Frontier Research Institute for Interdisciplinary Sciences
Tohoku University

Theoretical Astrophysics
Tohoku University

Emission from Black Hole Jets

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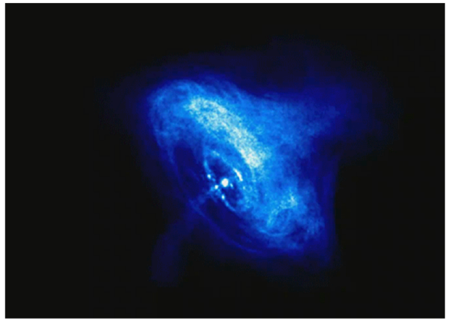
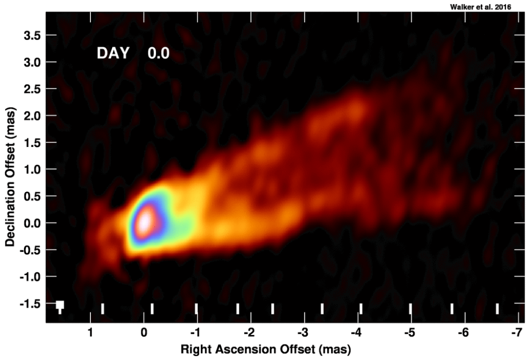
（木坂将大、A. Levinson, 木村成生、久世陸、荻原大樹、小川拓未、木村匡志、成子篤、原田知広、EHT Consortium、桑田明日香、冨田沙羅、霜田治朗）

Extreme Outflows in Astrophysical Transients @ Kyoto U, Aug 23-27, 2021

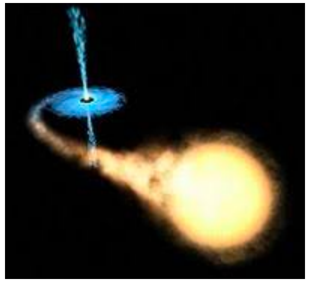
Outflows in high energy astrophysics



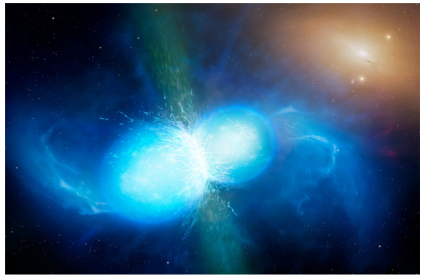
Pulsar Wind
Nebulae



AGN and jets



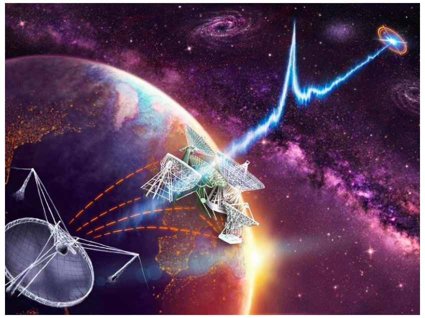
Micro-quasars



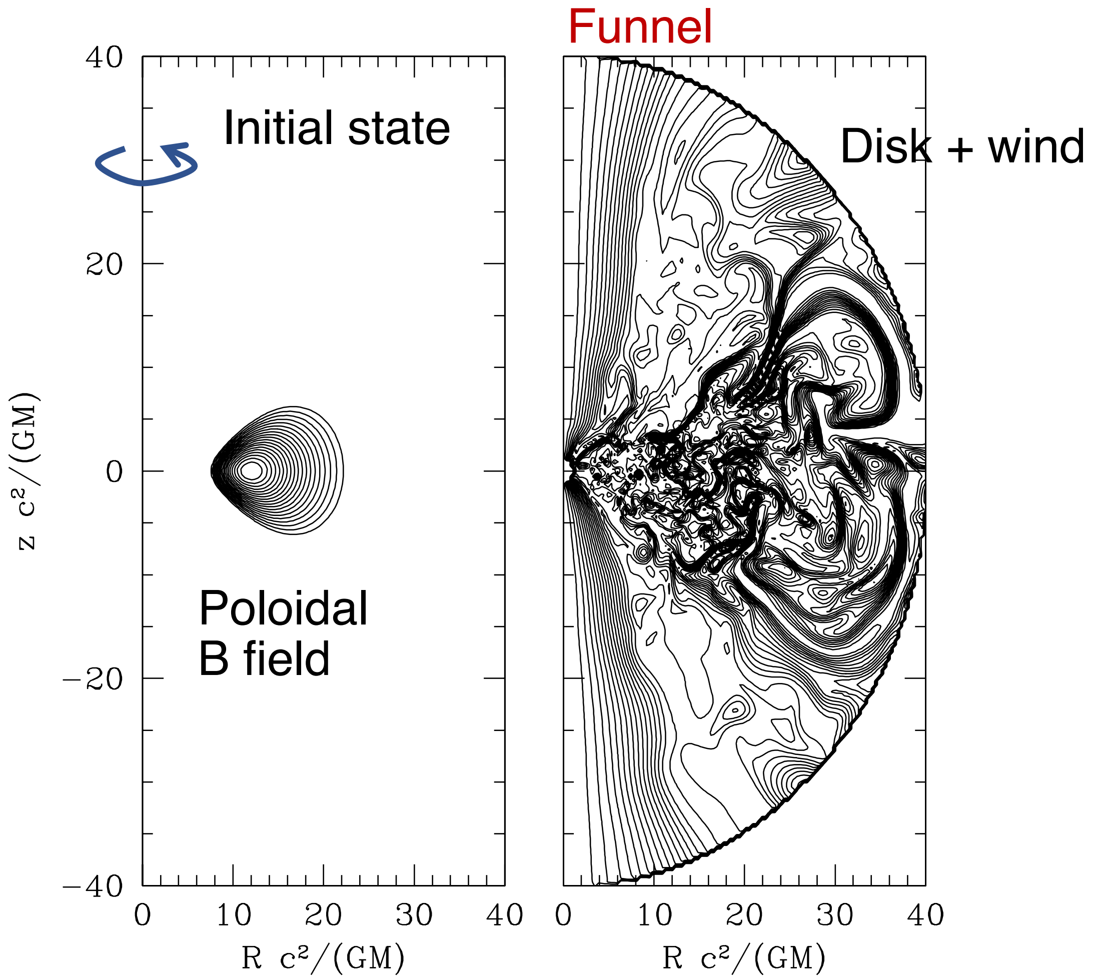
Gamma-Ray Bursts

Supernovae

Fast Radio
Bursts



Theoretical issues on black hole jets



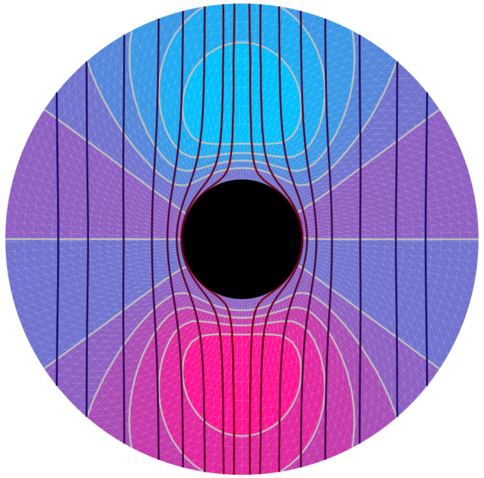
GR-MHD simulation

- Energy injection L_j
  - BH or disk? cf. King & Pringle 2021
- Mass injection $\dot{M}_j$
  - Outflow + inflow structure in funnel
- Acceleration
  - $\Gamma_{max} \sim L_j/\dot{M}_j c^2$

- B field flux
- Collimation
- Global/local stability
- Dissipation
- Emission

Koide et al. 2000; Komissarov 2001; McKinney & Gammie 2004; Barkov & Komissarov 2008; Tchekhovskoy et al. 2011; Ruiz et al. 2012; Contopoulos et al. 2013; Takahashi et al. 2016; Nakamura et al. 2018; Porth et al. 2019

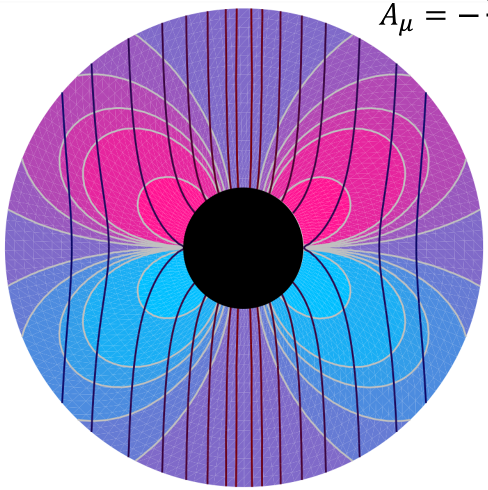
Debates on energy injection mechanism



Contour of
$\vec{E}\cdot\vec{B}$

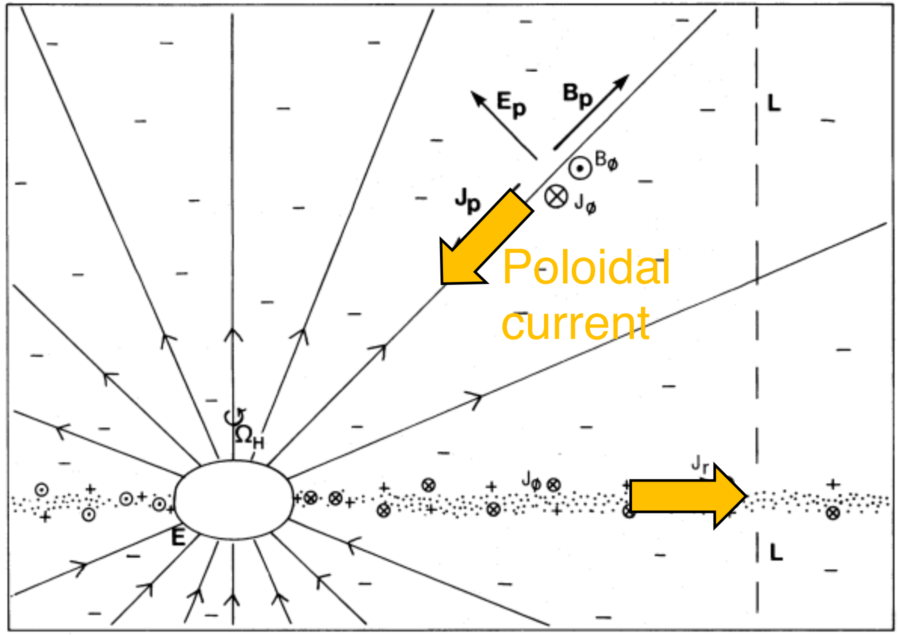
Vacuum solution of E/B field in Kerr spacetime

$$A_\mu = -\frac{B_0}{2}\left(\xi_\mu^{(\varphi)} + 2a\xi_\mu^{(t)}\right) + \frac{Q}{2}\xi_\mu^{(t)}$$



