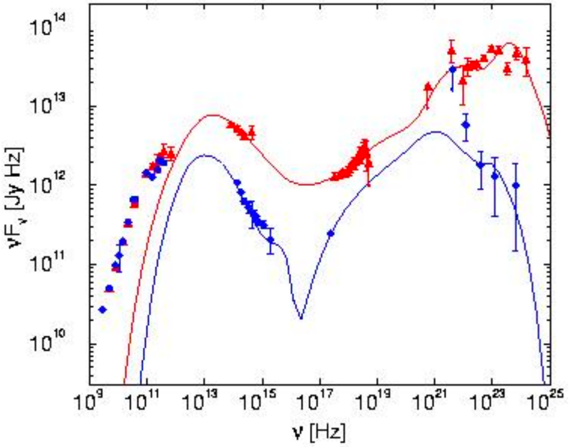
Jet formation, dissipation and HE emission in BH magnetospheres

Amir Levinson

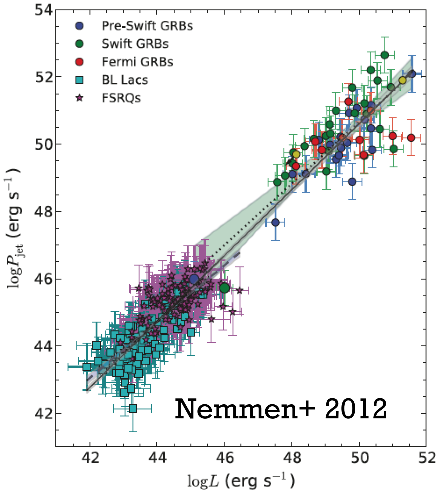
Tel Aviv university

Defining characteristics of blazers

Nonthermal emission

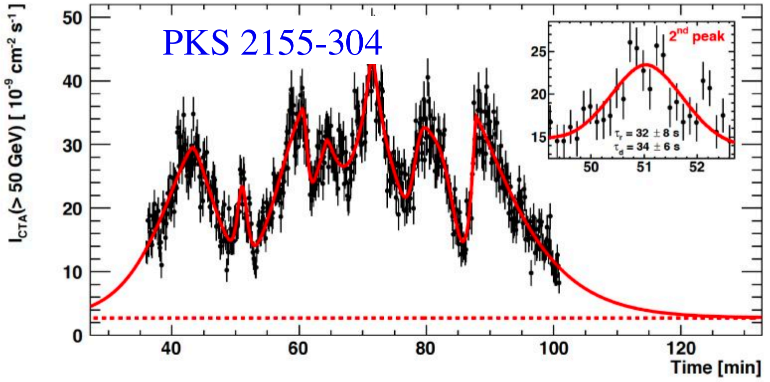


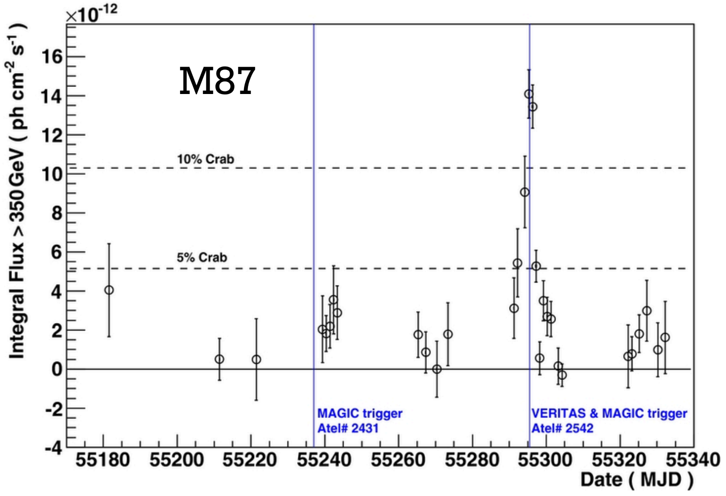
High efficiency



Nemmen+ 2012

Rapid variability





VHE from misaligned blazars

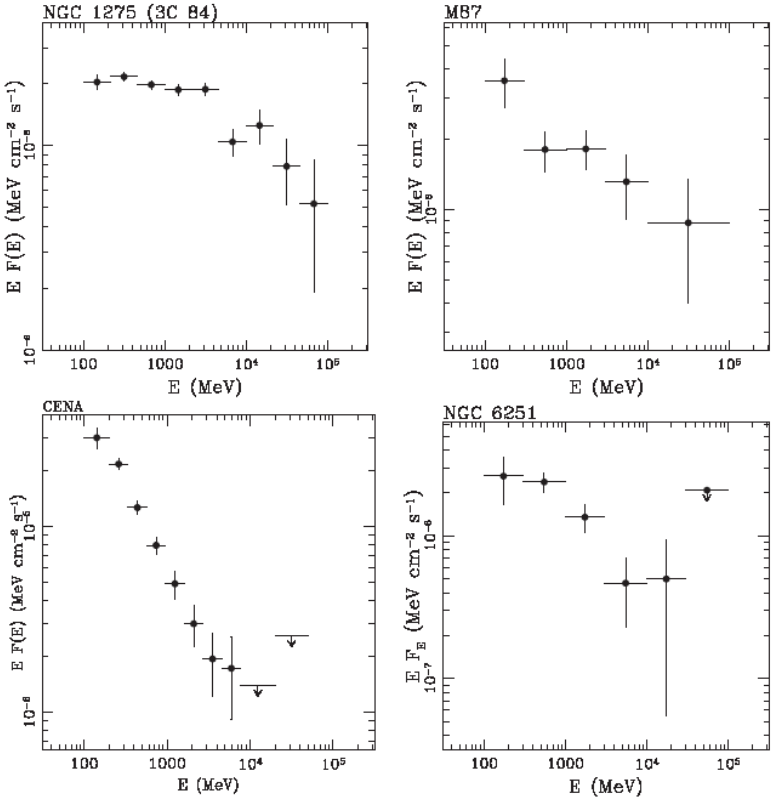


Figure 1. Spectral energy distributions (SEDs) of the FRI radio galaxies NGC 1275, M87, Cen A, and NGC 6251.

Table 2
Results of the *Fermi* LAT Analysis

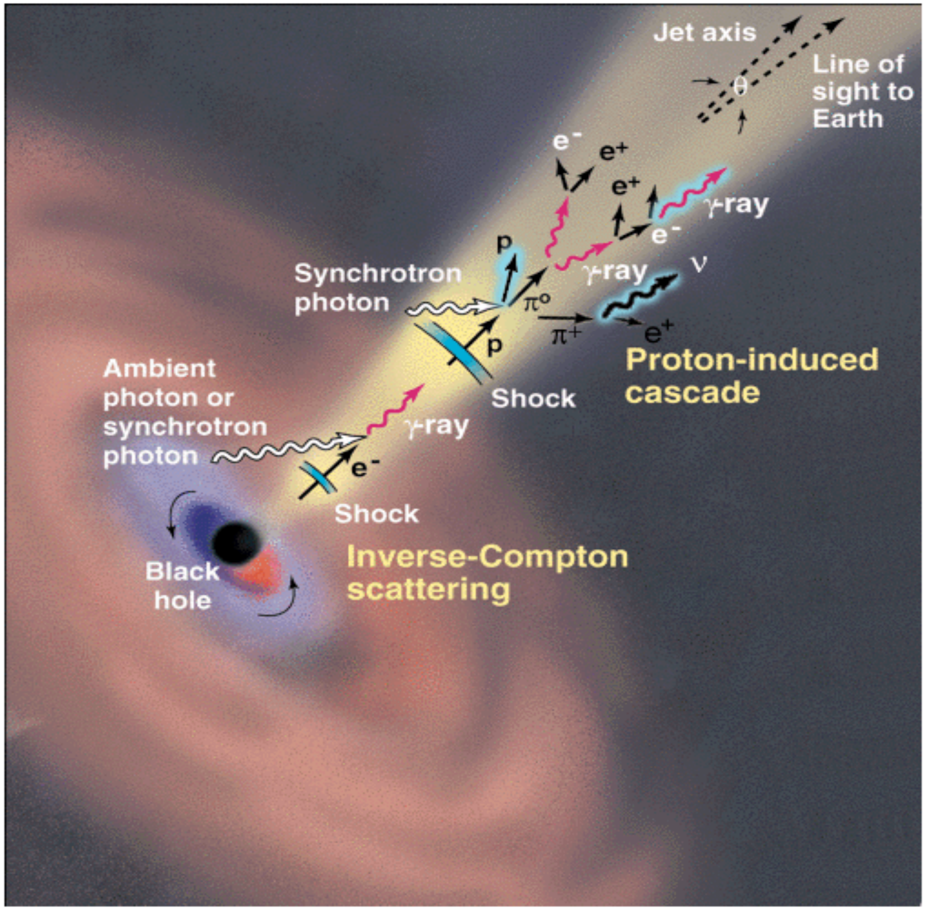
Object	TS	Γ	Flux[a] (>100 MeV)	logLum[b] (0.1–10 GeV)
3C 78/NGC 1218	35	1.95 ± 0.14	4.7 ± 1.8	42.84
3C 84/NGC 1275	4802	2.13 ± 0.02	222 ± 8	44.00
3C 111	34	2.54 ± 0.19	40 ± 8[c]	44.00
3C 120	32	2.71 ± 0.35	29 ± 17	43.43
PKS 0625−354[d]	97	2.06 ± 0.16	4.8 ± 1.1	43.7
3C 207	79	2.42 ± 0.10	24 ± 4	46.44
PKS 0943−76	65	2.83 ± 0.16	55 ± 12	45.71
M87/3C 274	194	2.21 ± 0.14	24 ± 6	41.67
Cen A	1010	2.75 ± 0.04	214 ± 12	41.13
NGC 6251	143	2.52 ± 0.12	36 ± 8	43.30
3C 380	95	2.51 ± 0.30	31 ± 18	46.57

Some are also TeV sources

Rapid variability occasionally seen

Emission region: Accretion disk? magnetosphere ? inner jet ?

