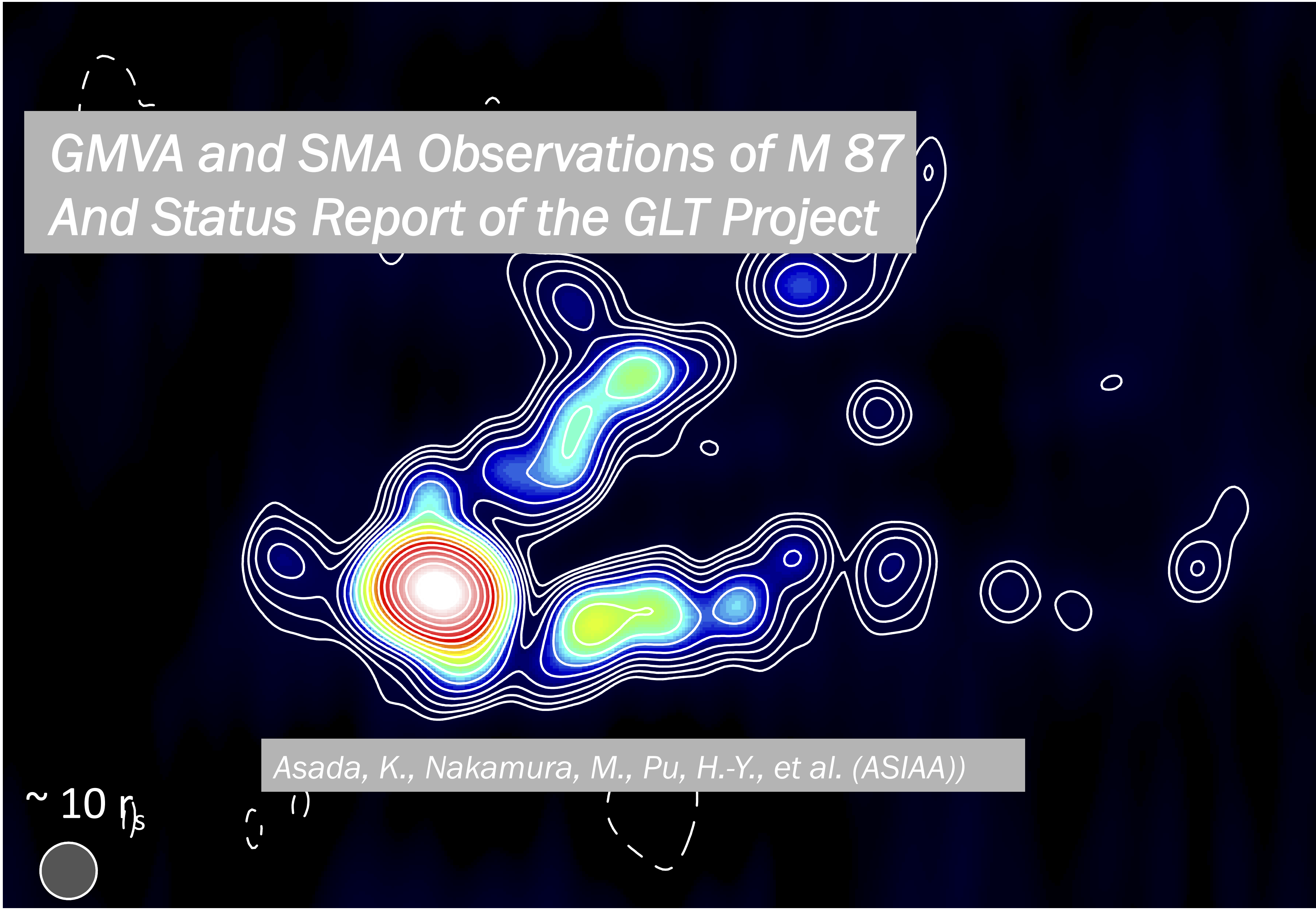
# GMVA and SMA Observations of M 87 And Status Report of the GLT Project

Asada, K., Nakamura, M., Pu, H.-Y., et al. (ASIAA))



# Academia Sinica, Institute of Astronomy and Astrophysics

- Research Manpower:
  - 42 research faculty
  - 43 engineers
  - 57 postdocs/contracted persons
  - + students and administrative stuffs

- Research Topics:
  - Extragalactic/Star Formation/ Interstellar Medium/Dust/Cosmology/ Planetary Sciences/radio and optical instrumentations

- Research Projects:
  - SMA/TAOS I, II/Computational astronomy/ AMiBA/CFHT/SUBARU/ALMA/GLT, JCMT/VLBI


# Outline of this talk

- Introduction of M 87 and GLT

- Mass Accretion rate of **M 87** with SMA observations

    Kuo, C.Y., Asada, K. et al. 2014, ApJL, 783, 33
    Asada, K., Rao, R., et al. in prep.

- Collimation of **M 87** jet with VLBI observations

    Asada, K. & Nakamura, M. 2012, ApJ, 745, 28
    Nakamura, M. and Asada, K. 2013, ApJ, 775, 118
    Asada, K., Nakamura, M., and Pu, H.-Y. to be submitted
    Asada, K. et al. in prep.

- Acceleration of **M 87** jet with VLBI observations

    Nakamura, M. and Asada, K. 2013, ApJ, 775, 118
    Asada, K. et al. 2014, ApJL, 781, 2

# Introduction

# Importance of M 87

□ M 87 (Virgo A*)

- $2^{nd}$ brightest galaxy in Virgo cluster

- Large BH mass

  BH mass: 6 (3)× $10^9$ $M_\odot$

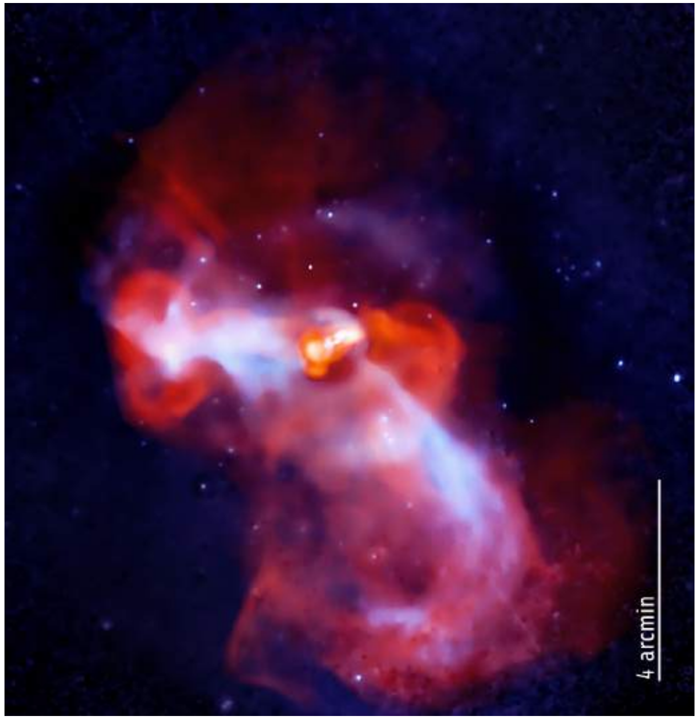
  Gebhardt and Thomas 09, 11

  (e.g. Ford+94, Harms+ 94, Walsh 2013)

- One of the nearest AGN

  Distance: 16.7 Mpc

  Jordan et al. 2005, ApJ, 634, 1002




- $2^{nd}$ largest apparent size of $r_s$ (radius of non-rotating BH)

  1 mas = 0.074pc (= 125 $r_s$)

# $1^{st}$ Discovered relativistic jet

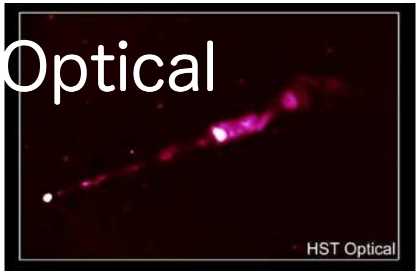
□ M 87 (Virgo A*)

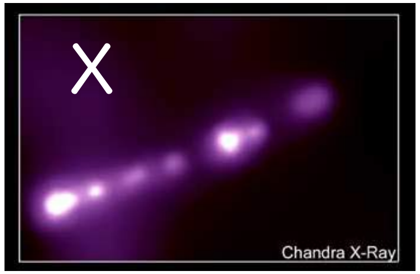
Resolution:

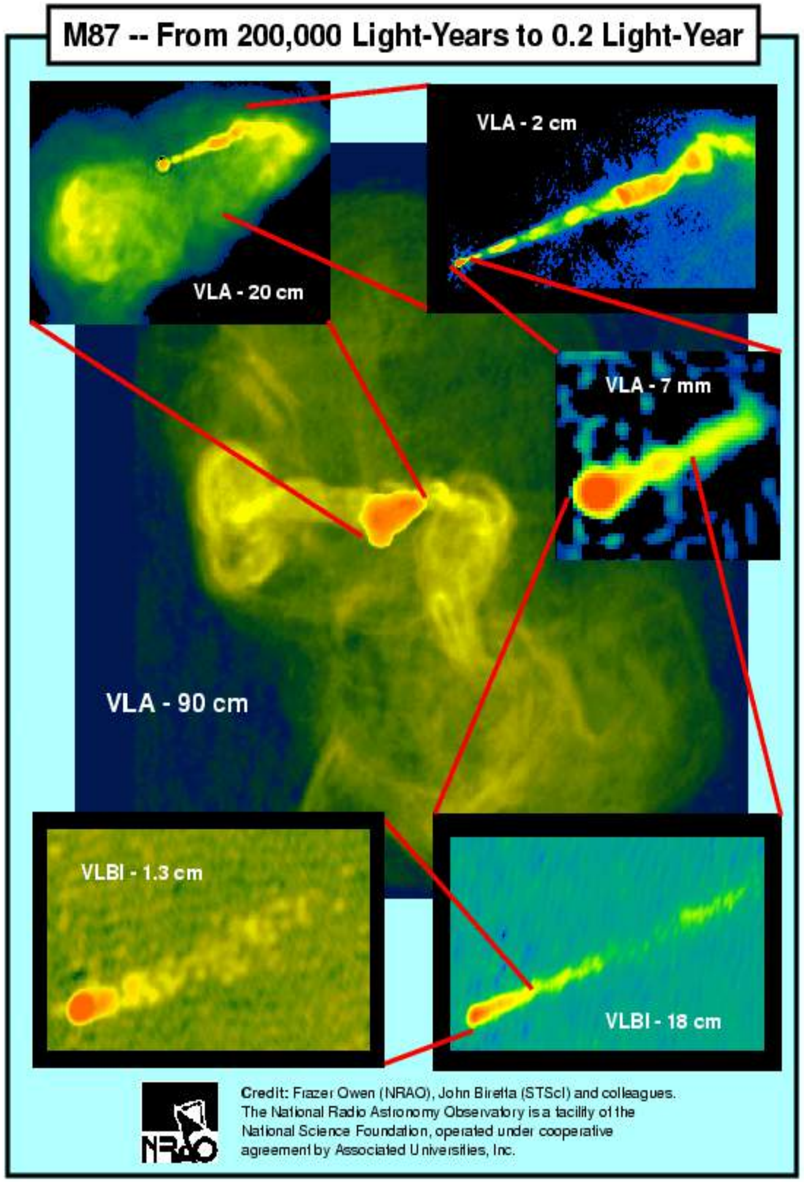
- arcmin (~ $10^7$ $r_s$) to sub-mas (~ 10 $r_s$)

Frequency:

- Radio – optical – X-ray – γ-ray

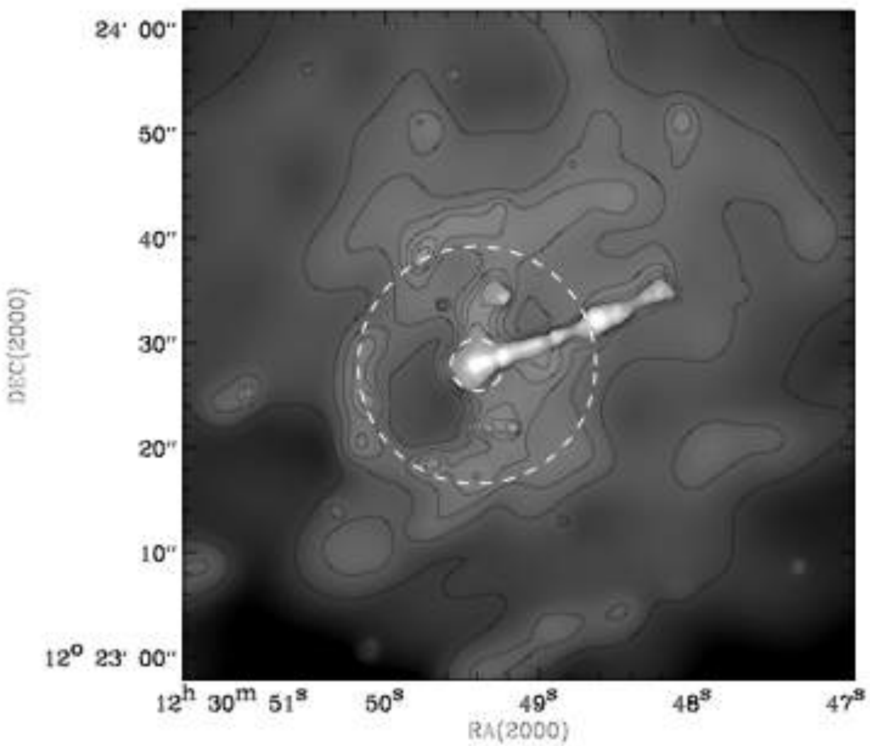



# Low-Luminosity AGN

- With Chandra Observation

Di Matteo et al. 2003, ApJ, 582,133

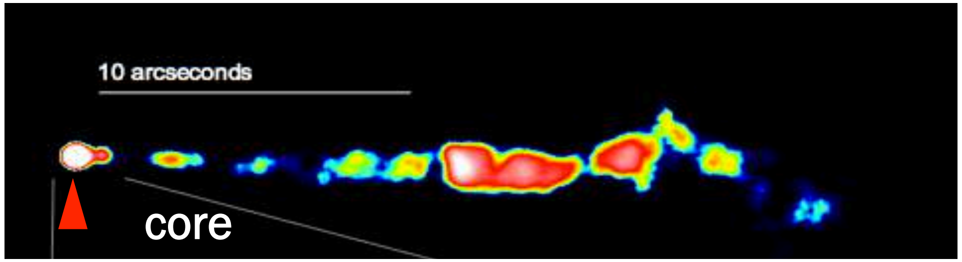


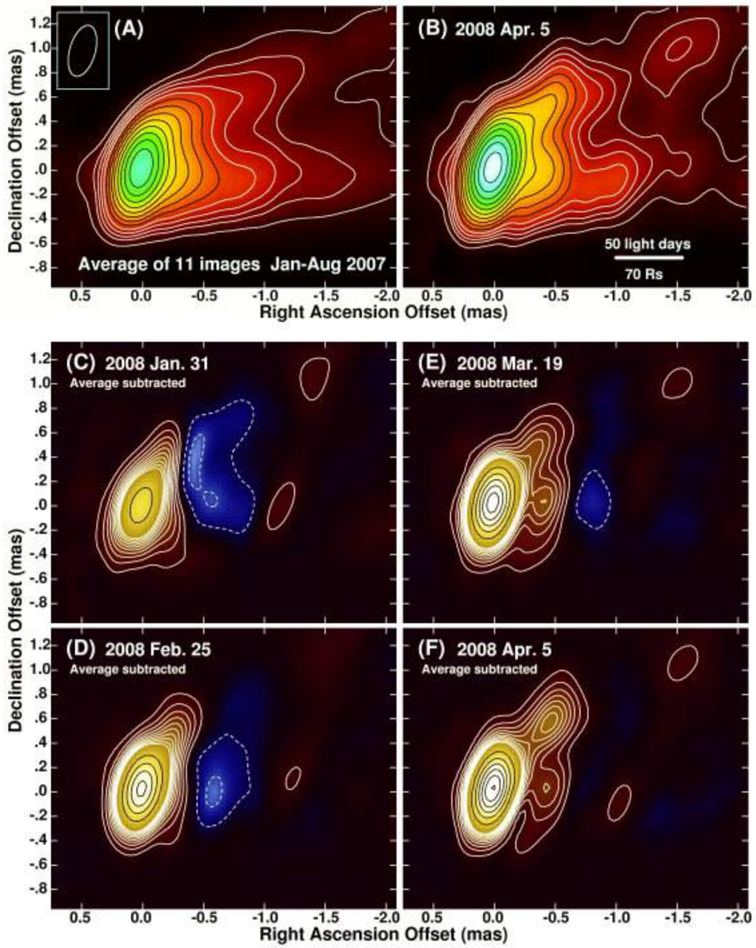

- $L_X \sim 7 \times 10^{40}$ erg $s^{-1}$

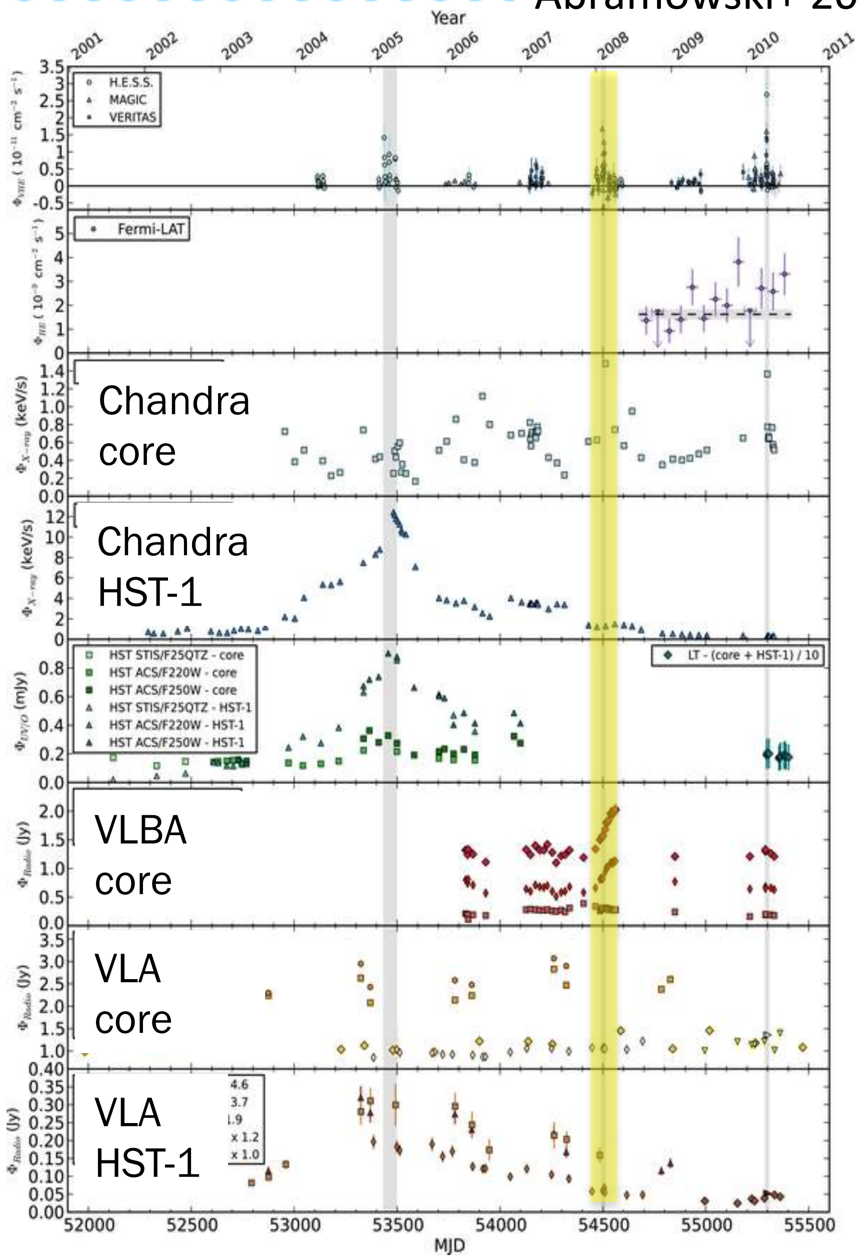
It's sub-eddington, and Probably has a Radiatvely Inefficient Accretion Flow (RIAF)

# X- and γ- ray flare

Abramowski+ 2012

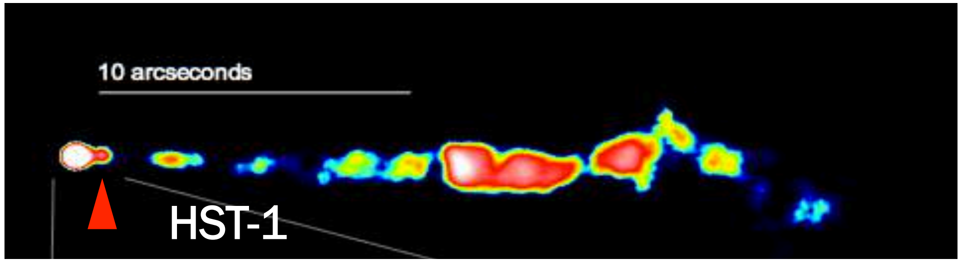


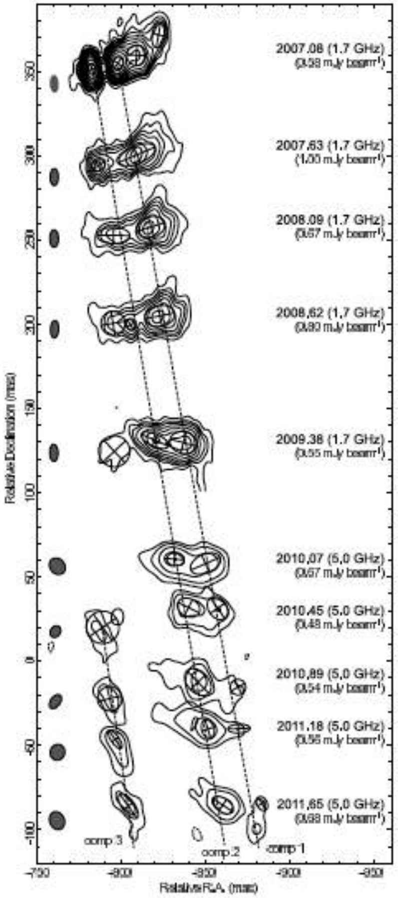



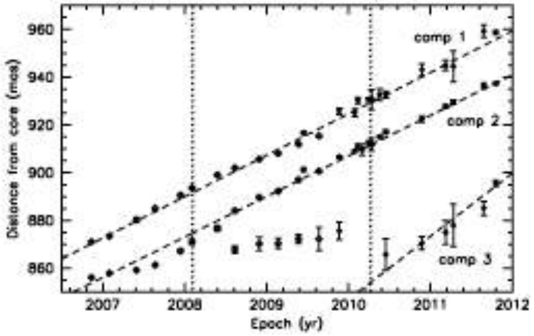



# X- and γ- ray flare

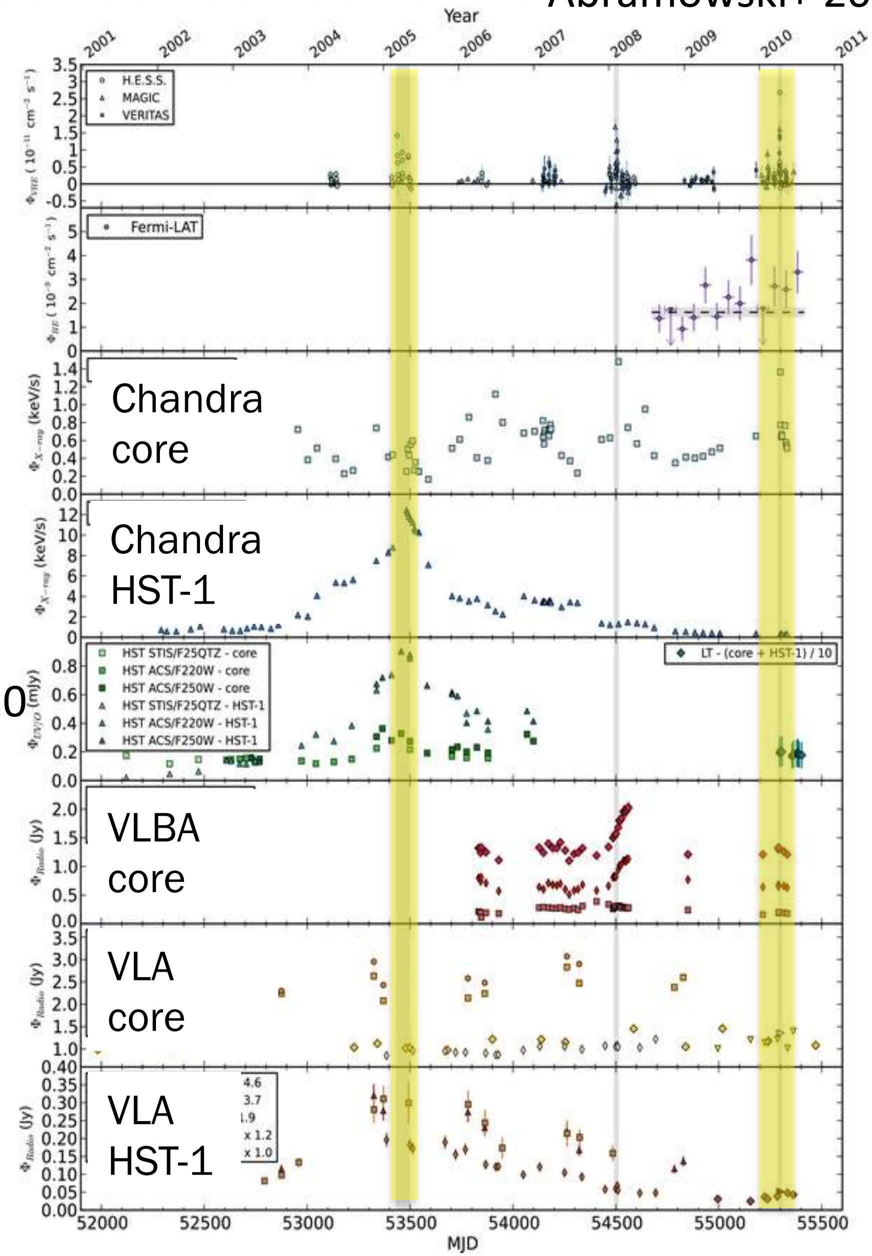
Abramowski+ 2012



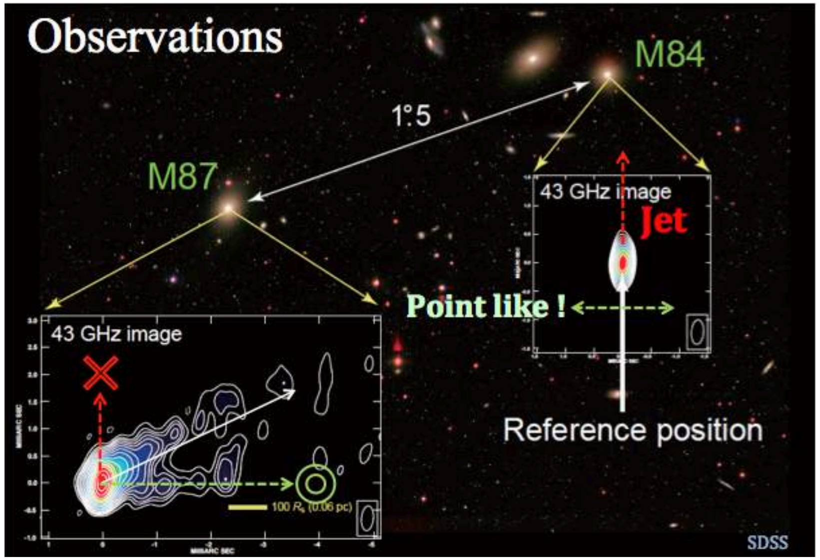



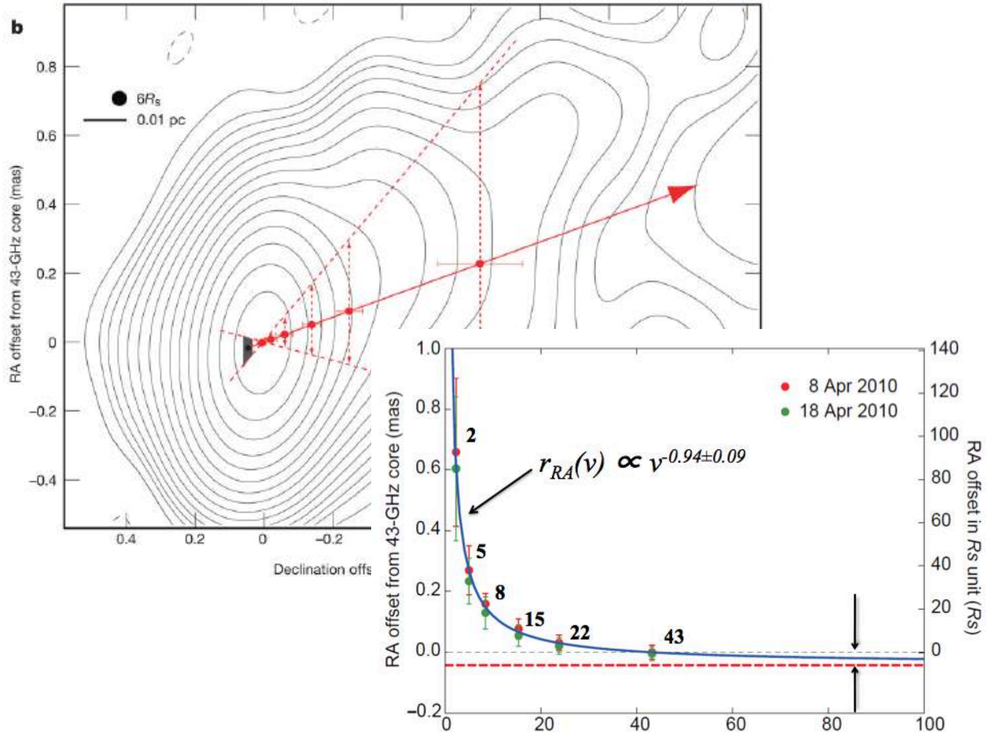



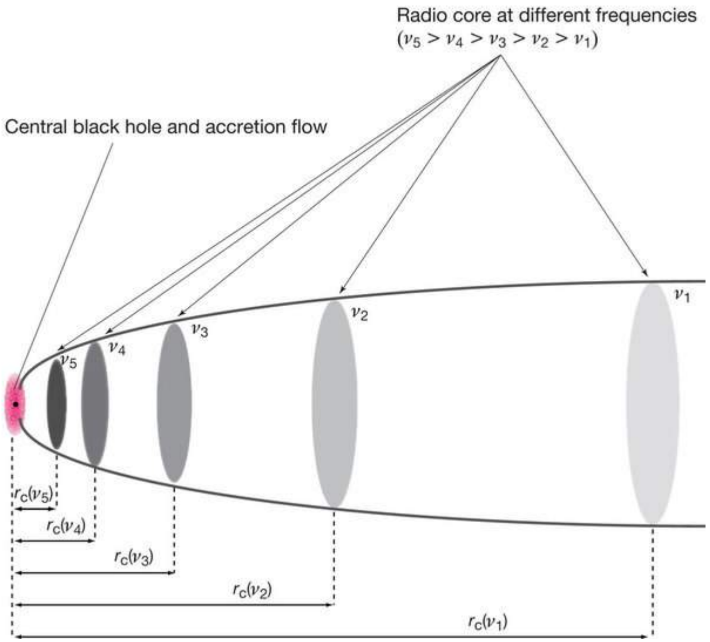

Giroletti+ 2012, A&A, 538, L10
Hada+ 2014, ApJ, 788, 165



# Location of the Central Engine




Hada+ 2011, Nature, 477, 185

Central engine is located at (41±12) μas (6±2 Rs) eastward of the 43-GHz radio core.

# Importance of M 87

□ M 87 (Virgo A*)

- 1st discovered relativistic jet

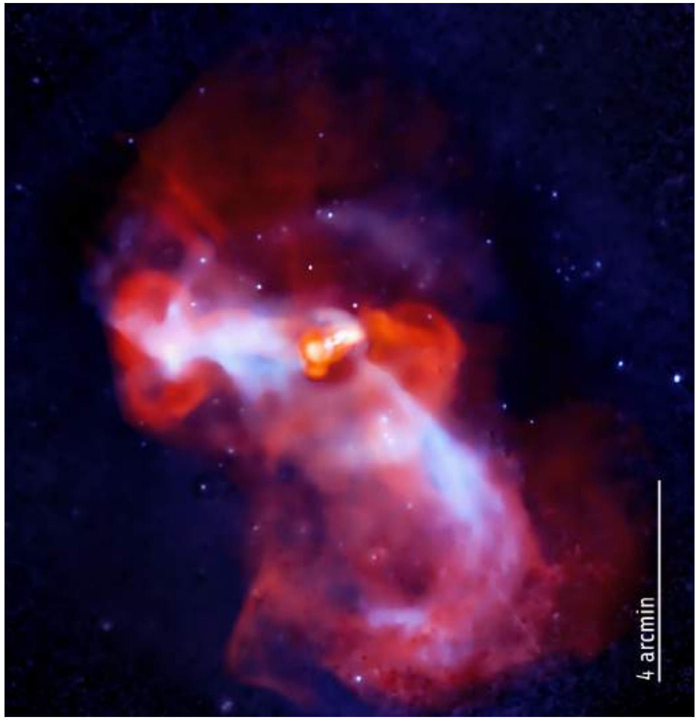
  Curtis 1918, Publications of Lick Observatory 13, 31

- Low-Luminosity AGN

  Typical AGN with radiatively inefficient accretion flow (RIAF)

- High Energy activities

  Up to TeV gamma-ray
  Miss-aligned Blaser?

