ブラックホール磁気圏での電磁カスケード
(Electromagnetic Cascade in Black Hole Magnetosphere)

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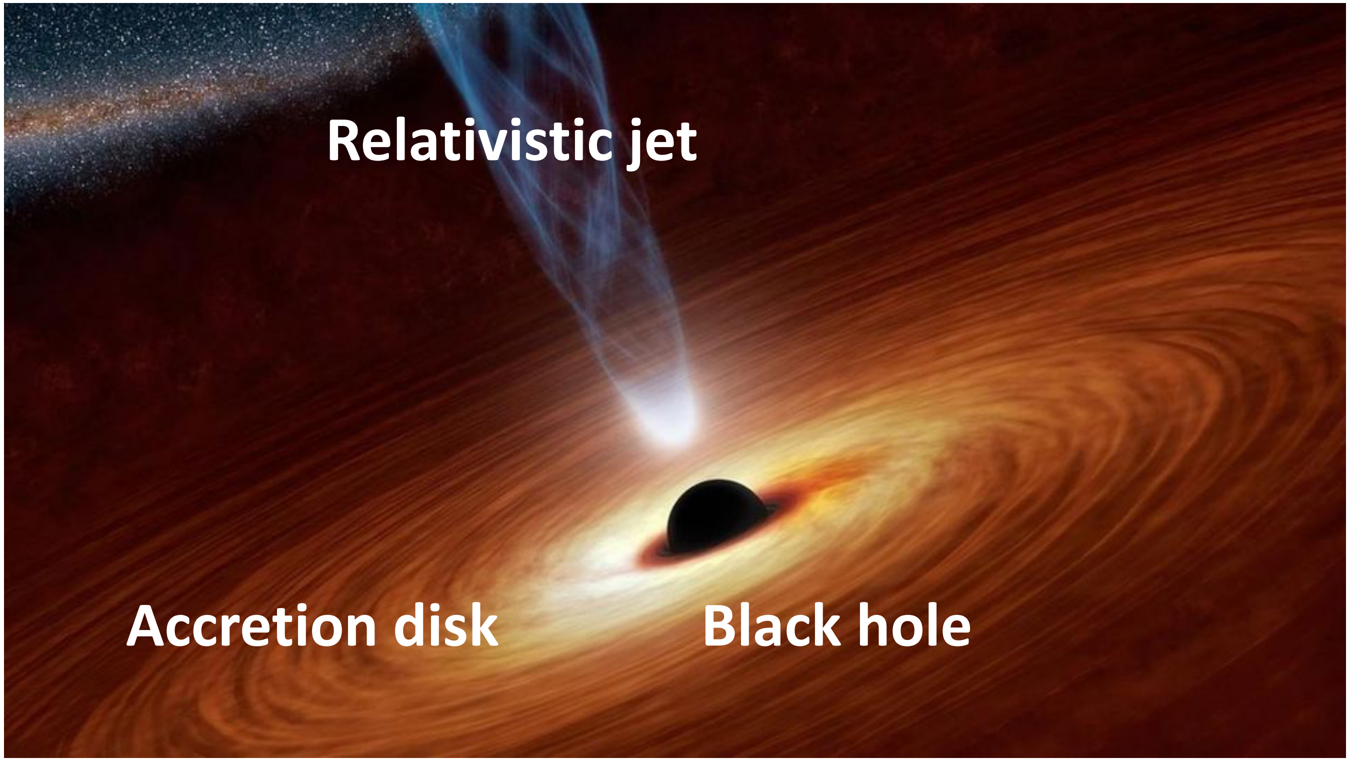
Relativistic jet

$\Gamma_{\rm j} \gg 1$



Theoretical issues

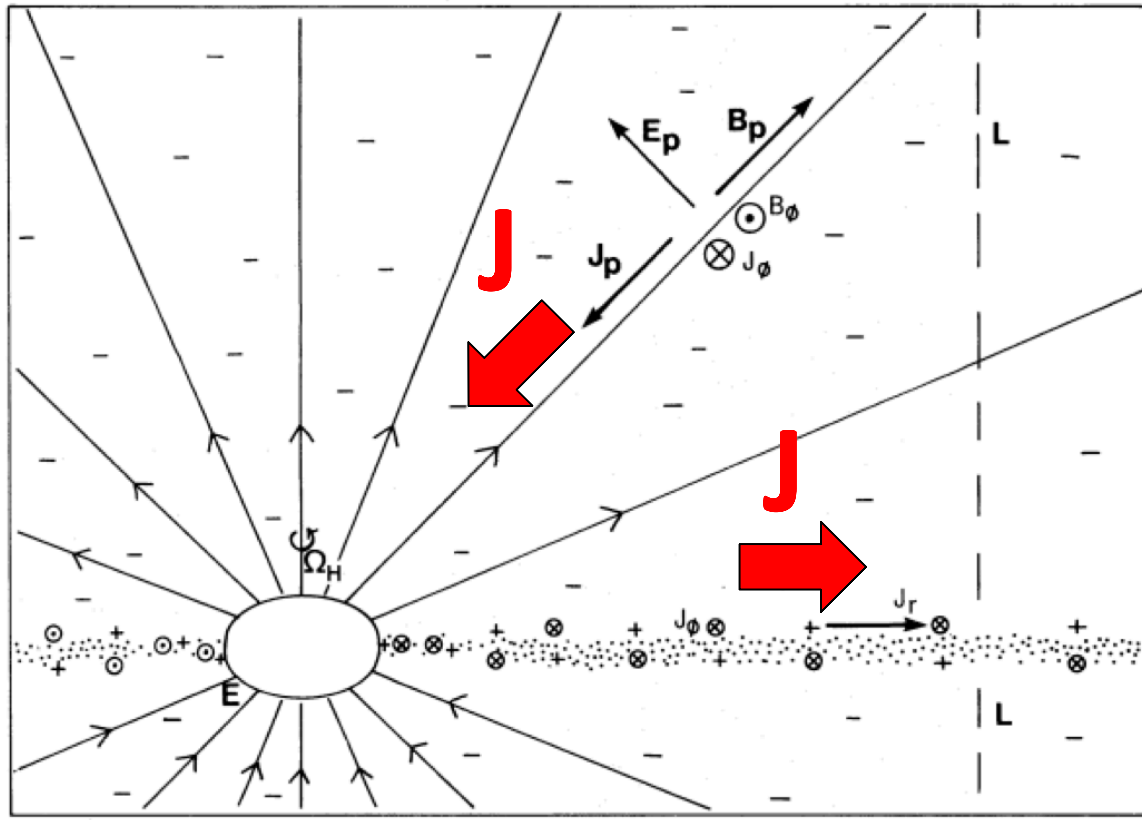
- Energy source?
- Acceleration?
- Collimation?
- Mass supply? $\Gamma_{\rm j} \gg 1 \Leftrightarrow \frac{L_{\rm j}}{\dot{M}_{\rm j} c^2} \gg 1$

Blandford-Znajek process

磁場を介してPoynting fluxとして回転エネルギーを引き抜く機構

Assumption

- Axisymmetry
- Rotating BH (a << 1)
- Split monopole B-field
- Force-free condition