General scheme



(Buckley, Science, 1998)

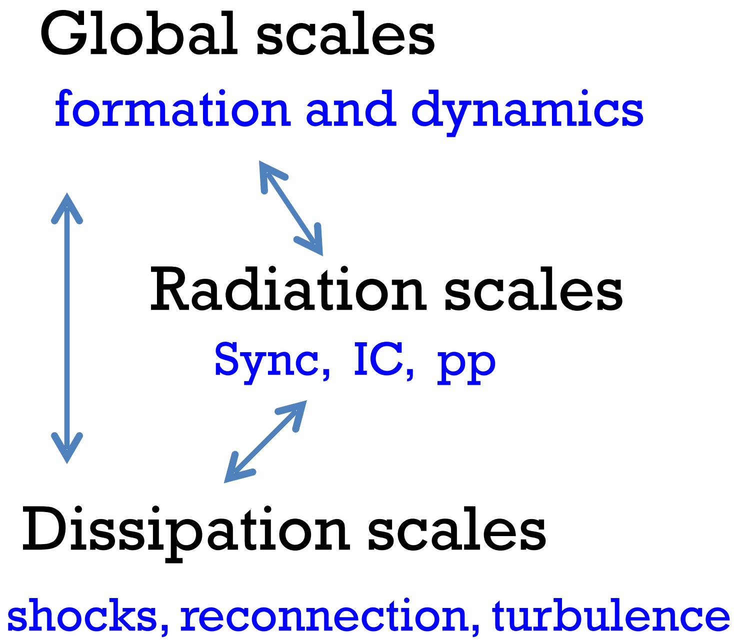
Accreting BH

→ relativistic outflow

→ dissipation

→ emission

BH magnetosphere and jet are multi-scale systems



Global scales

formation and dynamics

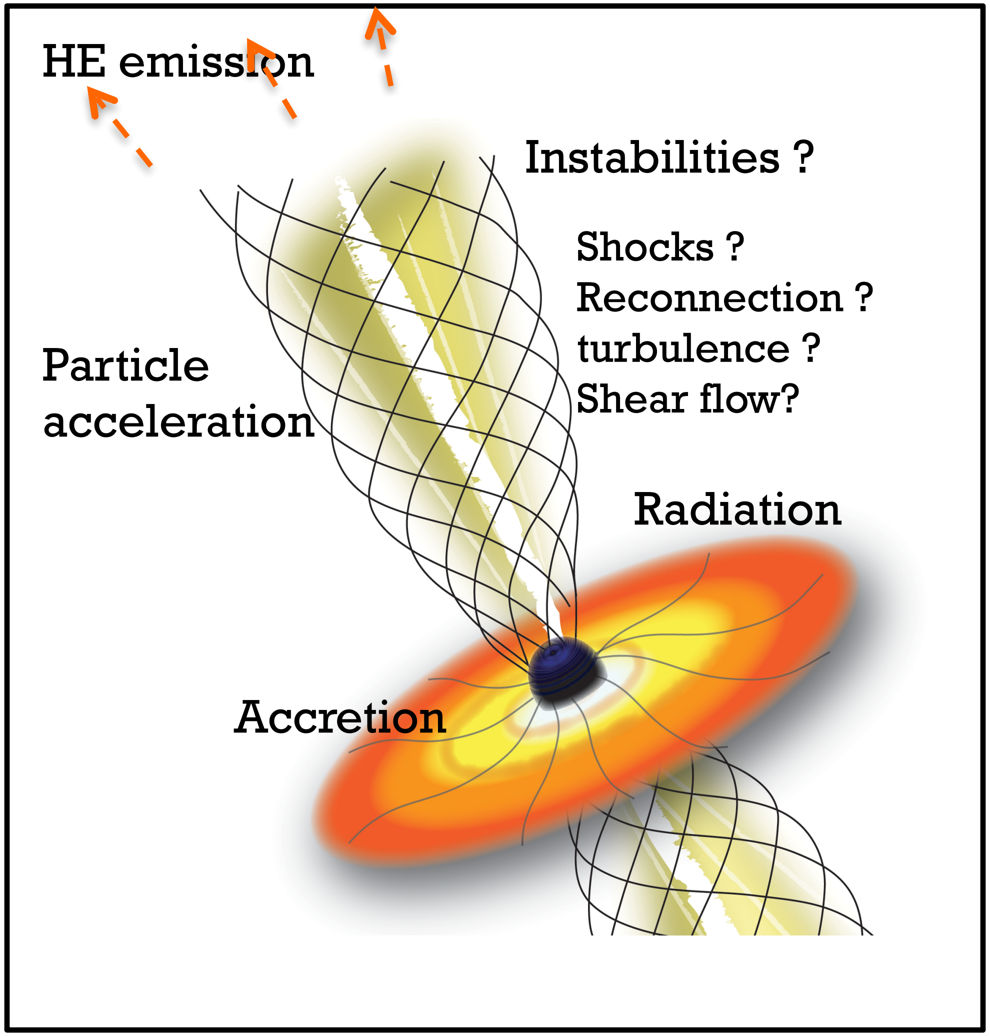
Radiation scales

Sync, IC, pp

Dissipation scales

shocks, reconnection, turbulence

How are they connected?



Modern approach to HE astrophysics

- Extensive numerical simulations to study macro and micro physics (combined with analytic calculations)

  e.g., GRMHD, GRFFE, PIC, Monte-Carlo, etc.

- Use insights from modern analyses to constraint models.

  → beyond phenomenological approach

- Global: use microphysics results as sub-grid models ?

Important: limitations of numerical methods must be well recognized

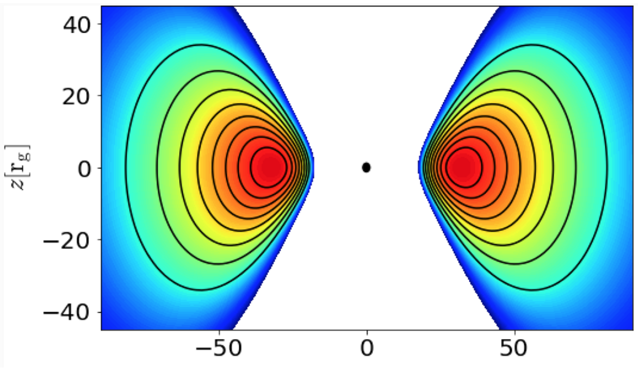
piecing the puzzle

Illustration

MAD accretion: High res 2D GRMHD simulations

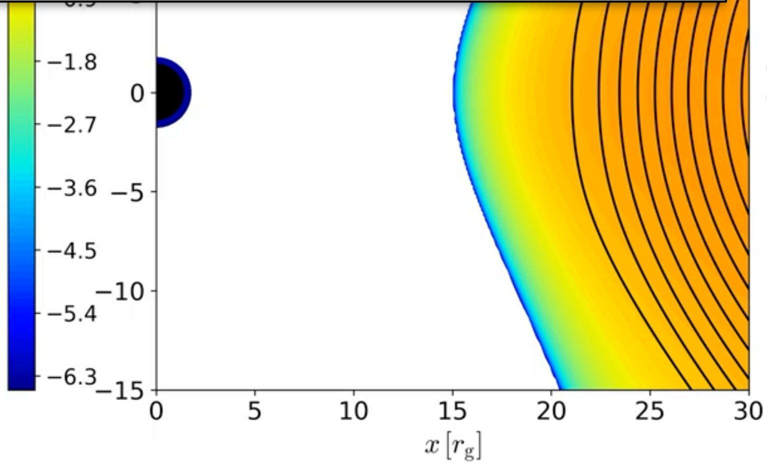
Chashkina, Bromberg, AL 21

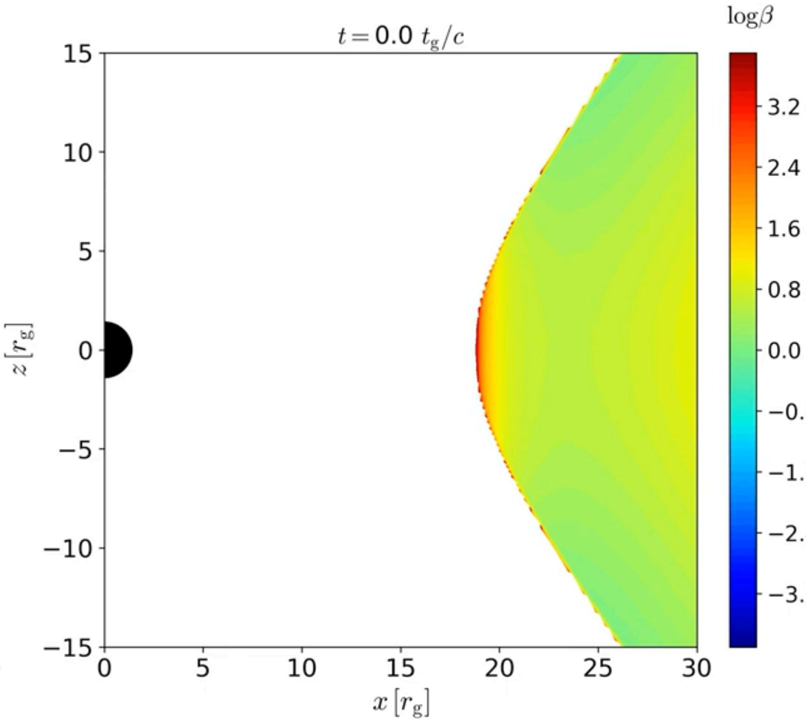
Initial state



This simulation doesn't tell us:

- How is plasma supplied to the magnetosphere ? →composition?
- How does magnetic energy dissipate?
- How do particles accelerate?
- Other accretion regimes (missing physics)





This talk focuses on

- Flares in MAD accretion
- Plasma injection and GRPIC simulations
- Jet acceleration and dissipation channels.

Characteristic parameters

$$\mu = m/m_p, \quad r_g = GM/c^2, \quad \mathscr{L}_j = L_j/L_{Edd}$$

- BH angular velocity: $\Omega_H = ac/2r_H \approx 10^{-4}\, M_9^{-1}$ Hz
- Magnetic field: $B = 10^4 \mathscr{L}_j^{-1/2}\, M_9^{-1/2}\, \tilde{r}^{-1}$ G
- GJ density: $n_{GJ} = \dfrac{\Omega\, B}{2\pi ec} \approx 10^{-2}\, B_4\, M_9^{-1}$ cm^{-3}

  minimum density required for BH activation

  multiplicity: $\kappa = n/n_{GJ}$

Magnetization parameter

$$\sigma = \frac{B^2}{4\pi\langle\gamma\rangle mc^2 n} = \frac{eBr_g}{\kappa\langle\gamma\rangle mc^2} \sim 10^{12}\frac{M_9 B_4}{\mu\kappa\langle\gamma\rangle}$$

- Magnetic extraction (BZ process): $\sigma \gg 1$
- Effective dissipation in shocks: $\sigma < 0.1$

  Requires gradual MHD acceleration, $\sigma \to \Gamma$
- Efficient shock acceleration: $\sigma < 10^{-3}\ (10^{-5})$

  At higher values in non-or-mildly relativistic shocks
- Relativistic reconnection & turbulence: $\sigma > 1$

  semirelativistic: $\sigma_i < 1,\ \sigma_e \gg 1$

microscopic scales

Collisionless plasma:

- Skin depth: $l = c/\omega_p$
- Larmor radius: $r_L = \frac{mc^2}{eB} = l/\sqrt{\sigma}$
- scale separation:

$$r_g/l = 10^{6.5}\sqrt{\frac{\kappa M_9 B_4}{\mu < \gamma >}}$$

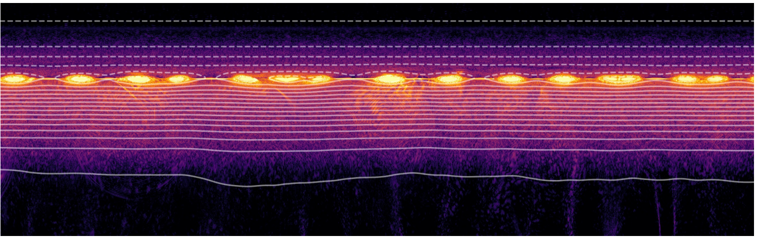
Note: for $B \propto r^{-1}$, $l/r \propto r^{-1}$

