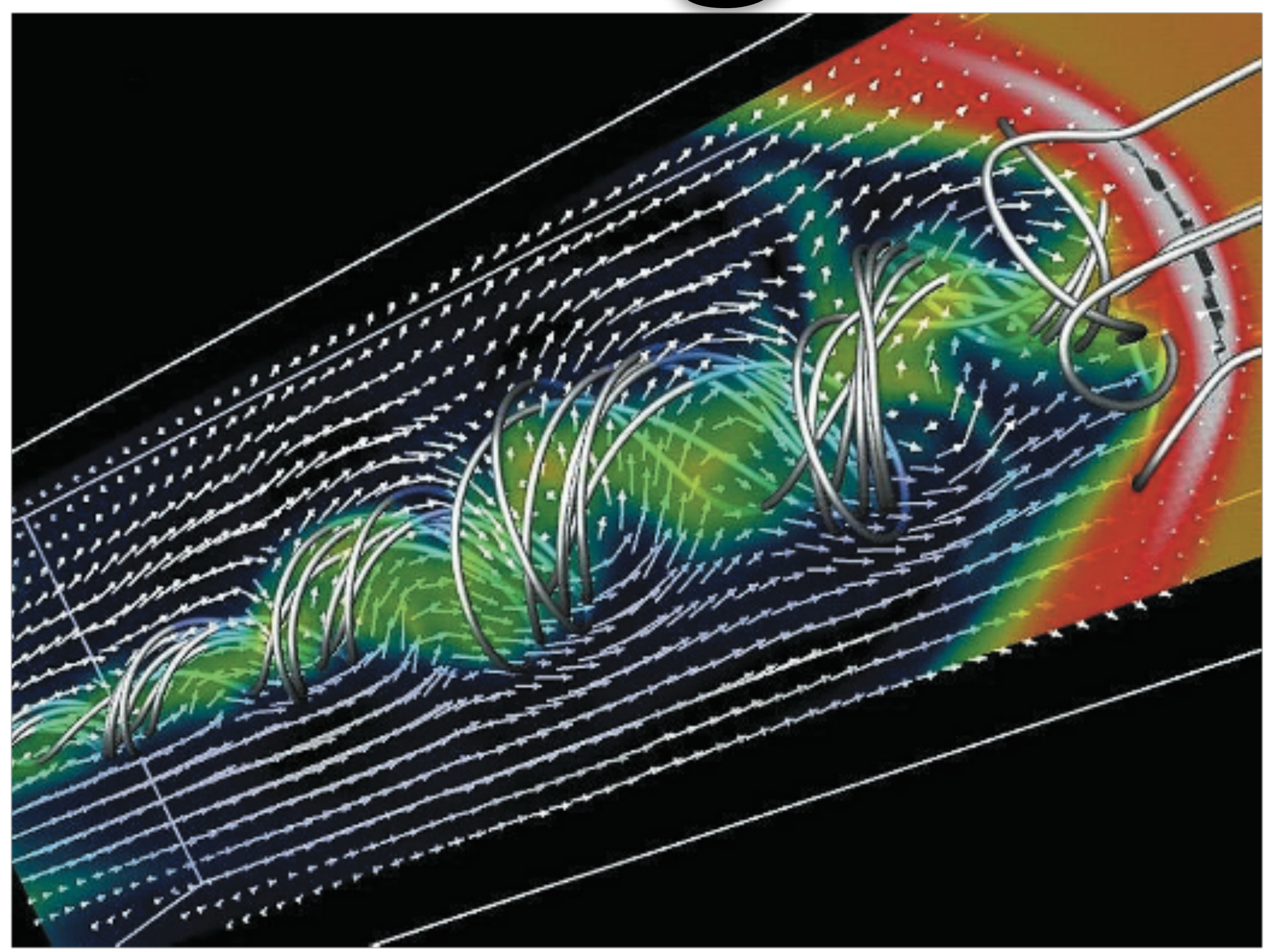
Simulations of AGN Jets: ^& Observation from Small to Large Scales



Masanori Nakamura (ASIAA, Taiwan)

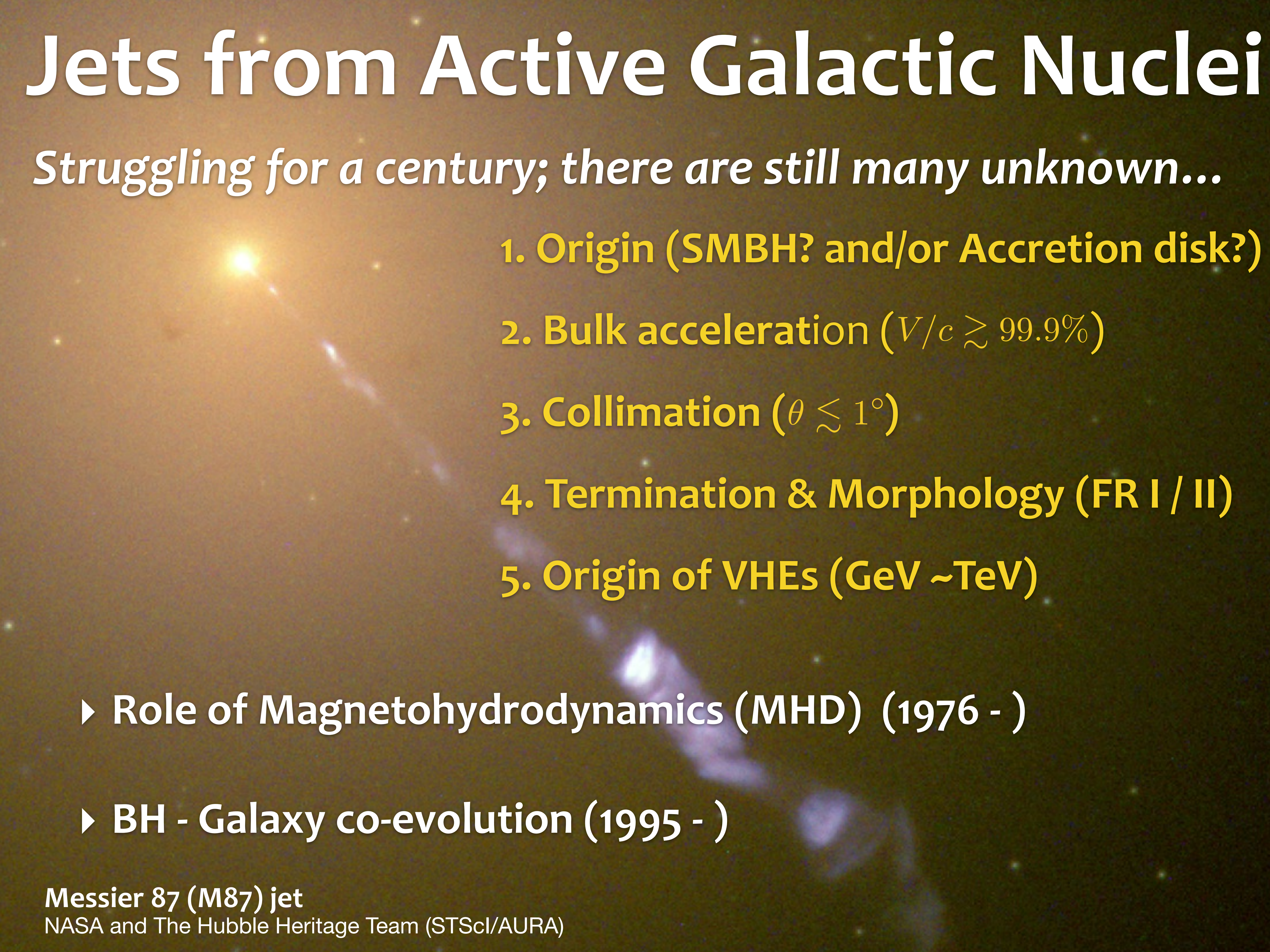
10/17 - 21, 2016 “Shining from the Heart of Darkness: Black Hole Accretion & Jets”, Kathmandu, Nepal

Jets from Active Galactic Nuclei

Struggling for a century; there are still many unknown…

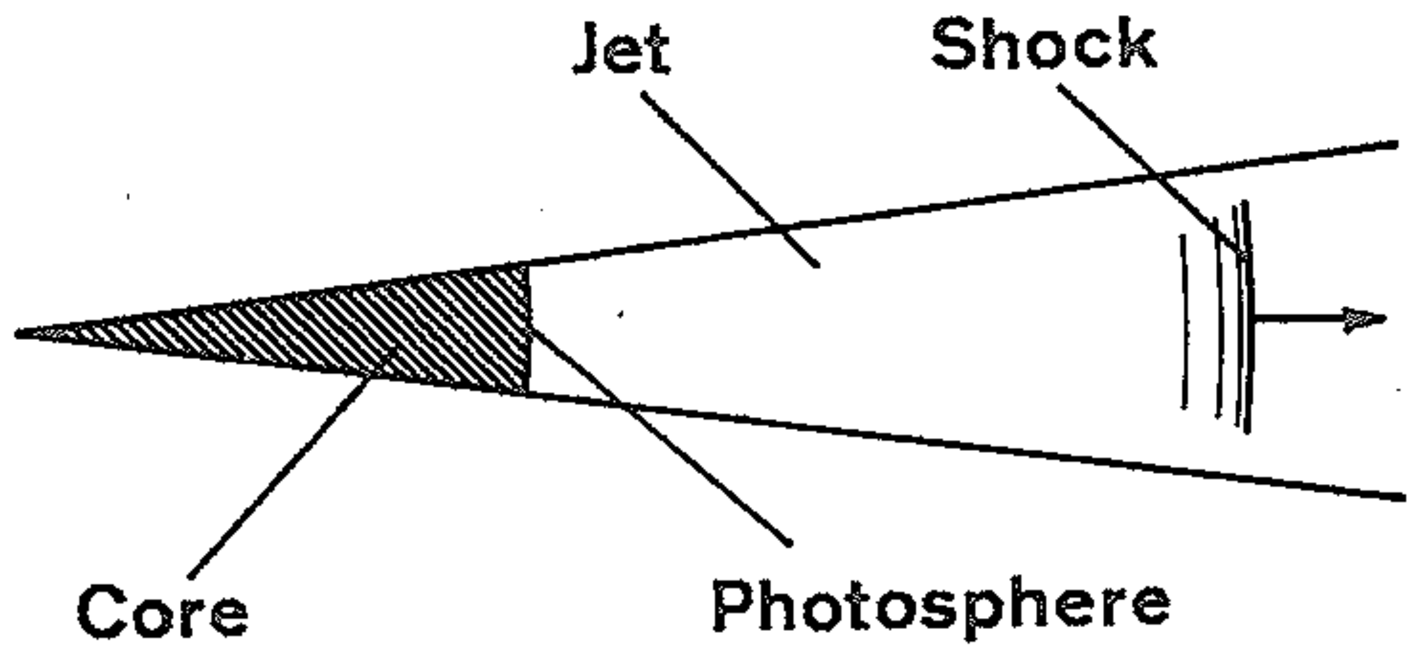
1. Origin (SMBH? and/or Accretion disk?)
2. Bulk acceleration ($V/c \gtrsim 99.9\%$)
3. Collimation ($\theta \lesssim 1^\circ$)
4. Termination & Morphology (FR I / II)
5. Origin of VHEs (GeV ~TeV)

- Role of Magnetohydrodynamics (MHD) (1976 -)
- BH - Galaxy co-evolution (1995 -)



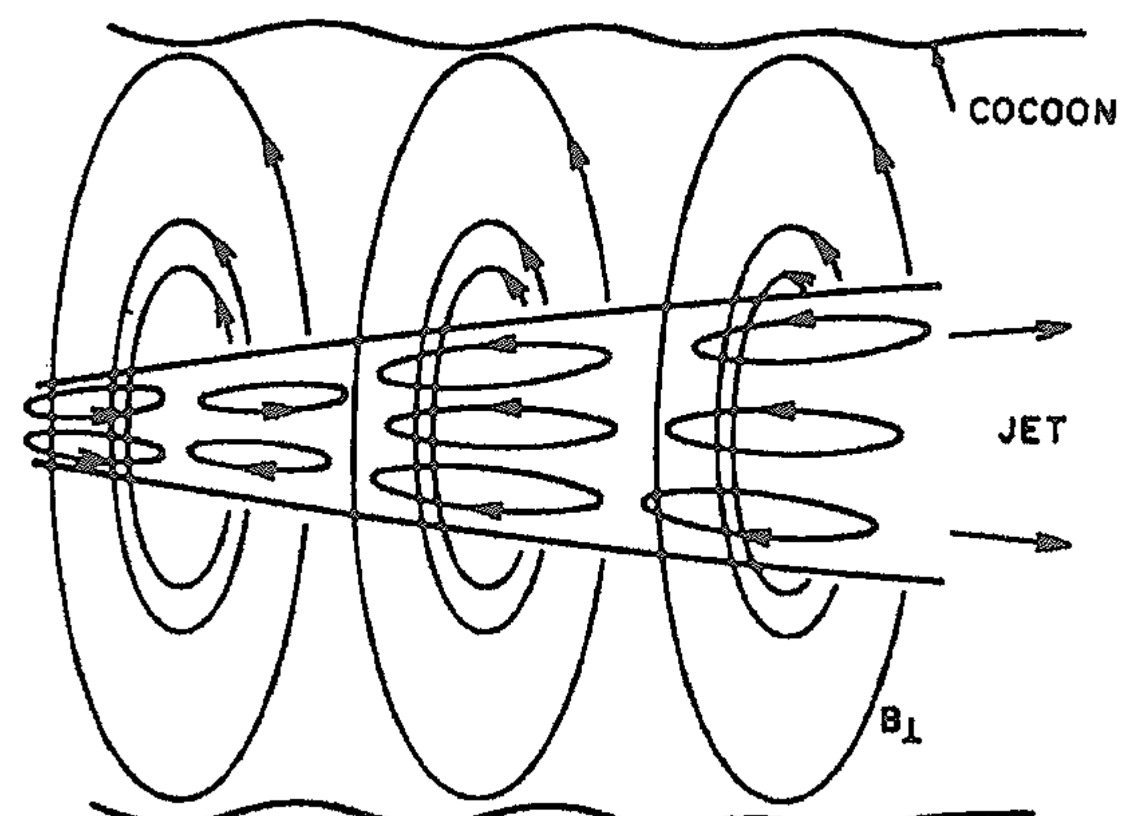
Messier 87 (M87) jet
NASA and The Hubble Heritage Team (STScI/AURA)

