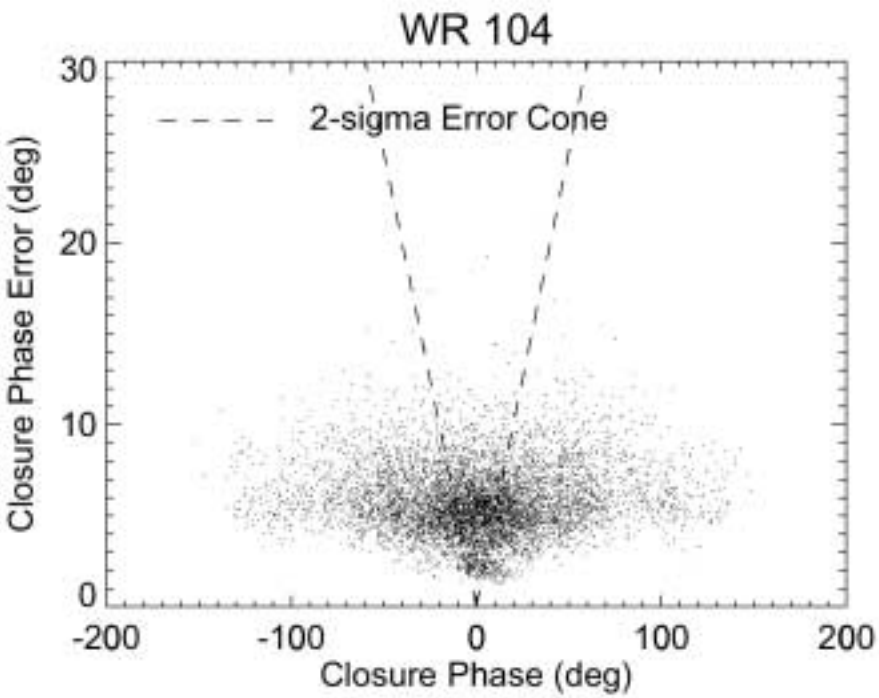
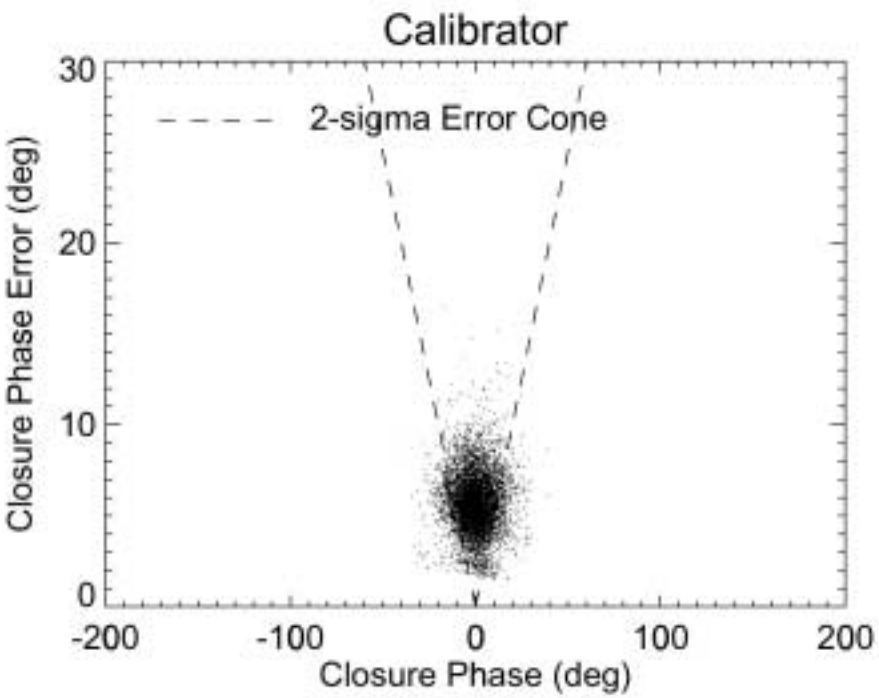
Inspecting the Closure Phases

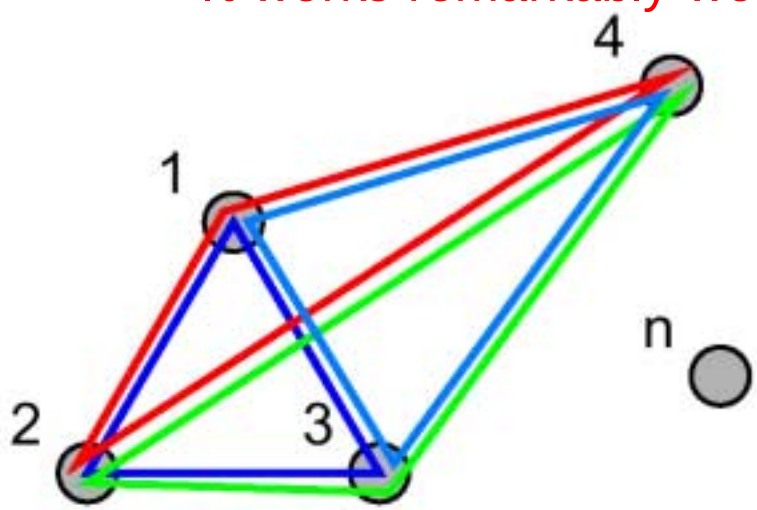




Visualizing the Closure Phases

Consider the baseline stretching from hole 1 to 2. You can estimate the Fourier Phase $\phi_{1,2}$ of this baseline by averaging all the Closure Phases which contain this baseline, $\Phi^{CP}_{1,2,k}$. This method allows you see correlations in the phase information in the Fourier Plane, although proper phase retrieval methods are needed for quantitative analysis.

It works remarkably well if you have good (u,v) coverage!



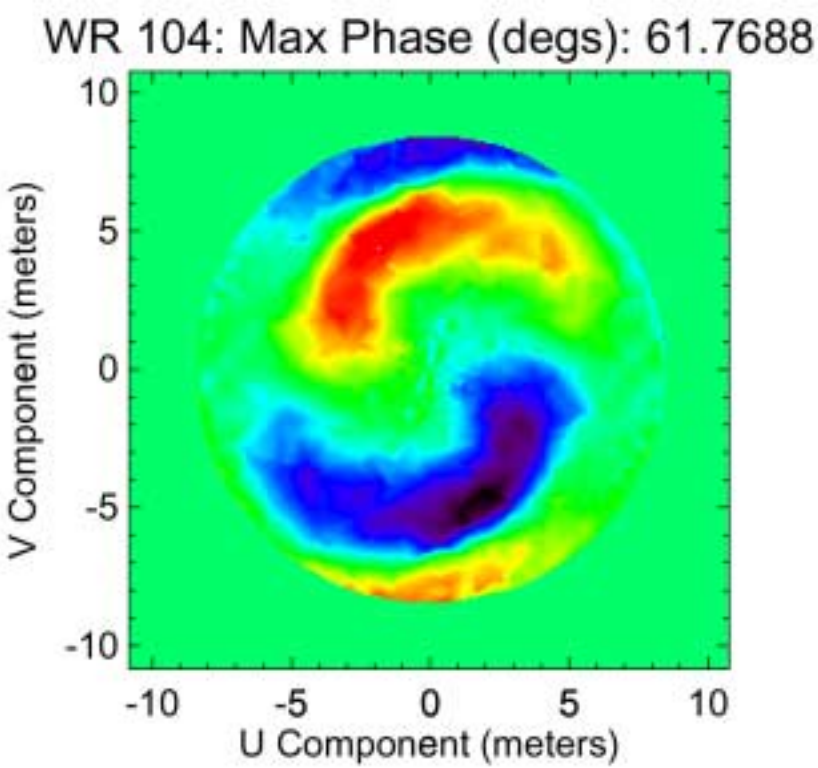
$$\phi_{i,j}(\vec{u}_{ij}) \approx \left\langle \Phi^{CP}_{i,j,k} \right\rangle_k$$

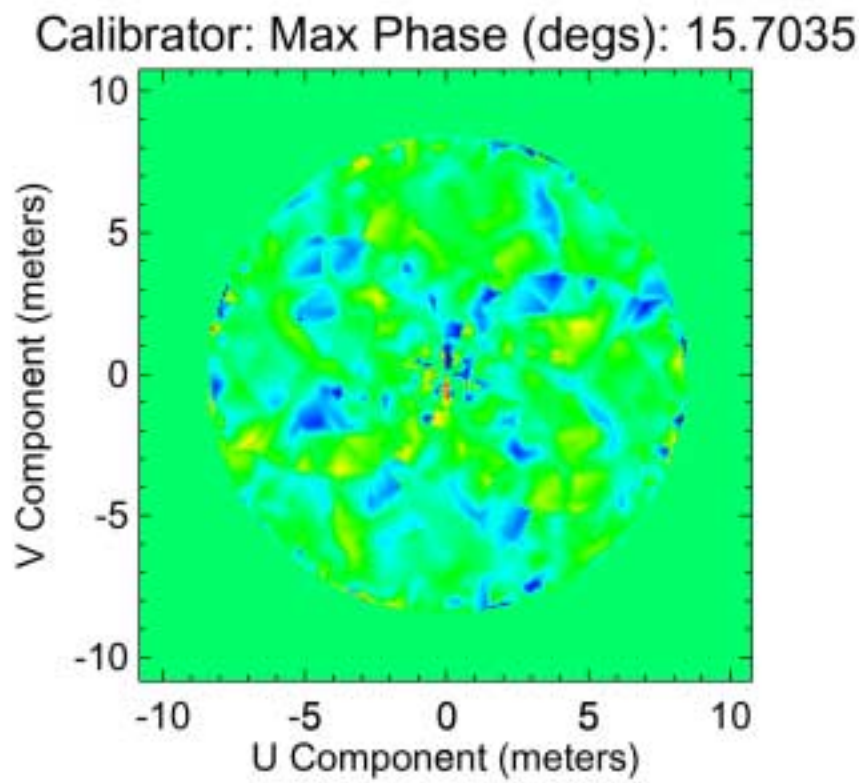
Fourier Phase to be estimated

Average over all the closure phases which contain this baseline

Visualizing the Closure Phases: Examples

$$\phi_{i,j}(\vec{u}_{ij}) \approx \left\langle \Phi^{CP}_{i,j,k} \right\rangle_k$$





