Jet Break in M87: Fundamental Property in AGN Jets

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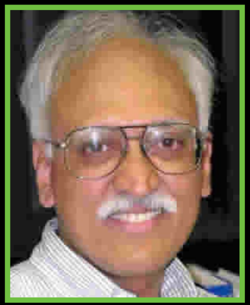
Institute for Theoretical Physics Seminar, Goethe University, Frankfurt, Germany, 12/04/2015

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

TOPICS

Registration & Abstract Submission (- 2016/02/15)

- SMBHs; mass, spin, and imaging of BH silhouettes
- BH accretion flows; from Bondi radius to the horizon
- BH Jets; from the horizon to galactic scale
- Co-evolution of galaxy and black hole: AGN feedback
- High energy emissions in LLAGNs; their sites and mechanisms

SOC: **P. Ho** (ASIAA, Chair)
L. Ho (KIAA, Vice-chair, keynote speaker)
R. Blandford (Stanford, keynote speaker)
A. Fabian (IoA, Keynote speaker)
R. Narayan (CfA, Keynote speaker)
K. Asada (ASIAA, Secretary)
M. Nakamura (ASIAA, Secretary)

Invited Speakers (*TBD):
K. Asada (ASIAA), **J. Biretta** (STScI), **G. Bower** (ASIAA), **A. Broderick** (U. Waterloo), **E. Churazov** (MPA), **S. Doeleman** (MIT Haystack), ***A. Doi** (JAXA), **J. Hawley** (U. Virginia), **A. Levinson** (Tel Aviv U.), **B. McNamara** (U. Waterloo), **H. Li** (LANL), ***D. Meier** (Caltech), **S. Mineshige** (Kyoto U.), **M. Mościbrodzka** (Radboud U.), **M. Nakamura** (ASIAA), **E. Perlman** (FIT), **W. Potter** (U. Oxford), **Ł. Stawarz** (Jagiellonian U.), **A. Tchekhovskoy** (UCB), ***C. Walker** (NRAO), **J. Walsh** (Texas A&M U.)

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
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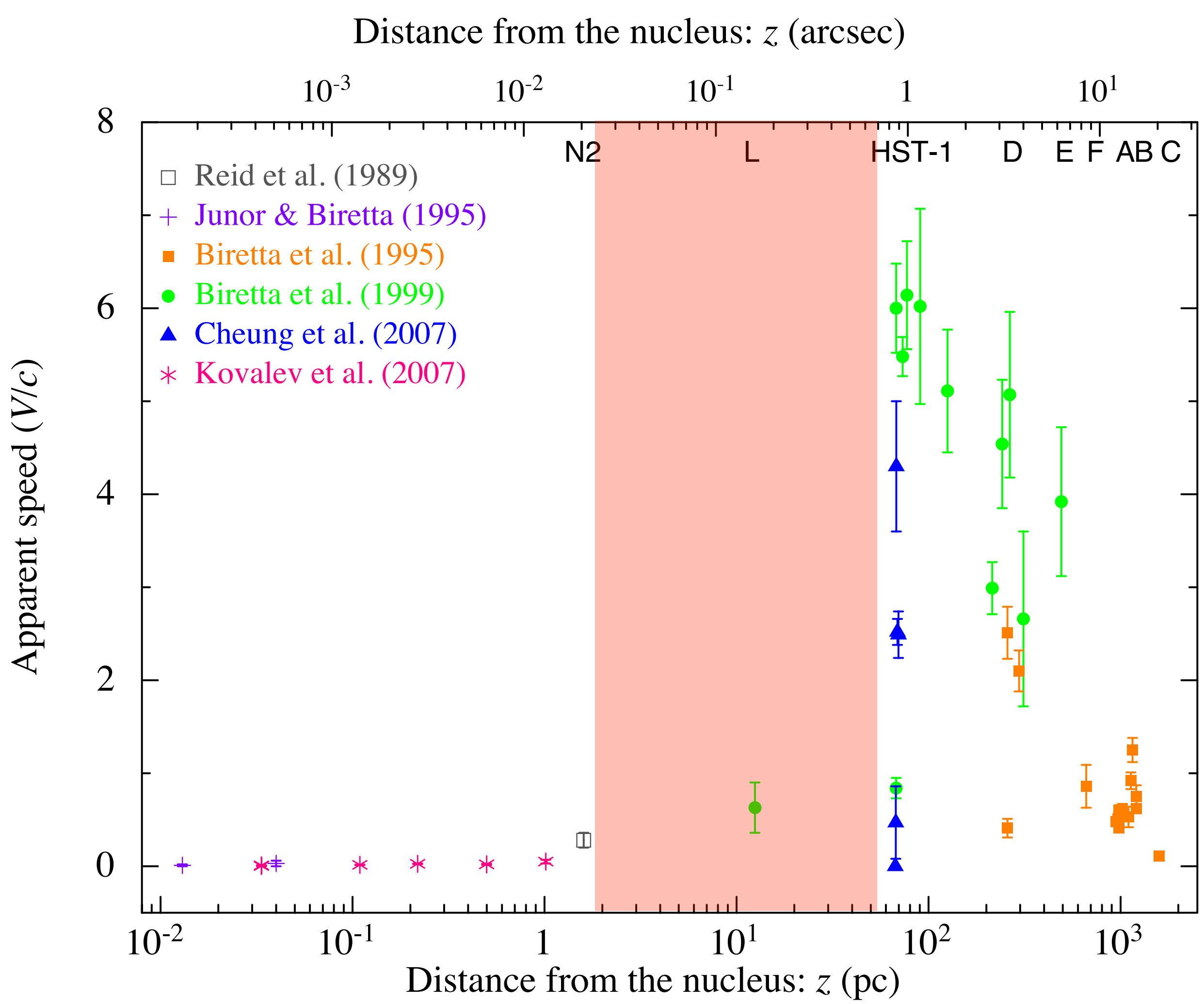
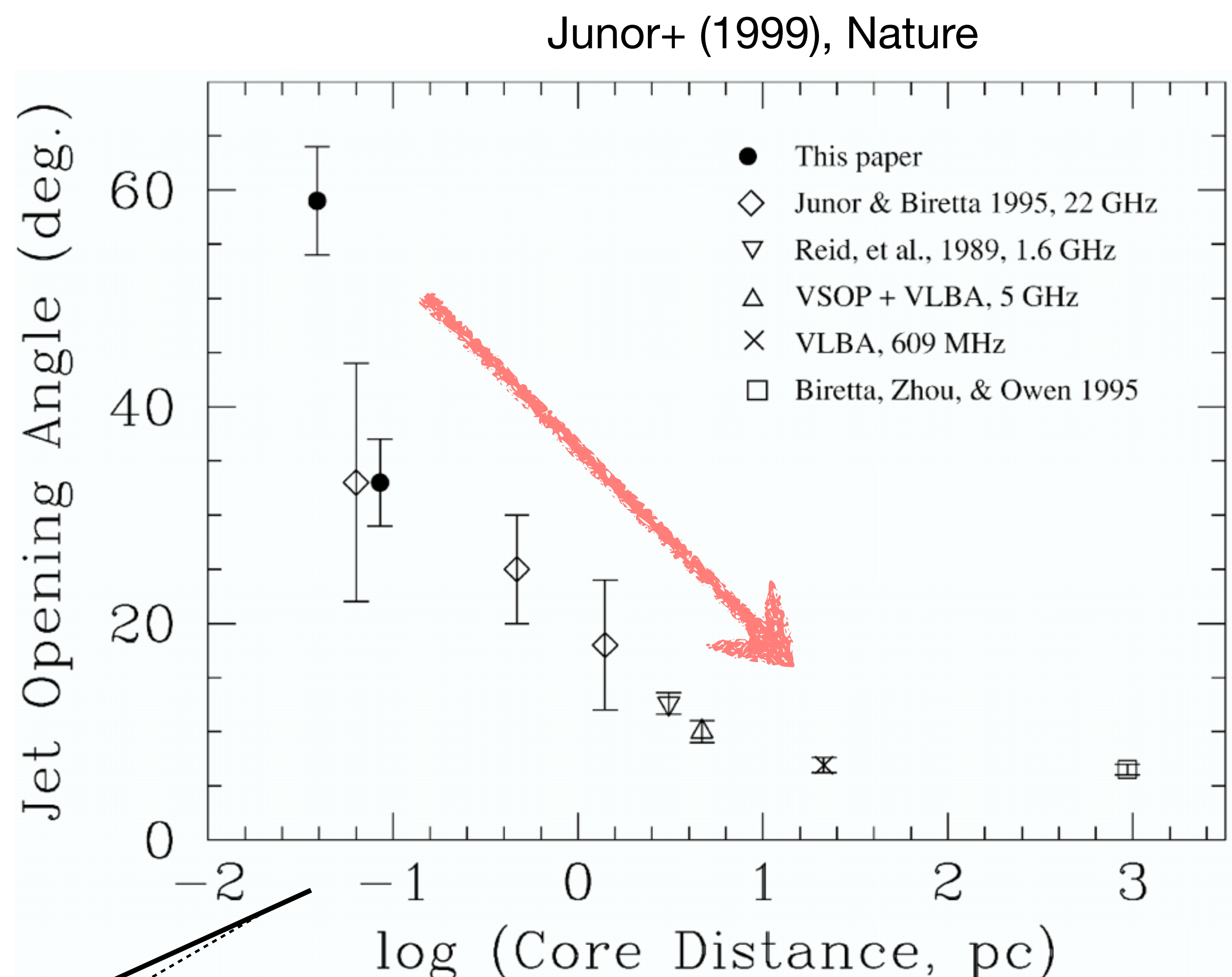
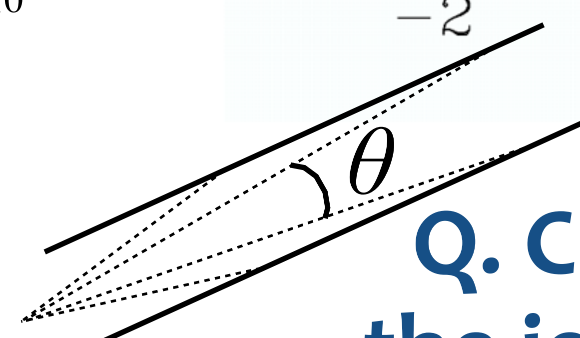
Puzzle Has Remained Unsolved During decades







Q. What is a large gap?

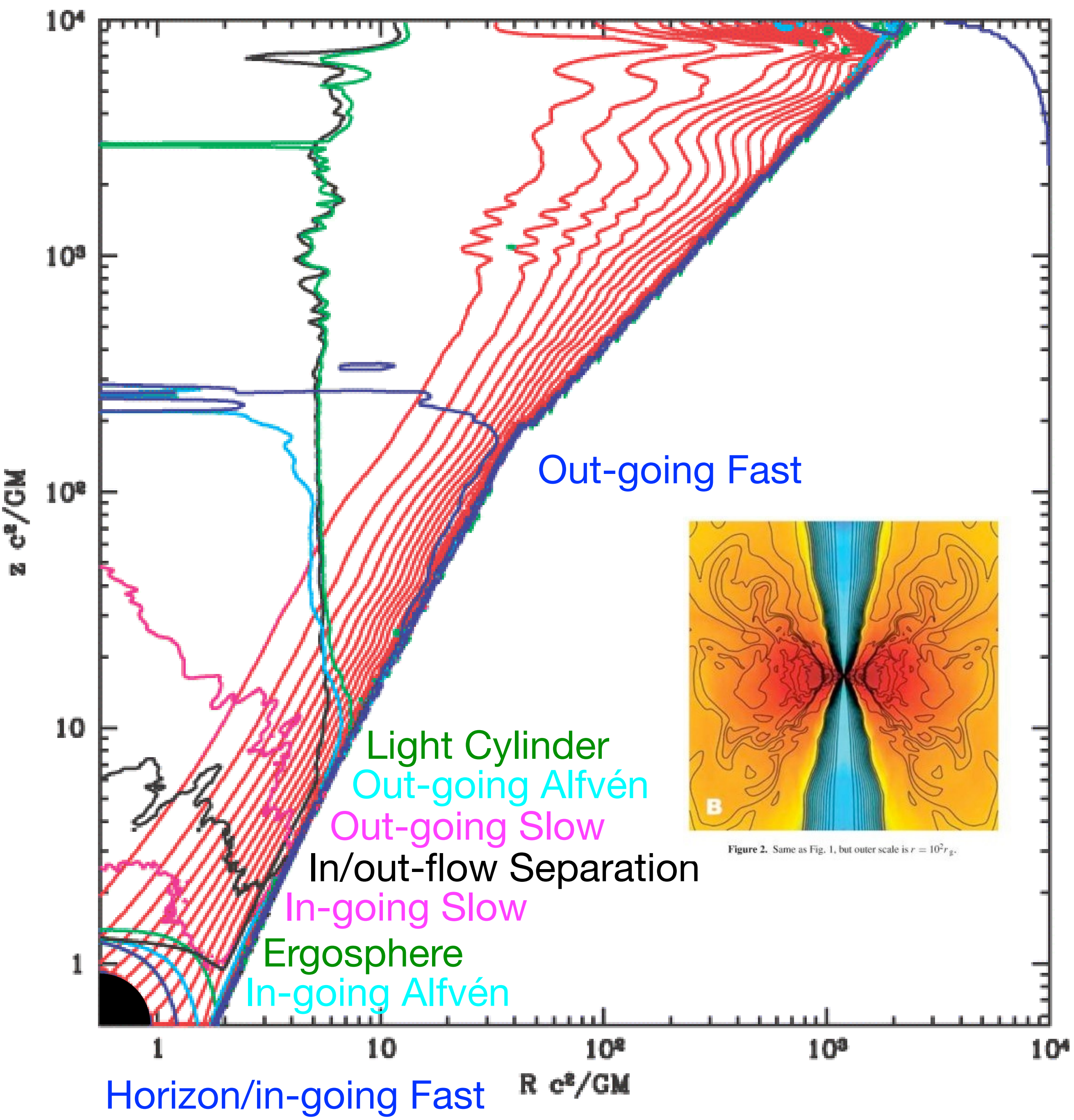
Q. Collimation is real (i.e. the jet is cylindrical *or not*)?

