Efficient acceleration of relativistic magneto-hydrodynamic jets: theoretical study

(Toma & Takahara 2013, Prog. Theor. Exp. Phys., 2013, 3E02)

Kenji TOMA
(Tohoku U, JAPAN)
Collaboration with F. TAKAHARA

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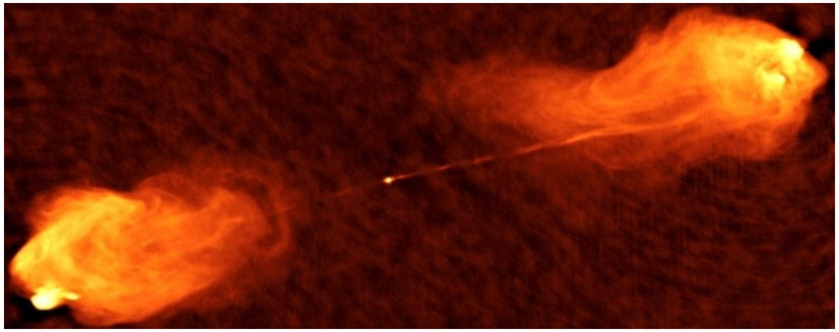
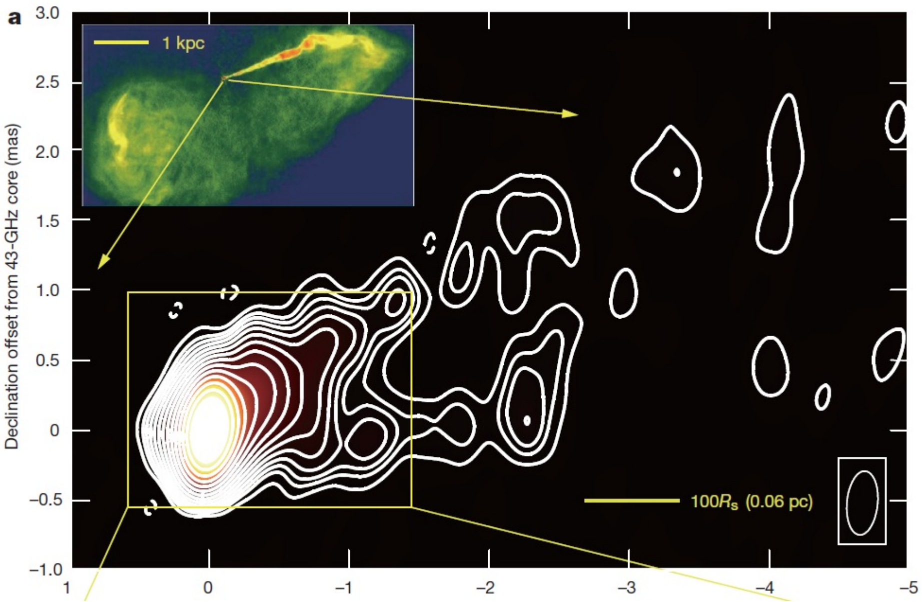
Relativistic Jets

- Active galactic nuclei, gamma-ray bursts, etc.
- Lorentz factor Γ~10-10^3(?)
- One of the major problems in astrophysics

- Those objects are candidates of high-energy CR, ν, and GW emitters.

