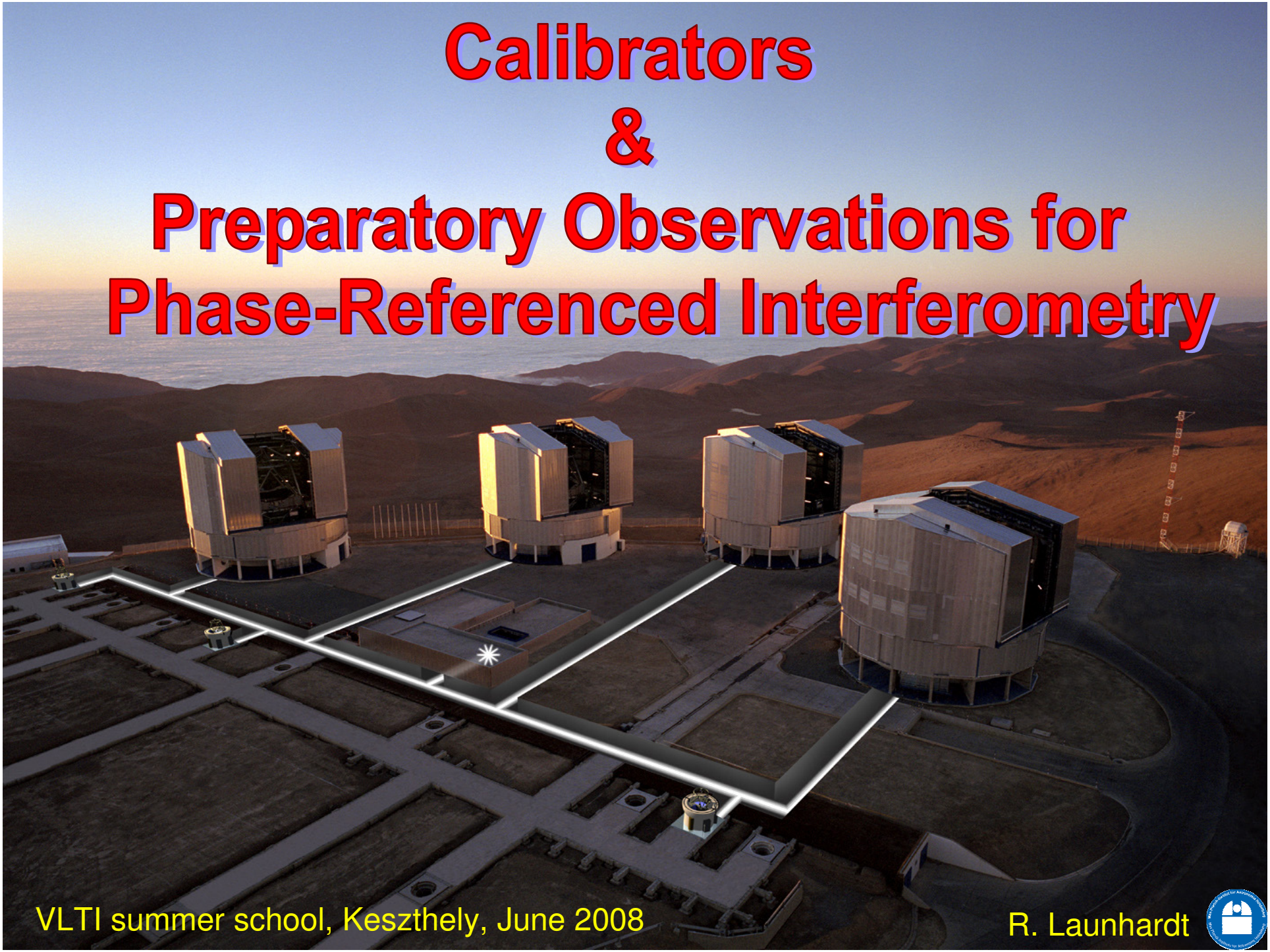
Calibrators & Preparatory Observations for Phase-Referenced Interferometry



VLTI summer school, Keszthely, June 2008

R. Launhardt

Outline:

1. **Calibrating interferometry data**

2. **Preparatory Observations**

3. **Example:** The ESPRI preparatory program

Calibrators

Calibration

- *„The Transformation of observables into physically meaningful quantities“*

Rember this for the rest of your scientific career:

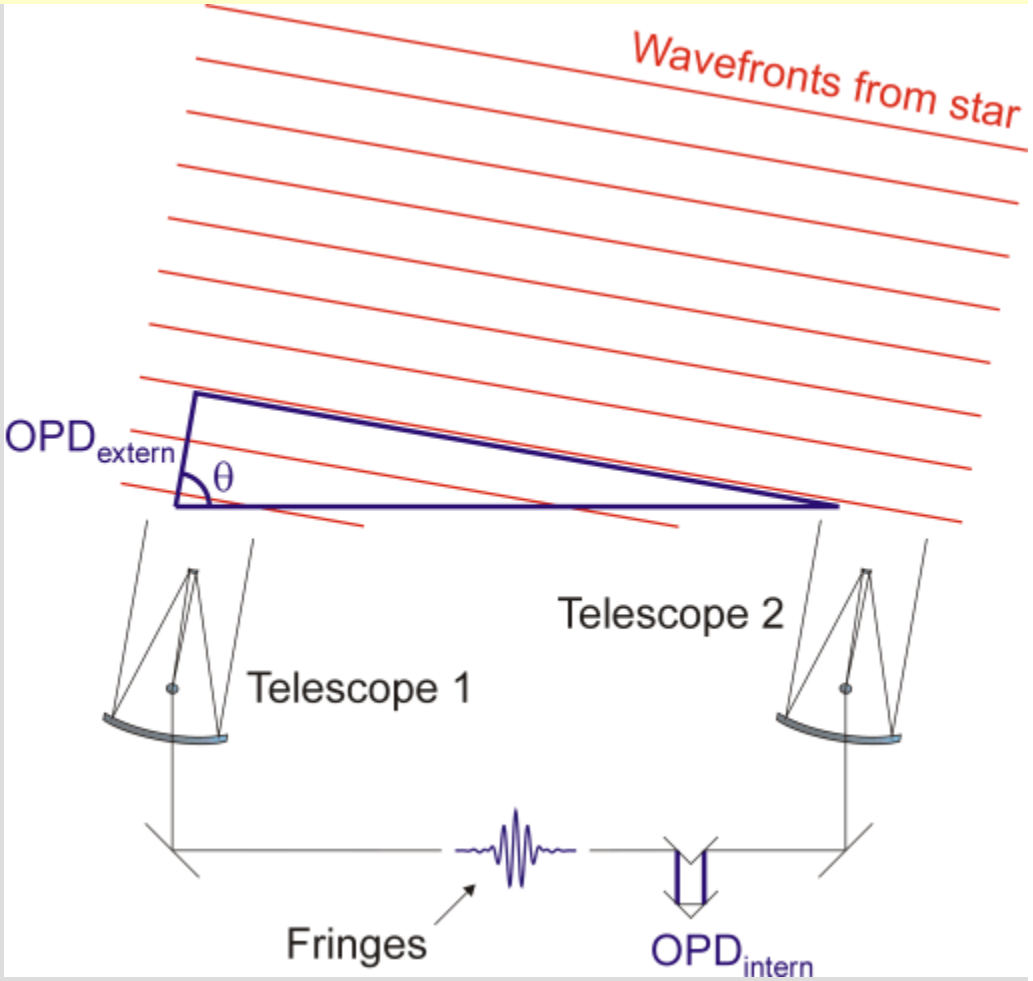
- **Data with insufficient calibration are worse than no data, because you have wasted time!**

- **In case of doubt, take a calibrator more!**

Interferometric observables

Interferometer:

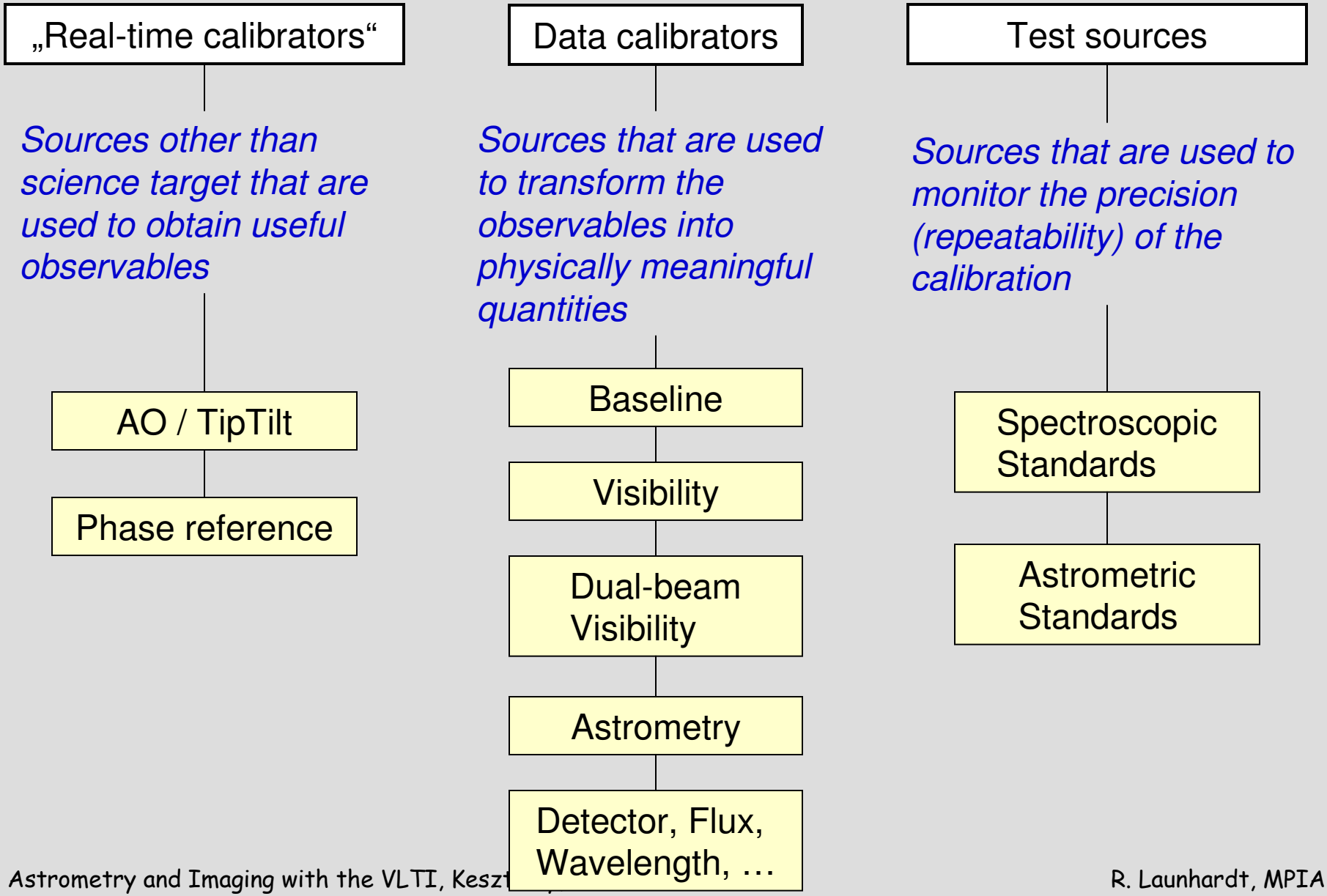
- ***samples the radiation field*** from a source at two or more points in space simultaneously
- Combines the sampled wavefront parts in a coherent way
- measures the ***Fourier transform*** of the sky brightness distribution



