

# Observation de binaires en interaction à très haute résolution angulaire

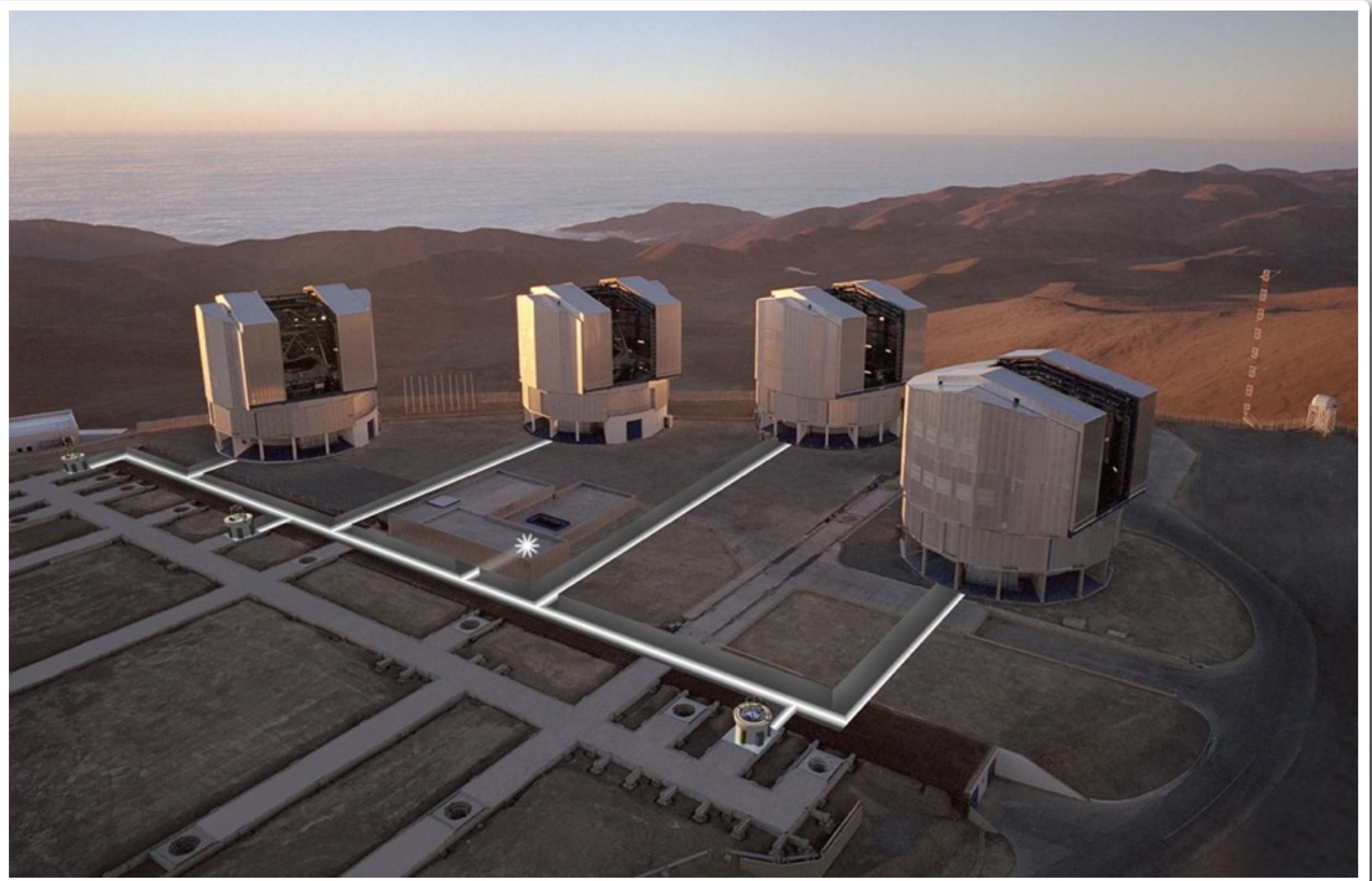
Suivi de franges pour  
l'interférométrie infrarouge

Soutenance de thèse  
**Nicolas BLIND**

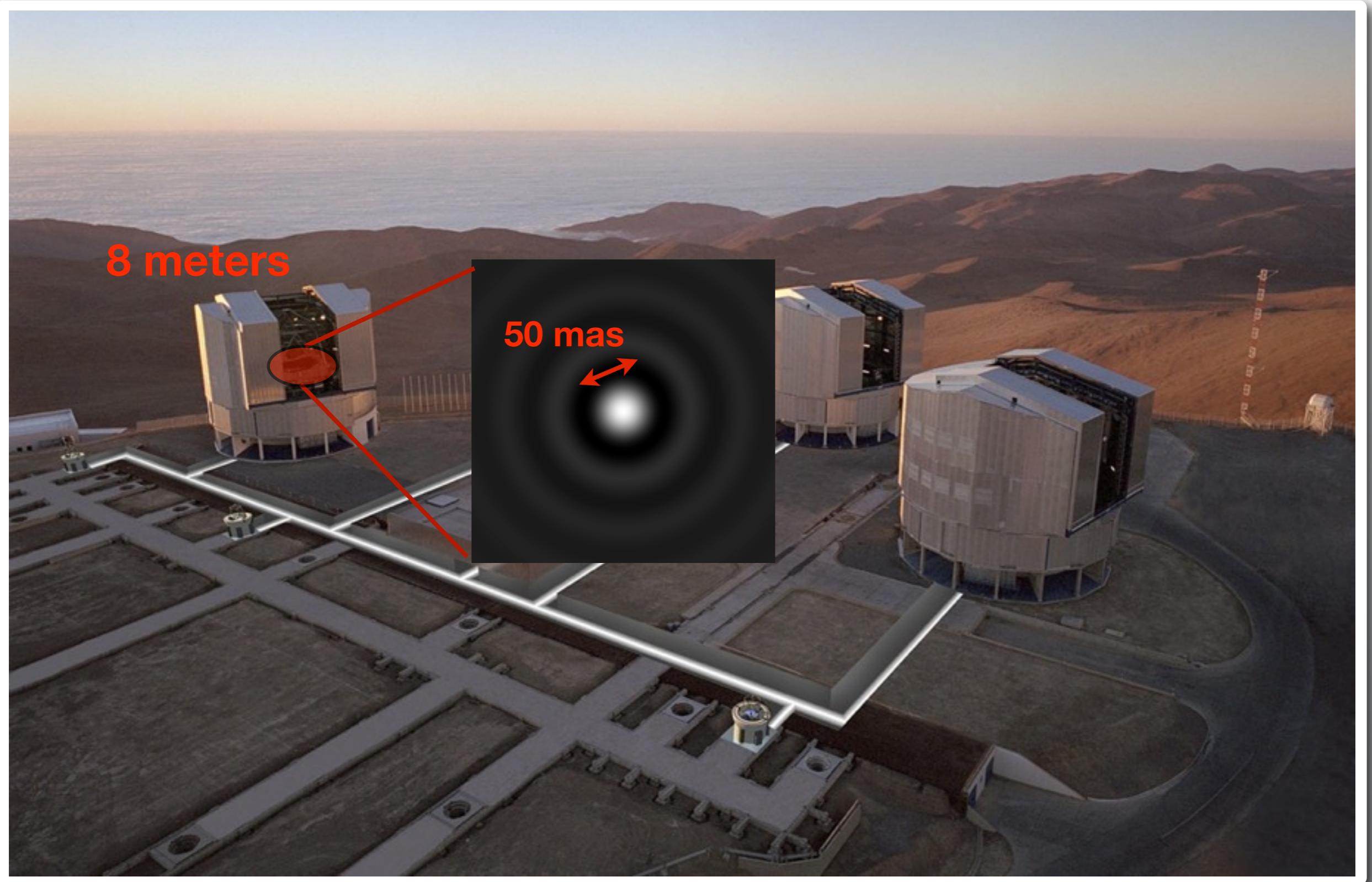
Directeurs de thèse  
Jean-Philippe BERGER  
Alain CHELLI



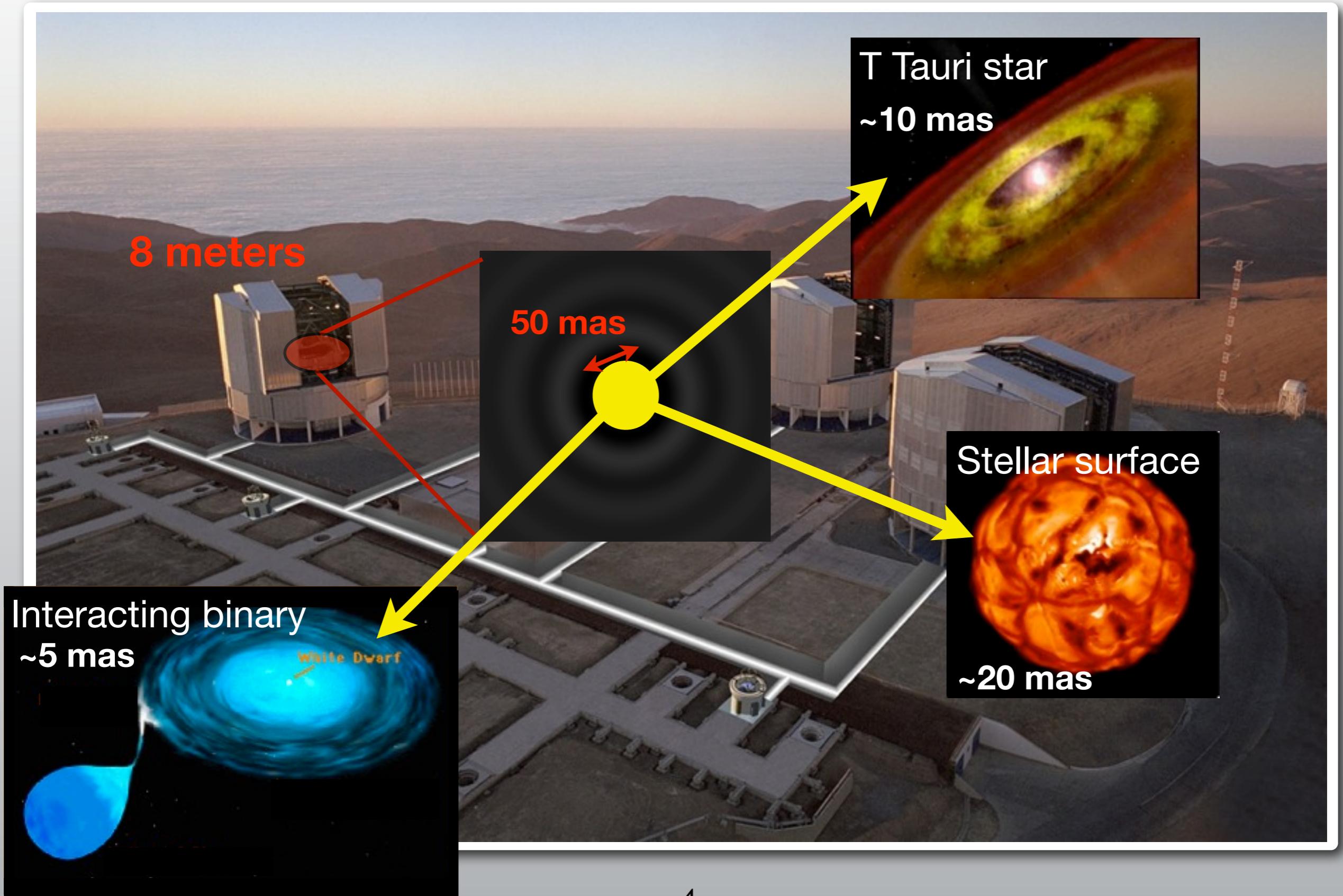
# The need for very high angular resolution



# The need for very high angular resolution

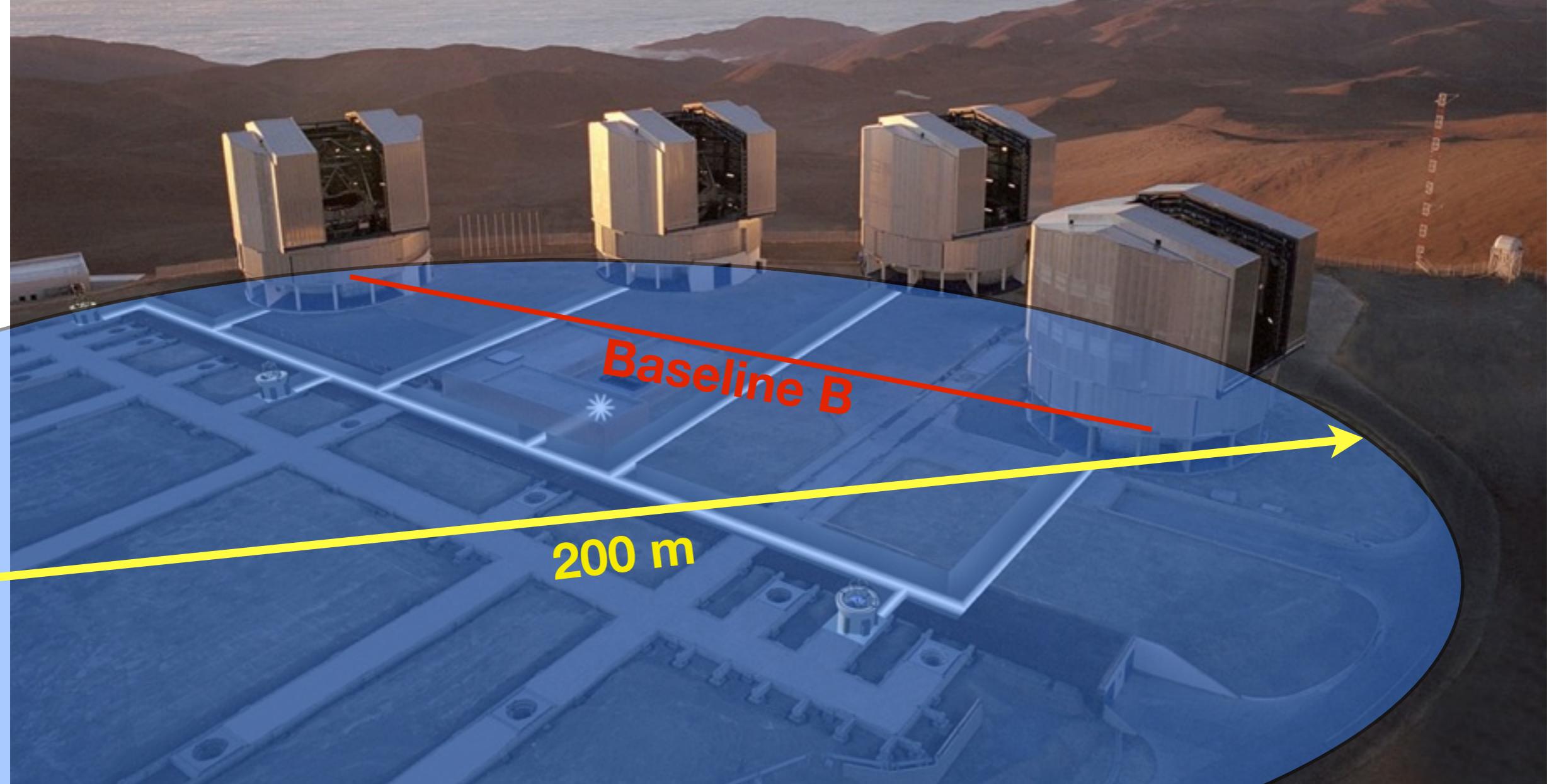


# The need for very high angular resolution



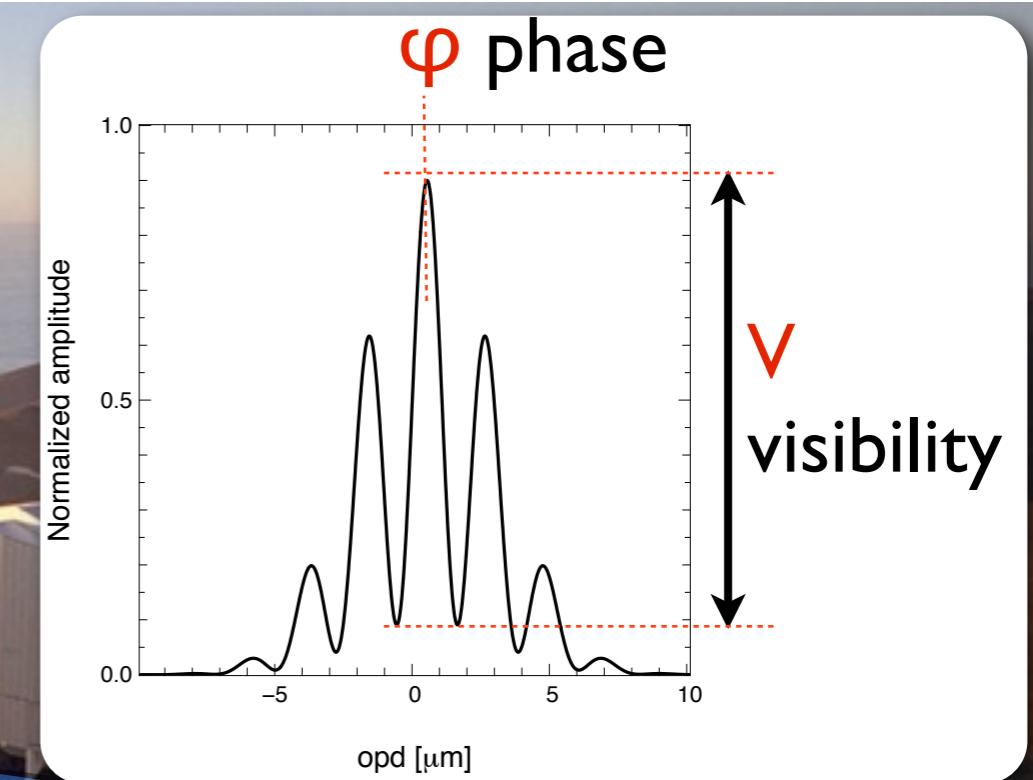
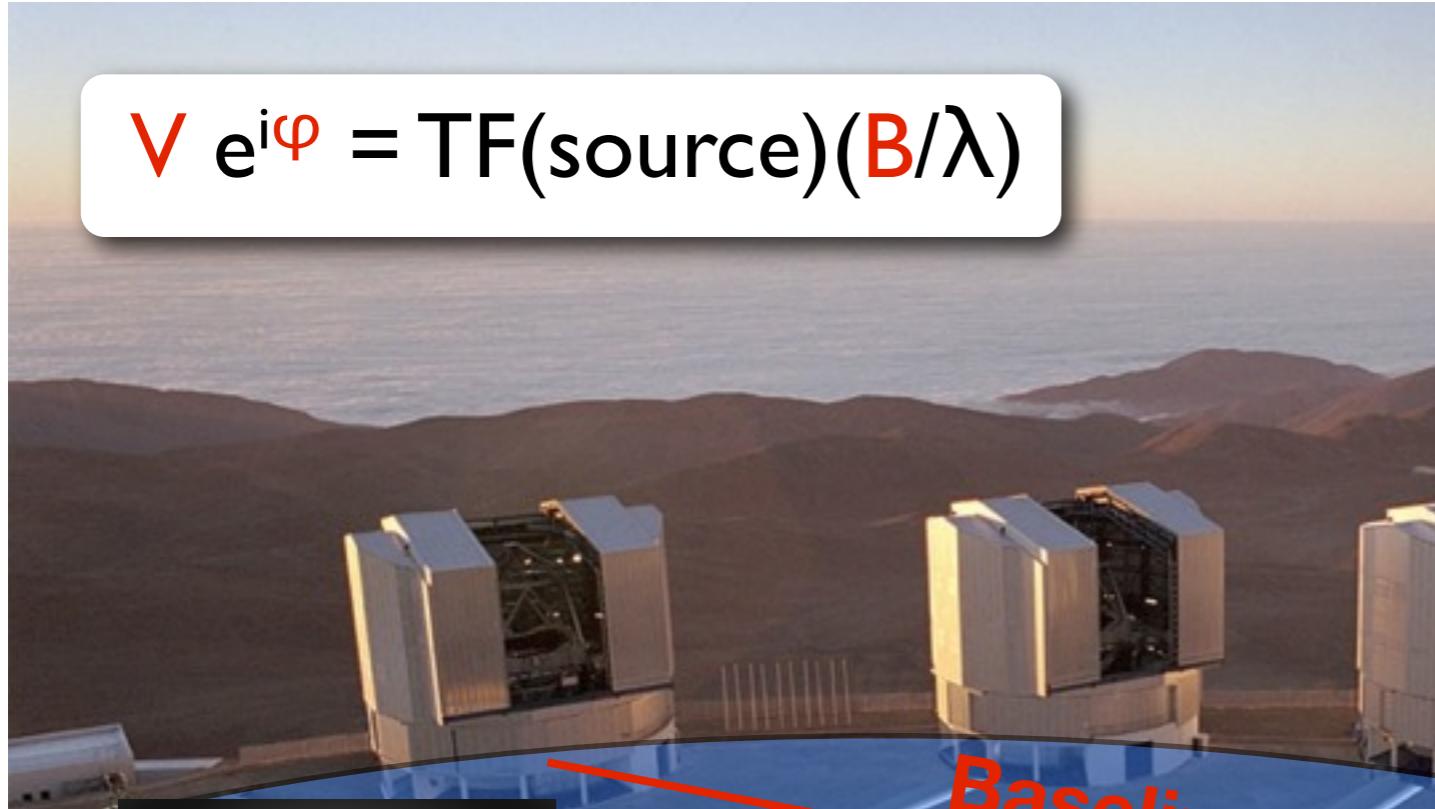
# The need for very high angular resolution

Synthesizing a giant telescope by combining several telescopes  
→ **angular resolution x25**

