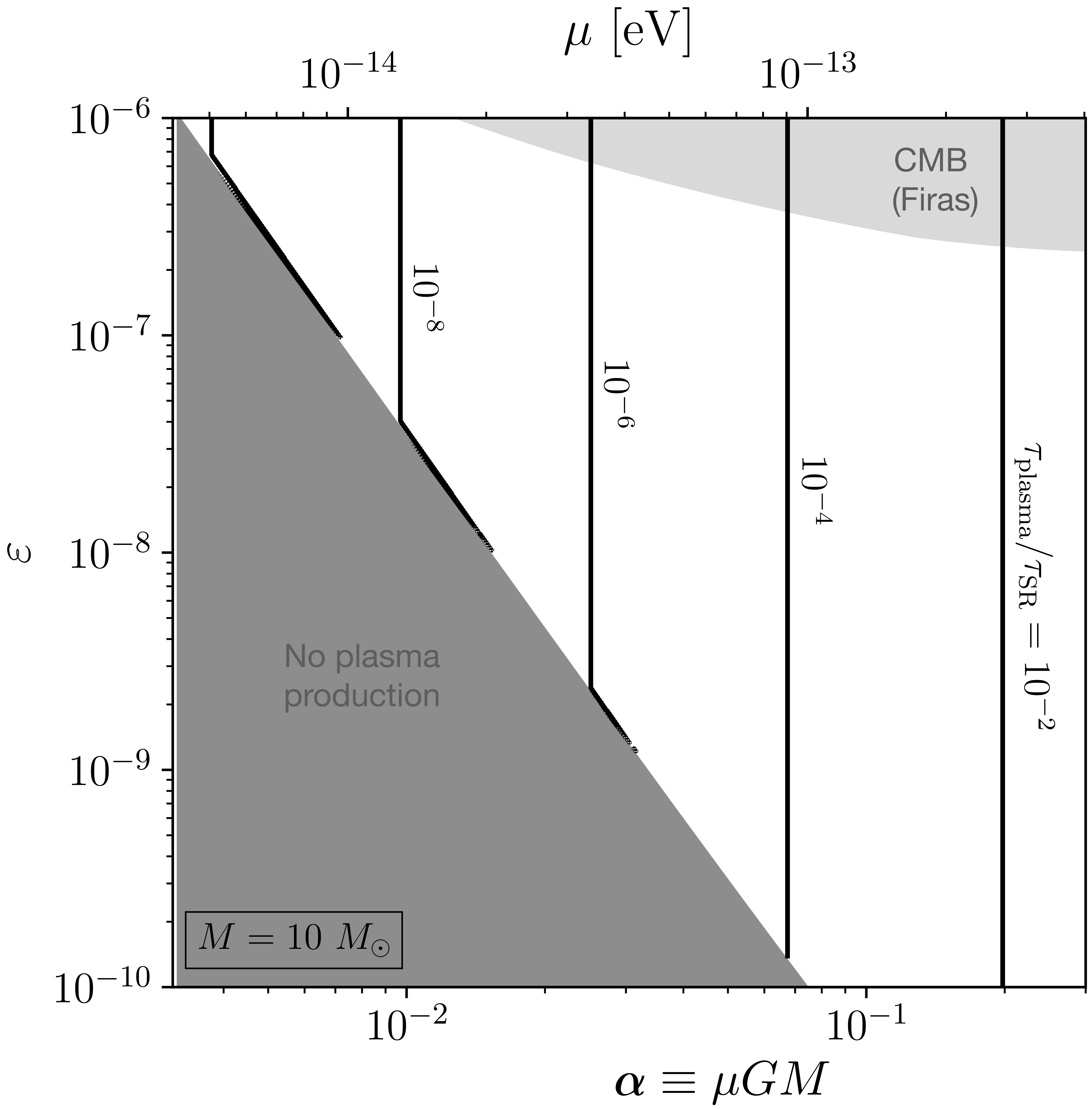
$$\tau_{\rm plasma} \ll \tau_{\rm SR}$$

Important timescales

$$\tau_{\mathrm{SR}} \simeq \frac{1}{4a_*\alpha^6\mu}$$

$$\tau_{\mathrm{plasma}} \simeq \frac{1}{\Gamma_{e^\pm}}$$

$$\tau_{\mathrm{plasma}} \ll \tau_{\mathrm{SR}}$$



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Electrodynamics: modeling the plasma

Ohm's law $\vec{J} = \sigma(\vec{E} + \vec{v} \times \vec{B})$

$\downarrow$

Conductivity

encodes microscopic particle physics of the plasma

→ We can solve numerically Maxwell's equation for the E and B fields

- $\sigma \to \infty$: perfect conductivity, fields are perfectly screened and the plasma is "force-free"
- Finite σ : resistive plasma, fields are not perfectly screened, dissipative effects are important