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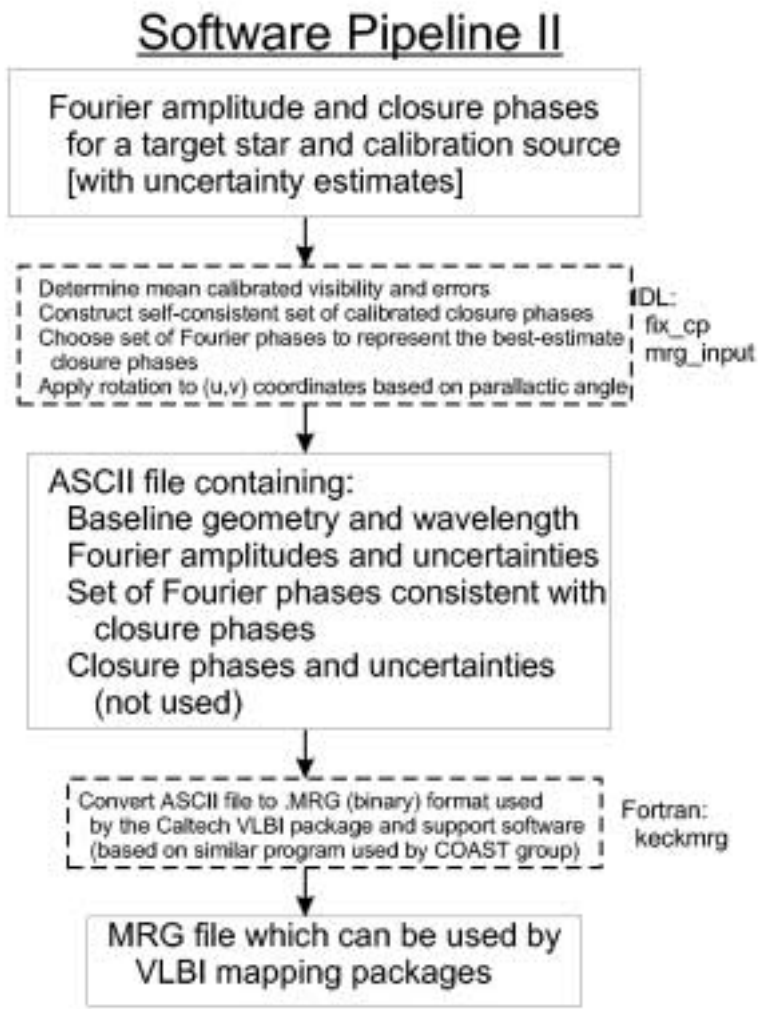
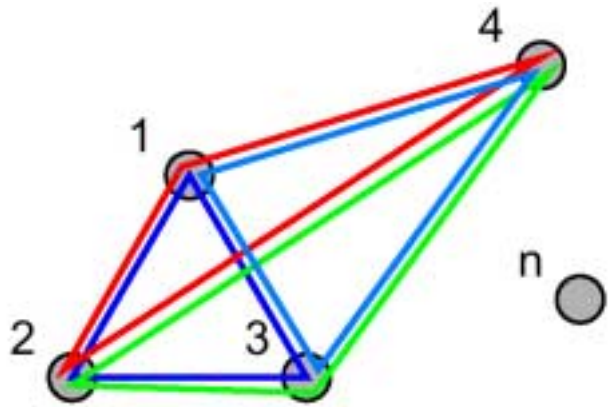
Software Pipeline II



Stuffing into VLBI Package

Find best set of Phases to approximate the Closure Phases

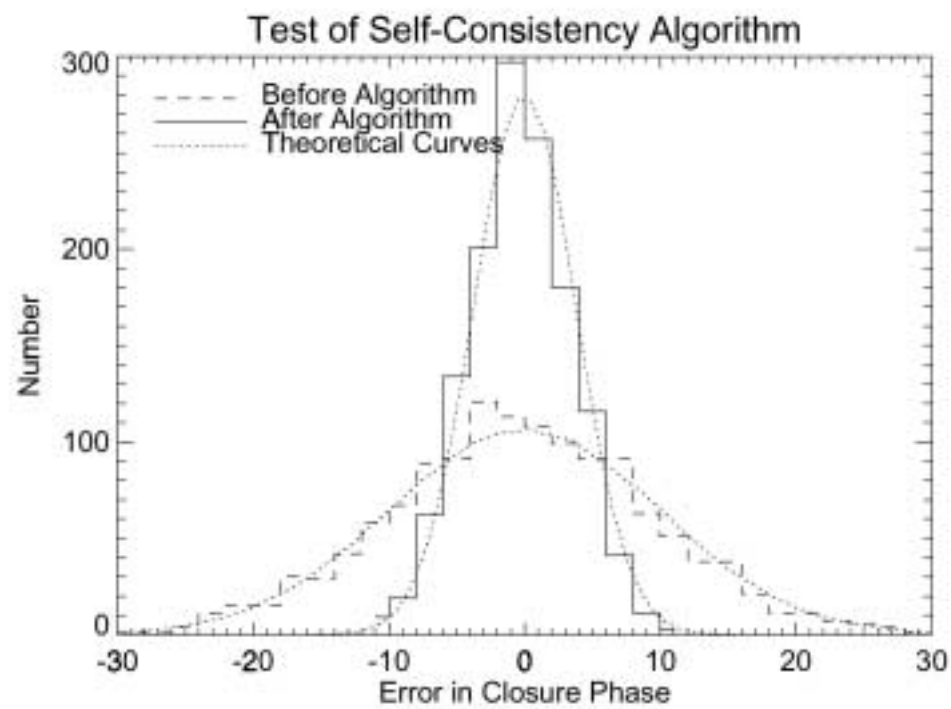
- Singular Value Decomposition (phase wrapping problems, no weighting)
- Best-fitting (phase wrapping problems, many local minima)
- Iterative Relaxation by Enforcing Closure Phase Self-Consistency



$\Phi(1\text{-}2\text{-}3) = \Phi(1\text{-}2\text{-}4) + \Phi(4\text{-}2\text{-}3) + \Phi(1\text{-}4\text{-}3)$

In General:

$\Phi(1\text{-}2\text{-}3) = \Phi(1\text{-}2\text{-}n) + \Phi(n\text{-}2\text{-}3) + \Phi(1\text{-}n\text{-}3)$



Deconvolution & Aperture Synthesis

- To reconstruct an image from sparsely sampled (u,v) data, one must interpolate into regions where data does not exist.
- This is Identical to multiplying the true Complex Visibility by an Aperture Function.
- Since Multiplication in the (u,v) space is the same as Convolution in image space (see Convolution Theorem), the problem can be re-cast as a Deconvolution problem.
- Popular methods of Deconvolution include CLEAN and the Maximum Entropy Method.

Maximum Entropy Method (MEM)

With finite (u,v) coverage and with noisy data, there are an <u>infinite</u> number of images which will fit the data.

So how do we choose?

Find "smoothest" image consistent with data ($\chi^2 \sim 1$)

MEM uses the "entropy" S to parameterize the "smoothness."

Fraction of flux in pixel i

Skilling & Bryan (1984)

Entropy $$S = -\sum_i f_i \ln \frac{f_i}{I_i}$$ Image prior

Sum over all pixels

Properties of MEM

$$S = -\sum_i f_i \ln \frac{f_i}{I_i}$$

- Naturally enforces positivity and finite extent of the image
- In the case of no data, reconstructed image will revert to the image prior I_i, a method of introducing *a priori* information
- Reconstructed images will contain some spatial frequency information beyond the diffraction limit due to the smoothness and positivity constraints, leading to moderate "super-resolution."
- Fields containing point sources embedded in extended nebulosity may show artifacts reminiscent of Airy rings

Self-Calibration

models intrinsic Fourier phases
plus telescope errors

$$\Phi^{intrinsic}_{ij} = \Phi^{measured}_{ij} - \underbrace{(\phi_i - \phi_j)}_{\text{telescope errors}}$$

Generate Fourier phases consistent with closure phases & begin with initial trial image

↓

Calculate complex visibility (amplitudes and phases) of trial image

↓

Adjust telescope errors so measured Fourier phases are best fit by combination of trial image phases plus telescope errors

↓

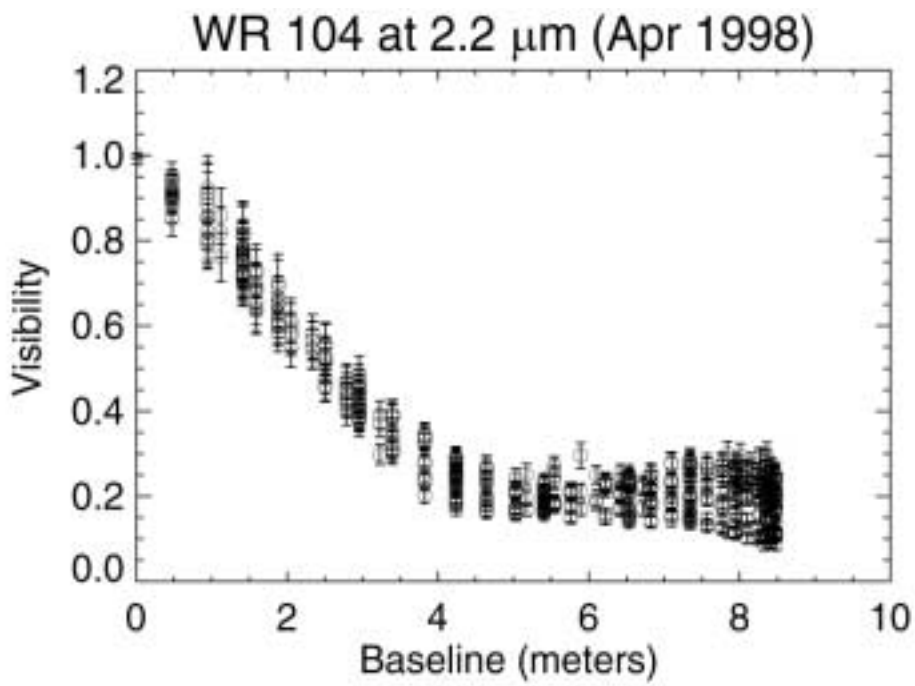
Correct trial phases based on new estimates of telescope errors, and map using CLEAN/MEM

