Ultra-High Angular Resolution VLBI

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MIT Haystack Observatory

Ultra-High Angular Resolution VLBI

enabled by mm-VLBI

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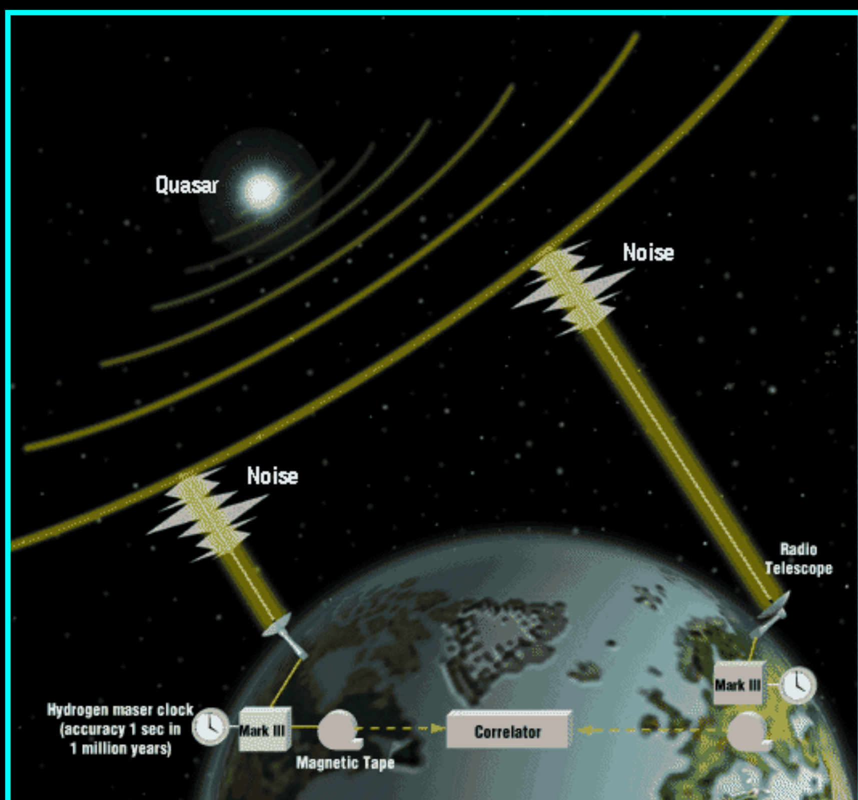
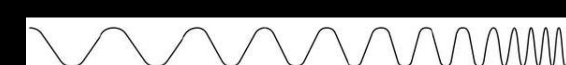
The quest for high resolution VLBI



typical resolution (ground-based):