Radiation:

Scattering: $\tau = \sigma_T \kappa n_{GJ} r_g << 1$

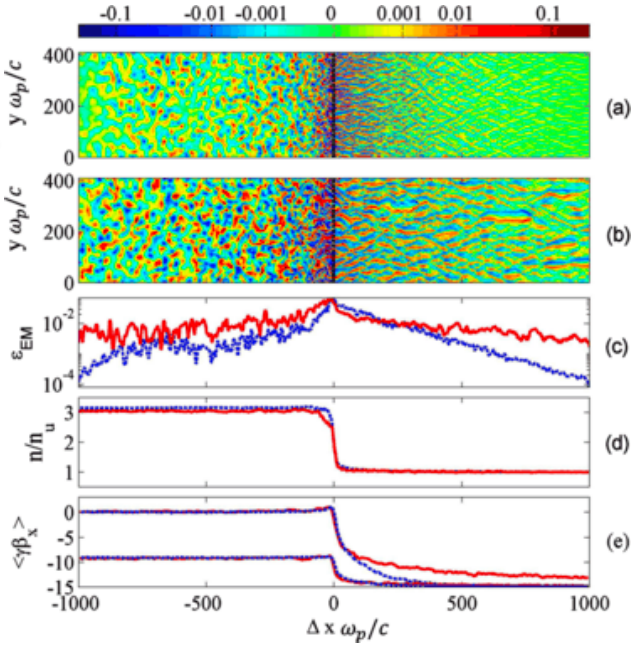
Pair production: $\tau_{pp} = \sigma_T n_{ph} r_g$

reconnection



Mahlmann +2022

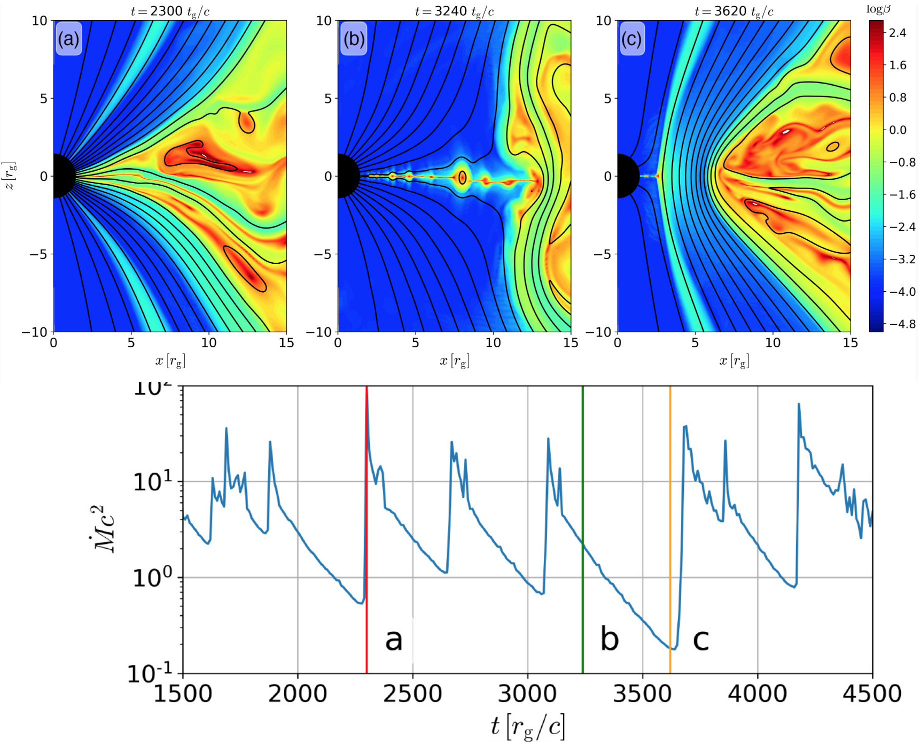
shocks



Sironi+2015

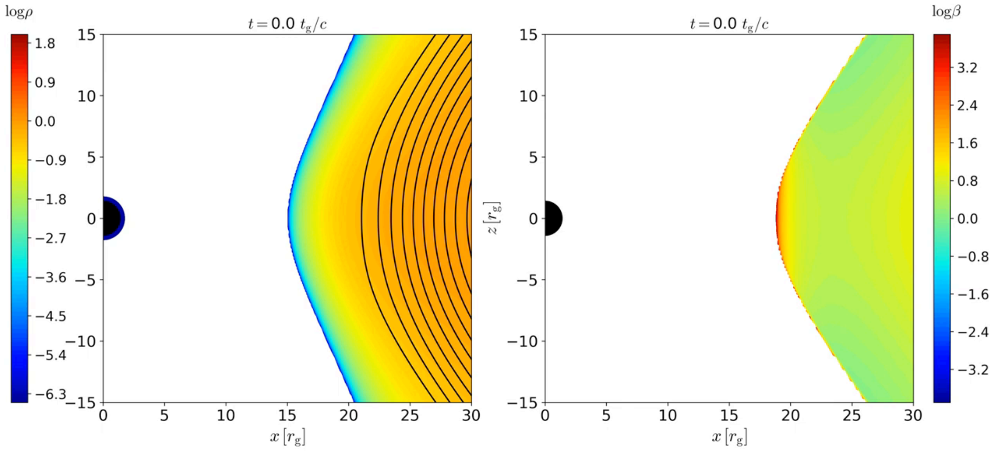
I. Accretion dynamics: HE emission from equatorial current sheets

- Accretion flow during MAD states exhibits cyclic behavior.
- During low accretion states current sheet forms
- Rapid reconnection ensues and the cycle repeats



2D Ripperda + 20, Chashkina + 21
Extreme resolution 3D, Ripperda + 22

Chashkina + 21



Emission from current sheet

- Available energy per particle: $\gamma_\sigma \approx \sigma_e \sim 10^{15}\ \kappa^{-1} M_9 B_4$
- Synchrotron cooling limit: $\gamma_{syn} \approx 3\times 10^5 B_4^{-1/2}$

peak at burn-off limit ~ 200 MeV

efficiency: $L_{rad} \sim 0.1\ L_{jet}$ (Bransgrove+ 21, Ripperda +22)

- IC energies: $h\nu_{IC} \approx \gamma_{syn}^2 h\nu_p \sim 1 B_4^{-1} \nu_{p,12}$ GeV

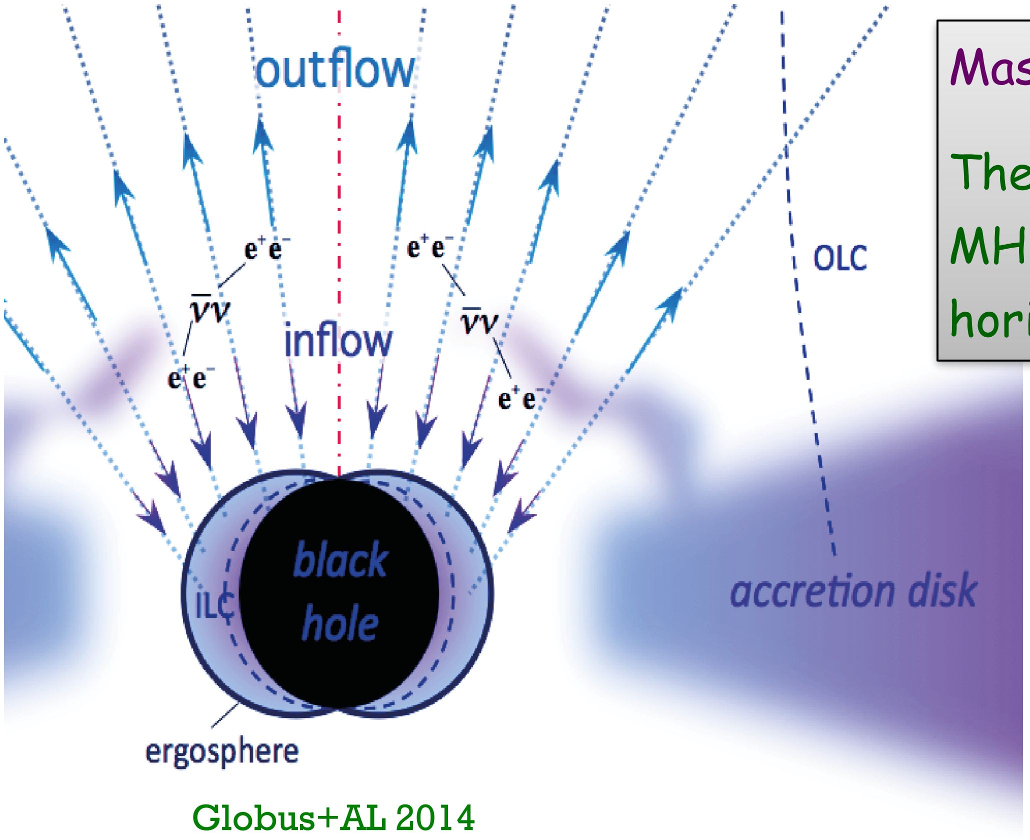
In M87 $h\nu_{IC} \sim$ a few TeV

Above estimates hold if the multiplicity $\kappa < 10^9\ B_4^{3/2}$

II. Plasma injection in magnetosphere

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 !

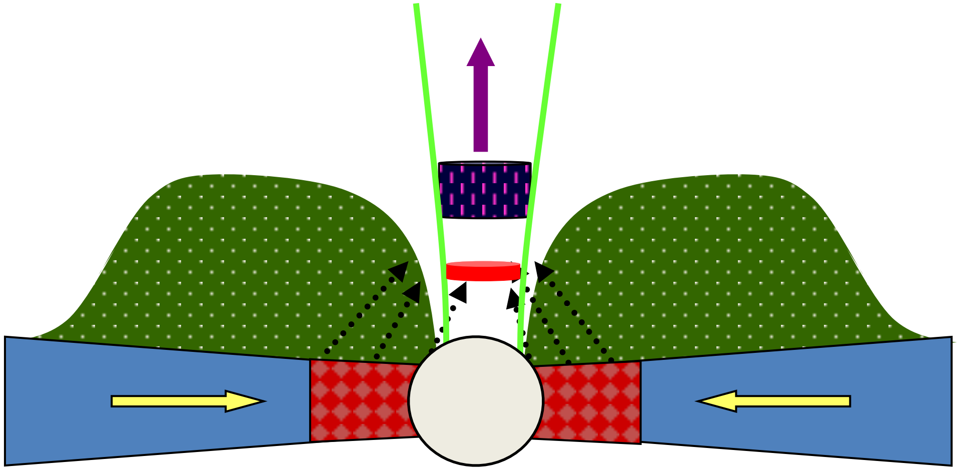
There can be no continuous ideal MHD solution that extends from the horizon to infinity.

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

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

mass loading ?

