Magnetospheric gaps around stellar mass black holes

Shota Kisaka

(Hiroshima University)

Collaborators

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

Summary

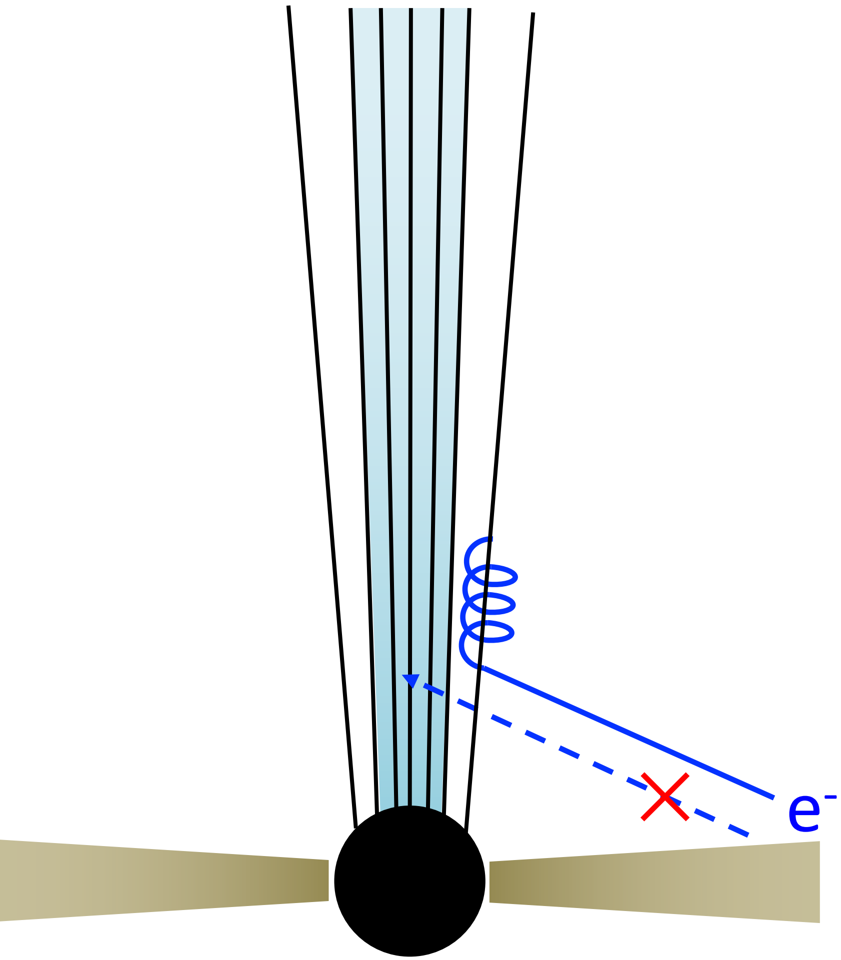
We perform 1D GRPIC simulation for pair cascade around **stellar mass black holes**.

As a case of supermassive black holes, quasi-periodic oscillating gap opens at the null surface of Goldreich-Julian charge density.

