Phases in Interferometry

EuroSummer School

Observation and data reduction with the Very Large Telescope Interferometer

Goutelas, France
June 4-16, 2006

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University of Michigan
07 June 2006

Phases in Interferometry
Outline

Review of Interferometric Phases

Phase Referencing and Astrometry

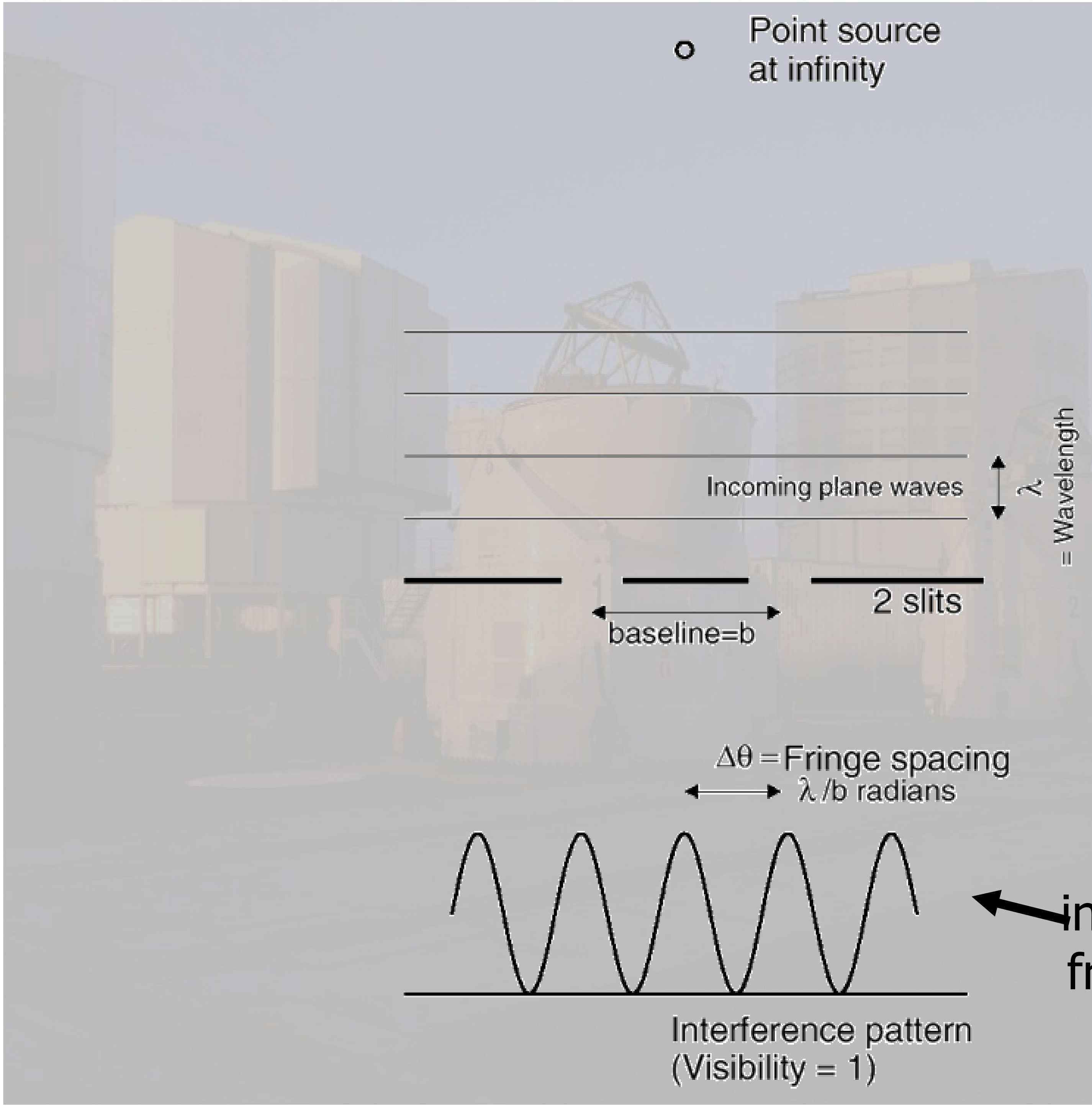
Differential Phase

Introduction of the Closure Phase

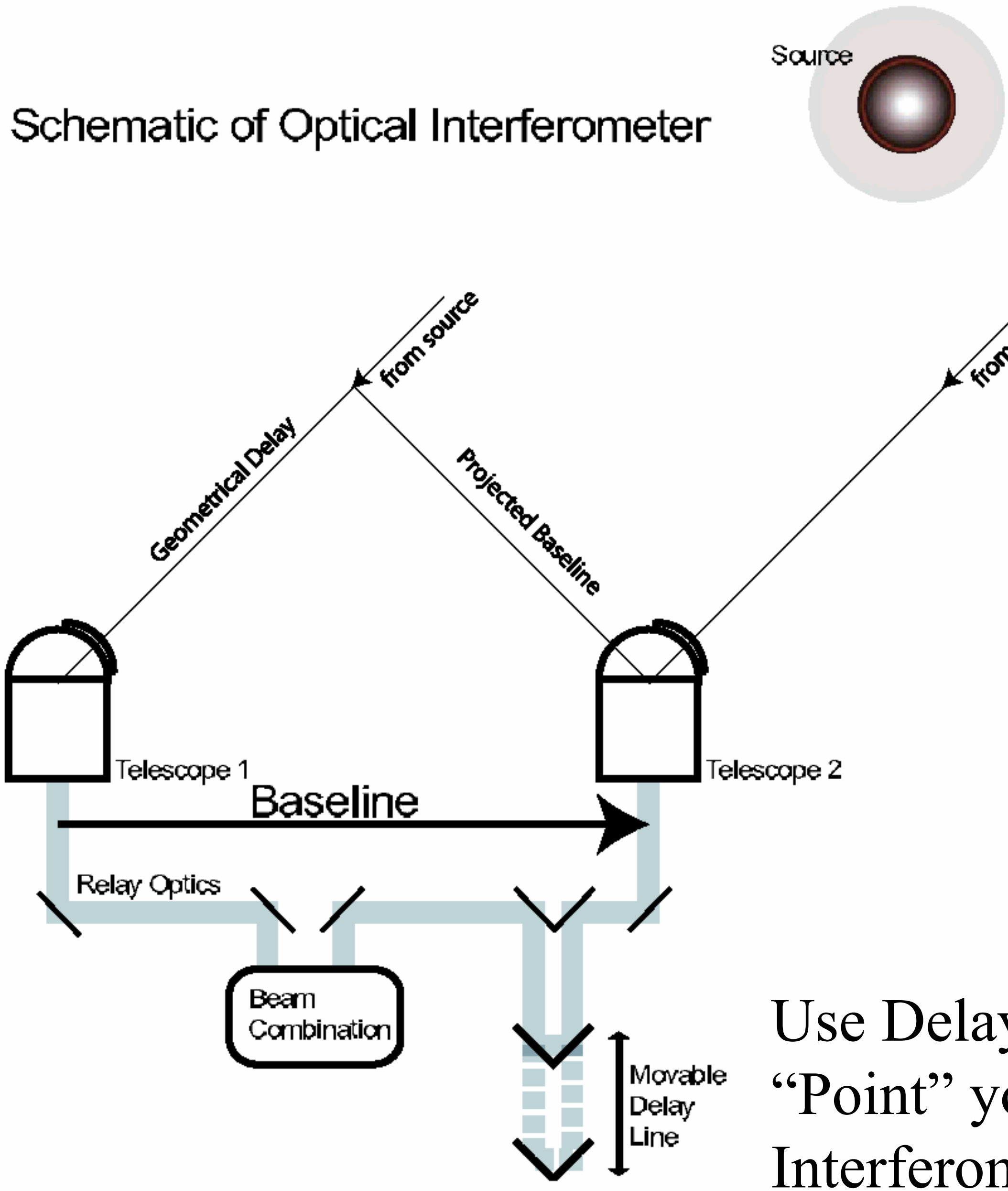
Quantitative Astrophysics – "Precision Interferometry" (Model Fitting)
- Binary Systems, Stellar Surfaces

Qualitative Astrophysics
- Asymmetries, Protoplanetary Disks around Young Stellar Objects
- Lots of new things!

Interferometric Imaging

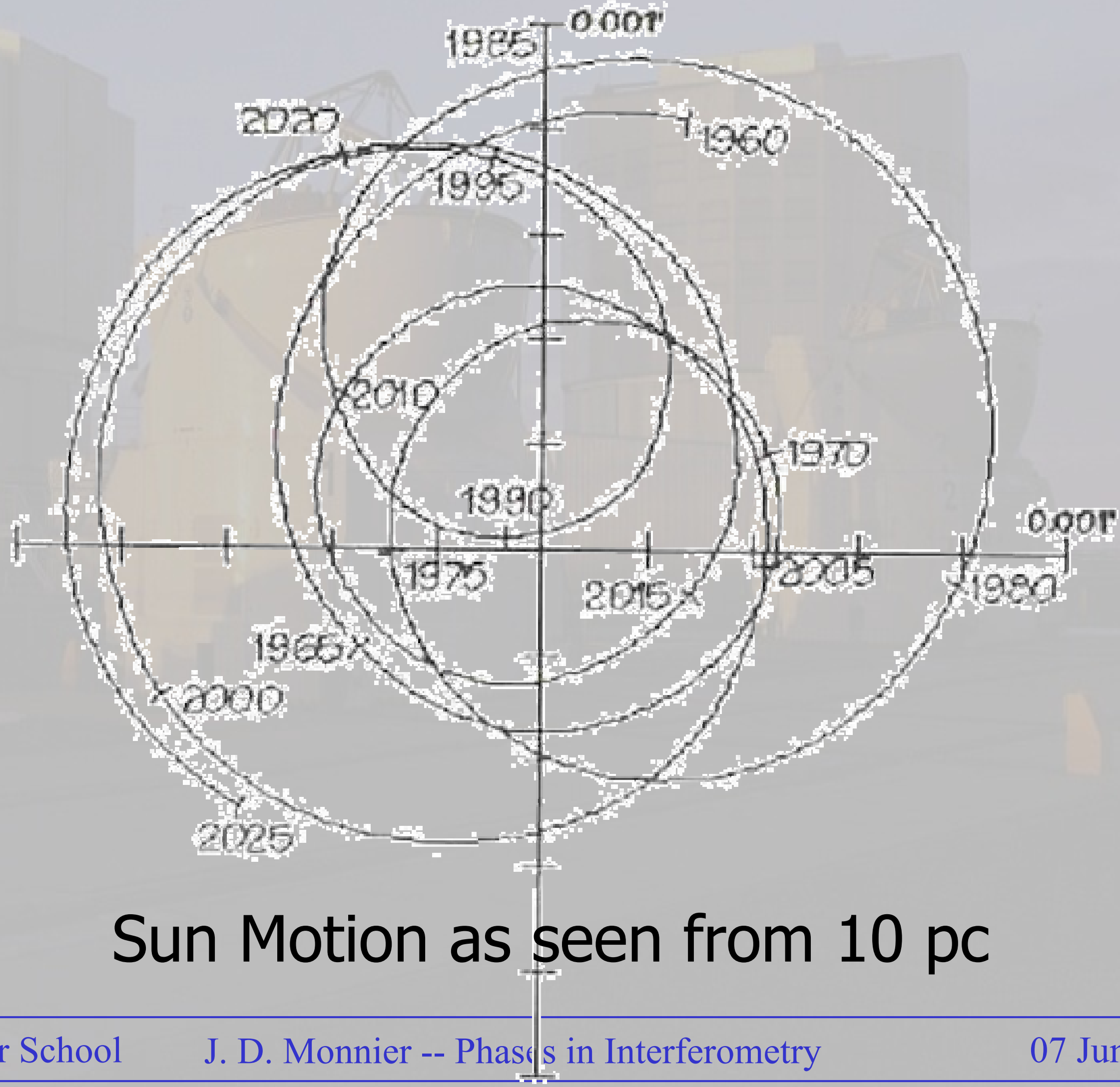


As star moves relative to interferometer, the fringe phase shifts



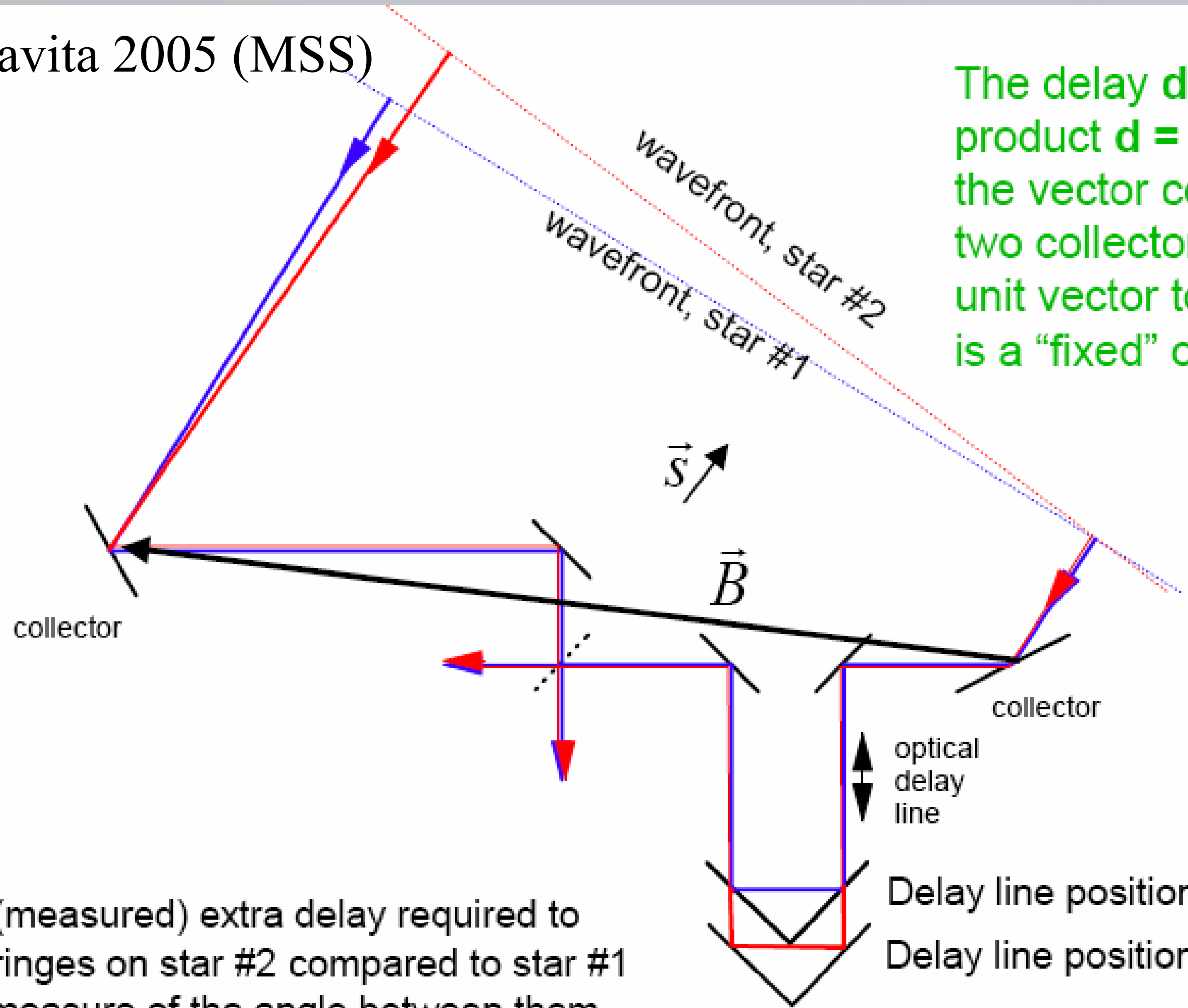
Use Delay Line to "Point" your Interferometer

Science Case:
Astrometry for Extra-solar Planets



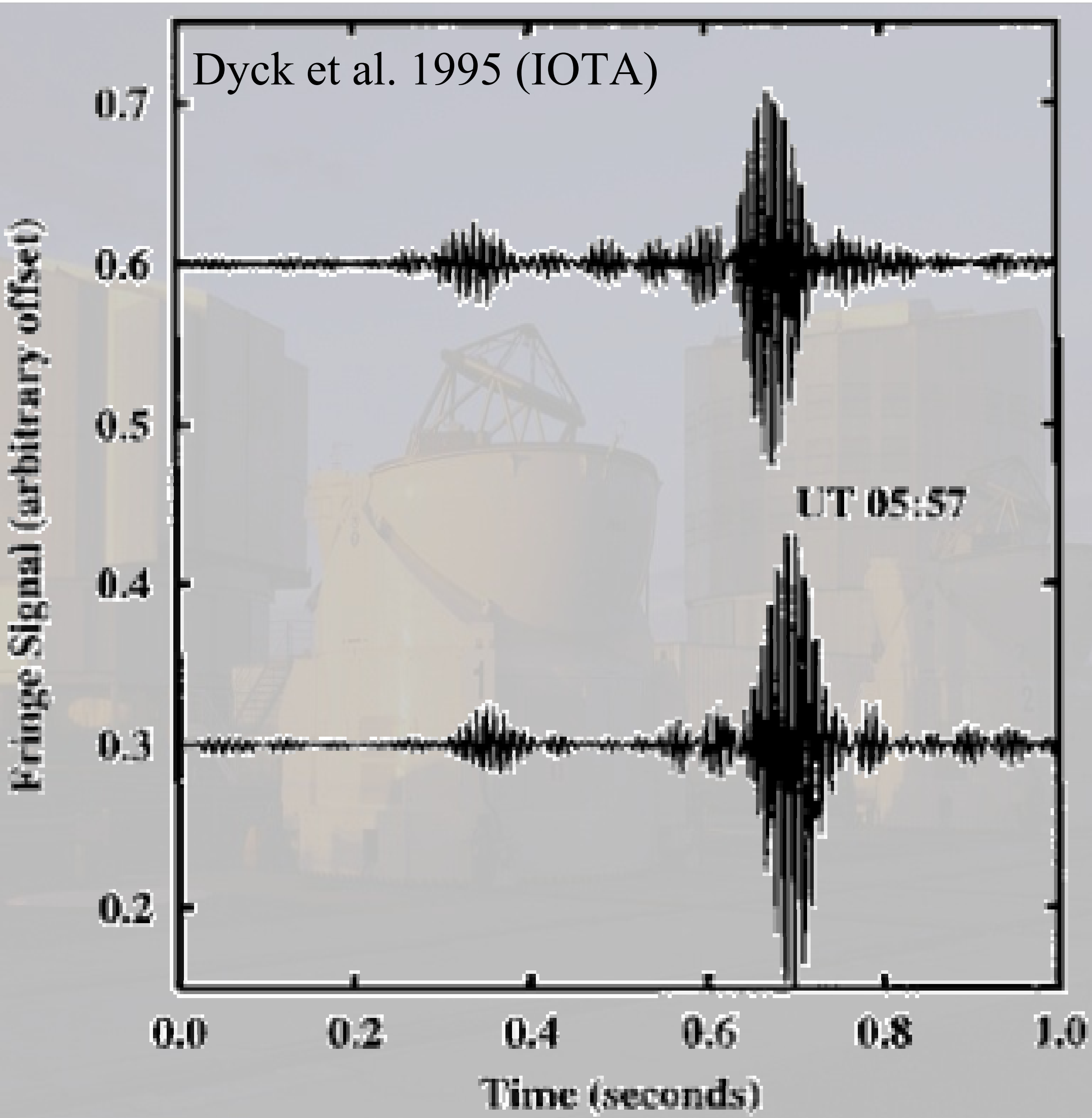
Sun Motion as seen from 10 pc

Colavita 2005 (MSS)

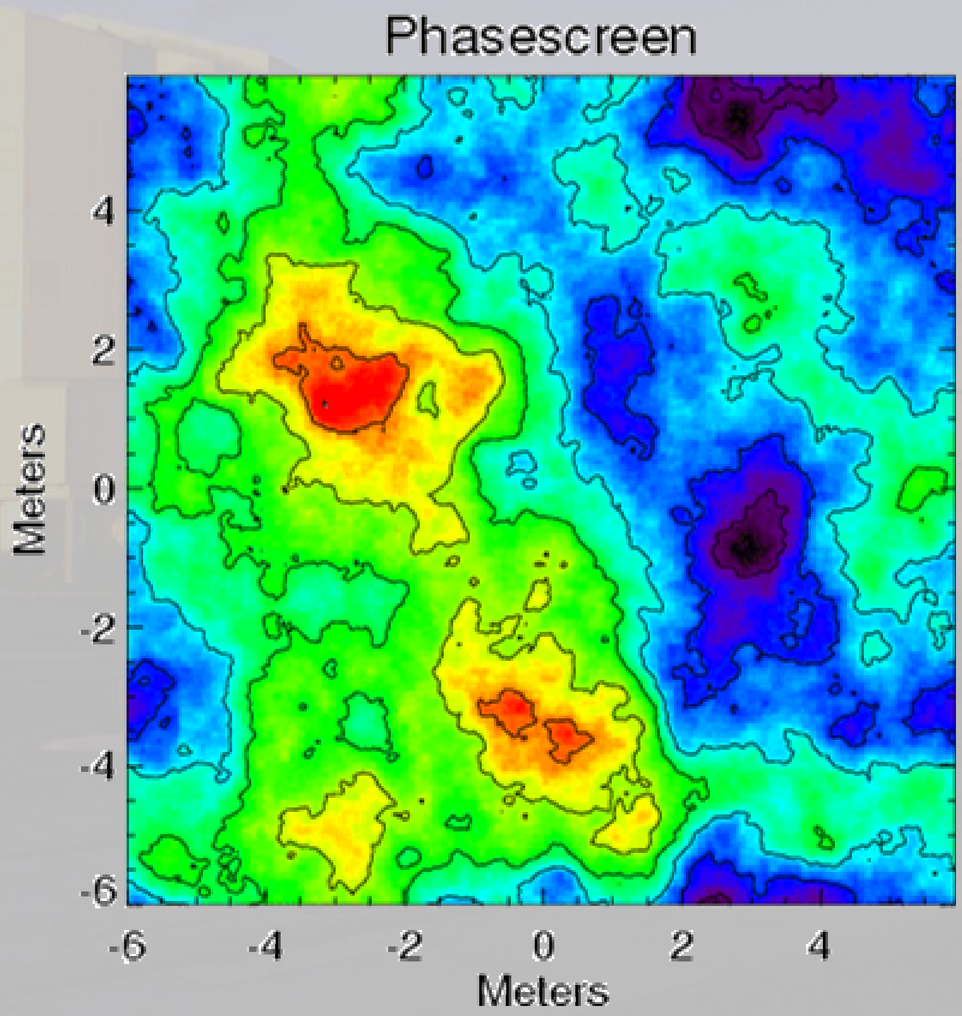


The delay **d** is the dot product **d = B·s + C** of the vector connecting the two collectors and the unit vector to the star; **C** is a "fixed" offset

The (measured) extra delay required to get fringes on star #2 compared to star #1 is a measure of the angle between them


Dyck et al. 1995 (IOTA)
0.7
0.6
0.5
0.4
0.3
0.2
Fringe Signal (arbitrary offset)
UT 05:57
0.0
0.2
0.4
0.6
0.8
1.0
Time (seconds)

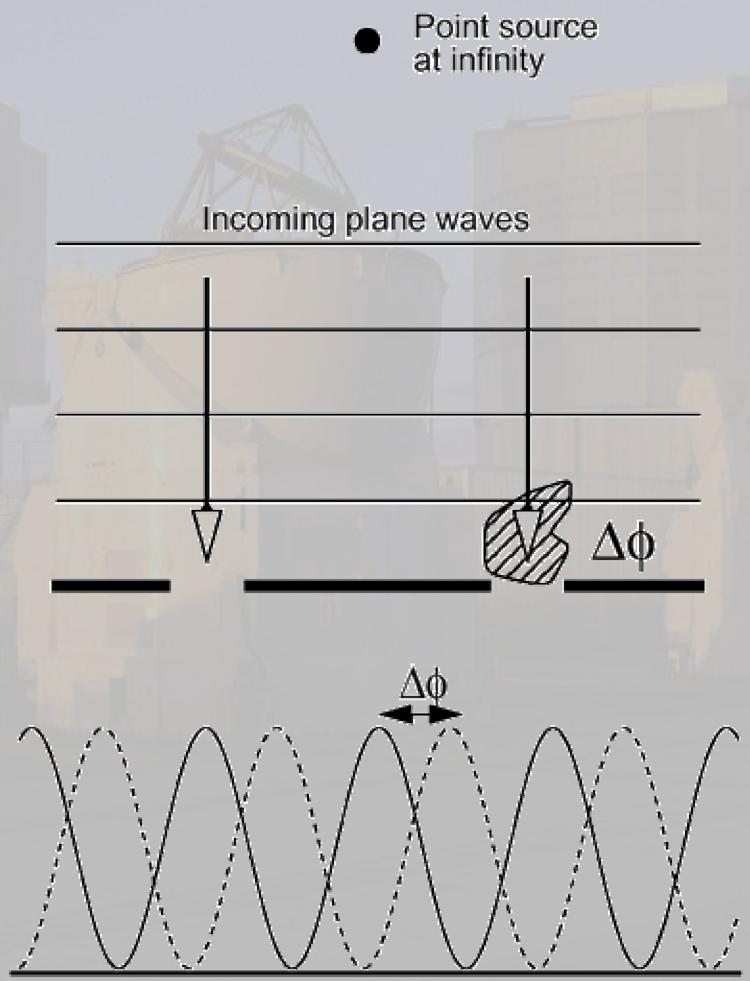
The Atmosphere…



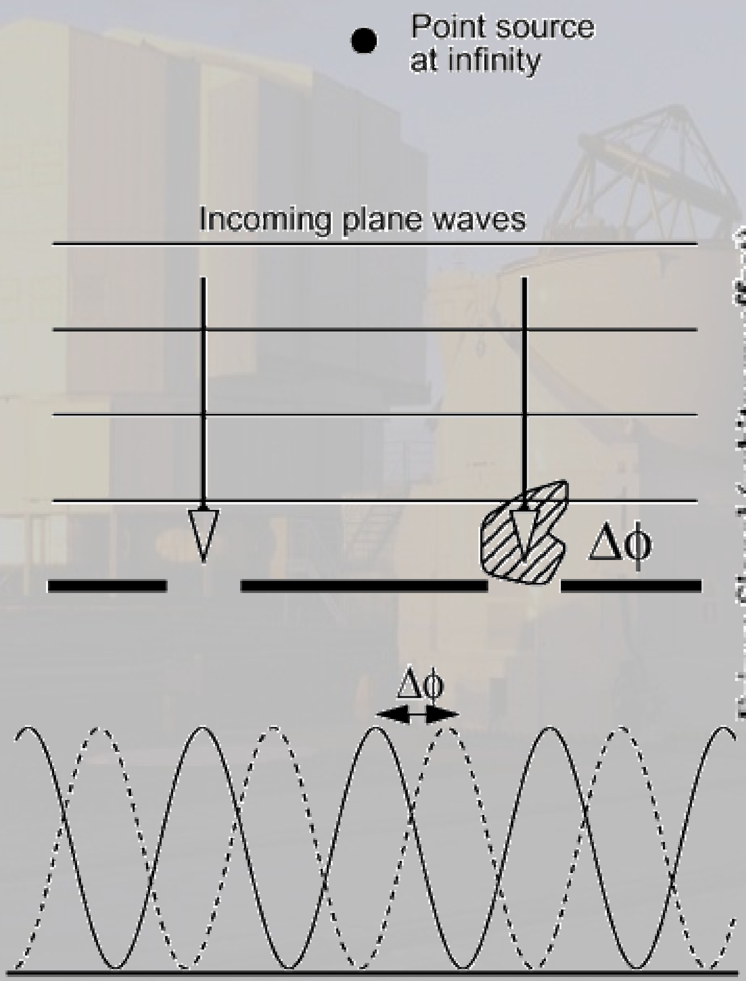
A 12m x 12m patch of atmosphere during typical good seeing

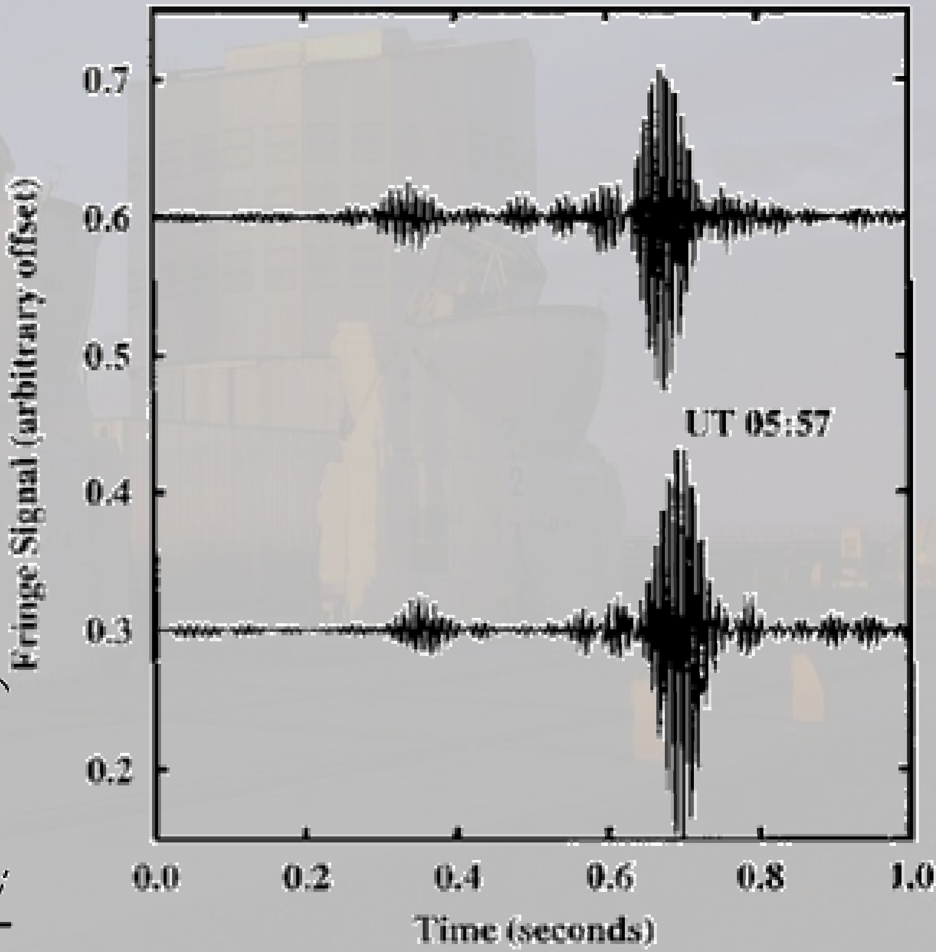
Each contour is one radian of phase delay of 2-micron light

