Plasma injection, sparks and HE emission in BH magnetospheres

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Some open questions re jet formation

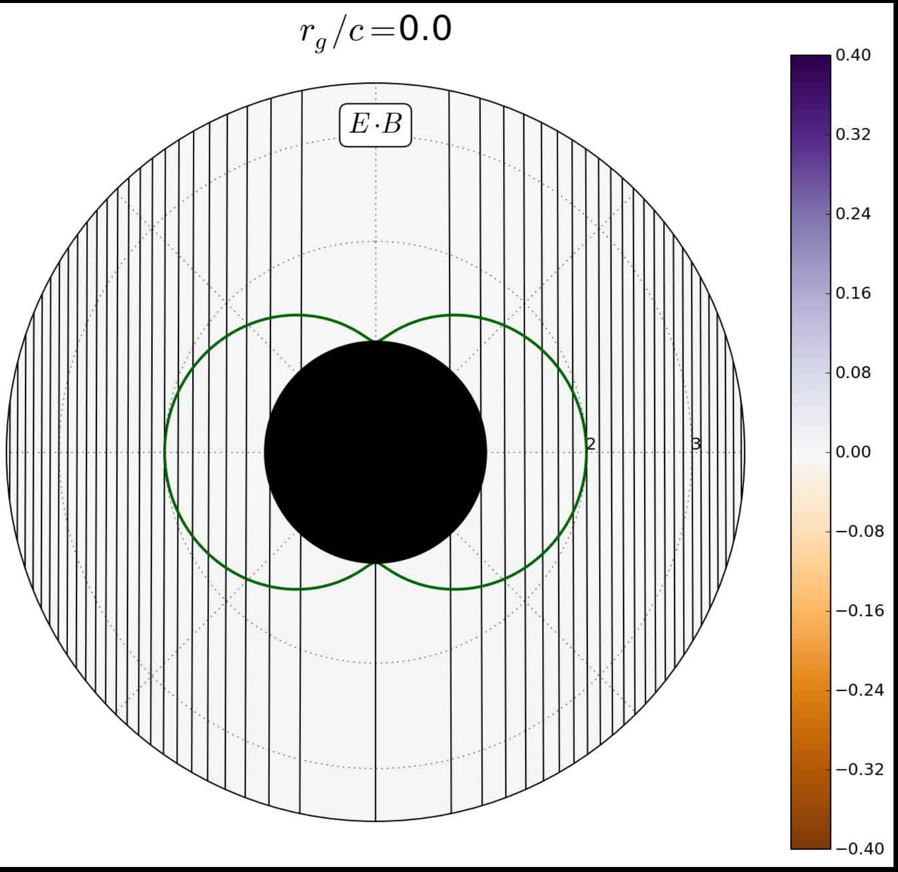
- what is the dissipation mechanism?
- origin of plasma source in the magnetosphere? (external pp, spark gap, etc)
- what is the loading process?

Vacuum Wald solution

Rotating BH in an asymptotically uniform magnetic field

Robert Wald 1974

Courtesy Benoit Cerutti



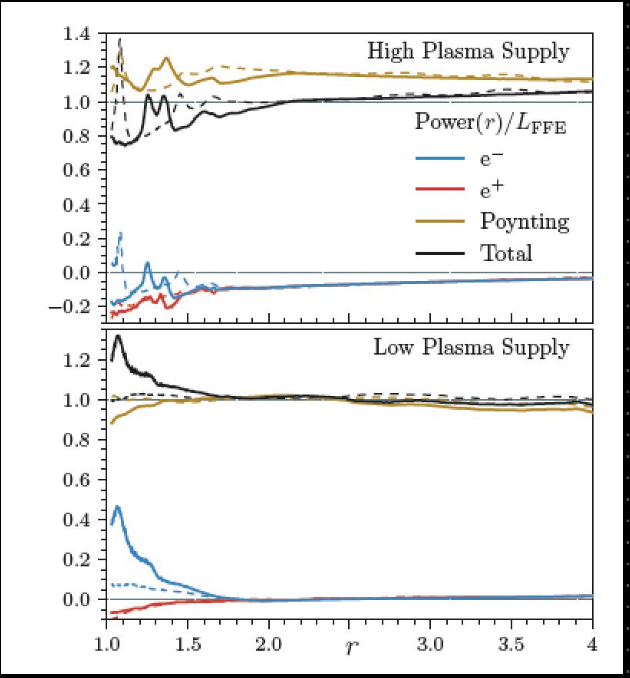
$$F_{\mu\nu} = \xi_{\mu;\nu} - \xi_{\nu;\mu}$$

- Electric field: $\vec{E} \cdot \vec{B} \neq 0$
- Injection of plasma will screen out the E field.
- $\Delta V \sim 10^{21} M_9 B_4$ volt
- The minimum energy state has a charge $Q = 2B_0 \mathrm{J}$

When plasma is injected

2D GRPIC simulations with artificial pair production

Parfrey+19



How much plasma is needed?

Charge density needed to screen out E field:

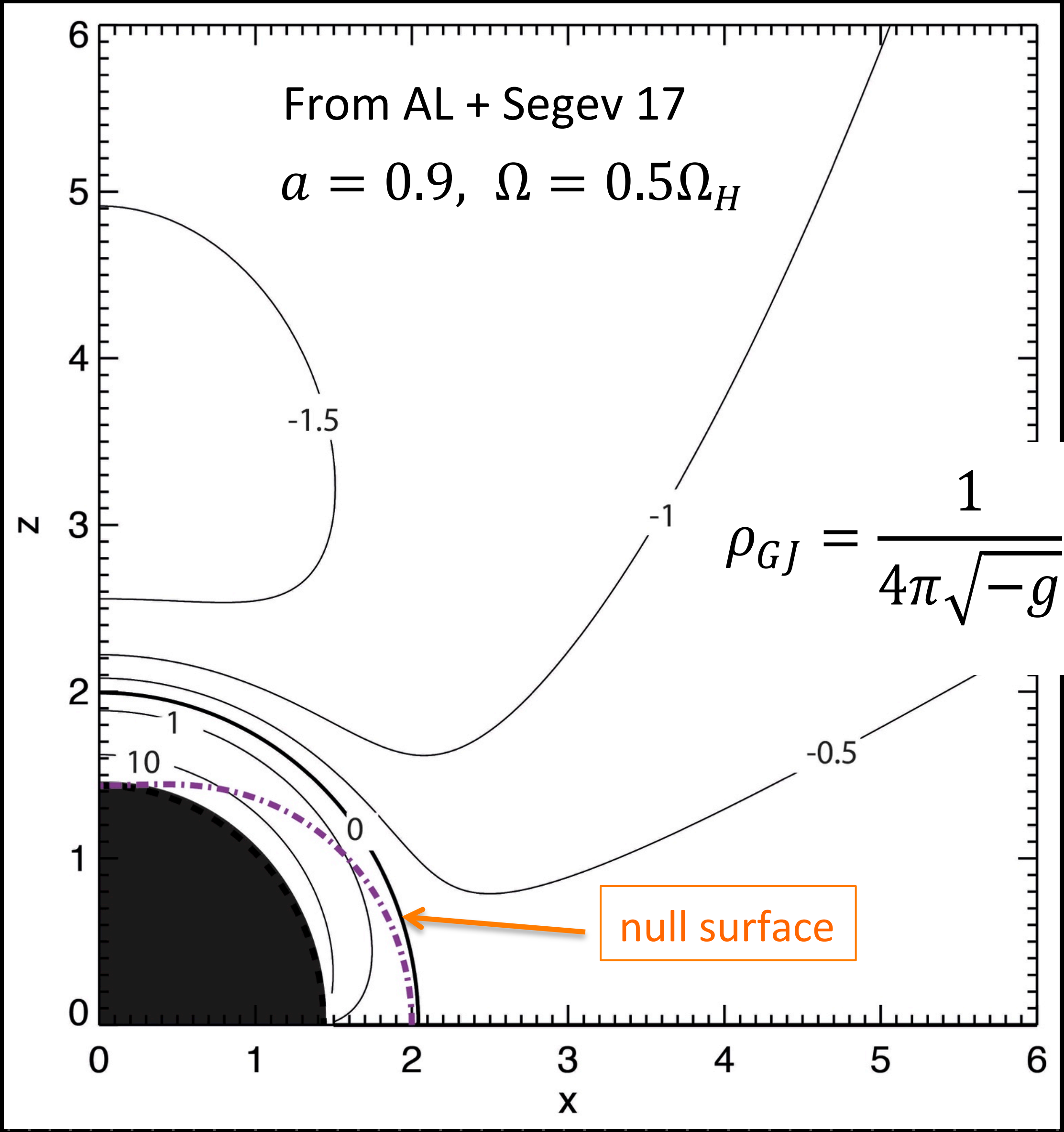
$$\vec{E}' = \gamma\left(\vec{E} + \vec{v}\times\vec{B}\right) = 0; \qquad \vec{v} = \vec{\Omega}\times\vec{r}$$

$$\rho_e = \frac{\nabla\cdot\vec{E}}{4\pi} = -\frac{\nabla\cdot\left(\vec{v}\times\vec{B}\right)}{4\pi} = -\frac{\vec{\Omega}\cdot\vec{B}}{2\pi} \equiv \rho_{GJ}$$