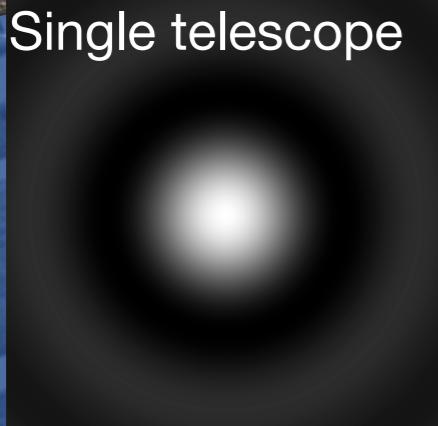


# Interferometric observables

$$V e^{i\varphi} = \text{TF(source)}(B/\lambda)$$



Single telescope

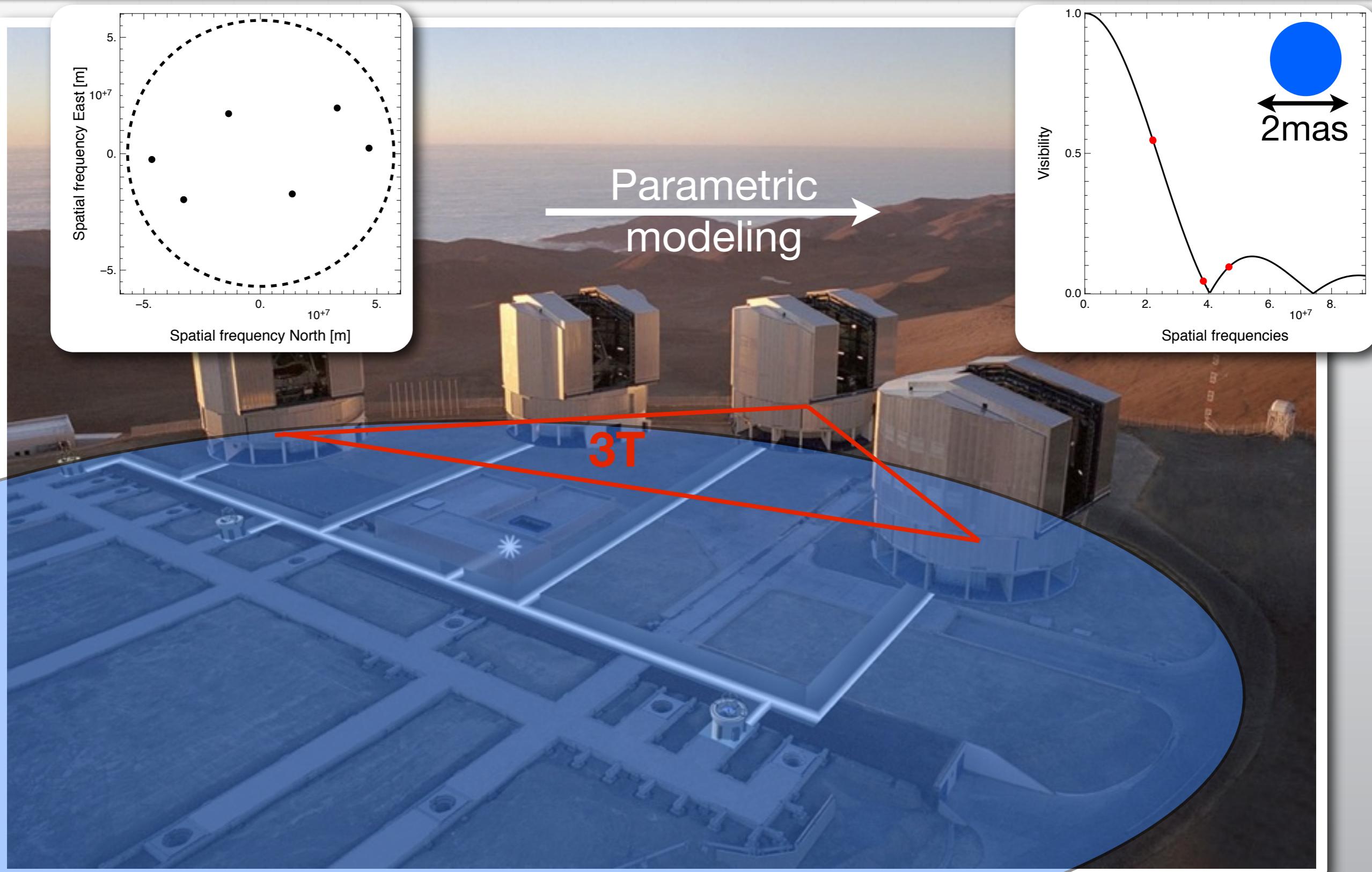


*Baseline B*  
*Spatial frequency B/λ*

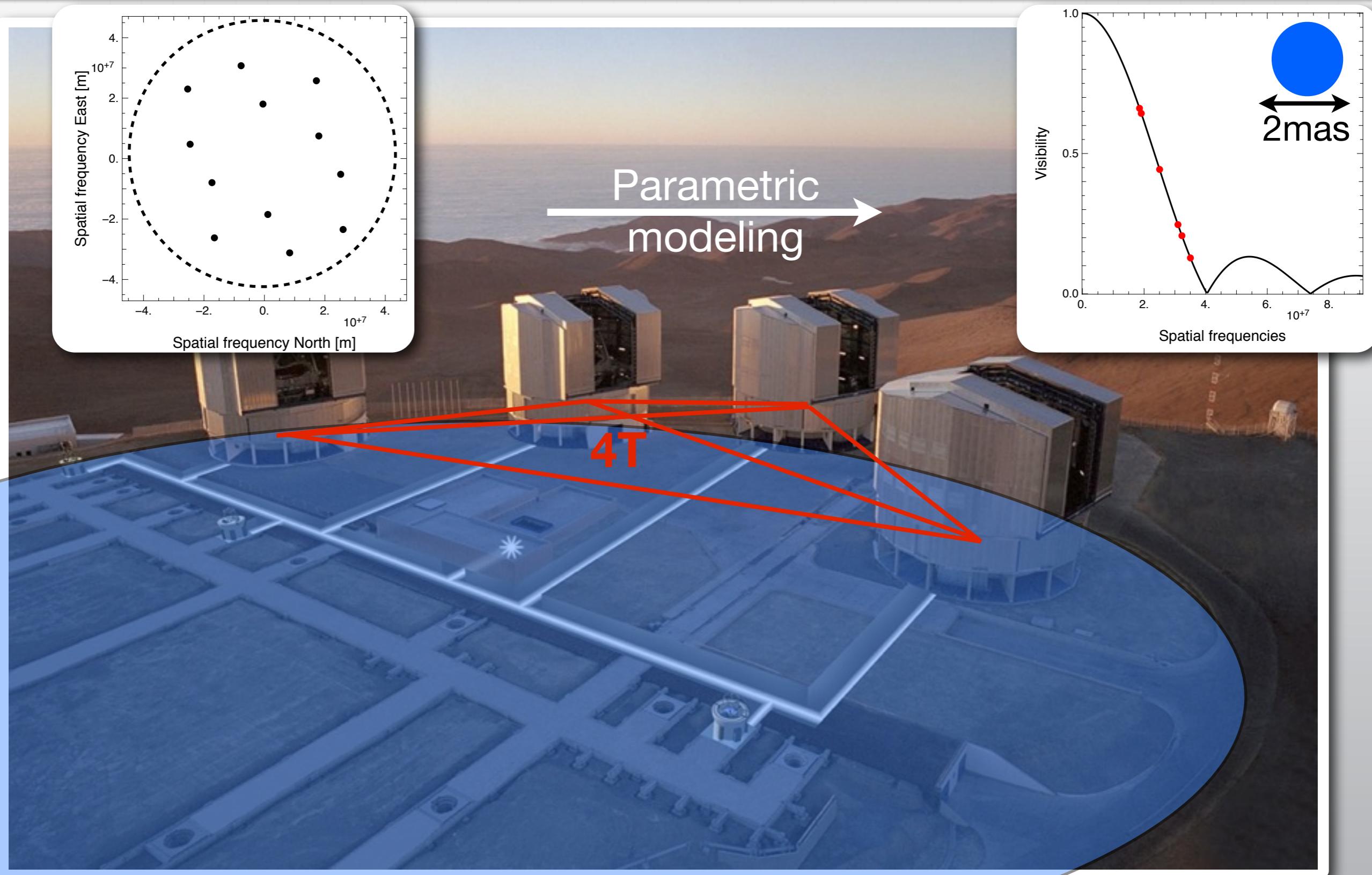
Interferometer

*Fringe pattern*

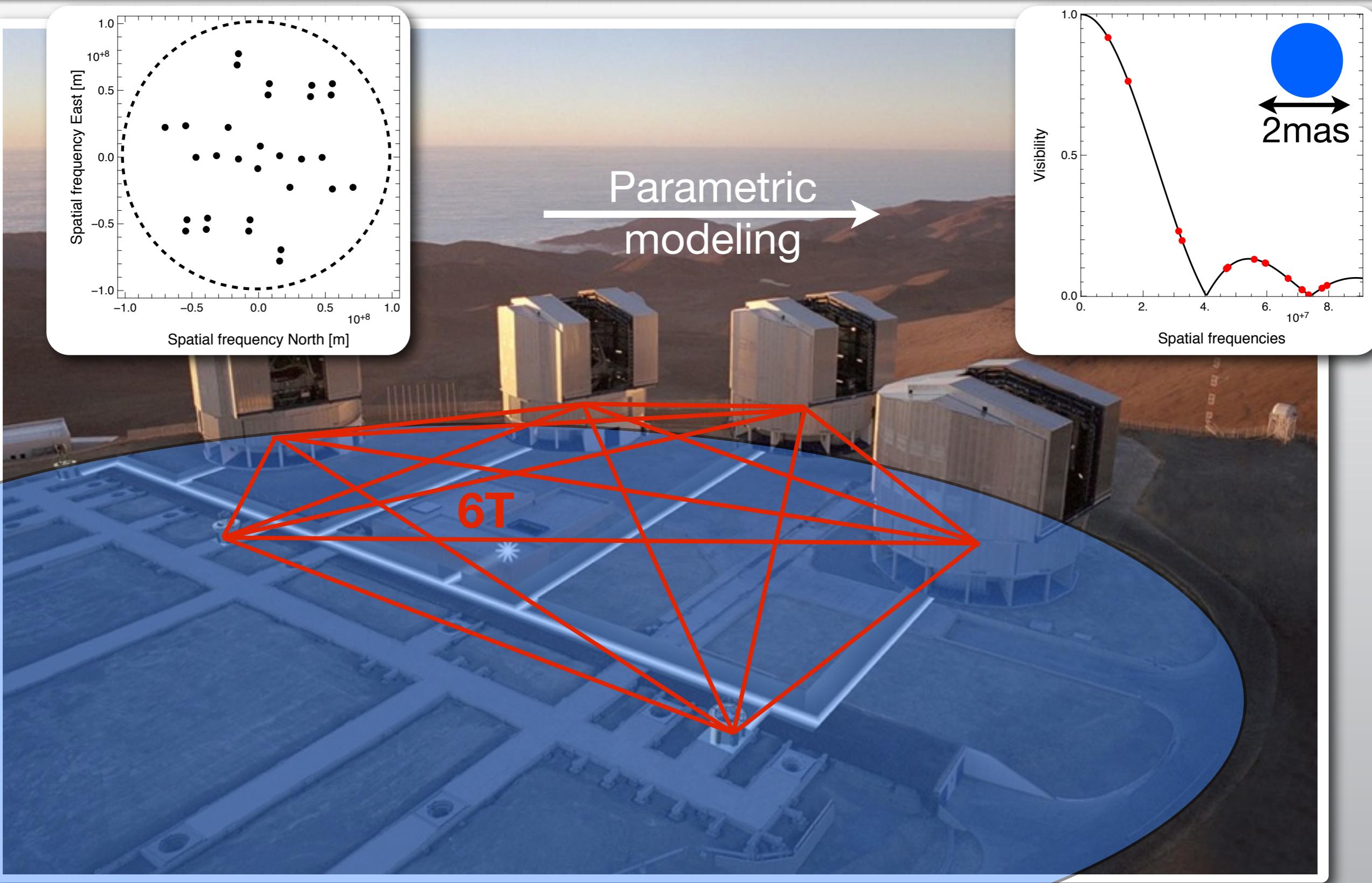
# Interferometric observables



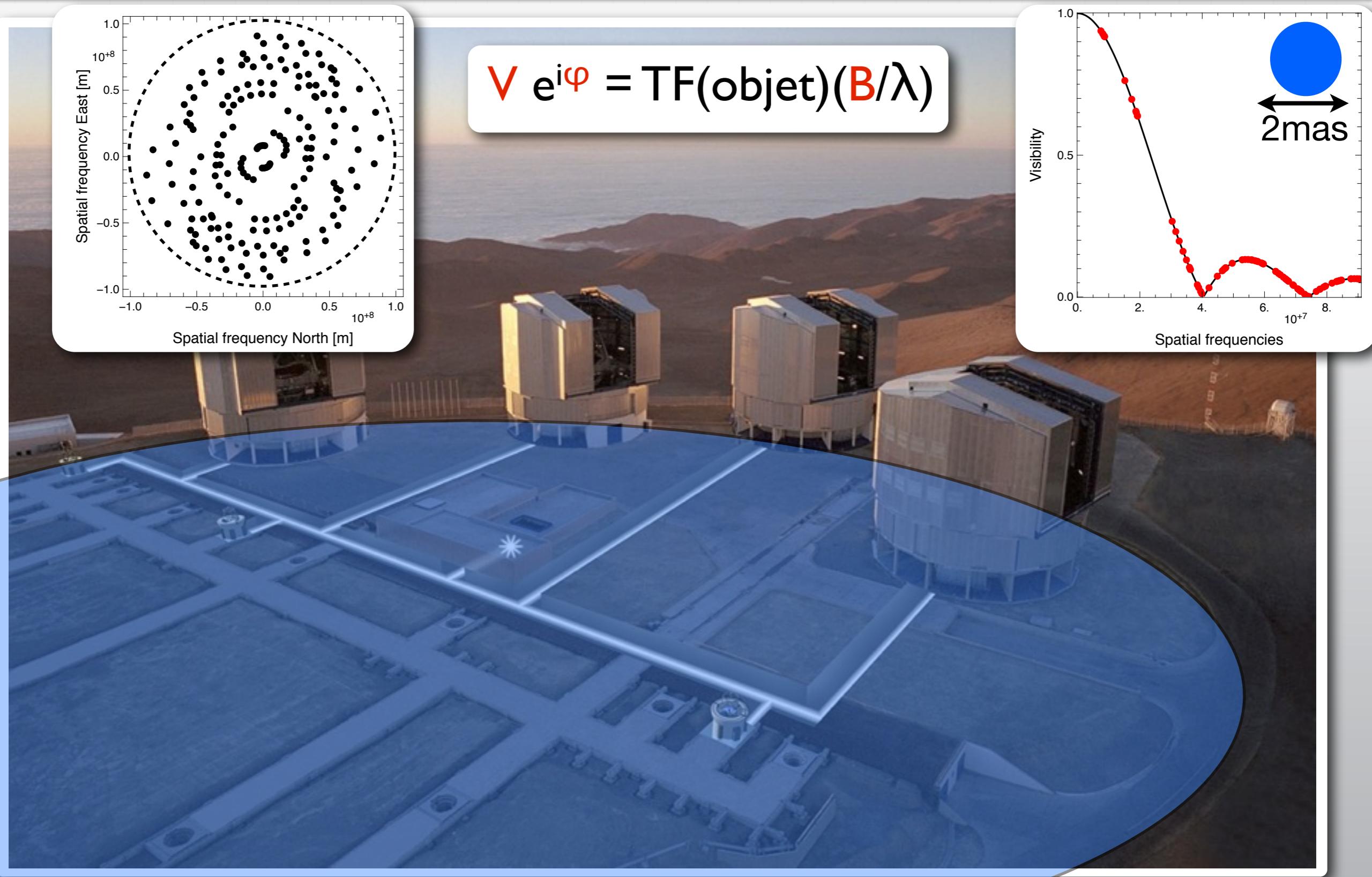
# Interferometric observables



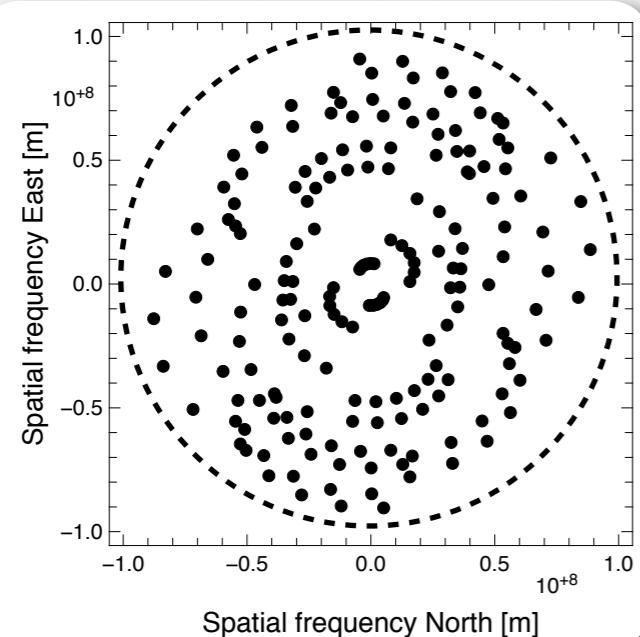
# Interferometric observables



# Interferometric observables



# Interferometric observables



$$\nabla e^{i\varphi} = \text{TF(source)}(B/\lambda)$$

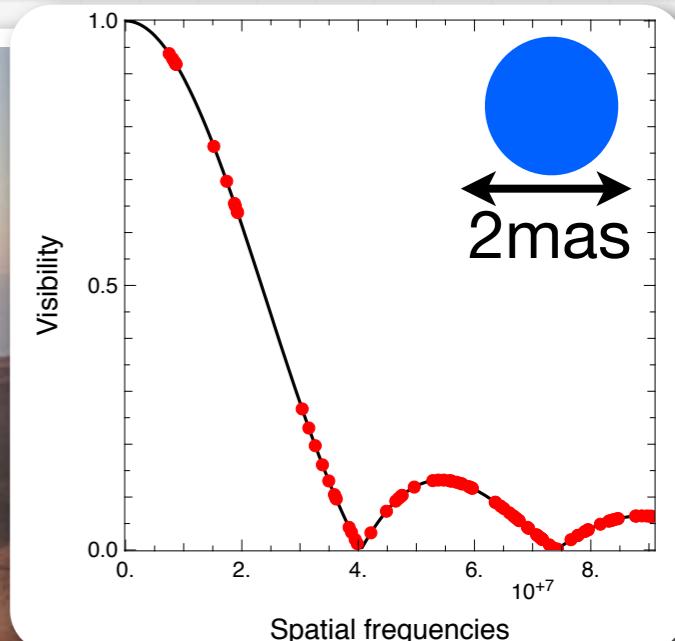
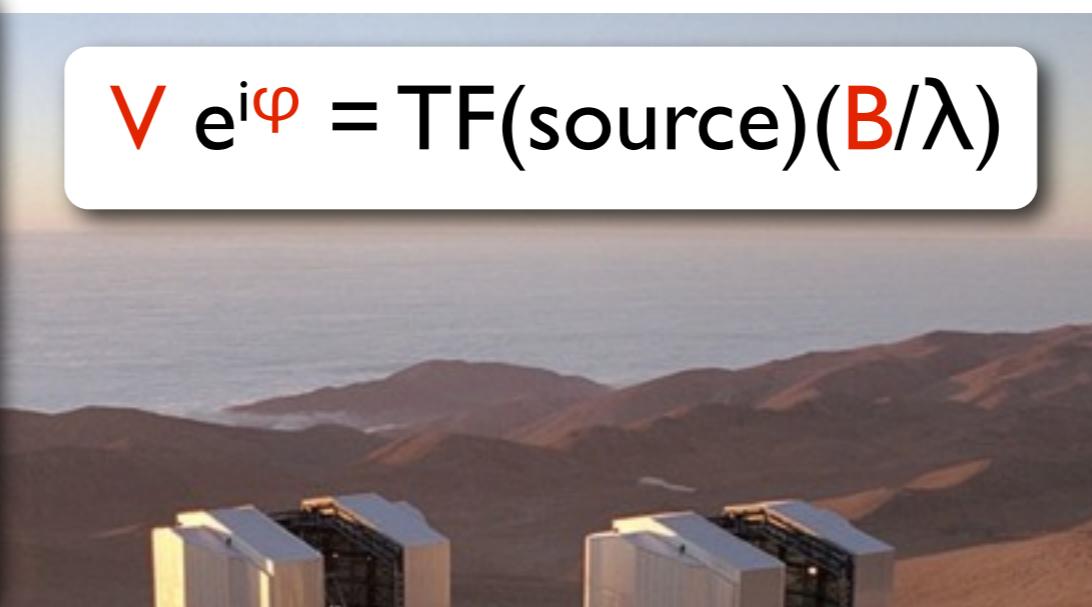
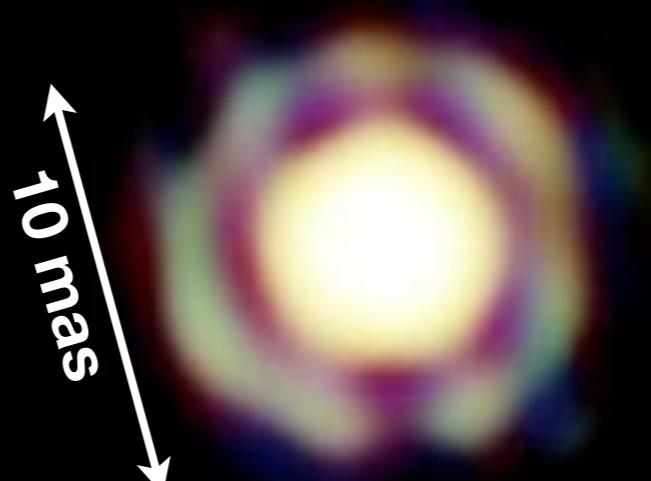


Image  
reconstruction

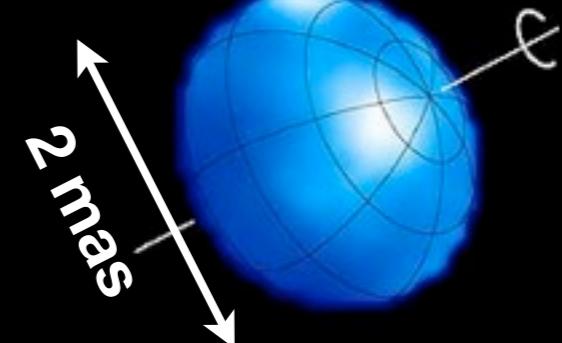
Parametric  
modeling

T Leporis: *Mira star*



Lebouquin et al A&A 2009

Altair: *Fast rotator*



Monnier et al. Science 2007

# Presentation outline

## An introduction to interferometry

### **PART I. Study of interacting binaries**

- Interest of interacting binaries
- The promises of interferometry
- The case of SS Leporis

### **PART II. Fringe trackers for imaging instruments**

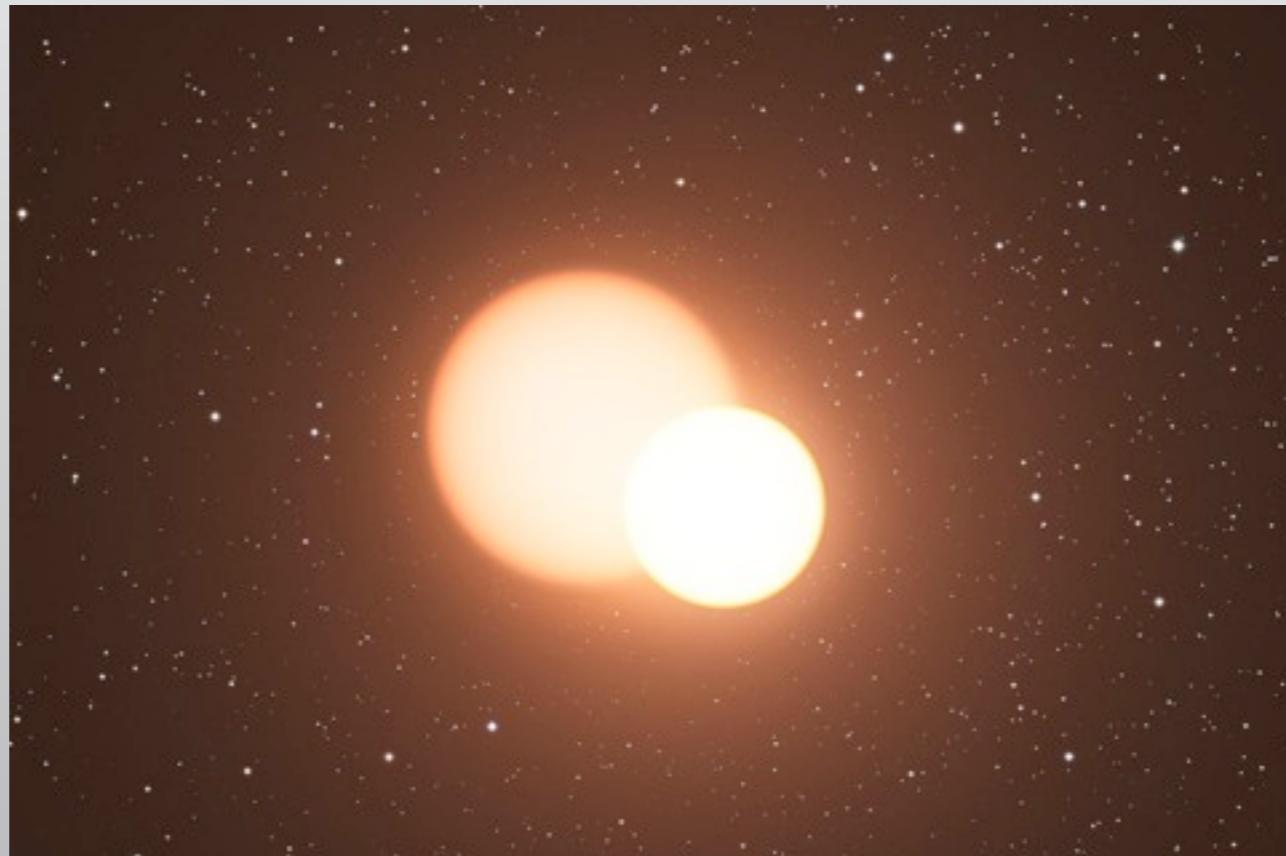
## Conclusions and perspectives

# Why to study interacting binaries?

At least 50% of stars are binaries

Determining mass

Constraints on stellar evolution models



# Why to study interacting binaries?

## Interacting binary:

2 stars exchanging matter  
+ complex structures  
(accretion disk, jets, nebula, etc.)



Properties relevant to  
many astrophysical objects

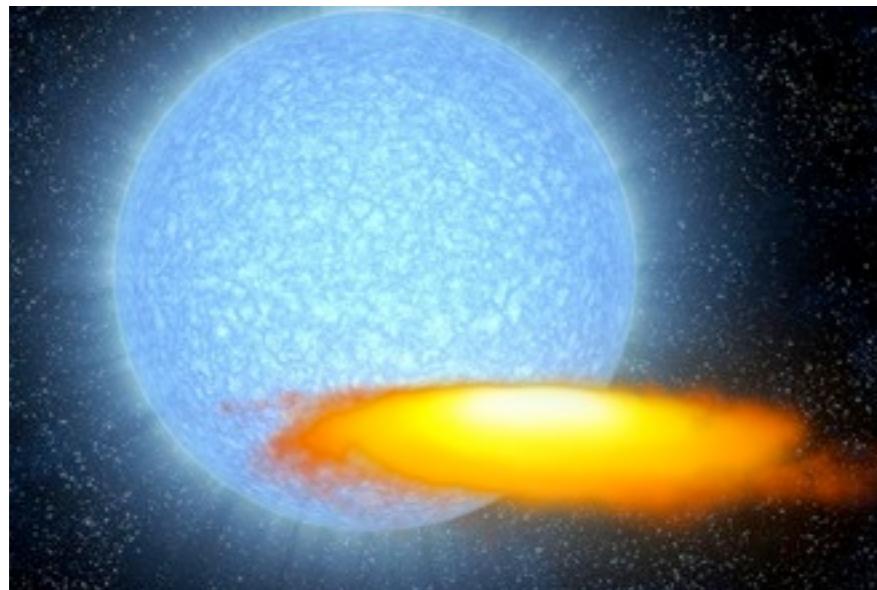
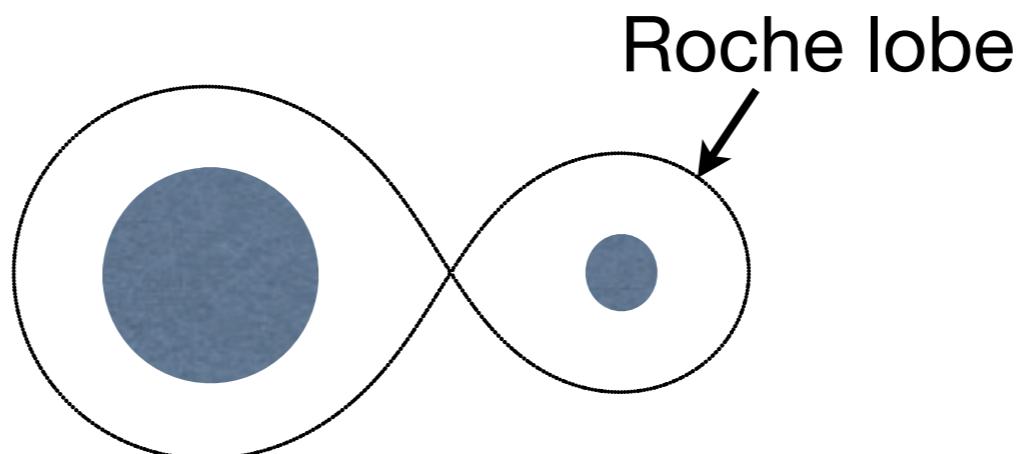


Excellent laboratories to study  
numerous physical processes

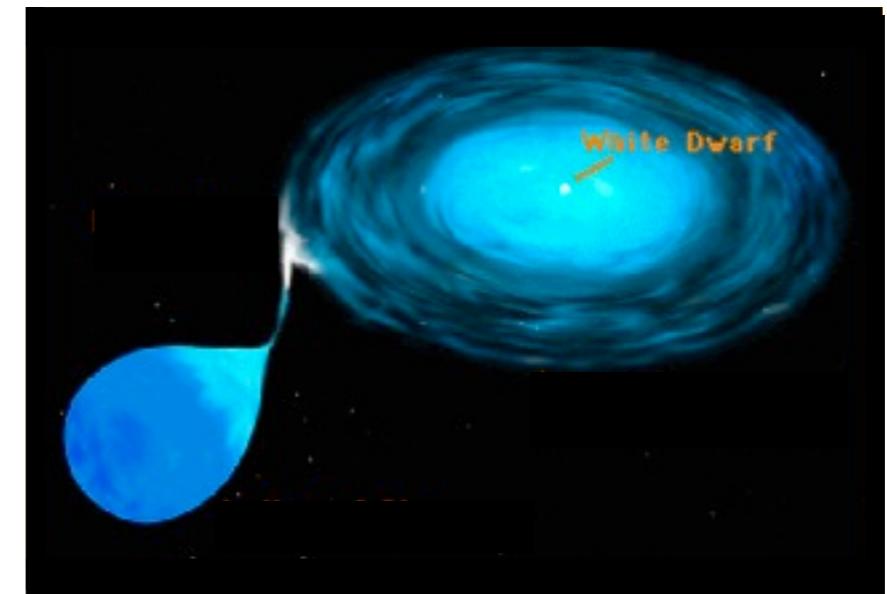
Evolution dominated by mass transfer processes

# Mass transfer processes

Evolution dominated by mass transfer processes



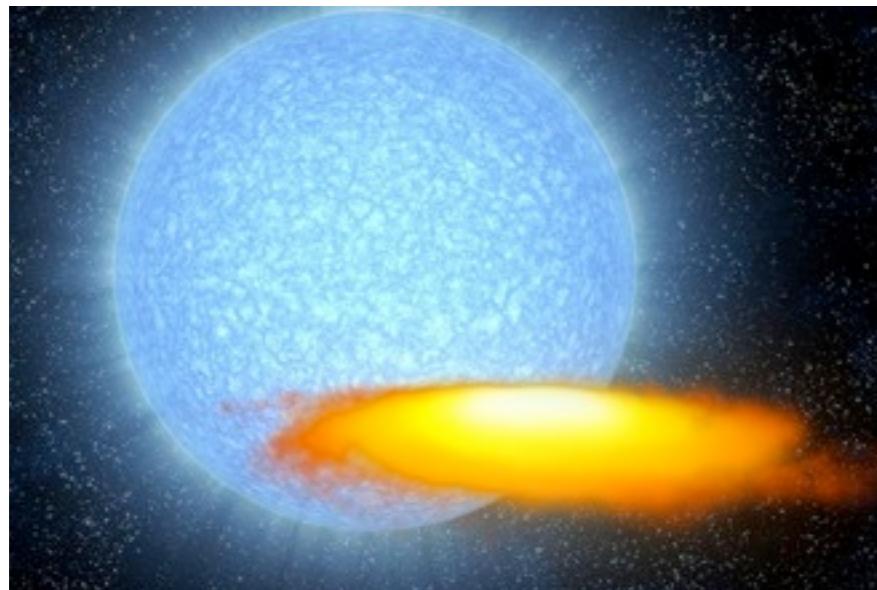
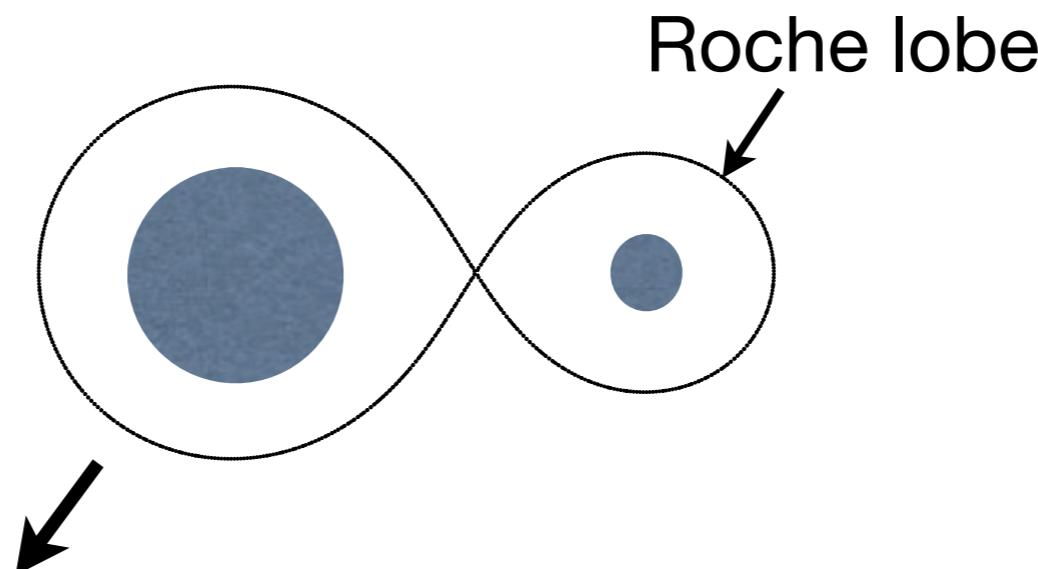
Stellar wind accretion



