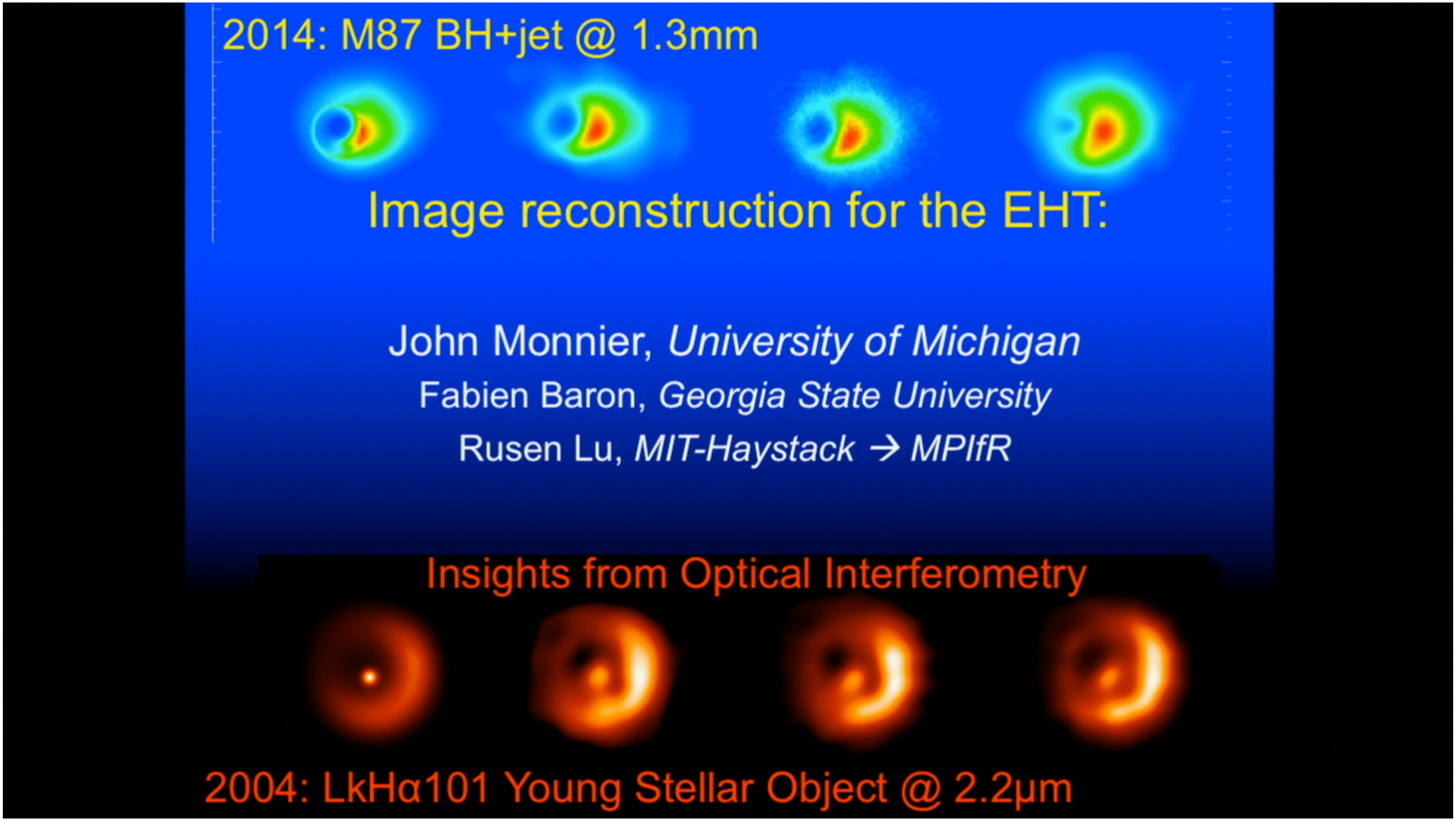
Title: Optimized Image Reconstruction: Insights from Optical Interferometry

