physical processes in jets

(a review)

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abstract

The physics of relativistic jets:

(0) introduction,

(1) launching and powering,

(2) acceleration and collimation,

(3) stability,

(4) energy dissipation,

(5) particle acceleration,

(6) radiative processes,

(7) plasma composition,

(8) origin of matter.

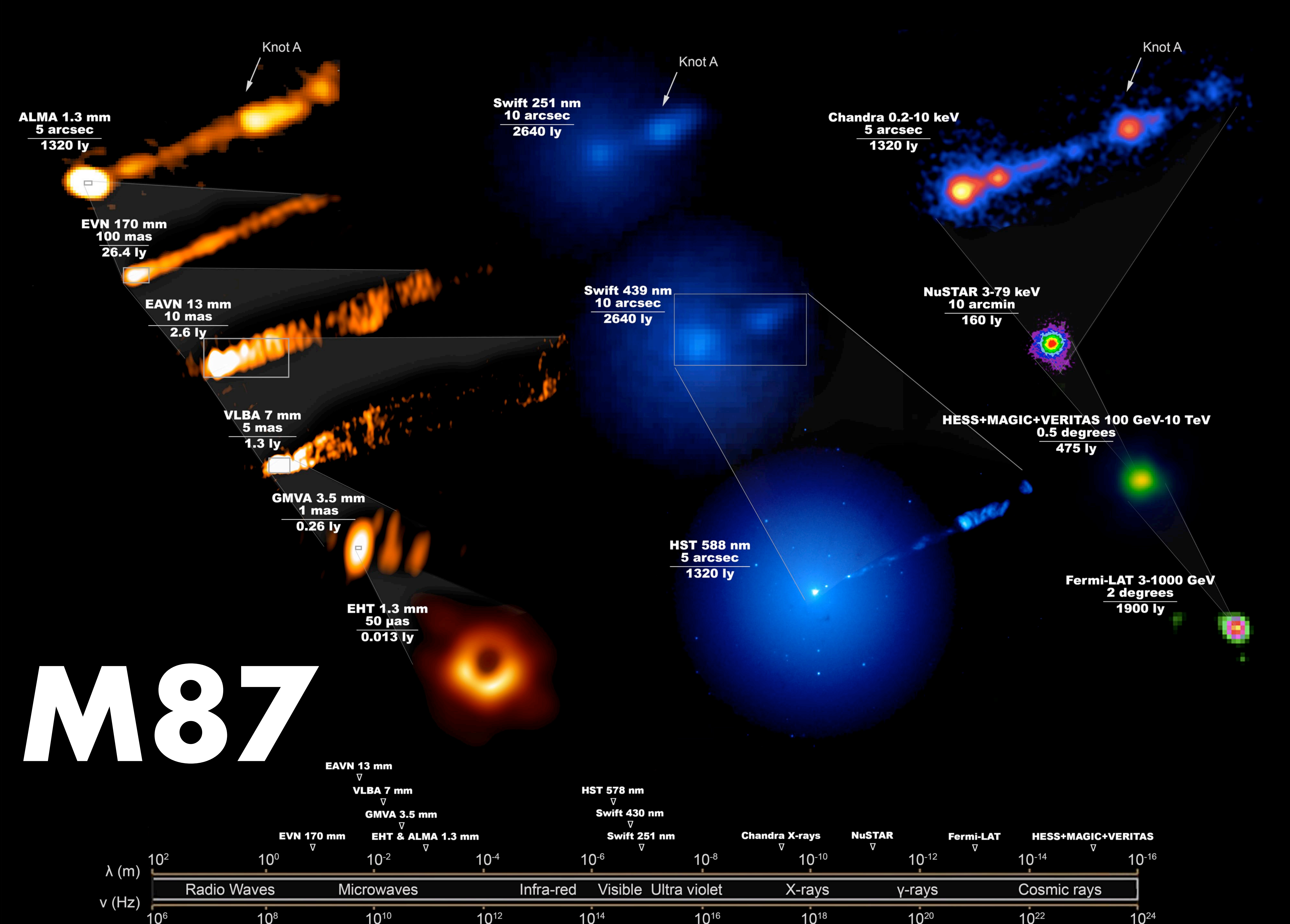
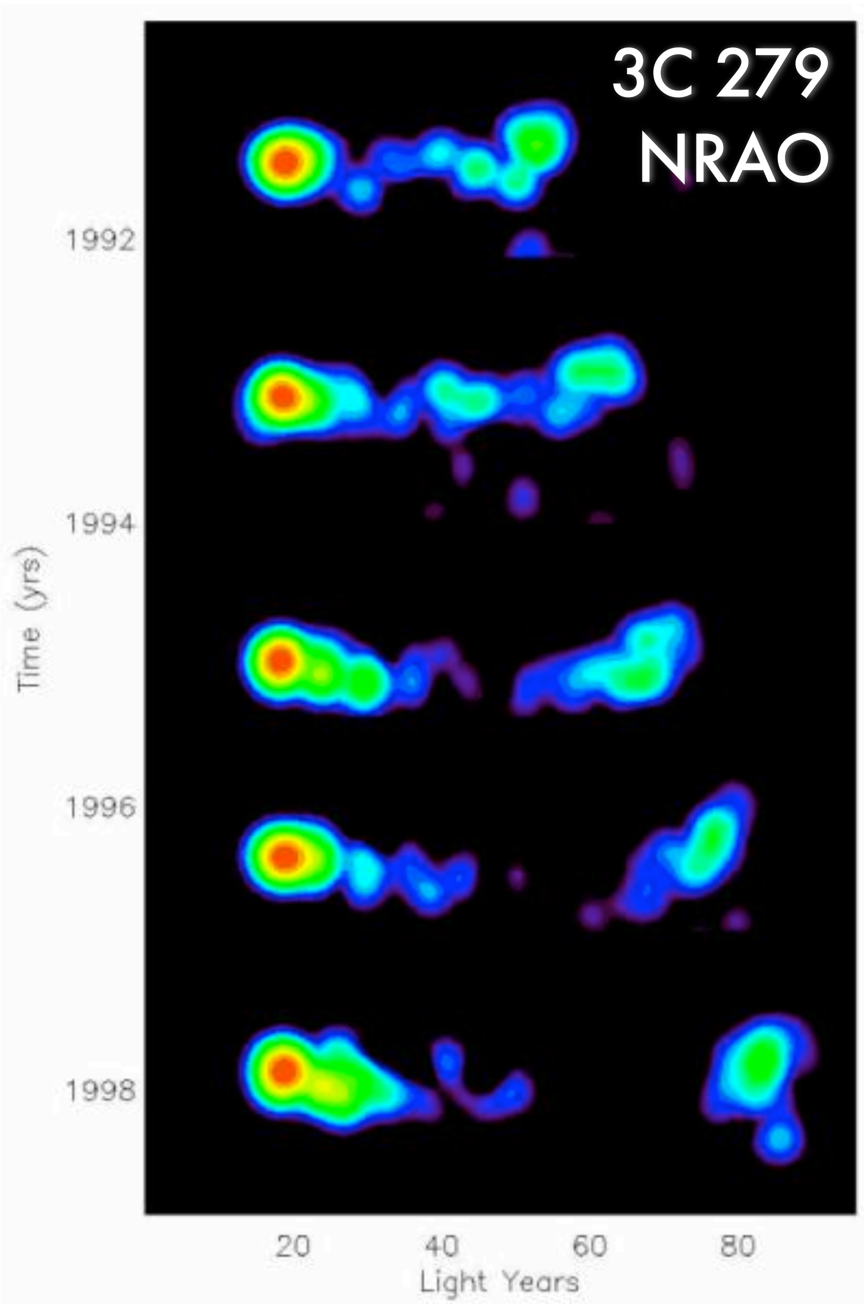


Image Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array; the Fermi-LAT Collaboration; the H.E.S.S collaboration; the MAGIC collaboration; the VERITAS collaboration; NASA and ESA. Composition by J. C. Algaba

relativistic jets in active galaxies

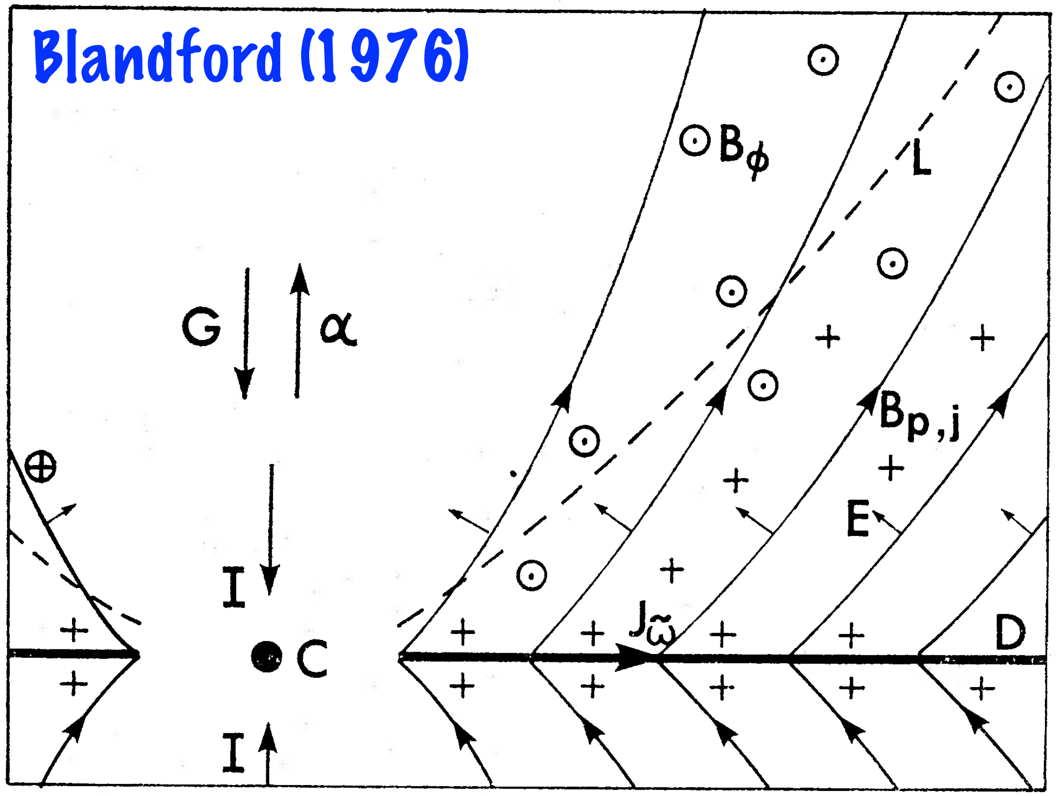


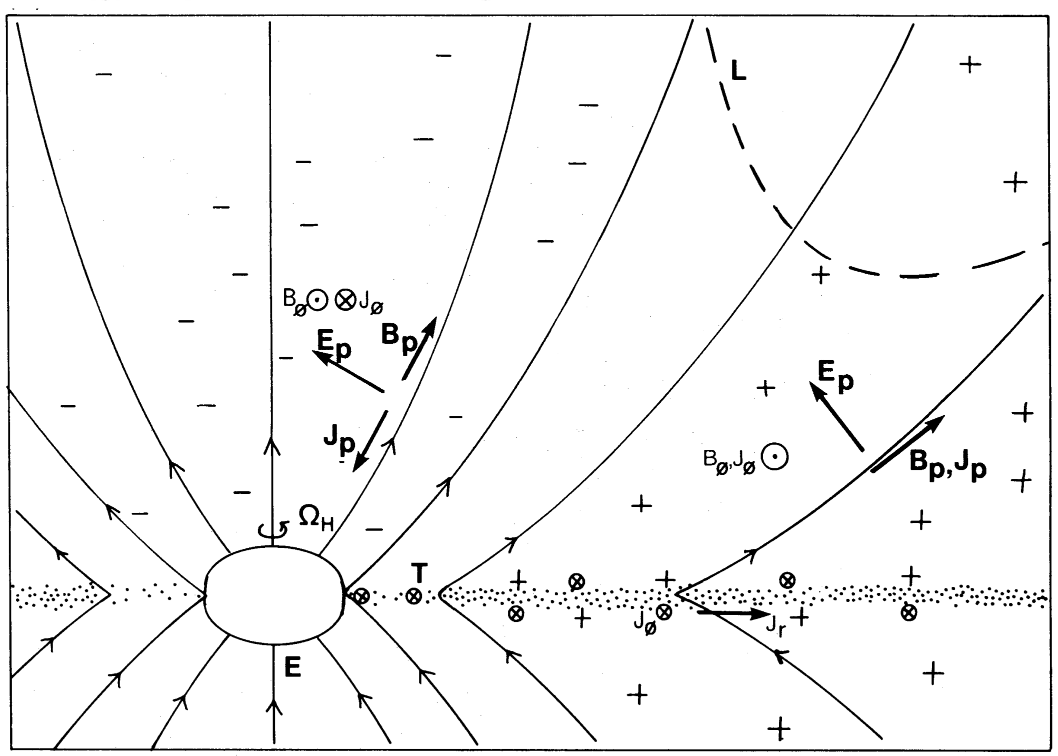
- tightly collimated outflows at apparently superluminal speeds
- true speeds subluminal but highly relativistic: $\Gamma = 1/\sqrt{1 - \mathrm{v}^2/c^2} \sim 20$
- huge luminosity boost $L_{\rm obs} \sim \Gamma^4 L'_{\rm em} \sim 10^5 L'_{\rm em}$ at small viewing angles $\theta_{\rm obs} \lesssim 1/\Gamma$ – blazars
- broad-band non-thermal electromagnetic spectra - efficient energy dissipation and particle acceleration

(1) launching and powering

rotating force-free magnetosphere

Blandford (1976)





Blandford & Znajek (1977)

- Force-free electrodynamics:
  $w = \rho c^2 + u + P \to 0;$
  $\sigma = B^2/4\pi w \to \infty;$
  $\vec{j} = \vec{j}(\vec{E}, \vec{B});$
  $\rho_e \vec{E} + (\vec{j} \times \vec{B})/c = 0.$

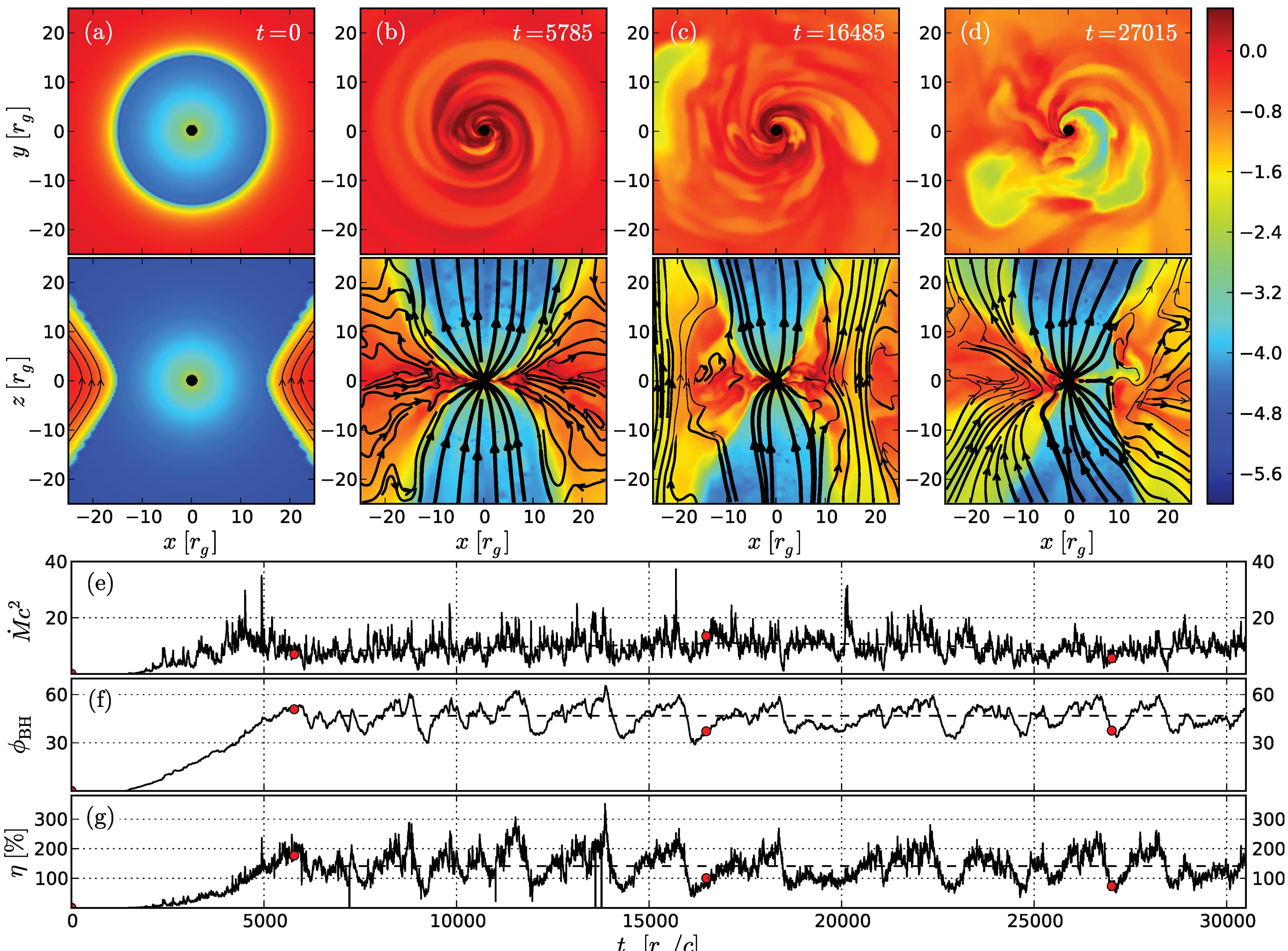
- Rotating magnetosphere with poloidal magnetic fields drives outflowing Poynting flux $\vec{S} = (c/4\pi)(\vec{E} \times \vec{B})$.