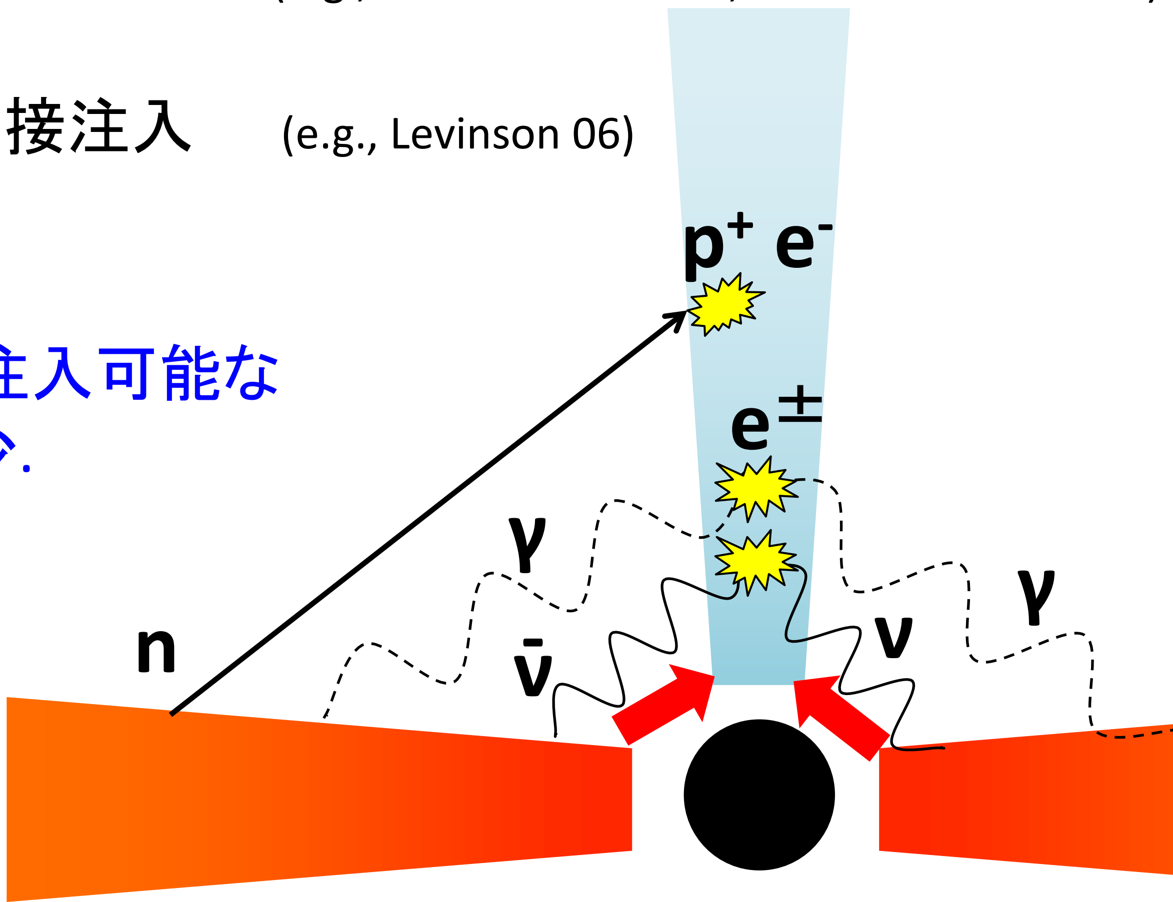
Blandford & Znajek 77

フォースフリー近似を満たして電流回路を維持するため, 十分な数のプラズマがブラックホール磁気圏内に連続的に供給される必要がある.

Plasma injection

- MeV以上の光子から電子陽電子対生成 (e.g., Levinson & Rieger 11)
- ニュートリノから電子陽電子対生成 (e.g., Zalamea & Beloborodov 11)
- 中性子のベータ崩壊 (e.g., Eichler & Wiita 78, Toma & Takahara 12)
- 円盤の一部の物質を直接注入 (e.g., Levinson 06)

降着率が下がるほど注入可能なプラズマの個数が減少.



MeV photon annihilation

Levinson & Rieger 11

Plasma injection rate = outflow rate

$$\sigma_{\gamma\gamma} n_\gamma^2 c \left(\frac{4\pi}{3}\right) r_{\rm g}^3 = 4\pi r_{\rm g}^2 n_\pm c$$

Photon number density

$$n_\gamma = \frac{L_{\rm d}}{2\pi r_{\rm d}^2 c \epsilon_\gamma}$$

Goldreich-Julian number denisty

$$\dot{m} \equiv \dot{M}/\dot{M}_{\rm Edd}$$

$$n_{\rm GJ} = \frac{\Omega B}{2\pi e c} \sim 5\times 10^{-2} \dot{m}^{1/2} M_9^{-3/2}\ {\rm cm}^{-3}$$

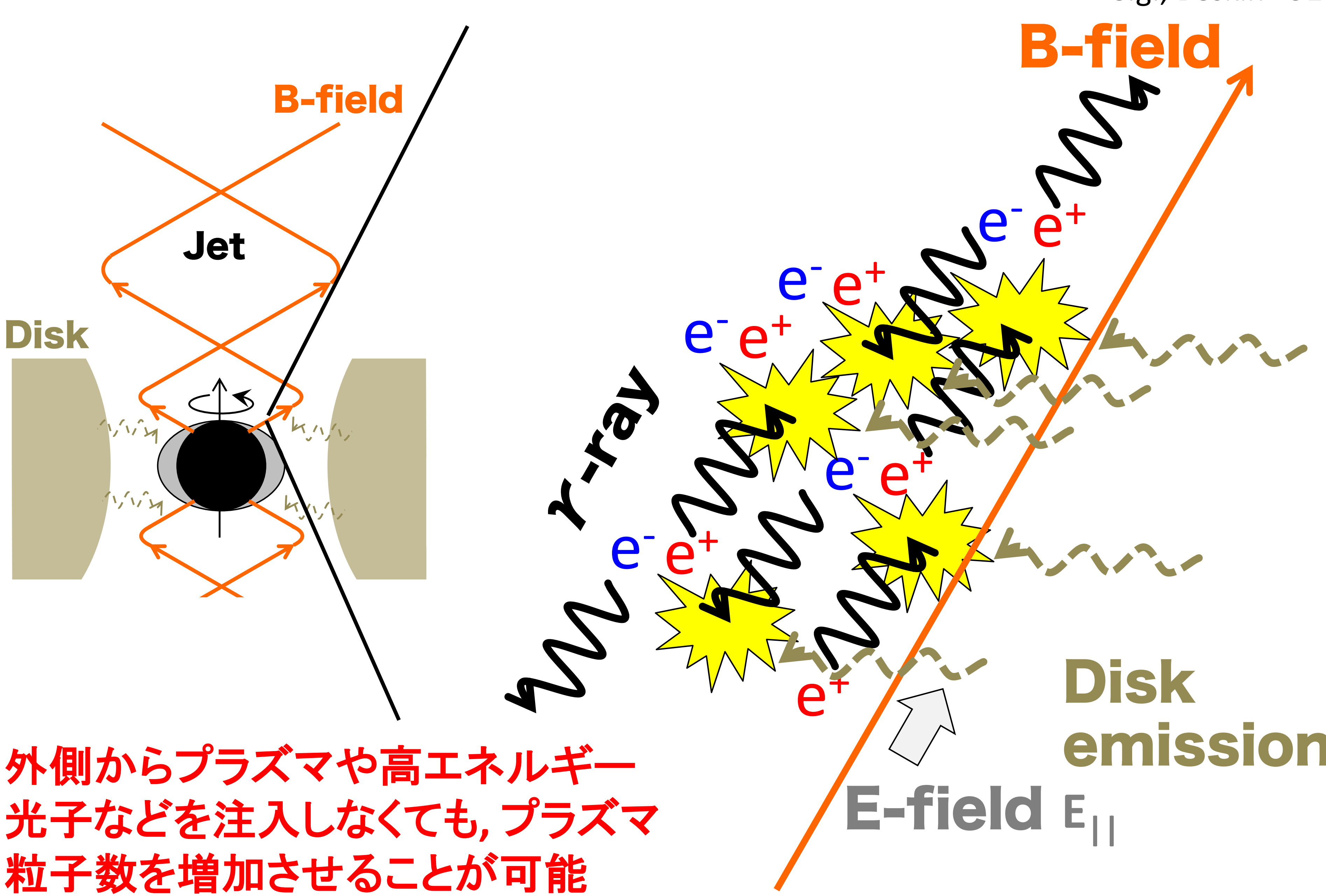
$$r_{\rm g} = \frac{2GM}{c^2}$$

$$\longrightarrow \quad \frac{n_\pm}{n_{\rm GJ}} \lesssim 1 \quad \Longleftrightarrow \quad \dot{m} \lesssim 2\times 10^{-4} M_9^{-1/7}$$

(M87, Sgr A*, isolated BH, merging BH-NS binary, ...)