Atmosphere Corrupts the Phase

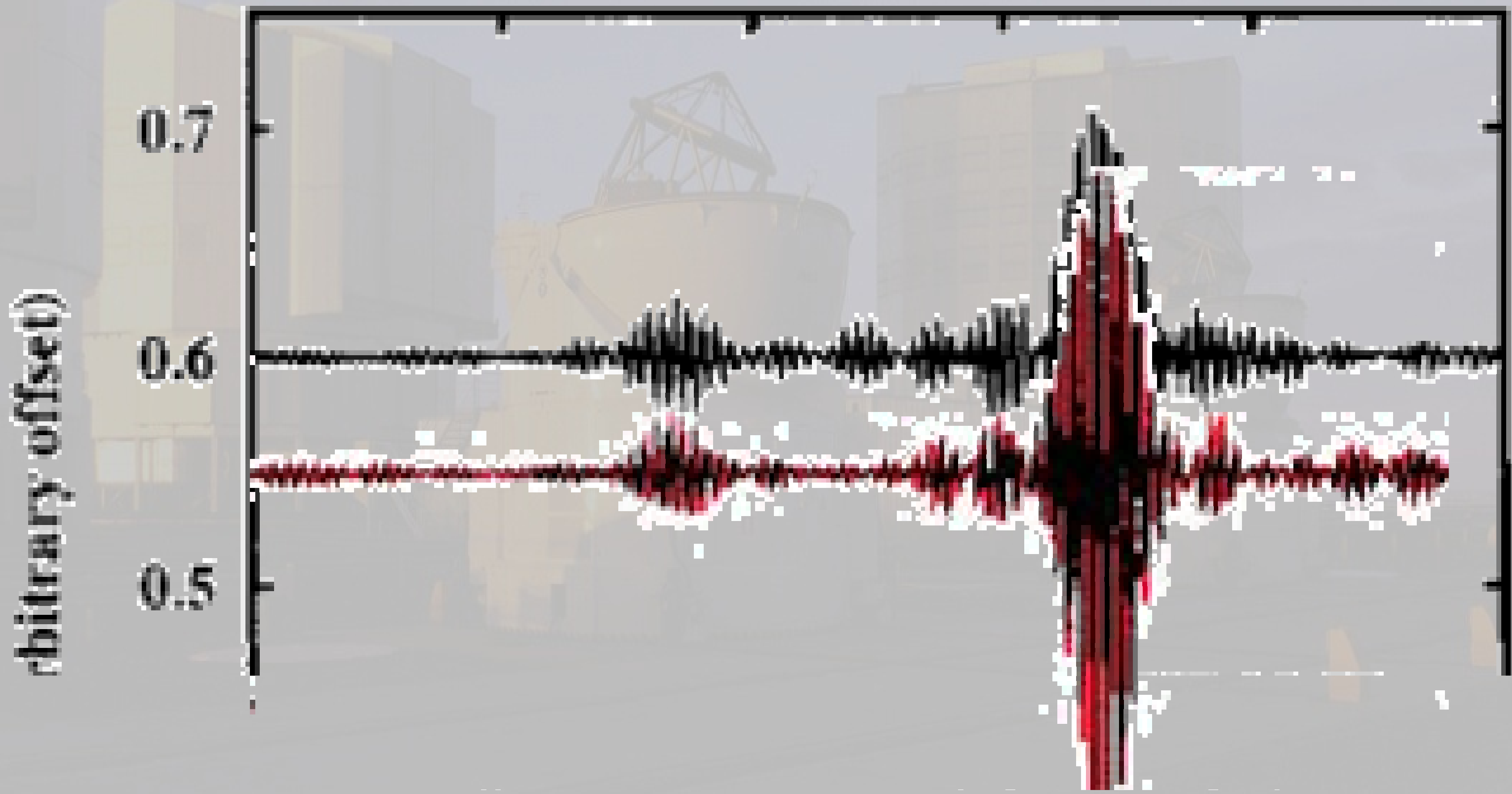


Atmosphere Corrupts the Phase





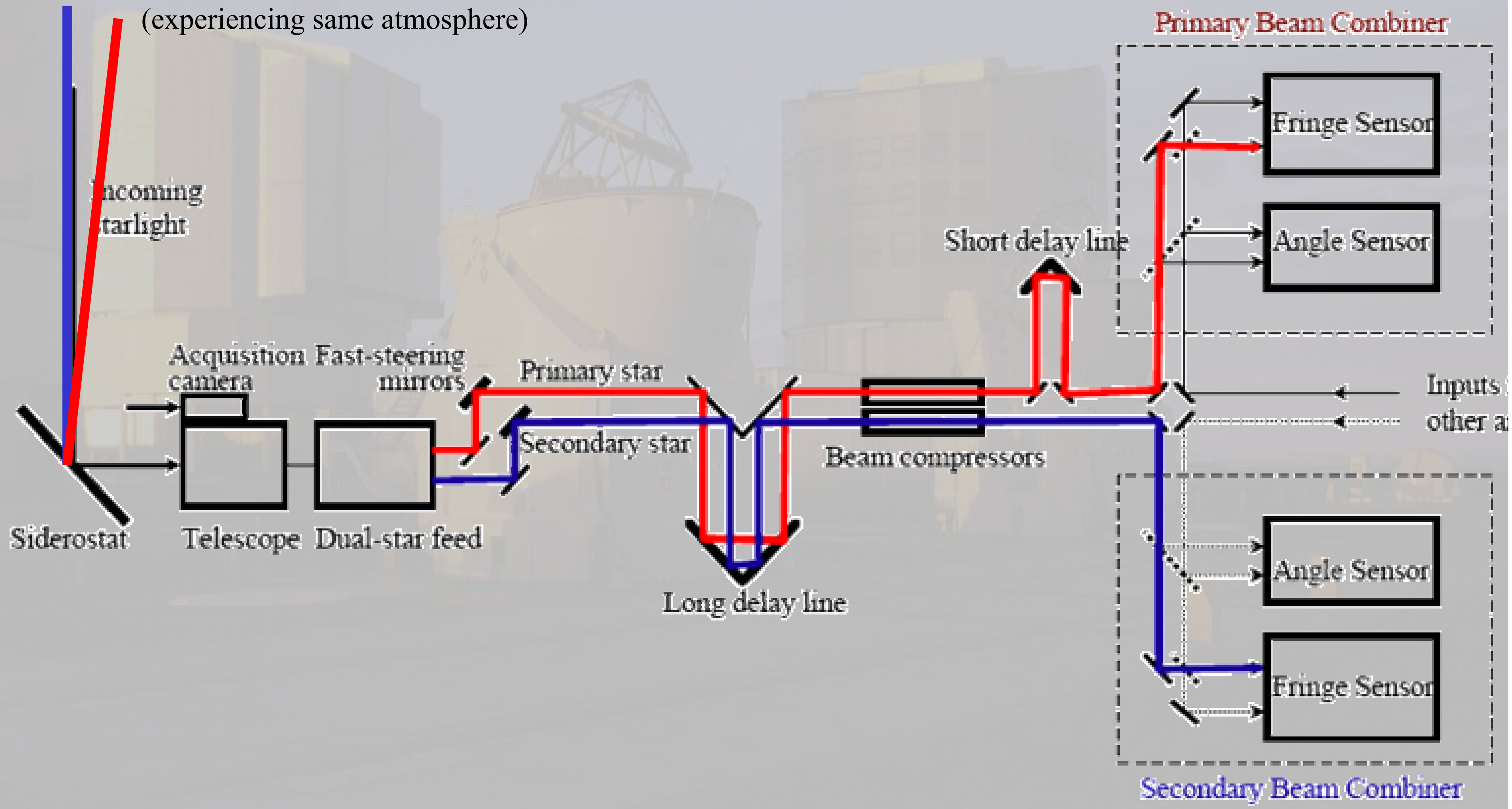
Atmosphere Corrupts Astrometry

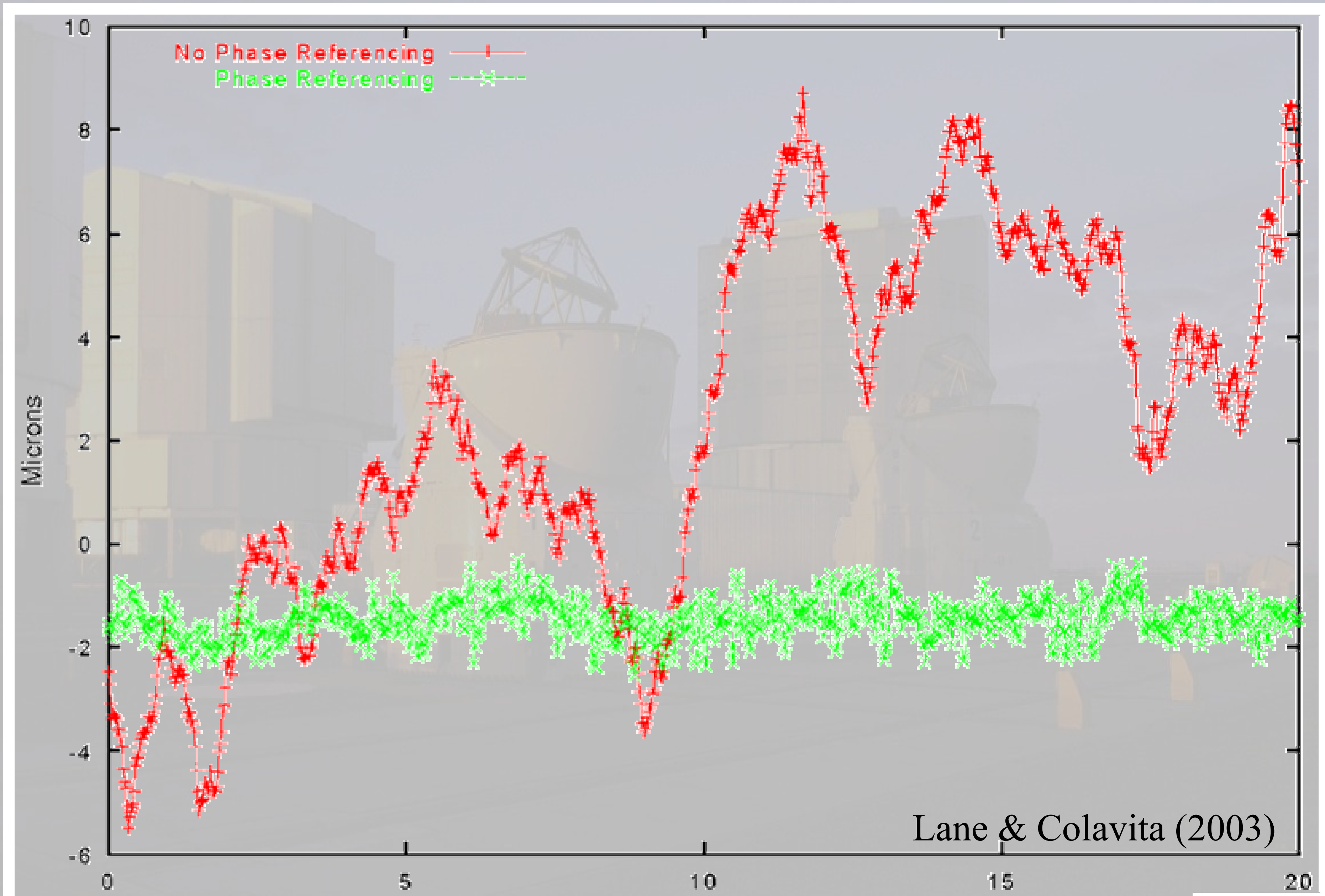


Colavita 2005 (MSS)

Dual-star, Narrow-angle Astrometry

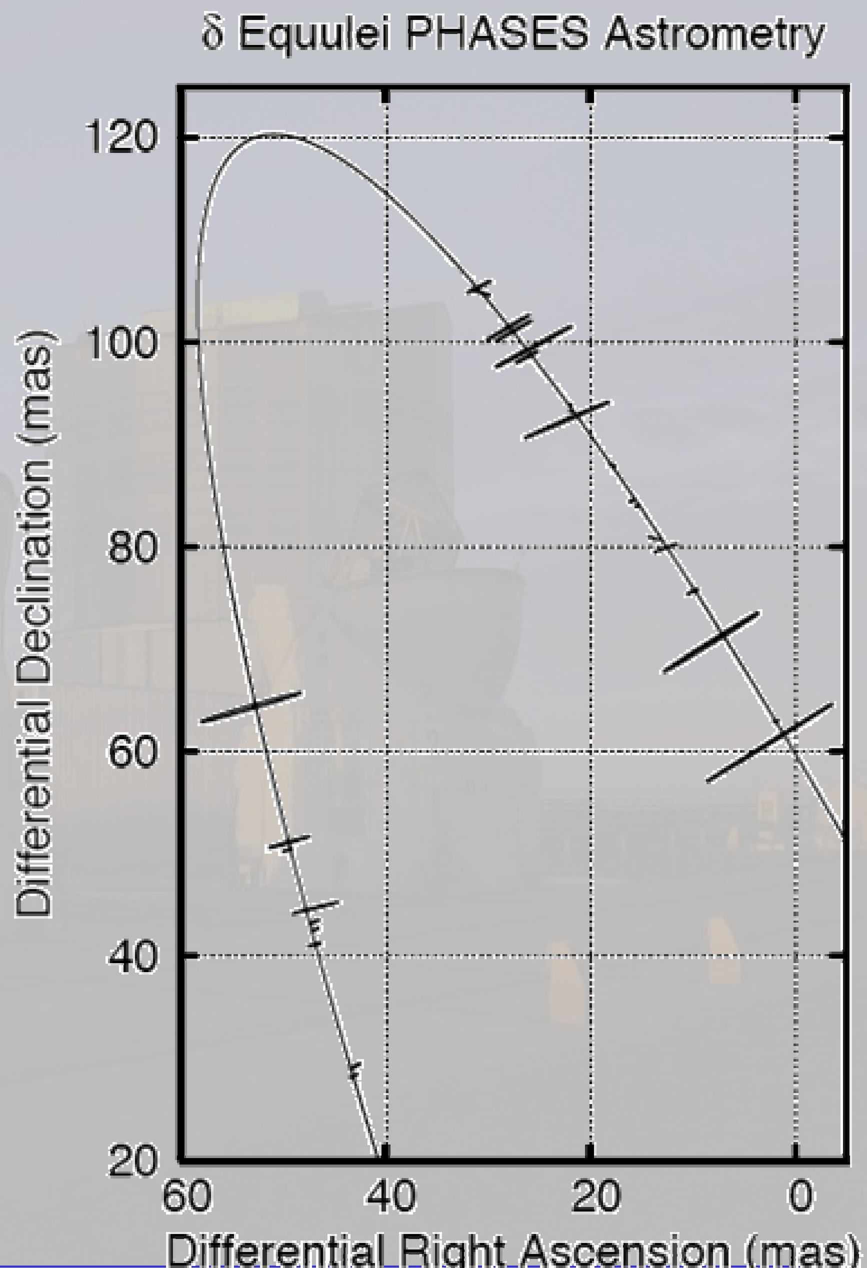
Two stars close together
(experiencing same atmosphere)




No Phase Referencing
Phase Referencing
Microns
10
8
6
4
2
0
-2
-4
-6
0
5
10
15
20
Lane & Colavita (2003)

Science Case: Extrasolar Planets in Close Binaries

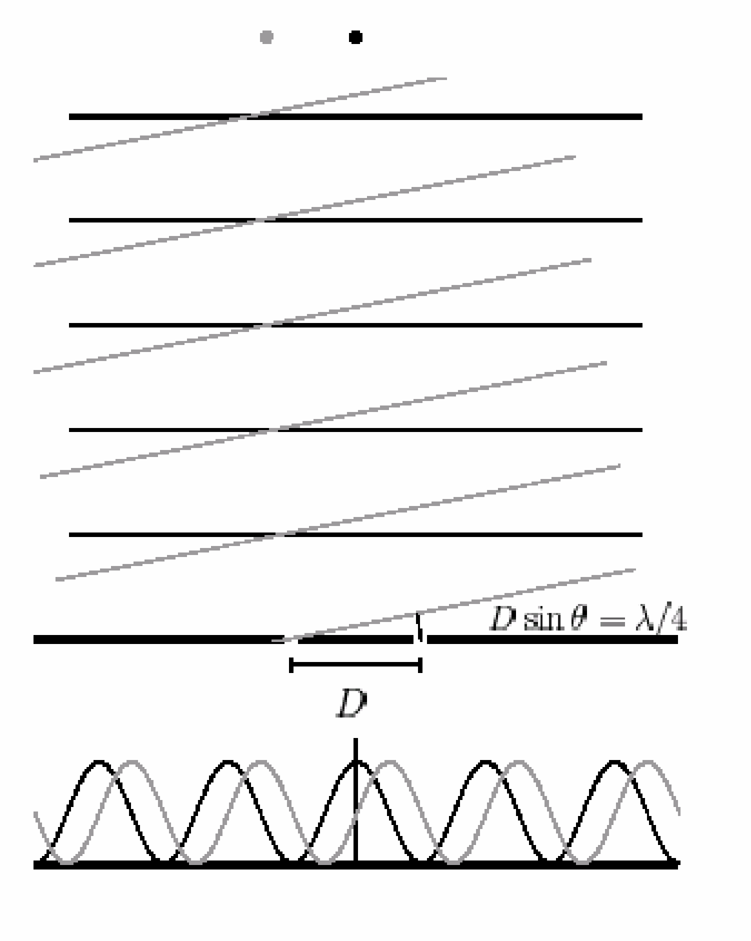
Muterspaugh et al. 2004 (PTI)



Phase Information in Interferometry

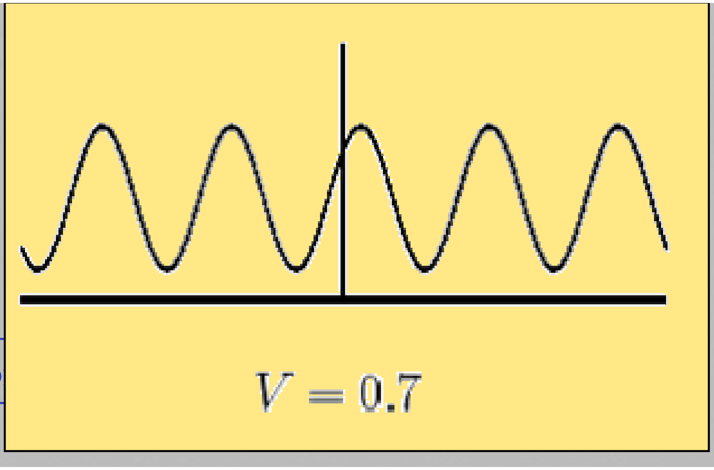
- Fringes are worth more than just location
- Fringe Visibilities are "complex"
  - Amplitude
  - Phase

- In order to reconstruct full information, we need to measure both pieces

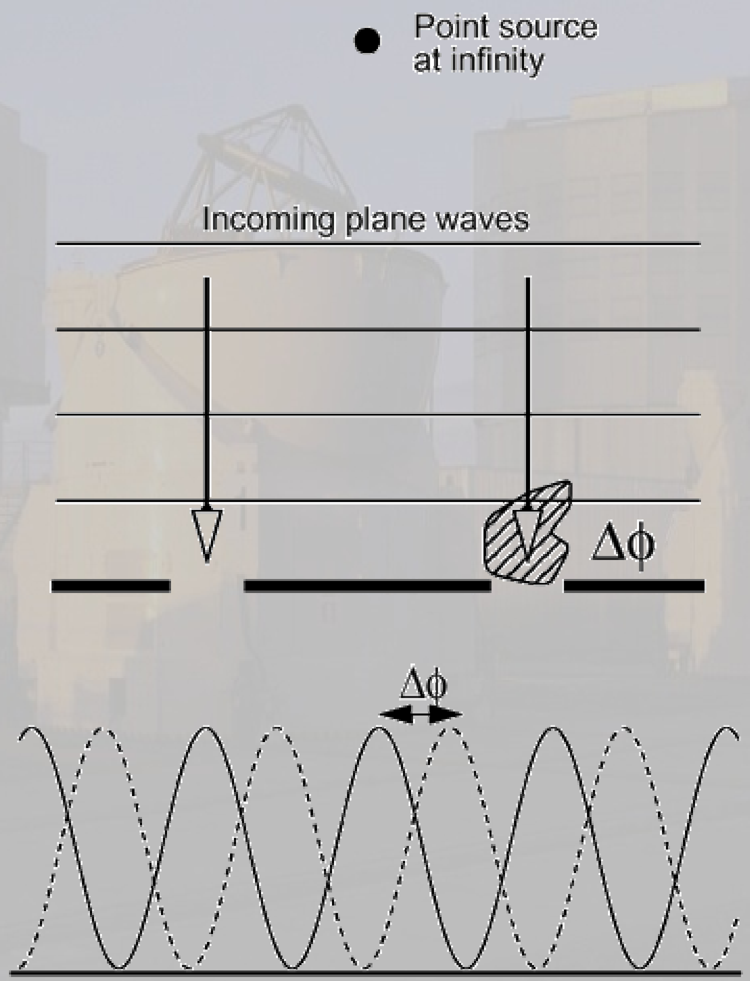


Van Cittert-Zernike Theorem

$$\left|\mathcal{V}_\nu\left(\frac{\vec{D}}{\lambda}\right)\right| e^{-i\phi_{\mathcal{V}_\nu}} = \frac{\int_{\delta\Omega} dx_\Omega \, dy_\Omega \, I_\nu(\vec{r}_\Omega) e^{-2\pi i((\vec{D}/\lambda)\cdot\vec{r}_\Omega)}}{\underbrace{\int_{\delta\Omega} dx_\Omega \, dy_\Omega \, I_\nu(\vec{r}_\Omega)}_{\text{Total specific flux}}}$$



Atmosphere Corrupts the Phase



Telescope-based Errors

$$\begin{aligned} \tilde{E}_i^{\text{measured}} &= \tilde{G}_i \tilde{E}_i^{\text{true}} \\ &= |G_i| e^{i\Phi_i^G} \tilde{E}_i^{\text{true}}. \end{aligned}$$

Telescope Gain
(e.g., coupling efficiency into single-mode fiber)

Telescope Phase Shift
(e.g., atmospheric piston, bad baseline, thermal drifts)

$$\text{Since} \quad \tilde{V}_{ij} \propto \tilde{E}_i \cdot \tilde{E}_j^*,$$

$$\begin{aligned} \tilde{V}_{ij}^{\text{measured}} &= \tilde{G}_i \tilde{G}_j^* \tilde{V}_{ij}^{\text{true}} \\ &= |G_i||G_j| e^{i(\Phi_i^G - \Phi_j^G)} \tilde{V}_{ij}^{\text{true}} \end{aligned}$$

Phase shift of detected Fringe

Dealing with Atmosphere

- •Space Interferometry
  - –Expensive
- •Fringe Tracking *(adaptive optics for interferometry)*
  - –Requires bright target (VLTI: FINITO)
- •Phase-Referencing
  - –Dual-star module (VLTI: PRIMA)
  - –Differential Phase (VLTI: AMBER, MIDI)
- •Closure Phase (most of this talk)
  - –Need 3+ telescopes
  - –VLTI: AMBER

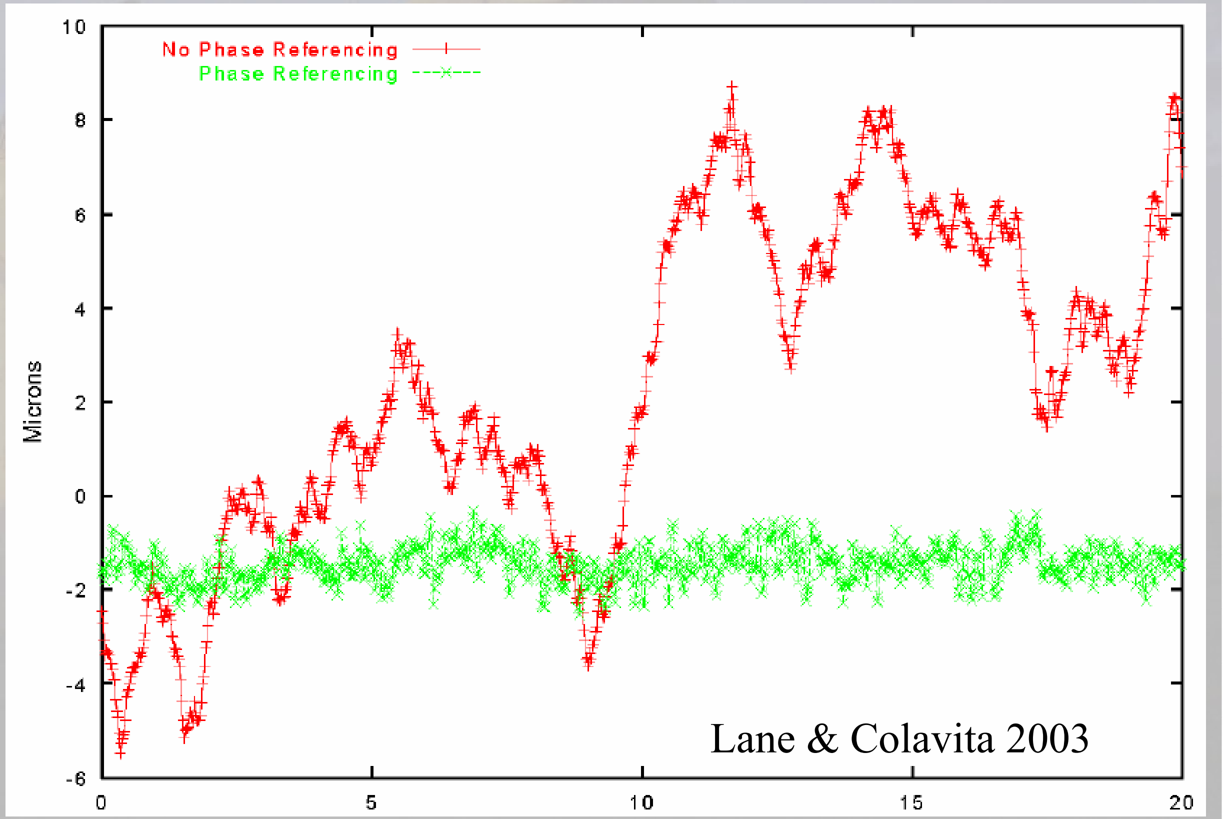
Dual-Star Module: Phase Referencing

(VLTI context: PRIMA in 2007ish)

Correct atmosphere by observing one star, and then 'coherently integrate' at some other delay

Measure complete complex visibility (phase & amp)

Observe fainter objects

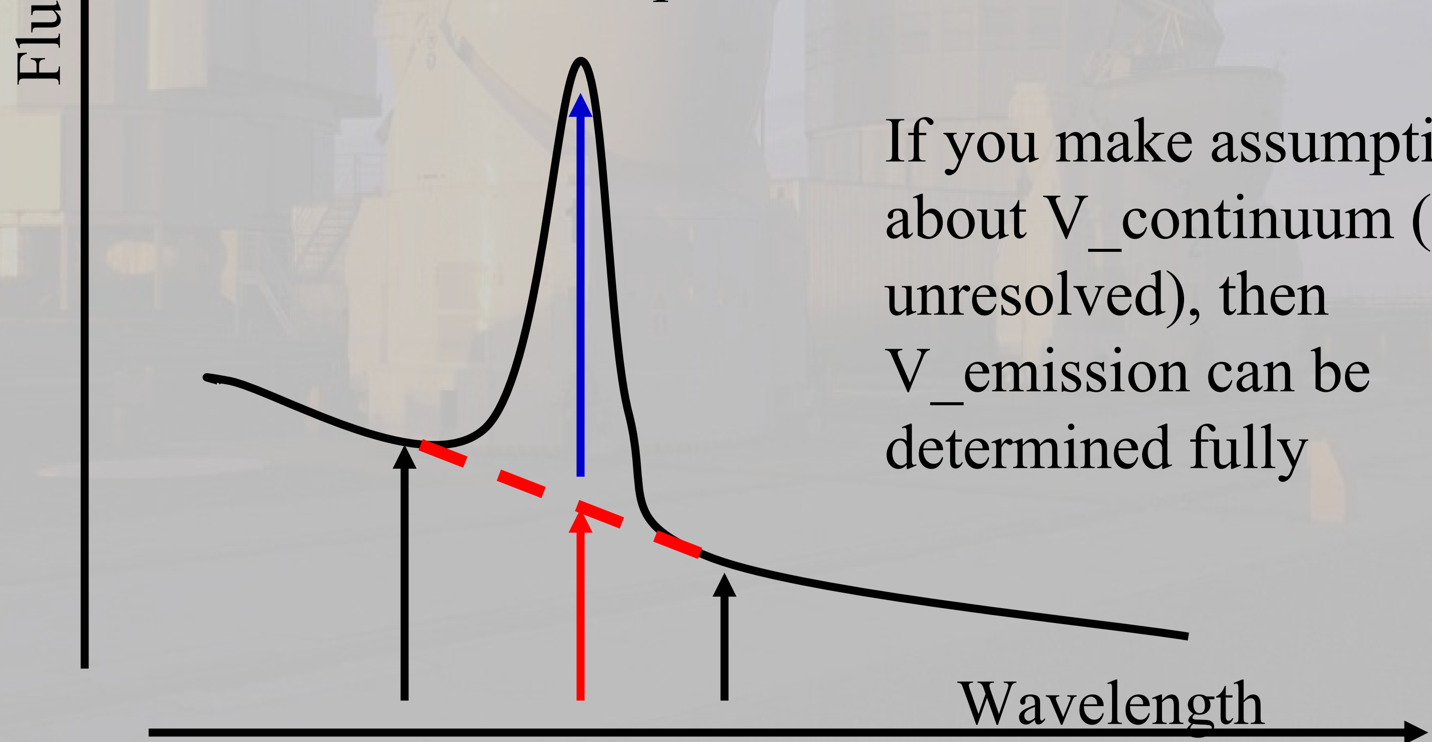


Differential Phase

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

Prime indicates corrupted by atmospheric piston

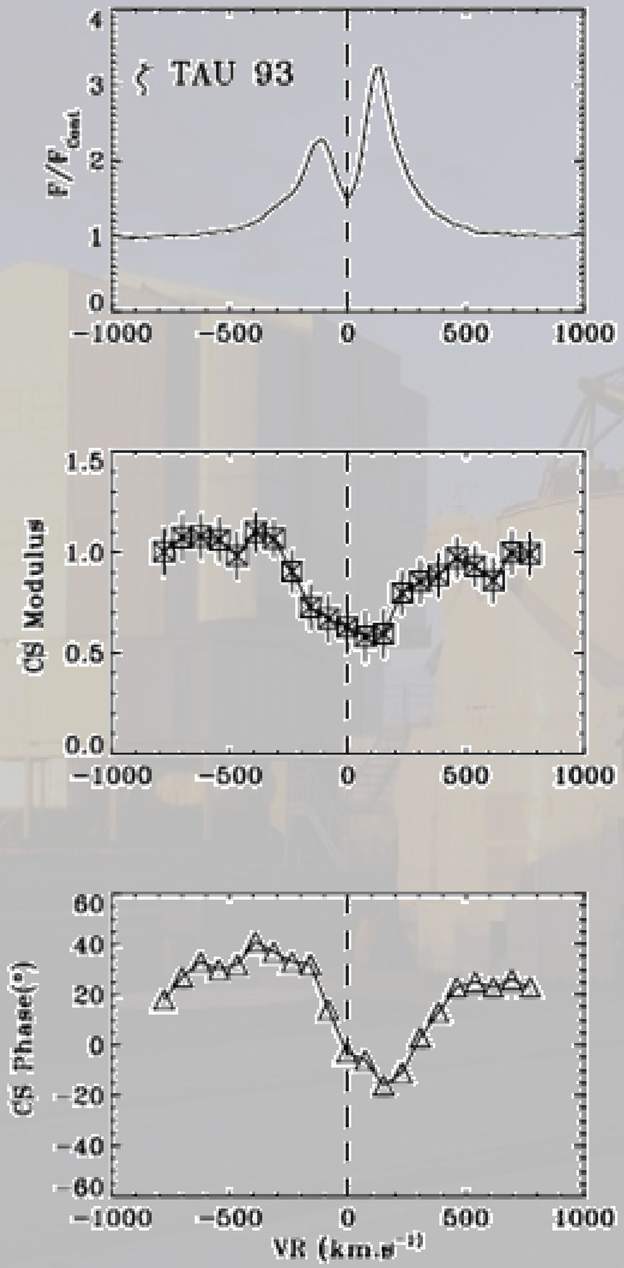
Measured Interpolated

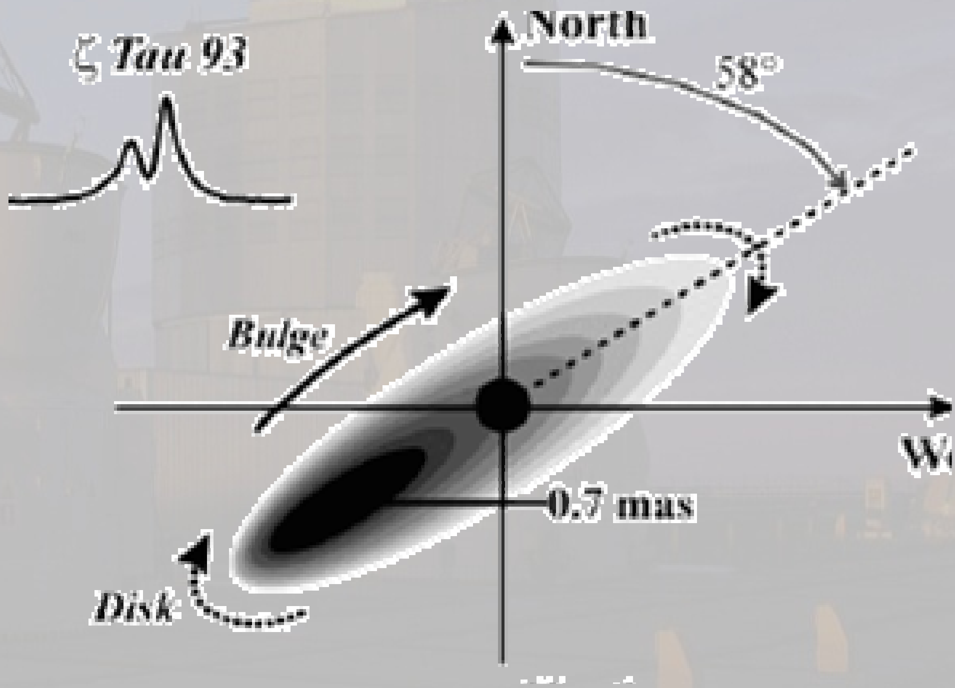


If you make assumption about V_continuum (e.g., unresolved), then V_emission can be determined fully