- This mechanism is qualitatively independent of the central object, on which the poloidal fields exert a torque.

- In the case of spinning (Kerr) black holes, poloidal field lines pass through the ergosphere, extracting the rotational energy of the black hole.

- The Blandford-Znajek formula for jet power: $P_{BZ} \propto (a/M)^2 \Phi_{BH}^2$, where a is the BH spin and Φ_{BH} is the BH magnetic flux.

jet power can exceed accretion power



- GRMHD simulations show that relativistic jets are entirely magnetically connected to the BH horizon (Tchekhoskoy et al. 2011).

$$\eta \simeq \frac{P_{\rm j}}{\dot{M}c^2}$$

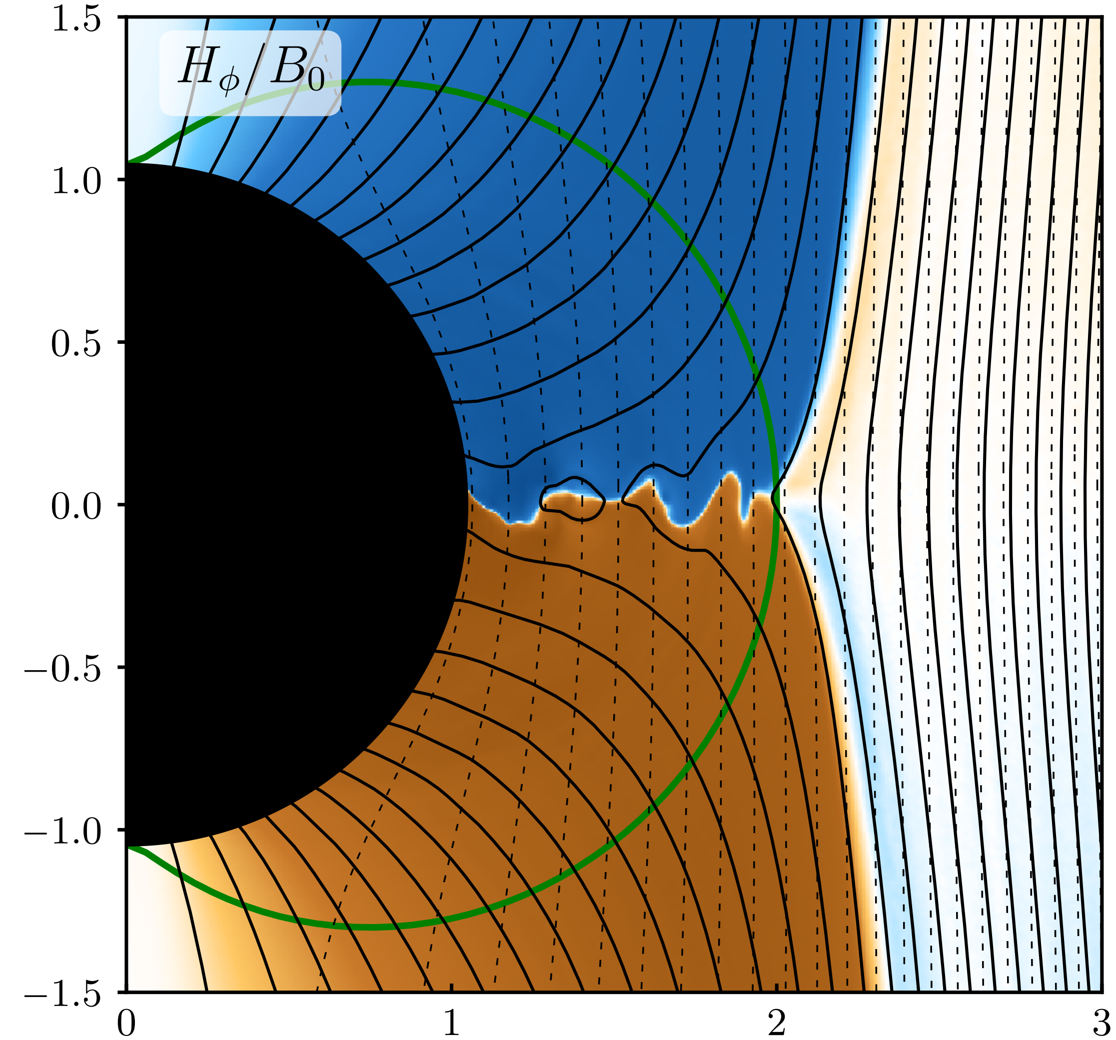
$\eta \sim 1.3$ for geometrically thick accretion flows

$\eta \sim 0.5$ for thin accretion disks (Liska et al. 2019)

recent studies of the Blandford-Znajek mechanism

- GRPIC simulations (with plasma represented by individual particles) show how the vacuum (Wald) solution connects to the BH horizon once plasma is seeded volumetrically (Parfrey et al. 2019).
- The BZ mechanism has been recently questioned on the ground that BHs should collect charge, leveling electrostatic potentials (King & Pringle 2021).
- However, it has been argued that even charged BHs produce electrostatic potentials, hence the BZ mechanism is viable (Komissarov 2021).

Parfrey et al. (2019)

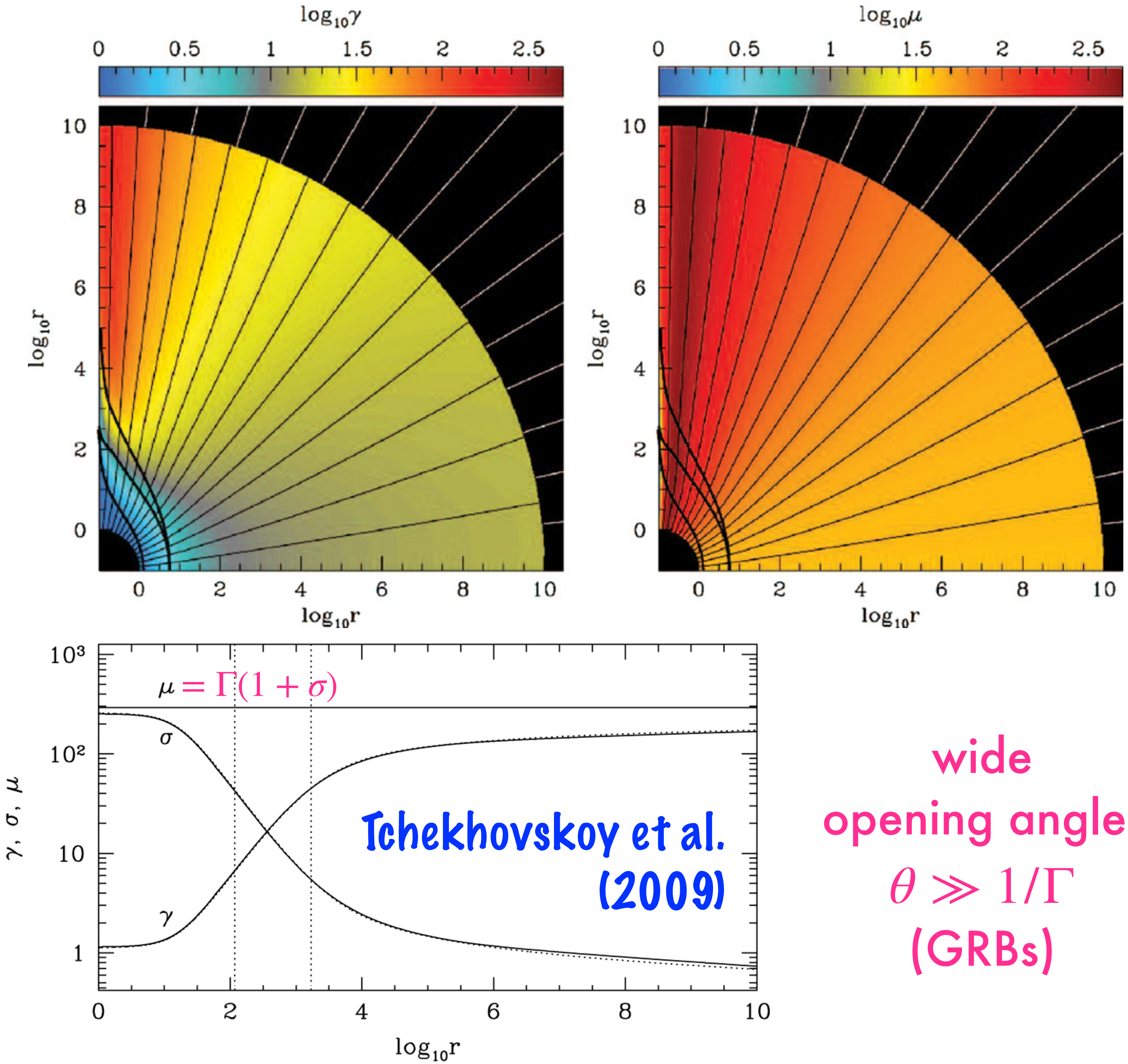


dashed lines: Wald solution (vacuum)
solid lines: numerical solution of plasma
color: toroidal magnetic field strength

(2) acceleration and collimation

acceleration with weak collimation

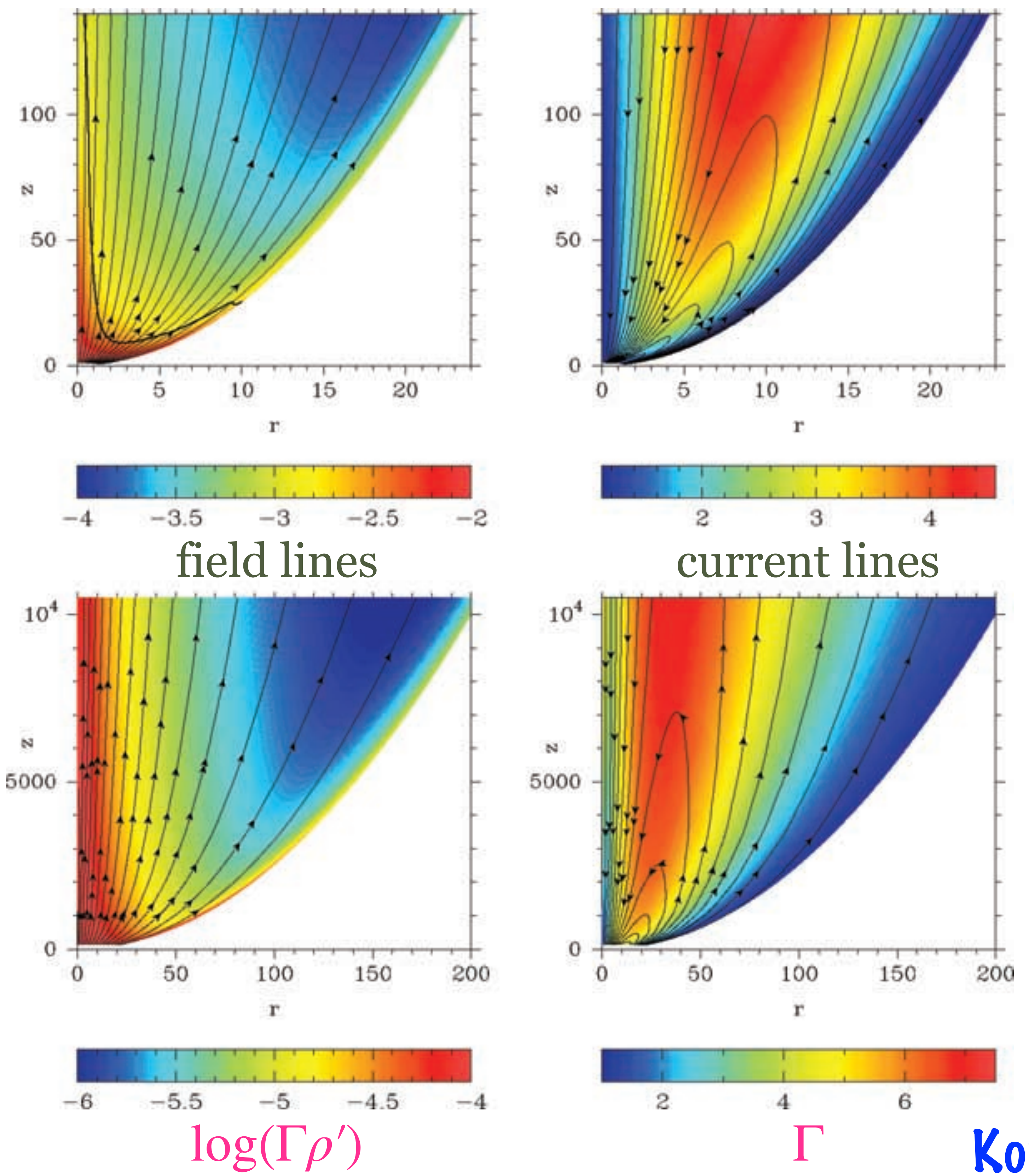
- Relativistic MHD: finite $\sigma = B^2/4\pi w$.
- Stationary relativistically magnetized ($\sigma \gg 1$) outflows accelerate to relativistic Lorentz factors ($\Gamma \gg 1$).
- Energy and mass conservations (Bernoulli/Michel): $\Gamma(1+\sigma) = \text{const.}$
- Momentum conservation: $\partial_i T^{ij} = 0$ - the hard part.



Tchekhovskoy et al. (2009)

wide opening angle: $\theta \gg 1/\Gamma$ (GRBs)

acceleration with strong collimation



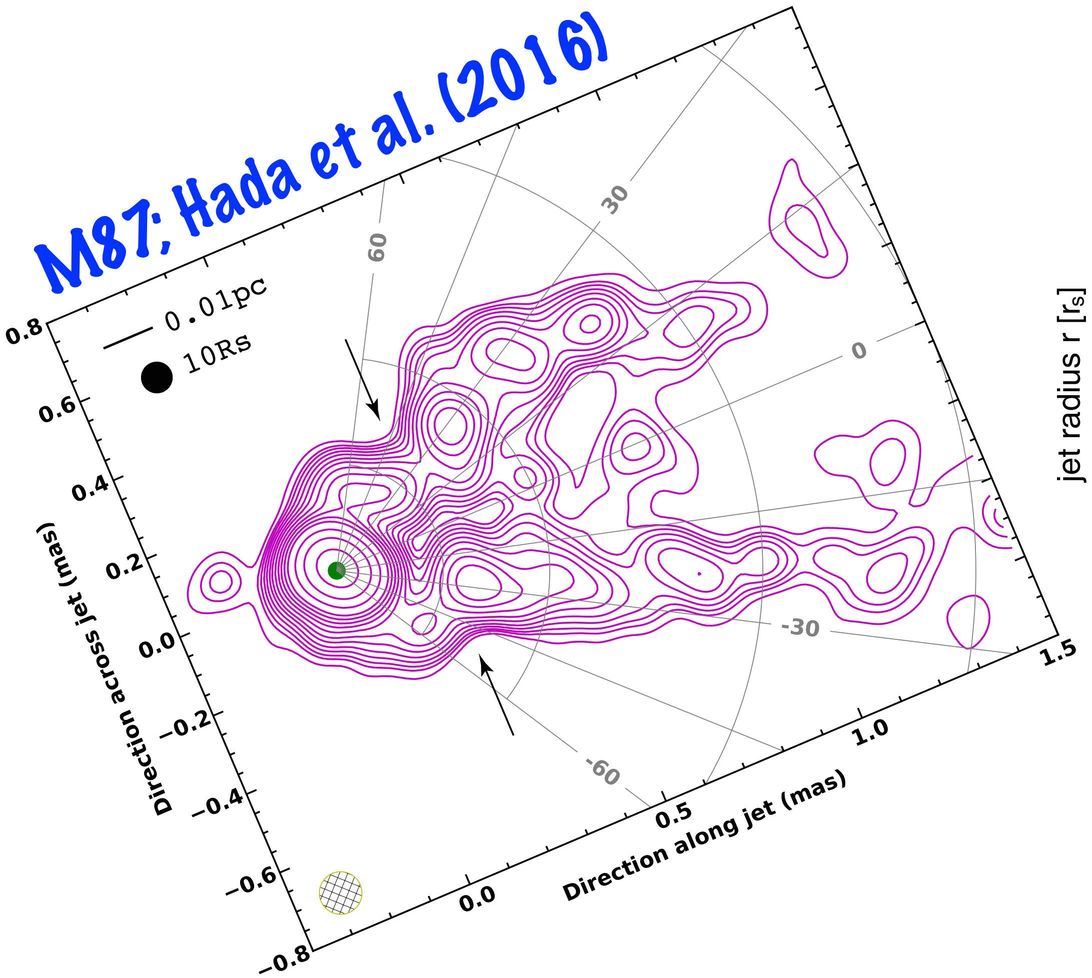
- Simulations within rigid wall boundaries imitate external pressure profiles.

