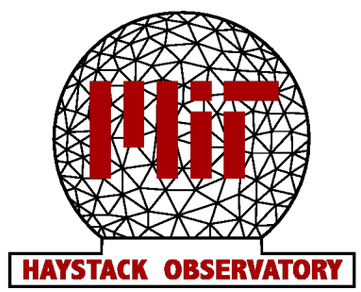
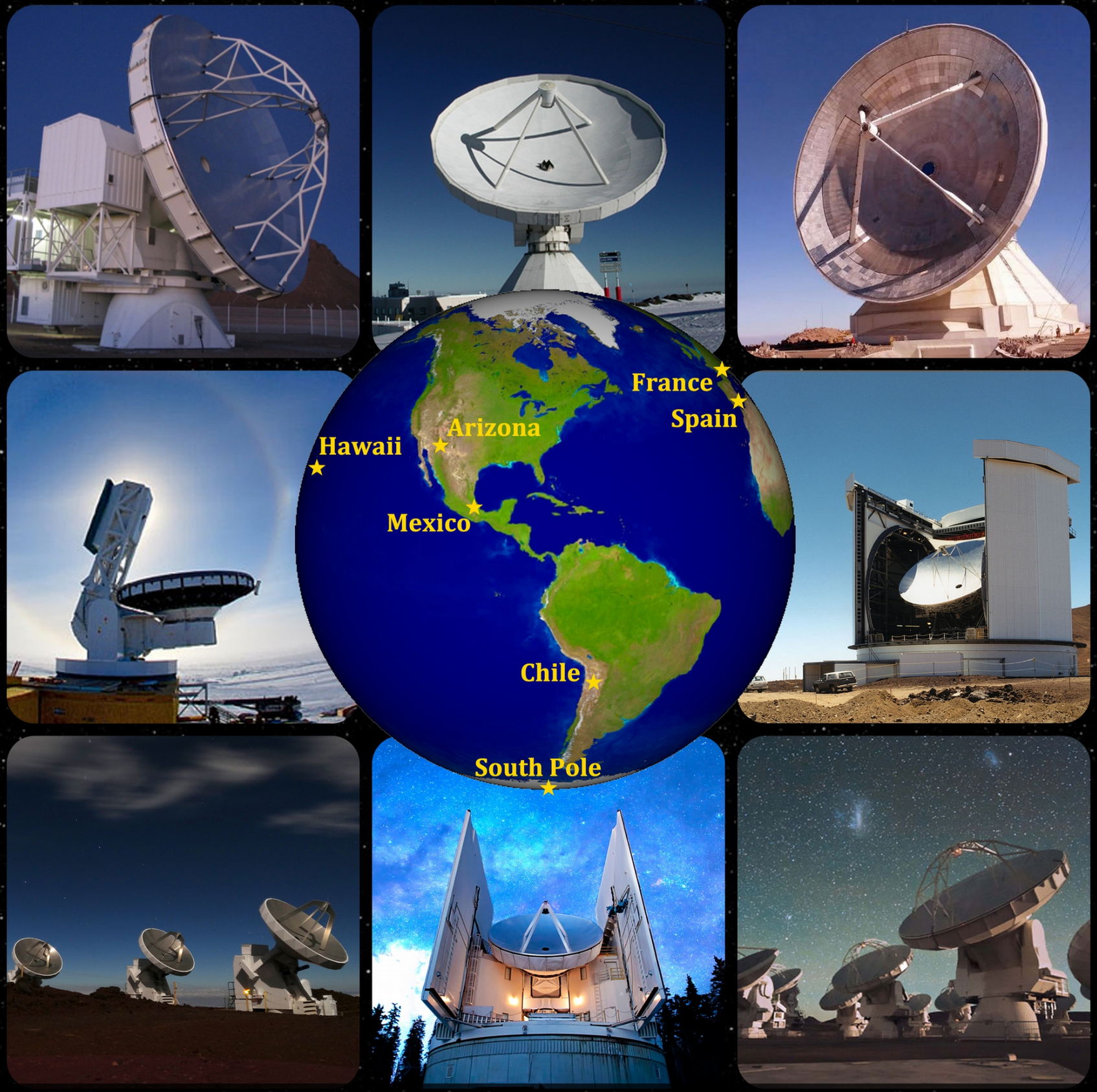
Observing Active Galactic Nuclei with the Event Horizon Telescope

Vincent Fish
MIT Haystack Observatory

1. What the EHT brings to AGN sources
2. Reconstructing VLBI images



The Event Horizon Telescope



1.3 mm

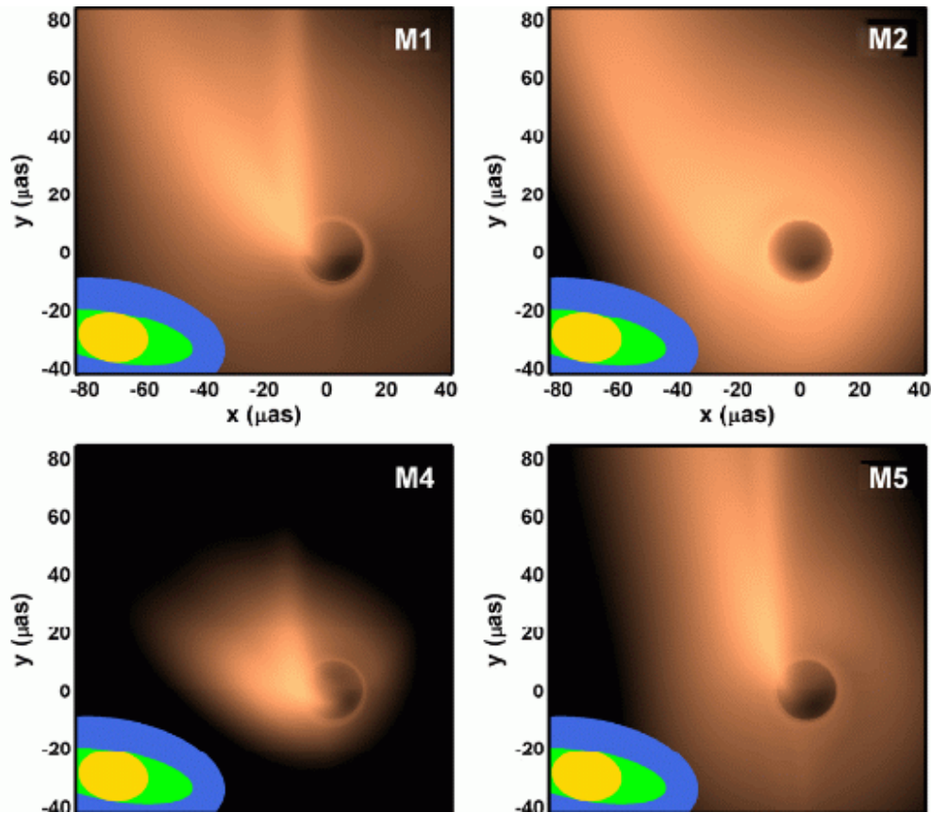
Image Credit: APEX, IRAM, G. Narayanan, J. McMahon, JCMT/JAC, S. Hostler, D. Harvey, ESO/C. Malin

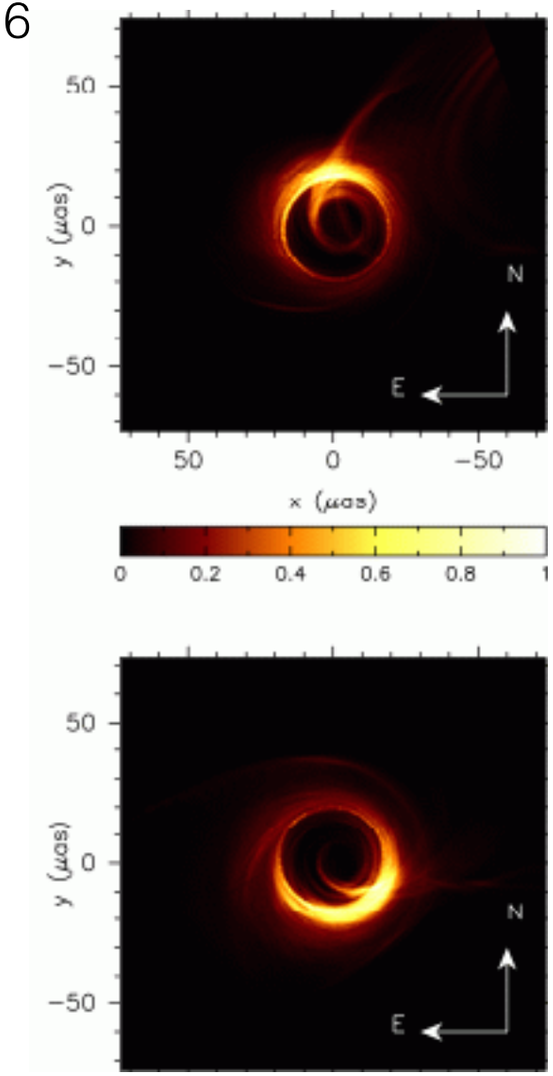
Event Horizon Telescope

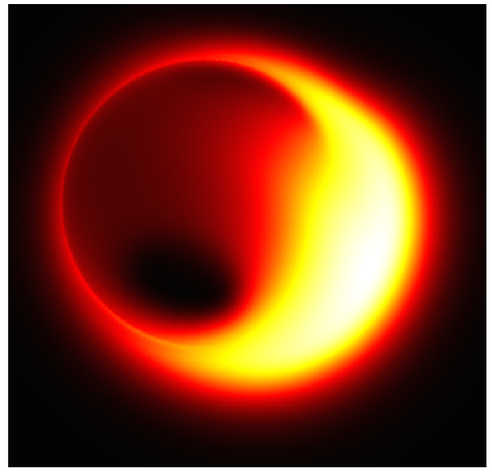
Primary goal: Image the environment immediately surrounding the black hole in Sgr A* and M87

