Beam combination in astronomical interferometers

OUTLINE:

2 telescopes interferometer
- what does it take to combine light from 2 telescopes ?
- phase and amplitude measurement

Multi (N<2) telescopes interferometry
- why >2 telescopes ?
- examples: VLT, CHARA

Technology:
- beam transport (delay lines discussed in next lecture)
- beam splitters
- fiber combiners
- image plane beam combination (also called Fizeau combination, or multi-axial combination)

From telescopes to interferometric signals: transporting and combining light beams from individual apertures

Telescopes collect the light, which needs to be **transported** and **combined** between telescopes.

Challenges:

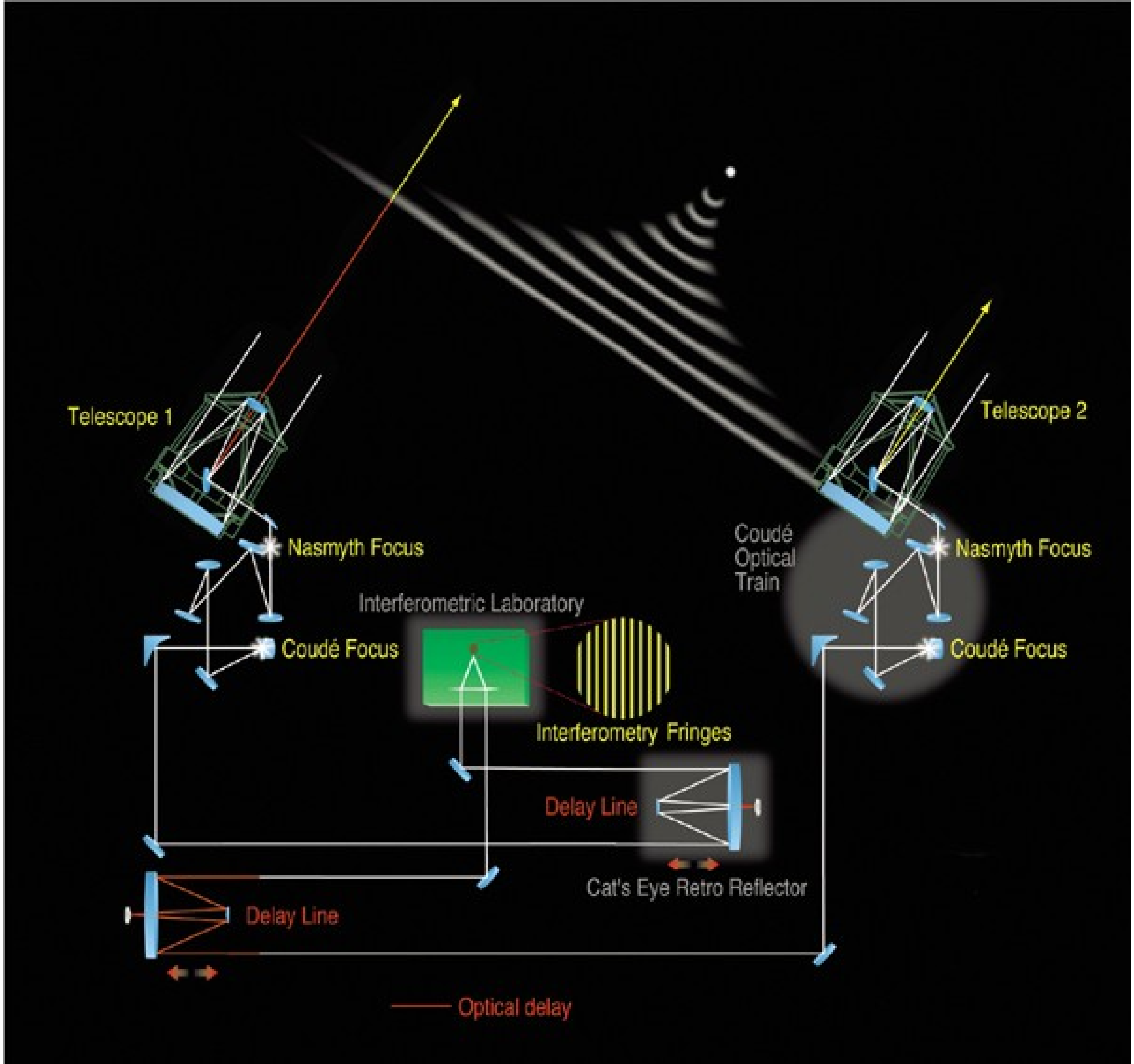
- Telescopes are moving structures, and light needs to be <u>efficiently</u> extracted from telescopes and injected into (usually) fixed optical train
- Optical Pathlength Difference (OPD) between arms of the interferometer needs to be a few waves at most. For a 100m baseline interferometer in optical, OPD is ~1e-8 of baseline. On the ground, telescopes are fixed (usually) relative to Earth, and object is continuously moving in the apparent sky : OPD is continuously changing
- OPD needs to be stable to $<<$ a wave during a single exposure

All above requirements must be satisfied over a finite wavelength range

An interferometer includes:

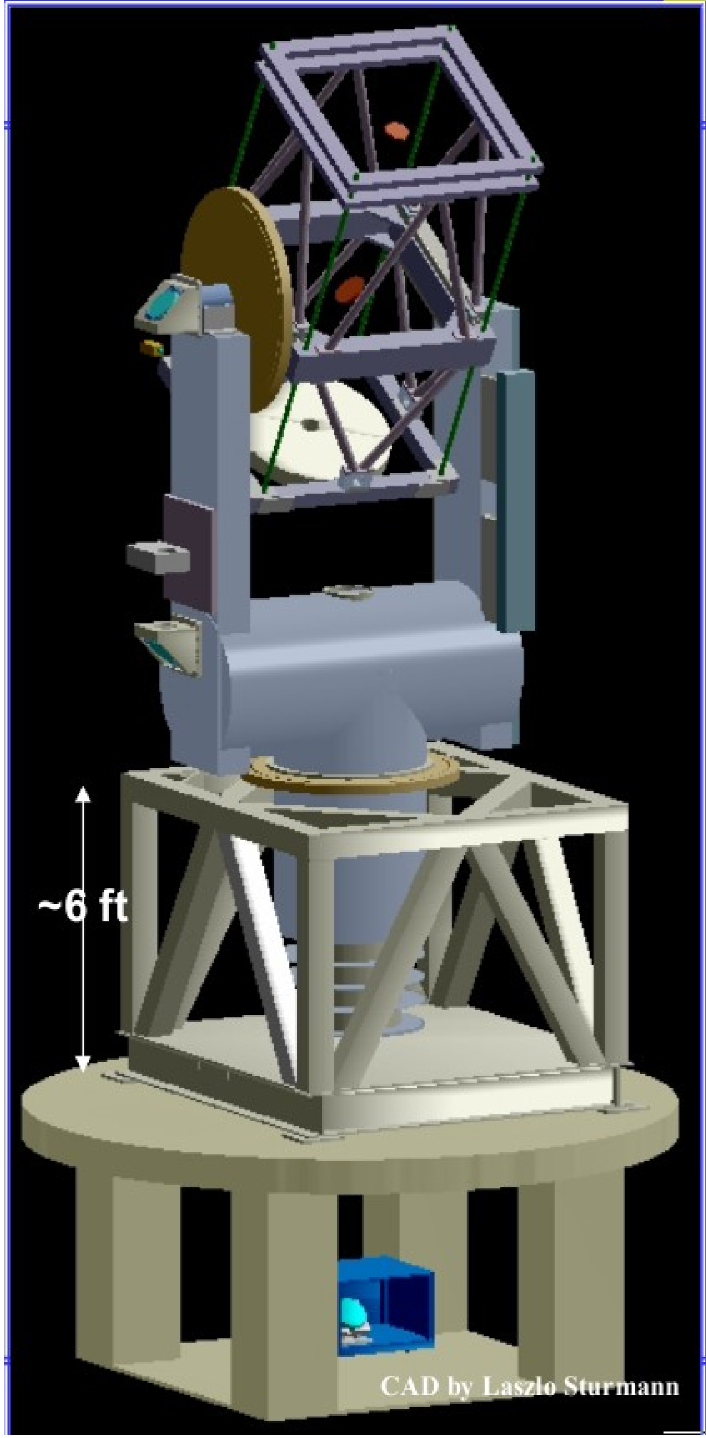
TELESCOPES : extract light from object
BEAM TRANSPORT OPTICS : transport light from telescopes to beam combiner
DELAY LINES : maintain near-zero OPD
BEAM COMBINER OPTICS : coherently mix light between telescopes
DETECTOR : measure interferometric signal

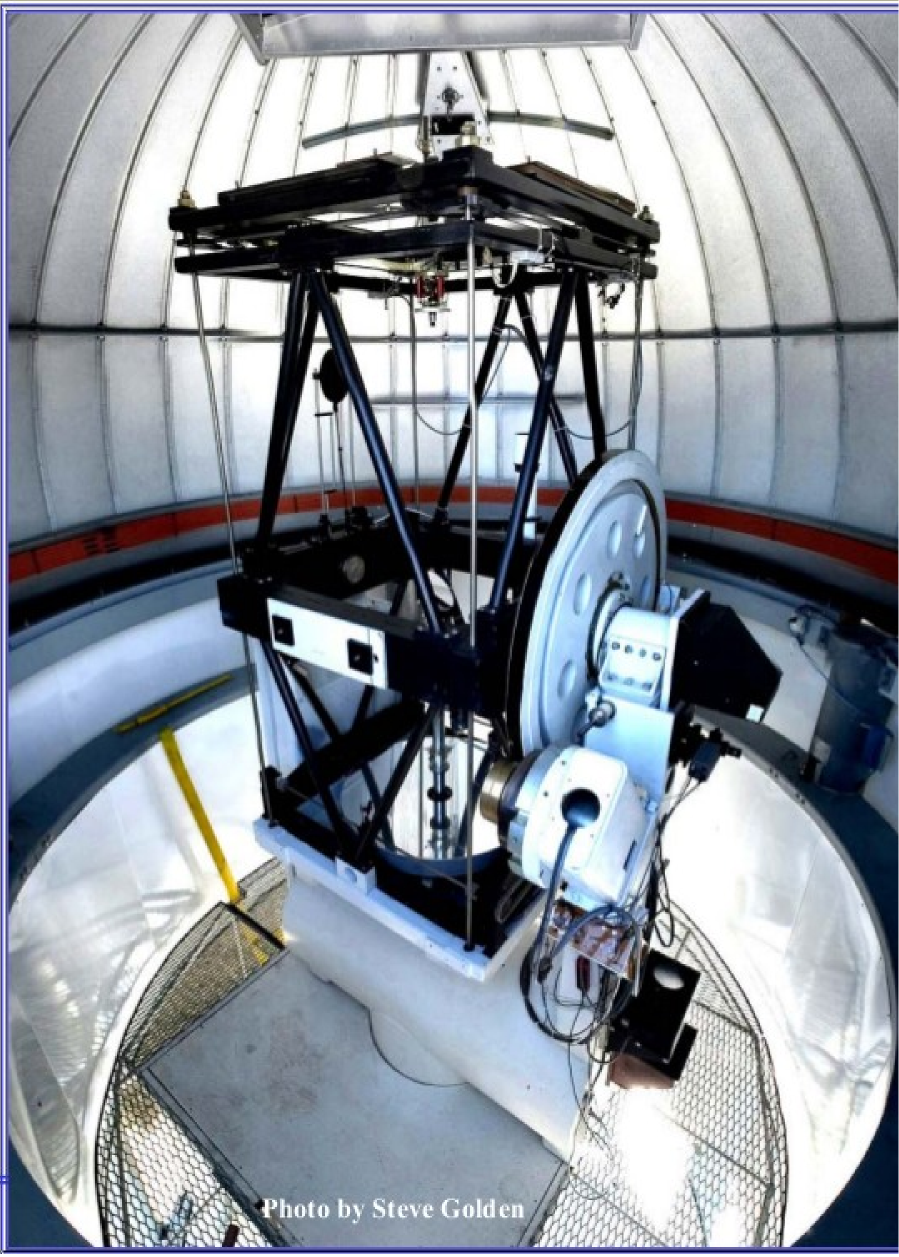
Next slide shows these steps (VLT, ESO)


