Towards the 100th Anniversary of the Discovery of Cosmic Jets

M87 Workshop

May 23-27 2016, ASIAA, Taipei

Web.: http://events.asiaa.sinica.edu.tw/workshop/20160523/index.php

Contact: m87ws2016@asiaa.sinica.edu.tw

Image courtesy (left: Francisco Diez, middle: J.-C. Algaba, right: Greenland telescope)

TOPICS

- Super/ultra-massive black holes
- Black Hole accretion flows
- Relativistic Jets from birth to termination
- Co-evolution of galaxy and black hole: AGN feedback
- High energy emissions in LLAGNs and their synergy to γ-ray blazars

Registration will be opened soon

SOC: **P. Ho** (ASIAA, Chair)

L. Ho (KIAA, Vice-chair, Keynote talk on SMBH)

R. Blandford (Stanford, Keynote talk on BH jet)

A. Fabian (IoA, Keynote talk on AGN feedback)

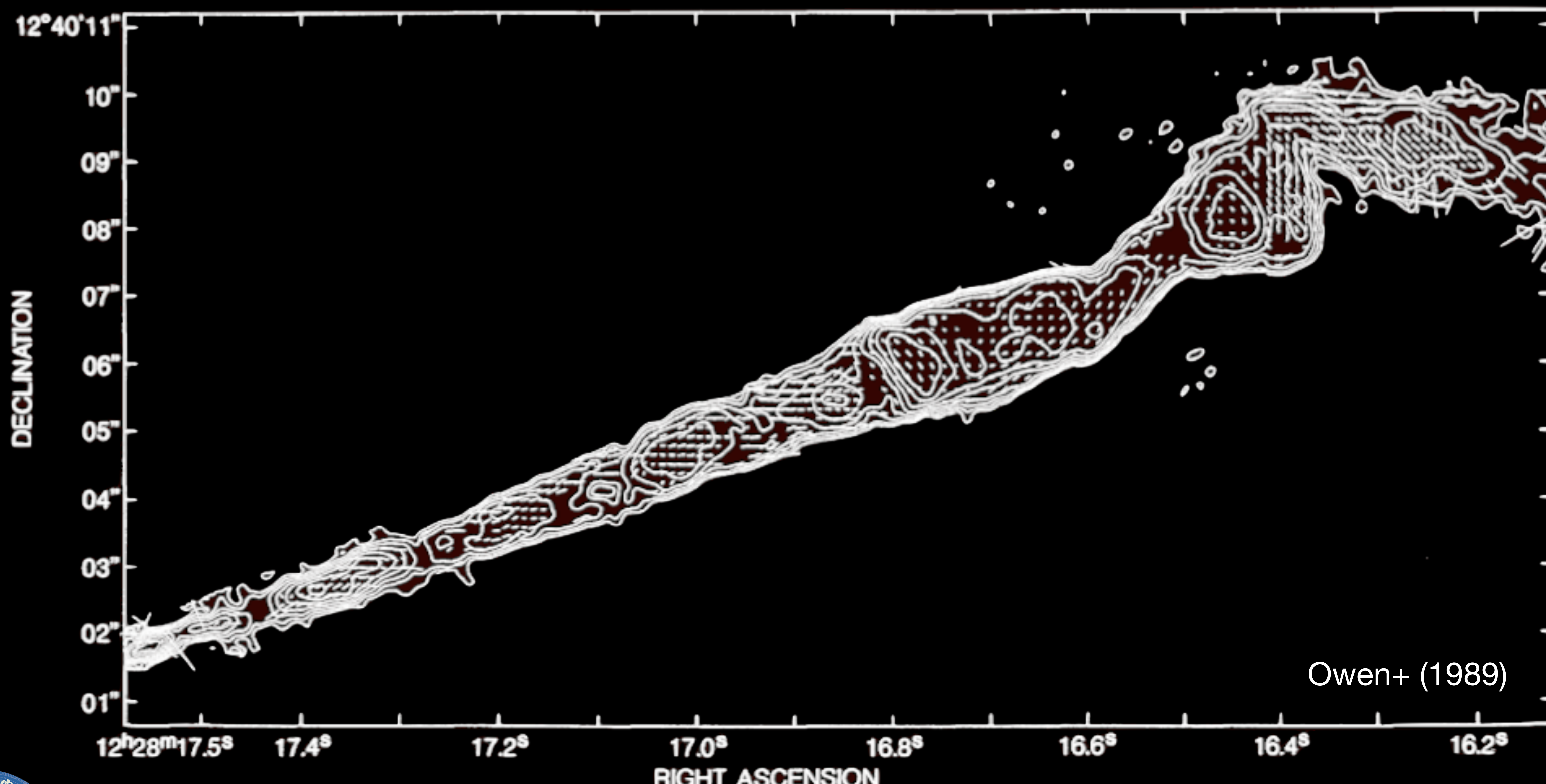
R. Narayan (CfA, Keynote talk on BH accretion)

K. Asada (ASIAA, Secretary)

M. Nakamura (ASIAA, Secretary)

Invited Speakers: To be announced

Magnetohydrodynamic Model of the M87 Jet



Masa Nakamura (ASIAA, Taiwan)

Extragalactic Relativistic Jets@ICTS, Bangalore, India 2015

Outline

- Introduction to M87; puzzle has remained unsolved on the jet acceleration/collimation
- MHD Jet global structure and dynamics under the BH gravitational influence and beyond
- Lessons learned from M87; "*jet break*" in AGNs may be norm in the BH-galaxy co-evolution?
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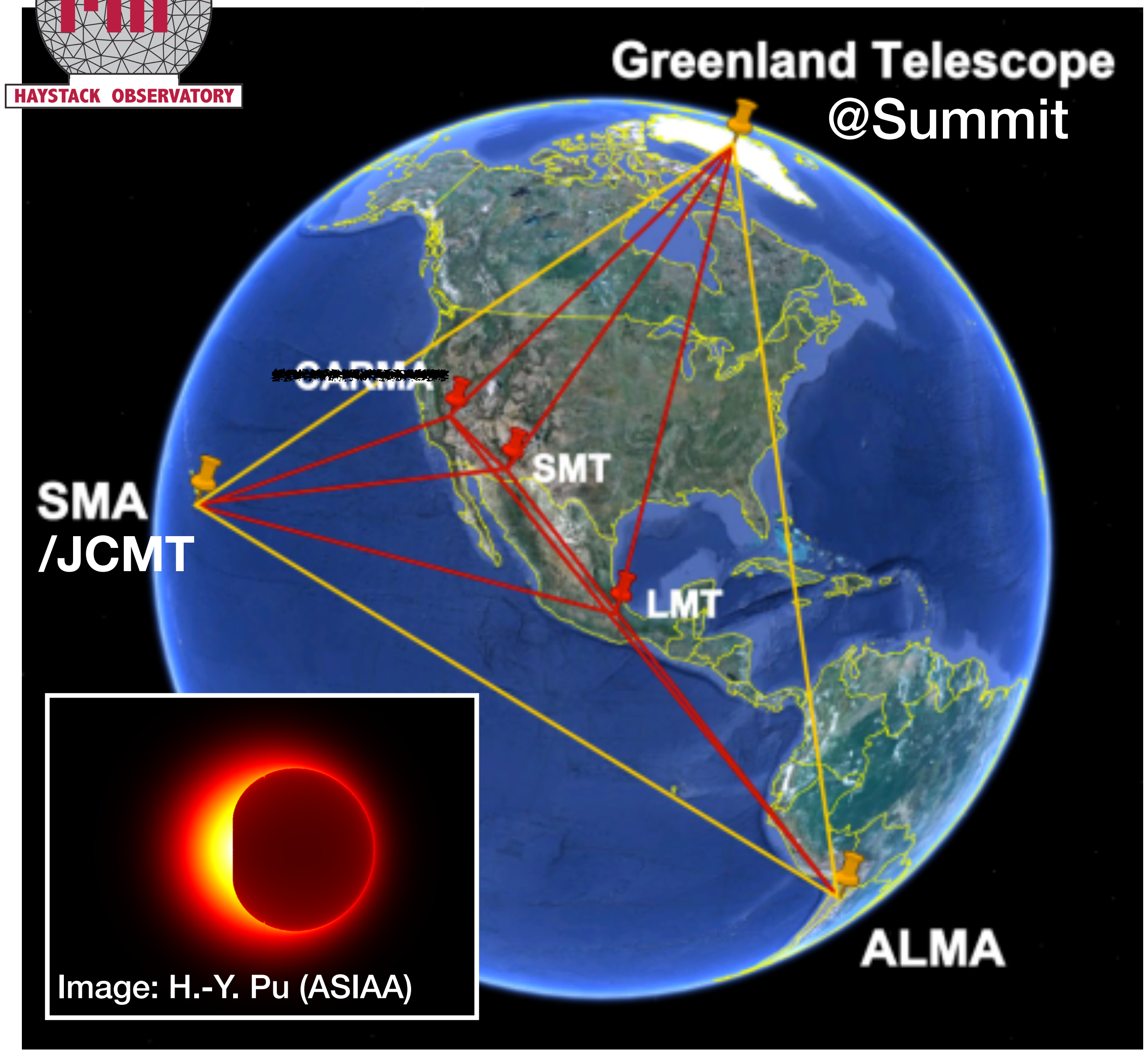
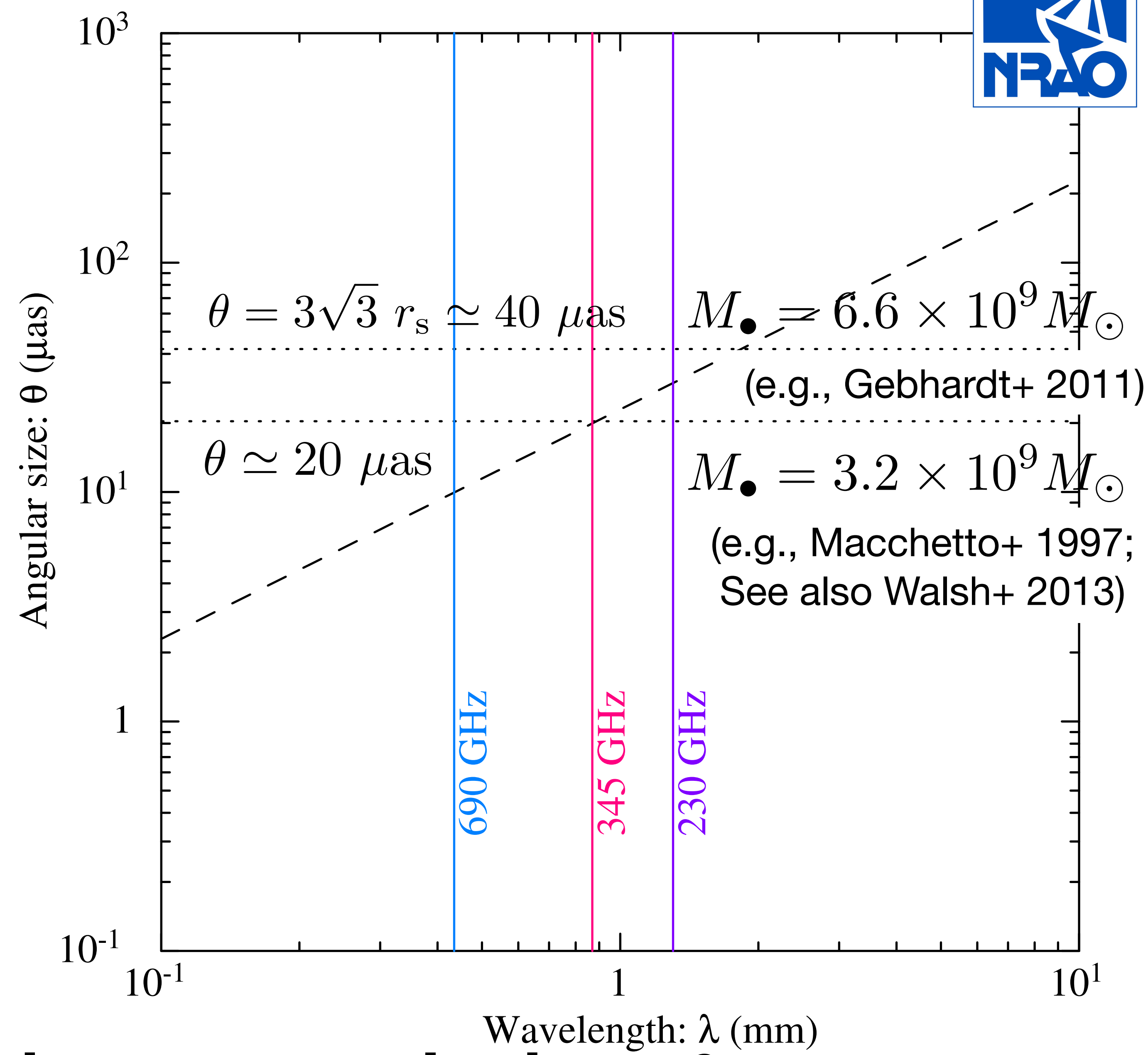
M87 (Virgo A; NGC4486)

- The 2nd brightest galaxies in Virgo cluster
- The 1st jet discovered (Curtis 1918)
- "***Rosetta Stone***" of AGN jet
  - 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 ($\theta_v \sim 14°$)

