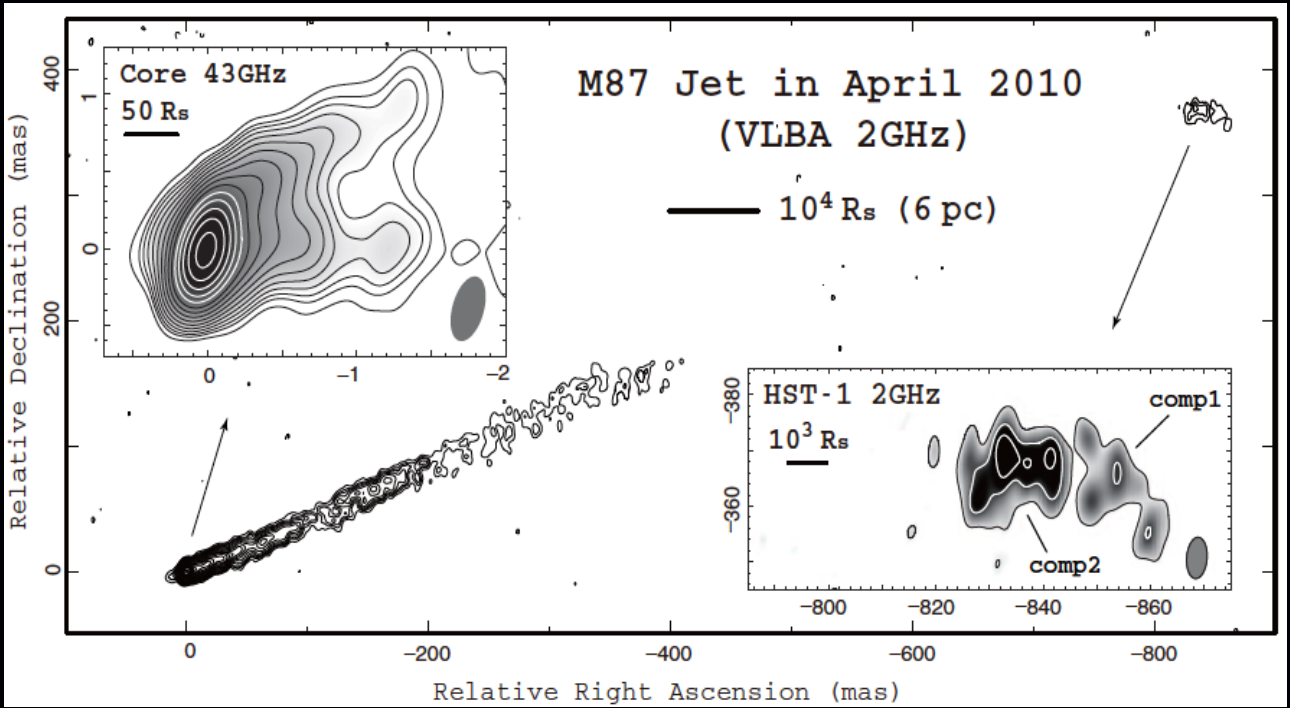
Probing the inner jet of M87 from the jet base to HST-1



Hada et al. 2012

和 弘 秦

Kazu-hiro Hada (IRA/NAOJ)

"The innermost regions of relativistic jets and their magnetic fields"

June 10-14 2013, Granada, Spain

Collaborators

- A.Doi(JAXA), M.Kino(JAXA), H.Nagai(NAOJ), M.Honma(NAOJ), Y.Hagiwara(NAOJ), N.Kawaguchi(NAOJ), K.Niinuma(Yamaguchi U.), T.Haga(JAXA), F.Takahara(Osaka U.)
- G.Giovannini(IRA), M.Giroletti(IRA), M.Orienti(IRA), C.Casadio(IAA), J.L.Gomez(IAA), C.C.Cheung(NRL) M.Beilicke(Washington U.), A.Cesarini(NUI), H.Krawczynski(Washington U.), N.P.Lee(SAO)

and many others

Outline

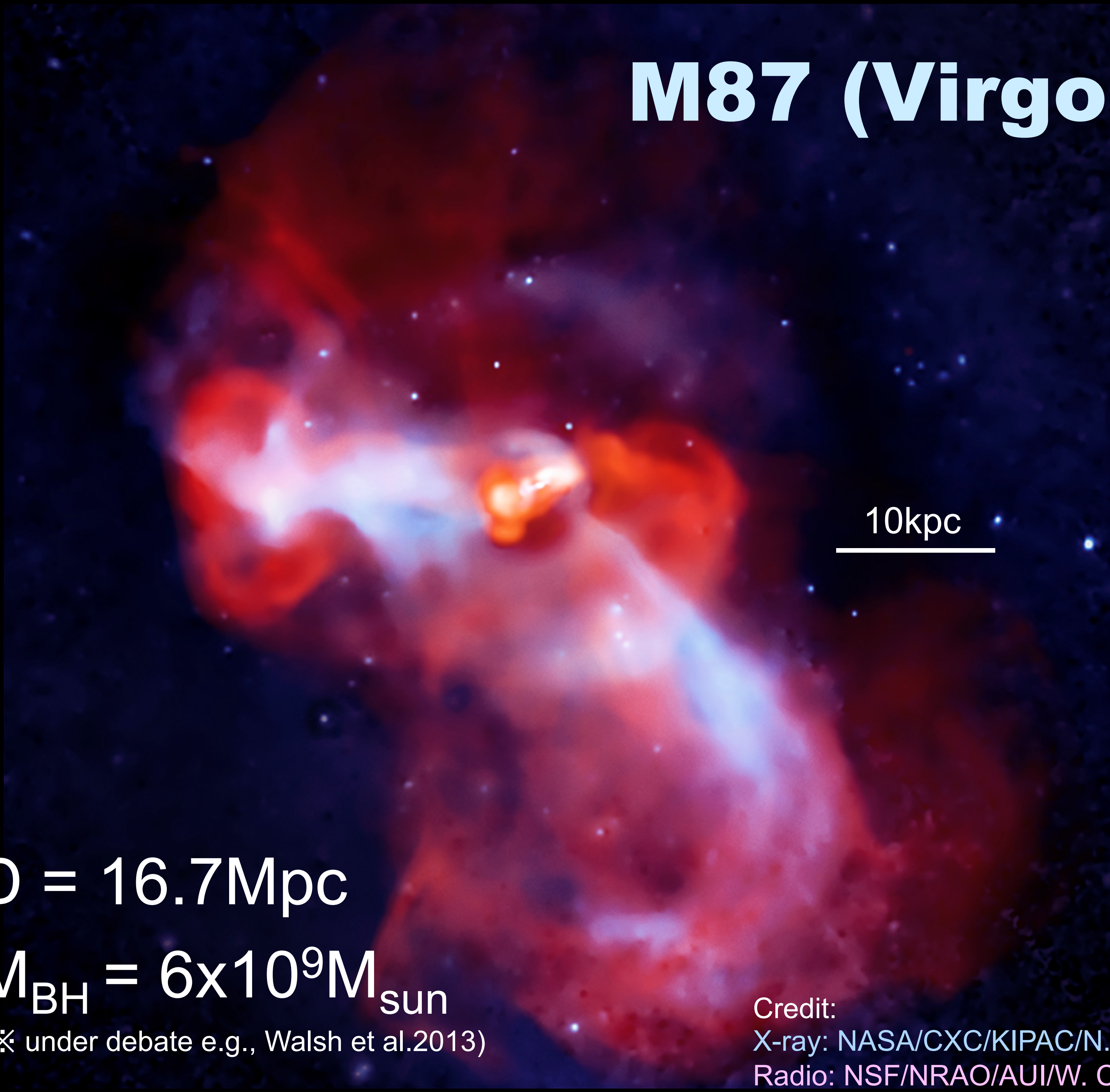
Overview our several ongoing projects for M87 inner jet

- Motivation - why M87?

1. Multi-frequency VLBI approach - core location, jet collimation
2. Multi-epoch VLBI approach - TeV sites, jet kinematics
   - HST-1 monitor with EVN
   - Core/jet base monitor with VERA
3. Further related studies for M87 and other sources
   - M87 with ALMA
   - Poynting dominated vs kinetic dominated at M87 jet base
   - Core shift astrometry for two-sided jet sources

- Summary

M87 (Virgo A)

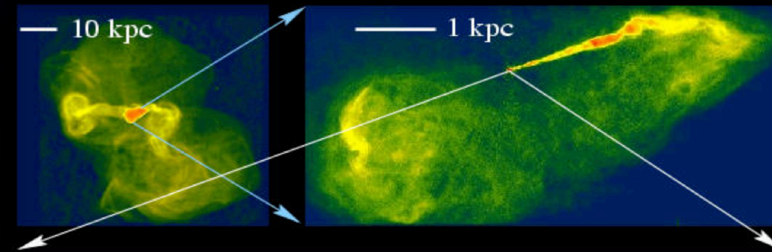


- D = 16.7Mpc
- $M_{BH} = 6 \times 10^9 M_{sun}$
  (※ under debate e.g., Walsh et al.2013)

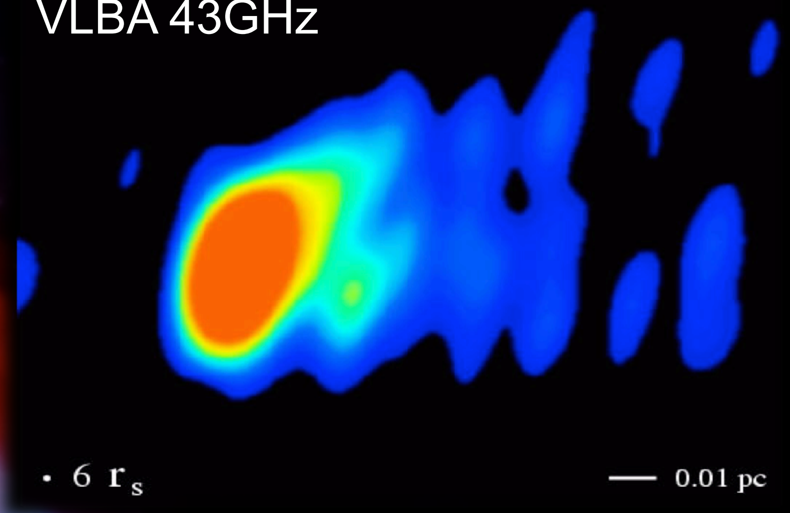
Credit:
X-ray: NASA/CXC/KIPAC/N. Werner et al
Radio: NSF/NRAO/AUI/W. Cotton

Why M87?

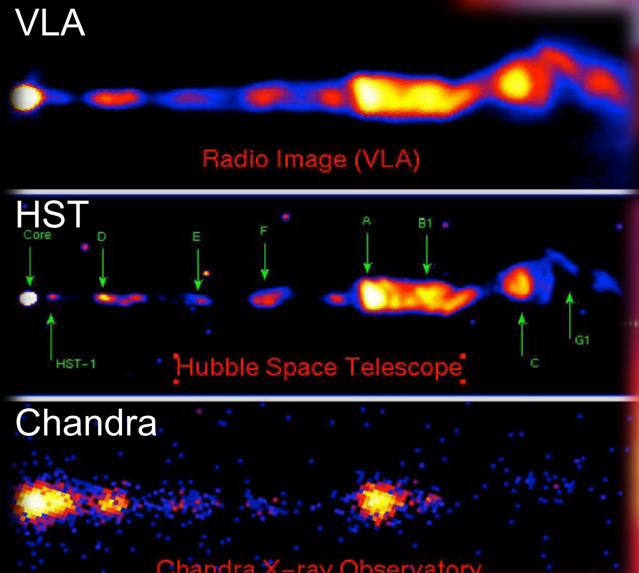
- **1mas = 0.08pc = 140Rs, 1*c* = 4mas/yr**
- VLBI can resolve/image <100Rs scale
- Accurate kinematic measurements
- Bright, well-studied jet from radio to X-ray
- TeV flares, GeV/MeV steady detections



VLBA 43GHz

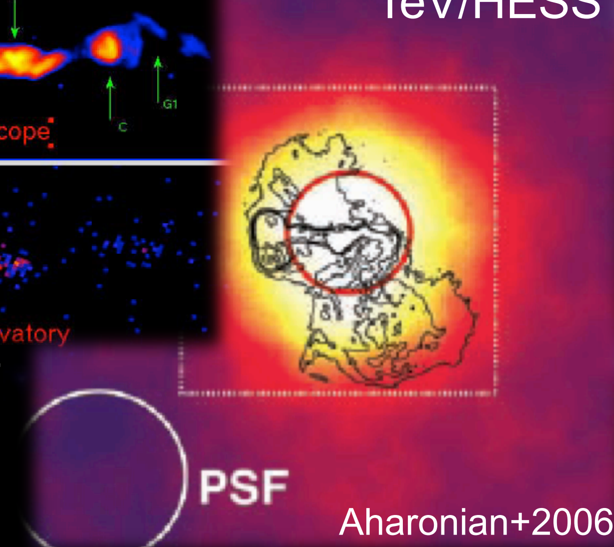


Junor+ 1999



Radio: F.Zhou, F.Owen (NRAO), J.Biretta (STScI)
Optical: NASA/STScI/UMBC/ E.Perlman et al.
X-ray: NASA/CXC/MIT/ H.Marshall et al.

