Astrometry using Optical Interferometry

Antoine Mérand

European Southern Observatory - Chile

ADeLA - Santiago - Sept 29th 2014

Single Dish Telescopes

- Diffraction limit: λ/D (~50mas for 8m in near IR)
- ~100-200μas astrometry reached with 8m class Telescopes (Kervella+ 2013, Sahlmann+ 2014, Lazorenkho+ 2014, Neichel+ 2014)
- Astrometry sub-λ/D feasible but limited by: distortion, atmosphere…
- Astrometric accuracy does not equal angular resolution

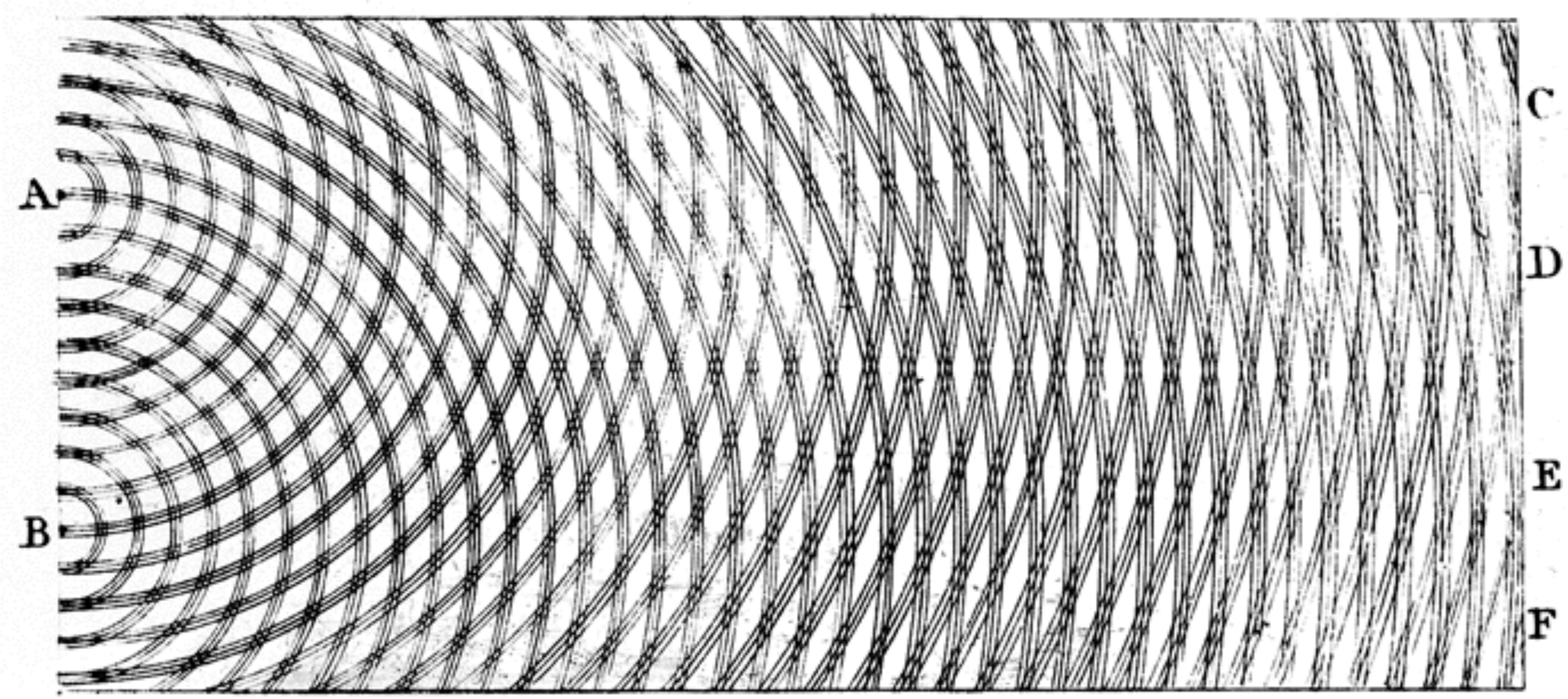
Optical Interferometry

- Combining telescopes separated by B>100m
- Diffraction limit: λ/B (~2mas 150m in NIR)
- a priori:
  - can separate objects few mas from each other
  - sub-diffraction astrometry in the 10µas regime

Outline

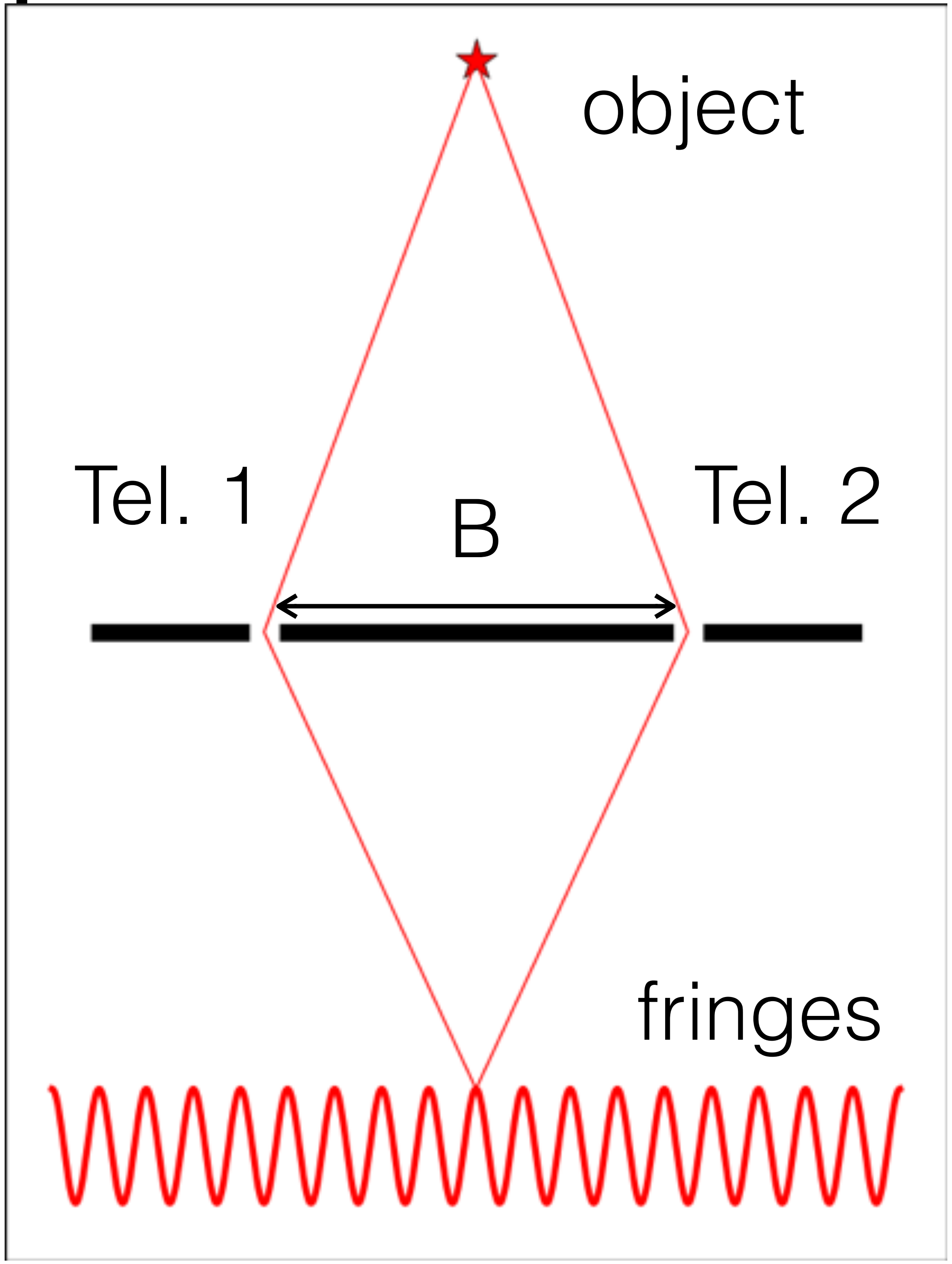
- Some principles of OI
- How can we do astrometry with OI?
- limitations
- Some examples