Nils Siemonsen

Electrodynamics: modeling the plasma

Ohm's law $$\vec{J} = \sigma(\vec{E} + \vec{v} \times \vec{B})$$

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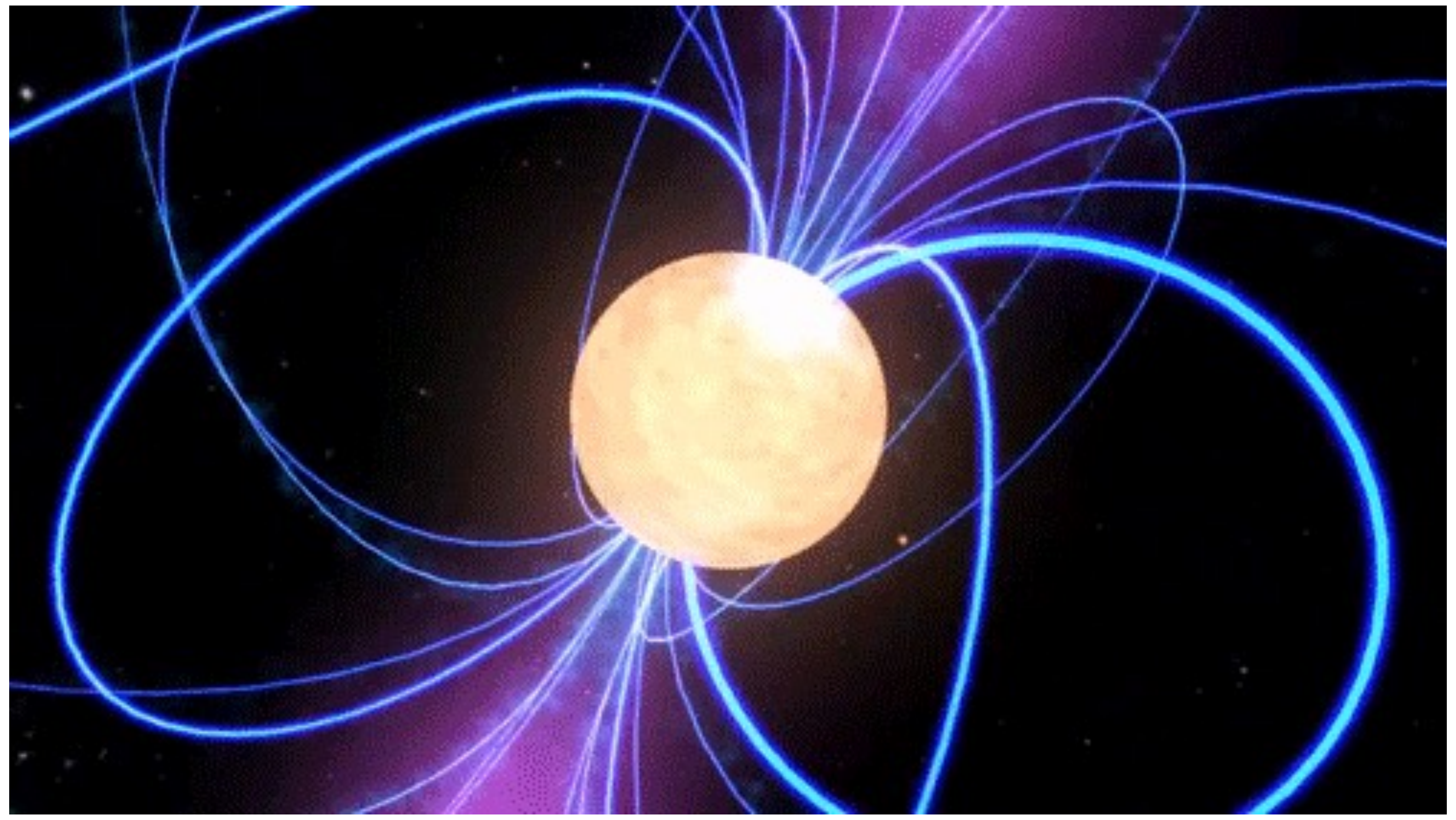
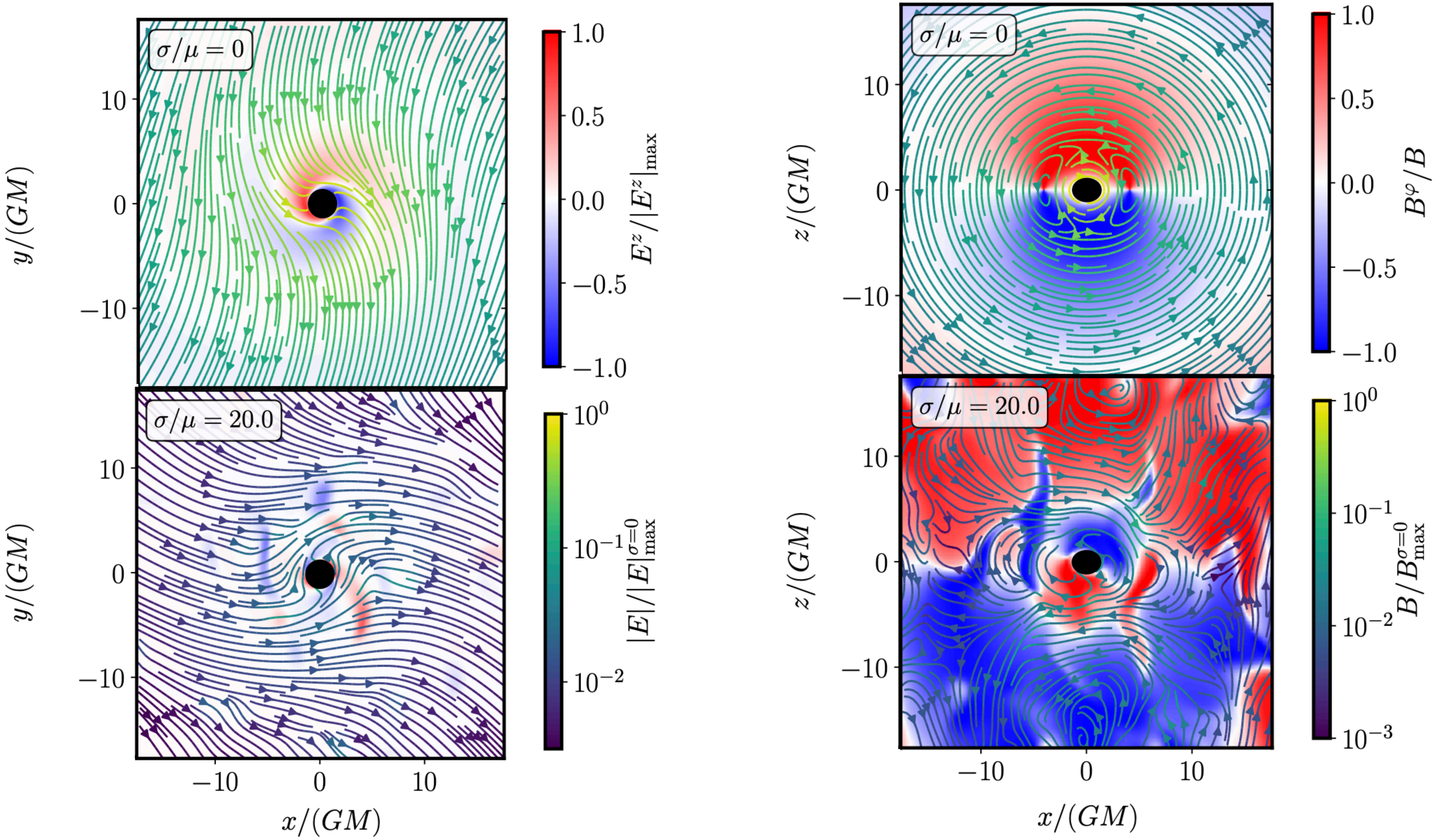
In a **neutron star pulsars** the magnetosphere is modeled as a force-free plasma



Electrodynamics: field solutions



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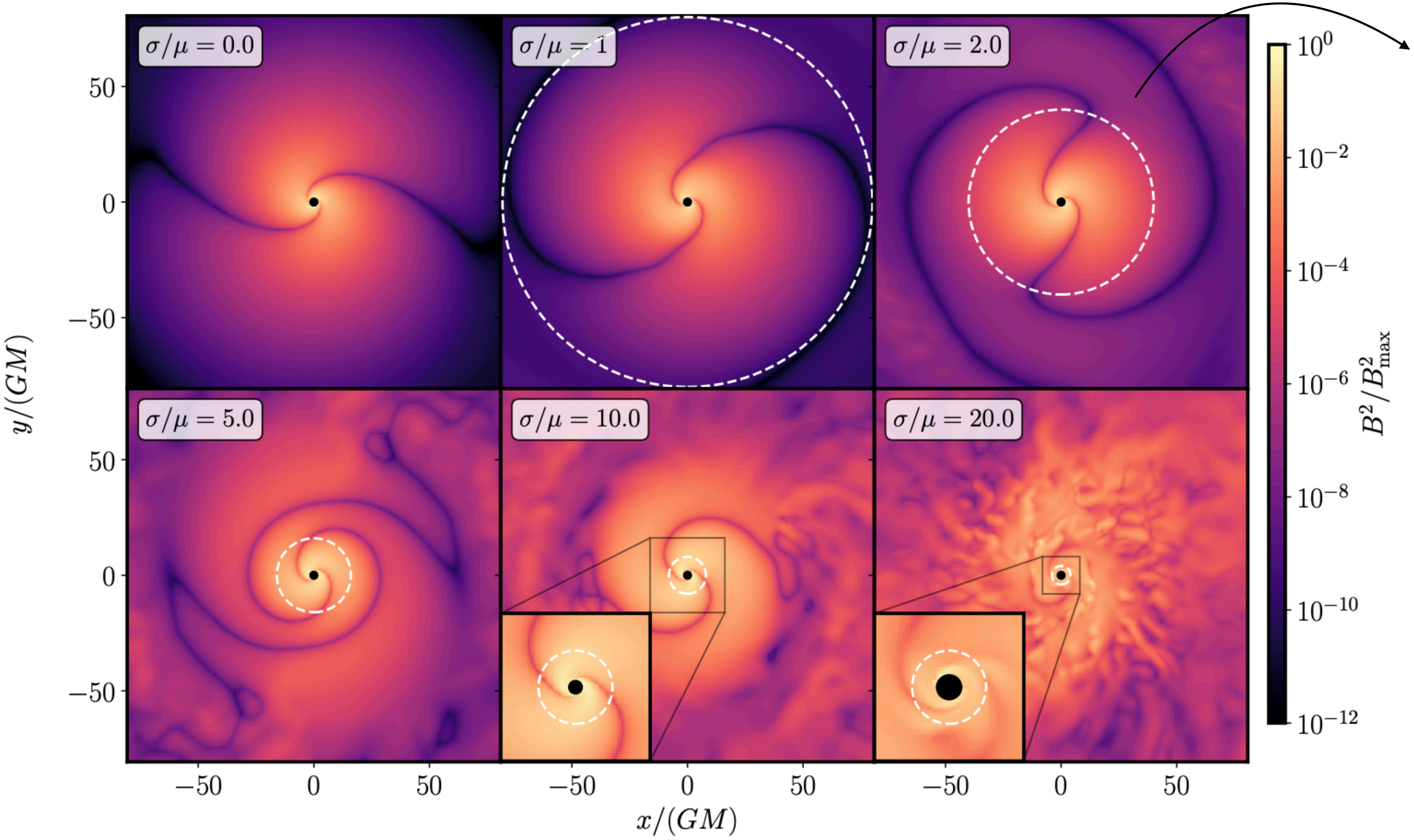
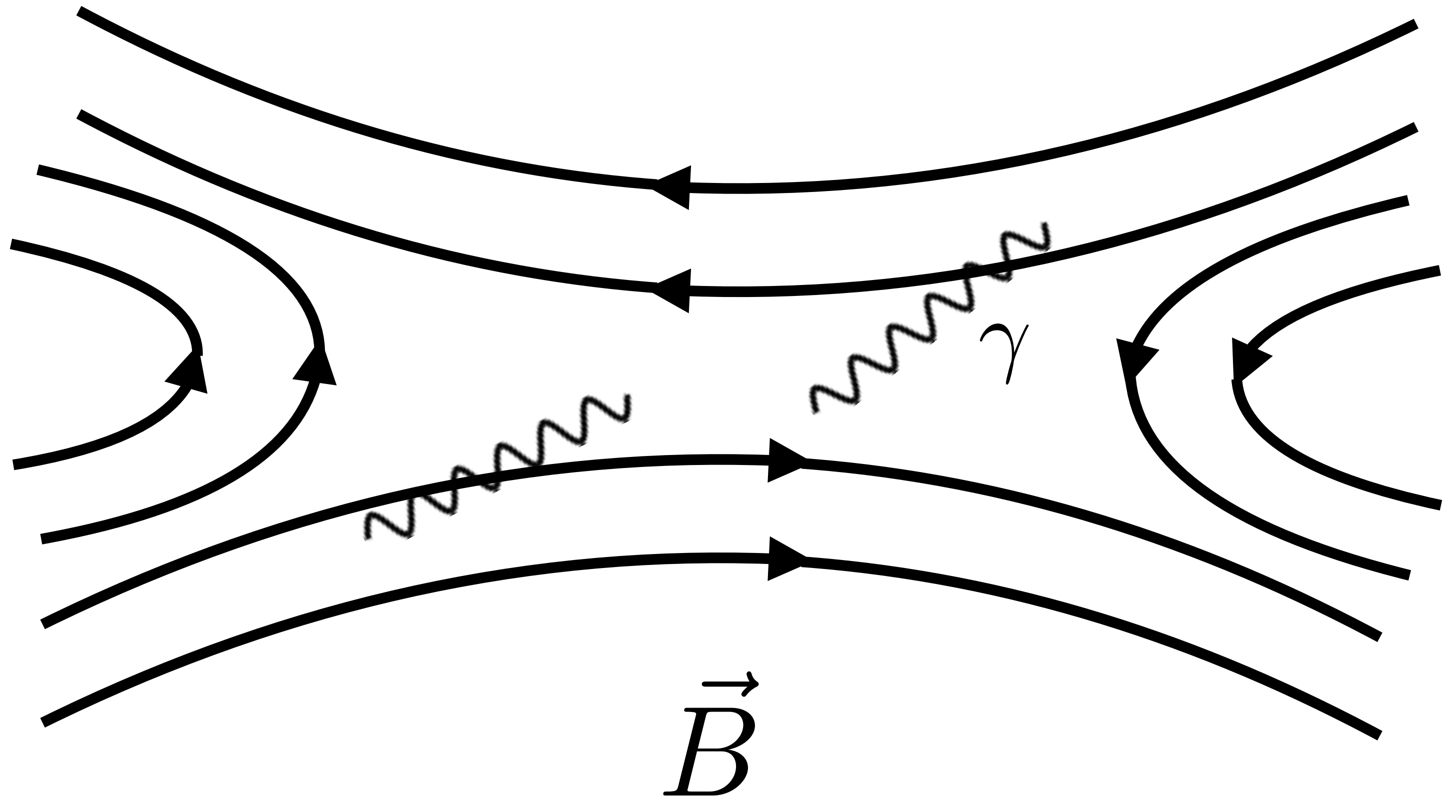


