Optical and Infrared Interferometry

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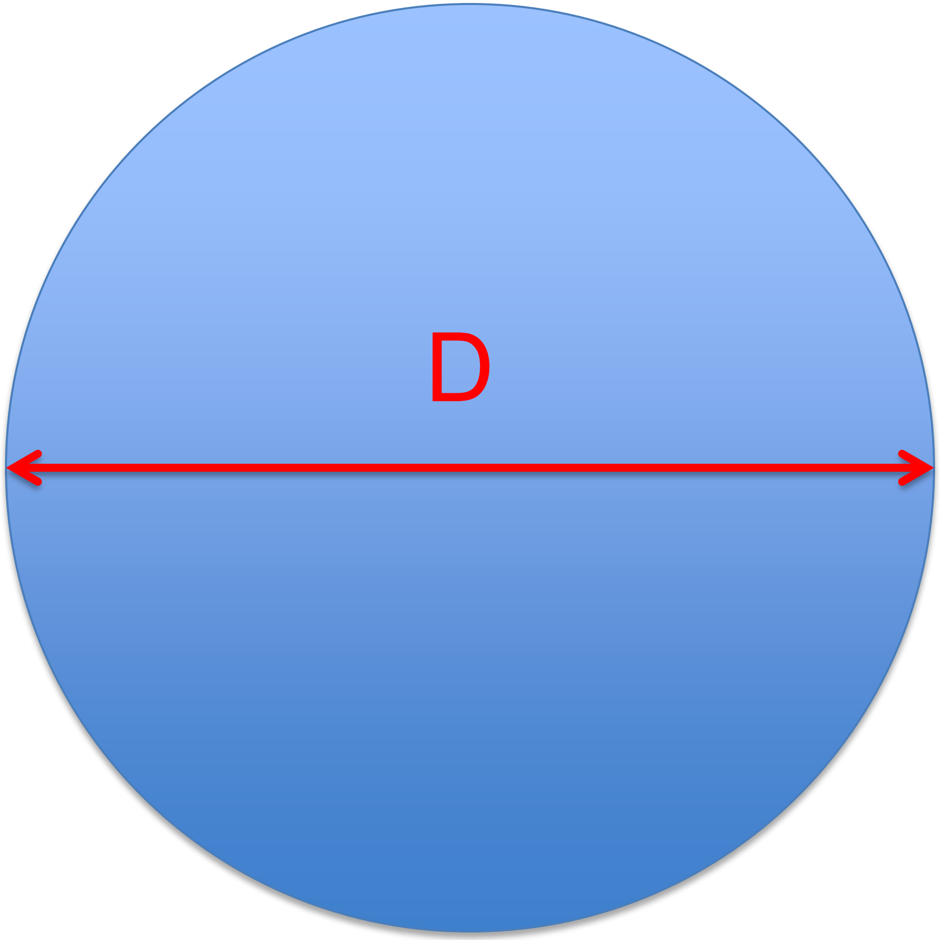
Outline

- General Principles of Interferometry
- Aperture Synthesis Imaging
- Spotlight on Optical Interferometry

- Readings
  - Volume 2 of Planets, Stars and Stellar System
  - Thompson/Moran/Swenson Chap 2-3, 10-11
  - Monnier Review 2003
  - Michelson Summer School 1999 Notes
    - https://core.ac.uk/download/pdf/79046071.pdf
  - Eisenhauer, Monnier, Pfuhl ARAA 2023

Angular Resolution



Diffraction-limit

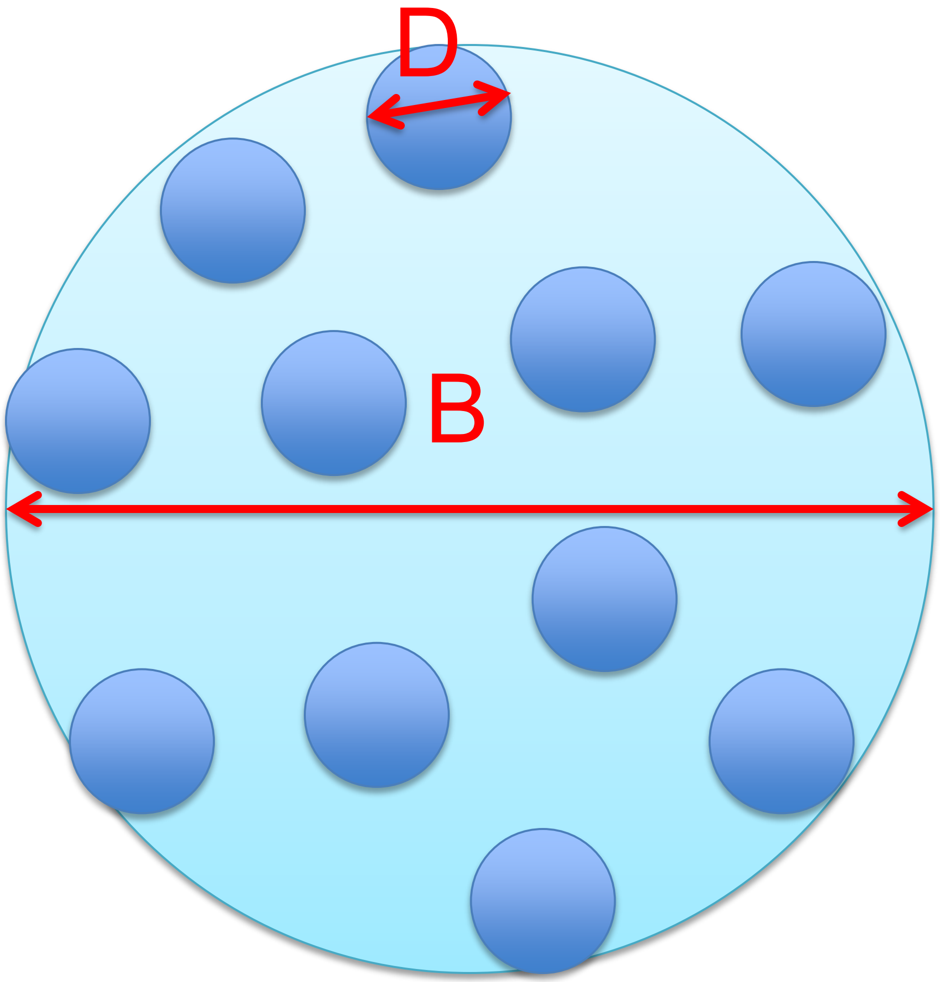
wavelength

$$\Theta \sim \frac{\lambda}{D}$$

Angular
resolution
in radians

diameter

Angular Resolution



Diffraction-limit

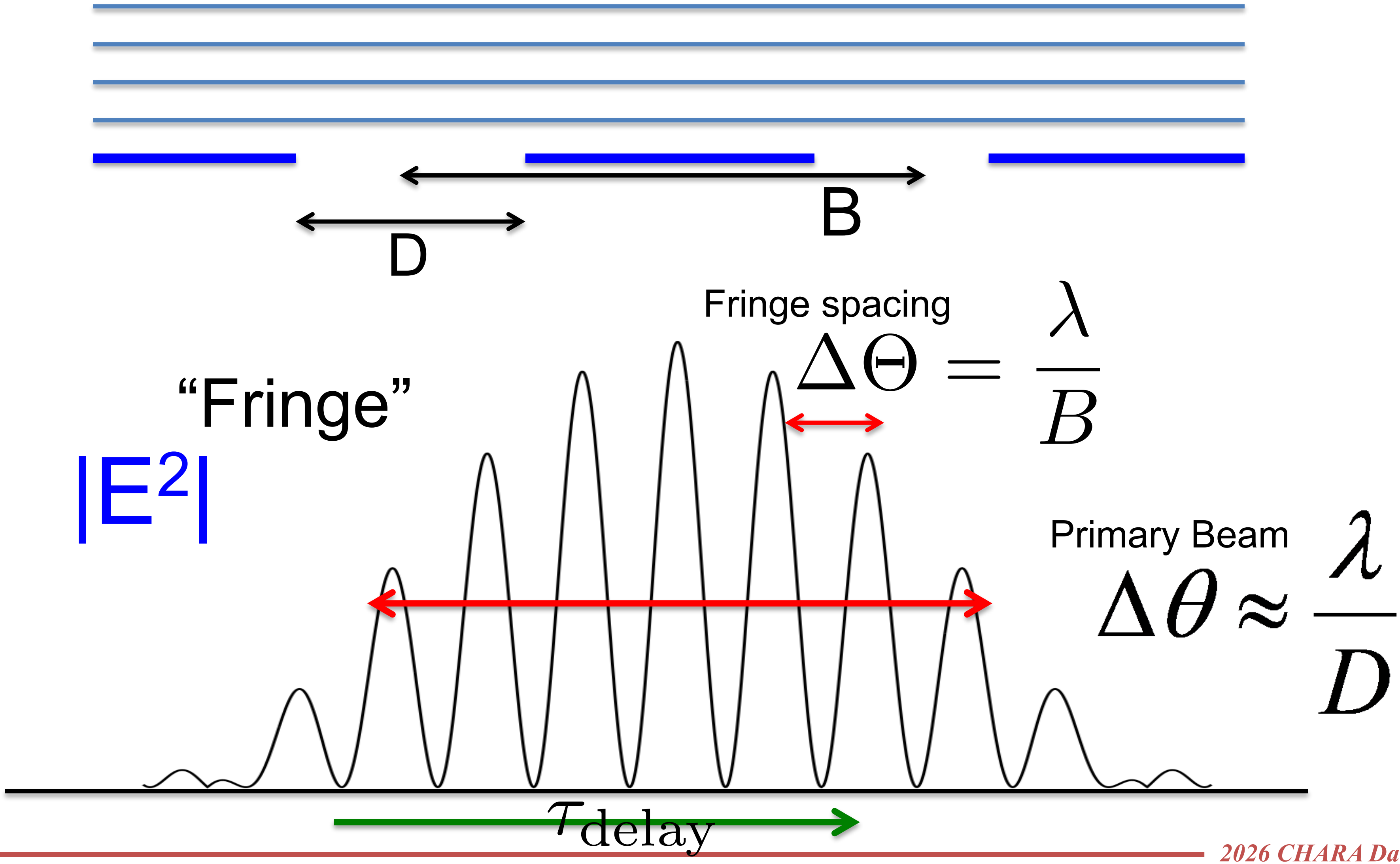
wavelength

$$\Theta \sim \frac{\lambda}{B}$$

Angular
resolution
in radians

Baseoine

Optical View of Interferometry

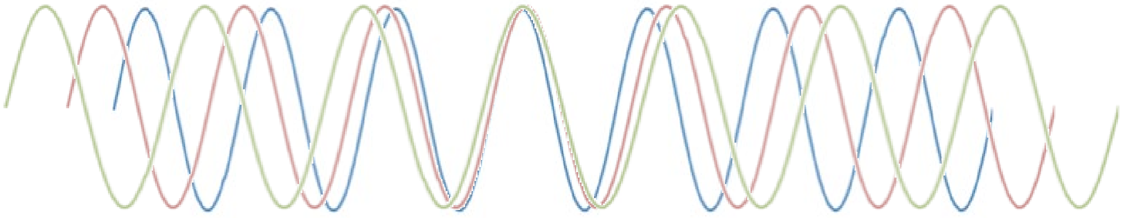


$$\Delta\Theta = \frac{\lambda}{B}$$

$$\Delta\theta \approx \frac{\lambda}{D}$$

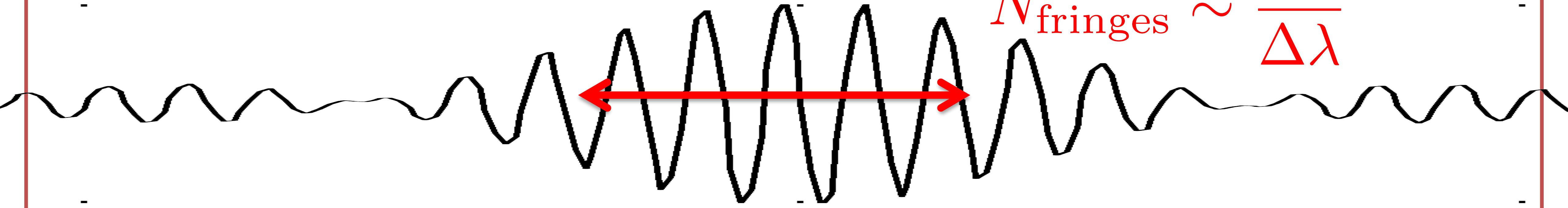
Polychromatic

$$< \vec{E}_1 \cdot \vec{E}_2 > \propto \cos 2\pi\nu(\tau_e - \tau_i)$$



$$\tau_{\text{delay}} = \tau_e - \tau_i$$

$$N_{\text{fringes}} \sim \frac{\lambda}{\Delta\lambda}$$



“Coherence Length”

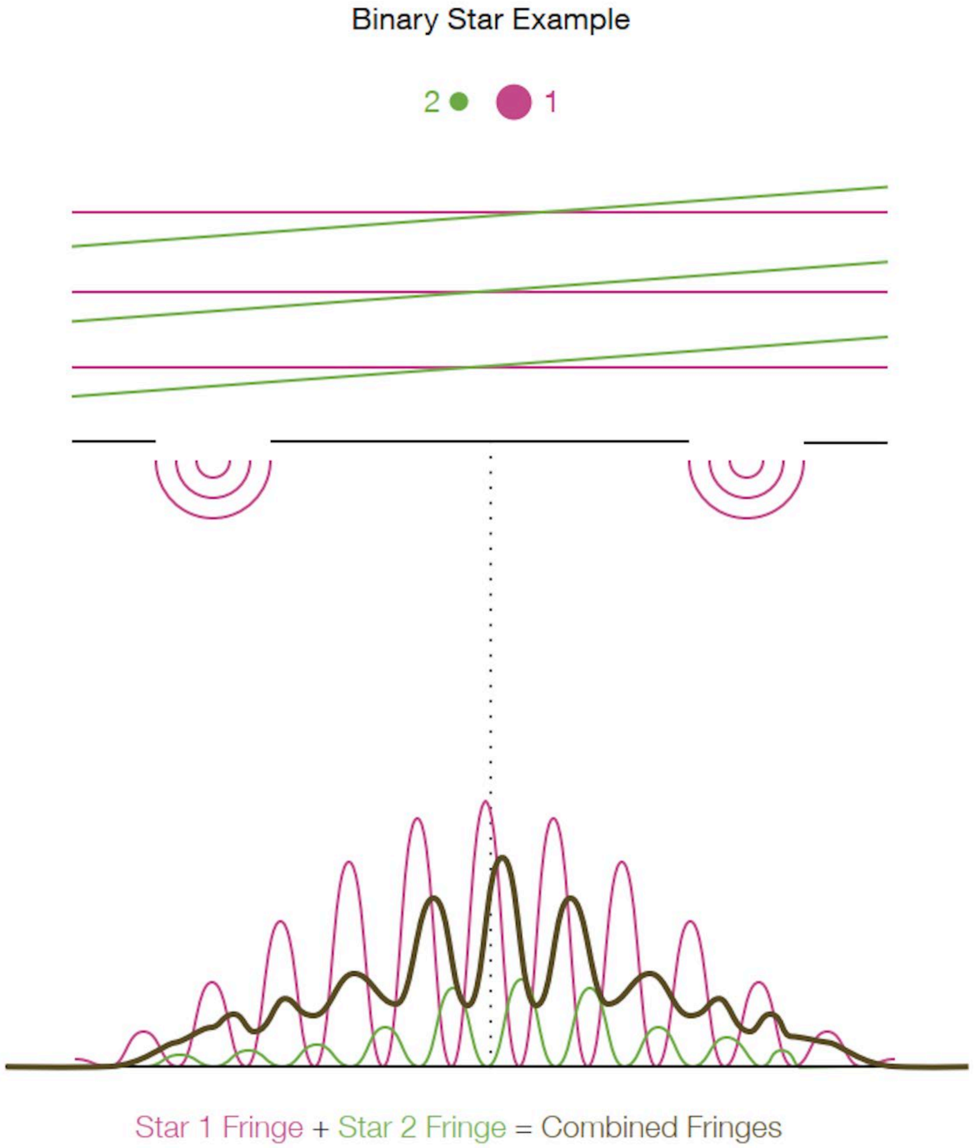
Table 3. Planning Interferometer Observations

Consideration	Equation
Angular Resolution	$\Theta = \frac{1}{2} \frac{\lambda}{B_{max}}$
Spectral Resolution	$R = \frac{\lambda}{\Delta \lambda} = \frac{\hat{\upsilon}}{\Delta \upsilon}$.
Field-of-View	
primary beam	$\Delta \Theta \square \frac{\lambda}{D_{Telescope}}$
bandwidth-smearing	$\Delta \Theta \square R \cdot \frac{\lambda}{B_{max}}$
time-smearing	$\Delta \Theta \square \frac{230}{\Delta t_{minutes}} \frac{\lambda}{B_{max}}$

CHARA: ~0.3”

R50: ~50mas
R200: ~200mas

van Cittert-Zernike Theorem



Complex Visibility

$$\tilde{\mathcal{V}}\left(\frac{B_{\mathrm{proj}}}{\lambda}\right) = \int I_\lambda(\delta)\cos\left(2\pi\frac{B_{\mathrm{proj}}}{\lambda}\delta\right)d\delta$$

One Fourier Component of the Image

Basics

- The amplitude of fringe corresponds to Fourier amplitude of a single Fourier component of brightness distribution