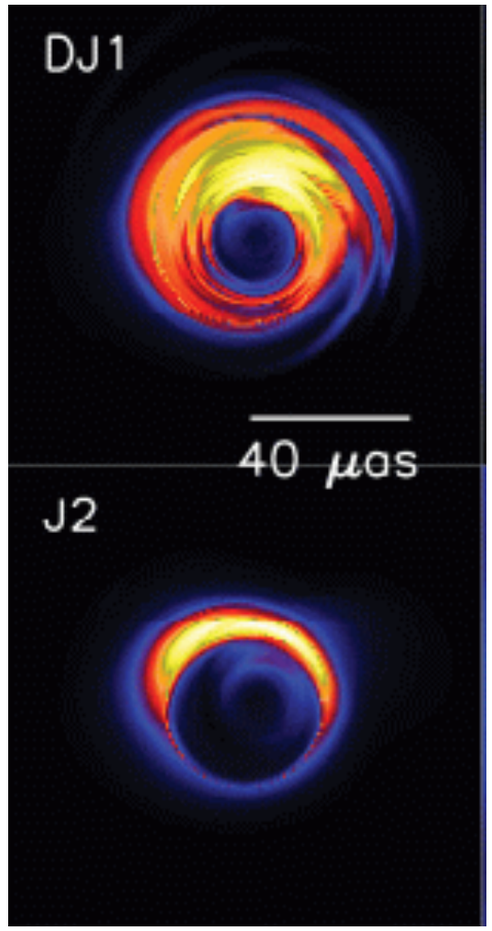
Resolution: better than ~25 μas

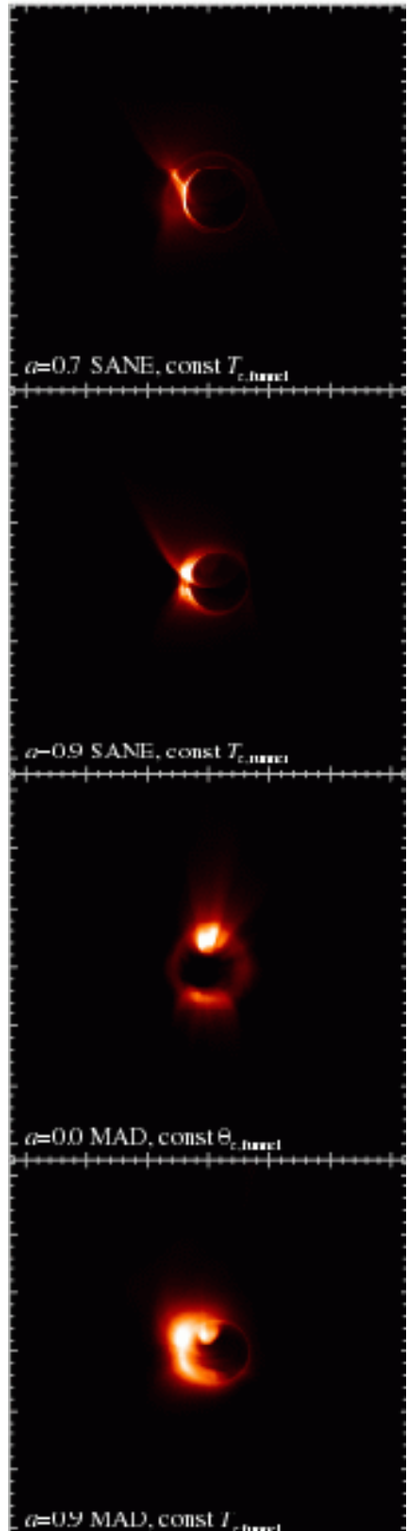
Models: Broderick+ 2009, 2016; Dexter+ 2012;
Chan+ 2015; Moscibrodzka+ 2016











The EHT's Greatest Hits, Volume 1

- Strengthened case for event horizons in Sgr A*, M87

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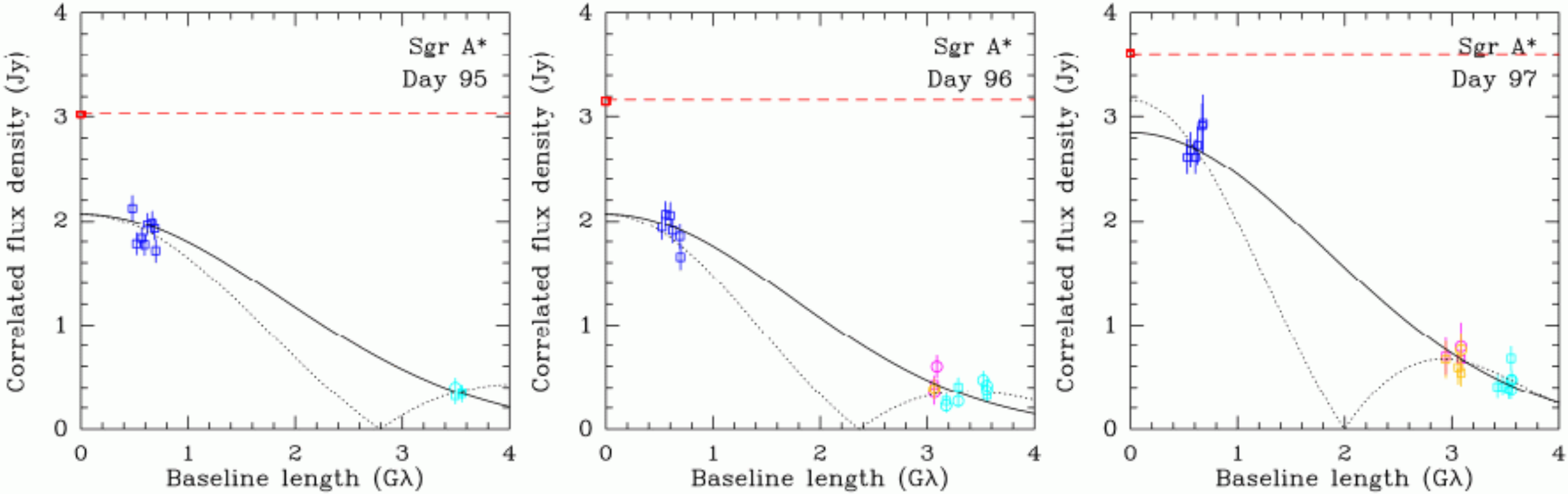

Fish+ 2011

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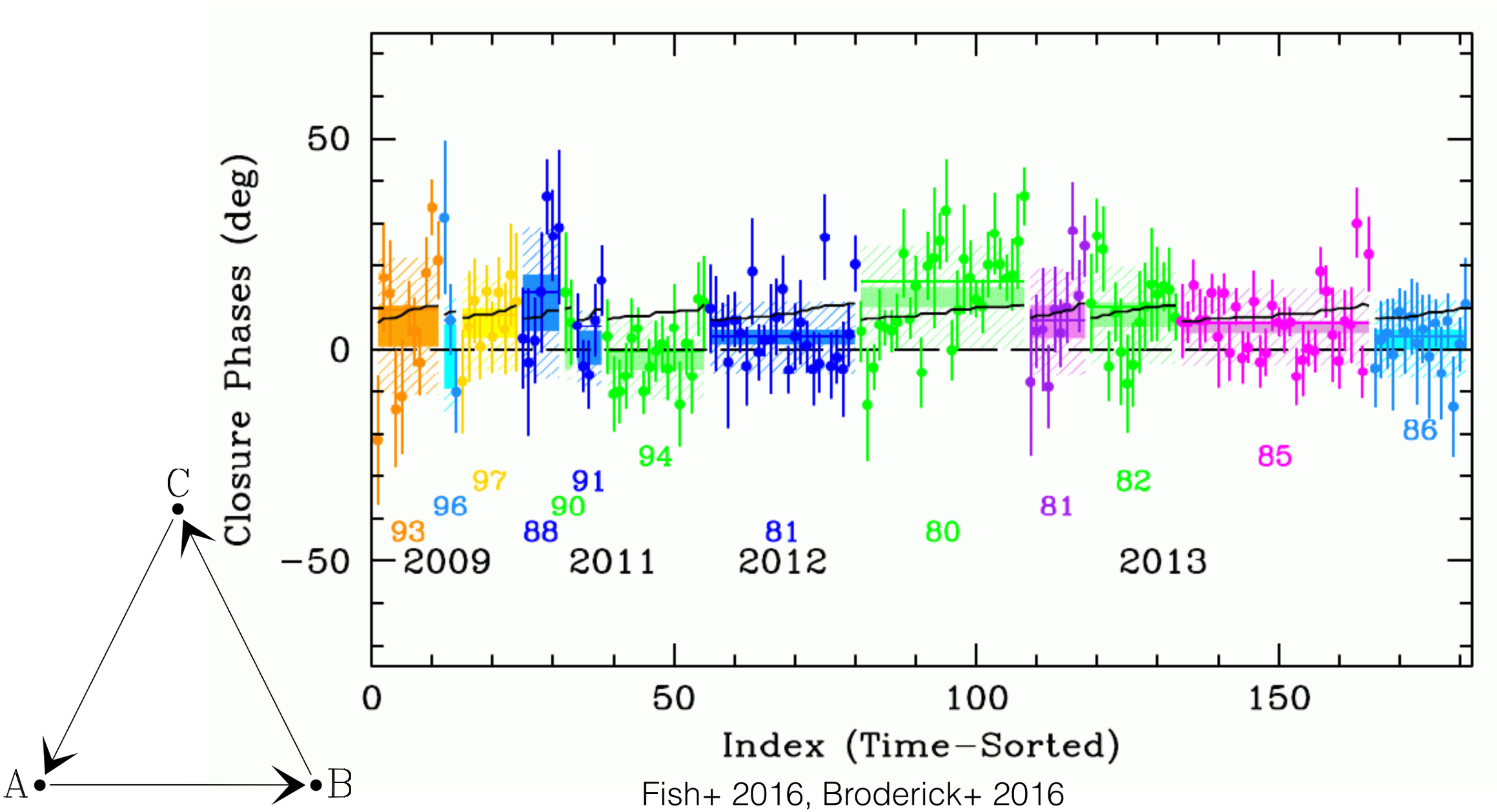
- Found persistent asymmetric structure on scales comparable to the shadow size



Fish+ 2016, Broderick+ 2016

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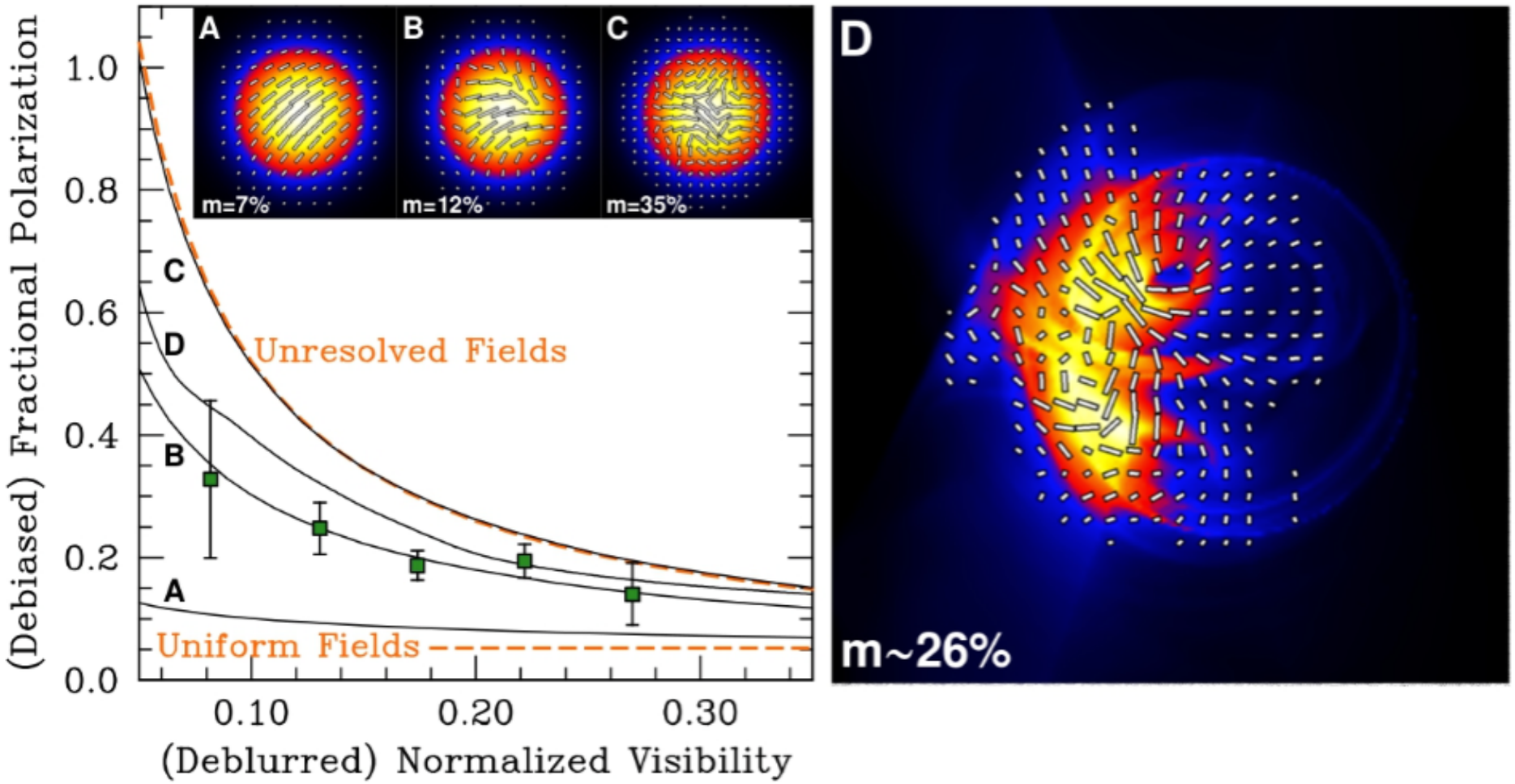

