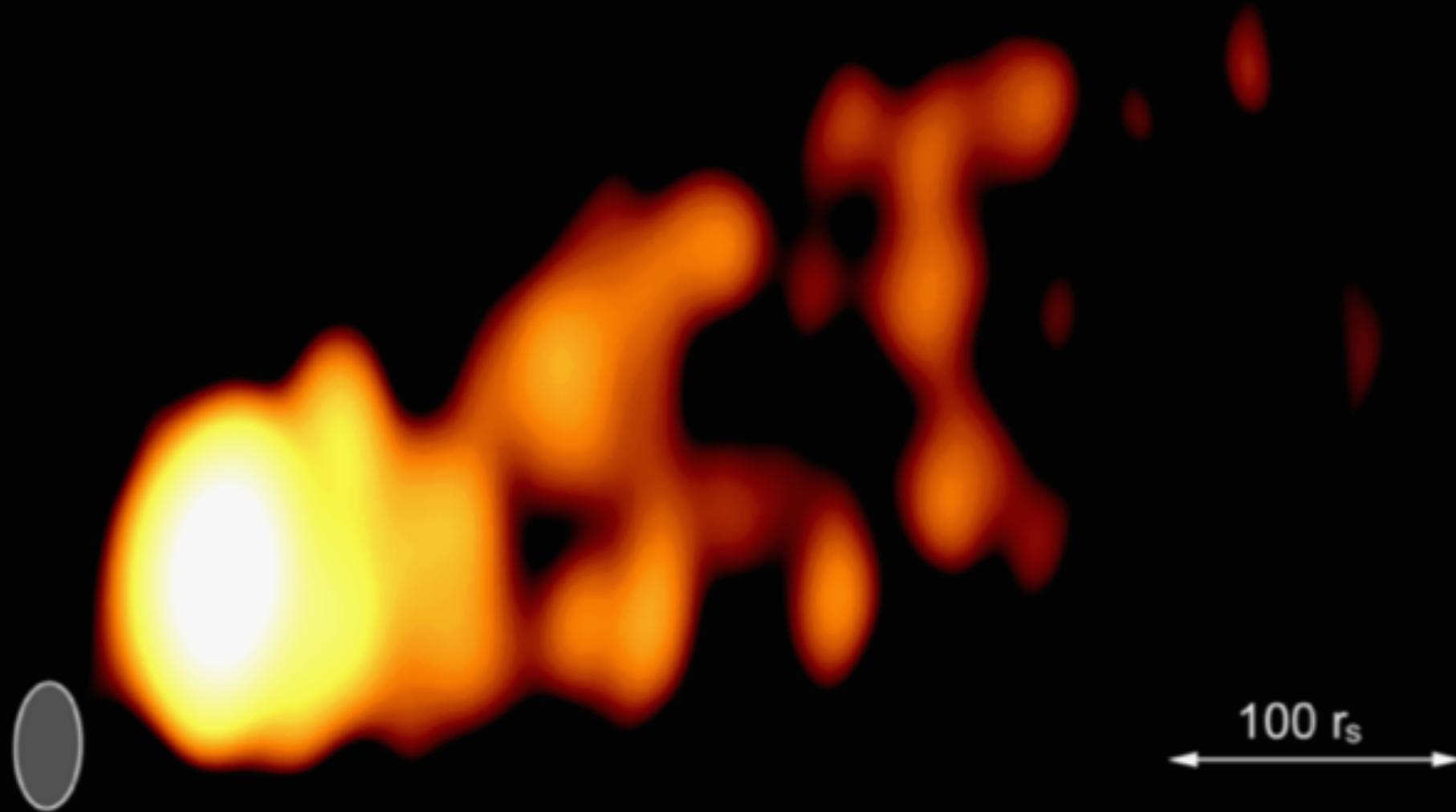


Structure & Magneto-hydrodynamics of the M87 Jet

◦ Size of Black Hole



Masanori Nakamura (ASIAA, TAIWAN)

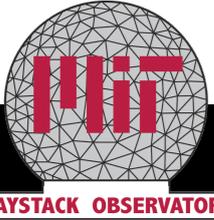


M87 (Virgo A; NGC4486)

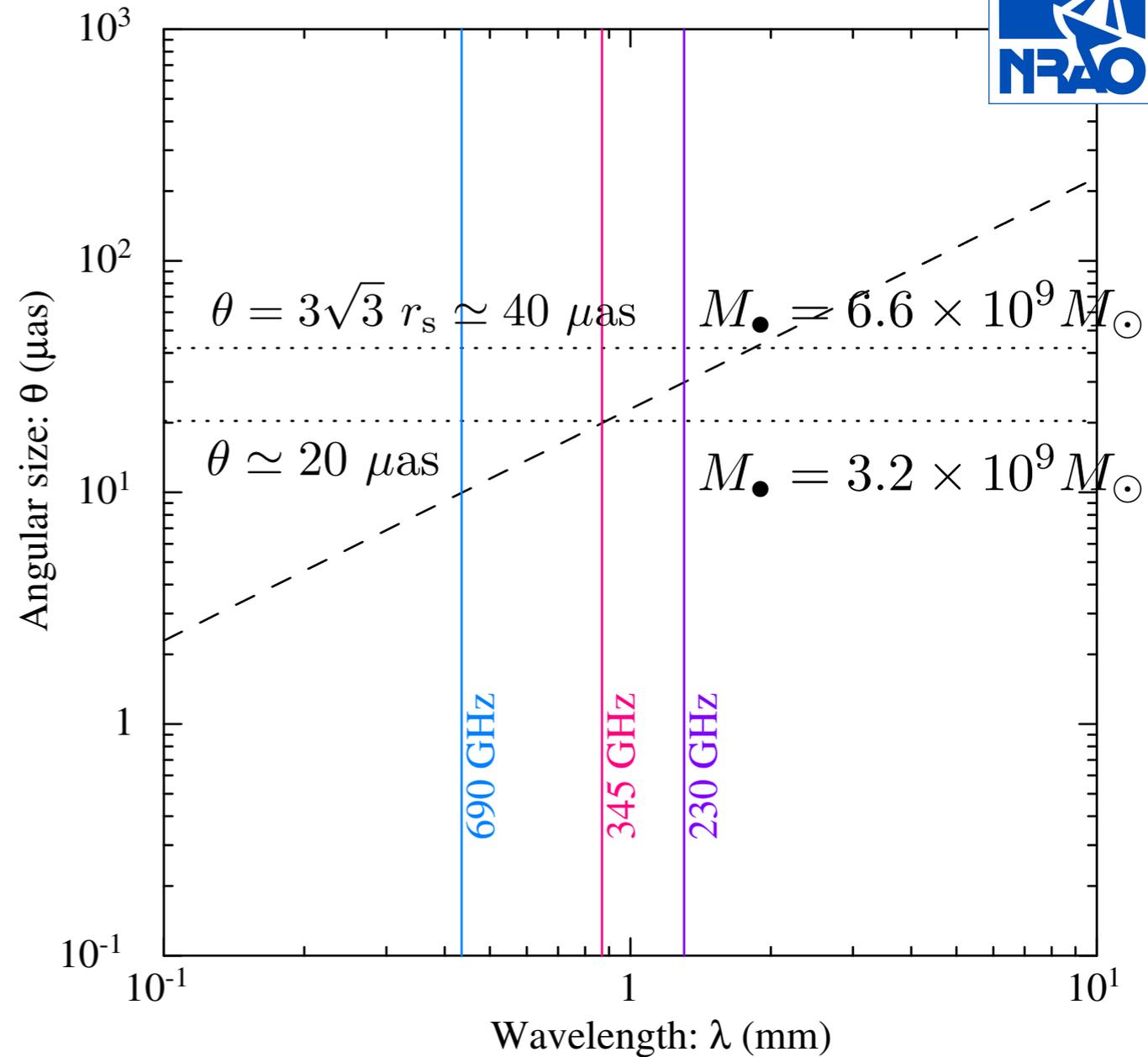
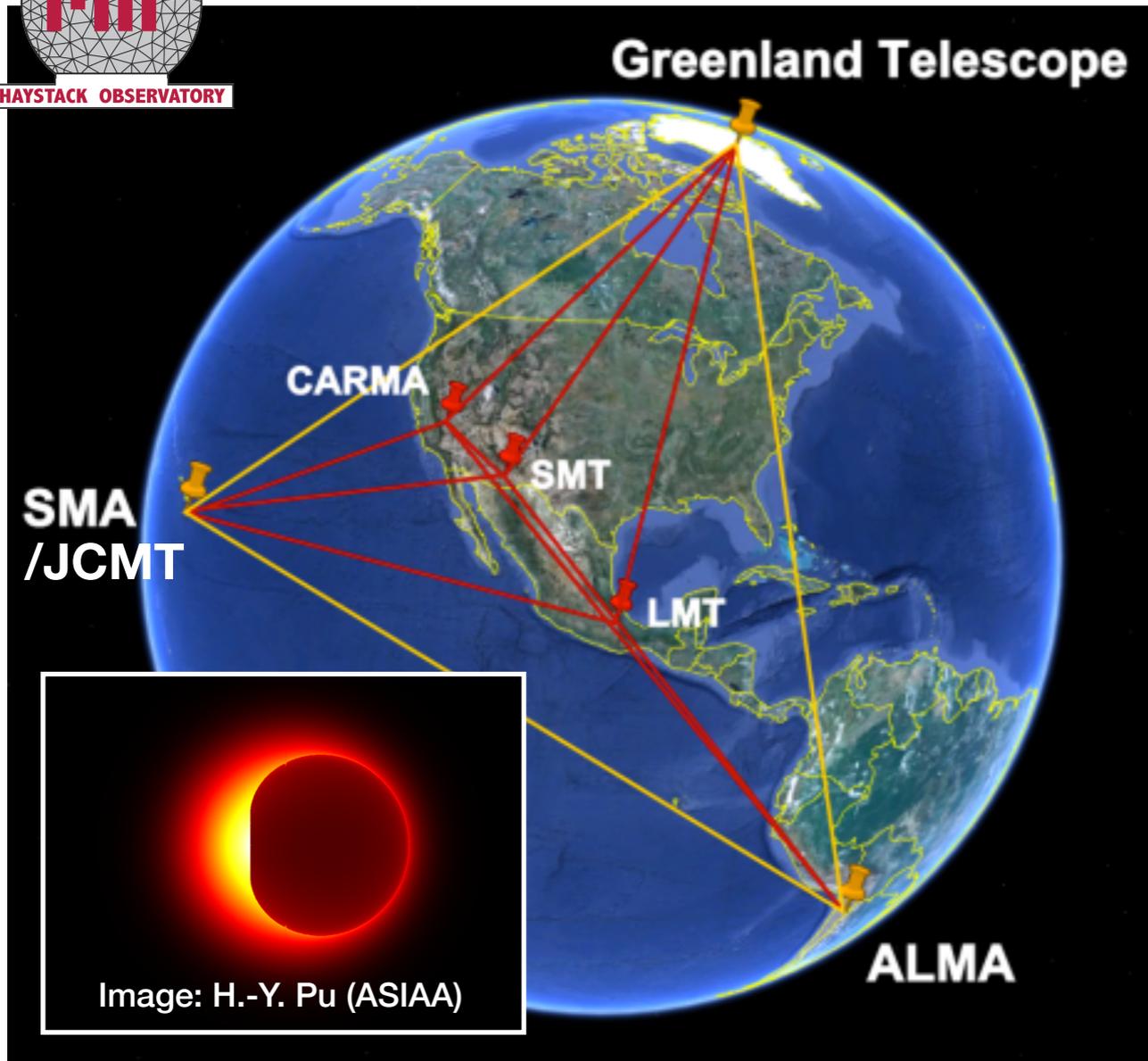
- The 2nd brightest galaxies in Virgo
 - The 1st jet discovered (Curtis 1918)
 - “**Rosetta Stone**” of AGN jets (Biretta 1993)
 - Nearby: $1 \text{ mas} \sim 125 r_s$
 - SMBH: $M_\bullet \sim (3 - 7) \times 10^9 M_\odot$
 - FR I / Misaligned BL Lac: $\theta_v \sim 14^\circ$
- (Blakeslee+ 2009; Macchetto+ 1997; Gebhardt+ 2011; Wang & Zhou 2009)

