GRPIC simulations of pair discharges in a starved BH magnetosphere

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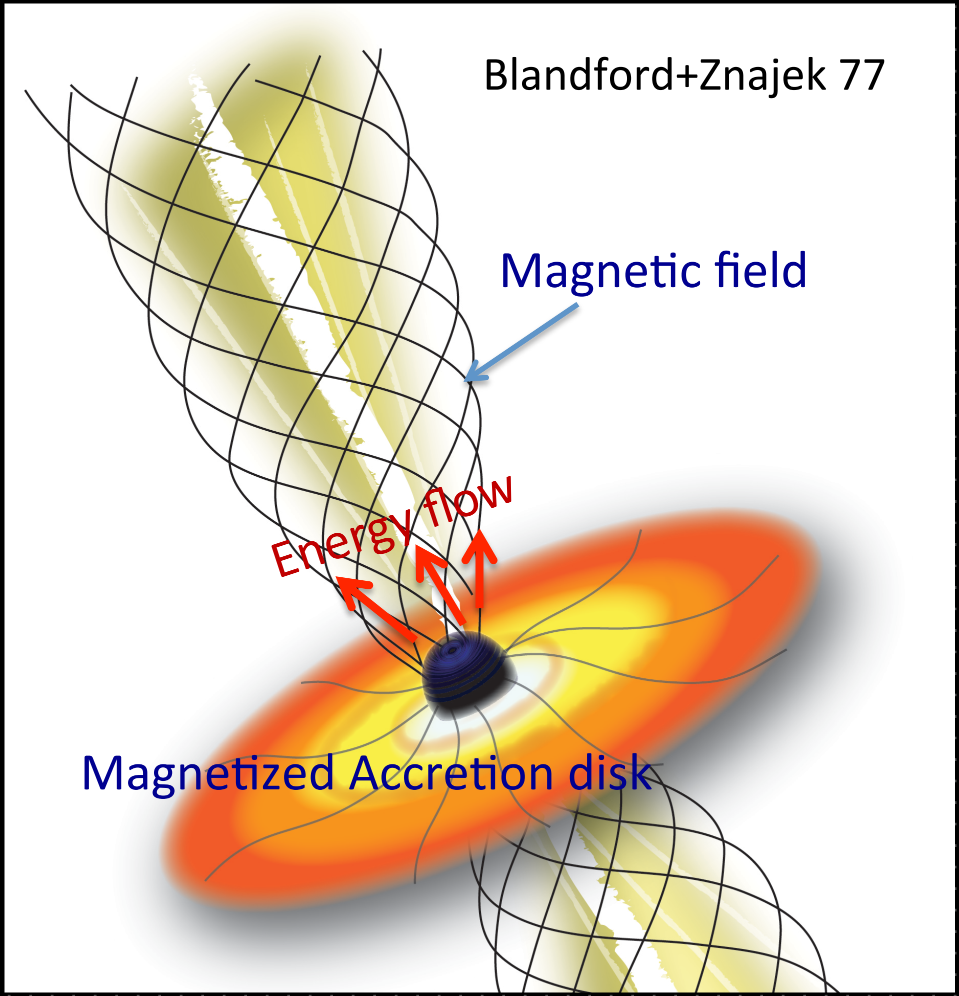
Outline

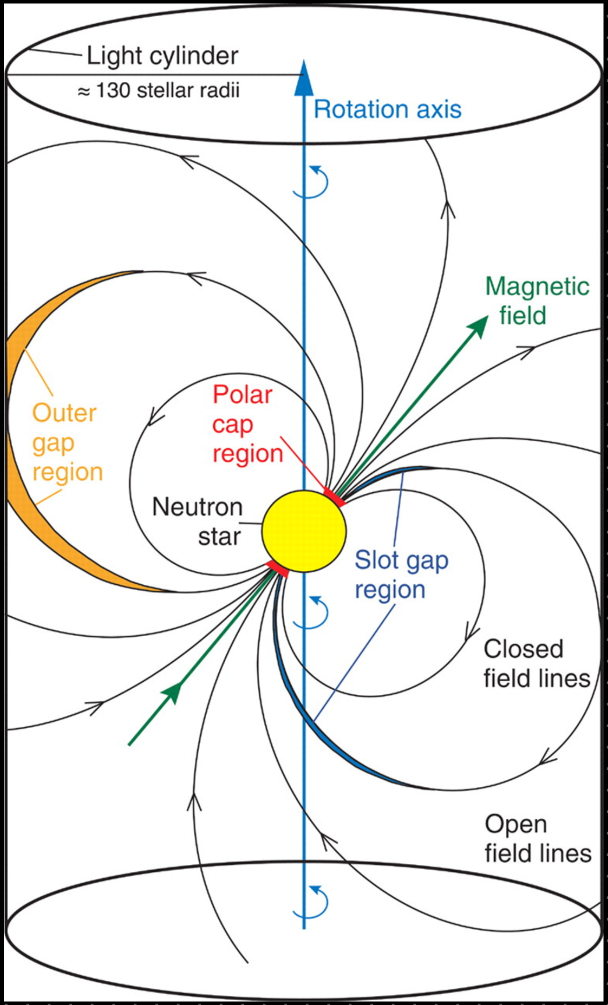
- Theoretical and observational motivation
- A comment on steady gap solutions
- GR PIC simulations

Outflow from a rotating magnetosphere

Kerr black hole



Neutron star



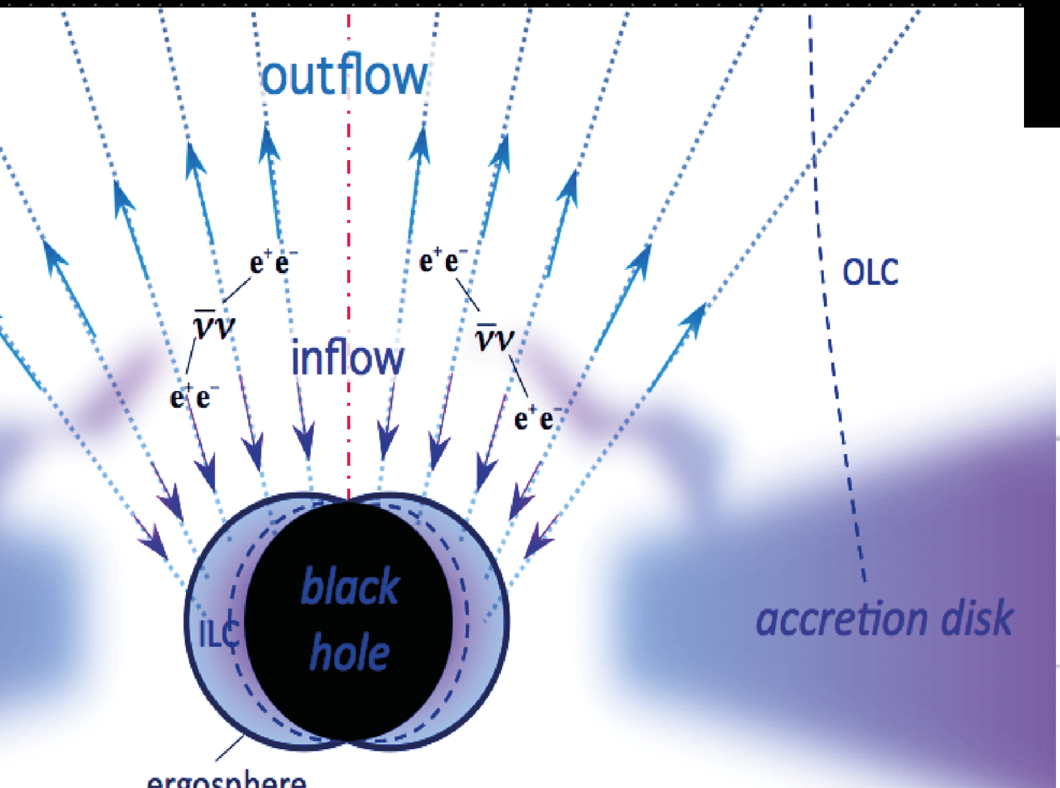
Plasma injection in the magnetosphere

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

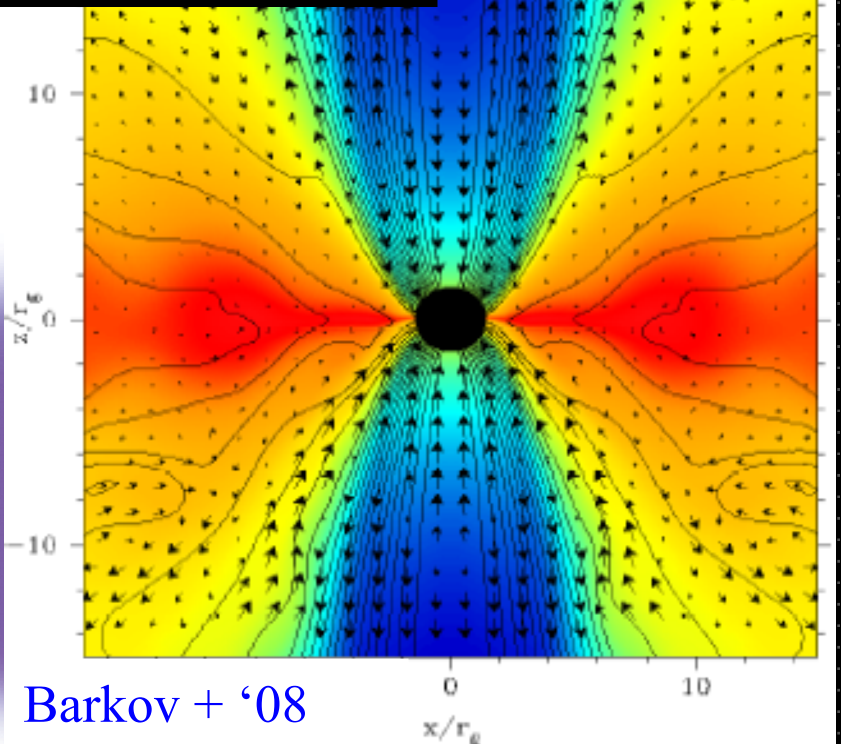
$\gamma\gamma \rightarrow e^{\pm}$ in AGNs

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

mass loading ?



