

Astronomical Optics

Phase correction in interferometers

OUTLINE:

Phase referencing in interferometers

- why phase referencing? beyond V^2 interferometry: astrometry, image synthesis, phase closure

Wavefront correction on individual apertures

tradeoff between calibration accuracy, efficiency and wavefront quality

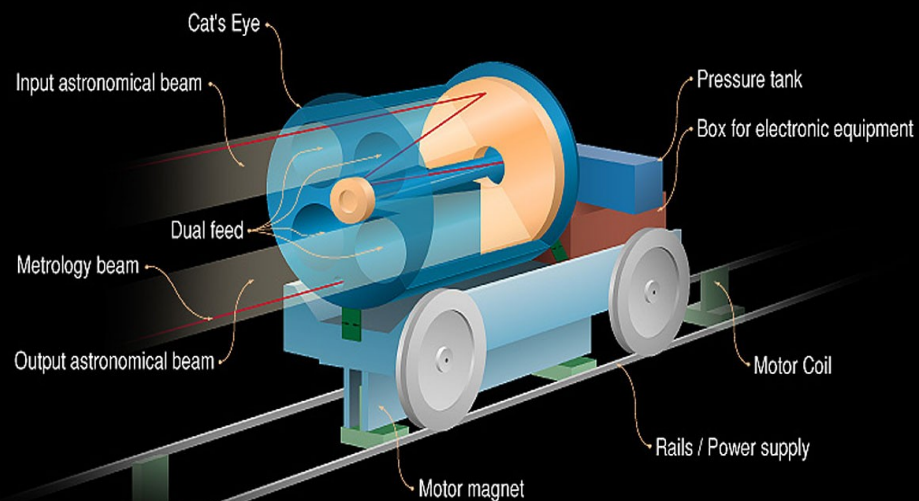
Technology:

- delay lines
- atmospheric dispersion compensation: vacuum delay lines, ADCs
- Adaptive optics correction in interferometers
- Calibration of residual phase errors with spatial filtering: pinhole, fiber interferometry

Delay lines

Must maintain near-zero Optical Pathlength Difference (OPD) between arms of the interferometer

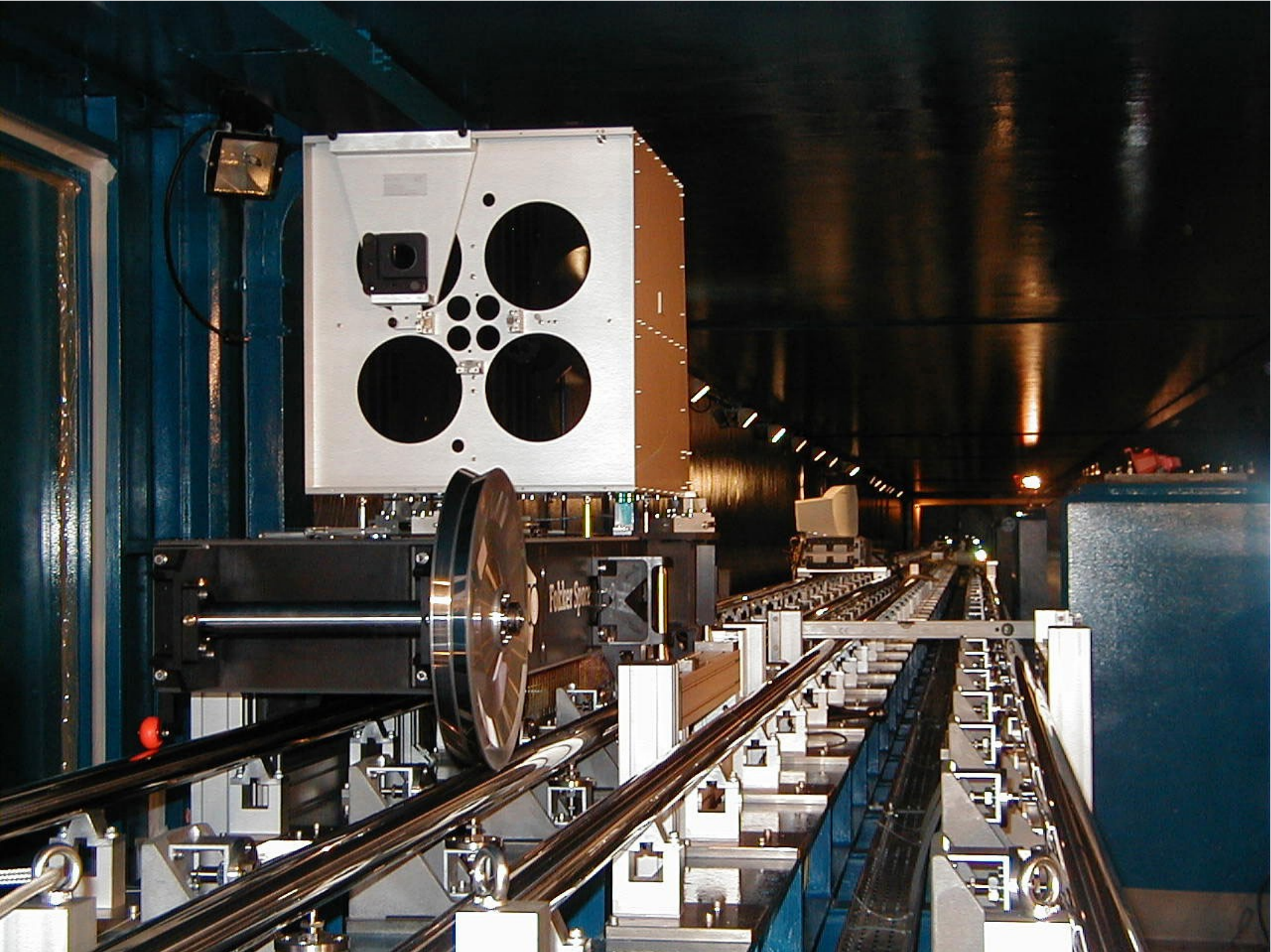
The VLTI Delay Line



VLTI delay line moving cart

Keck interferometer coarse delay lines





Part 1:

Control and calibration of visibility in interferometers

Scientific motivation

Why is fringe visibility accuracy important ?

Example below shows effect of fringe visibility measurement accuracy on measurement of stellar diameters (in this example, used to measure absolute distance to Cepheid stars)

$$V^2(B\theta/\lambda) = \left(2 \frac{J_1(\pi B\theta/\lambda)}{\pi B\theta/\lambda} \right)^2$$

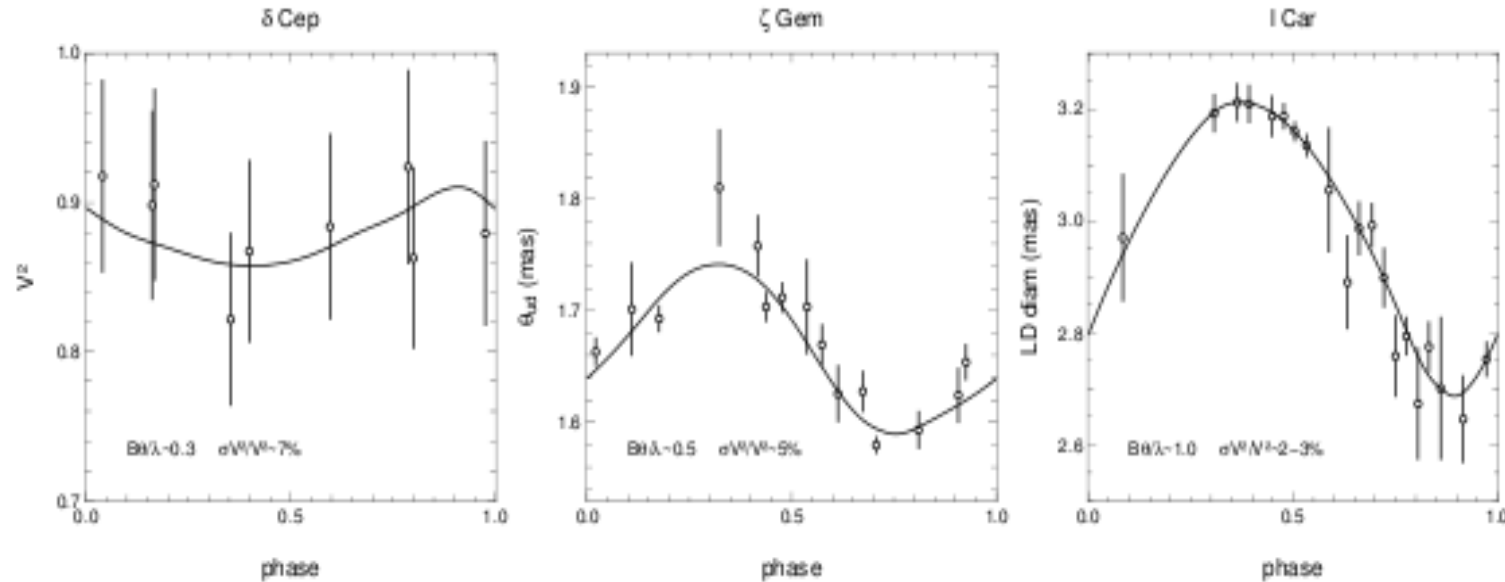


Figure 1. Different interferometric attempts to measure Cepheid angular diameter variations. From left to right: Mourard et al. (1997⁶), Lane et al. (2000⁷) and Kervella et al. (2004⁸). The left panel is V^2 as a function of phase, while the panels to the right are angular diameters with respect to phase. The thin, continuous line is the integration of the pulsation velocity (distance has been adjusted). From left to right, one can see the effect of increasing resolution ($B\theta/\lambda$) and improving precision ($\sigma V^2/V^2$). In the left panel, the pulsation was not claimed to be detected; the middle panel was the first detection, with a 10% precision on the distance; the right panel displays one of the best: 4% in the distance.

Sources of fringe visibility loss (discussed in next slides)

What can go wrong ? Why would the measured fringe visibility be < 1 on a point source ?

Amplitude difference between the 2 beams

Problem: If one beam is brighter than the other, fringe visibility < 1

- measure flux in each arm of the interferometer

Phase errors within each of the 2 beams

Problem: Wavefront is not flat before entering the beam combiner

- calibrate visibility loss by observing another star
- good adaptive optics for each of the telescopes
- spatial filtering to clean the beams, at the cost of flux

Phase between the 2 beams is changing within detector exposure time

Problem: Measurement is superposition of shifted fringes, with apparent $V < 1$

- calibrate visibility loss by observing another star
- reduce / calibrate internal sources of vibration
- if possible, fringe tracking on nearby bright source

Phase between the 2 beams is changing within the spectral band of the measurement

Problem: Dispersion in atmosphere and interferometer: measurement is superposition of shifted fringes, with apparent $V < 1$

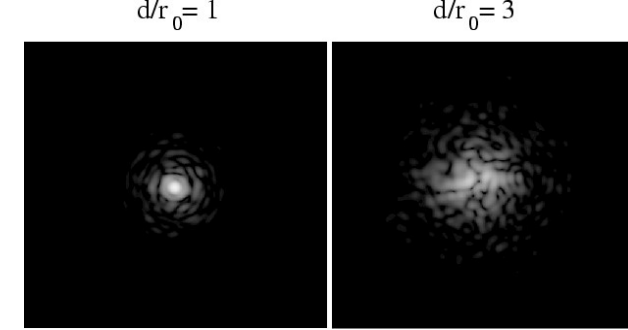
- optically compensate atmospheric dispersion
- calibrate visibility loss by observing another star
- disperse fringes on detector
- use vacuum delay lines

Polarization is different between the 2 beams

Problem: internal instrumental polarization in interferometer

- calibrate visibility loss by observing another star
- design telescopes, beam transport and delay lines to minimize differential polarization effects

Fringe visibility loss: phase errors in beams



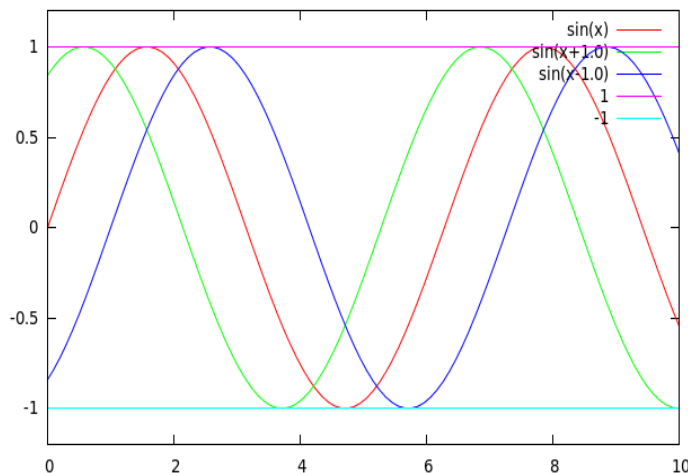
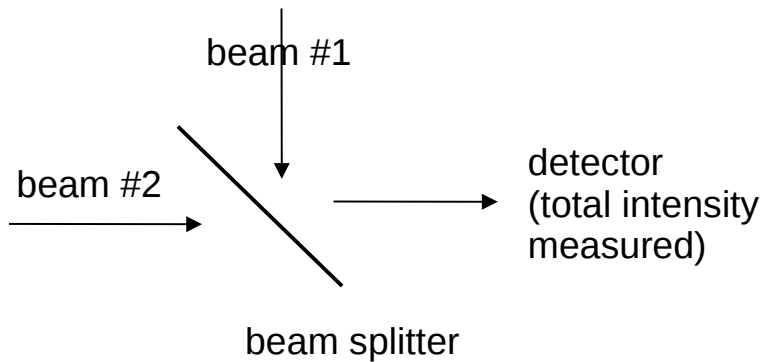
Example:

2 beams are combined with a beam splitter

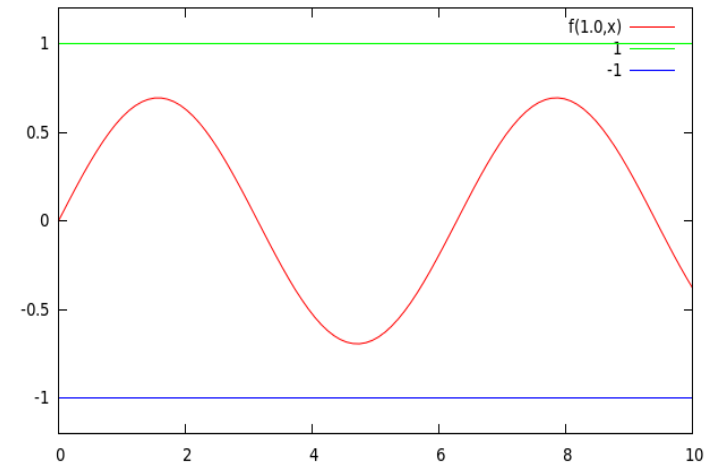
Each beam has phase errors, and differential phase error between the beams is ~ 1 rad

consider 3 points in the pupil:

- point 1: phase difference between 2 beams is -1 rad
- point 2: phase difference between 2 beams is 0 rad
- point 3: phase difference between 2 beams is $+1$ rad



for each of the 3 points, visibility is $= 1$, but phase is offset



What is observed is the total flux, the sum of the 3 curves on the left

Measured visibility $= 0.7 < 1.0$

problem:

Is measured visibility due to aberrations, or true object visibility

Same concept applies to variations of phase with time and wavelength

Fringe visibility loss: phase errors in beams

Solutions to problem

Visibility loss is approximately equal to Strehl ratio $\sim \exp(-\sigma^2)$

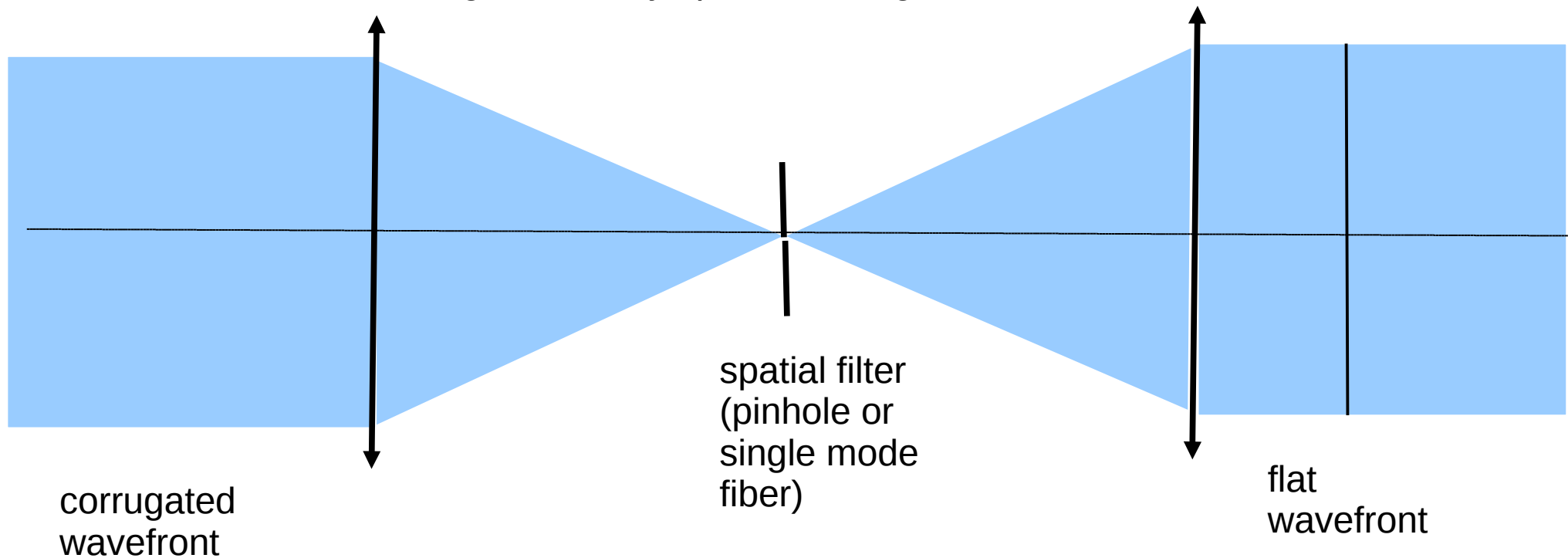
With $\sigma = 1$ radian RMS, visibility ~ 0.3

Good **adaptive optics correction** to reduce σ is essential on large telescopes

Spatial filtering can be used to clean beam:

Optically transforms aberrated wavefront into flat wavefront

With aberrated wavefront, light is lost by spatial filtering

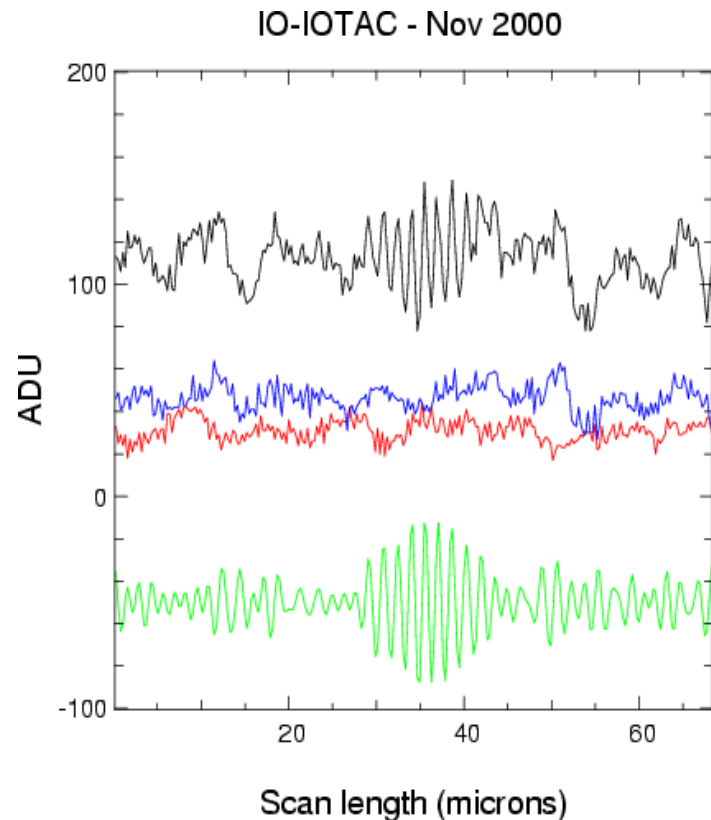
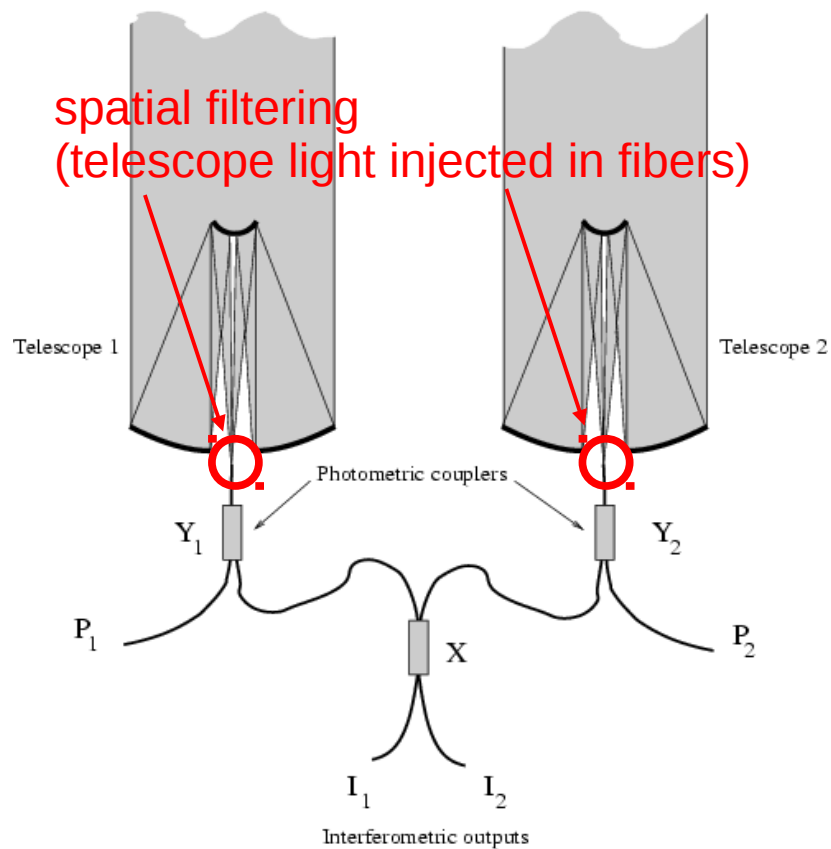


Spatial filtering

Spatial filtering alone does not help, as flux variations in interferometer arms are strong

Photometric calibration, achieved by measuring light in both arms of the interferometer AFTER spatial filtering, can calibrate visibility loss due to flux variations.

Spatial filtering + photometric calibration is powerful solution, and has achieved $< 1\%$ visibility accuracy on sky



Uncalibrated signal:
 I_1

photometric channels
 P_1, P_2

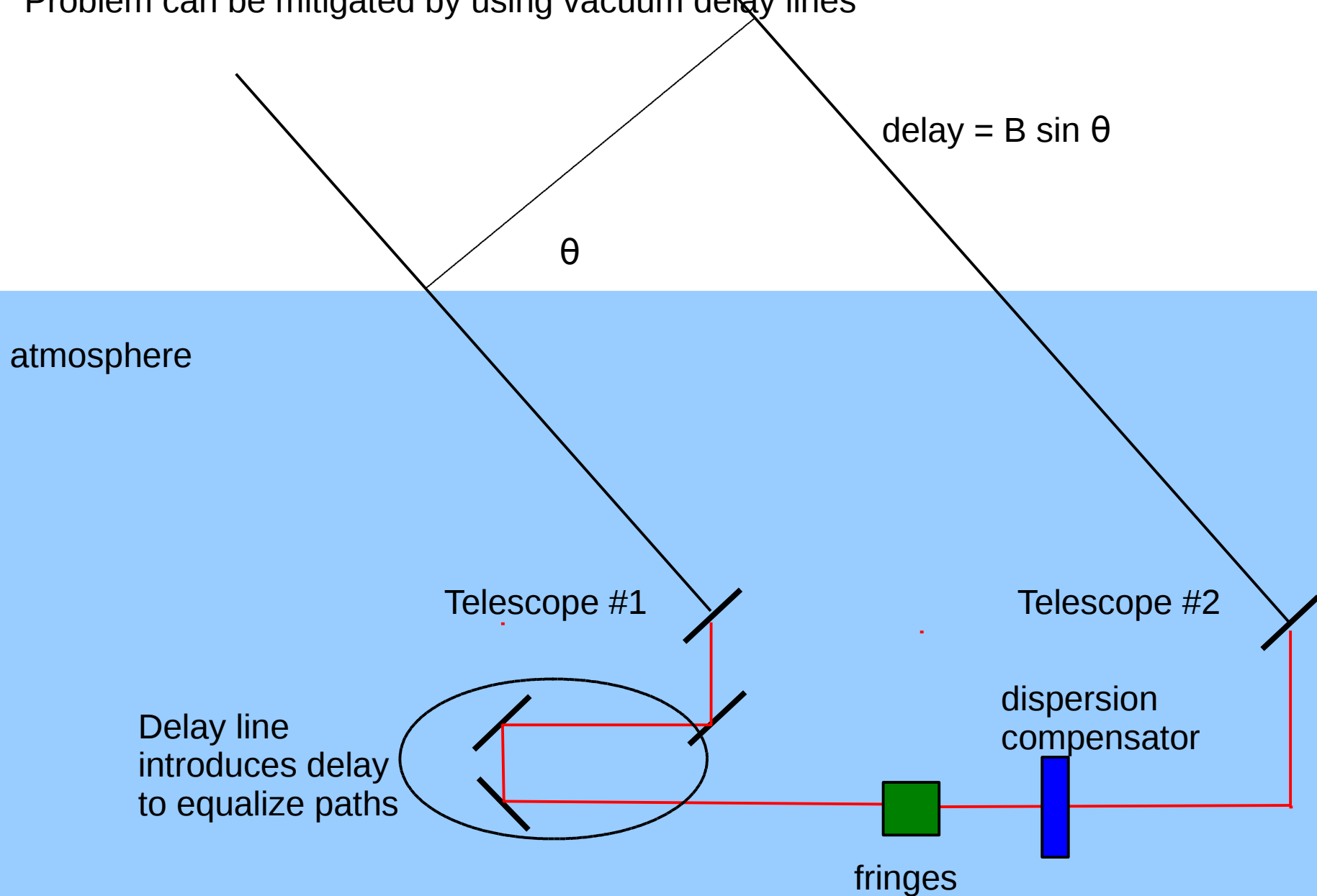
Calibrated
signal takes into
account mismatch
between P_1 and P_2

IOTA fiber interferometer (Berger et al. 2001)

Fringe visibility loss: chromatic dispersion

Atmosphere introduces strong chromatic dispersion which needs to be compensated
In conventional interferometer, delay line introduces a delay (in air) to compensate for a vacuum delay → dispersion compensator is required.