Image:
W. Sparks (STScI)

1. 2nd largest BH shadow ($\sim 40 \mu\text{as}$)
2. Relativistic outflows ($\leq 6 c$; $0.99c$)
3. VHE TeV emissions (core / HST-1)
4. AGN feedback (radio mode) in action



GLT Project



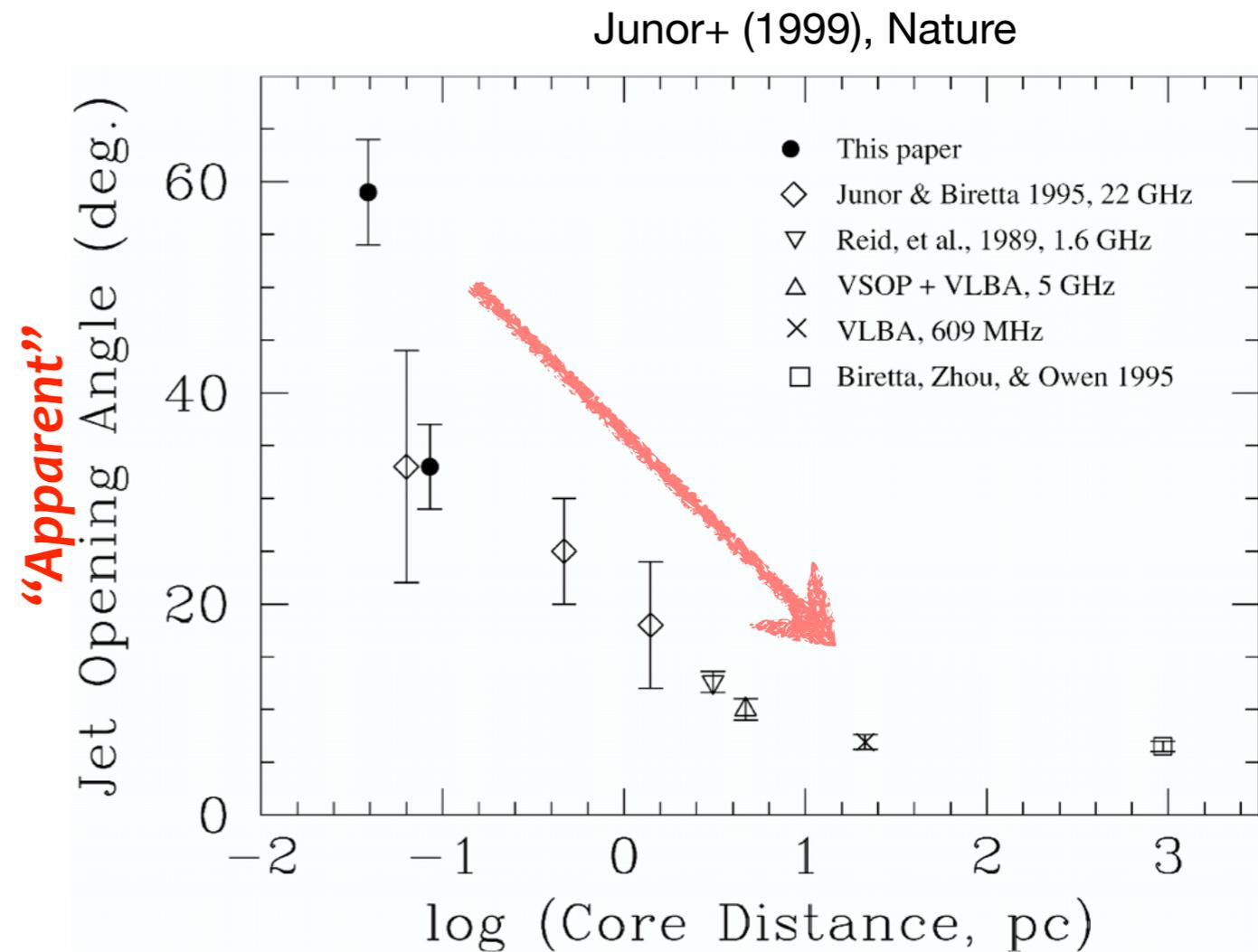
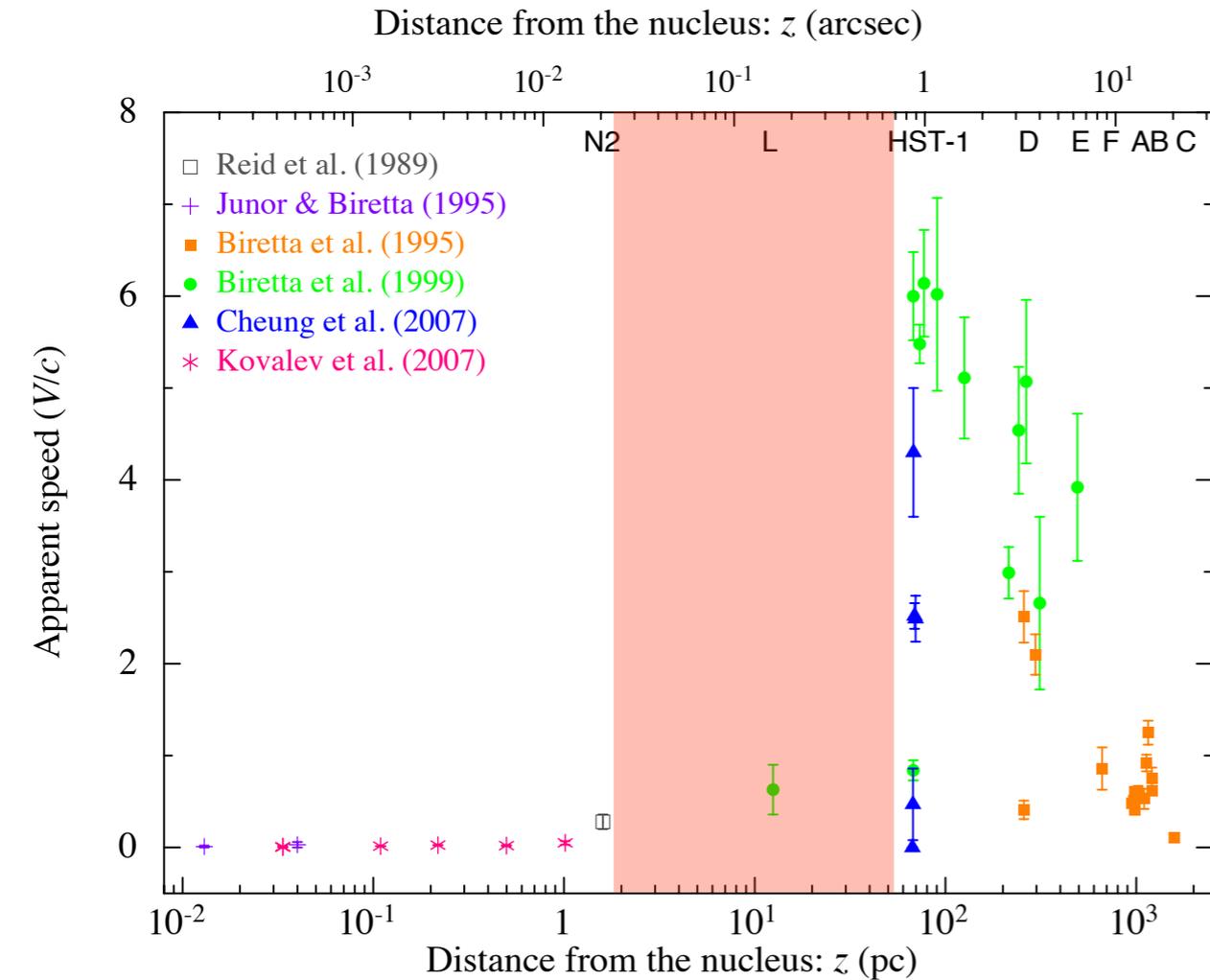
- A baseline 9,000+ km, giving a resolution $\theta \sim 20 \mu\text{as}$ to image the shadow for M87 ($\sim 2.5 R_s$ w/ $6.6 \times 10^9 M_{\odot}$)