We have no clear view of jet acceleration/ collimation even in the most studied AGN jet ...

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

GRMHD Simulation (a =0.9375)

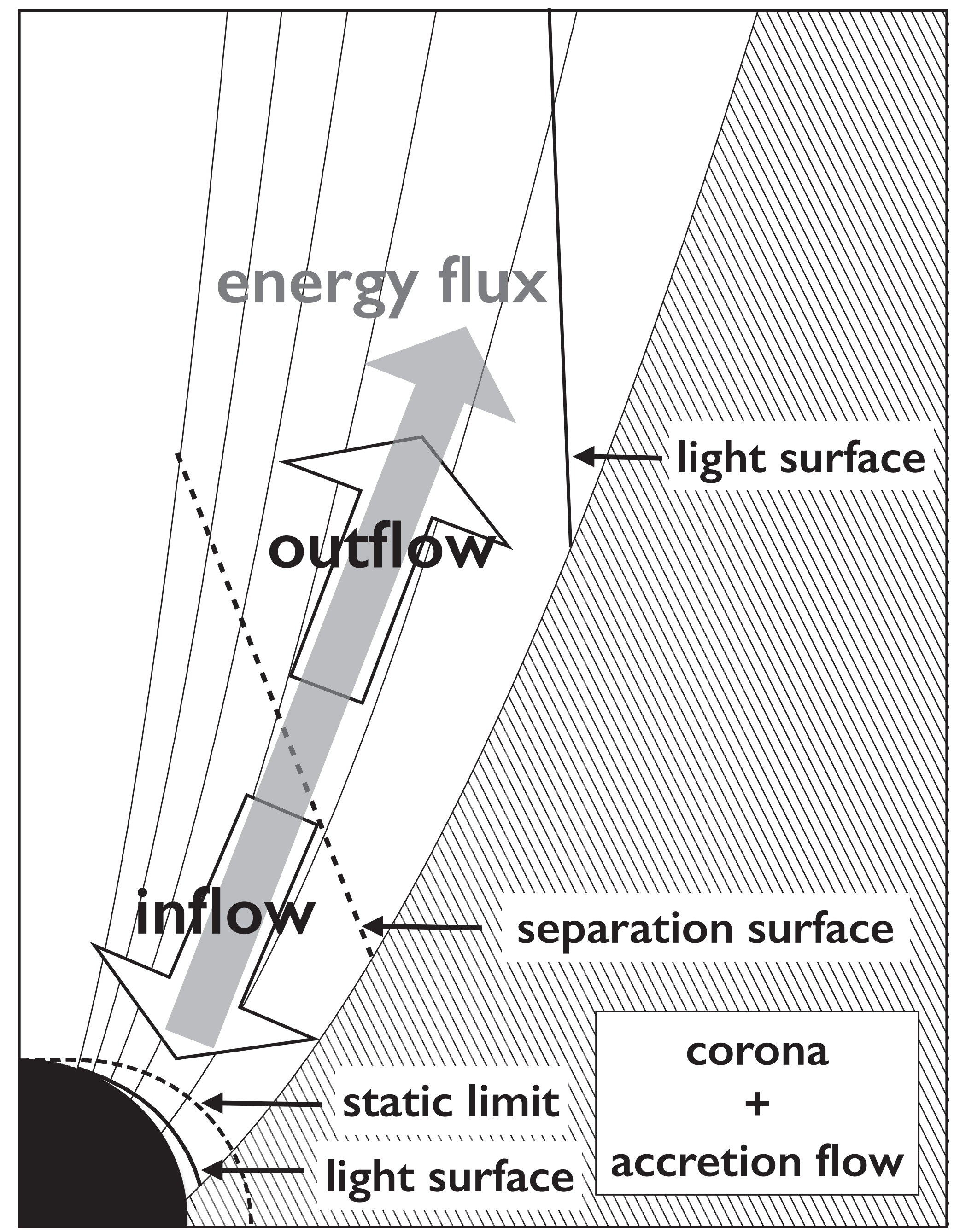
B_p field lines and characteristic surfaces



McKinney (2006)

Steady GRMHD (cold) solution (a =0.9375)

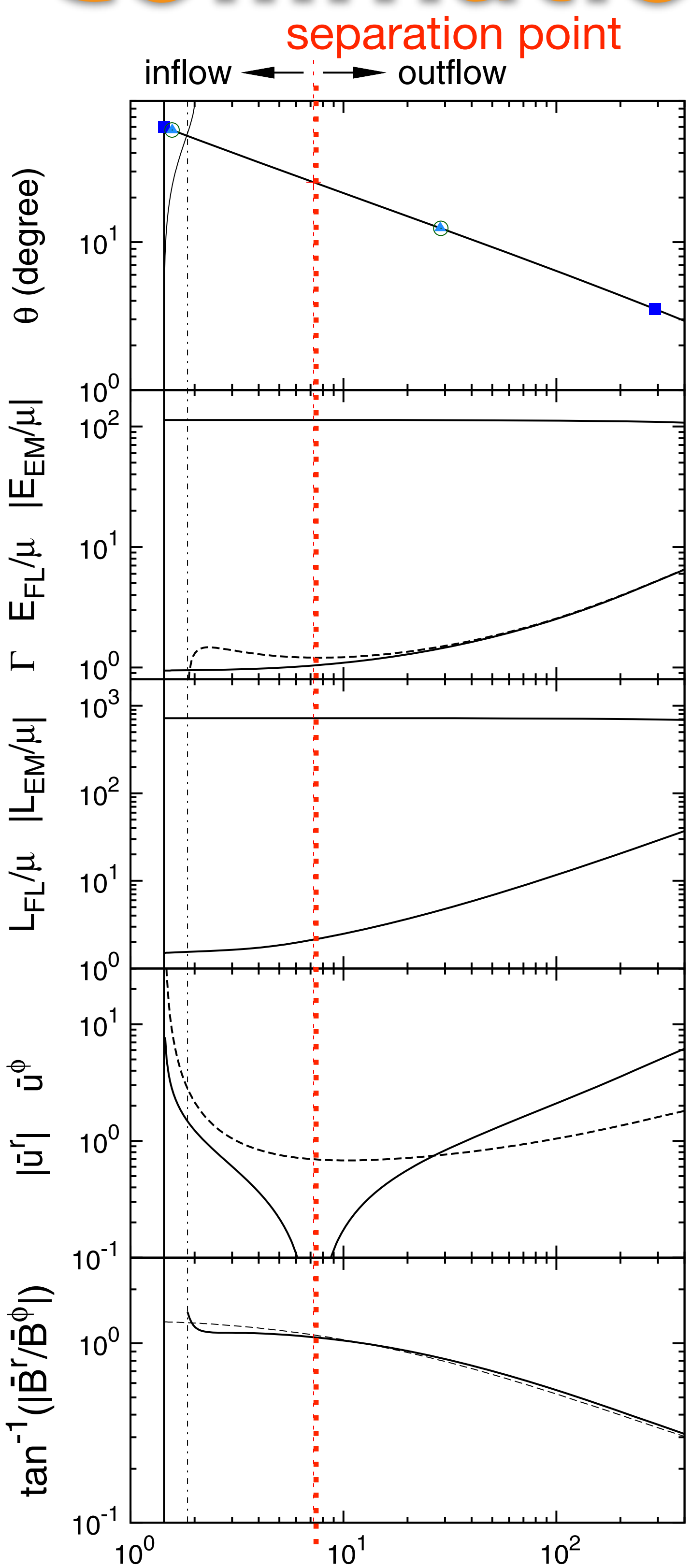
B_p field: parabolic solution (Blandford & Znajek 1977) + perturbation (Beskin & Nokhrina 2006)



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

Open Question 1: How Acceleration/ Collimation in MHD jets is Terminated?

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



r (c^2/GM) 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

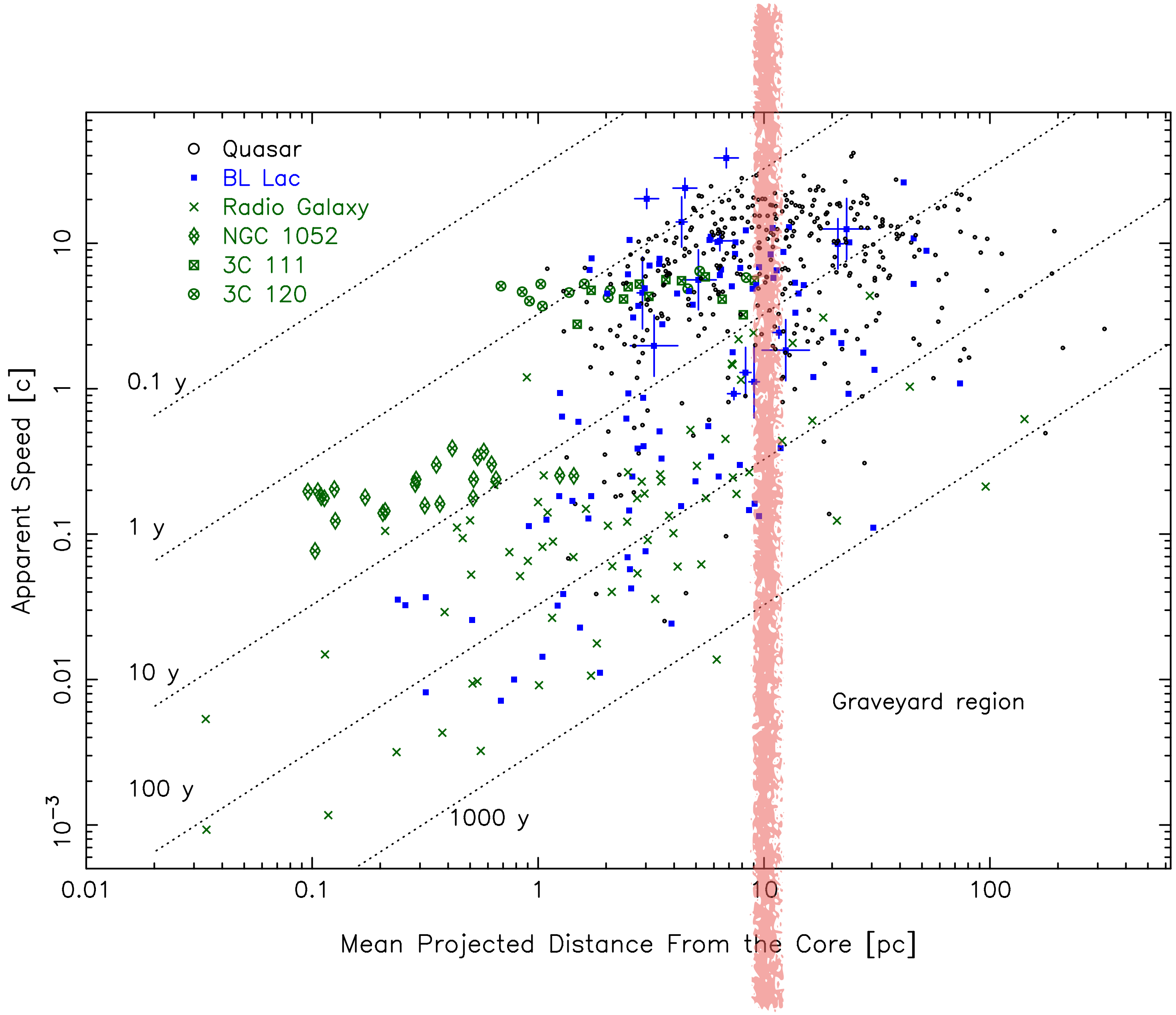
$$\gamma_\infty \simeq \mu \left(\sigma_\infty \simeq 0\right)$$