Problem can be mitigated by using vacuum delay lines



Part 2:

Control and calibration of fringe phases

Fringe tracking: essential to allow observation of faint sources

Throughput in an interferometer is often low, due to large number of optical elements:
telescope, beam transport, delay lines, beam combiner

Atmospheric turbulence and vibrations move fringes very rapidly

Measurement is only possible if individual exposure time \ll time it takes for fringe to move by a wavelength \rightarrow with no phase tracking, difficult to observe faint targets

Typical limiting magnitudes for interferometers: 5 to 10 in visible / near-IR

To extend this limit, one needs to track and lock fringes to allow long exposures

Observations typically requires 100-1000 Hz sampling to “freeze” the seeing.

Consider fringe sensing carried out in K band (2.0-2.4 microns):

- an 8 m aperture receives $\sim 15,000$ photons from a $K=10$ star in 1 ms.

- sky background is ~ 1500 photons/ms.

- Telescope background is $\sim 15,000$ photons/ms.

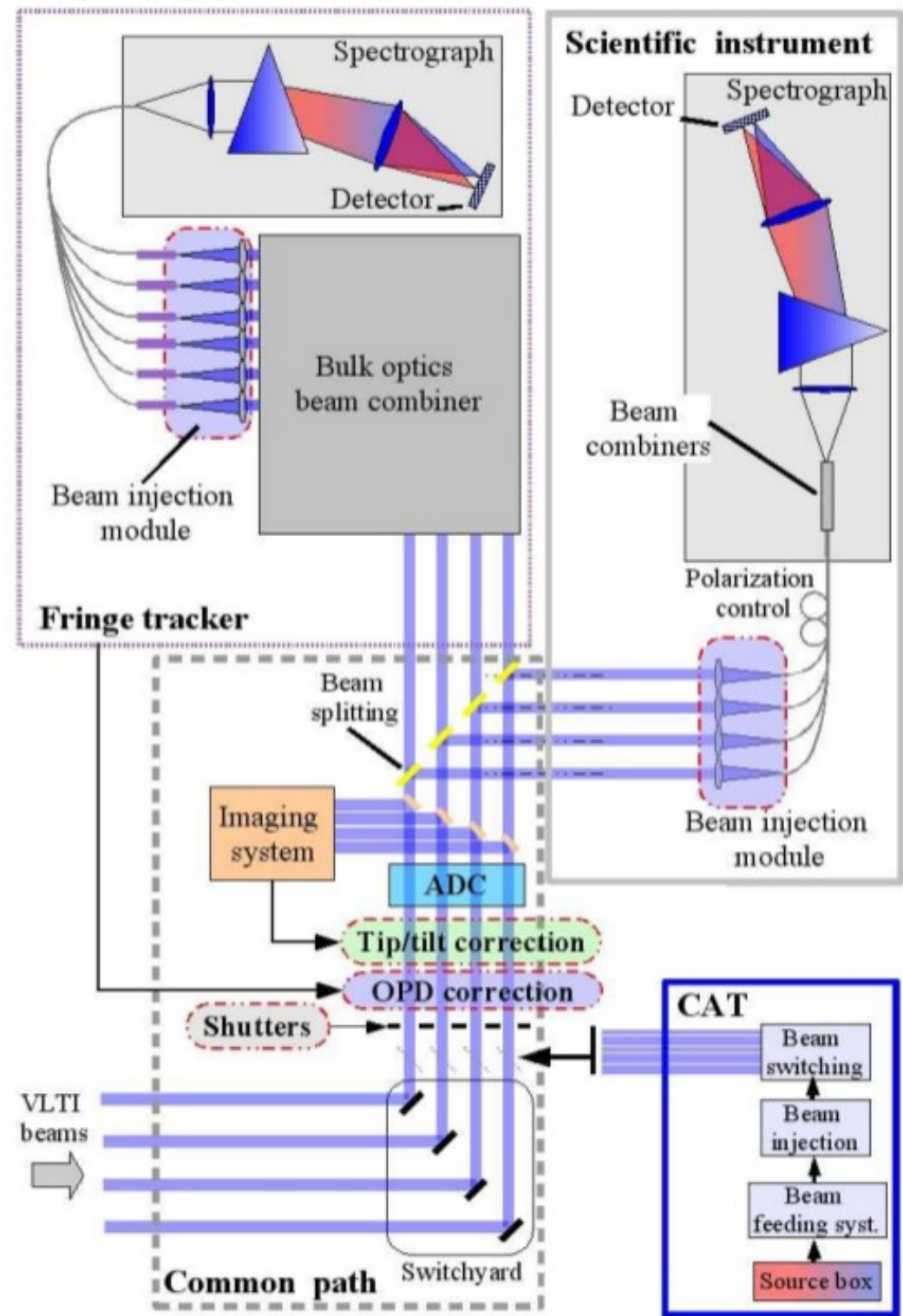
- throughput is 6%.

- This gives an SNR of 8 in a 1 ms exposure.

Fringe tracking

Fringe tracker measures rapidly fringe position, and actively controls optical pathlength corrector (=fast delay line) at the input of the beam combiner

Enables longer exposures with the scientific instrument



VLT fringe tracker shown at the upper left corner of this figure (Corcione et al., 2008)

Phase referencing

Scientific motivations

Image reconstruction with multiple baselines requires measurement of phases and visibilities (with no phases, only centro-symmetric component of the image can be estimated)

Astrometric measurement (measuring position of sources) requires fringe phase

On a single baseline: astrometric error [rad] = phase error [rad] \times ($\lambda / 2\pi$) / Baseline

How to reference phase ? - or what to use as a reference

A **nearby star** can be used to reference phase on a single baseline interferometer

Phase closure relationships can be used to separate instrumental phases from object phases (see next slides)

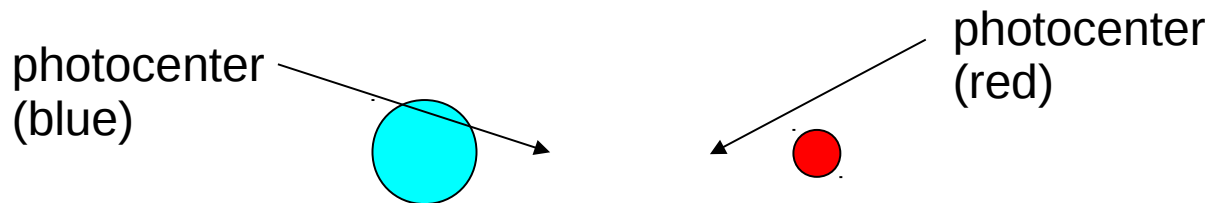
Phase can be measured as a function of wavelength:

object itself (at different wavelength) provides a reference

Example:

Accurately measuring photocenter as a function of wavelength with an interferometer can reveal planets, as hot planet is redder than star

See VLTI/Amber instrument for example



Phase closures

The fringe packet moves back and forth in an interferometer, due to phase changes that are caused by the atmosphere.

This variation causes the real phase to be unmeasurable for a single object.

Individual phases change with atmospheric terms, alpha:

$$\phi_{12} = \theta_{12} + \alpha_1 - \alpha_2$$

$$\phi_{23} = \theta_{23} + \alpha_2 - \alpha_3$$

$$\phi_{31} = \theta_{31} + \alpha_3 - \alpha_1$$

Define a **closure phase** which gets rid of the atmosphere:

$$\Phi_{123} = \phi_{12} + \phi_{23} + \phi_{31} = \theta_{12} + \theta_{23} + \theta_{31}$$

There are $(N-1)(N-2)/2$ closure phases in an array.

3: 1 closure phase, 3 visibilities -> 33% of phase information recovered.

10: 36 closure phases, 45 visibilities -> 80% of phase information recovered.