Poster 66. M87 BH Shadow Imaging by Pu et al.

Outline

- “Observation of the MHD jet” with M87
- MHD Jet acceleration/collimation takes place in the parabolic stream up to $\sim 10^5 r_s$ under the sphere of gravitational influence (SGI) of the SMBH
- “*Jet break*” in M87, giving a fate of the MHD jet evolution
- Parabolic stream changes into the conical stream through the jet over-collimation at HST-1, where the jet acceleration is presumably terminated
- Jet break gives a key ingredient for understanding how AGN jets interplay with SMBHs and their host galaxies

Puzzle Has Remained Unsolved Over Decades



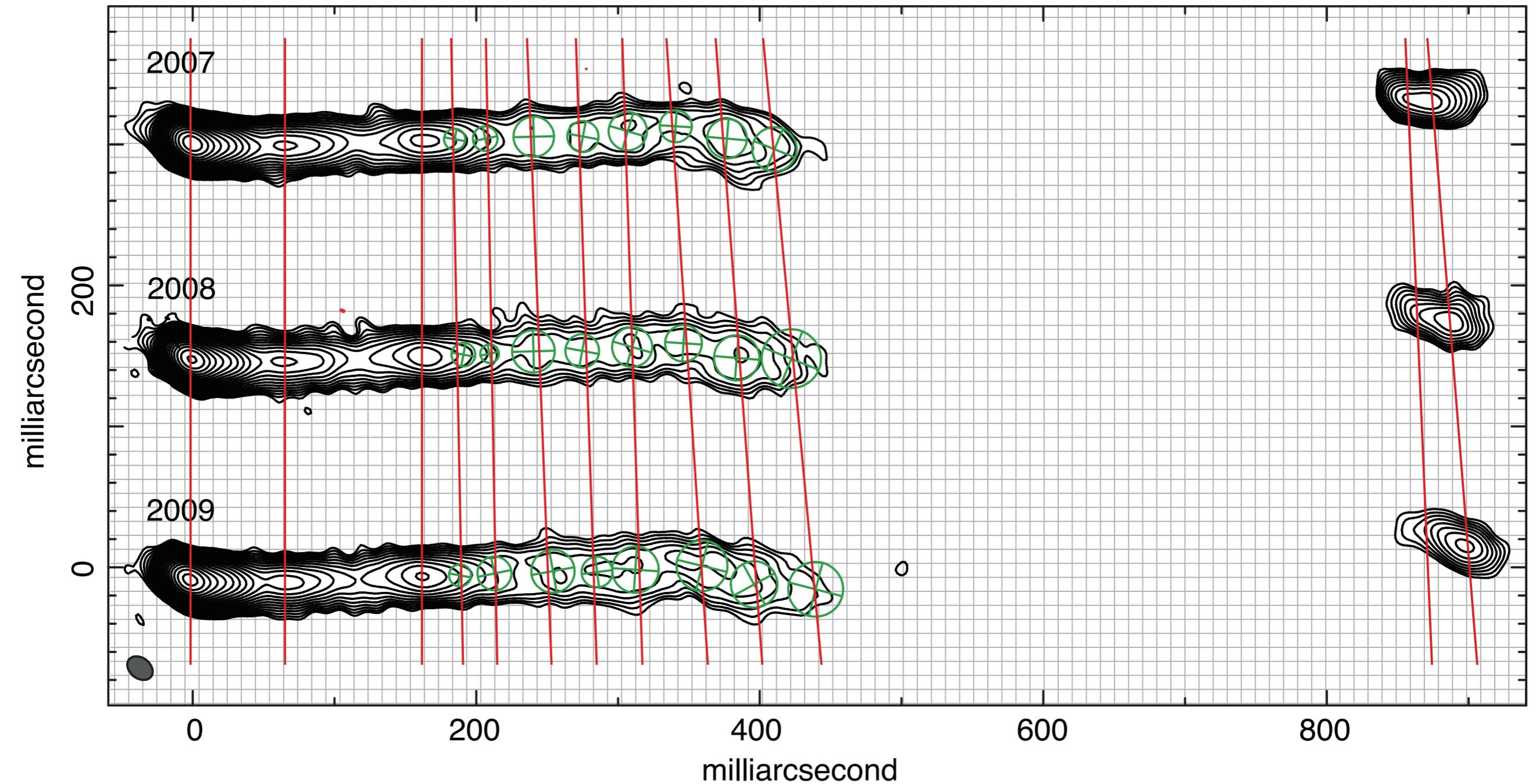
Q. What is a large gap?

