Study of an adaptive optics system for the astronomy in the visible

Sandrine Thomas,

A. Tokovinin, N. van der Bliek, B. Gregory,

R. Tighe, R. Cantarutti, P. Schurter, E. Mondaca, D. Sprayberry

NOAO

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AURA

Outline

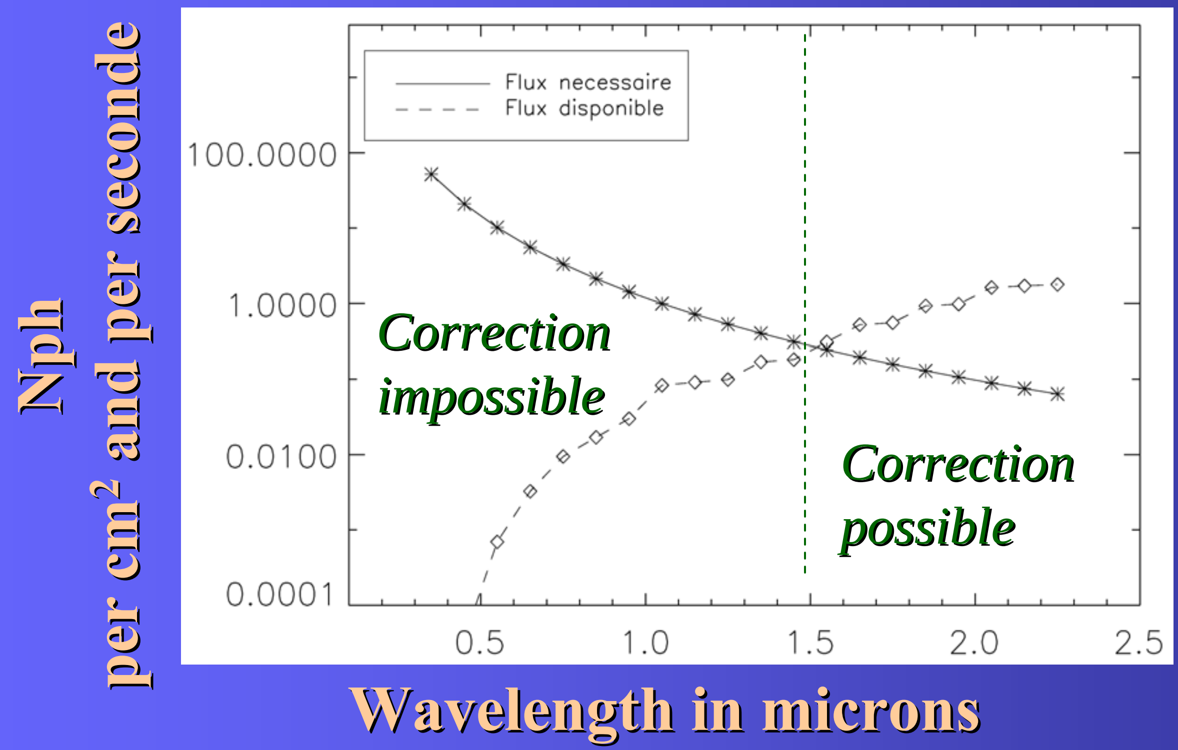
- Limitations of classical AOs
- GLAO technics (Ground Layer Adaptive Optics)

  Description and performance
- Example of SAM (SOAR Adaptive Module)

  TurSim, BIM60, Laser, WFS
- Shack-Hartmann WFS study

Main limitations of AO

- Low sky coverage
- Small isoplanetic angle (a few arcsec)
- Difficult correction in the visible



Solutions

- ***Sky coverage solution =*** laser guide star

  But: cone effect and

  Tip/tilt problem

- ***Anisoplanetism solution***: 3D turbulence reconstruction (tomography + MCAO)