Good Reference: Monnier 2007

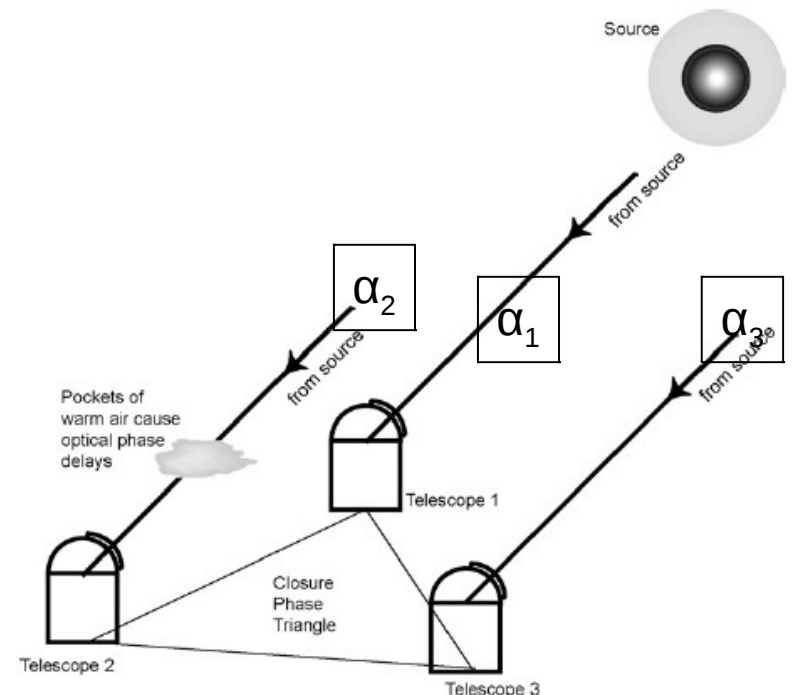
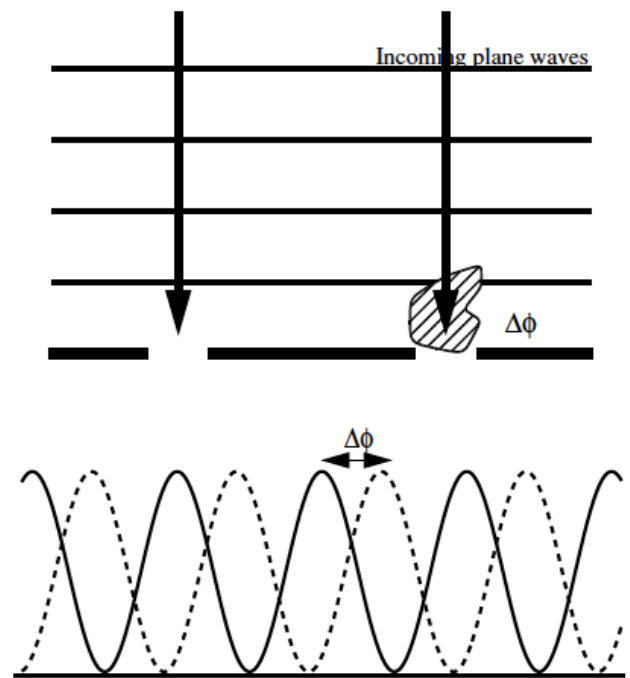
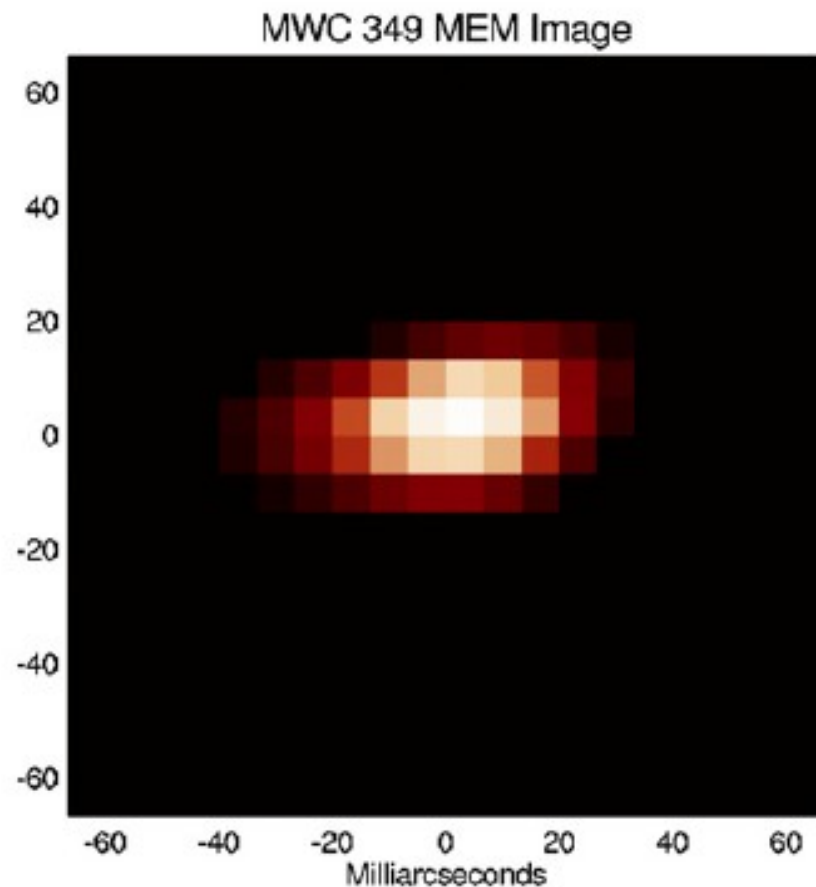
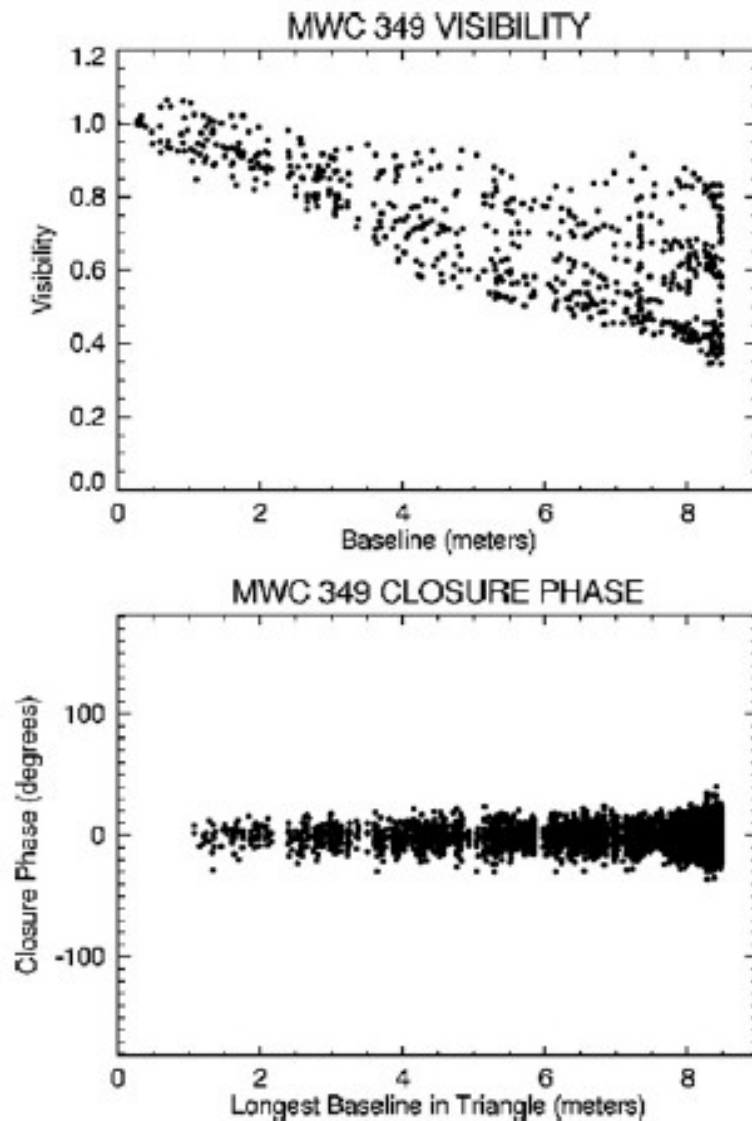
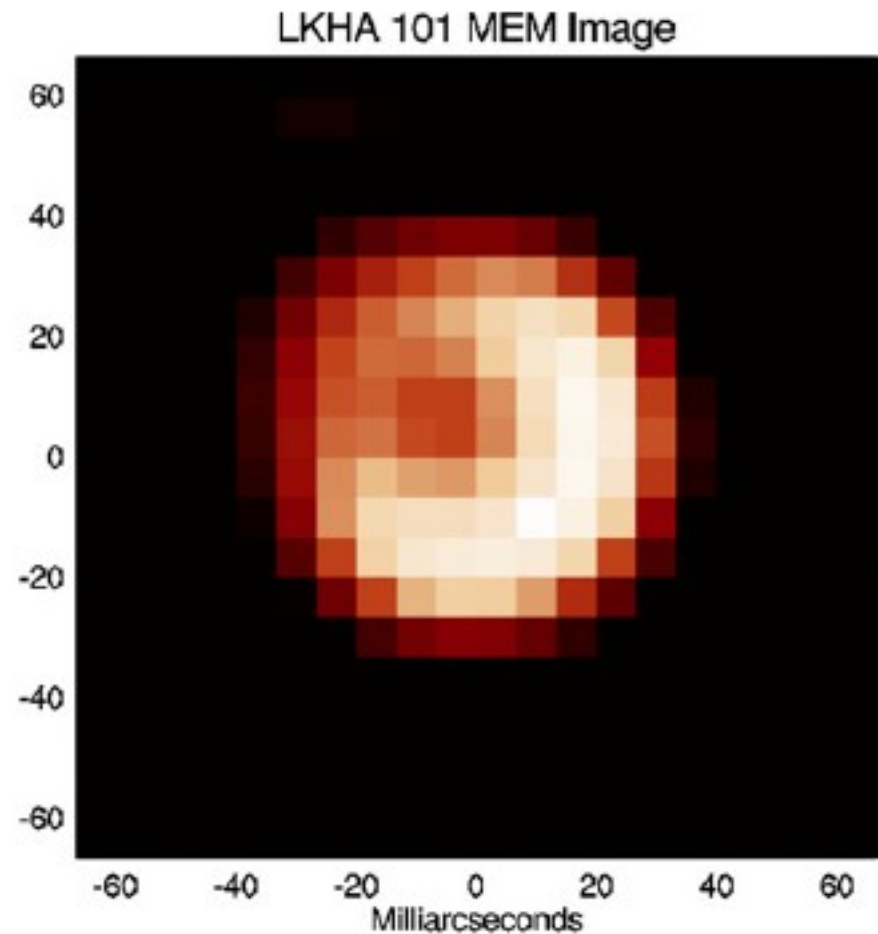
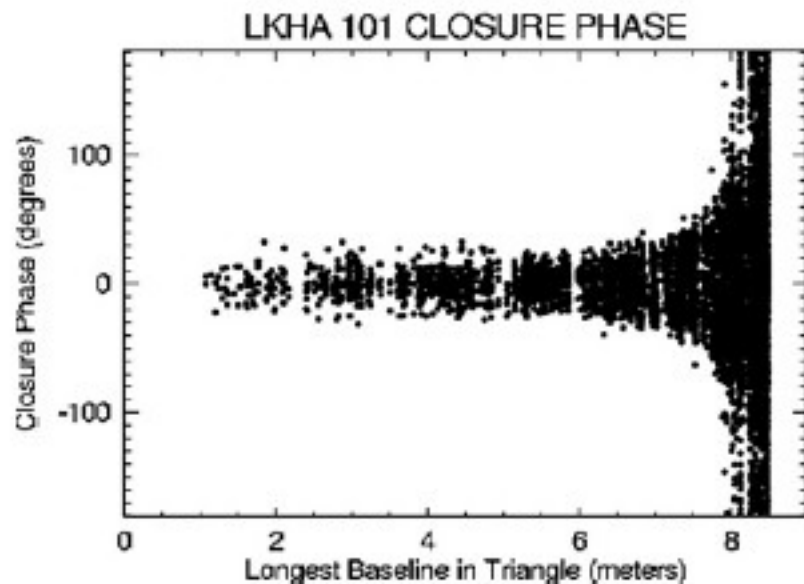
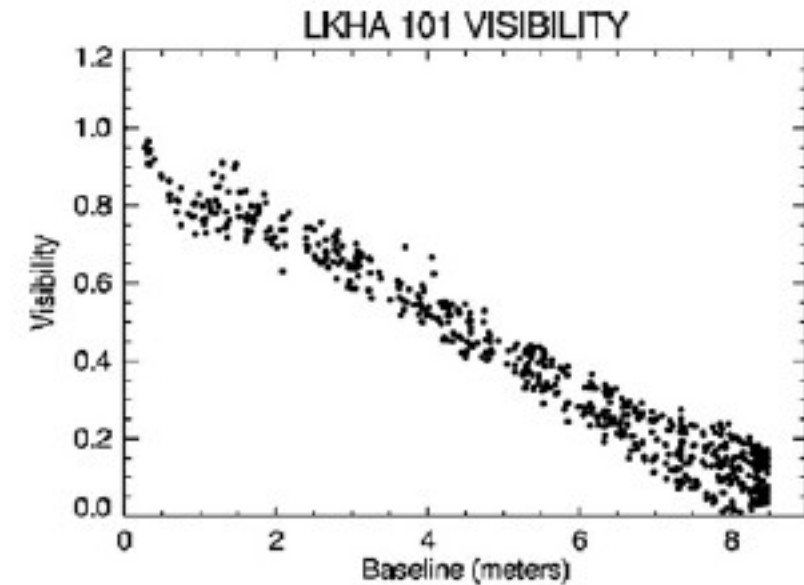


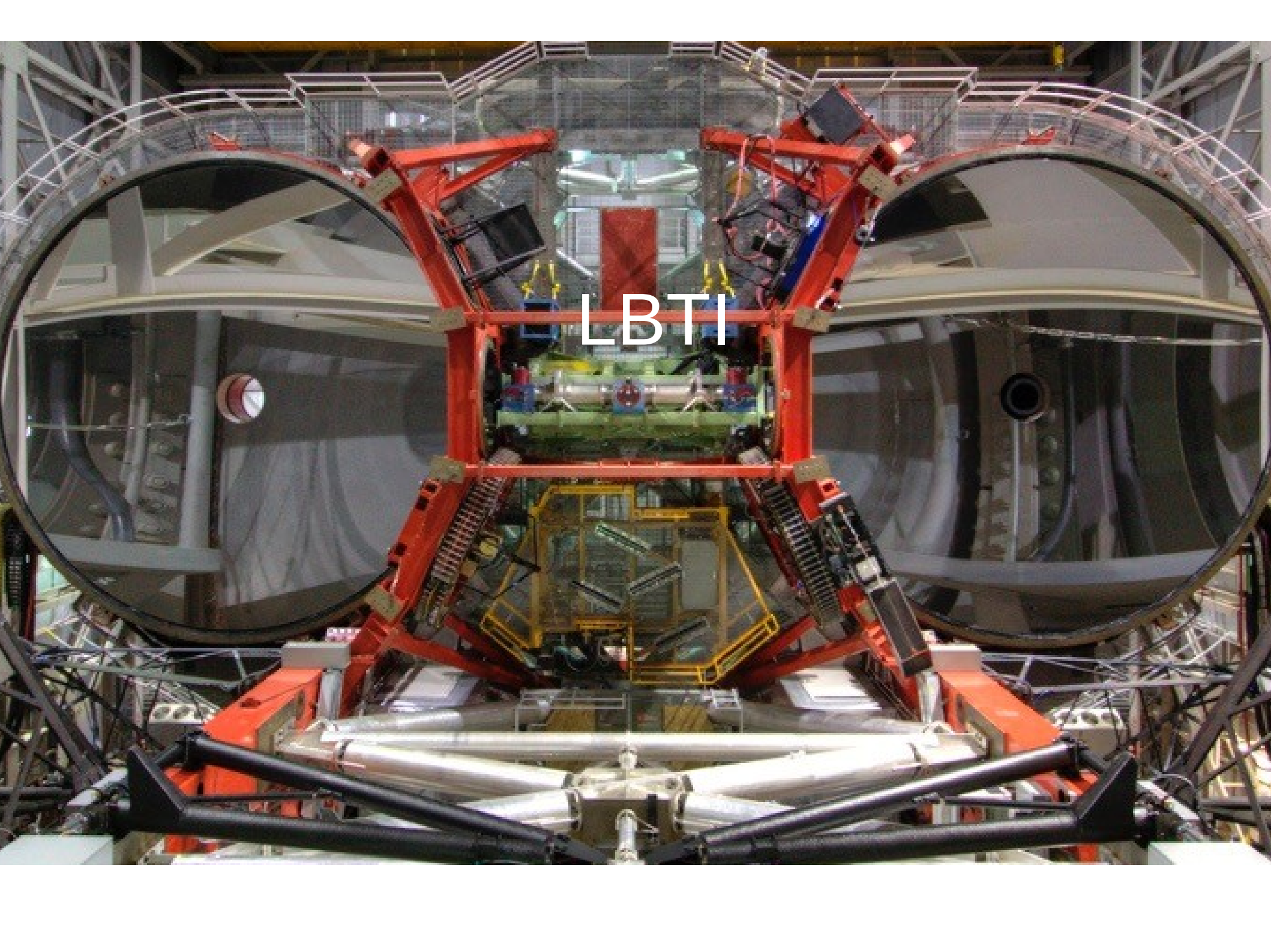
Fig. 4. Phase errors introduced at any telescope causes equal but opposite phase shifts in adjoining baselines, canceling out in the *closure phase* (see also Readhead et al., 1988; Monnier et al., 2006a).