Observables:

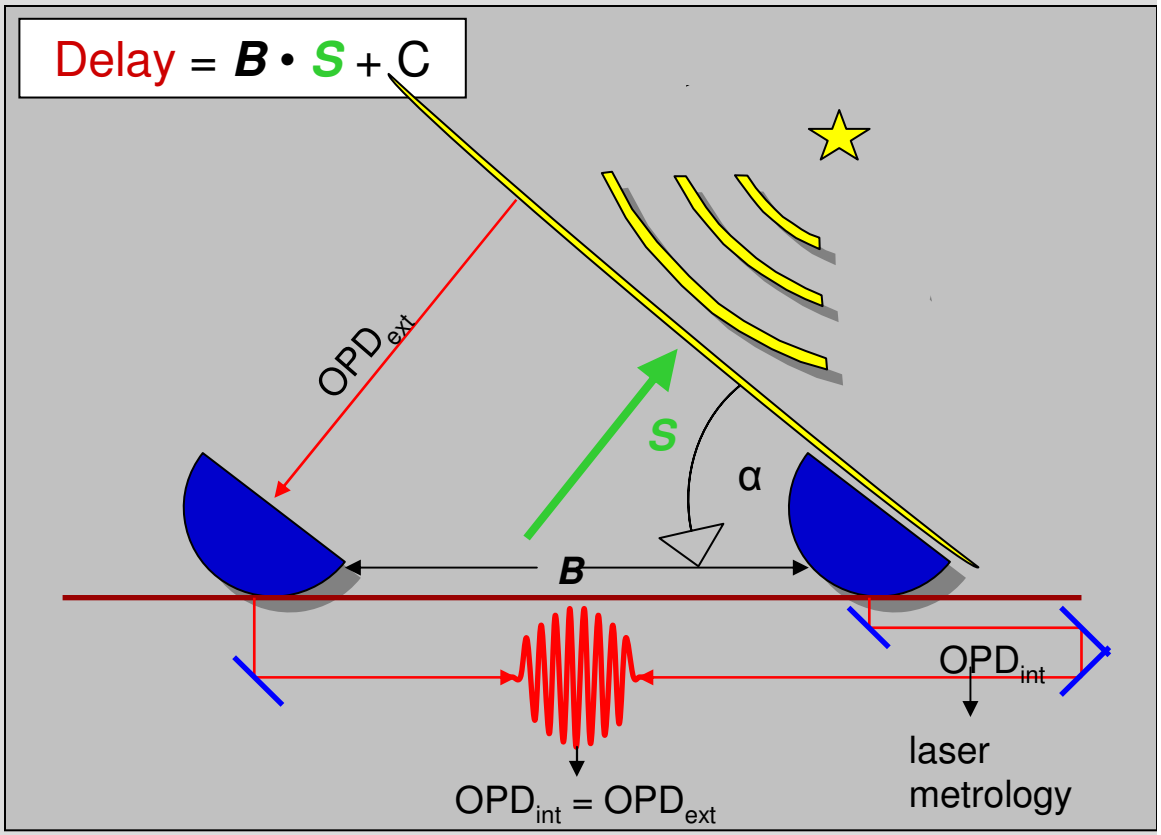
1. ***Complex visibility*** (amplitude and phase) from intensity modulations on detectors (*Fringes*)
2. ***Geometric delay*** from metrology system (*OPD*$_{intern}$)

Calibrators for interferometry



Calibrators: Baseline

- Baseline ties delay to source position
- Derived by observing stars with accurately known positions distributed over the sky
- Usually done by ESO
- Can be interspersed with science obsevations
- Science targets may be also used for baseline calibration



Calibrators: Visibility

- Measure the ***interferometer transfer function***, using sources with “known” properties.

- Anything can be used as calibrator *(as long as we get enough photons)*

- Make life easier: choose calibrators whose ***properties are simple***! => “point sources” (single stars, unresolved)

- More details: A. Boden => Goutelas school
  M. Wittkowski => Torun school

Calibrators: Visibility

How to find a good calibrator?

- Establish calibrator ***criteria*** => angular diameter *(small)*
  => brightness *(bright or equal to source)*
  => location *(near source)*
- ***Angular diameter***
  => from previous high resolution measurements
  (CHARM: Richichi et al. 2005, A&A, 431, 773)
  => Catalogs based on spectrophotometric measurements
  (Cohen 1999, Borde 2002, Merand 2005, MIDI catalog)
  => Find spectrophotometry in literature and derive angular diameter.

- ***Tools:*** => CalVin (ESO)
  => Aspro and SearchCal (JMMC: http://www.mariotti.fr)
  => getCal (MSC)

Calibrators: Dual-beam visibility

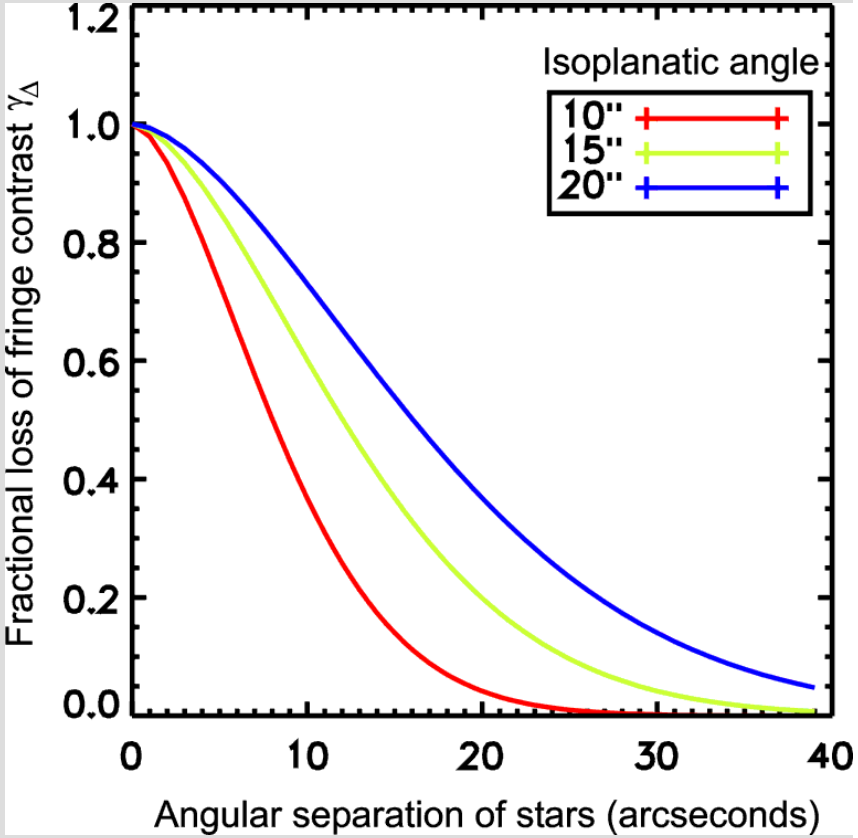
- **Wavefront distortions decorrelate** with increasing angular separation, due to **atmospheric turbulence**

  => visibility loss

- **Isoplanatic (Isopistonic) angle θ_0 :** Maximum angular separation for which the wavefront distortions are correlated

- θ_0 depends on λ, telescope size, atmospheric conditions (r_0, h_{turb})

- Paranal, K-band, ATs:
  → **θ_0 ~ 10 – 20 arcsec**



- **Potential calibrators:** visual binary stars with different angular separations (WDS: http://ad.usno.navy.mil/wds/)