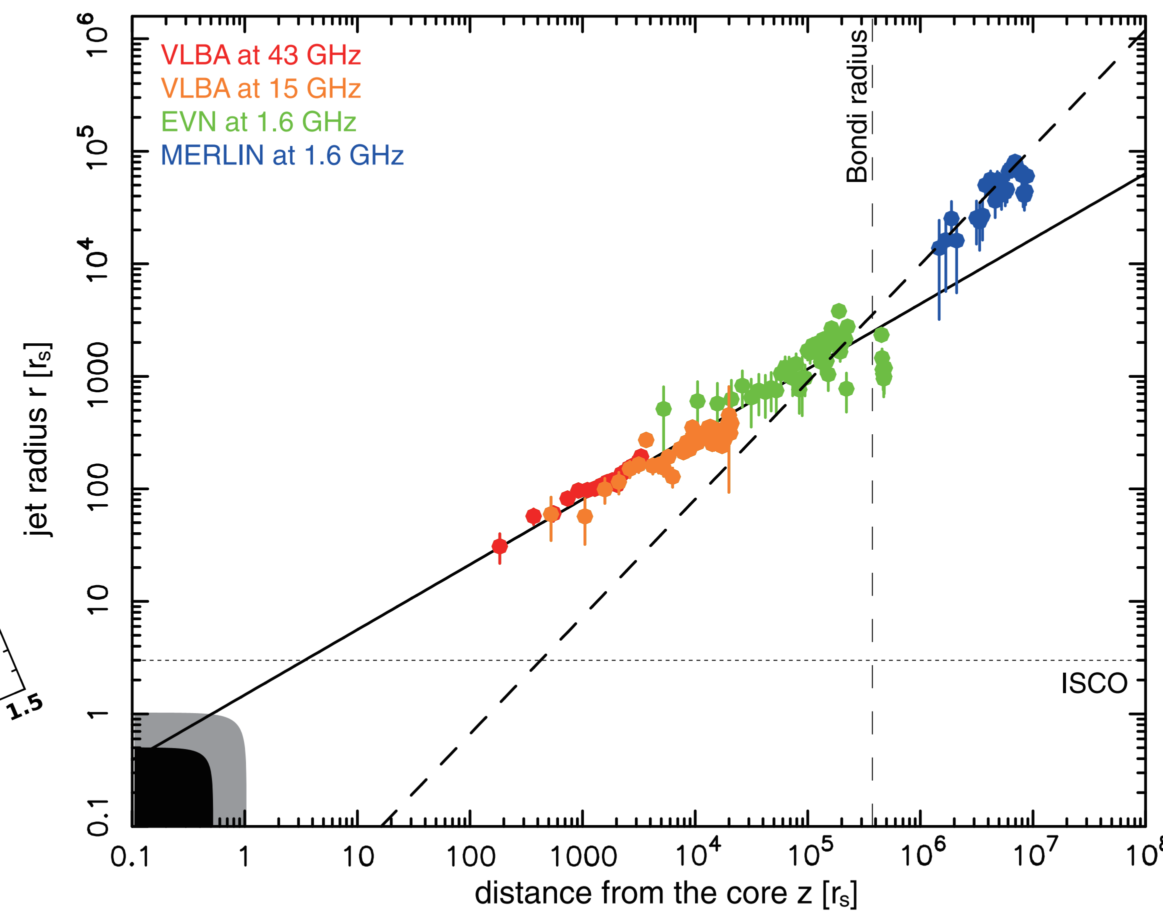
- narrow opening angle: $\theta < 1/\Gamma$ (AGN).

Komissarov et al. (2007)

resolving the collimation zone

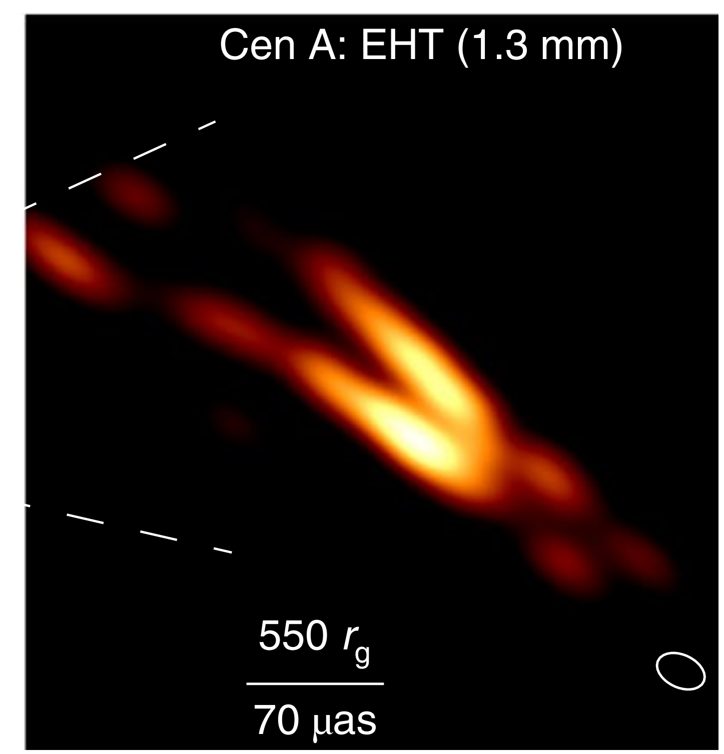
M87; Hada et al. (2016)





Asada & Nakamura (2012)

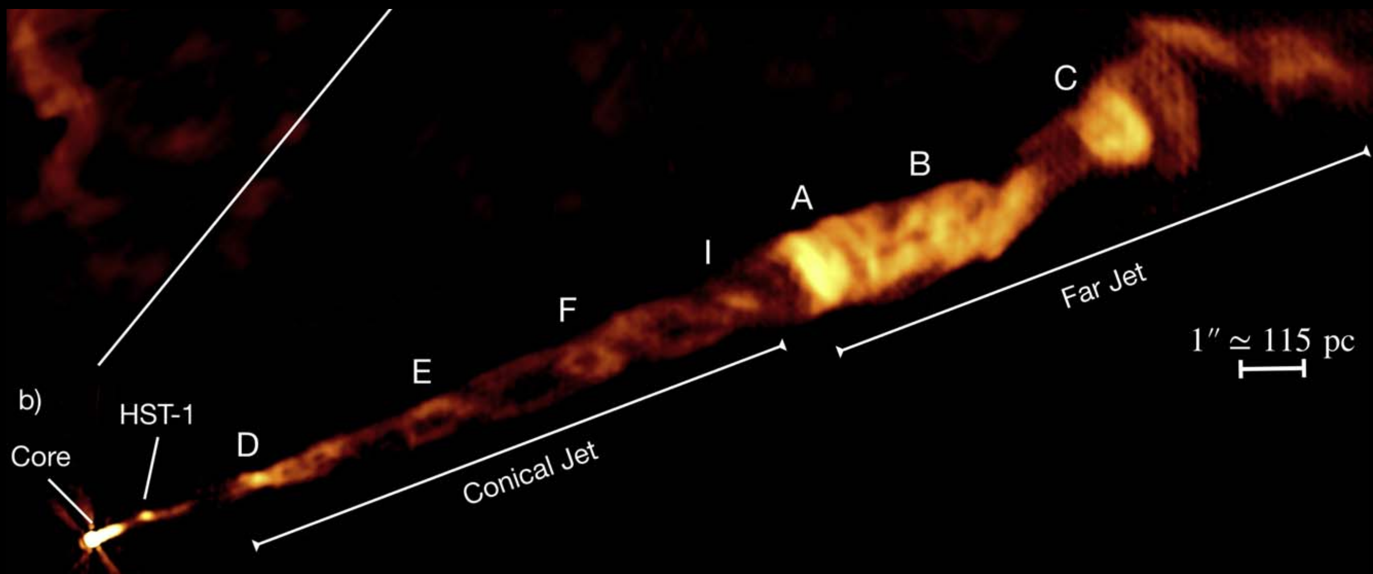
Janssen et al. (2021)

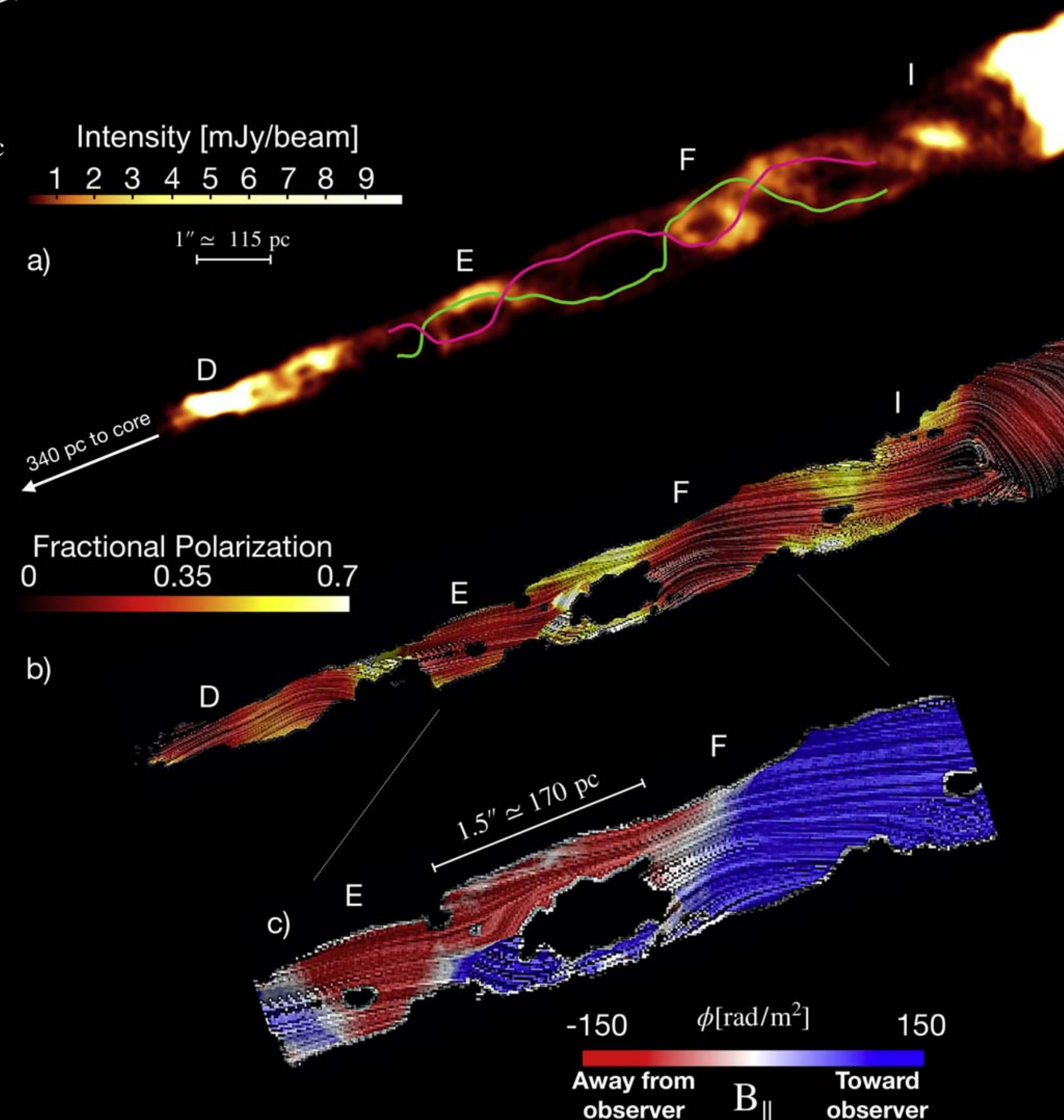


- VLBI observations show parabolic inner jets transitioning to conical.
- In some cases (e.g., M87) the transition is roughly at the Bondi radius.

(3) stability

jet of M87: radio

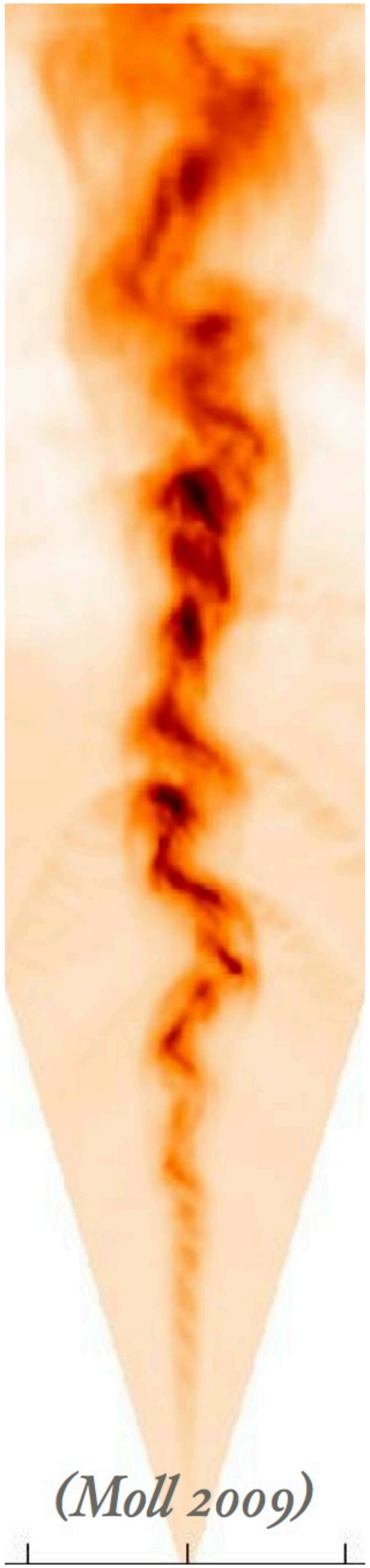




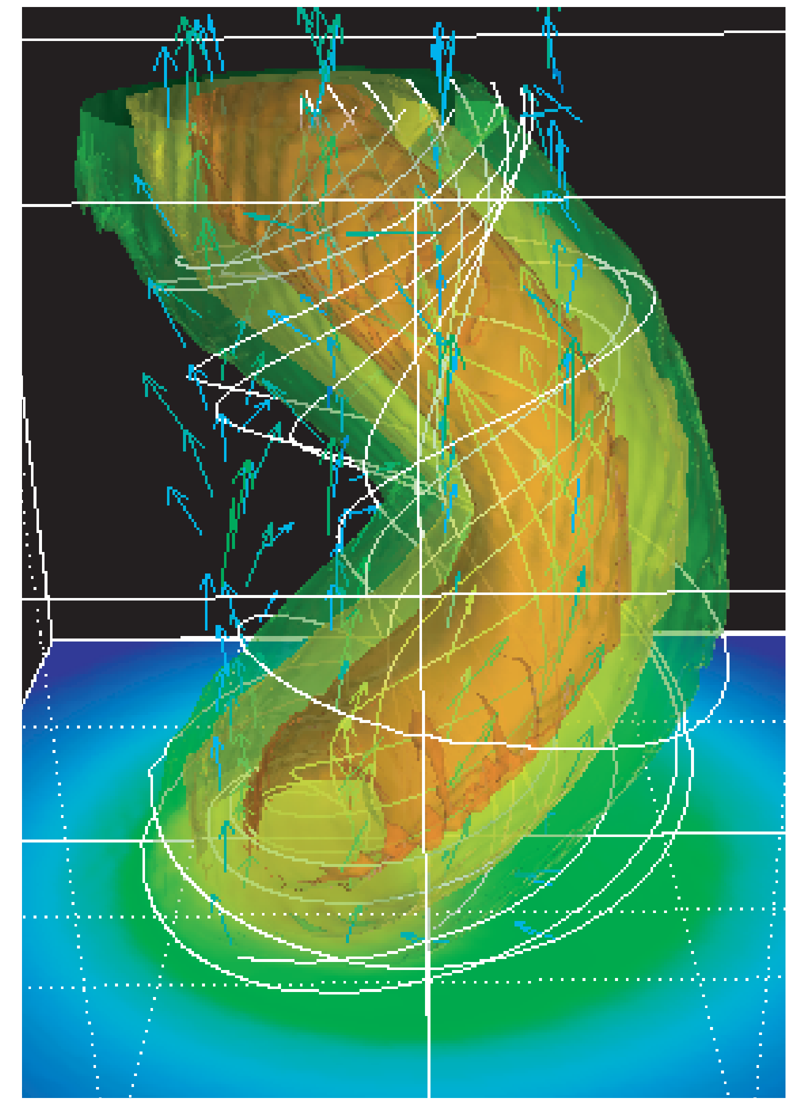
- doubly helical jet structure at sub-kpc scale in radio intensity, polarization and Faraday rotation