Classical Issue: *Collimated or not?*



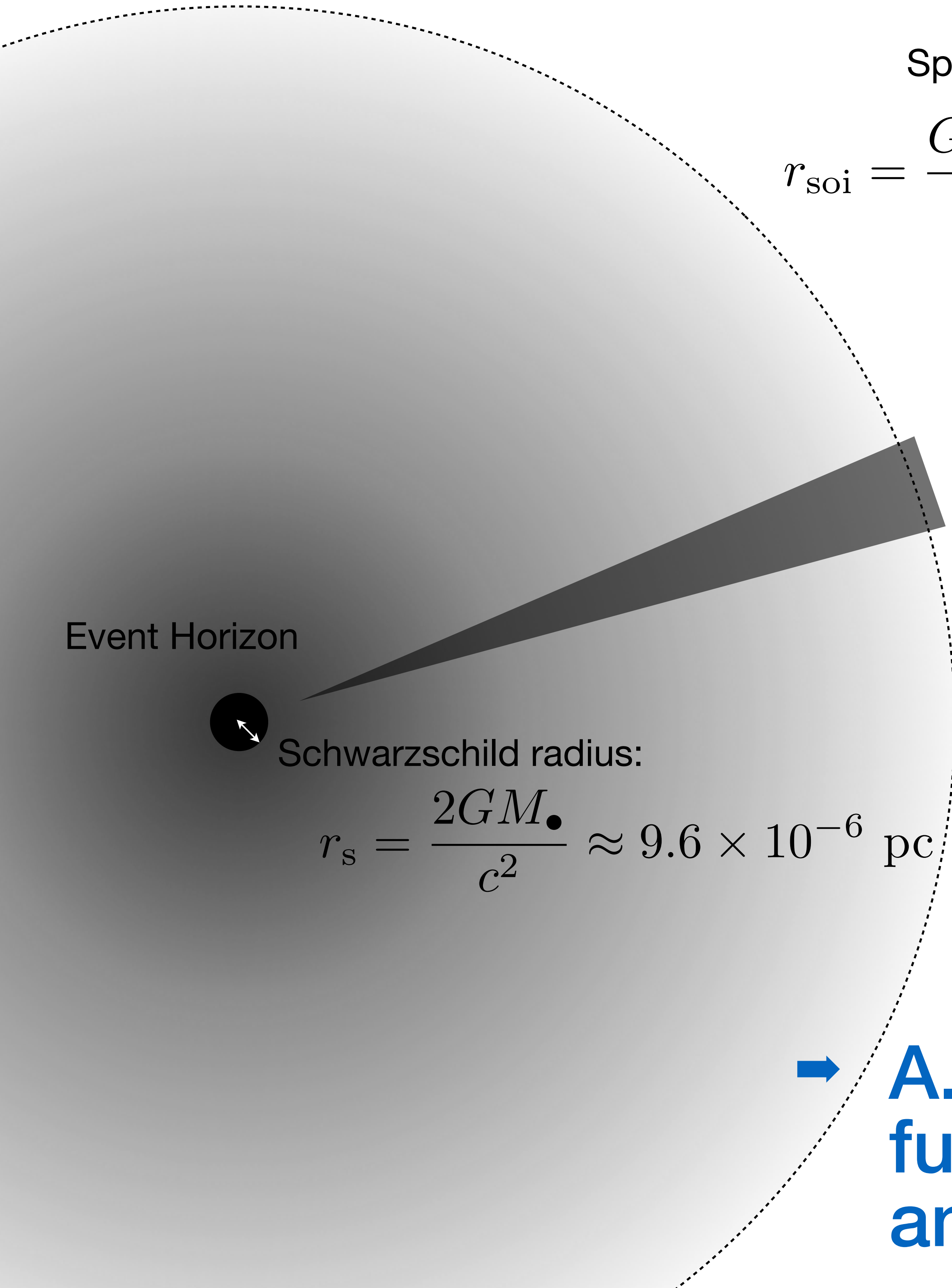
- Conical jet paradigm
  (e.g., Blandford & Königl 1979)

- Hoop-stress (collimation) paradigm
  (e.g., Sakurai 1985;
  Heyvaerts & Norman 1989)



Figures from Blandford+ (1990)

Jets under the BH-Gal. Co-evolution



Sphere of influence:

$$r_{\rm soi} = \frac{GM_\bullet}{\sigma^2} \approx 11~{\rm pc} \left(\frac{M_\bullet}{10^8 M_\odot} \right) \left(\frac{\sigma}{200~{\rm km}} \right)^{-2}$$

Q. How do the dynamical and geometrical properties of super-escape jets change beyond the SOI (*or not*)?

Schwarzschild radius:

$$r_{\rm s} = \frac{2GM_\bullet}{c^2} \approx 9.6 \times 10^{-6}~{\rm pc} \left(\frac{M_\bullet}{10^8 M_\odot} \right)$$

➡ **A. This is intimately related to the fundamental problem (“acceleration and collimation”) in AGN jets**

MHD Jets

Development During Four Decades

Faraday disc (Homopolar generators)

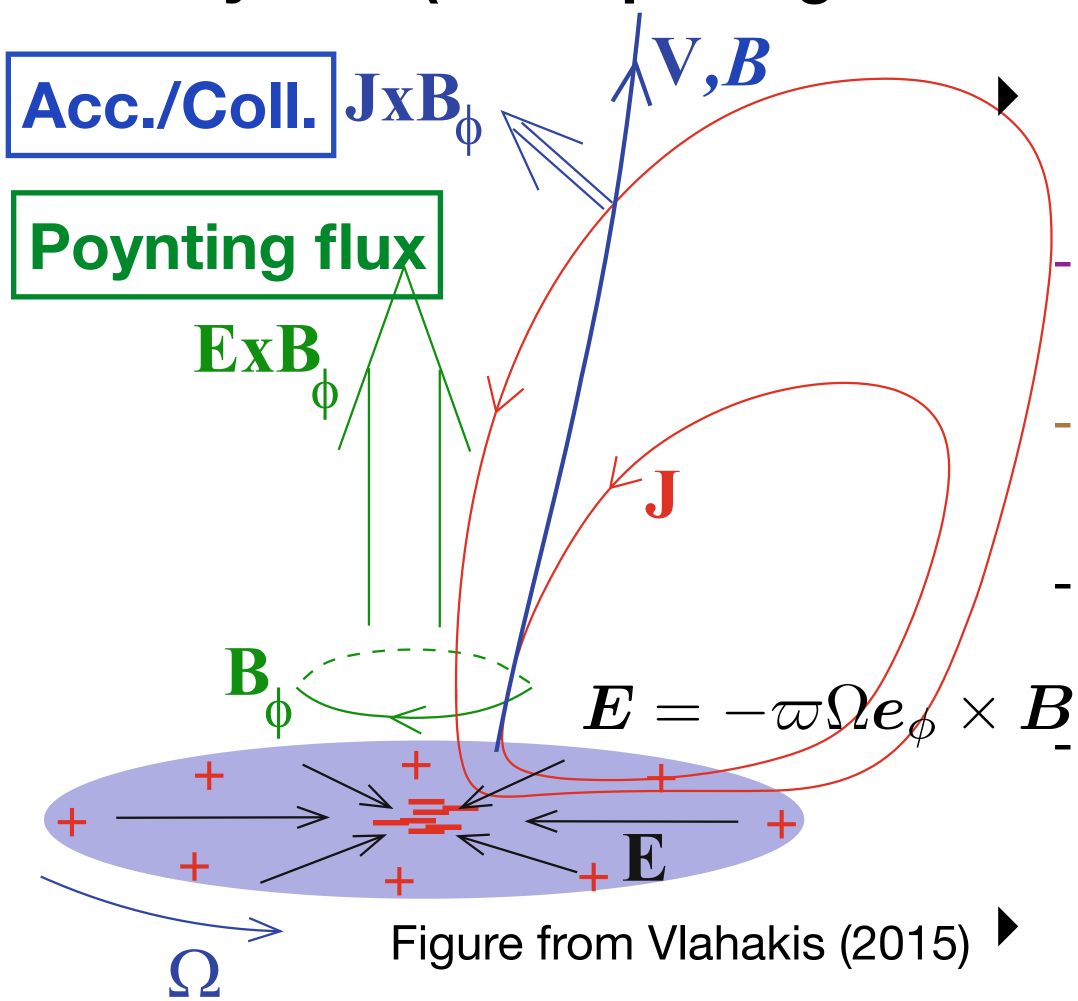


Figure from Vlahakis (2015)

Blandford & Payne (1982) Blandford & Znajek (1977)

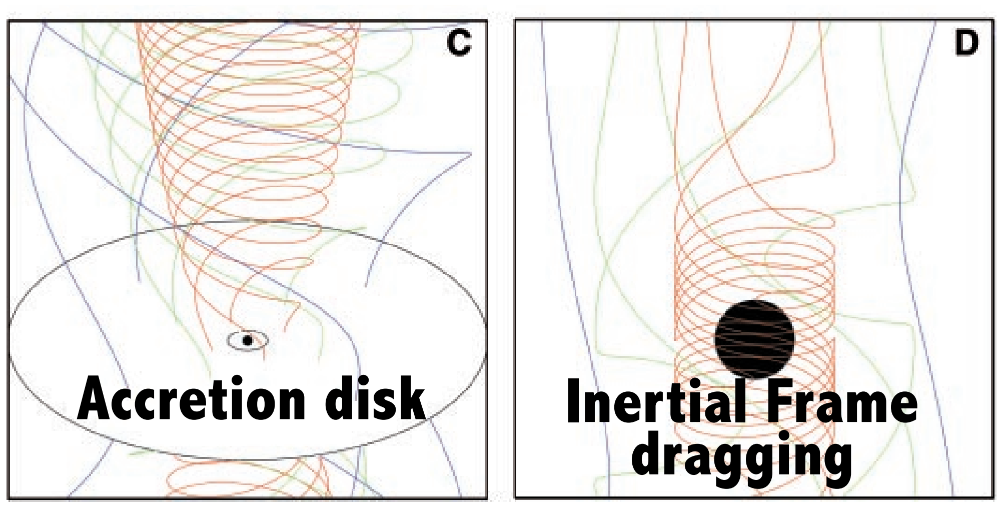
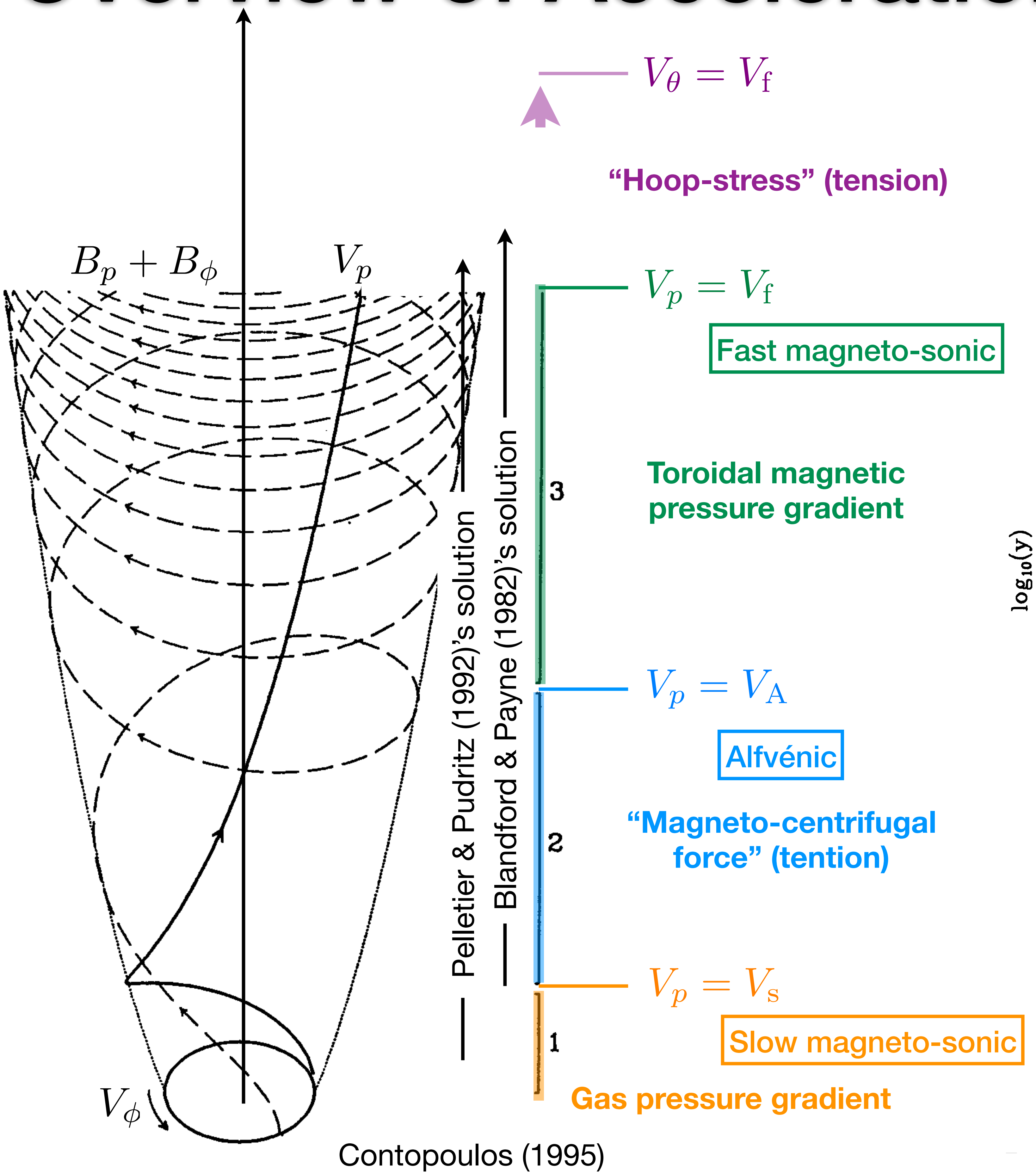
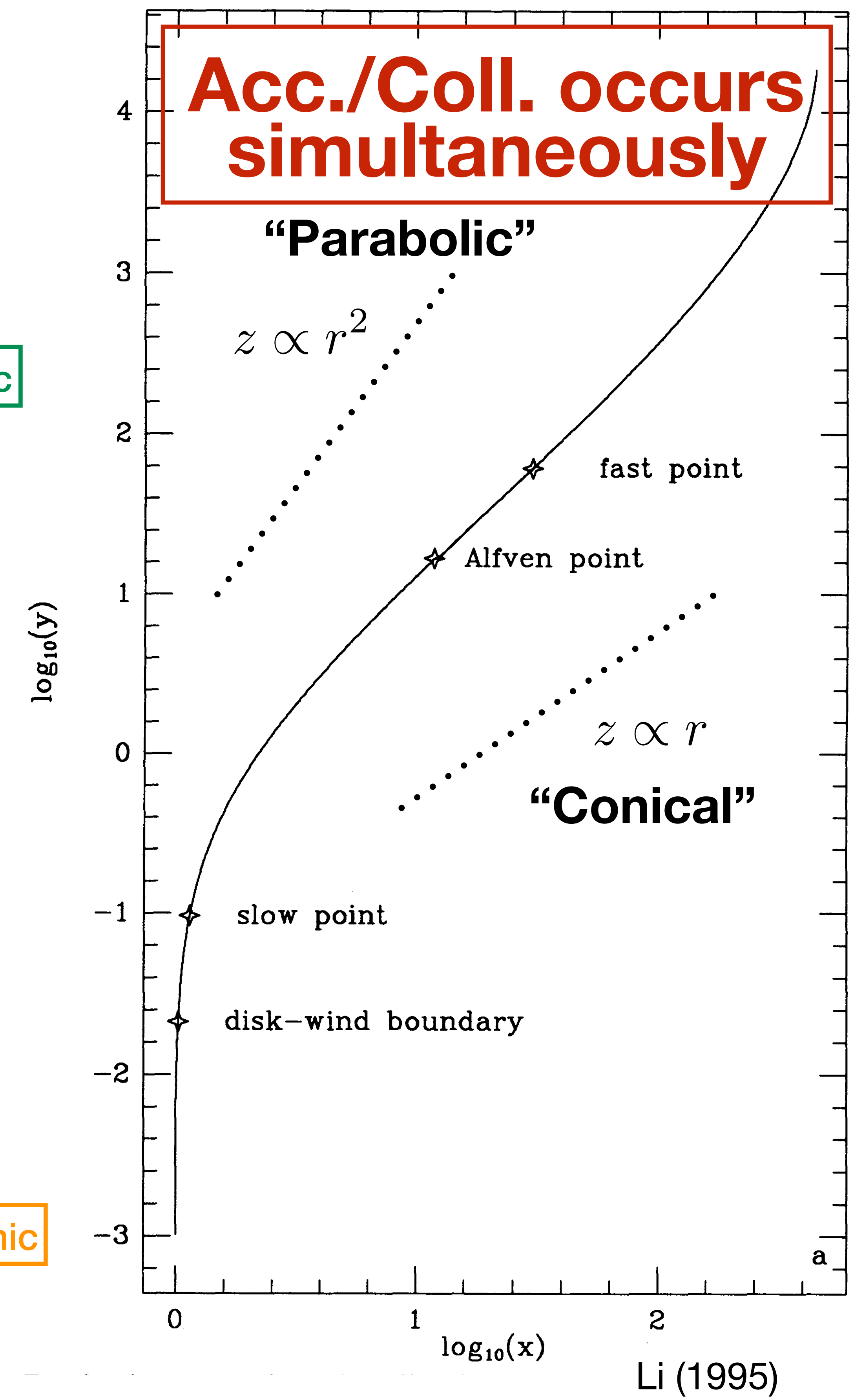


