ブラックホール磁気圏

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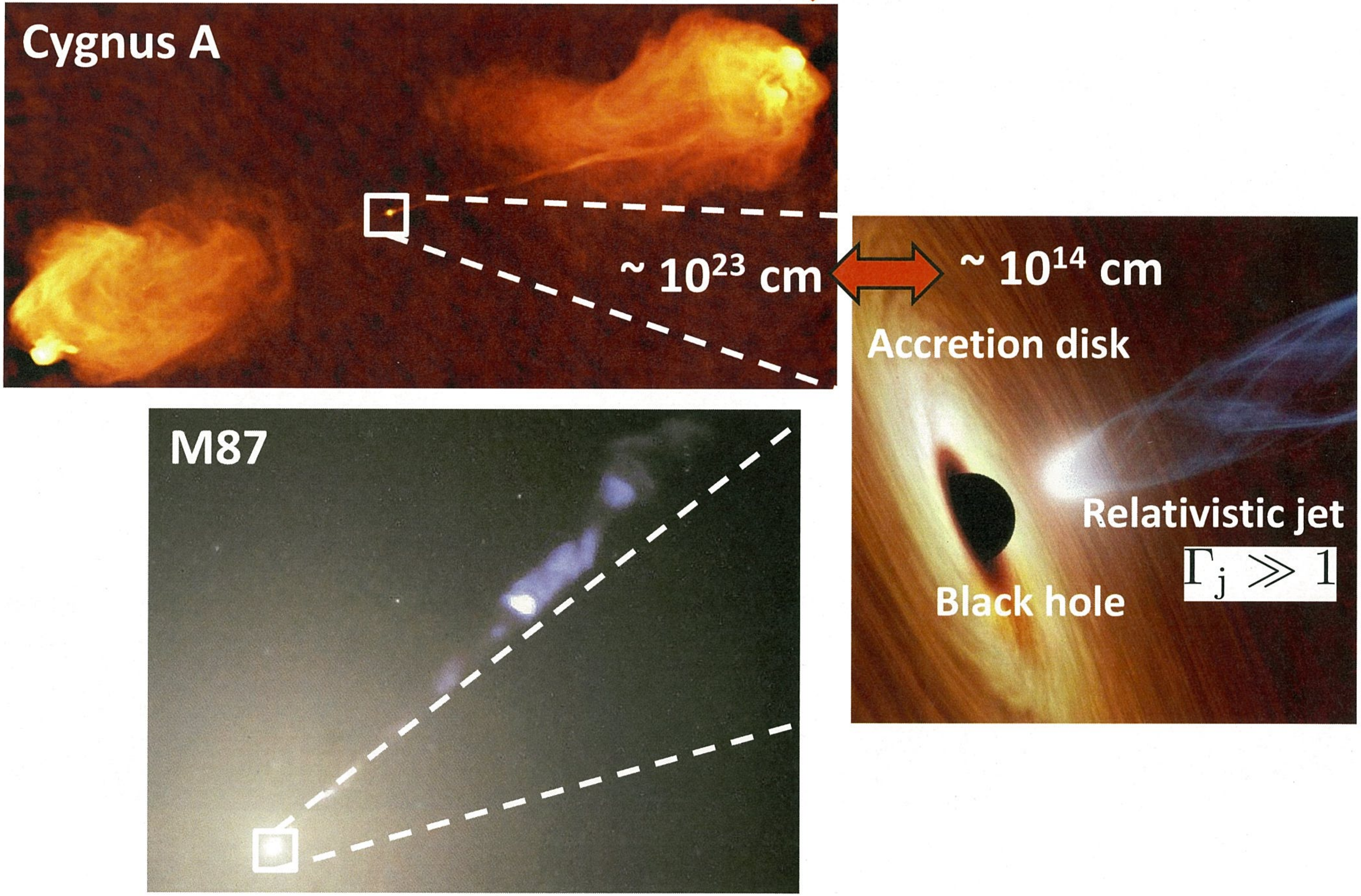
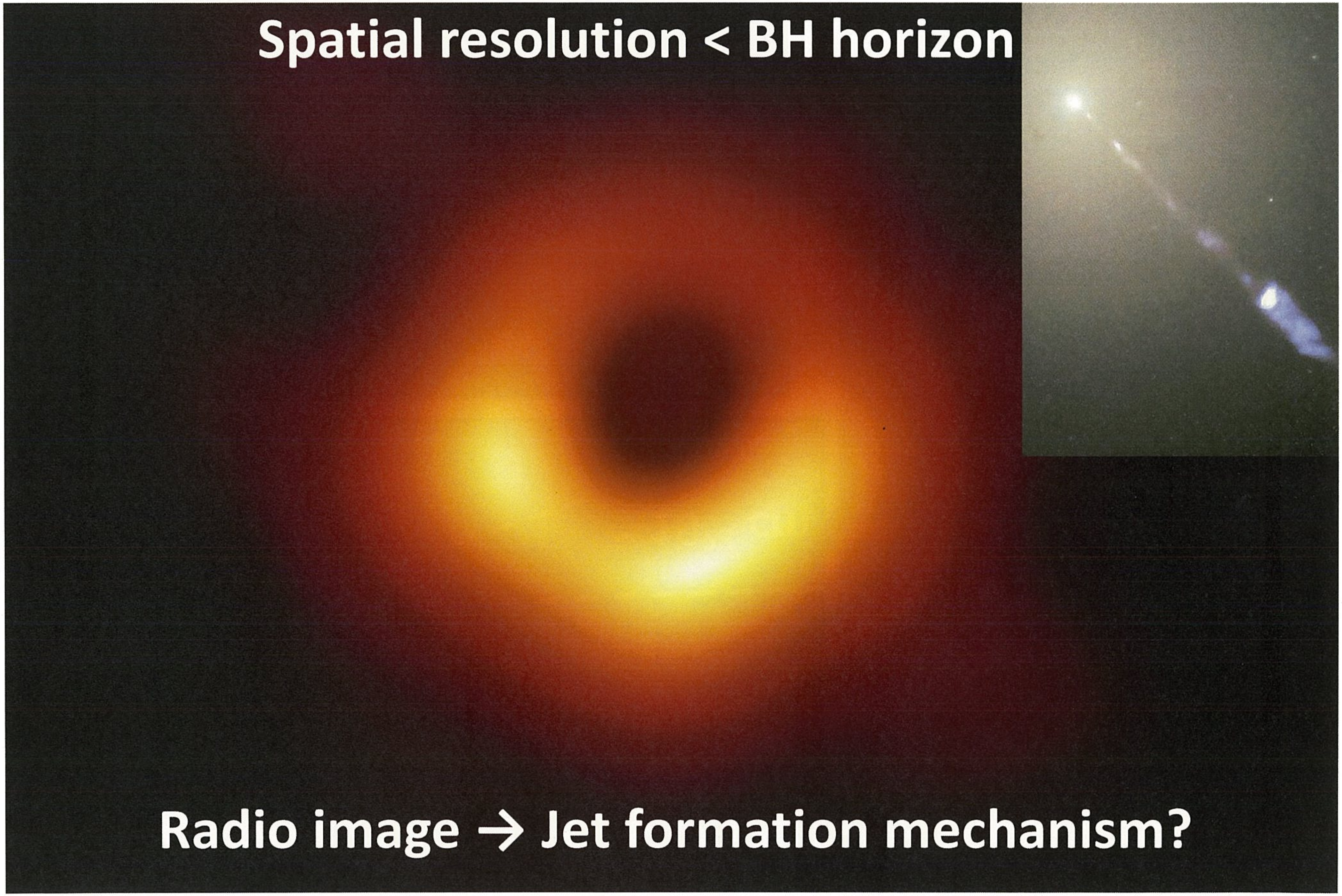
Contents