Calibrators: Astrometry

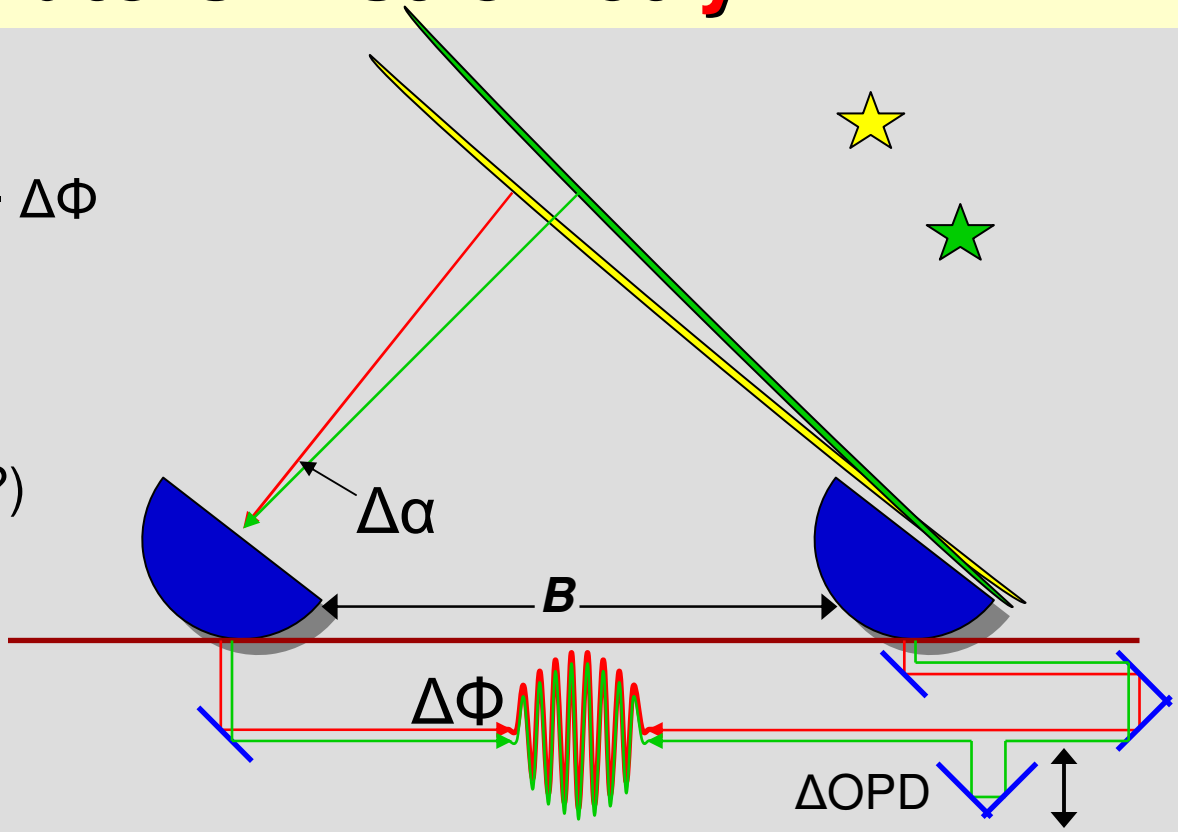
- $\Delta d = \boldsymbol{B} \bullet \Delta \boldsymbol{S} + C$

  $= \Delta OPD_* + (\lambda / 2\pi) \cdot \Delta\Phi$

- But:

  => $OPD_* \neq OPD_{Laser}$

  => $\Phi \rightarrow$ Delay (which λ?)



- **Differential measurements => relaxed calibration requirements**
- But, how to calibrate or verify the **absolute astrometric „plate scale“?**
- **Problem:** no instrument has measured yet with microarcsecond accuracy
- Possibility: **Transiting RV planets**

(known inclination => known astrometric signature)

Real-time calibrators: AO / TipTilt

- VLTI **UTs**: MACAO V < 17 mag, Δ < 57 arcsec

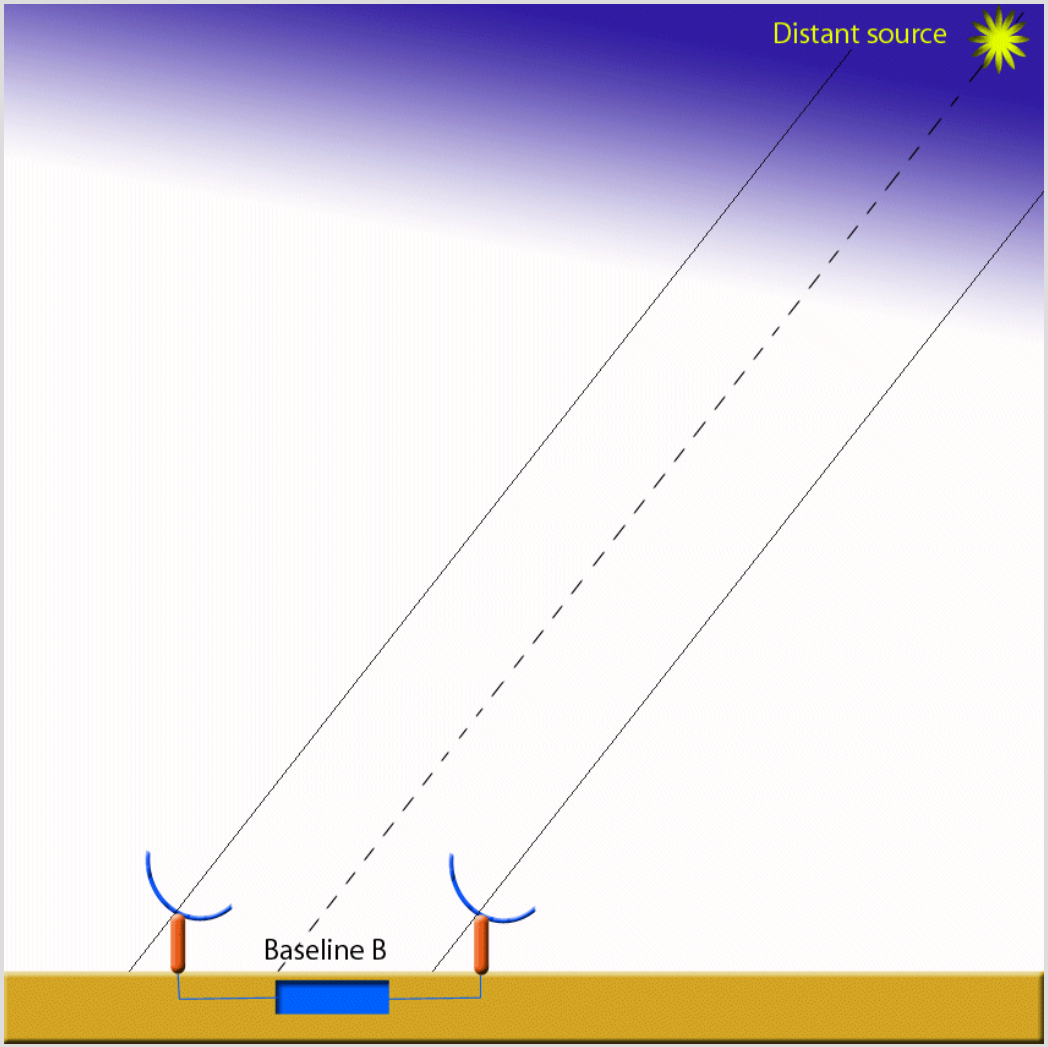
  (with FINITO: V < 13 mag, Δ < 15 arcsec)

- VLTI **ATs**: STRAP TipTilt V < 13 mag, Δ < 60 arcsec

- With PRIMA => use fringe tracking star

  (Planet search target stars: V ≈ 7 – 12 mag)

Real-time calibrators: Phase-reference stars



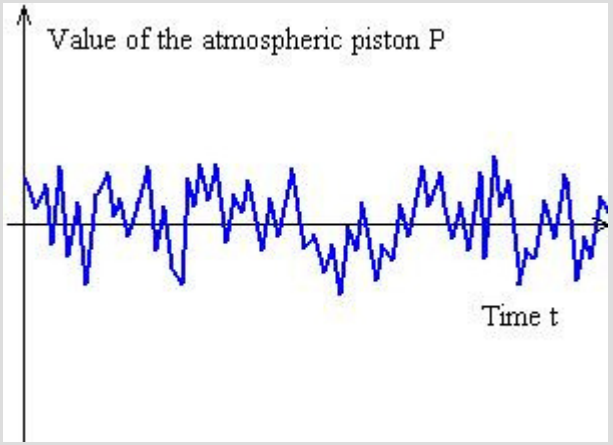
Atmospheric turbulence

⇩

Piston fluctuations

⇩

Measured position vector ***S*** fluctuates



But:

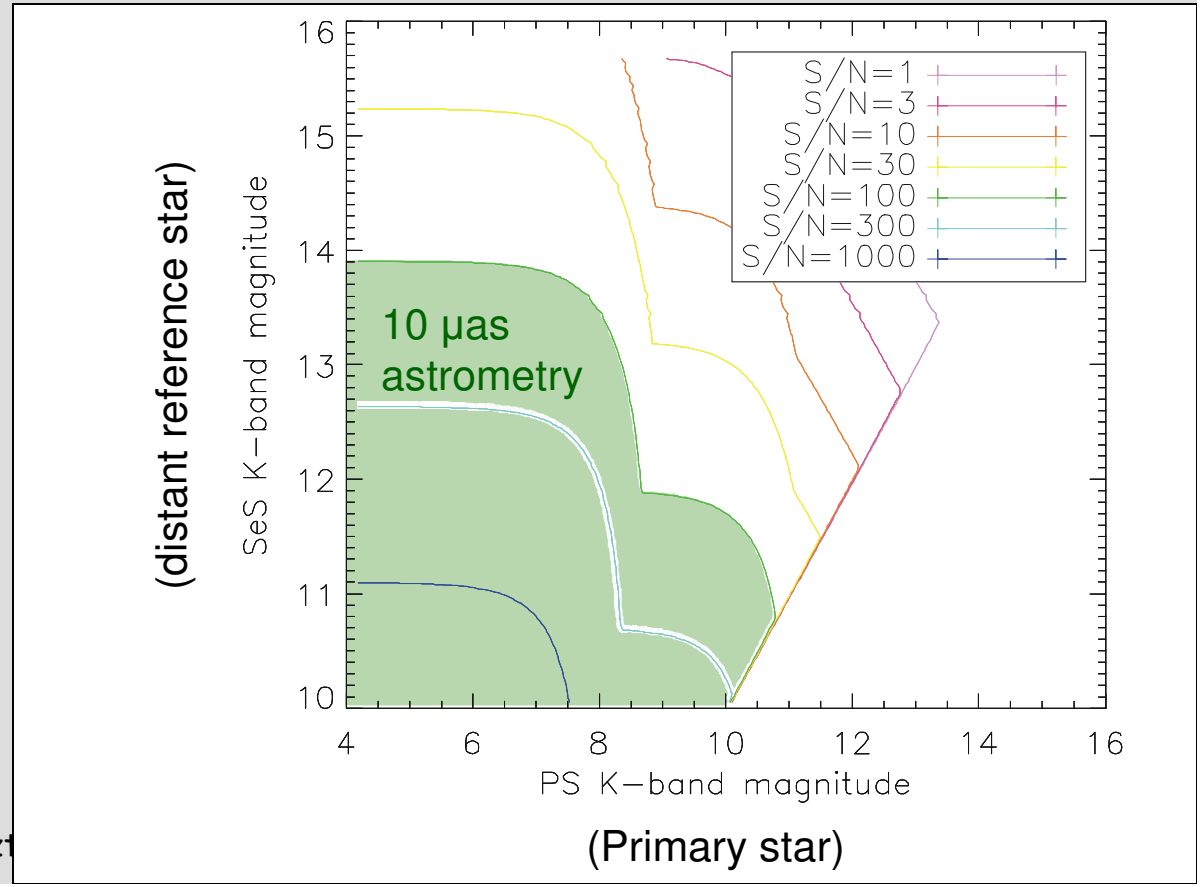
Fluctuations are correlated within the isopistonic angle

Real-time calibrators: Phase-reference stars

=> Need phase reference stars within the isopistonic angle
(10 – 20 arcsec for ATs in K-band)

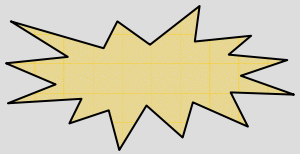
⇒ ***There is no standard list.***
Each target needs its own reference star!

