Greenland Telescope for submm VLBI

INOUE, Makoto

井上　允

and the GLT Project Team

Academia Sinica Institute of Astronomy and Astrophysics

Smithsonian Astrophysical Observatory

MIT Haystack Observatory

National Radio Astronomy Observatory

EAMA9, 14-17 Oct. 2013, NCU, Taiwan

Contents

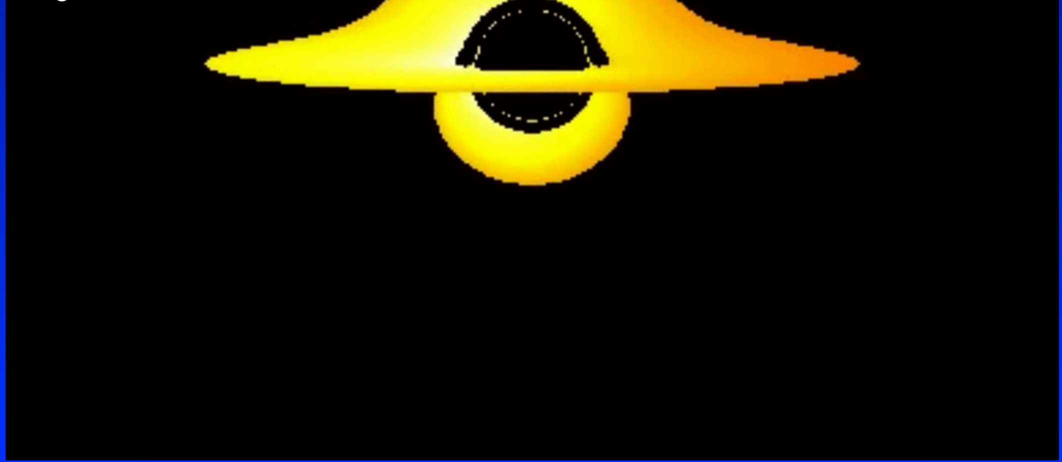
- Introduction
- Submm VLBI Observations
- Greenland Telescope
- Image simulations
- Jet studies
- Summary

Greenland Telescope (GLT) Project

- Goal: Image Supermassive (7×10^9 M_{sun}) Black Hole (SMBH), and measure its mass and spin (1st time ever)
- Awarded: NSF to ASIAA/Smithsonian AO Team (04.2011)
  ALMA-NA 12-m prototype telescope
- Site survey
- Many works are ongoing
  - Science, Antenna, Site construction, etc.
- Project Timeline: 2012 retrofit telescope
  2013 build ice/snow base on Greenland
  2014 re-assemble and test at Thule
  2014/15 transport telescope across ice sheet
  2016/17 first light

Objectives of SMBH studies

1. Imaging of Supermassive Black Hole Shadow
2. GR study under strong gravity field
3. Nature of Accretion disk and flows
4. Origin of Relativistic jets



Contents

- Introduction
- Submm VLBI Observations
- Greenland Telescope
- Image simulations
- Jet studies
- Summary

Submm VLBI Observations so far

Doeleman et al. 2008

Doeleman et al. 2012

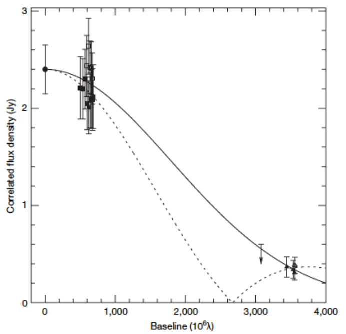
nature Vol 455|4 September 2008|doi:10.1038/nature07245

LETTERS

Event-horizon-scale structure in the supermassive black hole candidate at the Galactic Centre

Sheperd S. Doeleman[1], Jonathan Weintroub[2], Alan E. E. Rogers[1], Richard Plambeck[3], Robert Freund[4], Remo P. J. Tilanus[5,6], Per Friberg[5], Lucy M. Ziurys[4], James M. Moran[2], Brian Corey[1], Ken H. Young[2], Daniel L. Smythe[1], Michael Titus[1], Daniel P. Marrone[7,8], Roger J. Cappallo[1], Douglas C.-J. Bock[9], Geoffrey C. Bower[3], Richard Chamberlin[10], Gary R. Davis[5], Thomas P. Krichbaum[11], James Lamb[12], Holly Maness[3], Arthur E. Niell[1], Alan Roy[11], Peter Strittmatter[4], Daniel Werthimer[13], Alan R. Whitney[1] & David Woody[12]

The cores of most galaxies are thought to harbour supermassive black holes, which power galactic nuclei by converting the gravitational energy of accreting matter into radiation[1]. Sagittarius A* (Sgr A*), the compact source of radio, infrared and X-ray emission at the centre of the Milky Way, is the closest example of this phenomenon, with an estimated black hole mass that is 4,000,000 times that of the Sun[2,3]. A long-standing astronomical goal is to resolve structures in the innermost accretion flow surrounding Sgr A*, where strong gravitational fields will distort the appearance of radiation emitted near the black hole. Radio observations at wavelengths of 3.5 mm and 7 mm have detected intrinsic structure in Sgr A*, but the spatial resolution of observations at these wavelengths is limited by interstellar scattering[4–7]. Here we report observations at a wavelength of 1.3 mm that set a size of 37^{+16}_{-10} microarcseconds on the intrinsic diameter of Sgr A*. This is less than the expected apparent size of the event horizon of the presumed black hole, suggesting that the bulk of Sgr A* emission may not be centred on the black hole, but arises in the surrounding accretion flow.