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

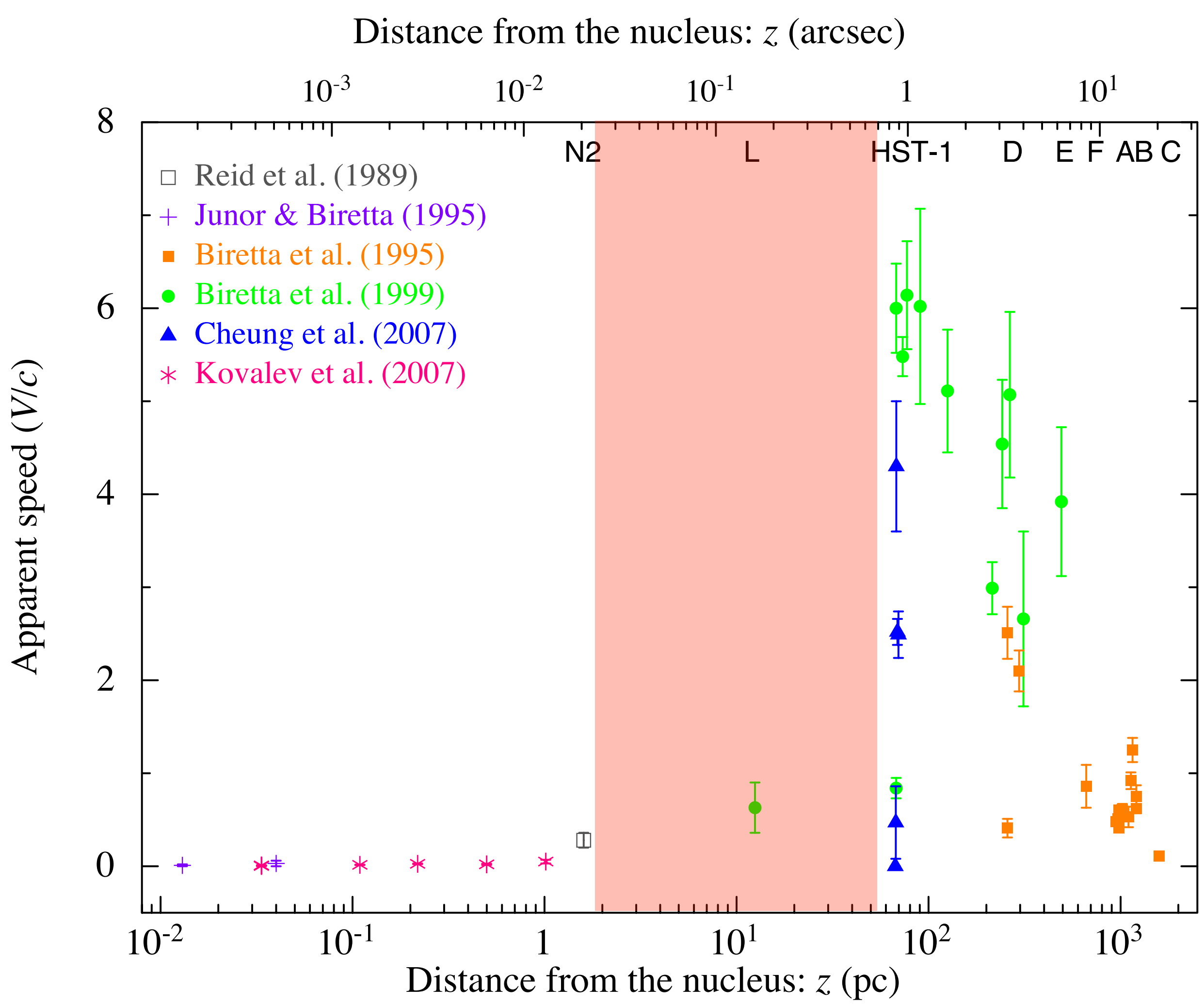
Greenland Telescope (GLT)



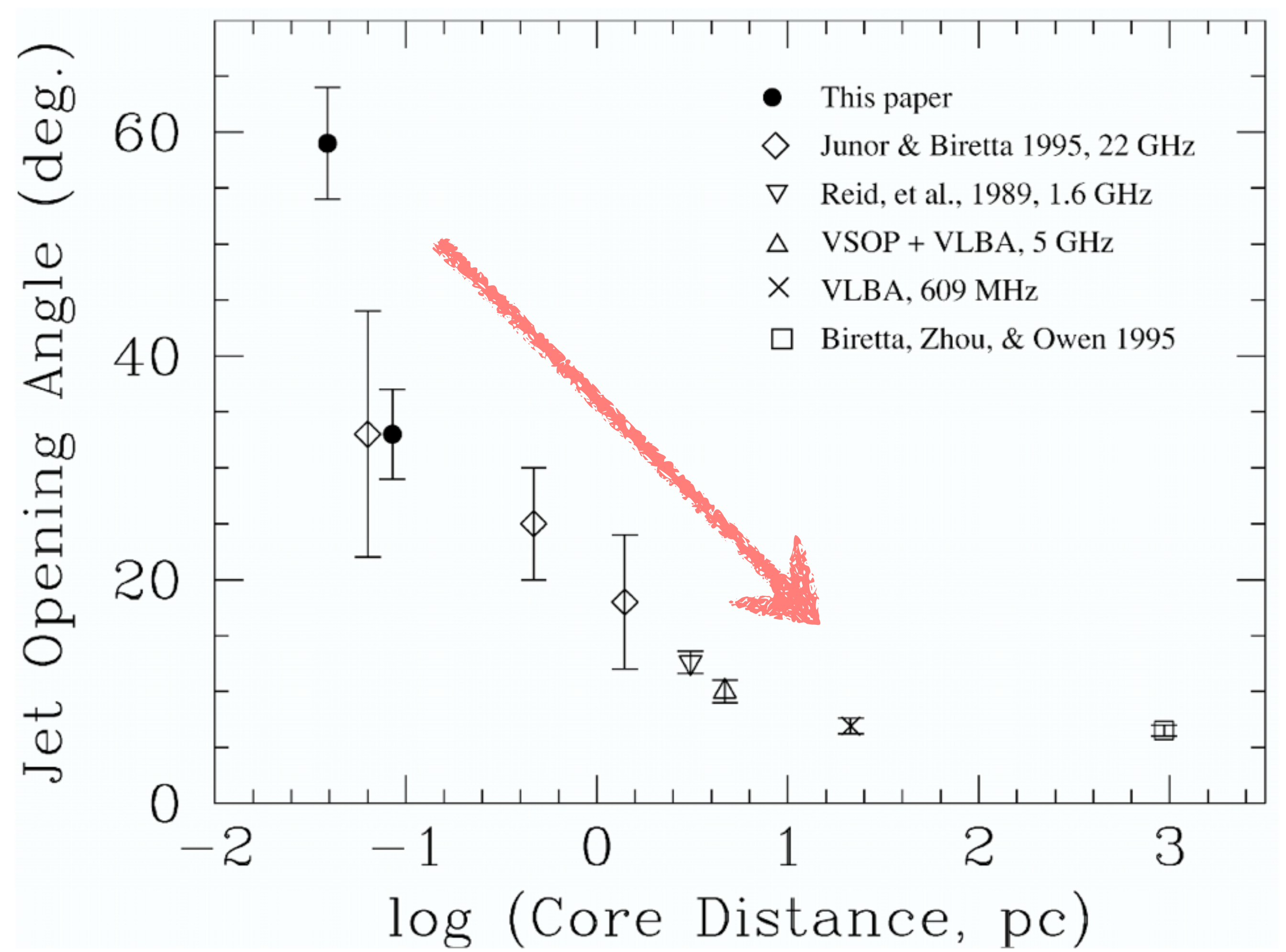


- A baseline 9,000+ km, giving a resolution $\theta \sim 20$ μas to image the BH shadow in M87($\sim 2.5 R_s$ w/ $6.6 \times 10^9\ M_\odot$)
- Shipping the GLT to Thule (2016-) for VLBI commissioning (86/230GHz)

Puzzle Has Remained Unsolved During decades



Junor+ (1999), Nature



Q. What is a large gap?

Q. Collimation is real (i.e. the jet is cylindrical or not)?

No clear view of jet acceleration/collimation even in the most studied AGN source…

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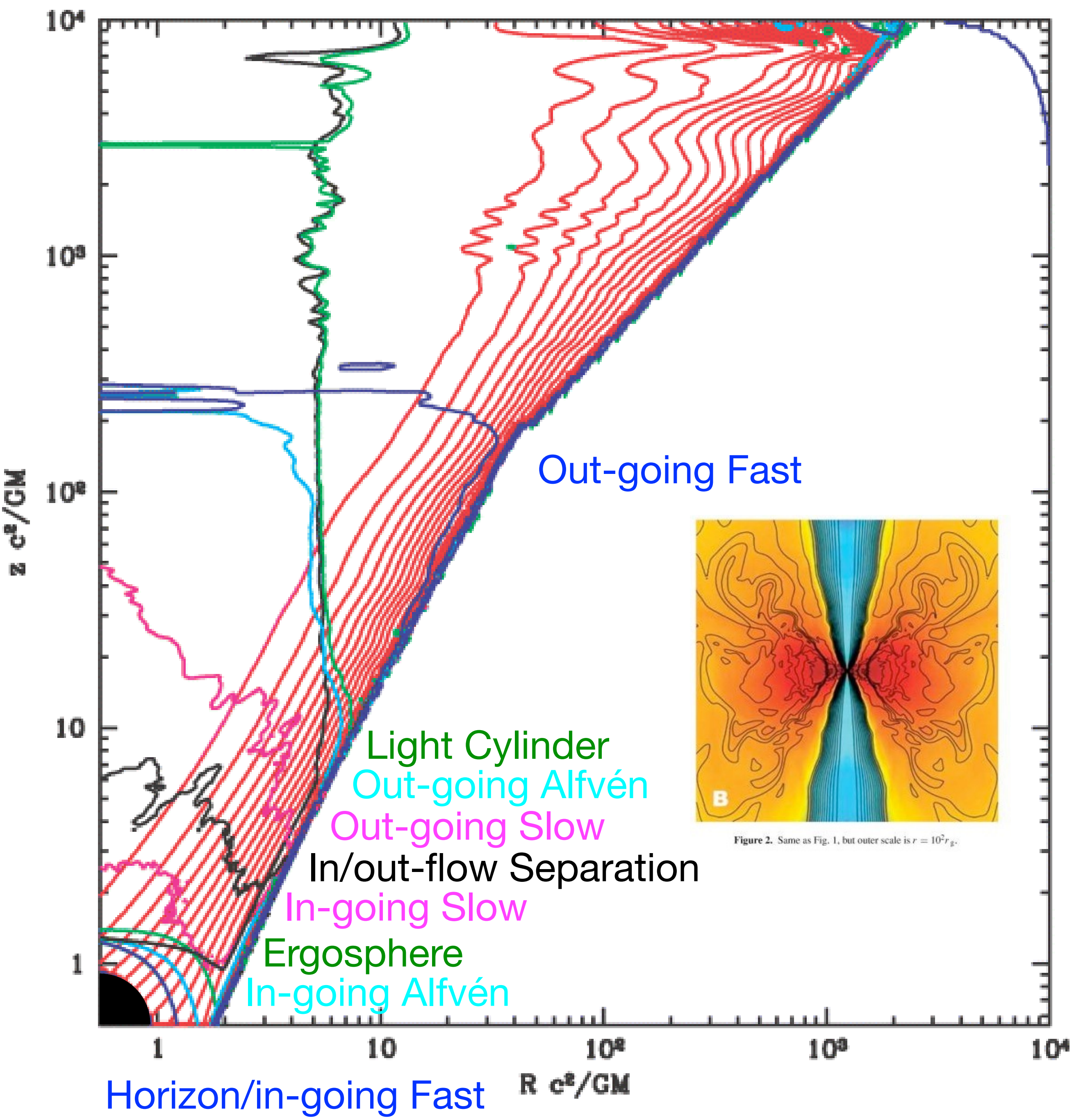
GRMHD (1st ever) Steady Inflow/Outflow Solutions for a Parabolic Streamline

GRMHD Simulation (a/M=0.9375)

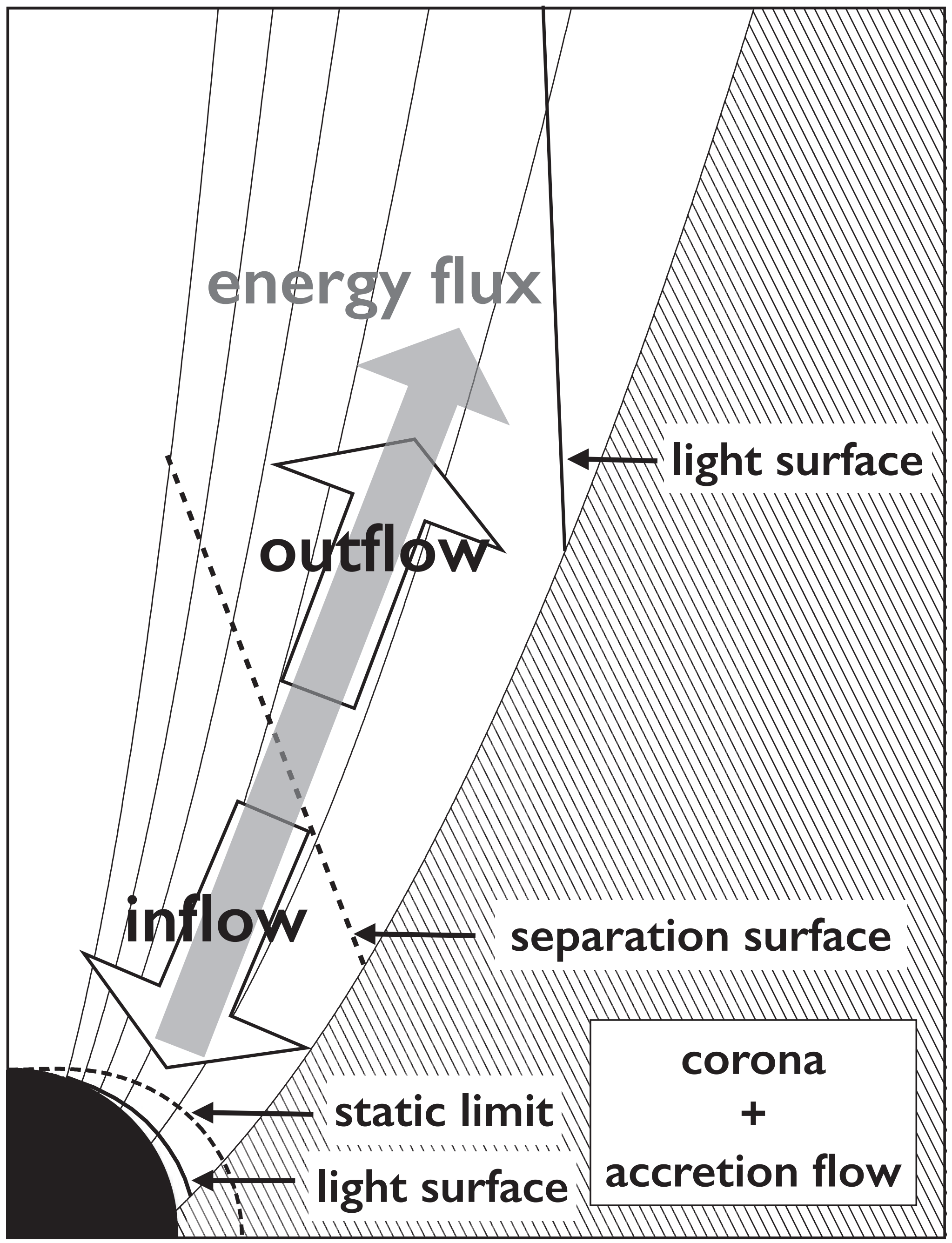
B_p field lines and characteristic surfaces



