Super-resolution Imaging of Jet Base and Core of M87 at 10-100 Rs Scale with Sparse Modeling

Fumie Tazaki
(National Astronomical Observatory of Japan)

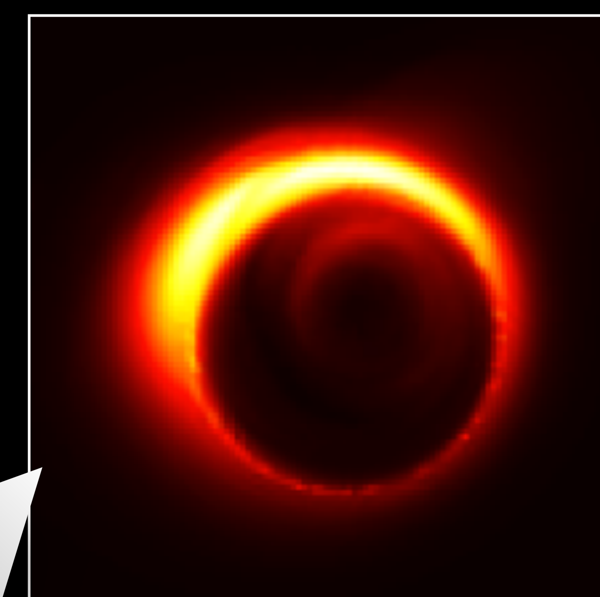
Collaborators:
K. Hada, M. Honma (NAOJ), K. Akiyama (MIT),
S. Ikeda (ISM), K. Kuramochi (U of Tokyo/NAOJ)

Sparse Modeling

We have developed "sparse modeling" imaging technique of the radio interferometry to get a snapshot of black hole shadow with Event Horizon Telescope (EHT).

Honma+2014, Ikeda+2016, Akiyama+2017bc, Kuramochi+2017 (in prep.)

mm/sub-mm VLBI with ALMA (2017 April ~)
angular resolution: ~20 μas (~1mm/9000km)

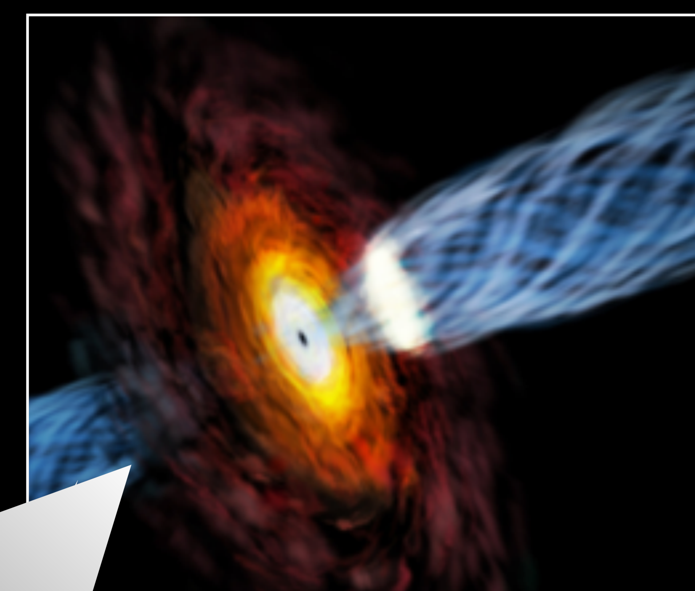


Dexter+2012, Akiyama+2017

Purpose of Our Study

The first application of new imaging technique to "real" observational data with non-EHT VLBI, targeting AGN jet base.

The Very Long Baseline Array (VLBA)
angular resolution: ~ 70 μas (~3mm/8600km)



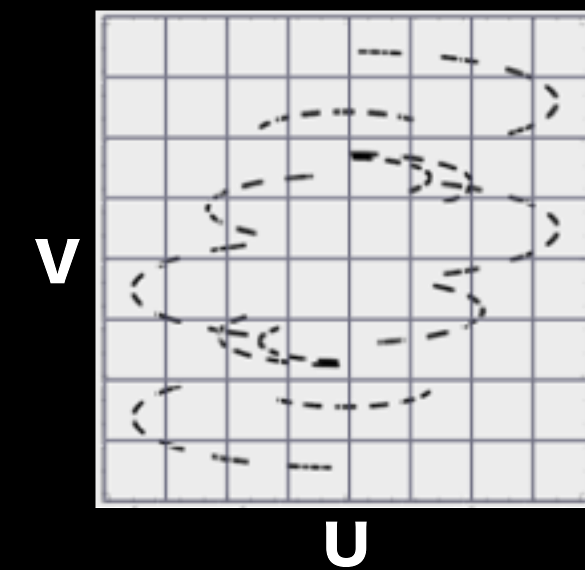
Credit: NAOJ/AND You Inc.

Interferometry Imaging

- Image is obtained with 2D Fourier transformation of observed complex visibility.