Young’s experiment



"On the Theory of Light and Colours”
Thomas Young, 1801

A Simple interferometer

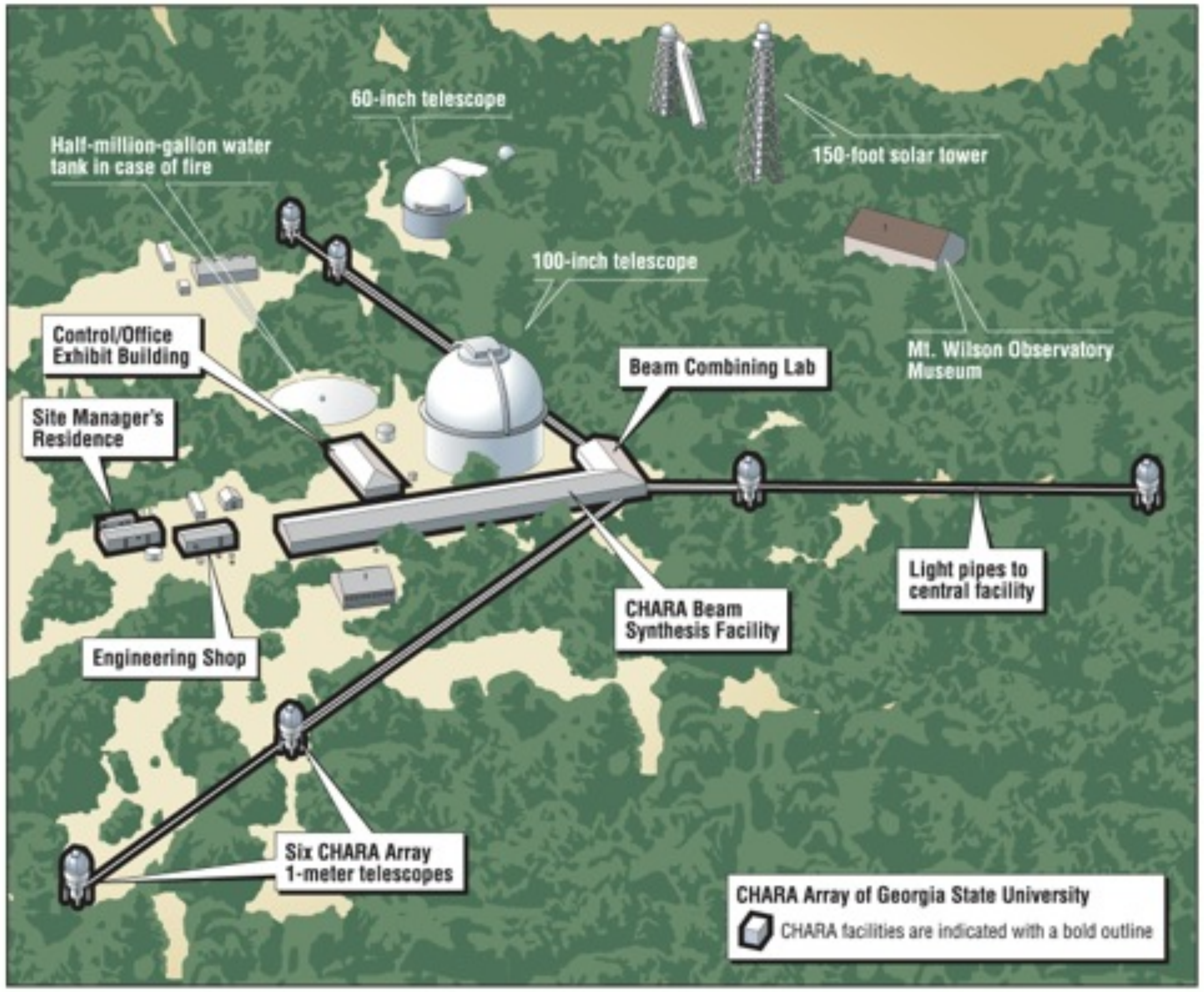


Real Interferometers

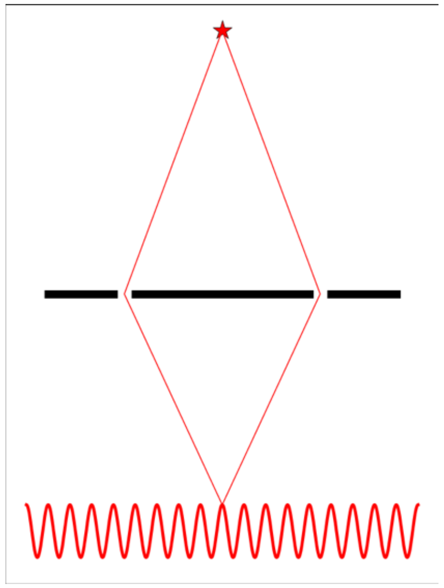
The VLT Array on the Paranal Mountain

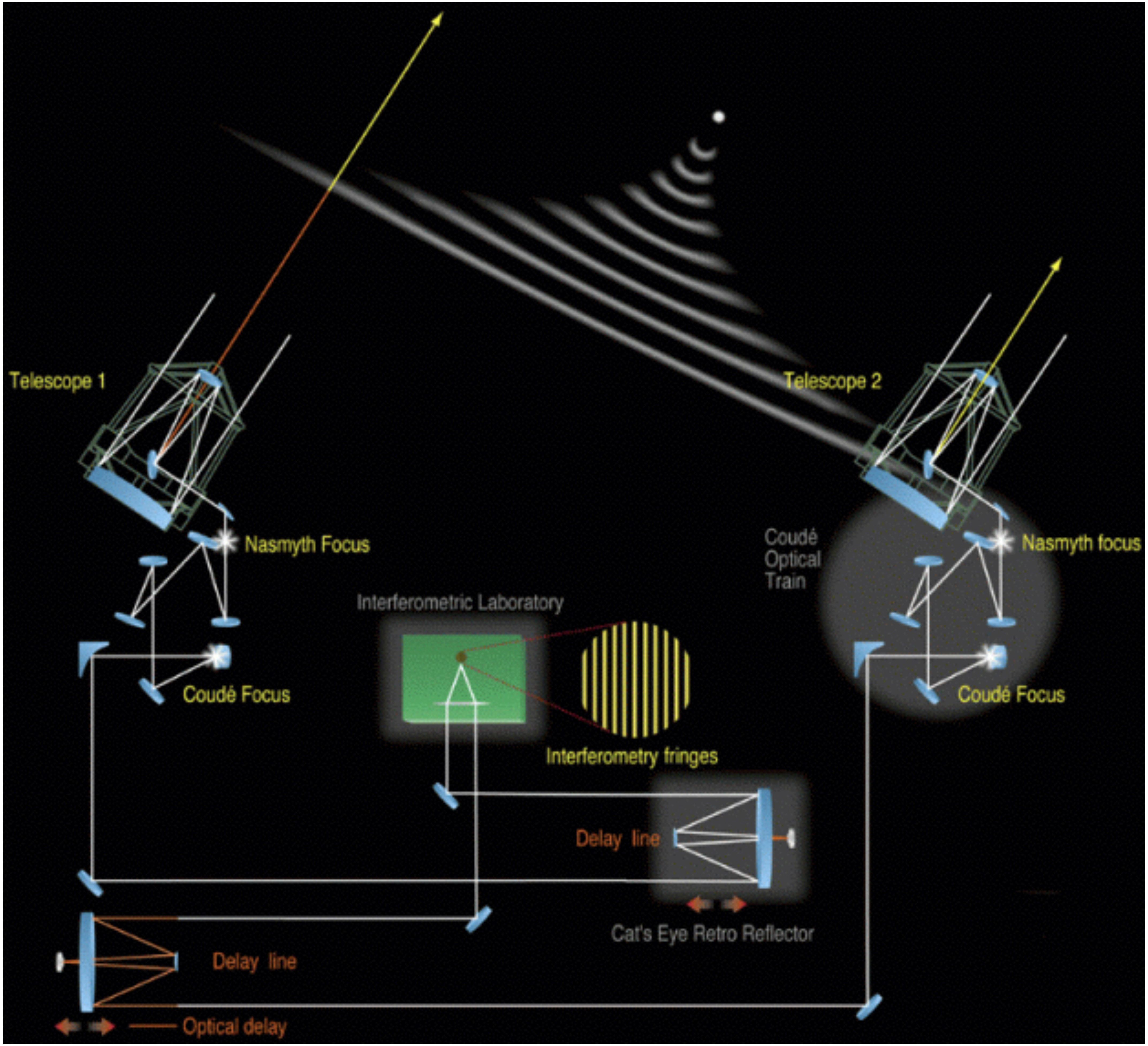
ESO PR Photo 14a/00 (24 May 2000)

©European Southern Observatory

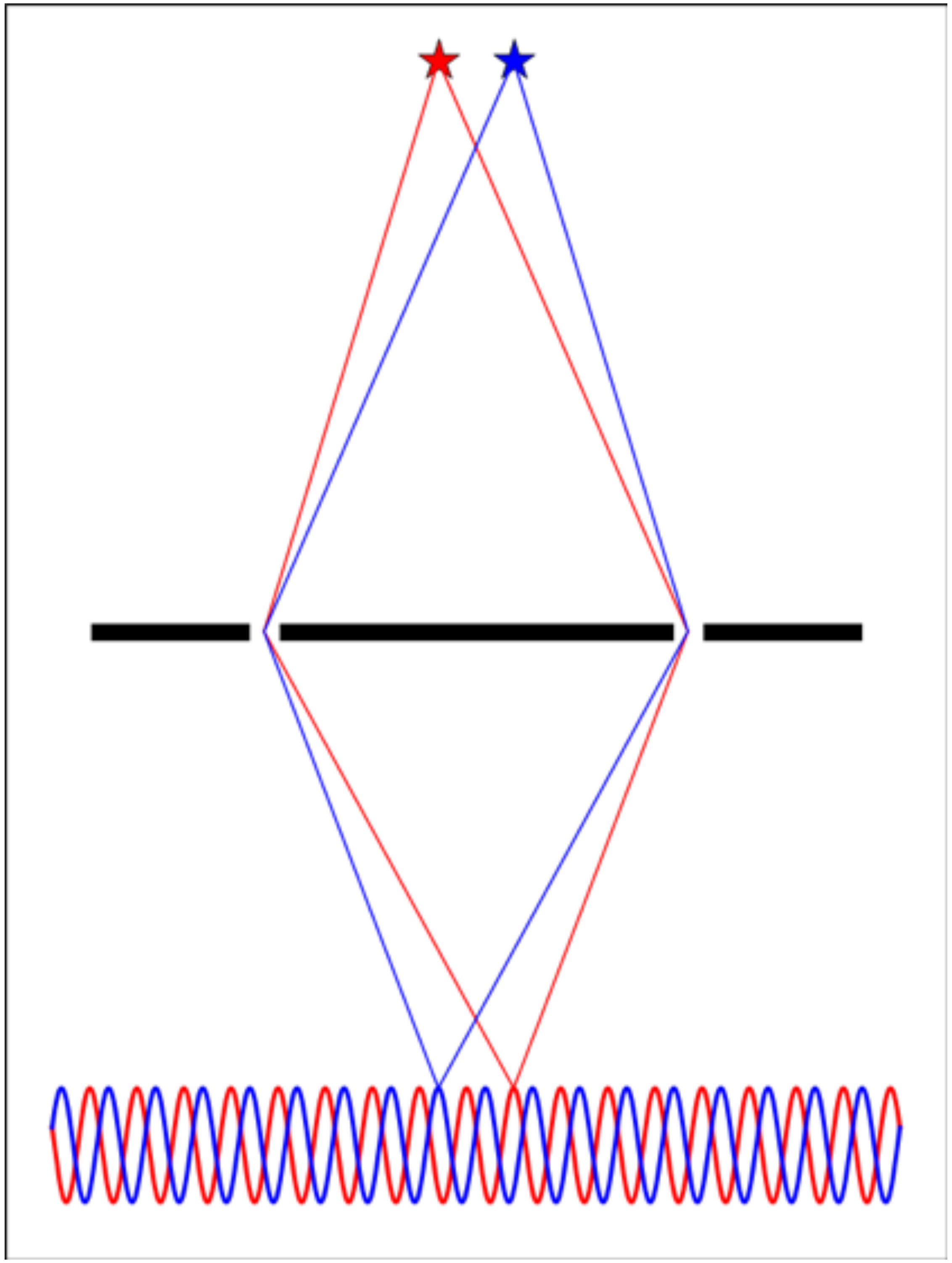


CHARA Array

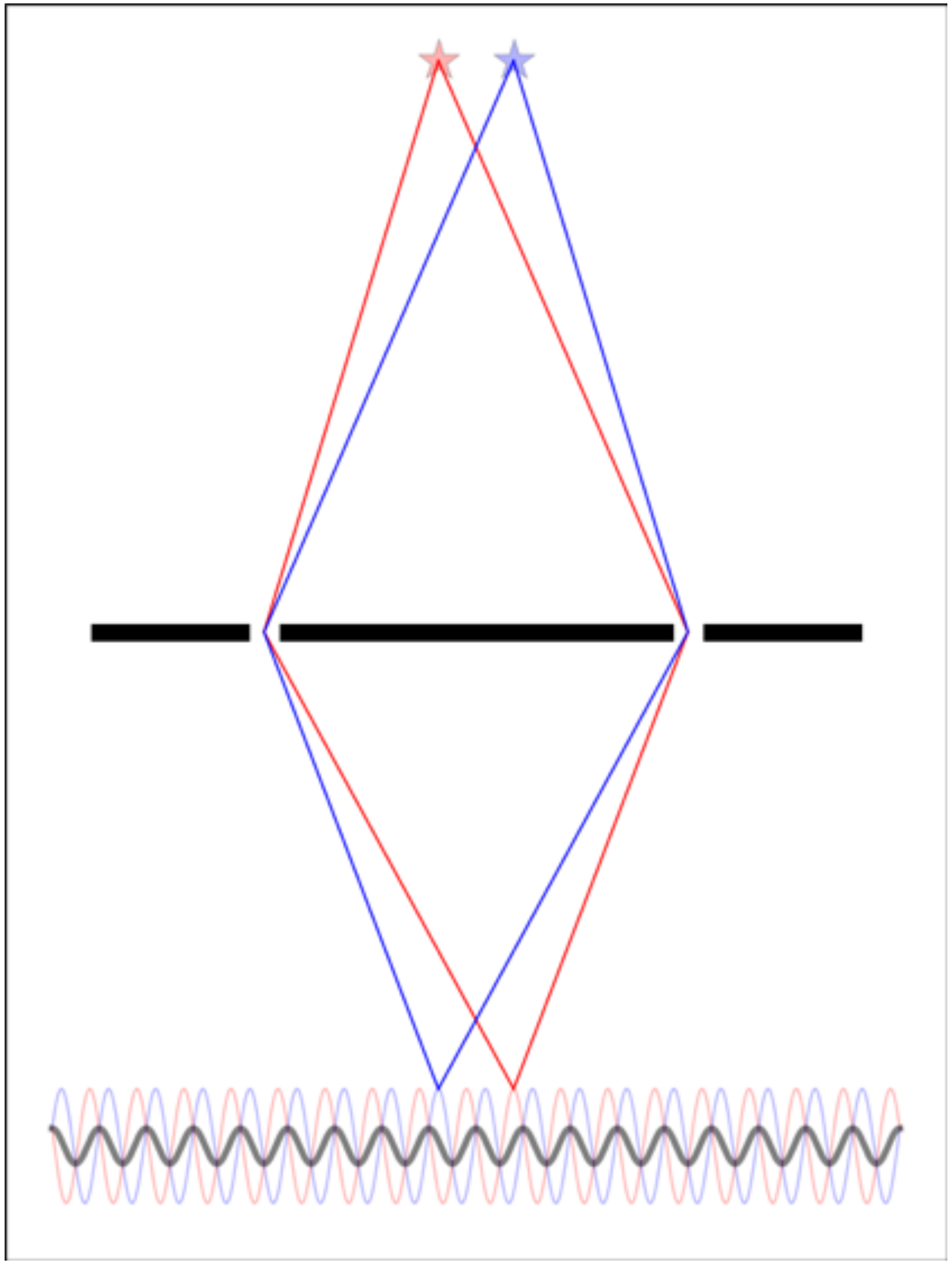



Telescope 1
Telescope 2
Nasmyth Focus
Coudé Optical Train
Nasmyth focus
Interferometric Laboratory
Coudé Focus
Coudé Focus
Interferometry fringes
Delay line
Cat's Eye Retro Reflector
Delay line
Optical delay

Angular Resolution



Angular Resolution



Basic principles

- Fringes Amplitude (“Visibility”) is the main observable
- 2 objects separated by angle **s** will produce fringes offset by **B.s**
- Fringes will disappear for **B.s = λ/2**
- If fringes amplitude is measured with accuracy, separation power < **λ/2B**

Fringes Visibility

- **Each point-like object creates a fringe pattern**
  - phase is proportional to position in sky
  - amplitude is proportional to flux
- Van Cittert-Zernike theorem: **$V(B,\lambda) \sim \mathrm{FTimage}(B/\lambda)$**
- Better angular resolution (higher spatial frequency): longer baselines and/or shorter wavelength
- Image reconstruction: **image = FT^{-1}(visibility)**