λ/D (cm) ~ 0.5 mas

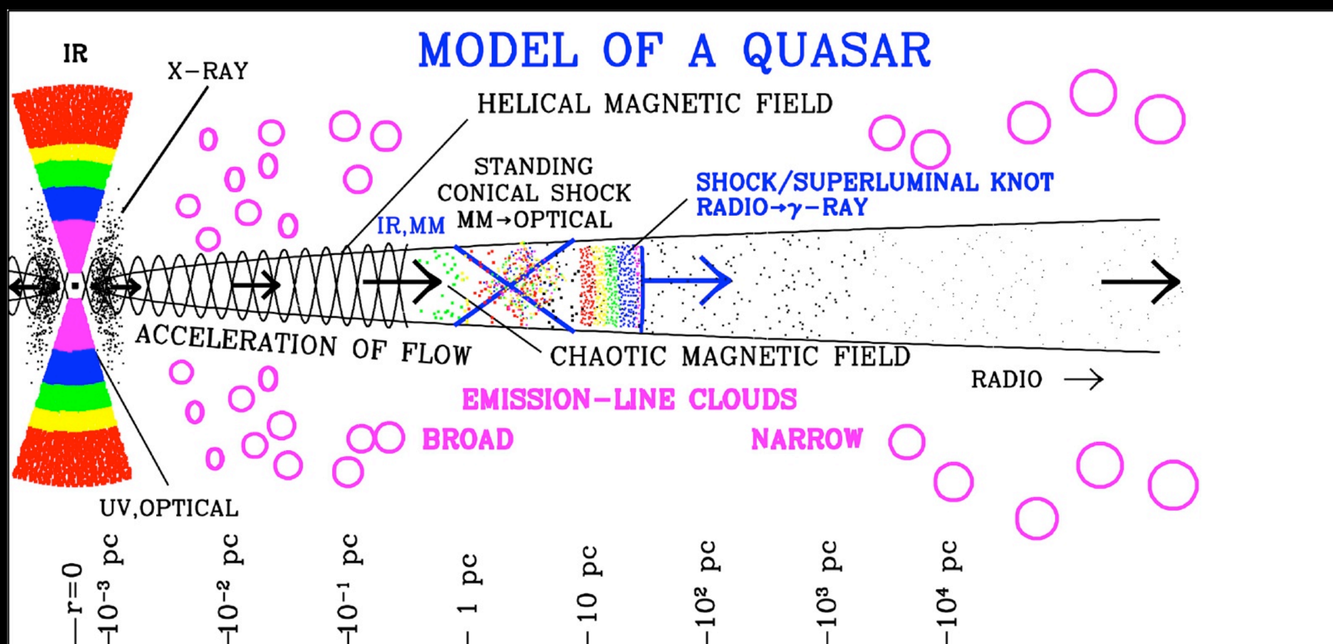
{ space VLBI
  shorter λ



Both are challenging, but feasible

future: space (sub)mm-VLBI

Advantages provided by mm-VLBI

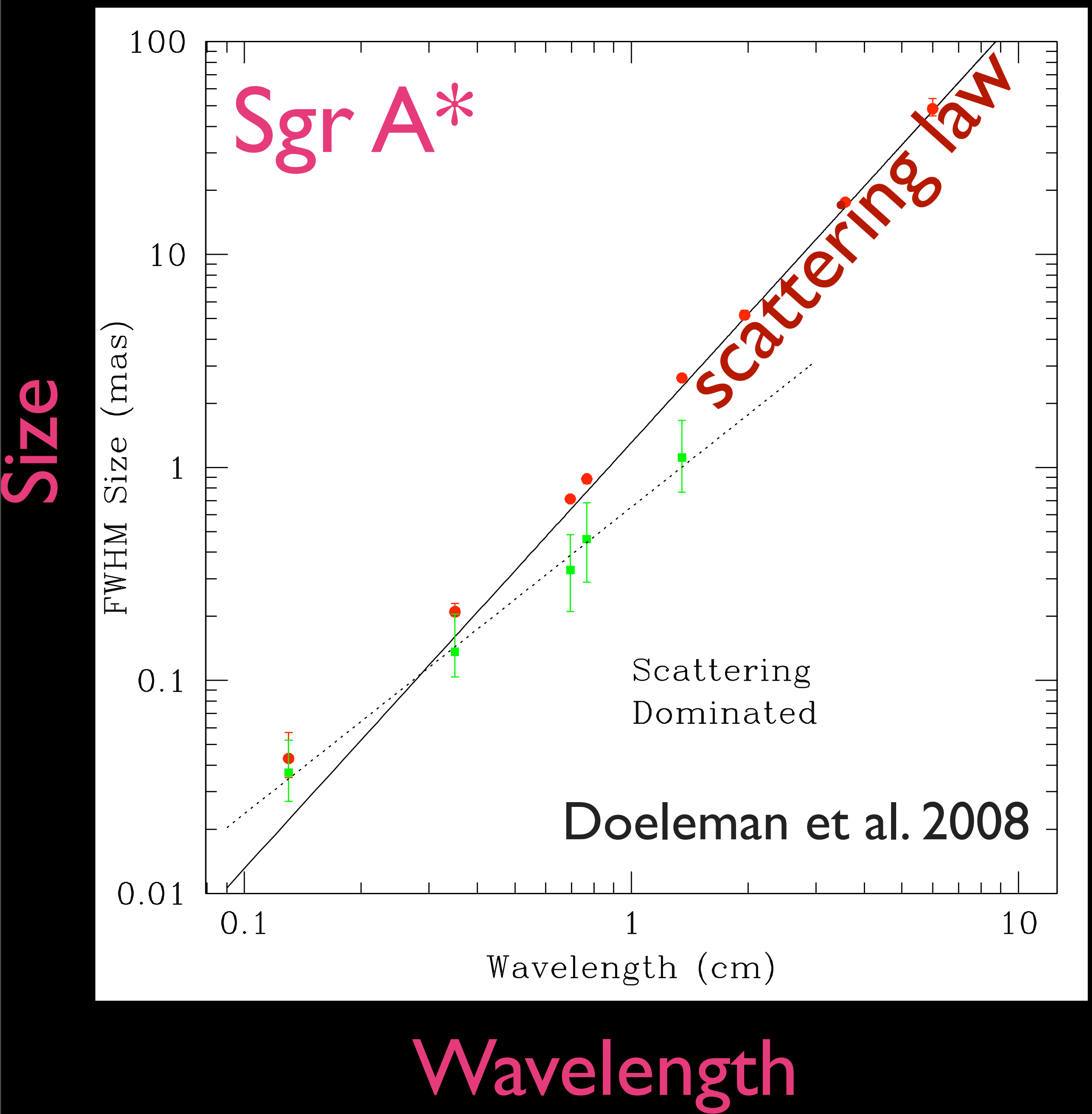


Marscher et al.

Self-absorption:

look “deeper”

Advantages provided by mm-VLBI



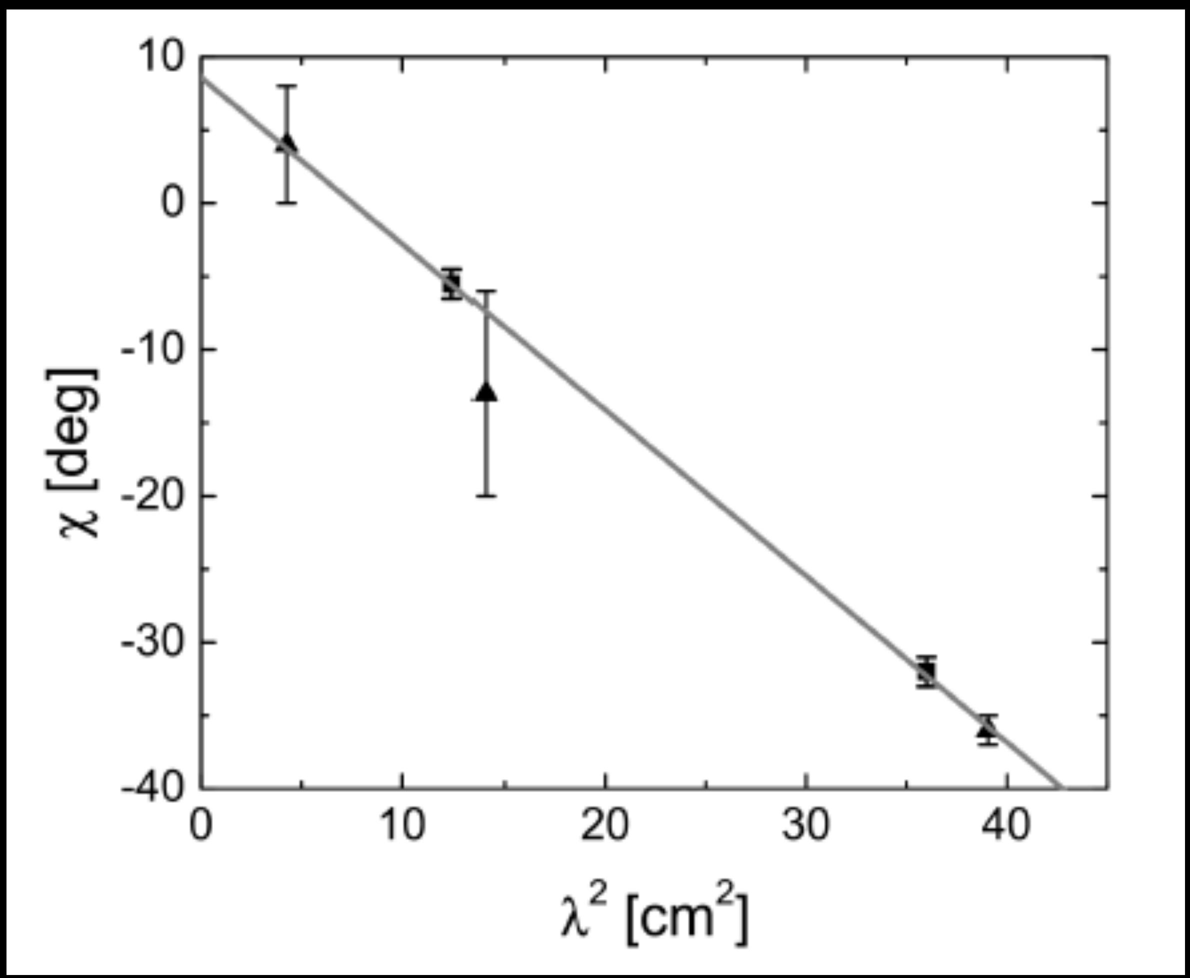
Self-absorption:

look "deeper"

Scattering in the ISM

$\theta_{scat} \propto \lambda^2$

Advantages provided by mm-VLBI



Self-absorption:

look "deeper"

Scattering in the ISM

$\Theta_{scat} \propto \lambda^2$

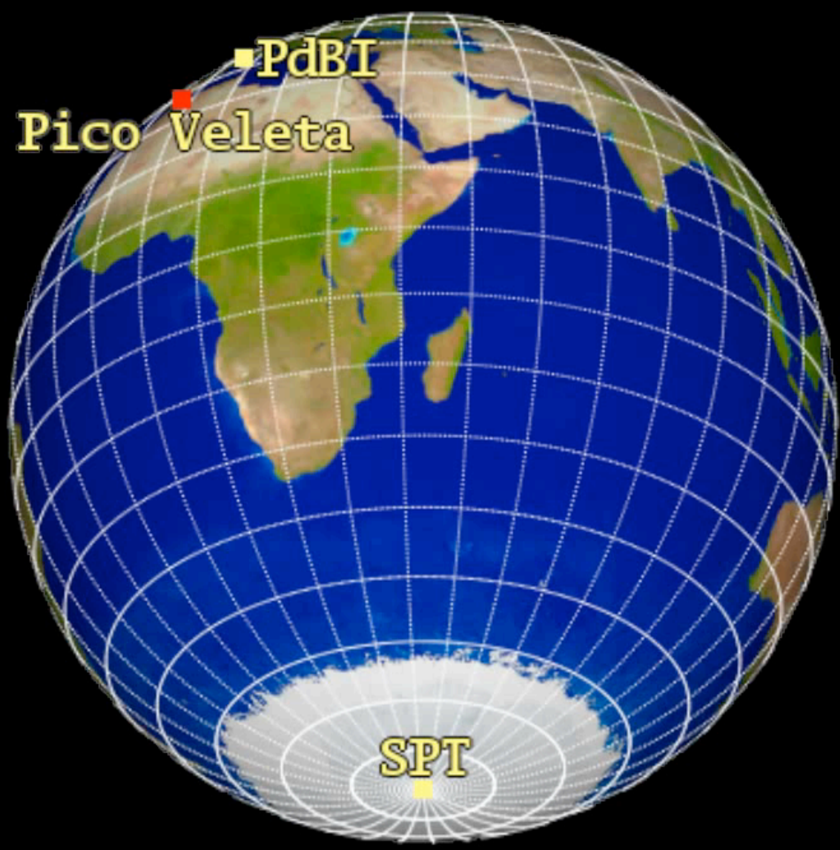
Faraday rotation:

$\chi \propto \lambda^2$

The Event Horizon Telescope:

(a global (sub)mm-VLBI array)

The EHT as viewed from Sgr A*



EHT Sites

- Mauna Kea, Hawaii:
  SMA (~8 x 6-m, single polarization)
  JCMT (15-m, single polarization)