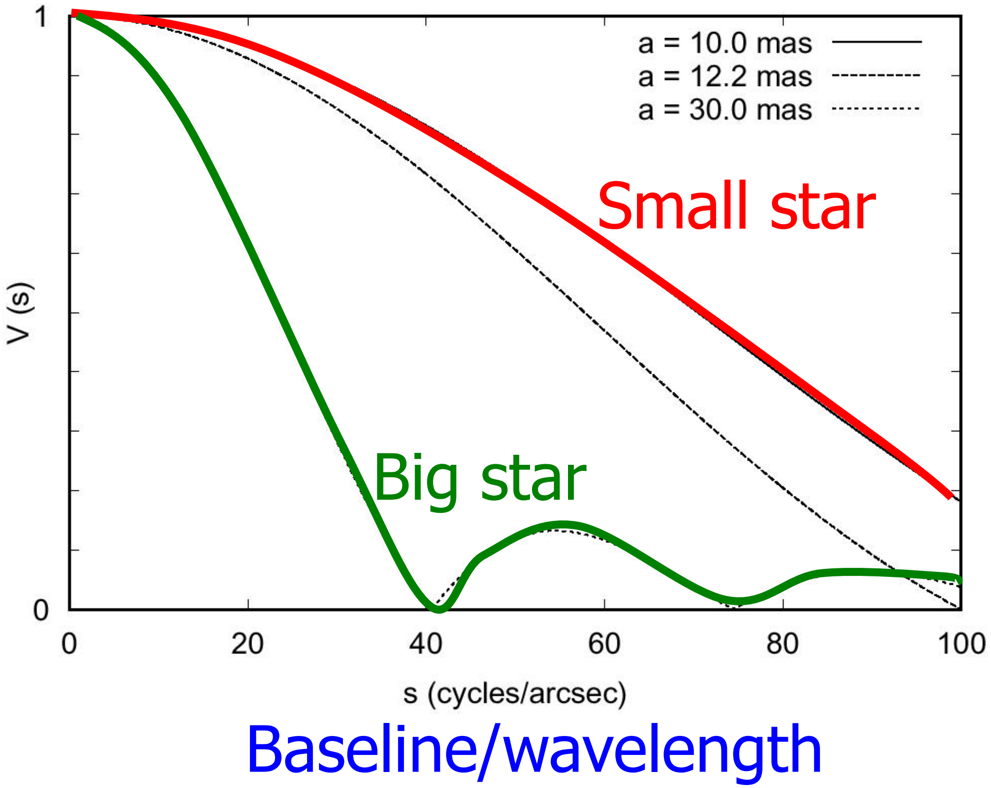
  Normalized to flux, 0 → 1

  For data analysis reasons, we often fit to **V^2**, not the amplitude

- The phase corresponds to the Fourier phase
- You need amplitudes & phases for imaging

Eisenhauer, Monnier, Pfuhl 2023

Examples of Visibilities: Stars

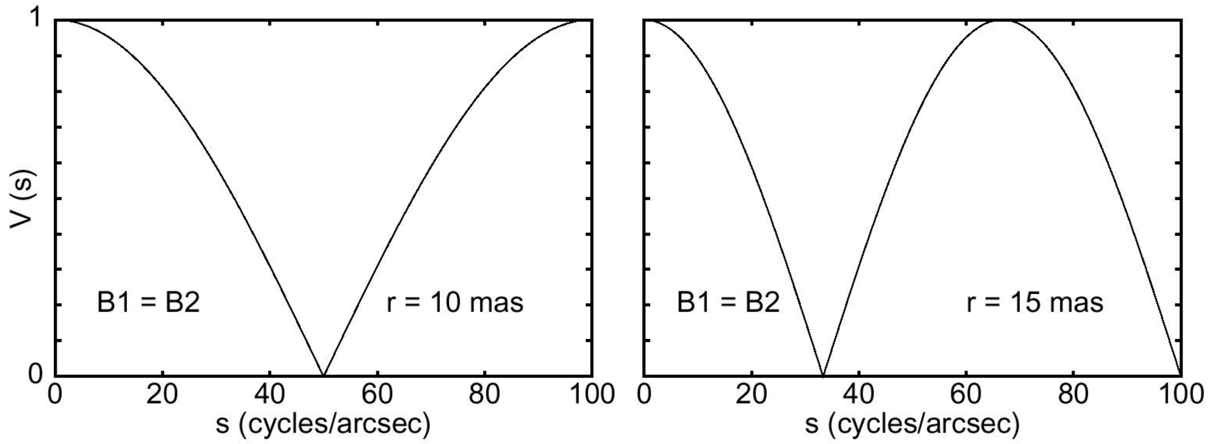


Uniform Disk:

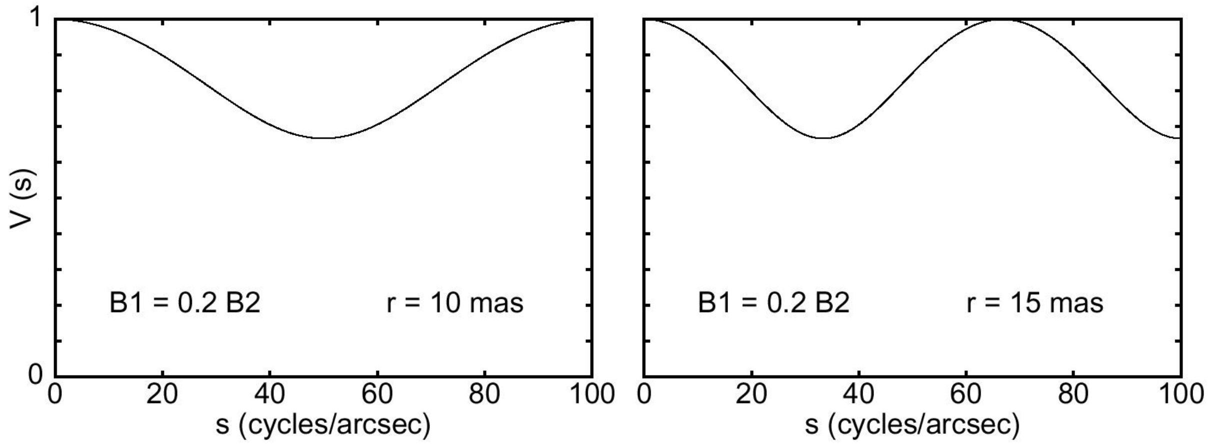
$$V(s) = \left| \frac{2J_1(\pi a s)}{\pi a s} \right|$$

Dyck (Michelson Summer School Notes 2000)

Examples of Visibilities: Binaries



Equal Brightness



Brightness Ratio 5:1

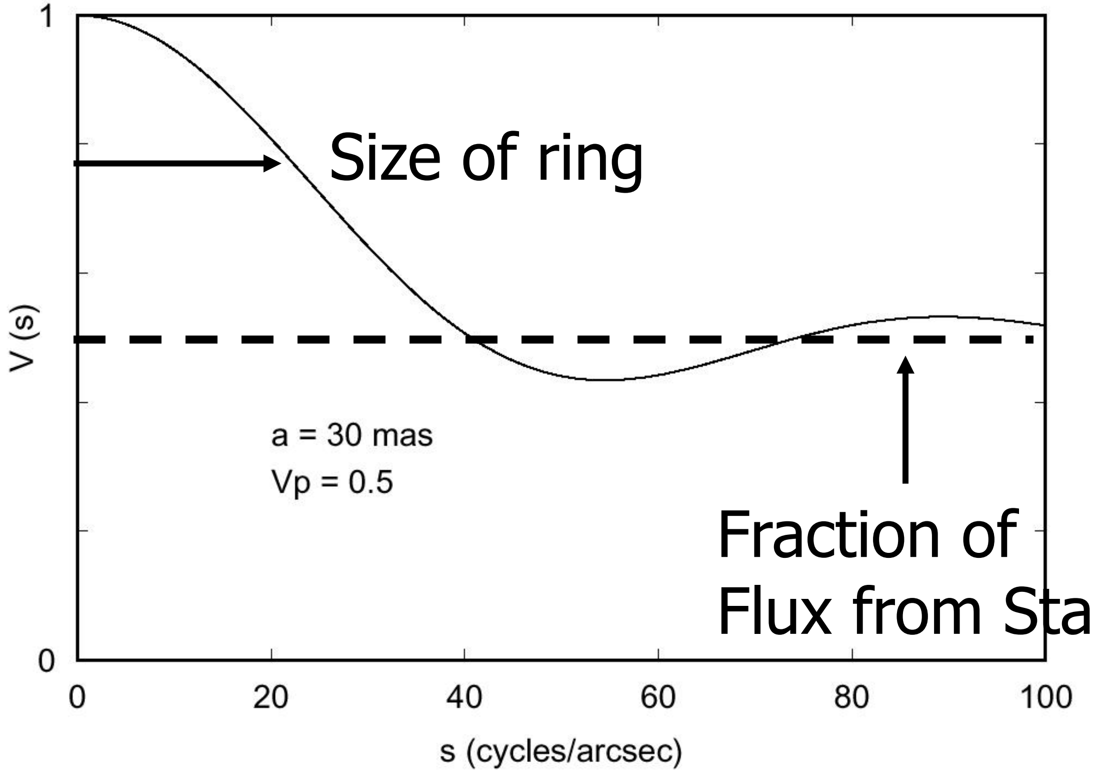
Increasing Binary Separation →

Dyck (Michelson Summer School Notes 2000)

Star + Dust Shell

Fourier Transforms are linear, so you can add up components in complex visibility

Visibility function for Star + Ring

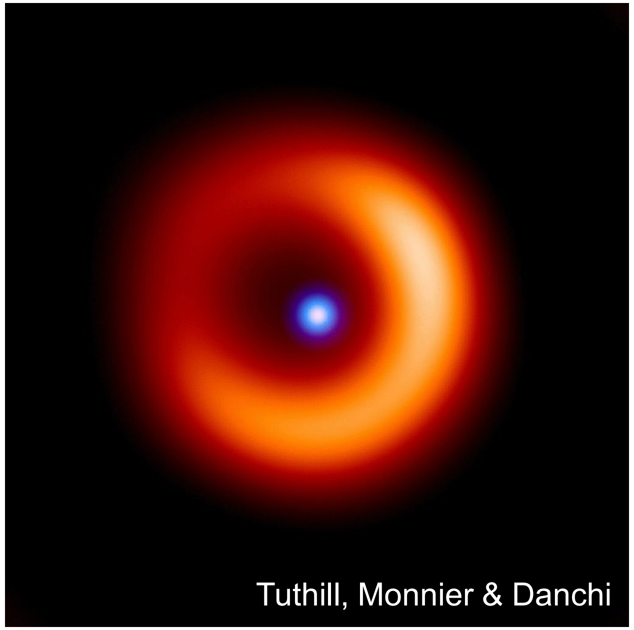


Size of ring

Fraction of Flux from Star

Baseline/wavelength

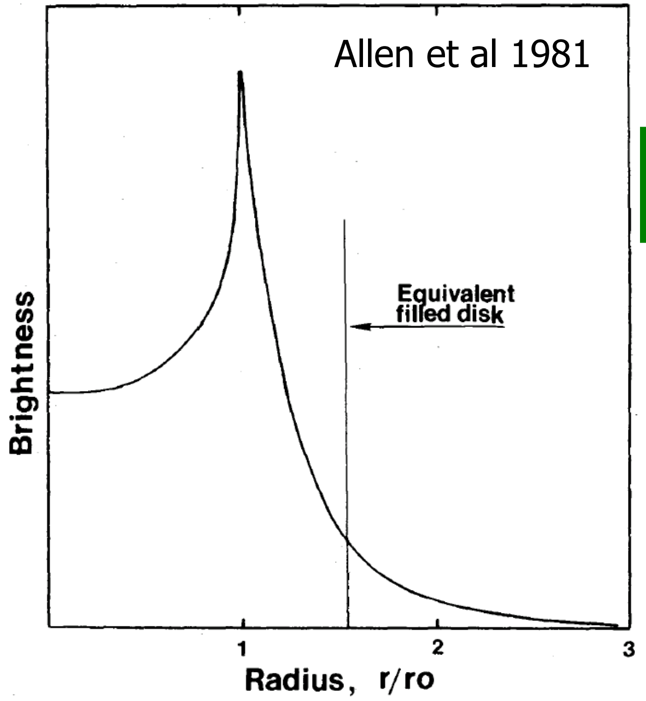
LkHα 101 (young star with disk)


Tuthill, Monnier & Danchi

Dyck (Michelson Summer School Notes 2000)

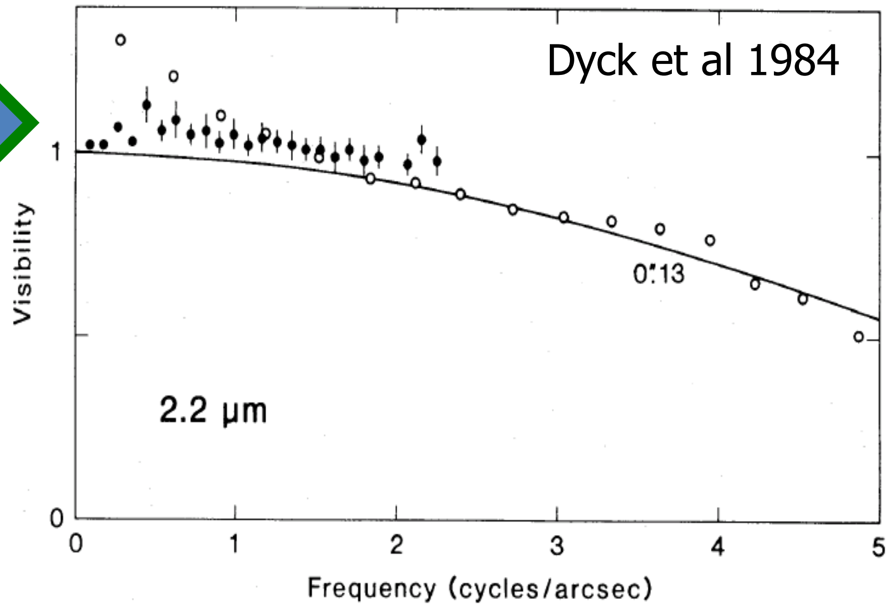
Radiative Transfer Modeling

Radial Profile of an Optically-Thin Dust Shell Model


Allen et al 1981

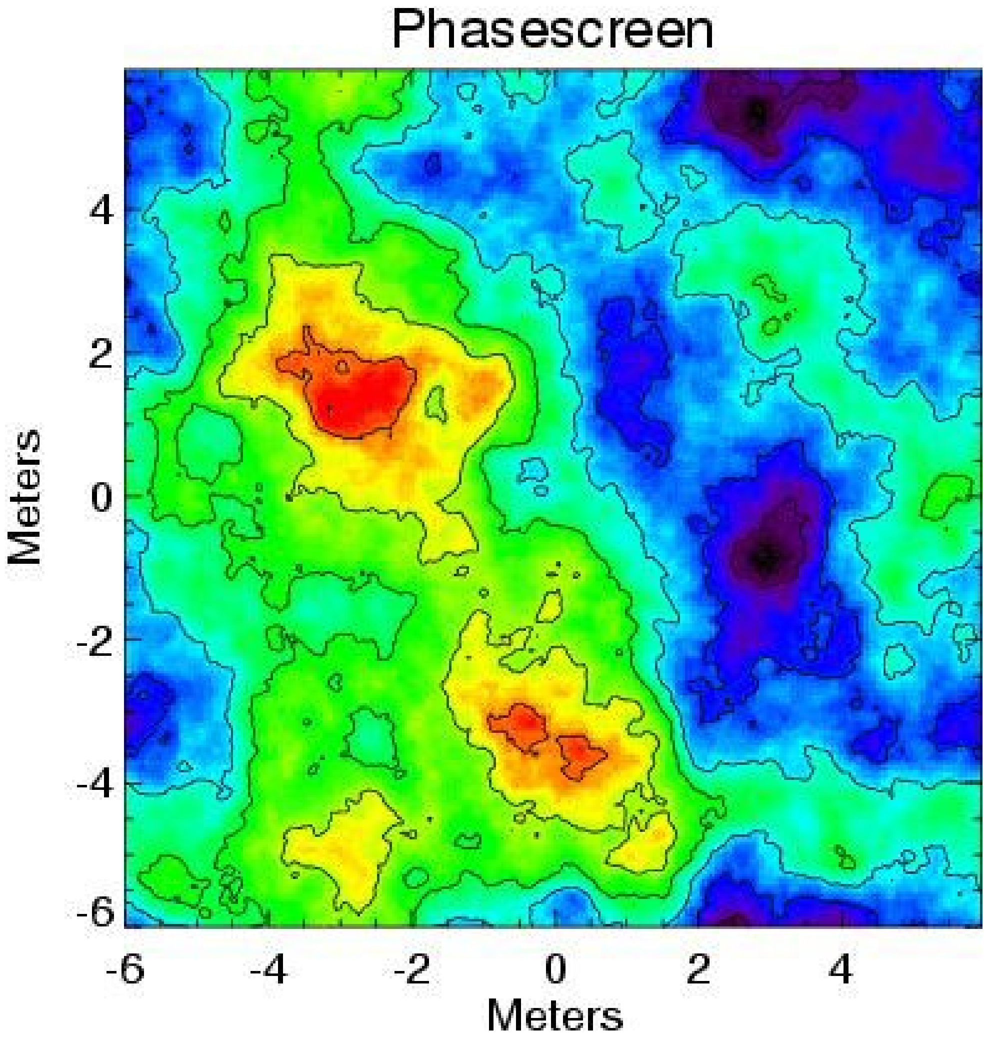
Fourier Transform

Calculated and Observed Visibilities


Dyck et al 1984

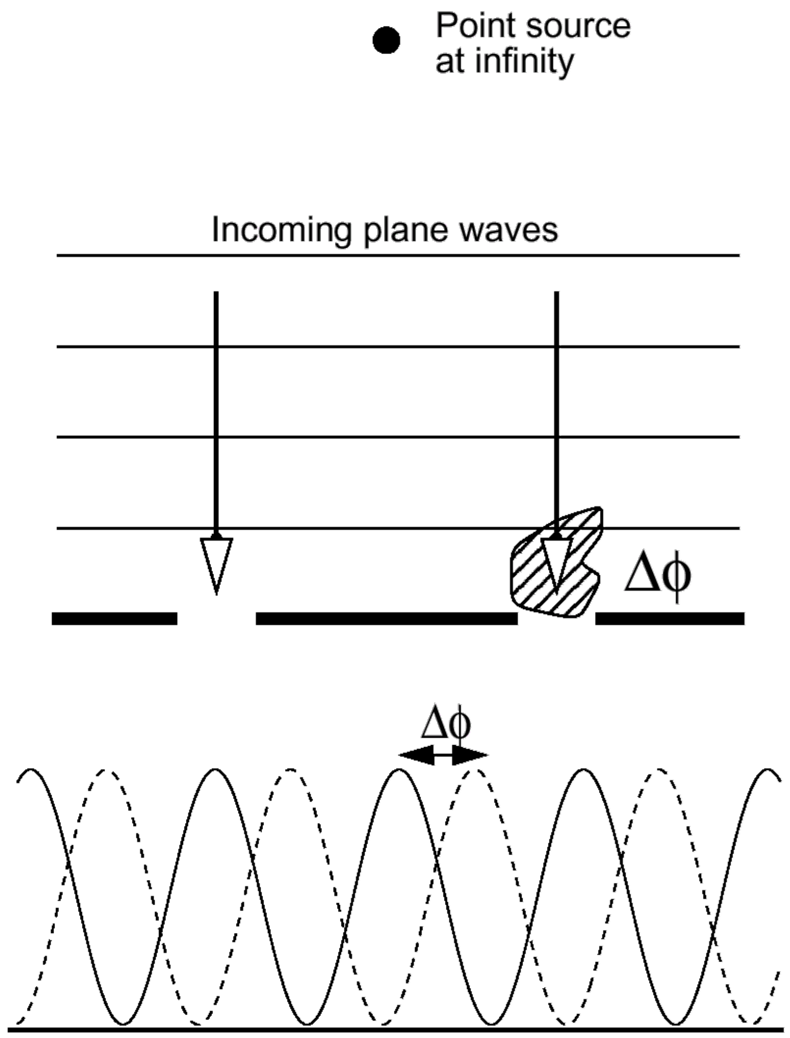
here the dust shell is ‘barely’ resolved and no details show up in the visibility curve

What about Phases? Atmosphere is bad.