BH charge Q = $2aB_0$

$$F_E \approx \frac{c}{64\pi} a^2 B_{\rm H}^2 \sin^2\theta$$



Force-free solution of E/B/ρ/J in (fixed) Kerr spacetime:
$\vec{E}\cdot\vec{B} = 0$ by plasma, outward Poynting flux (BZ process)

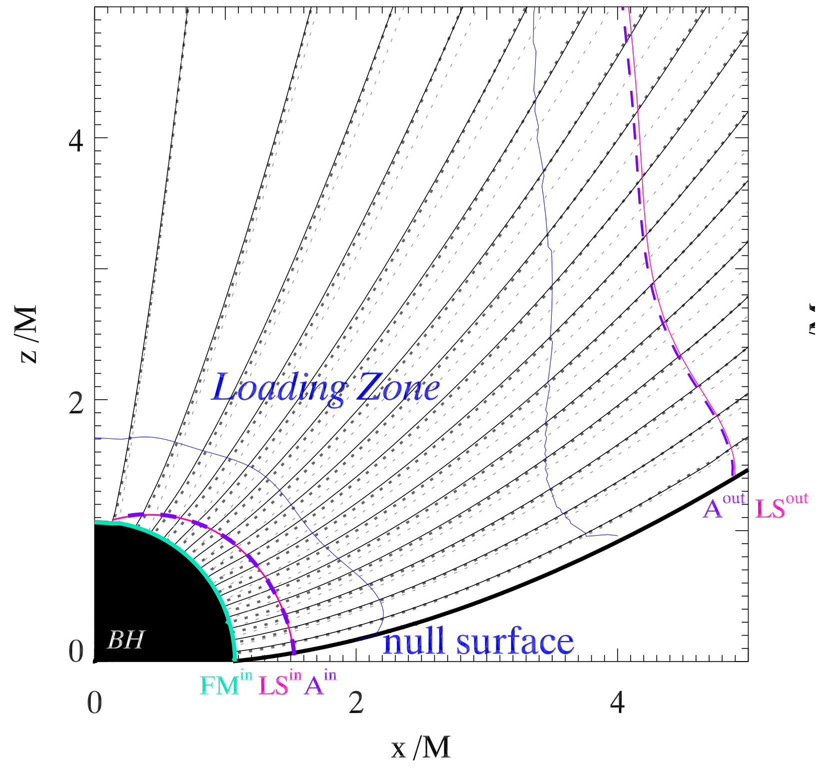
BZ process keeps Kerr spacetime

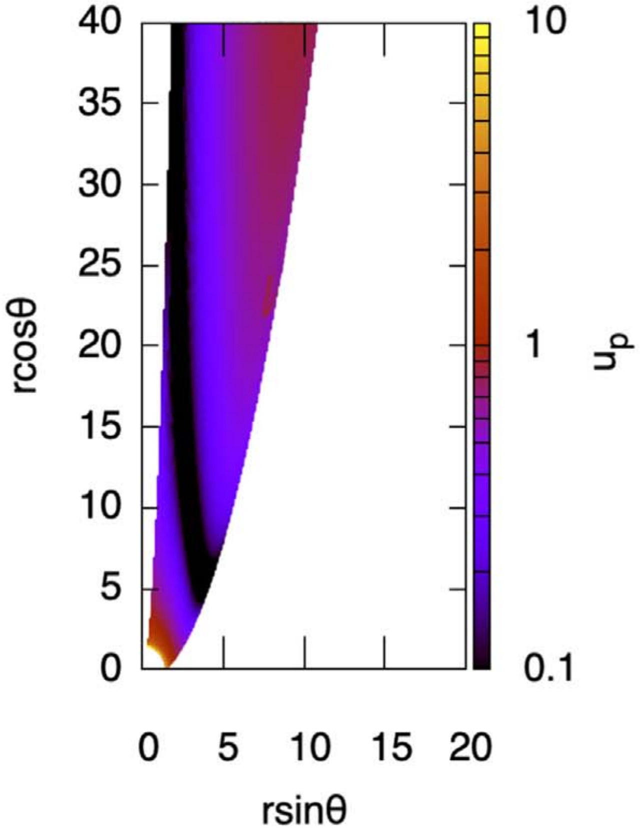
$$g_{\mu\nu}^{\rm Kerr} + g_{\mu\nu}^{\rm BZ} = g_{\mu\nu}^{{\rm Kerr}+(\delta\bar{M},\delta\bar{J})} + g_{\mu\nu}^{\rm other} + [\ell = 2 \text{ terms}] + \mathcal{O}(\alpha^3) + \mathcal{O}(\beta^2),$$

Wald 1974; Blandford & Znajek 1977; M. Kimura, Harada, Naruko & KT 2021; Komissarov 2021

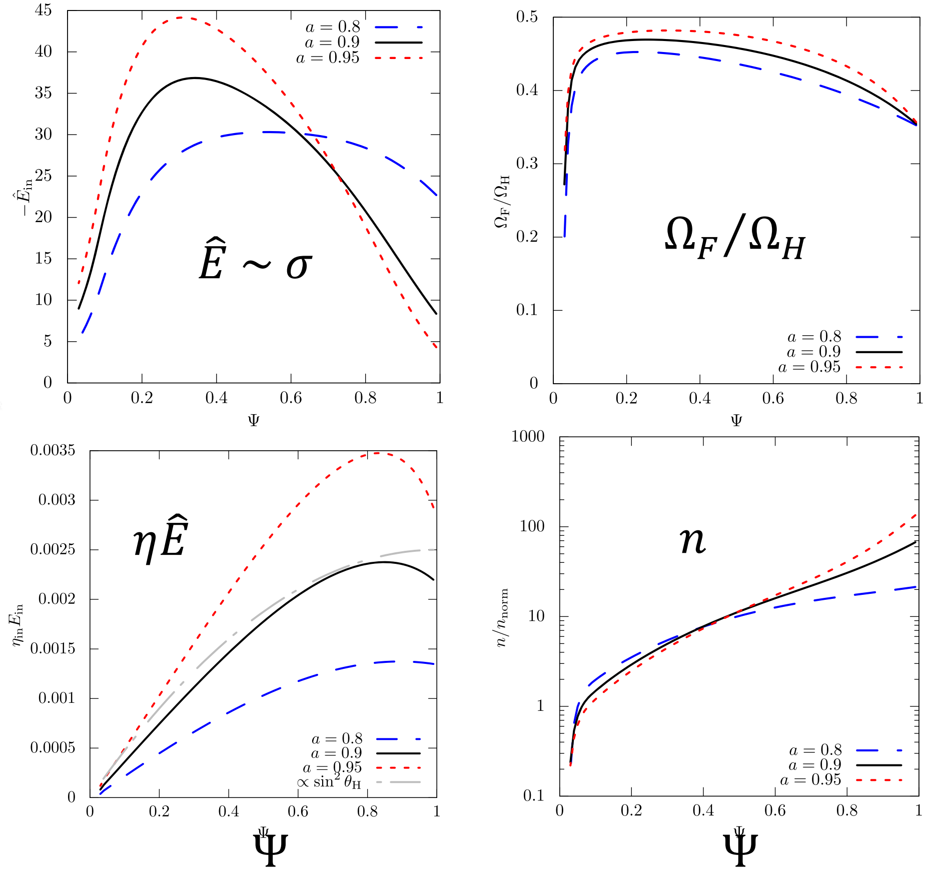
Ideal MHD steady axisymmetric solutions

Outflow + inflow structure





Transverse structure



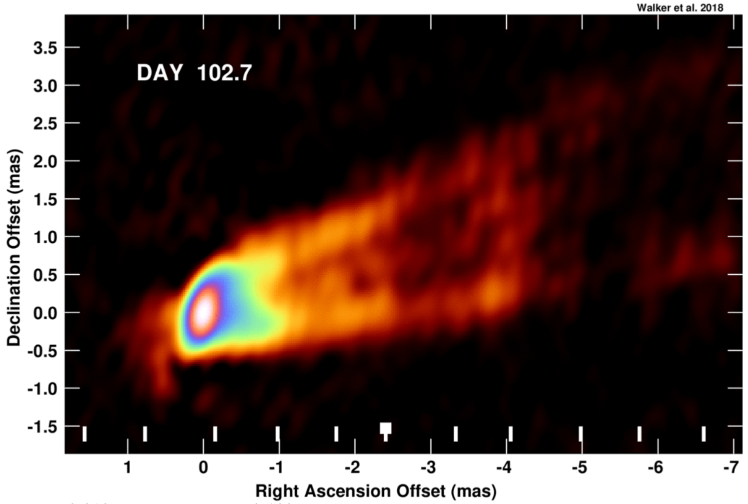
Loading zone (v=0) between the outflow and inflow

$\hat{E}(\Psi), \hat{L}(\Psi), \Omega_F(\Psi), \eta(\Psi)$ are determined by Znajek condition, given u_p at separation surface, outer fast point, and transverse force balance for given $\Psi(r, \theta)$

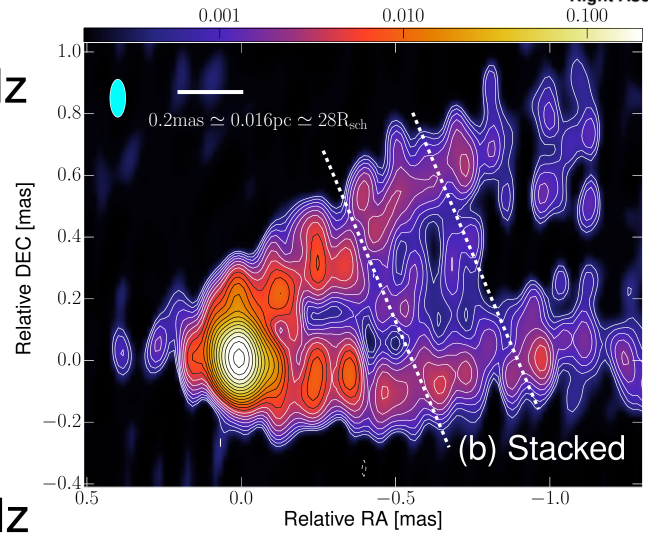
Huang, Pan & Yu 2020; Ogihara, Ogawa & KT 2021