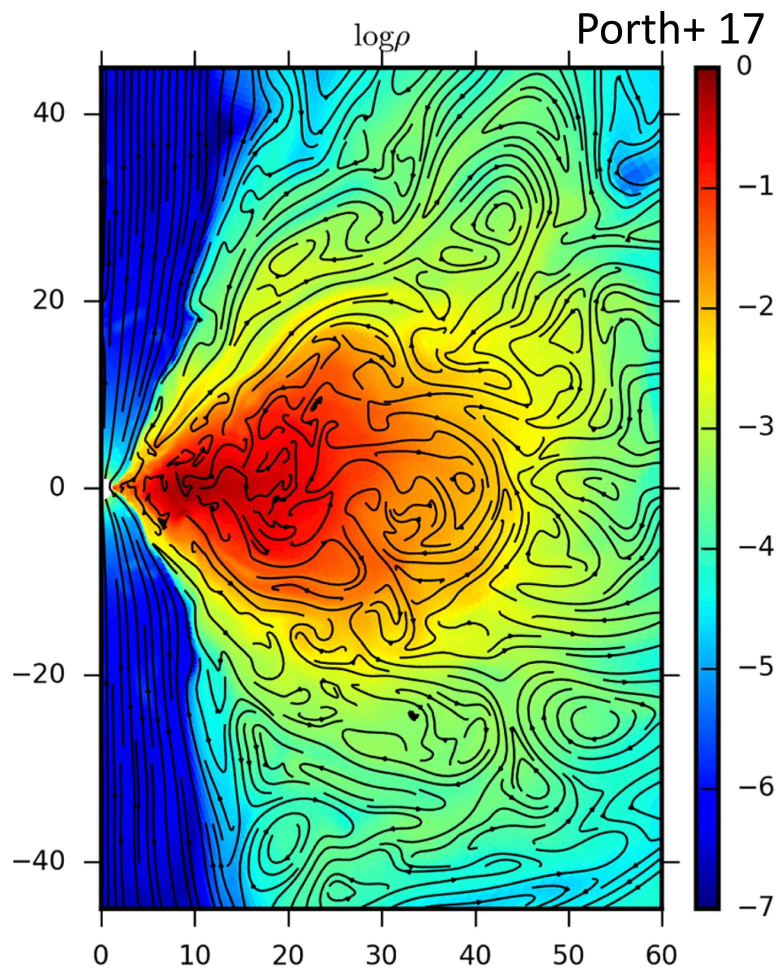
Observations by Fermi/LAT could detect the curvature radiation caused by electromagnetic pair cascade around stellar mass black holes with low accretion rate.

Plasma Injection Problem

Charged particles cannot cross the B-field.



Artificial mass supply in the jet region.



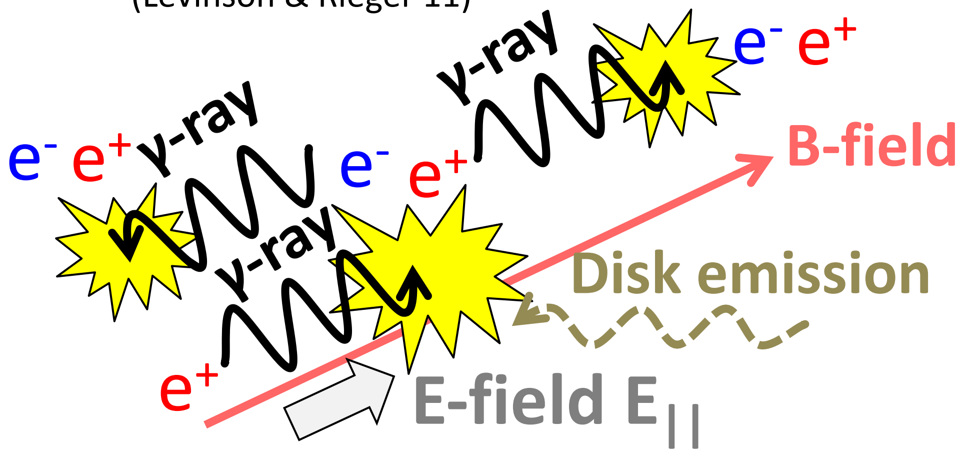
- **Where and how are plasmas injected?**
- **How does the injection mechanism probe?**