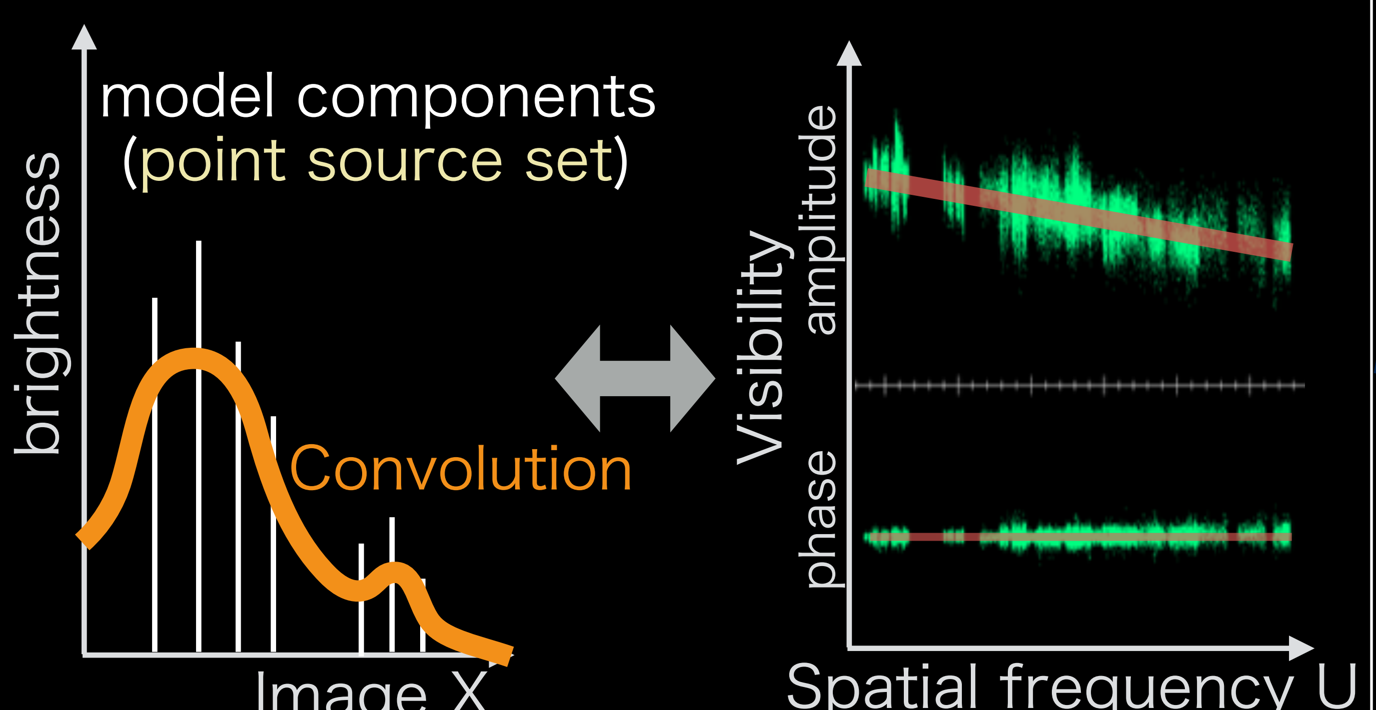
$$I_\nu(x,y) = \iint S_\nu(u,v) e^{-2\pi i(ux+vy)} du dv$$

- Complex visibilities are sampled in UV (spatial frequency: baseline vectors seen from the target source) plane.
- Sampled complex visibilities are imperfect.
  → "Ill-posed problem"



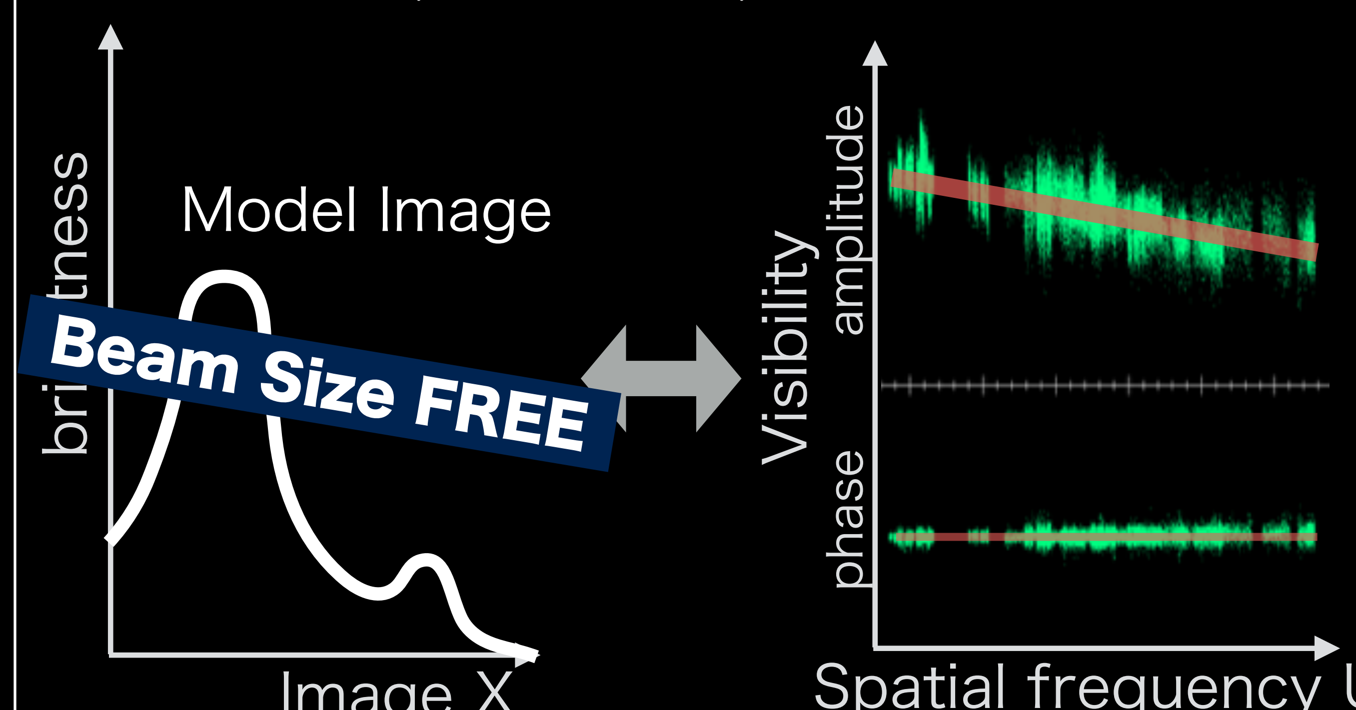
Conventional Technique (CLEAN)