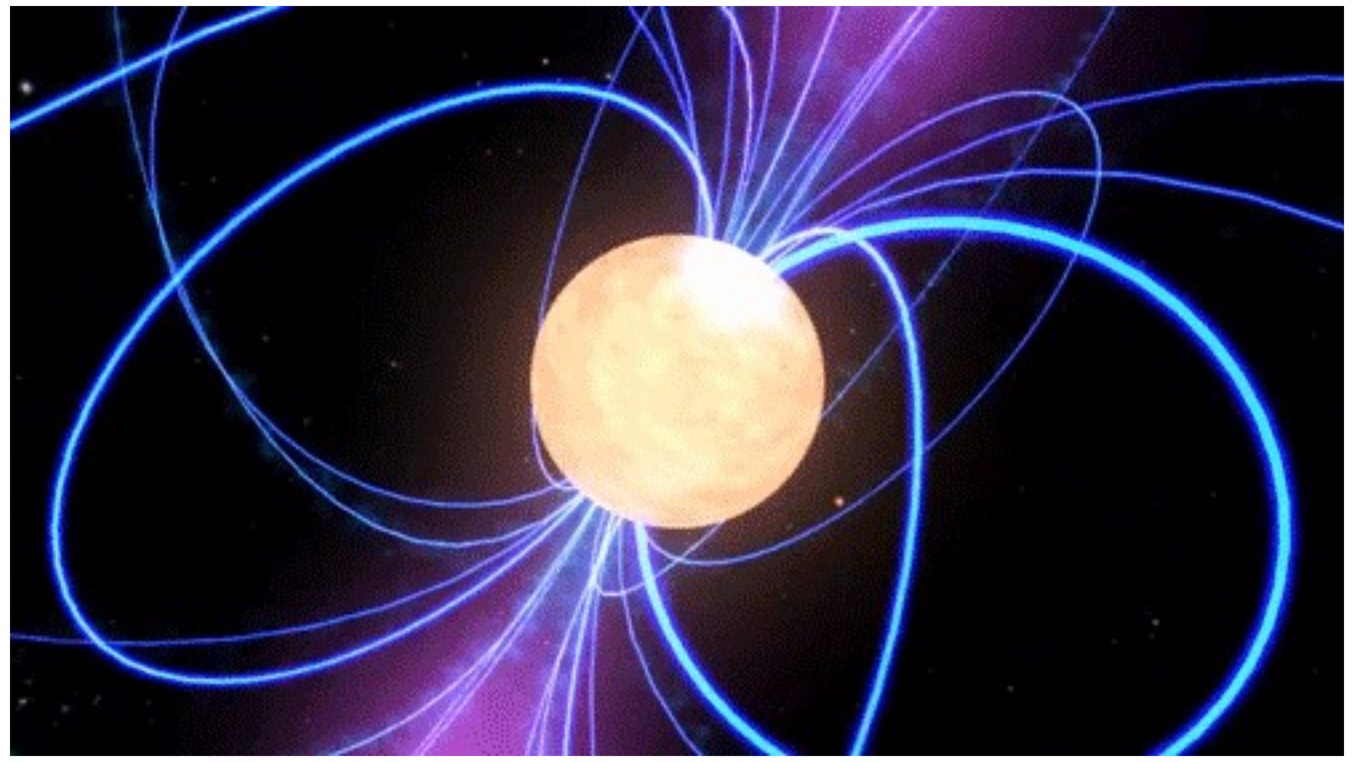
Differential rotation of the plasma and the fields