OI Astrometry

the fringes' phase in the astrometric information

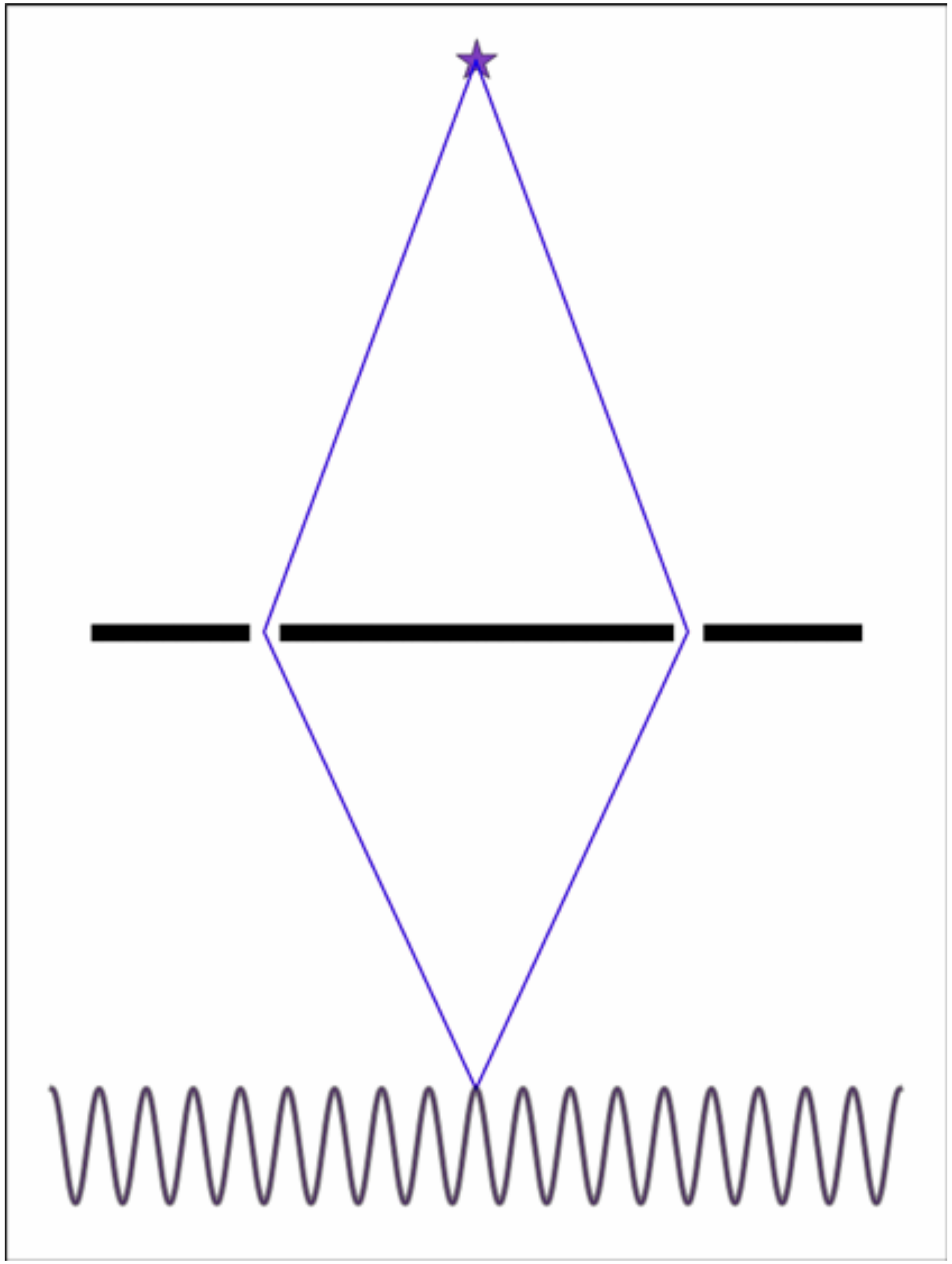
- phase shift is the **B**.**s**
- ambiguous phase info in pure monochromatic observation
- atmosphere gives a low frequency perturbation, ~10μm in amplitude in ~1 minute → 20mas rms

OI Astrometry

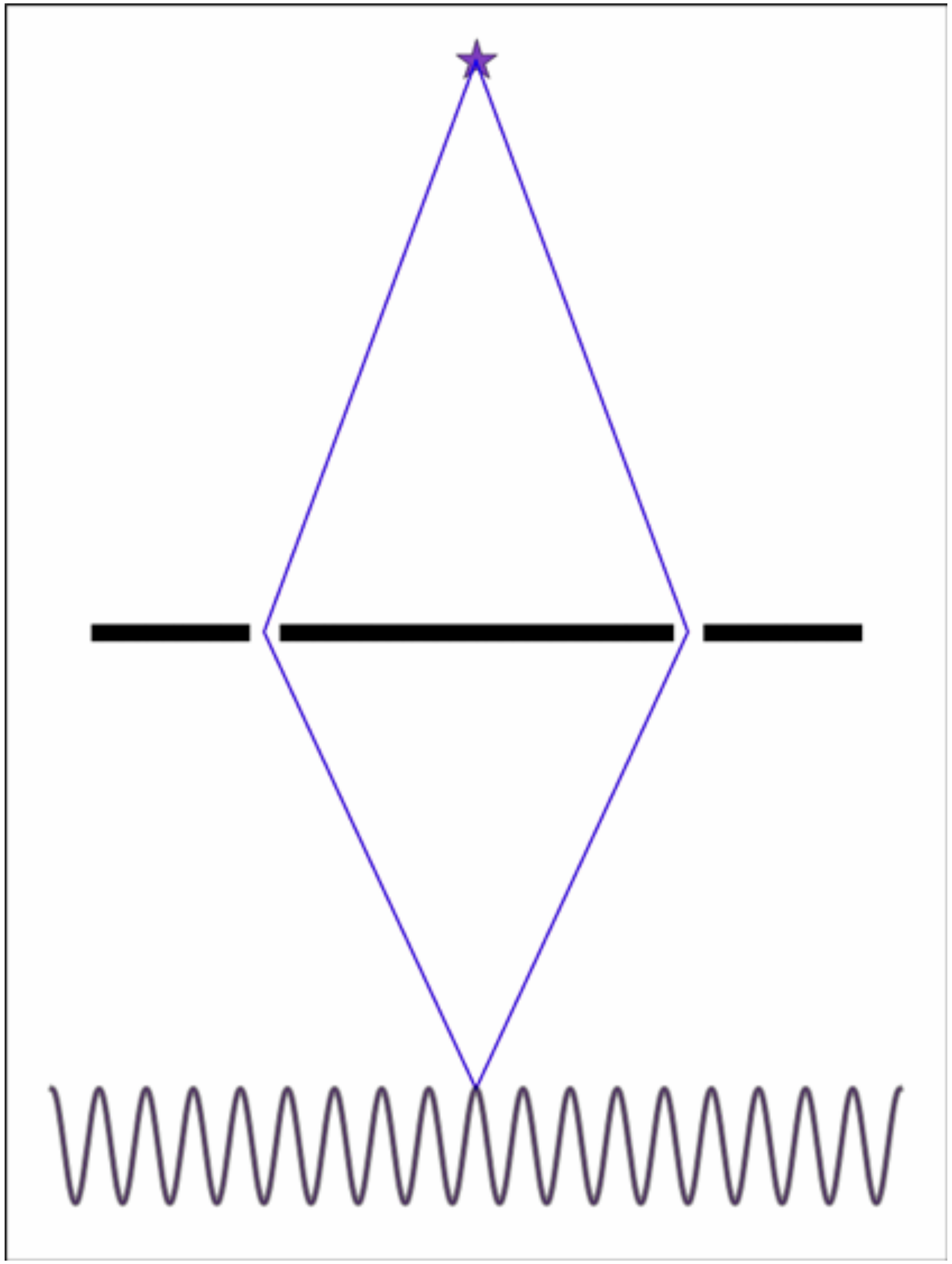
Astrometry within the field of view:

- observe visibilities
- inverse problem and reconstruct image
- do relative astrometry in image

Separation Ambiguity



Separation Ambiguity



How many observations do we need?

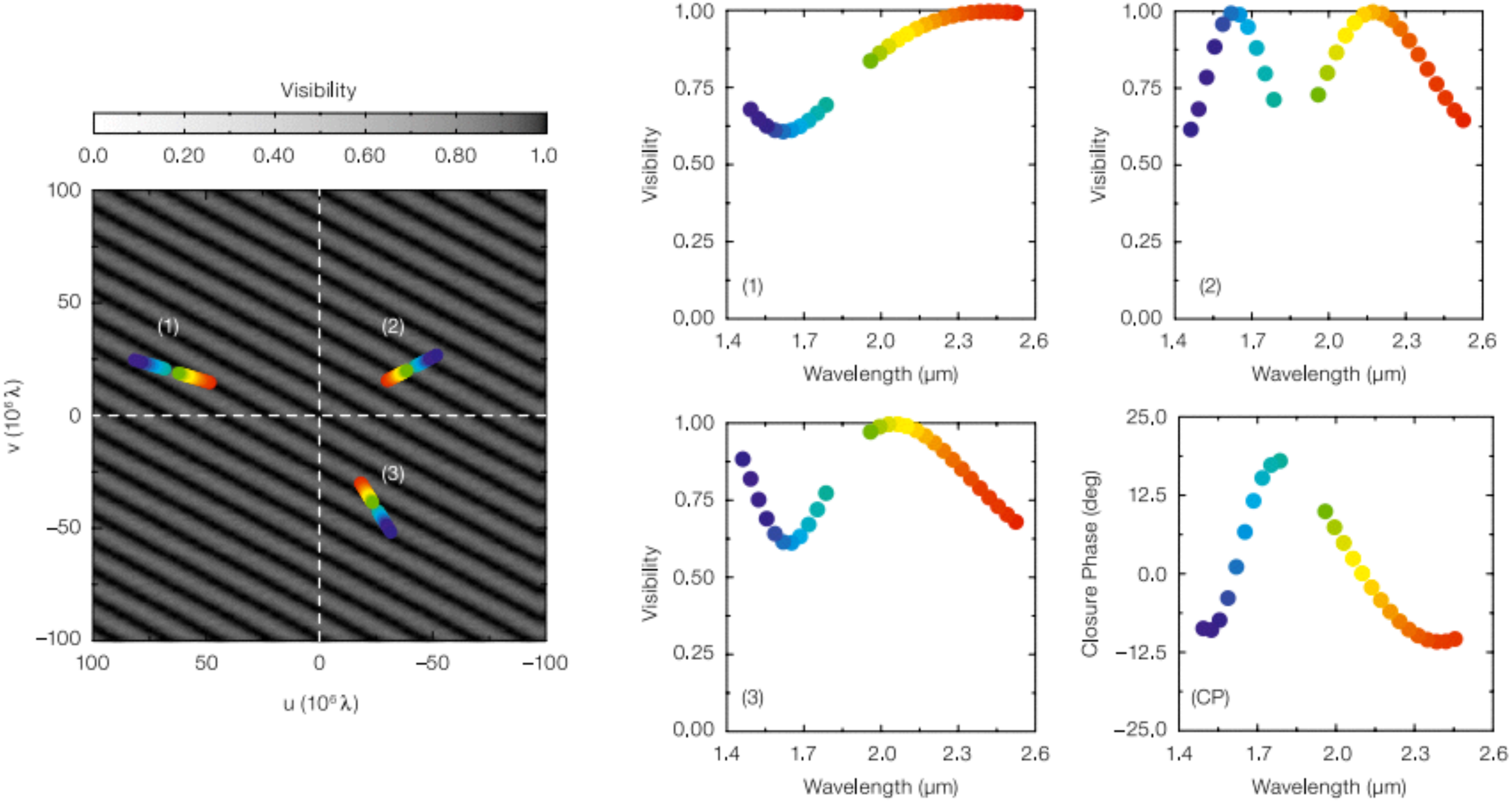
- un-ambiguous imaging only works if one has a lot of observations at different
- better approach: **fit an analytical visibility function**

star 1 *star 2* *modulation*

$$V(u,v,\lambda,x,y,f)=\frac{V_1(u,v,\lambda)+fV_2(u,v,\lambda)e^{2i\pi(xu+yv)/\lambda}}{1+f}$$