- Mount Graham, Arizona:
  SMT (10-m, dual polarization)

- Inyo Mountains, California:
  CARMA (5 x 10-m + 3 x 6-m, dual polarization;10-m, dual polarization, reference)

- Sierra Negra, Mexico: LMT (50-m)

- Atacama desert, Chile, APEX, (12-m)
- Atacama desert, ALMA, (85-m)

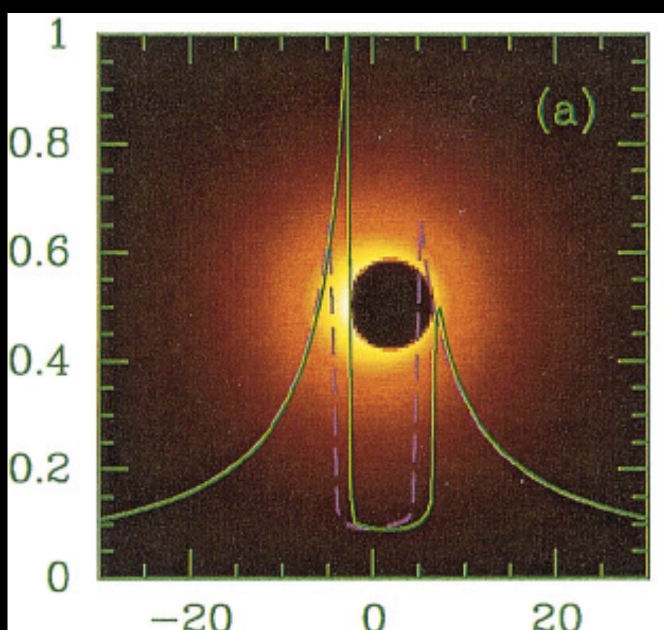
- Pico Veleta (Sierra Nevada, Spain, 30-m)
- Plateau de Bure (France, 35-m)

- South Pole Telescope (10-m)
- Greenland Telescope (12-m)

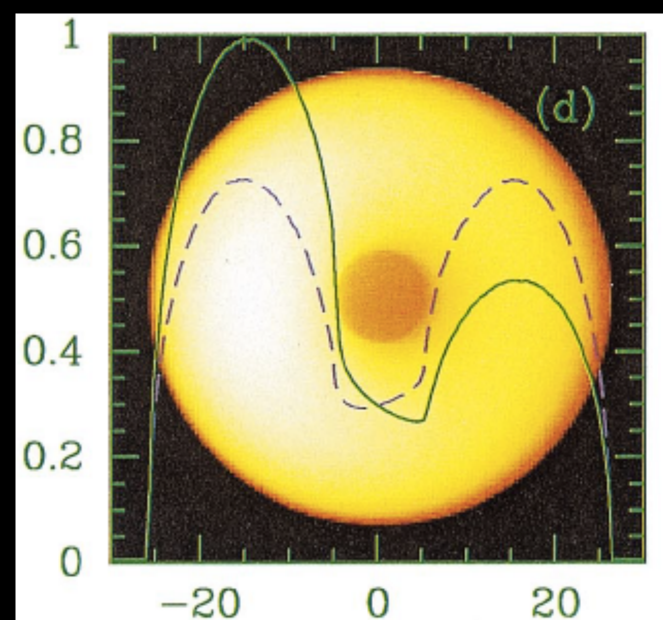
(near) Future goal: black hole shadow imaging

Not all black holes are created equal:

- Sgr A*: 4 million $M_\odot$ BH, Rsch = 10 µas
- M87: ~6.6 billion $M_\odot$ BH, Rsch = 7.5 µas



a=0.998



a=0

size = 9/2 * R_{sch}

size = sqrt(27)*R_{sch}

(Bardeen 1973, Falcke, Agol & Melia 2000)

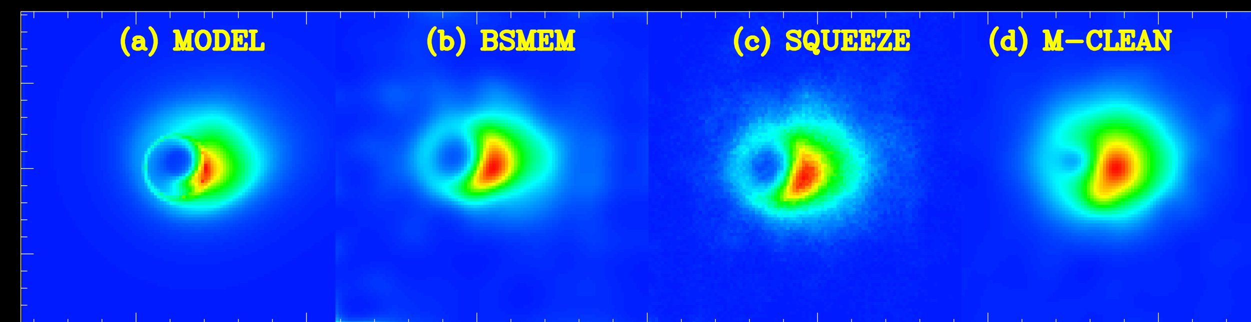
EHT provides well-matched resolution!

~ 30-20 µas

Imaging the BH shadow in M87

Varying Loading Radii

MEM, Bayesian approach



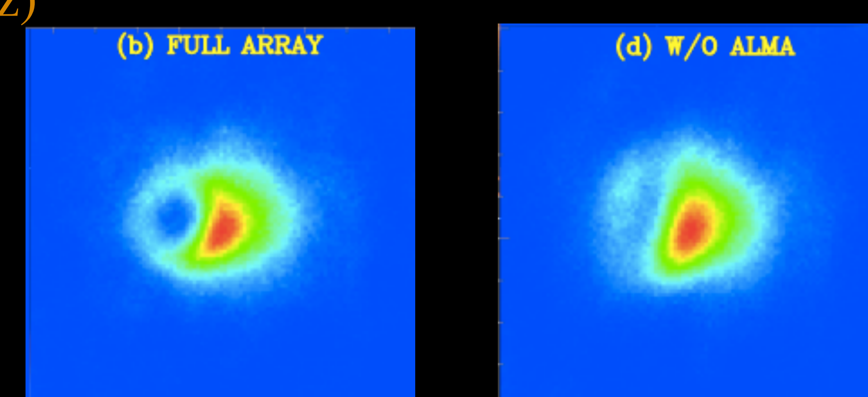
model

reconstruction

Minimum requirements:

1. The counter jet has to be sufficiently bright for the black hole to cast a jet against ($R_{load} \lesssim 11$ M)

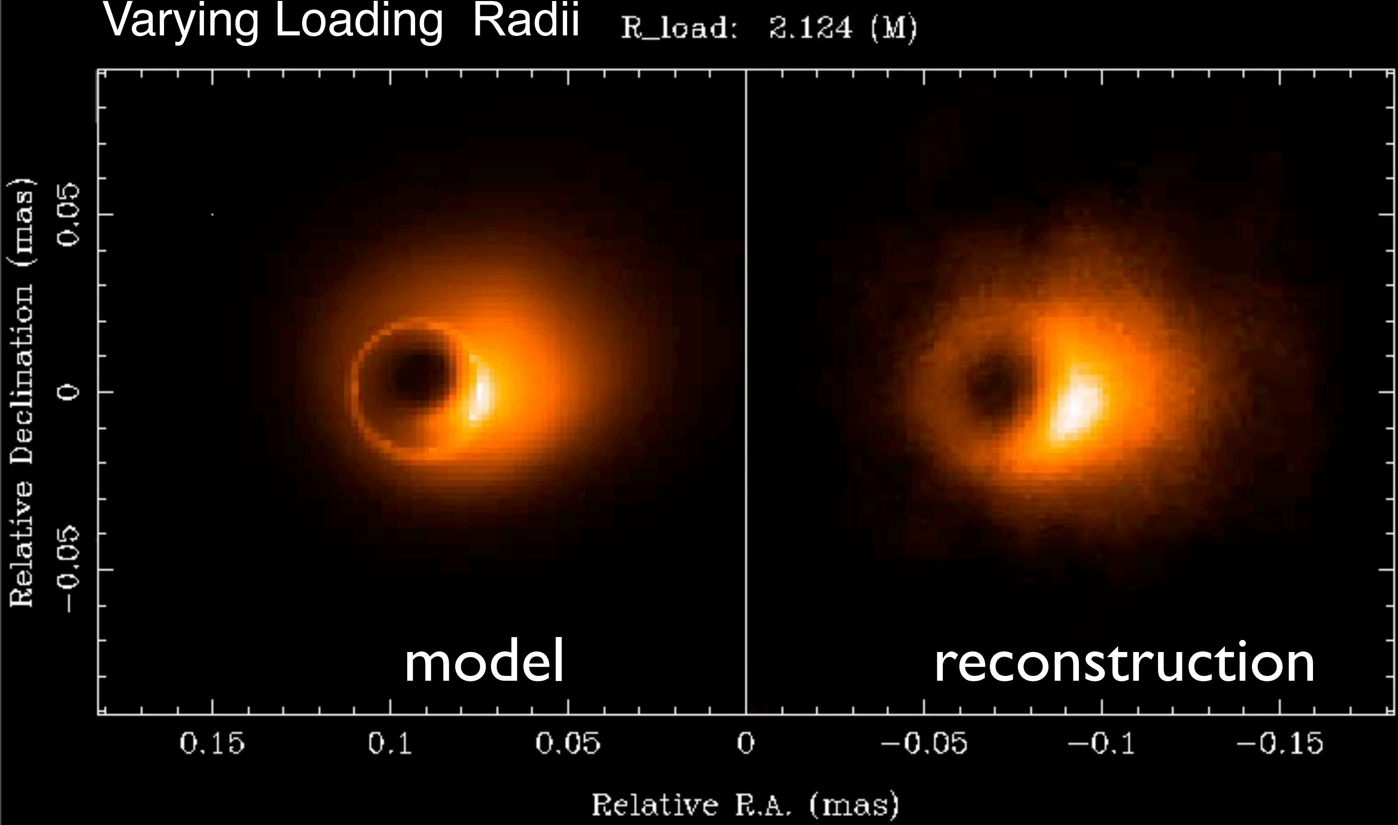
2. The phased ALMA has to be included in the array with bandwidth × coherence time ≳ 4GHz × 12 s at 230 GHz (more stringent requirement at 345GHz)



(Lu et al. 2014, ApJ, in press)

Imaging the BH shadow in M87

Varying Loading Radii



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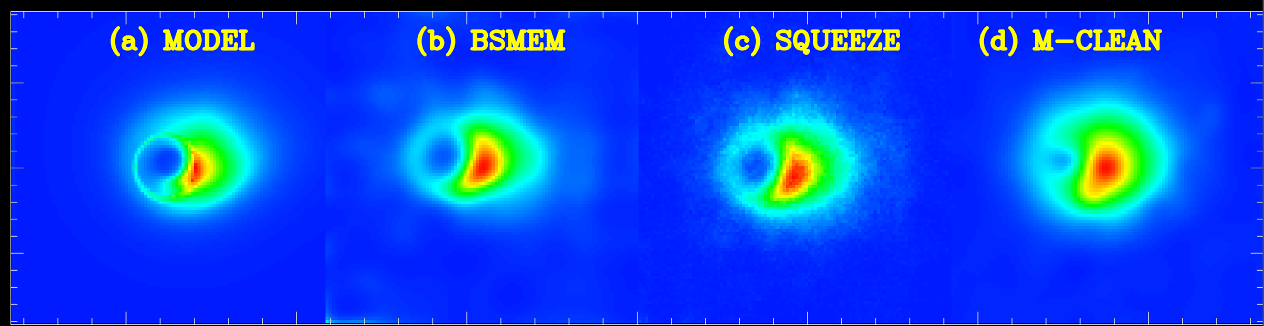
MEM, Bayesian approach



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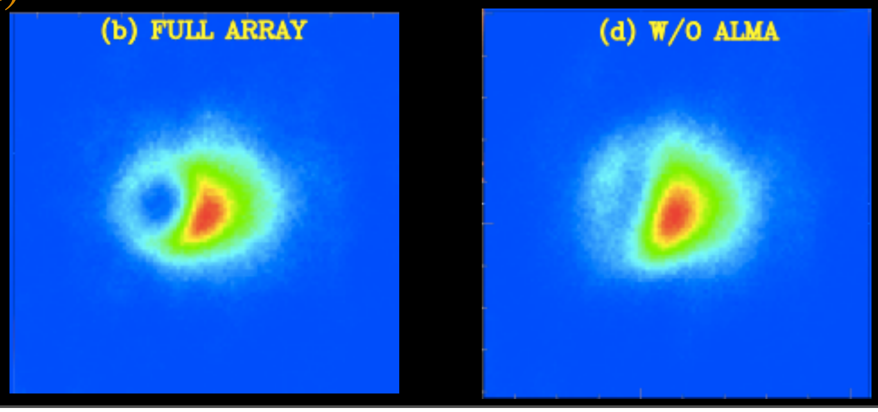
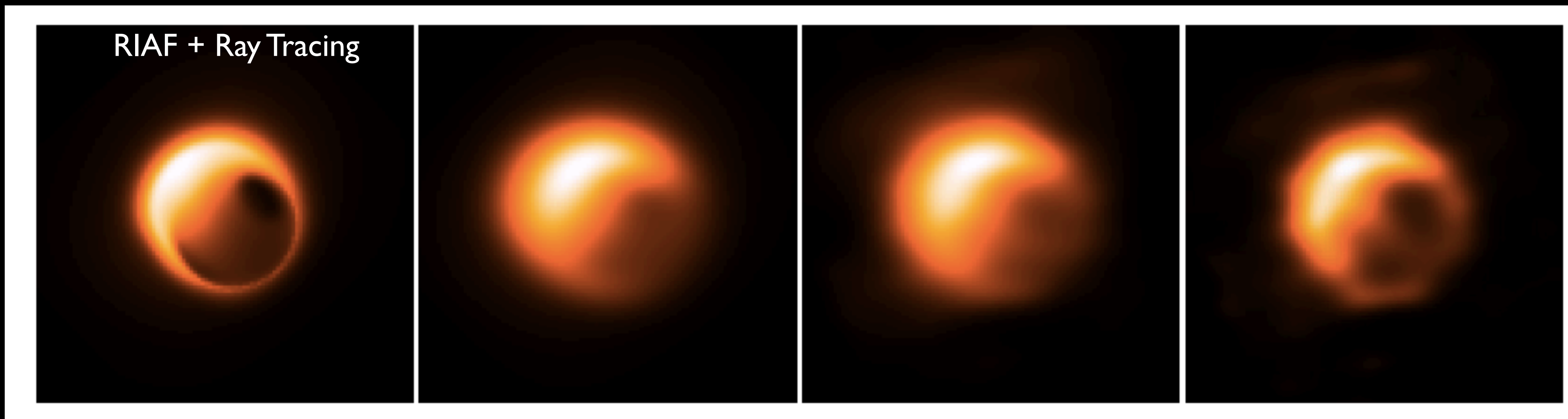


Imaging the BH shadow in Sgr A*
(overcome scattering broadening)