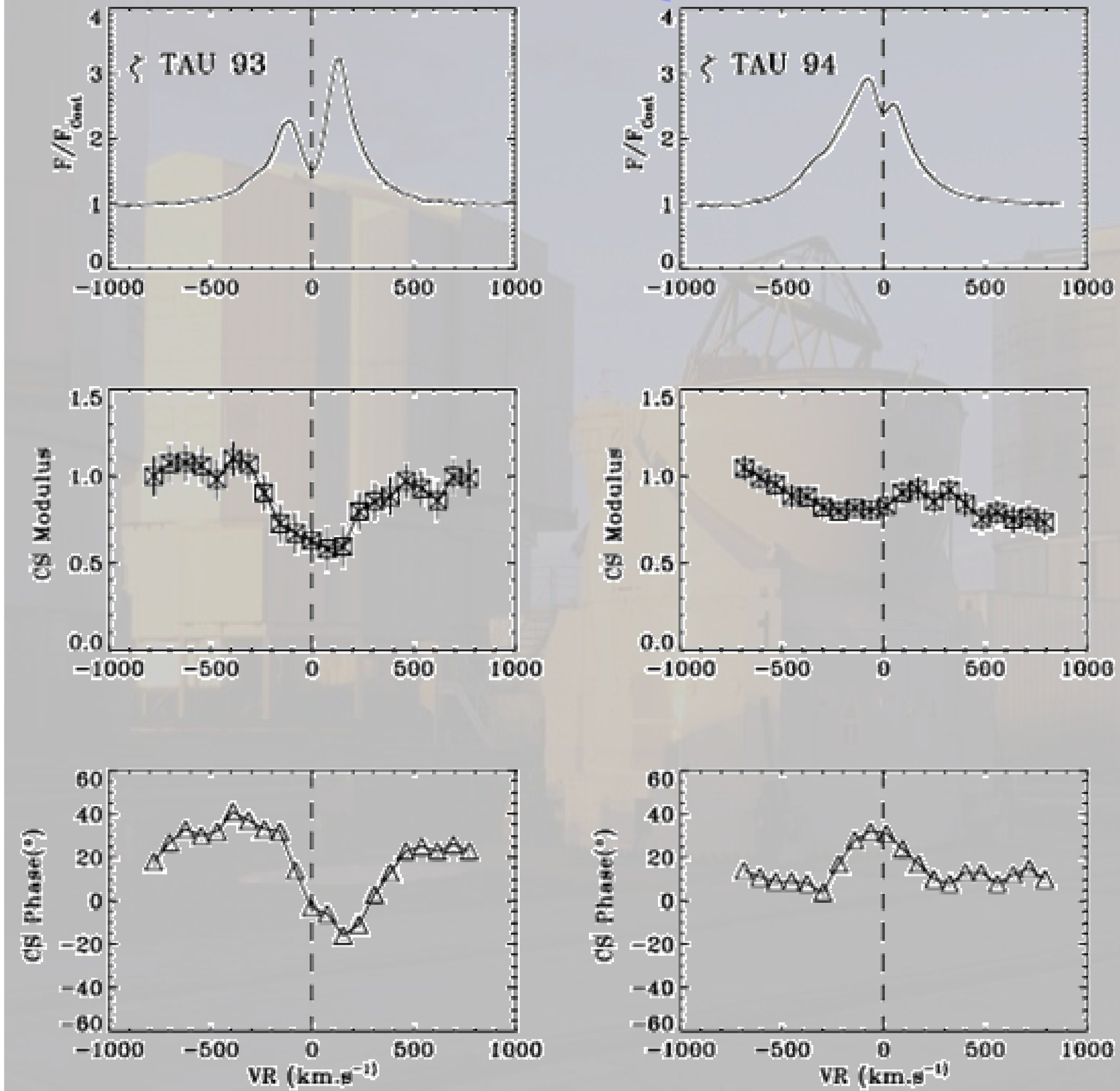
Vakili et al. 1998, GI2T

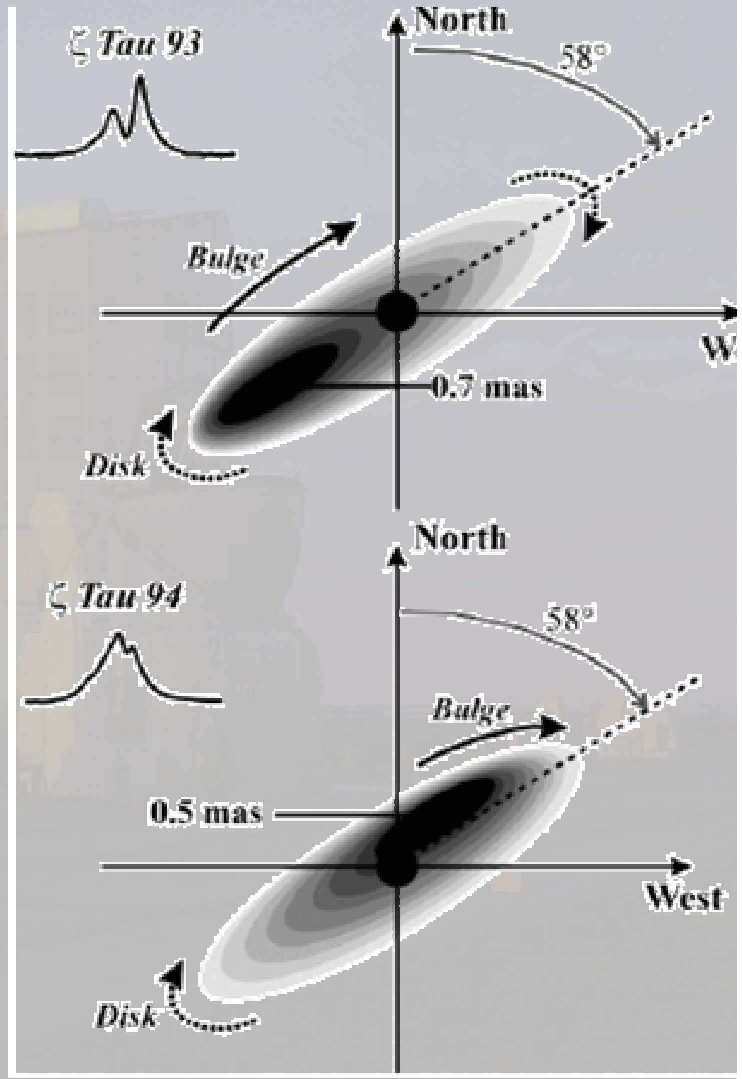
Science Case:
Hα Envelopes of Be Stars





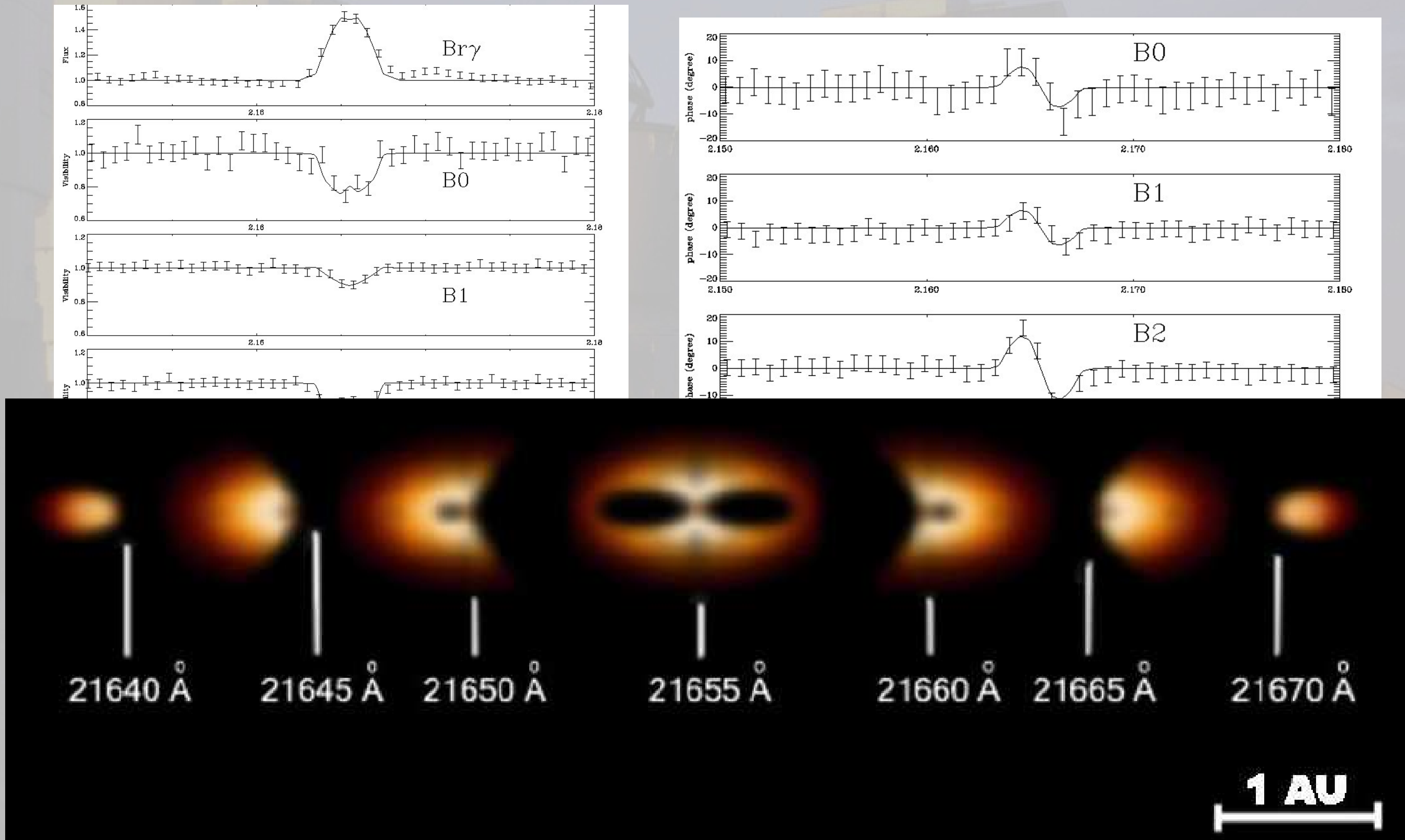
Quiz:





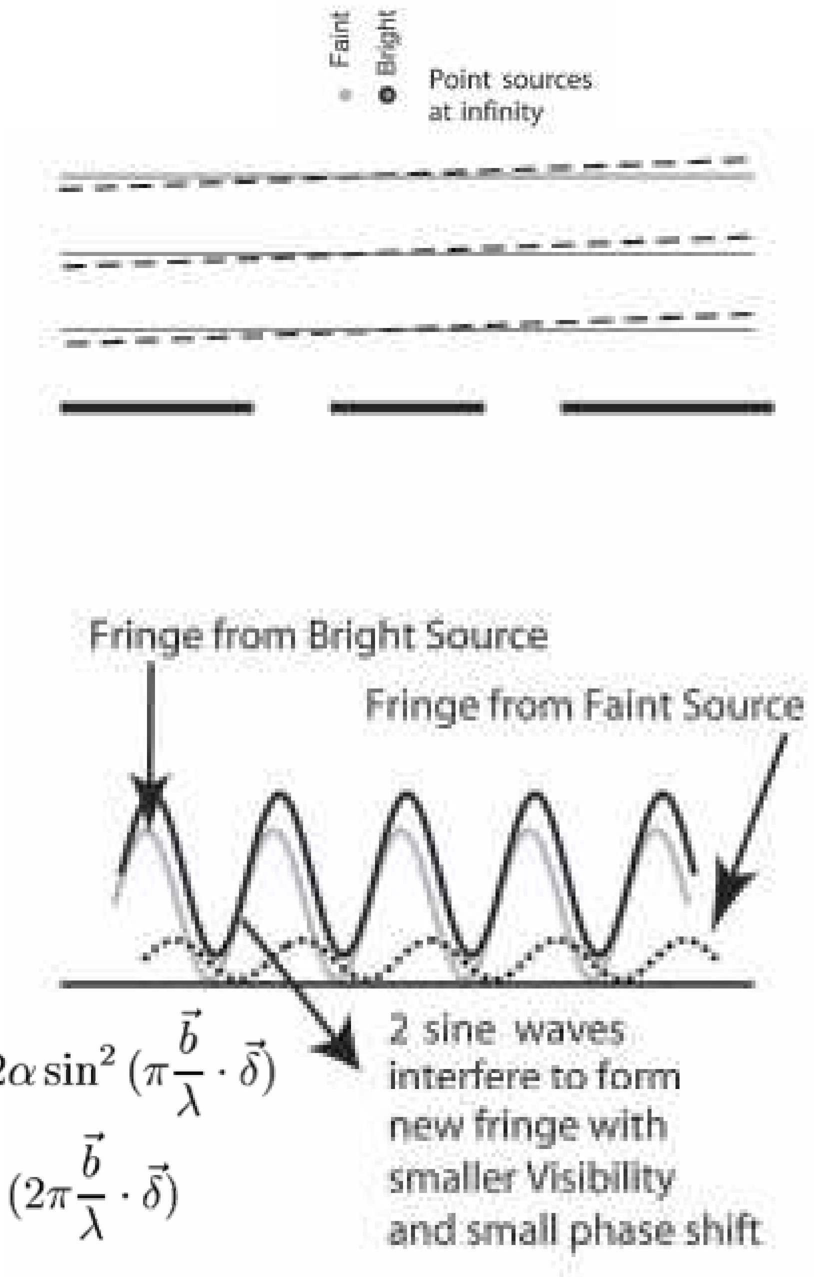
Vakili et al. 1998, GI2T

Differential Phases with VLTI-AMBER: What might this be?



Photocenter Shift

- Circumstellar emission can influence the location of the « center of light » (‘Photocenter’)
- Wobble of photocenter has been used for years to do astrometry (for parallax and binaries -- e.g., hipparcos)
- Photocenter shift is corrupted by atmosphere unless doing narrow-angle astrometry

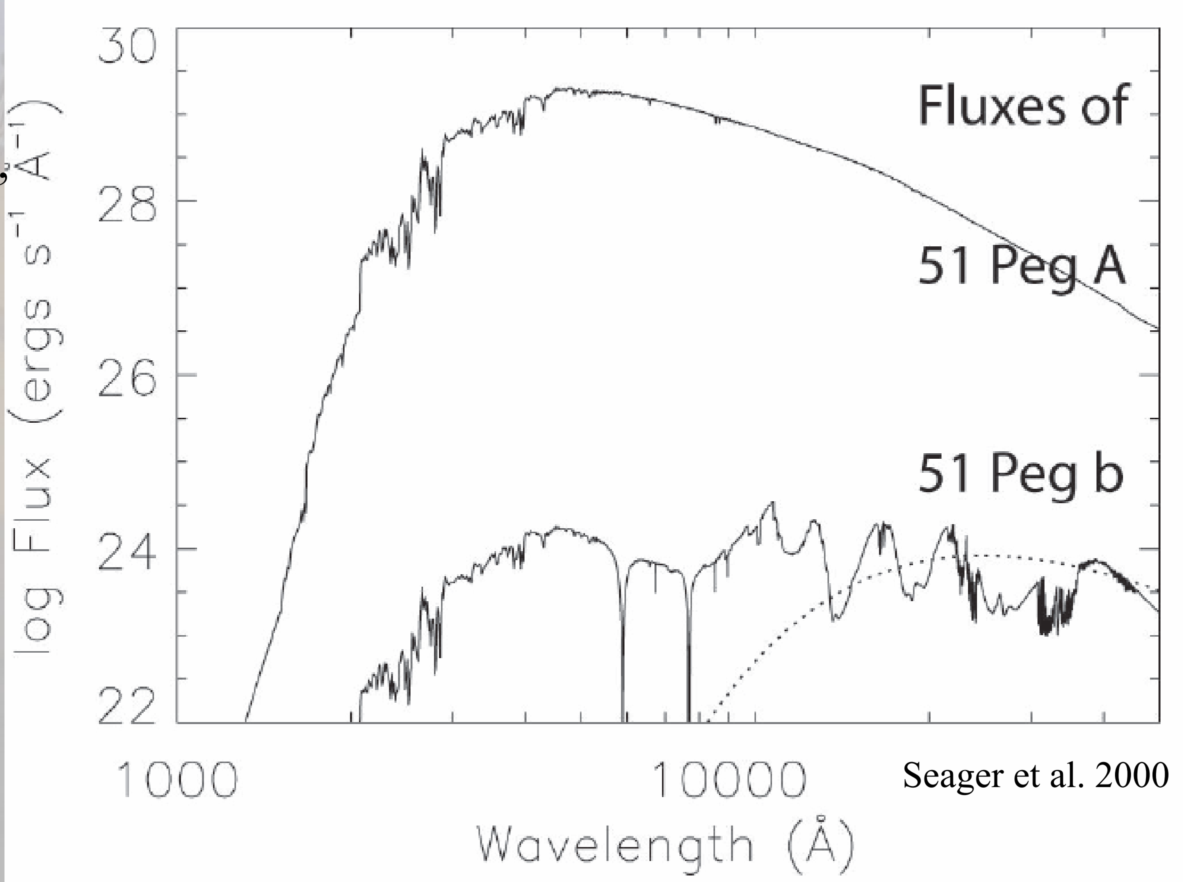


$$|V| \approx 1 - 2\alpha \sin^2 (\pi \frac{\vec{b}}{\lambda} \cdot \vec{\delta})$$

$$\Phi_V \approx \alpha \sin (2\pi \frac{\vec{b}}{\lambda} \cdot \vec{\delta})$$

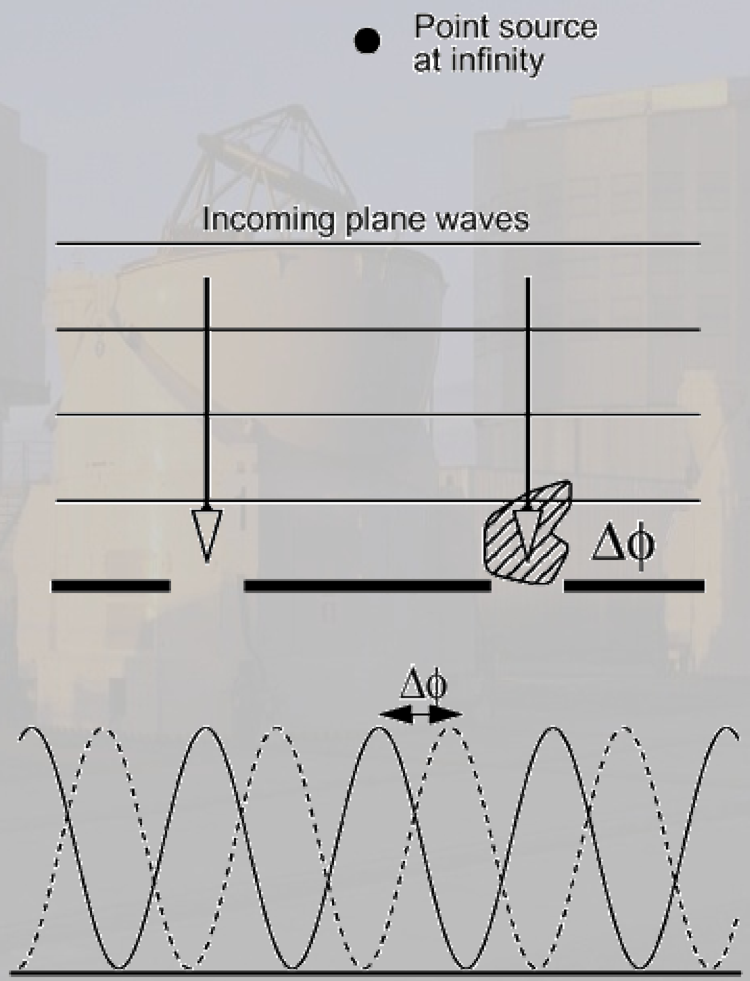
Science Case: Differential Phase for Exoplanet Detection

- Measure fringes simultaneous at two different wavelengths
- Since brightness ratio is different, there will be a « differential phase »
- Difficulties:
  - Differential dispersion (dry air vs. water vapor)
  - Best in thermal IR (4-20 microns)
- Prospectives:
  - VLTI: AMBER
  - Keck-I: DP mode cancelled/deferred

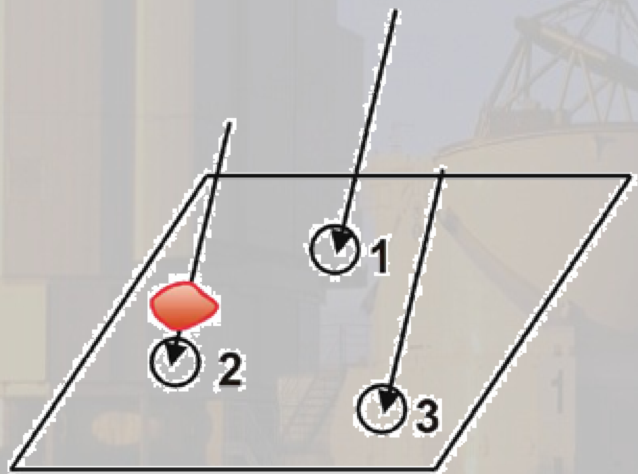


Seager et al. 2000

Introduction to Closure Phase



The "Closure Phase" Is Not Corrupted



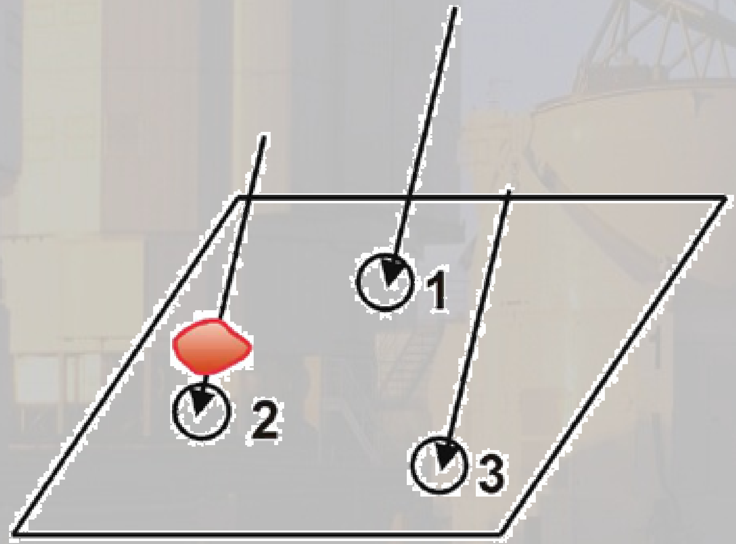
Observed		Intrinsic		Atmosphere
$\Phi(1\text{-}2)$	=	$\Phi_o(1\text{-}2)$	+	$[\phi(2)-\phi(1)]$
$\Phi(2\text{-}3)$	=	$\Phi_o(2\text{-}3)$	+	$[\phi(3)-\phi(2)]$
$\Phi(3\text{-}1)$	=	$\Phi_o(3\text{-}1)$	+	$[\phi(1)-\phi(3)]$

Closure Phase (1-2-3) $= \Phi_o(1\text{-}2)+\Phi_o(2\text{-}3)+\Phi_o(3\text{-}1)$

Related to the Bispectrum, B_{ijk}, used in Speckle Interferometry

$$\begin{aligned}
\tilde{B}_{ijk} &= \tilde{\mathcal{V}}^{\text{measured}}_{ij}\,\tilde{\mathcal{V}}^{\text{measured}}_{jk}\,\tilde{\mathcal{V}}^{\text{measured}}_{ki} \\
&= |G_i||G_j|\,e^{i(\Phi^G_i-\Phi^G_j)}\,\tilde{\mathcal{V}}^{\text{true}}_{ij}\cdot|G_j||G_k|\,e^{i(\Phi^G_j-\Phi^G_k)}\,\tilde{\mathcal{V}}^{\text{true}}_{jk}\cdot|G_k||G_i|\,e^{i(\Phi^G_k-\Phi^G_i)}\,\tilde{\mathcal{V}}^{\text{true}}_{ki} \\
&= |G_i|^2\,|G_j|^2\,|G_k|^2\,\tilde{\mathcal{V}}^{\text{true}}_{ij}\cdot\tilde{\mathcal{V}}^{\text{true}}_{jk}\cdot\tilde{\mathcal{V}}^{\text{true}}_{ki}.
\end{aligned}$$

The "Closure Phase" Is Not Corrupted



Observed		Intrinsic		Atmosphere
$\Phi(1\text{-}2)$	$=$	$\Phi_o(1\text{-}2)$	$+$	$[\phi(2)-\phi(1)]$
$\Phi(2\text{-}3)$	$=$	$\Phi_o(2\text{-}3)$	$+$	$[\phi(3)-\phi(2)]$
$\Phi(3\text{-}1)$	$=$	$\Phi_o(3\text{-}1)$	$+$	$[\phi(1)-\phi(3)]$

$$\text{Closure Phase (1-2-3)} = \Phi_o(1\text{-}2)+\Phi_o(2\text{-}3)+\Phi_o(3\text{-}1)$$

The Bispectrum or “Triple Amplitude”

Recall:

$$\begin{aligned}\tilde{\mathcal{V}}_{ij}^{\text{measured}} &= \tilde{G}_i \tilde{G}_j^* \tilde{\mathcal{V}}_{ij}^{\text{true}} \\ &= |G_i||G_j| e^{i(\Phi_i^G - \Phi_j^G)} \tilde{\mathcal{V}}_{ij}^{\text{true}}\end{aligned}$$

Thus we define the Bispectrum:

$$\begin{aligned}\tilde{B}_{ijk} &= \tilde{\mathcal{V}}_{ij}^{\text{measured}}\, \tilde{\mathcal{V}}_{jk}^{\text{measured}}\, \tilde{\mathcal{V}}_{ki}^{\text{measured}} \\ &= |G_i||G_j|\, e^{i(\Phi_i^G - \Phi_j^G)}\, \tilde{\mathcal{V}}_{ij}^{\text{true}} \cdot |G_j||G_k|\, e^{i(\Phi_j^G - \Phi_k^G)}\, \tilde{\mathcal{V}}_{jk}^{\text{true}} \cdot |G_k||G_i|\, e^{i(\Phi_k^G - \Phi_i^G)}\, \tilde{\mathcal{V}}_{ki}^{\text{true}} \\ &= |G_i|^2\, |G_j|^2\, |G_k|^2\, \tilde{\mathcal{V}}_{ij}^{\text{true}} \cdot \tilde{\mathcal{V}}_{jk}^{\text{true}} \cdot \tilde{\mathcal{V}}_{ki}^{\text{true}}.\end{aligned}$$

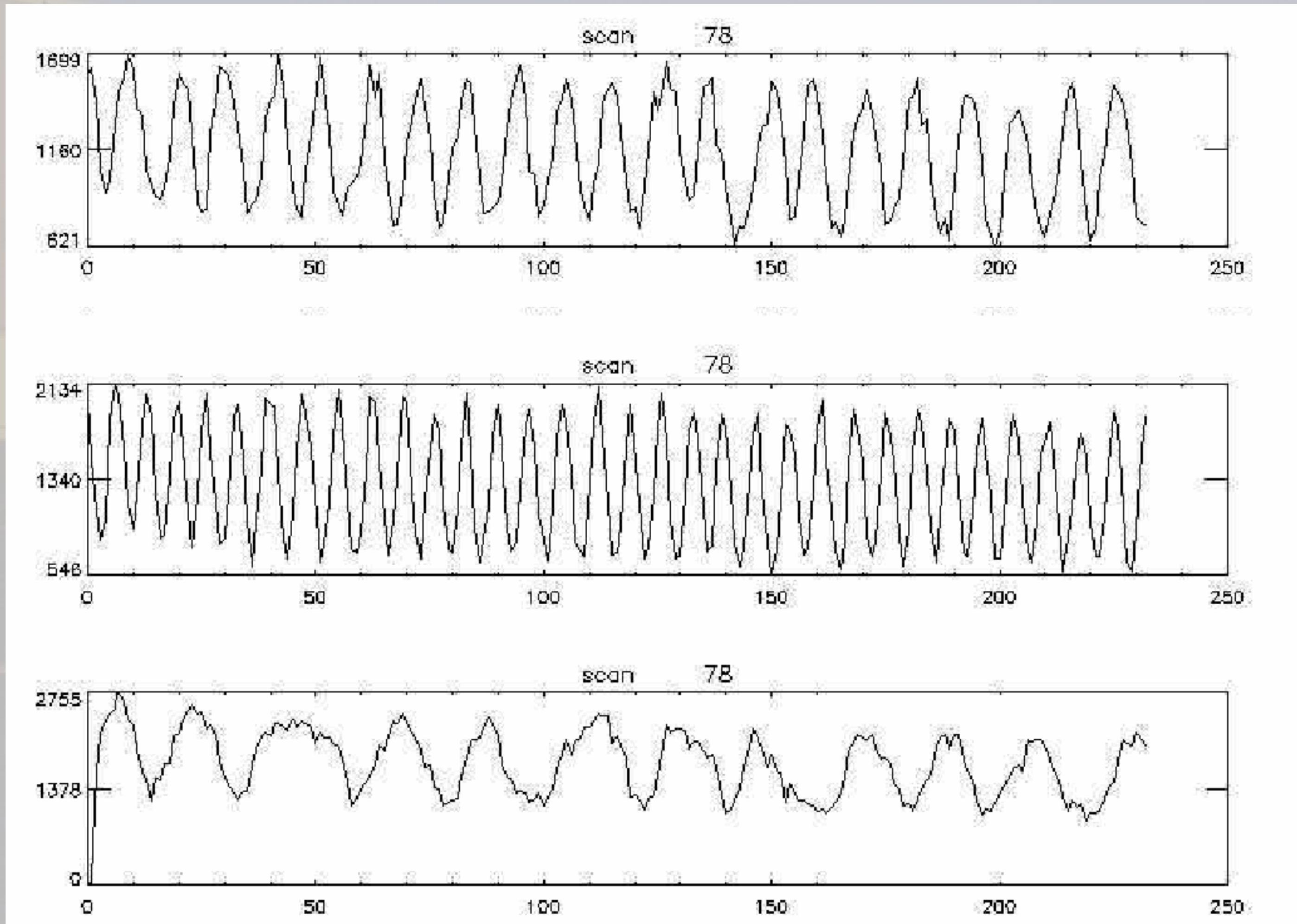
The ‘argument’ (or angle) of this complex quantity is the Closure Phase!