Relativistic jets



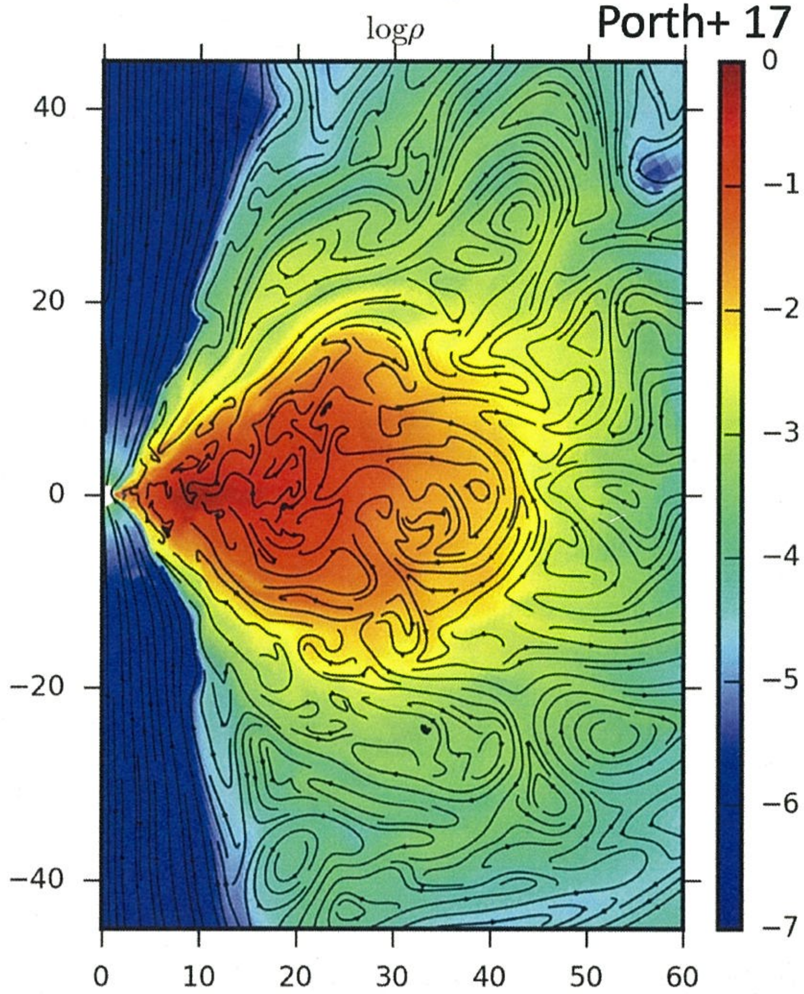
Event Horizon Telescope

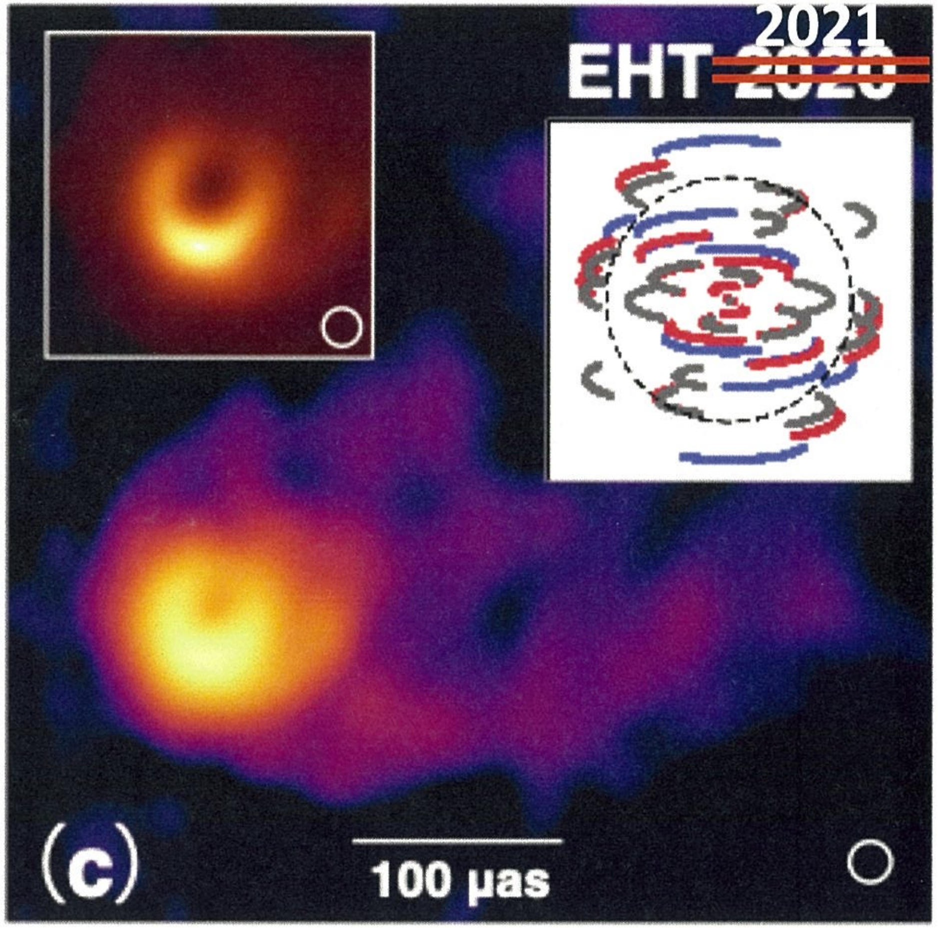


GRMHD Numerical Simulations

Artificial mass supply in the jet region.

Predictions of the emission from jet are highly uncertain.

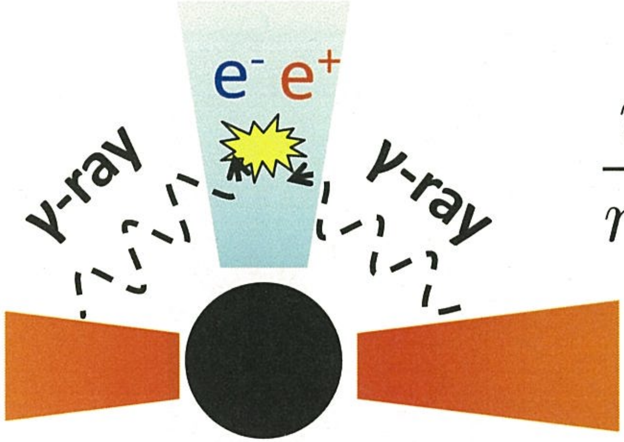




- Where and how are plasmas injected?
- How does the injection mechanism probe?

Plasma Injection Problem

▪ MeV Photon annihilation:



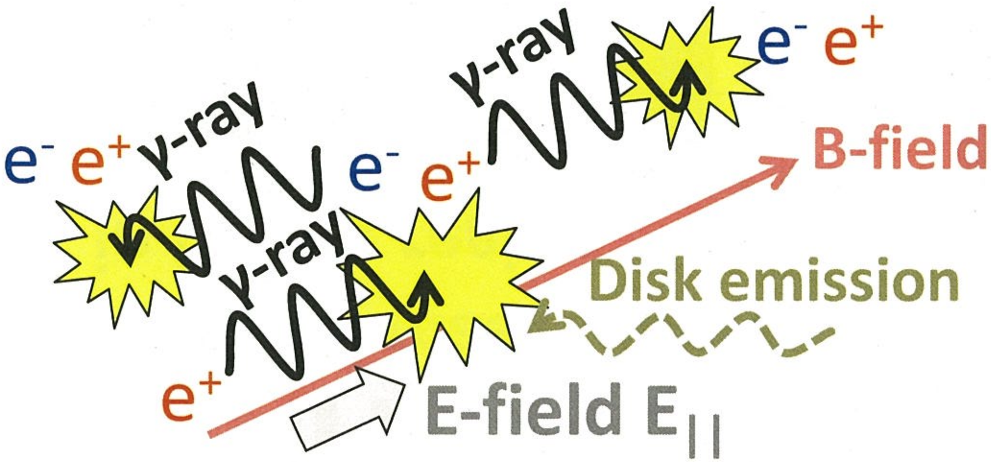
$$\frac{n_\pm}{n_{\rm GJ}} \gtrsim 1 \Longleftrightarrow \dot{m} \gtrsim 2 \times 10^{-4} M_9^{-1/7}$$

Levinson & Rieger 11
Hirotani & Pu 16

▪ Electromagnetic cascade:

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

$n_\pm \lesssim n_{\rm GJ}$ ➡ **Electric field** $E_\parallel = \dfrac{\mathbf{E}\cdot\mathbf{B}}{|\mathbf{B}|} \neq 0$

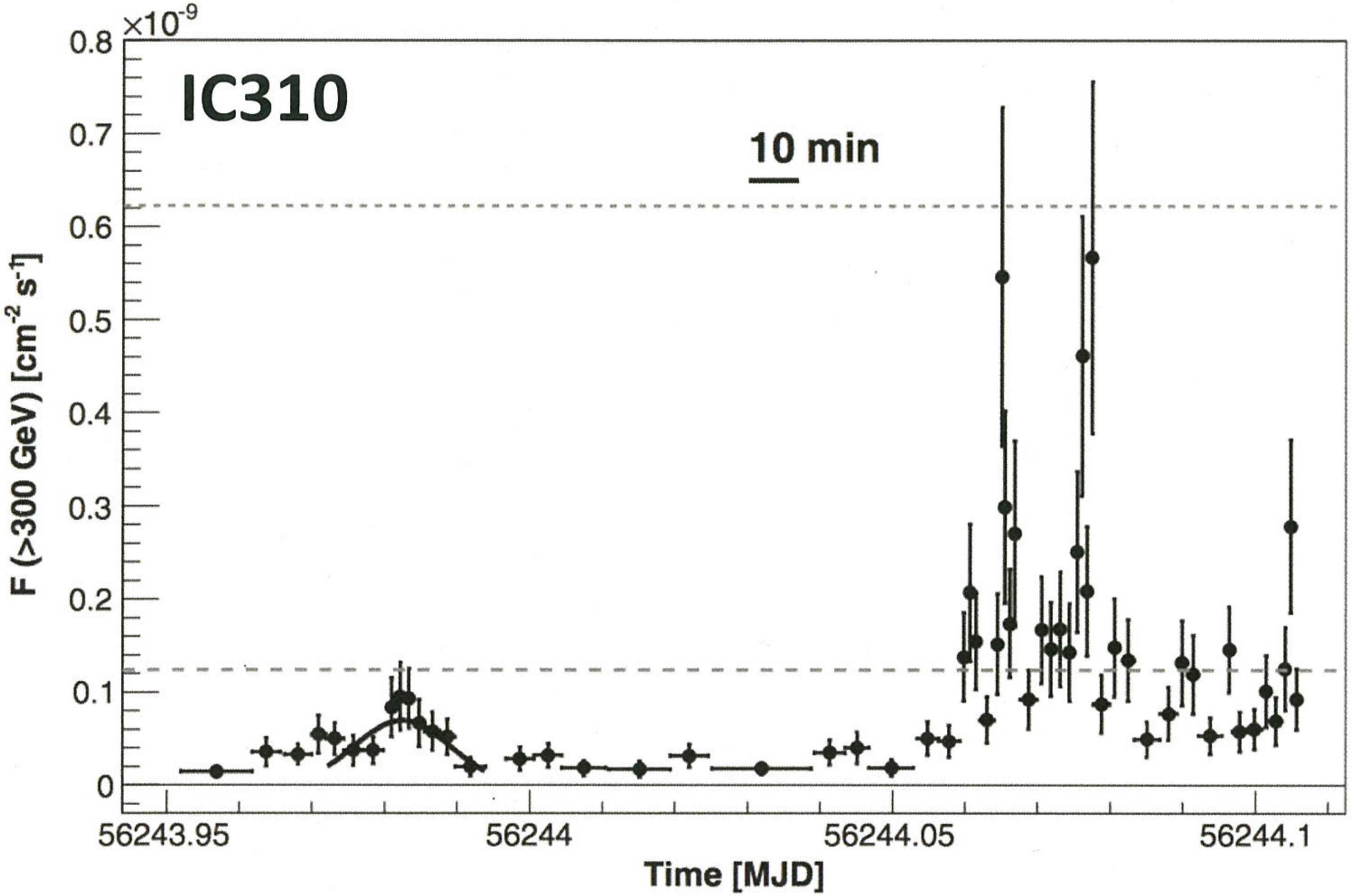


- Large σ (>> 1)
- Non-ideal MHD condition
- Non-neutral charge
- Particle acceleration
- Pair creation

Difficult in MHD simulation

Observational Evidence?

