

# Particle acceleration in a starved magnetosphere of a Kerr black hole

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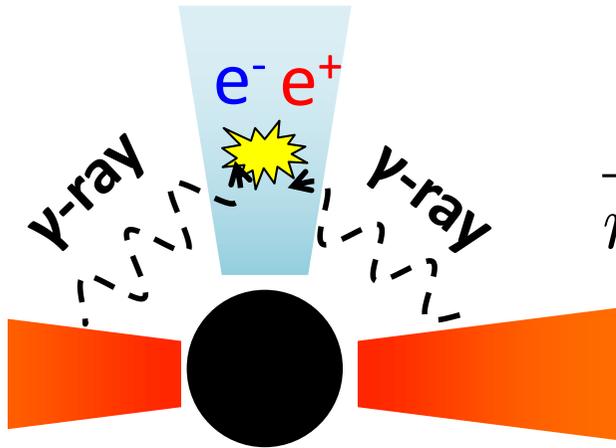
Amir Levinson (Tel Aviv Univ.)

Kenji Toma (FRIS, Tohoku Univ.)

Benoît Cerutti (Univ. Grenoble Alpes)

# Plasma Injection Problem

## • MeV Photon annihilation:



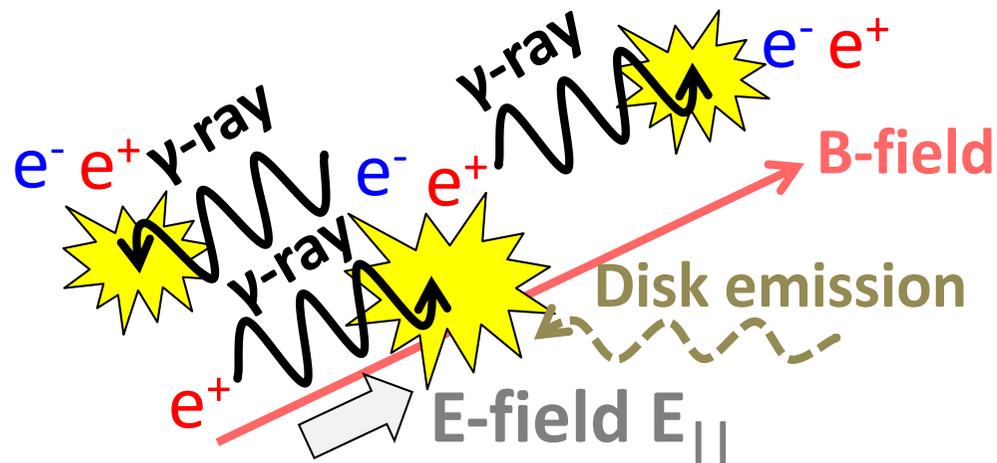
$$\frac{n_{\pm}}{n_{\text{GJ}}} \gtrsim 1 \iff \dot{m} \gtrsim 2 \times 10^{-4} M_9^{-1/7}$$

Levinson & Rieger 11  
Hirovani & Pu 16

## • Electromagnetic cascade:

(M87\*, Sgr A\*, isolated BHs, ...)

$$n_{\pm} \lesssim n_{\text{GJ}} \implies \text{Electric field } E_{\parallel} = \frac{\mathbf{E} \cdot \mathbf{B}}{|\mathbf{B}|} \neq 0$$

