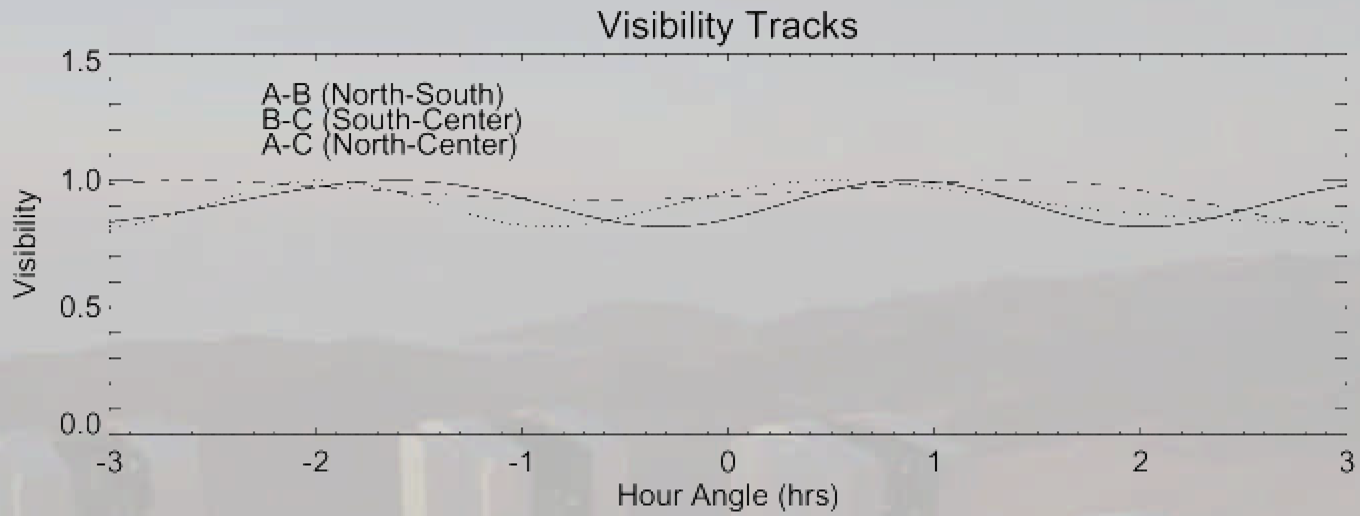
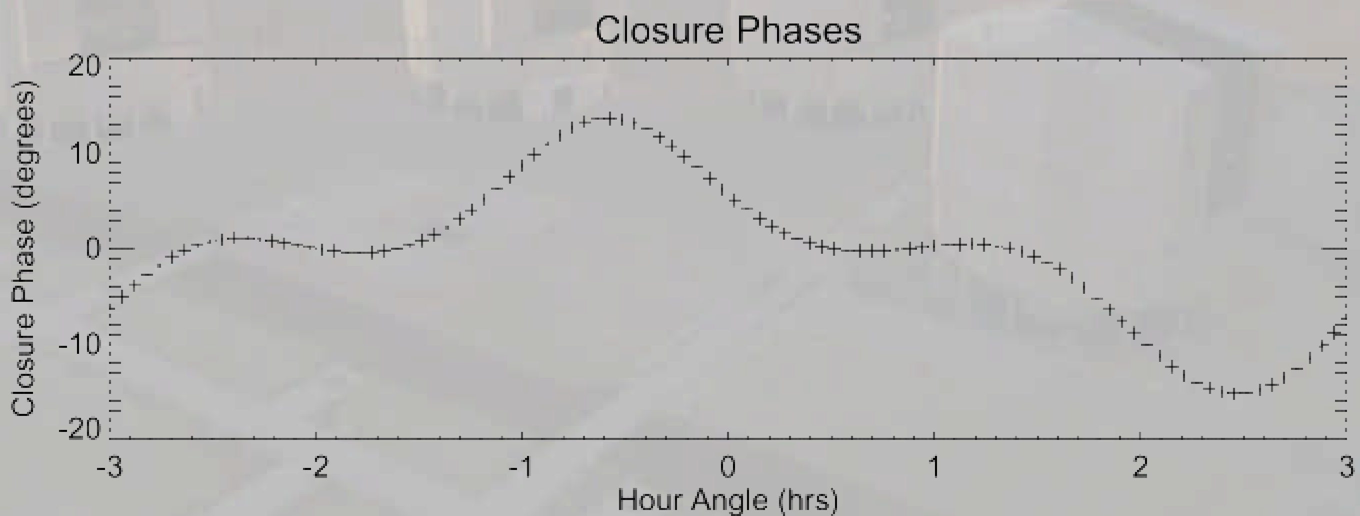
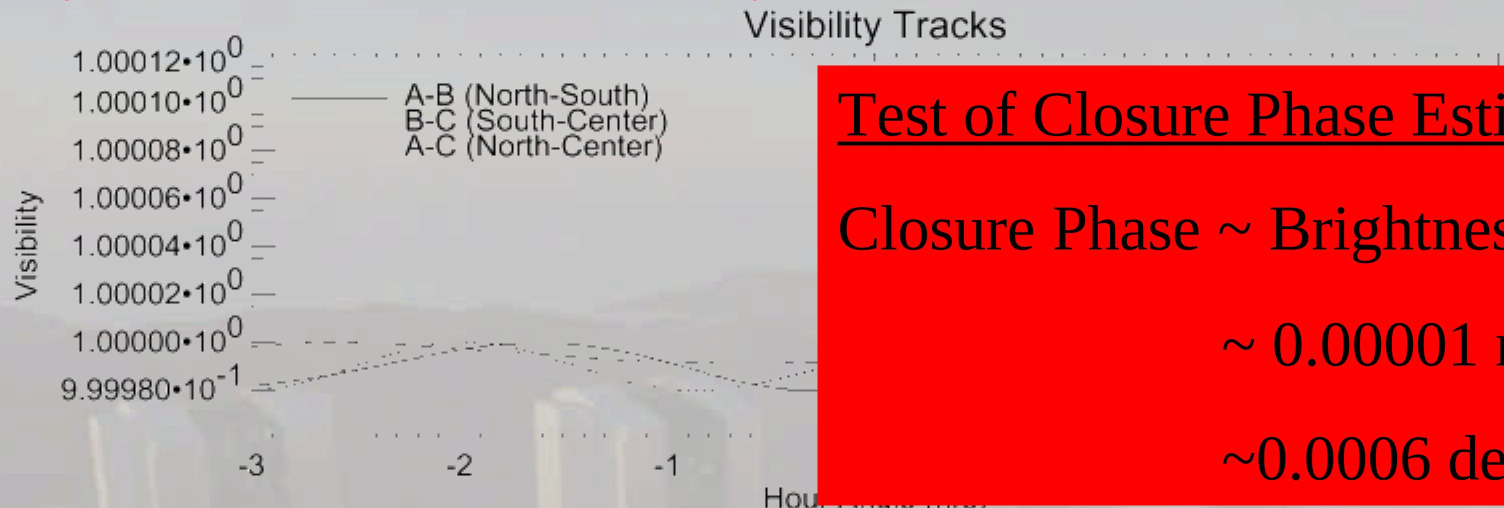
Unequal Binary: 10 to 1





Very Unequal Binaries: 10^5 to 1 (e.g.,“Planet”)

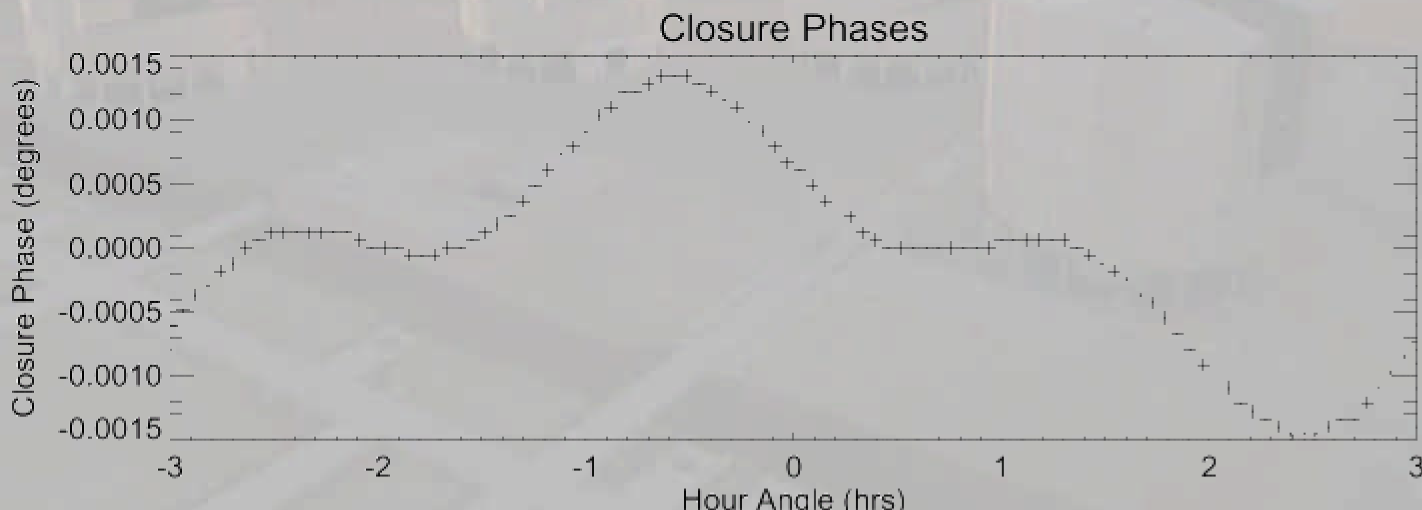


<u>Test of Closure Phase Estimate:</u>

Closure Phase ~ Brightness Ratio

~ 0.00001 radians

~0.0006 degs



A Few Remarks on Sensitivity

Common "Myths:" (eg readout nz limit)

$$\text{SNR Visibility} \propto (\text{Flux} \times \text{Visibility})^2$$

$$\text{SNR Triple Amplitude} \, (\& \, \Phi_{CP}) \propto (\text{Flux} \times \text{Visibility})^3$$

Only in the low SNR limit
(the *SENSITIVITY*)