Electromagnetic cascade

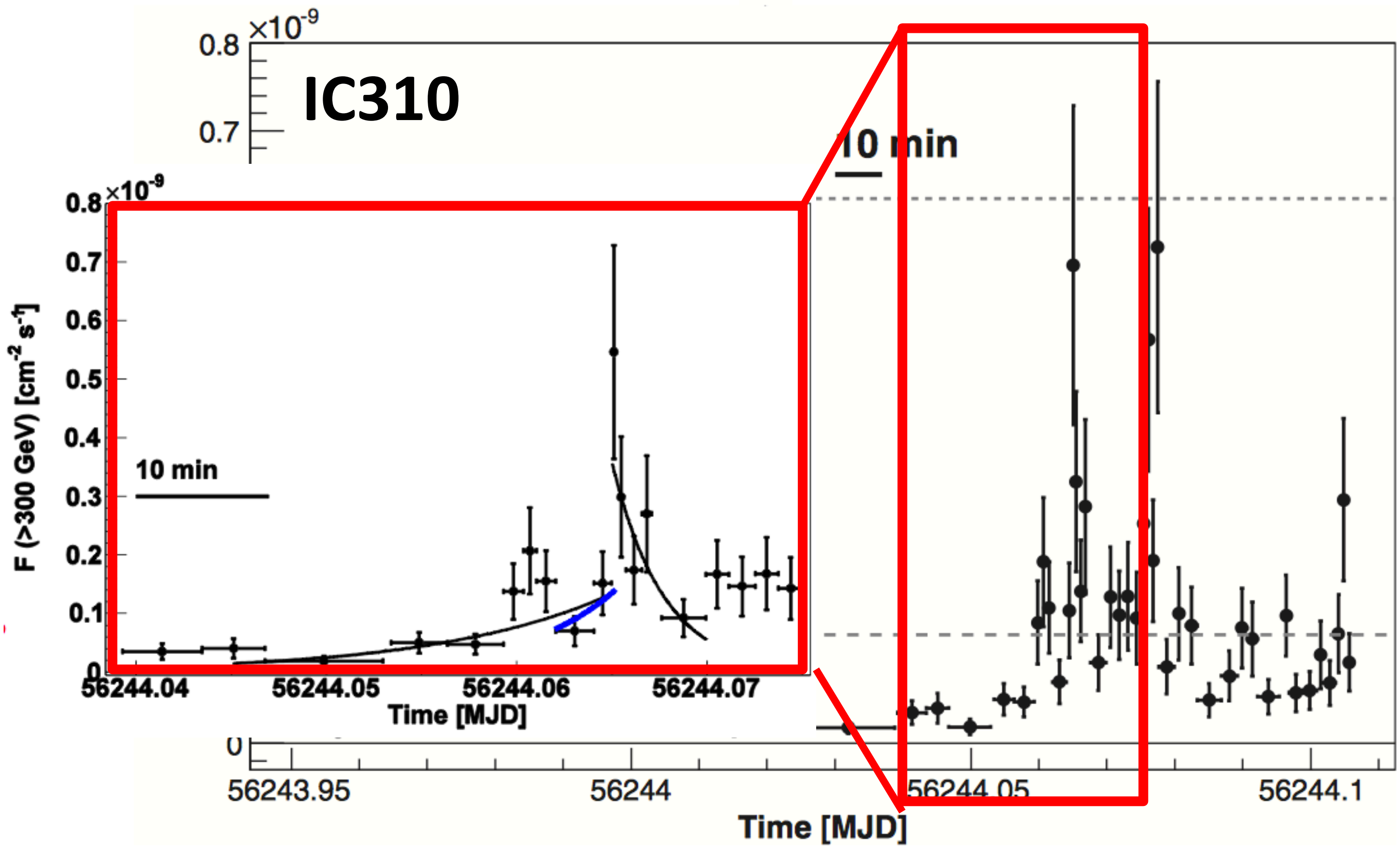
e.g., Beskin+ 92



外側からプラズマや高エネルギー光子などを注入しなくても，プラズマ粒子数を増加させることが可能

Observational evidence?

Aleksić+ 14

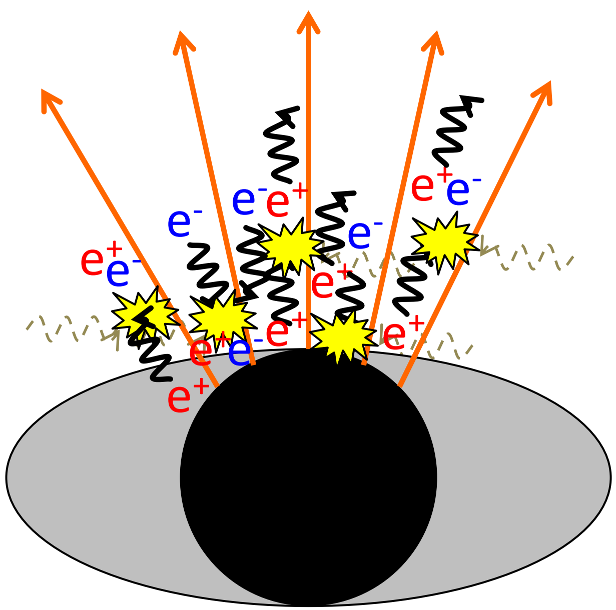


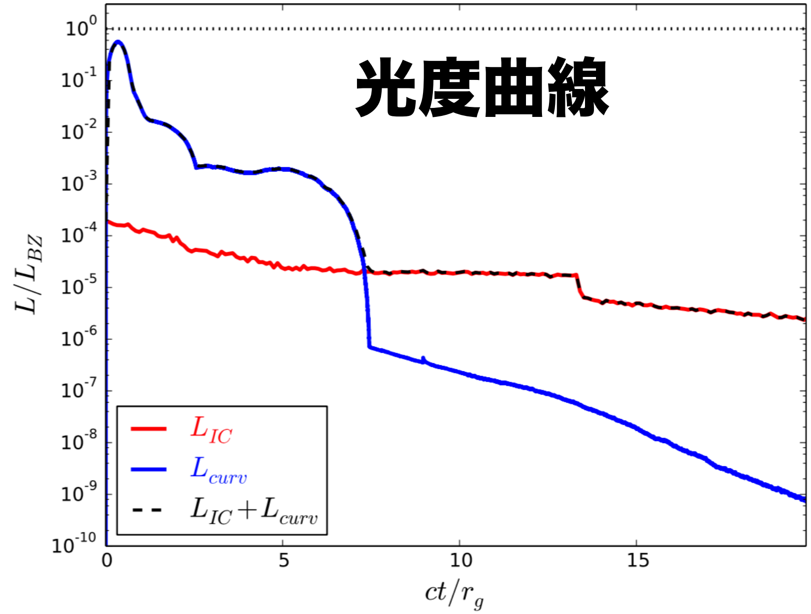
Flux doubling timescale < 4.8 min at 95% C.L.
corresponds to ~20% of the timescale r_g/c.

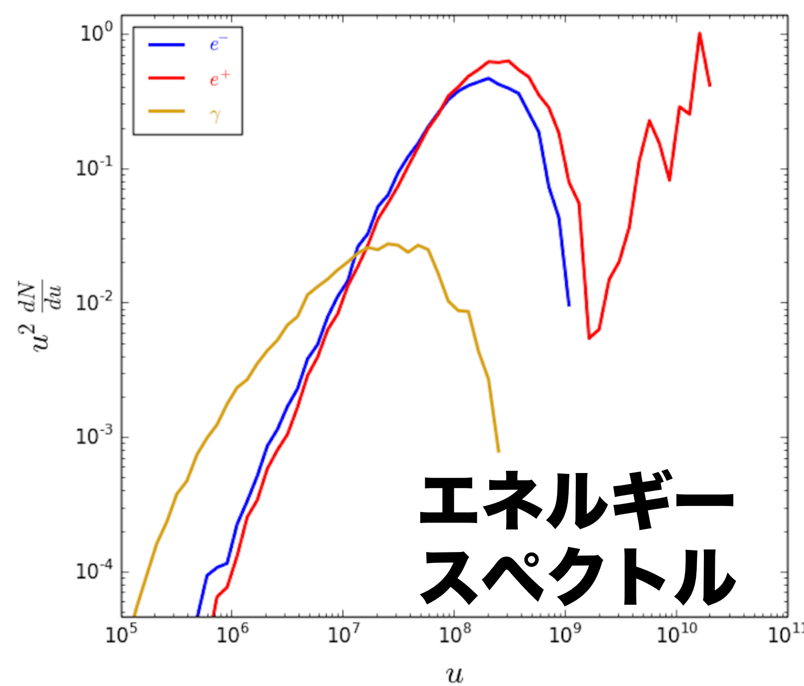
→ **Particle acceleration at sub-horizon scale?**

Aim

ブラックホール磁気圏で起こる
電磁カスケード現象を理解し、
光度曲線や粒子のエネルギー
スペクトルのパラメータ依存性を
明らかにする.







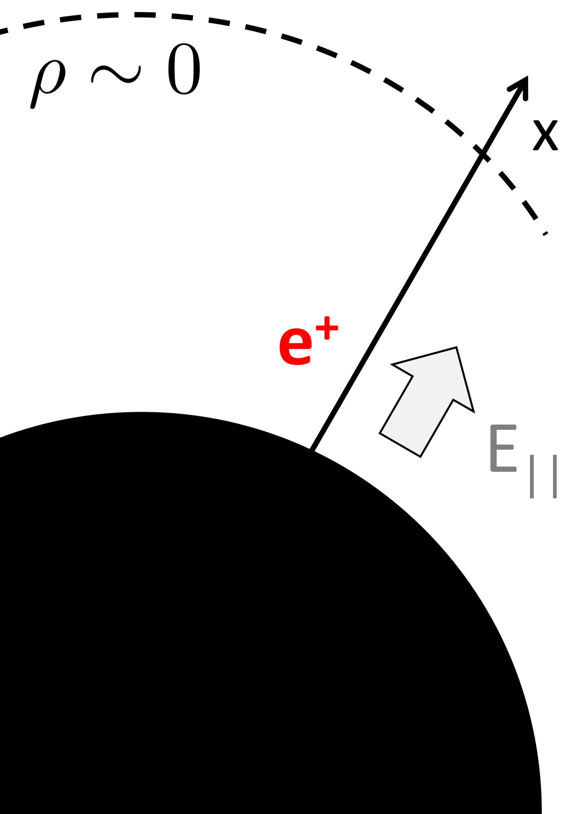
Contents

Steady-state model 重力場の効果を無視

ホライズン程度のスケールに, $E_{||} \sim B$ 程度の加速電場があるとする.