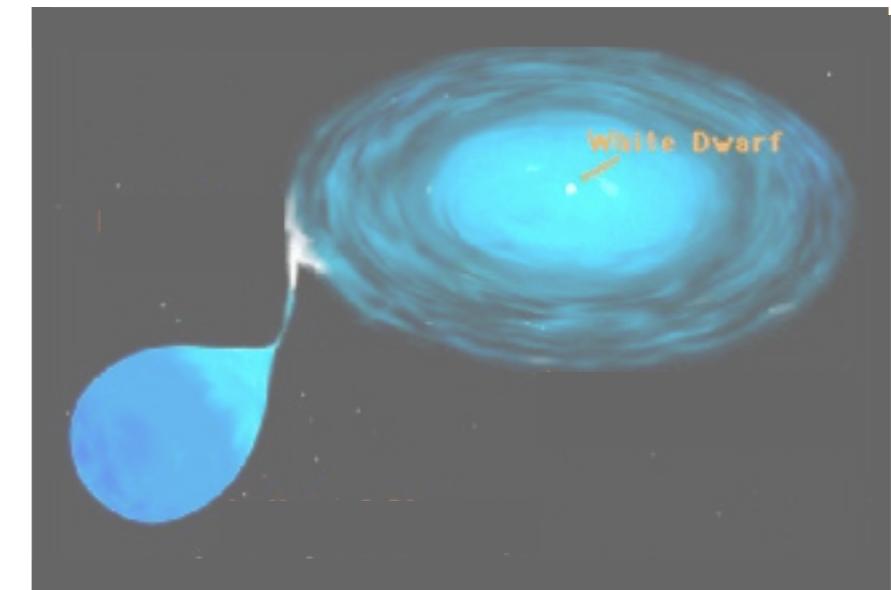
Roche lobe overflow (RLOF)

# Mass transfer processes

Evolution dominated by mass transfer processes



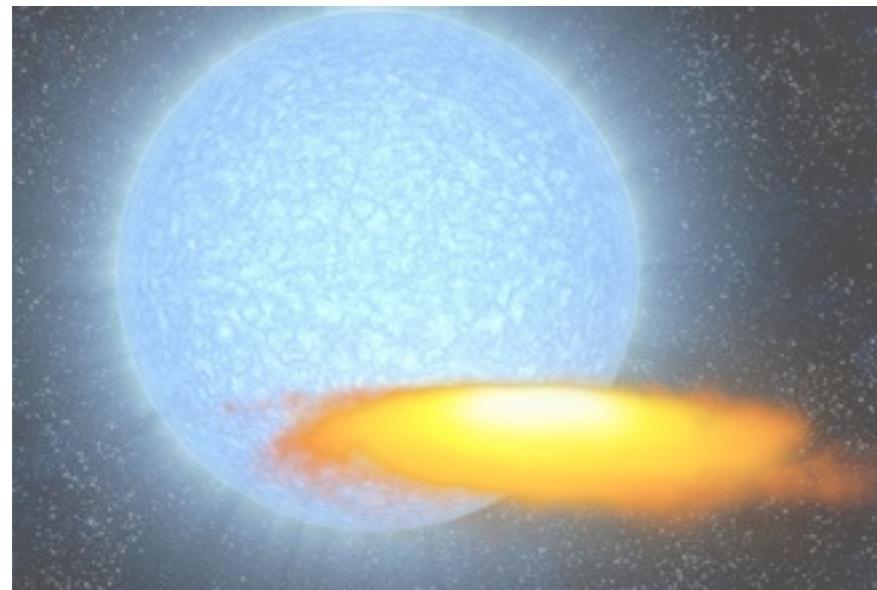
Stellar wind accretion



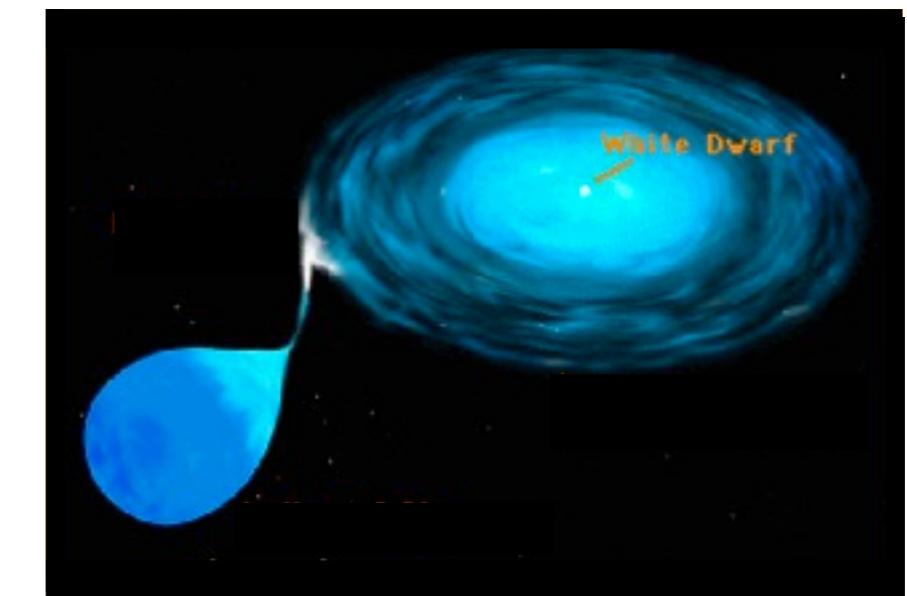
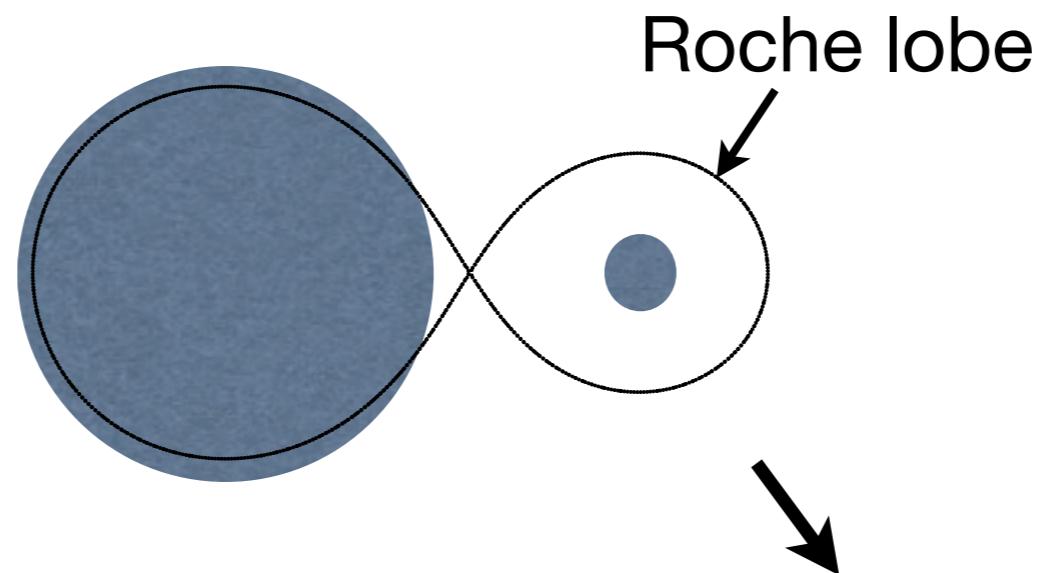
Roche lobe overflow (RLOF)

# Mass transfer processes

Evolution dominated by mass transfer processes



Stellar wind accretion



Roche lobe overflow (RLOF)

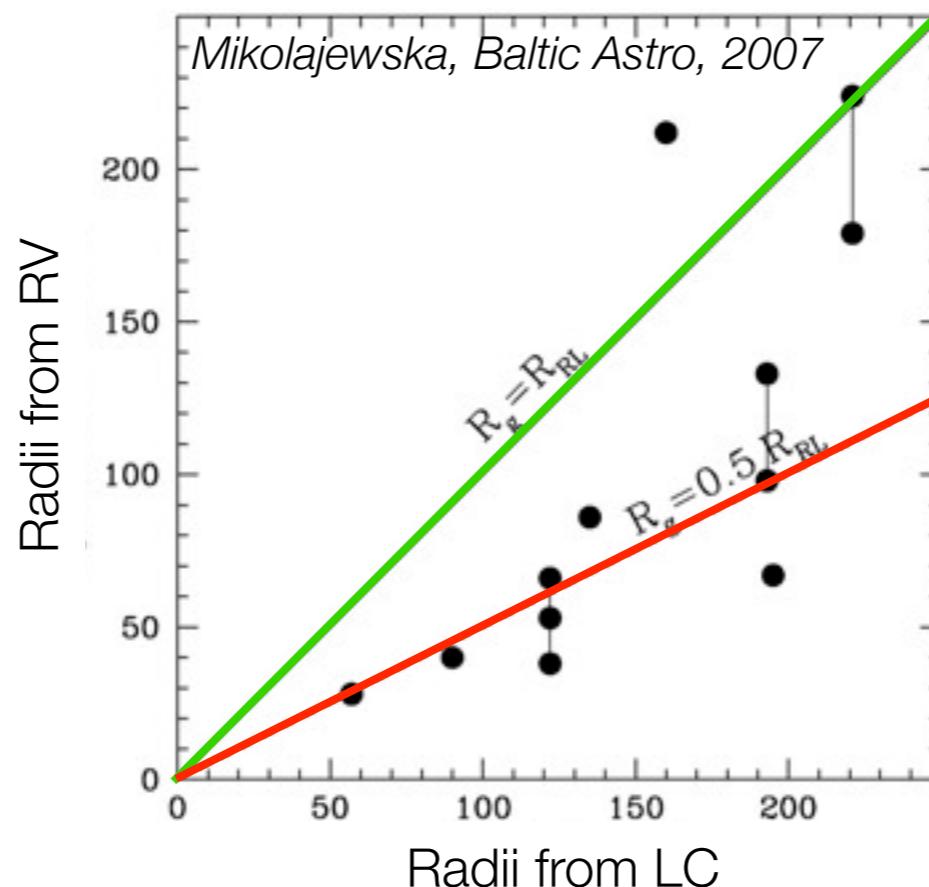
# Issues with indirect observables

## Spectroscopy or Photometry

- **Indirect observables**
- Assumptions required

Can lead to conflicting observations, e.g.:

Difference by a factor of 2 between stellar radii derived from  
Light Curve & Rotational Velocities



# The breakthrough of interferometry

## Spectroscopy or Photometry

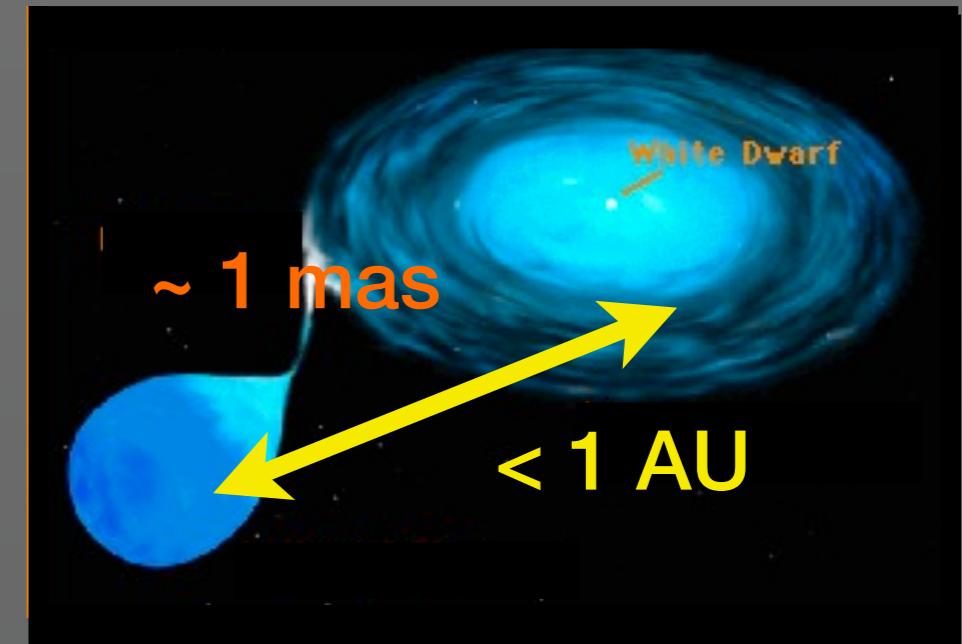
- **Indirect observables**
- Assumptions required

## Optical interferometry

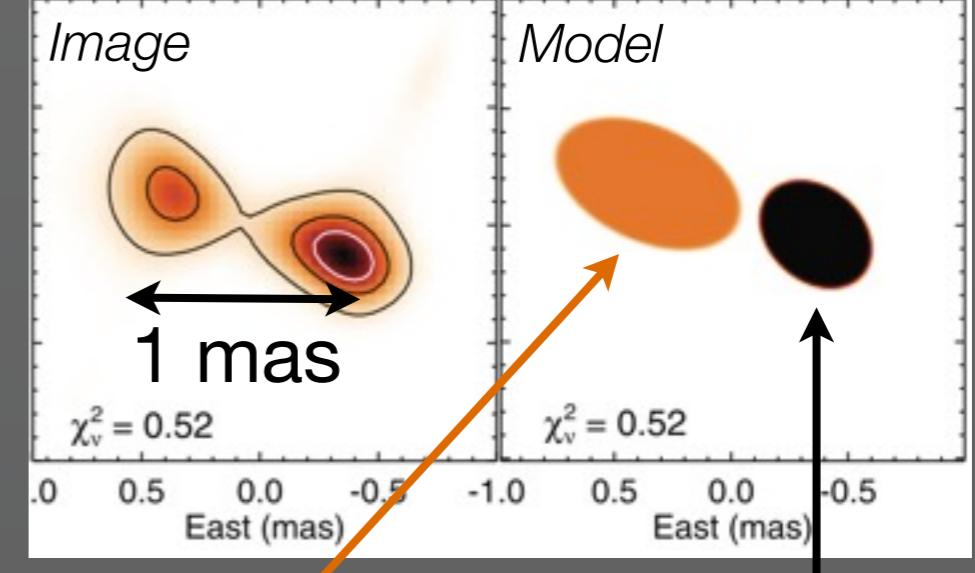
- **Direct observables**

Constraints on physical sizes,  
morphology

High benefits from  
new imaging capability



$\beta$  Lyr (Zhao et al. 2008)



Accretion disk

Distorted giant

# The case of SS Leporis

M giant + oversized A dwarf + dusty disk

## Algol paradox

Mass ratio  $M_A/M_M \sim 2$  to 4

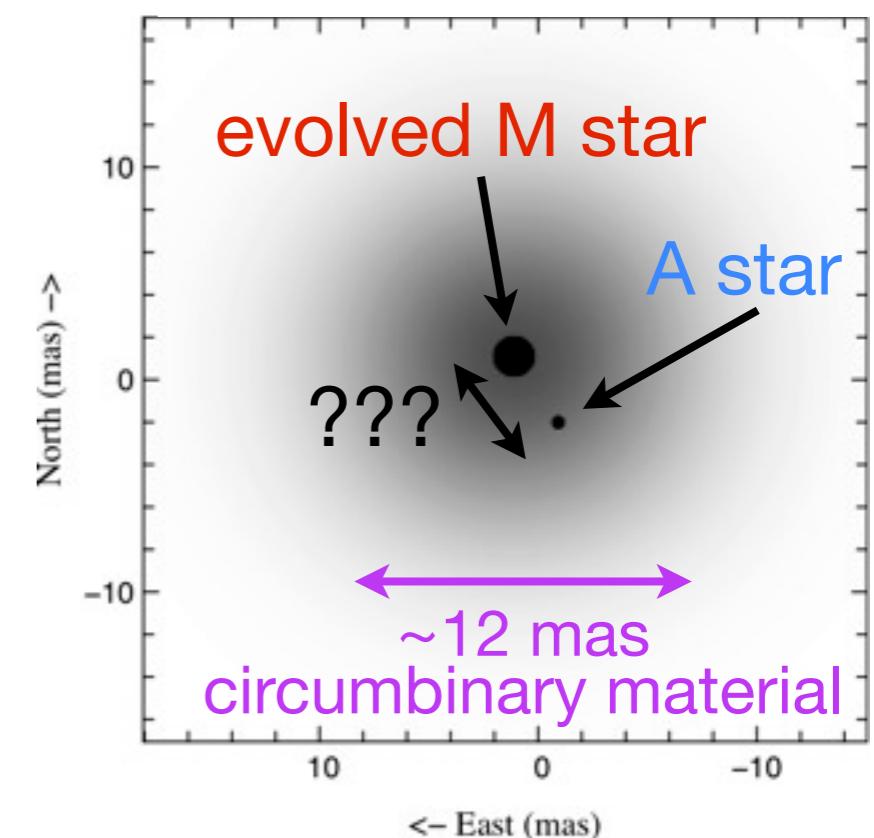
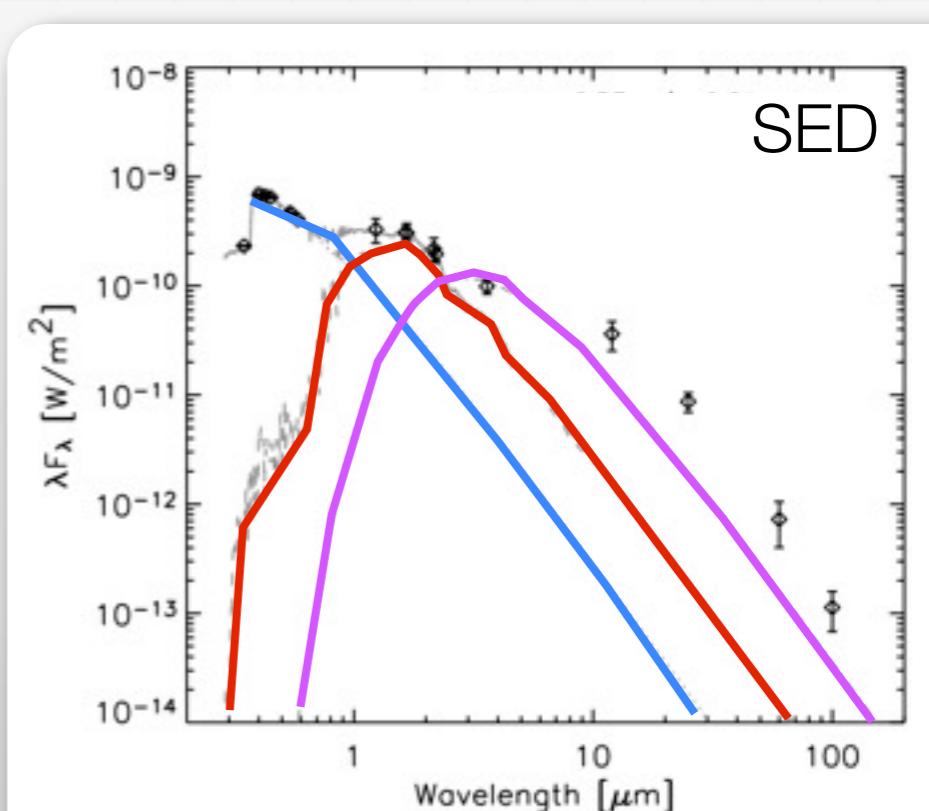
→ hints for mass transfer

## Roche lobe overflow

Distance ~ 270 to 370 pc

- Orbit:
- $P = 260\text{d}$
  - Quasi circular
  - Inclination estimated to  $30^\circ \pm 10^\circ$
  - Separation ???

Verhoelst et al. 2007, Welty et al. 1995, Jura et al. 2001



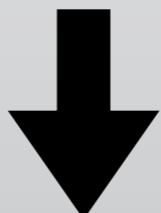
# VLTI observations

8 observations over 3 revolutions:

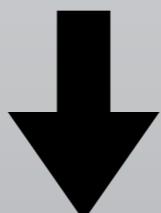
- 4 AMBER (3T), H&K, R~40
- 4 PIONIER (4T), H, R~40

Method:

1. Images with PIONIER
2. Parametric modeling: morphology, orbit & energy balance



**Fundamental parameters (M, T)**



Constraints on the mass transfer

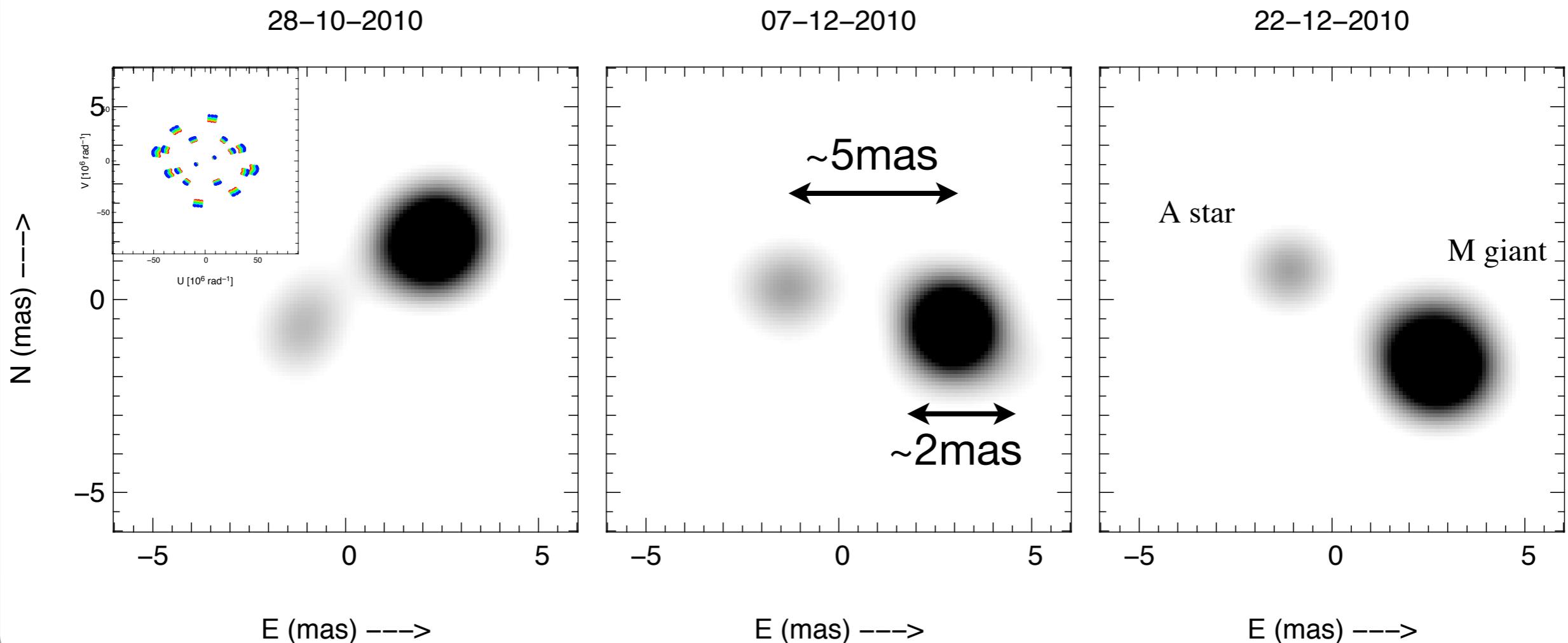
# VLTI observations

PIONIER images: **SS Lep as a visual binary @ 3 epochs**

Commissionning data: resolution ~1mas

Thanks to 4T, **image reconstructions in <4h hours** with MIRIA (*Thiebaut SPIE 2008*)  
→ with AMBER (3T) several nights required...

**1<sup>st</sup> images of an interacting binary & orbital motion @ VLTI**



# VLTI observations

Parametric modeling

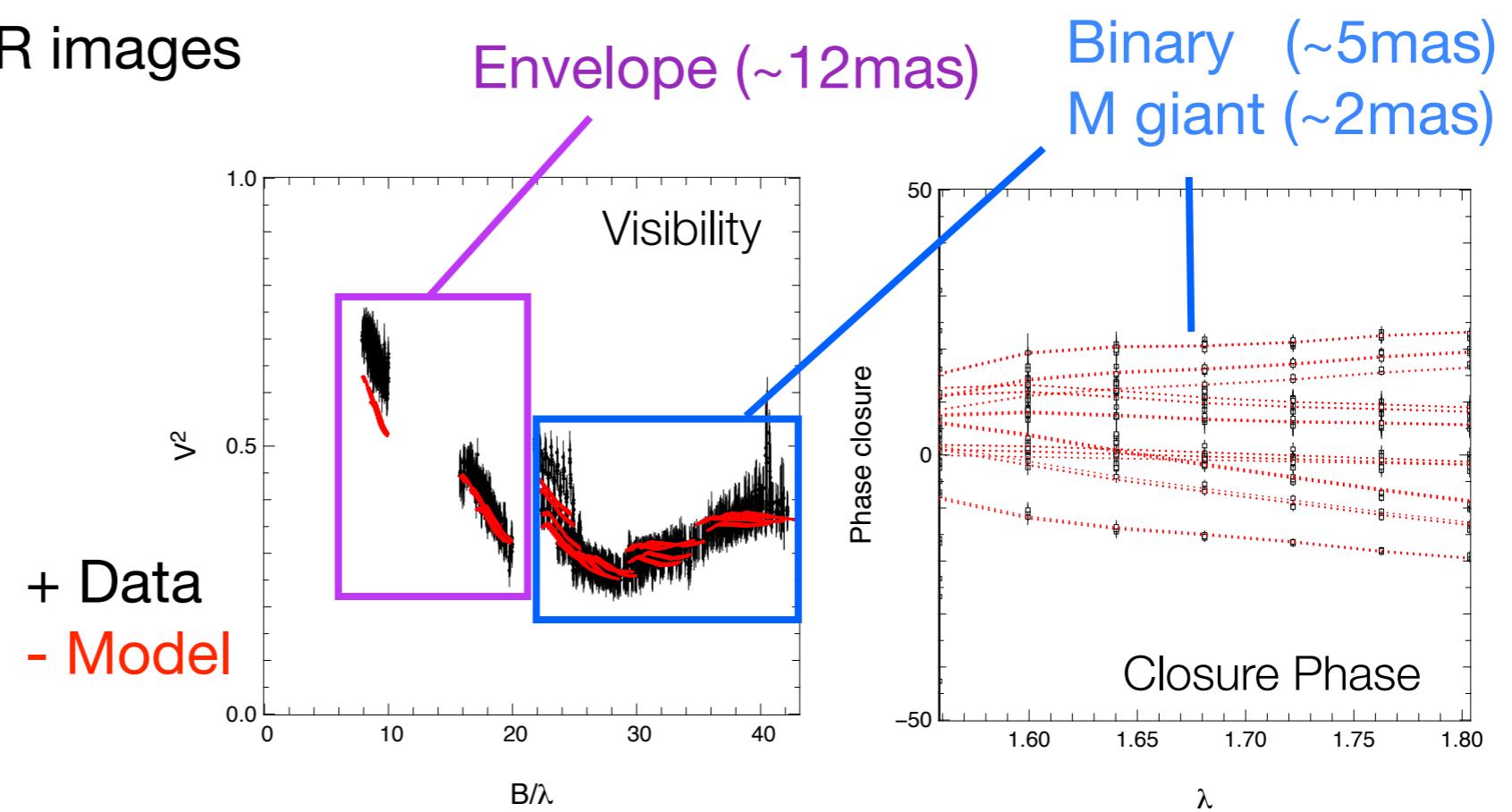
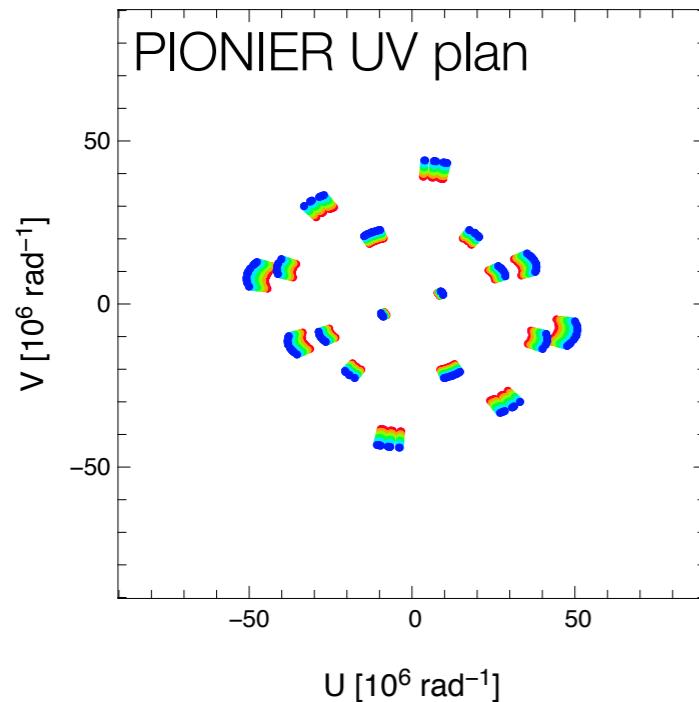
## Resolved M star + unresolved A star + circumbinary material

Free parameters:

- Binary separation & orientation
- M giant diameter (*Uniform disk*)
- Dusty envelope size (*gaussian shape*)

+ **Wavelength dependency of parameters: color**

Starting point: PIONIER images



# The energy balance

Individual spectroscopy of the 3 components at a 1-mas resolution

**M star** MARCS model

$3200 \pm 200$ K

Metallicity?