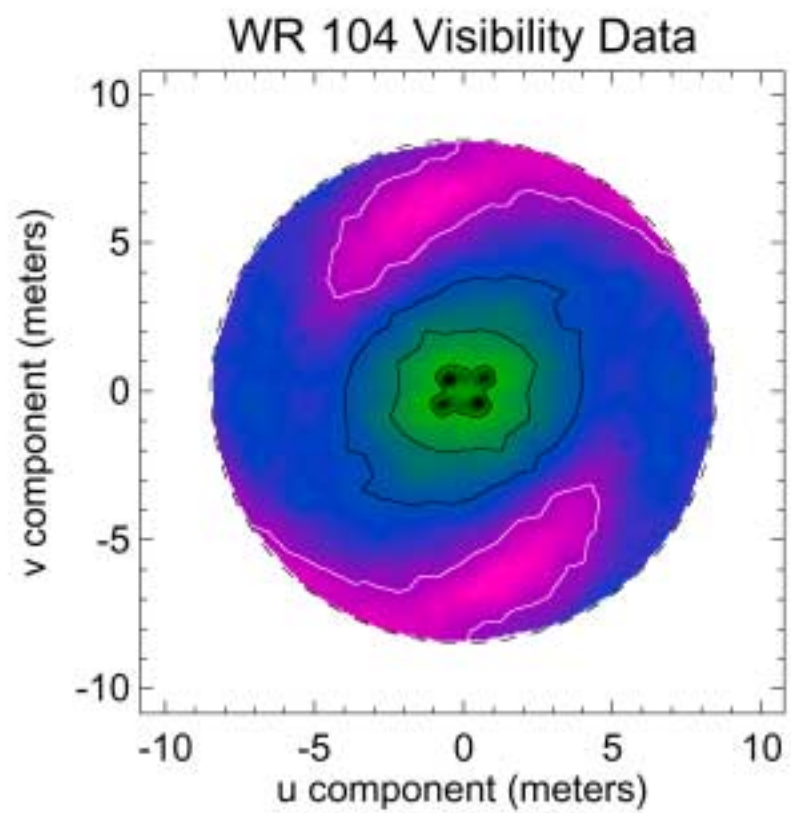
↓

If not converged, use this new map as the next trial image

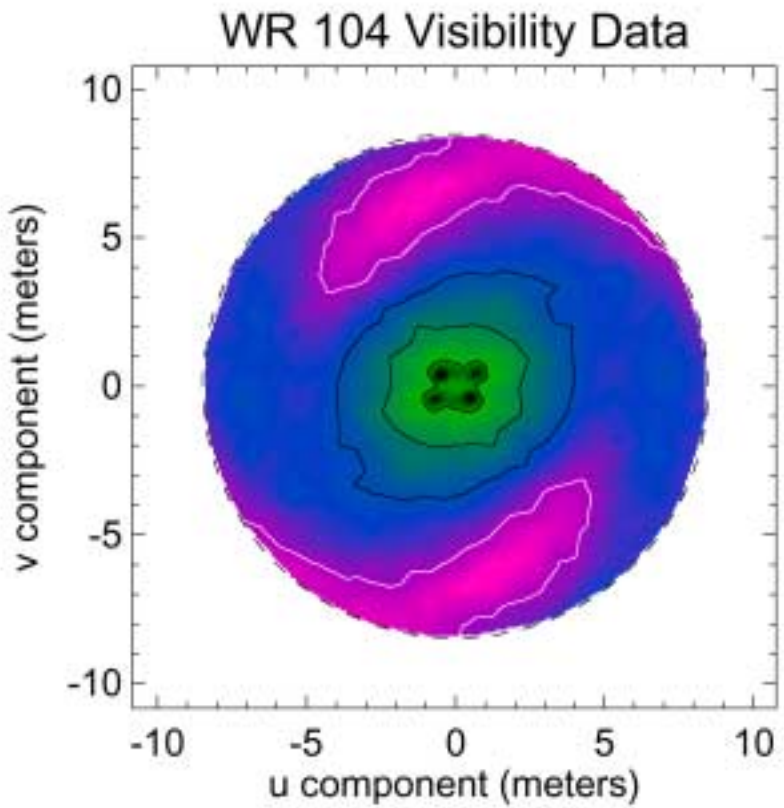
Based on Cornwell & Wilkinson (1981)

WR 104 Data

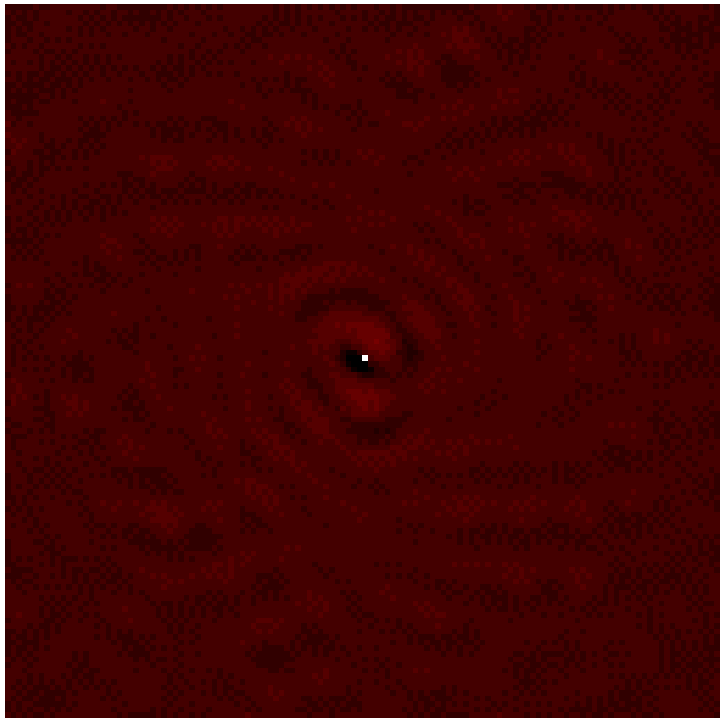

WR 104 at 2.2 μm (Apr 1998)
Visibility
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
Baseline (meters)


WR 104 Visibility Data
v component (meters)
10
5
0
-5
-10
-10
-5
0
5
10
u component (meters)

WR 104 MEM Reconstruction

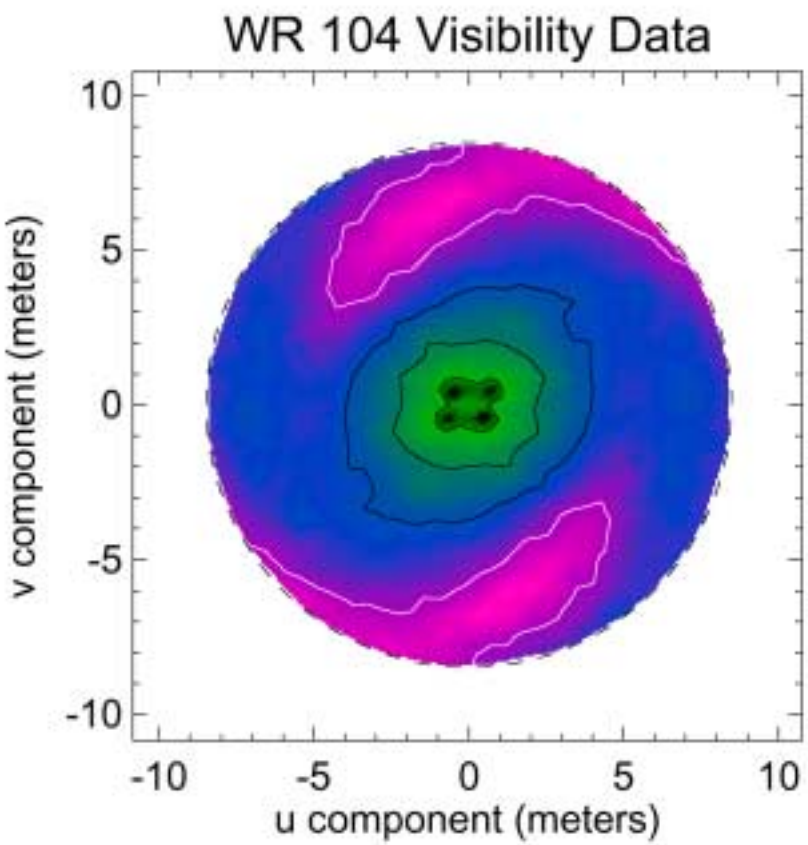


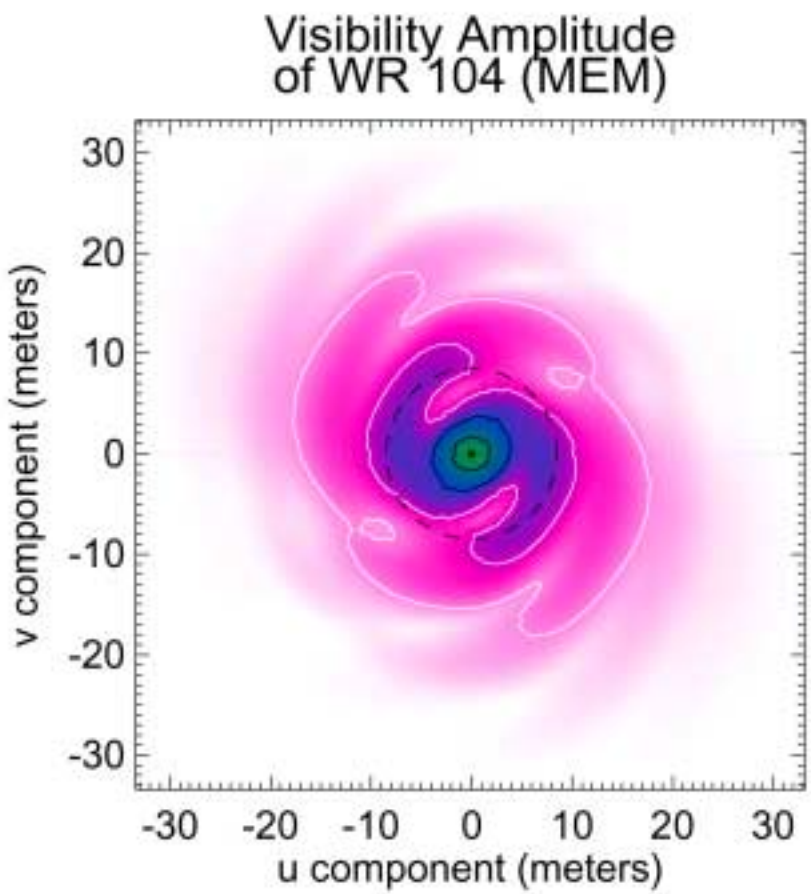
Iterations 1 to 30



WR 104 (2.2 microns)