Johnson+ 2015

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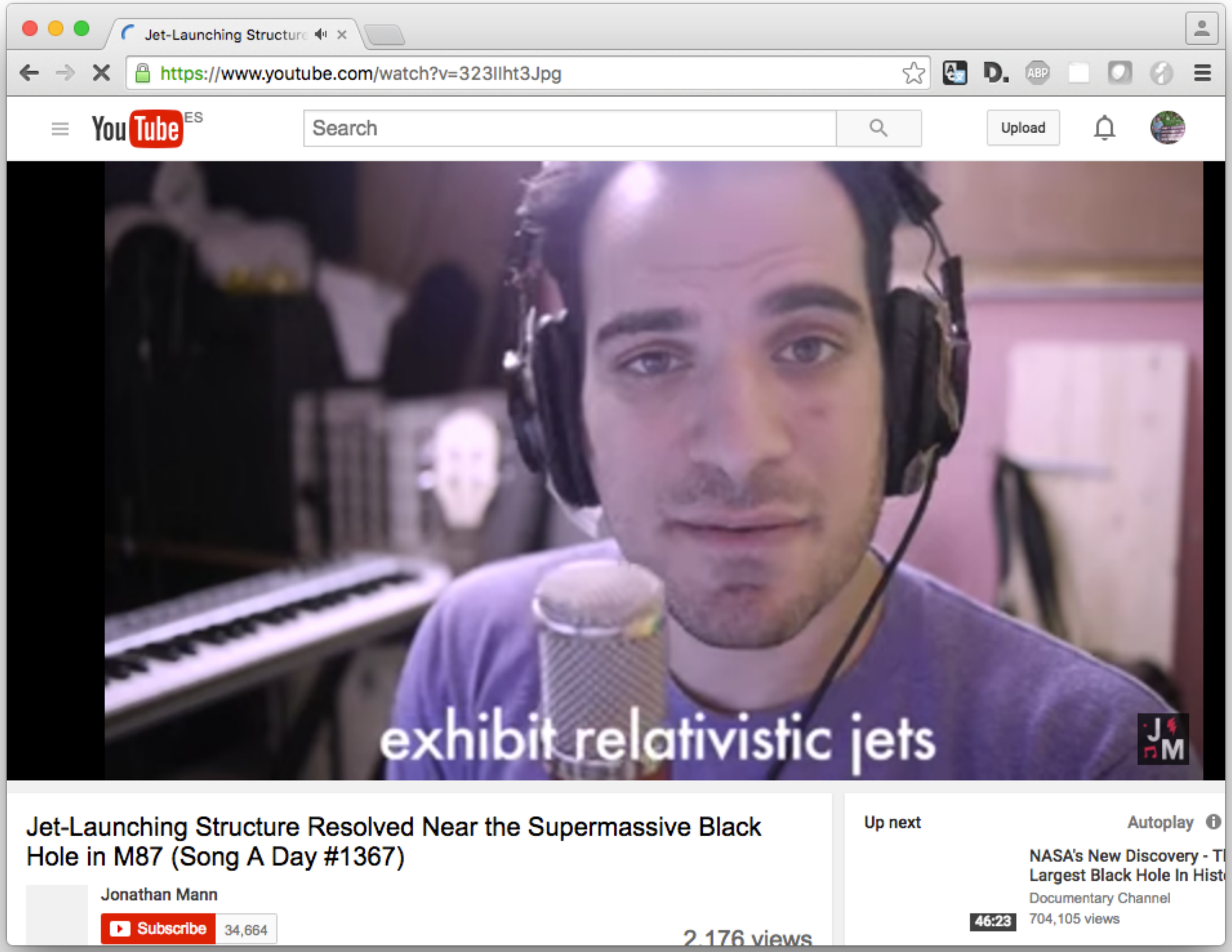

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- Look for Volume 2 after April 2017 (subject to ALMA TAC approval)

Event Horizon Telescope

Primary goal: Image the environment immediately surrounding the black hole in Sgr A* and M87

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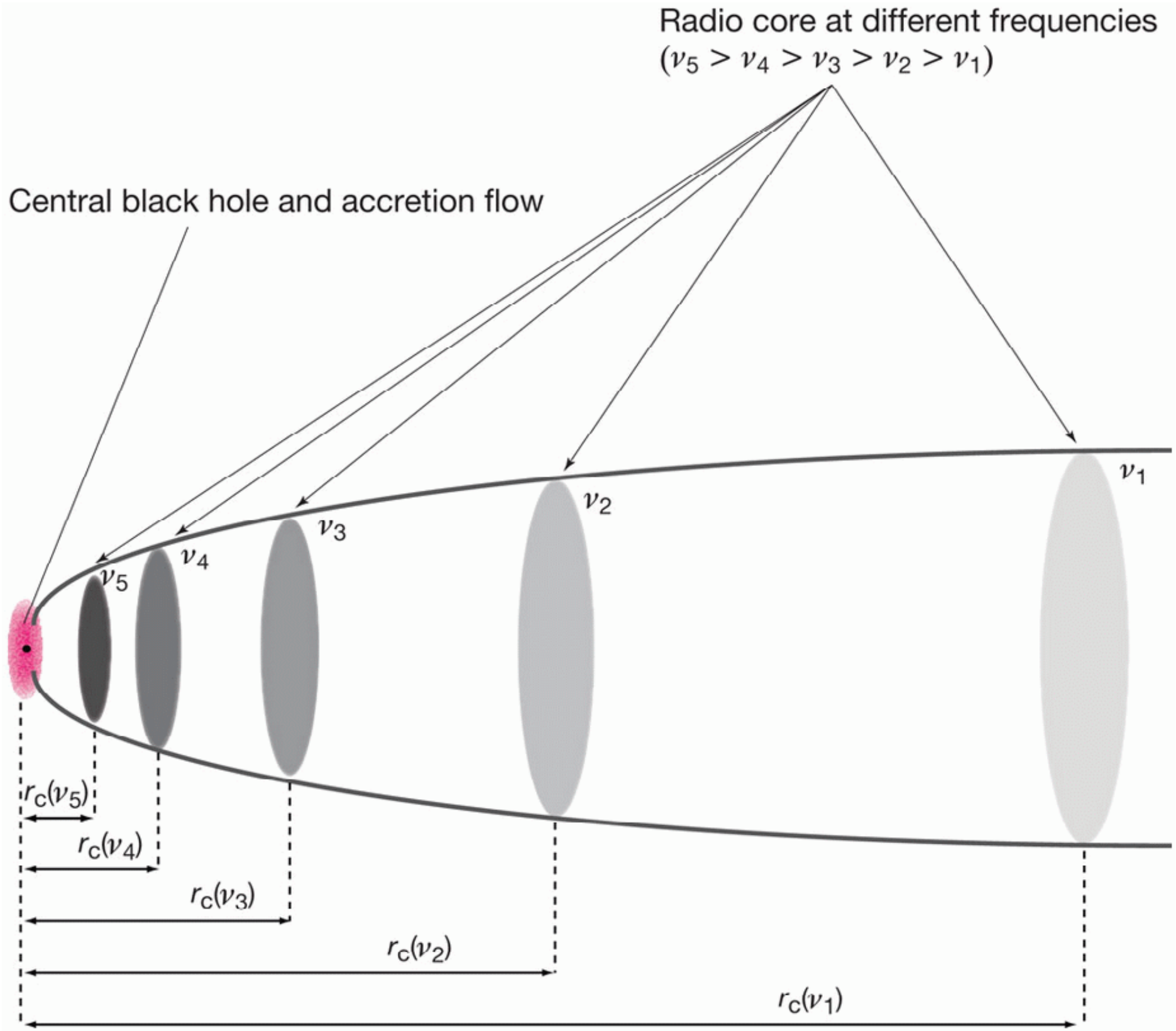
Also useful for AGN studies:

- Sensitive to emission deep within the core

Optical Depth



Hada+ 2011

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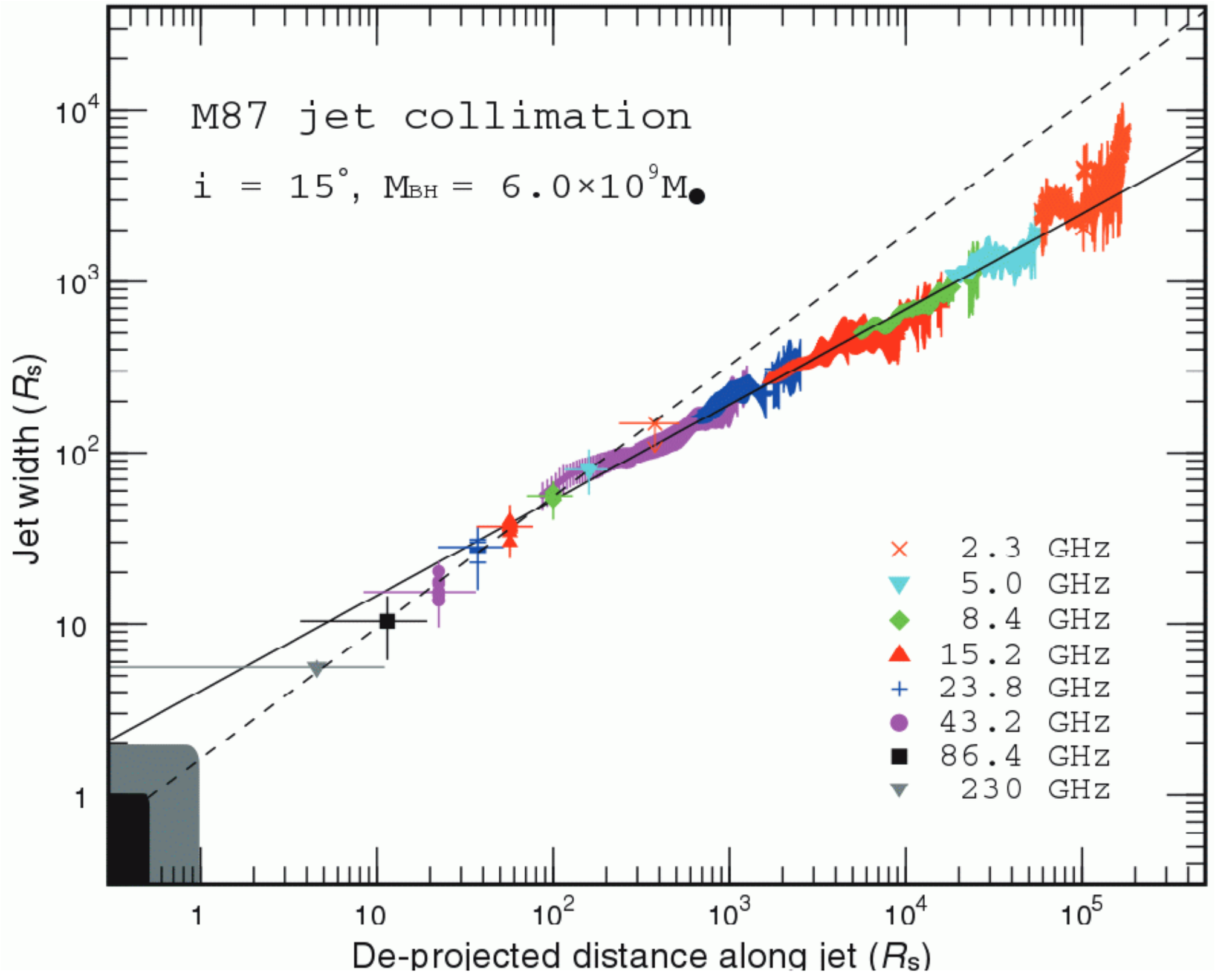
Optical Depth & Resolution



Hada+ 2013

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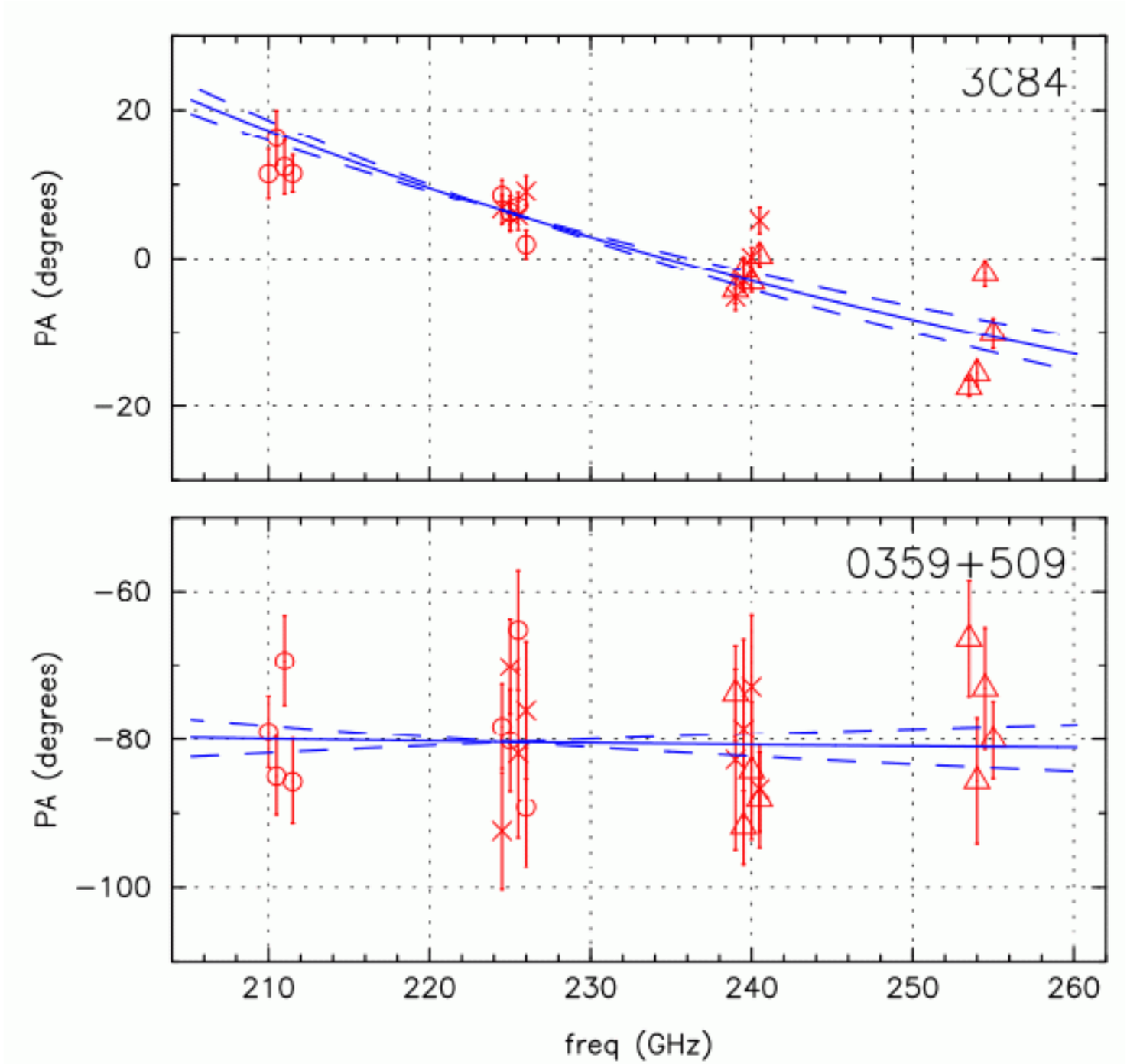
- Extremely high angular resolution
- Observation of high rotation measure regions

Rotation Measure

3C84: RM ~ 10^6 rad m^{-2}



Plambeck+ 2014

EHT+ALMA Call for Proposals

National Radio Astronomy Observatory
Enabling forefront research into the Universe at radio wavelengths

1mm VLBI Call for Proposals: Introduction

by Davis Murphy — last modified Mar 22, 2016 by Claire Chandler

The National Radio Astronomy Observatory (NRAO) invites proposals for 1mm Very Long Baseline Interferometry (VLBI) using the phased output of the Atacama Large Millimeter/submillimeter Array (ALMA) and the Event Horizon Telescope (EHT) during ALMA Cycle 4. Up to 5% of ALMA Cycle 4 observing time is available for VLBI, shared between 1mm and 3mm. *Note that the EHT without phased ALMA is not being offered as part of this Call.*

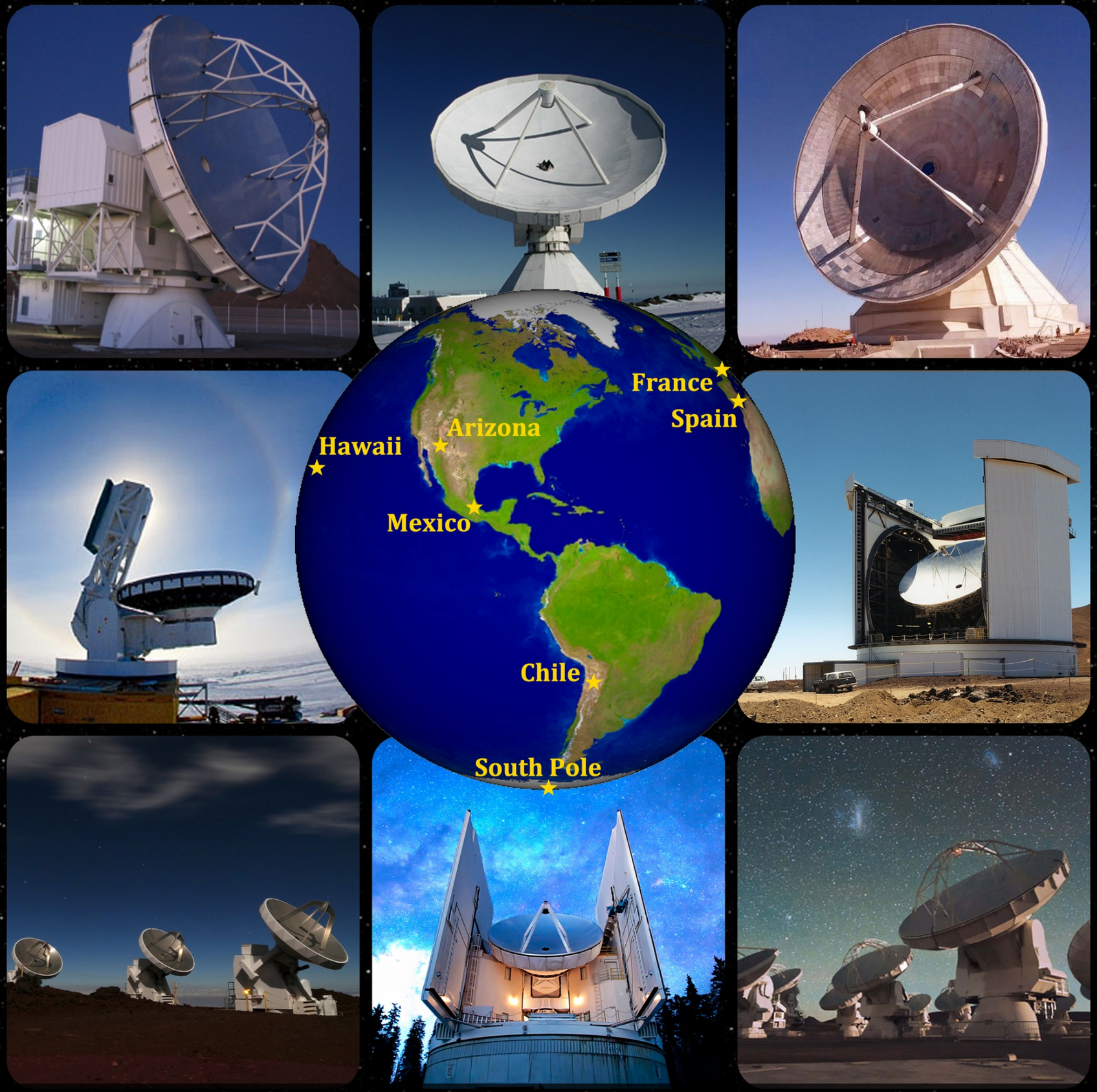
The submission deadline for 1mm VLBI proposals is Thursday, 28 April 2016, at 23:59 UT.

An overview of phased ALMA and the EHT is provided below, and further technical information to support proposal preparation is available at the Proposal Preparation link above, and at the EHT web page for 1mm VLBI with ALMA and the EHT.

The same proposal (including scientific and technical justification) must be submitted in response to this Call for Proposals as that submitted to the ALMA Cycle 4 Call to request phased ALMA. Proposal preparation is therefore through the ALMA Observing Tool (OT), which requires registration through the ALMA Science Portal beforehand. The ALMA OT Quickstart Guide provides more information on how to use OT. Proposers will then submit a PDF copy of their full ALMA Cycle 4 proposal through the 1mm VLBI Proposal Submission website by the above deadline. Additional information on proposing to ALMA may be found in the ALMA Cycle 4 Proposer's Guide.