230 GHz

Fish et al. in prep



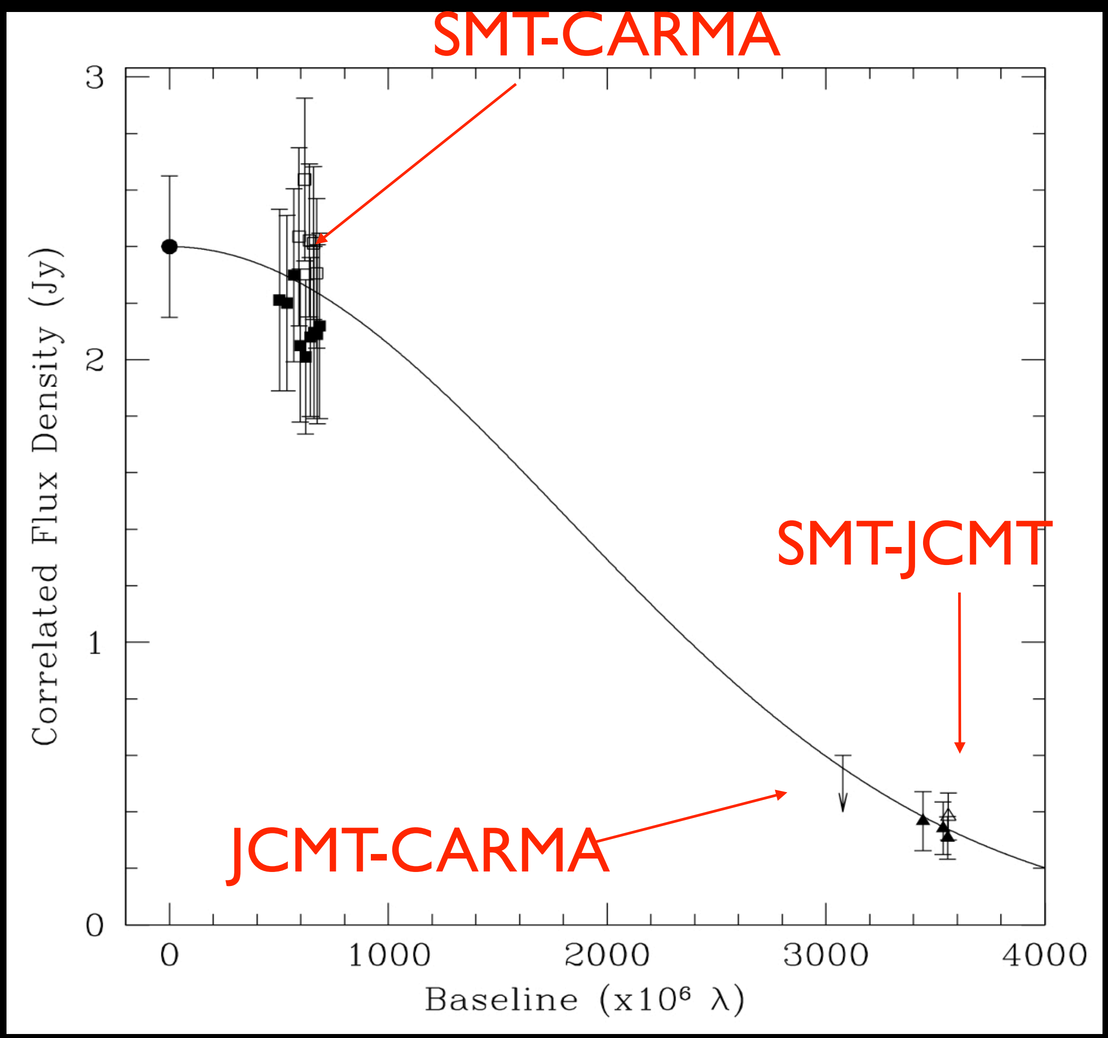
model | scattered | reconstruction | reconstruction of corrected visibilities

The effects of scattering can be mitigated by correcting the visibilities before reconstructing the image

other applications:
low frequency VLBA images of Sgr A*
or, other scatter-broadened sources(?)