Aleksić+ 14

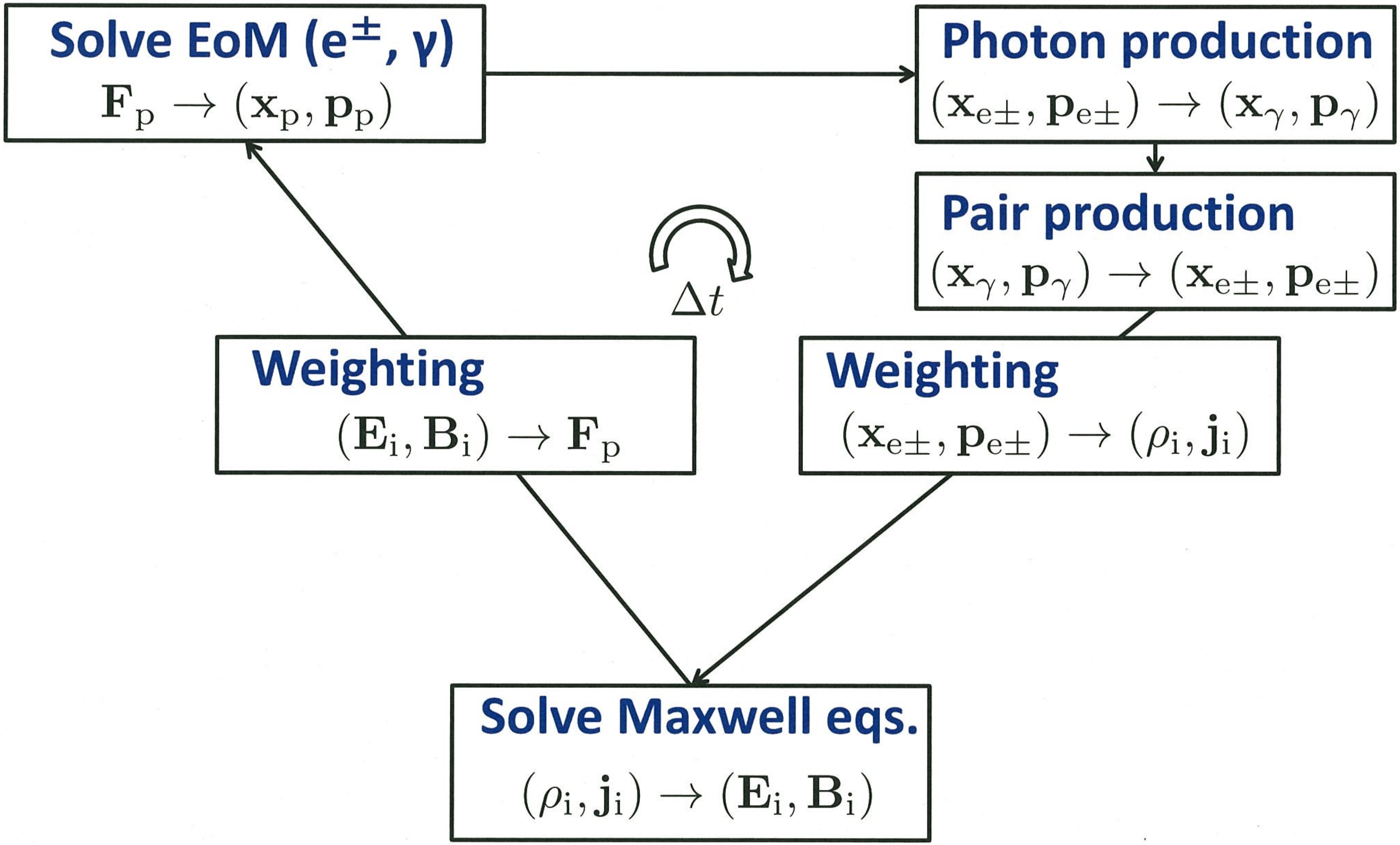


Flux doubling timescale < 4.8 min at 95% C.L. corresponds to ~20% of the timescale r_g/c.

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

Contents

Particle-in-Cell Simulation

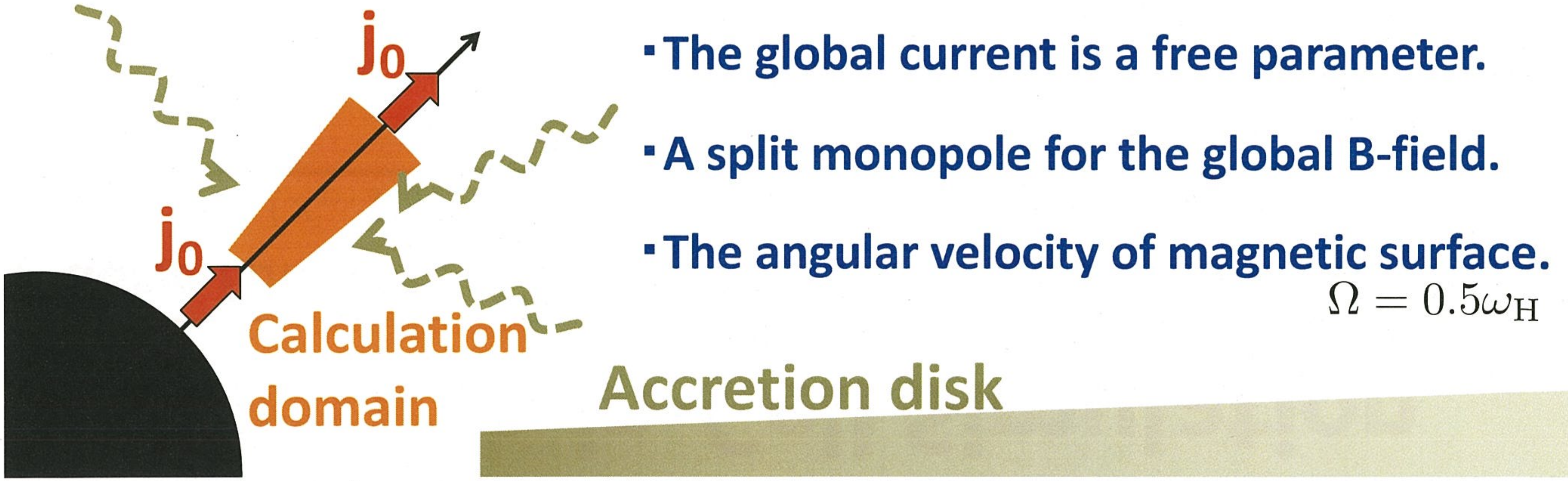


1D PIC Model

Levinson & Cerutti 18

- **1-dimensional structure**: the gap extends along a poloidal magnetic surface as a function of θ.
- **Emission mechanisms** : IC scattering and curvature radiation
- **Pair production** : IC scattered photon + disk photon → pairs
- **Disk photon** : Isotropic and uniform distribution

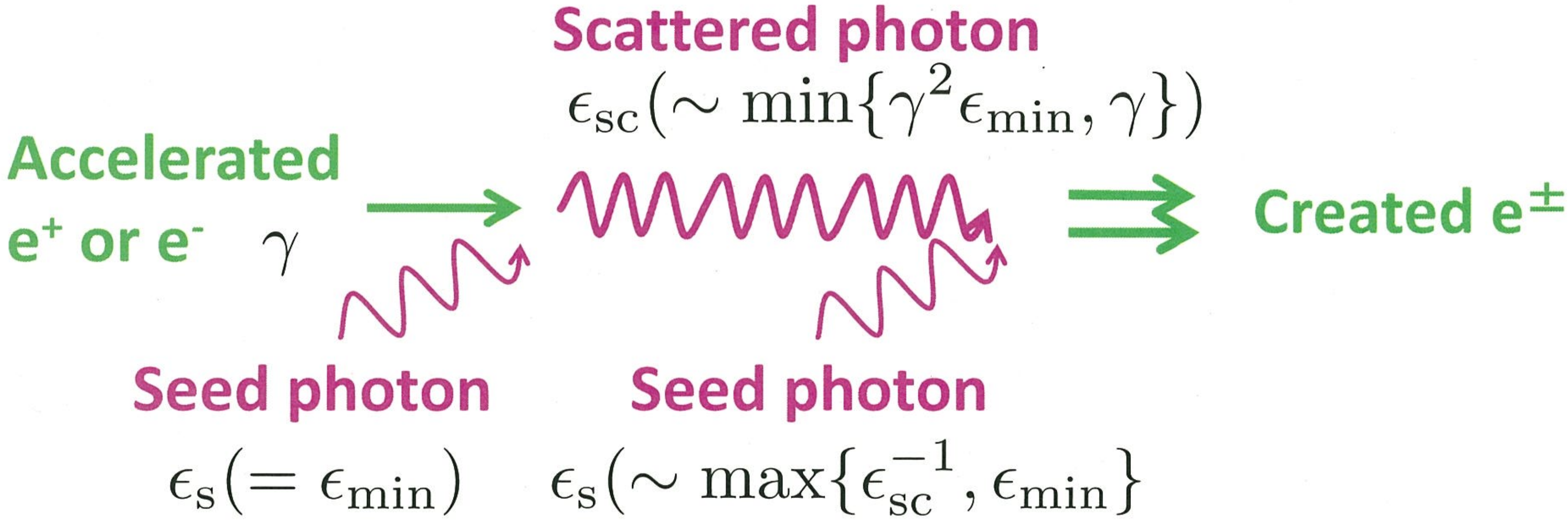
$$I_s(x^\mu, \epsilon_s, \mathbf{\Omega}_s) = I_0(\epsilon_s/\epsilon_{s,\min})^{-p}, \quad \epsilon_{s,\min} < \epsilon_s < \epsilon_{s,\max}$$



- **No external plasma source.**
- **The global current is a free parameter.**
- **A split monopole for the global B-field.**
- **The angular velocity of magnetic surface.**

$$\Omega = 0.5\omega_{\mathrm{H}}$$

Pair Cascade in Gap



Fiducial optical depth

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

Required multiplicity in the gap

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

Pair Cascade in Gap

$$\tau_0 \gtrsim \sqrt{\frac{\tau_0}{\tau_{\rm sc}} \frac{\tau_0}{\tau_{\gamma\gamma}}}$$

Fiducial optical depth

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

$e^{\pm}$ quickly accelerates to the terminal Lorentz factor.

