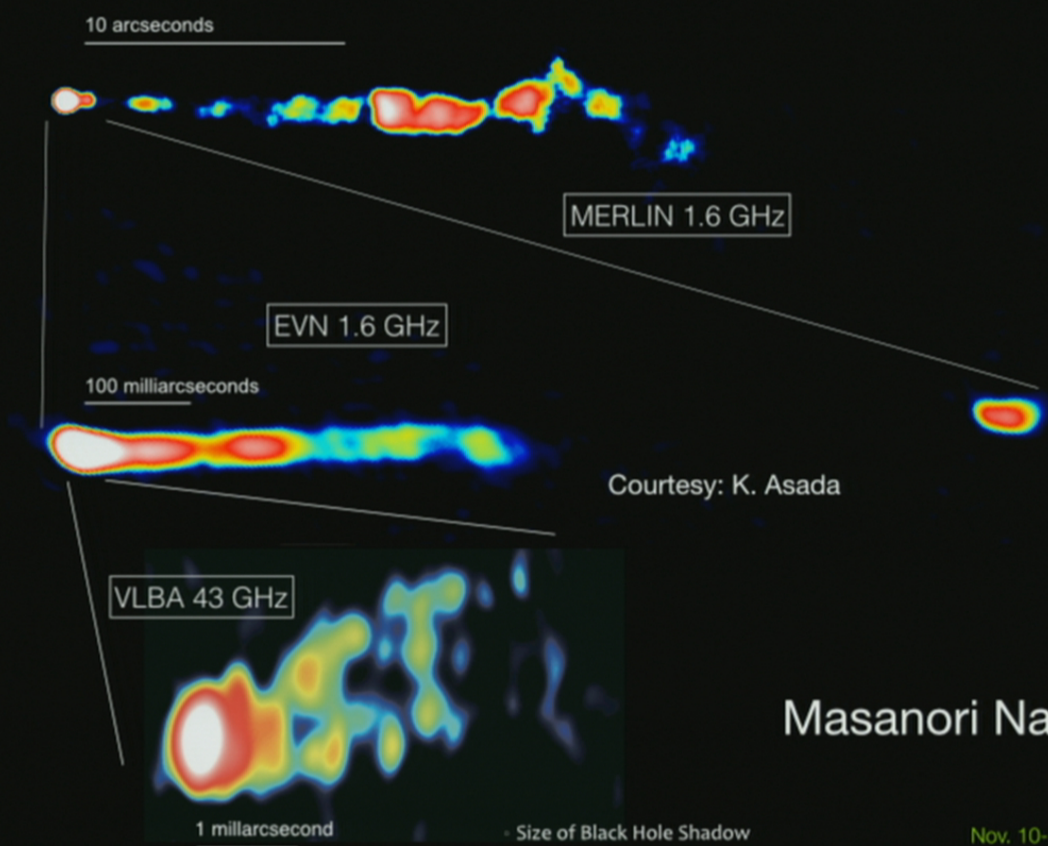
Title: Lessons from M87: Structure and Dynamics of AGN Jets

Date: Nov 11, 2014 10:45 AM

URL: http://pirsa.org/14110080

Abstract: We examine the structure and dynamics of the M87 jet based on both multi-frequency observations and MHD jet theories. Millimeter (mm) VLBI cores are considered as innermost jet emissions. Resolved parabolic streamline may suggest that the jet collimation maintains in five orders of magnitude in the distance starting from the vicinity of the supermassive black hole (SMBH), less than 10 r_s where the VLBI core at
1.3 mm is located. Observed sub-to-superluminal motions may indicate an MHD acceleration takes place from non-relativistic to relativistic regimes. We discuss that the M87 jet consists hybrid spine/sheath structure from either a spinning super massive black hole and or radiatively inefficient accretion flow. Future sub-mm VLBI imaging play an essential role in resolving the origin (i.e., formation mechanism) of the M87 jet as well as constraining the SMBH spin parameter. Based on our understanding of M87, we also discuss about the key science in other AGN jets with sub-mm VLBI experiments.

Lessons from M87:
Structure & Dynamics of AGN Jets



Masanori Nakamura (ASIAA)

Nov. 10-14 2014, EHT 2014@Perimeter Institute, Waterloo

M87 (Virgo A; NGC4486)

www.spacetelescope.org

Credit:
NASA, ESA, and G. Bacon (STScI)
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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), M. Nakamura (ASIAA), and G. Bacon (STScI)

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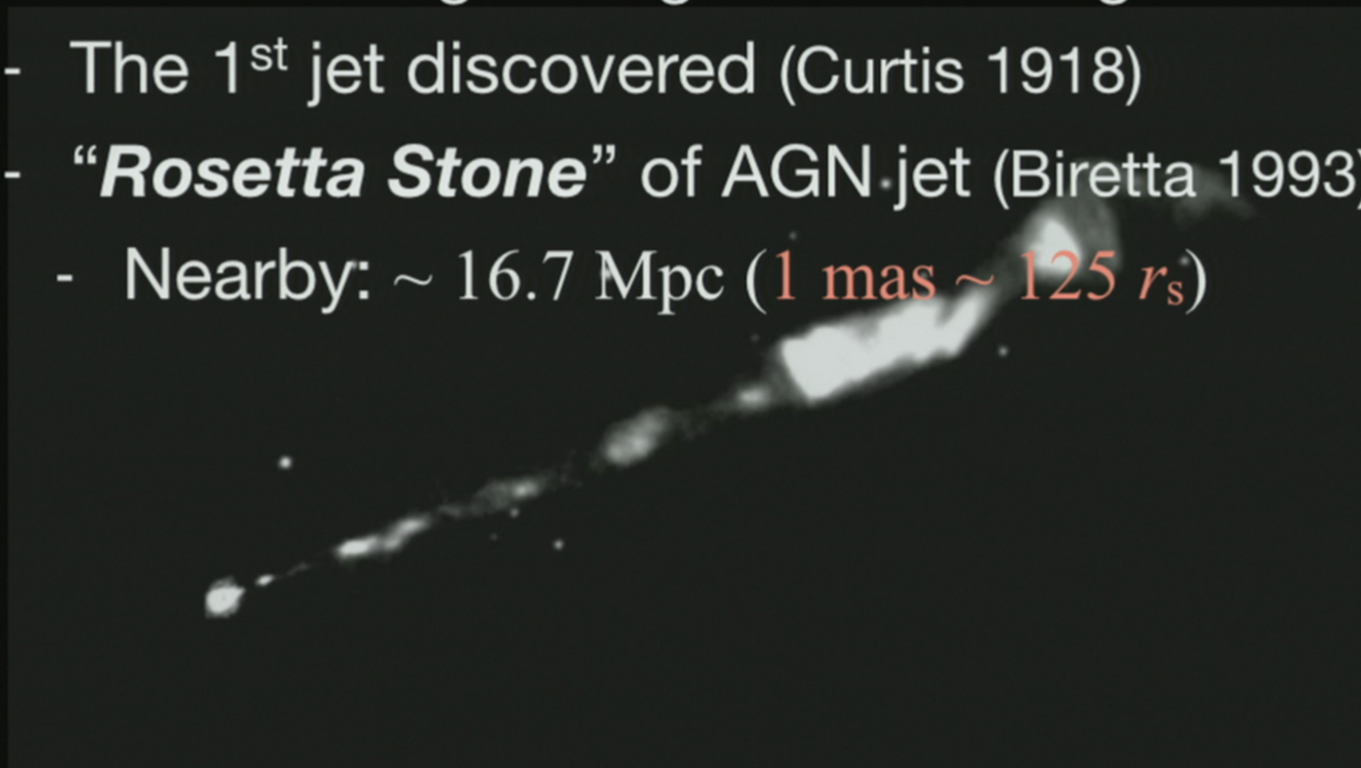

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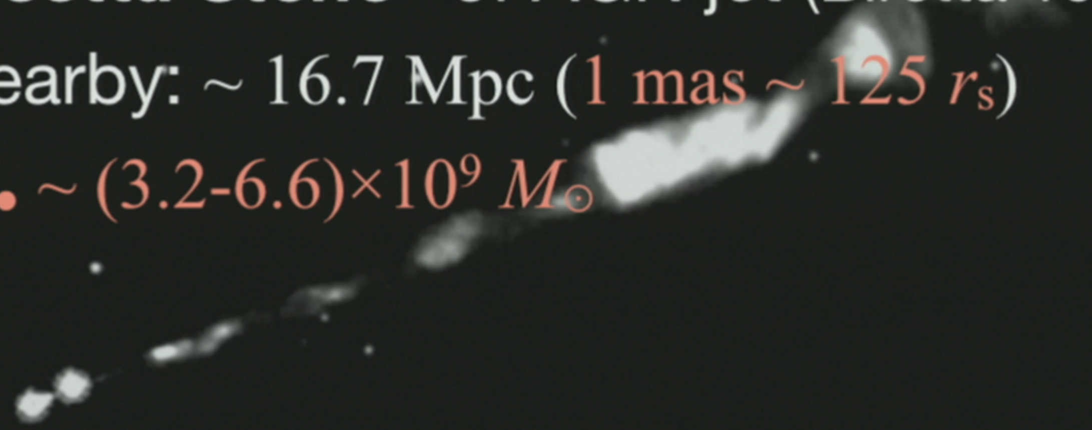