Globus+AL 2014



Barkov + '08

How much is needed?

E field in magnetosphere is screened out:

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

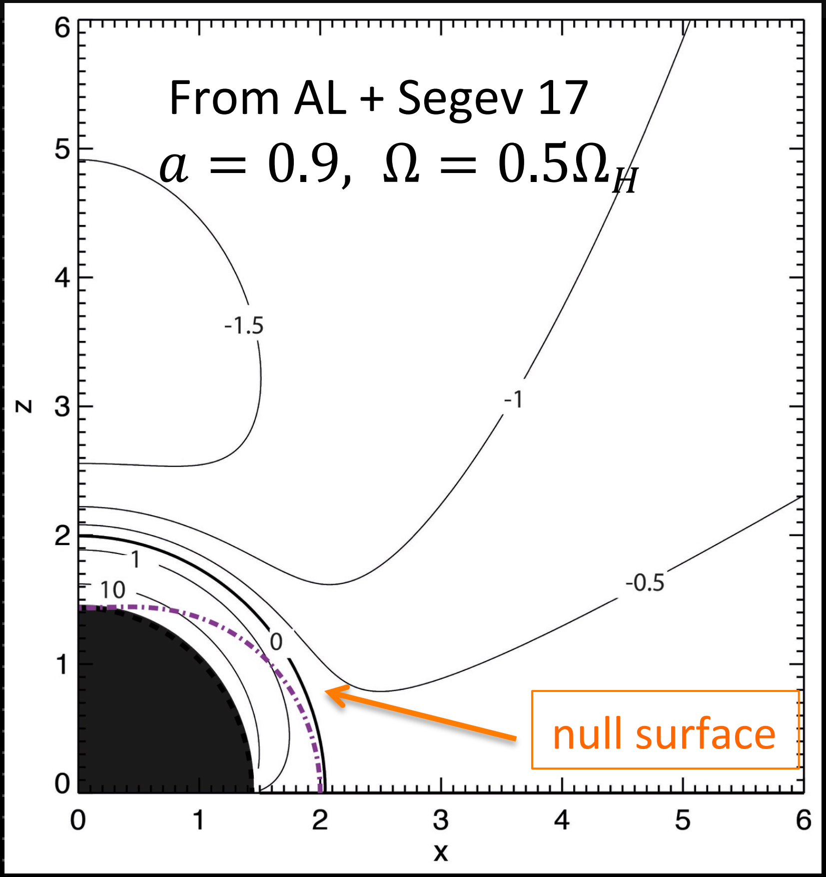
$$\rho_e = \frac{\nabla\cdot\vec{E}}{4\pi} = -\frac{\nabla\cdot\left(\vec{v}\times\vec{B}\right)}{4\pi} = -\frac{\vec{\Omega}\cdot\vec{B}}{2\pi} \equiv \rho_{GJ}$$

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

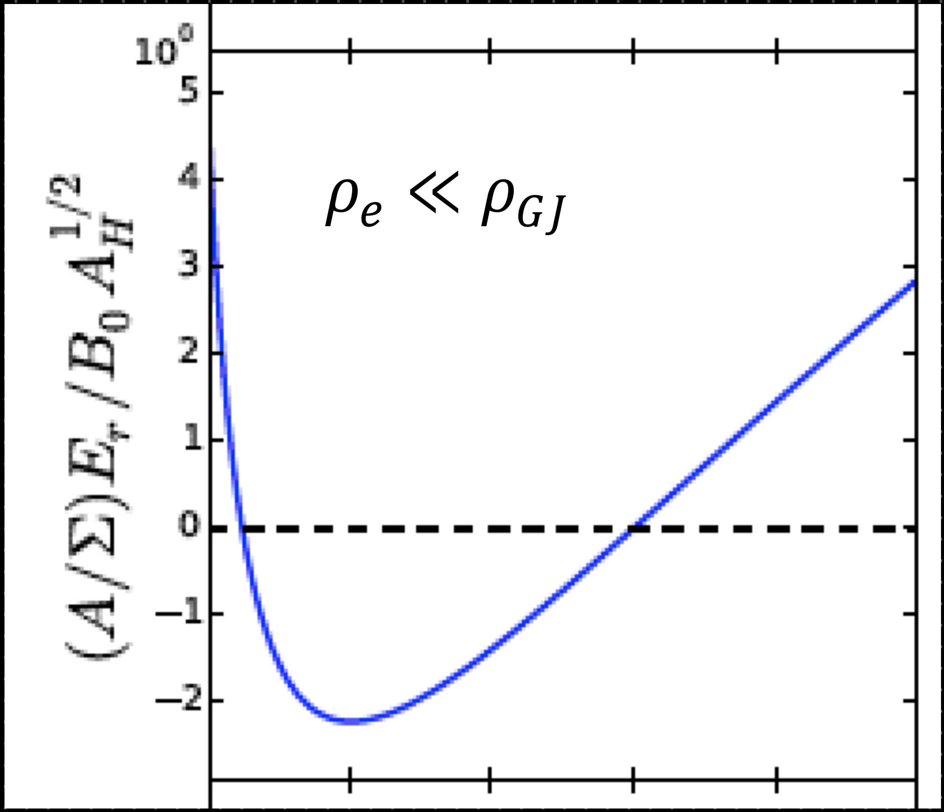
Otherwise the magnetospere becomes charge starved, $\vec{E}\cdot\vec{B} \neq 0$

In Kerr geometry

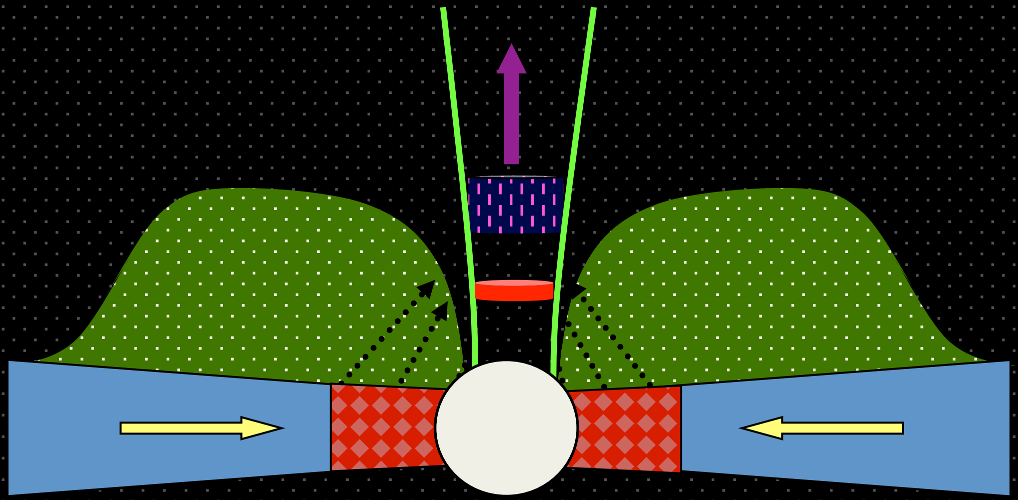
$$\rho_{GJ} = \frac{1}{4\pi\sqrt{-g}}\partial_\mu\left[\frac{\sqrt{-g}g^{\mu\nu}}{\alpha^2}(\omega-\Omega)F_{\nu\varphi}\right]$$



Electric flux in starved region



How to produce the required charge density?