Electromagnetic Cascade

Accretion rate — **Number density** — **Unscreened E-field**

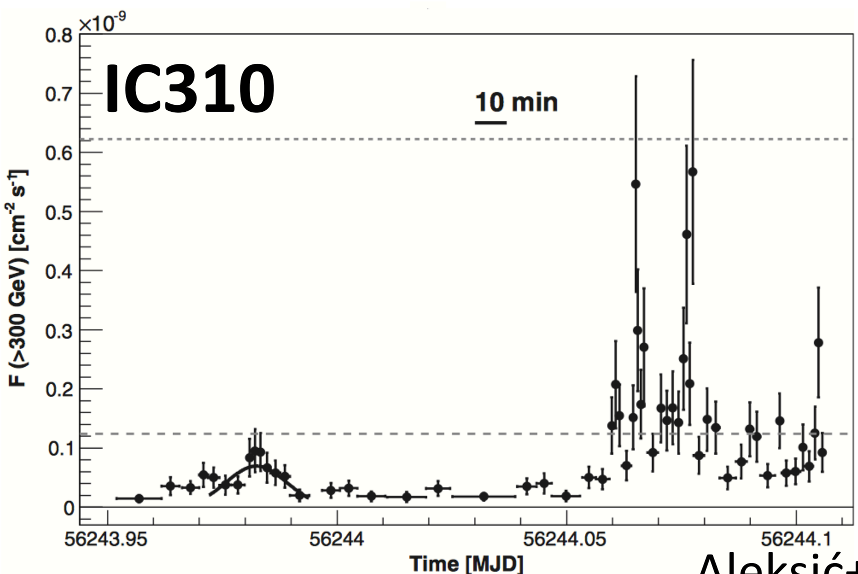
$$\dot{m} \lesssim 2 \times 10^{-4} M_9^{-1/7} \Leftrightarrow n_\pm \lesssim n_{\rm GJ} \Rightarrow E_\parallel = \frac{\mathbf{E}\cdot\mathbf{B}}{|\mathbf{B}|} \neq 0$$

(Levinson & Rieger 11)



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

→ **Particle simulation**



Aleksić+ 14

TeV flare with rapid variability

Flux doubling timescale $\delta t < 0.2\, r_g/c$

→ **Observational evidence for particle acceleration at sub-horizon scale?**

EM Cascade for Stellar Mass BH

Pair starved condition for stellar mass BH

$$\dot{m} \lesssim 3 \times 10^{-3} M_1^{-1/7}$$ (Levinson & Rieger 11)

Bondi accretion rate from the ISM

$$\dot{m} \sim 4 \times 10^{-3} n_2 M_1 V_6^{-3}$$

Significant number of isolated BHs could be pair starved.

Expected energy flux

$$F \sim 8 \times 10^{-11} \dot{m}_{-3} M_1 \left(\frac{d}{10 \text{ kpc}} \right)^{-2} \text{ erg cm}^{-2} \text{s}^{-1}$$

Candidates of un-ID gamma-ray sources.

Ioka+ 17
Hirotani+ 18

1D PIC Model

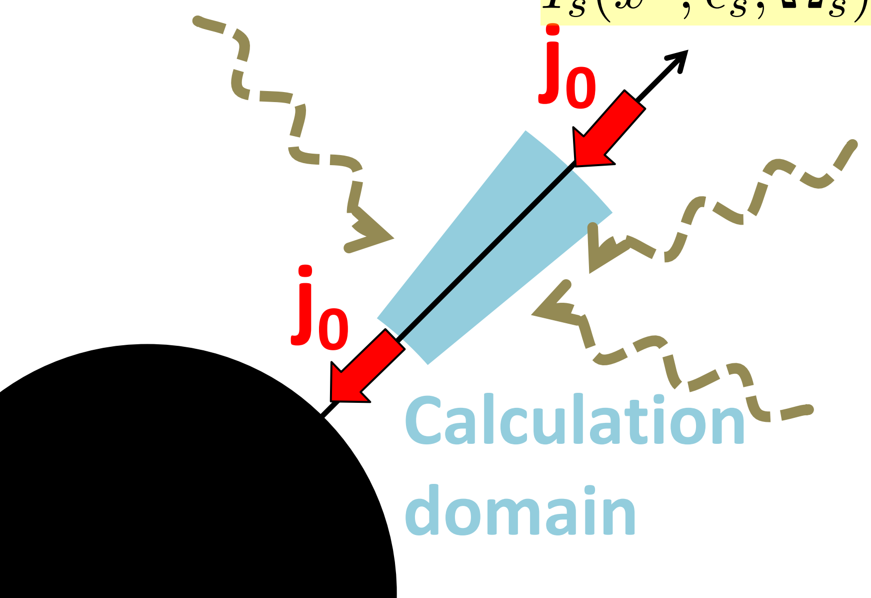
Levinson & Cerutti 18

- **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.