A Little Super-Resolution…





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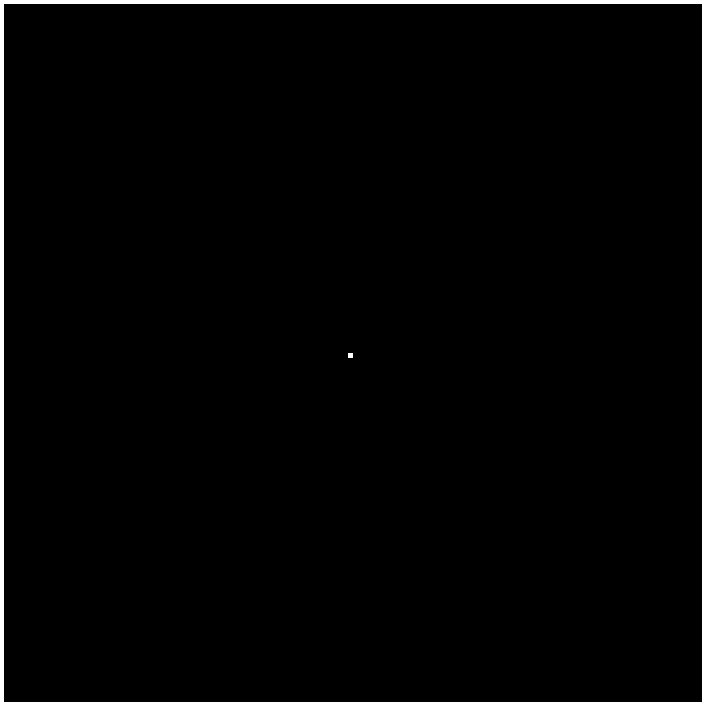
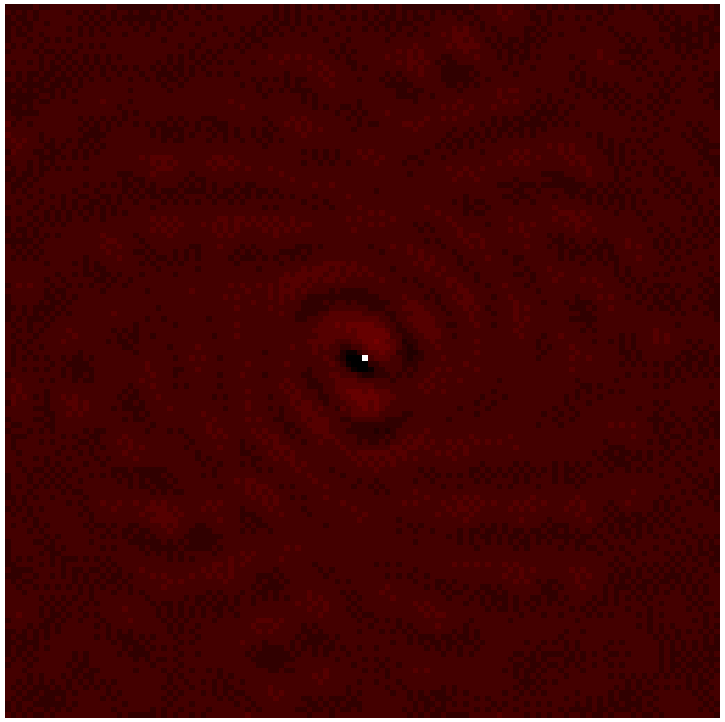
Imaging With MEM

MEM Reconstructions: Iterations 1 to 30

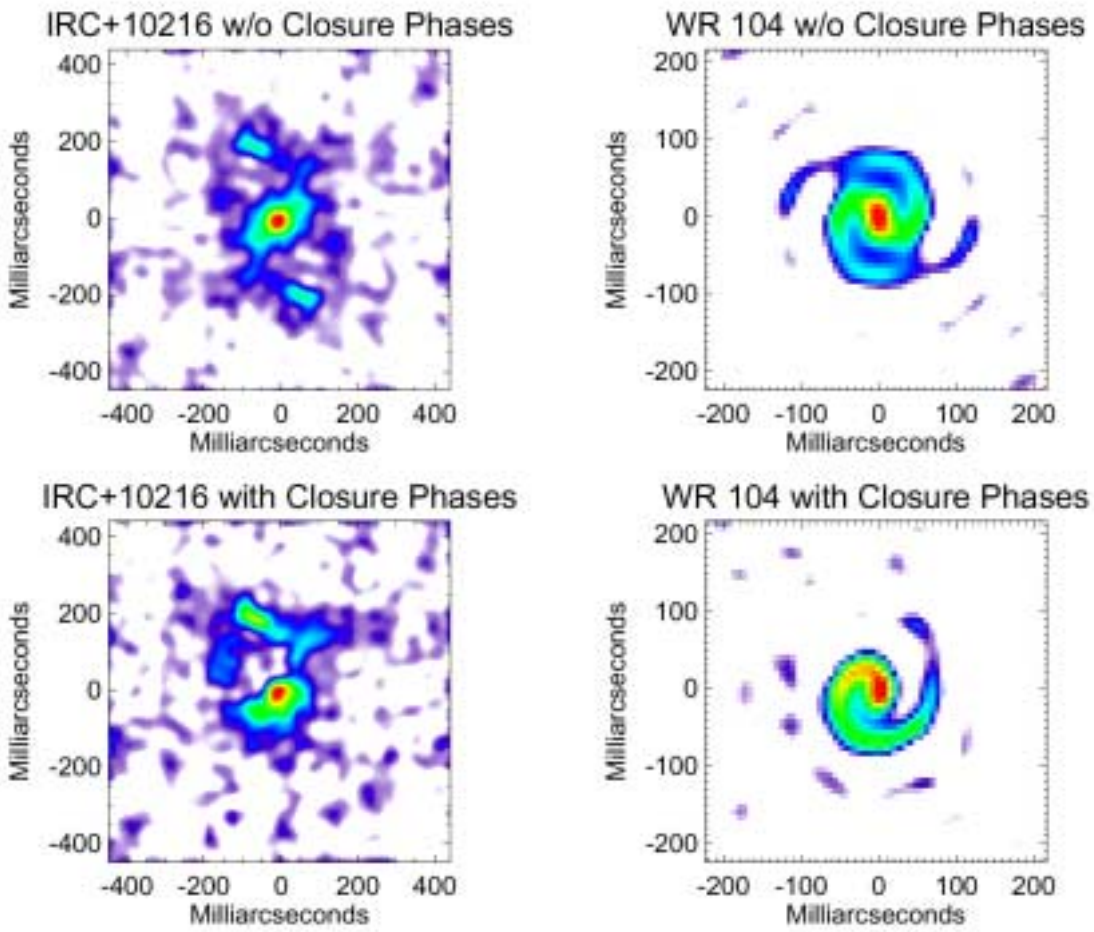


IRC +10216 (2.2 microns)



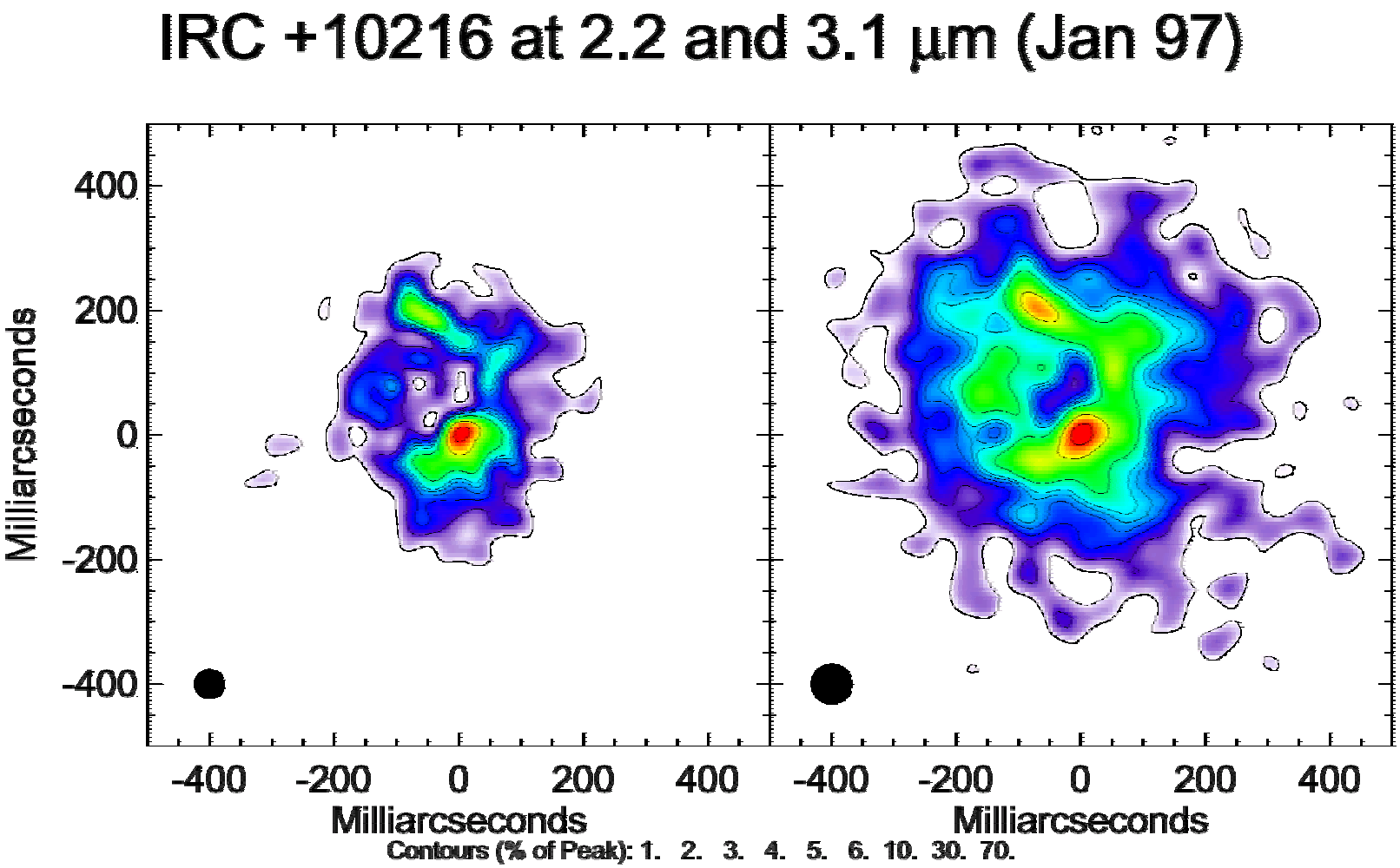
WR 104 (2.2 microns)

