ブラックホール磁気圏での粒子加速領域

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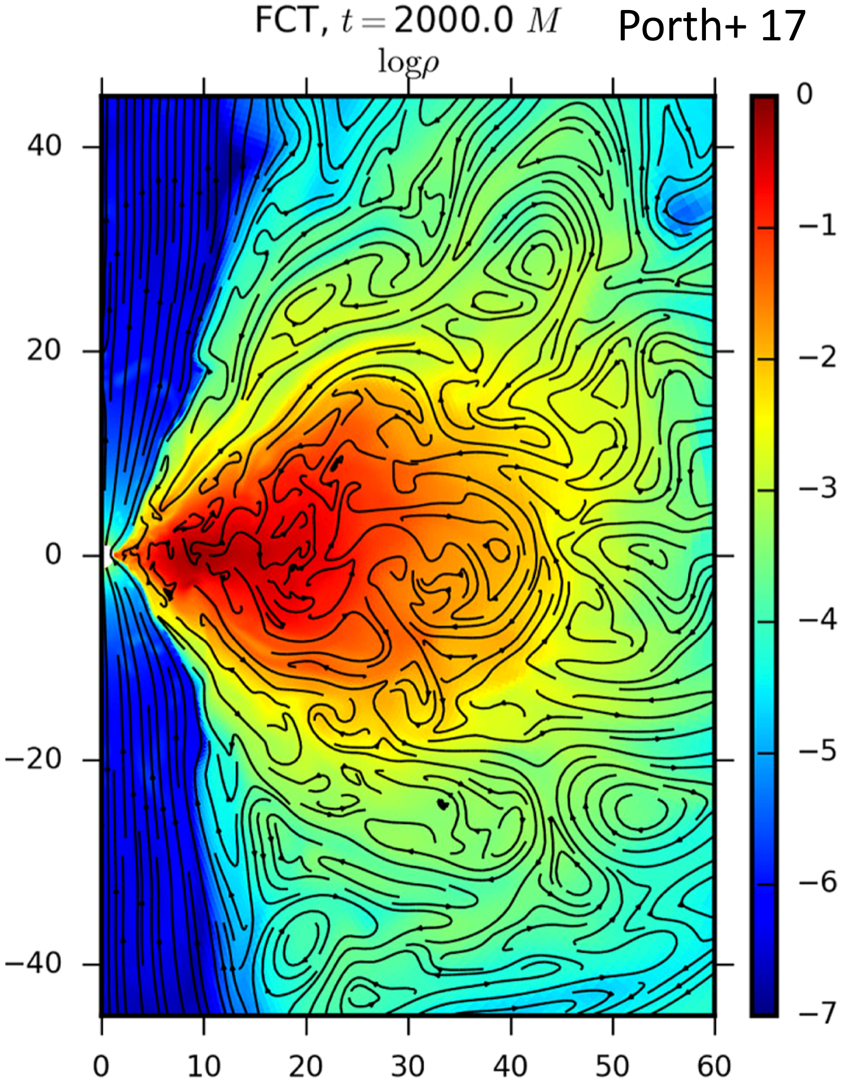
GRMHD Numerical Simulations

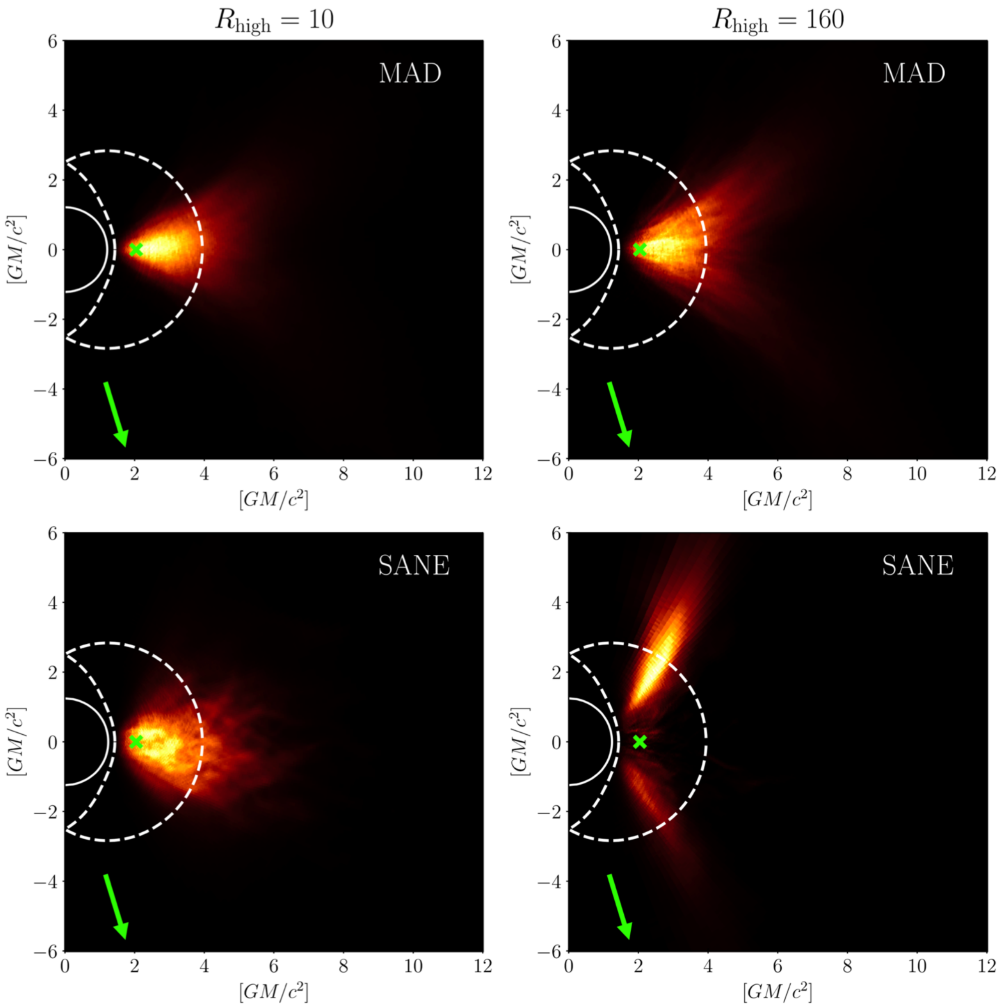
Artificial mass supply in the jet region.

Predictions of the jet emission are highly uncertain.



