Energy conversion efficiency in magnetospheric gaps around Kerr black holes

Shota Kisaka

(Hiroshima University)

Collaborators

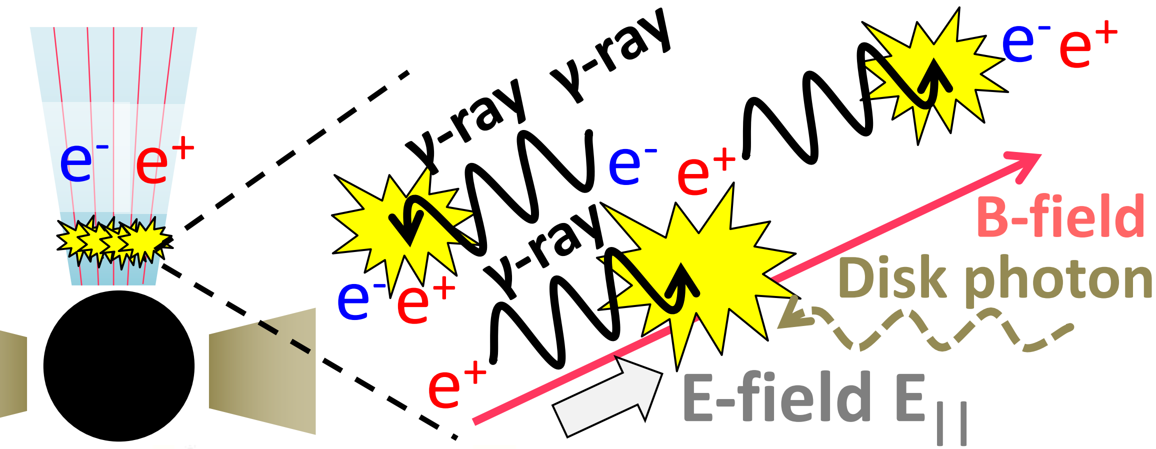
Amir Levinson (Tel Aviv Univ.), Kenji Toma (Tohoku Univ.)

Electromagnetic Cascade

Accretion rate | **Number density (photon injection)** | **Unscreened E-field**

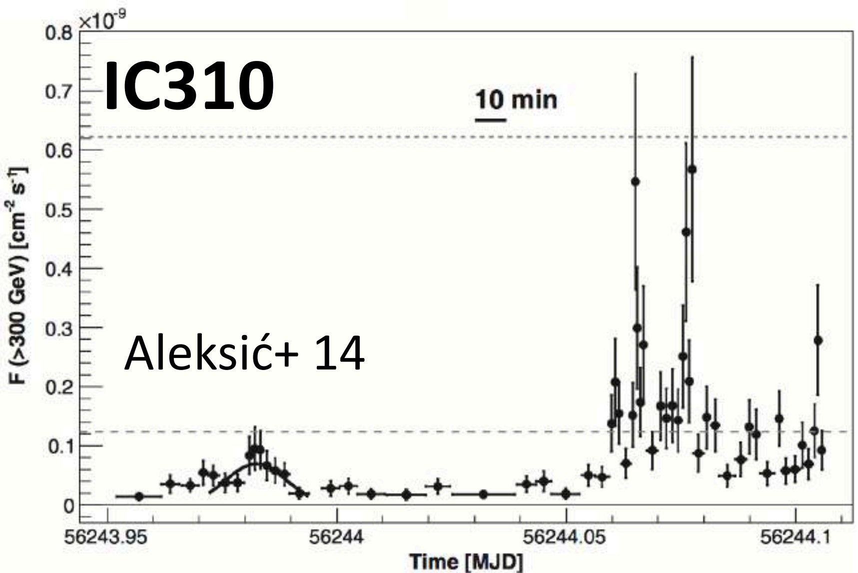
$$\dot{m} \lesssim 2 \times 10^{-4} M_9^{-1/7} \Leftrightarrow n_{\pm} \lesssim n_{\mathrm{GJ}} \Rightarrow E_{\parallel} = \frac{\mathbf{E} \cdot \mathbf{B}}{|\mathbf{B}|} \neq 0$$

(Levinson & Rieger 11)



- Large σ (>> 1)
- Non-ideal MHD condition
- Non-neutral charge
- Particle acceleration
- Pair creation

→ **Particle simulation**



Gamma-rays associated with EM cascade could be detected.

What are the conditions for bright gamma-ray flares?

1D PIC Model

Levinson & Cerutti 18

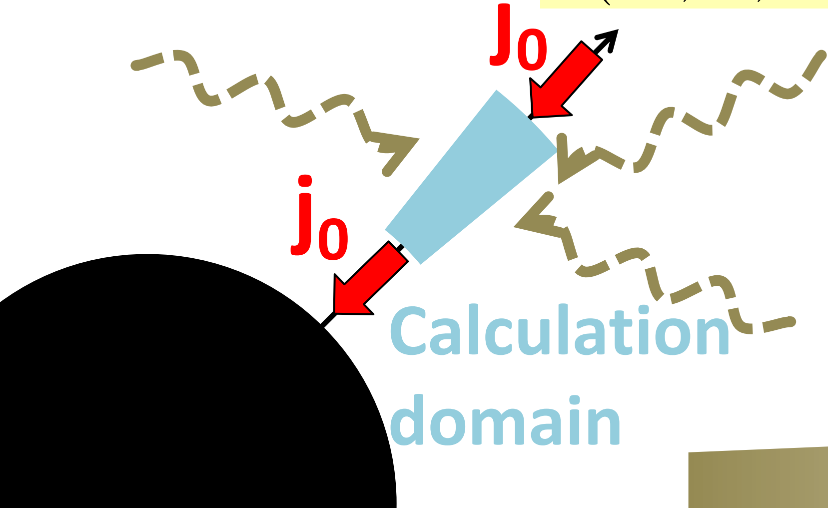
Full GR + Radiation + Pair creation

- **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.