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

$$\epsilon_{\rm min} = 10^{-8} \Rightarrow \gamma\epsilon_{\rm min} > 1$$ (Klein-Nishina regime)

Scattering optical depth $\tau_{\rm sc}/\tau_0 \sim (\gamma\epsilon_{\rm min})^{-1}$

Pair creation optical depth $\tau_{\gamma\gamma}/\tau_0 \sim (\gamma\epsilon_{\rm min})^{-1}$

Required optical depth for continuous injection $\tau_0 \gtrsim \gamma\epsilon_{\rm min}$

Parameters

Levinson & Cerutti 18

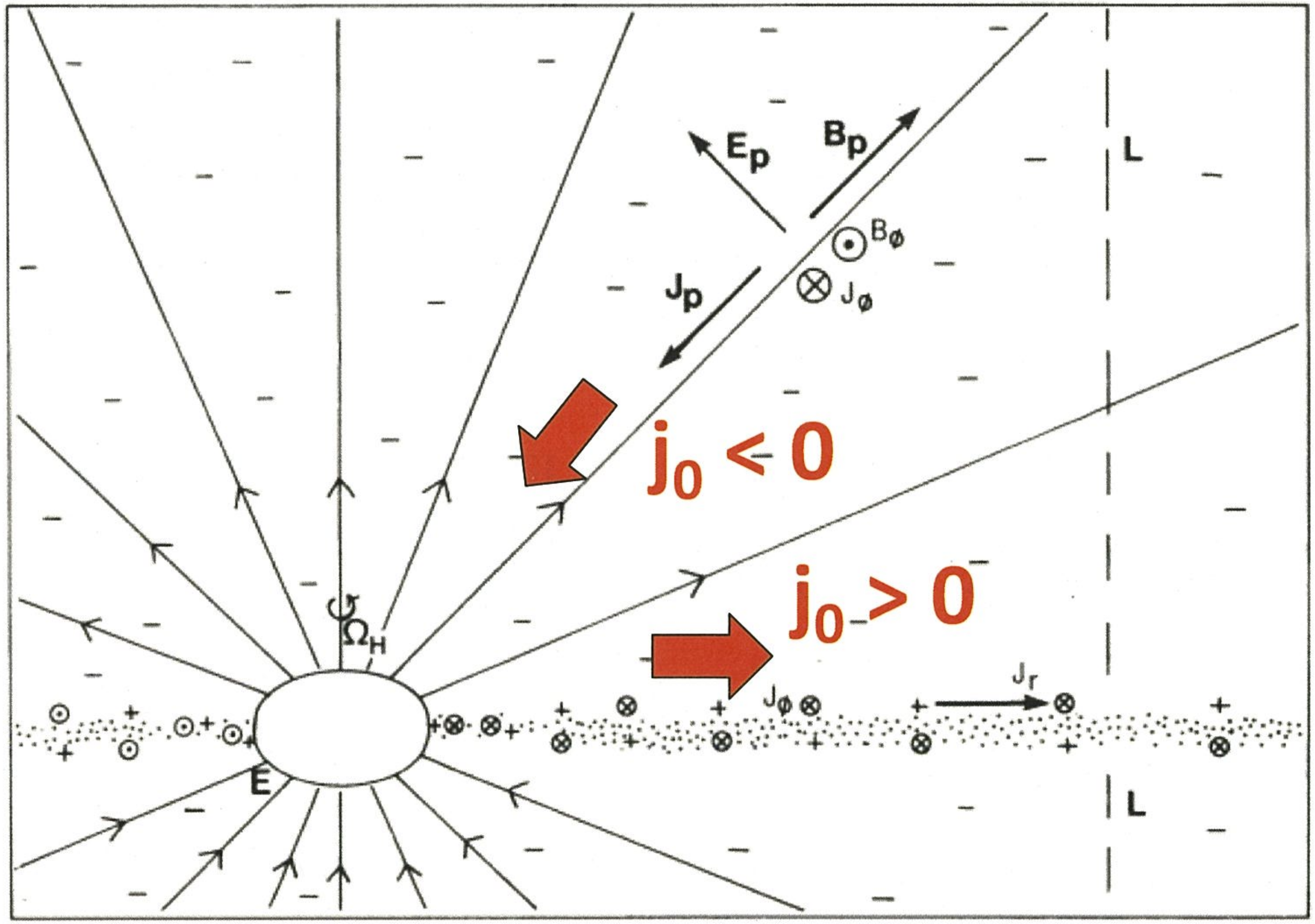
Fiducial optical depth	$\tau_0 = 4\pi r_g \sigma_{\rm T} I_0 / hc$	
Global current density	j_0	(normalized by $\rho_{GJ,H}c$)
Minimum energy of seed photon	$\epsilon_{s,\rm min}$	(normalized by $m_e c^2$)
BH mass	$M_{\rm BH} = 10^9 M_\odot$	
Dimensionless spin parameter	$a_* = 0.9$	
B-field on the horizon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

$$N = 32768 \gtrsim \frac{r_g}{l_{\rm p}} \sim 10^3 \sqrt{\frac{\kappa M_9 B_{\rm H,3}}{< \gamma_8 >}}$$

Current Distribution

Polar region : $j_0 < 0$

Equatorial region : $j_0 > 0$



Blandford & Znajek 77

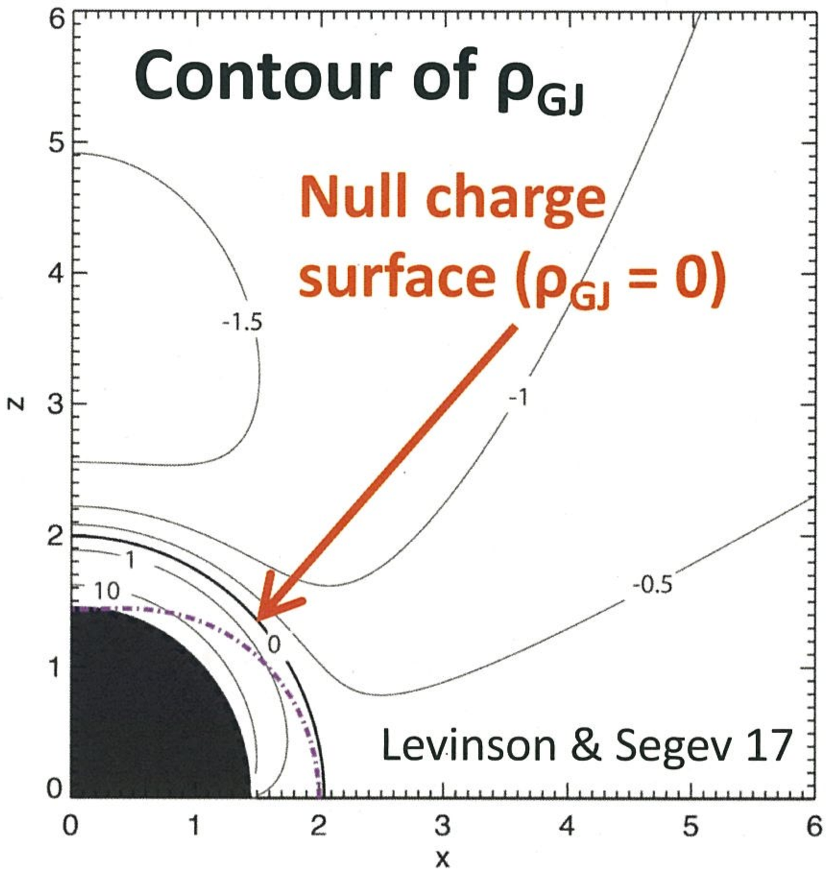
We set $j_0 = 1$ or -1

Maxwell equations

Gauss's law

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

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



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

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

Maxwell 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)

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

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

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

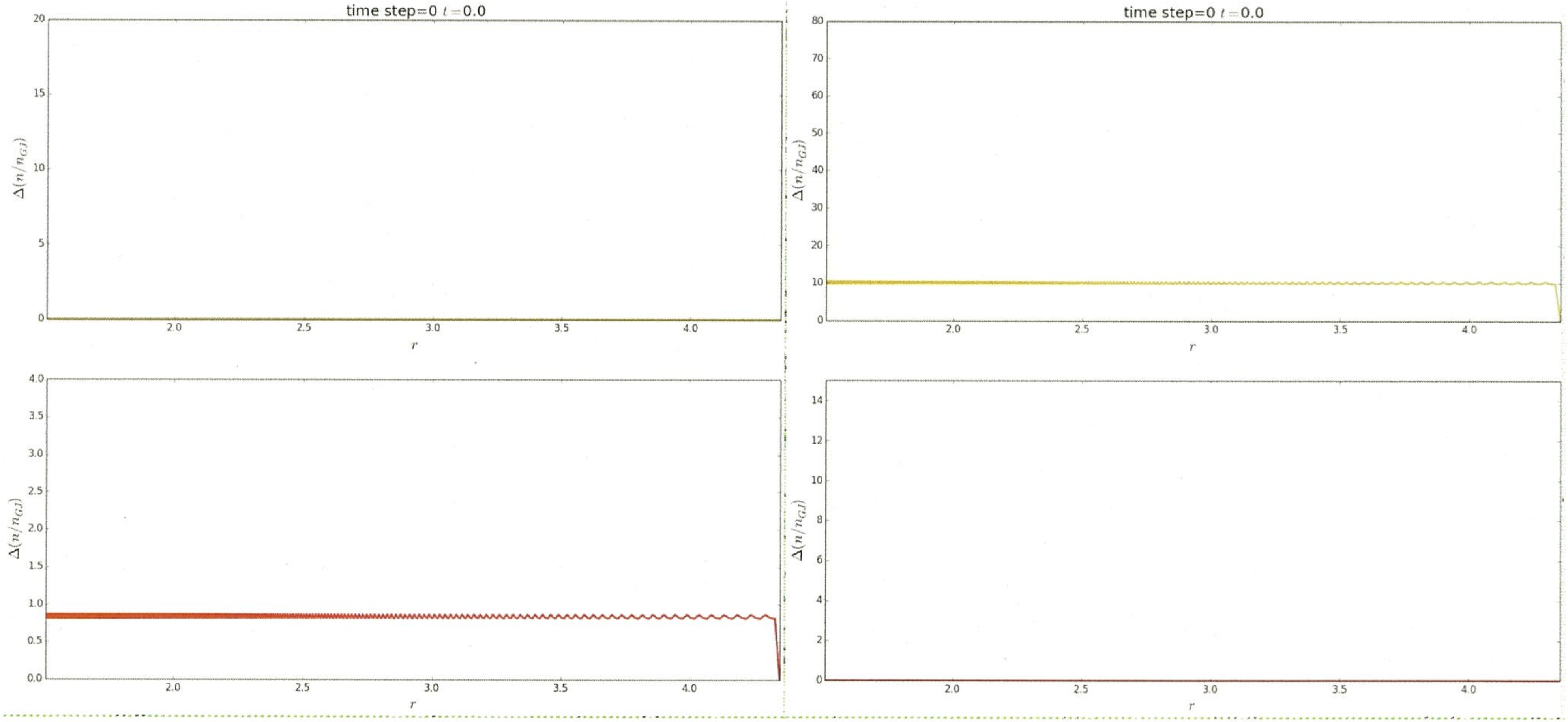
Comparison

	B-field $\tilde{B} \equiv \frac{eBr_g}{m_e c^2}$	Soft photon min. energy $\epsilon_{\rm min}$	Optical depth τ_0
M87	$\sim 5 \times 10^{13}$ (EHT Col. 19)	$\sim 10^{-9}$ (Abdo+ 09)	$< 10^3$ (Levinson & Rieger 11)
This work (Levinson & Cerutti 18)	$\sim 5 \times 10^{14}$	$\sim 10^{-8}$ - 10^{-9}	10 - 300
Chen & Yuan 19	$\sim 10^7$ - 10^9	$\sim 10^{-4}$ - 10^{-6}	3 - 1000
Crinquand+ 19 (2D)	$\sim 5 \times 10^5$	$\sim 5 \times 10^{-3}$	5 - 30