Example 1 from Monnier 2007



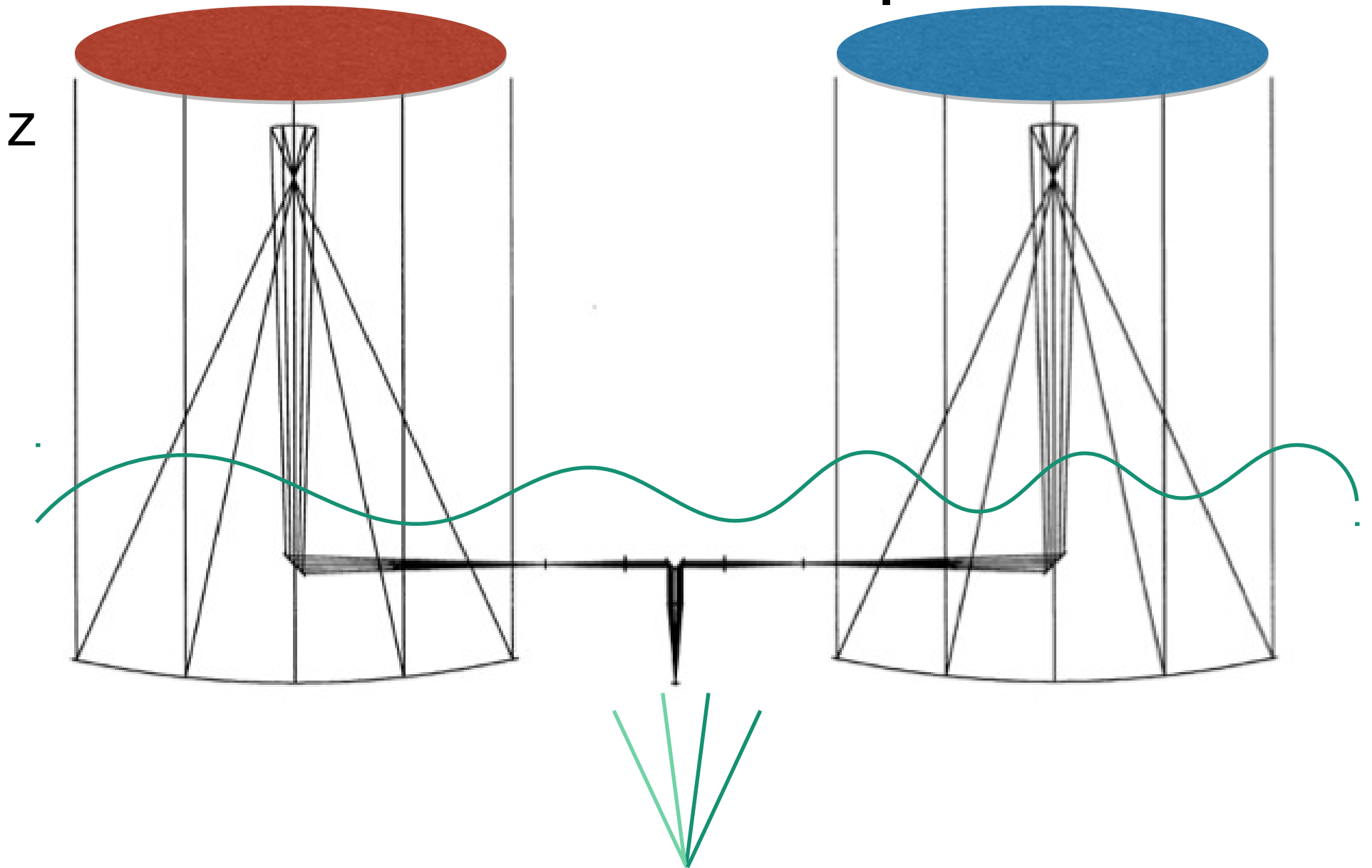
Example 2 from Monnier 2007



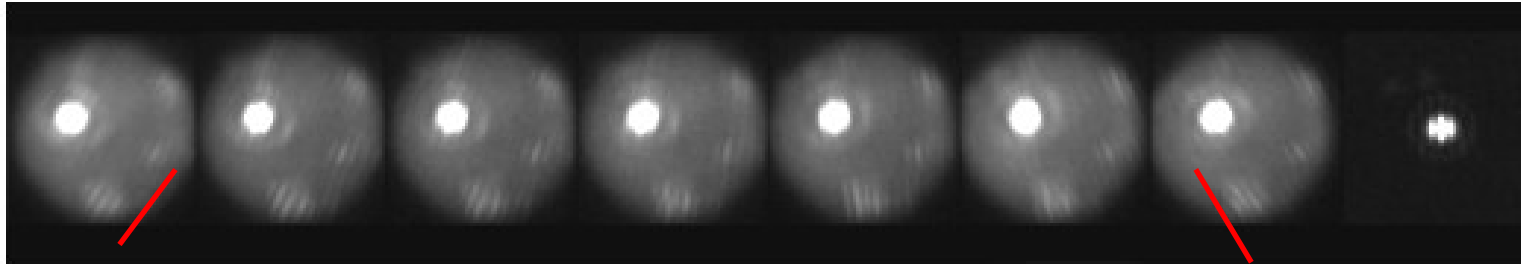
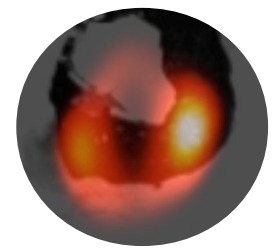


LBTI

LBTI Concept



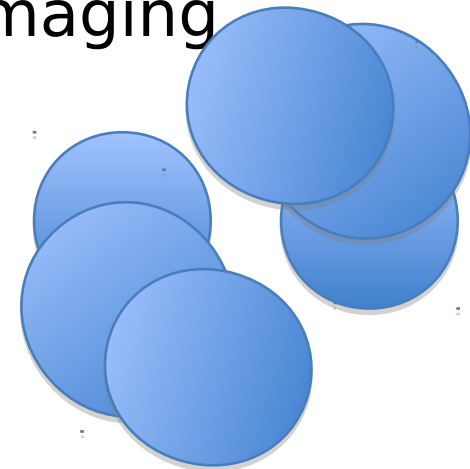
Loki Resolved - The Observation



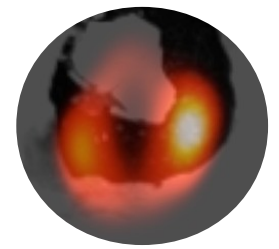
We observed Io with LBTI for one hour on Christmas Eve 2013

Epoch	Time (UT)	Hour Angle	Air- mass	SEL	Mean Parang
1	07:53	-0.47	1.022	286.59	-30.0
2	07:59	-0.37	1.020	287.44	-22.2
3	08:06	-0.25	1.018	288.43	-15.9
4	08:13	-0.13	1.016	289.42	-07.5
5	08:24	+0.05	1.016	290.97	+04.1
6	08:35	+0.23	1.017	292.53	+16.3
7	08:47	+0.43	1.021	294.22	+29.1

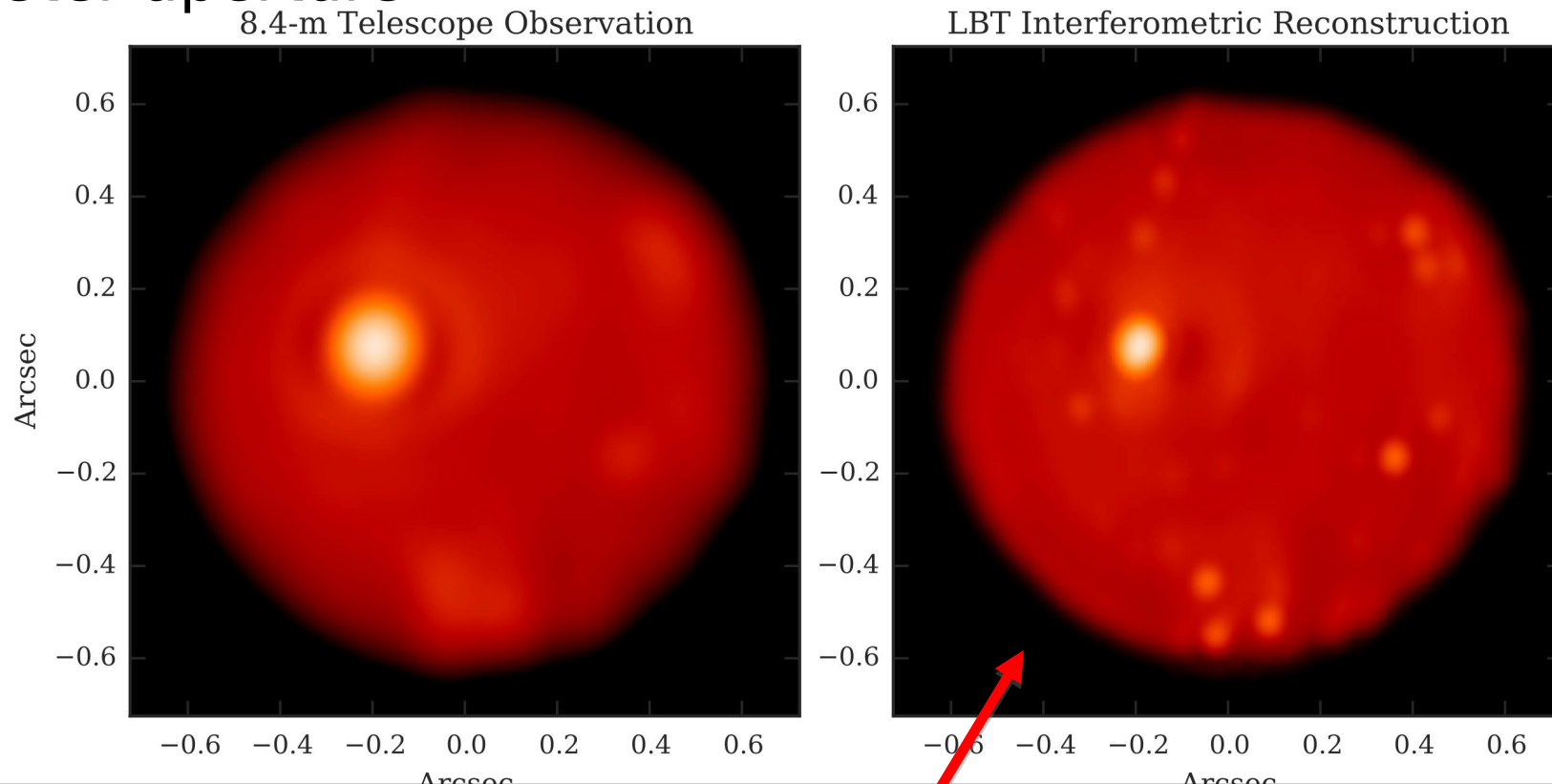
This value is critical for Fizeau imaging



Loki Resolved - Comparison

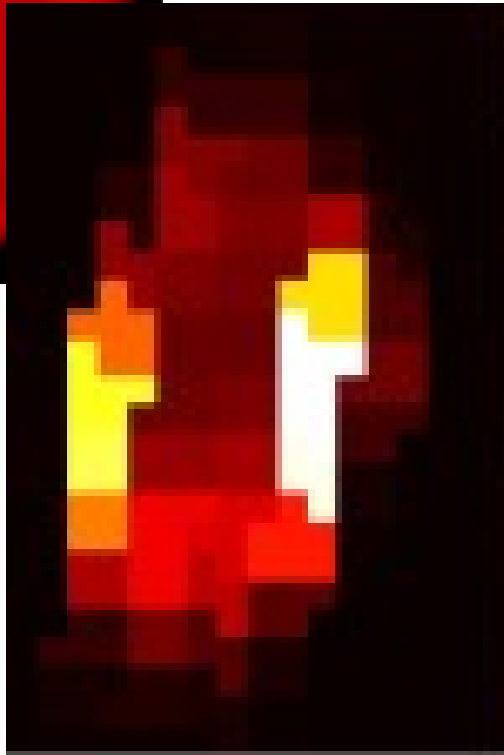
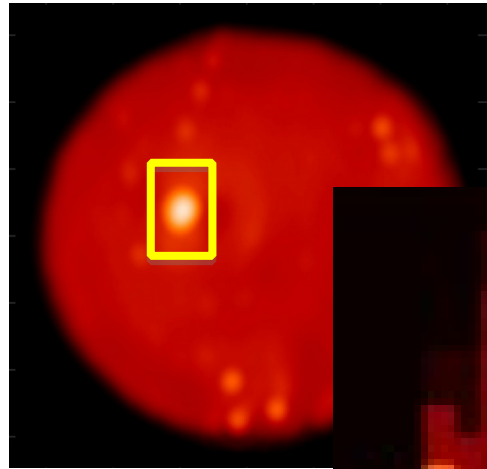
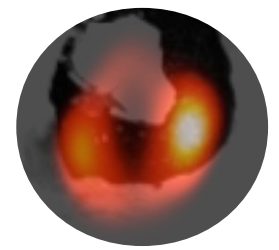


The resulting image provides better than twice the resolution achievable on a telescope with a single 8.4 meter aperture.



