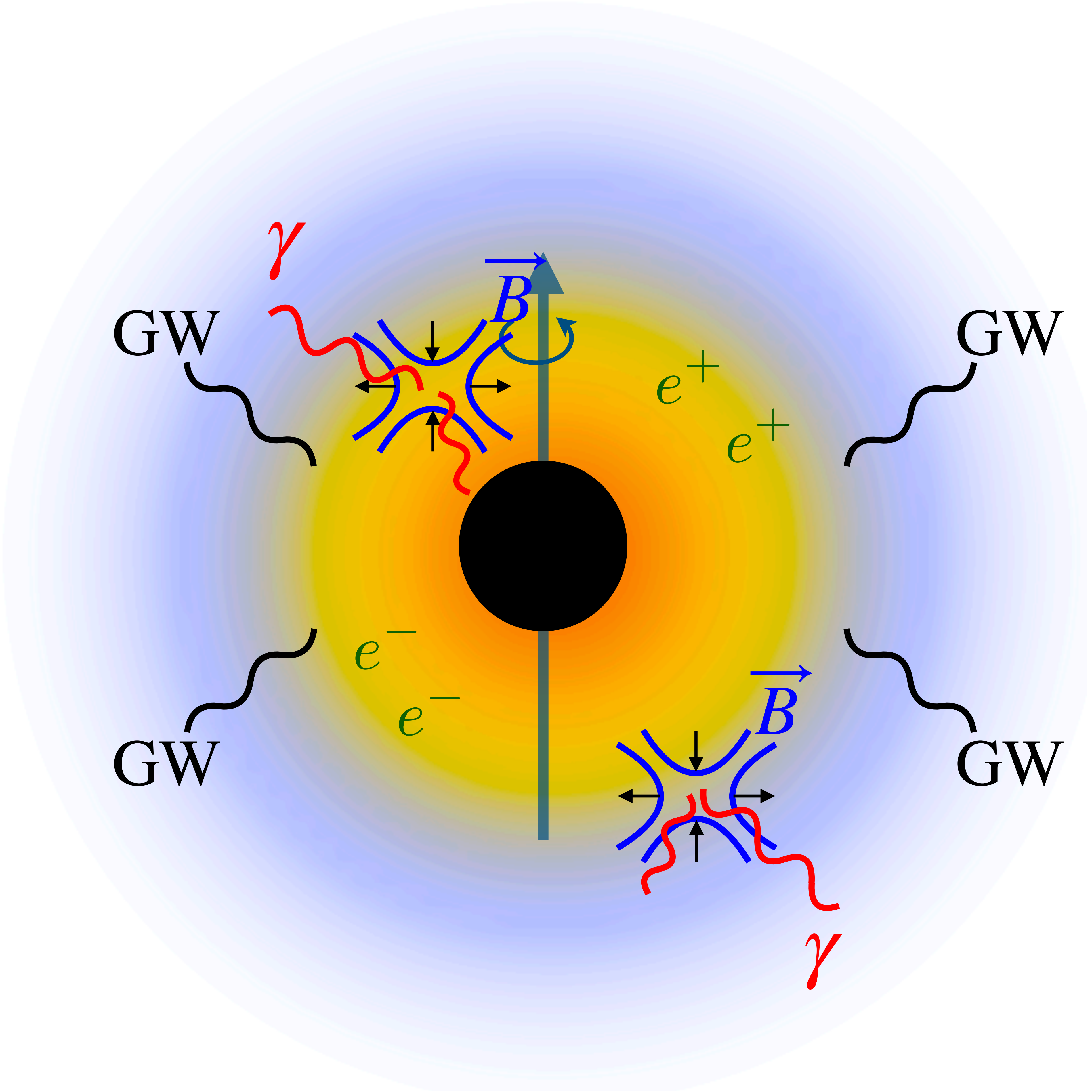


Multimessenger signals from dark photon superradiance

Cristina Mondino

PERIMETER INSTITUTE

Phys. Rev. D 107 075025, arxiv:2212.09772

With: Nils Siemonsen, Daniel Egaña-Ugrinovic, Junwu Huang, Masha Baryakhtar, and William E. East
+ ongoing work lead by Lorenzo Mirasola (U. Cagliari + CW group at INFN Roma/La Sapienza)

Pollica, 11th of September 2024

New ultralight bosons

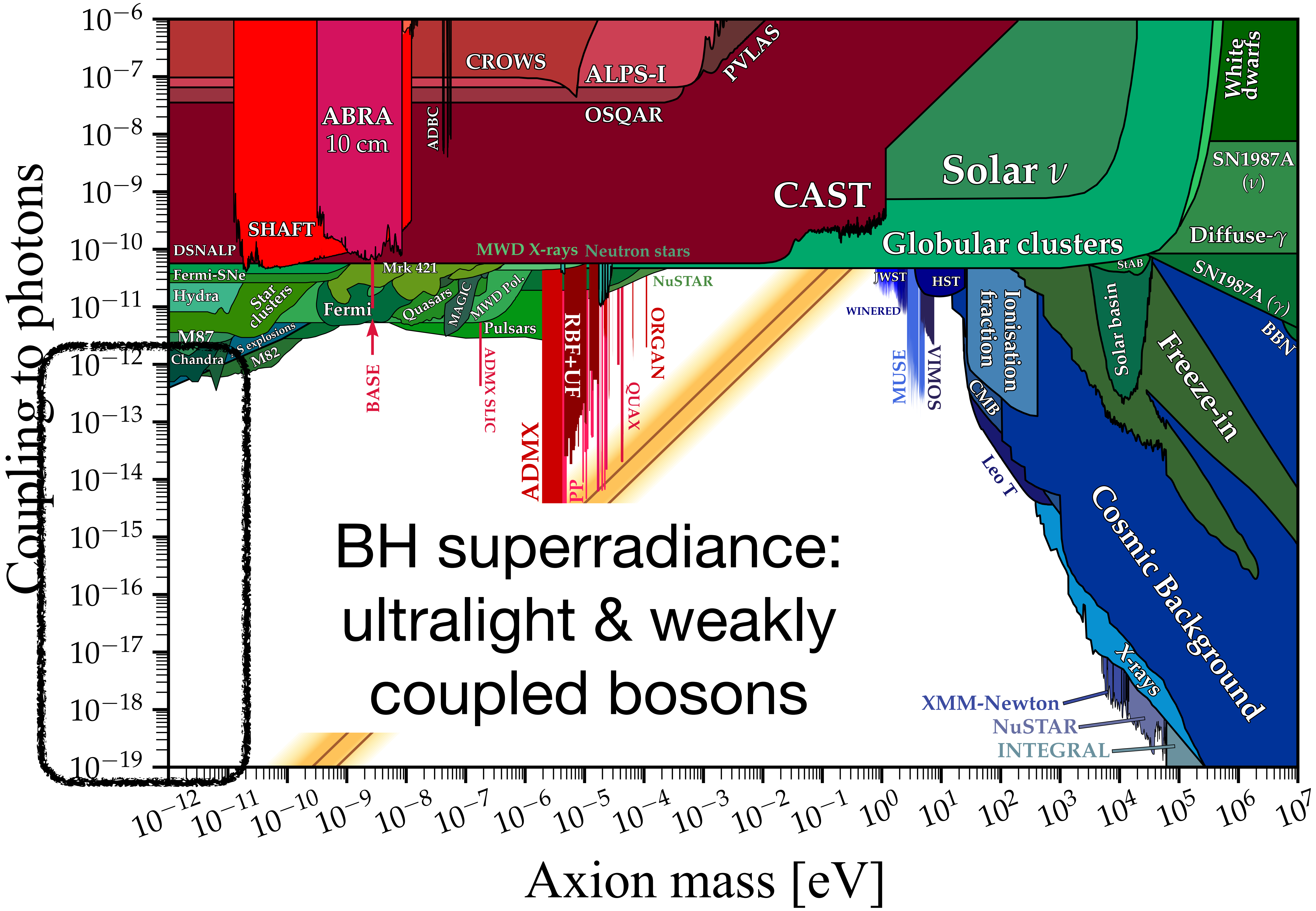
- Arise in several extensions of the DM (string theory)
- Good DM candidates or DM-SM mediators
- Naturally light (masses protected by approximate symmetries)
- Couple to SM particles

Spin 0 - QCD Axion/ALPs

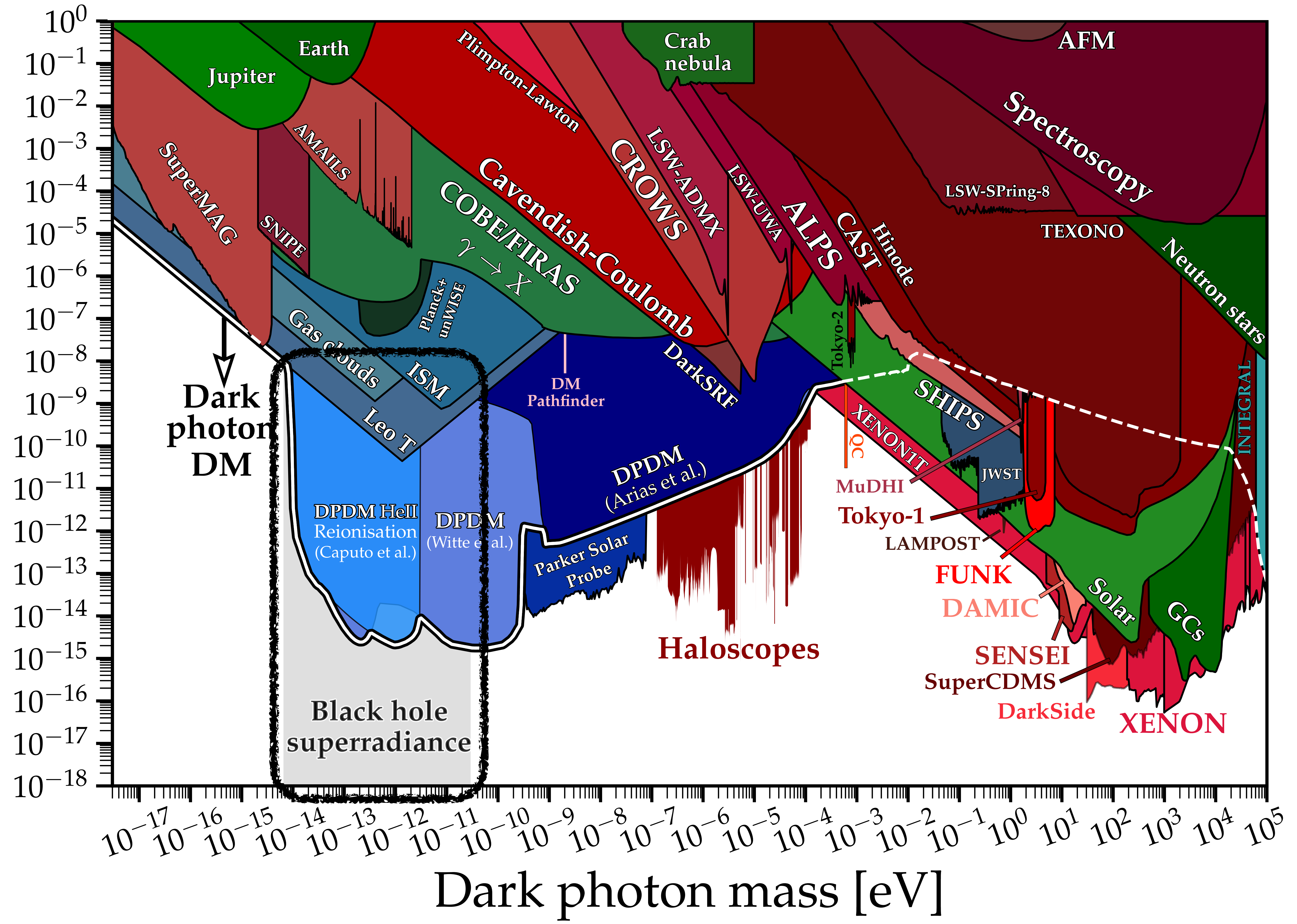
Spin 1 - Dark Photons

New bosons: coupling to photons

Spin 0 - QCD Axion/ALPs



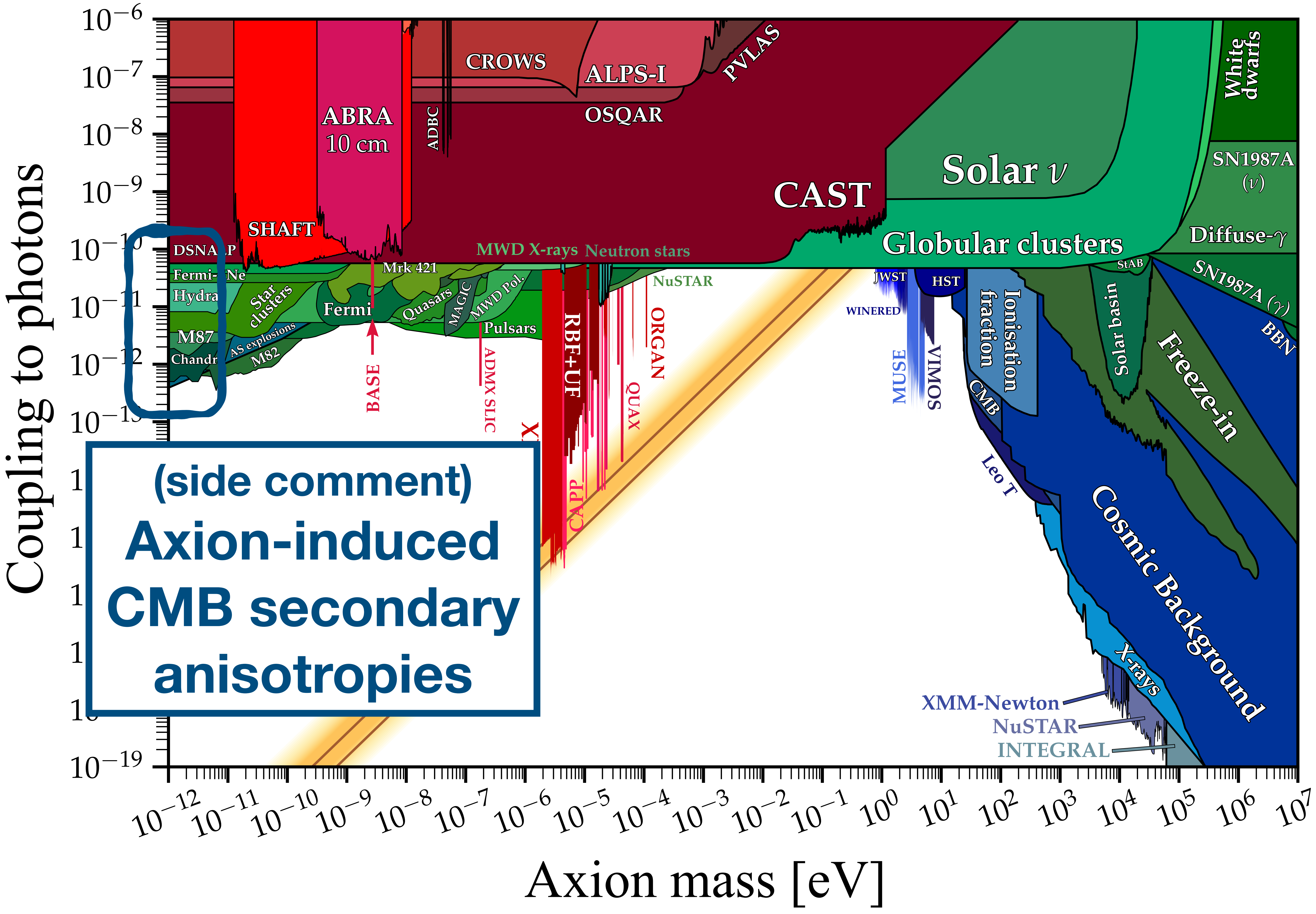
Spin 1 - Dark Photons



From Ciaran O'Hare (cajohare.github.io/AxionLimits/)

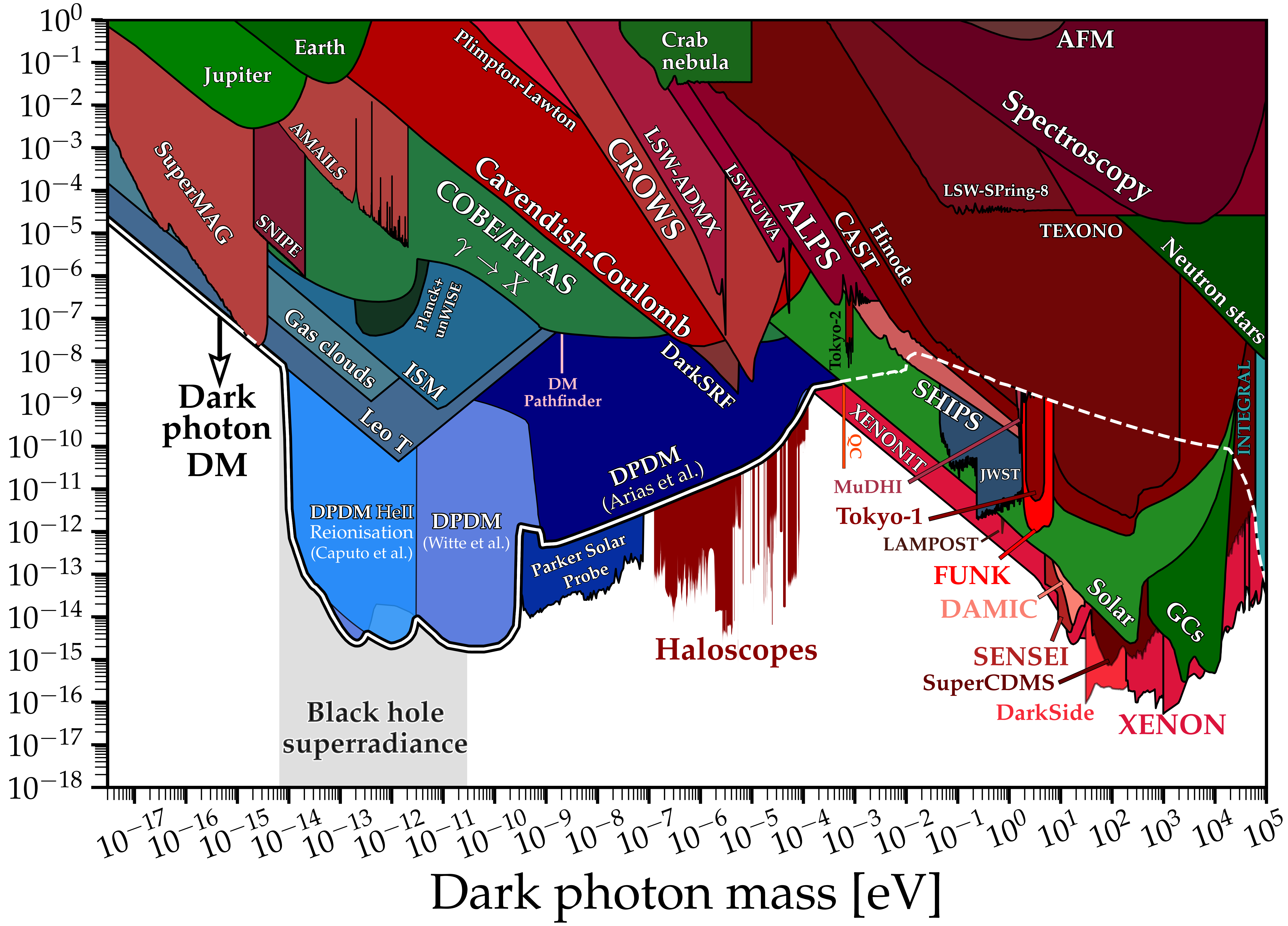
New bosons: coupling to photons

Spin 0 - QCD Axion/ALPs



(side comment)
Axion-induced CMB secondary anisotropies

Spin 1 - Dark Photons

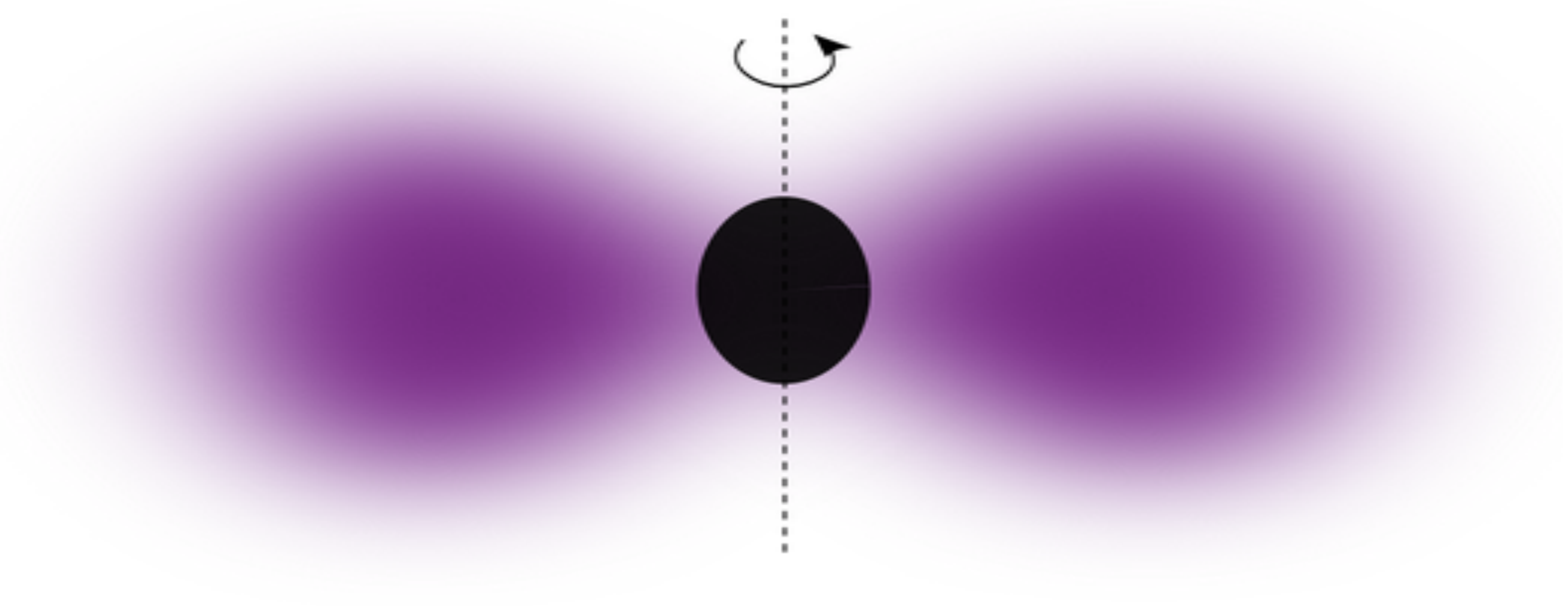


From Ciaran O'Hare (cajohare.github.io/AxionLimits/)

How are ultralight particles produced?

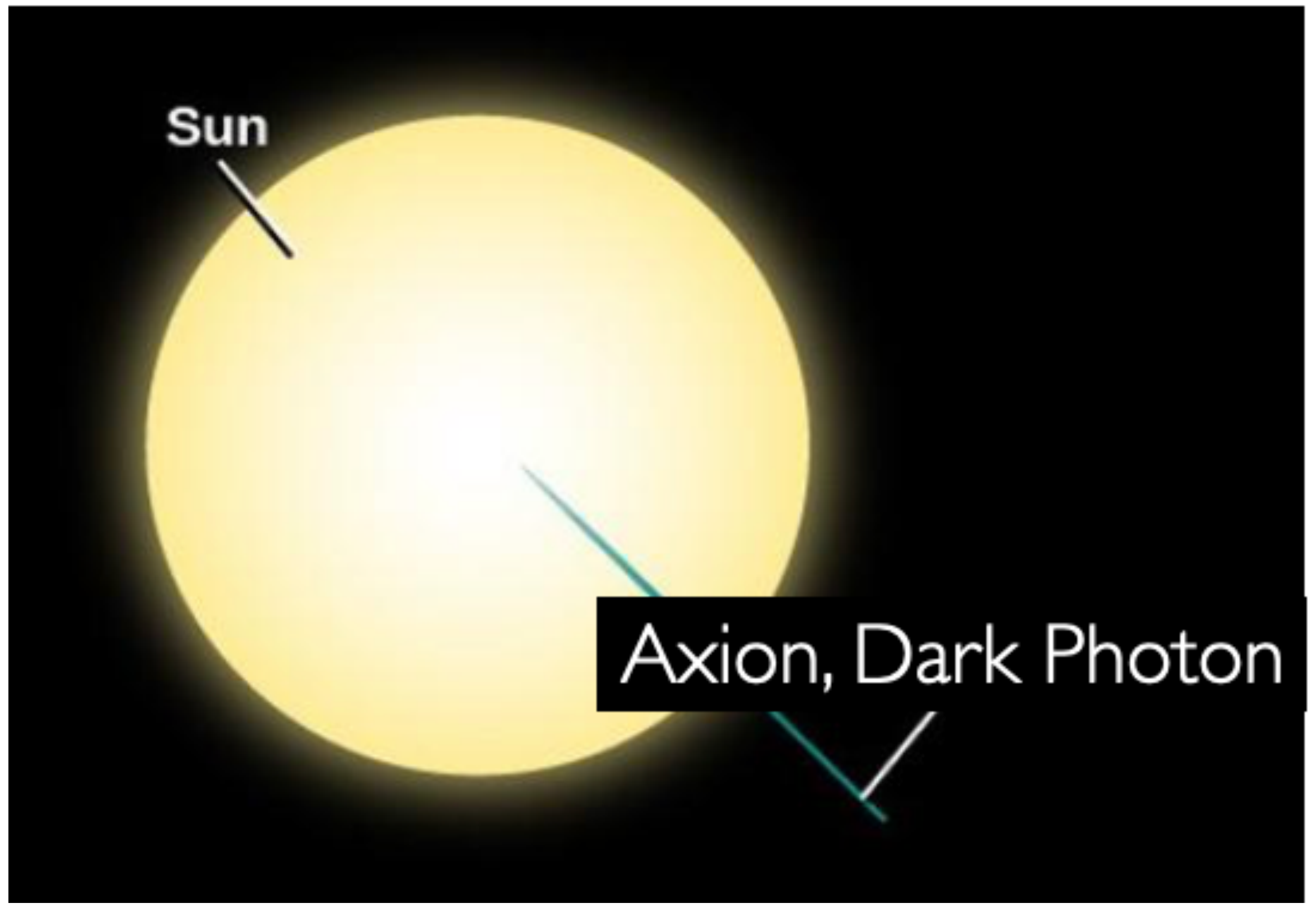
Gravitational coupling

- Around spinning black holes



Additional coupling

- Stars/SNe



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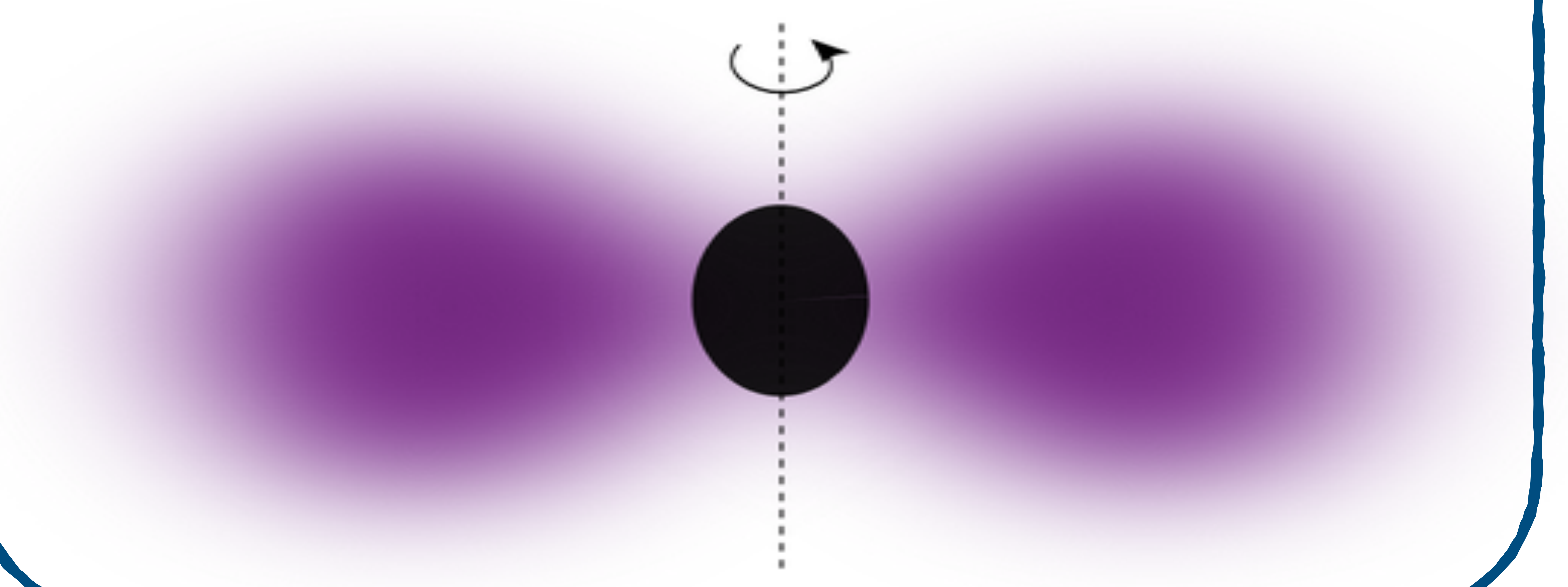

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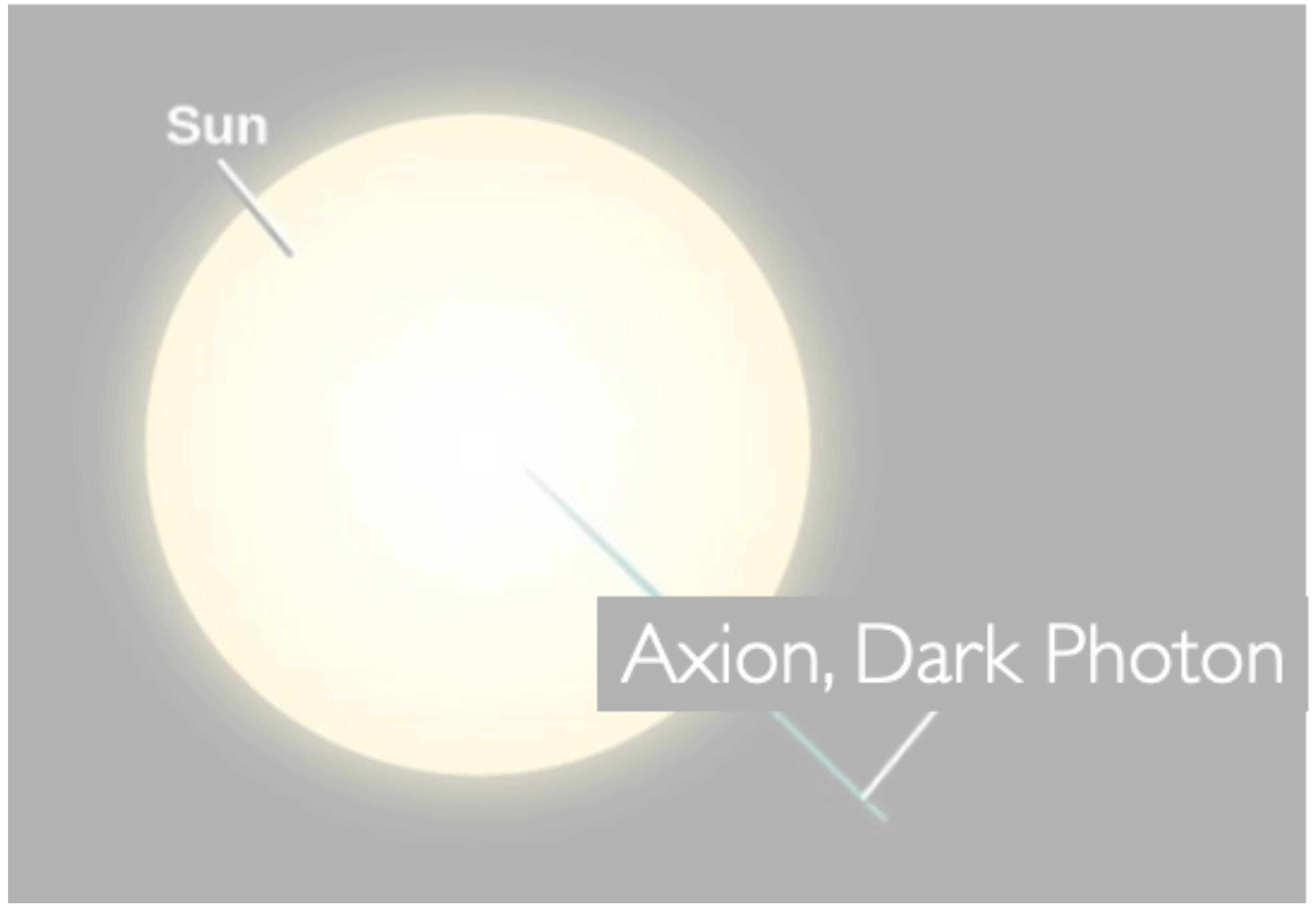


The existence of astrophysical BHs *guarantees* the production of these particles!

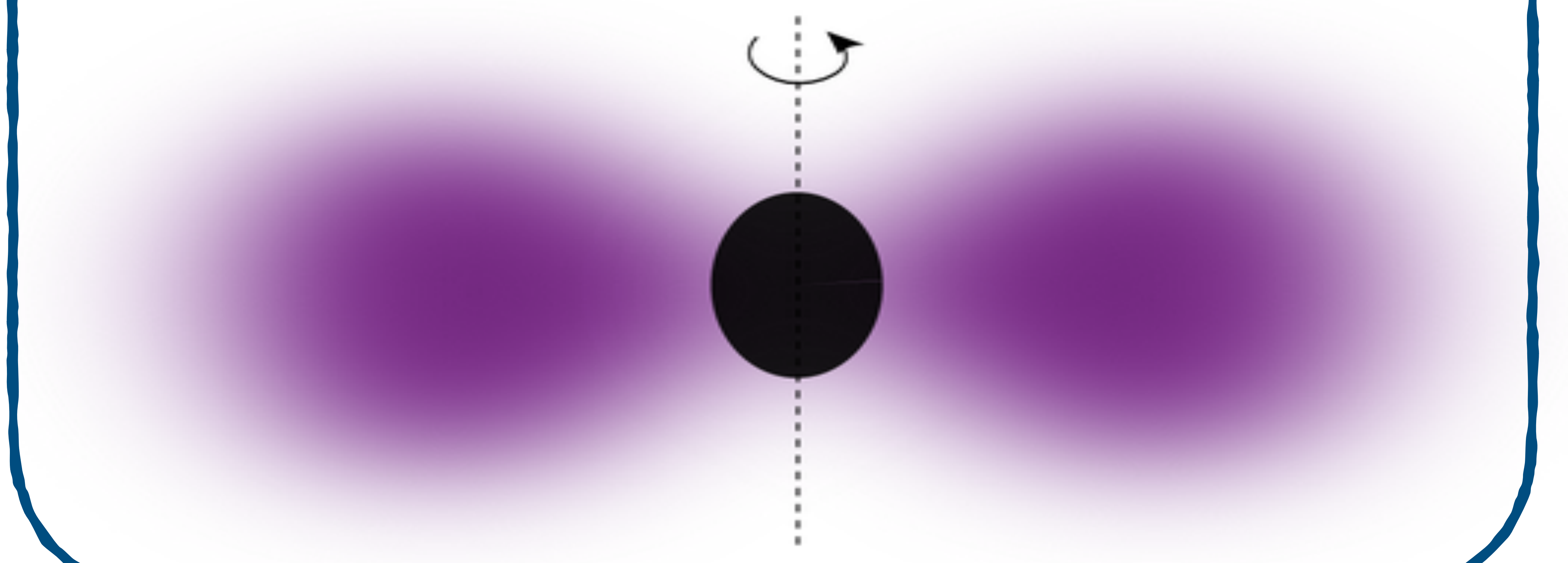
How are ultralight particles produced?