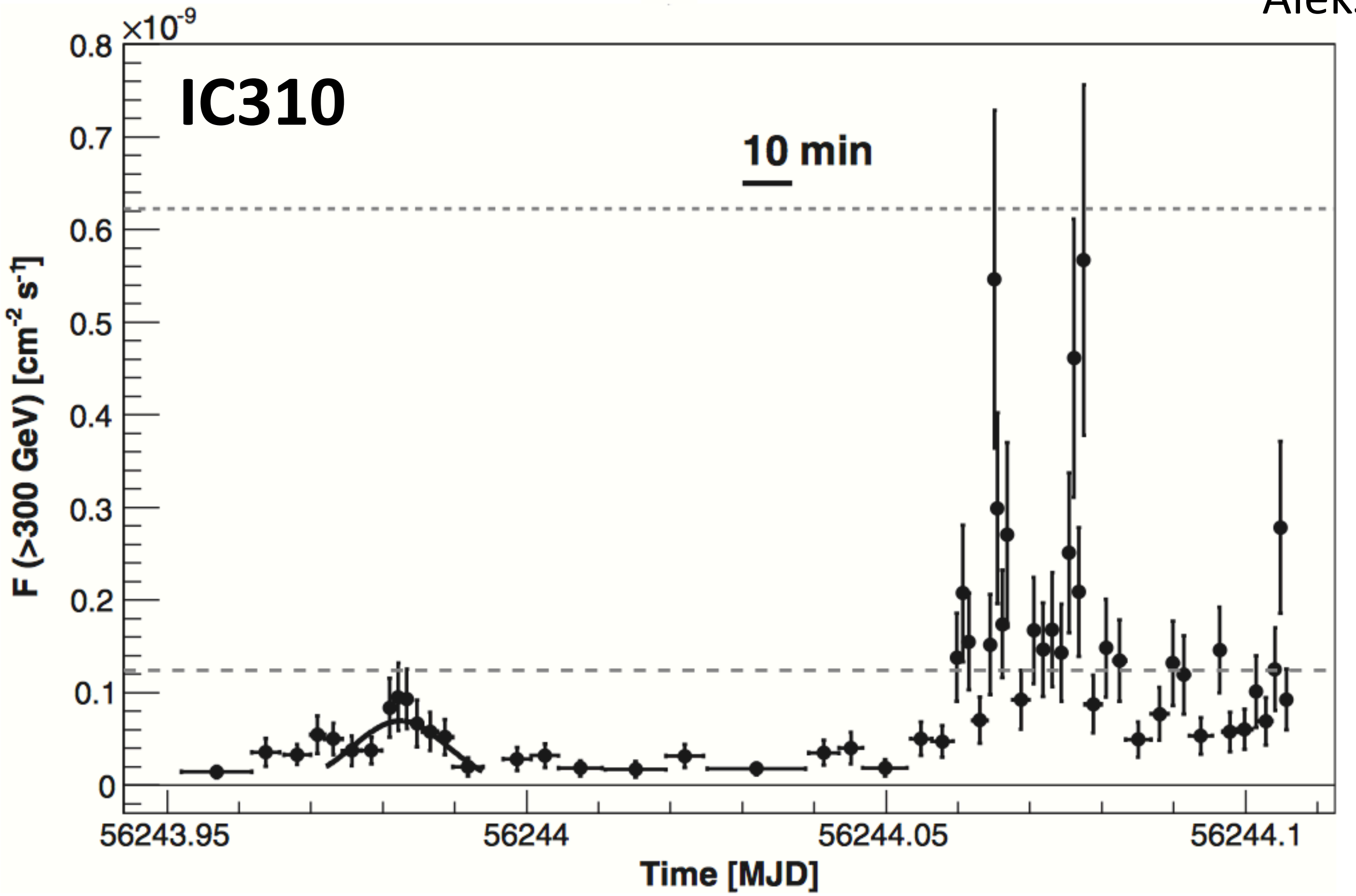
Porth+ 17

EHT Coll. 19



TeV flare from radio galaxy

Aleksić+ 14

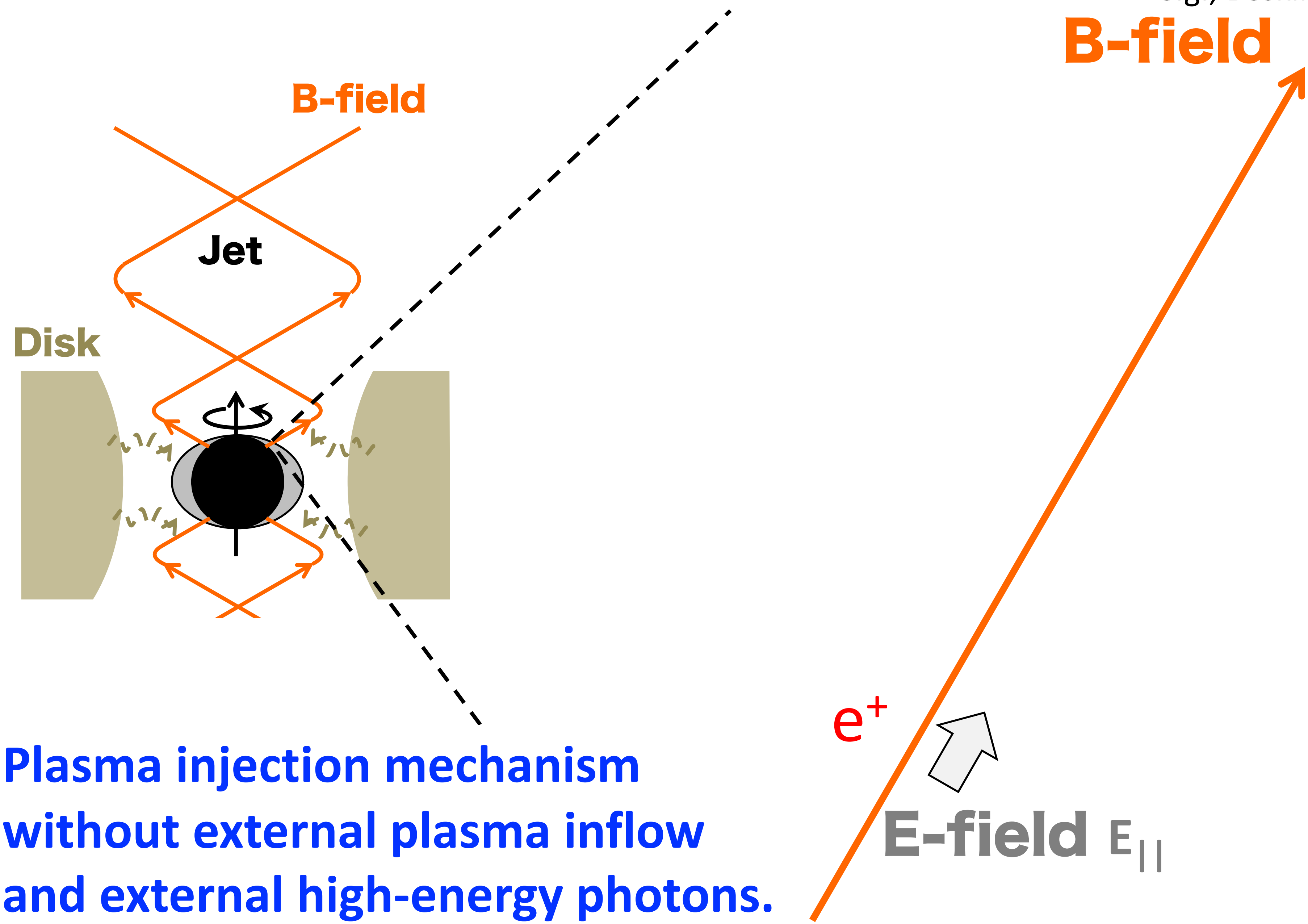


Flux doubling timescale < 4.8 min at 95% C.L. corresponds to ~20% of the timescale r_g/c.

→ Particle acceleration at sub-horizon scale?