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

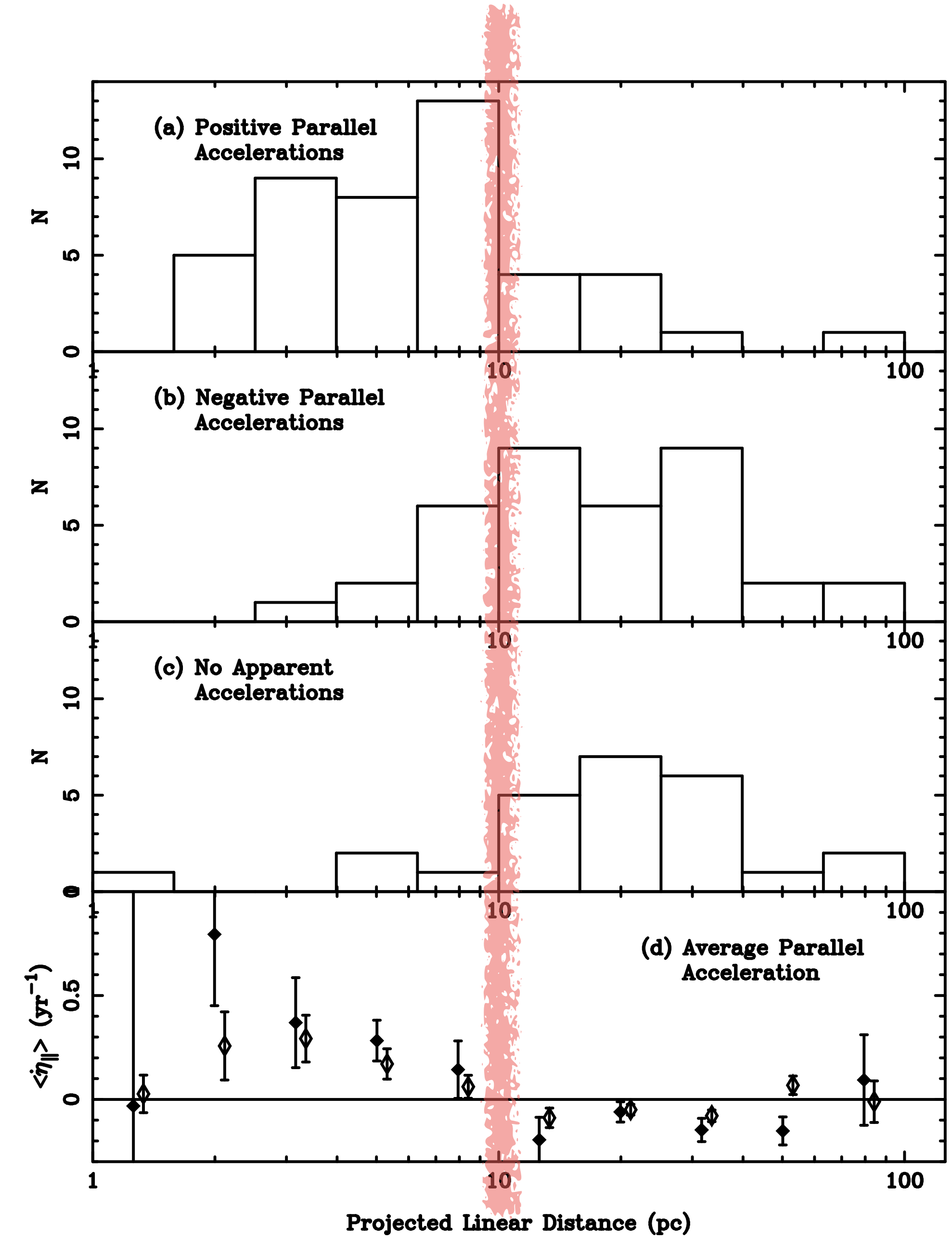
(Beskin 2010; Nokhrina+ 2015)

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

Transition found in MOJAVE AGNs



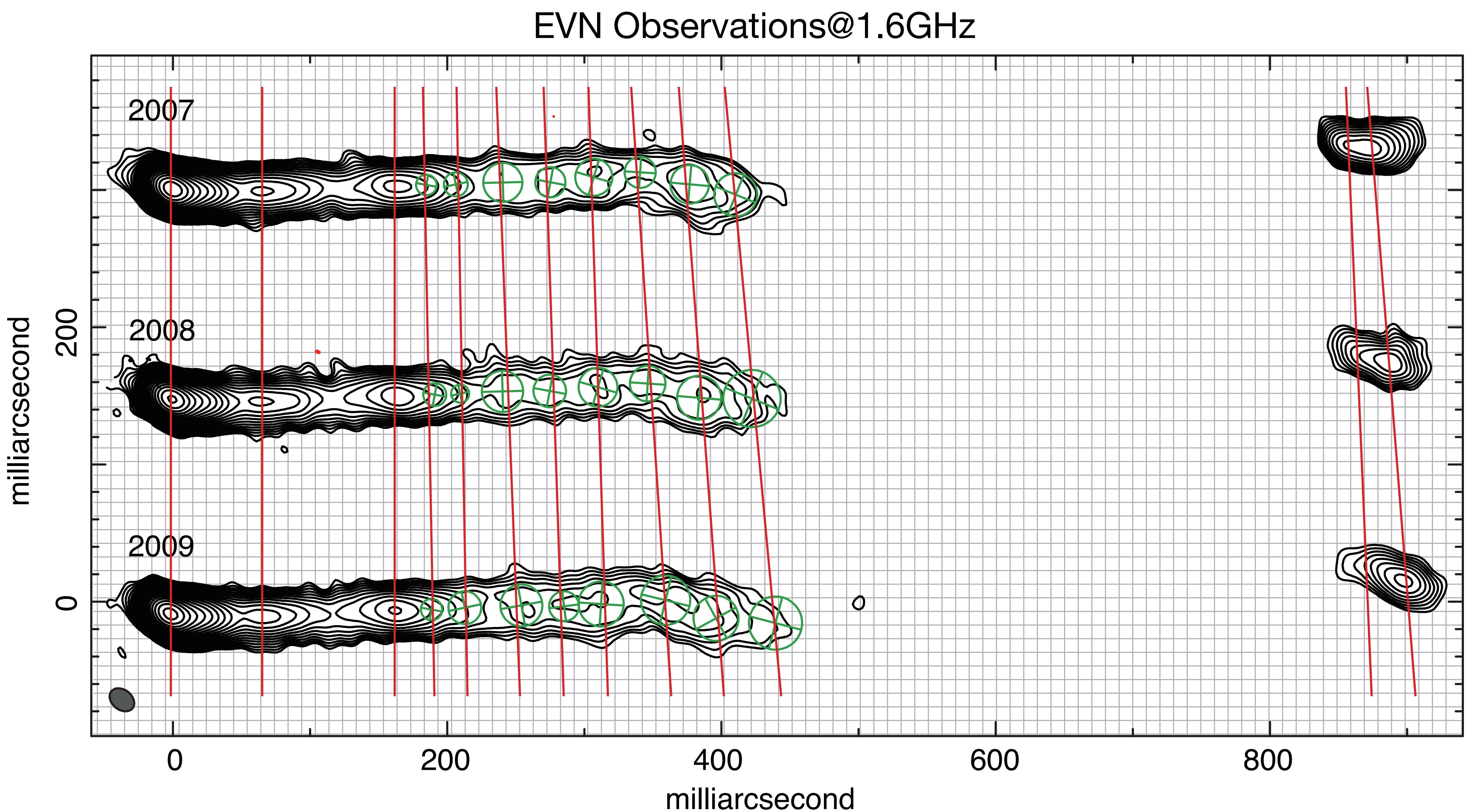
Lister+ (2013) (***see also Kellermann 2004; similar tendency can been seen***)



Homan+ (2015)

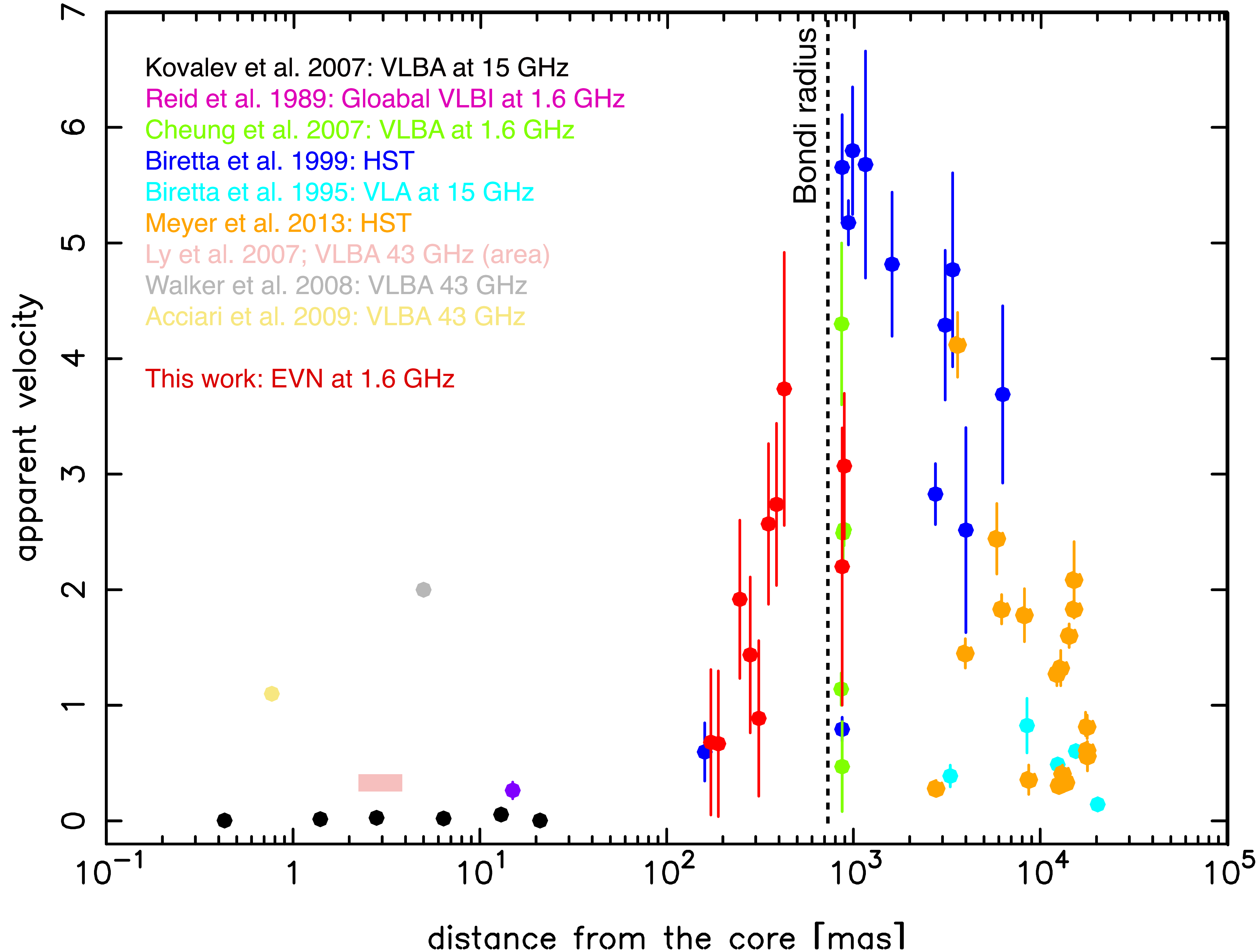
- A transition from positive to negative acceleration seems to locate at ~ 10 pc (Lister+ 2013; Homan+ 2015) ⇒ ~ 100 pc or longer in de-projection
- Non-ballistic flows are strongest at < 10 pc; jets are expanding less rapidly than $z \propto r$, so that jets is still being collimated (Homan+ 2014; also Pushkarev & Kovalev 2012 w/ $T_{\rm b}$ analysis)