Q. Collimation is real?

No clear view of jet acceleration/collimation even in most studied AGN source... $>0<$

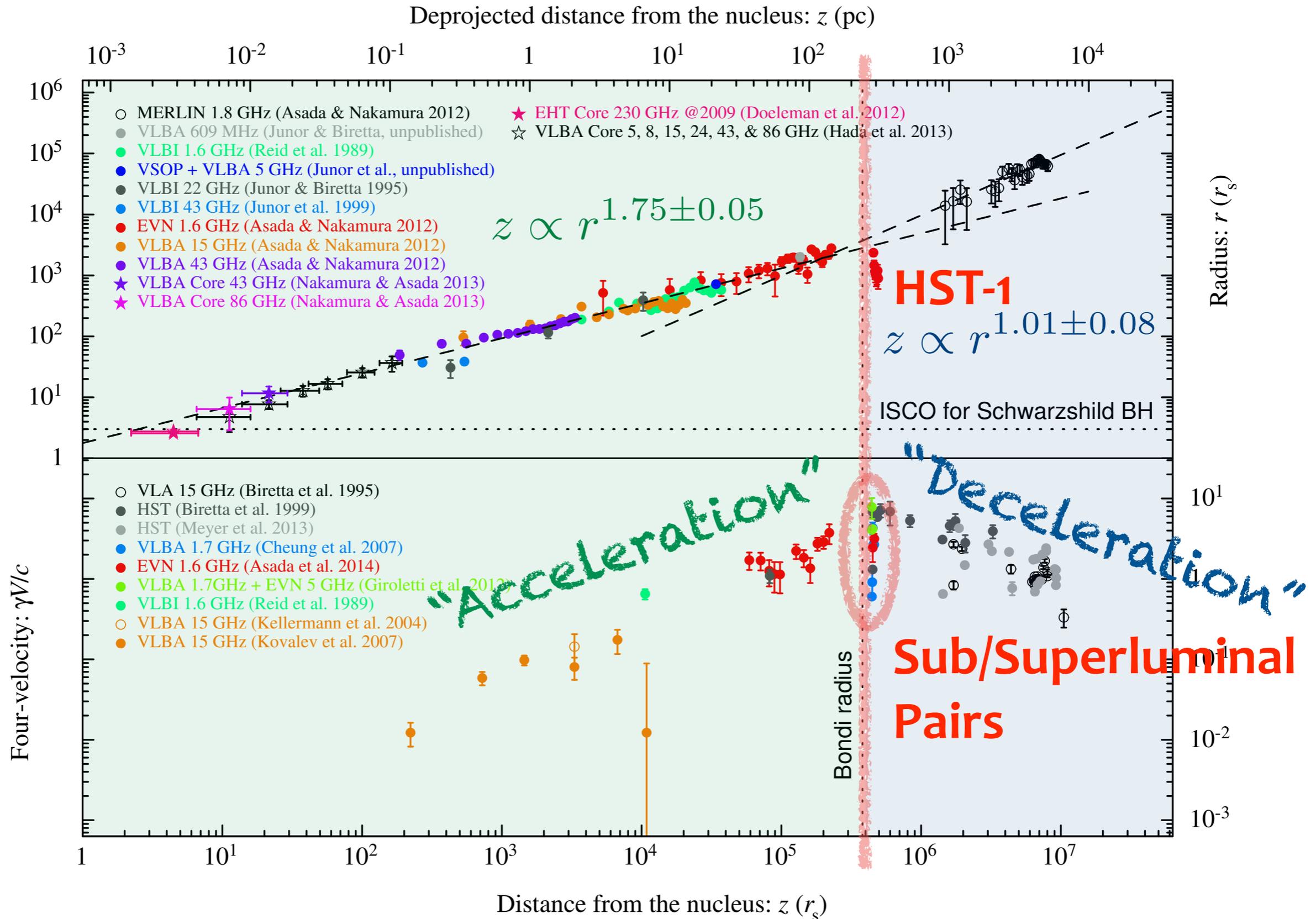
Superluminal Motions Upstream of HST-1

EVN Observations@1.6GHz



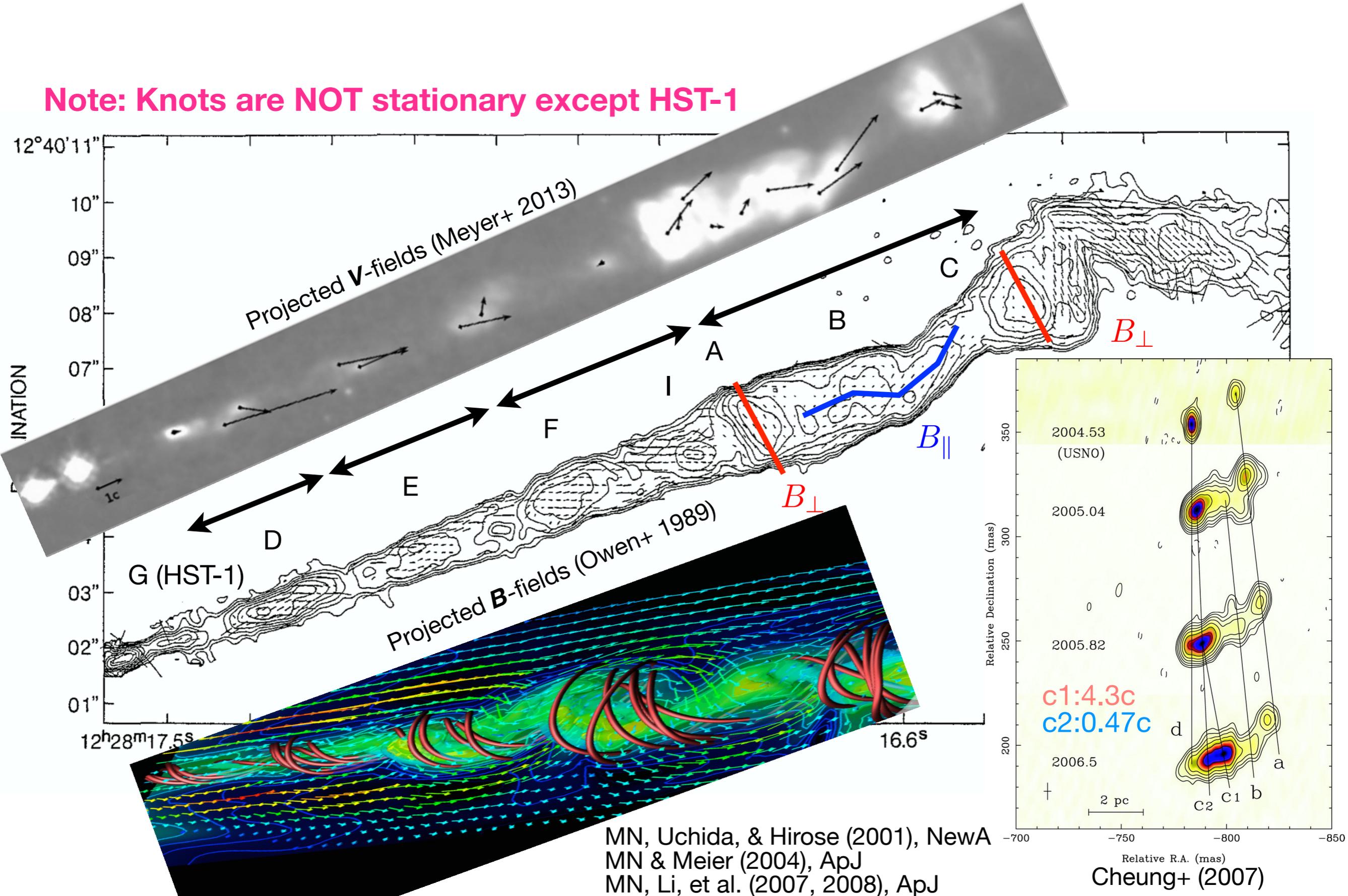
Asada, MN+ (2014), *ApJL*

Jet Structure and Dynamics in M87



Helical Motions of Components?