M87

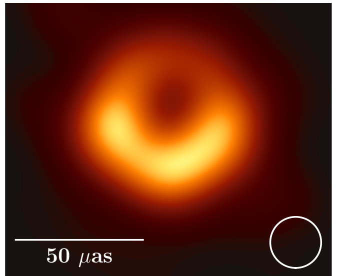
43 GHz



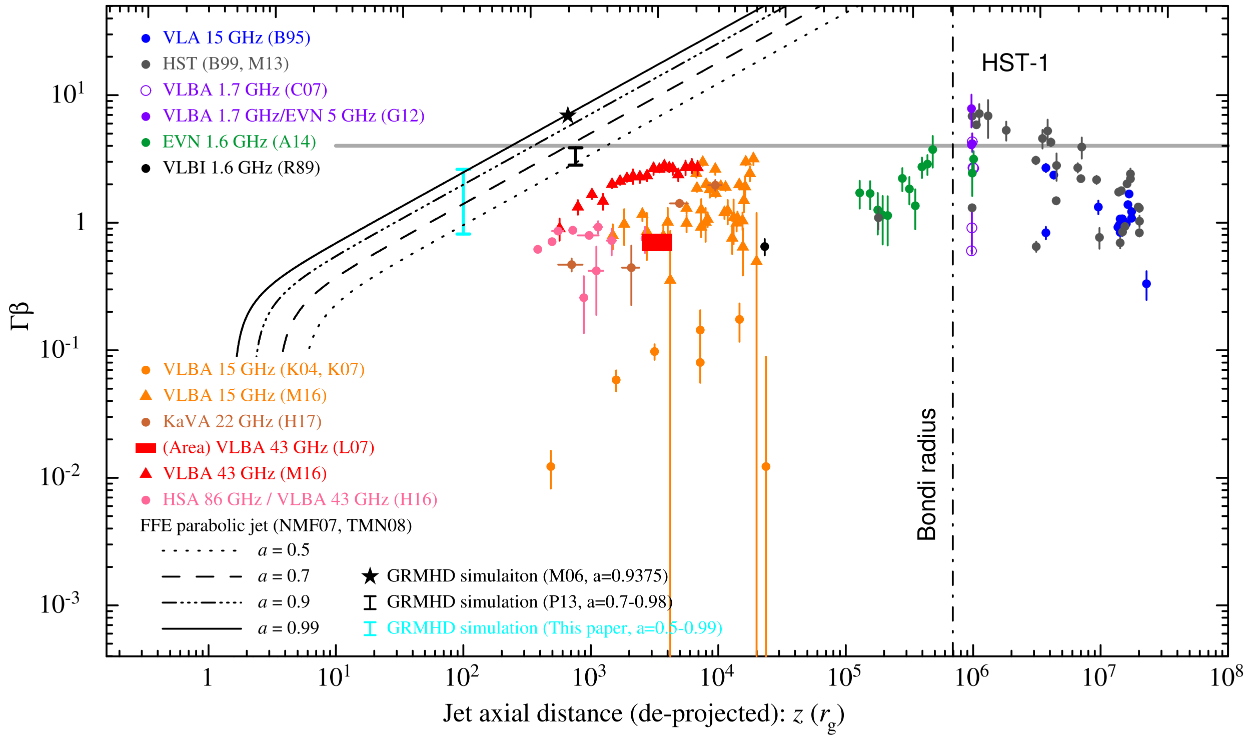
86 GHz



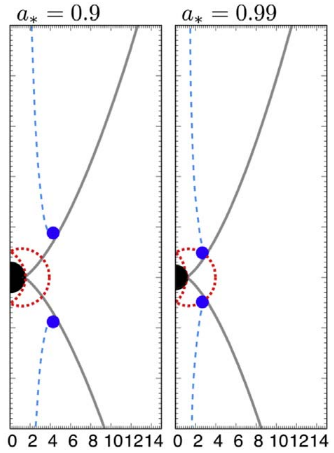
230 GHz

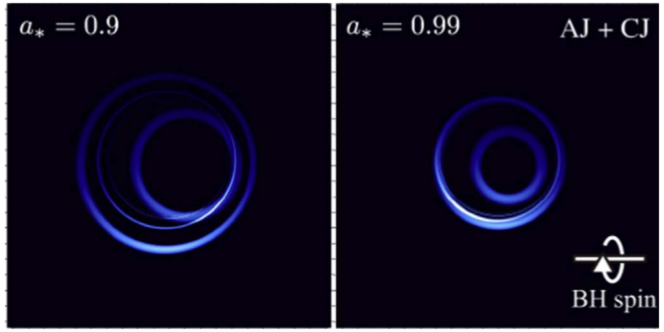


$10\ \mu as \sim 3\ r_g$



Radio jet emission is produced in funnel region(?)

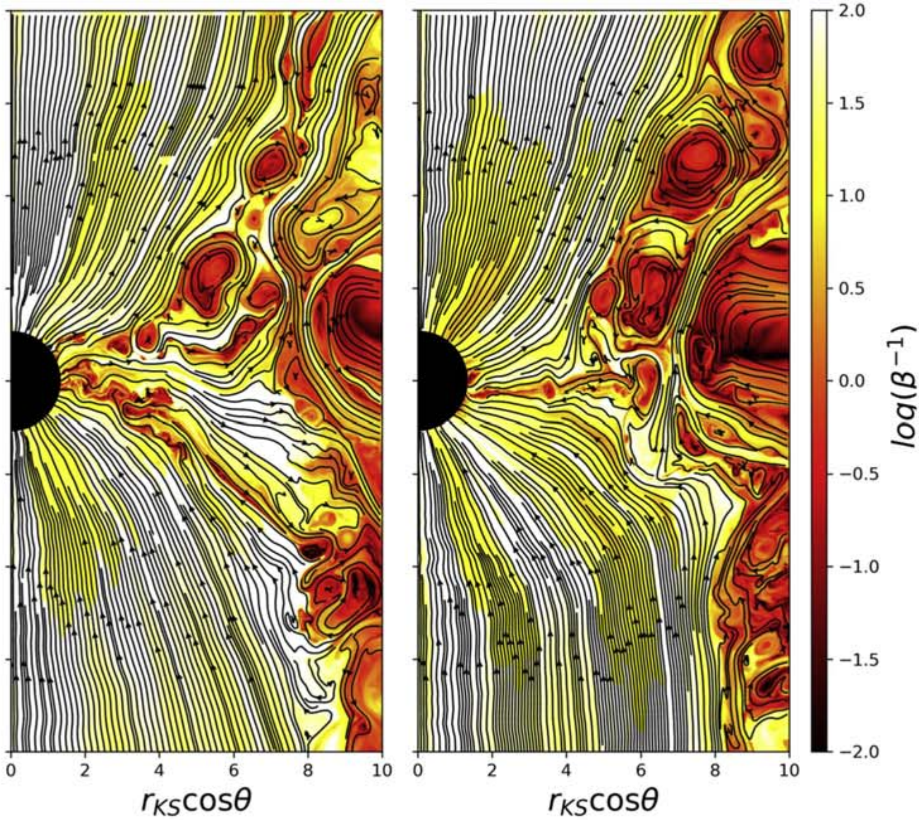




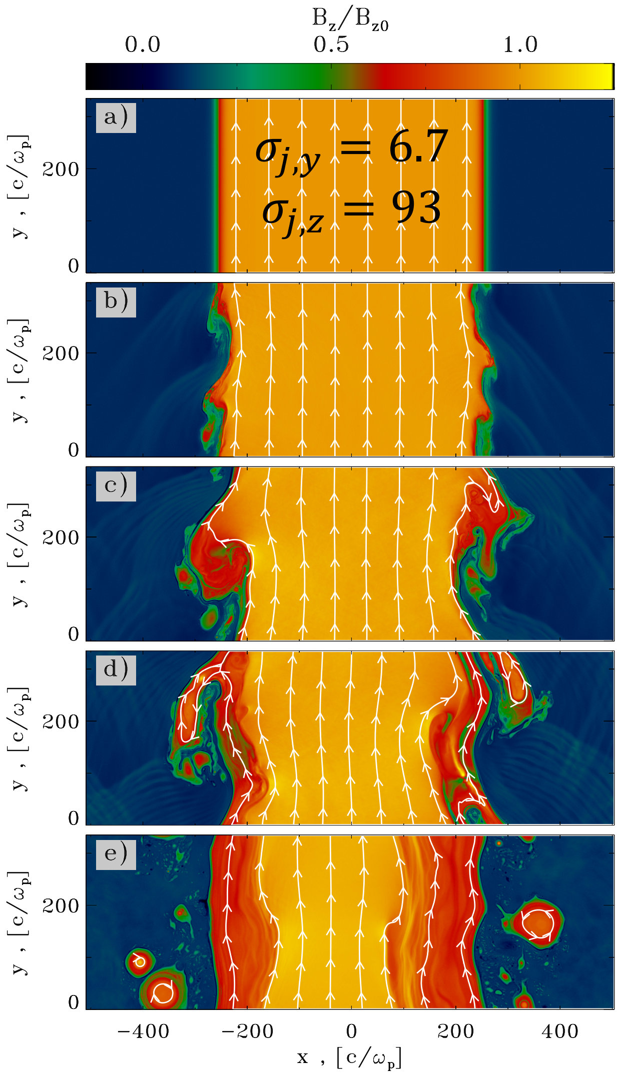
Kim+2018; Walker+2018; Nakamura+2018; EHT Collaboration 2019

Kawashima, KT et al. 2021

Funnel wall



Magnetic-Arrested-Disk
in 2D GR-resistive MHD simulation with AMR

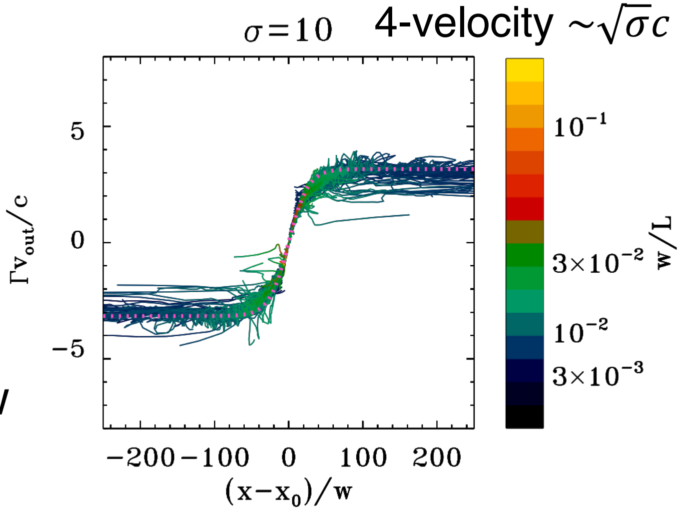


$\Delta = 64\, c/\omega_p$

2D PIC simulation of shear flow
(with thickness $\Delta \gg c/\omega_p$)

Can these blobs
accelerate to $\Gamma \sim$ several?