A Few Remarks on Sensitivity

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Only in the low SNR limit
(the *SENSITIVITY*)

Fringe-tracking requirements (SNR>1) mean Optical Interferometers almost never operate in the low–SNR limit, at least not for most baselines (e.g., phase bootstrapping)

$$\text{SNR Visibility} \propto (\text{Flux} \times \text{Visibility})$$

$$\text{SNR Triple Amplitude} (\& \Phi_{CP}) \propto \frac{1}{3} \times \text{SNR Visibility}$$

A Few Neat Tricks
(which might help get your proposal selected)

Using the Triple Amplitude

Differential Closure Phase

Closure Differential Phase (!?#)

Best ways to measure a weak fringe

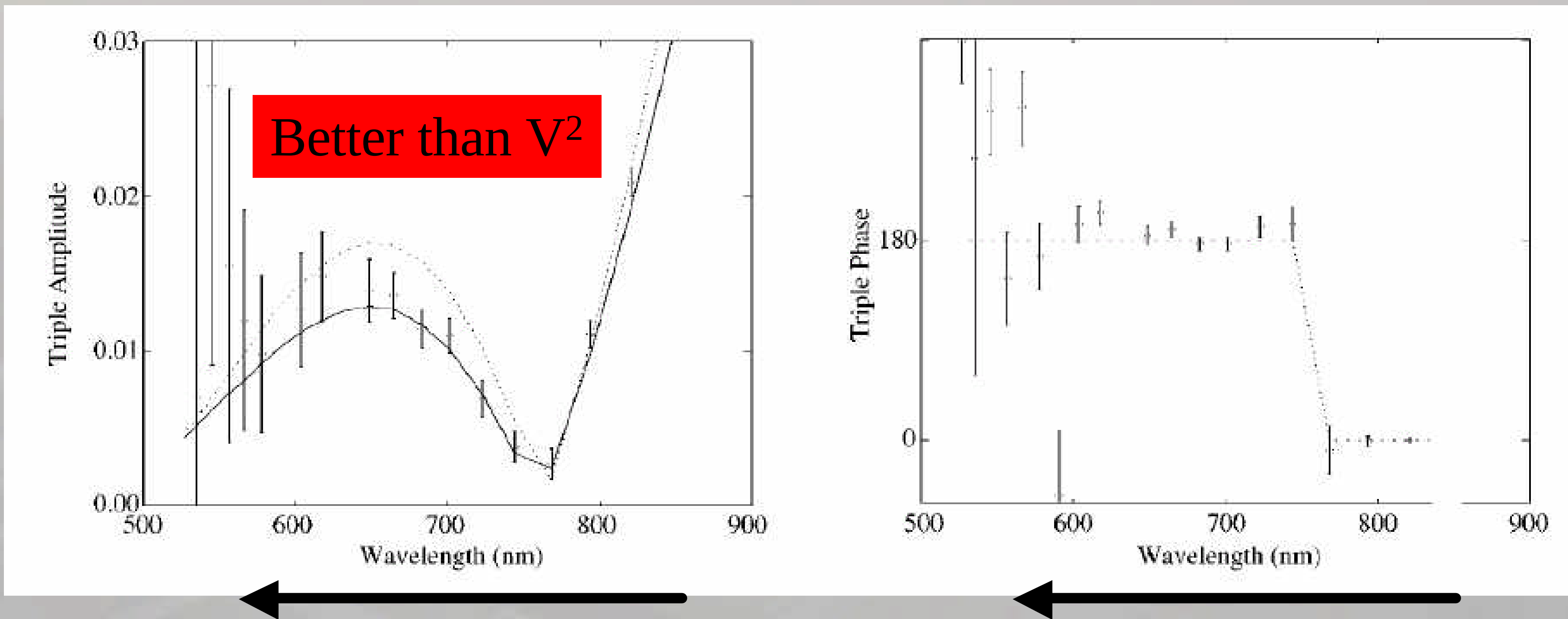
Methods to measure Visibility on a low SNR baseline:

1. Incoherent integration: SNR ~ Visibility^2. SLOW. Bias worries (subtracting large background from weak signal).
2. Coherently integrate fringe using phase bootstrapping, or some other phase referencing. Good idea, FAST. But hard to do. Bias worries (jitter). Maybe not possible.
3. Coherently average the Bispectrum, the Triple Amplitude + Closure Phase. If you can form a triangle of baselines with two strong fringes and one weak fringe then there is a big SNR advantage (but some bias issues). SNR ~ (Low Visibility)

And you get the closure phase for free

Triple Amplitudes: Limb Darkening

α Cas observed by NPOI (Haijan et al. 1998)

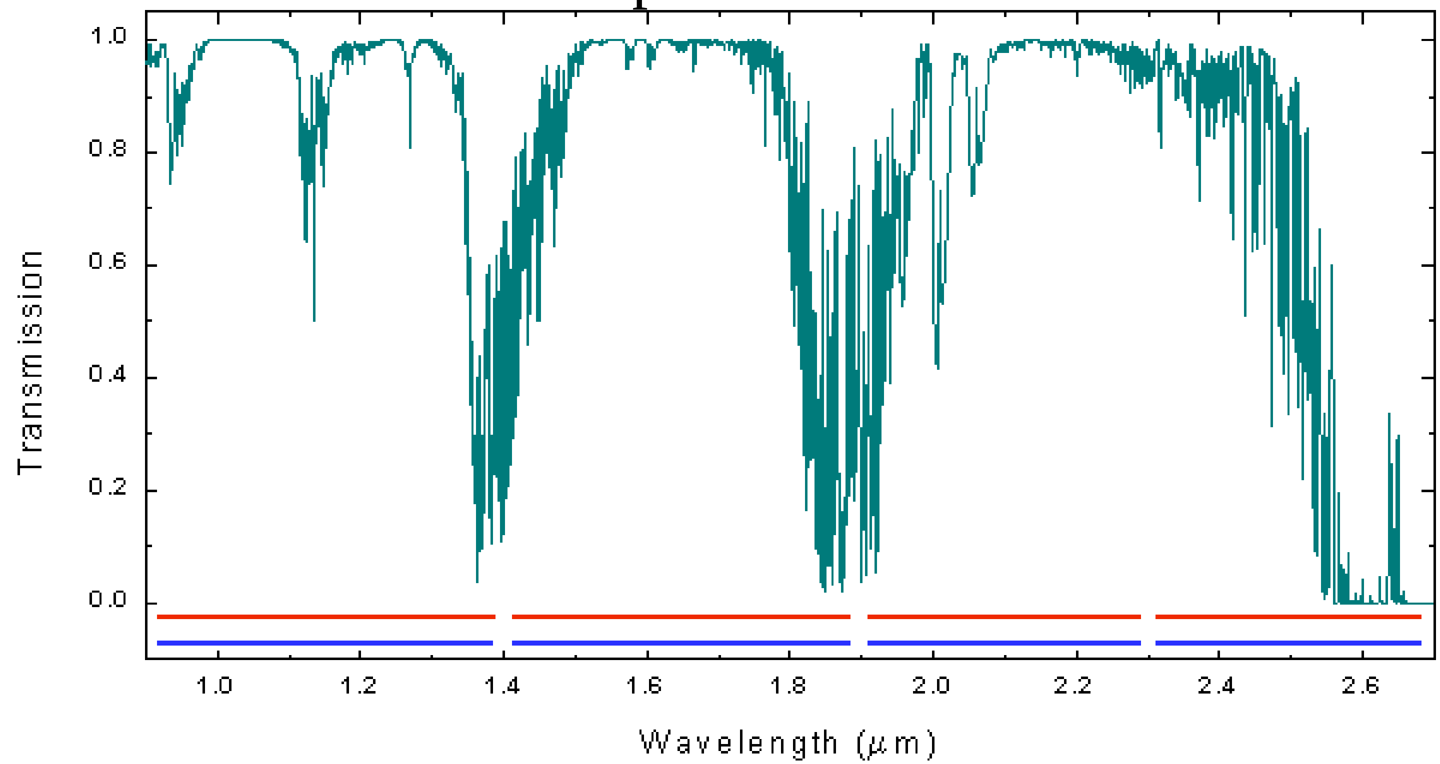


"Spatial Frequency" "Spatial Frequency"

Obvious Thing: Differential Closure Phase

Use Differential Closure Phase to empirically calibrate subtle biases for the maximum precision

Near-IR atmospheric Transmission



From Gemini webpages

Not-So-Obvious: Closure Differential Phase

Example: Jet from Young Stellar Object
(inspired from yesterday's presentation by Gil)

Problem: The near-IR continuum might be complicated! Phase referencing will deliver the relative phase of the spectral line with respect to the continuum but this can not be used unless the continuum phase is known (i.e., one must IMAGE the continuum)