baseline wavelength separation flux ratio

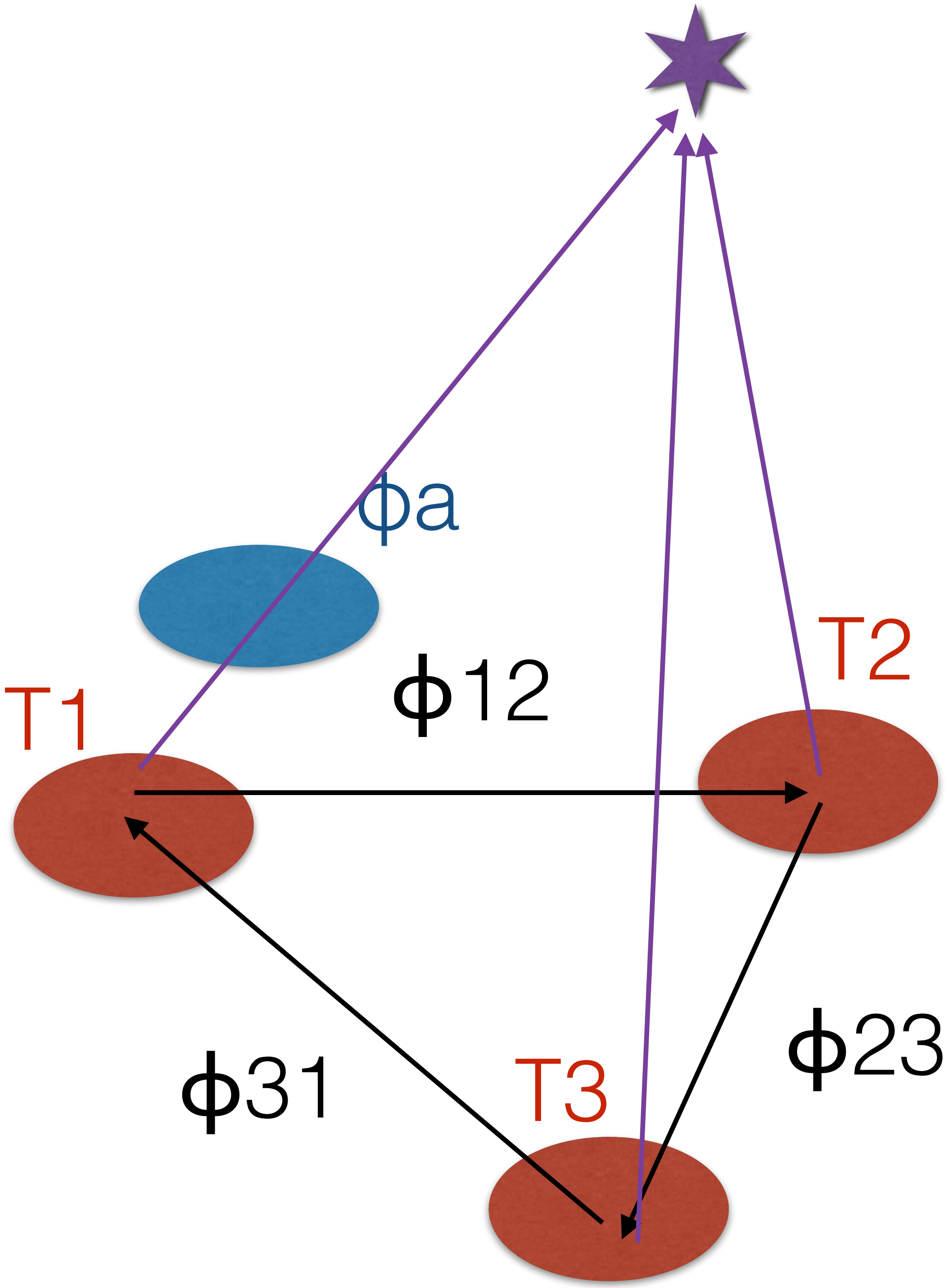
principles: AMBER/VLTI



Kraus+ 2009 (The Messenger 136)

principles: phase closure

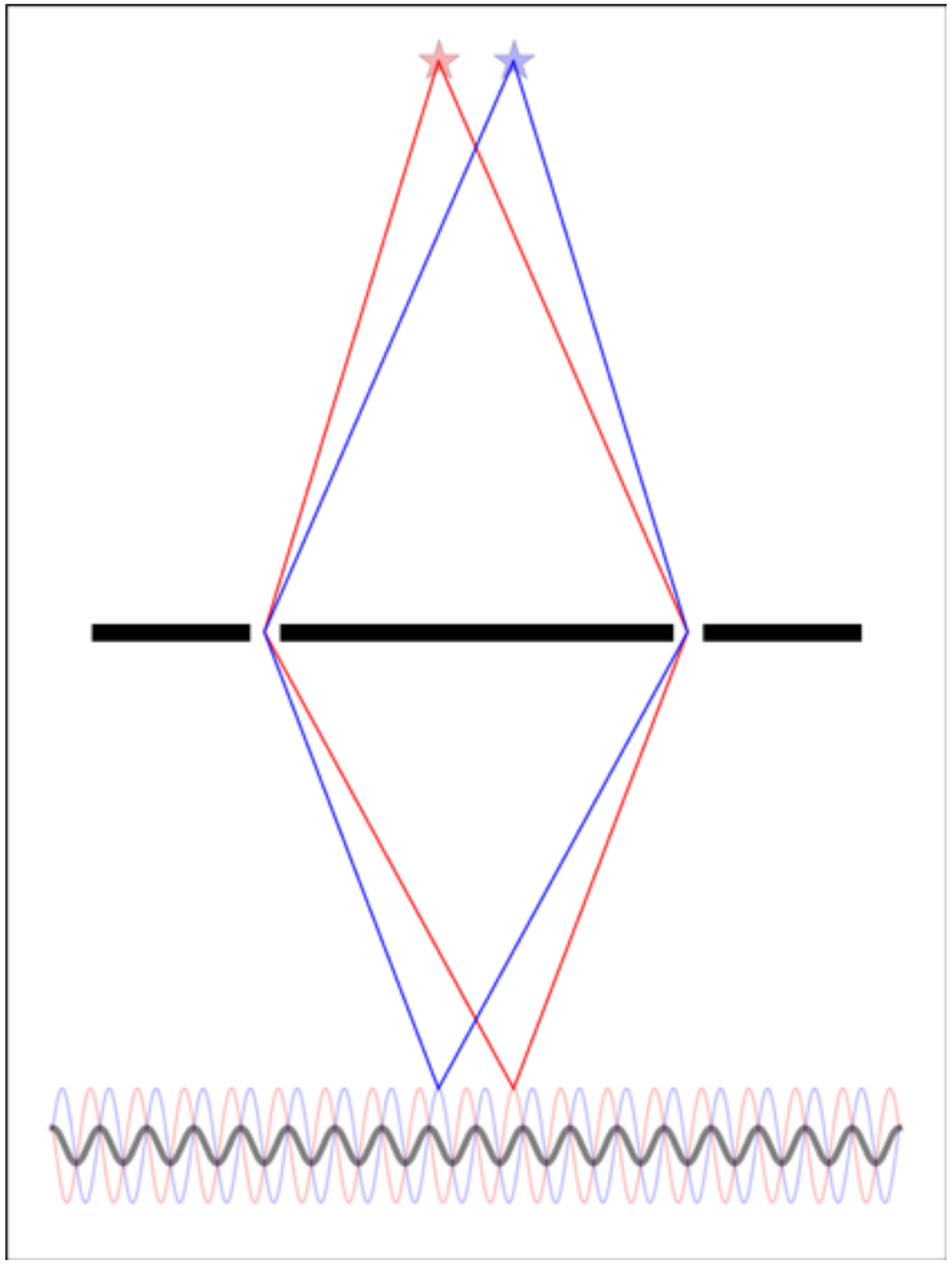
- astrometric info is in the fringes' phase
- phase is lost because of atmospheric turbulence
- CP = (ϕ12 + ϕa) + (ϕ23) + (ϕ31 - ϕa)
- CP is insensitive to atmospheric turbulence



OI in intrinsically good at astrometry

- Information is **multiplexed:** removes lots of biases

- Beam combiners are designed to measure visibility with **accuracy**



Limitations

- Measure V2, not compex V, but if nB>2, phase information in phase closure

- Field of view == diffraction pattern of telescope (!) ~ 100mas

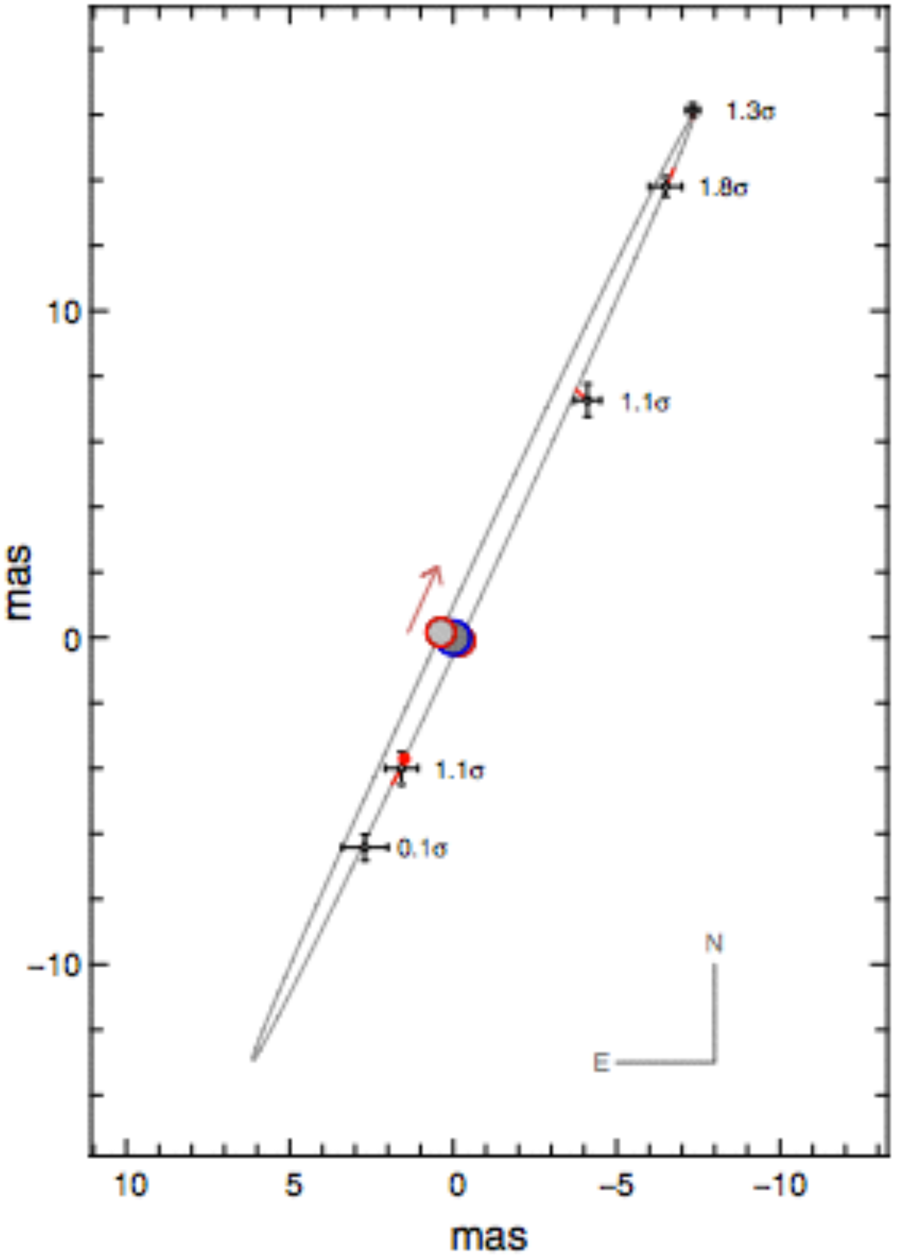
- Highest binary contrast ~ closure phase precision ~ 1%

- Best astrometric precision ~ visibility precision (limited by atmo. turbulence) ~ 1/50 x λ/B =60μas in H band at B=140m