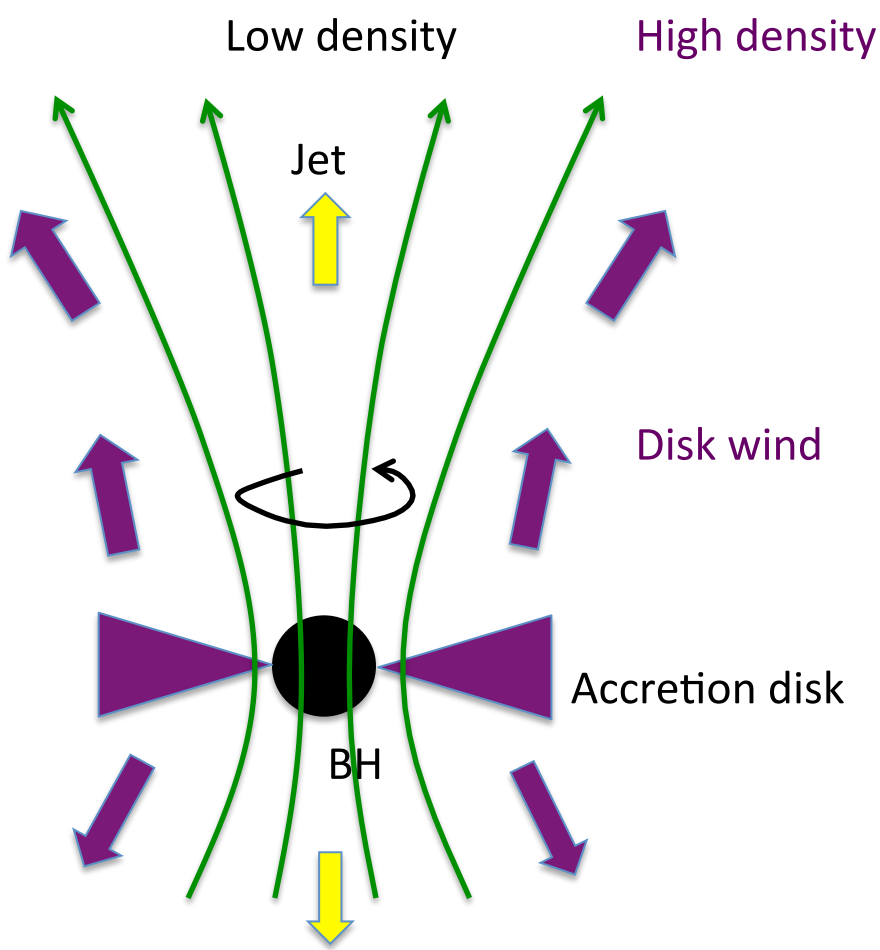


Radio image of Cygnus A



M87 (Hada+ 2011)

Promising Scenario



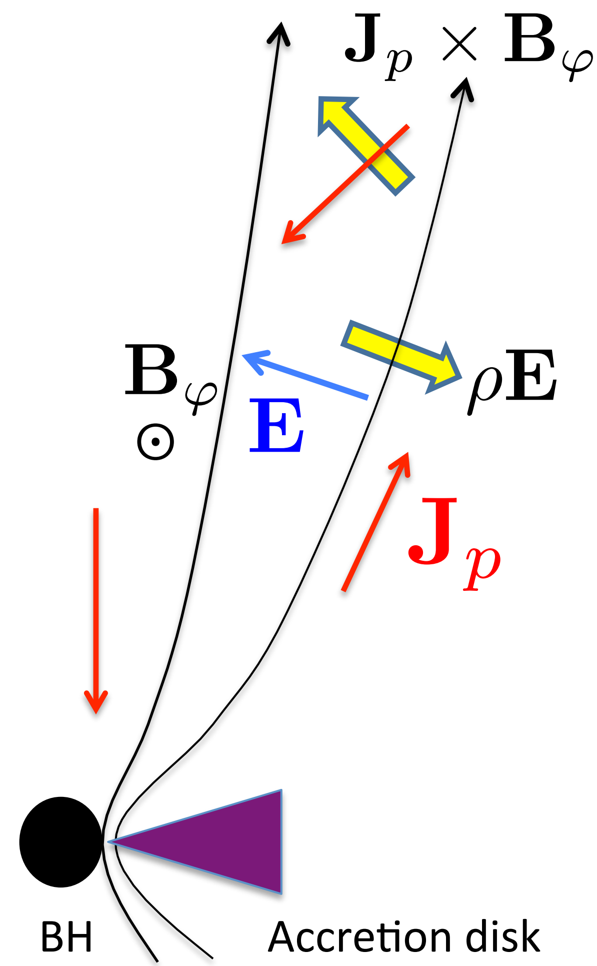
(see numerical simulations by J. McKinney, A. Tchekhovskoy, etc.)