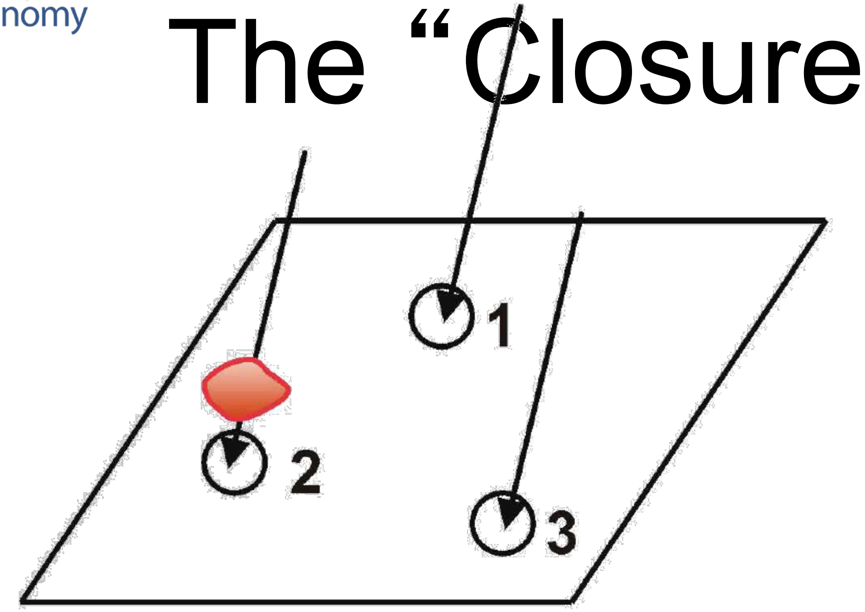
A Keck-sized patch of atmosphere during typical good seeing

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



Monnier (Michelson Summer School Notes 2000)

The “Closure Phase” Is Not Corrupted



Observed Intrinsic Atmosphere

$$\Phi(1\text{-}2) = \Phi_{n}(1\text{-}2) + [\phi(2)-\phi(1)]$$
$$\Phi(2\text{-}3) = \Phi_{n}(2\text{-}3) + [\phi(3)-\phi(2)]$$
$$\Phi(3\text{-}1) = \Phi_{n}(3\text{-}1) + [\phi(1)-\phi(3)]$$

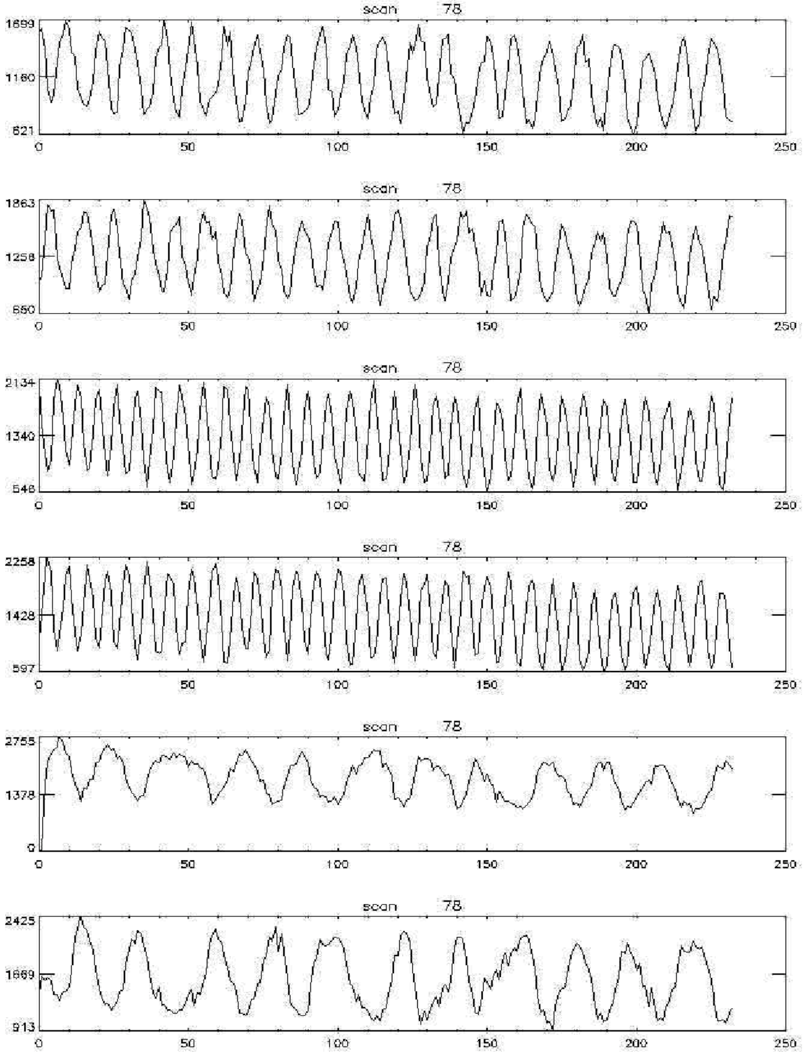
$$\boxed{\text{Closure Phase (1-2-3)} = \Phi_{o}(1\text{-}2)+\Phi_{o}(2\text{-}3)+\Phi_{n}(3\text{-}1)}$$

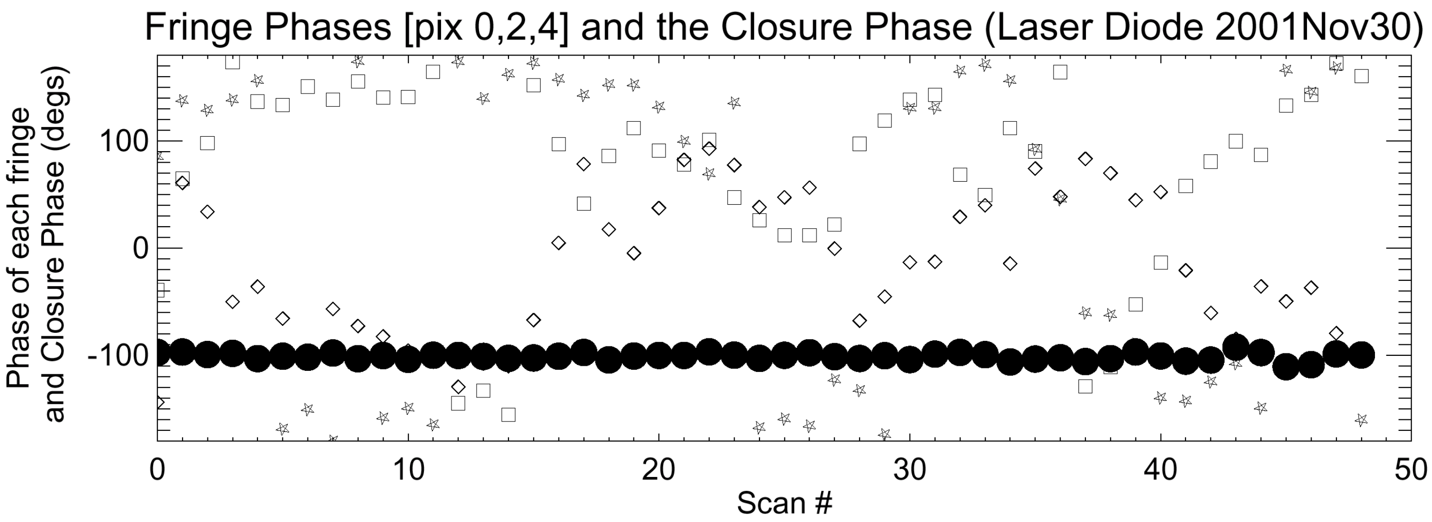
<u>Properties of Closure Phases</u>

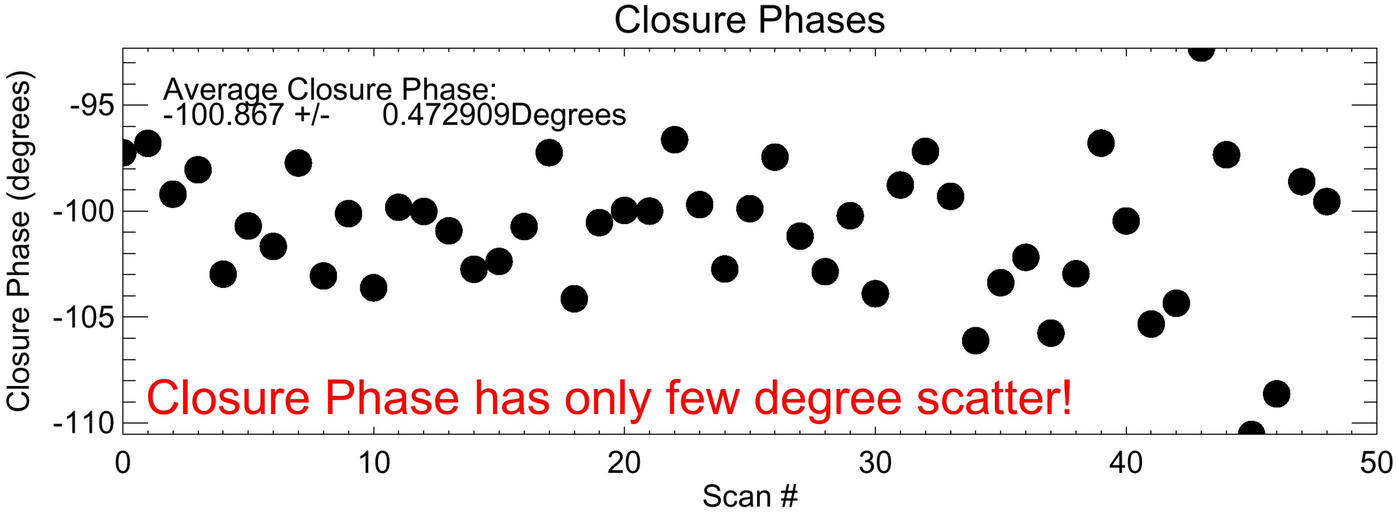
- 0° /180° for “centro”-symmetric objects
  - E.g., uniform disks, rings, elliptical disks, equal binaries
  - But otherwise not easy to interpret
- Not dependent on position on sky, so therefore no astrometry
- Related to ‘skewness’ of a distribution
- Immune to most calibration errors, so very robust!

Closure Phase is a Good Observable

Pair-wise Combination at IOTA







Closure Phase has only few degree scatter!

How Much Phase Information?

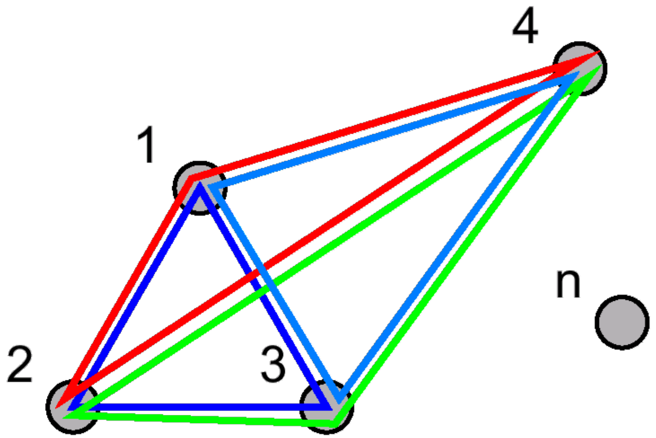
Closure Phases are not all independent from each other.

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%

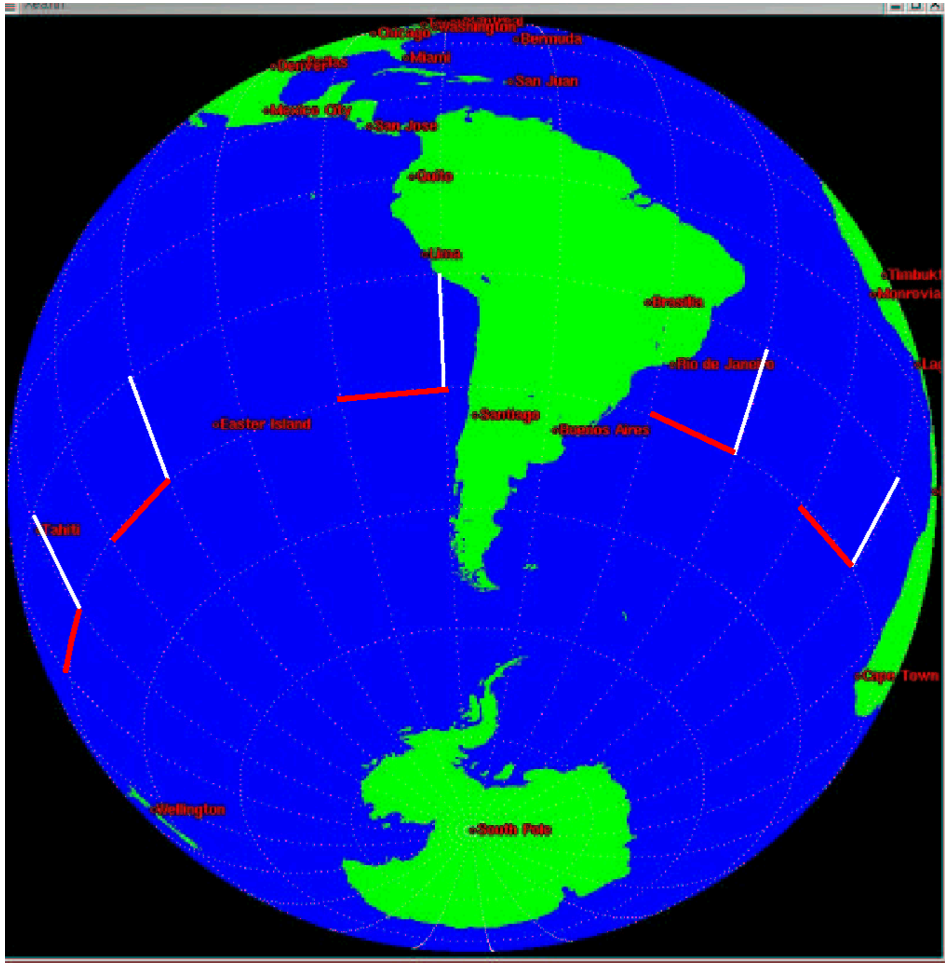
Basics of Interferometric Imaging

- How much data do you need?
  - The number of filled pixels ~> number of independent visibility measurements (degrees of freedom argument)
- What range of baselines?
  - Longest baselines sets your highest resolution
  - Diffraction-limit of individual telescope usually sets the maximum field-of-view of the interferometer
- Dynamic Range expected to be 1000:1 to 100:1
- How can you get enough data with only a few telescopes?