SL Motions Upstream of HST-1



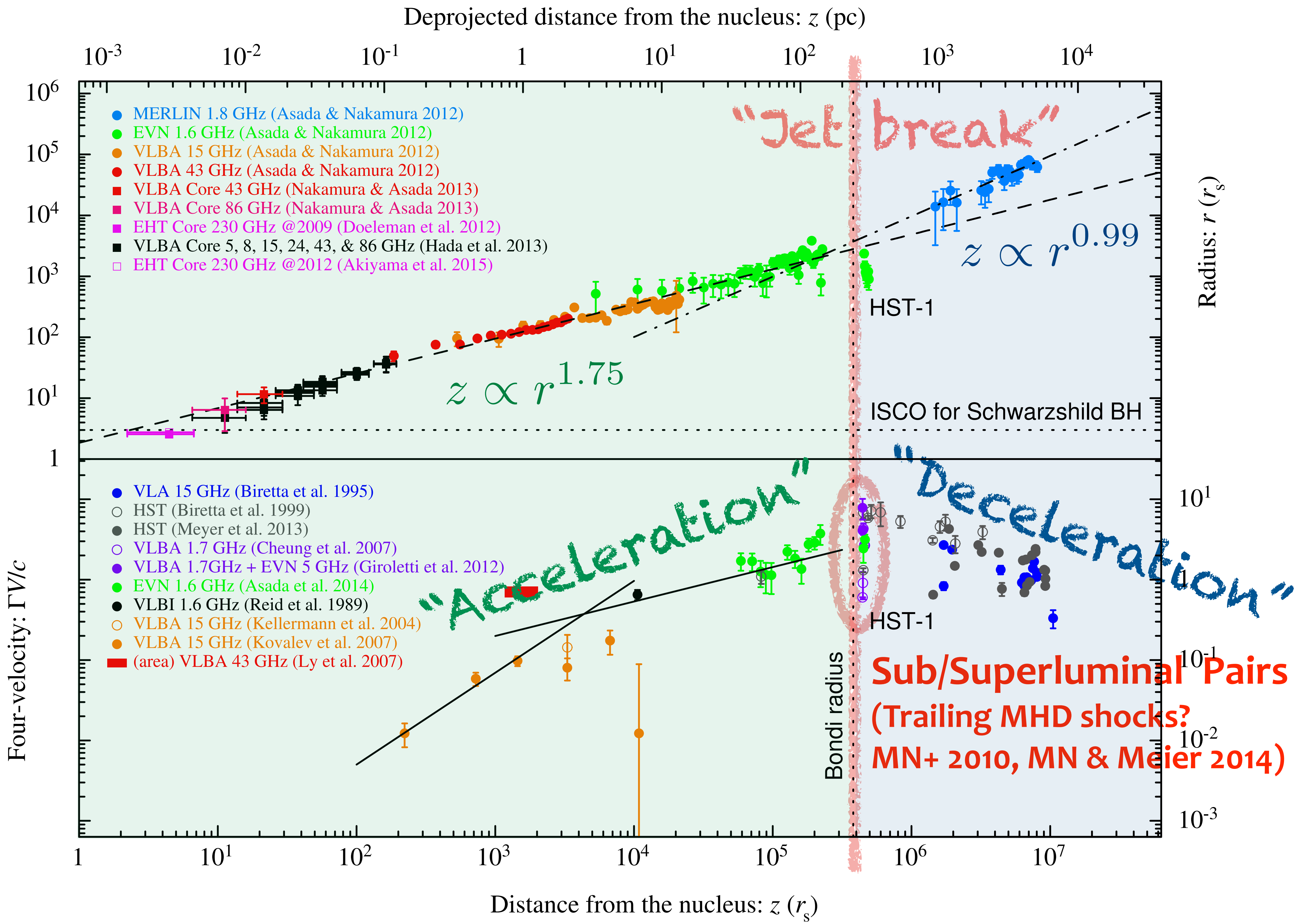
Asada, MN+ (2014), *ApJL*

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*

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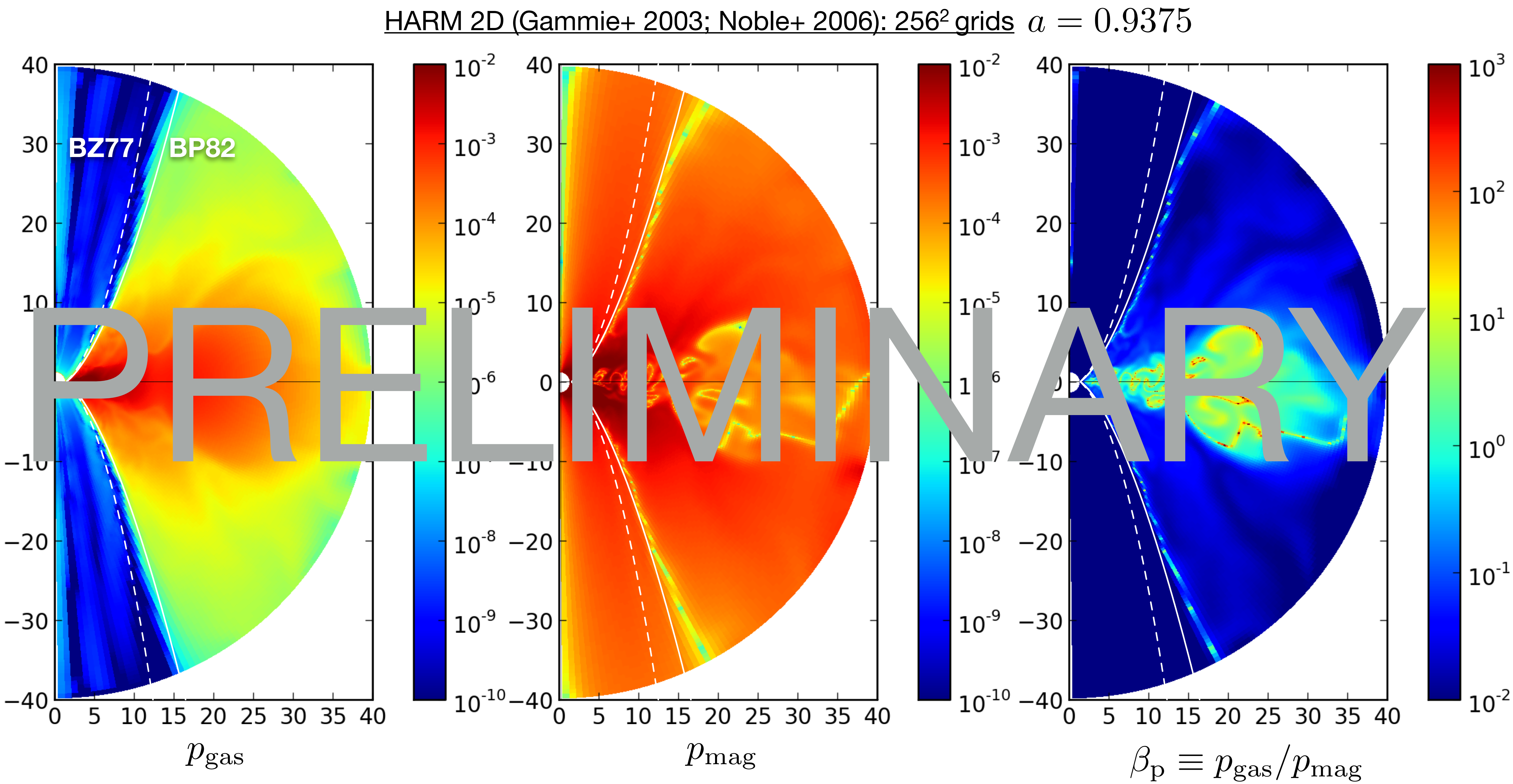
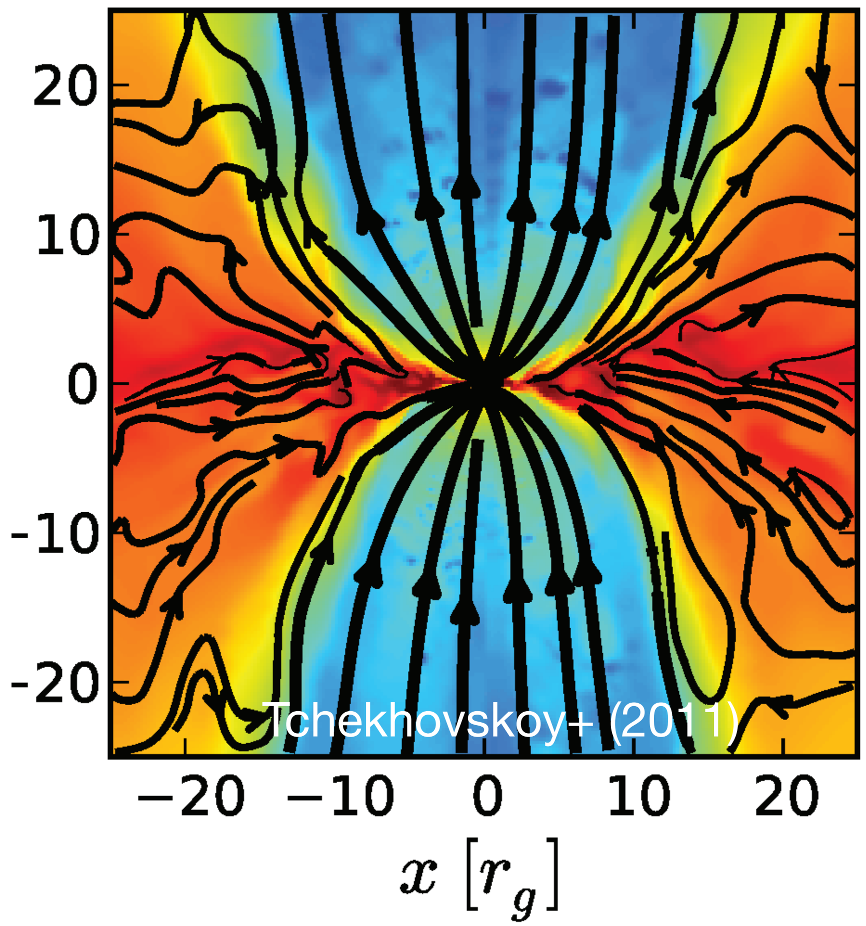
Open Question 2: How Are GRMHD Jets Confined?



- Quasi-steady jet is formed, while corona/wind are highly turbulent (~ 2,000 MG/c^3)
- Global jet structure is unchanged even after the MRI in the corona is saturated
- Gas pressure-dominated corona may not confine the jet, suggesting the jet and corona/wind may be a force-free on the small scale (< 100 r_s)