Gravitational coupling

- Around spinning black holes

(stellar mass BH)
Compton wavelength ~ km

$$m \sim \frac{1}{GM} \sim 10^{-12}\mathrm{eV}$$



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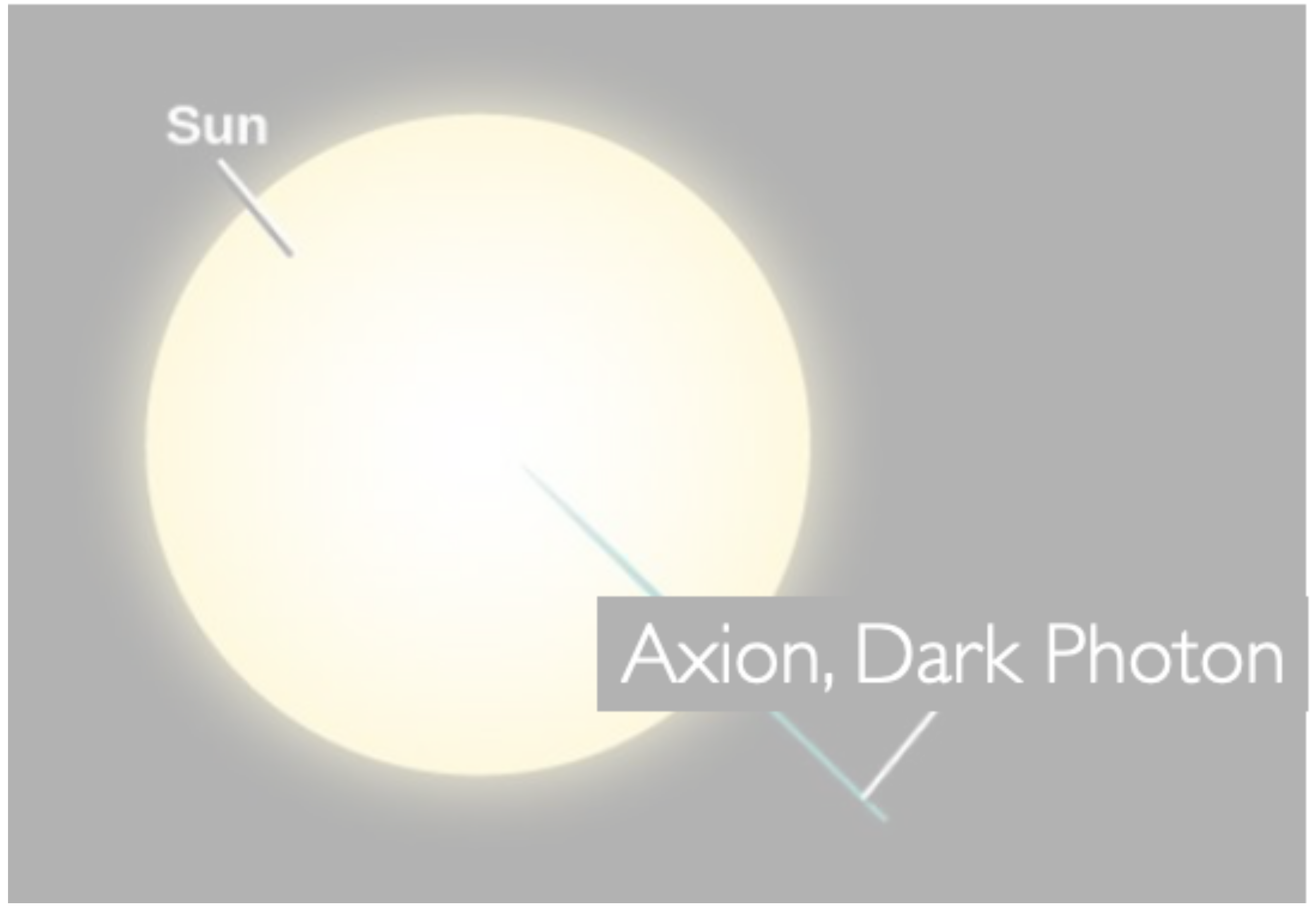


(very quick review of)

Black Hole Superradiance

— see also Will East talk next Wednesday —

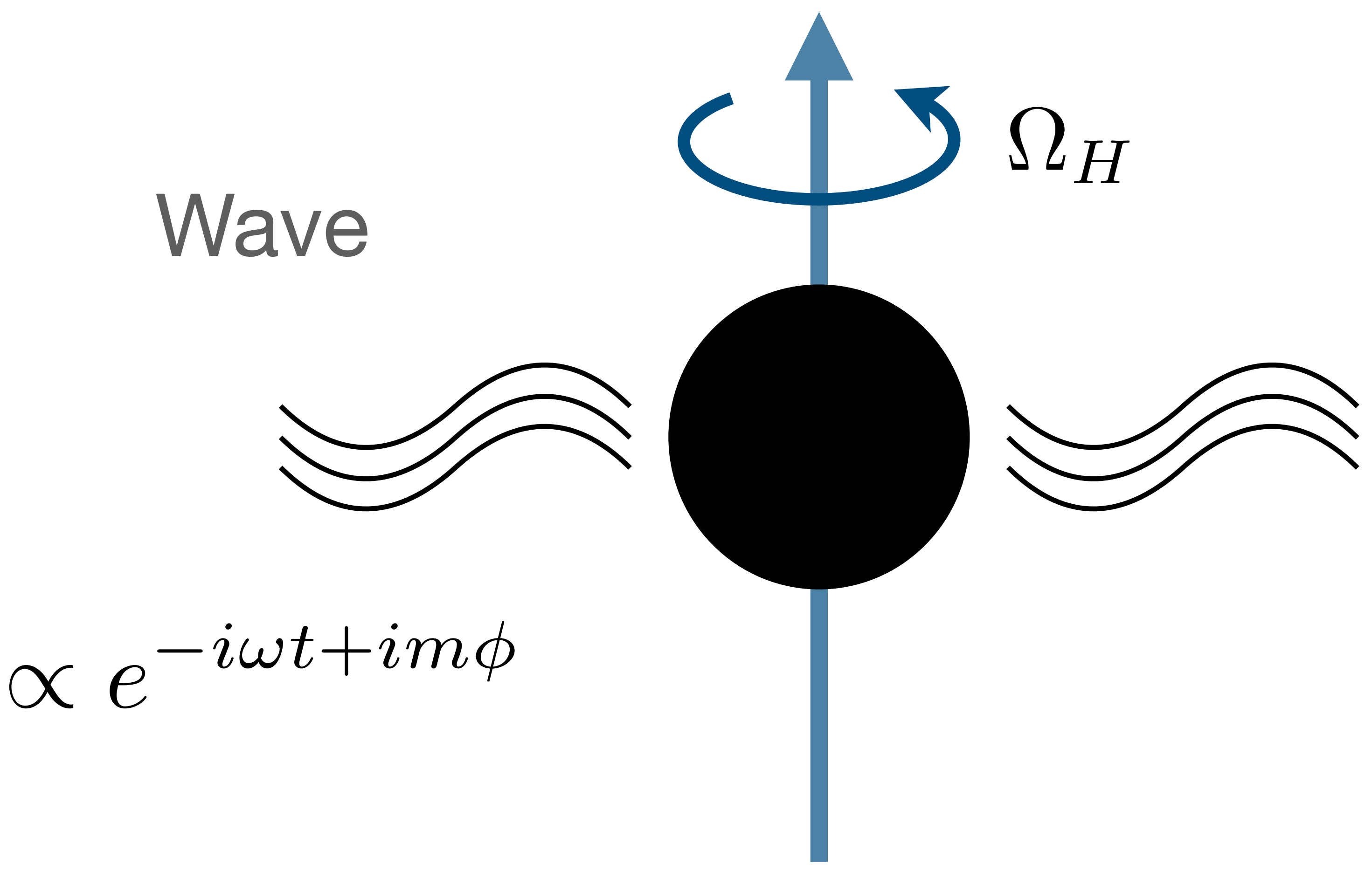
Cristina Mondino

Black hole superradiance

Y. B. Zeldovich, 1971
C. W. Misner, 1972
A. A. Starobinskii, 1973
S. L. Detweiler, 1980
....

Classical instability:

- Rotating object
- Perfect absorber
  (dissipation is necessary)



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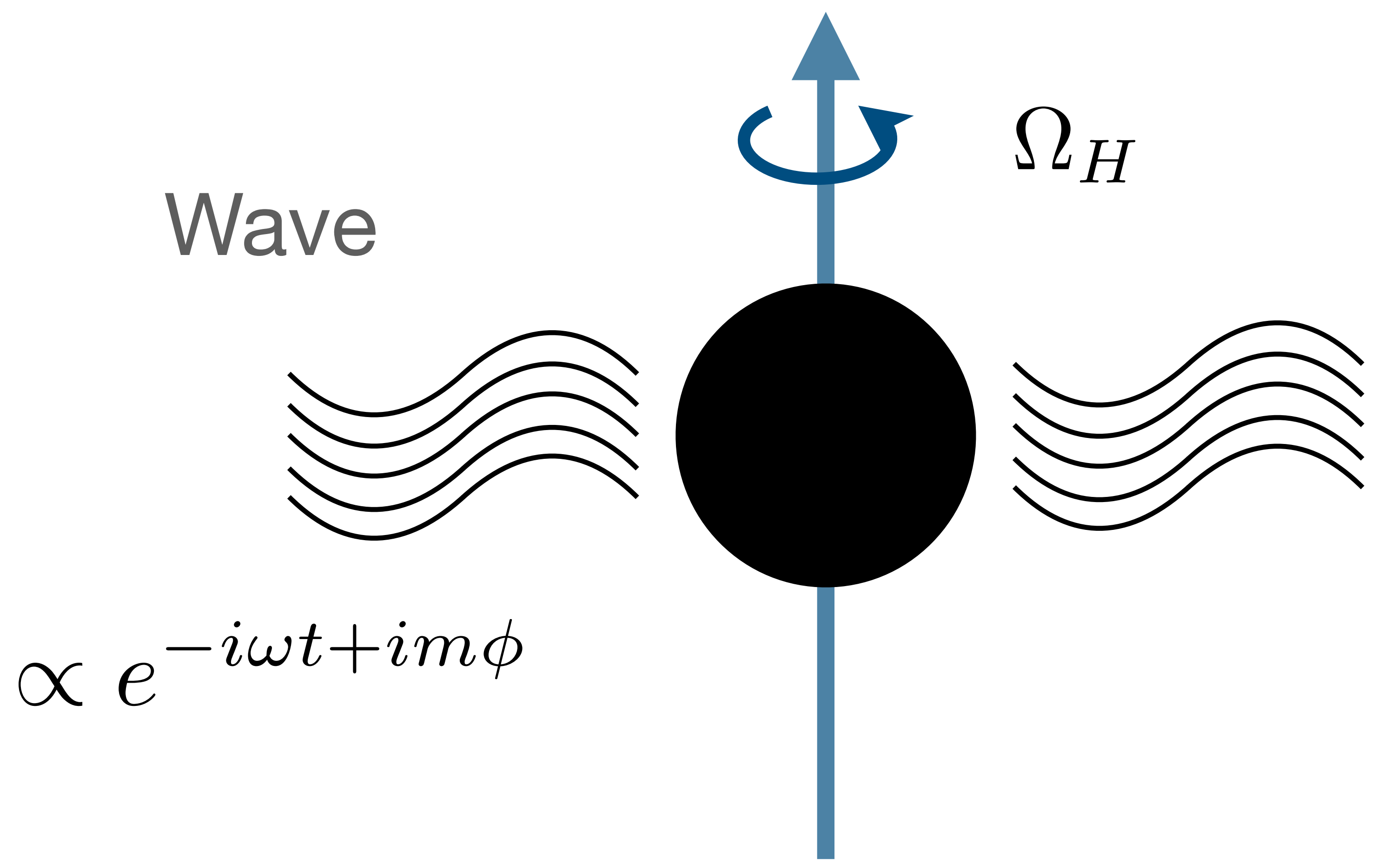

If $\dfrac{\omega}{m} < \Omega_H$:

- Wave is amplified
- BH spins down

Black hole superradiance

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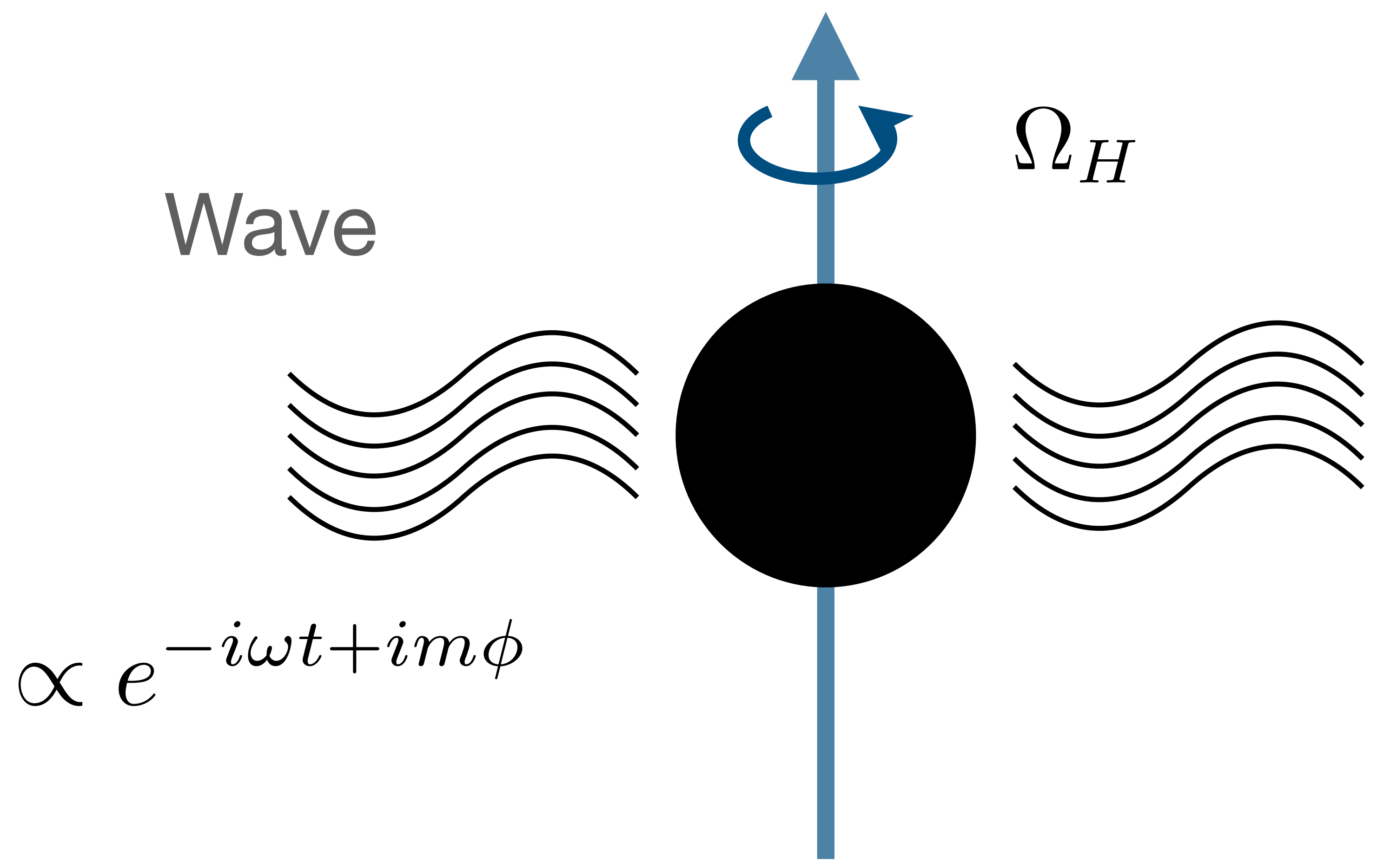

If $\dfrac{\omega}{m} < \Omega_H$:

- Wave is amplified
- BH spins down

Massive bosonic field with mass μ

$$V(r) = -\frac{GM\mu}{r}$$

- Gravitationally bound to the BH
- Occupation number of the "gravitational atom" grows exponentially

Black hole superradiance

Y. B. Zeldovich, 1971
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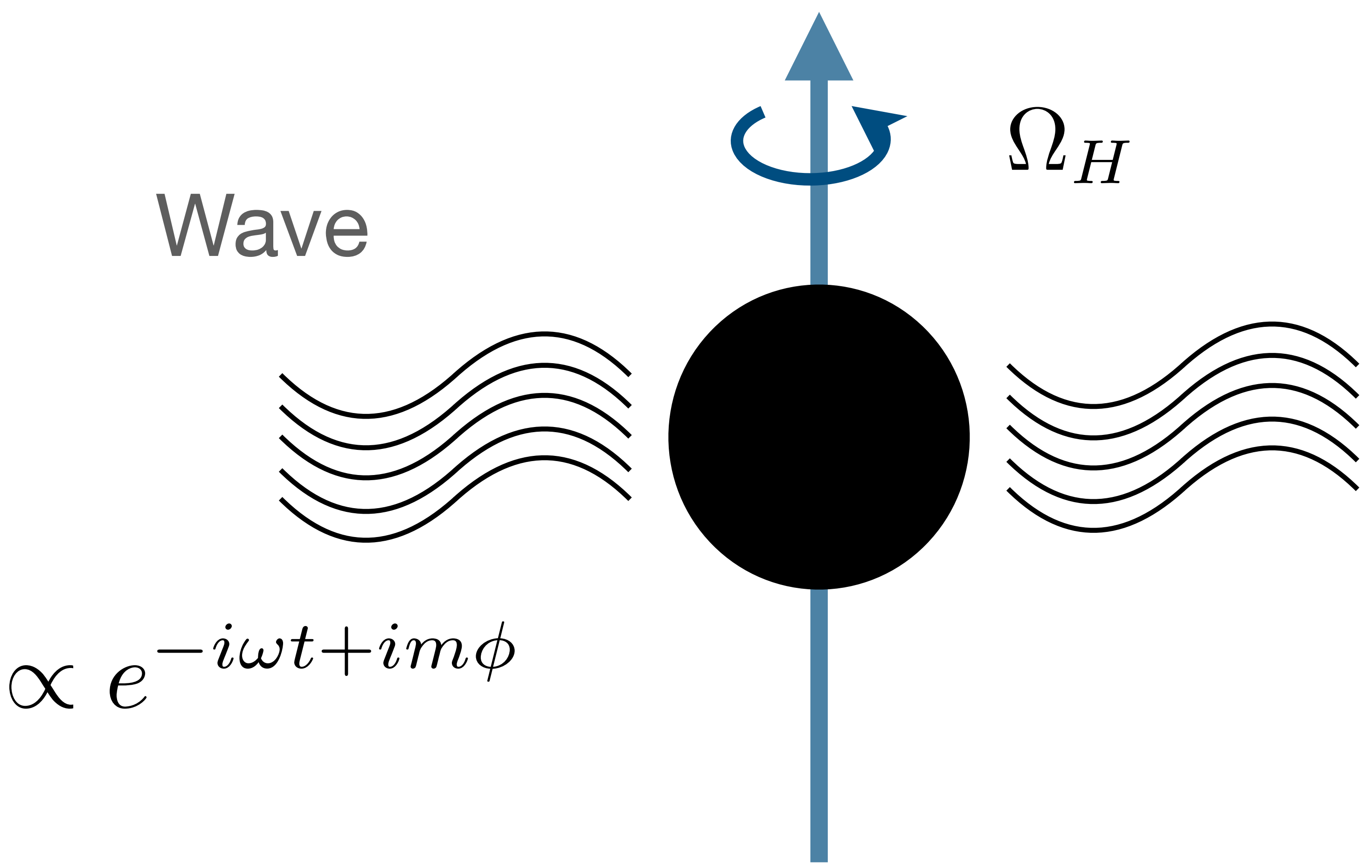

If $\dfrac{\omega}{m} < \Omega_H$:

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Massive bosonic field with mass μ

$$V(r) = -\frac{GM\mu}{r}$$

$GM\mu \rightarrow \alpha$

Superradiance condition for maximally spinning BH requires:

$$\frac{\alpha}{m} < \frac{1}{2}$$

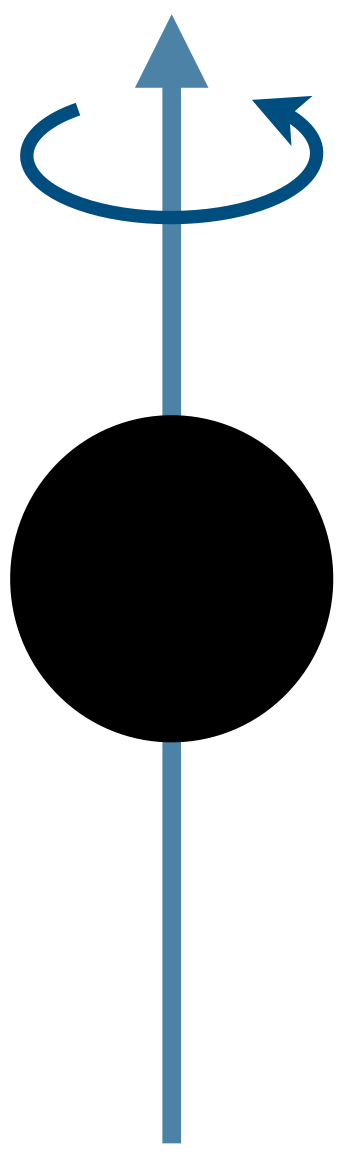
Non relativistic modes $\omega \simeq \mu$

Black hole superradiance - spin 1 field

M. Baryakhtar, R. Lasenby, M. Teo, PRD 2017
D. Bauman, H.S. Chia, J. Stout, L.T. Haar JCAP 2019

New massive vector boson

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



EOM in Kerr spacetime

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

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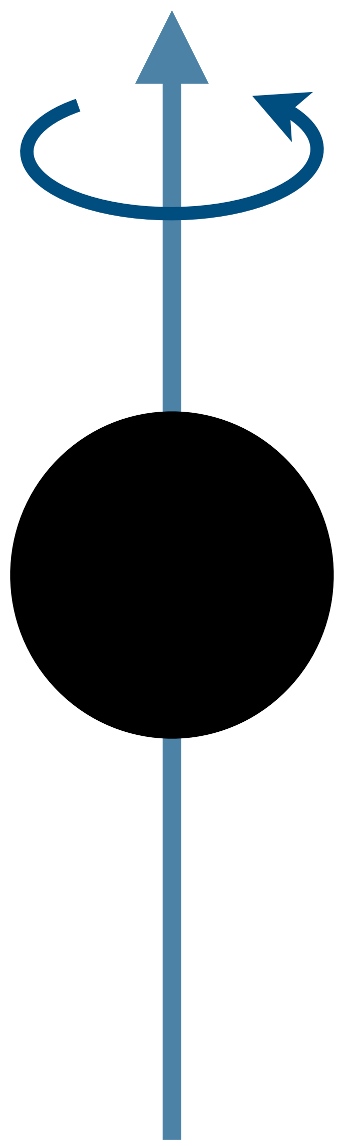

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- Hydrogen-like wave functions
- Energy with imaginary component if $\frac{\mu}{m} \lesssim \Omega_H$

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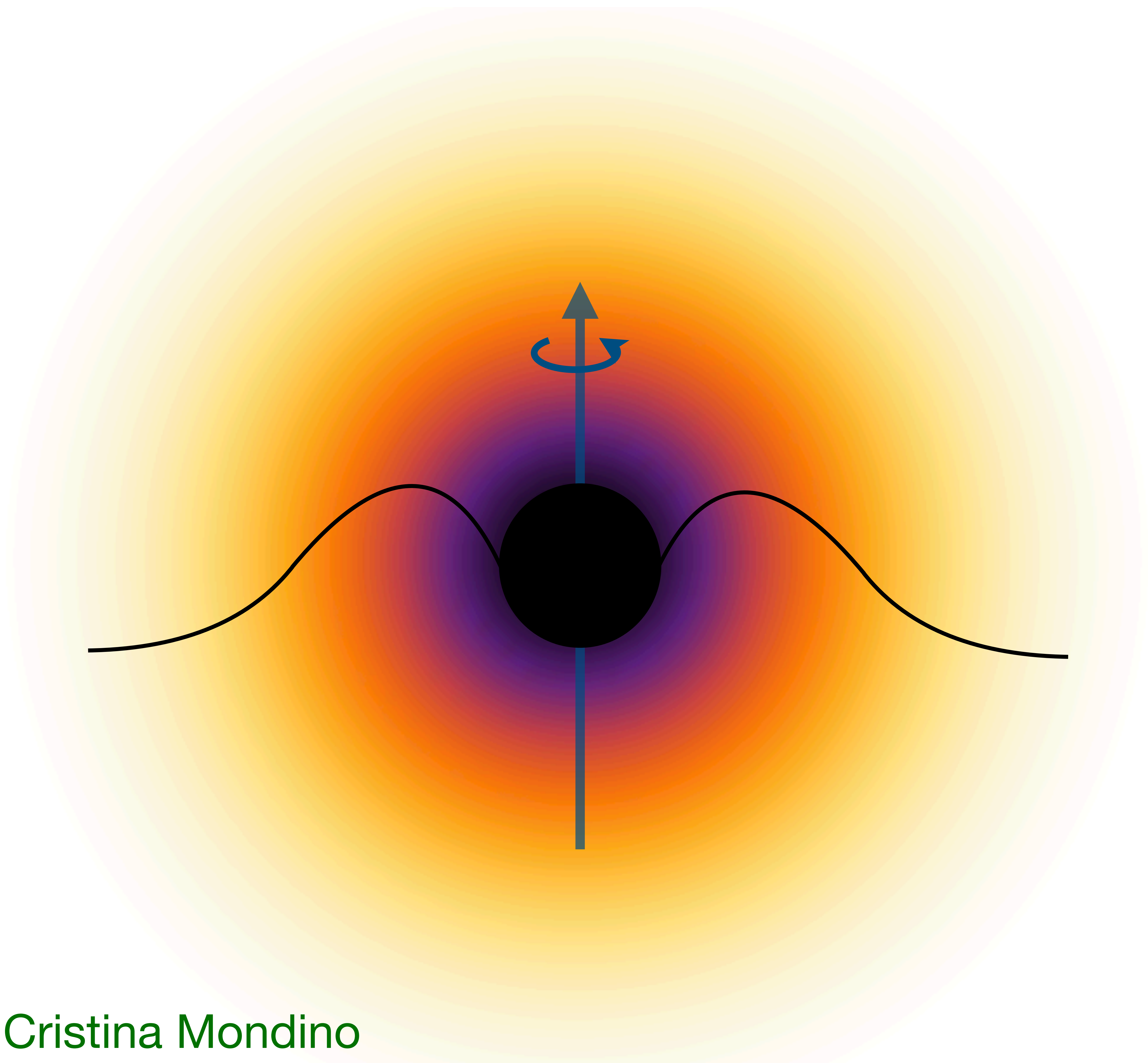

EOM in Kerr spacetime

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

- Hydrogen-like wave functions
- Energy with imaginary component if $\frac{\mu}{m} \lesssim \Omega_{\mathrm{H}}$

"Gravitational atom" with exponential growth of the occupation number.

$$N \simeq 10^{77}\left(\frac{M}{10\ M_\odot}\right)^2\left(\frac{\Delta a^*}{0.1}\right)$$

Black hole superradiance - spin 1 field

M. Baryakhtar, R. Lasenby, M. Teo, PRD 2017
D. Bauman, H.S. Chia, J. Stout, L.T. Haar JCAP 2019

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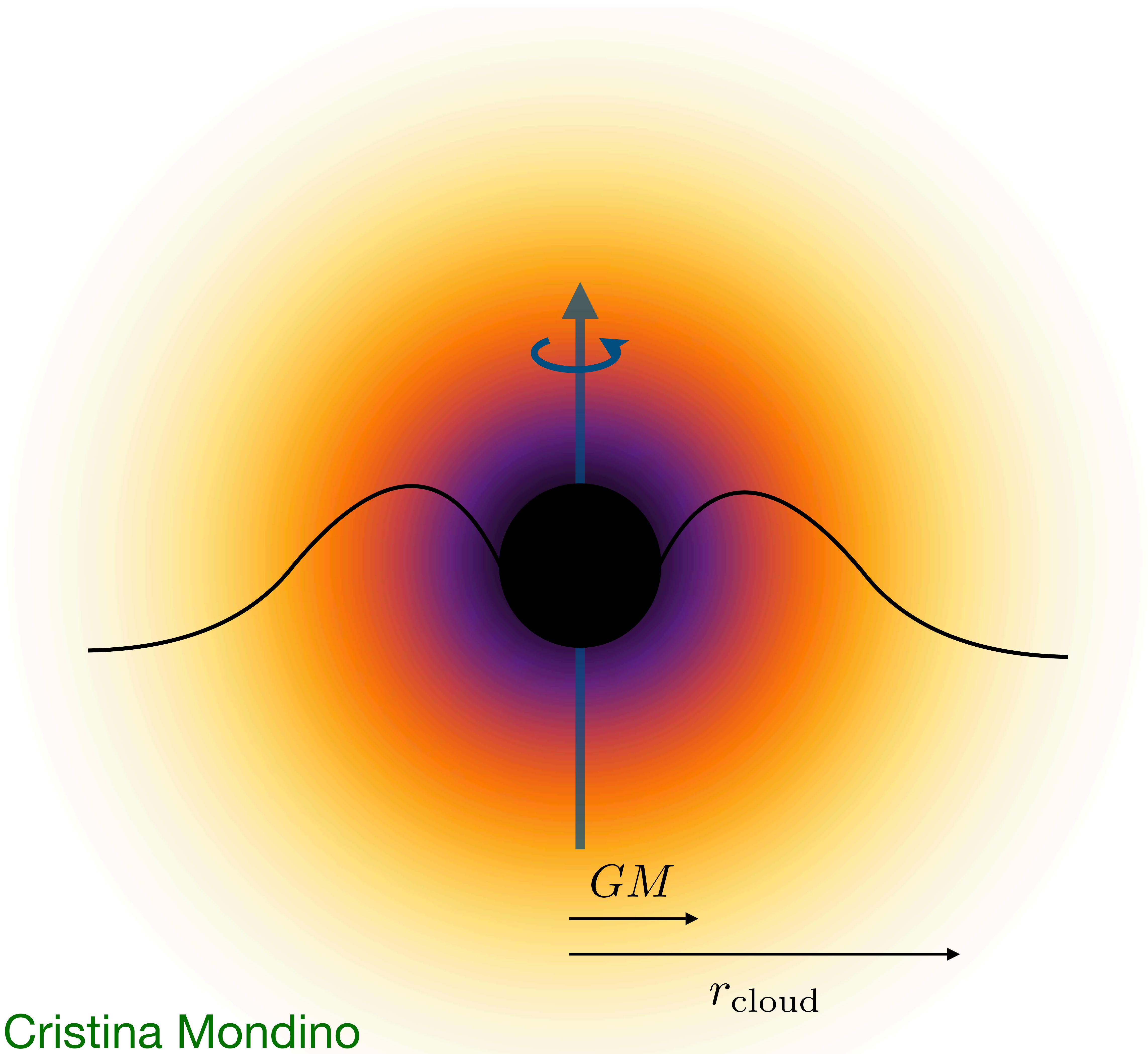

“Gravitational atom” with exponential growth of the occupation number.

Lowest energy level (n=0, l=0, m=1)

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

gravitational coupling $\alpha \equiv \mu GM$

Black hole superradiance - spin 1 field

M. Baryakhtar, R. Lasenby, M. Teo, PRD 2017
D. Bauman, H.S. Chia, J. Stout, L.T. Haar JCAP 2019

New massive vector boson

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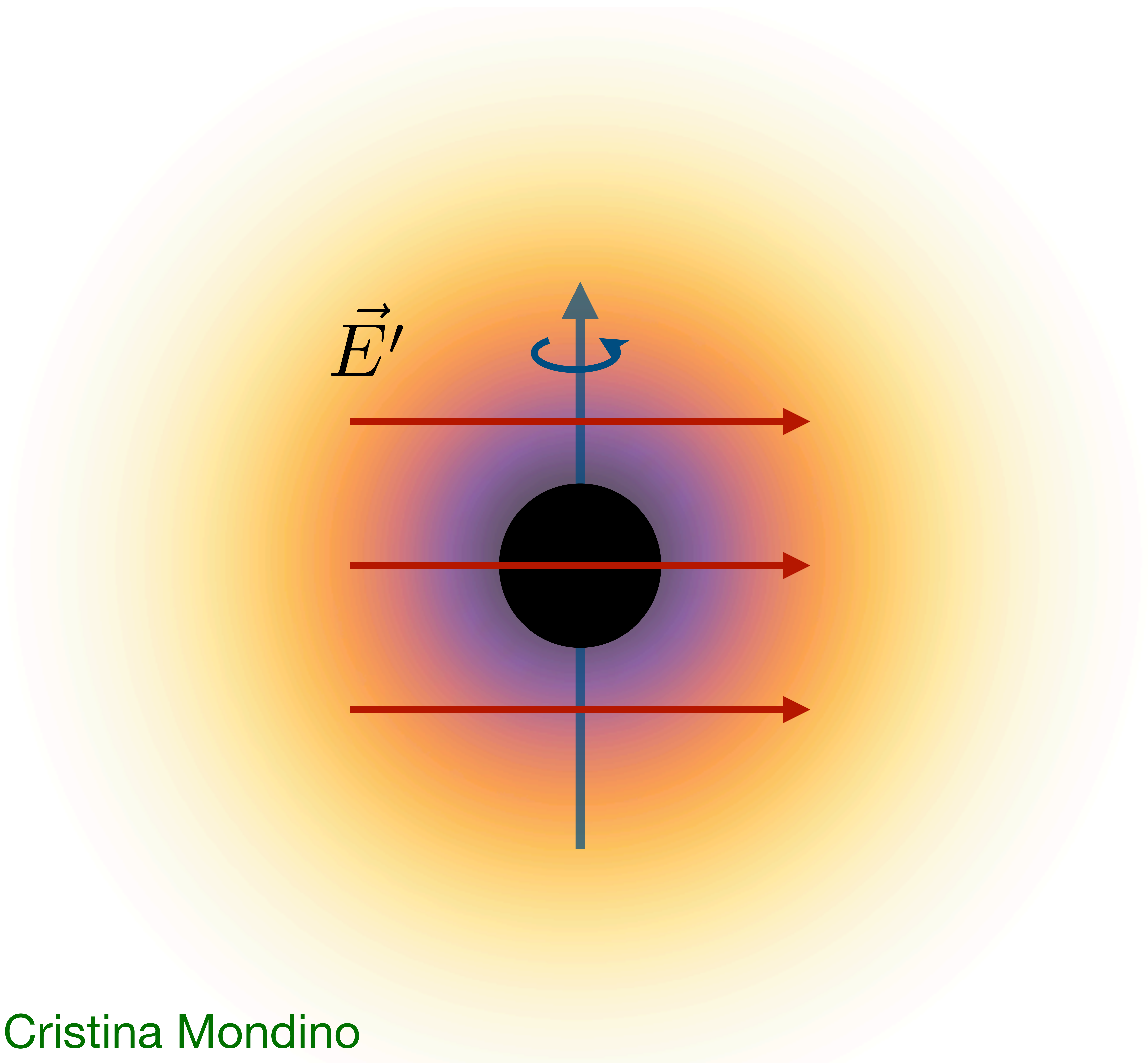


"Gravitational atom" with exponential growth of the occupation number.

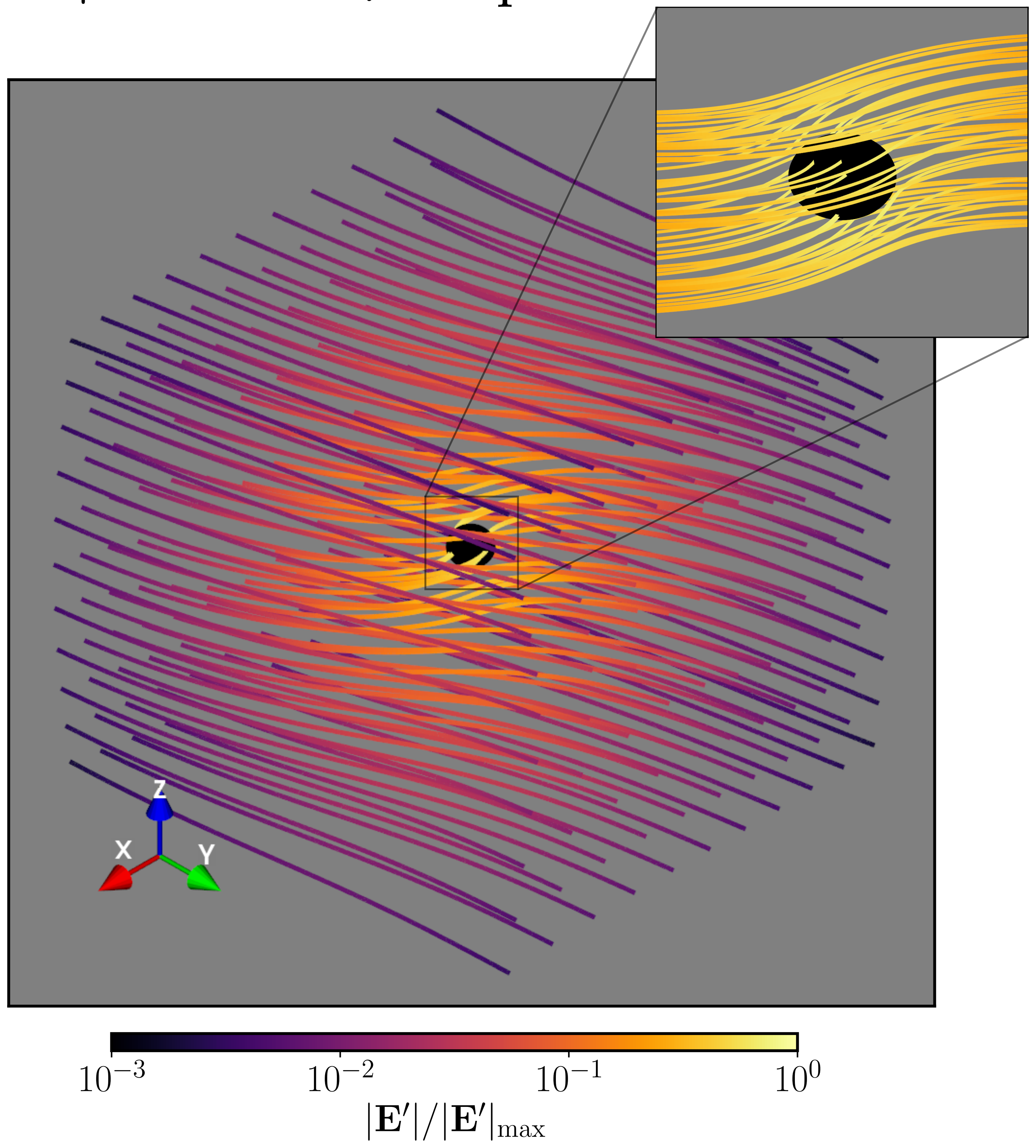
Large, rotating dark electric field

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

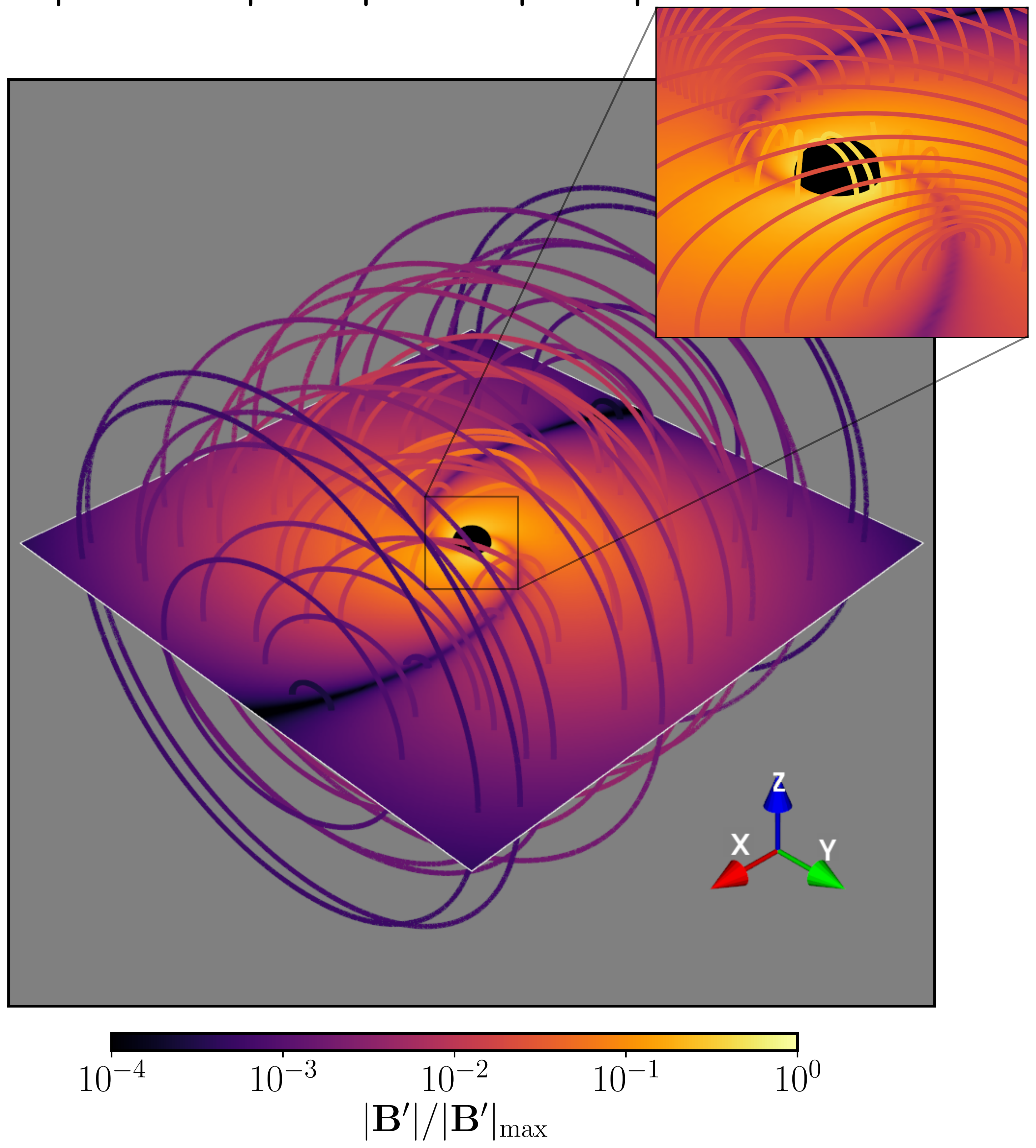
Rotating with period $\sim 2\pi/\mu$

Black hole superradiance - spin 1 field

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



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



Observational signatures

BH superradiance can be used to probe the existence of ultralight bosons

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

....