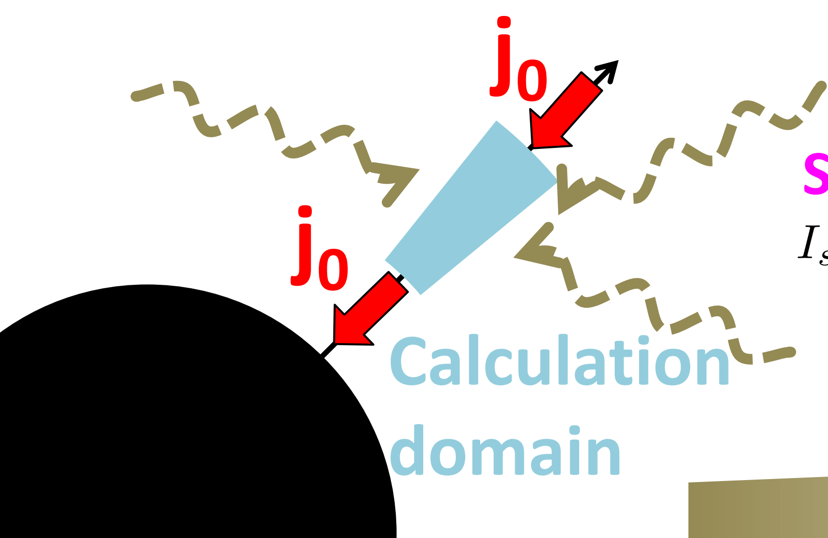
$$I_s(x^\mu, \epsilon_s, \mathbf{\Omega}_s) = I_0(\epsilon_s/\epsilon_{s,\min})^{-p}, \quad \epsilon_{s,\min} < \epsilon_s < \epsilon_{s,\max}$$



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

Model Parameters

Global current density	j_0
BH mass	$M = 10^9 M_\odot$
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	$\theta = 30^\circ$
Fiducial optical depth	$\tau_0 = 4\pi r_g \sigma_\mathrm{T} I_0 / hc$
Minimum energy of seed photon	$\epsilon_{s,\mathrm{min}}$
Slope of seed photon spectrum	p
Curvature radius	$R_\mathrm{cur} = r_g$
Number of cell	$N = 32768 \gtrsim \frac{r_g}{l_\mathrm{p}} \sim 10^3 \sqrt{\frac{\kappa M_9 B_{\mathrm{H},3}}{< \gamma_8 >}}$

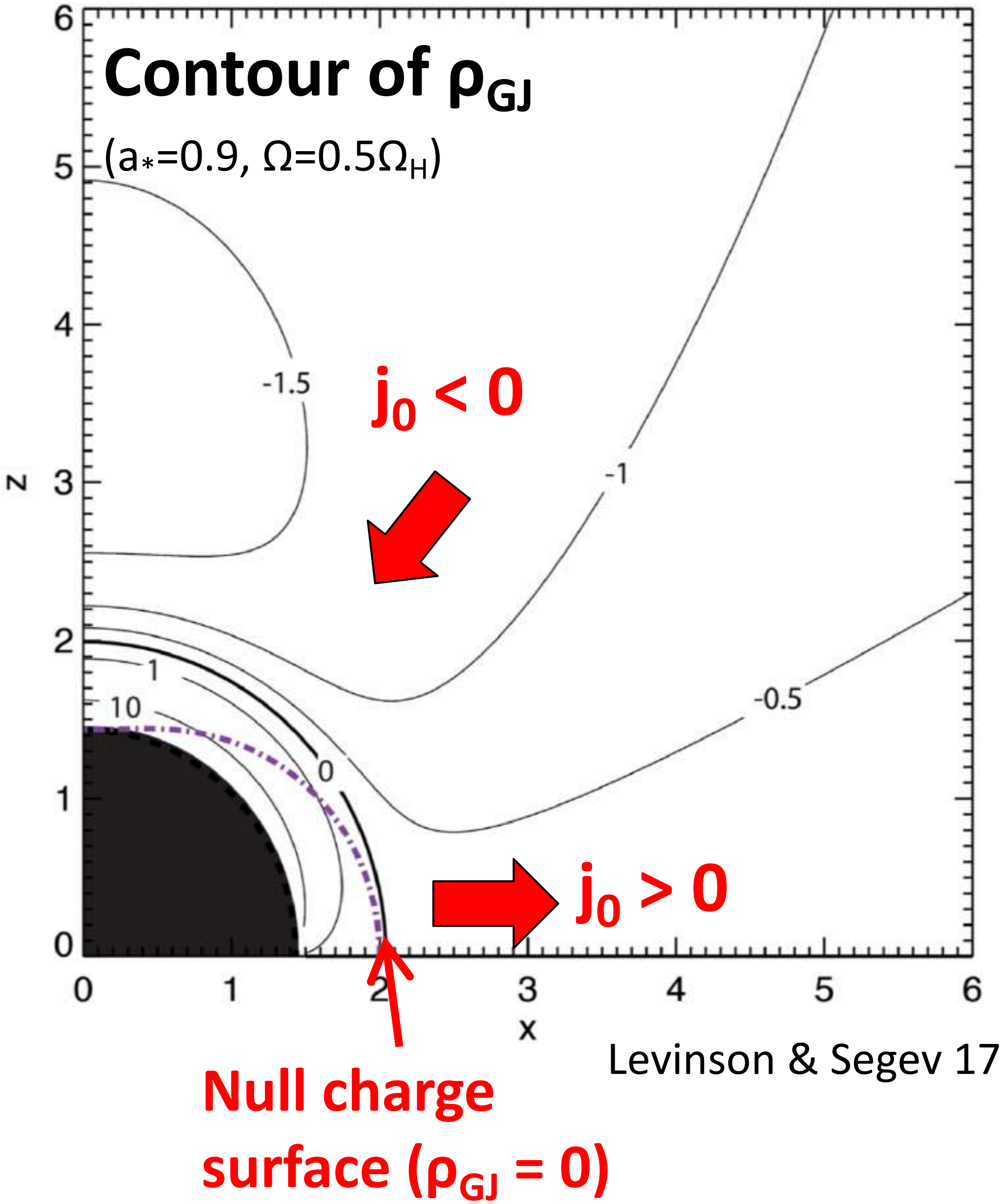


Soft photon spectrum

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

ϵ_s is normalized by $m_e c^2$.

Charge & Current Distributions



Levinson & Segev 17

Charge distribution

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

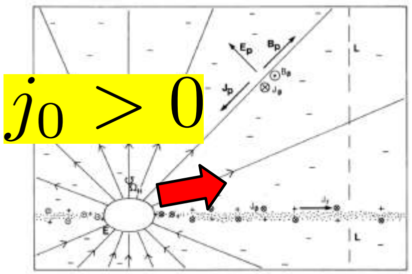
Sign of ρ_{GJ} changes along a B-field line.