Figure from Meier+ (2001)

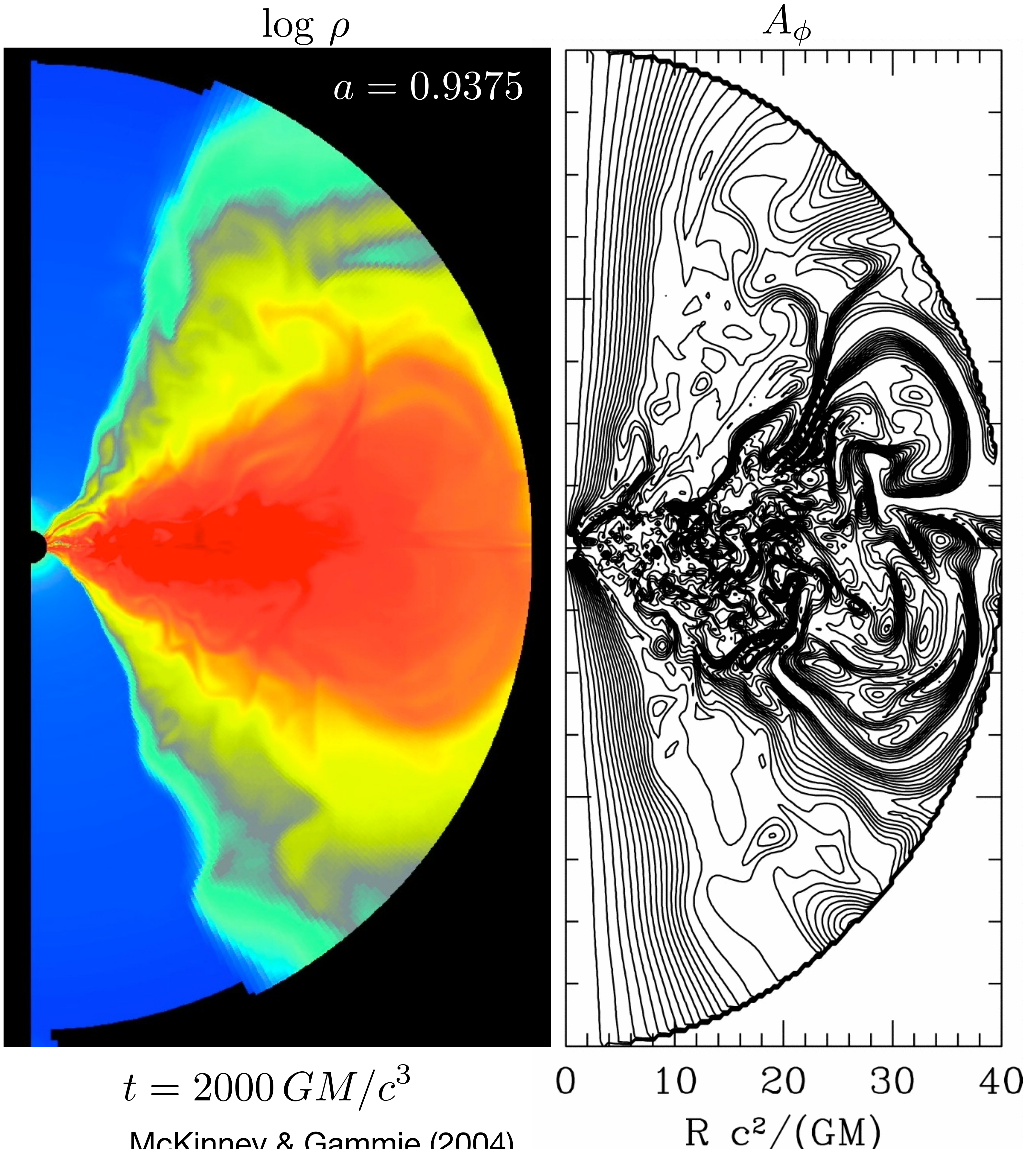
- **Steady, axisymmetric EM/MHD winds (e.g., Weber & Davis 1967; Goldreich & Julian 1969)**
  - Blandford & Znajek (1977): EM energy extraction from the Kerr black hole
  - Blandford & Payne (1982): self-similar NRMHD jets from the Kepler disk
  - Li+ (1992): generalized BP82 in the SRMHD regime (*see also* Vlahanigl 2003, Polko+ 2013)
  - Pu, MN+ (2015): generalized BZ77 in the GRMHD regime (inflow/outflow; c.f. McKinney+2006)
- **Non-steady MHD jets/winds**
  - Uchida & Shibata (1985): 2.5D NRMHD simulation of disk-magnetosphere interactions
  - Ustyugova+ (1995), Meier+ (1997), Ouyed & Pudritz (1997): long term simulations w/ a fixed disk boundary (→quasi-steady state)
  - SRMHD simulations w/ a fixed jet wall (Komissarov+ 2007, 2009; Tchekhovskoy+ 2009)
  - GRMHD simulations (Koide 1999; De Villiers+ 2004; McKinney & Gammie 2004; McKinney 2006; Tchekhovskoy+ 2010)

Overview of Acceleration & Collimation



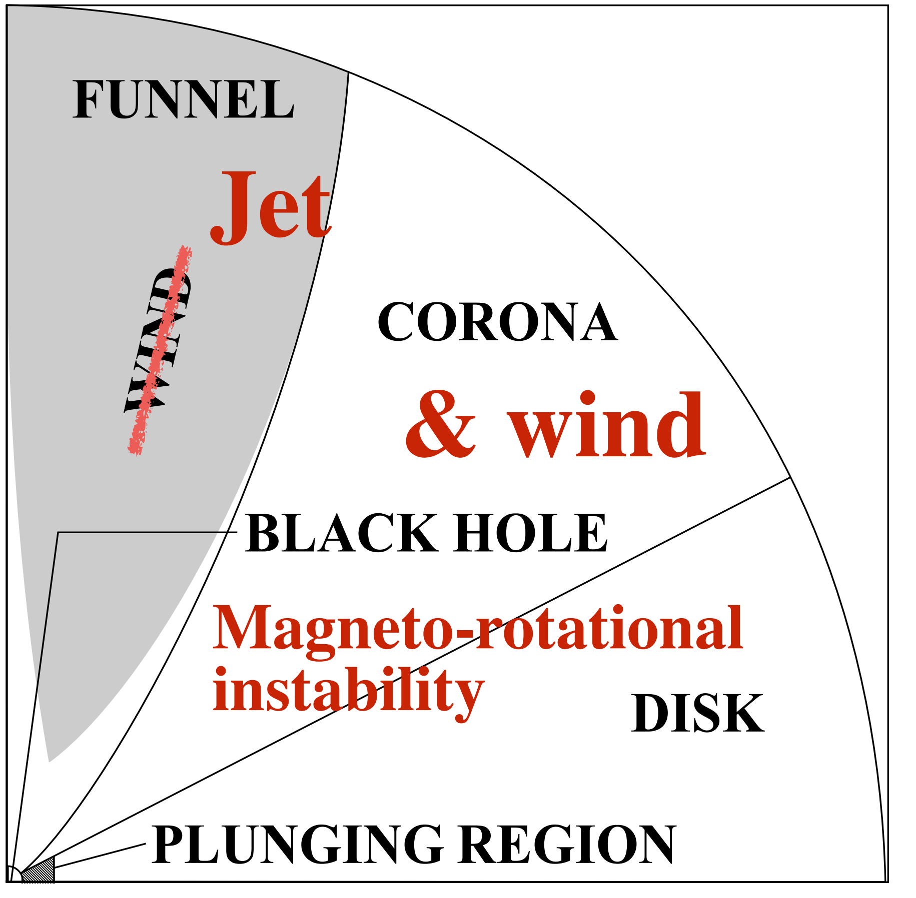


MHD Jets from Spinning BHs



McKinney & Gammie (2004)

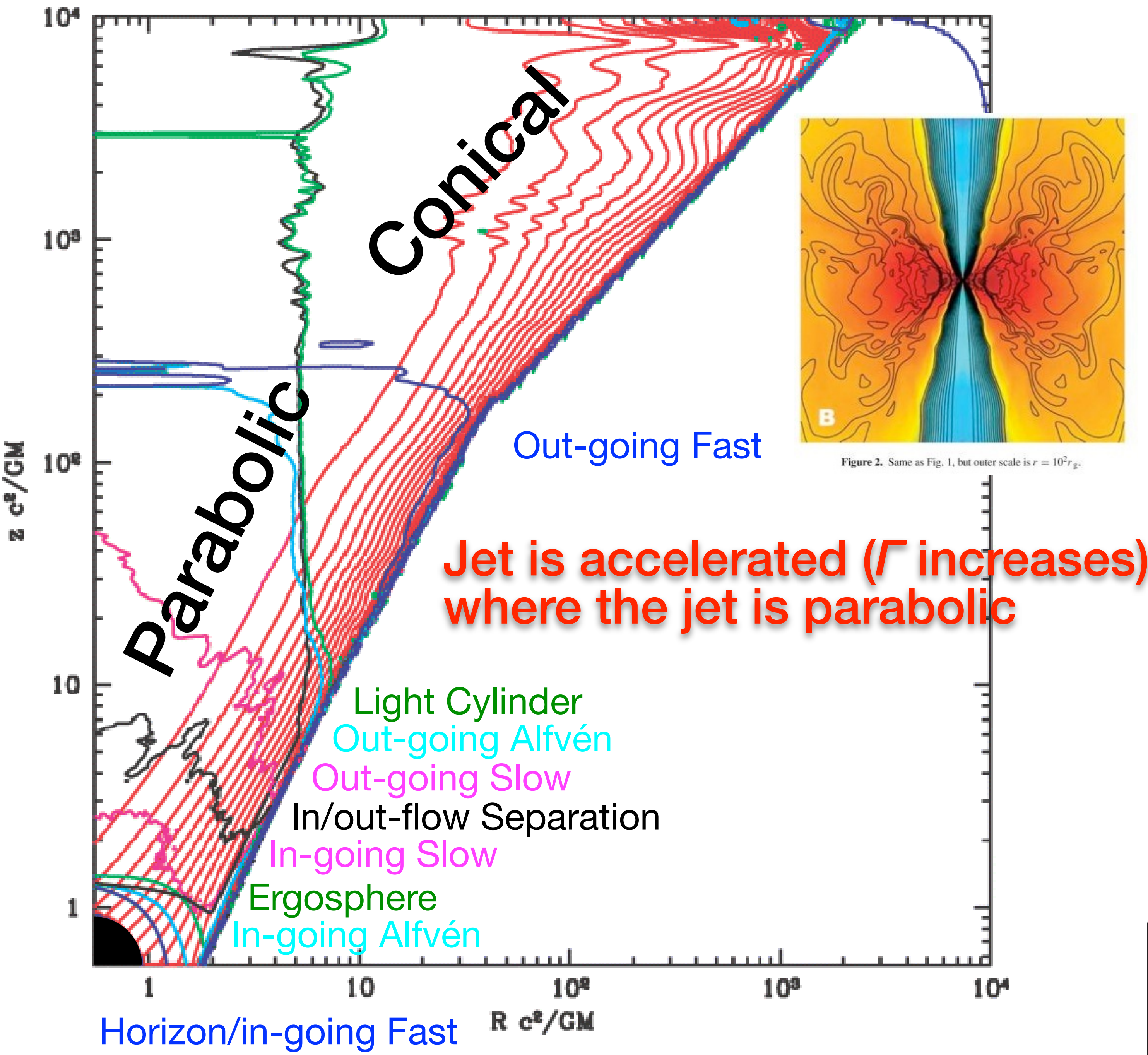
- GRMHD simulations of the radiatively inefficient accretion flow with poloidal fluxes
- Applicable to nearby LLAGNs (e.g., Sgr A*, M87, …)
- OTOH, broader emission components (in VLBA) could be the disc wind (McKinney 2006)?



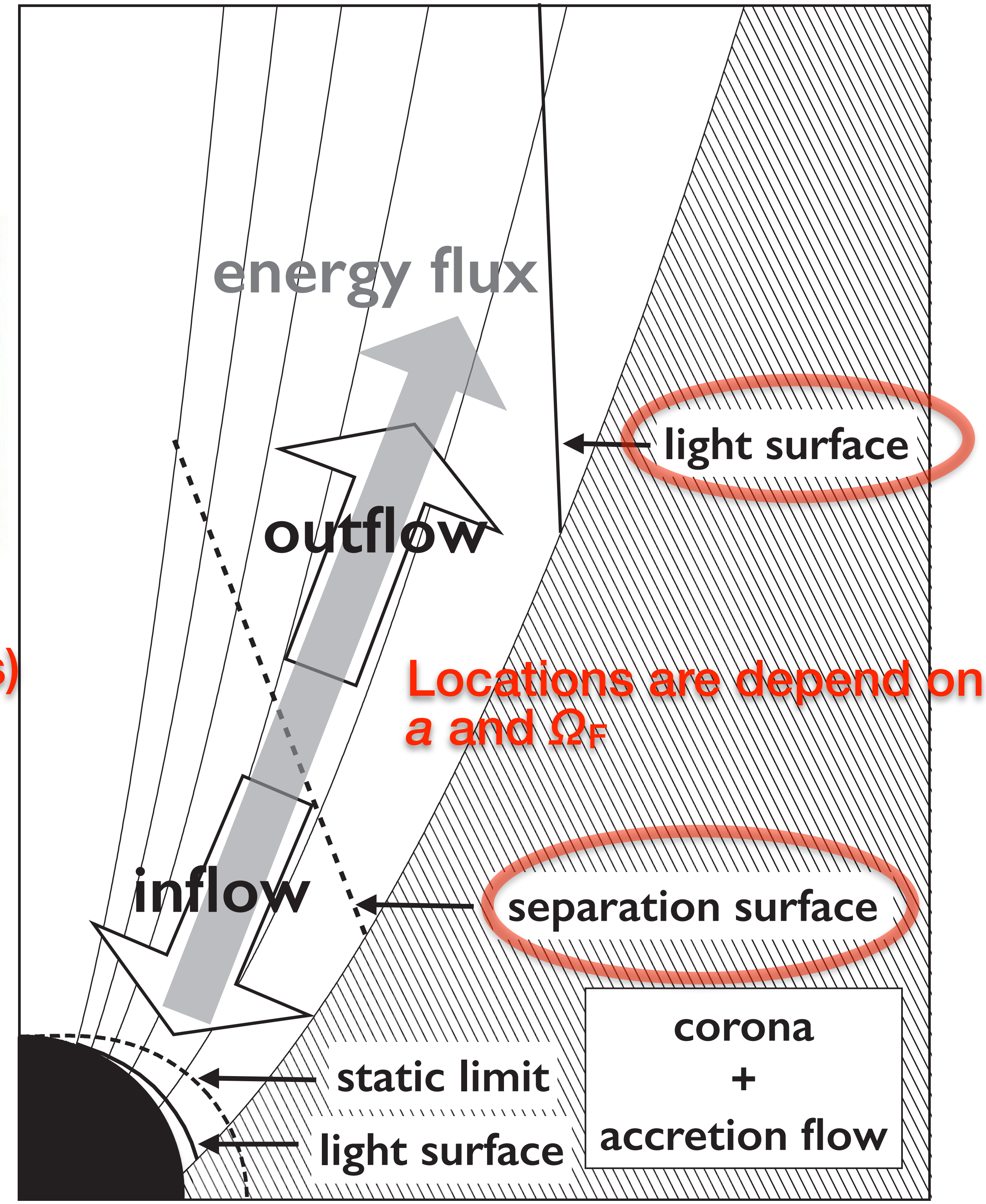
MHD Jets from Spinning BHs

GRMHD Simulation (a =0.9375)

B_p field lines and characteristic surfaces



McKinney (2006)



Pu, MN+ (2015)