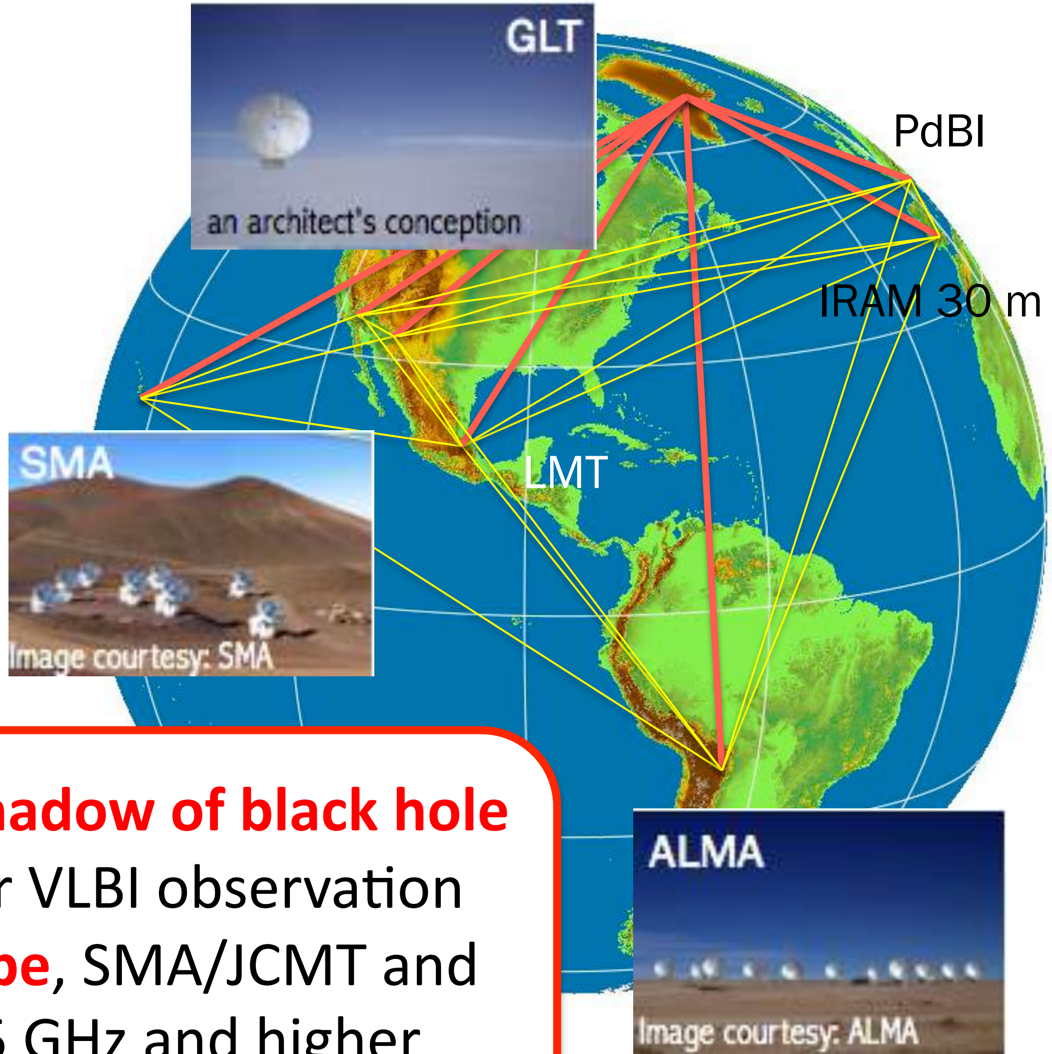



- 2nd largest apparent size of $r_s$ (radius of non-rotating BH)

It contains all contents of AGN !!

Best Source to understand AGN !!

# Goal of the Greenland Telescope Project


Primary objective: Image **a shadow of black hole** of **M 87** with sub-millimeter VLBI observation includes **Greenland Telescope**, SMA/JCMT and phased ALMA at 230, 345 GHz and higher frequency.

# Logistics of Greenland


- Peak of the Greenland ice cap (3,200 m) at 72°35'46.4"N 38°25'19.1”W
- Sponsored by the NSF, operated by CH2M Hill Polar Services (CPS)
- Camp population: 5 (winter) up to 50 (summer)
- Air National Guard provides LC-130 aircraft, twin otter aircraft or traverse.
- Network: Satellite link

- We have accessed the Summit Station since 2011 for the site testing.

# Logistics of Greenland

Our radiometer at the site

- Peak of the Greenland ice cap (3,200 m) at 72°35'46.4"N 38°25'19.1”W

perated by CH2M Hill Polar Services (CPS)

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# Logistics of Greenland

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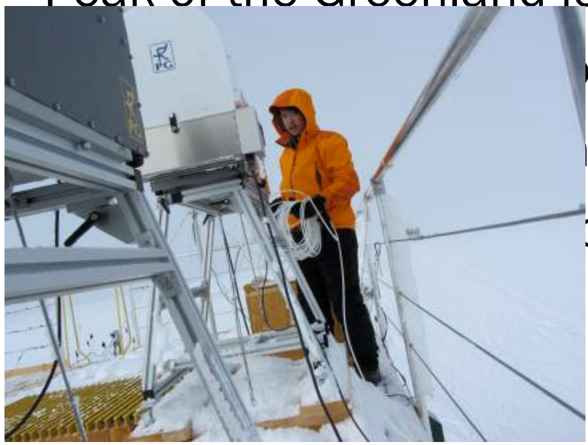
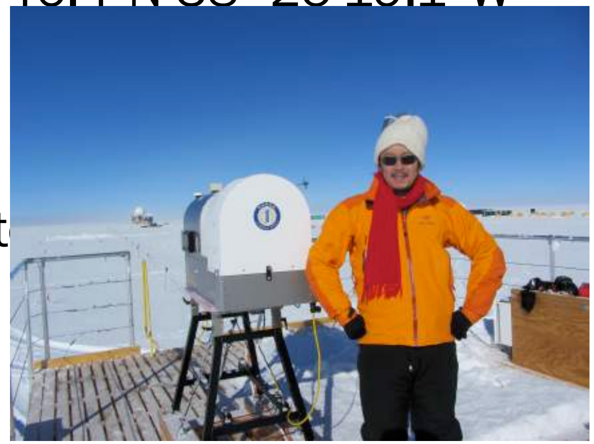




- We have accessed the Summit Station since 2011 for the site testing.

# Plan for 2016 and beyond

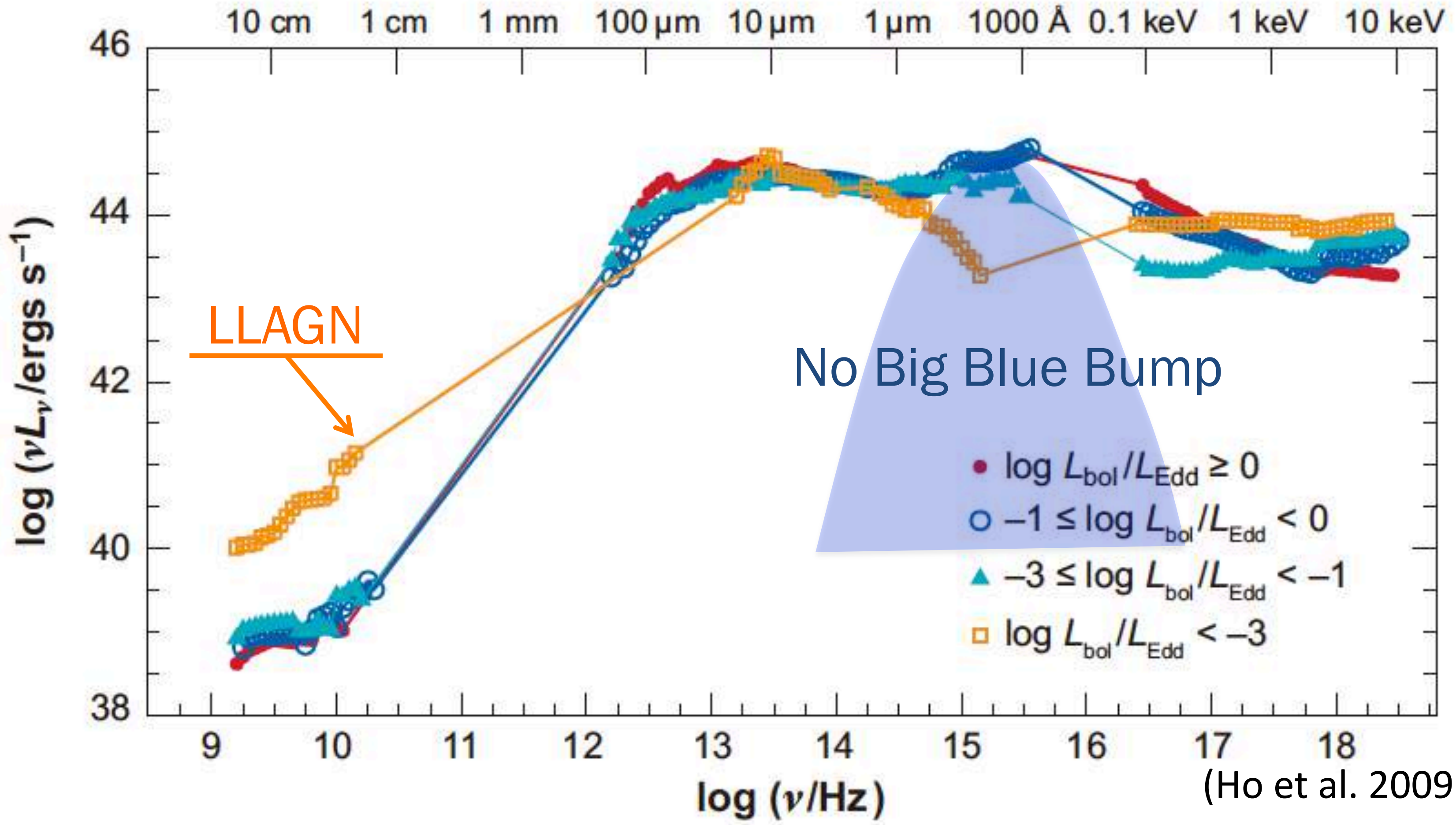
- Antenna shipping to Thule (2016).
- Antenna re-assemble and test at Thule, including VLBI test (2016-2019).
- Single-dish & VLBI first light at Thule (2017-2018).
- Transport antenna across ice sheet (2019).
- First light at the Summit Station (2019/20).



# Accretion flow onto SMBH of M 87

# M 87 and its Accretion Flows

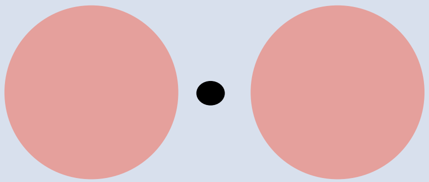
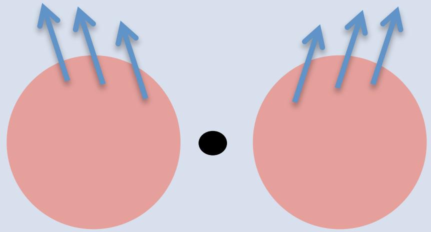
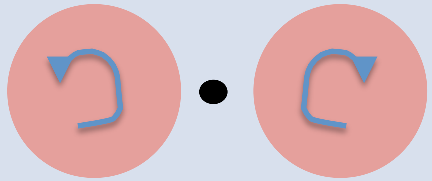
- Low-Luminosity AGNs are subclass of AGN. ($L < 10^{-3} L_{edd}$)
- LLAGNs (Ho et al. 1997) are considered to accommodate RIAF
- M 87 is categorized as LLAGN.



(Ho et al. 2009)

# Accretion flow of LLAGNs

Three types of RIAFs:

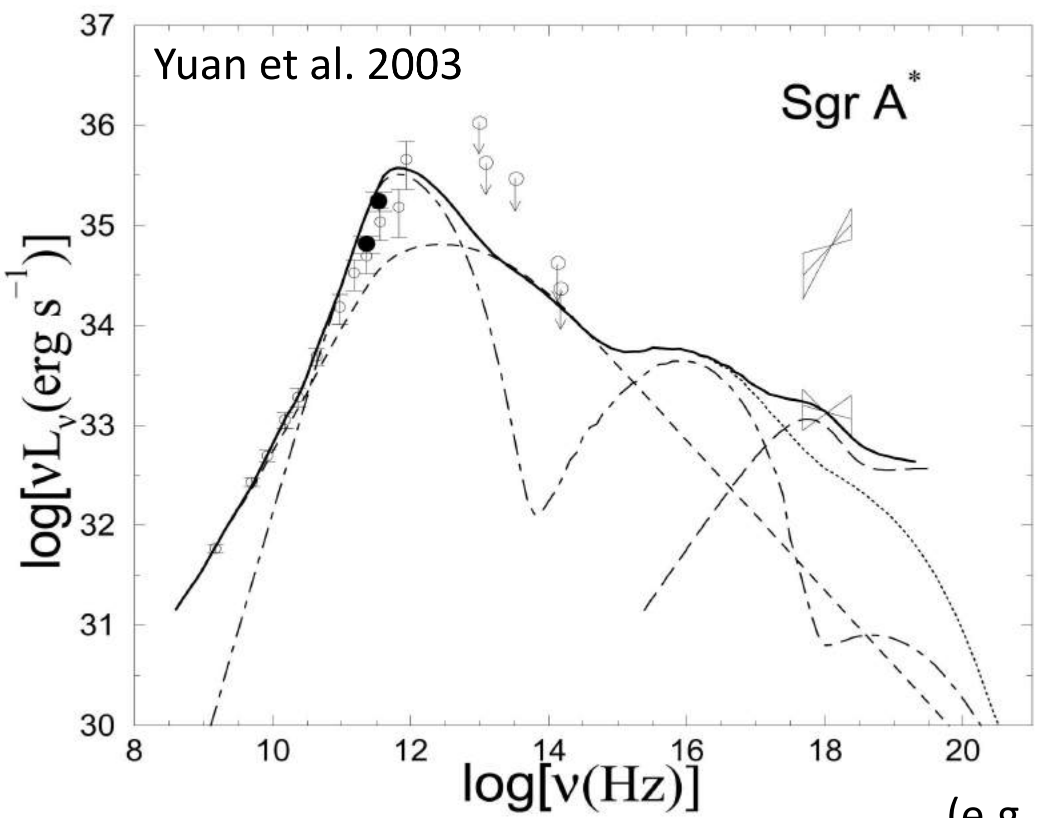
| | **ADAF** (Ichimaru 1977; Narayan & Yi 1995) | **ADIOS** (Blandford & Begelman 1999) | **CDAF** (Igumenshchev & Abramowicz 1999) |
|---|---|---|---|
| Structure |  |  |  |
| $\dot{M}$ | $\sim (r/r_B)^0$ | $\sim (r/r_B)^{0\text{-}1}$ | $\sim (r/r_B)^1$ |

$r_B$: Bondi radius ($\sim 10^{4\text{-}6}\, r_s$)

- Substantial decrease of the mass accretion rate can be expected for ADIOS and CDAF !!

Mass Accretion Rate is fundamental parameter to consider energy balance between $L_{acc}$ and $L_{rad}$ or $L_{jet}$.