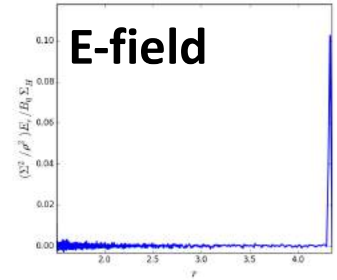
Current distribution

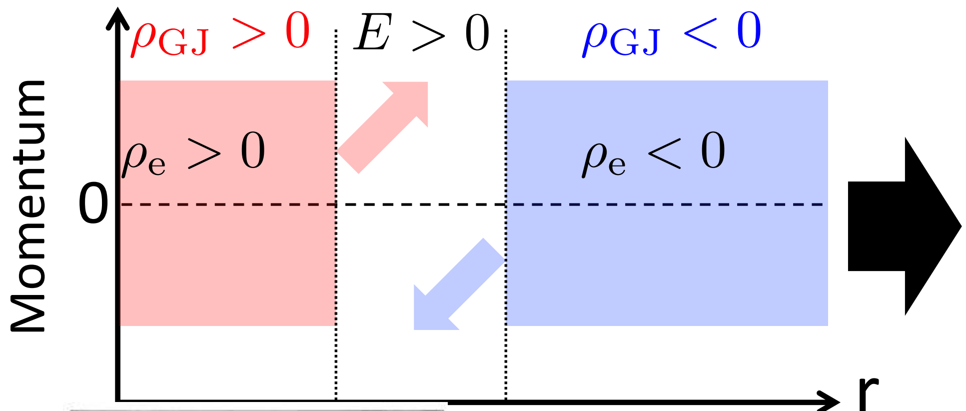
Polar region : $j_0 < 0$

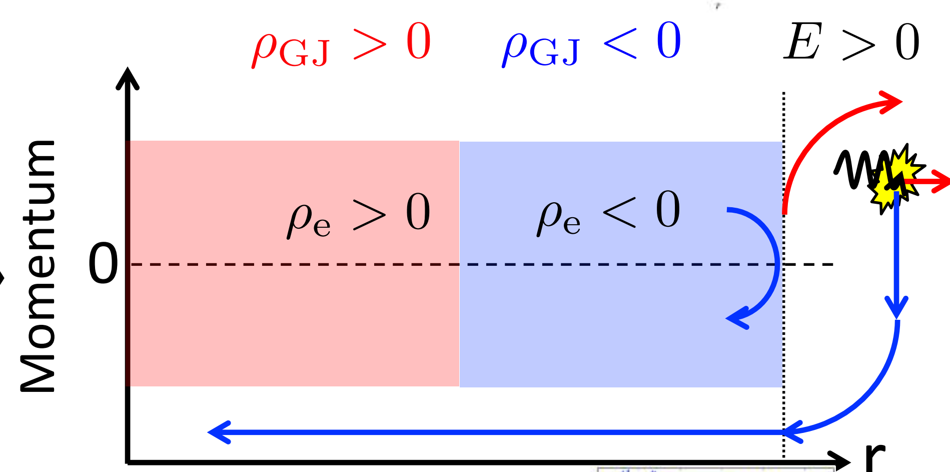
Equatorial region : $j_0 > 0$

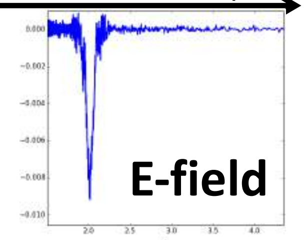
Gap Dynamics
(current direction)