Proposers who need assistance with proposal preparation or have questions regarding the Call should

The Event Horizon Telescope



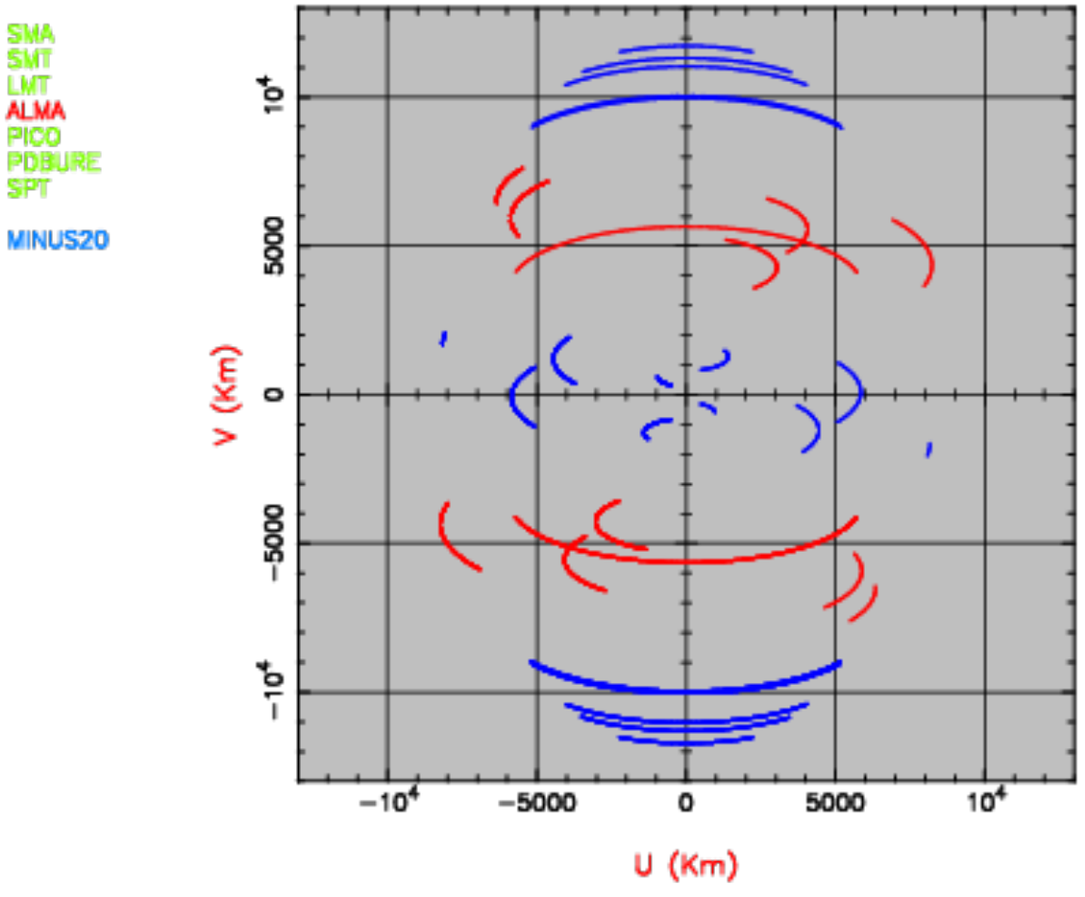
1.3 mm

Image Credit: APEX, IRAM, G. Narayanan, J. McMahon, JCMT/JAC, S. Hostler, D. Harvey, ESO/C. Malin

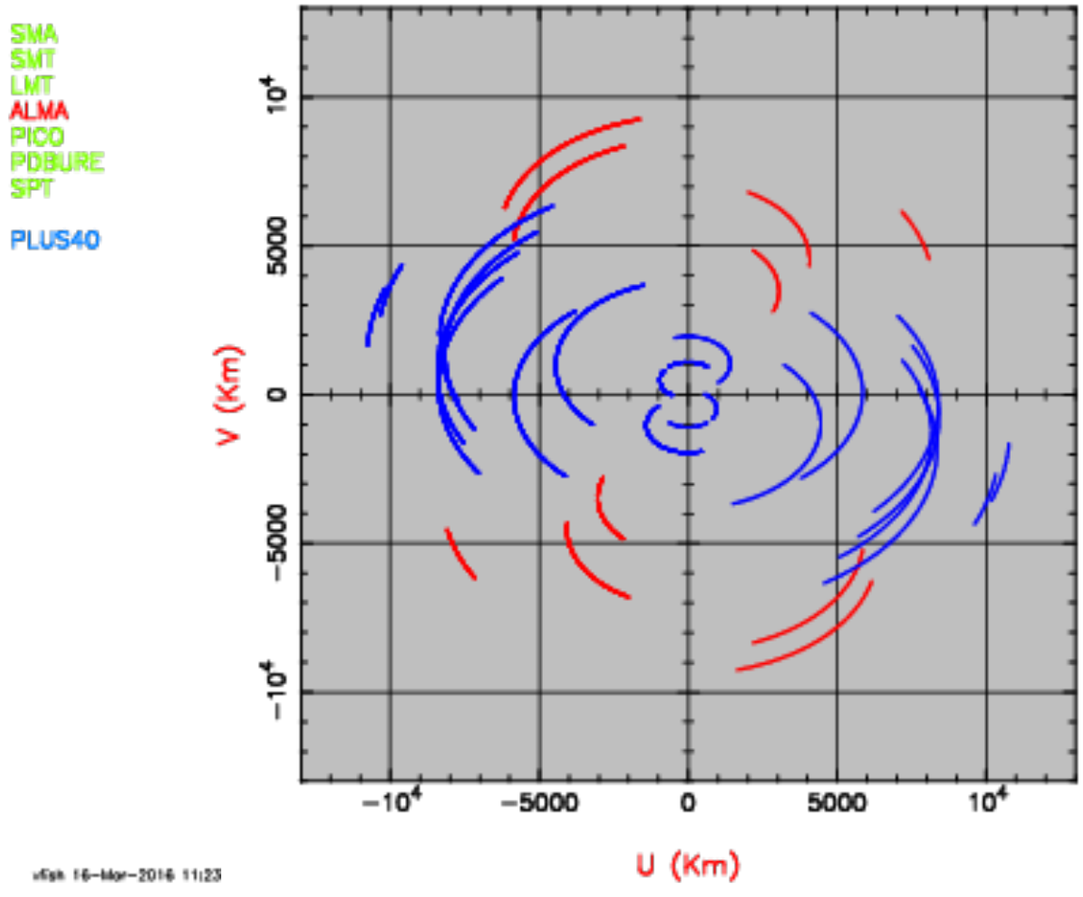
Baseline Coverage

ALMA provides the sensitivity and baseline coverage necessary for imaging AGN sources

Dec -20°



Dec +40°



Imaging

Reconstructing images is critical for making full use of EHT

Challenges to imaging:

- Sparse baseline coverage
- Atmospheric turbulence — must use good observables (e.g., polarimetric ratios, closure quantities)
- Predicted mix of smooth structure and sharp edges
- Need for (some) super-resolution
- Sgr A*: interstellar scattering and rapid variability

Standard radio interferometry imaging techniques (e.g., CLEAN) are not optimal for the EHT

Imaging techniques developed for the EHT can improve reconstructions at other wavelengths too

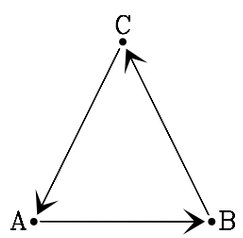
Imaging: Optical Interferometric Techniques

Optical interferometry (OI) faces similar challenges:

- Sparse baseline coverage
- Even more severe phase corruption

OI prefers forward imaging techniques over deconvolution

Examples:

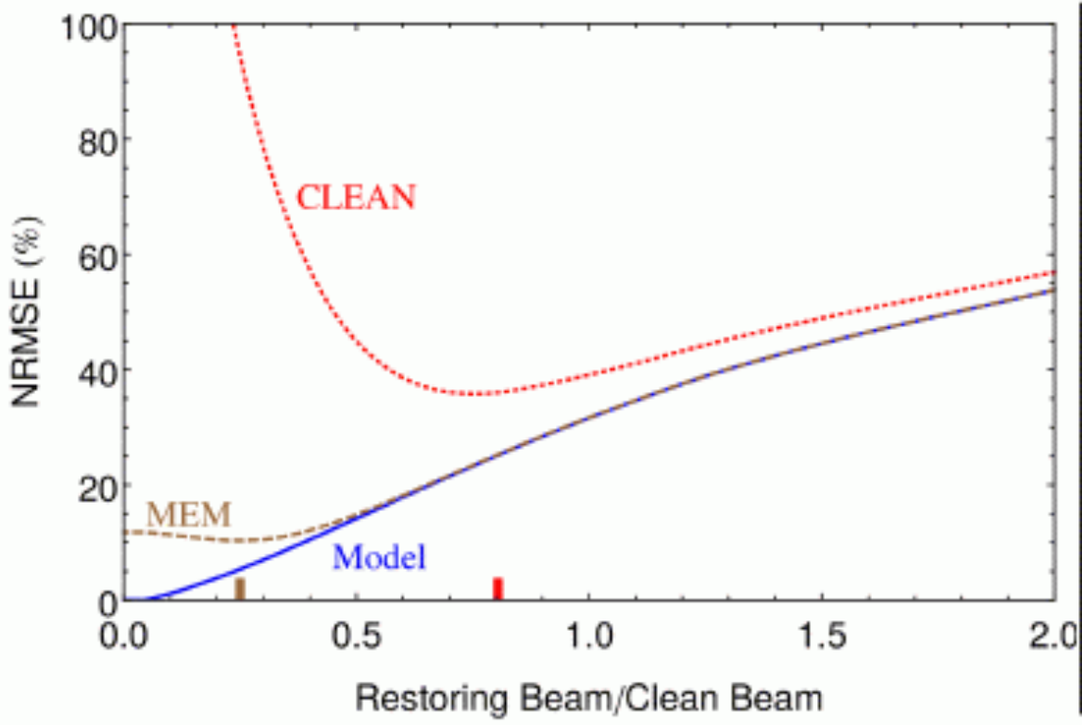


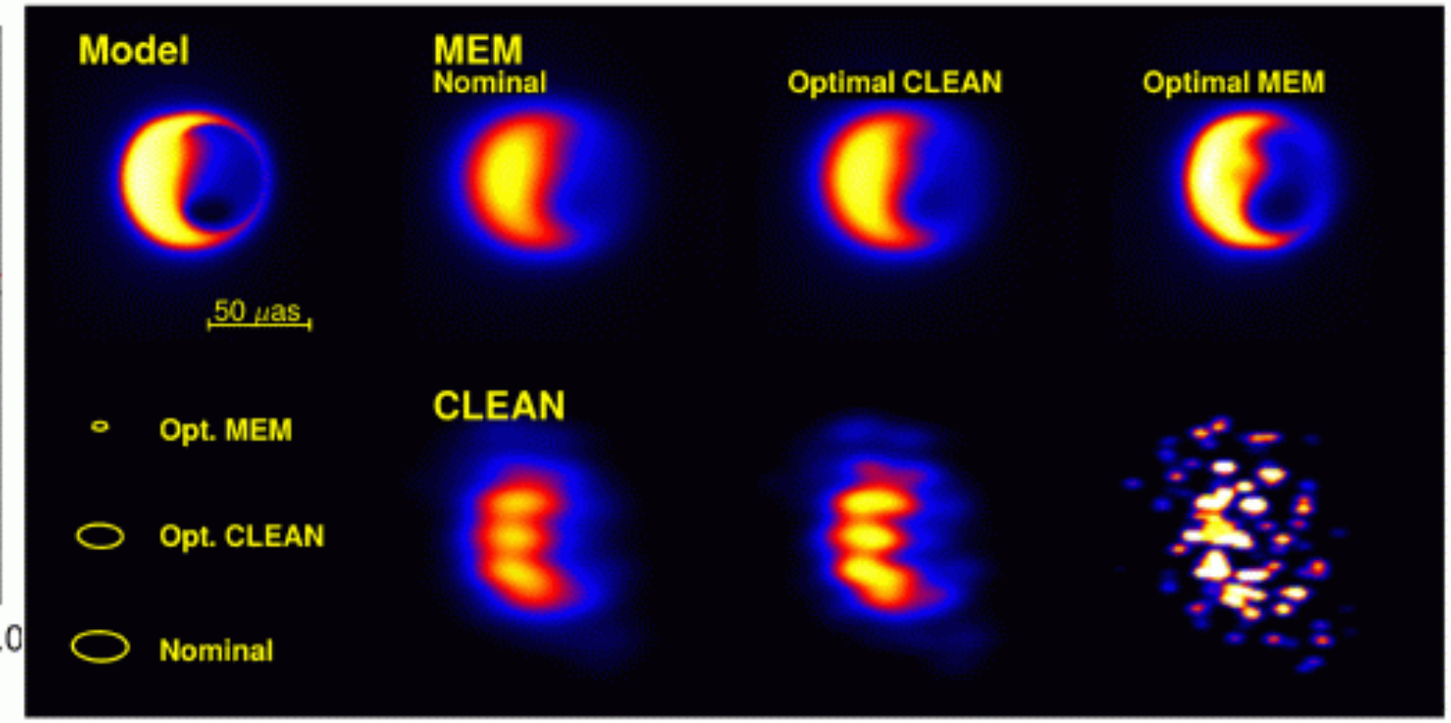
- BSMEM (BiSpectral Maximum Entropy Method)
- IRBis (Image Reconstruction software using the Bispectrum)
- MIRA (Multi-aperture Image Reconstruction Algorithm)
- SQUEEZE/MACIM (MArkov Chain IMager)
- WISARD
- …

Imaging: Maximum Entropy Methods

Compared with CLEAN, MEM:

- Handles smooth structure better
- Achieves greater effective spatial resolution





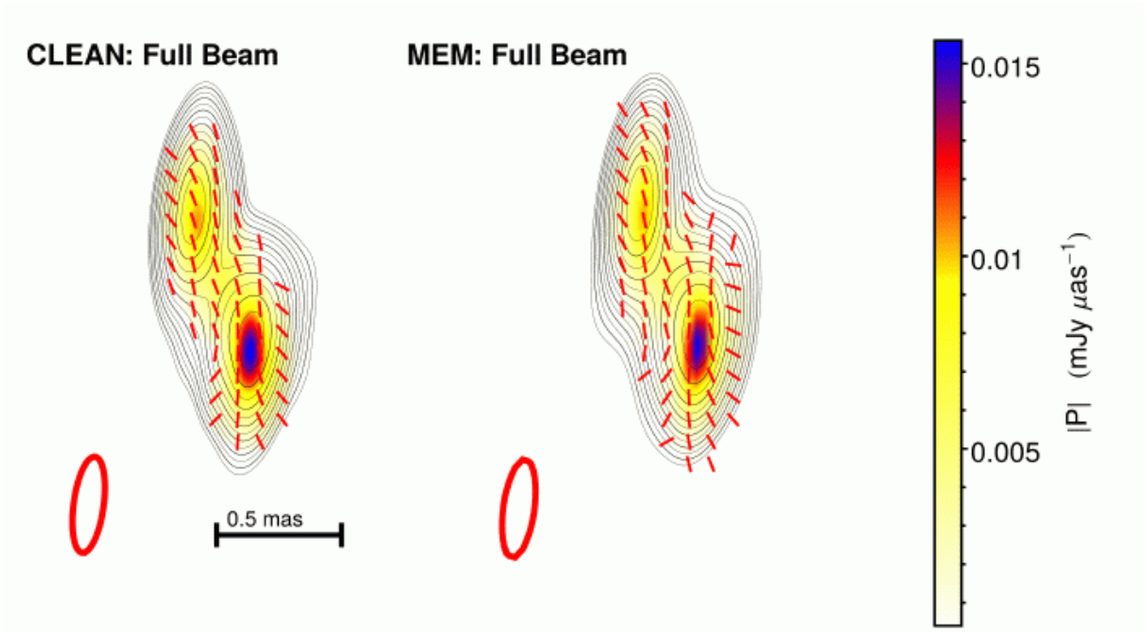
Chael+ in prep

Imaging: PolMEM

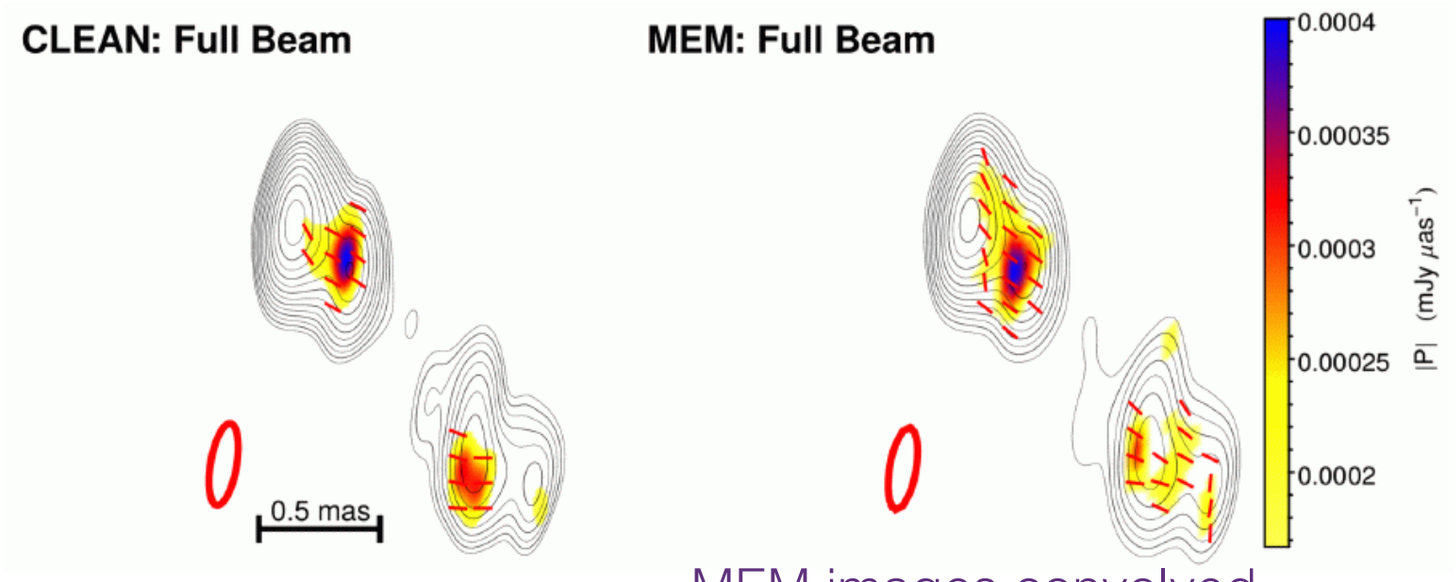
PolMEM extends MEM to full-polarimetric imaging

Validated on actual data

3C 279, 7mm



3C 273, 3 mm



MEM images convolved with CLEAN beam

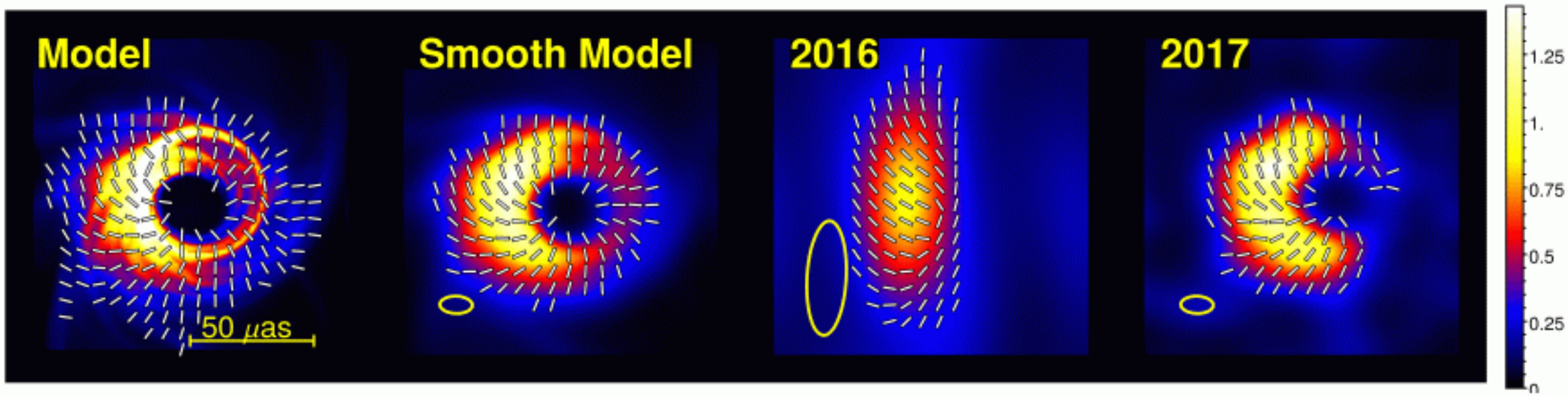
Chael+ in prep

Imaging: PolMEM

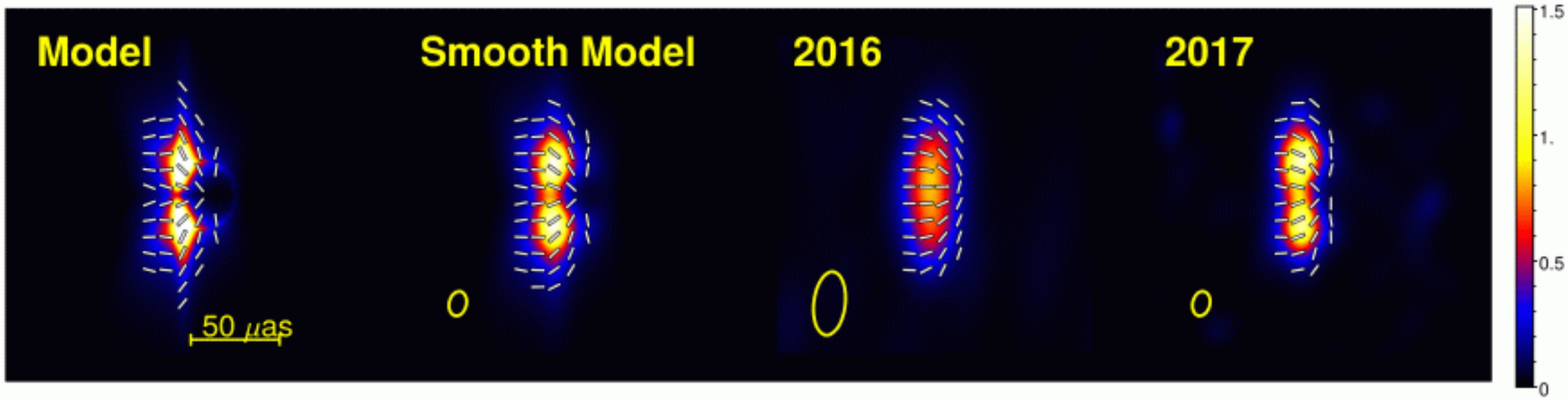
PolMEM extends MEM to full-polarimetric imaging