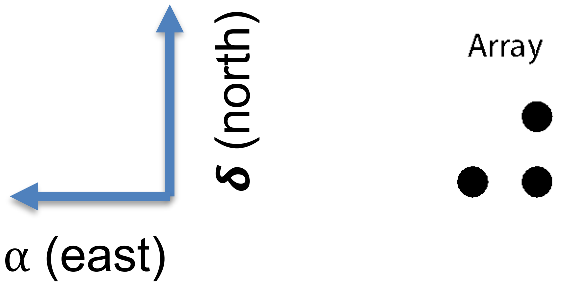
$$\mathrm{FT}(I(\alpha,\delta)) = \tilde{V}(u,v) = \int I_\lambda(\alpha,\delta) e^{-2\pi i (\vec{u,v})\cdot(\vec{\alpha,\delta})} d\alpha d\delta$$

(u,v) coverage

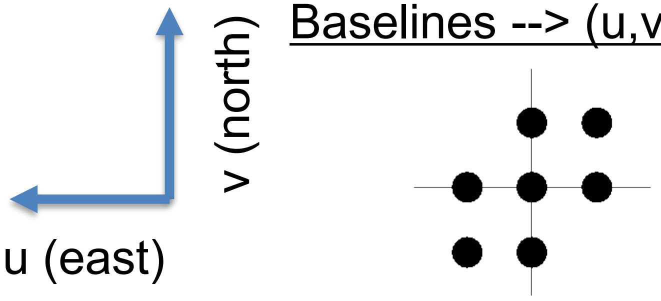
Earth Rotation Aperture Synthesis



Telescope positions

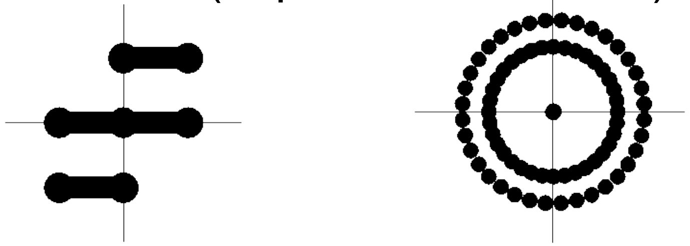


Baselines --> (u,v) coverage



“snapshot” coverage

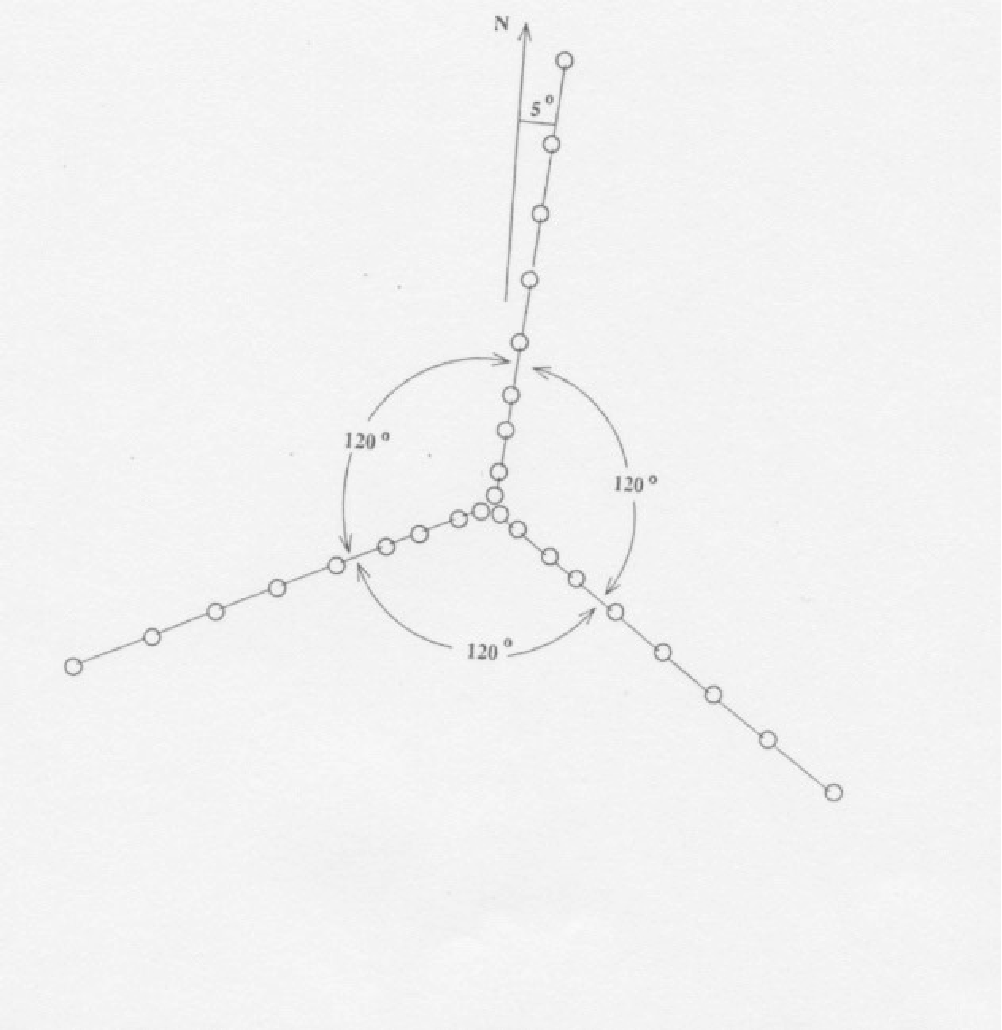
w/ Earth Rotation (depends on location)

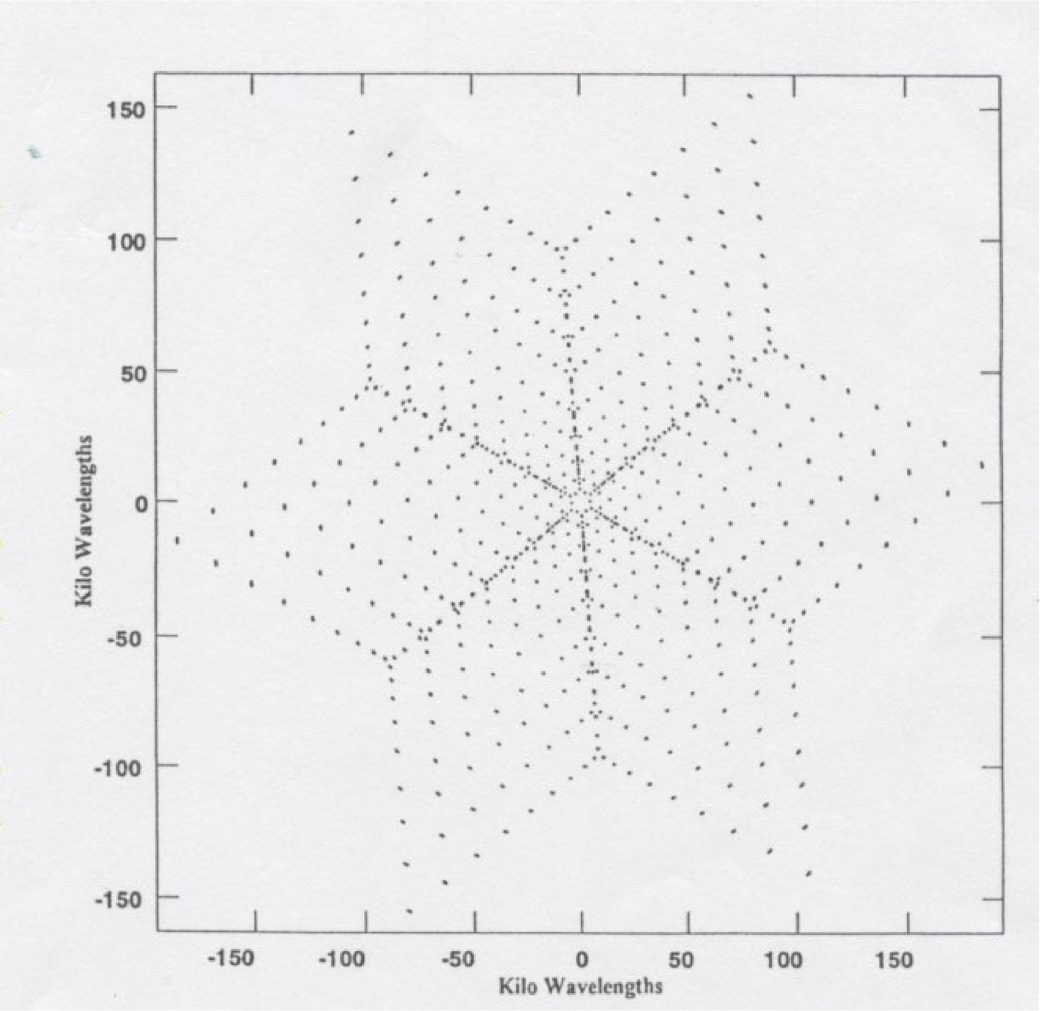


a) dec=0deg, lat=0deg
(12hr integration)

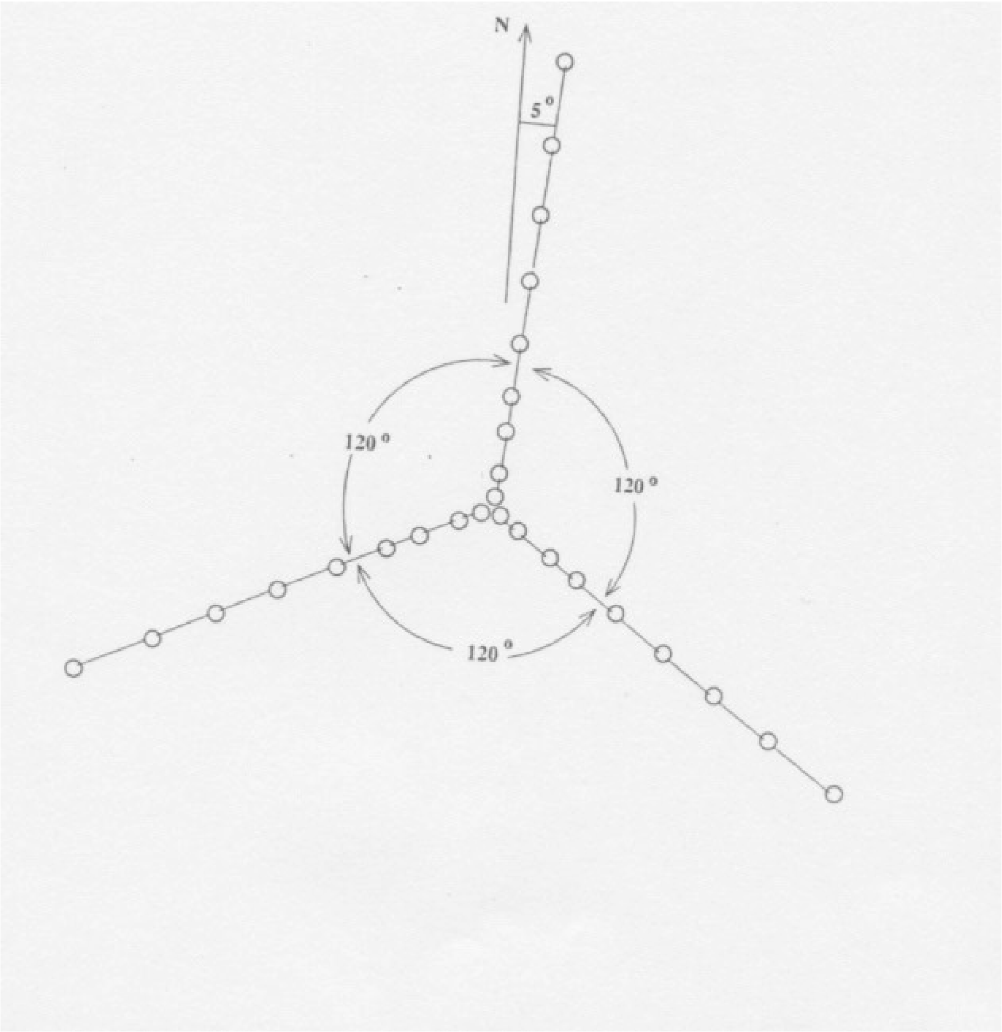
b) dec=90deg, lat=90deg
(24hr integration)
symbols are smaller to see better

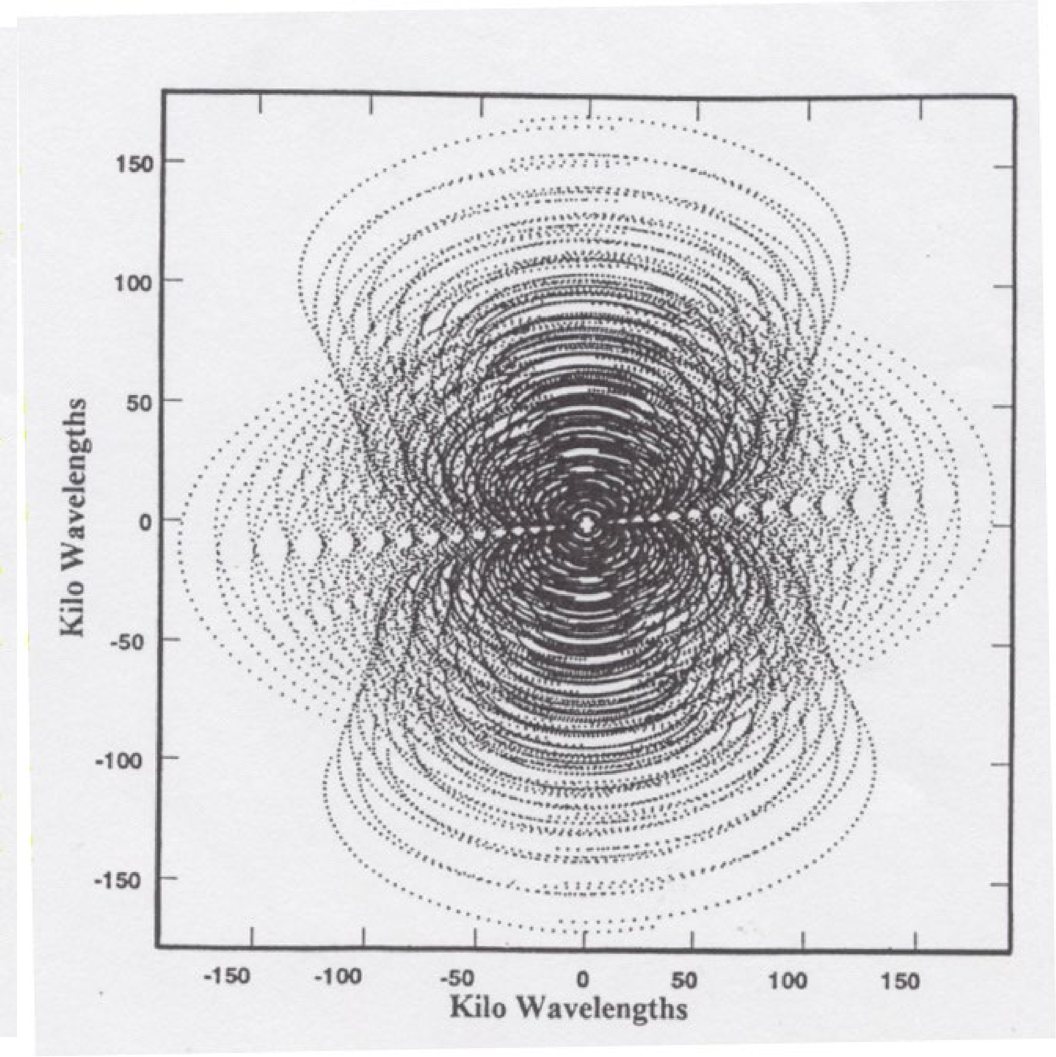
Very Large Array (VLA)





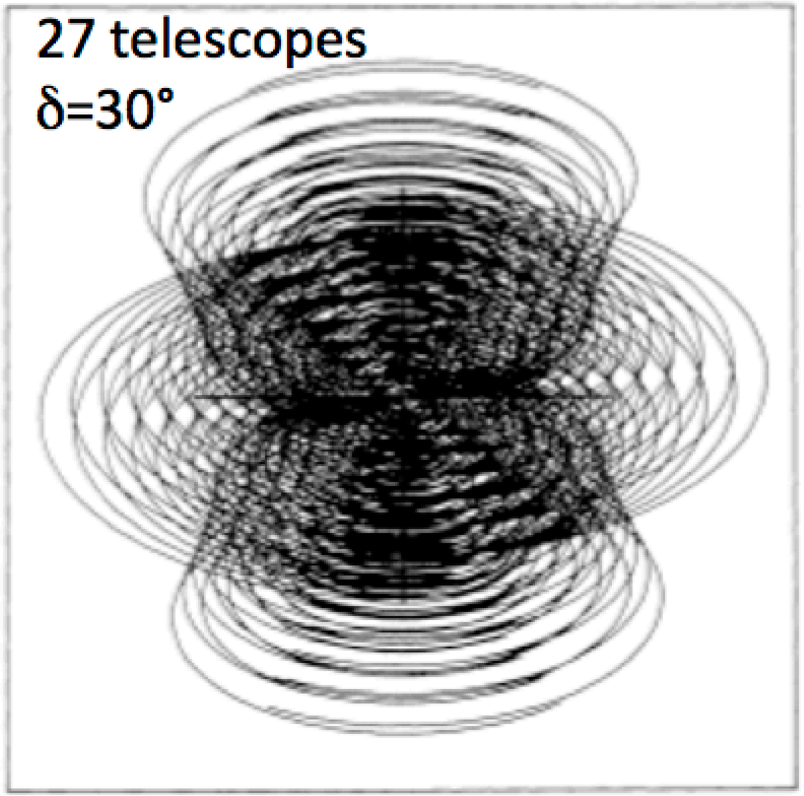
Very Large Array (VLA)



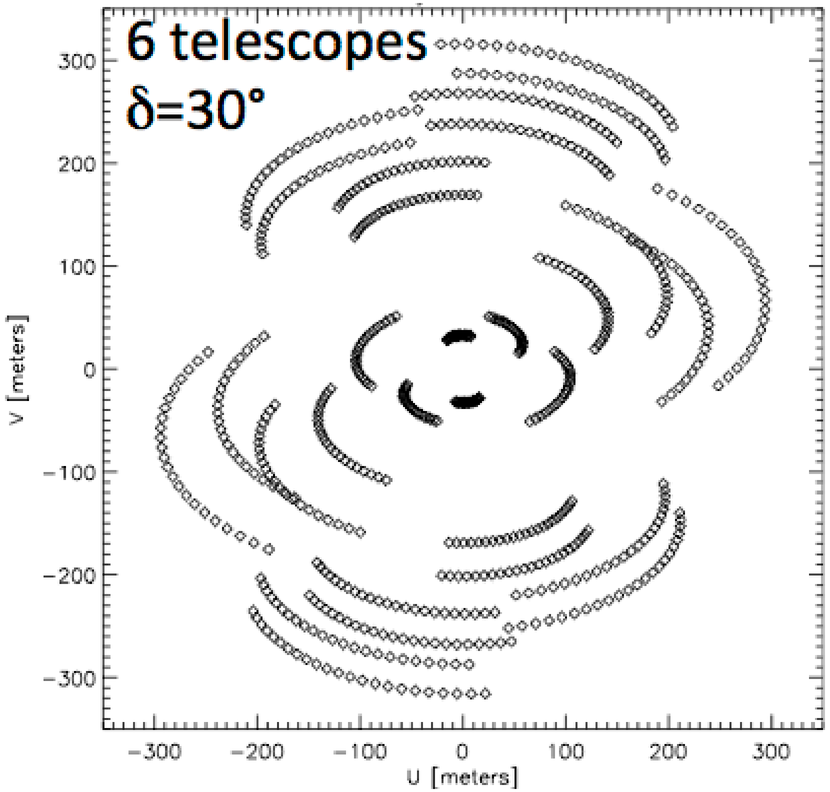


UV coverage: VLA (27) vs CHARA (6)