Electromagnetic Cascade

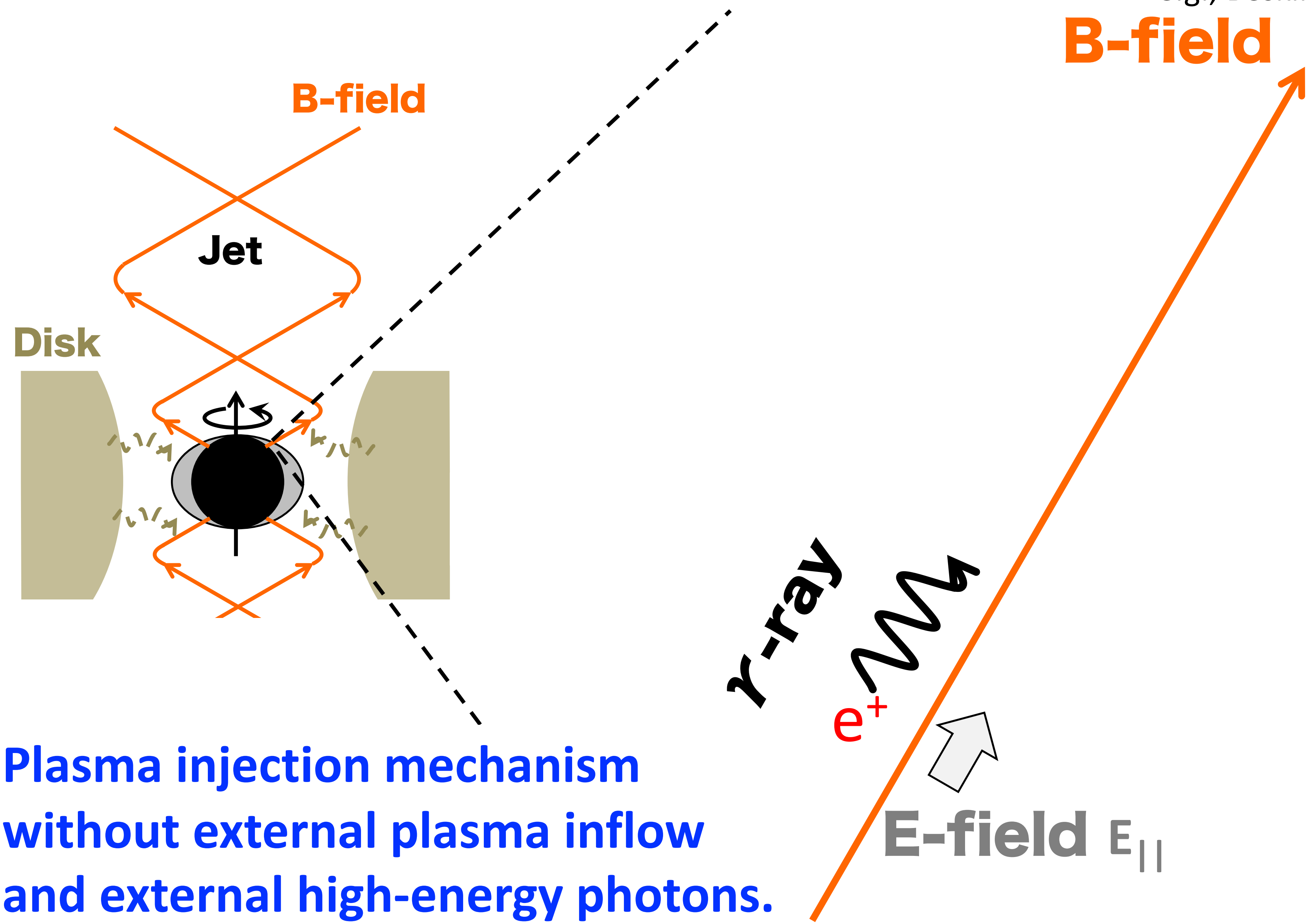
e.g., Beskin+ 92



Plasma injection mechanism without external plasma inflow and external high-energy photons.

Electromagnetic Cascade

e.g., Beskin+ 92



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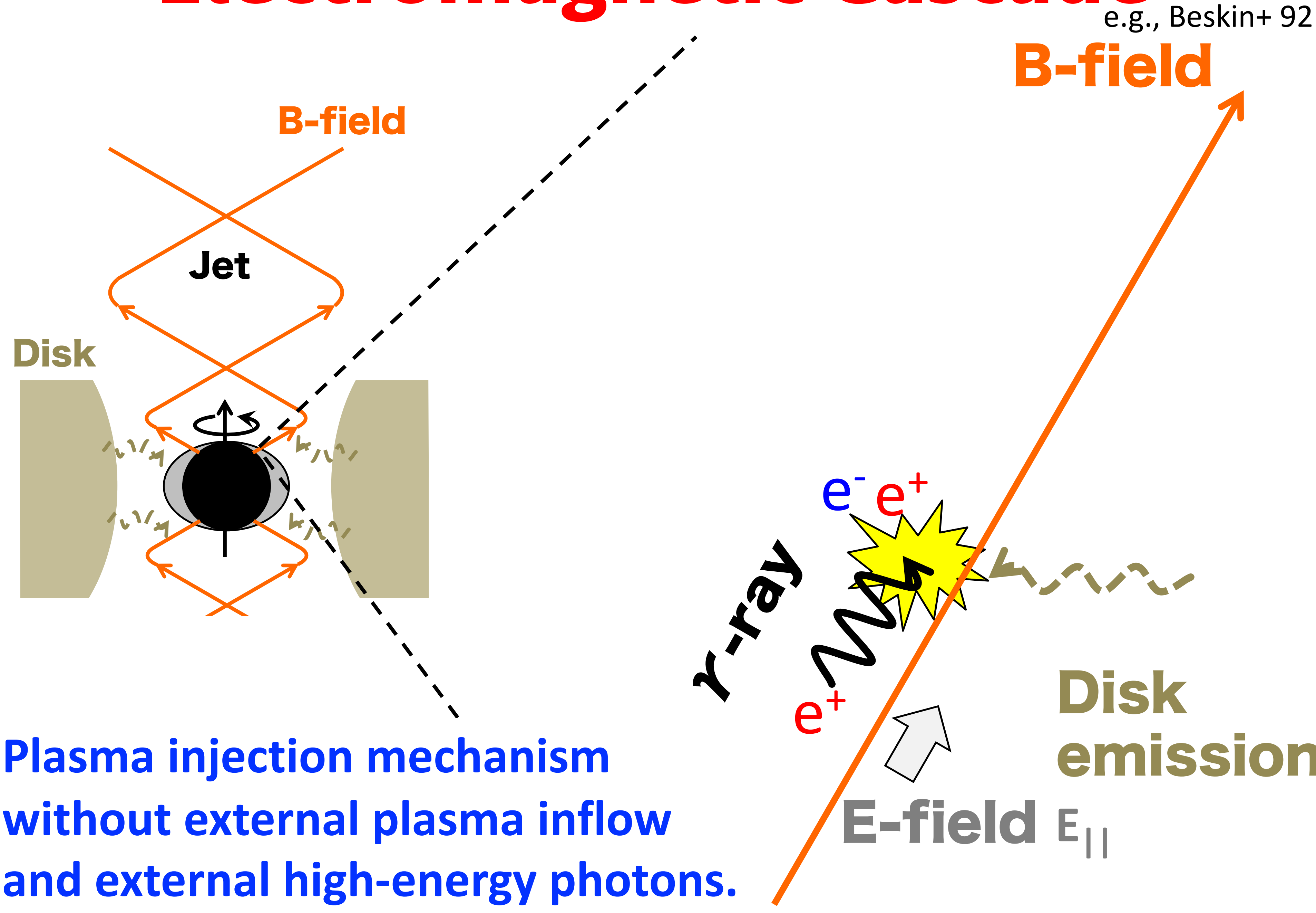