Importance of Closure Phases



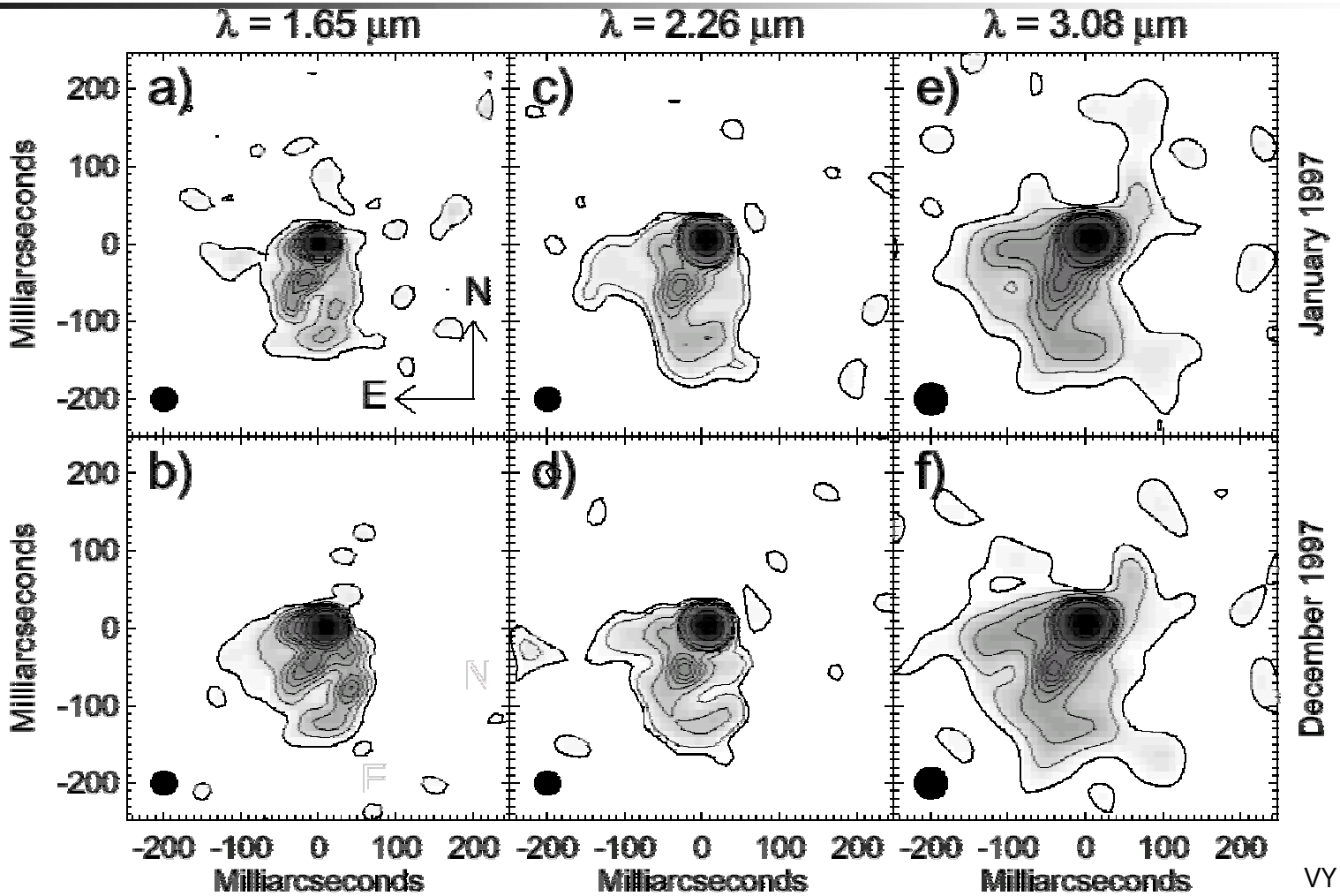
Michelson Summer School 2001 (Monnier)

Multi-Wavelength Coverage



Tuthill et al 2000

Good Imaging Reproducability

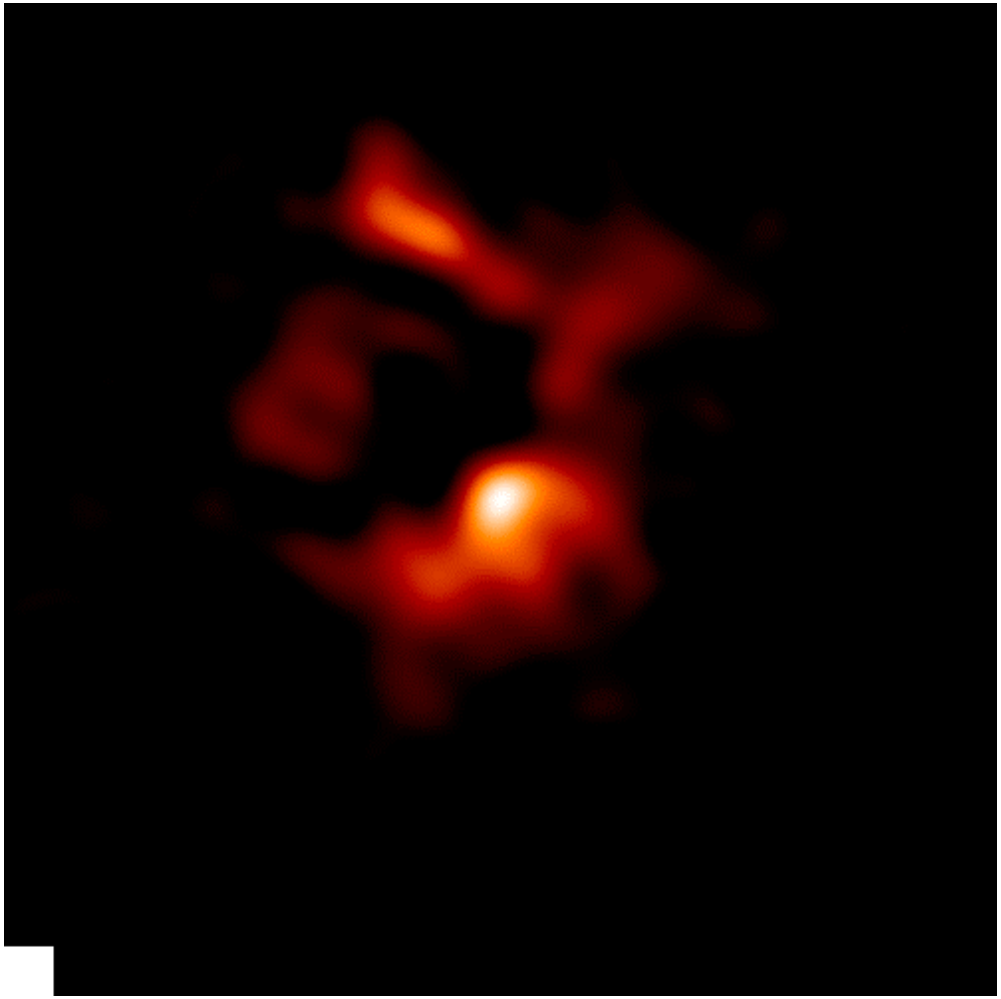


VY CMa
Monnier et al 1999

IRC +10216 Movie (3.5 years)

Robust imaging software is essential for long-term studies of complex sources.

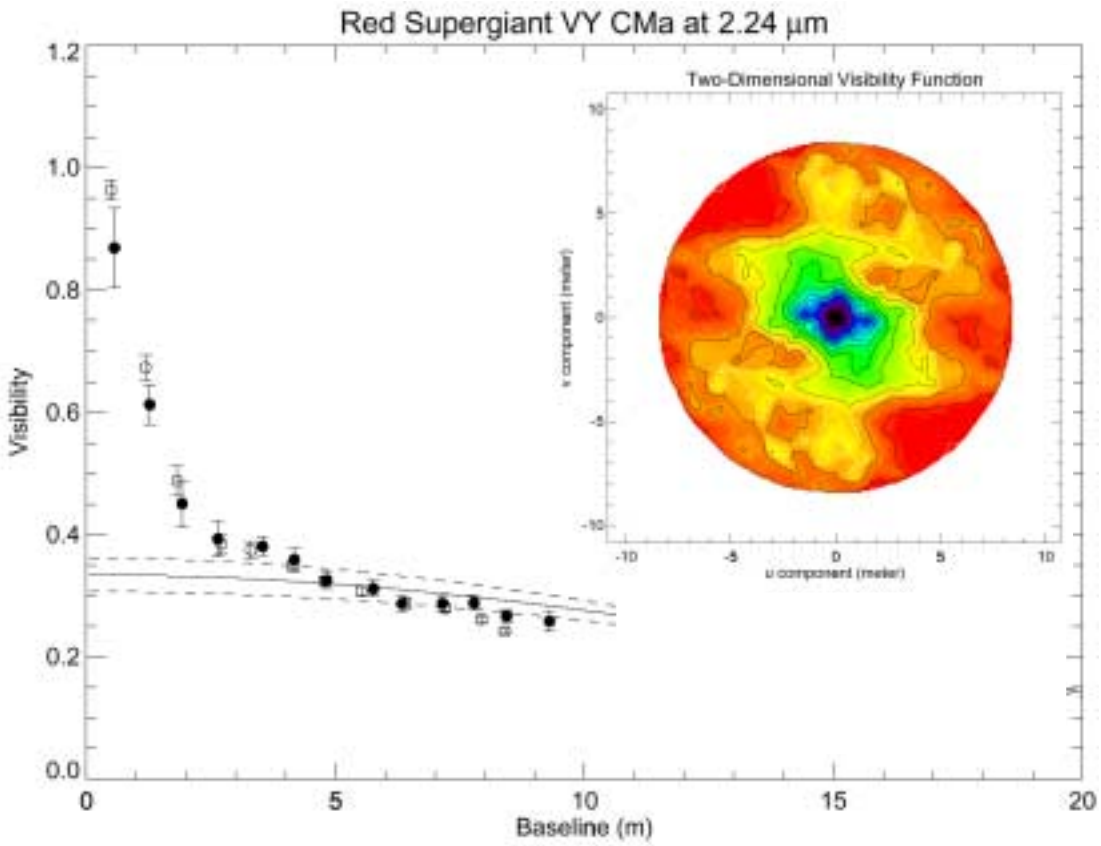
Time-variability studies will become an *Industry* with new imaging interferometers (already is for some).