Date: Nov 10, 2014 03:20 PM

URL: http://pirsa.org/14110072

Abstract: The radio community pioneered the use of closure phases to allow interferometric imaging even when fringe phases are compromised by atmospheric turbulence or unstable reference clocks. Eventually, better receivers and observing methods allowed phase referencing to provide direct measures of complex visibilities and eased the uncertainties using Fourier inversions required for imaging. At the same time, optical and infrared (O/IR) interferometers have been developed recently that can combine up to 6 telescopes simultaneously, at which point the inadequacies of classic imaging methods such as CLEAN were apparent. Here I report on dramatic progress within the O/IR interferometry to develop new image reconstruction techniques taking advantage of advances in ``compressed sensing" theory and new approaches afforded by modern computing. Because the Event Horizon Telescope must rely on closure phases instead of direct Fourier phases, the new algorithms from the O/IR could be essential to extracting the most information from EHT observations and we demonstrate promising results using simulated EHT data.


2014: M87 BH+jet @ 1.3mm
Image reconstruction for the EHT:
John Monnier, University of Michigan
Fabien Baron, Georgia State University
Rusen Lu, MIT-Haystack → MPIfR
Insights from Optical Interferometry
2004: LkHα101 Young Stellar Object @ 2.2μm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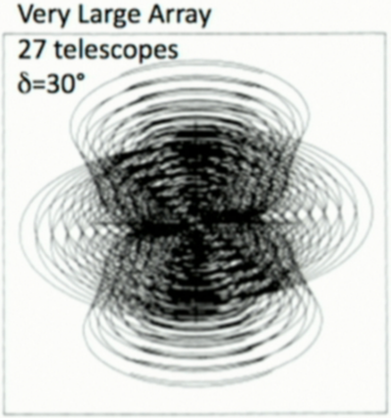
Optical interferometry and EHT

- 'Classic' radio interferometry (+ALMA)
  - Large number of antennas
    - Excellent UV coverage
  - Complex visibilities through phase referencing
  - Some recent software development
    - but CLEAN works most of the time…



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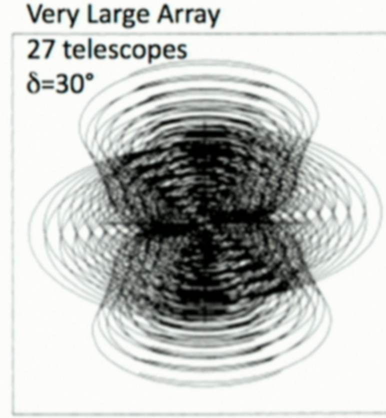
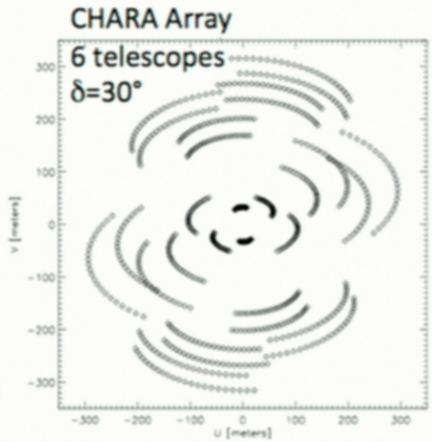
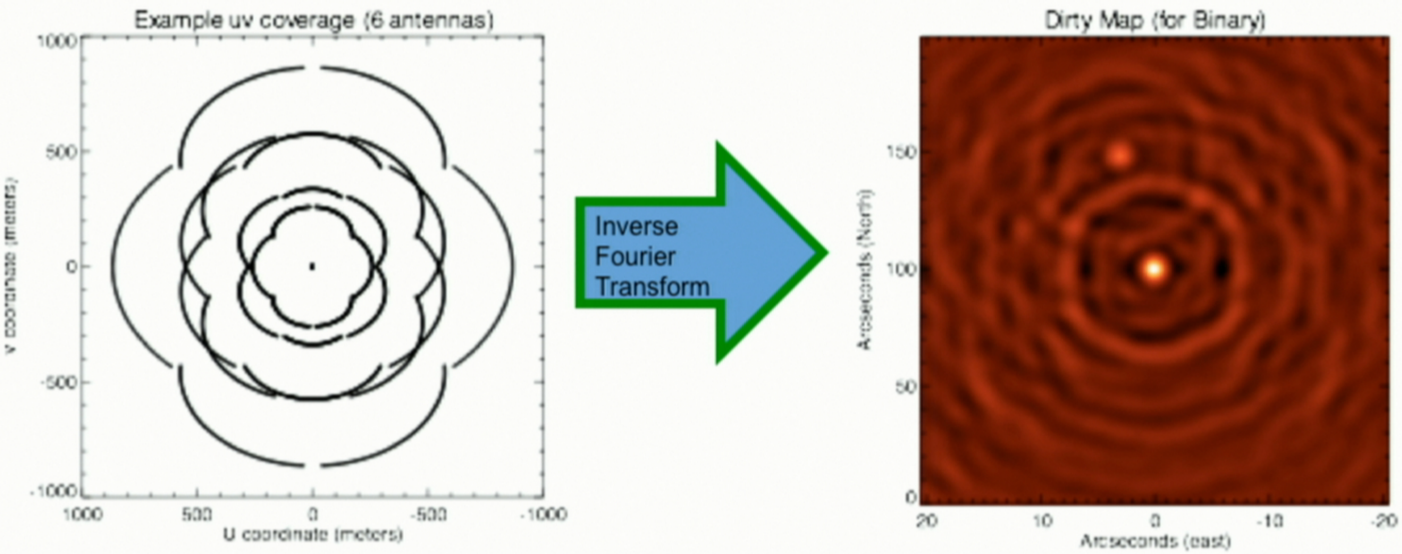