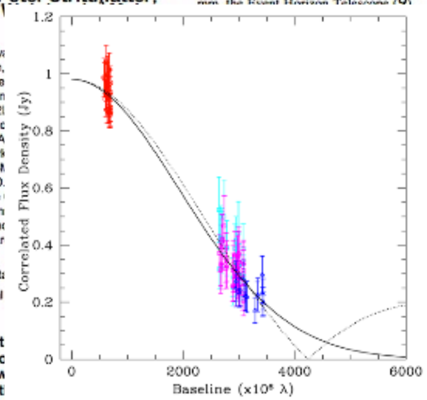
detected with high signal to noise on all three baselines allowing array

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 Weintroub,[3] Melvyn Wright,[4] Ken H. Young,[3] Lucy Ziurys[2]

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



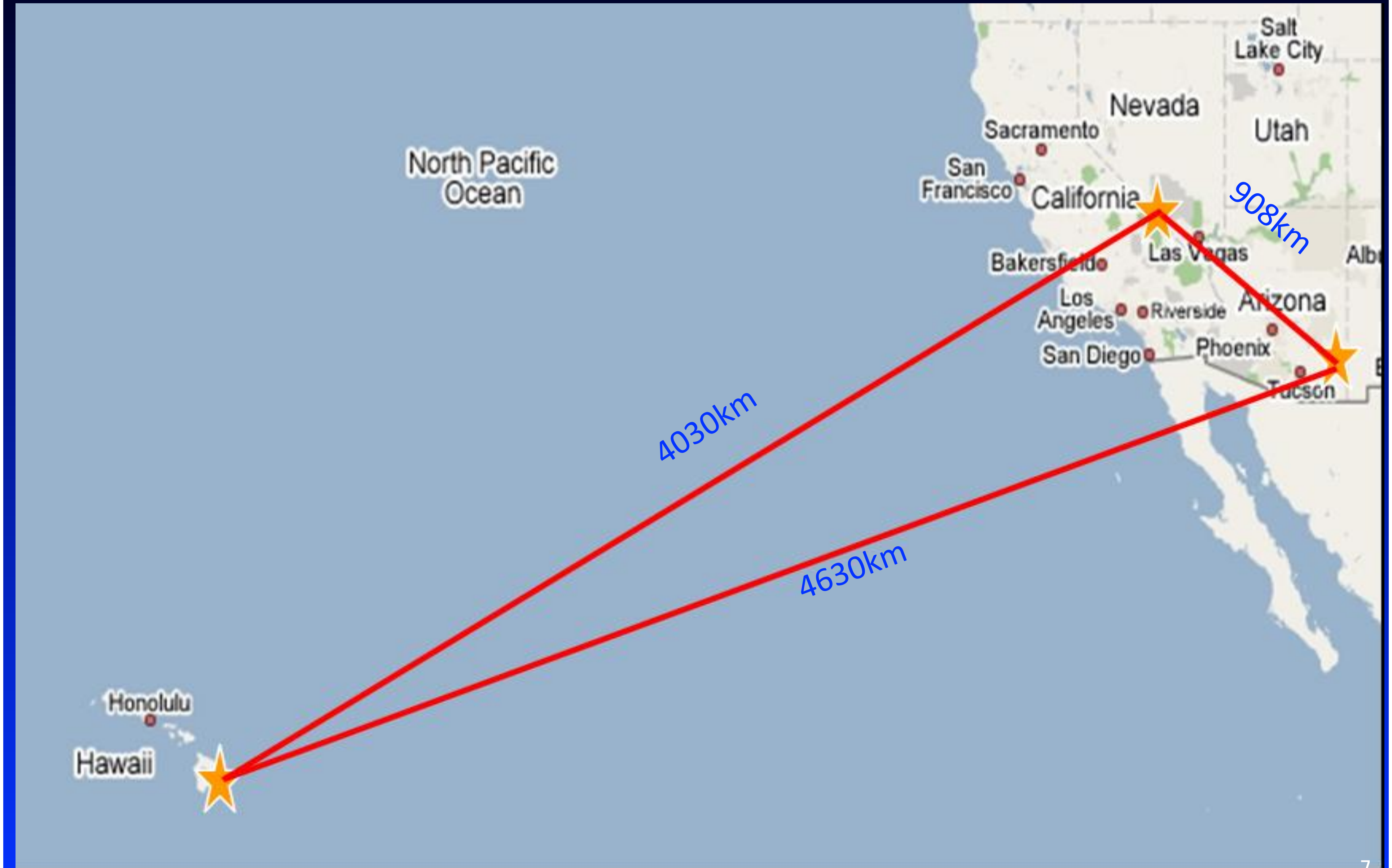
Sgr A*

Gaussian size ≈ 40 μas (≈4 r_s)

Vir A* (M 87)

Gaussian size ≈ 40 μas (≈5 r_s)

λ1.3-mm Observations



Issues to achieve

- Higher angular resolution
  - Longer baselines
- Good uv coverage
  - More stations
- High sensitivity
  - Phased ALMA
- Image simulations
  - GR, Disk model, MHD Jet, etc.

