Dynamics and Microphysics inside the Blazar Zone & M87

Philip Hardee *(U. Alabama, Tuscaloosa)*

Fermi meets Jansky, Bonn, June 2010

Introduction

Blazar emission shaped by:

- *The central engine (launching)*
  - BH + Accretion Disk
  - Variability
- *The jet (structure/stability)*
  - Poynting & Kinetic flux
  - Spine & Sheath
- *The external environment*
  - AGN Photon field
  - AGN pressure/density profile
- *Particle acceleration*
  - BH Magnetosphere
  - Magnetic reconnection
  - Velocity Shear & Shocks
- *Radiation production/location*
  - Synchrotron & IC
  - BH to mm core & beyond

Sikora, Begelman & Rees 94

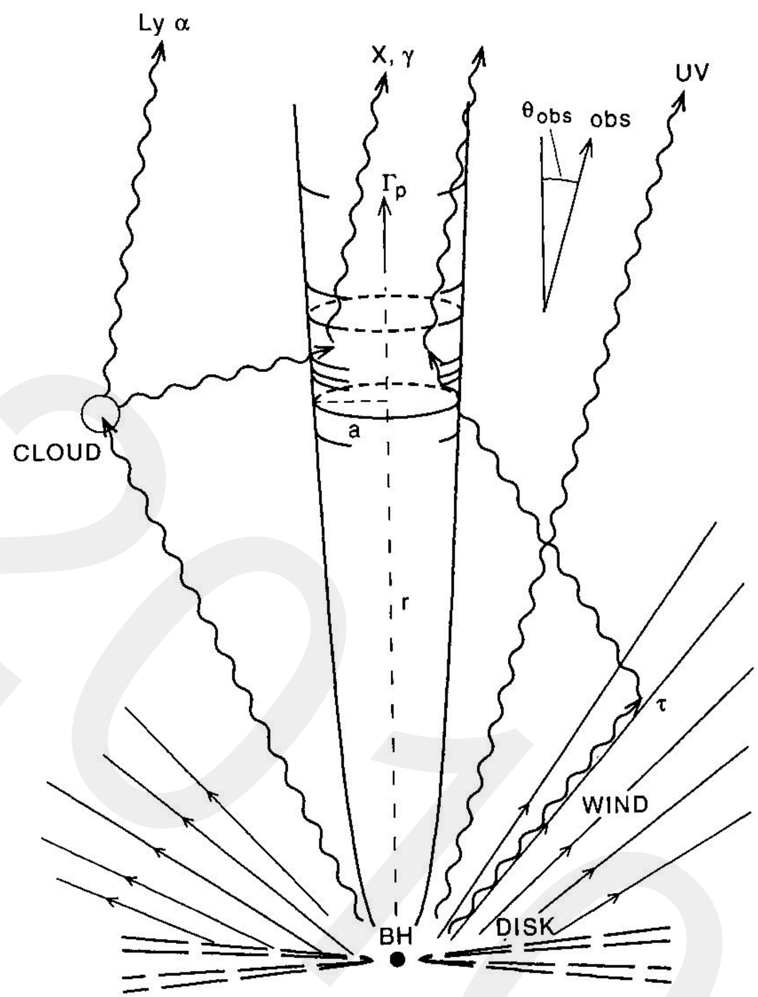
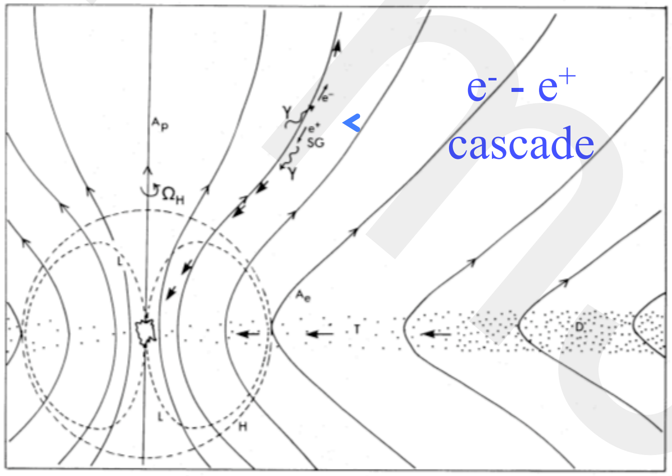


FIG. 2.—Geometry of the source. The radiating region, denoted by short cylinder of dimension a, moves along the jet with pattern Lorentz factor Γ_p. Underlying flow moves with Lorentz factor Γ, which may be different.

The Launching Region

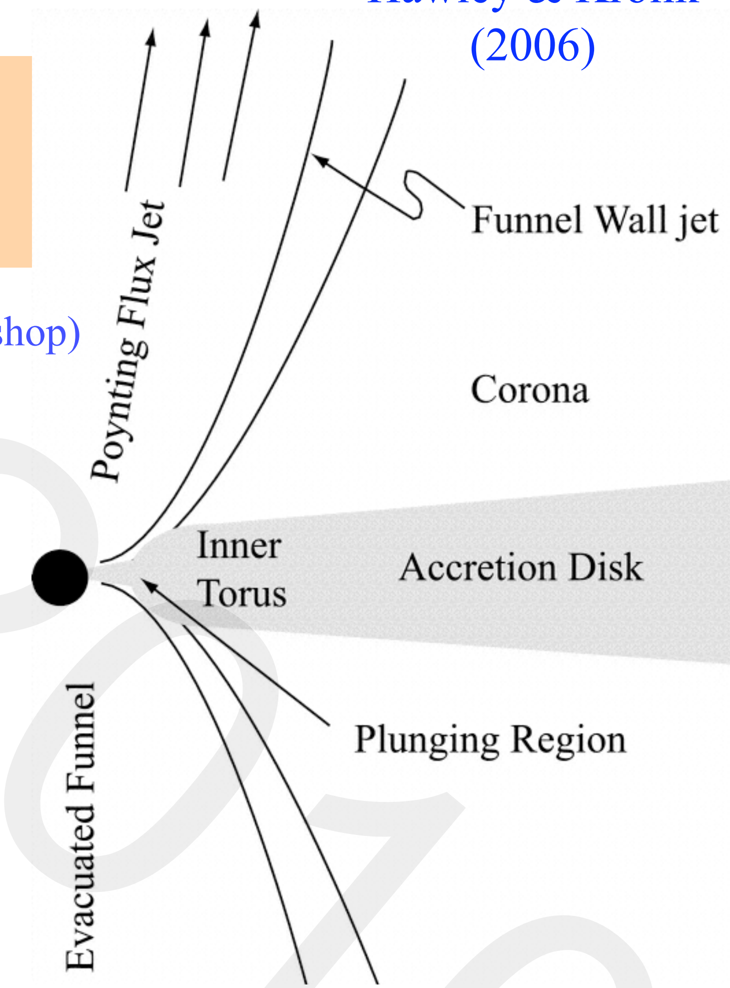
Blandford & Znajek (1977)



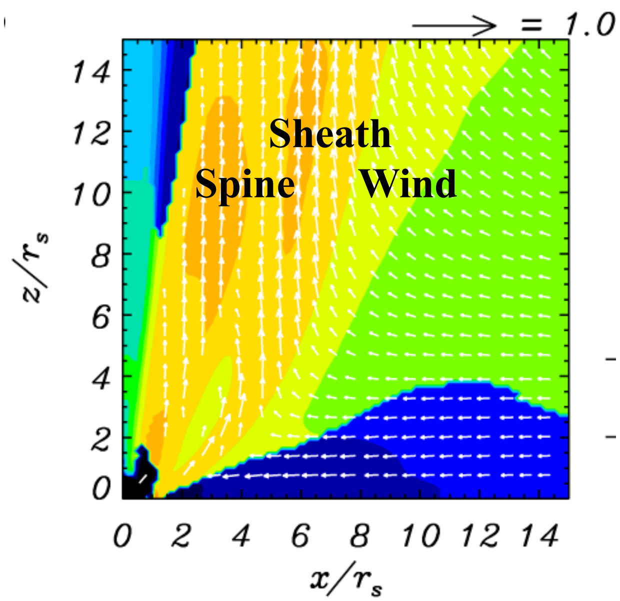
Vacuum Gap Particle Acceleration

Vincent (this workshop)

Hawley & Krolik (2006)



Hardee, Mizuno & Nishikawa (2007)



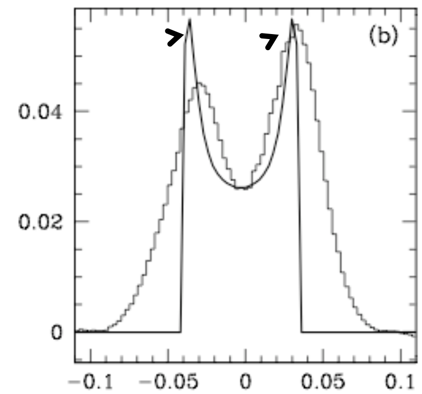
McKinney (2005)
McKinney & Narayan (2007)