Closure Amplitudes too

$$
\begin{aligned}
A_{ijkl} &= \frac{|\tilde{\mathcal{V}}_{ij}^{\rm measured}||\tilde{\mathcal{V}}_{kl}^{\rm measured}|}{|\tilde{\mathcal{V}}_{ik}^{\rm measured}||\tilde{\mathcal{V}}_{jl}^{\rm measured}|} \\
&= \frac{|\tilde{G}_i||\tilde{G}_j||\tilde{\mathcal{V}}_{ij}^{\rm true}||\tilde{G}_k||\tilde{G}_l||\tilde{\mathcal{V}}_{kl}^{\rm true}|}{|\tilde{G}_i||\tilde{G}_k||\tilde{\mathcal{V}}_{ik}^{\rm true}||\tilde{G}_j||\tilde{G}_l||\tilde{\mathcal{V}}_{jl}^{\rm true}|} \\
&= \frac{|\tilde{\mathcal{V}}_{ij}^{\rm true}||\tilde{\mathcal{V}}_{kl}^{\rm true}|}{|\tilde{\mathcal{V}}_{ik}^{\rm true}||\tilde{\mathcal{V}}_{jl}^{\rm true}|}.
\end{aligned}
$$

Need simultaneous fringes from minimum of 4 telescopes
(sorry VLTI!!)

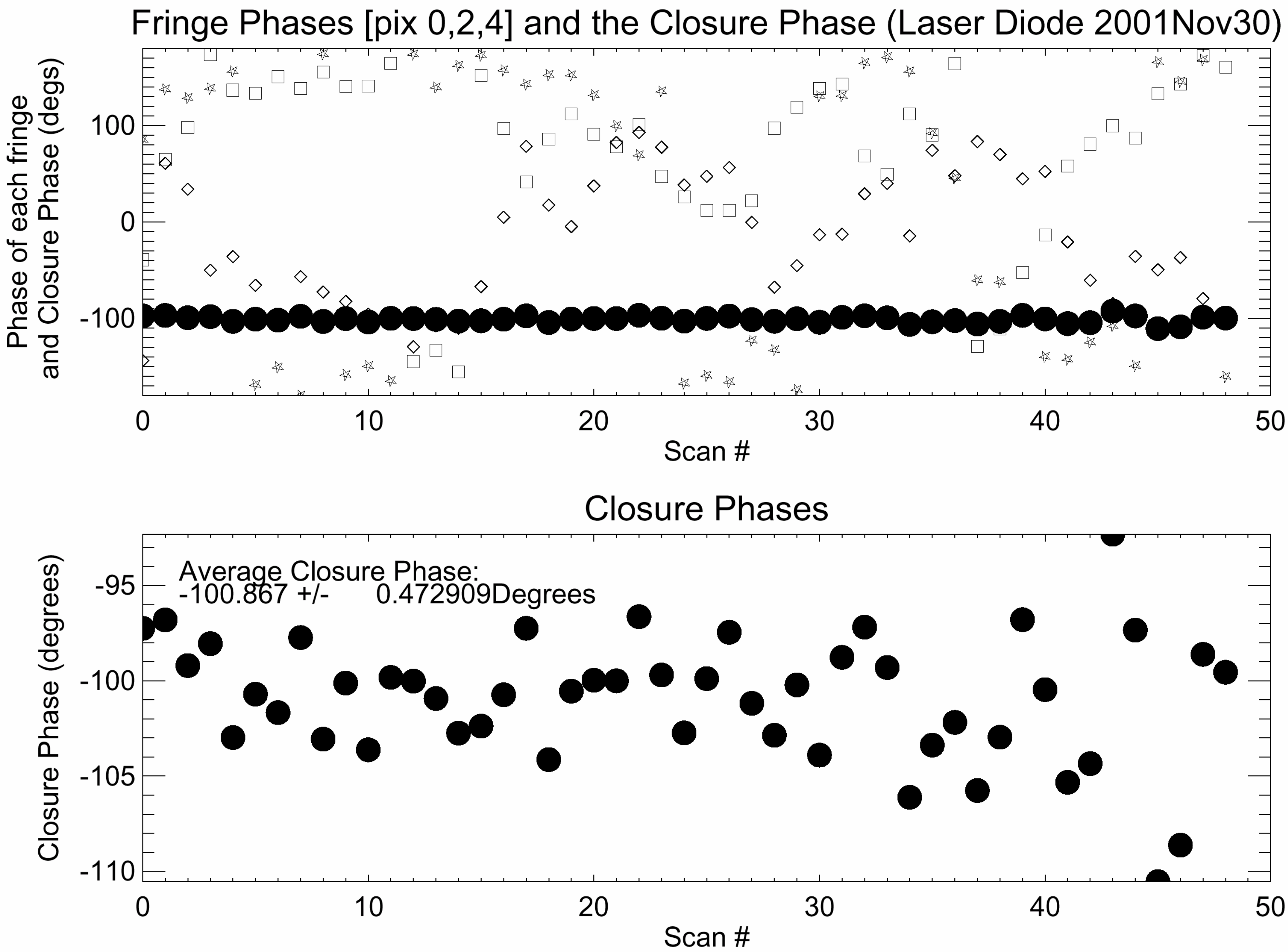
IOTA Example:
Pair-wise Combiner



Φ_1

Φ_2

Φ_3



Fringe Phases [pix 0,2,4] and the Closure Phase (Laser Diode 2001Nov30)
Phase of each fringe and Closure Phase (degs)
100
0
-100
0
10
20
30
40
50
Scan #
Closure Phases
Closure Phase (degrees)
Average Closure Phase:
-100.867 +/- 0.472909Degrees
-95
-100
-105
-110
0
10
20
30
40
50
Scan #

How Much Phase Information?

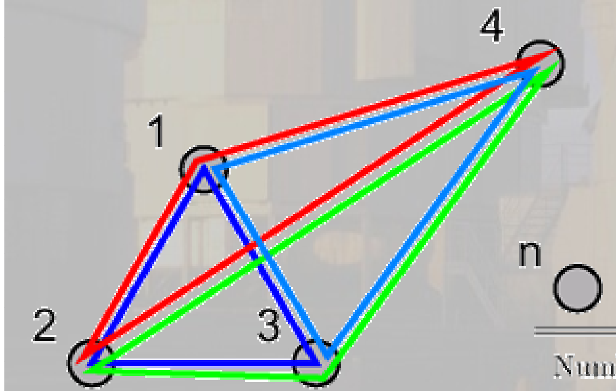
Closure Phases are not all independent from each other.

Number of Closure Phases

$$\binom{N}{3} = \frac{(N)(N-1)(N-2)}{(3)(2)},$$

Number of Fourier Phases

$$\binom{N}{2} = \frac{(N)(N-1)}{2}$$

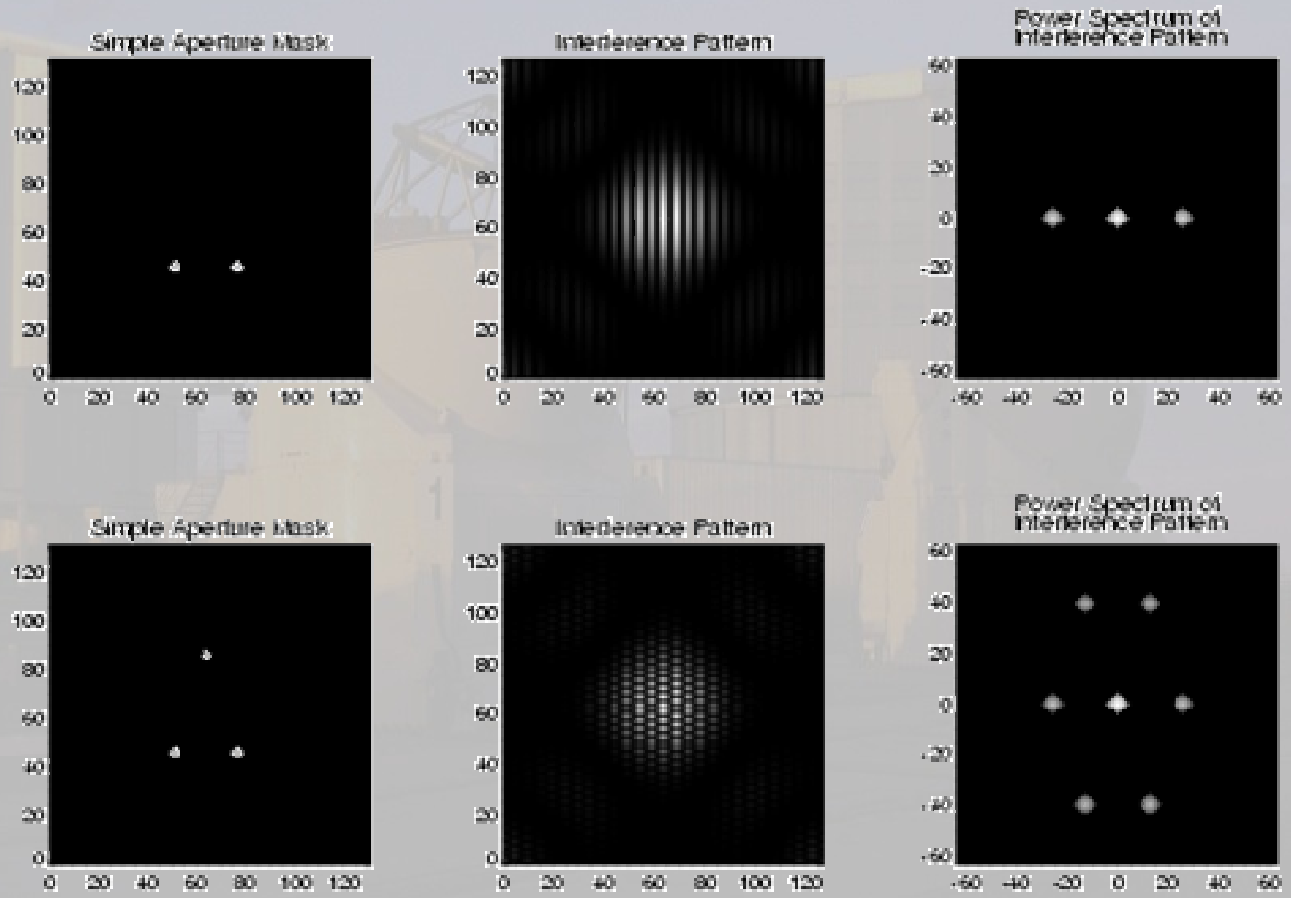


Number of Independent Closure Phases

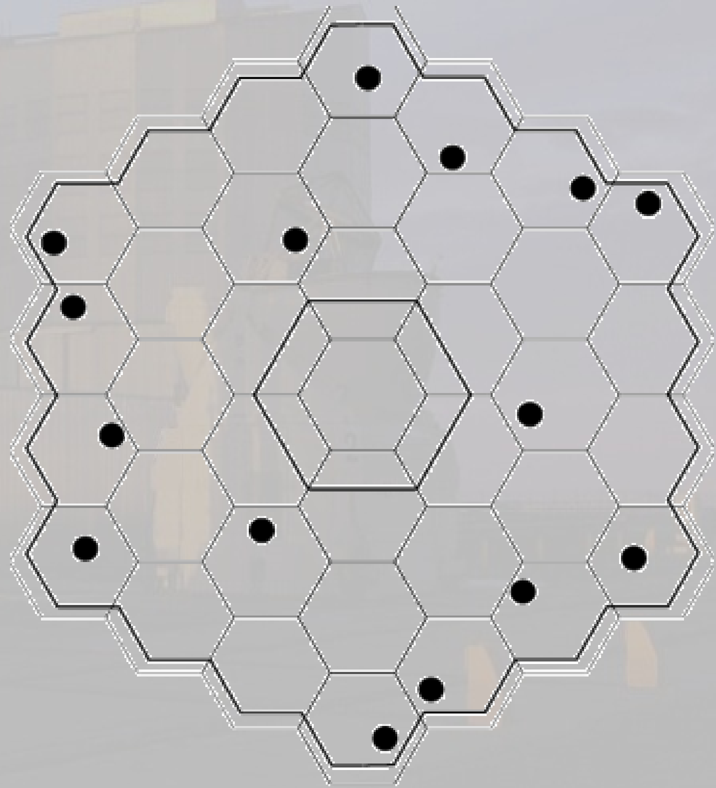
$$\binom{N-1}{2} = \frac{(N-1)(N-2)}{2}$$

Number of Telescopes	Number of Fourier Phases	Number of Closing Triangles	Number of Independent Closure Phases	Percentage of Phase Information
3	3	1	1	33%
7	21	35	15	71%
21	210	1330	190	90%
27	351	2925	325	93%
50	1225	19600	1176	96%