- Steady extraction of rotational energy of accretion disk or BH (Goldreich & Julian 1969; Blandford & Znajek 1977; see also KT & Takahara 2014) → Poynting-dom jet (Kino+ 15)
- Mass loading mechanism unknown. Unsteady process or diffusion of high-energy hadrons? (KT & Takahara 2012; Kimura et al. 2015)
- Matter acceleration by Lorentz force
- Collimation by external pressure

Matter acceleration, collimation

- Particles are accelerated by $J{\times}B$ force (= energy flux conversion from Poynting to kinetic)
- $J{\times}B$ force also collimates the flow
- But ρE force expands the flow
- In the relativistic flow, $E \sim -v_p{\times}B_\phi \sim B_\phi$ beyond the light cylinder ➔ $B_\phi{}^2$ stress is not effective for collimation (except for the region near the axis) (Komissarov+09; Lyubarsky 09)

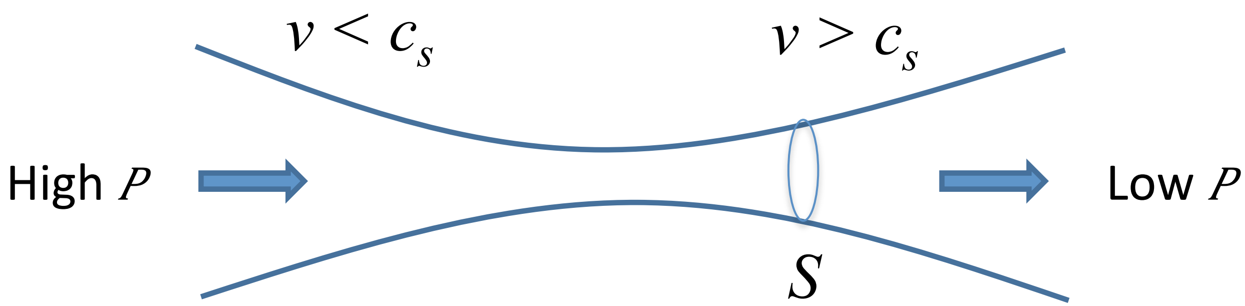
- Efficient acceleration requires expansion of magnetic flux tube (~ de Laval nozzle) (e.g. Begelman+94; KT & Takahara 2013)



Acceleration mechanism

De Laval nozzle:
one-dimensional hydrodynamic case

$$\left(1 - \frac{v^2}{c_s^2}\right)\frac{dv}{v} = \frac{-dS}{S}$$



Two-dimensional magneto-hydrodynamic case

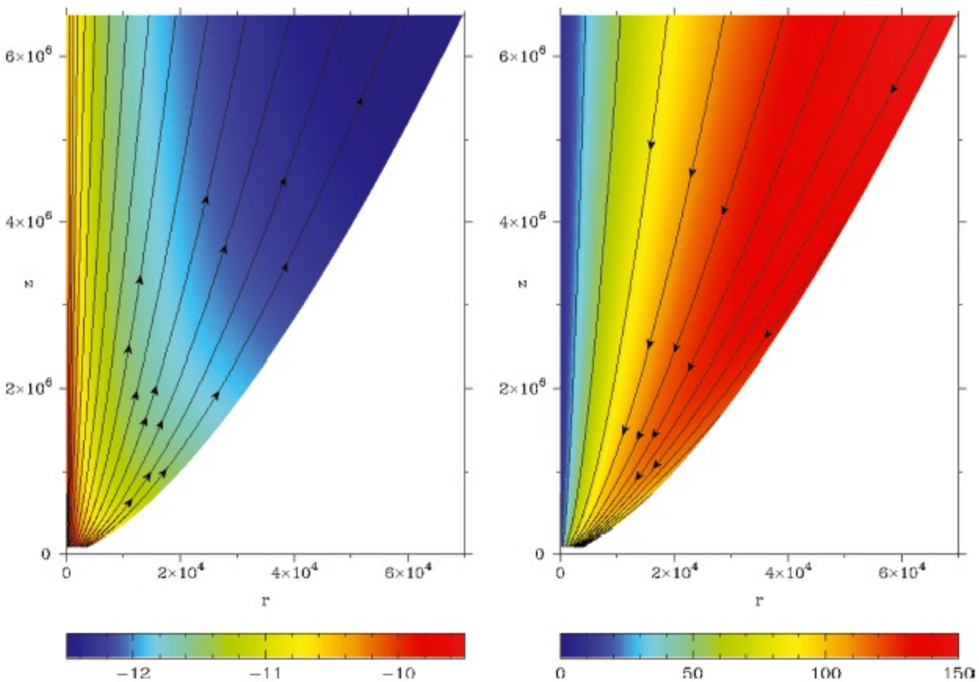
$$S = B_p\, r^2$$

$$\left(1 - \frac{u_f^2}{u_p^2}\right)\frac{d\Gamma}{\mathcal{E} - \Gamma} + \frac{c^2 \Gamma_{\rm in}}{r^2 \Omega^2 \Gamma}\frac{d\Gamma}{u_p} + \left(1 + \frac{2\Gamma_{\rm in}}{\Gamma}\right)\frac{(-v_\varphi d v_\varphi)}{v_p^2} = \frac{-d\mathcal{S}}{\mathcal{S}}.$$