Plasma density must satisfy: $\boldsymbol{n > \rho_{GJ}/e}$

Otherwise the magnetospere becomes charge starved, $\boldsymbol{\vec{E}\cdot\vec{B} \neq 0}$

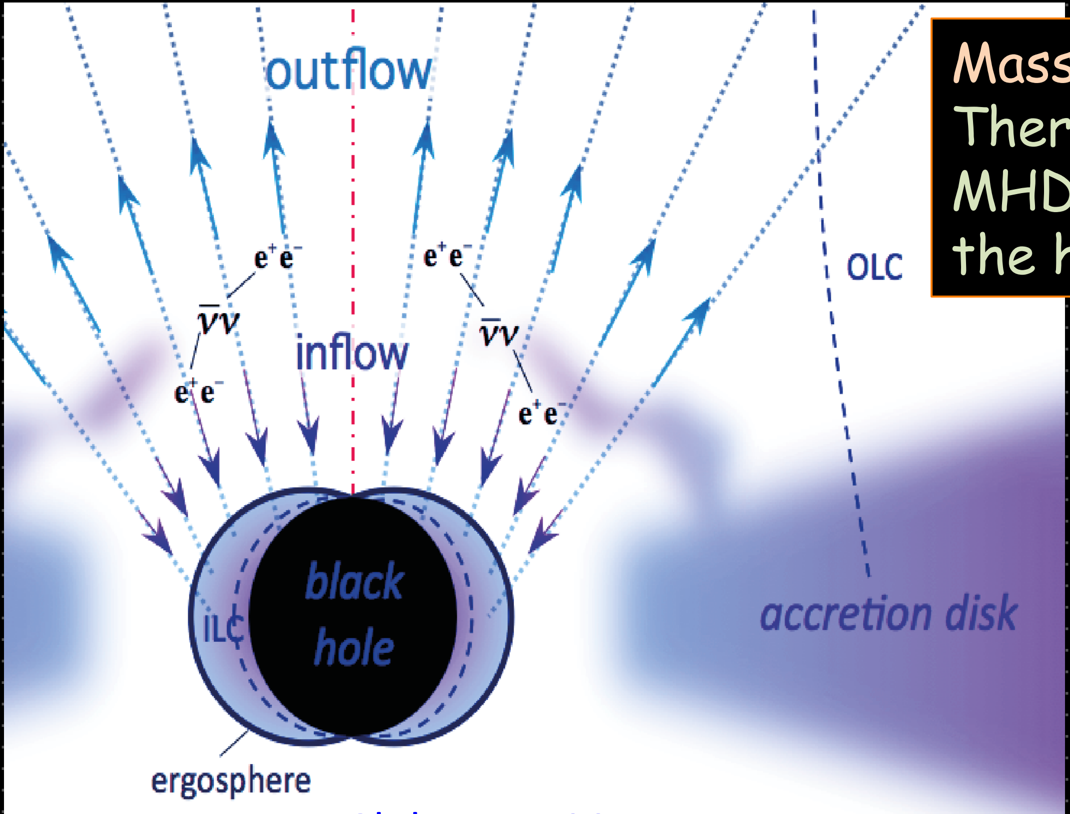
GJ density in Kerr geometry



$$\rho_{GJ} = \frac{1}{4\pi\sqrt{-g}}\partial_\mu\left[\frac{\sqrt{-g}\,g^{\mu\nu}}{\alpha^2}(\omega - \Omega)F_{\nu\varphi}\right]$$

Where plasma should be injected?

- plasma source between inner and outer Alfven surfaces
- escape time ≈ few r_g/c



Globus+AL 2014

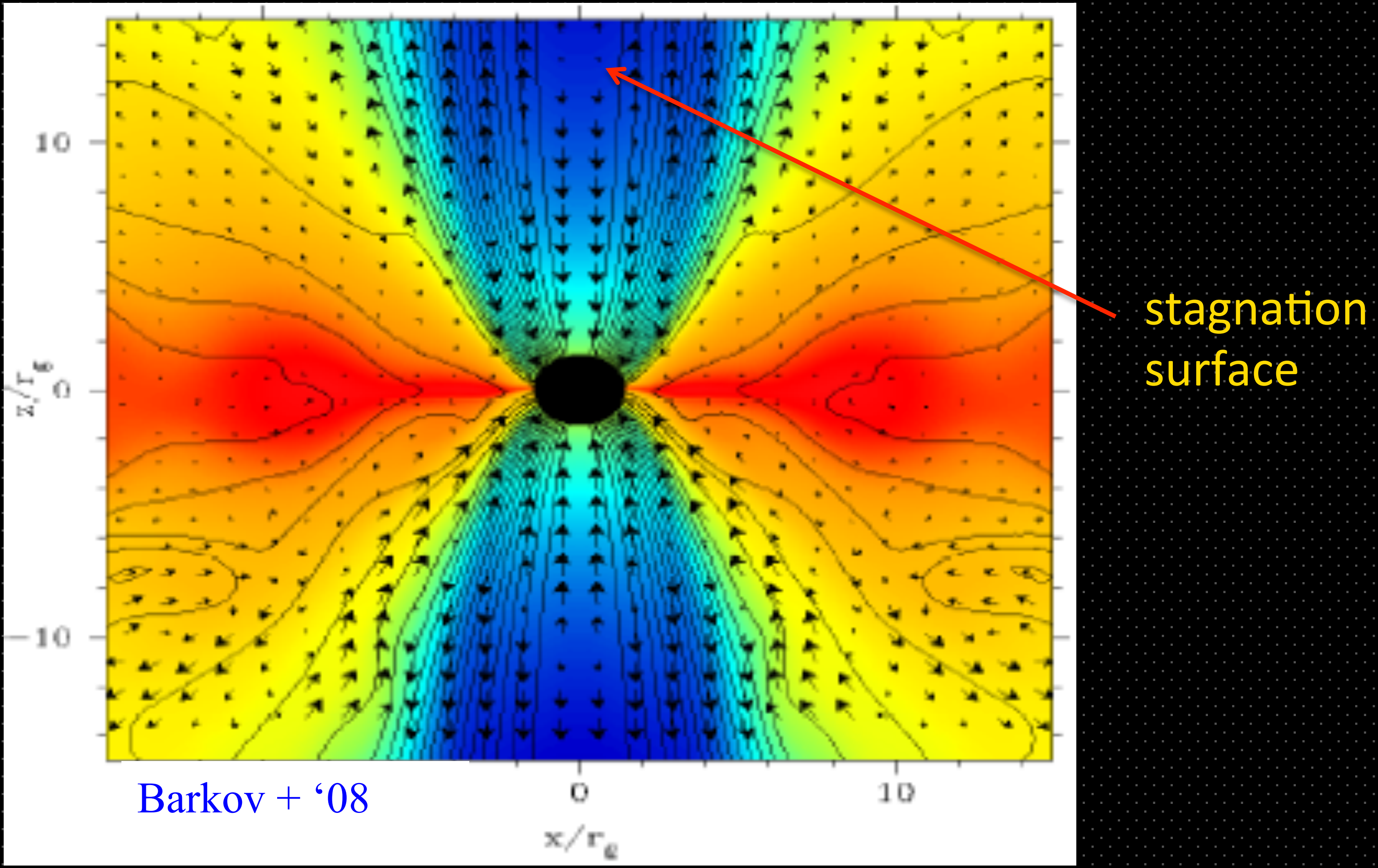
Mass flux not conserved !
There can be no continuous ideal MHD solution that extends from the horizon to infinity.