Telescope 1
Telescope 2
Nasmyth Focus
Nasmyth Focus
Coudé Optical Train
Interferometric Laboratory
Coudé Focus
Coudé Focus
Interferometry Fringes
Delay Line
Cat's Eye Retro Reflector
Delay Line
Optical delay

Telescopes I.

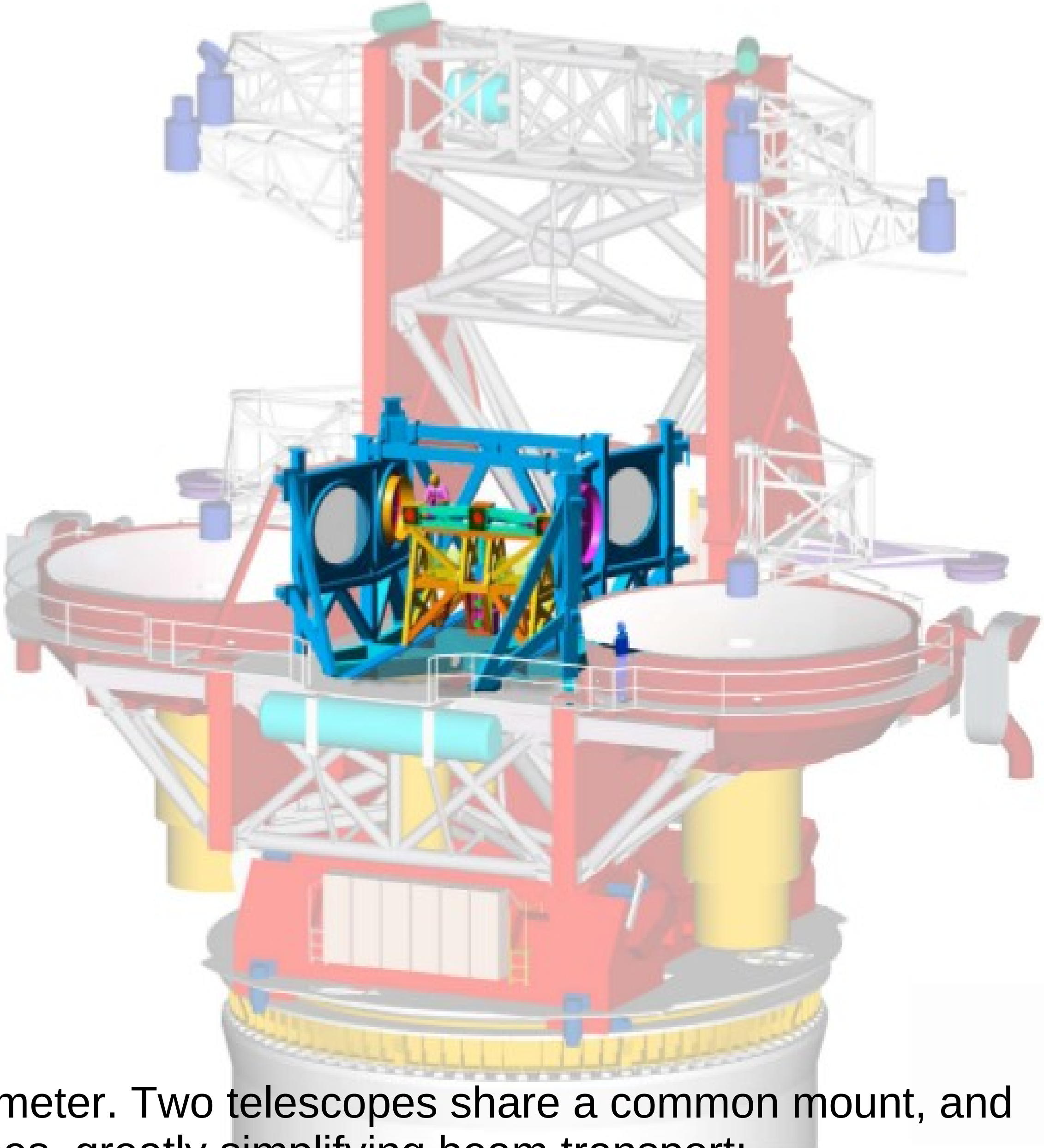
Telescope designs for interferometry





CHARA interferometer telescopes designed for easy beam extraction: beam travels through alt and az rotation axis of the telescope

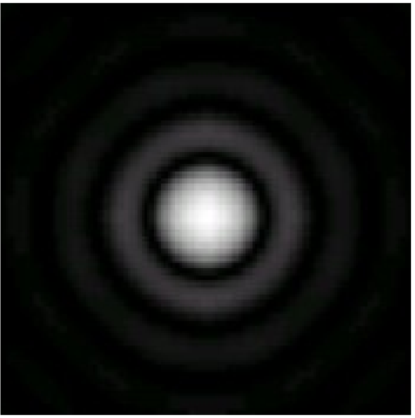
Telescope designs for interferometry

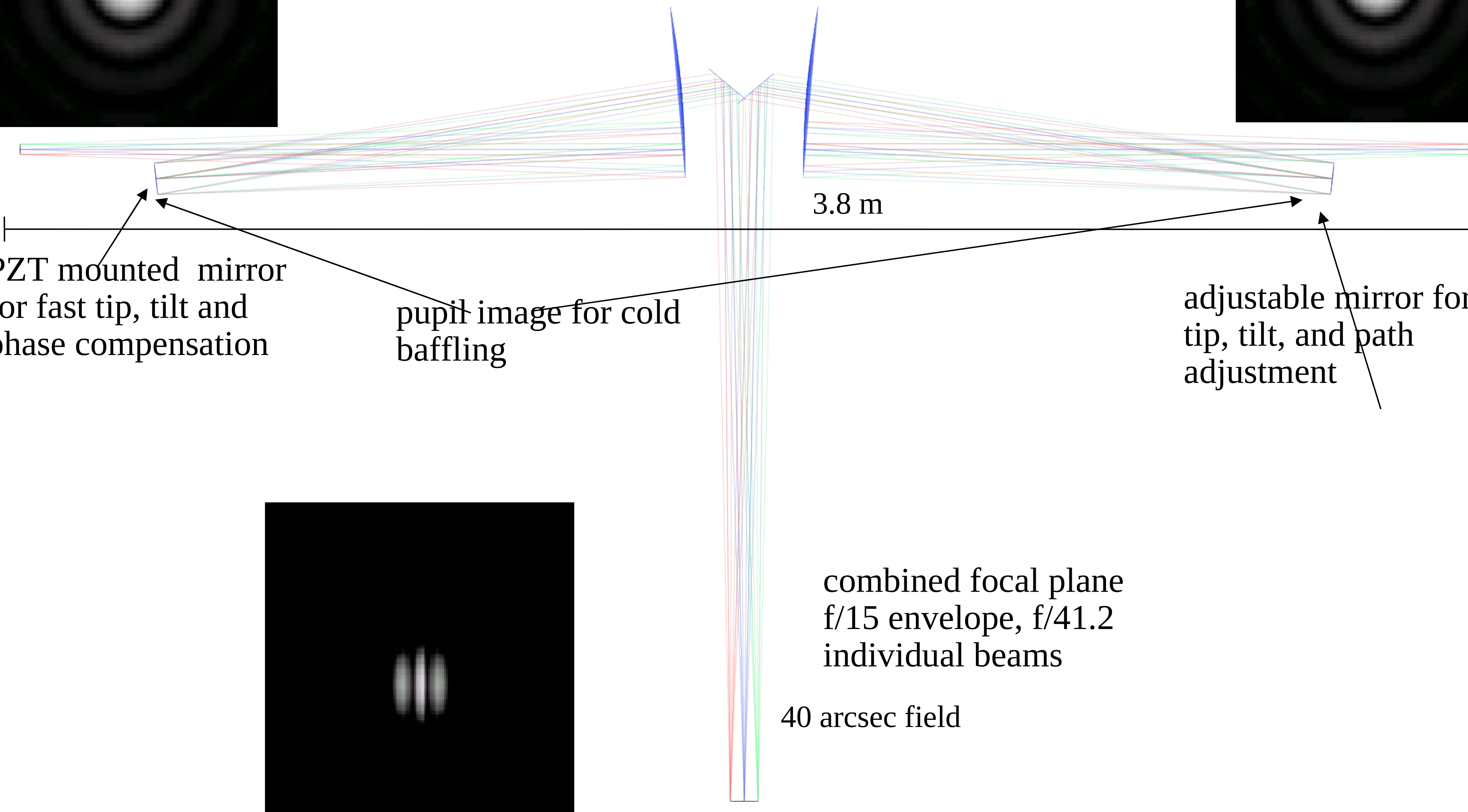


Large Binocular Telescope (LBT) interferometer. Two telescopes share a common mount, and the interferometer moves with the telescopes, greatly simplifying beam transport:
No need for long delay lines, or complex beam steering optics to carry light into inteferometer.

Advantage: higher throughput and lower emissivity in IR (fewer optics)
Common mount interferometer limited to short baselines on ground, but can be large in space.