# Probing Accretion Flow with SED fitting




(e.g., Narayan et al. 1995; Manmoto et al. 1997)

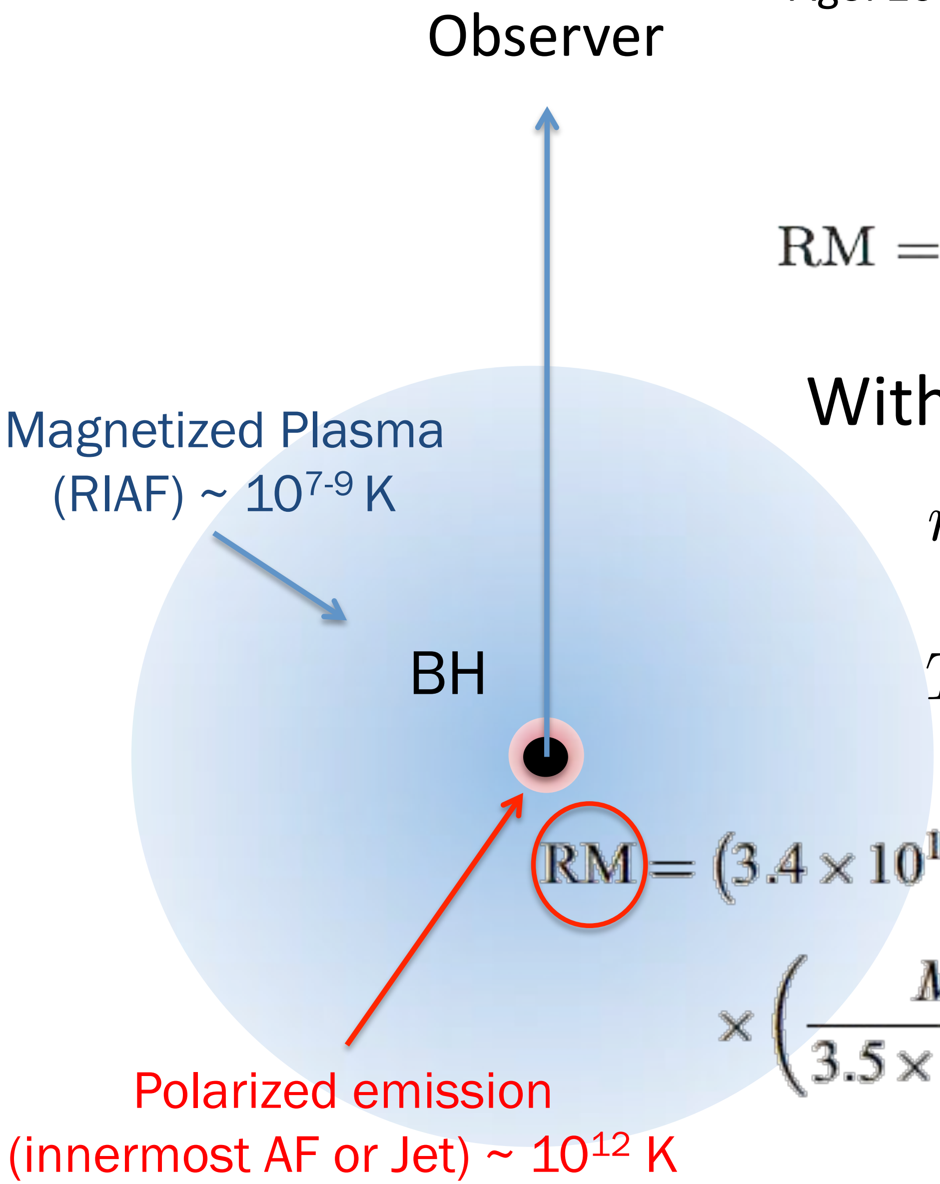
- Very succeeded method for Sgr A*

$$\dot{M} \sim 4 \times 10^{-8}\ M_{\odot}\ yr^{-1}$$

SED can be contaminated/dominated by jet….

# Probing Accretion Flow with Faraday Rotation

Agol 2000, Quataert & Gruzinov 2000, Bower et al. 2003, Marrone et al. 2006, Macquart et al. 2006




$$\mathrm{RM} = 8.1 \times 10^5 \int_{LOS} n_e B_{||} \, dl$$

## With RIAF model:

$$n(r) \sim \left(\frac{r}{r_s}\right)^{-\beta} \qquad \beta = 1/2 \ \text{(ADAF)}$$

$$= 3/2 \ \text{(CDAF)}$$

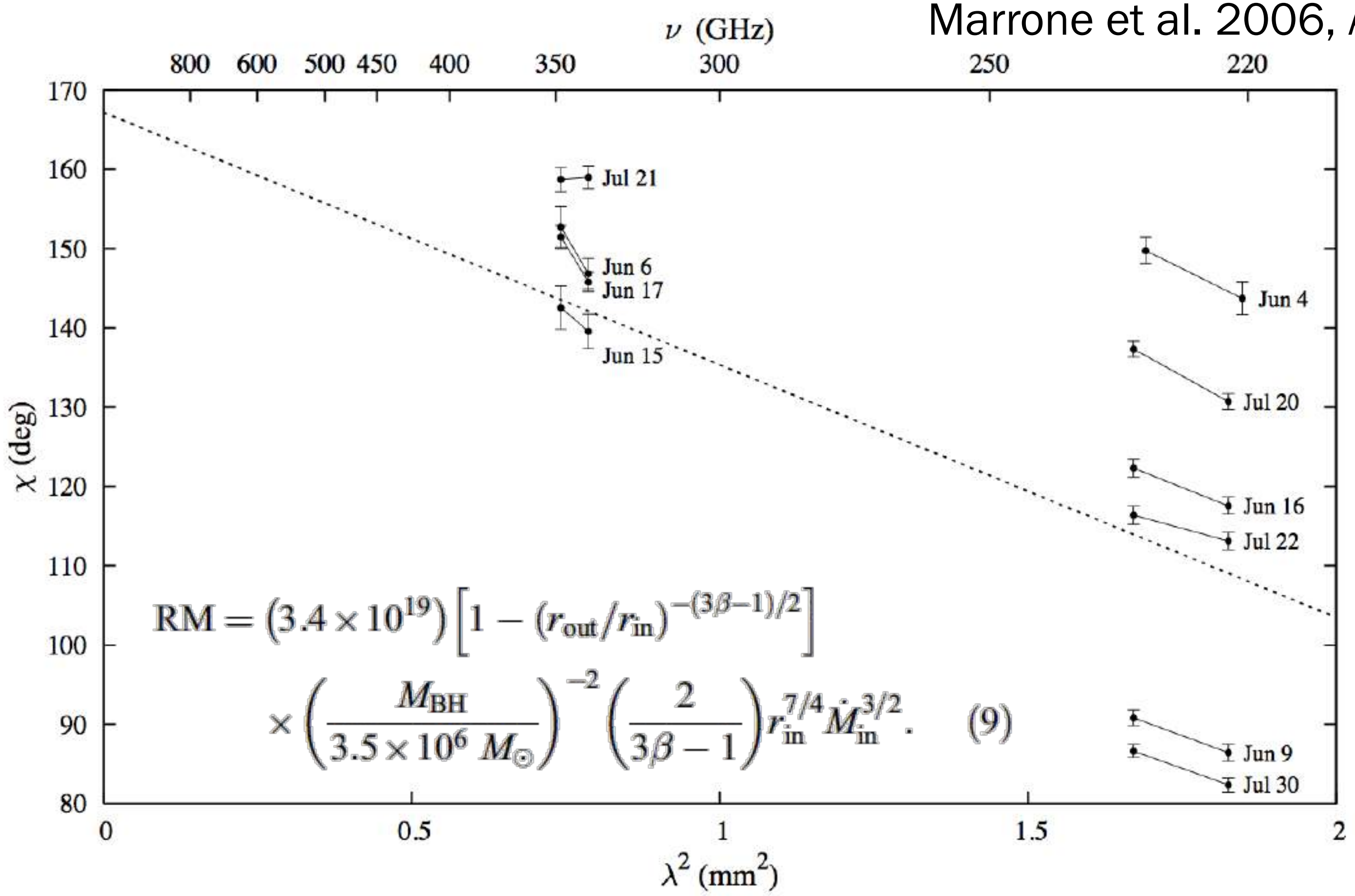
$$T(r) \sim \left(\frac{r}{r_s}\right)^{-1} \qquad = 1/2 - 3/2 \ \text{(ADIOS)}$$

$$\mathrm{RM} = (3.4 \times 10^{19}) \left[1 - (r_{\mathrm{out}}/r_{\mathrm{in}})^{-(3\beta-1)/2}\right] \times \left(\frac{M_{\mathrm{BH}}}{3.5 \times 10^6 \, M_\odot}\right)^{-2} \left(\frac{2}{3\beta - 1}\right) r_{\mathrm{in}}^{7/4} \dot{M}_{\mathrm{in}}^{3/2}. \qquad (9)$$

Marrone et al. 2006, ApJ, 640, 308

# SMA Polarimetry towards Sgr A*

Marrone et al. 2006, ApJ, 640, 308




RM observation with SMA towards Sgr A*

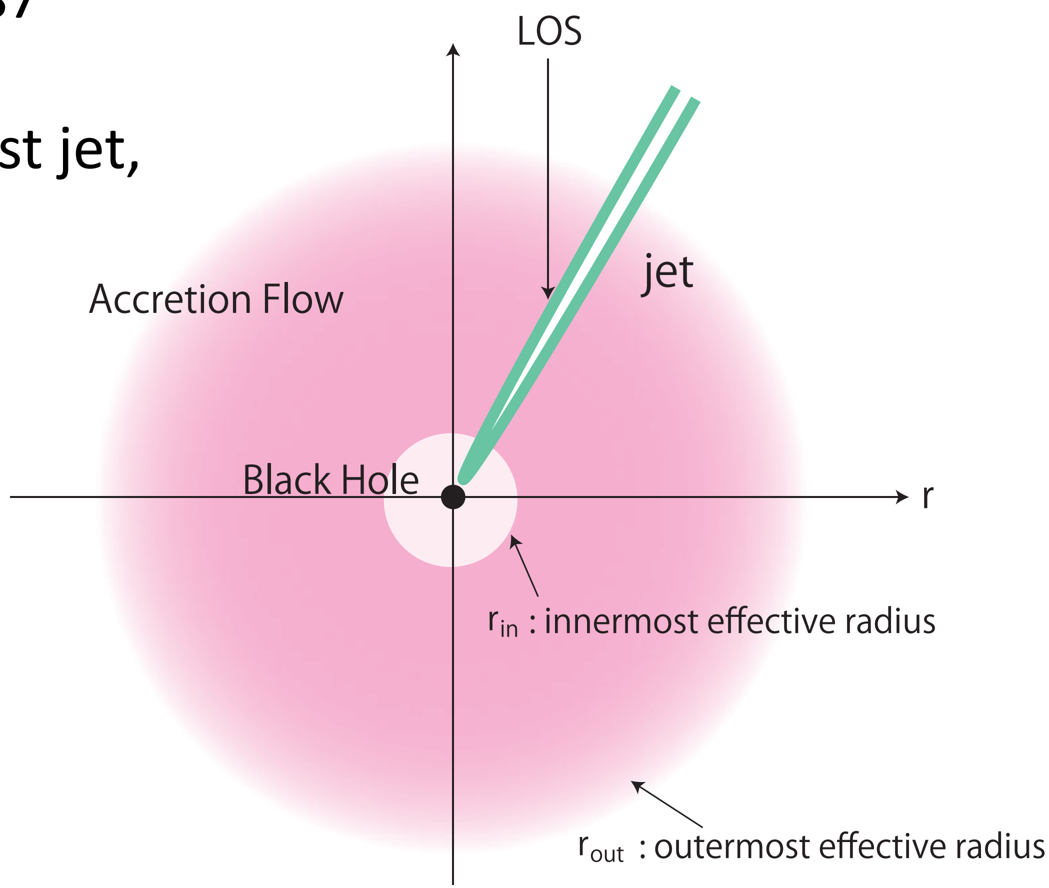
- RM = $(5.6 \pm 0.7) \times 10^5$ rad m$^{-2}$

▶ $\dot{M} = 2 \times 10^{-7} - 2 \times 10^{-9}\ M_\odot\ \mathrm{yr}^{-1}$

# In the case of M 87

- Apply the same scheme to M 87

  Back light would be innermost jet, not AF

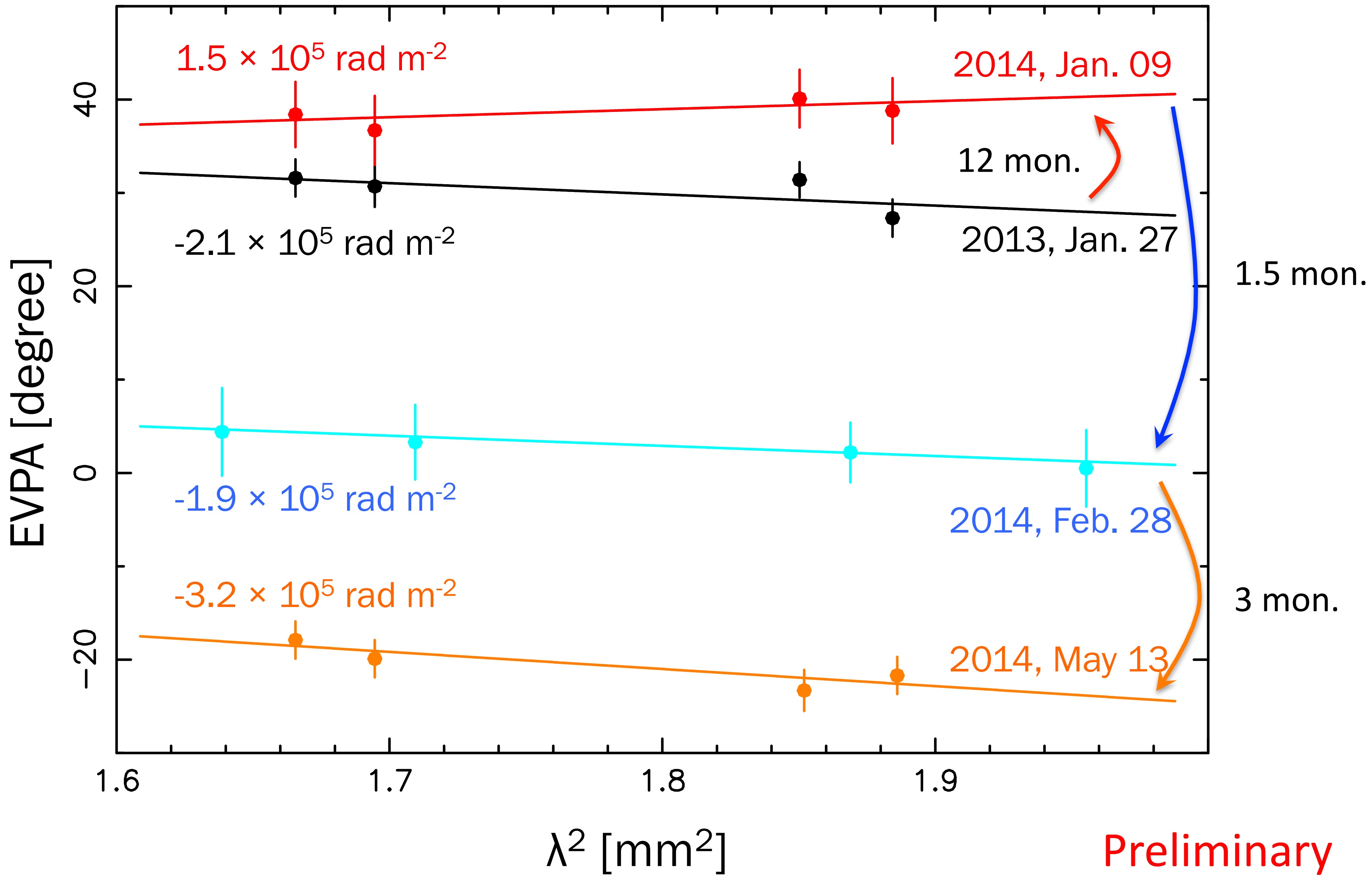



- With Chandra Observation
  - $r_B \sim 230$ pc ($3 \times 10^5$ $r_s$)
  - $P_B \sim 7 \times 10^{45}$ erg s$^{-1}$
  - $M_B \sim 0.12$ $M_\odot$ yr$^{-1}$

  Di Matteo et al. 2003, ApJ, 582,133

$$\dot{M} = 1.1 \times 10^{-8} \left[1 - (r_{\rm out}/r_{\rm in})^{-(3\beta-1)/2}\right]^{-2/3} \times \left(\frac{M_\bullet}{6.6 \times 10^9 M_\odot}\right)^{4/3} \left(\frac{2}{3\beta - 1}\right)^{-2/3} r_{\rm in}^{7/6} R M^{2/3}$$

# RM fitting towards M 87




Preliminary

# Mean RM and Mass accretion rate

Assuming no time variation,

$$\langle RM \rangle = (-1.8 \pm 0.3) \times 10^{5}\ \mathrm{rad\ m^{-2}}\ !!$$

First **"solid detection"** of RM !!

