Evidence of Magnetic Acceleration & Collimation in AGN Jets

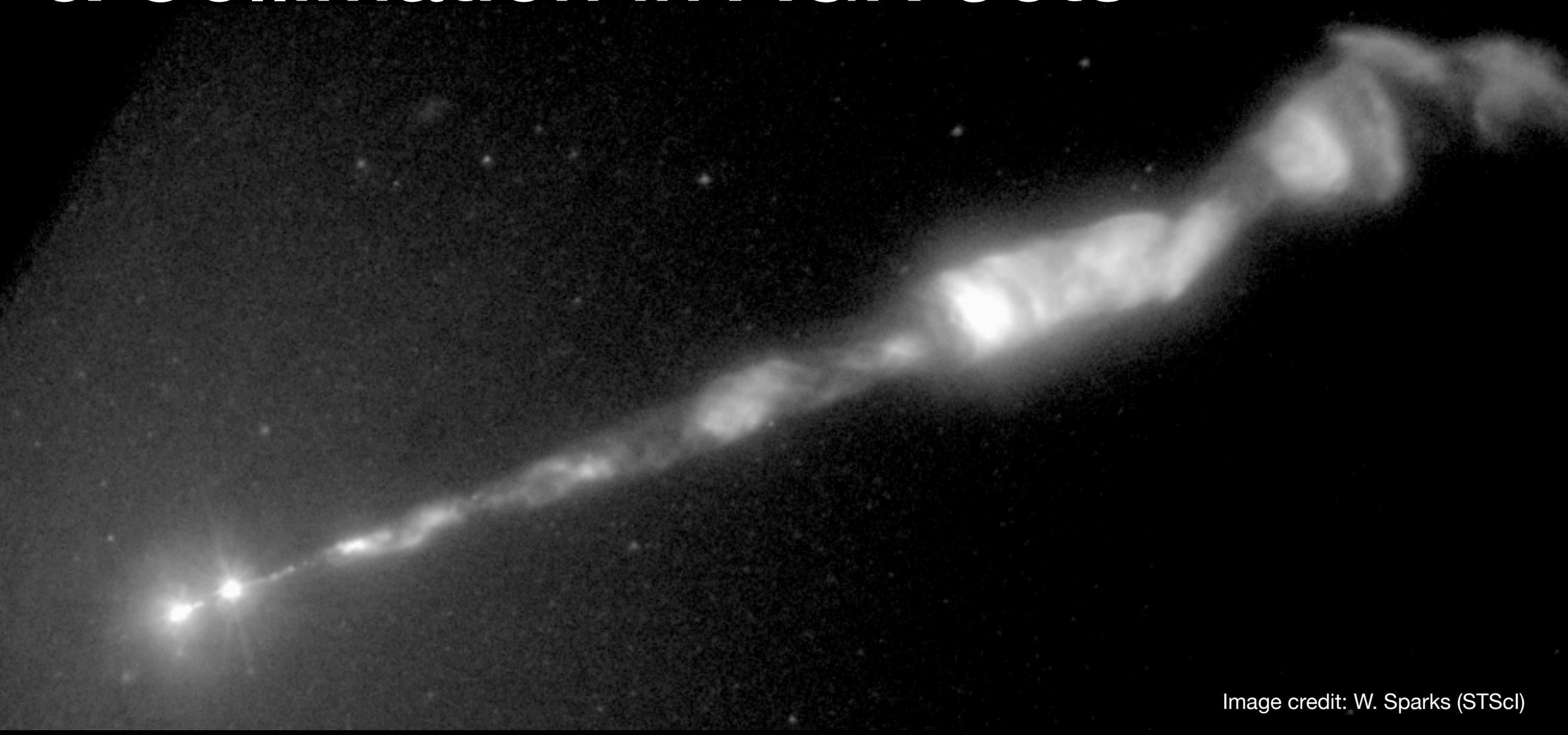


Image credit: W. Sparks (STScI)

Masanori Nakamura (ASIAA)

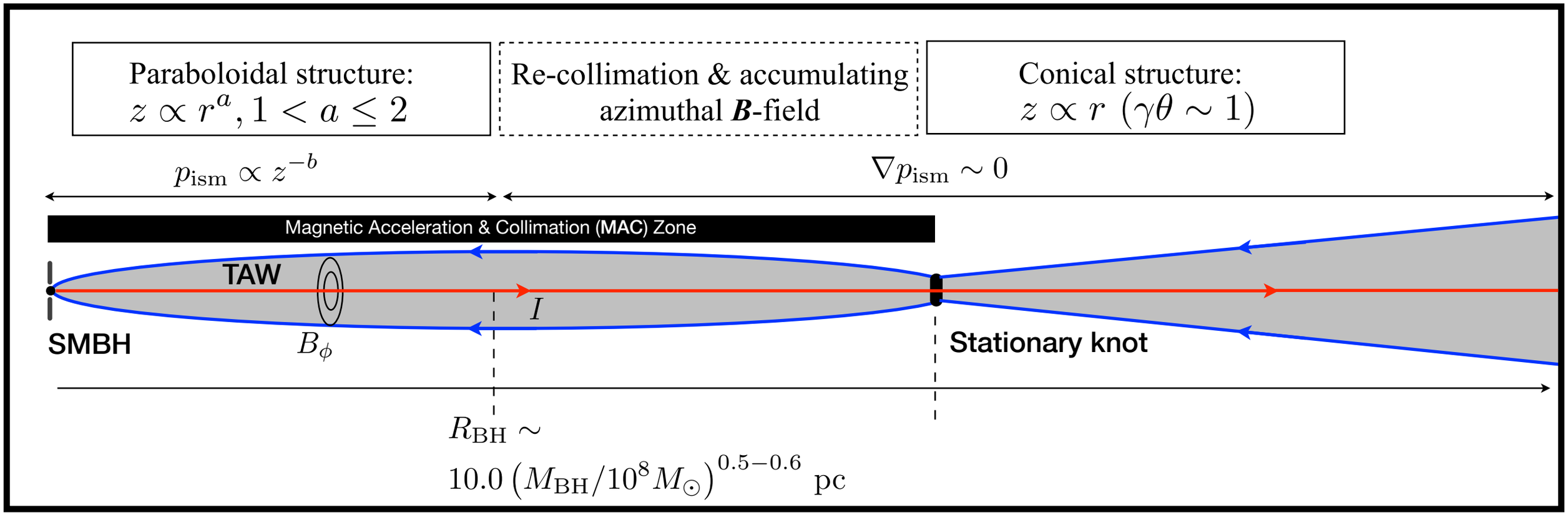
Collaborators: **K. Asada** (ASIAA), **J. Biretta** (STScI), **A. Doi** (JAXA), **D. Garofalo** (CSUN), **M. Inoue** (ASIAA), **D. Meier** (JPL), **H. Nagai** (NAOJ), **C. Norman** (JHU), **W. Sparks** (STScI)

NAASC Jets2012@Charlottesville, VA, Mar. 2012

SUMMARY of THIS TALK

- A constraint of magnetic acceleration & collimation (**MAC**) zone in the M87 jet; how does the flow become relativistic?
  → **MAC** zone may ***not*** be defined by only MHD jet theory (positions of re-collimation shocks in self-similar solutions)

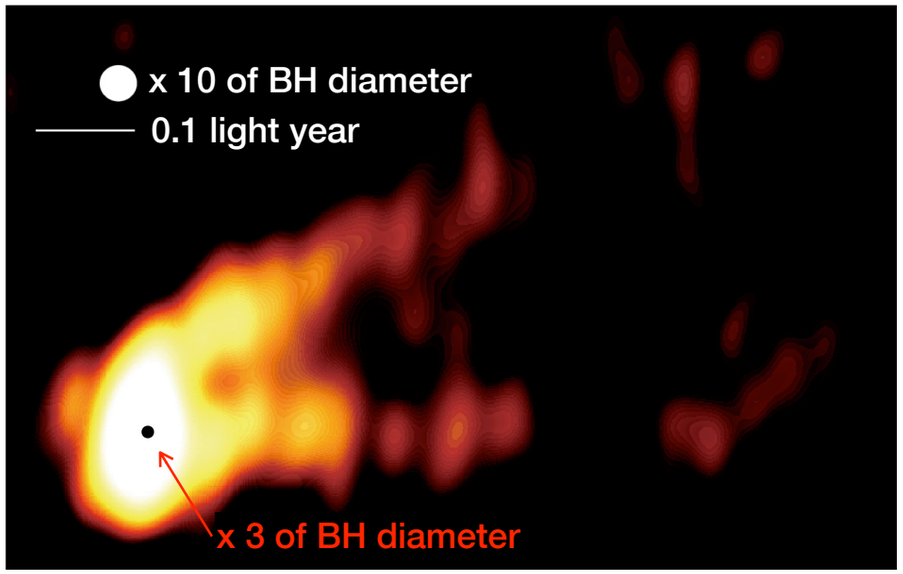
- Structural transitions of AGN jets scaled by $M_\bullet$; stationary features (re-collimation shocks) may play a role
  → An intrinsic correlation w/ the $M_\bullet$-σ relation and a potential connection to VHE emission regions



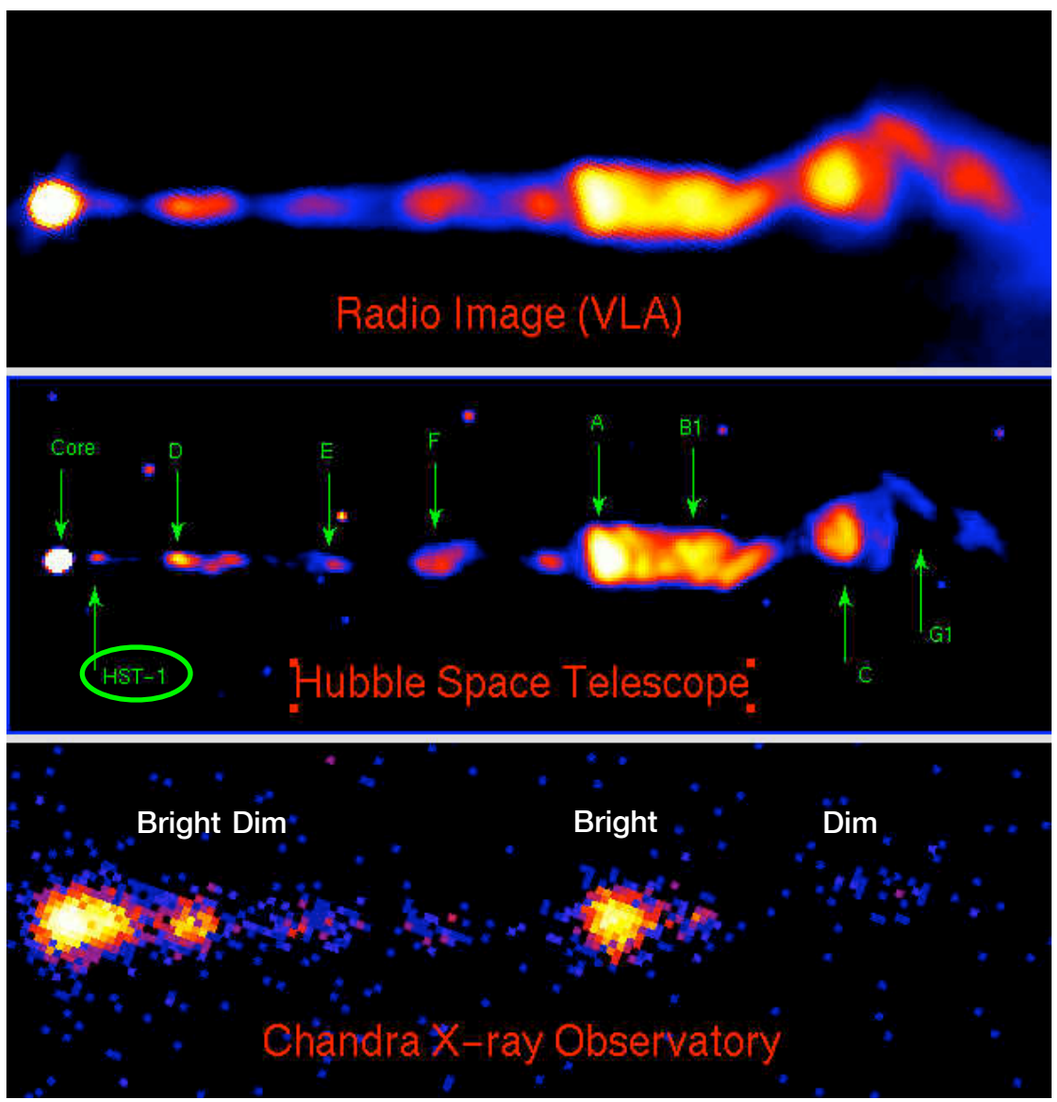
MN & Norman

M87 Observations

- *The "**Rosetta Stone**"* for studying relativistic jets
  - Nearby: $D \sim 16$ Mpc (1 mas$\sim$0.078 pc $\sim$125 r_s)
  - FR I: Misaligned BL Lac ($\theta_{\rm view} \sim 14^\circ$; Wang & Zhou 2009)
  - SMBH mass: $(6.6 \pm 0.4) \times 10^9 M_\odot$ (Gebhardt et al. 2011)
    - VLBA res. : 20 r_s at 43 GHz
    - Sub-mm VLBI res.: 3 r_s at 345 GHz (w/ **GLT**)

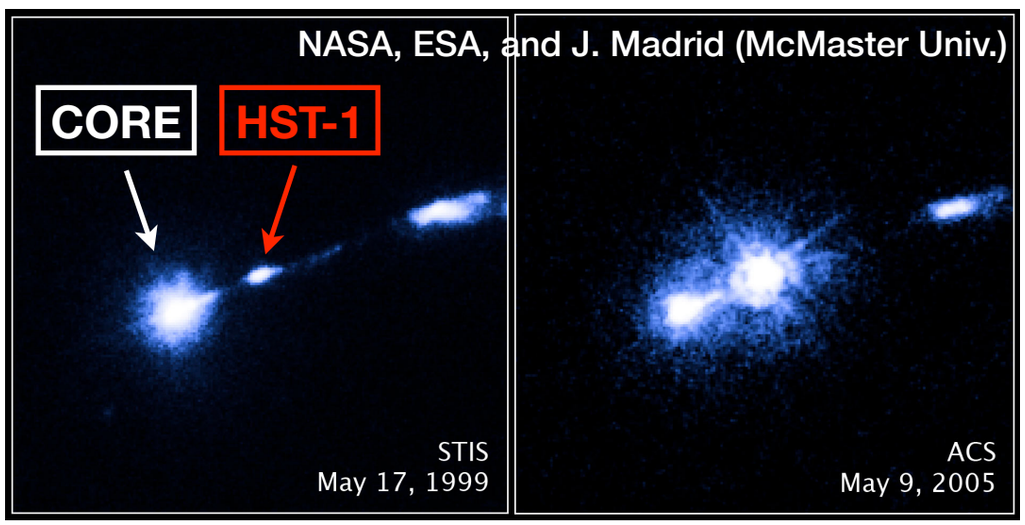


VLBA 43GHz (Hada et al. 2011)