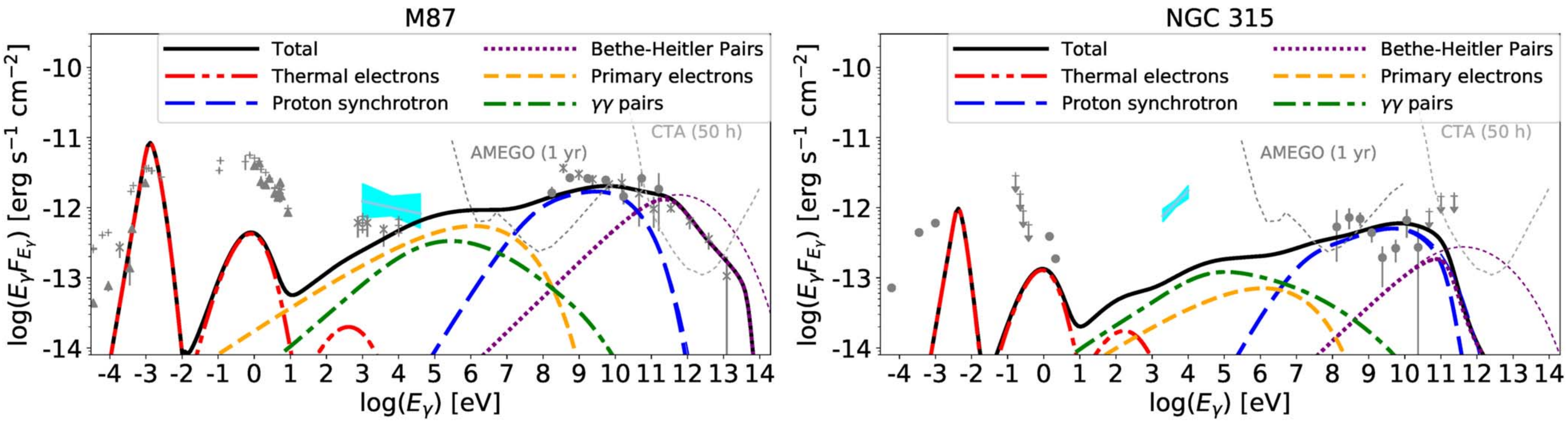
Small plasmoid
4-velocity $\sim\sqrt{\sigma}c$



2D PIC (e+e-) simulation of
magnetic reconnection

Ripperda et al. 2020; Wong et al. 2021; Sironi, Rowan & Narayan 2020; Sironi, Giannios & Petropoulou 2016

Hadronic emission



- One-zone steady MAD model (n~10^5 cm^{-3}, T_p~20 MeV, B~20 G for M87)
- Assume non-thermal p/e by relativistic magnetic reconnection and/or turbulence

α	β	$\mathcal{R}$	$\epsilon_{\rm dis}$	η	$\epsilon_{\rm NT}$	$s_{\rm inj}$
0.3	0.1	10	0.15	5	0.33	1.3

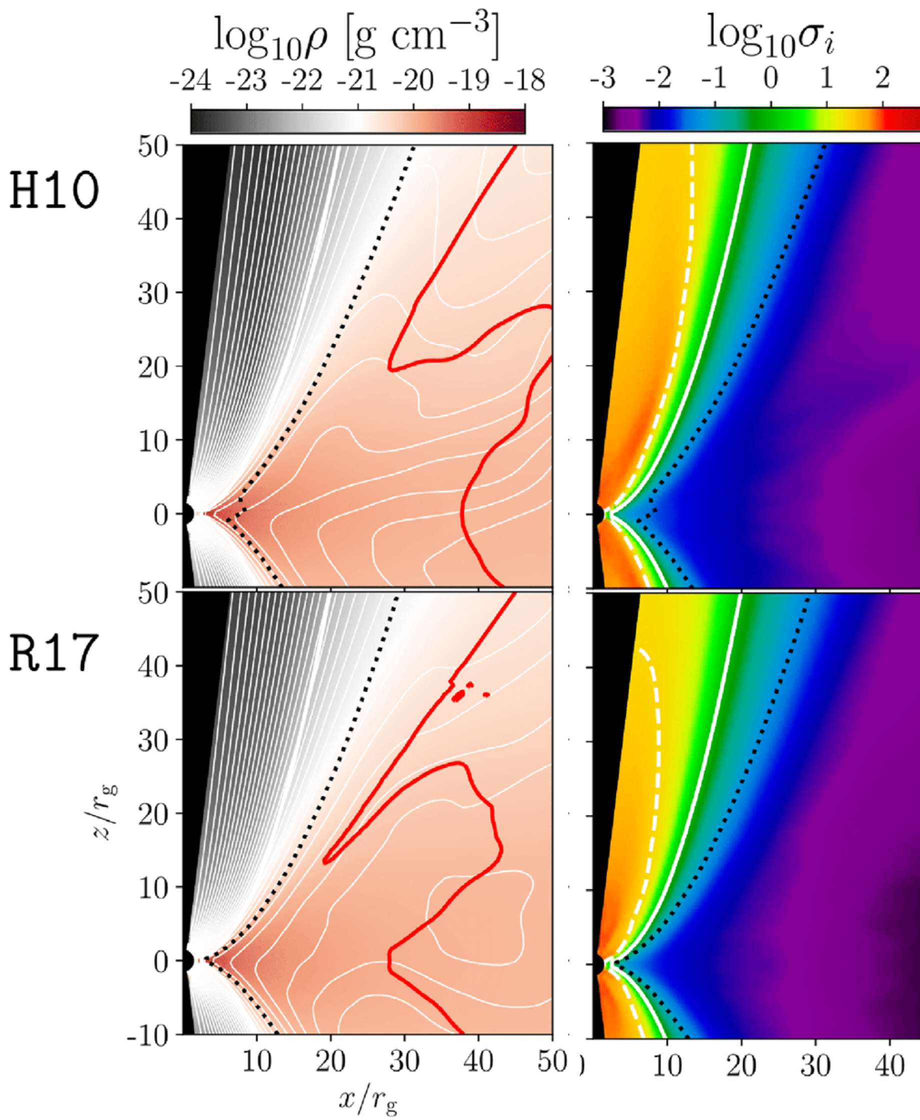
cf. Levinson & Rieger 2011; Moscibrodzka et al. 2011

- Bright GeV emission from disk lead to high rate of γγ annihilation in jet: $n_j \sim 100\, n_{GJ}$

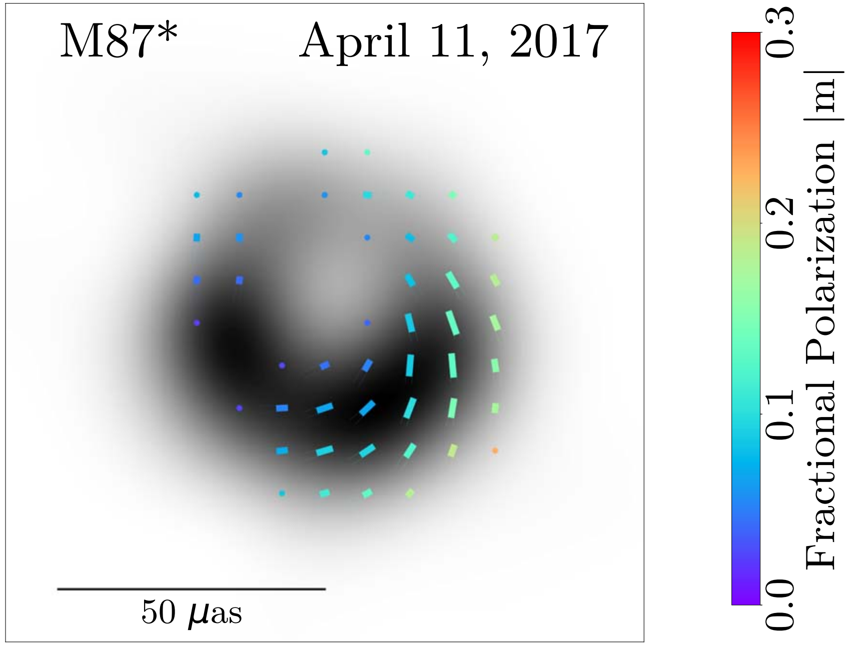
$$n_{\rm GJ} = \frac{\Omega_F B_h}{2\pi ec} \approx \frac{B_h}{8\pi e R_G} \simeq 5.6 \times 10^{-4} B_{h,3} M_9^{-1}\ {\rm cm^{-3}},$$