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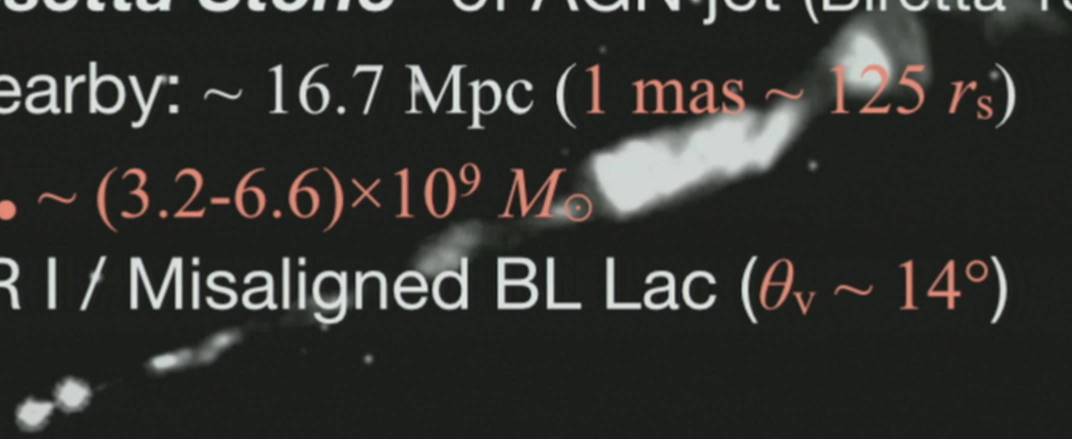

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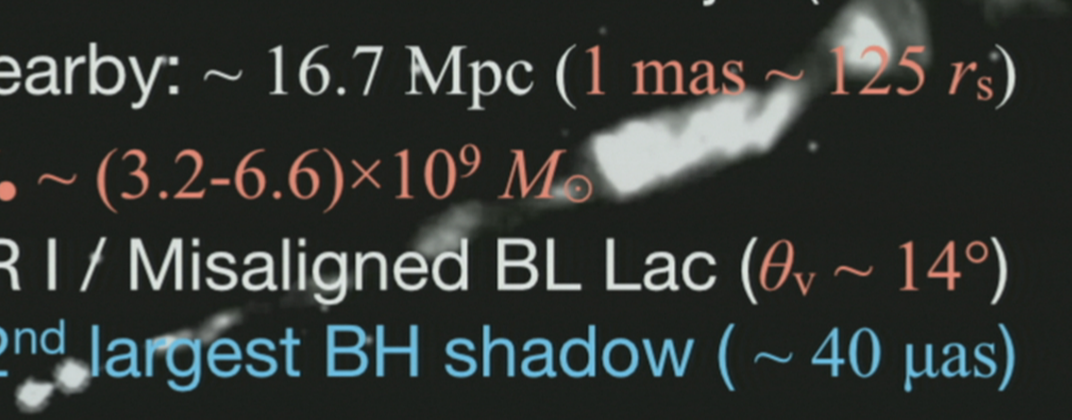

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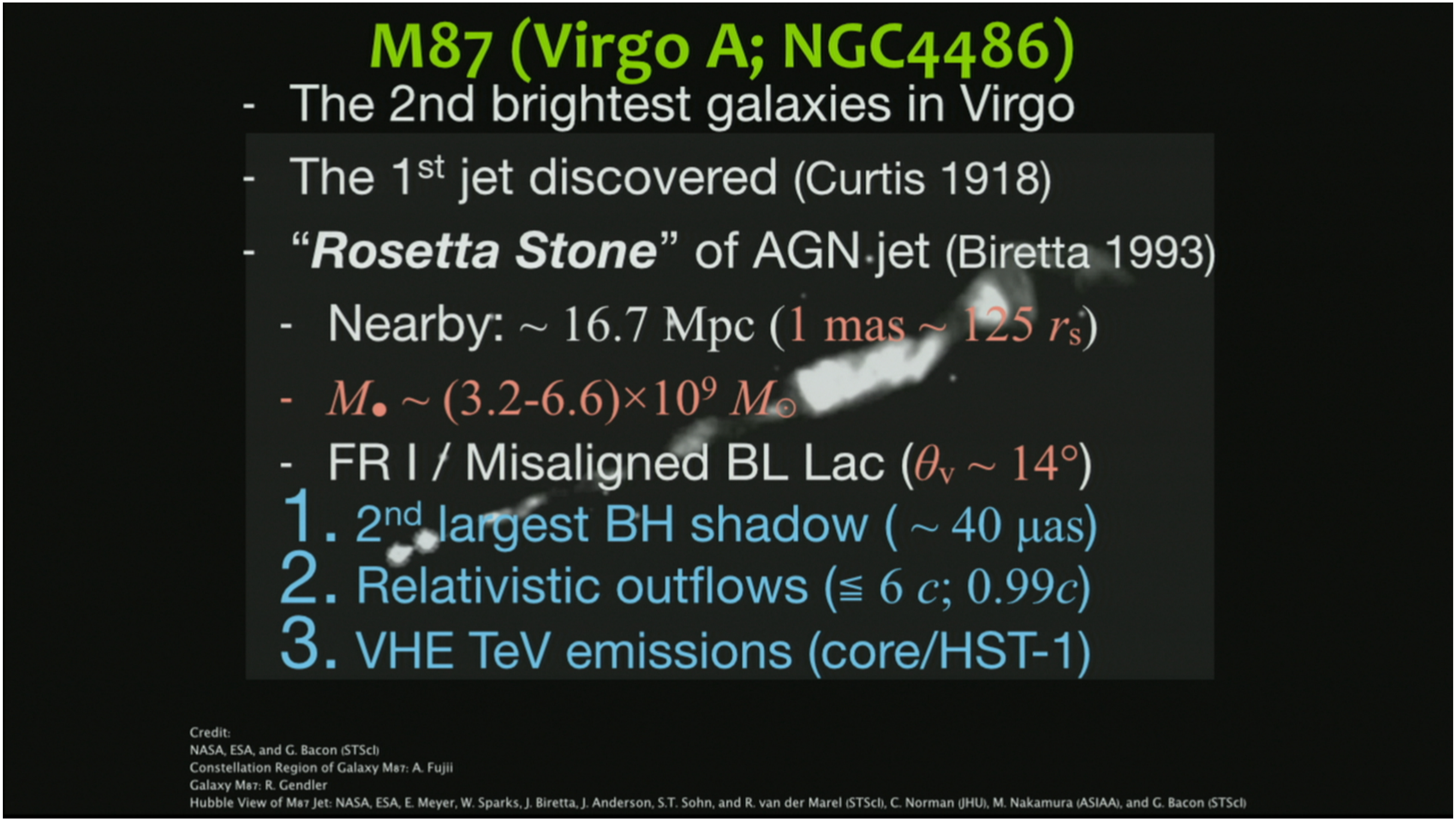
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3. VHE TeV emissions (core/HST-1)
4. AGN feedback (radio mode) in action

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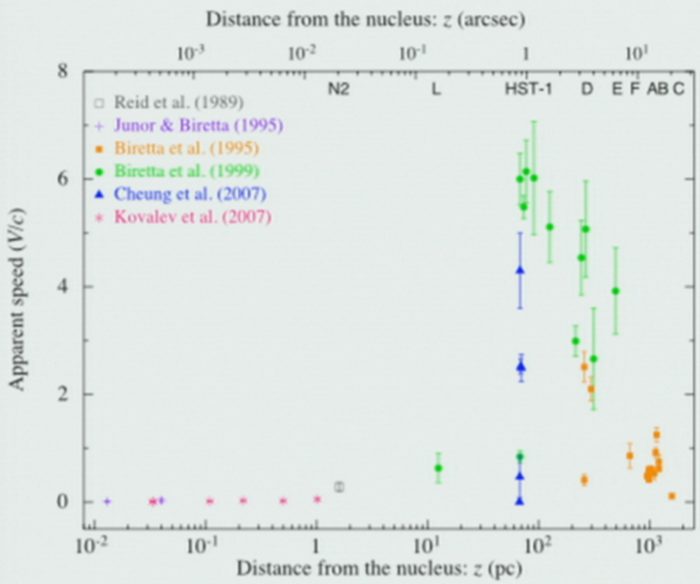
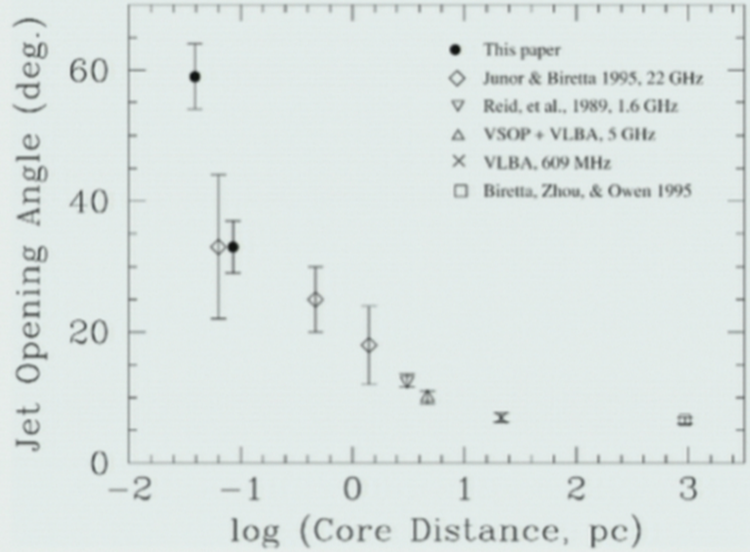
Topics To be Discussed

- Acceleration, collimation, and beyond; how to plug MHD jets into a real system
- Origin of the M87 jet; freq. depending VLBI core shift / spin depending stagnation shift
- "Jet break"; an interplay between SMBHs and host galaxies
- Role of sub-mm VLBI in the AGN jet study

Puzzle Has Remained Unsolved for Decades





Q. What is a large gap in proper motions?

Q. Collimation is real?

Junor+ (1999), Nature

- Intrinsic correlation between proper motion and structure?
- If so, how can we know MHD jet properties in M87?