  BUT: complex system

- ***Correction in the visible*** : increase of the number of actuators

  BUT: complex and flux problem

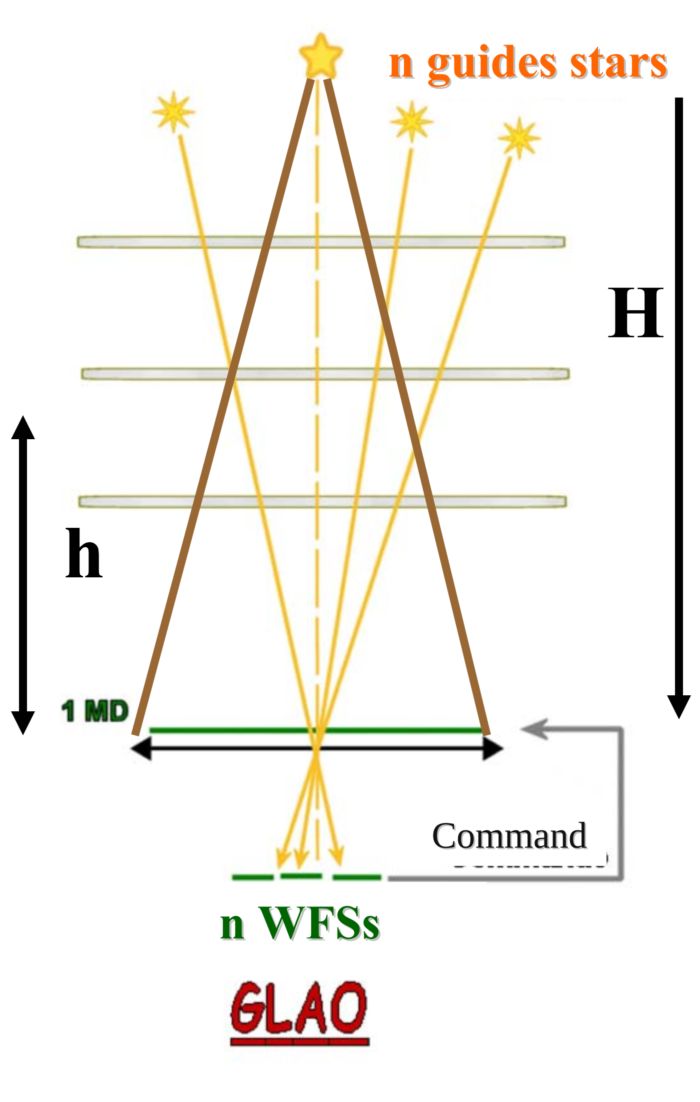
GLAO

- GLAO = measure and correction of the ground layer

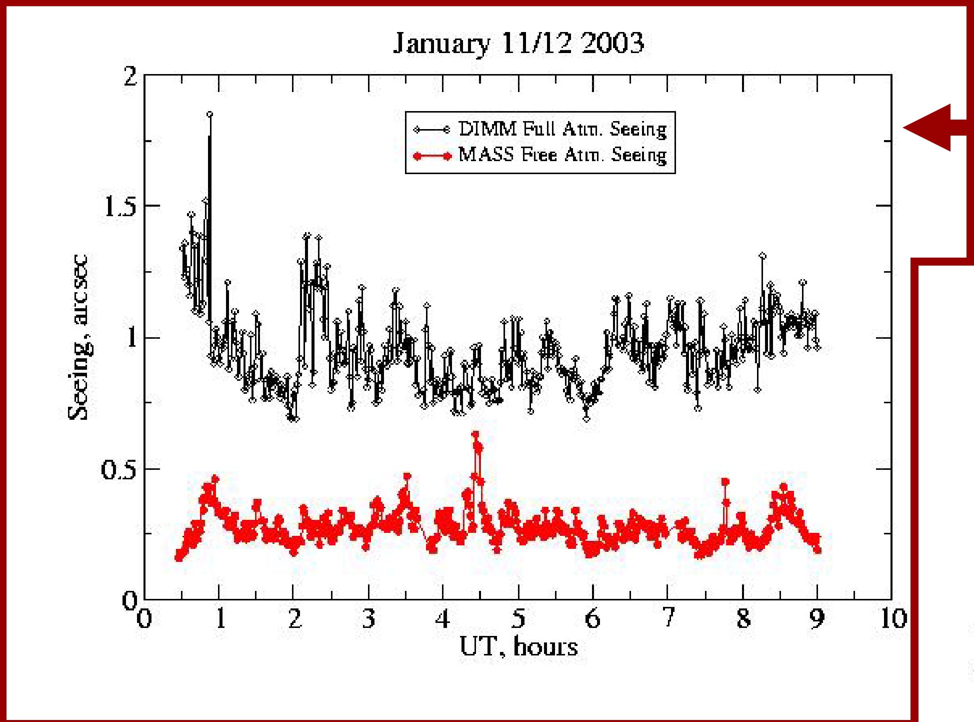
- Tomography = measure in 3D of the turbulence
- Only one star: use of the cone effet (+ measure of the tip/tilt)

$$\left\langle \alpha_{global}^{2} \right\rangle = \int \left\langle \alpha(h)^{2} \right\rangle (1 - h/H)^{2} \, dh$$