Observation of MHD Jets

Observation of Radio Galaxies

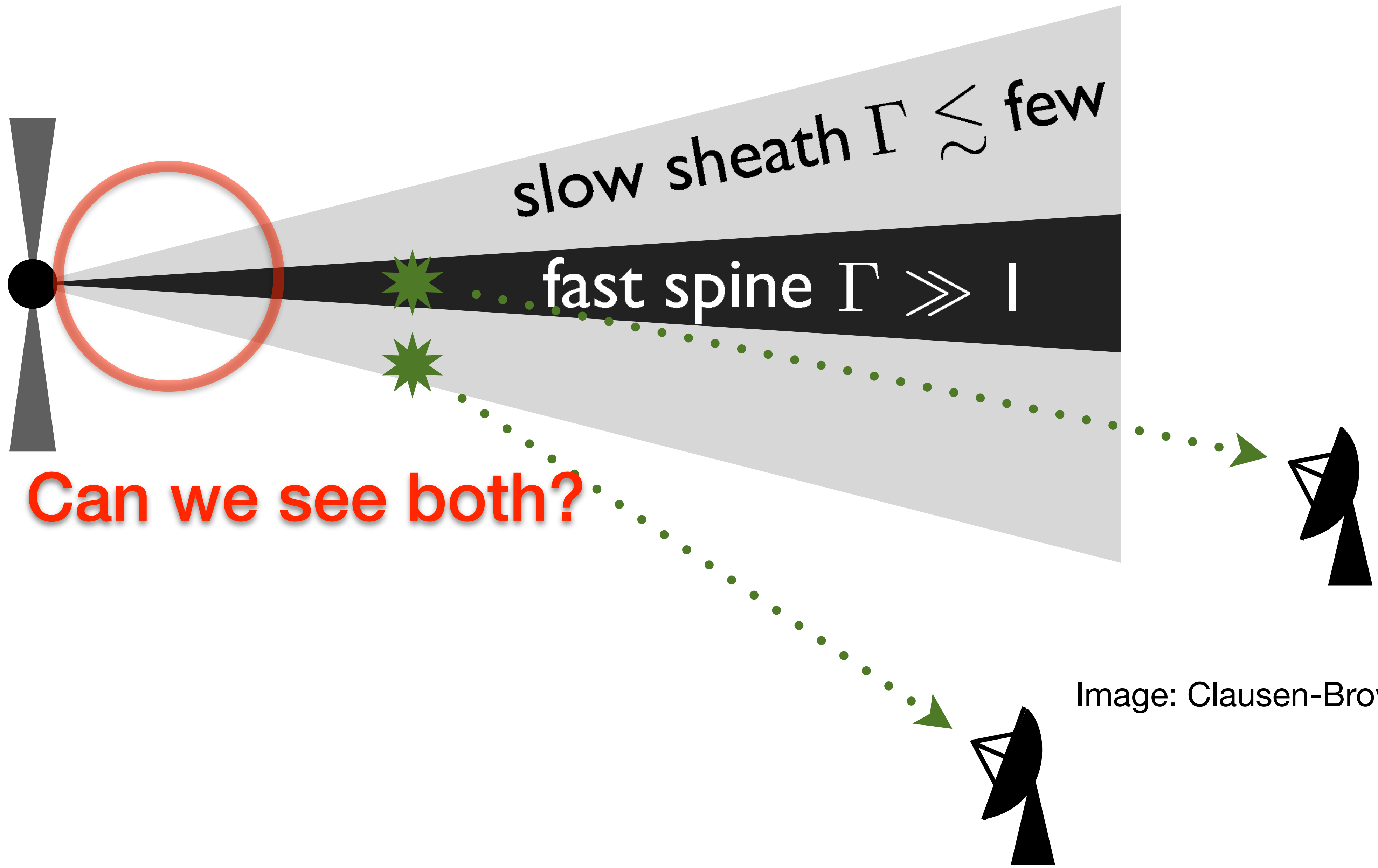


Image: Clausen-Brown+ (2013)

- **Relativistic jets can be spatially resolved**
  - **Proper motions from sub-to-superluminal regime (acceleration on sub-pc to pc/kpc)**
  - **Structure (collimation profile)**

⇔ MHD jet theory

M87 (Virgo A; NGC4486)

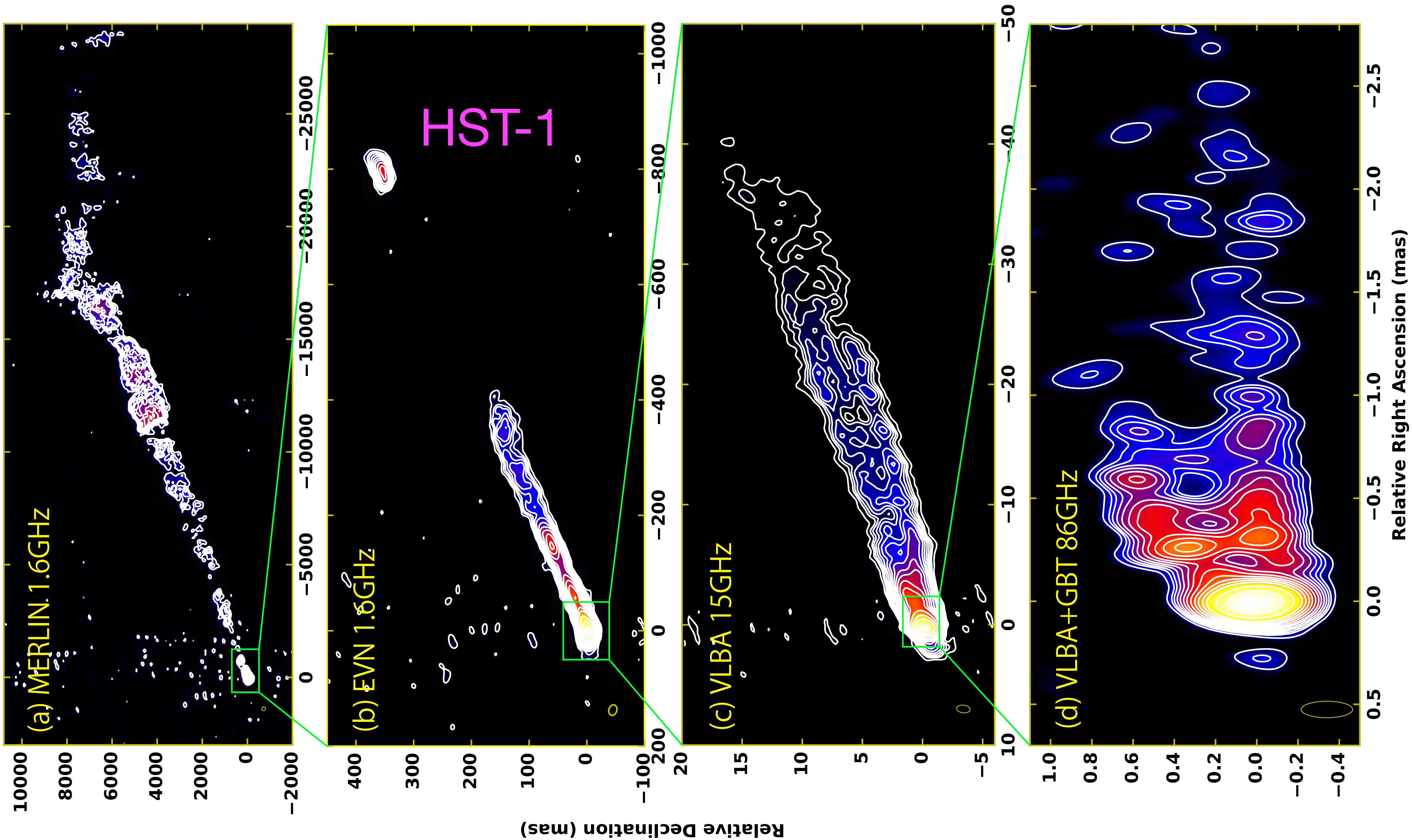
- The 1st jet discovered (Curtis 1918)
- "***Rosetta Stone***" of AGN jet (Biretta 1993)
  - Nearby: ~ 16.7 Mpc (1 mas ~ 125 r_s)
  - $M_\bullet \sim (3.2\text{-}6.6)\times10^9\,M_\odot$
  - FR I / Misaligned BL Lac ($\theta_v \sim 14°$)

esa
www.spacetelescope.org

1. 2nd largest BH shadow (~ 40 μas)
2. Relativistic outflows (≦ 6 c; 0.99c)
3. VHE TeV emissions (core/HST-1)
4. AGN feedback (radio mode) in action

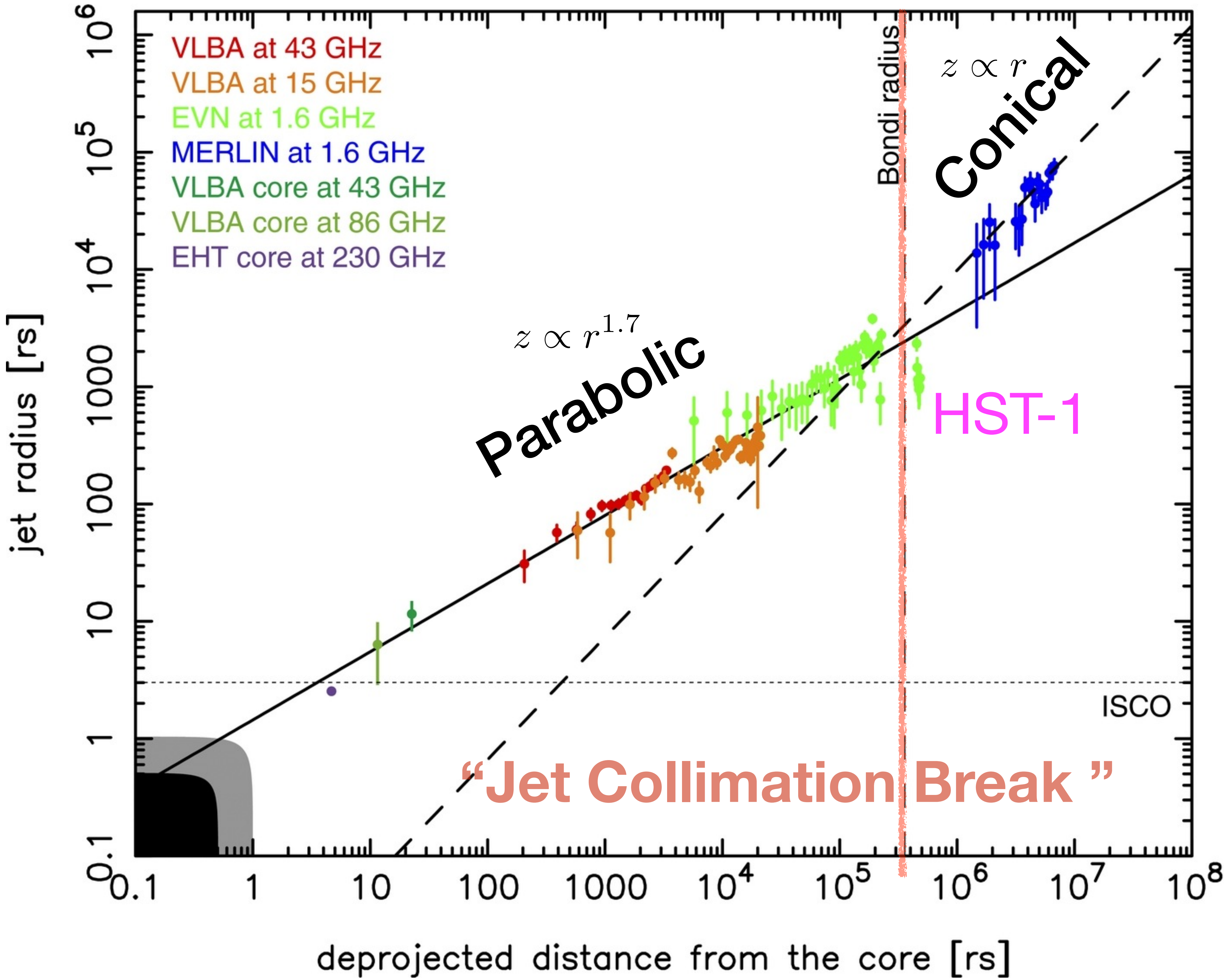
Credit:
NASA, ESA, and G. Bacon (STScI)
Constellation Region of Galaxy M87: A. Fujii
Galaxy M87: R. Gendler
Hubble View of M87 Jet: NASA, ESA, E. Meyer, W. Sparks, J. Biretta, J. Anderson, S.T. Sohn, and R. van der Marel (STScI), C. Norman (JHU), and M. Nakamura (ASIAA), and G. Bacon (STScI)

VLBI Observations of the M87 Jet



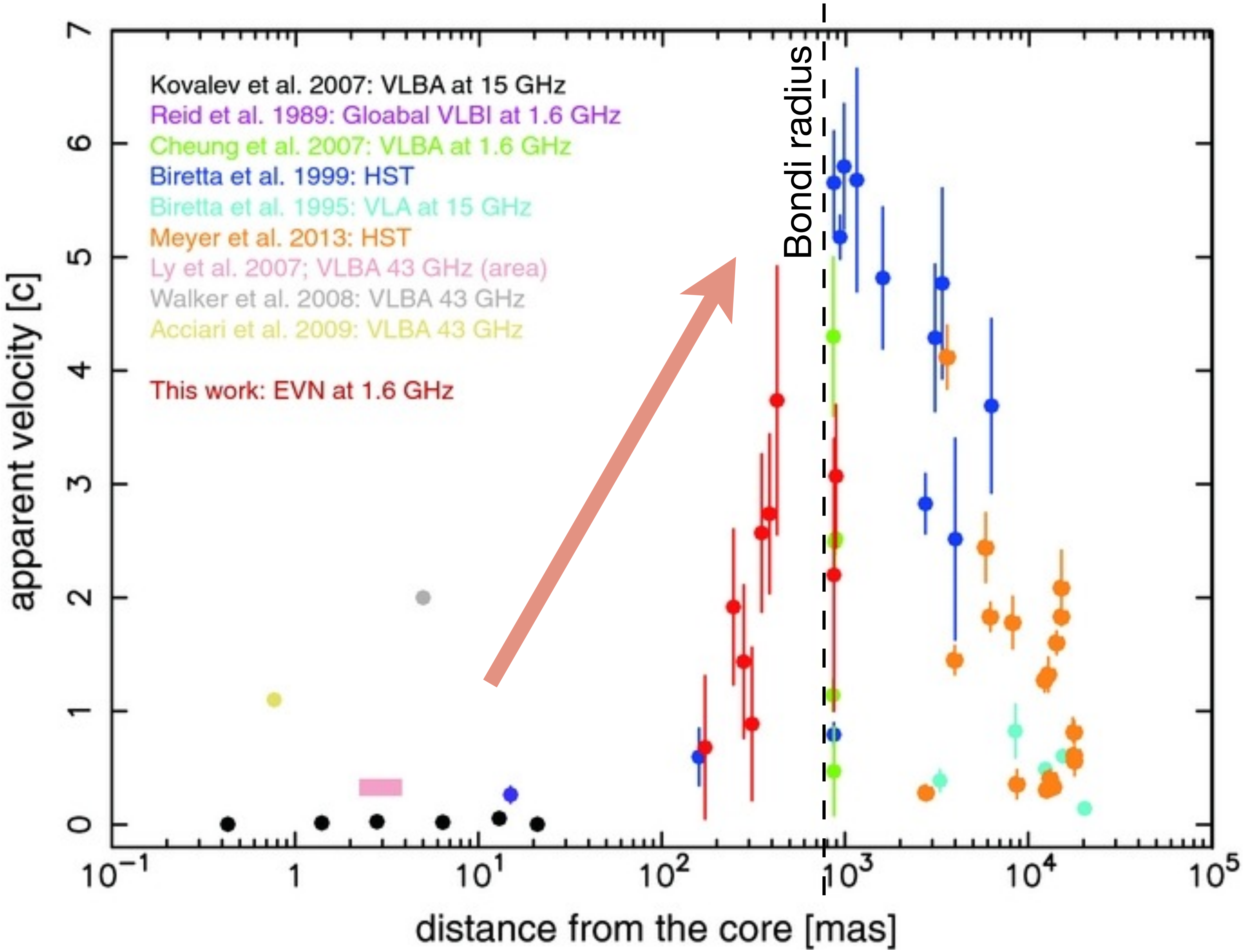
Asada & MN (2012); MN & Asada (2013); Hada+ (2013); Hada+ (2016)