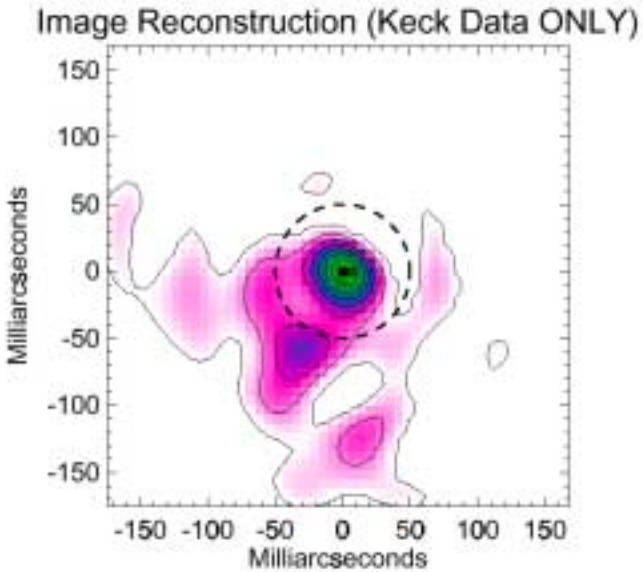


20 AU

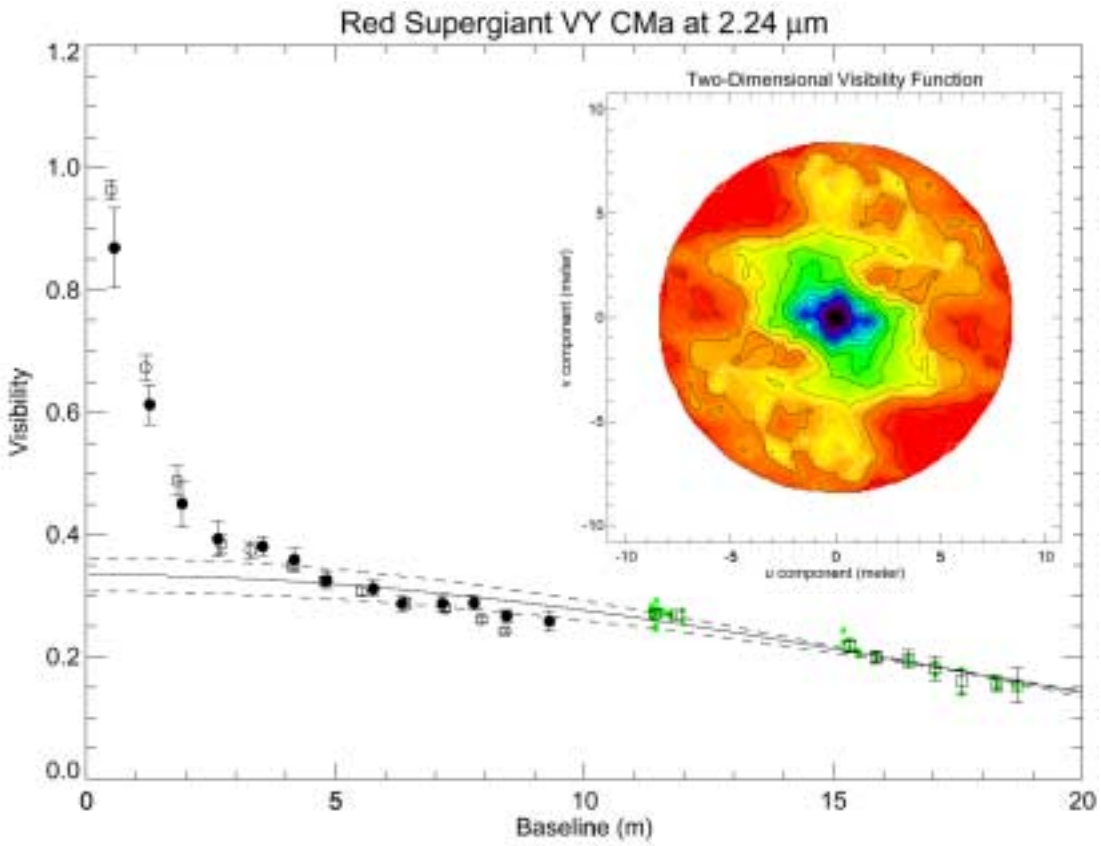
Tuthill et al 2000

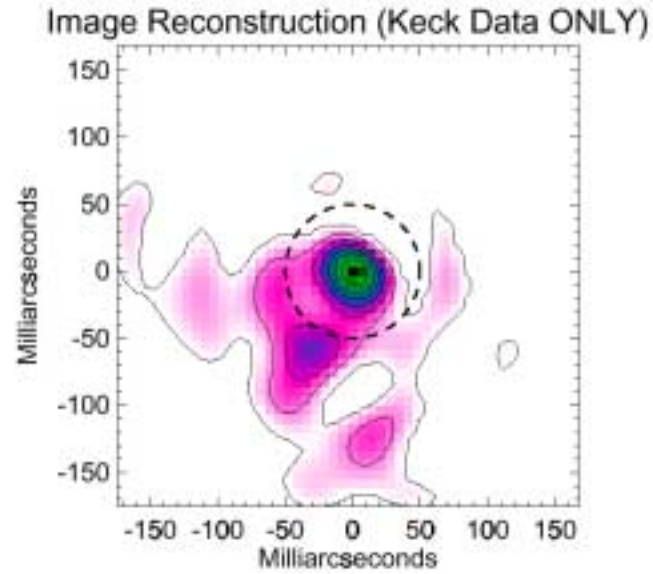
Imaging With MEM
... some problems

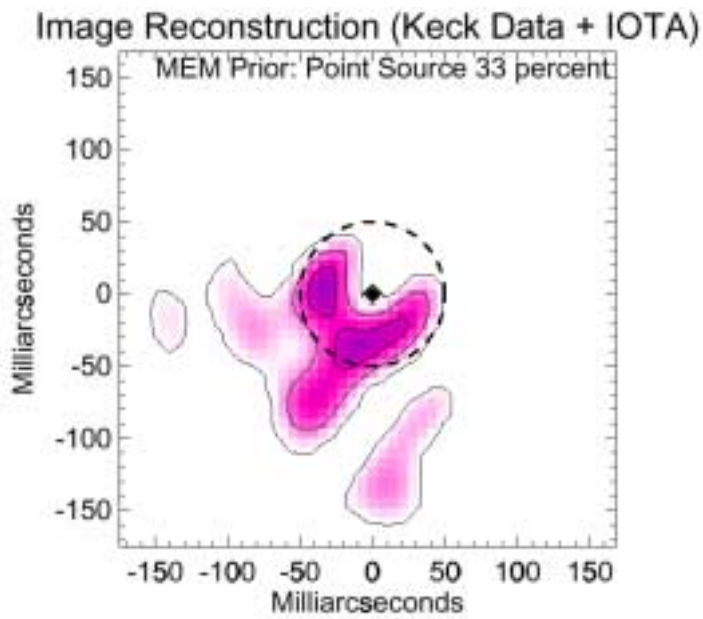




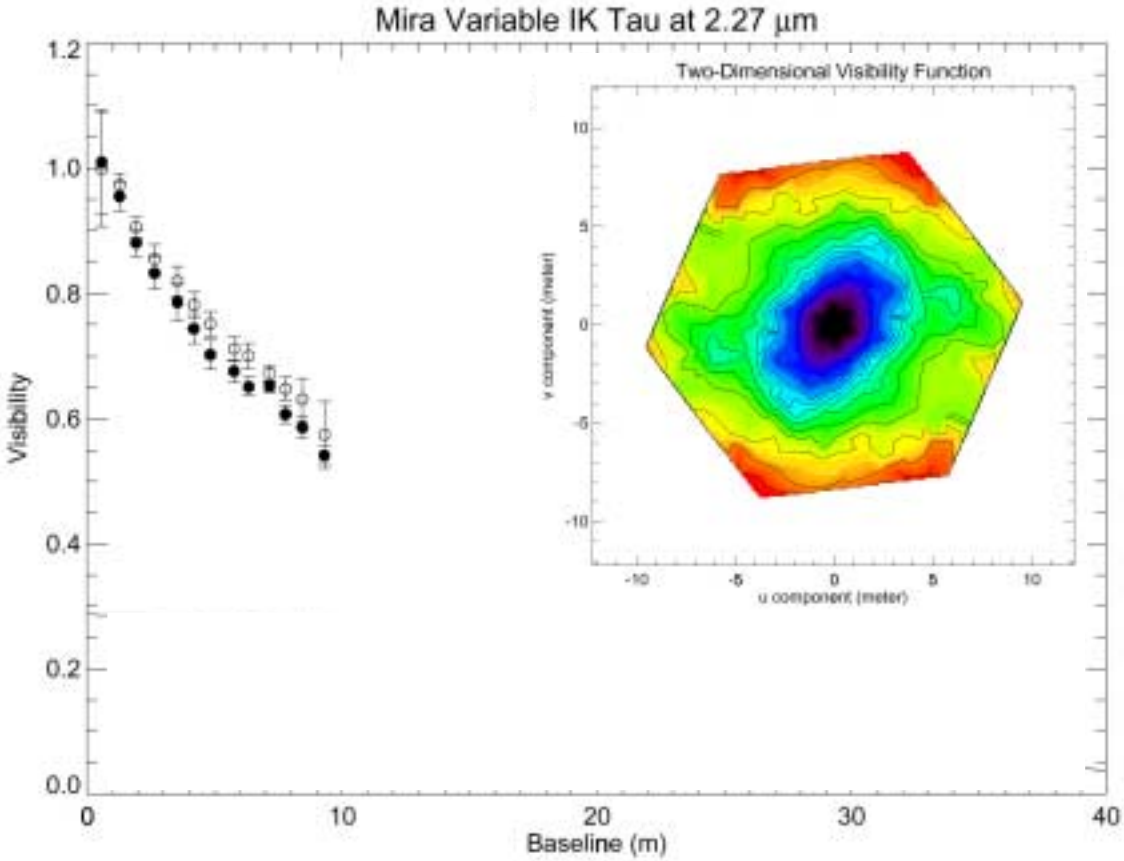
Imaging With MEM
... some problems