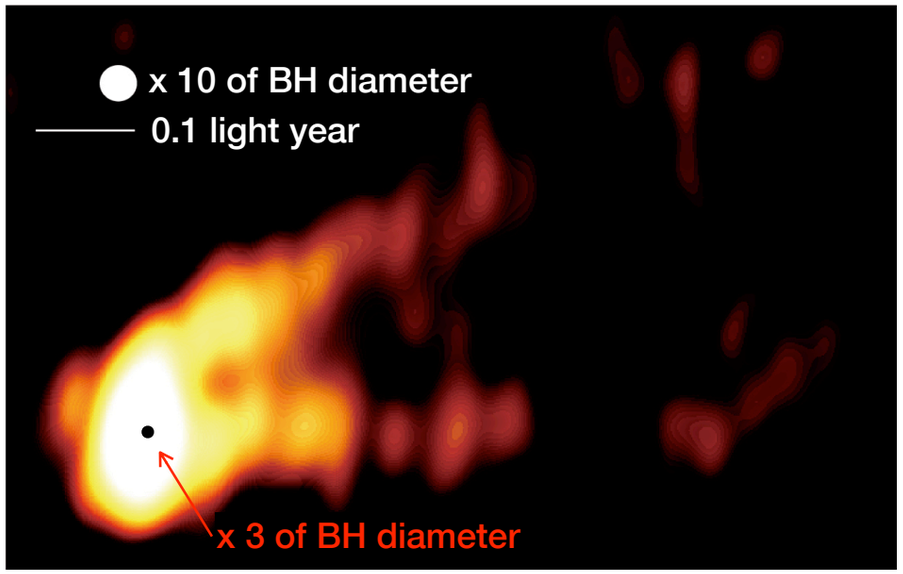
Well studied at wavelengths from radio to X-ray

- Proper motions (sub/super-luminal feature)
- Polarization (20 - 60%; ordered ***B***-fields)
- Substructure (limb-brightened, knots, wiggles,...)
- In situ particle acceleration at knots
- **HST-1** (Biretta et al. 1999): the site of flaring

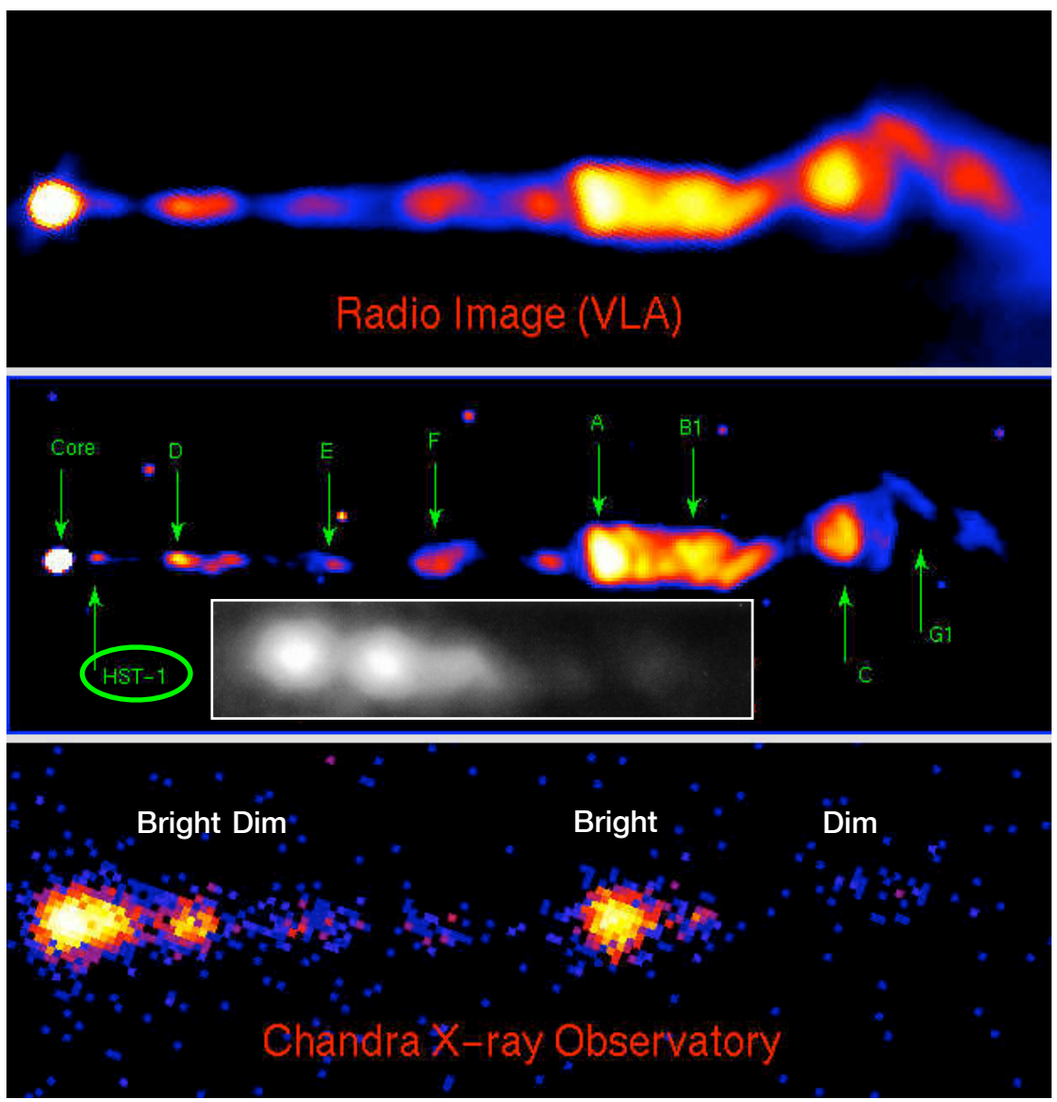


M87 Observations

- *The "**Rosetta Stone**"* for studying relativistic jets
  - Nearby: $D \sim 16$ Mpc (1 mas$\sim$0.078 pc $\sim$125 r_s)
  - FR I: Misaligned BL Lac ($\theta_{\rm view} \sim 14^\circ$; Wang & Zhou 2009)
  - SMBH mass: $(6.6 \pm 0.4) \times 10^9 M_\odot$ (Gebhardt et al. 2011)
    - VLBA res. : 20 r_s at 43 GHz
    - Sub-mm VLBI res.: 3 r_s at 345 GHz (w/ **GLT**)

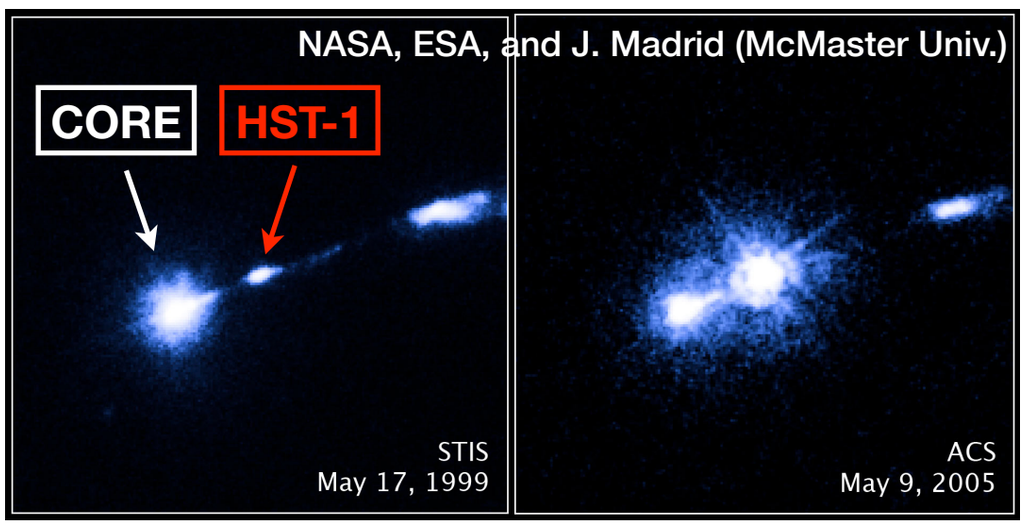


VLBA 43GHz (Hada et al. 2011)

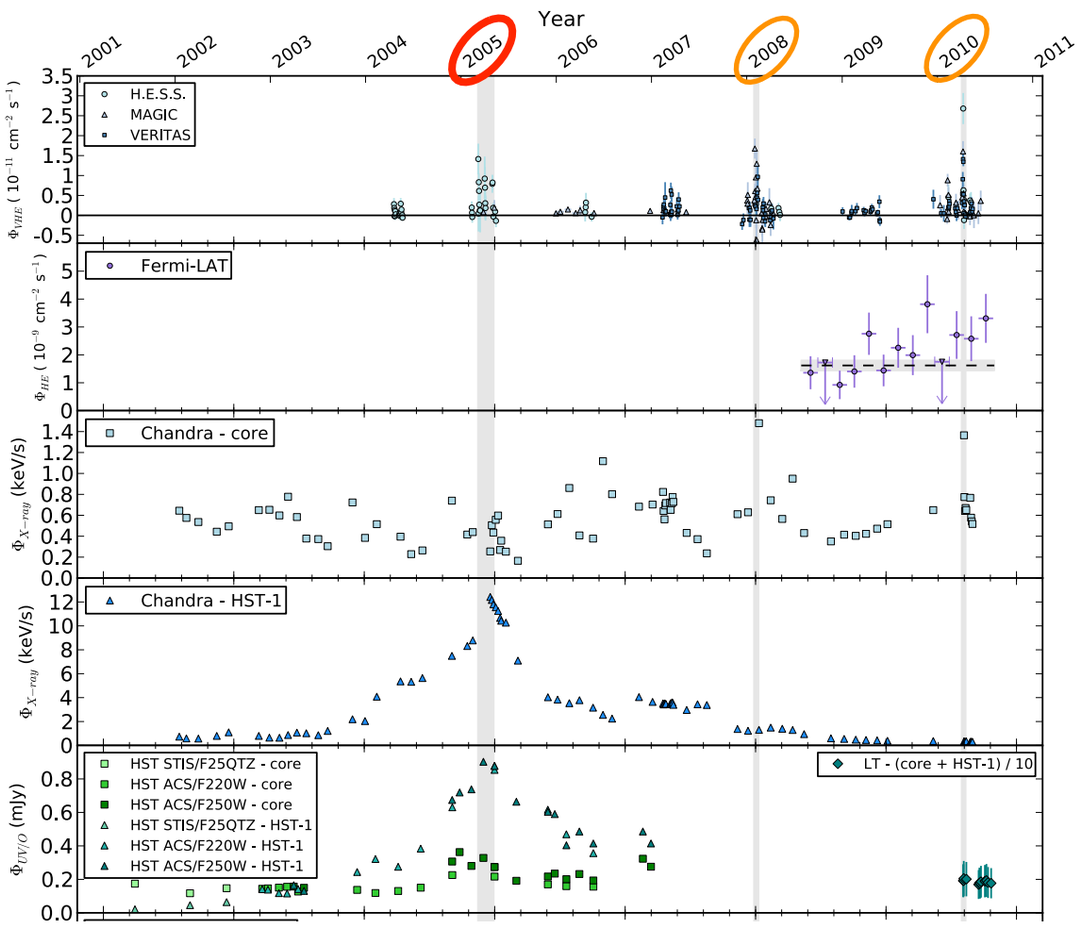


Well studied at wavelengths from radio to X-ray

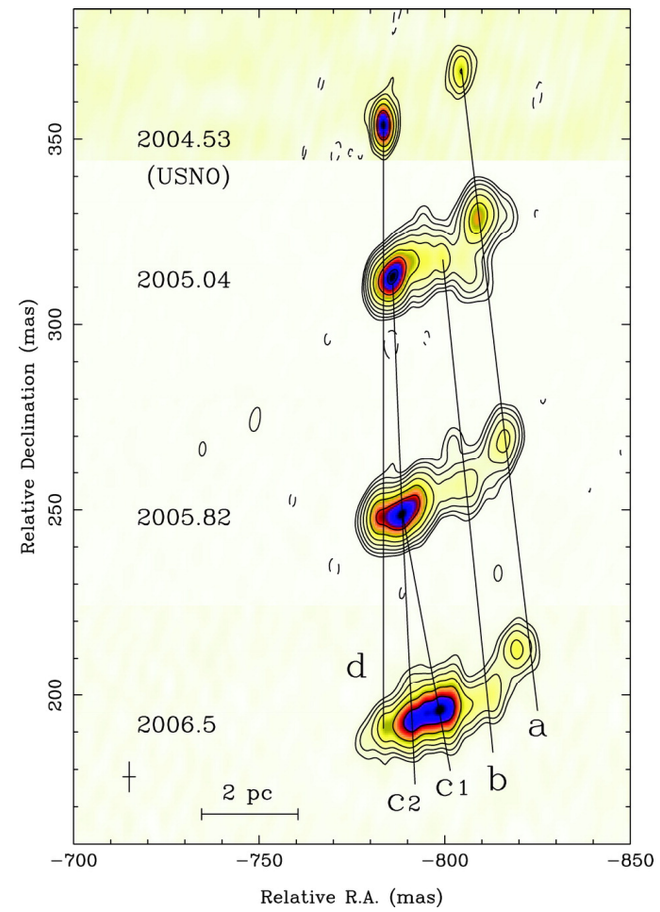
- Proper motions (sub/super-luminal feature)
- Polarization (20 - 60%; ordered ***B***-fields)
- Substructure (limb-brightened, knots, wiggles,...)
- In situ particle acceleration at knots
- **HST-1** (Biretta et al. 1999): the site of flaring