- Optical interferometry
  - 'poor' UV coverage, similar to EHT
    - at most 6 telescopes (CHARA/MIRC)
  - observables = Vis-Squared + Closure Phases
    - Similar to EHT
  - CLEAN is poor for marginally-resolved
    - <u>OI field had to innovate (no hardware solution!)</u>



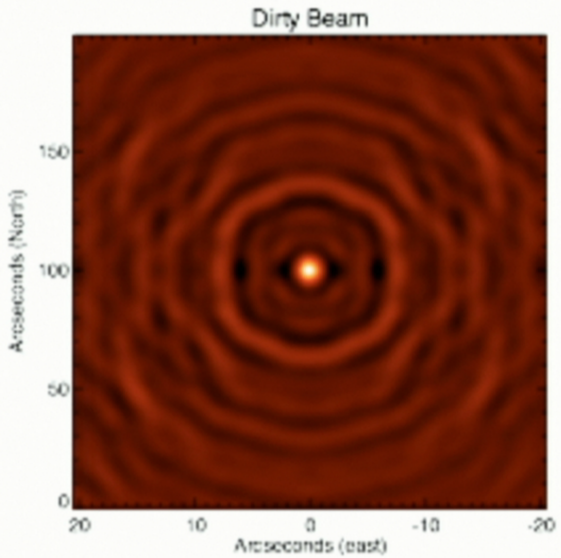
Imaging Methods

- Poor UV coverage leads to artifacts in your image



Deconvolution with CLEAN

"Point Spread Function"
From known UV coverage



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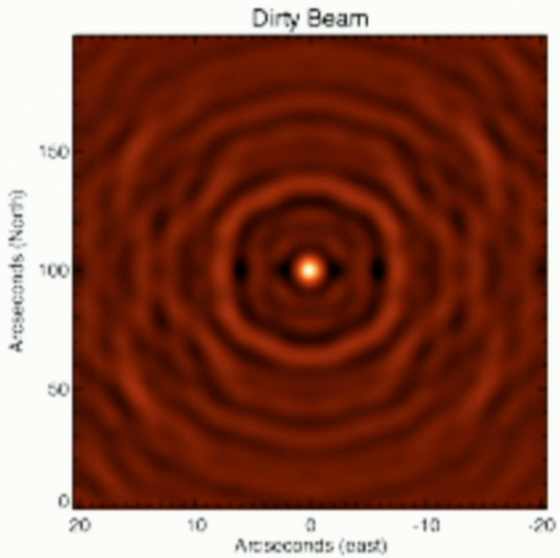