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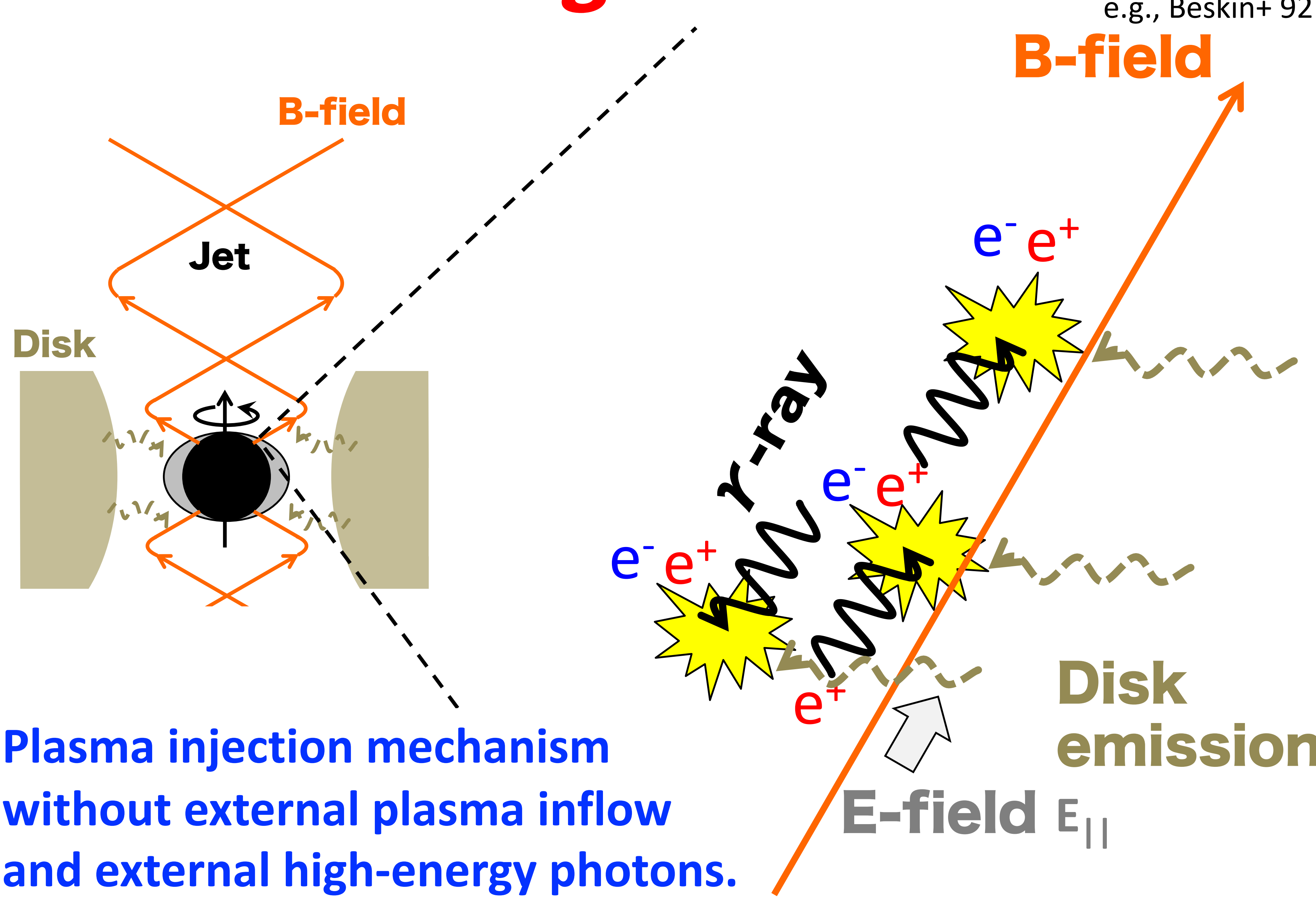

Plasma injection mechanism without external plasma inflow and external high-energy photons.

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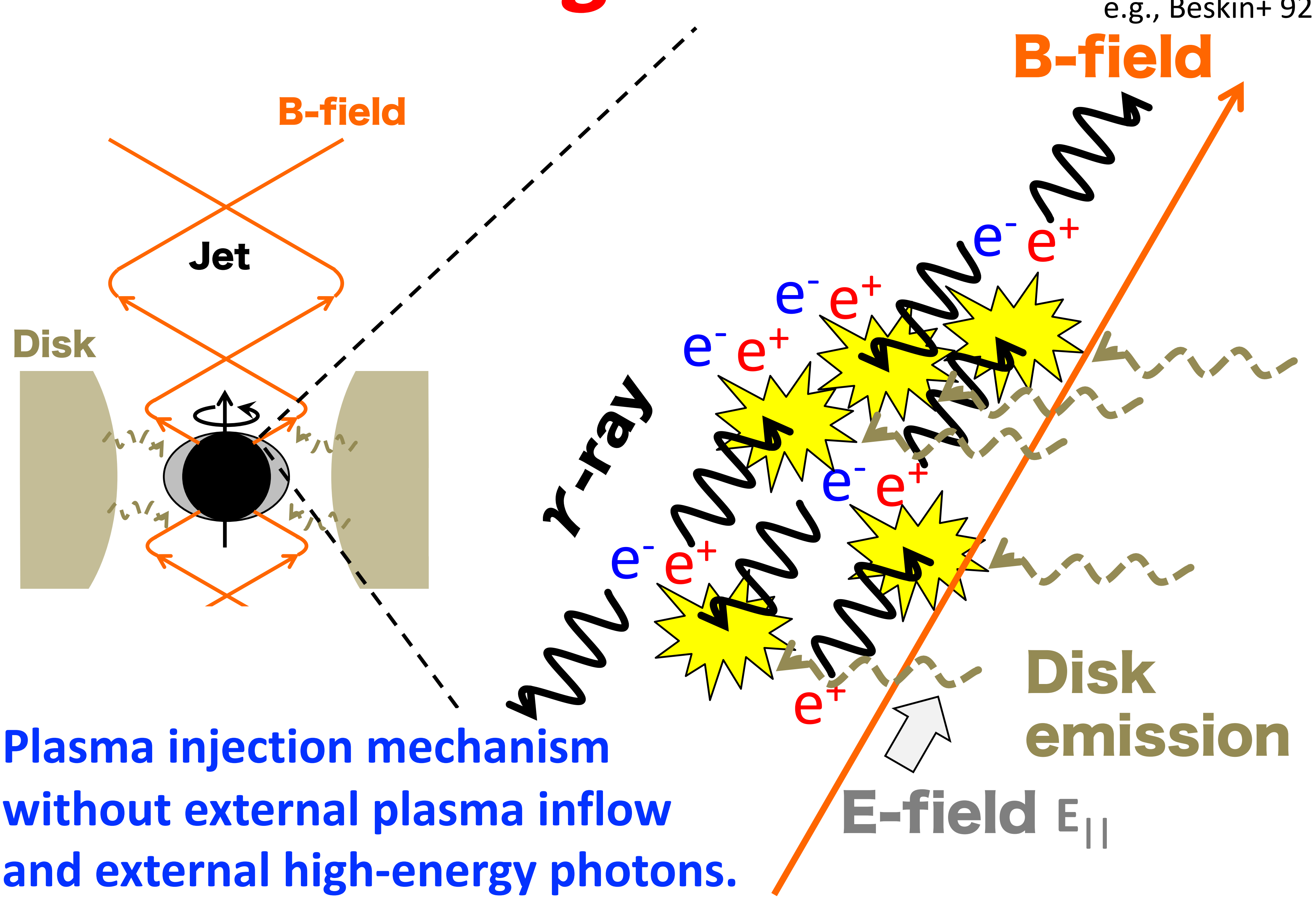


Plasma injection mechanism without external plasma inflow and external high-energy photons.