Validated on actual data, very encouraging for the EHT

Sgr A*



M 87



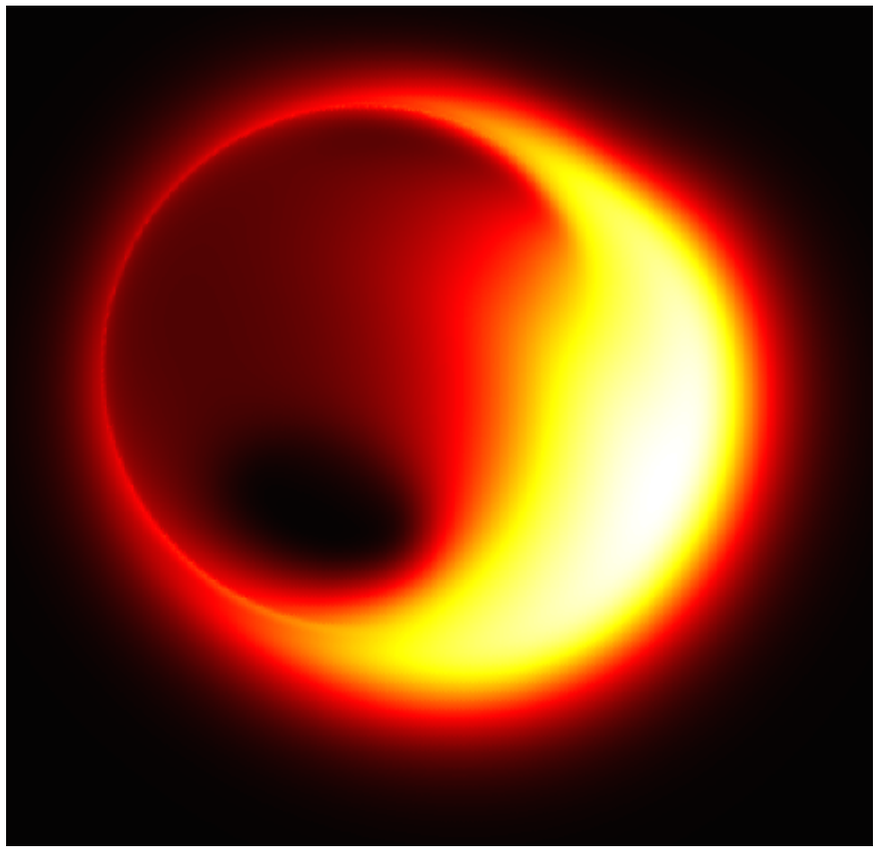
Chael+ in prep

Imaging: Bispectrum Sparse Modeling

Issues:

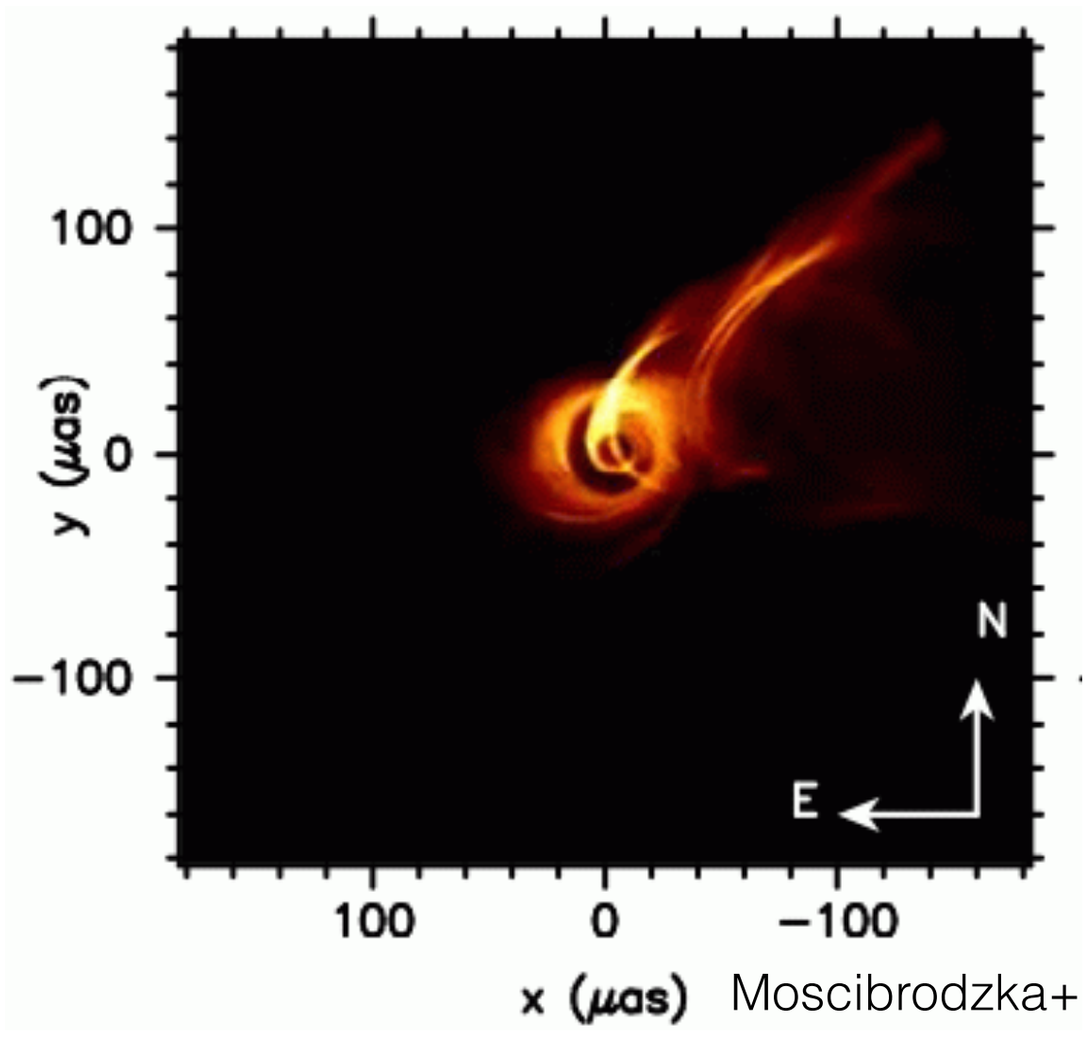
- Atmosphere corrupts visibility phases
- Expect reconstructed image to be mostly blank
- Expect some sharp edges in reconstructed image

Sgr A* Model, 1.3 mm



Broderick+ 2016

M87 Model, 3.5 mm



Moscibrodzka+ 2016

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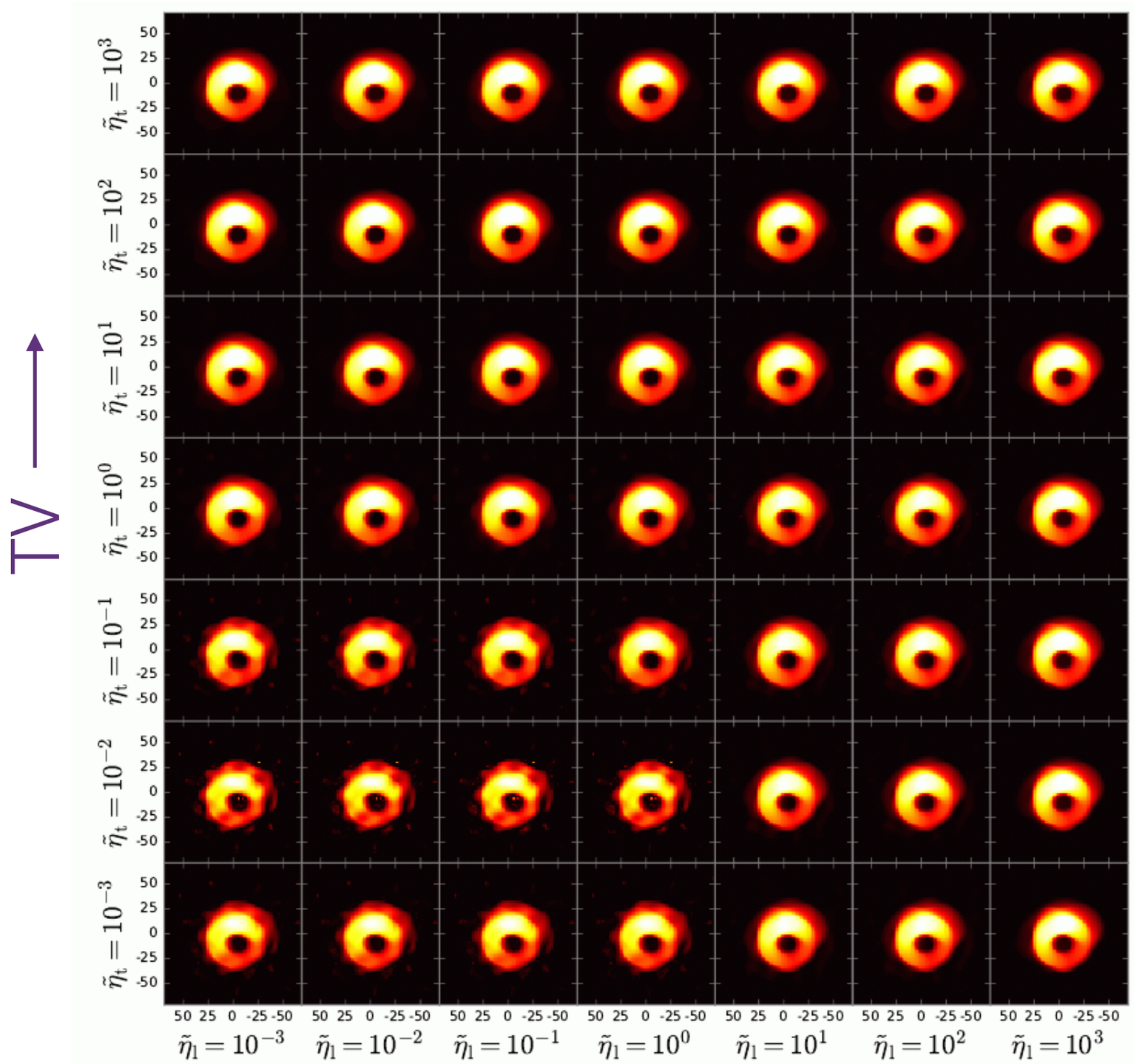
Bispectrum Sparse Modeling (Akiyama+ 2016):