Brightness requirement:



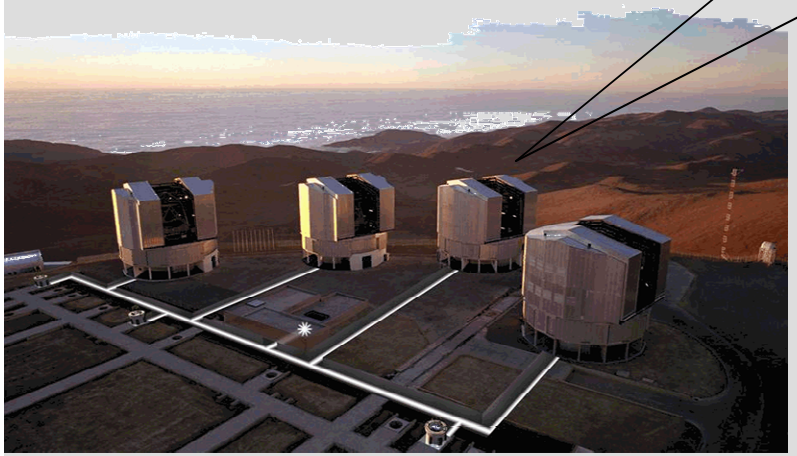
PRIMA reference stars: the imaging case

Extended (faint) source to be imaged



Science examples:

- YSOs
- Circumstellar disks
- Microjets
- Shells around evolved stars
- AGNs



$\alpha \leq \theta_0$

Bright star for fringe-tracking

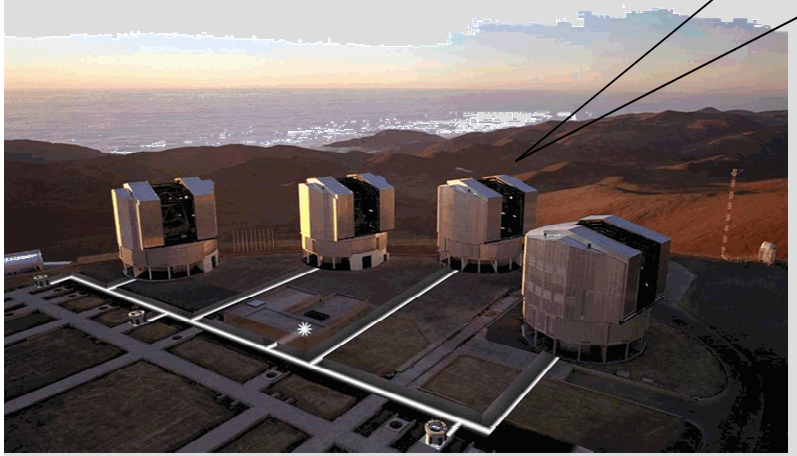
Nearly hopeless.

Possible strategy: Search for suitable imaging targets near good phase-reference stars

PRIMA reference stars: the astrometry case

Science examples:

- Distances
- Binary orbits
- Extrasolar planets
- Dynamics (Solar system, clusters, bulge)



Distant star (fainter) = position reference

$\alpha \leq \theta_0$

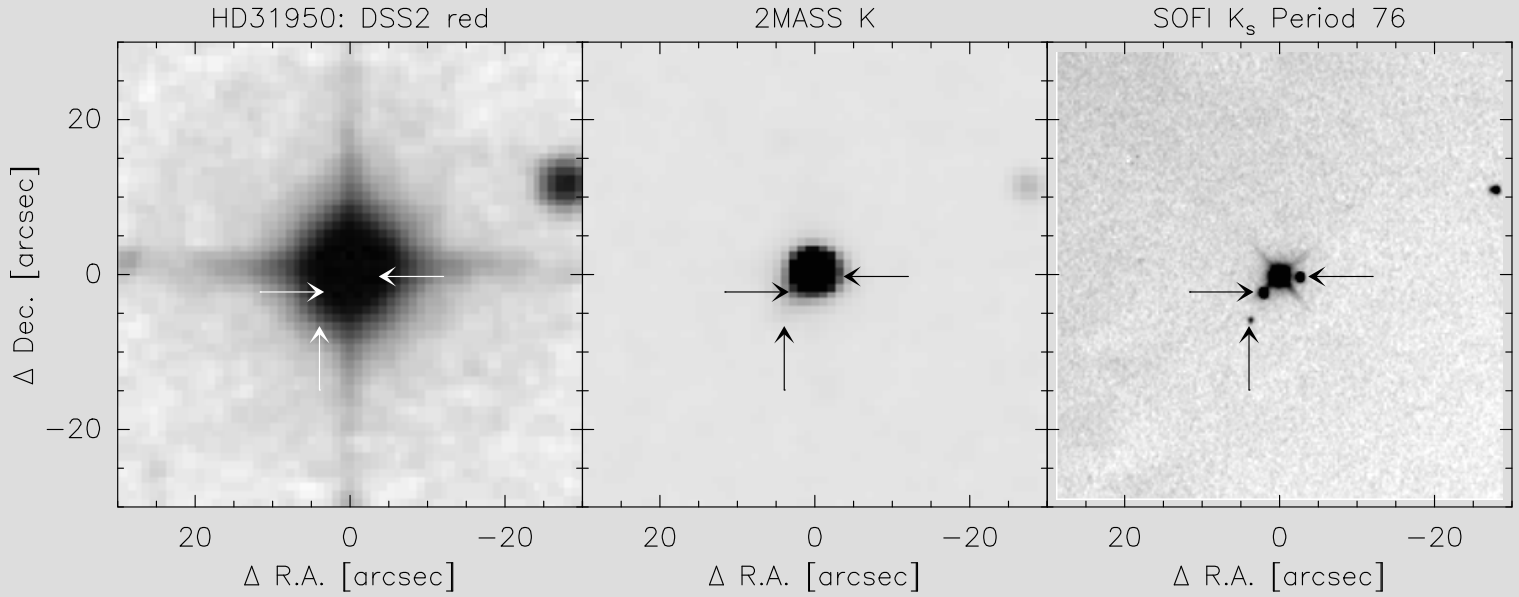
Nearby target star = Bright star for fringe-tracking

Measurement target =
angular separation between two stars.

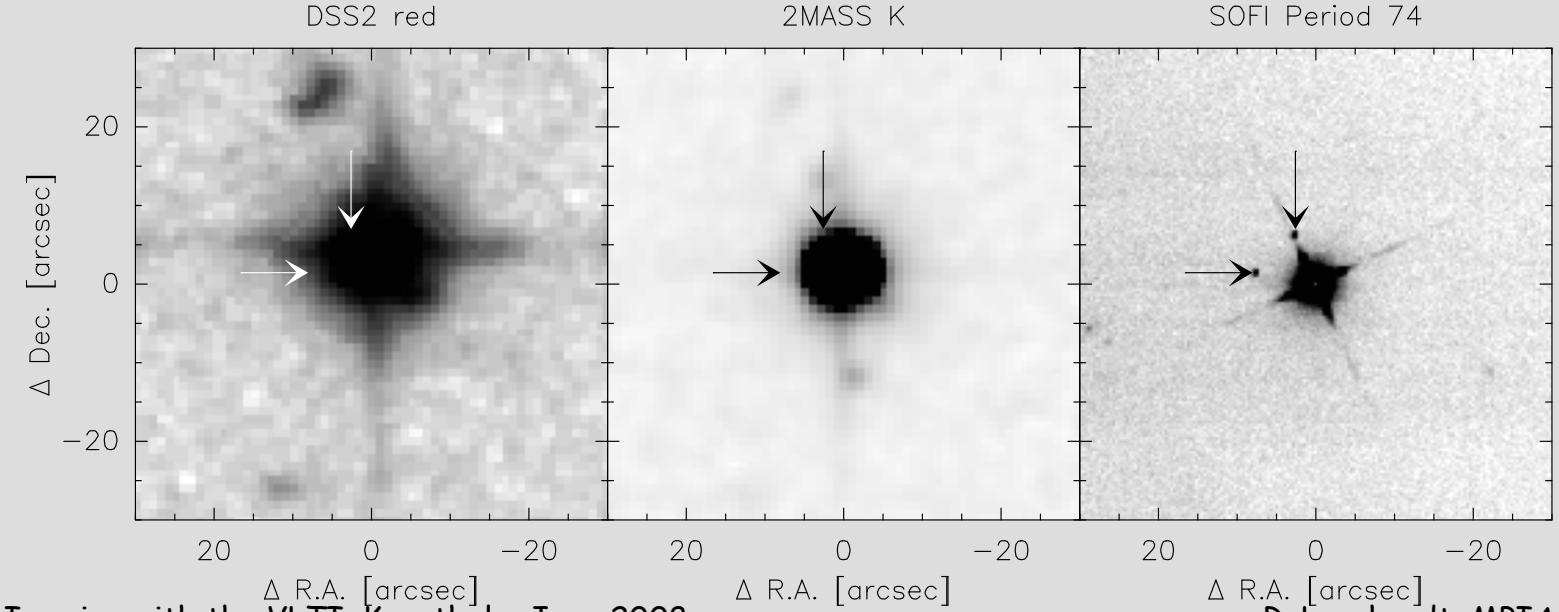
(It does not matter which one is used for fringe-tracking)

How to find reference stars?

HD 31950:



GJ 357:



Reference stars from public surveys?