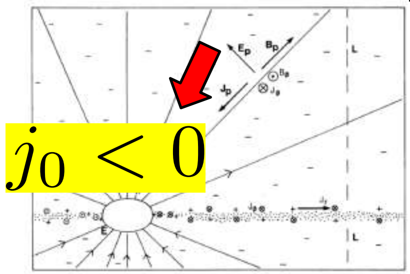


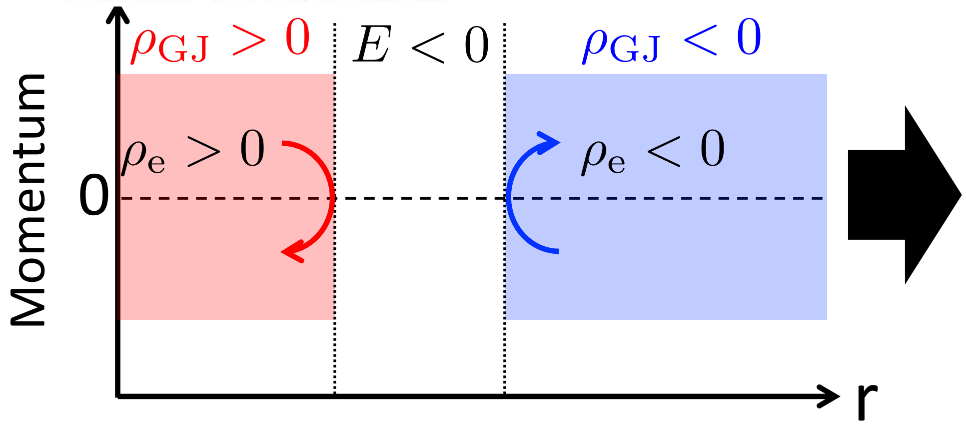


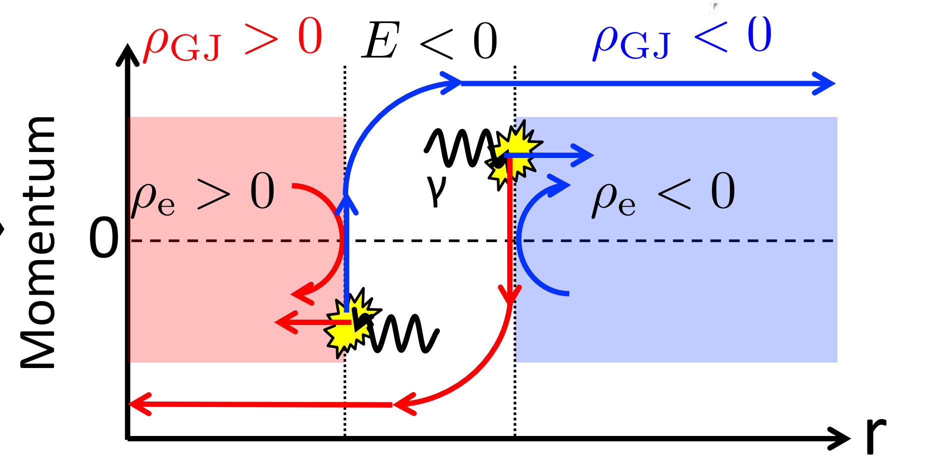




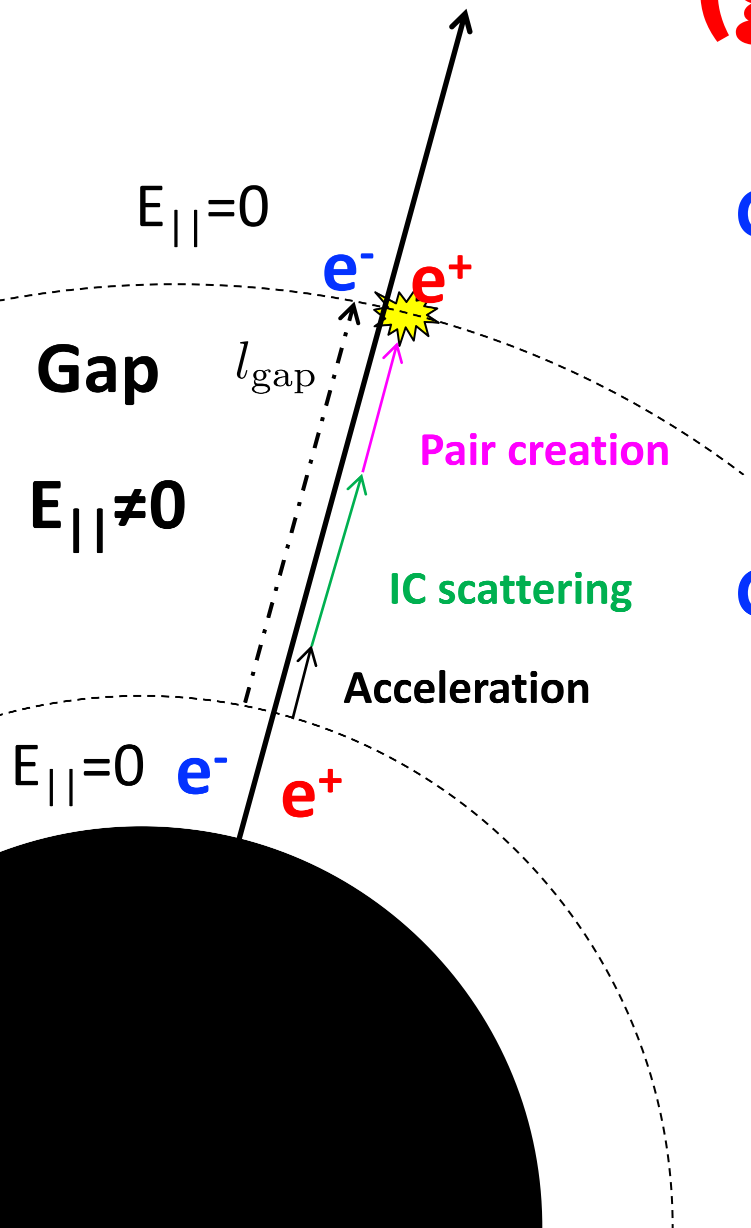








Gap Dynamics
(gap width)



$$\triangle\Phi_{\rm co} \equiv -4\pi\rho_{\rm GJ}$$

Gauss's Law

$$\triangle\Phi_{\rm nco} = -4\pi(\rho - \rho_{\rm GJ})$$

$$\rightarrow \Phi_{\rm nco} \sim -4\pi(\rho - \rho_{\rm GJ}) l_{\rm gap}^2$$

Gap width

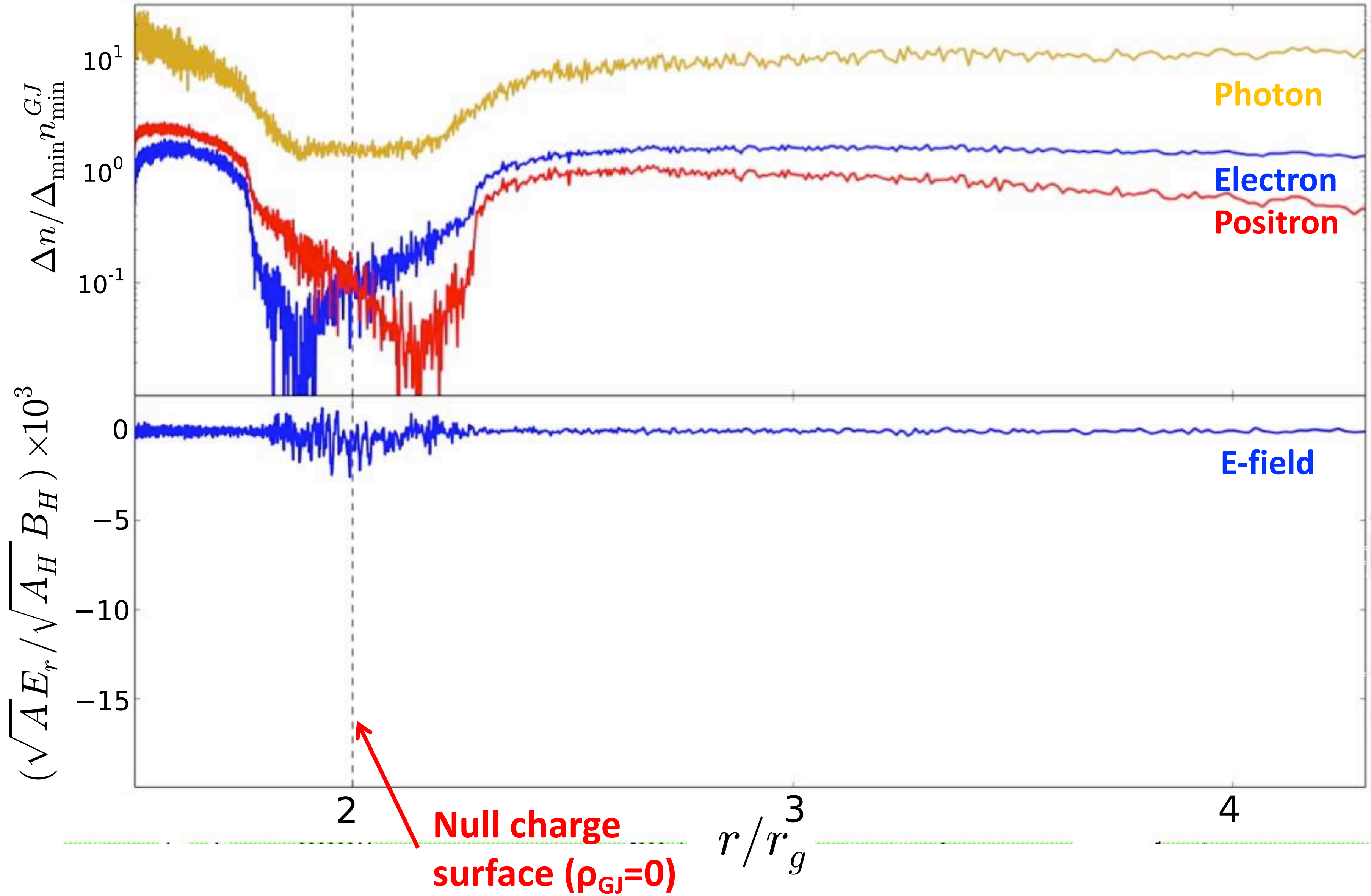
$$l_{\rm gap} \sim l_{\rm acc} + \underline{l_{\rm ic} + l_{\gamma\gamma}}$$