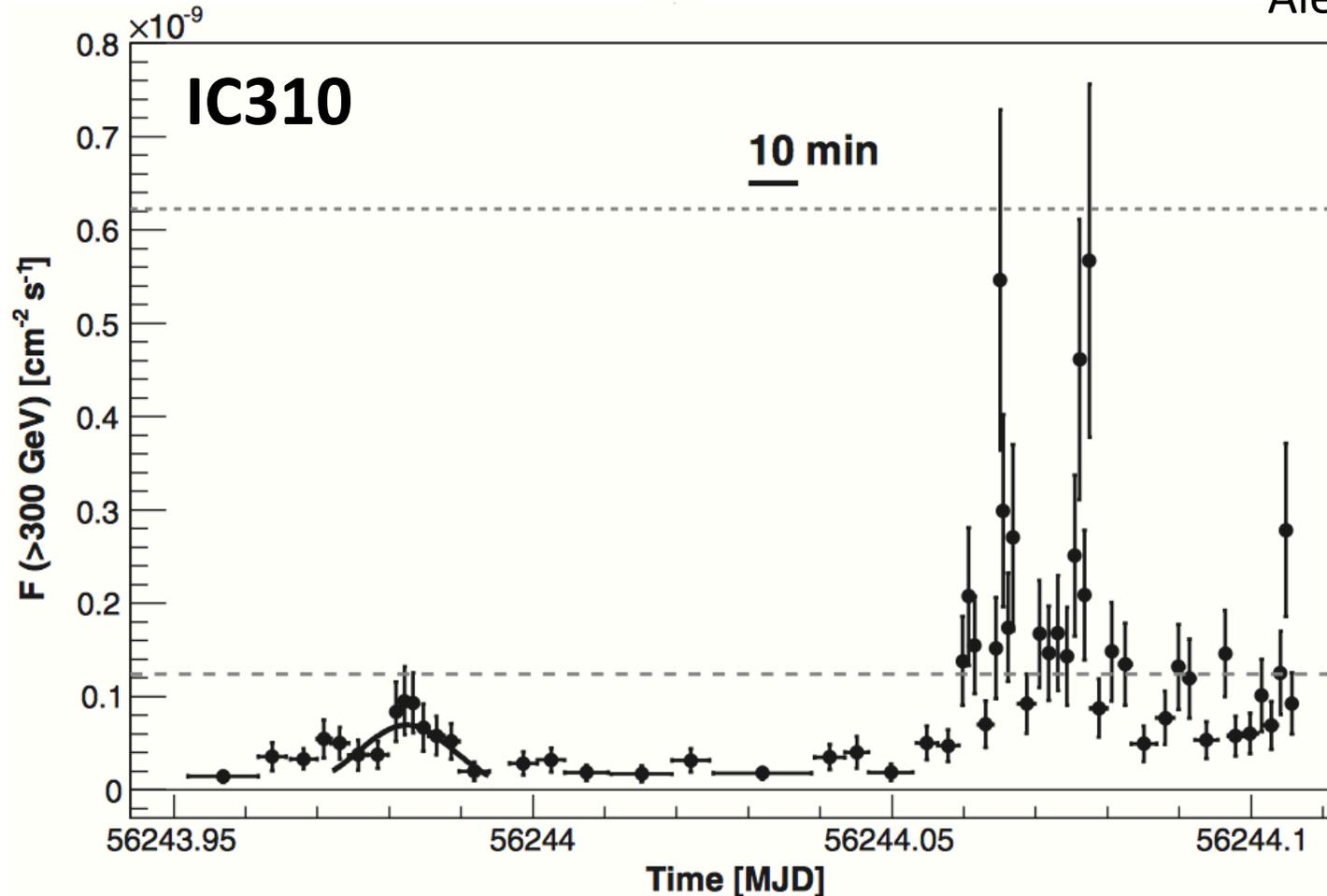


- Large  $\sigma$  ( $\gg 1$ )
- Non-ideal MHD condition
- Non-neutral charge
- Particle acceleration
- Pair creation

**Difficult in MHD simulation**

# TeV Flare from Radio Galaxy

Aleksić+ 14



Flux doubling timescale  $< 4.8$  min at 95% C.L.  
corresponds to  $\sim 20\%$  of the timescale  $r_g/c$ .

→ Particle acceleration at sub-horizon scale?

# Steady state?

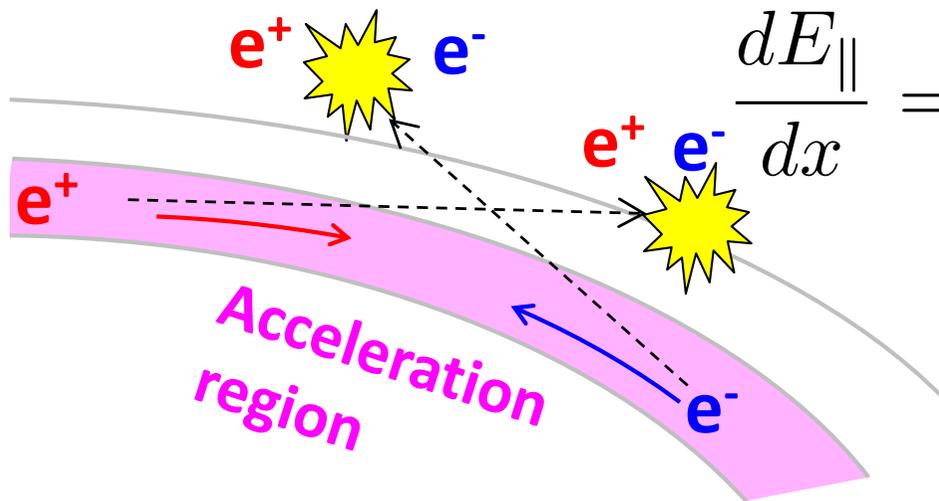
## Steady-state model

(Assuming the gap position)

Beskin+ 92, Hirotani & Okamoto 98  
Neronov & Aharonian 07, Rieger & Aharonian 08  
Levinson & Rieger 11, Broderick & Tchekhovskoy 15  
Hirotani & Pu 16, Hirotani+ 16, 17, 18a, 18b,  
Levinson & Segev 17, Song+ 17, Lin+ 17,  
Katsoulakos & Rieger 18