電場

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

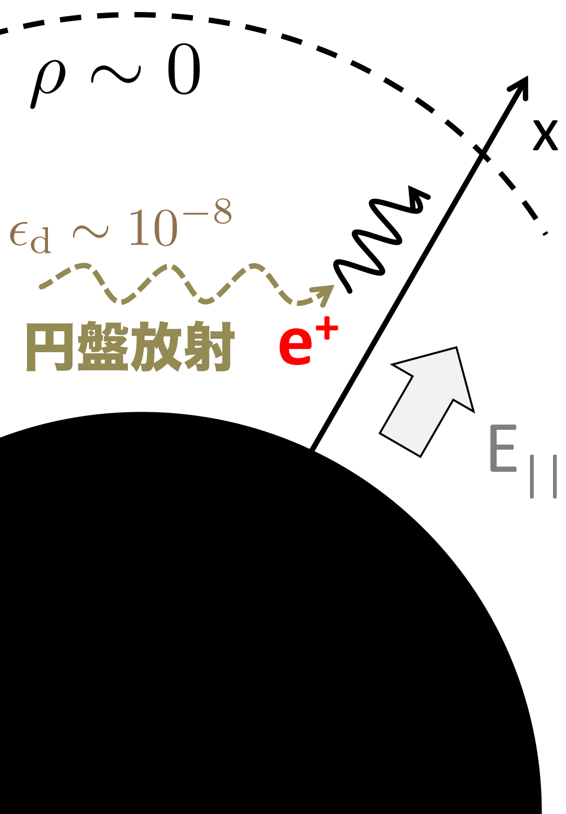


電子の最大エネルギー

$$\gamma_{\mathrm{max}} \sim \frac{eE_{\|} r_{\mathrm{g}}}{m_{\mathrm{e}} c^2} \sim 2 \times 10^{14} B_3 M_9$$

Steady-state model 重力場の効果を無視

ホライズン程度のスケールに, $E_{||} \sim B$ 程度の加速電場があるとする.



- Inverse Compton scattering

$$U_{\rm rad} = L_{\rm d}/(2\pi r_{\rm d}^2 c)$$
$$\epsilon \equiv E/(m_{\rm e}c^2)$$

$$eE_{||} = \sigma_{\rm T} U_{\rm rad} \gamma^2$$

$$\longrightarrow \gamma_{\rm IC} \sim 5 \times 10^9 r_{\rm d,1} L_{\rm d,41}^{-1/2} B_3^{1/2} M_9$$

$$\epsilon_{\rm IC} \sim 0.1 \gamma_{\rm IC}$$ (Klein-Nishina regime)

- Curvature radiation

$$eE_{||} = \frac{2}{3}\frac{e^2}{r_{\rm c}^2}\gamma^4$$

$$\longrightarrow \gamma_{\rm c} \sim 2 \times 10^{10} r_{\rm c,0}^{1/2} B_3^{1/4} M_9^{1/2}$$

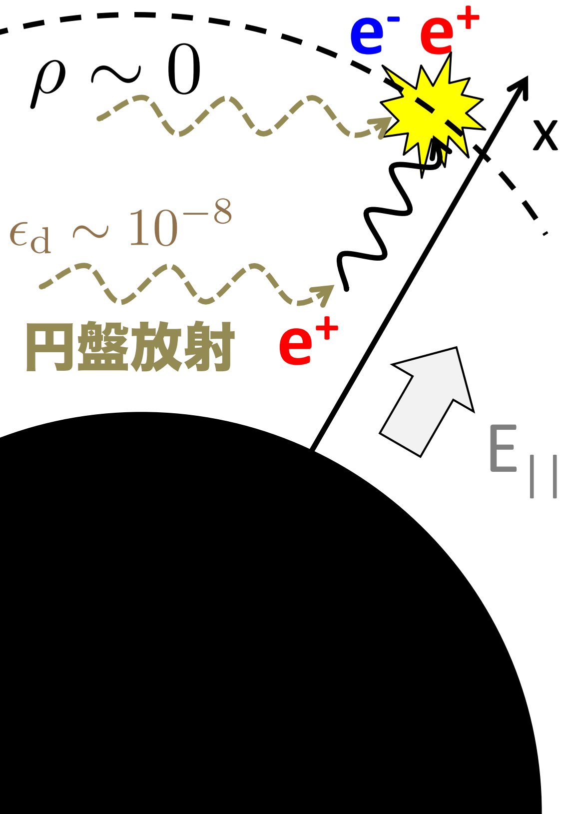
$$\epsilon_{\rm c} = \frac{3}{2}\frac{\hbar c}{r_{\rm c} m_{\rm e} c^2}\gamma^3 \sim 2 \times 10^6 r_{\rm c,0}^{1/2} B_3^{3/4} M_9^{1/2}$$

Steady-state model 重力場の効果を無視

ホライズン程度のスケールに, $E_{||} \sim B$ 程度の加速電場があるとする.

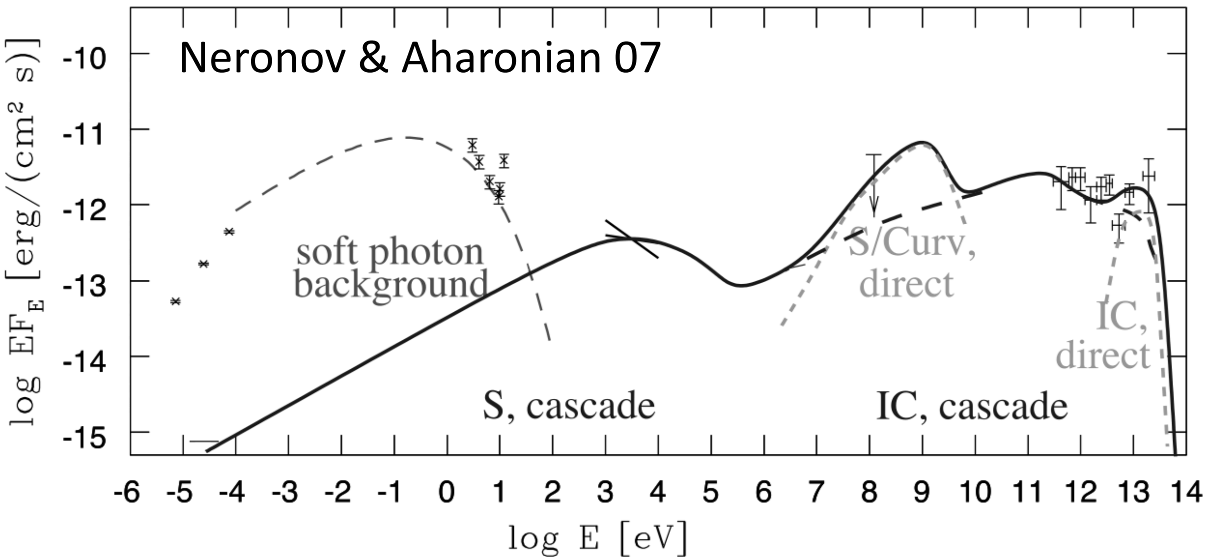
平均自由行程

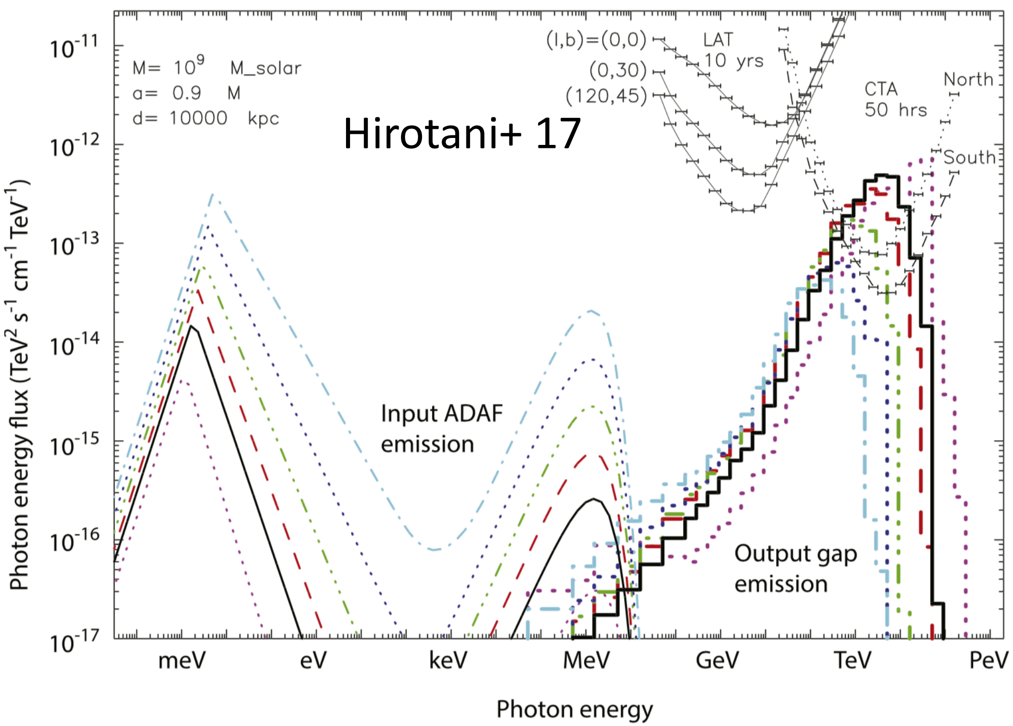
$$\frac{\lambda}{r_{\rm g}} \sim 0.1 L_{\rm d,41}^{-1} r_{\rm d,1}^{2} \epsilon_{\rm d,-8}$$



ホライズン程度のスケールの大きさだけ加速領域 (ギャップ) が存在し, カスケードによりプラズマを注入し続ける.