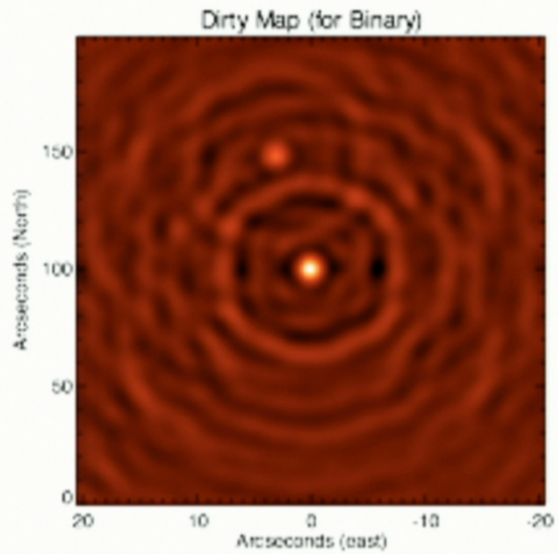

Astronomy

Limitations of CLEAN for OI/EHT

- CLEAN requires complex visibilities
  - Uses closure phase "self-calibration" loop for OI/EHT
  - Poor fidelity for small # telescopes
- Does not "naturally" deal with uneven sampling of uv plane or uneven errors bars
- "Super-resolution" in images is limited
  - Normally ok if you don't need the ultimate limit
  - You can't really spare it when only your object size is a few λ/B_{max}

Solving the image reconstruction problem

- With finite (u,v) coverage and with noisy data, there are an infinite number of images which will fit the data ($\chi^2 \sim 1$).

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Solving the image reconstruction problem

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- Use a "tie breaker" criteria to 'regularize' this ill-posed inverse problem

Posterior probability=
(probability of image given Data, Model)

$$\Pr(\boldsymbol{i}|\boldsymbol{D},\boldsymbol{M}) = \frac{\Pr(\boldsymbol{i}|\boldsymbol{M})\,\Pr(\boldsymbol{D}|\boldsymbol{i},\boldsymbol{M})}{\Pr(\boldsymbol{D}|\boldsymbol{M})}$$

i=image
D=Data
M=model of image formation

Classic Regularizers

- Pixel-based functions
  - Penalize fluxes depending on a default level

$$R(\boldsymbol{i}) = -\sum_k i_k \log \frac{i_k}{i_k^0}$$ Maximum Entropy (note: positivity built-in)