Contents

Insufficient Pair Creation

τ_0 = 10, $\gamma_{max}\varepsilon_{min}$ ~ 100, different initial condition



Initial condition: $e^{\pm}$ beams

Initial condition: a photon beam

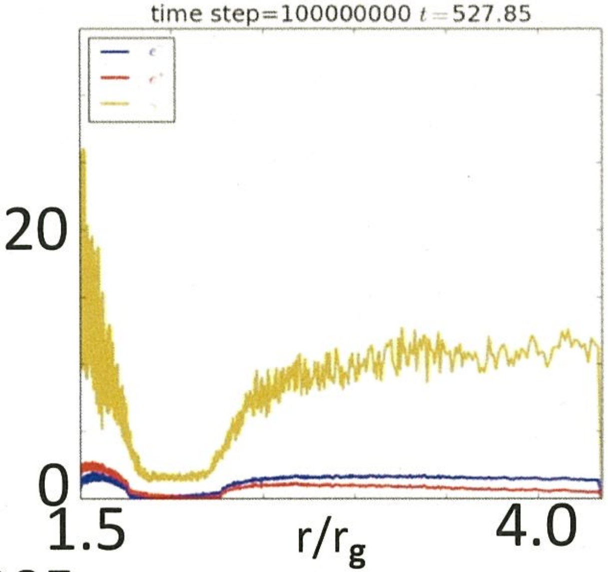
All photons and particles finally escape from the box.

Sufficient Pair Creation

$\tau_0 = 100$ ($> \gamma_{max}\epsilon_{min} \sim 10$)

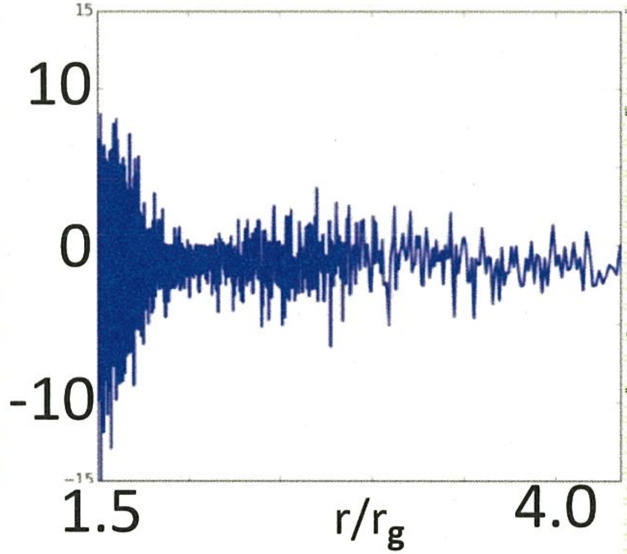
Number density

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



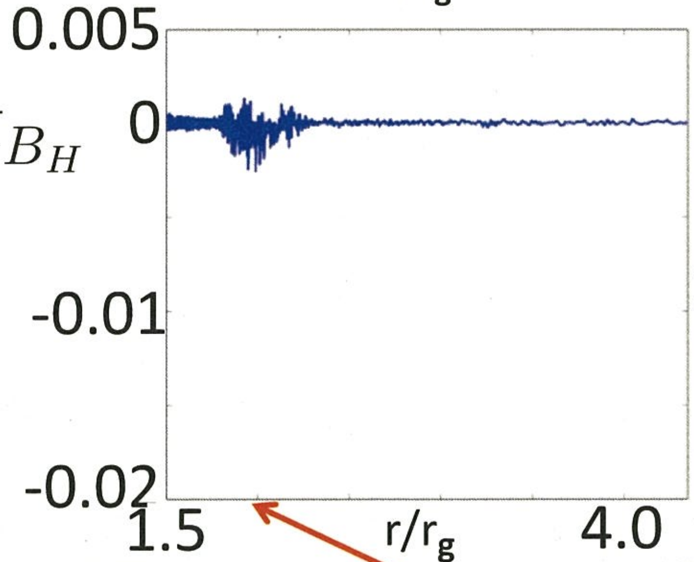
Current density

$\Sigma j^r/|J_0|$



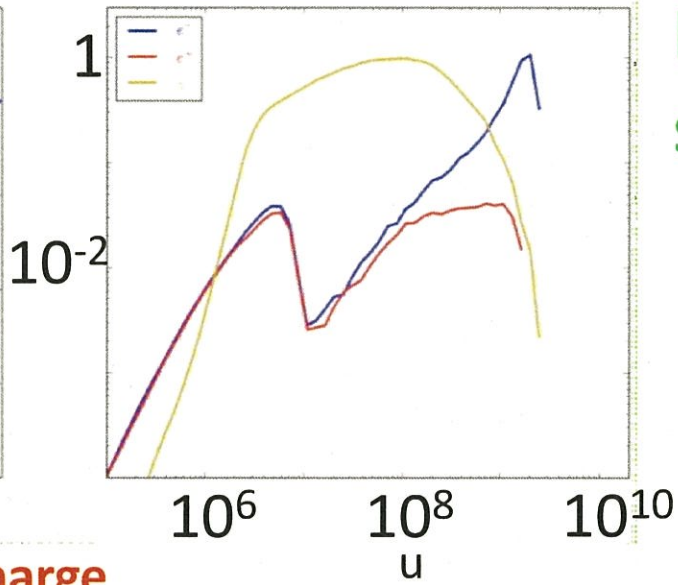
E-field

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



Energy spectrum

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

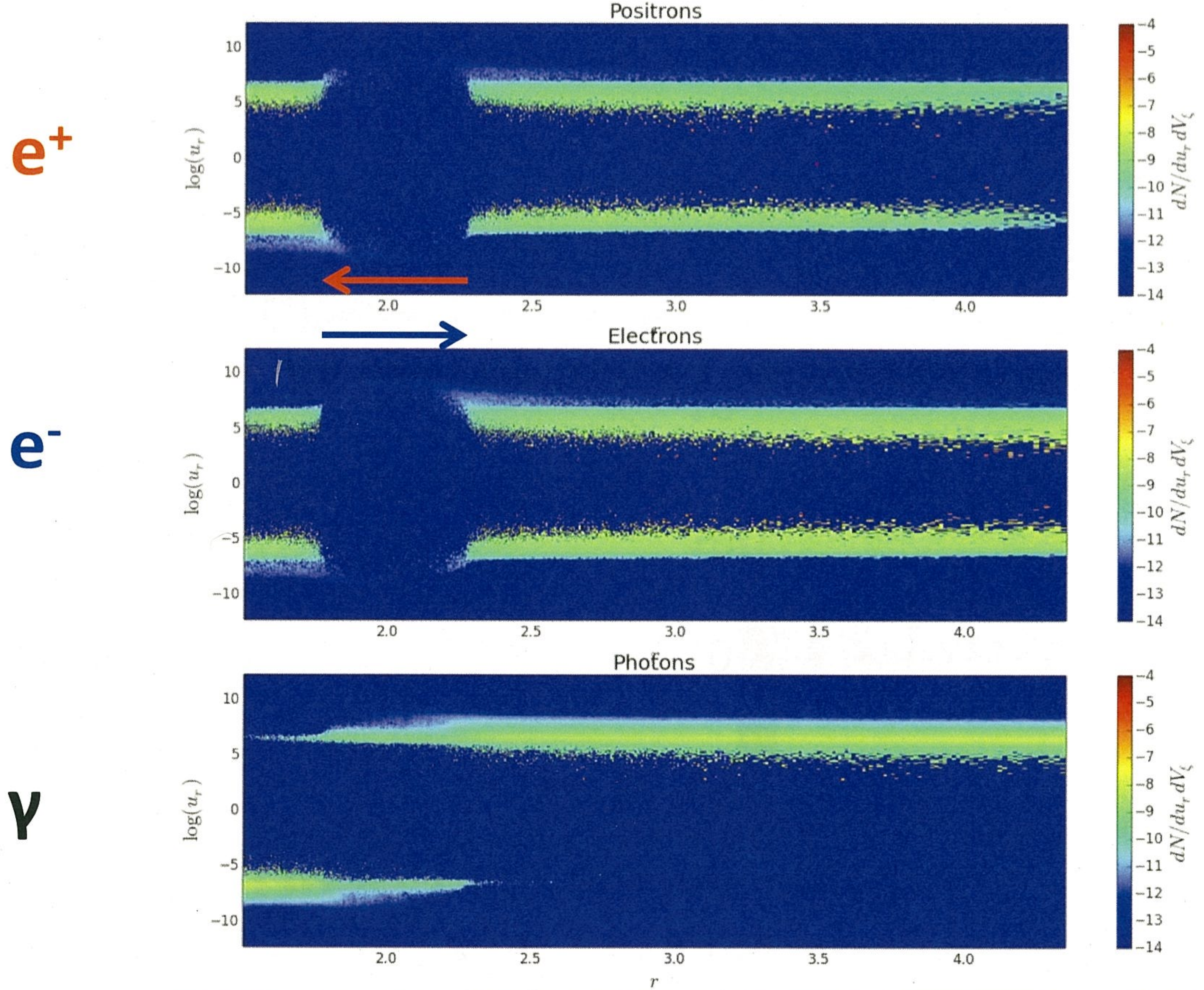


$$\rho_{\rm GJ} = \frac{B_{\rm H}\sqrt{A_{\rm H}}}{4\pi\sqrt{-g}}\left[\frac{\sin^2\theta}{\alpha^2}(\omega - \Omega)\right]_{,\theta}$$

Null charge surface (ρ_{GJ}=0)