- Phase REtrieval from CLosure phase (PRECL; Ikeda+ 2016) to derive visibility phases from closure phases assuming smoothness of phases in (u,v) plane
- Least Absolute Shrinkage and Selection Operator (LASSO; Tibshirani 1996) to ensure sparse solution
- Total Variation (TV; Rudin+ 1992) to ensure sparsity of solution in image gradient domain

Imaging: Bispectrum Sparse Modeling



Akiyama+ in prep

Imaging: CHIRP

Continuous High-resolution Image Reconstruction using Patch priors

Rooted in computational imaging and machine learning

Forward modeling using complex bispectra

Regularizer is an Expected Patch Log Likelihood derived from training on astronomical and other natural images

Image reconstruction using triangular pulses

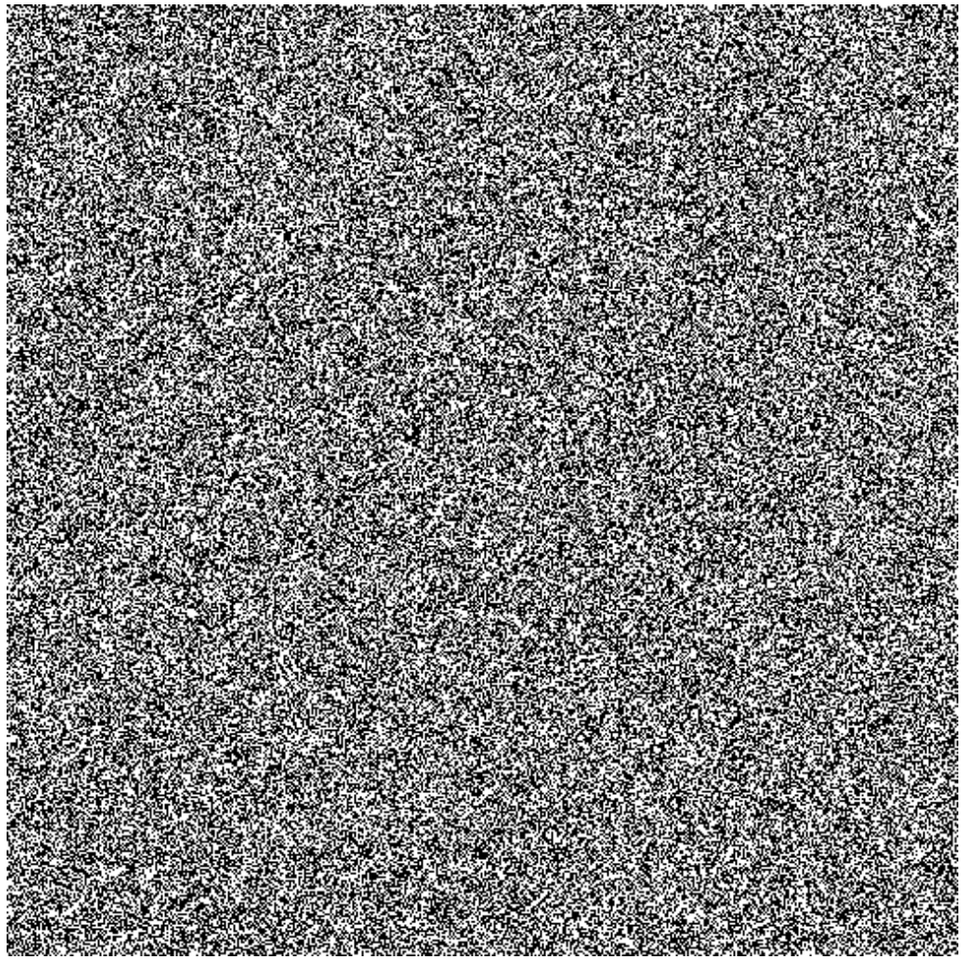
Imaging: CHIRP

Natural Image

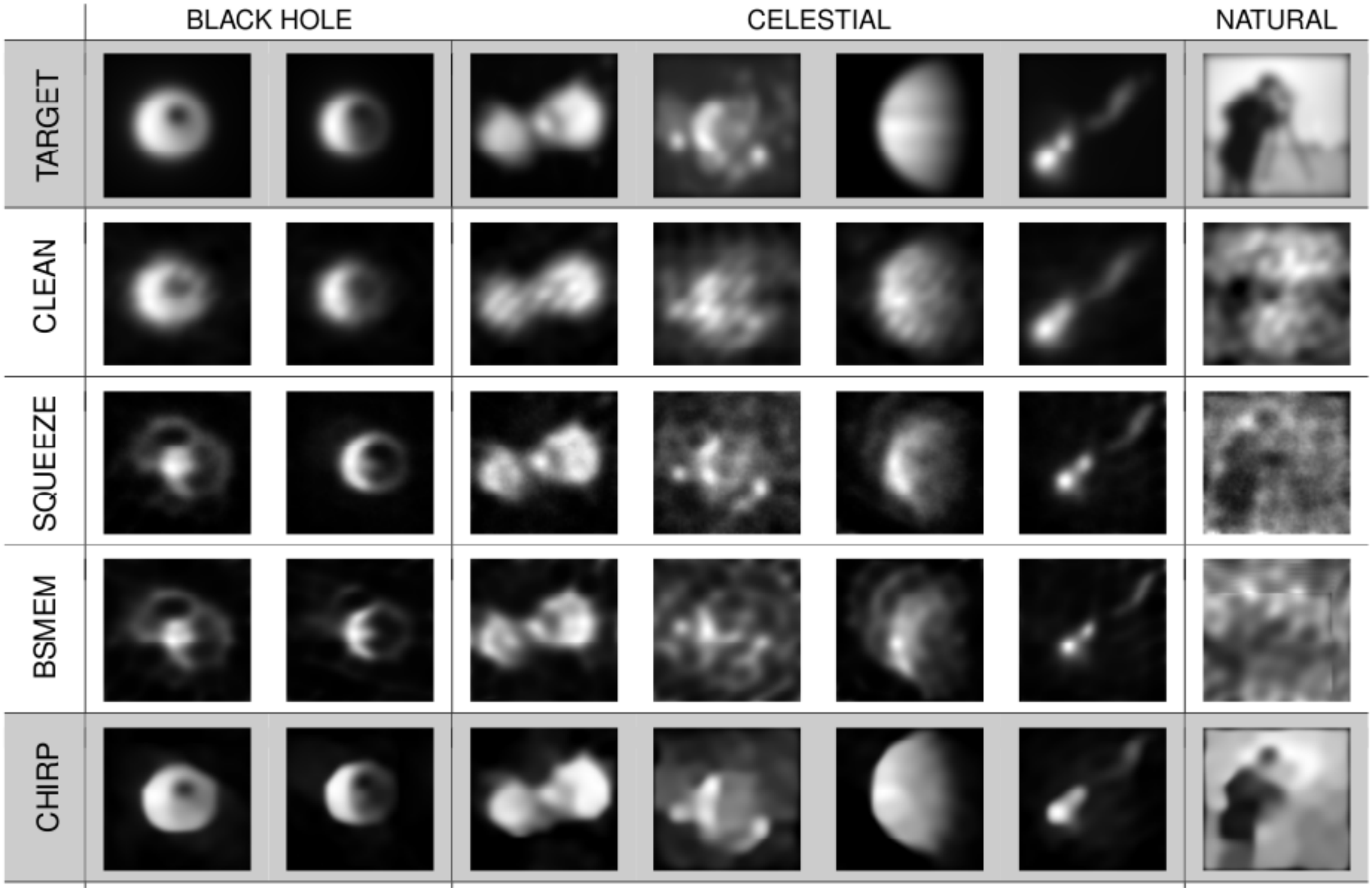
Imaging: CHIRP

Natural Image

Unnatural Image



Imaging: CHIRP



Bouman+ 2016

Imaging: CHIRP

Validation on real data

Images are less blurry, higher resolution than CLEAN

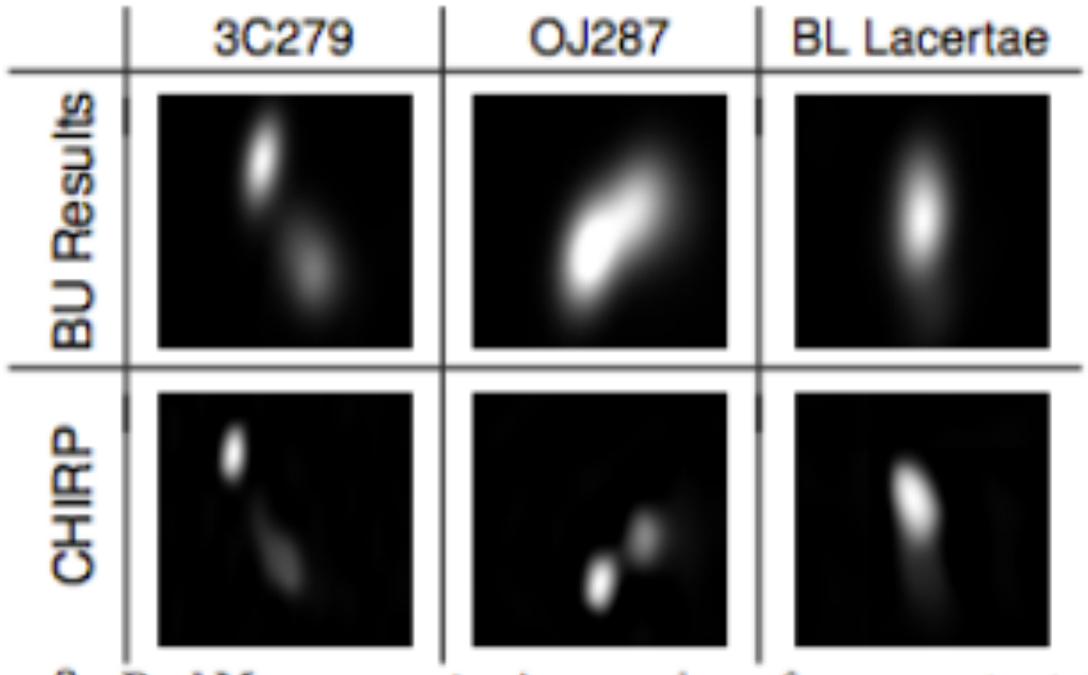


Figure 9. **Real Measurements:** A comparison of our reconstructed images to [23]'s results using CLEAN self-calibration. Note that we are able to reconstruct less blurry images, and are even able to resolve 2 separate, previously unresolved, bright emissions in blazar OJ287. Measurements were taken using the VLBA telescope array. The FOV for each image is 1.5, 1, and 1 milli-arcsecond respectively.

Bouman+ 2016

Summary

The EHT is not just for Sgr A* and M87!

The EHT is well suited to probing deeply into AGN sources at extremely high resolution.

There has already been an ALMA+EHT Call for Proposals.

State-of-the-art imaging techniques developed for the EHT and for optical interferometry far surpass CLEAN. Consider using a newer imager for your next dataset (even for lower-frequency VLBI)!