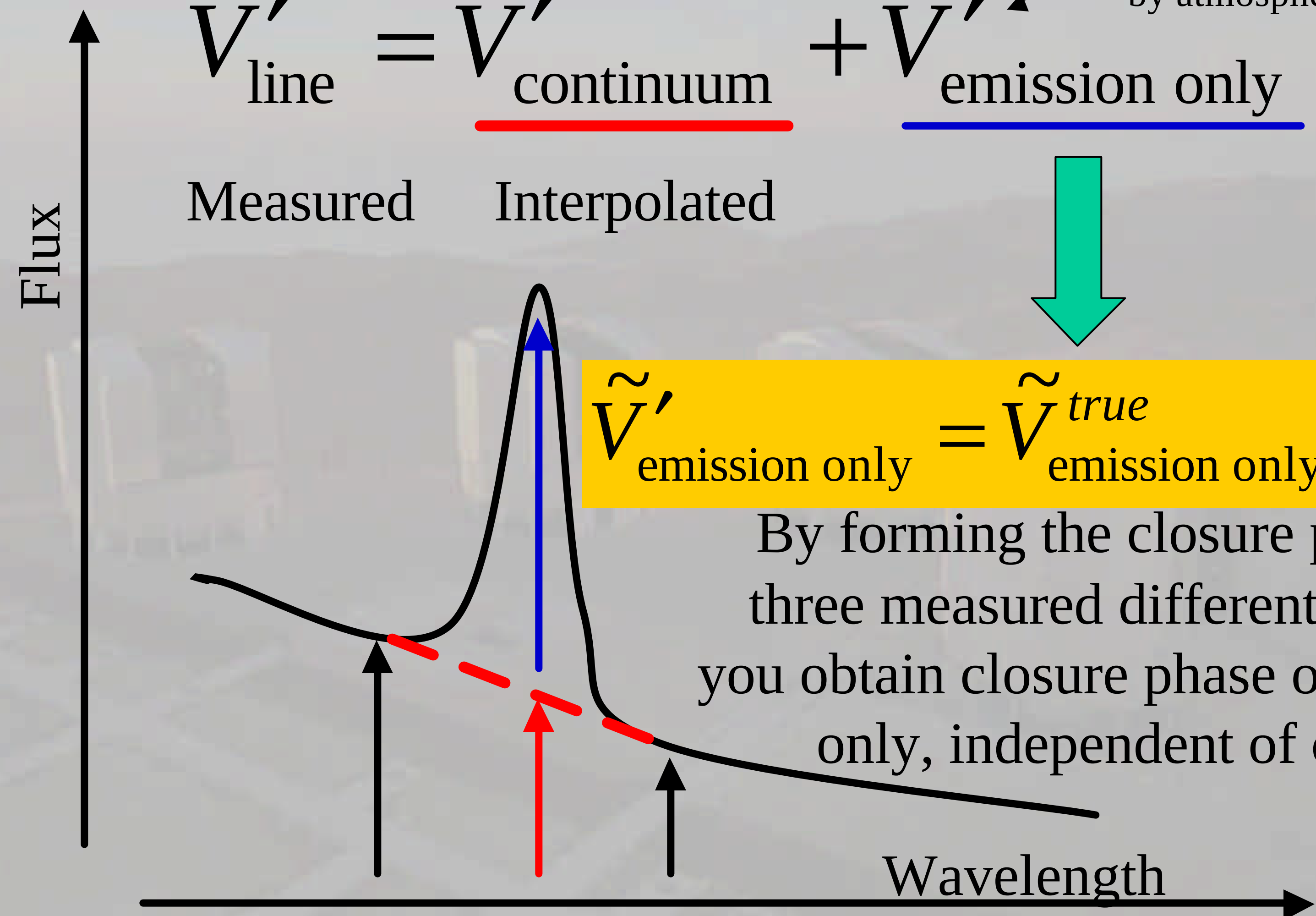
Solution(?): Closure Differential Phase

Closure Differential Phase

$$\tilde{V}'_{\text{line}} = \tilde{V}'_{\text{continuum}} + \tilde{V}'_{\text{emission only}}$$

Prime indicates corrupted by atmospheric piston

Measured Interpolated



$$\tilde{V}'_{\text{emission only}} = \tilde{V}^{\,true}_{\text{emission only}}\, e^{i\phi_{\text{atmosphere}}}$$

By forming the closure phase with three measured differential phases, you obtain closure phase of emission only, independent of continuum

Precision Interferometry with Closure Phases

(Secret: Not done yet)

Binary Stars

- Determine separation and brightness ratio
- Determine diameters of both stars
- Detect orbital motion, determine orbits
- Potential to find REALLY FAINT companions (hint hint)

Single Stars

- Pulsating star in a binary system (e.g., Cepheids)

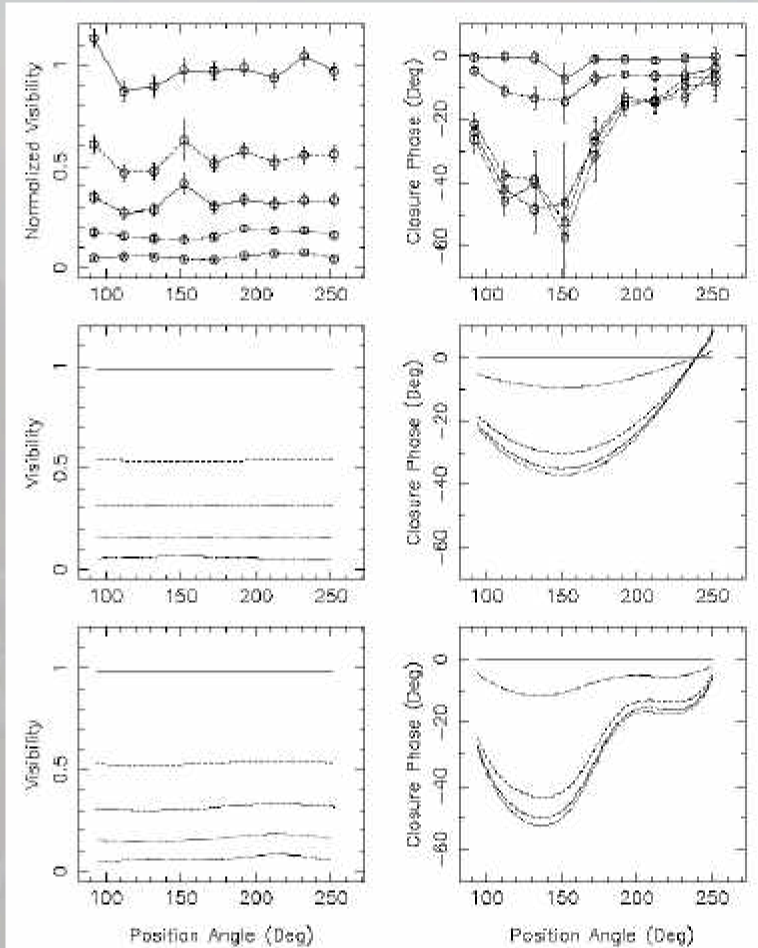
Multiple Systems

- Triples, etc.
- Crowded field astrometry
- Dynamics, proper motions

Others? Requires well-known model and some asymmetry

Stellar Surface Structure

The Data and Model Fits



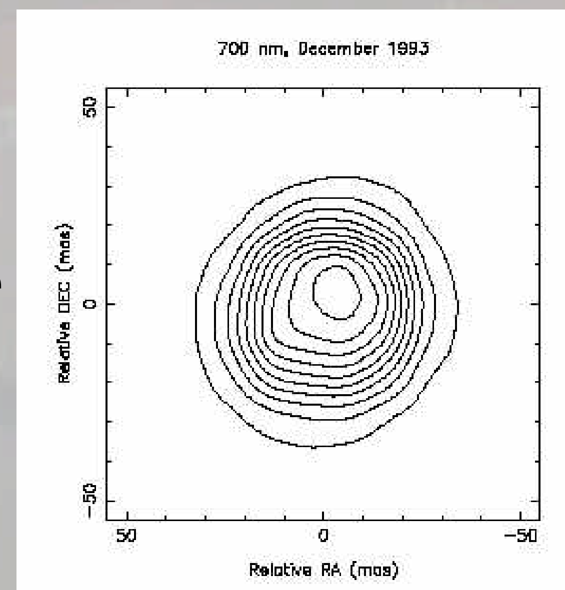
Mask at Different PAs

1-spot

2-spots

The Mask

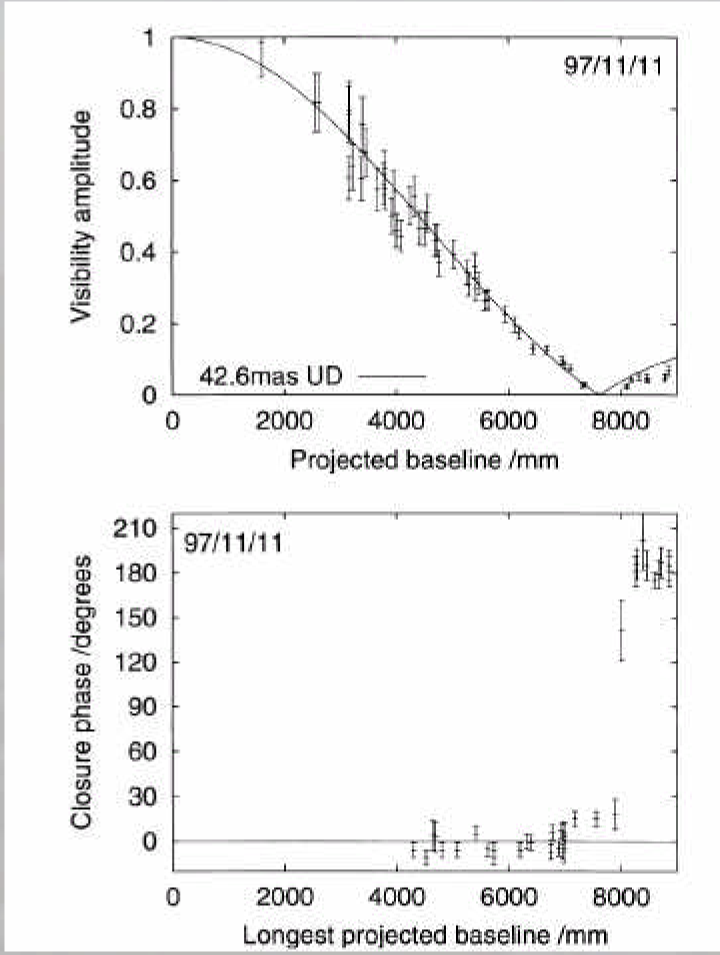
MEM Image



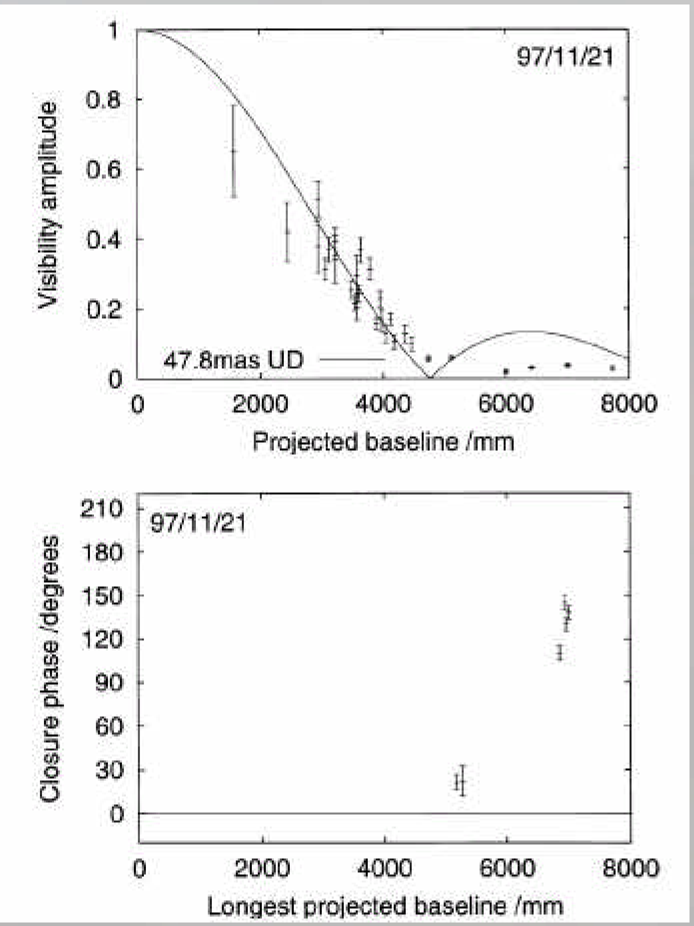
From Tuthill Thesis 1994

Stellar Surface Structure

Betelgeuse 1.29μm (COAST)



Betelgeuse 0.905μm (COAST)



From Young et al. 2000

Qualitative Astrophysics with Closure Phases: Dust Shells

Another important case: <u>a star surrounded by a dust shell</u>

We expect that dust emission, whether found in accretion disks or surrounding evolved stars, may be clumpy, complicated, and not representable by a simple model (we shall see!)