Intrinsic Spine Sheath Structure

The Spine-Sheath Interface

Jet edge brightening

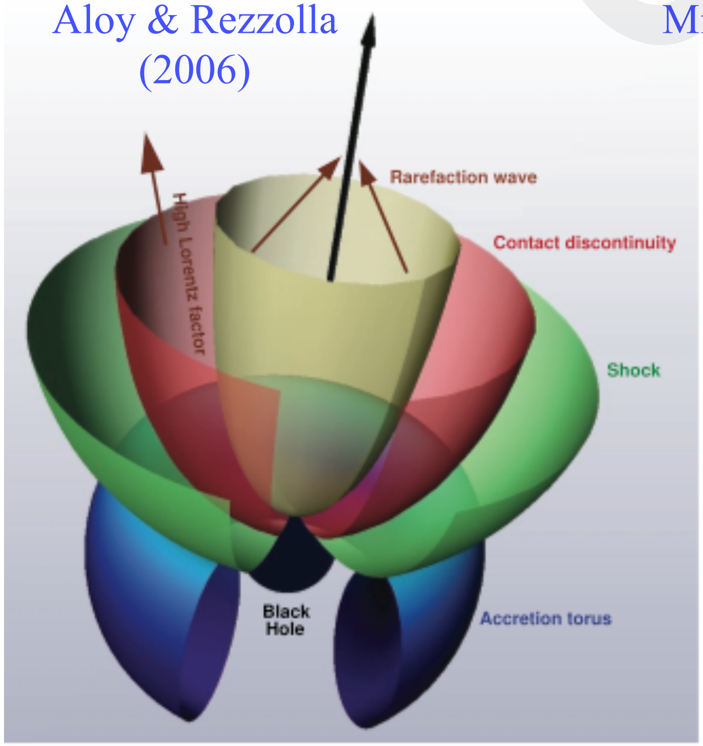
Intensity profile ~ M87 jet



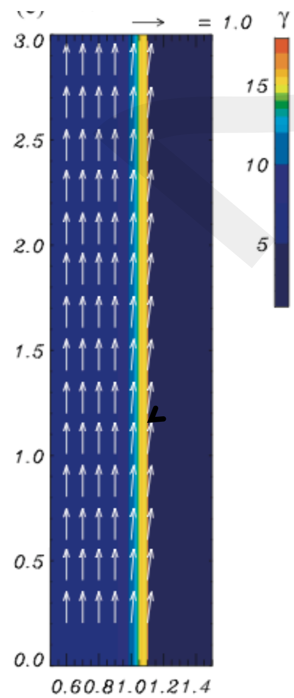
Zakamska et al. (2008)

Relativistic boost high Γ shear surface

Aloy & Rezzolla (2006)



Mizuno et al. (2008)



Layer likely too thin to affect intensity profile

Aloy & Mimica (2008)

Layer enhance velocity shear driven particle acceleration ?

Stawarz & Ostrowski (2002)

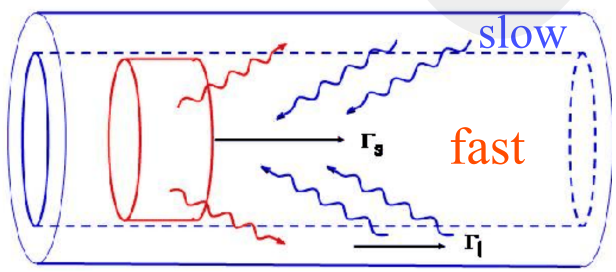
Decoupled Synchrotron & IC regions

One zone SSC models imply high Doppler & Lorentz factors!

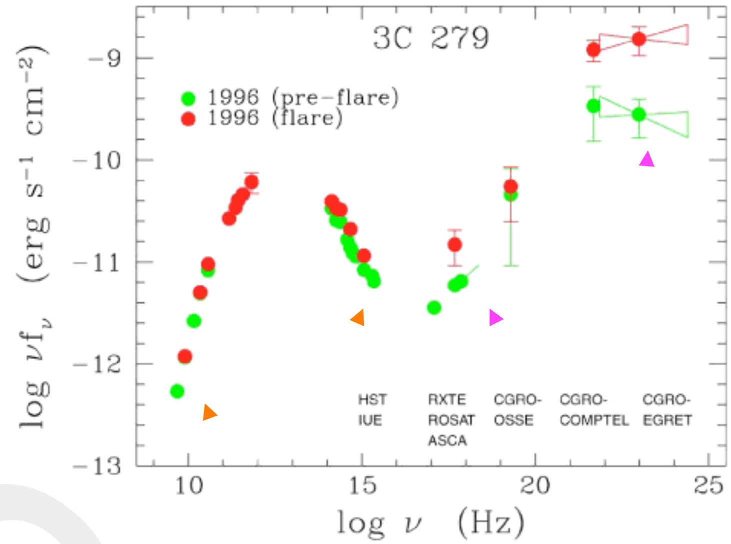
Slow pc-scale motions observed!

Global Scale: Fast Spine & Slow Sheath

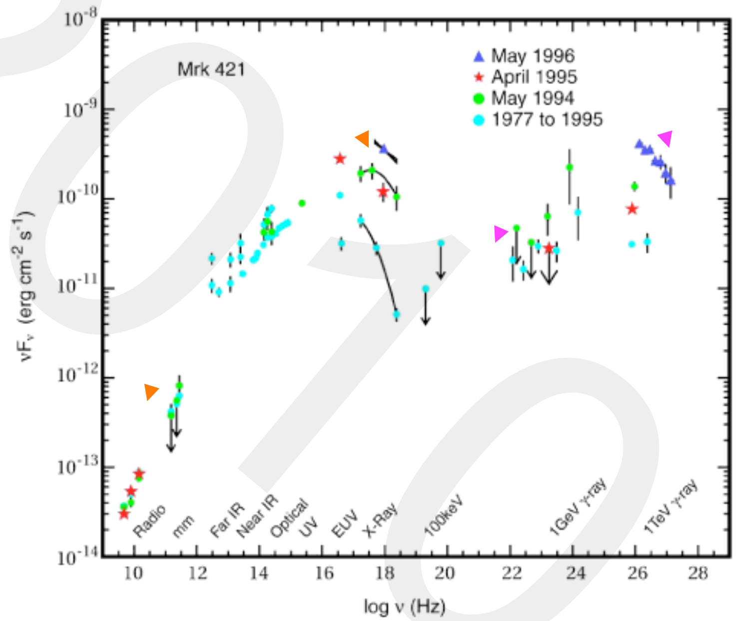
Emission modeling
$\Rightarrow$ 2 jet speed components
TeV BL Lacs



(Ghisellini et al. 2005)



Synchrotron Inverse Compton



Small Scale: Needles, Jet in Jet, Deceleration

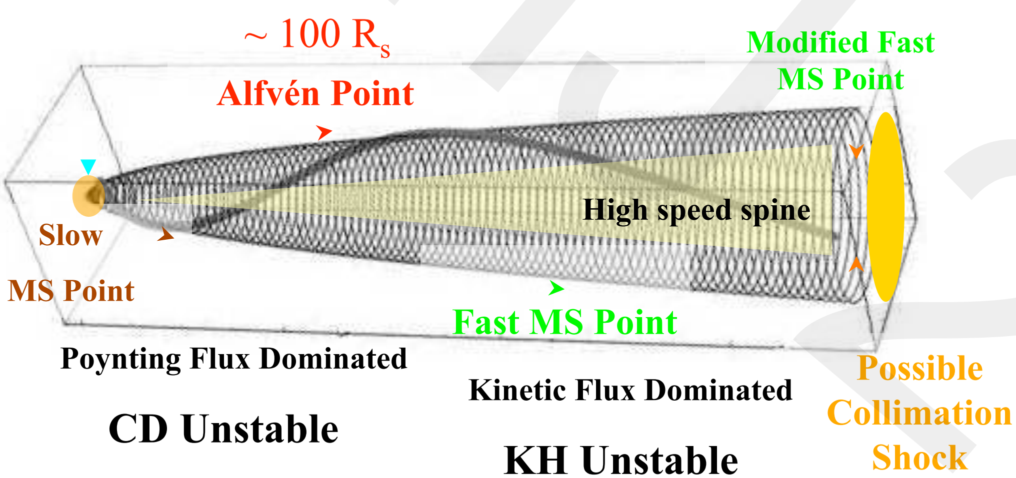
Ghisellini & Tavecchio (2008)

Giannios et al. (2009)

Georganopoulos et al. (2005); Levinson (2007)

The Collimation Region

Jet Launching Region | **Jet Collimation Region (10 –100 × Launching Region)**

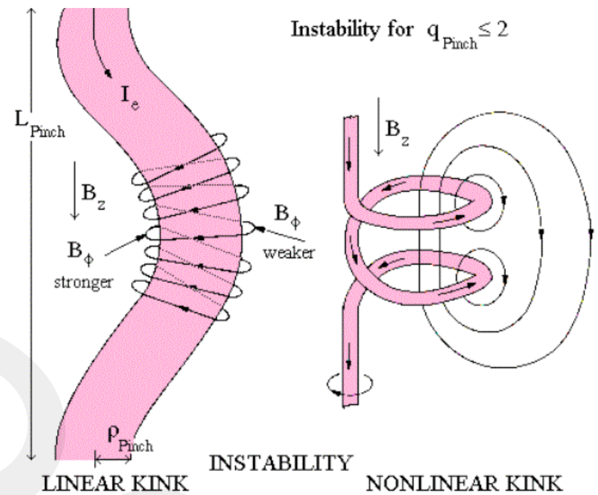


Modified from Graphic courtesy David Meier

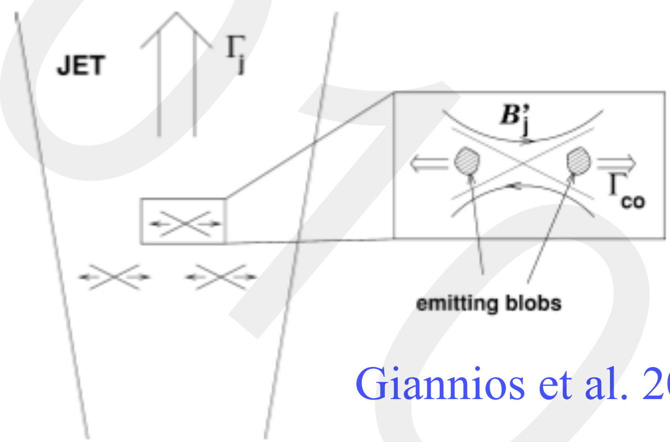
Particle Acceleration via CDI & Reconnection