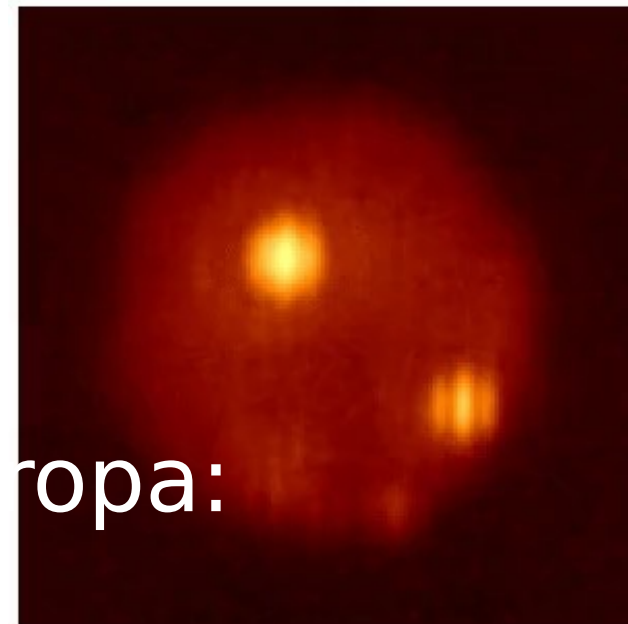
The resolution in this M-band image is like K-band on 8-10 meter telescopes (at K-band most volcanoes are

Loki Resolved – Bilobal Structure

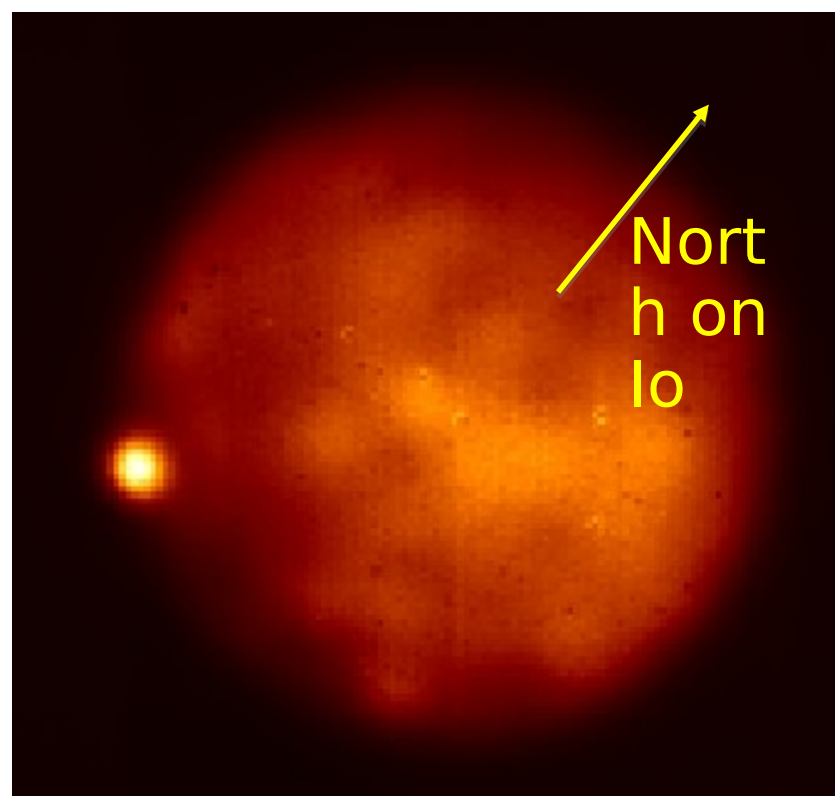
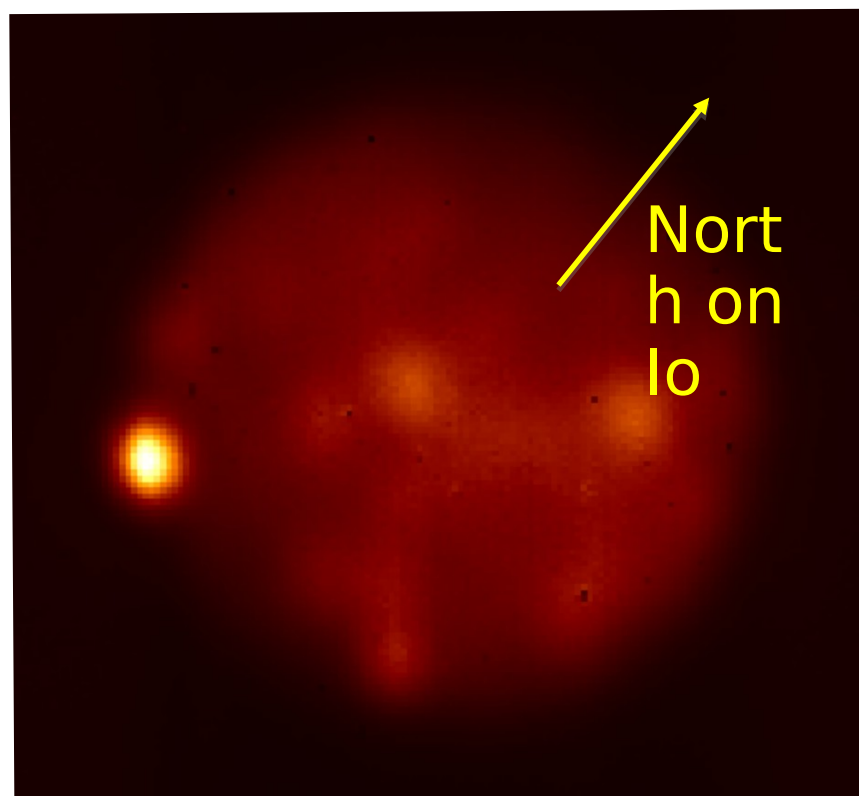
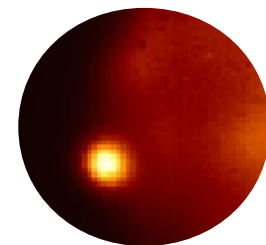


All volcanoes but Loki were unresolved

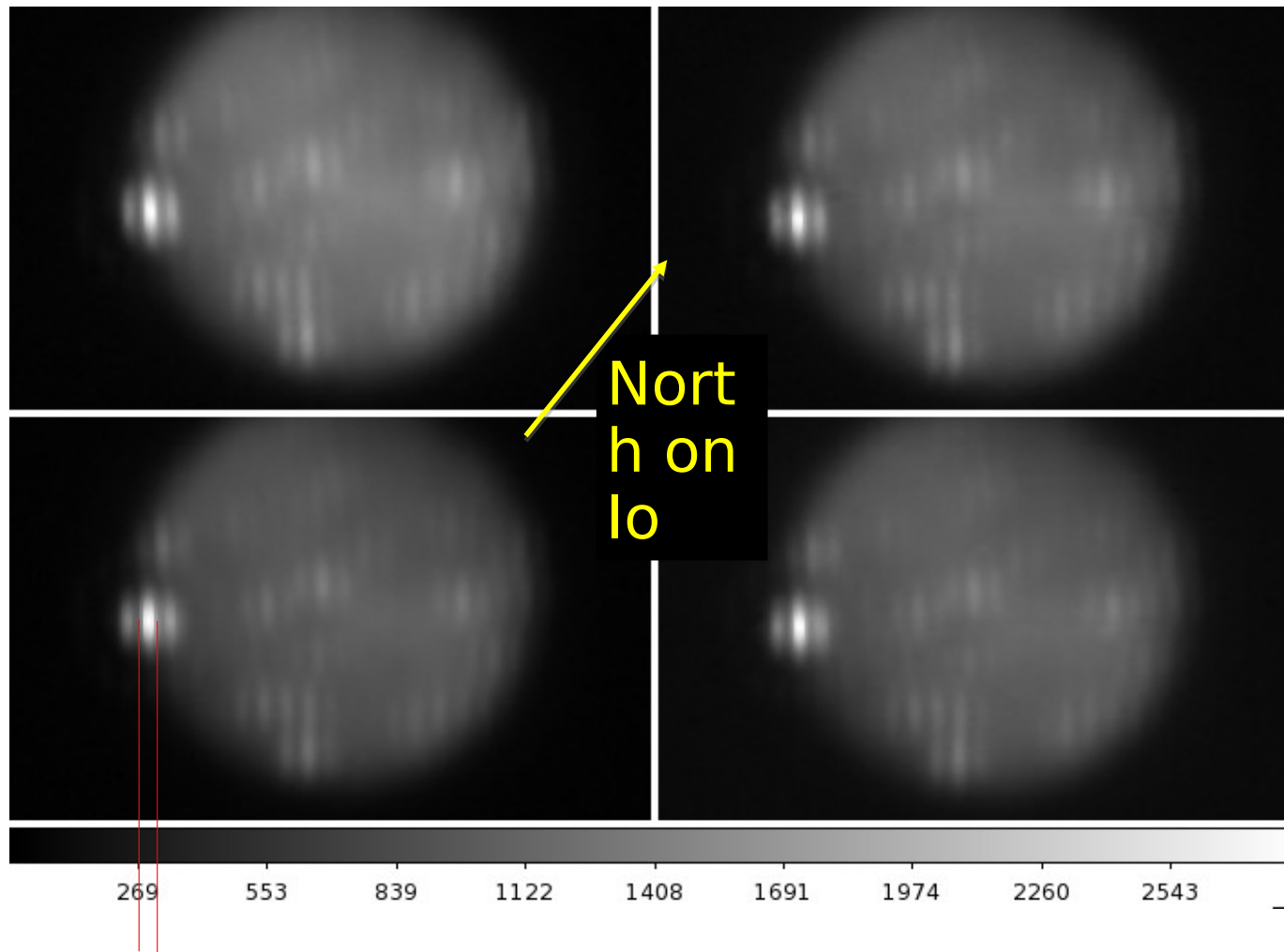
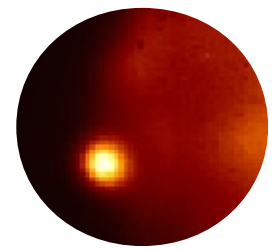
The M-band emission feature at Loki however was large enough to be resolved and revealed a bilobal structure.



Conrad, et al *AJ* 149 175 (2015)



Kurdalagon Eruption – Improved Resolution



The spatial resolution at L-band is approx. $0.022''$ (30% smaller than the $0.032''$ seen in the M-band images)

Imaging Sensitivity of Interferometers

Interferometers do not have the same sensitivity to point sources as a filled aperture equivalent.

Assume we have N elements, with d diameter, with a maximum baseline b .

Fill factor: $q = d^2/b^2 * N$ (LBT=26%, as an example)

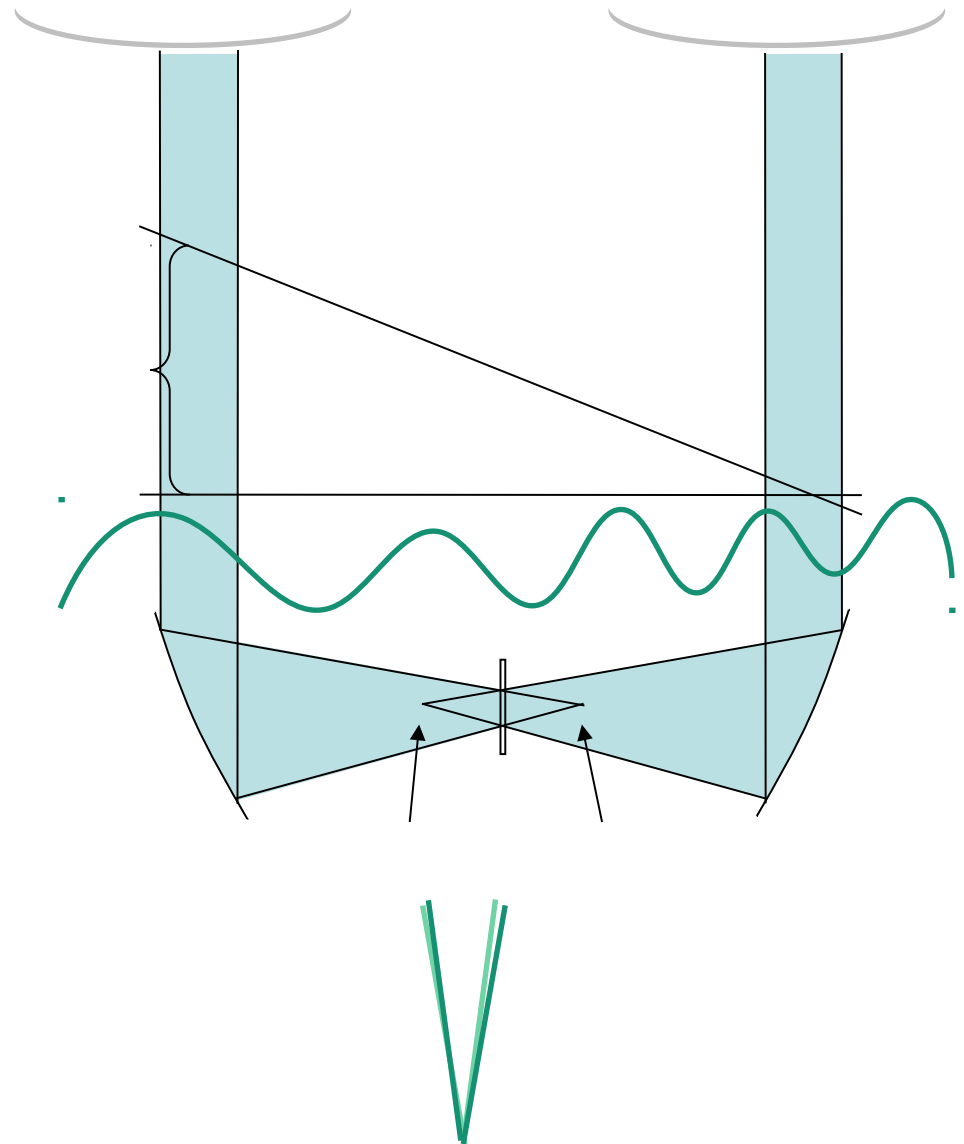
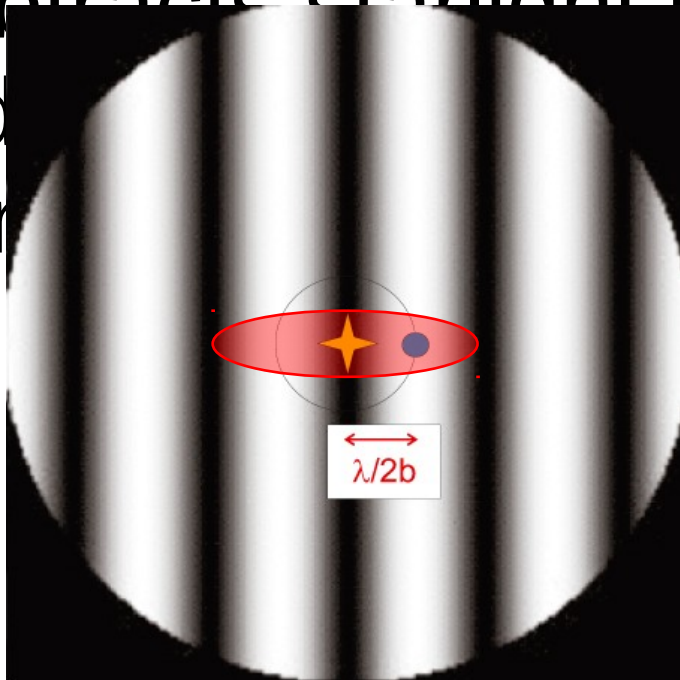
Resulting SNR loss for a point source is \sqrt{q} relative to an equivalent filled aperture.