1. Make model components with point sources.
2. Convolve with synthesized beam.



New Technique (Sparse Modeling)

1. Make a smooth model image directly, which reproduces complex visibilities.



Sparse Modeling Technique

Sparsity of Image:

Small number of pixels have effective information.

- Most pixels have zero value.

  → L1-norm regularization

- Most differences between two adjacent pixel values are zero.

  → Total Squared-Variation (TSV) regularizations

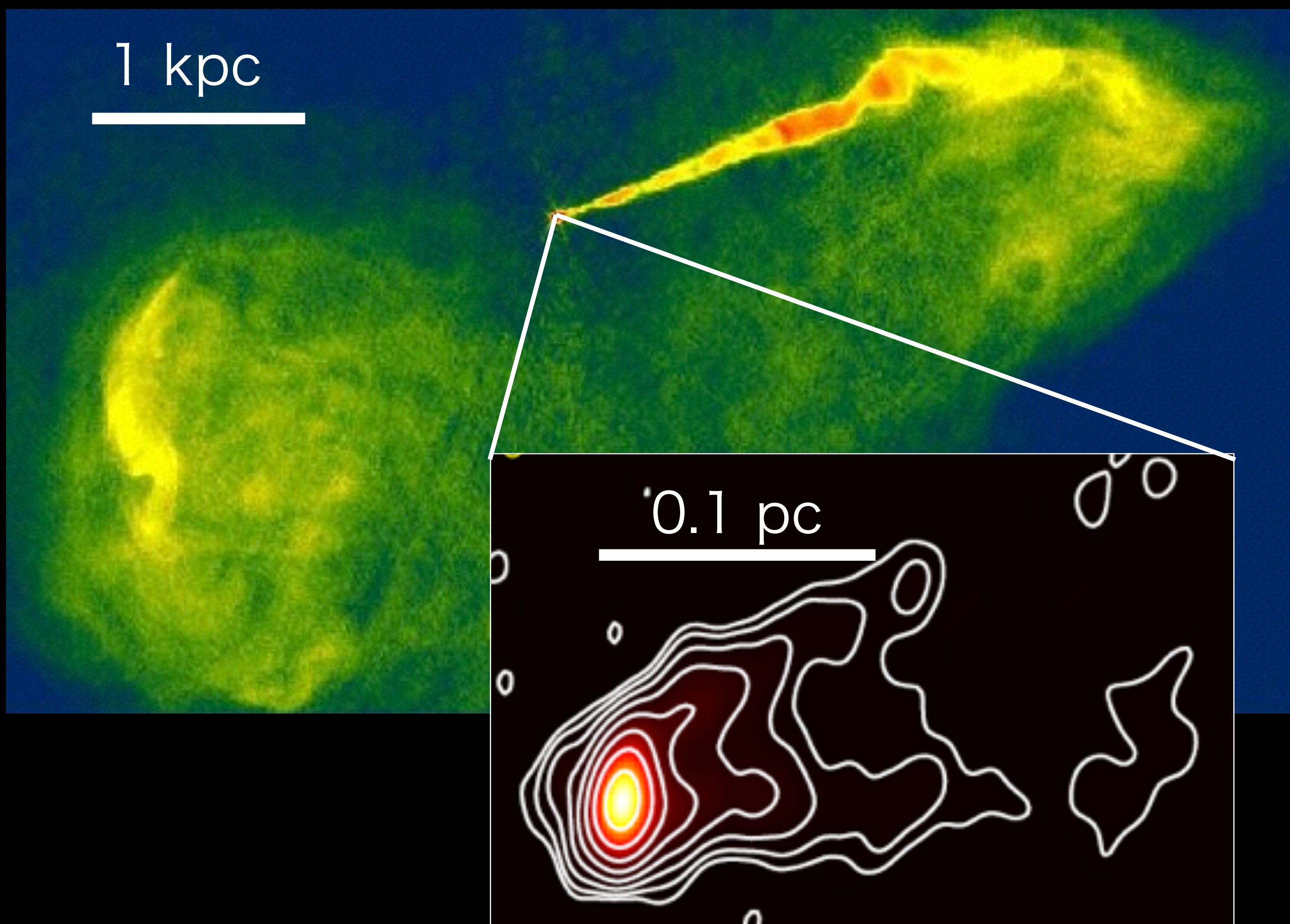
→ Smooth image

Minimizing equation

$$cost = ||\mathrm{S} - \mathrm{AI}||_2^2 + \lambda_1 ||\mathrm{I}||_1 + \lambda_{\mathrm{TSV}} \sum_{i,j} (|I_{\mathrm{i+1,j}} - I_{\mathrm{i,j}}|^2 + |I_{\mathrm{i,j+1}} - I_{\mathrm{i,j}}|^2)$$