Outer Boundary of GRMHD Jets

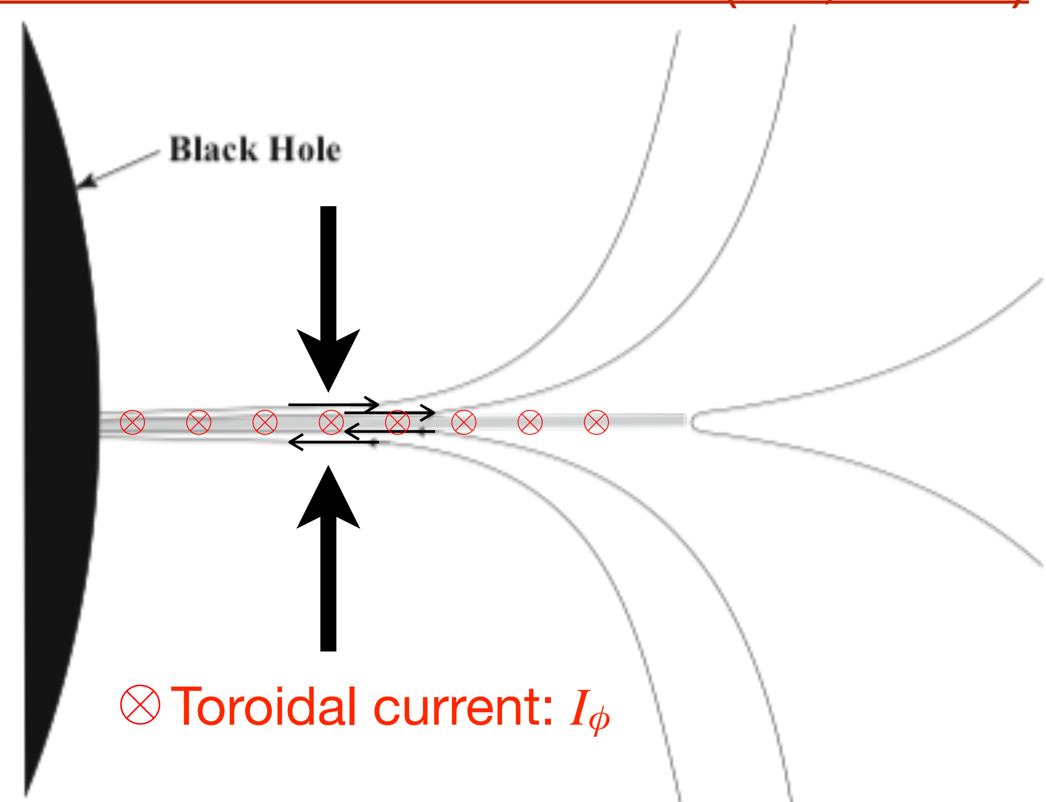


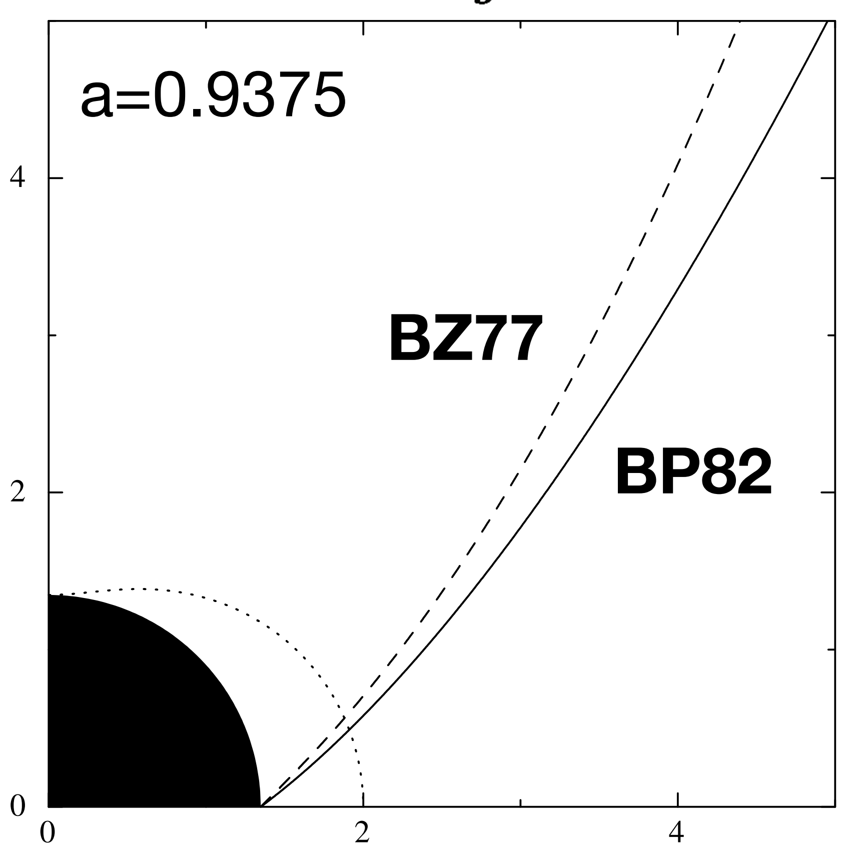
- A power-law dependence of the azimuthal current on the equatorial plane (McKinney & Narayan 2007):

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

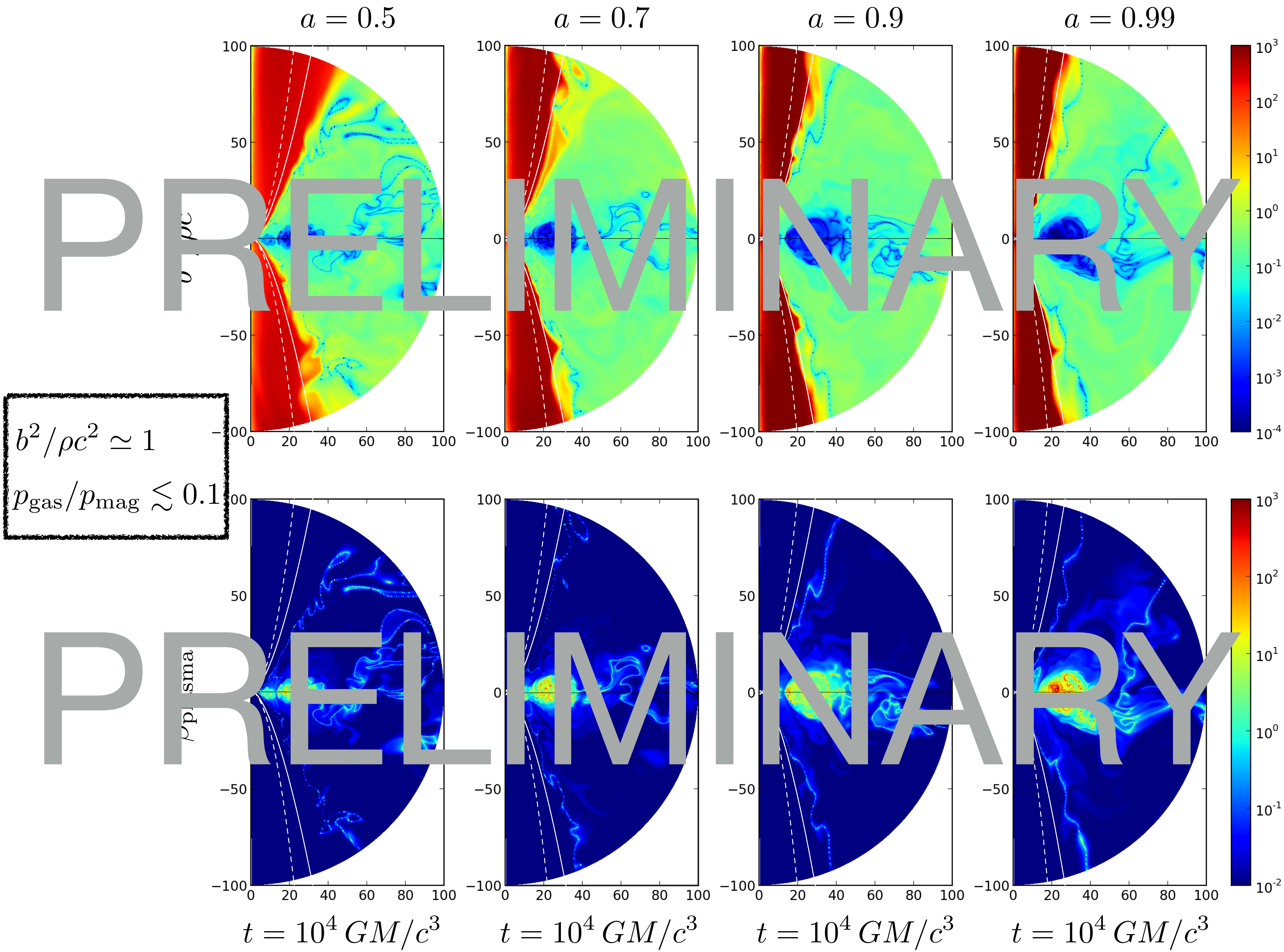
$\nu = 1$	(Parabolic, **Blandford & Znajek 1977**)
$\nu = 3/4$	(**Blandford & Payne 1982**)
$\nu = 0$	(split-monopole)

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



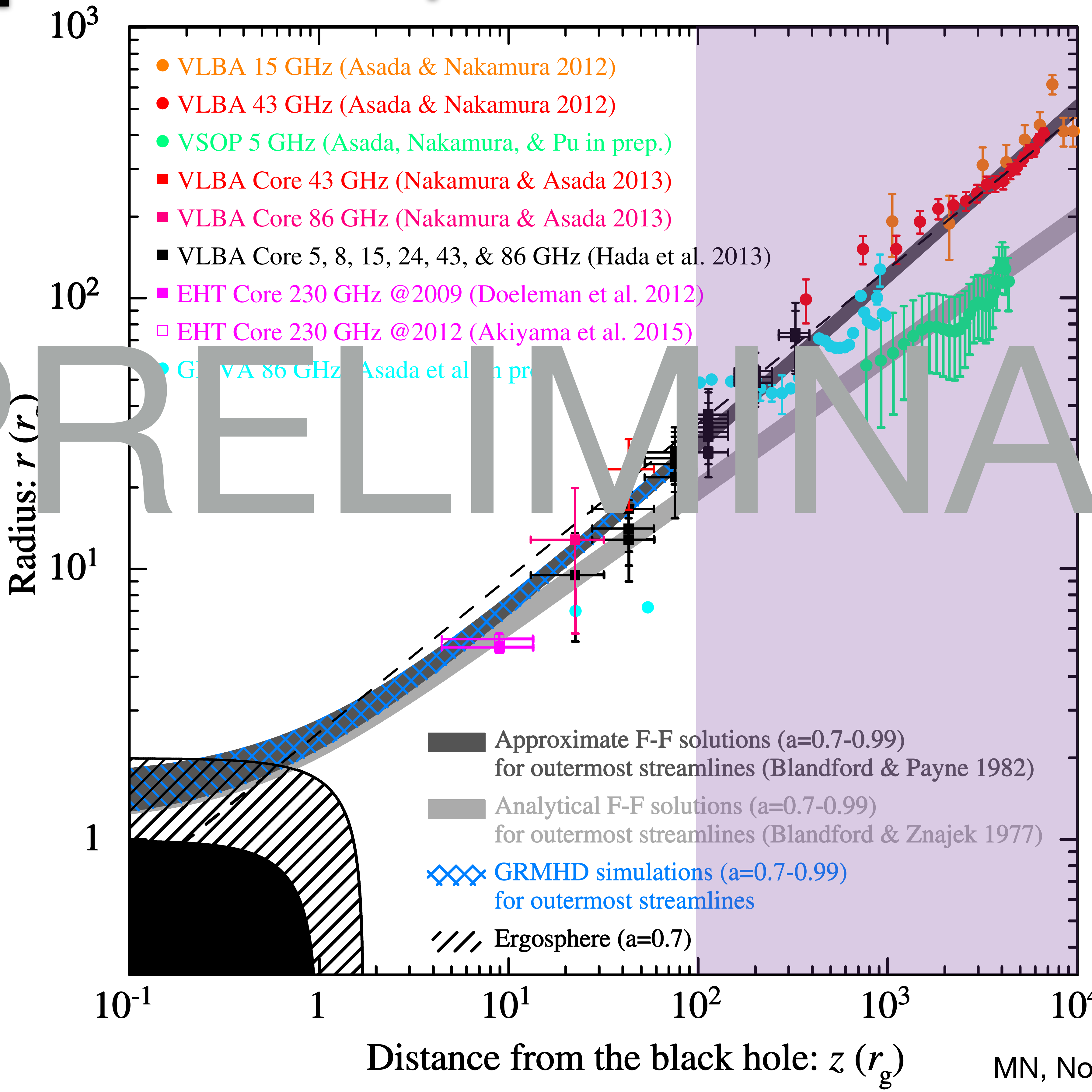


- Strong BH ***B***-field squeeze the accretion flow vertically down to *h/r* ~ 0.05 near the EH from ~ (0.3 - 1) at large distances (Tchekhovskoy 2015)