Most public surveys suffer from:

- **Wrong wavelength band** (→ DSS)
- **Not deep enough** (→ 2MASS)
- **Too low dynamic range**, „blind“ areas around bright stars (→ 2MASS)
- **Ghosts** around bright stars (→ USNO)
- **Insufficient sky coverage** (→ UKIDSS)

- Need **dedicated high-dynamic range imaging** at K-band
- **Preparatory observations**

Calibrators

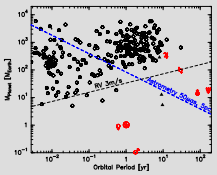
Summary

- **Baseline calibrators:** ESO
- **Visibility calibrators**: Online catalogs and tools
  Literature
- **Other calibrators** (guide stars, phot., spec., astrom.):
  => Online catalogs and tools, literature
- **Phase reference stars:** dedicated preparatory observations (high-dynamic range imaging)

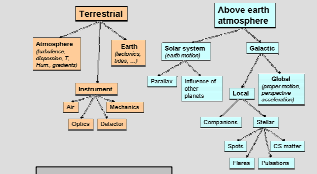
Preparatory Observations

Preparatory Roadmap

Science goals, detection domains, target groups

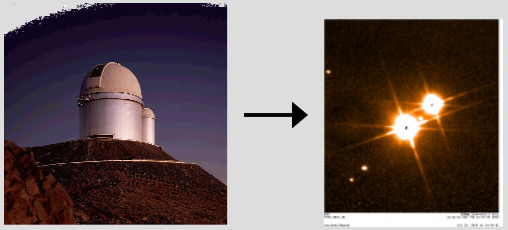


Error analysis and selection criteria

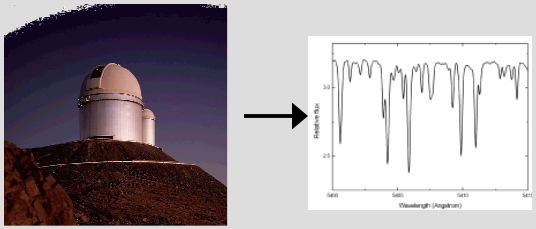


Pre-select target candidates

Search for reference stars



Characterize target and ref. stars



Select and prioritize

1. HD 12345
2. GJ 567
3. TW Hya

Derive target selection criteria

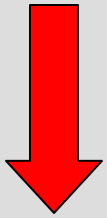
Scientific	Calibration	Technical
Type of source	Angular size	Location in sky
Distance	Astrometric stability	Brightness *(K≤8mag)*

Reference star selection criteria

- Angular separation from target star ($< \theta_0 \approx$10"-20")
- Brightness (K ≤ 14 mag)
- Astrometric stability (activity, distance, companions)
- (Angular size)

Pre-select target candidates

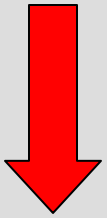
Study a particular source



You know your source!

Ask astrophysical question

Find the right sources



Catalogs (e.g., Simbad, CNS)

Apply selection criteria

=> *Now you have target candidates,*

but you don't know if you can observe them with PRIMA!

Search for reference stars

- **Faint stars** (K ≈ 13-15 mag)
  nearby (< 10-15 arcsec)
  very bright stars (K ≈ 4-8 mag)

- **High dynamic range K-band imaging**
  => r≥20" fields around target stars

- Need **reasonable seeing** (≤1-2")

- Sensitivity => use **2 – 4 m class telescope**

- **Use short DIT** (≤ 1 sec) and **small pixel scale** (<0.2")
  (*to minimize saturation effects*)

- Efficiency: detector should have **low readout overhead**

Search for reference stars

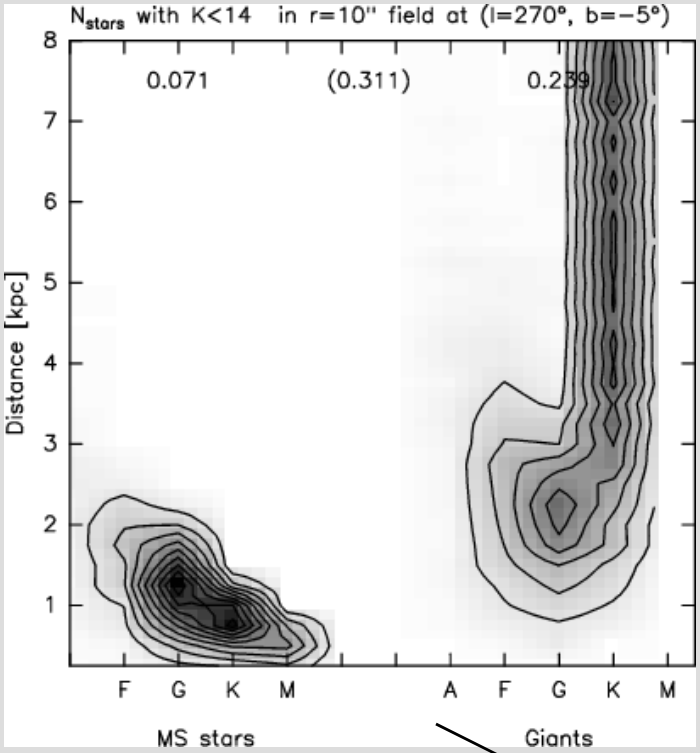
Telescopes and instruments:

- **Coronograph:** => not available
- **AO (**NACO**):** => FoV?
  => Dynamic range?
  => too „expensive“
- **VLT** (ISAAC) => too „expensive“ (8-m telescope not needed)

- Currently at ESO: **SOFI at the NTT**
- Other suitable telescopes and instruments?

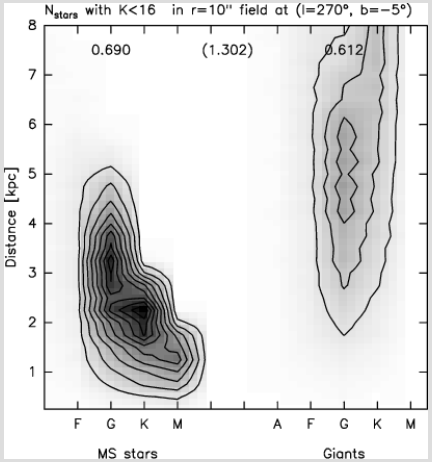
What are the typical reference stars?

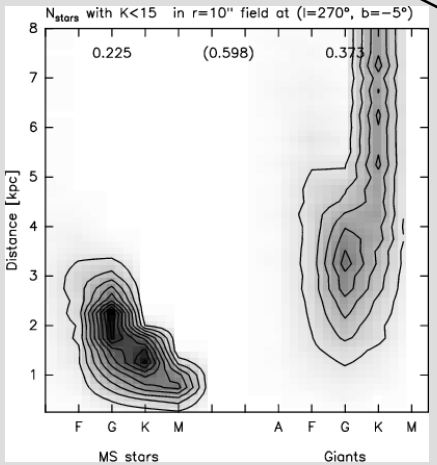
K ≤ 14 mag

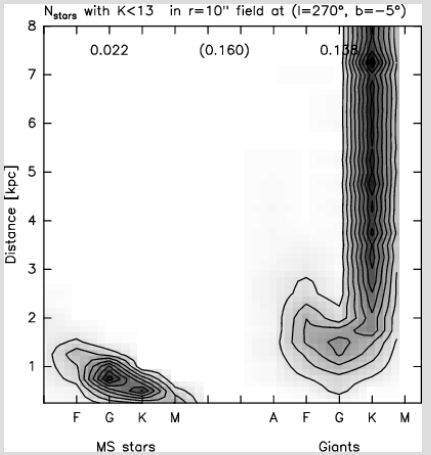


- Mostly K giants at >3 kpc
- Some G giants at ≈2 kpc
- 20% G and K dwarfs at 0.5 – 1.5 kpc

K ≤ 16







K ≤ 13

Angular diameter of reference stars

	R_*	D	ρ
Target stars	1	5 pc	2 mas
Reference stars	1	0.5 kpc	20 μas
	10	2 kpc	50 μas
	50	3 kpc	150 μas
1.2 λ/D (2.2μm / 100m)			5 mas

- Some visibility losses for the most nearby target stars *(but they are bright)*
- Background reference stars are always „point sources“ *(to first order)*

Preparatory Observations

Summary

- Reference stars for faint source imaging:
  => Bright stars from catalogs

- Reference stars for astrometry with bright targets:
  => **dedicated preparatory observations** (***mandatory!***)
  (high dynamic range NIR imaging)

- Characterize target and reference stars:
  => multi-color photometry, spectroscopy
  => helpful before
  => may be necessary after

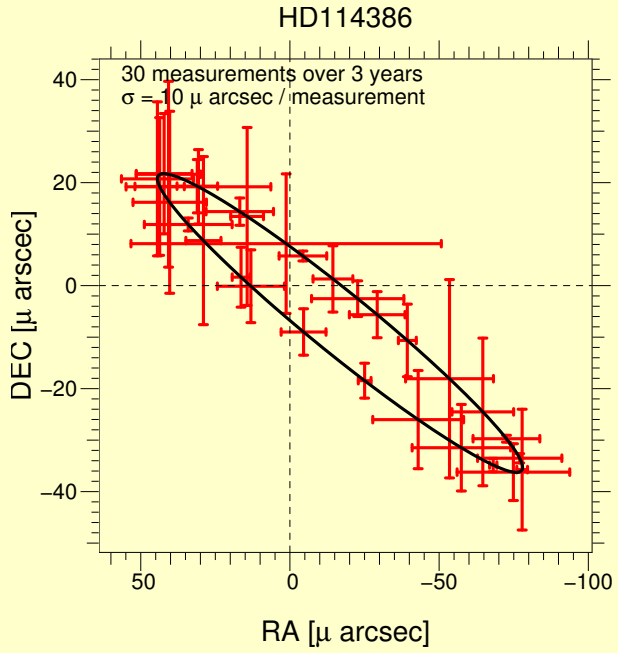
ESPRI Preparations

Example: Preparatory observations for ESPRI

- Astrometric **E**xoplanet **S**each with **PRI**MA
- One large coherent program with PRIMA and 2 ATs
- Consortium: Geneva, MPIA, LSW Heidelberg
- GTO for building the DDLs and developing astrometric software

Goal: Search for extrasolar planets and measure their orbits and masses by observing the reflex motion of the host stars in the plane of the sky

Preparatory observations: Search for reference stars around nearby planet search target stars & characterize target stars spectroscopically