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

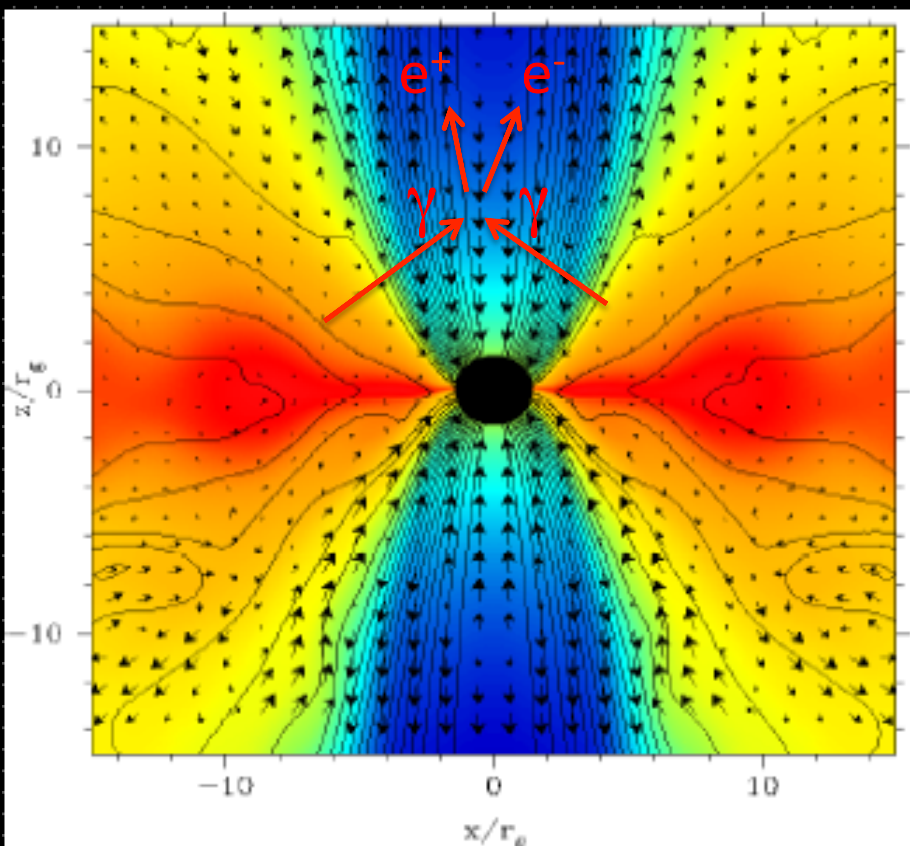
➢ Protons have to cross magnetic field lines. Diffusion length over accretion time extremely small.

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

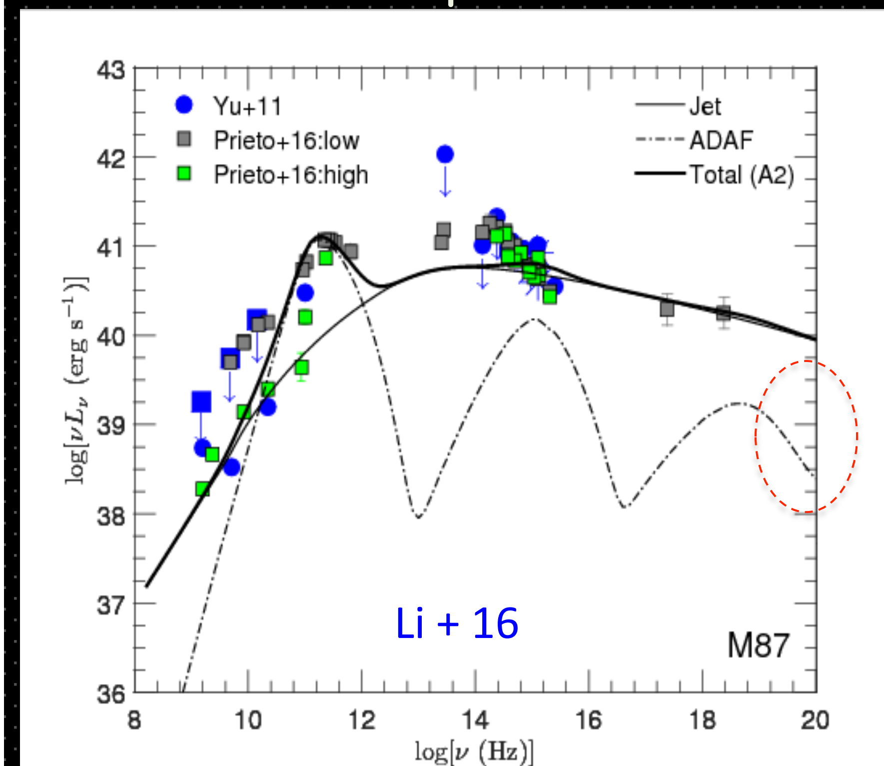
Direct pair injection by $\gamma\gamma \rightarrow e^{\pm}$

Requires emission of MeV photons:

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

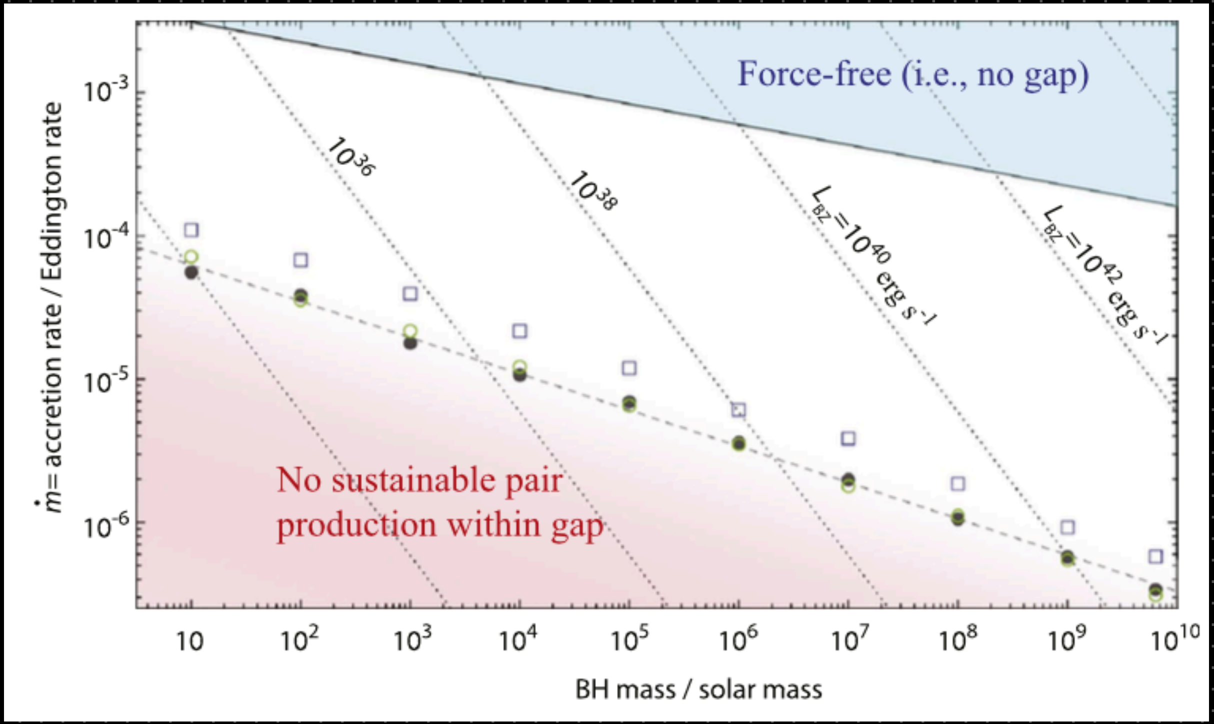


Example: M87



Direct pair injection

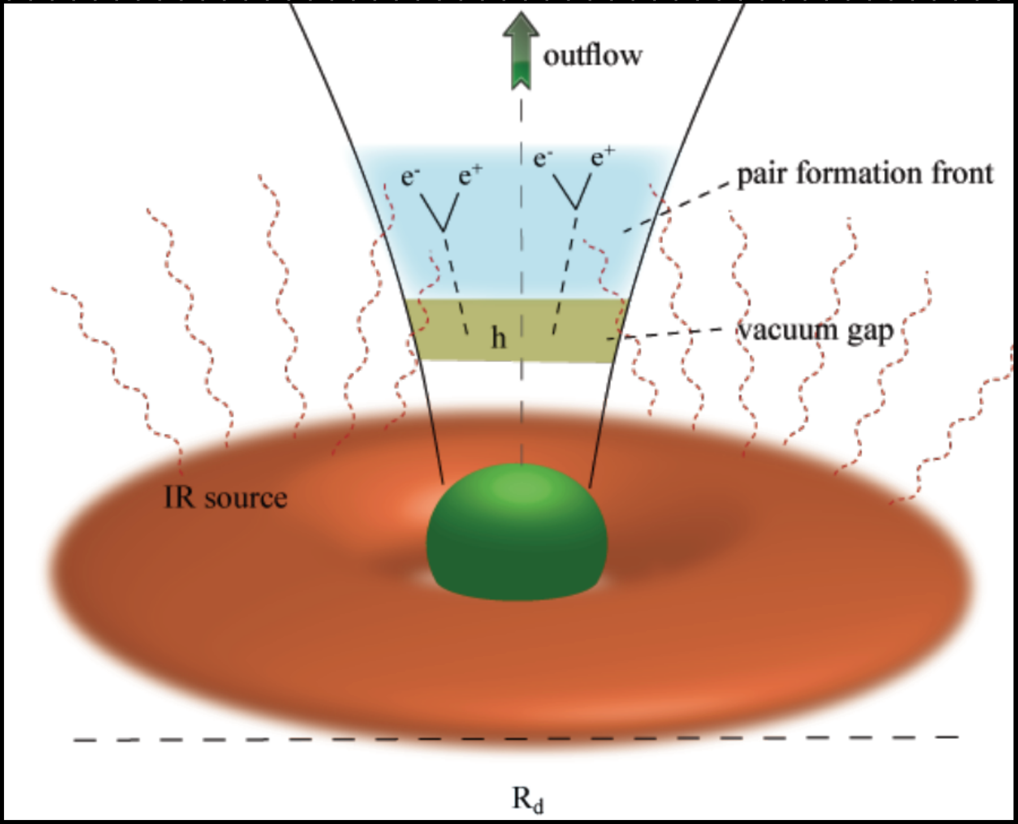
- Low accretion rates (RIAF): AC may be hot enough to produce gamma-rays above threshold (Levinson +Rieger 11, Hirotani + 16)



Conditions for gap formation (From Hirotani+ 16)

Activation of a spark gaps

AL 00; Neronov + '07, AL + Rieger '11, Broderick + 15; Hirotani+ 16, AL+Cerutti 18



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

Steady gap model in brief

Gap structure is determined by 2 input parameters:

- global magnetospheric current
- pair production opacity

- invoke B field geometry + properties of seed photon source,
- solve $\partial_\mu \left(\frac{\sqrt{-g}}{\alpha^2} F_t^{\mu} \right) = 4\pi\sqrt{-g}(\rho_e - \rho_{GJ})$

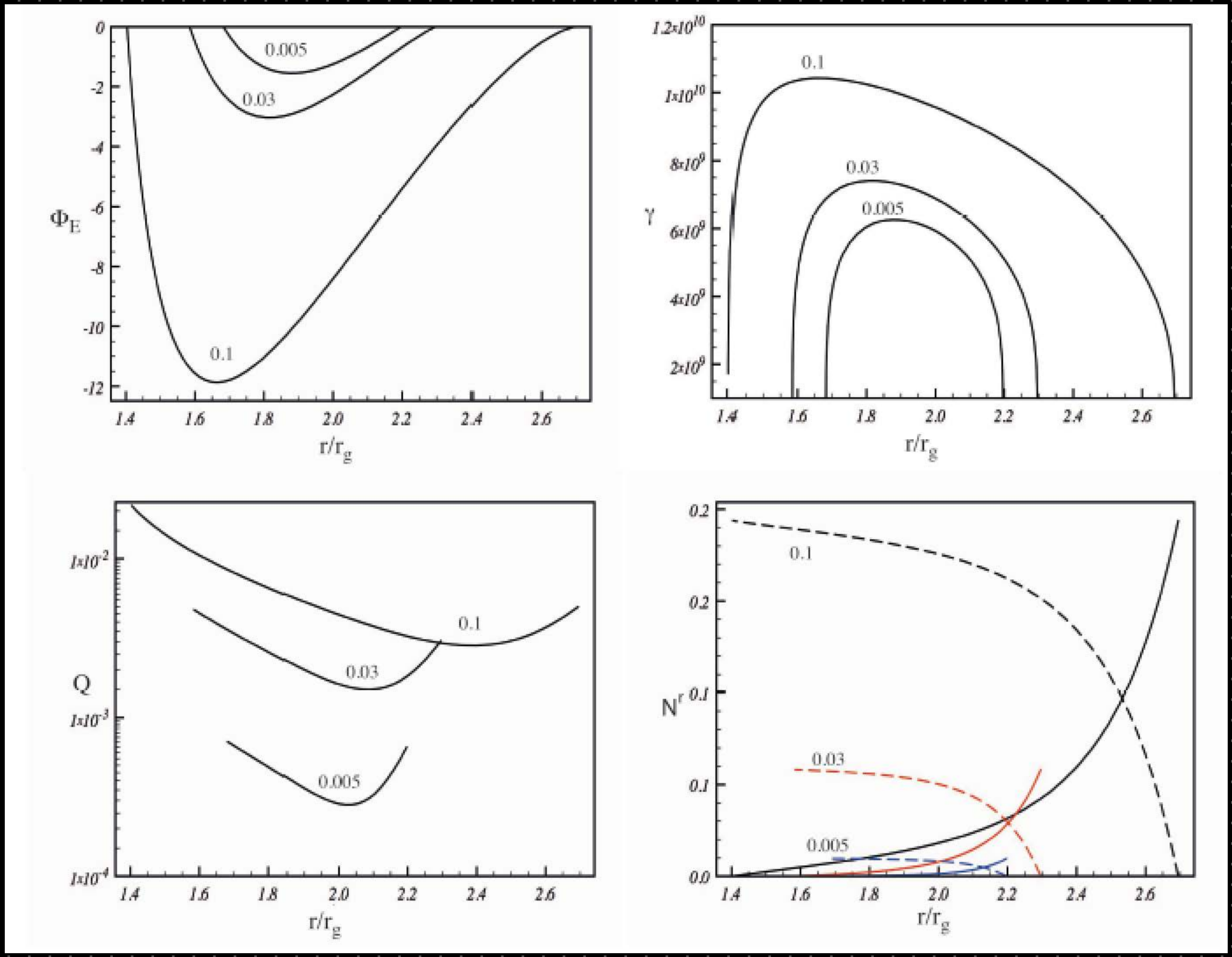
  +Eq of motion for pairs

  + radiative transfer (with IC and curvature sources)

  + pair production (continuity Eq)
- iterate until all boundary conditions are met.