Acceleration region

≠ Plasma injection region



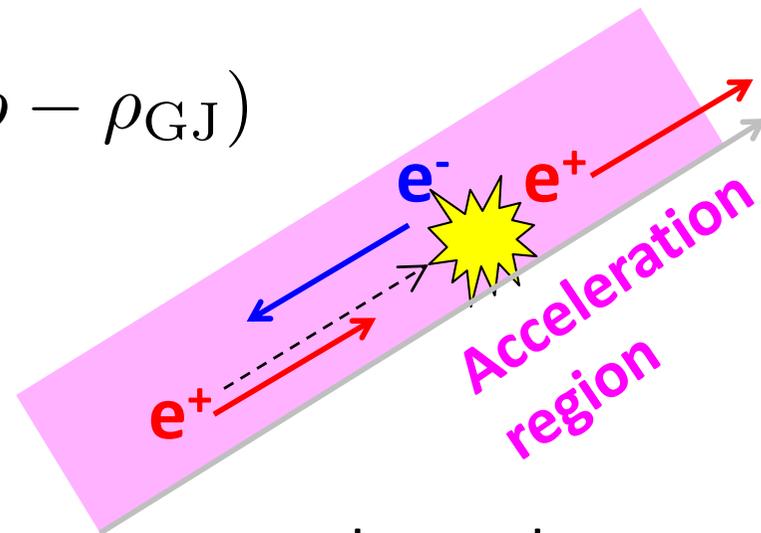
e.g., pulsar outer gap

## Dynamical model

Levinson & Cerutti 18  
Chen, Yuan & Yang 18  
Parfrey, Philippov & Cerutti 19  
Chen & Yuan 19

Acceleration region

= Plasma injection region



e.g., pulsar polar cap  
**black hole gap**

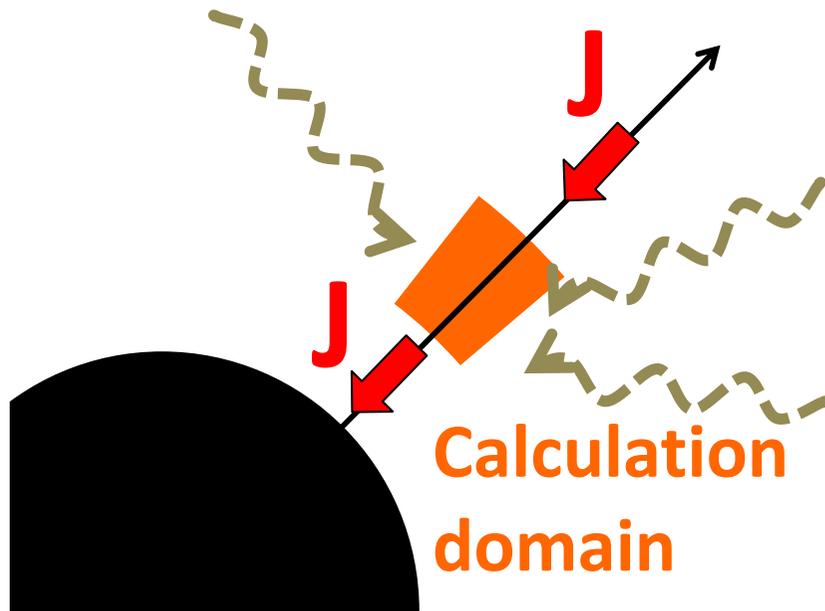
$$\frac{dE_{\parallel}}{dx} = 4\pi(\rho - \rho_{GJ})$$

# 1D PIC Model

Levinson & Cerutti 18  
See also Chen & Yuan 19

- **1-dimensional structure**: the gap extends along a poloidal magnetic surface as a function of  $\theta$ .  
→ Ignoring any MHD waves, considering only plasma oscillations.
- **The gap constitutes a small disturbance**.  
→ The activity does not significantly affect the global structure (the B-field geometry and the angular velocity).
- **Isotropic radiation field** (from accretion disk) for seed photons.

$$I_s(x^\mu, \epsilon_s, \Omega_s) = I_0(\epsilon_s/\epsilon_{s,\min})^{-p}, \quad \epsilon_{s,\min} < \epsilon_s < \epsilon_{s,\max}$$



- No external plasma source.
- The global current is a free parameter.
- A split monopole geometry for the global B-field.
- The angular velocity of magnetic surface  $\Omega = 0.5\omega_H$ .