⇒
- Uniform correction over a larger FoV
- Gain in resolution in the visible

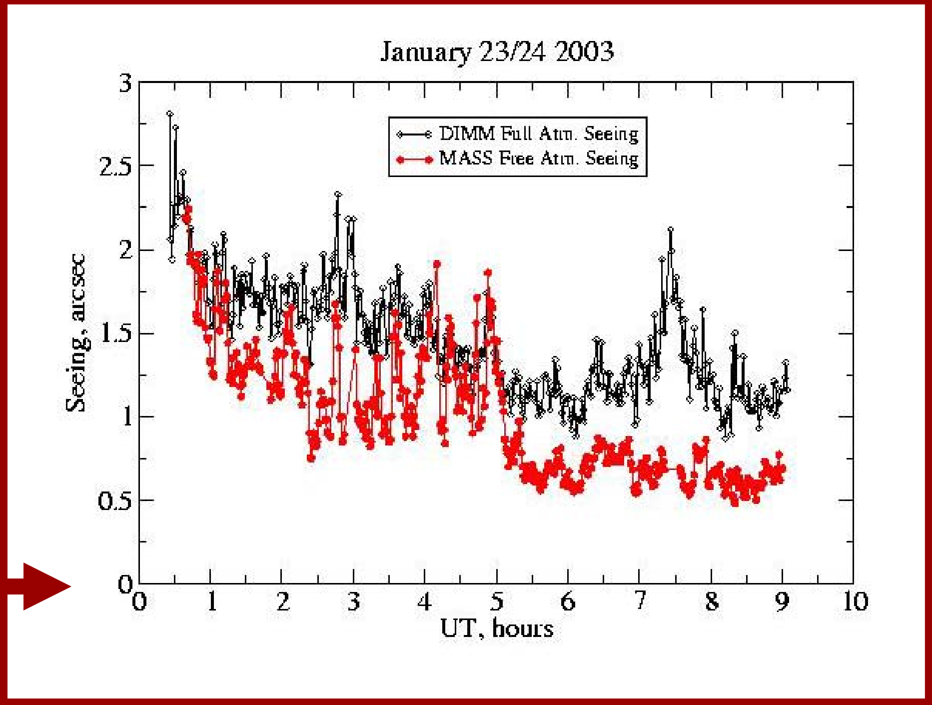


Why is it working?
Turbulence profiles



Good night

60%



Bad night

Tokovinin et al. 2003, campain at Cerro Pàchon

Performance of SAM

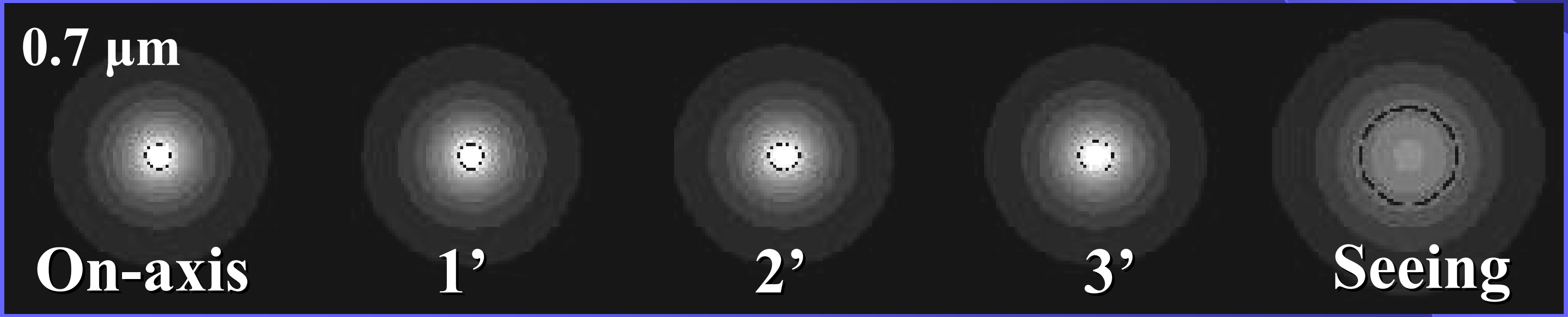
- Wide FoV
- Visible

⇒

GLAO
+
1 laser guide star

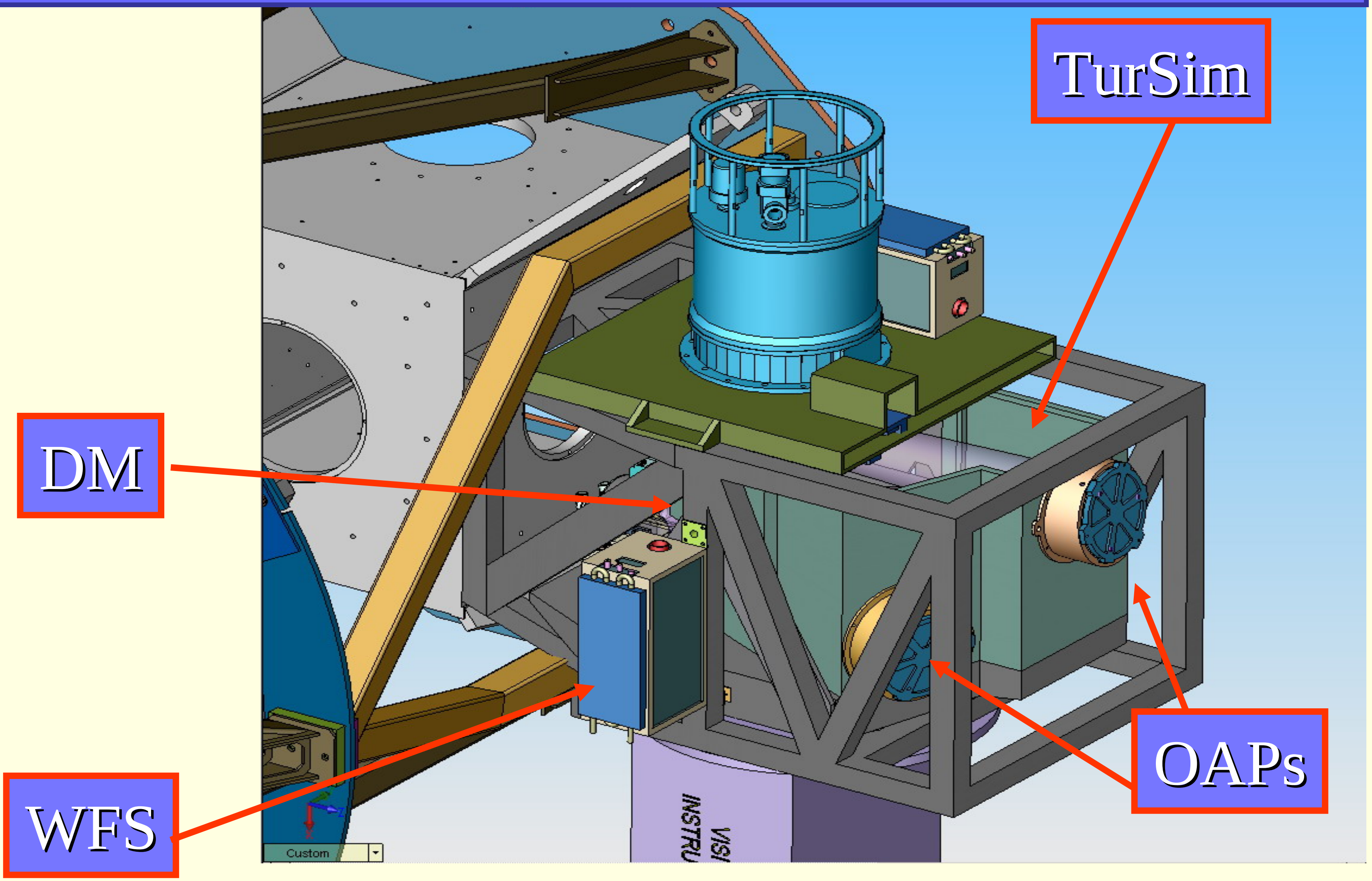
⇒

- Good sky coverage
- Improvement in FHWM (factor 2-5)