chi-squared **L1-norm** **TSV**

M87 Observation



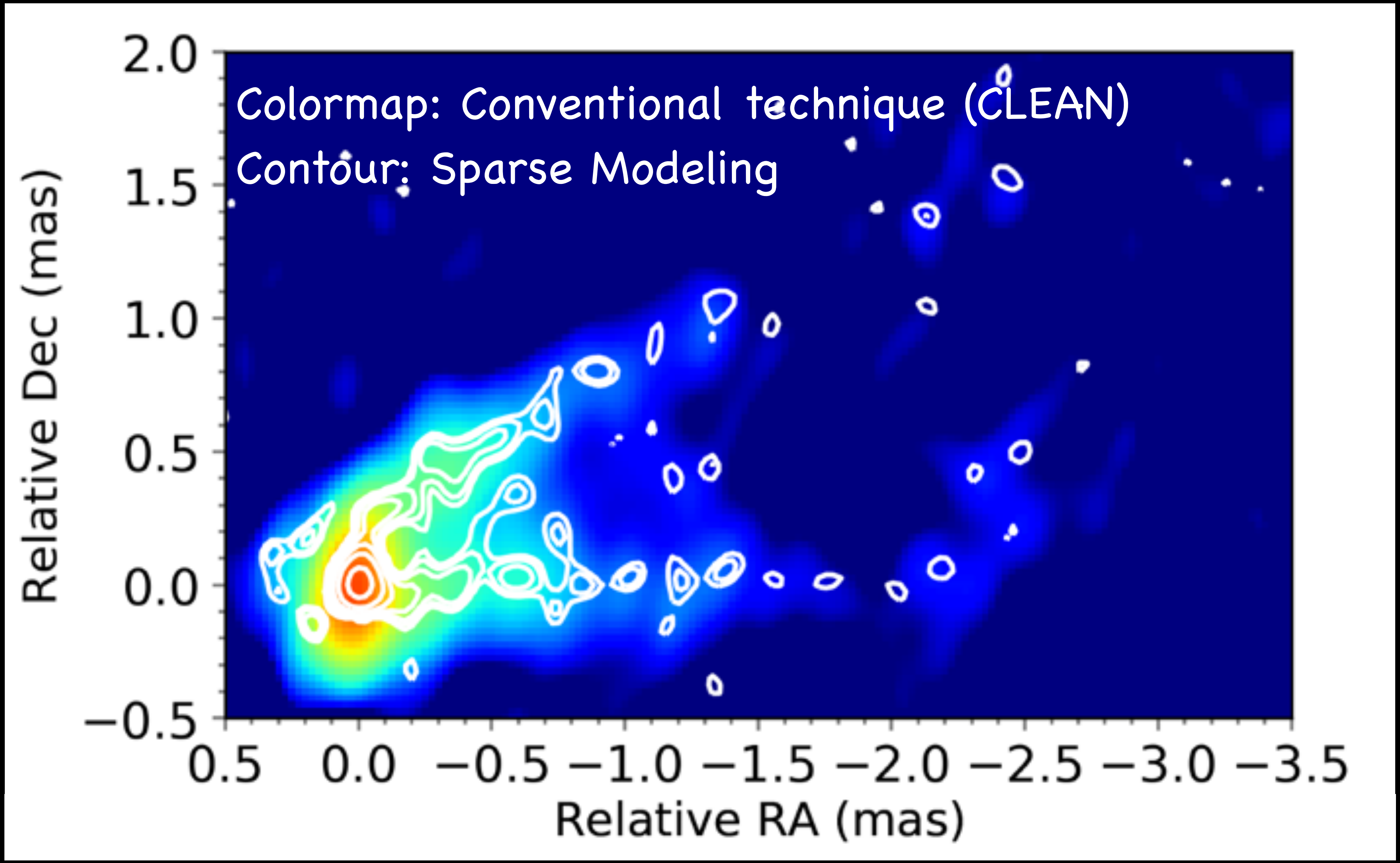
M87

- Suitable target for **jet base study**
- One of the closest powerful radio jet
- $D = 17$ Mpc
- $M_{BH} = (3\text{–}6) \times 10^9\ M_{sun}$
- 1 mas ~ 0.08 pc ~ 140 R_s