$$R(\boldsymbol{i}) = \sum_k \log i_k$$ Burg Entropy

$$R(\boldsymbol{i}) = \sum_k i_k^2$$ l2 norm (smoothness),Tikhonov regularizer

Finding the minimum

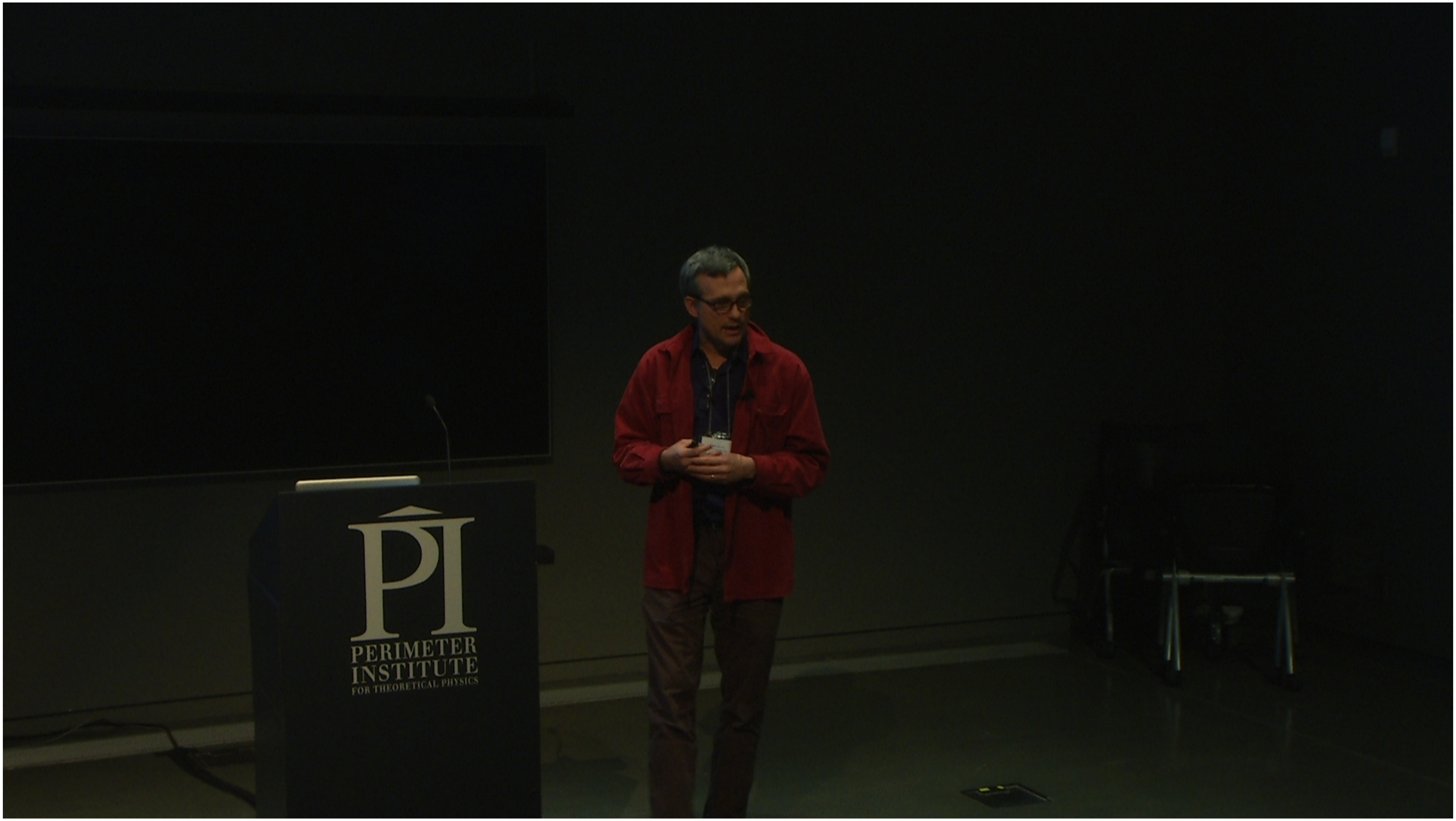
$$\boldsymbol{i}_{\mathrm{MAP}} = \underset{\boldsymbol{i}}{\operatorname{argmin}} \left[\chi^2(\boldsymbol{i}) + \mu R(\boldsymbol{i})\right]$$

Optical interferometrists have developed many imaging packages

- International Imaging Beauty Contests at SPIE serve as testbeds for algorithms on difficult (blind) synthetic datasets
- Two basic categories of algorithms…

Method 1. Gradient descent (semi-Newton, trust region)