COMPENSATION: wide FoV (ex 3’)

SAM and my contributions



Tokovinin A. et al, SPIE, 2004

Optical design

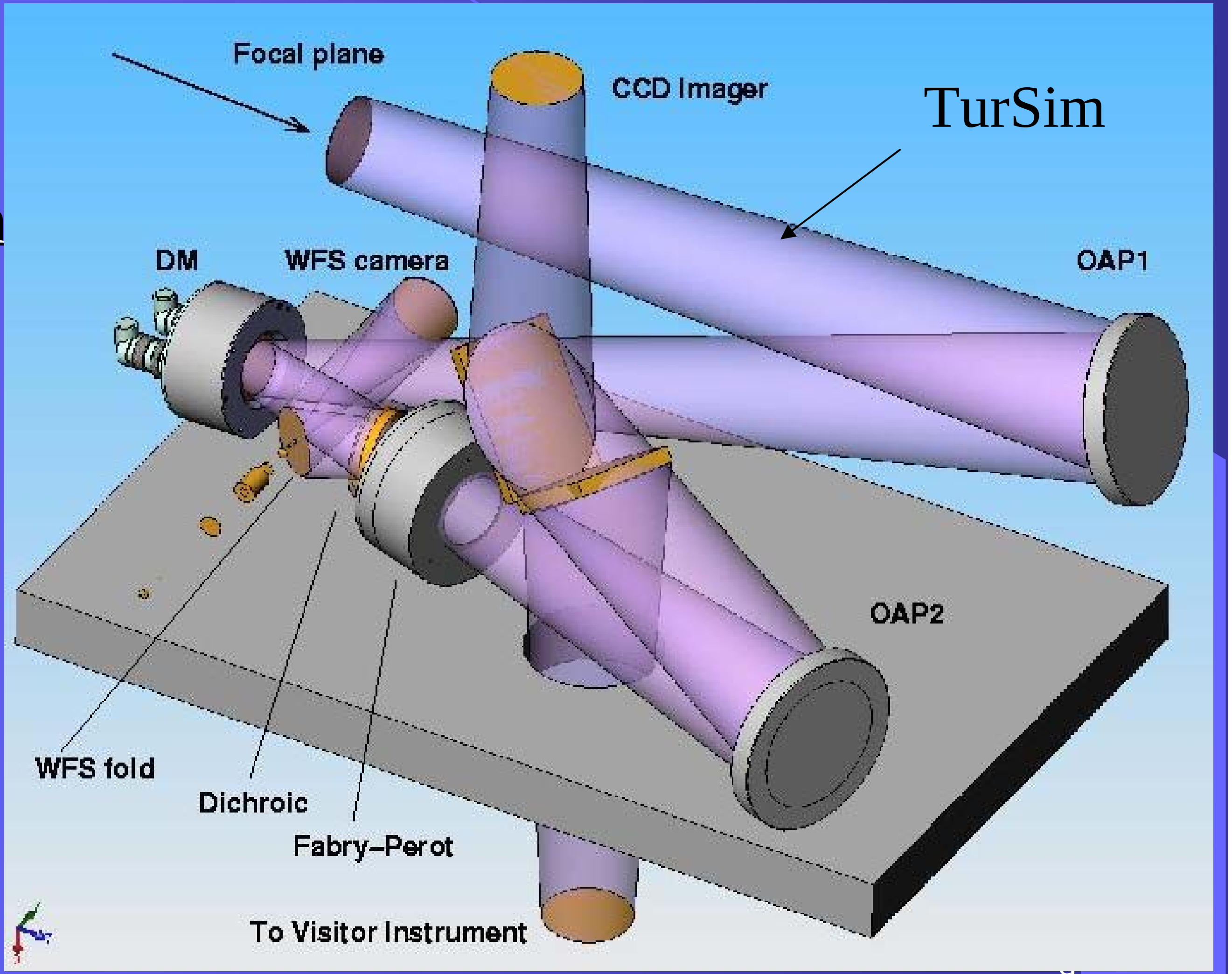
Total transmission

=

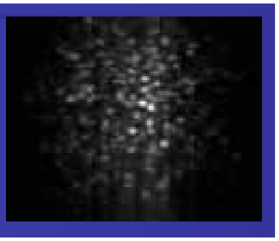
0.85-0.9

at

λ = [0.4-0.9]µm



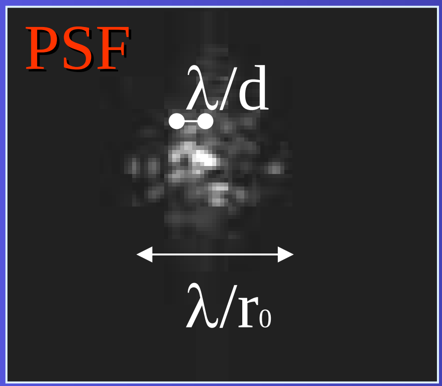
TurSim



Physical simulation of the atmospherical turbulence

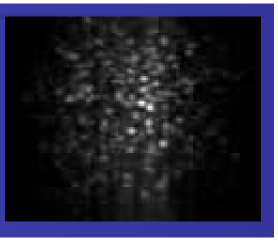
- Different atmospherical conditions possible
- Different speeds
- Different sources:

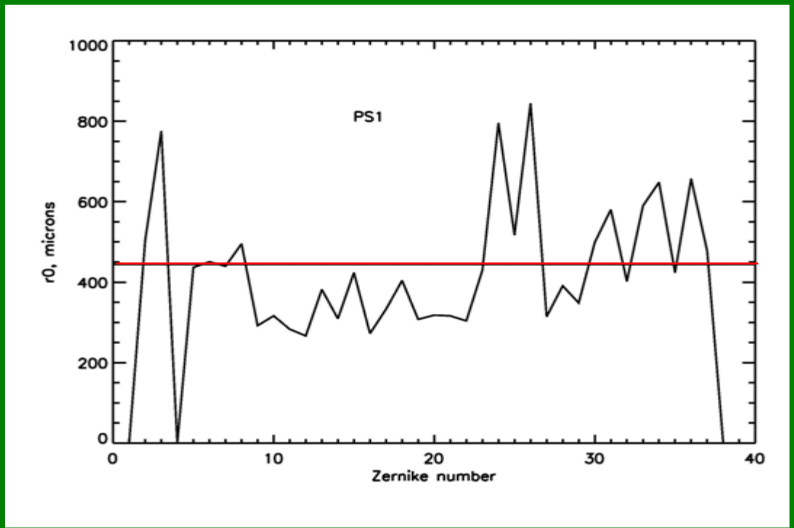
Diode laser, LED UV, LED white



$r_0 \approx 300$ µm
at 633 nm
Adjustable beam diameter
$\Rightarrow$
$d/r_0 < 45$

TurSim

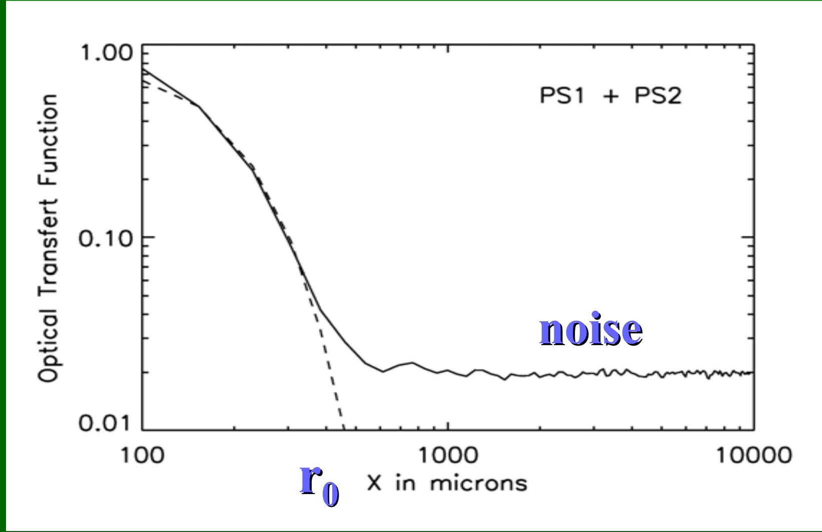




$$\varphi(r) = \sum_i a_i Z_i(r)$$

$$\sqrt{\langle a_i^2 \rangle} = \sqrt{N_i}\, D/r_0$$

Zernike decomposition



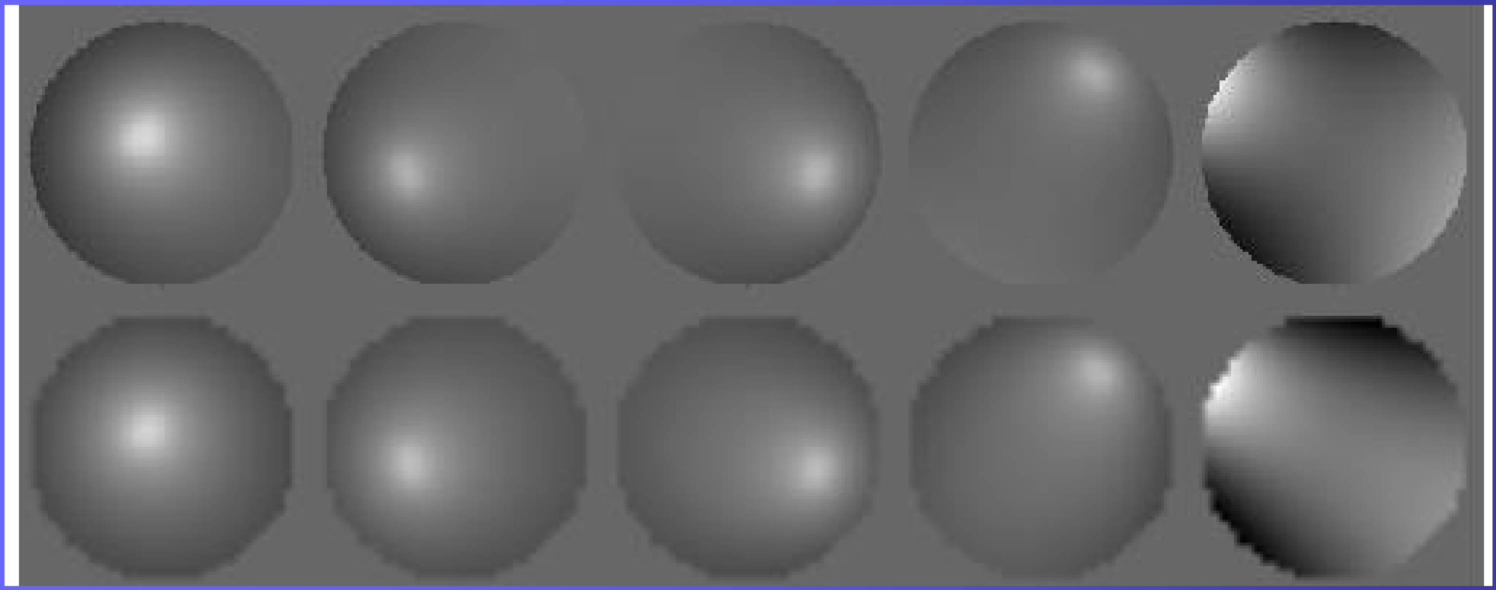
$$OTF(f) = \exp\left[-3.44(\lambda f / r_0)^{5/3}\right]$$