Without good imaging capability, why should one observe these sources with just a 3-element interferometer?

Closure Phases can discover qualitatively new information about some objects, much like measuring the polarization:

Informative but not unambiguous

Closure Phase Example: Dust Shell + Star

Source has two components:

"Large" Dust Shell and "Small" Star

<u>Three kinds of Triangles:</u>

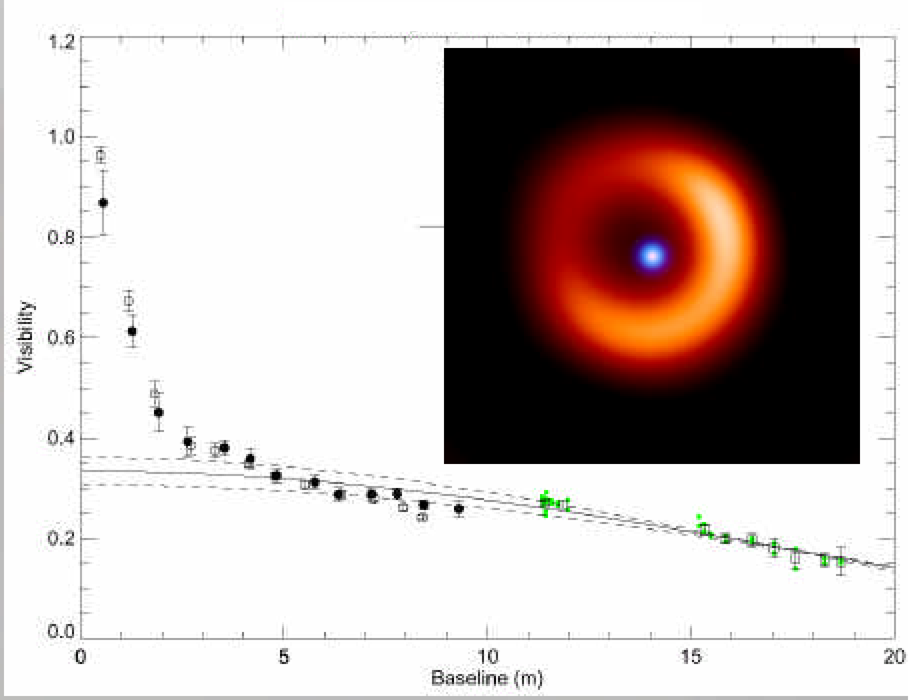
All Short Baselines

- Investigates structure of dust shell in standard way, but closure phase diluted in strength due to contribution of star

Three Long Baselines

- Dust shell fully resolved on all baselines
- Closure Phase => 0 degrees for small and/or symmetrical star

And….

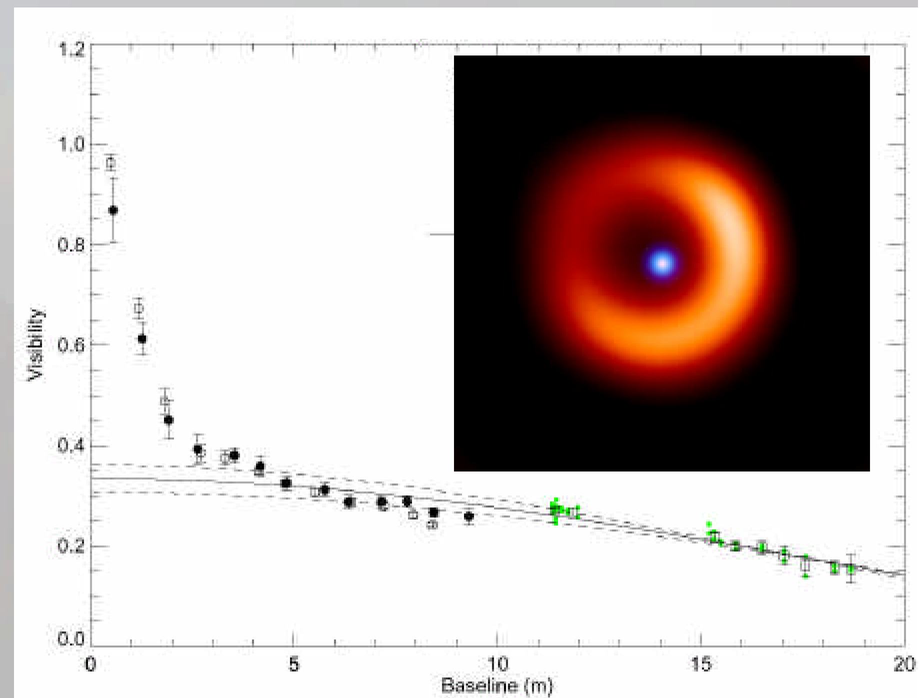


Dust Shell + Star (continued)

<u>Third kind of Triangle</u>

One Short &Two Long Baselines

- Dust Shell is Resolved out on Long Baselines, hence:
- Closure Phase = Phase of short baseline, using Star as phase center
- Non-zero closure phase for an off-center star, even for a symmetric dust shell (like for a star spot)

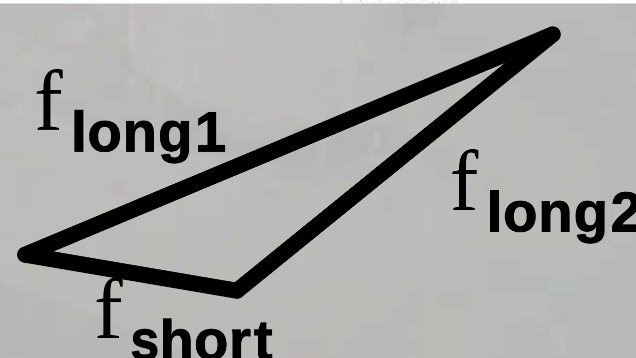


Closure Phase Φ

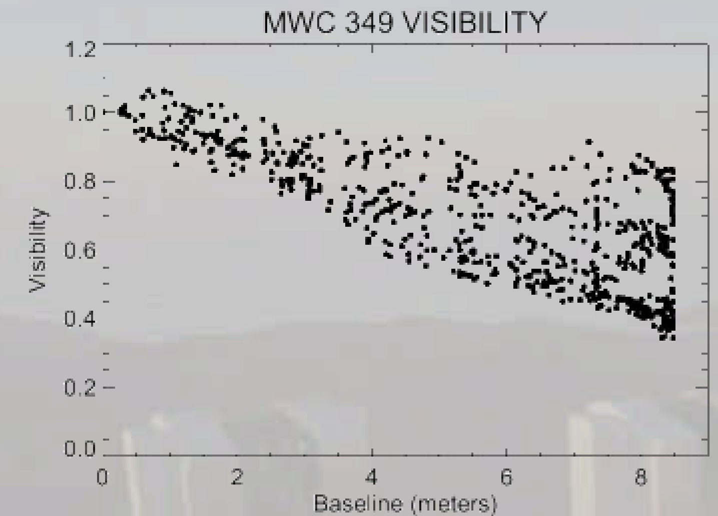
$$= \phi_{short} + \phi_{long1} + \phi_{long2}$$