Structural Transition



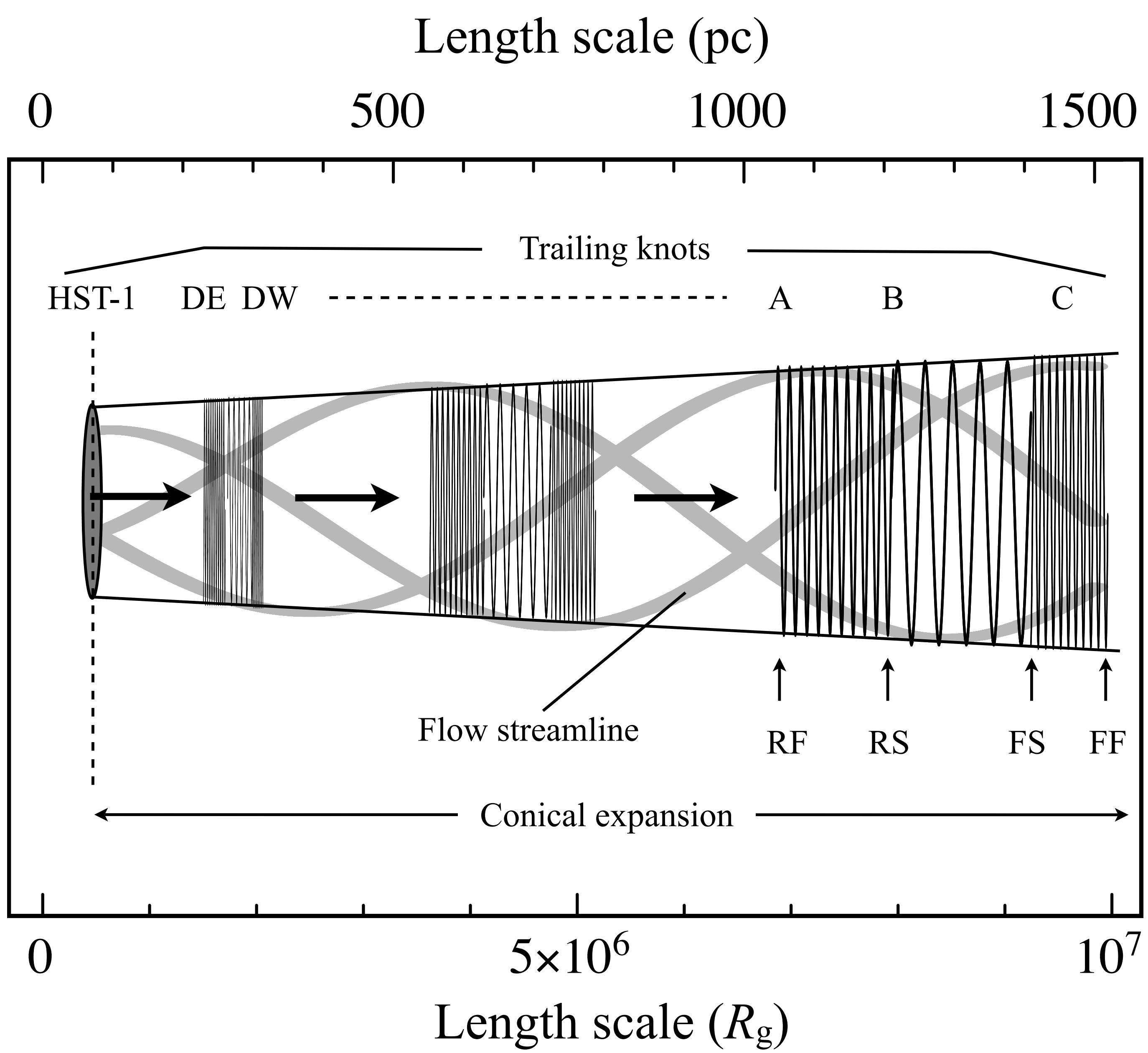
Asada & MN (2012) (*see also*, MN & Asada 2013; Hada+ 2011; 2013)

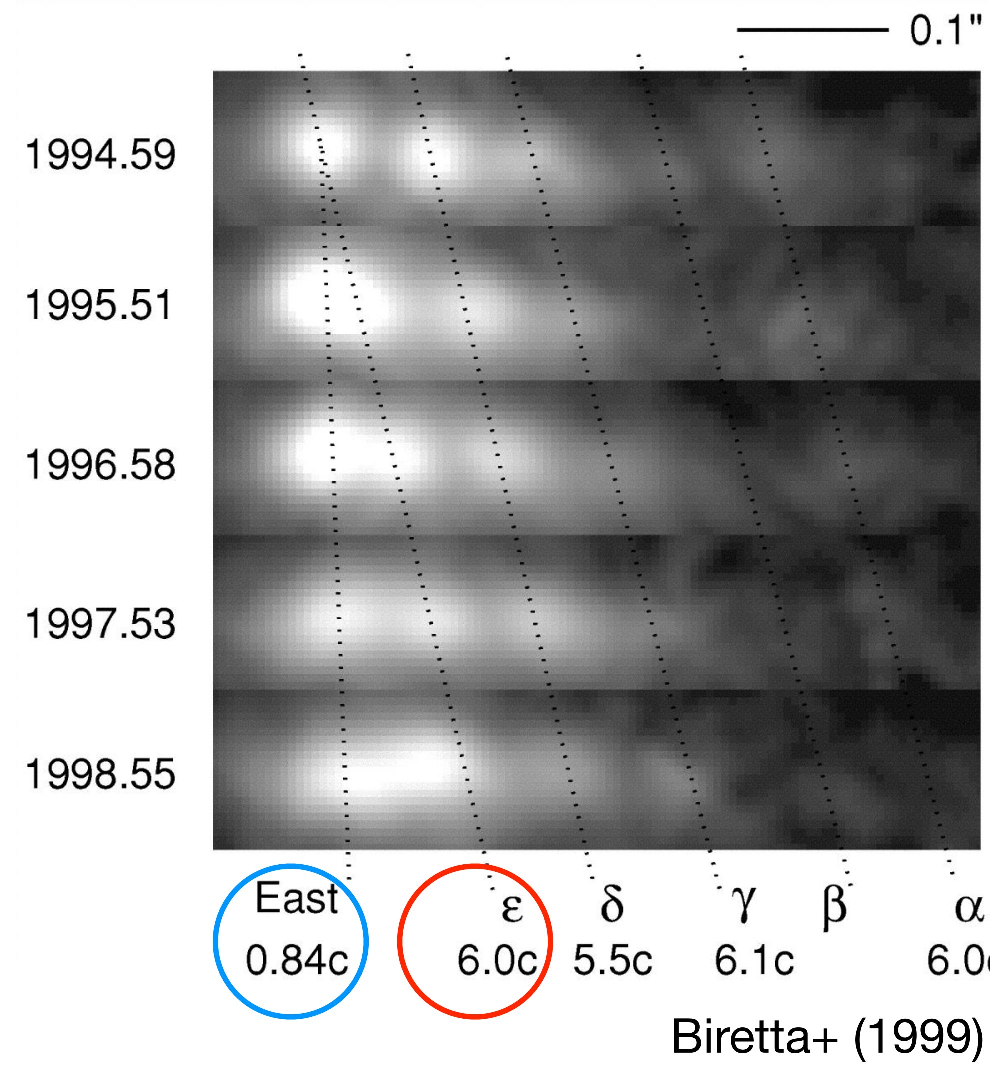
Jet Acceleration/Deceleration



Asada, MN+ (2014)

Trails of MHD Shocks?





$\theta_v \sim 14°$:
$V\varepsilon \sim 0.99\,c \Rightarrow$ FF
$V_{East} \sim 0.79\,c \Rightarrow$ RF

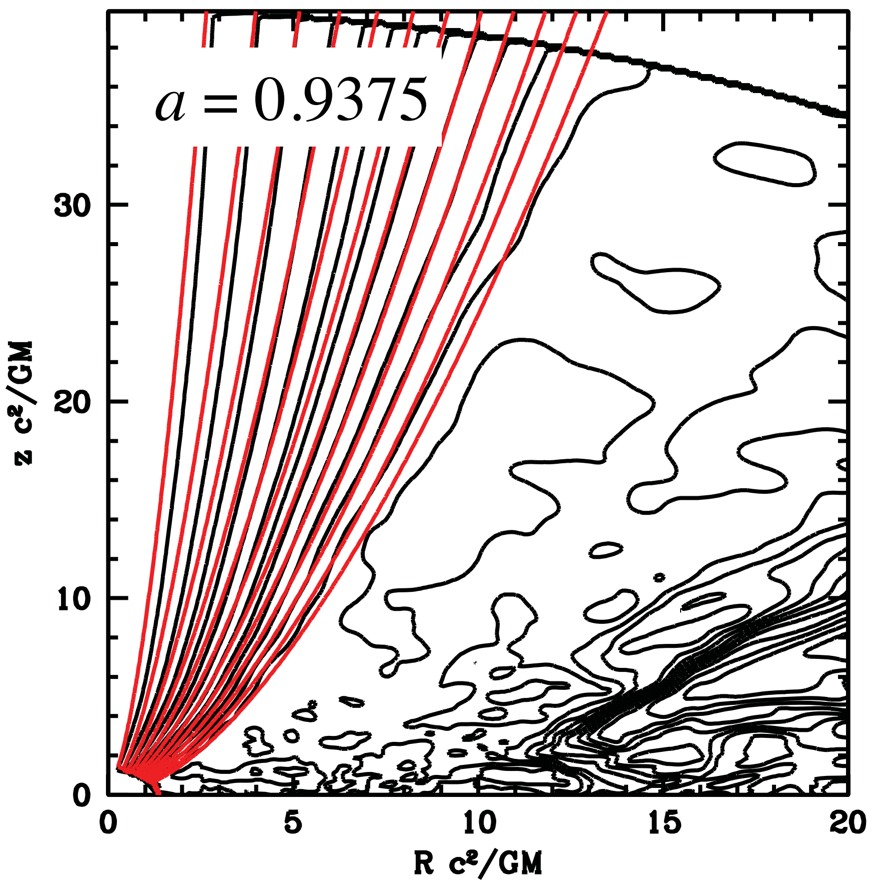
DSA (Fermi I acceleration via relativistic shock):

1. Proper compression
   $n(E) \propto E^{-\delta}$,
   $\delta = 2.2 - 2.3$
2. Low magnetization
   $\sigma \lesssim 0.5$
3. Low magnetic obliquity
   $\theta \lesssim 13°$

- **Quad-shock model** (MN, Garofalo, & Meier 2010; MN & Meier 2014)
  - A super-fast magnetosonic flow drives "forward/reverse-fast/slow" shocks in a helically twisted MHD jet
  - Pairs of super/sub-luminal motions (Biretta+ 1999; Cheung+ 2007) can be reproduced

Examination of Parabolic Stream in M87

Magnetic Field Structure of GRMHD Jets



- A power-law dependence of the azimuthal current on the equatorial plane (McKinney & Narayan 2007):

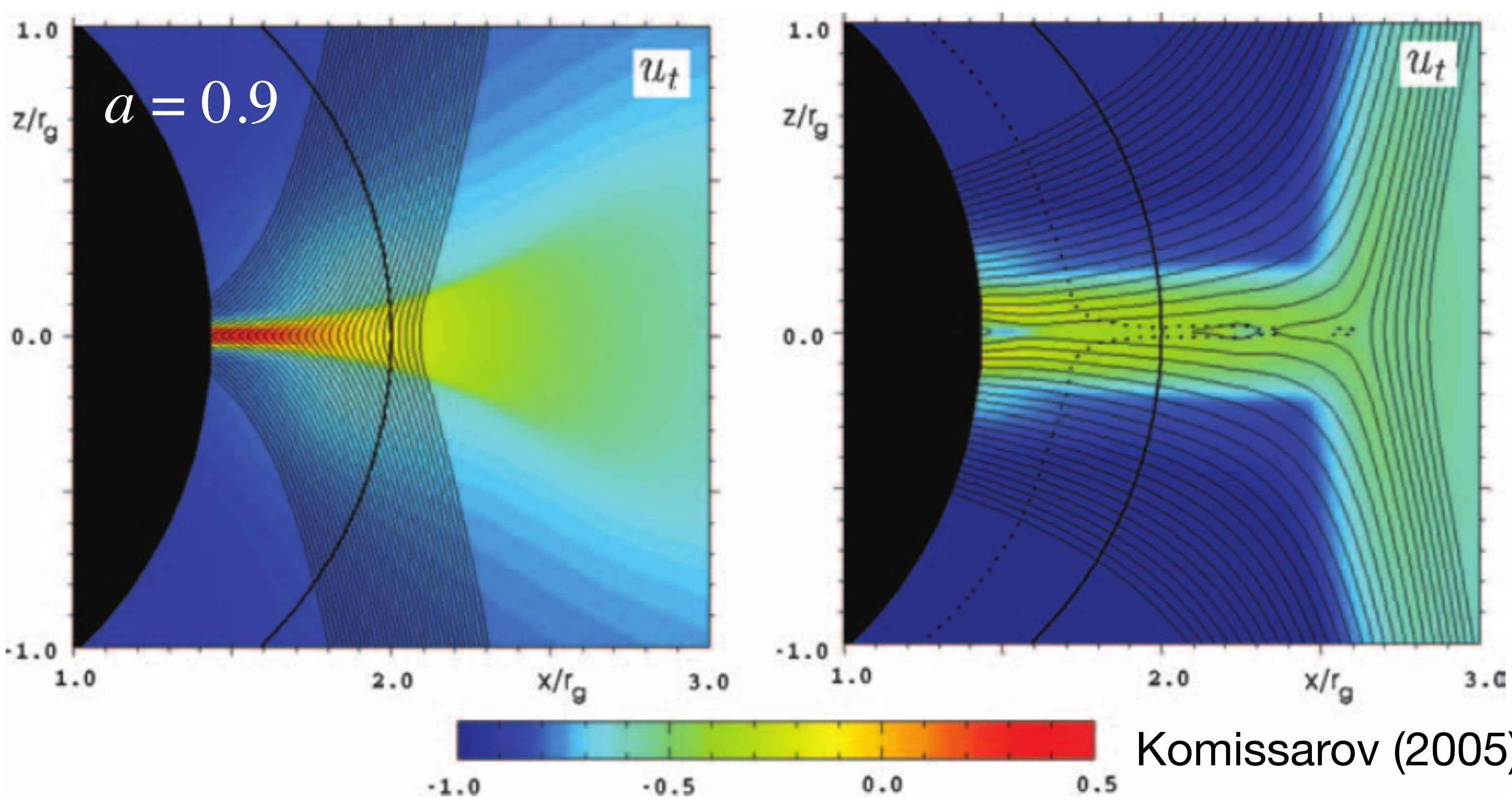
$$\frac{\mathrm{d}I_\phi}{\mathrm{d}r} \propto \frac{1}{r^{2-\nu}}$$

$\nu = 1$ (Parabolic, **Blandford & Znajek 1977**)

$\nu = 3/4$ (Quasi-parabolic, **Blandford & Payne 1982**)

$\nu = 0$ (split-monopole)

- GRMHD simulated jet agrees well with the force-free field solution for a *thin* disc with an $r^{-5/4}$ (i.e., BP82)