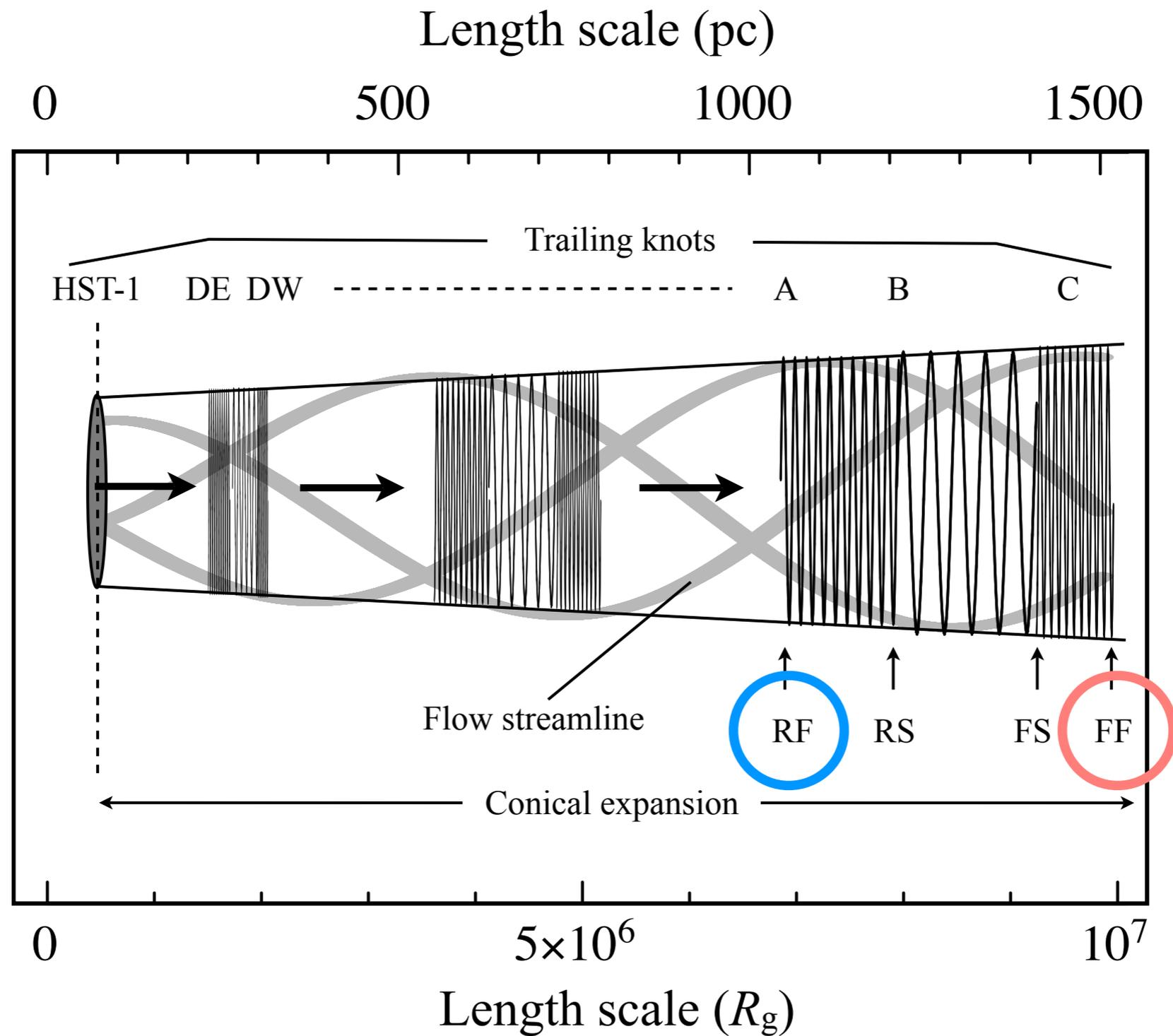
Note: Knots are NOT stationary except HST-1



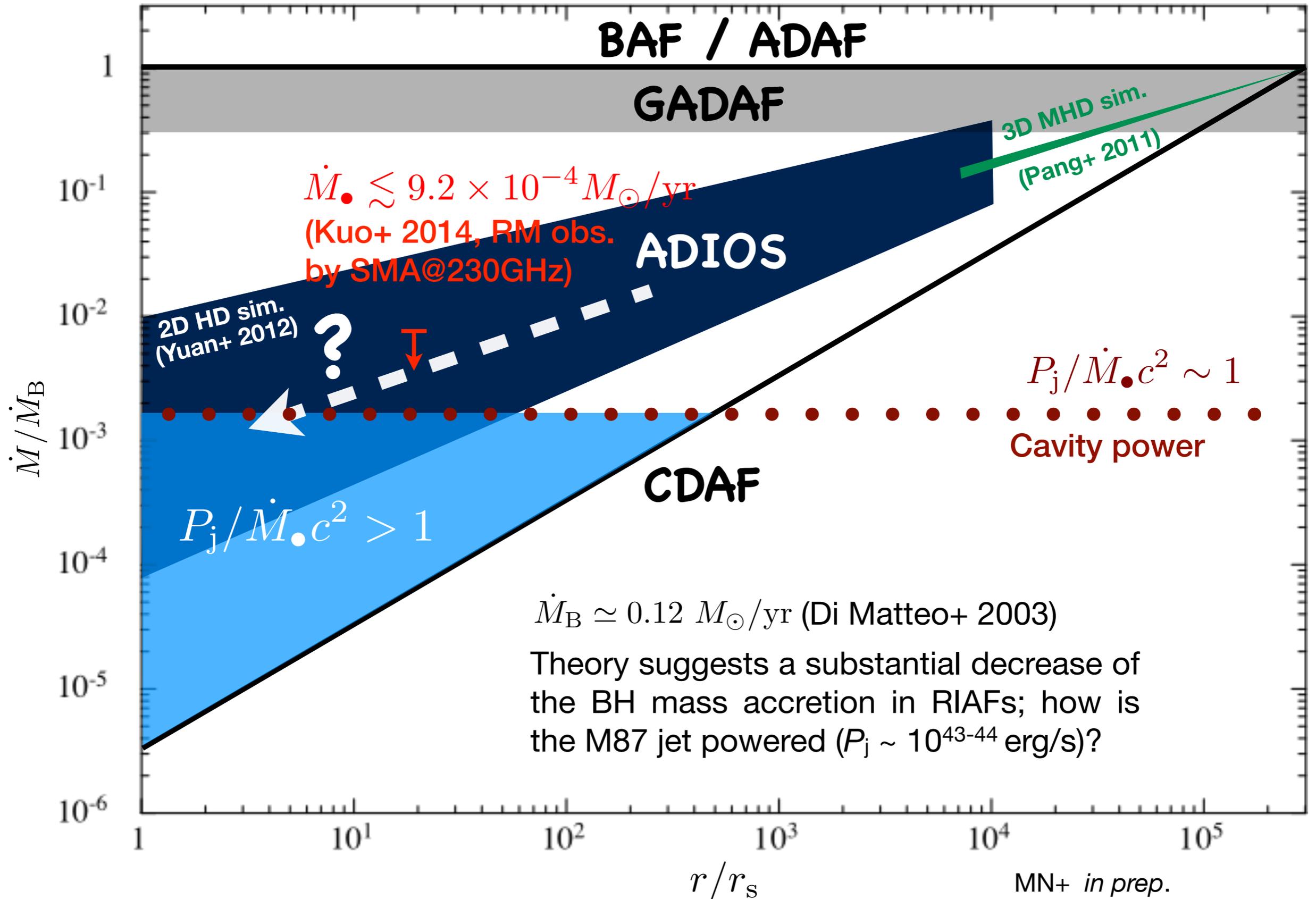
MN, Uchida, & Hirose (2001), NewA
 MN & Meier (2004), ApJ
 MN, Li, et al. (2007, 2008), ApJ

Cheung+ (2007)