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



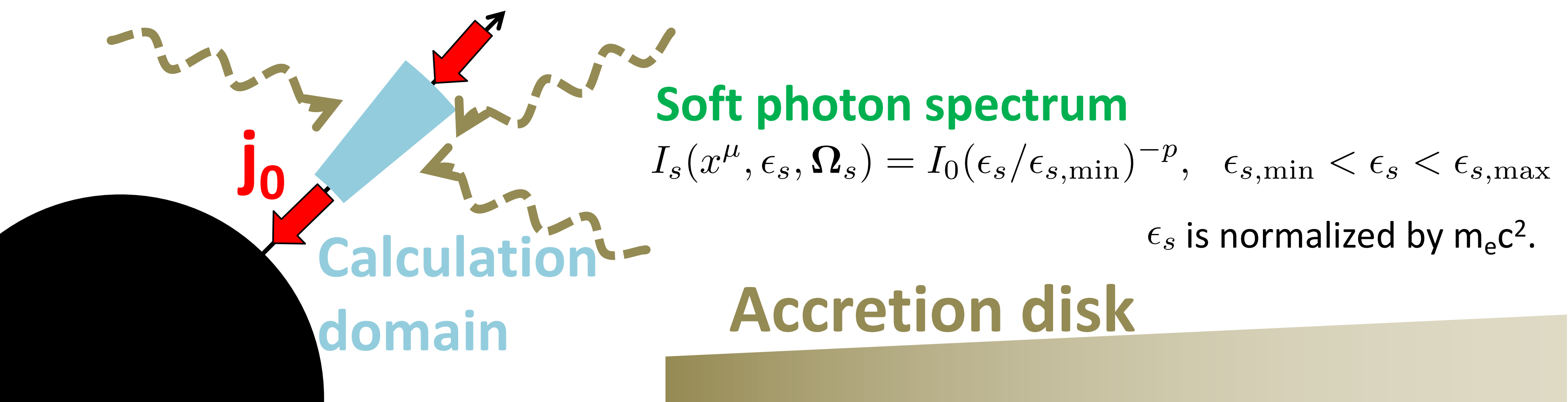
- No external plasma source.
- The global current is a free parameter.
- A split monopole geometry for the global B-field.
- The angular velocity of magnetic surface $\Omega = 0.5\omega_\mathrm{H}$.

Mass Dependence

BH mass	B-field	Maximum Lorentz factor	Minimum energy of seed photon
	$B_{\rm H} \propto M^{-1/2}$ From pressure balance	$\gamma_{\rm max} \propto M^{-3/8}$ From force balance $eE = \frac{2}{3}\frac{e^2}{R_{\rm c}^2}\gamma_{\rm max}^4$ E-field : $E \equiv \eta B$ Curvature radius : $R_{\rm c} = r_g$	$\epsilon_{\rm s,min} \lesssim \tau_0/\gamma_{\rm max}$ From continuous injection condition by IC photons (SK+ 20) Normalized by m_ec^2
$M = 10^9 M_\odot$	$2\pi \times 10^3$ G	1.7×10^{10}	10^{-9}
$M = 10 M_\odot$	$2\pi \times 10^7$ G	1.7×10^7	10^{-6}

Model Parameters

Global current density	$j_0 = -\rho_{\mathrm{GJ,in}} c$
BH mass	$M = 10 M_\odot$
Dimensionless spin parameter	$a_* = 0.9$
B-field on the horizon	$B_{\mathrm{H}} = 2\pi \times 10^7 \mathrm{G}$
Inclination angle of magnetic surface	$\theta = 30^\circ$
Fiducial optical depth	$\tau_0 = 4\pi r_g \sigma_{\mathrm{T}} I_0 / hc = 30, 100, 300$
Minimum energy of seed photon	$\epsilon_{s,\mathrm{min}} = 10^{-6}$
Slope of seed photon spectrum	$p = 2$
Curvature radius	$R_{\mathrm{cur}} = r_g$
Number of cell	$N = 32768 \gtrsim \frac{r_g}{l_{\mathrm{p}}} \sim 10^3 \sqrt{\frac{\kappa M_9 B_{\mathrm{H},3}}{< \gamma_8 >}}$