See Roddier and Ridgway 1999 for detailed comparison.

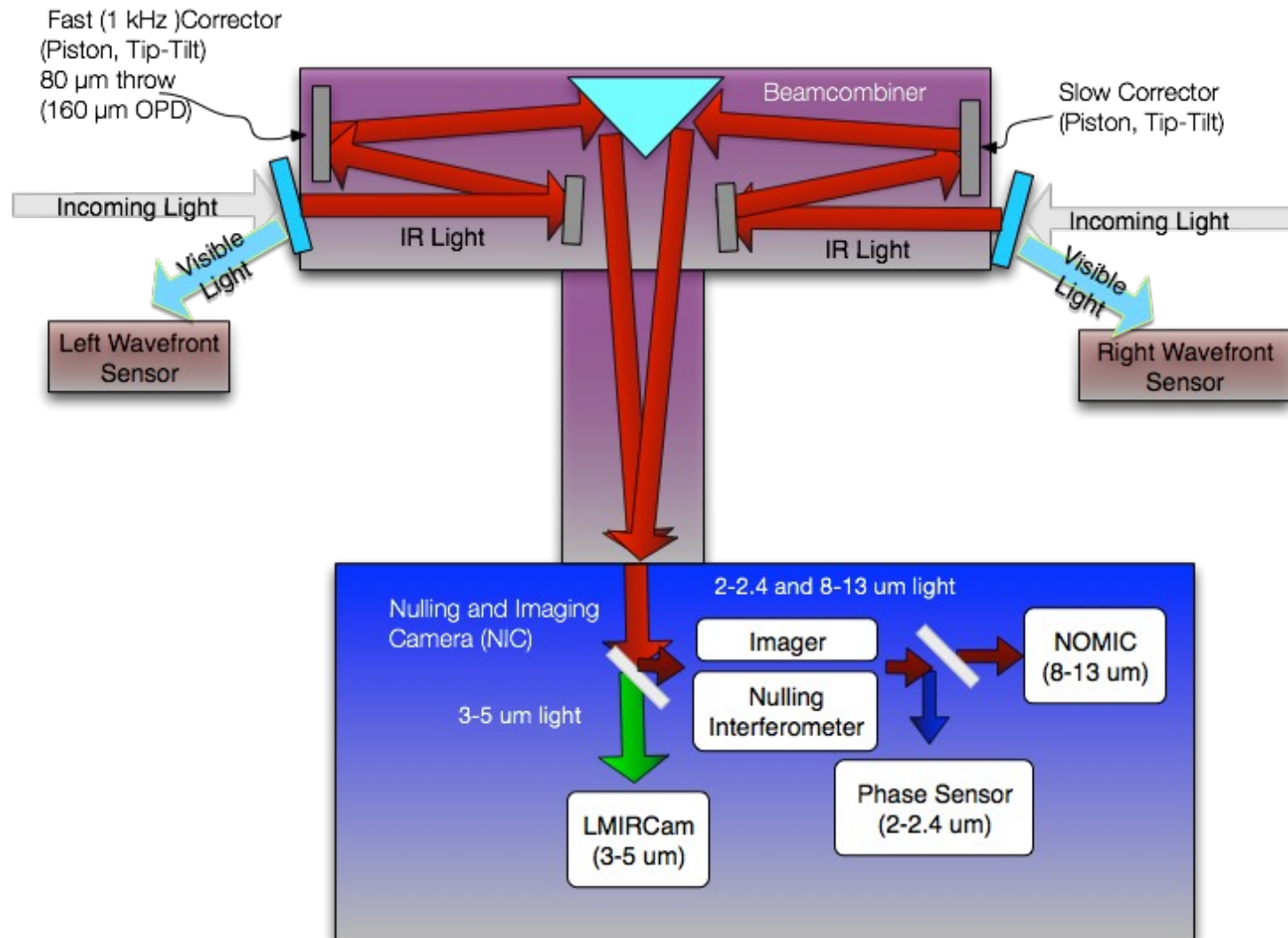
How nulling interferometry works

First proposed by
Bracewell (1978) to
directly detect “non-
Solar” planets;

Subtracts starlight by
canceling out the
in-phase light



LBTI: The Instrument



Discrete cold dewars

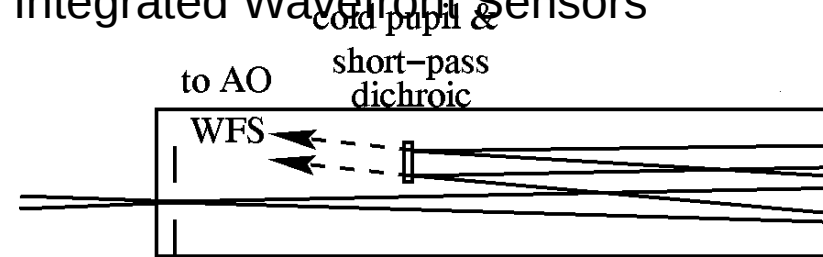
External Rigid Structure

General Purpose (Universal) Beam
Combiner (UBC)

Three Camera Ports

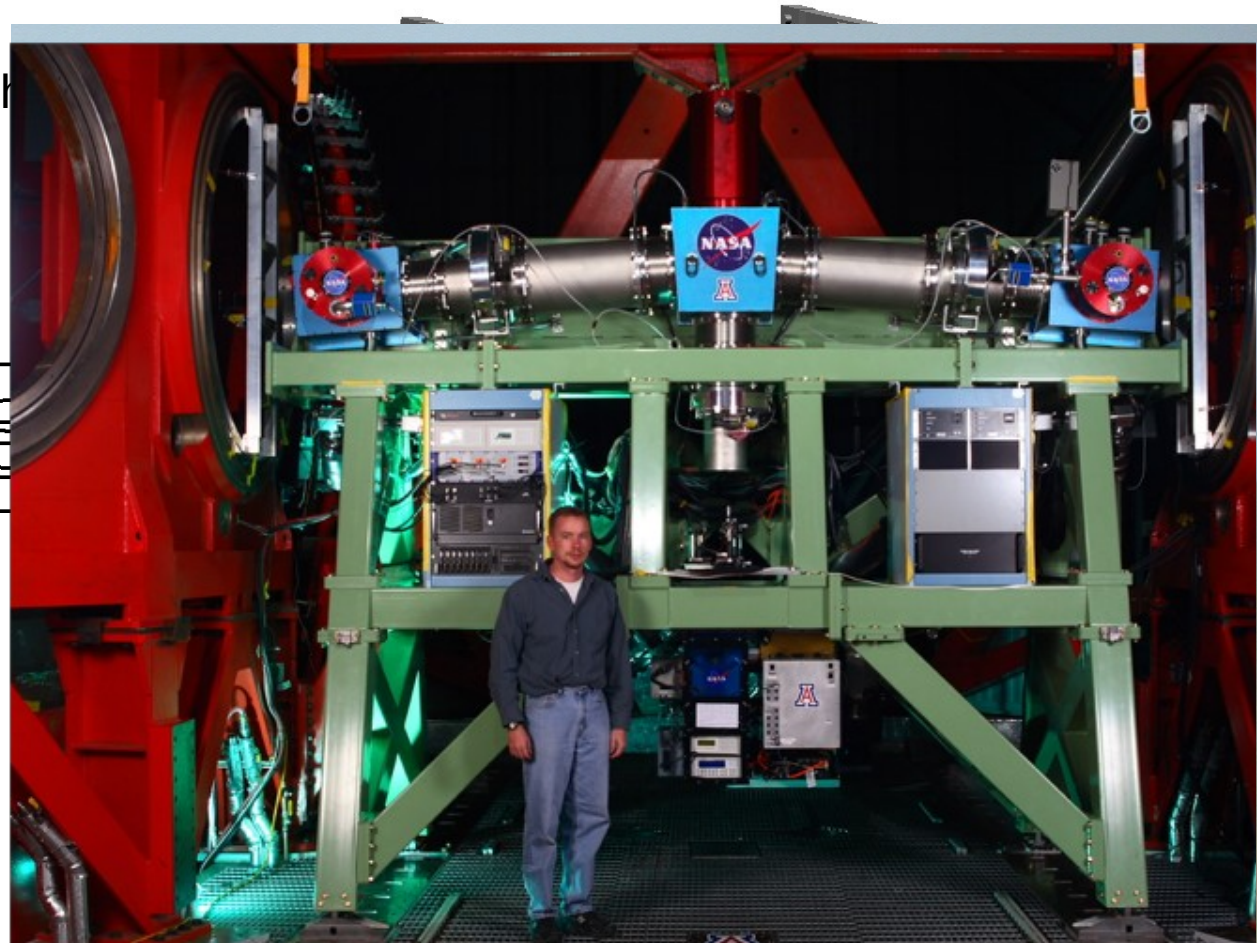
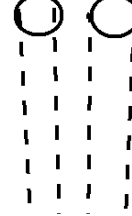
Nulling and Imaging Camera (NIC) is the
only camera at the moment.

Integrated Wavefront Sensors

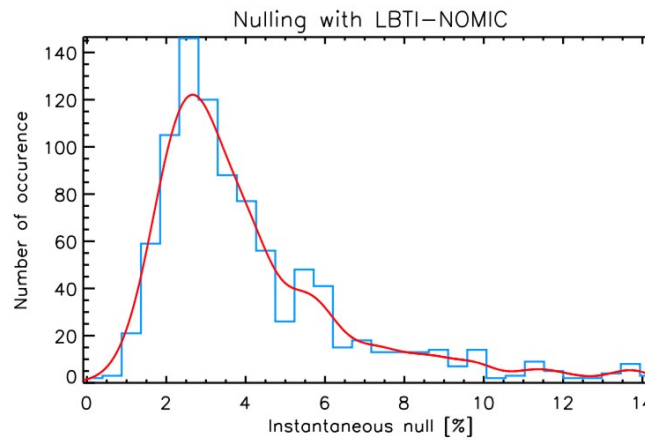
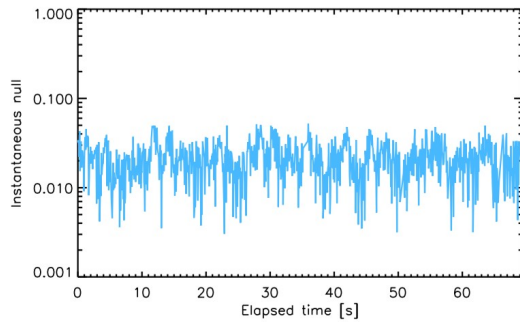


LBTI design

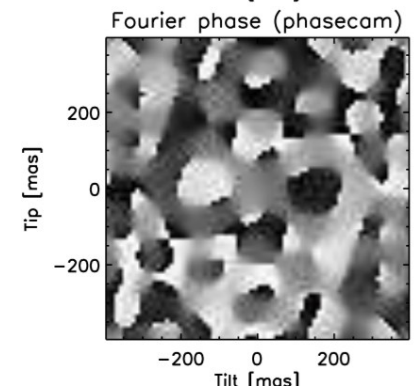
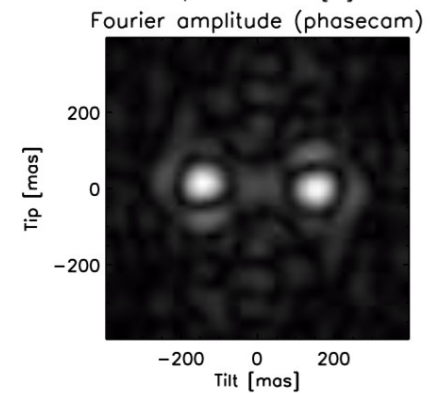
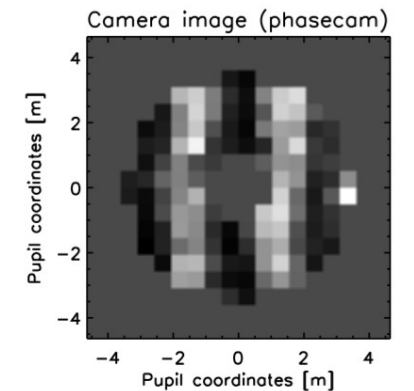
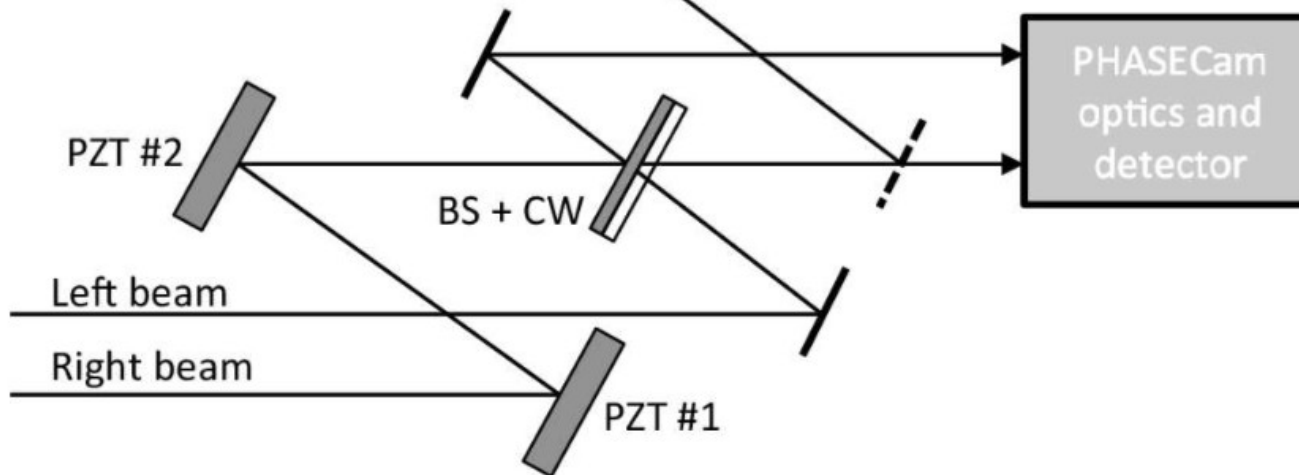
virtual exit pupil