McKinney (2006)

Steady GRMHD (cold) solution (a/M=0.9375)

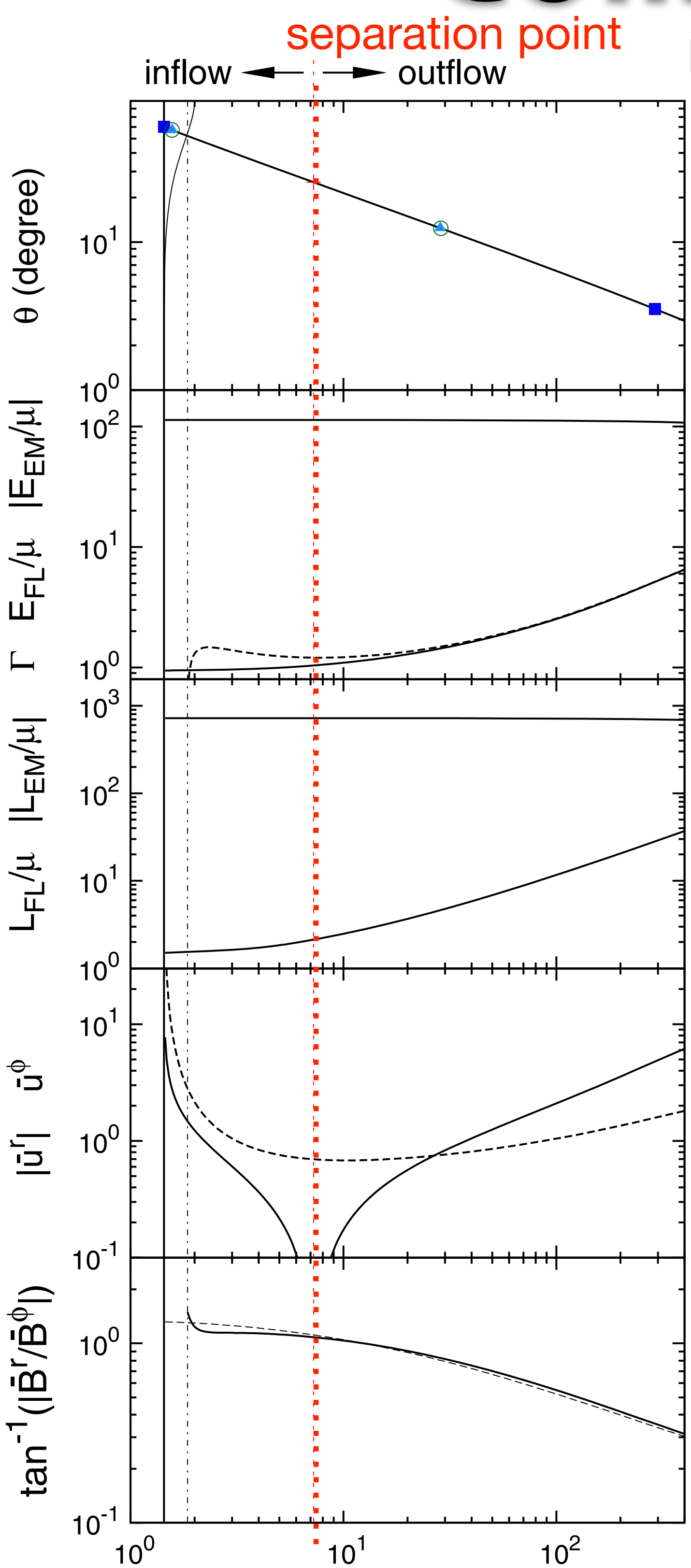
B_p field: parabolic solution (Blandford & Znajek 1977) + perturbation (Beskin & Nokhrina 2006)



Pu, MN, + (2015), *ApJ*

Fate of GRMHD Jets: How Acceleration/ Collimation is Terminated?

Pu, MN, + (2015), *ApJ*; qualitatively consistent with McKinney (2006)



along a streamline that threads the EH at mid-latitude (similar to McKinney 2006)

$\theta_{\rm j} \propto z^{(1-a)/a}$

$\Gamma \propto z^{(a-1)/a}$

$\Gamma\theta \sim 0.1$

c.f., Jorstad+ (2005)
Pushkarev+ (2009)
Clausen-Brown+ (2013)

$\Gamma \bar{B}^r / \bar{B}^\phi \simeq 1$

quasi F-F;
e.g., Lyutikov+ (2005)
Clausen-Brown+ (2011)

- 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 : Poynitng-to-matter energy flux ratio

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

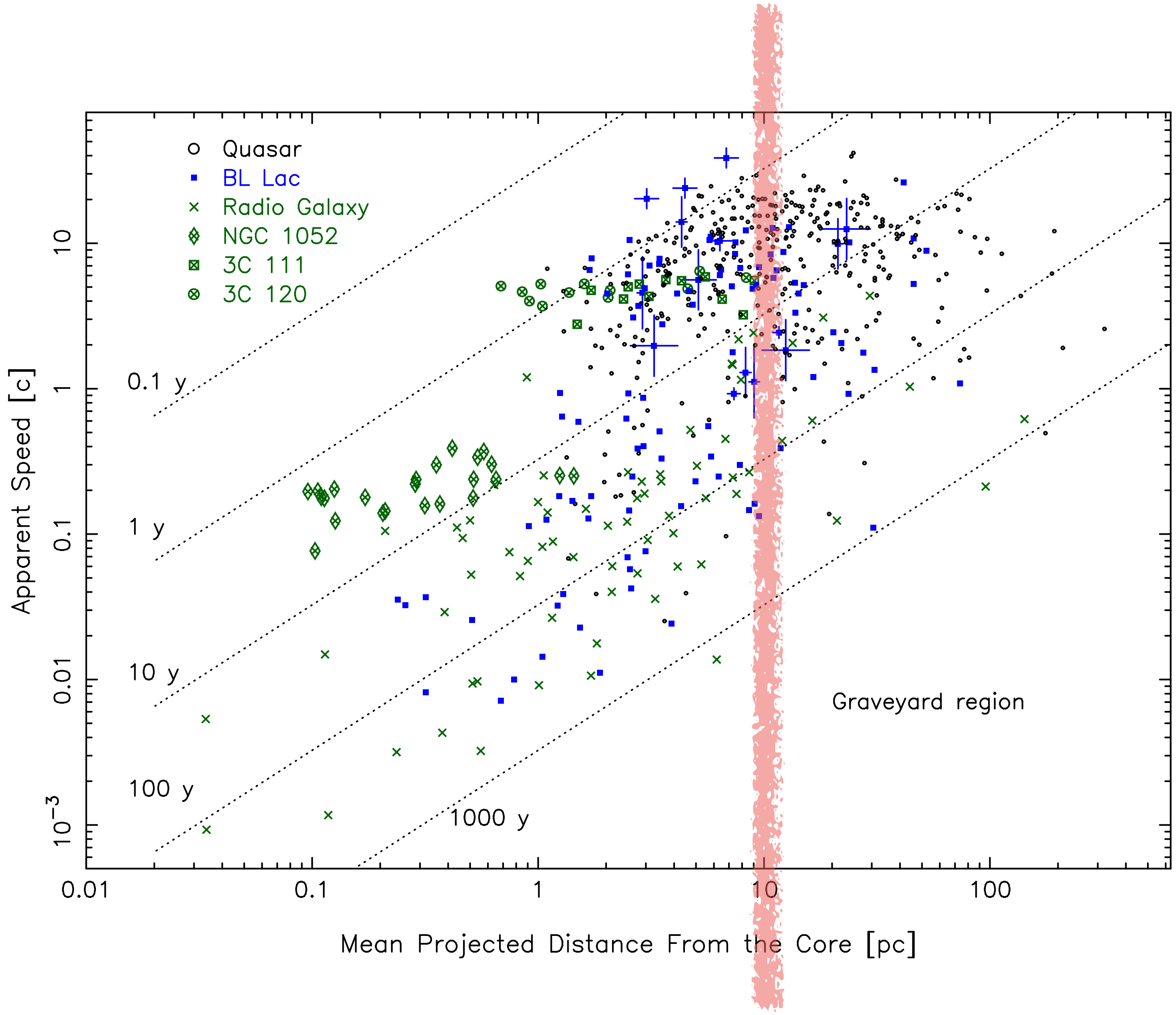
$$\mu \sim 10^{1-3}$$

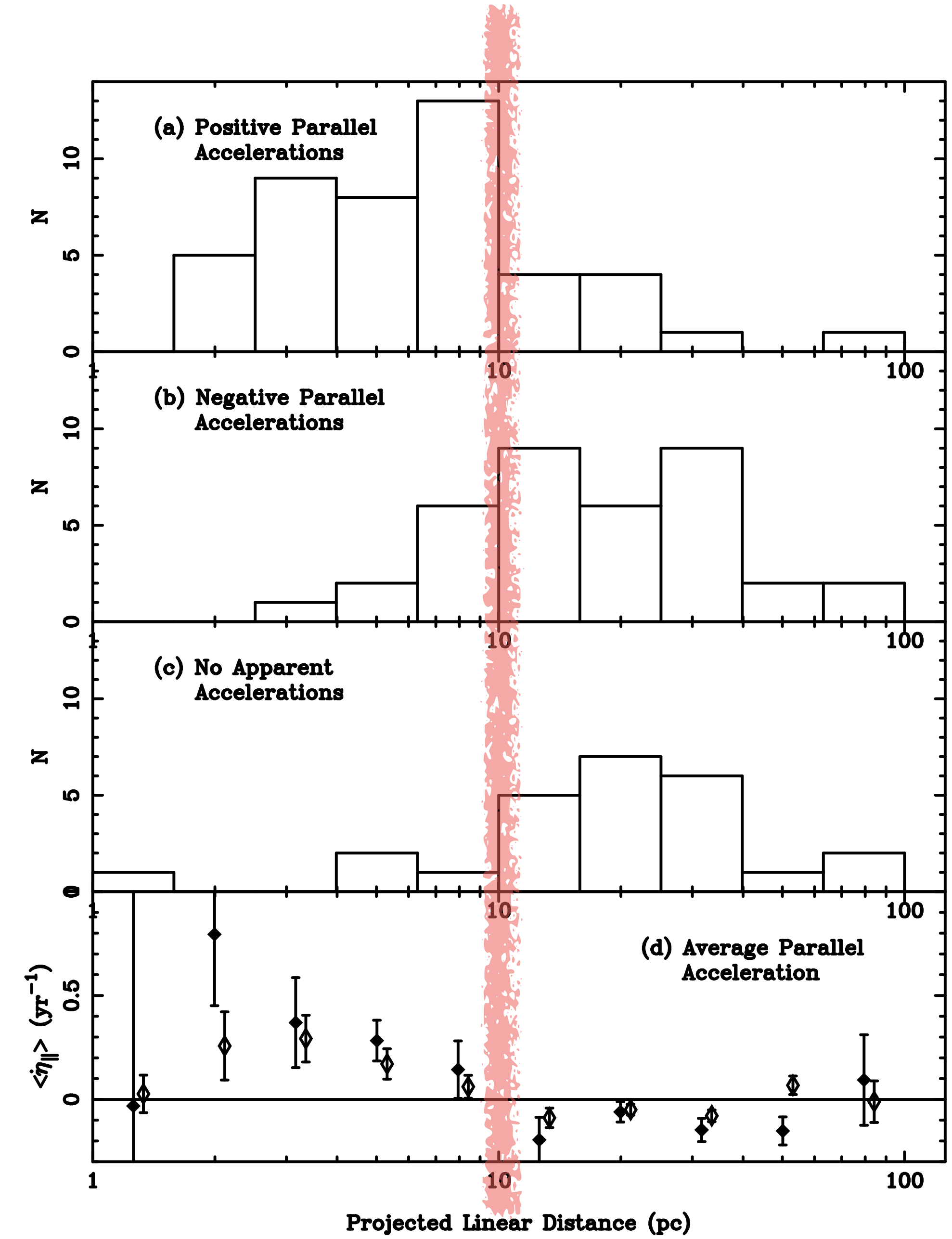
(Beskin 2010; Nokhrina+ 2015)

$\mu \simeq 10$
$\sigma_\infty \simeq 0$

would be norm?