Pasetto et al. (2021)
JVLA at 4-18 GHz

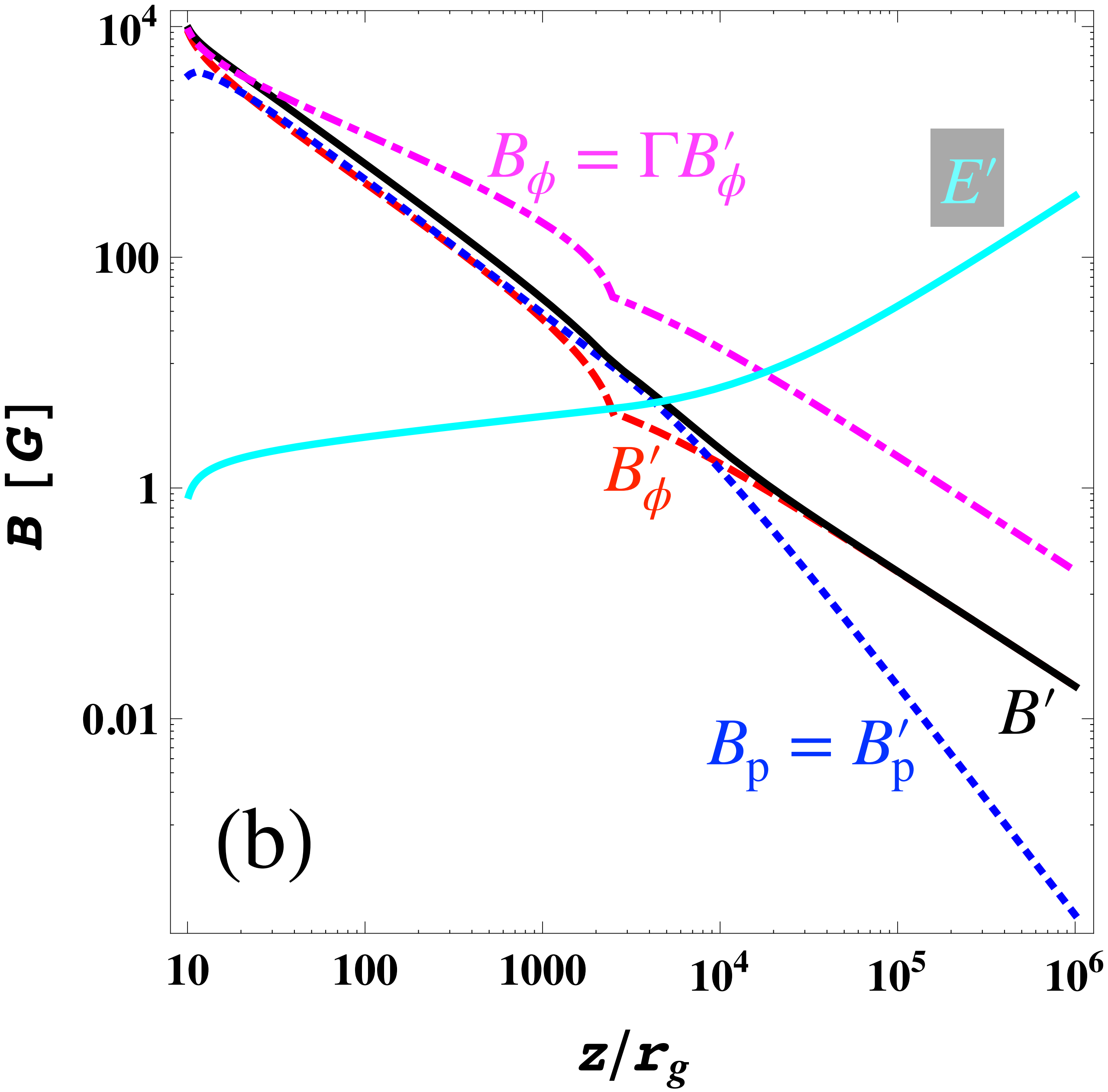
instabilities of jets with toroidal magnetic fields


(Moll 2009)

- toroidal magnetic field supported by gas pressure is unstable
  (Kruskal & Schwarzschild 1954)
- magnetic fields in expanding jets become increasingly toroidal
  $B_\phi \propto R^{-1}, B_\mathrm{p} \propto R^{-2}$
- instability can be driven by poloidal current or by gas pressure, depending on the force balance
- instability grows sufficiently rapidly to affect the jet dynamics and to enable dissipation by magnetic reconnection
  (Giannios & Spruit 2006)


Mizuno et al. (2011)

instability growth depends on jet structure

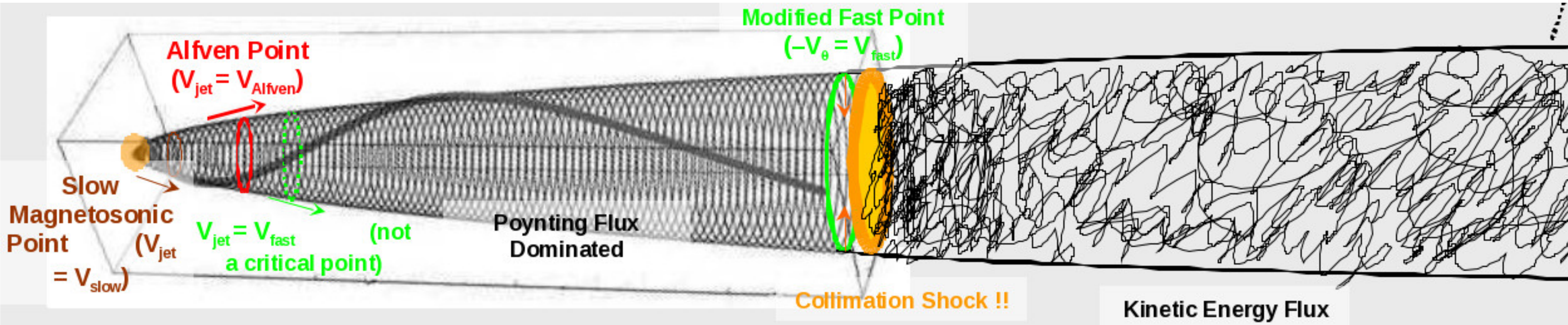


- A simple 1D model of magnetized relativistic jets suggests that $B'_\phi \lesssim B'_\mathrm{p}$ up to $10^4 R_\mathrm{g}$ (Zdziarski et al., arXiv:2204.11637).
- Current-driven kink mode amplitude E' in the jet co-moving frame grows rapidly for $B'_\phi > B'_\mathrm{p}$ (toroidal component of $\overrightarrow{B}'$ dominates the poloidal component).

(4) energy dissipation

beyond magnetically dominated jets

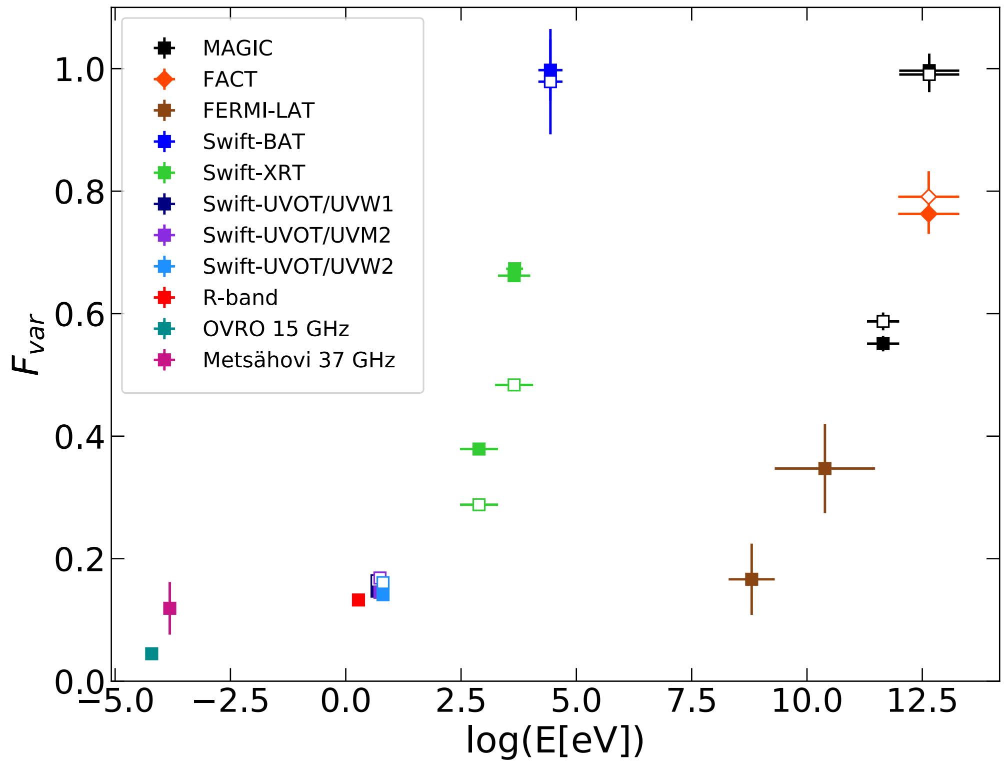
D. Meier



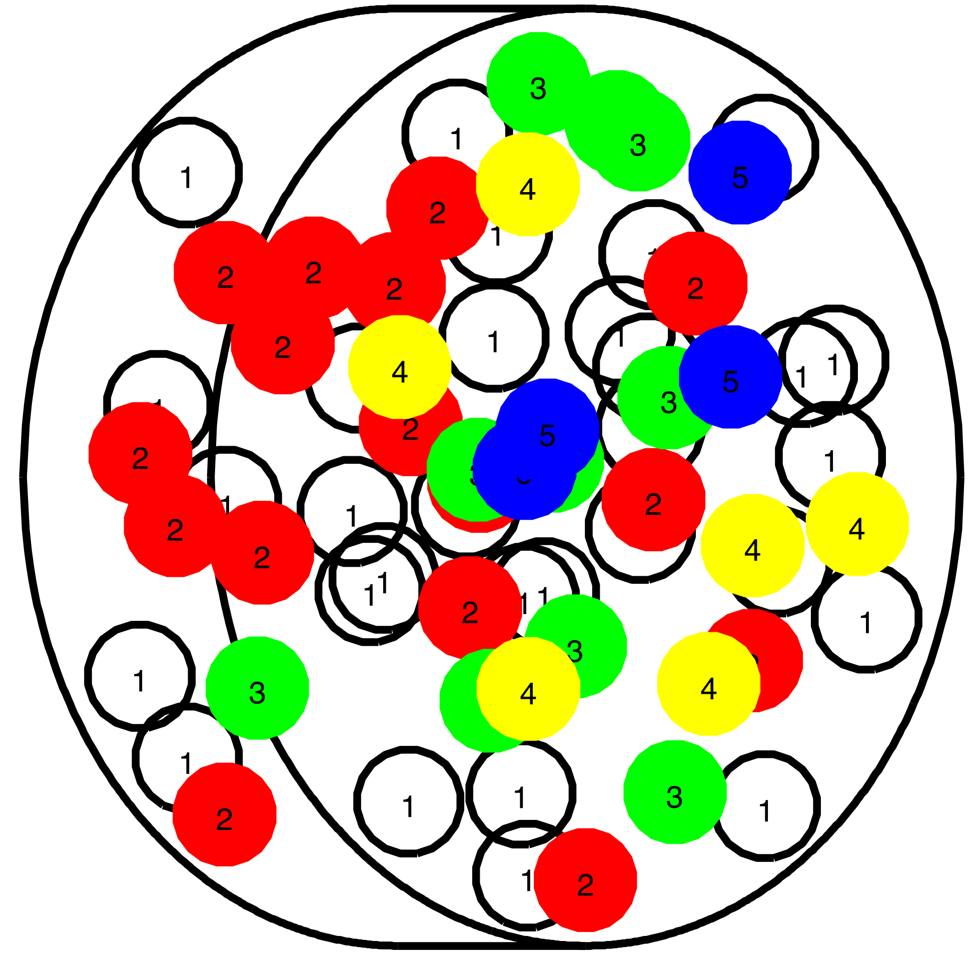
acceleration-collimation zone   dissipation (blazar) zone

- As the jets become relativistically fast, the convert from being dominated by magnetic energy (Poynting flux) to being dominated by kinetic energy (inertia).
- As the magnetic fields become weak, they may be subject to instabilities disrupting the ordered structure and leading to turbulent motions, making the fields chaotic.
- Dissipation of ordered energy (kinetic by shocks, magnetic by reconnection) leads to non-thermal particle acceleration and blazar emission.
- Whether shocks or reconnection, emitting regions close to equipartition, can be very different from the background (Sironi, Petropoulou & Giannios 2015).

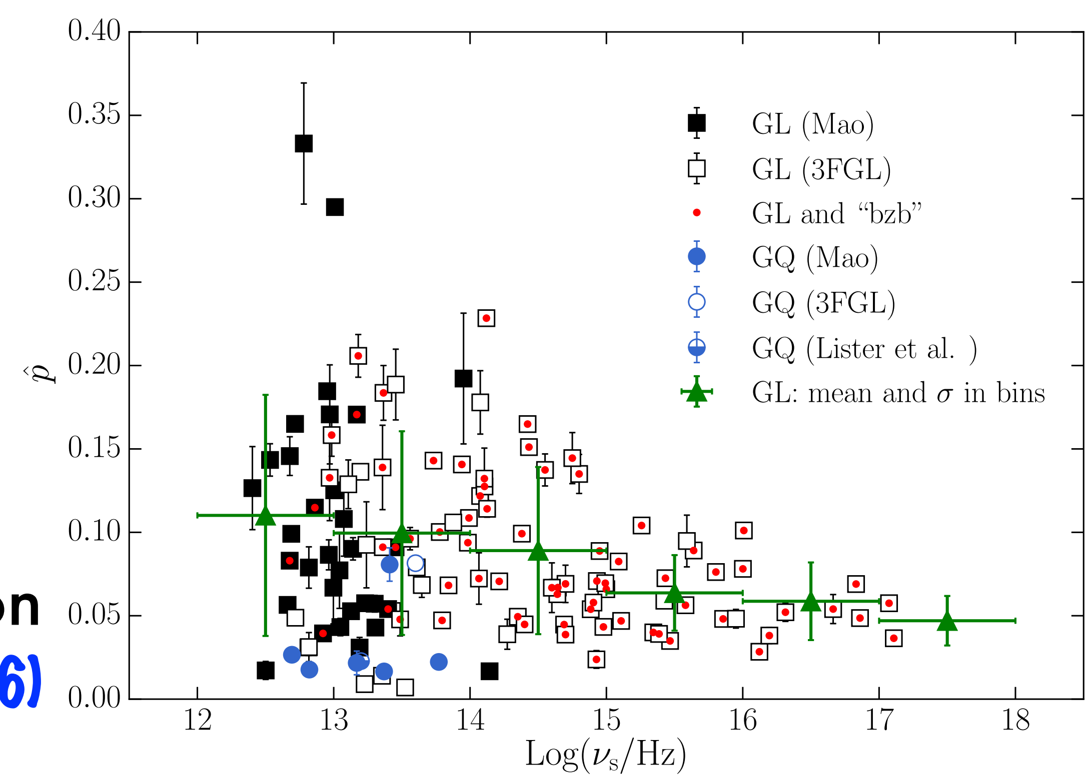
clues for turbulence in jets



fractional variability
Mrk 421
(Acciari et al. 2021)



Marscher & Jorstad (2010)



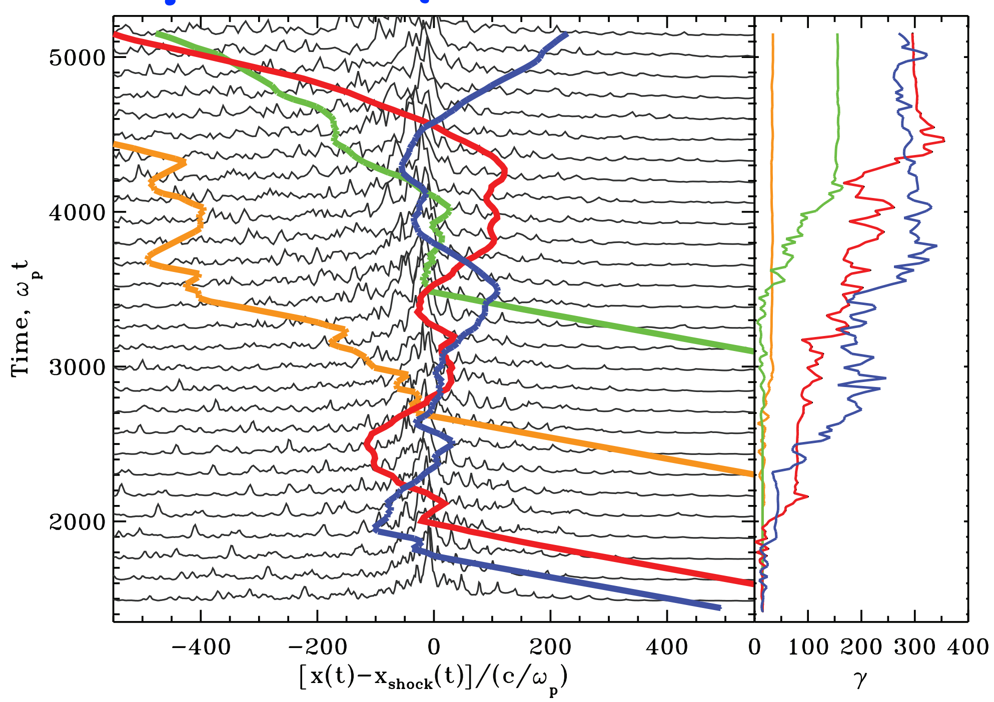
optical polarization
Angelakis et al. (2016)