Steady-state model





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

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Astronomy & Astrophysics

Particle-in-cell simulations of pair discharges in a starved magnetosphere of a Kerr black hole

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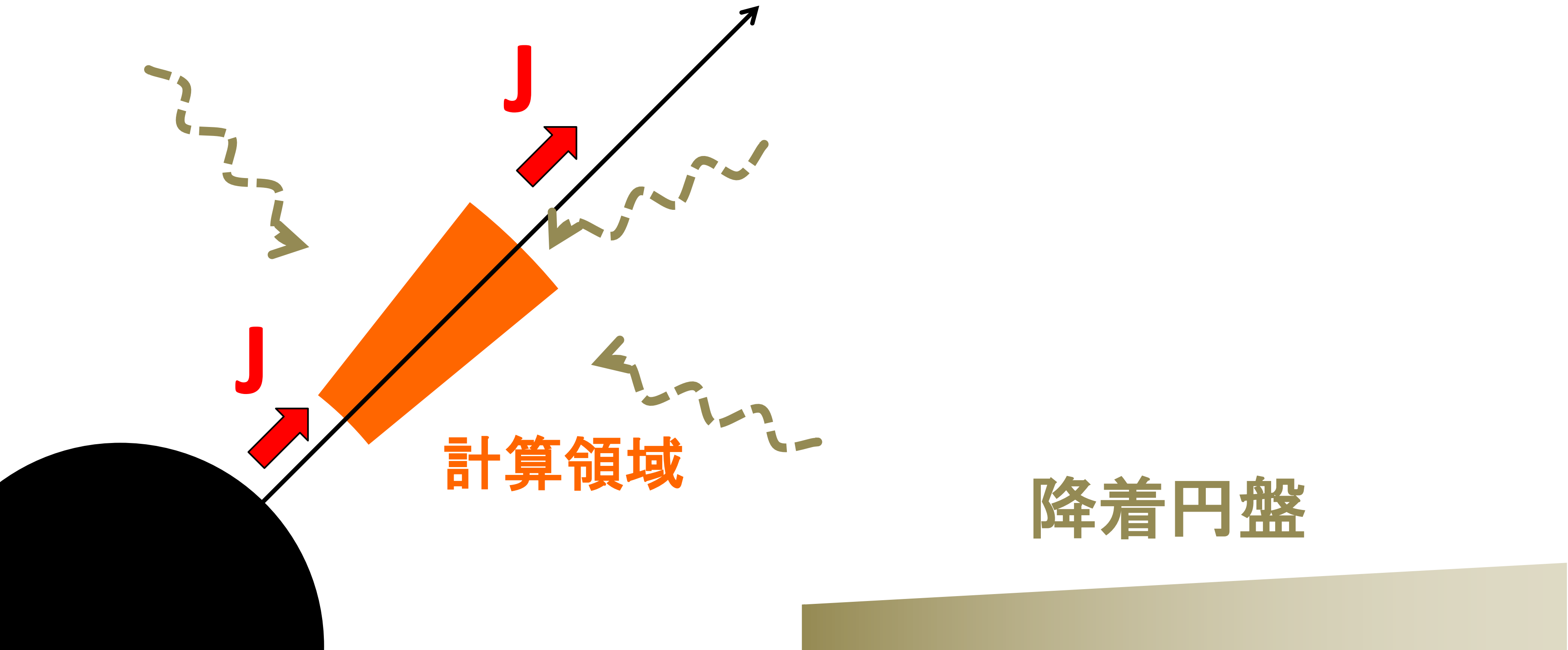
ABSTRACT

We investigate the dynamics and emission of a starved magnetospheric region (gap) formed in the vicinity of a Kerr black hole horizon, using a new, fully general relativistic particle-in-cell code that implements Monte Carlo methods to compute gamma-ray emission and pair production through the interaction of pairs and gamma rays with soft photons emitted by the accretion flow. It is found that when the Thomson length for collision with disk photons exceeds the gap width, screening of the gap occurs through low-amplitude, rapid plasma oscillations that produce self-sustained pair cascades, with quasi-stationary pair and gamma-ray spectra, and with a pair multiplicity that increases in proportion to the pair production opacity. The gamma-ray spectrum emitted from the gap peaks in the TeV band, with a total luminosity that constitutes a fraction of about 10^{-5} of the corresponding Blandford–Znajek power. This stage is preceded by a prompt discharge phase of duration $\sim r_g/c$, during which the potential energy initially stored in the gap is released as a flare of curvature TeV photons. We speculate that the TeV emission observed in M87 may be produced by pair discharges in a spark gap.

Key words. black hole physics – acceleration of particles – radiation mechanisms: non-thermal – methods: numerical – galaxies: individual: M87 – gamma rays: galaxies

Set up

- ホライズン近傍領域 (1.5-4 r_g) の磁力線に沿った
  1次元動径方向の粒子と光子の運動を扱う.
- グローバルの電流回路は固定. 計算領域内での
  電場の変動などはグローバルには影響を与えない.
- 円盤から一様等方かつ定常な放射が供給される.



Assumptions

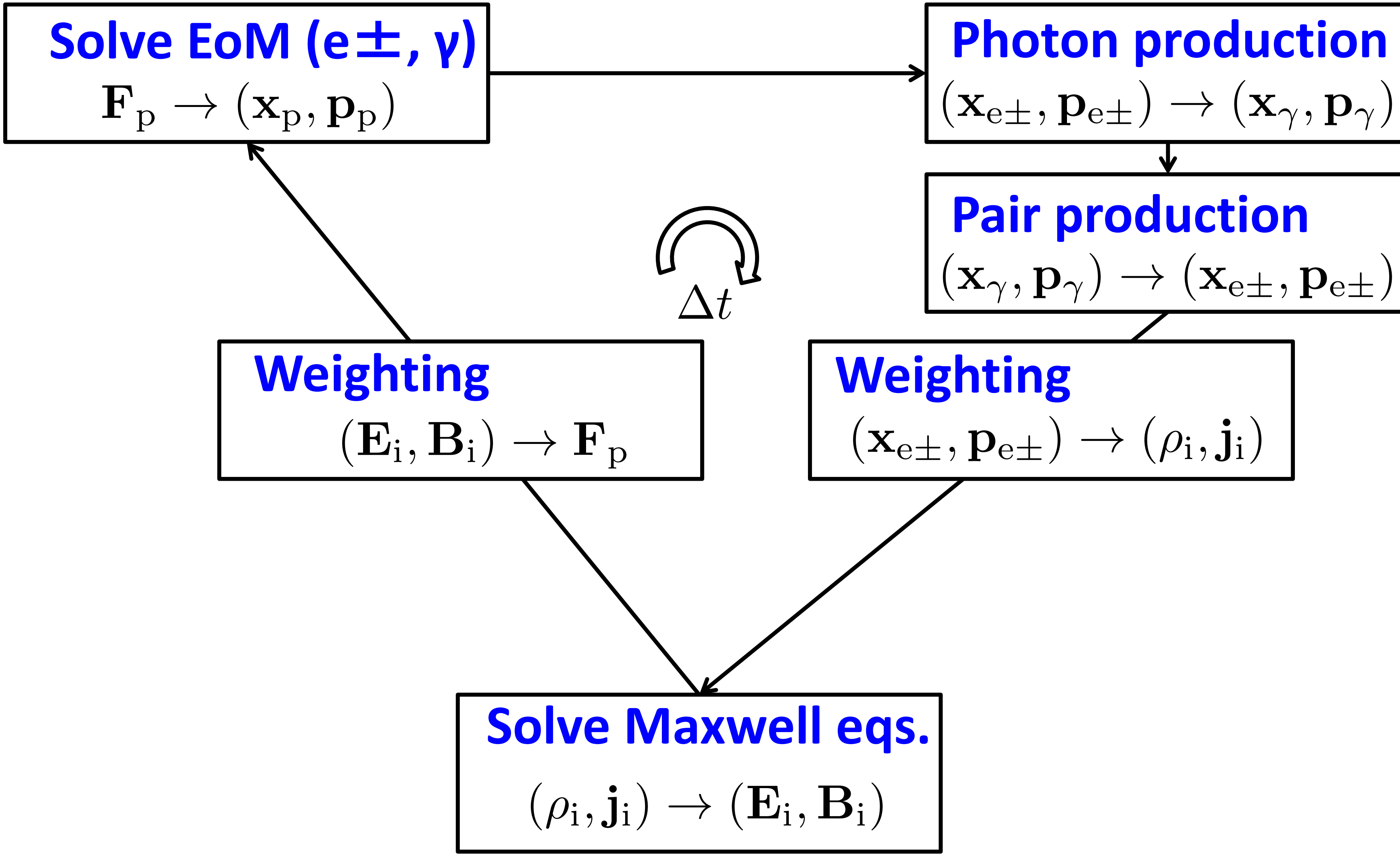
Levinson & Cerutti 18

- 1-dimensional structure: the gap extends along a poloidal magnetic surface as a function of θ.
  → Ignoring any MHD waves, considering only longitudinal plasma oscillations.
- No external plasma source.
- Isotropic radiation field (from accretion disk) for seed photons.