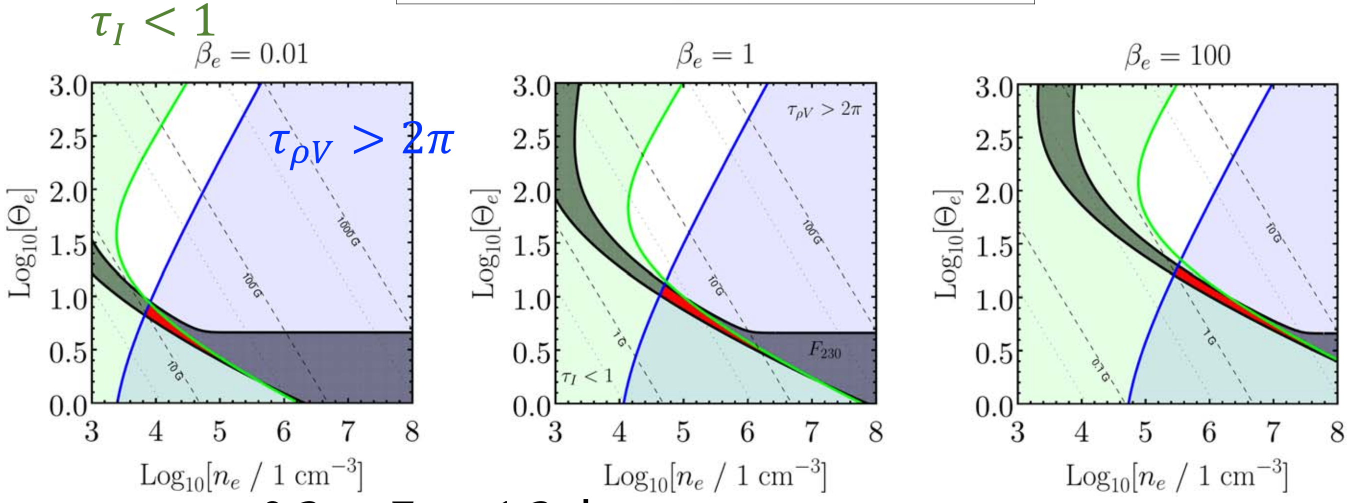
S. S. Kimura & KT 2020

M87: density and B field



$$\sigma_i = \frac{|B|^2}{4\pi n_i m_i c^2}.$$



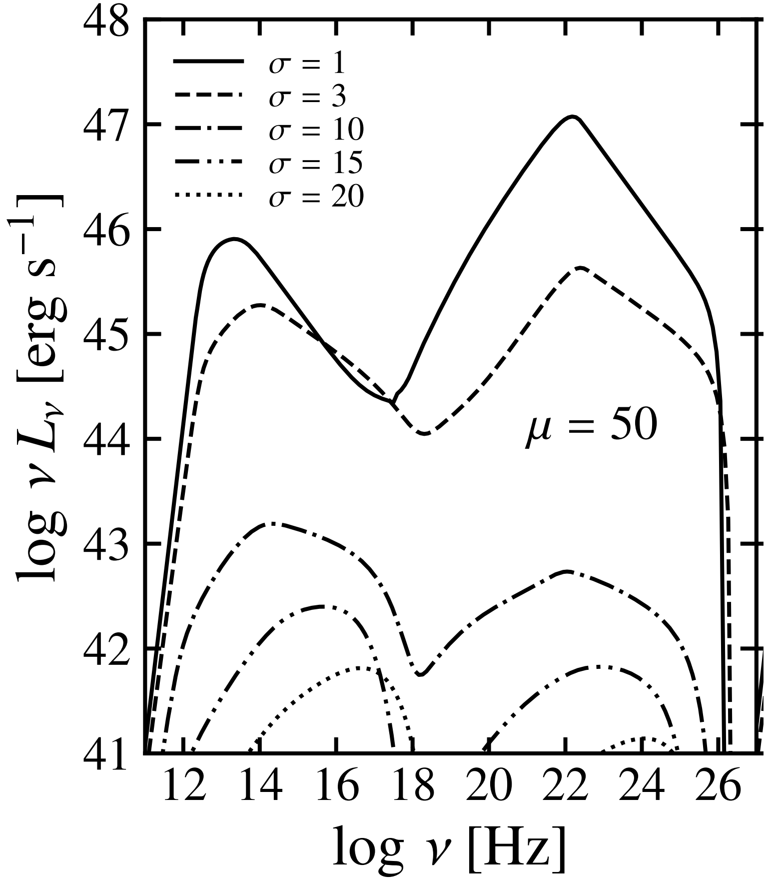


$0.2 < F_\nu < 1.2$ Jy

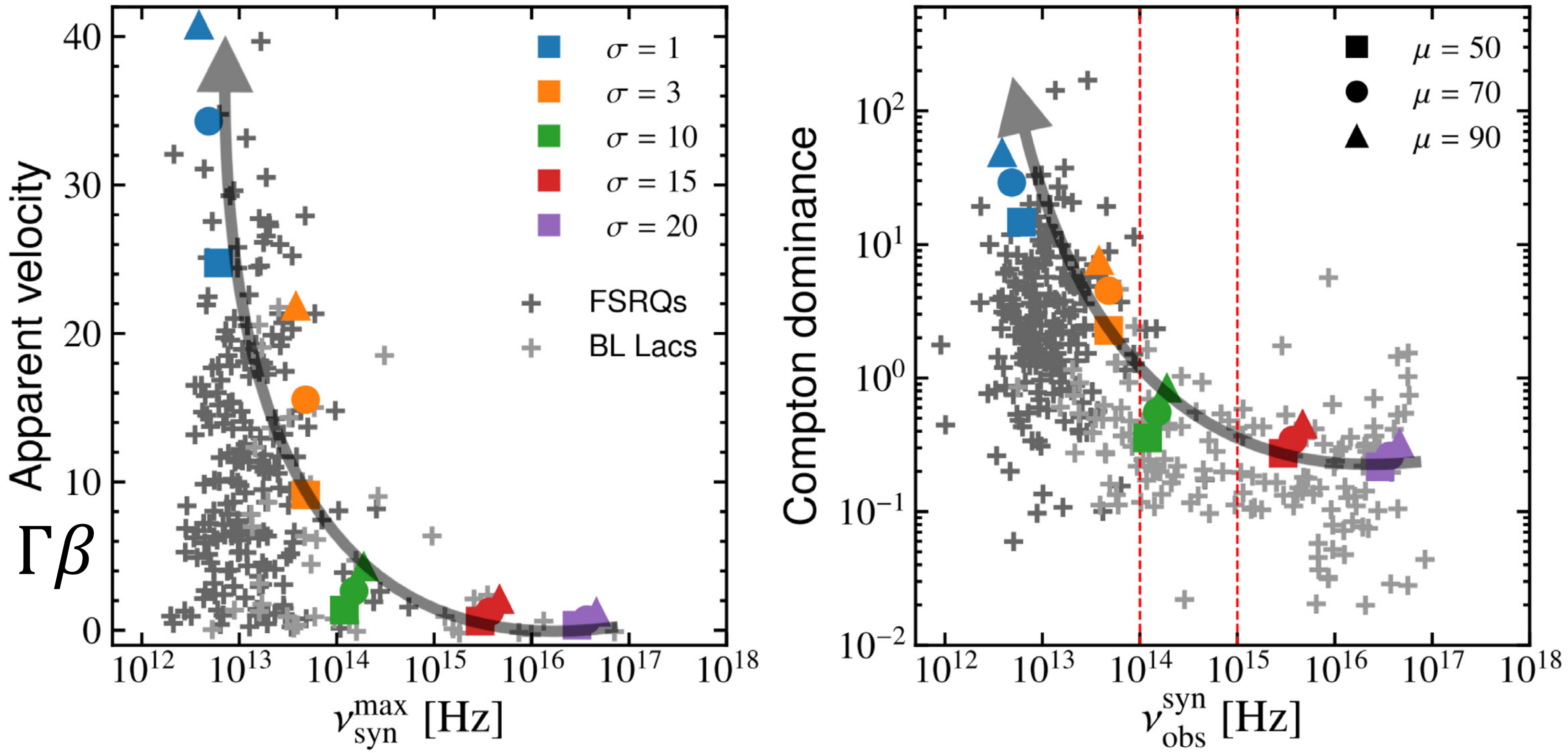
Two temperature GR-R-MHD: MAD model

Chael, Narayan & Johnson 2019; EHT Collaboration 2021

Blazars: jets viewed on-axis



~ $\Gamma\beta$



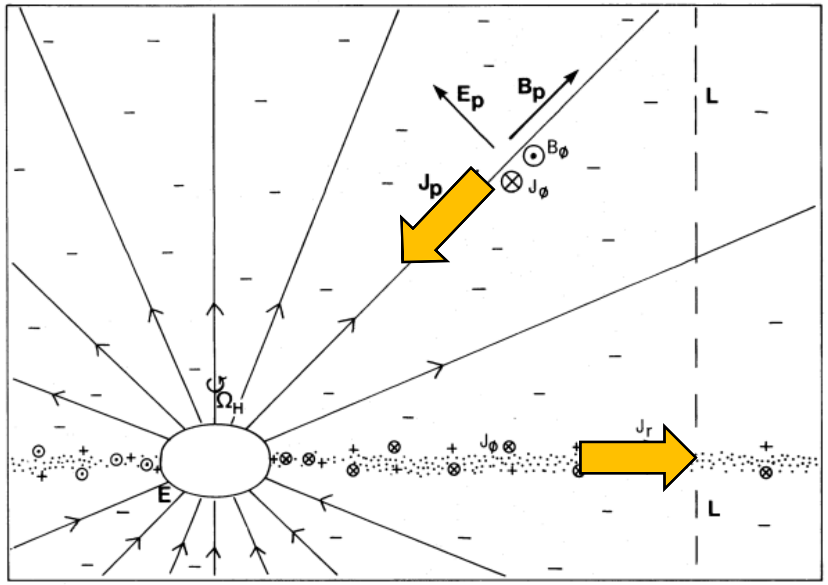
Energy per particle $\mu = \Gamma(1+\sigma),$

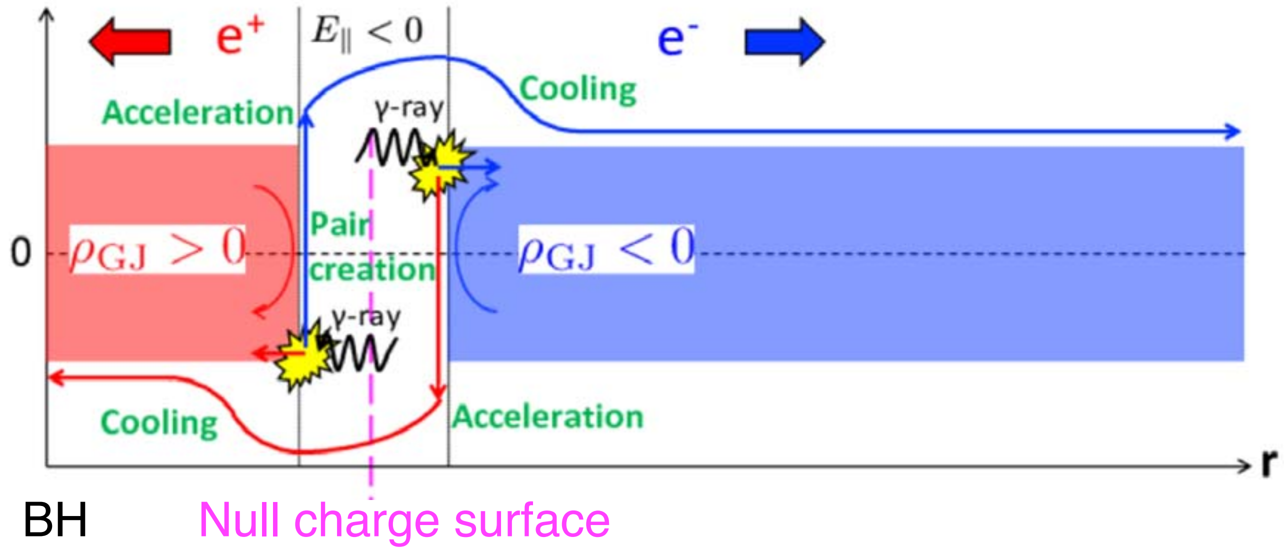
Emission region $R_{\rm BLR} \simeq 10^{17} L_{\rm d,45}^{1/2}$ cm

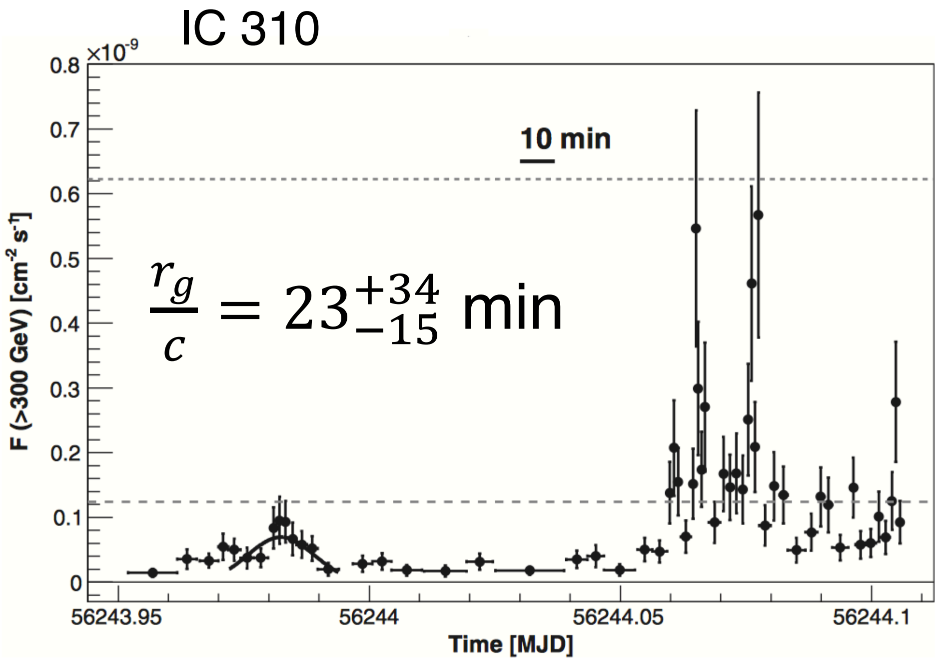
- BL Lacs: high σ, low Γ
- e-p plasma model

Rueda-Becerril, Harrison & Giannios 2021

Magnetospheric gaps







- For $n \sim n_{GJ}$ a pair-creation gap will open, where $\vec{E} \cdot \vec{B} \neq 0$
- Explain VHE γ-ray flares in M87, IC310?