$t_{acc} \sim t_{NL} > 100\ t_{Alfvén}$

Current Driven Instability



Magnetic Reconnection

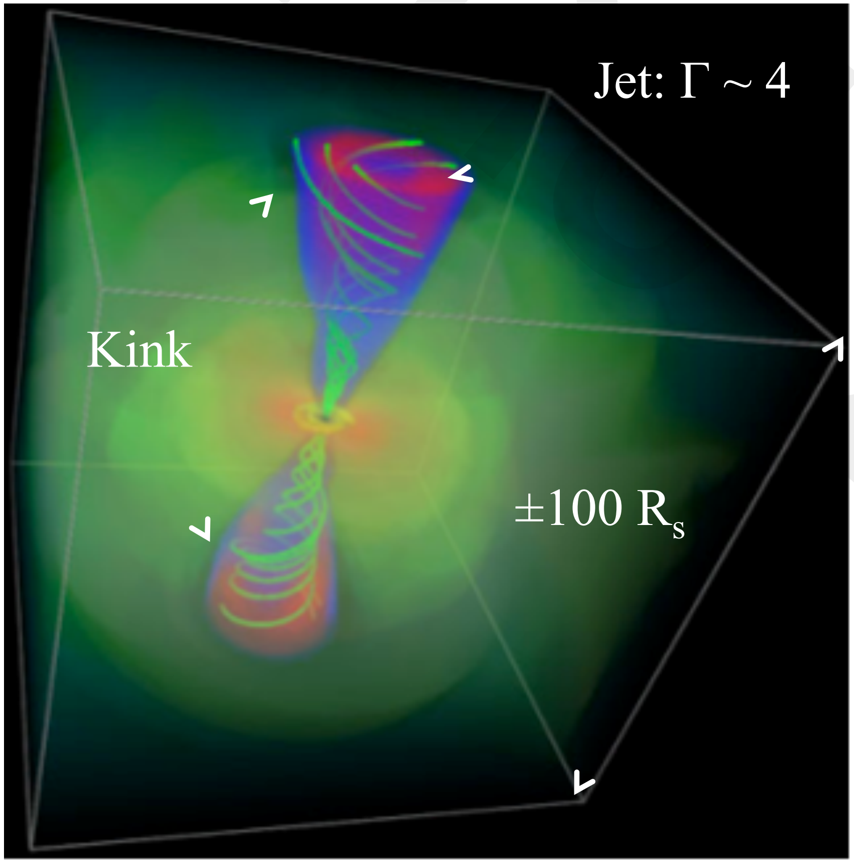


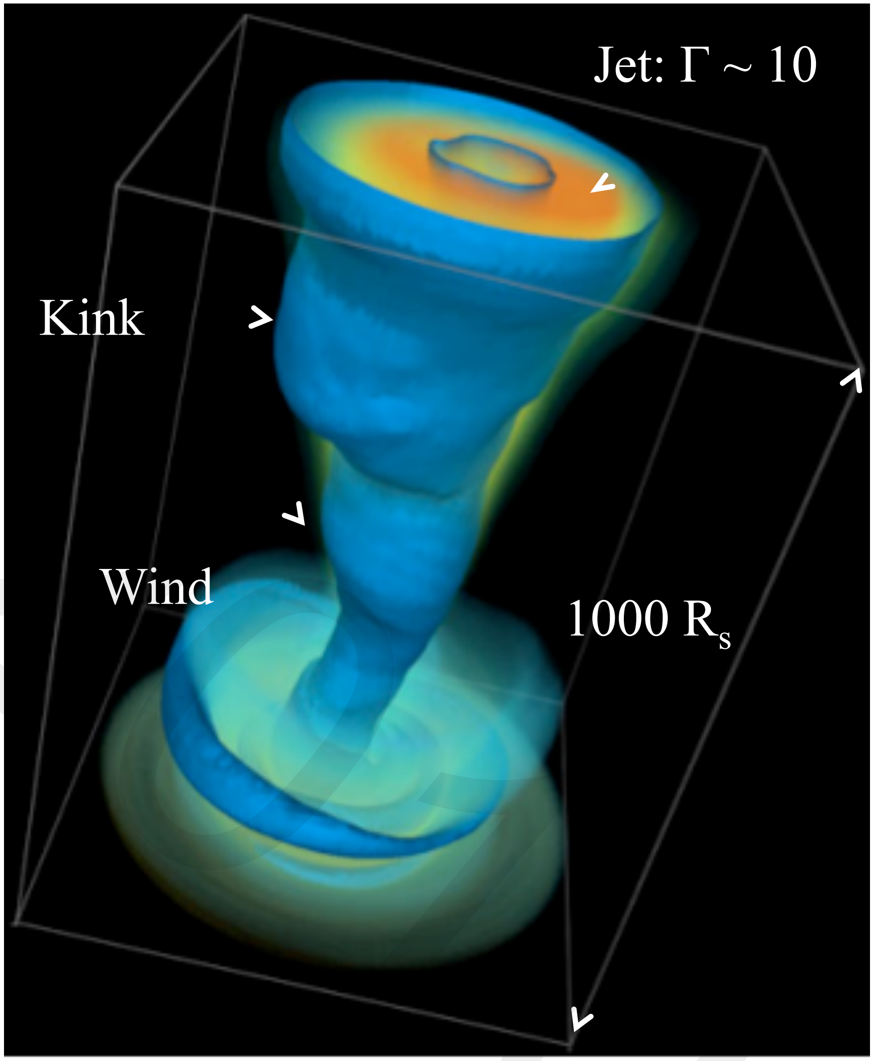
Giannios et al. 2009

Jet Stability/Structure

McKinney & Blandford 2009

Magnetically dominated jets
launched by BZ effect



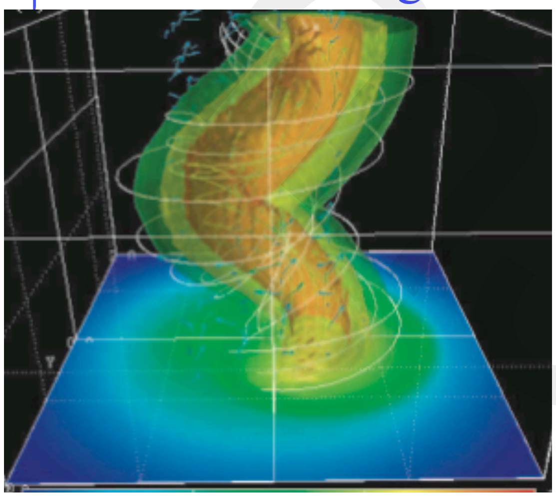


Kinked jet basically stable structure

Non-disruptive Kink/Helical flow

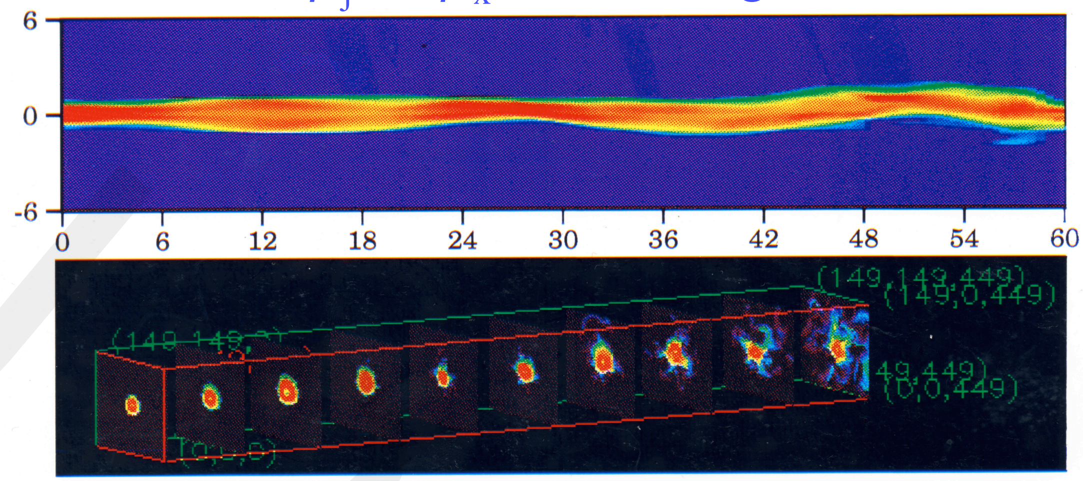
CD Kink Flow: (Mizuno et al. 2010)

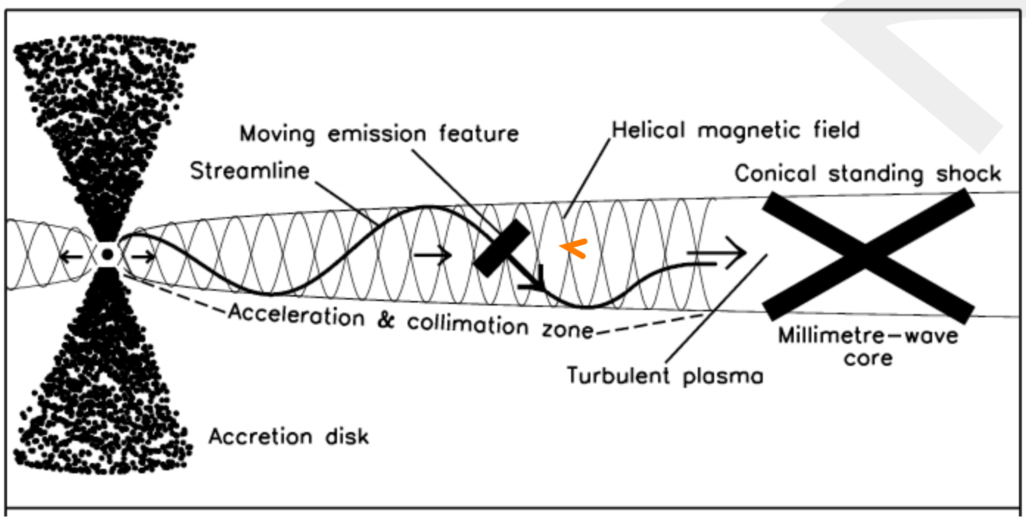
R_j << a: flow through kink



KH Kink Flow: (Rosen et al. 1999)

$\Gamma^2\rho_j << \rho_x$: flow through kink





BL Lac & PKS 1510-089

Marscher et al. (2008, 2010)