Horizon-scale structure in Sgr A*

SgrA* has the largest apparent event horizon of any black hole in the Universe



Doeleman et al. 2008, Nature

About 4 Schwarzschild radii across

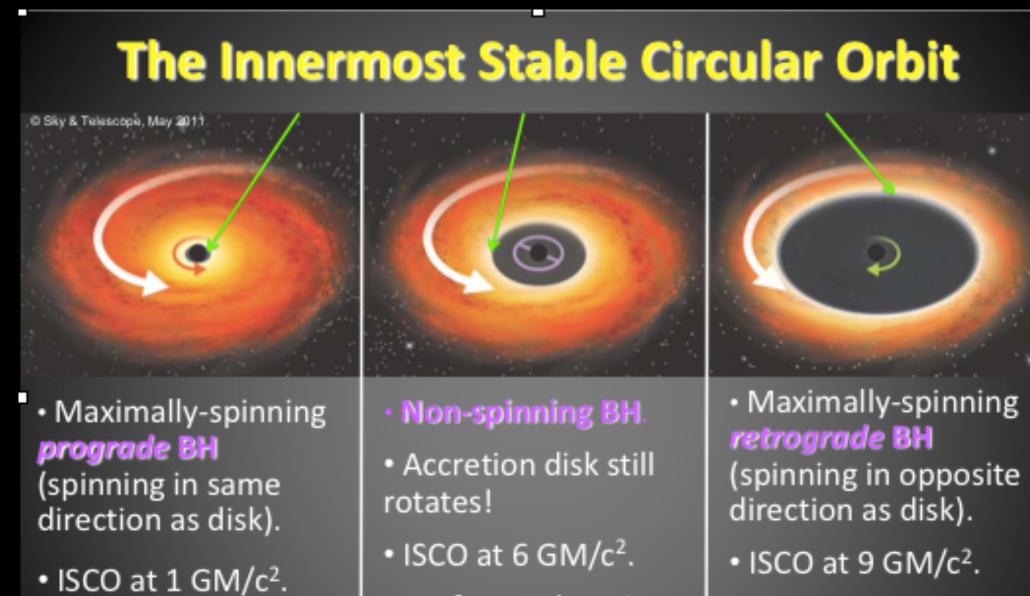
$$\rho = 10^{23} M_{\odot} pc^{-3}$$

1.3 mm emission offset from the BH

Resolving jet-launching structure in M87

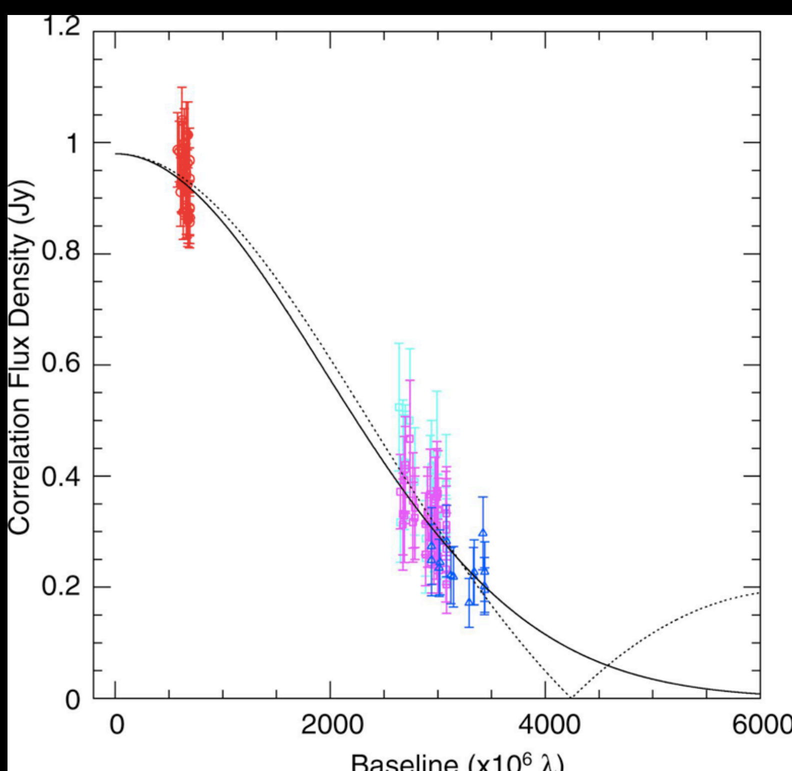
size of jet base

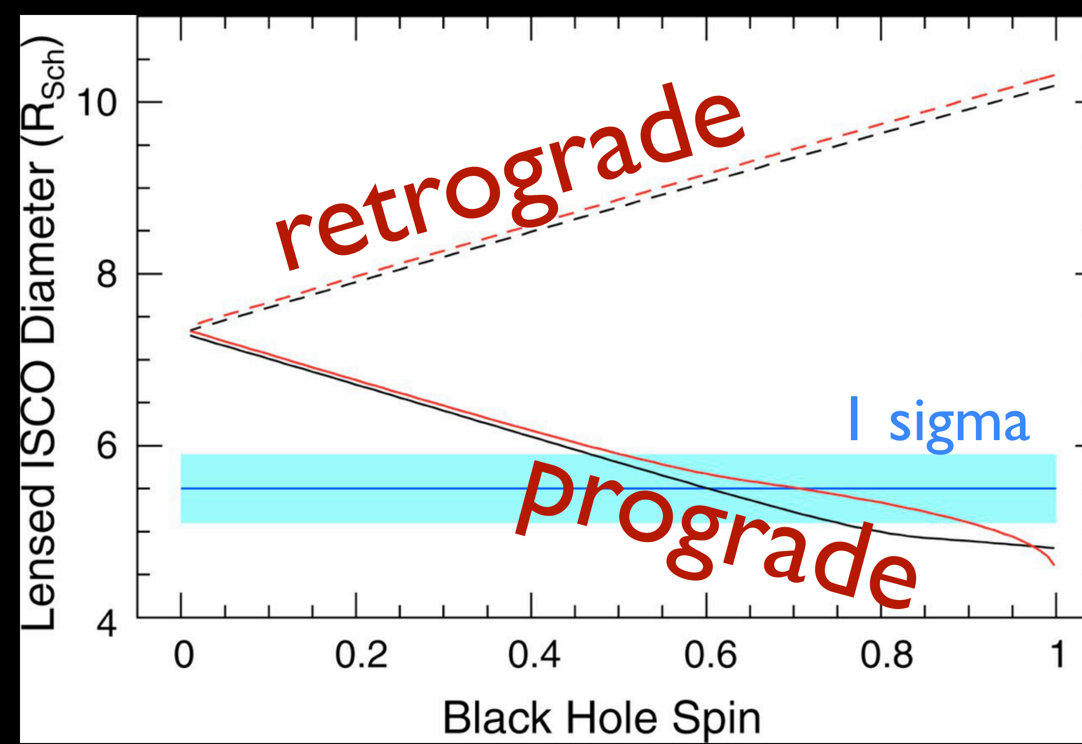
set by ISCO?



credit:Sky & Telescope

M87 measured size = 5.5 Rsch

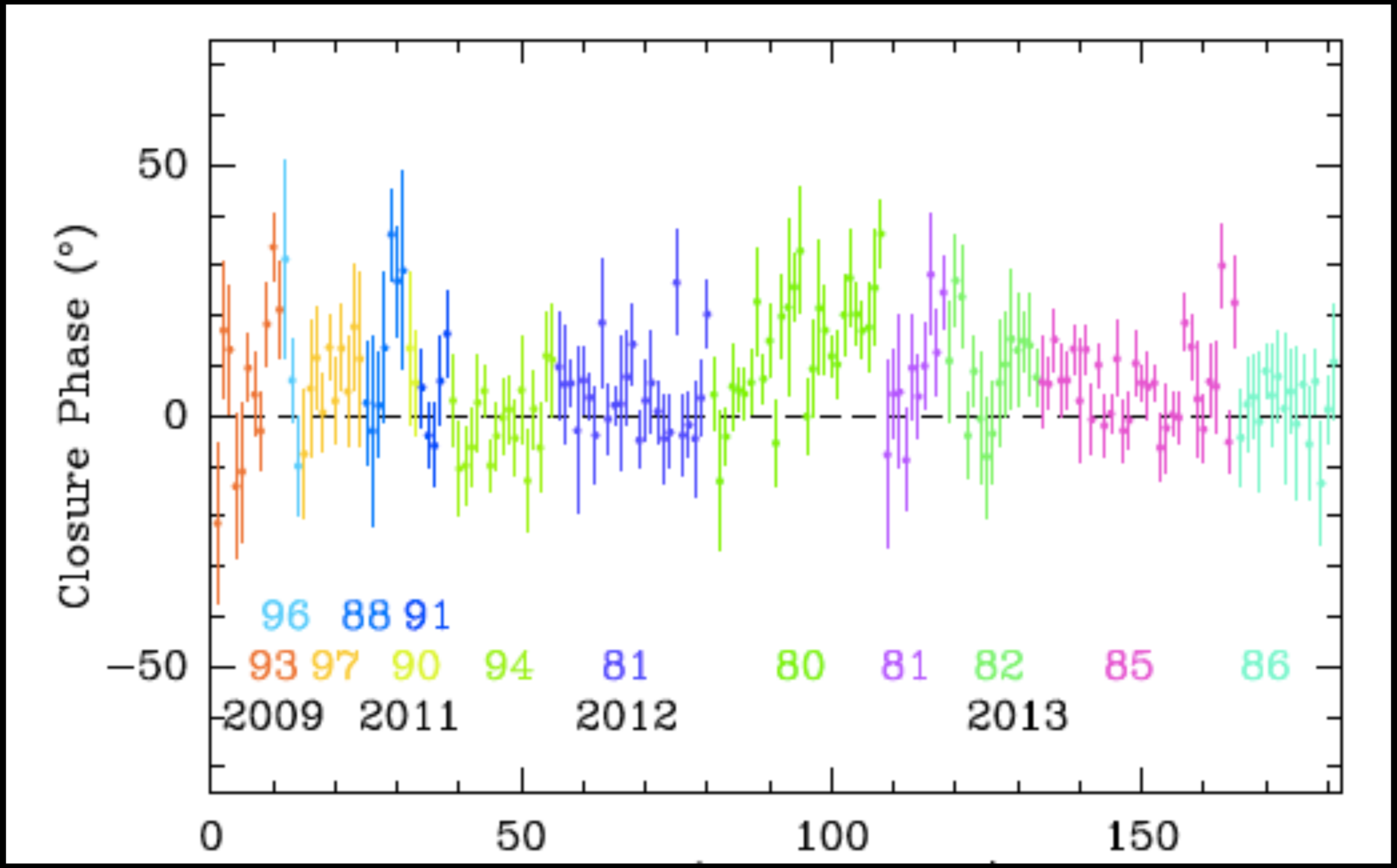




Doeleman et al. 2012, Science

Resolving structure in Sgr A*

Non-zero closure phase detected



Fish et al. in prep

Median closure phase (+6.3 deg) on the California-Hawaii-Arizona triangle

consistent sign (daily average) over many days over the course of multiple years [compare: characteristic timescale GM/c^3 ~ 20s]