Quad RMHD Shock Model



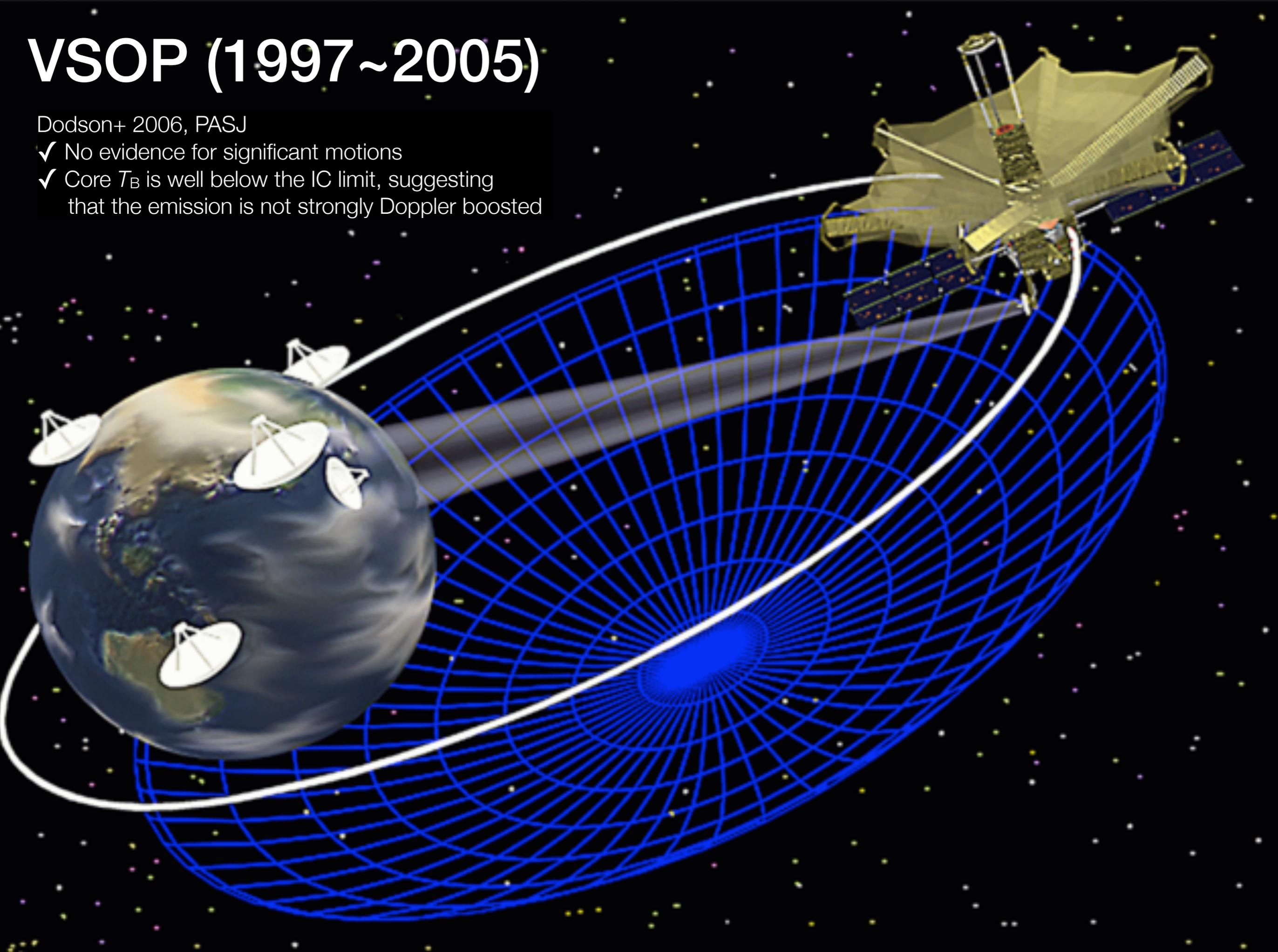
RIAF in M87



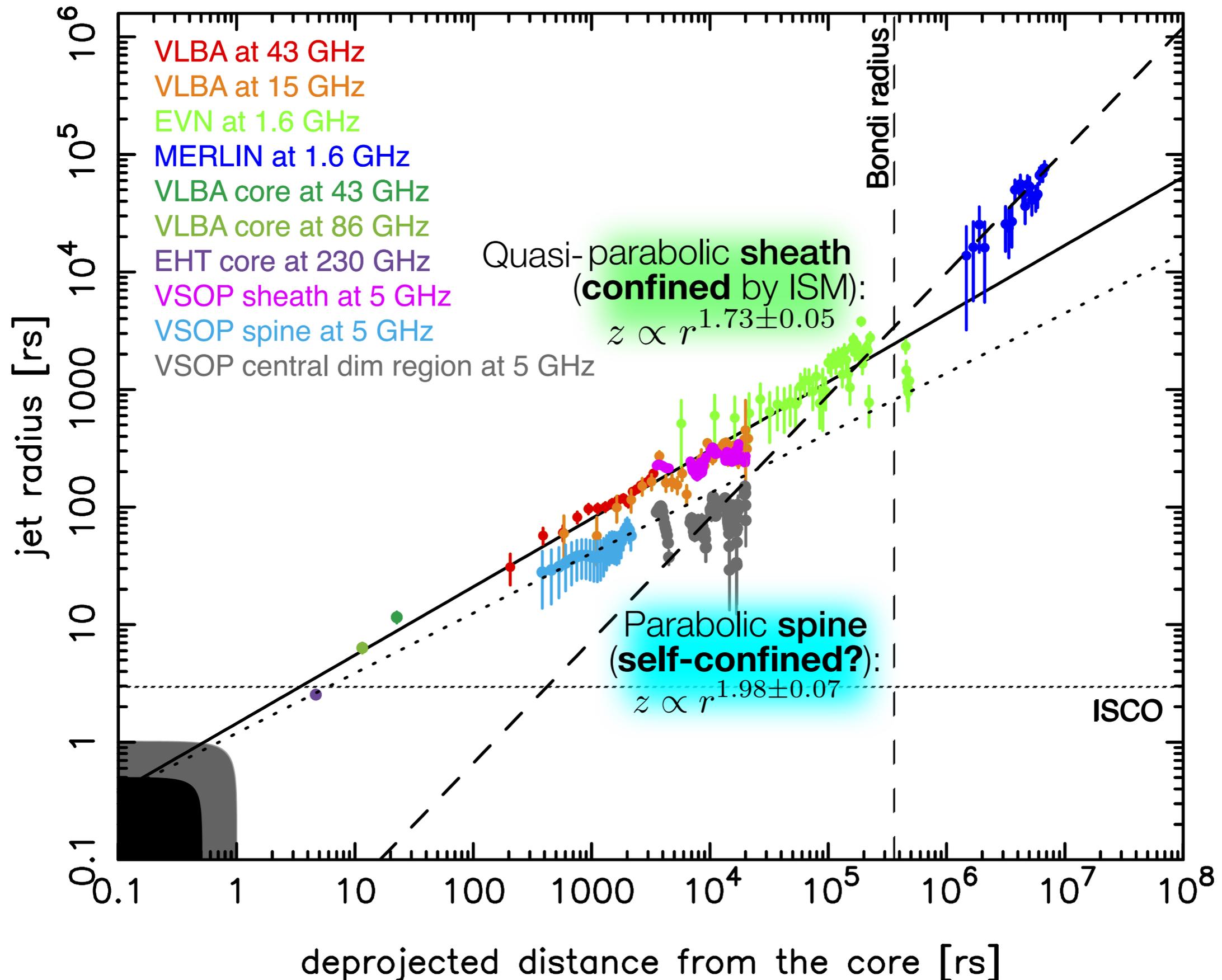
VSOP (1997~2005)

Dodson+ 2006, PASJ

- ✓ No evidence for significant motions
- ✓ Core T_B is well below the IC limit, suggesting that the emission is not strongly Doppler boosted