$\gamma\gamma \to e^{\pm}$ in AGNs

$\nu\nu \to e^{\pm}$ in GRBs

mass loading ?

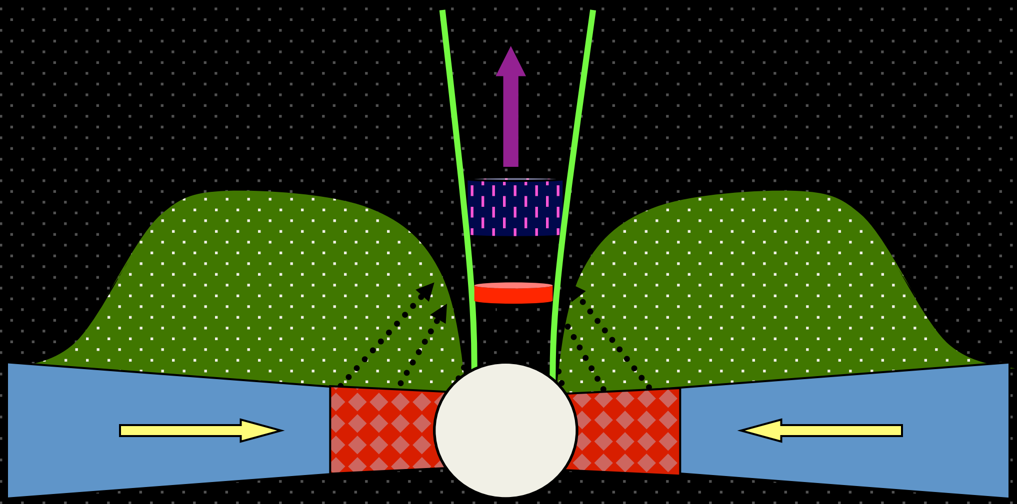
A snapshot from a simulation showing streamlines.



Limitations of GRMHD simulations

- Can't handle well force-free regions, particularly in dissipative regions
- Artificial plasma injection (floor density)
- No microphysics
- Limited initial states
- No radiation processes
- Runtime, box size, resolution

How to produce the required charge density?



- Protons from RIAF ?
- Protons from n decay ?
- $e^{\pm}$ from $\gamma\gamma$ annihilation ?
- Other source ?

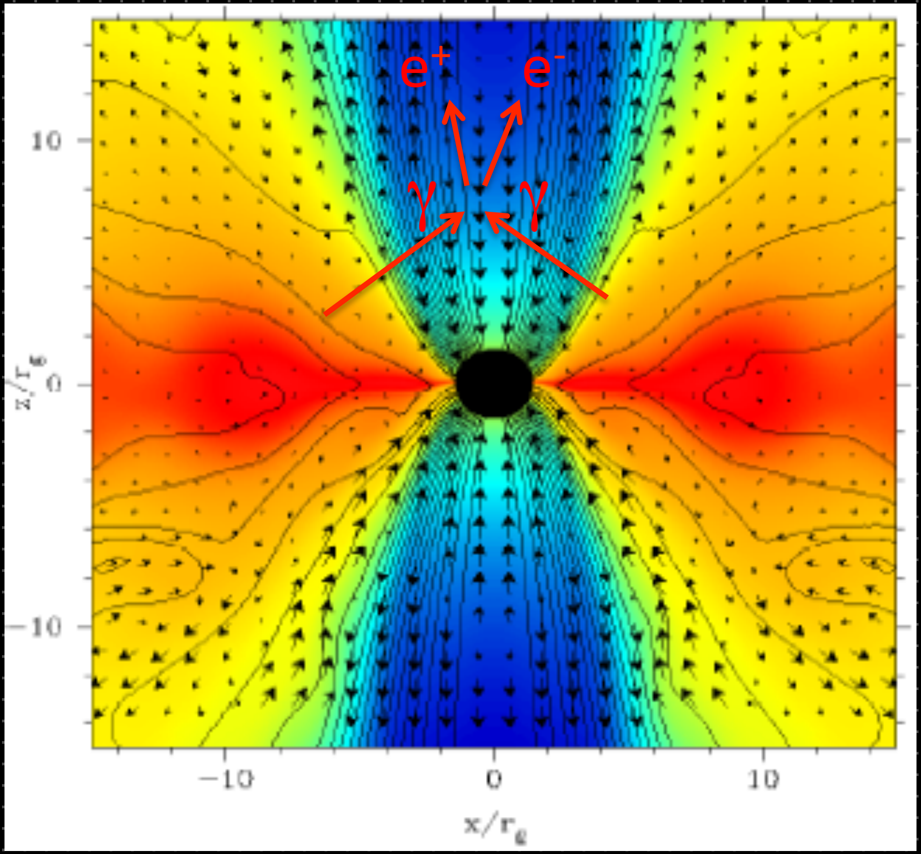
➢ Protons have to cross magnetic field lines. Diffusion length over accretion time extremely small.

➢ instabilities or field reversals. But intermittent spark gaps may still form.

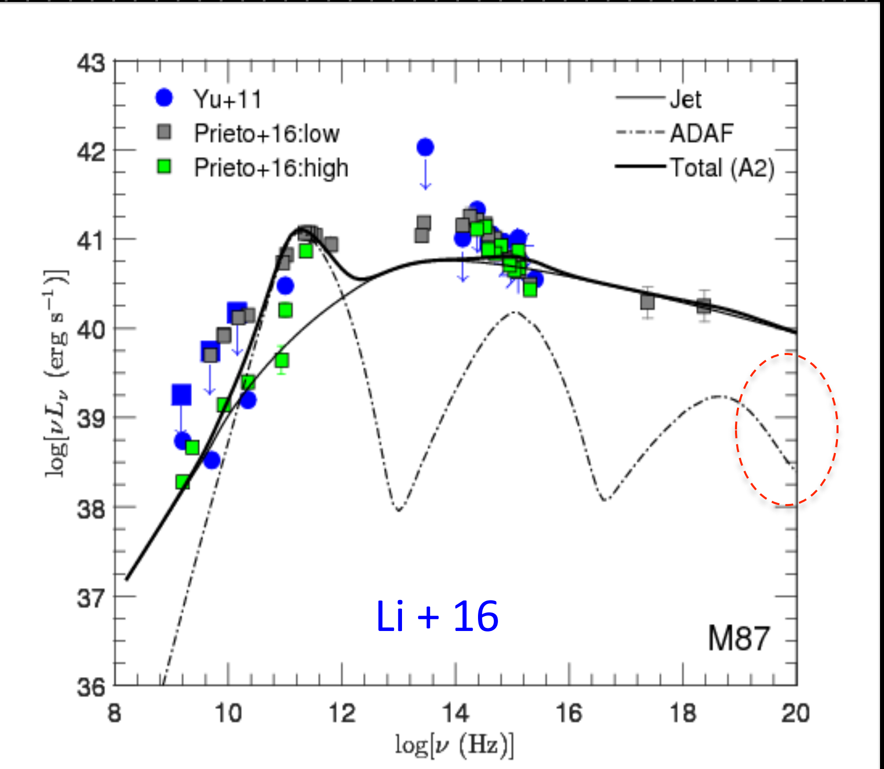
Direct pair injection by $\gamma\gamma \rightarrow e^+ e^-$

Requires emission of MeV photons:

- Low accretion rates: from hot accretion flow
- High accretion rate: from corona ?