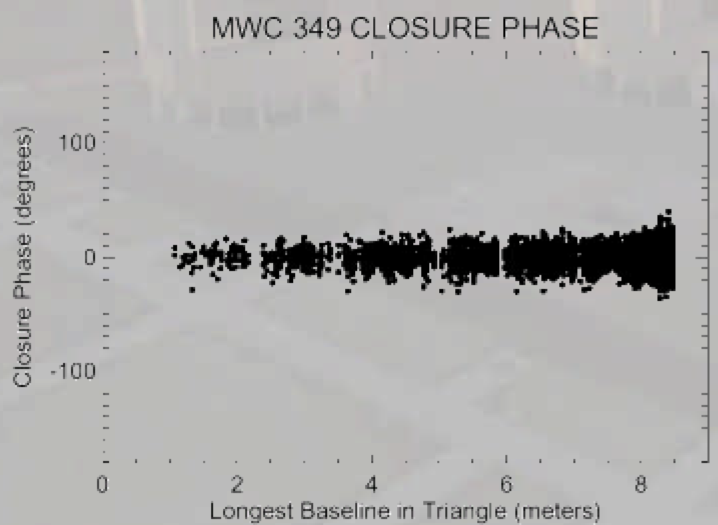
$$\sim \phi_{short} + 0 + 0$$

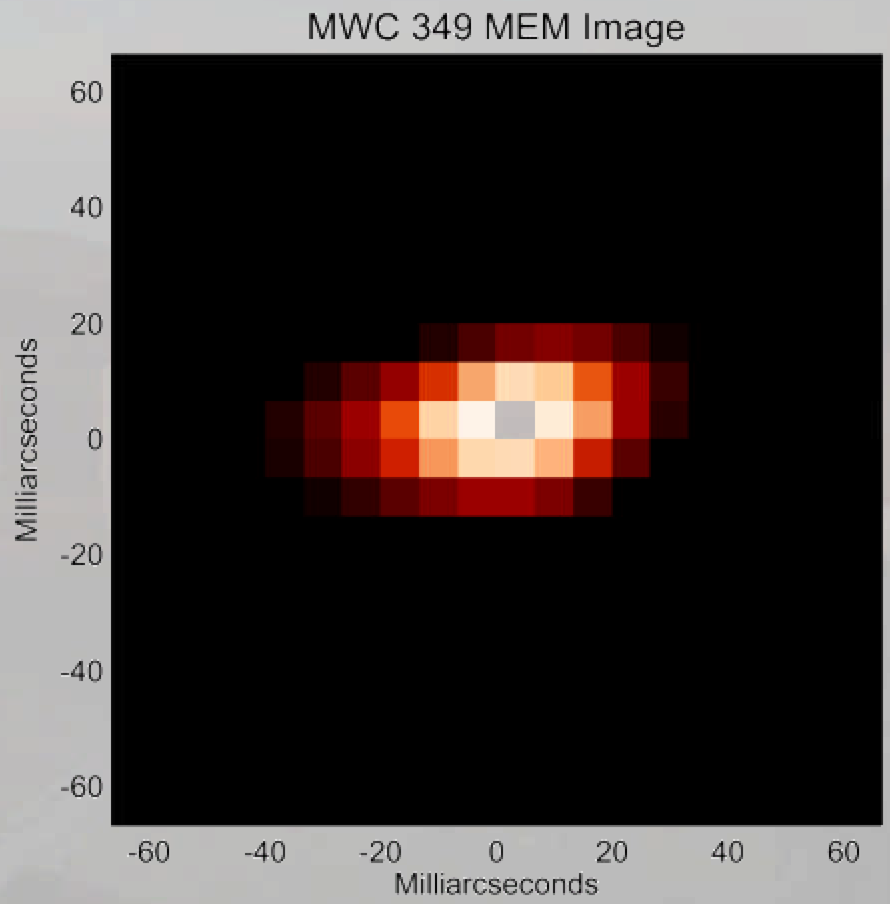
Closure Phase F ~ f_{short}



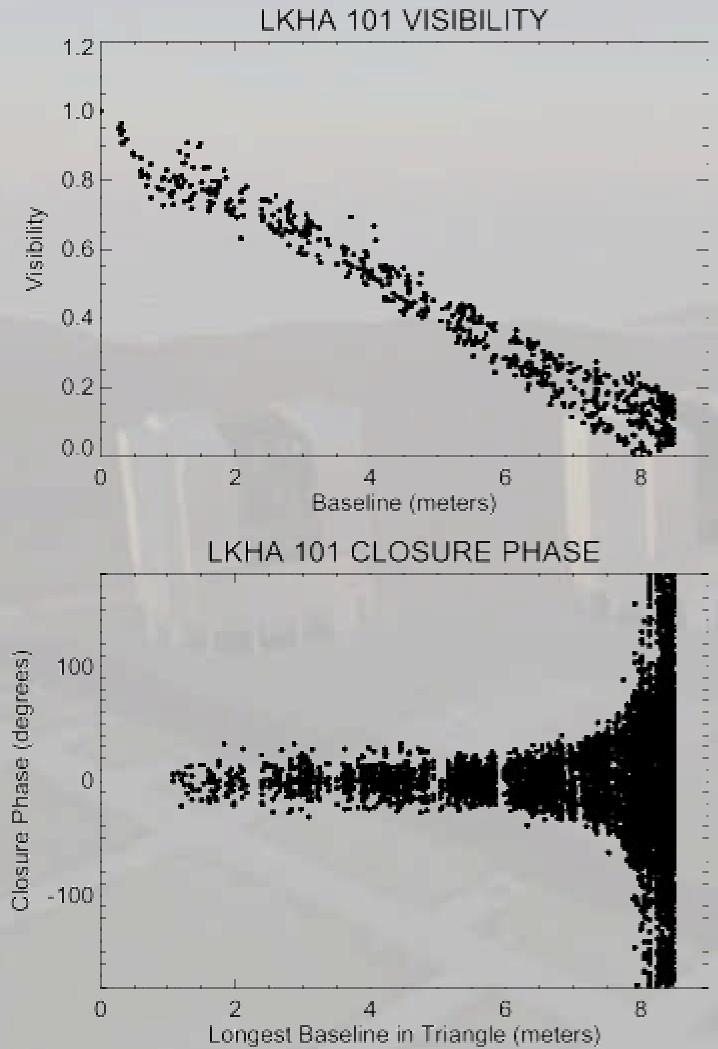
Example: Young Stellar Object #1

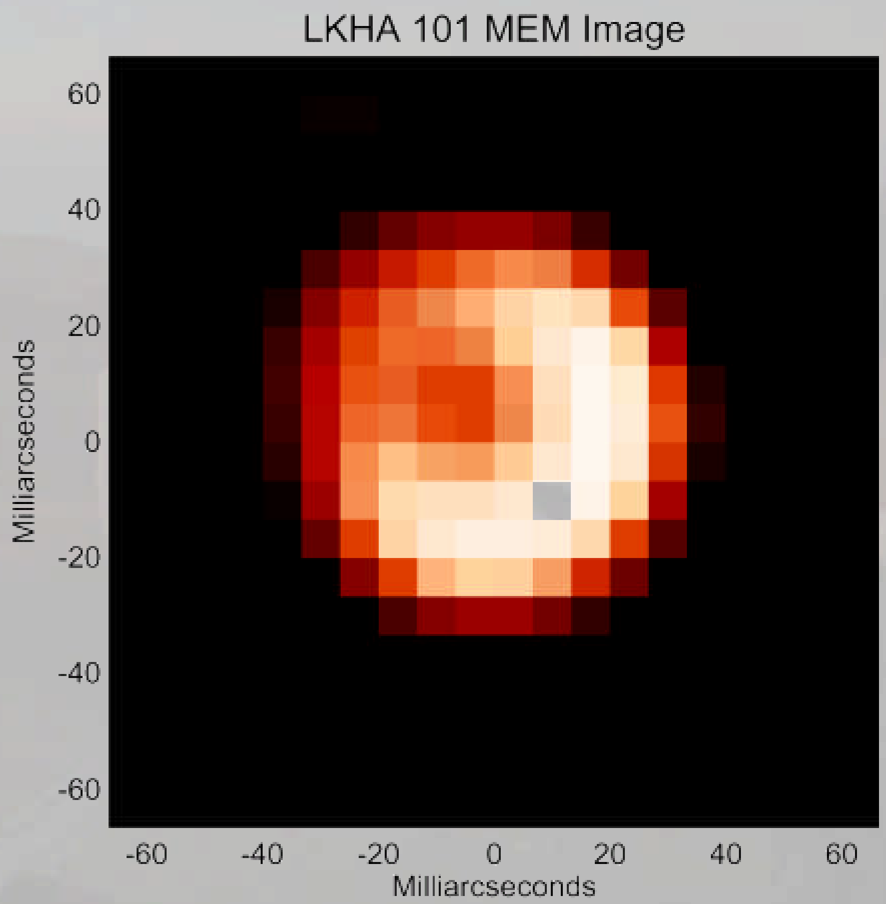




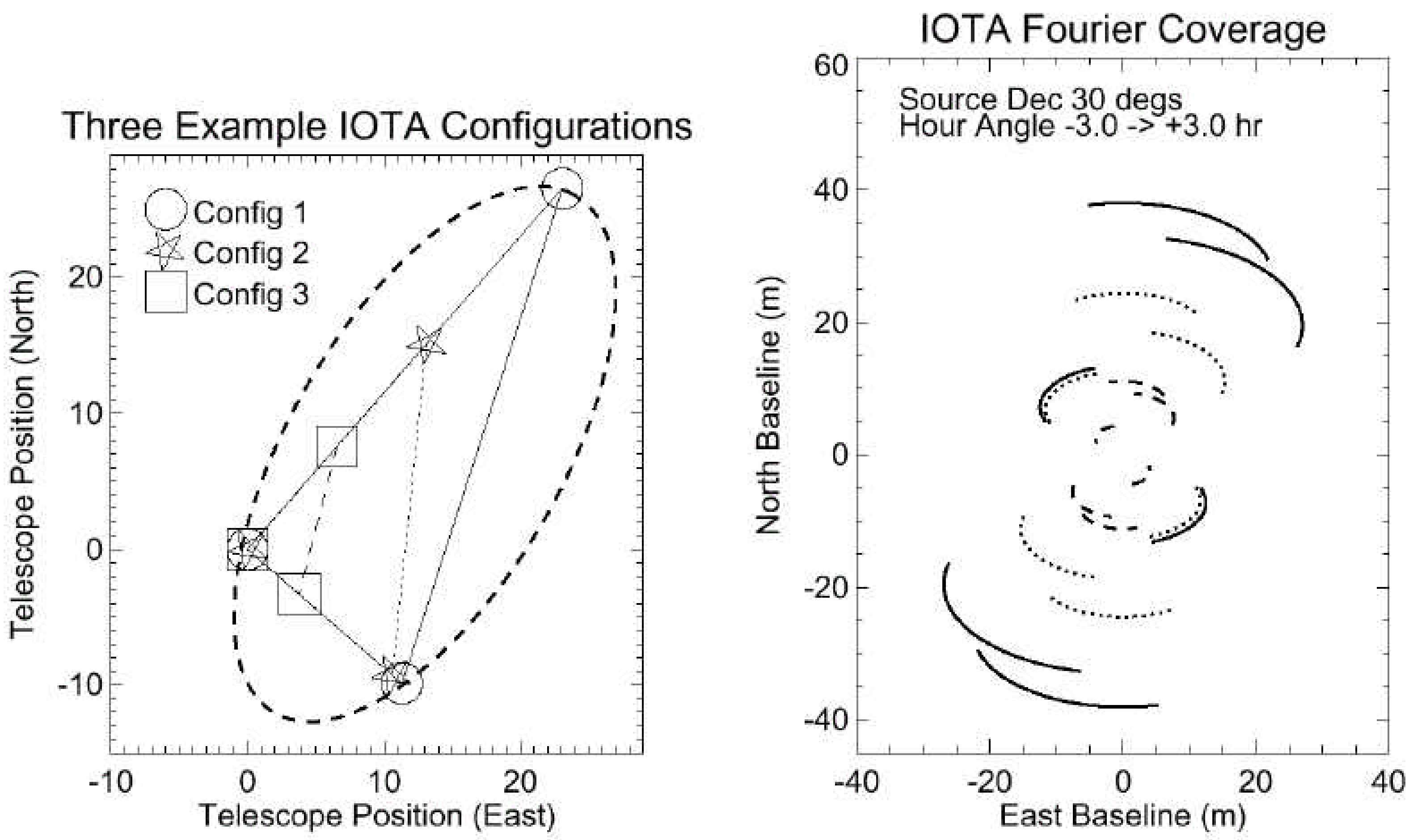


Example: Young Stellar Object #2

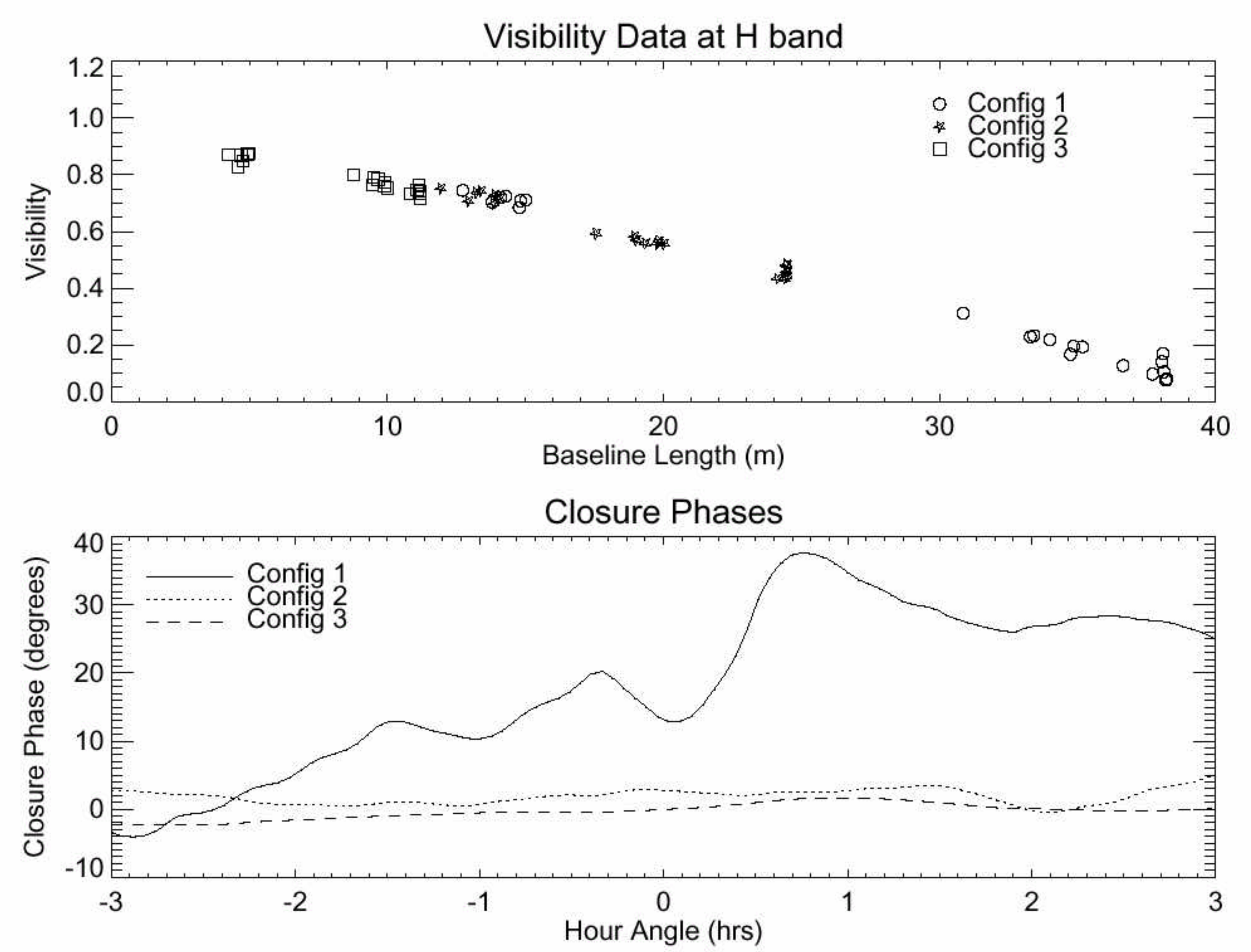