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 $\gamma\gamma \to e^+ e^-$

Requires emission of MeV photons:

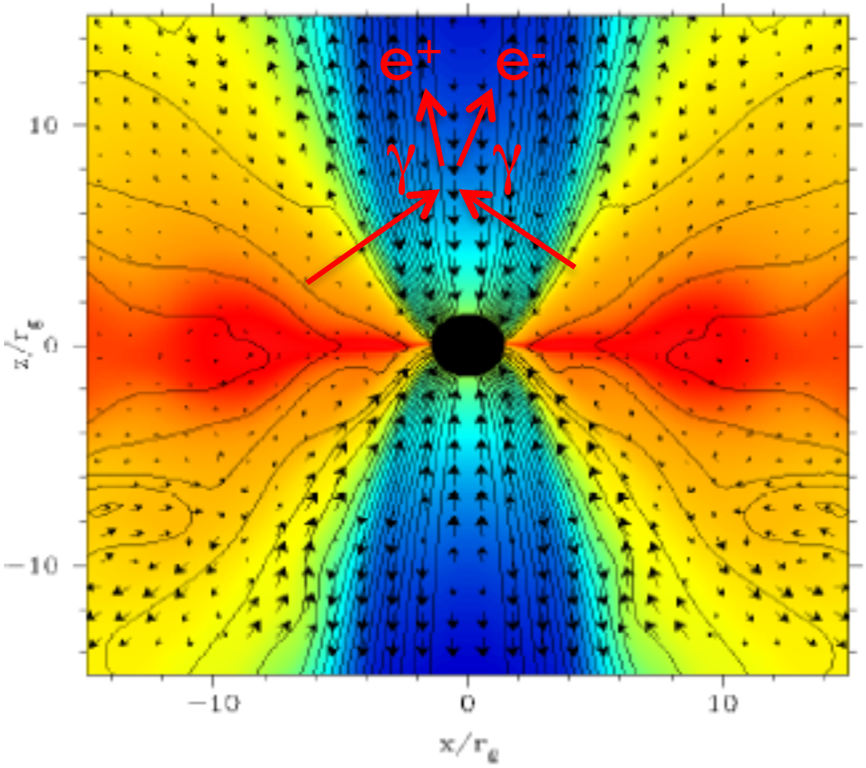
- Low accretion rates: from hot accretion flow

- High accretion rate: from corona ?

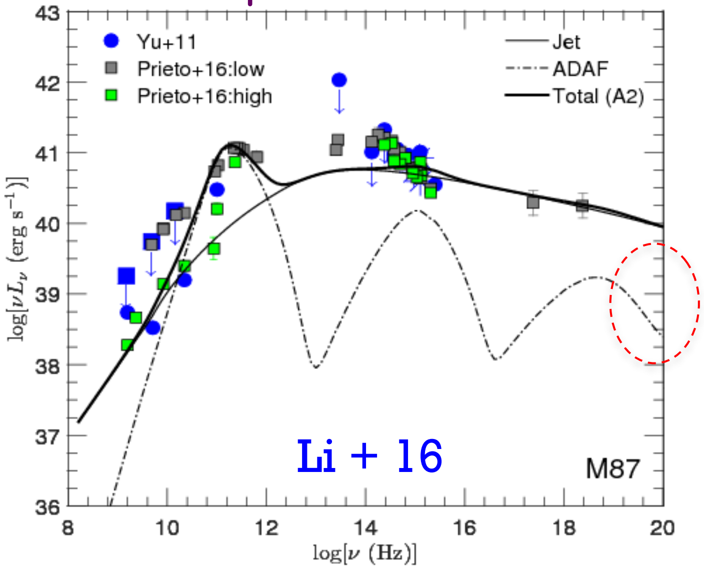
AL & Rieger 11

From naïve ADAF model

$$n_\pm / n_{GJ} \sim 0.05\, \dot{m}_{-4}^{7/2} M_9$$



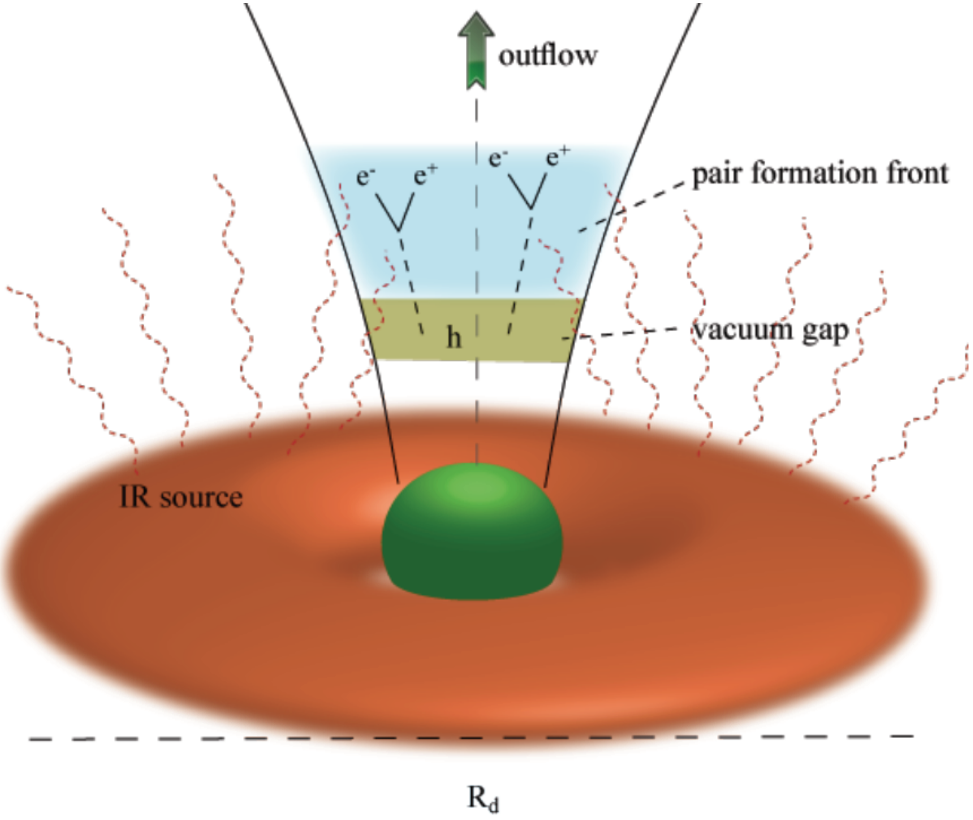
Example: M87



Li + 16

Activation of a spark gap

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)

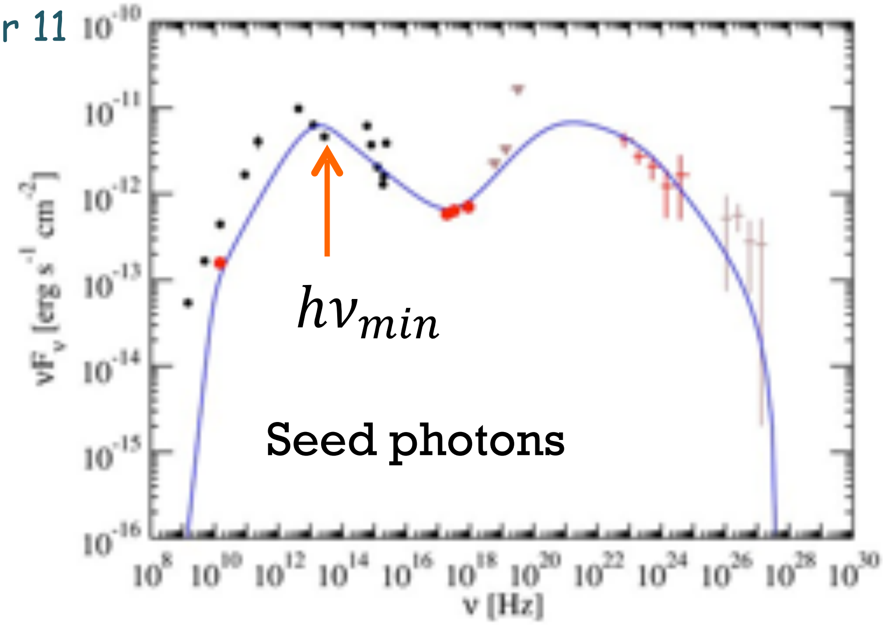
- particle acceleration to VHE by potential drop.

Gap emission

AL + Rieger 11

- Curvature radiation
- IC emission
- Regulated by pp

→ Highly nonlinear



$h\nu_{min}$

Seed photons

$$\epsilon_{th} \sim (m_e c^2)^2 / h\nu_{min} \sim 50\, \nu_{min,9}^{-1}\, TeV$$

$$\epsilon_{\mathrm{cr,max}} = \frac{3}{2}\frac{\hbar c \gamma_{\mathrm{max}}^3}{\rho} \leqslant 10 B_4^{3/4} M_9^{1/2} (h/r_s)^{3/4} (\rho/r_s)^{1/2}\ \mathrm{TeV}$$

$$\epsilon_{\mathrm{IC,max}} = m_e c^2 \gamma_{\mathrm{max}} \leqslant 10^3 B_4^{1/2} M_9 L_{41}^{-1/2} \mathcal{R} (h/r_s)^{1/2}\ \mathrm{TeV}$$

GRPIC Simulations

Zeltron code (Benoit Cerutti)
Recent works: AL & Cerutti, Kisaka + 20,22
Global 2D: Perfray+19, Crinquand + 20,21, El Mellah+ 22

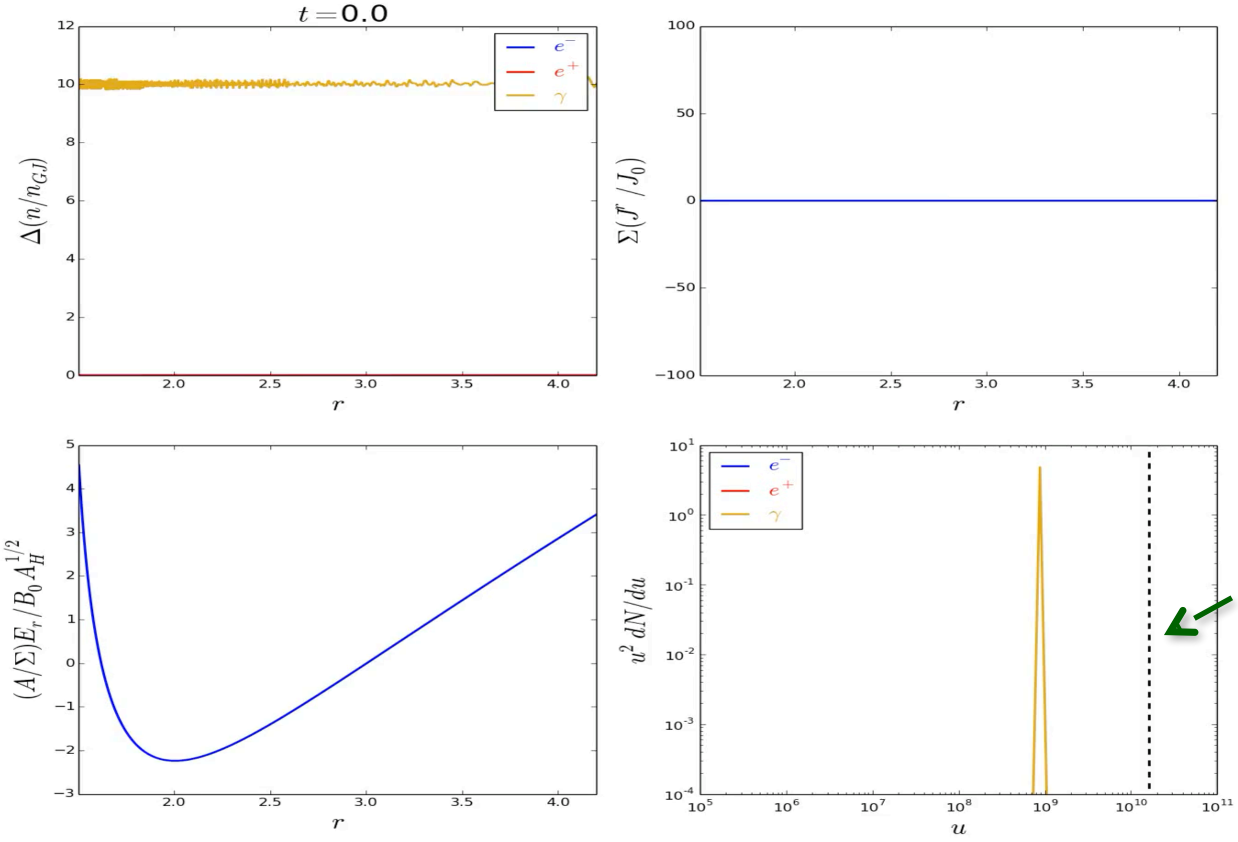
- Fully GR (in Kerr geometry)
- Inverse Compton and pair production are treated using Monte-Carlo approach.
- Curvature emission + feedback included
- Resolves skin depth in 1D