3C 279

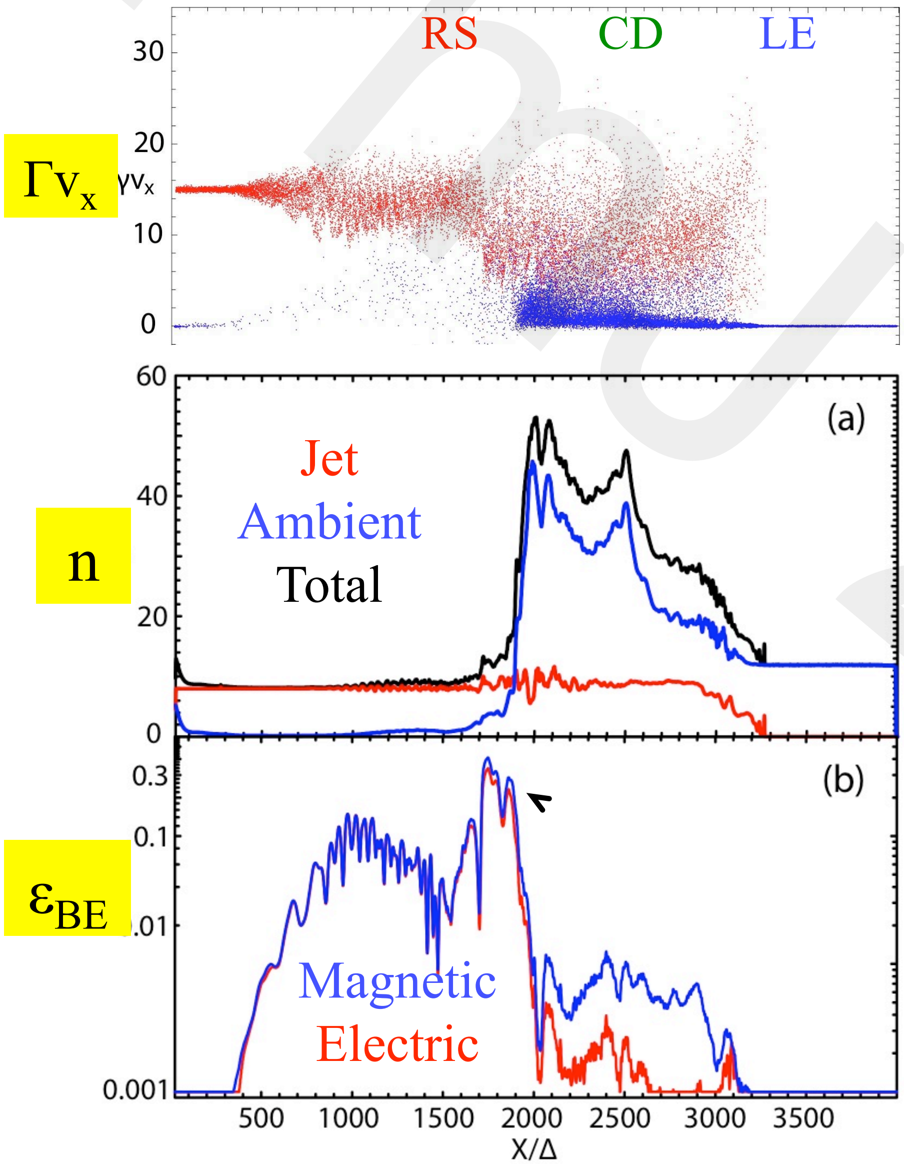
Abdo et al. (2010)

Rotation optical polarization vector

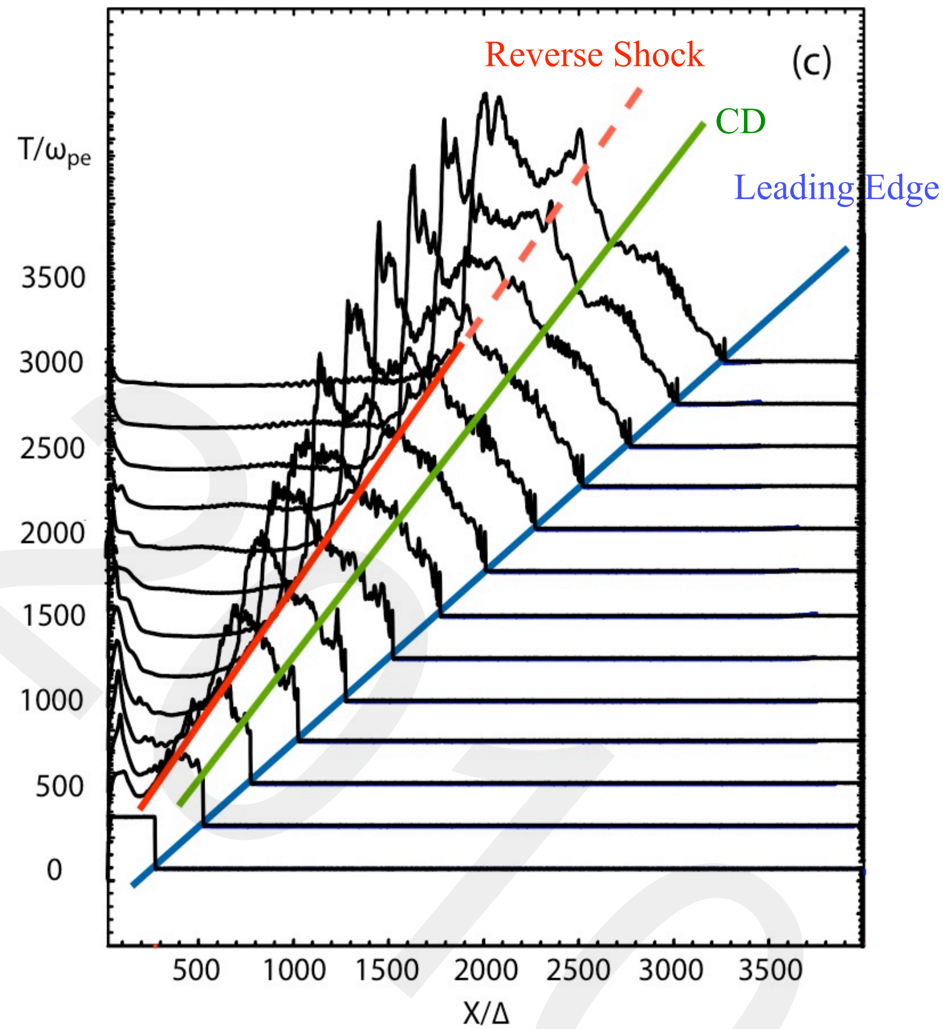
Signature shock moving along helix

Shock Microphysics

Jet & Ambient ($e^{\pm}$) Particles



Nishikawa et al (2009)

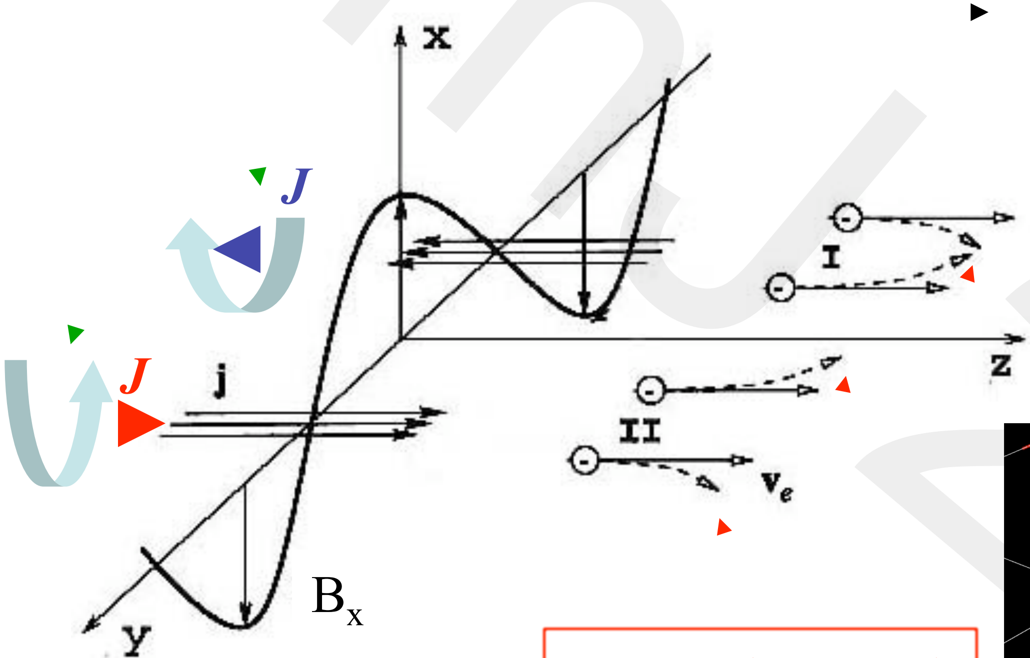


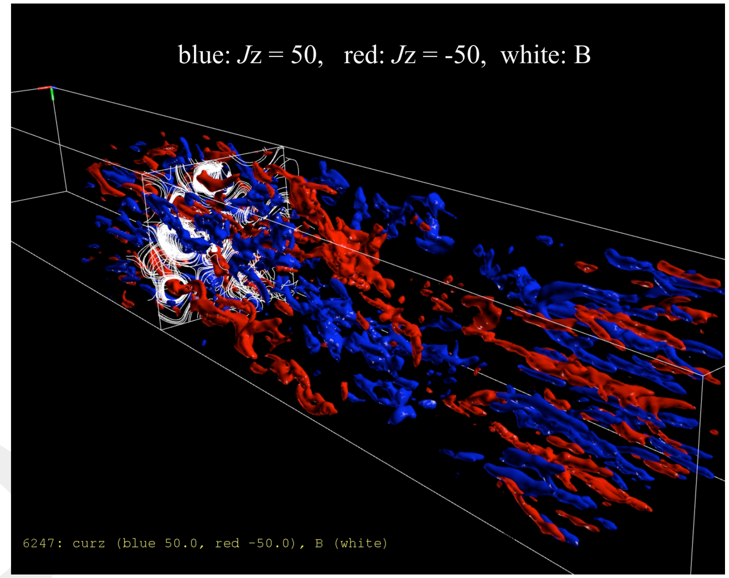
$\varepsilon_{BE} = \rho_{BE}/\rho_{KE} \sim 0.3$