Toward revealing the mechanism of collimation and acceleration of jets

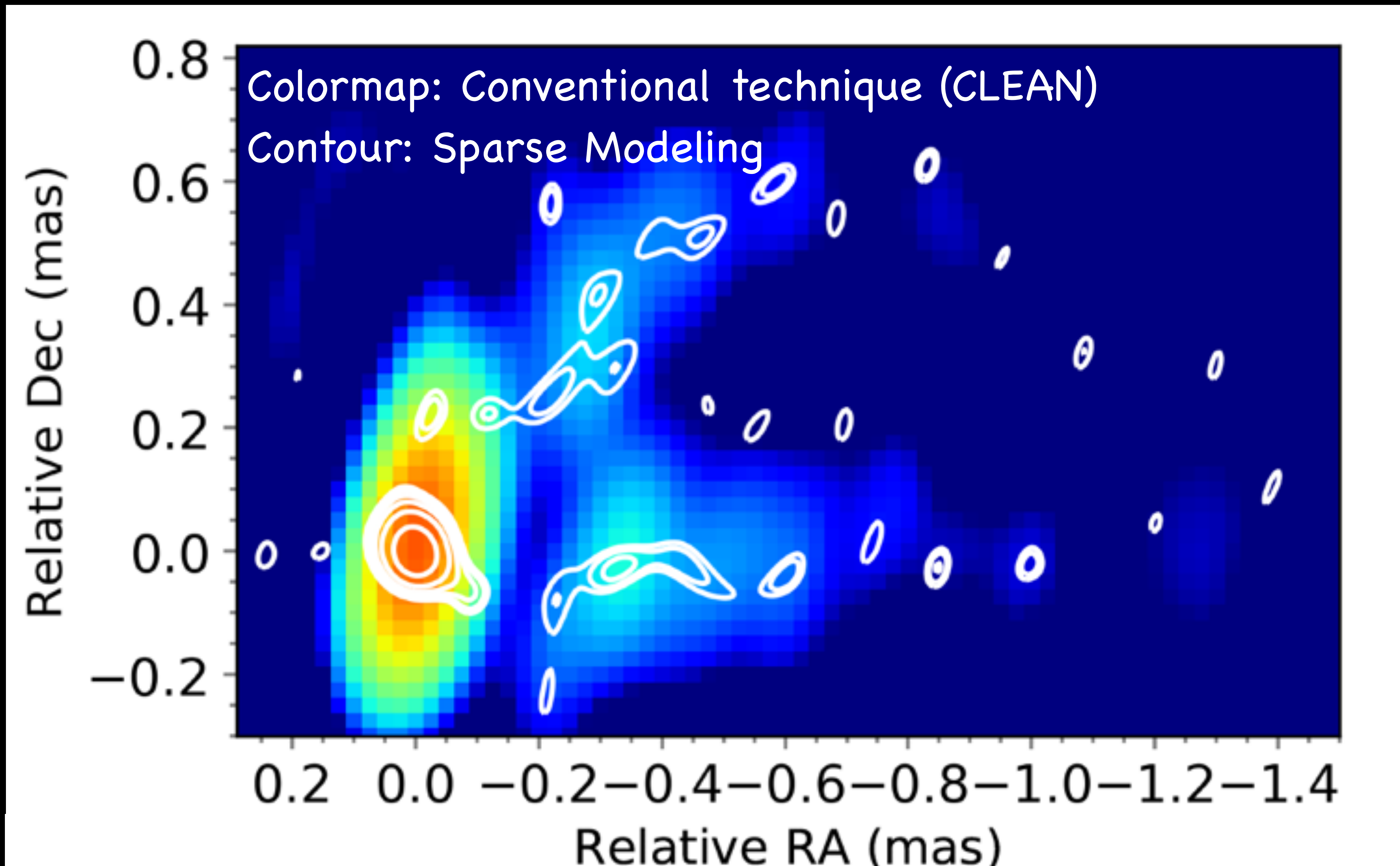
- 43 GHz: VLBA observation in Apr. 2010 (Hada+2011)
- 86 GHz: VLBA + GBT observation in Feb. 2014 (Hada+2016)

Imaging Results (43 GHz)



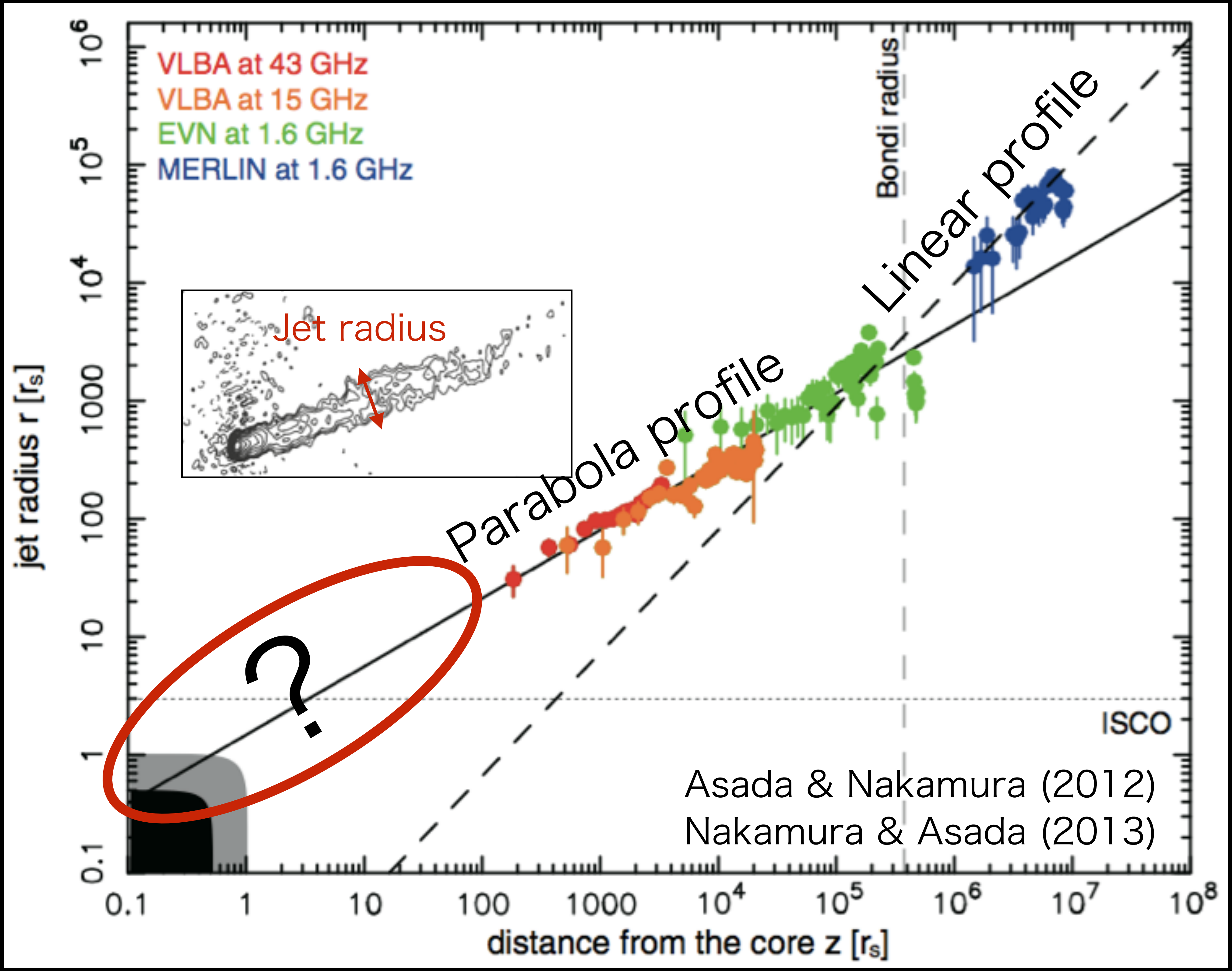
- Successfully reconstruct image of 43 GHz jet
- Clear counter-jet structure
- Continuous double-ridge structure from the core to ~ 1 mas