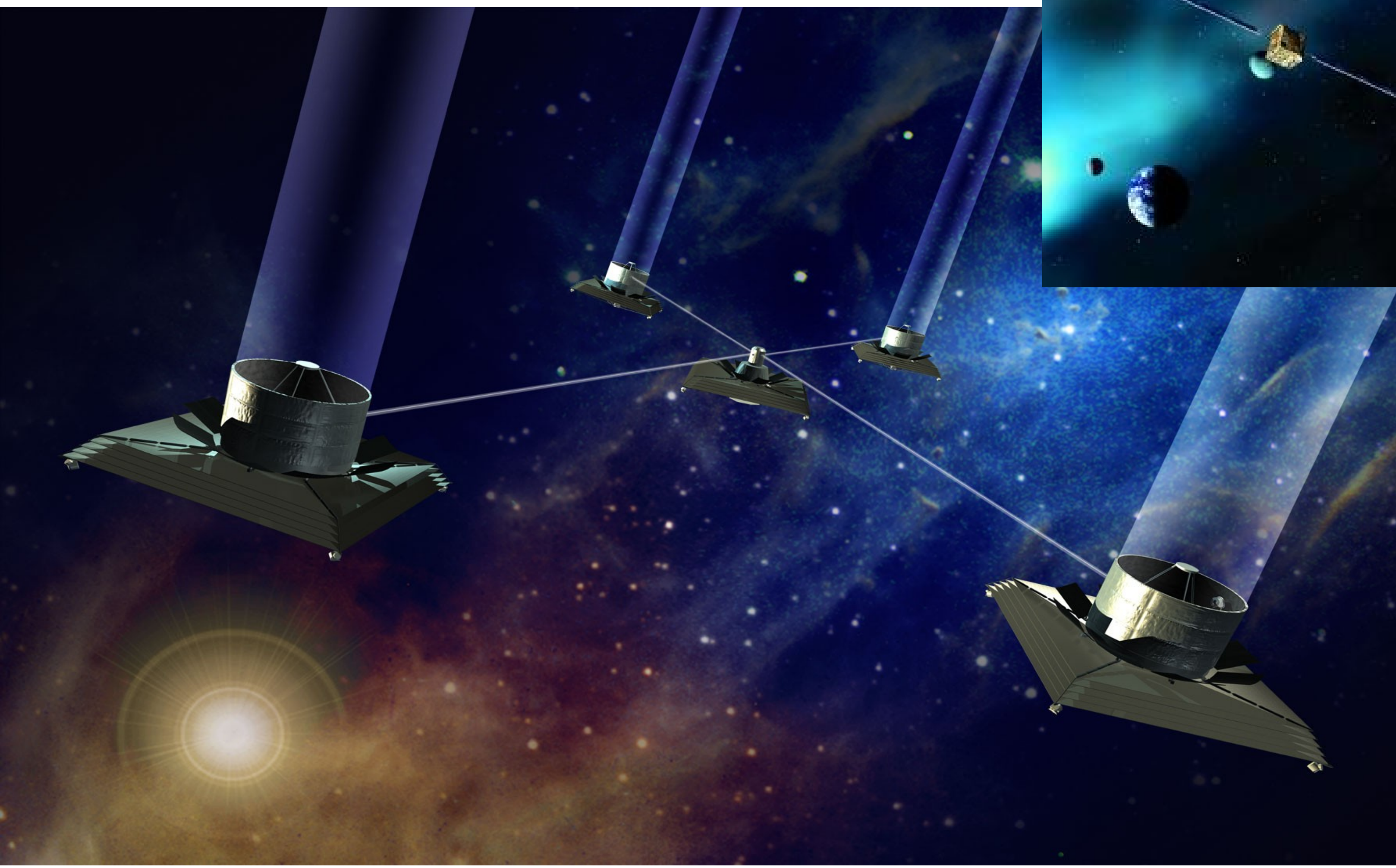
Beam Combination





Telescope designs for interferometry (Space)

Darwin mission concept (ESA)
Note: mission did not go beyond concept

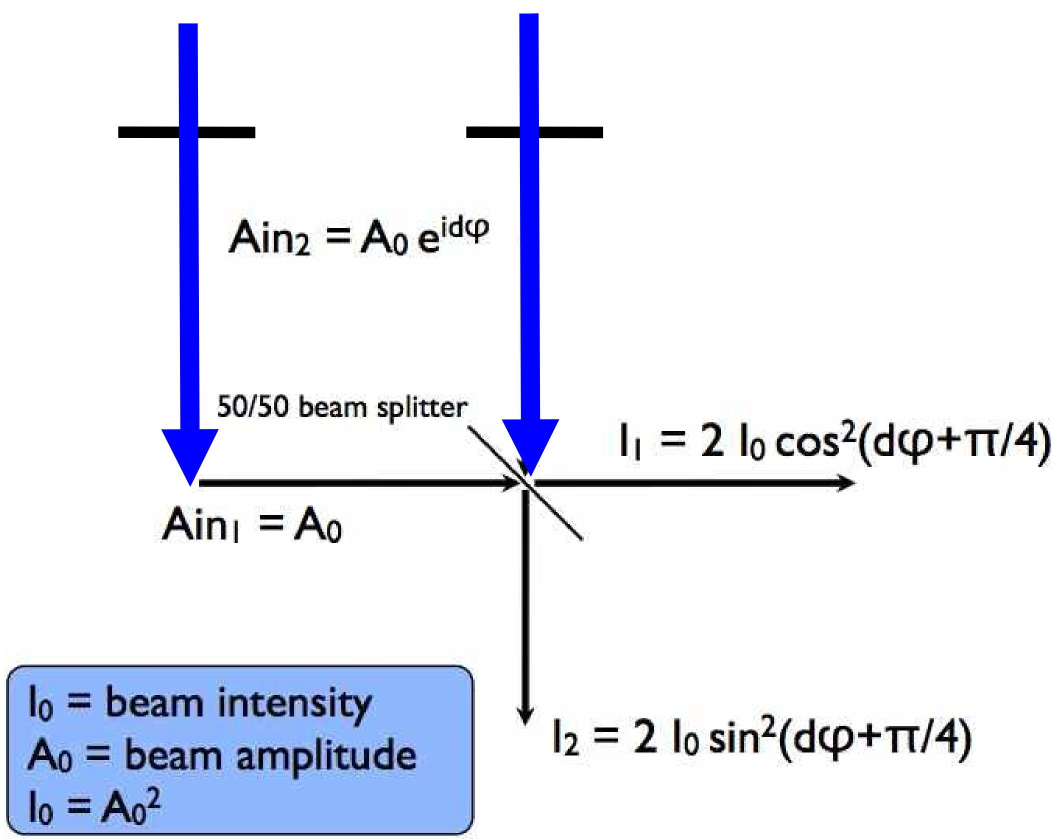


Terrestrial Planet Finder mission concept (NASA)
Note: mission did not go beyond concept

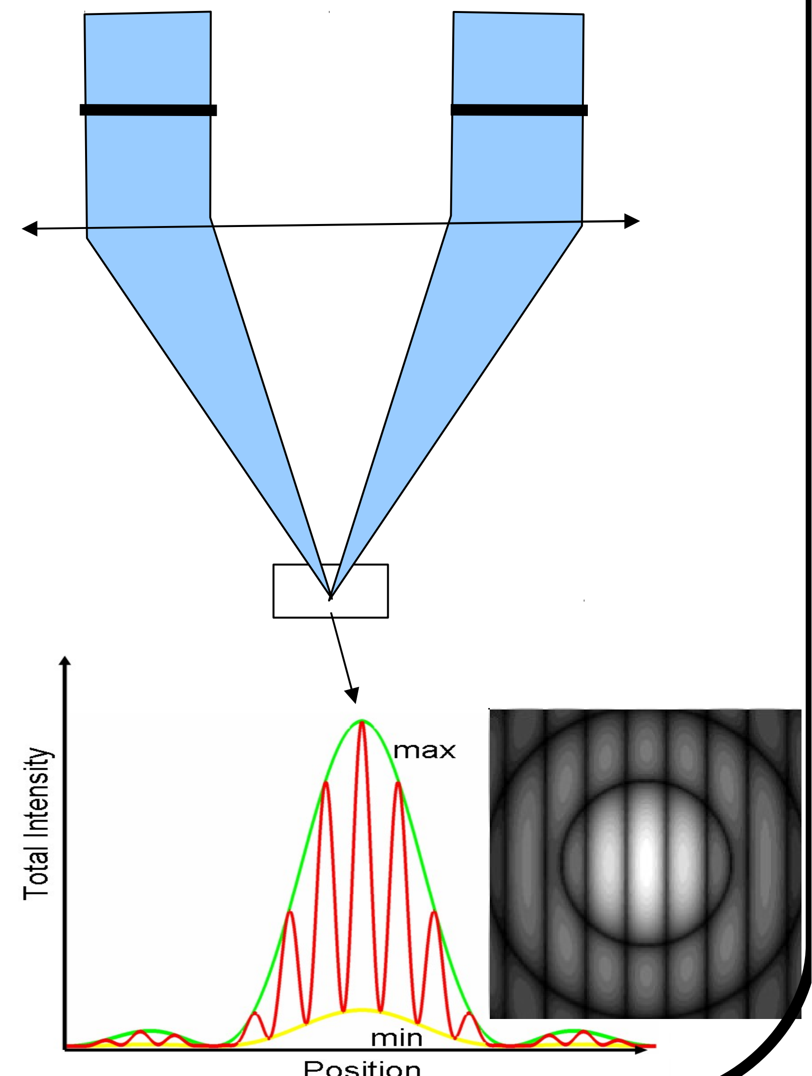
Space interferometry is possible without delay lines.
All telescopes at equal distance from central recombination hub.