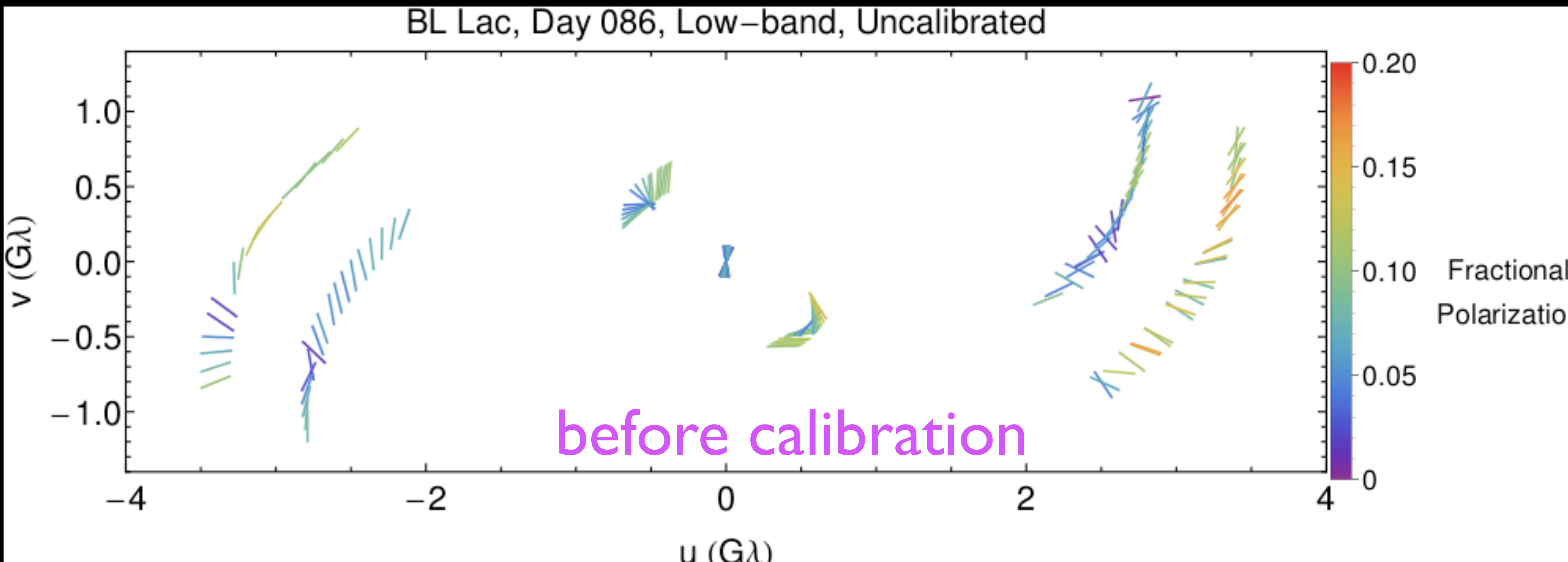
sign of day-to-day variability

no point symmetry: elliptical Gaussian, uniform ring, two-sided jet in the sky plane etc.

call for physically motivated models

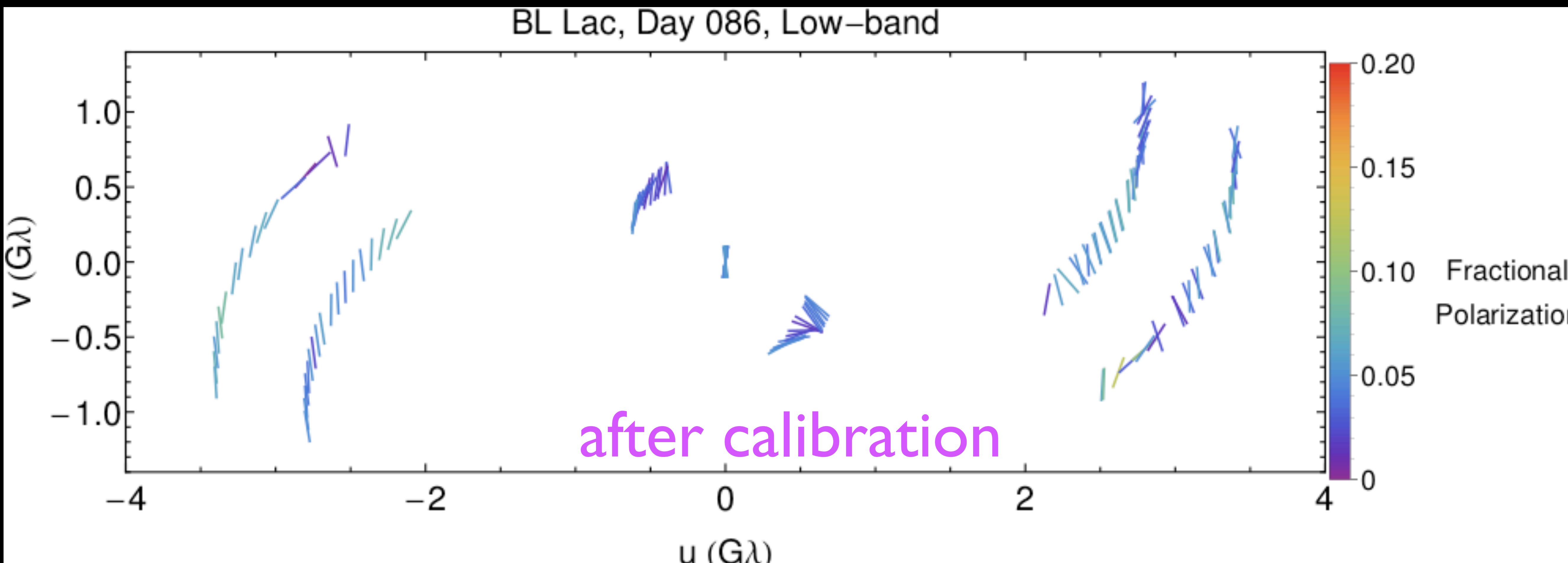
EHT polarimetry calibration

Johnson et al.



EHT polarimetry calibration

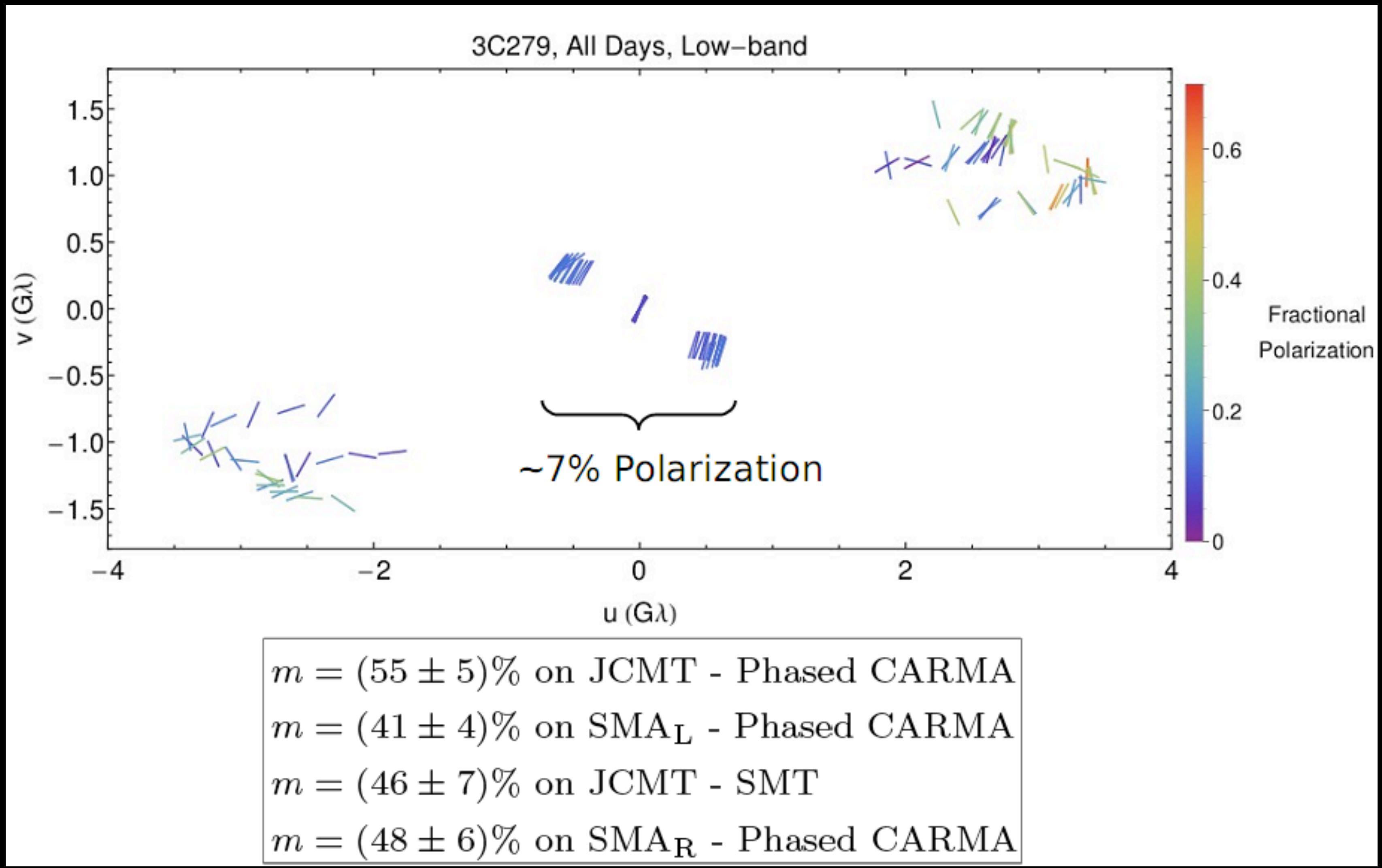
Johnson et al.