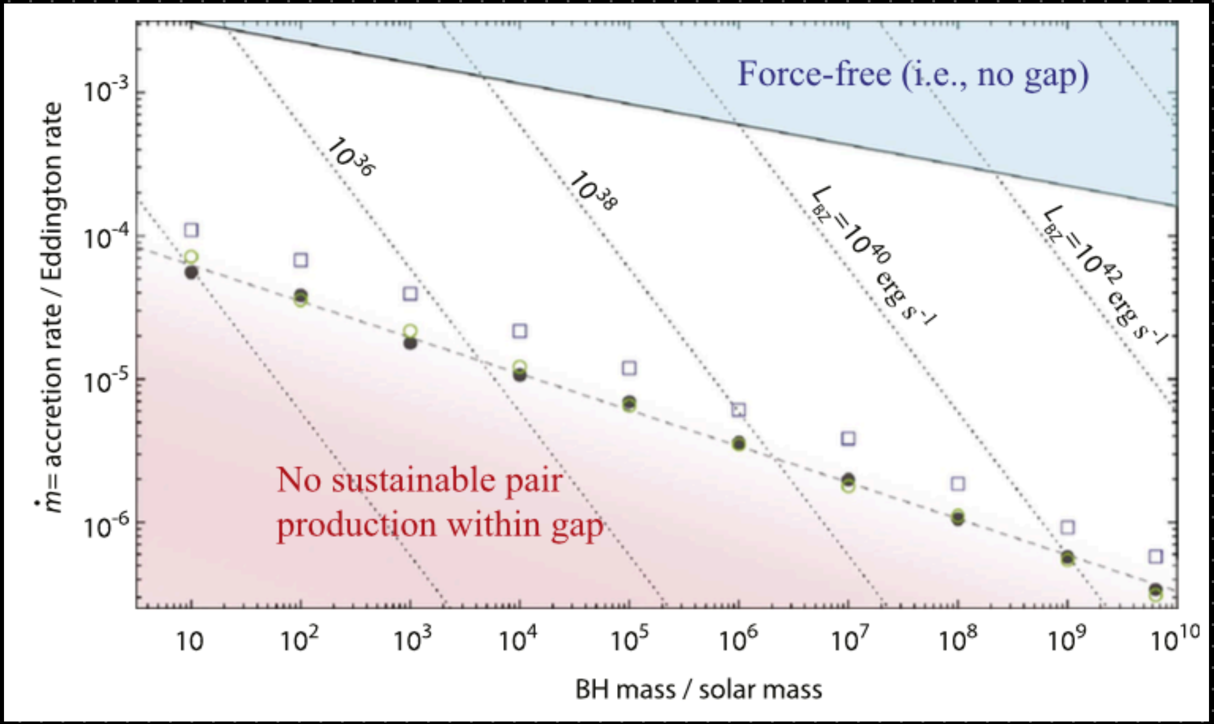


Example: M87



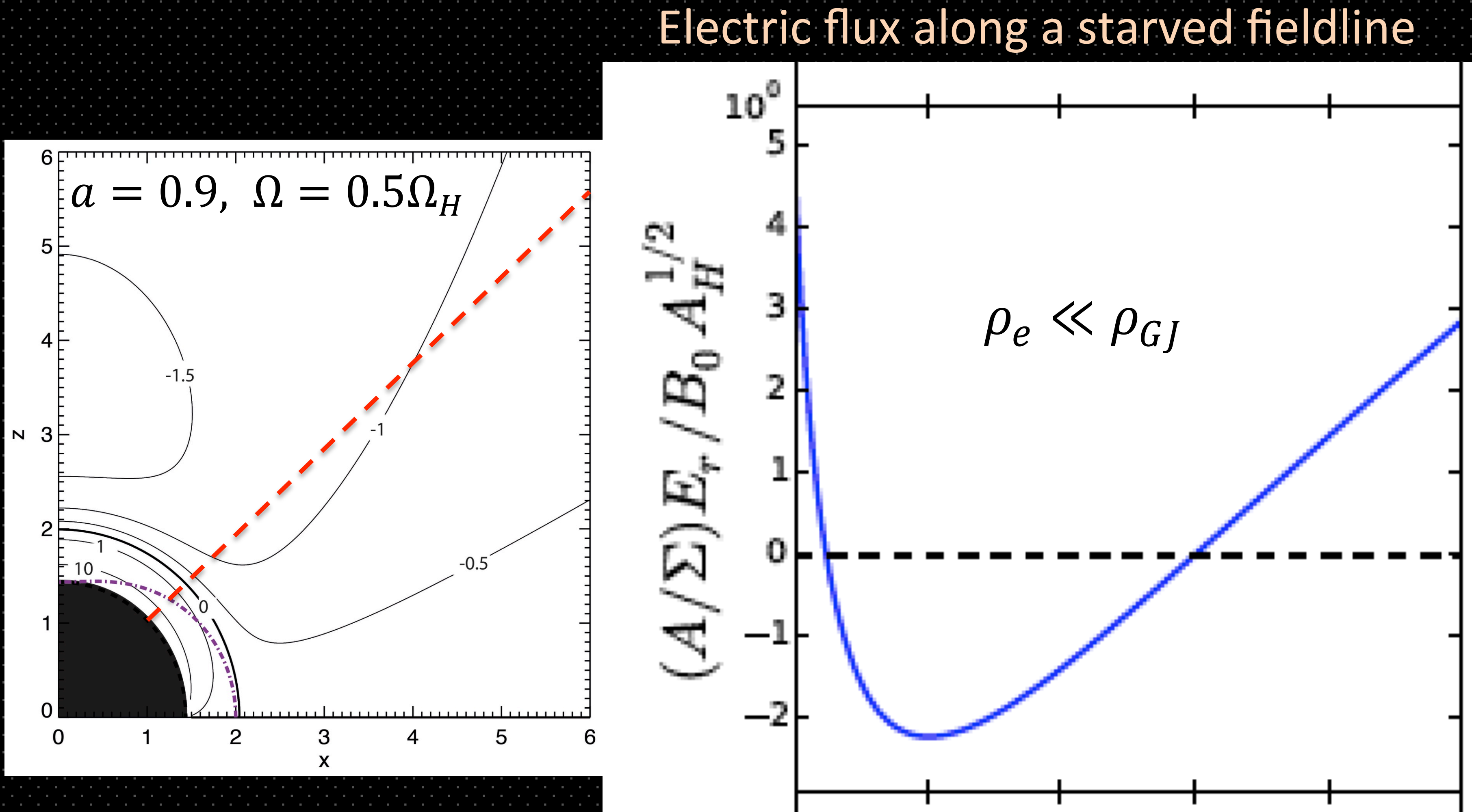
Direct pair injection

- Low accretion rates (RIAF): AC may be hot enough to produce gamma-rays above threshold (Levinson +Rieger 11, Hirotani + 16)



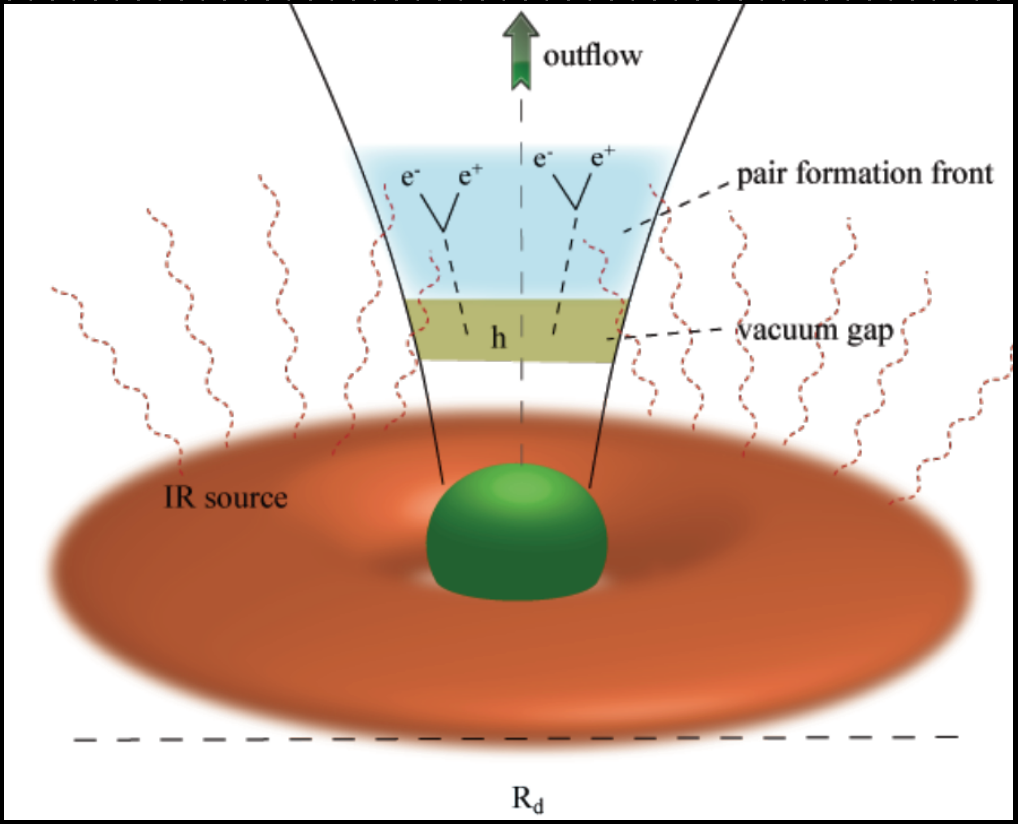
Conditions for gap formation (From Hirotani+ 16)