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

- The gap constitutes a small disturbance.
  → The activity does not significantly affect the global structure (the B-field geometry and the angular velocity).
- The global current is a free parameter.
- A split monopole geometry for the global B-field.
- The angular velocity of magnetic surface $\Omega = 0.5\omega_{\rm H}$.
- Ignoring the curvature photons as a source of pair creation.

Particle-in-Cell simulation



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

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

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

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

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

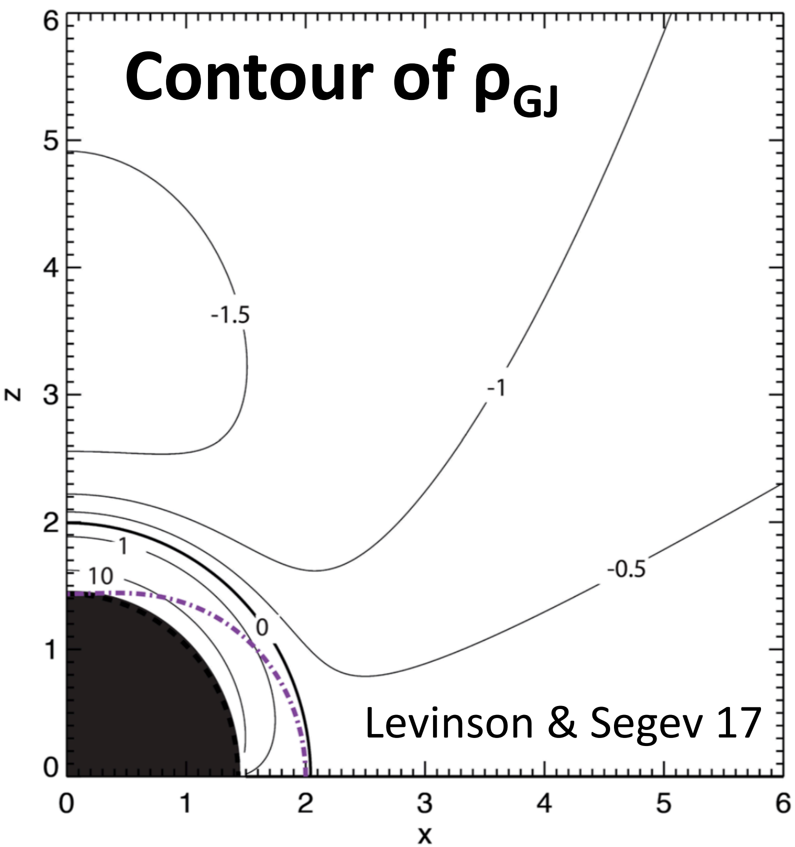
Basic equations

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

Gauss's law

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

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

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

Ampère's law (radial component)

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

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

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

Basic equations

Levinson & Cerutti 18

Equation of motion for *i*-th particle

Curvature loss term

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

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

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

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

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

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

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

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	$\tau_0 = 4\pi r_g \sigma_{\mathrm{T}} I_0 / hc = 2.5$
Global current density	$j_0 = 1.0$
BH mass	$M_{\mathrm{BH}} = 10^9 M_\odot$
Dimensionless spin parameter	$a_* = 0.9$
B-field on the horizon	$B_{\mathrm{H}} = 2\pi \times 10^3 \mathrm{G}$
Inclination angle of magnetic surface	$\theta = 30^\circ$
Minimum energy of seed photon	$\epsilon_{s,\mathrm{min}} = 10^{-8} m_{\mathrm{e}} c^2$
Slope of seed photon spectrum	$p = 2$
Curvature radius	$R_{\mathrm{cur}} = r_g$
Number of cell	$N = 32768$

$$\gtrsim \frac{r_g}{l_{\mathrm{p}}} \sim 10^3 \sqrt{\frac{\kappa M_9 B_{\mathrm{H},3}}{< \gamma_8 >}}$$

Example (τ_0=10, j_0=1)