eclipsing binary* δ *Vel

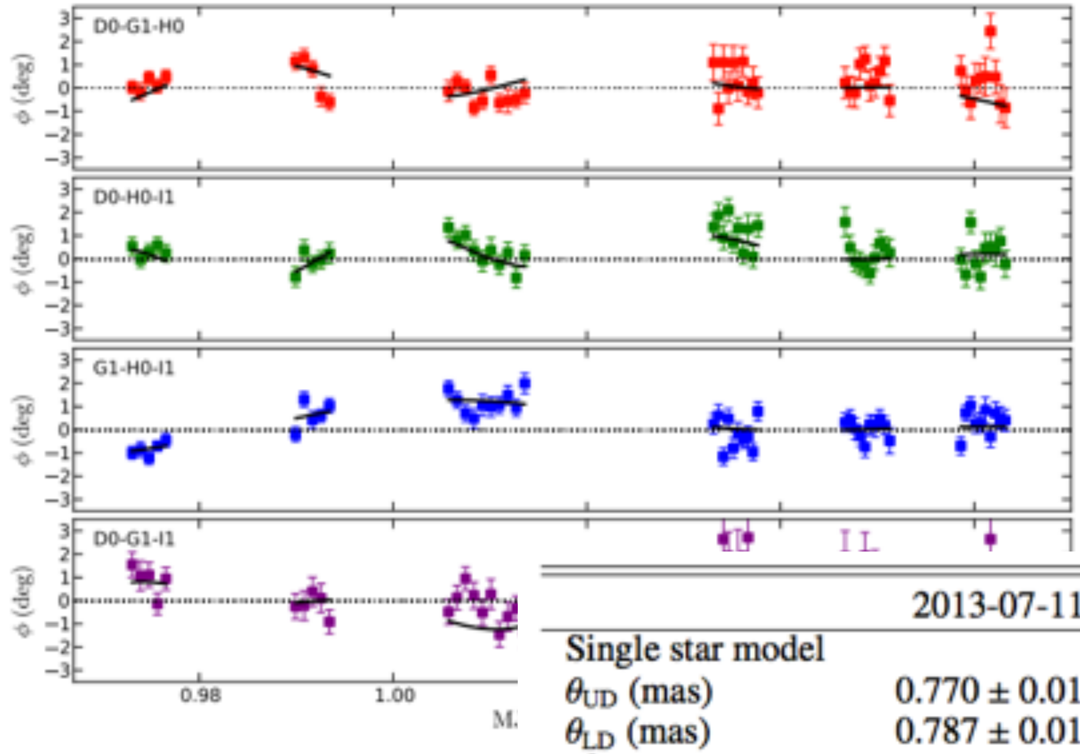
a=16.50±0.16mas

masses, dist. at 1%



Mérand+ 2011

Cepheid AX Cir

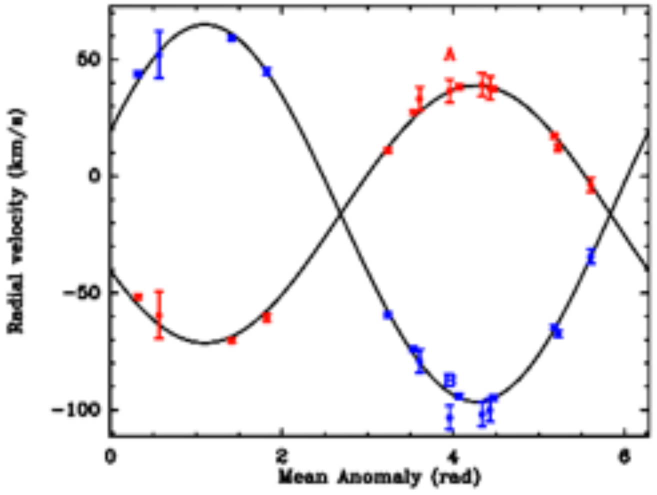


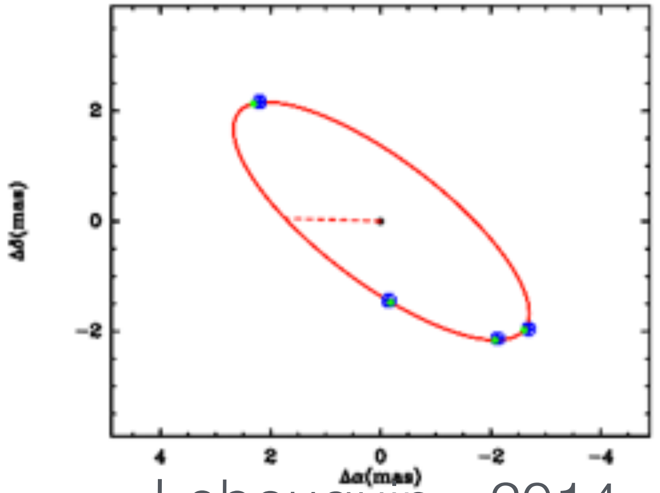
Phase Closure

	2013-07-11	2012-07-14
Single star model		
θ_{UD} (mas)	0.770 ± 0.016	0.931 ± 0.019
θ_{LD} (mas)	0.787 ± 0.016	0.952 ± 0.020
χ^2_r	1.45	1.09
Binary model		
θ_{UD} (mas)	0.726 ± 0.020	0.821 ± 0.022
θ_{LD} (mas)	0.742 ± 0.020	0.839 ± 0.023
f (%)	0.75 ± 0.17	0.90 ± 0.10
$\Delta\alpha$ (mas)	6.421 ± 0.198	6.153 ± 0.155
$\Delta\delta$ (mas)	−28.366 ± 0.366	−28.584 ± 0.229
χ^2_r	1.17	0.72

Gallenne+ 2014

χ Lup: *a=3.27±0.07mas*





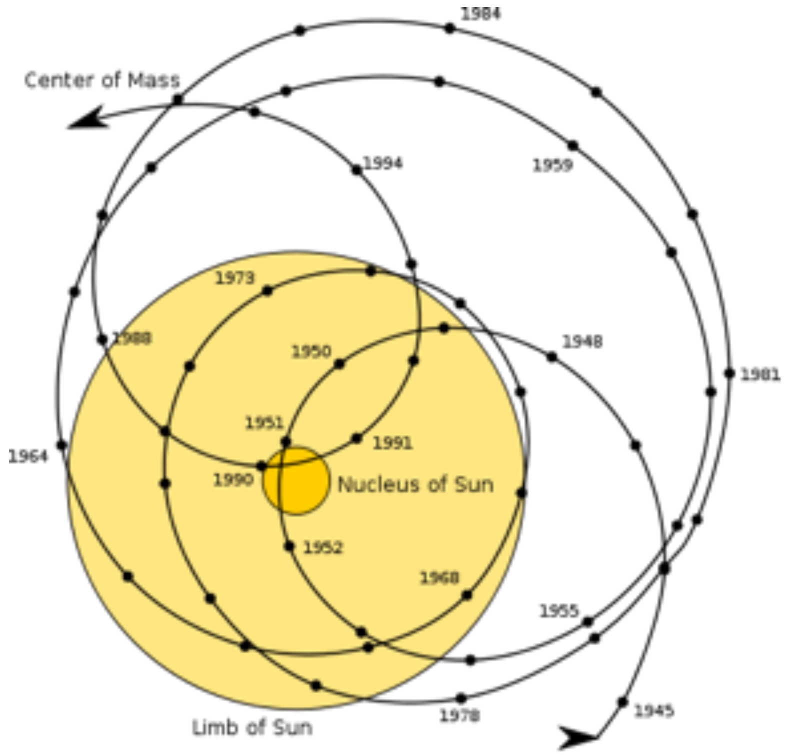
Lebouquin+ 2014

Why beat the diffraction limit?

~50µas astrometry for object >1” apart?

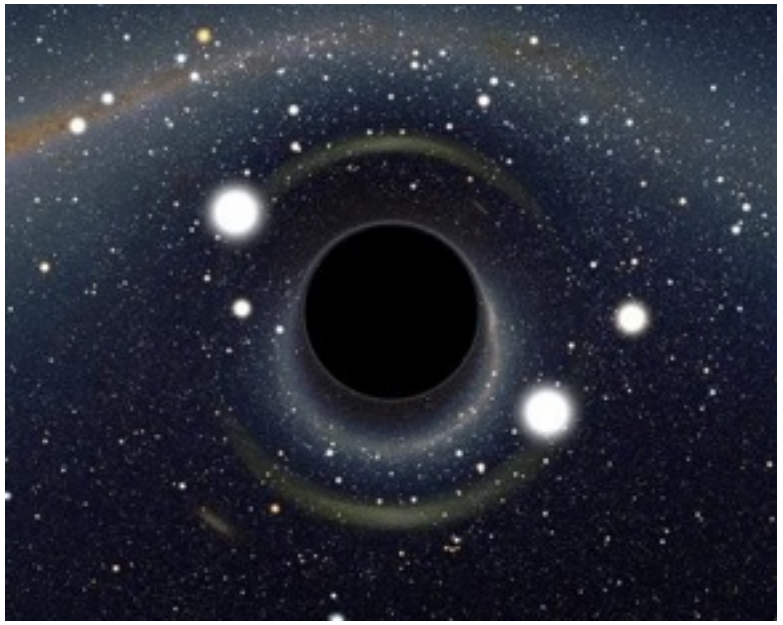
Object of interest + reference target:

- exoplanets
- galactic center
- …



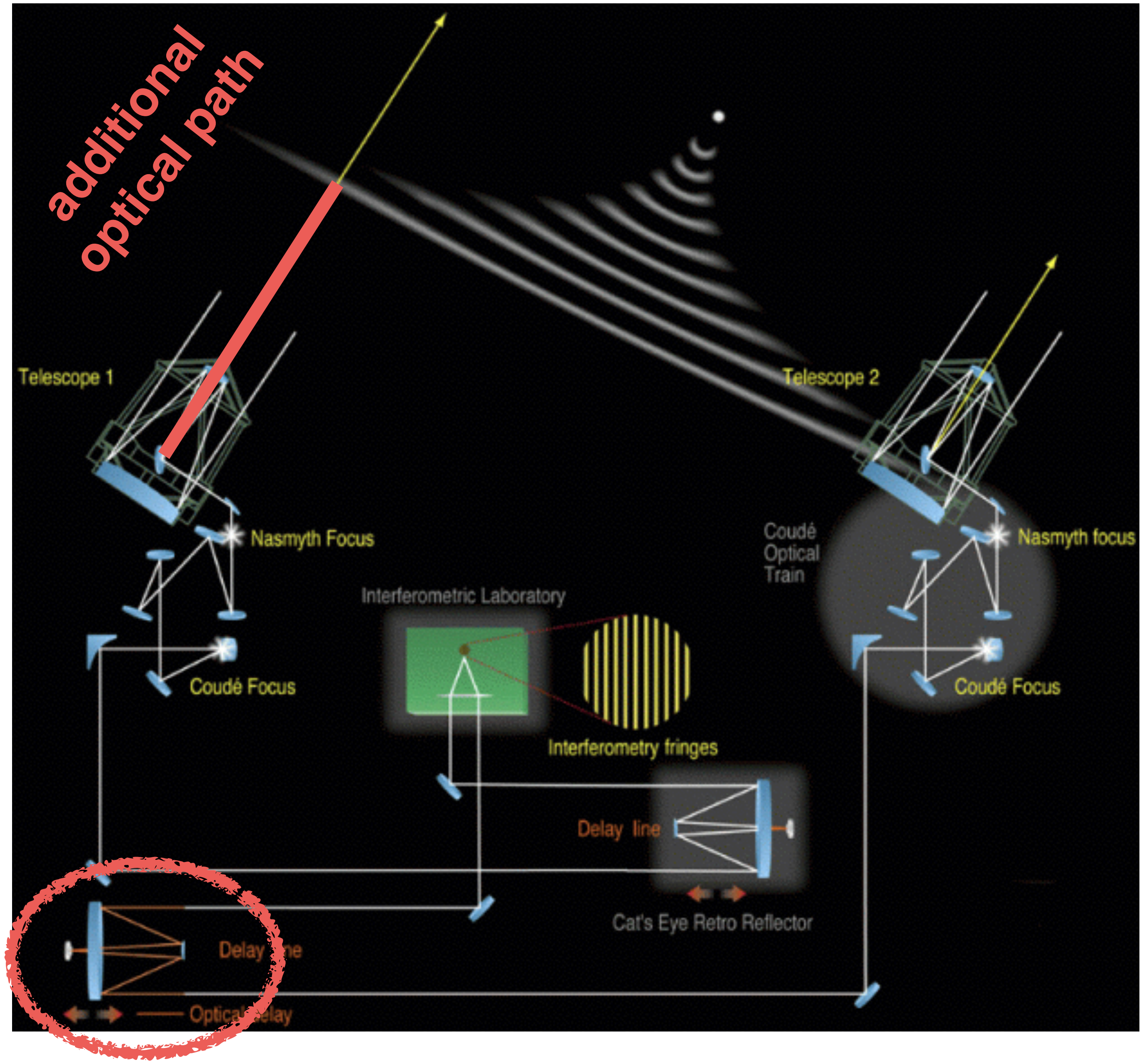
reflex motion of the Sun compared ot its size

apparent Schwarzschild radius of Sgr A 10 µas*



Basic ideas

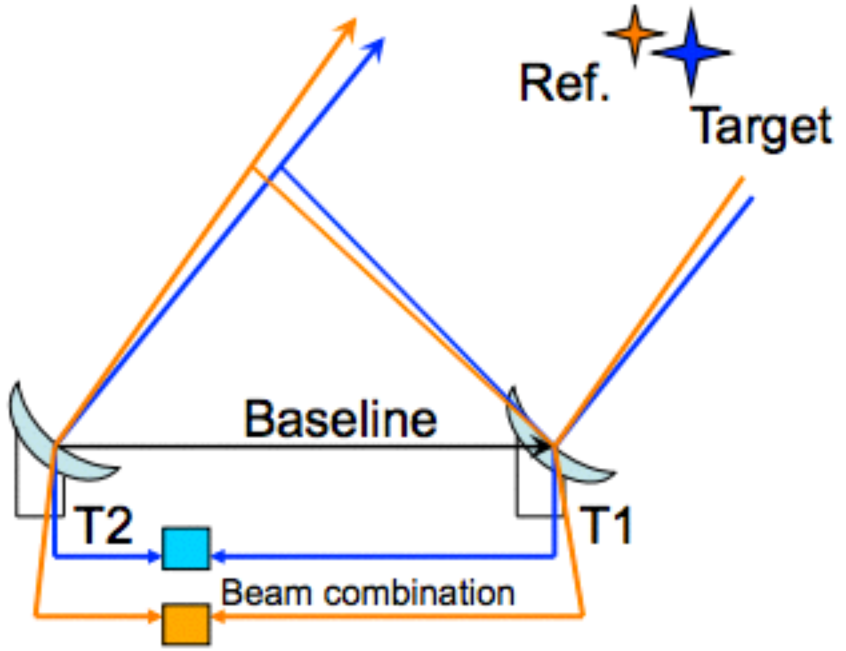
- We already know: **phase of the fringes ⇔ position in the sky**
- In real interferometer: **position in sky ⇔ optical path delay (OPD)**