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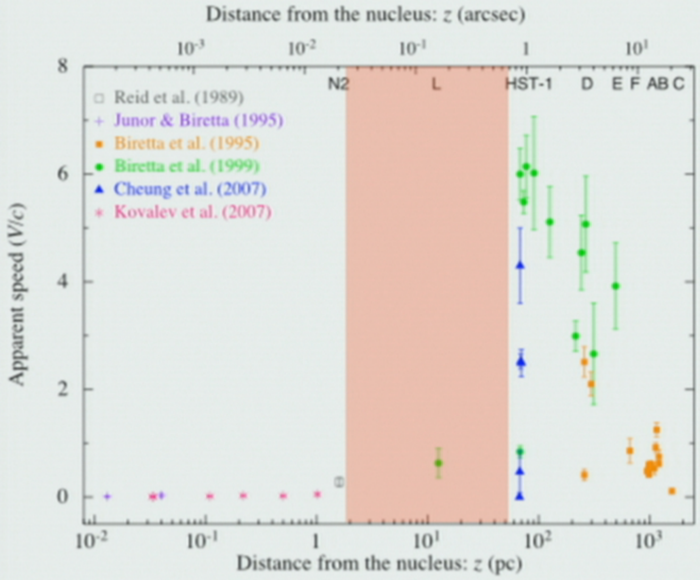

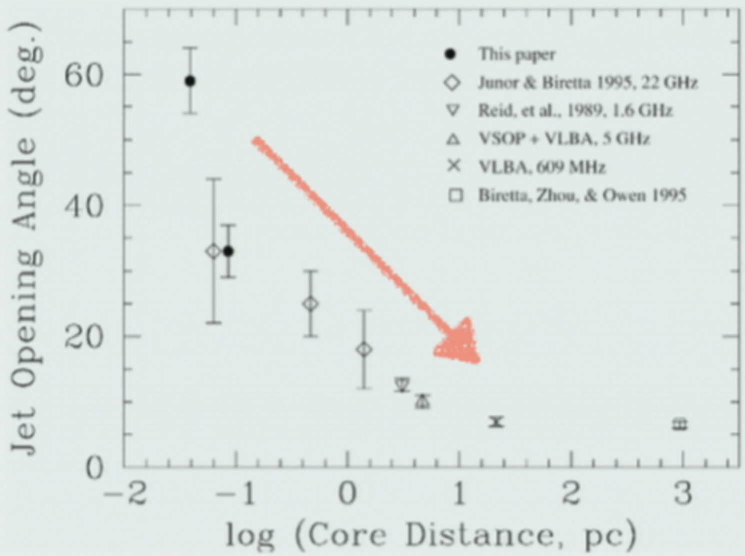

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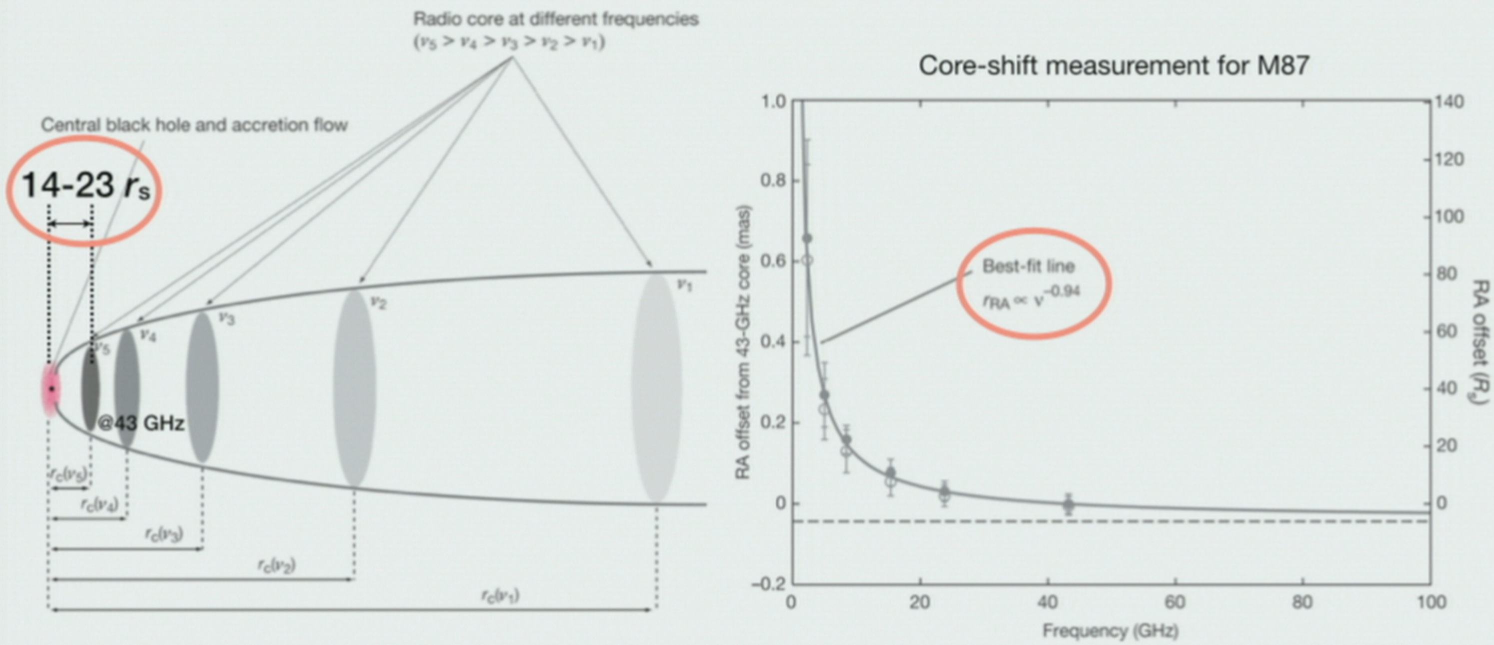
VLBI Core Shift in M87



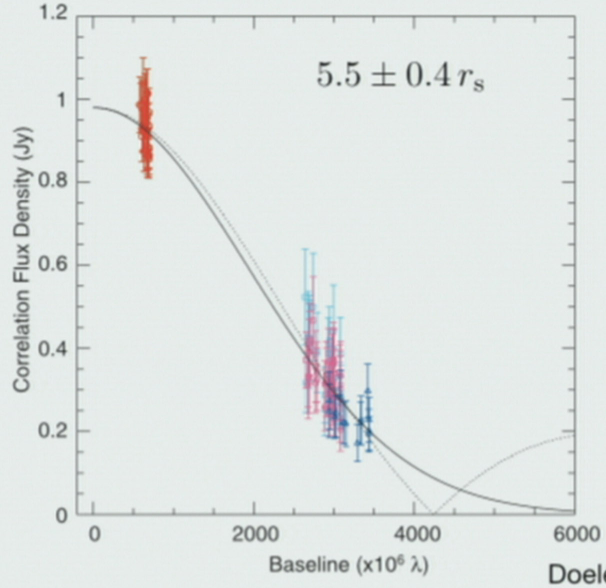
Hada+ (2011), Nature

Blandford & Königl (1979); Unresolved core to be identified with the innermost, optically thick region ($\tau_{SSA} = 1$) of the approaching jet at:

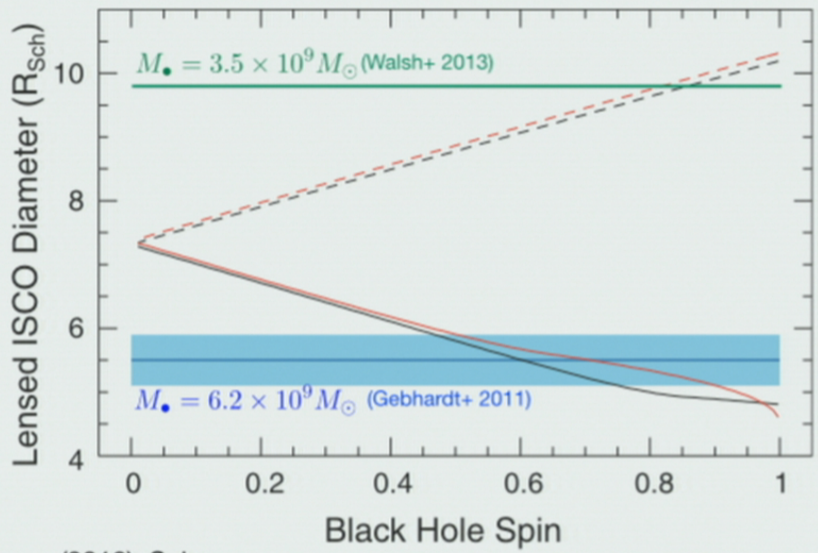
$$z_{\rm core}(\nu) \propto \nu^{-1/k_z},\ k_z = f(\alpha, m, n),\ B \propto z^{-m}, N_{\rm e} \propto z^{-n}$$

First EHT Obs. of M87

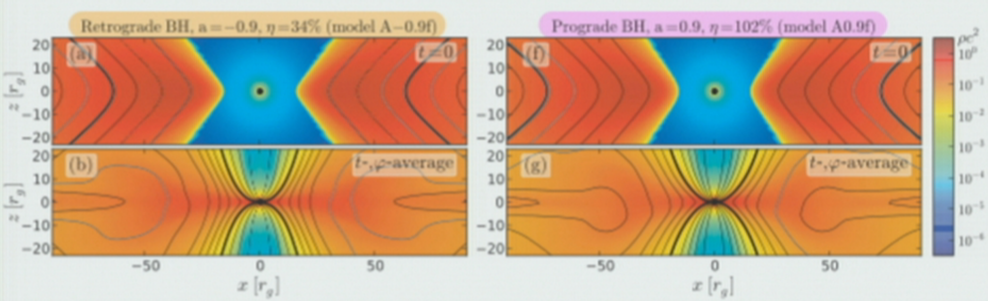
Measuring the size of the M87 core w/ 1.3-mm VLBI