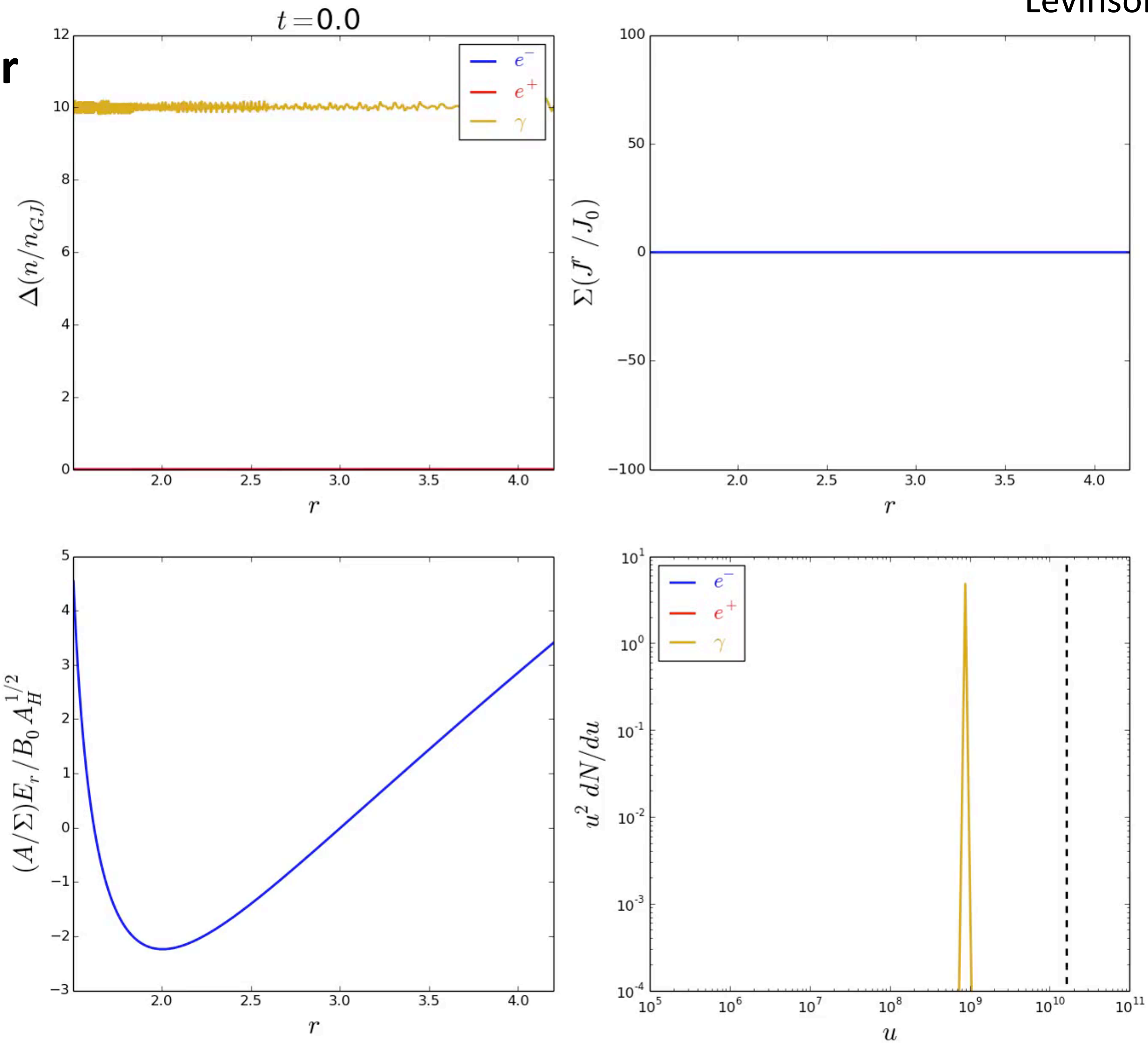
Levinson & Cerutti 18

Number density

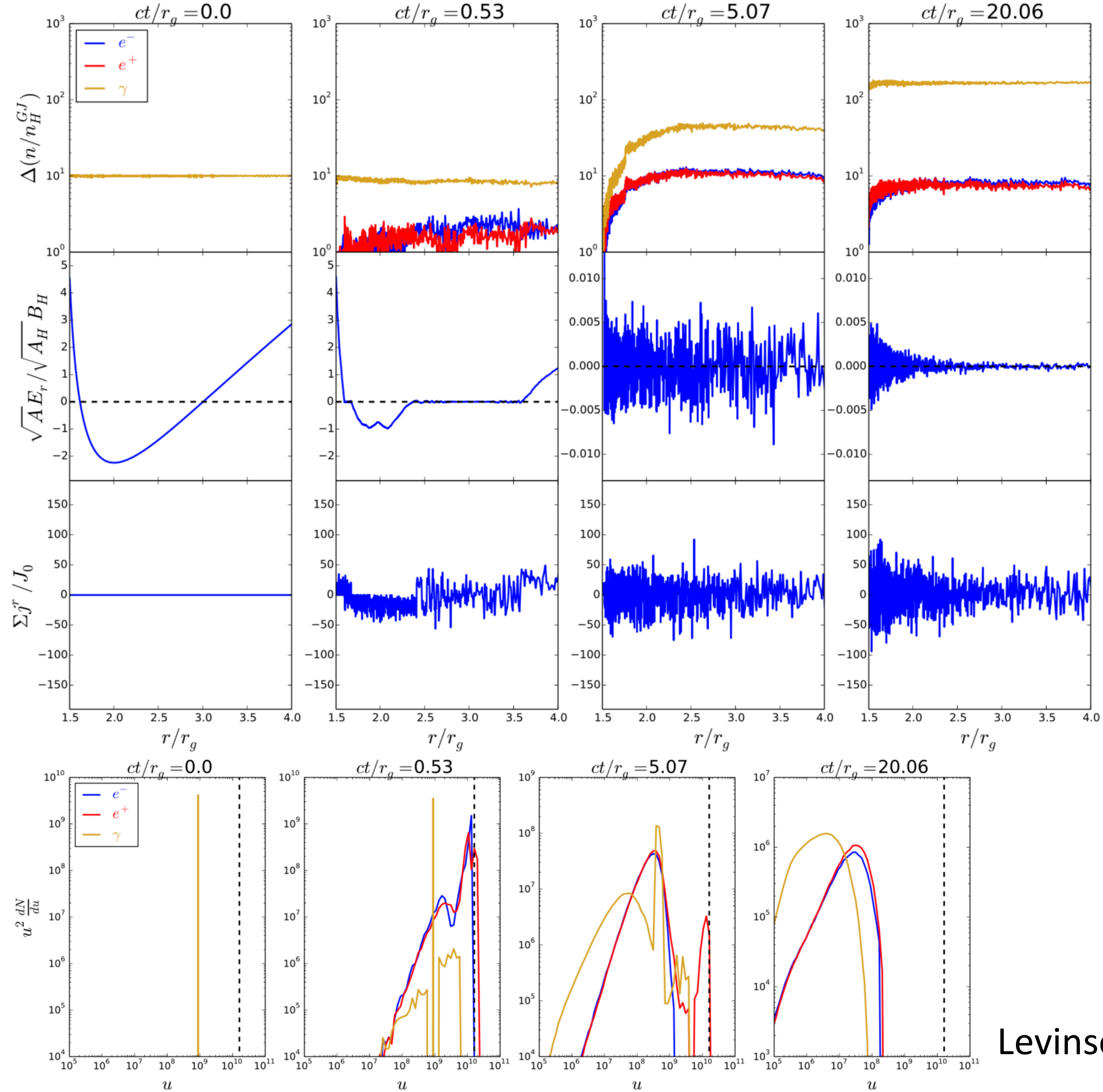
Current density

E-field

Energy spectrum



Example (τ_0=10, j_0=1)