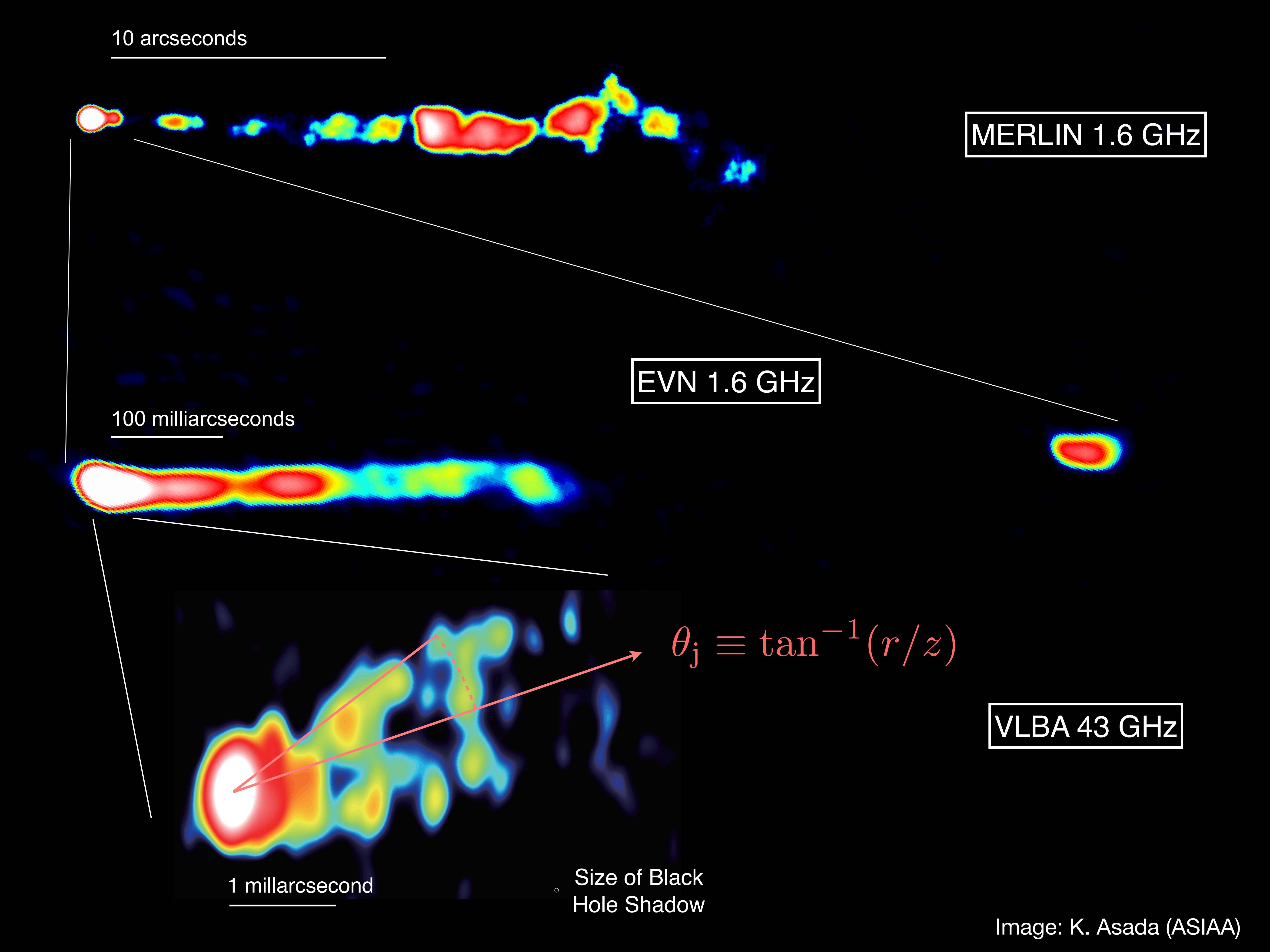
Transition found in MOJAVE AGNs



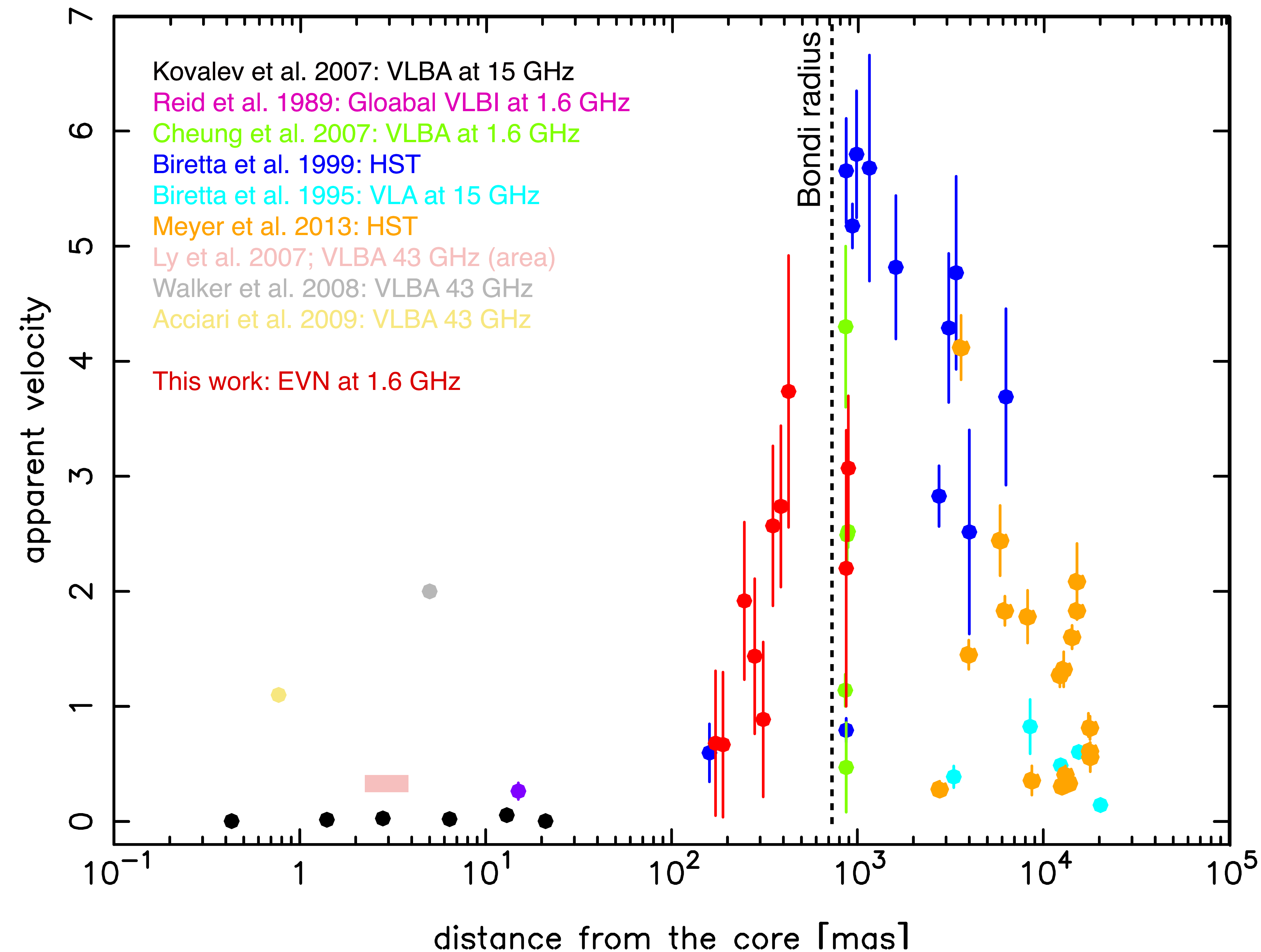


Lister+ (2013) (***see also Kellermann 2004; a tendency can been seen***) Homan+ (2015)

- 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 $z \propto r$, so that jets is still being collimated (Homan+ 2014; also Pushkarev & Kovalev 2012 w/ T_b analysis)

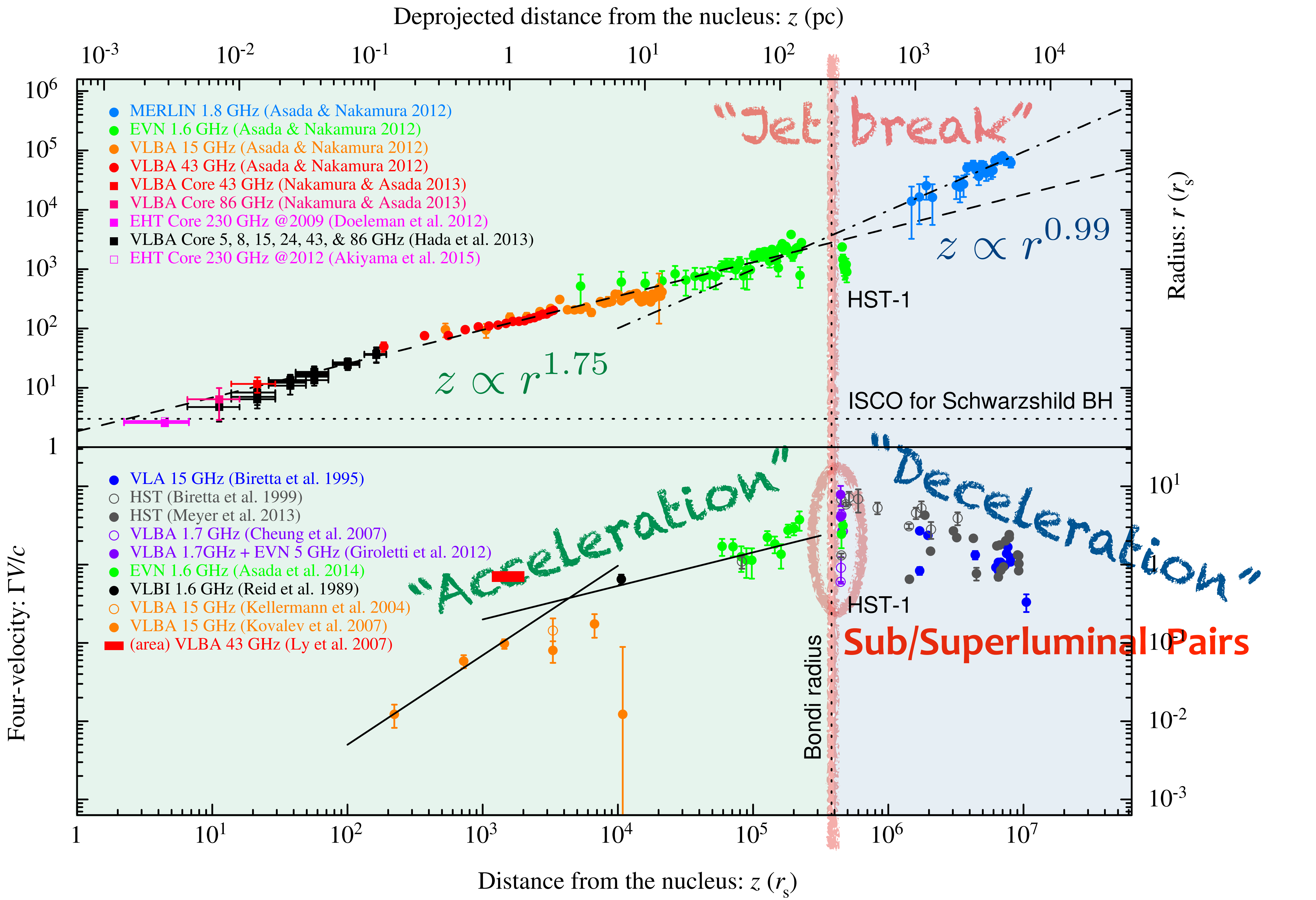

10 arcseconds
MERLIN 1.6 GHz
EVN 1.6 GHz
100 milliarcseconds
$\theta_{\rm j} \equiv \tan^{-1}(r/z)$
VLBA 43 GHz
1 millarcsecond
Size of Black Hole Shadow
Image: K. Asada (ASIAA)