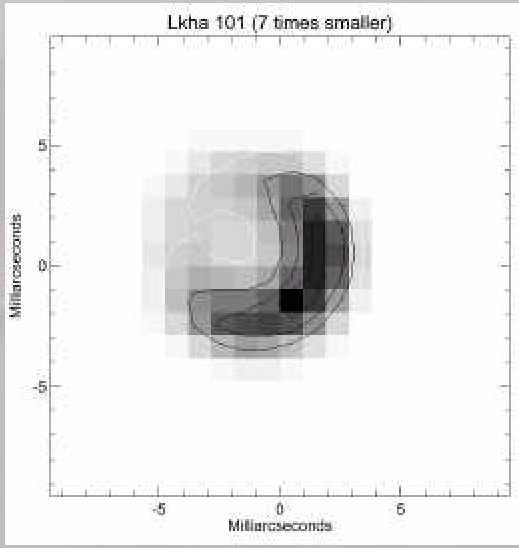


YSO disks with a *realistic* interferometer

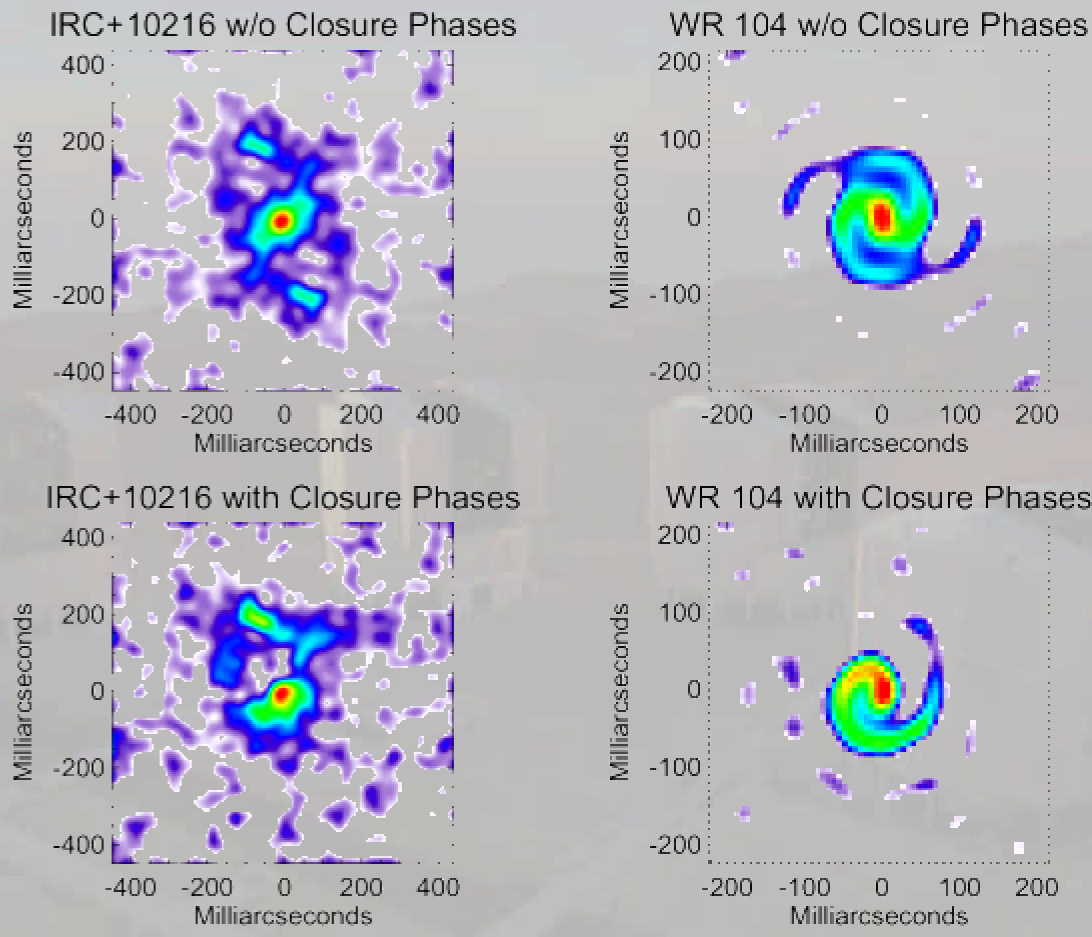


YSO disks with IOTA *(simulation)*





Importance of Closure Phases in Imaging



Maximum Entropy Method (MEM)

With finite (u,v) coverage and with noisy data, there are an infinite 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