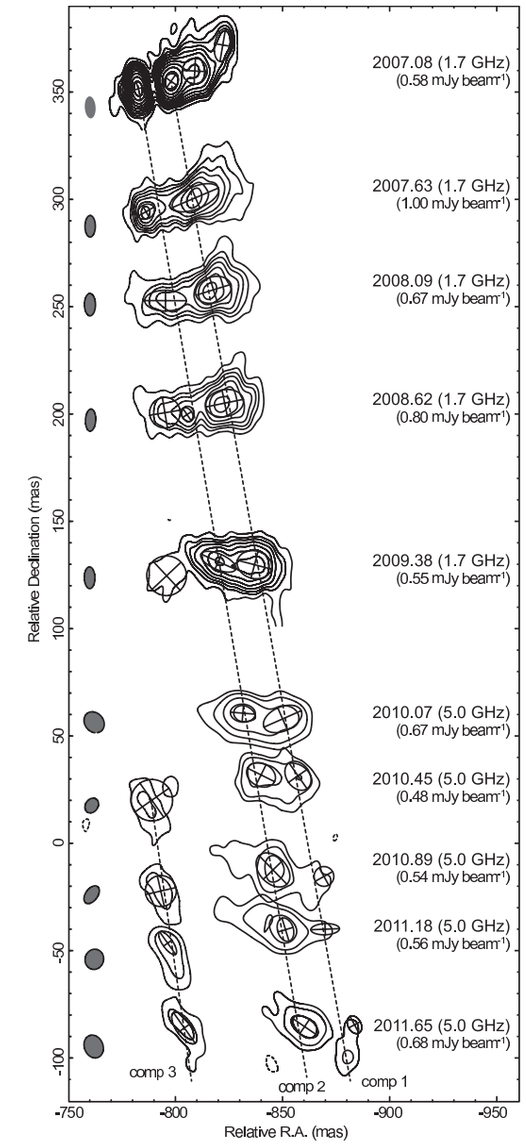
A New Components After the TeV Flaring



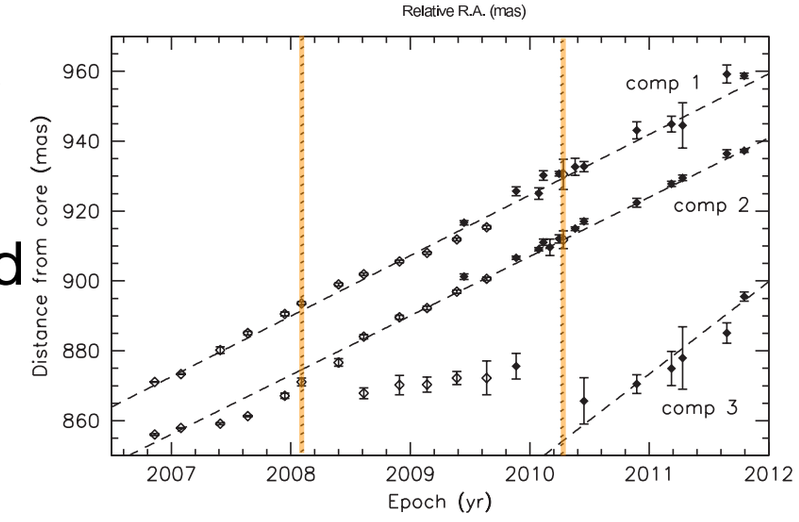
Abramowski et al. (2012)



VLBA: Cheung et al. (2007)

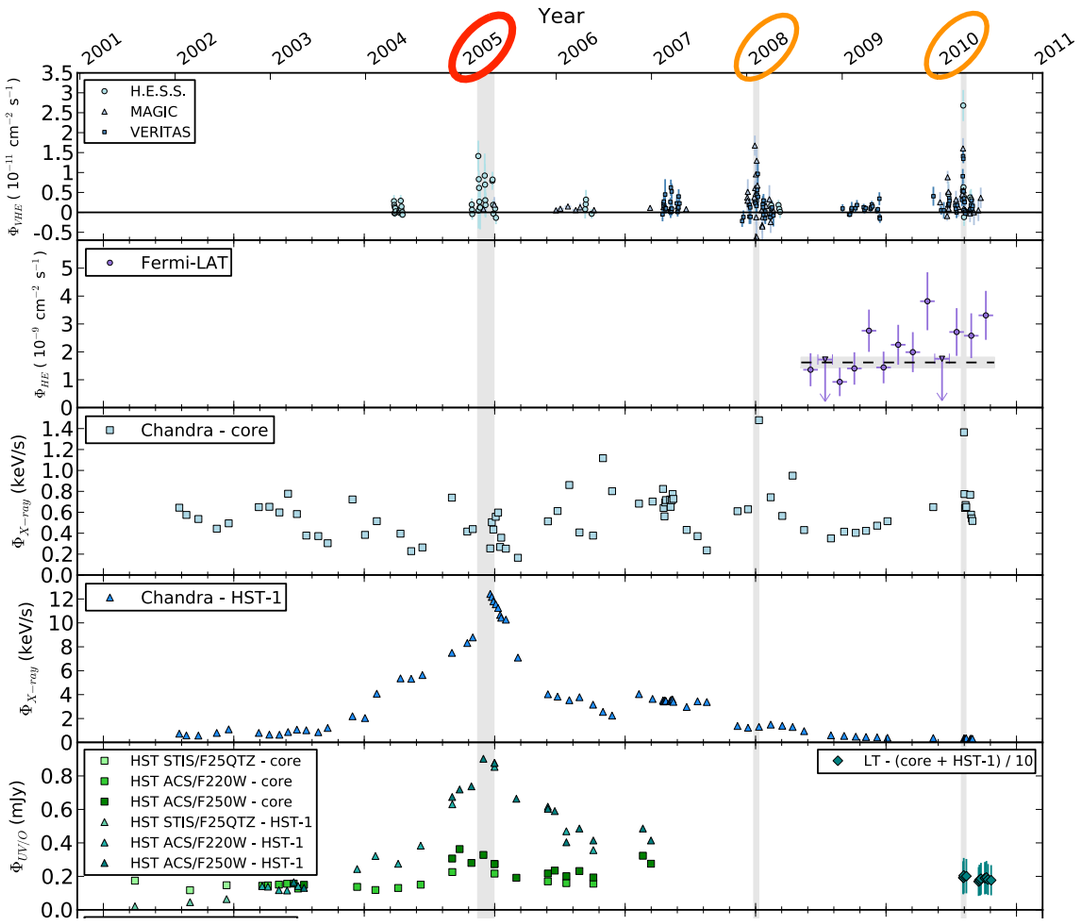


- A flaring from radio through optical to X-ray (factor ~ 50) bands (Harris et al. 2006) at HST-1, **indicating a site for TeV γ-ray emissions** (Harris et al. 2009)
- HST-1c: **two roughly equally bright knots: superluminal** and **trailing sub-luminal** components during 2005 - 2006 (Cheung et al. 2007) → **Quad relativistic MHD shocks** (foward/reverse fast/slow) by MN, Garofalo, & Meier (2010)

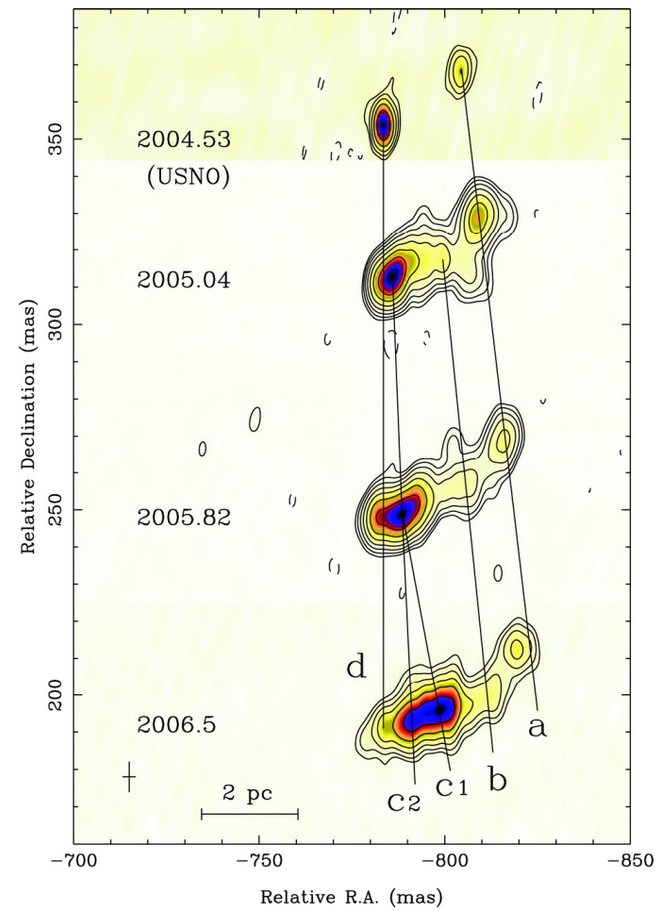


VLBA + EVN : Giroletti et al. (2012)

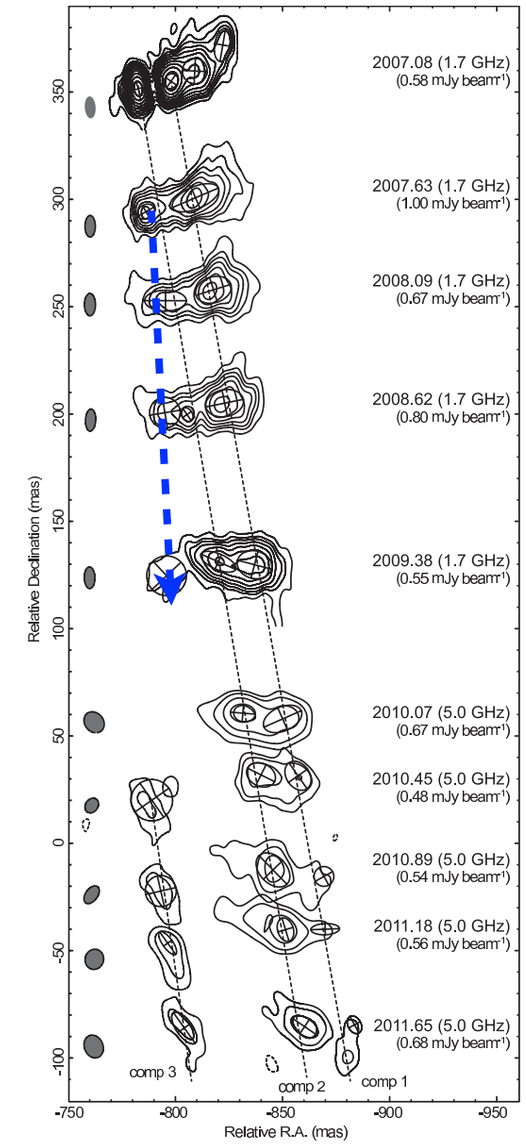
A New Components After the TeV Flaring



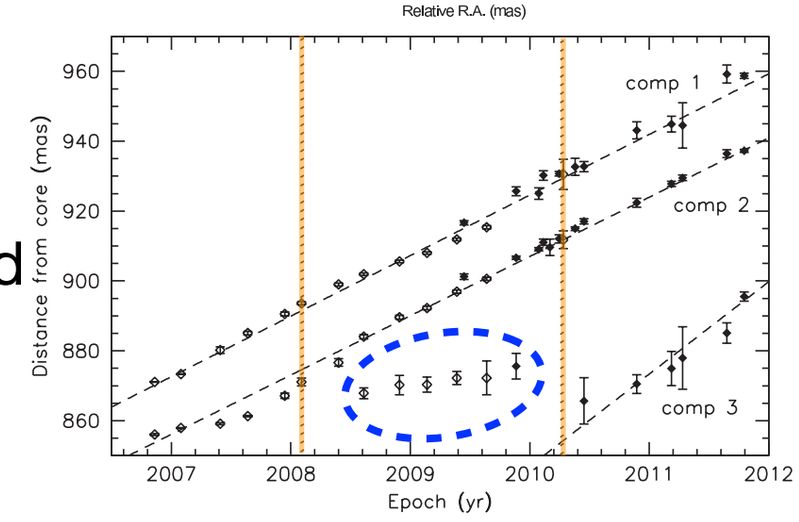
Abramowski et al. (2012)



VLBA: Cheung et al. (2007)