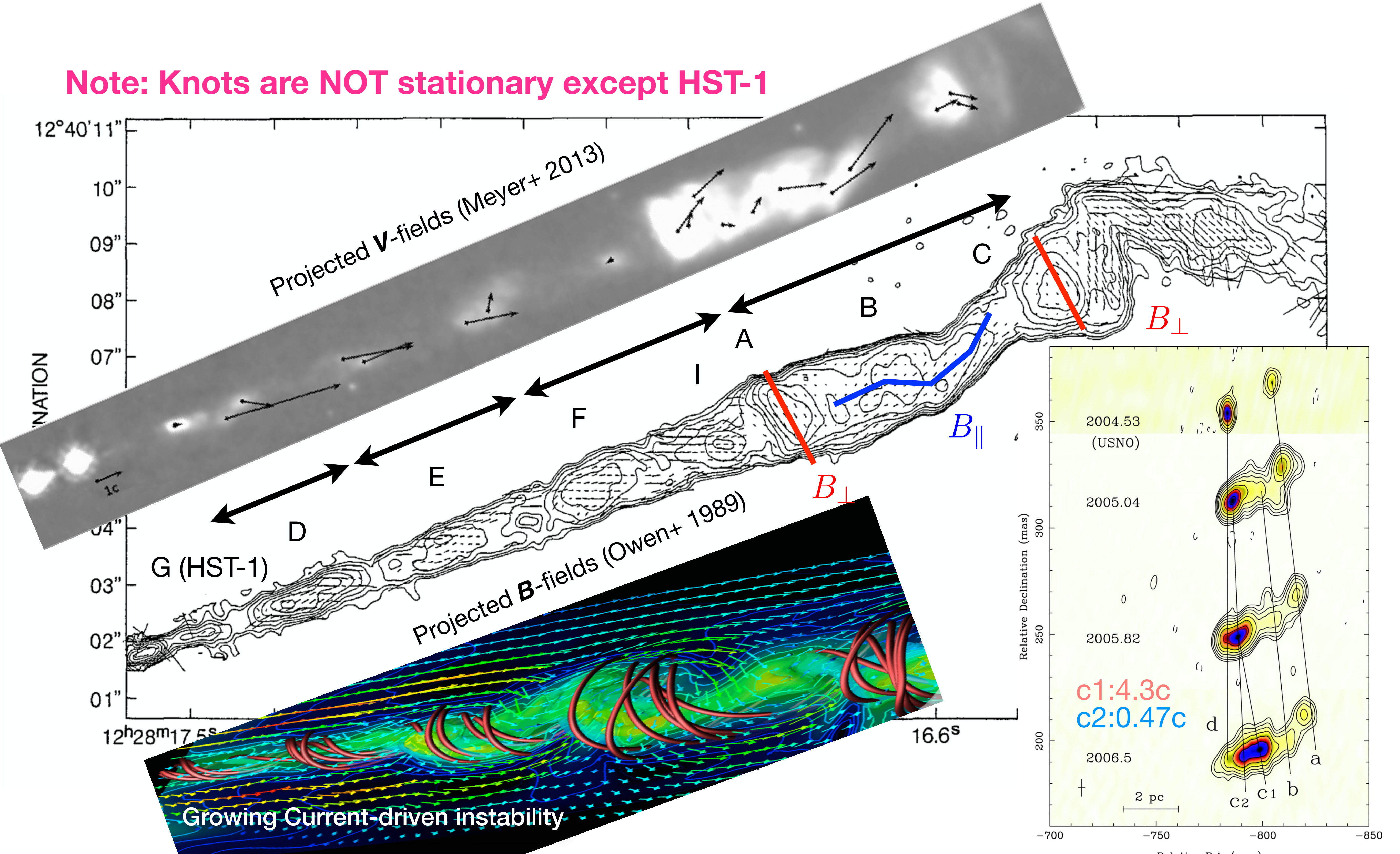
$a = 0.5$
$a = 0.7$
$a = 0.9$
$a = 0.99$
$b^2/\rho c^2 \simeq 1$
$p_{\rm gas}/p_{\rm mag} \lesssim 0.1$
$t = 10^4\, GM/c^3$
$t = 10^4\, GM/c^3$
$t = 10^4\, GM/c^3$
$t = 10^4\, GM/c^3$
PRELIMINARY
PRELIMINARY

Comparison w/ Observations in M87



MN, Noble+ *in prep*.

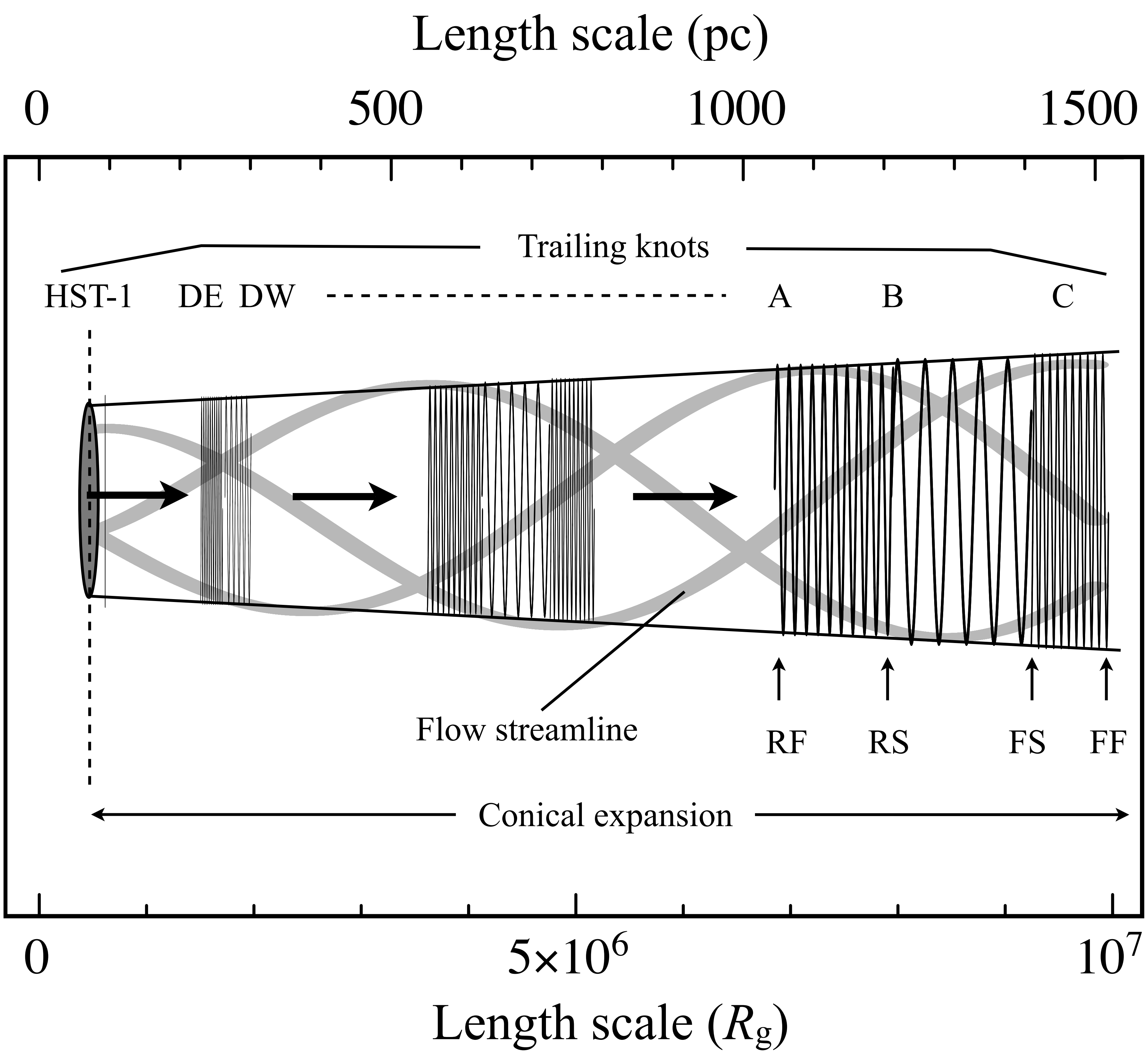
Trails of Components?



MN+ (2001); MN & Meier (2004)

Cheung+ (2007)

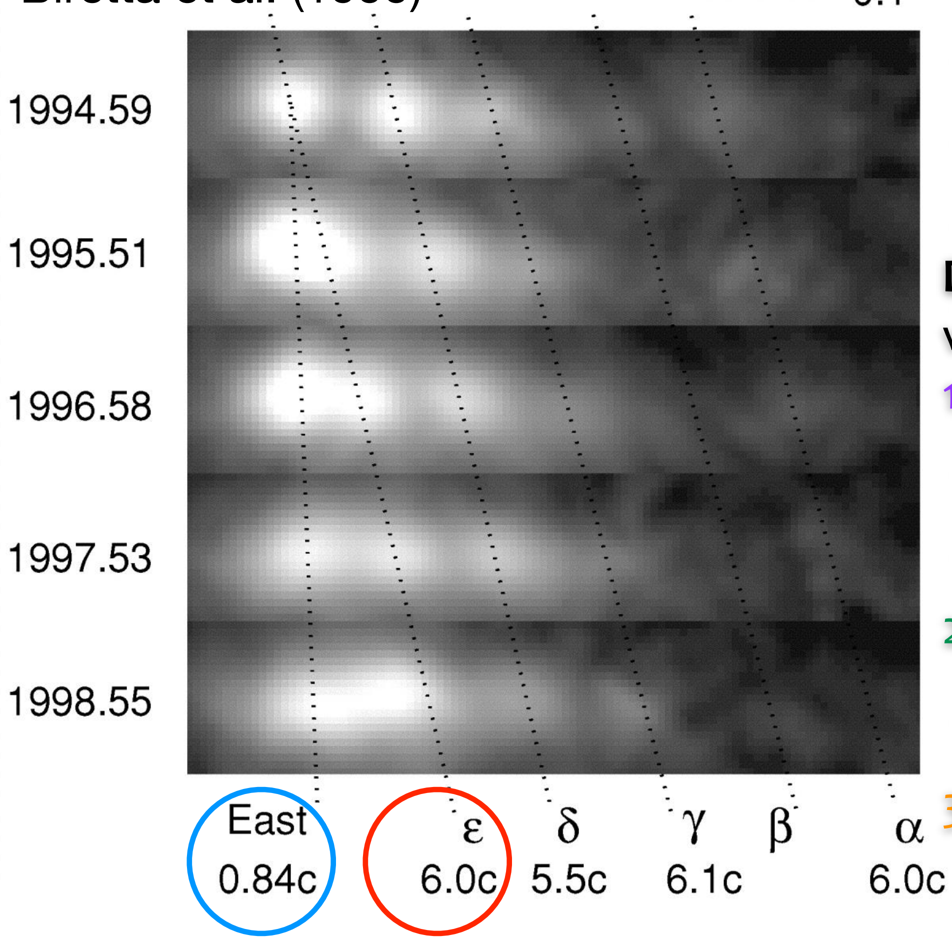
Trails of MHD Shocks?



MN, Garofalo, & Meier (2010), ApJ

Quad RMHD Shock Model

Biretta et al. (1999)



$\theta_{\rm v} \sim 14°$:

$V\varepsilon \sim 0.99\,c$ ⇒ FF

$V_{\rm East} \sim 0.79\,c$ ⇒ RF

DSA (Fermi I acceleration via relativistic shock):