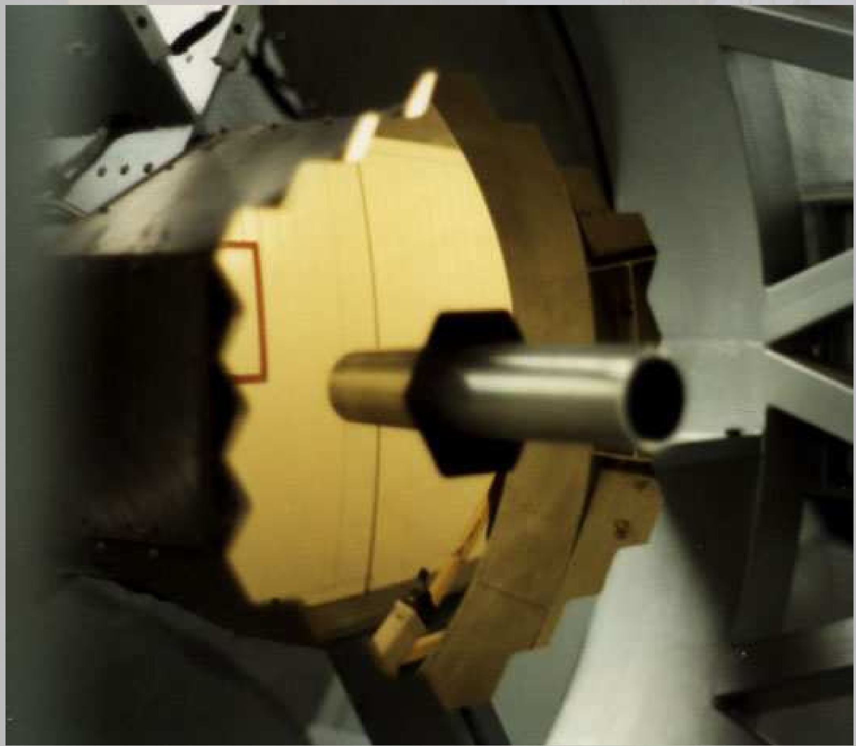
Aperture Masking: Examples

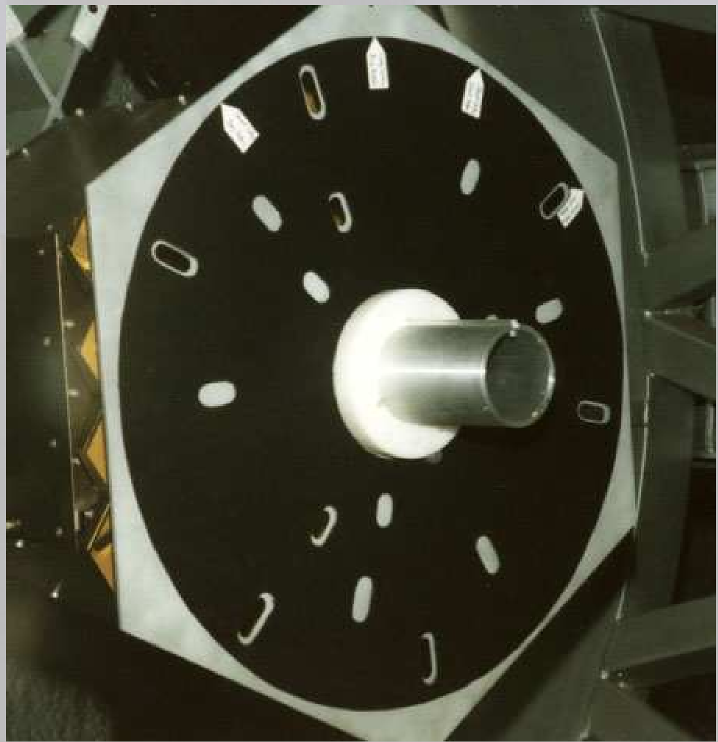


Keck-I Telescope:
10-m Segmented Primary



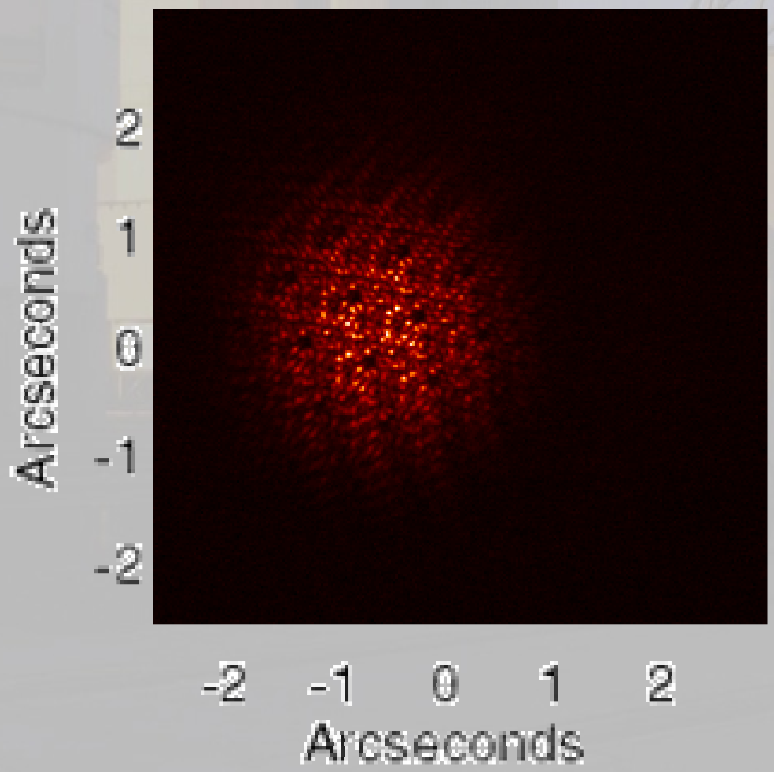
The Secondary Mirror & Mask

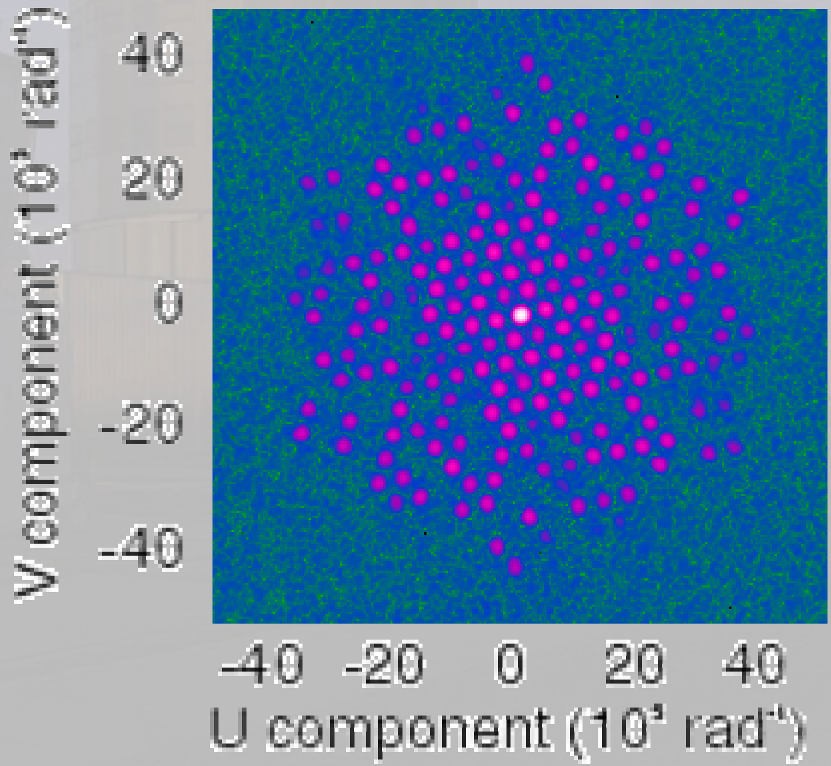




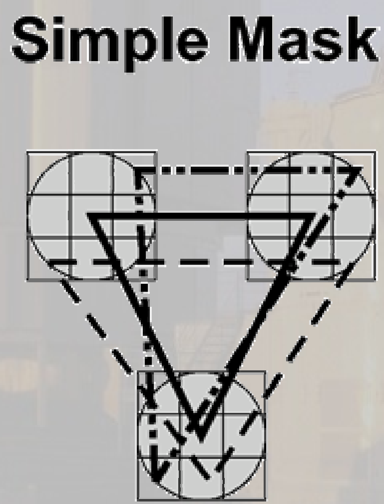
Speckles and Power Spectra

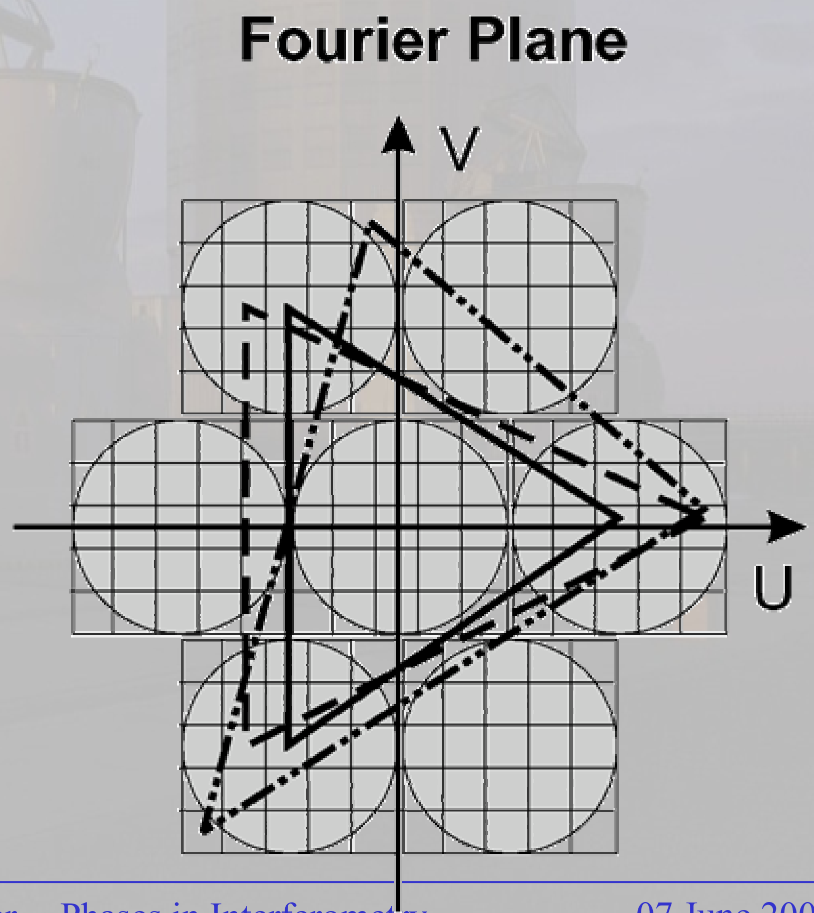
FFT



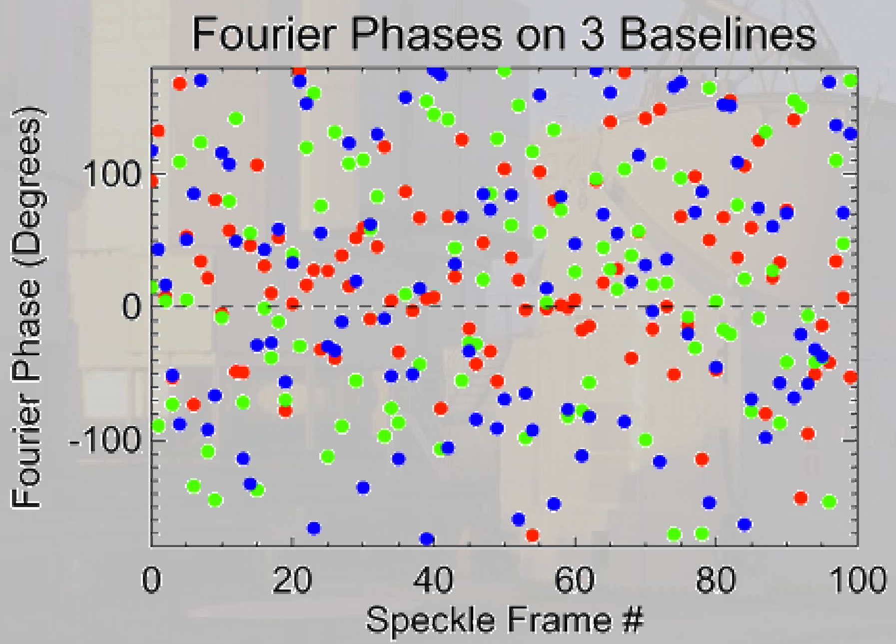


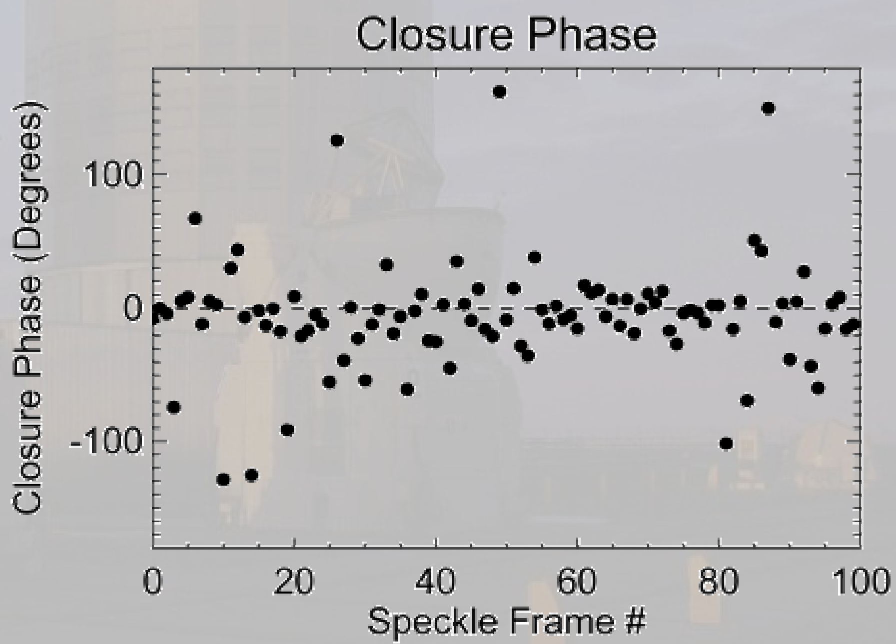
Closure Triangles must CLOSE





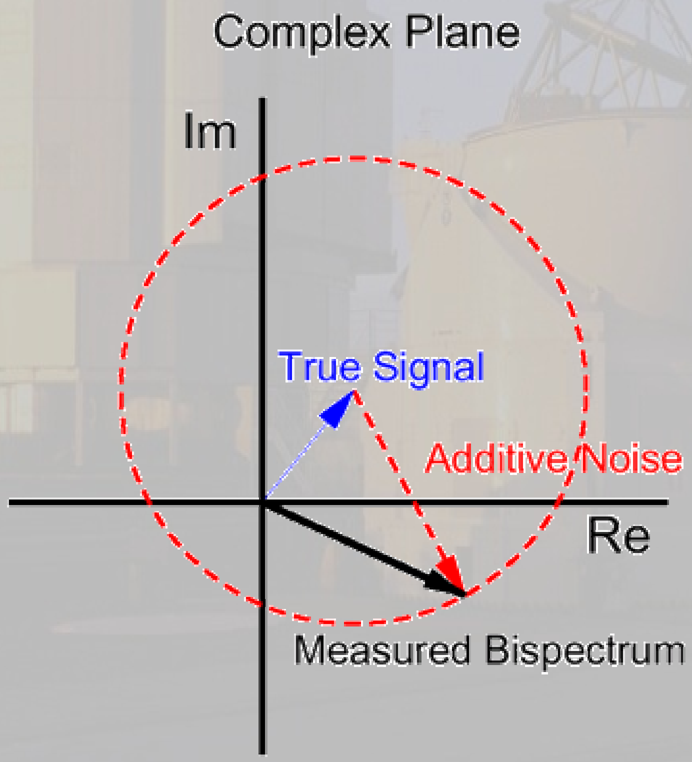
Closure Phase is a Good Observable

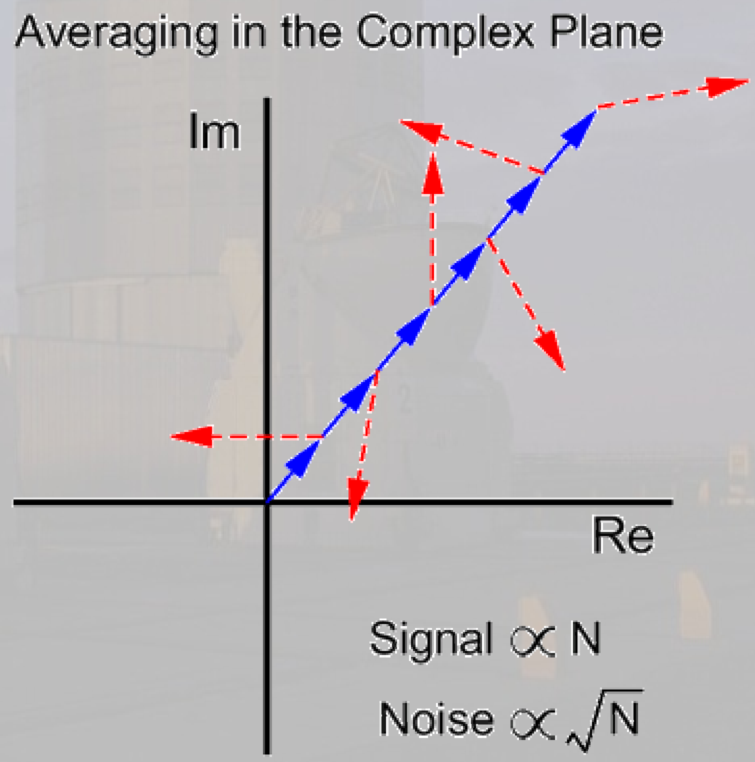




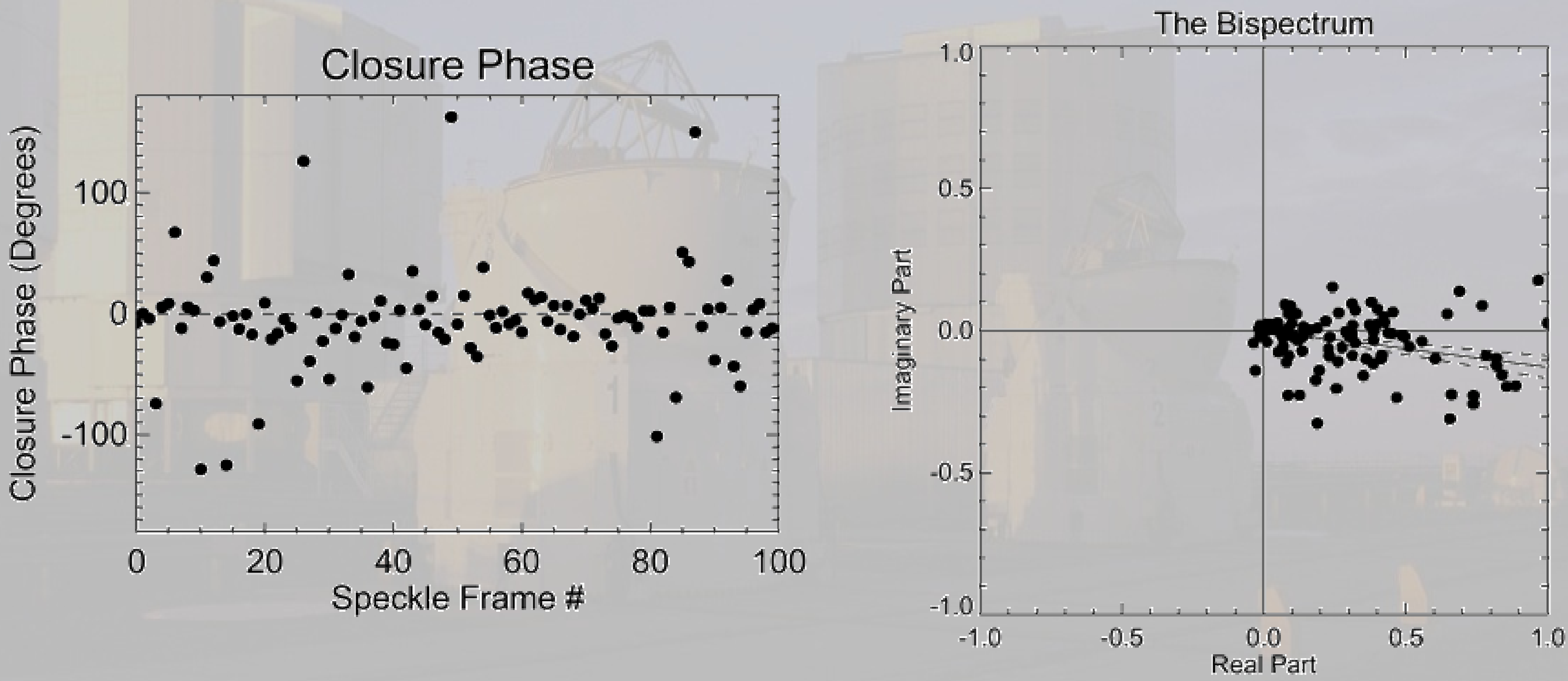
Aperture Masking Example

Closure Phase Averaging





Bispectrum in the Complex Plane



Important Properties of Closure Phases

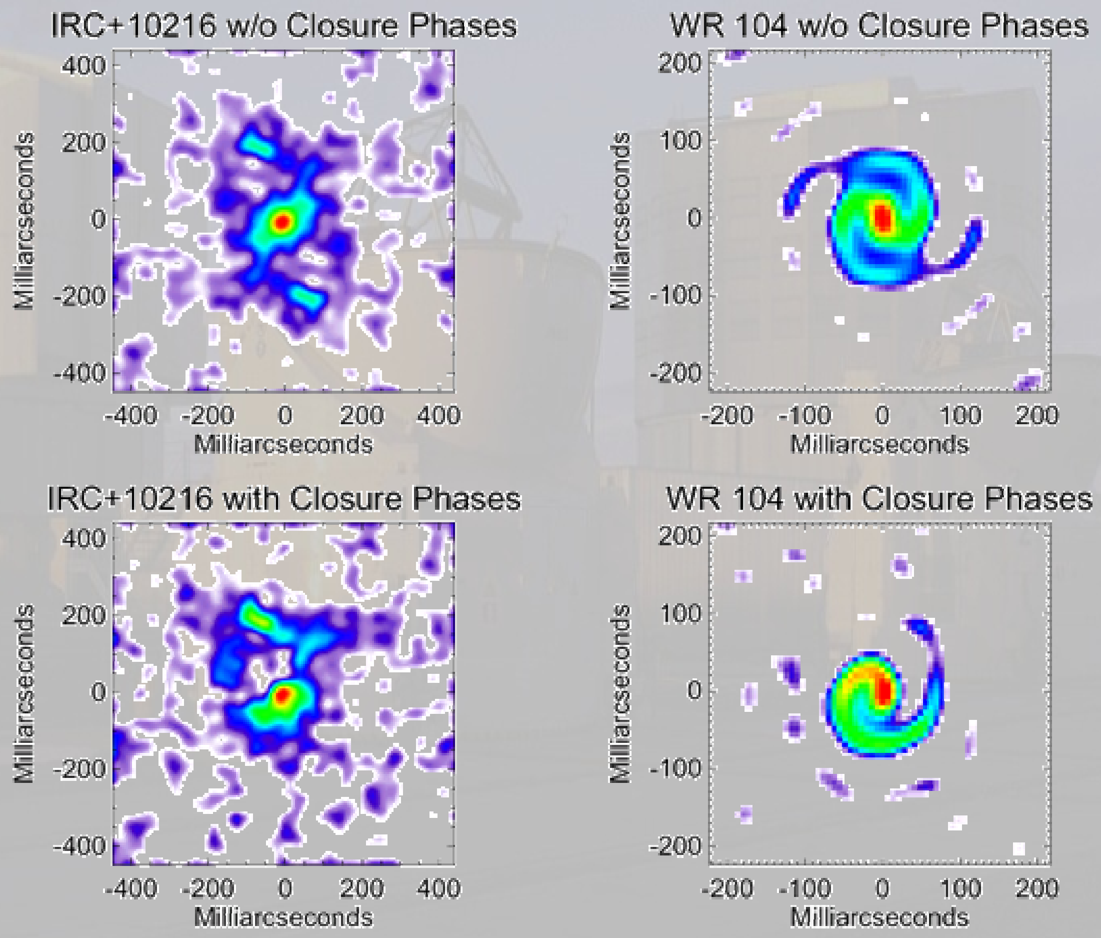
More robust to calibration error

- Atmospheric turbulence generally does not bias measurement (unlike Visibility^2)
- Reasonable hope of measurement error reducing as root N (unlike Visibility^2)
- There can be biases due to chromatic effects (just like Visibility^2)

Sensitive to asymmetries in brightness distribution

- Bispectrum REAL for point-symmetry (Φ_{CP} = 0 or 180 degs)
- Must resolve object to have significant signal
- Critical for validating Vis^2 modeling
- Necessary for imaging (if no phase referencing)

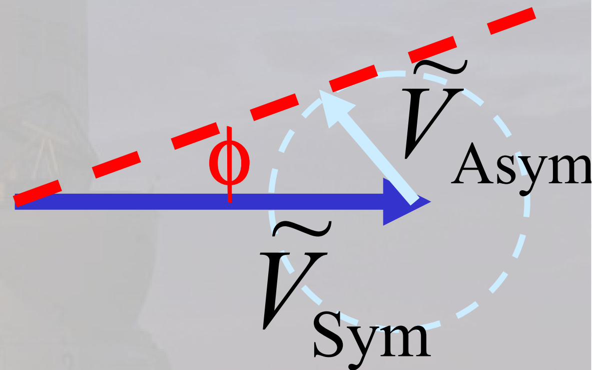
Importance of Closure Phases in Imaging



Estimate the Magnitude of Closure Phase

It is straightforward to obtain an order-of-magnitude estimate for the "typical" closure phase for a known object distribution:

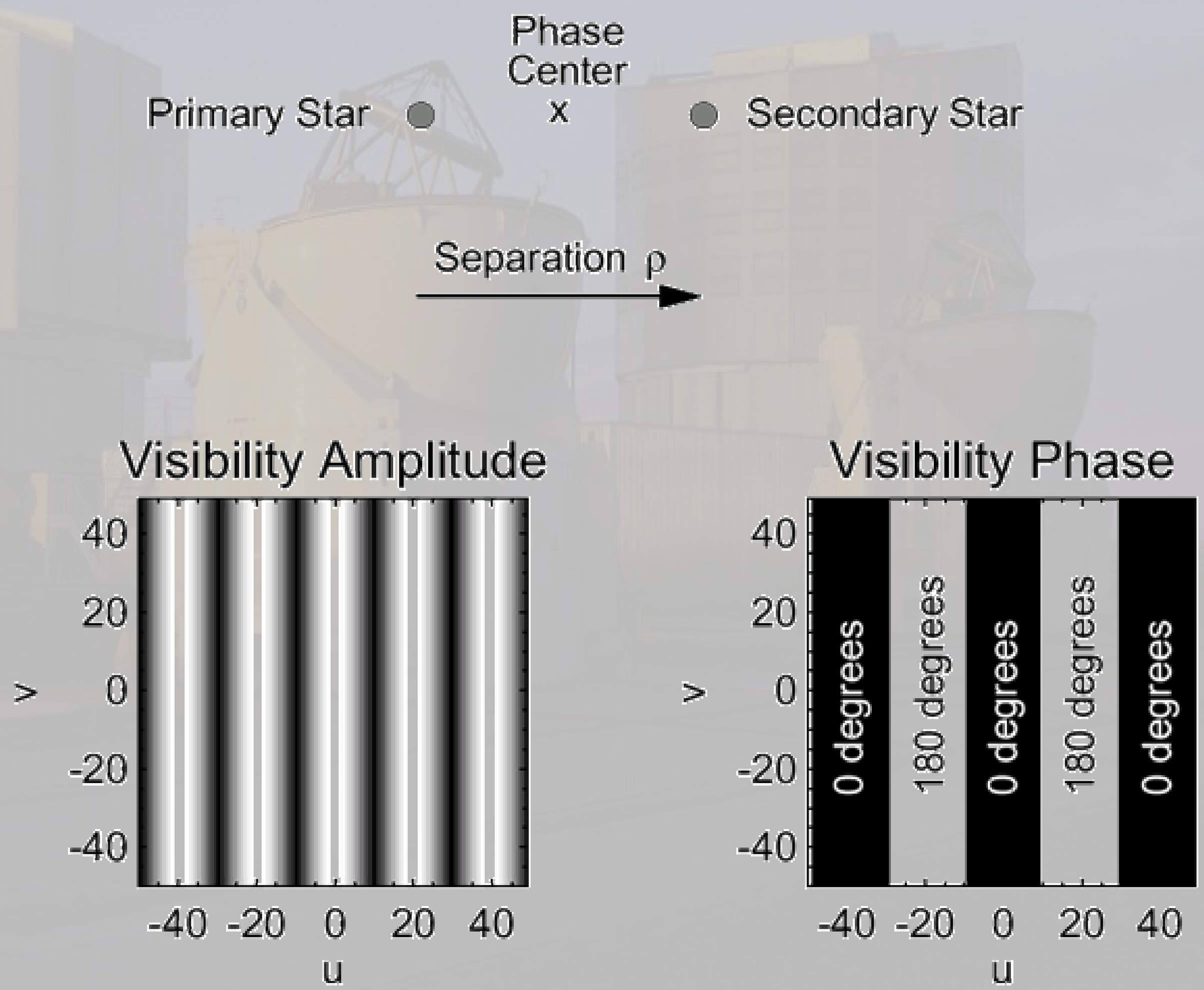
$$\left|\text{Closure Phase (radians)}\right| \approx \frac{\text{Asymmetric Flux}}{\text{Symmetric Flux}}$$



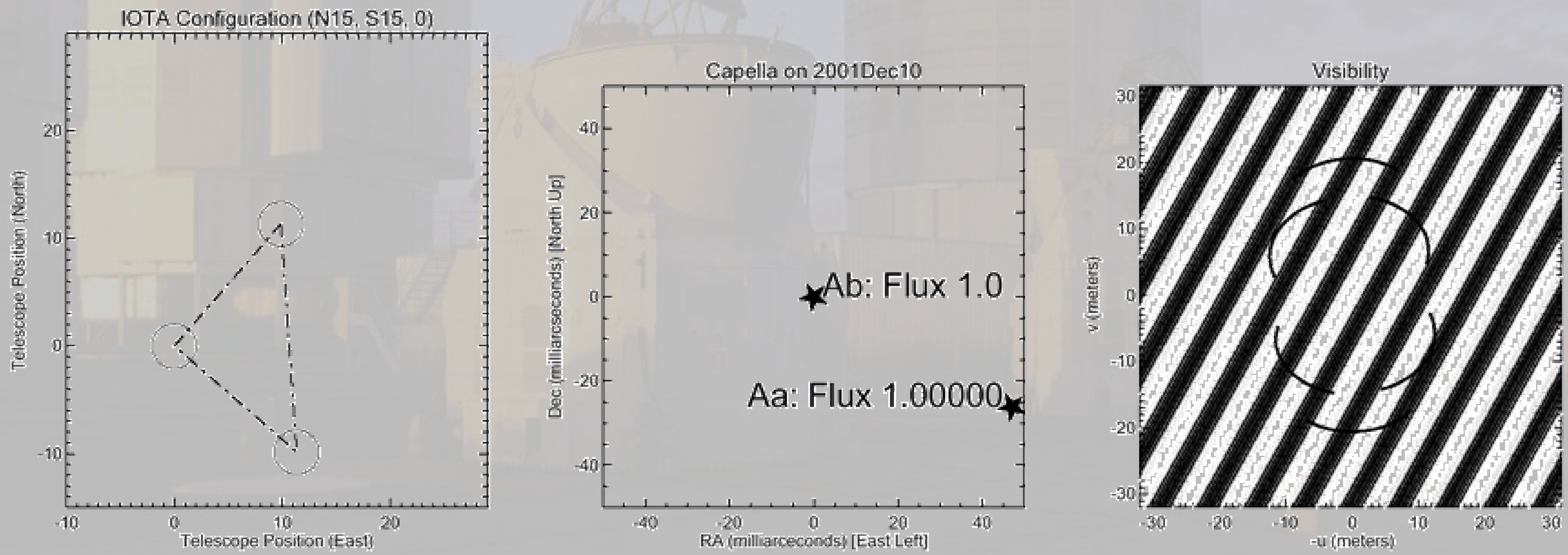
The amount of "Asymmetric" Flux should be based on the resolution of the baselines (Nothing is asymmetric if its unresolved!)

Example: For an unequal binary system, a closure phase measurement (radians) will typically be roughly the brightness ratio if the binary separation is resolved.

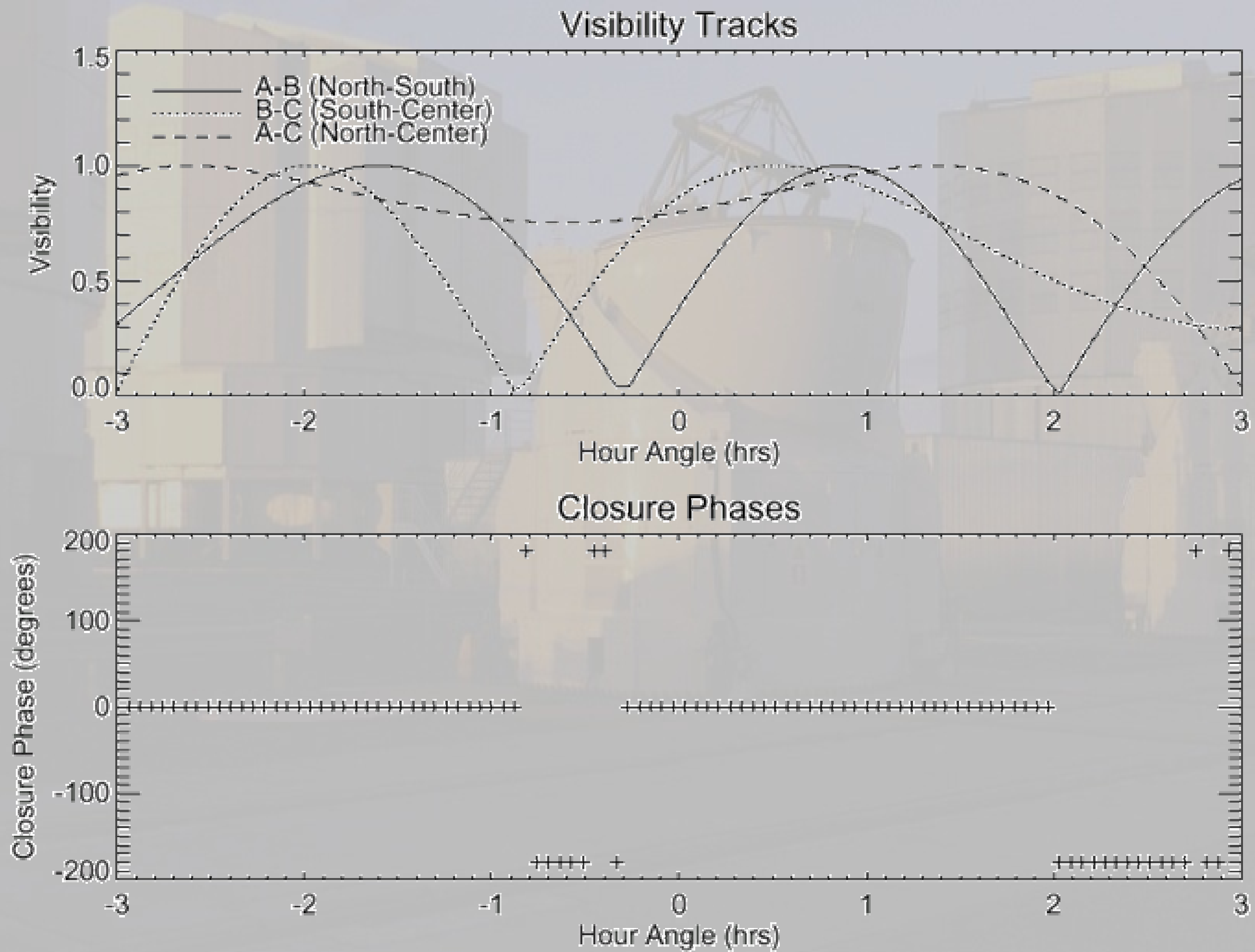
Closure Phase Example: Binaries

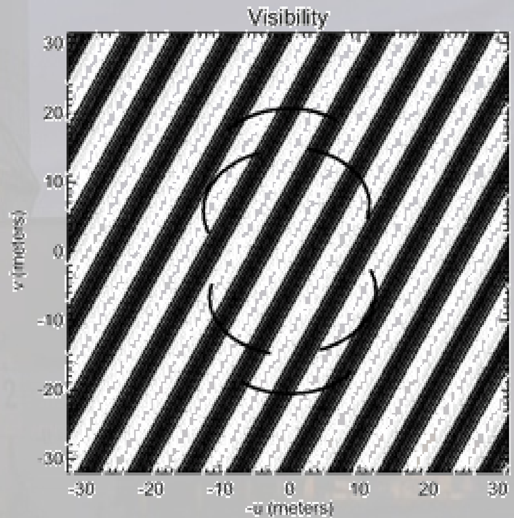


Equal Binary with 3 Telescopes

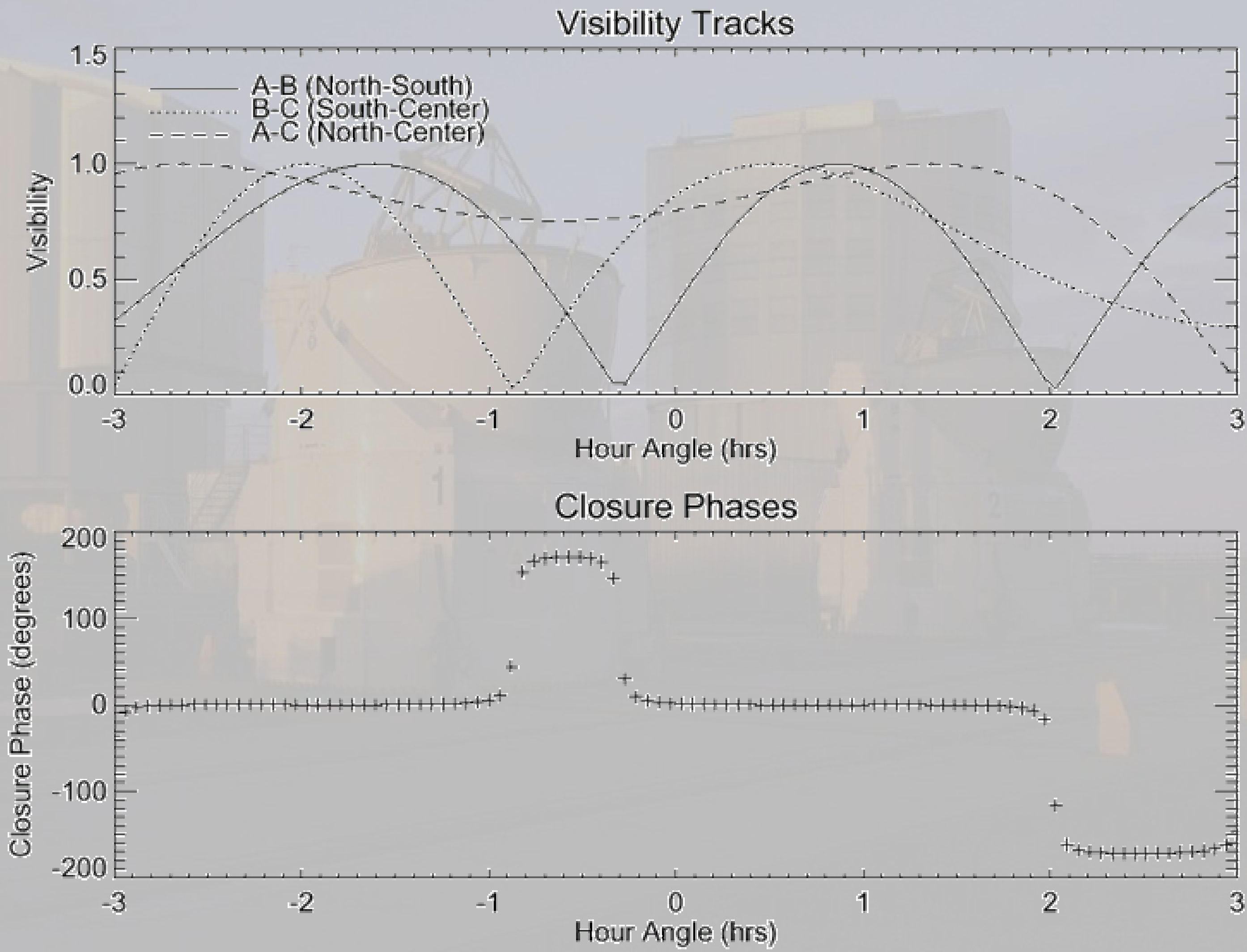


Equal Binary with 3 Telescopes (cont)



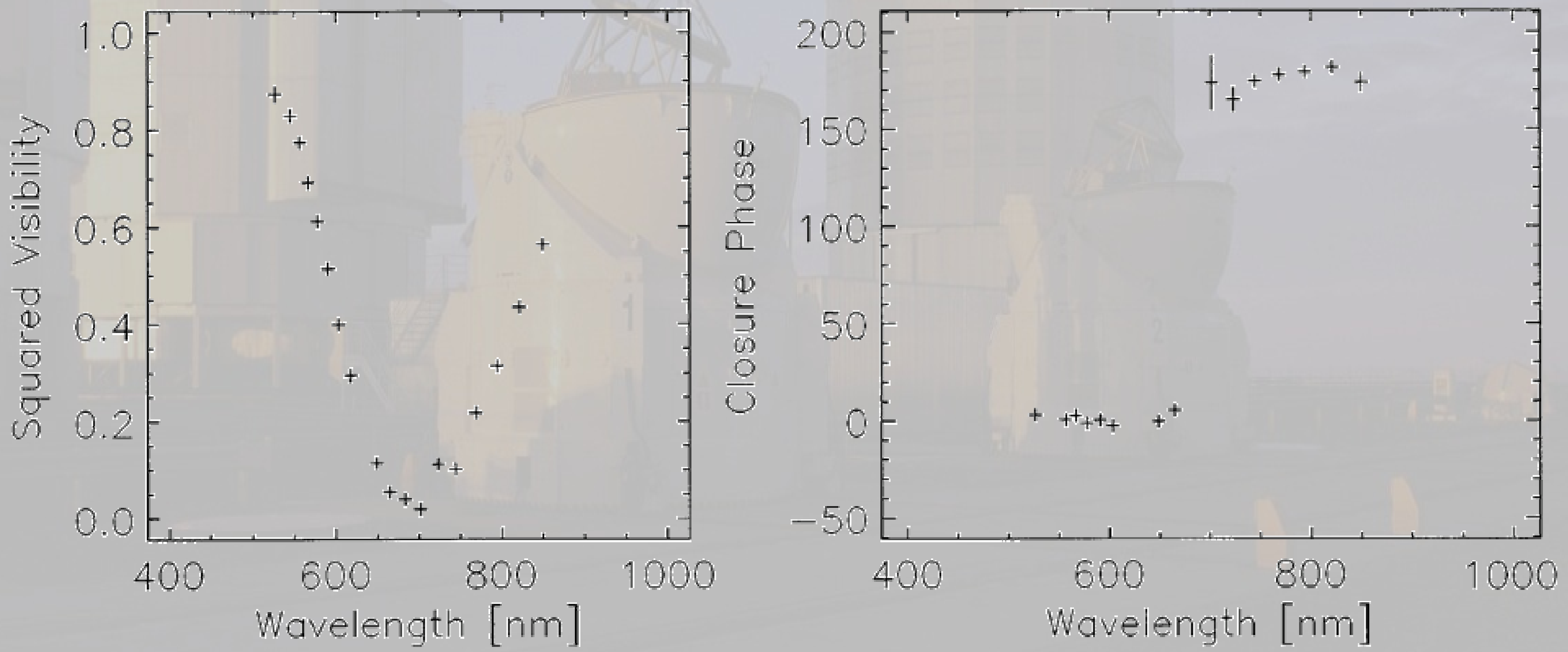


Almost Equal Binary: 1.05 to 1

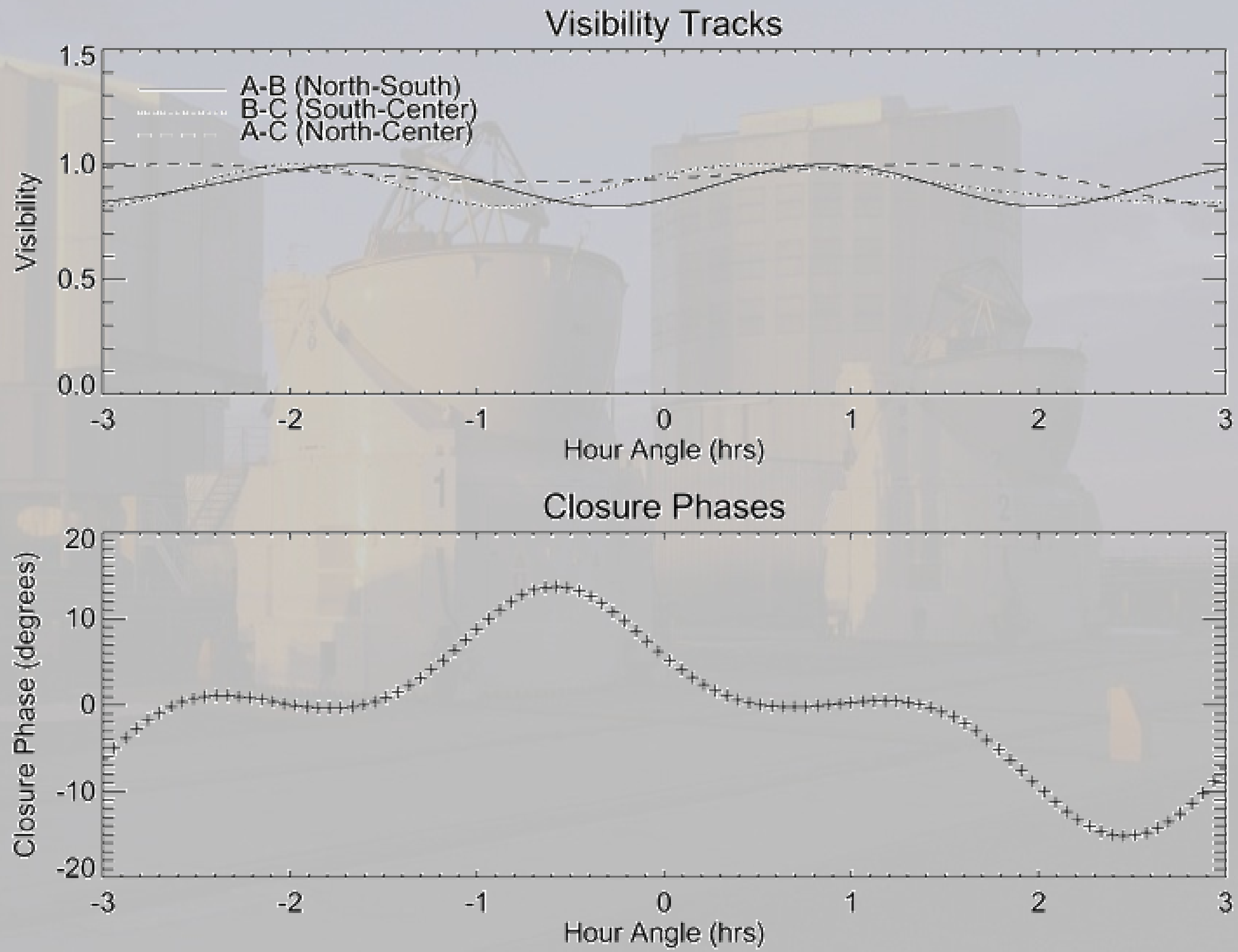


Binary Star Example: Mizar by NPOI

Mizar (Nearly Equal Binary) – NPOI (Benson et al. 1997)