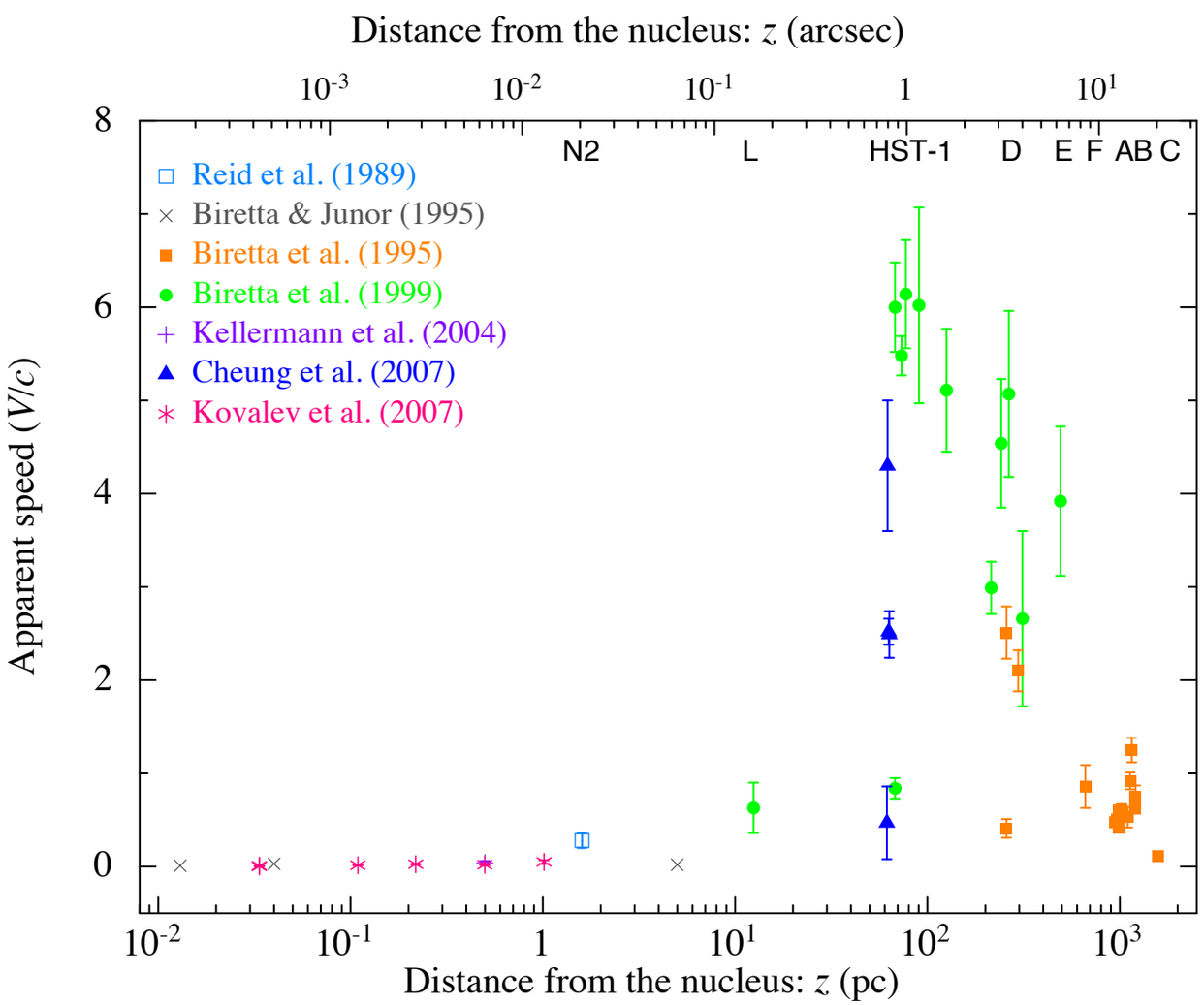


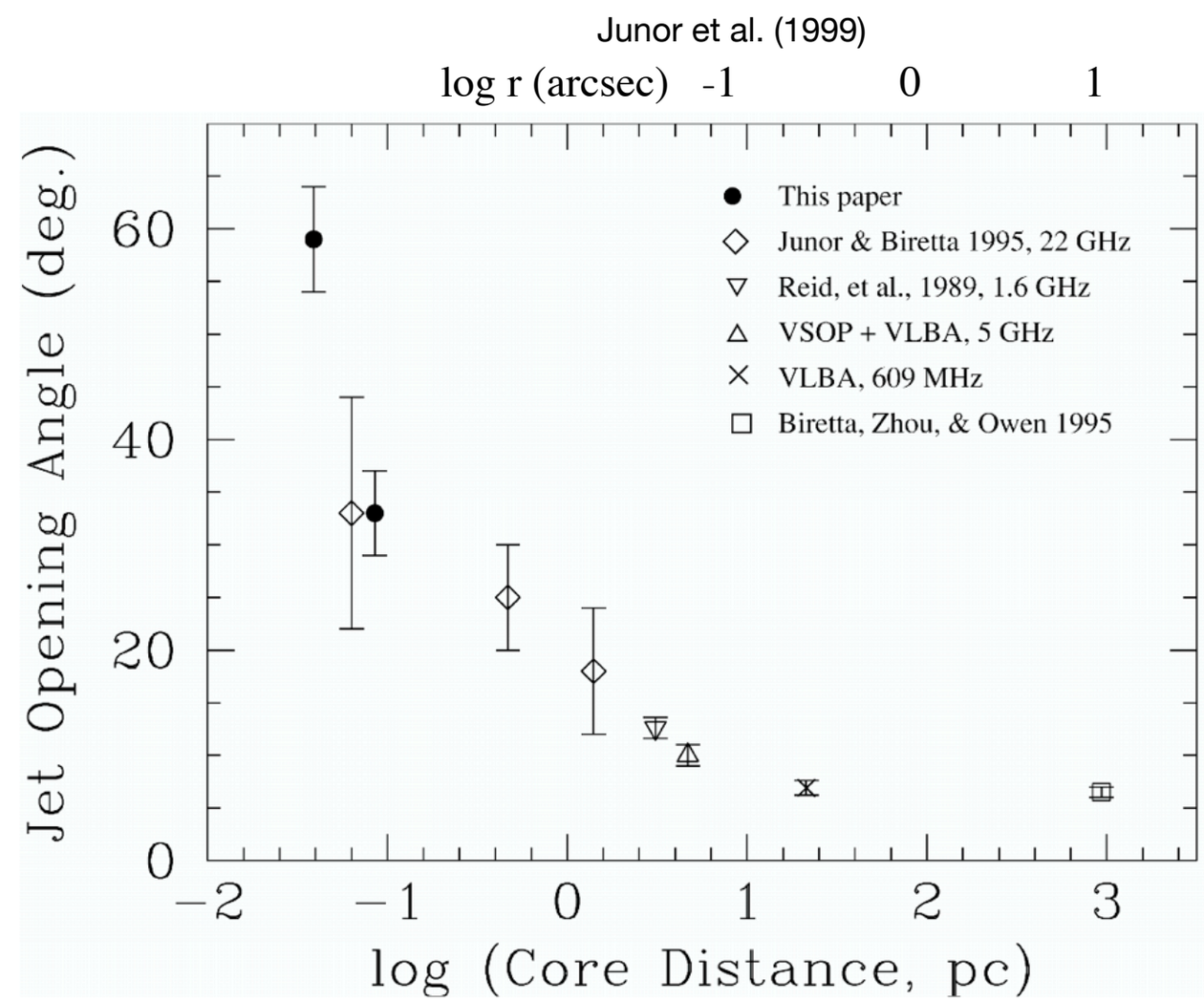
- A flaring from radio through optical to X-ray (factor ~ 50) bands (Harris et al. 2006) at HST-1, **indicating a site for TeV γ-ray emissions** (Harris et al. 2009)
- HST-1c: **two roughly equally bright knots: superluminal** and **trailing sub-luminal** components during 2005 - 2006 (Cheung et al. 2007) → **Quad relativistic MHD shocks** (foward/reverse fast/slow) by MN, Garofalo, & Meier (2010)



VLBA + EVN : Giroletti et al. (2012)

Puzzle Remains Unsolved for 2 Decades



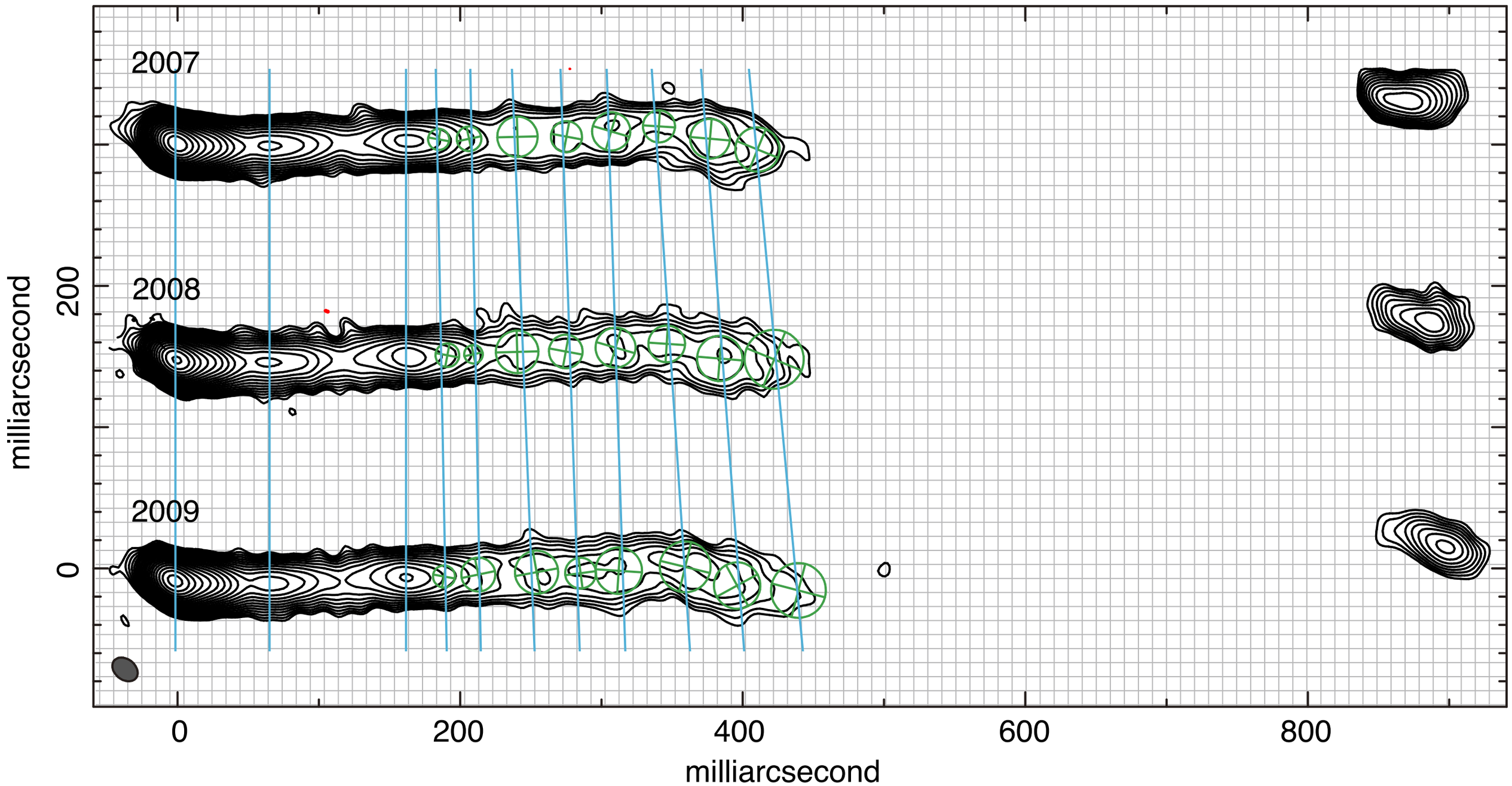


- ***Superluminal motions begin at HST-1***, lying about 1" ($\sim$ 80 pc) from the nucleus
- Many VLBI observations show **sub-luminal motions *upstream of HST-1***
- Visible pc-scale features may reside in **slower layers near the surface** (Biretta et al. 1999) or possibly **standing shocks and/or instability patterns** (Kovalev et al. 2007)?

➡ Q. No "systematic" acceleration towards HST-1 exists ***although collimation occurs asymptotically?*** Or proper motions do not correspond to the flow speed at all?

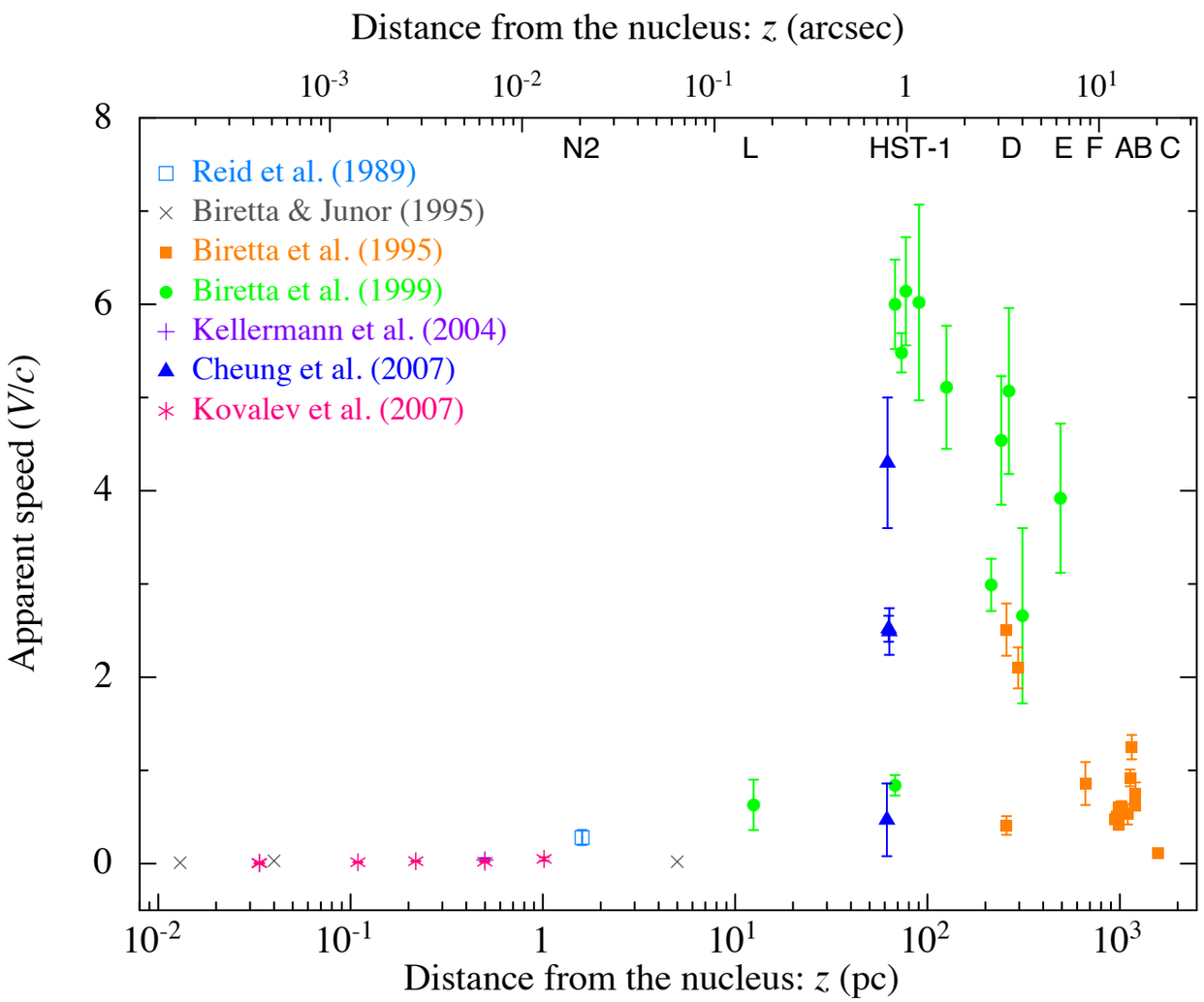
Superluminal Motions Upstream of HST-1

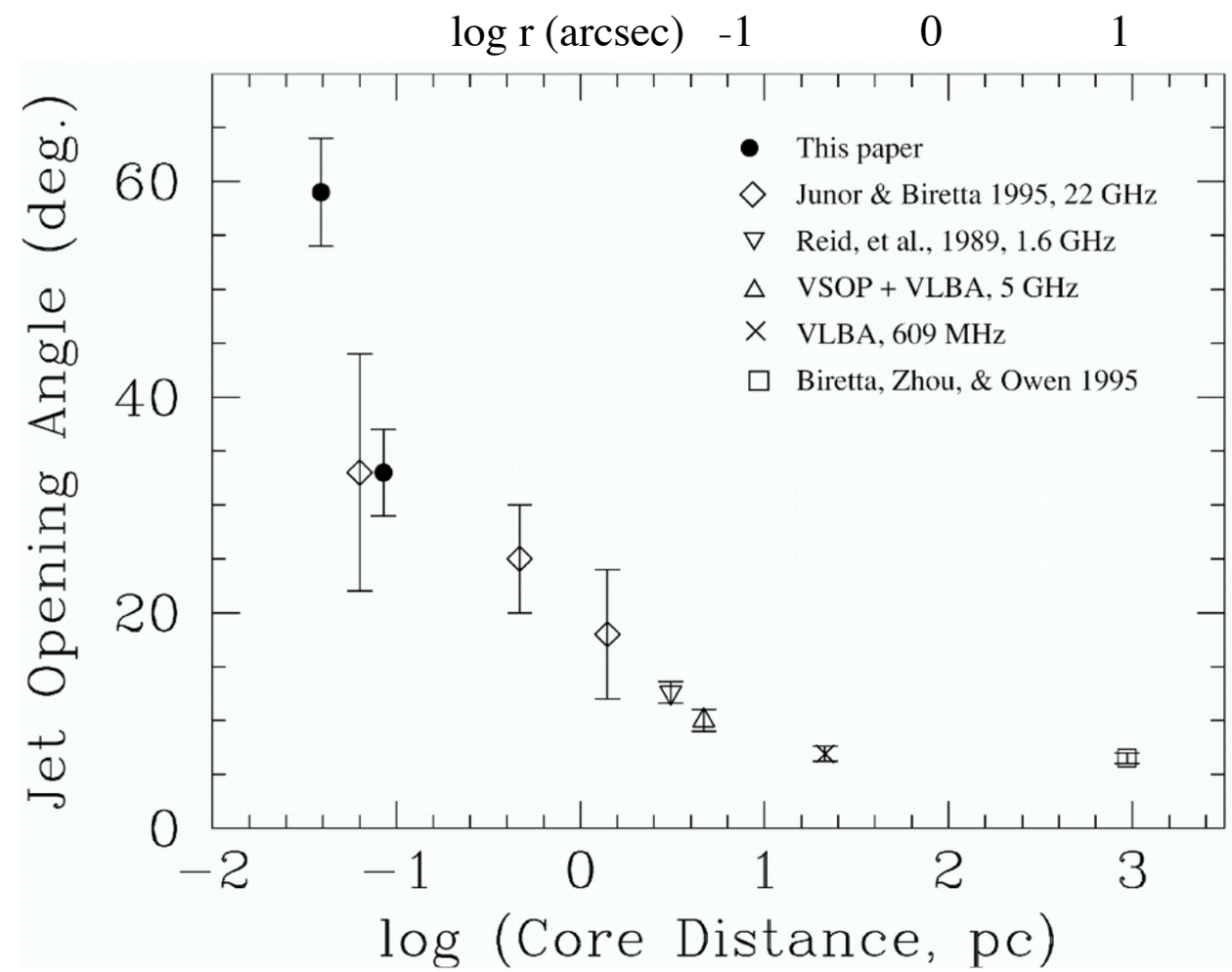
3 years monitoring of the M87 jet using European VLBI Network (EVN) at 1.6GHz



Asada, MN, et al.