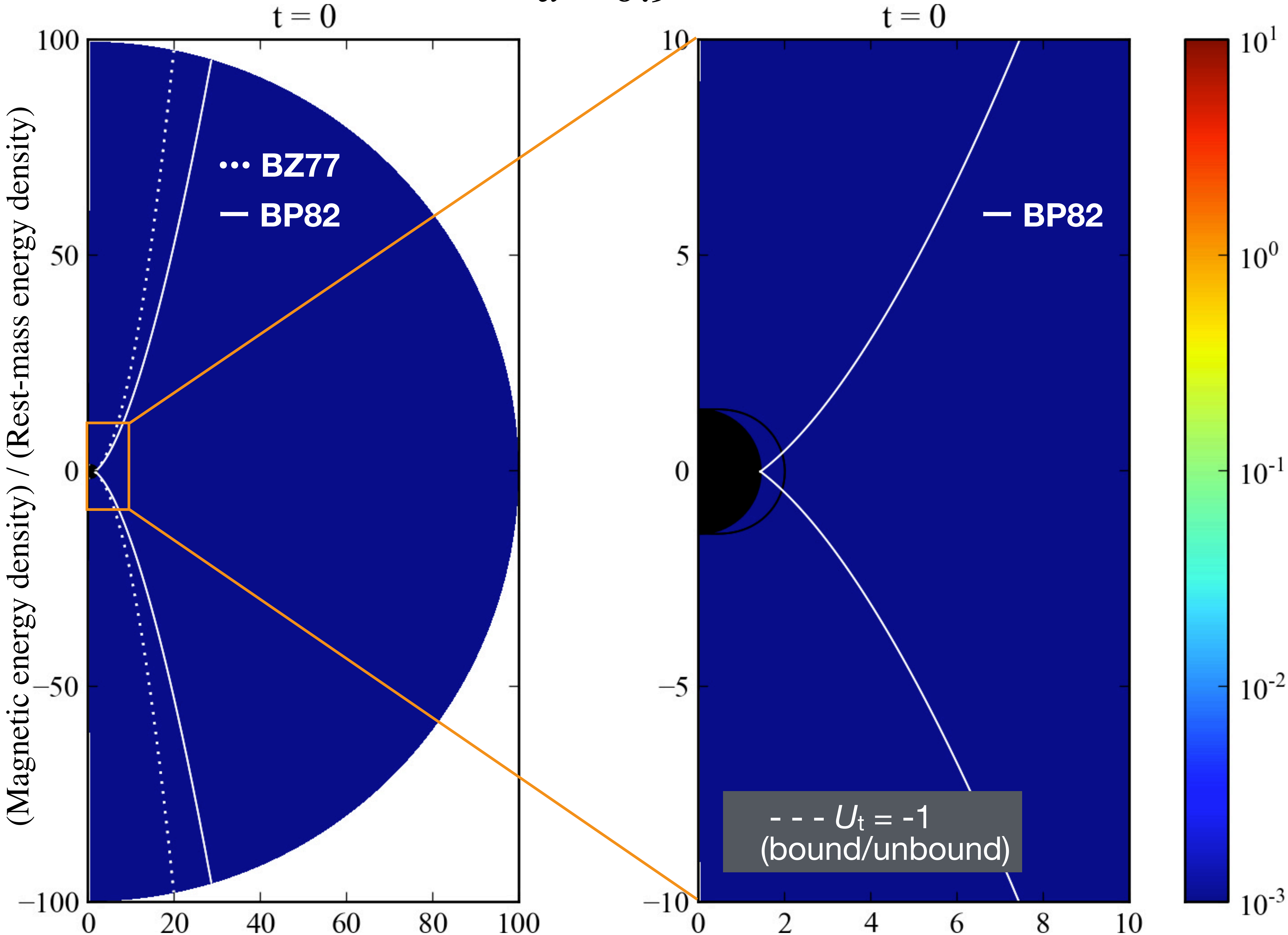


Komissarov (2005)

- All magnetic field lines threading the ergo spheric disk have a turning point in the equatorial plane and do NOT cross the event horizon

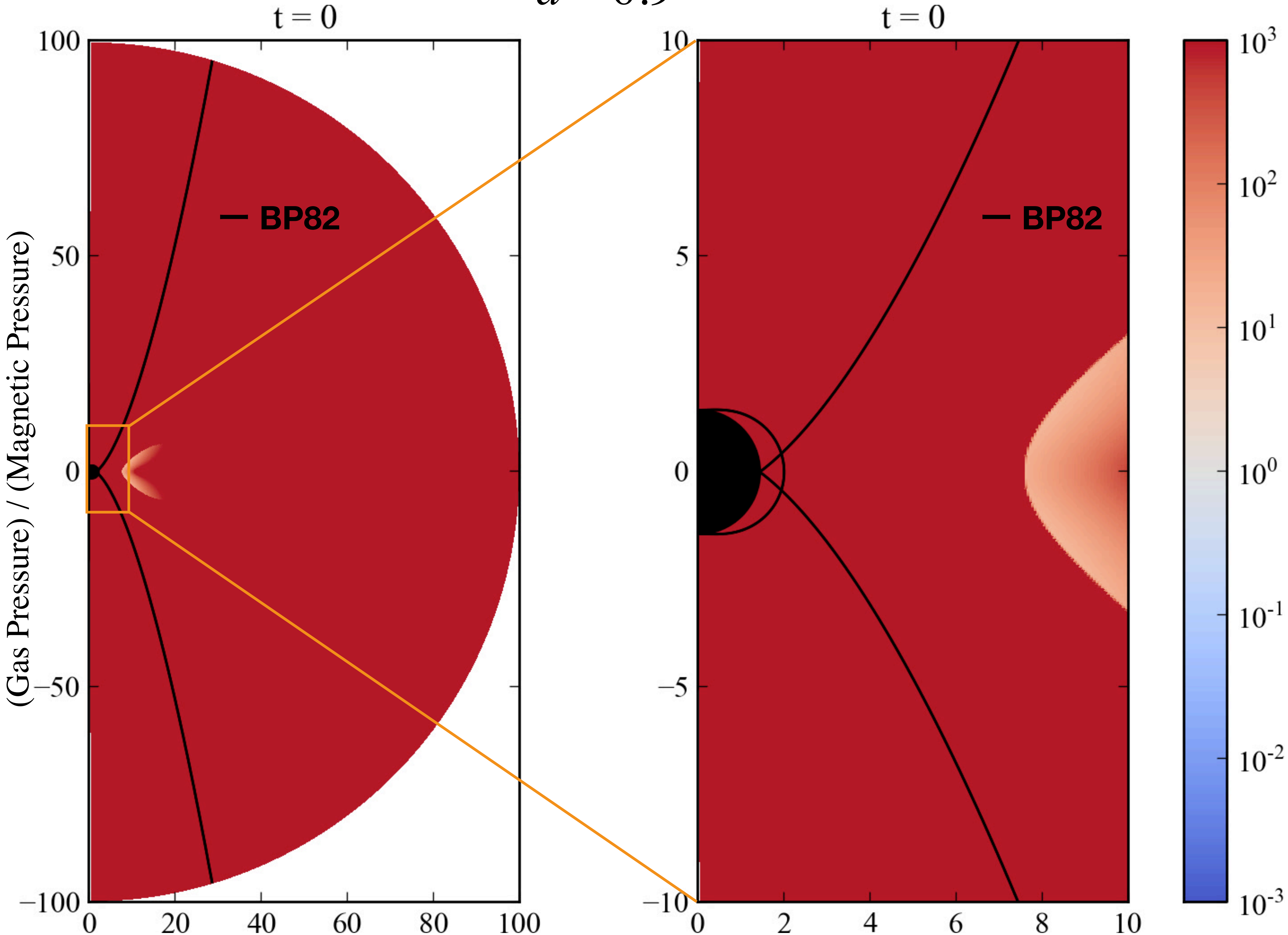
- At some point the magnetic configuration would have to change so that all magnetic field liens entering the ergosphere also penetrate the event horizon

$a = 0.9$



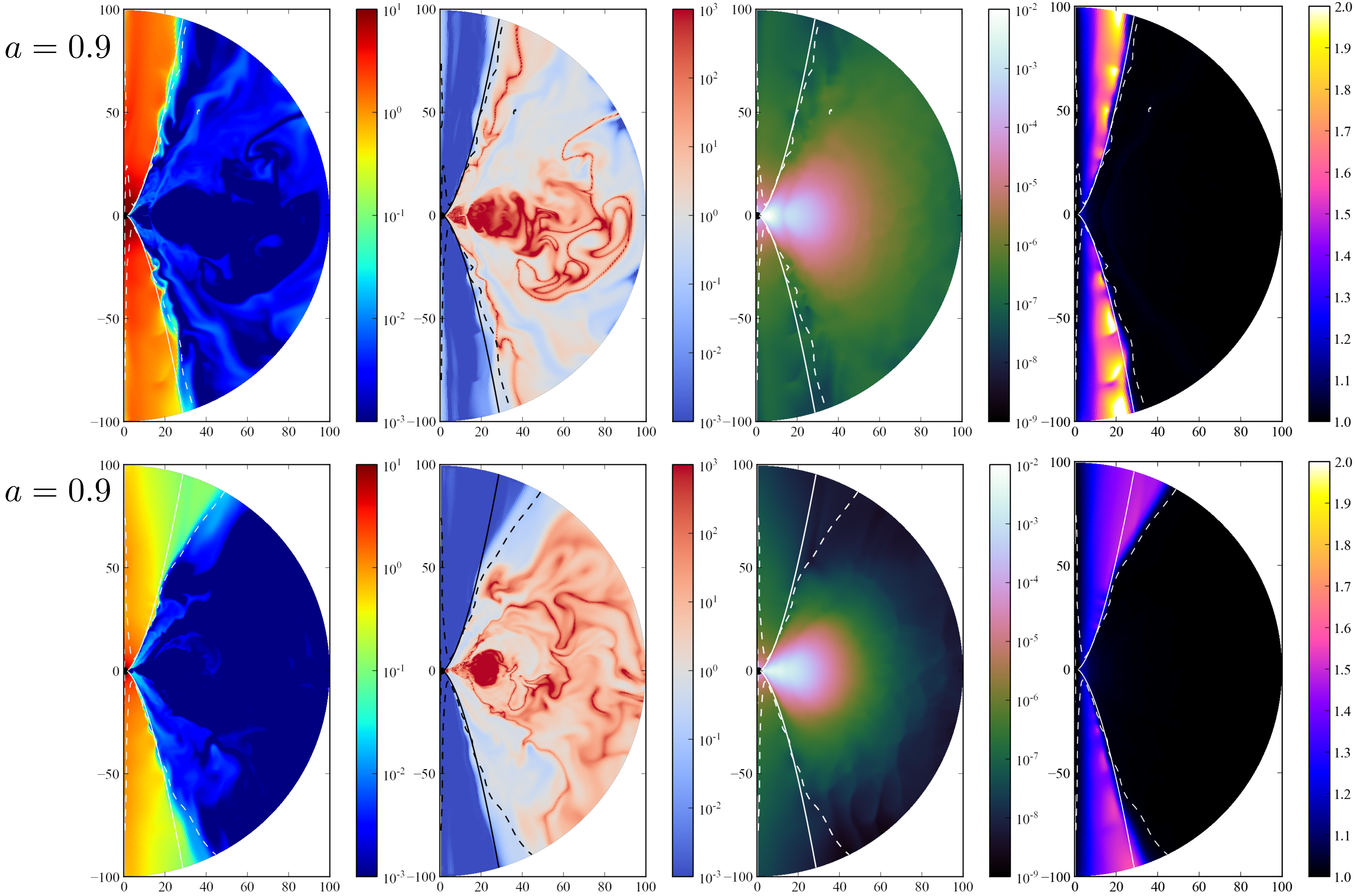
Comparison w/ analytic solutions: HARM 2D (Gammie & McKinney 2003; Noble+ 2006)

$a = 0.9$



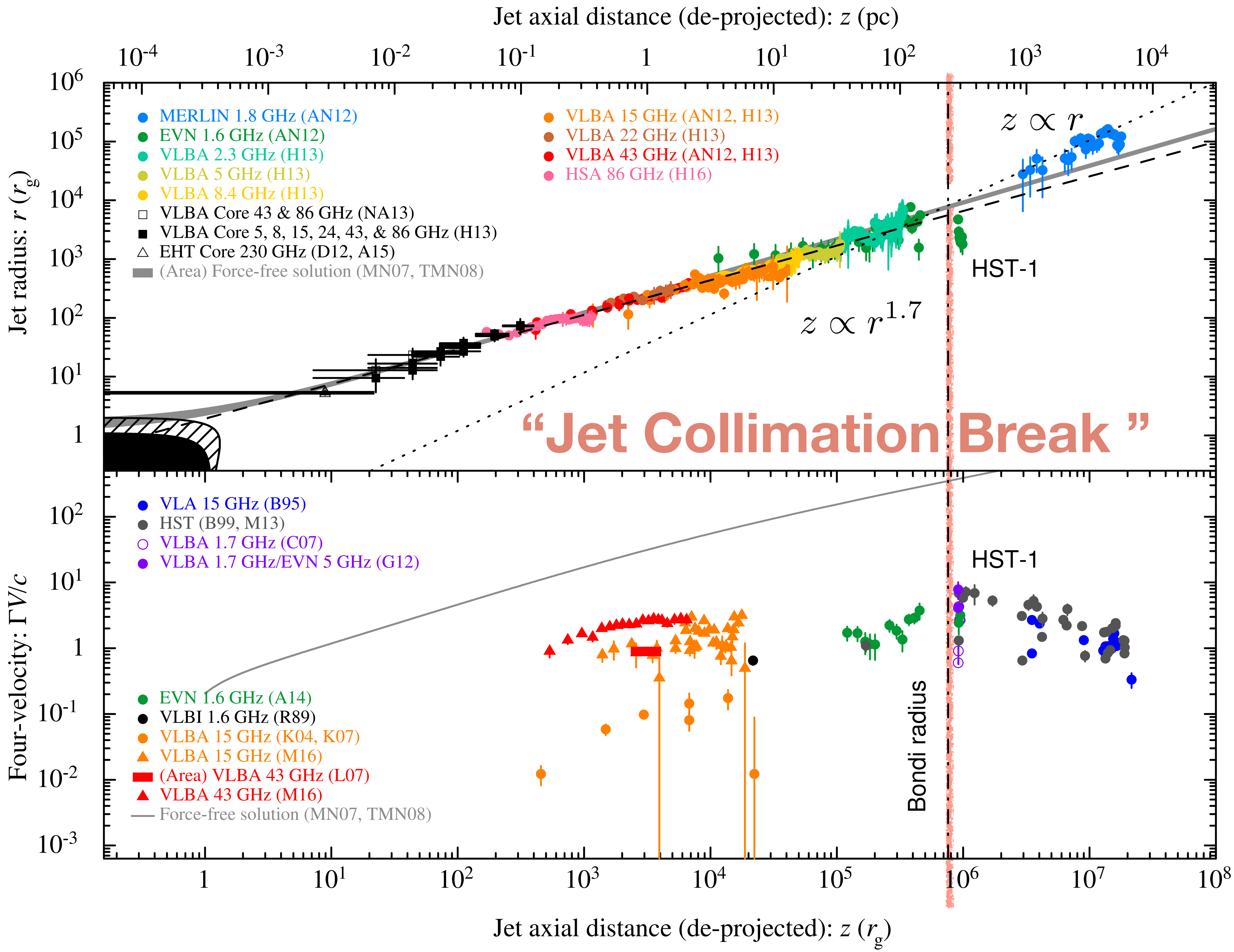
Comparison w/ analytic solutions: HARM 2D (Gammie & McKinney 2003; Noble+ 2006)