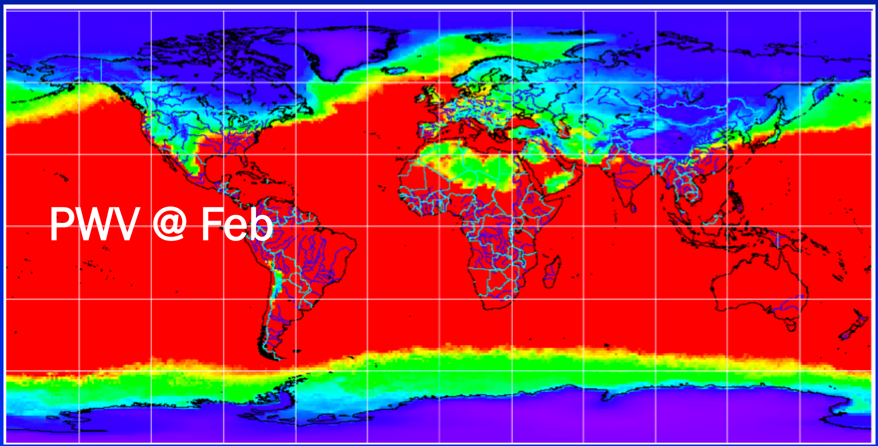
Contents

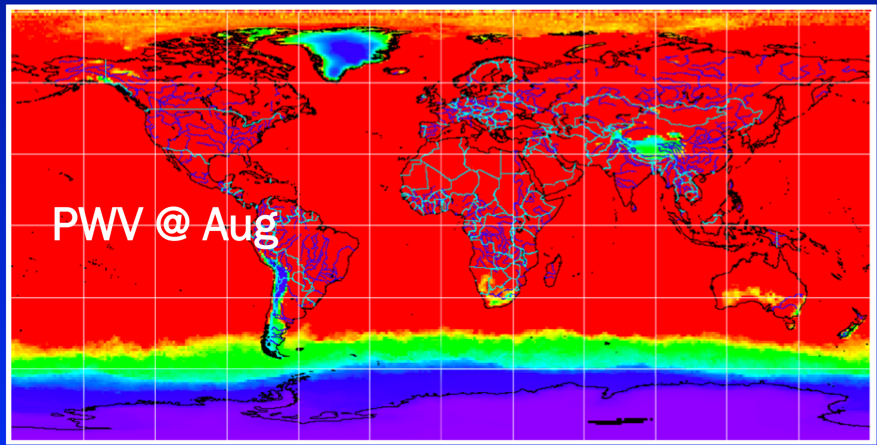
- Introduction
- Submm VLBI Observations
- Greenland Telescope
- Image simulations
- Jet studies
- Summary

Site selection

For the submm VLBI site

1. Low Precipitable Water Vapor (PWV)
   Low temperature/High mountain/Desert
2. Outstanding contribution to submm VLBI
3. Mutual visibility with ALMA and SMA
4. Easy to access (including infrastructures)





PWV > 10 mm in red color

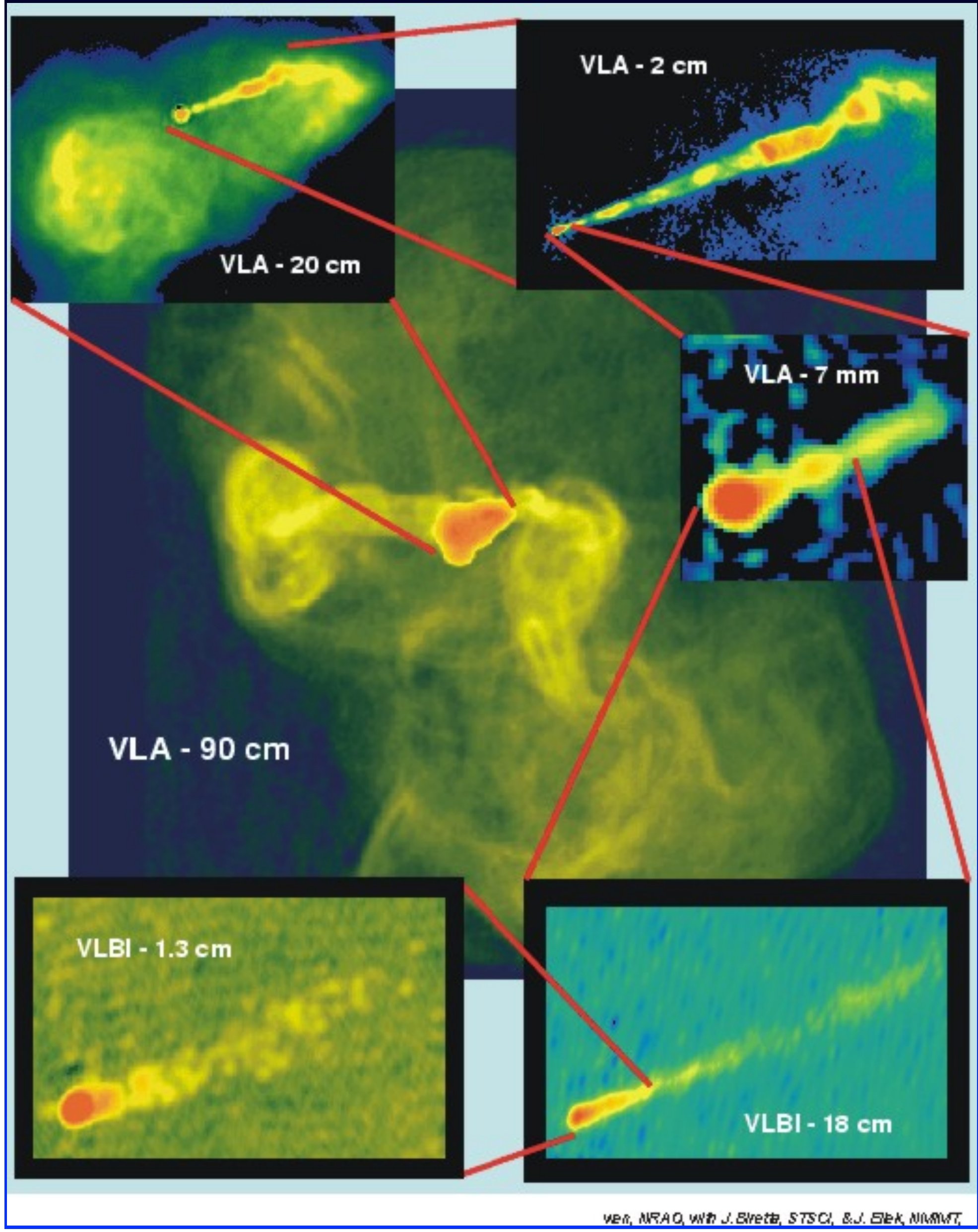
Distribution of PWV by Terra and Aqua (NASA)