- Requires gradient of the criterion with respect to the image pixels
- Explores the parameter space much faster, but will fall into local minimum
- Baron 2008, Le Besnesrais 2008, Meimon 2008, Thiebaut 2010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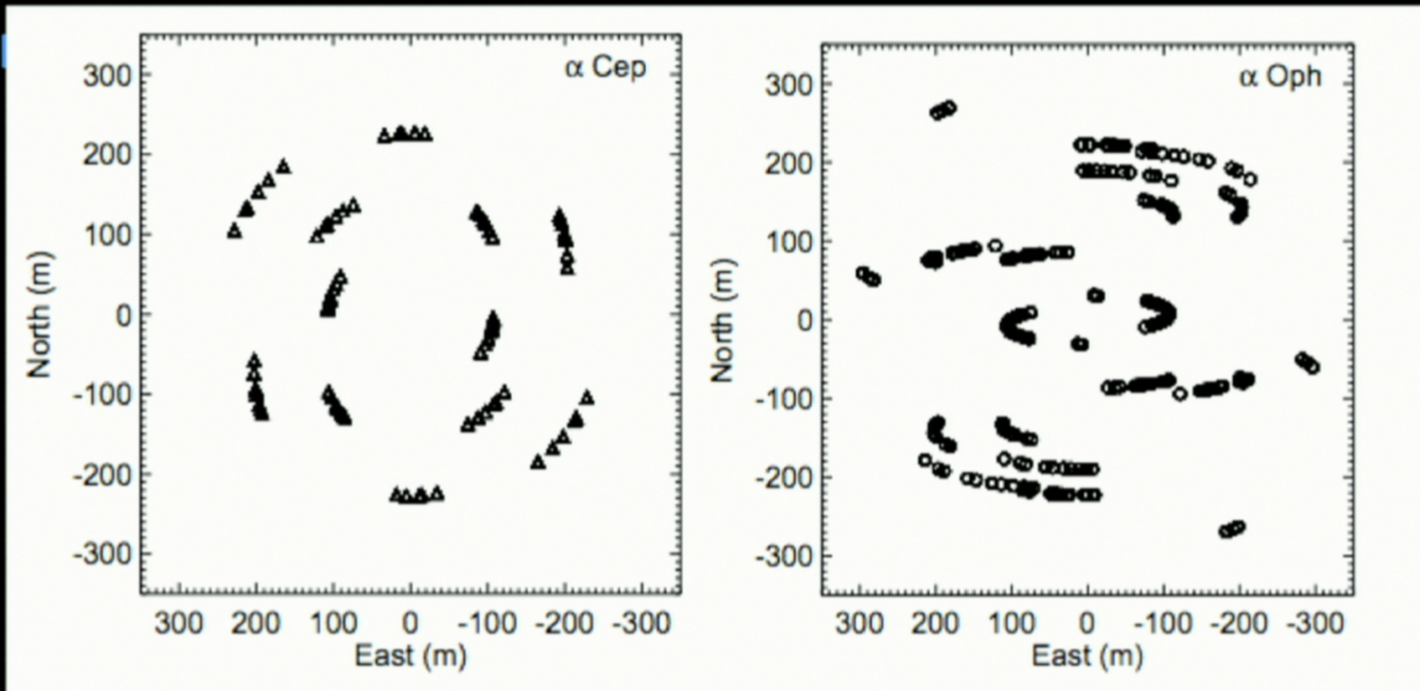
What can you do with much poorer UV coverage from only 4 or 6-telescopes?



from recent review by Ming Zhao

2 R_{sun}

EHT Simulations: M87 jet, detection of shadow

The Astrophysical Journal, 788:120 (10pp), 2014 June 20

doi:10.1088/0004-637X/788/2/120

IMAGING THE SUPERMASSIVE BLACK HOLE SHADOW AND JET BASE OF M87 WITH THE EVENT HORIZON TELESCOPE

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This study addressed a number of topics:

- Detectability BH shadow with realistic imaging fidelity
- Comparison of BSMEM vs. SQUEEZE vs CLEAN
- Robustness of EHT imaging to dropping a station
- Imaging quality vs observing bandwidth