example

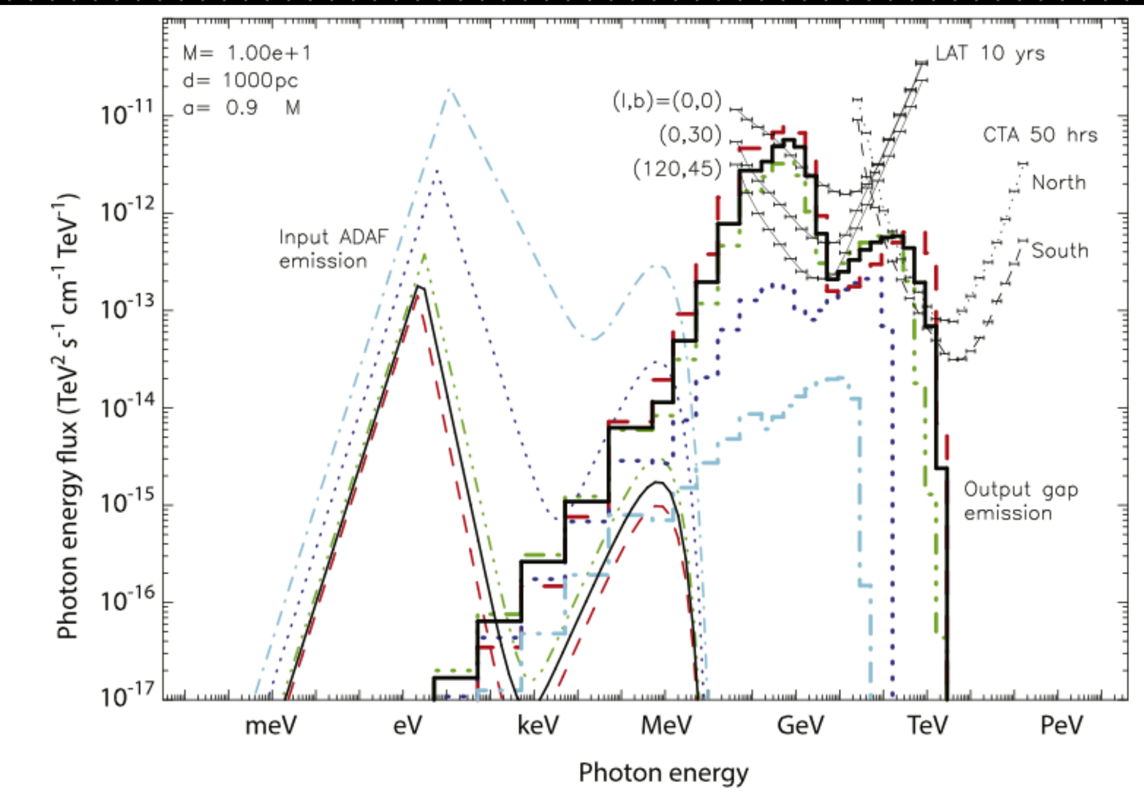
AL + Segev 17



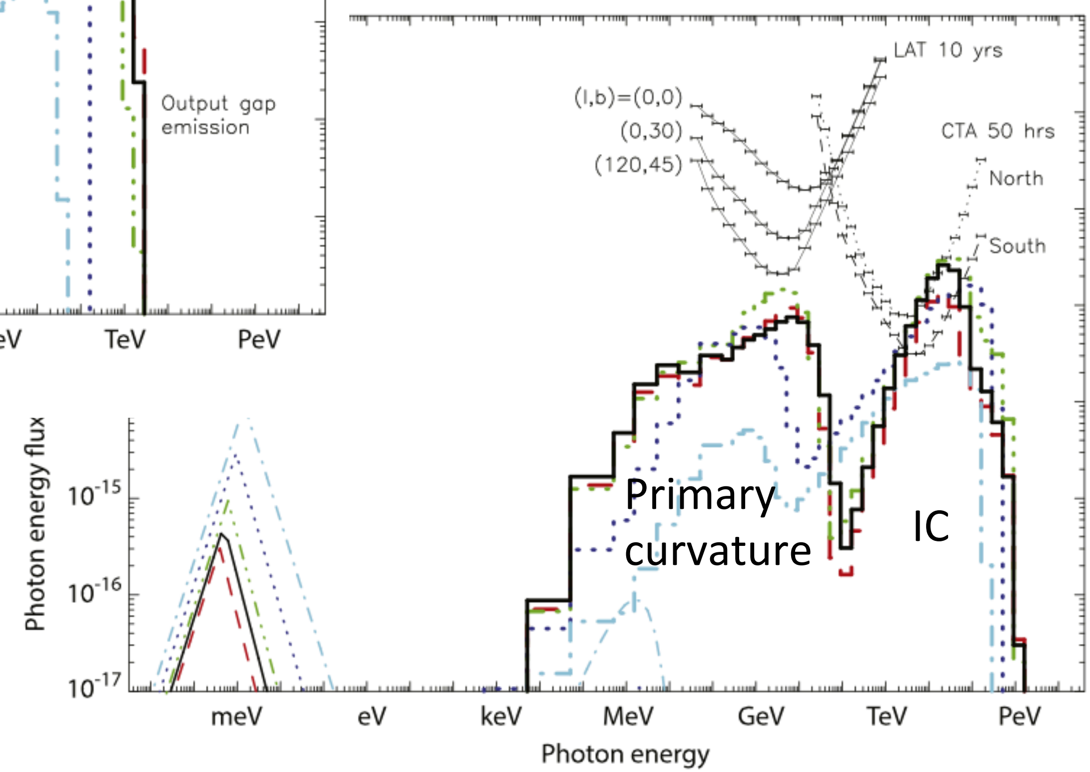
Gap location is fixed by magnetospheric current and disk luminosity

Gap spectra (Hirotani + 16, 17)

Stellar BH (M=10)



supermassive BH (M=10^9)

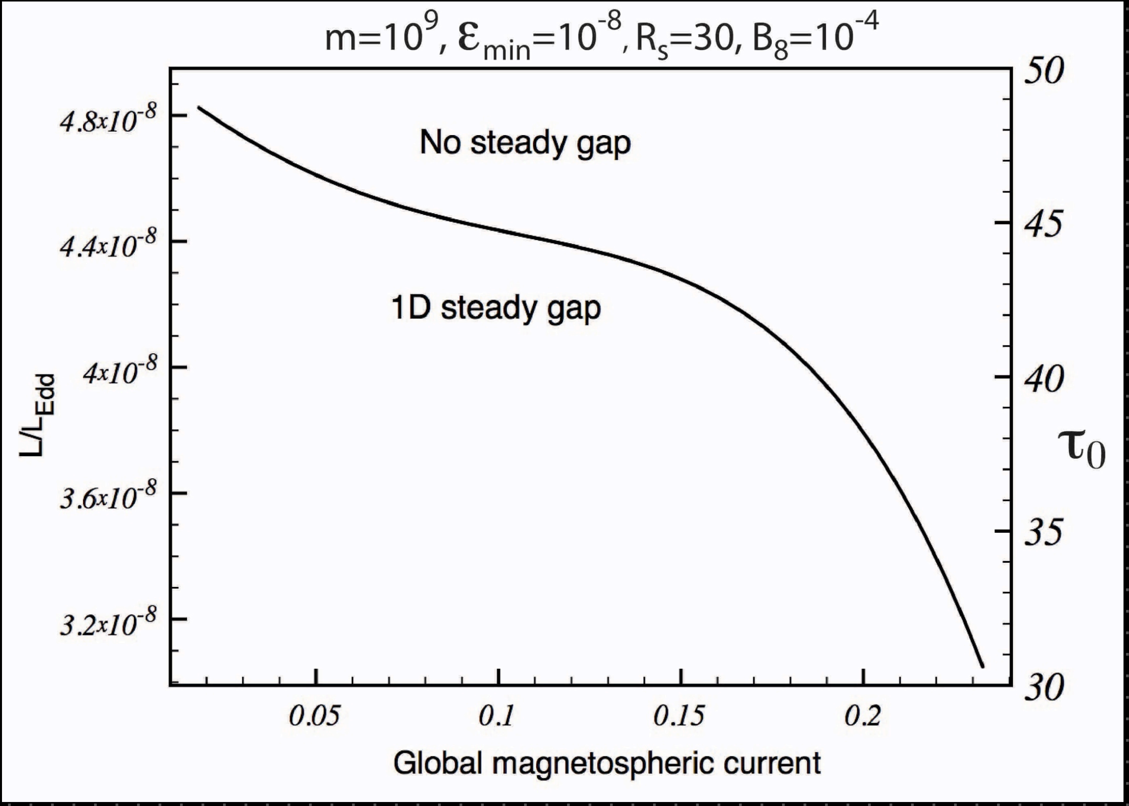


Peak energy scales roughly as $M_{BH}^{1/4}$

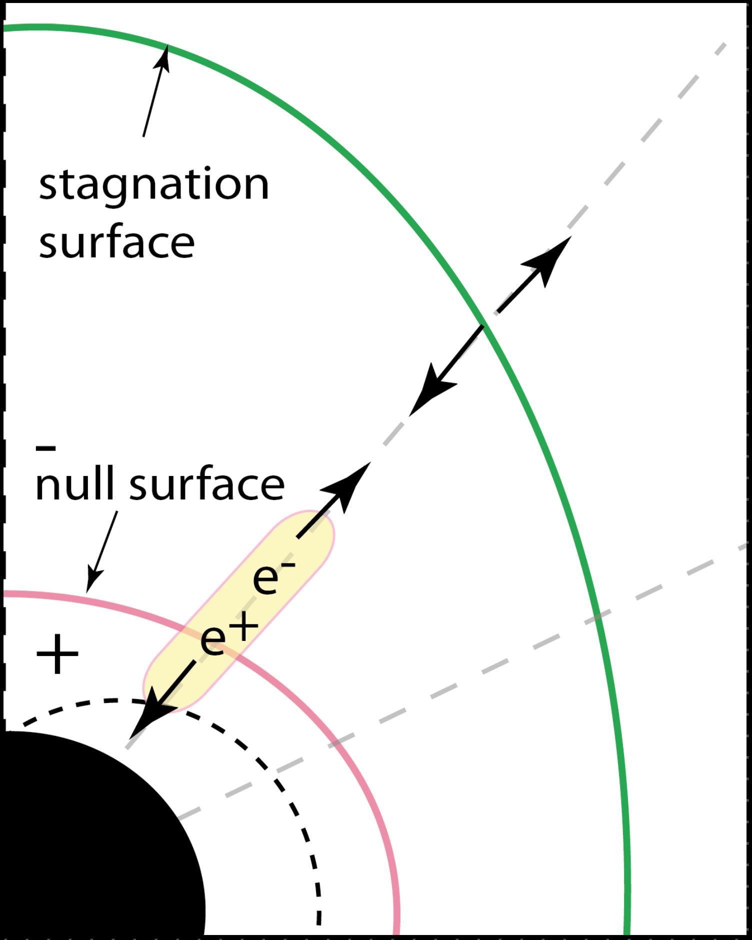
Inherent intermittency

AL + Segev 17

Local condition



Global inconsistency



Reason: multiplicity =1 by construction

GRPIC Simulations

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

We used Boyer-Lindquist tortoise coordinate, with r replaced by a tortoise coordinate:

units $d\xi = r_g^2 dr/\Delta$). It is related to r through:

$$\xi(r) = \frac{1}{r_+ - r_-} \ln\left(\frac{r - r_+}{r - r_-}\right), \tag{3}$$