Moderately Magnetized Corona is important



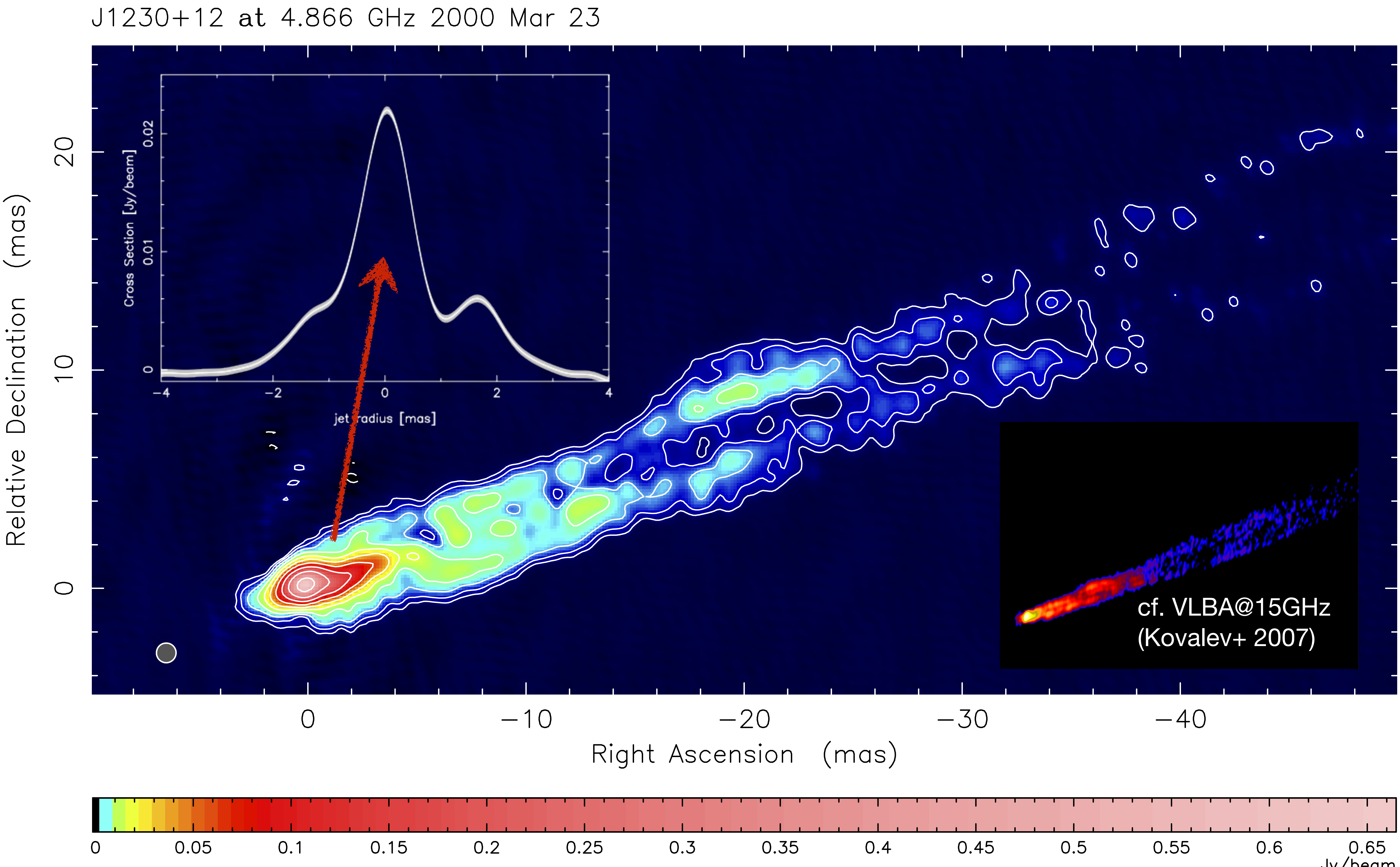
Comparison w/ analytic solutions: HARM 2D (Gammie & McKinney 2003; Noble+ 2006)

M87 Jet: Obs. vs. Theory (1)



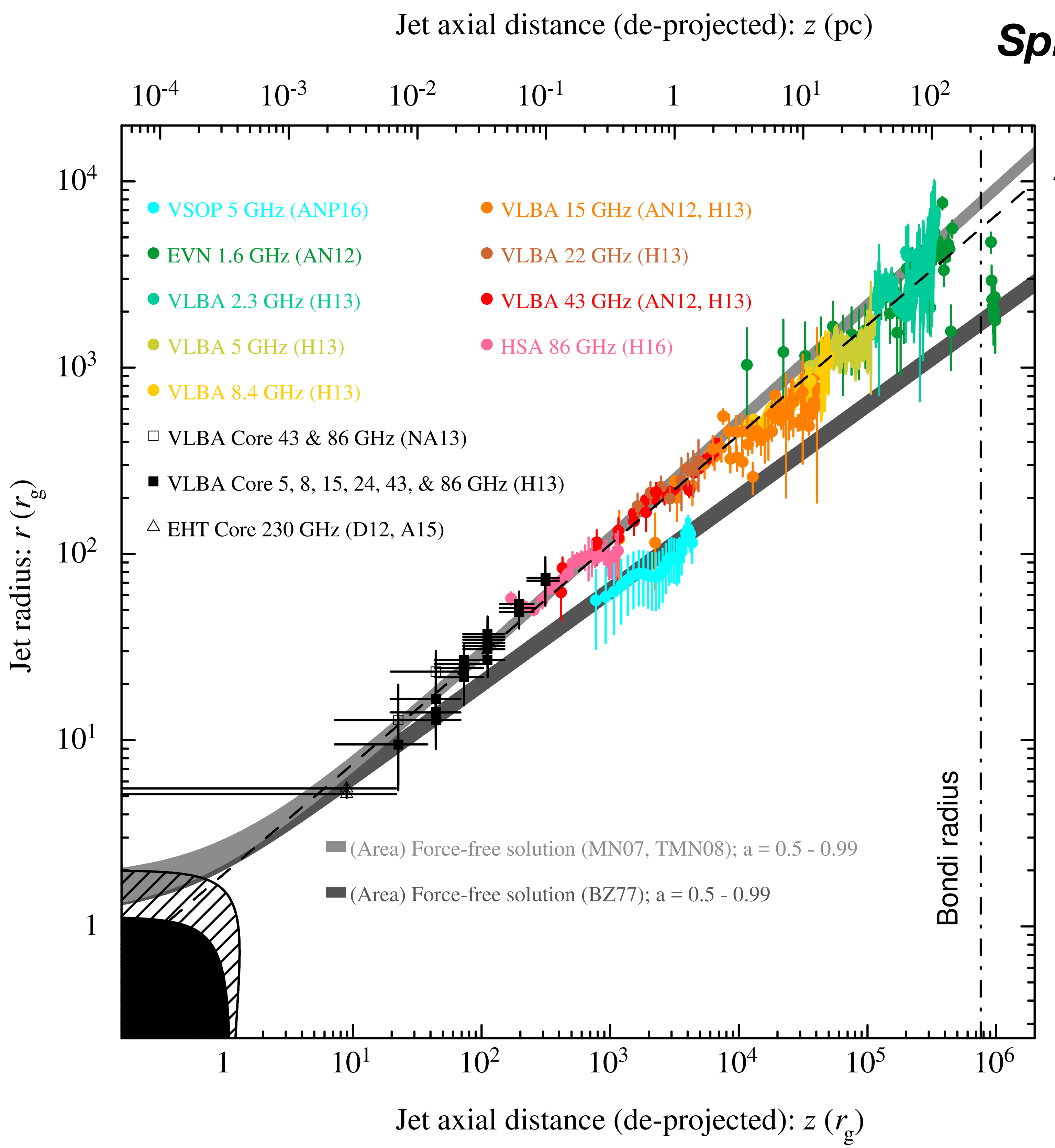
Refs. Reid+ (1989); Biretta+ (1995, 1999); Kovalev+ (2007); Cheung+ (2007); McKinney & Narayan (2007); Ly+ (2007); Tchekhovskoy+ (2008); Doeleman+ (2011); Giroletti+ (2012); Asada & Nakamura (2012); Hada+ (2013); Nakamura & Asada (2013); Meyer+ (2013); Asada+ (2014); Akiyama+ (2015); Hada+ (2016); Mertens+ (2016)

Spine Jet Resolved by Space-VLBI



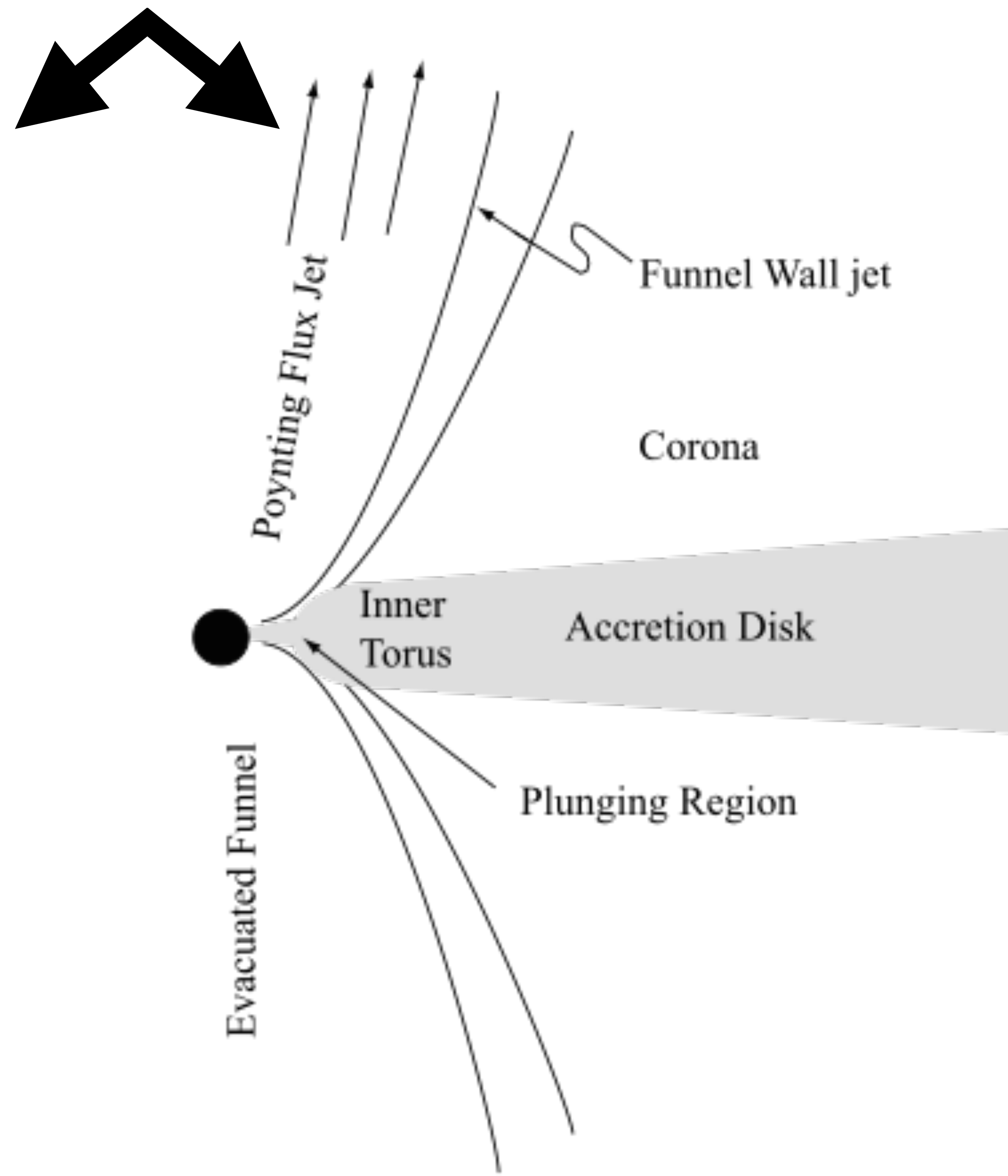
Asada, MN, & Pu, *ApJ in press*

M87 Jet: Obs. vs. Theory (2)



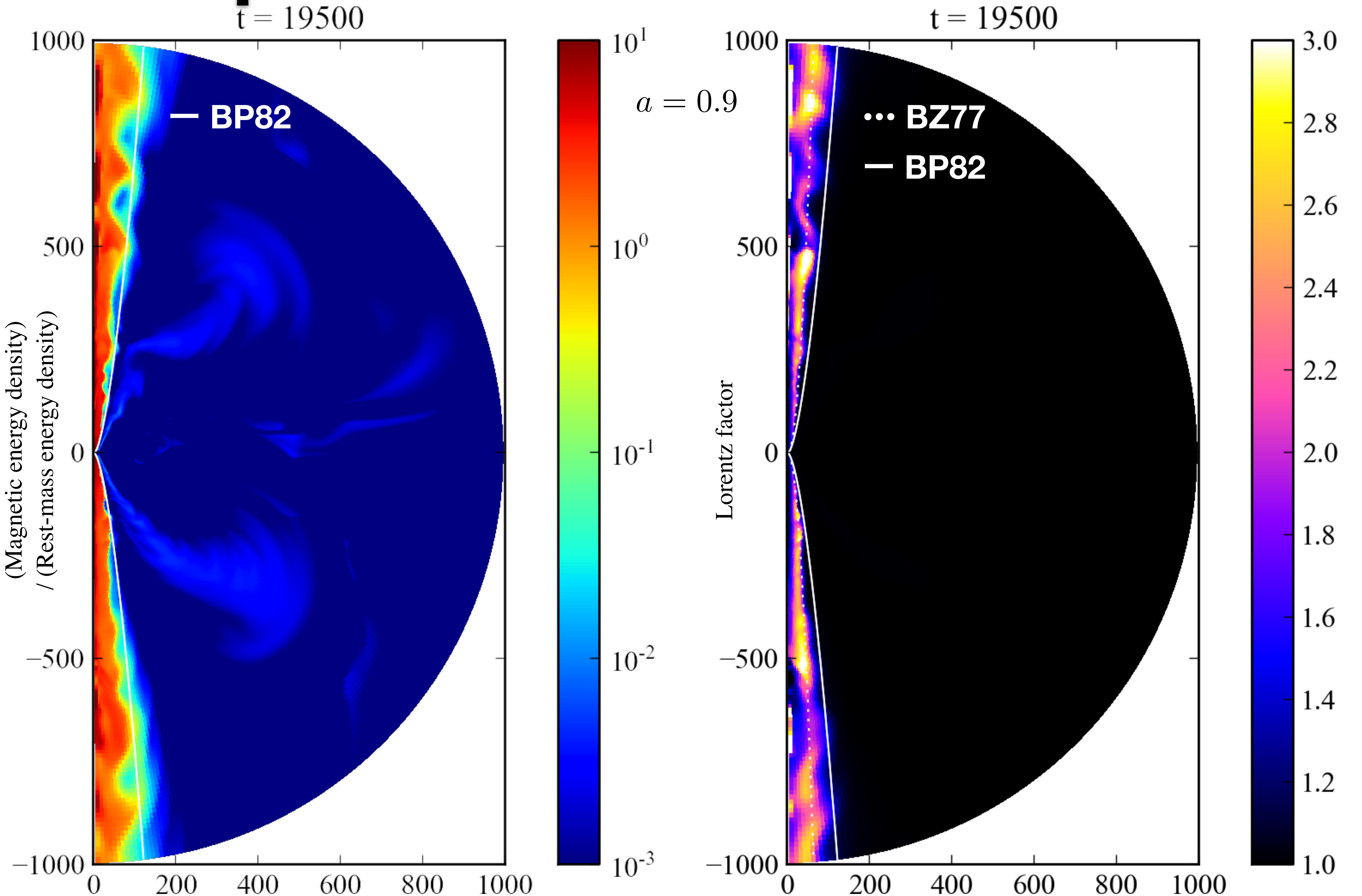
MN, Asada, Hada+, in prep.

Spine-sheath structure?