Magnetic reconnection

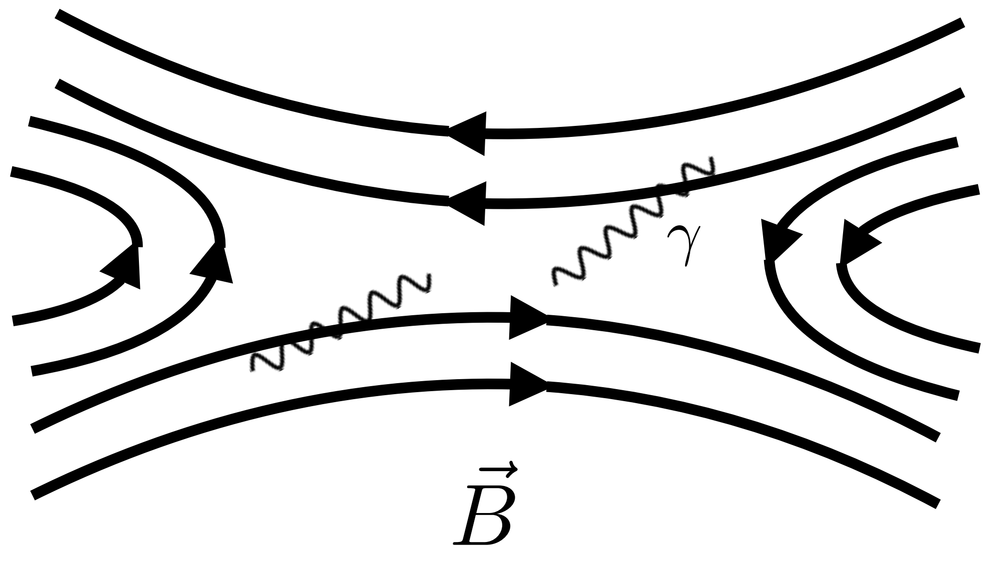


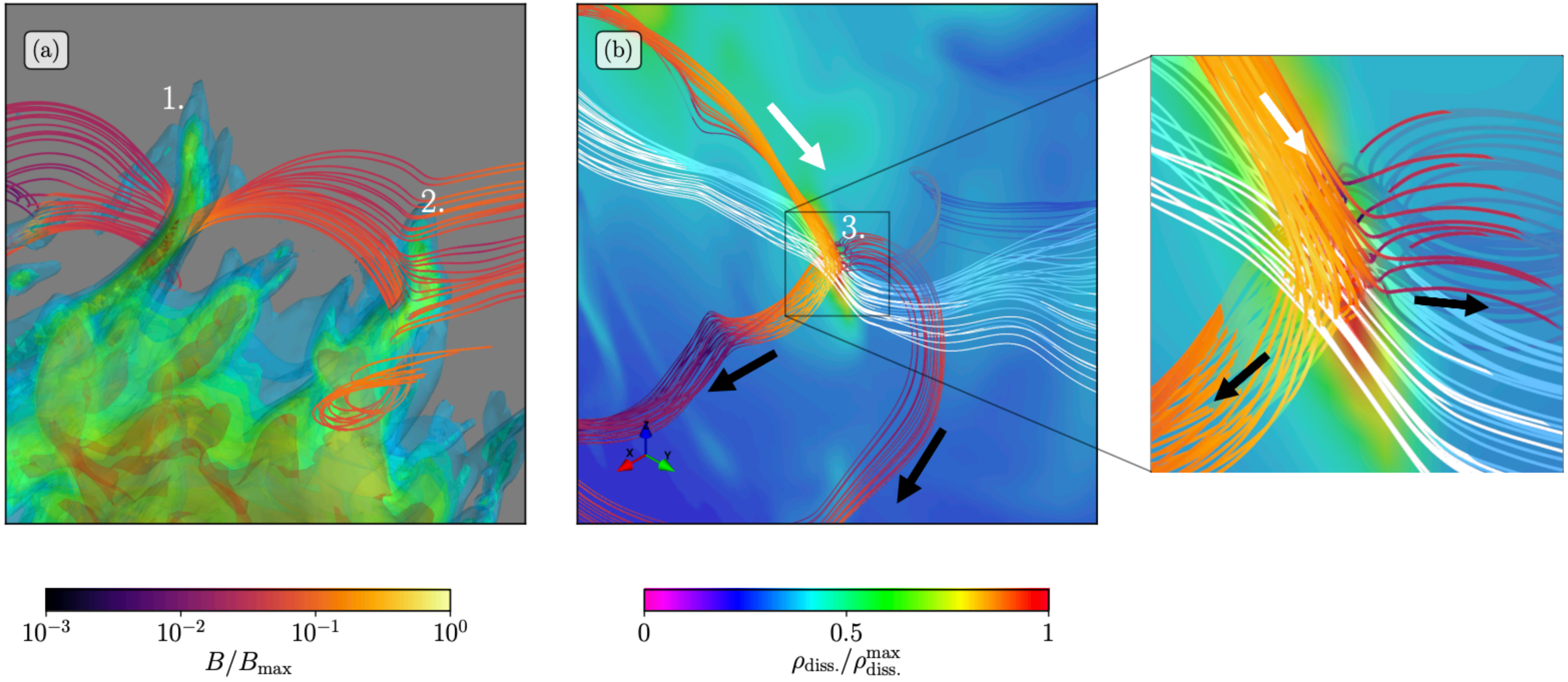
Field energy dissipated into particle acceleration and EM emissions

In a **neutron star pulsars** magnetic reconnection happens in the current sheets



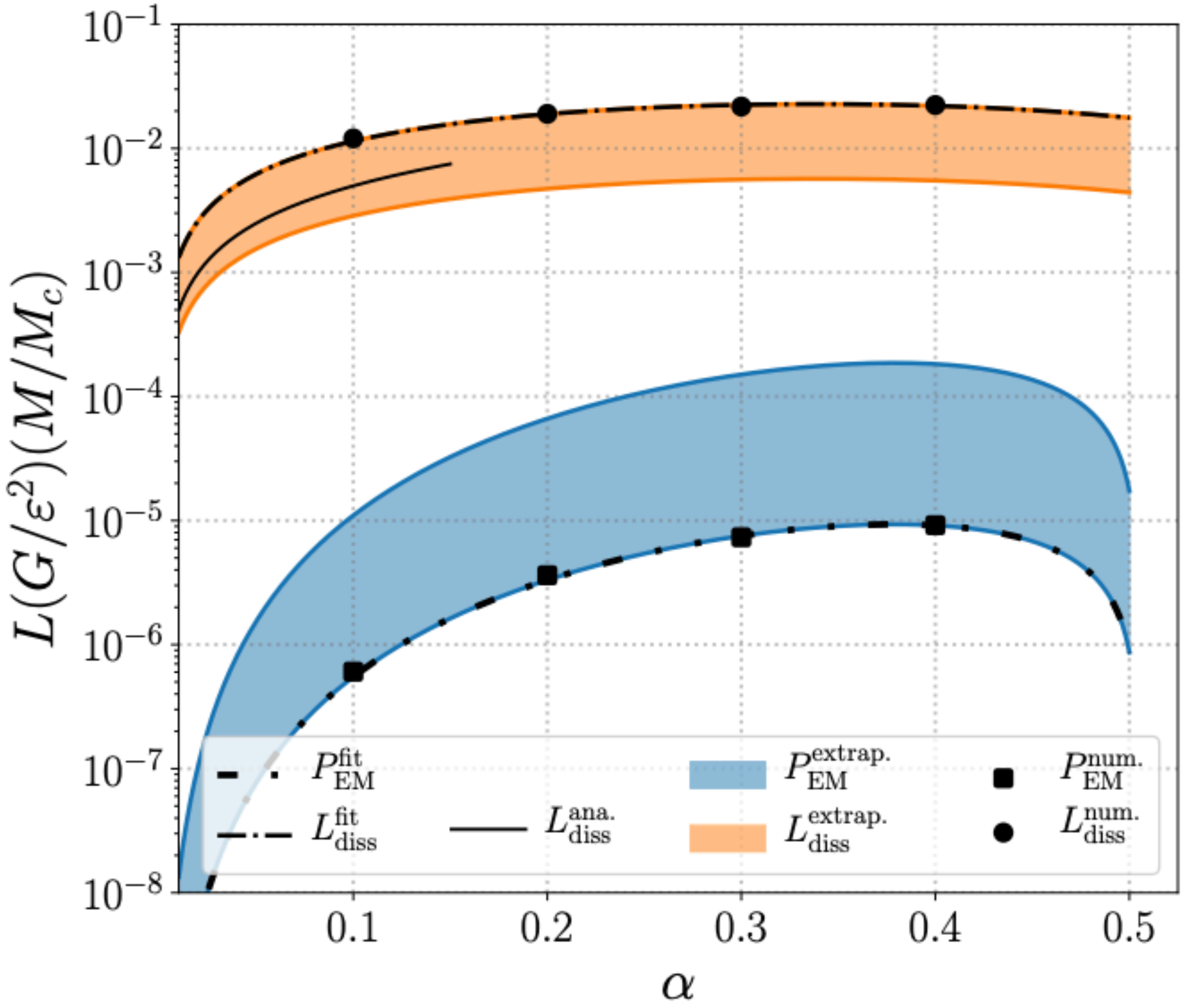
Magnetic reconnection





Electrodynamics: power output

Numerical solutions and fit



Power emitted:

- Poynting flux

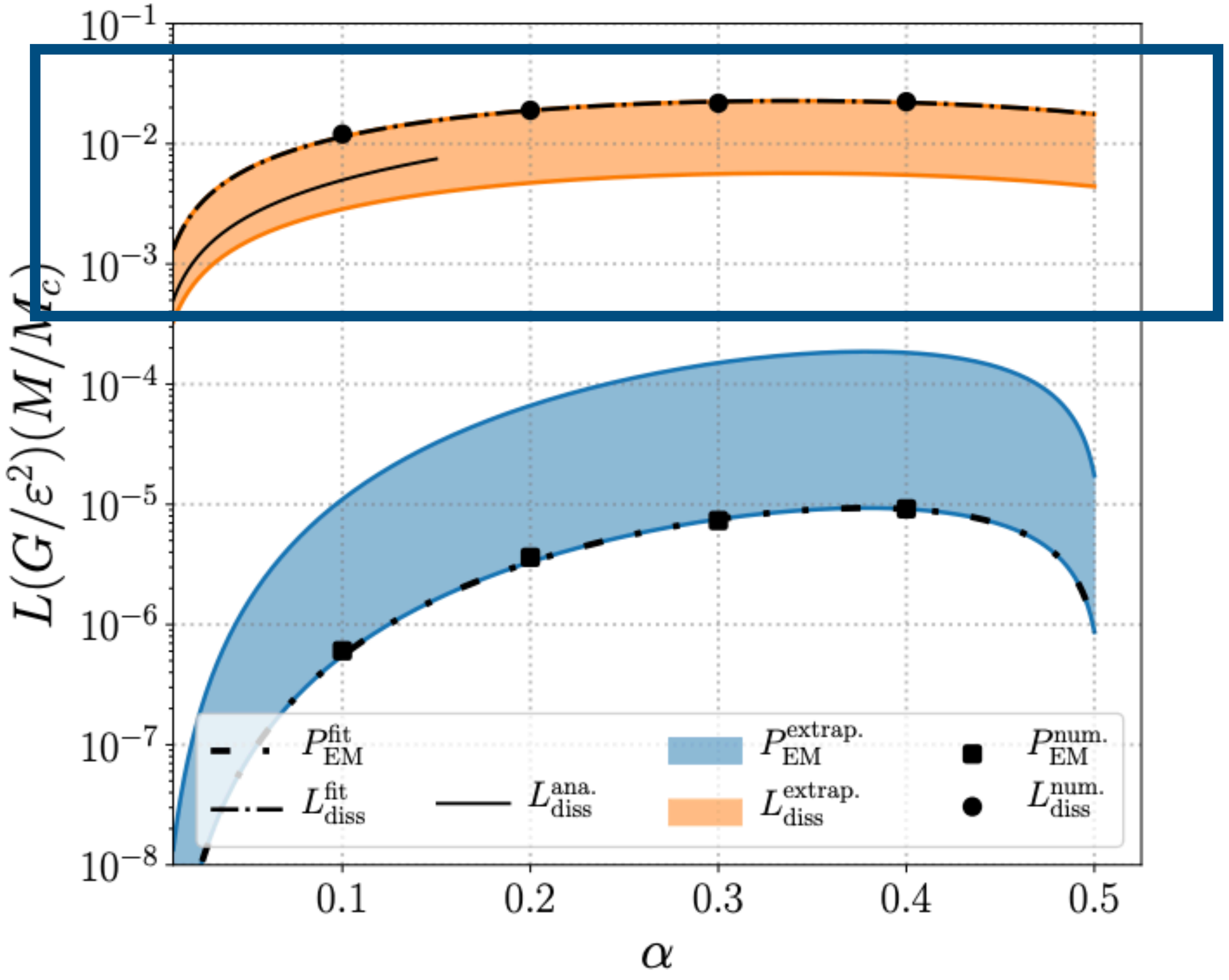
$$P_{\rm EM} = \oint dS\; \vec{r} \cdot (\vec{E} \times \vec{B})$$

- Dissipative losses

$$L_{\rm diss} = \int dV\, \vec{E} \cdot \vec{J}$$

Electrodynamics: power output

Numerical solutions and fit



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$$L_{\rm fit} = \varepsilon^2 F(\alpha) \frac{M_c}{GM}$$

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EM emissions

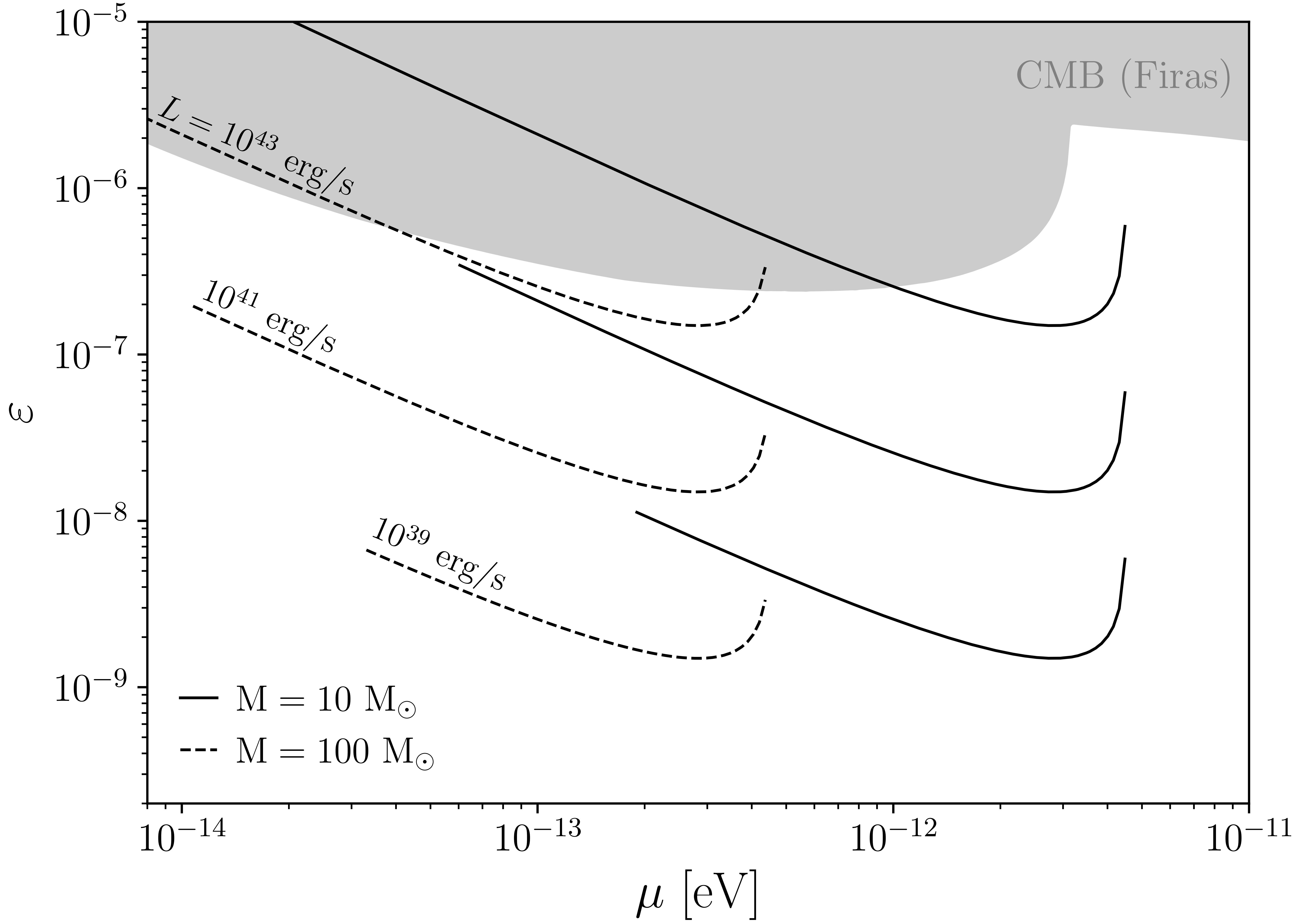
Luminosity of the dark photon superradiance cloud

$$L_{\text{fit}} = \varepsilon^2 F(\alpha)\frac{M_c}{GM}$$

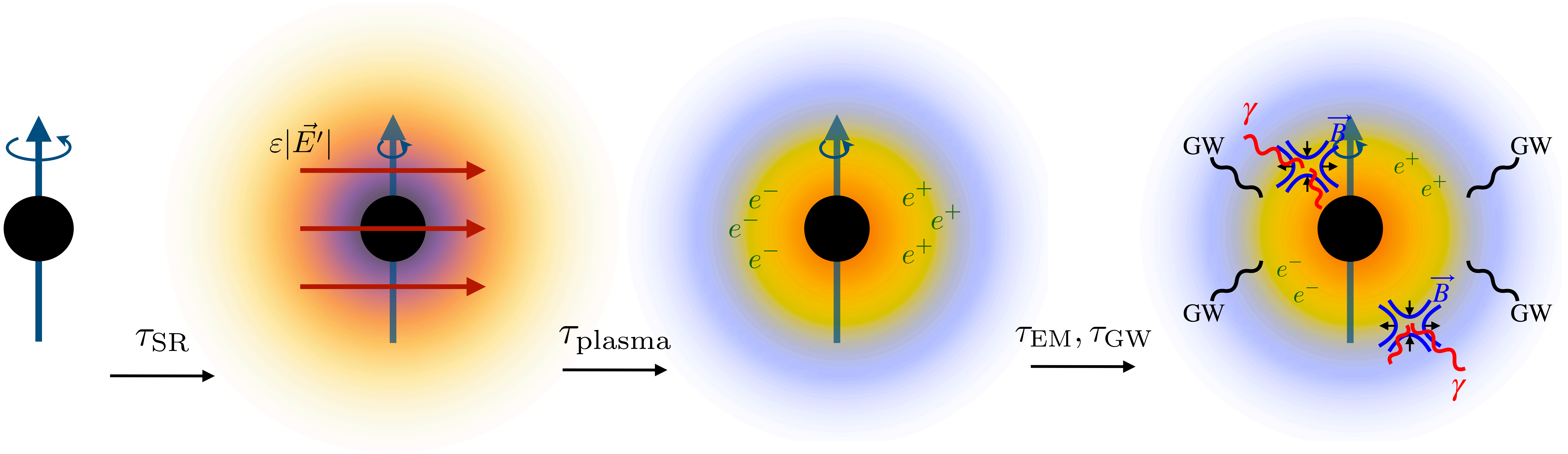
Crab pulsar $L_{\text{crab}} \simeq 10^{38}\ \text{erg/s}$