1. Spin distribution of BH population
2. Continuous gravitational wave signal

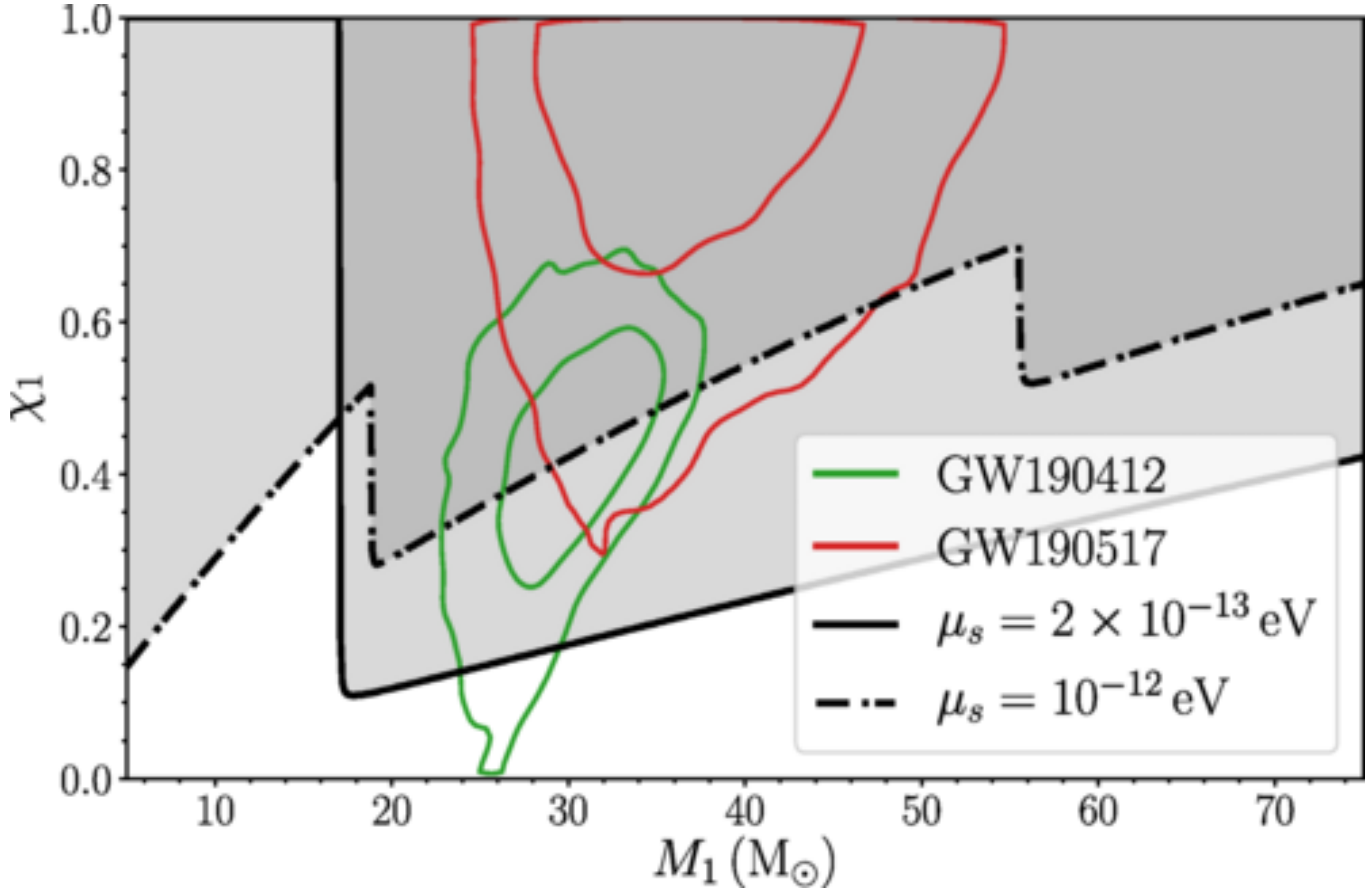
Observational signatures

BH superradiance can be used to probe the existence of ultralight bosons

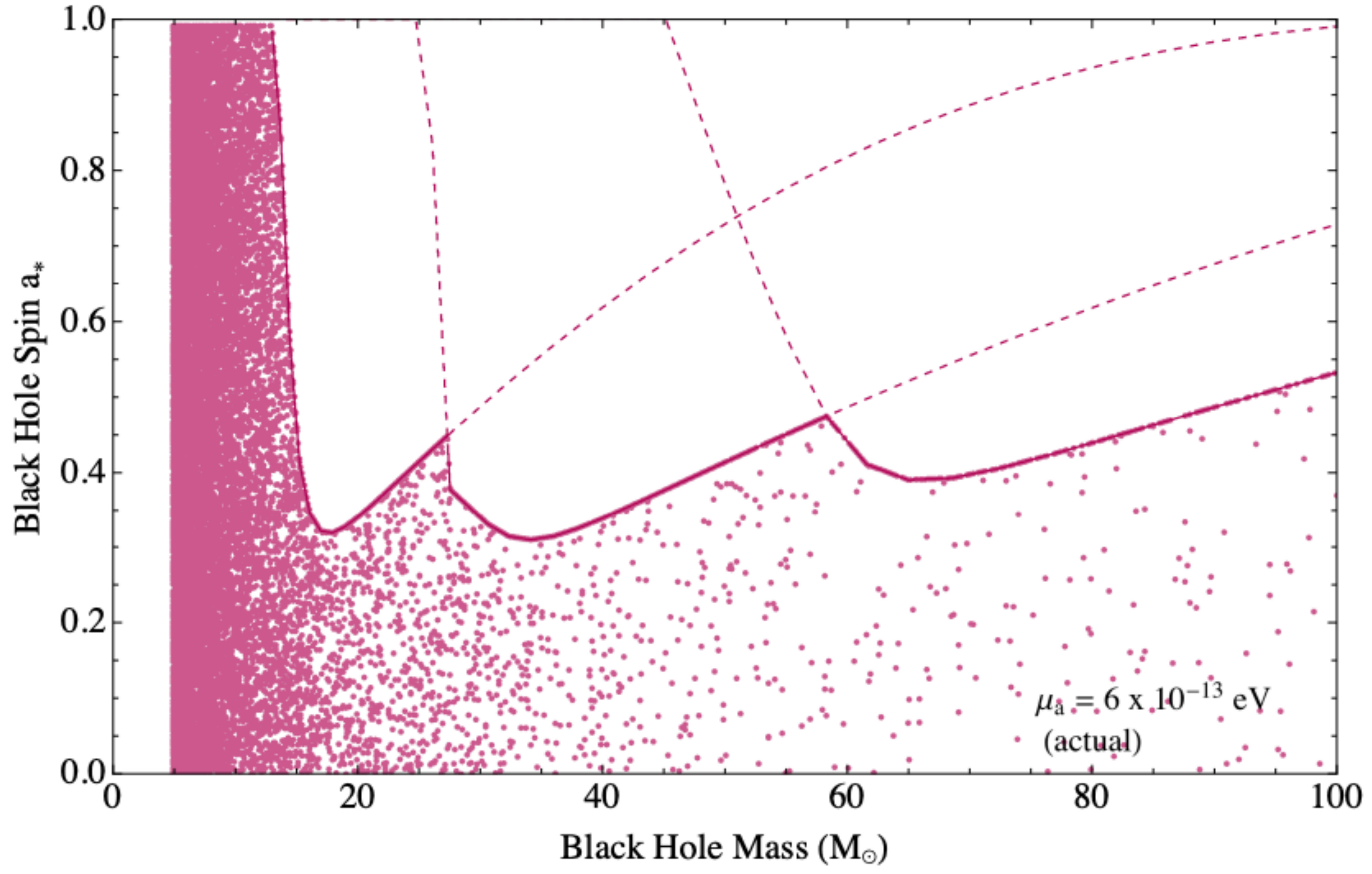
1. Spin distribution of BH population

Axion masses around 10^{-13} eV already disfavored!

Ng, Vitale, Hannuksela, and Li PRL 2021



Arvanitaki, Baryakhtar, Dimopoulos, Dubovsky, Lasenby PRD 2017



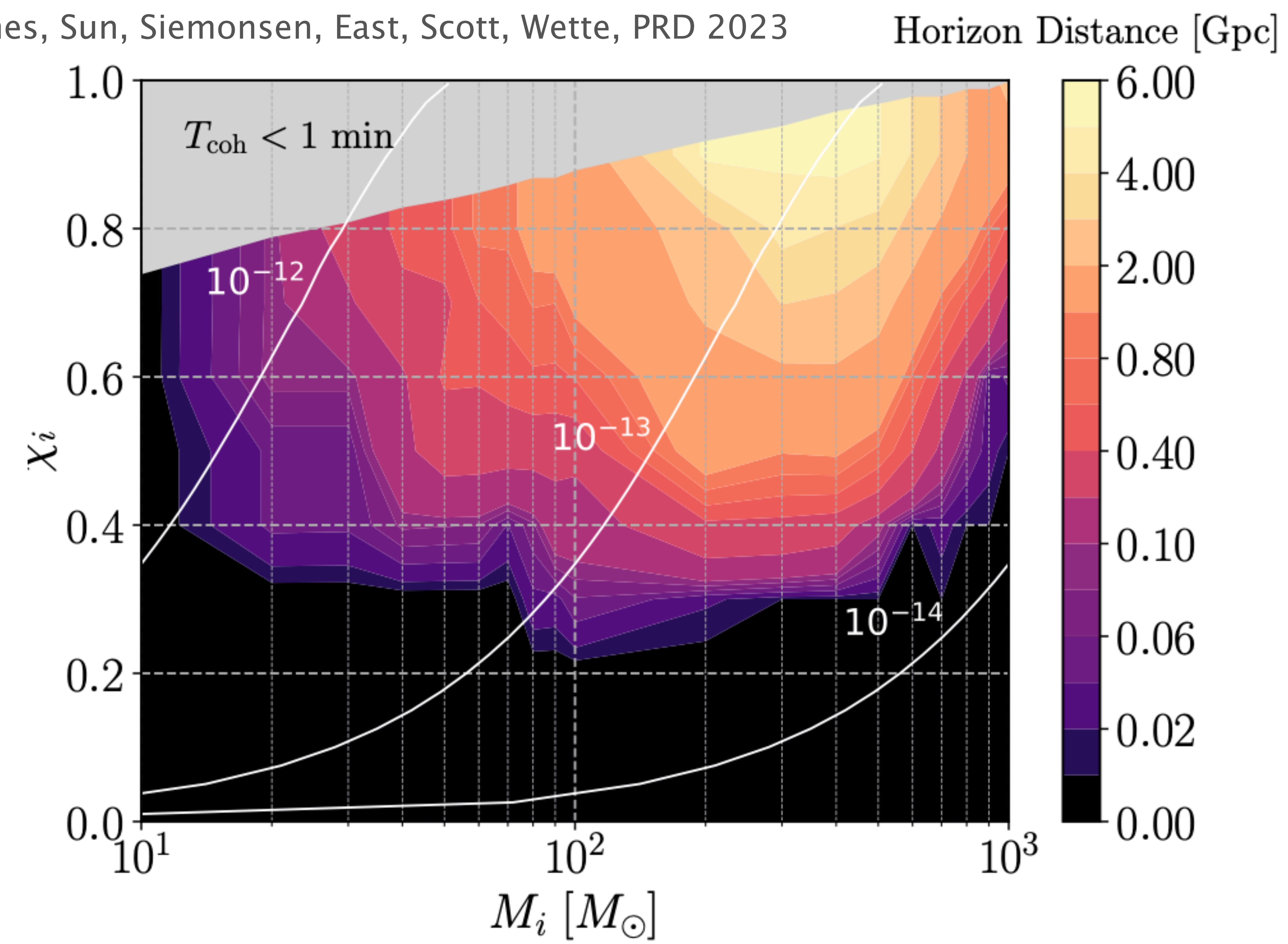
* depends on the time between BH formation and the merger (longer merger time, longer time for SR to grow)

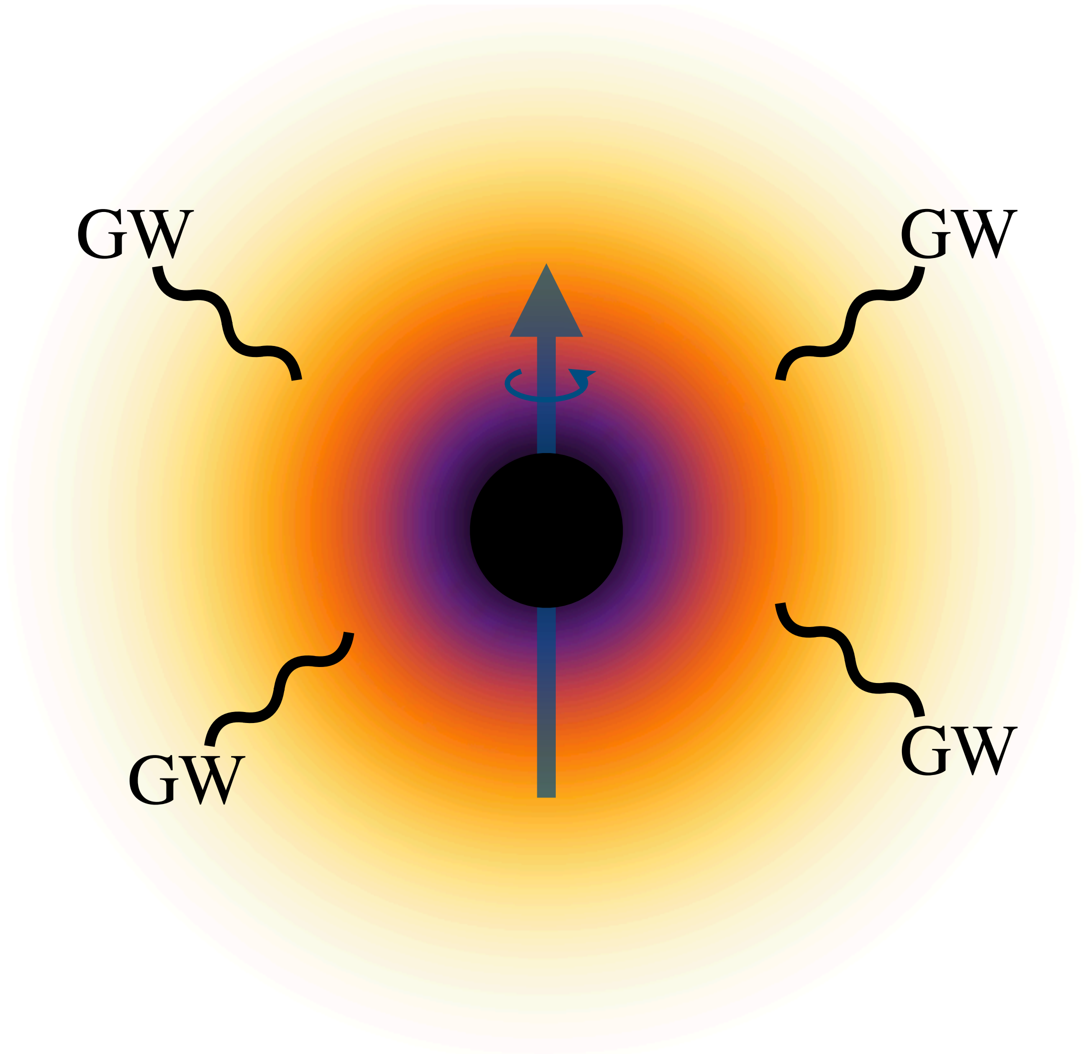
Observational signatures

BH superradiance can be used to probe the existence of ultralight bosons

2. Continuous gravitational wave signal

Jones, Sun, Siemonsen, East, Scott, Wette, PRD 2023





Vector boson clouds could be seen with targeted CW searches of BH merger remnants in future LVK observing runs!

* needs good sky localization

Kinetically-mixed dark photon superradiance

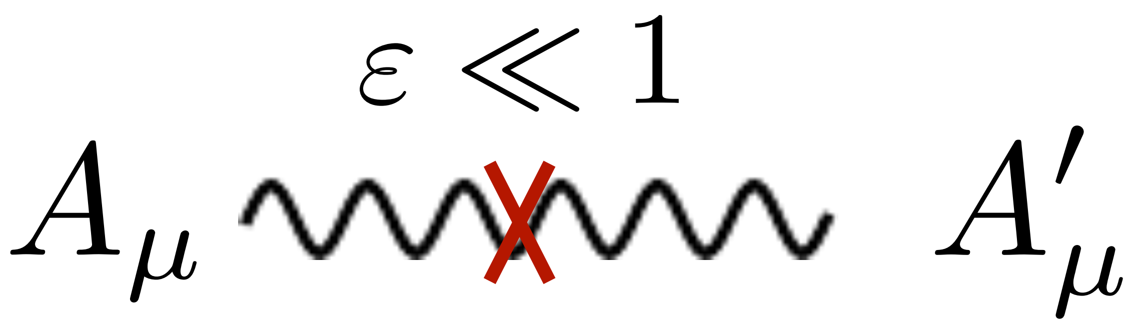
Phys. Rev. D (2023), arxiv:2212.09772
N. Siemonsen, **CM**, D. Egaña-Ugrinovic, J. Huang, M. Baryakhtar, W. E. East

See also:
S. Xin and E. R. Most, Dark magnetohydrodynamics: Black hole accretion in superradiant dark photon clouds, 2406.02992

Dark photon kinetic mixing

Standard Model photon

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



Dark photon kinetic mixing

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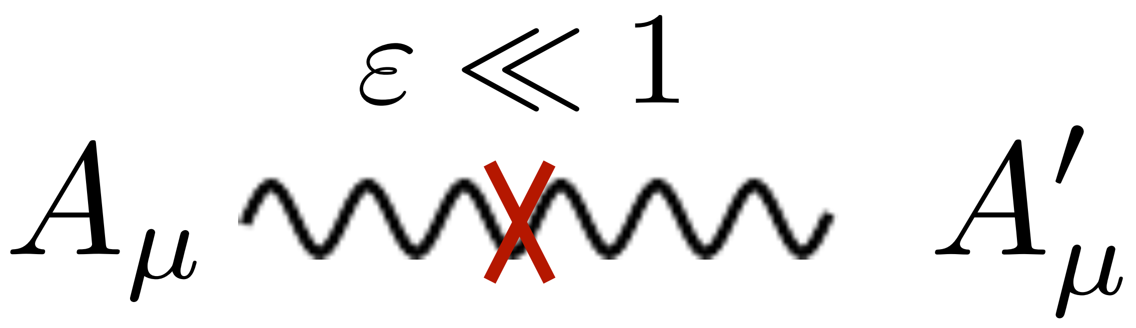


$$A_\mu \to A_\mu + \varepsilon A'_\mu$$

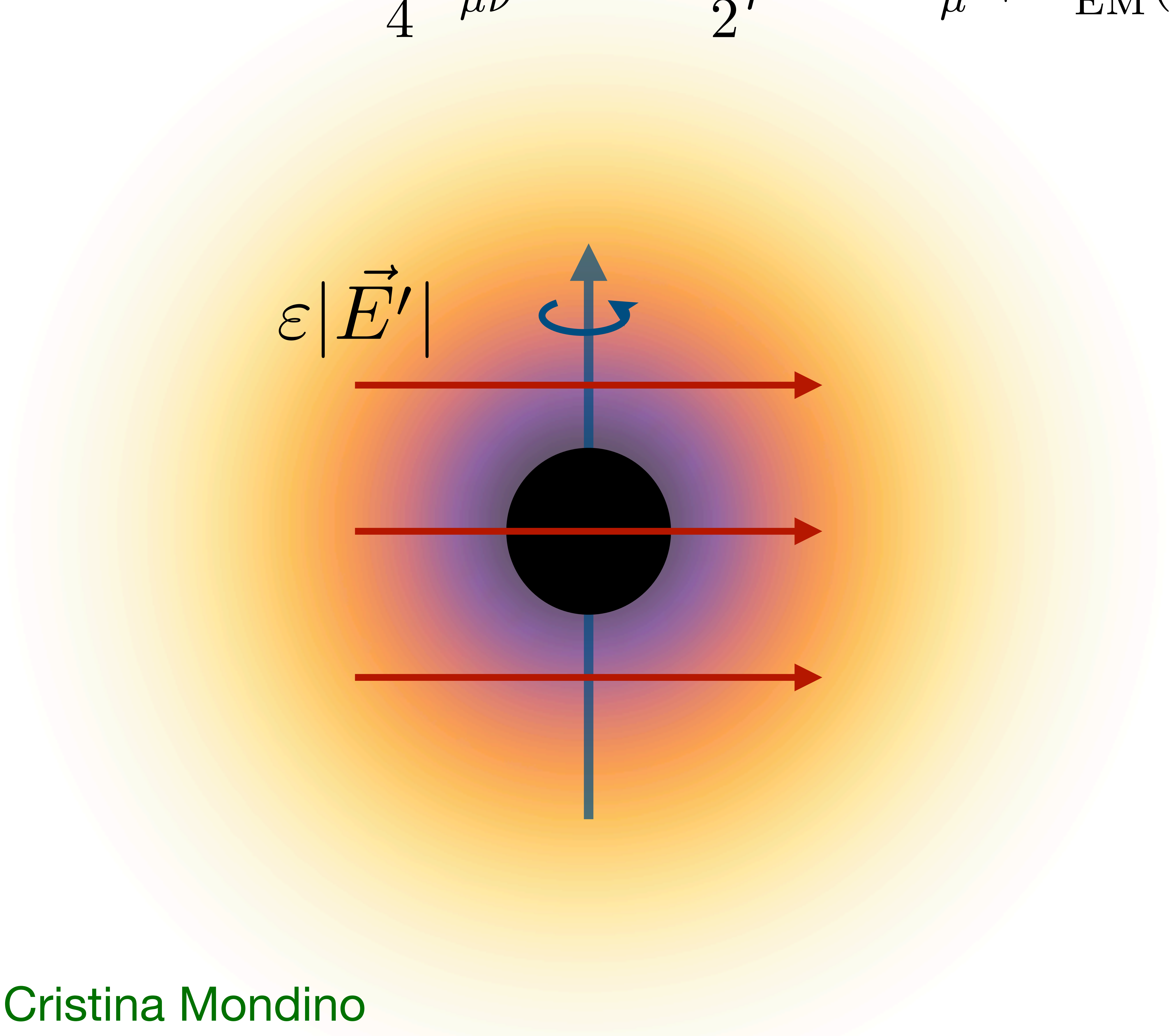
$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}\mu^2 A'^{\mu}A'_{\mu} + \boxed{J^{\mu}_{\rm EM}(A_\mu + \varepsilon A'_\mu)}$$

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

Dark photon kinetic mixing

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

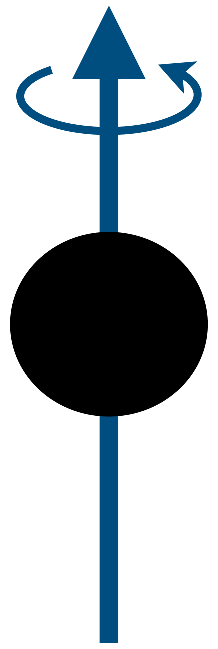
Coupling to SM charged particles: $e\varepsilon$

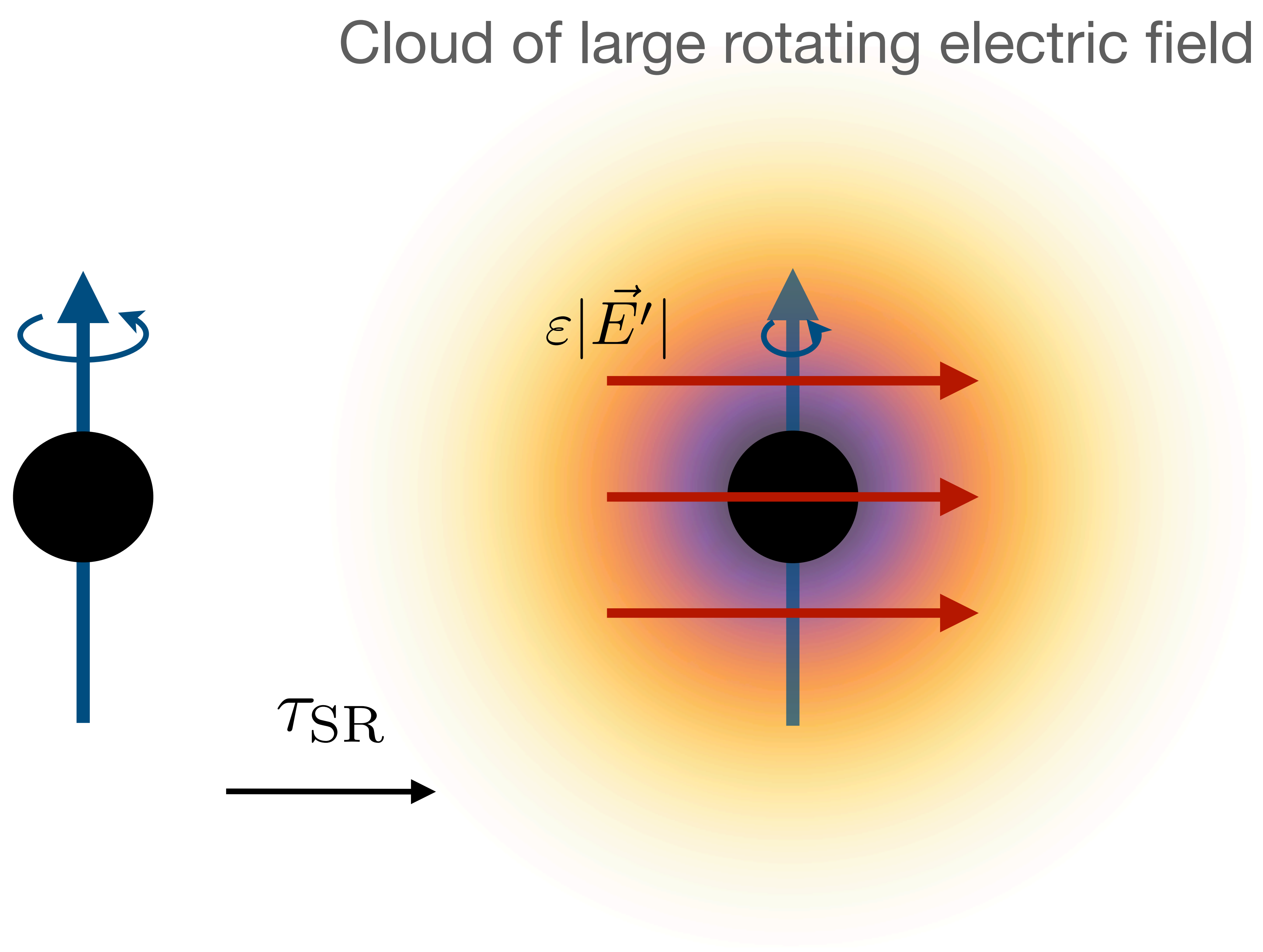


Large, rotating electric field

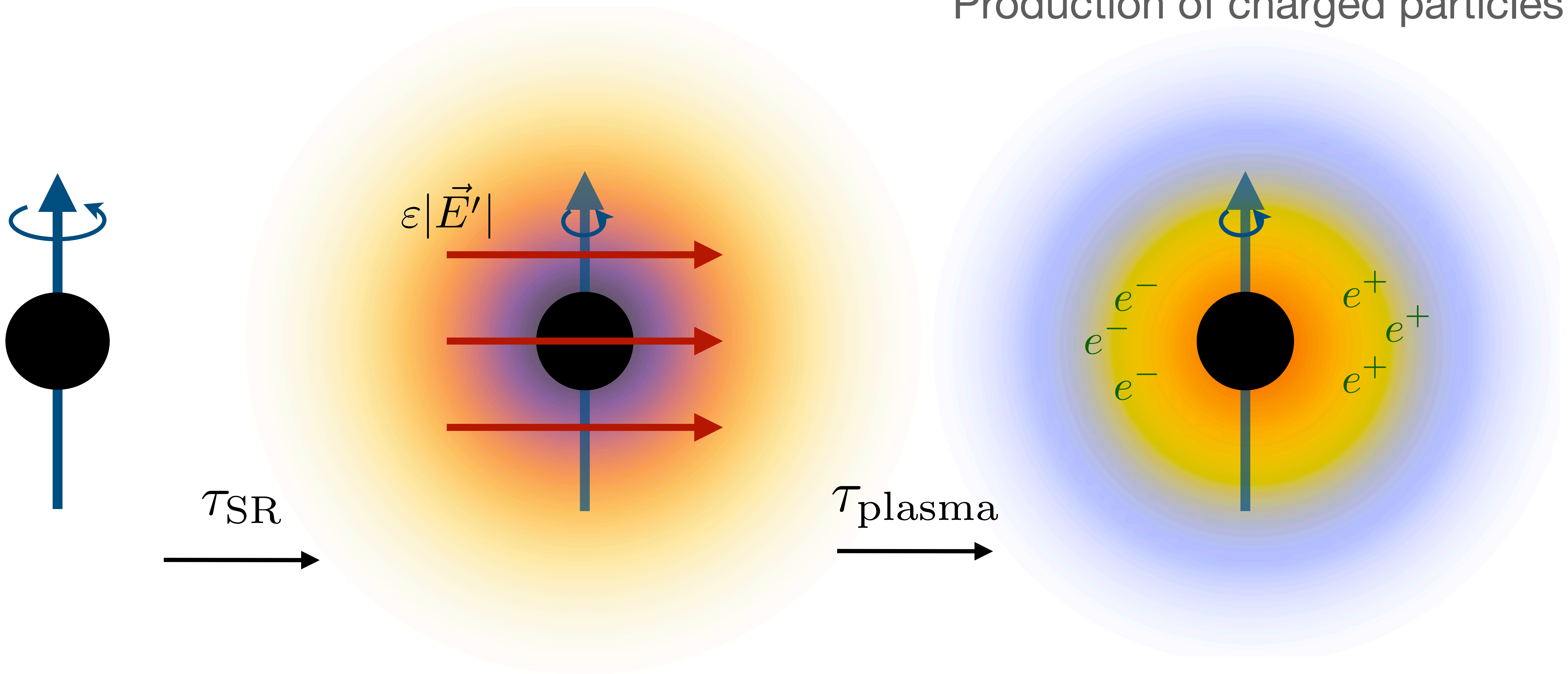
$$|\vec{E}| = \varepsilon|\vec{E}'| \sim \varepsilon\alpha^{5/2}\mu M_{\rm pl}$$

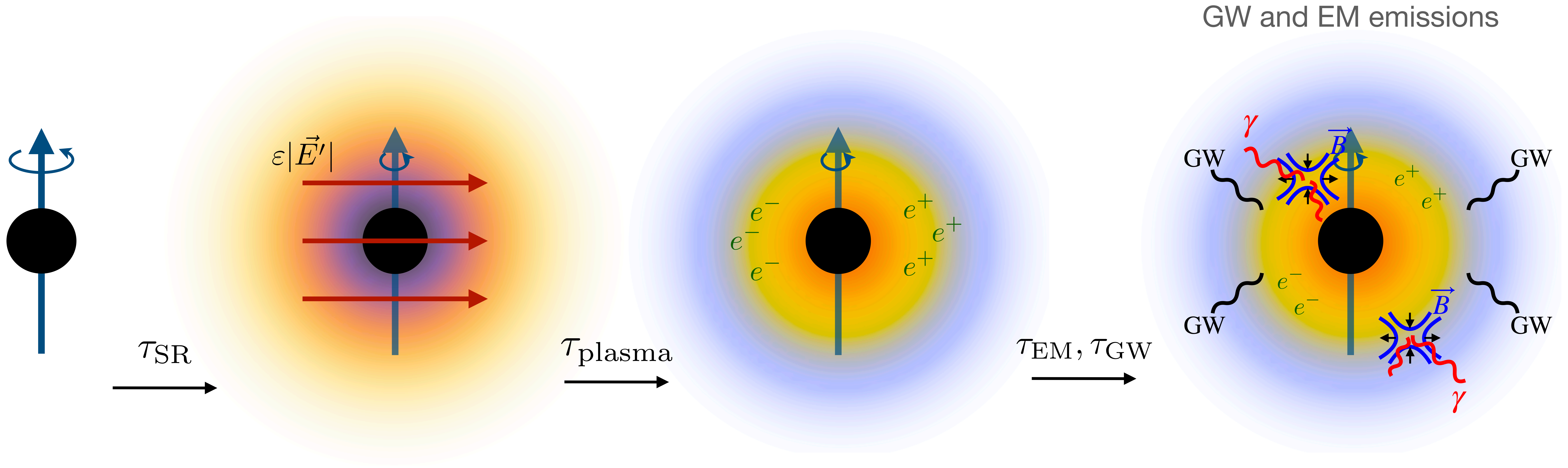
$$|\vec{E}| \sim 10^{13}\ \mathrm{V/m}\left(\frac{\varepsilon}{10^{-7}}\right)\left(\frac{\alpha}{0.1}\right)^{5/2}\left(\frac{\mu}{10^{-12}\,\mathrm{eV}}\right)$$