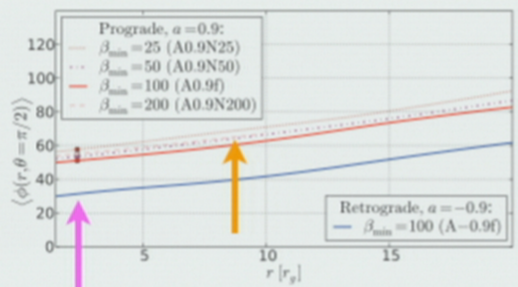


Diameter of the ISCO for a BH of arbitrary spin



Doeleman+ (2012), Science

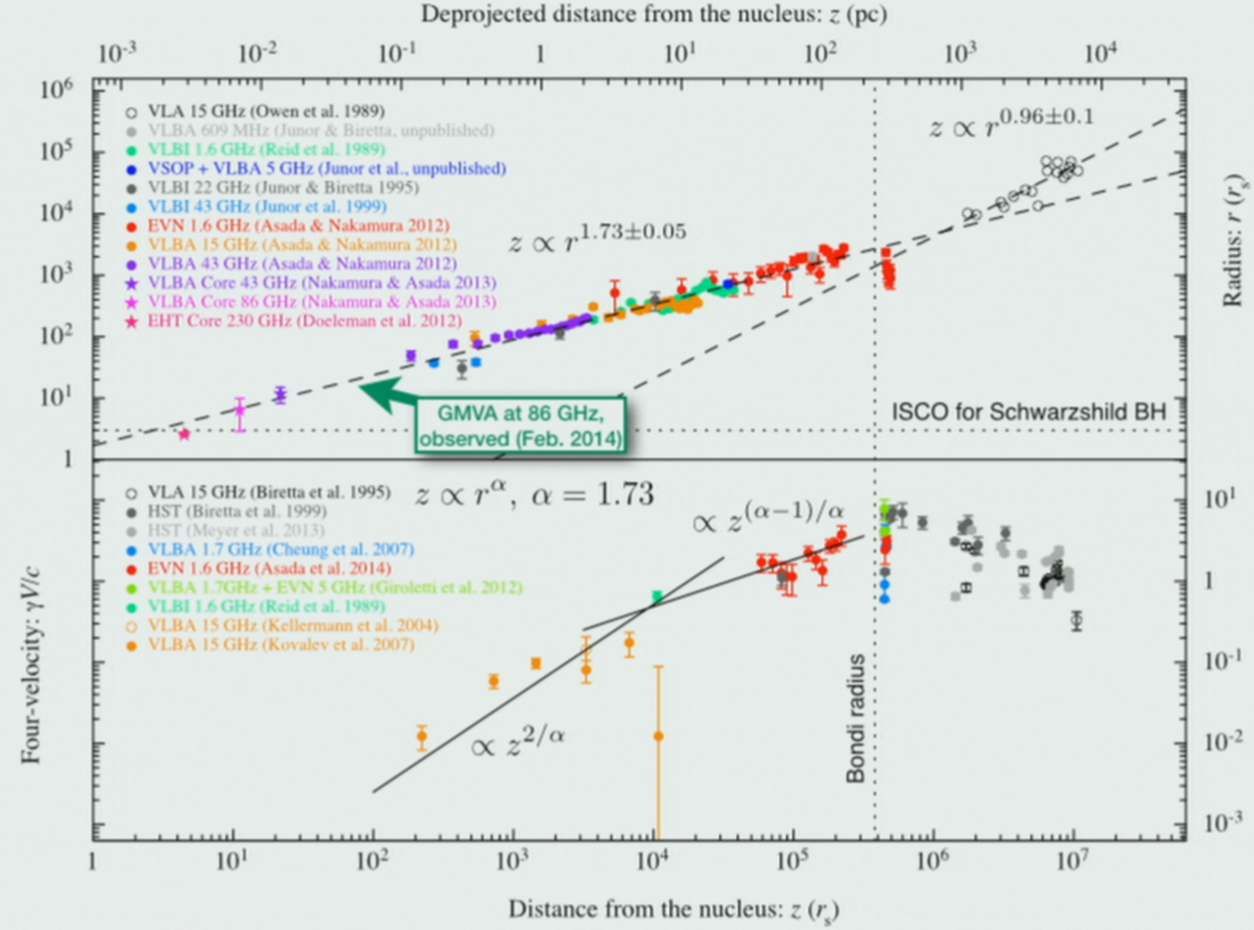




Tchekhovskoy & McKinney (2012)

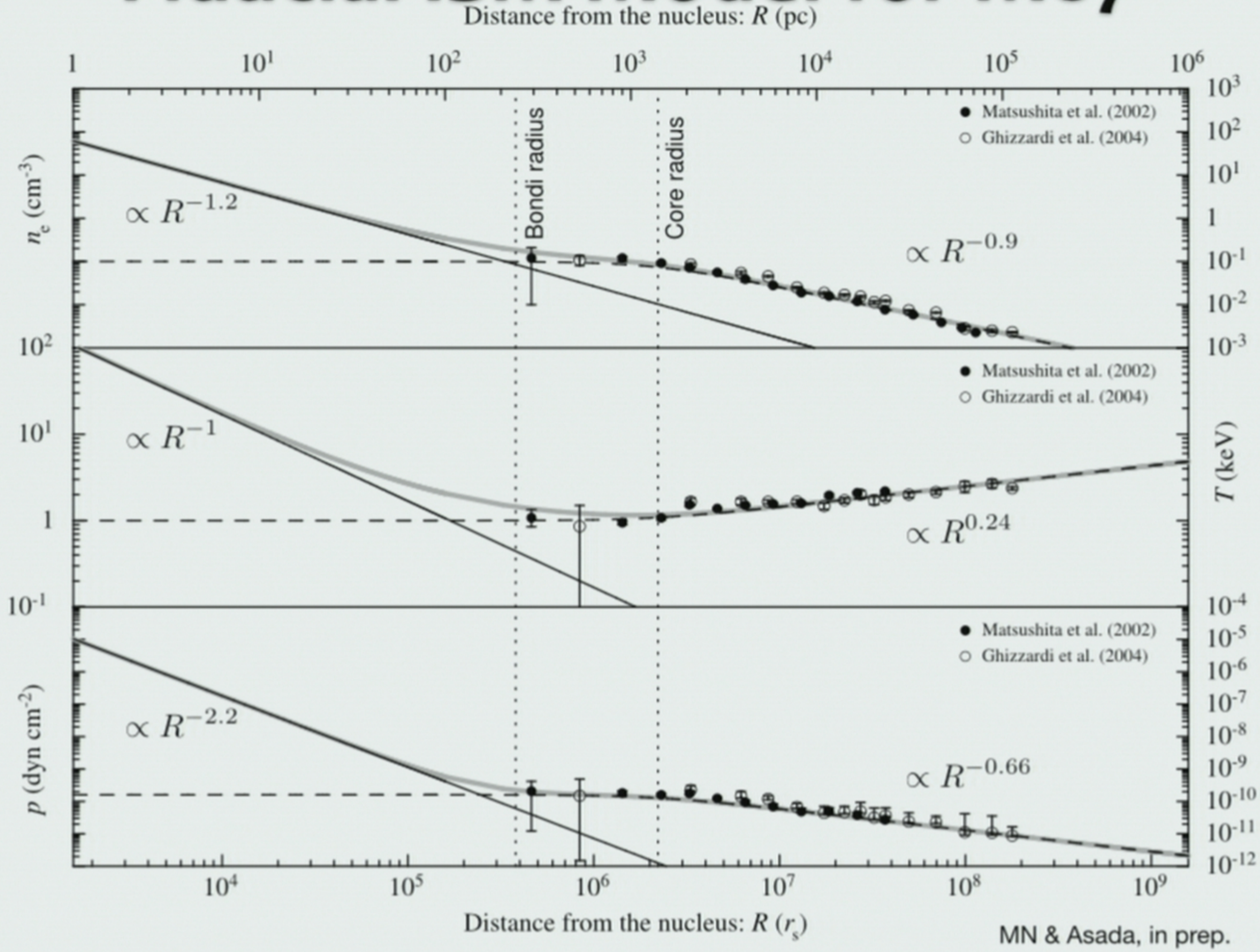
ISCO (a=0.9) ISCO (a=-0.9)

Structure & Dynamics of the M87 Jet



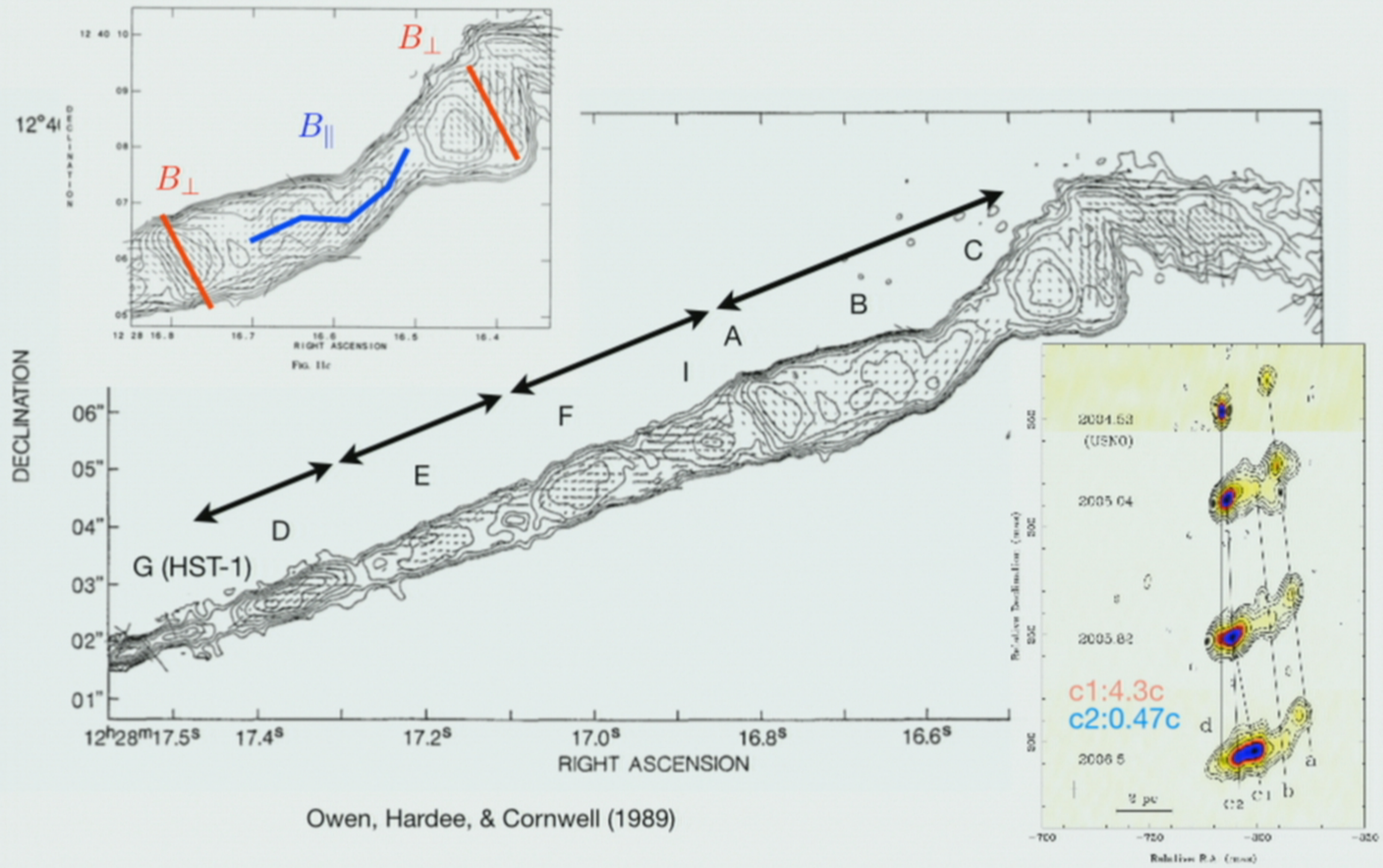
Asada & MN (2012), *ApJL*; MN & Asada (2013), *ApJ*; Asada, MN, et al. (2014), *ApJL*; MN & Asada, in prep.