Imaging Results (86 GHz)

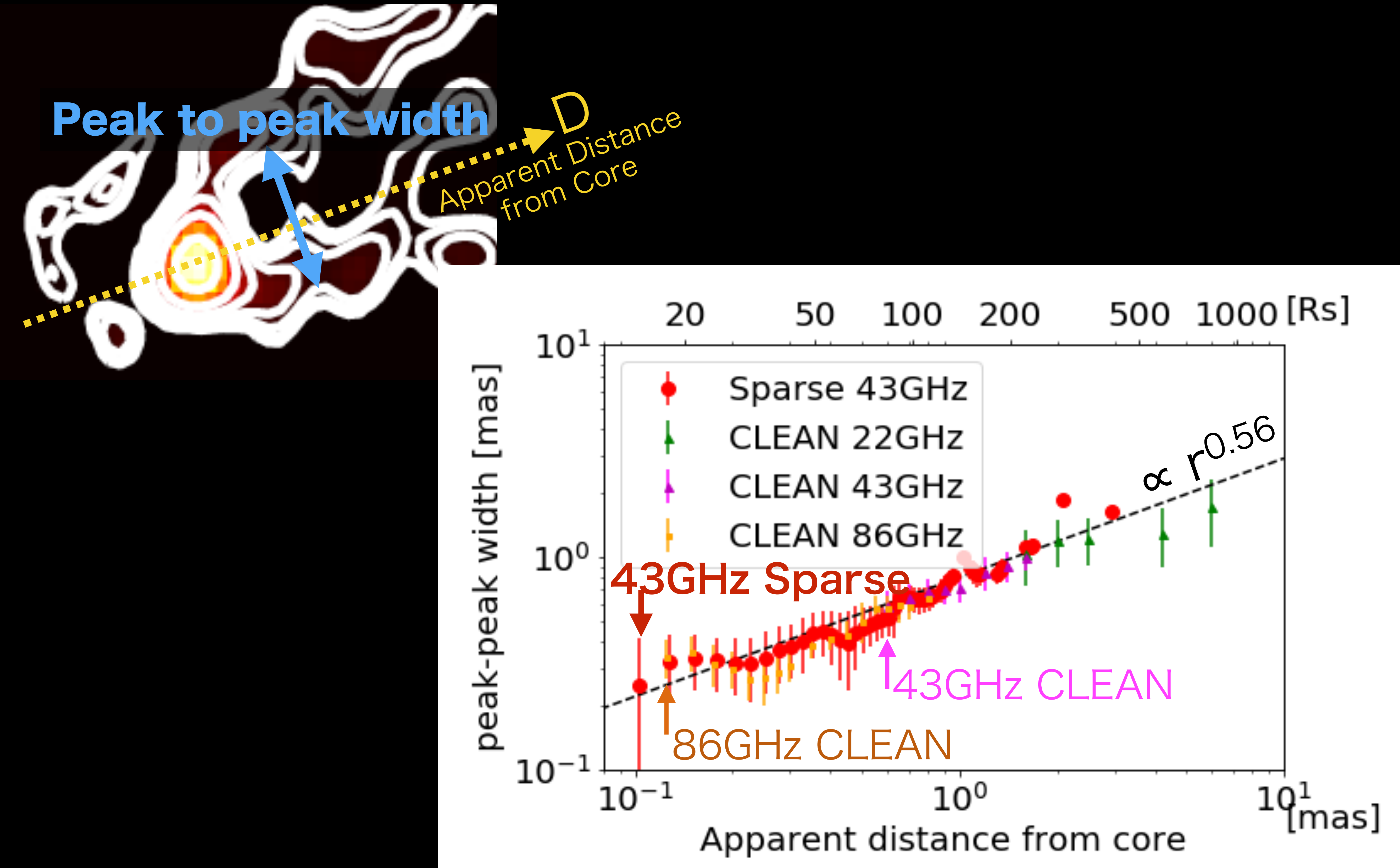


- Successfully reconstruct images of 86 GHz jet
- Extremely narrow ridges
- Discontinuity of ridge structure?