Co-axial vs. Multi-axial beam combination

Co-axial: pairwise combinations using beam splitters



Multi-axial: beams sent to a single imaging optical system



The Sine Condition (also called the golden rule)

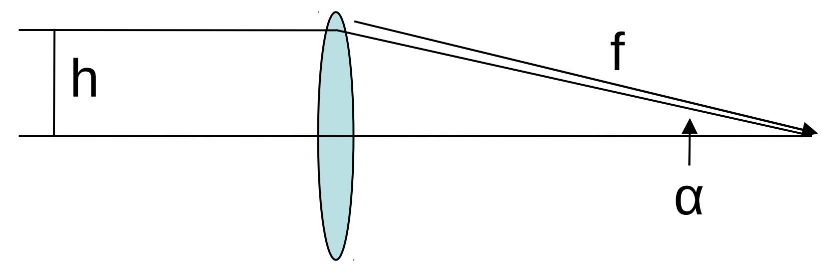
Properly designed imaging systems obey the sine condition for the relation of the object plane to the image plane. For imaging systems with the object at infinity the relation becomes

$$\sin \alpha = h/f$$

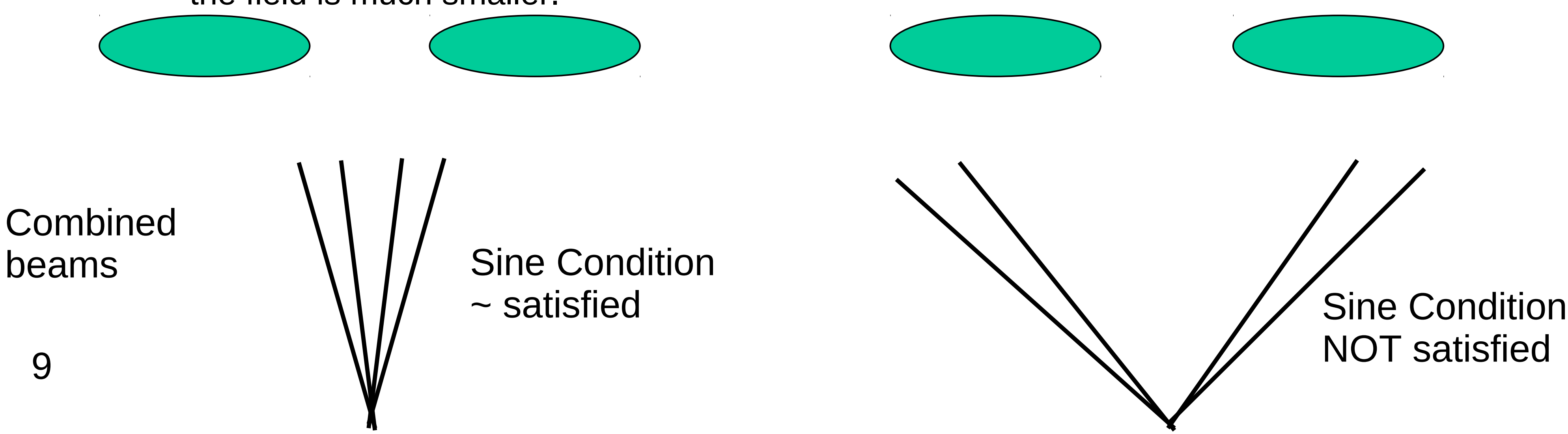
where h is the height of the ray from the optical axis and f is the focal length of the system.

For interferometers, obeying this design constraint results in interference fringes for a source anywhere in the focal plane.

For interferometers not obeying this constraint the field is much smaller.



Example: Michelson's Stellar Interferometer



Co-axial vs. Multi-axial beam combination

Co-axial combination
Advantages:

- Efficient use of detector pixels
- Each beam is treated as a single mode
  - → spatial filtering techniques can be used (fibers, pinholes) to clean beams
  - → easy to transport beams over large distances
  - → high accuracy calibration is possible

Limitations:

- Information accross individual apertures is erased
- small field of view (usually limited to diffraction limit of a single aperture)
- becomes complicated with large number of apertures: number of beam splitters grows as ~N^2

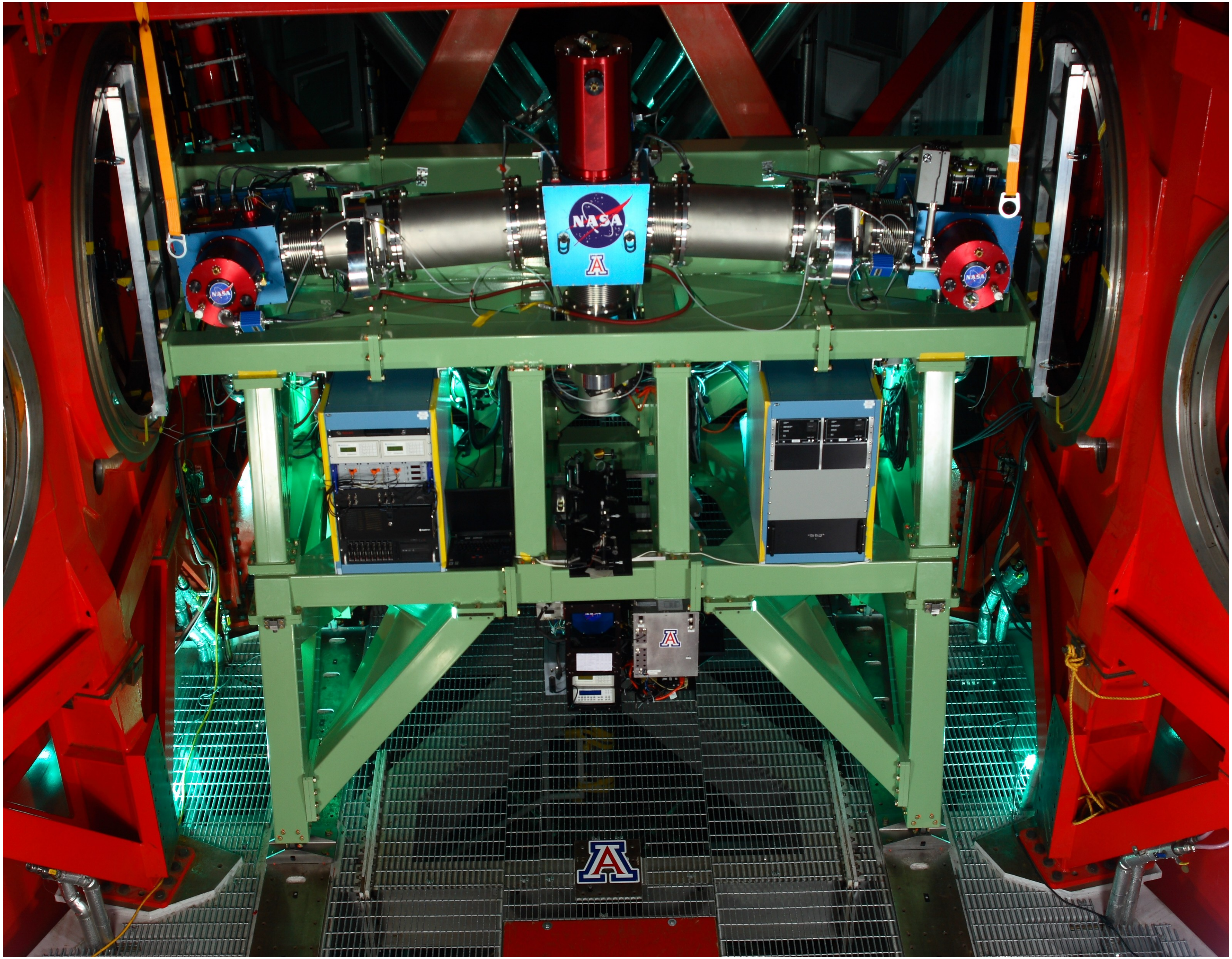
Co-axial combination is usually preferred for long baselines / single object interferometry.
Most current interferometers use co-axial combination

Examples: CHARA, Keck, VLTI

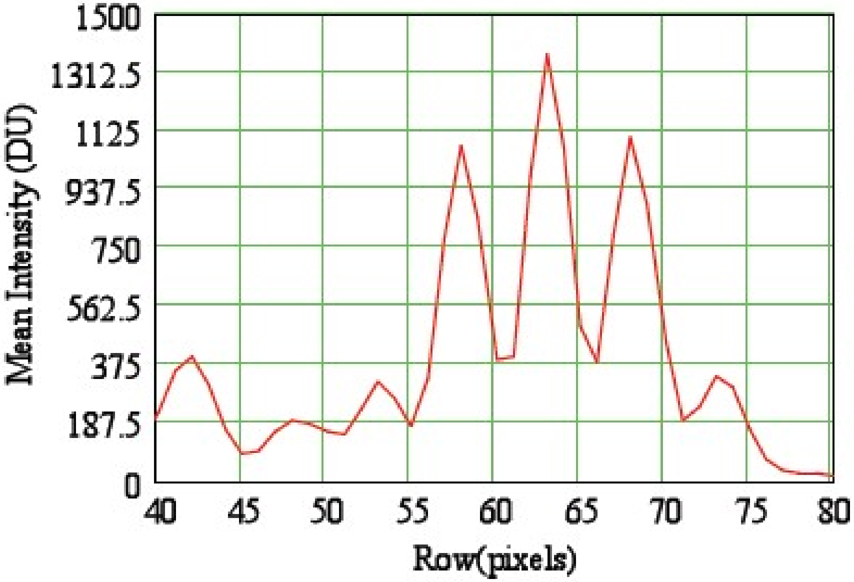
Multi-axial (Fizeau) combination is required for wide field of view, and is attractive when telescopes aperture is comparable to baseline

Example : LBTI

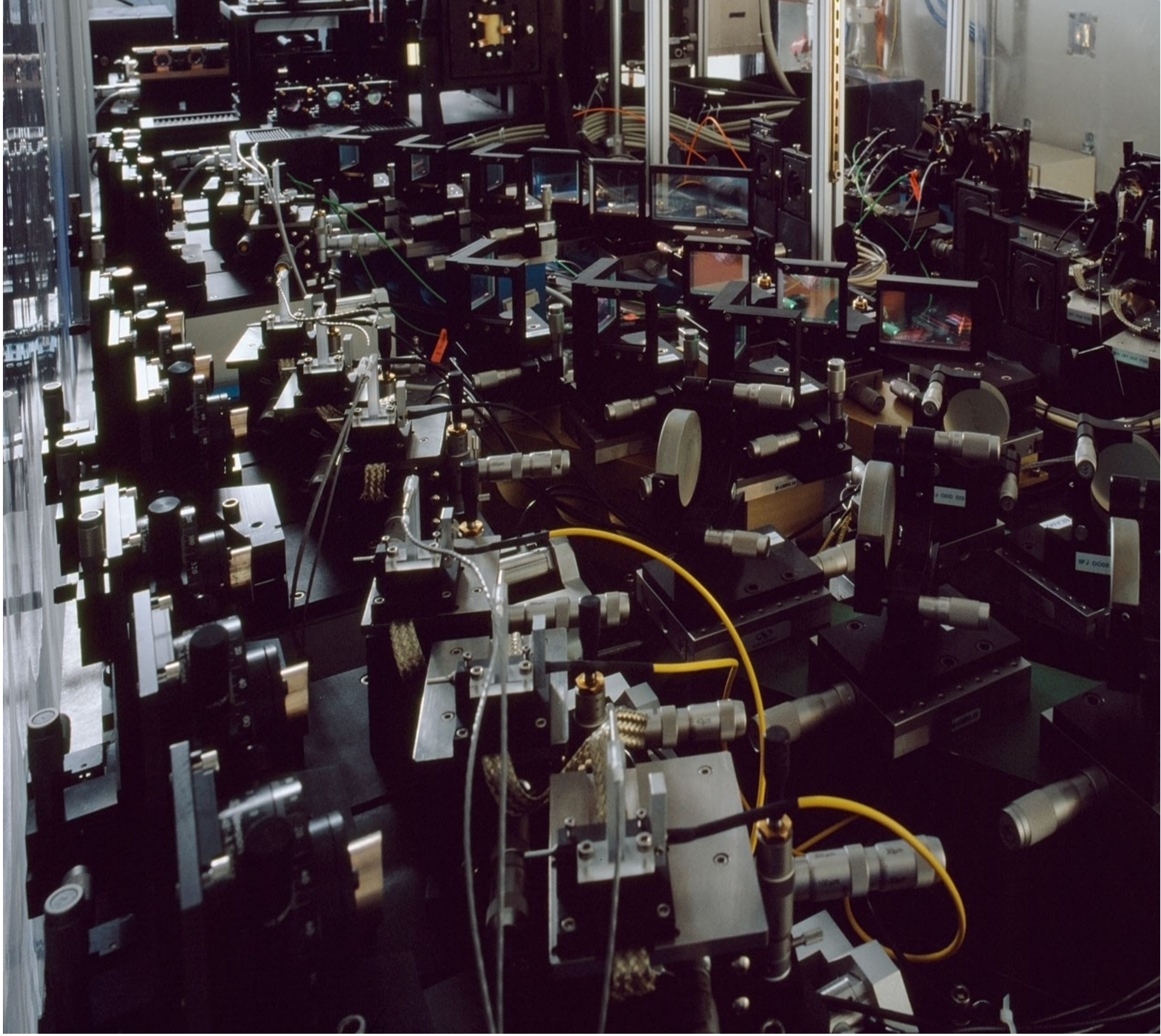
LBTI on the LBT



Coaxial beam Combination
(LBTI First Fringes)