A Missing Link Found





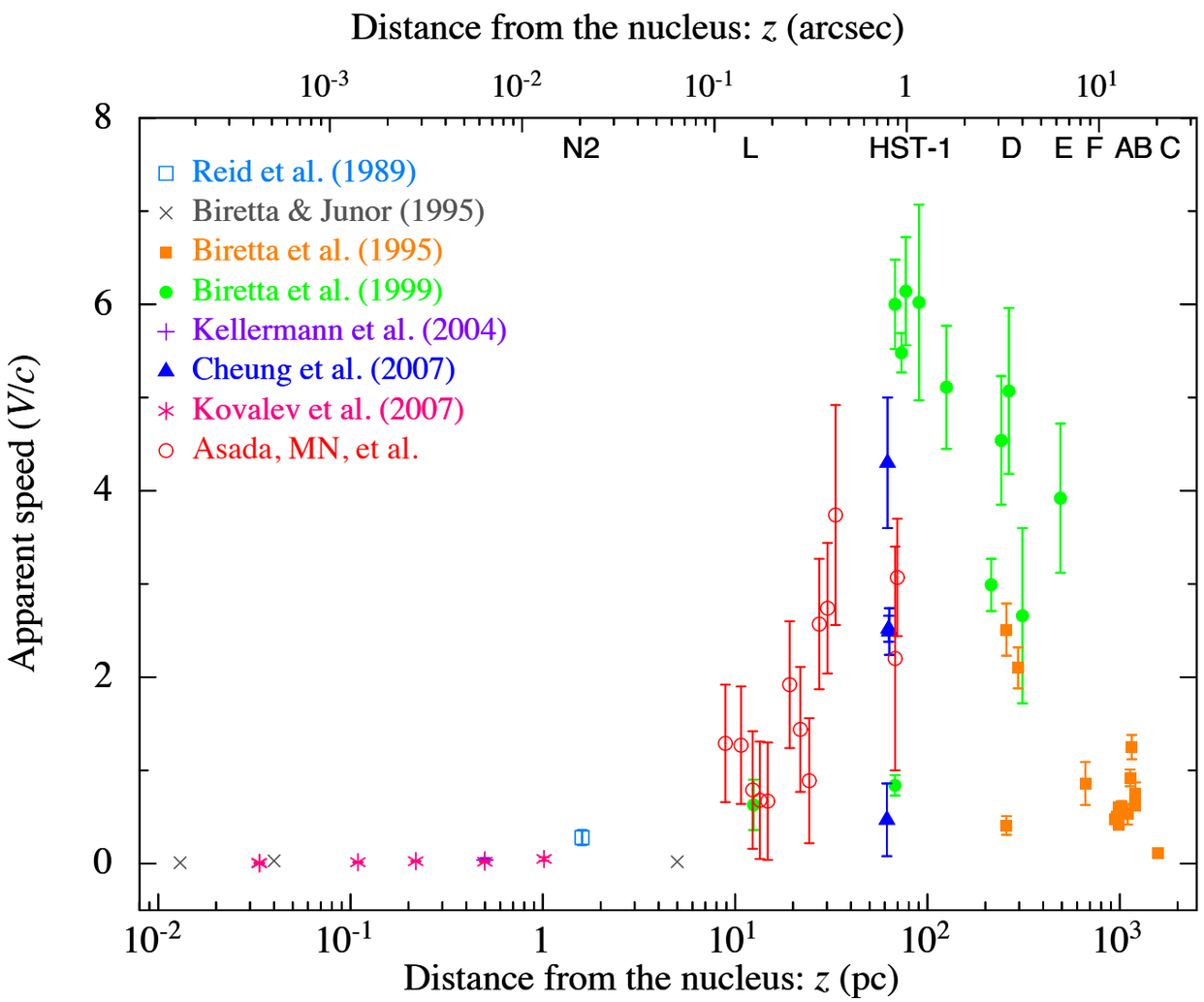
Junor et al. (1999)

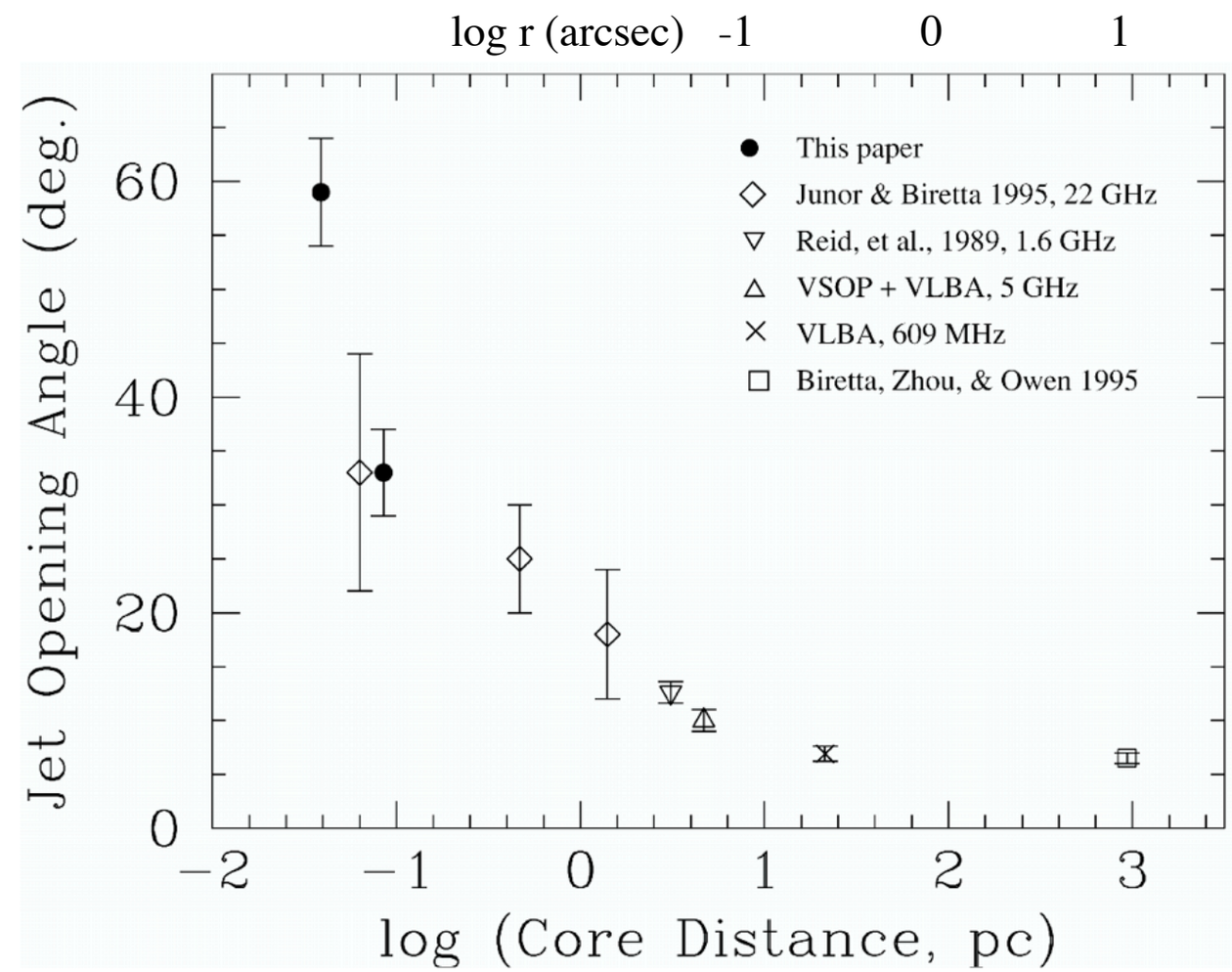
✓ **Yes, We found final pieces of the puzzle**, but how they will match into the MHD jet?

- The (bulk) acceleration (γ) and collimation (θ) are correlated in a parabolic streamline ($z \propto r^a, 1 < a \leq 2$) (Zakamska et al. 2008; Komissarov et al. 2009): $\gamma\theta \lesssim 1$
- Acceleration/collimation occurs ***slowly*** (Tchekhovskoy et al. 2008; Komissarov 2009): $\gamma \propto z^{(a-1)/a}$

We need to determine the jet structure (a)

A Missing Link Found





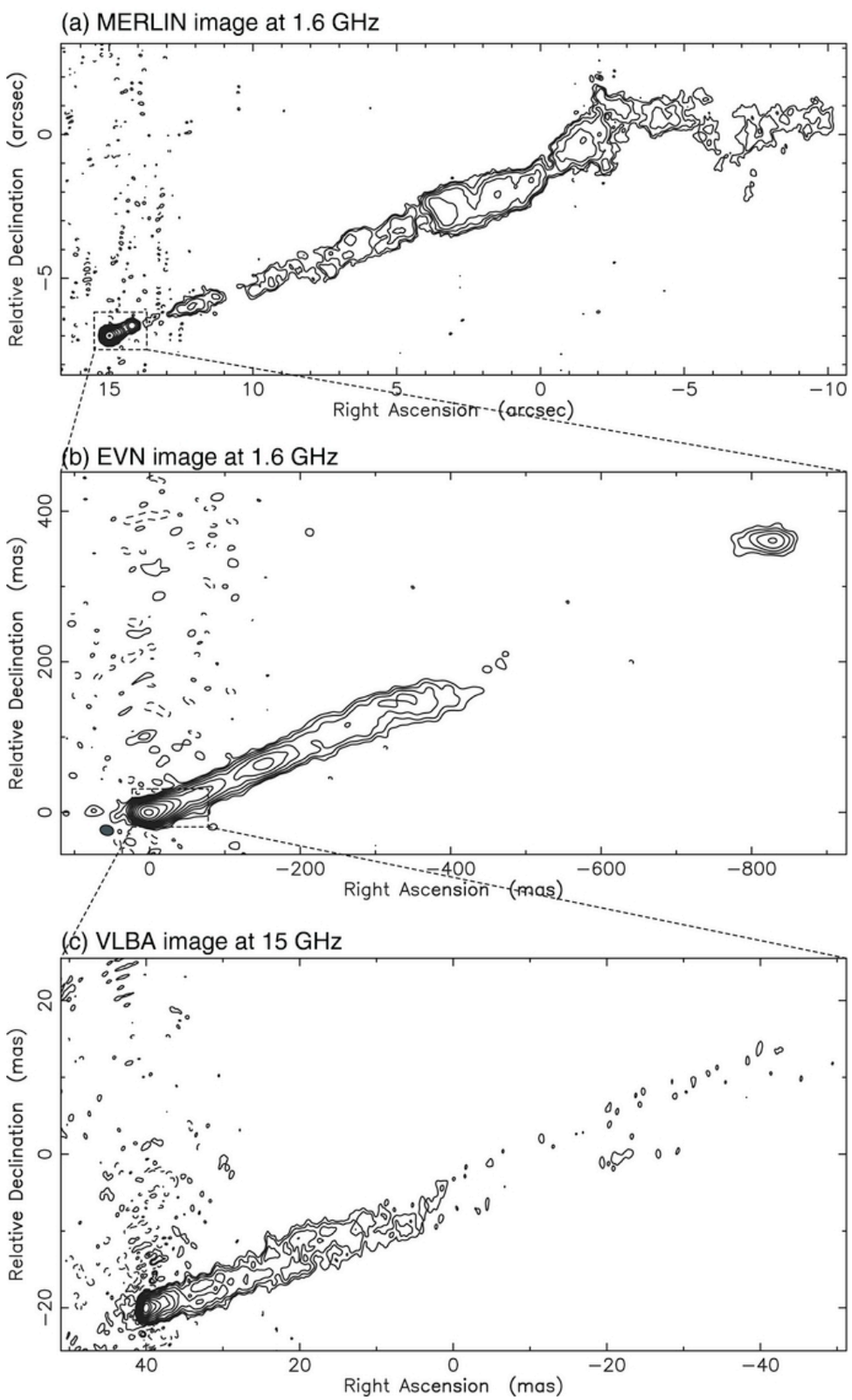
Junor et al. (1999)

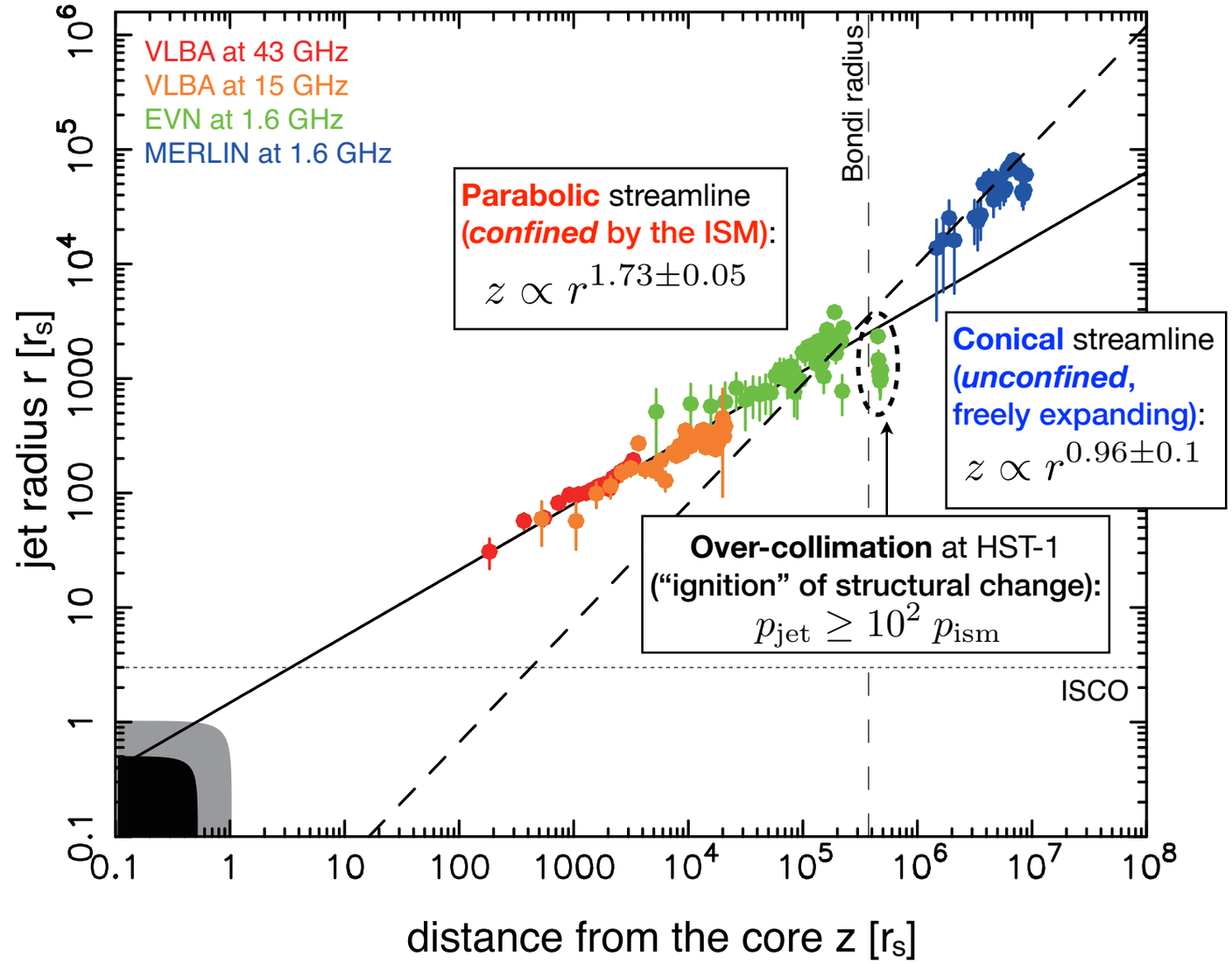
✓ **Yes, We found final pieces of the puzzle**, but how they will match into the MHD jet?