Jet Collimation Profile



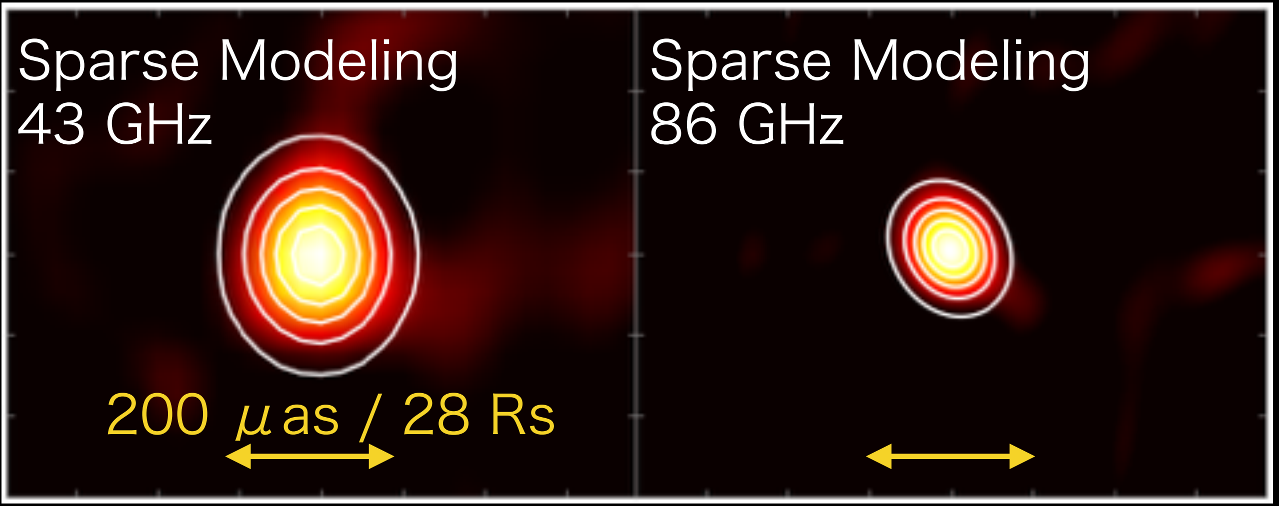
Peak to peak Profile



Resolution Improvement

- Sparse modeling image achieves several times higher resolution than CLEAN image.