Unequal Binary: 10 to 1



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

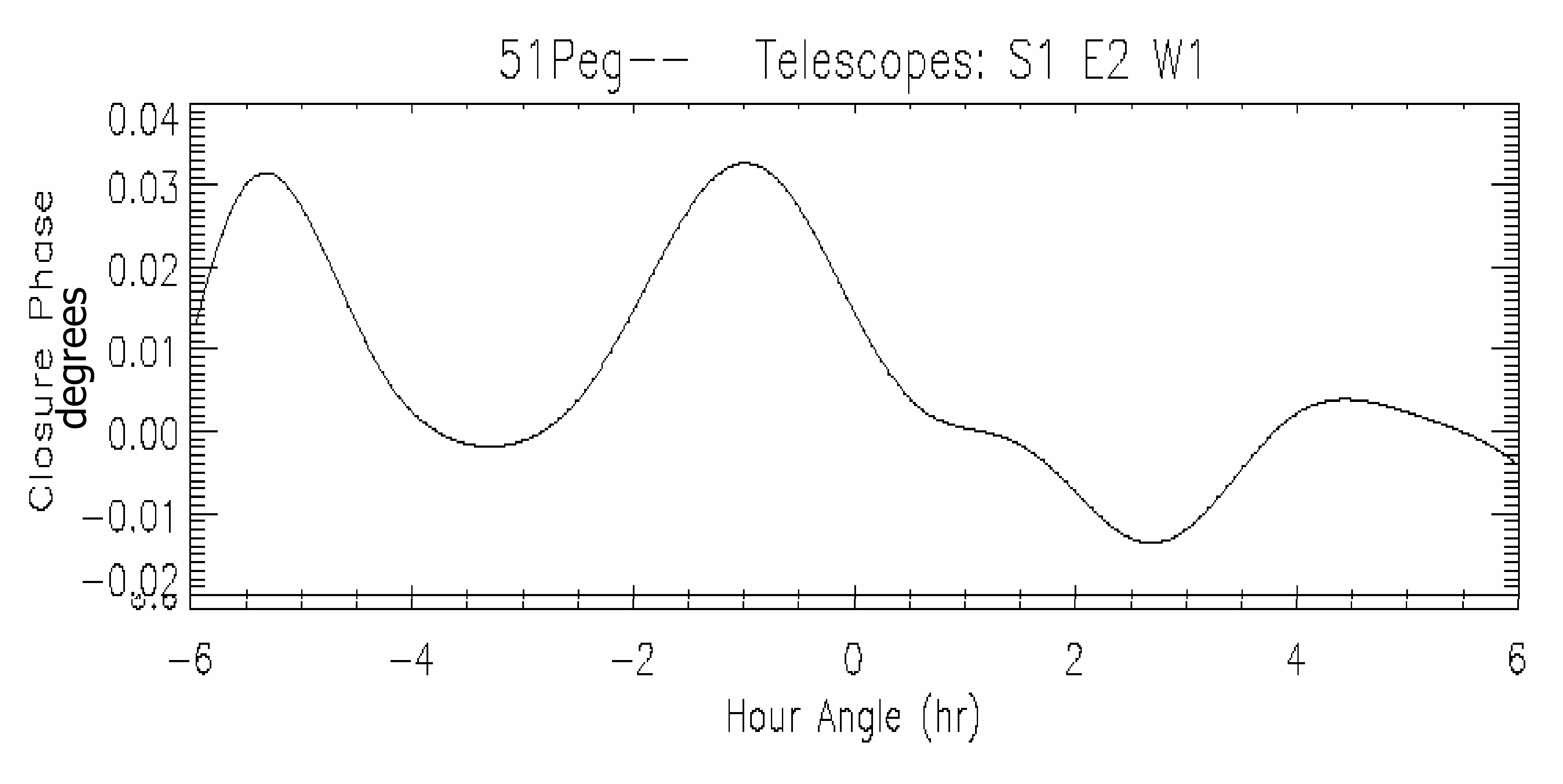
<u>Test of Closure Phase Estimate:</u>

Closure Phase ~ Brightness Ratio

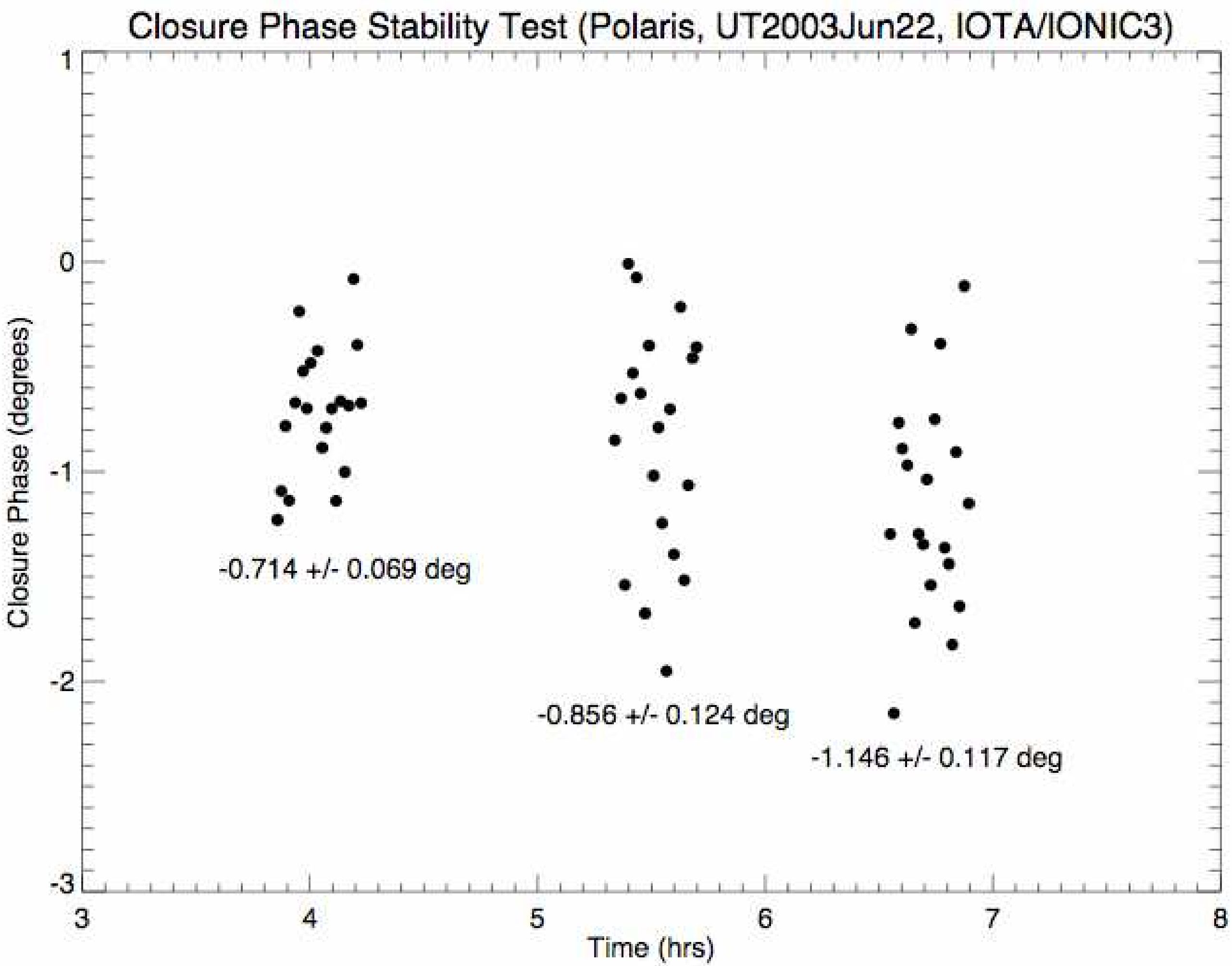
~ 0.00001 radians

~0.0006 degs

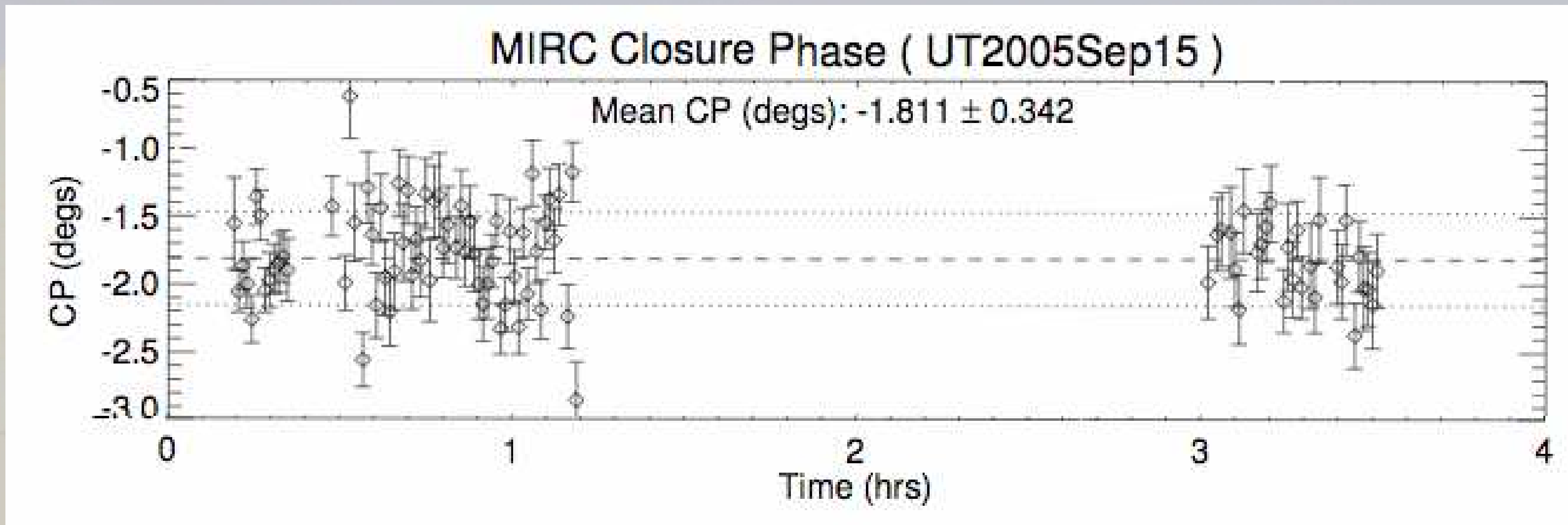
Science Case: Measuring Spectra of Hot Jupiters



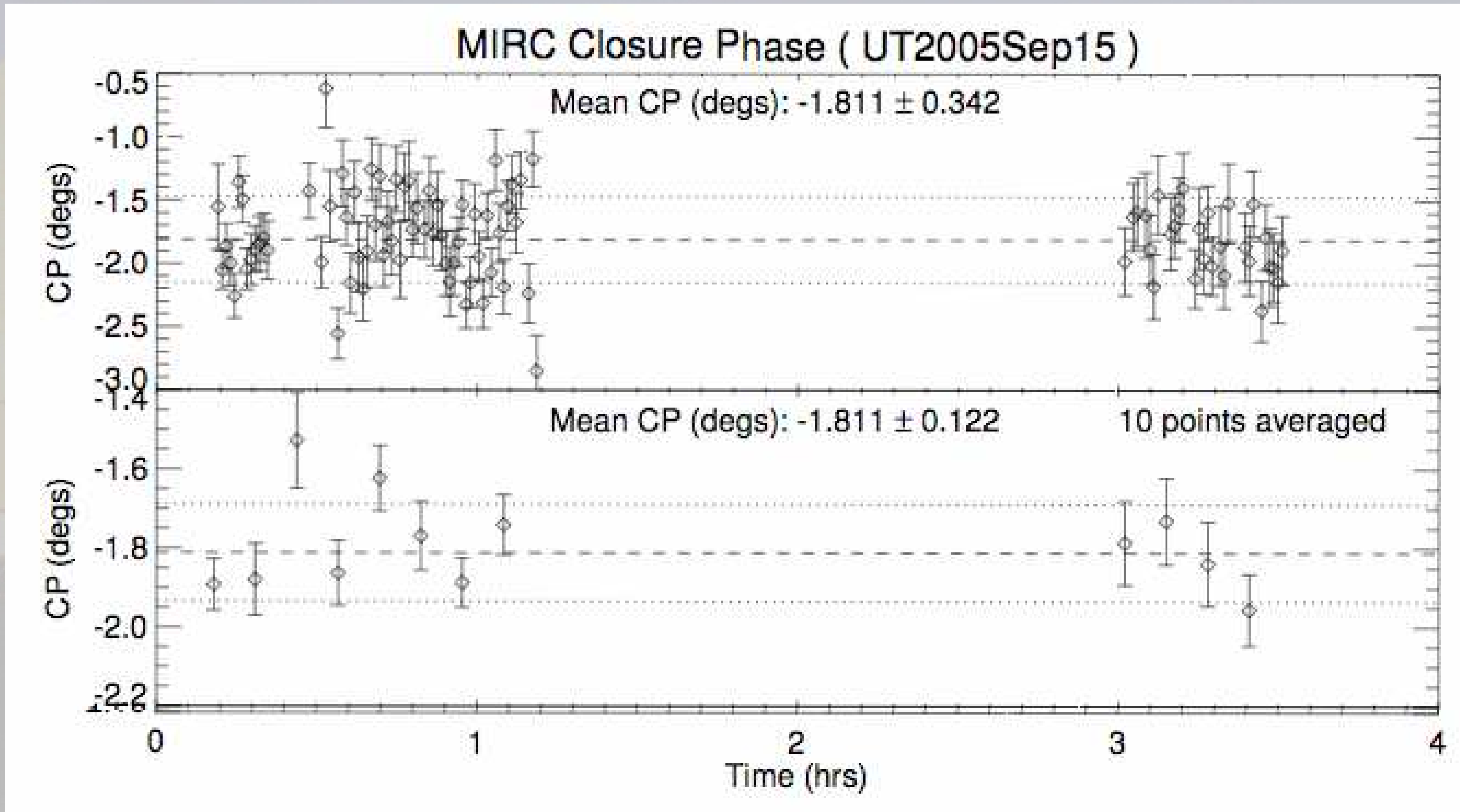
Precision Closure Phase -- State of the Art



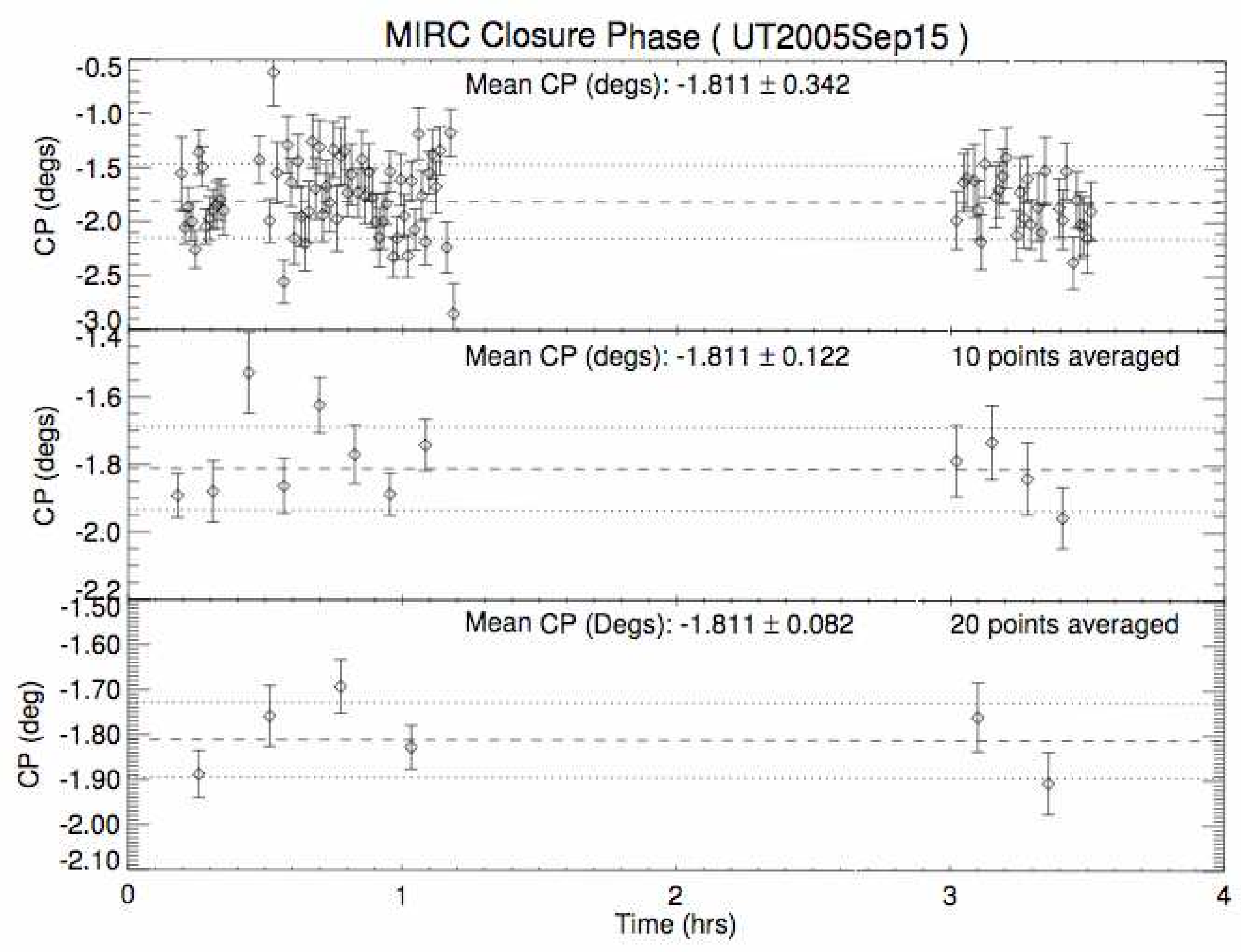
First Peek at CHARA Closure Phases



First Peek at CHARA Closure Phases



First Peek at CHARA Closure Phases



Zhao
et al

A Few Remarks on Sensitivity

Common "Myths:"

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

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

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

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)

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

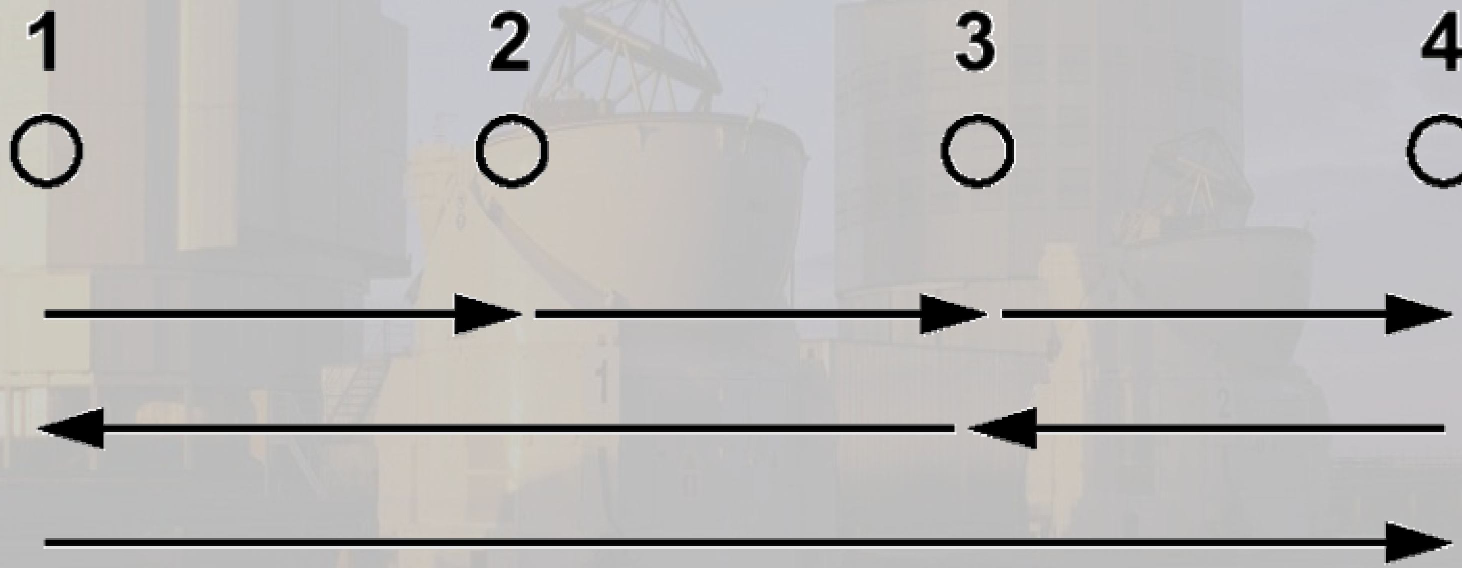
$$\text{SNR Triple Amplitude} (\& \, \Phi_{CP}) \propto \frac{1}{3} \times \text{SNR Visibility}$$

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 phase referencing.
   Good idea, FAST. But hard to do. Bias worries (jitter).
3. Coherently average the Bispectrum (the Triple Amplitude + Closure Phase)
   If 2 baselines strong, then SNR ~ (Lowest Visibility)

Baseline Bootstrapping



Track fringes on two shorter baselines

Allows the third fringe to be detected after averaging – does not require realtime detection!

Why Triple Amplitude?

$$V_{13}^2 = V_{small} \times V_{small}$$

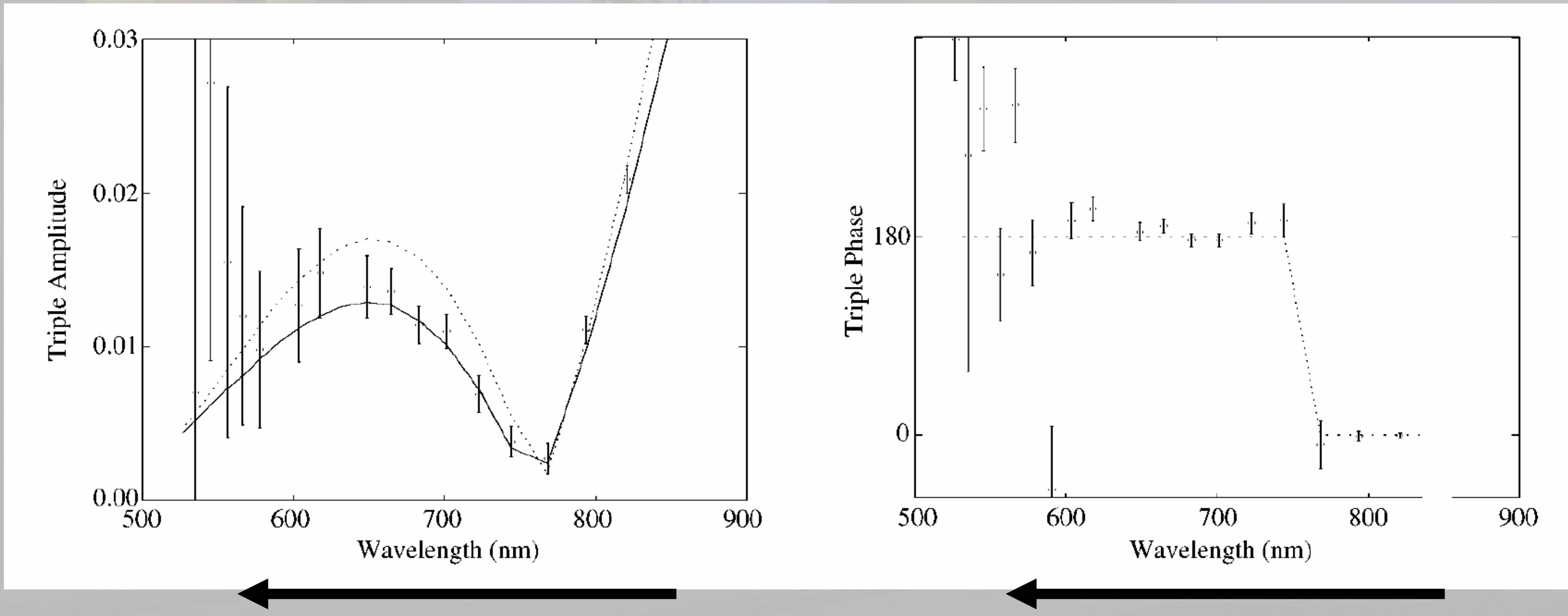
$$\tilde{T}_{123} = \tilde{V}_{12} \times \tilde{V}_{23} \times \tilde{V}_{31}$$

$$= \tilde{V}_{small} \times \tilde{V}_{big} \times \tilde{V}_{big}$$

Triple Amplitude is sometimes better than Visibility^2

Triple Amplitudes: Limb Darkening

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



"Spatial Frequency"   "Spatial Frequency"

Precision Interferometry with Closure Phases

Binary Stars

- Determine separation and brightness ratio
- Determine diameters of both stars
- Detect orbital motion, determine orbits

Single Stars

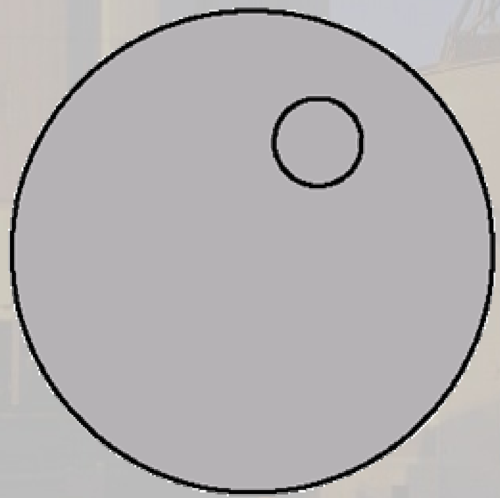
- Pulsating star in a binary system (e.g., Cepheids)
- Diameter: Measuring location of CP jump (0--180 degs)

Multiple Systems

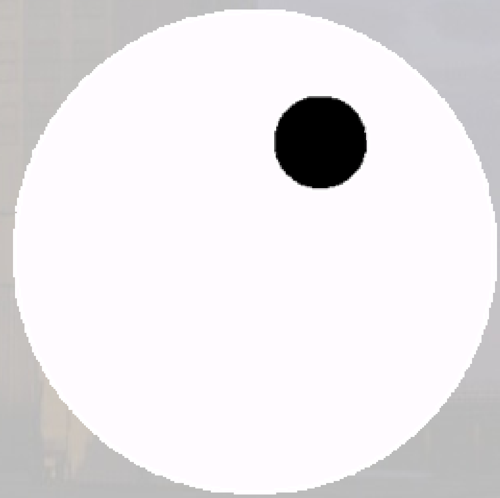
- Triples, etc.
- Crowded field astrometry
- Dynamics, proper motions

Others? Requires well-known model and some asymmetry

Closure Phase Common Sense: Spots



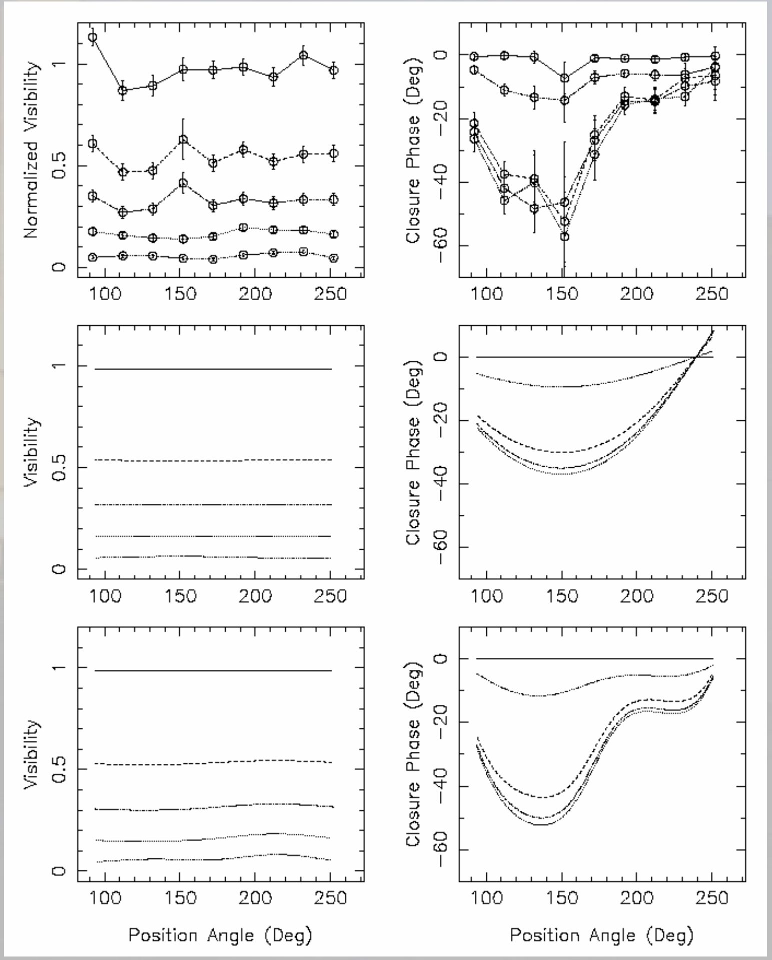
At low resolution, stellar disk dominates: Point-symmetric.



At highest resolution, stellar disk is resolved. Hotspot by itself is also Point-symmetric.