A Missing Link Has Been Filled



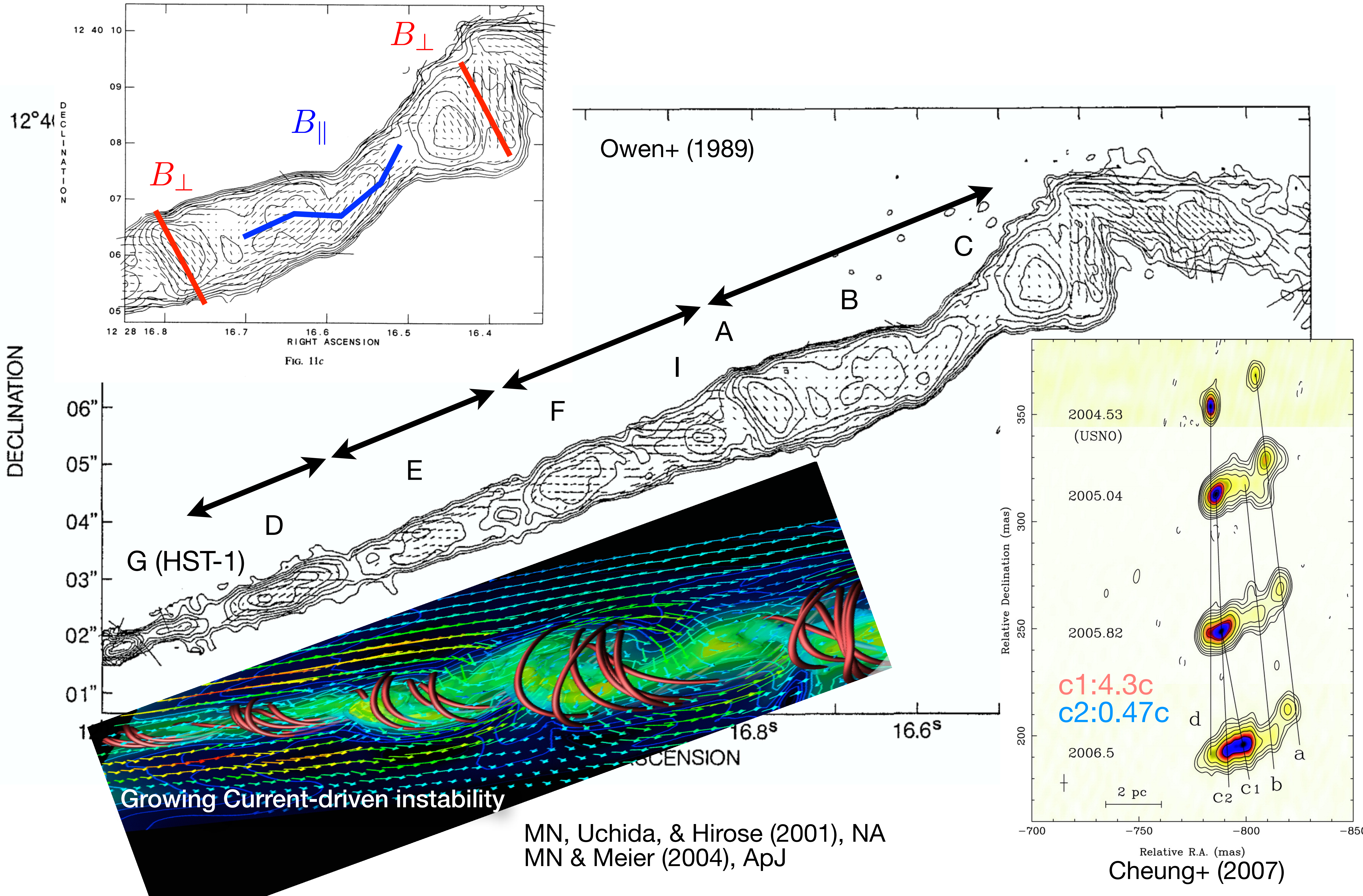
Asada, MN+ (2014), *ApJL*

Jet Structure and Dynamics in M87



Asada & MN (2012), *ApJL*; MN & Asada (2013), *ApJ*; Asada, MN, +(2014), *ApJL*

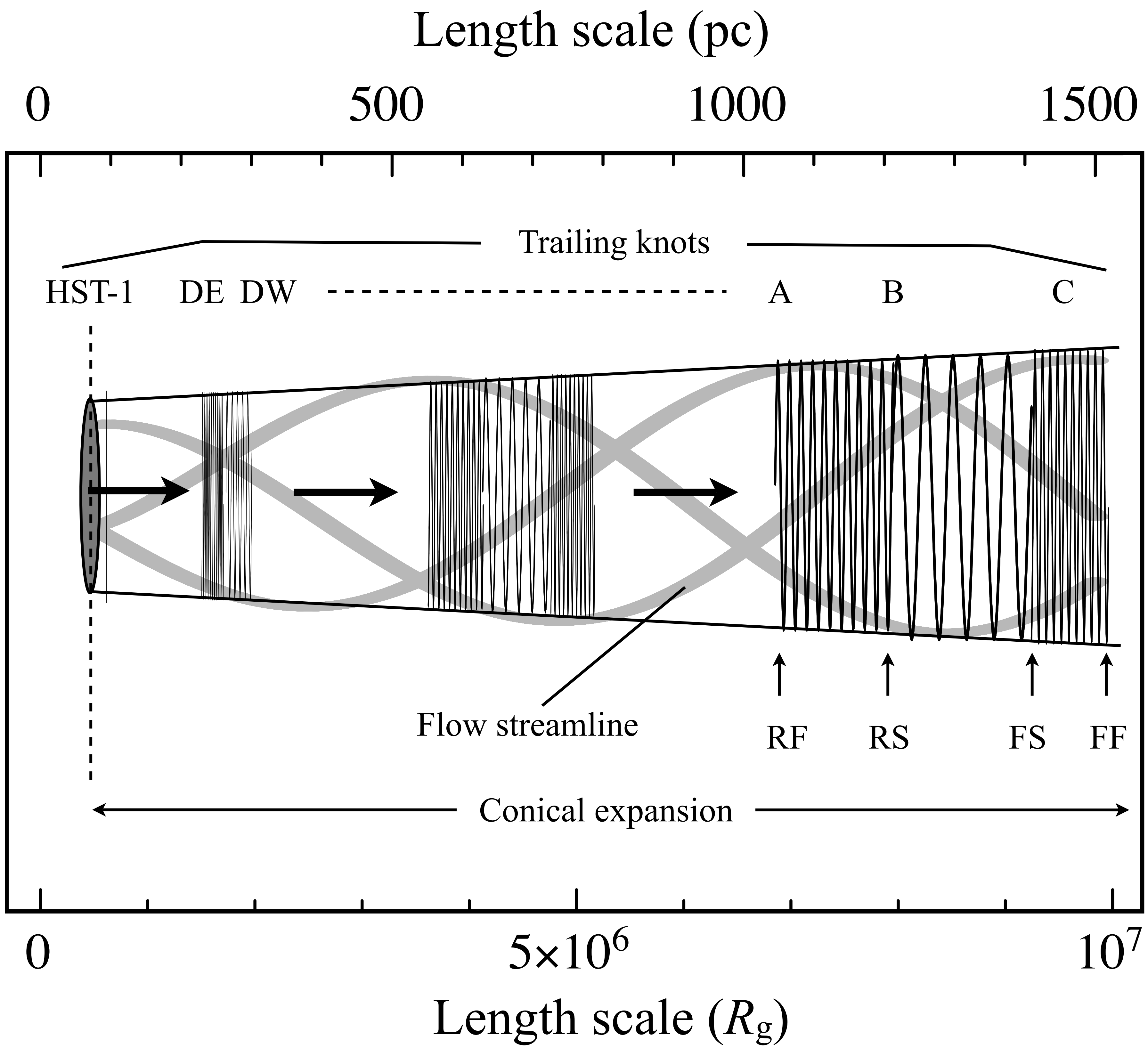
Trails of Components?



MN, Uchida, & Hirose (2001), NA
MN & Meier (2004), ApJ

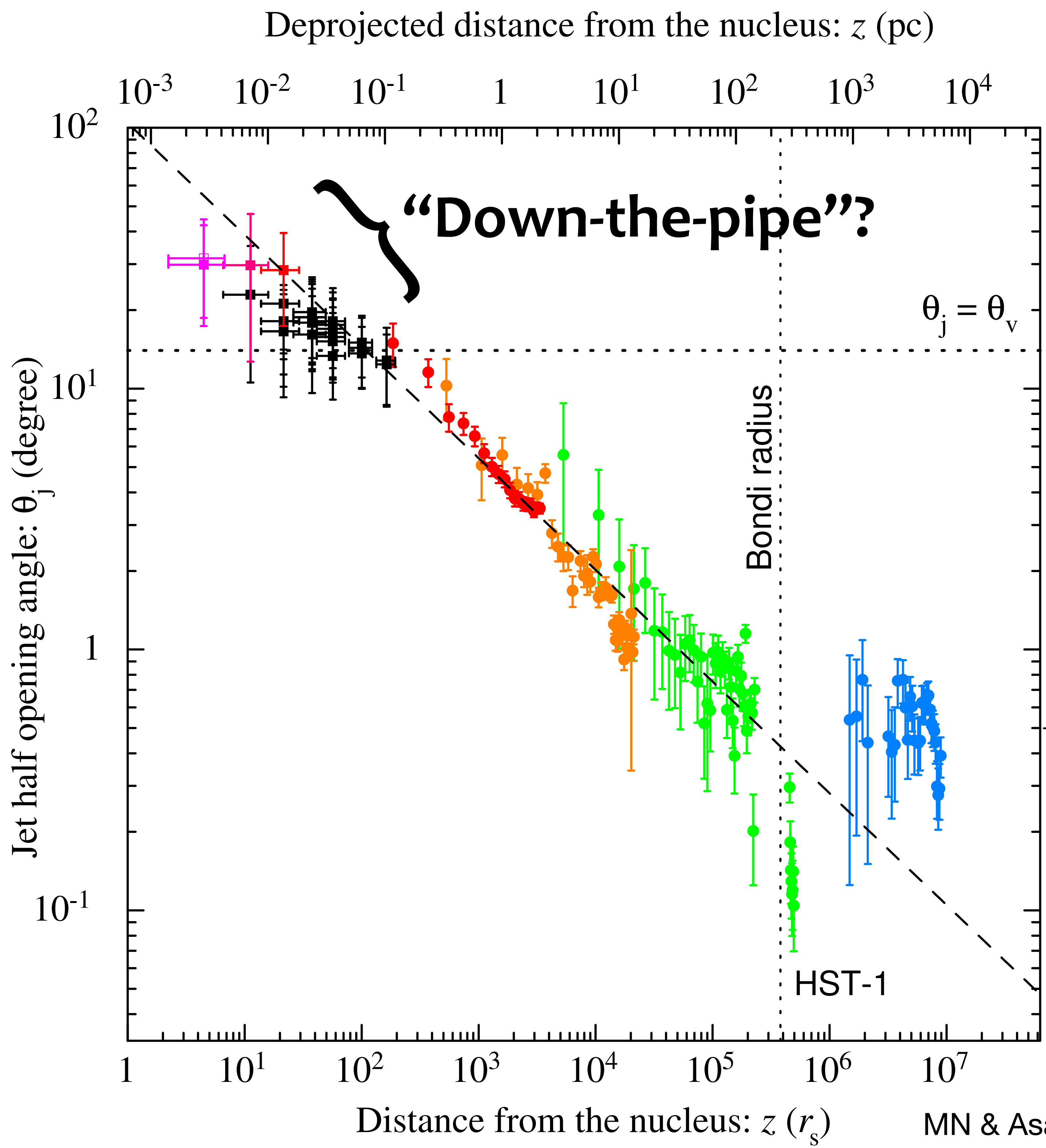
Cheung+ (2007)

Trails of MHD Shocks?



MN, Garofalo, & Meier (2010), ApJ; MN & Meier (2014)

Hints by Jet Opening Angle



MN & Asada, *in prep.*

$$\Gamma \approx \frac{a}{\sqrt{a-1}}\frac{z}{r} \propto z^{(a-1)/a}$$

(e.g., Komissarov+ 2009)

$$\theta_j \approx \frac{r}{z} \propto z^{(1-a)/a}$$

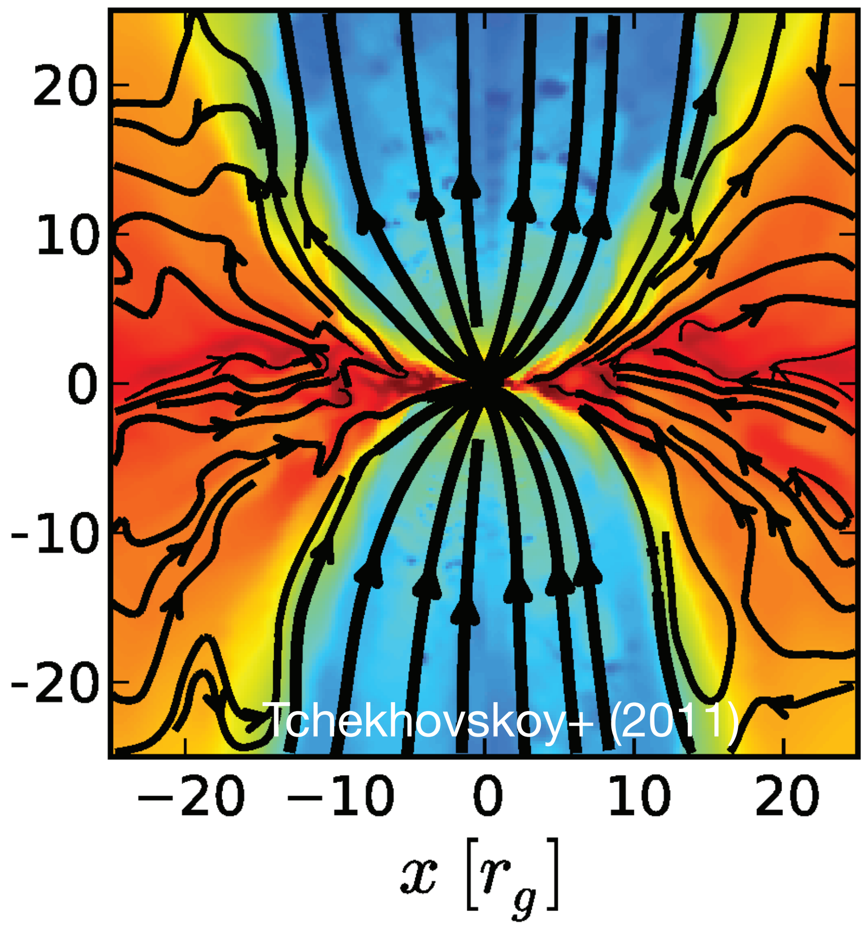
$$\Gamma\theta_j \sim 0.1$$

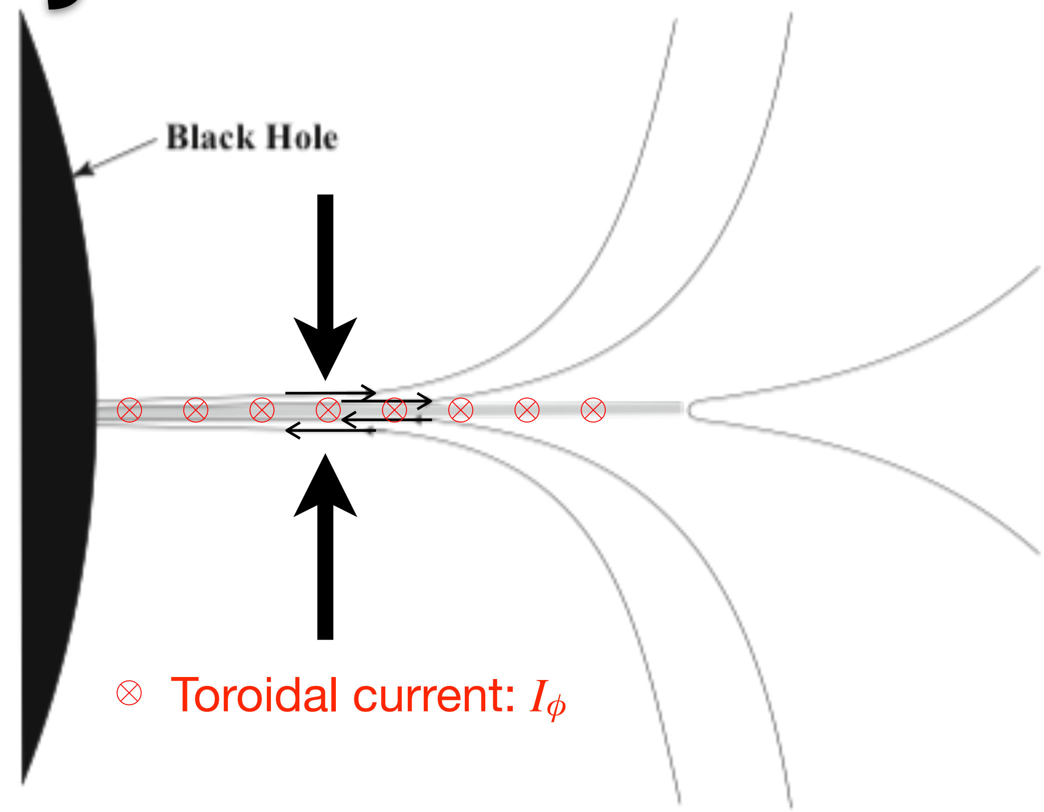
(e.g., Jorstad+ 2005; Pushkarev 2009; Clausen-Brown+ 2013)