resolve core region directly

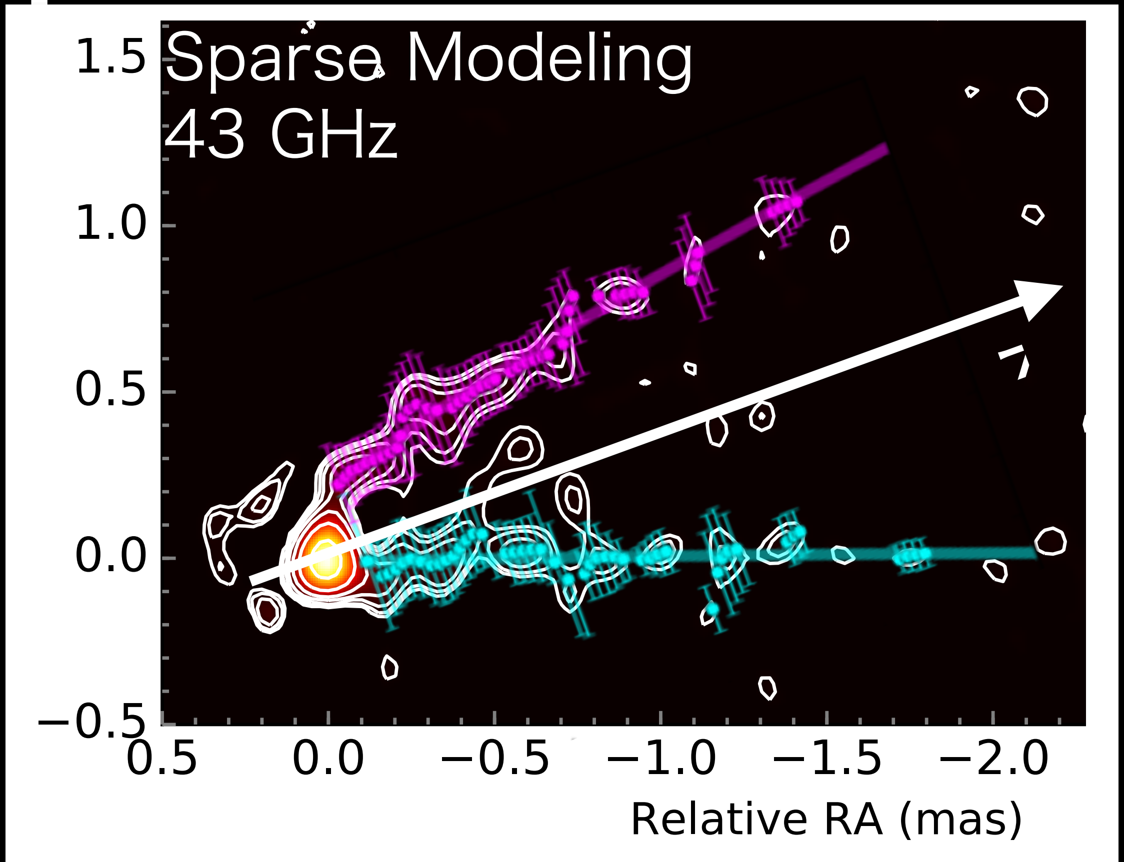


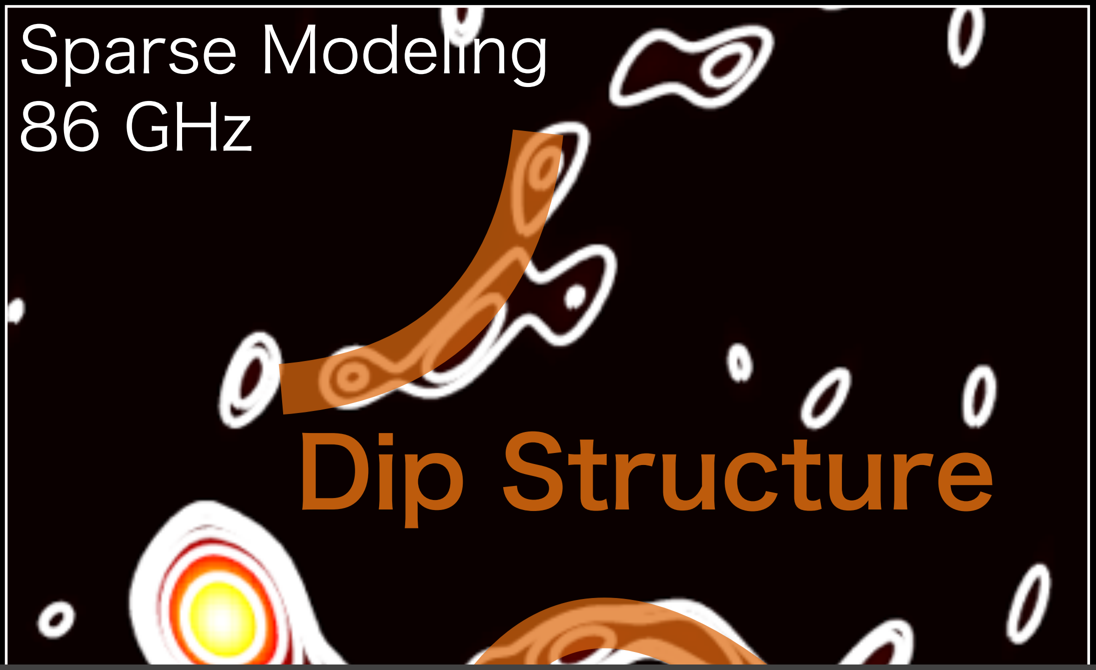
Sparse Modeling	θ_{maj} x θ_{min}
@43GHz	**160 x 130 μas (22 x 18 R_s)**
@86GHz	**90 x 80 μas (13 x 11 R_s)**

Get multi-wavelength core information with EHT.

Future Prospects

- With better quality (higher SNR) data
  - Jet ridge width and profile measurement.
  - Connection (or disconnection) between core and jet base.
- With 230 GHz data by EHT
  - Core spectrum
  - → magnetic field strength of core
- With monitoring data
  - Time variation of dip structure in the jet base.





Sparse modeling technique expands jet study!

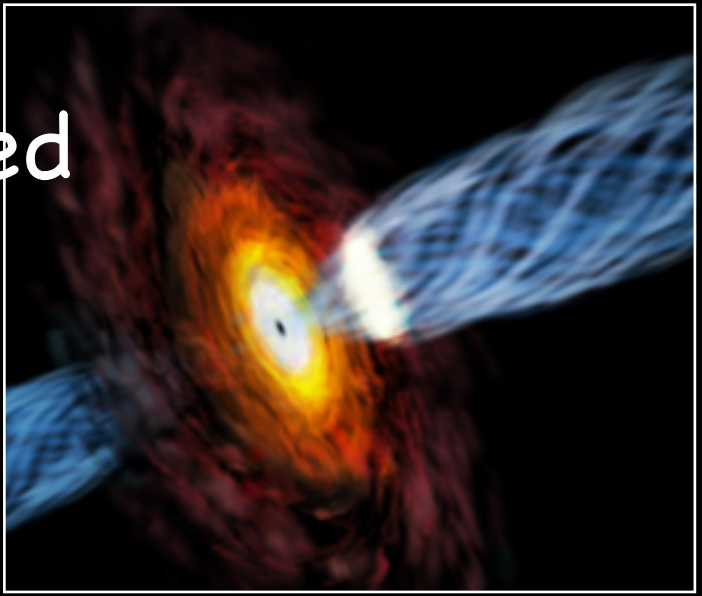
Summary

- Successfully reconstruct sparse modeling images of M87 jet base.

- Sparse modeling images are more highly resolved than CLEAN images, which enables to measure the double ridge structure in the jet base several times closer to the core.

- Core size is directly measured with images.

- Core and jet physics can be investigated with sparse modeling in the future.



Credit: NAOJ/AND You Inc.