TeV/HESS



Aharonian+2006

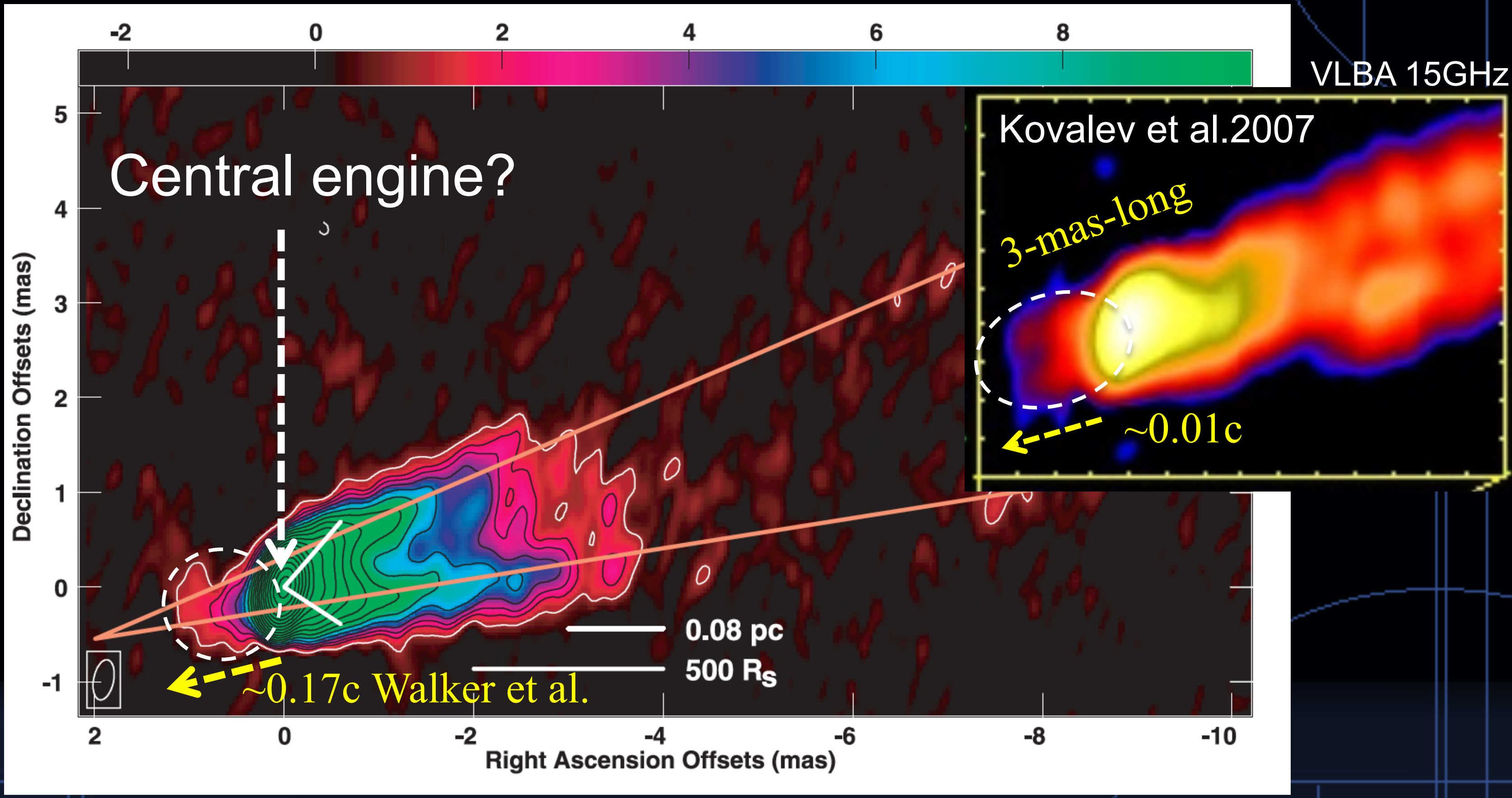
- Better observational constraints on
  - Jet launch/collimation
  - Kinematics
  - Origin/Location of γ-ray

1. Multi-frequency VLBI approach

- Core location (Hada+2011)
- Jet collimation profile (current progress)

Location of the M87 core

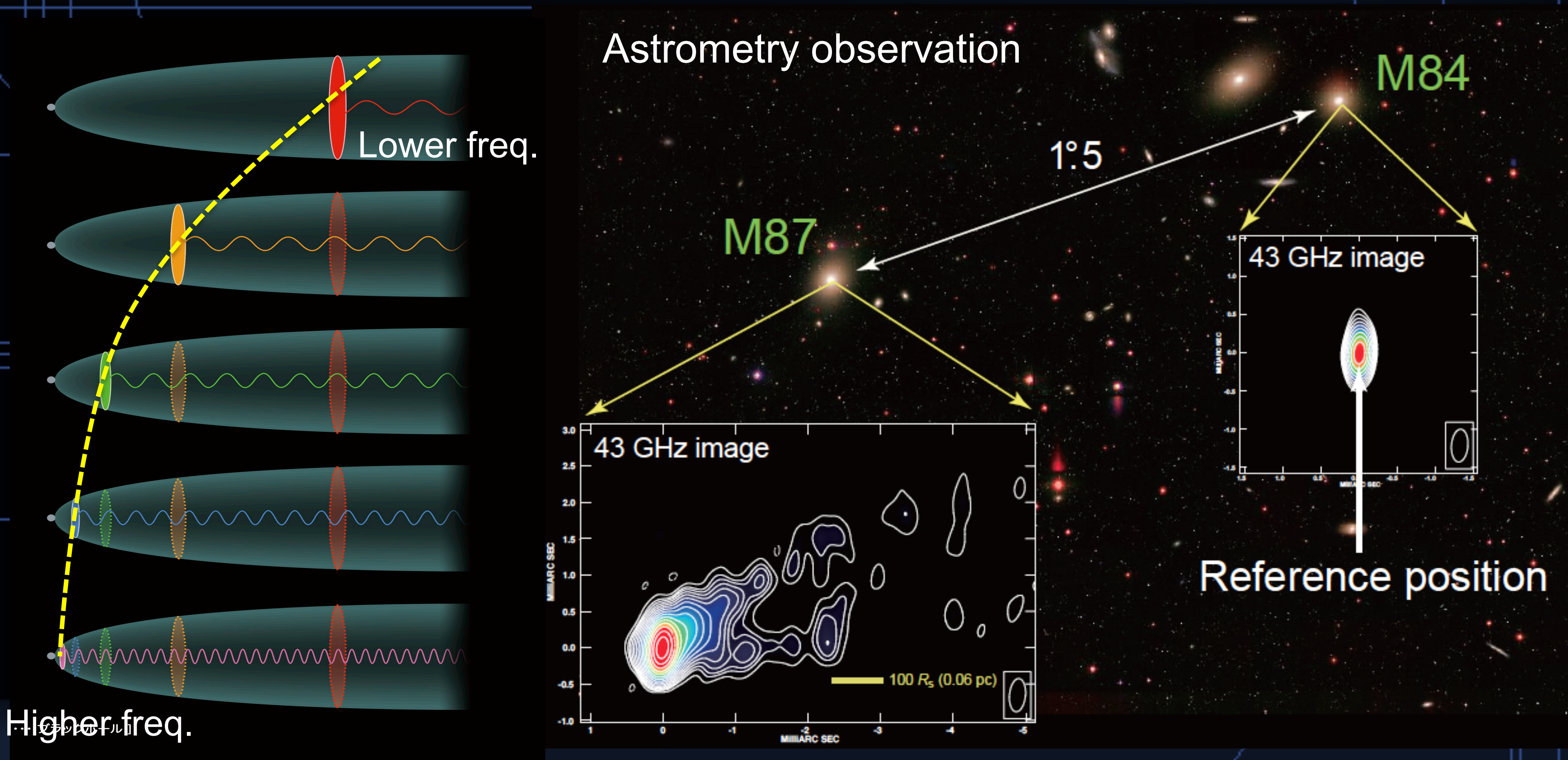
Ly, Walker, Junor 2007



- Radio core: a surface of synchrotron-self-absorption (τ_{ssa}~1) or a standing shock feature
- Large BH-core offsets (10^{4-6}Rs) for some blazars (eg, BLLac; Marscher et al. 2008)

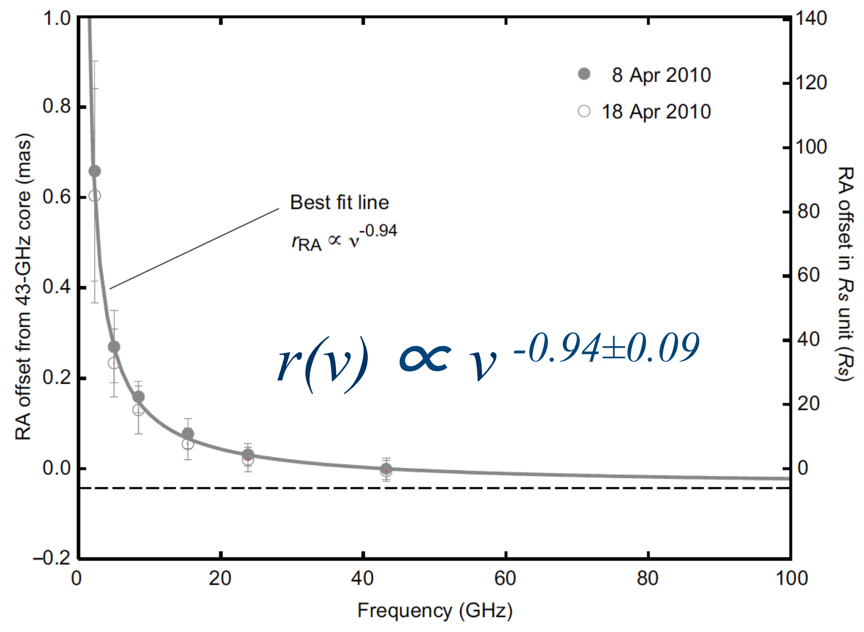
Walker et al.

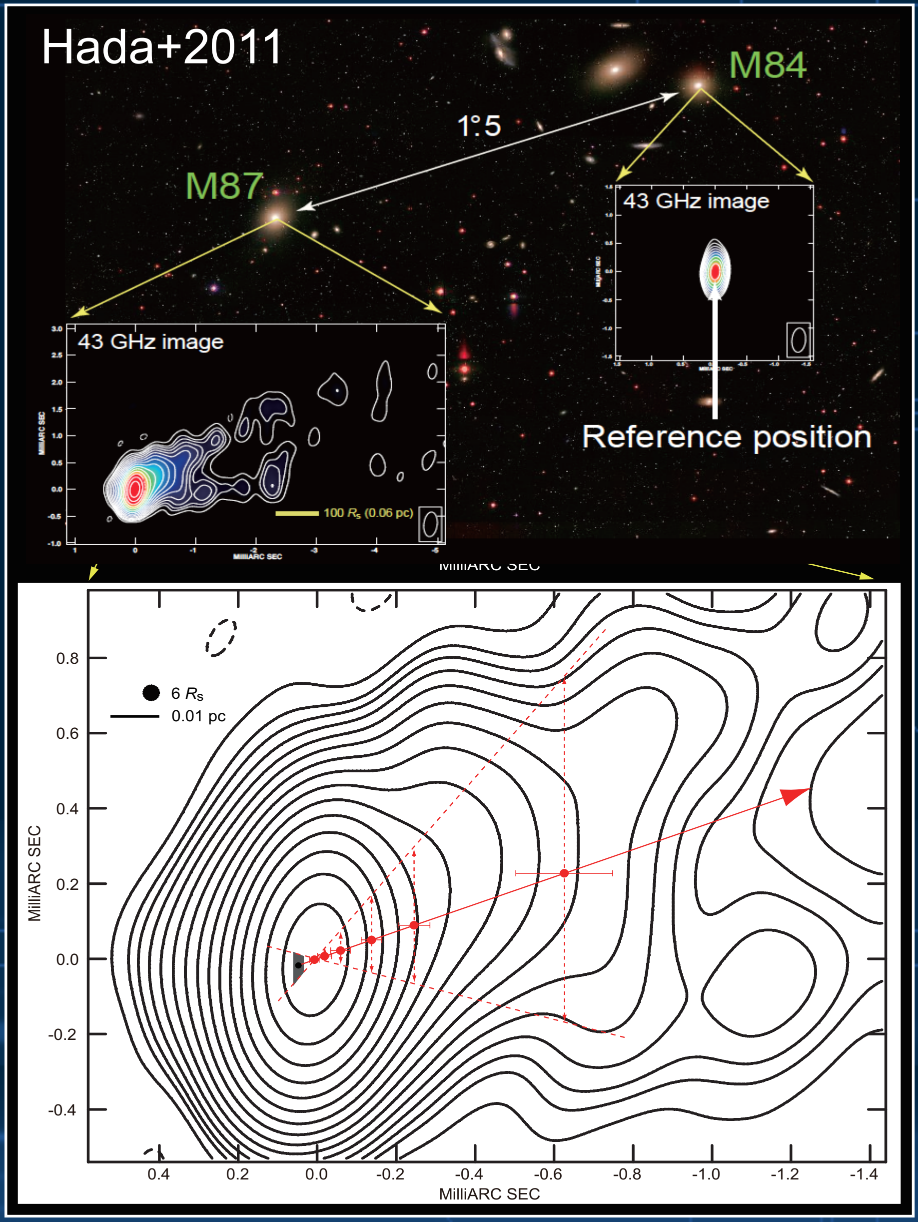
Approaching the BH:
Core shift measurements with multi-ν astrometry



- $\tau_{ssa}\sim 1$ surface approaches BH at higher frequencies
- Astrometry achieves tens of μas position accuracy
  - ~10Rs scale for M87