Magnetic flux tube must be expanded when the super-fast flow is accelerated.

Acceleration mechanism

(Komissarov, Vlahakis, Konigl & Barkov 2009)



Poloidal B field lines & Density

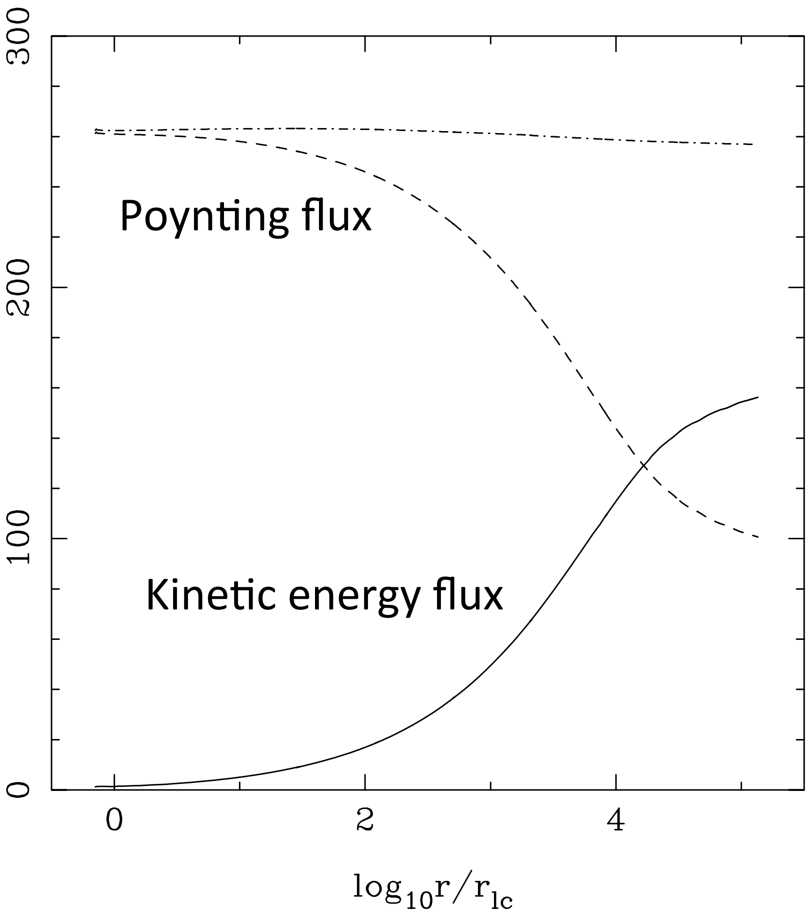
Poloidal currents & Lorentz factor

- Steady axisymmetric MHD solution
- BH gravity neglected
- External rigid wall (parabolic)
- Gradual acceleration
- Collimation near the axis leads to expansion of outer region

(see also Lyubarsky 2009; Asada, Nakamura et al. 2014)