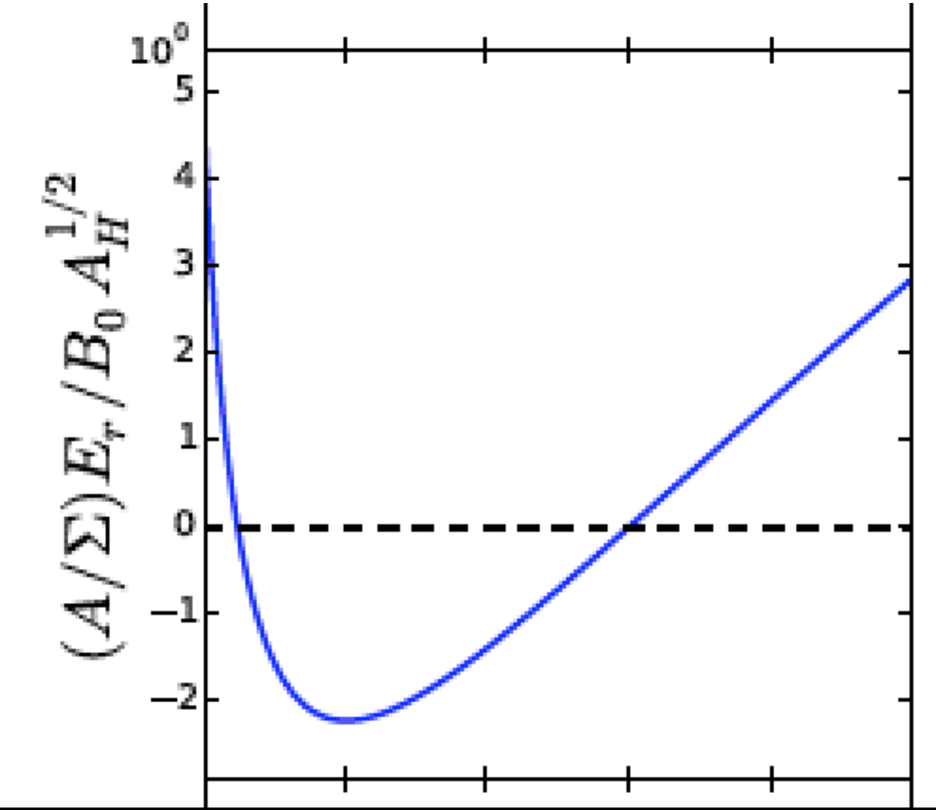
with $r_\pm = 1 \pm \sqrt{1 - \bar{a}^2}$. Note that $\xi \to -\infty$ as $r \to r_H = r_+$,