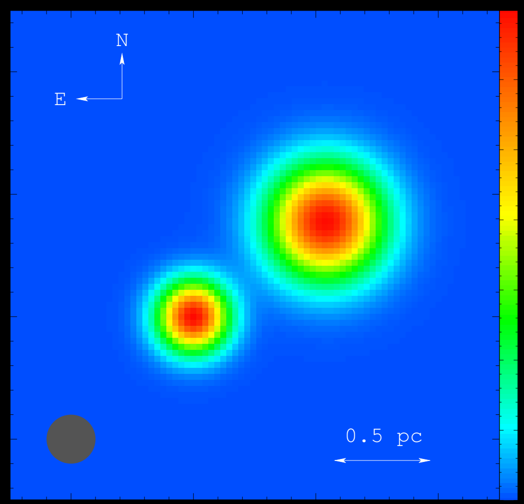
Fractional Polarization due to instrumentation is removed
modest and slow varying polarization in BL Lac

EHT polarimetry: 3C279

Johnson et al.



Lu et al. 2013



3C 279, EHT@230GHz

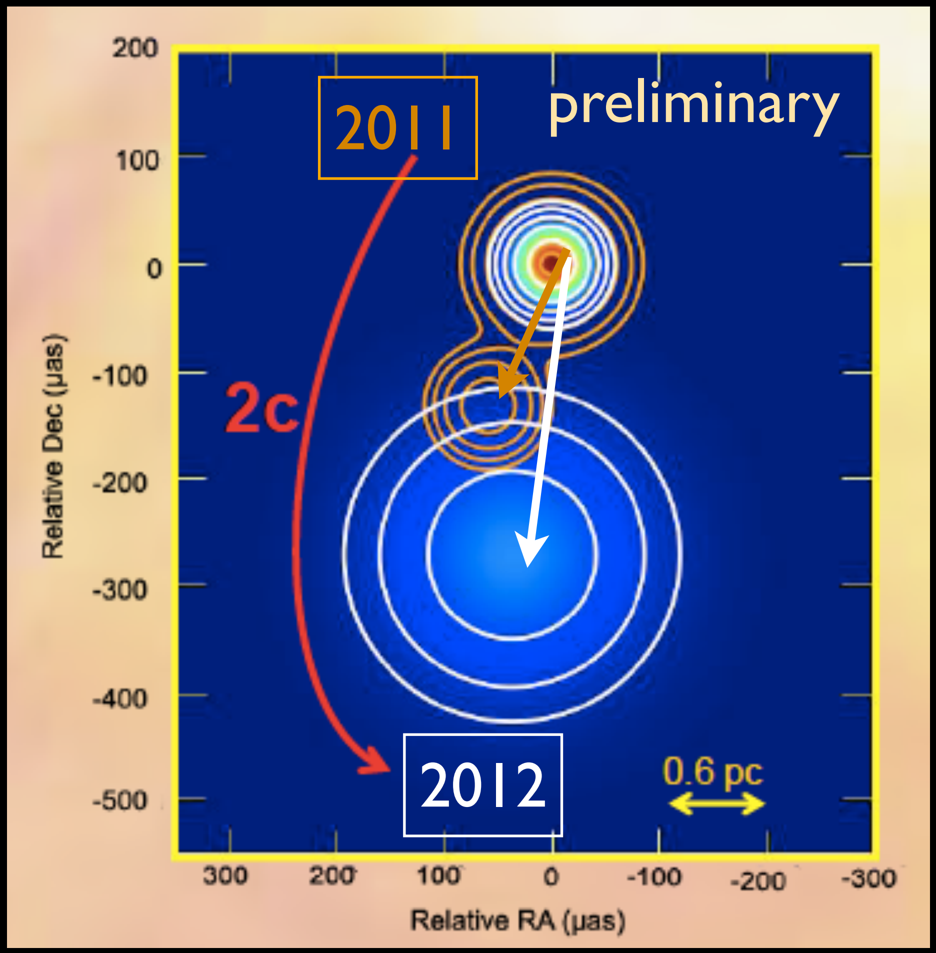
low polarization on short baselines (beam depolarization?)

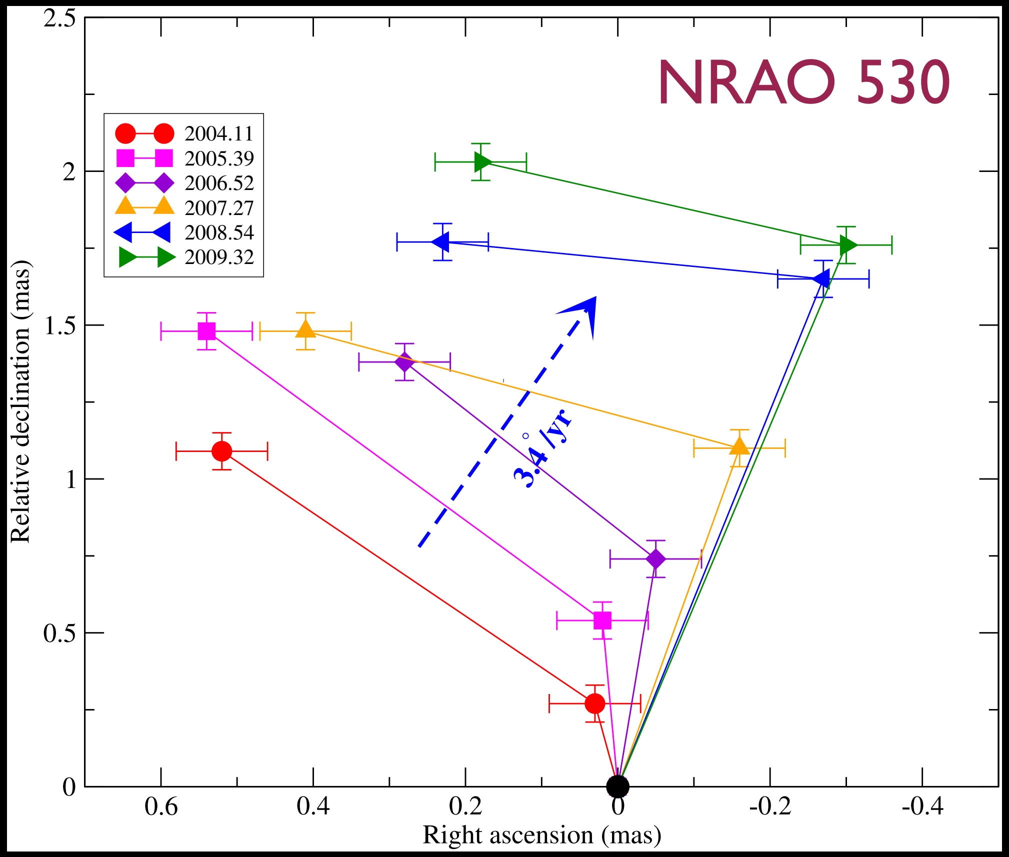
high polarization on long baselines

→ fine-scale structures are polarized

Probing inner structure of AGN jets: an example

3C 279





Lu, Krichbaum & Zensus, 2011

multi-epoch data to study jet acceleration & “precession”?

(may need to combine low frequency data)

Summary

Horizon-scale structures in Sgr A* and M 87 detected

Imaging black hole shadow in Sgr A* and M87 demonstrated (within reach in next few years)

Polarimetry as a new tool to probe B field structure in the vicinity of nearby black holes

New data point towards "complex" and extremely compact structures in Sgr A*

Study AGN jet formation and propagation on sub-pc scales (horizon scales for M87)