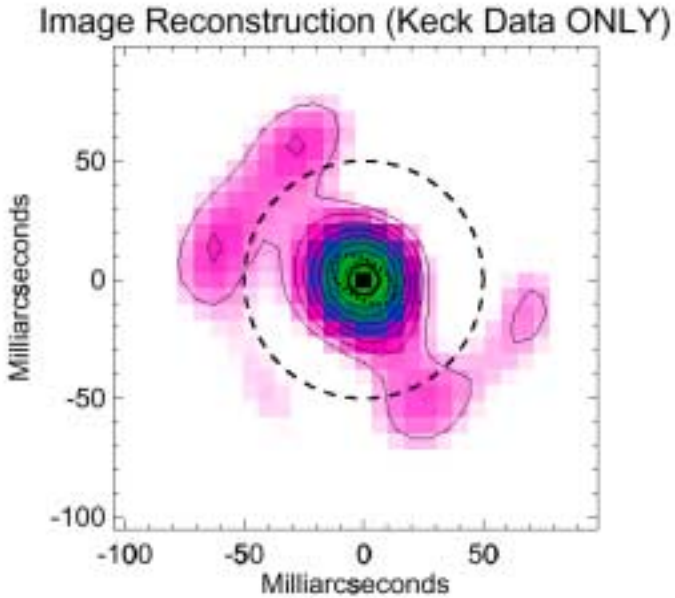






One always needs …





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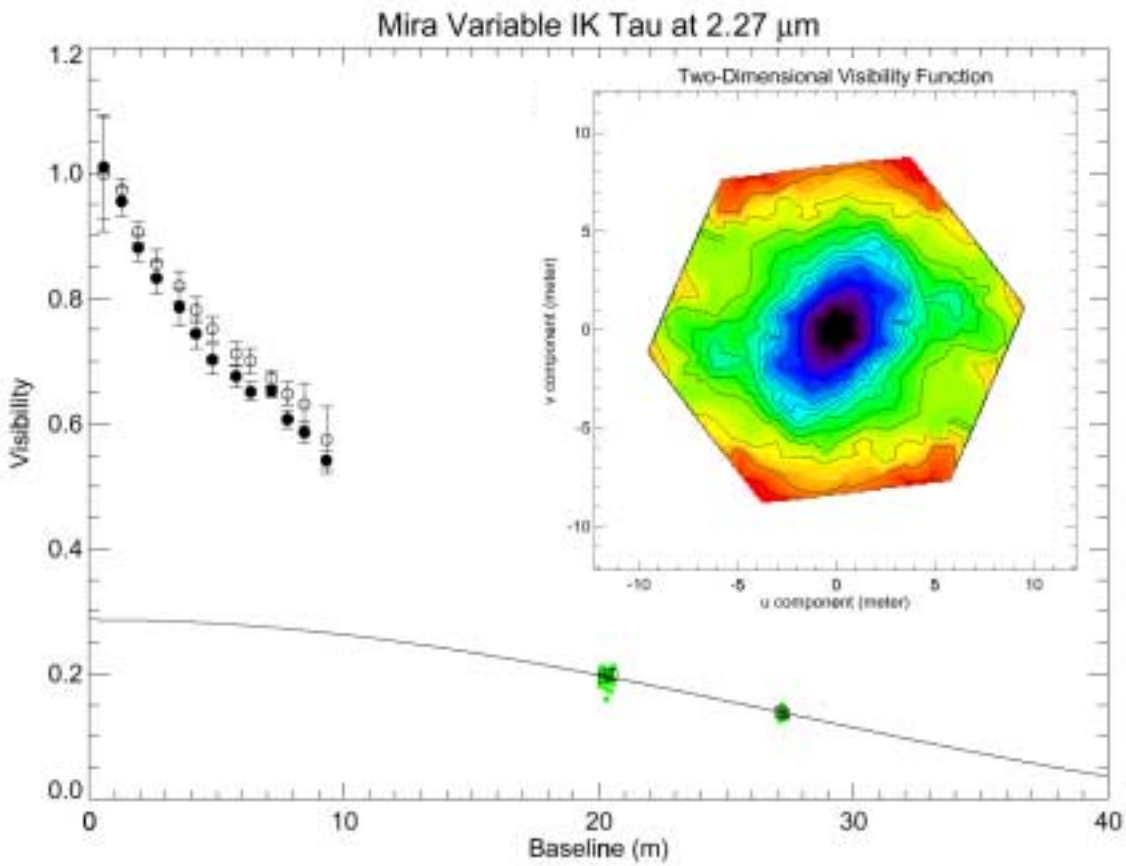
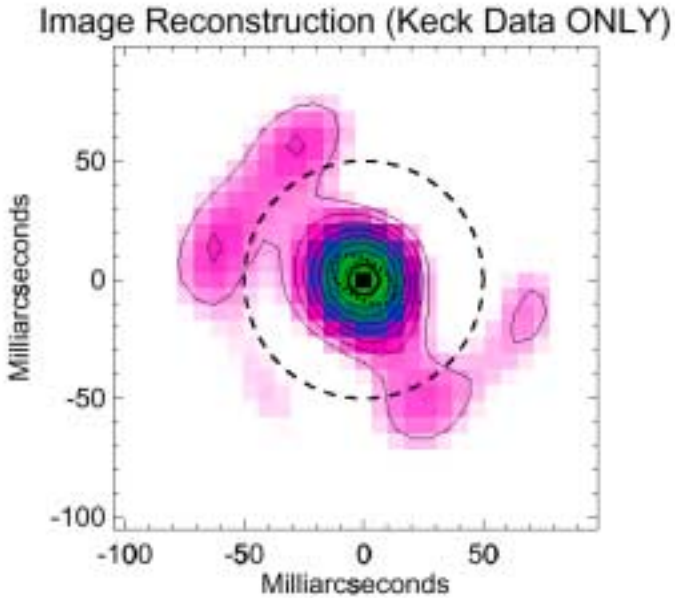
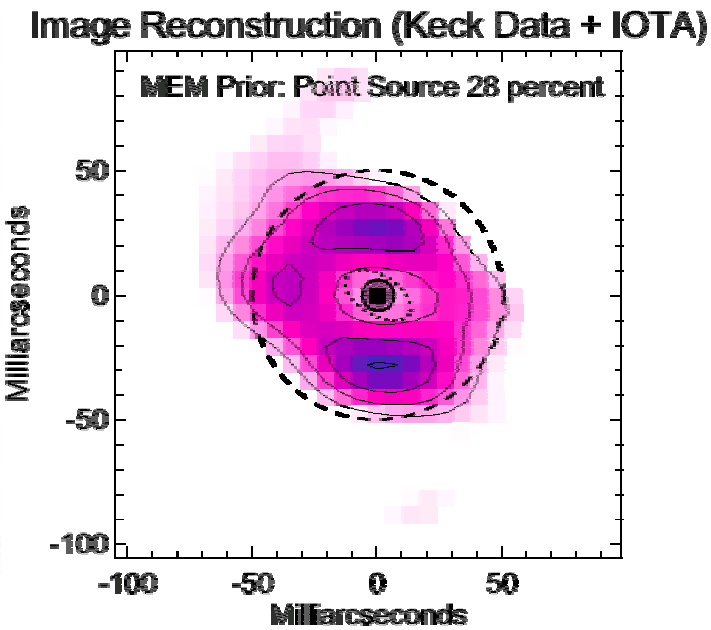
One always needs ...enough resolution