**A star** Rayleigh-Jeans, 9000K (SED)

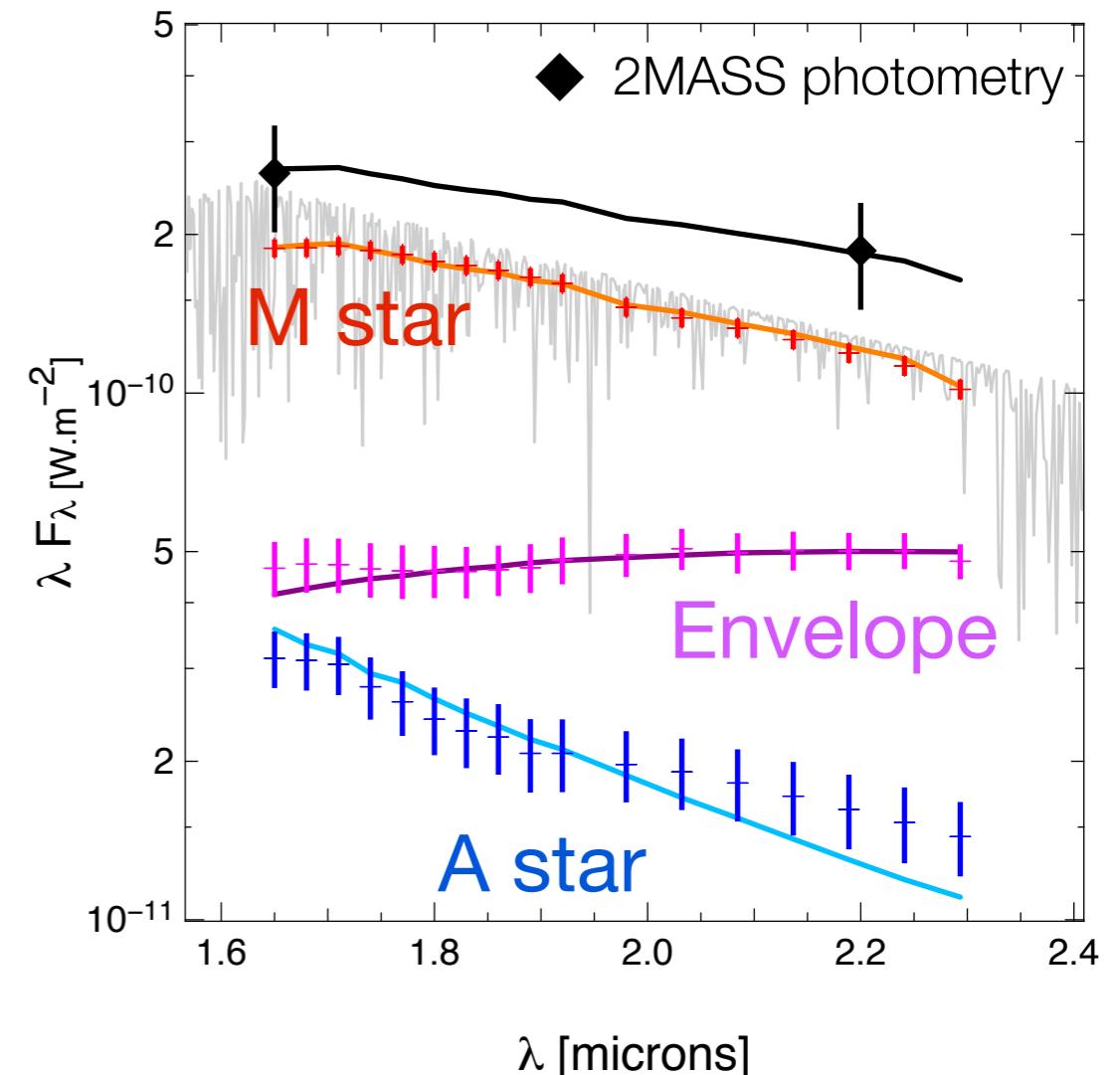
10x oversized ( $\varnothing \sim 18R_\odot$ ) ?

OR

accretion disk ?

**Envelope** BB@1700K, gaussian

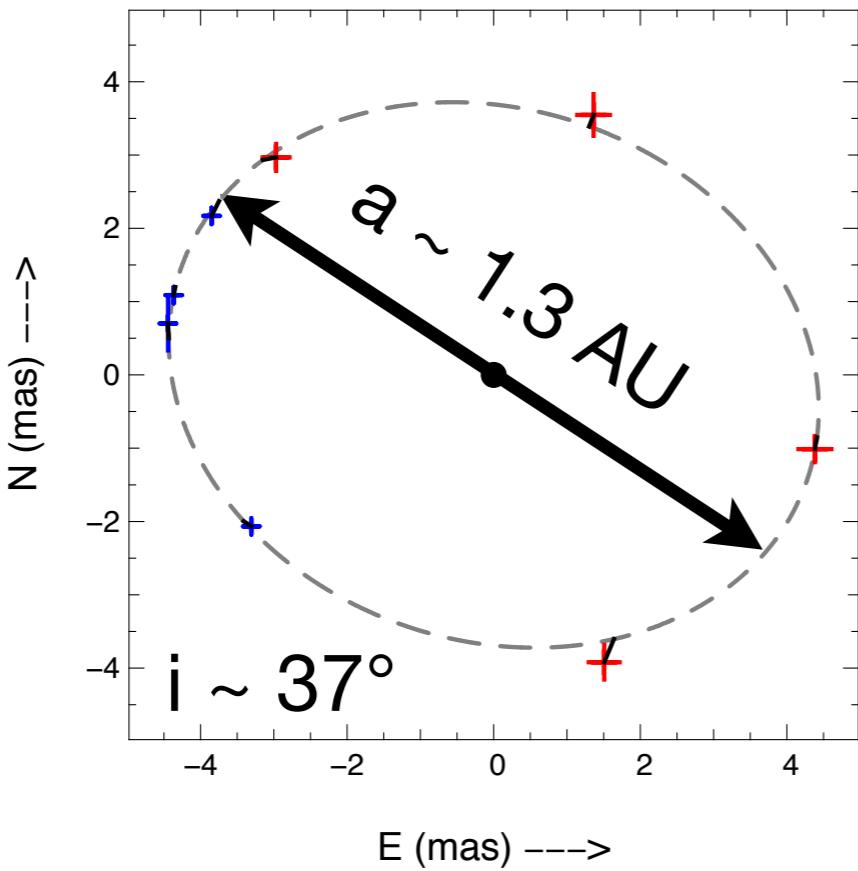
FWHM ~8mas



Sharper analysis: need for a high resolution spectrum

# The orbit and masses

Radial velocity + astrometry



PIONIER: unambiguous  
positions

AMBER: good orbit  
sampling

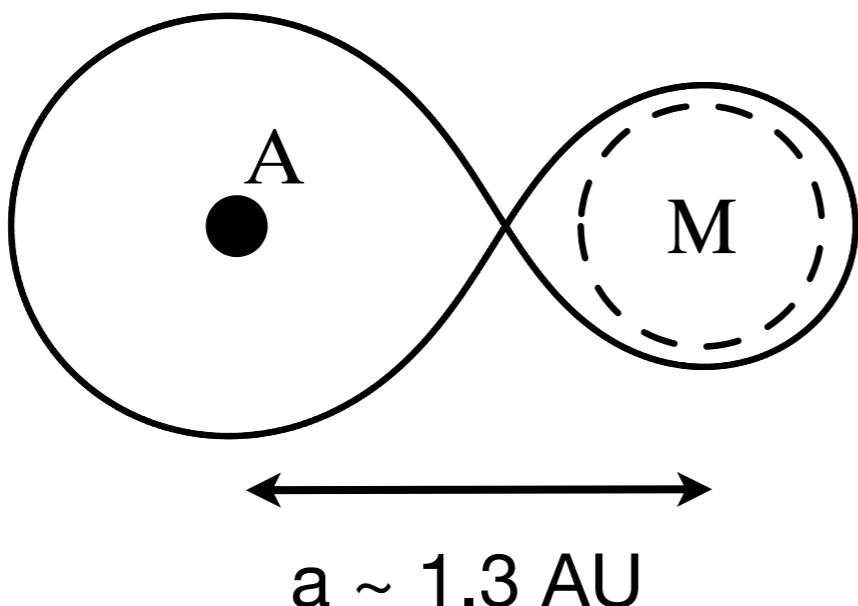
	Before	Now
$d$ [pc]	$330 \pm 70$	<b><math>280 \pm 25</math> (Hipparcos)</b>
$M_A$ [ $M_\odot$ ]	$2 \sim 3$	$2.7 \pm 0.3$
$M_M$ [ $M_\odot$ ]	$0.35 \sim 1$	$1.3 \pm 0.3$
$M_A/M_M$	<b><math>4 \pm 1</math></b>	<b><math>2.2 \pm 0.3</math></b>

Errors dominated by the distance uncertainty

# Mass transfer: stellar wind accretion!

	Before	Now
$\varnothing_M$ [mas]	$3.1 \pm 0.3$	$2.2 \pm 0.01$
d [pc]	$330 \pm 70$	$280 \pm 25$
$\varnothing_M$ [ $R_\odot$ ]	$220 \pm 60$	$130 \pm 7$
Roche lobe filling	<b><math>140 \pm 20\%</math></b>	<b><math>85 \pm 3\%</math></b>

Errors dominated by the distance uncertainty



No Roche  
lobe overflow



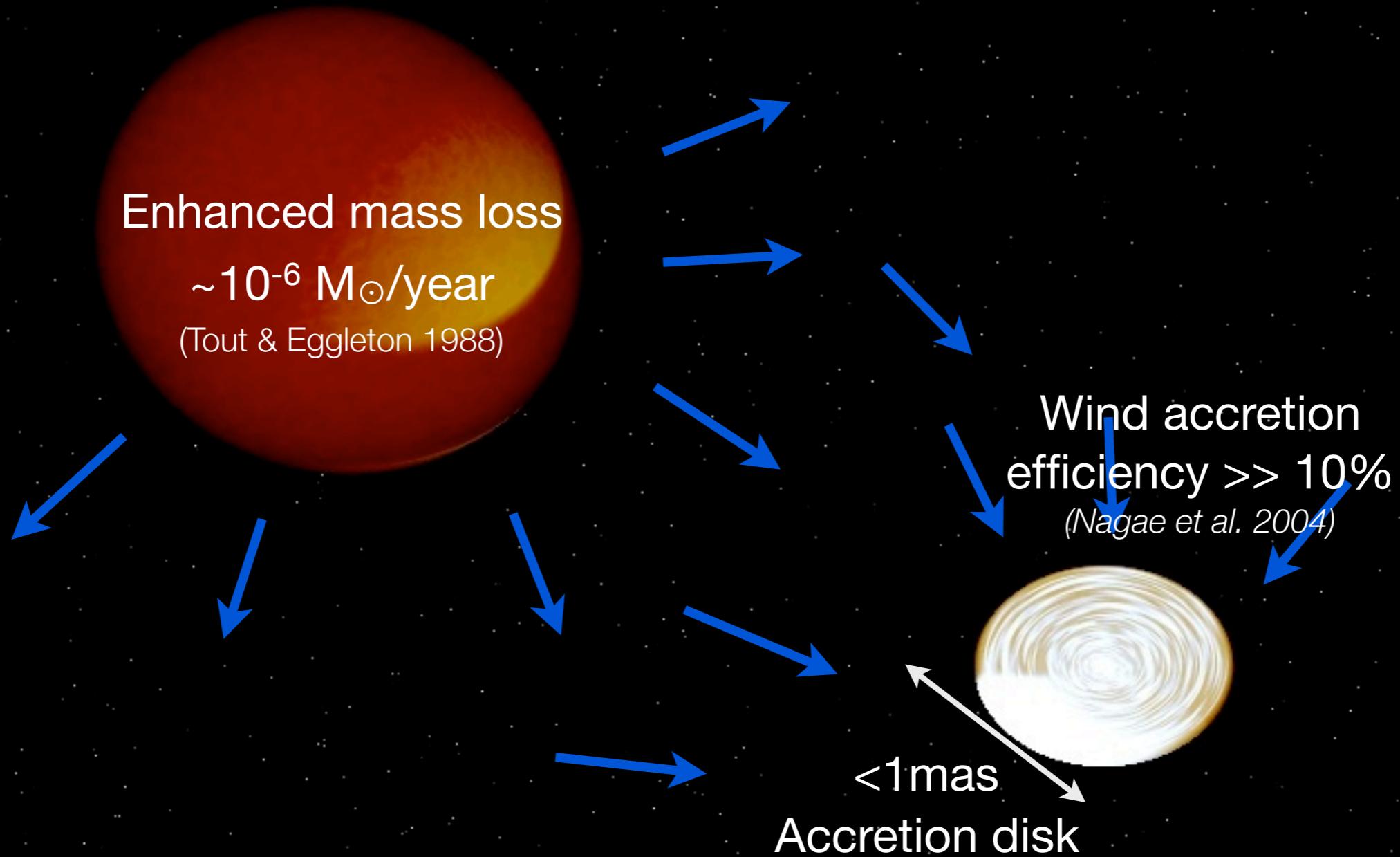
Stellar wind  
accretion

# A new vision of SS Lep

Coll. H. BOFFIN

Scenario for the accretion process

Ideal candidate to test theories of accretion & mass loss



# Perspectives for SS Lep

New vision of the system, important constraints on the mass transfer

Related publications and communications:

- Conf **Evolution of compact binaries (03/2011)**
- Conf **10 years VLTI (10/2011)**
- Publi. **Blind et al. A&A accepted**
- Press release **ESO (30/11/2011), A&A**

Future work on SS Lep:

- Circumbinary envelope morphology → NaCo/SAM + PIONIER
  - Tidal distortion of the M giant ? → PIONIER
  - Accretion disk or oversized star? → VEGA/CHARA
- + simultaneous spectro/photometry

10/2011 - SS Lep observed with VEGA-3T  
**«P Cygni» H $\alpha$  line spatially & spectrally resolved**

# How to go further ?

To do more physics, we need:

- More objects: Increasing limiting magnitude
- Spectro-imaging: More telescopes + spectral resolution



Increasing sensitivity  
of the observations



**Need for a multi-telescope  
fringe tracker**

# Presentation outline

An introduction to interferometry

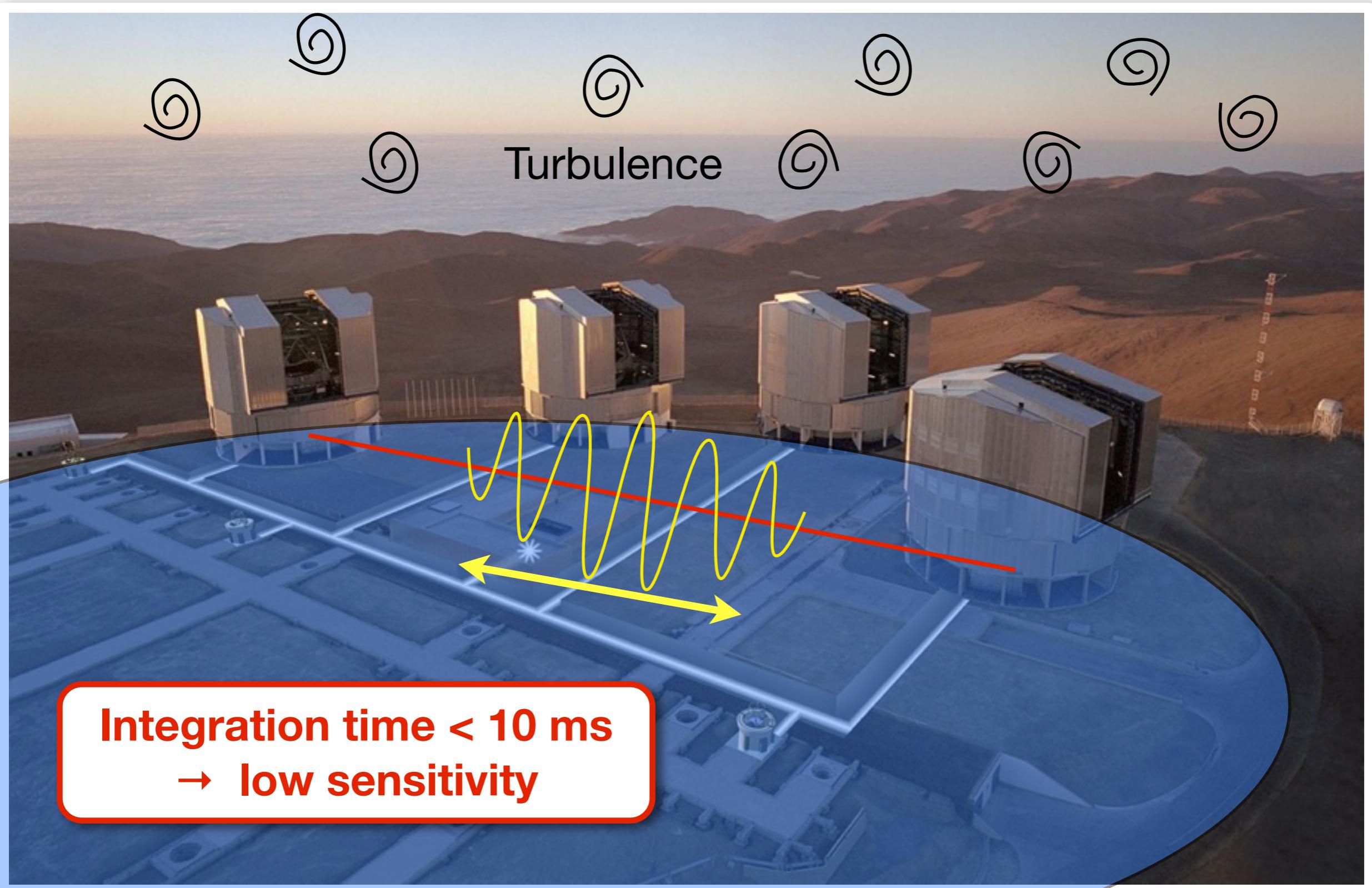
**PART I. Study of interacting binaries**

**PART II. Fringe trackers for imaging instruments**

- Context
- Definition of a fringe tracker concept
- The POPS concept

Conclusions and perspectives

# Dealing with the atmosphere...



# ... by using a fringe tracker

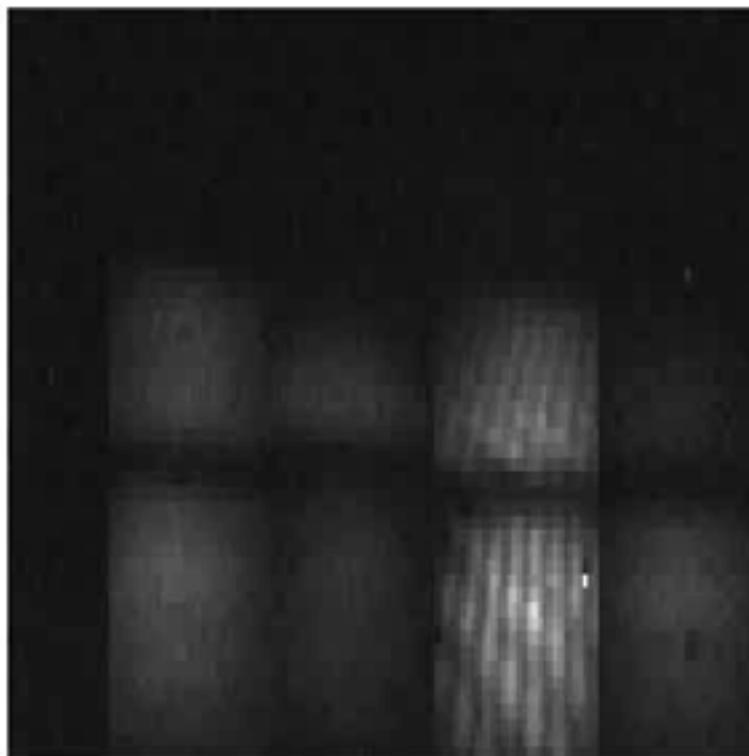
**Fringe tracking:** measuring and compensating in real time the randomly varying fringe position → sensitivity x1000



**Fringe tracker OFF**

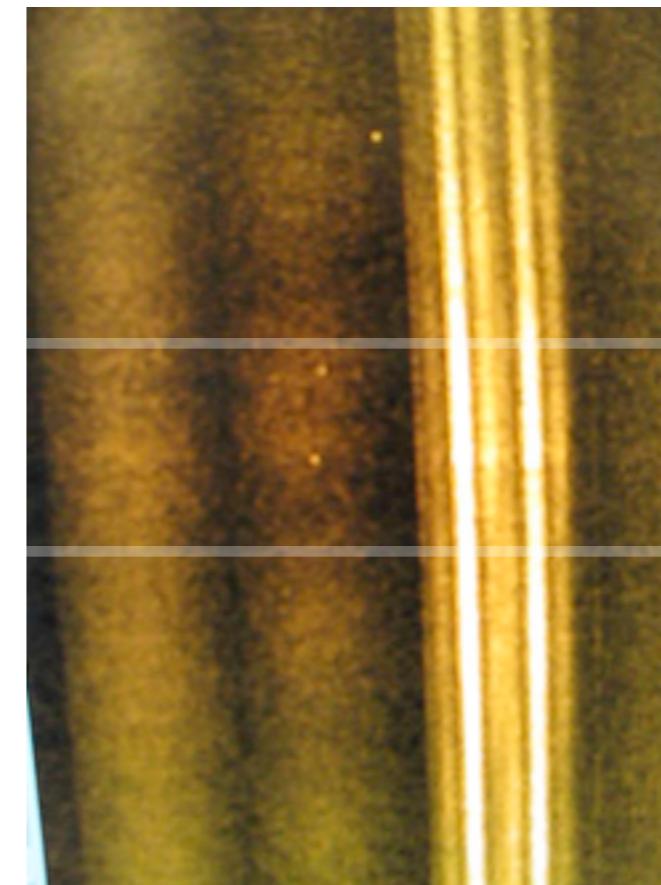
Integration time ~**10ms**

Amber 3T JHK LowResolution Fringes !



**Fringe tracker ON**

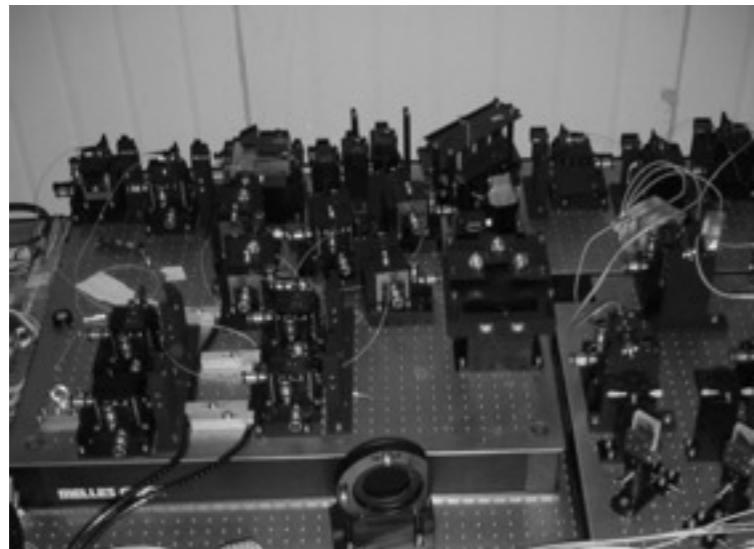
Integration time ~**5s** !



Faint emission line  
SPECTROSCOPY !

# Fringe tracking at VLTI today

**FINITO**



3T - **2 baselines**

**Temporal** fringe sampling

*Lebouquin et al SPIE 2008*

**PRIMA-FSU**



2T

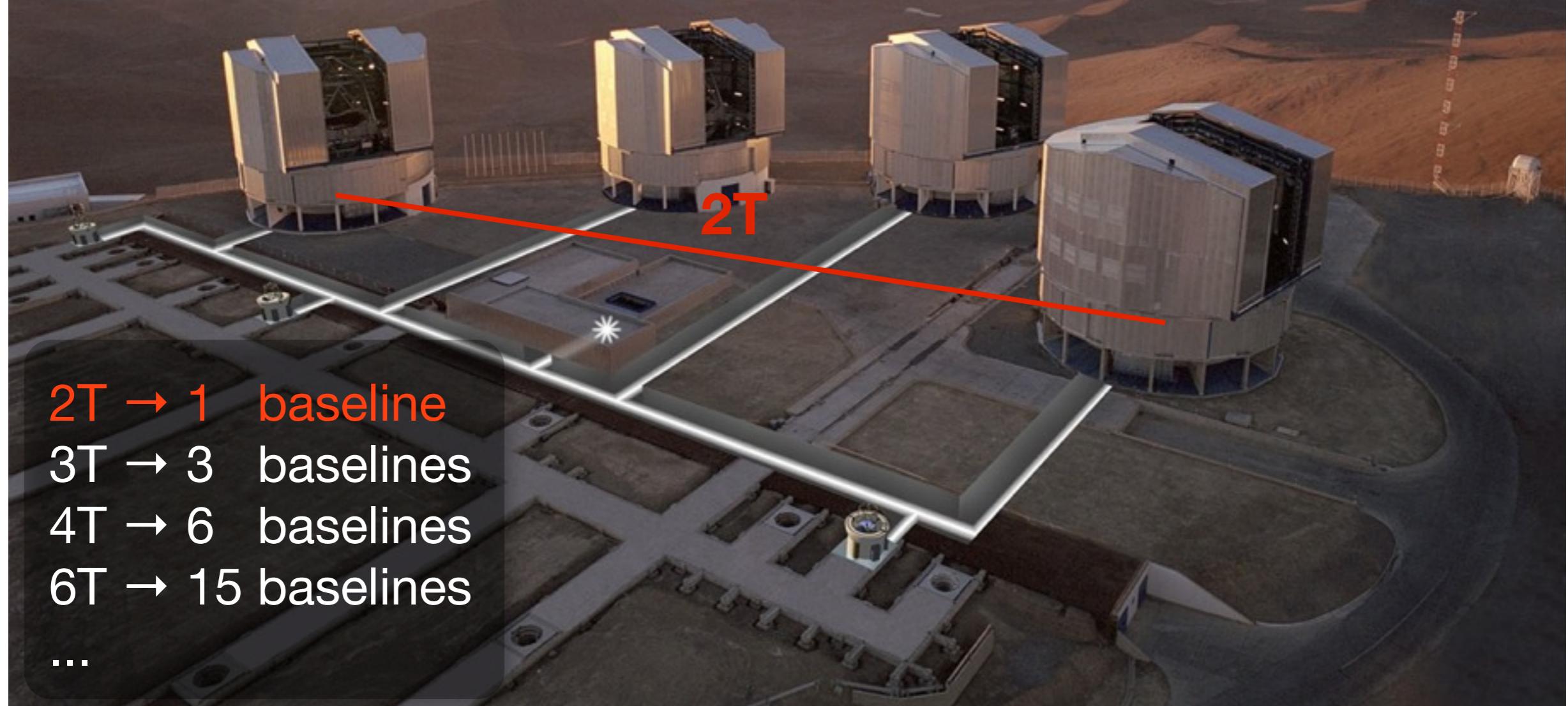
**Static** fringe sampling  
Off-axis tracking

*Sahlmann et al A&A 2009*

Performances	FINITO + ATs	PRIMA + ATs	PRIMA + UTs
Fringe tracking	<b>5.5</b>	~ 8	<b>9</b>
Fringe detection	-	~ 10	11.7

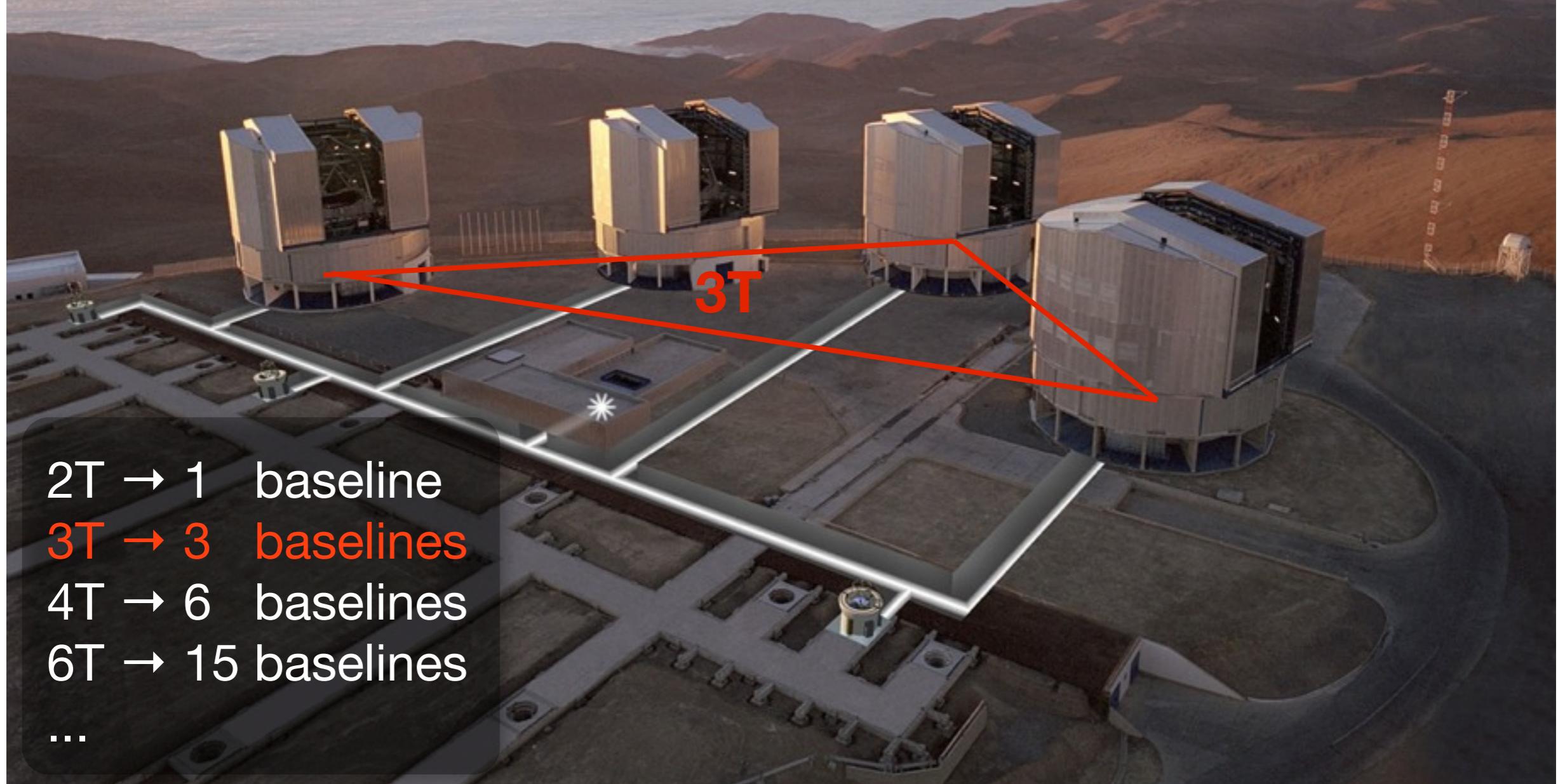
# A fringe tracker at VLTI tomorrow...