Very Large Array

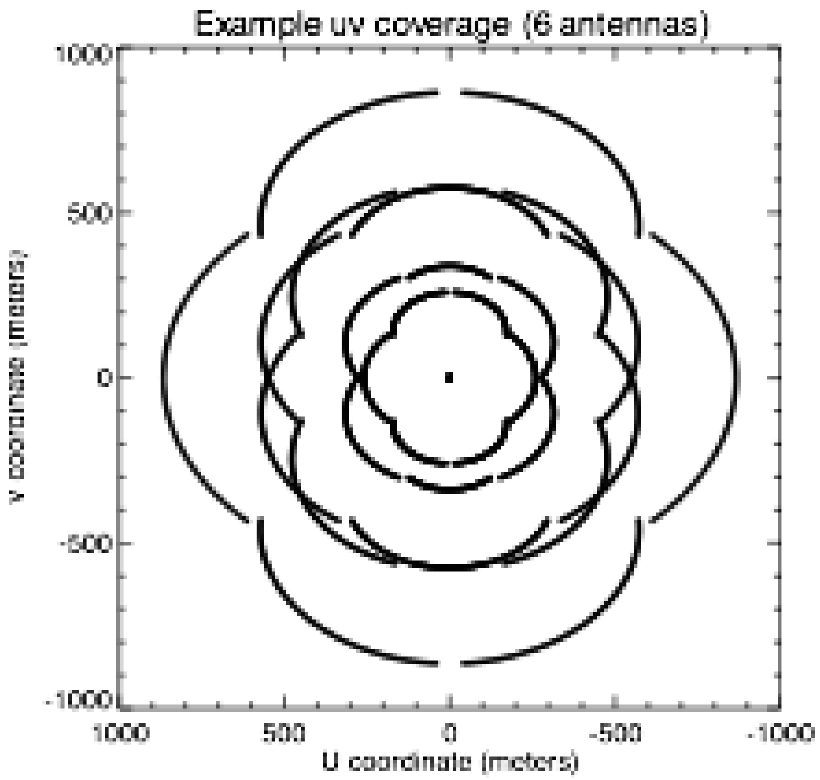


CHARA Array

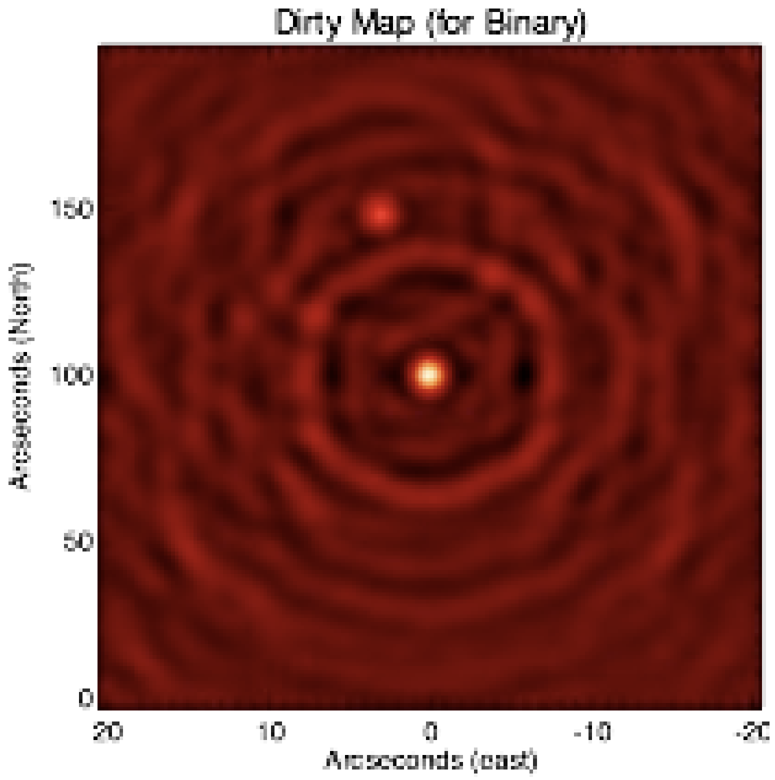


Imaging Methods:
Direct Fourier Transform

- Poor UV coverage leads to artifacts in your image



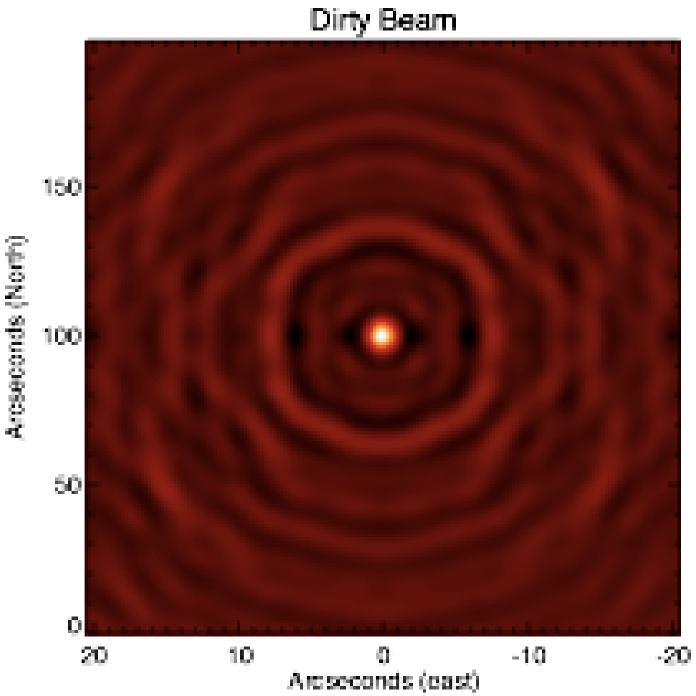
Inverse Fourier Transform



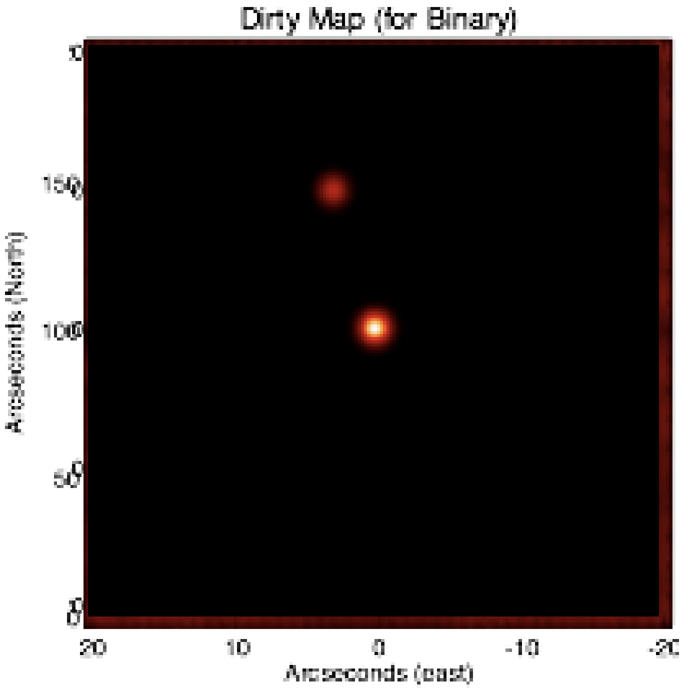
Deconvolution with CLEAN

*CLEAN requires phases, so we incorporate closure phases iteratively "self-calibration"

"Point Spread Function"
From known UV coverage



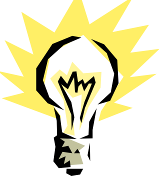
Deconvolution



Forward Model Example: 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."

MEM is one of many possible "regularizers," other include total variation, sparsity, 'UD' regularizer, etc.

Fraction of flux in pixel i

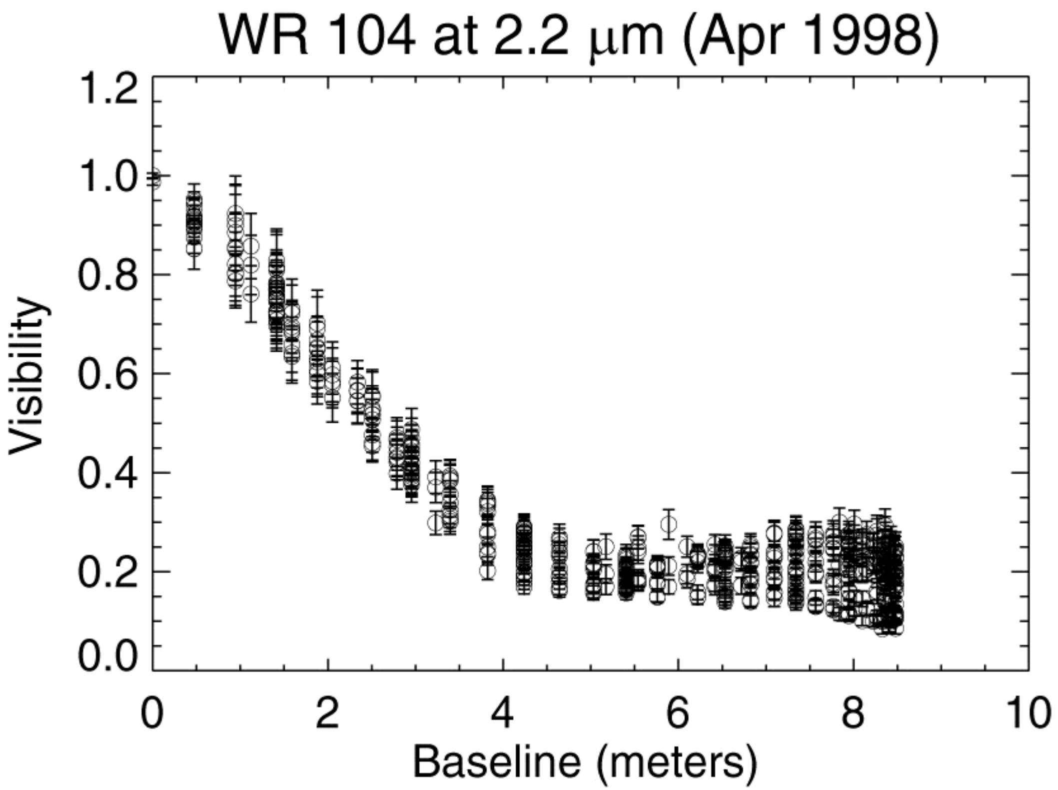
Skilling & Bryan (1984)

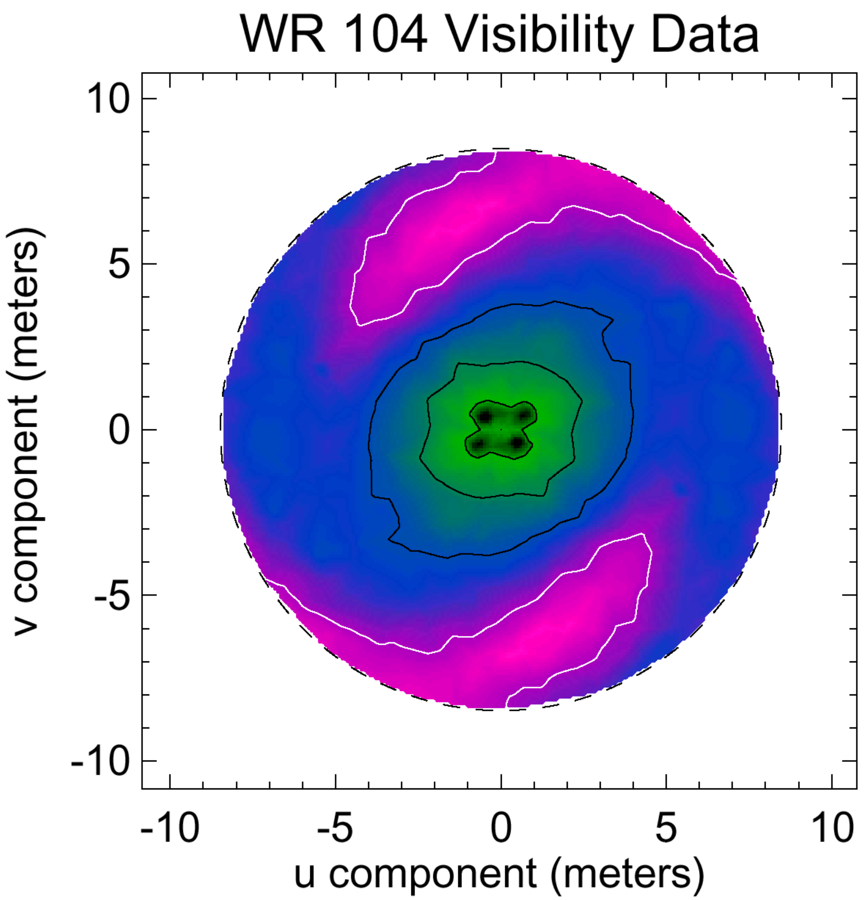
Entropy $$S = -\sum_i f_i \ln \frac{f_i}{I_i}$$

Image prior

Sum over all pixels

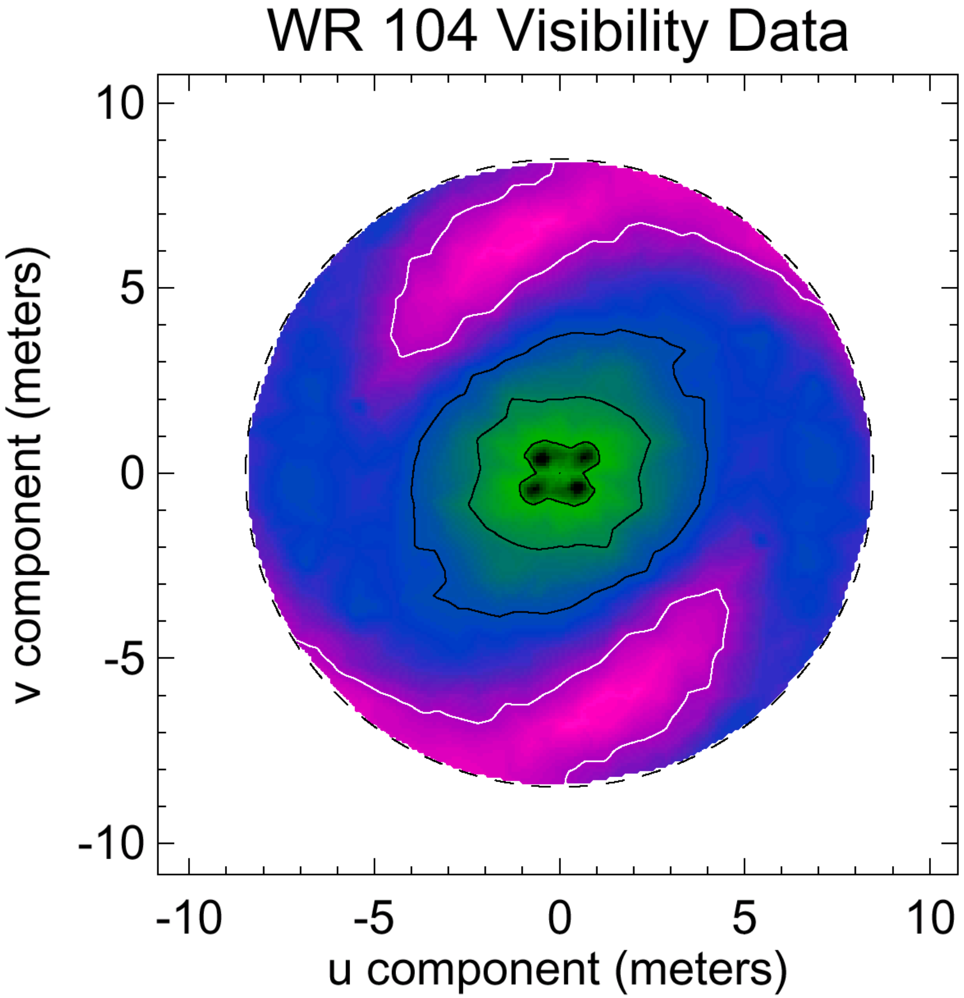
WR 104 Data


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)

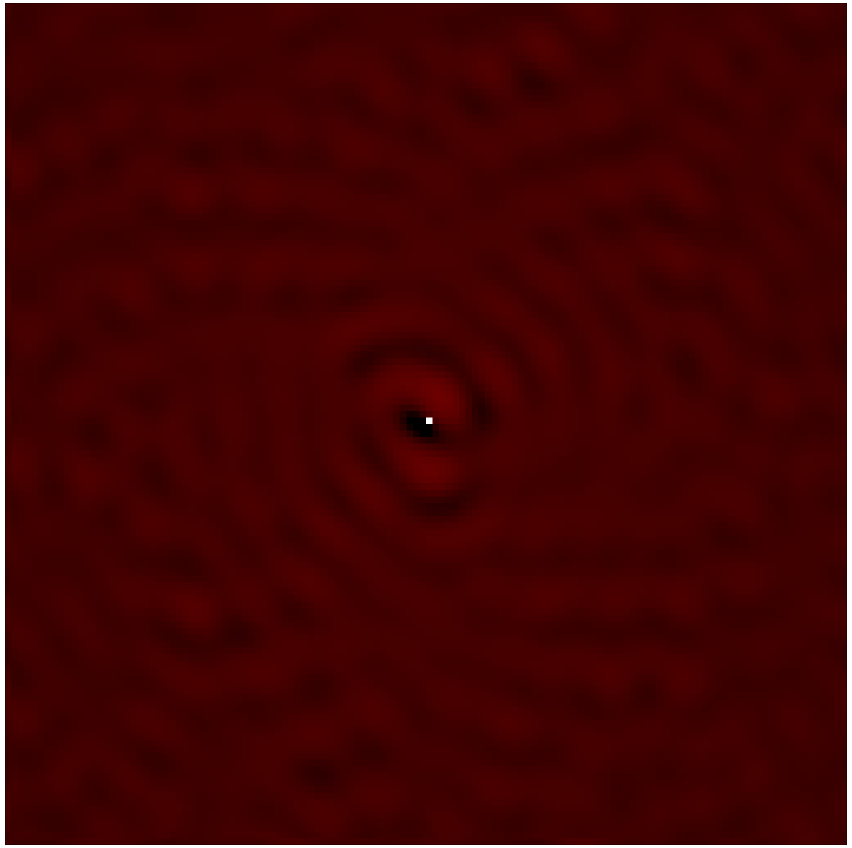

WR 104 Visibility Data
v component (meters)
10
5
0
-5
-10
-10
-5
0
5
10
u component (meters)