1D PIC Model

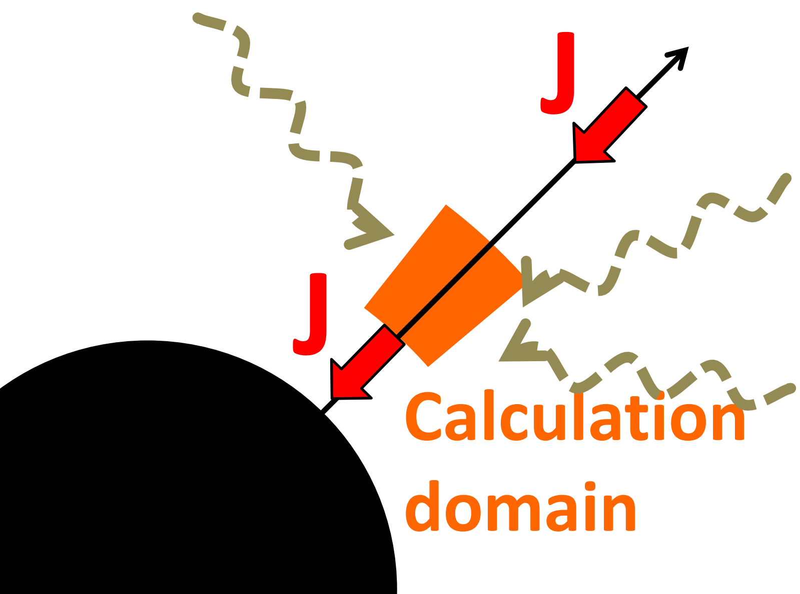
Levinson & Cerutti 18

- 1-dimensional structure: the gap extends along a poloidal magnetic surface as a function of θ.
  → 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.

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



- 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 $\Omega = 0.5\omega_{\rm H}$.

Background spacetime

Kerr metric given in BL coordinates

$$ds^2 = -\alpha^2 dt^2 + g_{\varphi\varphi}(d\varphi - \omega dt)^2 + g_{rr}dr^2 + g_{\theta\theta}d\theta^2$$

$$\alpha^2 = \frac{\Sigma\Delta}{A}; \quad \omega = \frac{2ar_g r}{A}; \quad g_{rr} = \frac{\Sigma}{\Delta};$$

$$g_{\theta\theta} = \Sigma; \quad g_{\varphi\varphi} = \frac{A}{\Sigma}\sin^2\theta,$$

$$\Delta = r^2 + a^2 - 2r_g r, \Sigma = r^2 + a^2\cos^2\theta, A = (r^2 + a^2)^2 - a^2\Delta\sin^2\theta$$

Tortoise coordinate

$$\xi(r) = \frac{1}{r_+ - r_-}\ln\left(\frac{r - r_+}{r - r_-}\right)$$

$$\xi \to -\infty \text{ as } r \to r_H = r_+$$

$$\xi \to 0 \text{ as } r \to \infty$$

$$r_\pm = 1 \pm \sqrt{1 - \tilde{a}^2}$$

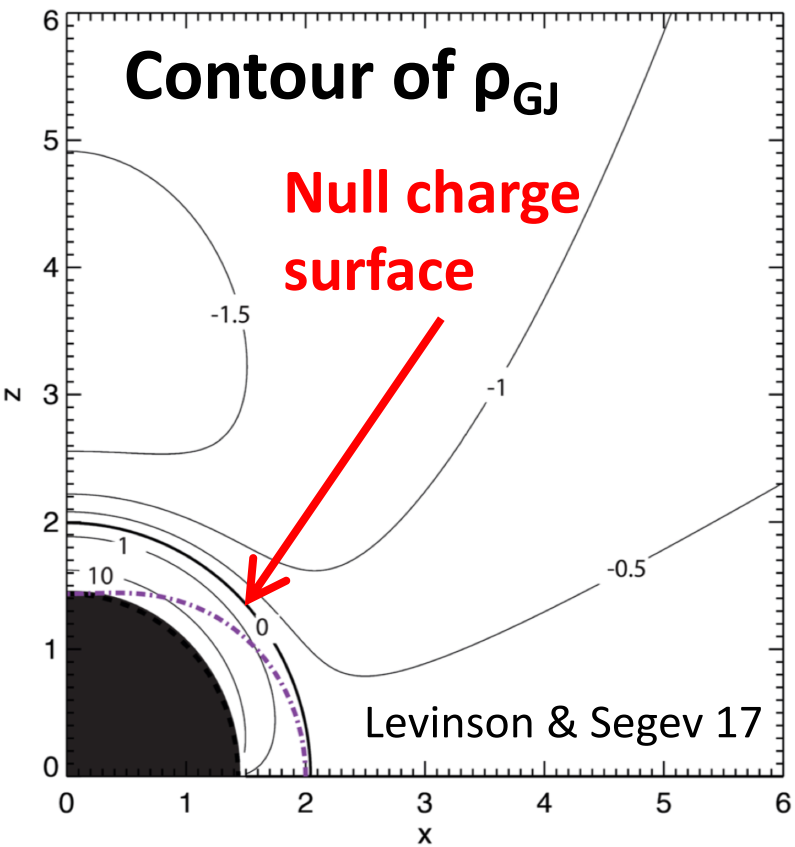
Basic equations

Levinson & Cerutti 18

Gauss's law

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

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



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

Basic equations

Levinson & Cerutti 18

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

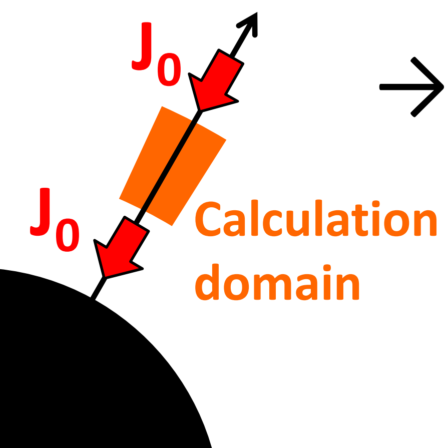
$$\rightarrow \partial_\xi(\sqrt{A}E_{\mathrm{r}}) = 4\pi\Delta\Sigma(j^t - \rho_{\mathrm{GJ}})$$

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

Ampère's law (radial component)

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

$$\rightarrow \partial_{\mathrm{t}}(\sqrt{A}E_{\mathrm{r}}) = -4\pi(\Sigma j^r - J_0)$$