Phase Plot

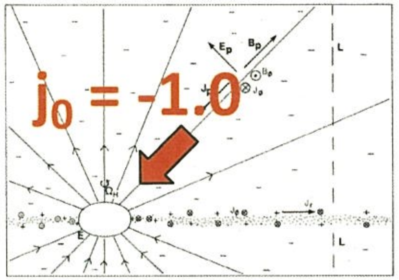
$\tau_0 = 100$



Results

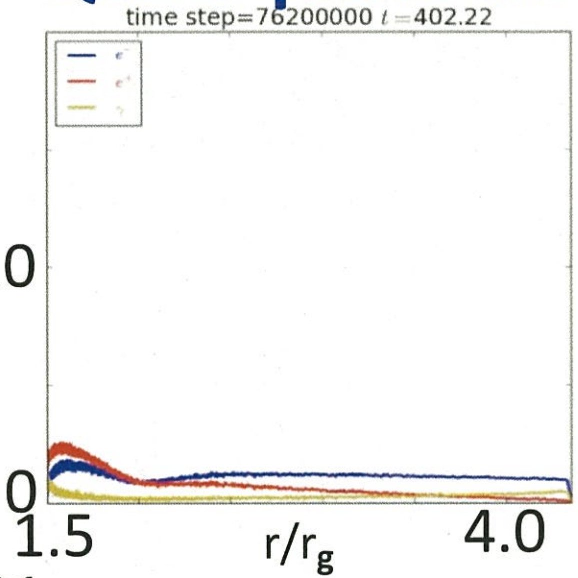
$\tau_0 = 300$

Quasi-periodic oscillation



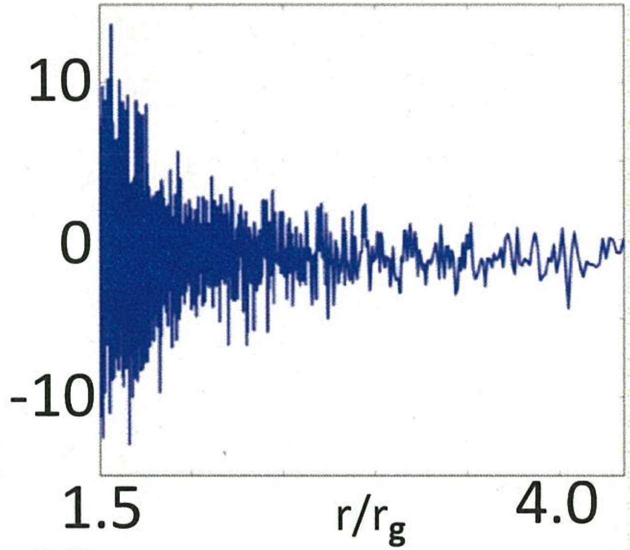
Number density

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



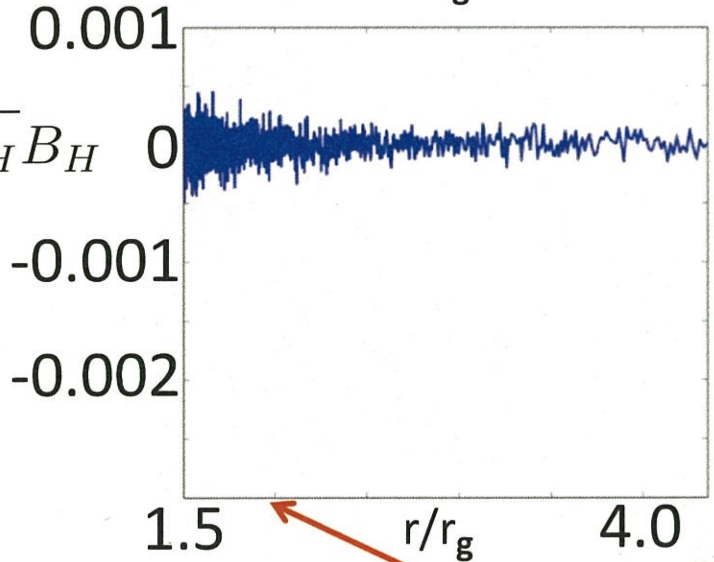
Current density

$\Sigma j^r/|J_0|$



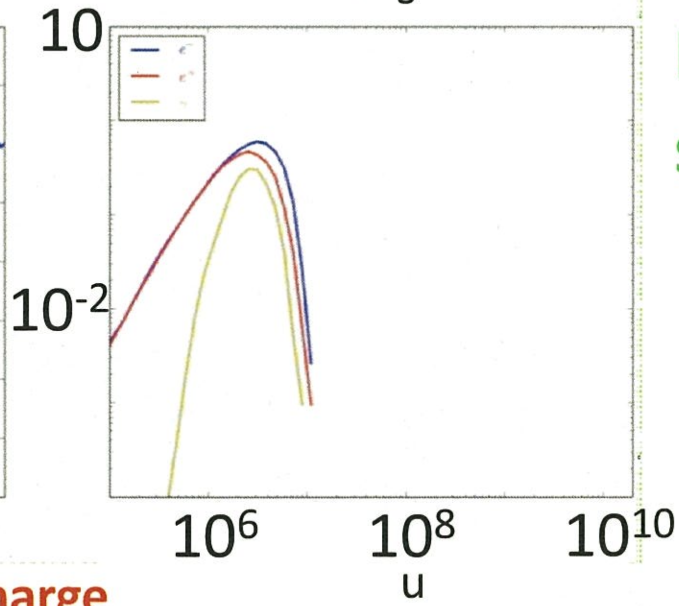
E-field

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



Energy spectrum

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

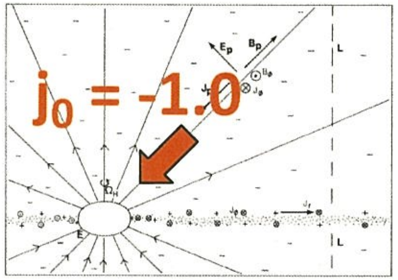


Null charge surface ($\rho_{\rm GJ}=0$)

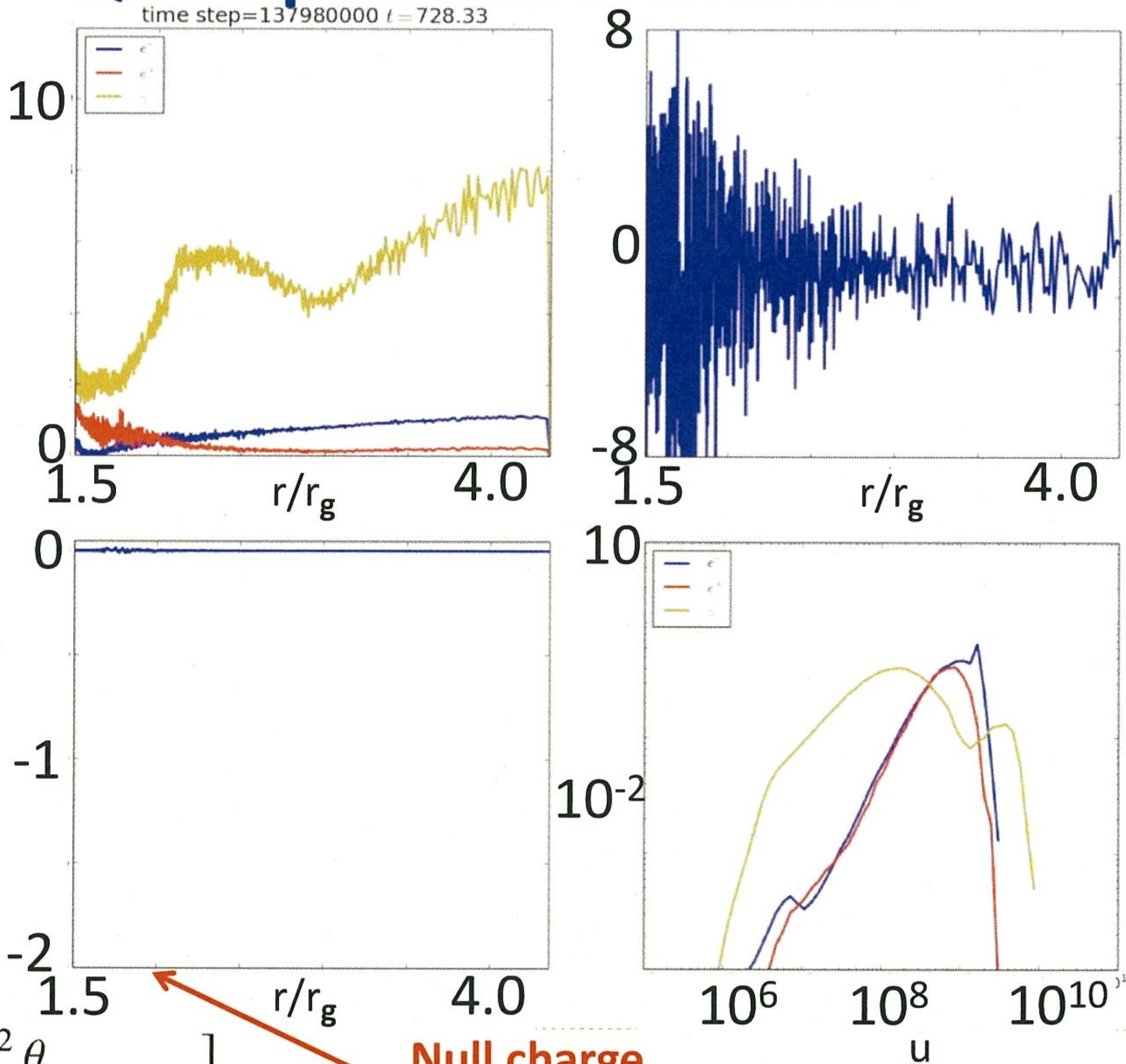
$$\rho_{\rm GJ} = \frac{B_{\rm H}\sqrt{A_{\rm H}}}{4\pi\sqrt{-g}}\left[\frac{\sin^2\theta}{\alpha^2}(\omega-\Omega)\right]_{,\theta}$$

Results

$\tau_0 = 30$



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

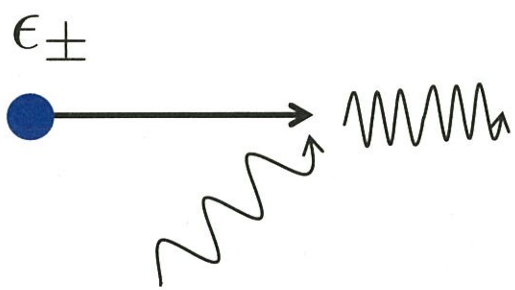
$u^2\frac{dN}{du}$

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

Null charge surface (ρ_{GJ}=0)

High Energy Emission

Inverse Compton scattering



Characteristic energy

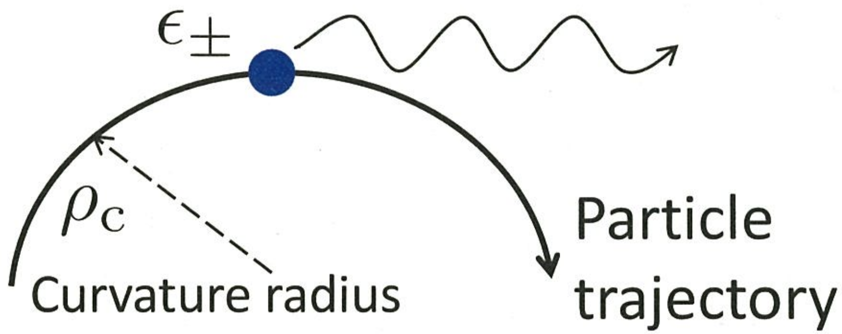
$$E_{\rm IC} \sim \gamma^2 E_{\rm d} \quad \text{(Thomson)}$$

$$\sim \gamma m_{\rm e} c^2 \quad \text{(Klein-Nishina)}$$

Radiation power

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

Curvature radiation



Characteristic energy

$$E_{\rm CR} = \frac{3}{2}\gamma^3 \hbar \frac{c}{\rho_{\rm c}}$$

Radiation power

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

High Lorentz factor → Curvature radiation dominant

(Other works do not calculate the curvature radiation.)