Fiducial ISM Model for M87



MN & Asada, in prep.

Trails of Components?

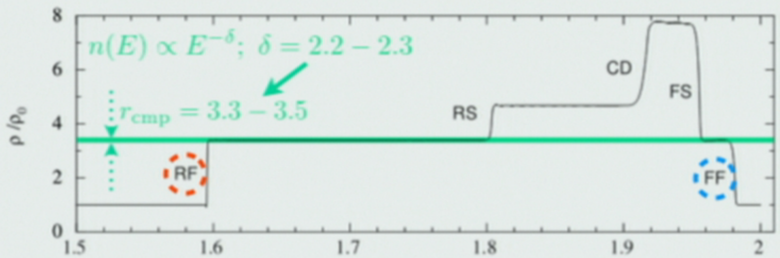


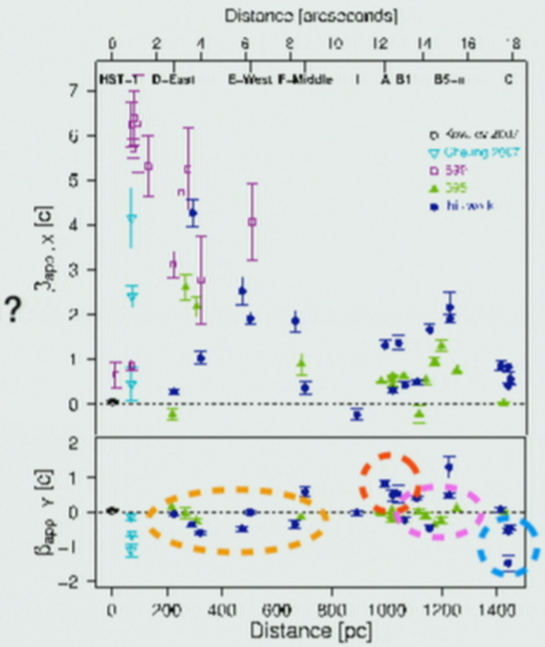
Owen, Hardee, & Cornwell (1989)

Cheung+ (2007)

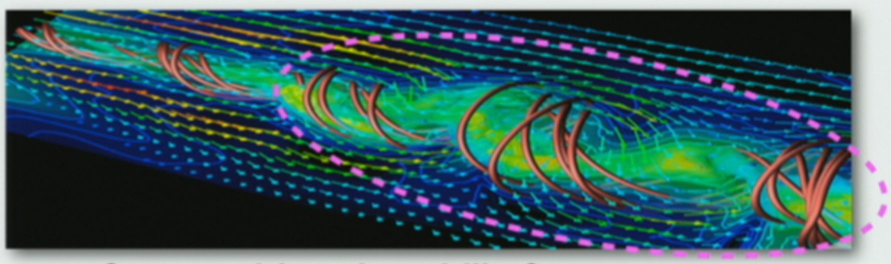
Helical Motions in Projection?

Doppler boosted motions (toward an observer)? Counter-rotaional motions (A/C)?





- Re-current RMHD quad-shock ejections at HST-1?
  - VLBA knots (MN, Garofalo, & Meier 2010, ApJ)
  - Optical knots (MN & Meier 2014, ApJ)

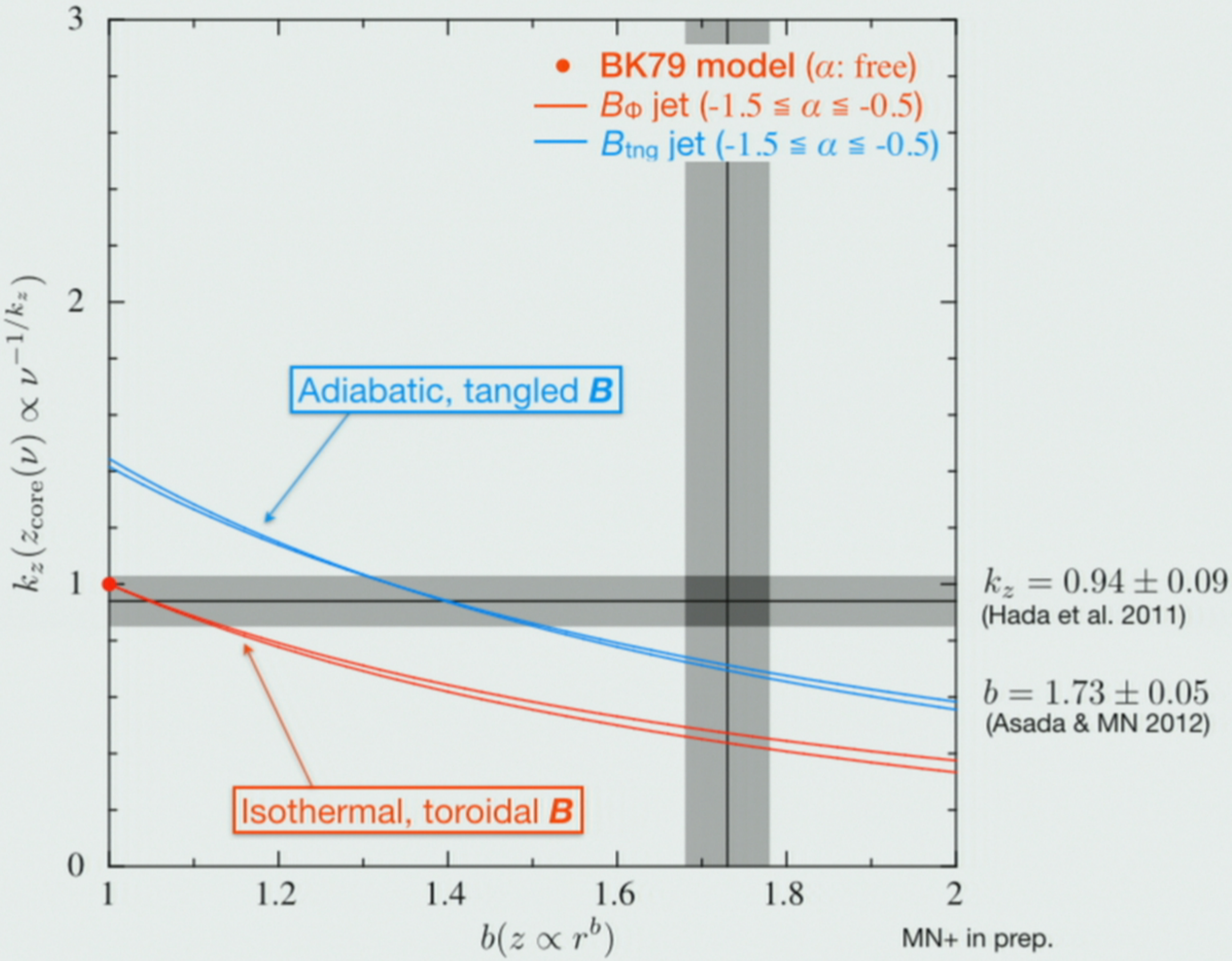


- **Current-driven instability?** (MN & Meier 2004, ApJ)