Soft photon spectrum

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

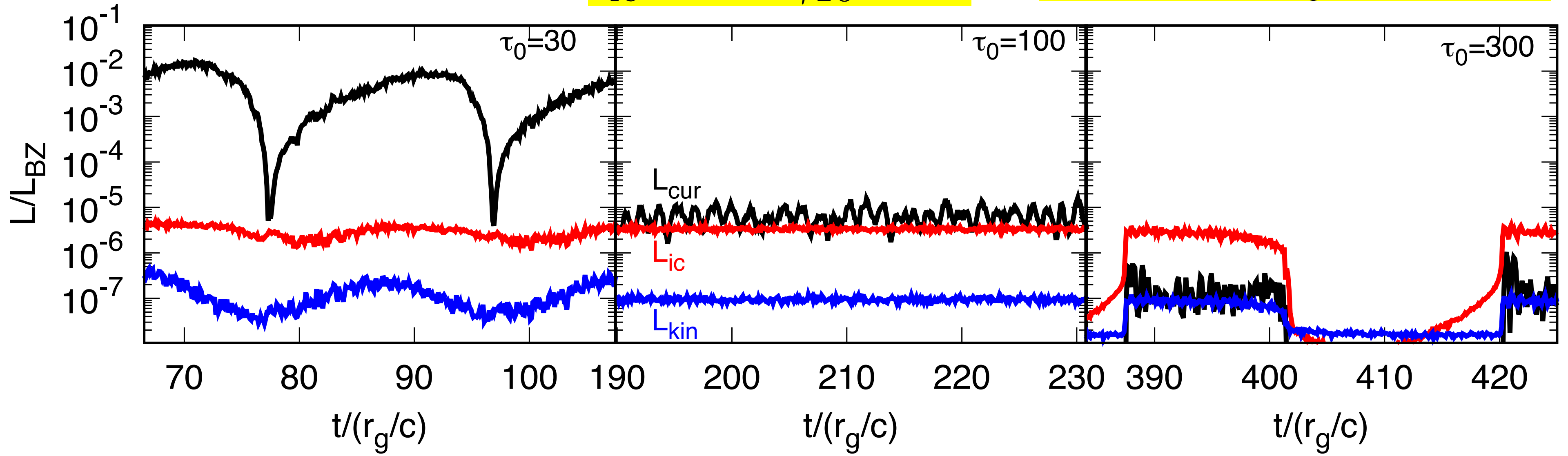
ϵ_s is normalized by $m_e c^2$.