More telescopes → increasing complexity



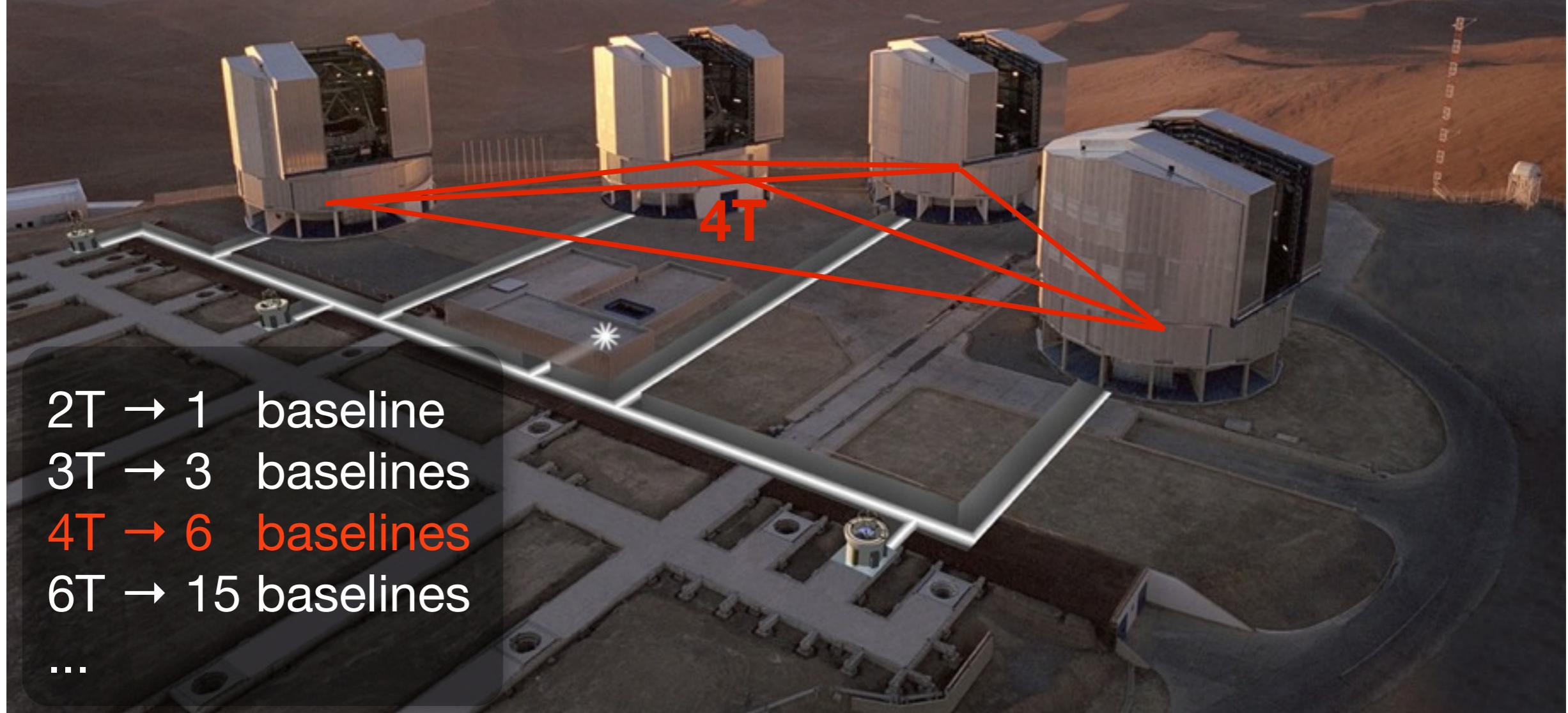
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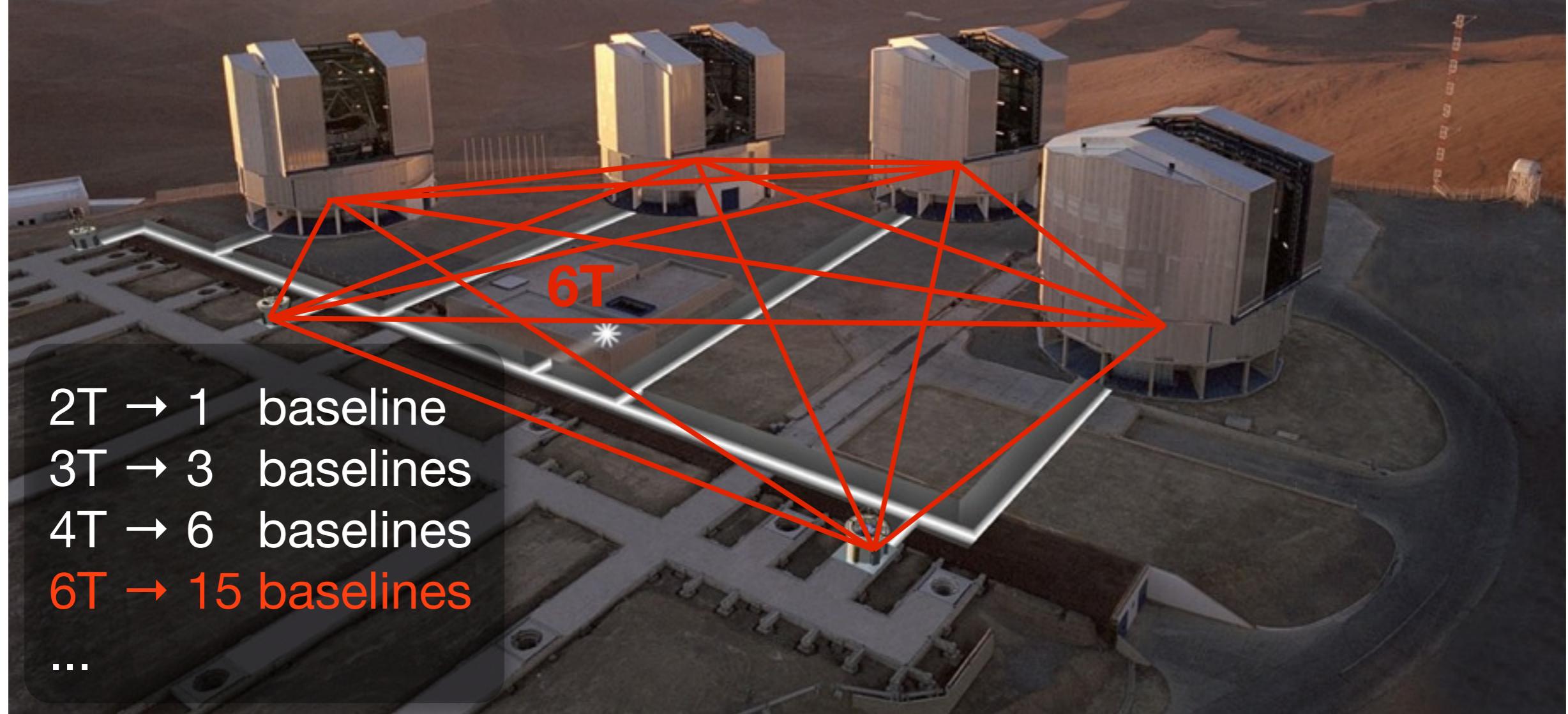
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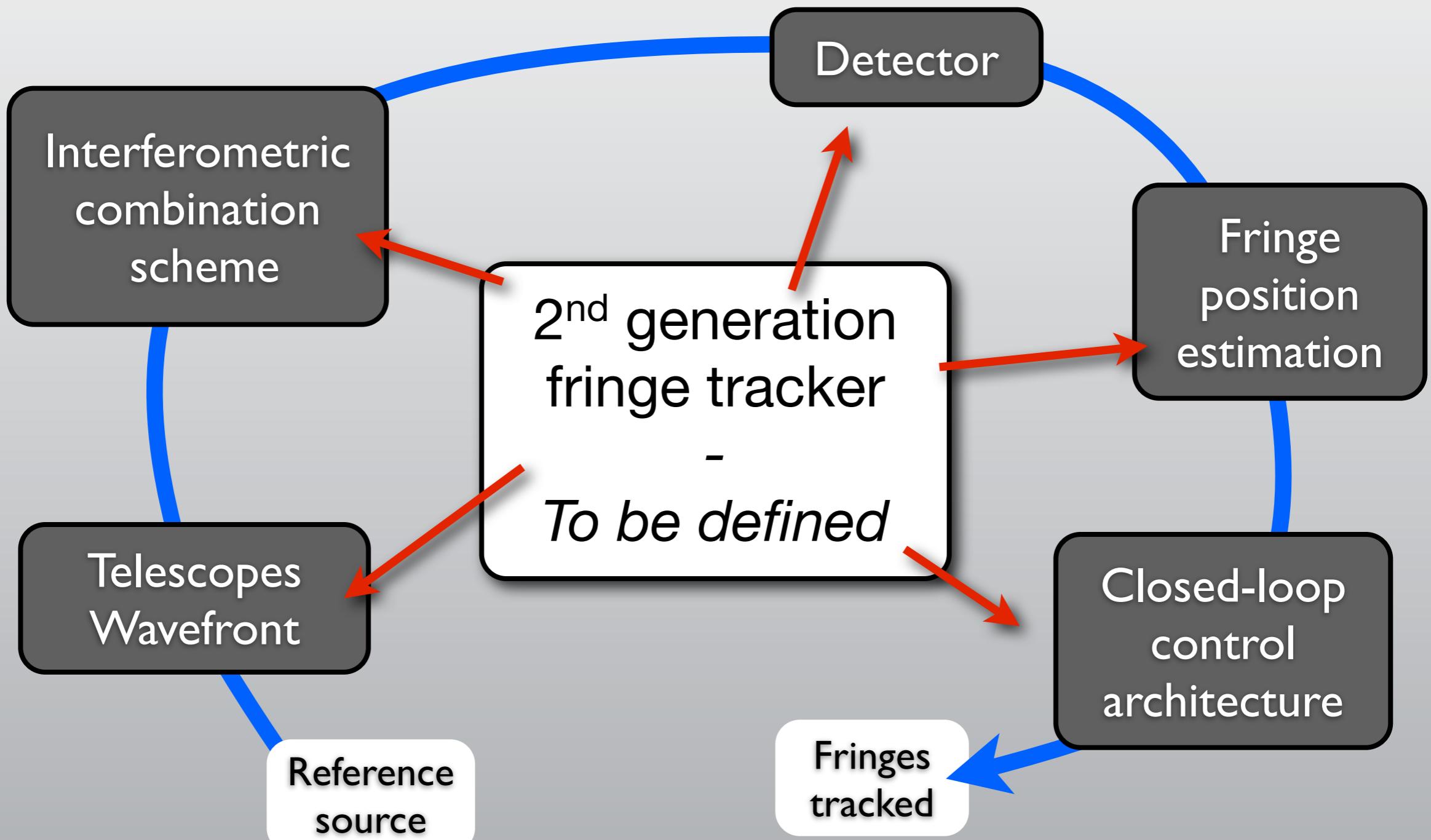
More telescopes → increasing complexity



# A fringe tracker at VLTI tomorrow...

Context: phase A study for ESO 2GFT

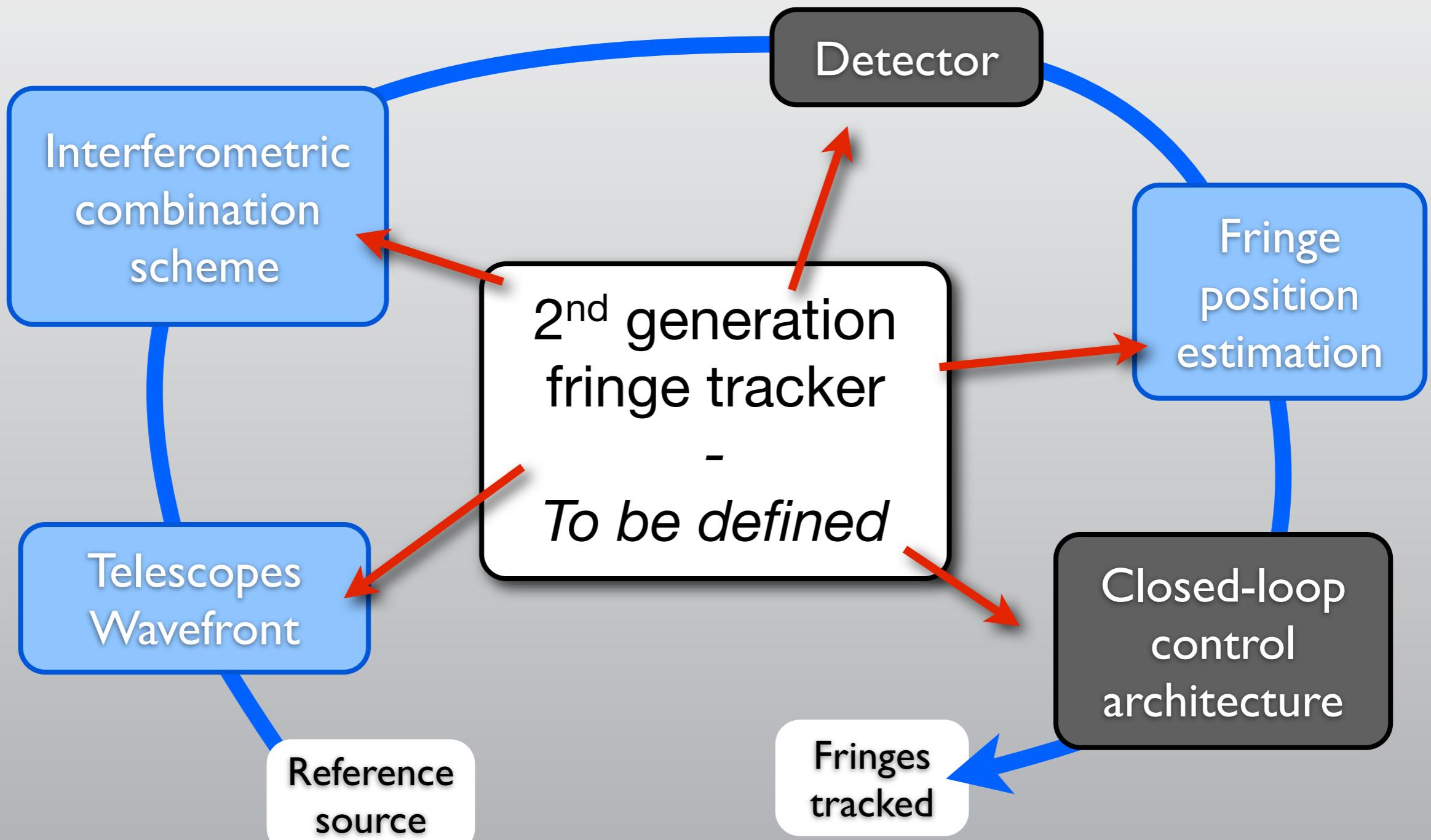
My implication: system analysis



# A fringe tracker at VLTI tomorrow...

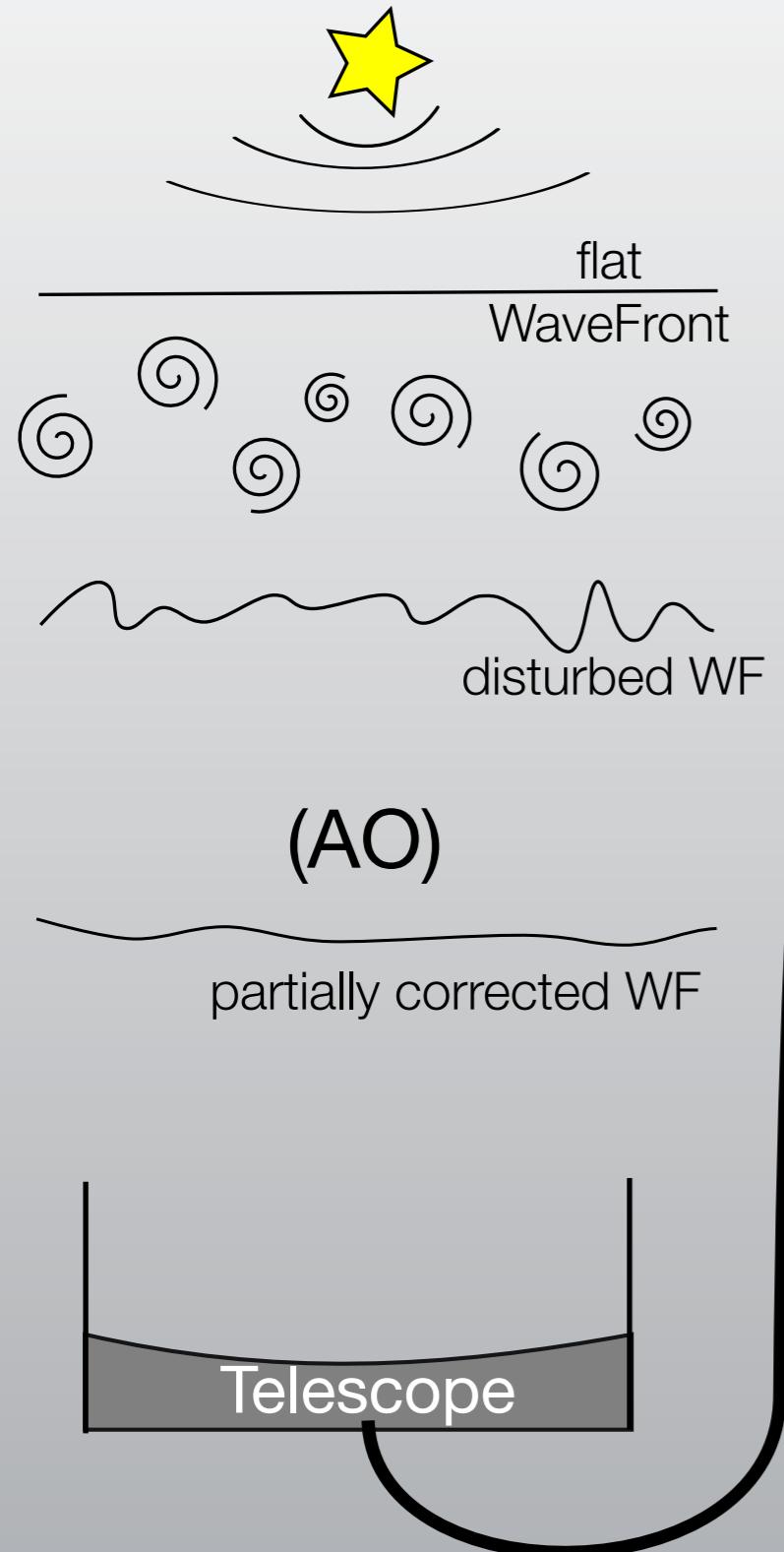
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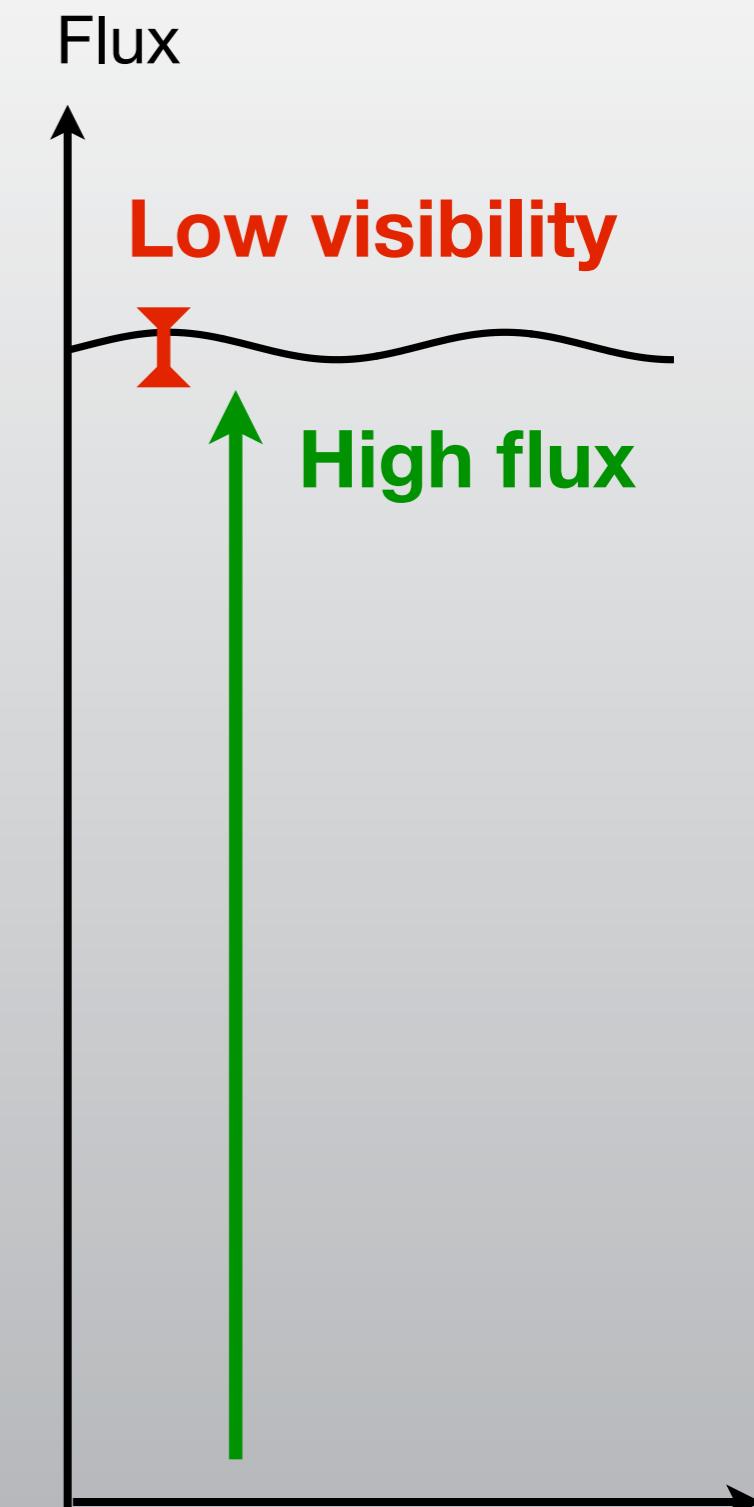
# 1. To filter or not to filter?