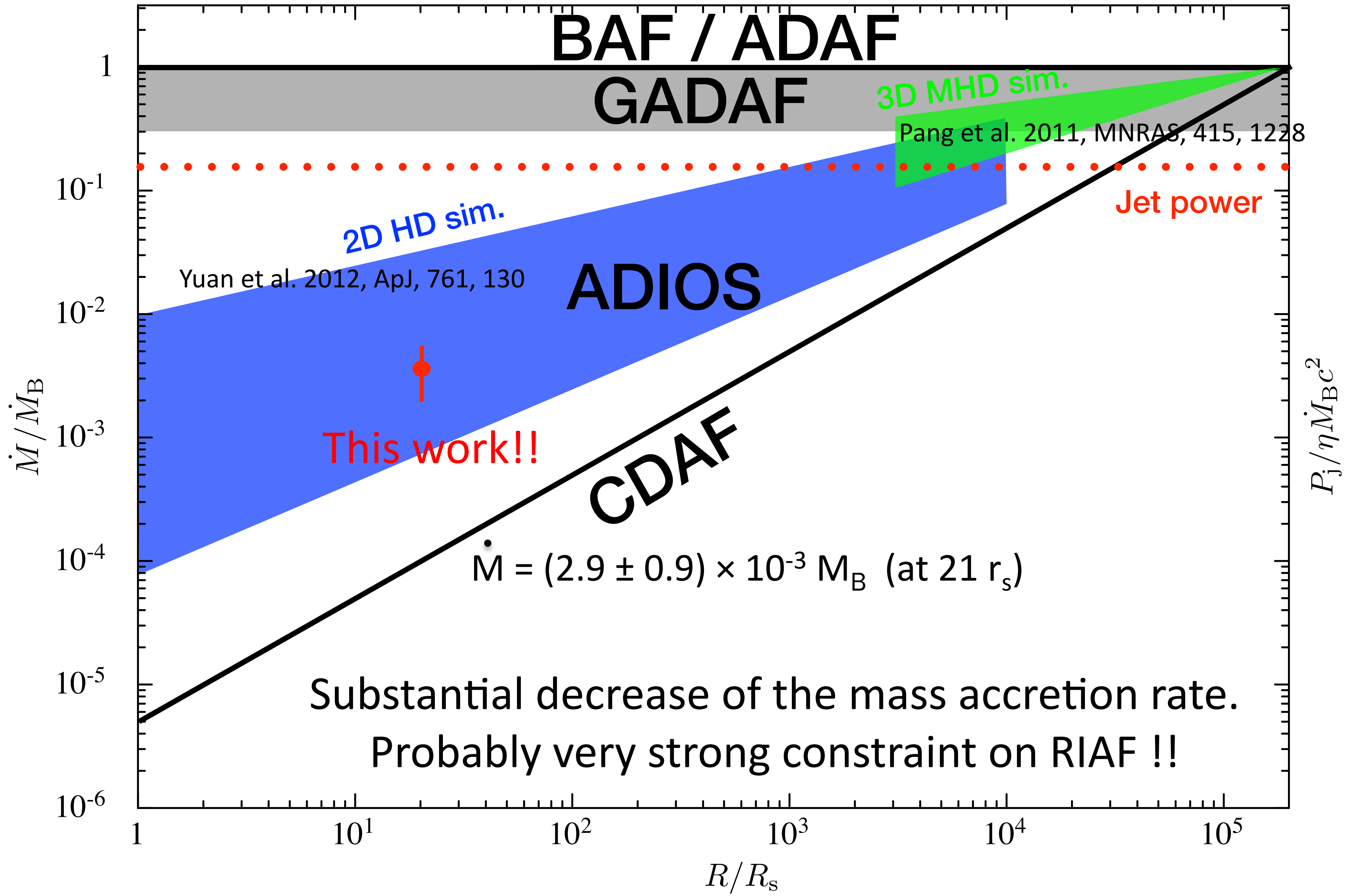
Our **"ALMA band 3"** and "SMA at 230 and 345 GHz" observations were conducted in 2015!!

$$\dot{M} = 1.1 \times 10^{-8} \left[1 - (r_{\rm out}/r_{\rm in})^{-(3\beta-1)/2}\right]^{-2/3} \times \left(\frac{M_\bullet}{6.6 \times 10^{9} M_\odot}\right)^{4/3} \left(\frac{2}{3\beta - 1}\right)^{-2/3} r_{\rm in}^{7/6} RM^{2/3}$$

$$\dot{M} = (3.6 \pm 1.1) \times 10^{-4}\ M_\odot\ \mathrm{yr^{-1}}\ (\text{at } 21\ r_s)$$

$$\dot{M} = (2.9 \pm 0.9) \times 10^{-3}\ M_B\ \ (\text{at } 21\ r_s)$$

# RM fitting towards M 87



# Comparison with Jet Power

Accreting Power :$P_{acc}$ (= $\dot{M}c^2$) ~ 2 × $10^{43}$ erg $s^{-1}$

**Table 3**
Jet Power from the Published Literature

| $L_j$/erg $s^{-1}$ | Ref. |
|---|---|
| $\sim 10^{44}$ | Bicknell & Begelman (1996) |
| $2 \times 10^{43}$ | Reynolds et al. (1996) |
| $\sim 10^{44}$ | Owen et al. (2000) |
| $3 \times 10^{42}$ | Young et al. (2002) |
| $\sim 10^{44}$ | Stawarz et al. (2006) |
| $5 \times 10^{43}$ | Bromberg & Levinson (2008) |

Li+ 2009, ApJ, 699, 513

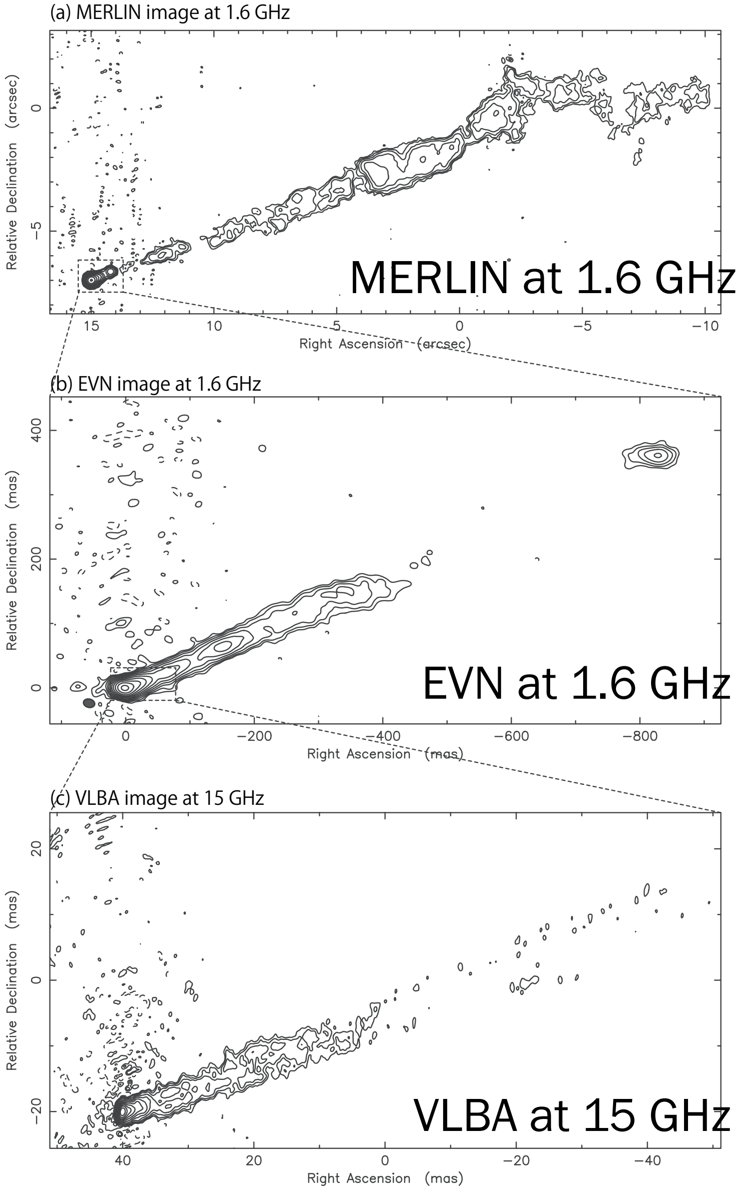
Even if 10 % of $P_{acc}$ used for jet, it's slightly smaller than $L_{jet}$

Another possibilities to support jet power:

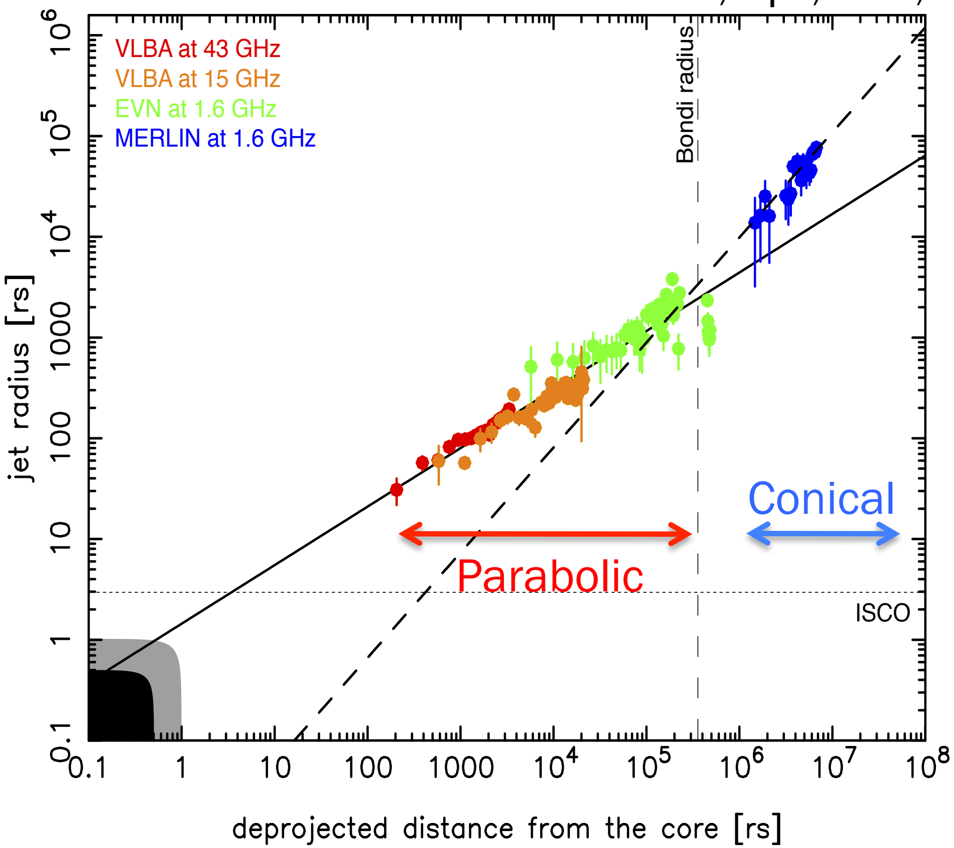
▶ Jet would be supported by "BH spin" !!

# Collimation of M 87 jet

# Revisit structure of M 87 jet



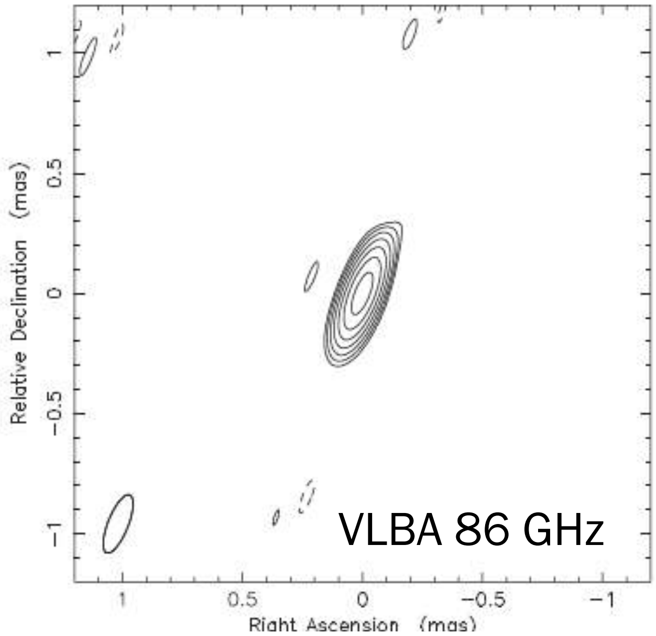

Asada & Nakamura 2012, ApJ, 745, 28

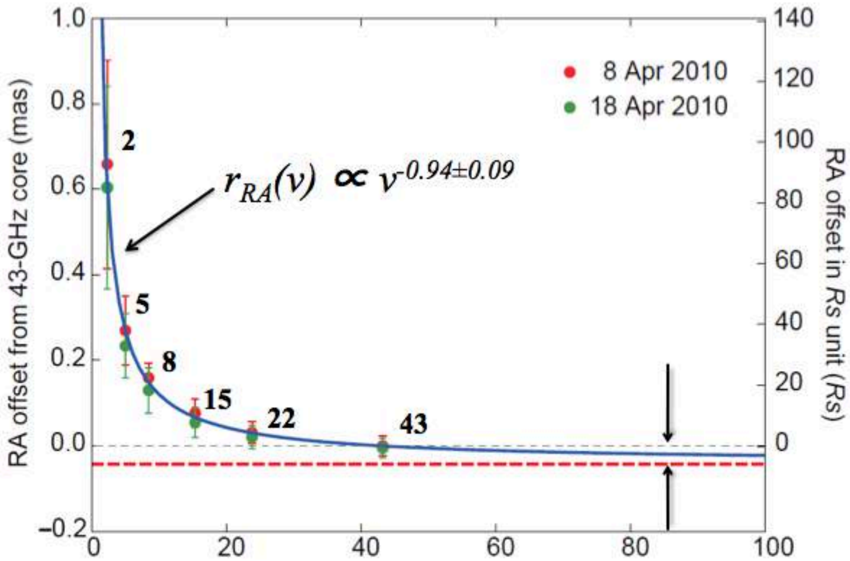



- Jet can described with two power-law lines
  - Parabolic stream with $z = r^{1.7}$ ( - $10^5$ $r_s$)
  - Conical stream with $z = r^1$ ($10^5$ $r_s$ – )

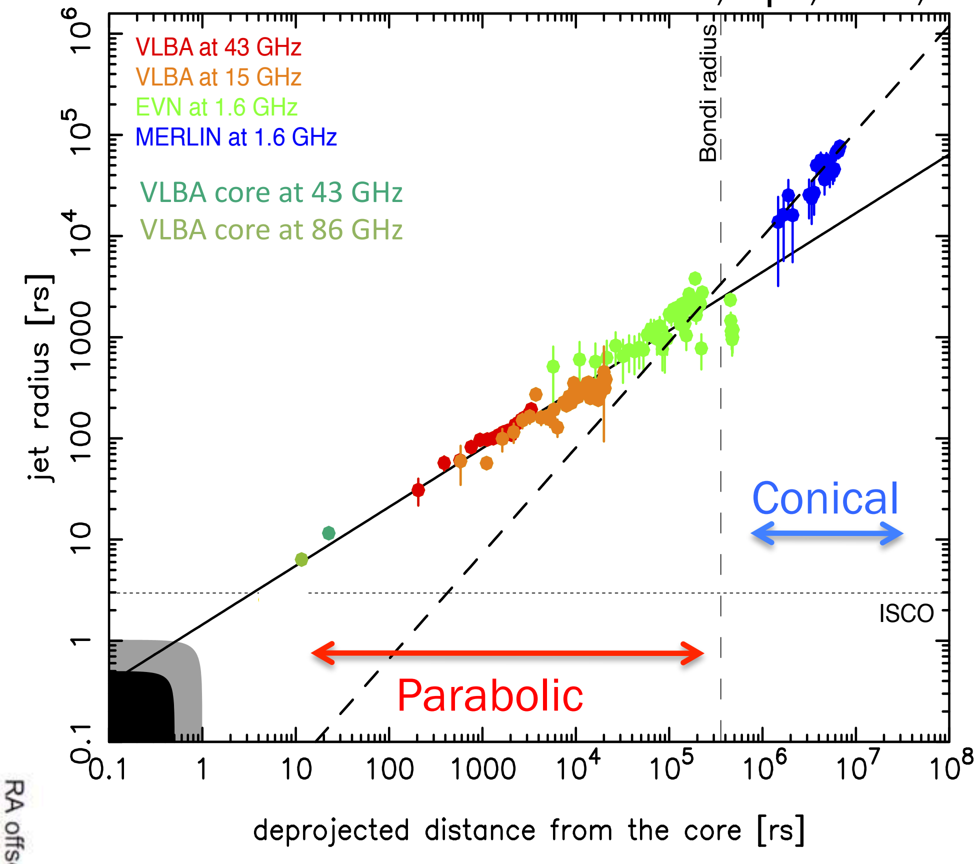
- Transition at ~ $10^5$ $r_s$ !!