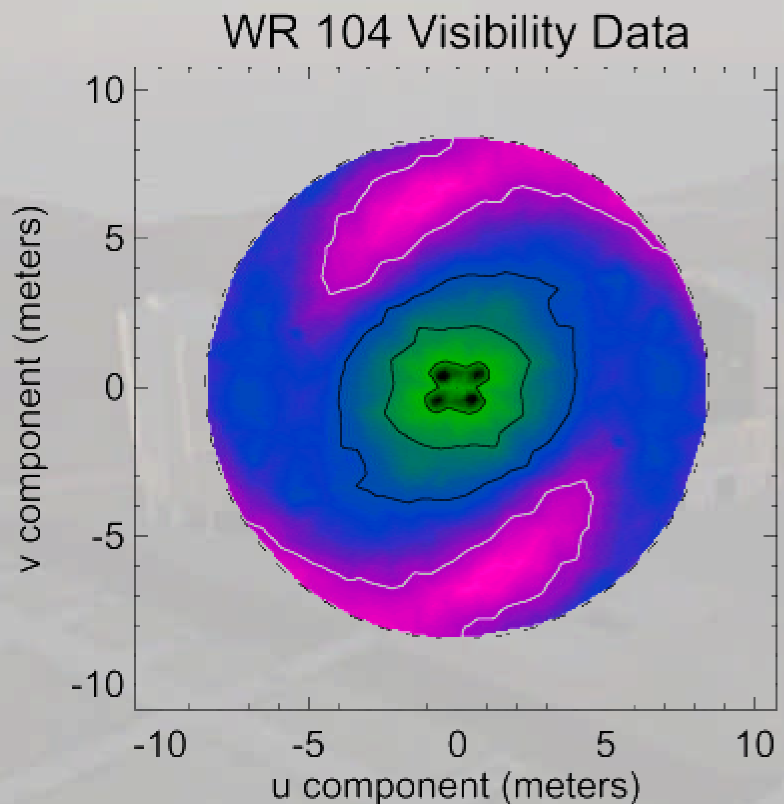
Skilling & Bryan (1984)

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

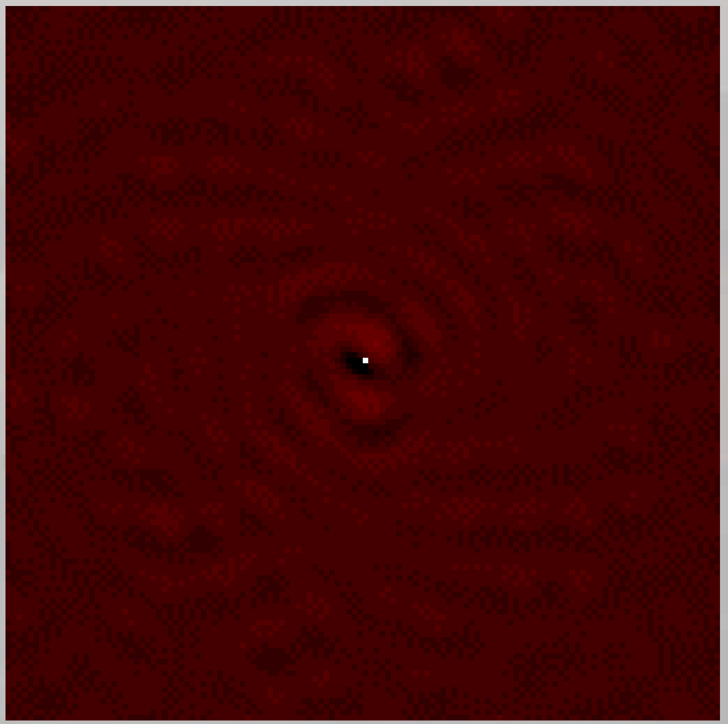
Image prior

Sum over all pixels

WR 104 MEM Reconstruction



Iterations 1 to 30

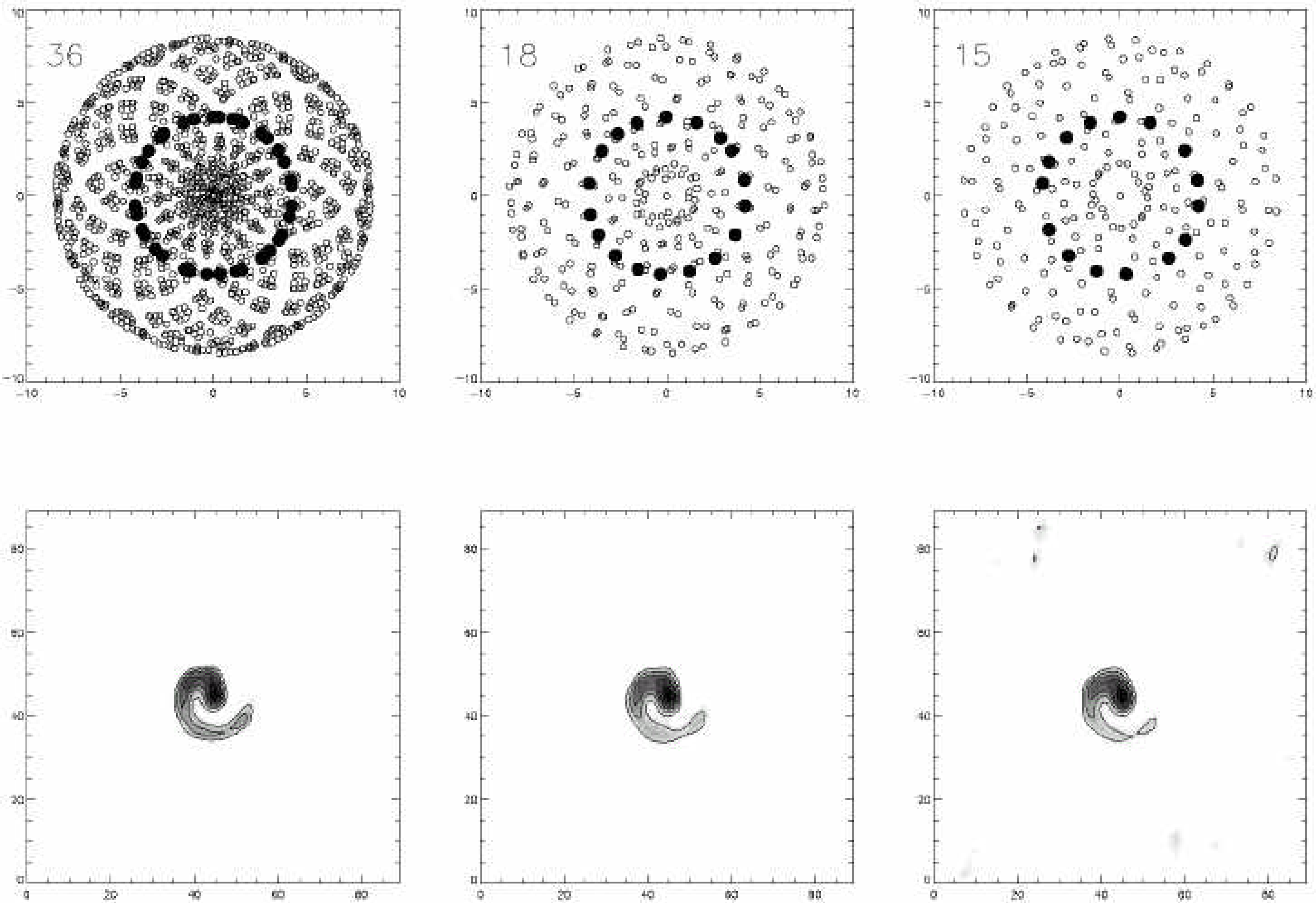


WR 104 (2.2 microns)

Summary of Software Problems

- Need flexible new data format for Optical Interferometry data
  - Must save Vis^2, the Bispectrum (closure phases and triple amplitudes), more?
- VLBI/AIPS/AIPS++ do not 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 (VLTI)?
- Lots of good thesis topics

How many Telescopes do you need?



Tuthill & Monnier (CHARA Report 2000)