Meyer, ..., Norman, & MN (2013), ApJL

Origin of the M87 Jet

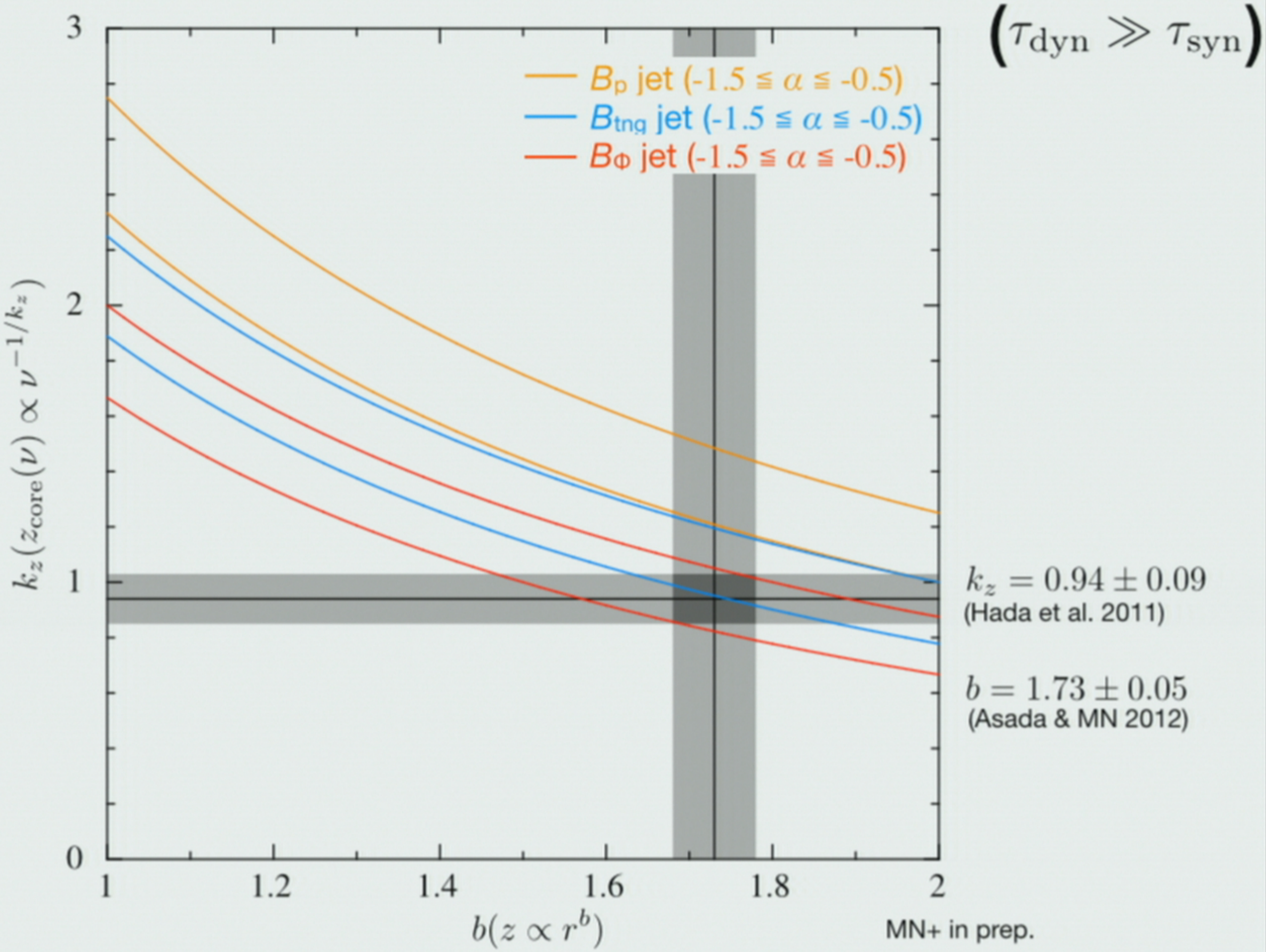
Equipartition



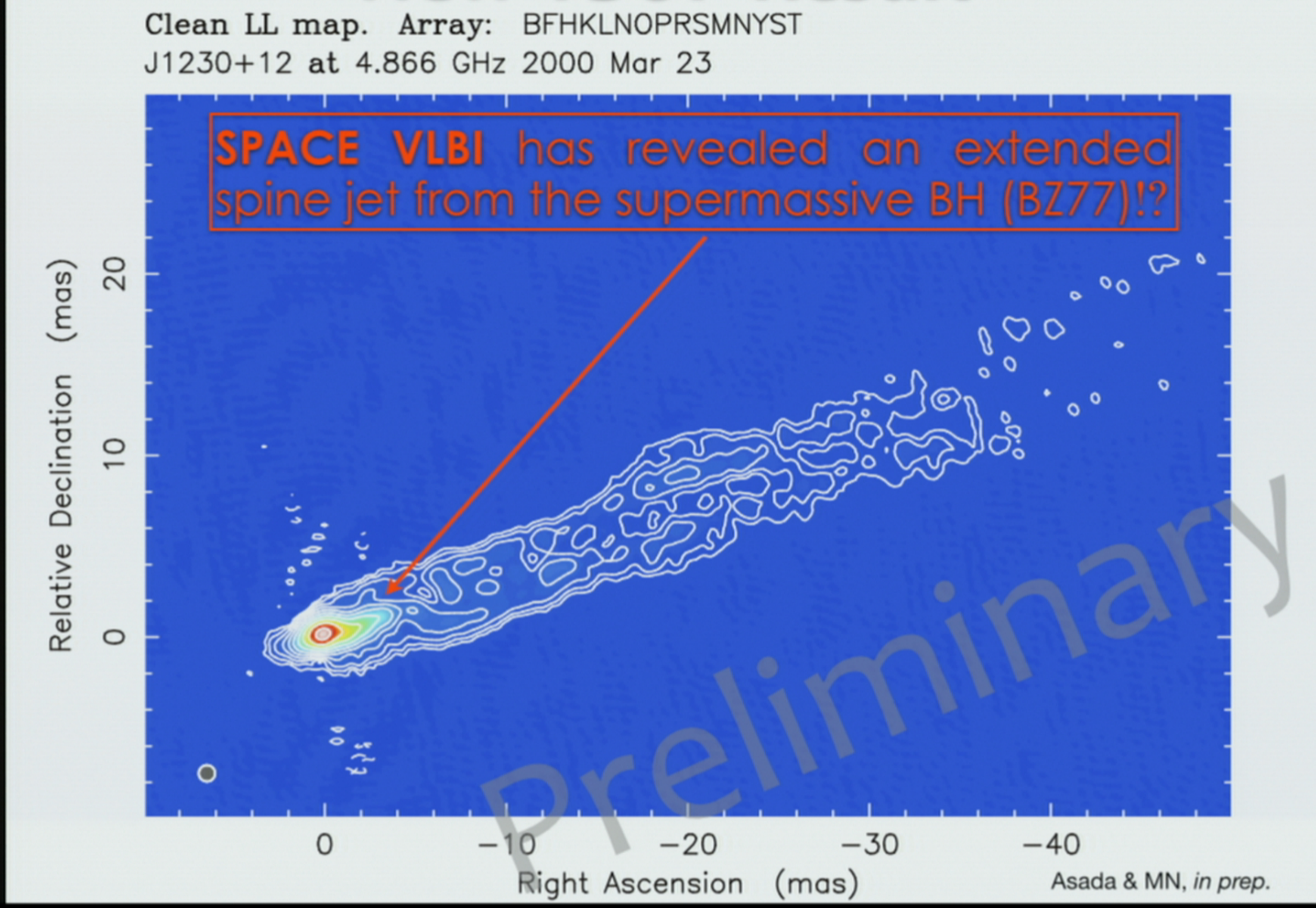
Revisiting BK79 Model

- Jet: supersonic, free (i.e., conical) & constant speed
- Convected ***B***-field by the jet will scale as z^{-1}
- Continuous acceleration of relativistic electrons (i.e., to be an isothermal; $N_e \propto U_e \propto z^{-2}$) w/ $\alpha = -0.5$
- An energy equipartition between the particle and toroidal ***B***-field (**only if** $m = 1$; Königl 1981)
- Non-conical and/or adiabatic expansion/synchrotron coolings (e.g., Marsher 1980; Georganopoulos & Marscher 1996; Lobanov 1998; Kaiser 2006); worth to consider in M87?

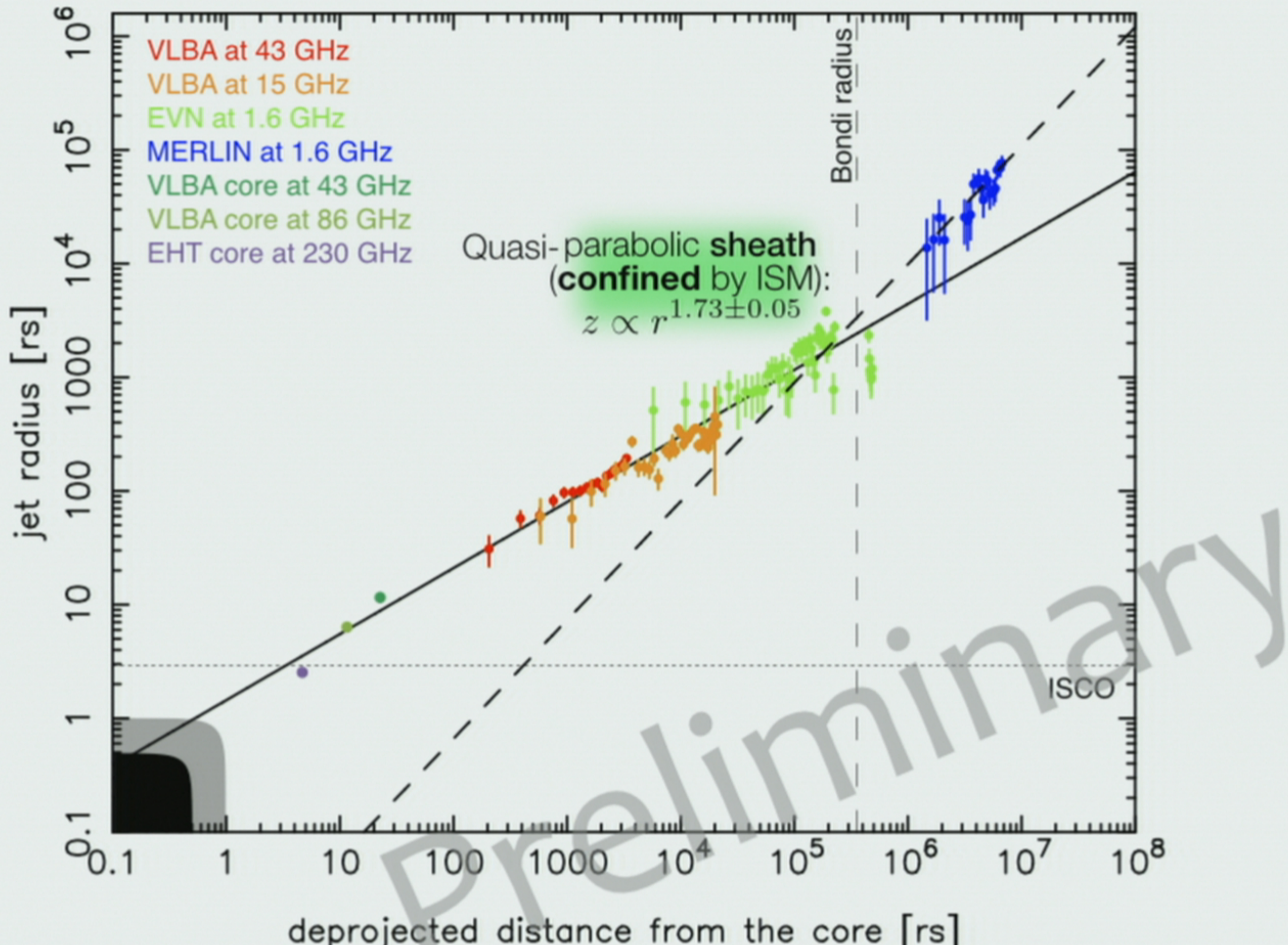
Adiabatic Expansion + Sync. Cooling



New VSOP Result



Resolved Spine-sheath Parabolic Streams?