Supernova $L_{\text{SN}} \simeq 10^{43} - 10^{45}\ \text{erg/s}$

Peak luminosity



Evolution of the system

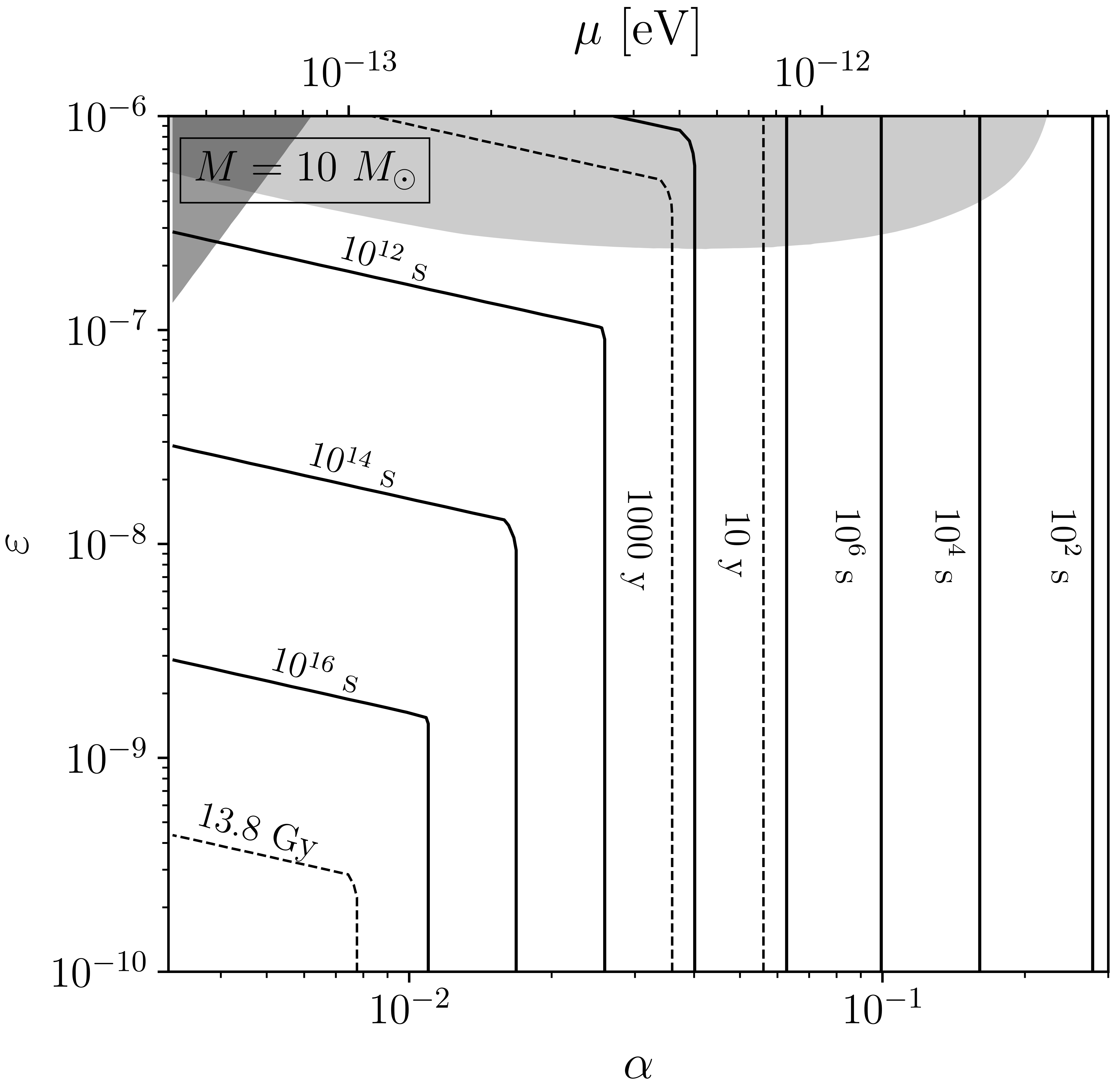


Decay of the superradiance cloud through gravitational wave and EM emissions.

Lifetime of the system

$$\tau_{\mathrm{GW}} \approx \frac{GM}{17\alpha^{11}\Delta a_*}$$

$$\tau_{\mathrm{EM}} \approx \frac{GM\ln 2}{\varepsilon^2 F(\alpha)}$$



EM emissions

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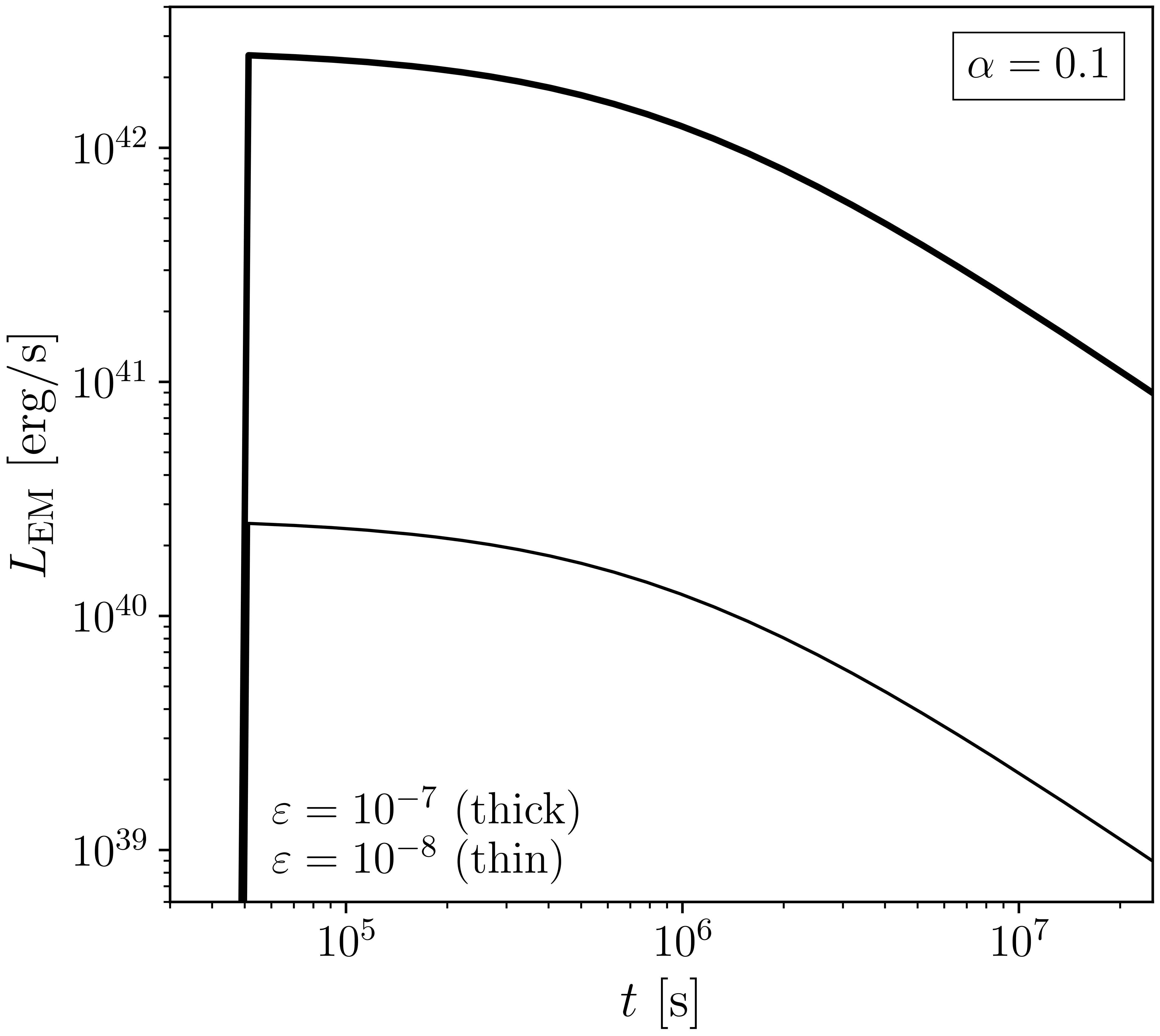
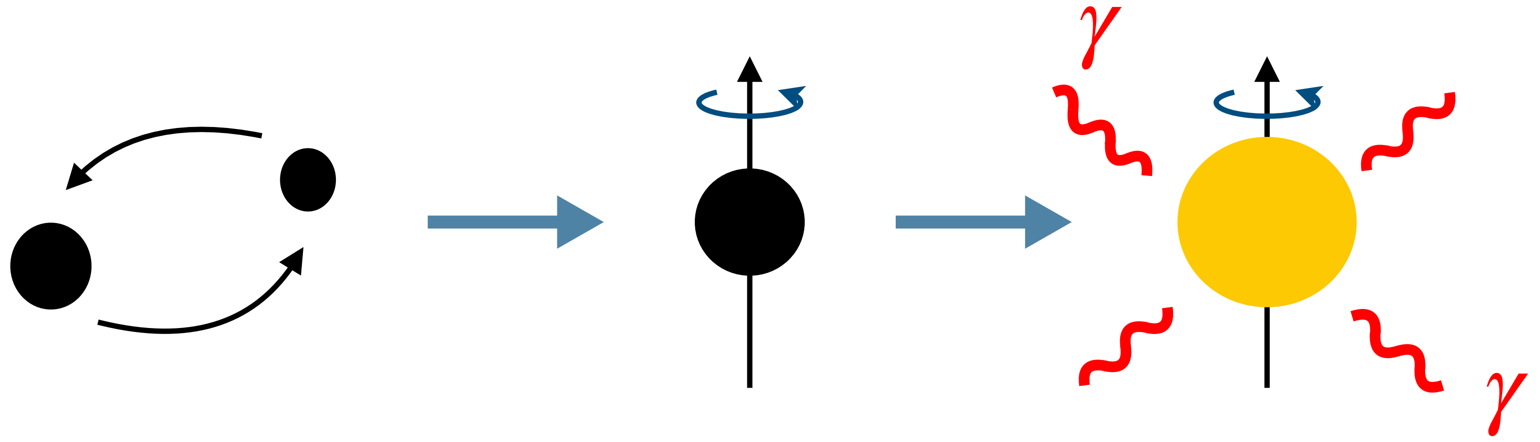
Time evolution