- individual turbulent eddies may produce electron distributions with different $\gamma_{\rm max}$ and random polarization angles
- distribution of $\gamma_{\rm max}$ values would explain fractional variabilities $F_{\rm var}(\nu_{\rm obs})$ and polarization degrees $\Pi(\nu_{\rm obs})$

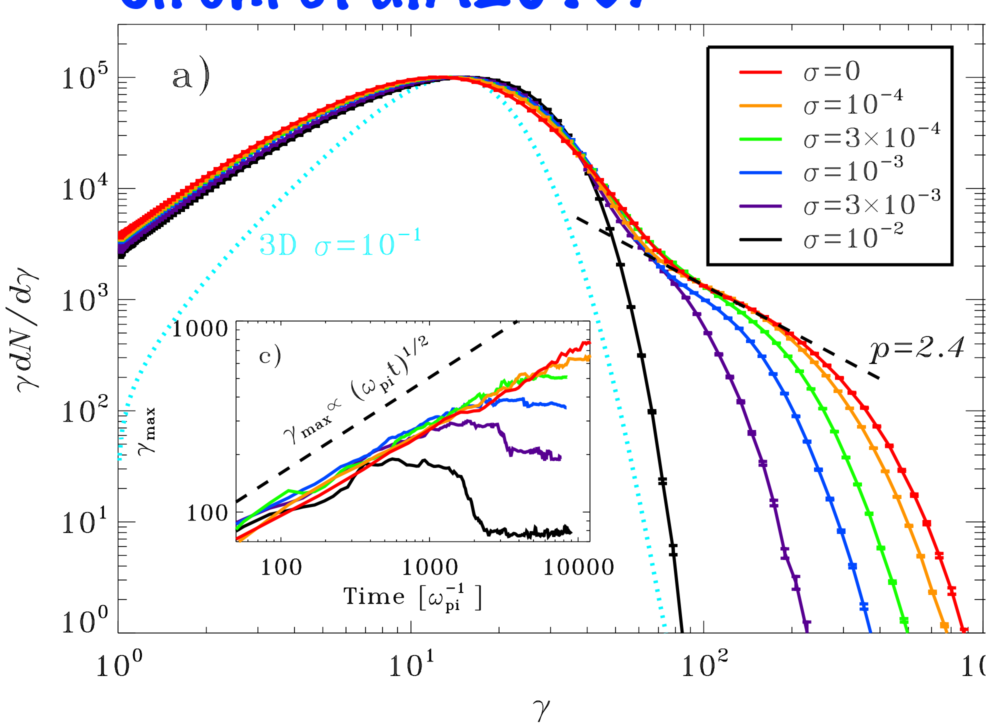
(5) particle acceleration

particle acceleration at collisionless shocks

Spitkovsky (2008)



Sironi et al. (2013)

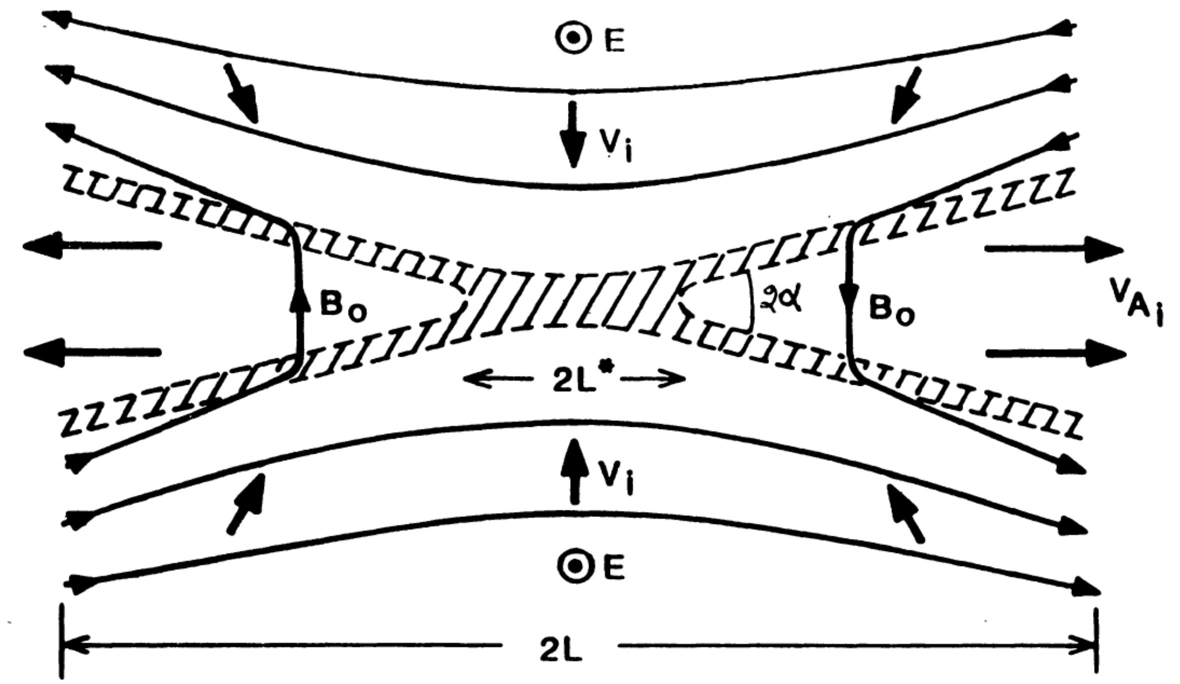


- In low-density plasma where particle collisions can be neglected, shock waves develop complex structures on kinetic scales.
- Lucky particles can be accelerated when crossing the shock multiple times (diffusive shock acceleration, a first-order Fermi process).
- Maximum particle energy is strongly limited by plasma magnetization $\sigma = B^2/4\pi w$.

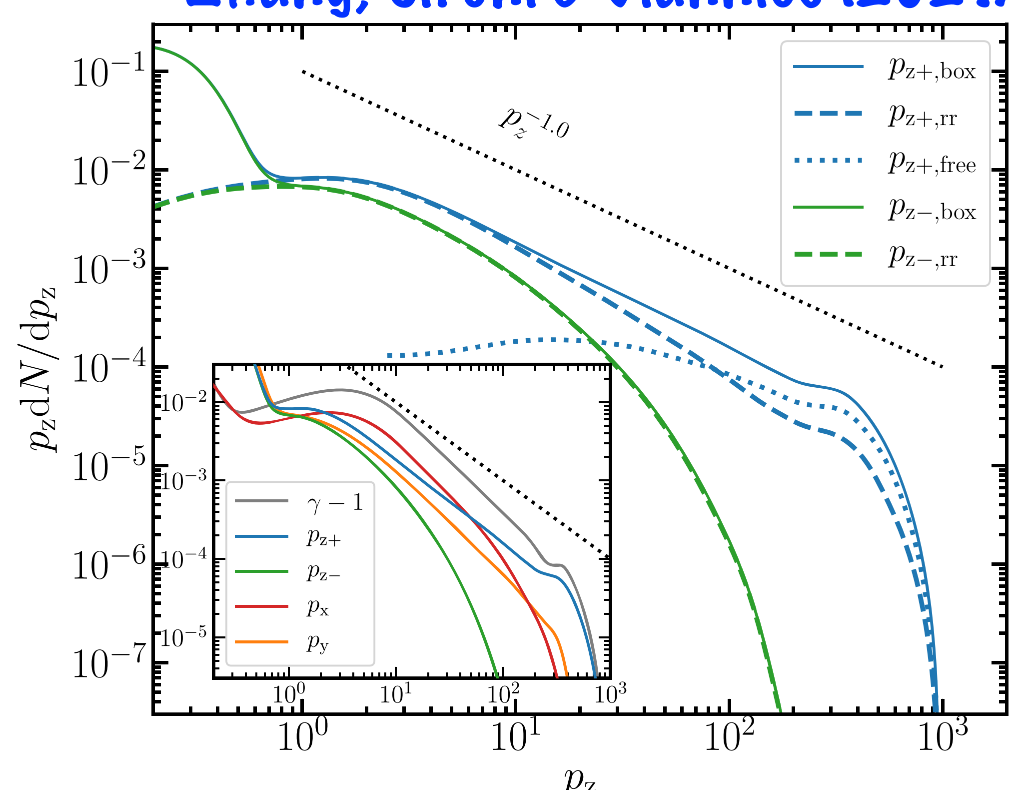
hard particle spectra in relativistic reconnection

- Reconnection produces power-law distributions that are hardening with increasing sigma $\mathrm{d}N/\mathrm{d}\gamma \propto \gamma^{-p}$ with $p \to 1$ for $\sigma \gg 1$ (Sironi & Spitkovsky 2014, Guo et al. 2014, Werner et al. 2016, Zhang et al. 2021).
- High-energy cut-off is exponential with $\gamma_{\max} \sim \mathcal{O}(\sigma)$.

Lakhina (2000)

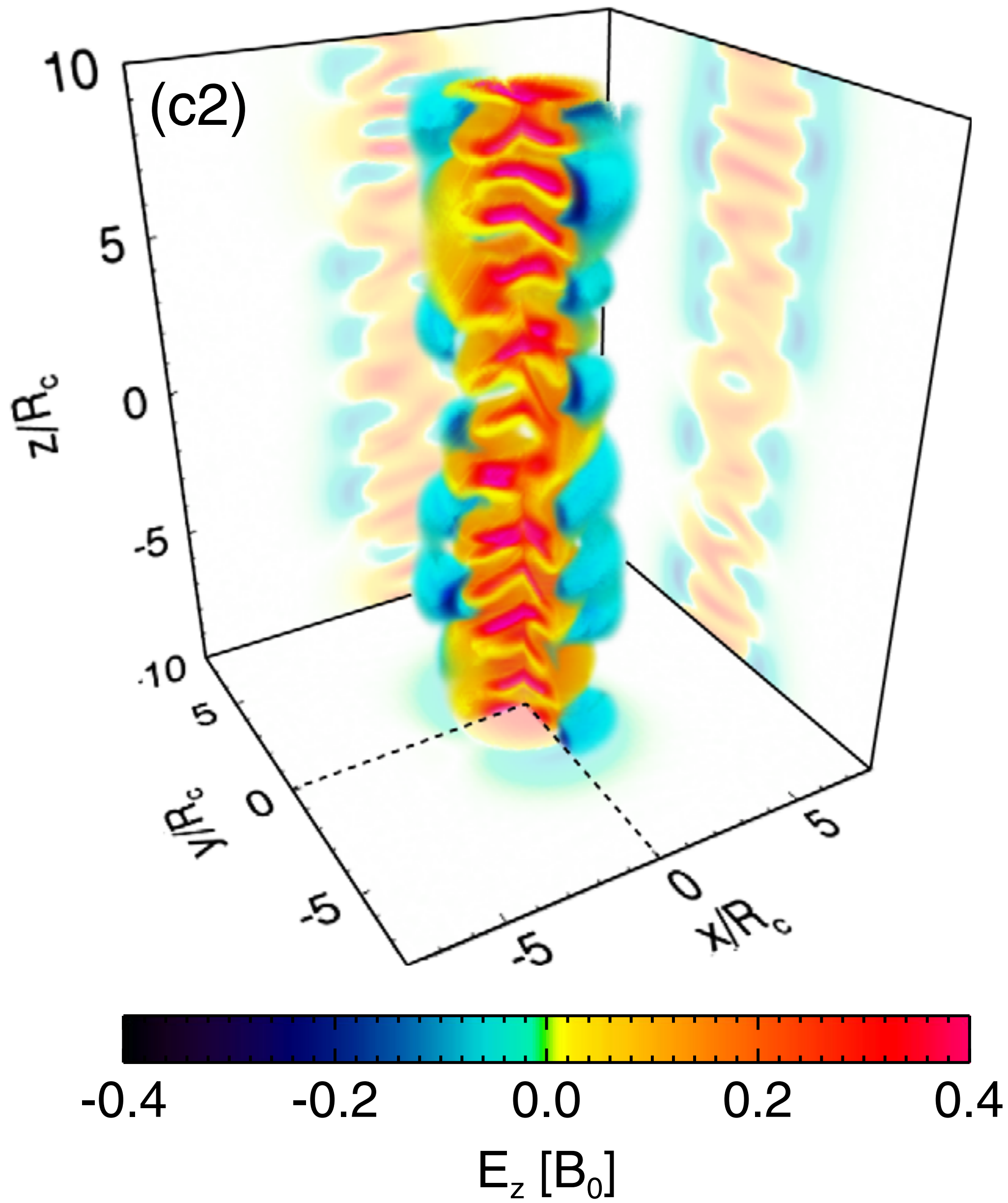


Zhang, Sironi & Giannios (2021)



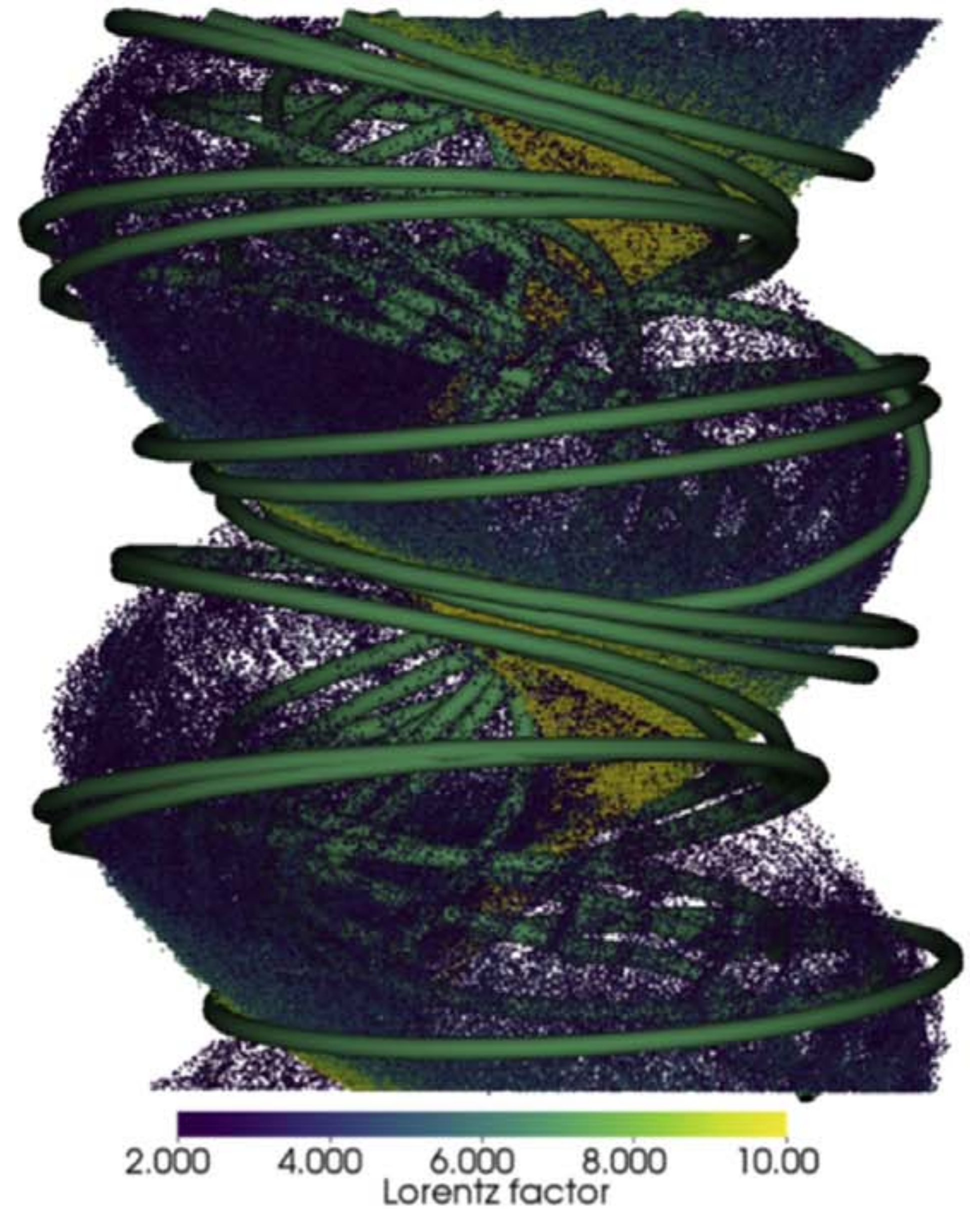
kinetic simulations of instabilities in cylindrical jets with toroidal magnetic fields

gas pressure balanced
(Z-pinch)