Field dynamics

$$\partial_t(\sqrt{A}E_r) = -4\pi(\Sigma j^r - J_0),$$

Initial state

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



Initial electric flux in simulation box

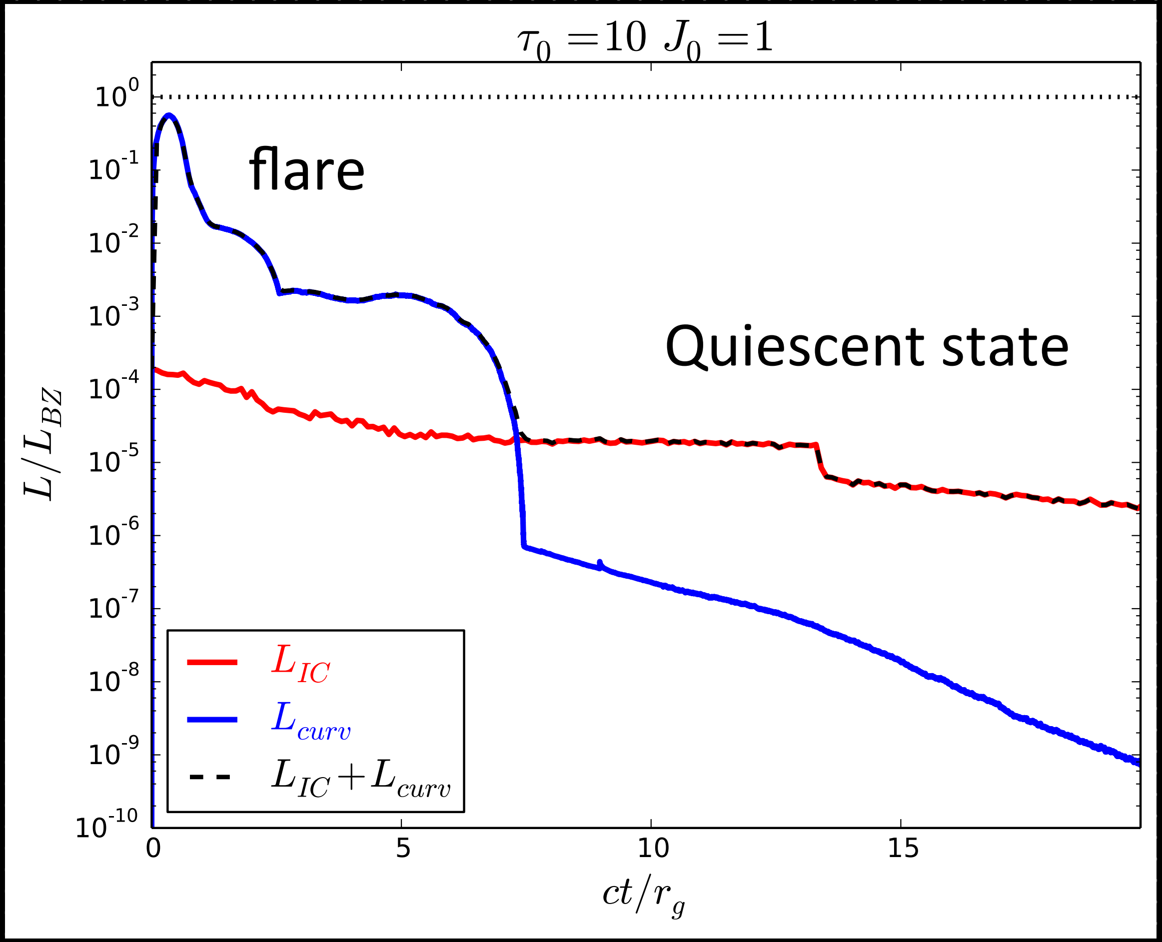
Example

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

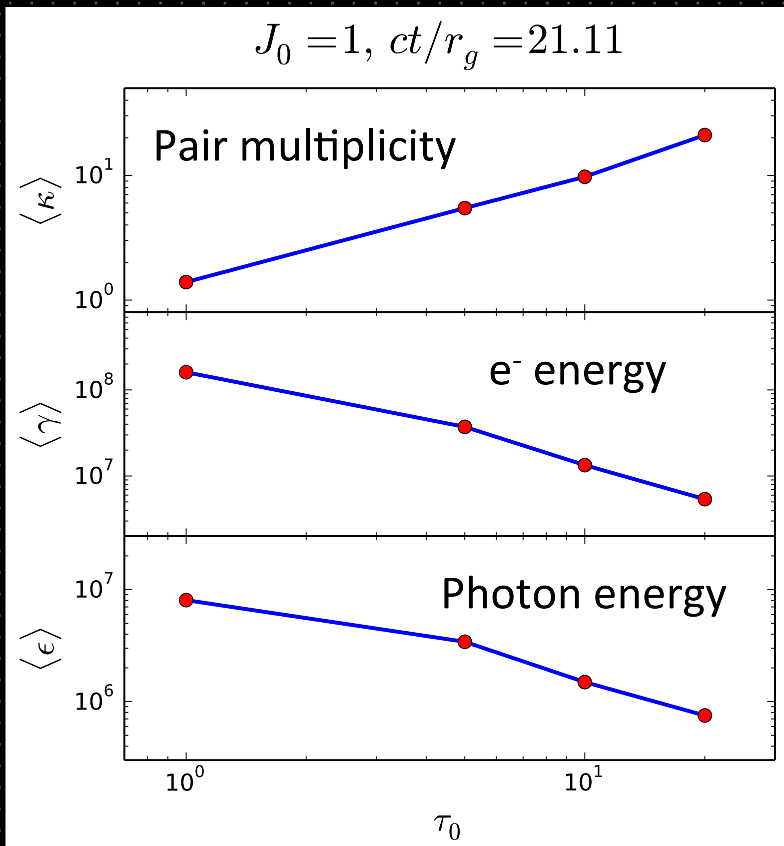
$$\tau_0 = 10$$

Radiation reaction limit

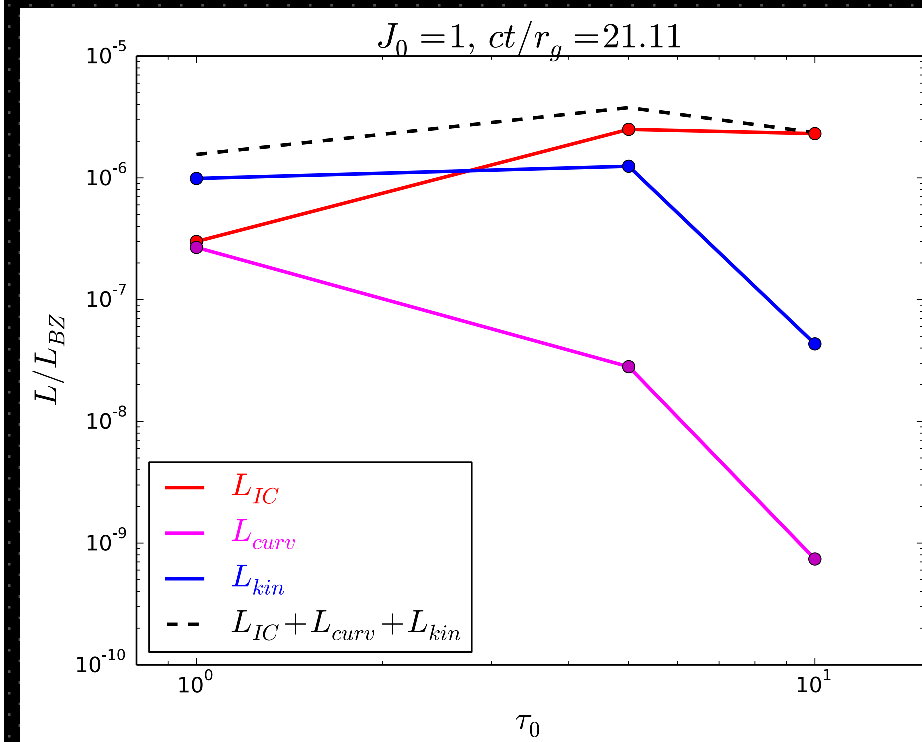
Light curve



$\tau_0 = 10 \; J_0 = 1$
flare
Quiescent state
L/L_{BZ}
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0
5
10
15
ct/r_g
L_{IC}
L_{curv}
$L_{IC}+L_{curv}$

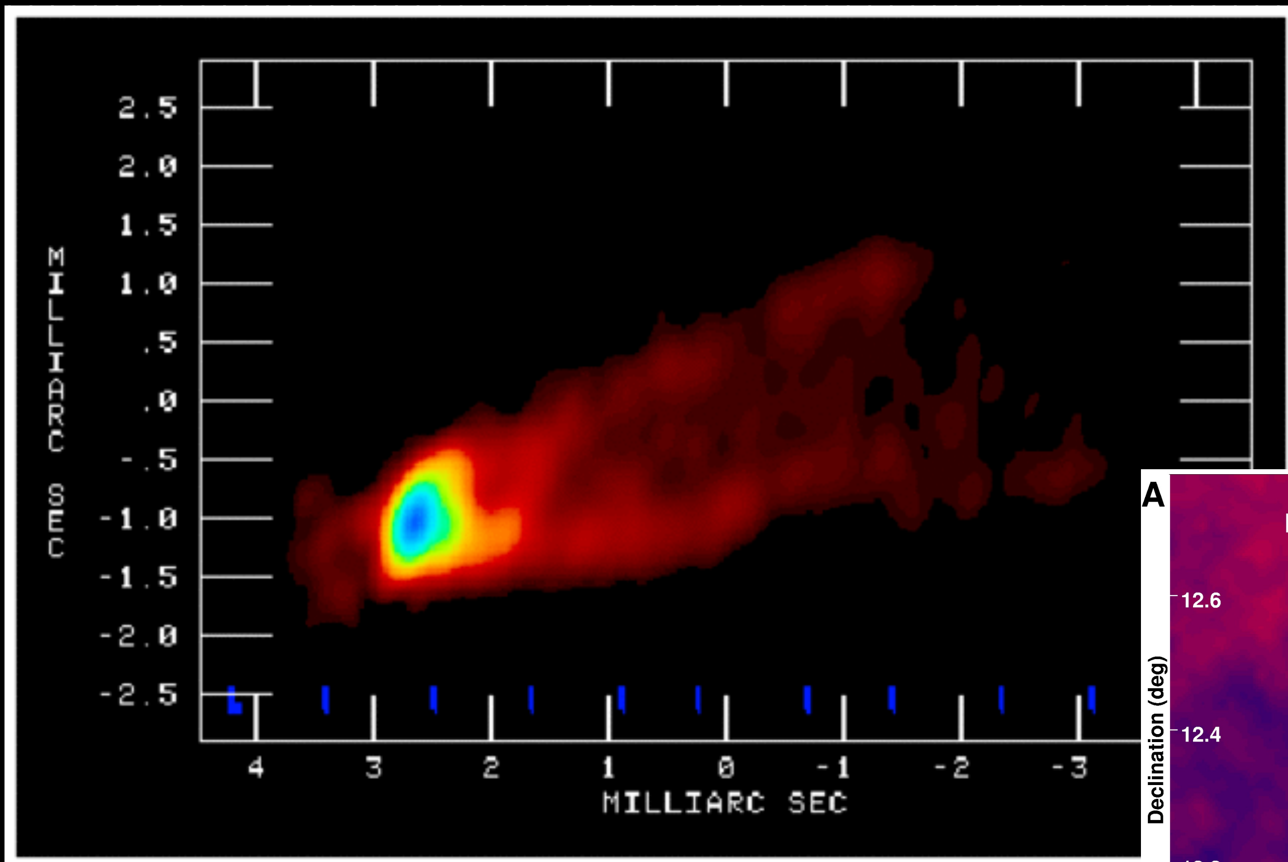


Luminosity during quiescent state

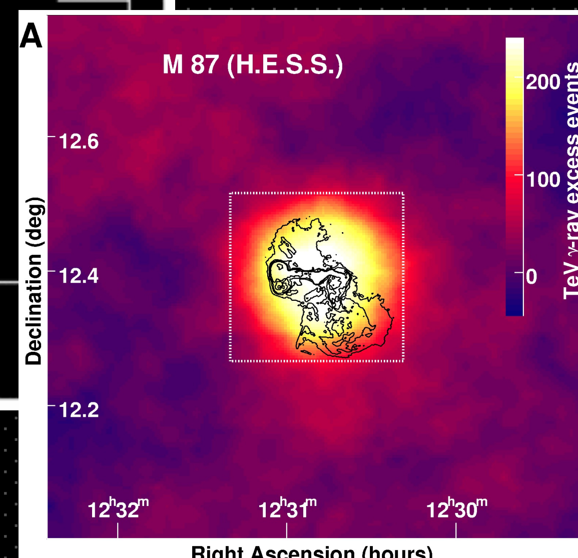


$\tau_0 = 0.01$

M87 VLBA movie (43 GHz)