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

Basic equations

Levinson & Cerutti 18

Equation of motion for *i*-th particle

Curvature loss term

$$\frac{du_i^\mu}{d\tau_i} = -\Gamma^\mu{}_{\alpha\beta} u_i^\alpha u_i^\beta + \frac{q_i}{m_e} F^\mu{}_\alpha u_i^\alpha + \underline{s_i^\mu}$$

$$\frac{\mathrm{d}u_{i\,\mu}}{\mathrm{d}\tau_i} = \Gamma_{\alpha\mu\beta} u_i^\alpha u_i^\beta + \frac{q_i}{m_e} F_{\mu\alpha} u_i^\alpha + \underline{s_{i\,\mu}}$$

$$\rightarrow \frac{\mathrm{d}u_i}{\mathrm{d}t} = \sqrt{g^{\mathrm{rr}}}\left[-\gamma_i \partial_{\mathrm{r}}(\alpha) + \frac{q_i}{m_e} F_{\mathrm{rt}}\right] - \frac{s_{it}}{u_i}$$

$$= -\sqrt{g^{\mathrm{rr}}}\gamma_i \partial_{\mathrm{r}}(\alpha) + \alpha\left(\frac{q_i}{m_e} E_{\mathrm{r}} - \frac{P_{\mathrm{cur}}(\gamma_i)}{m_e v_i}\right)$$

$$\rightarrow \frac{\mathrm{d}\xi_i}{\mathrm{d}t} = \frac{1}{\Delta}\frac{\mathrm{d}r_i}{\mathrm{d}t} = \frac{1}{\Delta}\frac{u_i^r}{u_i^t} = \frac{v_i}{\sqrt{A}}$$

$$\partial_{\mathrm{r}}(\alpha) = \frac{\alpha}{A}\left(\frac{2r^2\tilde{a}^2\sin^2\theta}{\Sigma} + \frac{r^4 - \tilde{a}^4}{\Delta}\right)$$

$$P_{\mathrm{cur}}(\gamma) = \frac{2}{3}\frac{e^2\gamma^4 v^4}{R_{\mathrm{c}}^2}$$

Basic equations

Levinson & Cerutti 18

Equation of motion for *i*-th photon

$$\frac{\mathrm{d}\tilde{p}_k^r}{\mathrm{d}t} = -\sqrt{g^{rr}}\,\tilde{p}_k^t \partial_\mathrm{r}(\alpha)$$

$$\frac{\mathrm{d}\xi_k}{\mathrm{d}t} = \frac{1}{\sqrt{A}}\frac{\tilde{p}_k^r}{\tilde{p}_k^t}$$

IC scattering

$$\delta\tau_{\mathrm{sc}} = \int_{r(t)}^{r(t+\delta t)} \kappa_{\mathrm{KN}}\sqrt{g_{rr}}dr$$

Pair production

$$\delta\tau_{\mathrm{pp}} = \int_{r(t)}^{r(t+\delta t)} \kappa_{\mathrm{pp}}\sqrt{g_{rr}}dr$$

Parameters

Fiducial optical depth	$\tau_0 = 4\pi r_g \sigma_{\rm T} I_0 / hc$
Global current density	j_0
BH mass	$M_{\rm BH} = 10^9 M_\odot$
Dimensionless spin parameter	$a_* = 0.9$
B-field on the horizon	$B_{\rm H} = 2\pi \times 10^3 {\rm G}$
Inclination angle of magnetic surface	$\theta = 30^\circ$
Minimum energy of seed photon	$\epsilon_{s,{\rm min}}$
Slope of seed photon spectrum	$p = 2$
Curvature radius	$R_{\rm cur} = r_g$
Number of cell	$N = 32768 \gtrsim \frac{r_g}{l_{\rm p}} \sim 10^3 \sqrt{\frac{\kappa M_9 B_{{\rm H},3}}{< \gamma_8 >}}$

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

Pair multiplicity in gap

Pairs quickly accelerate to the terminal Lorentz factor in the gap.

$$eE_{\|} = P_{\rm rad}/c \quad \Rightarrow \quad \gamma_{\rm max} \sim 10^{10}$$

$$\tau_0 = 4\pi r_g \sigma_{\rm T} I_0/hc$$

Minimum energy of soft photons

$$\epsilon_{\rm min} = 10^{-9} m_{\rm e} c^2$$

Scattering optical depth (KN)

$$\tau_{\rm IC}/\tau_0 \sim O(10^{-1})$$

Pair creation optical depth

$$\tau_{\gamma\gamma}/\tau_0 \sim O(10^{-1})$$

Pair multiplicity in the gap

$$O(10^{-2}) \times \tau_0$$

cf. Levinson & Cerutti 18

$\epsilon_{\rm min} = 10^{-8} m_{\rm e} c^2$

$\tau_0 = 10$

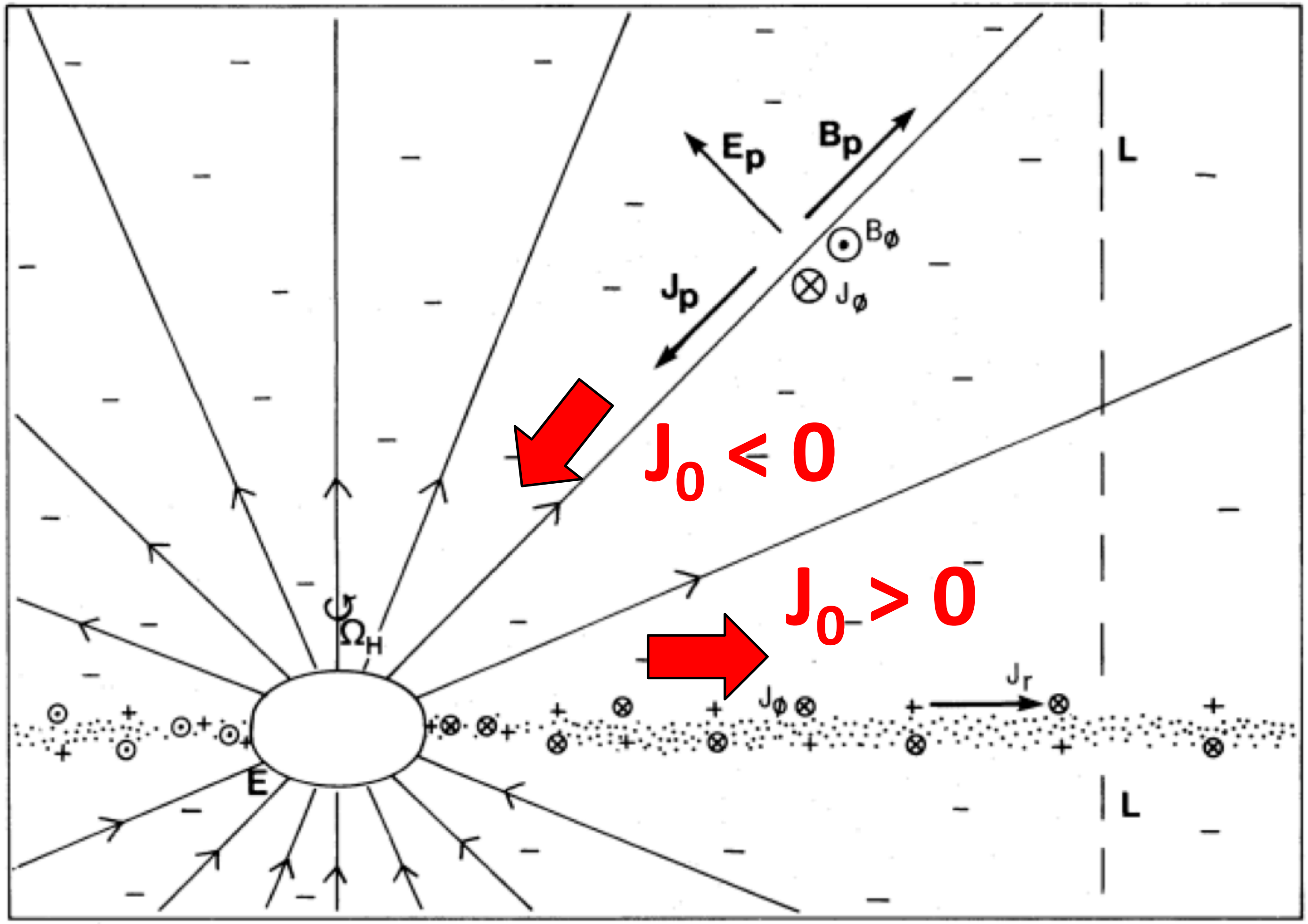
Muitiplicity O(10^{-3})