- The (bulk) acceleration (γ) and collimation (θ) are correlated in a parabolic streamline ($z \propto r^a, 1 < a \leq 2$) (Zakamska et al. 2008; Komissarov et al. 2009): $\gamma\theta \lesssim 1$
- Acceleration/collimation occurs ***slowly*** (Tchekhovskoy et al. 2008; Komissarov 2009): $\gamma \propto z^{(a-1)/a}$

We need to determine the jet structure (a)

Global Structure of the M87 Jet

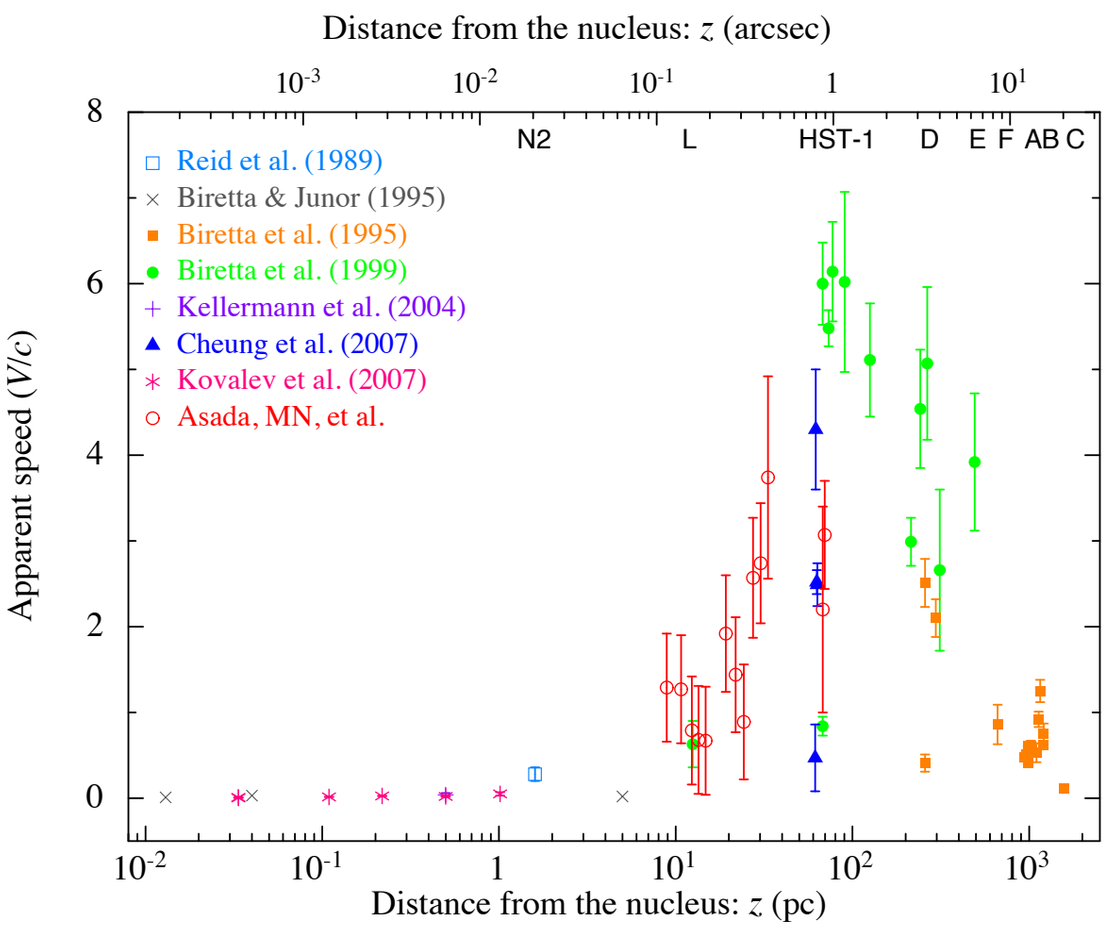


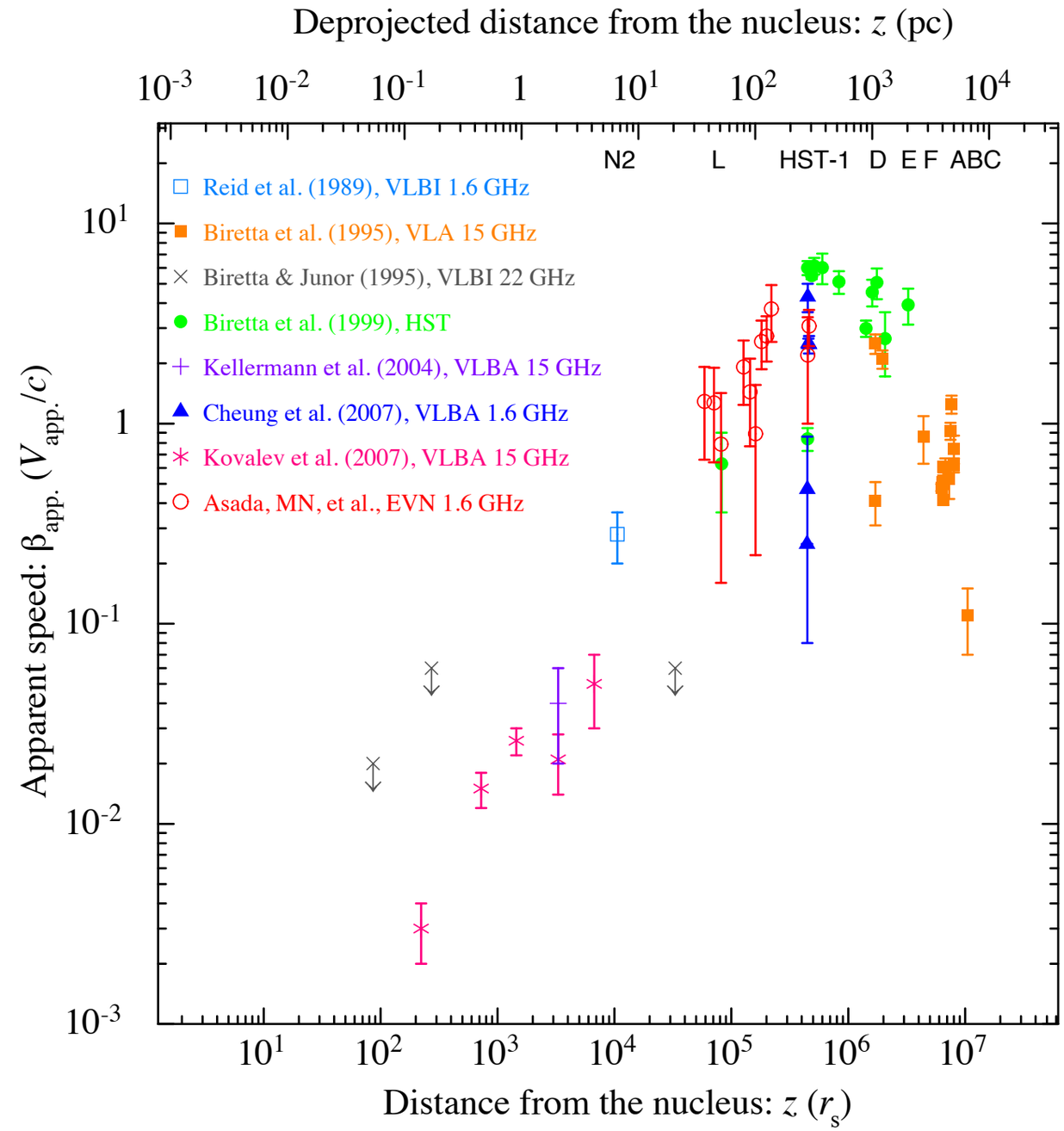


- ✓ The MHD jet maintains the parabolic structure over $10^5\, r_s$, balanced with the stratified ISM gas pressure
- ✓ A transition of streamlines presumably occurs at an ISM transition beyond the gravitational influence of the SMBH
- ✓ Stationary feature HST-1 as a consequence of the jet recollimation due to the pressure imbalance w/ the ISM

Asada & MN (2012)