Optical transfert function

Choice of the DM

Tests of the electrostatic mirror OKO79 from OKOTECH then of the bimorph miroir BIM60 from CILAS:

- Stroke and inter-actuators stroke
- Aberrations
- Influence functions ….



Simulated

BIM60

Measured

Tokovinin A., Thomas S., Vdovin G., SPIE, 2004

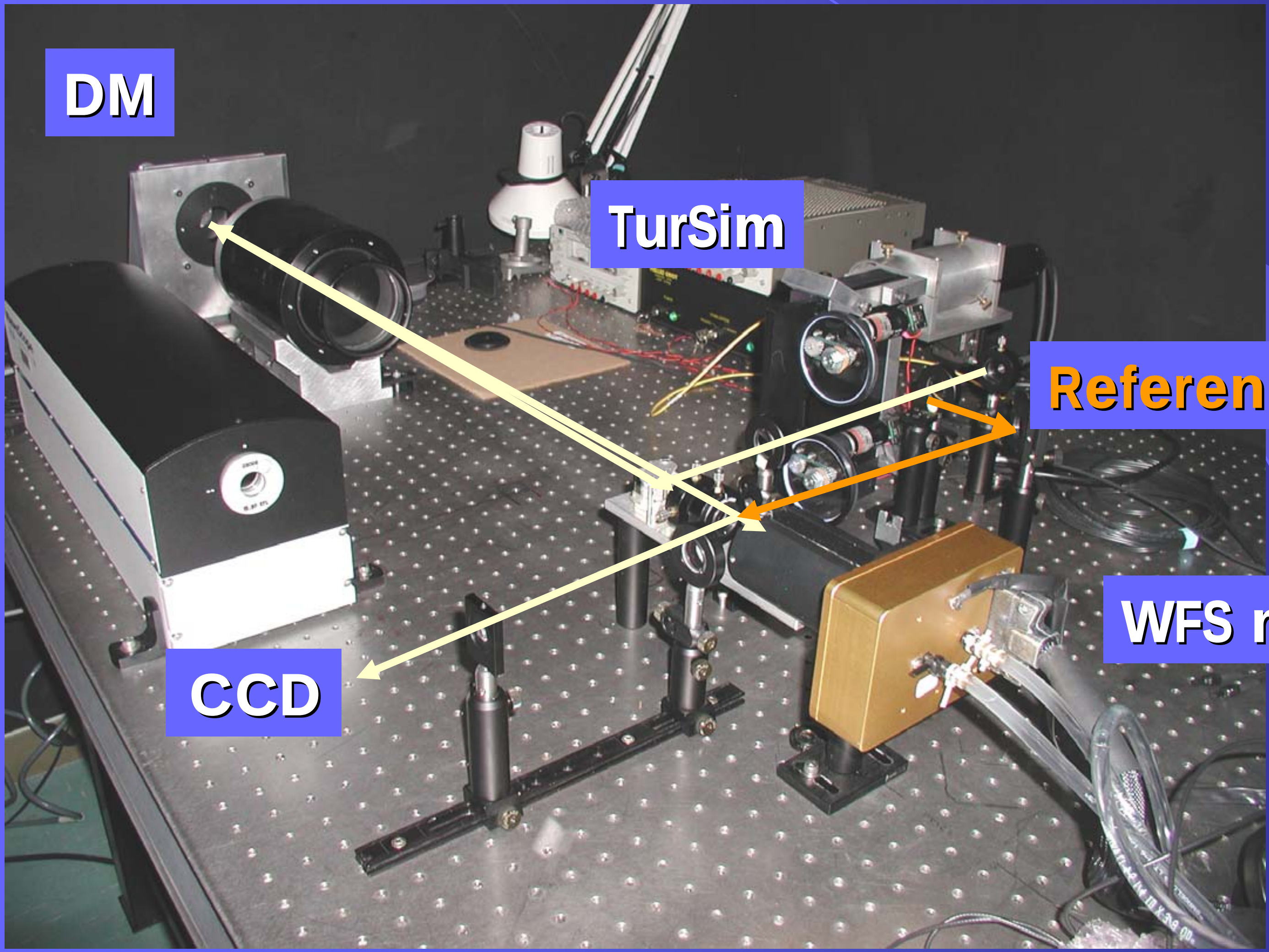
SAM's DM

- Pupil = 60 mm

  but 50 mm used
- 60 actuarors
- Radius of curvature

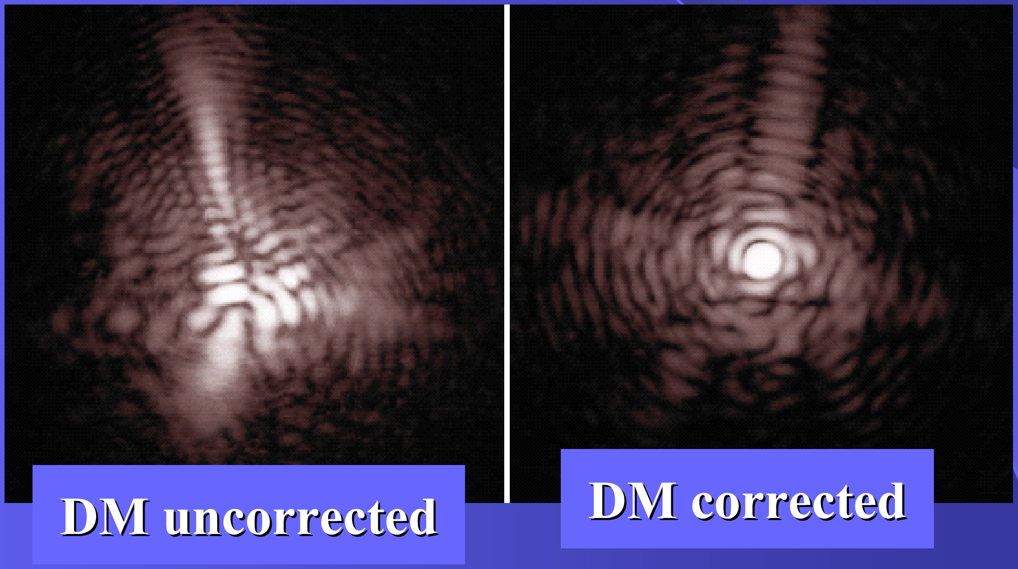
  = ±16.2 m
- Astigmatism = 3 μm