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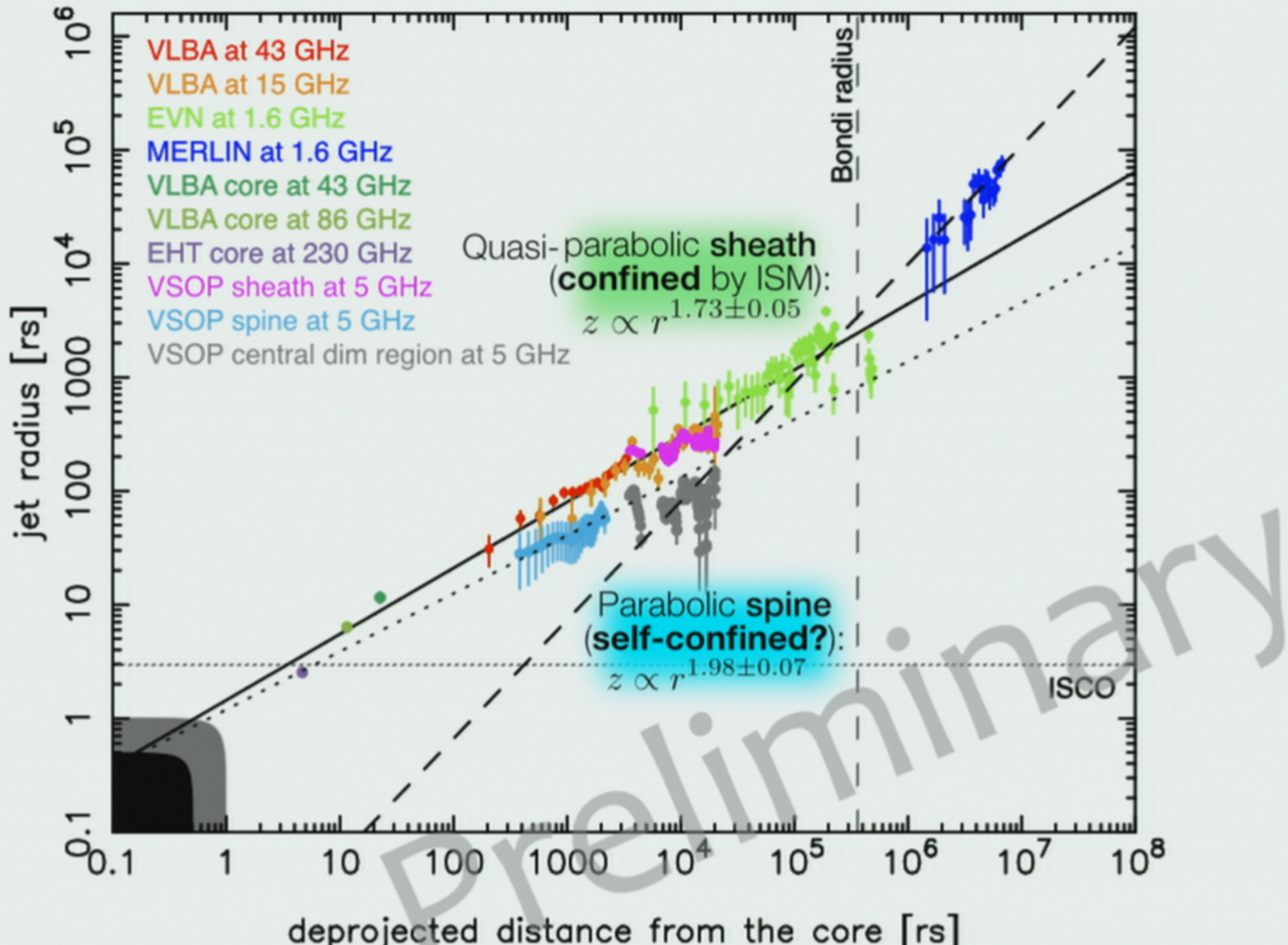

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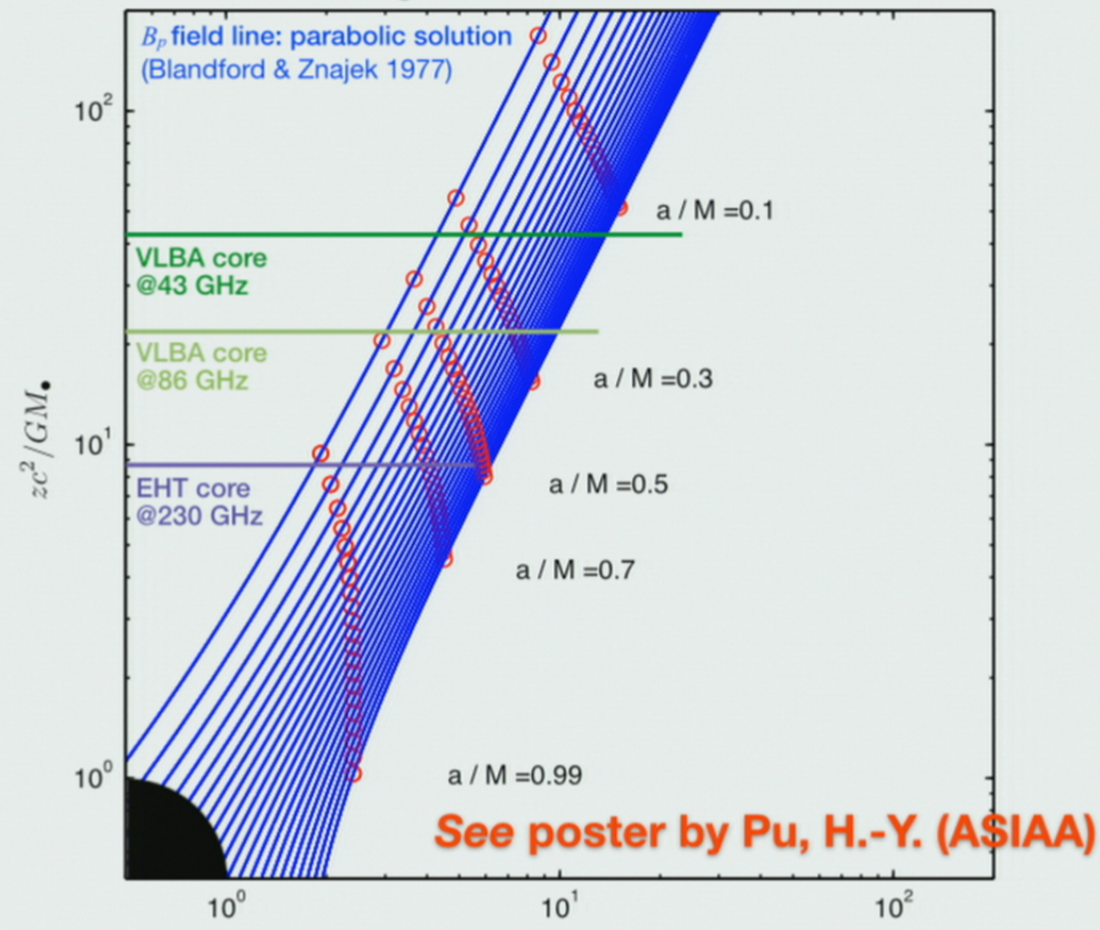
A Constraint of BH Spin w/ BZ77 & BK79

$M_\bullet = 6.6 \times 10^9 M_\odot$ (Gebhardt+ 2011)