Acceleration efficiency

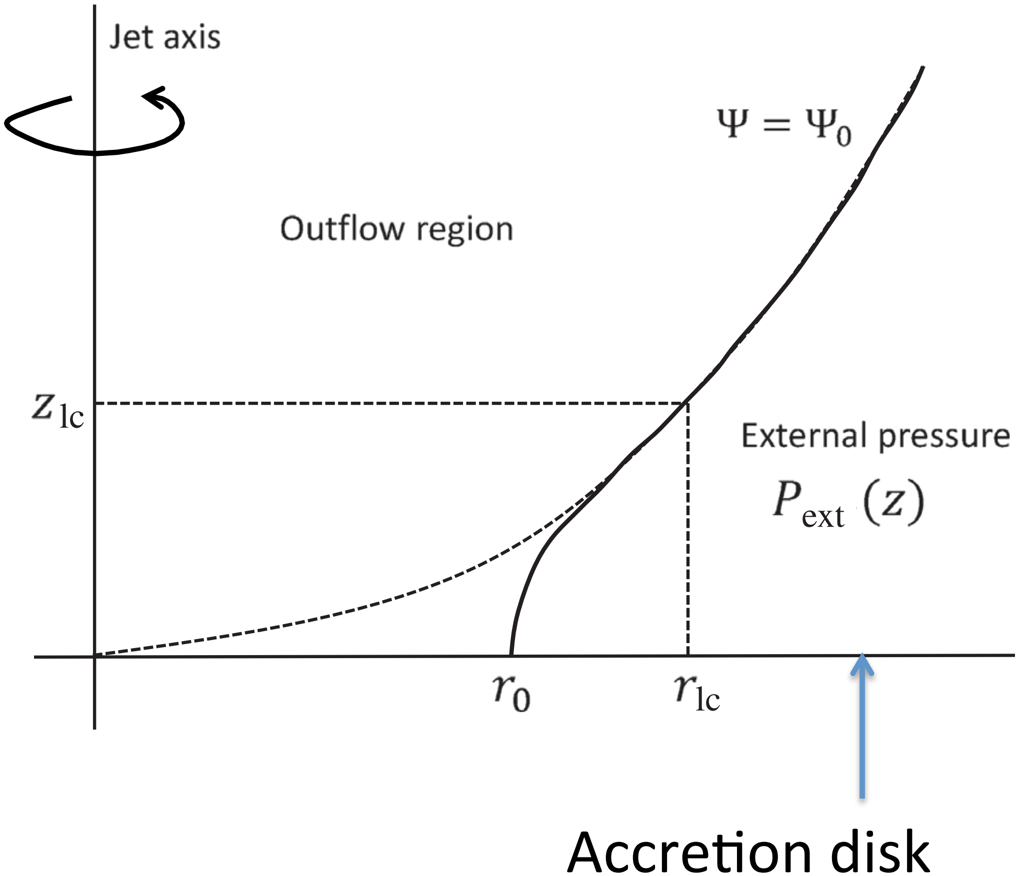
(Komissarov, Vlahakis, Konigl & Barkov 2009)



- Poynting/kinetic ~ 1 at r ~ 10^4 r_{lc} (z ~ 10^6 r_{lc}) which is extremely large distance
- But observations of blazars imply Poynting/kinetic < 0.1 at r ~ 10^3 r_{lc} (e.g. Kino+ 2002; Sikora + 2005)
- (Efficient magnetic dissipation?)

We look for boundary conditions for more efficient acceleration

Field line near the boundary



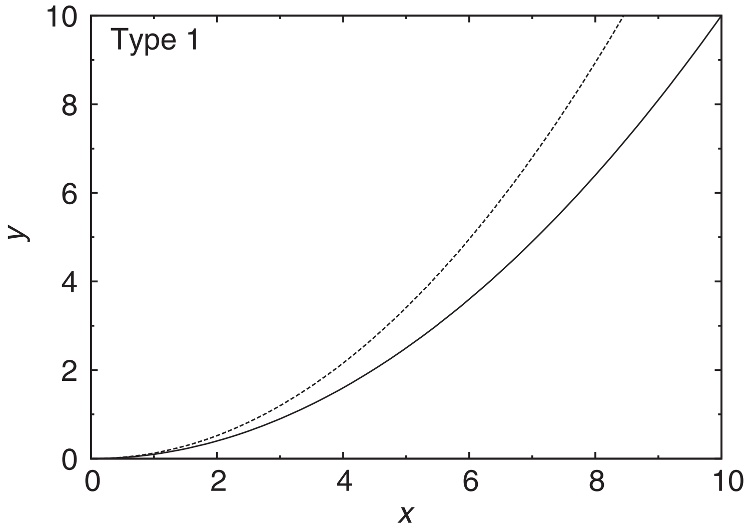
- Focus on the fluid motion along the field line near the boundary (not solving transverse structure)
- Assume the shape of the boundary
- Look for field structure for efficient acceleration