Hawley & Krolik (2006)

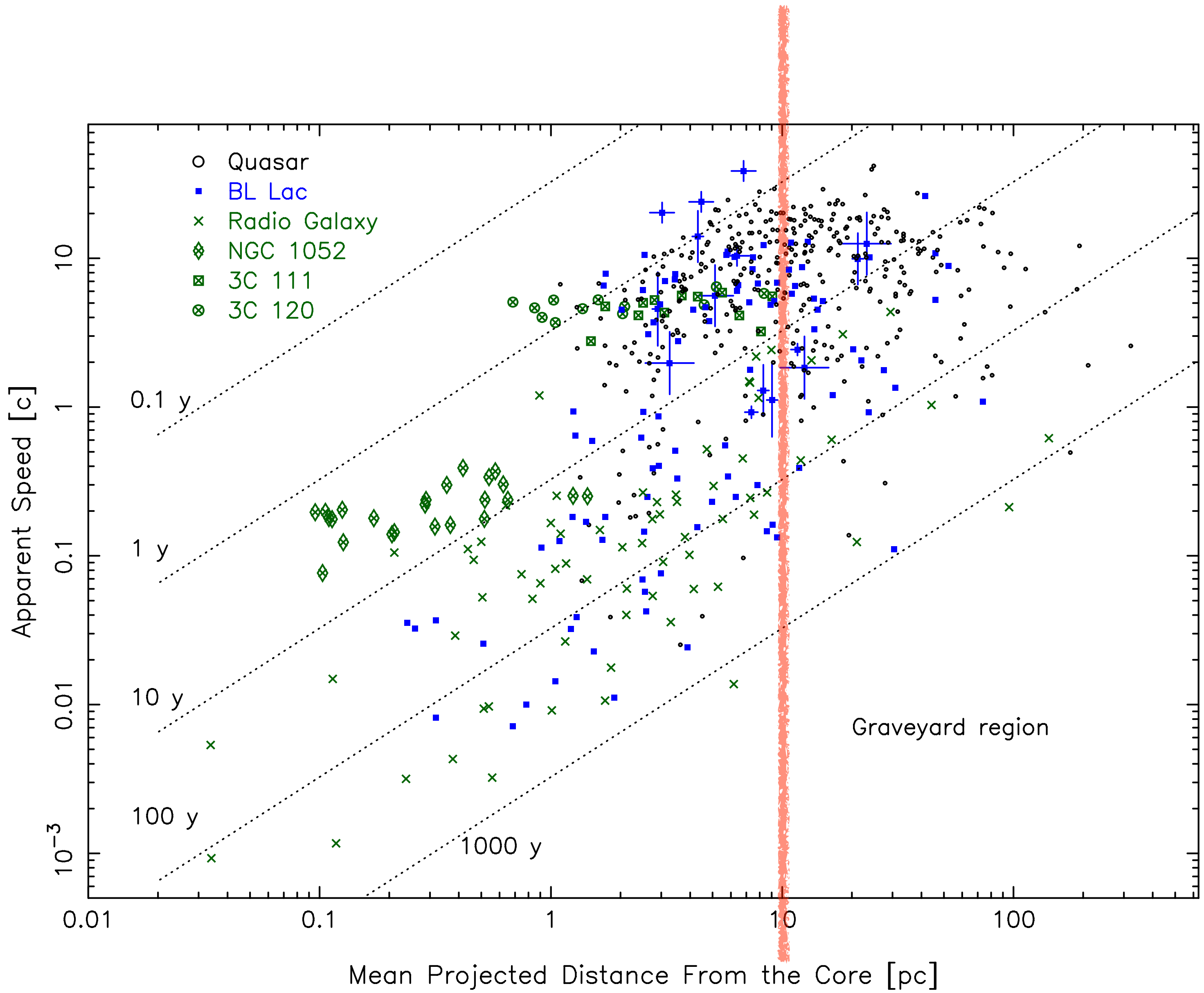
Spine-Sheath as Observed?



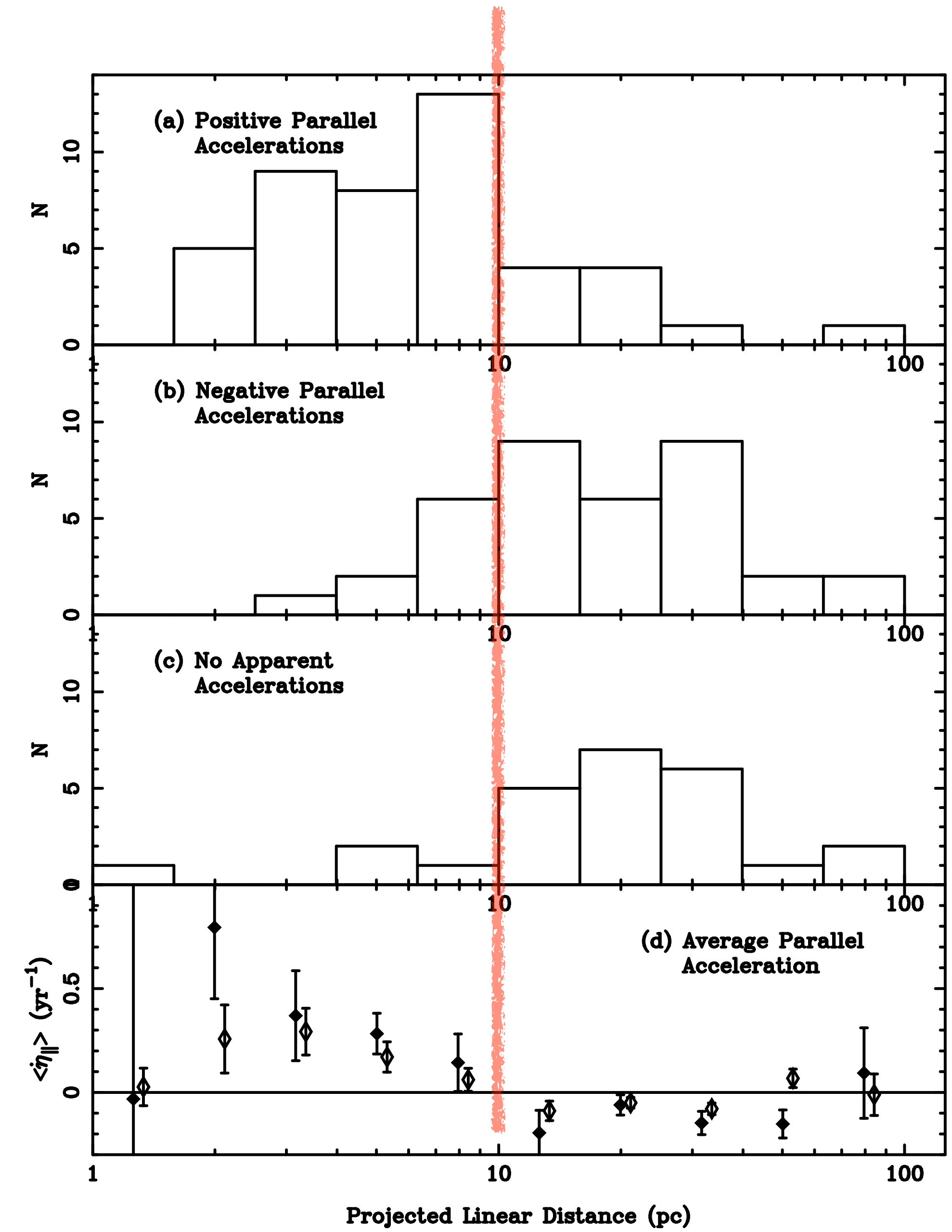
Comparison w/ analytic solutions: HARM 2D (Gammie & McKinney 2003; Noble+ 2006)

Structural Transition is Norm?

Transition found in MOJAVE AGNs



Lister+ (2013)

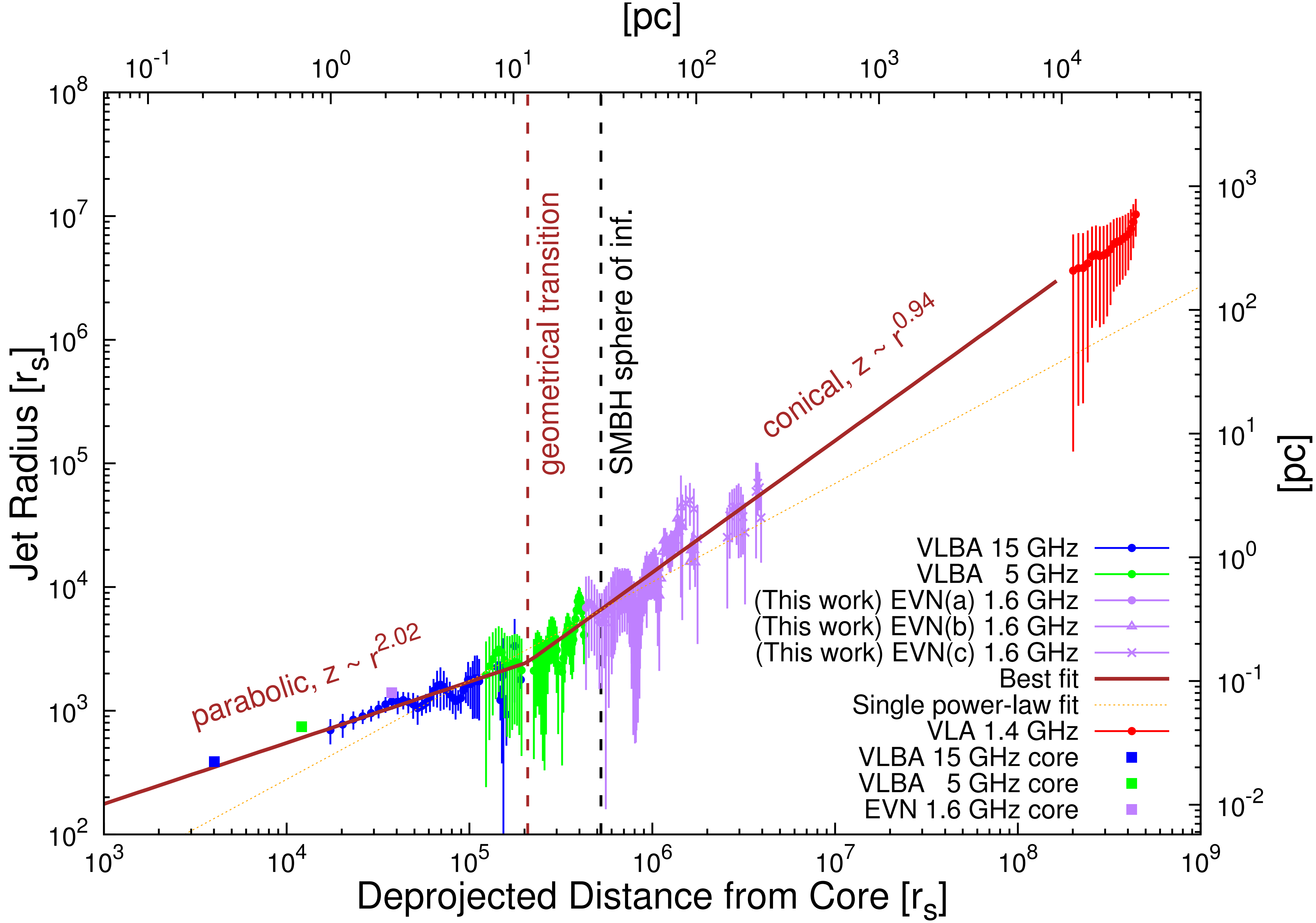


Homan+ (2015)

- ***A transition from positive to negative acceleration*** seems to locate at ~ 10 pc (Lister+ 2013; Homan+ 2015) ⇒ ~ 100 pc or longer in de-projection
- ***Non-ballistic flows are strongest*** at < 10 pc; jets are expanding less rapidly than $z \propto r$, ⇒ ***jets are still being collimated*** (Homan+ 2015)

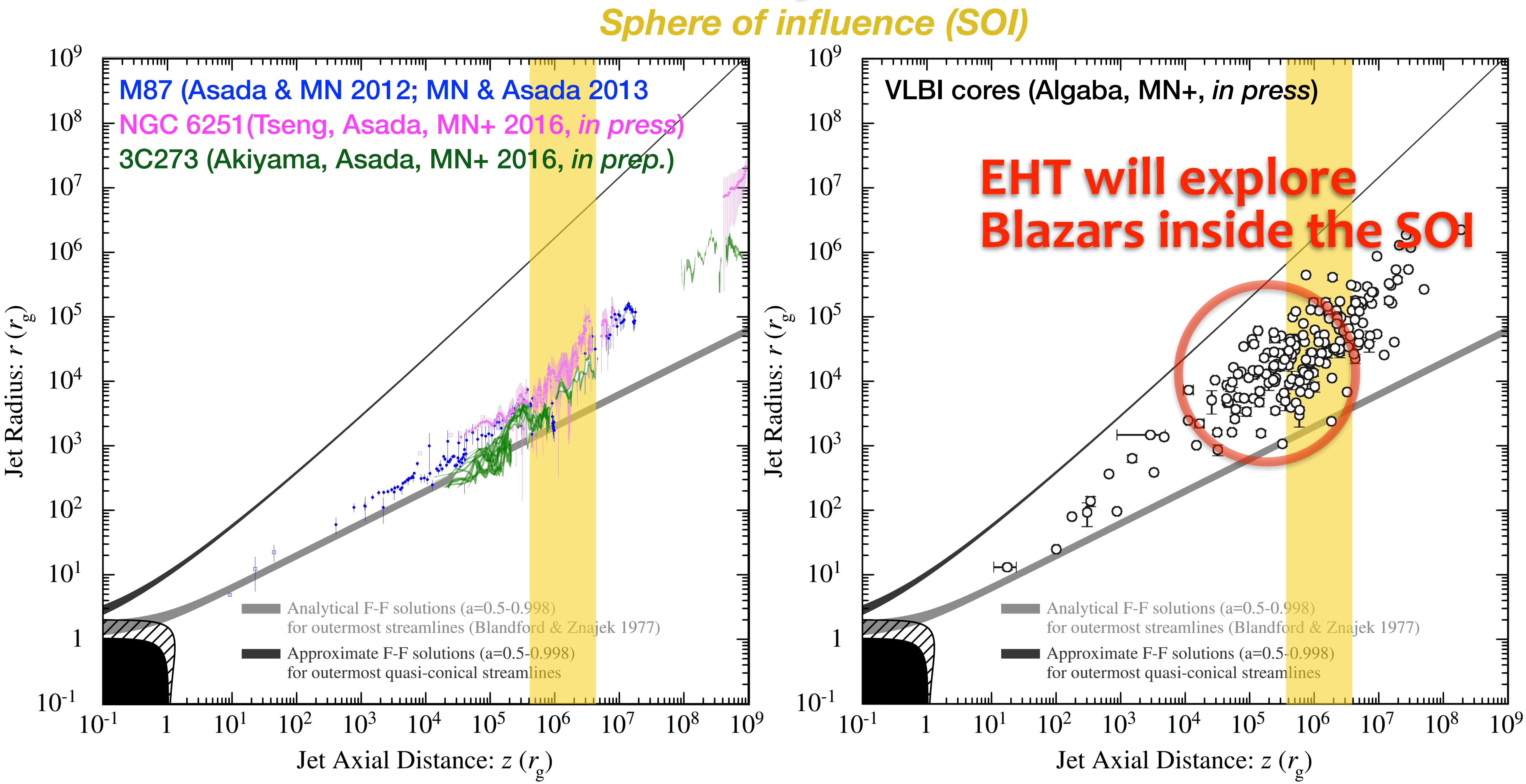
Second Case: FRI RG

NGC 6251(0.5 pc/mas = 8700 r_s), log $M_\bullet$ = 8.78, θ_V=19°



Tseng, Asada, MN+, *in press*

Preliminary Results



- Similarity of the jet structural transition between QSOs and RGs ⇒ Is the "*jet collimation break*" fundamental in AGNs?
- "Conical jet paradigm" (Blandford & Königl 1979) may need to be re-examined w/ sub-mm VLBI observations

Summary & Future Work

- M87 provides us the best understanding of the structure and the dynamics of relativistic jets; sub-mm VLBI will access the origin of the jet ($< 10\ r_g$)
- GRMHD simulations reproduce the observed jet structure in M87, suggesting the Blandford-Znajek process in action
- A transition of acceleration/collimation to deceleration/de-collimation is norm? → Observing blazars w/ sub-mm VLBI is essential for re-examining "conical jet paradigm"
- "*Jet collimation break*" gives a clue to see how AGN jets behaves under the co-evolution between SMBHs and host galaxies