Cloud of large rotating electric field
$\varepsilon|\vec{E}'|$
$\tau_{\rm SR}$

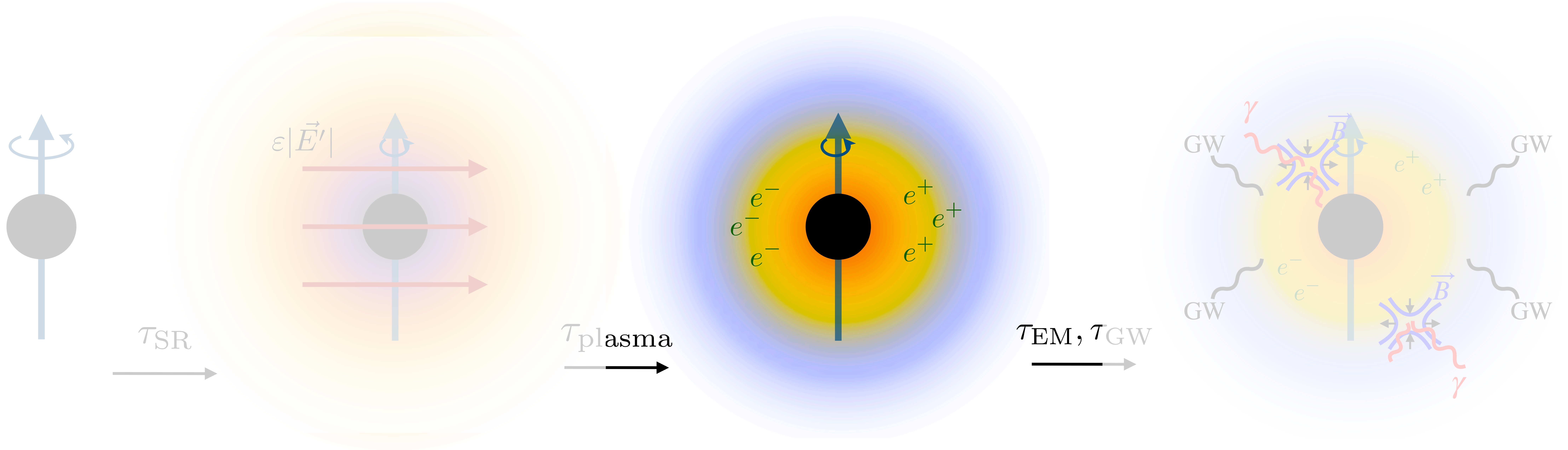
Production of charged particles



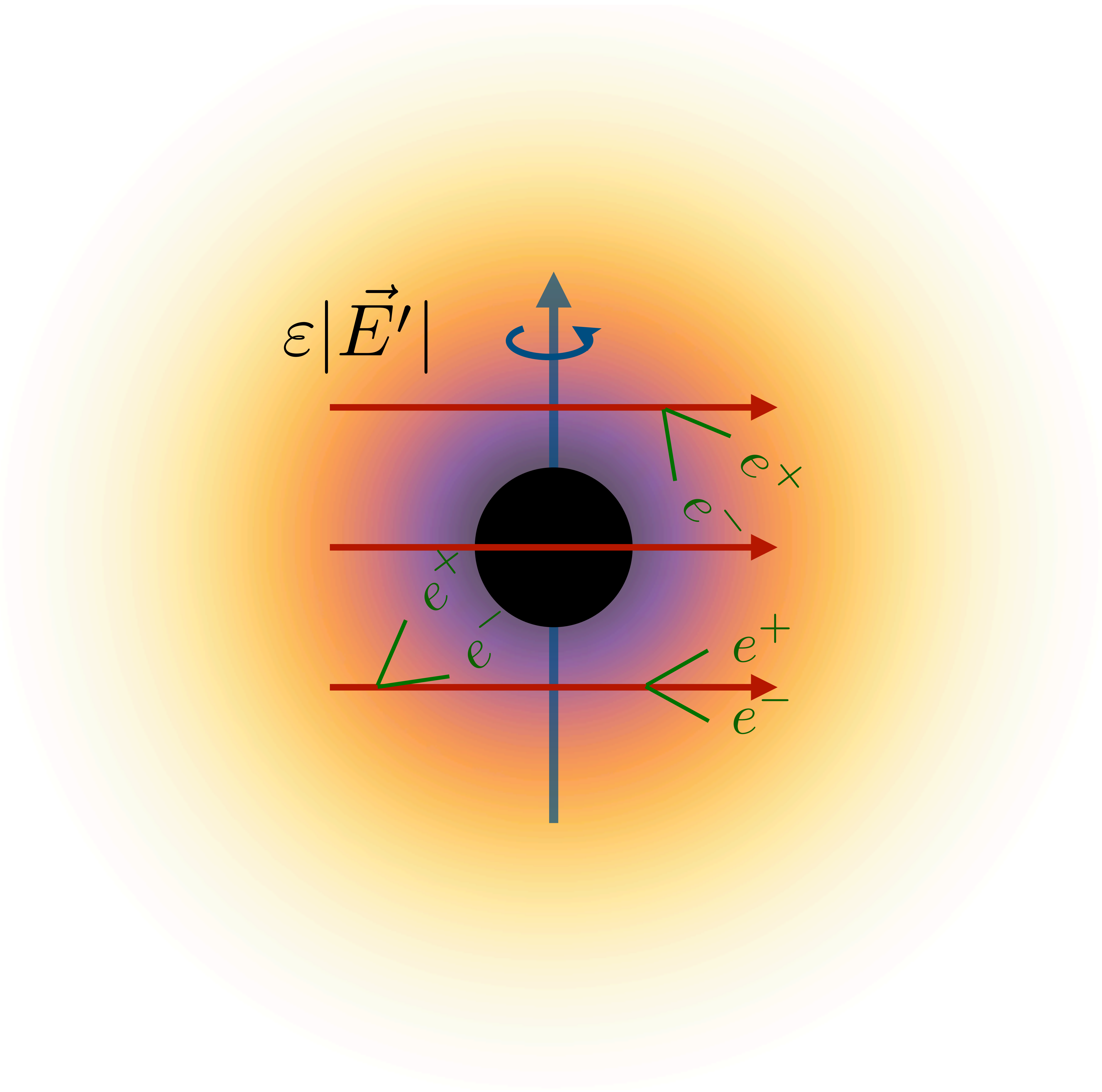


$\tau_{\rm SR}$
$\varepsilon|\vec{E}'|$
$\tau_{\rm plasma}$
e^-
e^-
e^-
e^+
e^+
e^+
$\tau_{\rm EM}, \tau_{\rm GW}$
GW and EM emissions
GW
GW
GW
GW
γ
γ
$\vec{B}$
$\vec{B}$
e^+
e^+
e^-
e^-

Plasma production



Plasma production

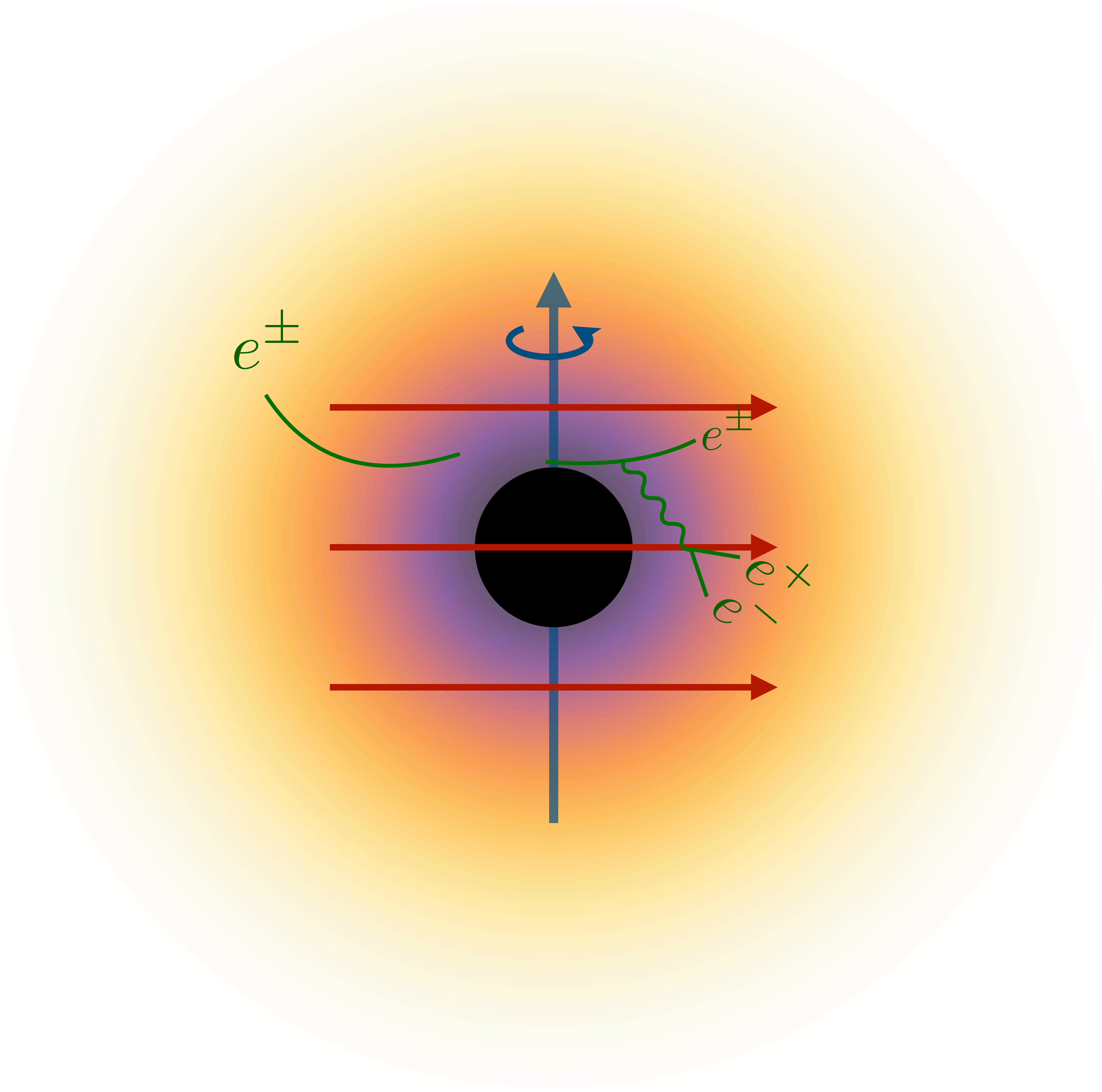


Large electric field spontaneously decays to $e^{\pm}$ pair!

(Schwinger pair production)

$$|\vec{E}| \sim m_e^2 \sim 10^{18}\ \mathrm{V/m}$$

Plasma production



$$|\vec{E}| = \epsilon|\vec{E}'| \sim 10^{13}\ \mathrm{V/m}$$

Synchrotron emission of high energy photons

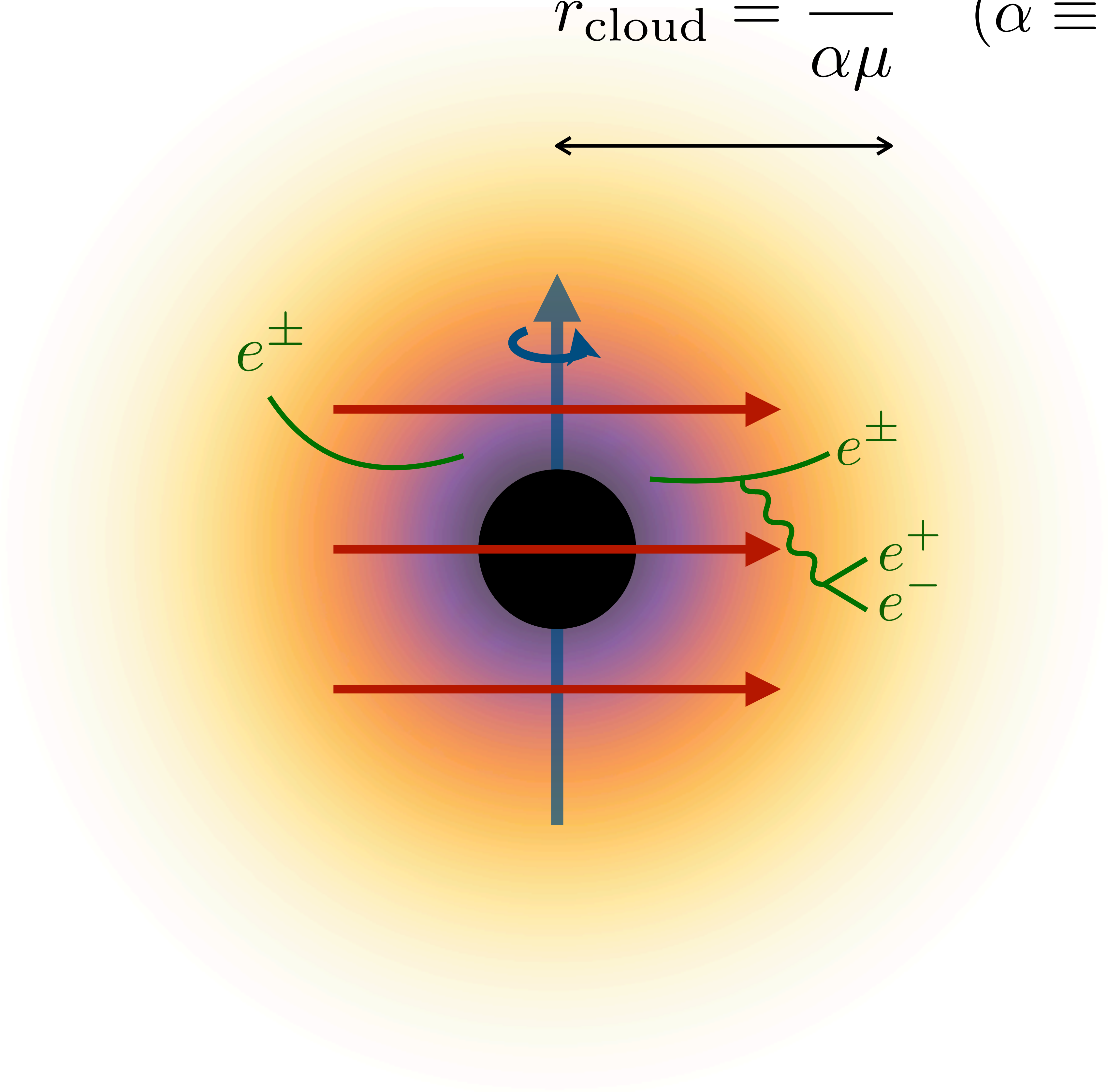
$$\omega_{\rm syn} \simeq \gamma_e^3 \mu \gg m_e$$

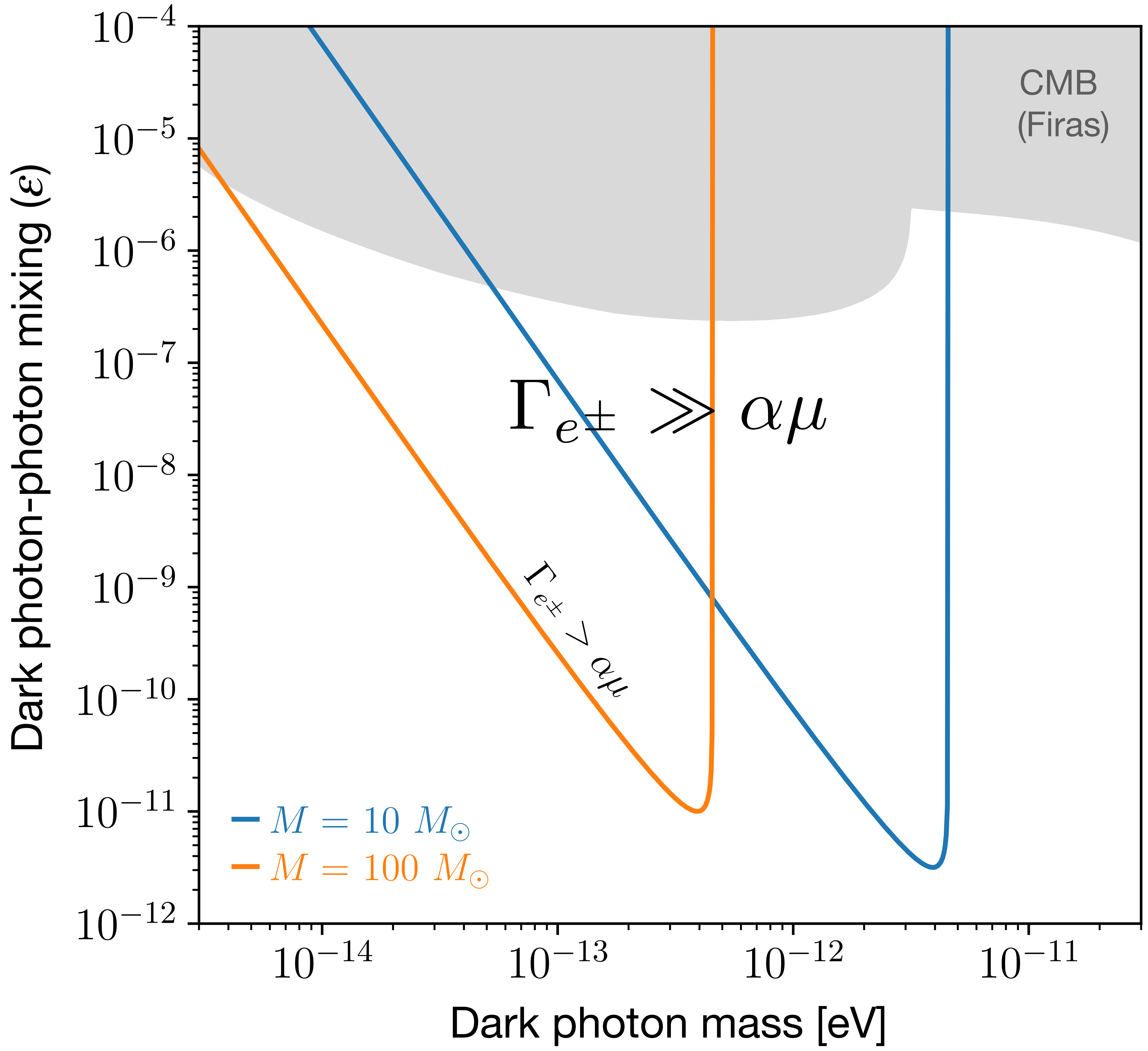
Photon-assisted Schwinger pair production

$$\Gamma_{e^{\pm}}$$

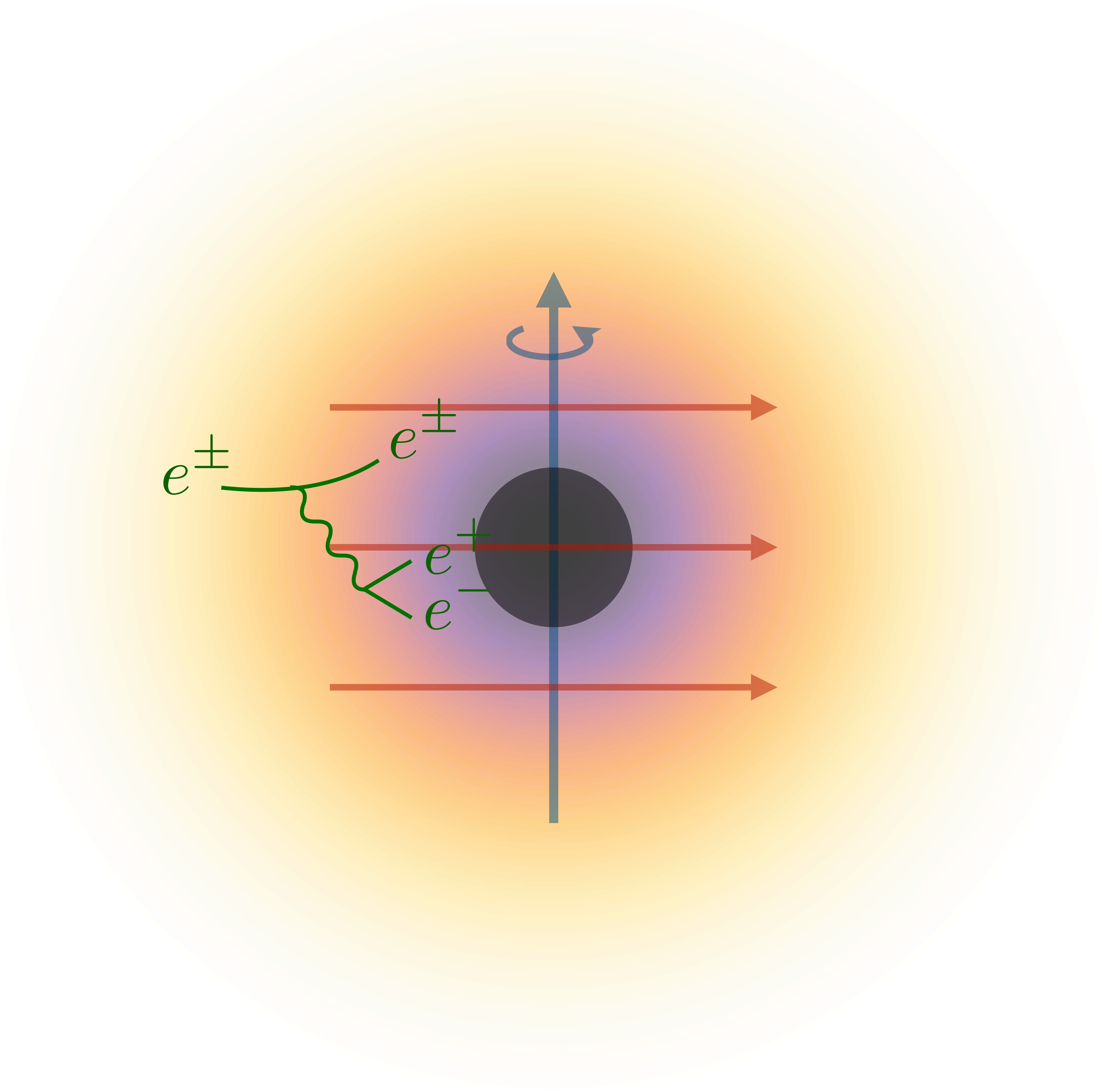
Efficient plasma production

$$r_{\text{cloud}} = \frac{1}{\alpha\mu} \quad (\alpha \equiv \mu G M)$$



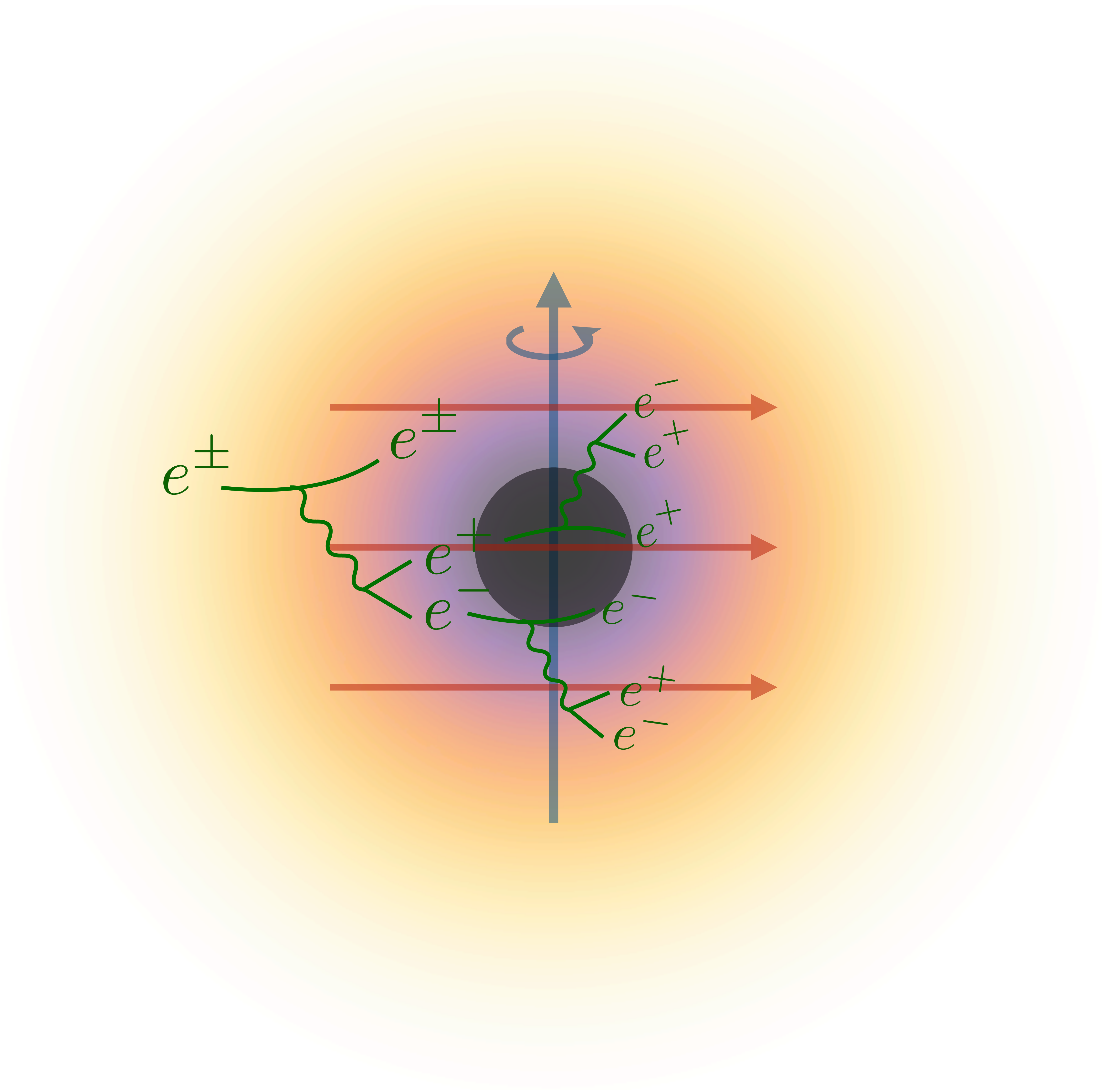


Production cascade



$$|\vec{E}| = \epsilon|\vec{E}'| \sim 10^{13}\ \mathrm{V/m}$$

Production cascade



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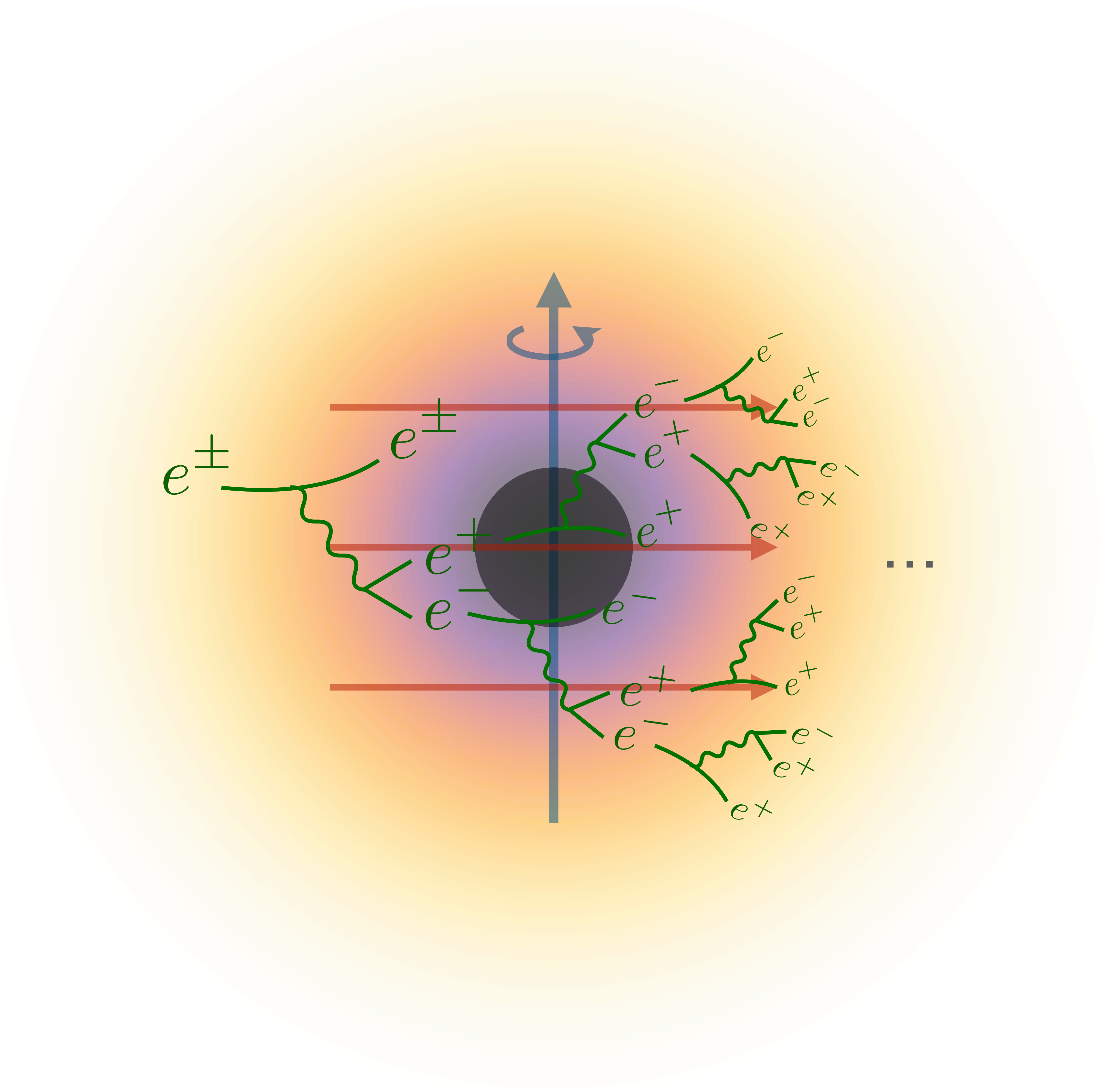
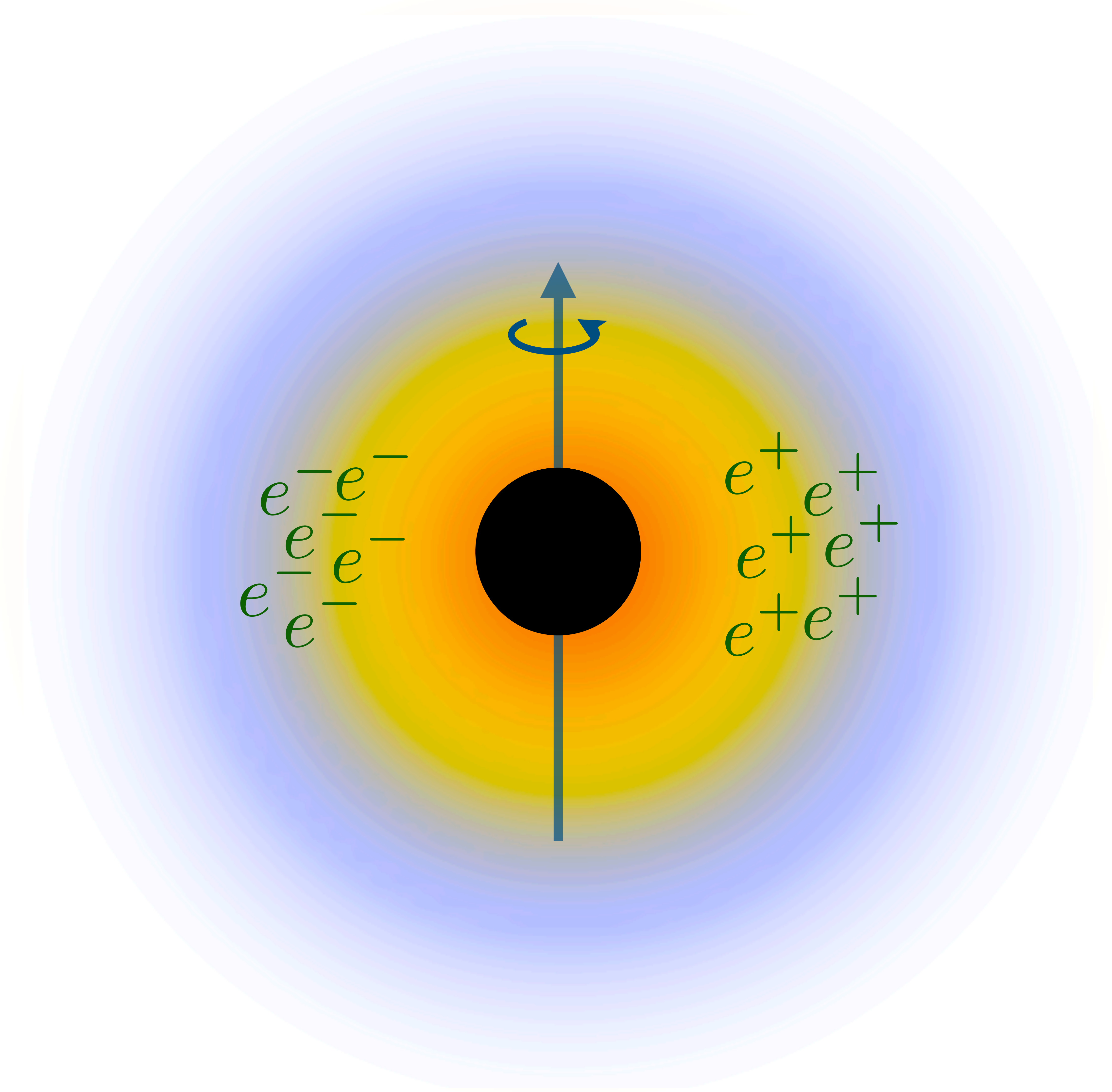


$$|\vec{E}| = \epsilon |\vec{E}'| \sim 10^{13}\ \mathrm{V/m}$$

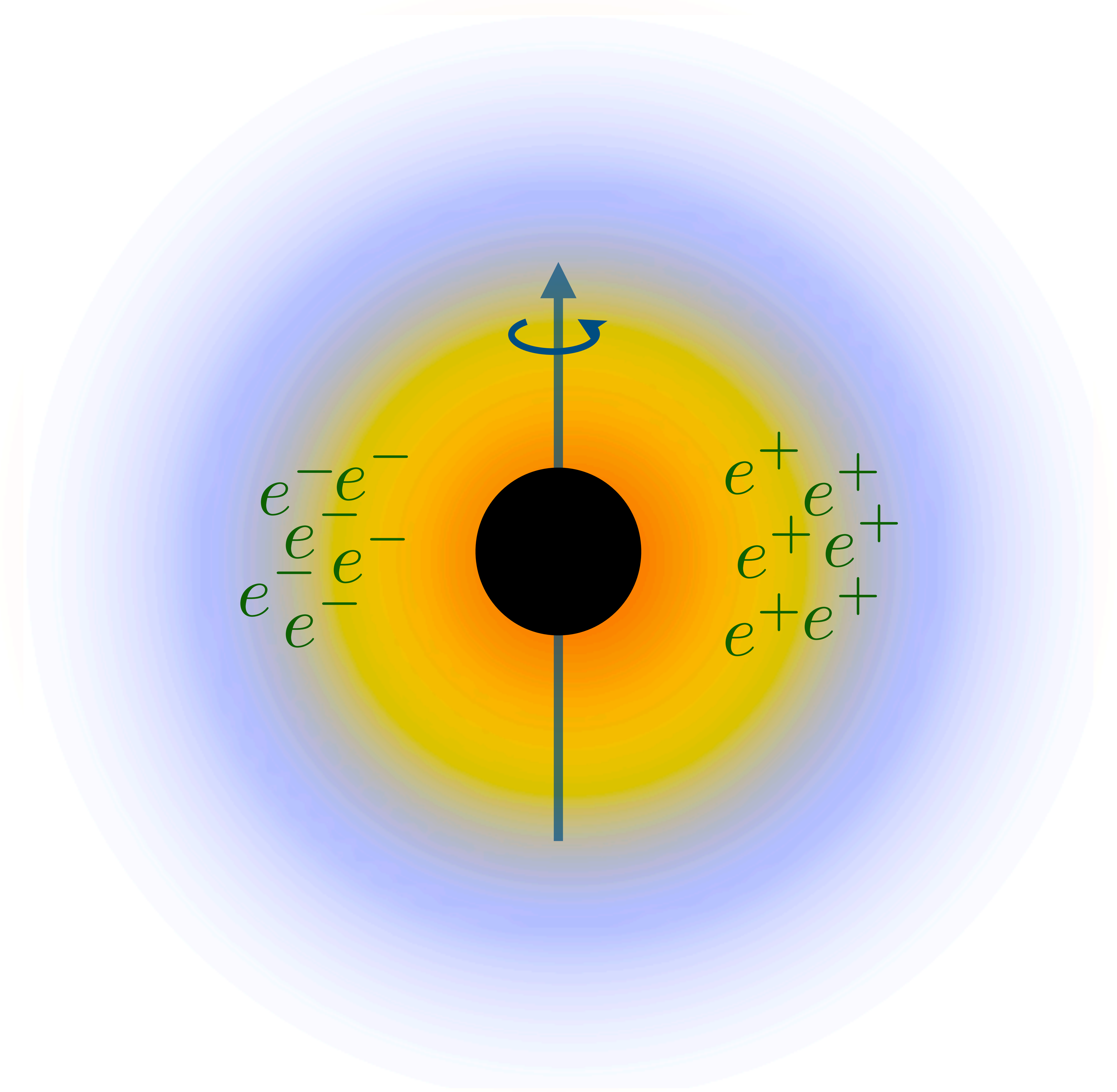
Screening



$$en_e \simeq \varepsilon \nabla \cdot \vec{E}'$$

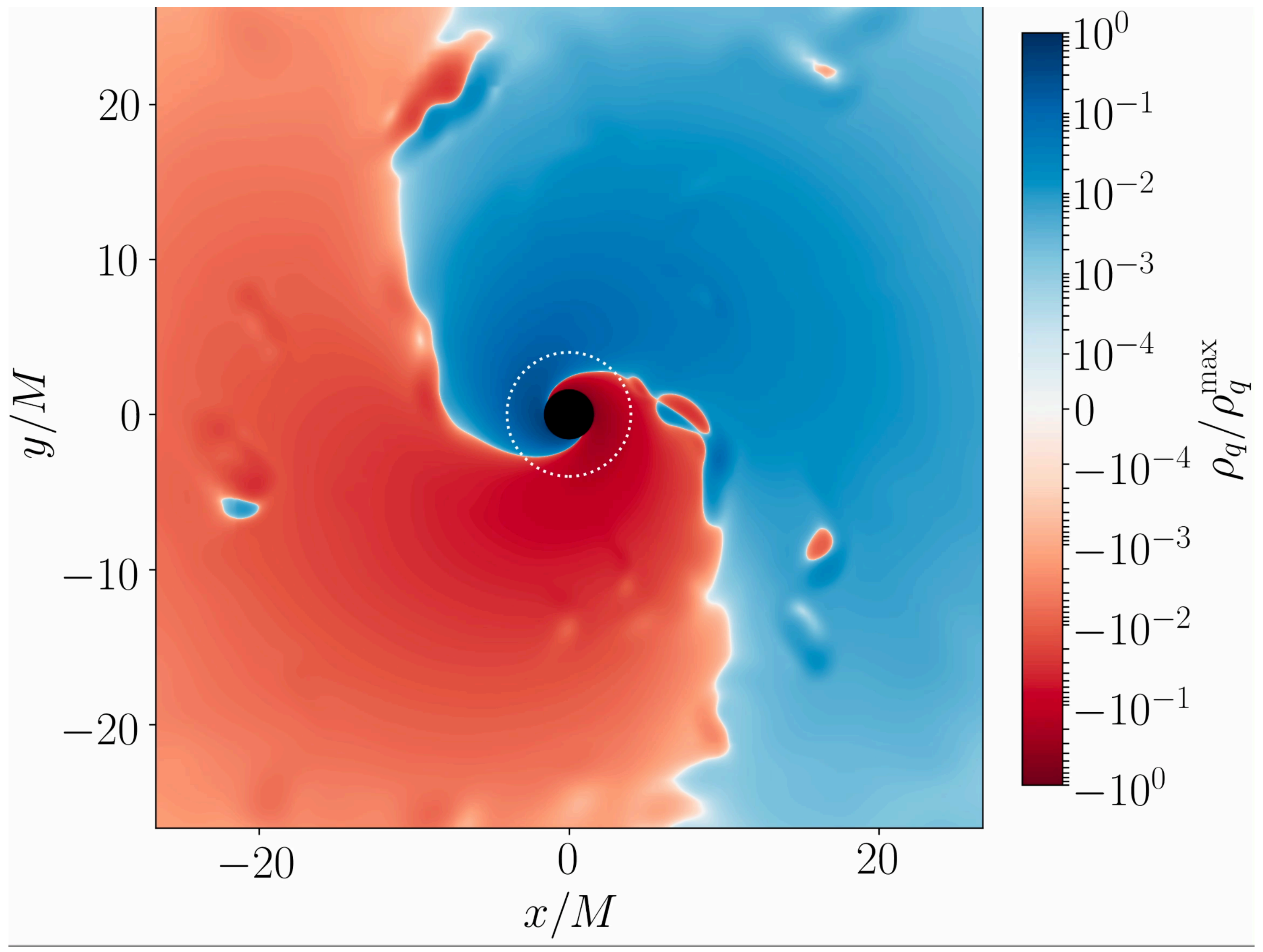
Charges separate and screen the background electric field