# Revisit structure of M 87 jet



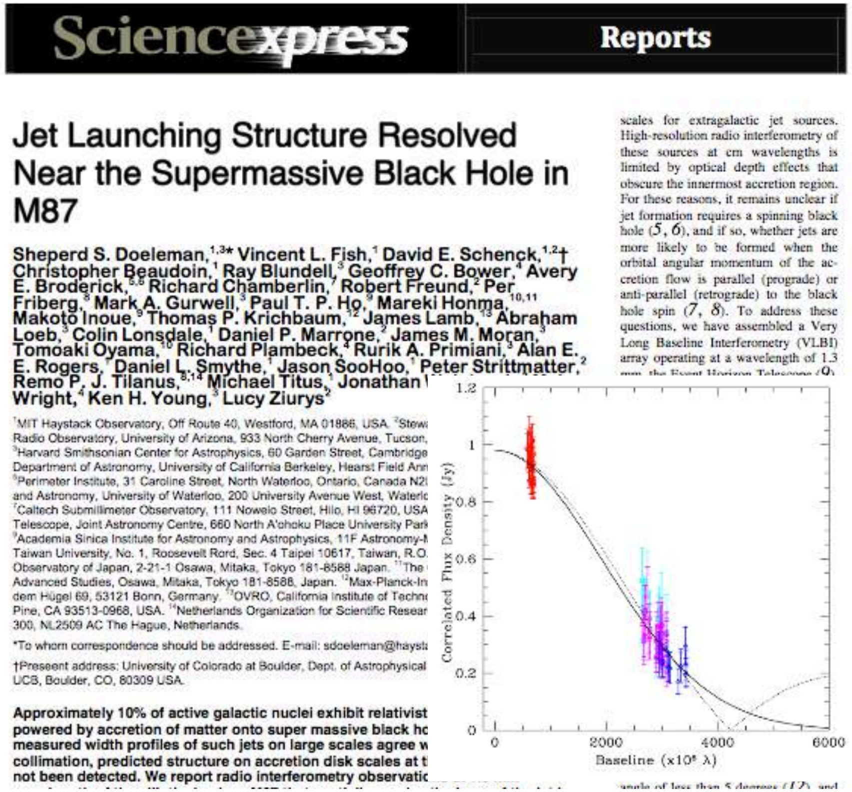

Nakamura and KA 2013, ApJ, 775, 118




- VLBI core = innermost jet with
  τ = 1 surface at observing freq.

# Revisit structure of M 87 jet

Doeleman et al. 2012 Science, 338, 355



Sciencexpress

Reports

## Jet Launching Structure Resolved Near the Supermassive Black Hole in M87

Sheperd S. Doeleman,[1,3]* Vincent L. Fish,[1] David E. Schenck,[1,2]† Christopher Beaudoin,[1] Ray Blundell,[3] Geoffrey C. Bower,[4] Avery E. Broderick,[5,6] Richard Chamberlin,[7] Robert Freund,[2] Per Friberg,[8] Mark A. Gurwell,[3] Paul T. P. Ho,[9] Mareki Honma,[10,11] Makoto Inoue,[9] Thomas P. Krichbaum,[12] James Lamb,[13] Abraham Loeb,[3] Colin Lonsdale,[1] Daniel P. Marrone,[2] James M. Moran,[3] Tomoaki Oyama,[10] Richard Plambeck,[4] Rurik A. Primiani,[3] Alan E. E. Rogers,[1] Daniel L. Smythe,[1] Jason SooHoo,[1] Peter Strittmatter,[2] Remo P. J. Tilanus,[8,14] Michael Titus,[1] Jonathan … Wright,[4] Ken H. Young,[3] Lucy Ziurys[2]

[1]MIT Haystack Observatory, Off Route 40, Westford, MA 01886, USA. [2]Stew…
Radio Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, …
[3]Harvard Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge …
Department of Astronomy, University of California Berkeley, Hearst Field Ann…
[5]Perimeter Institute, 31 Caroline Street, North Waterloo, Ontario, Canada N2…
and Astronomy, University of Waterloo, 200 University Avenue West, Waterlo…
[7]Caltech Submillimeter Observatory, 111 Nowelo Street, Hilo, HI 96720, USA …
Telescope, Joint Astronomy Centre, 660 North A'ohoku Place University Park …
[9]Academia Sinica Institute for Astronomy and Astrophysics, 11F Astronomy-…
Taiwan University, No. 1, Roosevelt Rord, Sec. 4 Taipei 10617, Taiwan, R.O. …
Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588 Japan. [11]The …
Advanced Studies, Osawa, Mitaka, Tokyo 181-8588, Japan. [12]Max-Planck-In…
dem Hügel 69, 53121 Bonn, Germany. [13]OVRO, California Institute of Techn…
Pine, CA 93513-0968, USA. [14]Netherlands Organization for Scientific Resear…
300, NL2509 AC The Hague, Netherlands.

*To whom correspondence should be addressed. E-mail: sdoeleman@hayst…

†Preseent address: University of Colorado at Boulder, Dept. of Astrophysical …
UCB, Boulder, CO, 80309 USA.

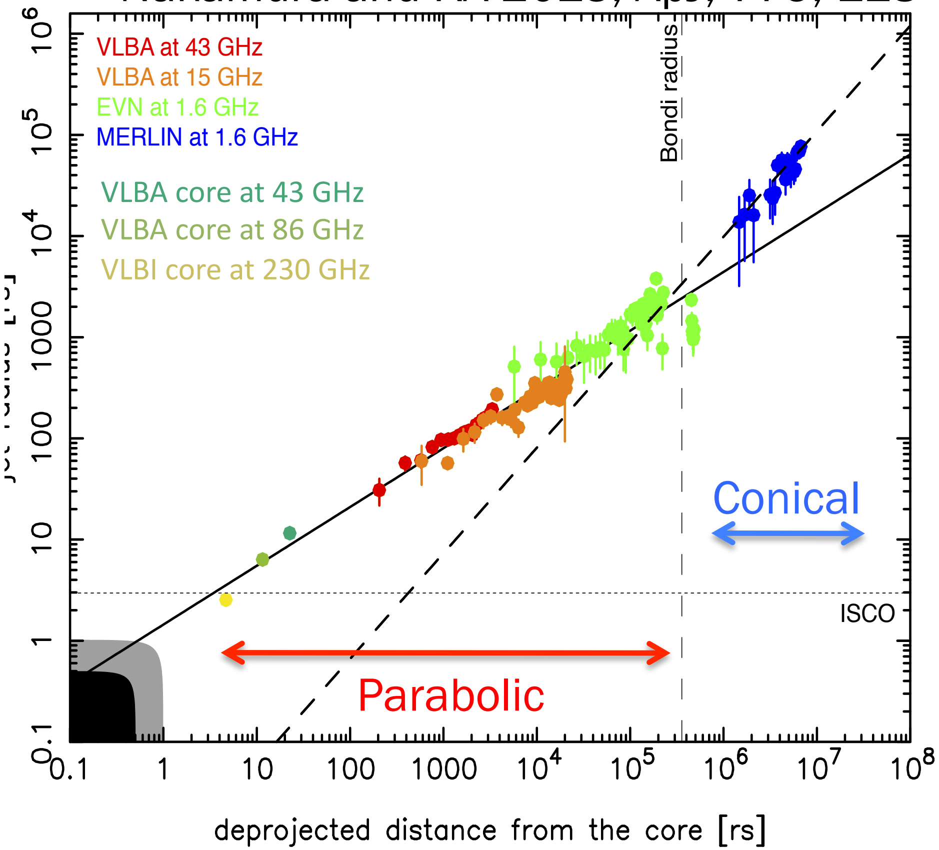
**Approximately 10% of active galactic nuclei exhibit relativist… powered by accretion of matter onto super massive black h… measured width profiles of such jets on large scales agree w… collimation, predicted structure on accretion disk scales at t… not been detected. We report radio interferometry observati…**

scales for extragalactic jet sources. High-resolution radio interferometry of these sources at cm wavelengths is limited by optical depth effects that obscure the innermost accretion region. For these reasons, it remains unclear if jet formation requires a spinning black hole (5, 6), and if so, whether jets are more likely to be formed when the orbital angular momentum of the accretion flow is parallel (prograde) or anti-parallel (retrograde) to the black hole spin (7, 8). To address these questions, we have assembled a Very Long Baseline Interferometry (VLBI) array operating at a wavelength of 1.3 …



Size ~ 40 μas

Nakamura and KA 2013, ApJ, 775, 118

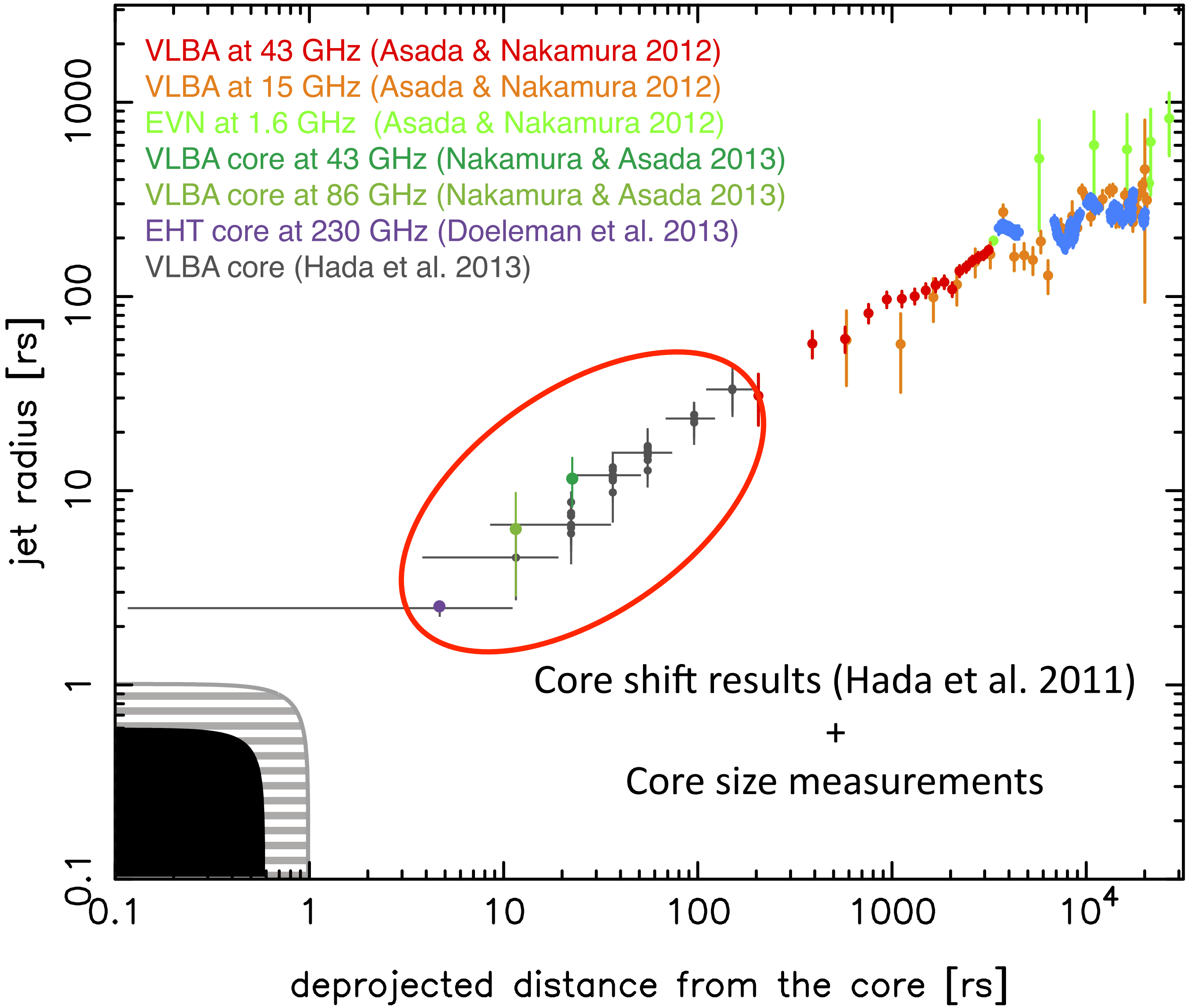




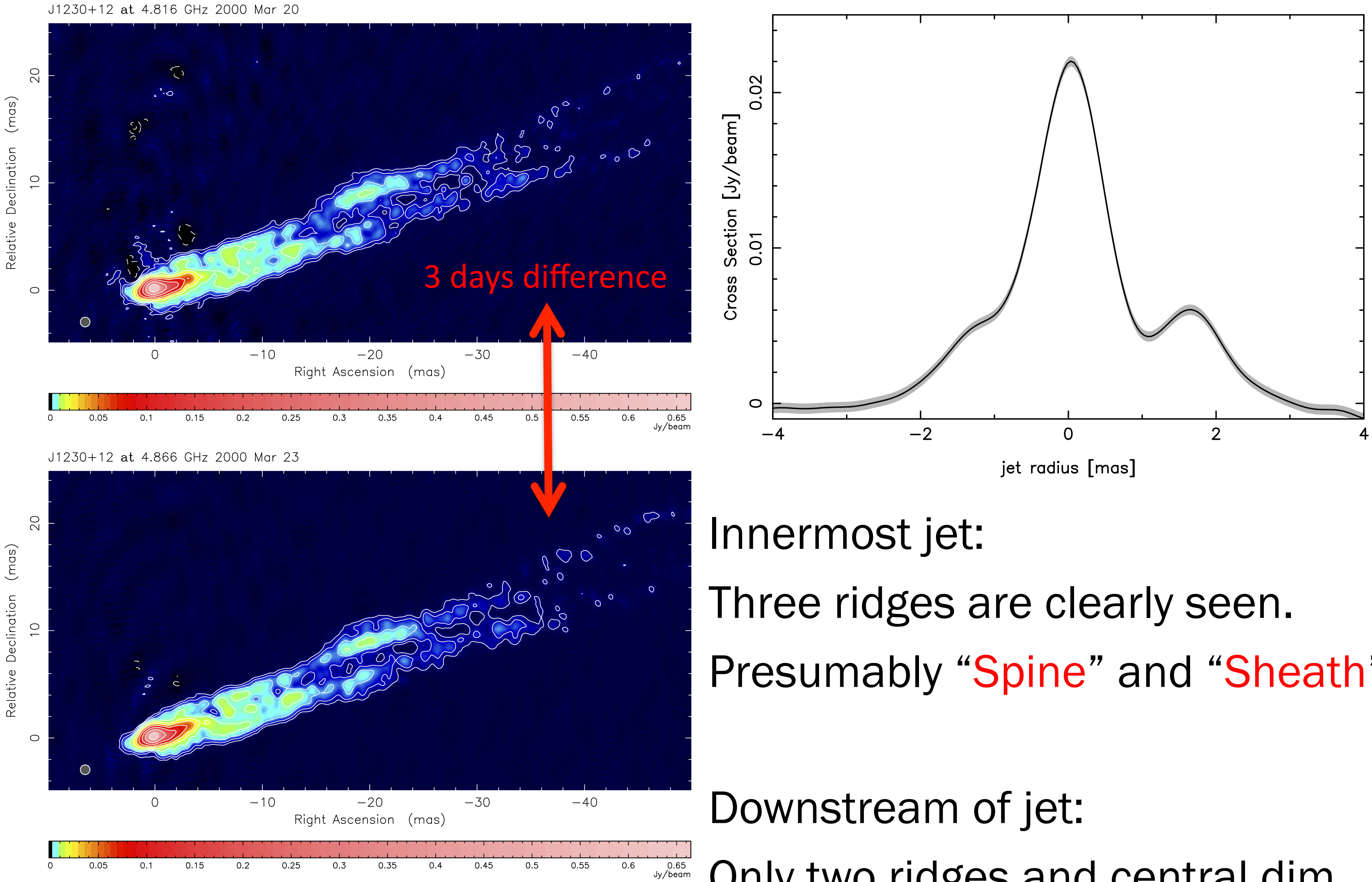
- VLBI core = innermost jet with $\tau$ = 1 surface at observing freq.