Image Reconstruction: Insights from Optical Interferometry

Typical imaging results

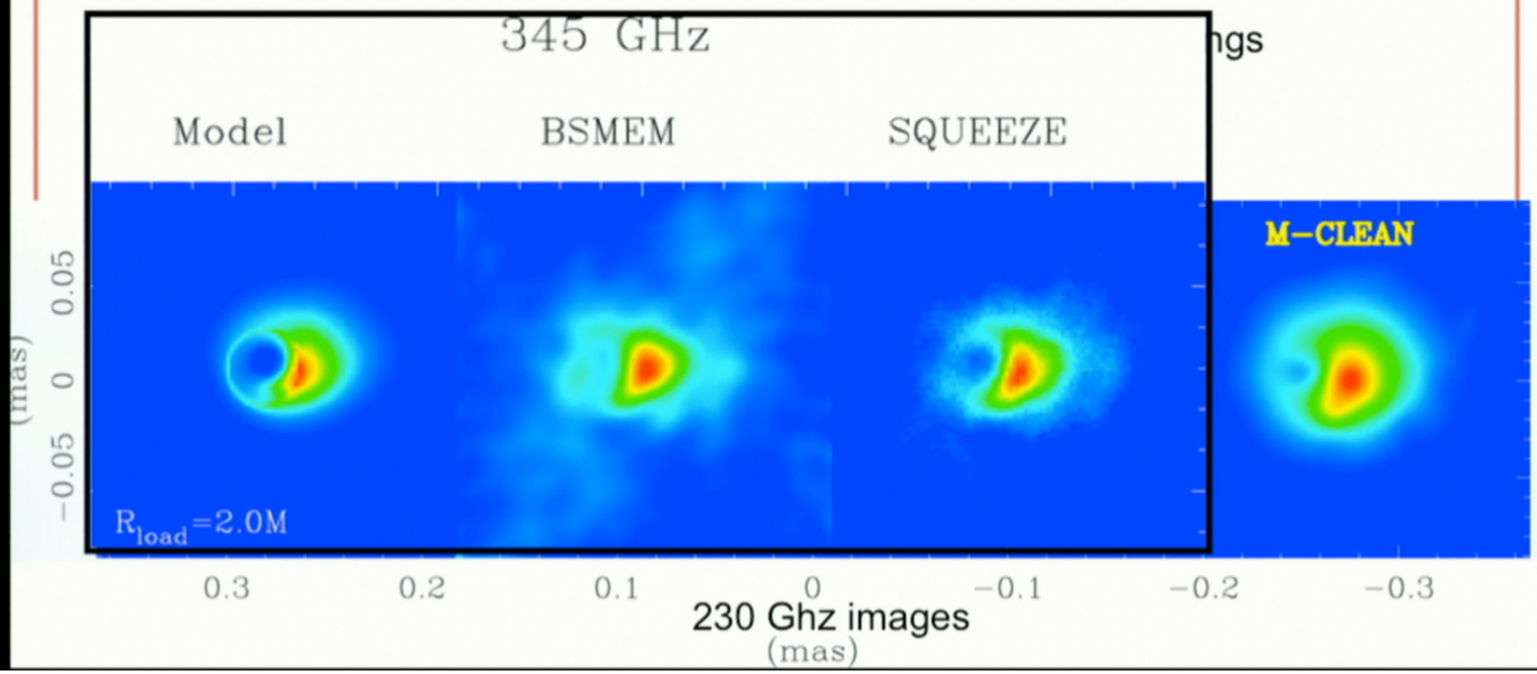
Reconstruction settings

MultiScale CLEAN (Greisen et al., 2009)

- Used Complex visibilities with no atmospheric
- Not realistic (no self-calibration loop)

BSMEM and SQUEEZE:

- Used squareed-visibilities and closure phases, more realistic!
- Regularization = entropy



230 Ghz images

What's Next?

Transtemporal reconstruction

- Reconstruction of a movie: jet/shadow/disc
- Tracking orbiting features?
- Use the previous and next images to improve reconstruction of current image

Polarimetry: Full Stokes reconstructions

- Need to devise transpolarization regularizers
- Positivity constraint not available (Stokes Q,U,V)
  - Literature exists adapting MEM, e.g., Ponsonby 1973
- Markov-Chain might explore both image (x,y) and Poincaré Sphere (Q,U,V)