Screening

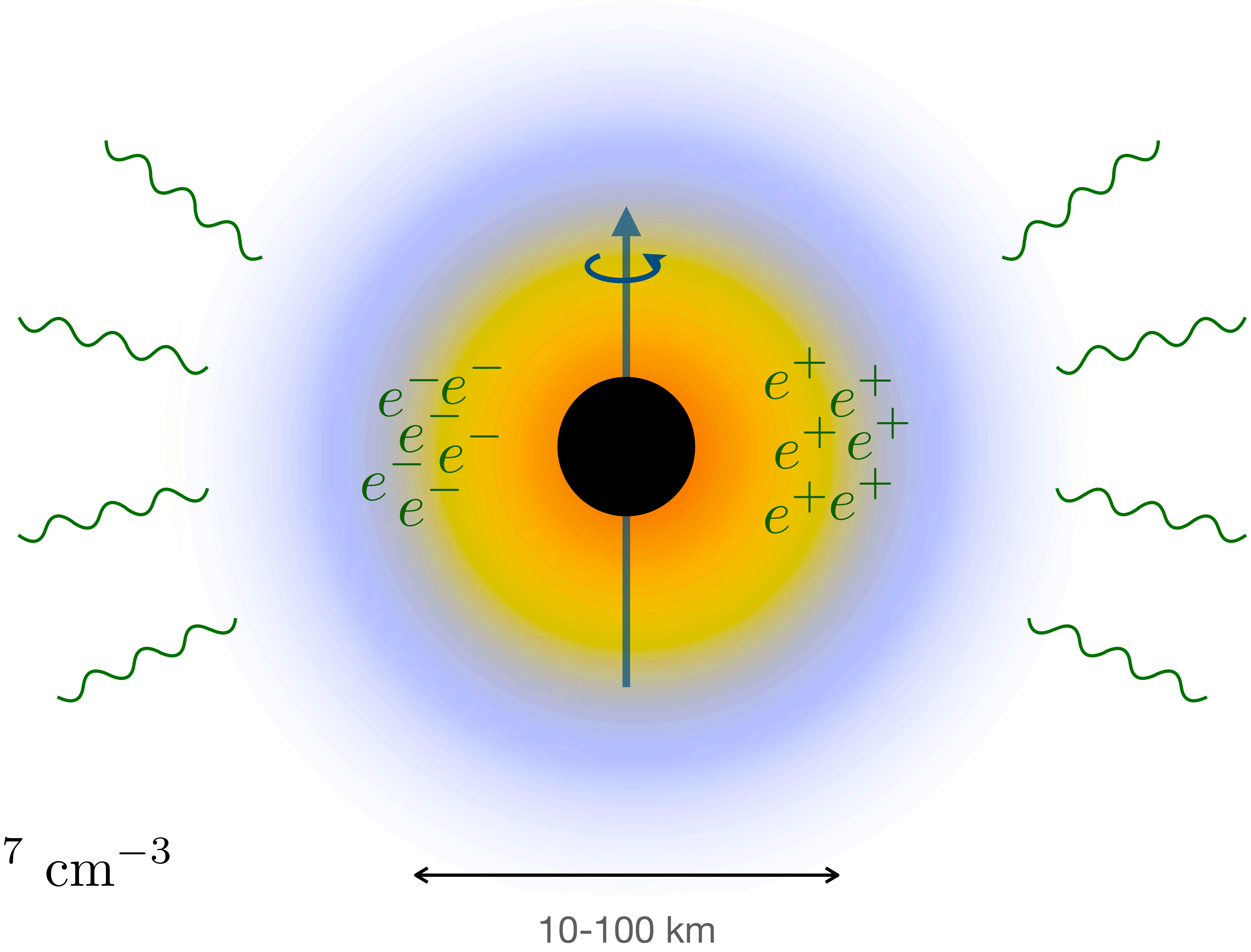


$$en_e \simeq \varepsilon \nabla \cdot \vec{E}'$$

Charges separate and screen the background electric field



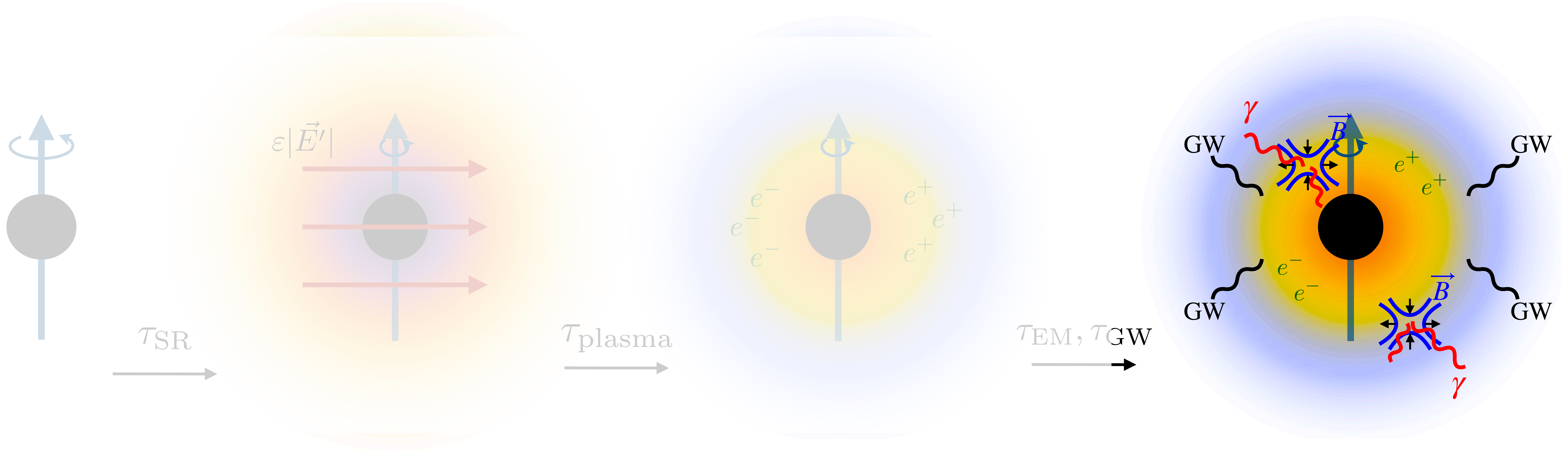
Rotating dipole



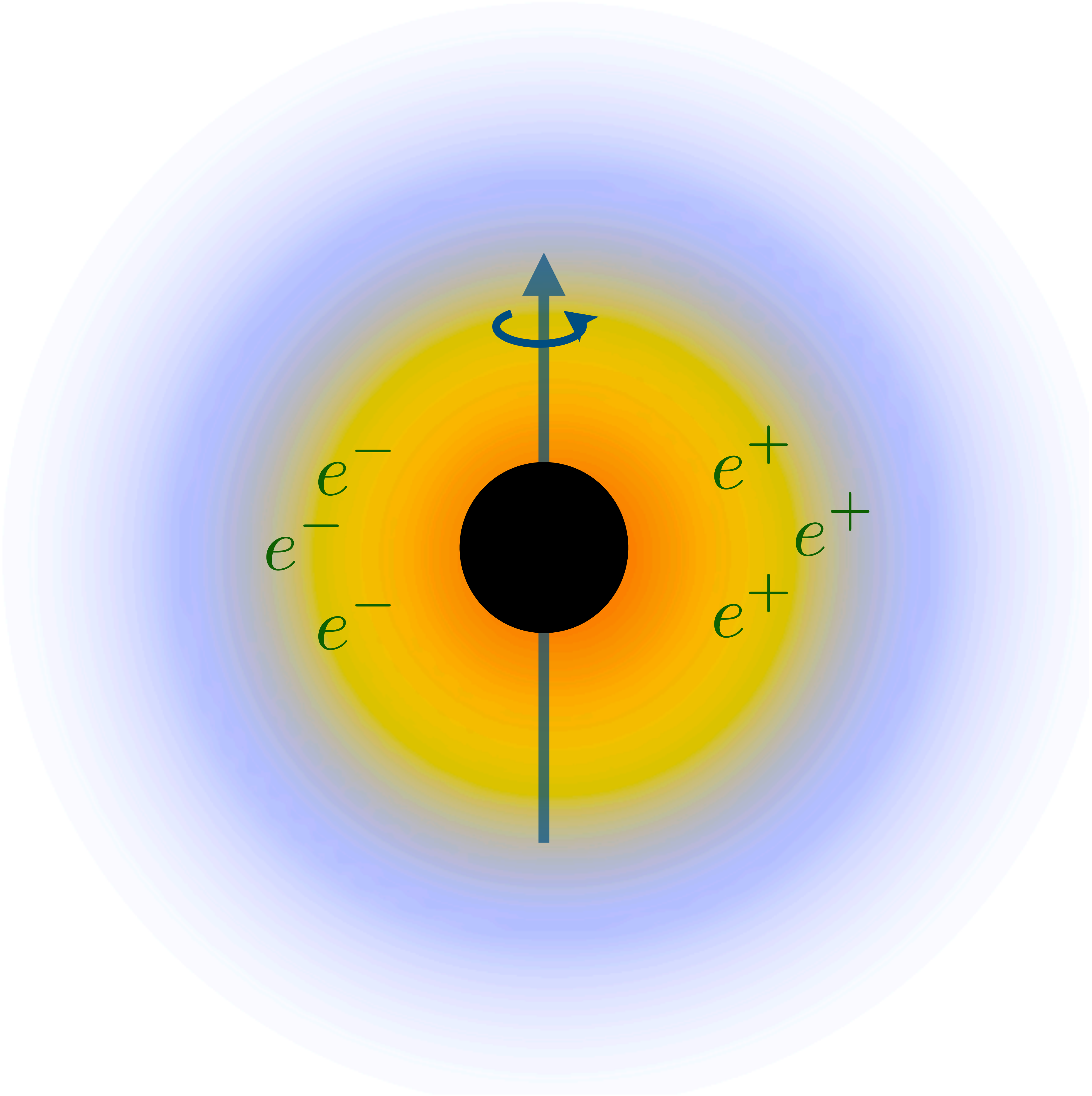
Large amount of EM radiation!

$$en_e \simeq 10^7 \text{ cm}^{-3}$$

EM emissions



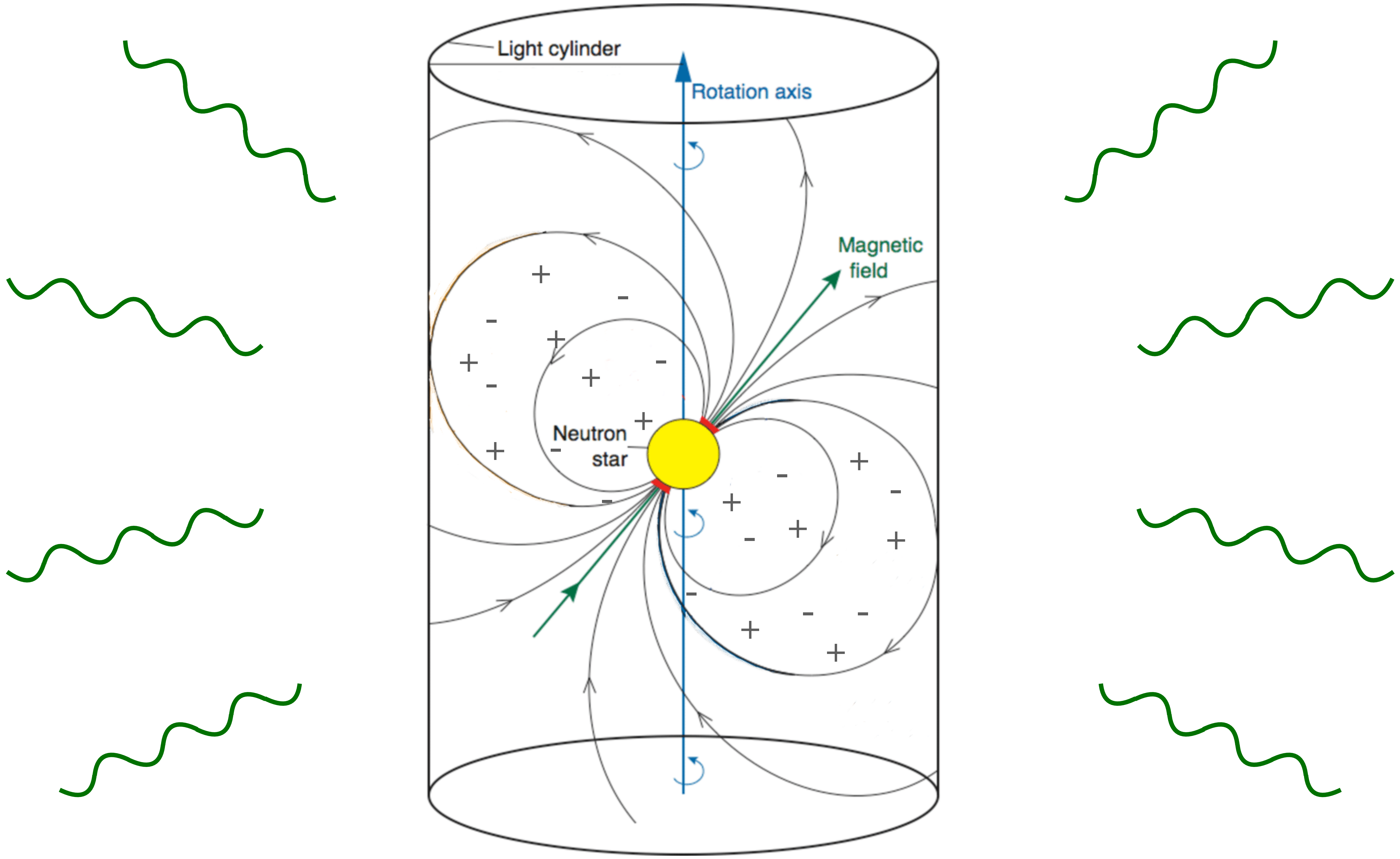
SR cloud + plasma



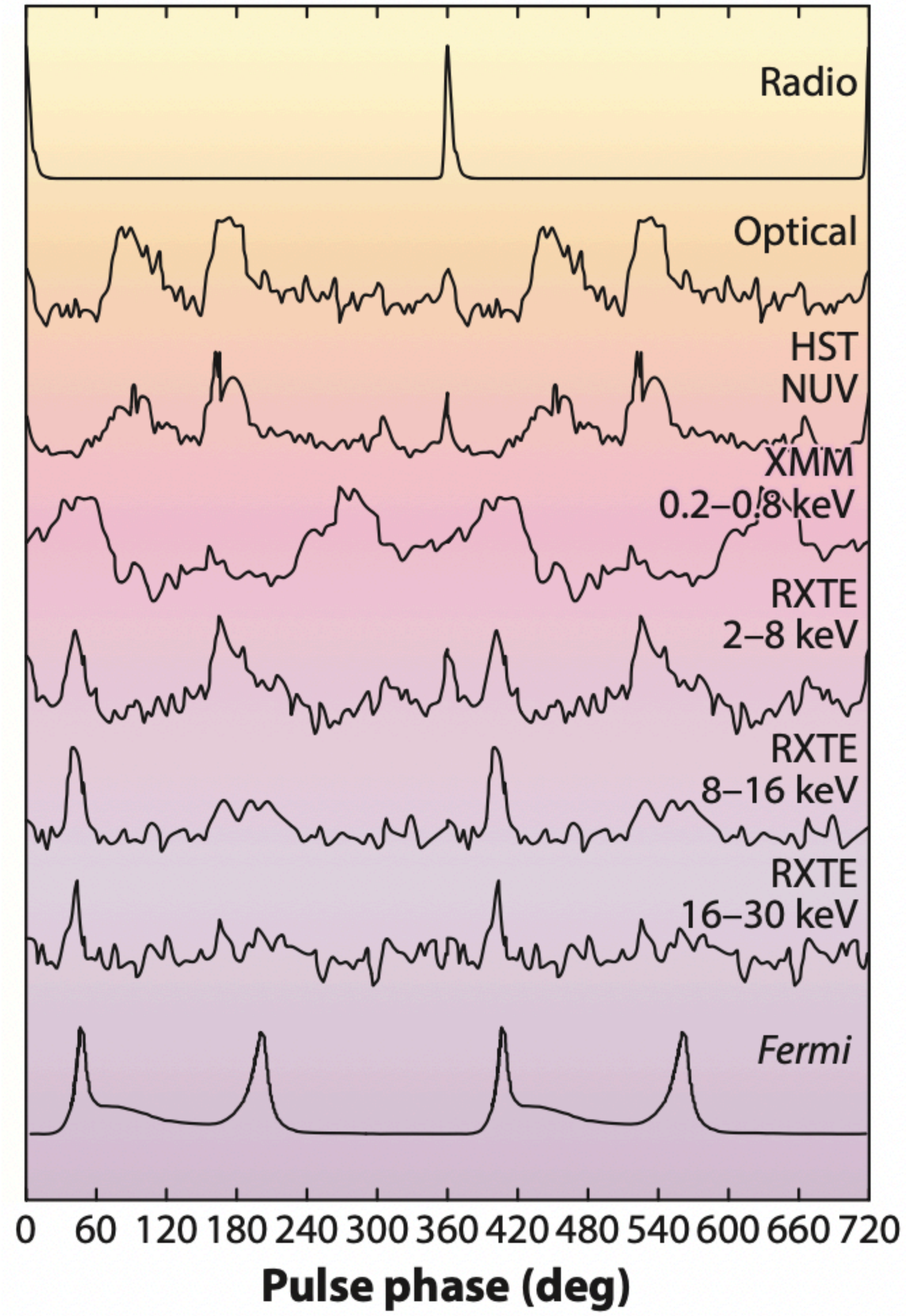
?

Nuetron star pulsar

Magnetosphere of neutron star pulsar

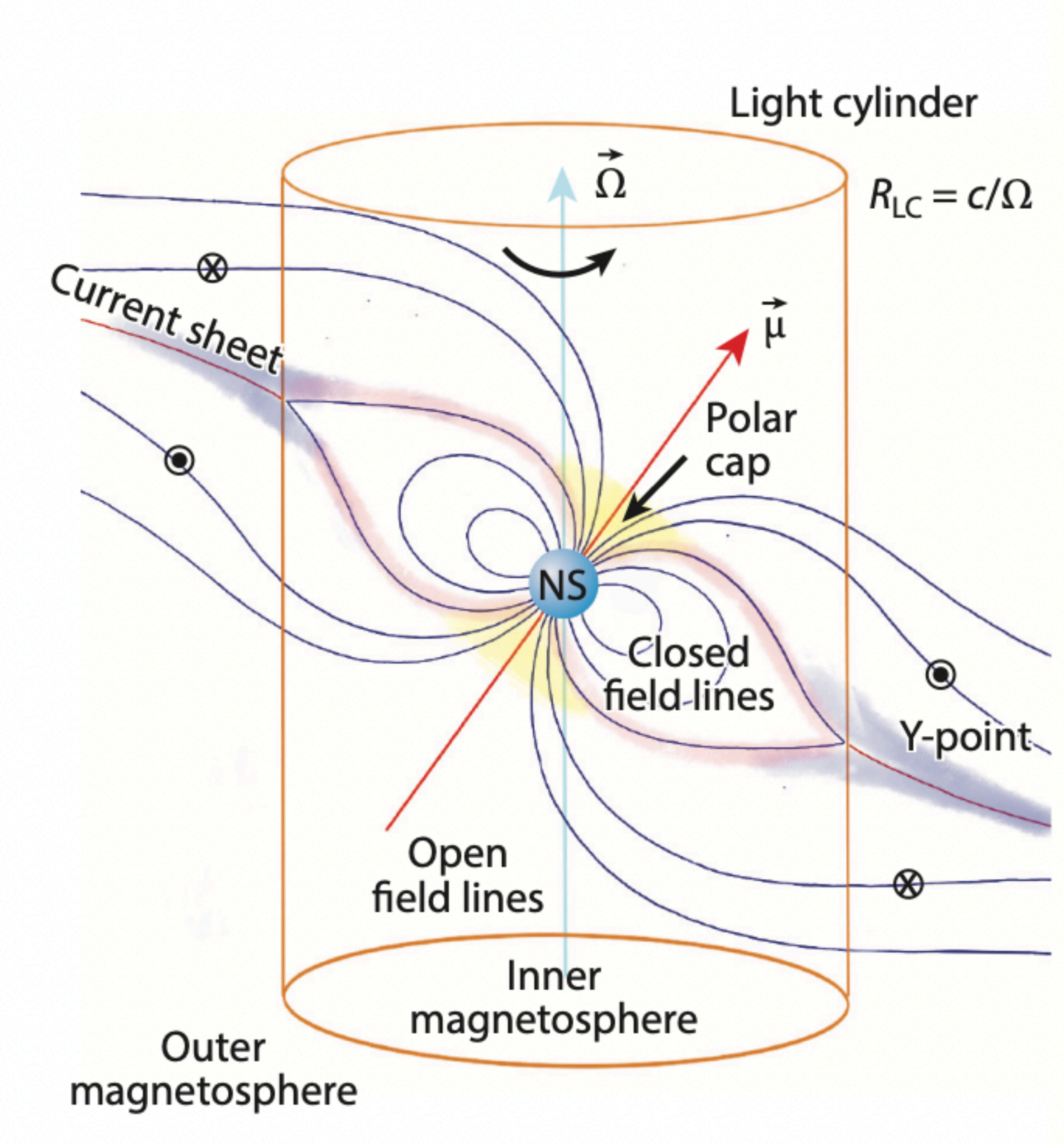


Emission spectra of the Vela pulsar

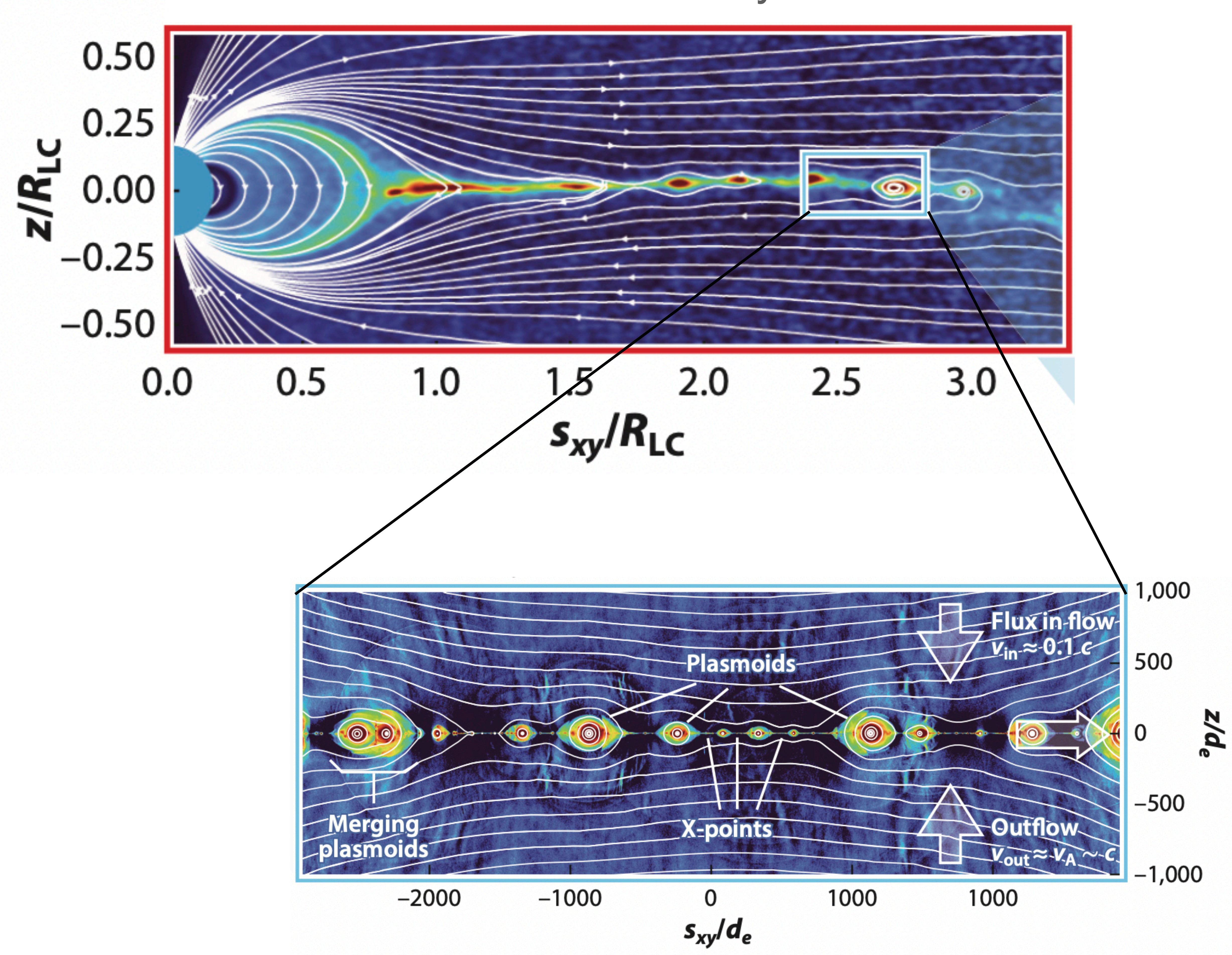


From *Pulsar Magnetospheres and Their Radiation*
A. Philippov and M. Kramer
Annu. Rev. Astron. Astrophys. 2022

Nuetron star pulsar



Plasma density



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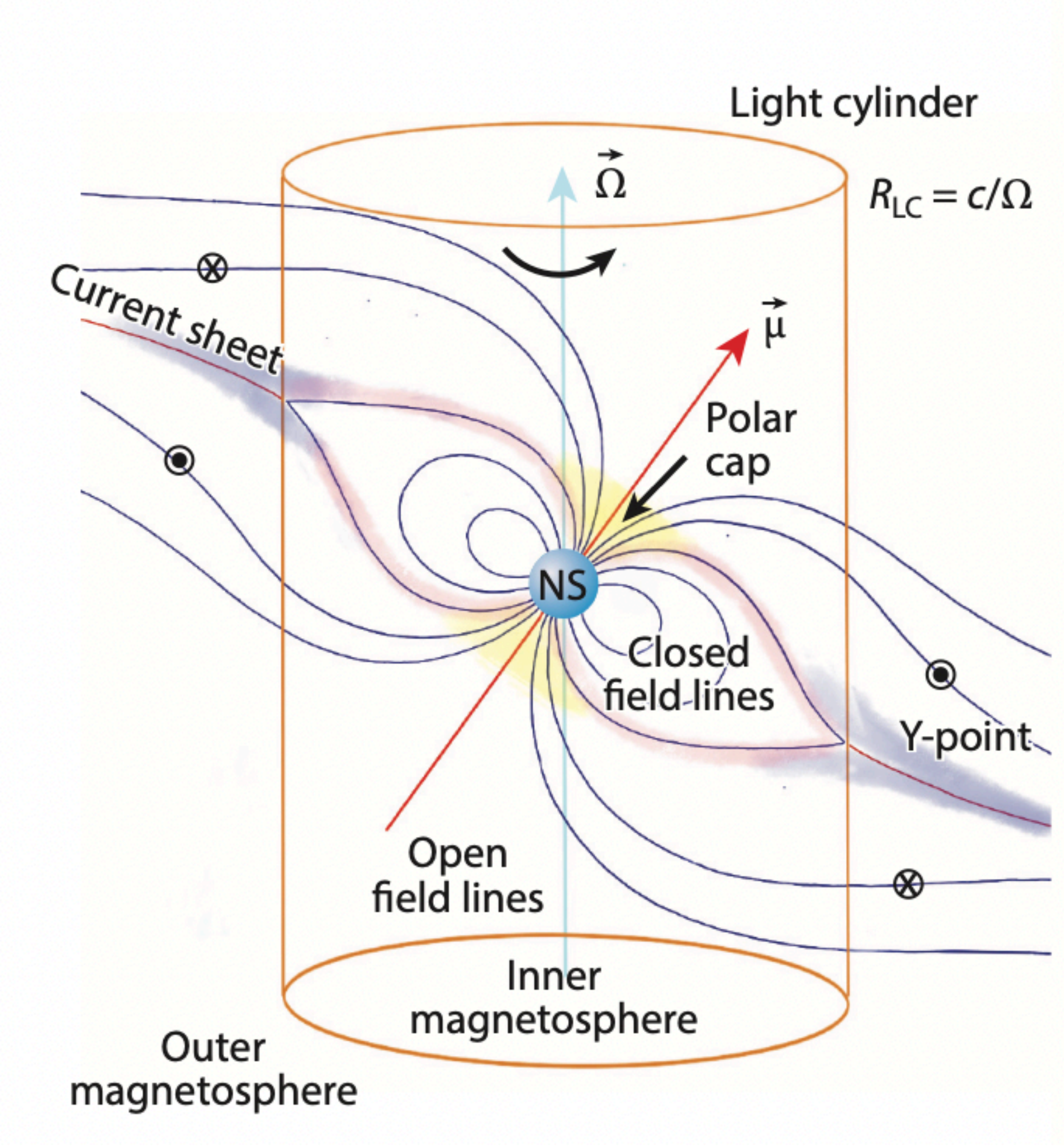


1)
$$\partial_t \vec{B} = -\nabla \times \vec{E}$$
$$\partial_t \vec{E} = \nabla \times \vec{B} - \vec{J}$$

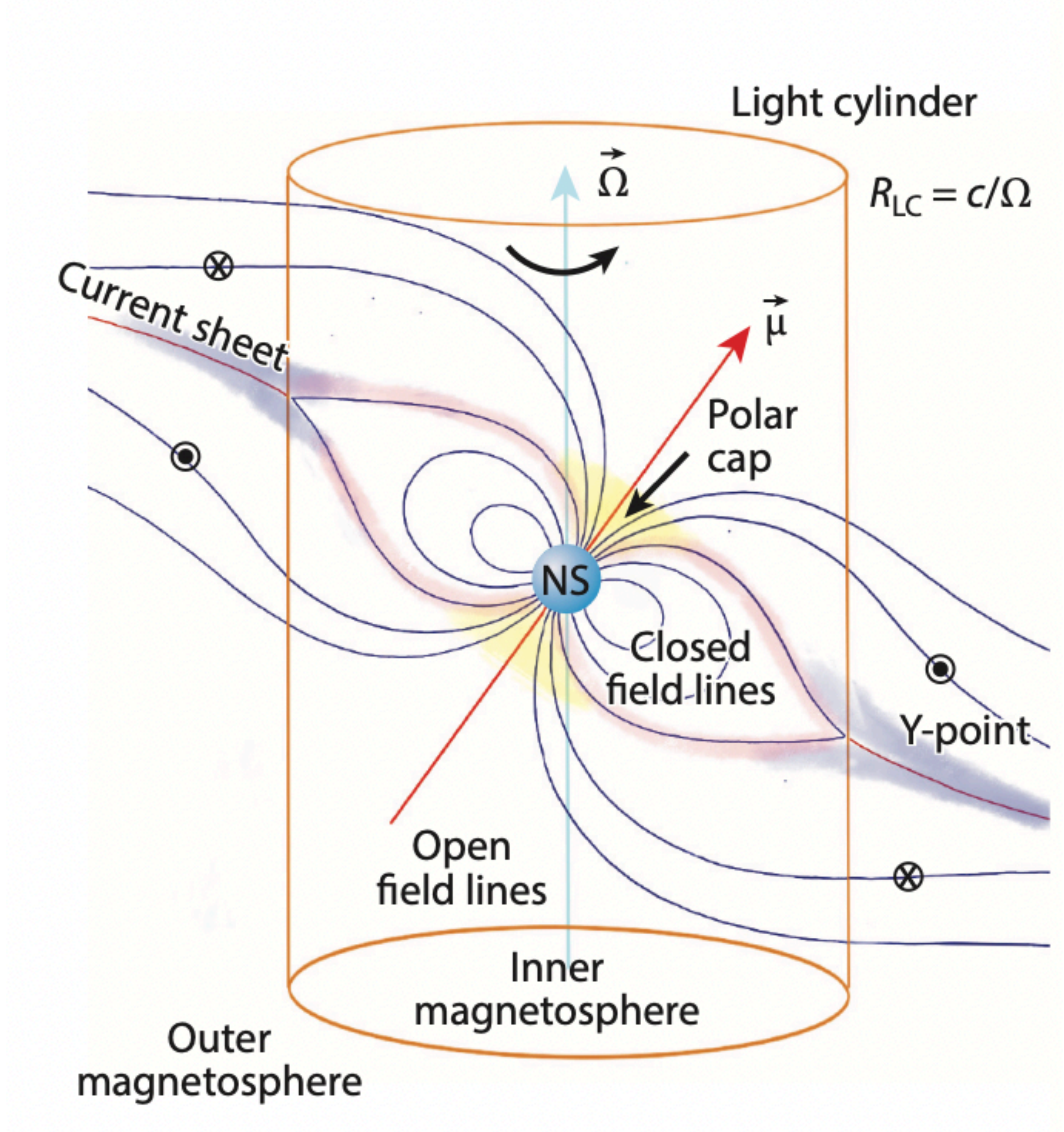
2)
$$\rho \vec{E} + \vec{J} \times \vec{B} = 0 \qquad (\rho = \nabla \cdot \vec{E})$$

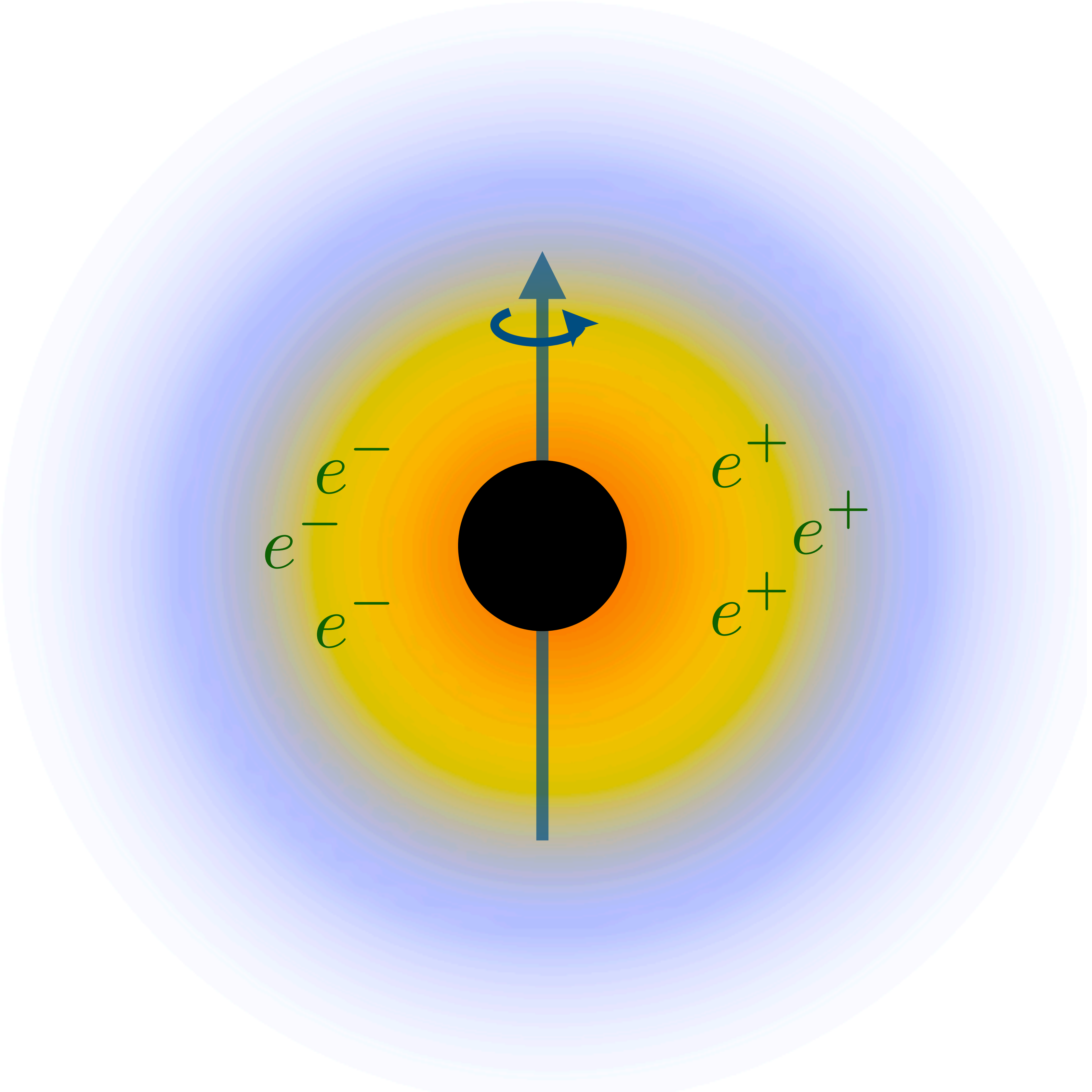
"Force-free" plasma (perfect conductor)