- VLBA @ 2,5,8,15,22,43GHz
- Stable reference M84

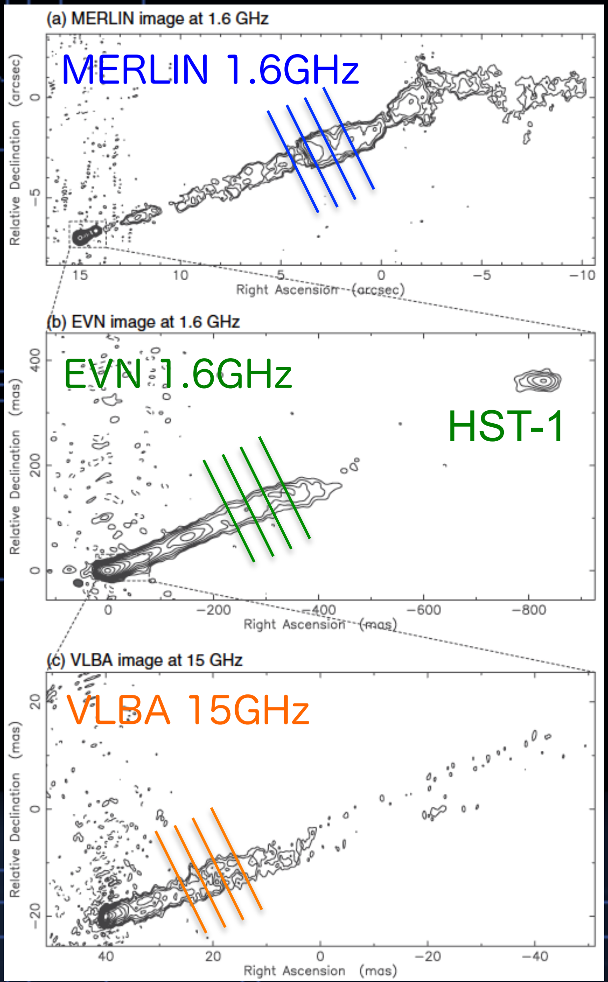


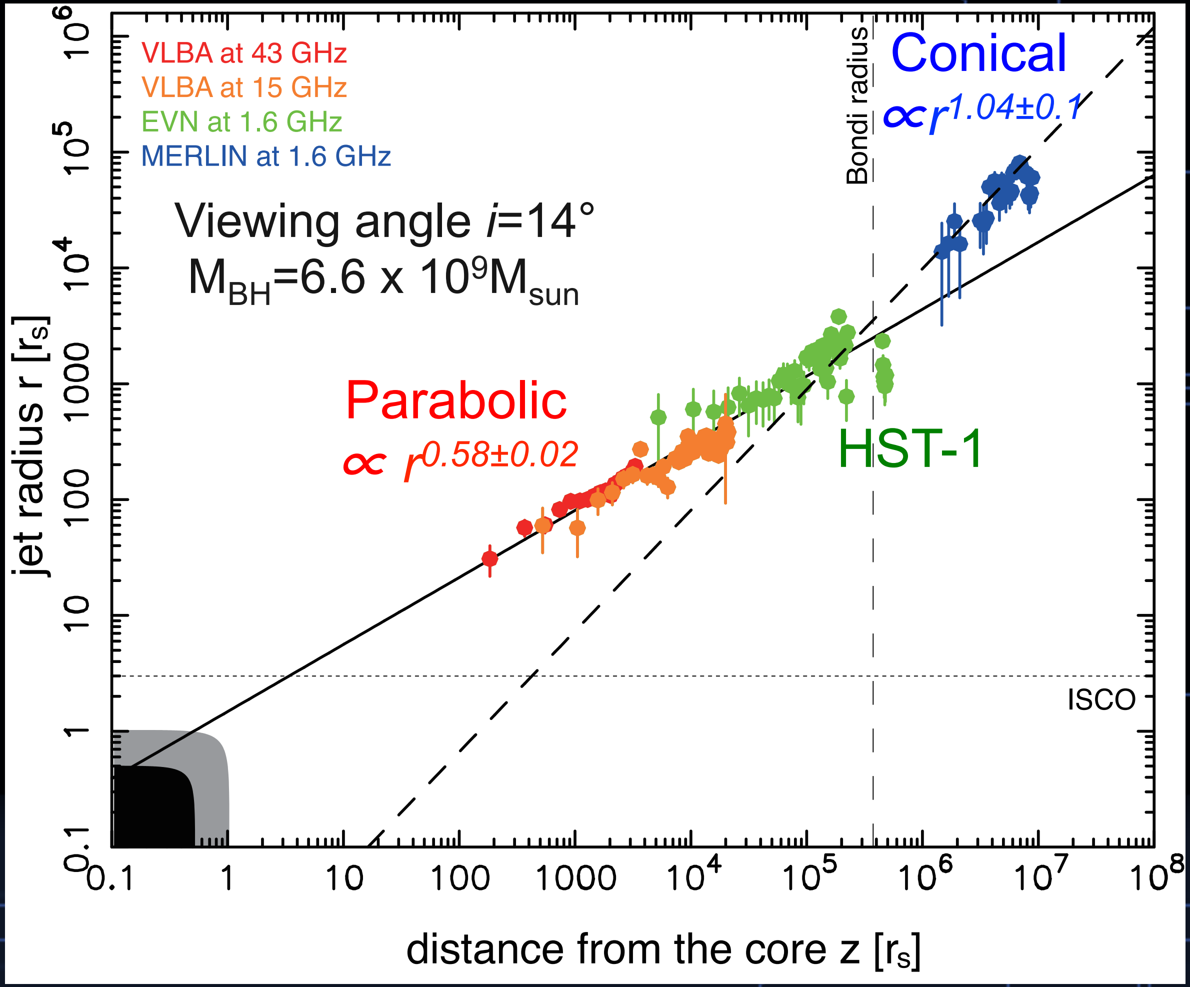


- Core shift converges ~14-23Rs upstream of the 43GHz core (de-projected distance for jet inclination *I* = 15°-25°)
- Consistent with the counter jet detections/motions
- Core-BH separation: large difference between M87 and some other sources
  - Useful to investigate other nearby sources (end of talk)

The structure of M87 jet

Asada&Nakamura 2012

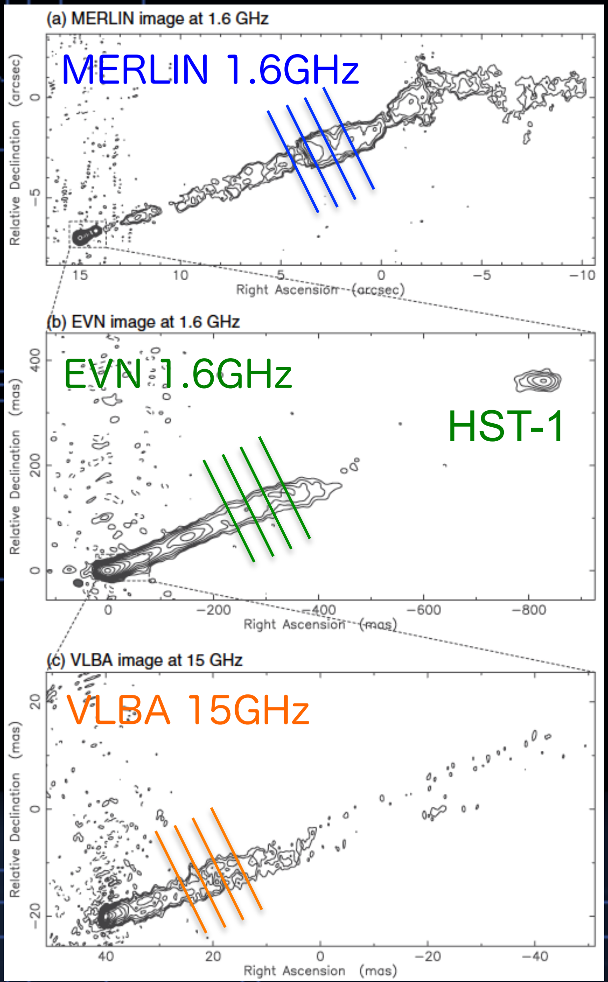


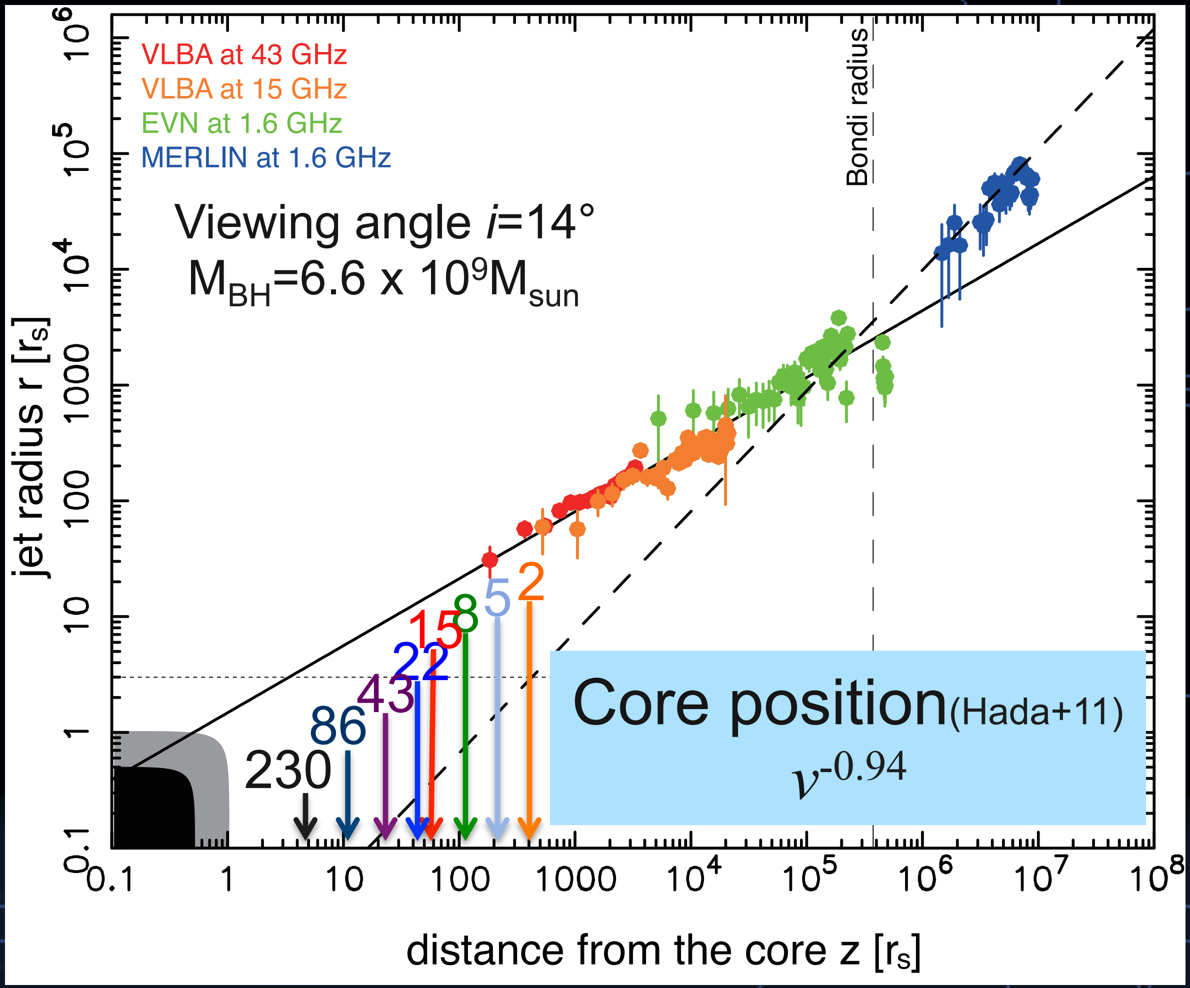


Parabolic profile between ~100 and ~10^5Rs from BH

The structure of M87 jet

Asada&Nakamura 2012

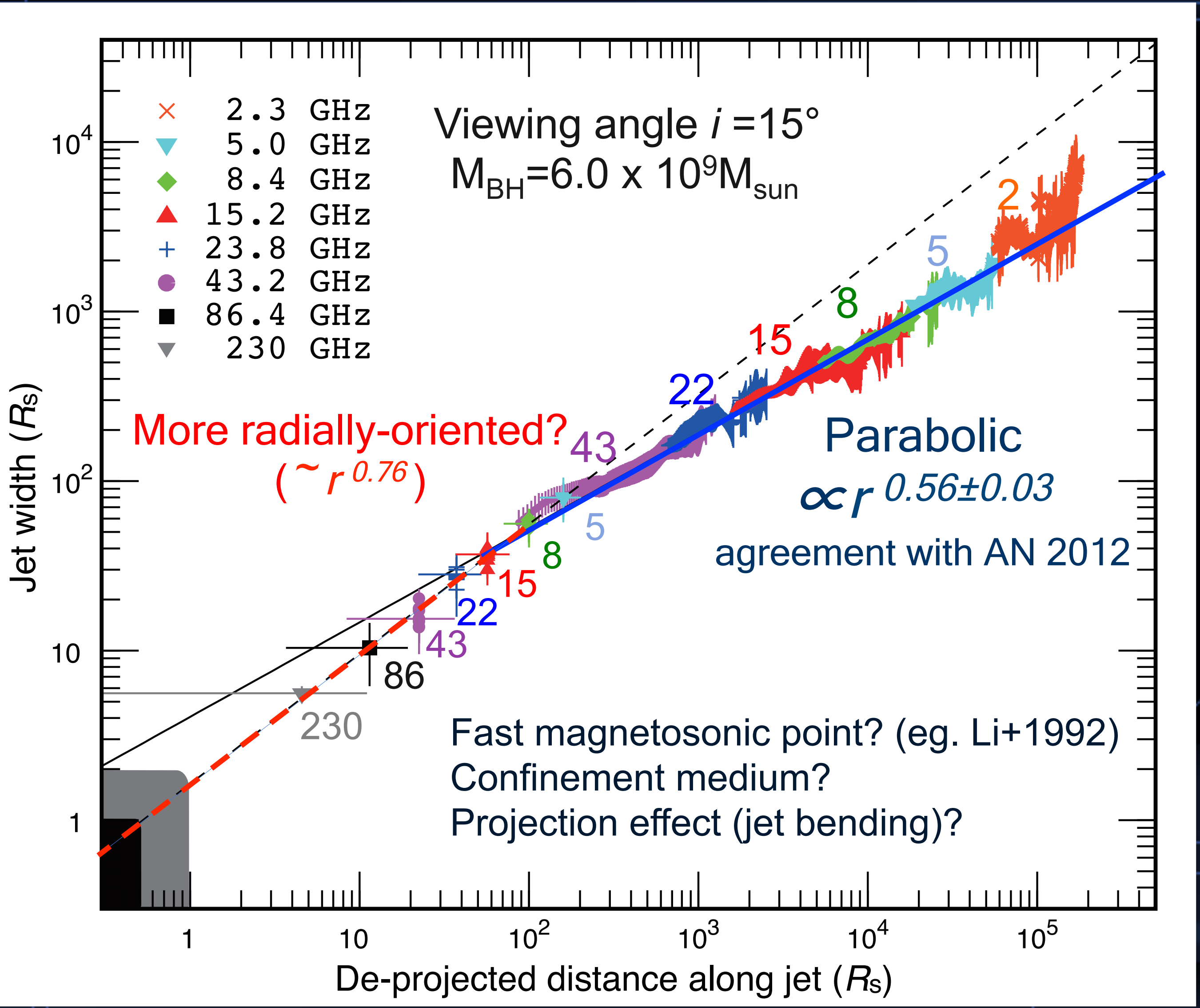




We can fill the gap by adding the core shift astrometry!