SMBH Shadow size

$D_{shadow} \approx 5\ R_{sch}$

Name	Shadow (μas)	Mass ($10^6 M_{sun}$)	Dist (Mpc)
Sgr A*	50	4.1±0.6	0.008
M87	39	6600±400	17.0
M31	18	180±80	0.80
M60	12	2100±600	16.5
N5128	7	310±30	4.4

M87 properties

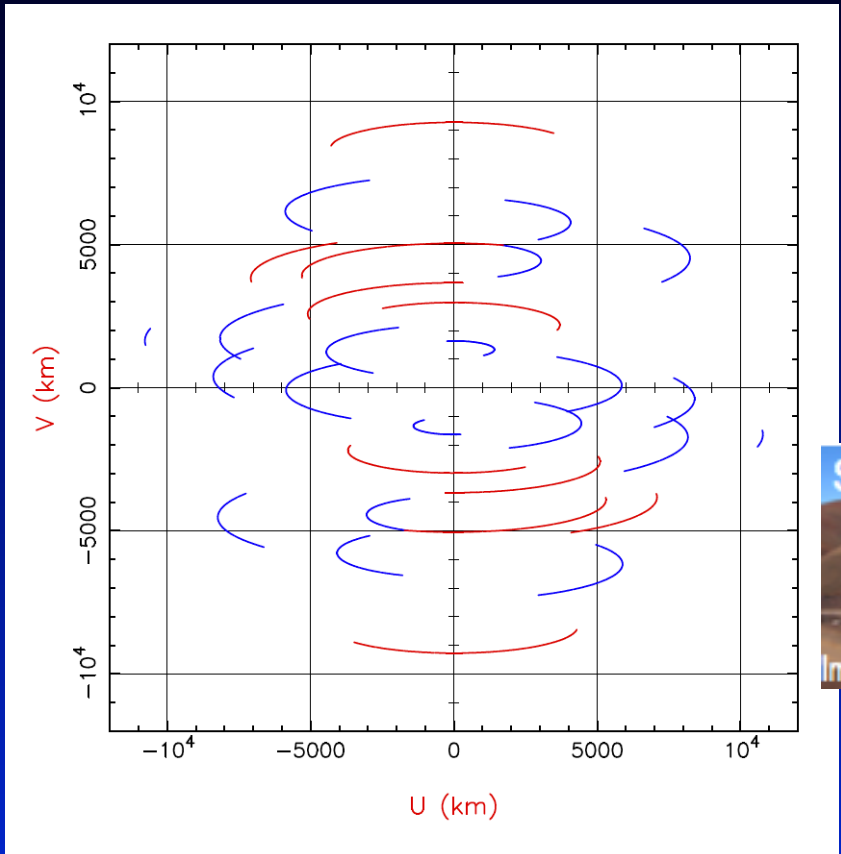


- Huge SMBH mass
  - ✓Comparable angular size with Sgr A*
  - ✓Longer rotation period in accretion disk >> 1 day
- Prominent jet