ESPRI: Reference star selection criteria

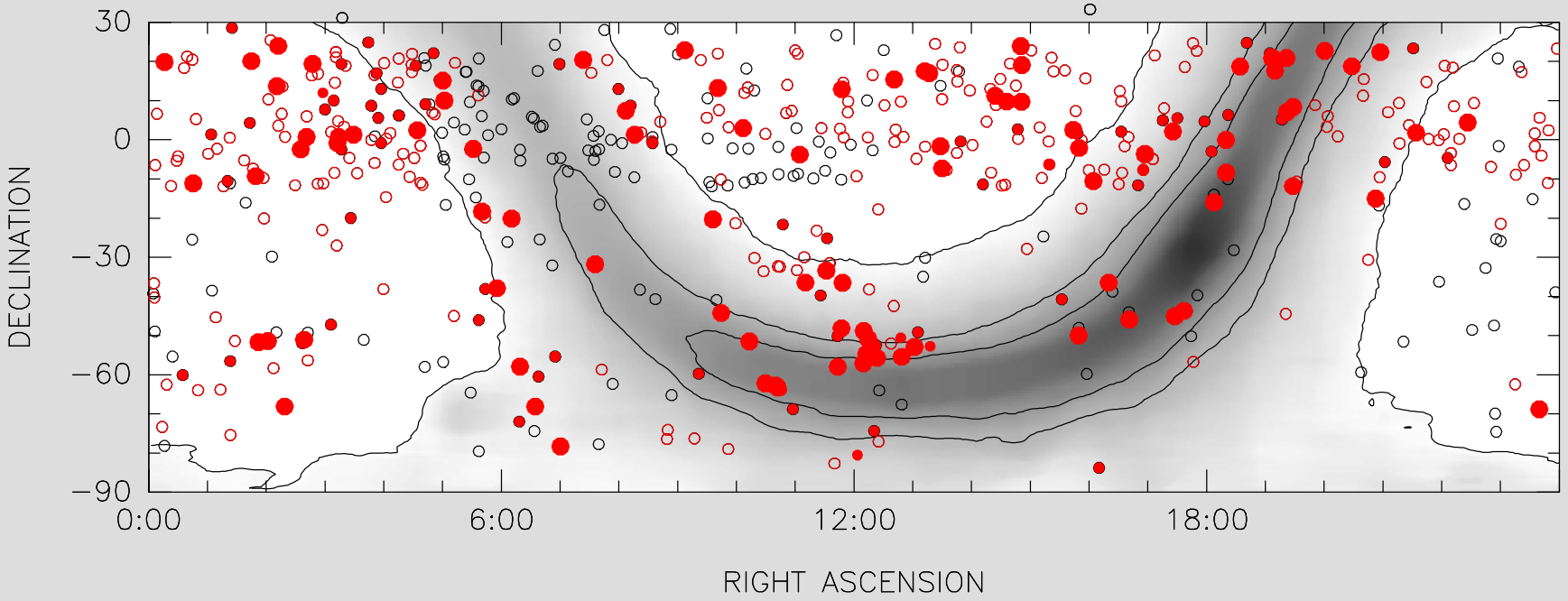
- **Angular separation:**

2“ - 10“	10“ – 20“	>20“
high	low	no

- **Brightness:** Select all with K < 16 mag
  Qualify only K < 14 mag

- **Other:** De-select „bad“ SBs and very nearby dwarfs

ESPRI reference star search



Preliminary NIR imaging results (SOFI + ESO archive + Calar Alto) observed: 655; reduced: 396

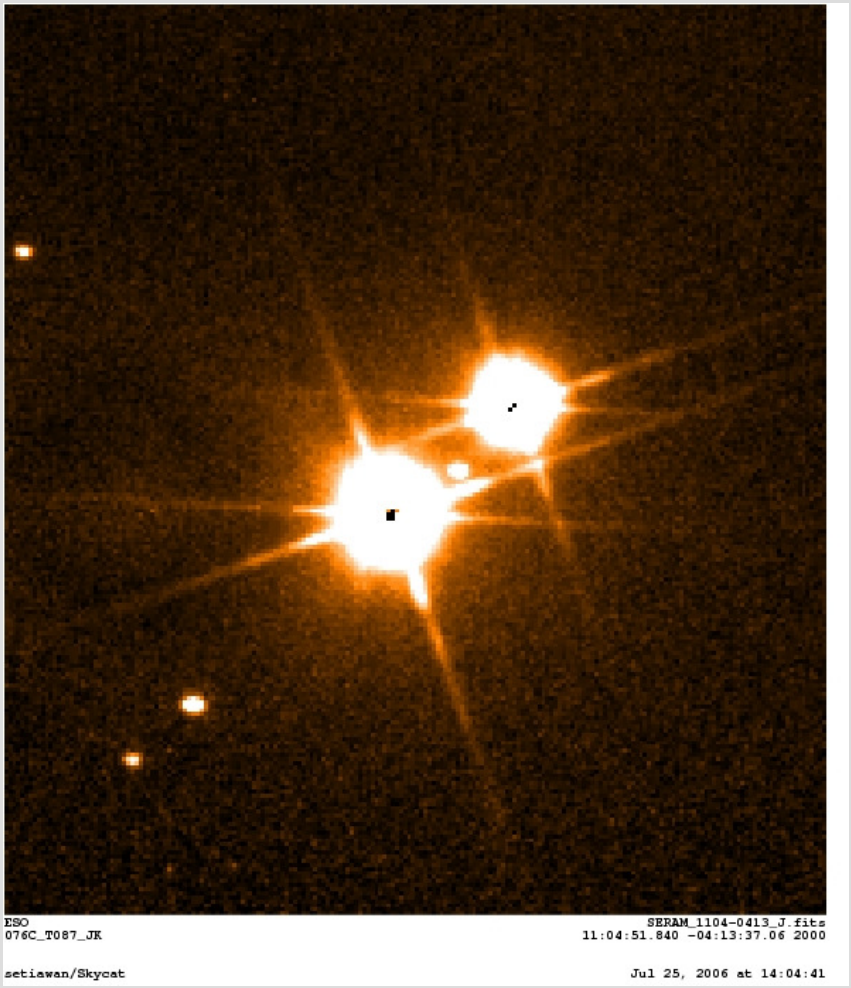
- ○ Observed, but not yet reduced
- ○ No SeS found within 20''
- • At least one SeS with K<16mag found within 20'' (163 = 41%)
- ● At least one SeS with K<16mag found within 10'' (92 = 23% / model = 19%)

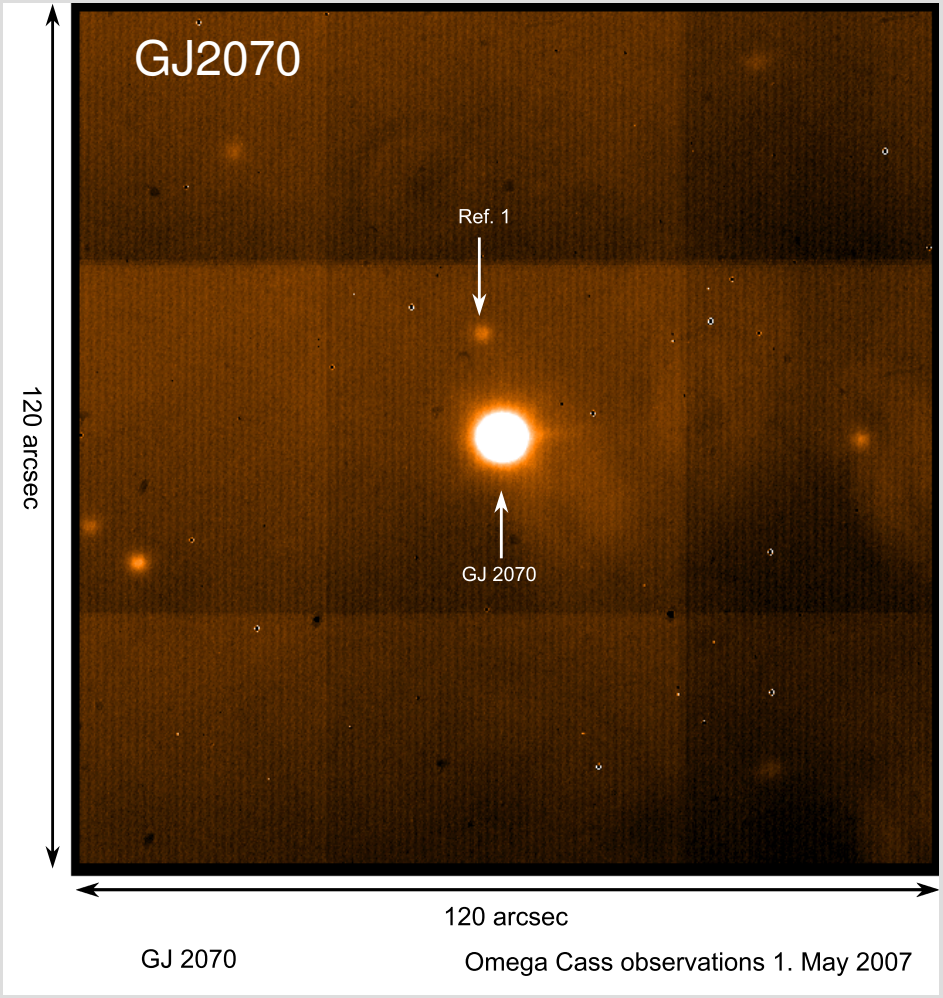
=> Overal detection rate for reference stars (10arcsec, K≤14mag): 17%