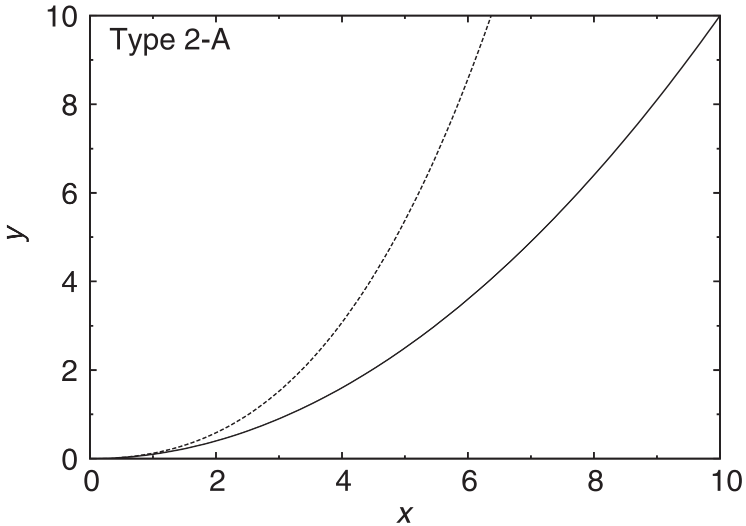
- External pressure

$$\left(\frac{B_p^2 + B_\varphi^2 - E^2}{8\pi}\right)\Bigg|_{\Psi=\Psi_0} = P_{\rm ext}(z).$$