Depending on the ambient photon fields

$j_0 = -\rho_{\mathrm{GJ,in}} c$

Gap Dynamics

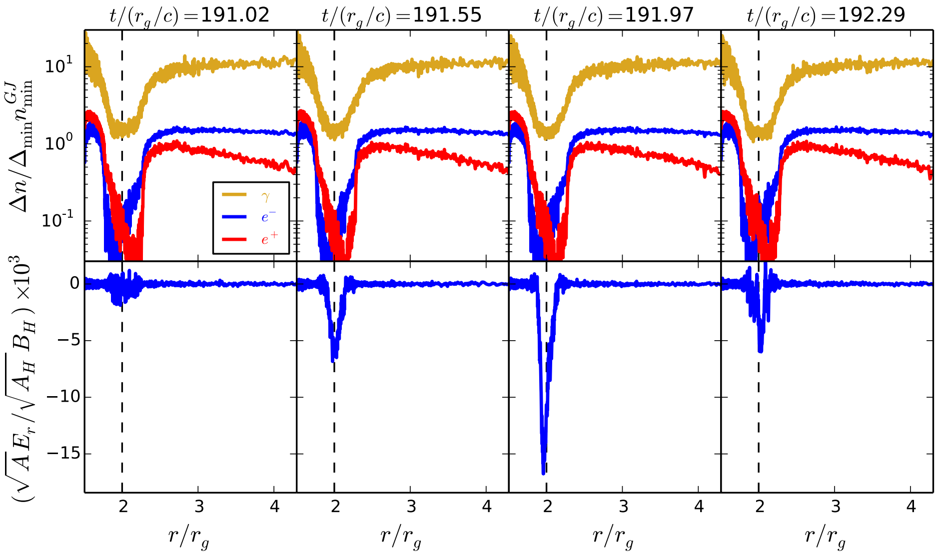
quasi-periodic activity



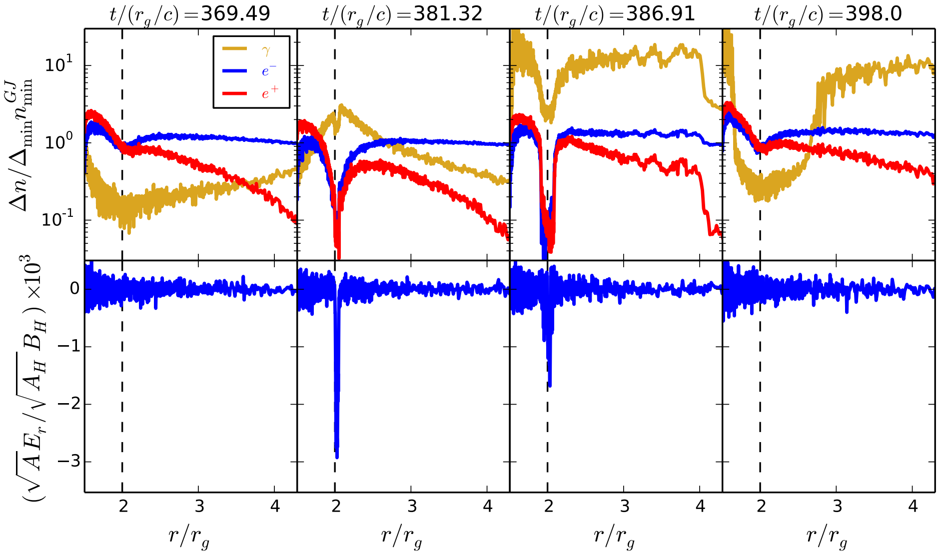
$j_0 = -\rho_{\rm GJ,in} c$

Gap Dynamics

$\tau_0 = 100$



$\tau_0 = 300$



$\tau_0 = 30$

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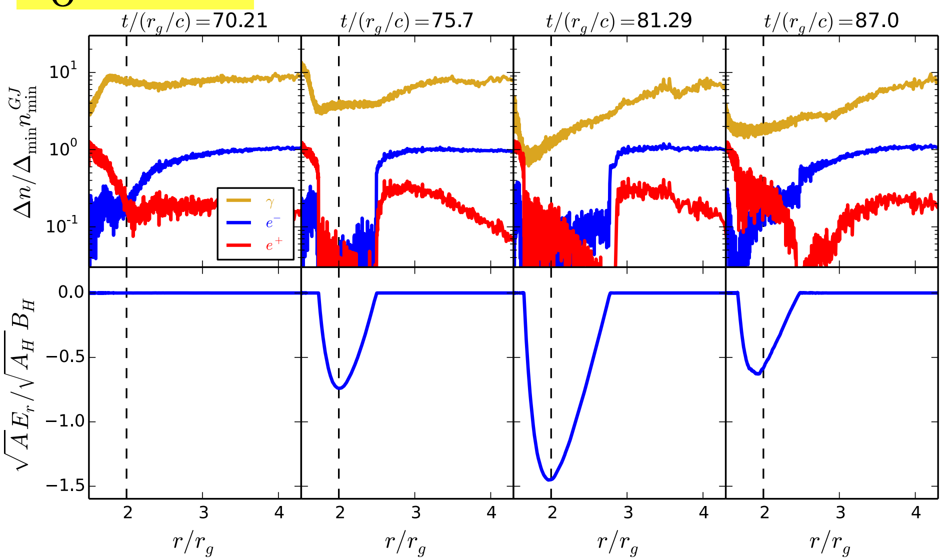
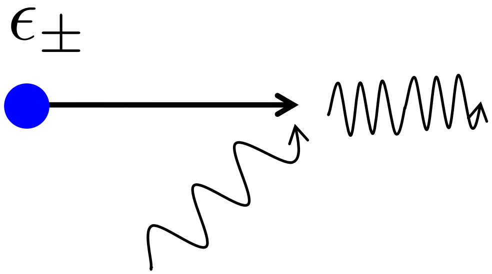