Aleksic+2014; Abramowski+2012; Aharonian+2006

Maxwell equations on fixed Kerr spacetime

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = -\alpha^2 dt^2 + \gamma_{ij}(\beta^i dt + dx^i)(\beta^j dt + dx^j),$$

$$\nabla_\nu {}^*F^{\mu\nu} = 0$$
$$\nabla_\nu F^{\mu\nu} = 4\pi I^\mu$$

Boyer-Lindquist 座標

$$\alpha = \sqrt{\frac{\varrho^2\Delta}{\Sigma}}, \quad \beta^\varphi = -\frac{2ar}{\Sigma}, \equiv -\Omega$$

$$\gamma_{\varphi\varphi} = \frac{\Sigma}{\varrho^2}\sin^2\theta, \quad \gamma_{rr} = \frac{\varrho^2}{\Delta}, \quad \gamma_{\theta\theta} = \varrho^2,$$

$$\varrho^2 = r^2 + a^2\cos^2\theta, \quad \Delta = r^2 + a^2 - 2r,$$
$$\Sigma = (r^2 + a^2)^2 - a^2\Delta\sin^2\theta,$$

$$r \to \infty : a \to 1, \Omega \to 0$$

$$r \to r_{\mathrm{H}} : a \to 0(\Delta \to 0)$$

$$E^\mu = \gamma^{\mu\nu}F_{\nu\alpha}\xi^\alpha, \quad H^\mu = -\gamma^{\mu\nu\,*}F_{\nu\alpha}\xi^\alpha$$

$$D^\mu = F^{\mu\nu}n_\nu, \quad B^\mu = -{}^*F^{\mu\nu}n_\nu$$

$$\nabla\cdot\boldsymbol{B} = 0, \quad \partial_t\boldsymbol{B} + \nabla\times\boldsymbol{E} = 0,$$

$$\nabla\cdot\boldsymbol{D} = 4\pi\rho, \quad -\partial_t\boldsymbol{D} + \nabla\times\boldsymbol{H} = 4\pi\boldsymbol{J},$$

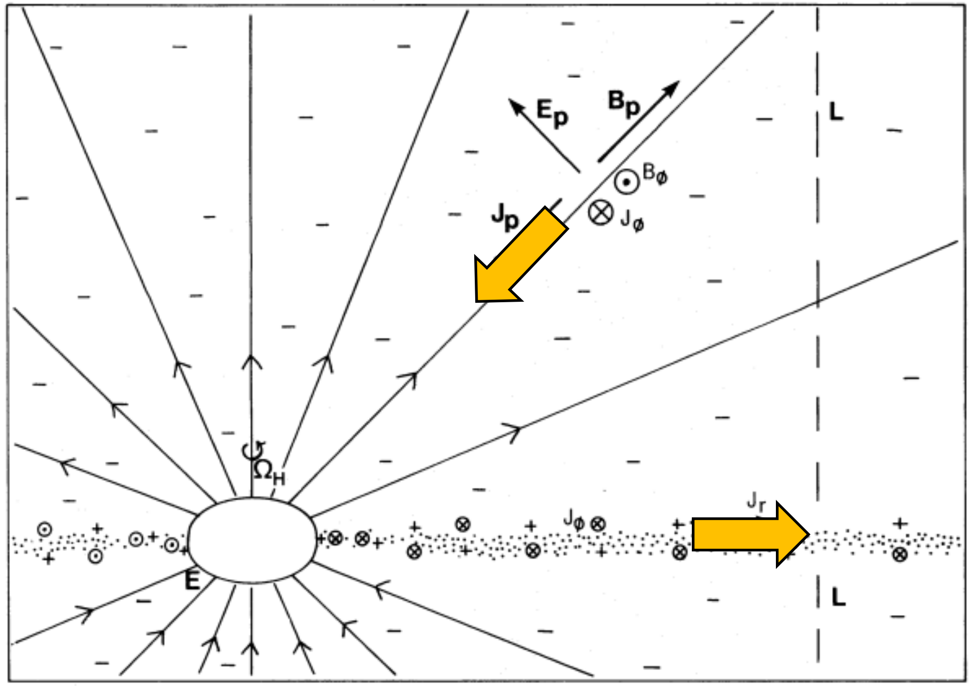
$$\boldsymbol{E} = \alpha\boldsymbol{D} + \boldsymbol{\beta}\times\boldsymbol{B},$$

$$\boldsymbol{H} = \alpha\boldsymbol{B} - \boldsymbol{\beta}\times\boldsymbol{D},$$

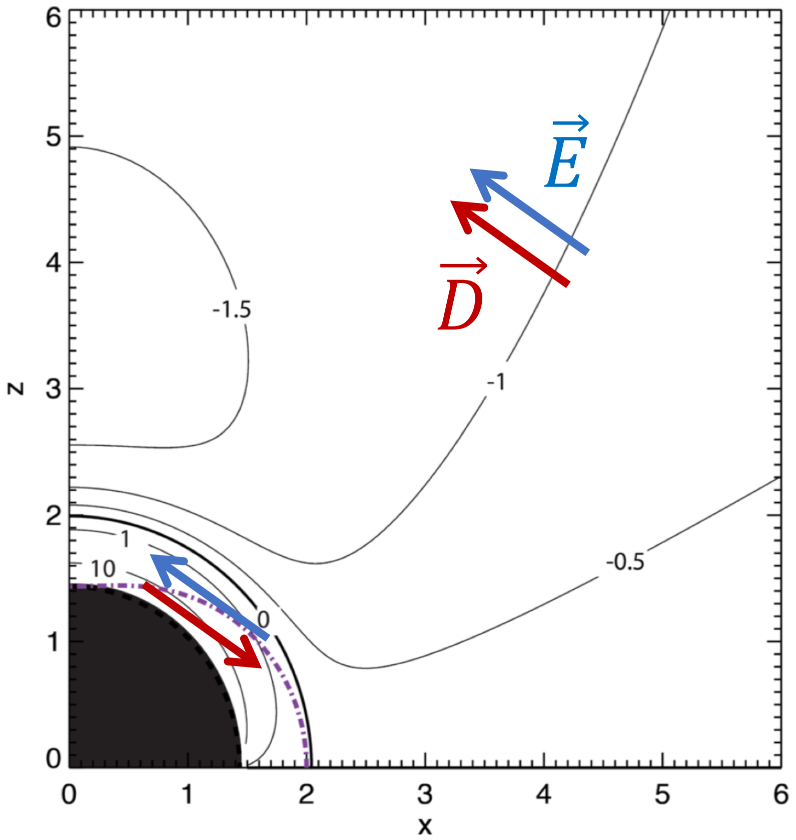
Landau & Lifshitz 1975; Komissarov 2004

BH magnetospheres

Poynting flux $\mathbf{S}_\mathrm{p} = \frac{\mathbf{E} \times \mathbf{H}_\varphi}{4\pi} \quad (H_\varphi = \alpha B_\varphi)$



$\rho_{GJ} = \nabla \cdot \vec{D}/4\pi$



$\nabla \times \mathbf{E} = 0, \Rightarrow \mathbf{E} = -\nabla\phi$

$\mathbf{E} \cdot \mathbf{B} = 0$ (force-free/ MHD条件)

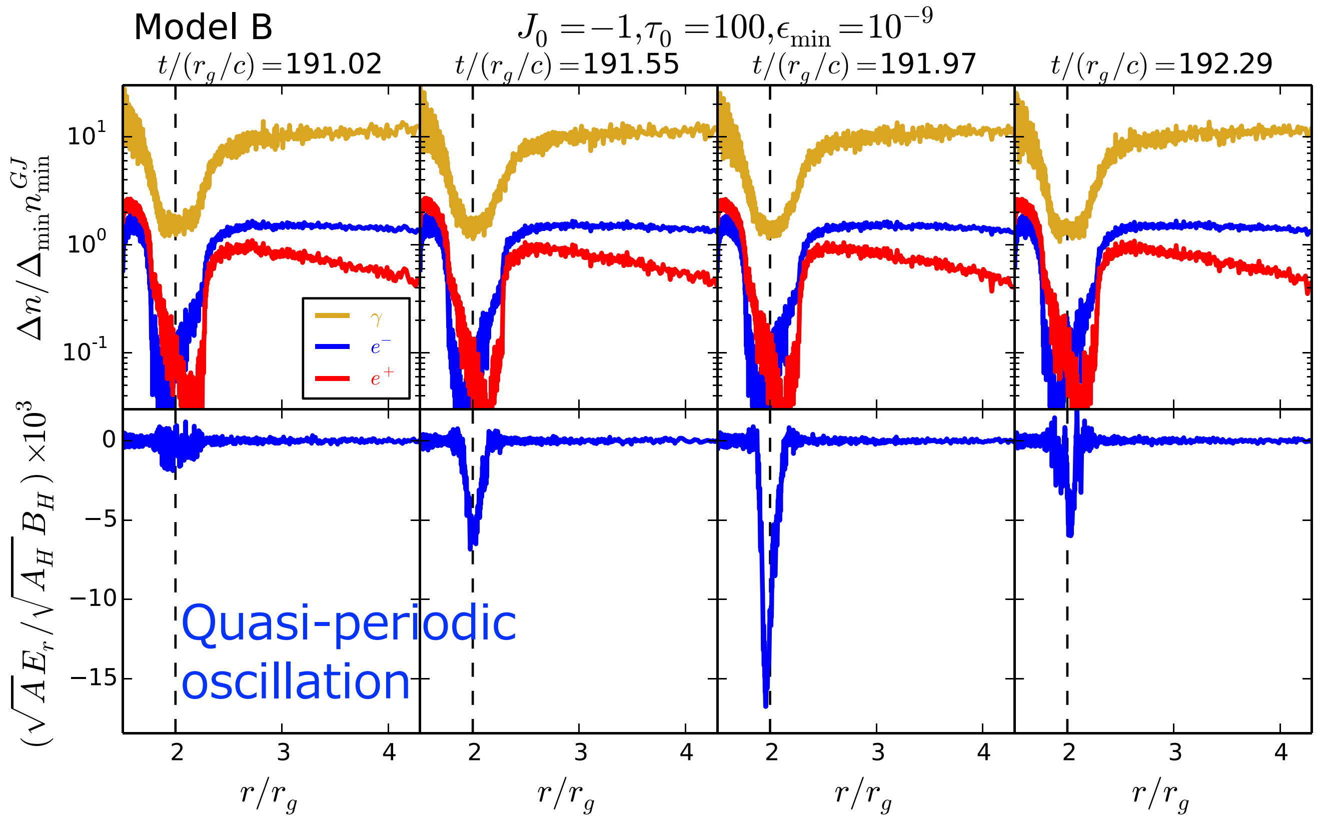
$$\mathbf{E} = -\Omega_\mathrm{F} \mathbf{e}_\varphi \times \mathbf{B} \Rightarrow \mathbf{D} = -\frac{1}{\alpha}(\Omega_\mathrm{F} - \Omega)\mathbf{e}_\varphi \times \mathbf{B}$$