Sub-to Superlumial Transition



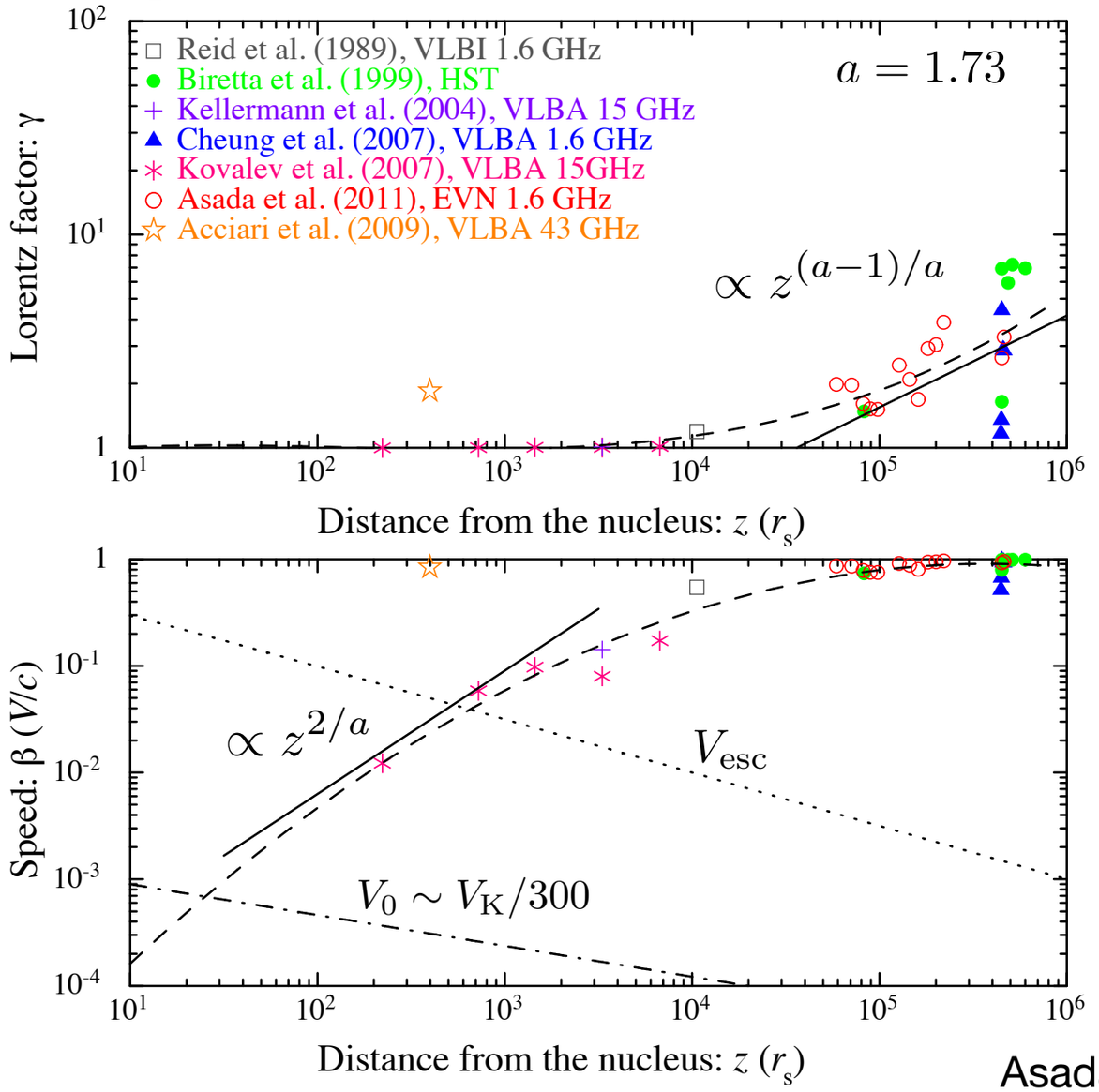


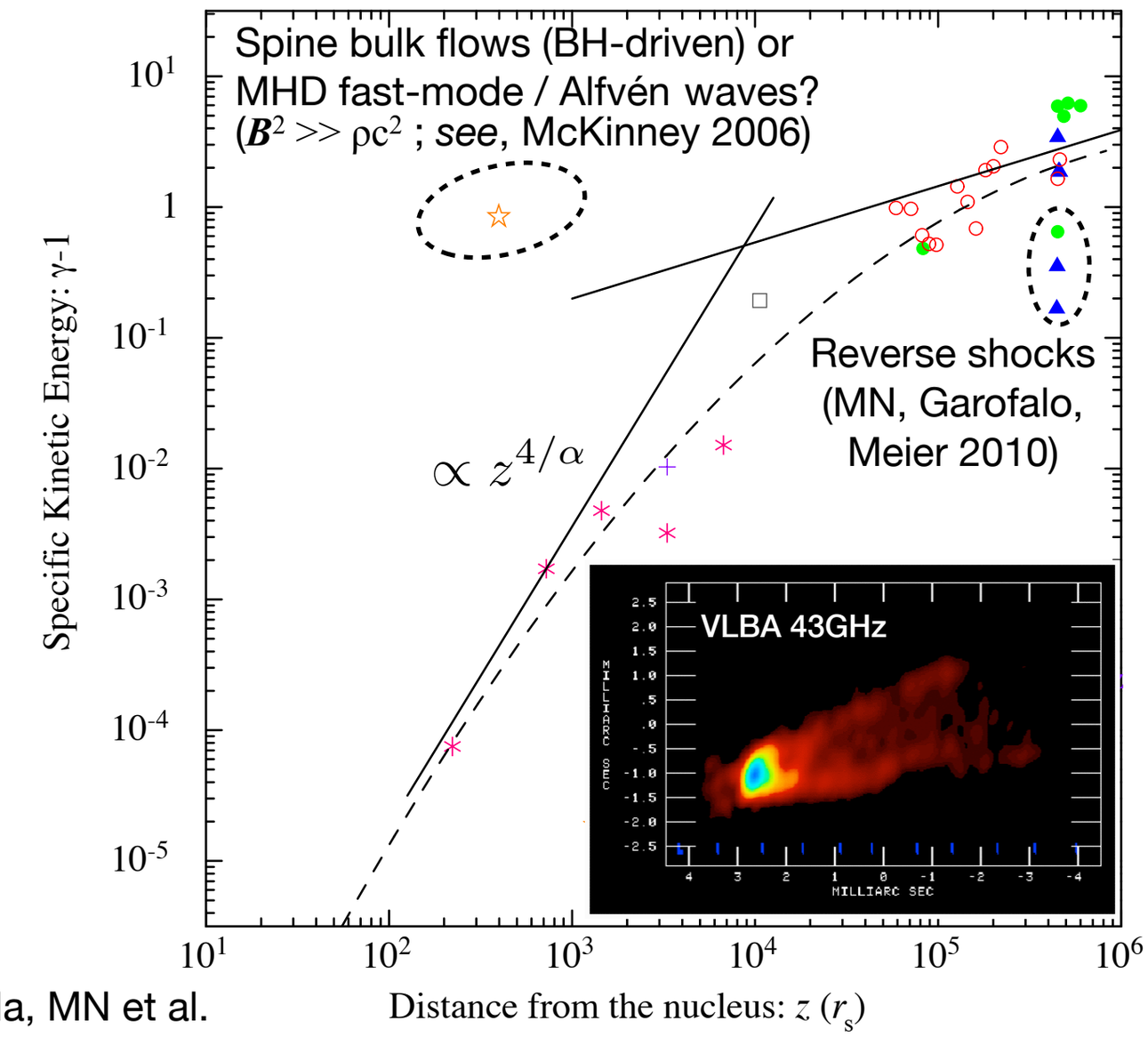
Asada, MN et al.

Q. Do they exhibit **an asymptotic acceleration from non-relativistic** (0.01*c*) **to relativistic speed** (0.99*c*) over an extremely large scale $10^{2\text{-}5}$ r_s?

Q. What determines **a peak of proper motions** as well as **a transition from parabolic to conical streamlines**?

Magnetic Acceleration & Collimation (MAC) Zone



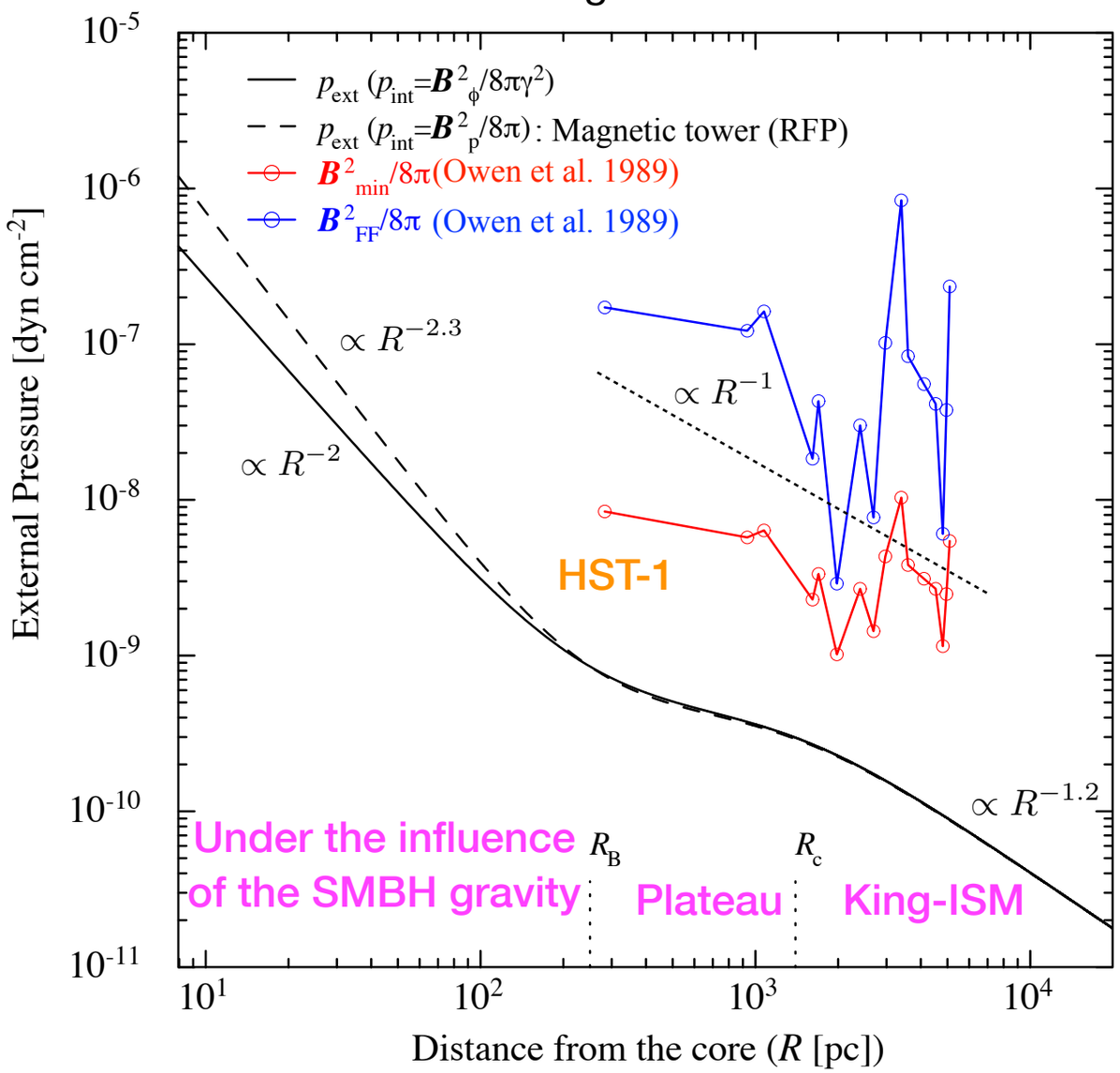


Asada, MN et al.

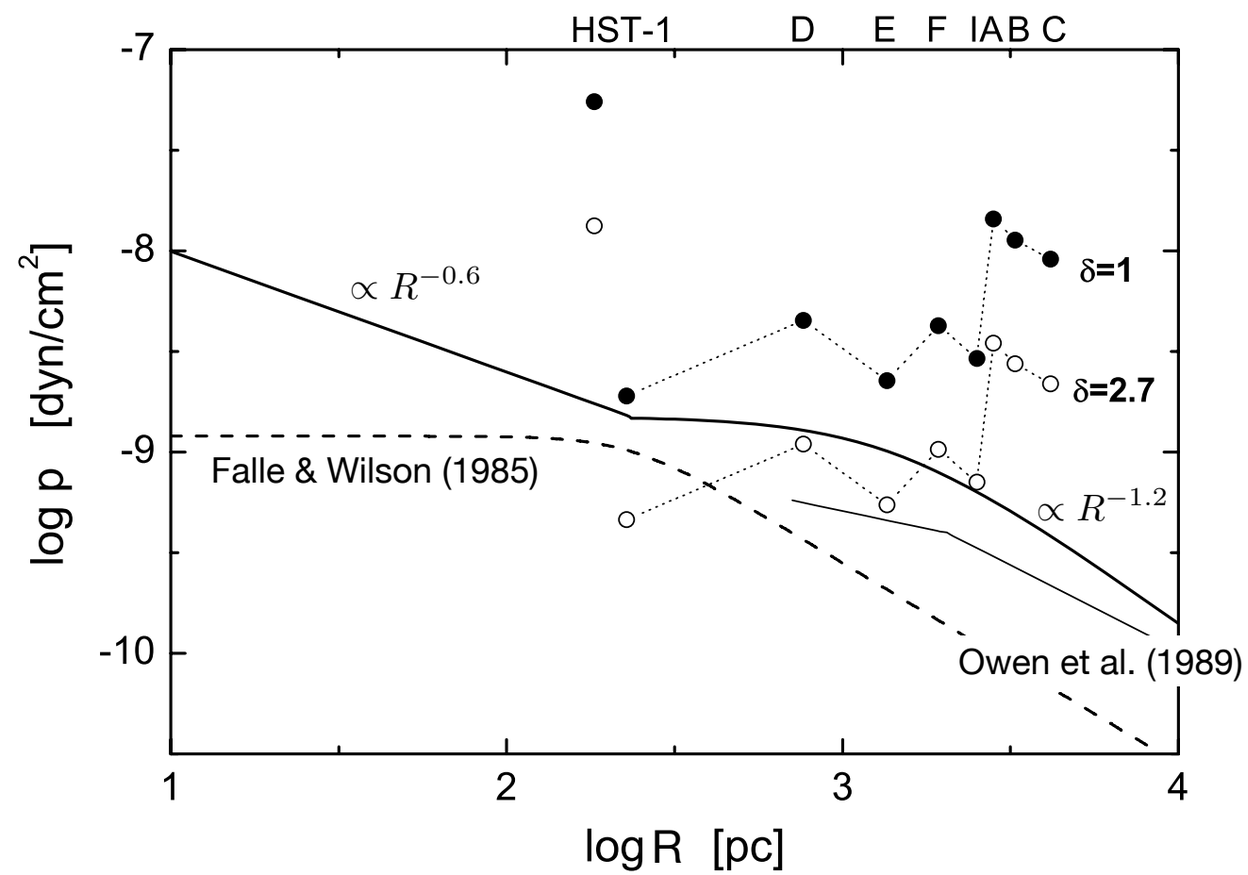
- ✓ Identified the jet "**MAC**" zone powered by **TAW** in a real jet system upstream of the conical region
  - The Lorentz factor follows the power-law slope constrained by the parabolic stream ($\gamma\theta \lesssim 1$)
  - Sub-luminal motions at around mas scale is likely to be a trans-Alfvénic flow
- ✓ The jet kinetic energy increases as a conversion from Poynting flux
  - Estimation of the jet total power by Poynting flux: $L_j = 10^{42-44}\ \mathrm{erg\,s^{-1}}$
  - The system possesses the axial current flowing: $I_z = 10^{16-17}\mathrm{A}$

ISM Gas Pressure

Bondi + King Model: MN et al.



Cusp + King Model: Stawarz, et al. (2006)



- Parabolic MHD jet is confined by the stratified external gas
- Radial pressure balance: $p_{\rm int}$ (mag.) = $p_{\rm ext}$ (gas), indicating a **giant ADAF** which extends beyond the Bondi radius down to the SMBH (Narayan & Fabian 2011: $p_{\rm ism} \propto R^{-b}$, $b \gtrsim 2$)
- Analytical study of RMHD jet supports $b \sim 2$ for a parabolic jet streamline (Komissarov et al 2009): $z \propto r^a, 1 < a \leq 2$

- A shallow gradient of the external gas, caused by a central stellar cusp
- Freely expanding (conical hydrodynamic) jet is converging into the reconfinement shock (Sanders 1983: $p_{\rm ism} \propto R^{-b}$, $b < 2$) at HST-1

What Can We Know about BLAZAR from the M87 Study?

Milli-mm wave *radio core includes the jet ACZ & a stationary shock* (Marscher et al. 2008)
→ Constraint is UNCLEAR ...