Innermost structure of M87 jet

(Hada et al.)

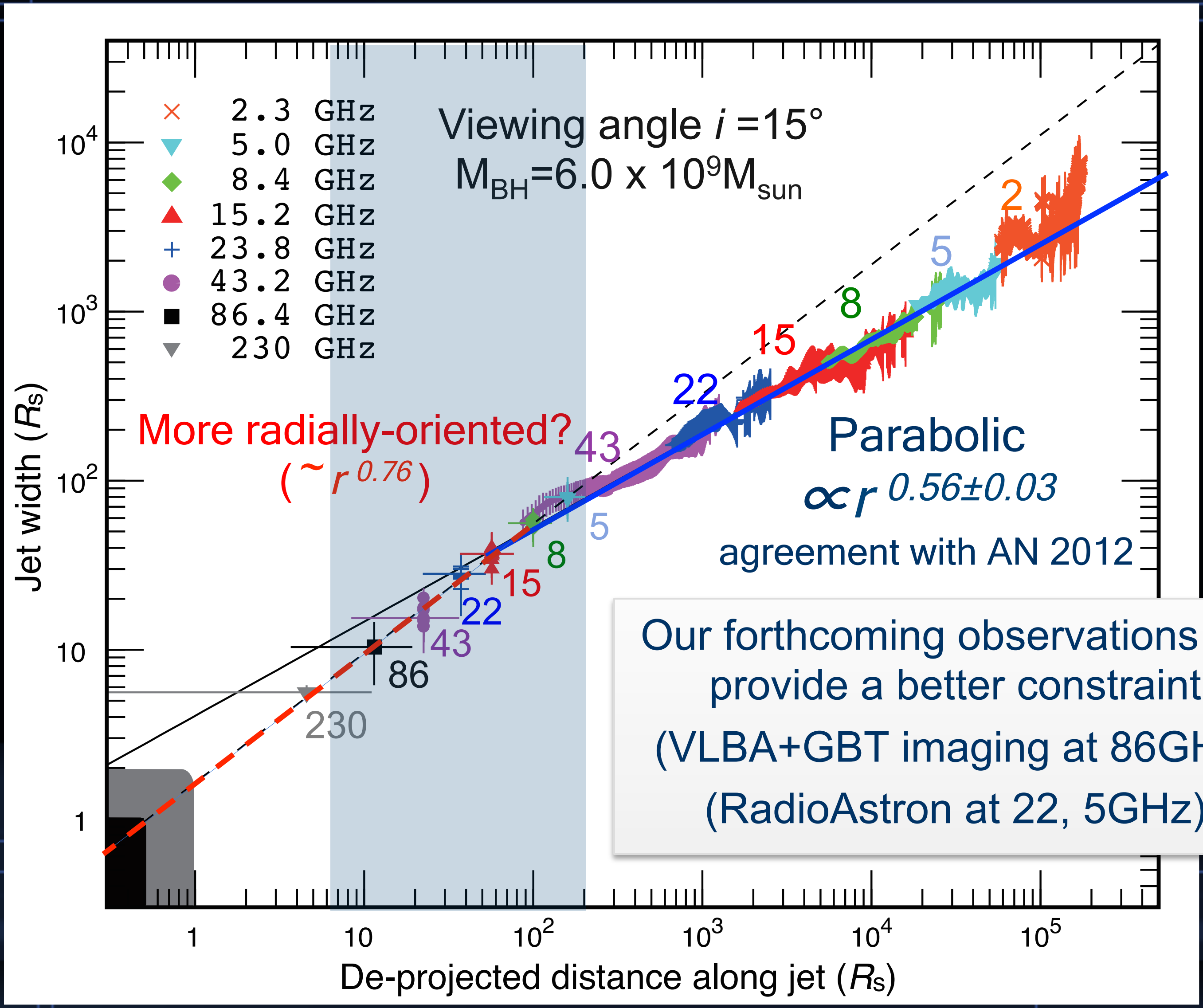


Note1: width = radius x 2

Note2: BH location assumed at the core-shift convergence point in H11

Innermost structure of M87 jet

(Hada et al.)



Note1: width = radius x 2

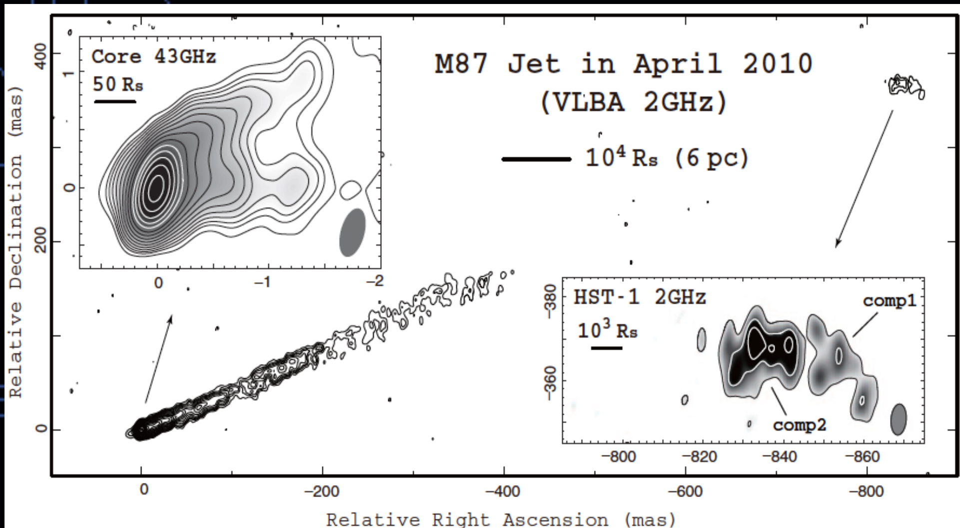
Note2: BH location assumed at the core-shift convergence point in H11

2. Multi-epoch VLBI approach

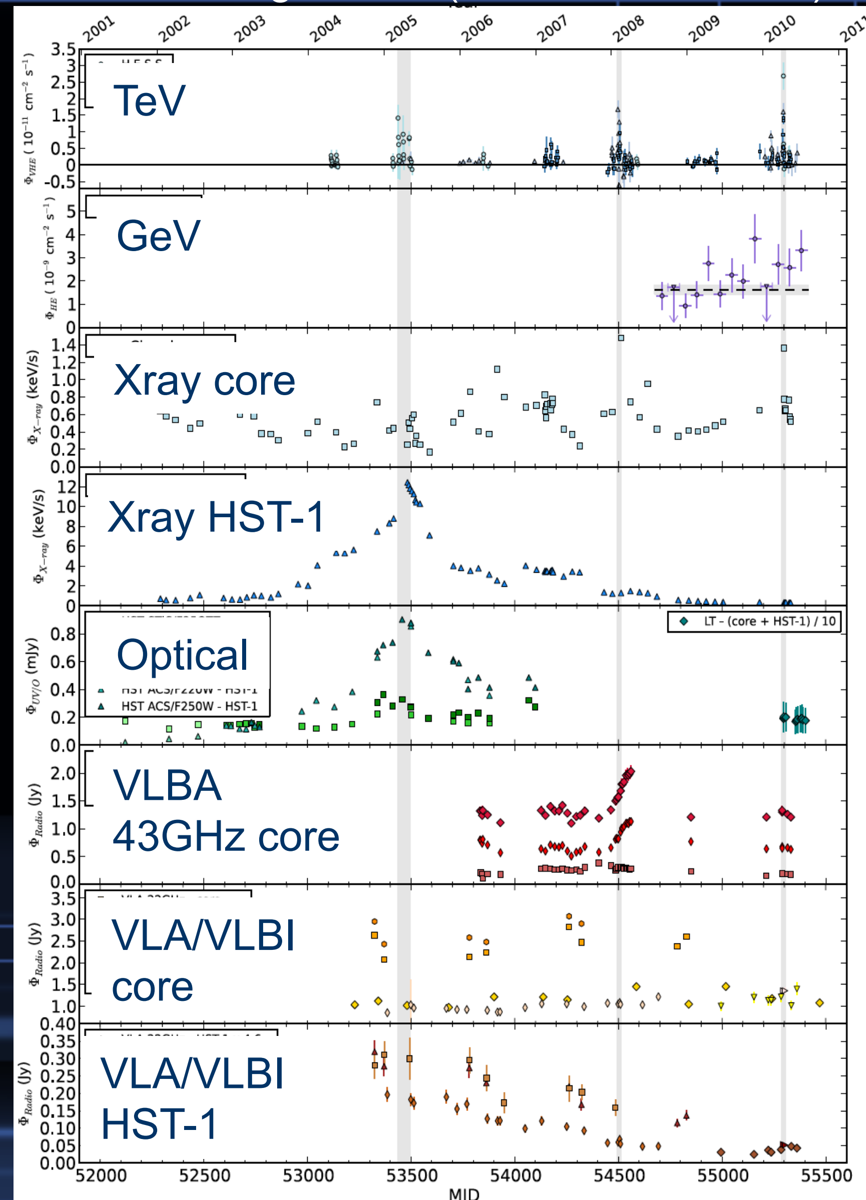
- HST-1 monitor with EVN
- Core/jet base monitor with VERA

Why M87 VLBI monitor ?

Hada+2012

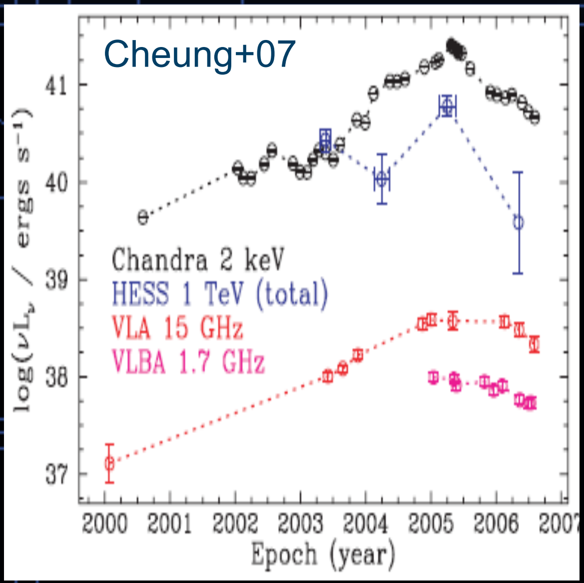


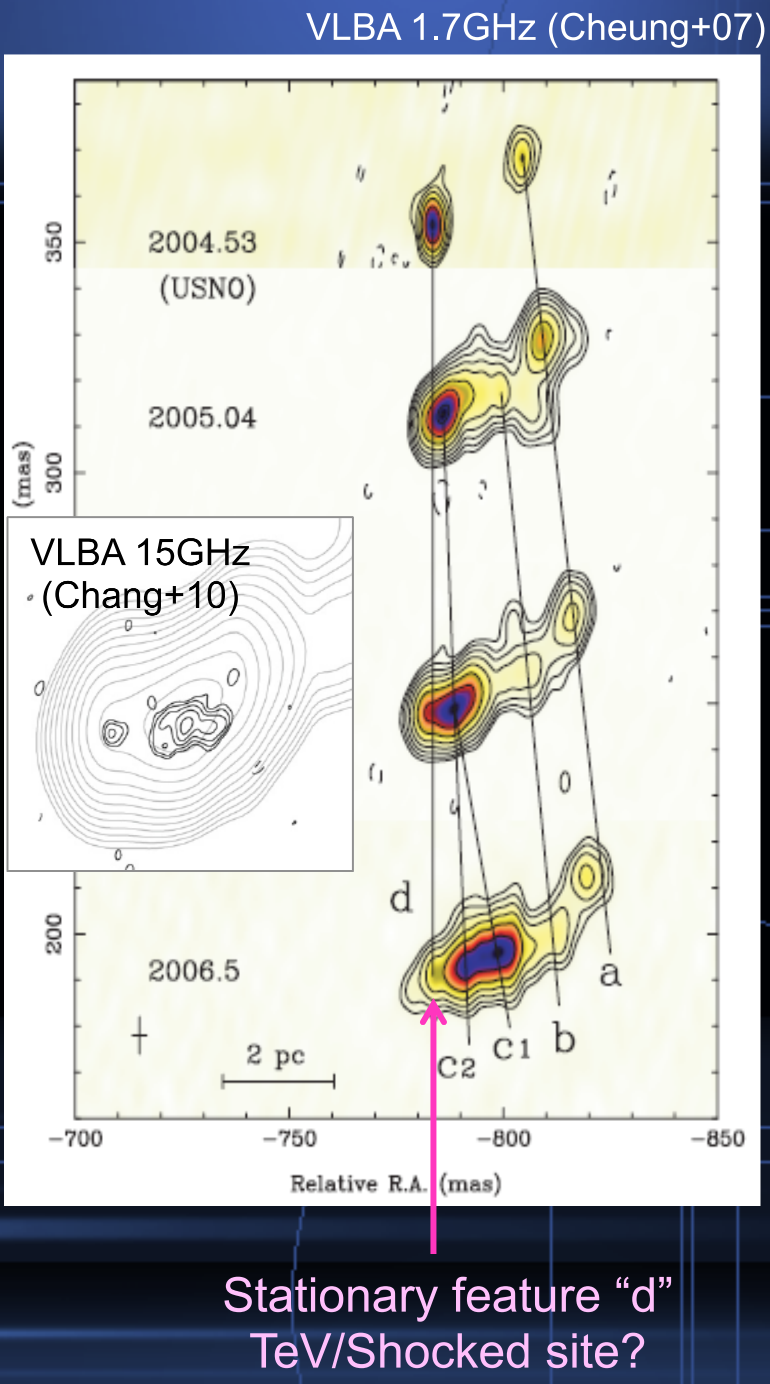
Multi-λ lightcurve (Abramowski+2012)