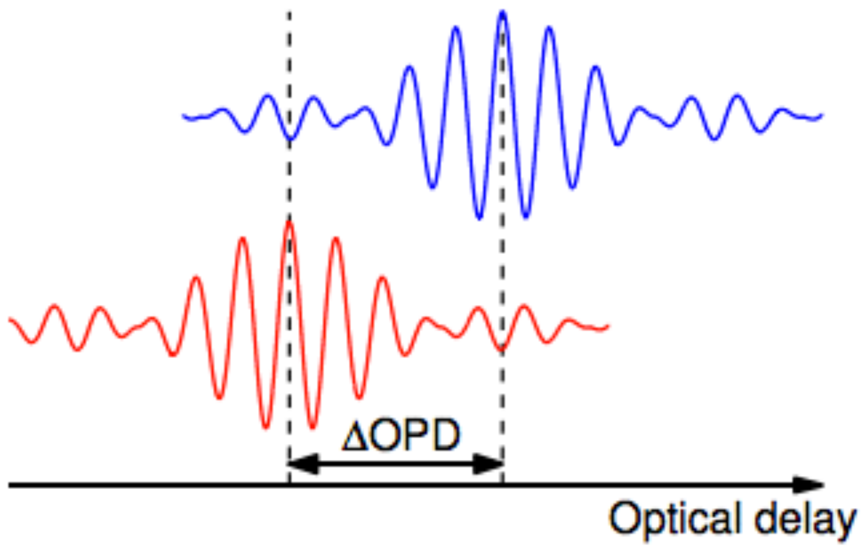


phase reference astrometry

We need

- two fields: **Star Separators**
- a way to add differential OPD to target object: **Differential Delay Lines**
- form fringes in 2 fields: **dual bean combiner**
- a way to measure the phase difference (differential OPD): **Laser Metrology**

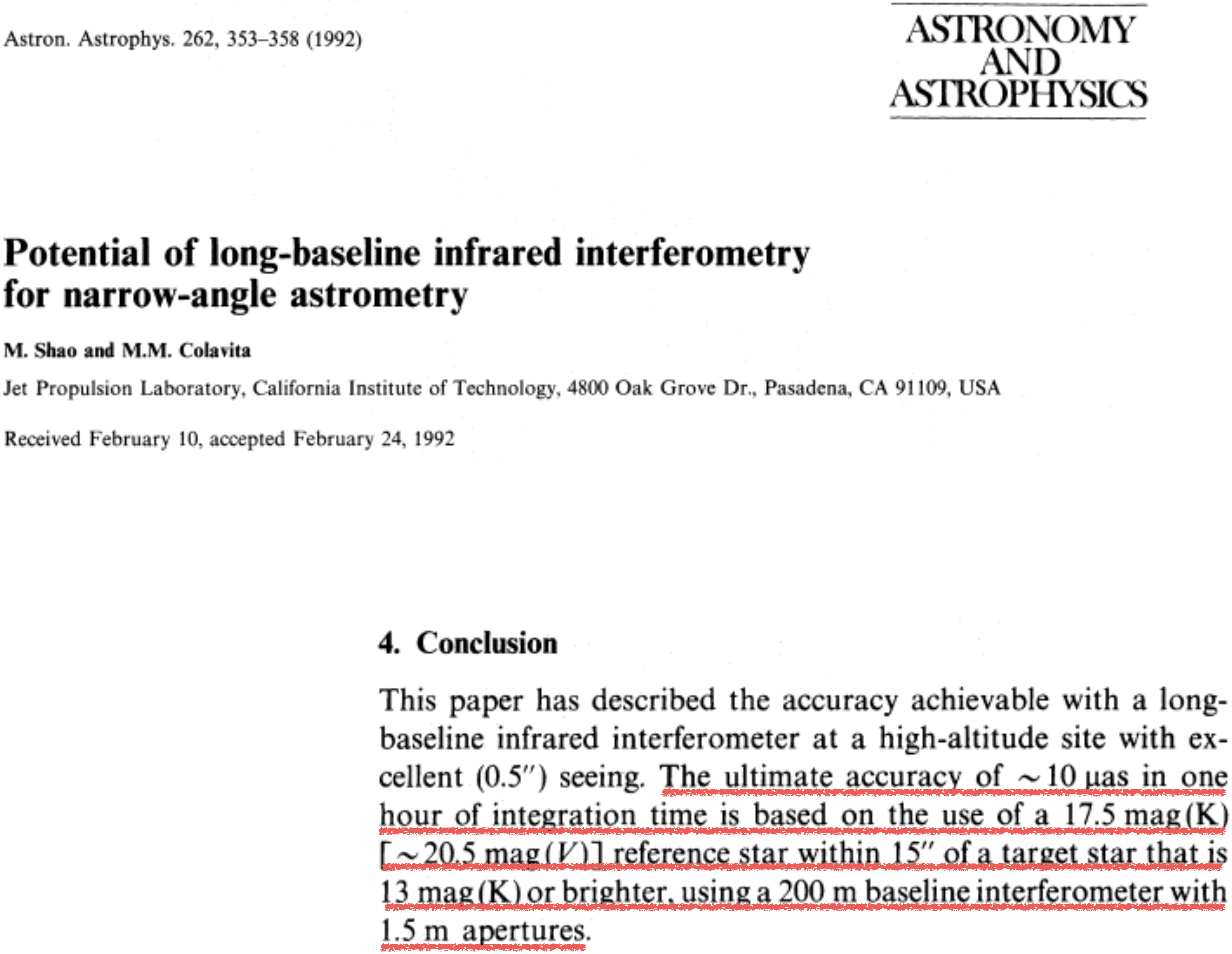




Limitations

- How accurately do we need to now ΔOPD?
  - **B** ~ 100m, σ**s** ~ 10µas → 5nm
- How accurate do we need to know **B**?
  - **B**.σ**s** > σ**B**.**s** → σB < 100µm

100m 10µas 10”



Astron. Astrophys. 262, 353–358 (1992)

ASTRONOMY
AND
ASTROPHYSICS

Potential of long-baseline infrared interferometry for narrow-angle astrometry

M. Shao and M.M. Colavita

Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109, USA

Received February 10, accepted February 24, 1992

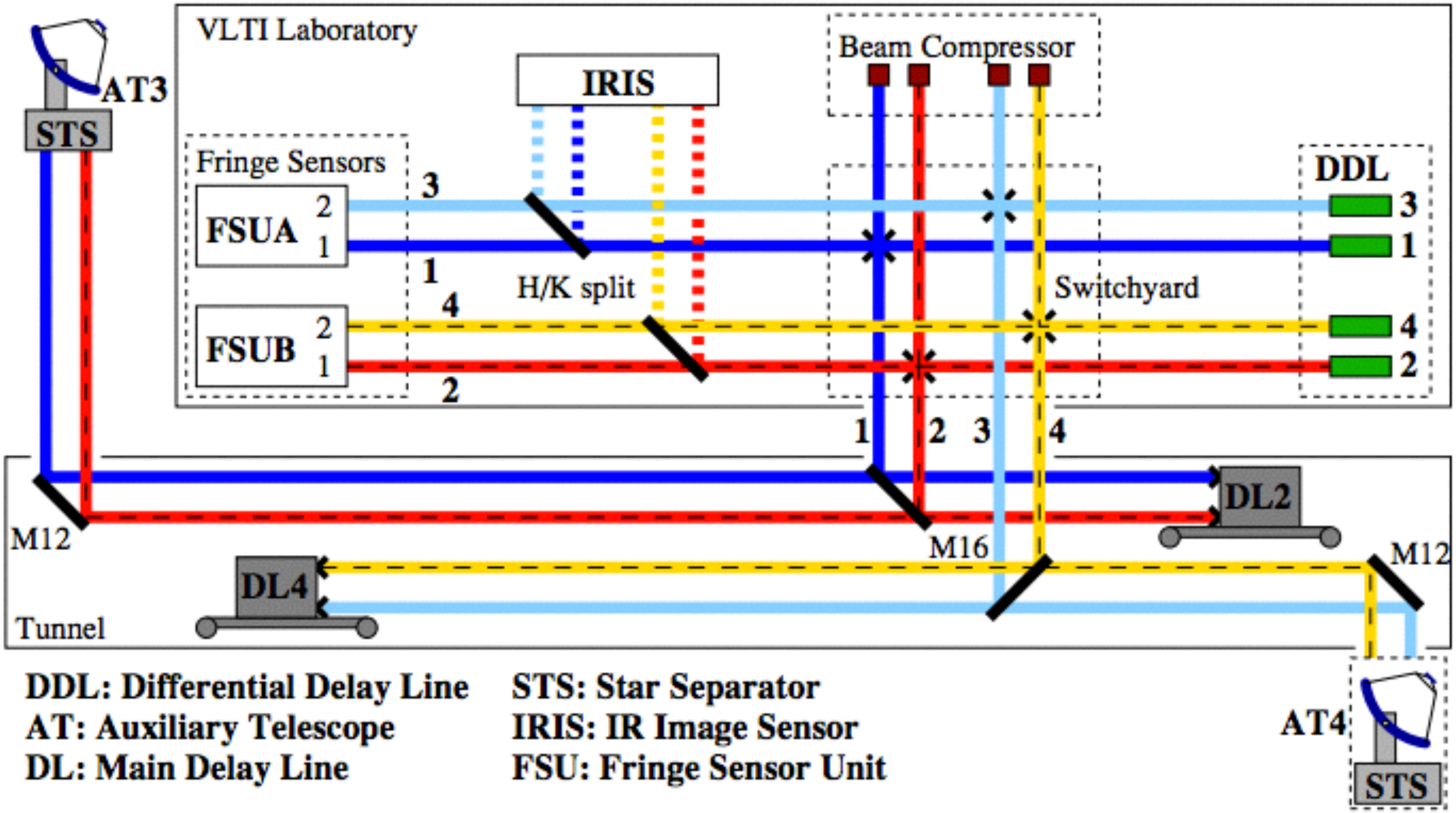
4. Conclusion

This paper has described the accuracy achievable with a long-baseline infrared interferometer at a high-altitude site with excellent (0.5″) seeing. The ultimate accuracy of ~ 10 μas in one hour of integration time is based on the use of a 17.5 mag(K) [~ 20.5 mag(V)] reference star within 15″ of a target star that is 13 mag(K) or brighter, using a 200 m baseline interferometer with 1.5 m apertures.

History

- **1992**: theoretical foundation (Shao & Collavita 1992)
- **1990’s**: Proposal for Keck+outriggers astrometry and VLTI-PRIMA
- **1999**: 160µas with 2 siderostats and 100m baseline (PTI, Shao+ 1999)
- **2006**: Keck outriggers canceled
- **2008**: PRIMA installed on VLTI

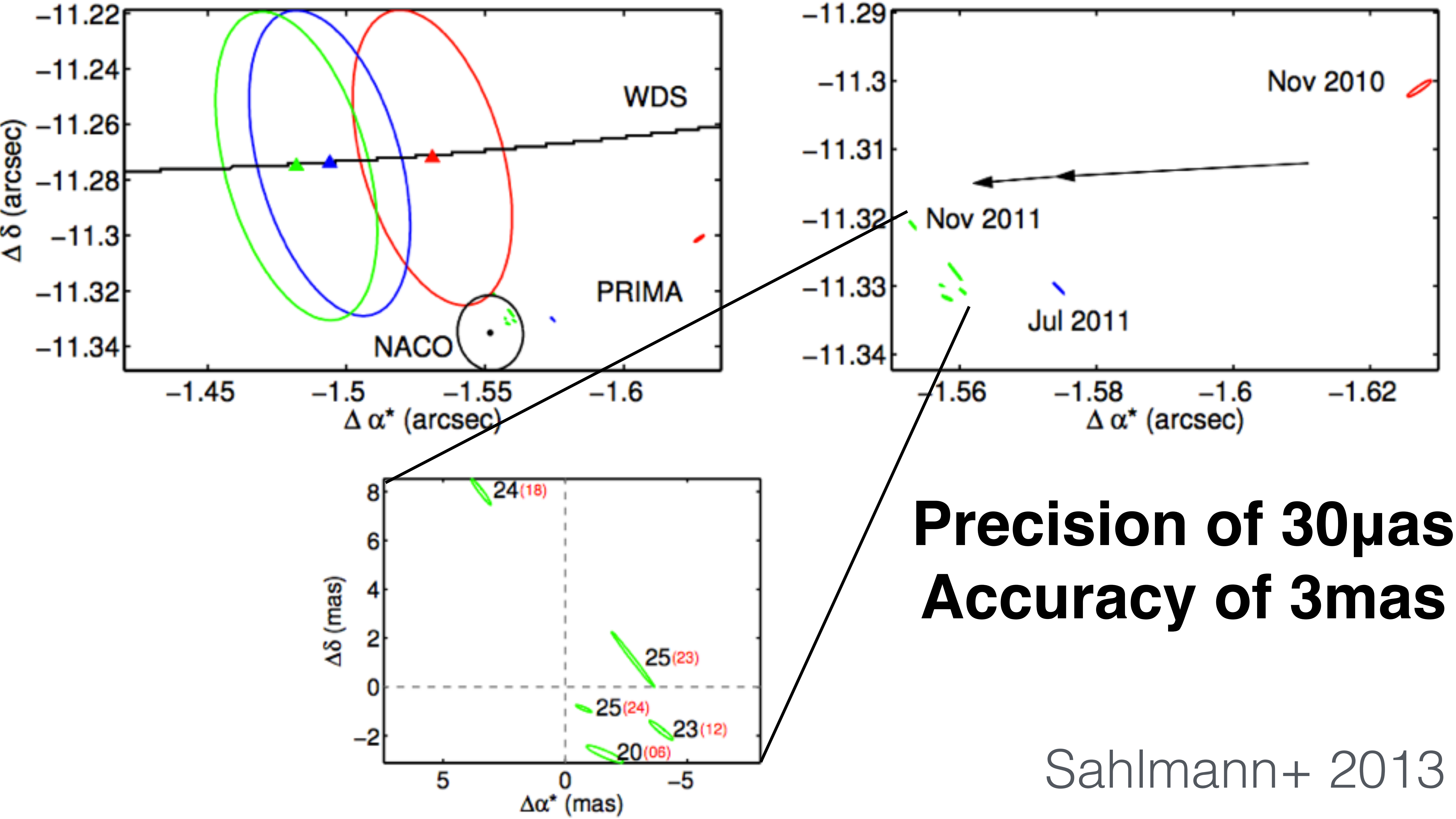
PRIMA



DDL: Differential Delay Line
AT: Auxiliary Telescope
DL: Main Delay Line
STS: Star Separator
IRIS: IR Image Sensor
FSU: Fringe Sensor Unit