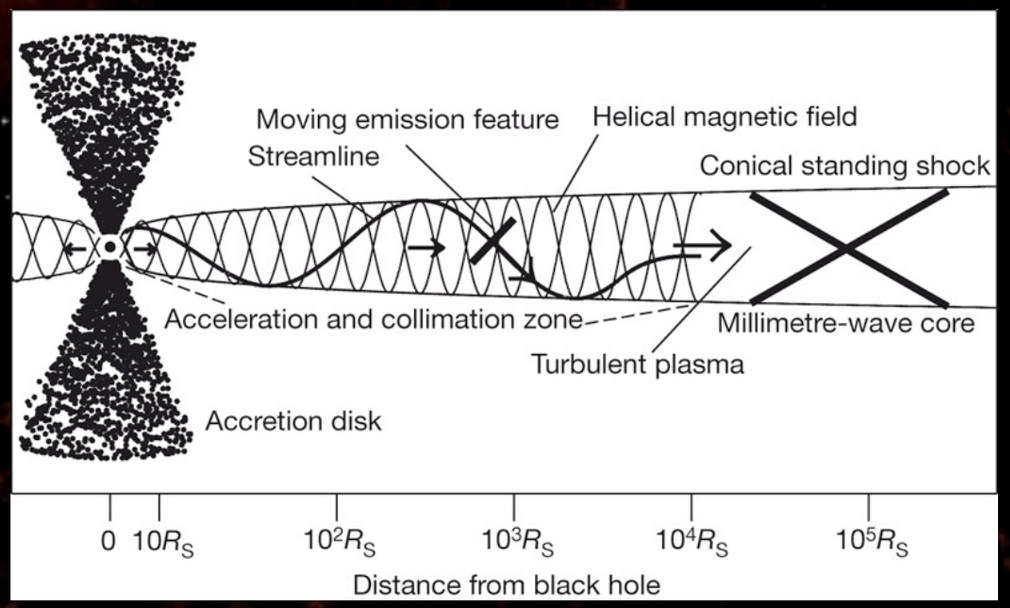
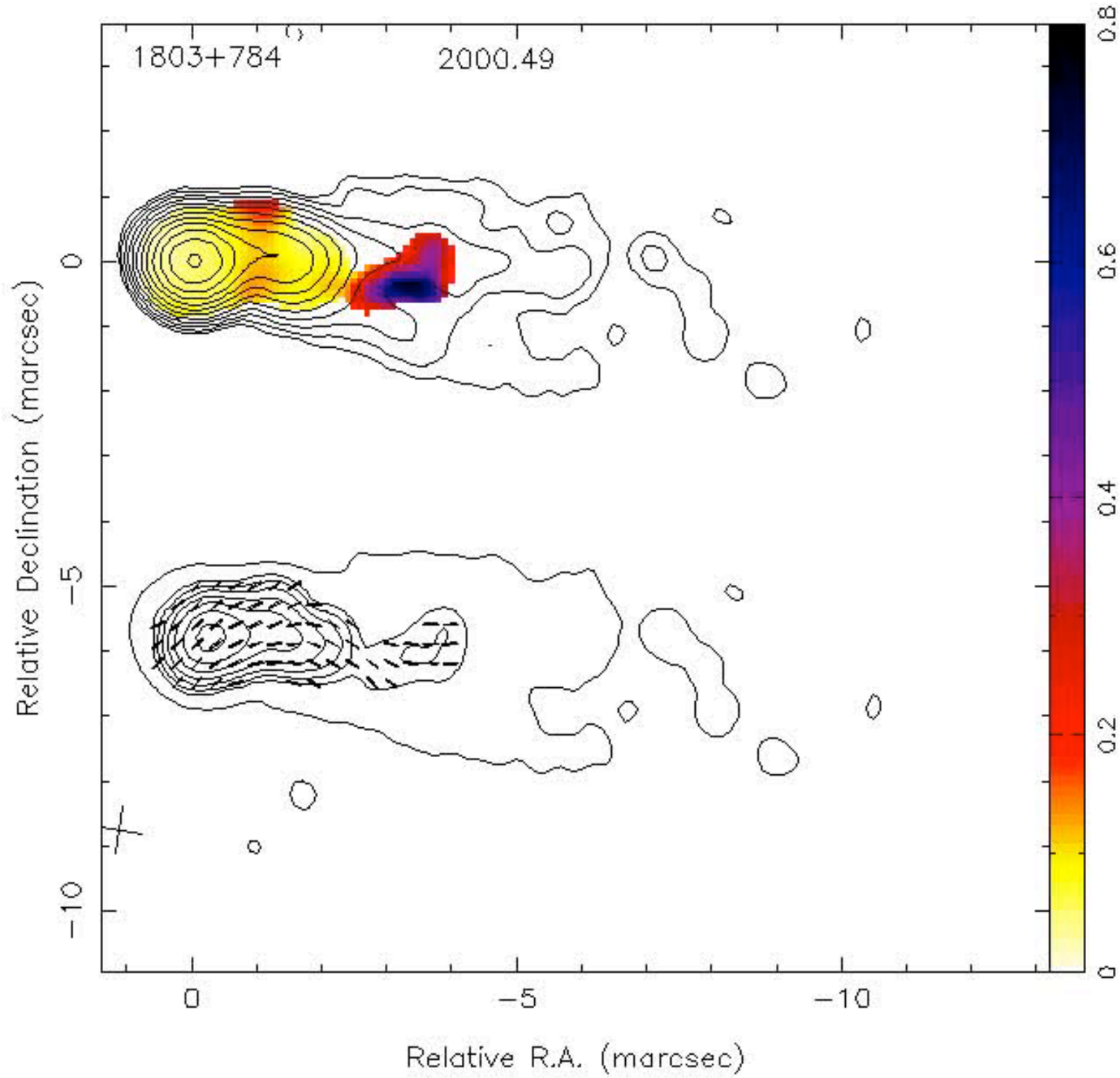
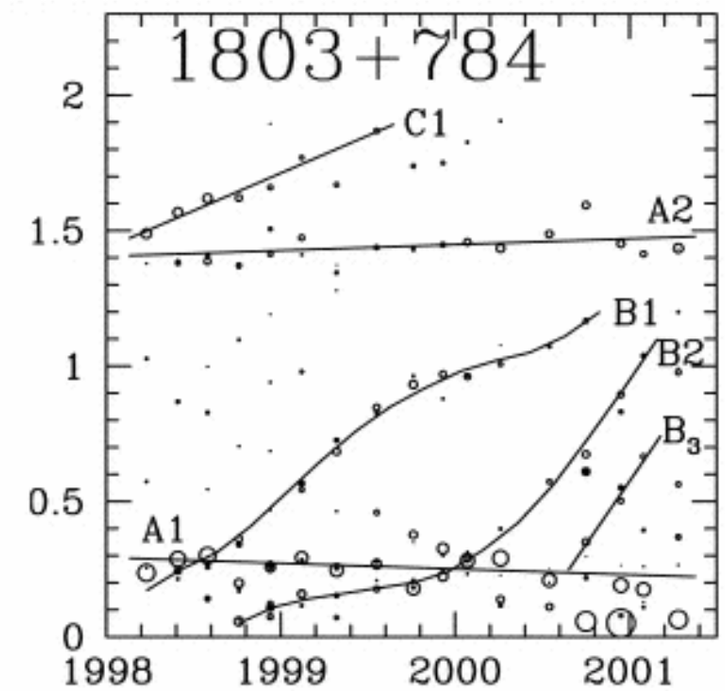


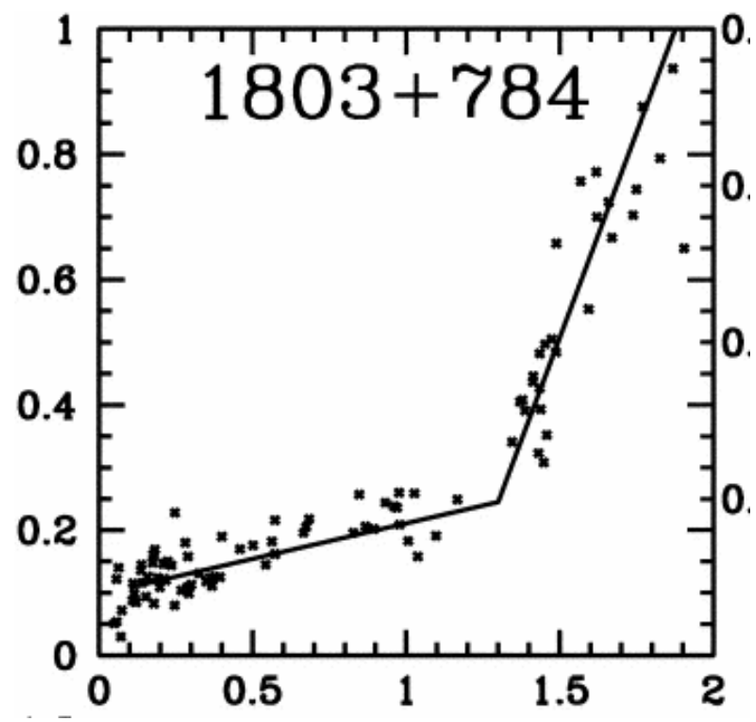
Image Credit: W. Steffen

BL Lac: 1803+784

MOJAVE Movie

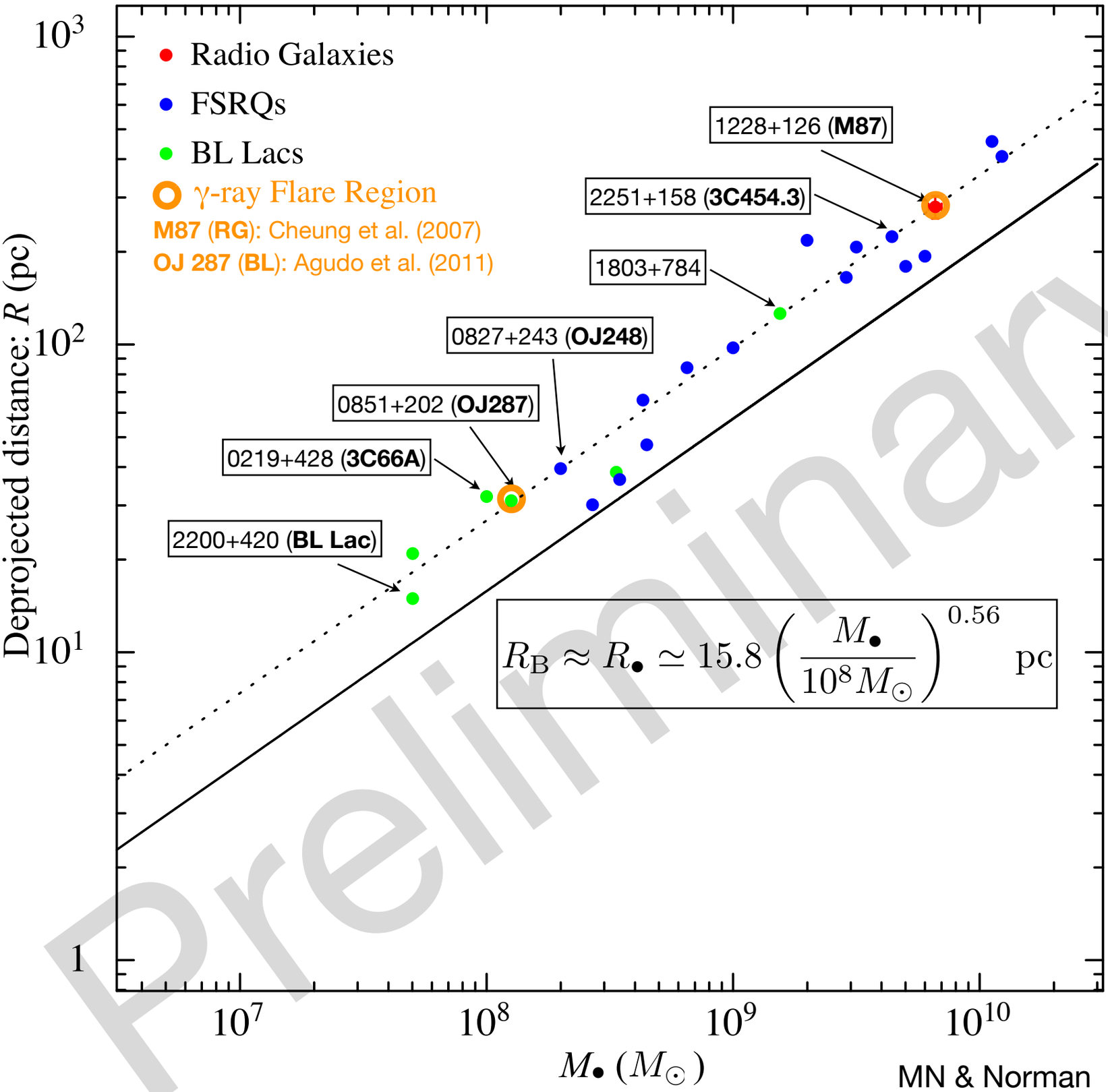






Jorstad et al. (2005)

Distance of Stationary Knot (SK) - $M_\bullet$



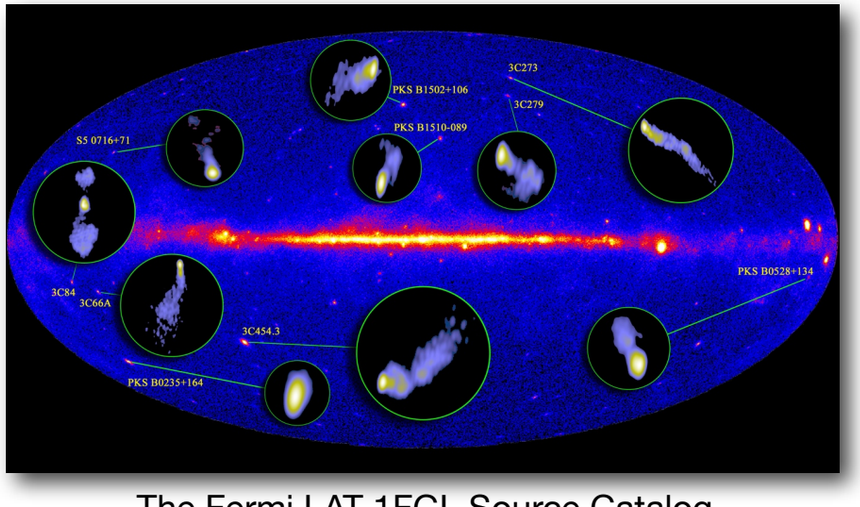
MN & Norman

- A best fitting of $R_{\rm SK}$ - $M_\bullet$:

$$R_{\rm SK} \simeq 26.4 \left(\frac{M_\bullet}{10^8 M_\odot}\right)^{0.56} \text{pc}$$

$\rightarrow M_\bullet \propto \sigma^{4.53}$ (e.g., McConnell *et al.* 2011)

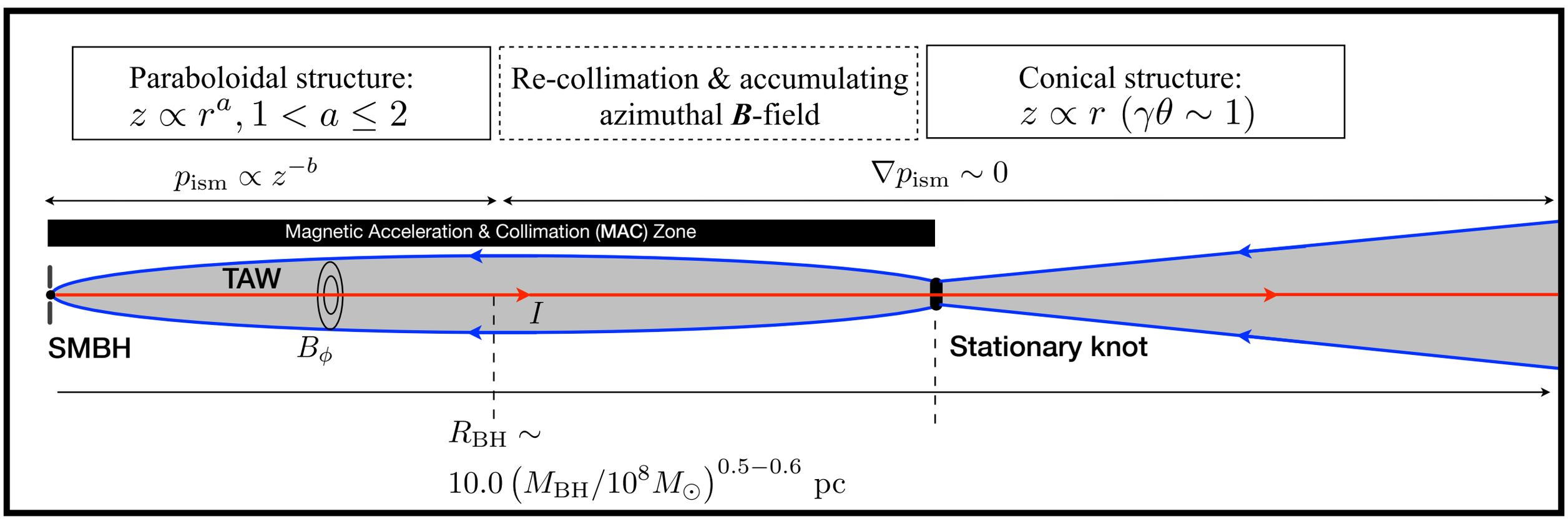
- Indicating a link between AGN jets and $M_\bullet$-σ relation
- Suggesting the unification of B (Urry & Padovani 1995)
- VHE γ-ray emission region can be presumably scaled by $M_\bullet$?



The Fermi LAT 1FGL Source Catalog + MOJAVE (VLBA) image

Summary

- Jets scaled by **SMBH**($M_\bullet$): $M_\bullet$ - σ relation & **AGN** Unification
  - **M87**: "***Rosetta stone***" of **AGN** jets
    - Jet **MAC** nozzle powered by the **TAW**
    - Transition of streamlines beyond a stationary knot
    - **VHE** γ-ray emissions & ejections of superluminal knots



MN & Norman