Accretion disk

# Basic Equations

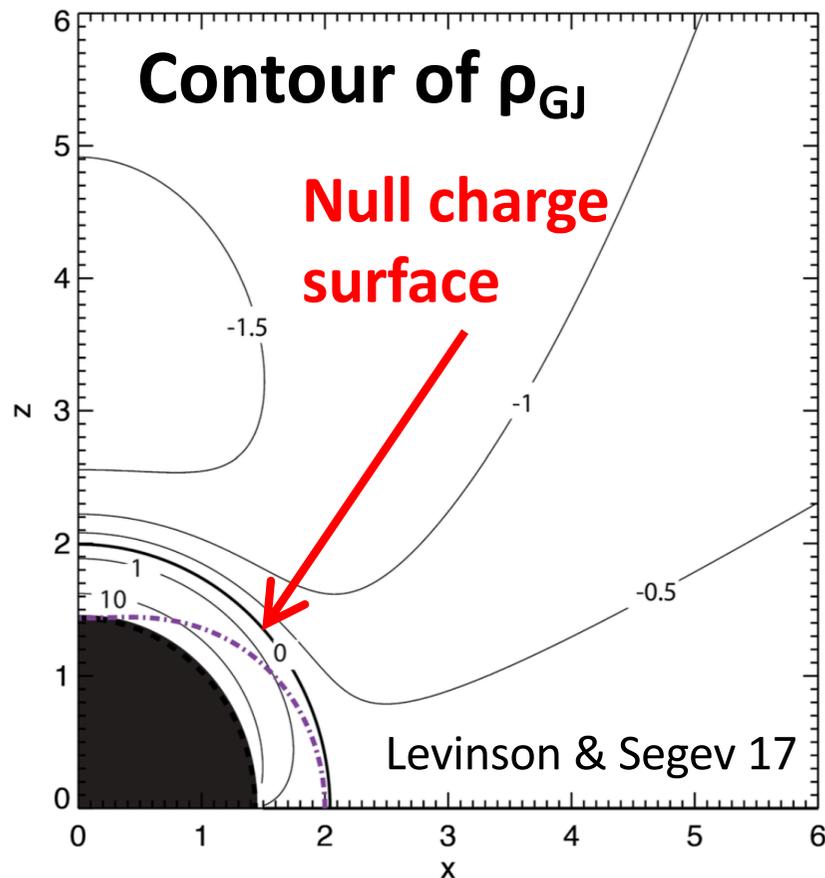
Levinson & Cerutti 18

## Gauss's law

$$\partial_{\mu}(\sqrt{-g}F^{t\mu}) = (\sqrt{-g}j^t)$$

$$\rightarrow \partial_{\xi}(\sqrt{A}E_r) = 4\pi\Delta\Sigma(j^t - \rho_{\text{GJ}})$$

$$\rho_{\text{GJ}} = \frac{B_{\text{H}} \sqrt{A_{\text{H}}}}{4\pi \sqrt{-g}} \left[ \frac{\sin^2 \theta}{\alpha^2} (\omega - \Omega) \right]_{,\theta}$$



# Basic Equations

Levinson & Cerutti 18

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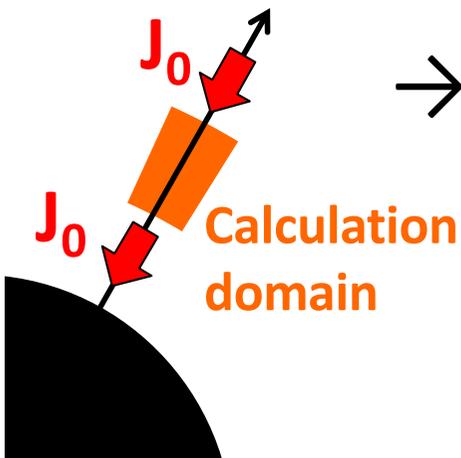
## Ampère's law (radial component)

$$\rho_{\text{GJ}} = \frac{B_{\text{H}}\sqrt{A_{\text{H}}}}{4\pi\sqrt{-g}} \left[ \frac{\sin^2\theta}{\alpha^2}(\omega - \Omega) \right]_{,\theta}$$