Starvation


Electric flux along a starved fieldline
$a = 0.9,\ \Omega = 0.5\Omega_H$
-1.5
-1
-0.5
1
10
0
z
x
$(A/\Sigma)E_r/B_0 A_H^{1/2}$
10^0
$\rho_e \ll \rho_{GJ}$

Activation of a spark gaps

AL 00; Neronov + '07, AL + Rieger '11, Broderick + 15; Hirotani+ 16, 17



- activated when $n < n_{GJ}$. Expected in M87 when accretion rate < 10^{-4} Edd.
- must be intermittent (Segev+AL 17).
- particle acceleration to VHE by potential drop.

Challenges

Analysis of gap dynamics requires GRPIC simulations

Multi-scale problem:

Global : $> 10 r_g$

Radiation (Thomson length): $\lambda = r_g/\tau$

Plasma (skin depth): $l = \frac{c}{\omega_{pe}} < \sqrt{\frac{\langle\gamma_e\rangle m_e c^3}{4\pi e^2 n_{GJ}}} \sim 10^{-7}\sqrt{\langle\gamma_e\rangle}\, r_g$

Possible in 1D for local gaps.

Needs rescaling in global 2D sim.

GRPIC Simulations

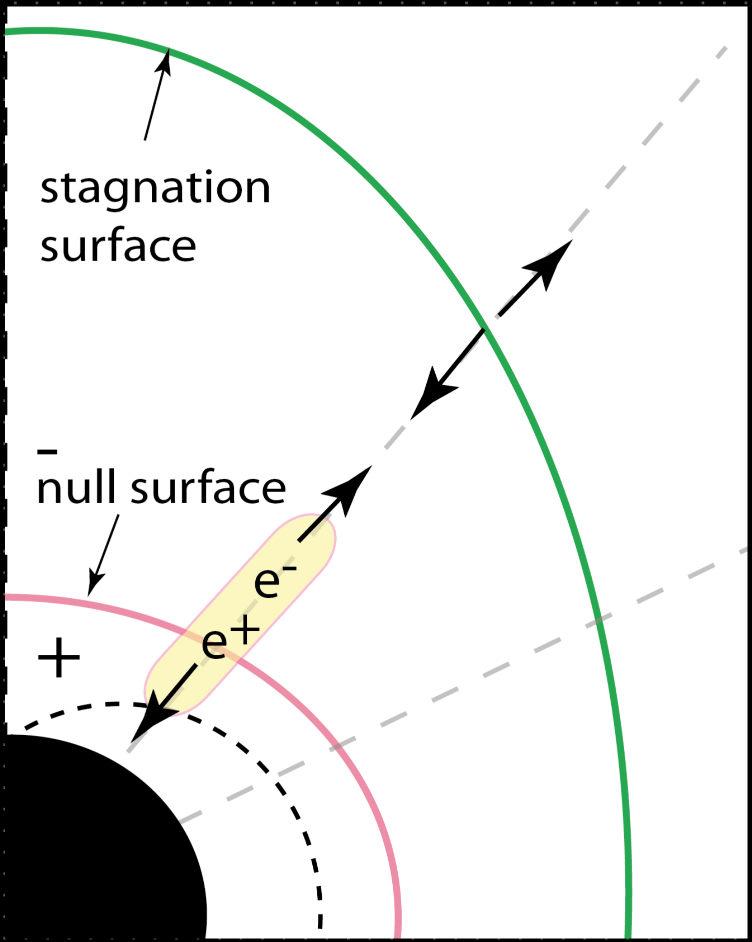
With Benoit Cerutti and his Zeltron code

- Fully GR (in Kerr geometry)
- Inverse Compton and pair production are treated using Monte-Carlo approach.
- Curvature emission + feedback included
- Currently 1D local gaps
- Goal: 2D global simulations

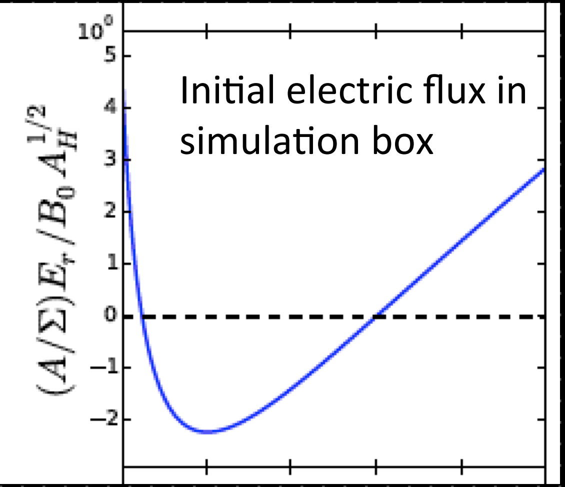
1D model

AL + Cerutti 18

Global structure



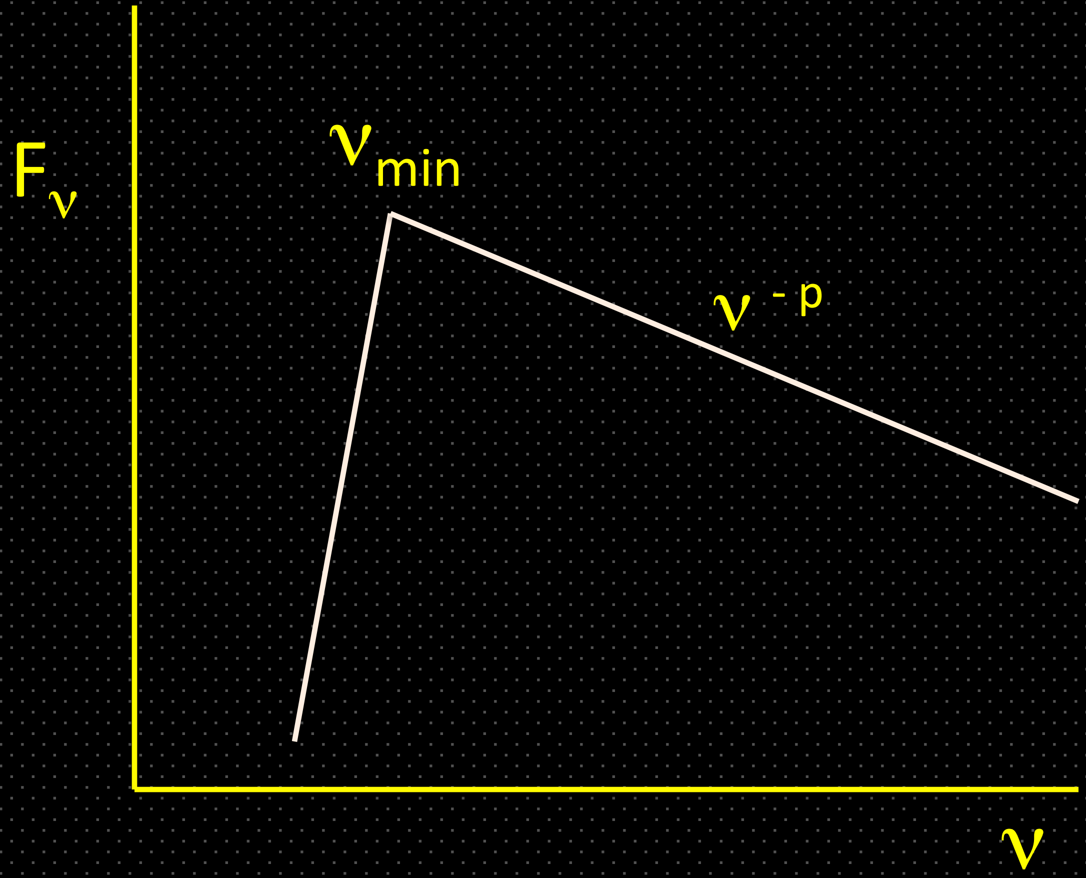
- Solves GRPIC equations along a particular field line
- Magnetospheric current is a given parameter