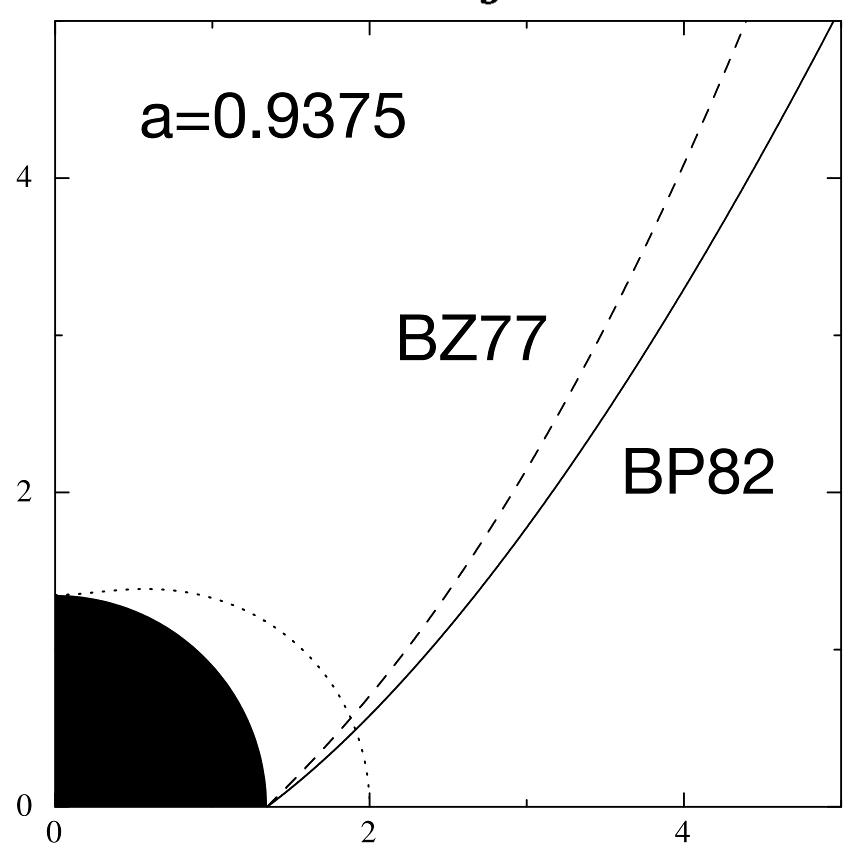
$$\Gamma \sim 11.5$$

Quad RMHD shock model for explaining super/sub-luminal pair at HST-1 (Biretta+ 1999) needs this underlying flow (MN & Meier 2014), while observed superluminal motions are $\lesssim \Gamma \sim 1/\theta_v$ in the upstream of HST-1 (Asada, MN+ 2014) … **missing a fast spin component?**

Outer Boundary of GRMHD Jets







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

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

$\nu = 1$ (Parabolic, BZ77)

$\nu = 3/4$ (Blandford & Payne 1982)

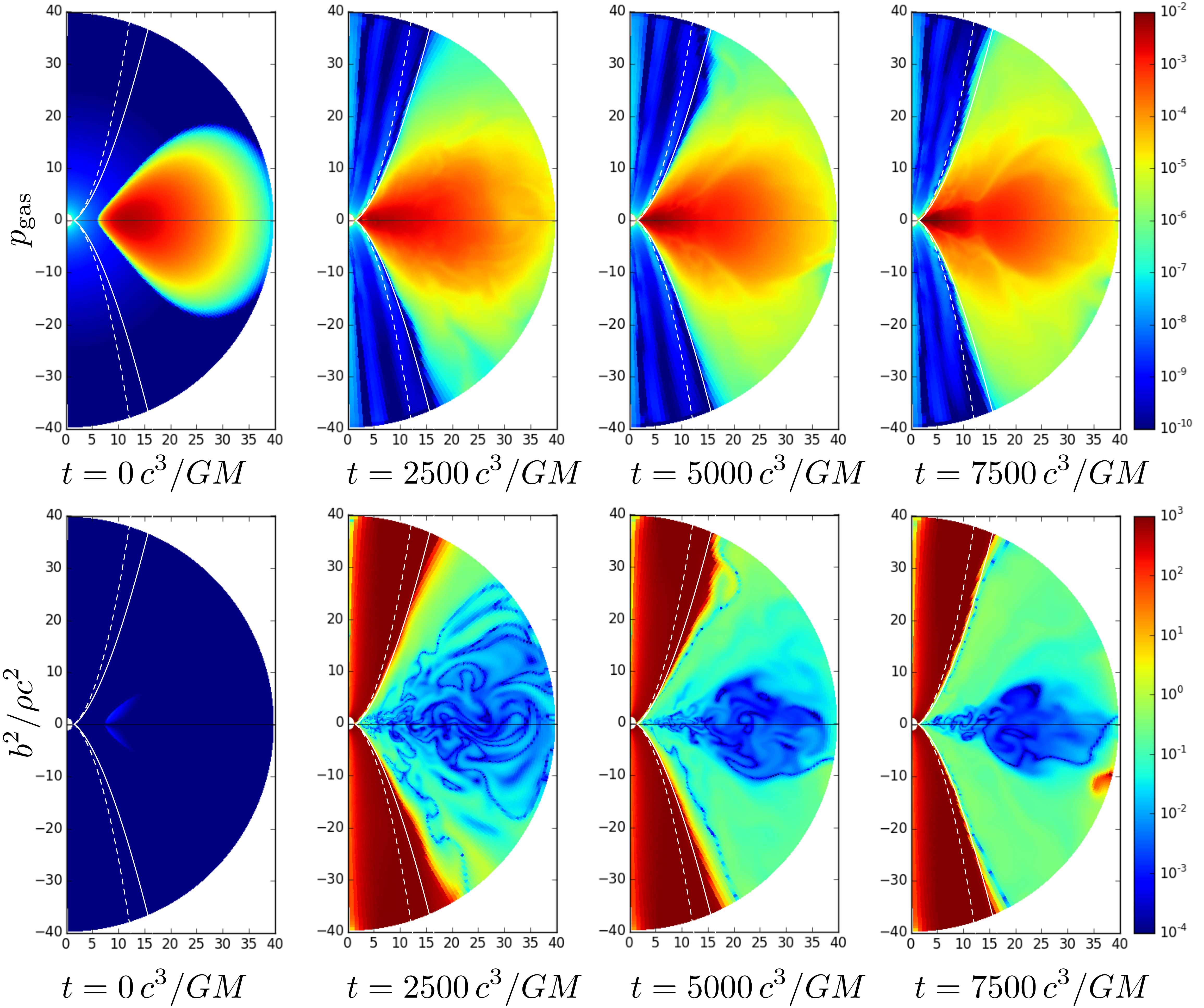
$\nu = 0$ (split-monopole)

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

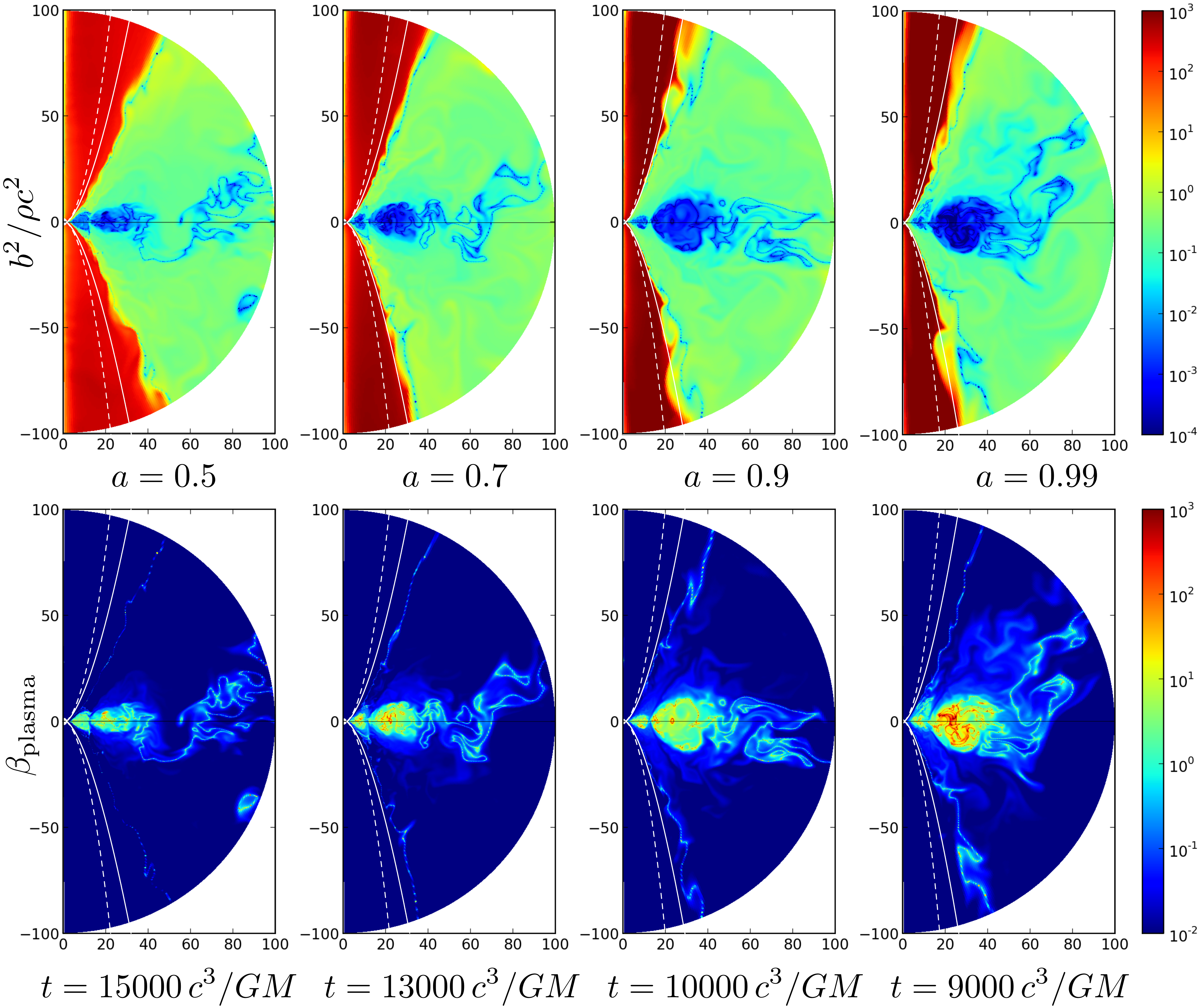
- Strong BH ***B***-field squeeze the accretion flow vertically down to *h/r* ~ 0.05 near the EH from ~ (0.3 - 1) at large distances (Tchekhovskoy 2015)

HARM Ver. 1.0
(Gammie+ 2003;
Noble+ 2006);
256^2 grids

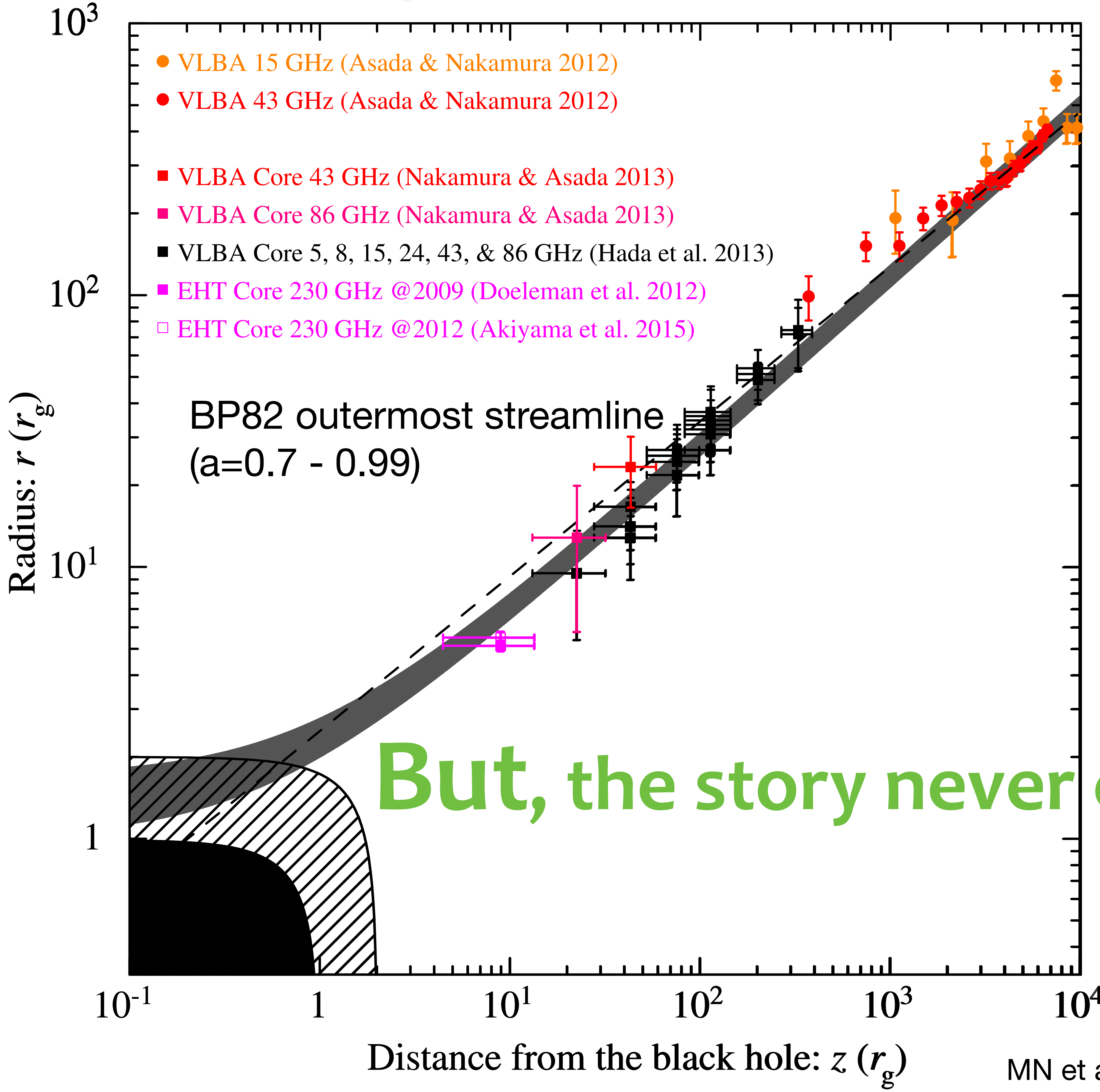
$a = 0.9375$



HARM Ver. 1.0
(Gammie+ 2003; Noble+ 2006);
512^2 grids



Comparison w/ Observations in M87



But, the story never ends ...