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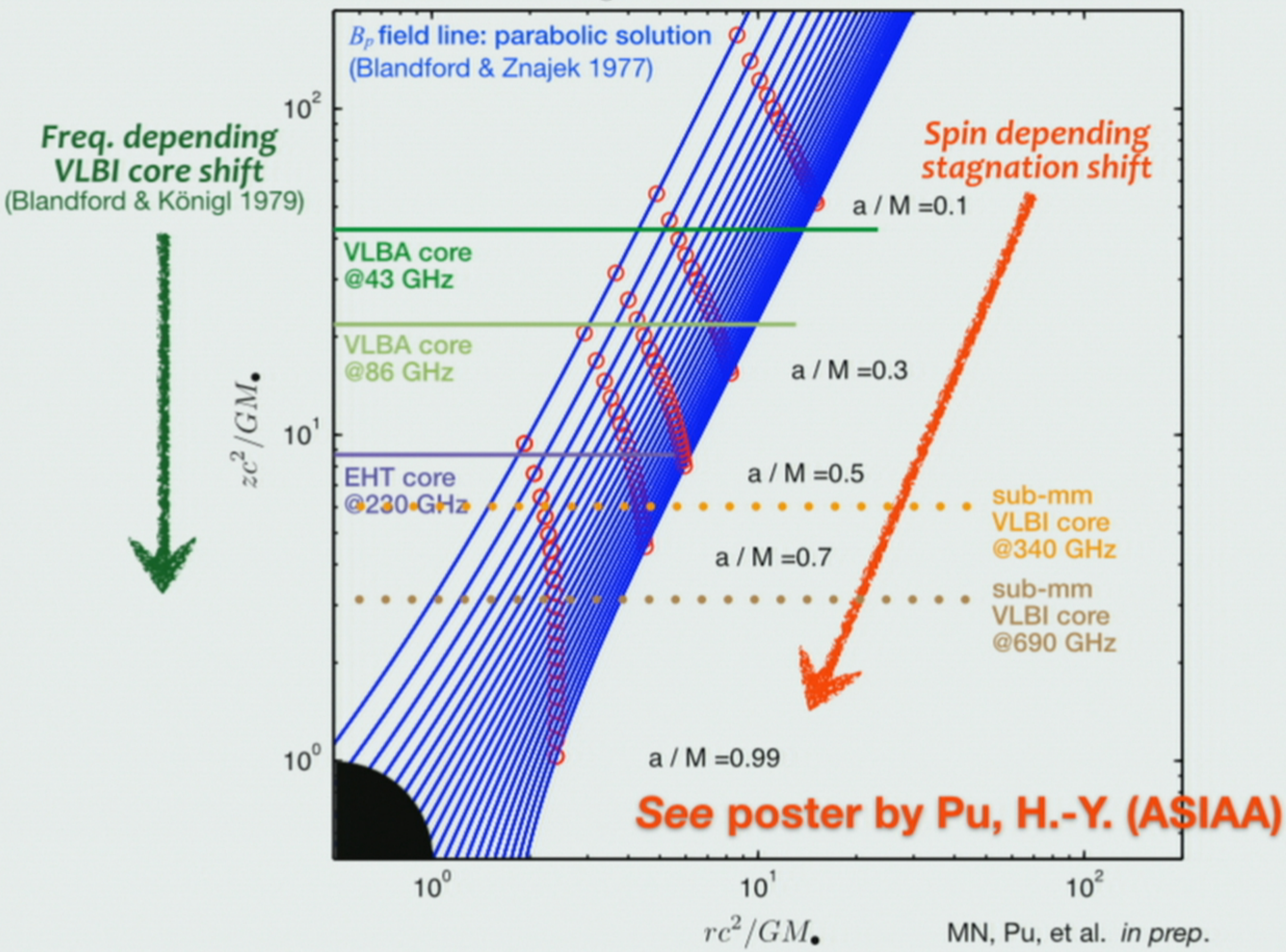
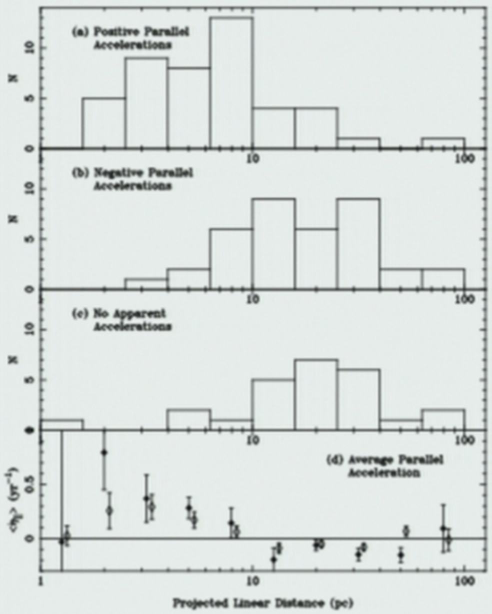


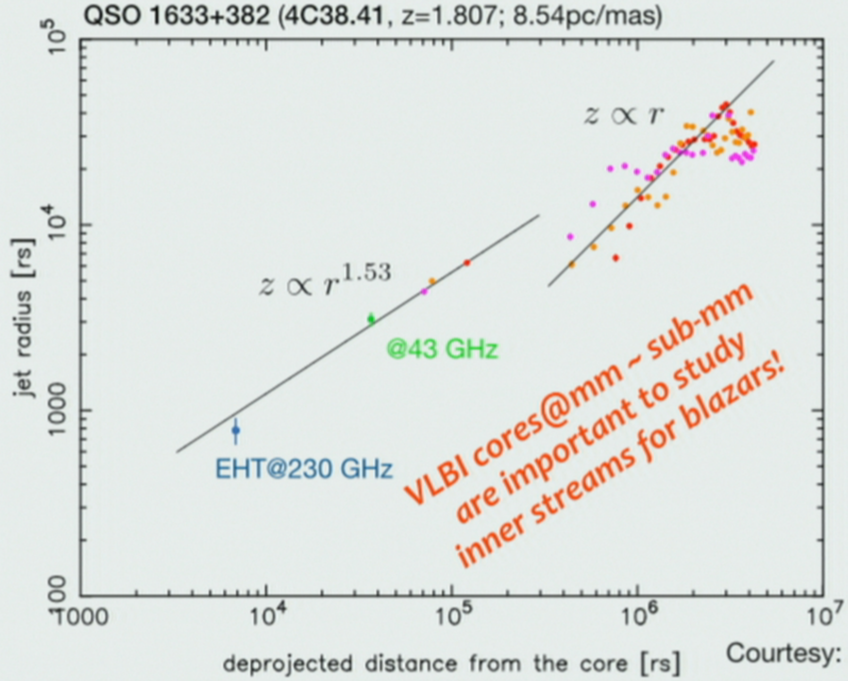
MN, Pu, et al. *in prep.*

Lessons from M87 & Prospects in Blazars

- A transition from positive to negative acceleration seems to locate at ~ 10 pc in MOJAVE sample (Lister+ 2013; Homan+ 2014)
- Non-ballistic flows are strongest at < 10 pc; jets are expanding less rapidly than $r \propto z$, so that jets is still being collimated (Homan+ 2014)
- "Jet break", induced by a stationary component, is one of the key observables toward an AGN jet unification (MN & Norman, in prep.)

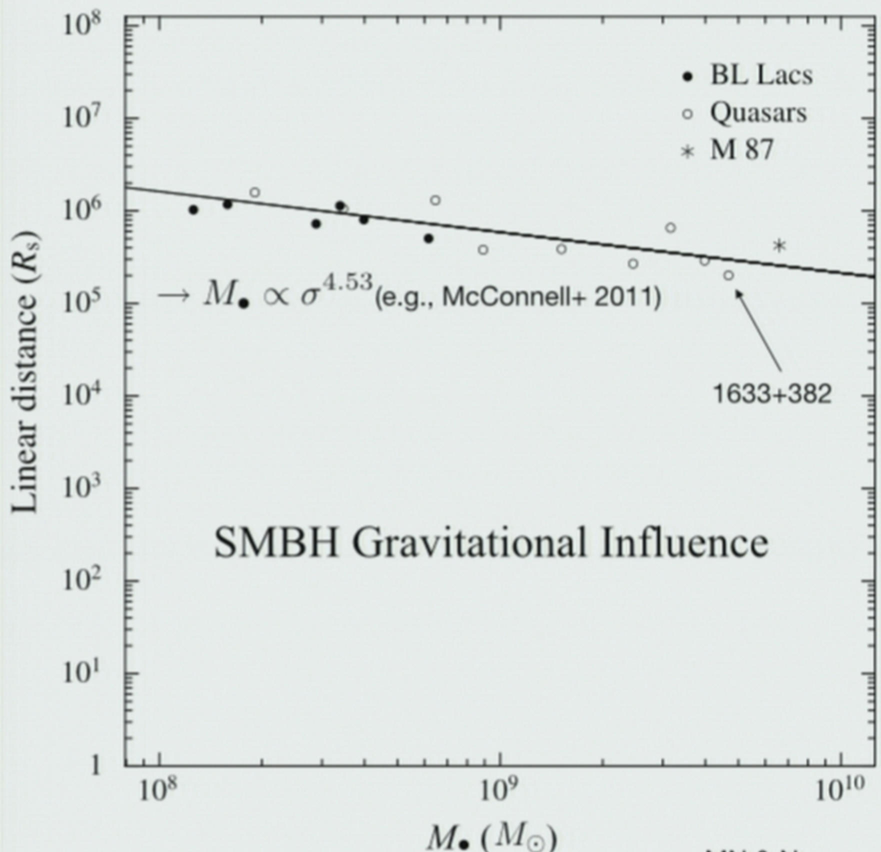


Homan+ (2014)



Courtesy: K. Asada

Scaling Stationary Knots with M• in "Parabolic to Conical Jet Break"



MN & Norman, in prep.

1) Footprints of co-evolutions among SMBHs - Jets - host gals.

2) Potential sites of VHE γ-ray flares

3) Jet acceleration and collimation, if they are magnetically powered, could be up to $10^{5\text{-}6}$ r_s scales

4) Conversion from EM to kinetic energy may be suspended by the Jet break, suggesting, Poynting-flux dominated jets in VLBI scale

5) A unified view of AGN jets in VLBI scale

Summary

- M87; a prototype of relativistic jets in AGNs, showing nice example of the global structure & dynamics in all scales from less than 10 r_s to 10^7 r_s

- mm VLBI core@230GHz of M87 can be the inner parabolic jet emission from the spinning BH ($a/M \geqq 0.5$ for $6.6\times10^9\ M_\odot$)
  - ➡ Sub-mm VLBI (345 GHz or higher; including GLT) is important to explore the jet origin in M87; long baselines 9,000+ km (ALMA-SMA/JCMT-GLT), giving a resolution $\theta \sim 20$ μas ($\sim 2.5 R_s$)
  - ➡ Inflow/outflow separation of BH-driving GRMHD jets is also key for imaging simulations; ***See poster*** for "1st ever steady GRMHD in/out-flow solutions in a parabolic streamline" (Pu, MN+ 2014, submitted)

- "Jet break", scaled by $M_\bullet$, gives a crucial understanding of AGN jets, interplaying with co-evolving SMBHs and their host galaxies
  - ➡ We propose the structural analysis with (sub-mm) VLBI cores as a key science case in AGN jets for building their unification scheme

~ Head to the 100th Anniversary of Discovering Cosmic Jets \^o~/

"M87 Symposium"

2016 Spring (TBD), Taipei, Taiwan

Pre-SOC: **P. Ho** (ASIAA, Chair), **L. Ho** (KIAA, Vice-chair), **R. Blandford** (SLAC), **A. Fabian** (IoA), **R. Narayan** (CfA), **M. Reid** (CfA)

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