Filamentation Instability

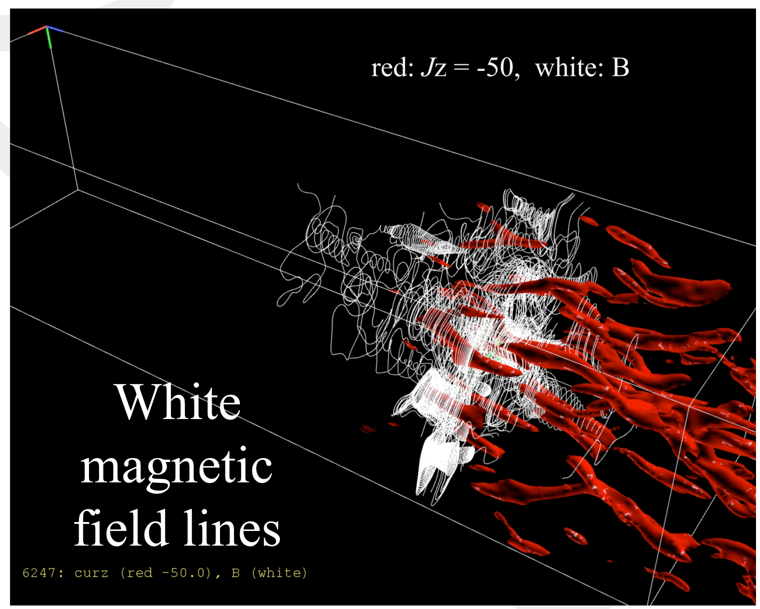
Current filaments &
induced magnetic fields

Jet





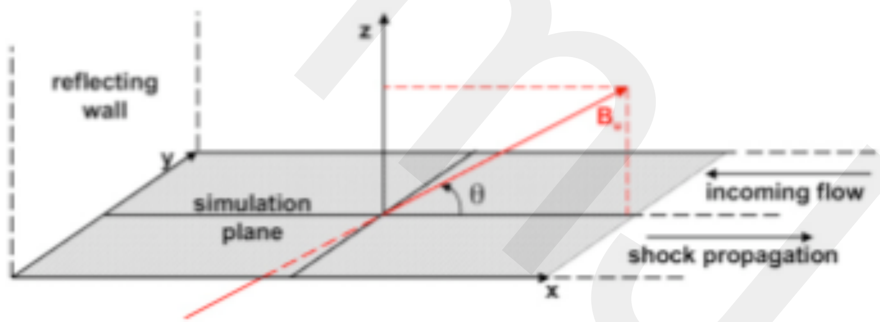
$$F = -e\ (v_z \times B_x)$$



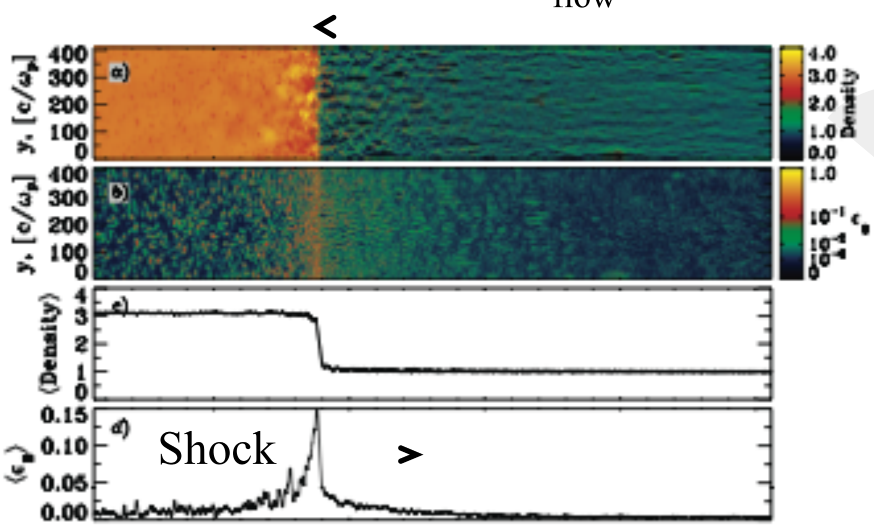
Acceleration timescale ~ few $1000(\omega_p)^{-1}$

Particle Acceleration & Emission

Simulation: Spitkovsky (2008)

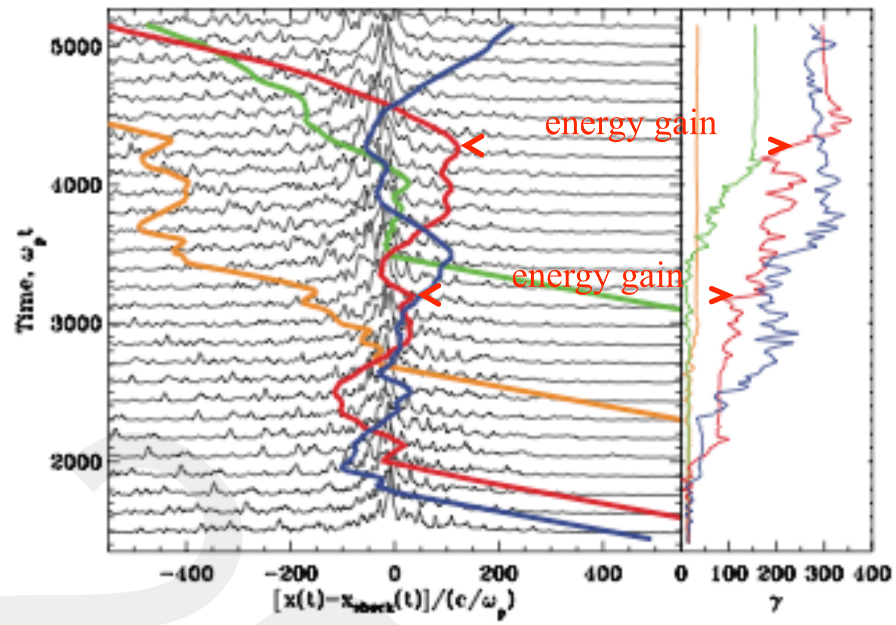


$\Gamma_{flow} = 15$

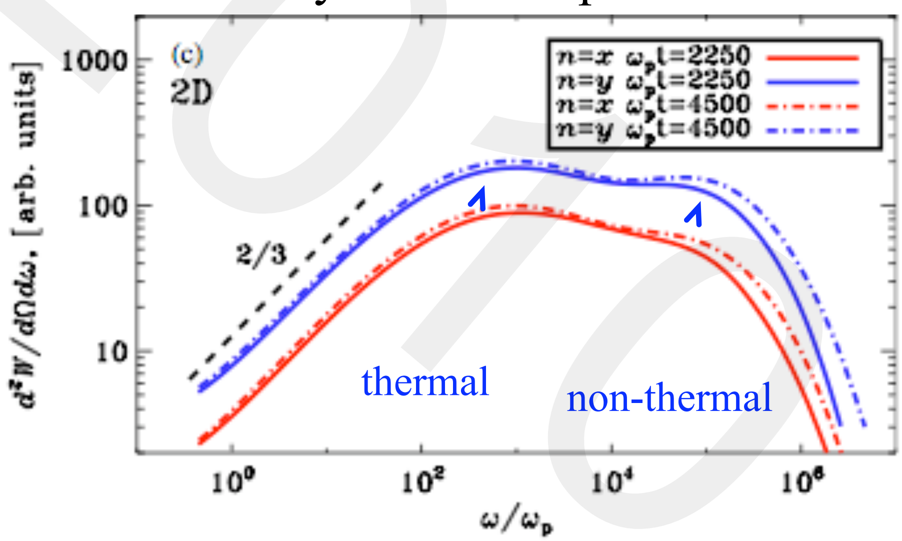


Sironi & Spitkovsky (2009a,b)

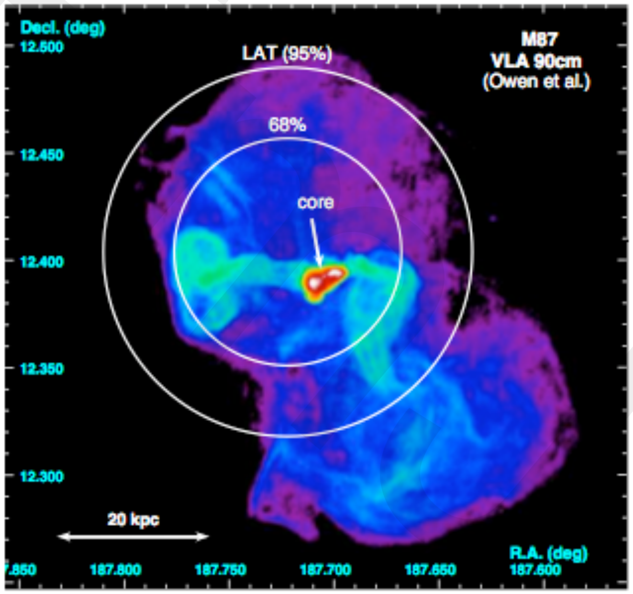
Fermi (?) acceleration: $\Gamma_{shock} = 26$