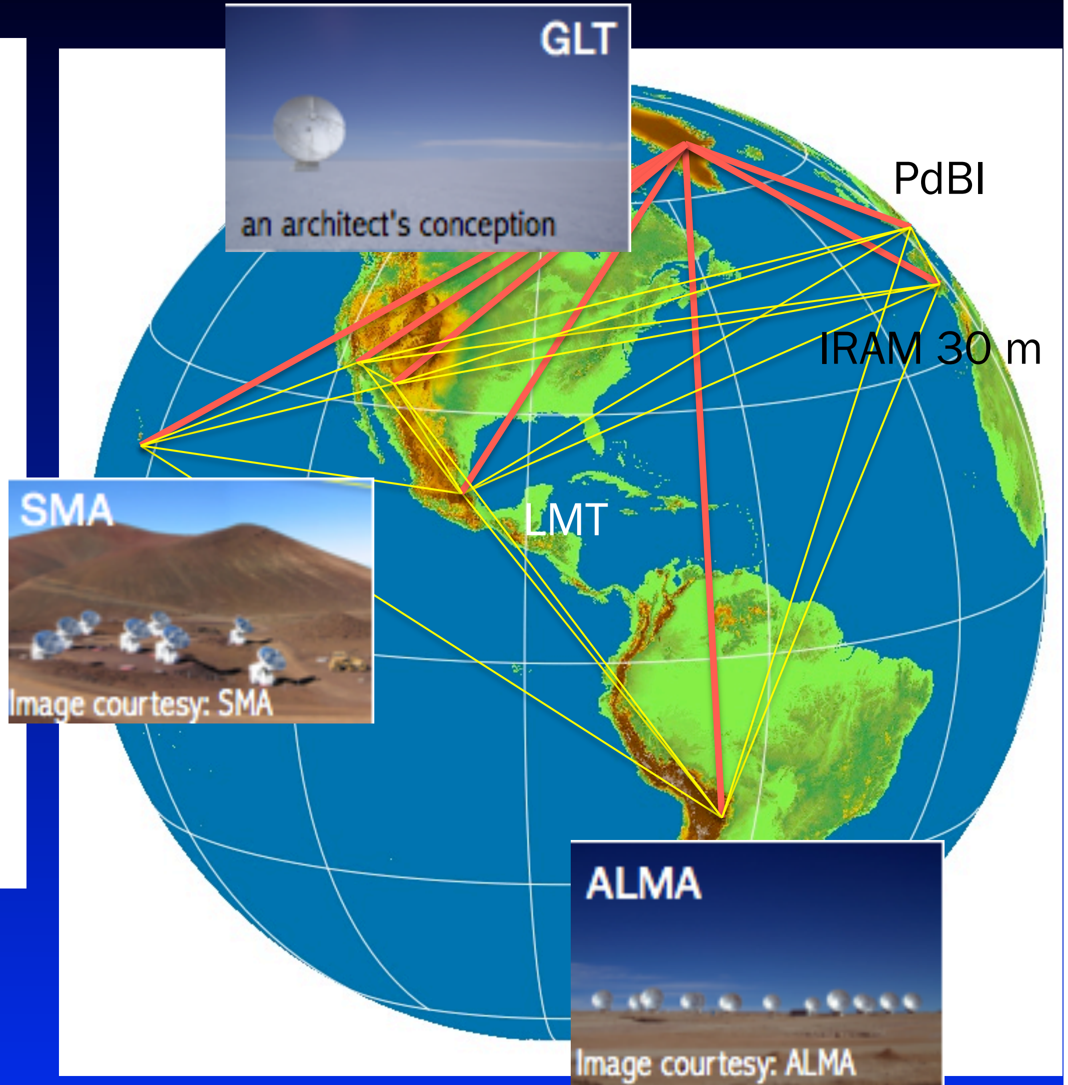
<u>Compared to Sgr A*;</u>

- Easier
  - ✓Period ≈20 days
  - ✓Orientation by jet
- Complex
  - ✓jet

Expected uv coverage with GLT



uv coverage for M 87 with GLT, SMA, ALMA, SMT, LMT and IRAM 30m. The Baselines with GLT are shown in red.



Baselines >9,000 km provides 20 μas resolution at 345 GHz!