1. Proper compression

   $n(E) \propto E^{-\delta}$,

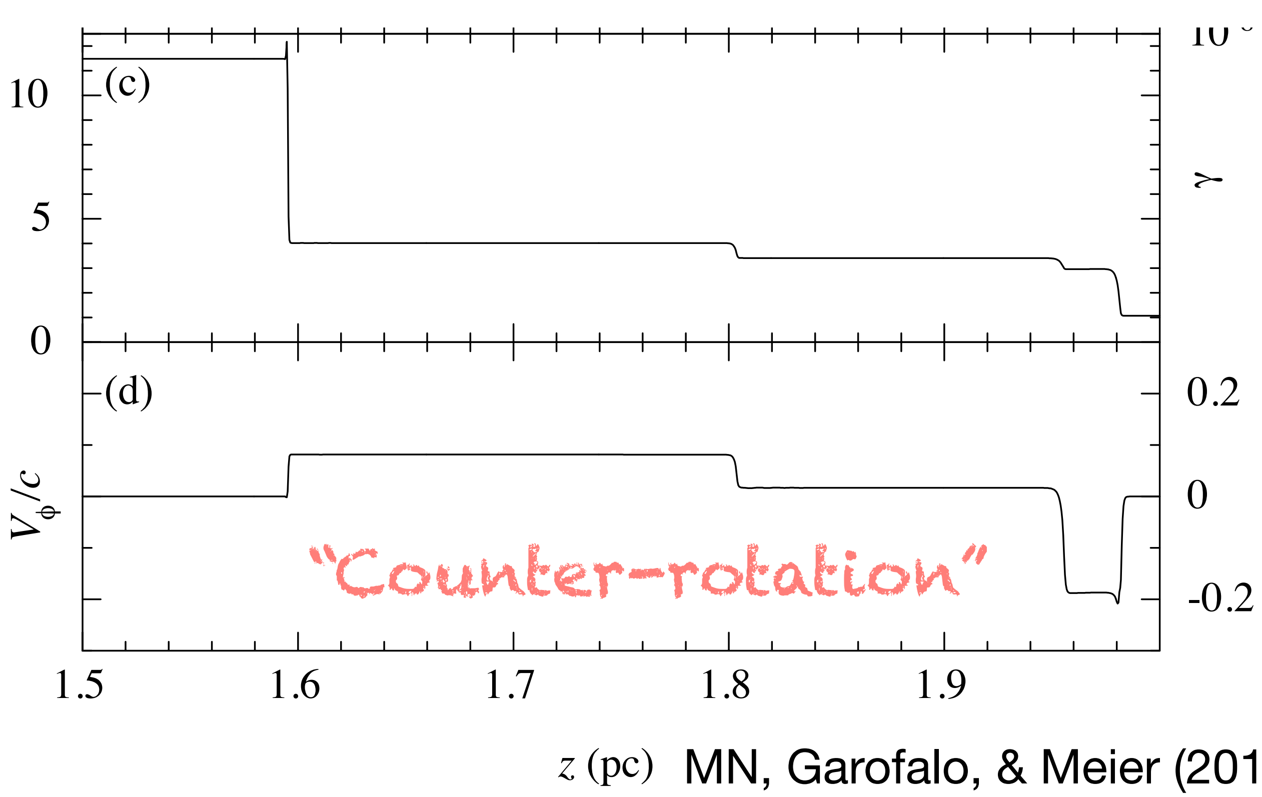
   $\delta = 2.2 - 2.3$

2. Low magnetization

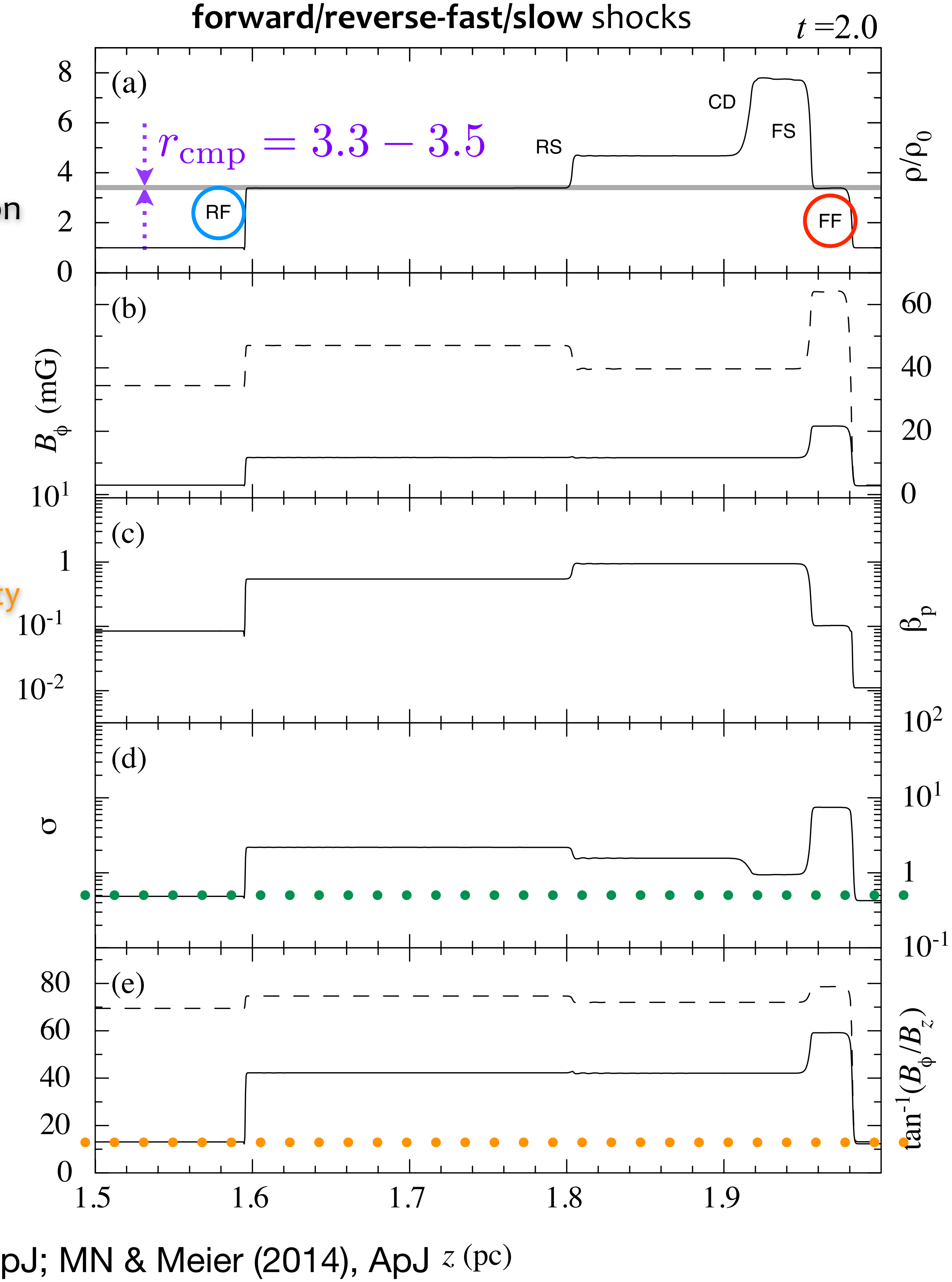
   $\sigma \lesssim 0.5$

3. Low magnetic obliquity

   $\theta \lesssim 13°$



A super-fast magnetosonic flow drives **forward/reverse-fast/slow** shocks



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

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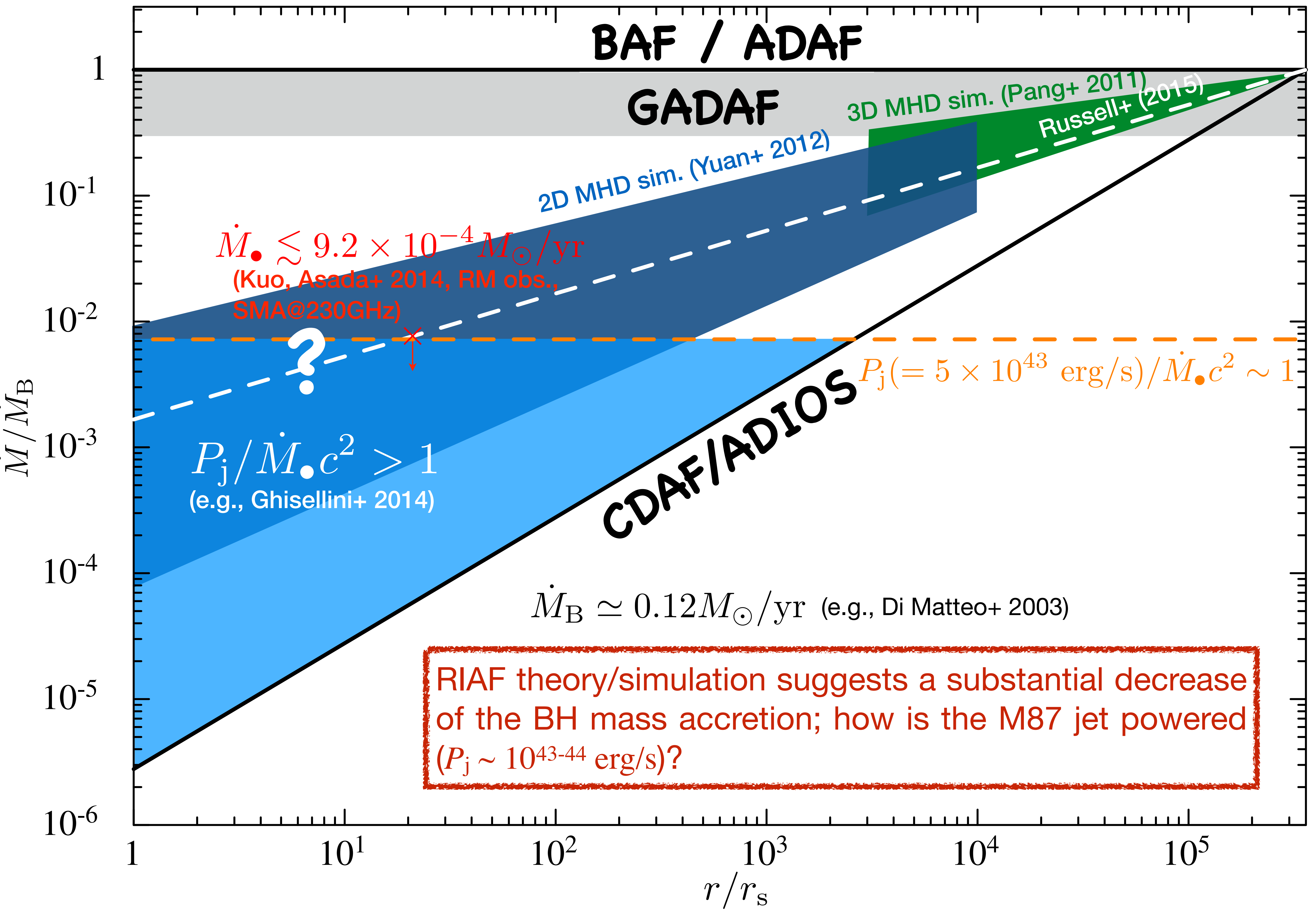
RIAF in M87



BAF / ADAF
GADAF
3D MHD sim. (Pang+ 2011)
Russell+ (2015)
2D MHD sim. (Yuan+ 2012)
$\dot{M}_\bullet \lesssim 9.2\times10^{-4} M_\odot/\mathrm{yr}$
(Kuo, Asada+ 2014, RM obs., SMA@230GHz)
?
$P_\mathrm{j}(=5\times10^{43}\ \mathrm{erg/s})/\dot{M}_\bullet c^2 \sim 1$
$P_\mathrm{j}/\dot{M}_\bullet c^2 > 1$
(e.g., Ghisellini+ 2014)
CDAF/ADIOS
$\dot{M}_\mathrm{B} \simeq 0.12 M_\odot/\mathrm{yr}$ (e.g., Di Matteo+ 2003)
RIAF theory/simulation suggests a substantial decrease of the BH mass accretion; how is the M87 jet powered ($P_\mathrm{j} \sim 10^{43\text{-}44}$ erg/s)?
$\dot{M}/\dot{M}_\mathrm{B}$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
r/r_s
1
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}

MAD in Action in M87?

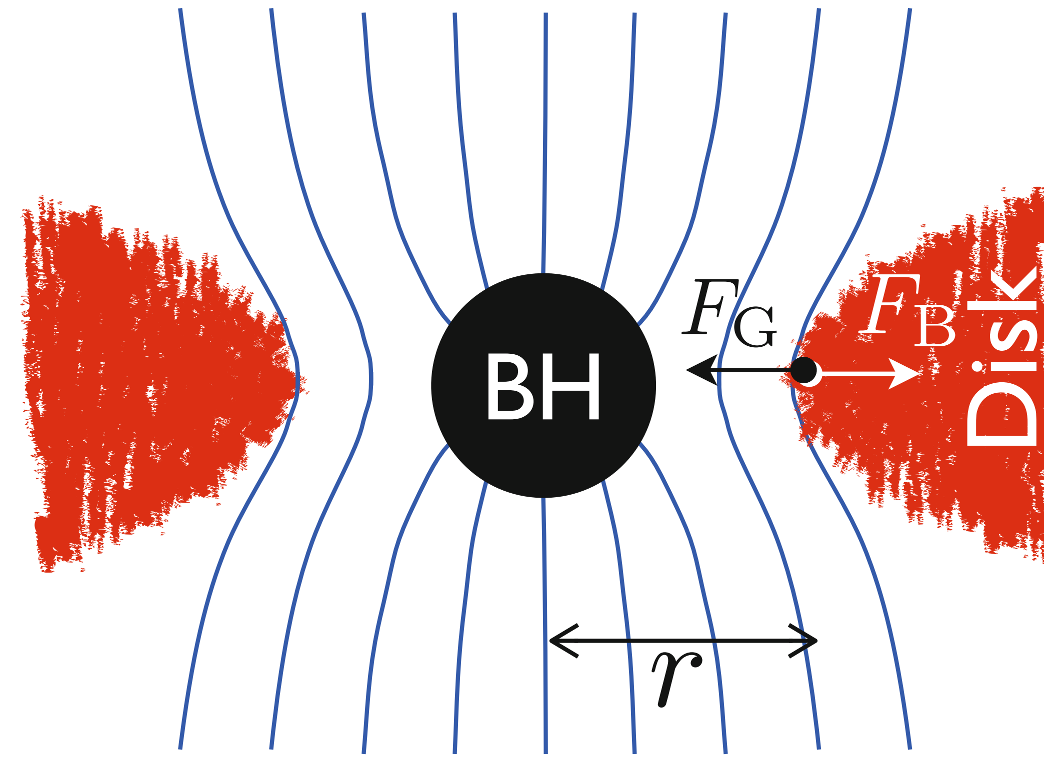
- Magnetically Arrested Disk (MAD)
  (Bisnovatyi-Kogan & Ruzmaikin 1974, 1976; Narayan 2003; Tchekhovskoy+ 2011; Tchekhovskoy & McKinney 2012; Zamaninasab+ 2014)

$$\phi_\bullet = \frac{\Phi_\bullet}{(\langle \dot{M}_\bullet \rangle r_{\rm g}^2 c)^{1/2}} \approx 50 \ (\text{spin}-\text{average})$$