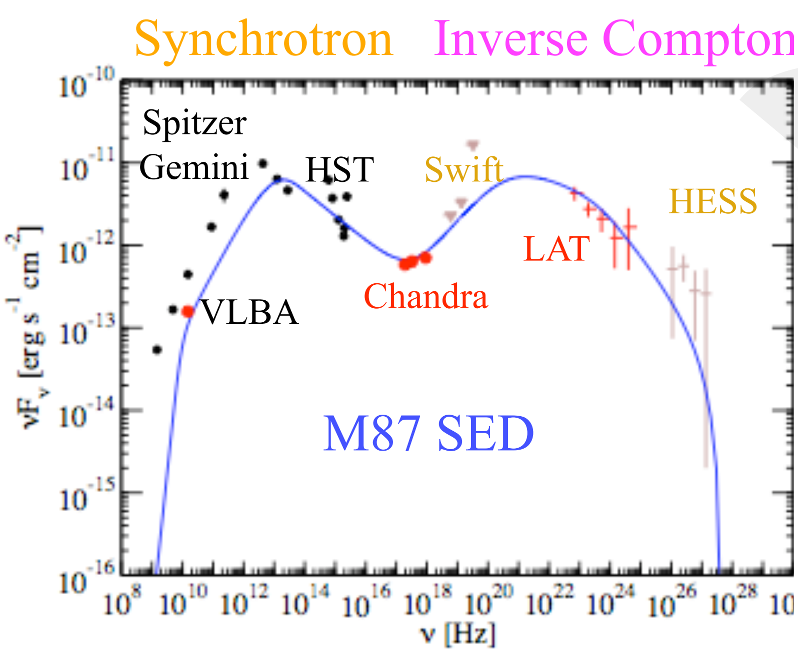


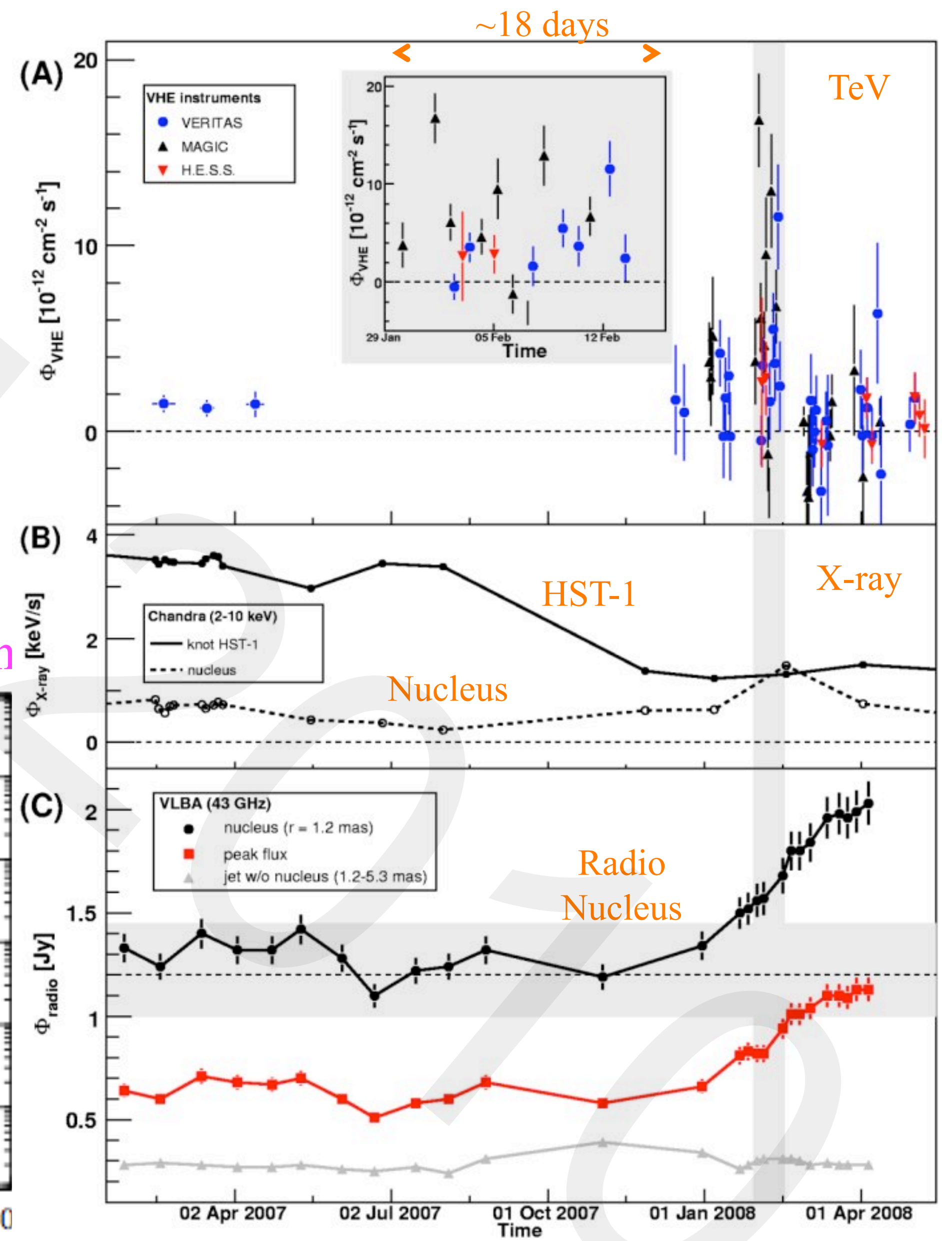
Synchrotron spectrum



M87: TeV Flare, X-ray, & Radio Flux

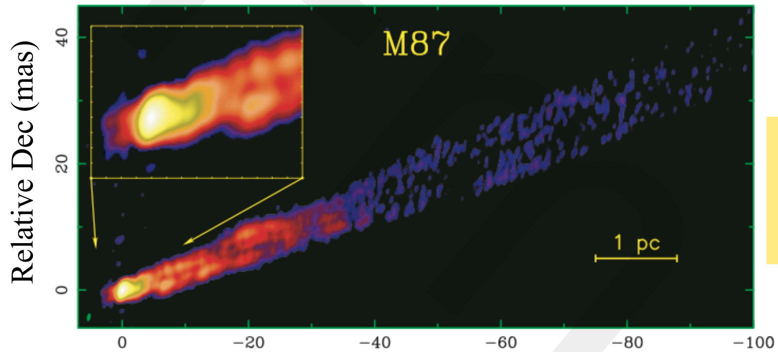






M87: Structure, Speed & Viewing Angle

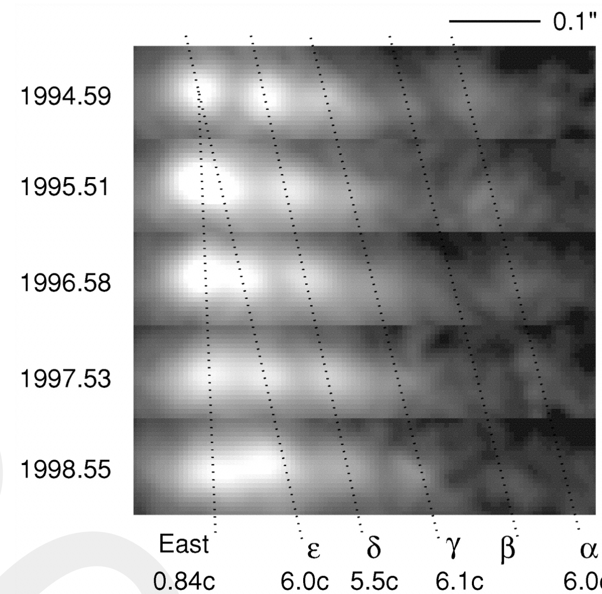
(Kovalev et al. 2007)



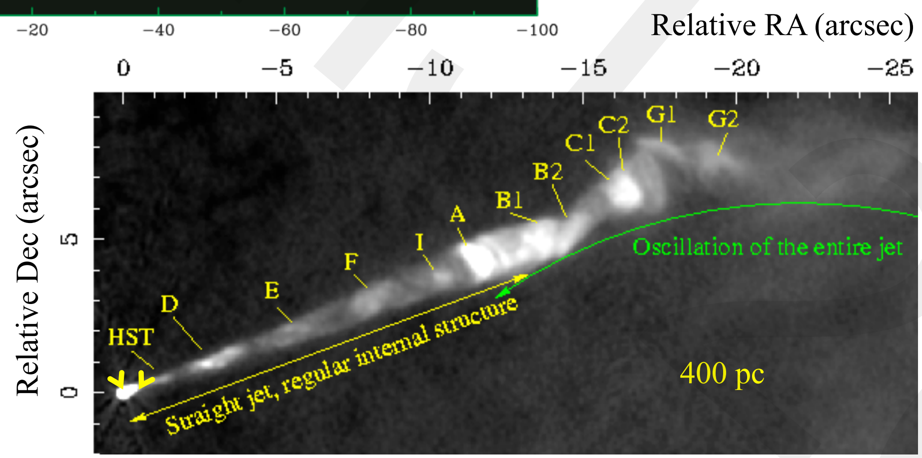
Similar structure
sub-pc to kpc

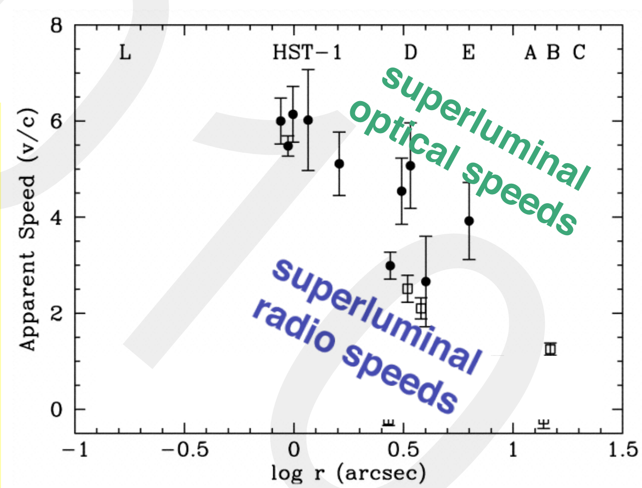
HST-1: proper motions

(Biretta, Sparks & Macchetto 1999)