Larger optical depth
→ Narrower gap width
→ Weaker E-fields

High Energy Emission

Inverse Compton scattering



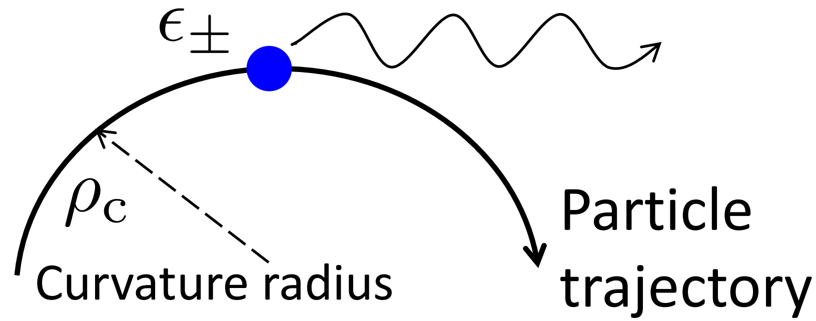
Characteristic energy

$$E_{\rm IC} \sim \gamma^2 E_{\rm d} \quad \text{(Thomson)}$$
$$\sim \gamma m_{\rm e} c^2 \quad \text{(Klein-Nishina)}$$
$$\sim 10^4 \gamma_{10}\ {\rm TeV}$$

Radiation power

$$P_{\rm IC} = \frac{4}{3}\sigma_{\rm T} c \underline{\gamma^2} U_{\rm d} \quad \text{(Thomson)}$$

Curvature radiation



Characteristic energy

$$E_{\rm CR} = \frac{3}{2}\gamma^3 \hbar \frac{c}{\rho_{\rm c}}$$
$$\sim 0.3 M_9^{-1} \gamma_{10}^3\ {\rm TeV}$$

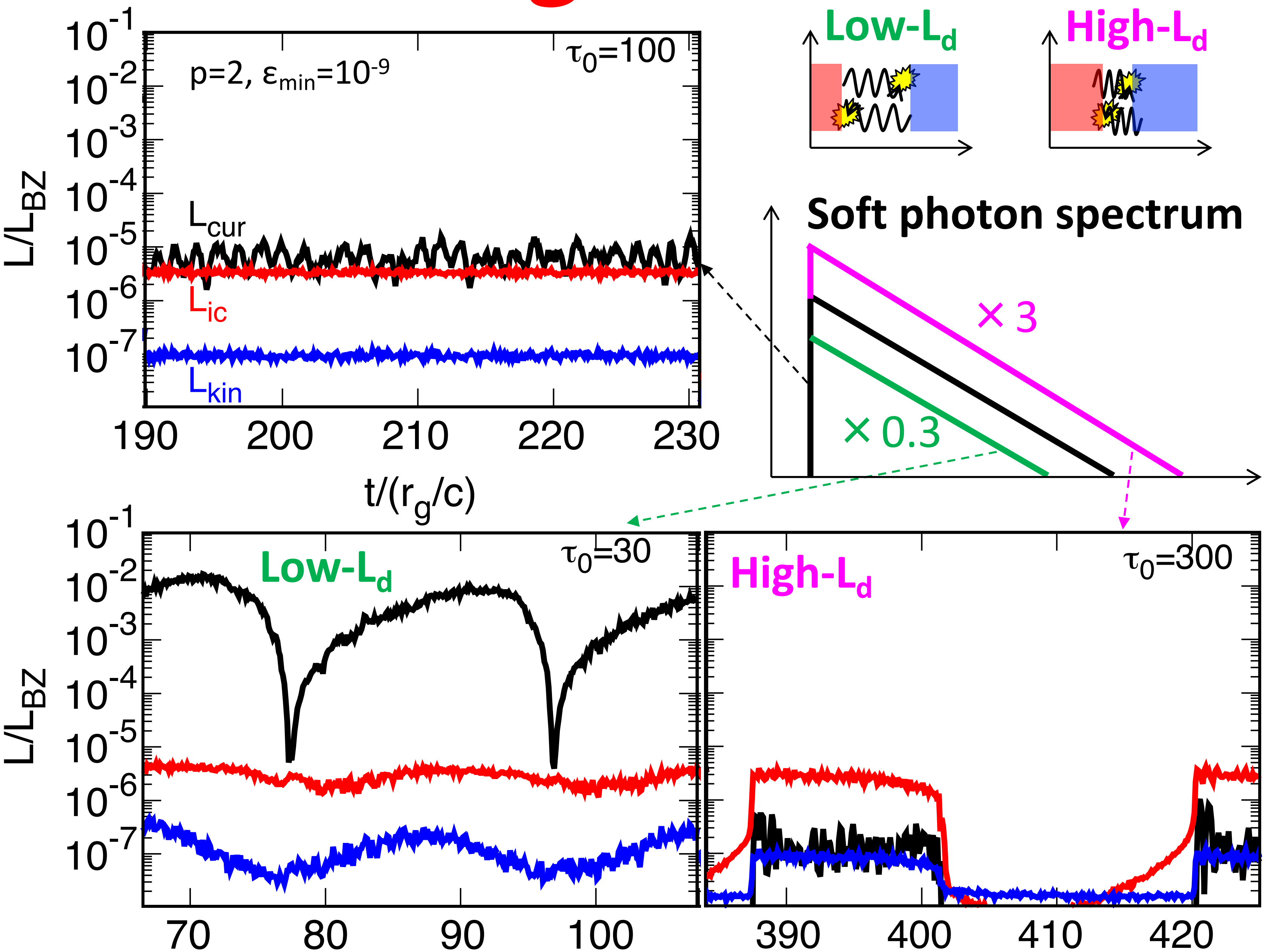
Radiation power

$$P_{\rm CR} = \frac{2e^2}{3c}\underline{\gamma^4}\left(\frac{c}{\rho_{\rm c}}\right)^2$$

High Lorentz factor → Curvature radiation dominant

(Most other works neglect the curvature radiation.)