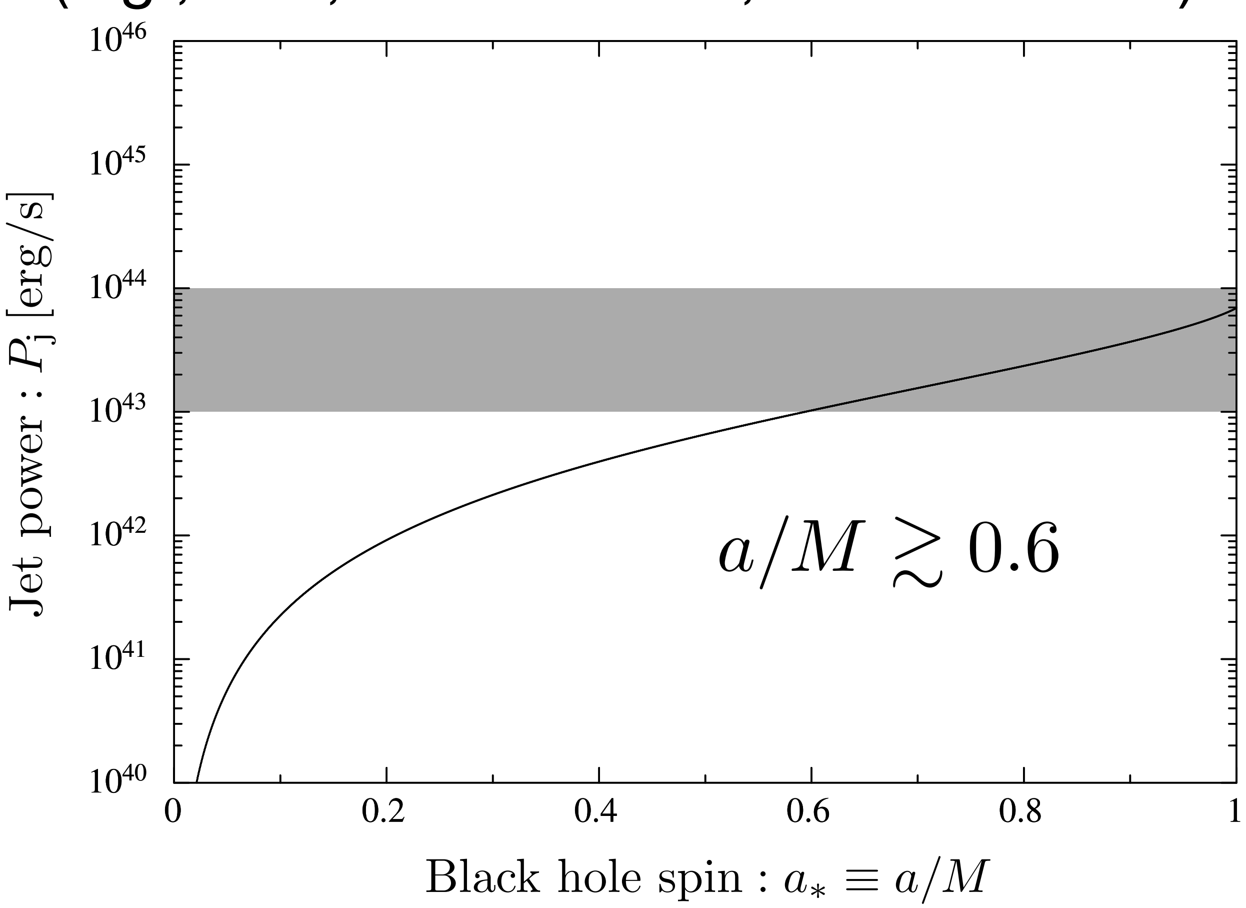
for a MAD state ($F_{\rm G} \approx F_{\rm B}$)

$$\dot{M}_\bullet \simeq 6.3 \times 10^{-4} \left(\frac{R}{10 r_{\rm s}}\right)^{0.5} \ M_\odot/\text{yr}$$

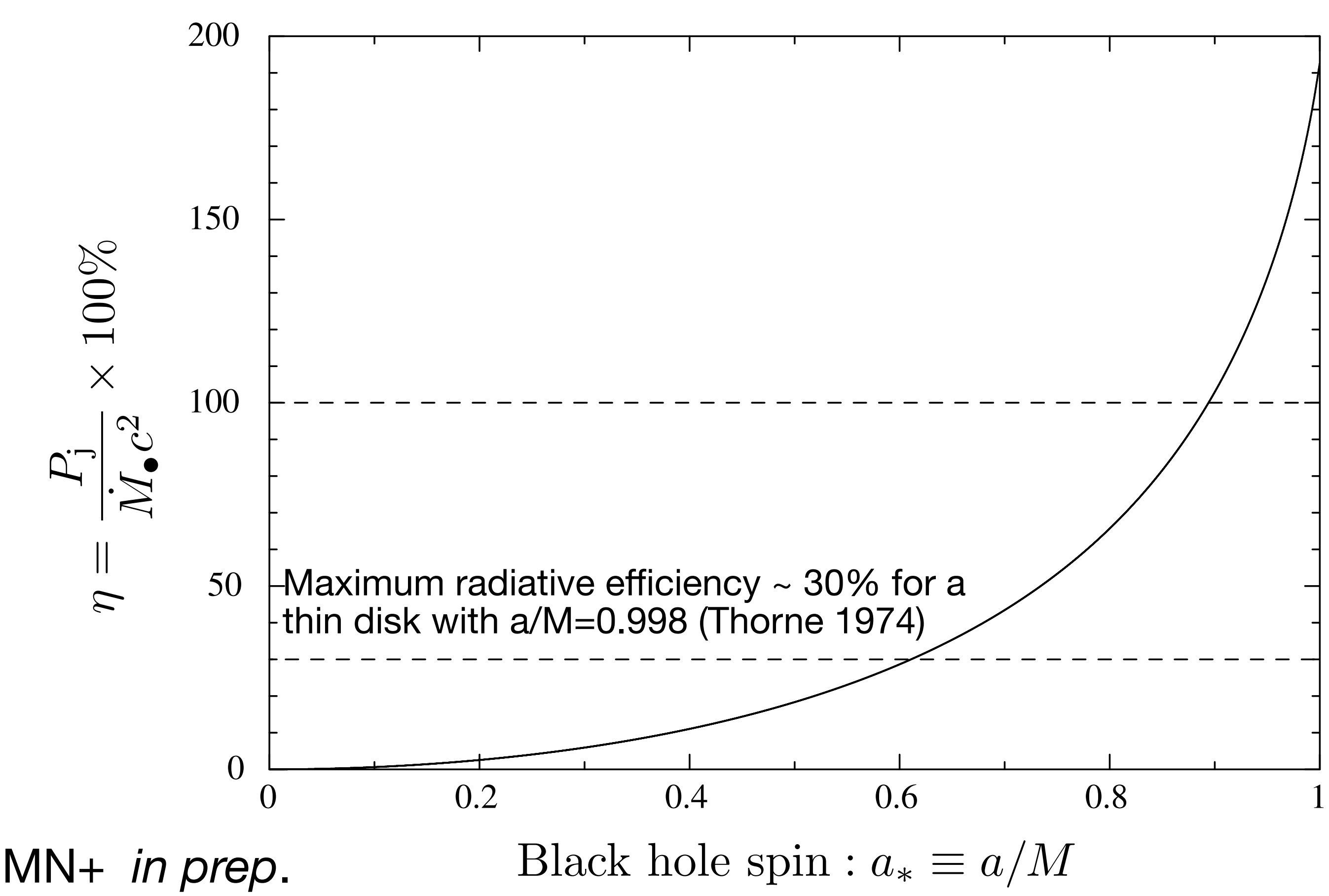
(e.g., Kuo, Asada+ 2014; Russell+ 2015)



e.g., Tchekhovskoy (2015)



MN+ *in prep.*



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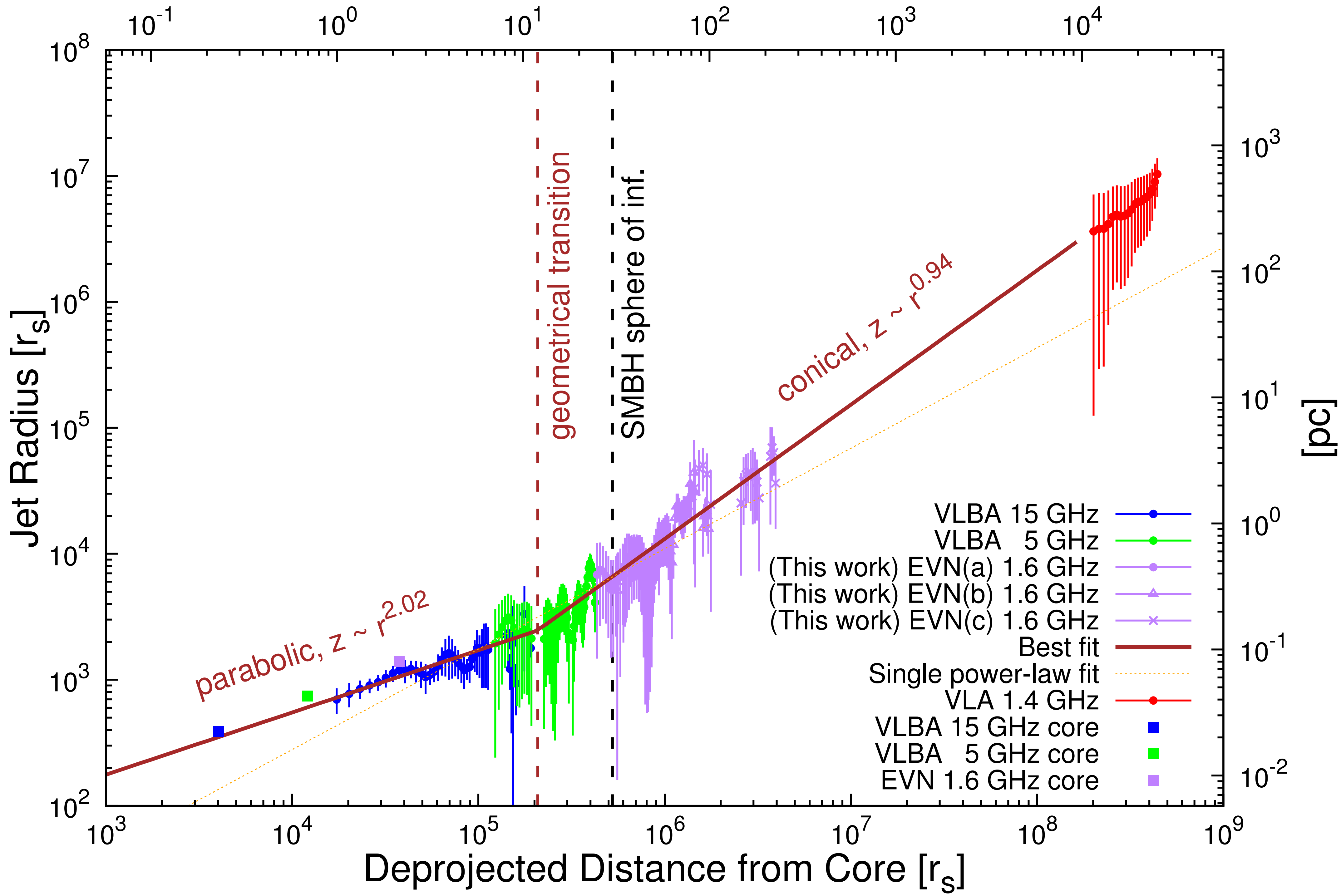
Case 2: FRI RG

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



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

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. GRMHD jet sim./MAD scenario may give the BH spin as $a > 0.7$
5. We propose that the "*Jet Break*" (from parabolic; BP82 to conical; BK79) may be norm in AGNs