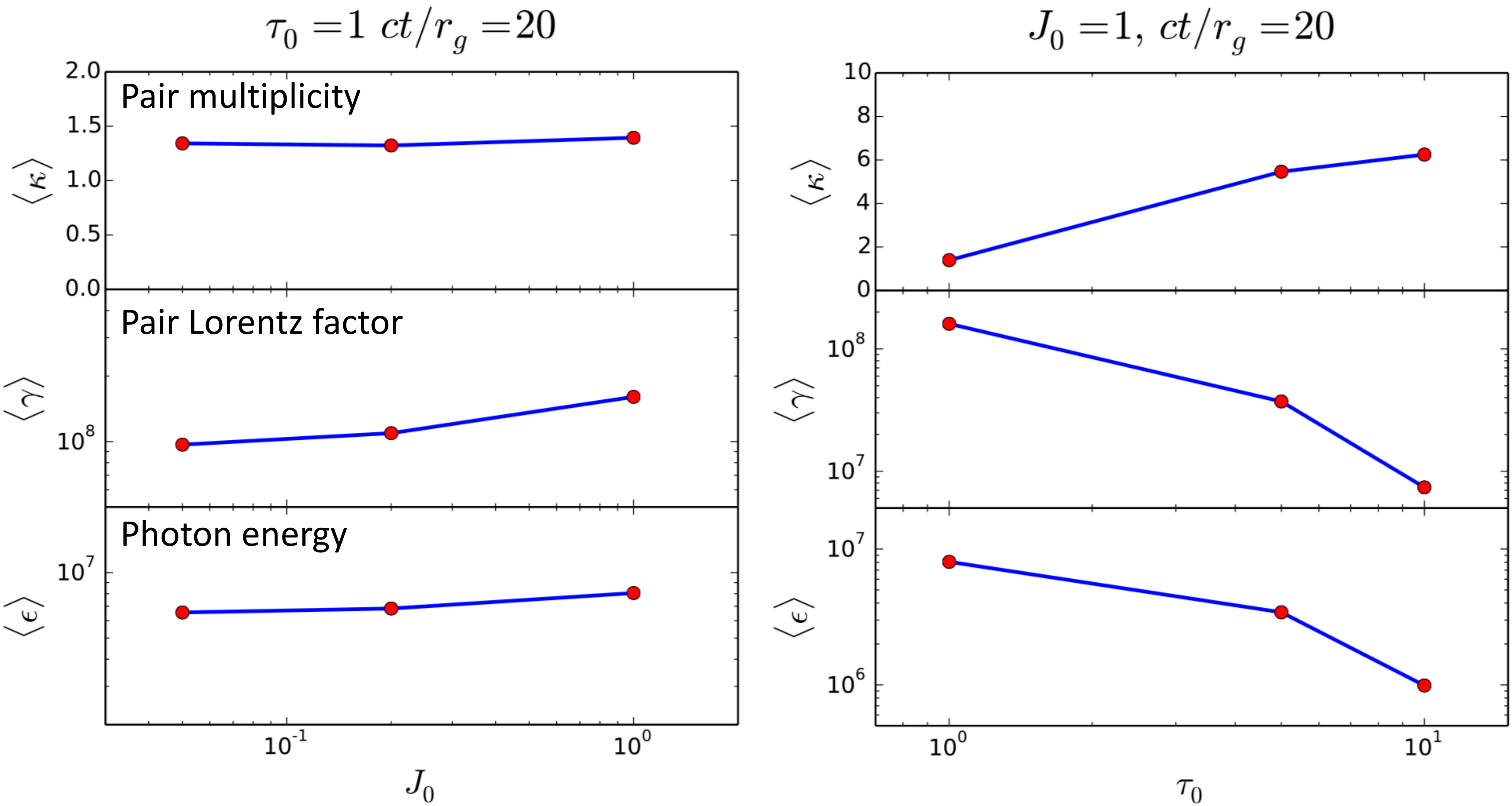
E-field is screened

Steady-state

Levinson & Cerutti 18

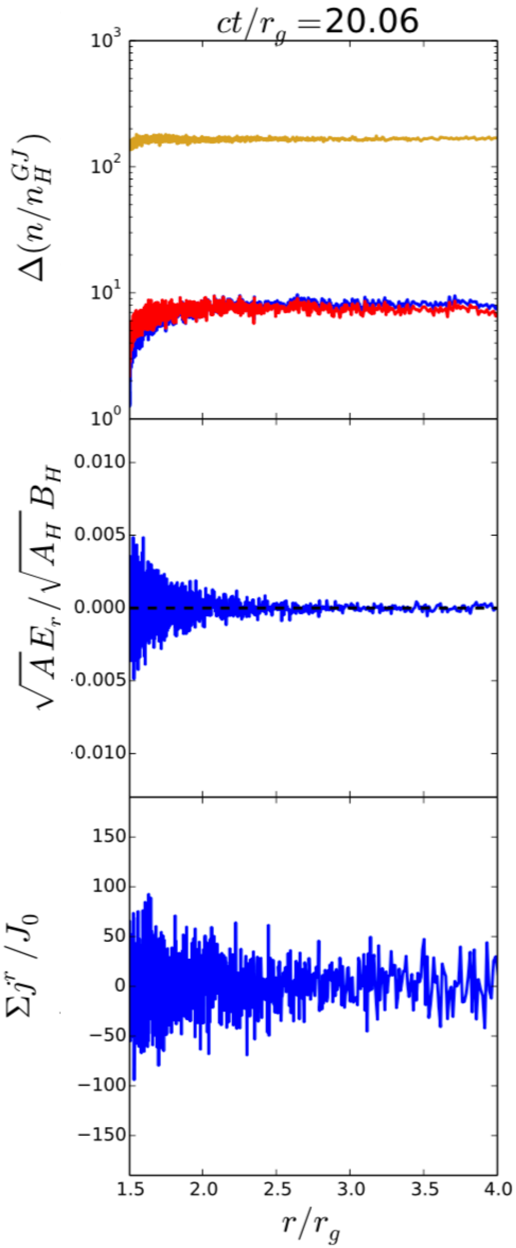
Parameter dependence

Levinson & Cerutti 18



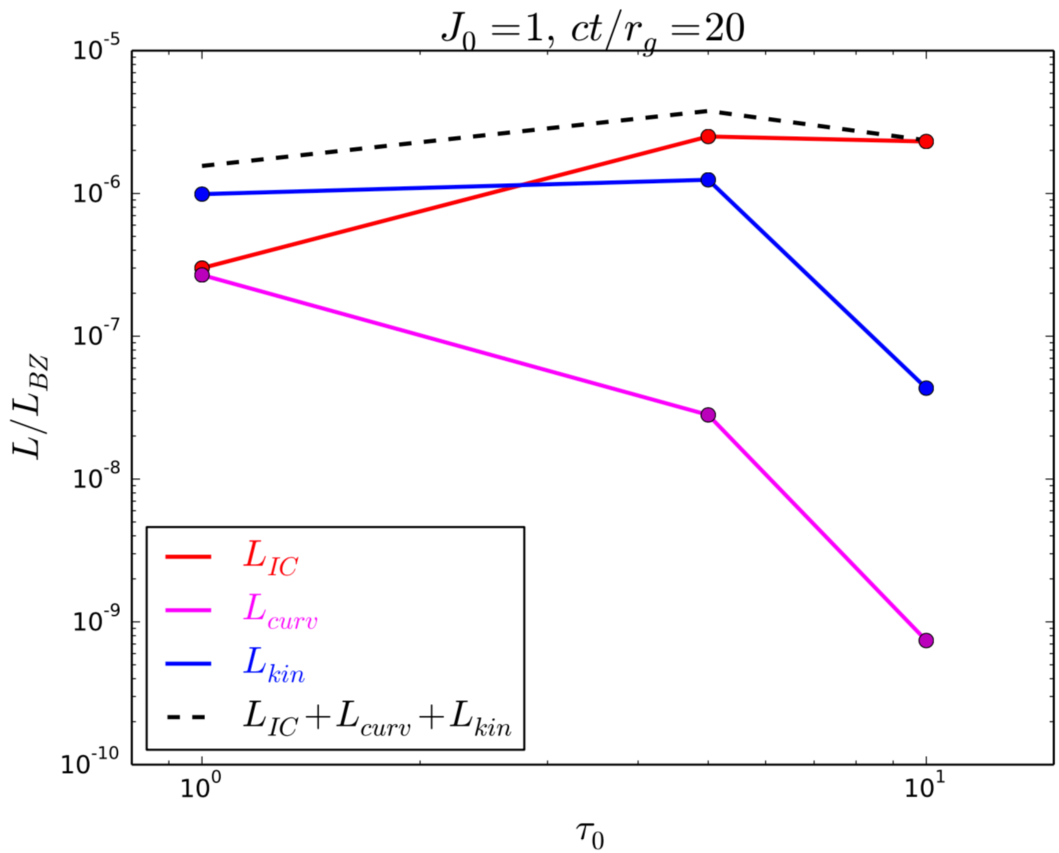
Energy conversion

Levinson & Cerutti 18



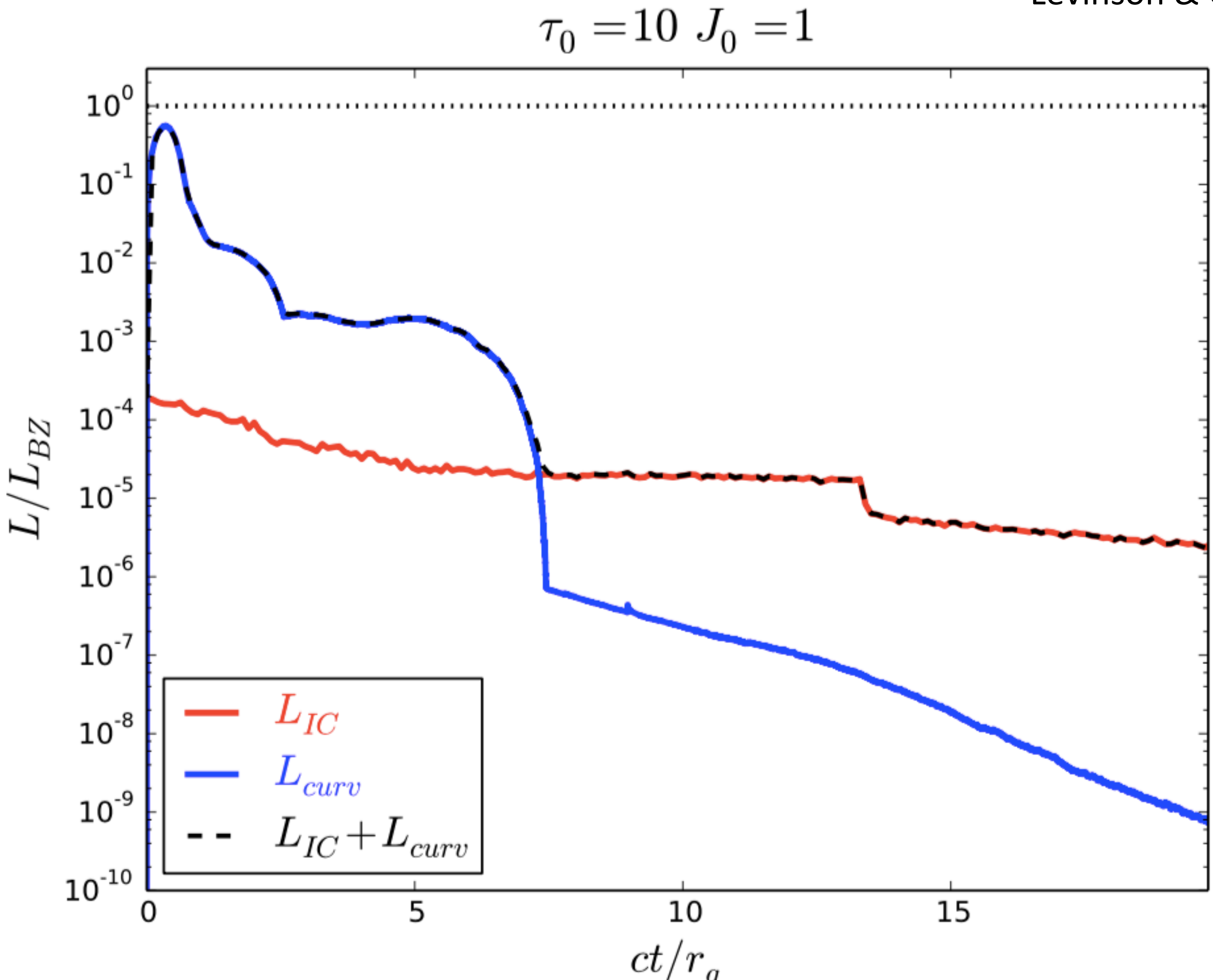
Quasi-steady state

$(L_{kin} + L_{rad})/L_{BZ} \sim 10^{-6}$



Light Curve

Levinson & Cerutti 18



Summary

- 低降着率のBHからのジェットでは, BH磁気圏での電磁カスケードにより粒子が注入されているだろう.

- 先行研究は定常モデルだが, 本質的には非定常.

- 粒子シミュレーションによる研究が始まった (Levinson & Cerutti 18). 結果として, 電場が遮蔽された状態が準定常に続くと主張されている.

- 電場遮蔽は, 曲率放射起源の光子からの粒子生成, もしくは optical depth が十分大きい場合に実現されそうだが, 準周的な振る舞いが期待される.