Light Curves



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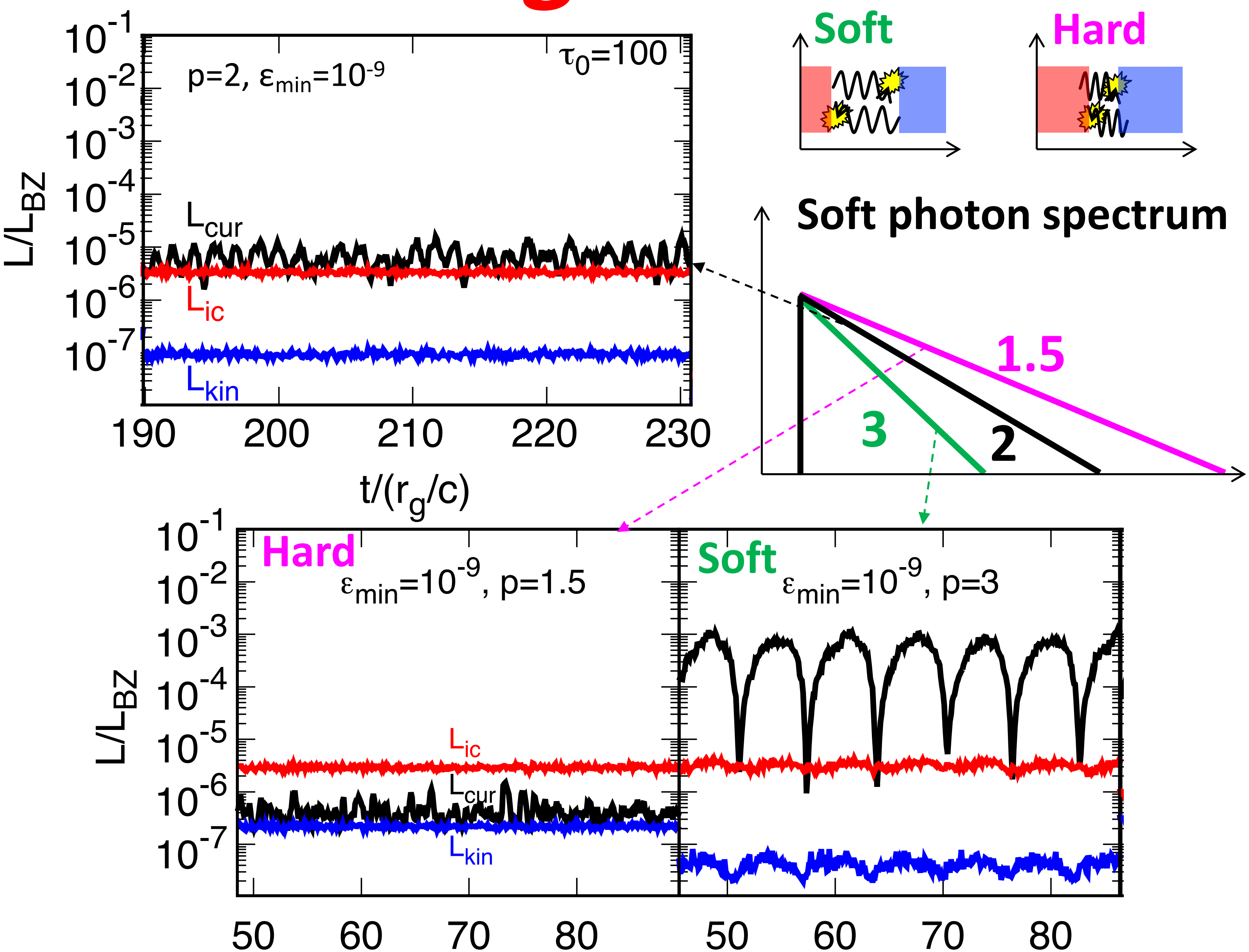
Light Curves