Combining beams with beam splitters

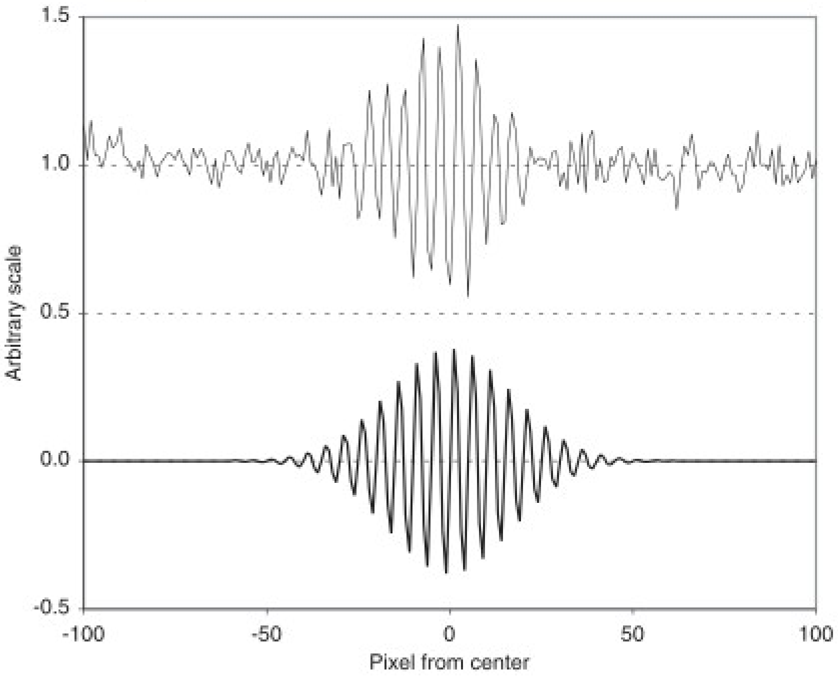


AMBER beam combining optics (VLT, ESO)
Several beam splitters are seen in this picture

Temporal scan of phase: fringe packet

Single measurement with a beam splitter does not provide sufficient information, as intensity, fringe visibility and phase (3 parameters) need to be measured.
Two approaches:

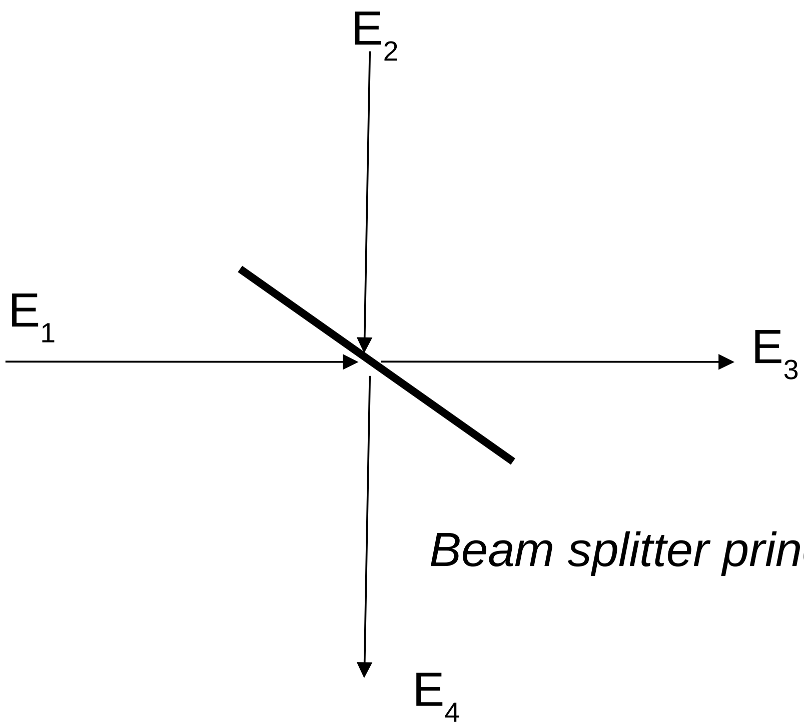
- more beam splitters, and phase shifts to sample sine wave on at least 4 points
- single beam splitter, but temporal known variation of phase: fringe scanning. The measurement is a fringe packet



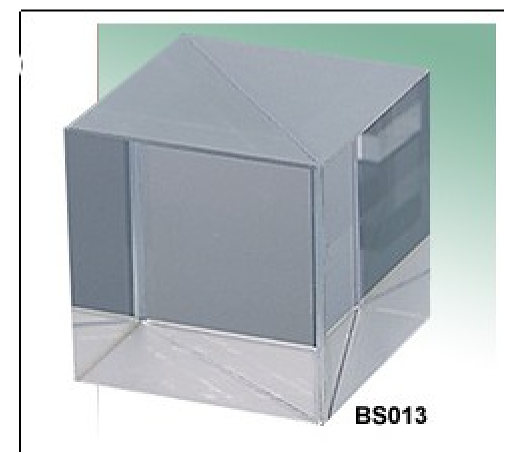
Fringe packet width is limited by coherence length

x axis: time, OPD

Combining beams with beam splitters



Beam splitter principle



output
(complex numbers)

input
(complex numbers)

$$\begin{pmatrix} E_3 \\ E_4 \end{pmatrix} = \boxed{\begin{matrix} T_{31} & R_{32} \\ R_{41} & T_{42} \end{matrix}} \begin{pmatrix} E_1 \\ E_2 \end{pmatrix}$$

beam splitter matrix
Unitary matrix (conserves flux)

$T_{31} = T_{42} = T = |T|e^{i\phi t}$
$R_{32} = R_{41} = R = |R|e^{i\phi r}$

$R^2 + T^2 = 1$

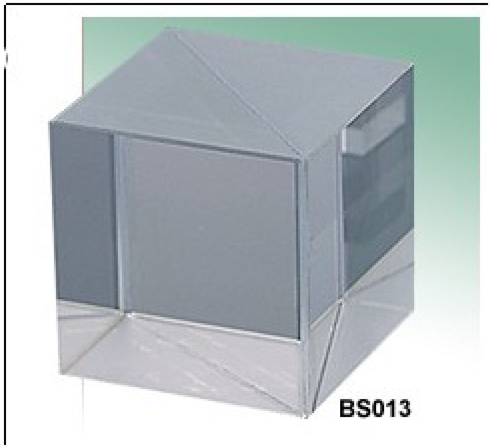
$|\phi r - \phi t| = \pi/2$

For 50/50 beam splitter:
$|R| = |T| = 1/\mathrm{sqrt}(2)$

Example:

Wavefronts arrive in phase at a 50% BS with $\phi t=0$ -> $\phi r= \pi/2$.

E1 is given a phase shift of $\pi/2$.



$T_{31} = T_{42} = T = |T|e^{i\phi t}$
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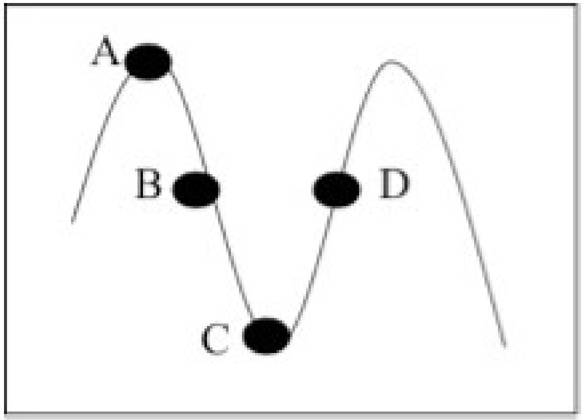
For 50/50 beam splitter:
$|R| = |T| = 1/\text{sqrt}(2)$

Coaxial Observations

Measure fringe at 4 points over one wavelength of OPD (or derive these values from a fit).



Then if:

X=A-C

Y=B-D

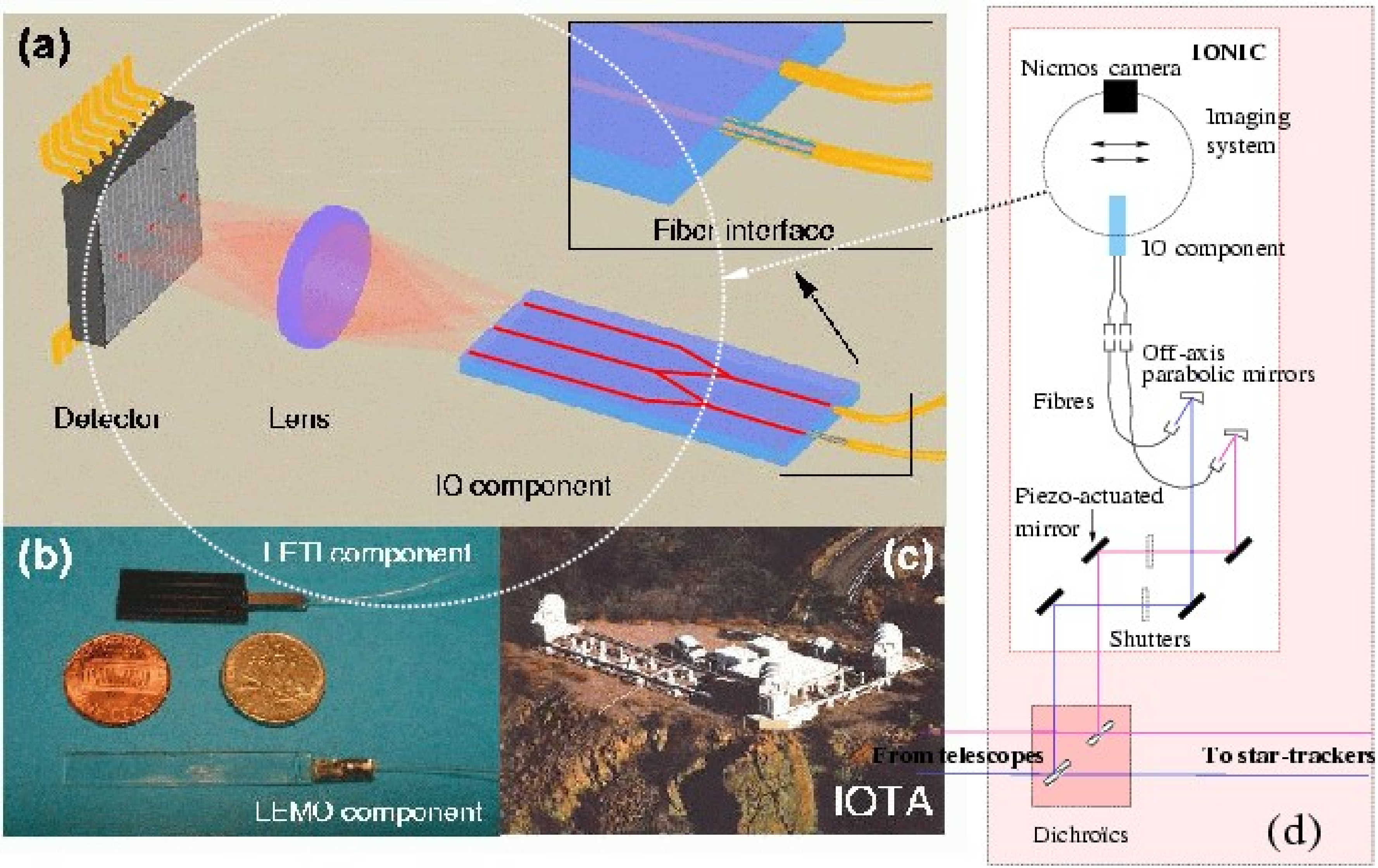
N=A+B+C+D

$$V^2 = \frac{\pi^2}{2} \frac{X^2 + Y^2}{N^2}$$

$$tan\phi = \frac{Y}{X}$$

See Colavita 1999 for discussion of data analysis.

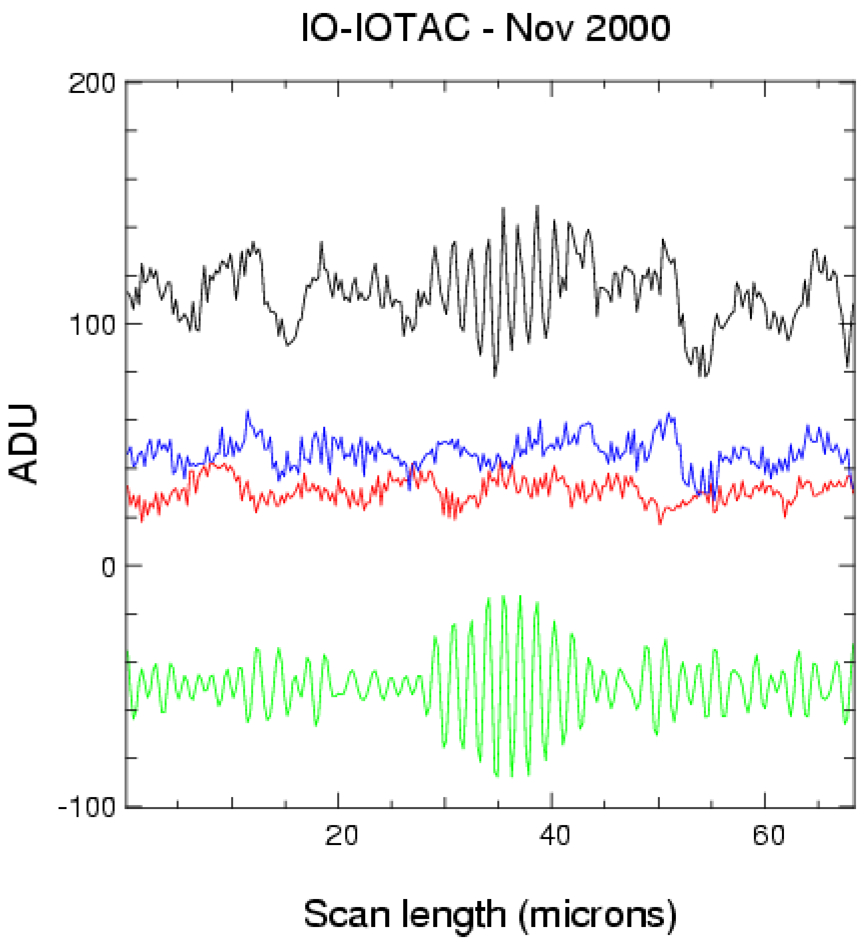
Combining beams with single-mode optical fibers



IOTA interferometer near-IR 2-beam integrated optics beam combiner (Berger et al. 2001)

Fiber beam combiner in integrated optics

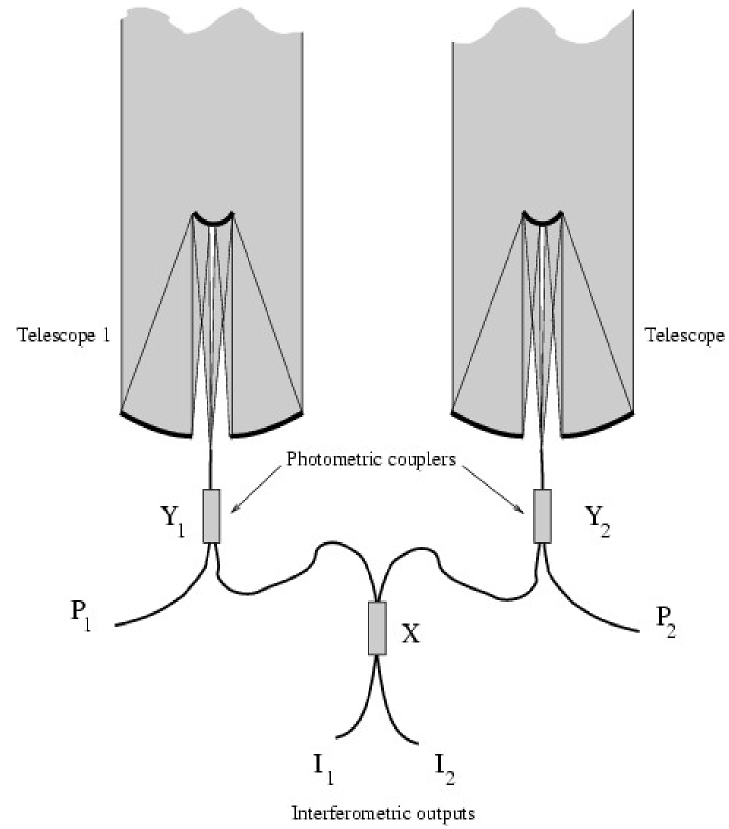
This slide shows how photometric outputs are used to calibrate interferometric fringes in an interferometer



I1

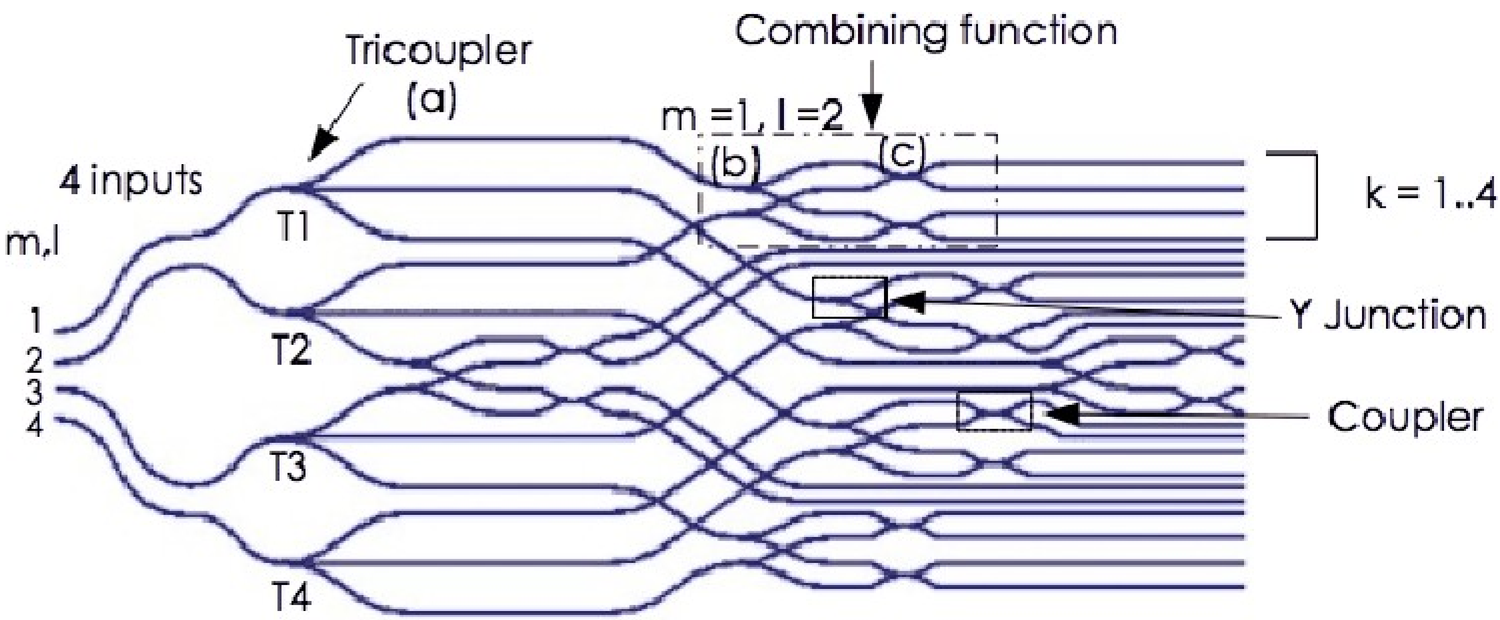
P1, P2

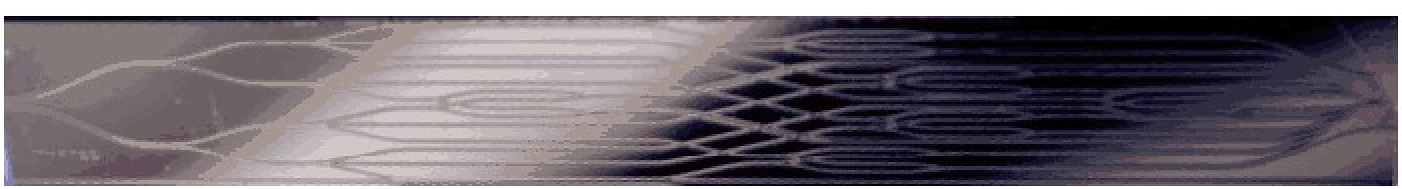
Calibrated signal takes into account mismatch between P1 and P2