Delplancke+ 2008

PRIMA 2010



Precision of 30µas
Accuracy of 3mas

Sahlmann+ 2013

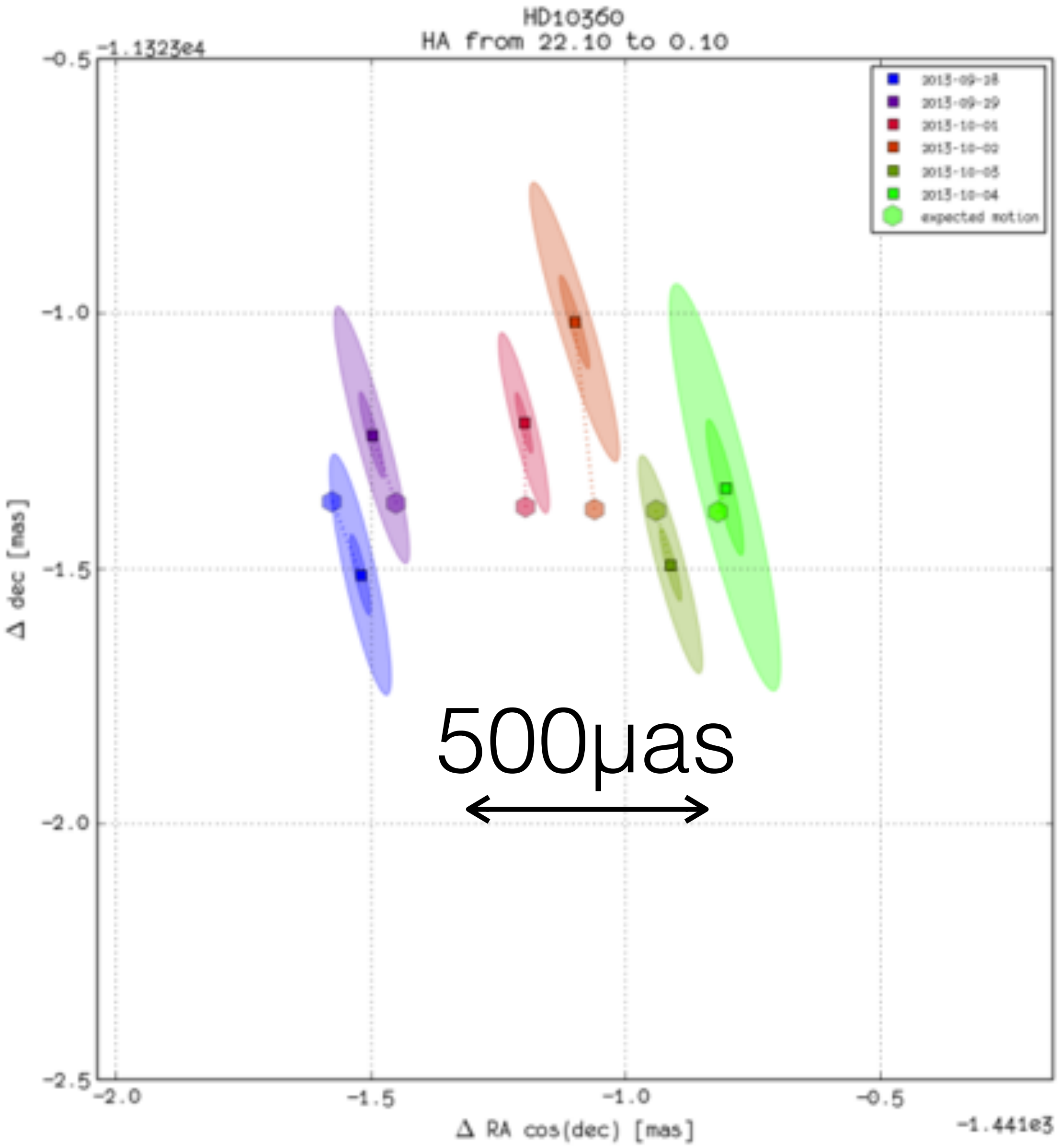
PRIMA 2013

we solved

- non-common path OPD: metrology M10 → M2
- Polarizations issue

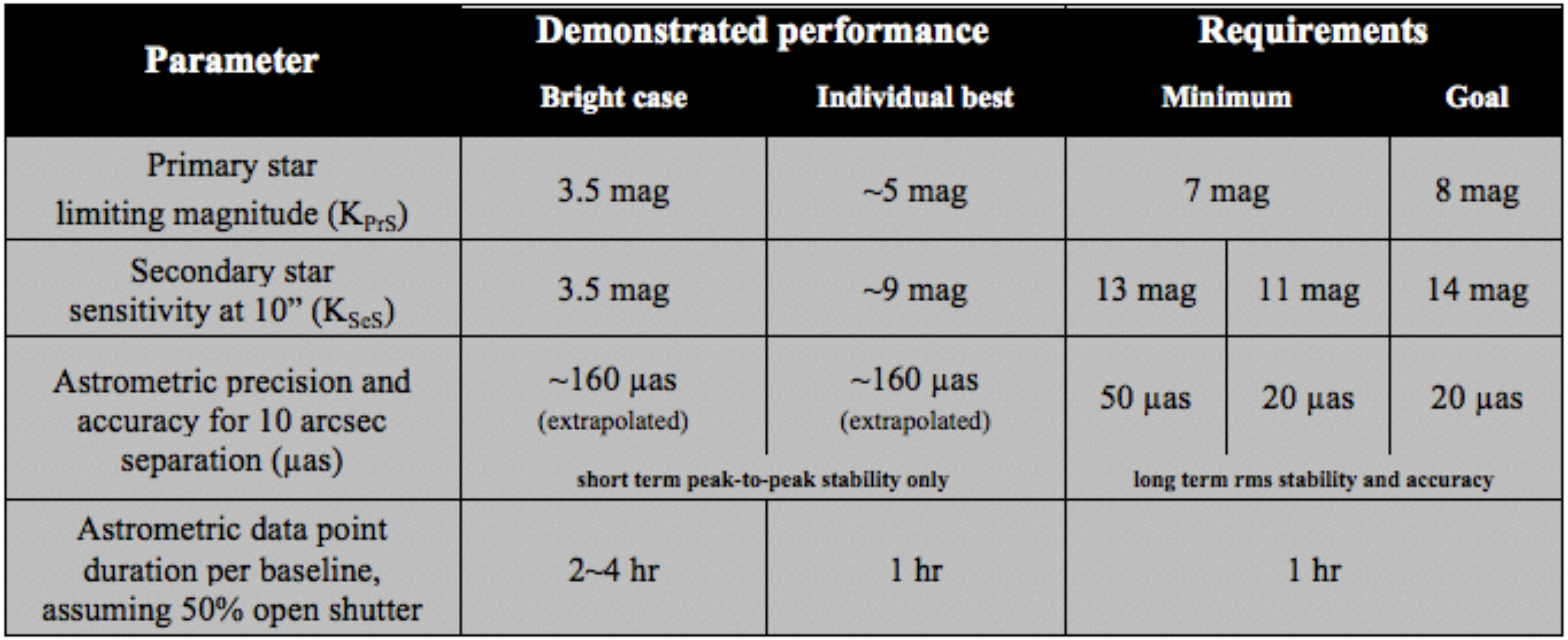
we get

- 800µas accuracy in unfavorable config
- 160µas extrapolated accuracy



Woillez+ 2014

PRIMA 2014

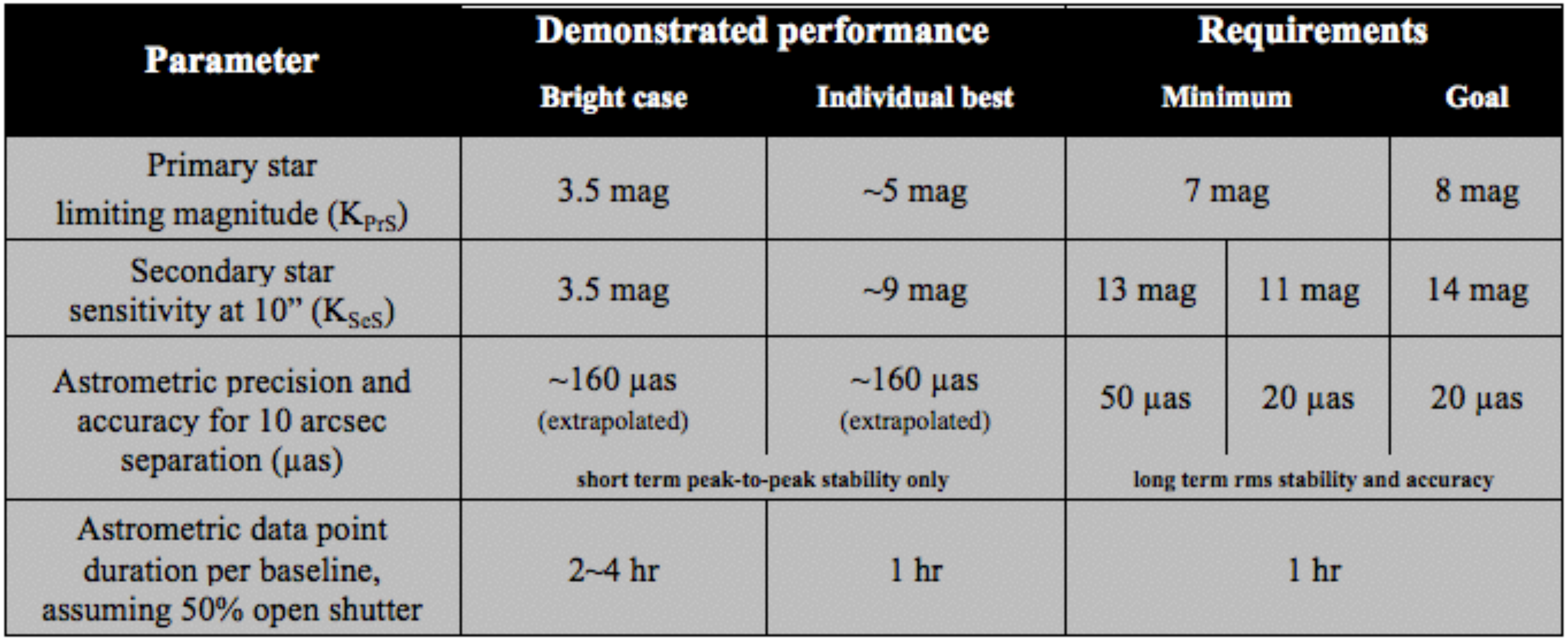


Parameter	Demonstrated performance		Requirements		
	Bright case	Individual best	Minimum		Goal
Primary star limiting magnitude (K_{PrS})	3.5 mag	~5 mag	7 mag		8 mag
Secondary star sensitivity at 10” (K_{SeS})	3.5 mag	~9 mag	13 mag	11 mag	14 mag
Astrometric precision and accuracy for 10 arcsec separation (μas)	~160 μas (extrapolated)	~160 μas (extrapolated)	50 μas	20 μas	20 μas
	short term peak-to-peak stability only		long term rms stability and accuracy		
Astrometric data point duration per baseline, assuming 50% open shutter	2~4 hr	1 hr	1 hr		

Woillez+ 2014

PRIMA 2014

CANCELLED



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Woillez+ 2014

VLTI-GRAVITY (2015)

4T beam combiner for VLTI: imaging and astrometry

Sensitive

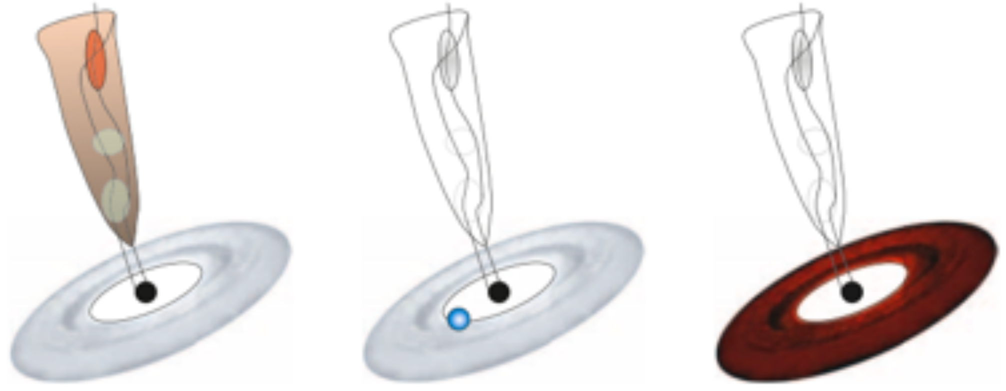
- beam combiner: Integrated optics + IR APDs
- Active control: IR WFS for AO, Kalman fringe tracking