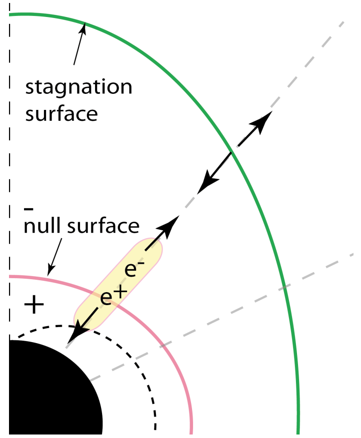
1D simulations - example

AL & Cerutti 18

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

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



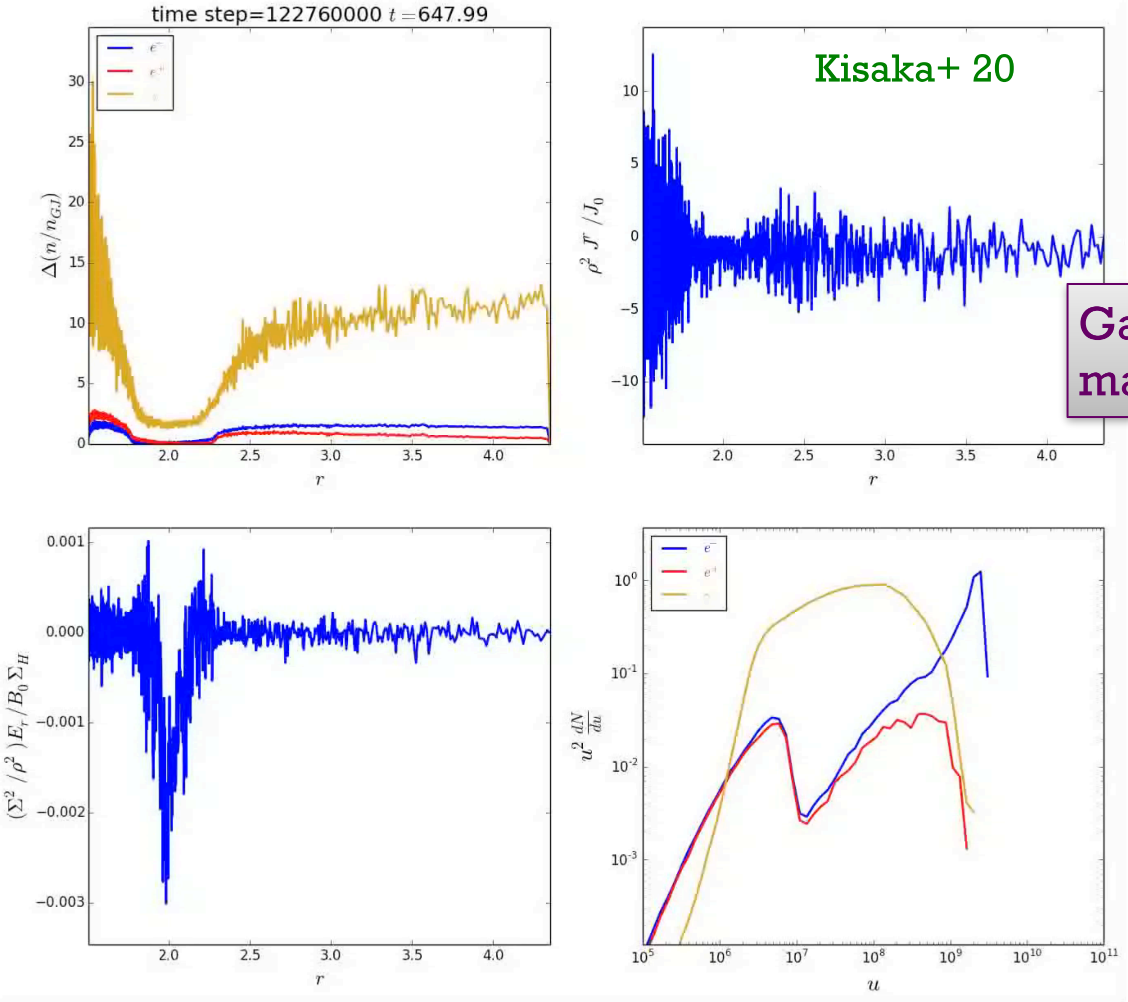


Radiation reaction limit

Gap oscillations

$\tau_0 = 100$

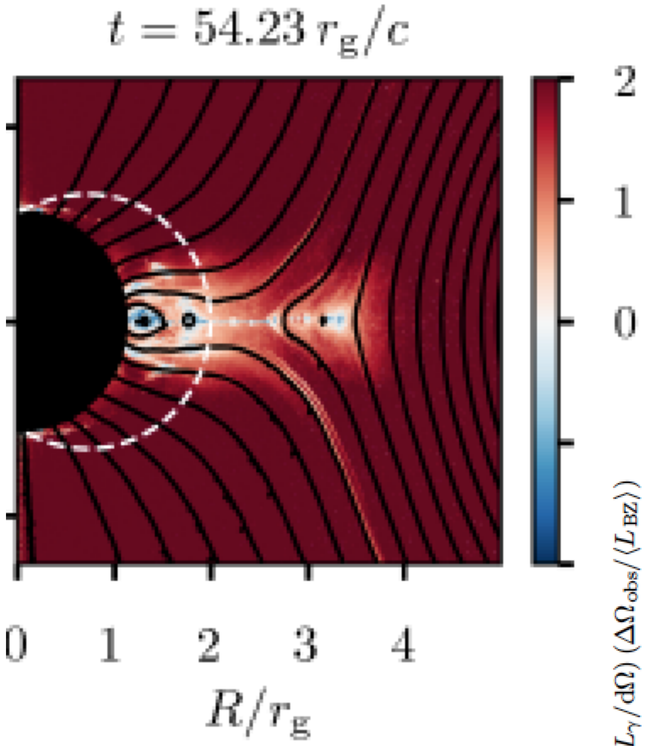
Chen & Yuan 20
Kisaka, AL + 20



Gap dynamics depends on global magnetospheric current!

2D GRPIC with radiation

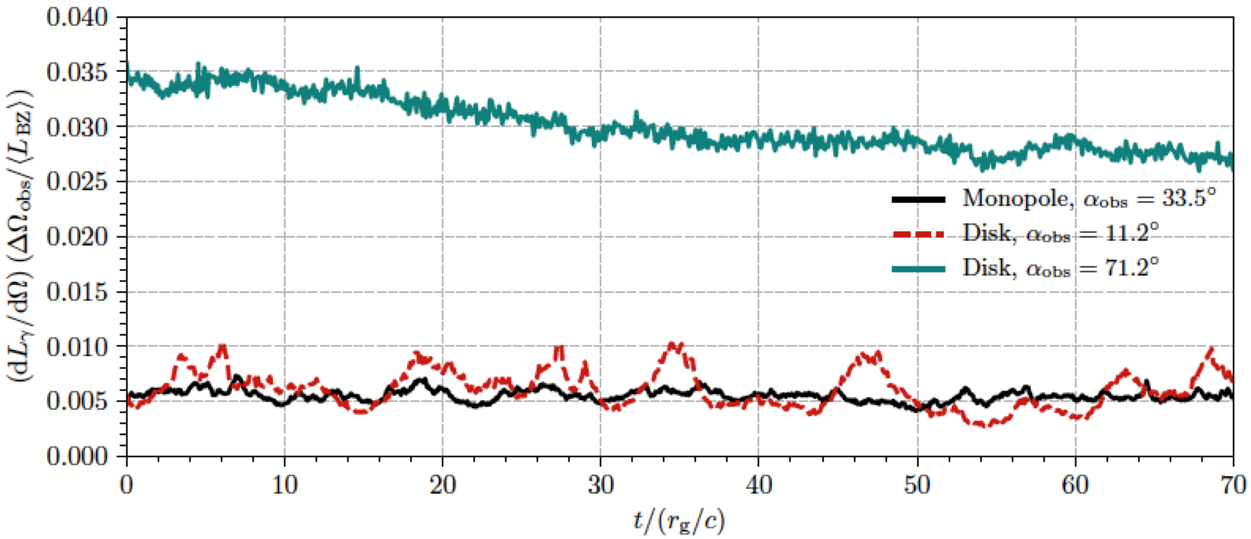
Crinquand + 20, 21
El Mellah + 22



Radiation: $\lambda = r_g/\tau$

Plasma (skin depth):

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



III. Dissipation of magnetized jets

Large scale (ordered) B fields:

efficient jet production (MAD, MCAF, etc.), but stable!

- dissipation requires rapid growth of instabilities
- MHD acceleration (at best $\sigma \sim 1$)

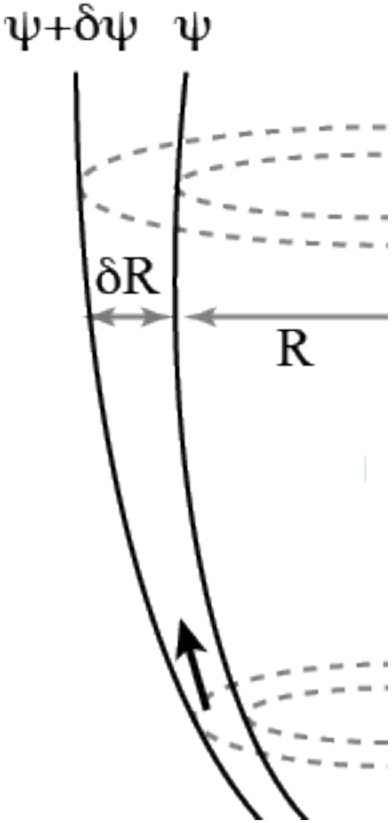
Small scale B field:

quasi-striped configuration (good for dissipation)

but how efficient ?