IOTA fiber interferometer (Berger et al. 2001)

Fiber combiners can enable compact instruments thanks to integrated optics





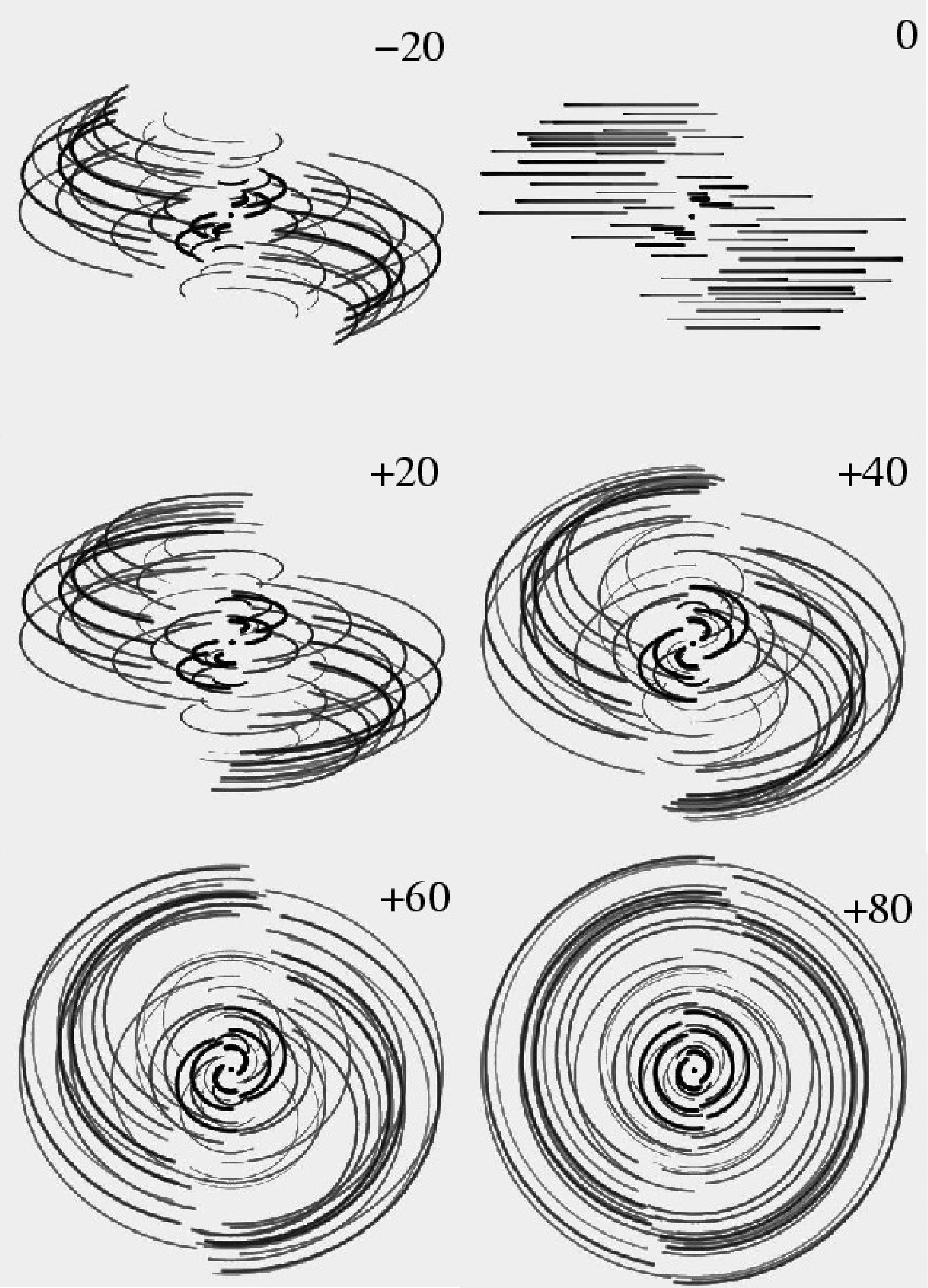
Prototype near-IR 4-beam combiner (Benisty et al. 2009)

Multi (N<2) telescopes interferometry: why >2 telescopes ?

Number of independent measurements increases rapidly with N:

Number of baselines for an interferometer with N apertures = N(N-1)/2
→ 2x more apertures ~ 4x more baselines

Since the number of measurements increases faster than the number of apertures, with large N, it becomes possible to calibrate out measurement errors with **phase closures** (discussed in next lecture)

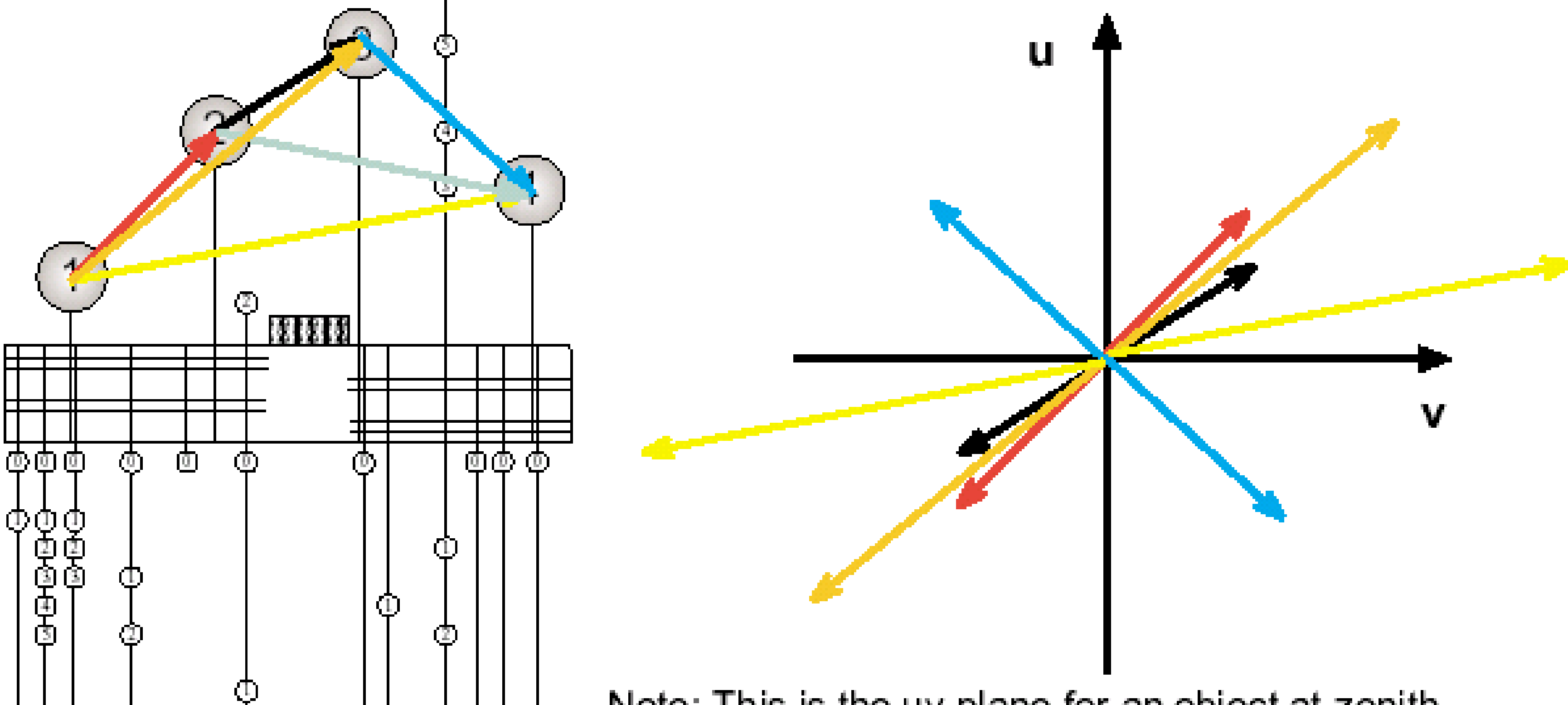


Simulated (u,v) plane coverage for telescopes atop Mauna Kea, as a function of source DEC

VLTI u-v plane coverage

The uv-plane

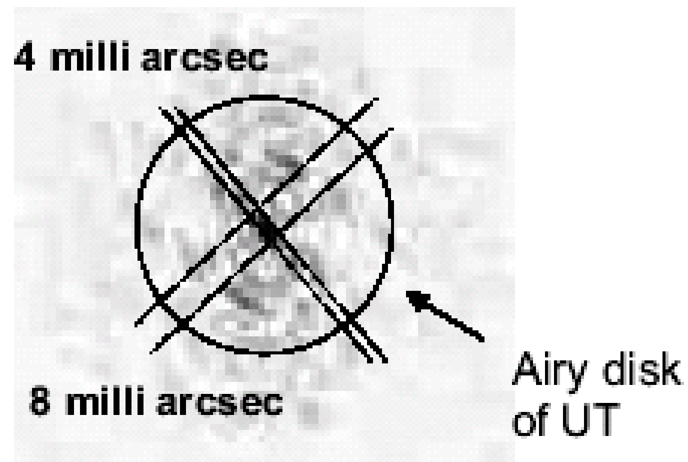
This is the uv-plane:



Note: This is the uv-plane for an object at zenith.
In general, the projected baselines have to be used.