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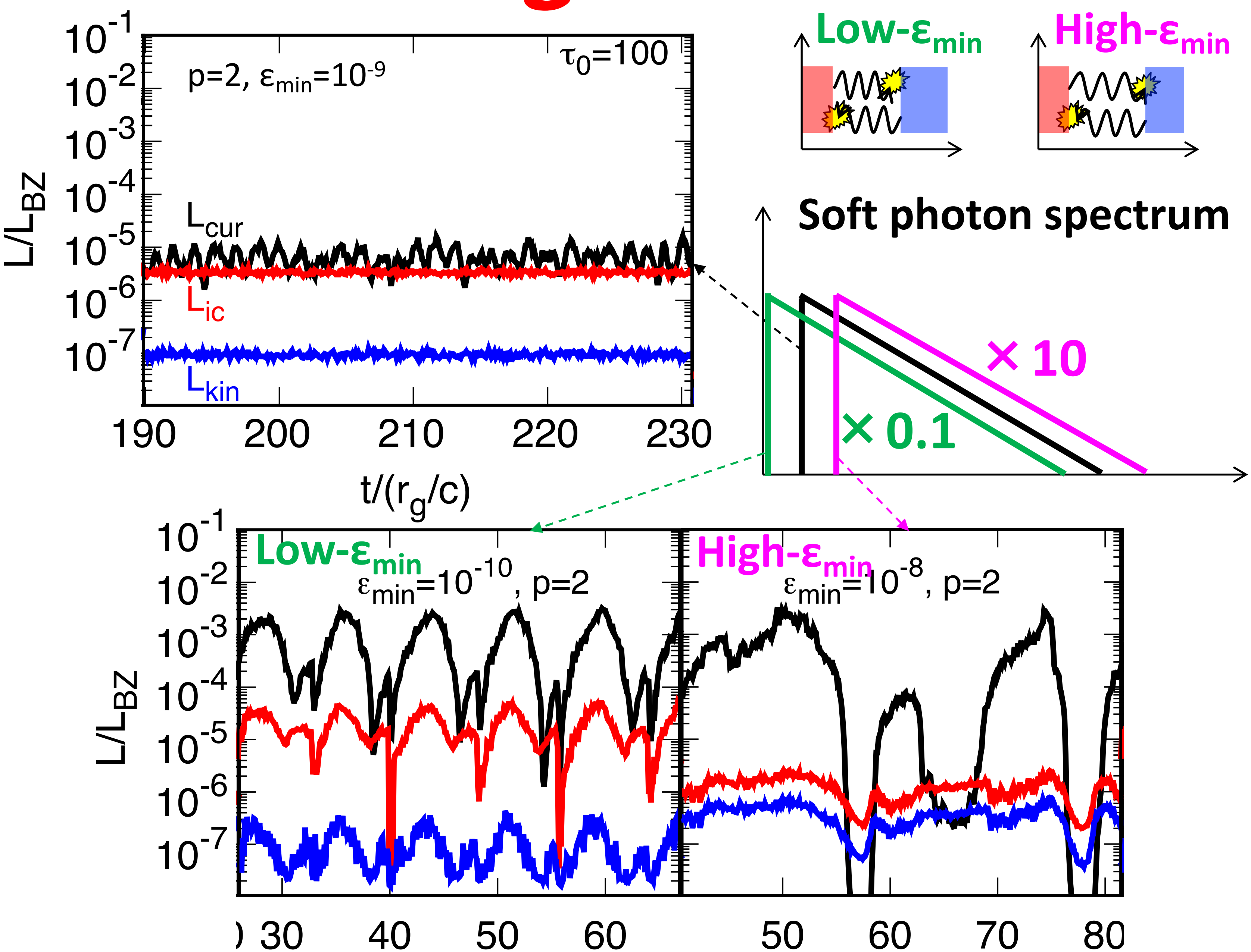
Light Curves



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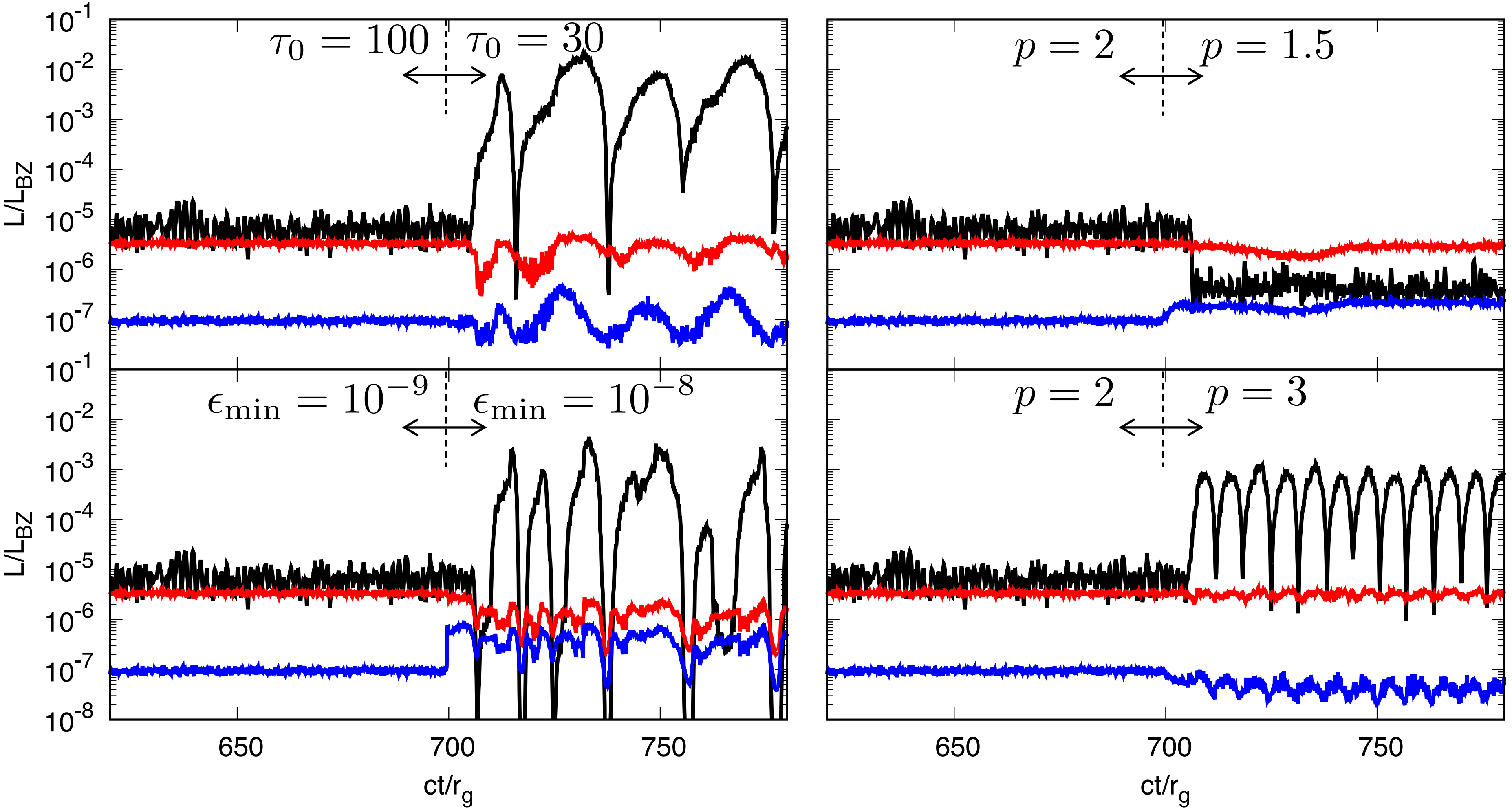
Transition

The state transition timescale ~ l_{gap}/c.

The flux maximum during the transition is comparable to the maximum amplitude in a quasi-periodic state.



Summary

We perform 1D GRPIC simulation for pair cascade.

Energy conversion efficiency depends on the properties of ambient photon. Curvature radiation is brighter for longer mean free path for inverse Compton scattering and pair creation if the continuous injection condition is satisfied.

No flux enhancement during the state transition. The flux maximum corresponds to the maximum amplitude for a given state.