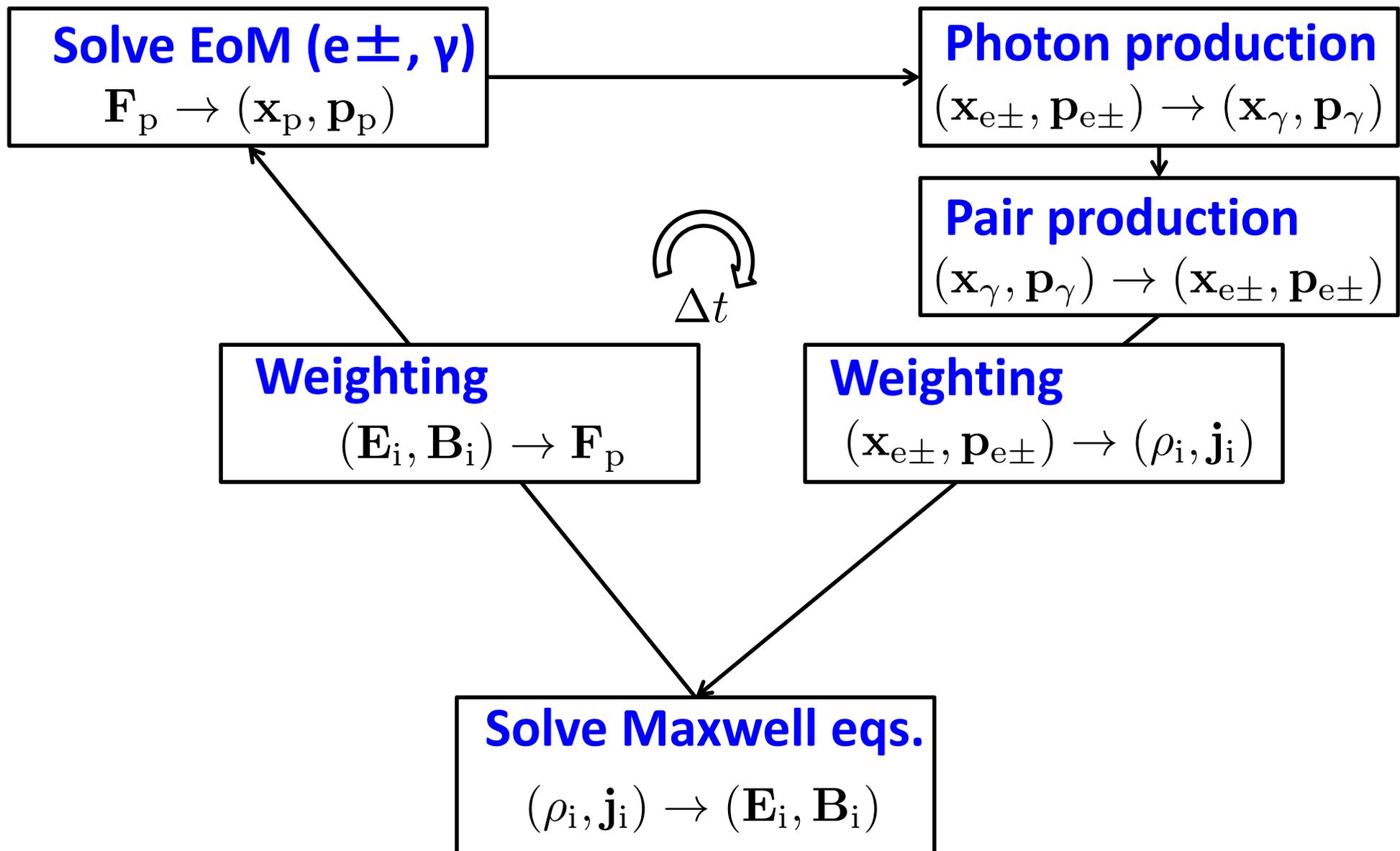
$$\partial_{\mu}(\sqrt{-g}F^{r\mu}) = (\sqrt{-g}j^r)$$

$$\rightarrow \partial_t(\sqrt{A}E_r) = -4\pi(\Sigma j^r - J_0)$$

$$J_0 = \frac{1}{4\pi\sin\theta} \left( \frac{\Delta\sin\theta}{\Sigma} F_{r\theta} \right)_{,\theta}$$