External radiation field

$\tau_0 = \sigma_T n_{ph} r_g \sim$ Pair-production opacity across gap

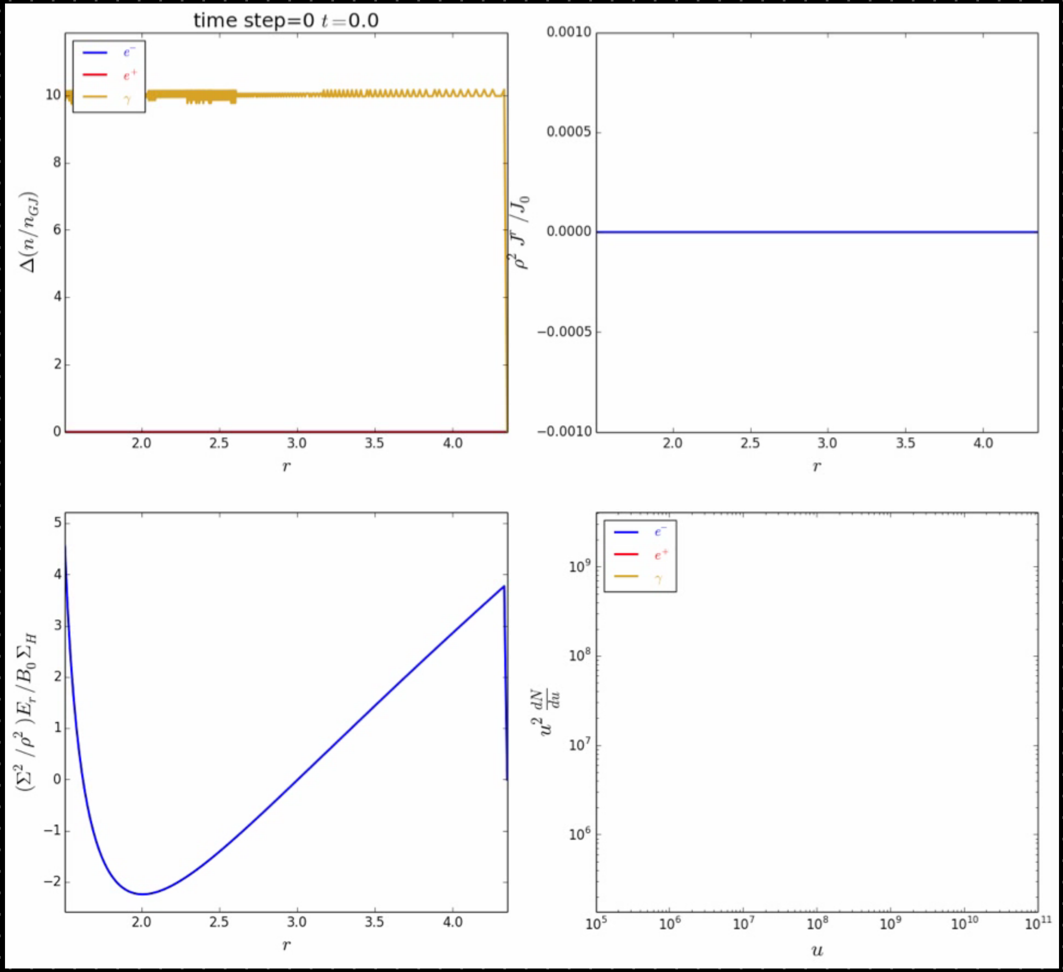
$$\varepsilon_{min} = h\nu_{min}/m_e c^2$$



Example

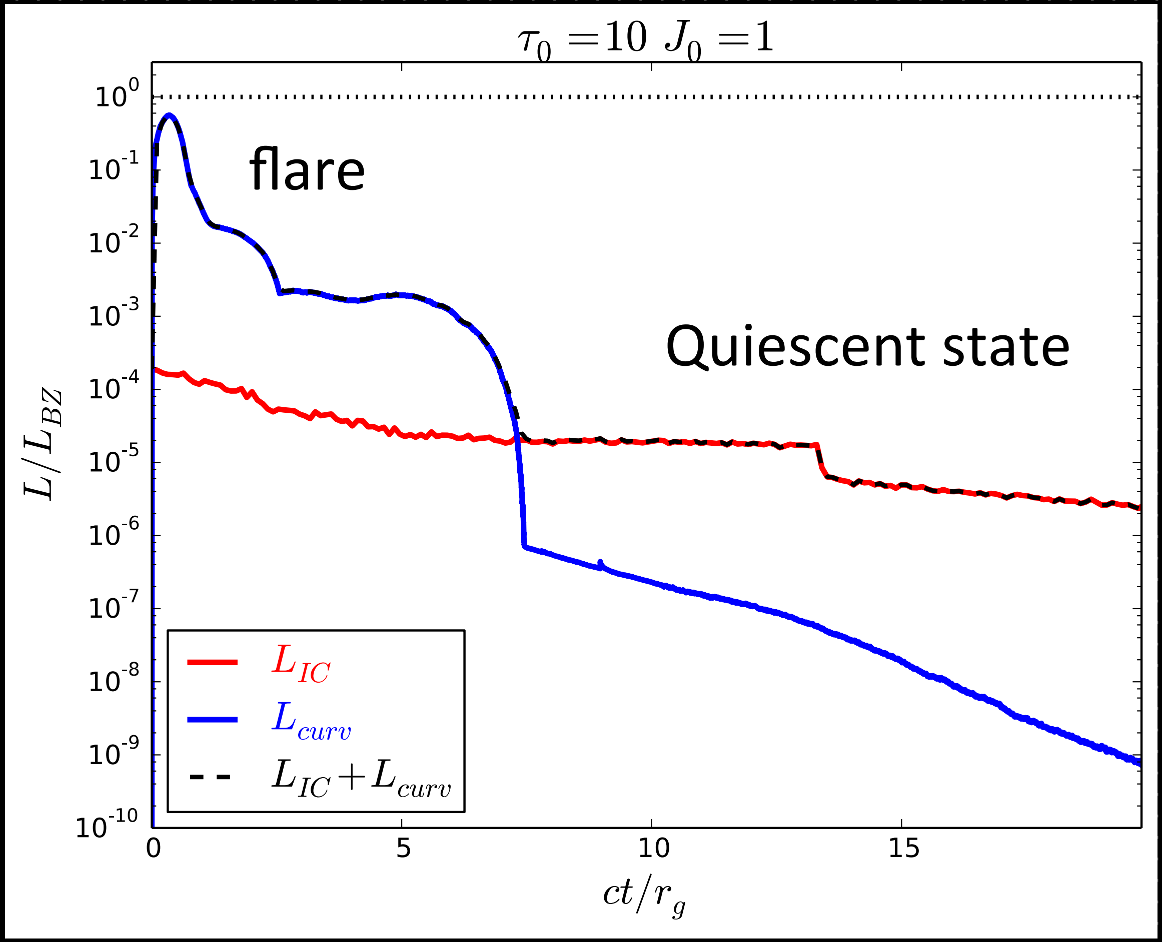
$\tau_0 = \sigma_T n_{ph} r_g \sim$ Pair-production opacity across gap