Alves, Zrake & Fiuza (2018)

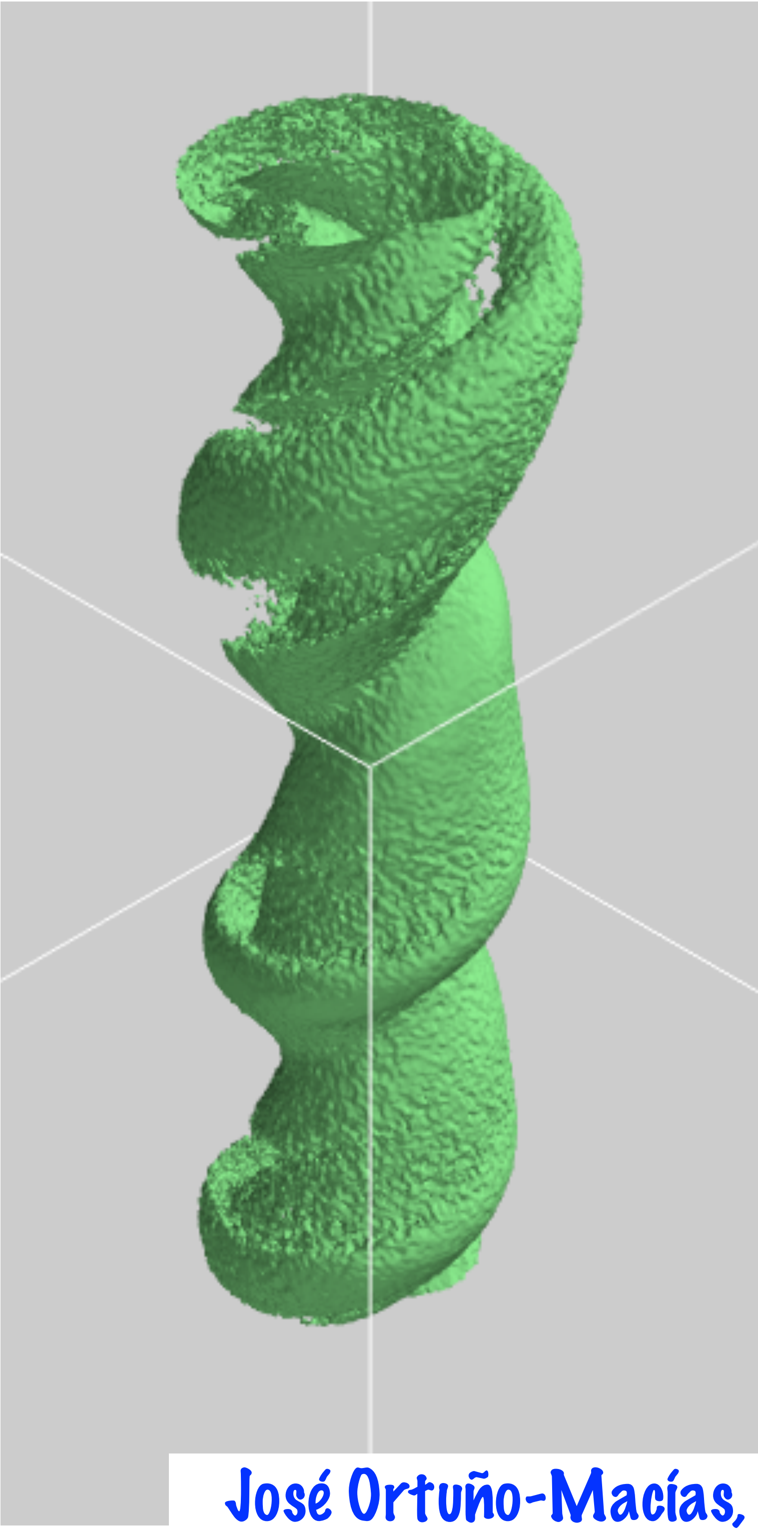
axial magnetic field balanced
(force-free screw-pinch)



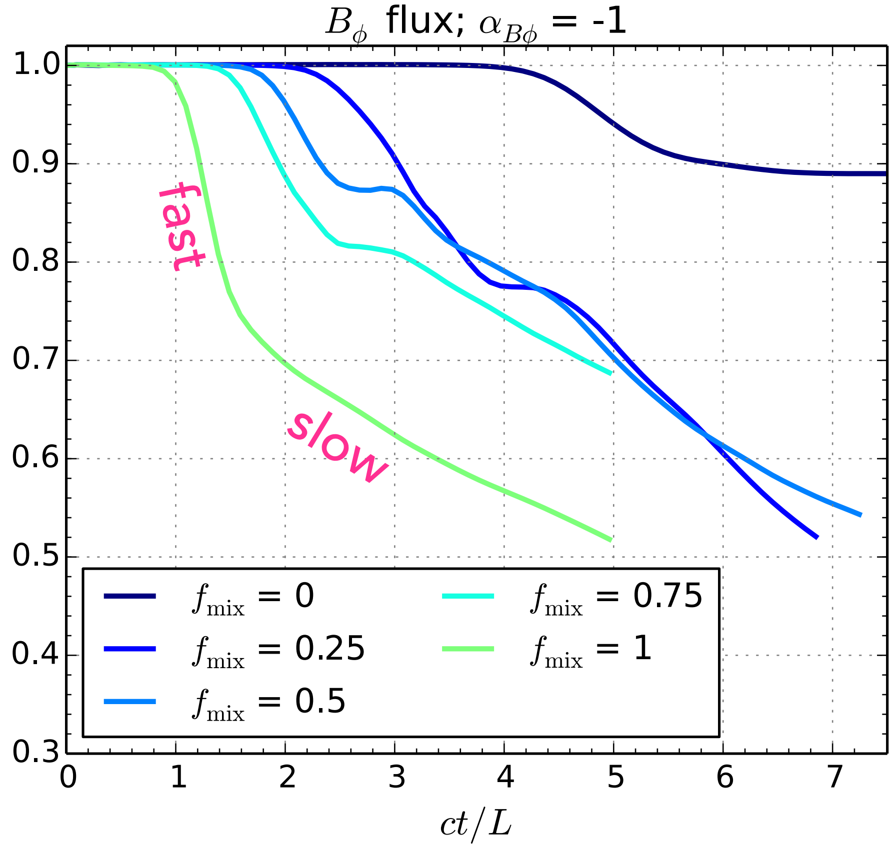
Davelaar, Philippov, Bromberg & Singh (2020)

efficient particle acceleration found in both cases

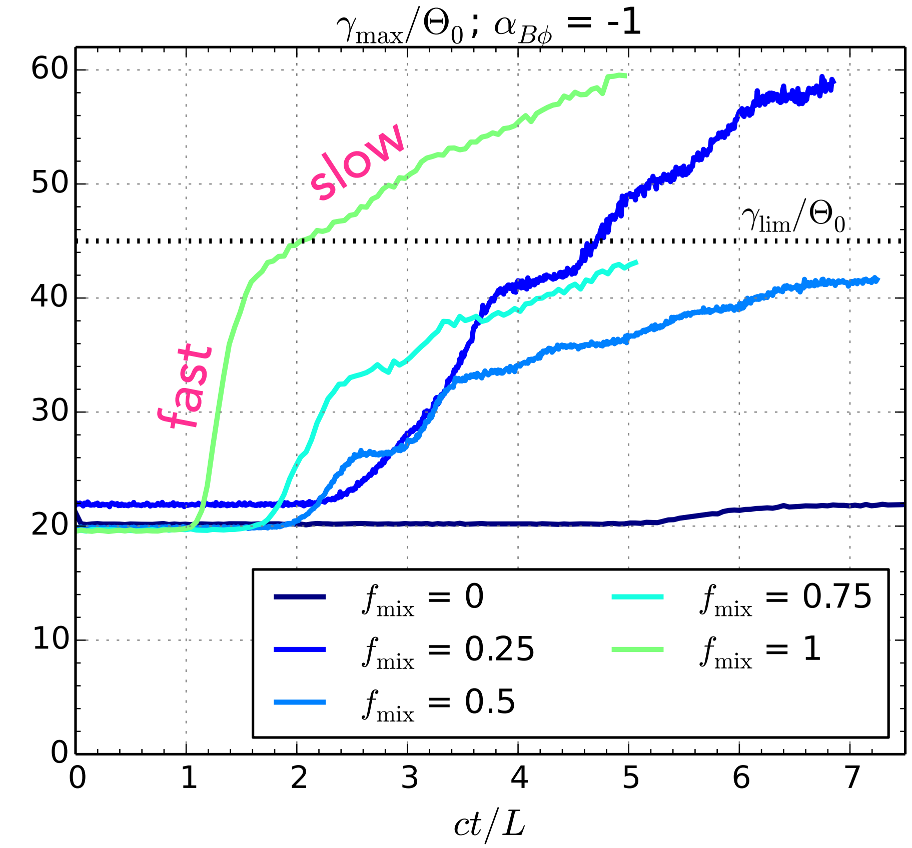
kinetic simulations of instabilities in cylindrical jets with toroidal magnetic fields



B_ϕ flux dissipation



particle acceleration



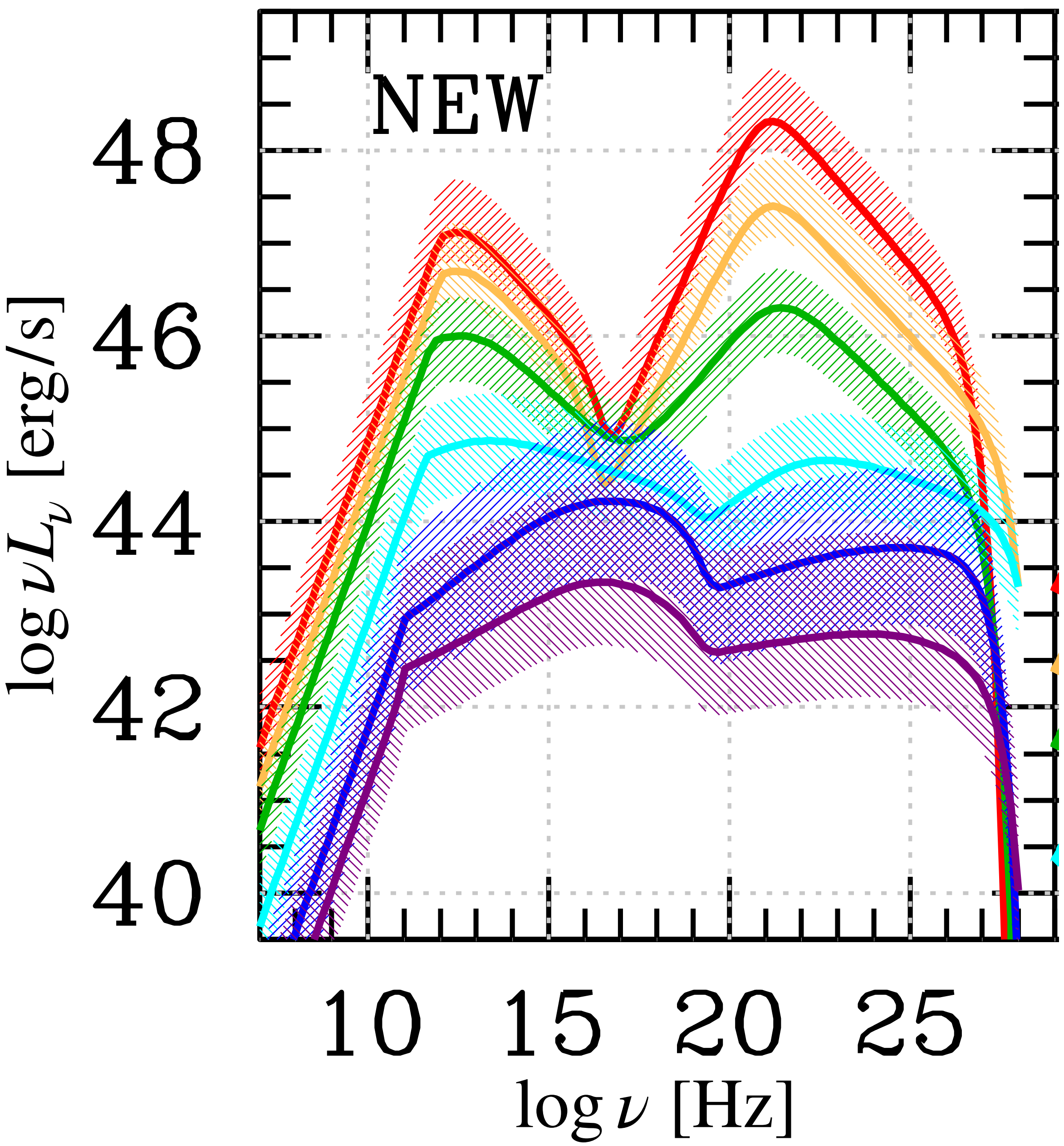
- fast magnetic dissipation and particle acceleration by $\vec{E} \perp \vec{B}$ until the confinement limit $\gamma_{\rm lim} = eB_0R_0/mc^2$ **(Alves et al. 2018)**

José Ortuño-Macías, KN, D. Uzdensky, M. Begelman, G. Werner, A. Chen, B. Mishra (ApJ in press)

(6) radiative processes

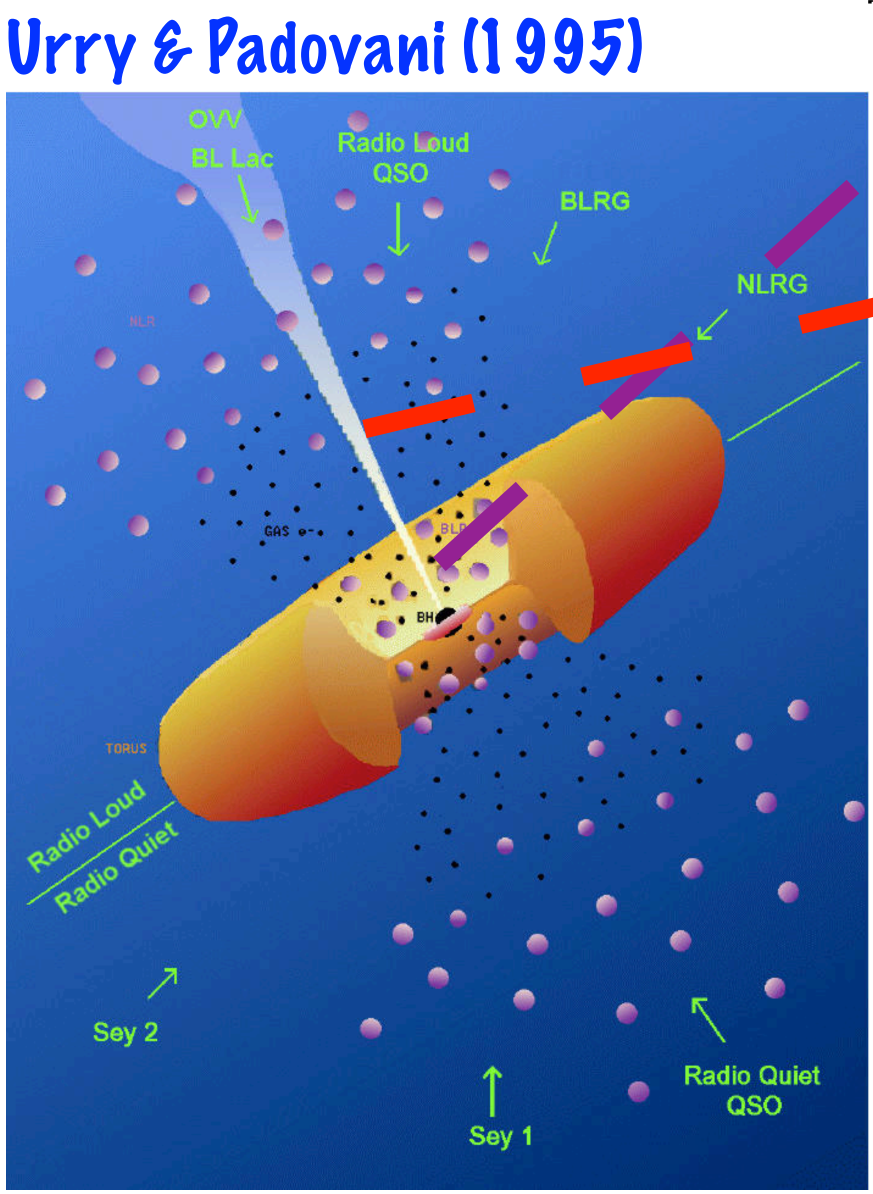
spectral energy distributions of blazars