# Particle-in-Cell Simulation



# Parameters

Fiducial optical depth

$$\tau_0 = 4\pi r_g \sigma_T I_0 / hc$$

Global current density

$$\dot{j}_0 \quad (\text{normalized by } \rho_{\text{GJ,H}} c)$$

BH mass

$$M_{\text{BH}} = 10^9 M_{\odot}$$

Dimensionless spin parameter

$$a_* = 0.9$$

B-field on the horizon

$$B_{\text{H}} = 2\pi \times 10^3 \text{G}$$

Inclination angle of magnetic surface  $\theta = 30^\circ$

Minimum energy of seed photon

$$\epsilon_{\text{min}} = 10^{-9} \quad (\text{normalized by } m_e c^2)$$

Slope of seed photon spectrum

$$p = 2$$

Curvature radius

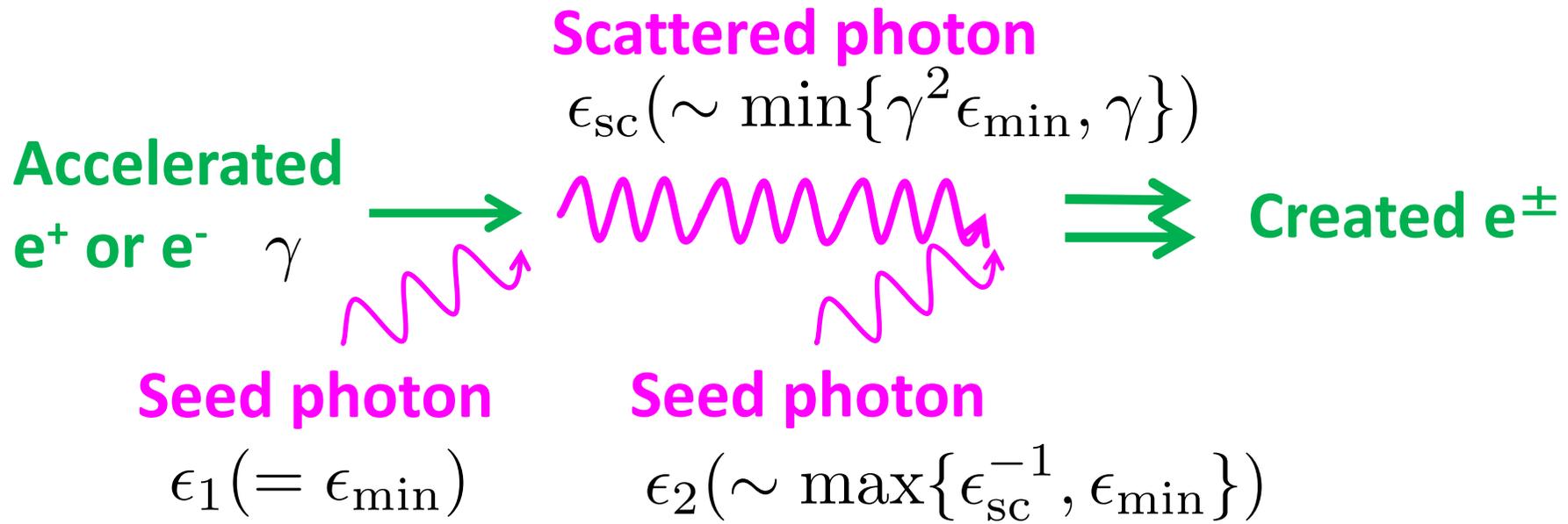
$$R_{\text{cur}} = r_g$$

Number of cell

$$N = 32768 \\ \gtrsim \frac{r_g}{l_p} \sim 10^3 \sqrt{\frac{\kappa M_9 B_{\text{H},3}}{\langle \gamma_8 \rangle}}$$

We neglect the scattering of particles with  $\gamma < 10^7$ .

# Pair Multiplicity in Gap



## Required multiplicity in the gap

$$k \sim \tau_{sc} \tau_{\gamma\gamma} \gtrsim 1 \quad \rightarrow \quad \tau_0 \gtrsim \sqrt{\frac{\tau_0}{\tau_{sc}} \frac{\tau_0}{\tau_{\gamma\gamma}}}$$

# Pair Multiplicity in Gap

$$\tau_0 \gtrsim \sqrt{\frac{\tau_0}{\tau_{\text{sc}}} \frac{\tau_0}{\tau_{\gamma\gamma}}} \quad \tau_0 = 4\pi r_g \sigma_T I_0 / hc$$

$e^\pm$  quickly accelerate to the terminal Lorentz factor.

$$eE_{\parallel} = P_{\text{rad}}/c \quad \rightarrow \quad \gamma \sim \gamma_{\text{max}} \sim 10^{10}$$

$$\epsilon_{\text{min}} = 10^{-9} \quad \rightarrow \quad \gamma\epsilon_{\text{min}} > 1 \quad (\text{Klein-Nishina regime})$$