SAM's prototype



Closed-loop

- Image quality after correction of the mirror aberrations 20 nm rms



- Turbulence characteristics
- Closed-loop study

Laser

- **Laser:**
  - **Nd:YAG 355nm triple, 8W at 10 kHz**
  - **LLT: D = 30cm, behind secondary, H=10km**
  - **Gating: KD*P Pockels cell, dH=150m**
- **Tip/tilt Measurement: 2 NGS (R<18)**
  - **Quad cell**
  - **APDs connected to fiber optics**

Why UV?

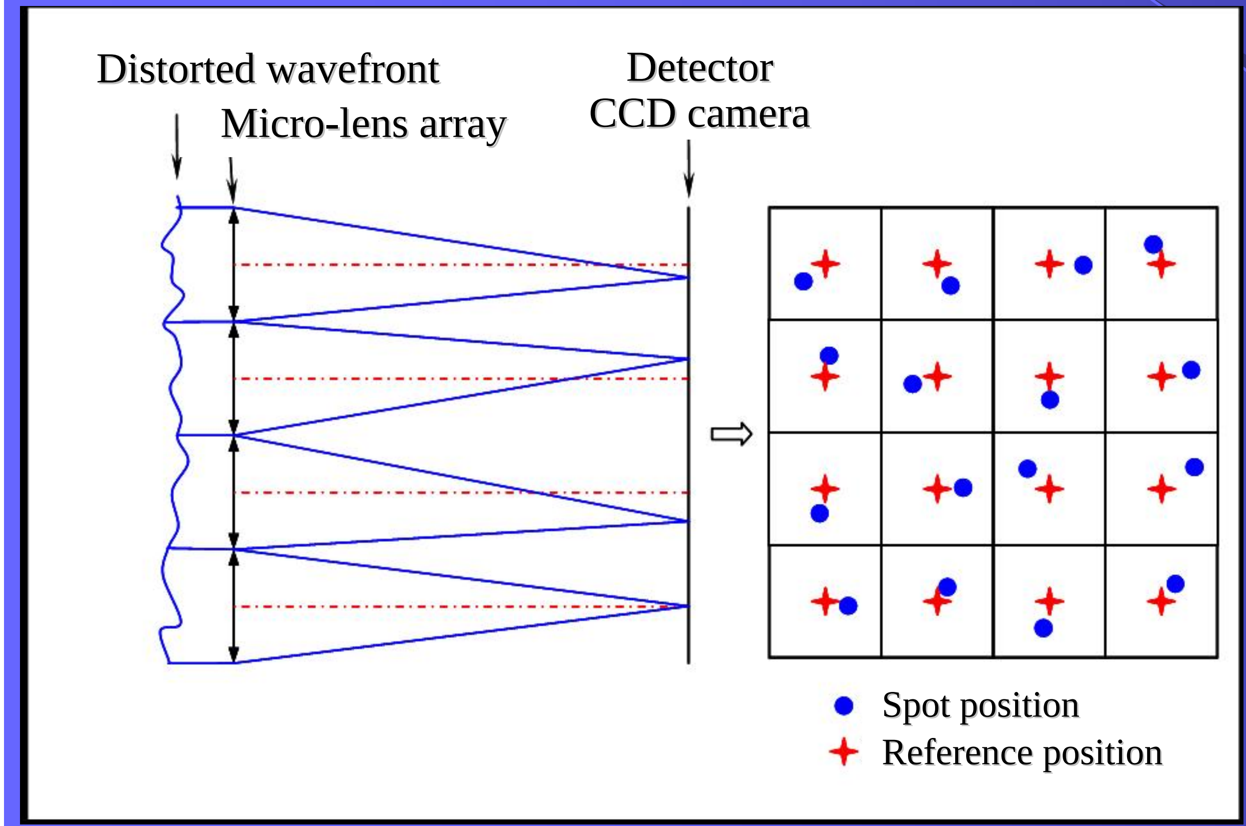
High Rayleigh diffusion (λ^{-4})