BSMEM developed first by Dave Buscher

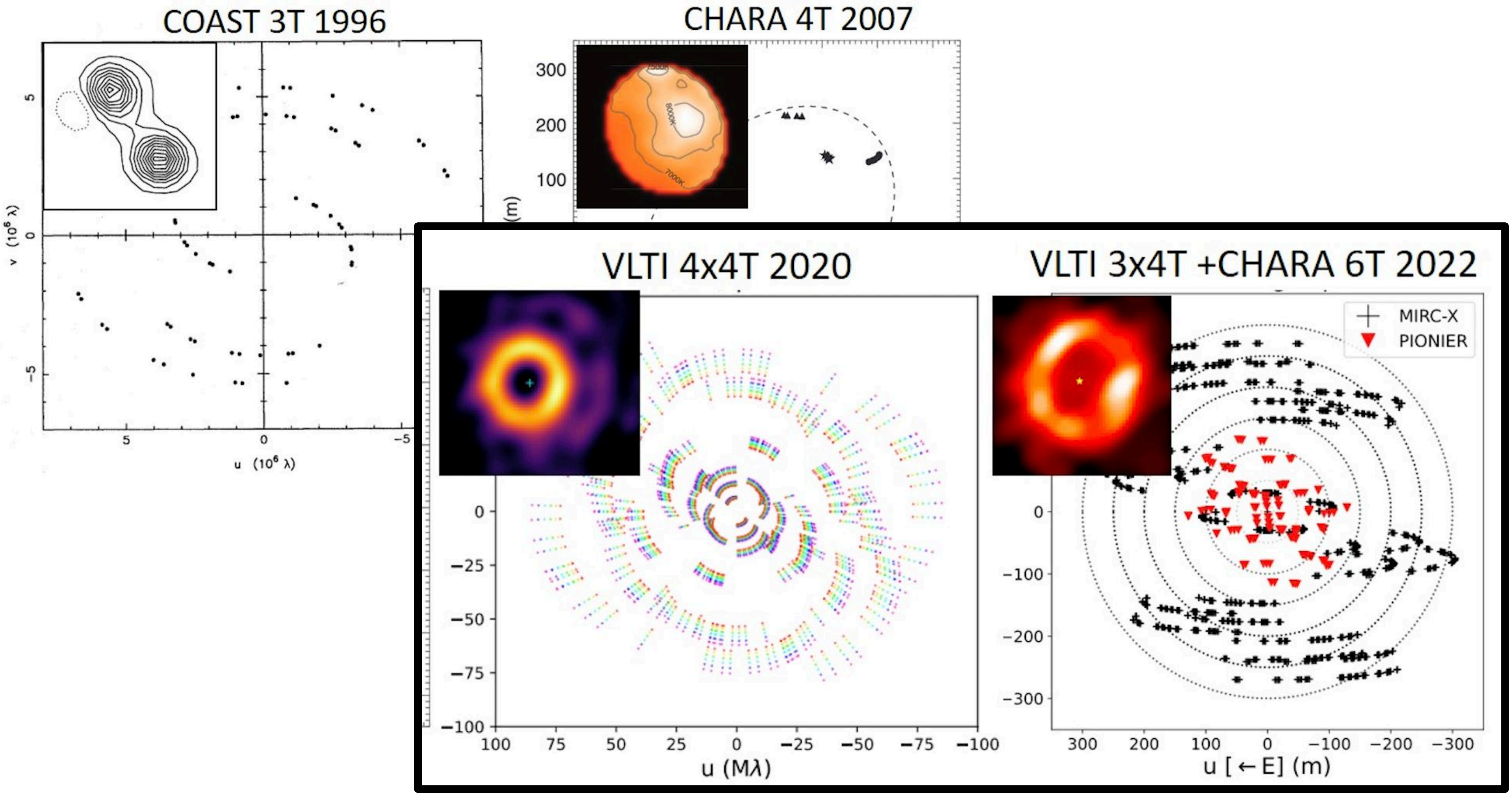
WR 104 MEM Reconstruction



Iterations 1 to 30



WR 104 (2.2 microns)


COAST 3T 1996

CHARA 4T 2007

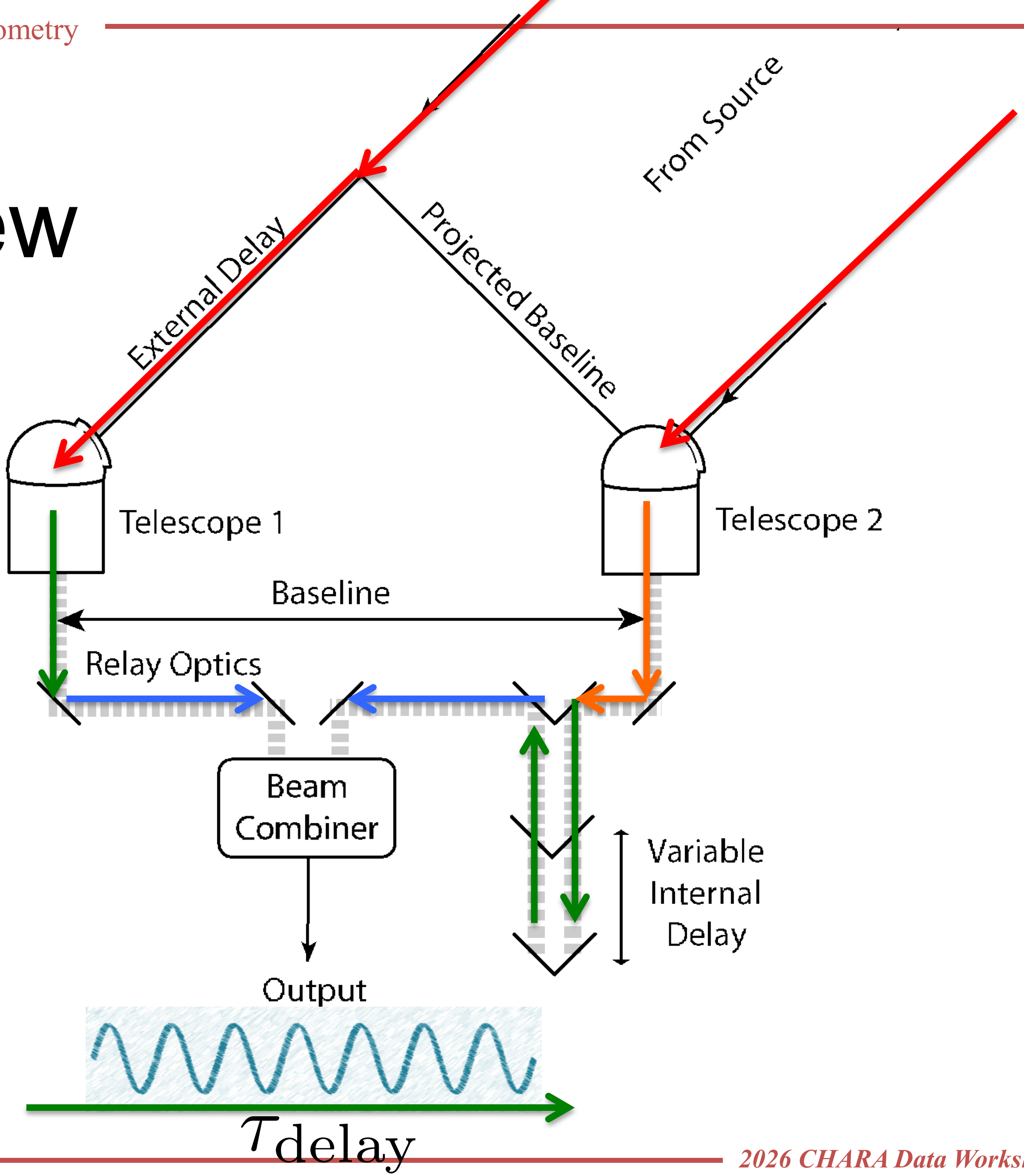
VLTI 4x4T 2020

VLTI 3x4T +CHARA 6T 2022

Eisenhauer, Monnier, Pfuhl 2023

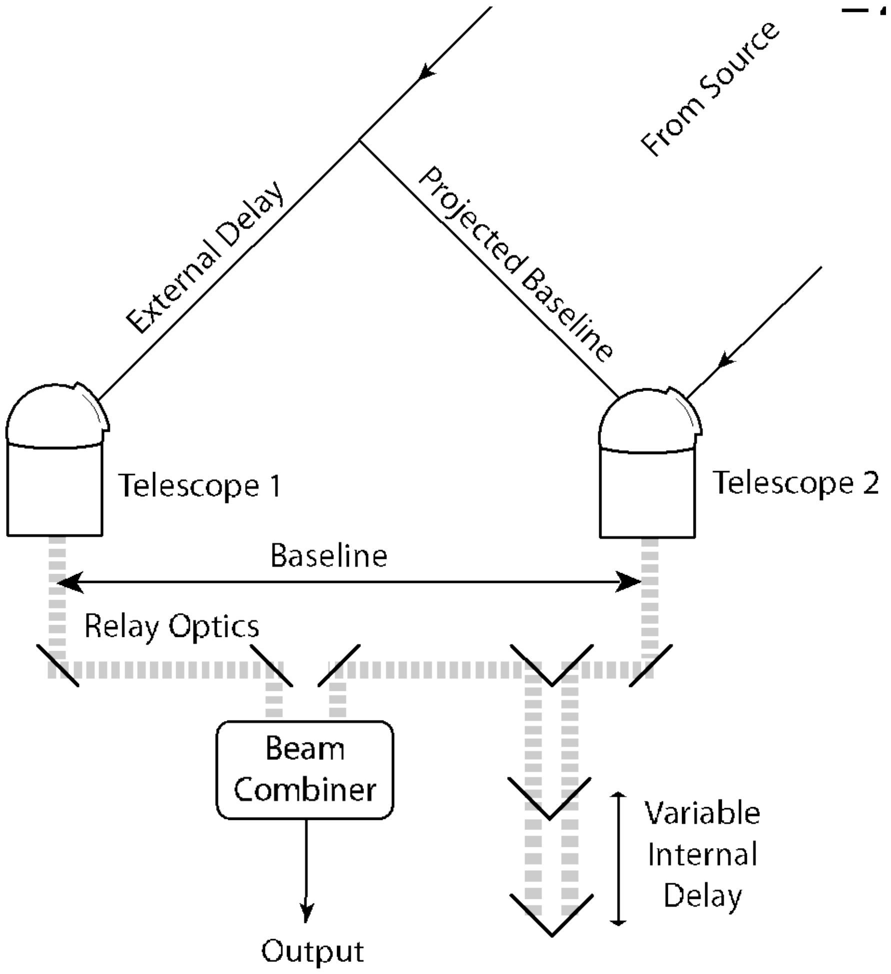
Spotlight:
Optical Interferometry

More Realistic View



Realistic Interferometers

Light Collectors



Monnier & Allen 2012

(a)

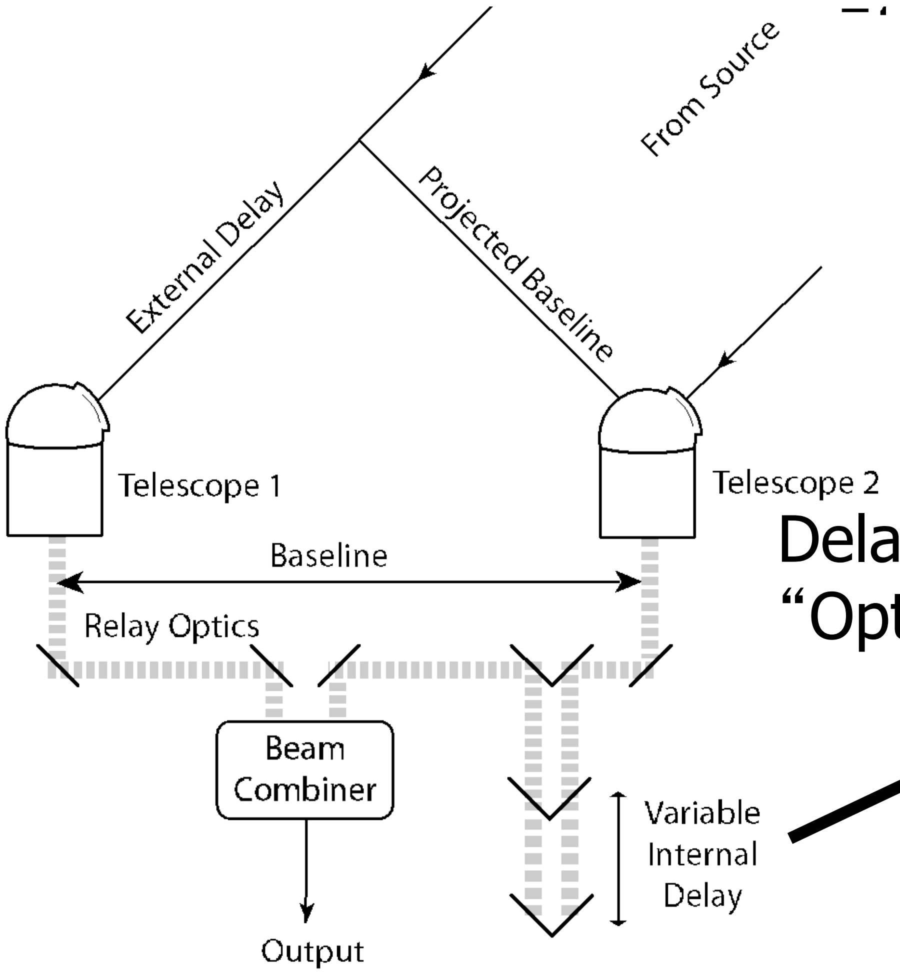
(b)

(c)

(d)

Some images from ten Brummelaar 1999

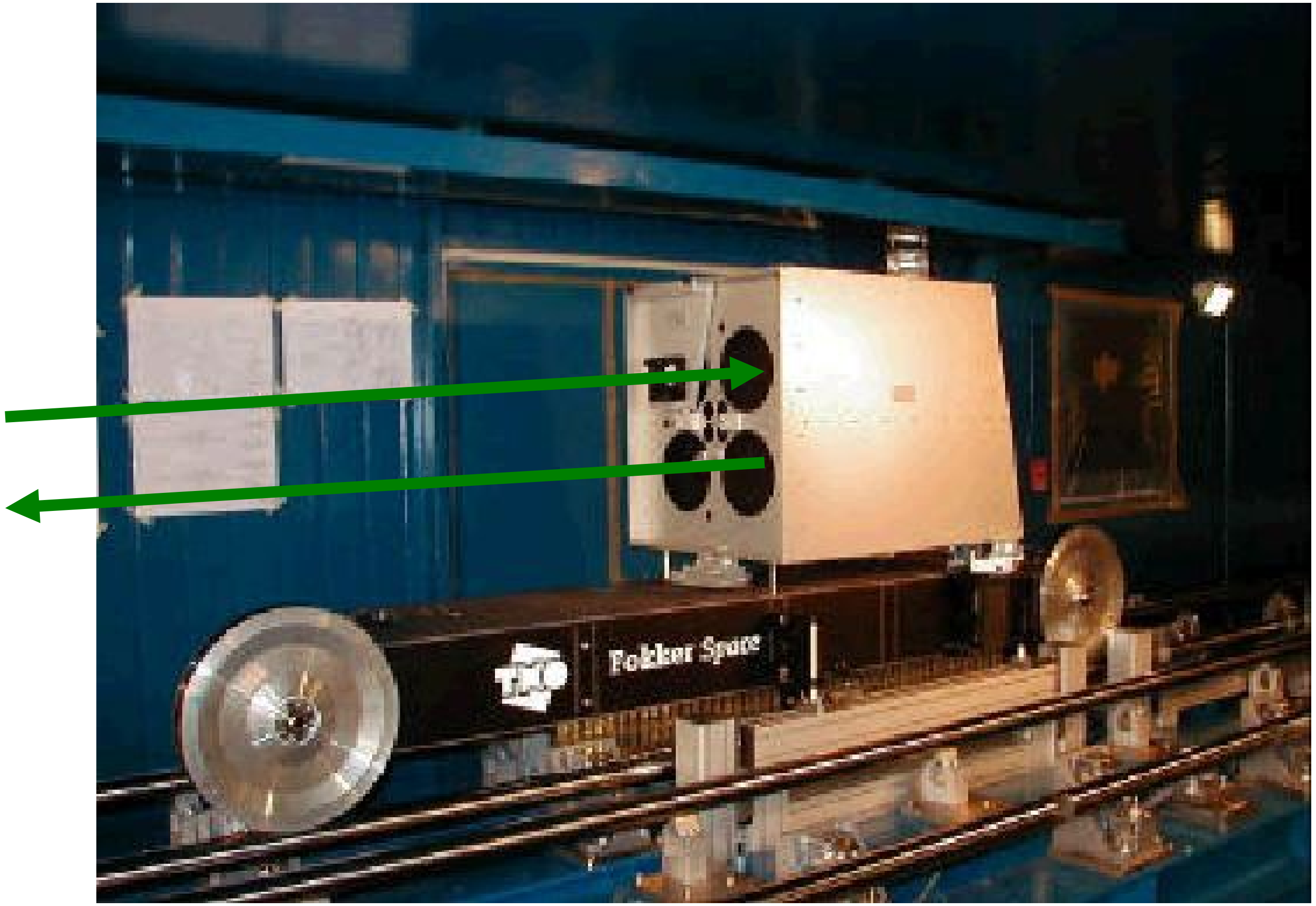
Realistic Interferometers



Delay Lines
“Optical Trombones”