Science Case: Stellar Surface Structure

The Data and Model Fits

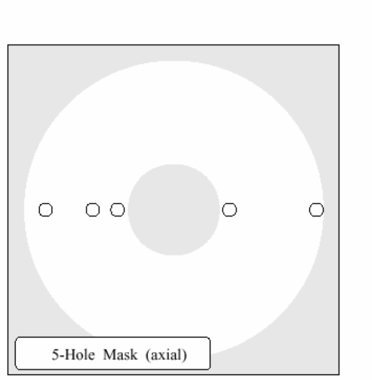


Mask at Different PAs

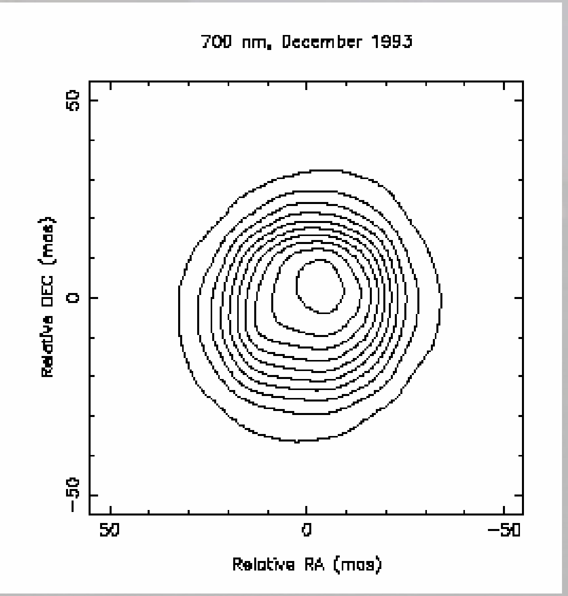
1-spot

2-spots

The Mask



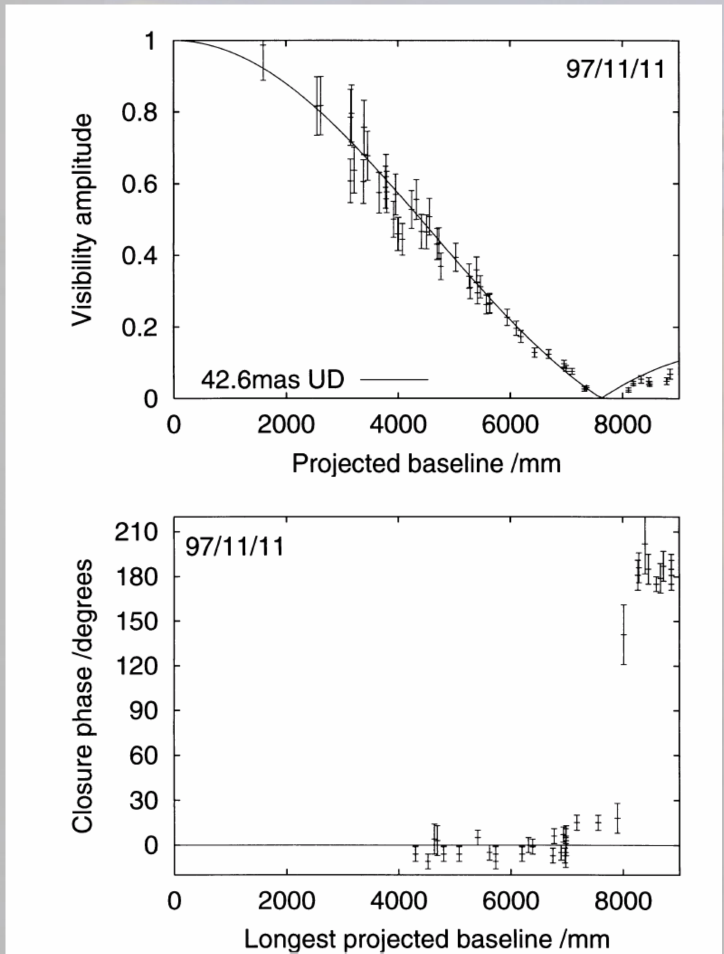
MEM Image



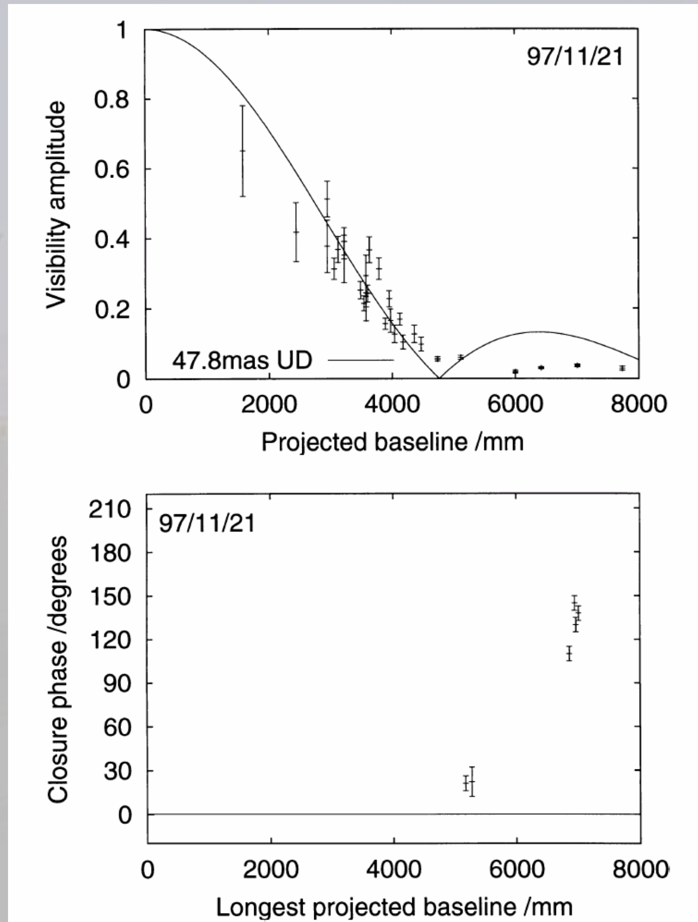
From Tuthill Thesis 1994

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>

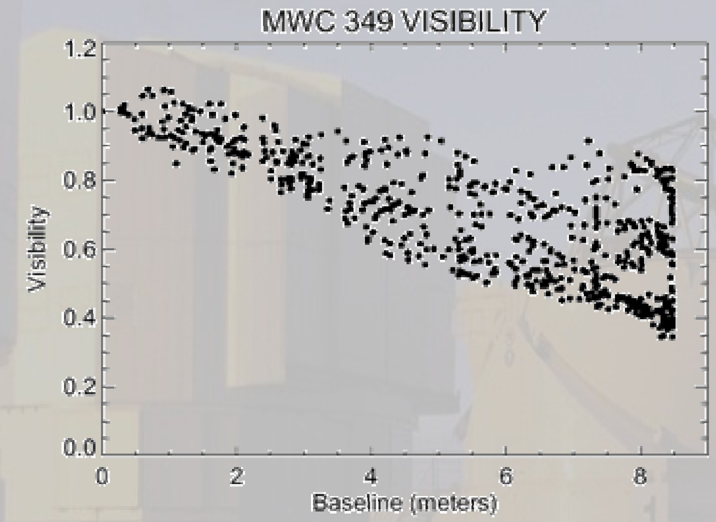
Evolved Stars, Young Stars: uncertain models of complex phenomena

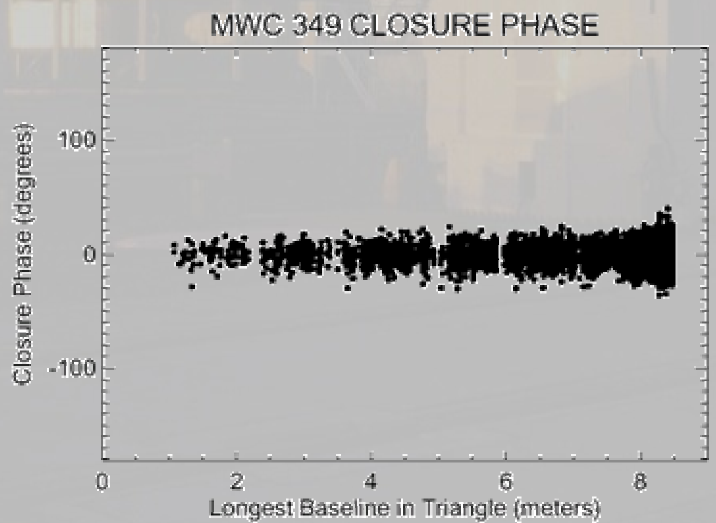
Without good imaging capability, why should one observe these sources with a 3-element interferometer?

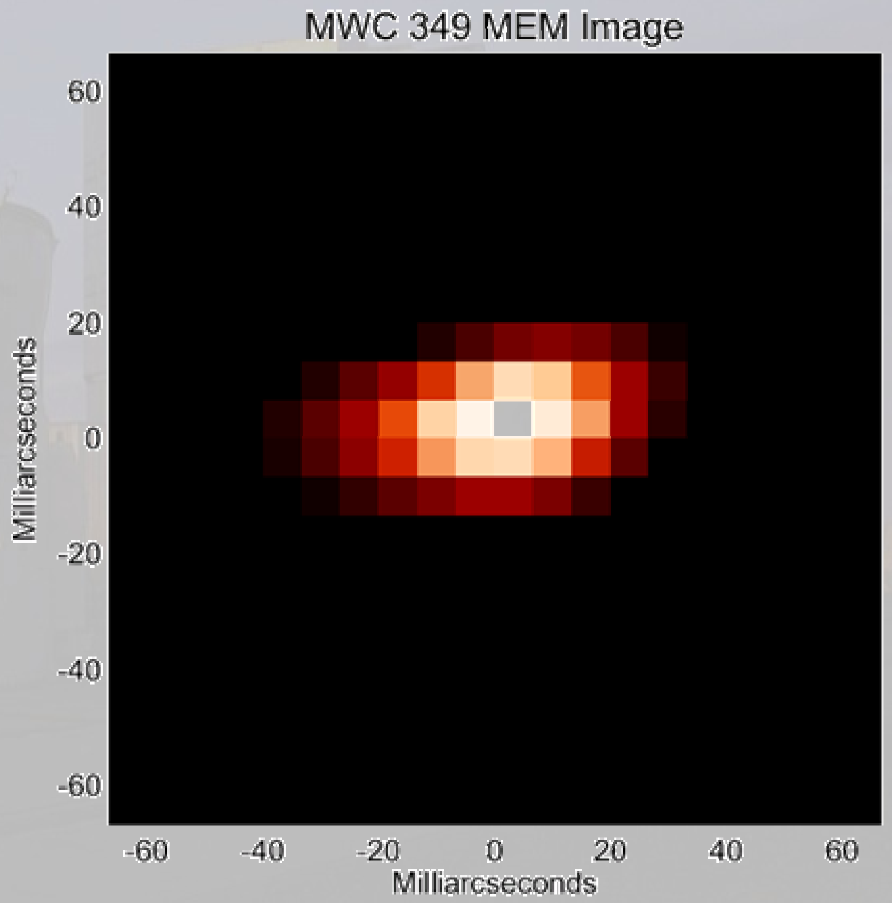
Closure Phases can discover qualitatively new information about some objects, much like measuring the polarization:

Informative but not unambiguous

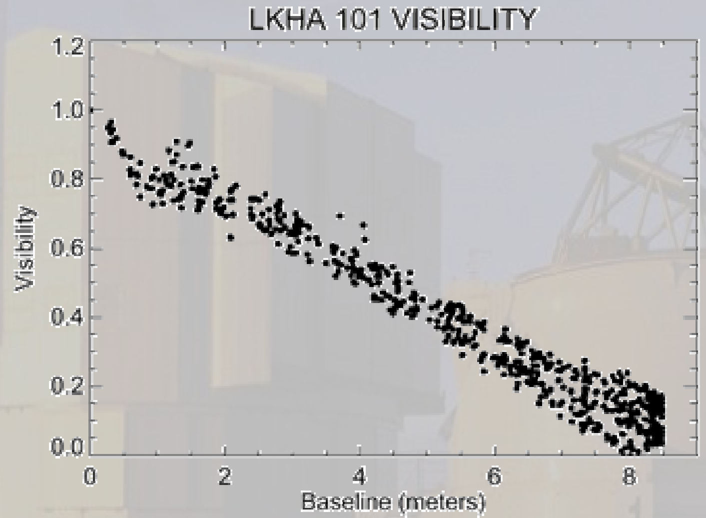
Example: Young Stellar Object #1

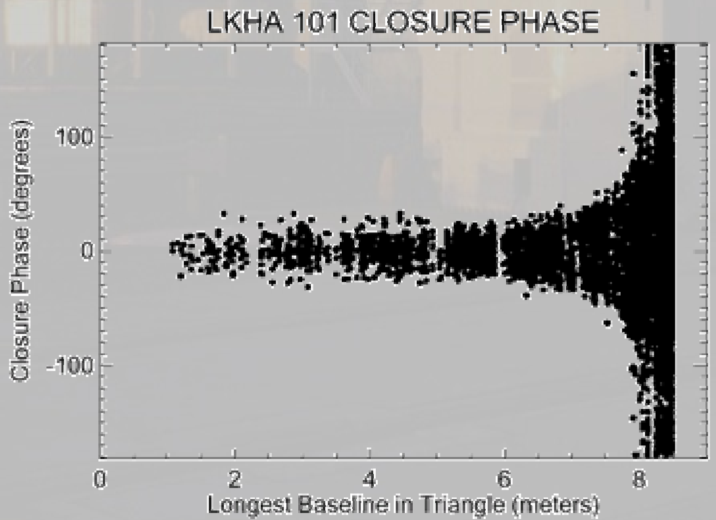


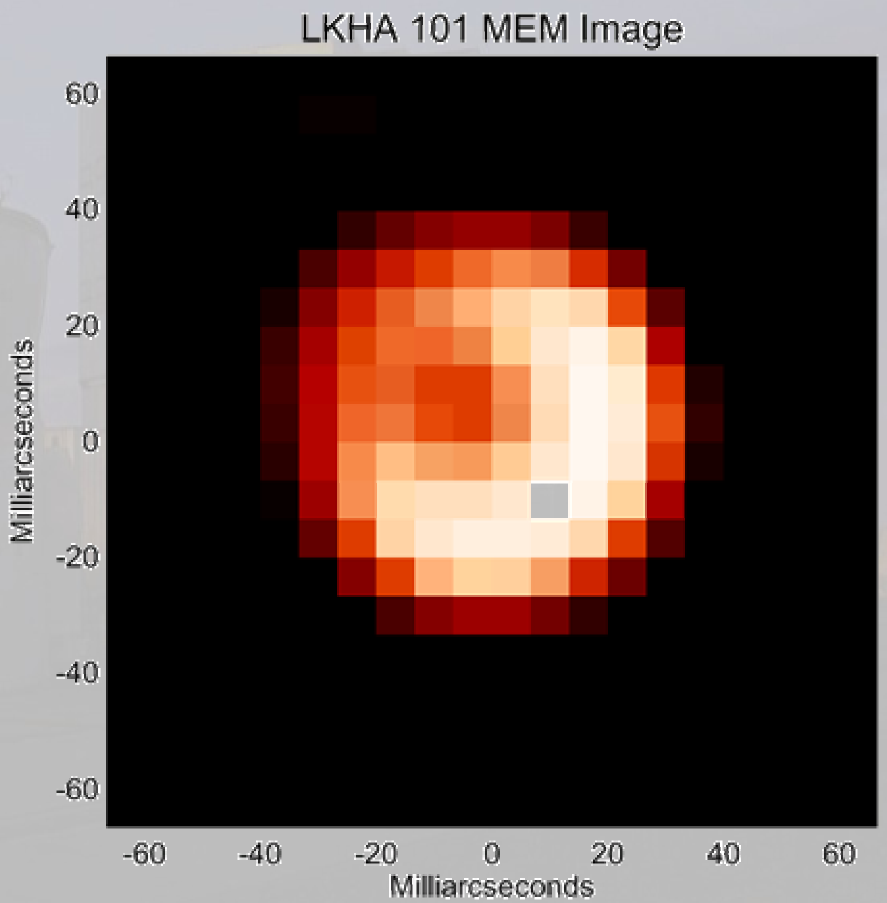




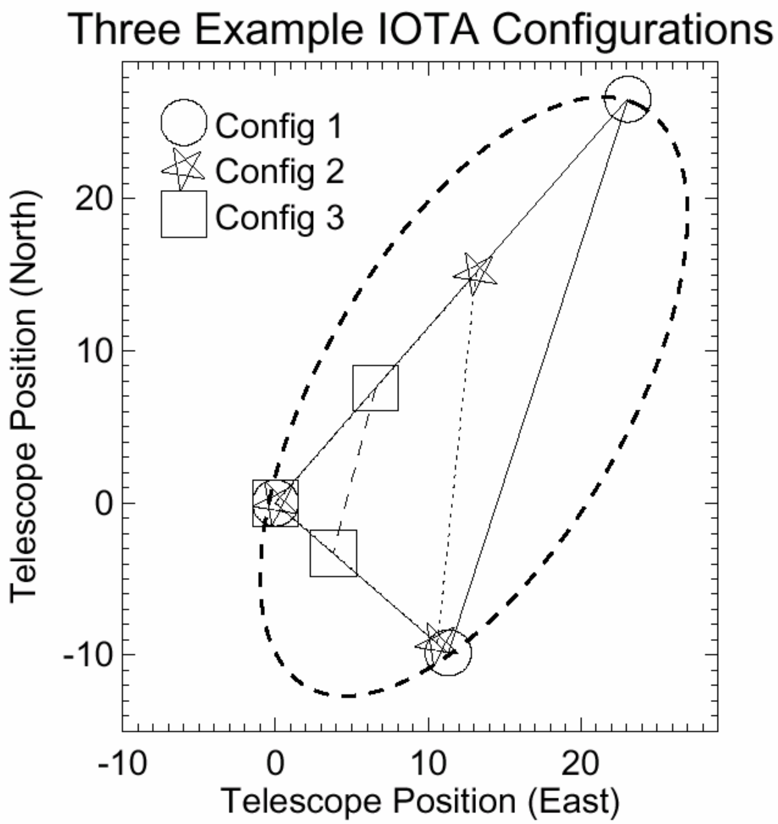
Example: Young Stellar Object #2

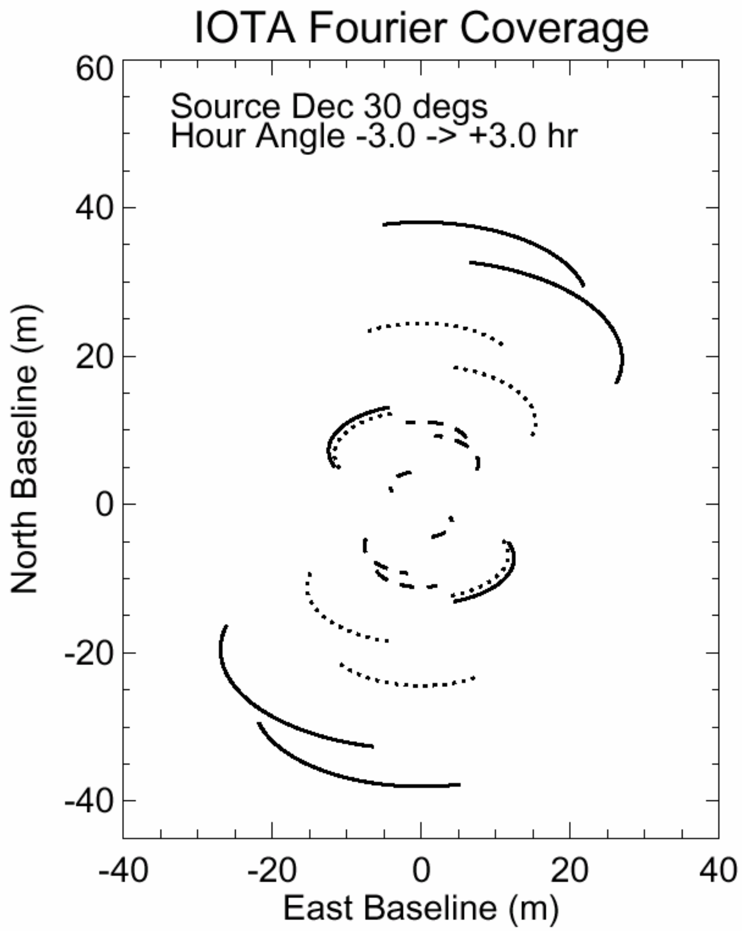




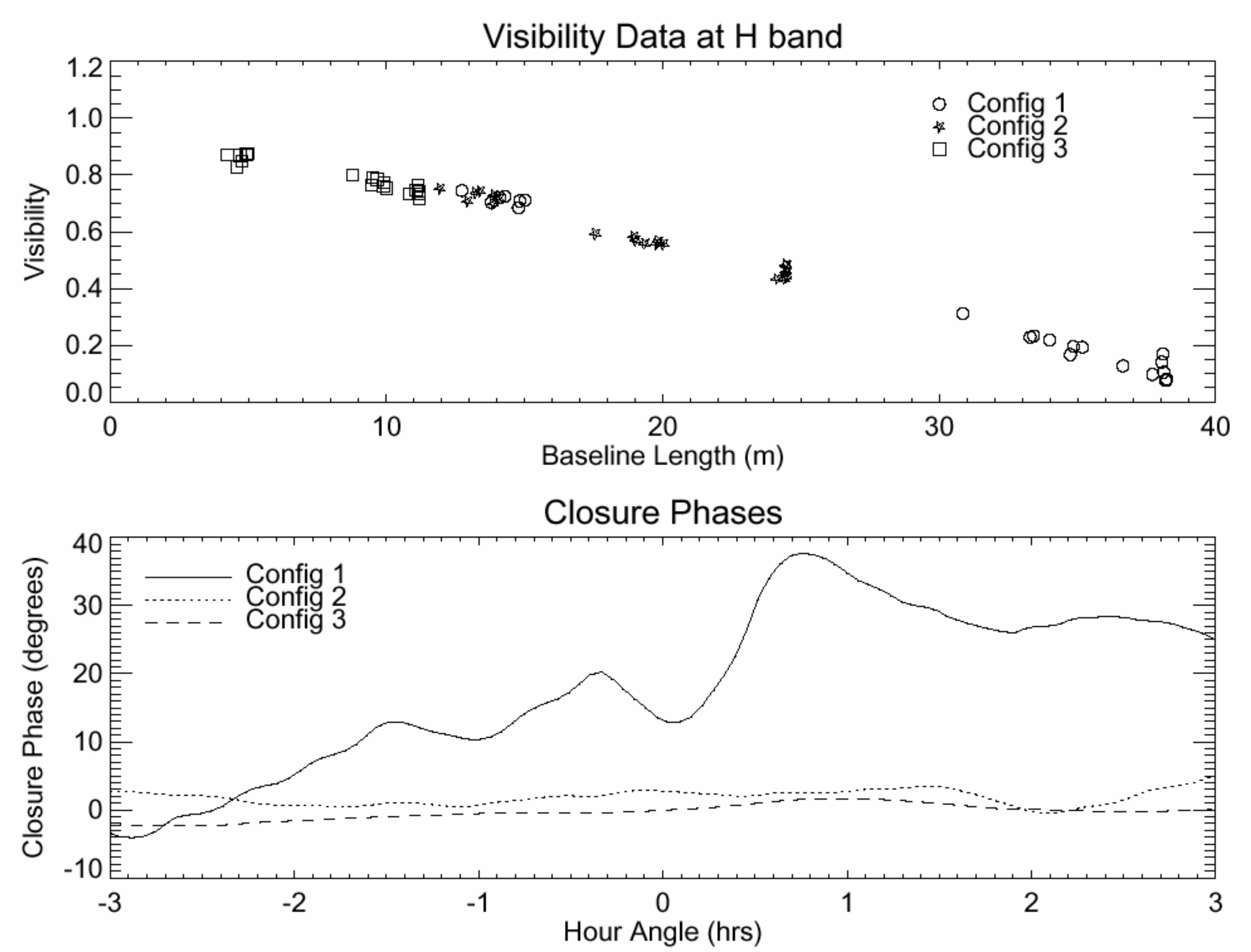


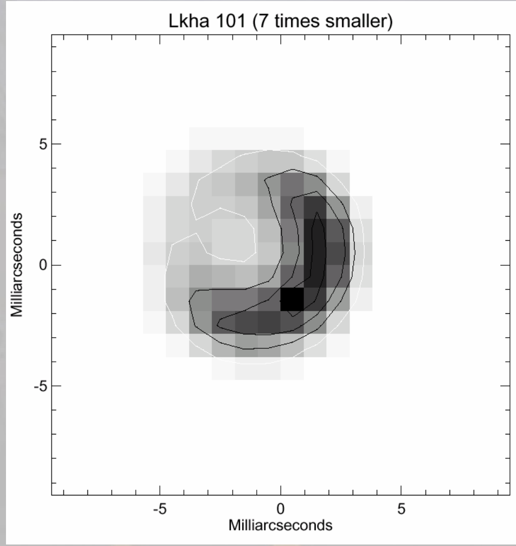
YSO disks with a *realistic* interferometer





YSO disks with IOTA *(simulation)*





More Closure Phase Common Sense: Case of Dust Shell + Star

Source has two components:

"Large" Dust Shell and "Small" Star

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

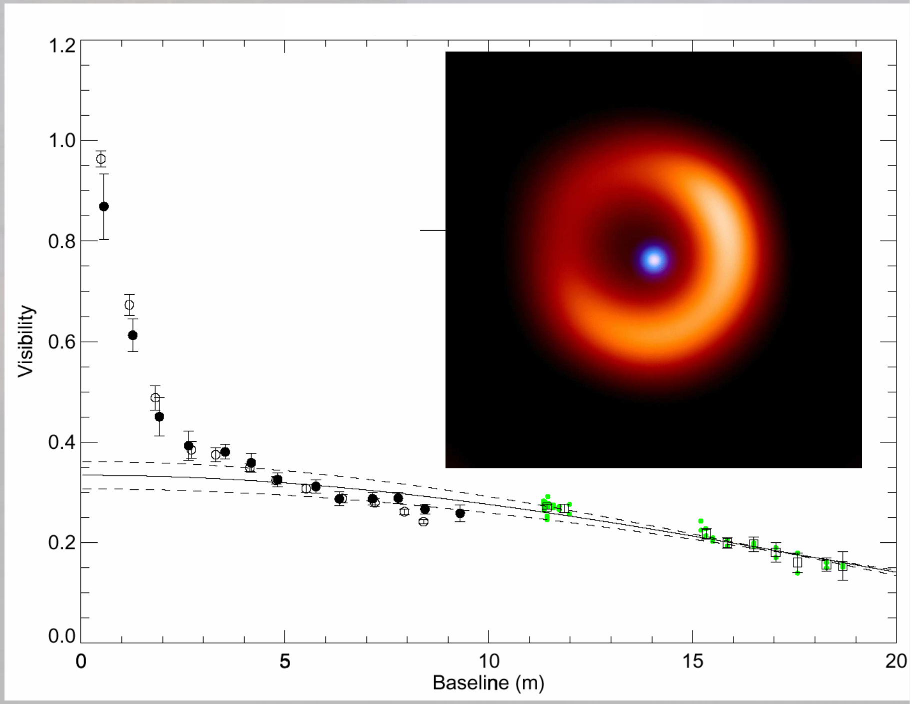
All Short Baselines

- 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….

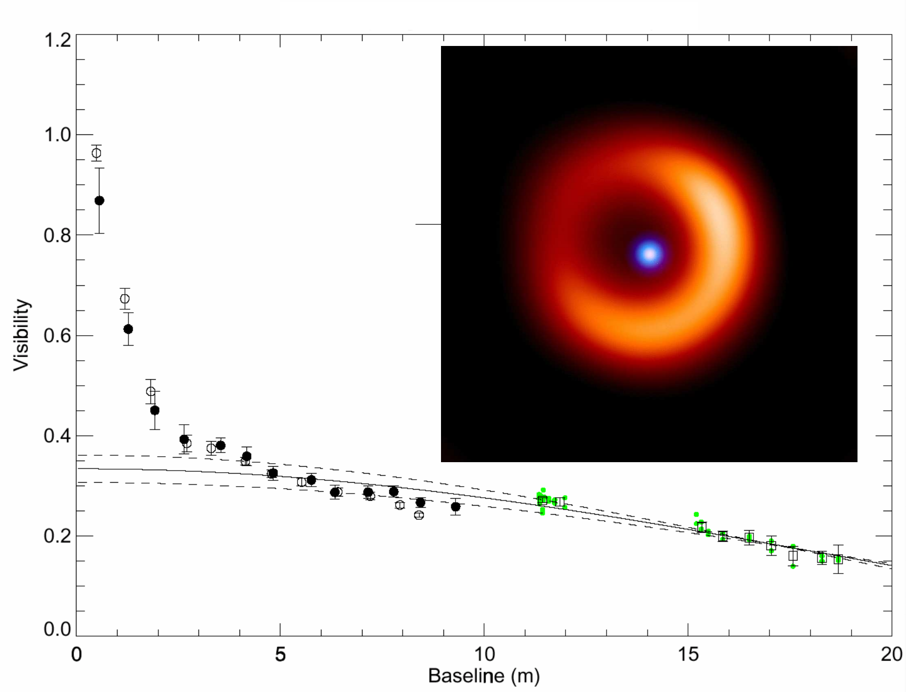


Common Sense (continued)

Third kind of Triangle

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)

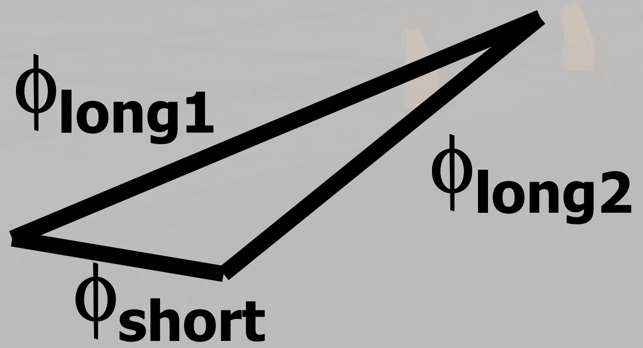


Closure Phase Φ

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

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

Closure Phase $\Phi \sim \phi_{short}$



Summary of a few Important Points

The closure phases are independent of all **telescope-specific** phase errors. Non-zero closure phases from a point source result from having non-closing triangles, phase delays after splitting beams

The bispectrum is real for sources with **point symmetry**. That is, the closure phases are all 0 or 180 degrees

Closure phases are not sensitive to an overall translation of image.