=> ≈ Factor of 2 loss or gain per mag

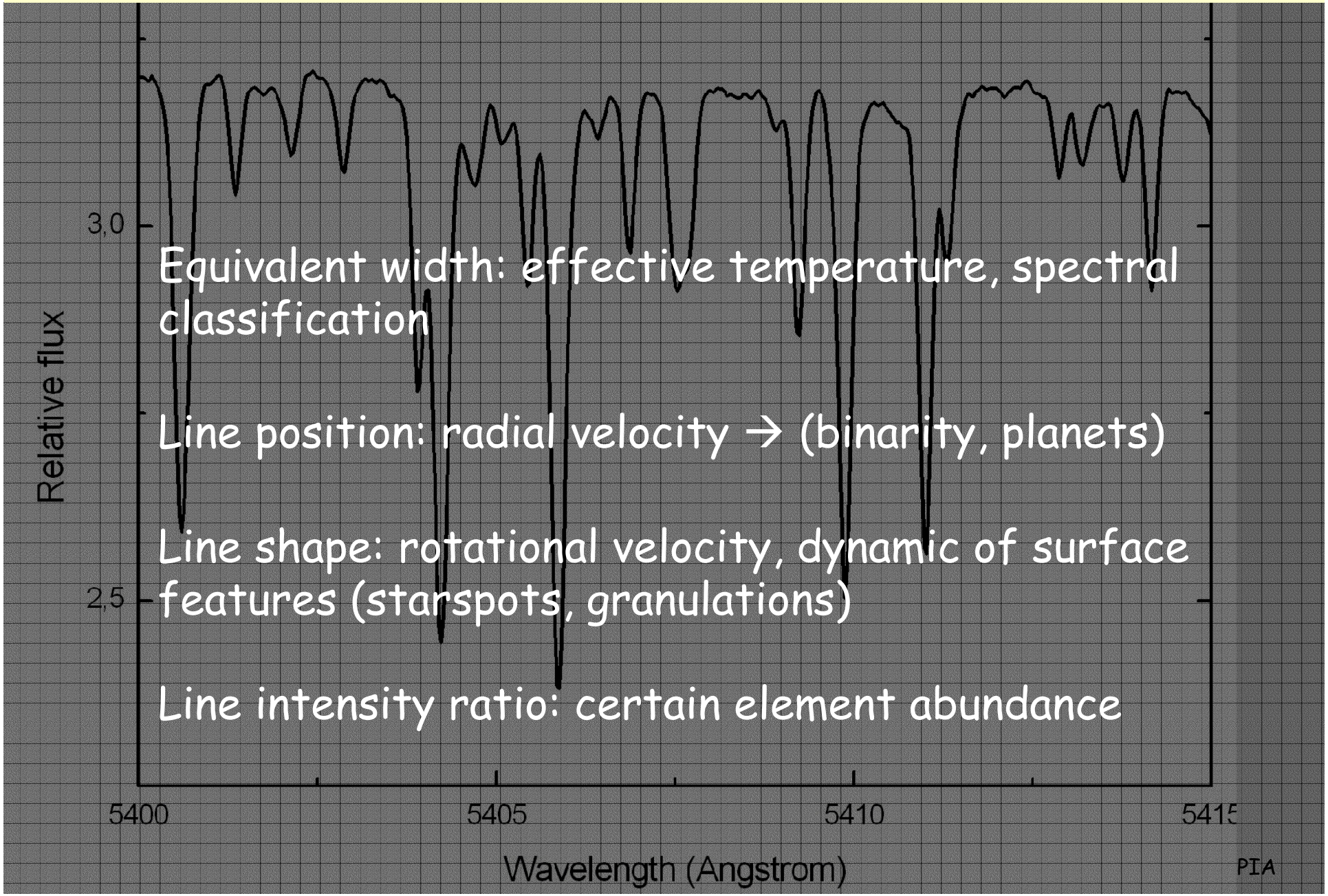
=> ≈30% of these are physical companions and not background stars

ESPRI reference stars - examples





Spectral characterization of target stars



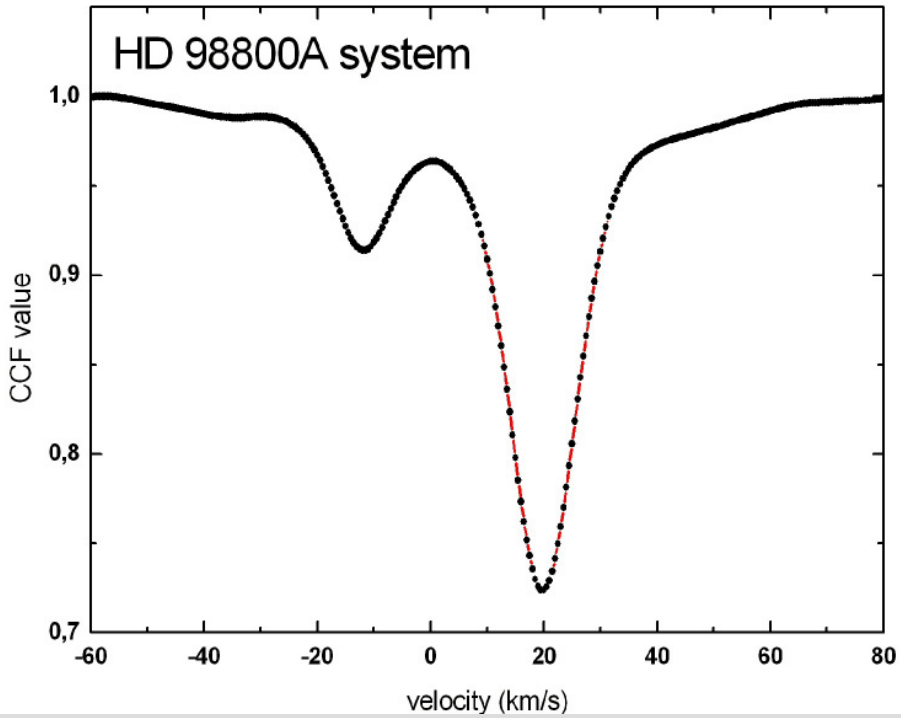
Equivalent width: effective temperature, spectral classification

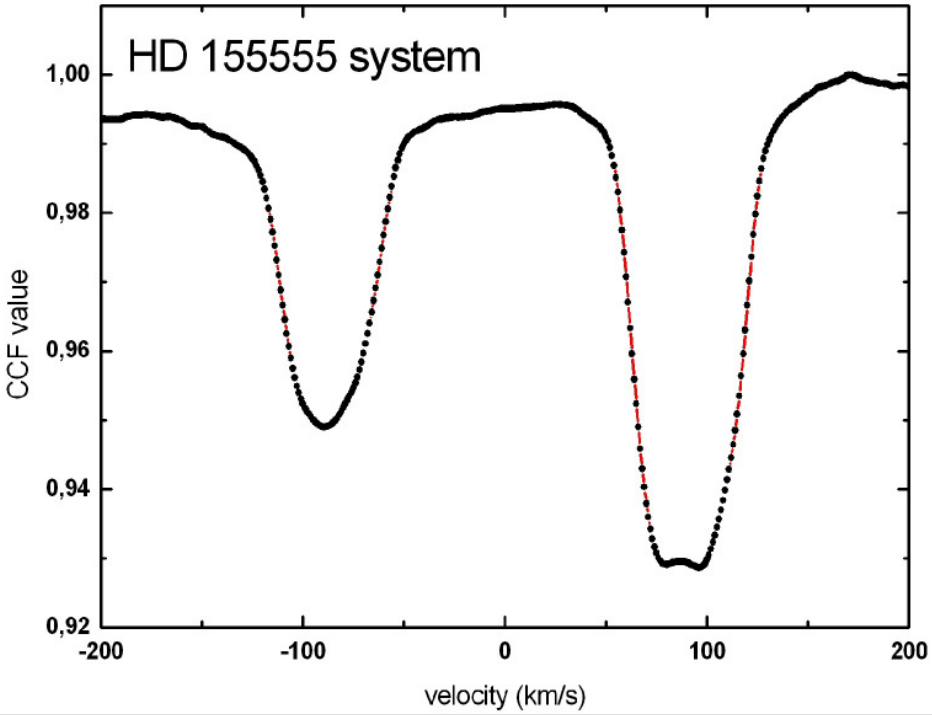
Line position: radial velocity → (binarity, planets)

Line shape: rotational velocity, dynamic of surface features (starspots, granulations)