$$\tau_0 = 10\,, \varepsilon_{min} = 10^{-8}, p = 2$$

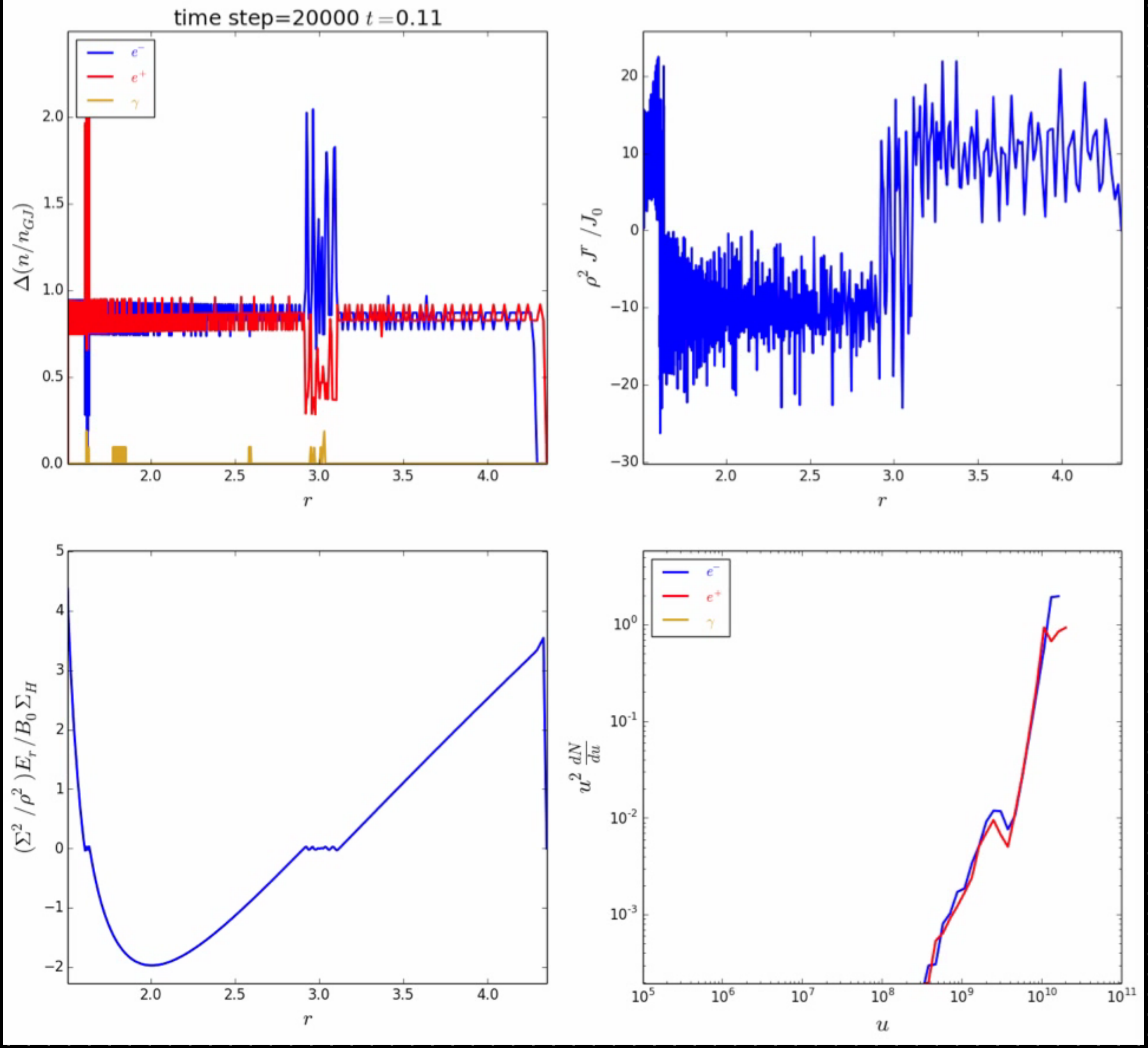


Radiation reaction limit

γ Light curve



$\tau_0 = 10\,, \varepsilon_{min} = 10^{-8}$, p=2

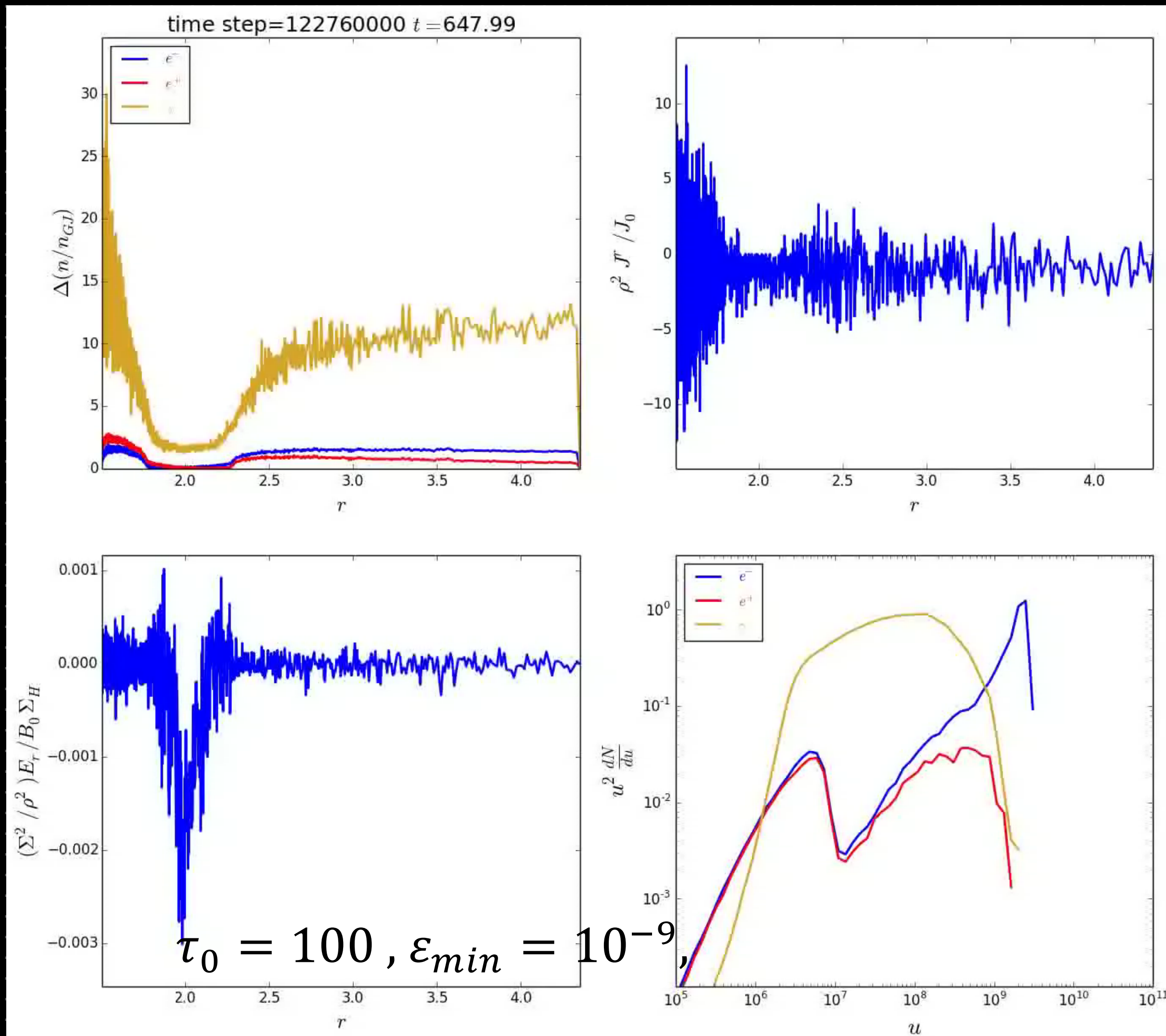


Shota Kisaka+AL

Gap oscillations

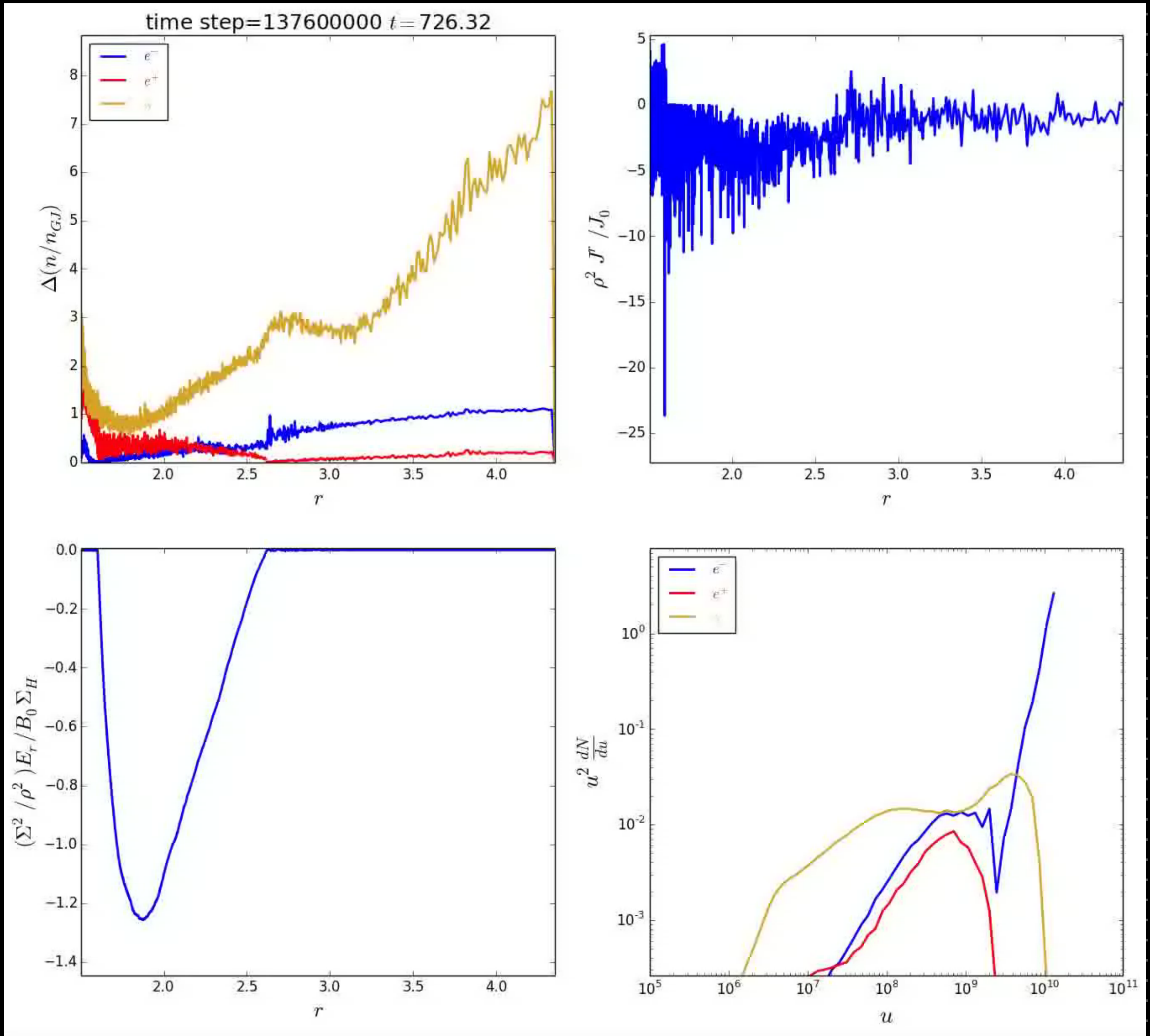
Shota Kisaka+AL

$\tau_0 = 100$



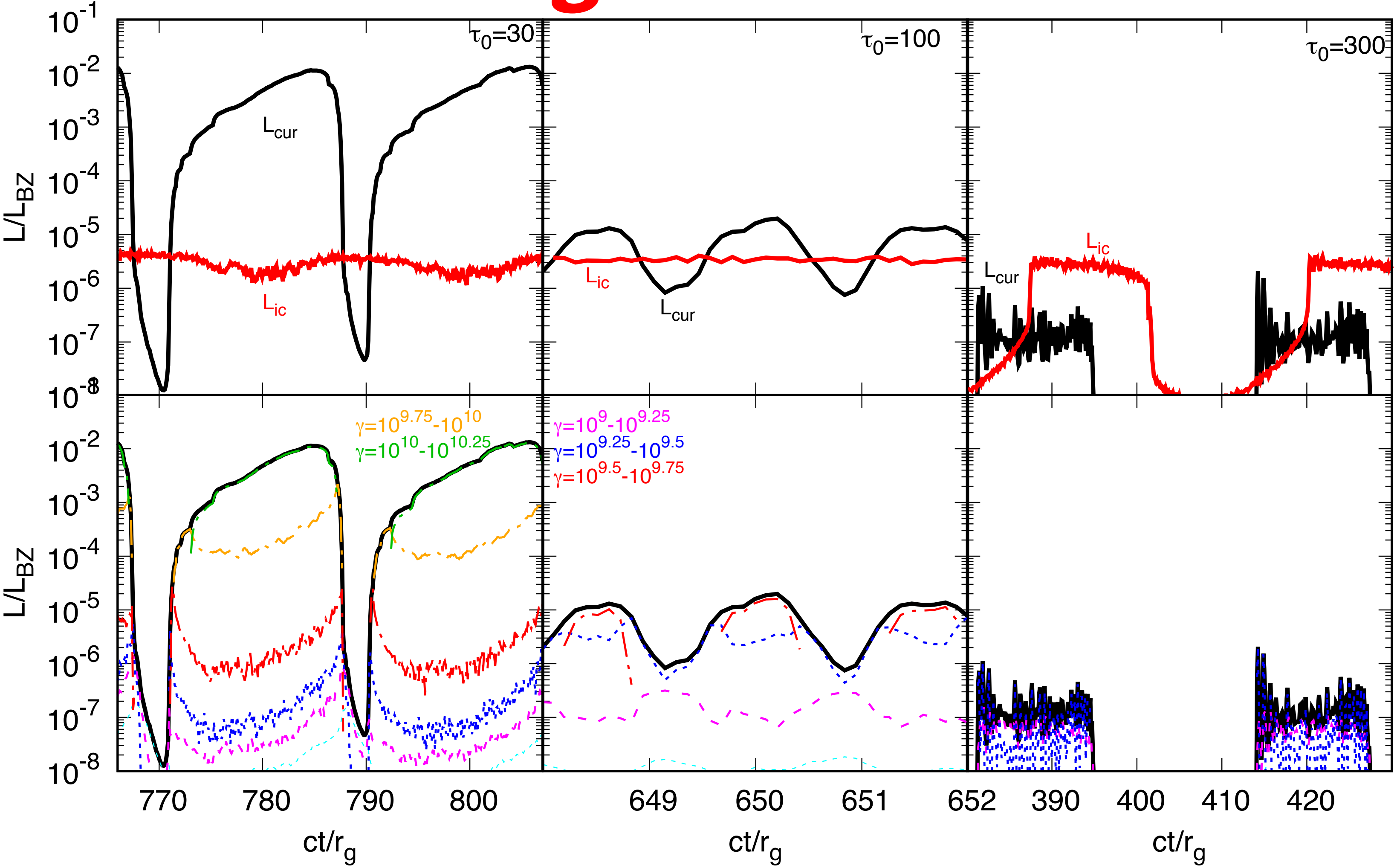
$\tau_0 = 100\,, \varepsilon_{min} = 10^{-9},$

$\tau_0 = 30$



time step=137600000 $t=726.32$
$\Delta(n/n_{GJ})$
e^-
e^+
r
$\rho^2\ J^r\ /J_0$
$(\Sigma^2\ /\rho^2\ )E_r/B_0\Sigma_H$
$u^2\frac{dN}{du}$
u

Light curve



Characteristic energy of curvature radiation $\epsilon_{\rm cur} \sim 10^6 \gamma_{10}^3$

Global 2D GRPIC experiments: Challenges

- System is rescaled to resolve skin depth

Radiation: $\lambda = r_g/\tau$

Plasma (skin depth):

$$l = \frac{c}{\omega_{pe}} < 10^{-7}\sqrt{\langle \gamma_e \rangle}\, r_g$$

(Parfrey+19)

Conclusions

- spark gaps may form if survival time of coherent magnetic domains exceeds a few dynamical times. May be the production sites of variable VHE emission.
- gaps are inherently intermittent, or cyclic.
- strong TeV flares can be produced if gap is restored
- Future, global GRPIC sims, may shade more light, but need careful rescaling.