Nulling Implementation



NOMIC
optics and
detector

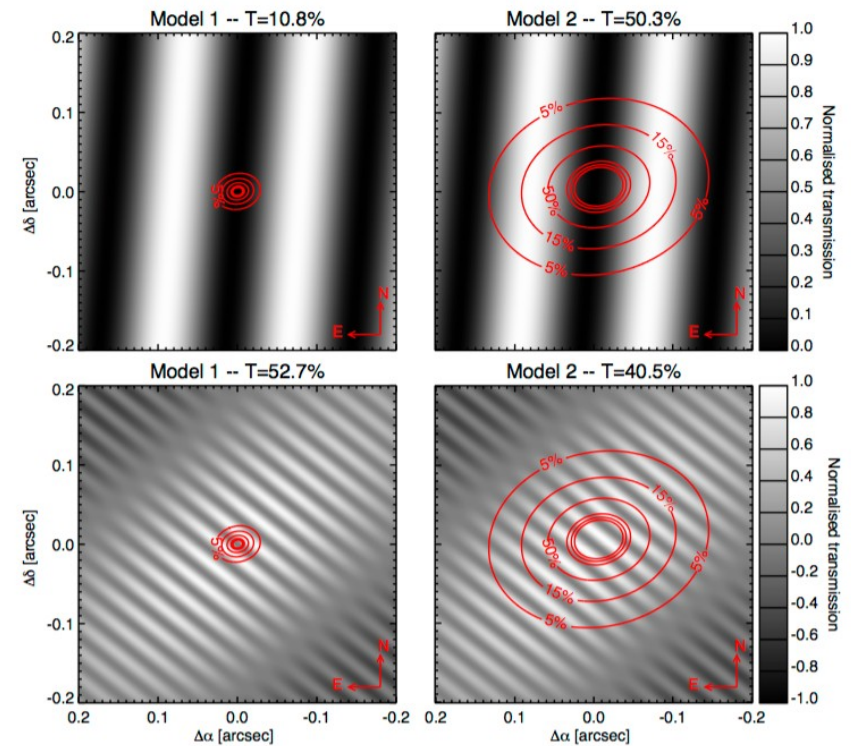
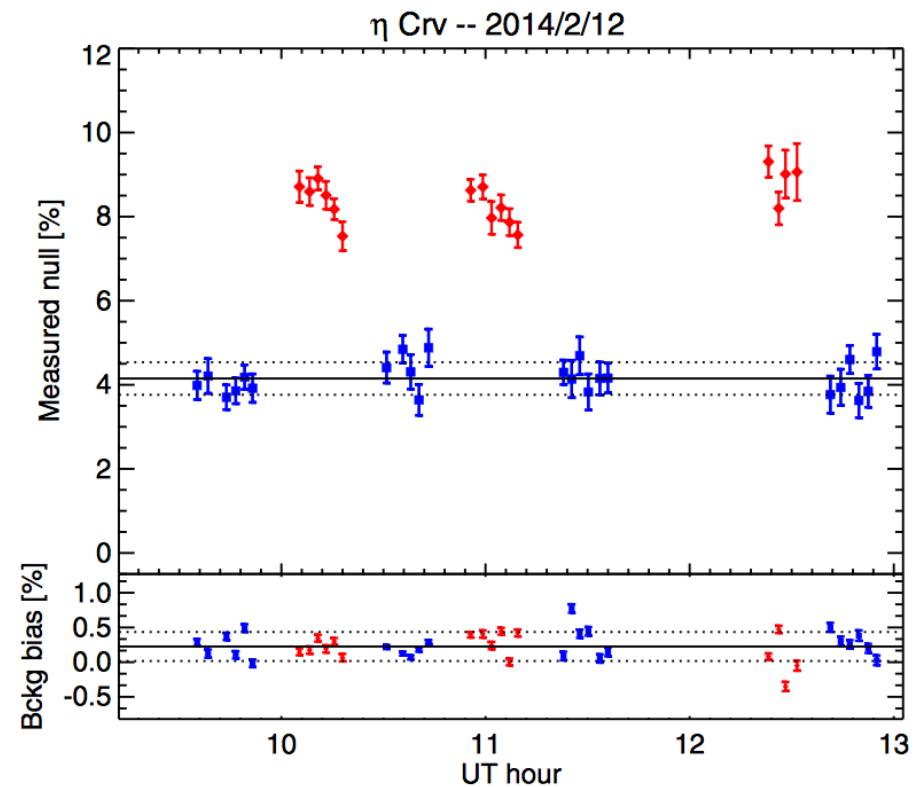


LBTI nulling first light

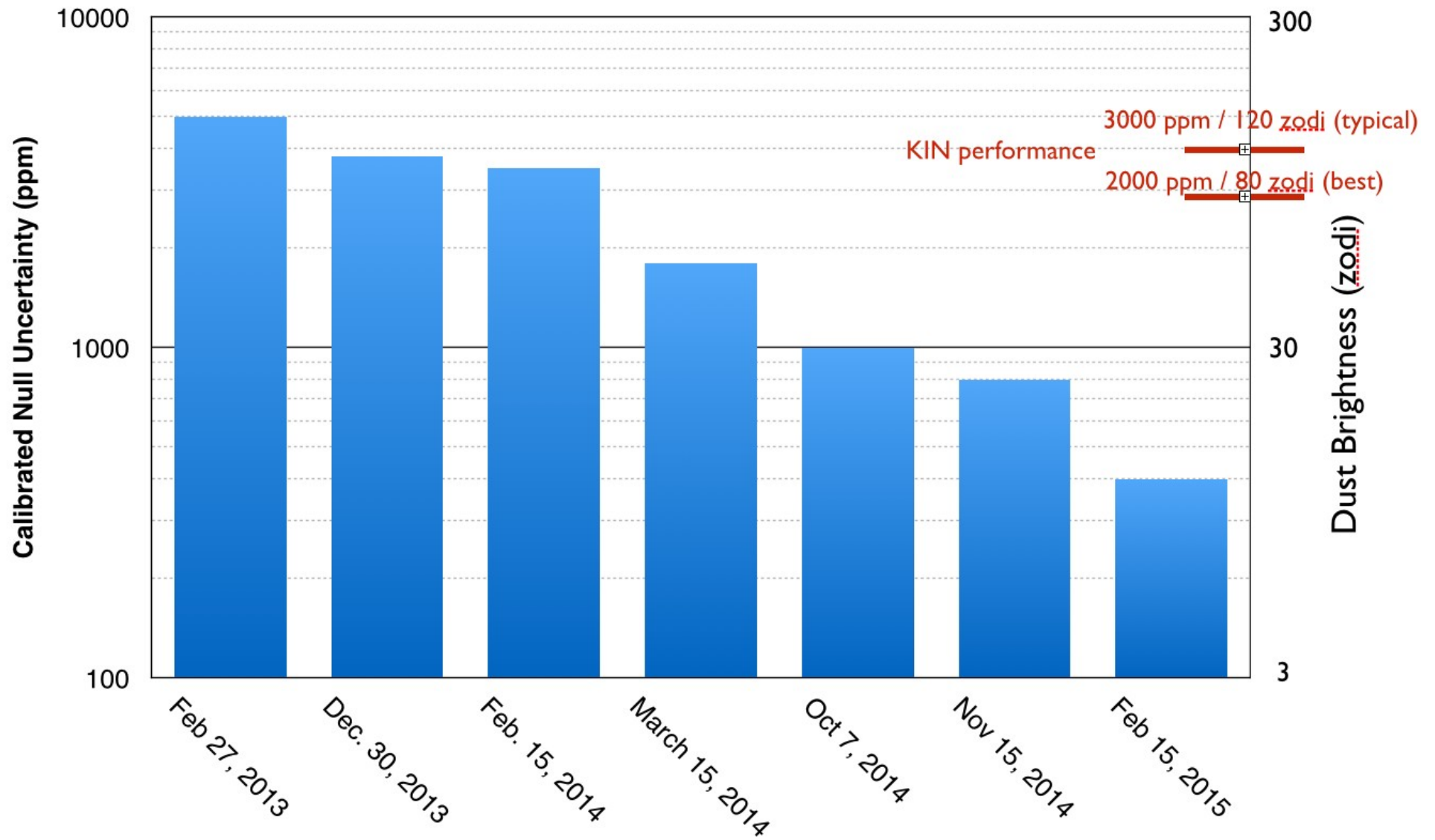
Commissioning tests on the star eta Crv detected a bright disk (Defrere et al. 2015).

Modeling indicates dust is at < 1 AU (Kennedy et al. 2015).

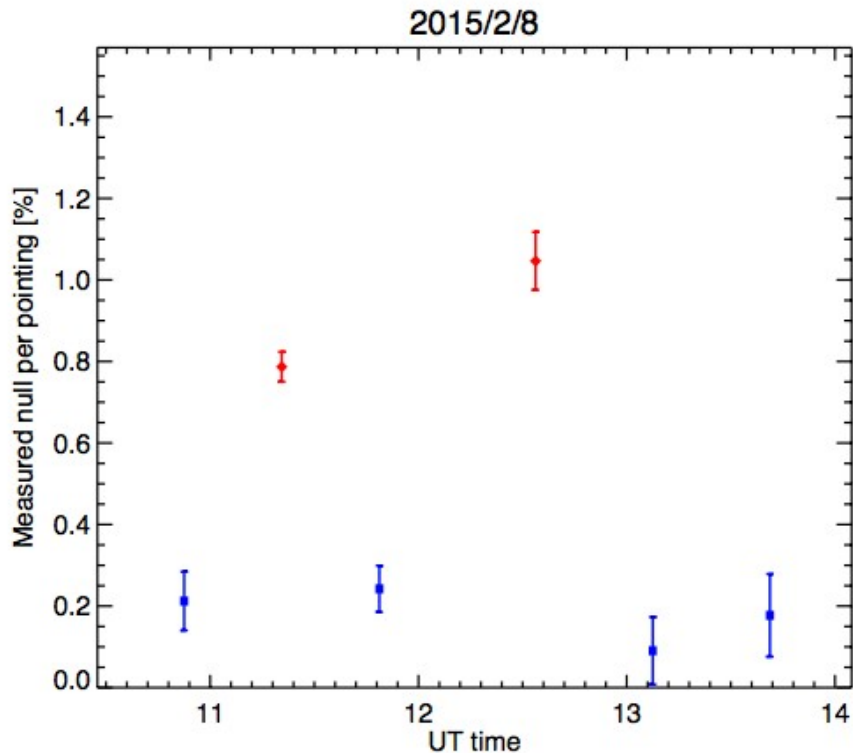
Data are consistent with a ~ 1200 zodi surface density in the habitable zone (although the model actually predicts most of the dust is inside of the HZ).



LBTI Null Uncertainty

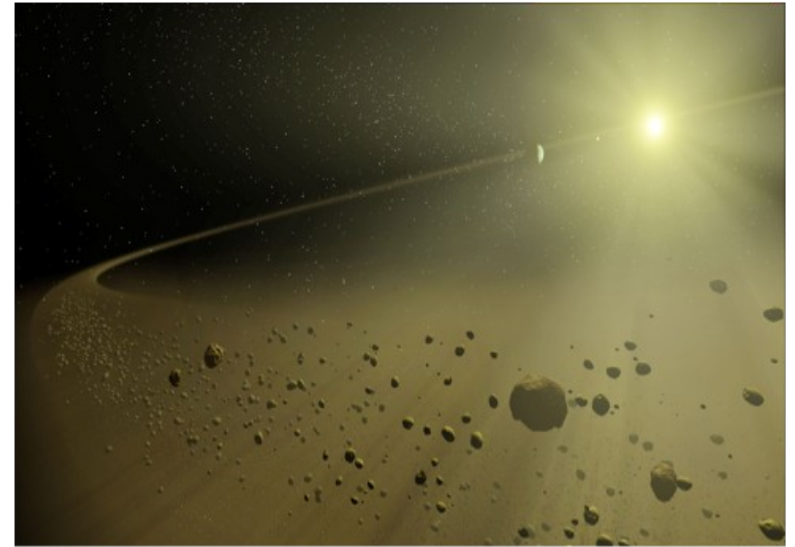


HOSTS Target 1: beta Leo



Commissioning tests on the star β Leo detected a disk at the level of 6000 ± 500 ppm.

This corresponds to a disk that is **90 ± 8 zodi.**



Cold disk known from Herschel to be at $R=40$ AU.

$11 \mu\text{m}$ emission detected by LBTI is likely at ~ 4 AU.