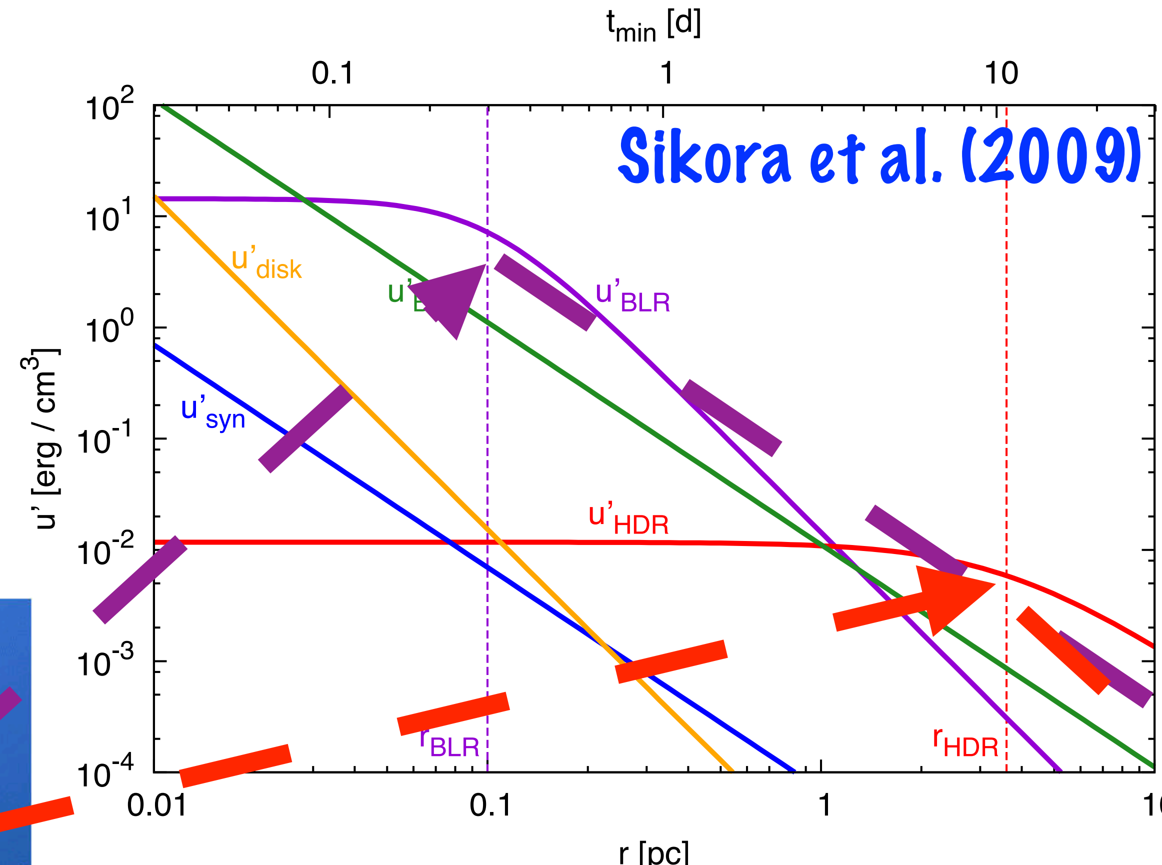
Ghisellini et al. (2017)



- blazars (AGN with a relativistic jet at small viewing angle) are dominated by non-thermal SEDs extending from radio to gamma rays
- blazar SEDs consist of two major components that follow an observational 'sequence' (anti-correlation between peak frequency and peak luminosity)
- high-luminosity blazars are known as FSRQs (flat spectrum radio quasars), low-luminosity ones are called BL Lac objects
- the low-energy SED component is synchrotron emission, the high-energy SED component may be due to leptonic (inverse Compton) or hadronic processes

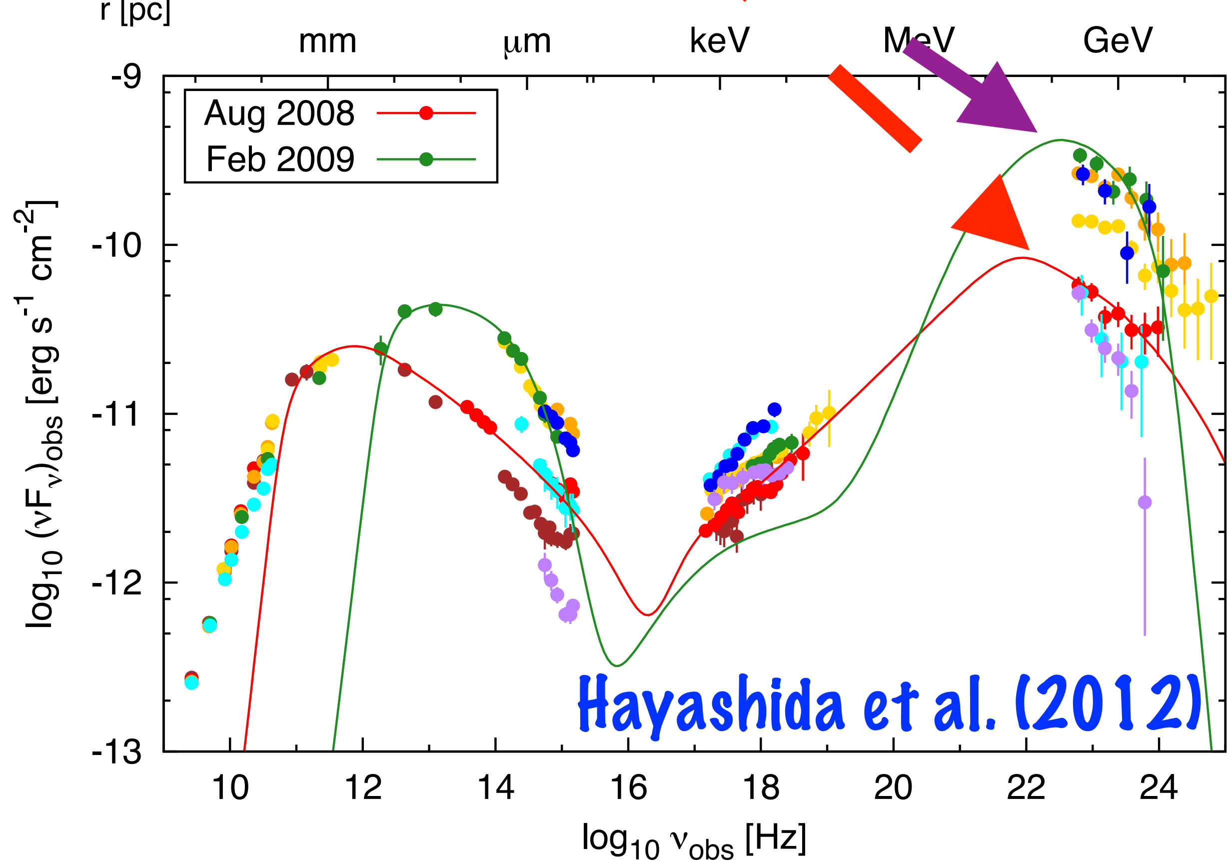
radiative environment of quasar jets



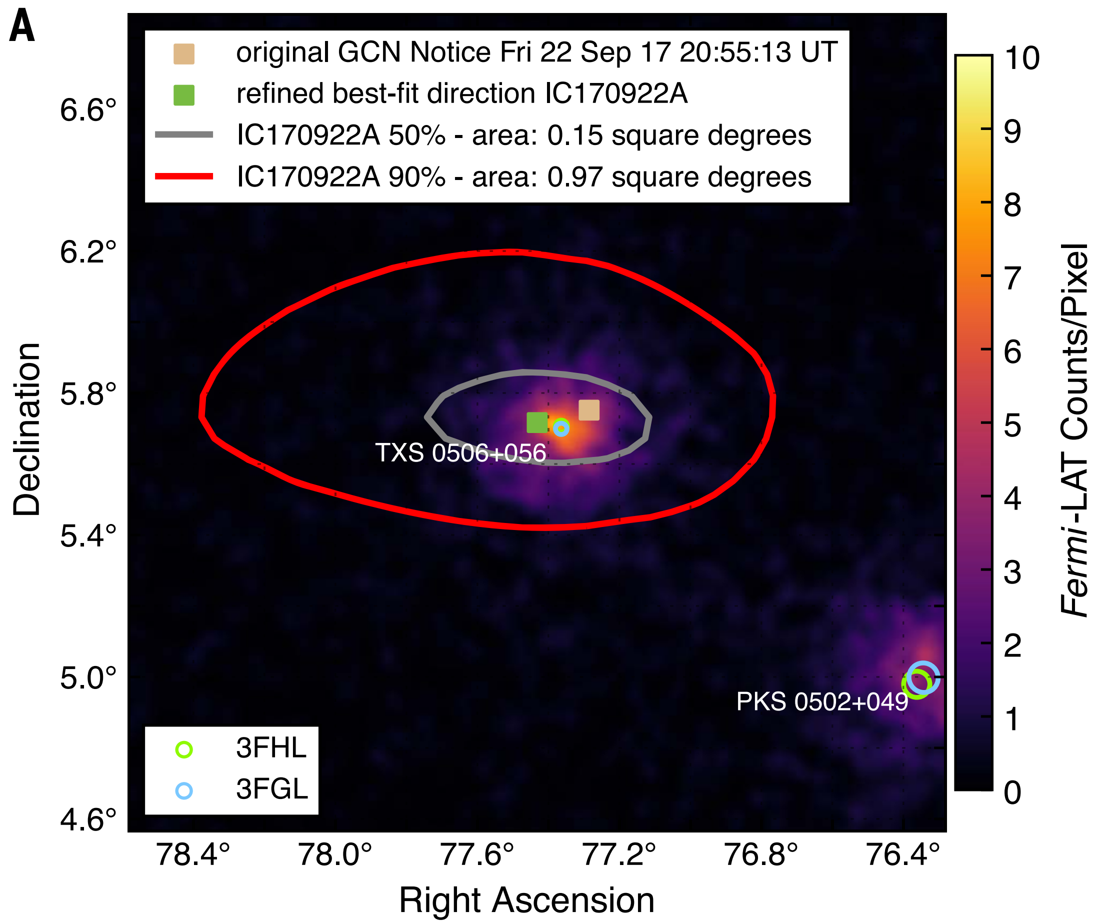


$$\frac{L_{\rm syn}}{L_{\rm IC}} \simeq \frac{u'_{\rm B}}{u'_{\rm ext}}$$

$$u'_{\rm ext} \sim \frac{\xi\Gamma_{\rm j}^2 L_{\rm acc}}{4\pi c r_{\rm ext}^2}$$

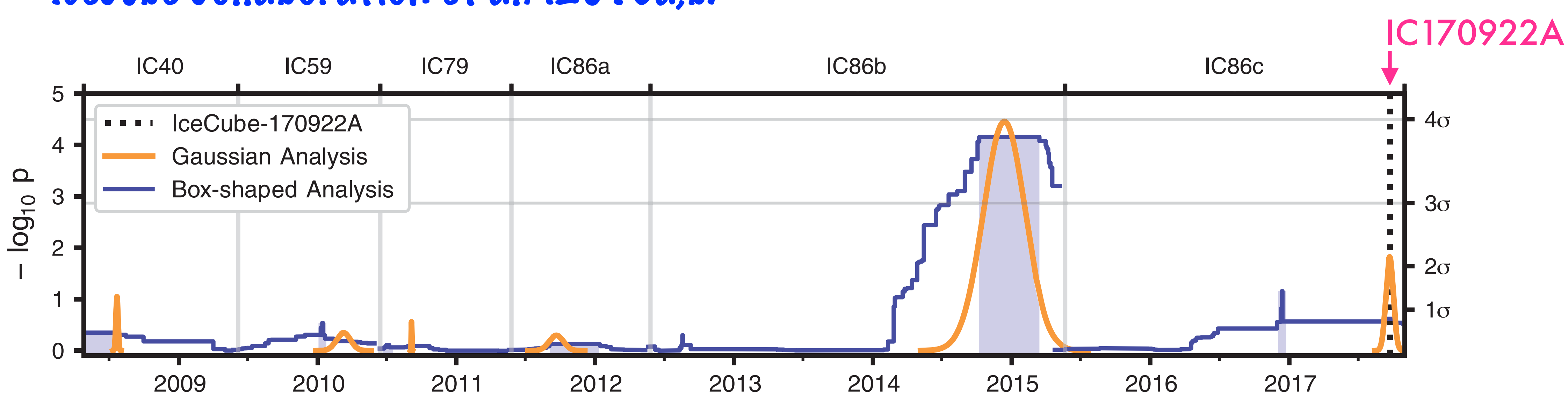


neutrinos from blazars



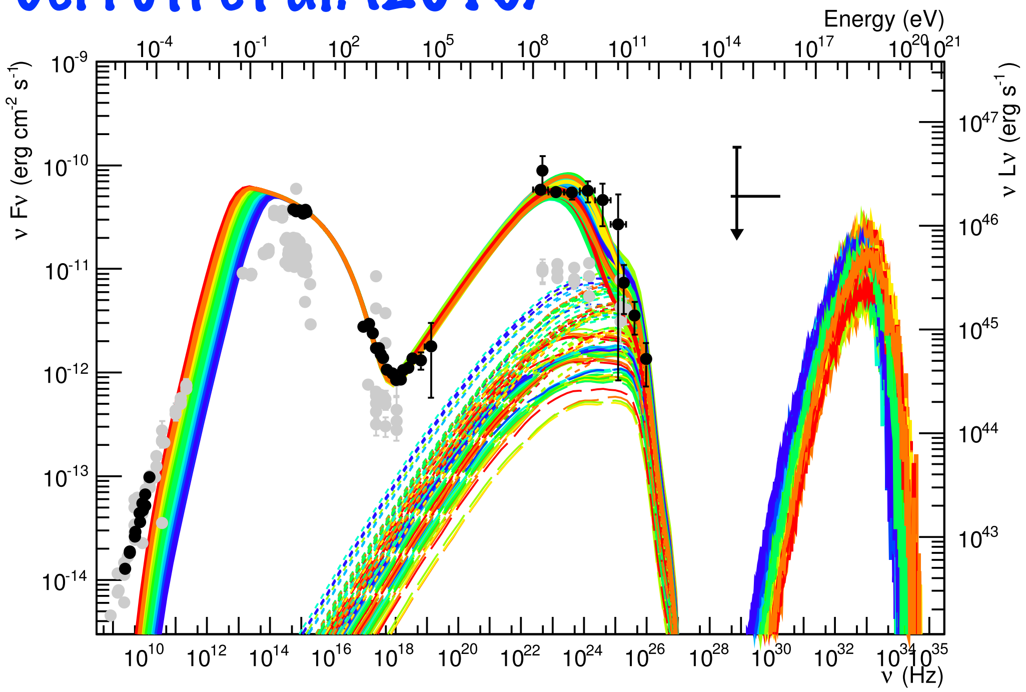
- neutrinos of ~PeV energy are detected by observatories like IceCube
- single neutrinos have been associated with several blazars, e.g., IC170922A with TXS 0506+056 (supported by an excess of lower-energy events in 2015)
- further associations: PKS 1502+106 (2019), 3HSP J095507.9+35510 (2020), etc.