- Pinpoint γ-ray emission sites
  - Jet base (e.g., Acciari+09)
  - HST-1 (e.g., Cheung+07)
- Jet kinematics
  - Exact kinematic properties of M87 jet not uniquely determined yet
    - Sub-luminal (Ly+2007, Kovalev et al. 2007, Chang+2010)
    - Super-luminal (Cheung+07, Acciari+09)
    - Stationary (Cheung+07)

HST-1

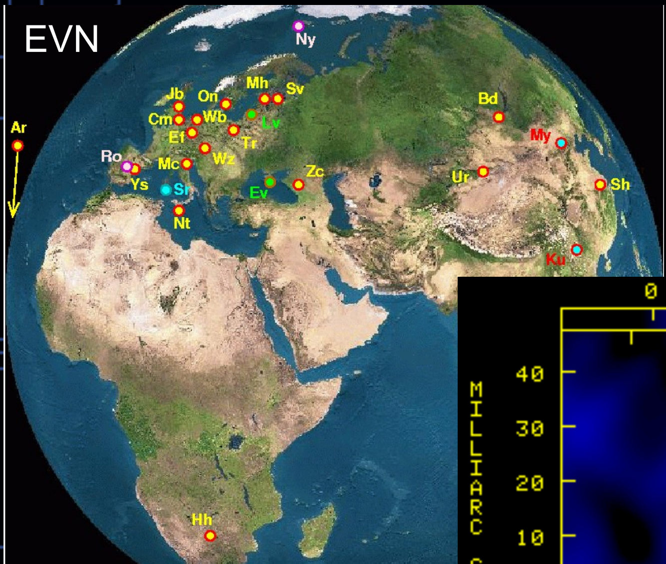


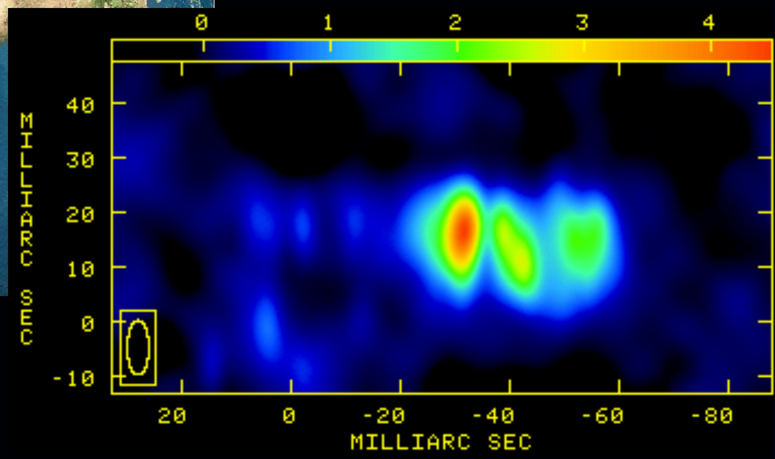


- Unusual feature ~80pc/10^4Rs downstream of the jet base (projected)
- Stationary feature "d" (upstream edge; Cheung+2007)
- Super-luminal (~4c) ejection near the TeV flare
  - Hallmark of a blazar core (Cheung+07, Harris+08)
  - HST1 upstream marks a recollimation shocked region (Stawarz+06)
- Sub-luminal (~0.6c) + optically thin ($\alpha_{1.7\text{-}15}$~ -0.8)
  - Not find evidence of a blazar nature (Chang+10)

HST-1/M87 monitor project with EVN

(Giovannini+ 2010; Giroletti, KH+ 2012)



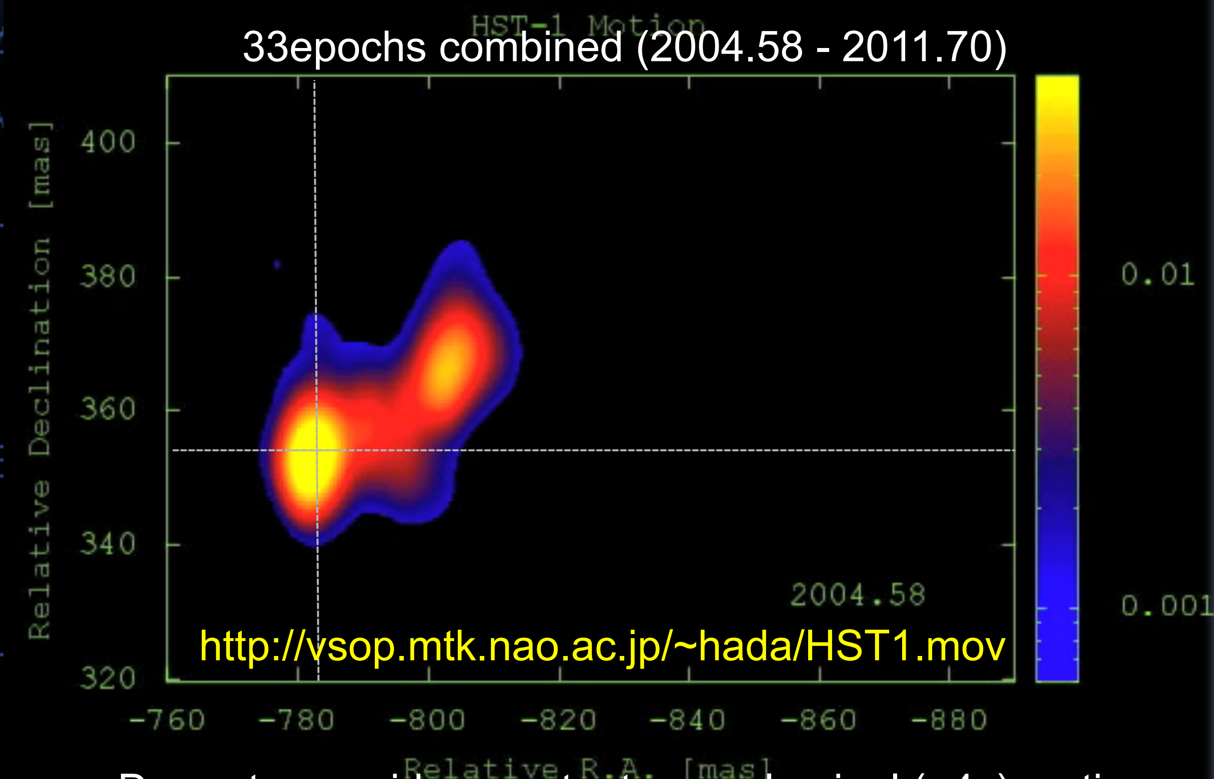


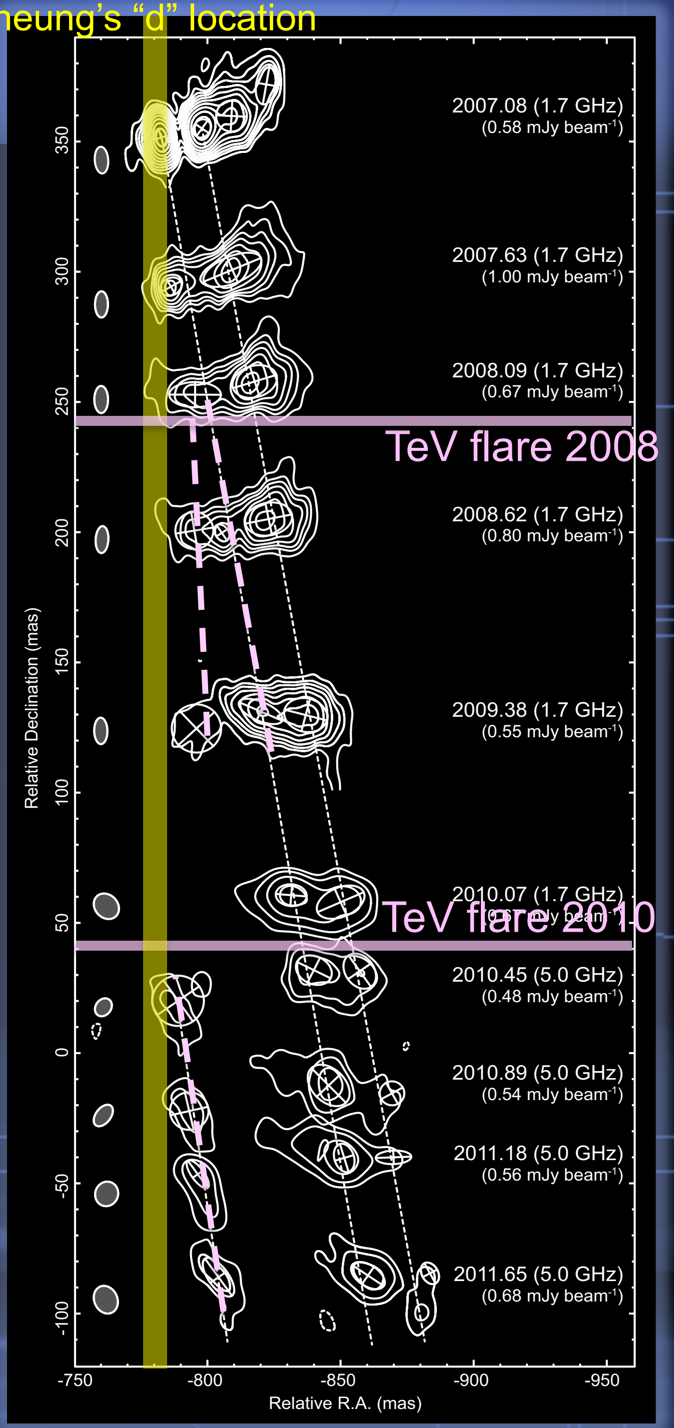
- 5GHz, from mid 2009
- Good resolution (1~10mas), sensitivity (0.1~0.3mJy/bm)
- A few (weeks~months) intervals
- Followed a large TeV flare in Apr/2010
- More than 20 epochs obtained up to now
- Extend back to the past by adding 1.7GHz VLBA data

VLBA 1.7GHz	EVN 5.0GHz
2005/01/13	2009/08/22
2005/05/06	2009/11/19
2005/05/22	2010/01/27
2005/10/27	2010/02/10
2005/12/16	2010/03/02
2006/02/03	2010/03/30
2006/05/11	2010/05/18
2006/06/30	2010/06/14
2006/07/12	2010/11/23
2006/11/11	2011/03/09
2007/01/30	2011/04/12
2007/05/28	2011/06/02
2007/08/20	2011/08/25
2007/12/14	2011/10/17
2008/02/02	2012/01/11
2008/05/27	2012/03/20
2008/08/12	2012/06/19
2008/11/29	2012/10/09
2009/02/21	2013/01/15
2009/05/21	2013/05/03
2009/06/13	And more…

Initial outcomes & movie

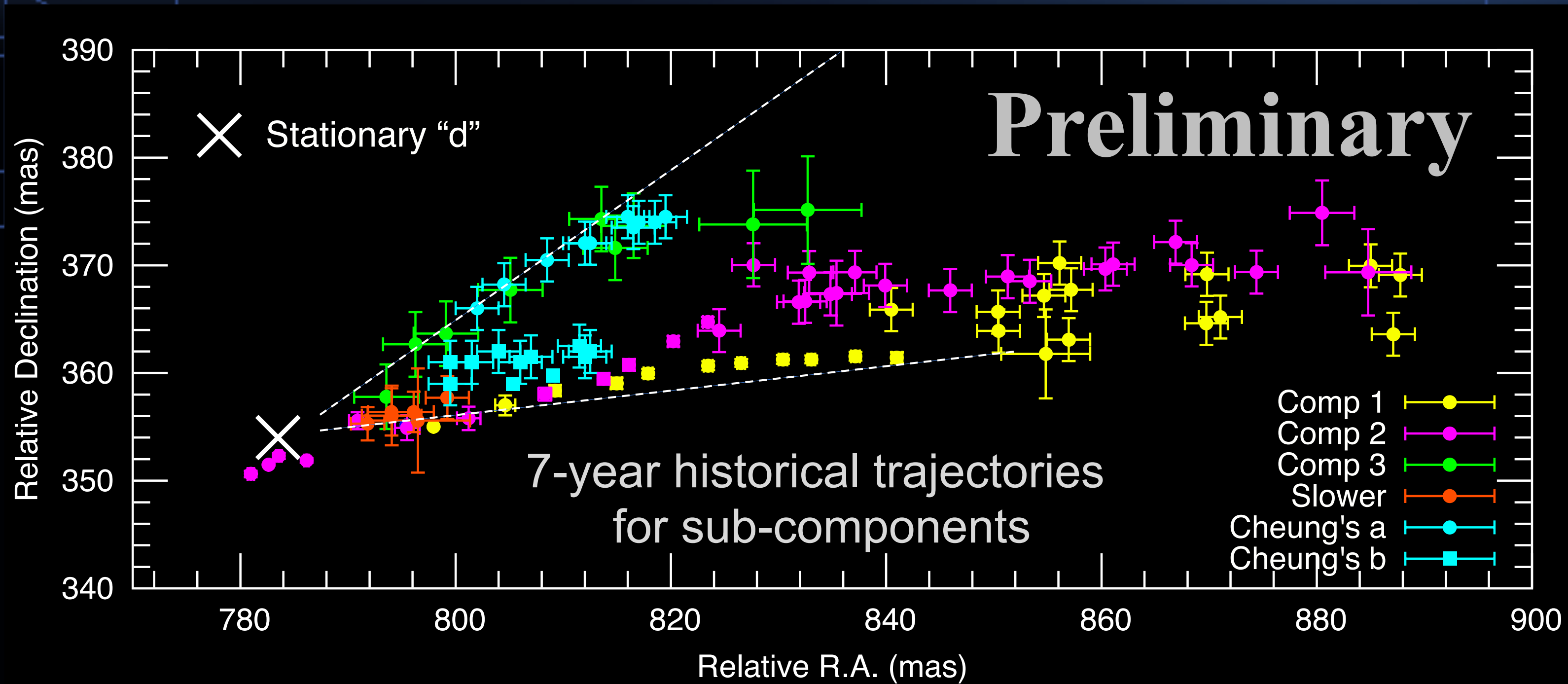
(Giroletti, KH+ 2012)