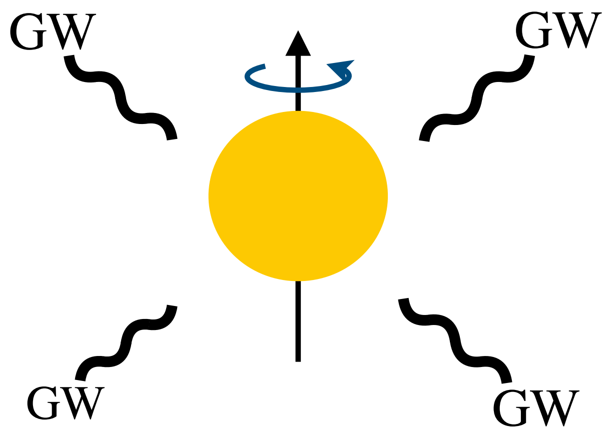


Observational strategies

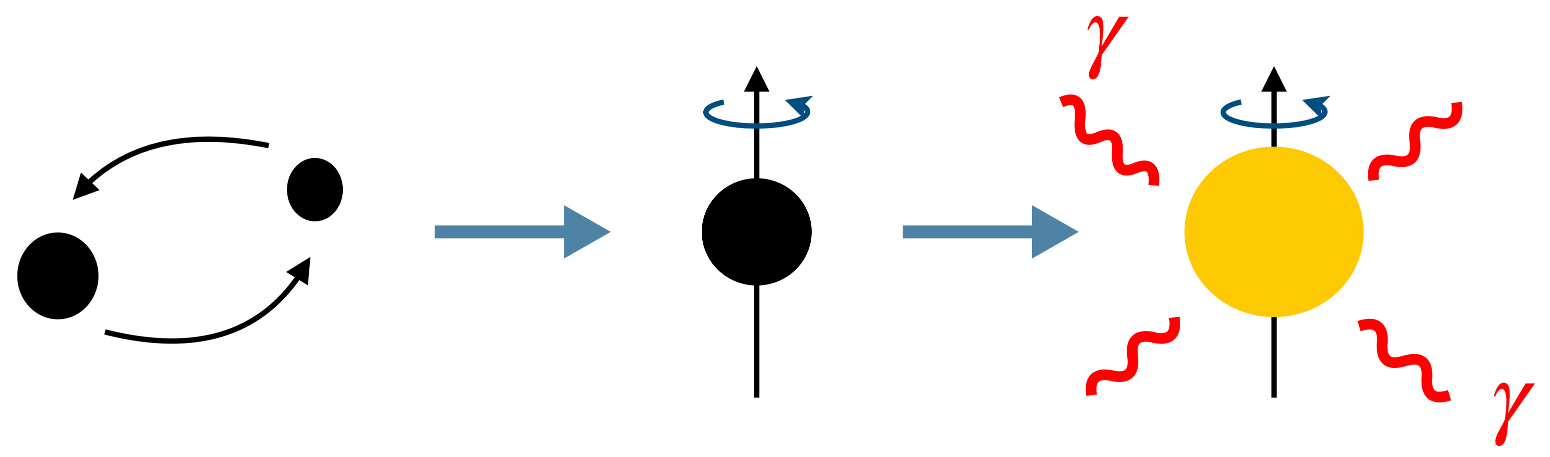
1. EM follow-ups of compact binary mergers
   (large α)