Pairs from Curvature Photons?

Pair injection rate $\dot{N}_{\pm} = (L_\gamma/\epsilon_\gamma)\tau_{\gamma\gamma}$

Inverse Compton scattering

$L_{\rm ic} \sim 10^{-5} L_{\rm BZ}$ $\quad \epsilon_{\rm ic} \sim 1\ \mathrm{PeV}$ $\quad n_{\rm s}(\epsilon_{\rm ic}^{-1}) = n_{\rm min}$

Curvature radiation

$L_{\rm cur} \sim 10^{-2} L_{\rm BZ}$ $\quad \epsilon_{\rm cur} \sim 1\ \mathrm{TeV}$ $\quad n_{\rm s}(\epsilon_{\rm cur}^{-1}) = 10^{-6} n_{\rm min}$

→ $\dot{N}_{\pm\rm cur} \sim \dot{N}_{\pm\rm ic}$

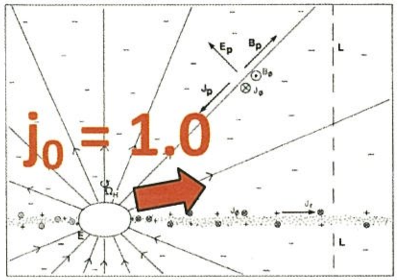
$$n_{\rm s} = n_{\rm min}\left(\frac{\epsilon_{\rm s}}{\epsilon_{\rm s,min}}\right)^{-2}$$

$$\epsilon_{\rm s,min} = 10^{-9}$$

Curvature photons would significantly contribute to pair creation for $\tau_0 < 30$ and $p < 2$.

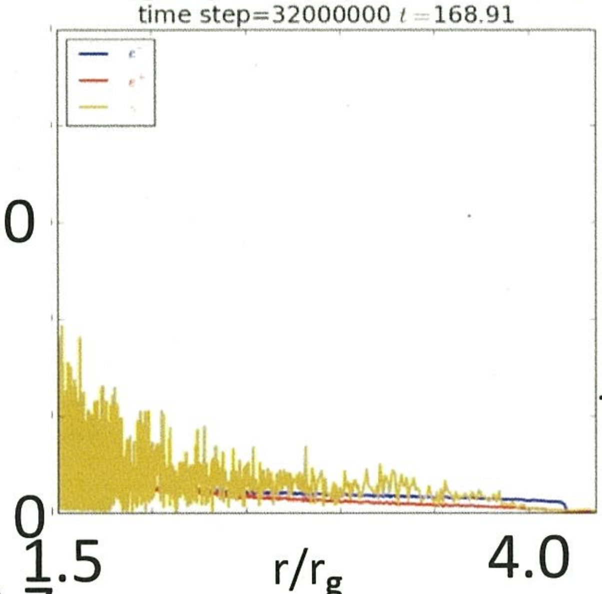
Results ($j_0 = 1$)

$\tau_0 = 100$ ($> \gamma_{max}\varepsilon_{min} \sim 10$)