IceCube Collaboration et al. (2018a,b)

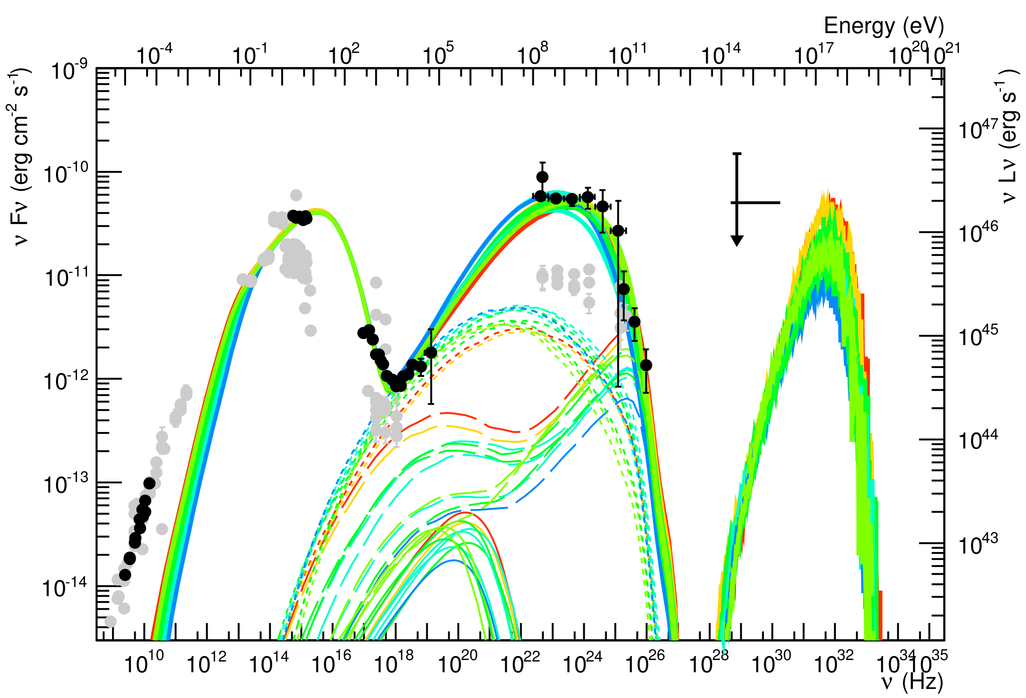


hadronic radiative processes

Cerruti et al. (2019)



(a) Proton synchrotron modeling of TXS 0506+056

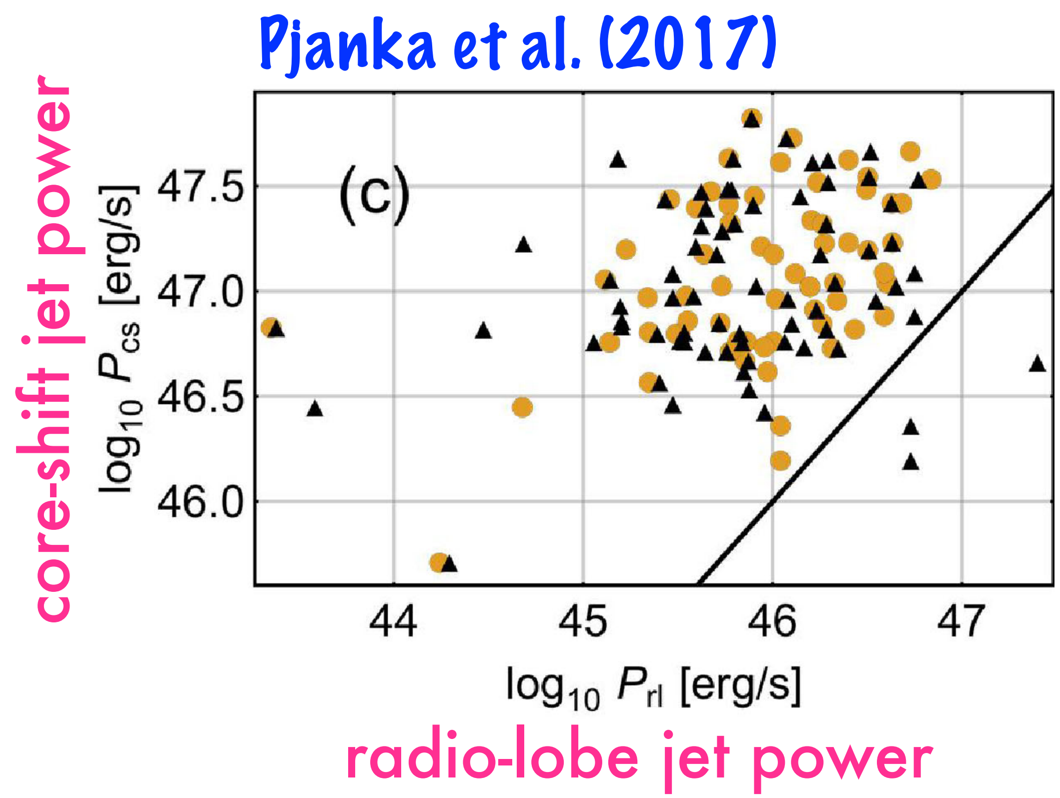


(b) Lepto-hadronic modeling of TXS 0506+056

- protons may be accelerated to ultra-high energies (up to 10^{20} eV) in AGN jets
- ~PeV protons may produce ~TeV photons through photo-mesonic cascades (pions, neutrinos, etc.) or in the proton synchrotron process
- hadronic processes are generally less efficient than leptonic processes (Sikora et al. 2009), often requiring super-Eddington jet powers (Zdziarski & Böttcher 2015)

(7) plasma composition

electron-positron pairs



$P_{\rm rl} \sim P_{\rm cs}/10$

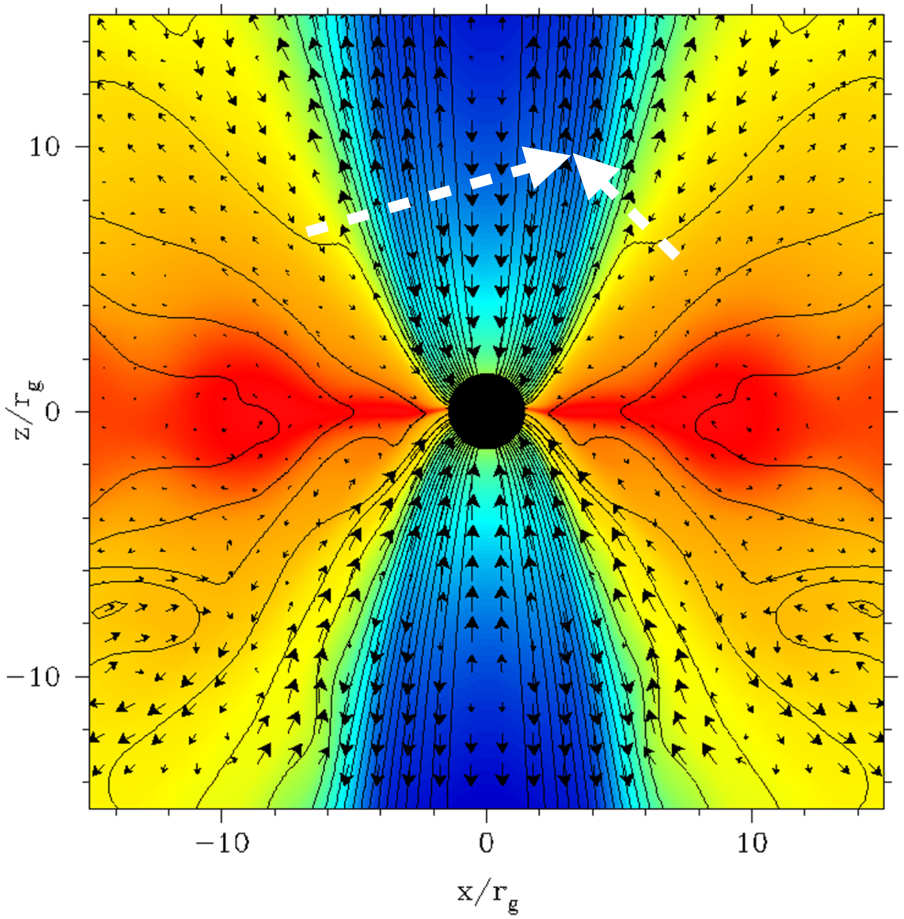
100 kpc-scale jet power a small fraction of the pc-scale jet power:
- intermittency at pc scales;
- abundant pairs at pc scales, radiating their energy by kpc scales.

- electron-positron pairs may be abundant in relativistic jets, ~20 leptons per proton (Sikora et al. 2020) (cf. the talk of R. Anantua)
- evidence: energetics of radio lobes, pc-scale jet powers (modeling blazar SEDs, radio core shifts)
- however, no pairs inferred by, e.g., Ghisellini et al. (2014)

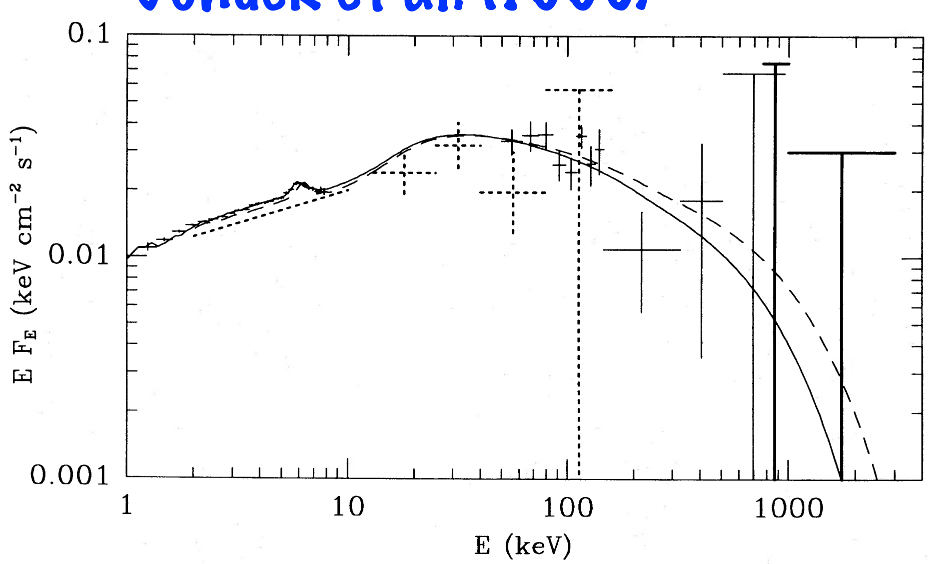
(8) origin of matter

loading with pairs

Barkov & Komissarov (2008)



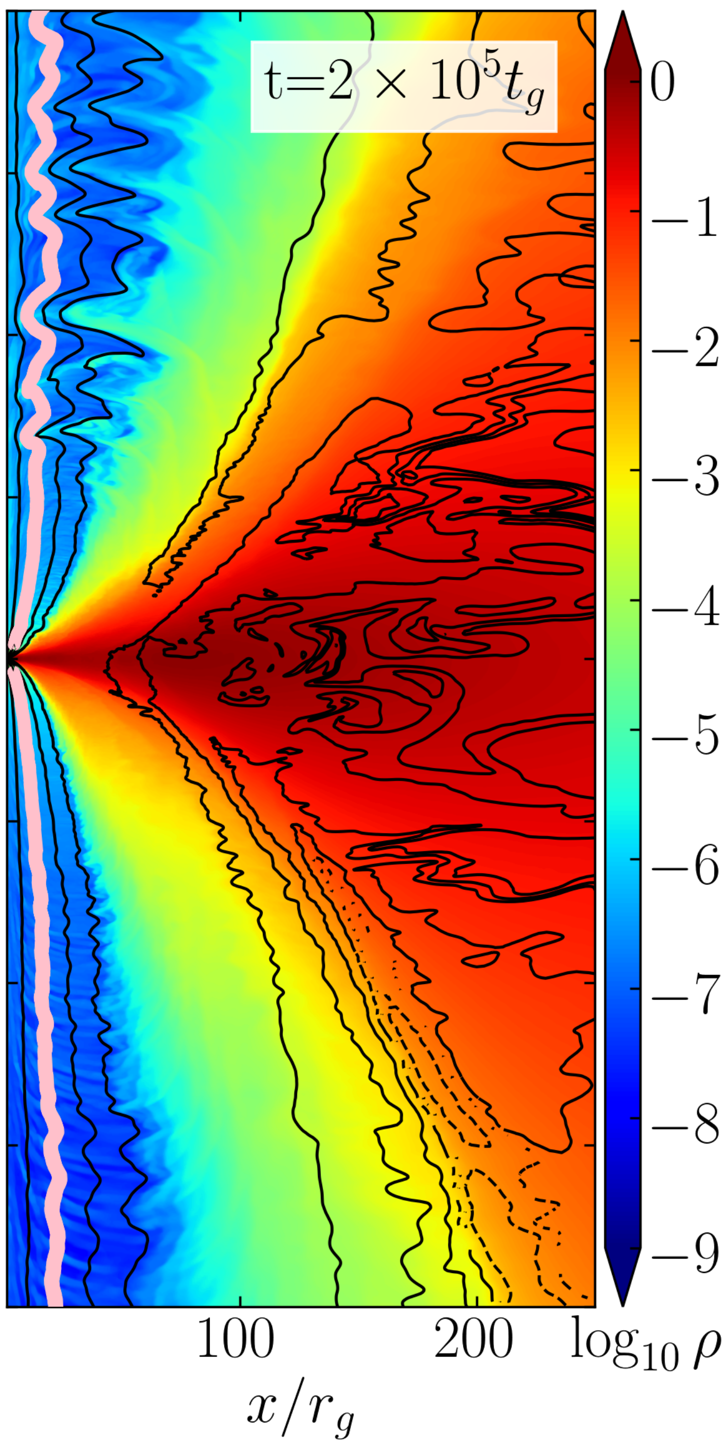
Gondek et al. (1996)

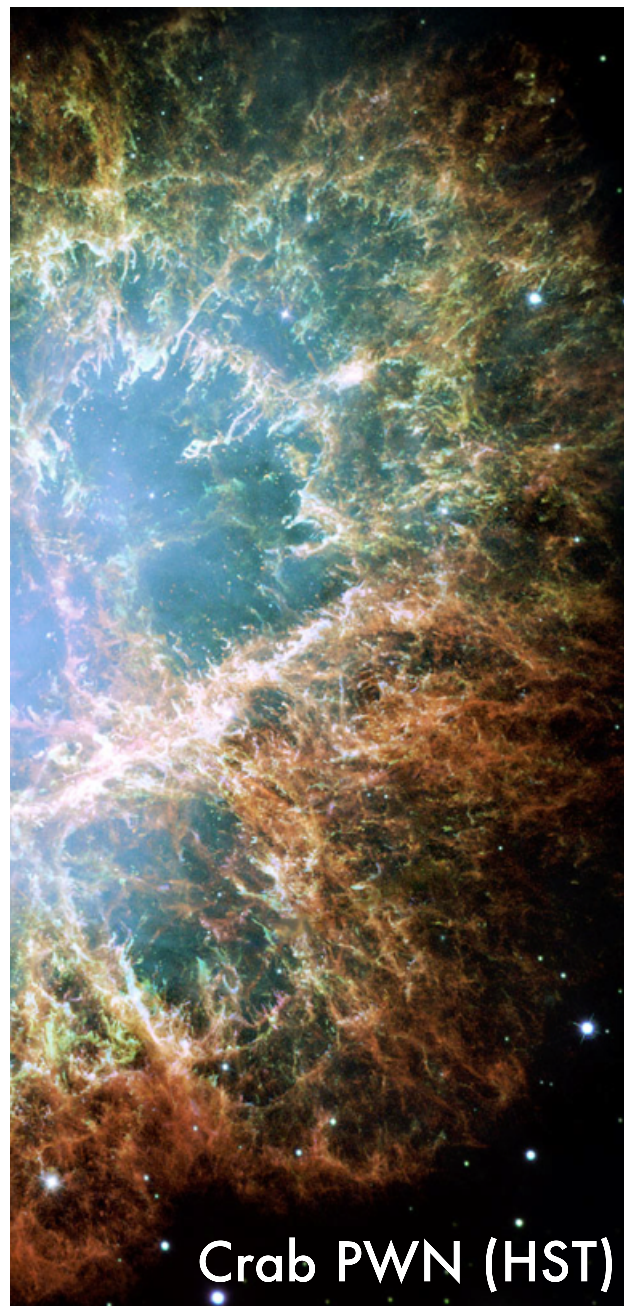


- photon-photon pair production from soft gamma-ray (~MeV) emission of accretion disk coronae; efficiency uncertain due to poor data on MeV spectra of AGN (Sikora et al. 2020)
- or pair production by $\gtrsim$GeV gamma rays produced in the inner jet interacting with low-energy radiation (Blandford & Levinson 1995)
- or cascades produced by particles accelerated in magnetospheric gaps (Broderick & Tchekhovskoy 2015)
- volumetric process providing uniform particle density (KN 2016)

loading with protons

Chatterjee et al. (2019)





- protons must be advected from the jet environment
- proton loading may proceed through instabilities, e.g., interchange (magnetic Rayleigh-Taylor)
- filamentary loading may lead to highly non-uniform particle density (KN 2016)

1. Relativistic jets are most likely launched from spinning black holes with poloidal magnetic flux in the Blandford-Znajek mechanism.

2. Jets are accelerated to relativistic speeds by pressure of toroidal magnetic fields, converting initially relativistic magnetization. Acceleration distance scale can be reduced to $\sim 10^3 R_{\rm g}$ due to jet collimation by external pressure.

3. Jets are remarkably stable globally to kpc scales, yet the can be unstable locally to current- and pressure-driven modes.

4. Energy dissipation may proceed by collisionless shocks in matter-dominated regions or by magnetic reconnection in magnetically dominated regions, most likely involving turbulence.

5. Particle acceleration mechanism is closely related to the dissipation process, if limited by radiative cooling, it is a rather slow process (energy diffusion or second-order Fermi).

6. Radiative processes are still debated for the high-energy emission. Leptonic processes (inverse Compton scattering of synchrotron or external radiation) are favored due to lower energetic requirements. Hadronic processes (photo-mesonic cascades or proton synchrotron) are now motivated by associations of PeV neutrinos with a few blazars.

7. Jet plasma is most likely composed of protons and electron-positron pairs, with $n_{\rm e}/n_{\rm p} \sim 20$.

8. The magnetized jets must be loaded by matter. Leptonic pairs can be seeded across the jets by external soft gamma rays. Protons must be introduced by contact instabilities (e.g., interchange).

thank you

Krzysztof Nalewajko (CAMK PAN, Poland, knalew@camk.edu.pl), Kathmandu, 17 May 2022