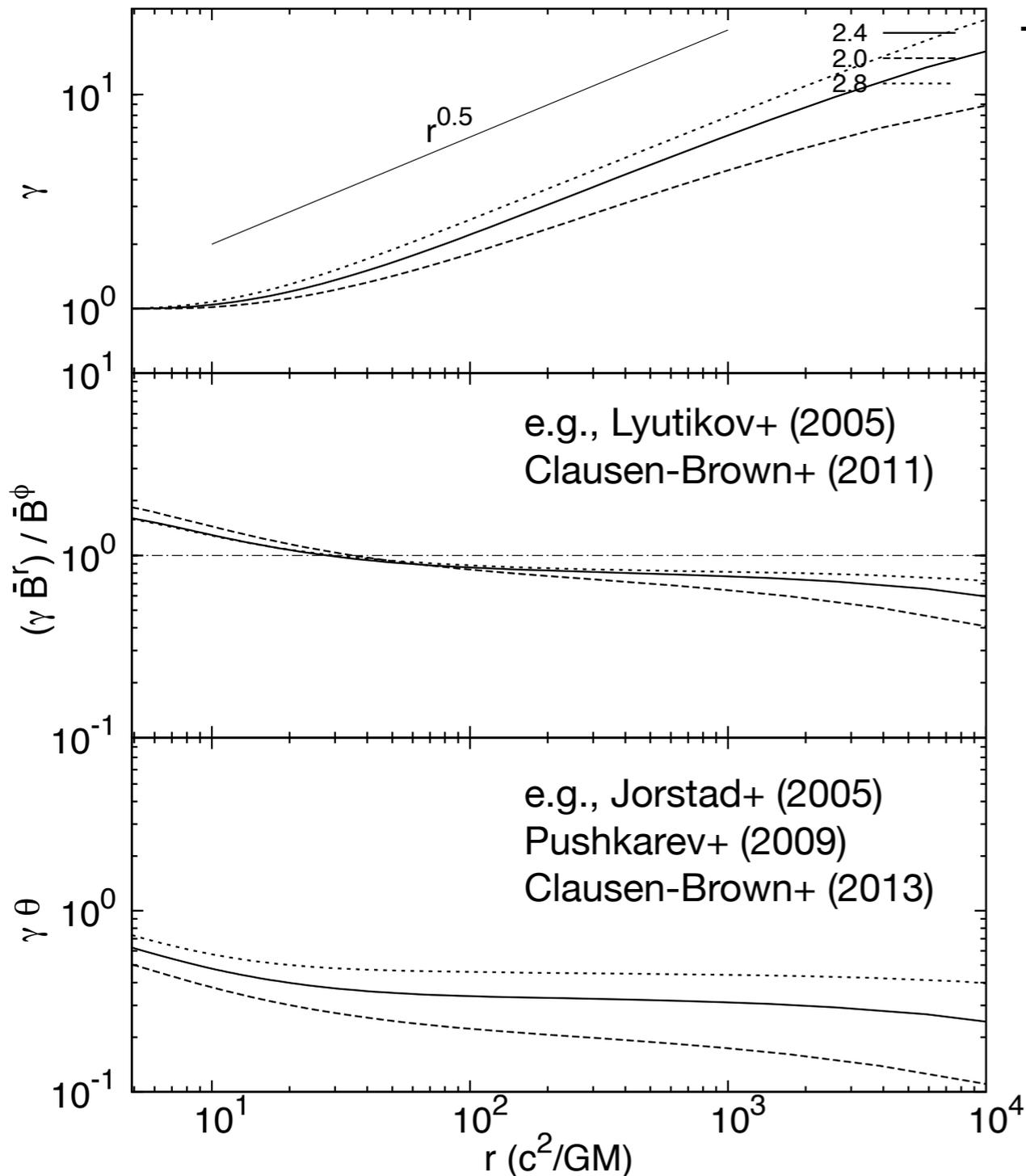


Resolved Spine-sheath Parabolic Streams?



Fate of GRMHD Jets: How to terminate Acceleration/Collimation?

Pu, MN+ in prep.



- Capability of cold RMHD jet acceleration can be measured by the total (matter + Poynting)-to-matter energy flux ratio:

$$\frac{\mu}{\gamma} = 1 + \sigma$$

σ : Poynting-to-matter energy flux ratio

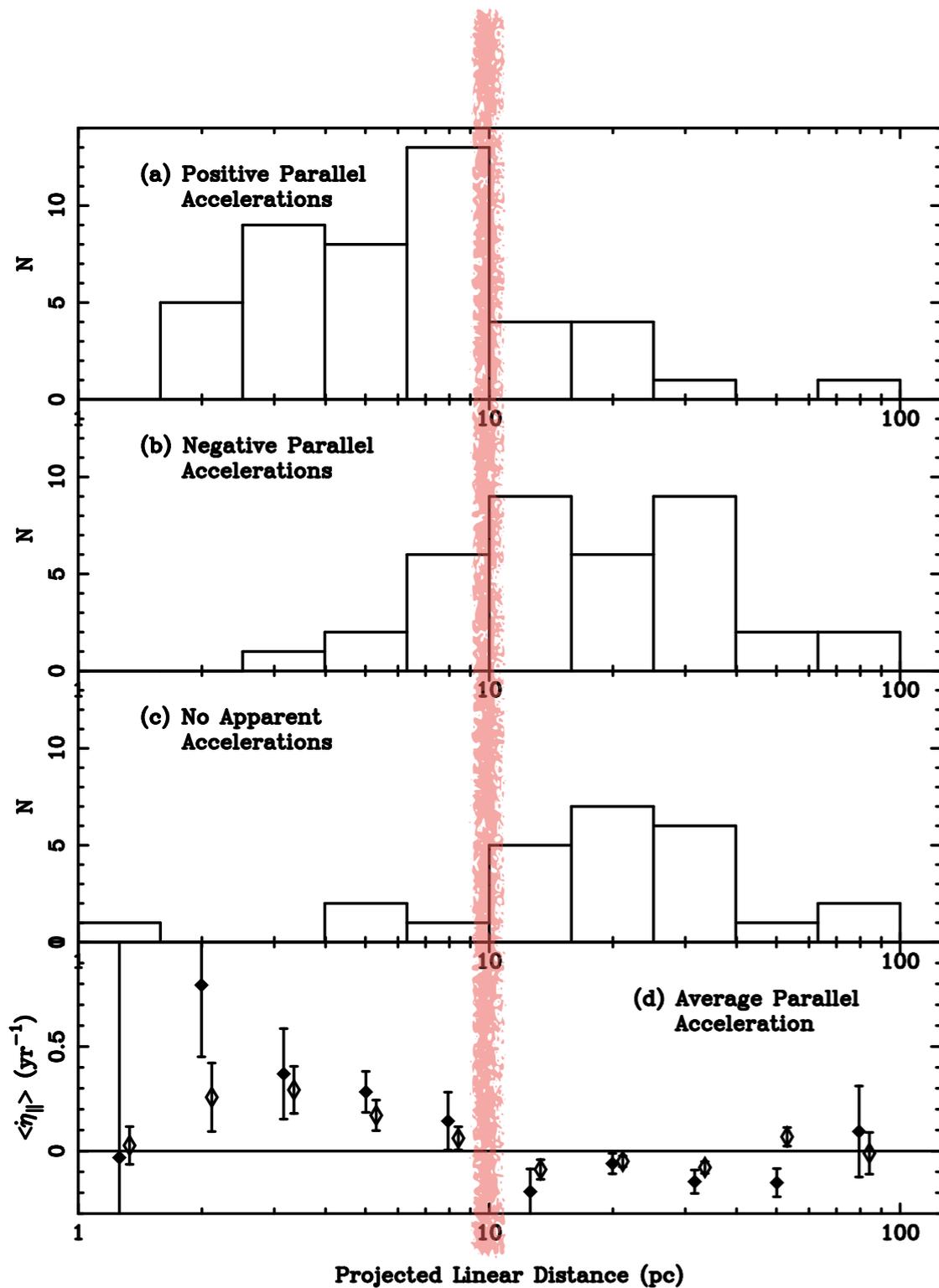
$$\gamma_\infty \simeq \mu (\sigma_\infty \simeq 0)$$

$$\mu \sim 10^{1-3}$$

(Beskin 2010; Nokhrina+ 2015)

$\mu \simeq 10$ would be
 $\sigma_\infty \simeq 0$ universal?