$\Omega_F \sim \Omega_H/2$

Blandford & Znajek 1977; Levinson & Segev 2017

1D GR Particle-In-Cell simulations

- Local simulations in Kerr spacetime with a = 0.9
- e+, e-, IC photons' creation & propagation
- Curvature radiation loss



E field evolution: Ampere law

$$-\partial_t \boldsymbol{D} + \nabla \times \boldsymbol{H} = 4\pi \boldsymbol{J},$$

$$\partial_t(\sqrt{\Sigma} D_r) = -4\pi(\varrho^2 J^r - I_0)$$

I_0: assumed MHD value ($=\nabla \times H \sim r^2 \rho_{GJ} c$)

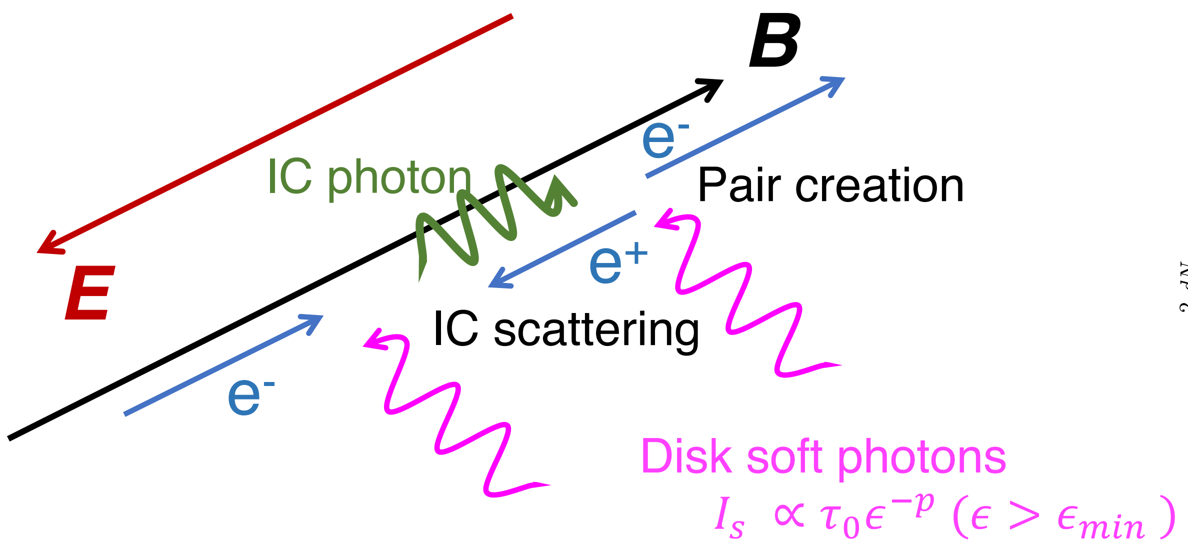
Constraint: Gauss law

$$\nabla \cdot \boldsymbol{D} = 4\pi\rho,$$

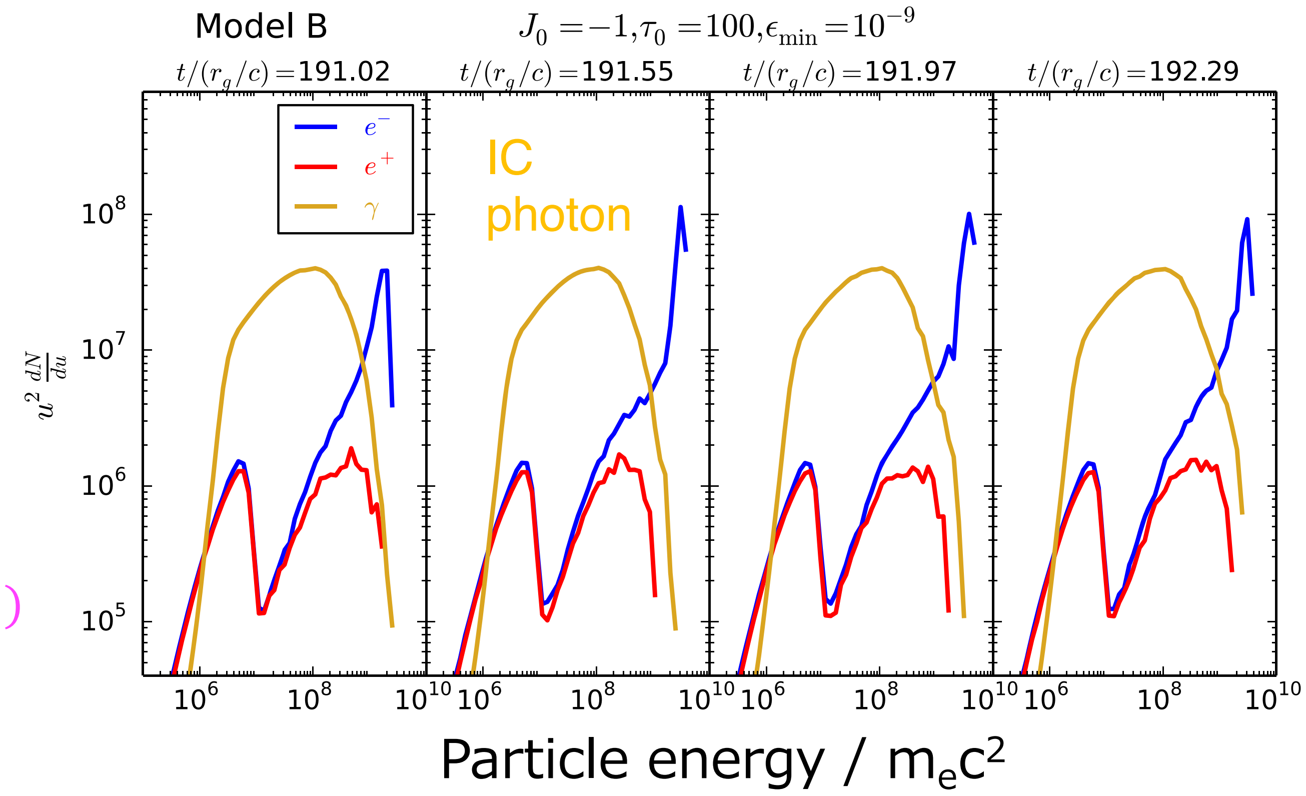
$$\partial_\xi(\sqrt{\Sigma} D_r) = 4\pi \Delta \varrho^2 (\rho - \rho_{\rm GJ})$$

Kisaka, Levinson & KT 2020; Levinson & Cerutti 2018 (see also Chen & Yuan 2020; Crinquand+2020; 2021)

Pair creation, current recovery



Spectra of outgoing particles

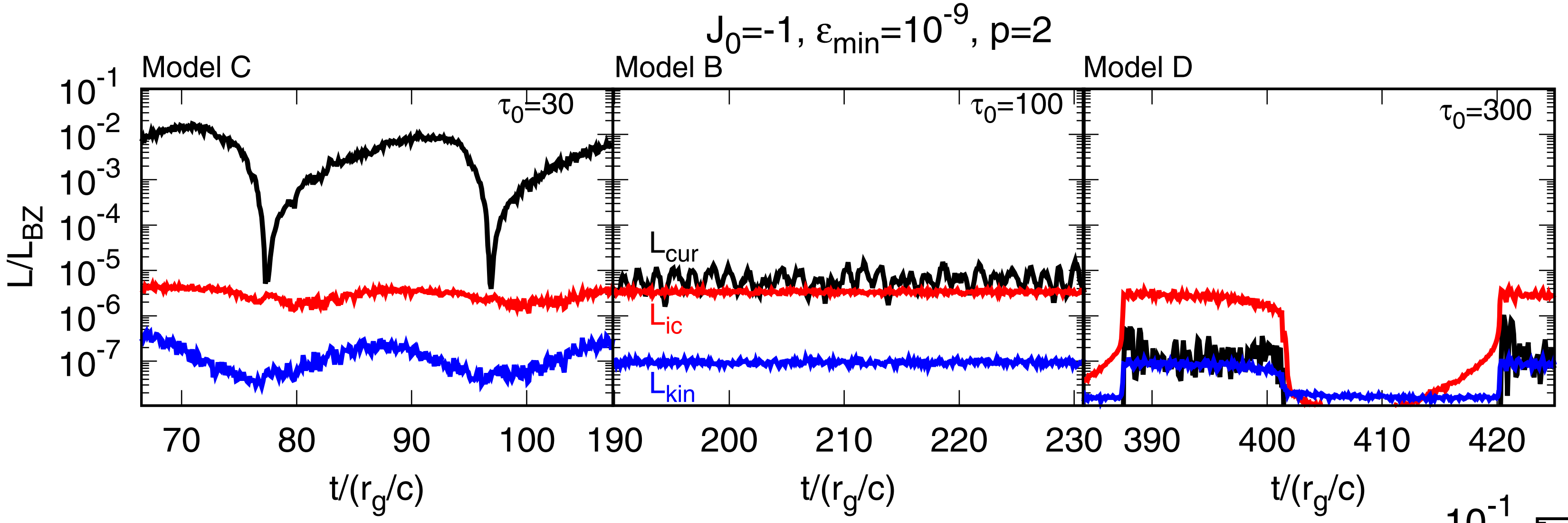


Condition for the gap oscillation

$$\tau_{\rm ic}\tau_{\gamma\gamma} \gtrsim 1. \quad \Rightarrow \quad \tau_0 \gtrsim \sqrt{\frac{\tau_0}{\tau_{\rm ic}}\frac{\tau_0}{\tau_{\gamma\gamma}}} \sim \begin{cases} 10^{1/2}(\gamma\epsilon_{\rm min})^{-p} & (\gamma\epsilon_{\rm min} \lesssim 1) \\ 10^{1/2}(\gamma\epsilon_{\rm min}) & (\gamma\epsilon_{\rm min} \gtrsim 1). \end{cases}$$

$$\gamma_{\rm max}\epsilon_{\rm min} \sim 10(E_{\parallel}/B)_{-2}^{1/4} B_3^{1/4} M_9^{1/2} \epsilon_{{\rm min},-9}$$