Gradual MHD acceleration

$$\sigma_0 \gg 1 \rightarrow \sigma \gtrsim 1$$



- Requires differential collimation

  Tchekhovskoy + 08; Komissarov + 09; Lyubarsky 09, 11

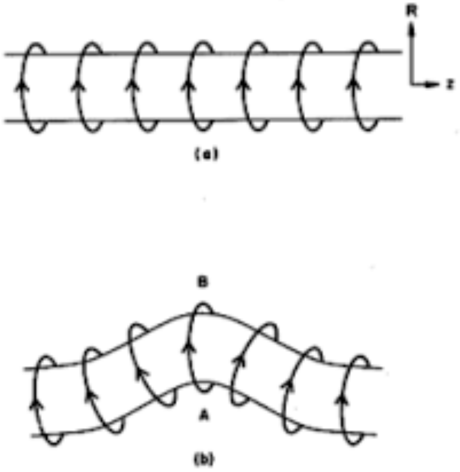
- Jet must be causal: $\Gamma\theta < \sqrt{\sigma}$
- Max Lorentz factor: $\Gamma < \left(\frac{\sigma_0}{\sin^2\theta}\right)^{1/3}$
- For strong causality, $\Gamma\theta \leq 1,\ \Gamma \sim \sigma$
- Even in optimal case $\sigma \gtrsim 1$

Shock acceleration requires further conversion of magnetic field,

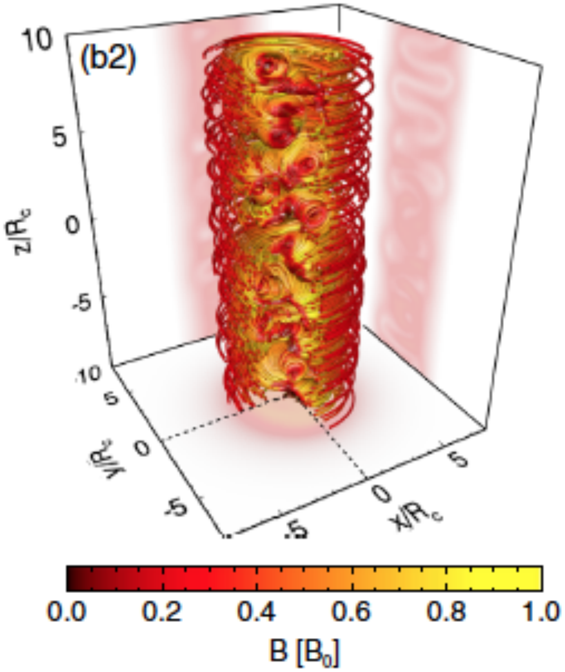
$$\sigma \gtrsim 1 \rightarrow \sigma \ll 1$$

e.g., Zech & Lemoine 21 in case of extreme TeV blazars

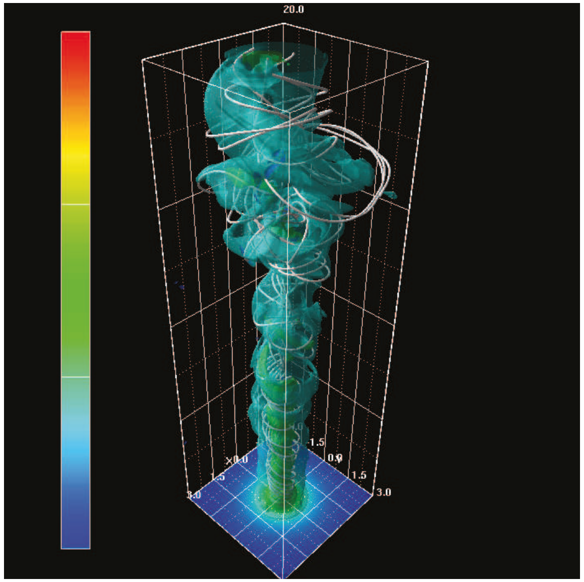
Kink instability



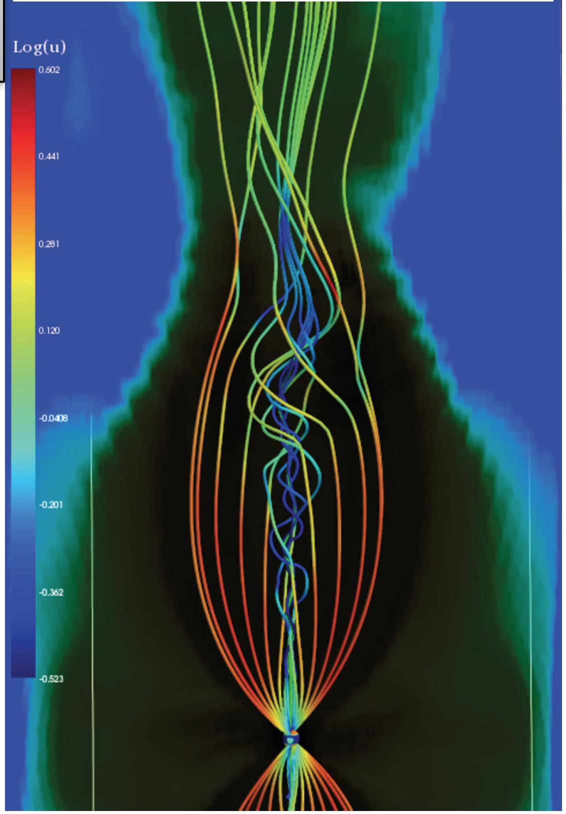
- Toroidal field is unstable to kink modes
- Generates helical twist, leads to turbulence and reconnection
- Proper growth rate > 100 a/c (bromberg + 19)



Alves + 18



Mizuno + 14



Bromberg & Tchekhovskoy 16

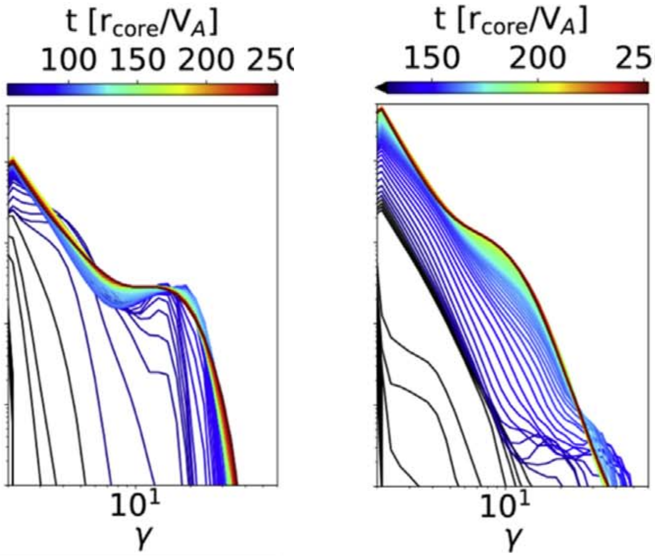
Simulations of kink instability with rotation

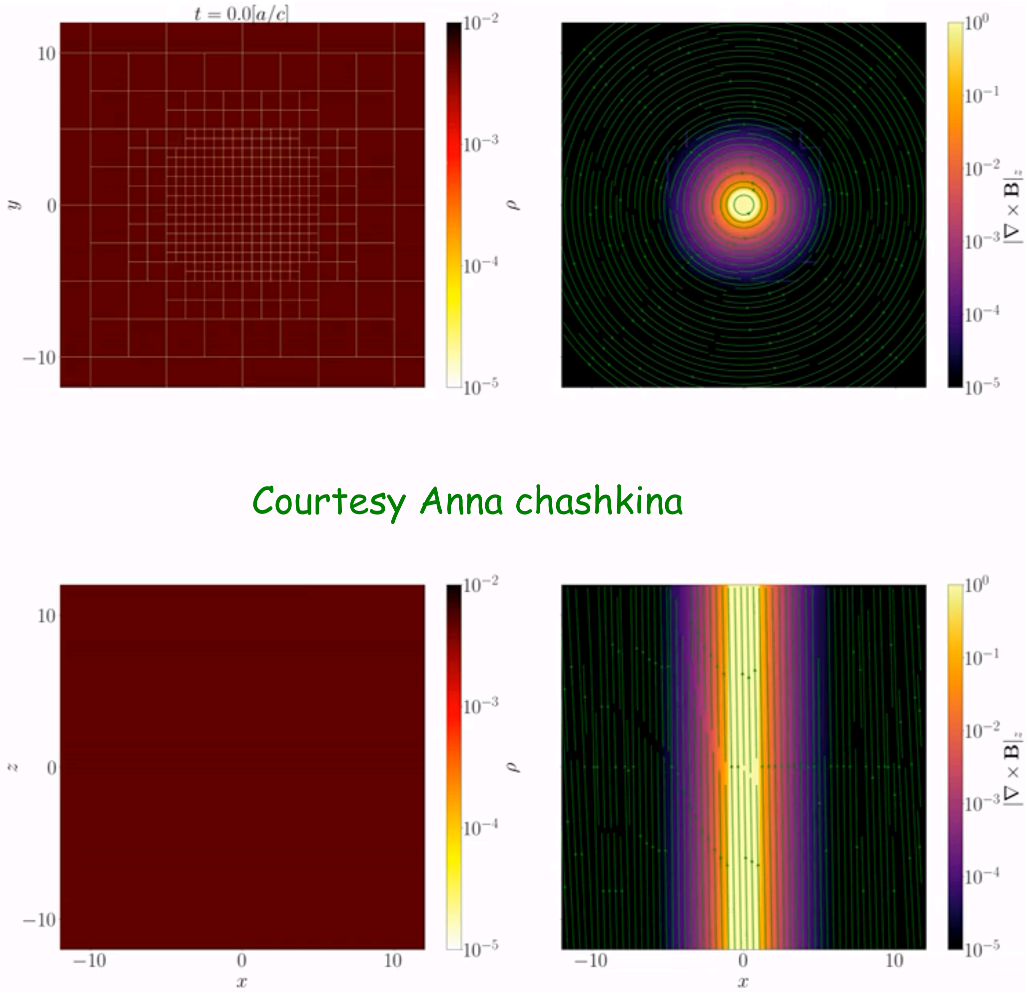
Bart Ripperda, Anna Chashkina, Alexander Chernoglazov, Sasha Philippov, Jordy Davelaar, Omer Bromberg and Lorenzo Sironi

PIC simulations, Davelaar + 20

No hard component of particle DF due to:

1. strong guid field
2. low amplitude turbulence





Courtesy Anna chashkina

Kink saturates at $\sigma \sim 1$

Relativistic turbulence & reconnection

see previous talk by Martin Lemoine

- Leads to reconnecting current sheets

  But are they important?

- Efficient particle acceleration ?