Air/Traverse Towards the Summit Station

Facilities at Summit Station

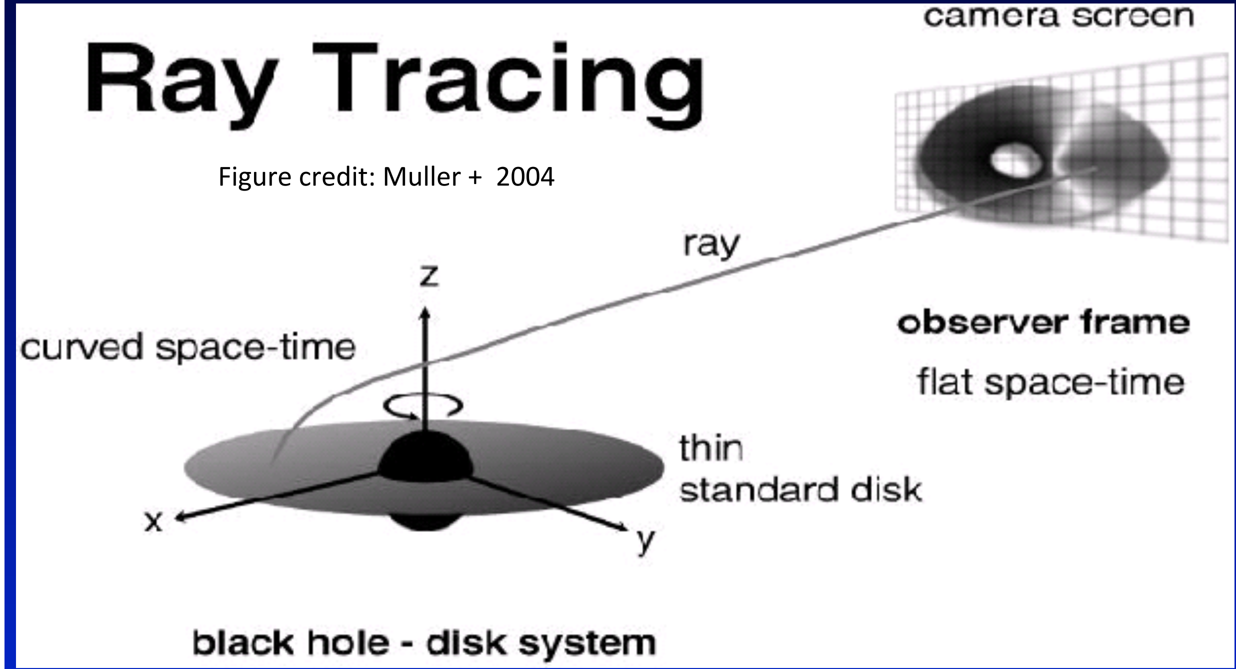
ALMA Phase-up Project

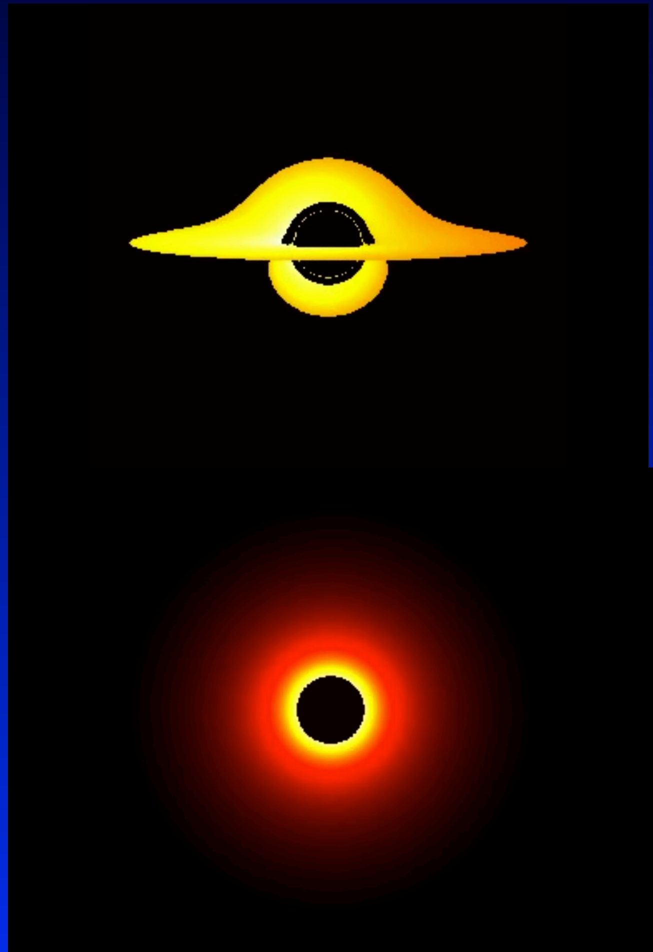
- To get high sensitivity
- Post Processing tasks in DiFX
  - Different sampling rate: 125 vs. 128 MHz
    - Apply Zoom Band Mode in DiFX: ASIAA
  - Polarization conversion: Linear to Circular
    - Direct correlation (XY $\otimes$ RL): MPIfR
- DiFX Enhancements and …
  - DiFX correlator for submm VLBI

Contents

- Introduction
- Submm VLBI Observations
- Greenland Telescope
- Image simulations
- Jet studies
- Summary

Tracing the Photon "Backward in Time"





Disk model provides:

- Matter distribution
- Emissivity/absorption (in local frame)
- Dynamical structure (in local frame)

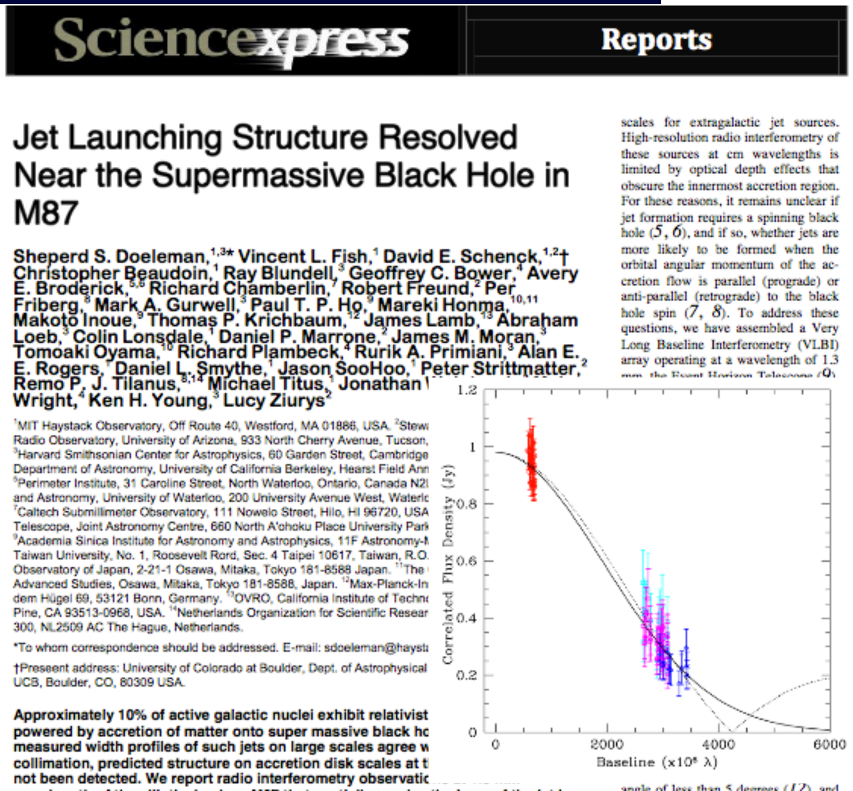
courtesy of Pu H.-Y.