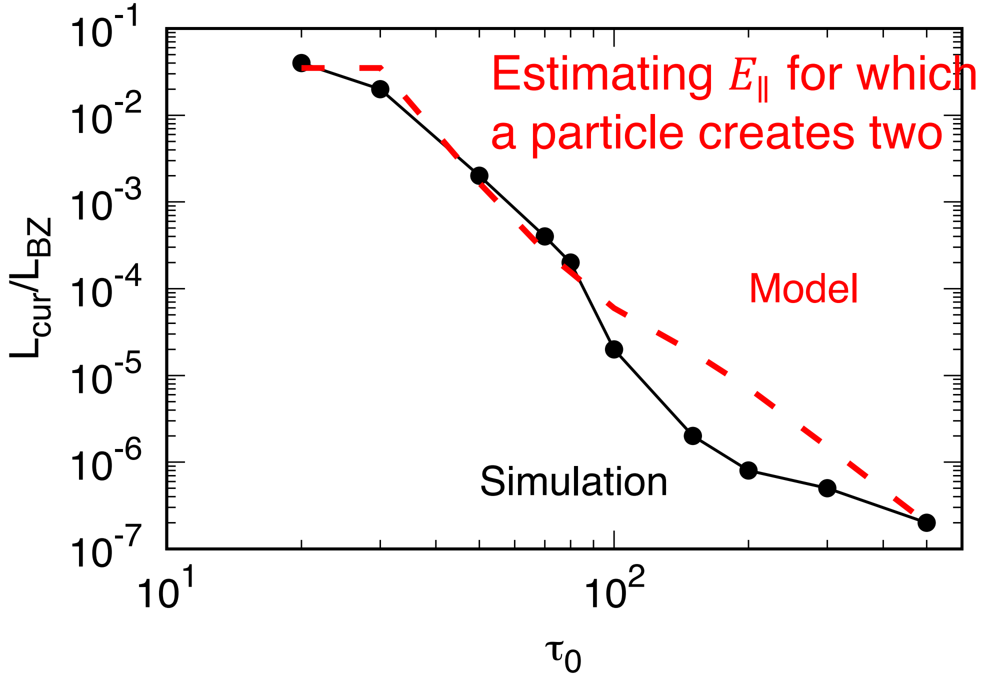
Bright curvature radiation



Curvature photon

$$\epsilon_c = \frac{3}{4\pi}\frac{h}{R_c m_e c}\gamma^3$$
$$\sim 3 \times 10^5 M_9^{-1}\gamma_{10}^3,$$
(200 GeV)

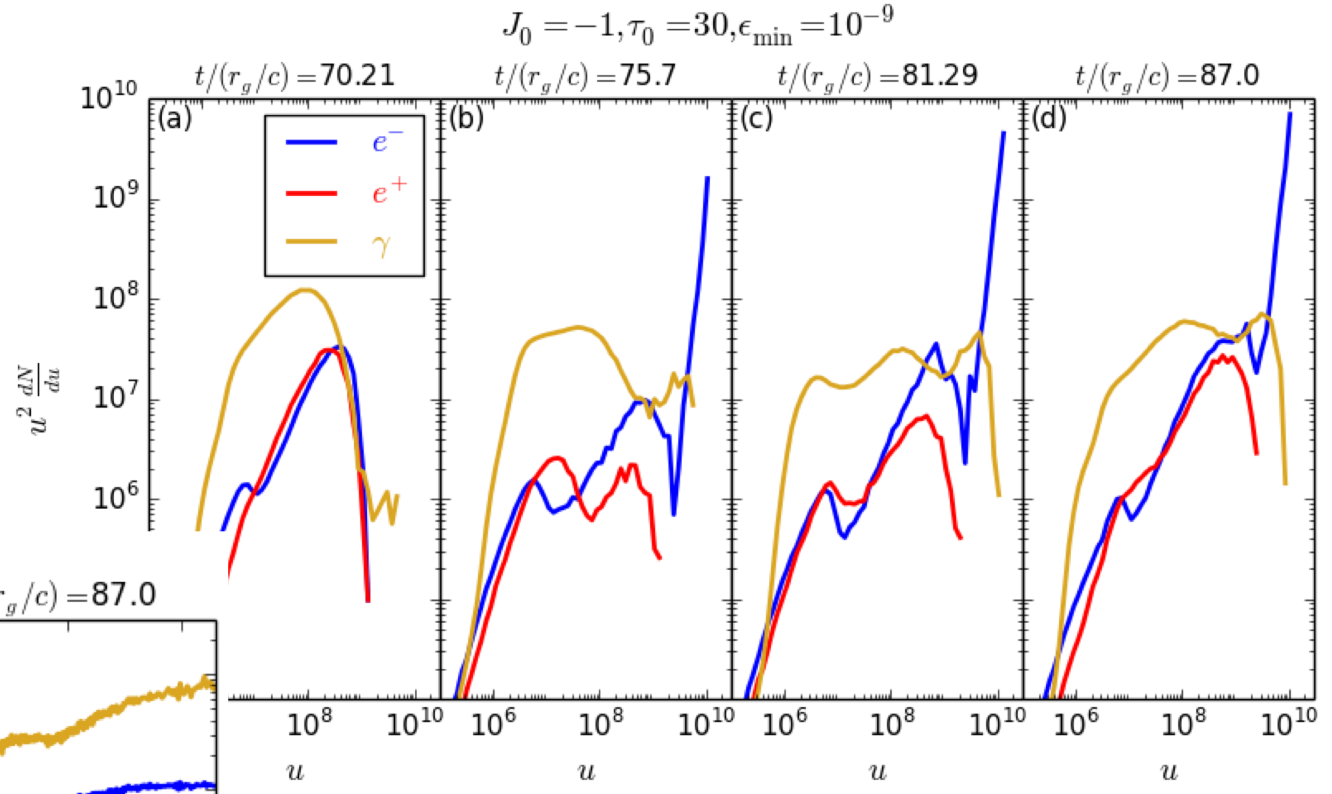
- Curvature luminosity ($\propto \gamma^4$) sensitive to τ_0
- Variation of τ_0 makes flares at 0.1-1 TeV
- Flare rise time ~ gap crossing time
- Need GR ray tracing
- Reverberation mapping?



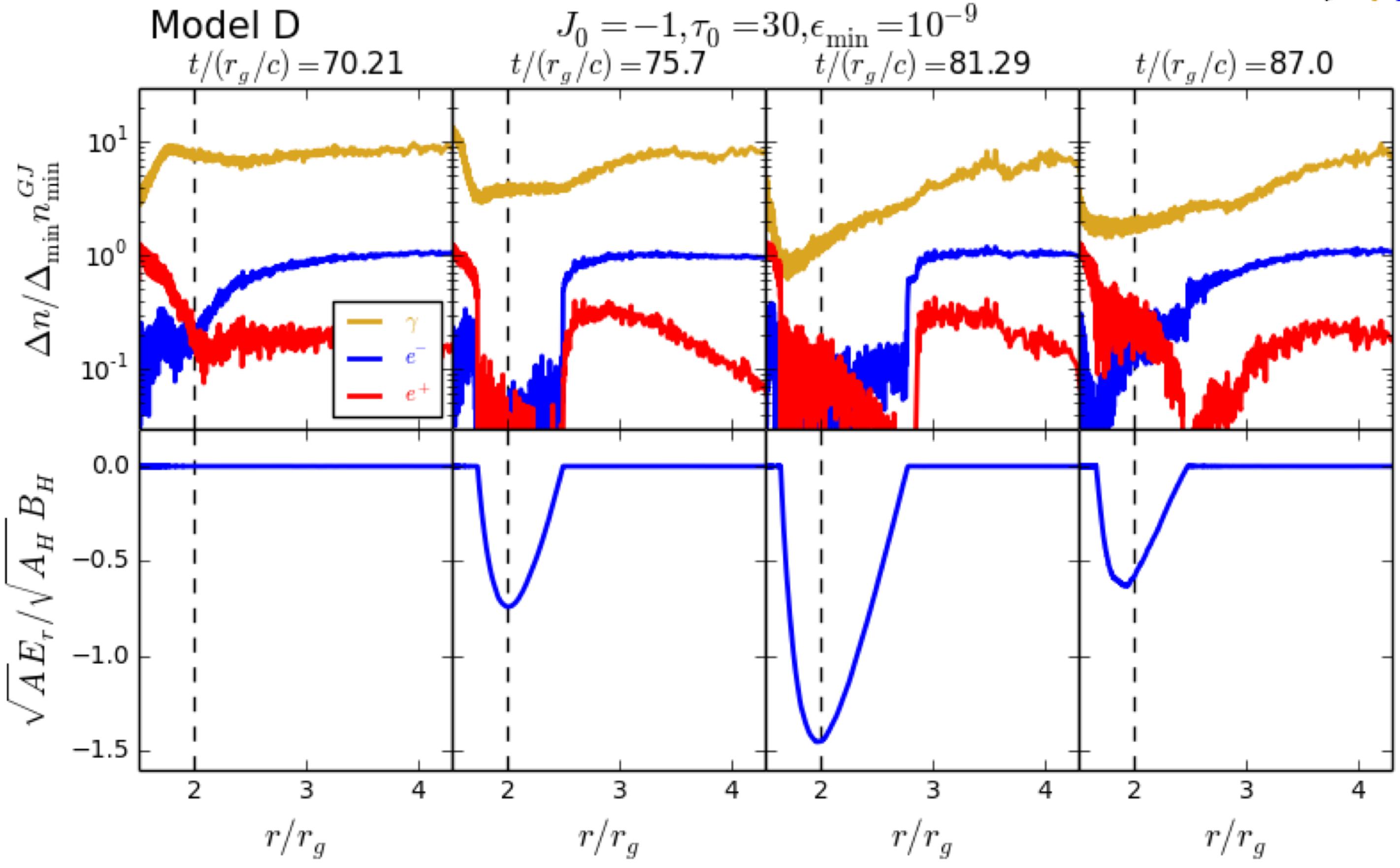
Kisaka, Levinson & KT 2020; Kisaka, Levinson, KT & Niv 2021

Summary

- High-resolution radio observations have stimulated simulation studies of black hole + accretion disk system
- Energy injection of jets is probably the BZ process, but no observational evidence yet → Emission mechanism of jets?
- Density of funnel ($\lesssim 100\, n_{GJ}$) seems too low to shine in radio for RIAF
- Funnel wall dissipation is interesting
  - Magnetic reconnection, hadronic process
  - KH instability
  - Superluminal motion?
- Funnel can shine in gamma-ray at magnetospheric gaps
  - 1D GR-PIC simulations show periodic opening of a gap at null charge surface
  - Bright curvature radiation
  - Reverberation mapping?
  - Effects of light surfaces, e+e- injection, etc. to be explored



$J_0 = -1, \tau_0 = 30, \epsilon_{\rm min} = 10^{-9}$
$t/(r_g/c) = 70.21$
$t/(r_g/c) = 75.7$
$t/(r_g/c) = 81.29$
$t/(r_g/c) = 87.0$
(a)
(b)
(c)
(d)
e^-
e^+
γ
$u^2 \frac{dN}{du}$
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
u



Model D
$J_0 = -1, \tau_0 = 30, \epsilon_{\rm min} = 10^{-9}$
$t/(r_g/c) = 70.21$
$t/(r_g/c) = 75.7$
$t/(r_g/c) = 81.29$
$t/(r_g/c) = 87.0$
$\Delta n / \Delta_{\rm min} n^{GJ}_{\rm min}$
10^{-1}
10^{0}
10^{1}
γ
e^-
e^+
$\sqrt{A} E_r / \sqrt{A_H} B_H$
0.0
−0.5
−1.0
−1.5
2
3
4
r/r_g