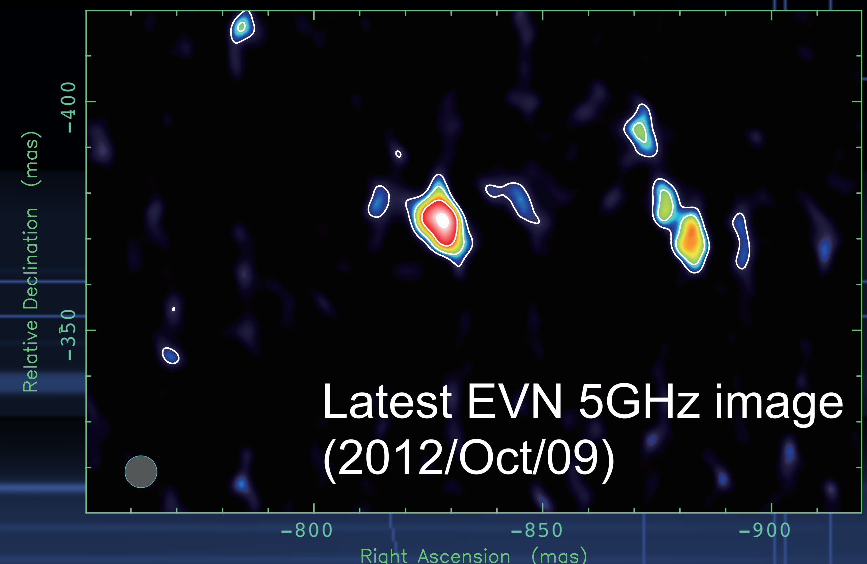


- Downstream side: constant super-luminal (~4c) motions over 5years
- Upstream side: split of a weak slower feature, emergence of a new super-luminal feature
- Progressive rotation of overall structure
- No "prominent" stationary features confirmed. But the structural variations always happen near "d" location.
- The epochs close to TeV events, but the jet base also correlates with TeV in 2008/2010 (Acciari+09/Hada+12)

Current status

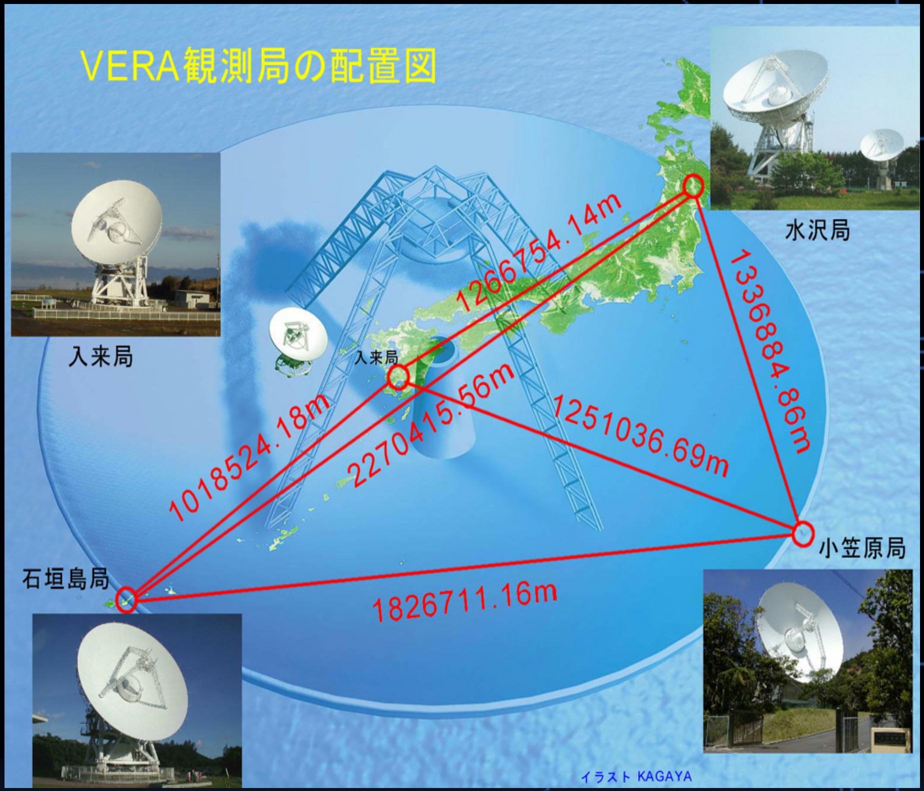


- EVN monitor at 1.7GHz from May/2013
- New VLBA observations at 2/5GHz, EVLA at 15/22/43GHz with polarimetry (talk by Casadio)



M87 core/jet base monitor with VERA (2010/Oct~)

- Strategies & advantages
  - Very dense, continuous monitor (every ~1-3weeks, roughly full-year)
  - Mainly 22GHz but also 43GHz
  - Core spectrum, spectral index and their time evolutions
  - Astrometry, core-shift
- Aims
  - Dense lightcurves for the core
  - Kinematics near BH
  - Radio/γ-ray correlation at jet base
  - Nuclear opacity, *B*-strength
  - Complementary study with the EVN monitor

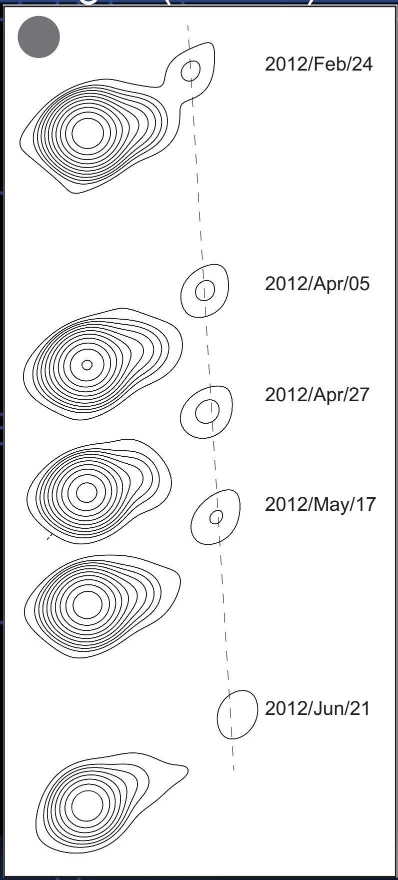


- Resolutions ~1.2mas (22GHz)
  ~0.6mas (43GHz)
- Dual-beam astrometry capability

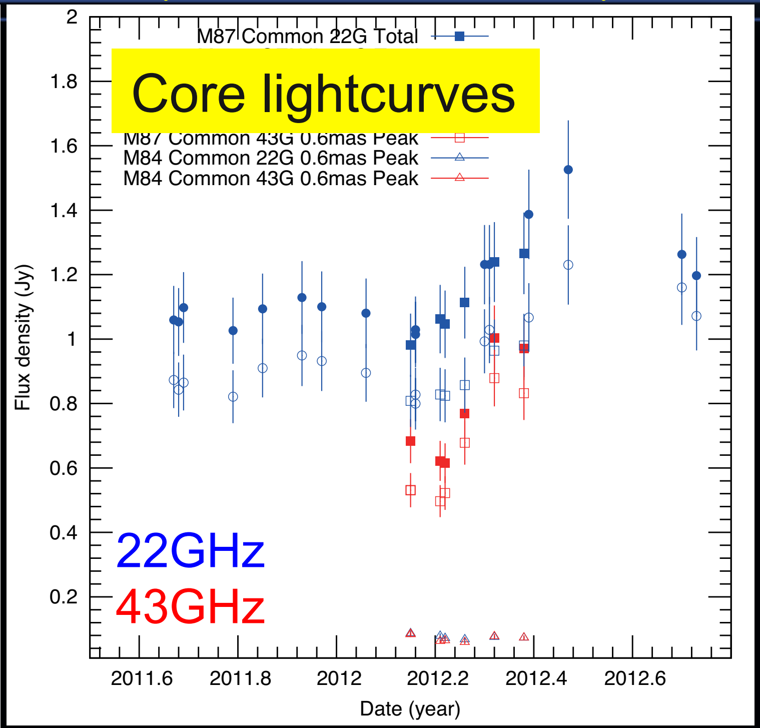
See also ***GENJI*** programme; Nagai+2013

Some preliminary results

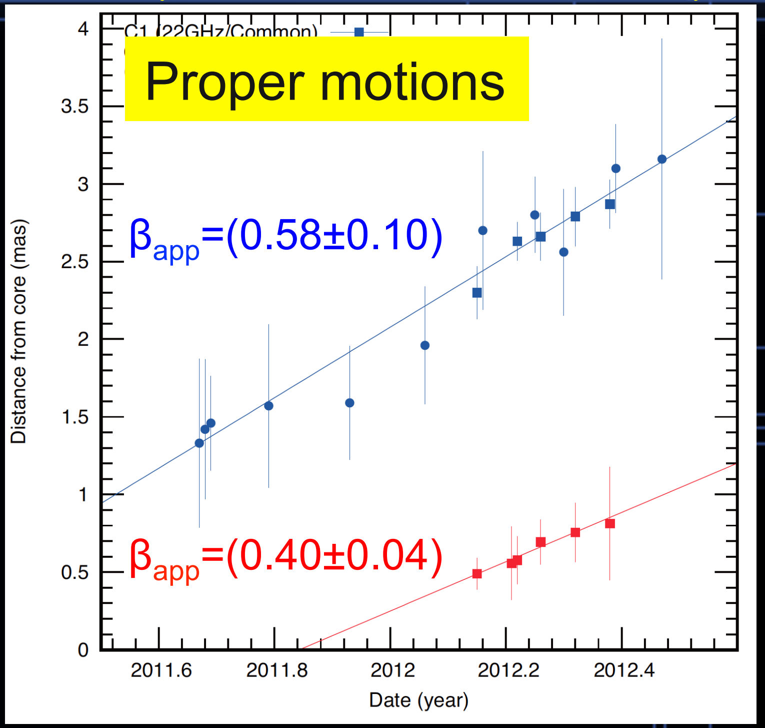
Images (22GHz)



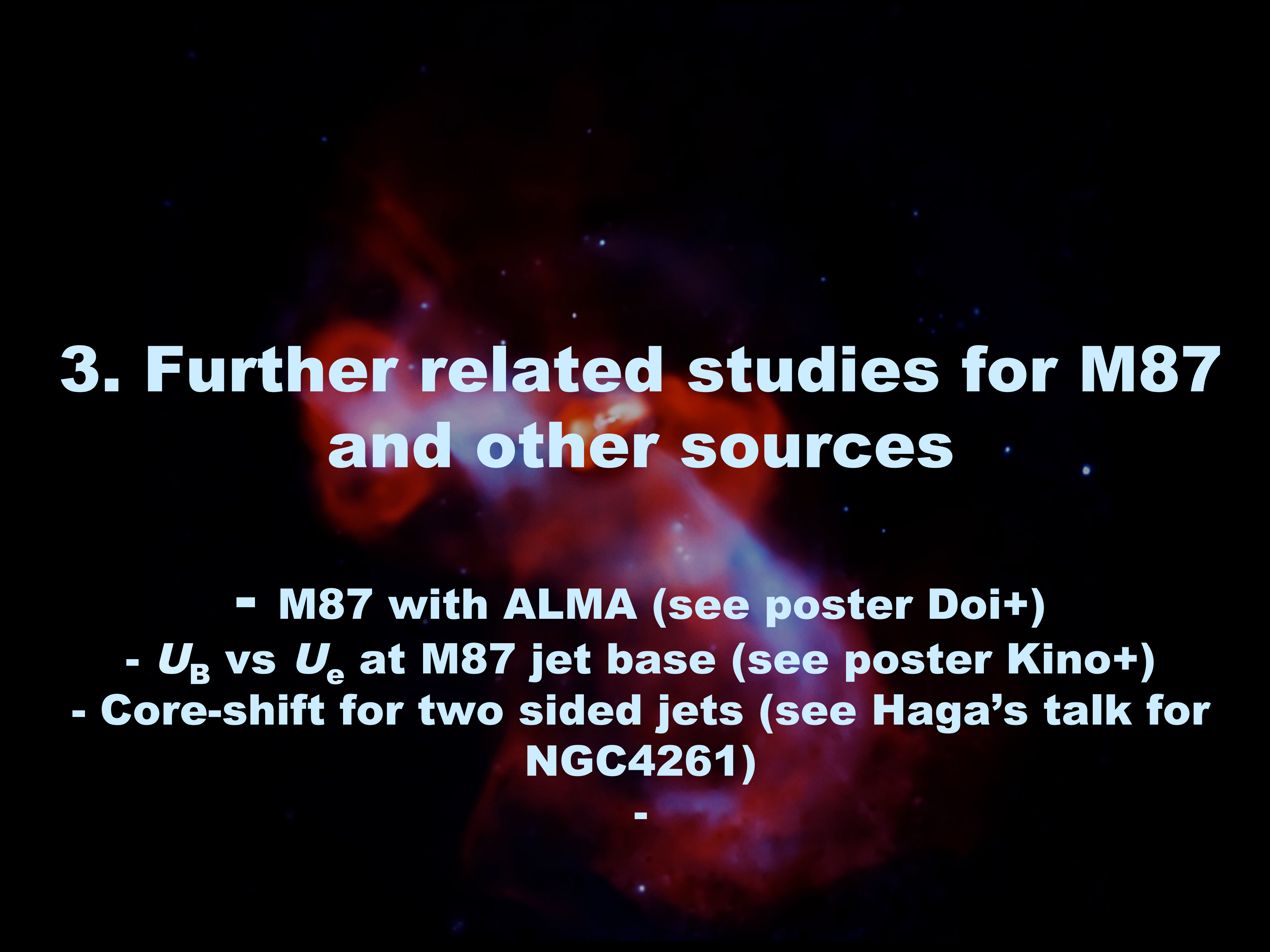
1 year



1 year



- VERA demonstrating a very nice ability for tracking M87 jet base evolutions
- More than 20 epochs within 1year (22GHz)
- Detection of ~50% radio flare (& decay) (22/43GHz)
- Sub-luminal (0.4~0.6c) apparent speeds at r ~$10^{2\text{-}3}$Rs
  - c.f. months-scale monitor@15GHz shows <0.05c; Kovalev et al.2007
- Astrometry/coreshift analysis in progress