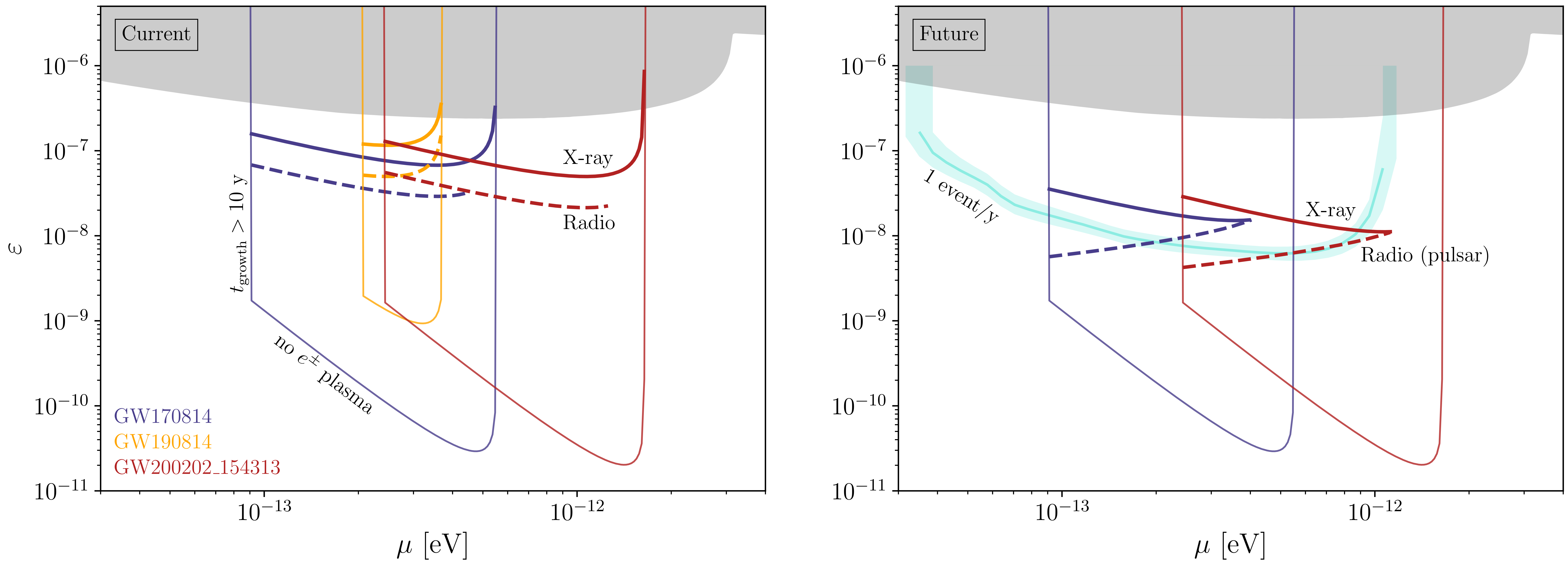


2. GW follow-ups of anomalous pulsars
   (small α)

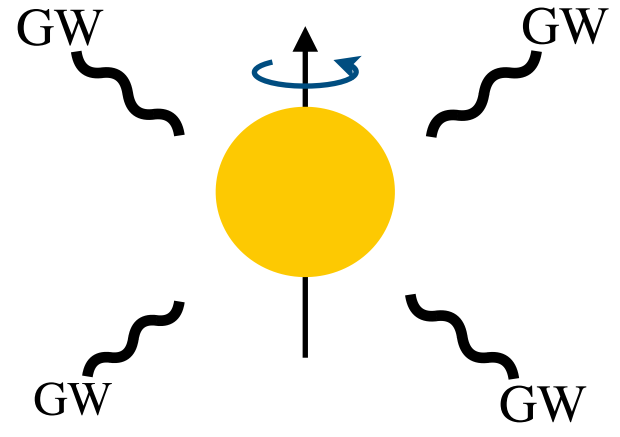


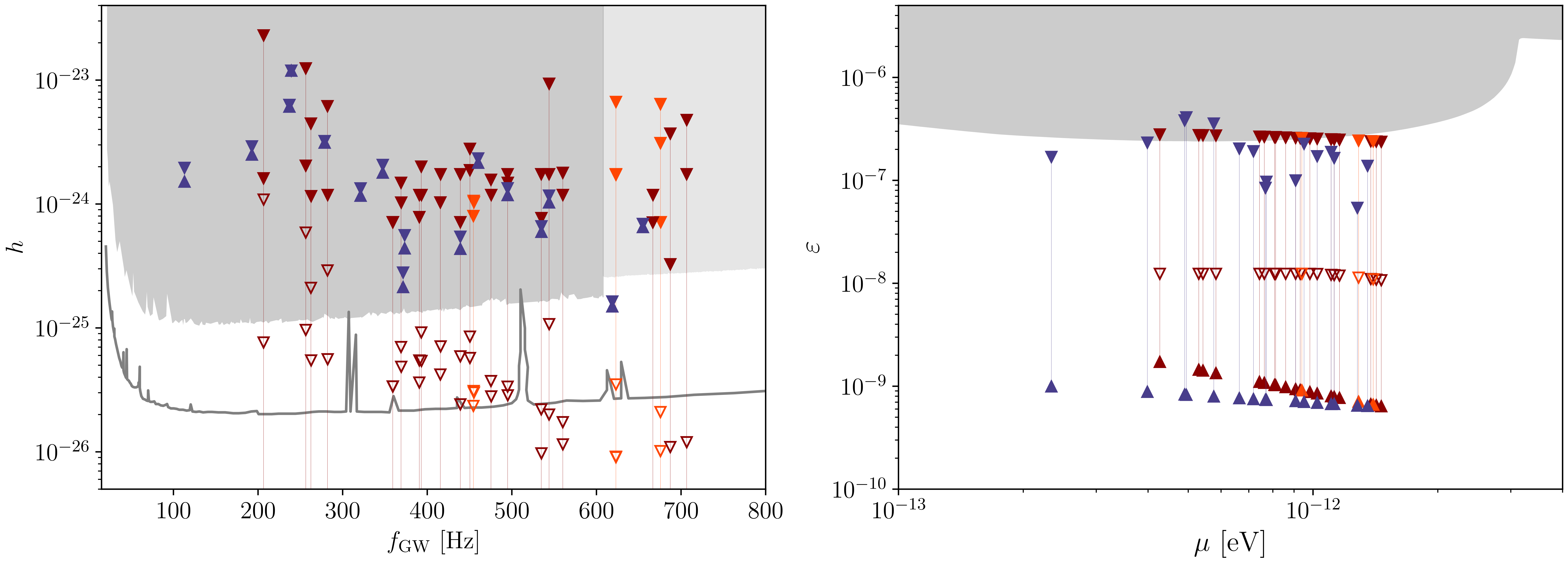
EM follow-up of BH mergers



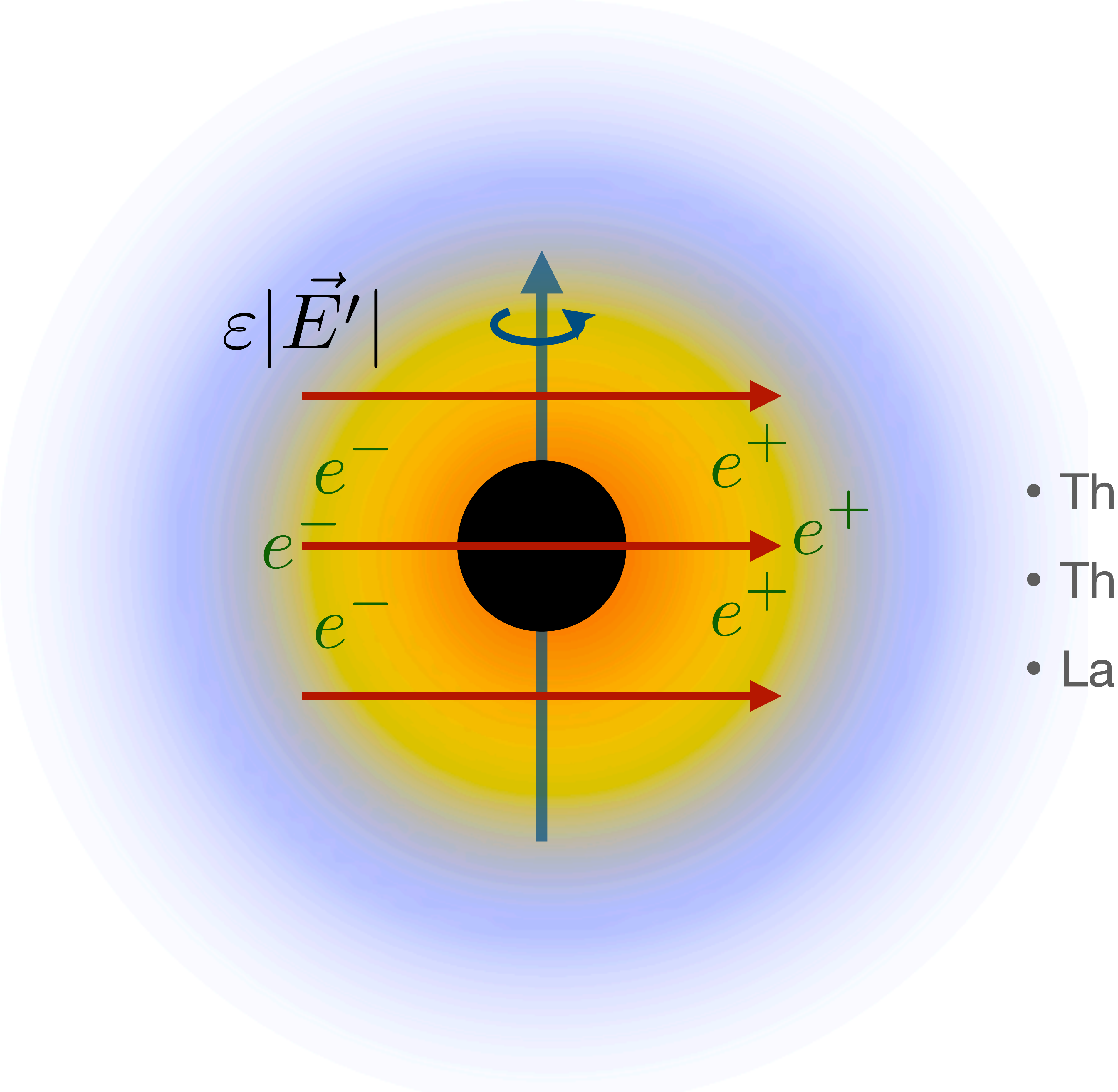


GW follow-up of anomalous pulsars





Summary



Black hole superradiance can probe ultralight dark photons with small kinetic mixing.

- The superradiance cloud is filled with a plasma of charged particles.
- The electrodynamics of the plasma + fields can be modeled in analogy to a pulsar.
- Large electromagnetic emissions are released.

Future directions:

- More robust predictions for the emission spectra and the periodicity.
- Ultraluminous X-ray sources or FRB.
- Supermassive BH.