Coll. E. TATULLI



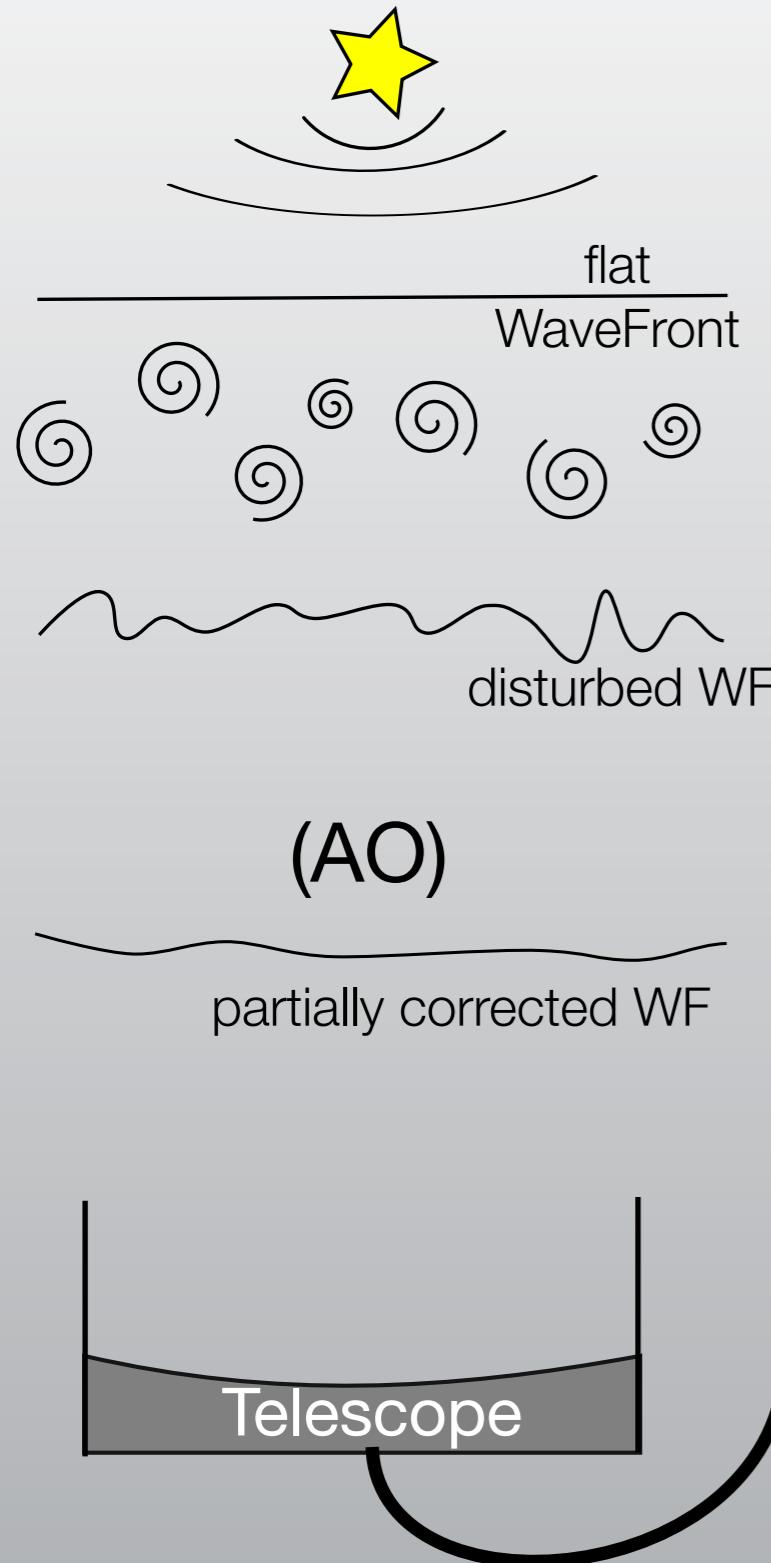
Without filtering  
Bulk optics

With filtering  
Fibers  
Integrated optics



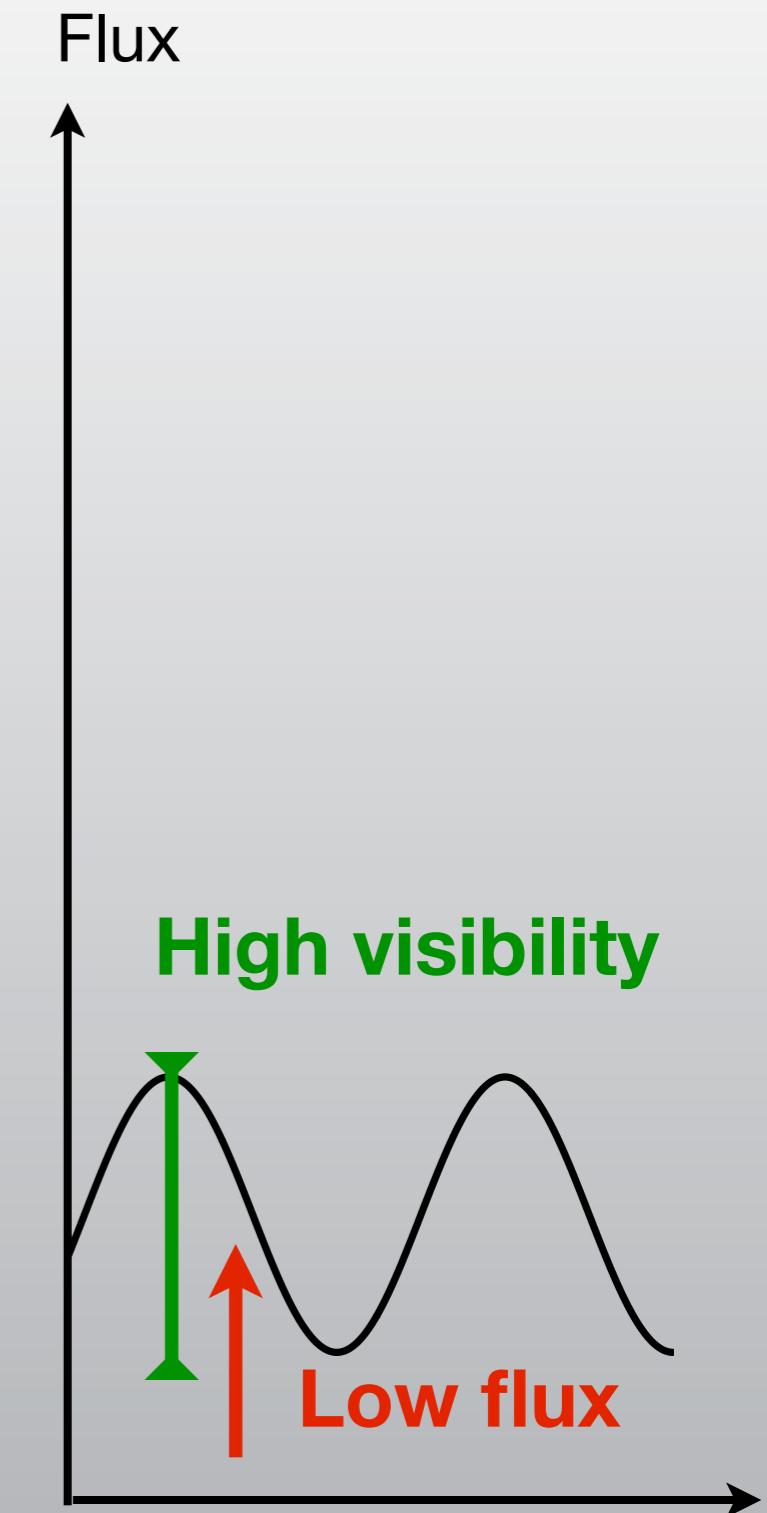
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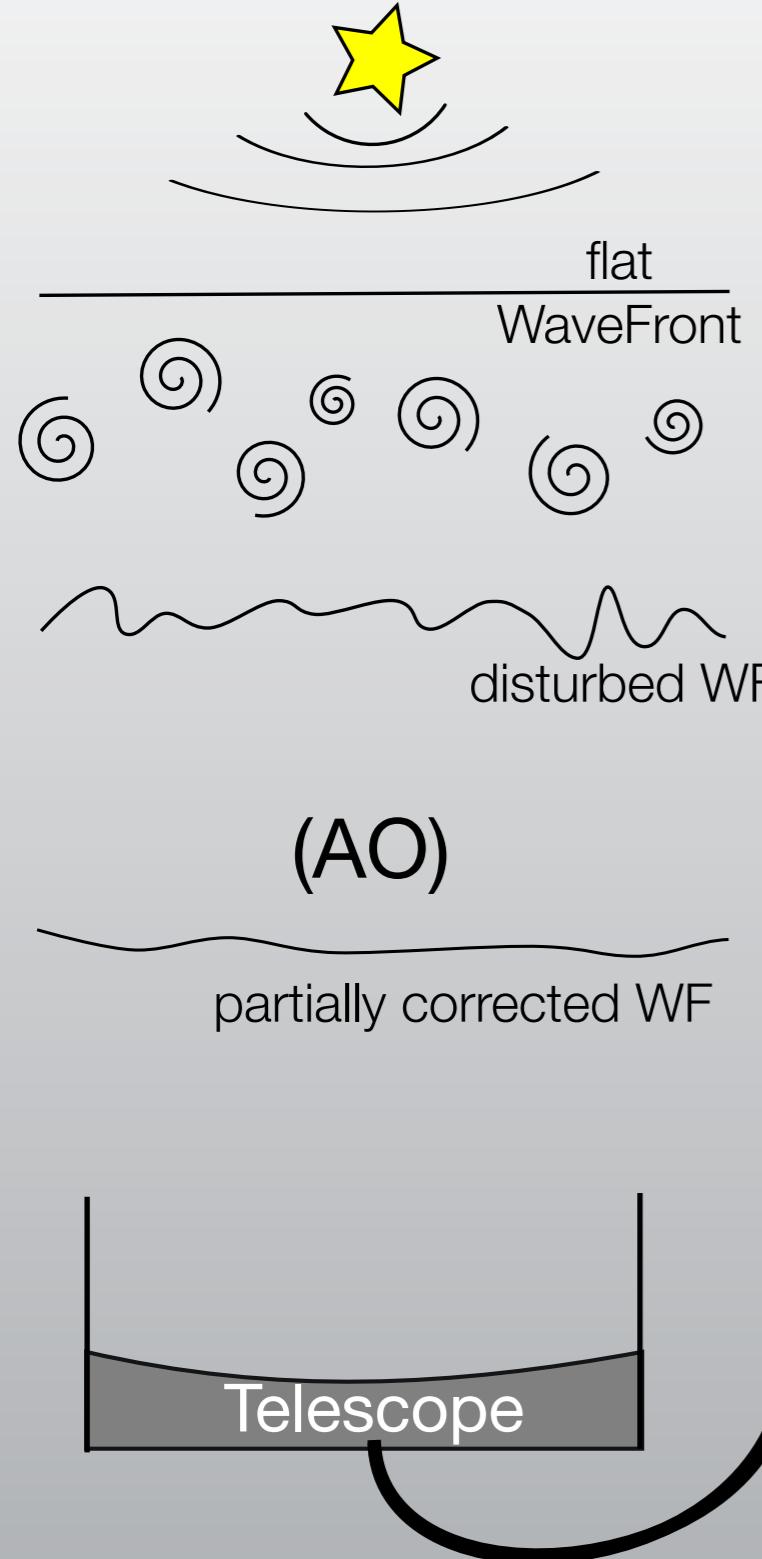
Without filtering  
Bulk optics

With filtering  
Fibers  
Integrated optics



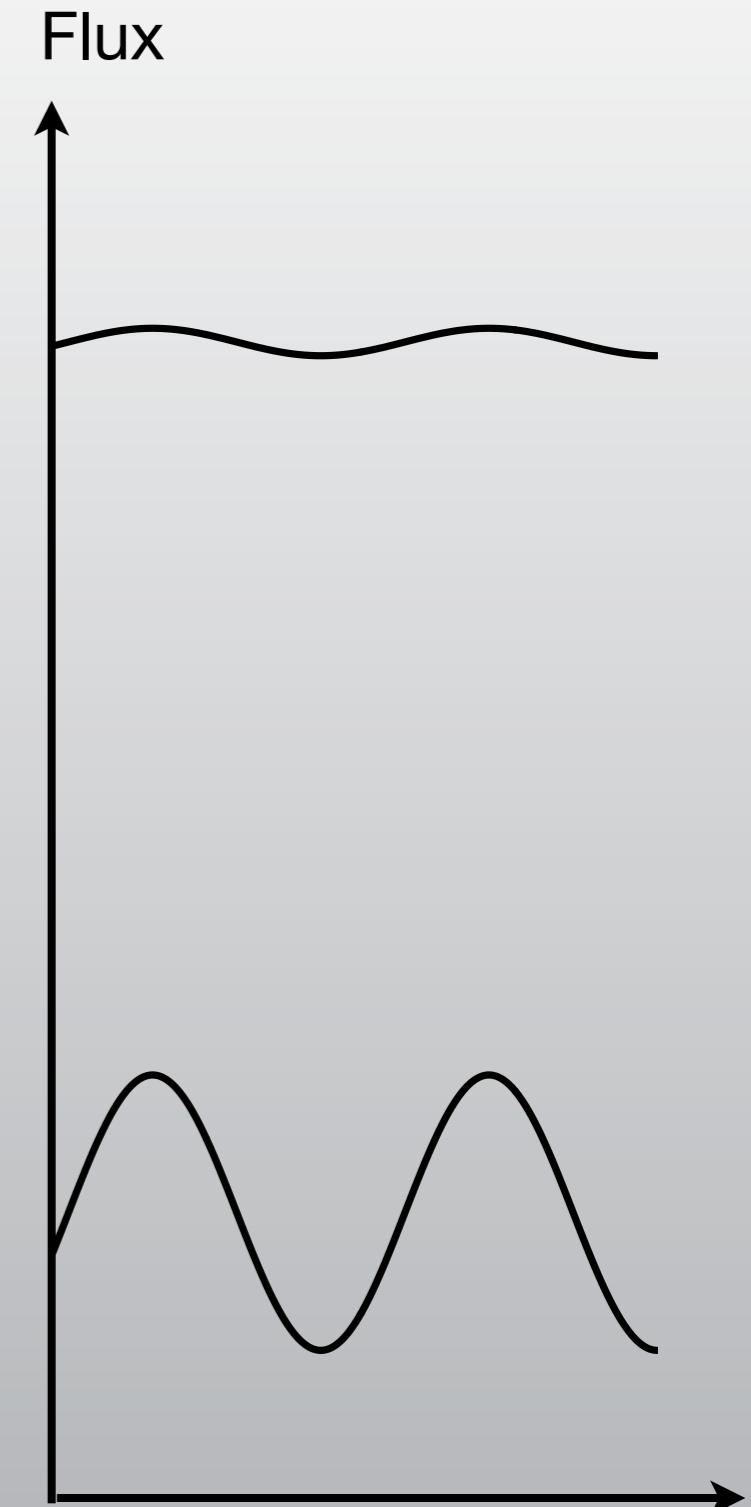
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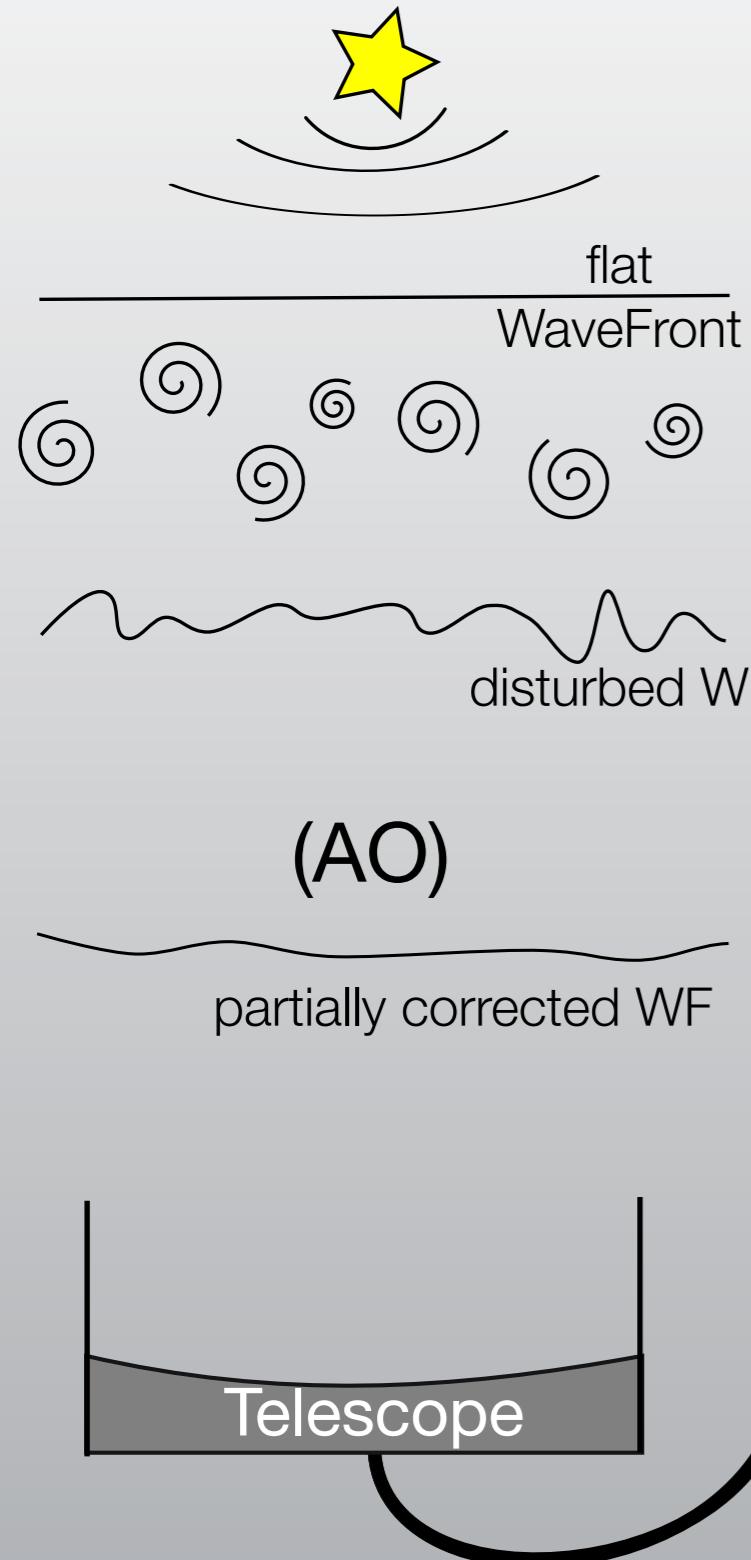
Without filtering  
Bulk optics

With filtering  
Fibers  
Integrated optics



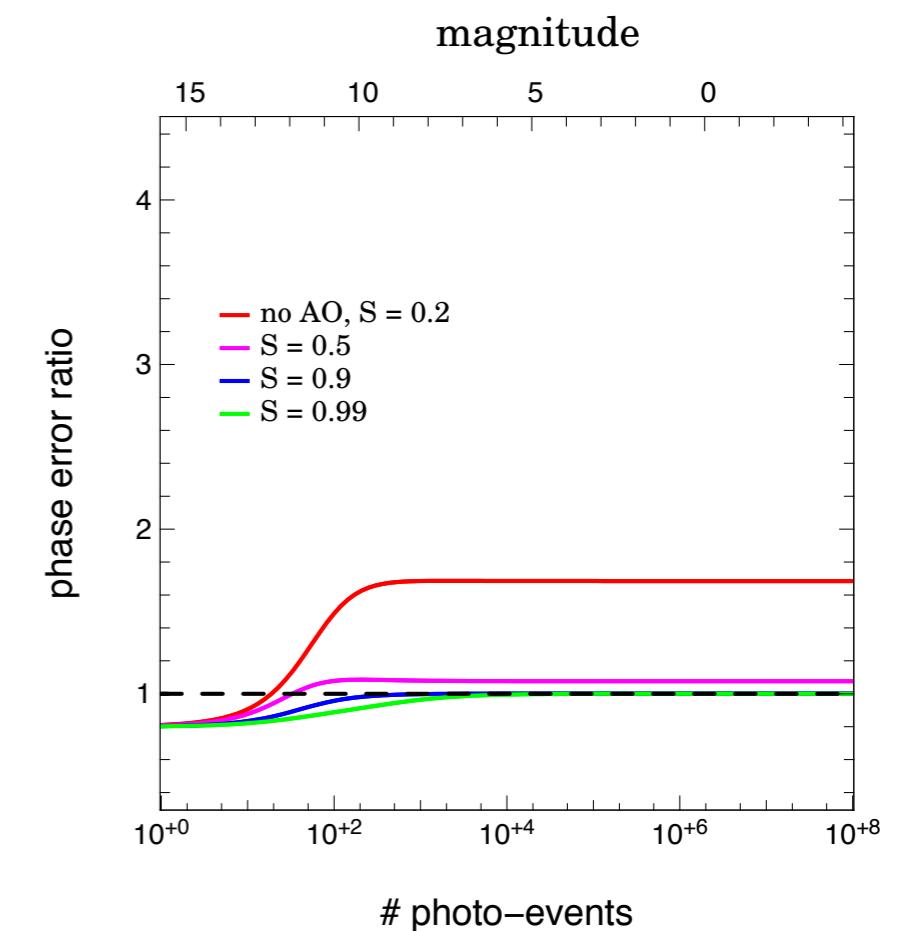
# 1. To filter or not to filter...

Coll. E. TATULLI



Without filtering  
Bulk optics

With filtering  
Fibers  
Integrated optics

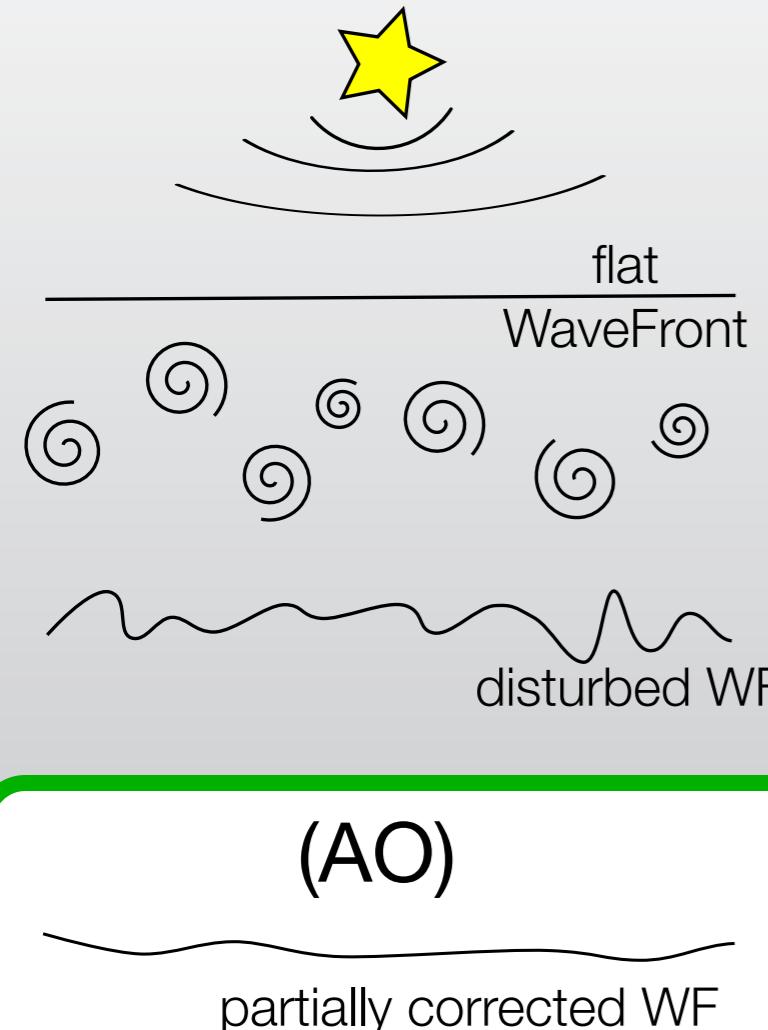


Equivalent  
performances

*Tatulli, Blind et al.  
A&A, 2010*

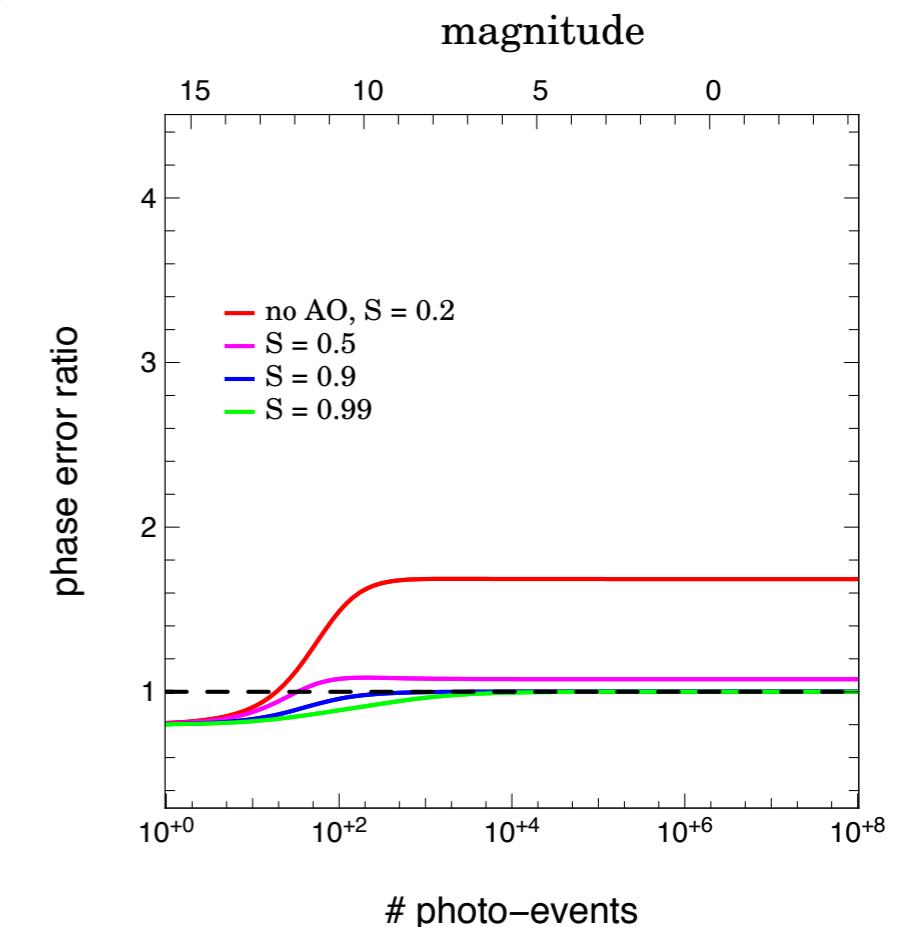
# 1. More important: use an AO!