Monnier & Allen 2012

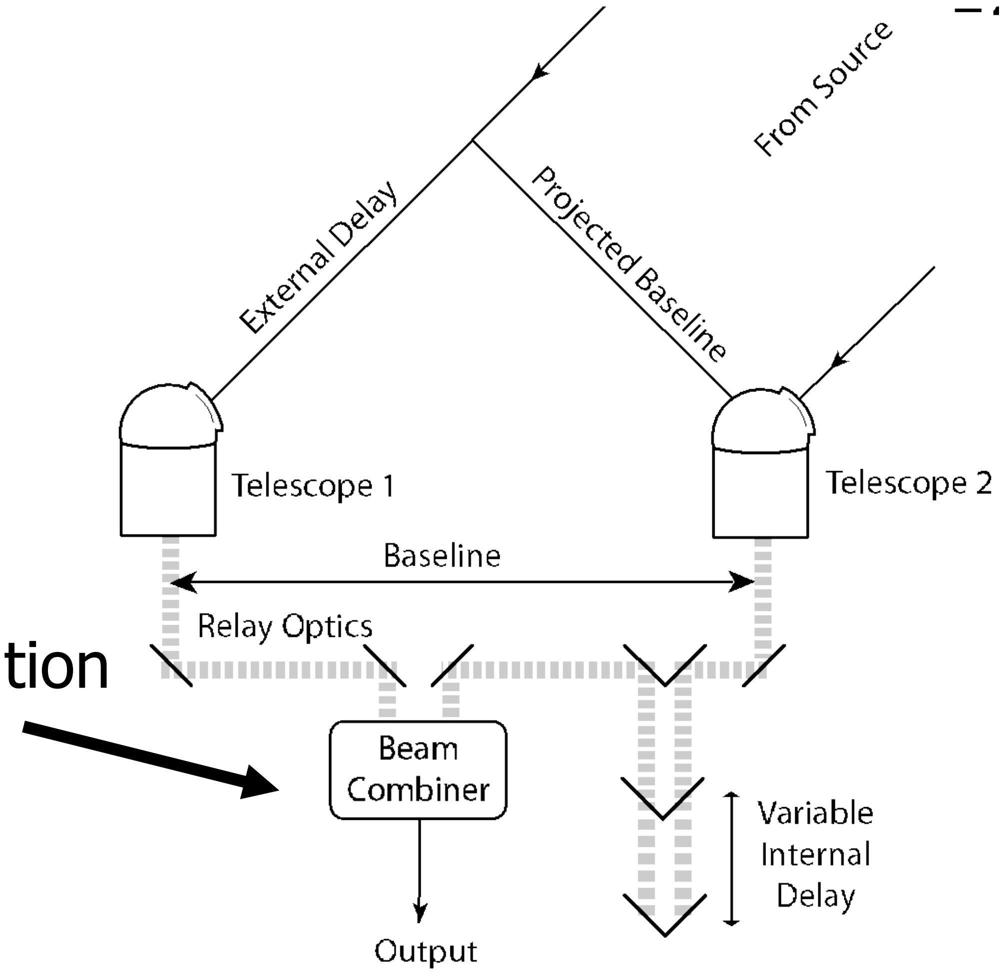
Delay Lines



From ten Brummelaar 1999

Realistic Interferometers

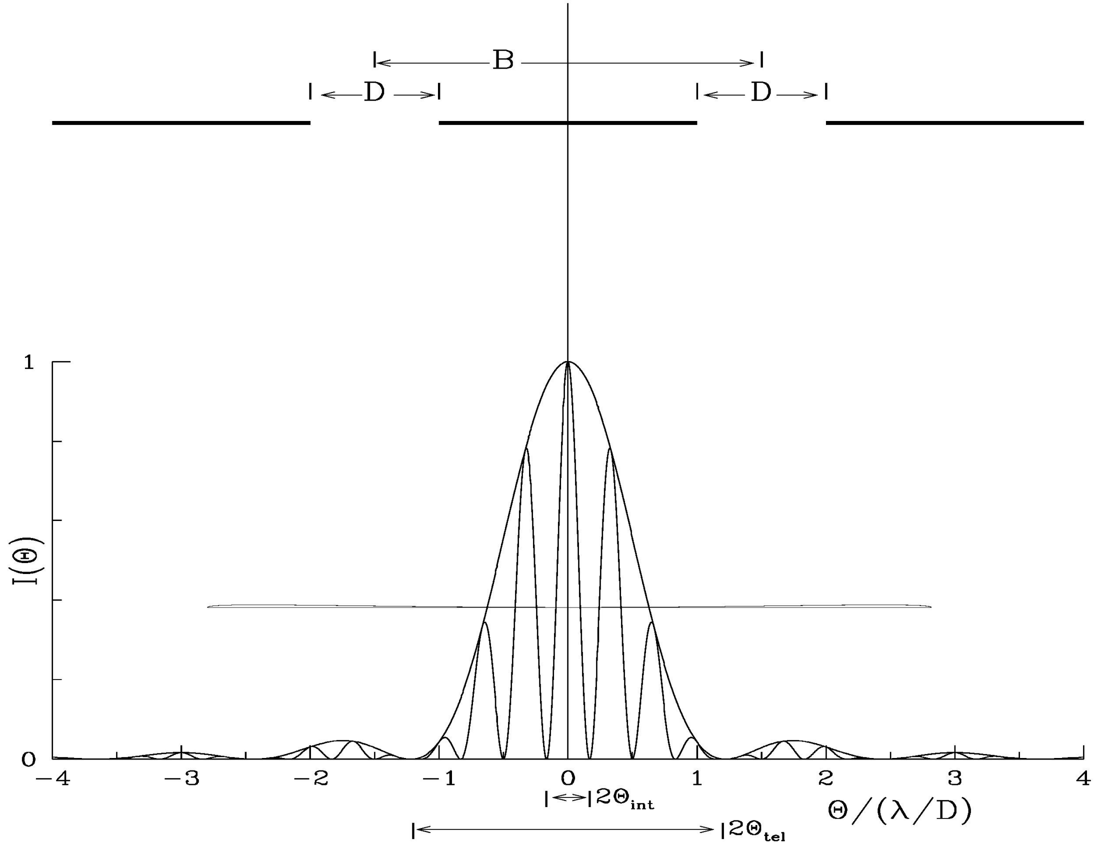
Beam Combination



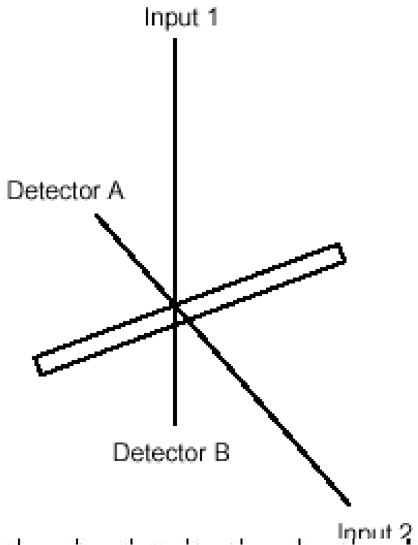
Monnier & Allen 2012

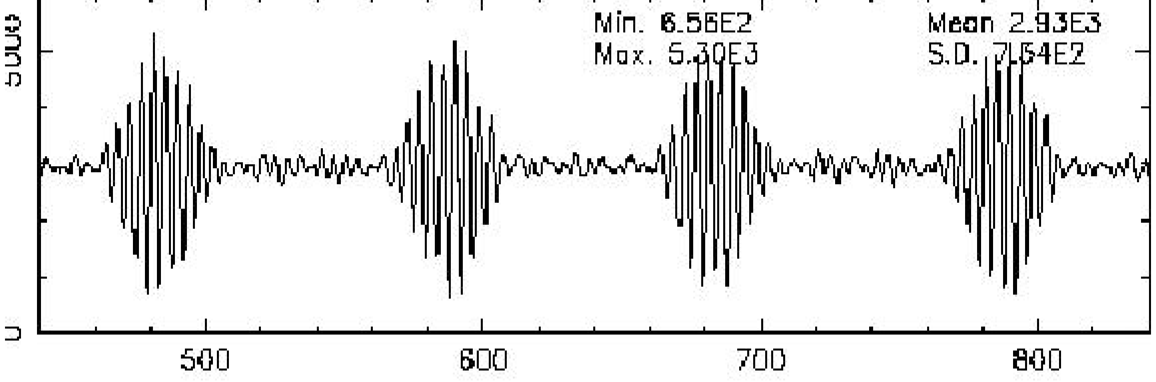
Beam Combination

Image-Plane Combination

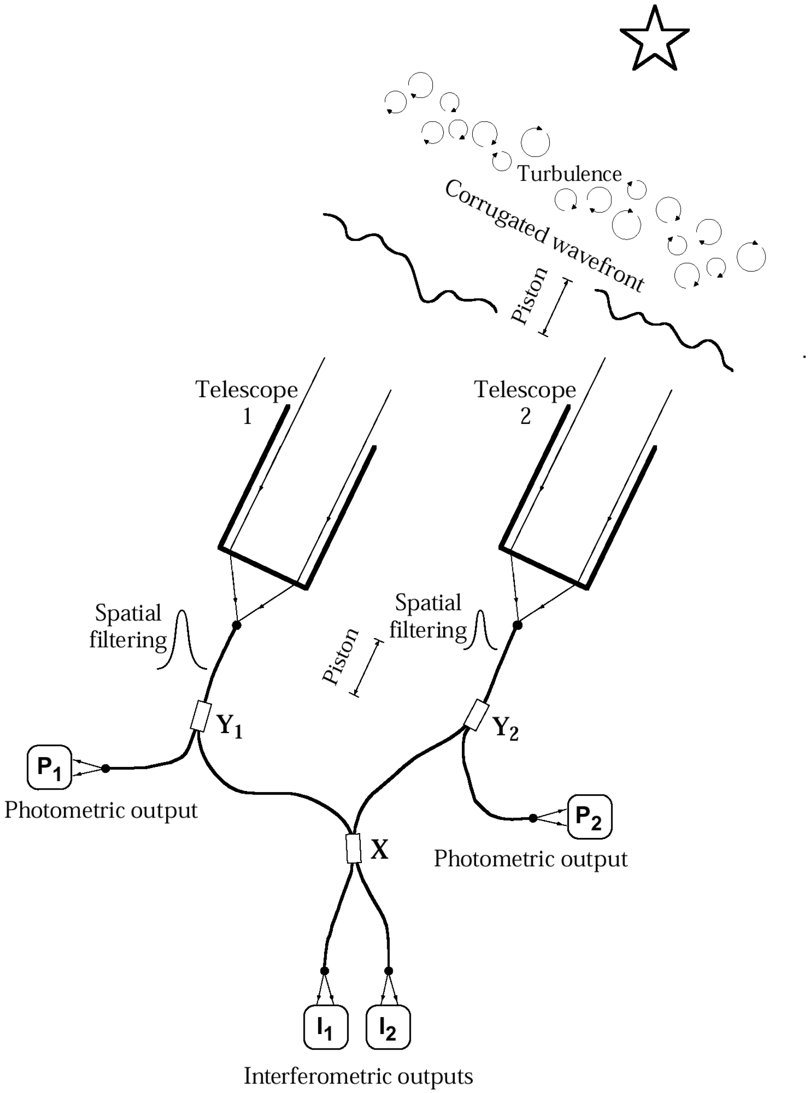


Pair-wise "pupil plane" With temporal scanning

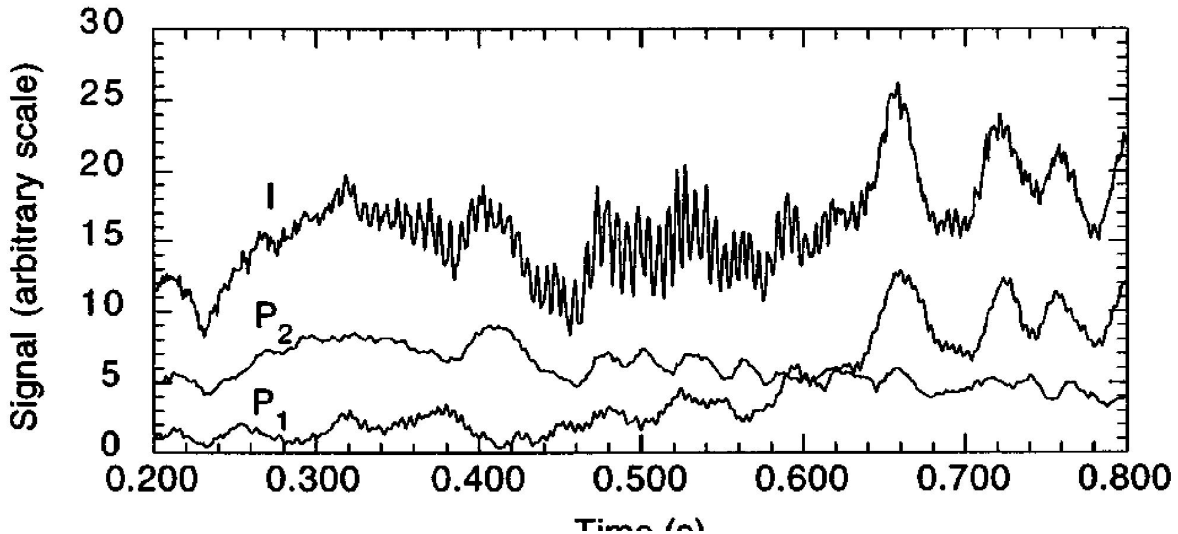


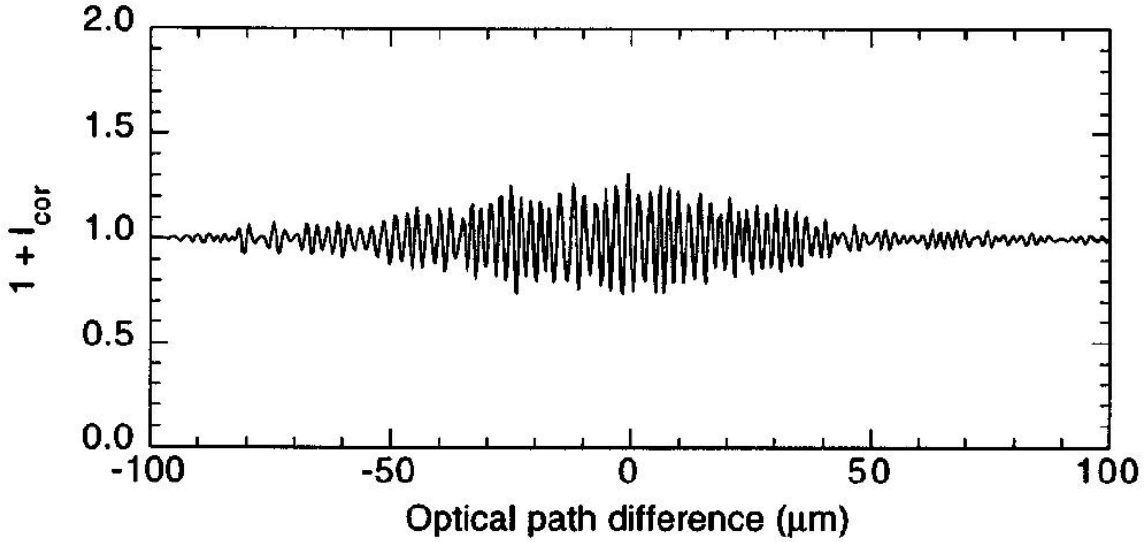


SM Fibers: How They Work

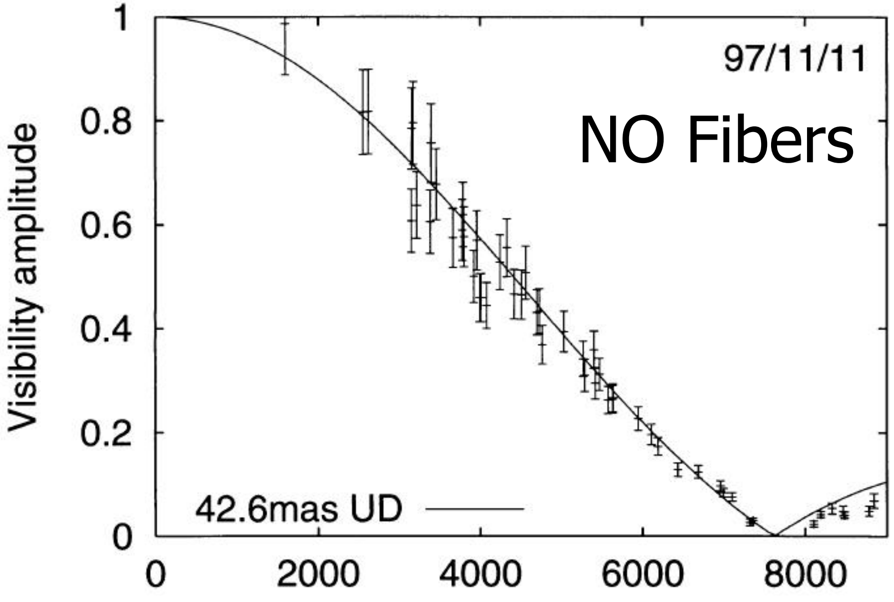


From Foresto et al 1997

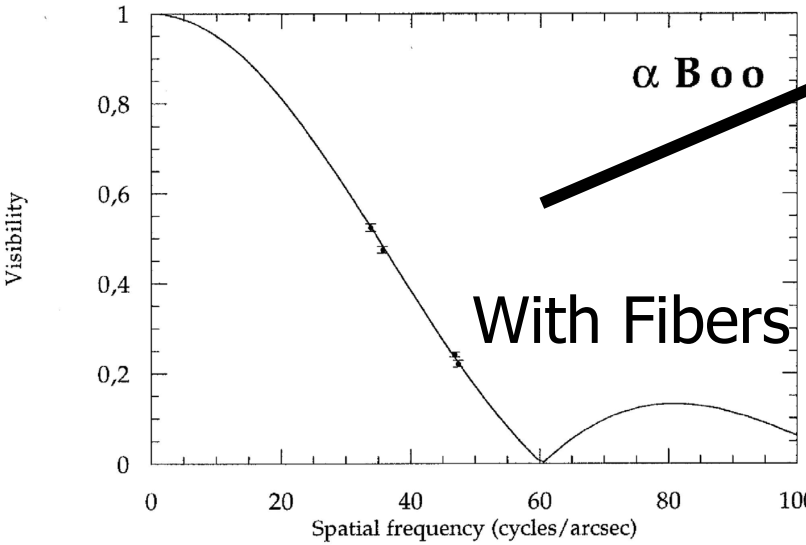




Calibration Improvement

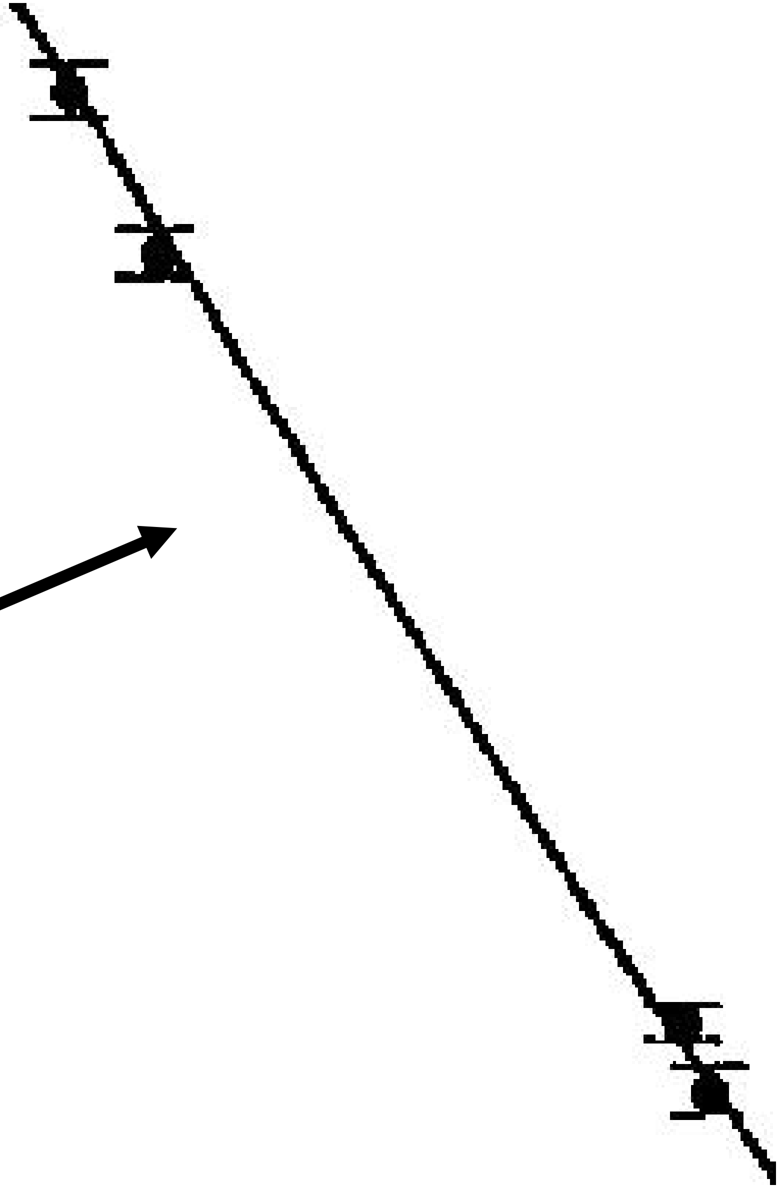


NO Fibers



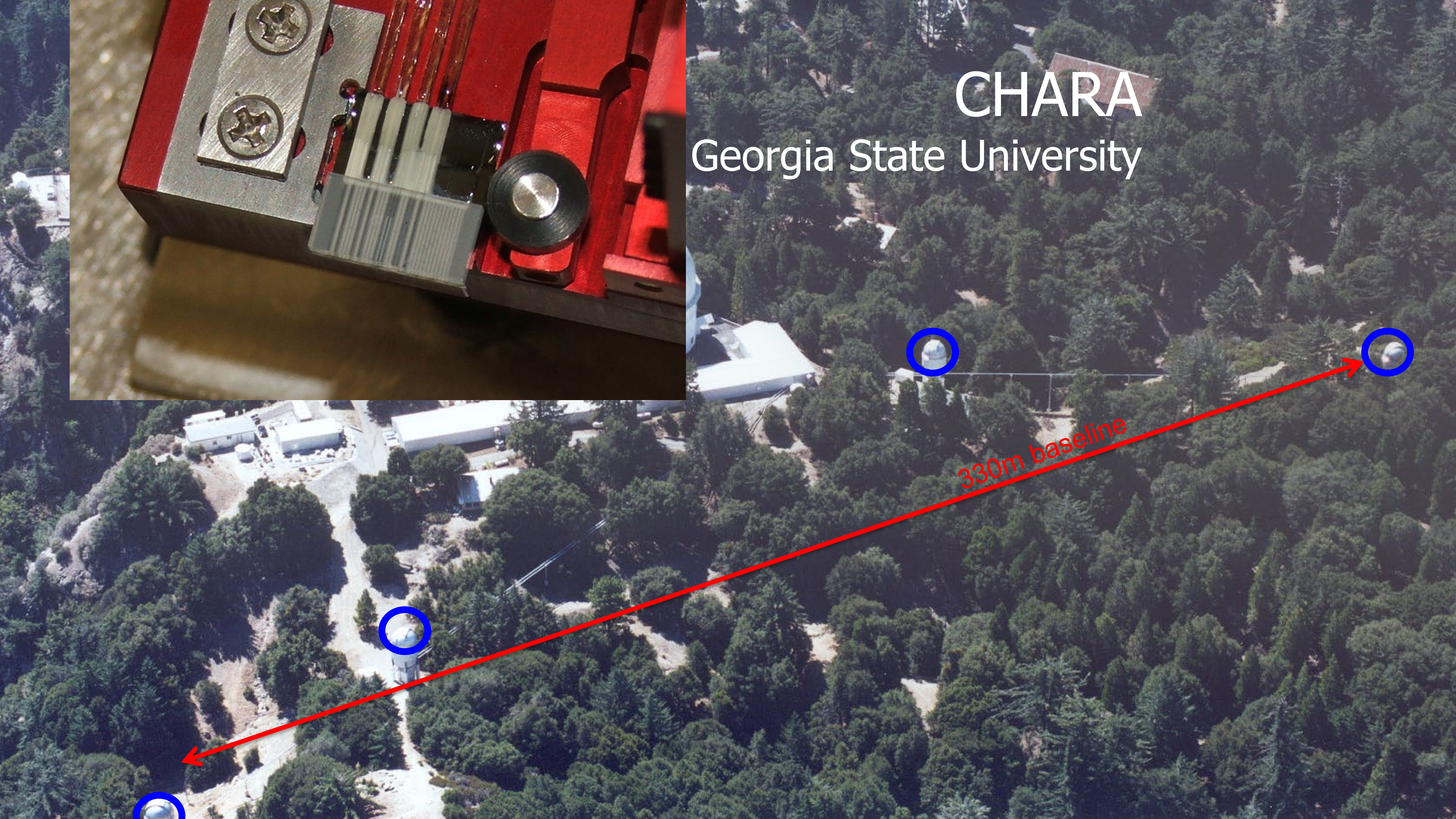
With Fibers

Zoom



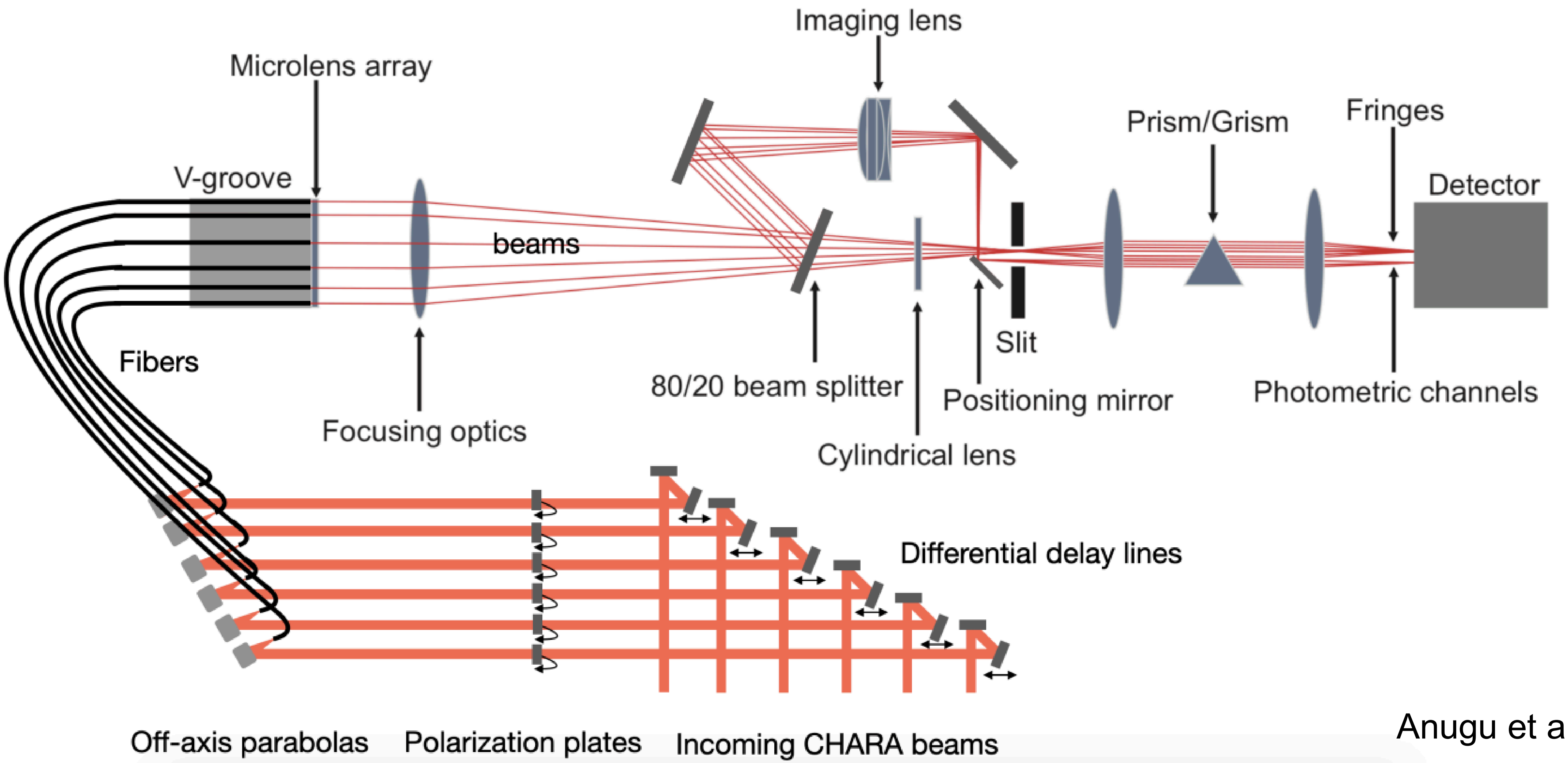
CHARA

Georgia State University



“MIRC-style” All-in-One Combiners:

MIRC, VISION, MIRC-X, MYSTIC, SPICA



Anugu et al. 2022

Photometric Channels

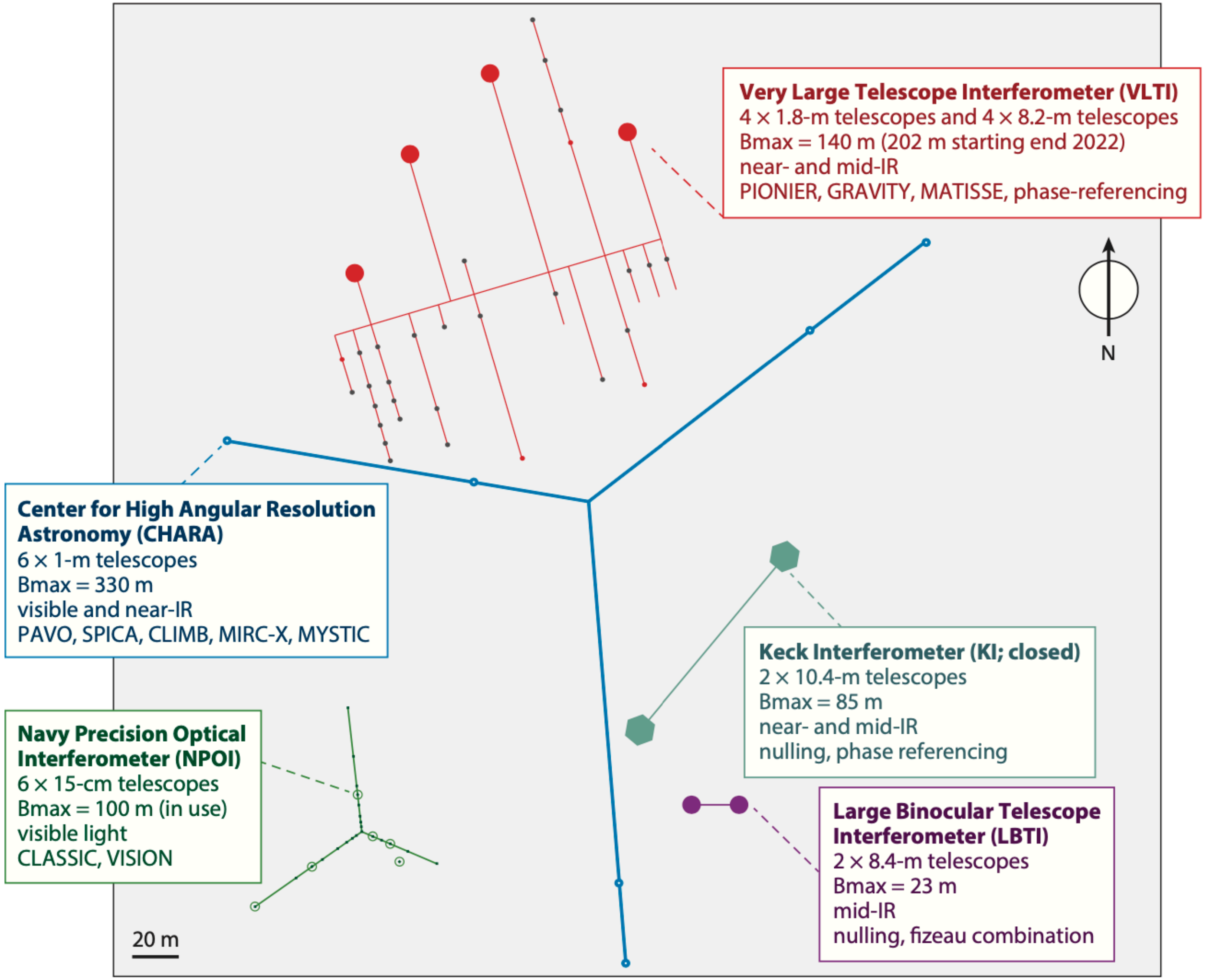
Fringes vs Wavelength

Fringes:
One Spectral Channel

Essential Points

- Interferometers measure Fourier components of images
  - With enough data, imaging is possible
  - Most commonly, we fit models to the interferometric observable: V^2 and Closure Phases
- Optical/Infrared Interferometry is technically demanding, but now routine