Light Curves

$M = 10^9 M_\odot$

$\epsilon_{\rm ic} \sim 10^4 \gamma_{10}$ TeV

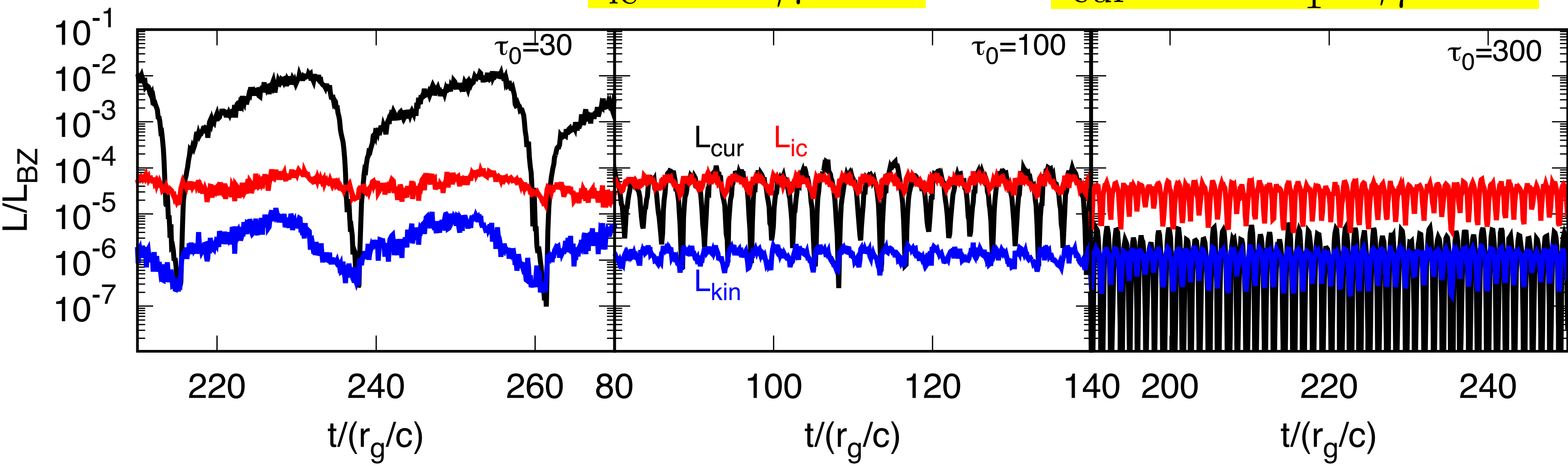
$\epsilon_{\rm cur} \sim 0.3 M_9^{-1} \gamma_{10}^3$ TeV



$M = 10 M_\odot$

$\epsilon_{\rm ic} \sim 10 \gamma_7$ TeV

$\epsilon_{\rm cur} \sim 30 M_1^{-1} \gamma_7^3$ GeV



Detectability

$$M = 10M_\odot, B_\mathrm{H} = 2\pi \times 10^7\ \mathrm{G}, \tau_0 = 30, \epsilon_\mathrm{min} = 10^{-6}$$

Curvature radiation

$$F_\mathrm{cur} \sim 10^{-12} \left(\frac{d}{10\ \mathrm{kpc}}\right)^{-2}\ \mathrm{erg\ cm^{-2}s^{-1}}$$ @30 GeV

Comparable to Fermi LAT 10 yrs detection limit.

Inverse Compton scattering

$$F_\mathrm{ic} \sim 10^{-14} \left(\frac{d}{10\ \mathrm{kpc}}\right)^{-2}\ \mathrm{erg\ cm^{-2}s^{-1}}$$ @1 TeV

An order of magnitude lower than CTA 50 hrs detection limit.

Discussion

- **Pair creation by curvature photons** (Not considered in the simulation)

Condition for continuous injection by curvature photons

$$N_c \tau_{\gamma\gamma} \gtrsim 1$$

N_c : Number of curvature photons
$\tau_{\gamma\gamma}$: Two photon pair creation opacity

$$\longrightarrow \tau_0 \gtrsim 40 \left(\frac{L_{\rm cur}}{10^{-2} L_{\rm BZ}} \right)^{-1} B_7^{-1} \gamma_7^{-3} \epsilon_{\rm s,min,-6}^{-2}$$

cf. Condition for IC

$$\tau_0 \gtrsim 10 \gamma_{\rm max,7} \epsilon_{\rm s,min,-6}$$

The contribution is comparable to IC photons.

- **Magnetic pair creation** (Not considered in the simulation)

Escapable photon energy for magnetic pair creation

$$\tau_{\rm B\gamma}(\epsilon_{\rm esc}) \sim 1 \longrightarrow \epsilon_{\rm esc} \sim 6 \times 10^5 B_7^{-1}$$

Radius of soft photon emission zone

$$R_{\rm s,1} \equiv R_{\rm s}/10 r_g$$

cf. Two photon pair creation $\epsilon_{\rm esc} \sim 4 \times 10^5 \epsilon_{\rm s,min,-6}^{-1} \tau_{0,2}^{-1/2} R_{\rm s,1}^{-1/2}$

The contribution is comparable to two photon pair creation.
Important to determine the pair multiplicity.

We will include these in the future works.