Scattering optical depth

$$\tau_{\text{sc}}/\tau_0 \sim (\gamma\epsilon_{\text{min}})^{-1}$$

Pair creation optical depth

$$\tau_{\gamma\gamma}/\tau_0 \sim (\gamma\epsilon_{\text{min}})^{-1}$$

**Required optical depth  
to screen E-field**

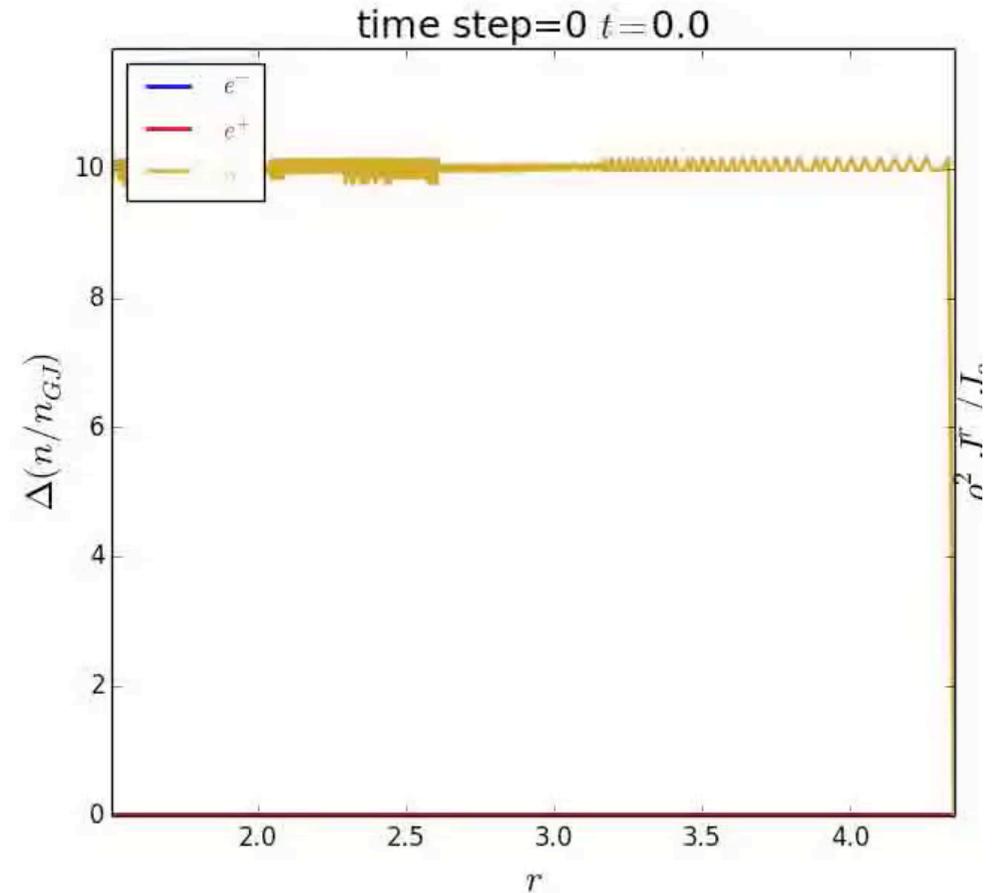
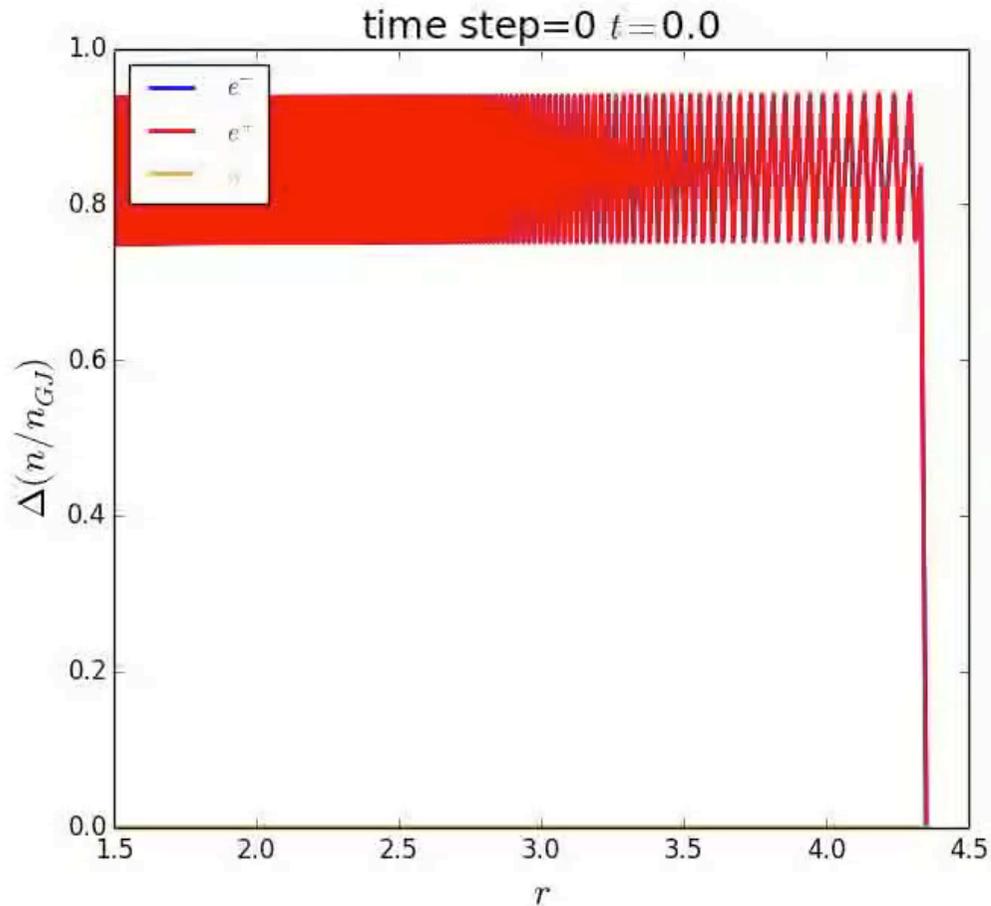
$$\tau_0 \gtrsim \gamma\epsilon_{\text{min}}$$

# Insufficient Pair Creation

$\tau_0 = 10$ ,  $\gamma_{\max} \epsilon_{\min} \sim 100$ , different initial condition