Coll. E. TATULLI



**AO: gain up to  
3 mag on ATs !!!  
(sensitivity x15)**

Without filtering  
Bulk optics



With filtering  
Fibers  
Integrated optics

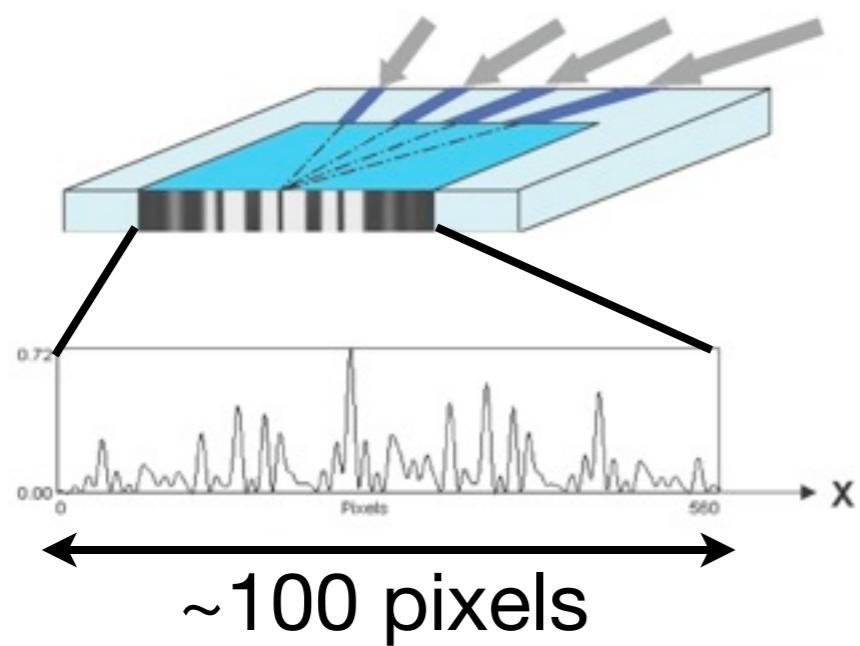
Equivalent  
performances

*Tatulli, Blind et al.  
A&A, 2010*

## 2. Combination concept: the issue

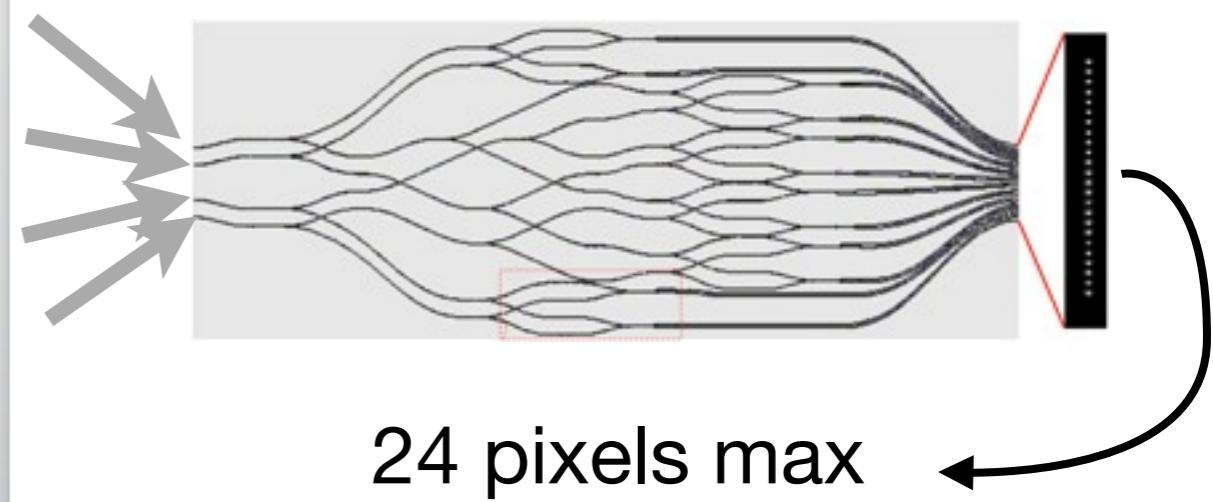
4T case

All-in-one multi-axial



Tarmoul et al. SPIE 2010

Pairwise co-axial

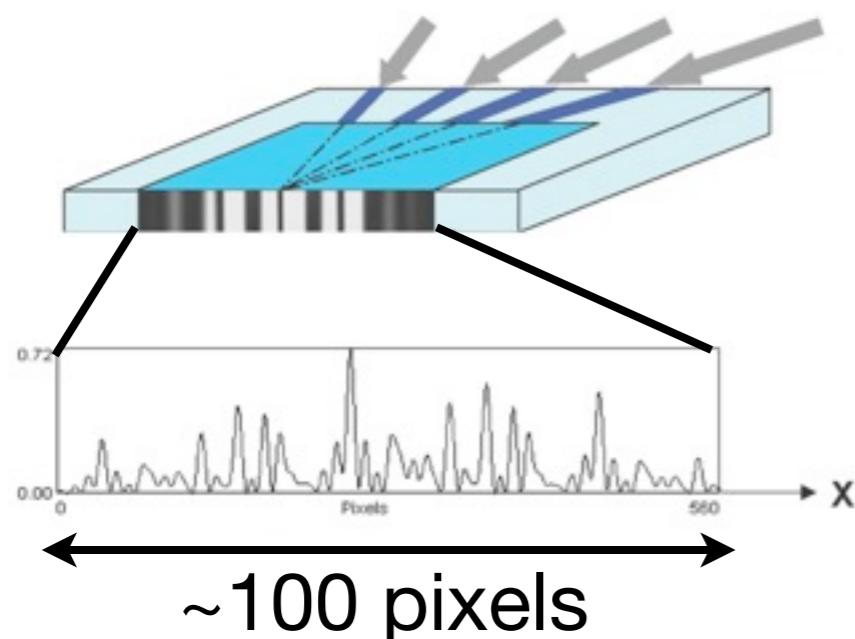


24 pixels max

## 2. Co-axial combination concept

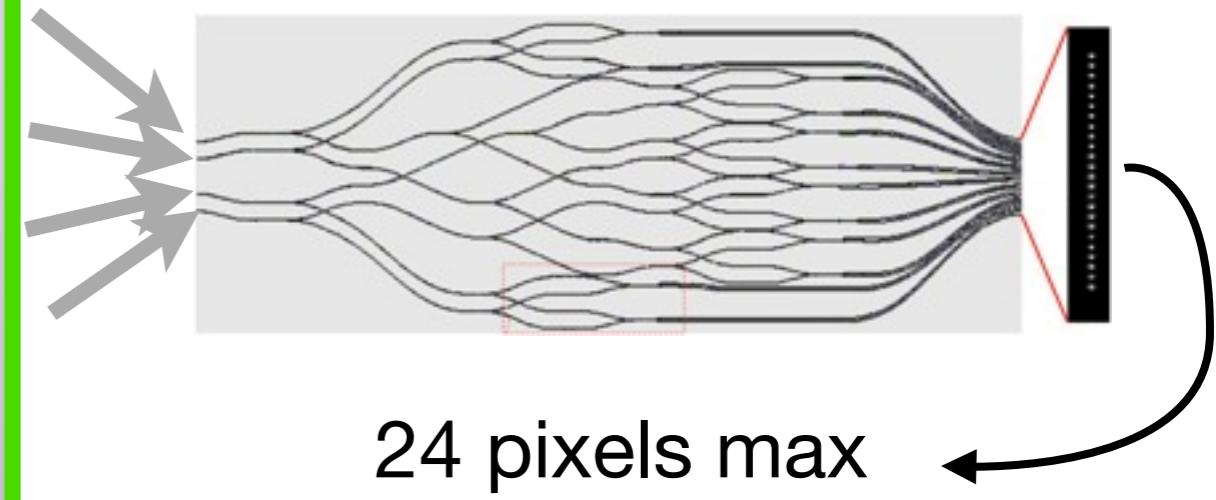
4T case

All-in-one multi-axial



Tarmoul et al. SPIE 2010

Pairwise co-axial

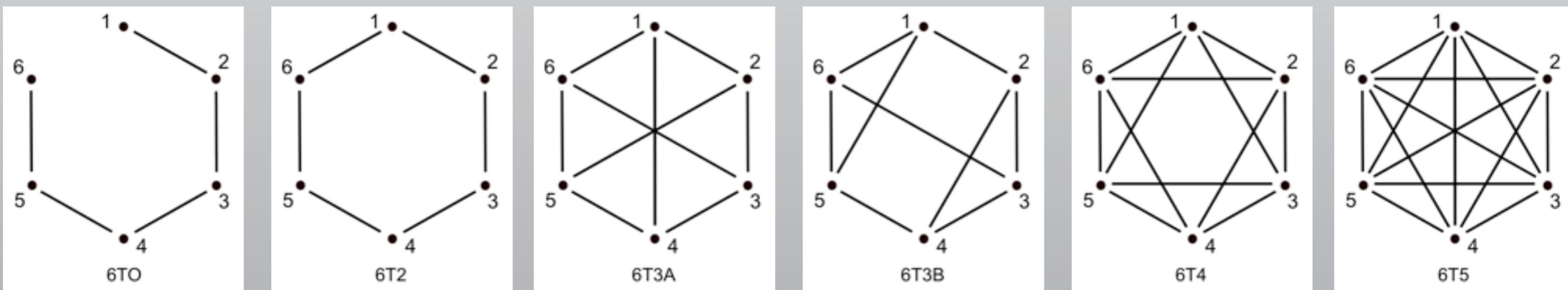
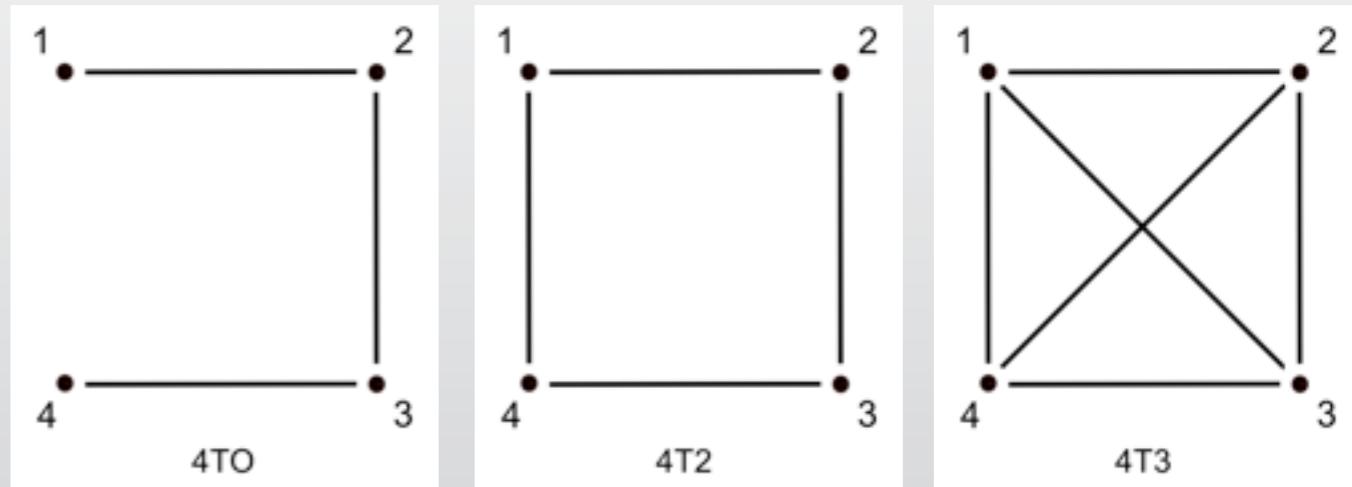


Limitation: **slow and noisy detectors** (HAWAII RG)

→ All-in-one multi-axial handicapped by the high number of pixels

## 2. Co-axial pairwise combination schemes

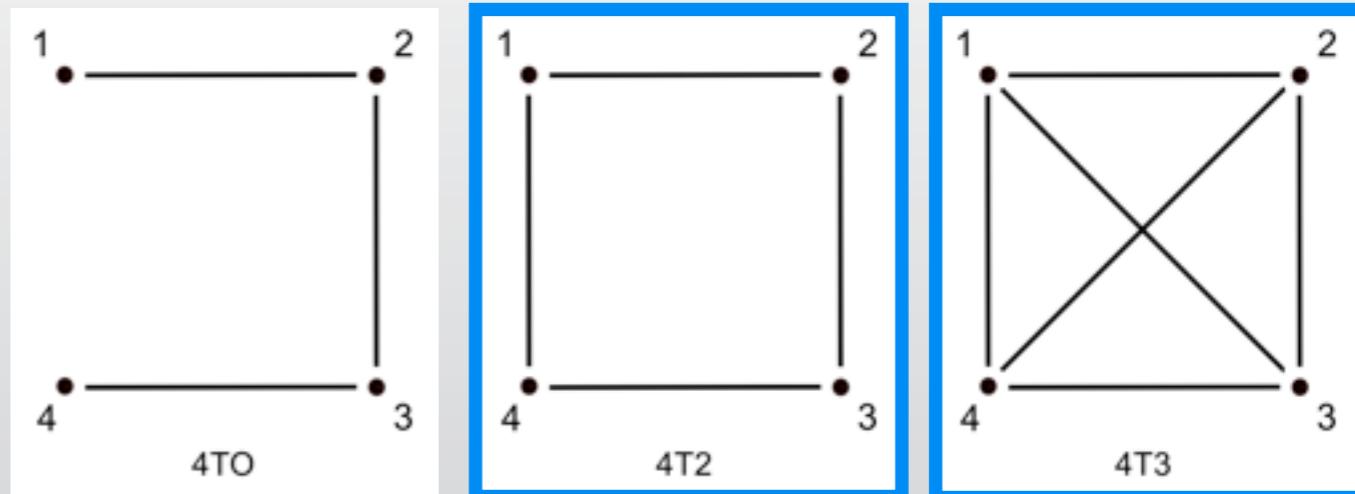
Cophasing N telescopes requires N-1 to  $N(N-1)/2$  baselines



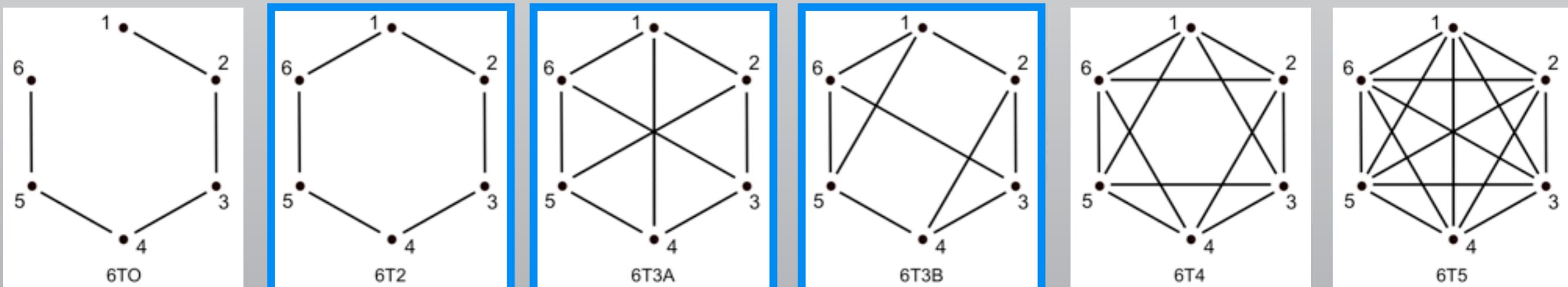
## 2. Co-axial pairwise combination schemes

Cophasing N telescopes requires N-1 to  $N(N-1)/2$  baselines

Precision



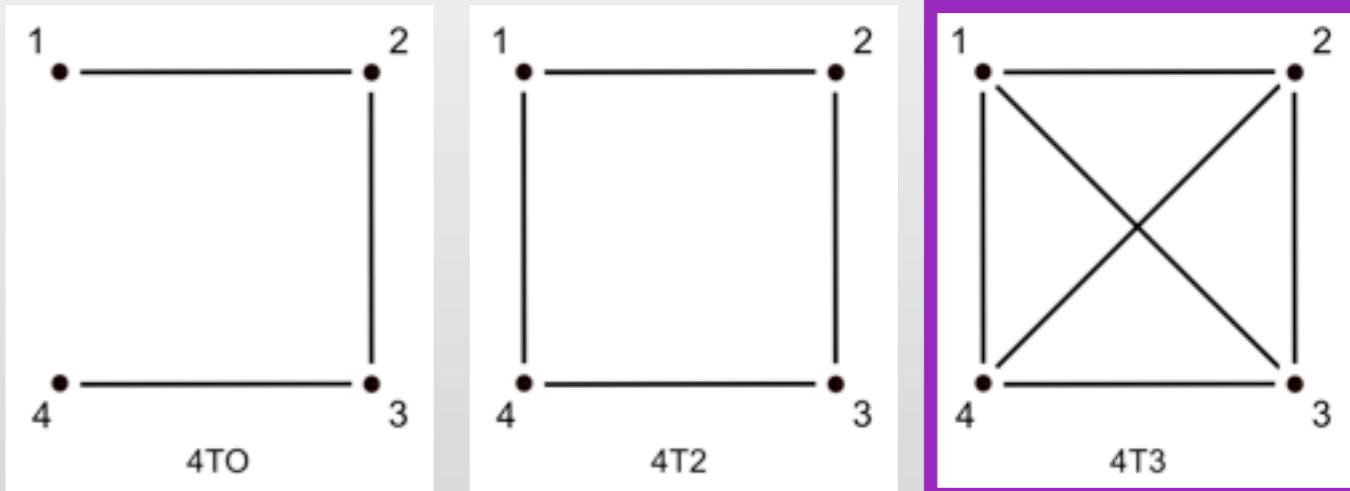
1. Ideal conditions: every baseline equivalent
2. Resolved source: 1 baseline with low visibilities
3. Low flux: several baselines with low flux and visibility



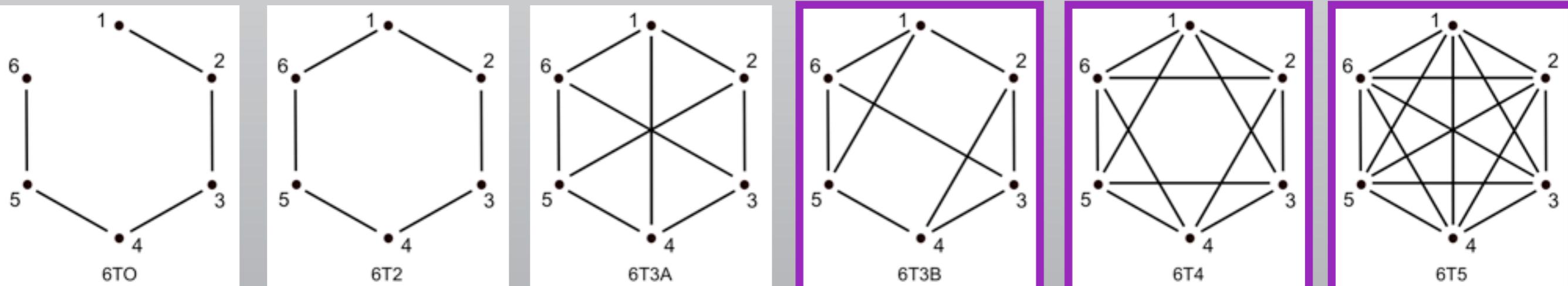
## 2. Co-axial pairwise combination schemes

Cophasing N telescopes requires N-1 to  $N(N-1)/2$  baselines

Precision  
Photometry

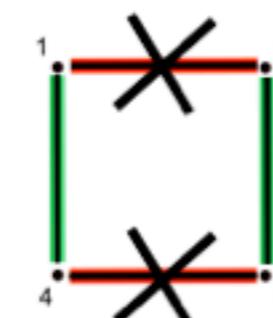
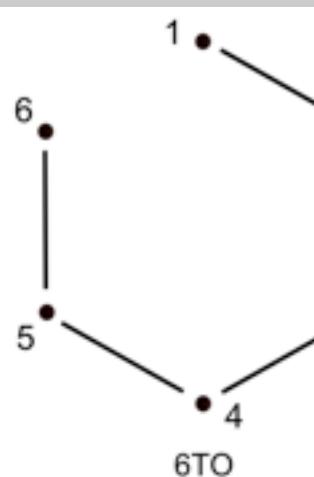
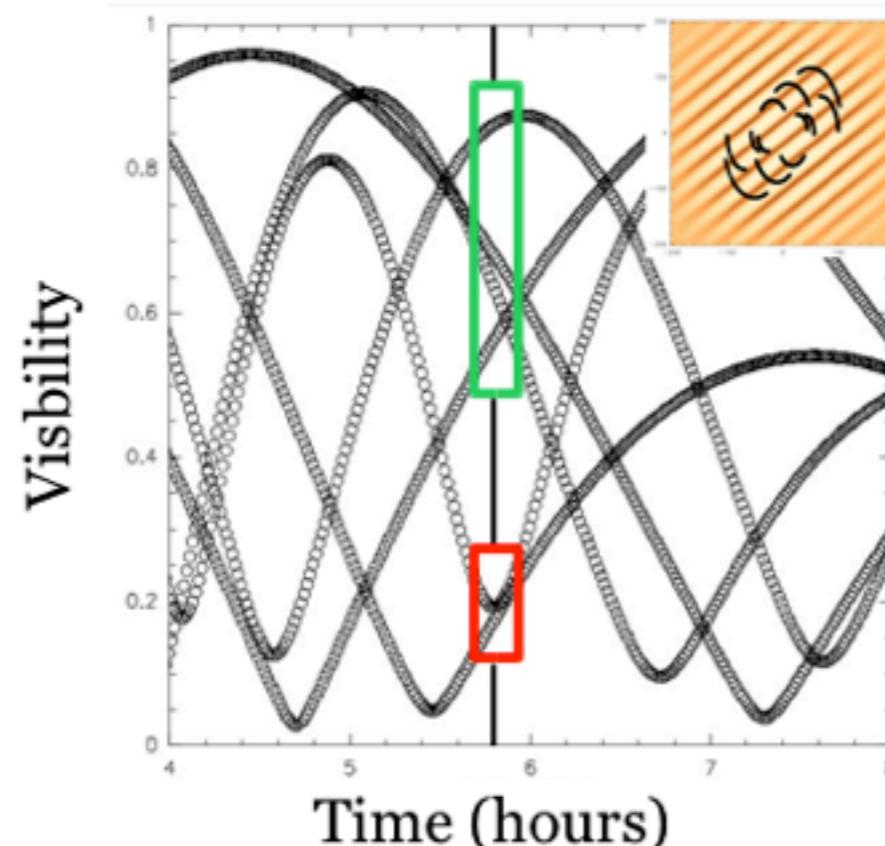
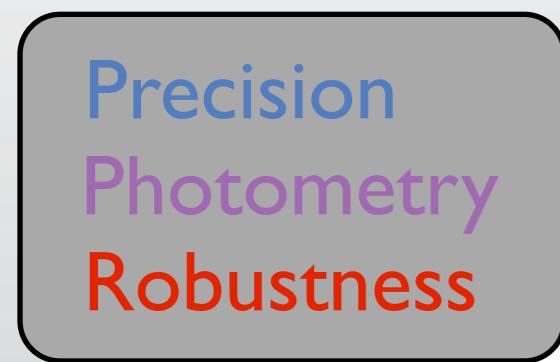


*Extracting the photometry from the fringe signal is only possible for telescopes part of a sub-array constituted of an odd number of telescopes*

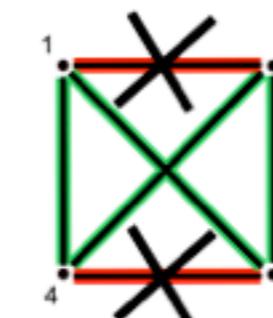


## 2. Co-axial pairwise combination schemes

Cophasing N telescopes requires N-1 to  $N(N-1)/2$  baselines



Partially cophased array



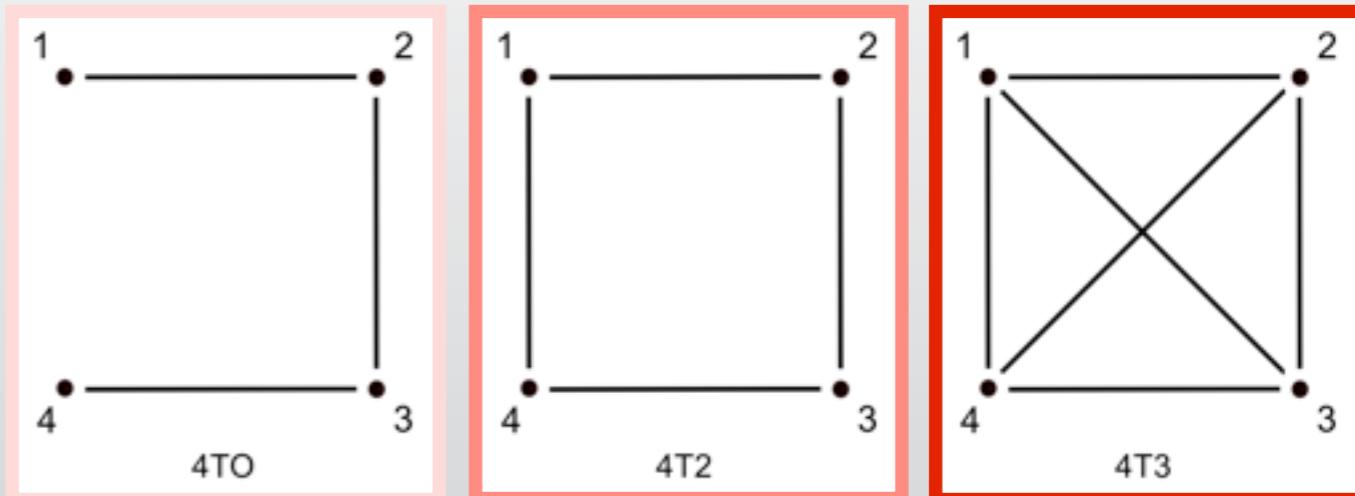
Totally cophased array

More baselines = more robustness

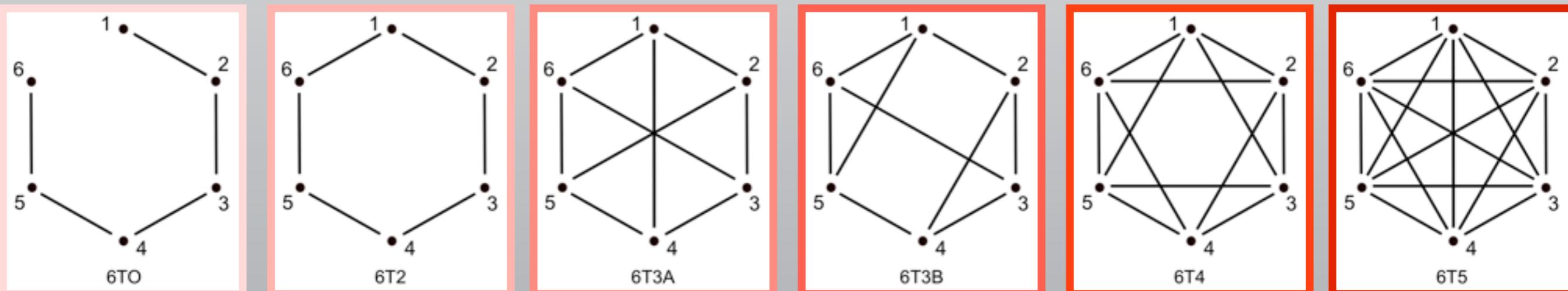
## 2. Co-axial pairwise combination schemes

Cophasing N telescopes requires N-1 to  $N(N-1)/2$  baselines

Precision  
Photometry  
Robustness



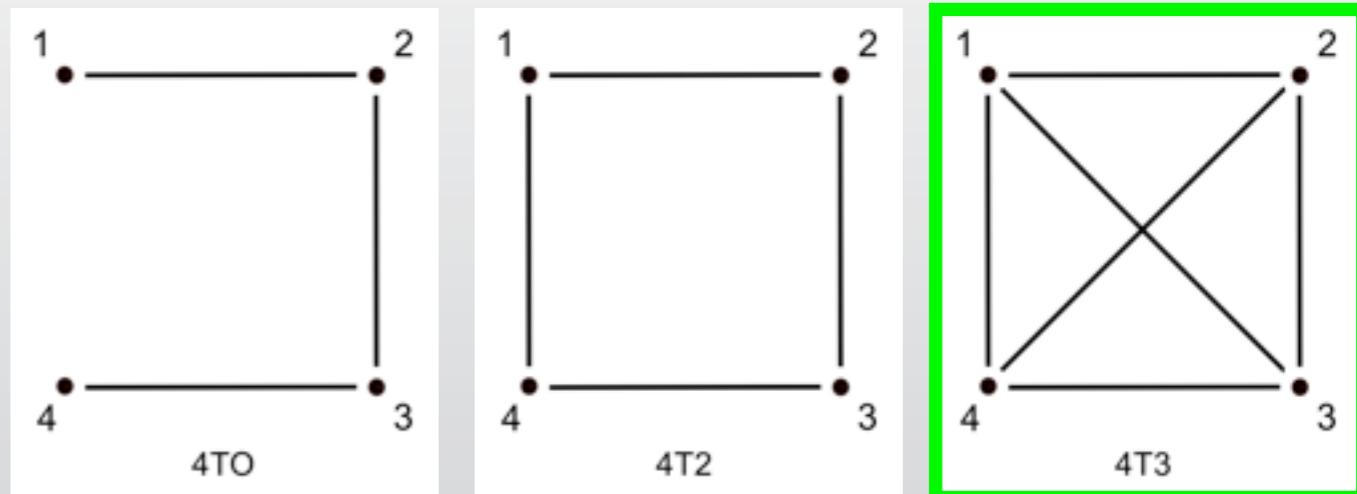
More baselines = more robustness



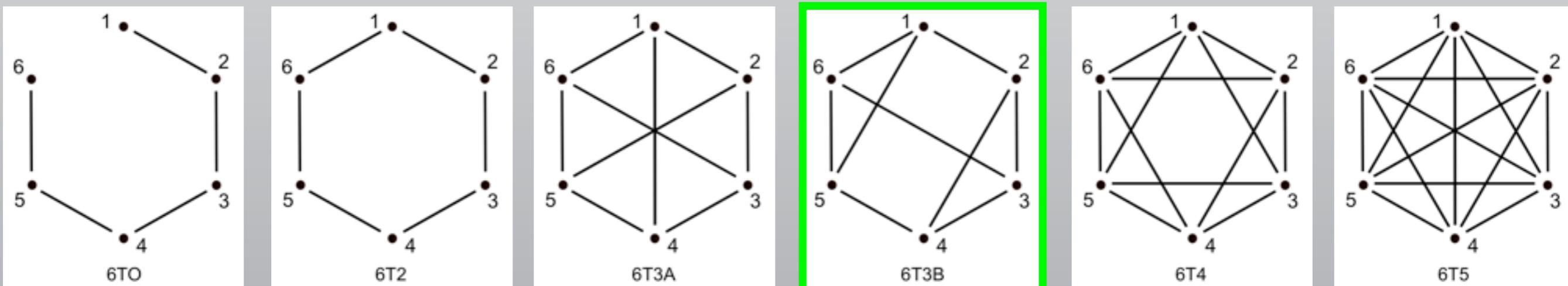
## 2. Co-axial pairwise combination schemes

Cophasing N telescopes requires N-1 to  $N(N-1)/2$  baselines

Precision  
Photometry  
Robustness

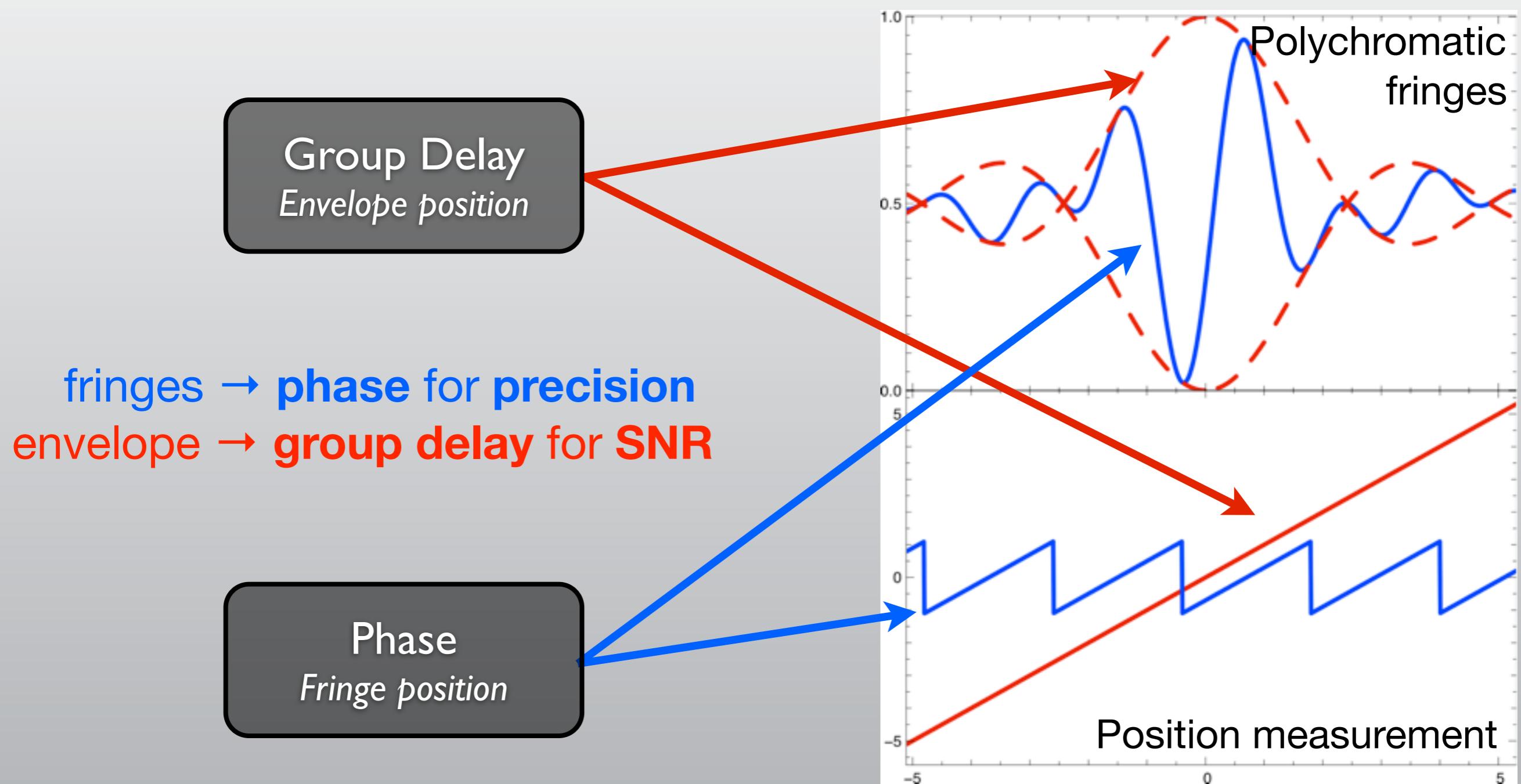


*Blind et al, A&A, 2011*



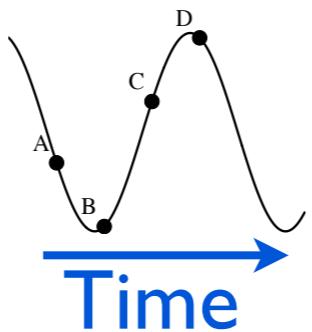
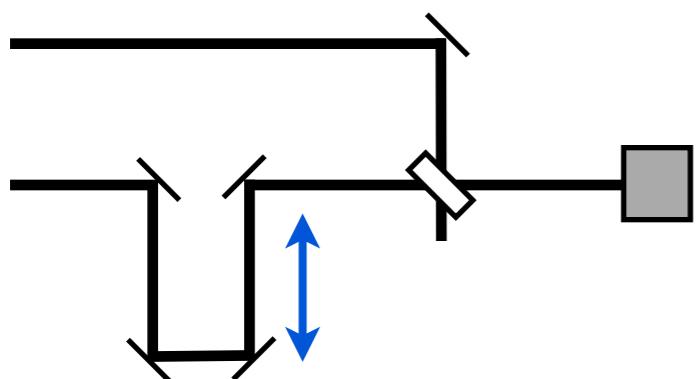
### 3. Measuring the fringe position

In practice, 2 different fringe positions:



# 3a. Measuring the phase: issue

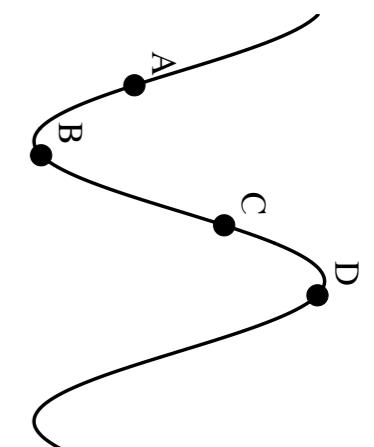
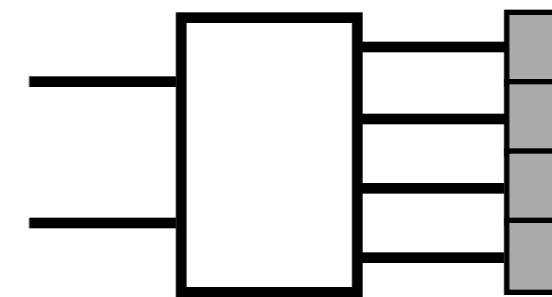
Temporal



Delayed measurements  
→ disturbances between samples

Ex: FINITO, CHAMP

Static



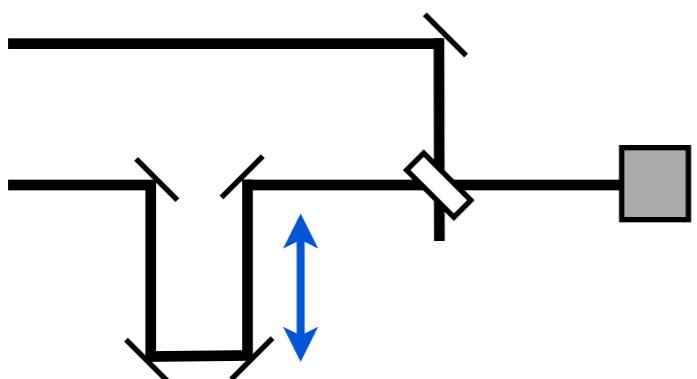
Simultaneous measurements  
→ each sample is equivalent

Ex: PRIMA, GRAVITY

Fundamental noises (photon, RON, etc.): strictly equivalent concepts !