Graphic courtesy Lobanov





Optical (Biretta et al. 1999) $\beta_{ob} \sim 6c$ **@ HST-1** $\Rightarrow$ **viewing angle** $\theta < 19^o$

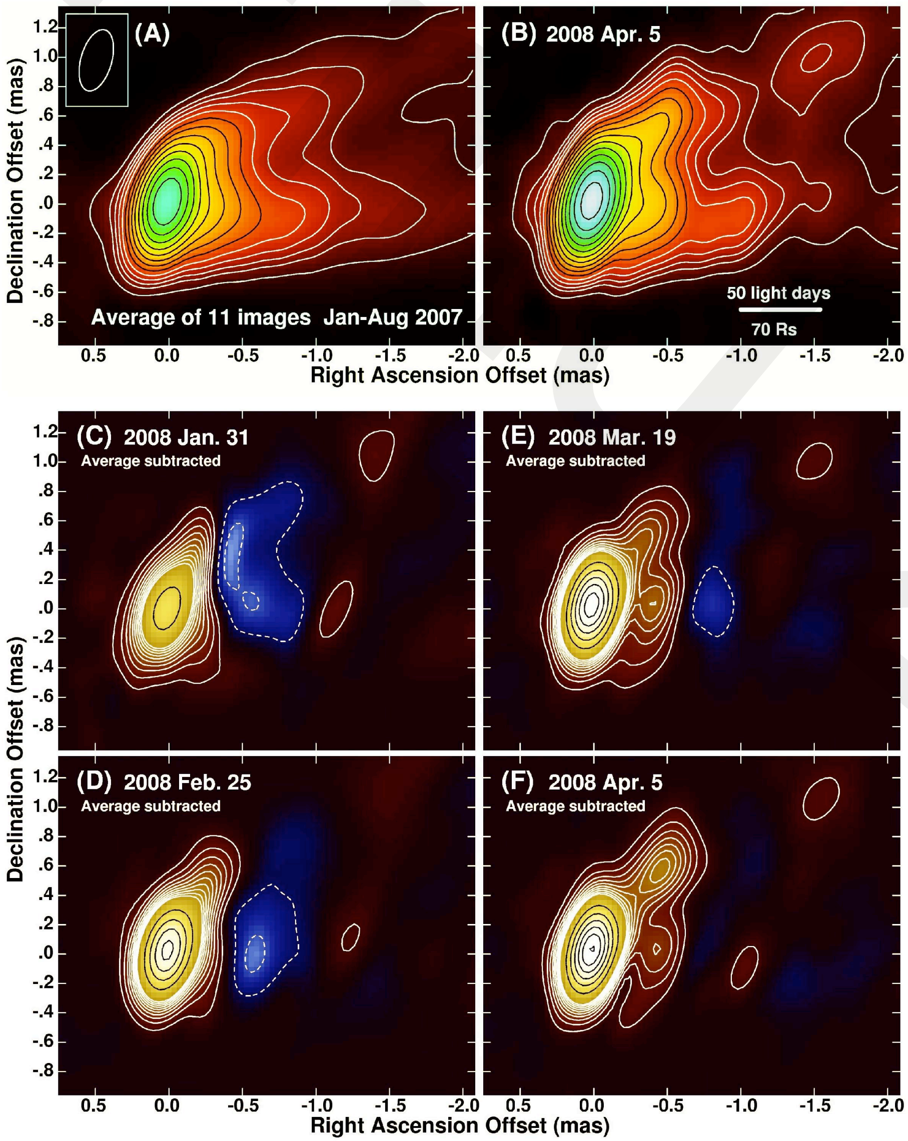
Radio (Cheung et al. 2007) $\beta_{ob} \sim 4c$ **@ HST-1**

Suggest: Viewing angle $\Rightarrow$ $\theta \sim 15^o$

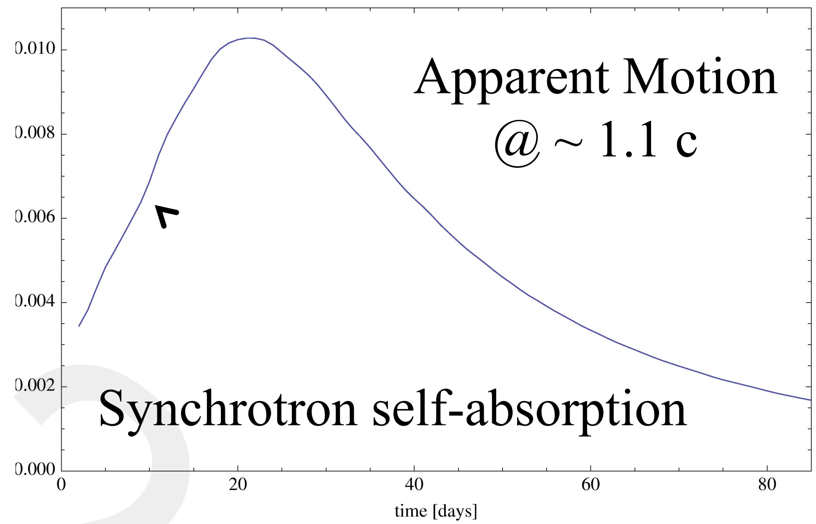
Optical $\Rightarrow$ **jet spine** $\Gamma_{spine} \geq 7.5$

Radio $\Rightarrow$ **jet sheath** $\Gamma_{sheath} \leq 4.5$

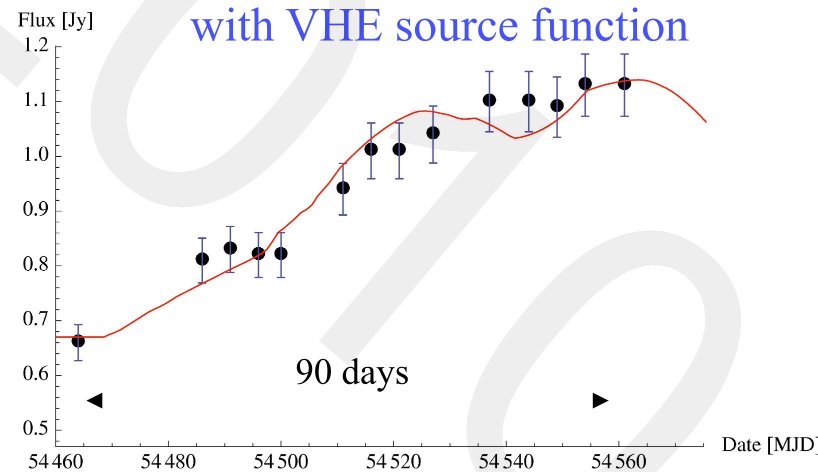
VLBA Radio Structure & Timing



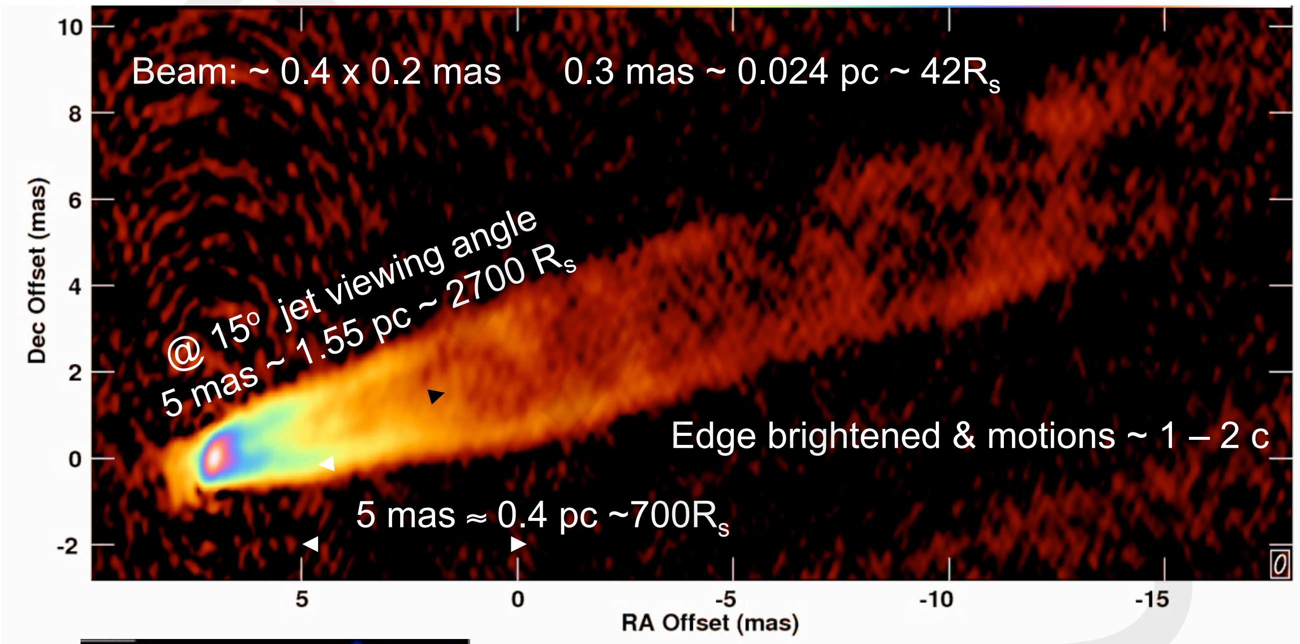
Radio Flux Rise: single injection



Radio Flux Rise: multiple injections
with VHE source function



M87: Jet Launching & Collimation Region



M87

Walker et al. (2008)

Jet launching region:

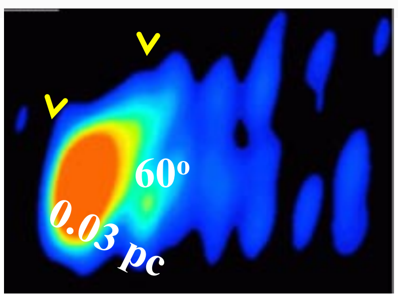
$< (0.4\text{mas}/\sin 15^0) \sim 200\ R_s$

Jet collimation region:

$\sim (7.5\text{mas}/\sin 15^0) \sim 4000\ R_s$

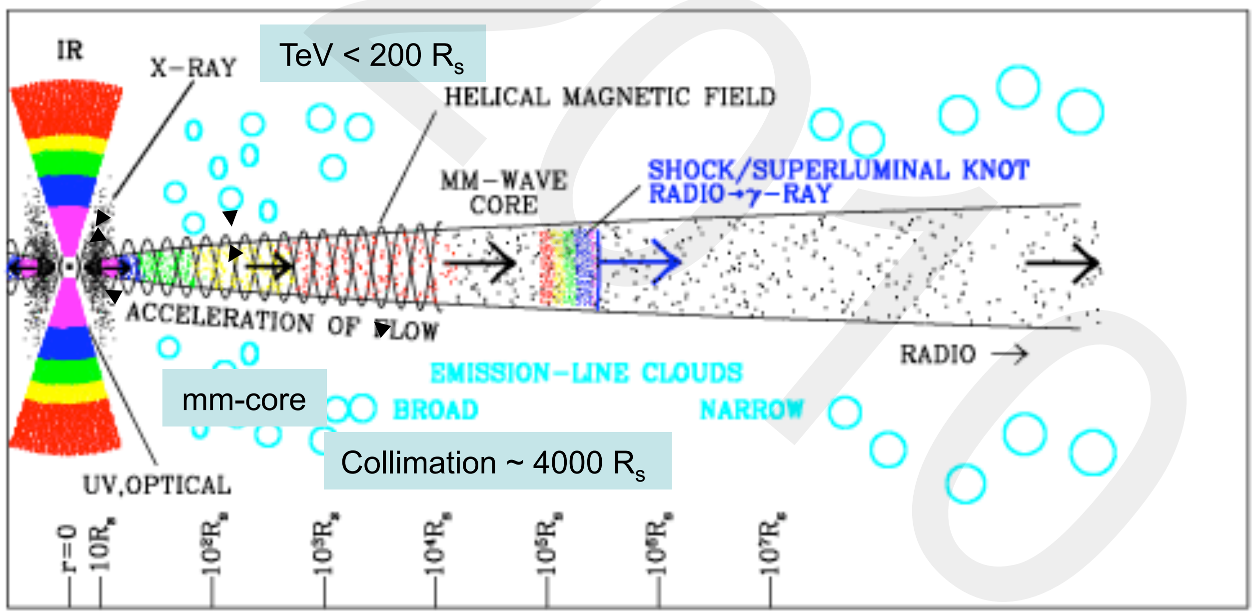
Bulk: $\Gamma \sim 2$ - 10

Particle: $\gamma > 10^7$

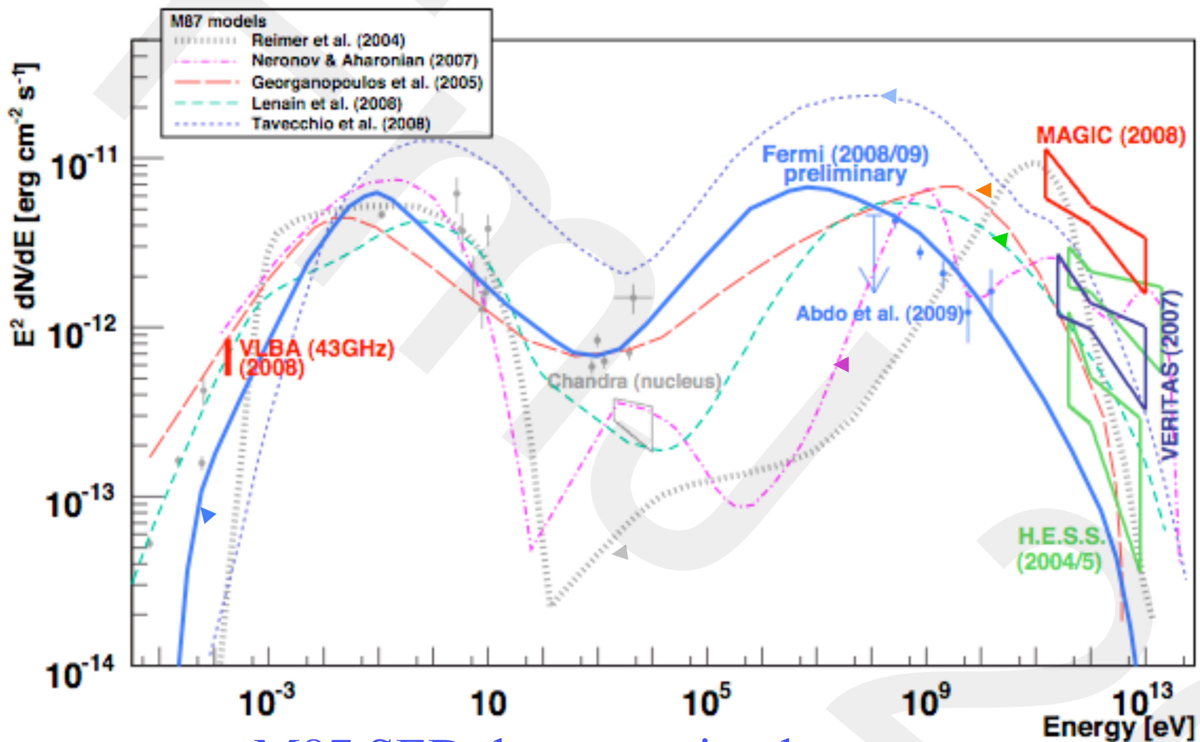


Junor, Biretta & Livio (1999)

Ly, Walker & Wrobel (2004)



M87: Probing the Jet Base



M87 SED data non-simultaneous

Tavecchio 08 – spine/sheath

Georganopoulos 05 – decel.

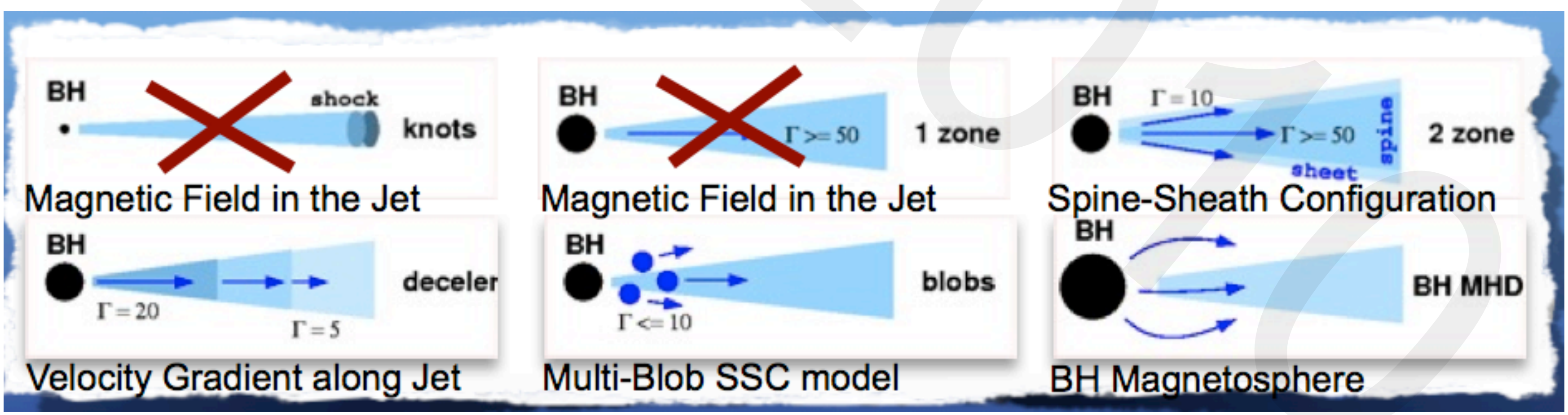
Lenain 08 – blobs

Neronov 07 – BH MHD

Reimer 04 – Hadronic

Hadronic: unlikely (high B)

Leptonic: likely tunable



M87 Summary & Implications

Jet axis viewing angle, $\theta \sim 15°$, Global Spine-Sheath: $\Gamma_{spine} \geq 7.5$, $\Gamma_{sheath} \leq 4.5$

TeV inside 230 R_s $\Rightarrow$ within broad opening angle jet base ($\geq 17°$)

$\delta < \delta_{max} = 2\,\Gamma \sim 15$ (HST-1: $\Gamma = 7.5$ & $\theta = 0°$)

TeV ~ 1 day variability $\Rightarrow t_{acc} << \Delta t_{int} < \delta_{max}\, \Delta t_{obs} \sim 15 \times 10^5$ sec

$\Delta l_{int} << \delta_{max}\, \Delta t_{obs}\, c \sim 25\, R_s$

VLBA 43 GHz $\Rightarrow$ multiple ejection event & synchrotron self-absorption delay

M87 Implication $\Rightarrow$ non-steady processes on small scales $< R_s$

[e.g., Lyutikov; Marscher & Jorstad; Rachen et al. (this workshop)]

BH MHD - [e.g., Vincent & LeBohec (this workshop); Neronov & Aharonian (2007)]

Vacuum gap lepton acceleration & cascade

Jet-in-a-jet (Poynting domain < 100 R_s) - [Giannios et al. (2009)]

Small scale CDI magnetic reconnection – $r_{acc} < (t_{int}/100)\, c \sim 0.25\, R_s$

Blobs-in-a-jet (Kinetic domain > 100 R_s) - [Lenain et al. (2008)] $r \sim 0.05\, R_s$

Small scale shock/shear driven particle acceleration – $t_{acc} \sim$ few 1000 $(\omega_p)^{-1}$

Needles/spine-sheath (Kinetic domain) - [Ghisellini & Tavecchio; Tavecchio & Ghisellini (2008)]

Small scale shock/shear driven particle acceleration

Needle/blob deceleration (Kinetic domain) - [Georganopoulos et al. (2005); Levinson (2007)]

Small scale shock/shear driven particle acceleration