  - Wavelengths are small; atmosphere is unkind
- ~1 milliarcsecond resolution is interesting
  - Stellar diameters and stellar evolution, Planet-forming disks, stellar surfaces, interacting binaries, mass loss, exoplanets, AGN, and more!

Current Optical and Infrared Interferometers



Eisenhauer, Monnier & Pfuhl ARAA 2023

- Center for High Angular Resolution Astronomy (CHARA)
  - 6Tx1m, 330m (mag 7.5)
- Very Large Telescope Interferometer
  - 4Tx1.8m, 200m (mag 9)
  - 4Tx8m, 140m **(mag 20 !)**
- Navy Precision Optical Interferometer
  - 6Tx15cm, 100m (mag 6)
- Large Binocular Telescope Interferometer
  - 2Tx8.4m, 23m nulling
- Magdalena Ridge Interferometer (MROI)
  - 2Tx1.4m, 8m (mag 9.1)
  - More to come!

Available Instruments

- CHARA
  - PAVO. R band. 2T. Limit R~9 (at one point…)
  - SPICA. R band. 6T. Limit R~ ? (recent improvements..)
  - MIRCX. H band 6T. Limit H~9 (soon to add J band)
  - MYSTIC. K band 6T. Limit K~9
  - Silmaril. H band 3T. Limit H~9
- VLTI
  - PIONIER. H band. AT limit H~8.5, UT limit H~10
  - GRAVITY. K band. AT limit K~8.5, UT limit H~13 (→20 w/ phase referencing)
  - MATISSE. LMN band. ATs: L ≈ 6.0 mag, M ≈ 4.8 mag, N ≈ 0.8 mag.
    UTs: L ≈ 9.0 mag, M ≈ 7.9 mag, N ≈ 3.9 mag.
  - BIFROST/NOTT/Asgard Suite. J + L band nulling. Commissioning soon.
- MROI
  - Fourier. YJHK bands. 2T. Limit ~9 (with room for improvement!)