# 3a. Measuring the phase: be static!

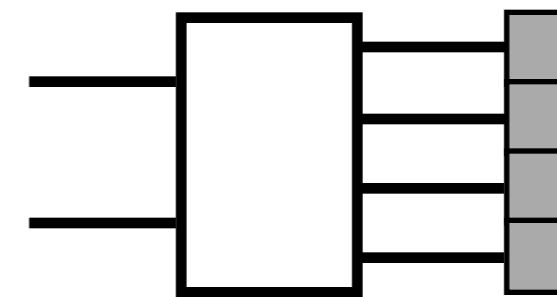
Temporal



Delayed measurements  
→ disturbances between samples

Ex: FINITO, CHAMP

Static



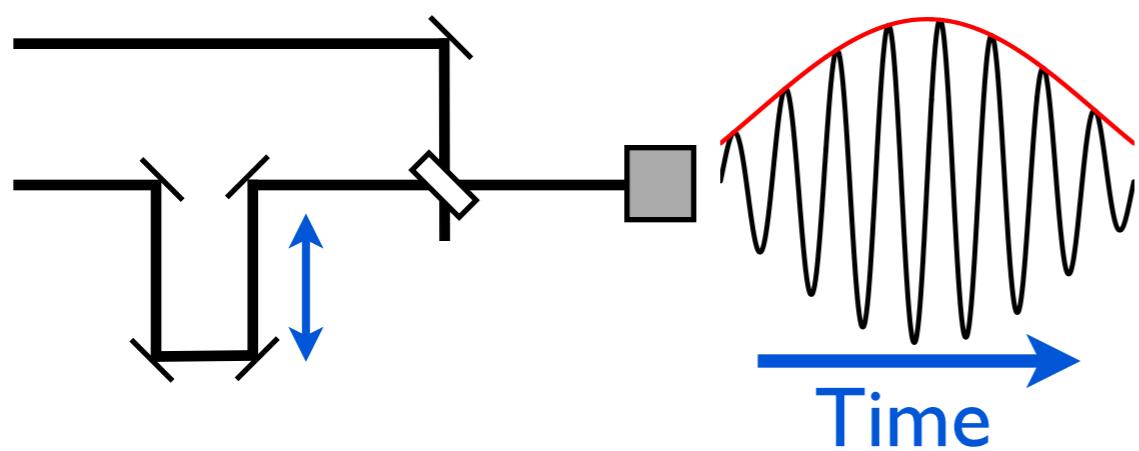
Simultaneous measurements  
→ each sample is equivalent

Ex: PRIMA, GRAVITY

Static estimator far less sensitive to  
external disturbances

# 3b. Measuring the Group Delay: issue

Temporal: broadband fringes

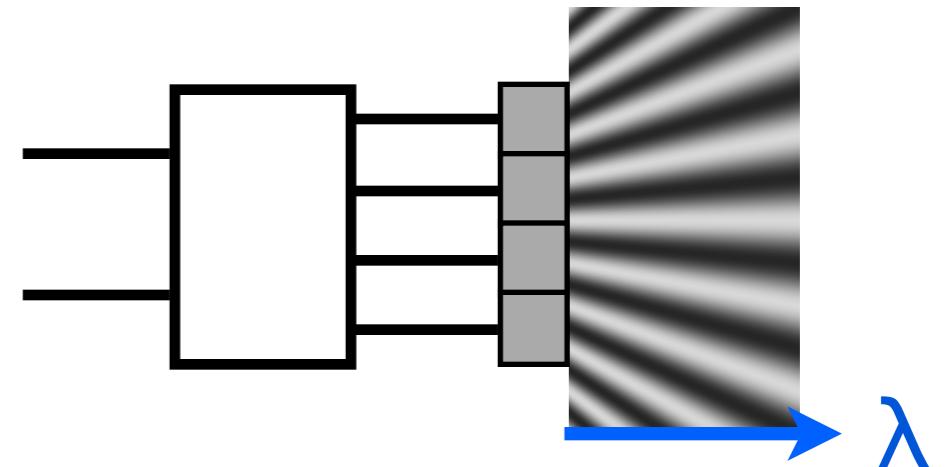


Delayed measurements

→ disturbances between samples

Ex: FINITO, CHAMP

Static: dispersed fringes



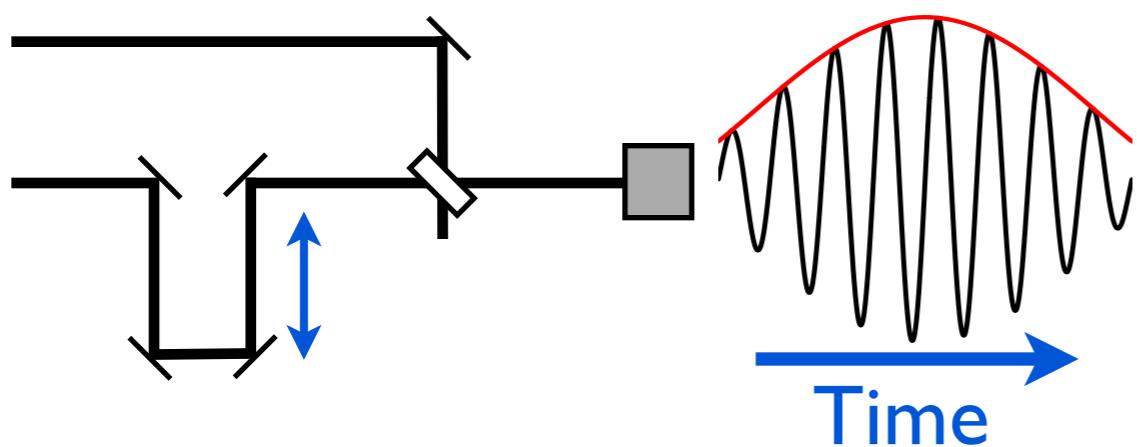
Simultaneous measurements

→ each sample is equivalent

Ex: PRIMA, GRAVITY

### 3b. Measuring the Group Delay: be static!

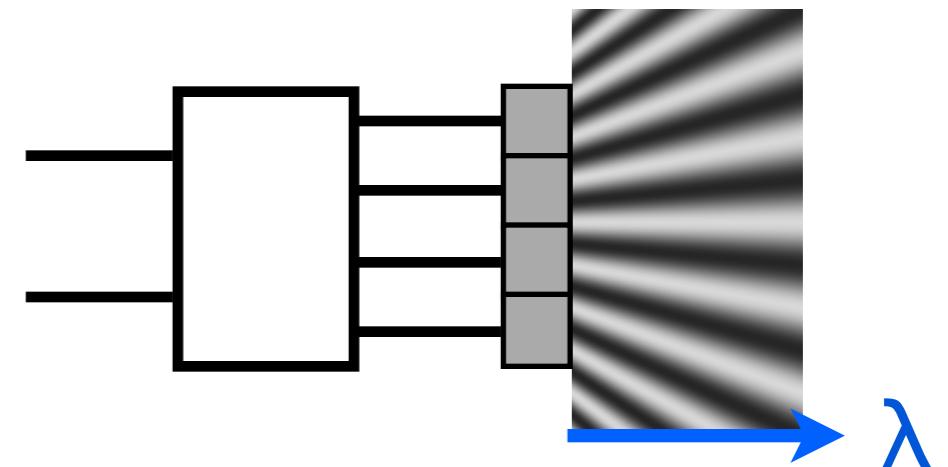
Temporal: broadband fringes



Delayed measurements  
→ disturbances between samples

Ex: FINITO, CHAMP

Static: dispersed fringes

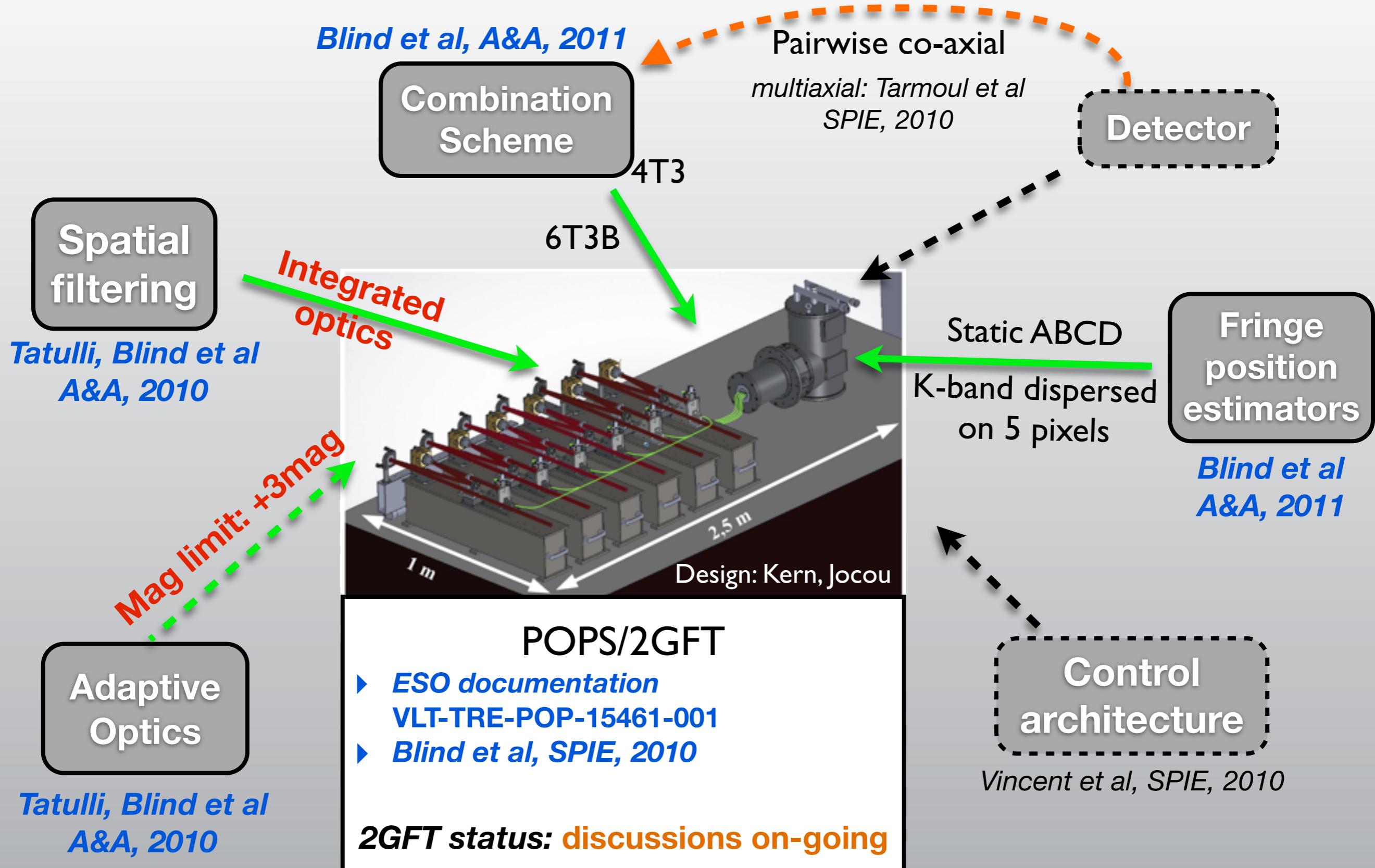


Simultaneous measurements  
→ each sample is equivalent

Ex: PRIMA, GRAVITY

Static estimator far less sensitive to  
external disturbances

# Result: the POPS concept



# Result: expected POPS performance

End-to-end simulations of O. Absil (*details in Blind et al, A&A, 2011*)

4T concept

Limiting magnitude	AT	UT
Fringe tracking	~ 7 <span style="color:red">★</span>	~ 9
Fringe detection	~ 9	~ 11 <span style="color:green">★</span>

Fringe tracking: SNR>4, 95%  
(dit=10ms)

Fringe detection: SNR~4  
(dit=25ms)

★ FINITO & ATs: fringe tracking limiting magnitude = **5.5**  
3T - 2 baselines (open scheme); temporal estimators.

★ PRIMA & UTs: fringe detected at K=11.7  
2T; static estimators.

Limiting magnitude -1mag from excellent to bad conditions

# Presentation outline

An introduction to interferometry

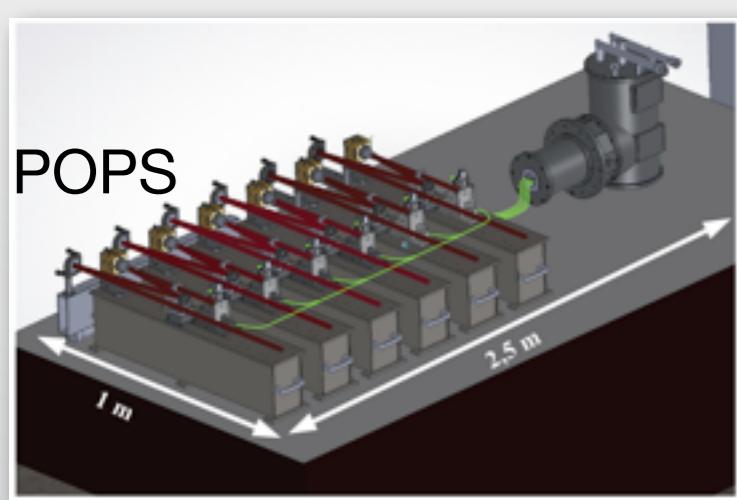
**PART I. Study of interacting binaries**

**PART II. Fringe trackers for imaging instruments**

**Conclusions and perspectives**

# Summary

## System analysis



- Interest of spatial filtering
- High benefit of AO
- Benefit of static estimators
- Optimal combinations

*Blind et al, SPIE, 2010*

*Tatulli, Blind et al A&A, 2010*

*Blind et al, A&A, 2011*

## Signal processing Data reduction (not presented)



- Signal processing for static ABCD
- Bench validation



## Data analysis & modeling



- Potential of interferometry for interacting binaries
- Interest of imaging

18/03/2011  
4UTs & PIONIER



*Blind et al, A&A, accepted*

# Perspectives

## Interacting binaries

**Important potential of interferometry for interacting binaries** with model-independent imaging:

- Wind, molecular layers around giant → spectro-interfero
- Precise morphology (tidal distortions, etc) → imaging
- Detection of accretion disks → visible, longer baselines
- Very compact systems → astrometry



### Future work:

- ▶ Deeper studies of SS Lep with H. Boffin
- ▶ Survey @ VLTI proposed  
with T. Verhoelst, M. Hillen et al.

[Wish list for the VLTI](#): limiting magnitude → **AO !!!**, fringe trackers  
longer baselines

# Perspectives

## Fringe tracking

- ▶ Rapid & low noise IR detectors:
  - Sensitivity gain ~1mag
  - Multi-axial solution to reconsider: simpler, 6T ~optimal for 4T
- ▶ Off-axis fringe tracking (PRIMA, GRAVITY) → blind integration
- ▶ Predictive algorithms, real-time characterization of atmosphere (?)



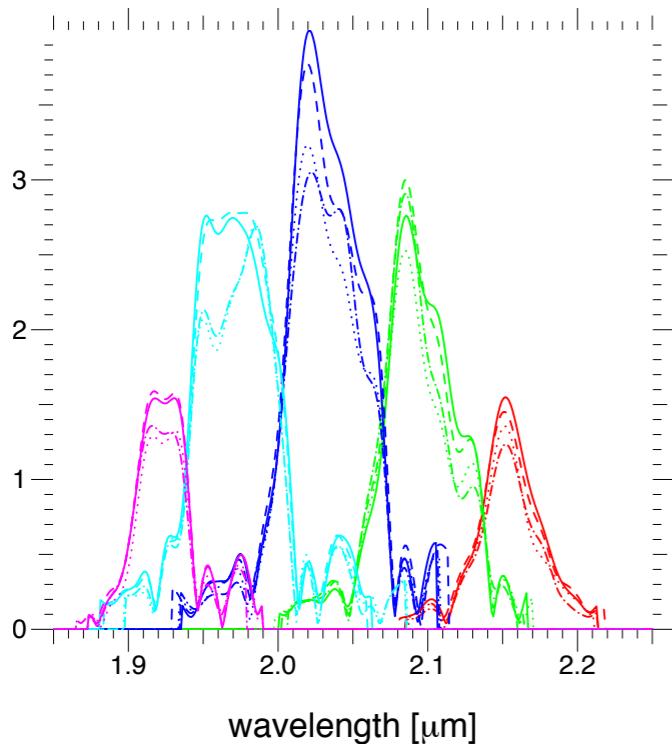
VLTI in 2025 will really need  
a good fringe tracker...



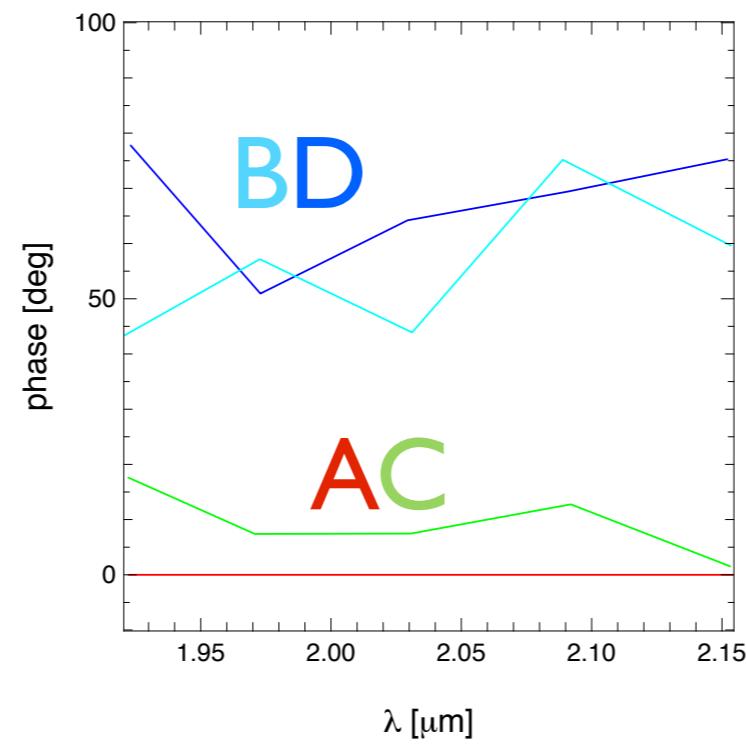


# Laboratory fringes

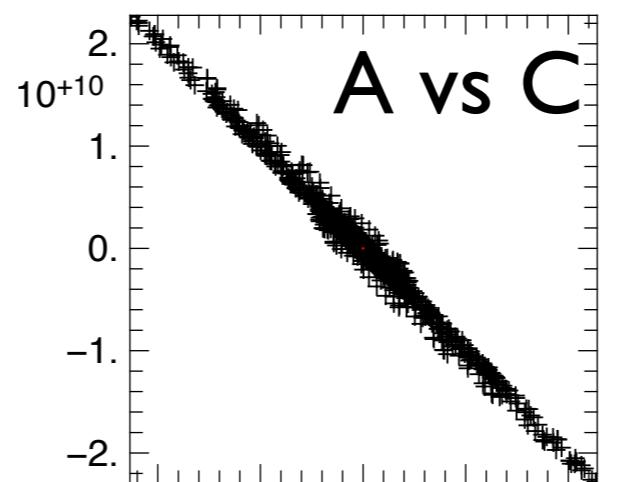
Realistic data reduction for IOC: compensating for the defaults  
Validation on an interferometric testbench



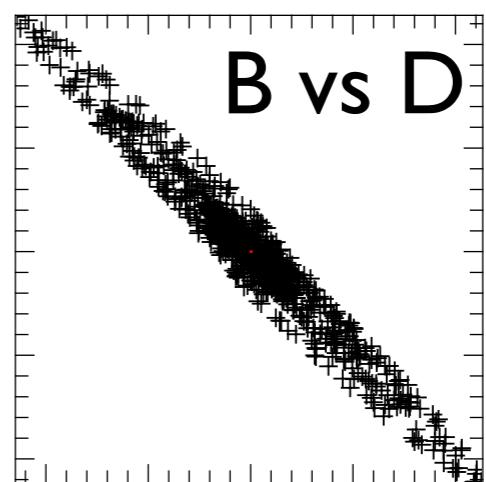
Calibration



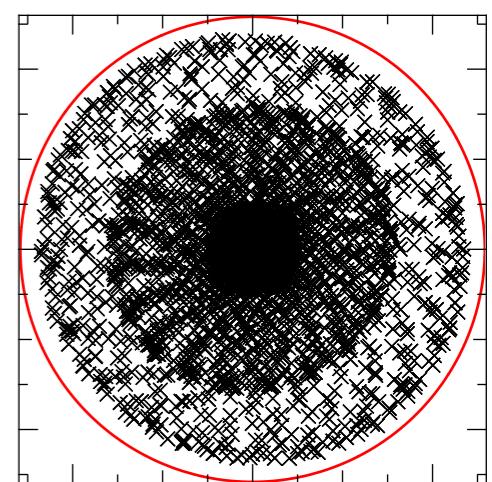
K-band 2T-ABCD IOC



A vs C



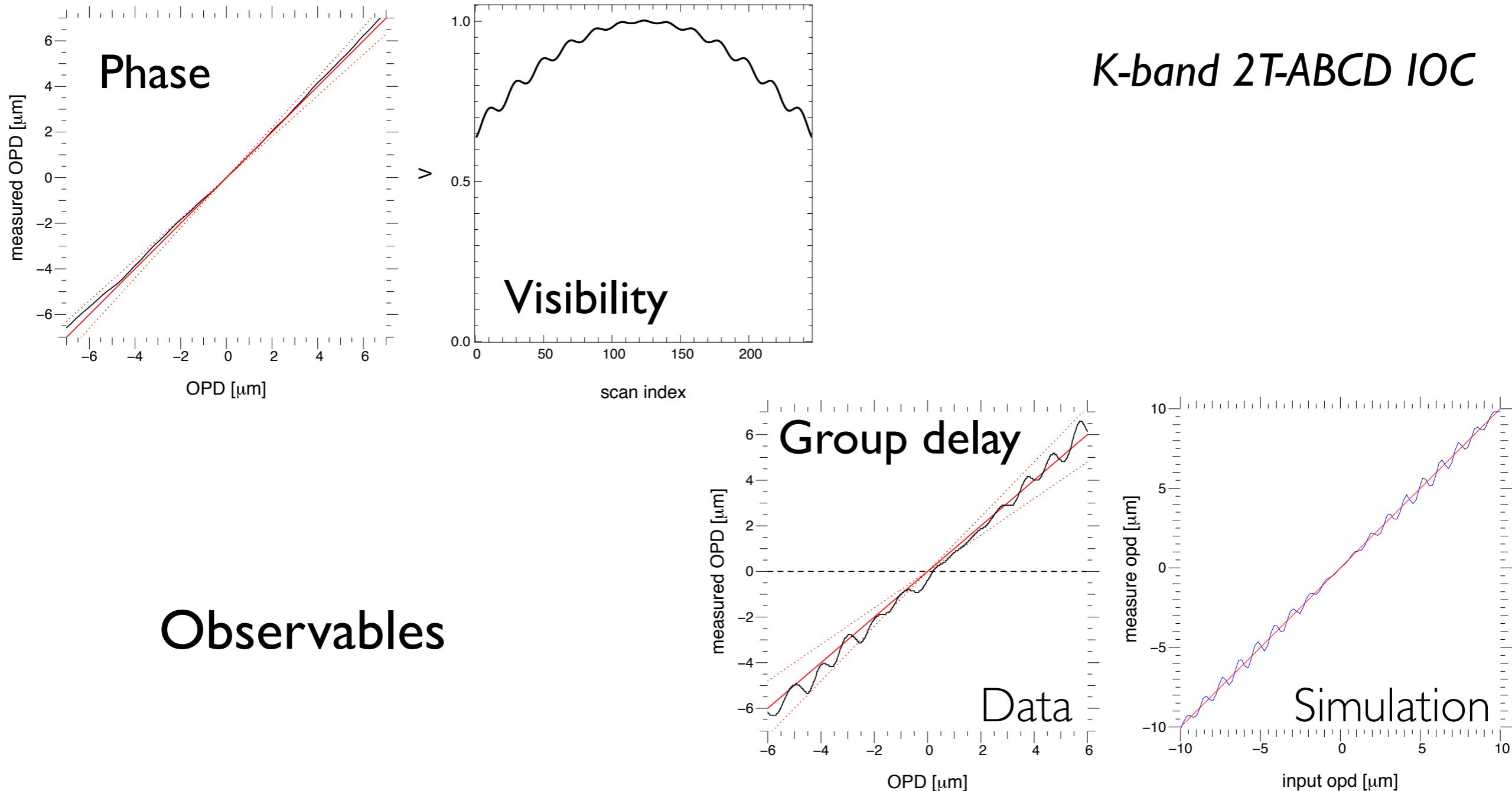
B vs D



AC vs BD

# Laboratory fringes

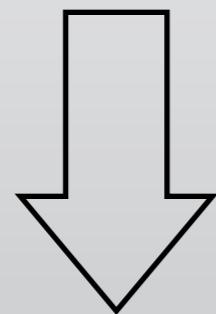
Realistic data reduction for IOC: compensating for the defaults  
Validation on an interferometric testbench



# SS Lep: Results from Verhoeilst et al 2007

## VINCI observations:

- Single baseline, no phase information
- Limited number of spatial frequencies  
+ position angle 55° to 90°
- 1-year obs VS binary period ~260d !



Not possible to disentangle  
the M giant signature  
from the binary one in visibilities