Contents

- Introduction
- Submm VLBI Observations
- Greenland Telescope
- Image simulations
- Jet studies
- Summary

Origin of relativistic jets

Doeleman et al. 2012



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]Stewa… 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…

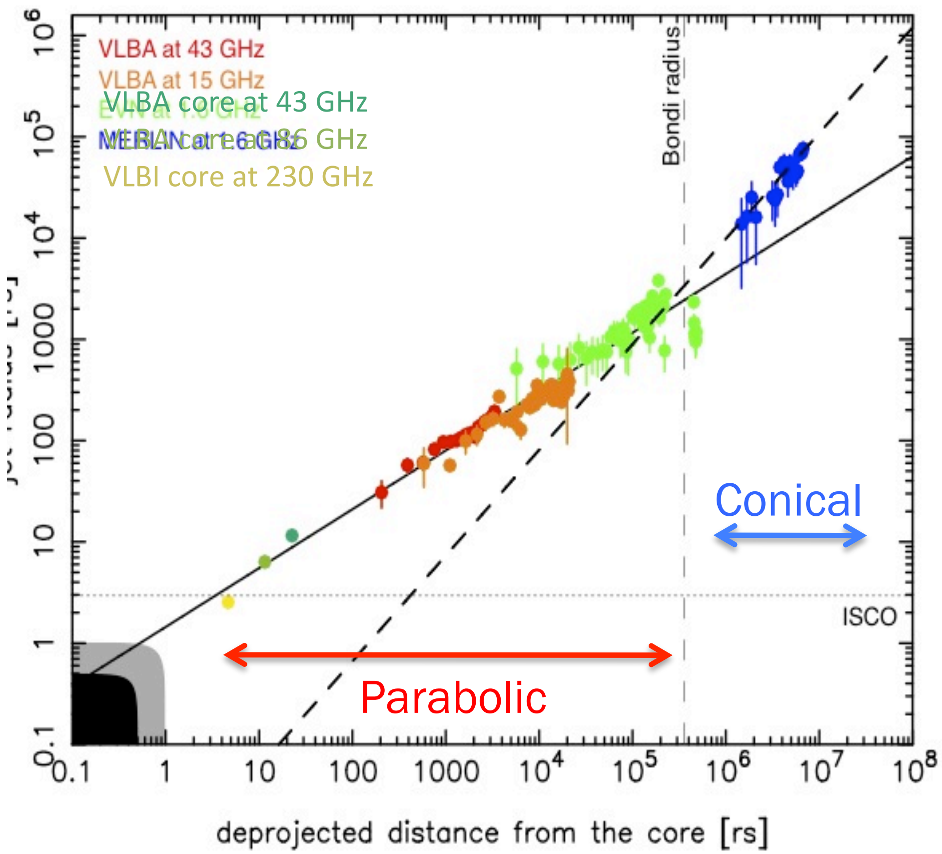
†Preseent address: University of Colorado at Boulder, Dept. of Astrophysical … UCB, Boulder, CO, 80309 USA.

Approximately 10% of active galactic nuclei exhibit relativist… powered by accretion of matter onto super massive black ho… 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 observatio…

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 mm, the Event Horizon Telescope (9)…