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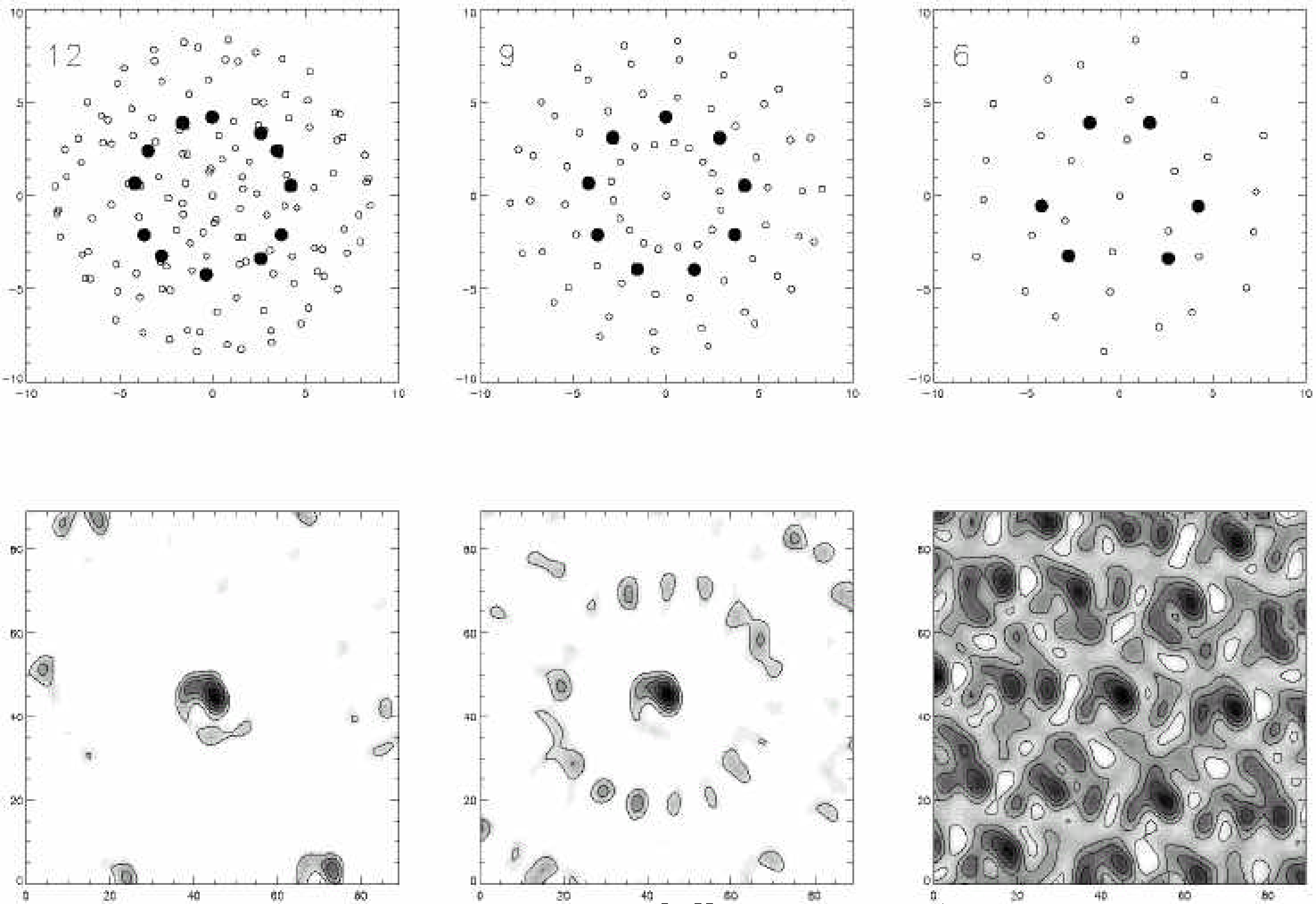
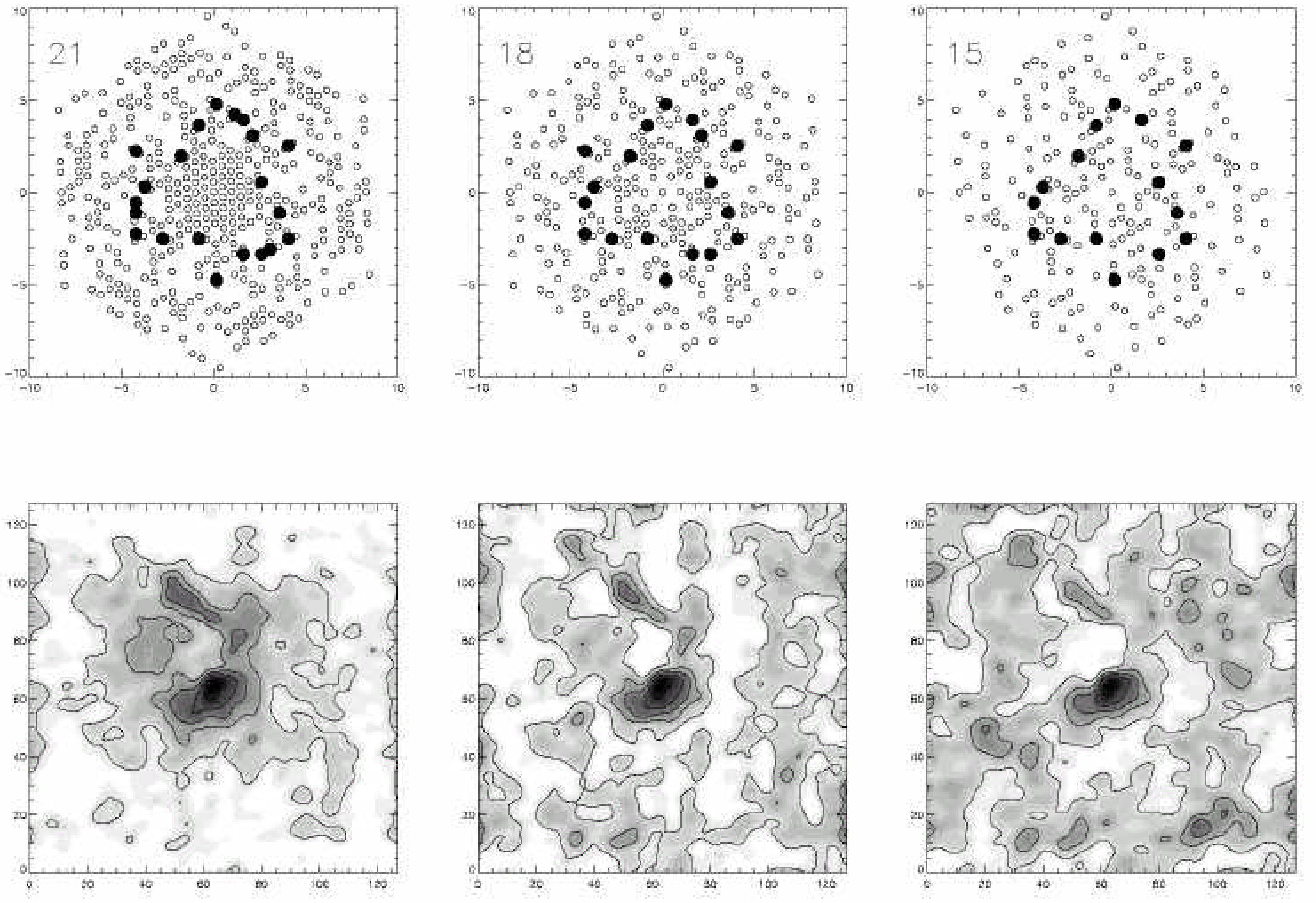


Tuthill & Monnier (CHARA Report 2000)

You need more telescopes for wider fields



Tuthill & Monnier (CHARA Report 2000)

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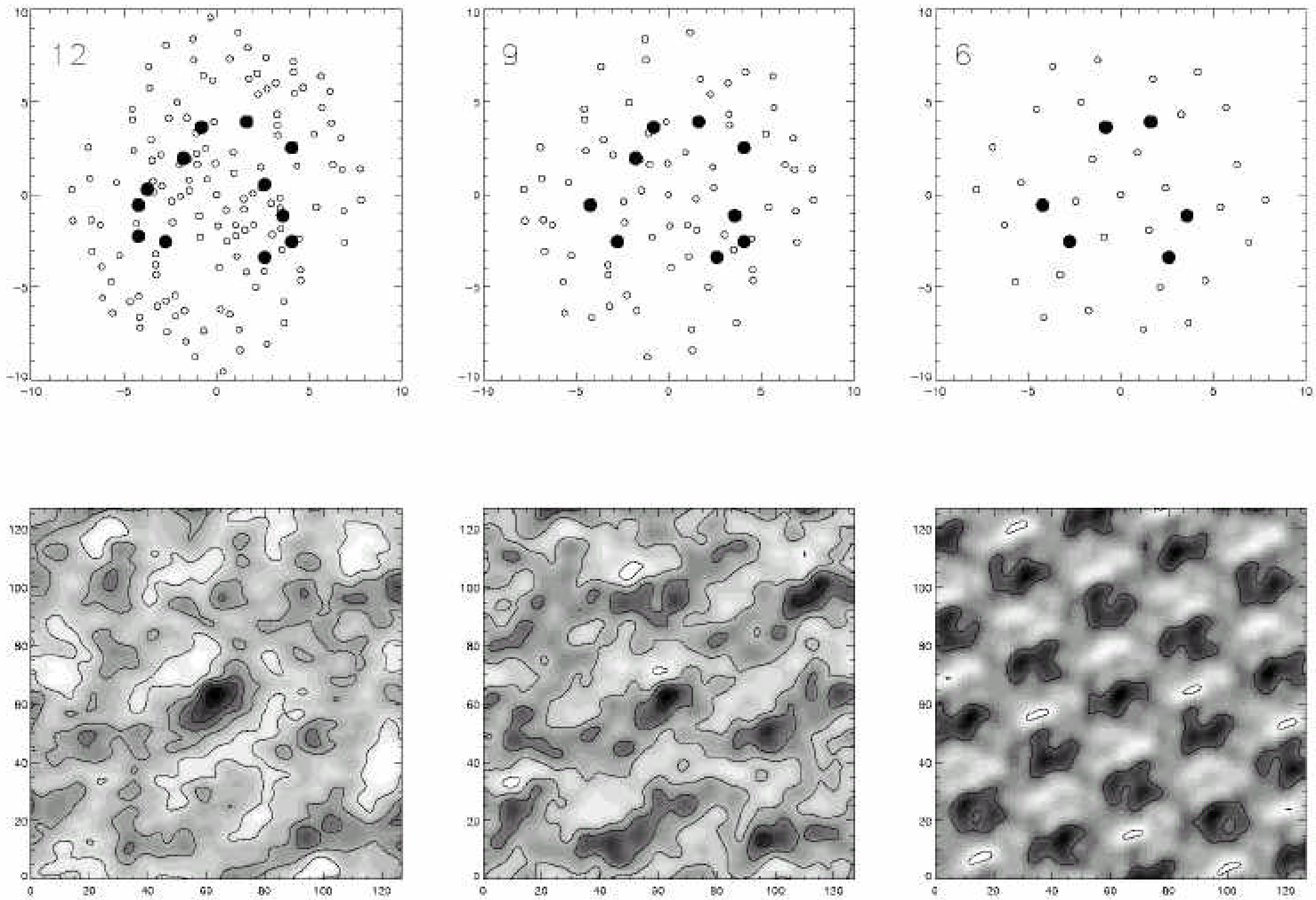


Tuthill & Monnier (CHARA Report 2000)

Imaging: How Many Telescopes?

Using "Real" Optical Interferometry Data (Keck Aperture Masking), Tuthill & Monnier (CHARA Technical Report 86, 2000) found:

Compact Emission (FOV = 5 X Diffraction-Limit)

- 9-12 telescopes in Snapshot Mode
- 5-7 with Earth-Rotation Aperture Synthesis (e.g, CHARA, iKeck)
- Even Fewer needed if array is re-configurable (e.g., VLTI, IOTA, NPOI)

Extended Objects (FOV >10 X Diffraction-Limit)

- 18-21 telescopes in Snapshot Mode
- Will be challenge for all current arrays

Lots of CAVEATs: SNR can be much improved over masking data; earth rotation (u,v) coverage different than "snapshot"; real arrays will have far fewer closure phases

Astrophysics with Closure Phases

Precision Interferometry

- Excellent opportunities for Model Fitting
- Better Sensitivity through closure phases and triple amplitudes

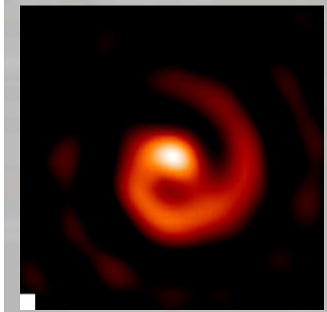
New Probe of Asymmetries

- YSOs, Wolf-Rayets, R CrB, Be, Novae, AGB shells, PPN …

Parametric Imaging

- Some simple objects CAN be "imaged." But what?
- Requires thoughtful source selections, lots of observing time

True Imaging



More telescopes (and delay lines) are needed

VLTI has unique capabilities as future imaging interferometer with movable telescopes, dedicated facilities, active constituency