- Same power-law index for 6 order !!

# Revisit structure of M 87 jet



# VSOP images




Innermost jet:

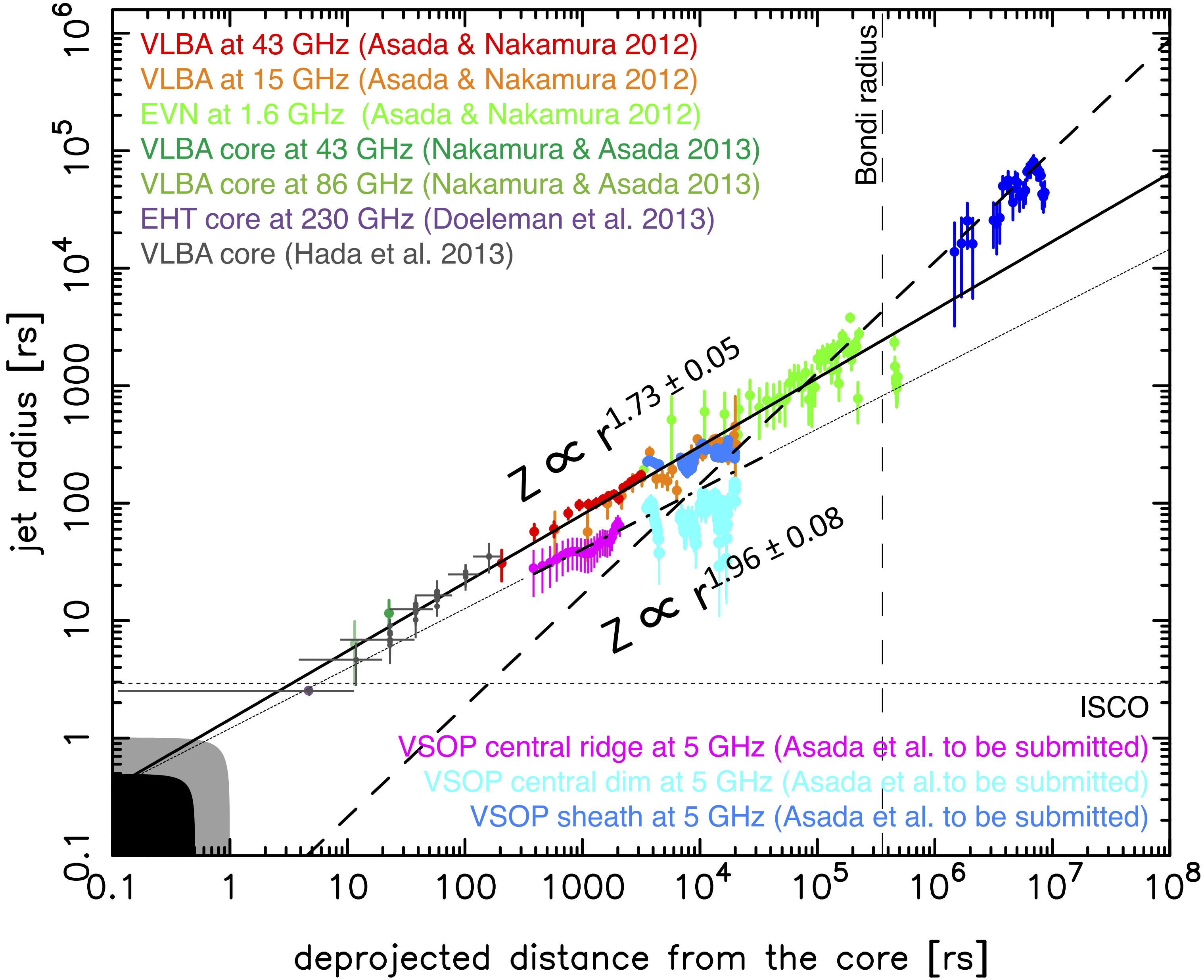
Three ridges are clearly seen.

Presumably “Spine” and “Sheath”.

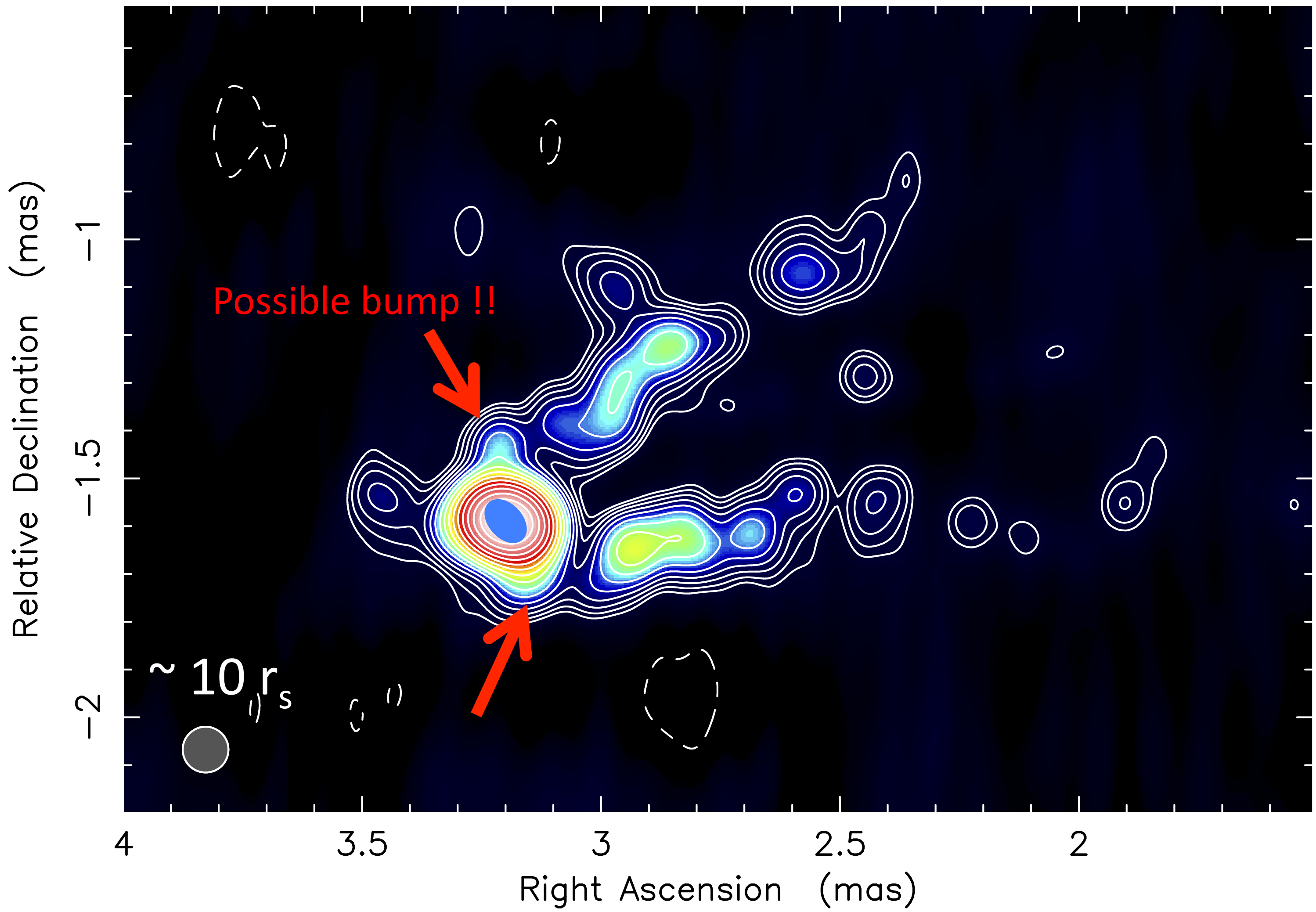
Downstream of jet:

Only two ridges and central dim.

# Updated Streamline with VSOP image

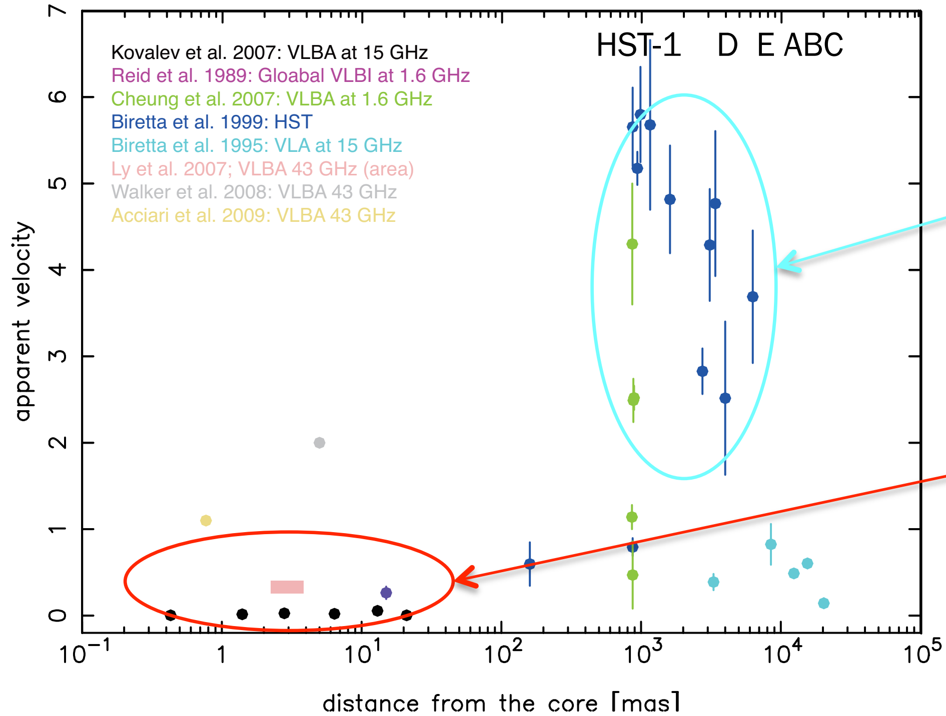


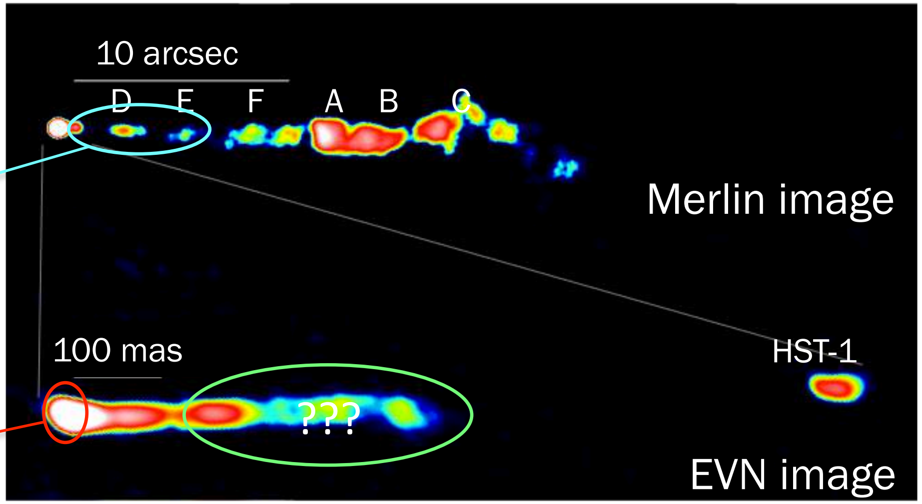
# GMVA image


Possible bump !!
~ 10 $r_s$
Relative Declination (mas)
−1
−1.5
−2
4
3.5
3
2.5
2
Right Ascension (mas)

# Acceleration of M 87 jet

# Velocity Field of the M 87 jet




HST monitoring (Biretta+99)
0.84 - 6.14 c (for HST-1)
2.7 - 5.1 c (for knot D)
3.9 c (for knot E)

VLA monitoring (Biretta+95)
0.41 - 2.51 c (for knot D)
0.48 - 0.51 c (for knot A)
0.62 - 1.25 c (for knot B)

VLBI monitoring (Reid+89)
0.28 c (knot L)

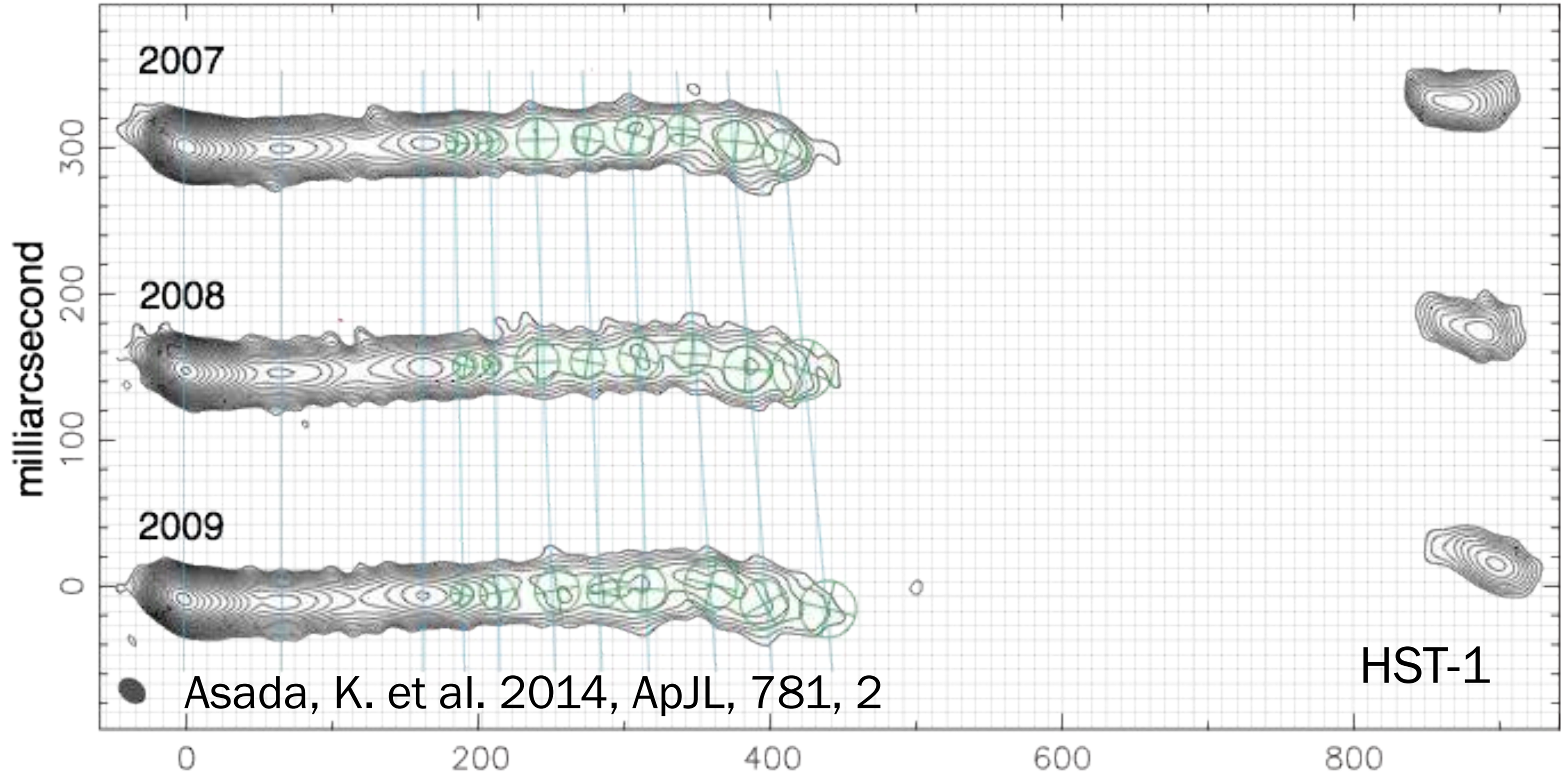
VLBA monitoring (Junor & Biretta 95)
0.01 c (< 21 mas)

VLBA monitoring (Kovalev+07)
0.00 - 0.05 c (< 21 mas)

VLBA monitoring (Chueng+07)
0.47 - 4.3 c (HST-1)

# EVN observations

Three epoch EVN and Merlin observations at 1.6 GHz
from 2007 March to 2009 March.