Examples of field line structure

- Boundary: $y = 0.1\ x^2$
- Plot the field line of $\Psi = 0.95\ \Psi_0$



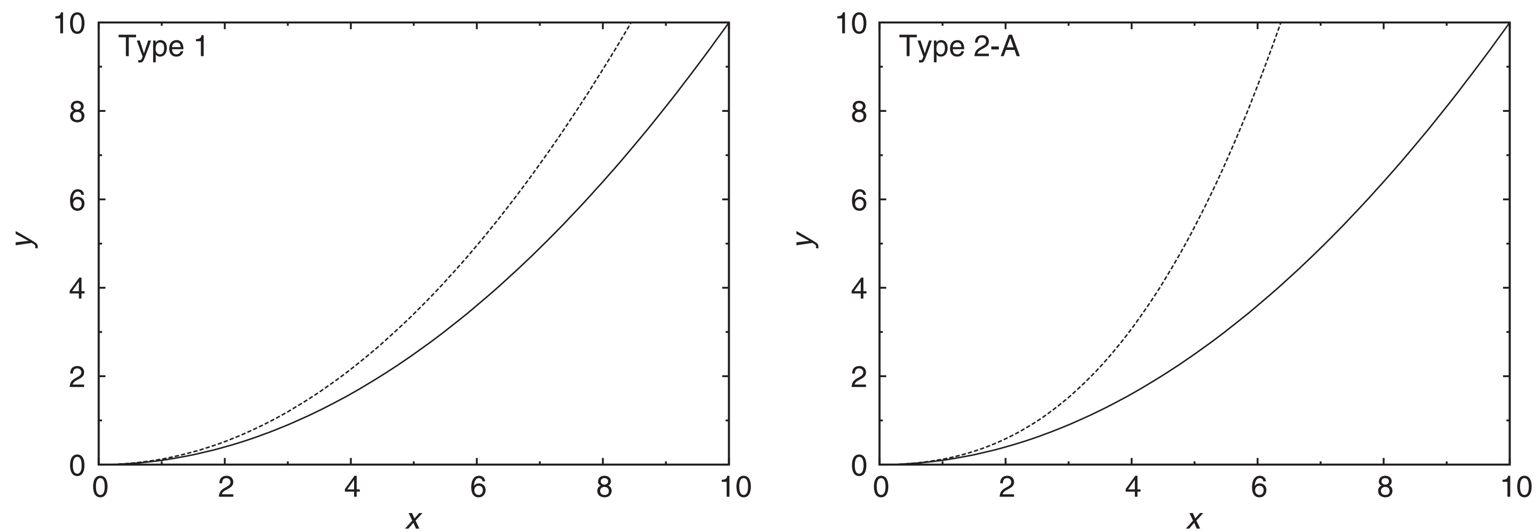


$$y = D\left(\frac{x}{d}\right)^{a(\psi)},$$

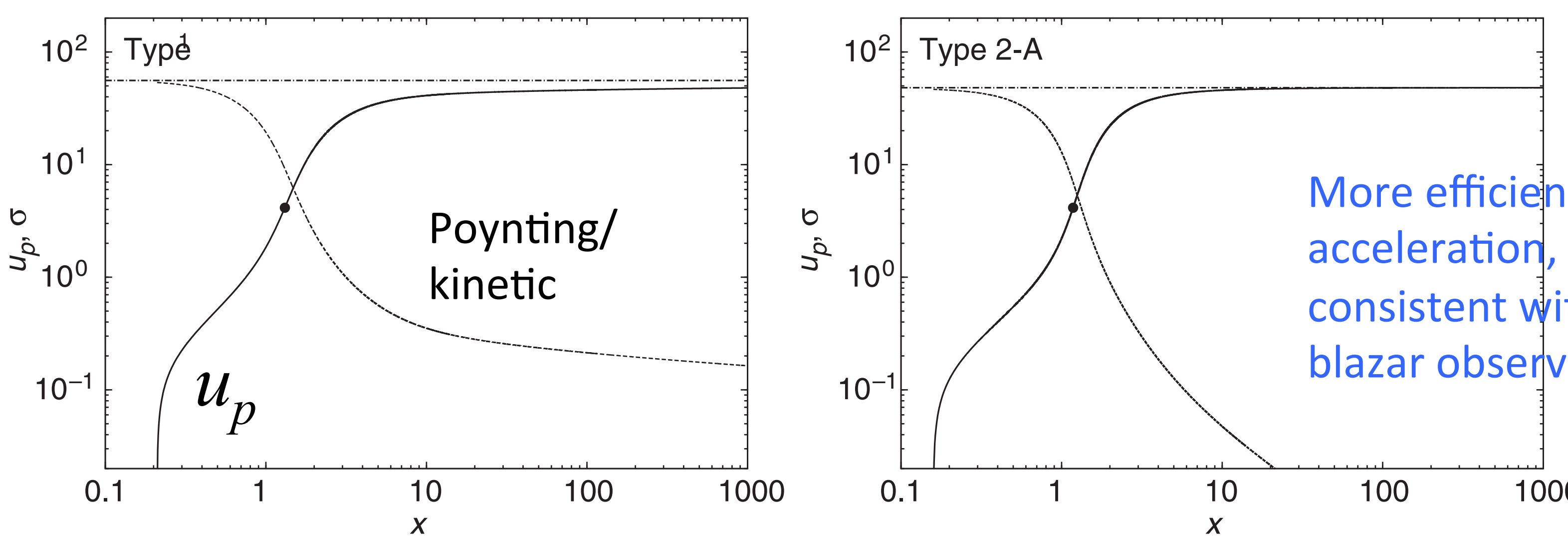
$$y = A_0 x^{a_0} + F(\psi) x^b,$$

More efficient acceleration

Solutions of cold MHD wind eq.