→ $\vec{J} = f(\vec{E}, \vec{B})$

- Solve equations for the E, B fields
- Compute EM energy emitted

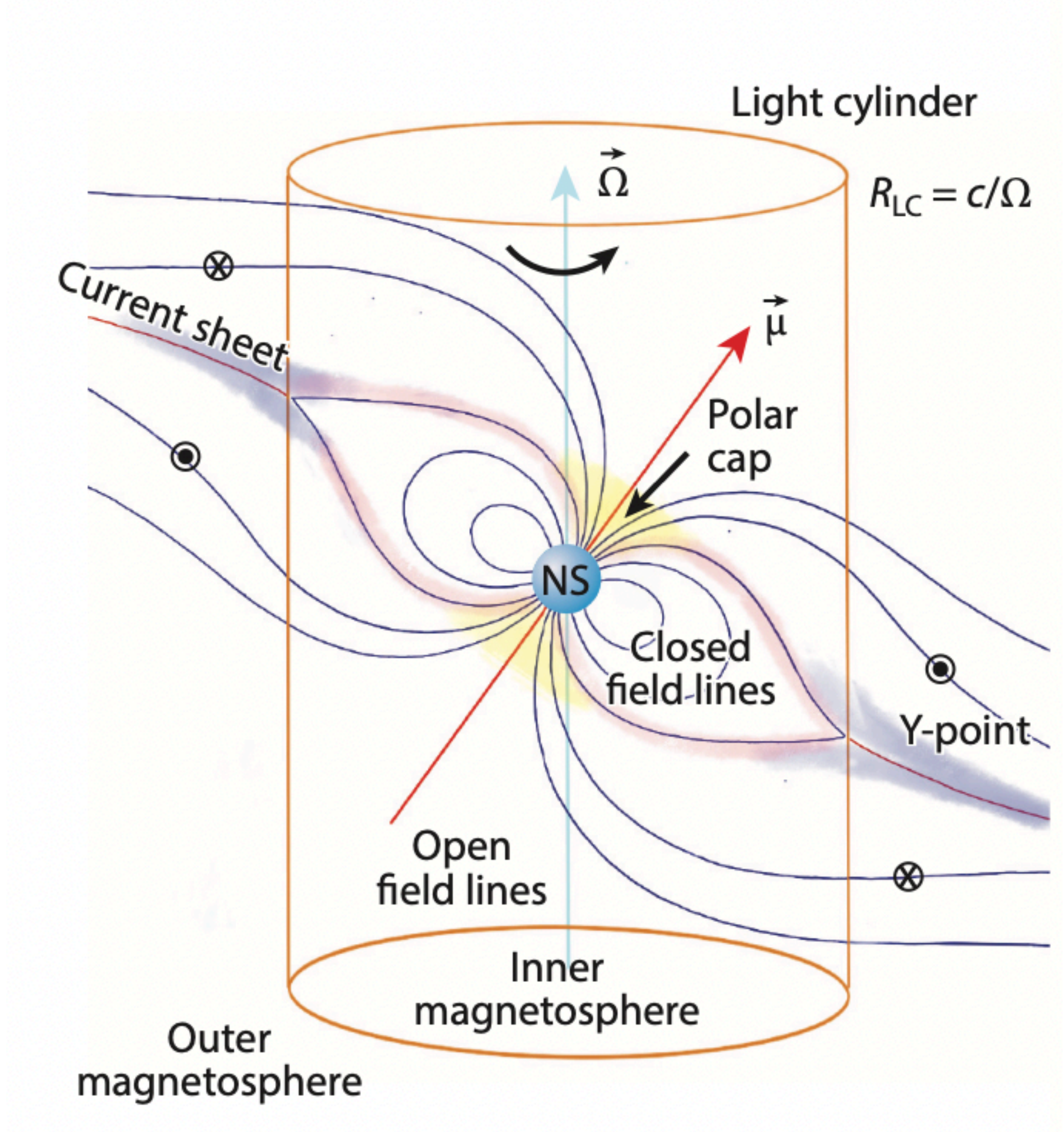
Analogy





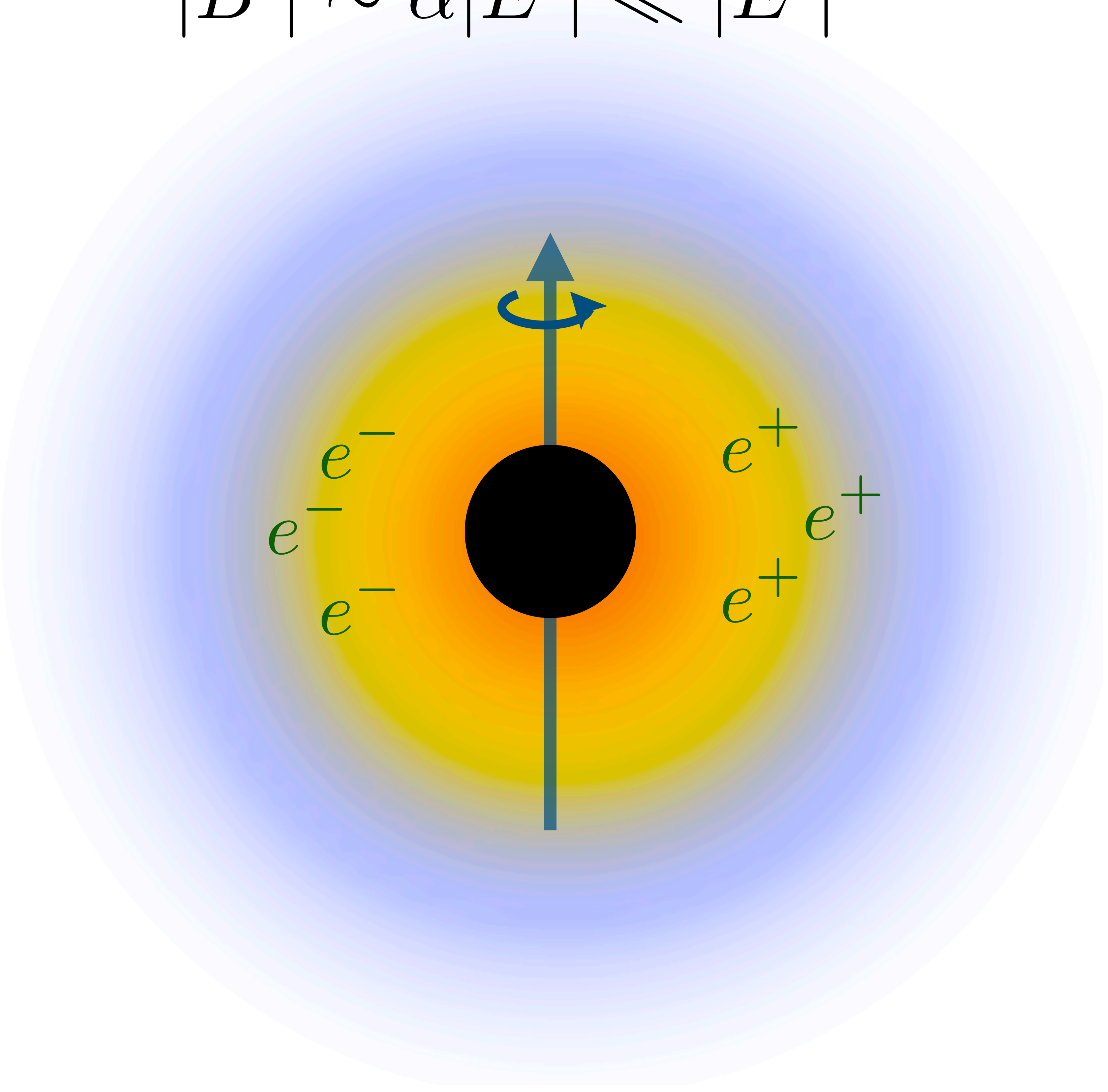
- Large EM fields
- Rotating objects (~ ms periods)

Difference



Magnetically dominated

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

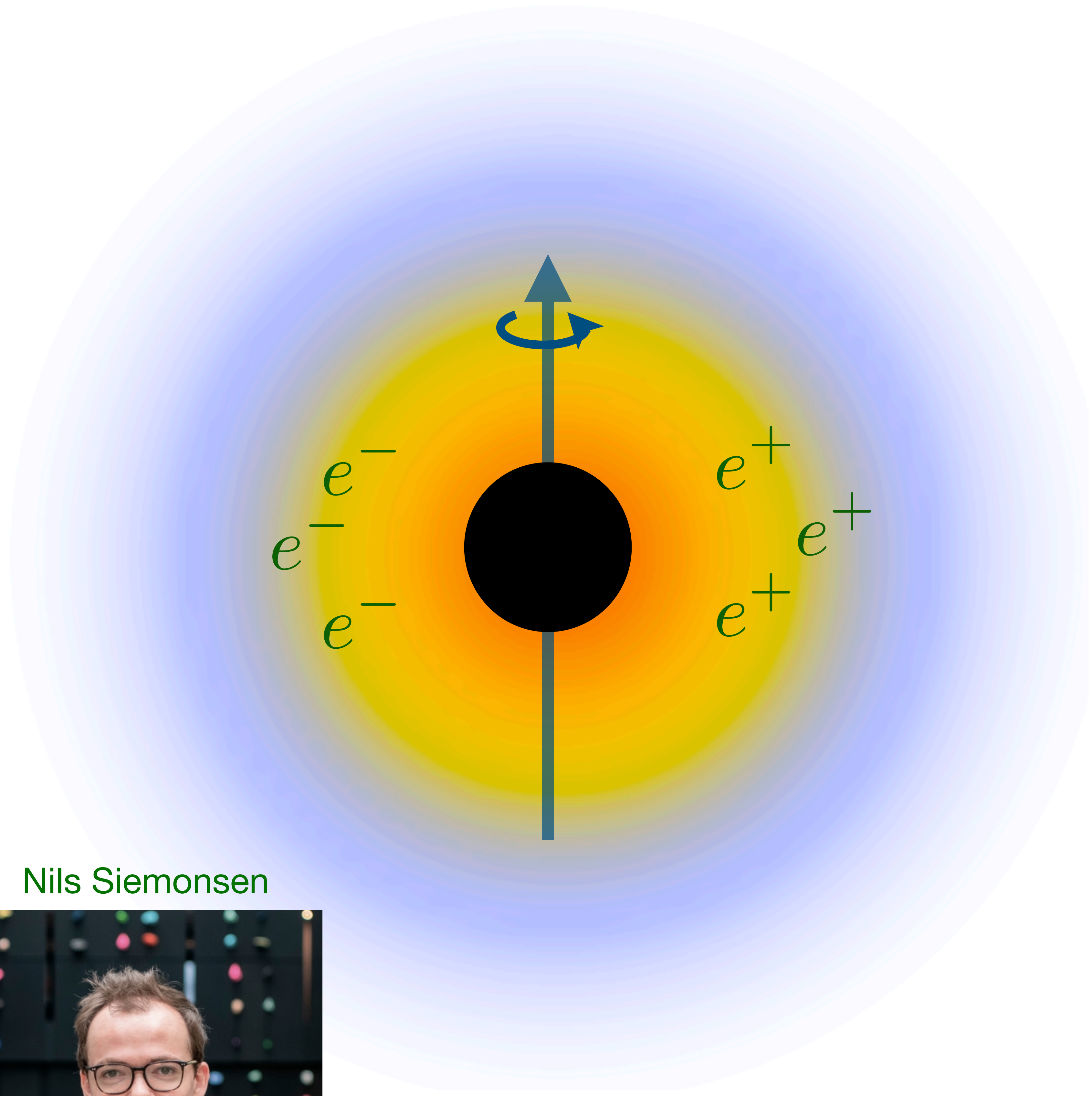


Electrically dominated

↓

Dissipation is important

SR cloud + plasma model



Nils Siemonsen

Full GR numerical simulation
(talk to Nils next week!)

Superradiance field (source)

$$\partial_t \vec{B} = -\nabla \times \vec{E}$$

$$\partial_t \vec{E} = \nabla \times \vec{B} - \vec{J} + \epsilon\mu^2 \vec{A}'$$

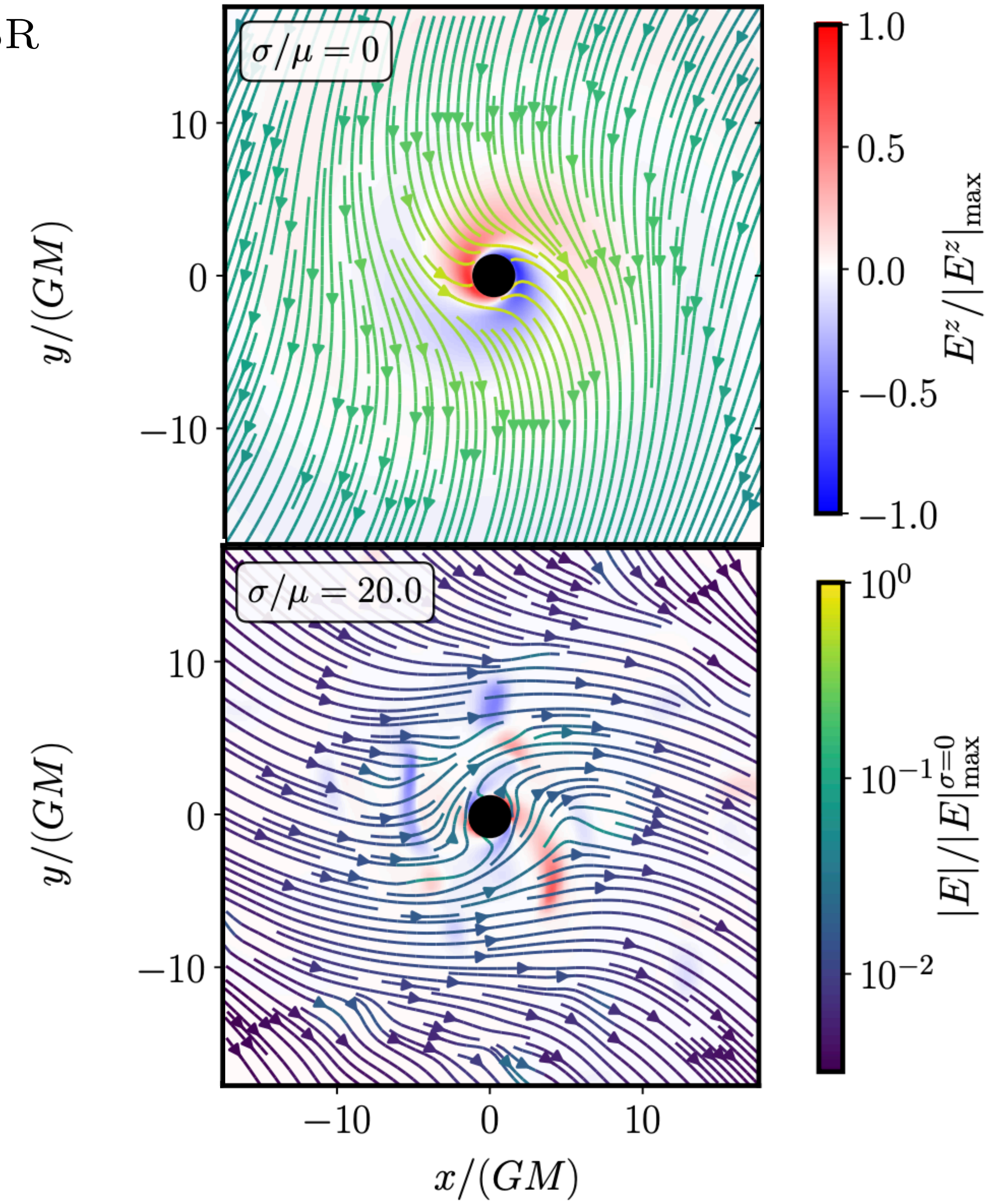
Ohm's law $\vec{J} = \sigma(\vec{E} + \vec{v} \times \vec{B})$

- Solve equations for the E, B fields
- Compute EM energy emitted for $\sigma \to \infty \quad (\sigma \gg \mu)$

Simulation: E field

Vacuum (no screening)

$$\vec{E} = \epsilon \vec{E}_{\rm SR}$$

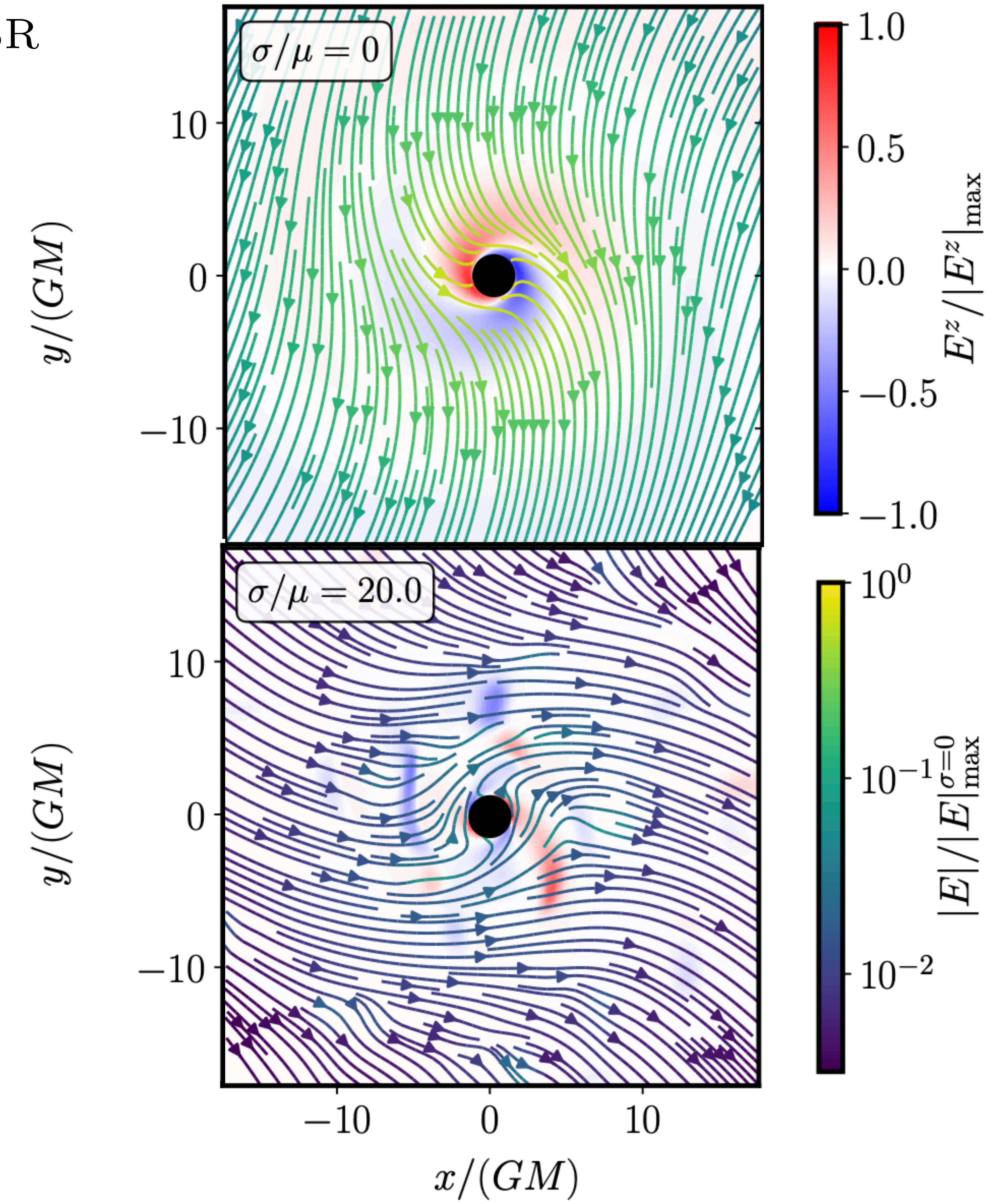


Highly conducting plasma: the E field is screened

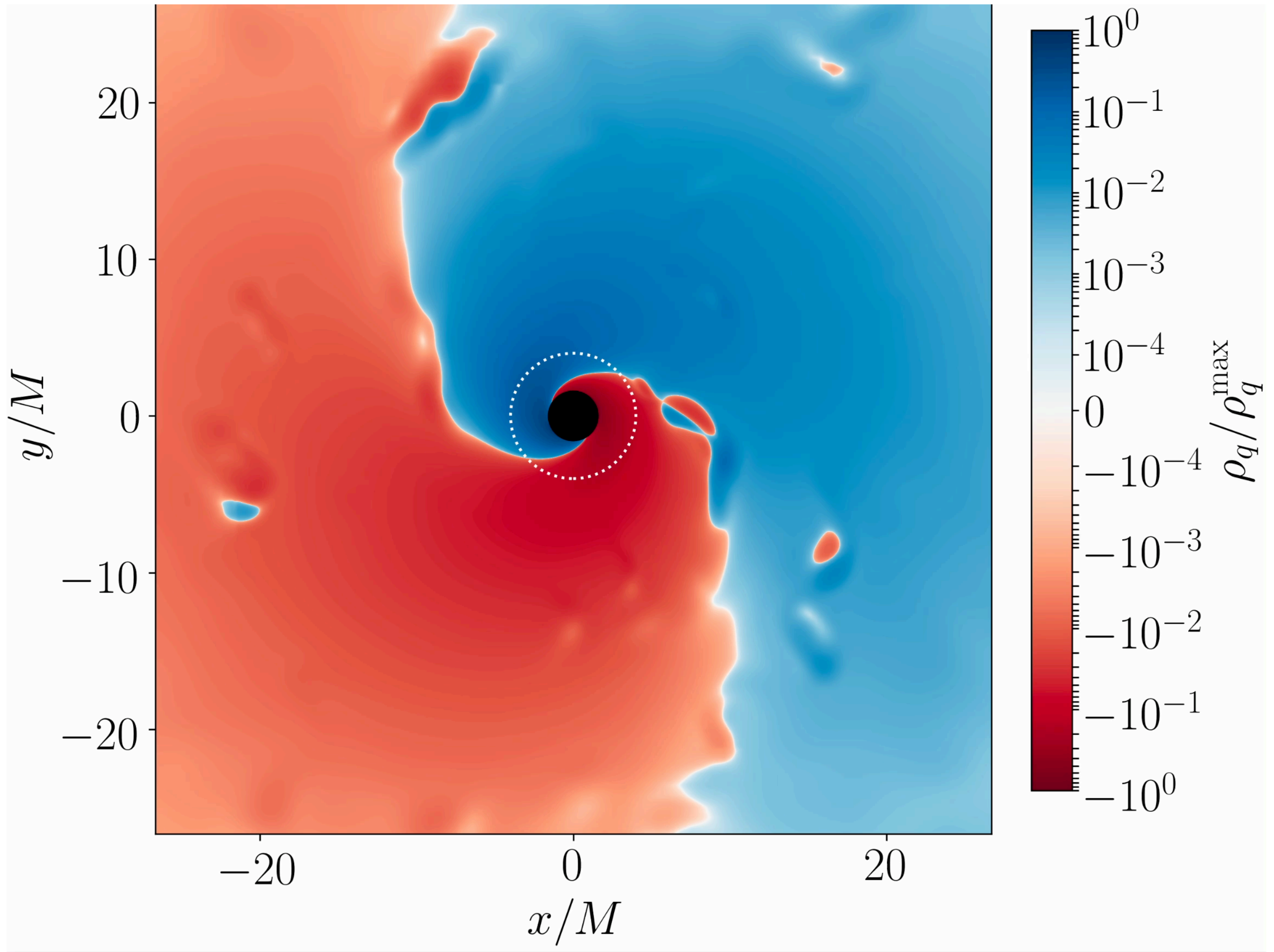
Simulation: E field

Vacuum (no screening)

$$\vec{E} = \epsilon \vec{E}_{\rm SR}$$



Charge density



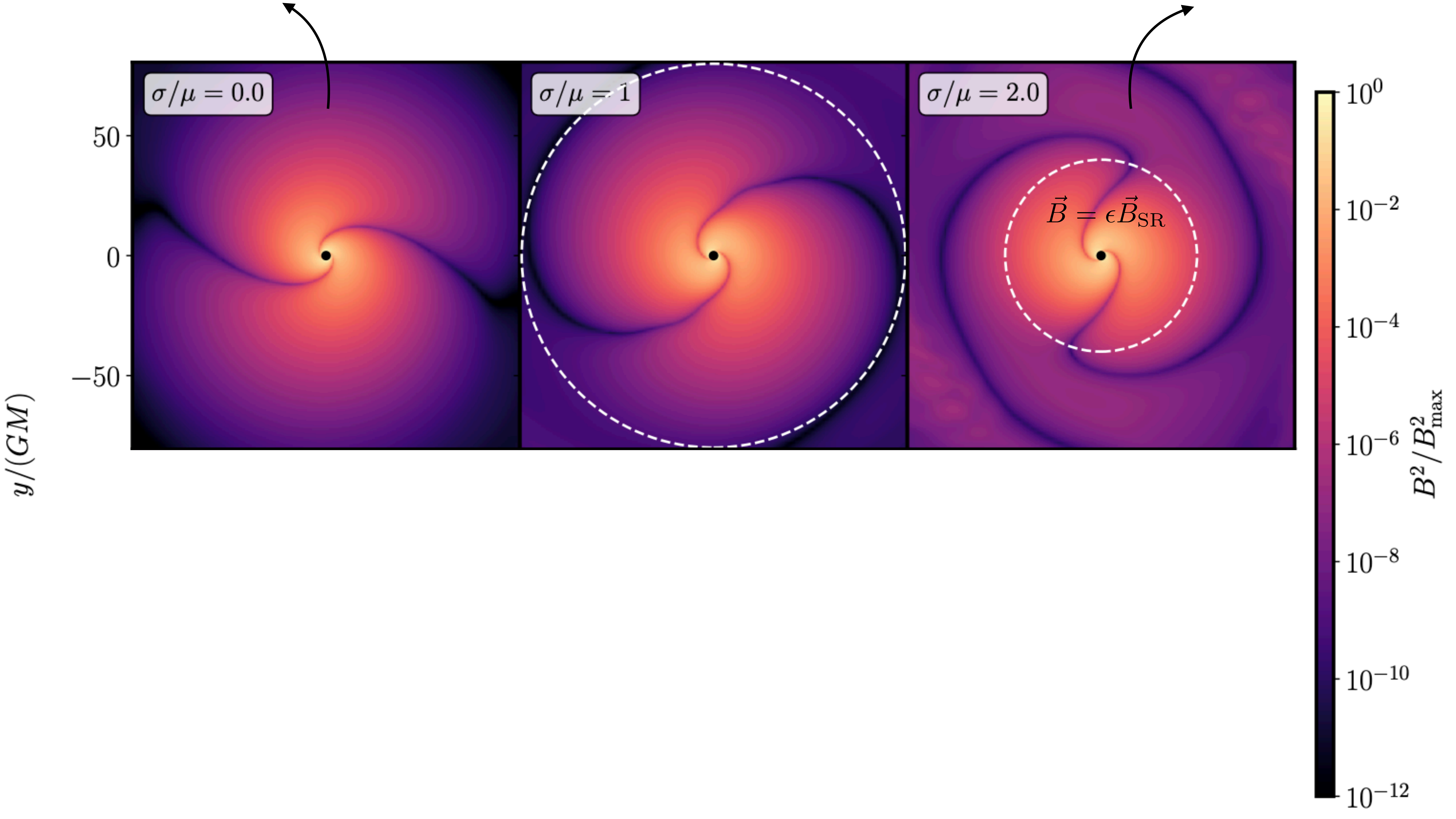
Rotating dipole

Highly conducting plasma: the E field is screened

Simulation: B field

Vacuum $\vec{B} = \epsilon \vec{B}_{\rm SR}$

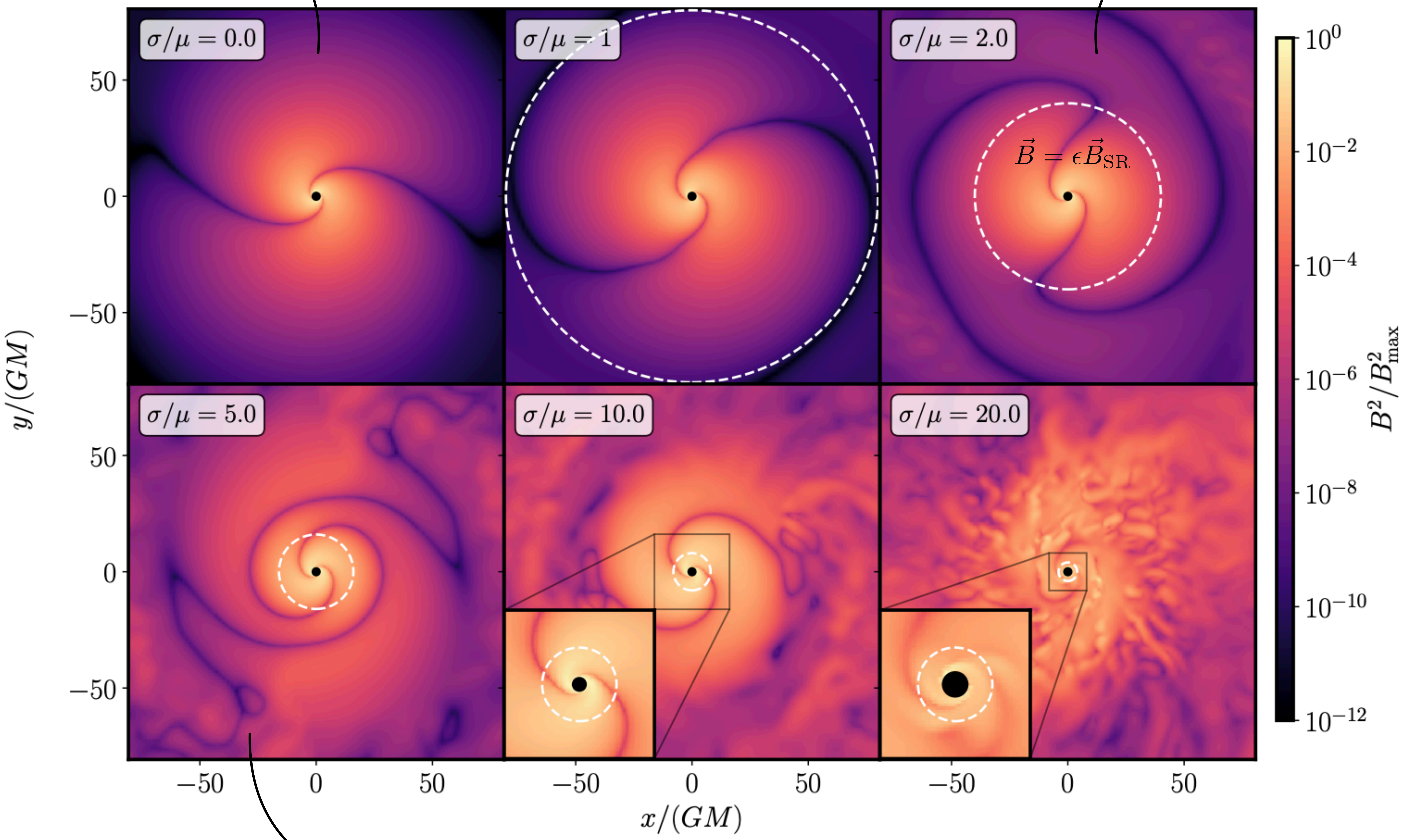
$\vec{B}$ determined by plasma dynamics



Simulation: B field

Vacuum $\vec{B} = \epsilon \vec{B}_{\rm SR}$

$\vec{B}$ determined by plasma dynamics

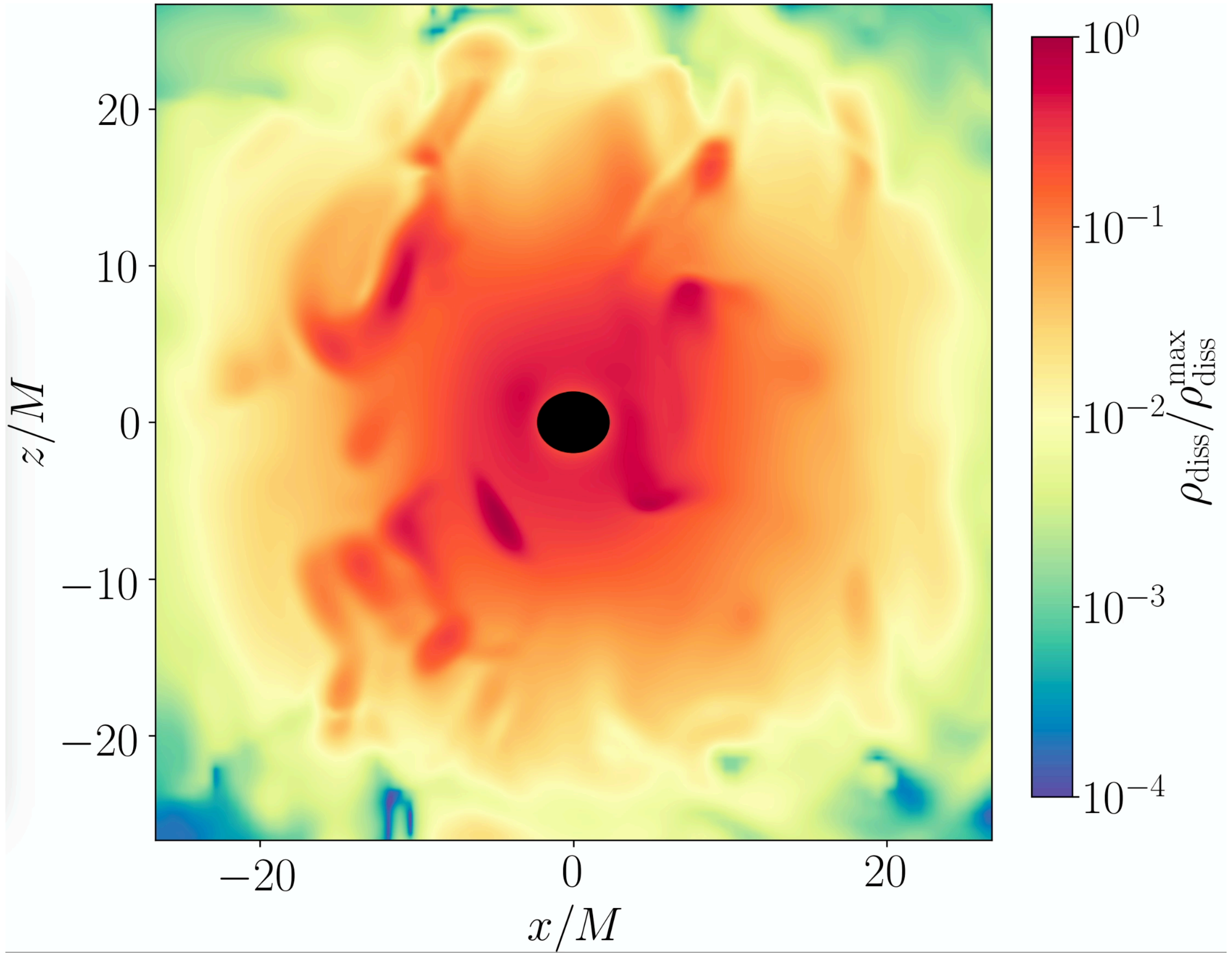


Far from the BH, the plasma cannot keep up with field rotation at frequency $\sim \mu$

Turbulent field structure!