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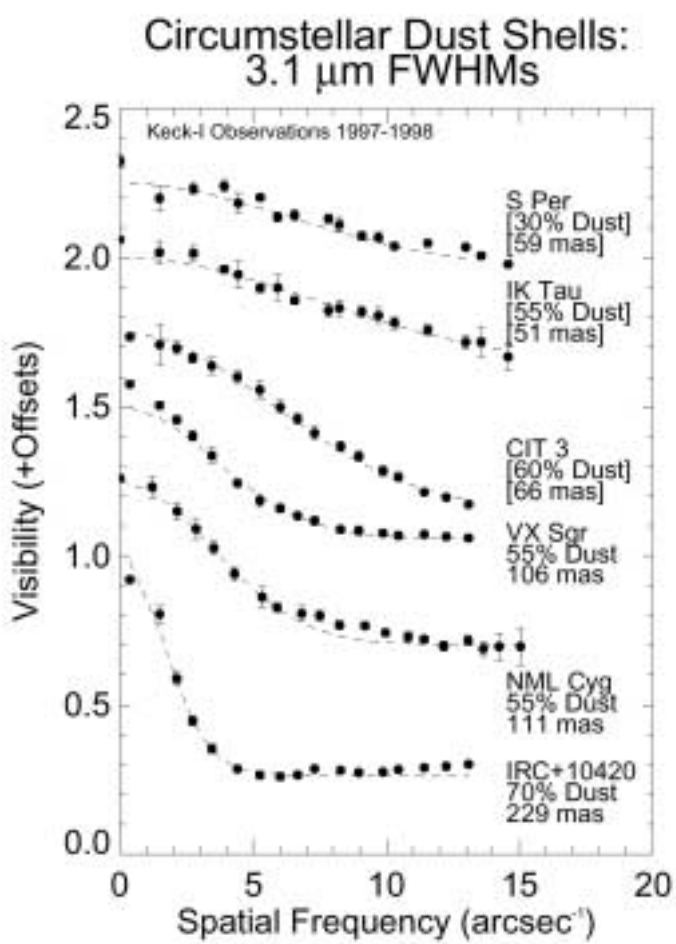
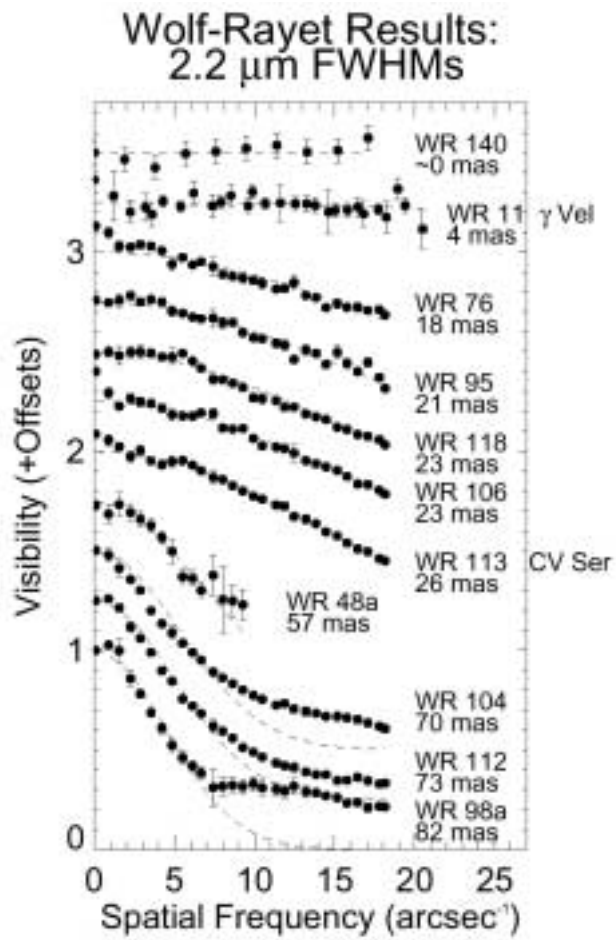
Modeling the “Round” Dust Shells





Michelson Summer School 2001 (Monnier)

Monnier et al 2000

Summary of Software Problems

- Need flexible new data format for Optical Interferometry data
  - Must save Vis^2, the Bispectrum (closure phases and triple amplitudes)
- VLBI/AIPS/AIPS++ do not really deal directly with closure phases
  - Excludes proper handling of closure phase uncertainties
- Imaging software
  - Need “multi-resolution” techniques
  - How to deal with *very* sparse Fourier coverage?

Conclusions

- Despite the high detector read-noise at Keck, aperture masking in the infrared succeeds at imaging dusty sources down to Kmag ~ 5
- Closure Phases contain enough phase information to allow image reconstructions of complex astrophysical sources
- Software written for radio interferometers is useful, but not well-suited to our problems

Imaging Interferometers

Long-Baseline Interferometer

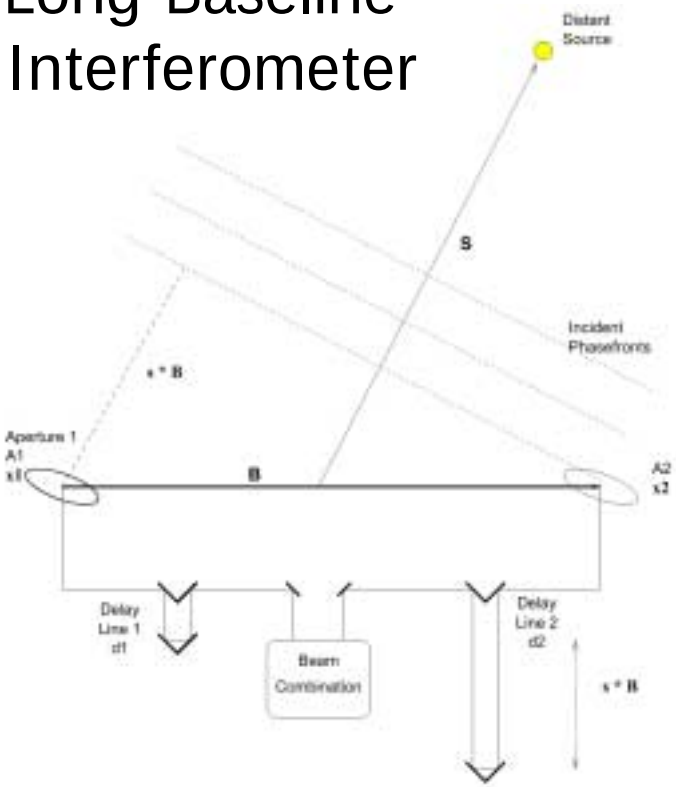
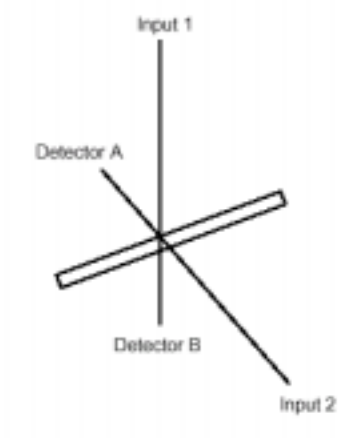
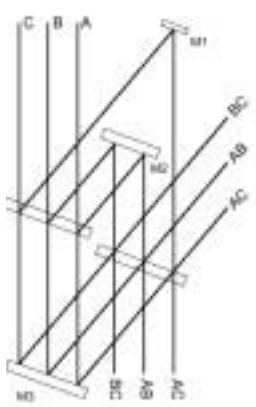


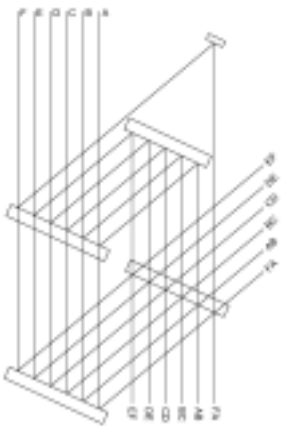
Figure 2.1: Idealized Interferometer.

Boden 2000

Beam Combination



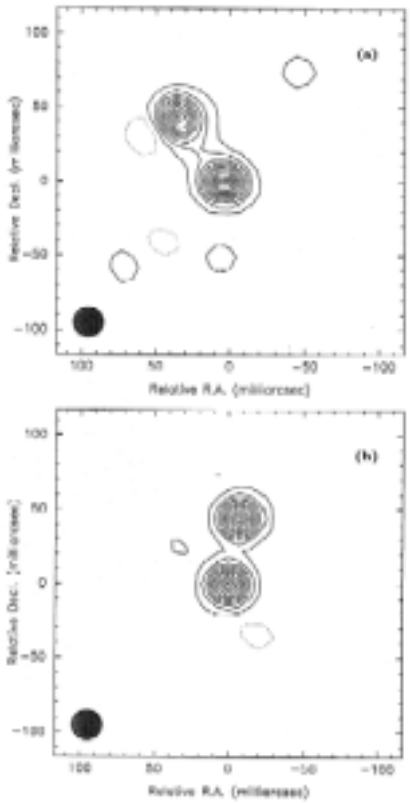




Mozurkewich 2000

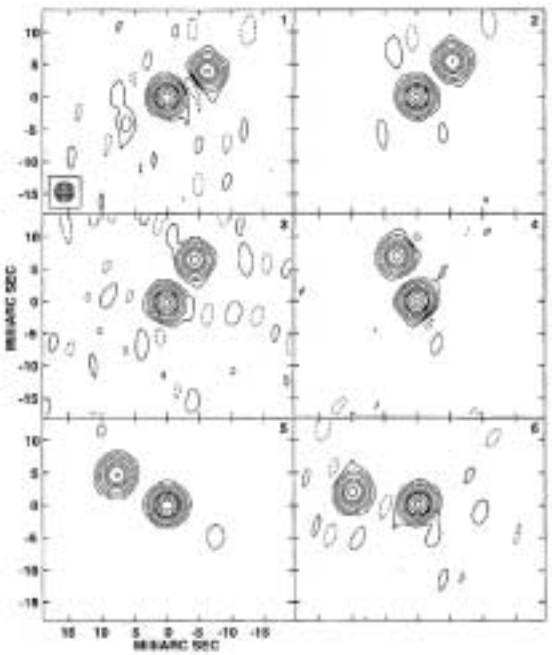
Imaging w/ Real Interferometers

COAST 1996



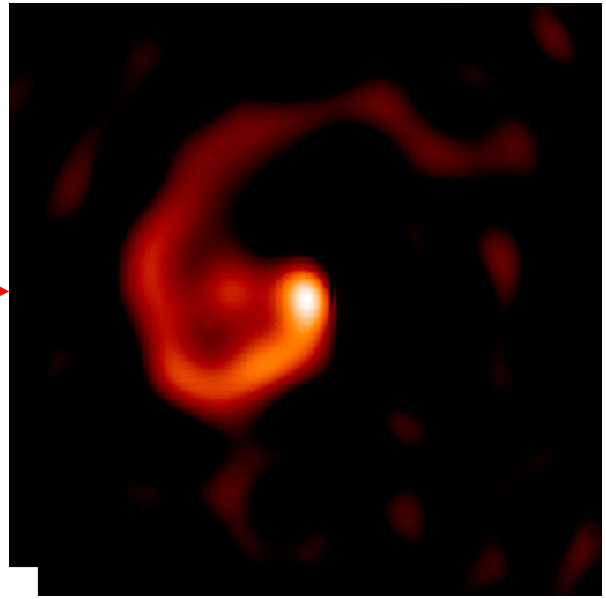
Capella

NPOI 1997



ζ UMa

Coming soon to an interferometer near you!



WR 98a