TeV source

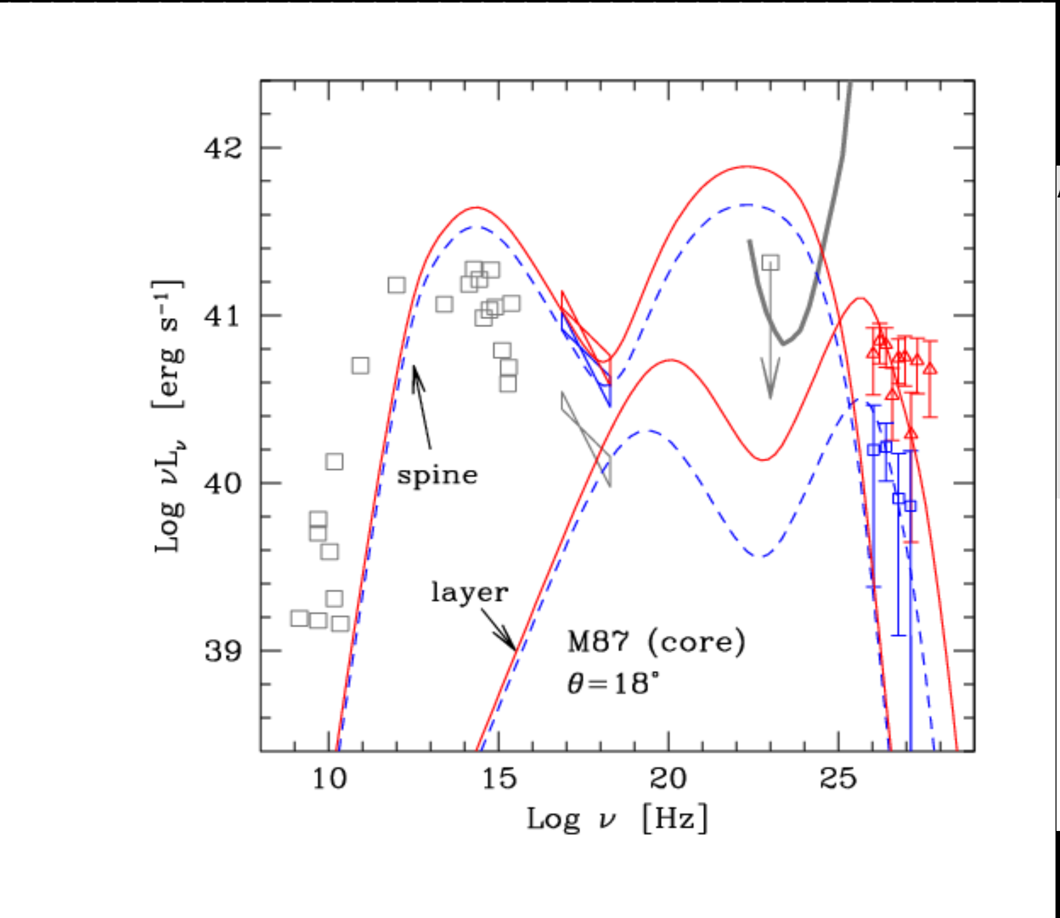


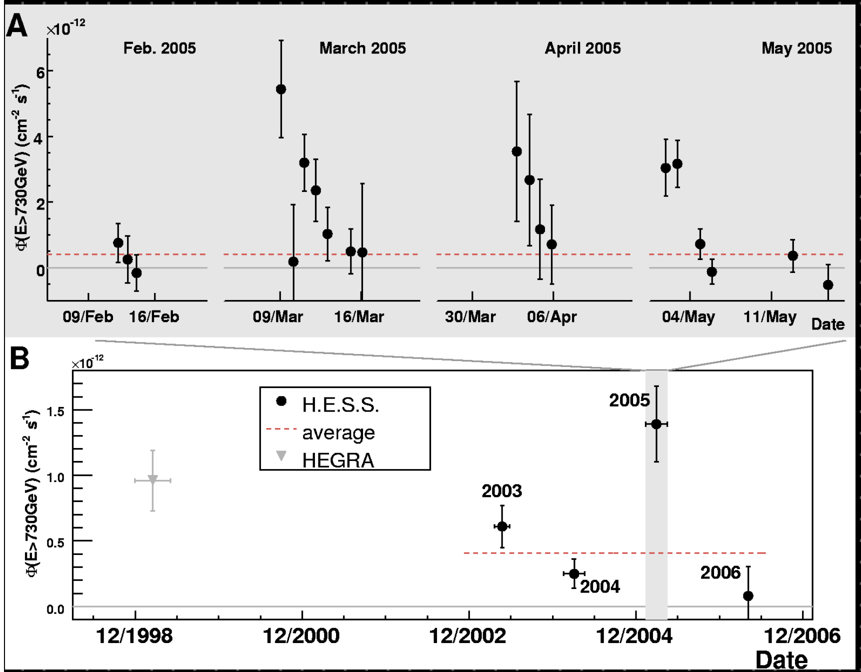
M87- VHE emission

Strong flares observed in 2005, 2008, 2010

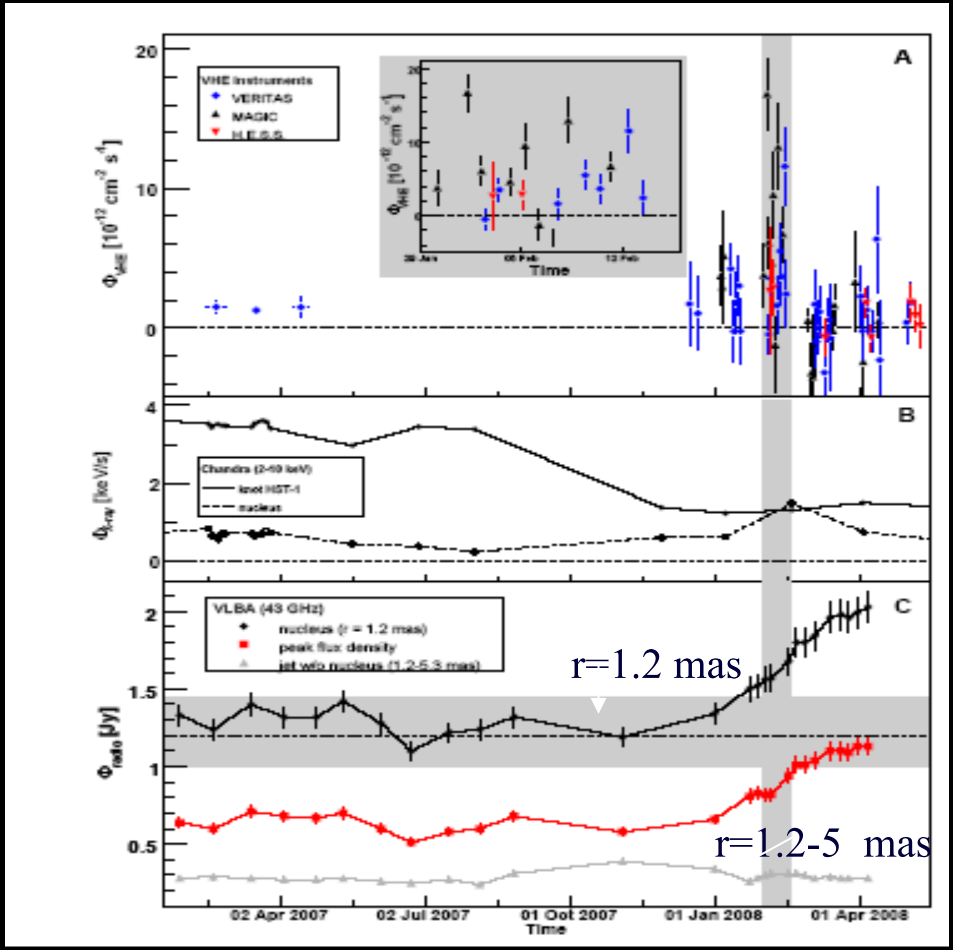
$L_j \approx 10^{44}\ \mathrm{erg}\ s^{-1}, \qquad L_\gamma \approx 10^{40} - 10^{41}\ \mathrm{erg}\ s^{-1}$

Variability time ≈ 1 day ≈ r_g

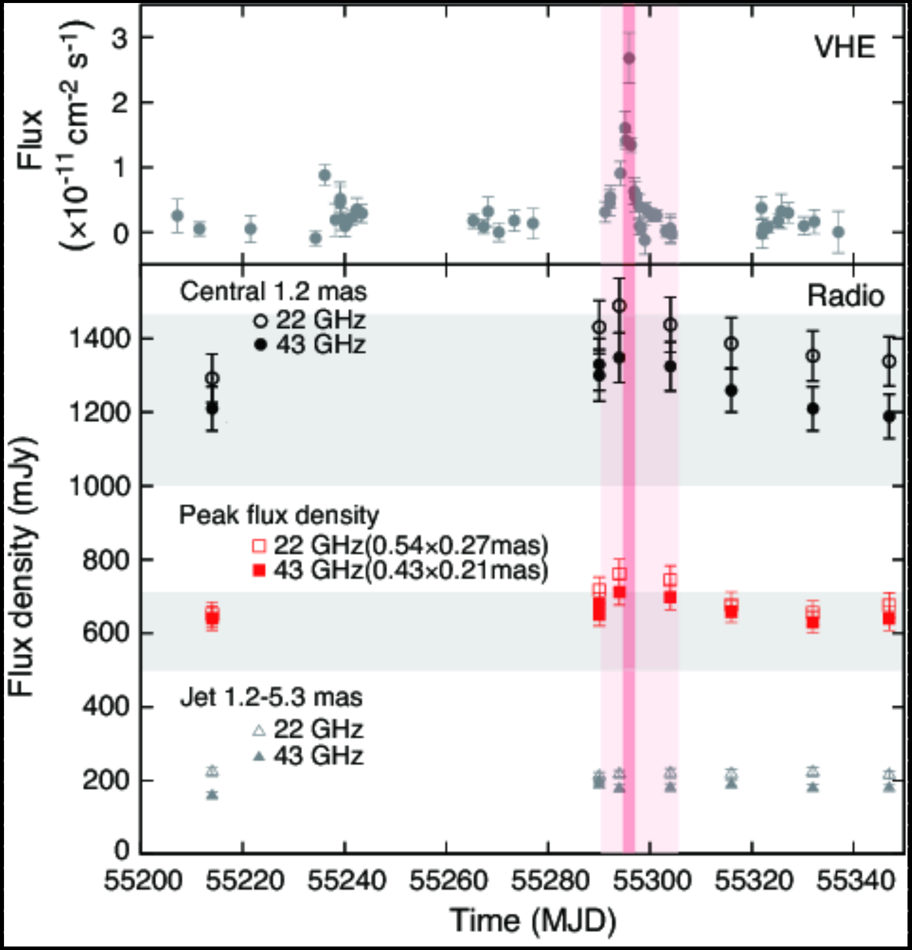




2008 flare (Acciari + 09)



2010 flare (Hada + 12)



Variable TeV emission correlated with radio flux from innermost region.
No significant activity on larger scales, particularly HST-1

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.
- Pair discharges by rapid plasma oscillations, emitting TeV photons with $L_{TeV}/L_{BZ} \sim 10^{-5}$.
- strong TeV flares can be produced if gap is restored