3. Further related studies for M87 and other sources
- M87 with ALMA (see poster Doi+)
- U_B vs U_e at M87 jet base (see poster Kino+)
- Core-shift for two sided jets (see Haga's talk for NGC4261)
-

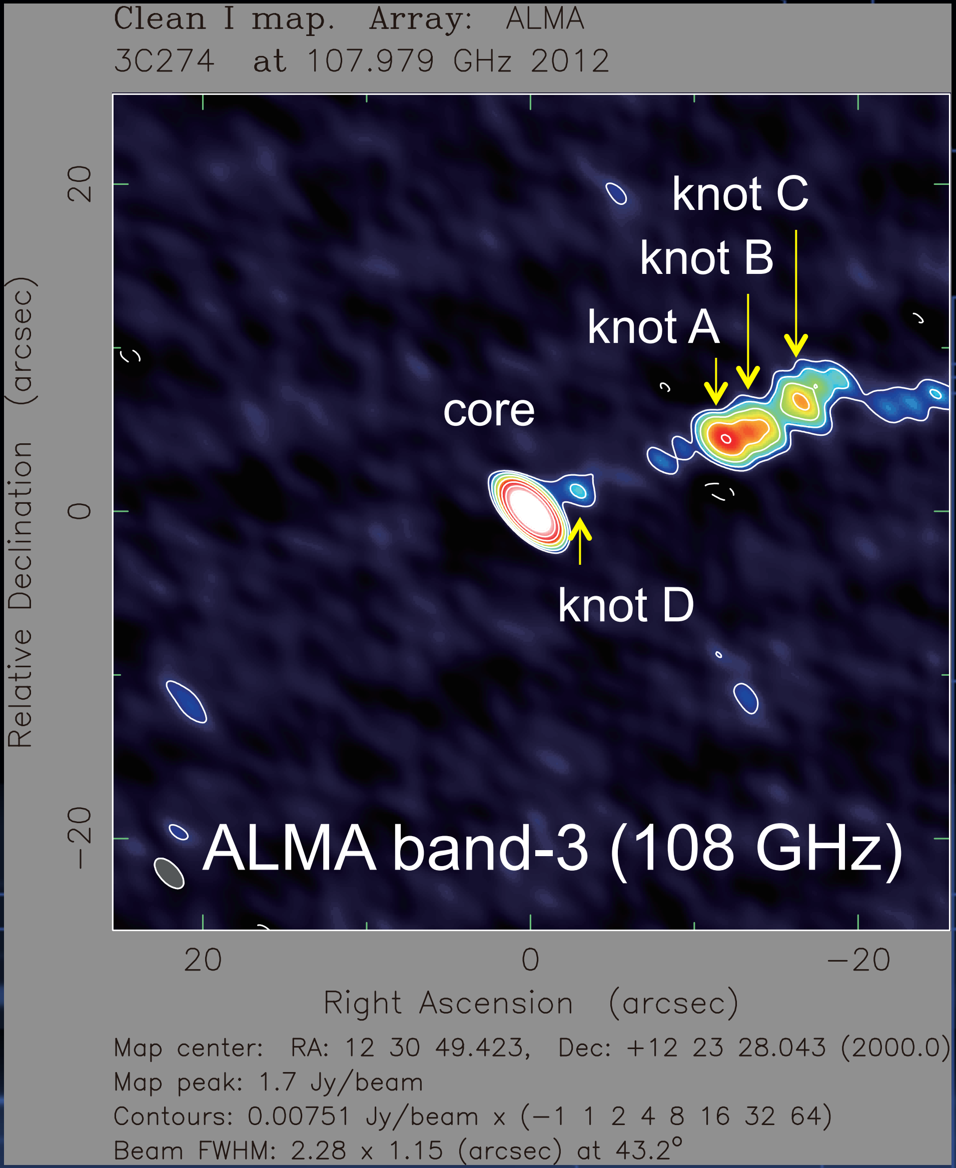
M87 with ALMA

Credit:ESO

- Another important approach to probe the innermost region of M87 is to examine the spectral properties at mm/submm
- We can extract emission from BH vicinity (Doeleman+12). Spectral shape tells us physical properties for this region.
- ALMA is the best instrument for spectral studies at mm/submm

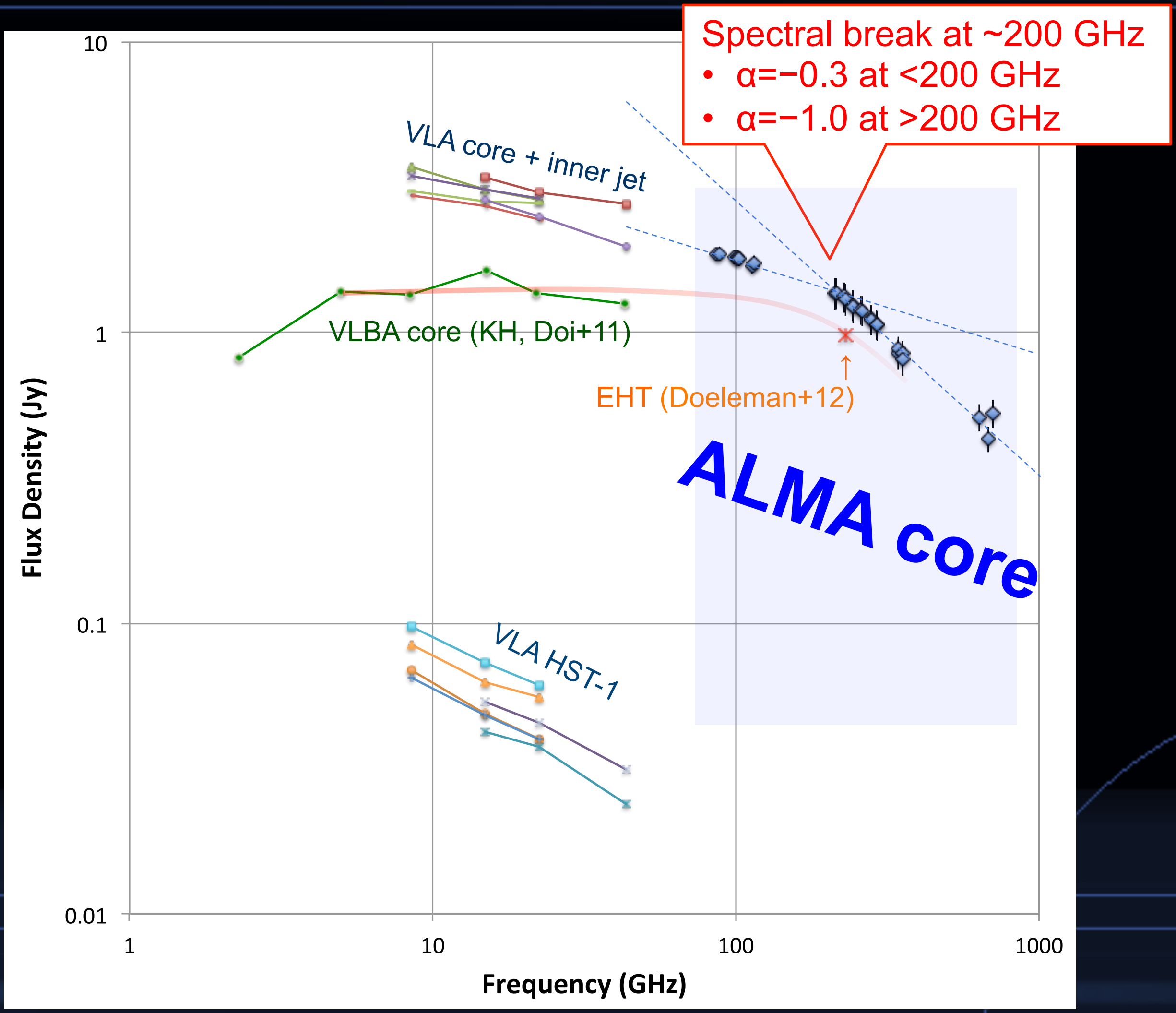
The first ALMA image of M87
(Doi, KH+ in prep)

- 36 frequencies (quasi-simultaneous)
  - 90--700 GHz
- 0.2--2.3 arcsec beam
- 0.1--6.6 mJy/beam rms
- Core, knot A,B,C,D
  - HST-1 not detected



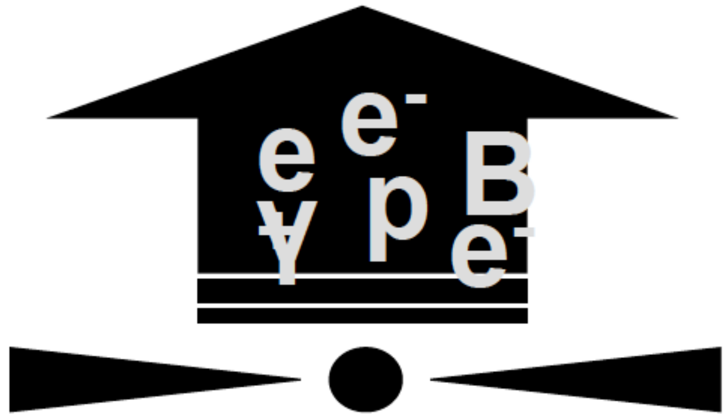
Cm-submm spectrum

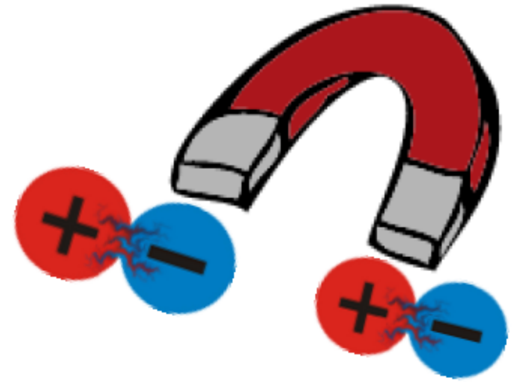
(Doi, KH+ in prep, see poster)

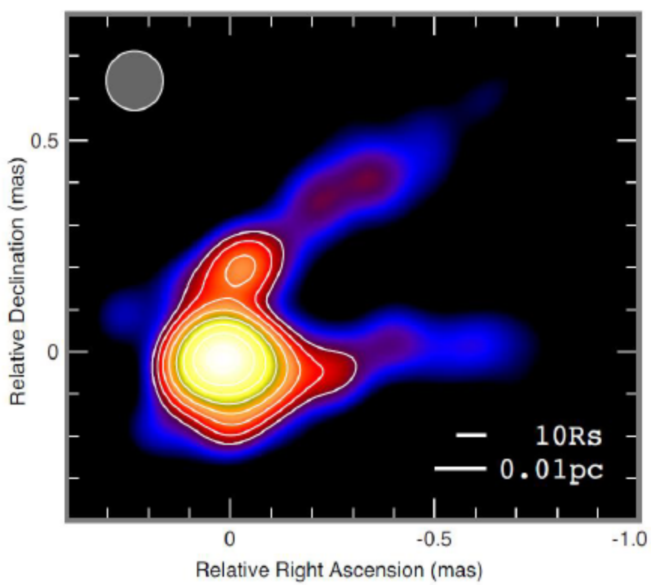


- Discovery of a spectral break for the core at ~200GHz

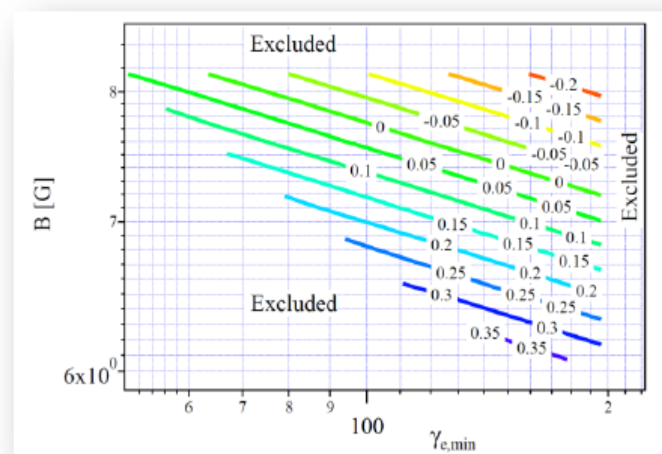
Poynting or kinetic power dominated in M87?
(see poster by Kino, Takahara, KH+)