Twisting of the magnetic field lines

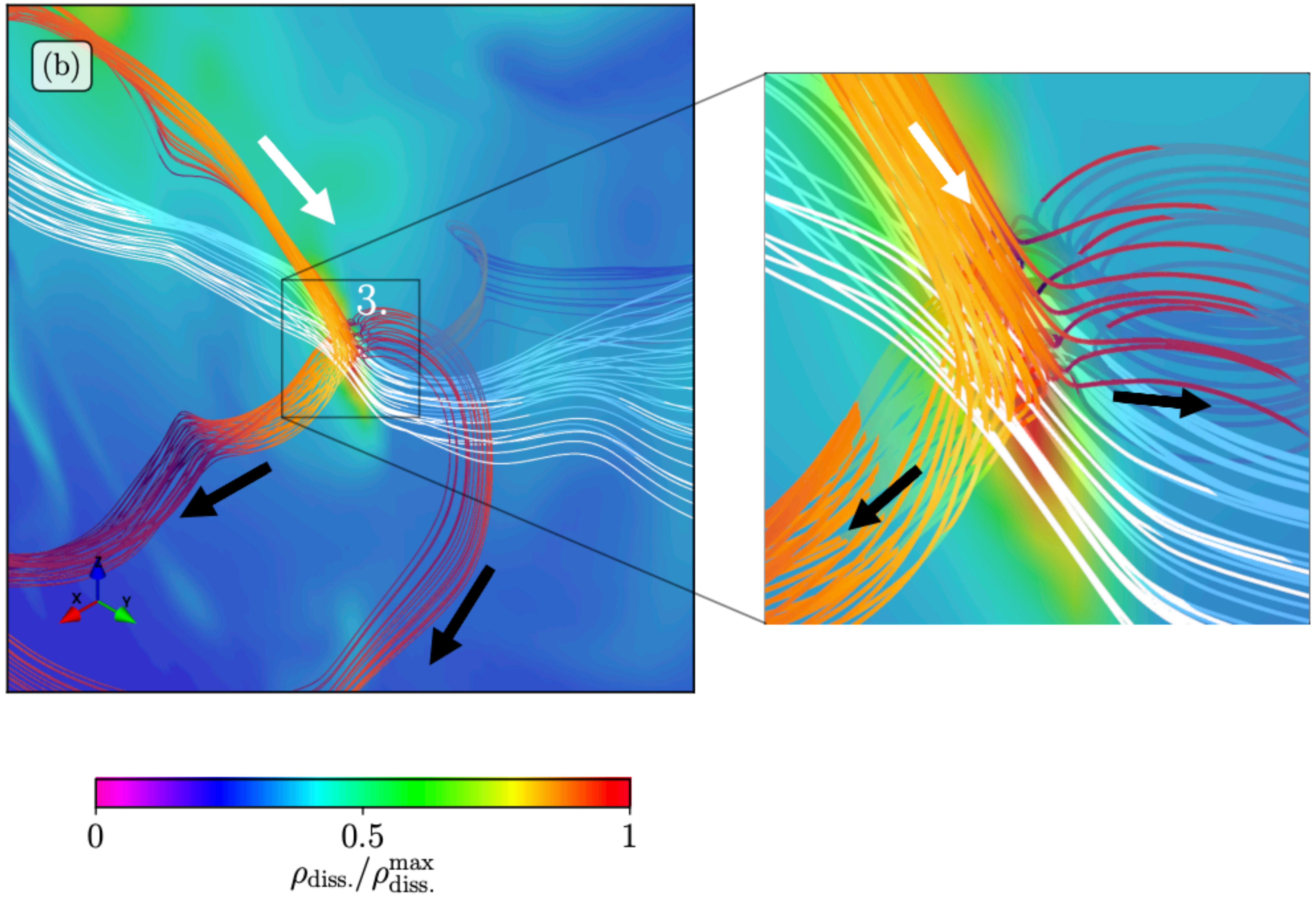
Simulation: energy dissipation



$$\rho_{\rm diss} = \vec{E} \cdot \vec{J}$$

Turbulent structure in the dissipative energy density!

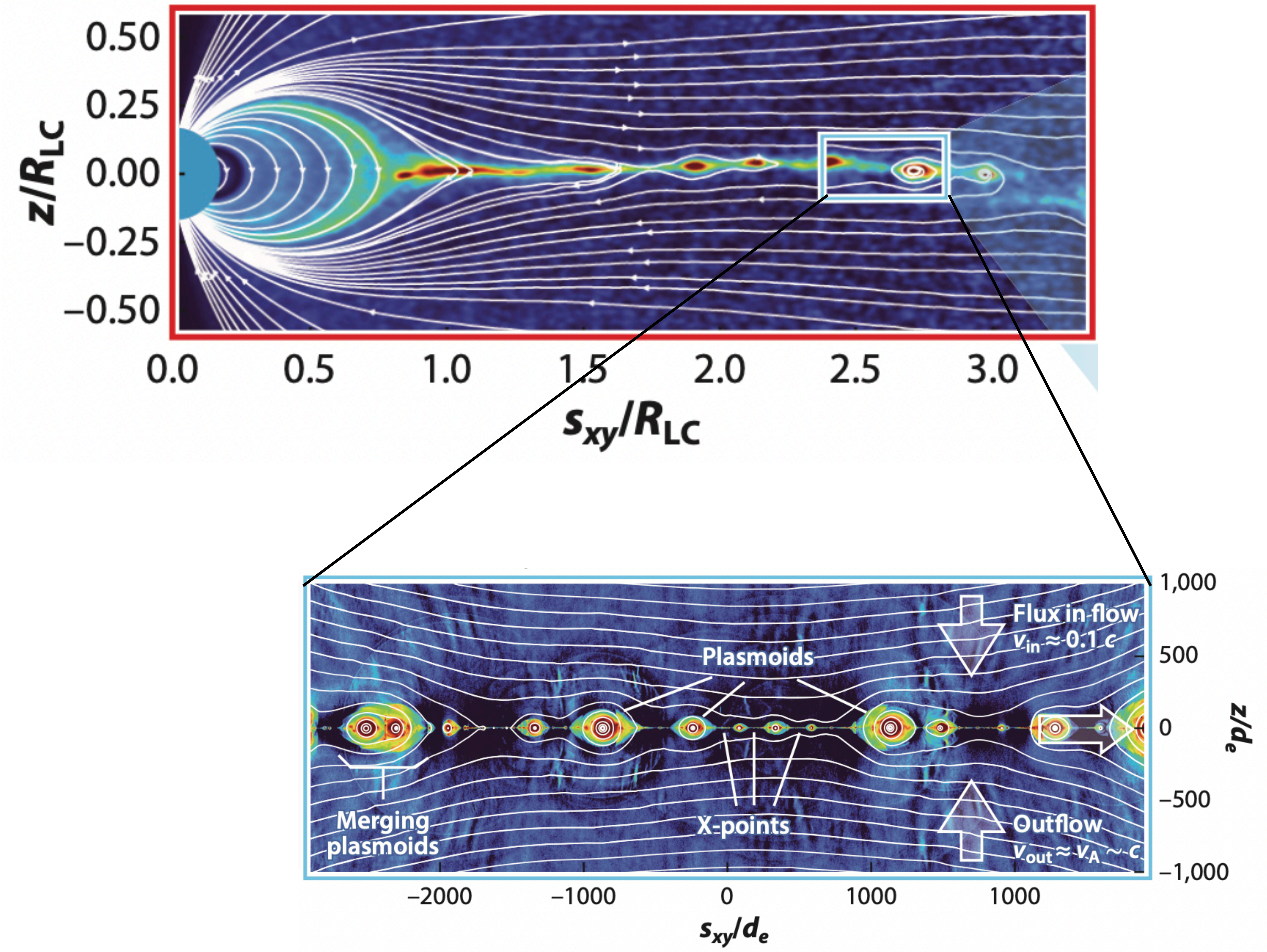
Simulation: energy dissipation



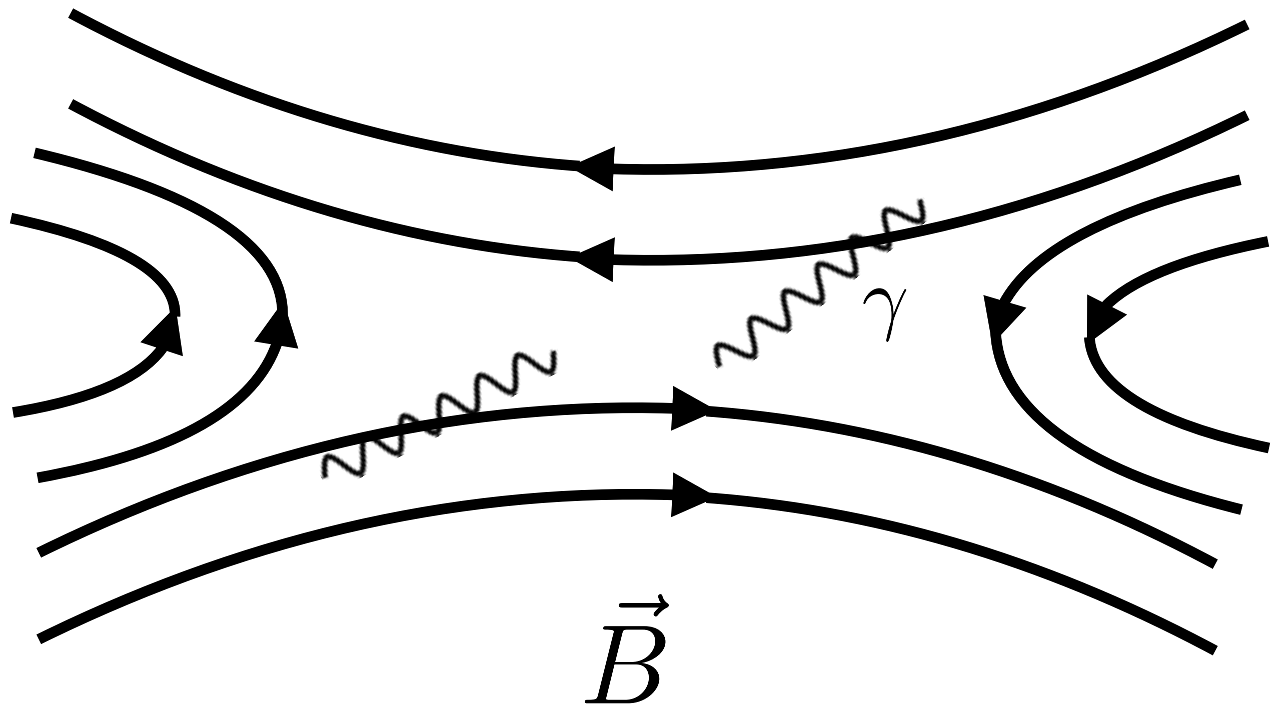
The dissipative energy density is maximal in the regions of magnetic field lines reconnection.

Magnetic reconnection

Plasma density



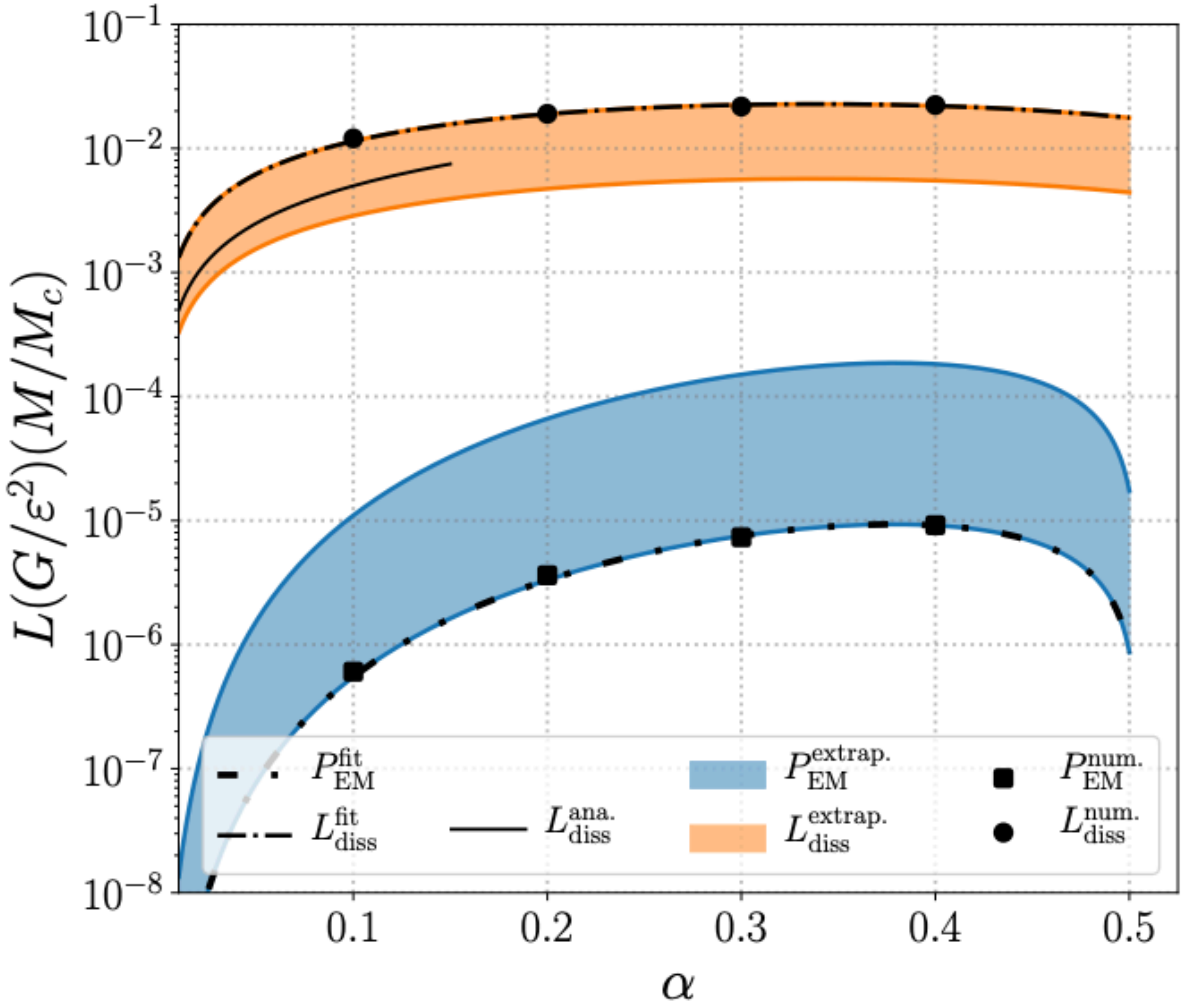
- Discontinuity in the magnetic field lines
- In a **neutron star pulsars** it happens on the equatorial plane (2d structures “current sheets”)



Field energy dissipated into particle acceleration and high energy emissions

Simulation: power output

Numerical solutions and fit

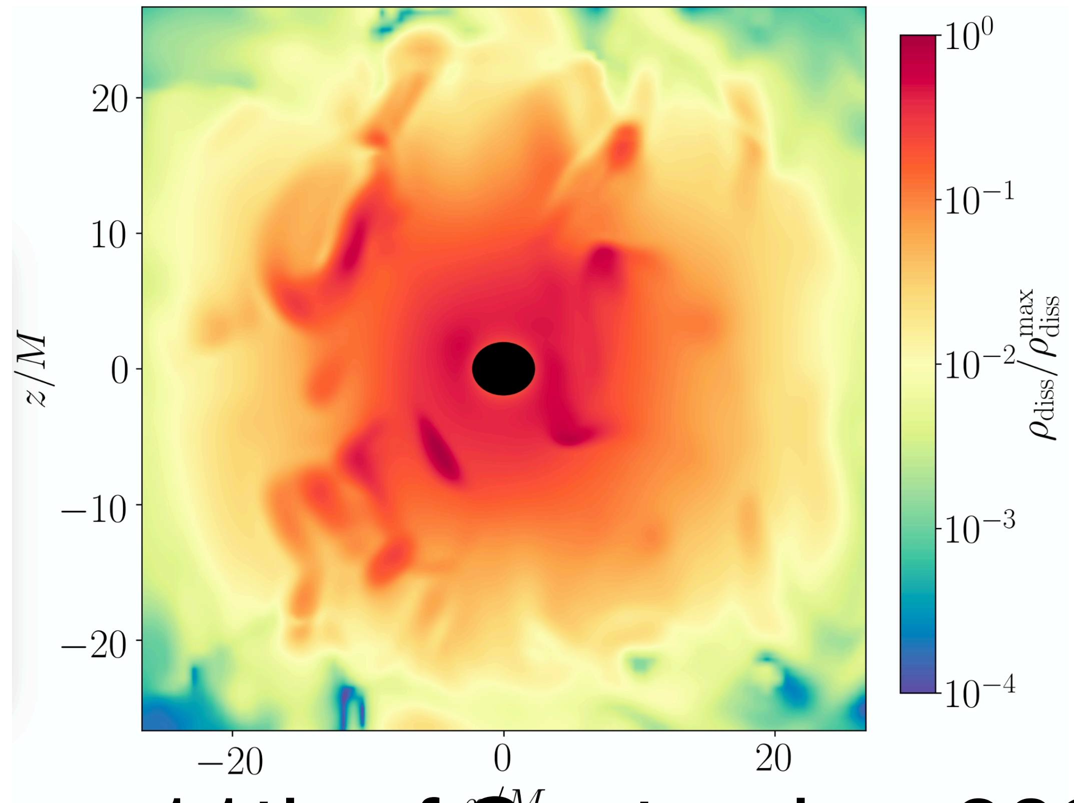


- Poynting flux

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

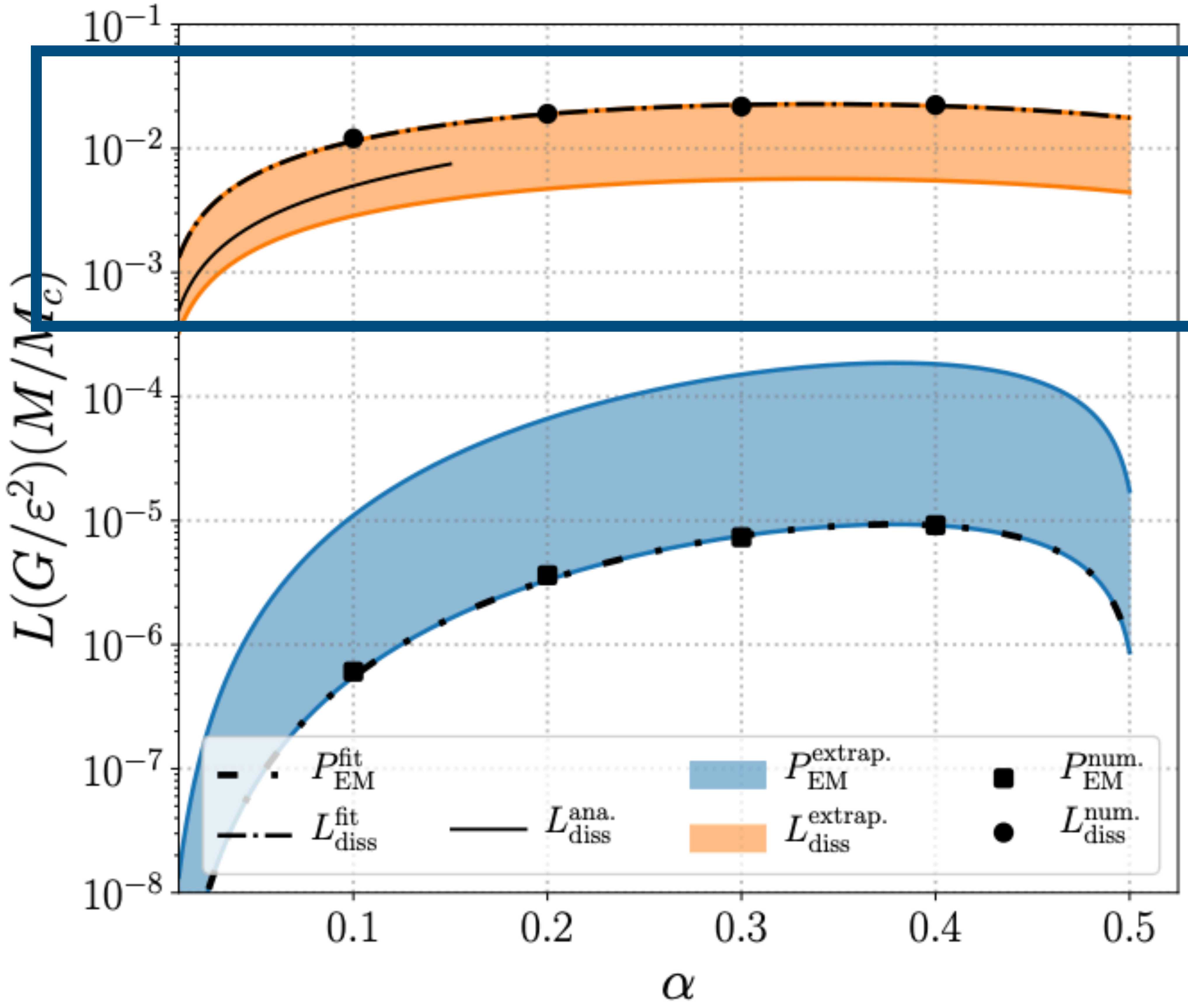
- Dissipative losses

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



Simulation: power output

Numerical solutions and fit



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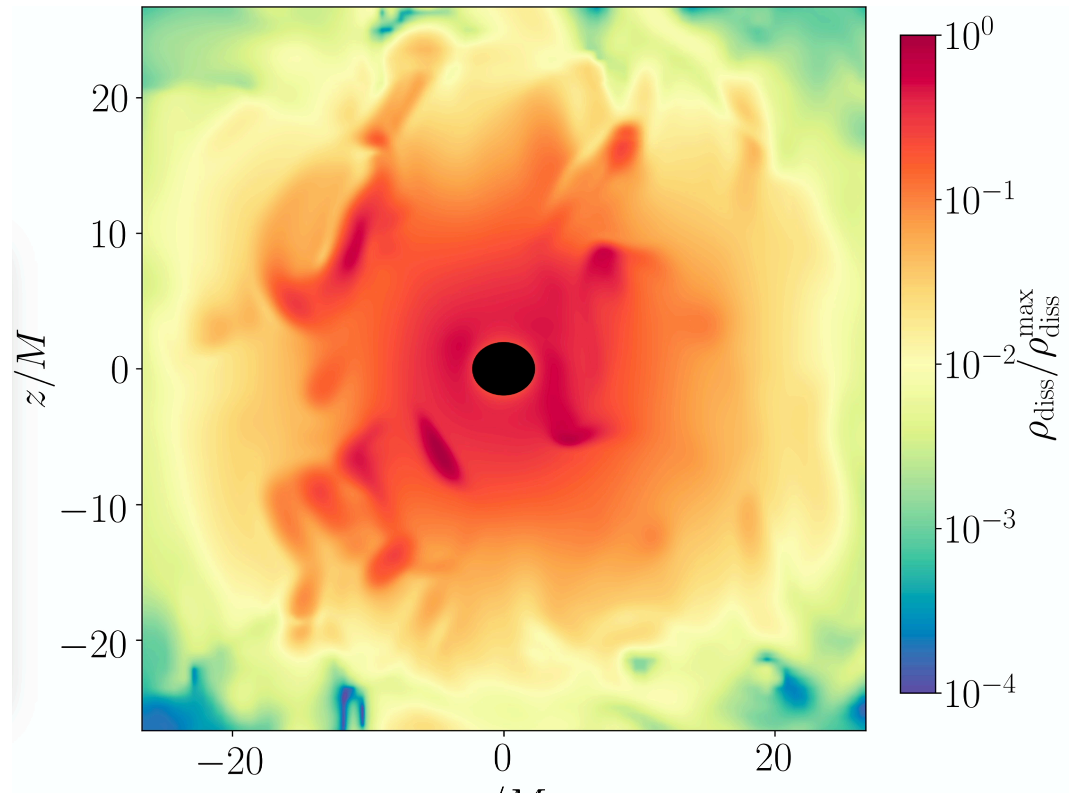
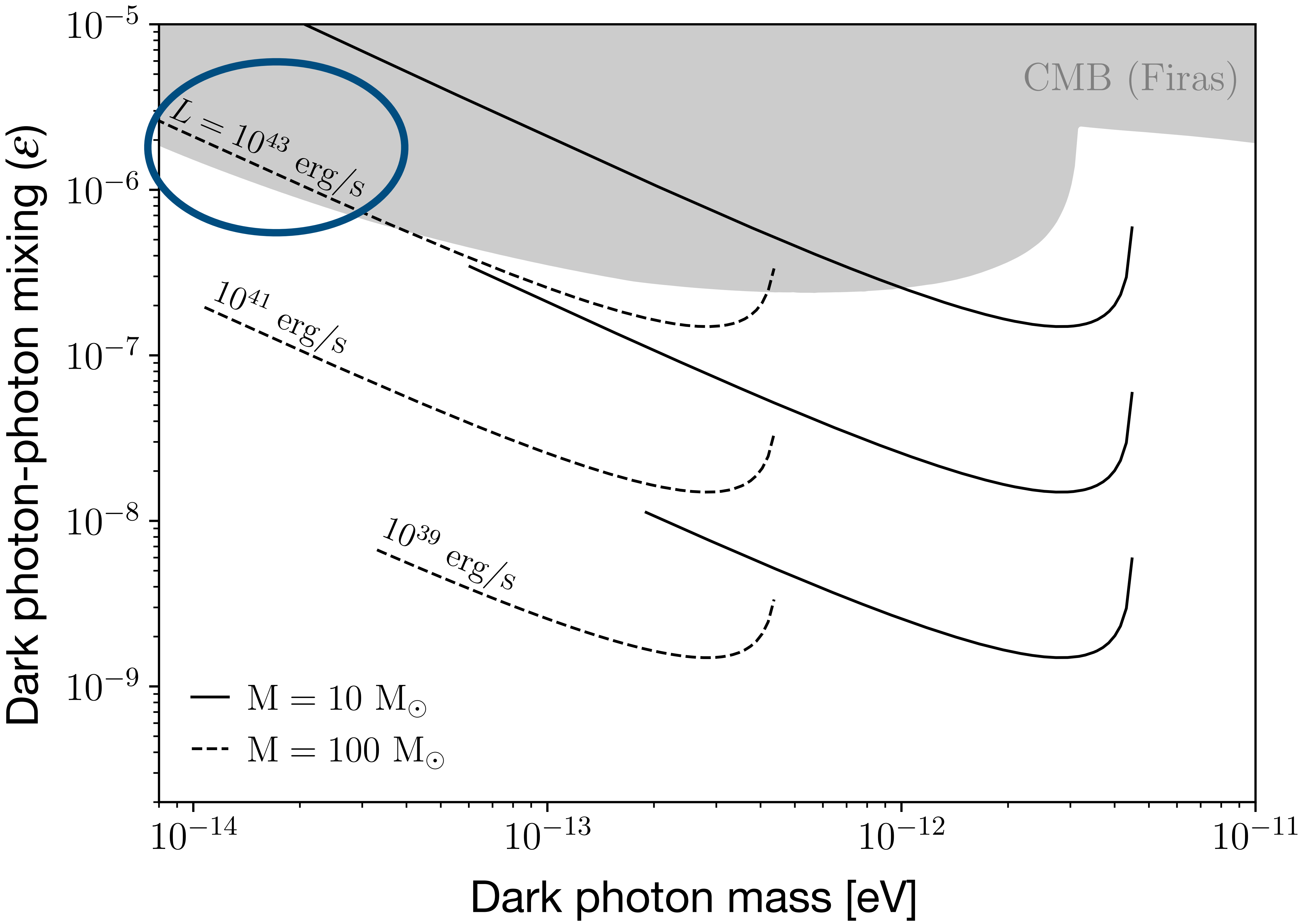


Simulation: power output

Peak luminosity



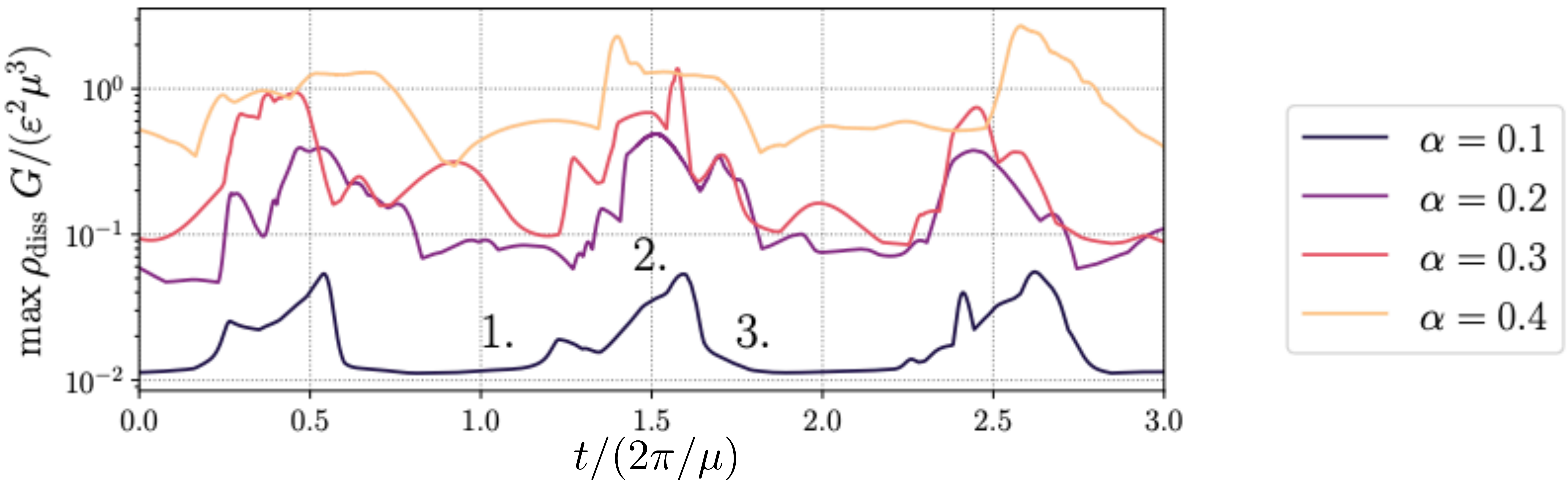
$$L_{\rm fit} = \varepsilon^2 F(\alpha) \frac{M_c}{GM} \simeq 10^{43} \text{ erg/s}$$

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

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

Can be observed at cosmological distances!!!

Simulation: periodicity?



- Fundamental time scale of the system $2\pi/\mu$
- Weak evidence of periodicity from our simulation
- Pulsar analogy

Simulation: spectrum?

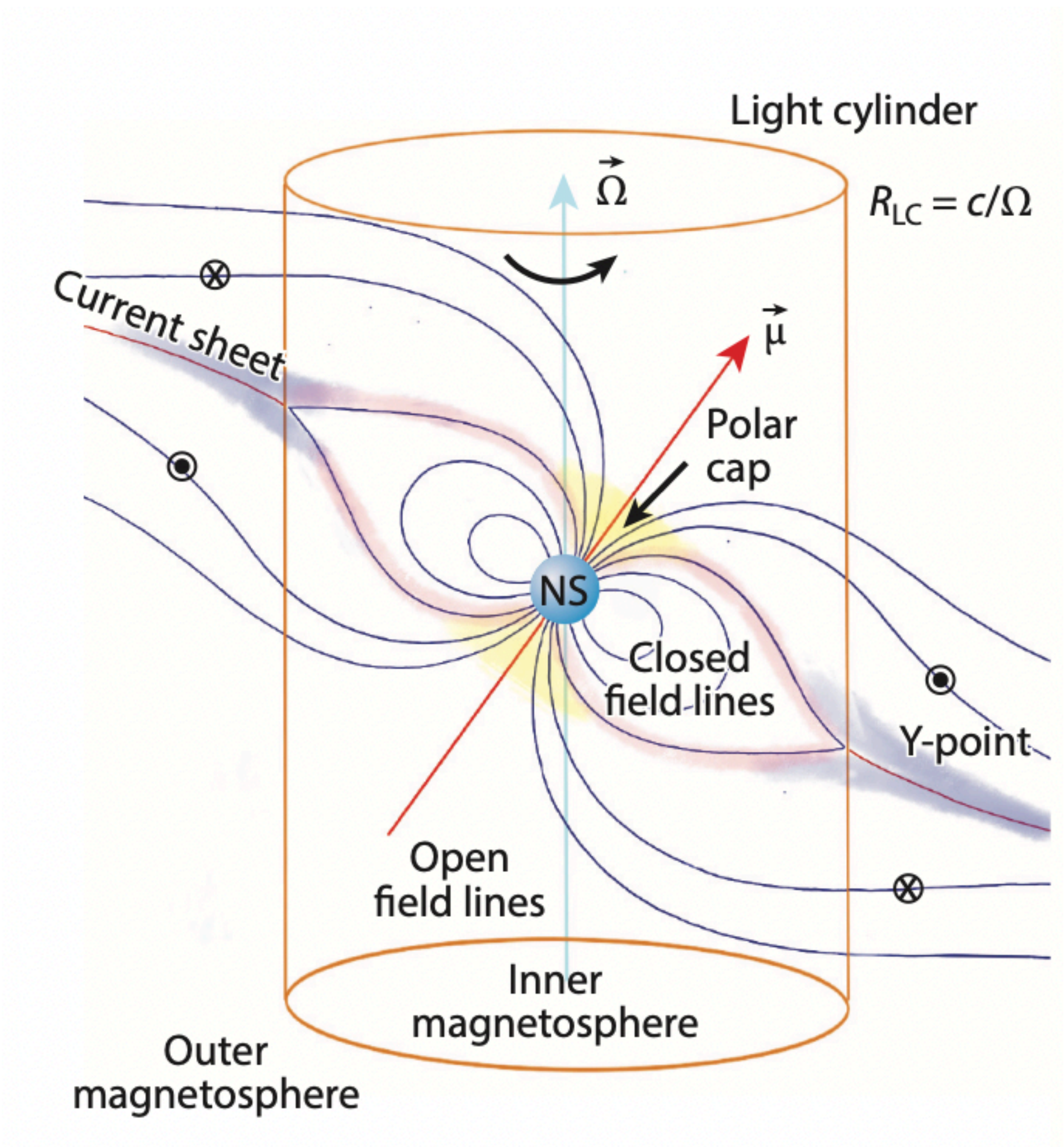
- Synchrotron emission of highly boosted particles

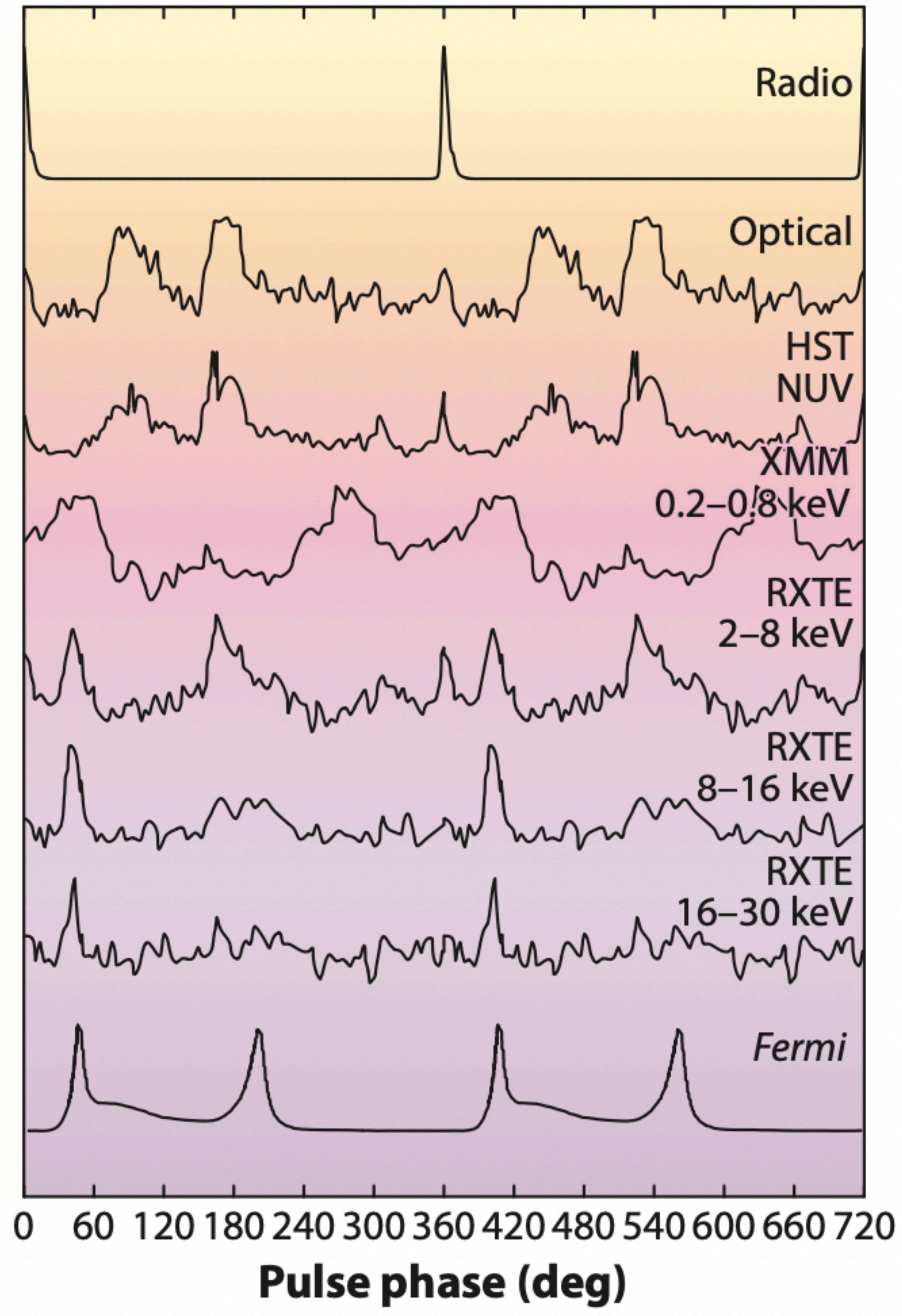
  $e^{\pm}$ boosted to $\gamma \sim \mathcal{O}(10^3)$

  synchrotron photons ~ few keV to MeV

- Coherent low-energy radio emission (continuous + periodic) ?