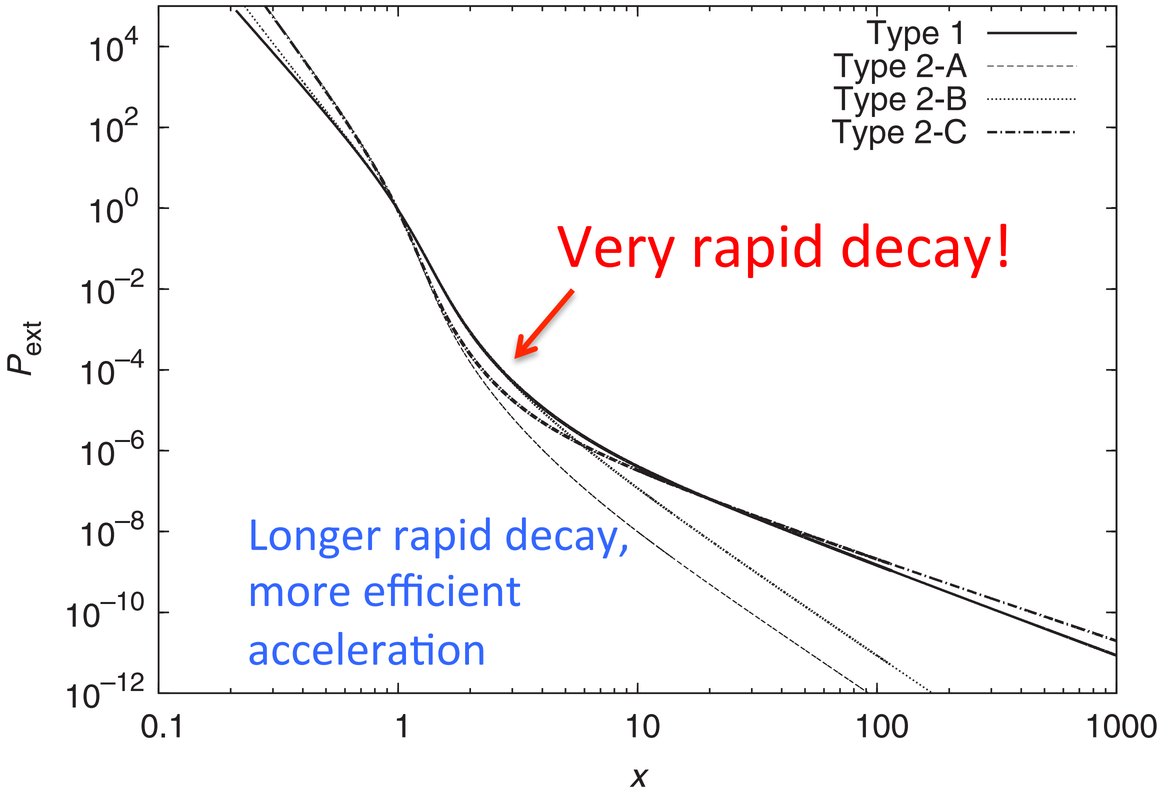


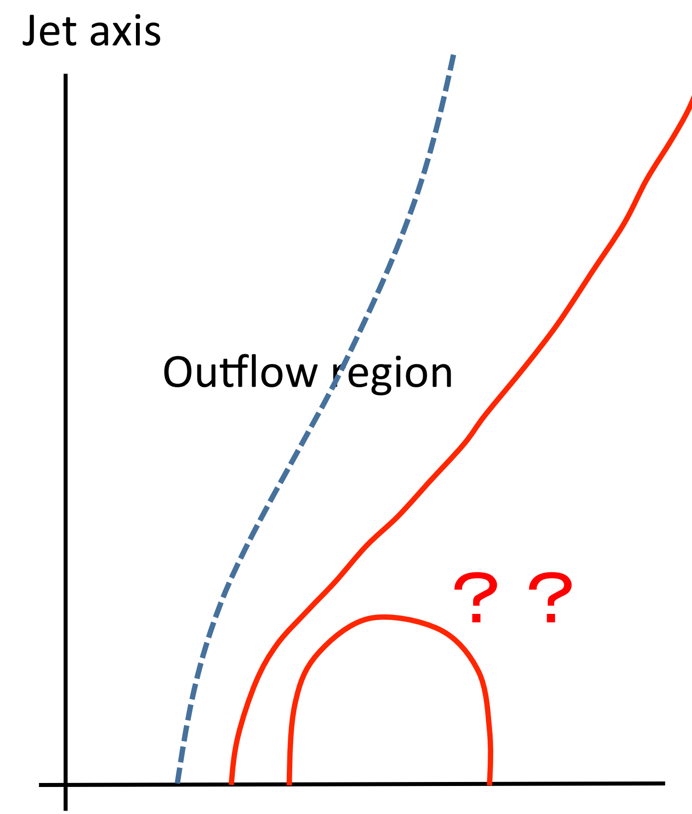
Both cases show Poynting/kinetic ~ 0.3 at r ~ 3 r_{lc}



More efficient acceleration, consistent with blazar observations

Solutions: external pressure





External medium could be the corona with closed field loops?

Summary

- MHD jet can accelerate the particles to relativistic speeds (e.g. Komissarov+ 2009) (consistent with radio observations of M87 jet… Asada+ 2014; Kino+ 2015)
- More efficient acceleration is needed for explaining the blazar gamma-ray spectra
- We show boundary conditions for very efficient acceleration, which correspond to very rapid decay of external pressure
- Another possibility is efficient magnetic dissipation (whose mechanism is not clear yet)