VLTI u-v plane coverage

The uv-plane with the UTs



uv coverage for object at -15°

8 hour observation with all UTs

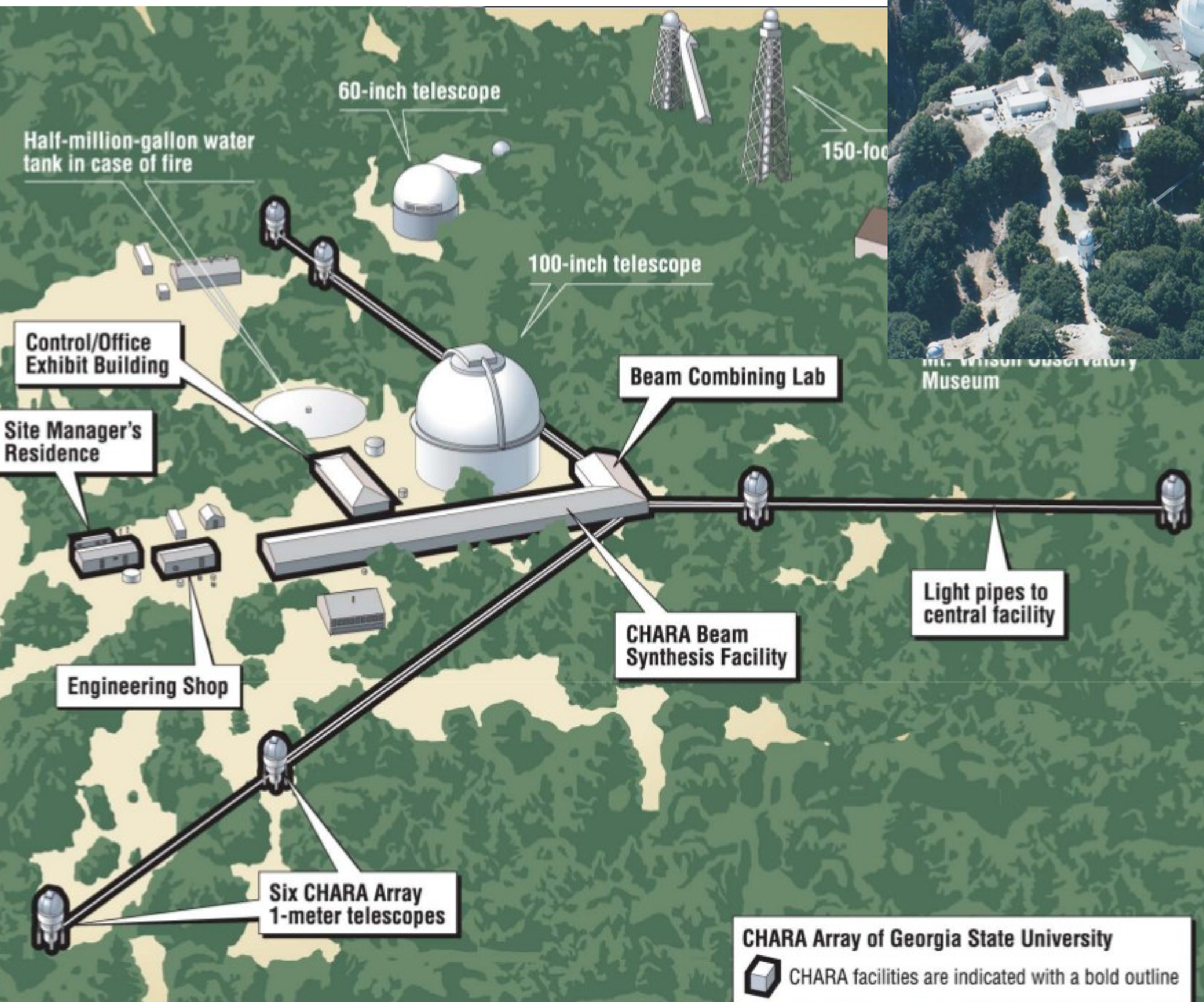
Resulting PSF is the Fourier transform of the visibilities

λ = 2.2μm (K-band)

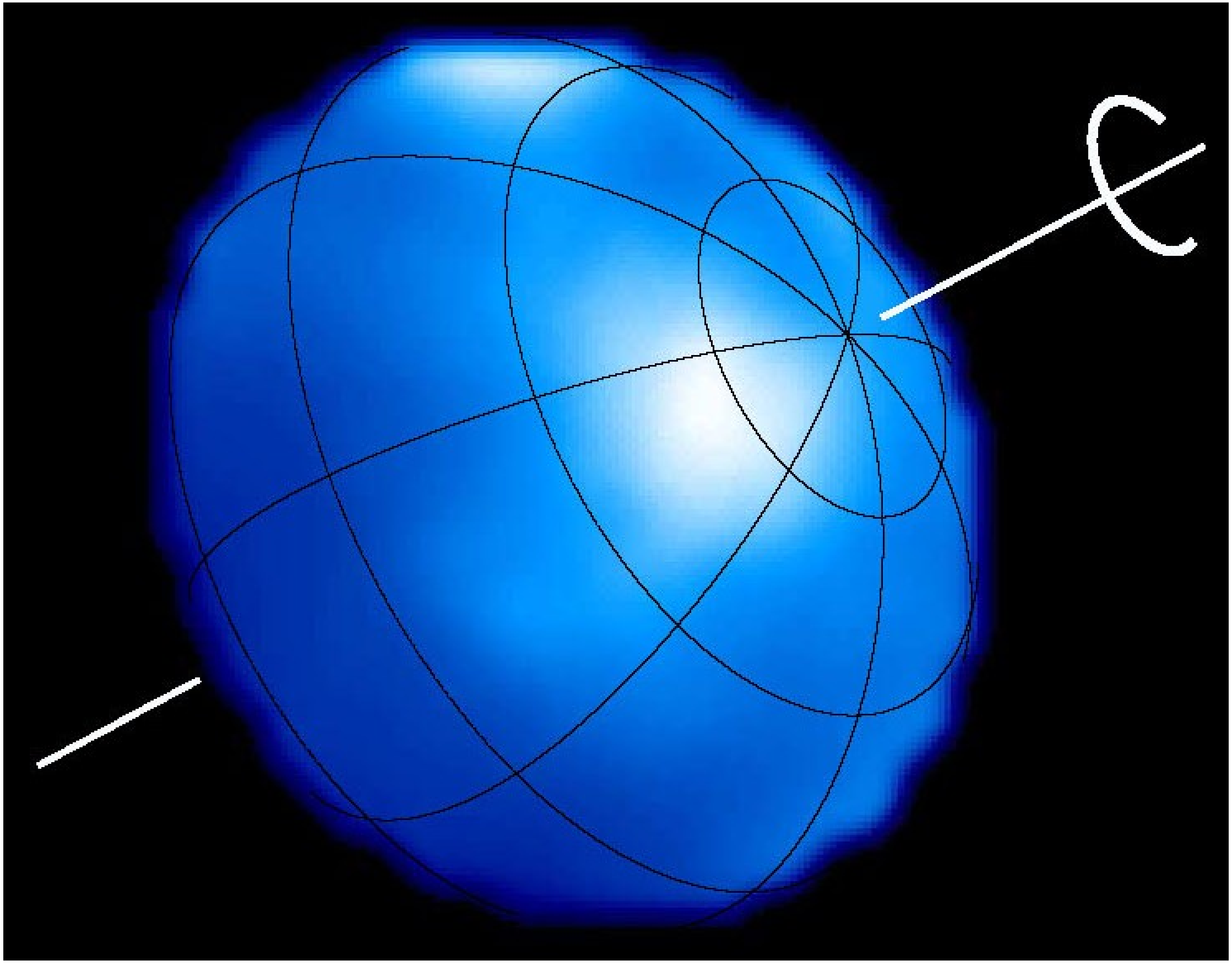
Need to measure visibility and phase to synthesize image.

VLT interferometer: 4 large 8m telescopes + smaller 1.8m auxillary telescopes

CHARA array: six 1-m telescopes (Mt Wilson, USA)

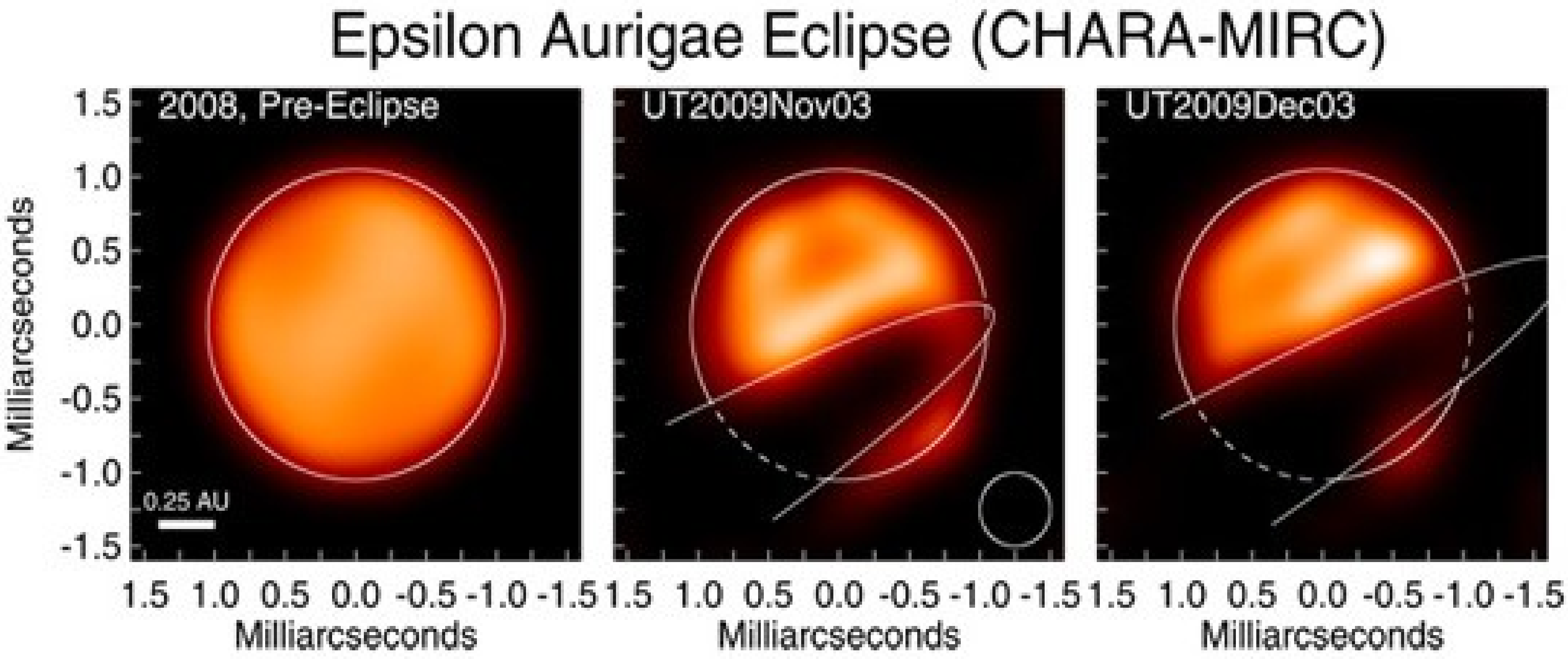


CHARA image of Altair



CHARA image of Epsilon Aurigae

Large number of apertures (6) + Earth's rotation allow sufficient uv plane coverage to reconstruct images of complex sources.
Epsilon Auriga is a bright naked eye star periodically eclipsed by a disk-bearing companion.



Flux limitation in interferometers

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 << time it takes for fringe to move by a wavelength

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, need to be able to track and lock fringes to allow long exposures
this will be discussed in next lecture

Brightness Estimation

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 ~15,000 photons from a K=10 star in 1 ms.
- sky background is ~1500 photons/ms.
- Telescope background is ~15,000 photons/ms.
- throughput is 6%.
- This gives an SNR of 8 in a 1 ms exposure.
- Astrometric precision of measurement:

$$\delta x = {}^{\lambda}/_{B}\, {}^{1}/_{SNR}$$