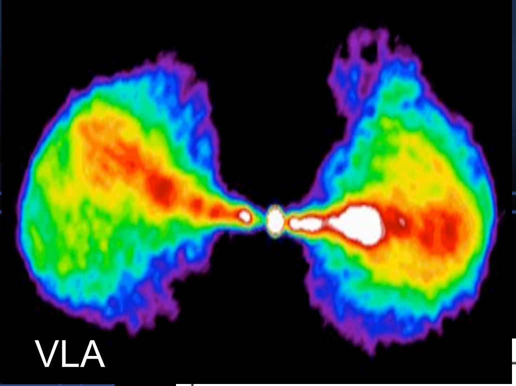




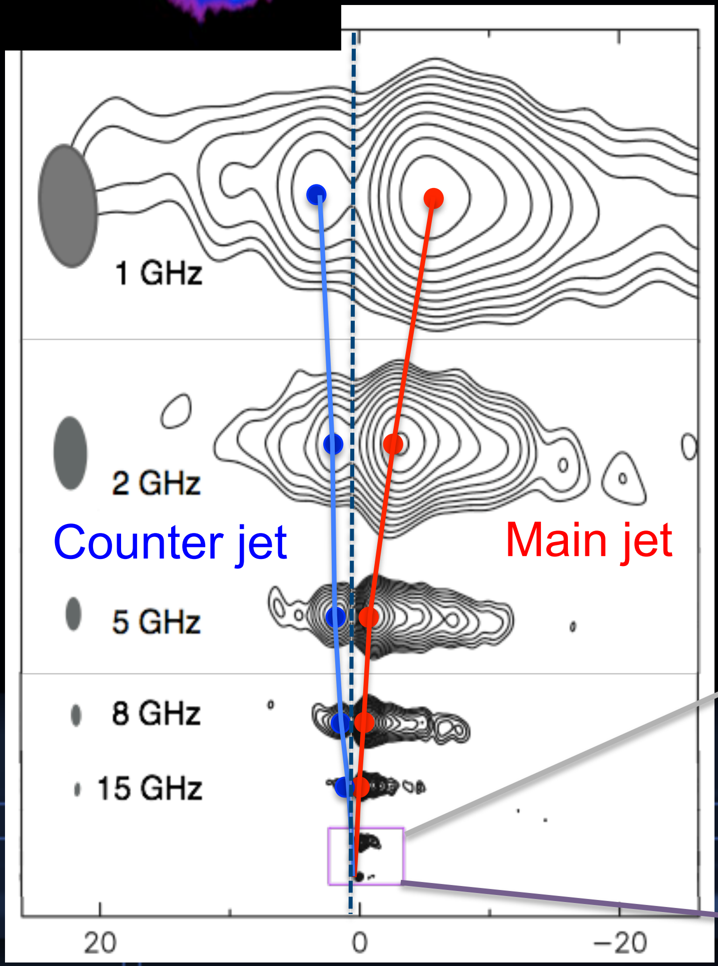
See Poster Kino, Takahara, KH +

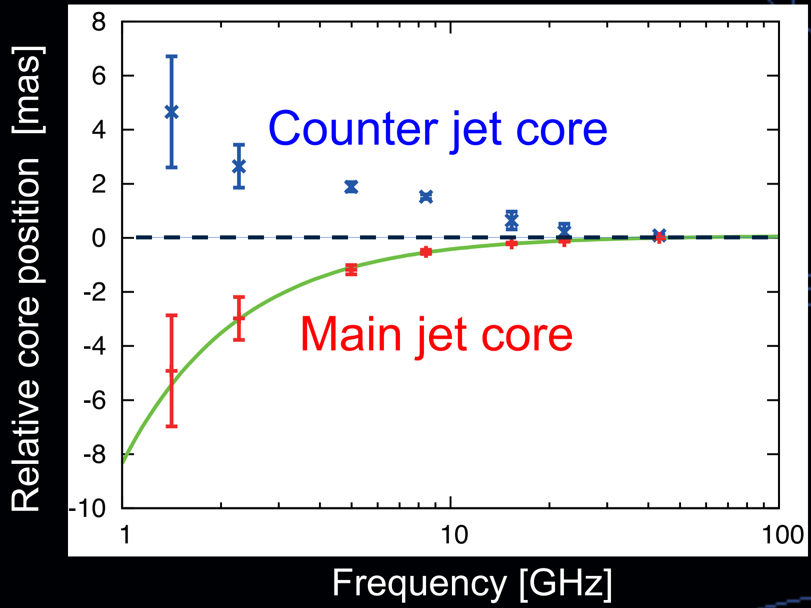


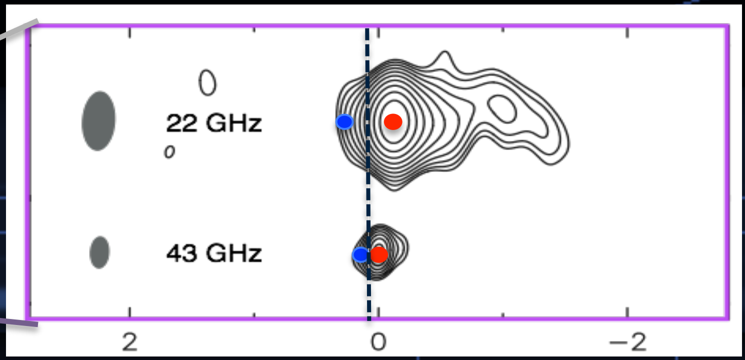
Core shift astrometry for two-sided jet sources



NGC4261 VLBA (talk by Haga)







Also observing 3C84, CenA, CygA, 3C338 and Mrk348

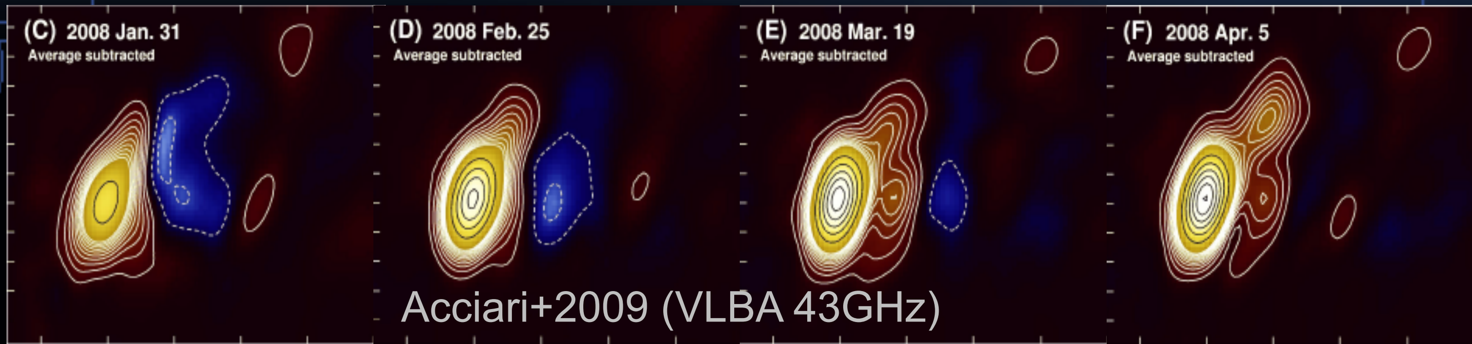
Summary

Overviewed our ongoing projects for the inner jet of M87

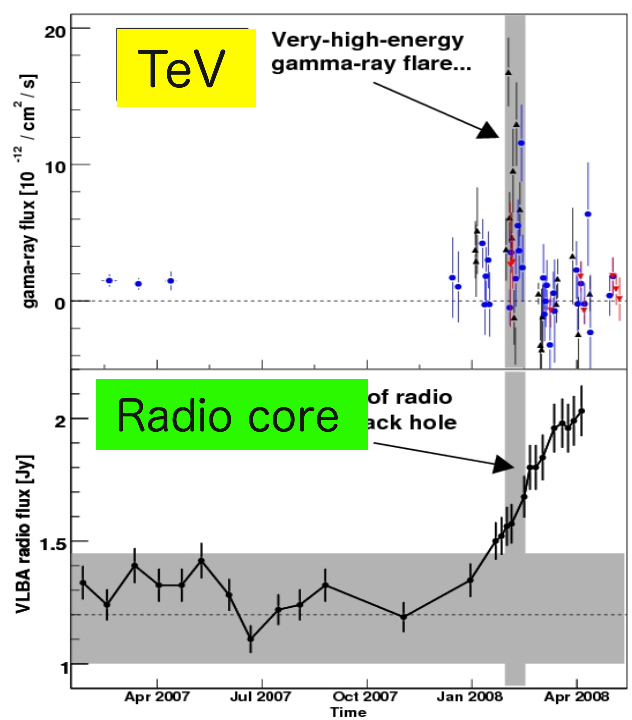
- M87 is a unique target to probe jet collimation, velocity field, origin/locations of TeV γ-ray
- Multi-frequency astrometry approach
  - Core location: close to BH (~20Rs@43GHz)
  - Innermost collimation profile: possible transition from a parabolic to a more radially-oriented shape (r~10-100Rs)?
- Deep monitor with EVN(weeks~months) / VERA(~1-3weeks)
  - Jet speeds
    - Sub-luminal (0.4~0.6c) jet base
    - Super-luminal (~4c) HST-1 downstream
  - Peculiar nature of the HST-1 upstream edge: recollimation shocked region related to TeV events?
- Mm/submm spectra with ALMA
  - Discovery of a spectral break for the core at ~200GHz
- U_B vs U_e at M87 jet base
- Core shift astrometry for two-sided jet sources

Supplementary slides

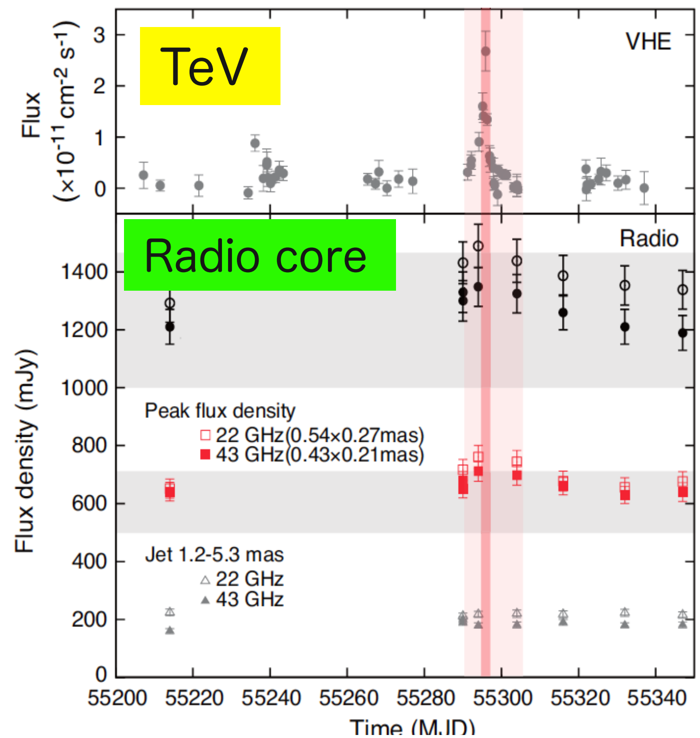
Core/jet base



2008 (Acciari+2009)

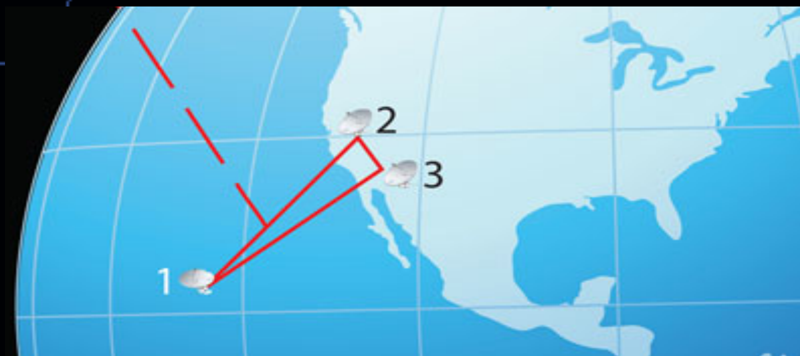


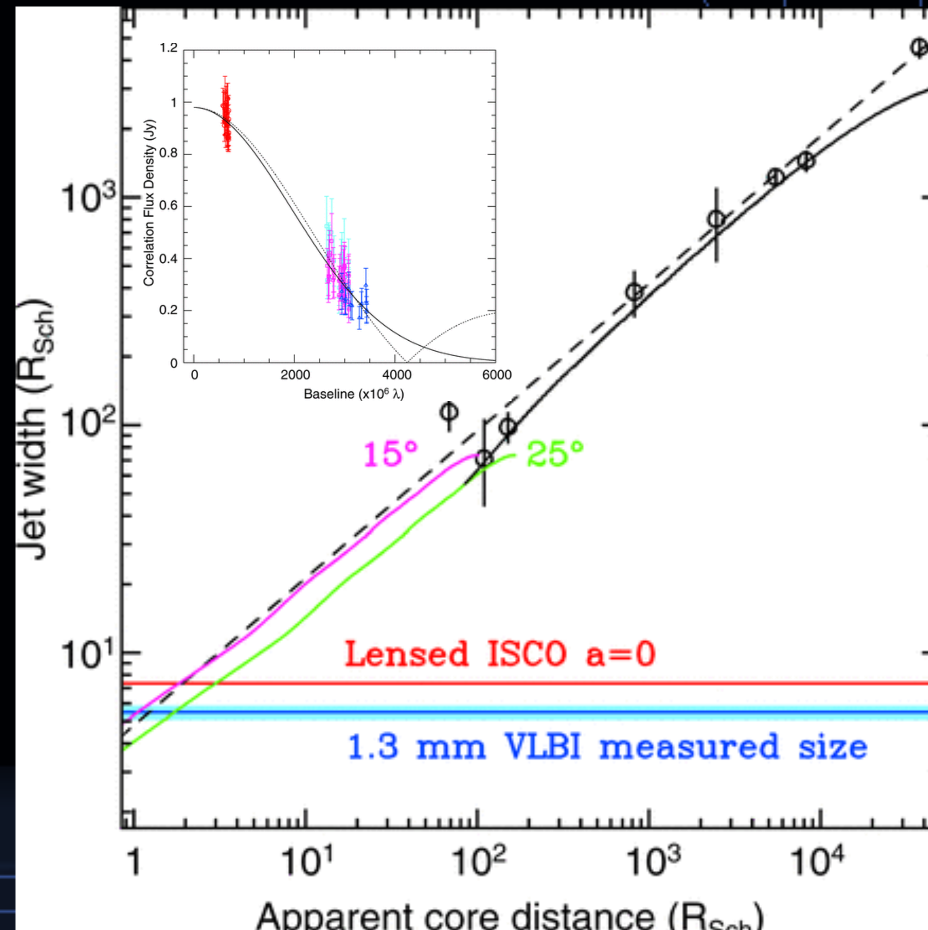
2010 (Hada+2012)



Jet launch size

(Doeleman et al. 2012)





- 1.3mm (230GHz) VLBI
- Jet launch size
  - 40μas = 5Rs

HST-1 motions
(Giroletti, KH et al. 2012)