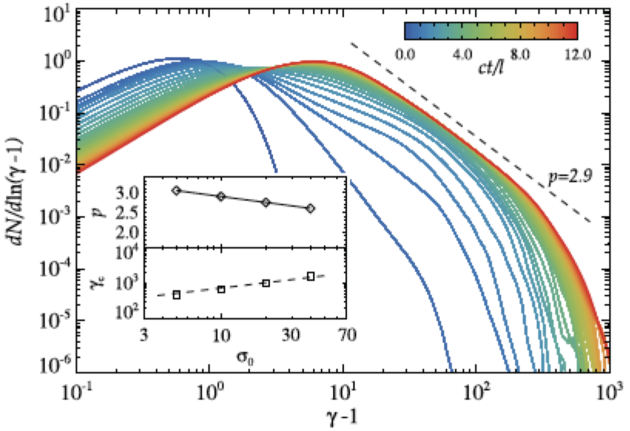
  depends on various factors

- Strong cooling has a dramatic effect

- Anisotropic pitch angle distribution

  affects emission properties

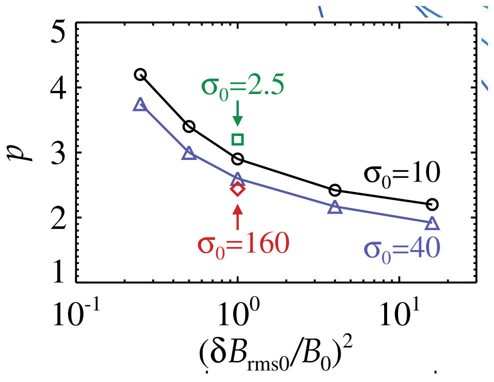
Comisso, Sironi 19,20,21

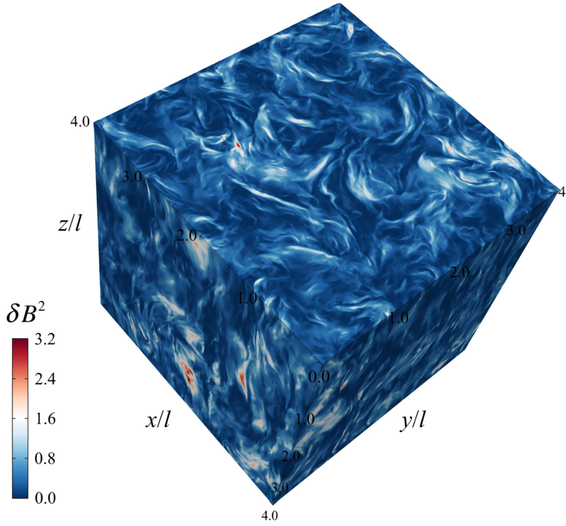


Wan + 15

Zhdankin + 17,19,20

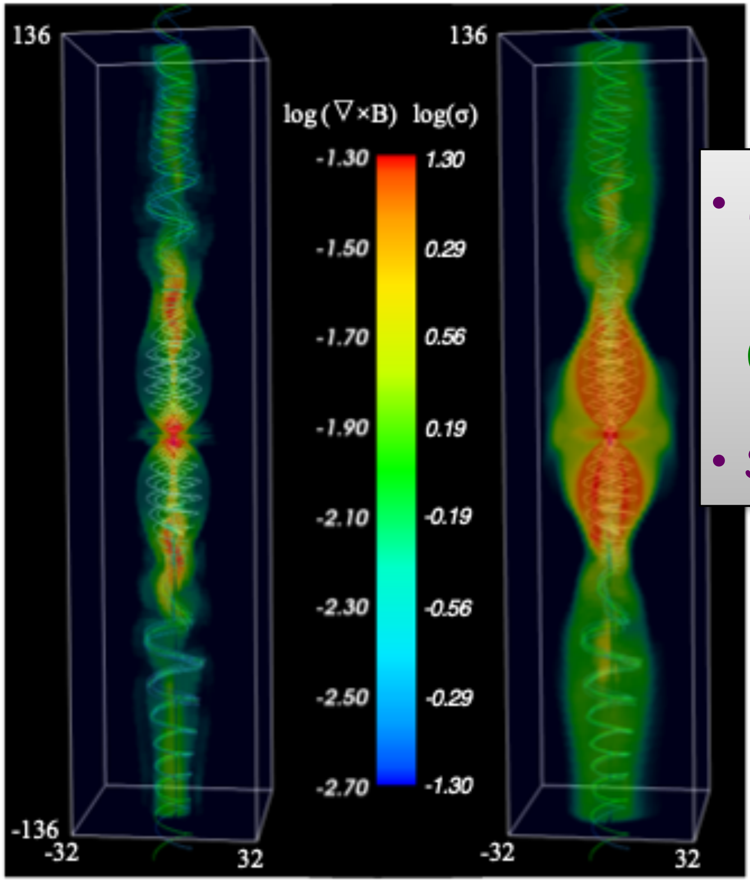
Demidem + 20





When is Kink instability generated?

3D simulations of a magnetic jet propagating in a star



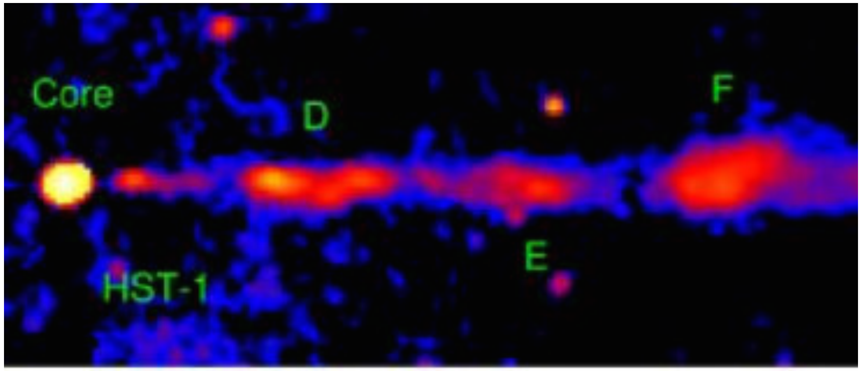
Bromberg & Tchekhovskoy 16

- kink instability requires strong collimation, $\Gamma\theta < 1.$

  Develops fastest in a collimation nozzle.

  (Bromberg&Tchehovskoy 16, Lyubarsky 12, Sobacchi + 17)

- Saturates at equipartition, $\sigma \sim 1$



Naive estimate

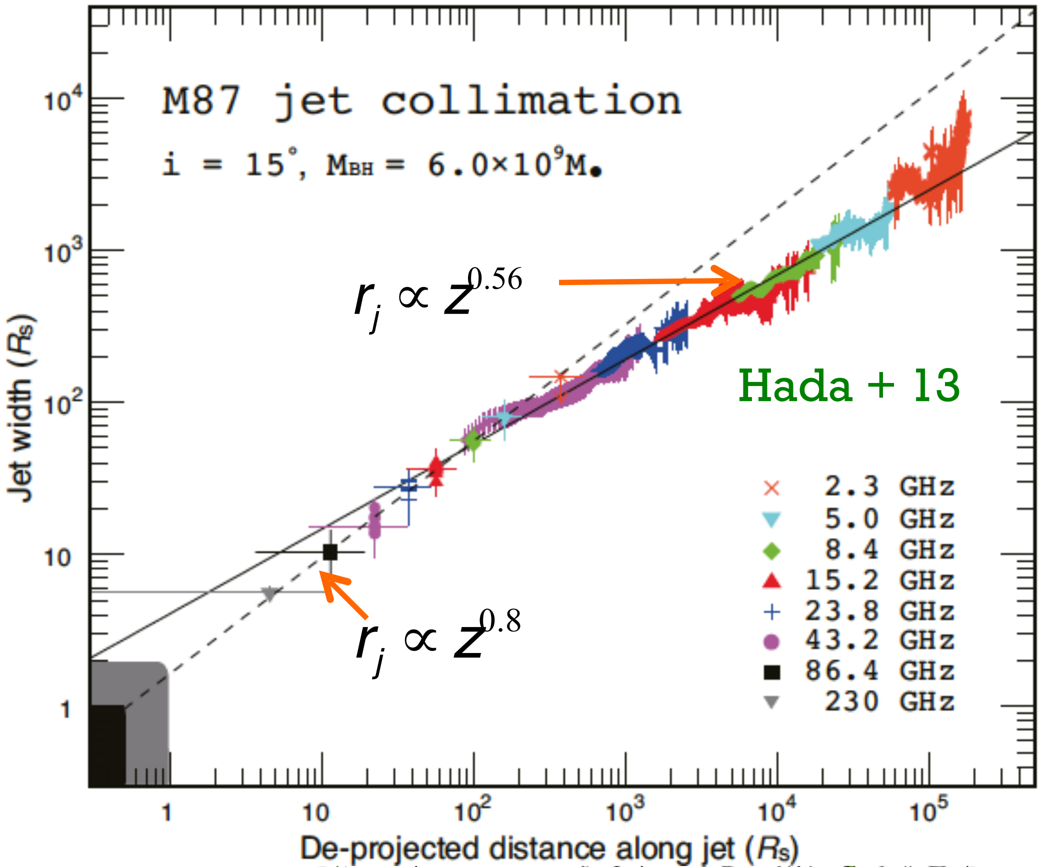
Light cylinder: $r_L \sim 5 - 20\, r_g$

Growth length:

$$ct_{kink} \sim 100\, a\Gamma$$

$$\approx 10^4 (a/30\, r_g)(\Gamma/10)\, r_g$$

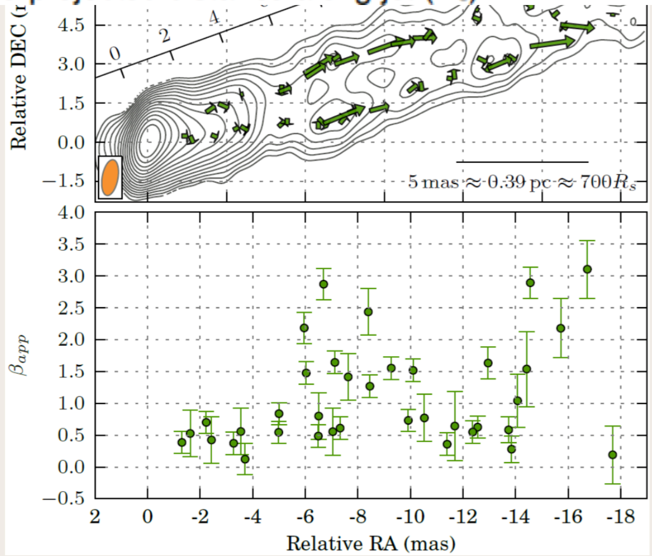
Variability: $t_{var} \geq 12$ days



$r_j \propto z^{0.56}$

$r_j \propto z^{0.8}$

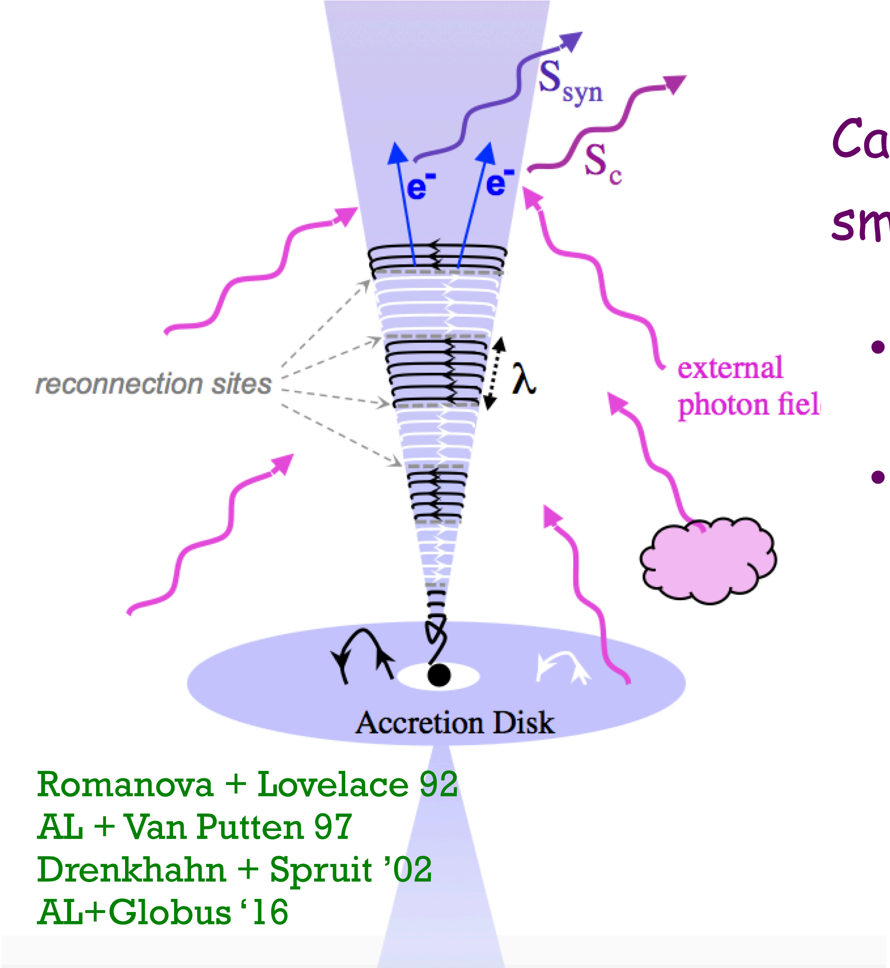
Hada + 13



Mertens + 16

quasi-striped jet

Reconnection of non-symmetric component



Romanova + Lovelace 92
AL + Van Putten 97
Drenkhahn + Spruit '02
AL+Globus '16

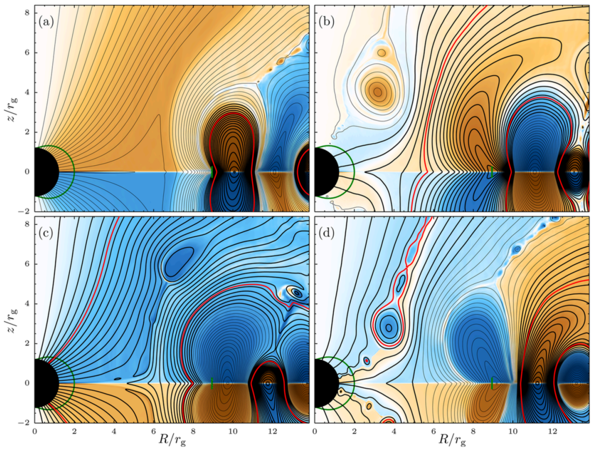
Can a jet form upon advection of small scale field?

- Can lead to effective dissipation
- Can alleviate the loading problem

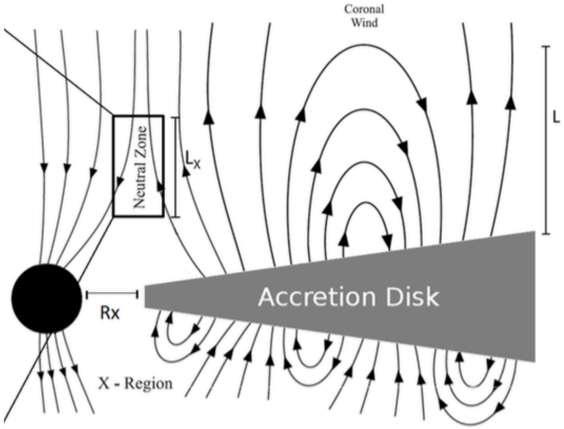
Accretion of magnetic loops

Spruit, uzdenski, goodman

Reconnection can lead to electron acceleration in the jet + sheath. Potential site of VHE emission.

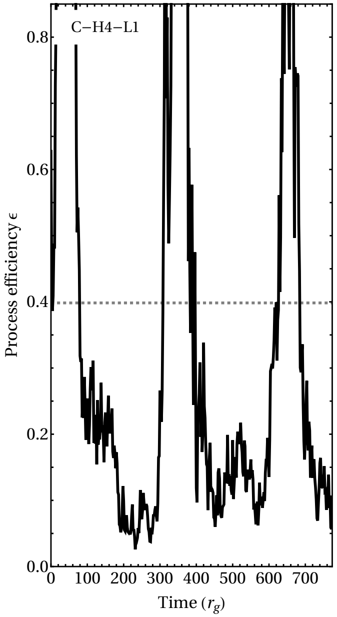


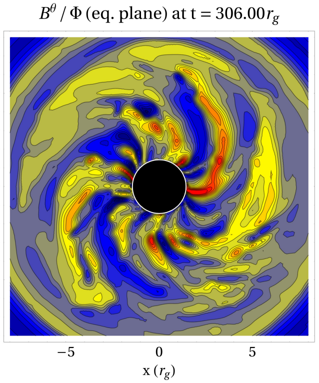
2D FF simulations: Parfrey + 15



Kadowaki, de Gouveia Dal Pino + 15

Van Putten + AL 03



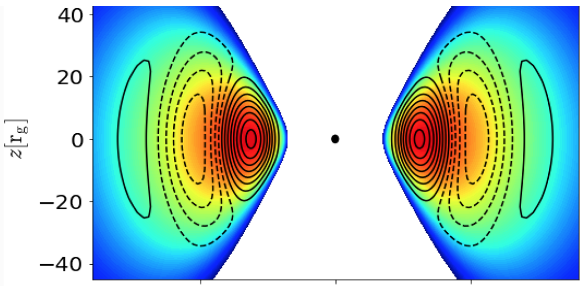


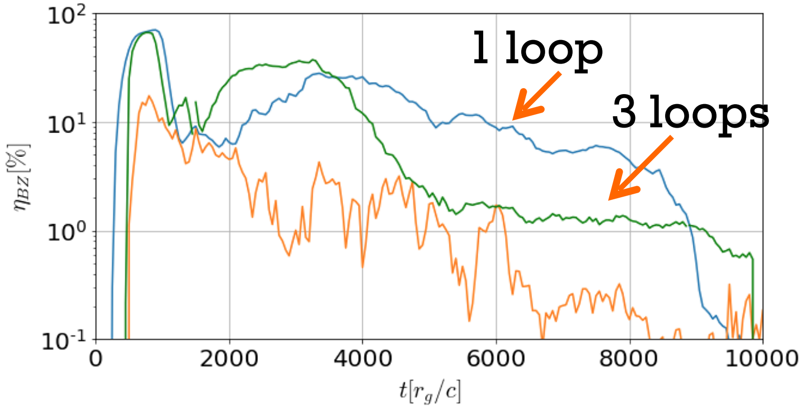
3D FF simulations, Mhalmann, AL, Alloy 21

Example: 2D & 3D GRMHD simulations

Chashkina, Bromberg, AL 21

- Initial state: 3 magnetic loops with opposite polarity
- Striped jet forms, but with lower efficiency
- Can power corona (lamppost models)

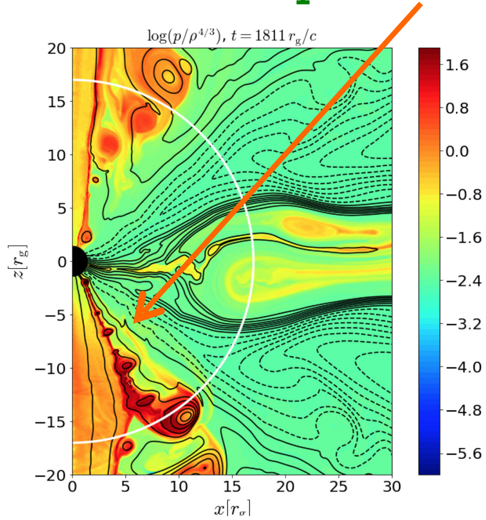


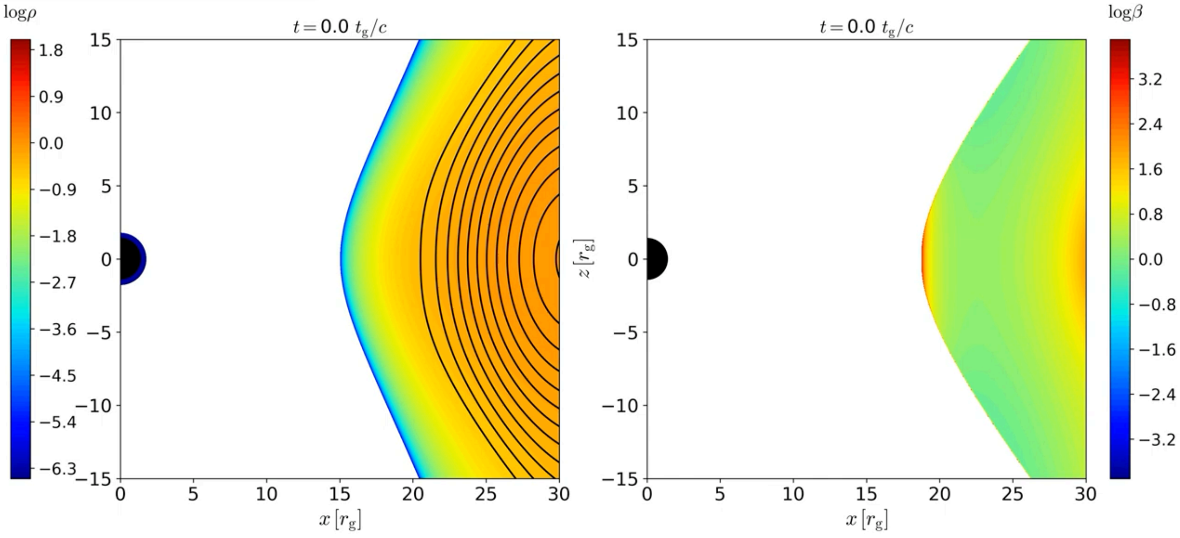


1 loop

3 loops

plasmoids





Summary

- Current sheets formed during MAD states may produce HE emission.

  depending on multiplicity which is unknown

- Nature of plasma source in the inner magnetosphere and polar jet is yet unresolved. Do spark gaps form?

  spark gaps are natural TeV emitters.

- How jet magnetic field dissipates ? kink instability seems ineffective.

- Can powerful striped jets form via accretion of small scale field?