Gaussian size ~ 40 μas

Nakamura & Asada 2013

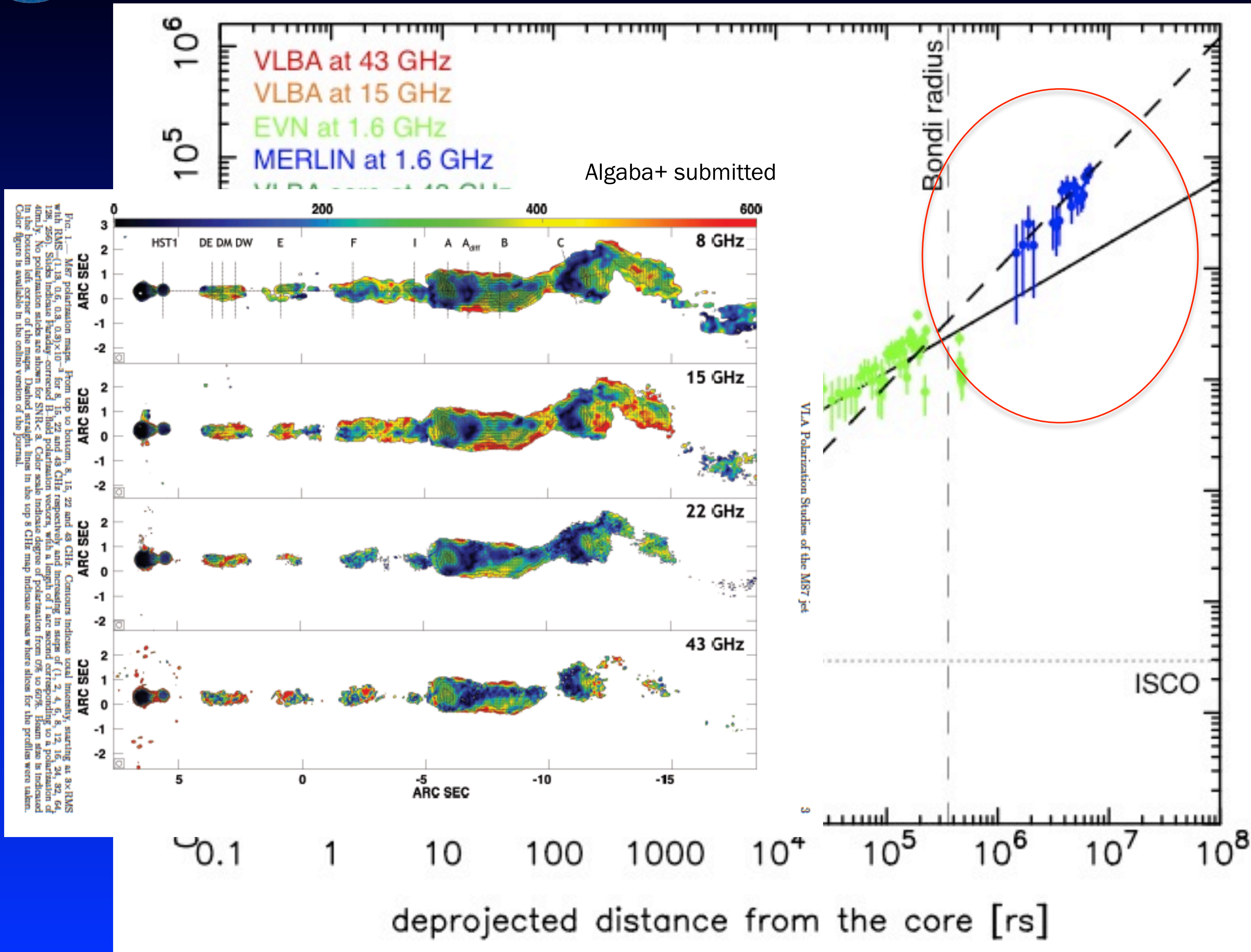


Jet can be described with two power-law lines

Parabolic stream with $z = r^{1.7}$ (- 10^5 r_s)

Conical stream with $z = r^1$ (10^5 r_s –)

Outer jet

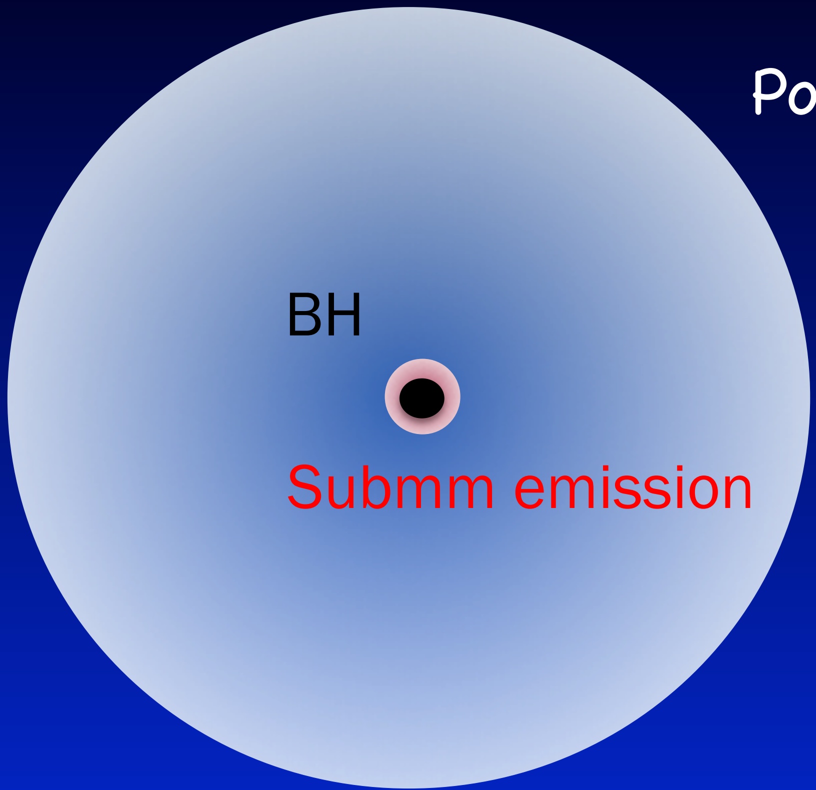

VLBA at 43 GHz
VLBA at 15 GHz
EVN at 1.6 GHz
MERLIN at 1.6 GHz
Algaba+ submitted
Bondi radius
ISCO
8 GHz
15 GHz
22 GHz
43 GHz
HST1
DE DM DW
ARC SEC
VLA Polarization Studies of the M87 jet
deprojected distance from the core [rs]

Contents

- Introduction
- Submm VLBI Observations
- Image simulations
- Jet feature
- Other studies
- Summary

Nature of Accretion Flow

Kuo+ in prep.



Potential energy of accreting matter

Luminosity of AGN

$$L = \eta \dot{M} c^2$$

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

$$\dot{M} = 2.2 \times 10^{-9} \left[1 - (r_{out}/r_{in})^{-(3\beta-1)/2}\right]^{-2/3} \times \left(\frac{M_{BH}}{6.6 \times 10^9 M_\odot}\right)^{4/3} \left(\frac{2}{3\beta - 1}\right)^{-2/3} r_{in}^{7/6} RM^{2/3}$$

Important constraint to accretion disk model and jet-disk connection.

Essential for understanding the BH shadow property.

Summary

- Submm VLBI is capable to image SMBH shadow
- ASIAA is building a submm VLBI station in Greenland: GLT Project to observe M87
- Image simulations to understand physics and observed images
- Jet studies to investigate the origin and MHD performance
- Studies of SMBHs, accretions, …
- Collaborations: RX, DiFX, cold environments, etc.