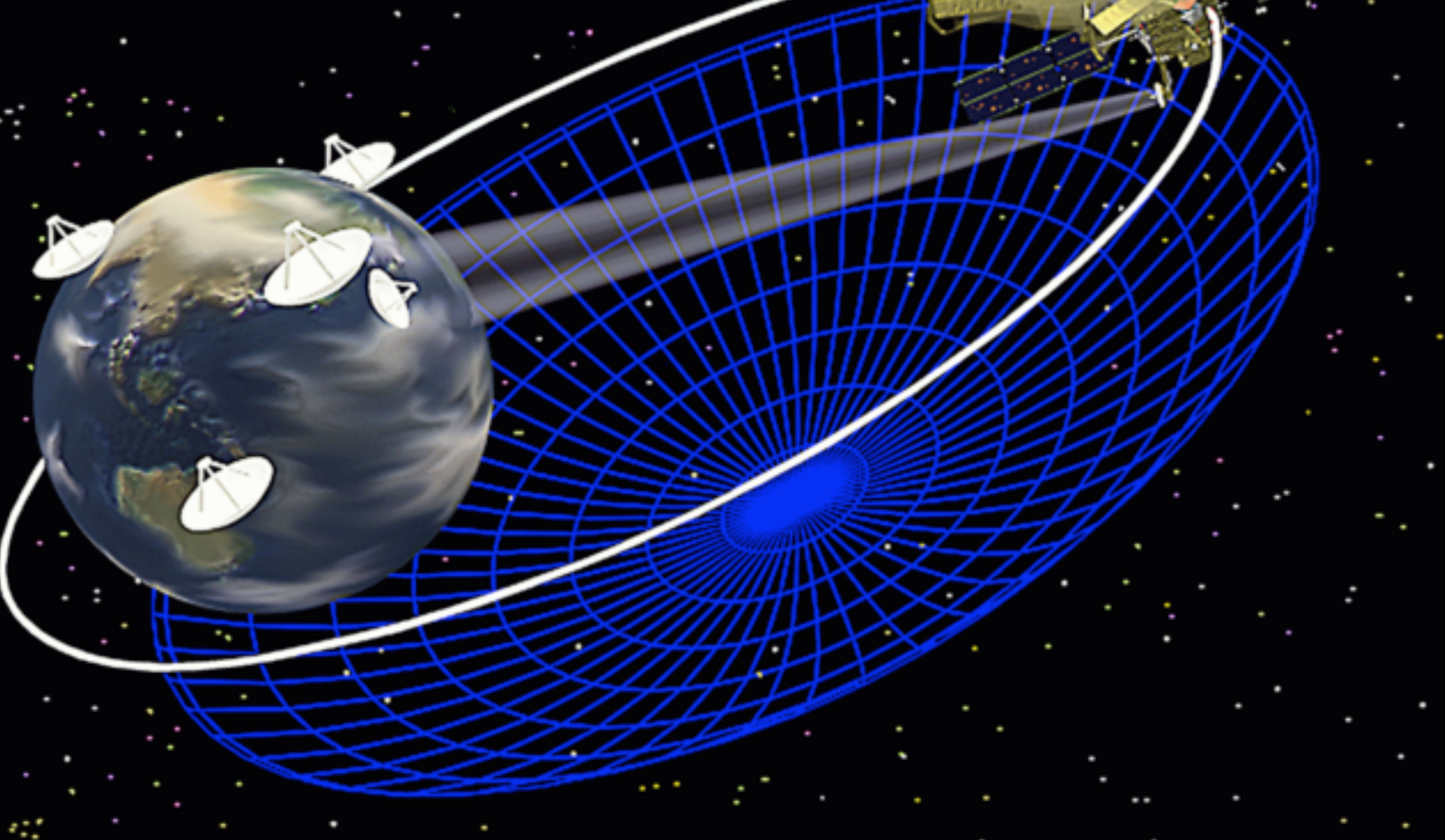
MN et al. *in prep*.

VSOP (1997~2005)

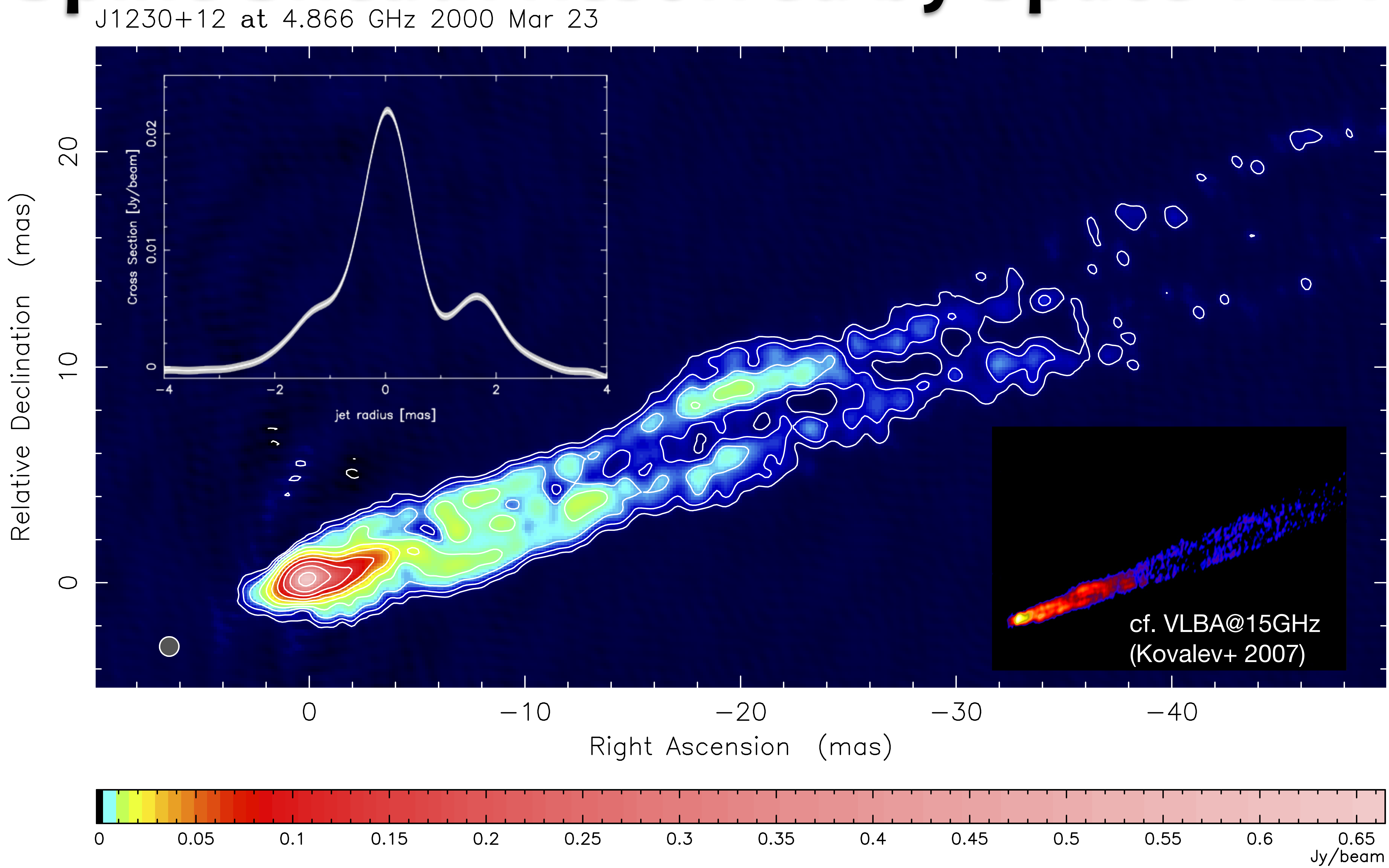
Dodson+ 2006, PASJ

✓ No evidence for significant motions

✓ Core T_B is well below the IC limit, suggesting that the emission is not strongly Doppler boosted