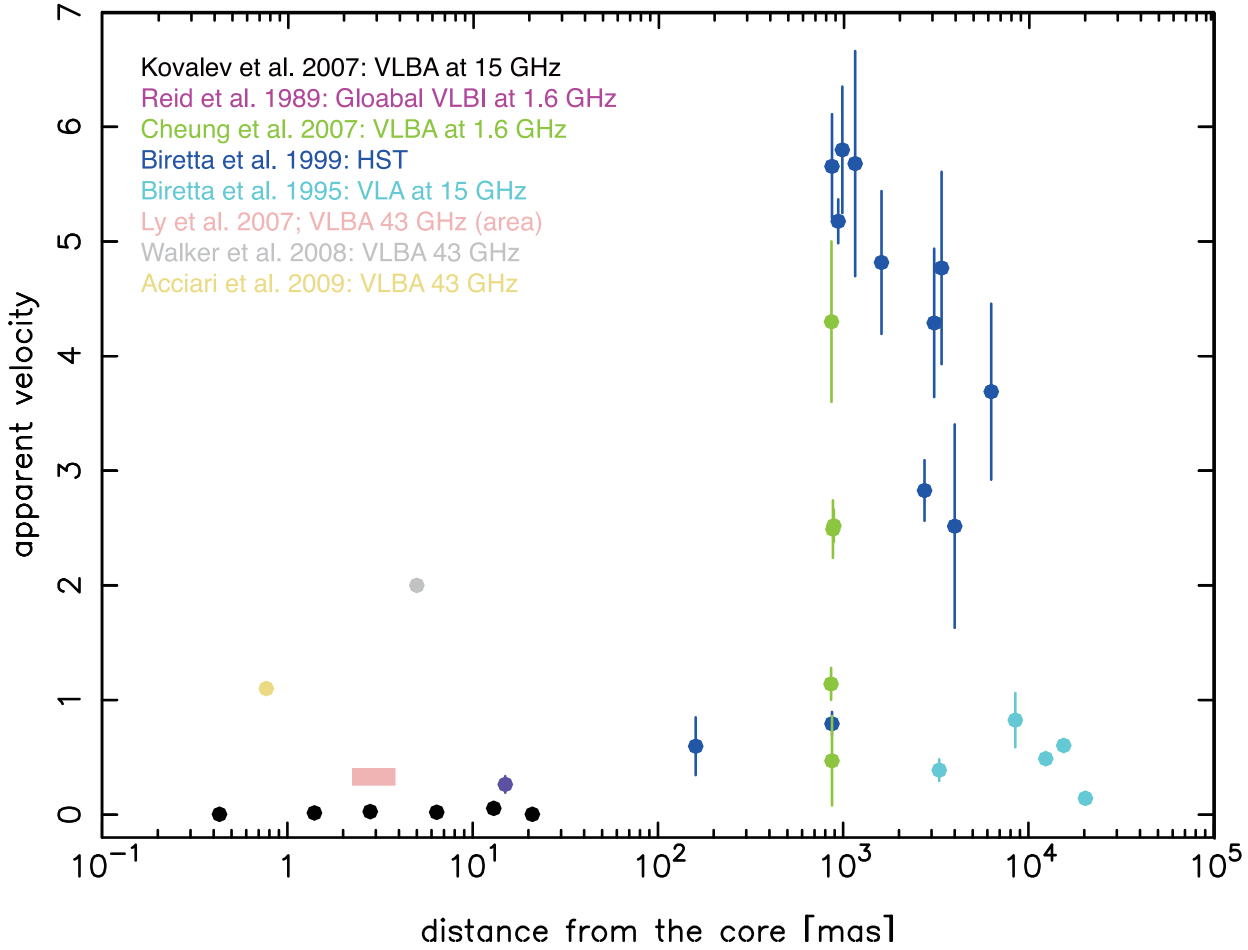

No proper motions within 160 mas from the core.

Superluminal motions of 2.5 - 3.5 c in HST-1 region.

Detection of proper motions between 160 mas and HST-1 !!

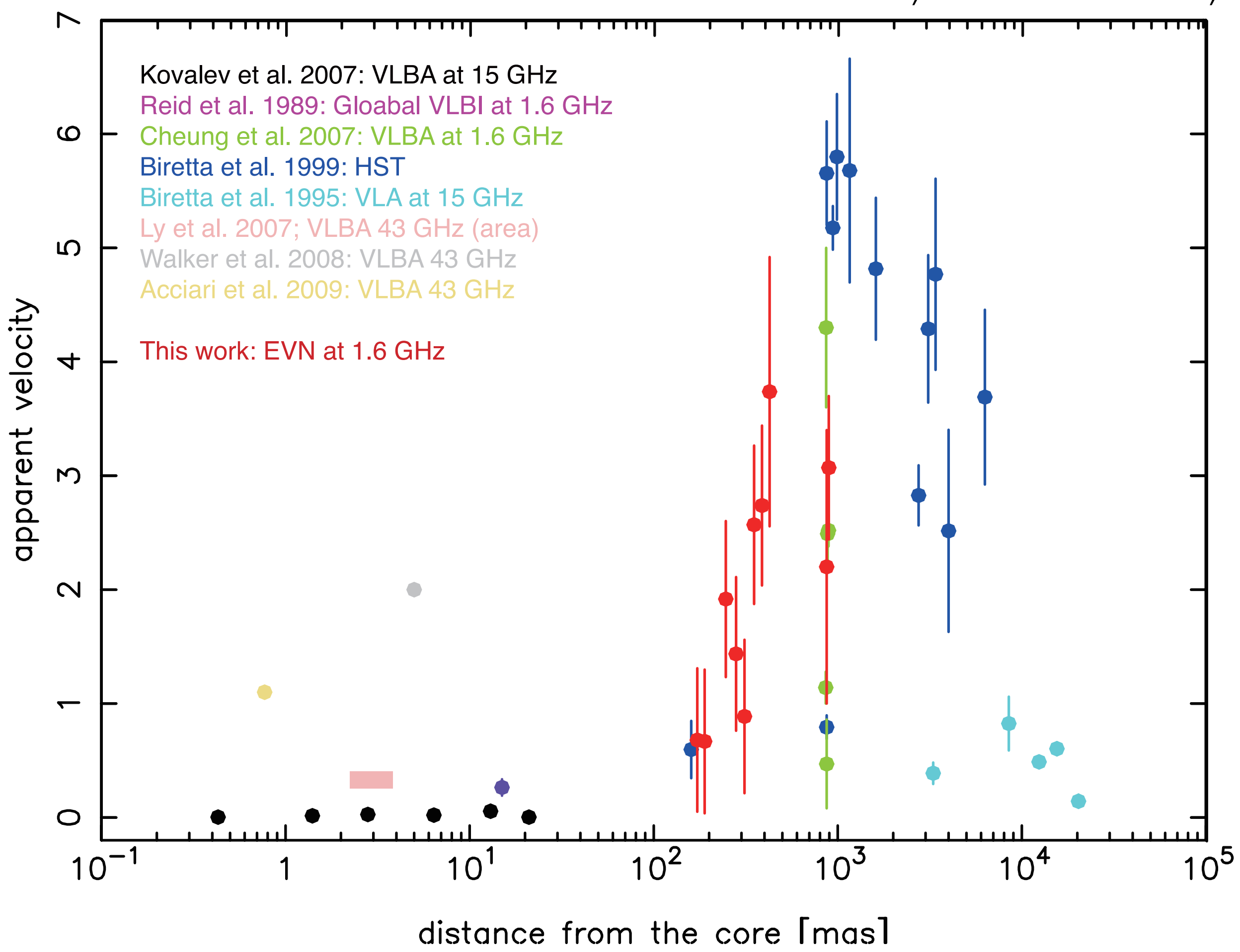
# Updated Velocity Field of M 87 jet

Asada, K. et al. 2014, ApJL, 781, 2



# Updated Velocity Field of M 87 jet

Asada, K. et al. 2014, ApJL, 781, 2

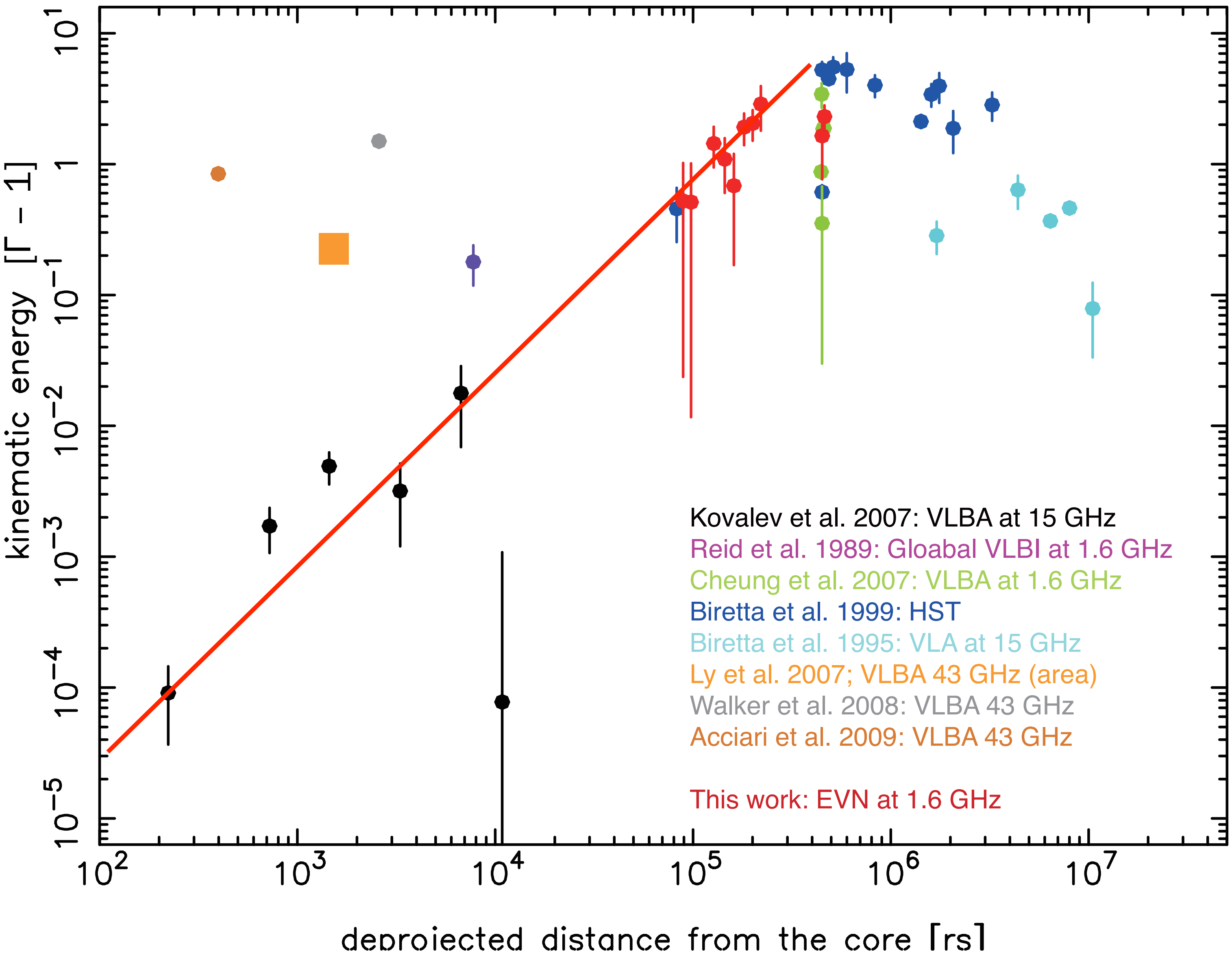



Superluminal motions upstream of HST-1 for the first time !!

This velocity field is a direct evidence for the acceleration region !!

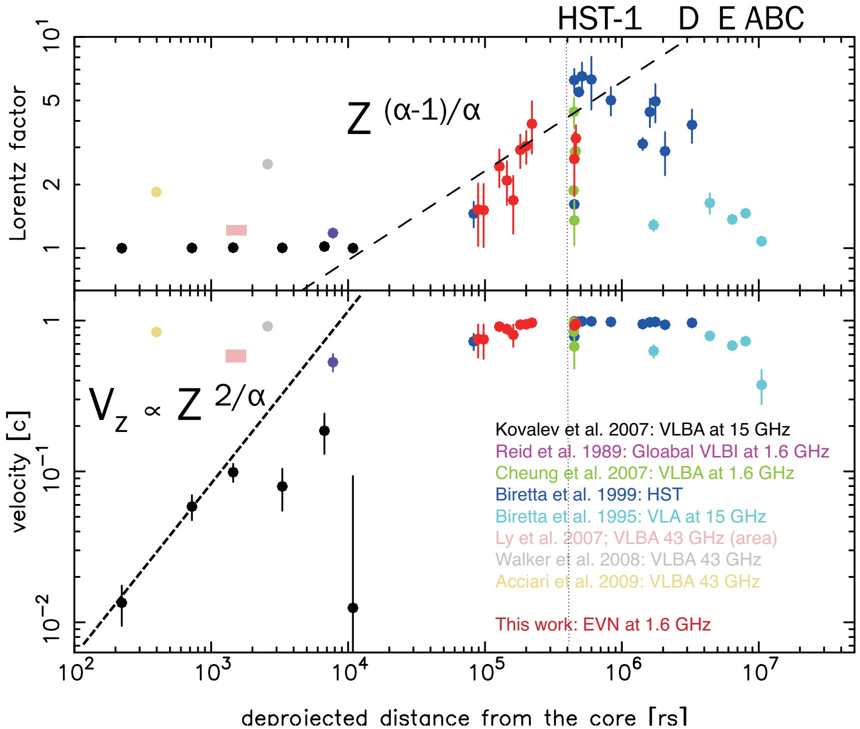
# Updated Velocity Field of M 87 jet

Asada, K. et al. 2014, ApJL, 781, 2

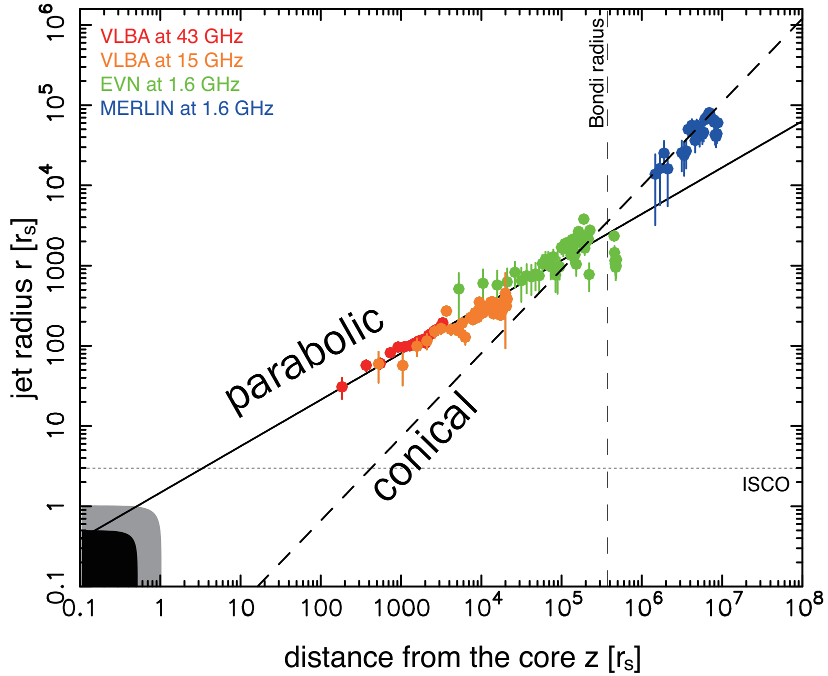


# Streamline and Acceleration of the jet

Asada, K. et al. 2014, ApJL, 781, 2




Asada & Nakamura 2012, ApJ, 745, 28




α: power-law index of streamline (= 1.7)

In relativistic regime,

$$\Gamma \propto Z^{(\alpha-1)/\alpha}$$

Komissarov et al. 2009 MNRAS, 394, 1182

In non- relativistic regime,

$$V_z \propto Z^{2/\alpha}$$

Nakamura & Asada 2013, ApJ,

# Summary

# Summary

- SMA polarimetry to measure RM associated with AF of M 87
- M is estimated to be $3.6 \pm 1.1 \times 10^{-4}\ M_{\odot}\ yr^{-1}$
- M is substantially decreased, consistent with CDAF/ADIOS
- Accreting Power may not be enough to support Kinetic Power of Jet.

- VLBI observations to probe acceleration and collimation properties
- Parabolic streamline up to $10^5\ r_s$, while conical streamline beyond.
- Transition is corresponds to Bondi radius
- Gradual acceleration of proper motions up to $10^5\ r_s$ as well.
- Simultaneous acceleration  and collimation indicates MHD mechanism

Extra

# The same food with different way of eating

Japanese way

Italian way

German way