Initial condition:  $e^\pm$  beams

Initial condition: a photon beam

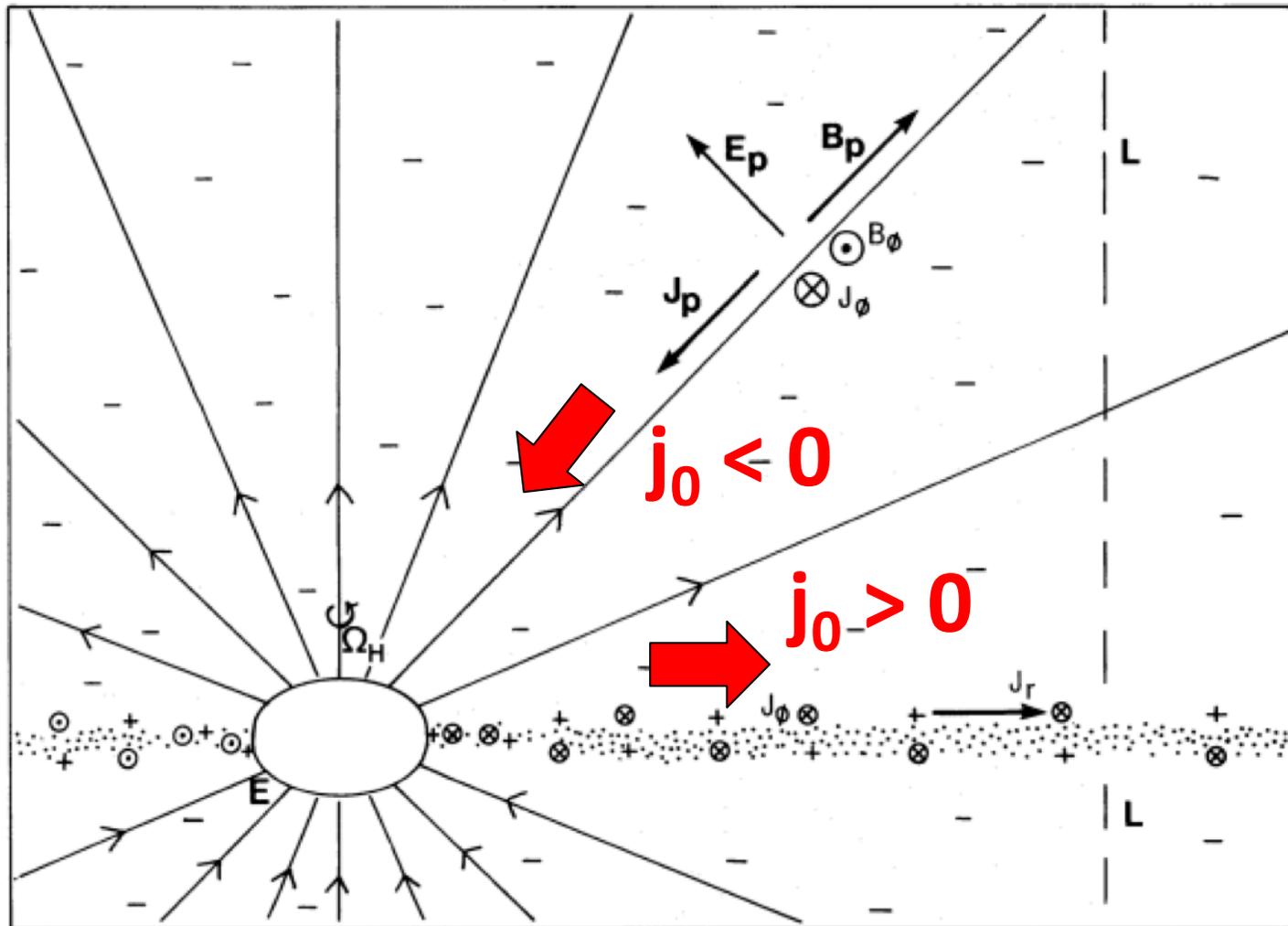


All photons and particles finally escape from the simulation box if  $\tau_0 < \gamma_{\max} \epsilon_{\min}$ .

# Electric Currents

Polar region :  $j_0 < 0$

Equatorial region :  $j_0 > 0$



Blandford & Znajek 77

$j_0 = -1.0, 1.0$  (normalized by  $\rho_{GJ,Hc}$ )

# Parameters

Fiducial optical depth

$$\tau_0 = 30, 100, 300 > \gamma_{\max} \epsilon_{\min} \sim 10$$

Global current density

$$j_0 = -1.0, 1.0 \text{ (normalized by } \rho_{\text{GJ,Hc}})$$

BH mass

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# Summary

**We perform 1D GRPIC simulation for pair cascade in a starved magnetosphere of a Kerr black hole.**