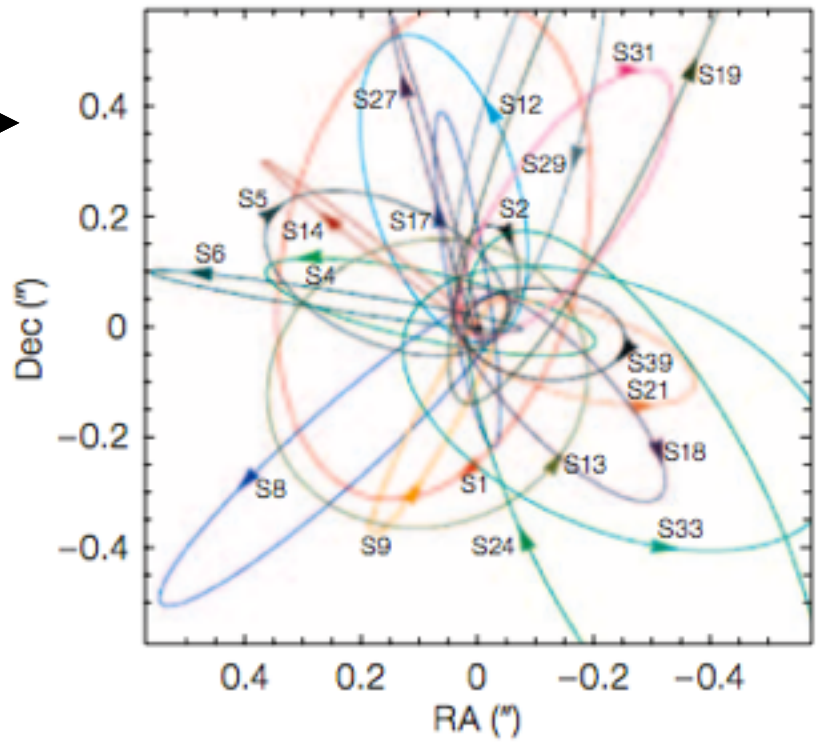
Astrometry

- star separator (fields up to 4” apart)
- full metrology (→primary space)
- pupil and polarization control

Main Science Case

- What is the nature of the flares in Sgr A*?
- What is the spin of a BH?
- How can we resolve the “Paradox of Youth” of the stars in its vicinity?
- Does the theory of general relativity hold in the strong field around SMBHs?

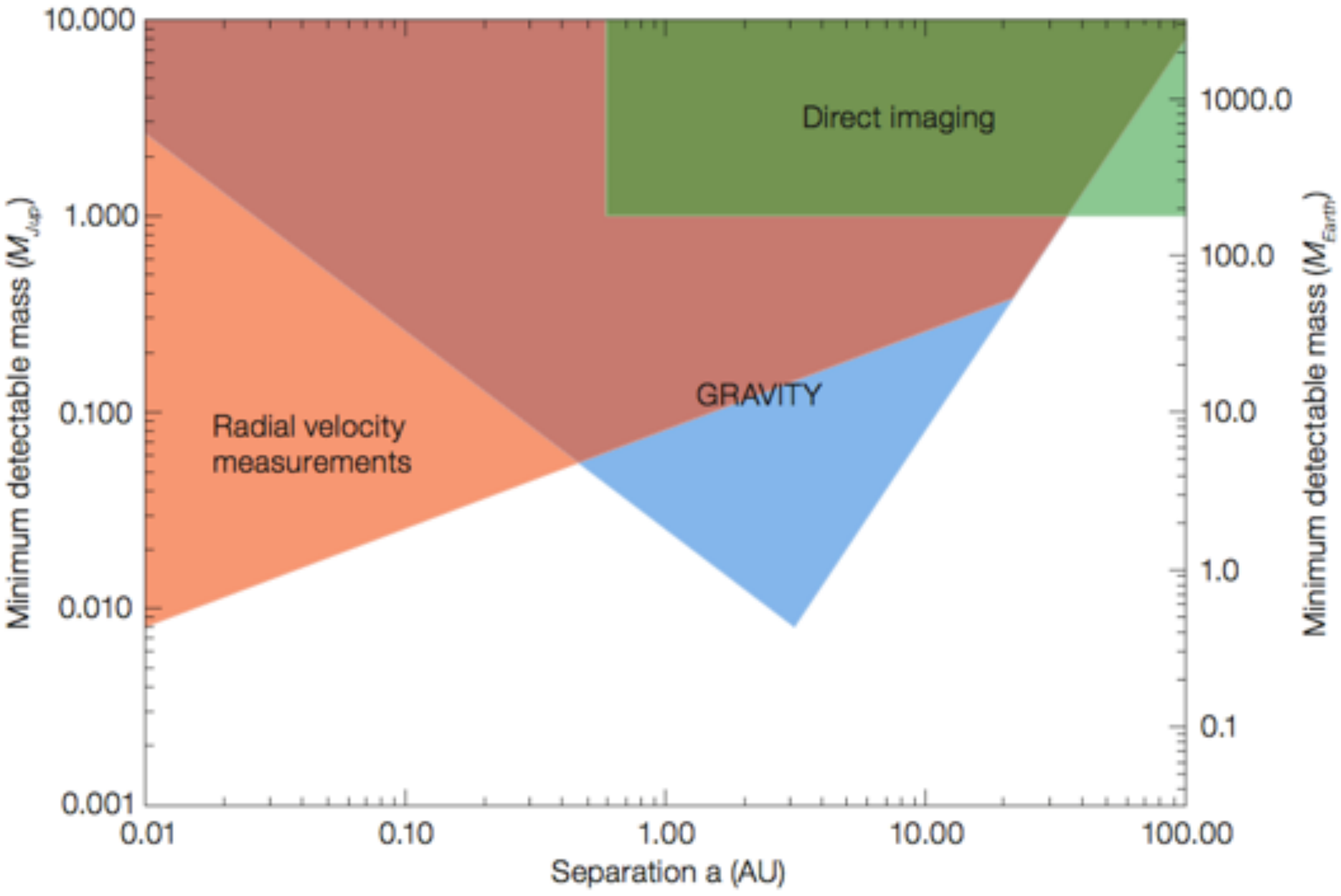




Eisenhauer+ 2011

Other Science Cases

- Exo-planet detection
- imaging AGNs
- X-Rays binary
- jet in young stars
- …



Eisenhauer+ 2011

Technical Challenges

- Sensitivity is ambitious but realistic
- No other working astrometric interferometer…
- lessons learned from PRIMA
- What is the astrometric baseline?

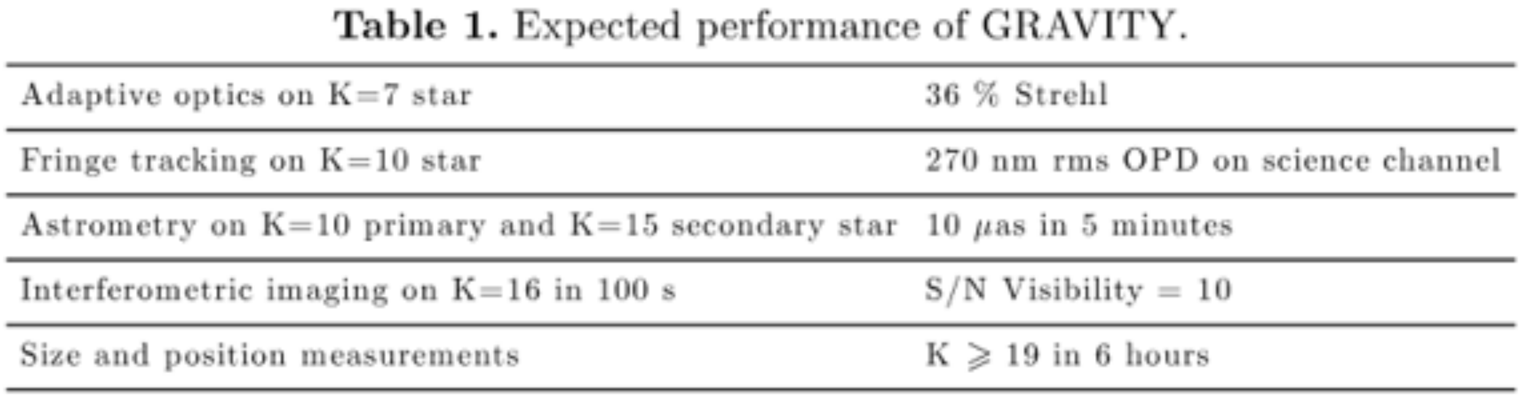
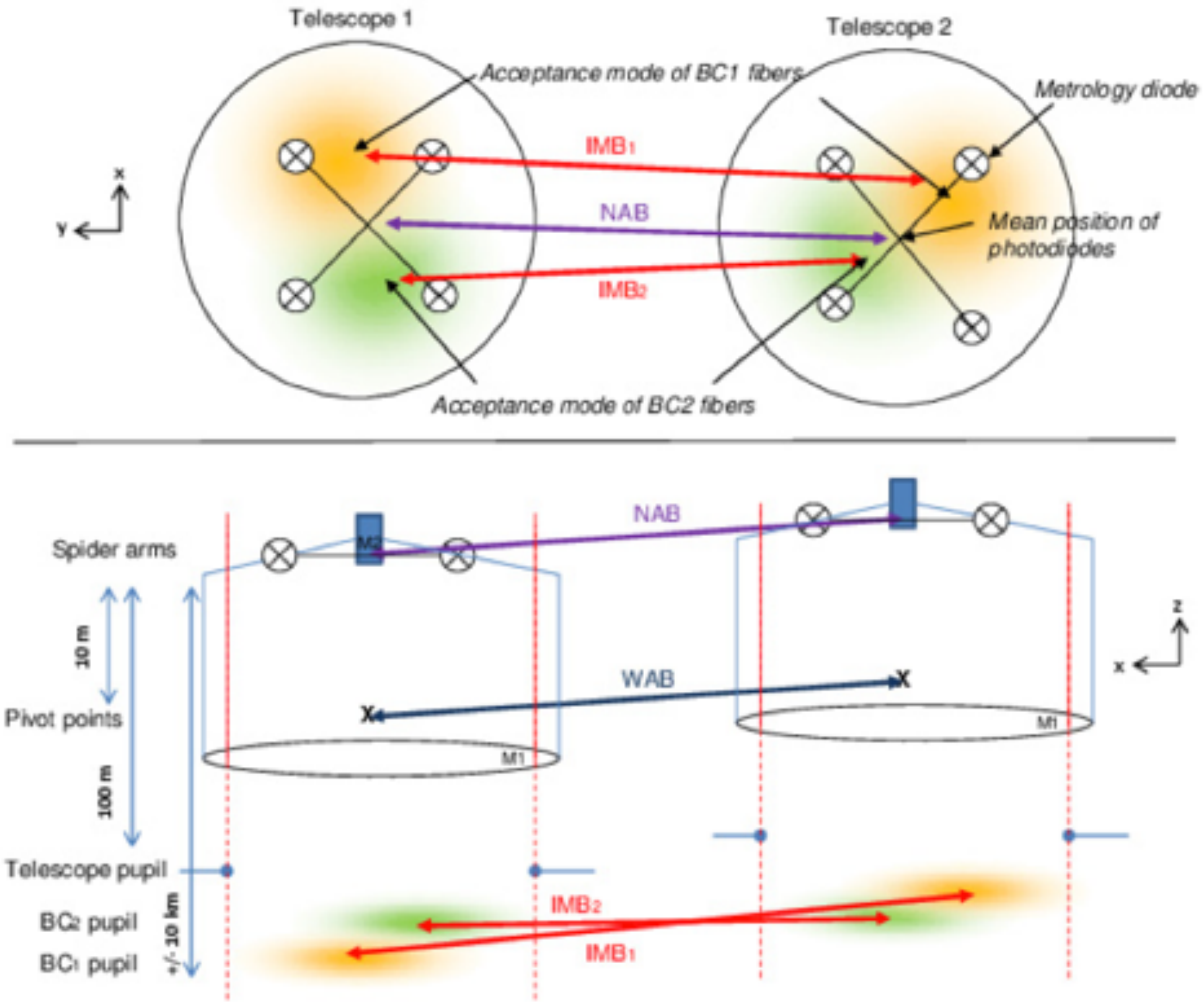


Table 1. Expected performance of GRAVITY.

Adaptive optics on K=7 star	36 % Strehl
Fringe tracking on K=10 star	270 nm rms OPD on science channel
Astrometry on K=10 primary and K=15 secondary star	10 μas in 5 minutes
Interferometric imaging on K=16 in 100 s	S/N Visibility = 10
Size and position measurements	K $\geqslant$ 19 in 6 hours

Eisenhauer+ 2008



Lacour+ 2014

Conclusions

- Interferometry has un-rivaled angular resolution (~1mas)
- Interferometry is intrinsically good at relative astrometry within the diffraction limit of a single aperture (~100mas)
- phase reference astrometry is extremely difficult…
- … but should allow to reach 10µas from the ground