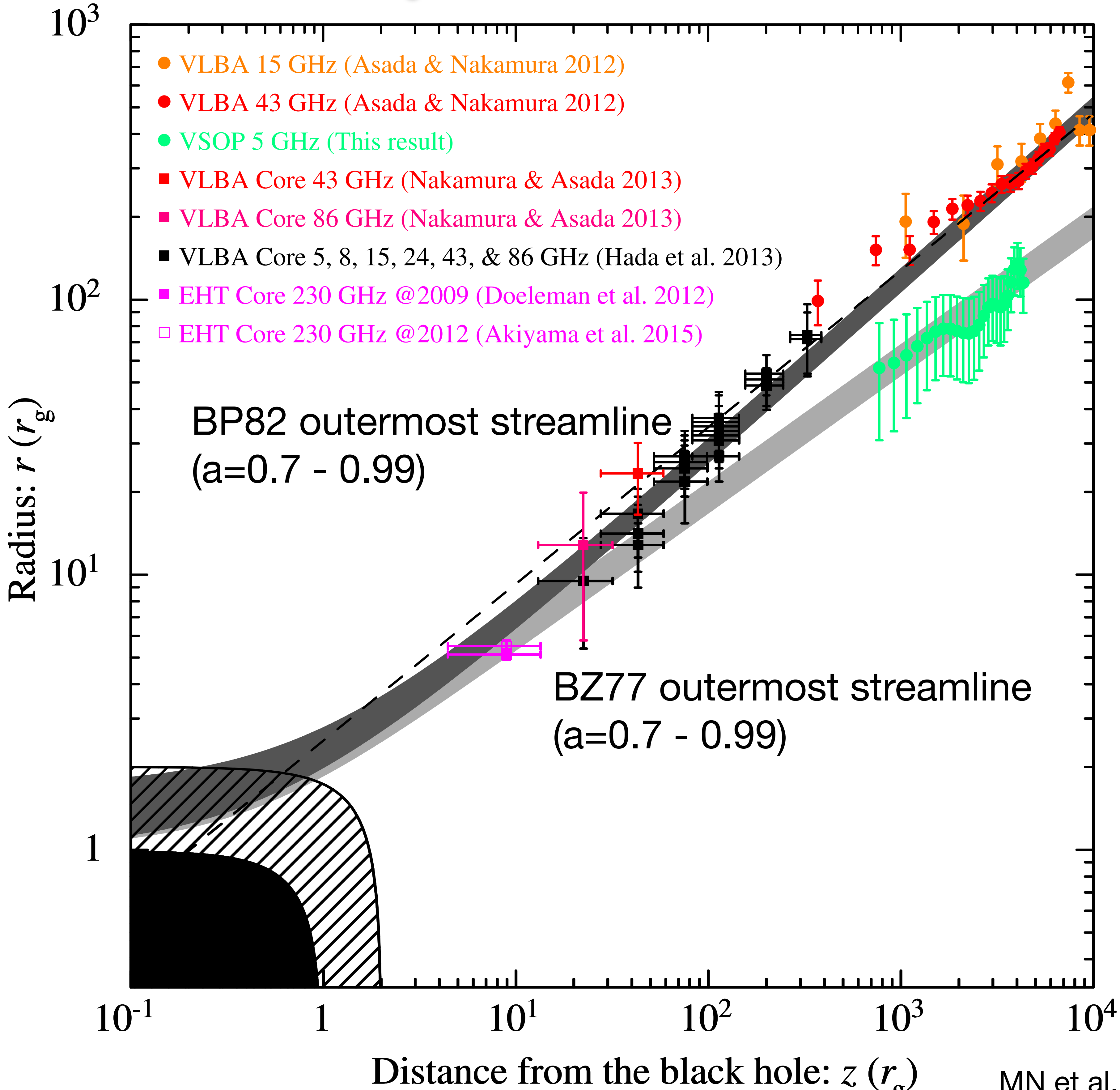


Spine-Sheath Resolved by Space-VLBI



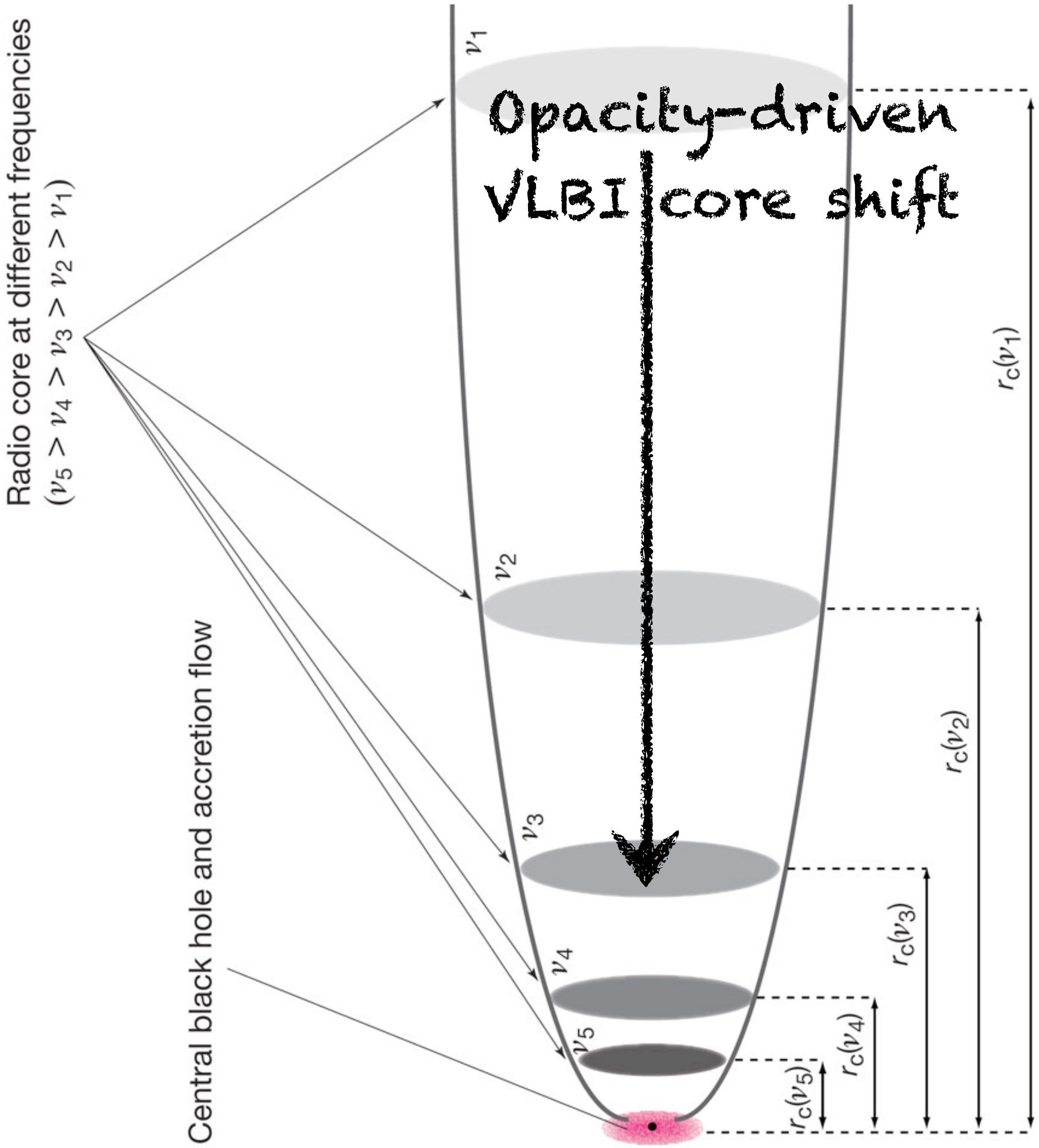
Asada et al., *in prep.*

Comparison w/ Observations in M87

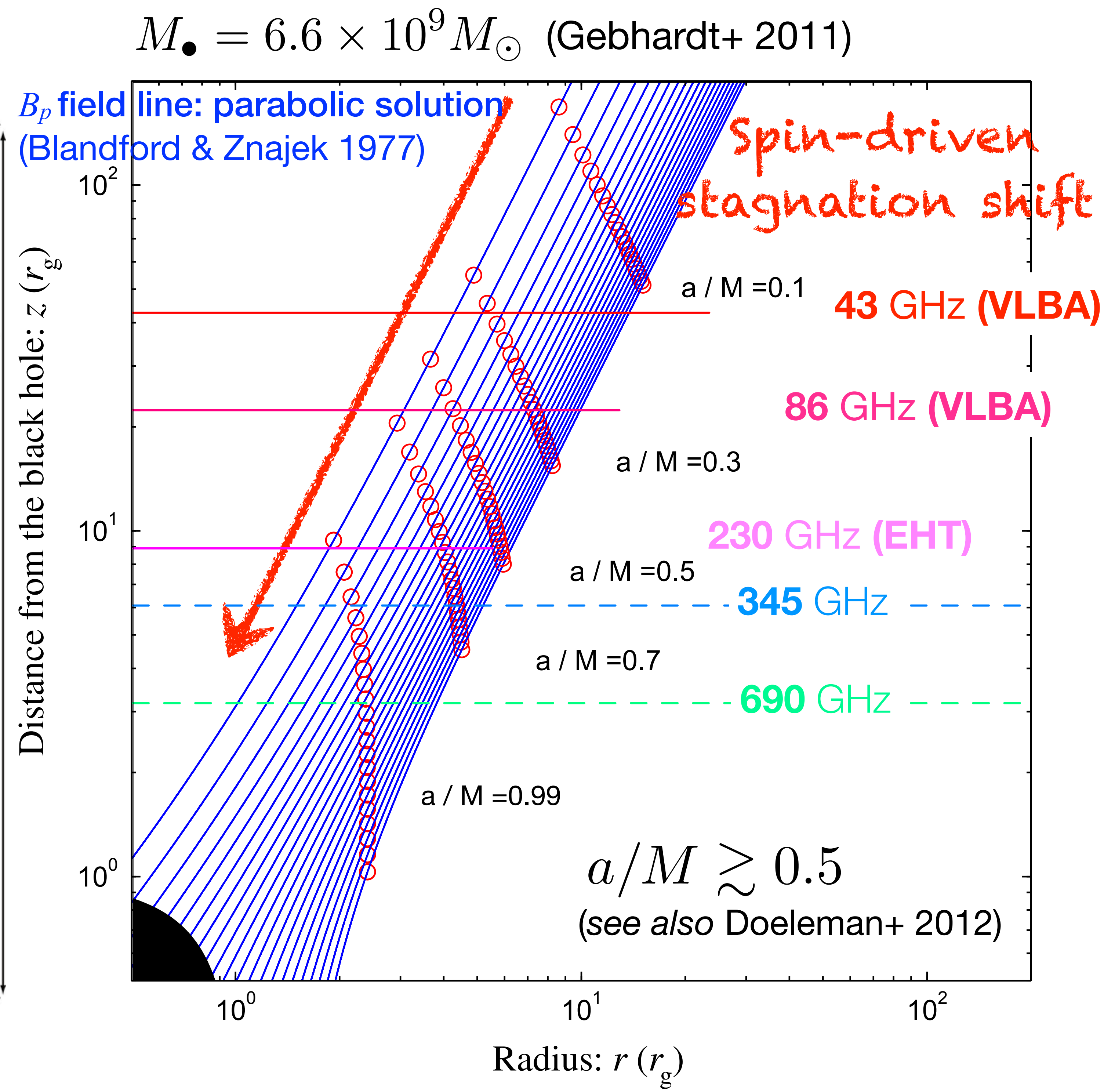


MN et al. *in prep*.

A Constraint of BH Spin w/ BZ77 & BK79



Blandford & Königl (1979); Hada+ (2011)



MN & Pu, *in prep.*

The inflow/outflow stagnation surface:

- **A origin of the jet, depending on the black hole spin (MN & Pu, in prep.)**
- **A natural site of pair formation/particle acceleration? (Broderick & Tchekhovskoy 2015)**

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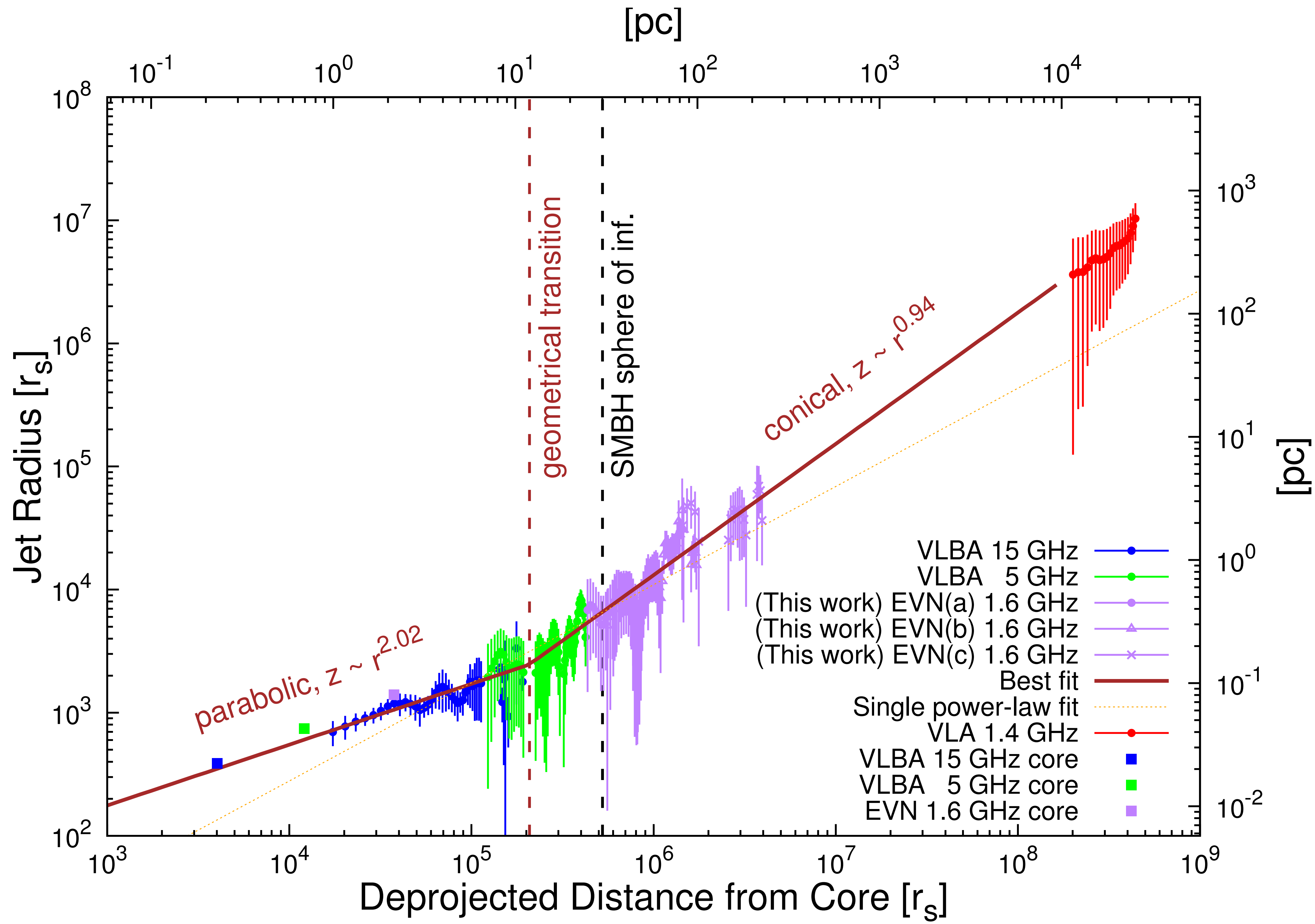
Case 2: FRI RG

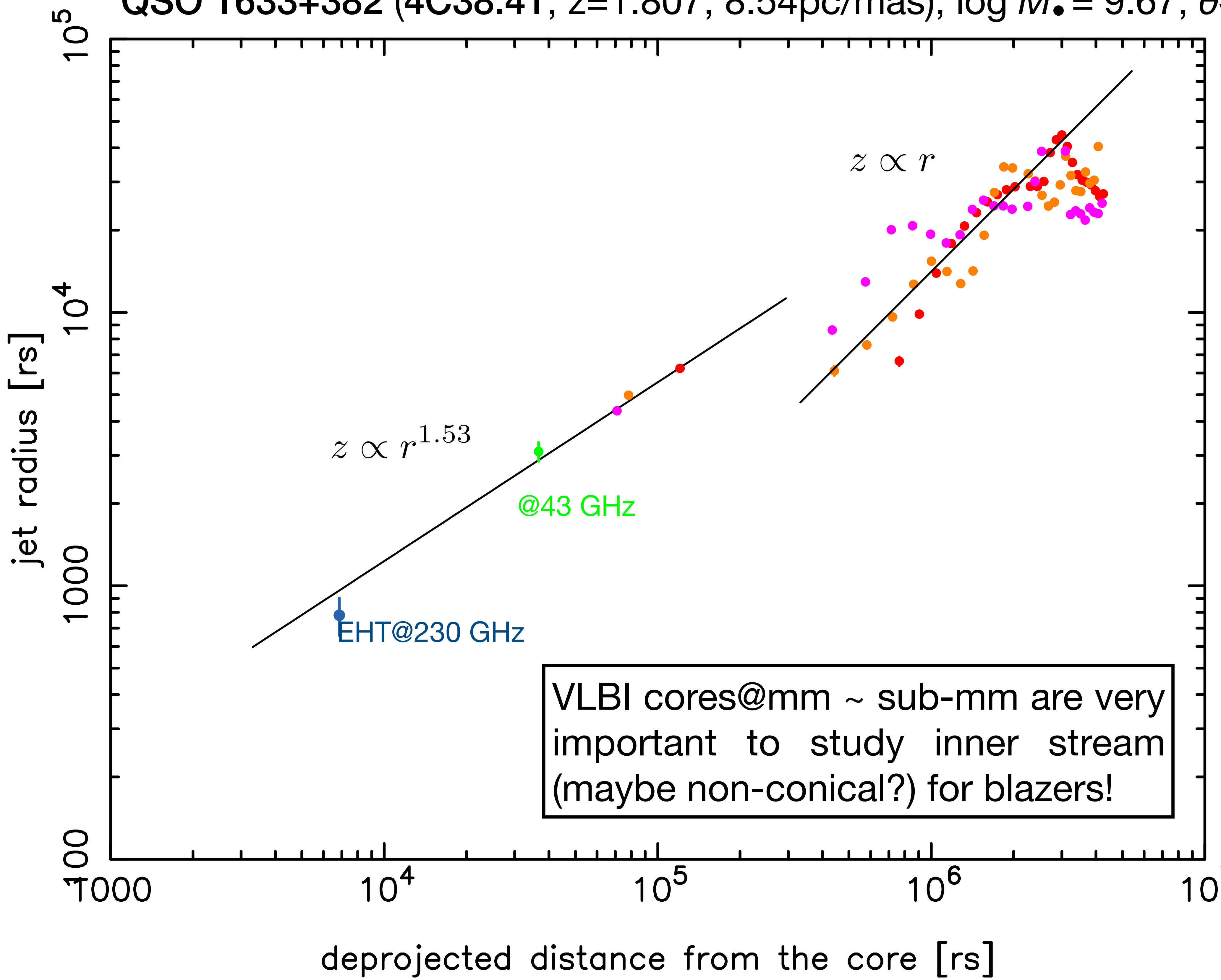
NGC 6251 (0.5 pc/mas = 8700 r_s), log $M_\bullet$ = 8.78, θ_V=19°



Tseng, Asada, MN+, *submitted* to ApJL

Case 3: Blazar

QSO 1633+382 (**4C38.41**, z=1.807; 8.54pc/mas), log $M_\bullet$ = 9.67, θ_v=2°.6



Asada, MN+ *in prep*. ***See also*, BL Lac objects; 1803+784, 3C 66A (Jorstad+ 2005)**

Summary

- M87: The best observable for examining the AGN jet with the highest angular resolution (1 mas ~ 125 r_s)

1. Sub-mm VLBI will reveal the origin of the jet in M87 *as well as the jet inner structure for blazers (non-BK79?)*
2. VSOP obs. reveals the jet spine (BZ77), while the jet sheath may be the outermost streamline (BP82) from BH
3. Jet acceleration/collimation takes place in the parabolic stream up to ~ 10^5 r_s (inside the sphere of BH influence)
4. We propose that the "*Jet break*" (from parabolic to conical) may be norm (*see also*, Potter's talk) in AGNs

⇒ MHD jet paradigm in a realistic galactic environment will be examined in the coming years