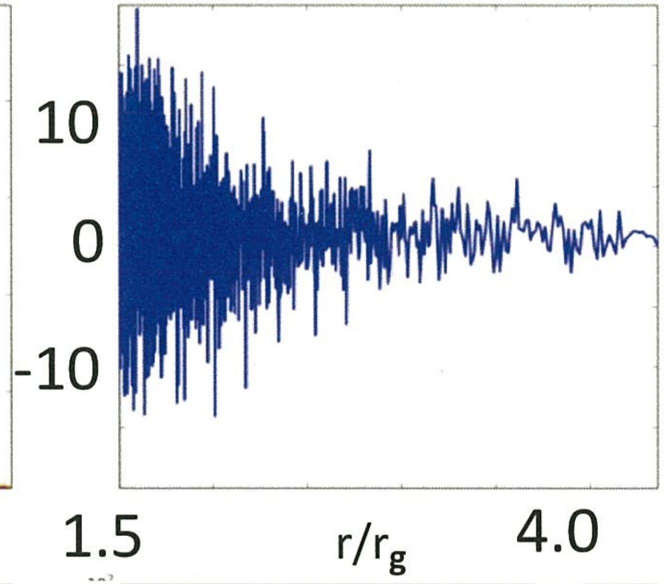


The gap appears **at the outer boundary.**

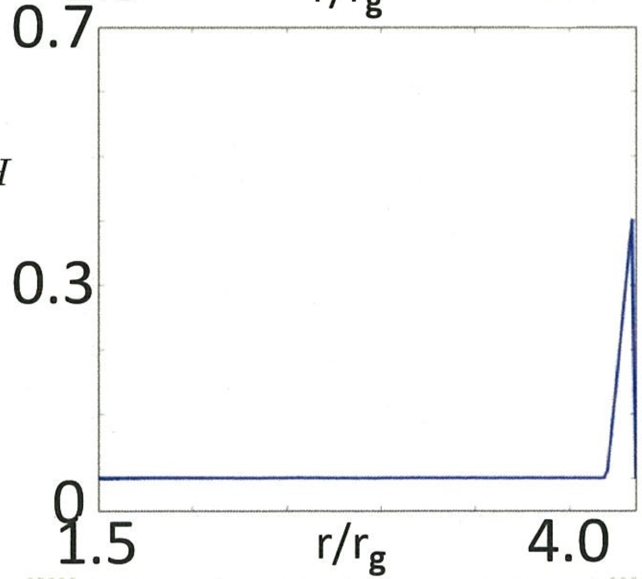
Number density $\Delta(n/n_{\rm GJ})$



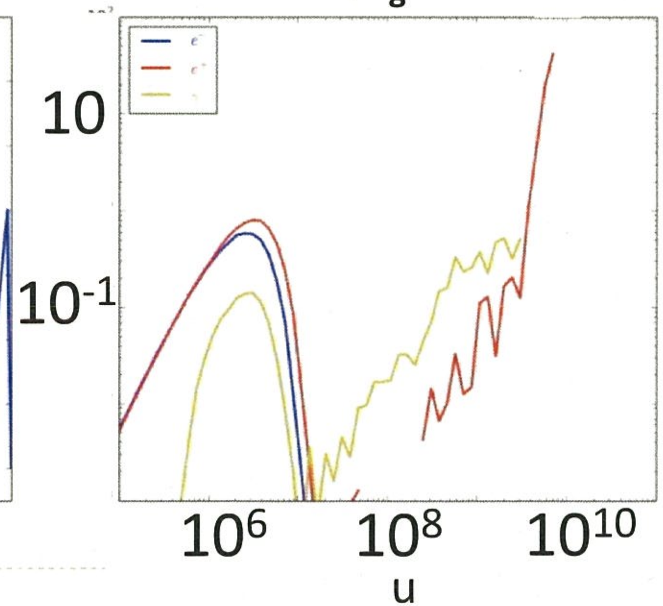
Current density $\Sigma j^r/|J_0|$



E-field $\sqrt{A}E_r/\sqrt{A_H}B_H$

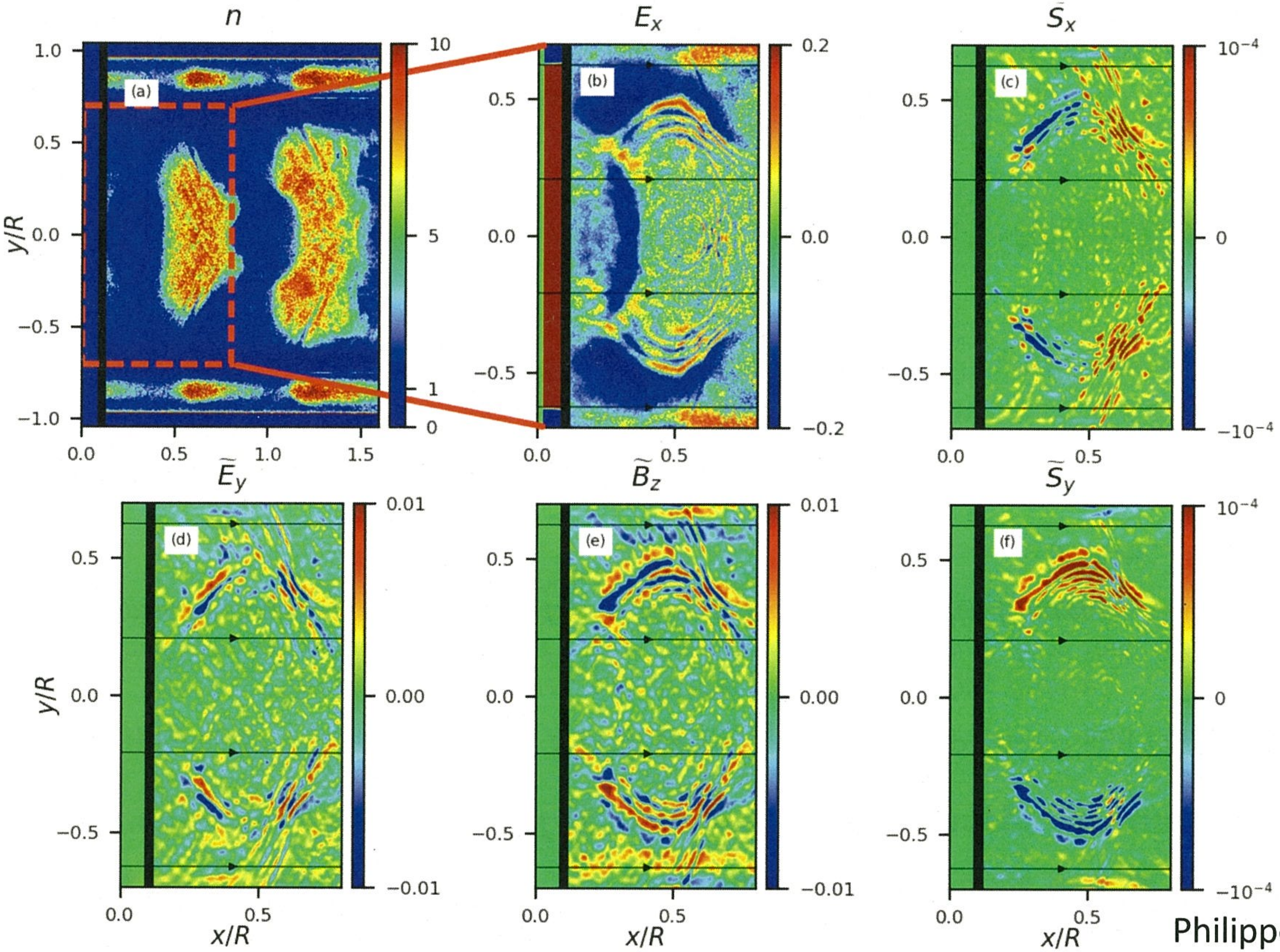


Energy spectrum $u^2\dfrac{dN}{du}$



Coherent EM emission?

Propagating pair burst → coherent electromagnetic wave



Philippov+ 20

Recent 2D PIC simulation

Multi-dimensional simulations of ergospheric pair discharges around black holes

Benjamin Crinquand,[1,*] Benoît Cerutti,[1] Alexander Philippov,[2] Kyle Parfrey,[3] and Guillaume Dubus[1]

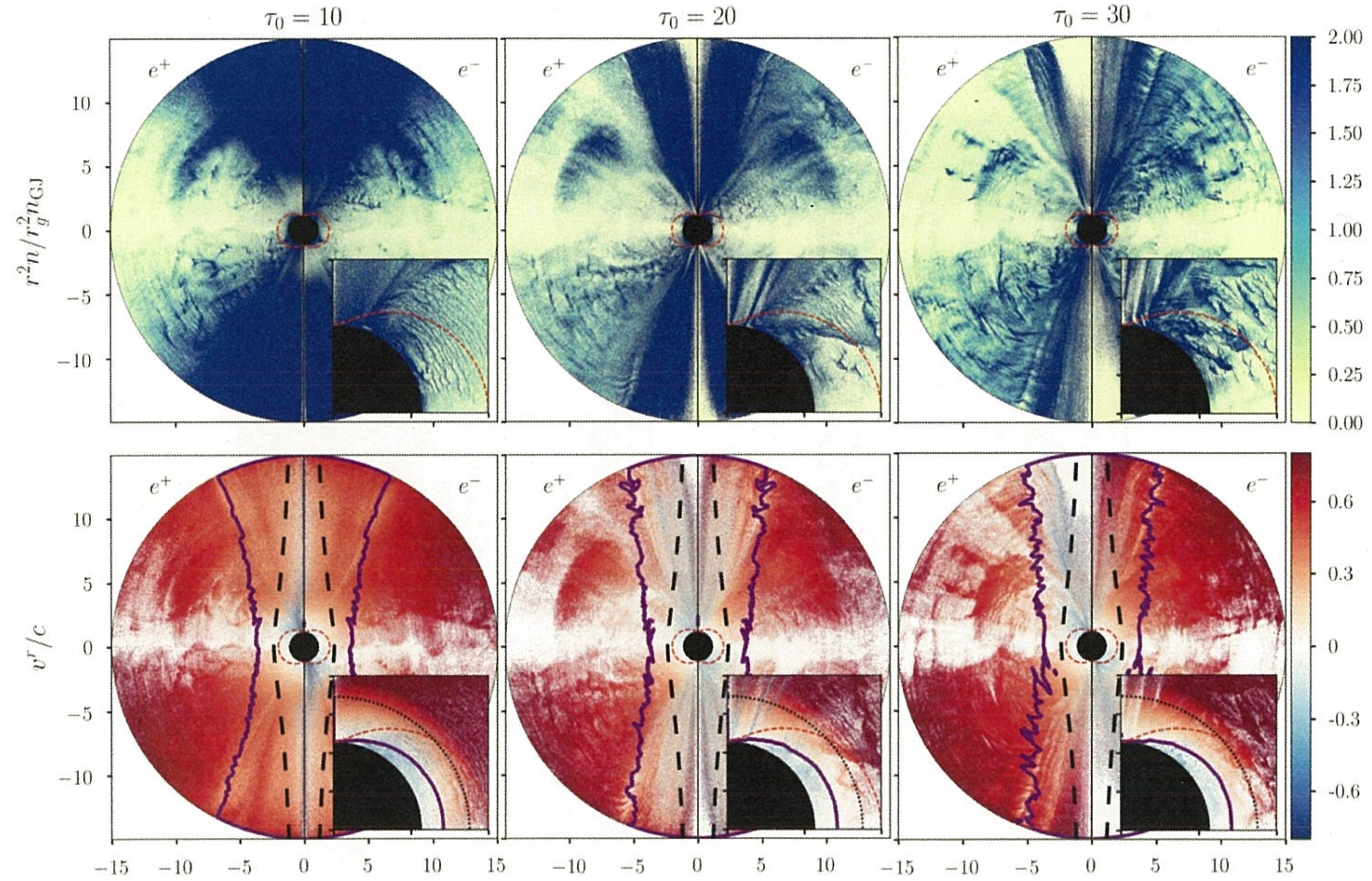
[1] *Univ. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France*

[2] *Center for Computational Astrophysics, Flatiron Institute, 162 Fifth Avenue, New York, NY 10010, USA*

[3] *Department of Astrophysical Sciences, Peyton Hall, Princeton University, Princeton, NJ 08544, USA*

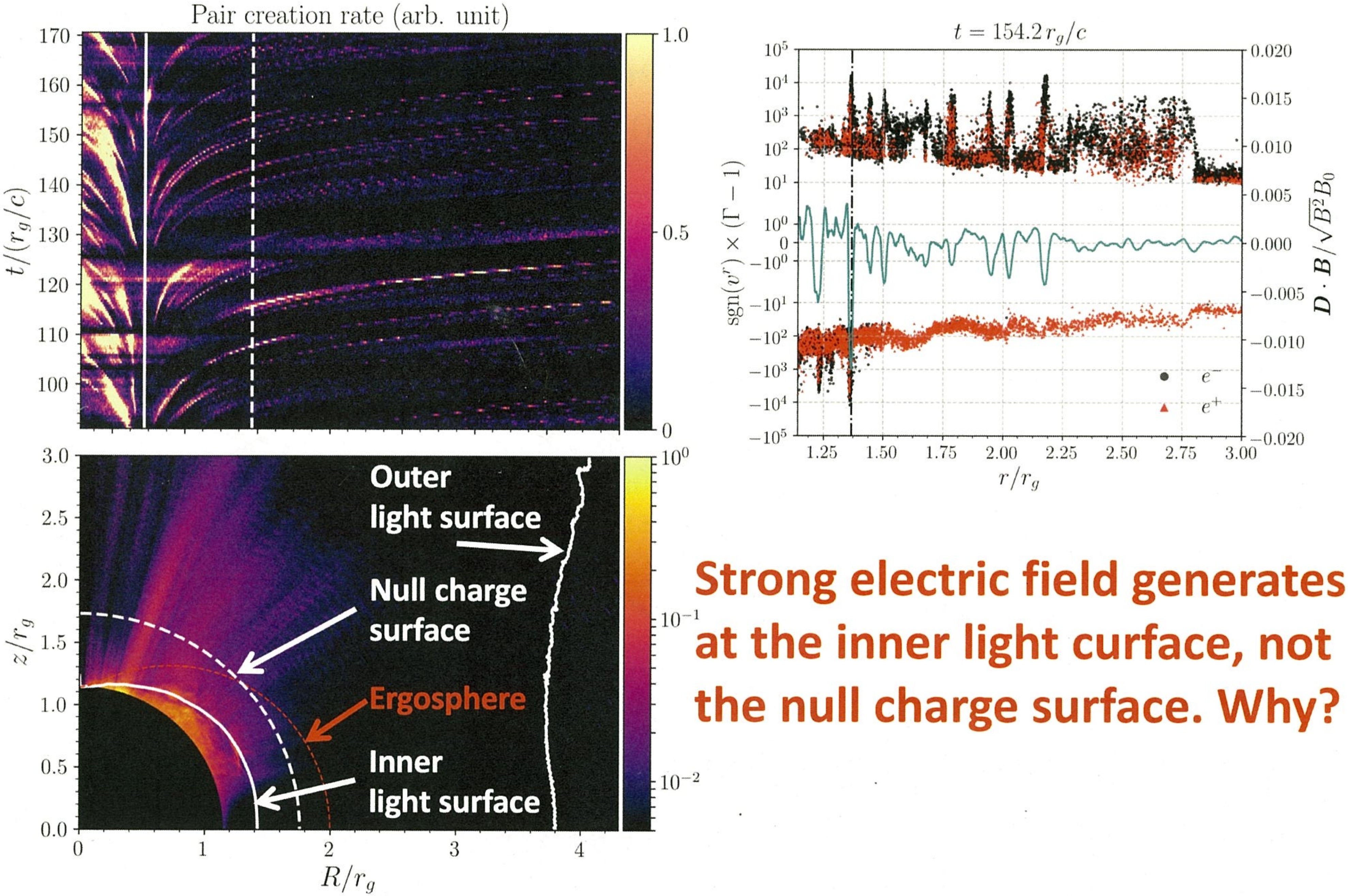
(Dated: March 10, 2020)

arXiv:2003.03548



- 2D GRPIC
- Monopole B-field (not split-monopole)
- IC scattering and γ-γ pair creation

Gap = inner light surface?



Strong electric field generates at the inner light curface, not the null charge surface. Why?

Summary

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