Object must be resolved (~> half fringe spacing B/λ) to have non-zero CP

-- CP $\propto$ (baseline)^3

-- Phase $\propto$ (baseline)

Interferometric Imaging

Non-zero
Closure phase

Point source
reference

- Recall: Interferometers measure Fourier Components of your image
- Images must be reconstructed from *noisy and incomplete* Fourier components
- Optical Interferometers usually measure Closure Phases, not Phases…

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

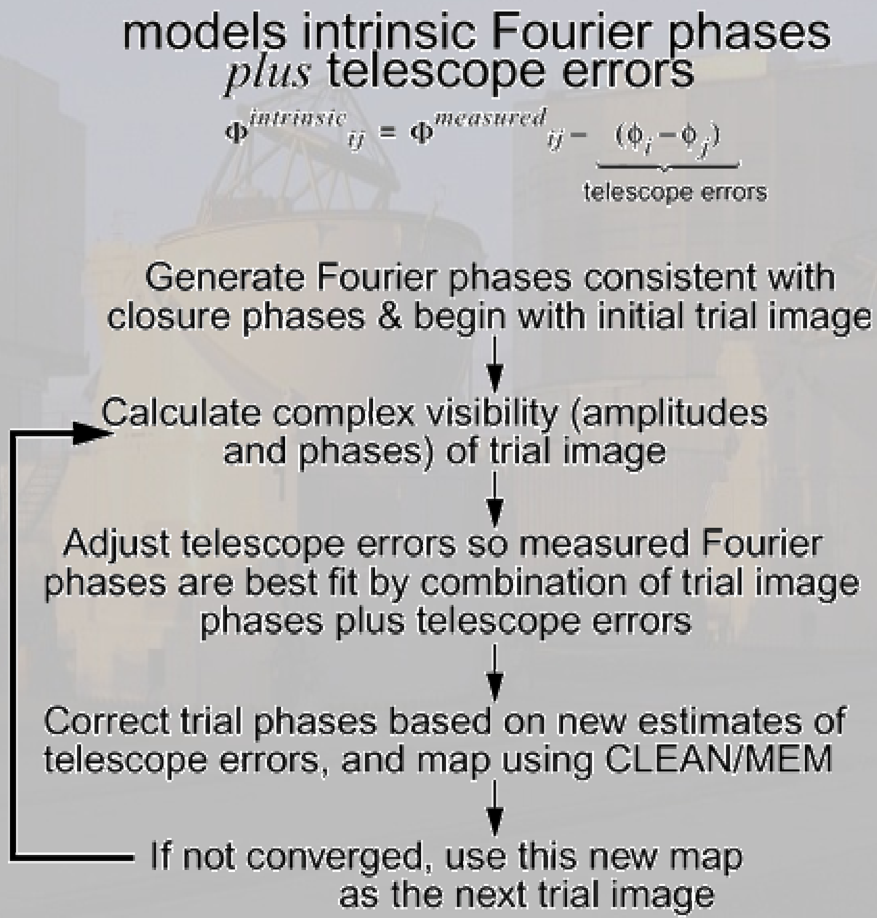
Sum over all pixels

Properties of MEM

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

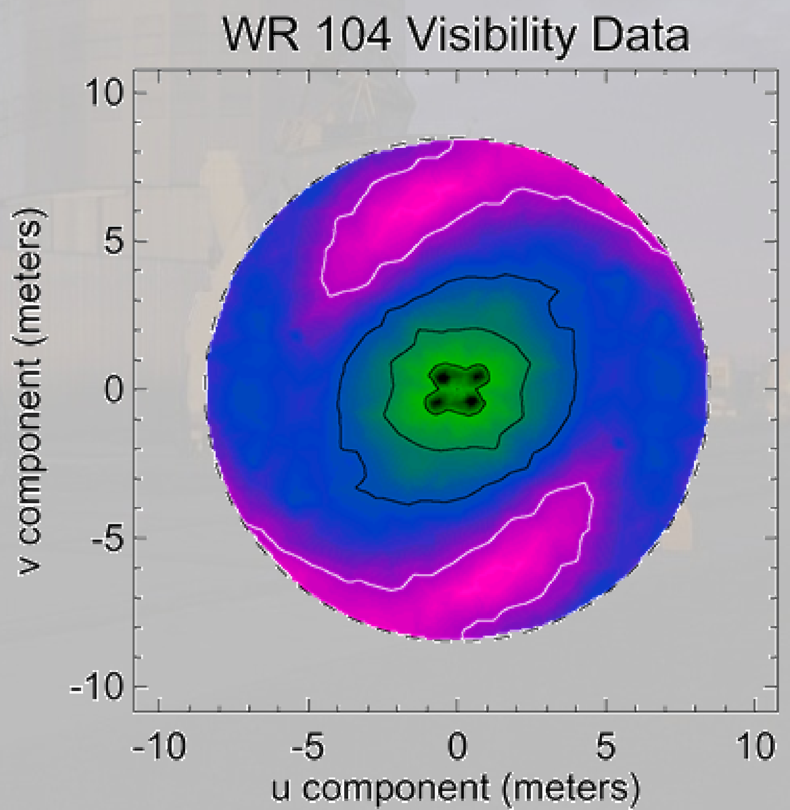
- Positive and limited FOV
- Image prior I_i, a method of introducing *a priori* information
- "Super-resolution"
- Fields containing point sources embedded in extended nebulosity may show artifacts reminiscent of Airy rings

Self-Calibration

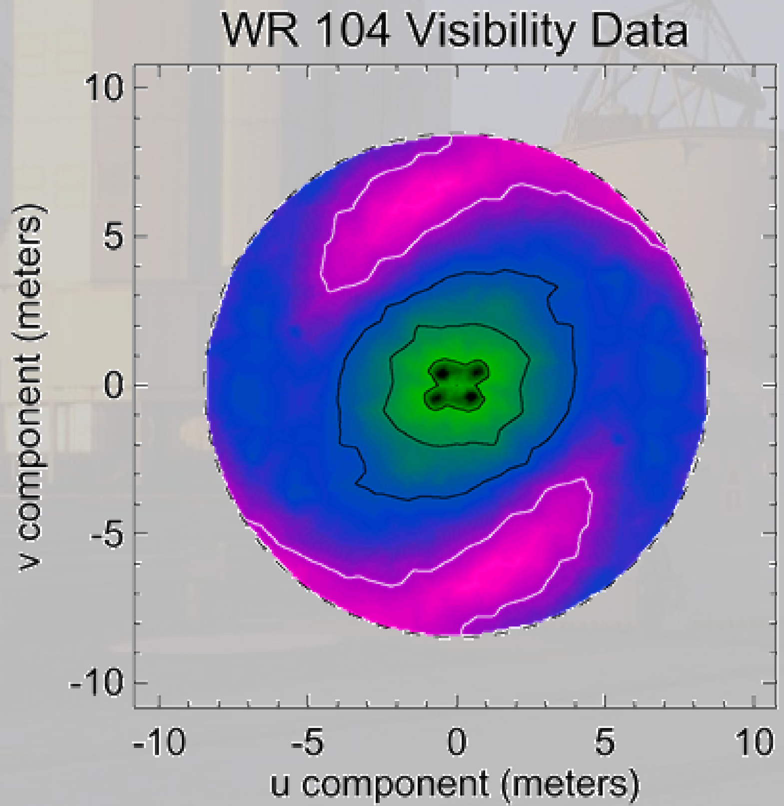


Based on Cornwell & Wilkinson (1981)

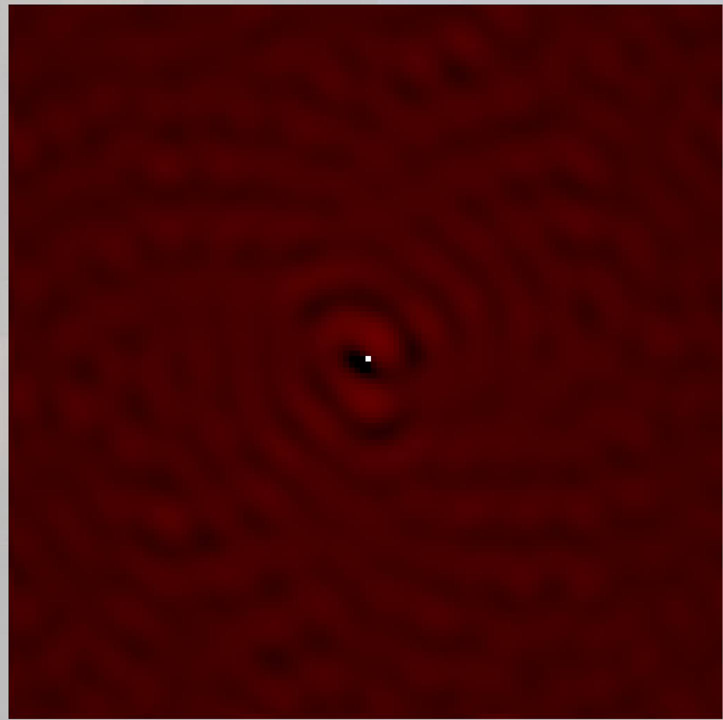
WR 104 Data


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

WR 104 MEM Reconstruction

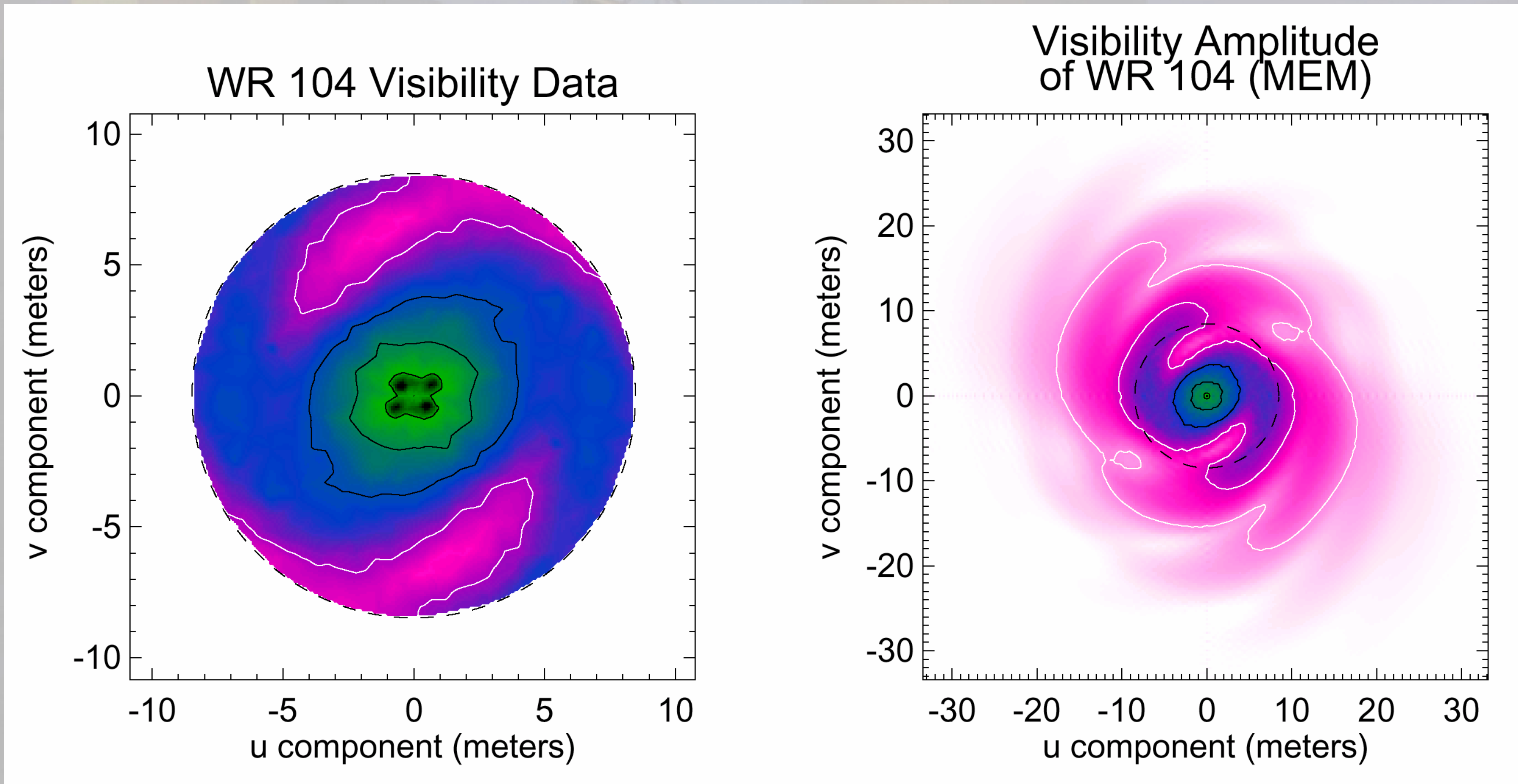


Iterations 1 to 30

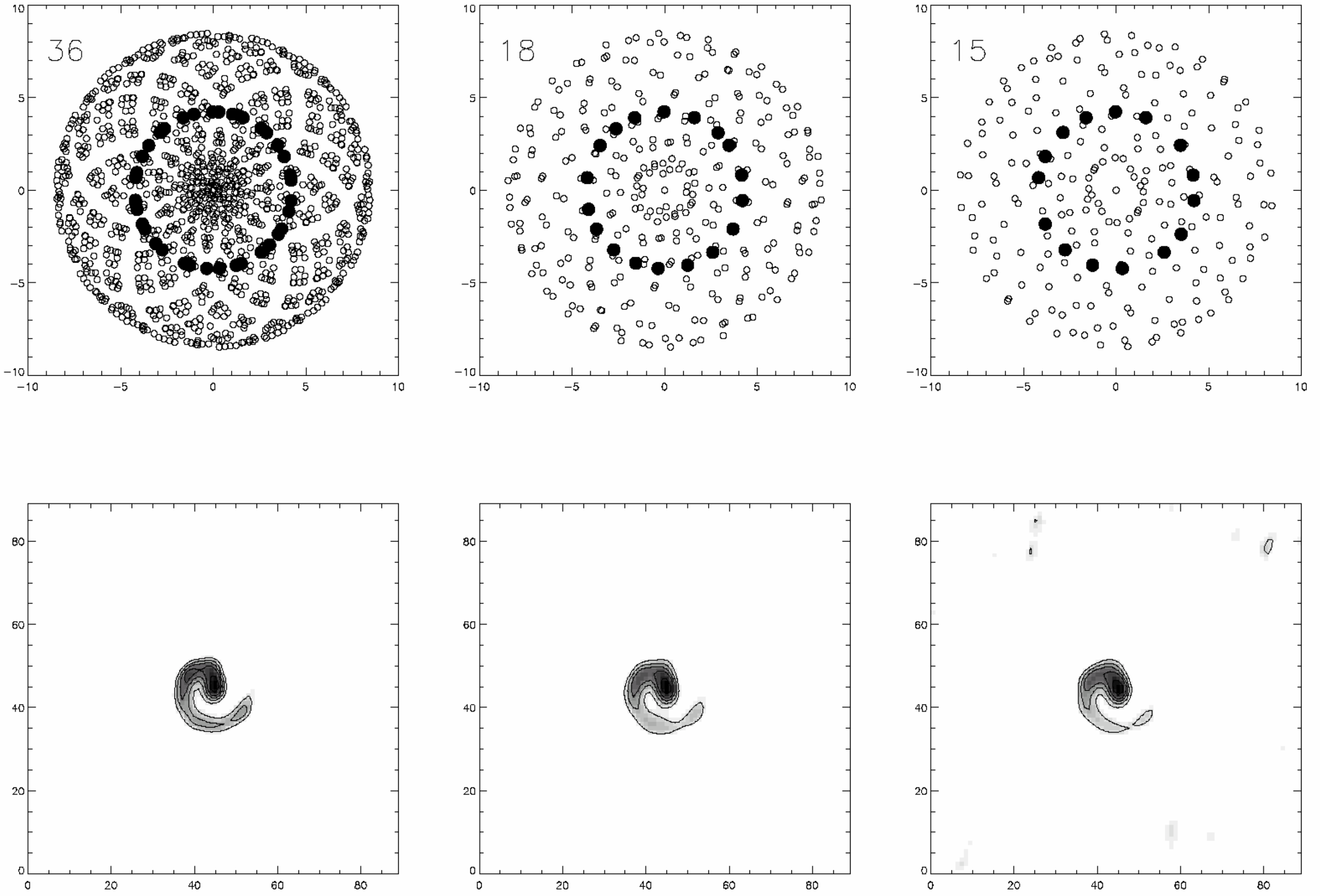


WR 104 (2.2 microns)

A Little Super-Resolution…

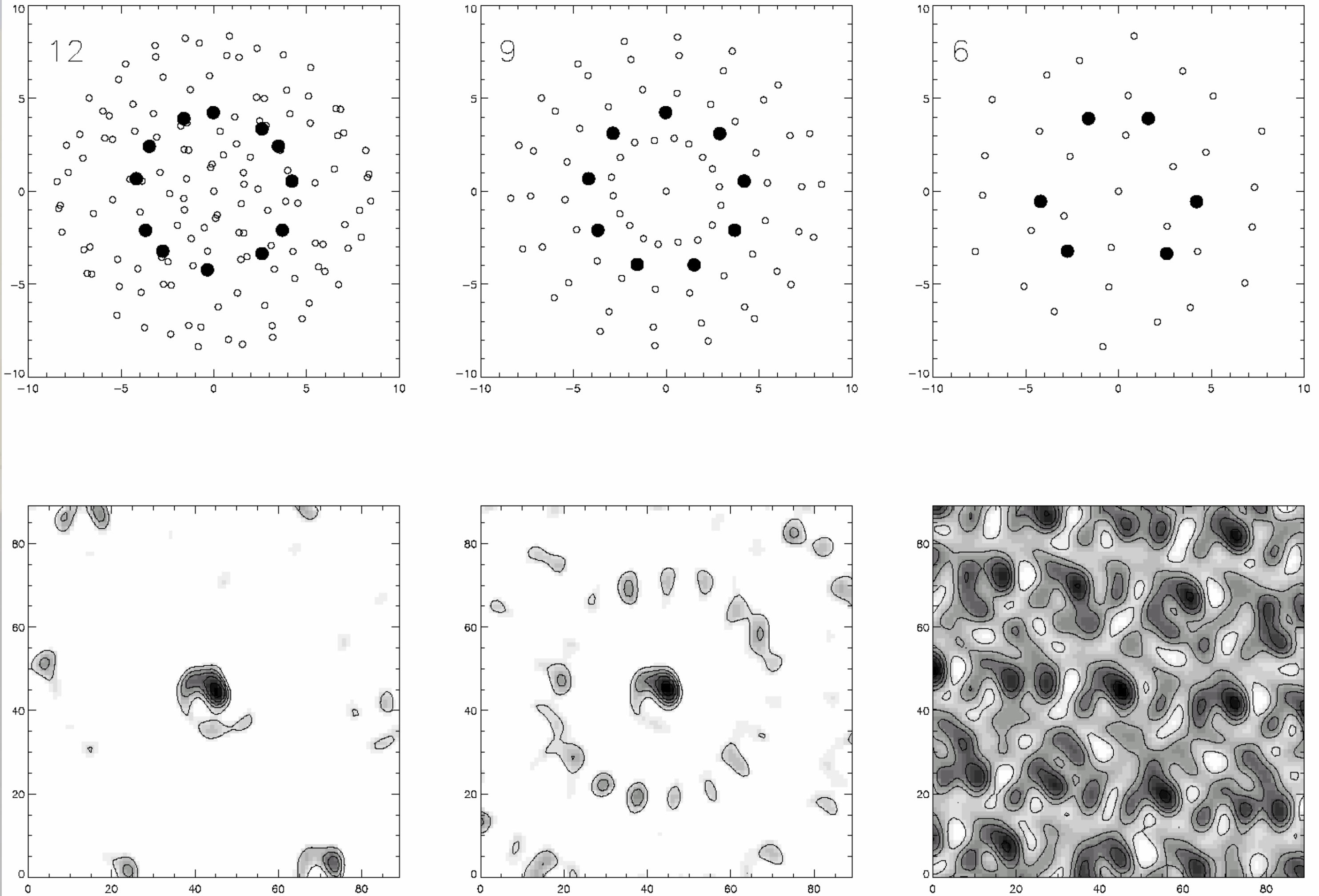


How many Telescopes do you need?



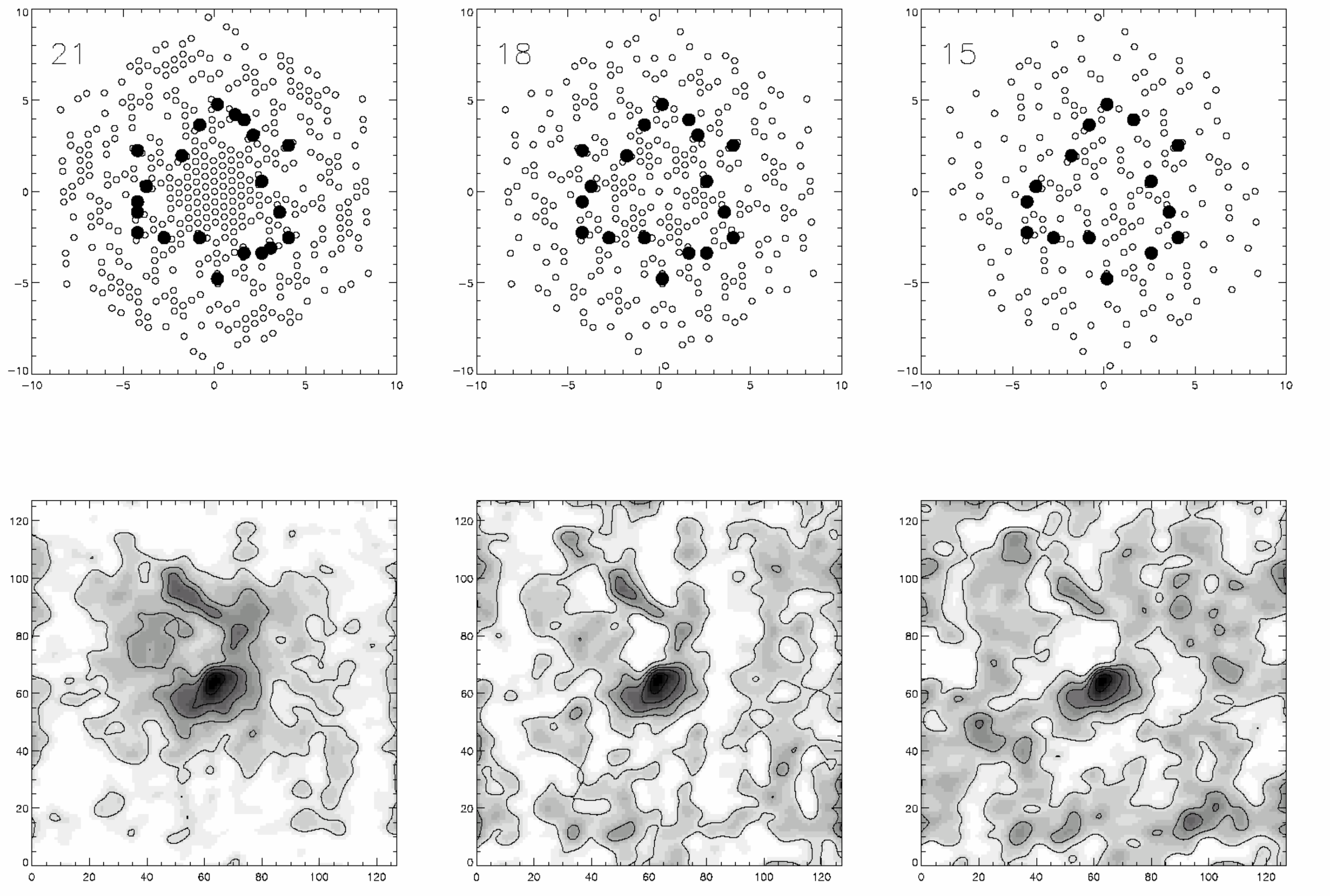
Tuthill & Monnier (CHARA Report 2000)

How many Telescopes do you need?



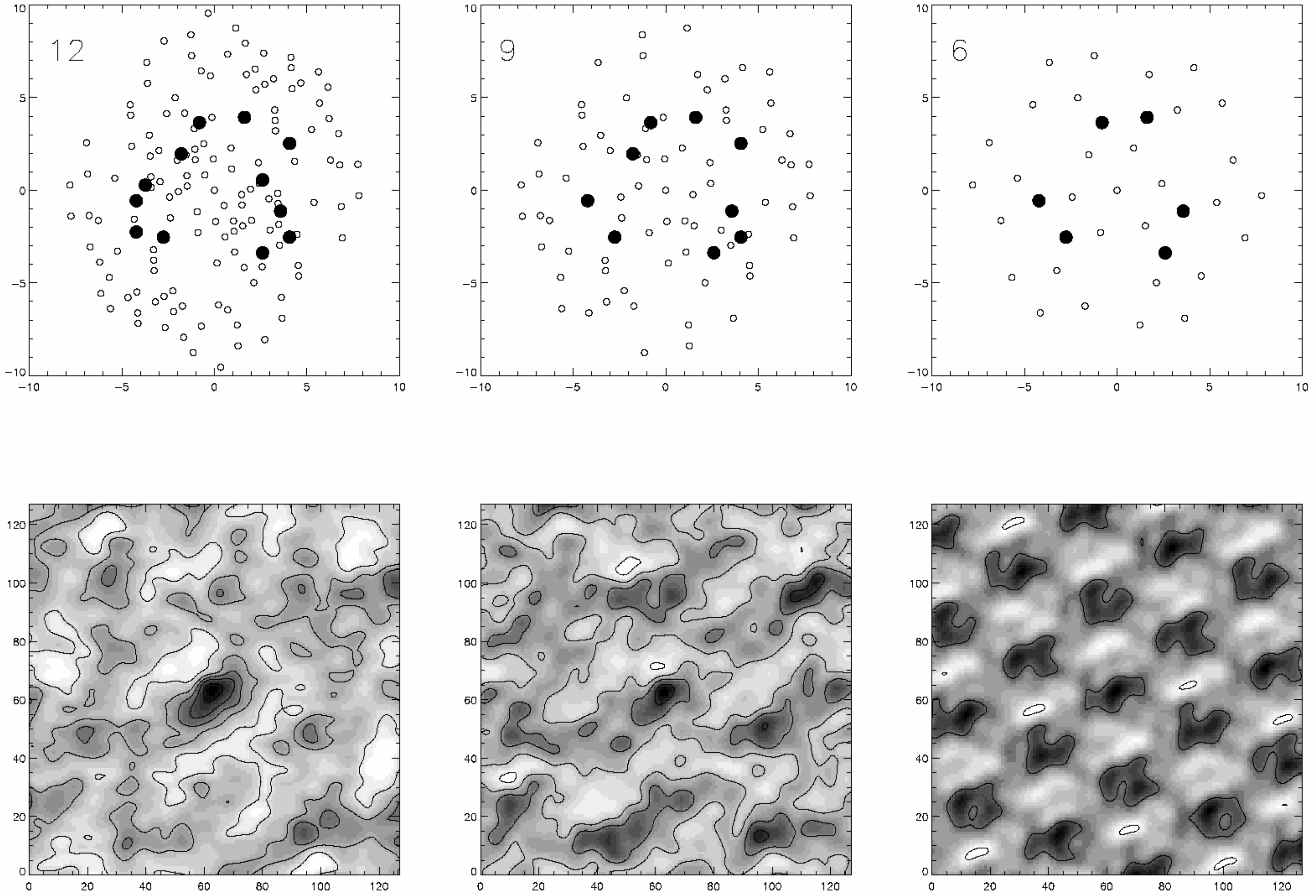
Tuthill & Monnier (CHARA Report 2000)

You need more telescopes for wider fields



Tuthill & Monnier (CHARA Report 2000)

You need more telescopes for wider fields



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 Objects (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 with Spatial Filtering
for masking here, SNR (vis) ~ 10, closure phase error ~ 8 degs

Summary of Software Issues

- 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
- New Data Exchange Format: OIFITS (Pauls et al. 2005)
  - www.mrao.cam.ac.uk/~jsy1001/exchange/ C/python code
  - www.astro.lsa.umich.edu/~monnier/Resources.html IDL Code

- Imaging software
  - Need "multi-resolution" techniques
  - How to deal with *very* sparse Fourier coverage?
  - SPIE "Beauty Contest" has encouraged new software development

Other observables possible:
Closure Differential Phase

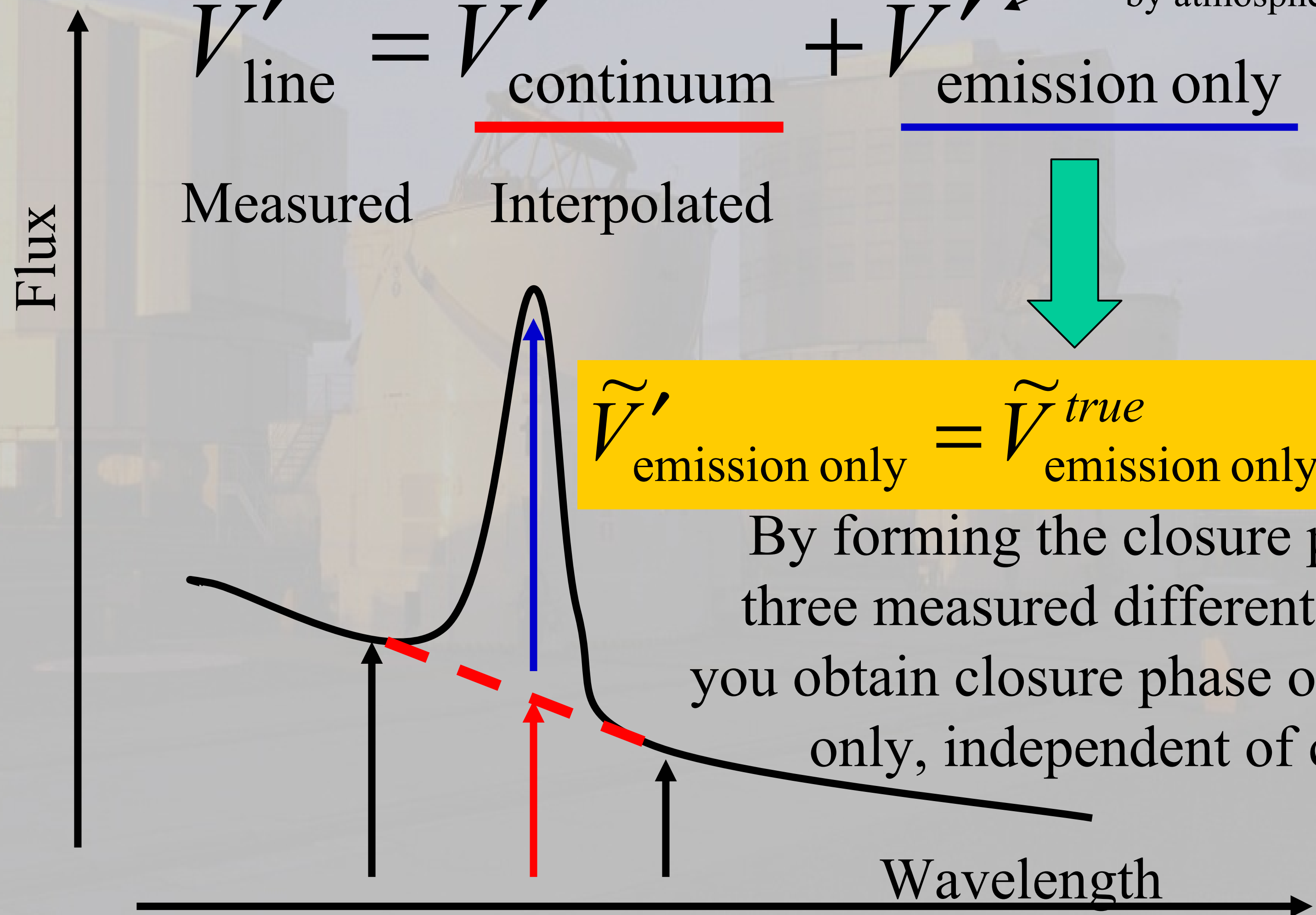
$$\widetilde{V}'_{\text{line}} = \underbrace{\widetilde{V}'_{\text{continuum}}}_{} + \underbrace{\widetilde{V}'_{\text{emission only}}}_{}$$

Prime indicates corrupted by atmospheric piston

Measured Interpolated

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

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



Closure Phase Challenges!

Consider yourself a "Closure Phase Expert" if you can prove the following:

- Closure Phase is independent of position of source (phase center)
- Closure Phase is 0 or 180 degrees for point-symmetric object
- Photon noise biases the bispectrum towards 0 degrees for all-in-one combination but not for pair-wise detection

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