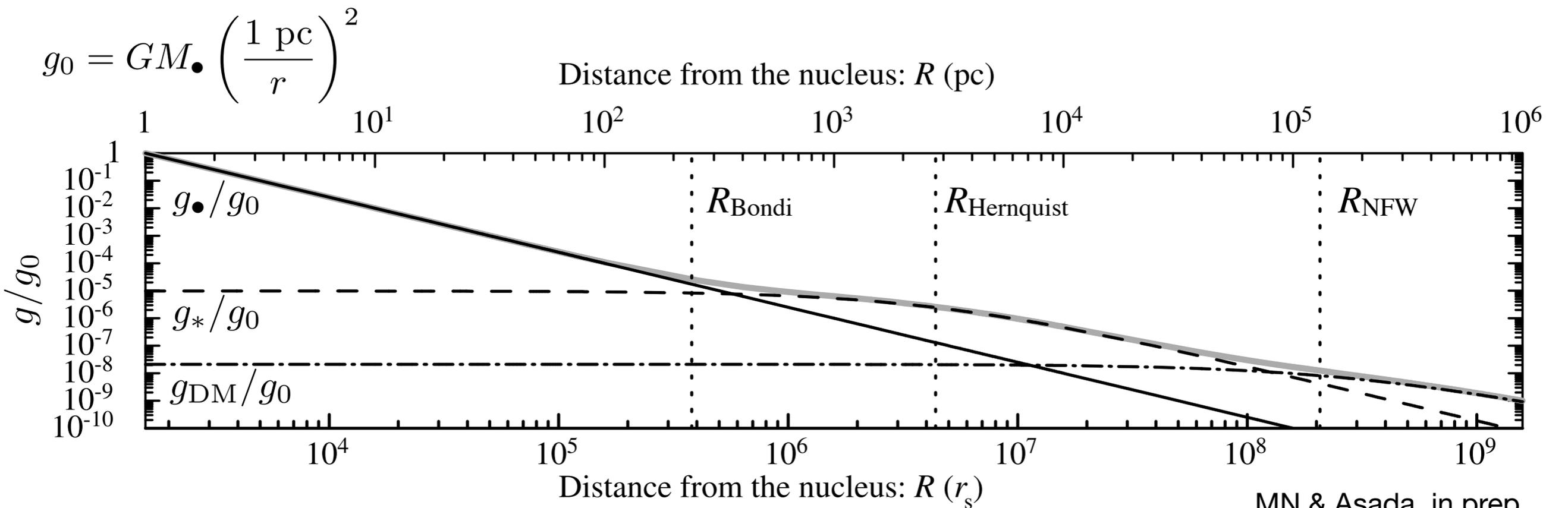
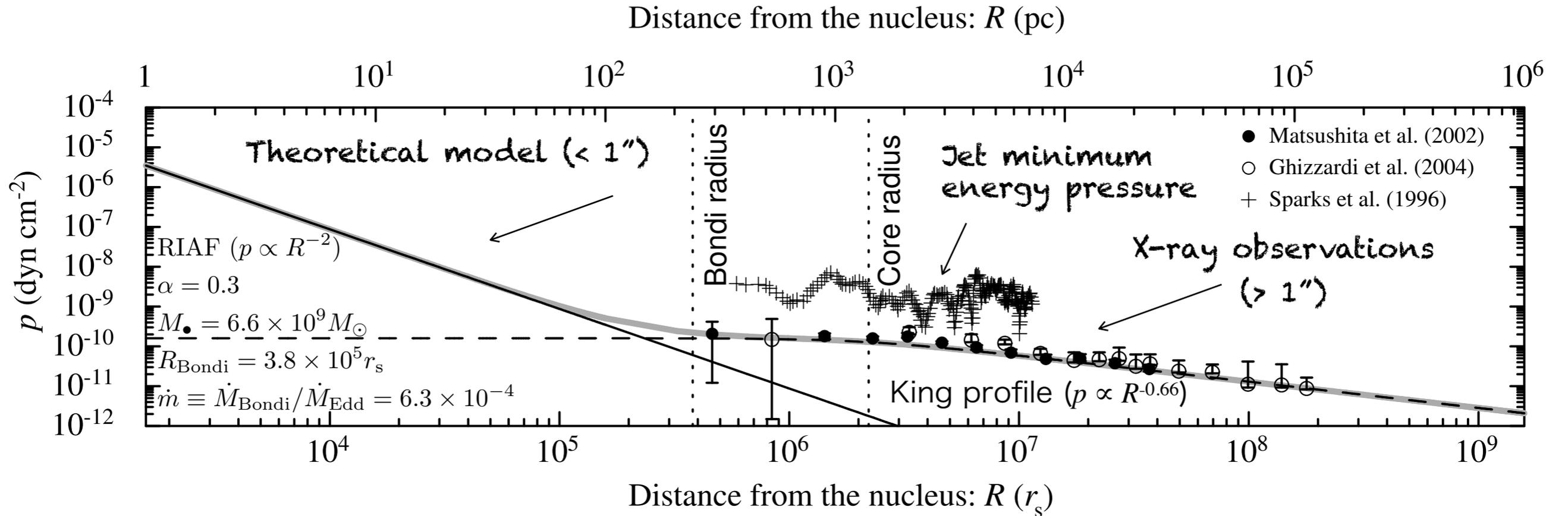
Similarity found in MOJAVE AGNs



Homan+ (2015)

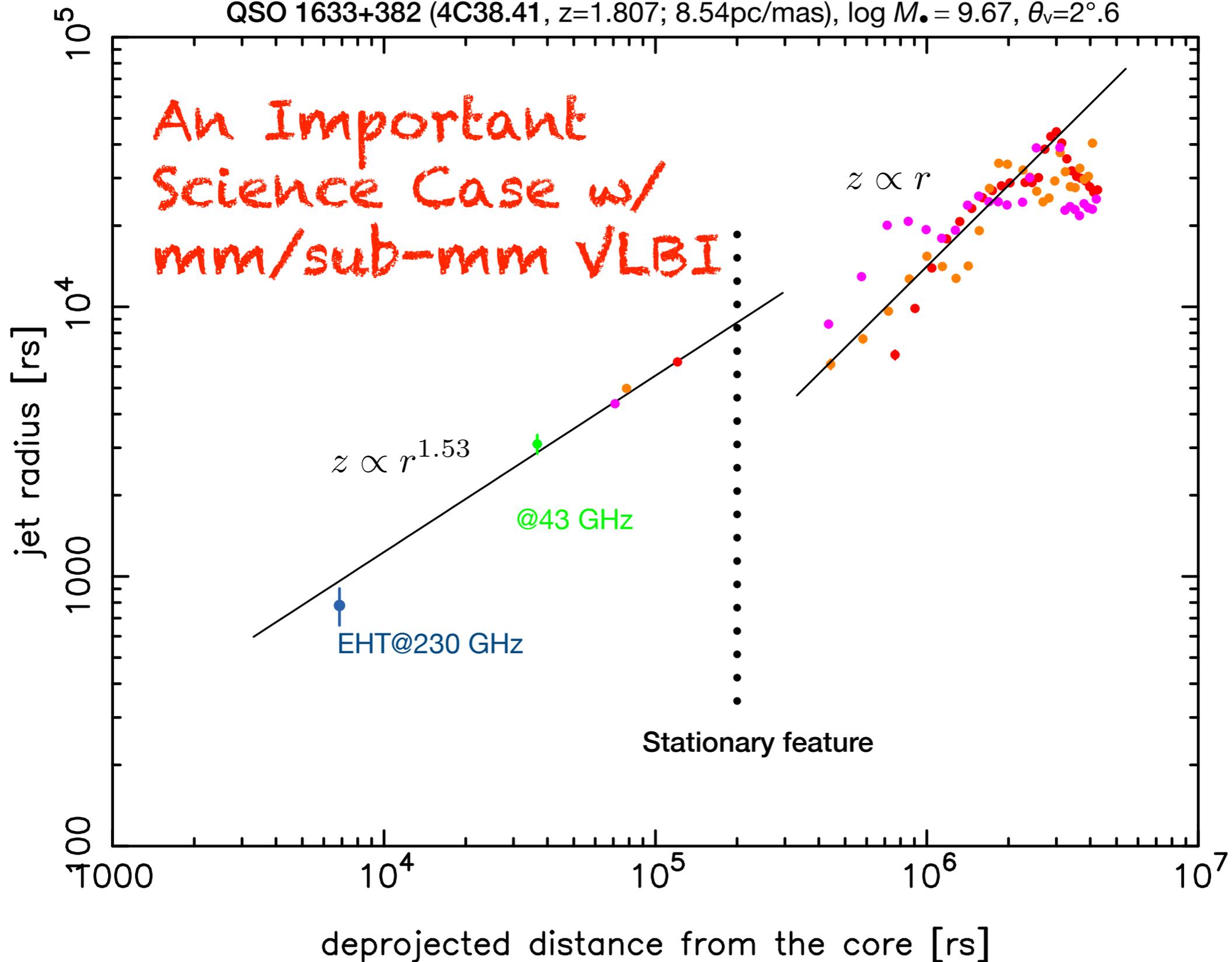
- A transition from positive to negative acceleration seems to locate at ~ 10 pc (Lister+ 2013; Homan+ 2014)
 $\Rightarrow \sim 100$ pc in de-projection w/ $\theta_V \sim 5^\circ$
- Non-ballistic flows are strongest at < 10 pc; jets are expanding less rapidly than $z \propto r$, so that jets is still being collimated (Homan+ 2014; also Pushkarev & Kovalev 2012 w/ T_b analysis)
- “Jet break”, induced by a stationary component; one of the key observables (MN & Norman, in prep.)

Hierarchical Structure of ISM



Jet Break in Blazar

QSO 1633+382 (4C38.41, $z=1.807$; 8.54pc/mas), $\log M_{\bullet} = 9.67$, $\theta_v=2^{\circ}.6$



Courtesy: K. Asada

Summary

- **M87; a prototype of relativistic jets in AGNs, showing fundamental properties of the global structure & dynamics**
- **mm/sub-mm VLBI towards M87 (blazars) will give a certain clue for the jet formation (acceleration/collimation)**
- **Slow acceleration and collimation appears to be the norm in AGNs (Need a matching between theory and obs.)**
- **“Jet break” gives a crucial understanding how AGN jets interplay with SMBHs and their host galaxies**
- **Theoretical investigation of RMHD jets, interacting with stratified ISMs, is essential (on-going)**