$$\epsilon_{\rm min} = 10^{-9} m_{\rm e} c^2 \rightarrow \tau_0 \gtrsim 100$$

Electric Currents

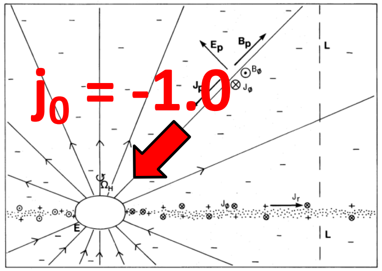
Polar region : $J_0 < 0$

Equatorial region : $J_0 > 0$



Blandford & Znajek 77

$$j_0 = -1.0, 1.0$$



Results

$\tau_0 = 300$

Quasi-periodic oscillation

Number density

$\Delta(n/n_{\rm GJ})$

Current density

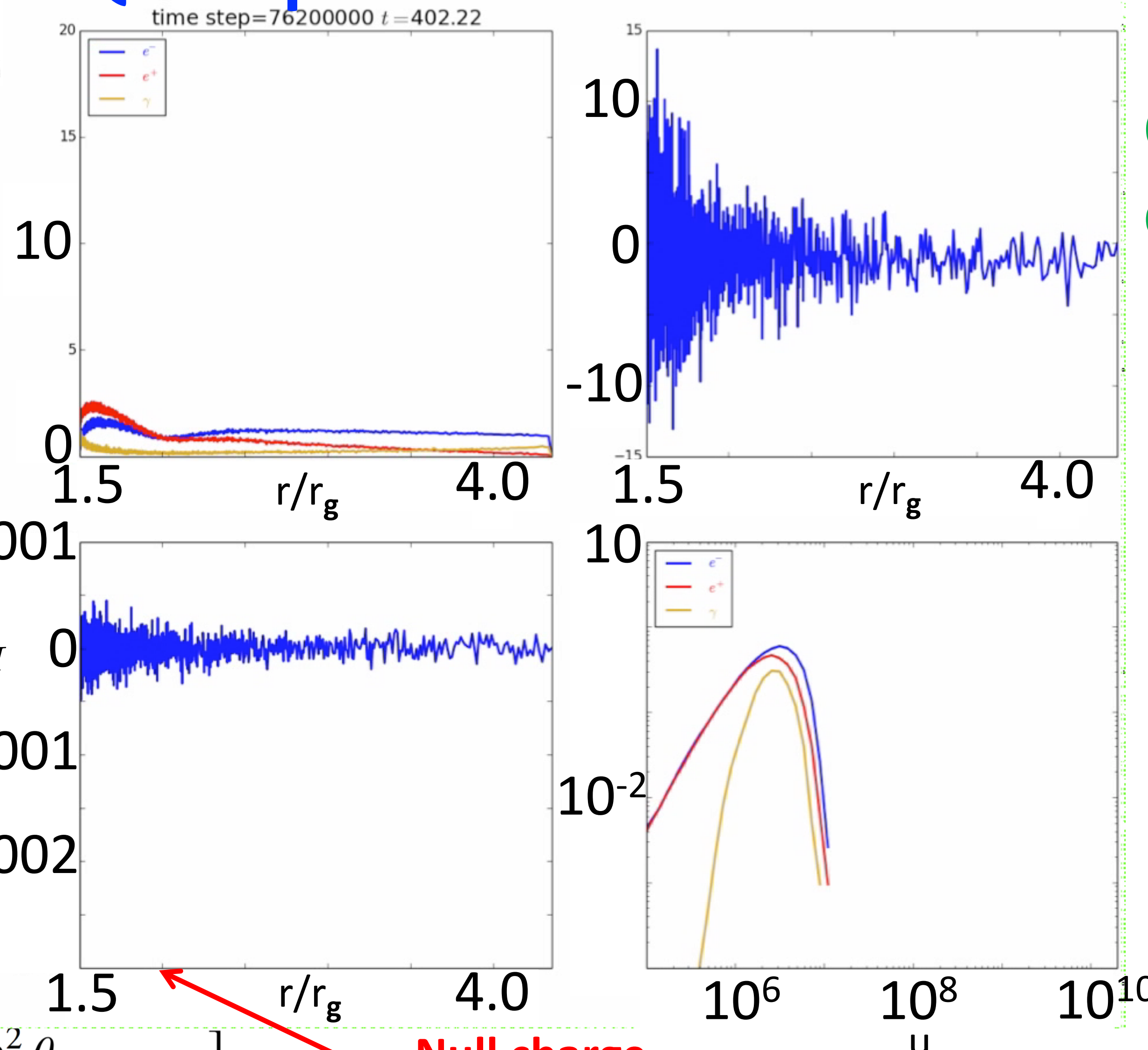
$\Sigma j^r/|J_0|$

E-field

$\sqrt{A}E_r/\sqrt{A_H}B_H$

Energy spectrum

$u^2\frac{dN}{du}$



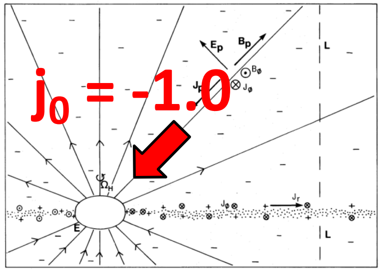
$$\rho_{\rm GJ} = \frac{B_{\rm H}\sqrt{A_{\rm H}}}{4\pi\sqrt{-g}}\left[\frac{\sin^2\theta}{\alpha^2}(\omega-\Omega)\right]_{,\theta}$$

Null charge surface (ρ_{GJ}=0)