Line intensity ratio: certain element abundance

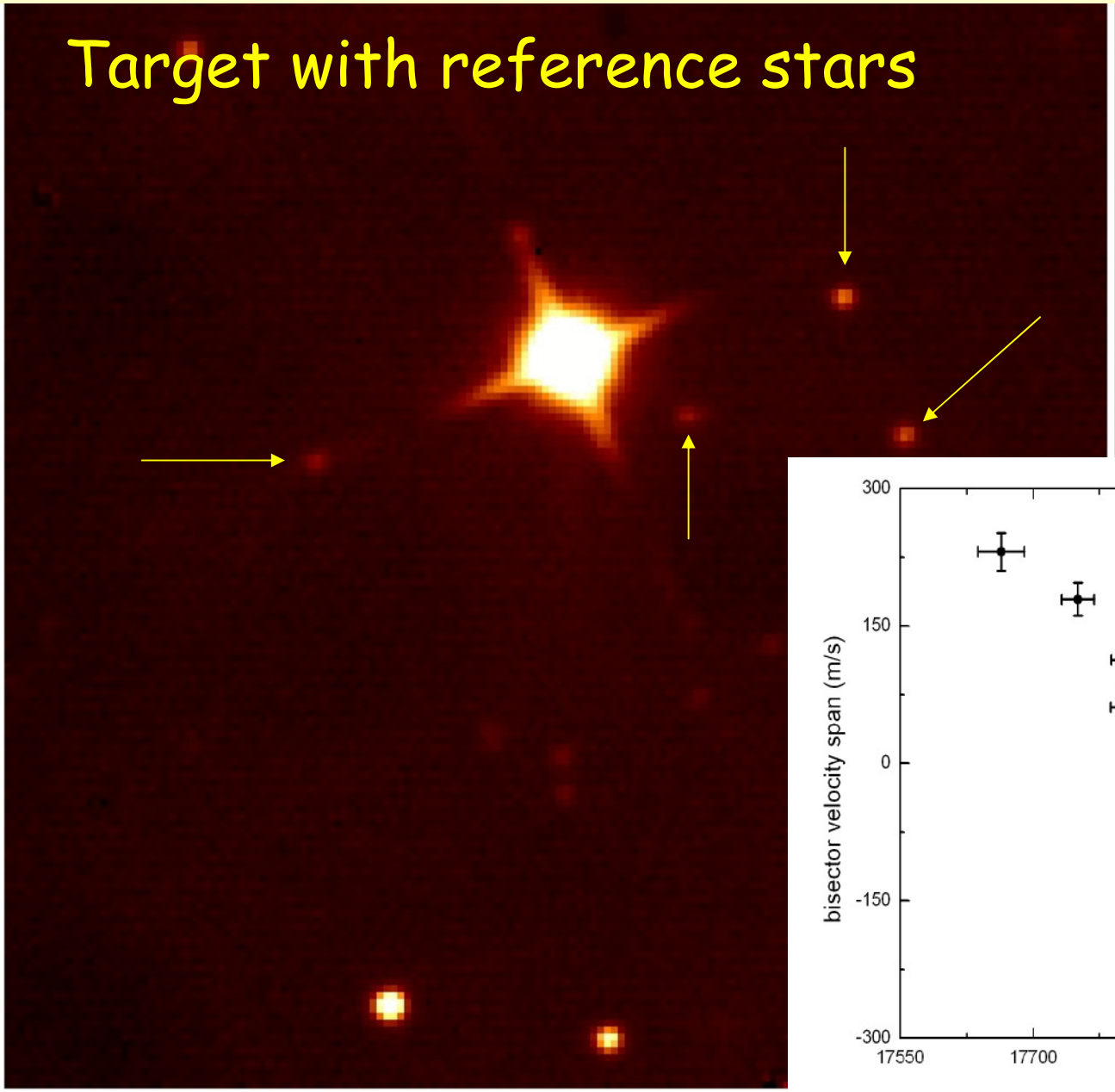
Binary and multiple systems





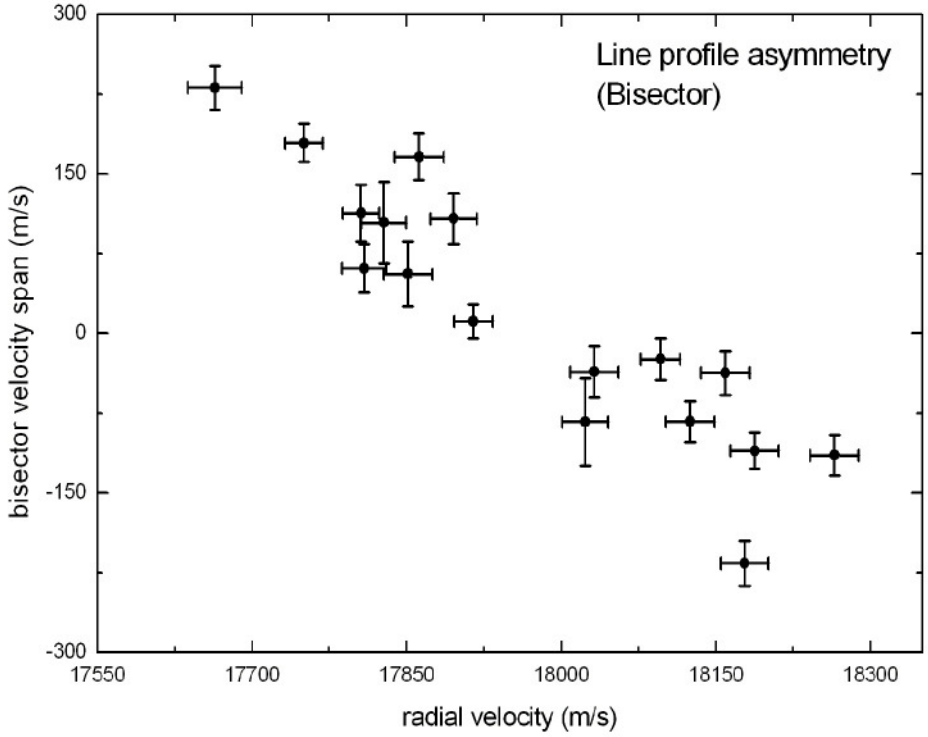
possibly quadrupole system

Starspots => astrometric noise

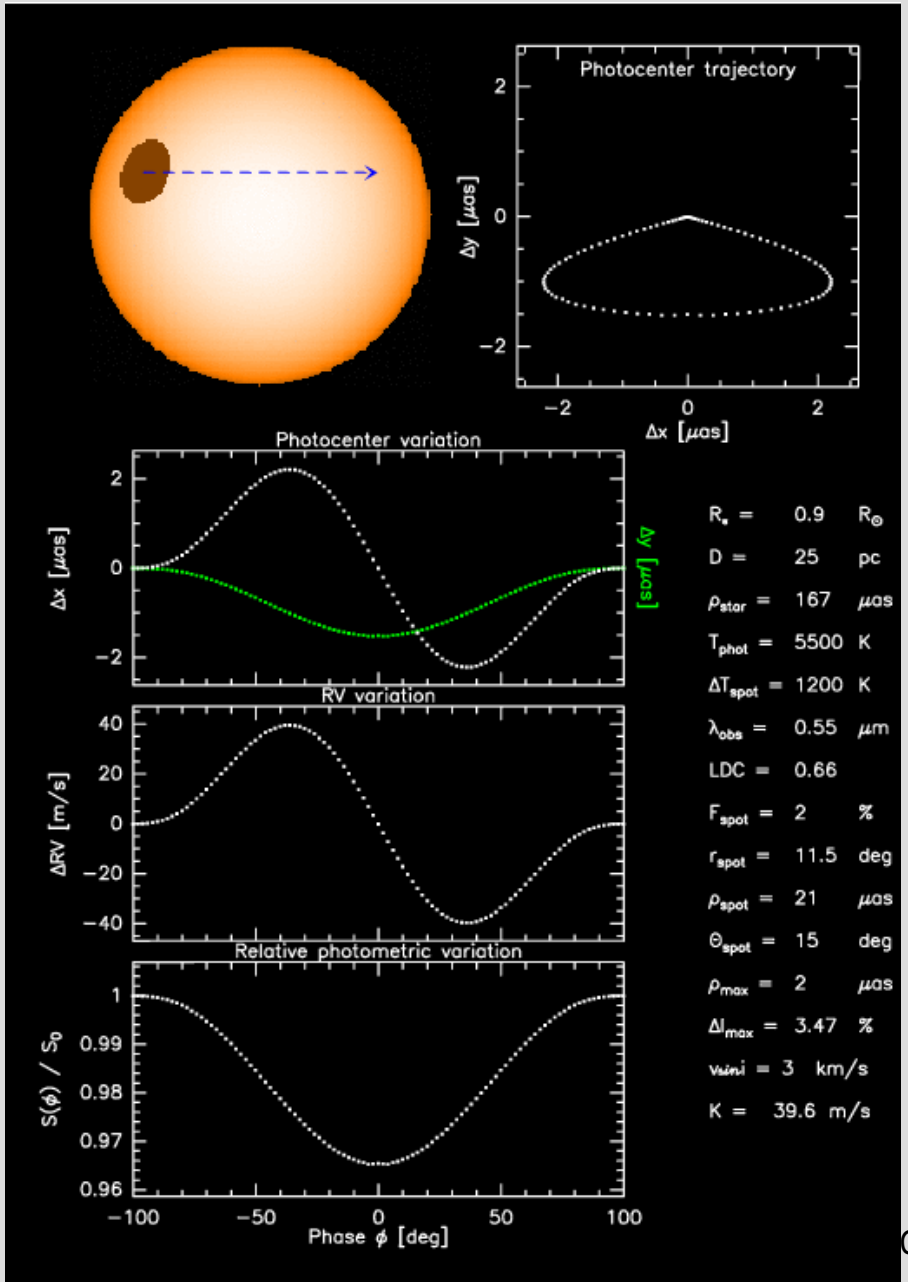


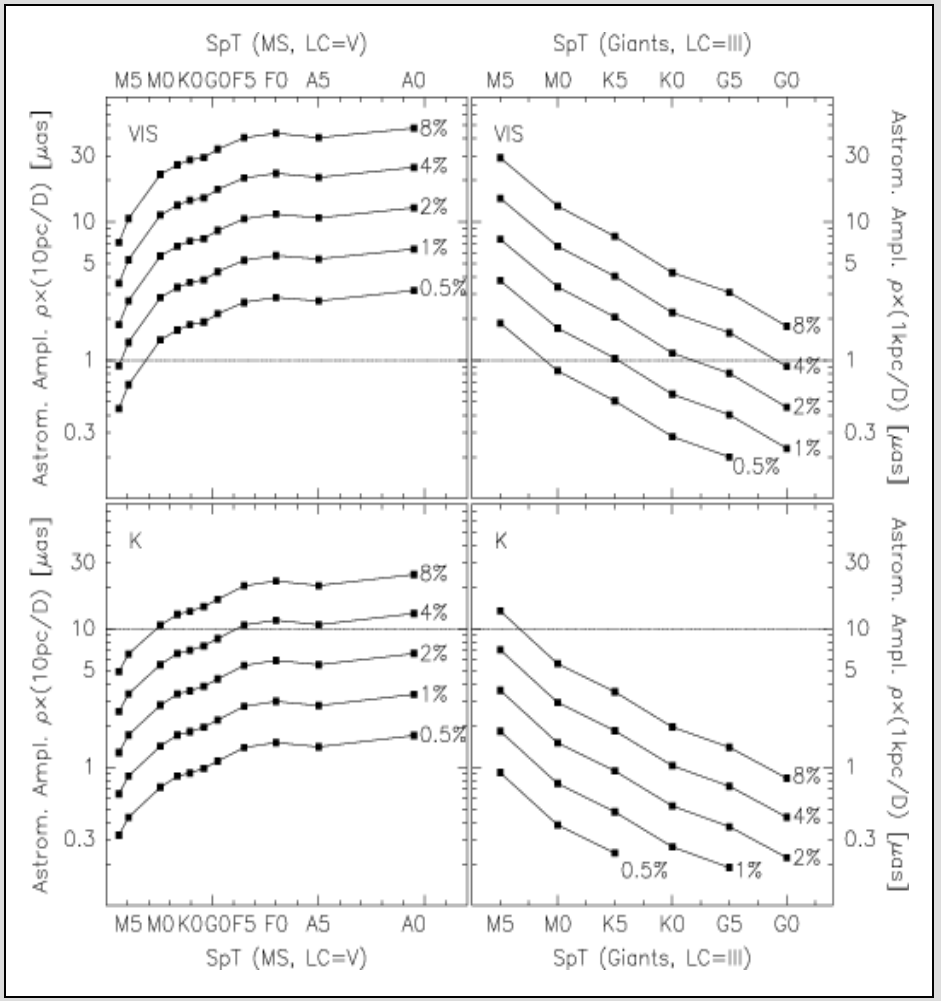
Starspots!

astrometric "noise" of few tens of μas



Star spots => astrometric noise





Preparatory Observations for ESPRI

Summary

- **Reference star search:**
  => 4 year program at NTT and Calar Alto
  => Special high dynamic range NIR imaging
  => 650 out of 850 fields done
  => Expect 80-120 good target - reference pairs

- **Spectroscopic observations of target stars:**
  => Could sort out young stars with excessive activity
  => Identified several new SBs
  => Measure various stellar parameters

- **Lesson**: ***plan well, start early!***