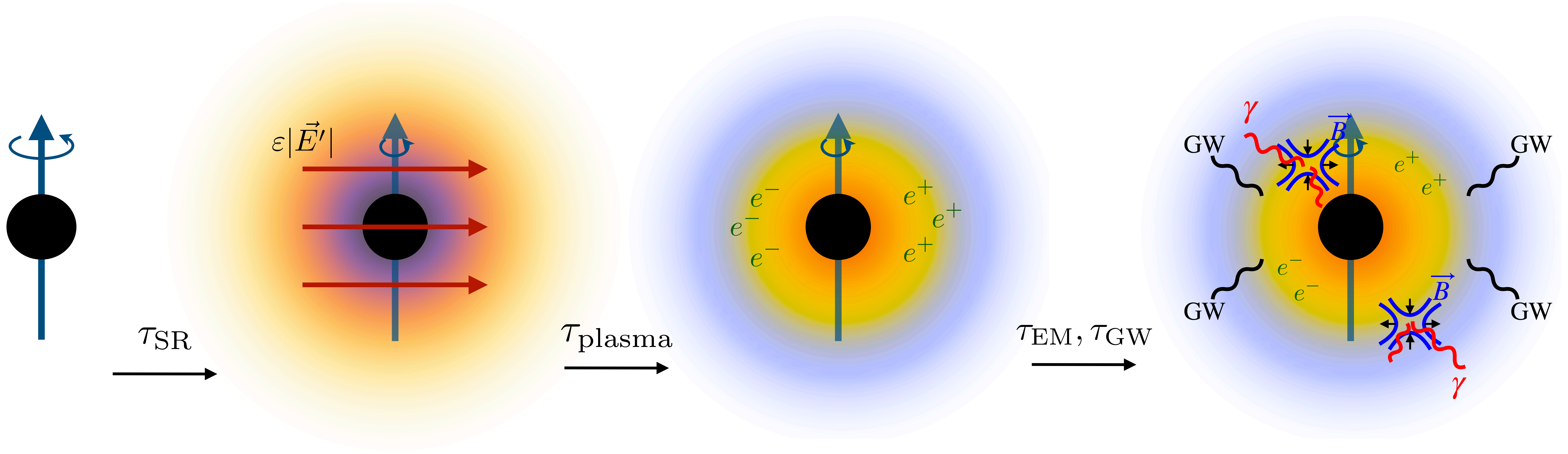
Periodicity and spectrum





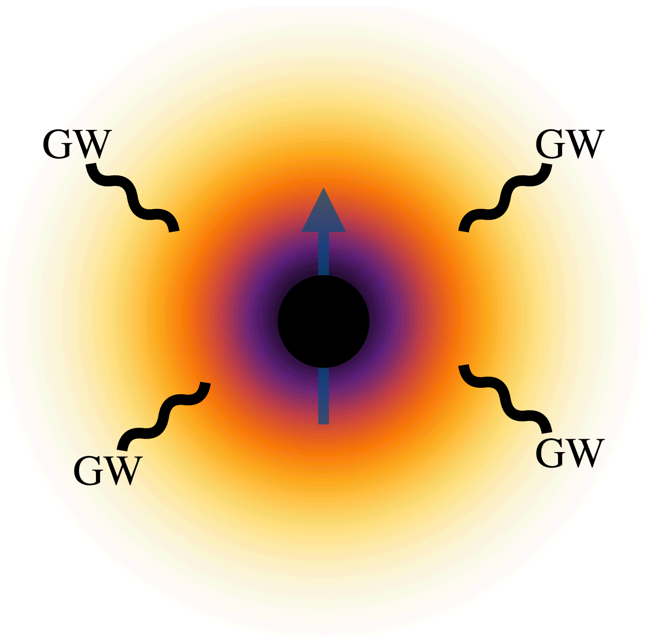
Multimessenger signatures

Evolution of the system



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

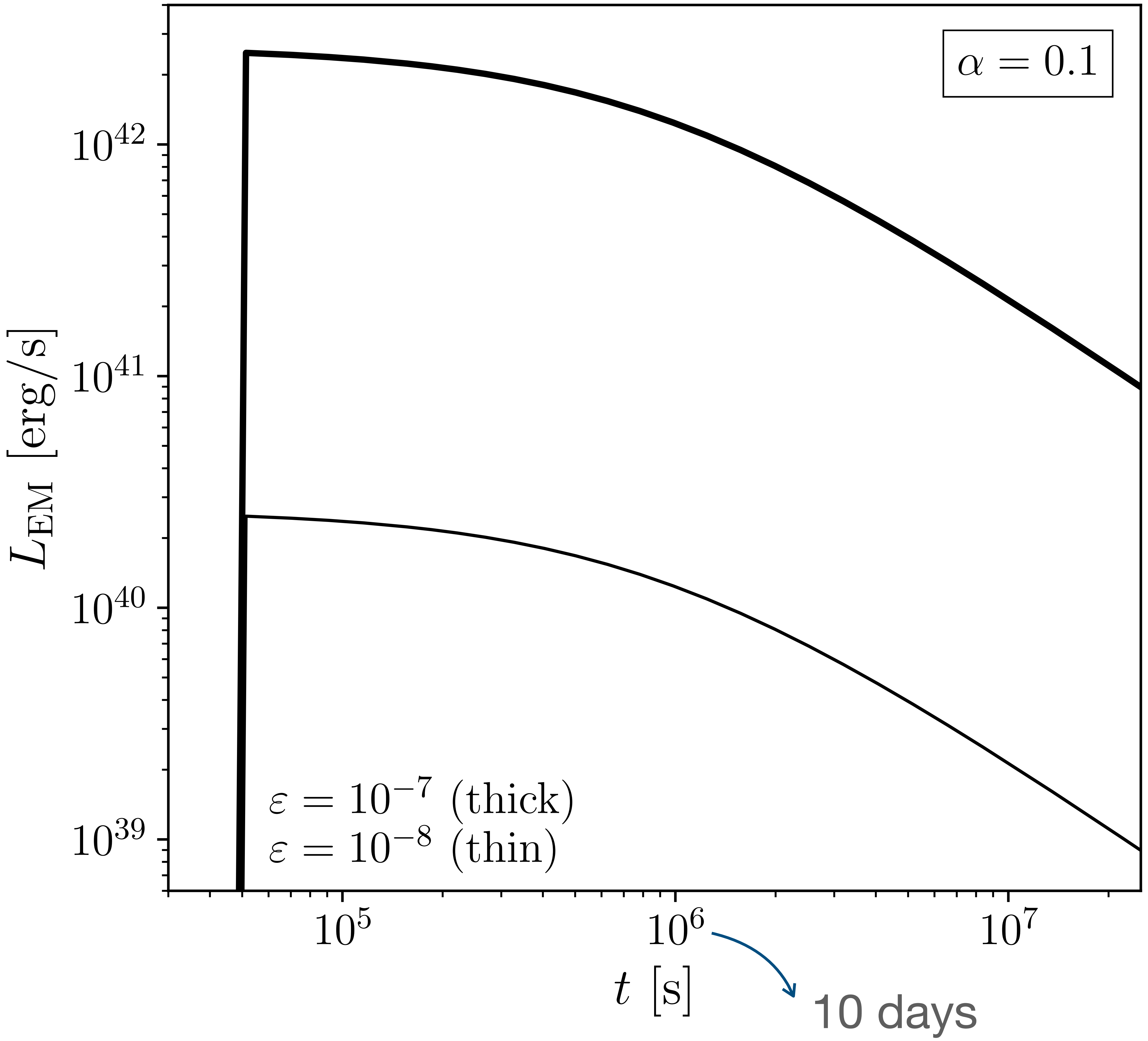
Time evolution



Luminosity of the dark photon superradiance cloud

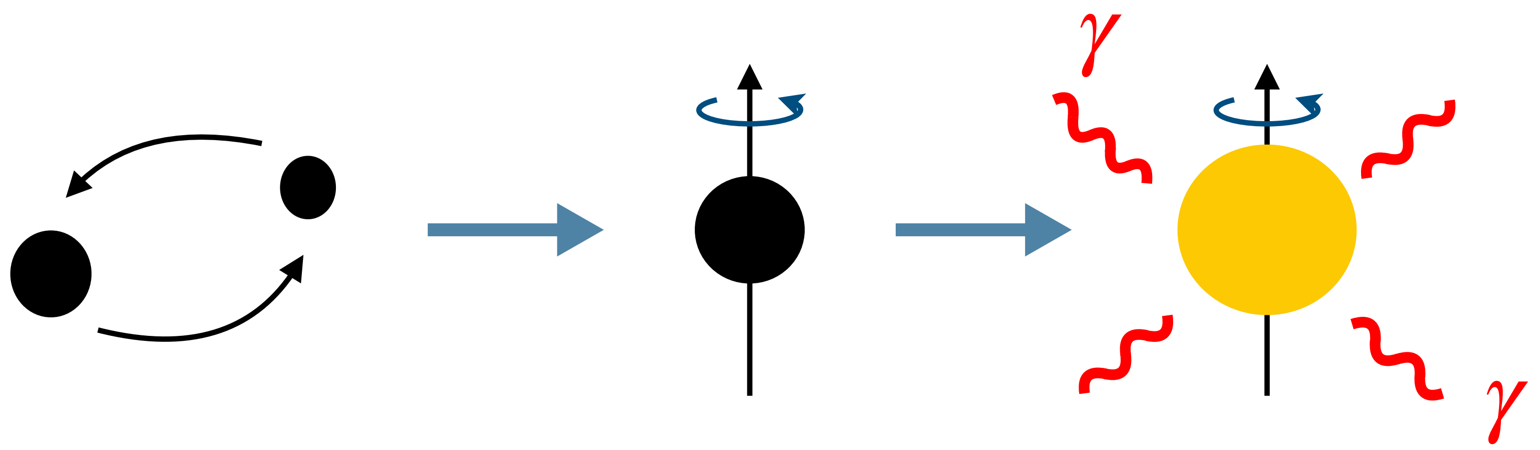
$$L_{\rm fit} = \varepsilon^2 F(\alpha) \frac{M_c(t)}{GM}$$

$$M_c(t) = \frac{M_c(t_0)}{1 + (t - t_0)/\tau_{\rm GW}}$$

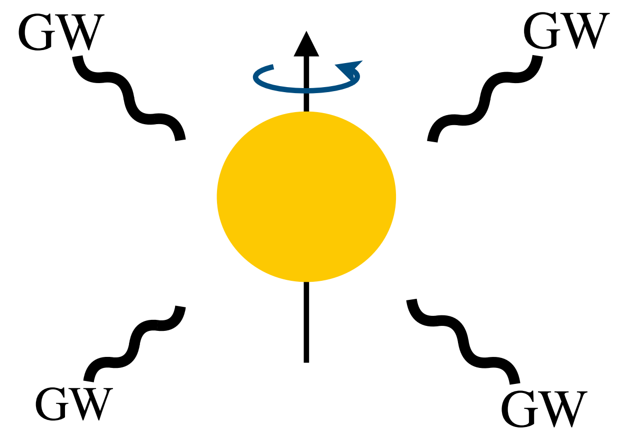


Multimessenger signatures

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



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



Multimessenger signatures

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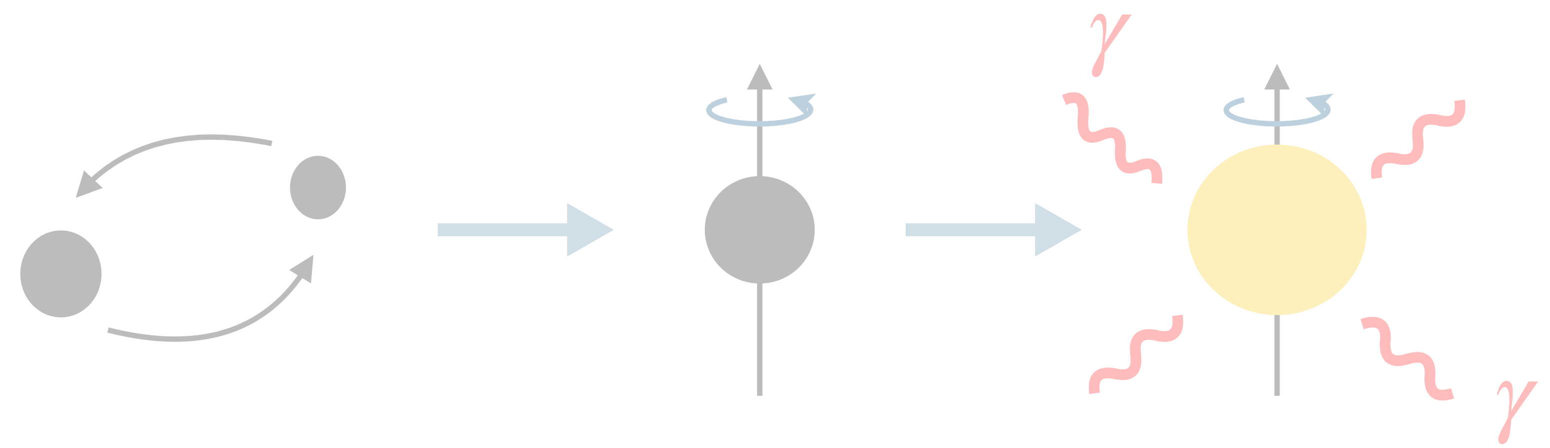

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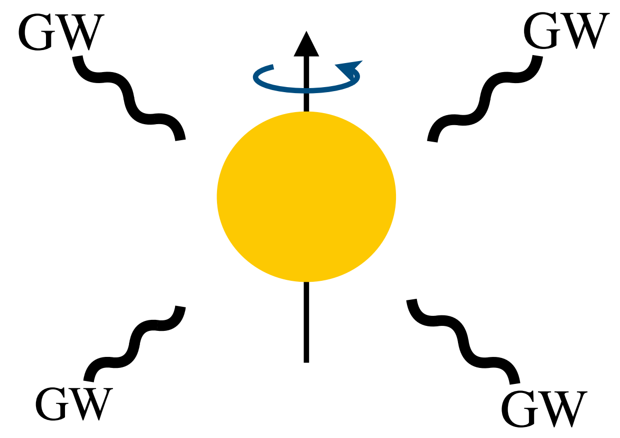
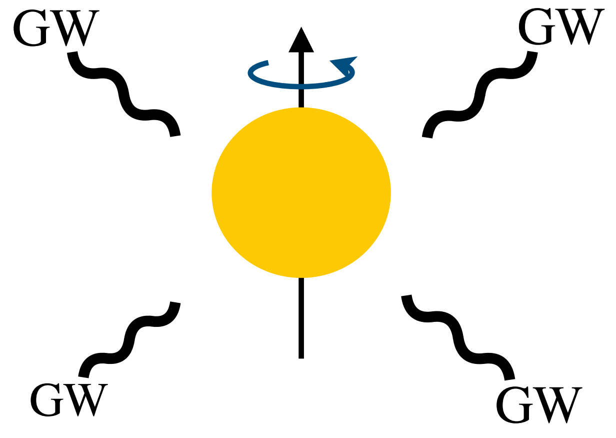


GW follow-up of “anomalous” pulsars



Small α, old system

- Some of the observed pulsating sources could be old BHs with radiating SR cloud

- Search in existing catalogs:

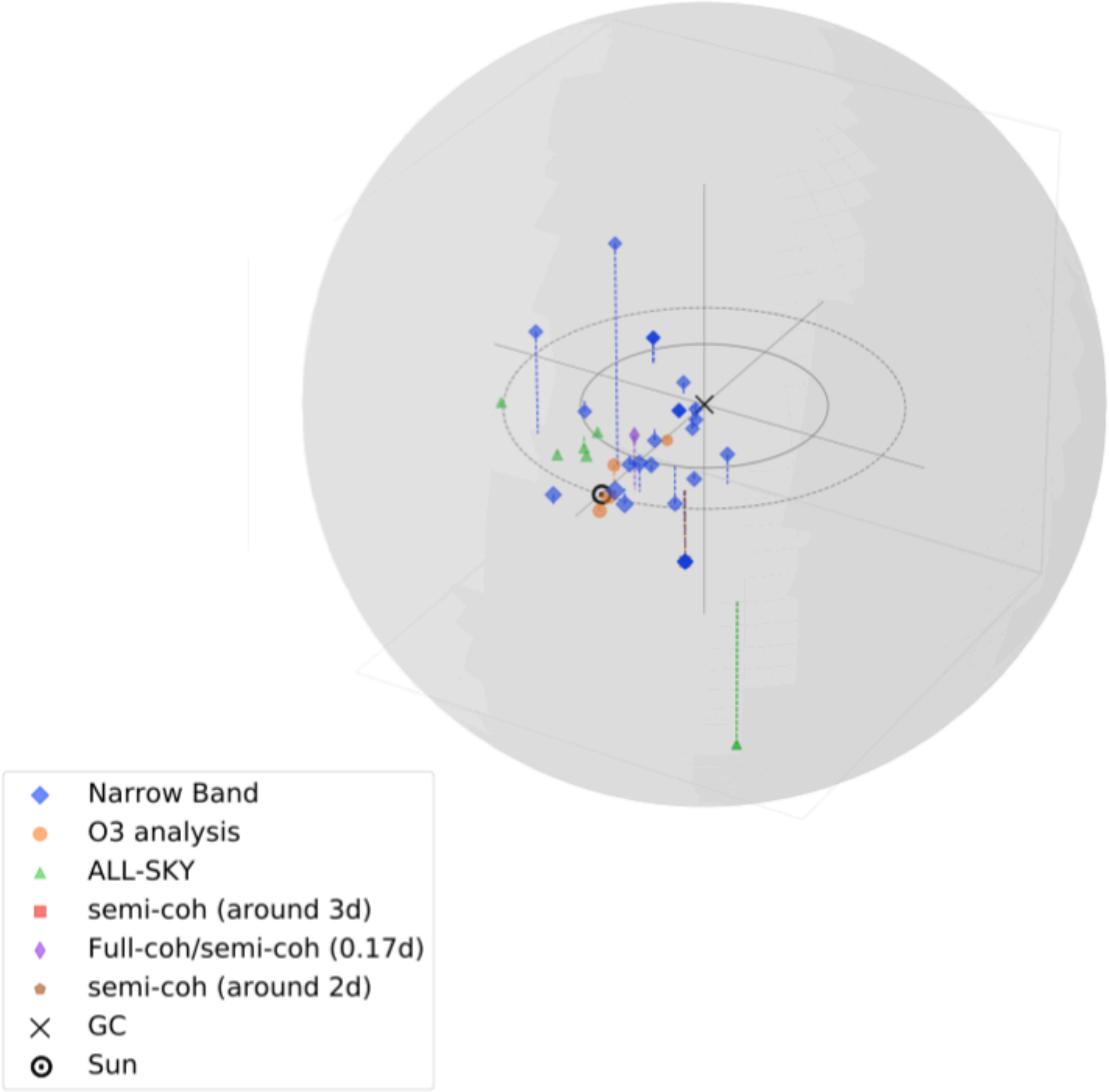
  1. Pulsating sources with the same frequency $\sim 2\pi/\mu$
  2. Sources that spin-up over time

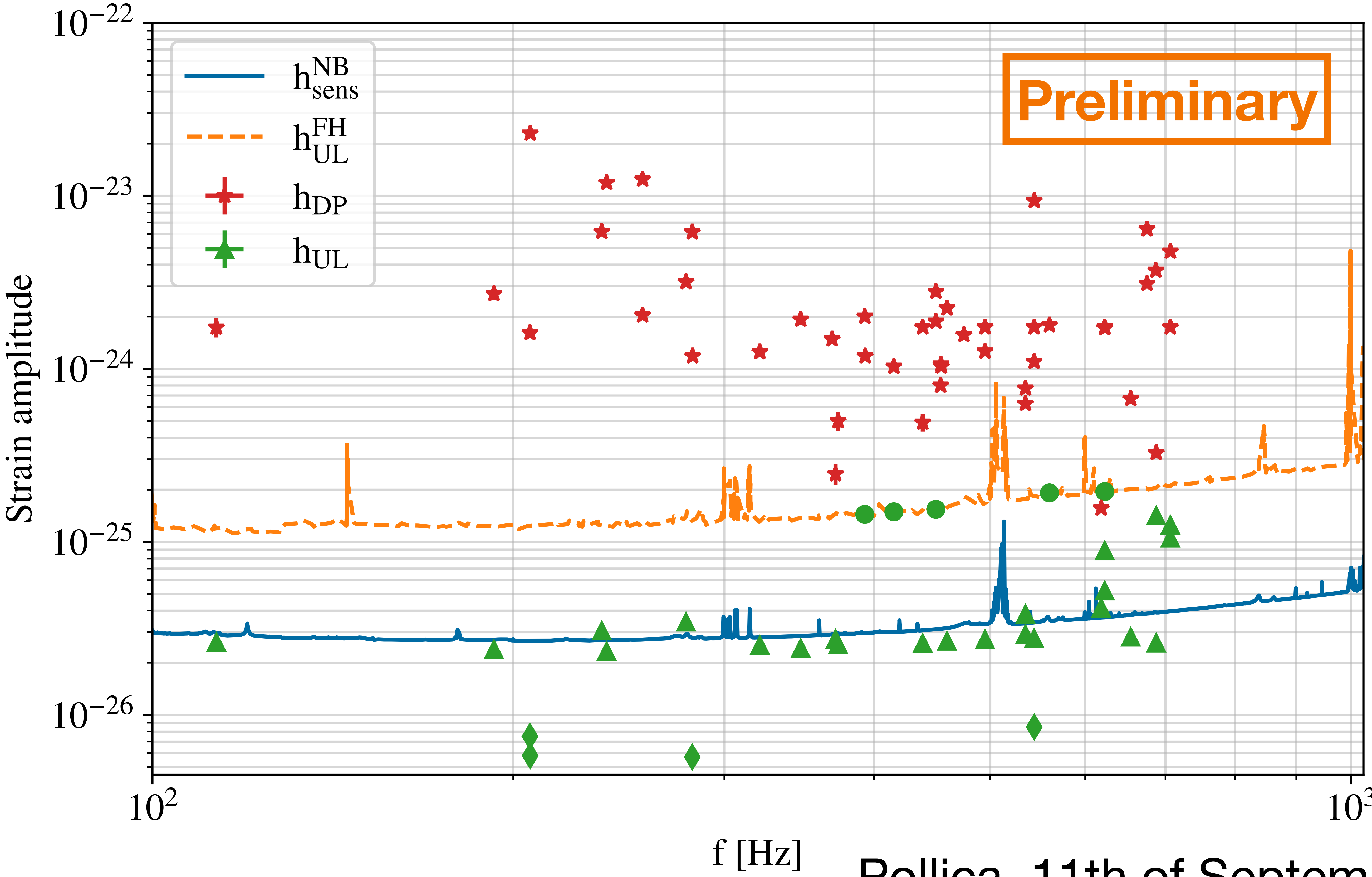
$$\dot{f}_{\rm int} \simeq \frac{5}{8\pi}\alpha\mu^2 G P_{\rm GW}$$

→ Target for continuous GW searches!

GW follow-up of “anomalous” pulsars

Analysis lead by **Lorenzo Mirasola**, with C. Palomba, P. Astone, P. Leaci, S. Mastrogiovanni, L. D’Onofrio, S. D’Antonio, F. Amicucci

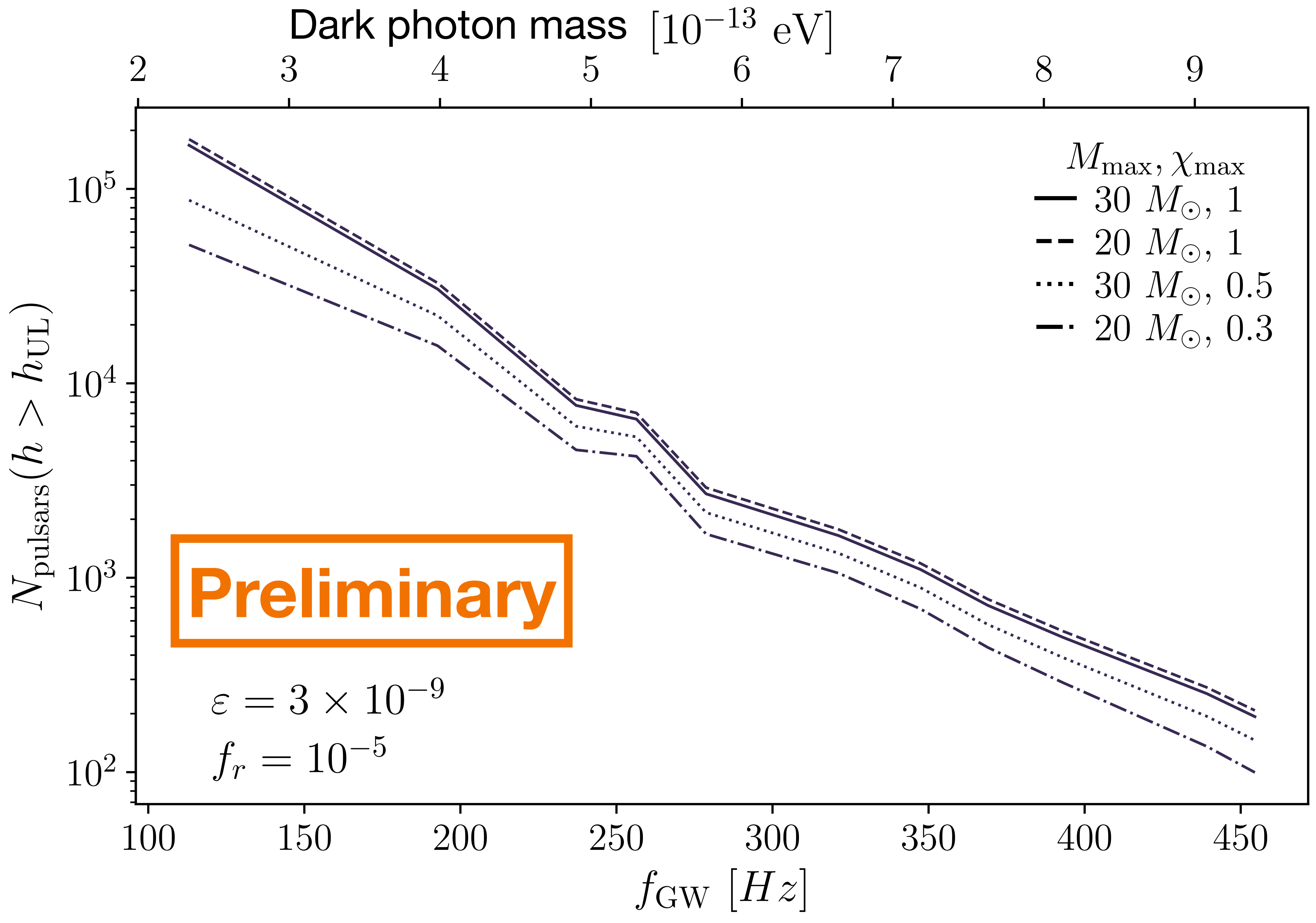


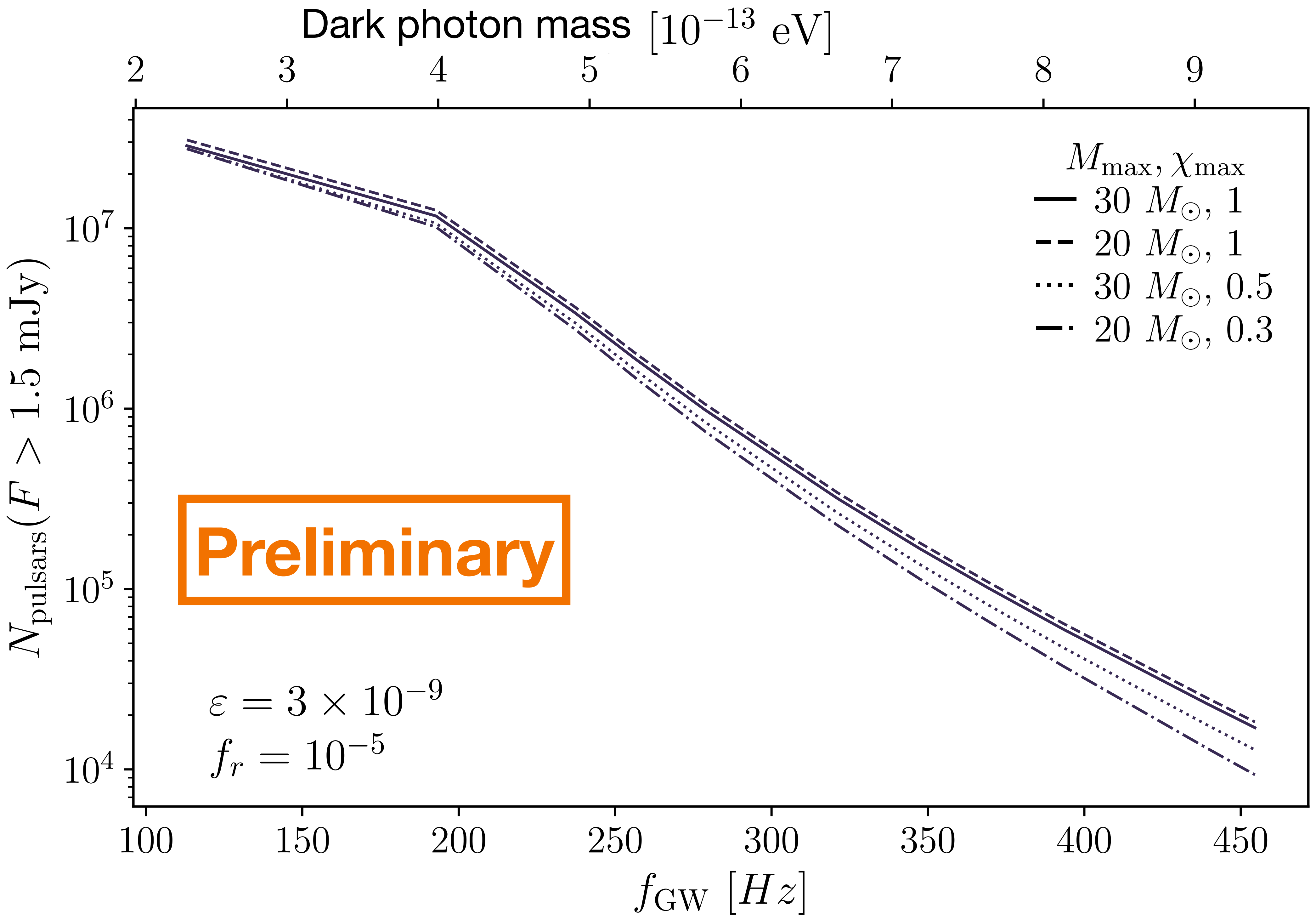


Interpretation?

- Galactic BHs population
- Dark Photon parameters (mass & coupling)

→ “Predict” number of expected observables events

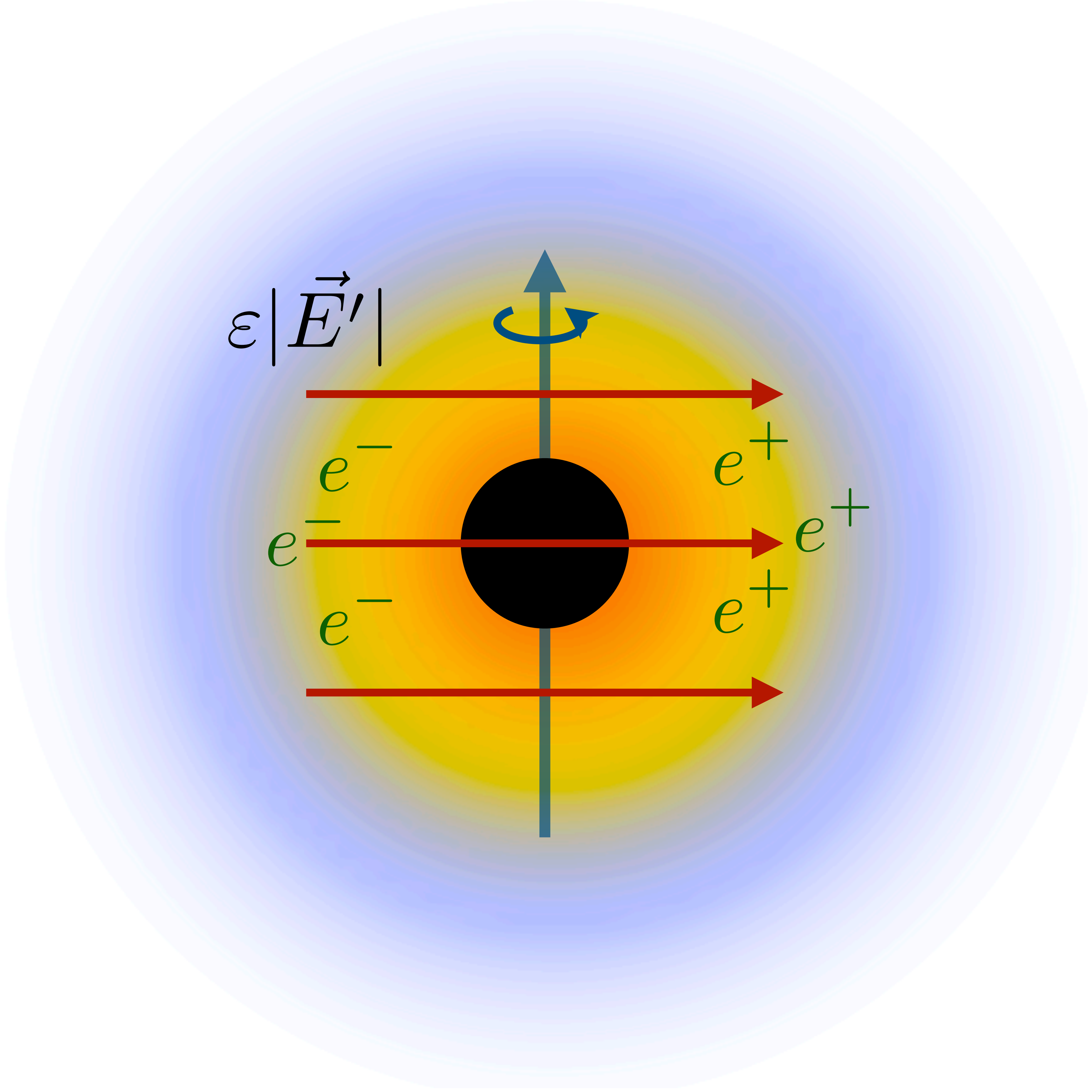




Dark photon masses around 10^{-13} eV with small kinetic mixing parameters are disfavored

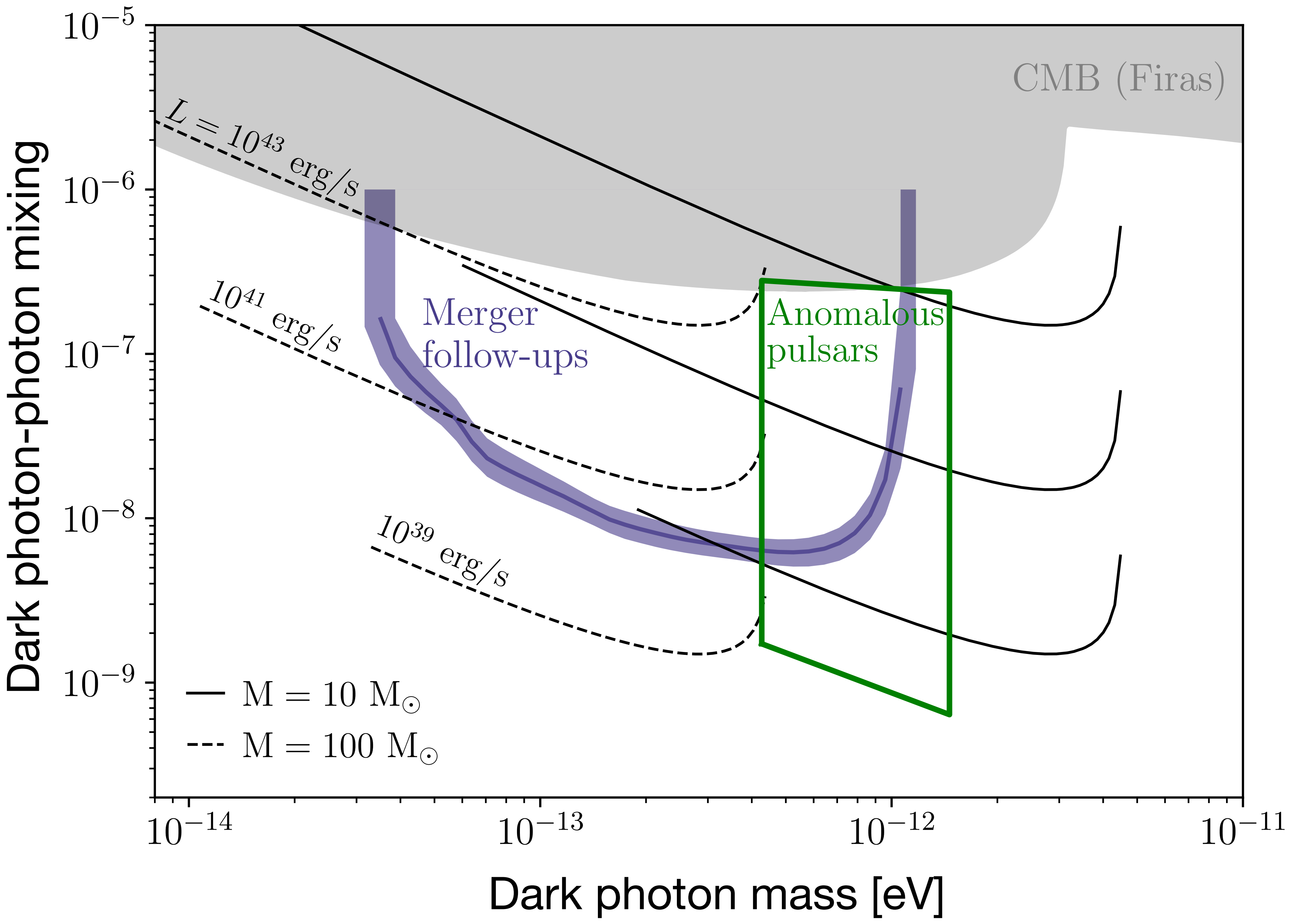
* up to modeling uncertainties of the “new pulsar”

Summary



- Rotating black holes produce clouds of weakly coupled bosons through superradiance

Thank you!



- Dark photons that mix with the photon will lead to dramatic dynamics around the black hole: perhaps, a “new pulsar”!