Results

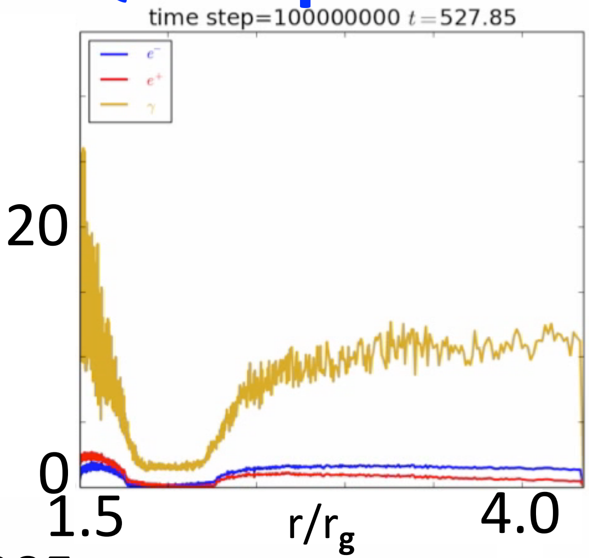
$\tau_0 = 100$

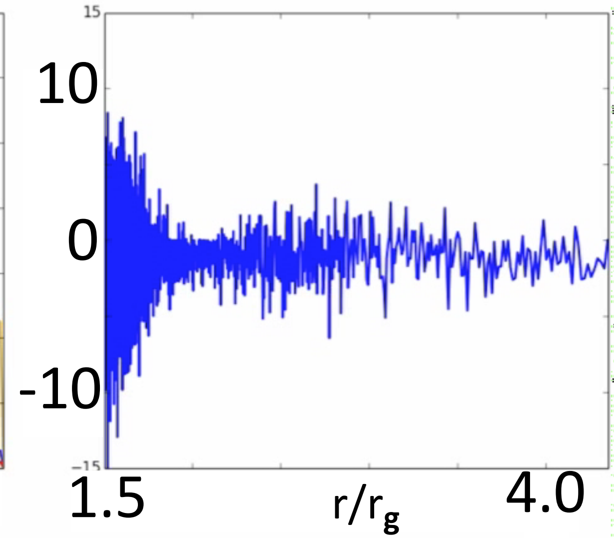
Quasi-periodic oscillation



Number density

$\Delta(n/n_{\mathrm{GJ}})$



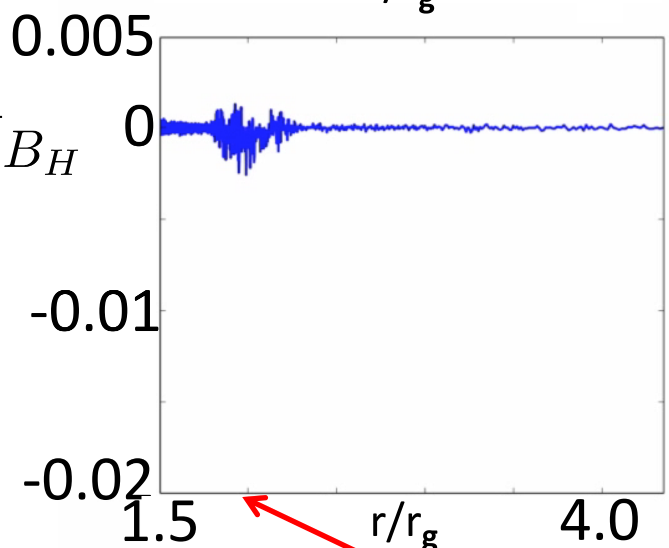


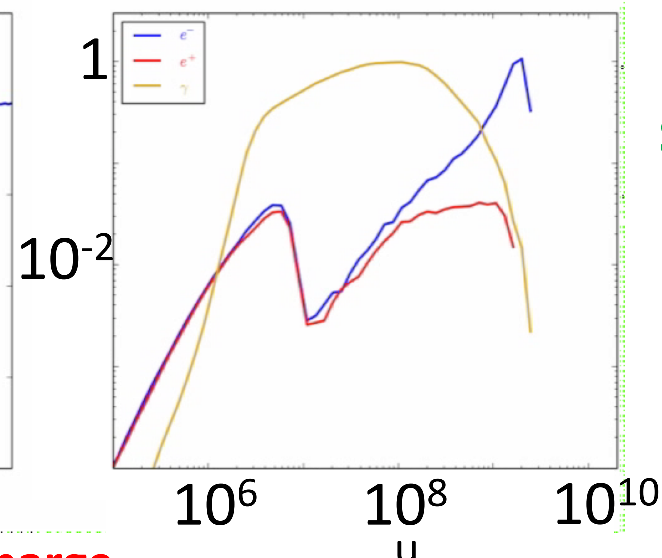
Current density

$\Sigma j^r/|J_0|$

E-field

$\sqrt{A}E_r/\sqrt{A_H}B_H$





Energy spectrum

$u^2 \frac{dN}{du}$

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

Null charge surface ($\rho_{GJ}=0$)

Acceleration model

For simplicity, GR effects are neglected.

Considering the gap until the pair formation front.

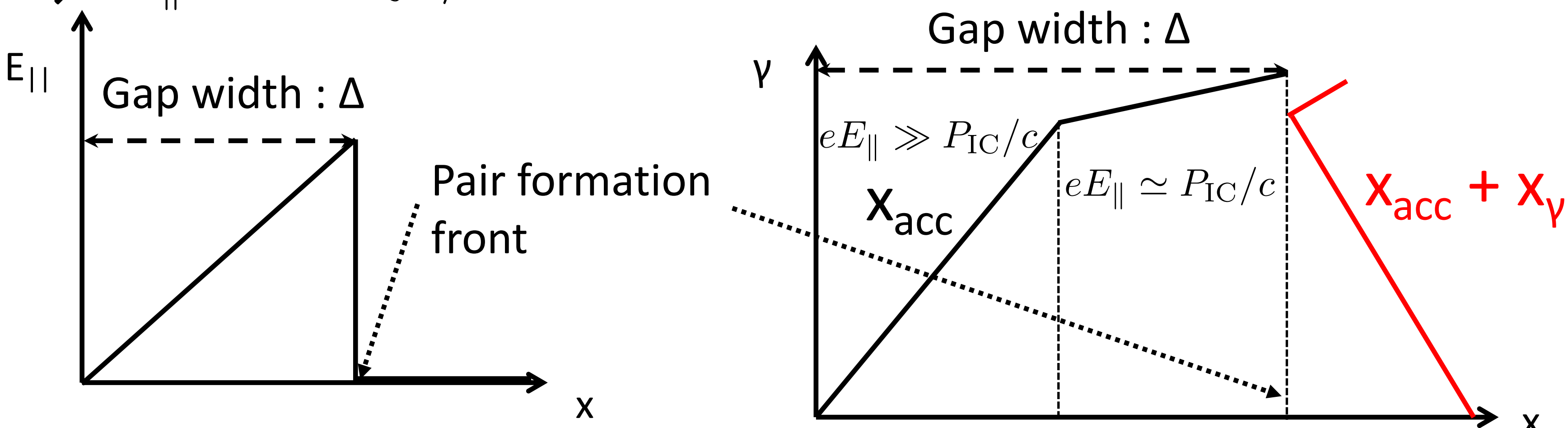
Electric field

$$\nabla \cdot E_{\parallel} = -4\pi(\rho_{\rm e} - \rho_{\rm GJ})$$

$$\rightarrow E_{\parallel} = 2\Omega B \xi x / c$$

Lorentz factor

$$\frac{d(\gamma m_{\rm e} c)}{dt} = eE_{\parallel} - \frac{P_{\rm IC}}{c} - \frac{P_{\rm cur}}{c}$$



$\xi \equiv (\rho_{\rm GJ} - \rho_{\rm e})/\rho_{\rm GJ}$, $\rho_{\rm GJ} \sim \Omega B/(2\pi c)$

Gap width Δ is the minimum value of the sum of the acceleration length $x_{acc}(\gamma)$ and the mean free path $x_{\gamma}(\gamma)$.

$$\rightarrow \Delta / r_{\rm g} \sim 9 \times 10^{-3} \tau_2^{-\frac{1}{3}} \epsilon_{{\rm min},-9}^{-\frac{1}{3}} a_{0.9}^{-\frac{1}{3}} B_4^{-\frac{1}{3}} M_9 \xi^{-\frac{1}{3}}$$

$B_2 \equiv B/10^2$ G

$$\rightarrow E_{\parallel}/B \sim 2\xi a \Delta / r_{\rm g} \sim 2 \times 10^{-2} \tau_2^{-\frac{1}{3}} \epsilon_{{\rm min},-9}^{-\frac{1}{3}} a_{0.9}^{\frac{2}{3}} B_2^{-\frac{1}{3}} M_9 \xi^{\frac{2}{3}}$$

Summary

We perform 1D GRPIC simulation for pair cascade in the black hole magnetosphere.