Easy separation between science and WFS

No visual hazard

The SHWFS

(in collaboration mainly with T. Fusco, A. Tokovinin)



Good precision of the position measurement

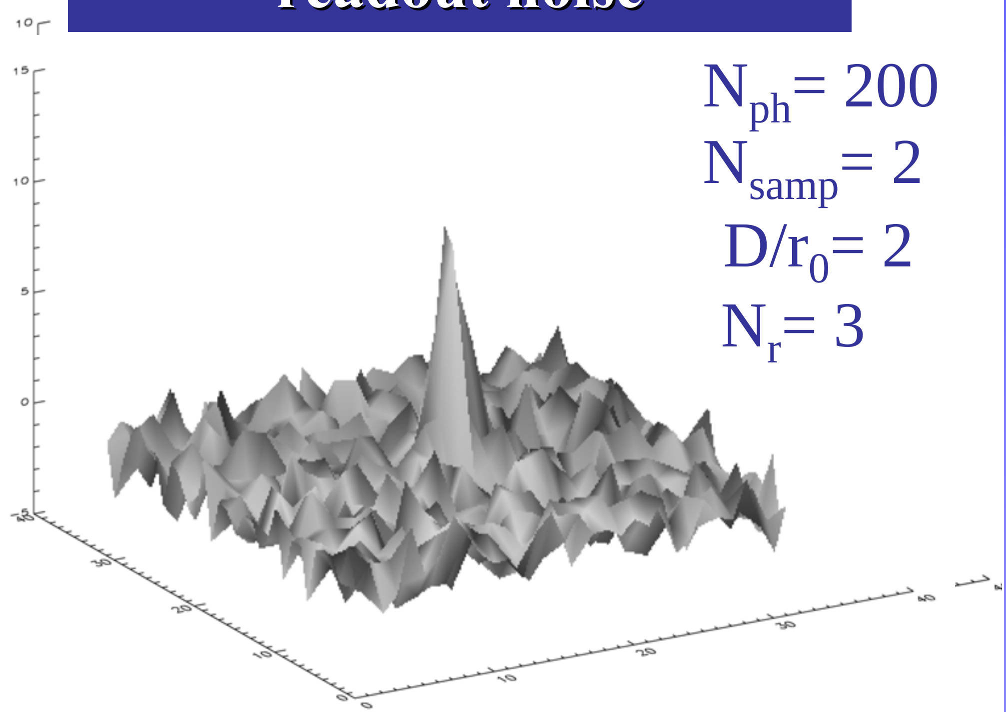
⇓

Good reconstruction of the distorted wavefront

$$\sigma^2_{err} = \langle (C_{mes} - C_{true})^2 \rangle_{1000\ iter}$$

Context

Atmosphere + photon and readout noise



Monte-Carlo simulation

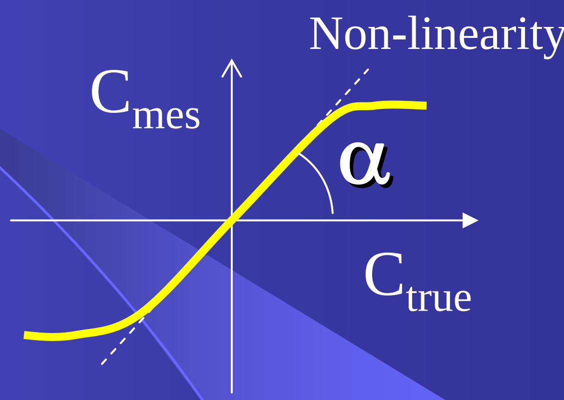
Parameters of the study

- Spot shape
- Turbulence strength r_0
- Photon number per subaperture: N_{ph}
- Readout noise: N_r
- Subaperture FoV
- Spatial resolution: *Nyquist, Nyquist/2*

Centroid calculation methods

- CoG:
  - Thresholding, T
  - Windowing, W
  - Weighted CoG, F_w

$$C_x = \alpha \frac{\sum_{i,j} x_i I_{i,j} F_{w,i,j}}{\sum_{i,j} I_{i,j}}$$



- Quad Cell

$$C_x = \alpha \frac{Il - Ir}{Il + Ir}$$

- Correlation

$$F_{corr}(x,y) = I \otimes F_w = \sum_{i,j} I_{i,j} F_w(x_i + x, y_i + y)$$

Correlation peak estimation:

- CoG + thresholding, T
- Parabola fitting
- Gaussian fitting

Error variance expression

$\sigma^2_{err} = \langle (C_{mes} - C_{true})^2 \rangle$ **1000 iter**

$$\sigma^2_{err} = (\sigma^2_{N_r} + \sigma^2_{N_{ph}}) + (\alpha - 1)^2 \langle x_0^2 \rangle + f_{nl}(x_0) + \sigma^2_{atm}$$

Noise terms

Response coefficient

Non-linearity term

Term from atmospherical distortions

Noise terms

N_s = pixels number
N_t = spot FWHM
N_{samp} = Sampling
δ = correlation function FWHM
W = FoV

Hyp: Nyquist, diffraction spot

- CoG

$$\sigma^2_{N_{ph}} = 2\frac{W}{N_{ph}} \qquad \sigma^2_{N_r} = \frac{\pi^2}{3}\frac{N_r^2}{N_{ph}^2}\frac{N_s^4}{N_{samp}^2}$$

- WCoG (corrected by α)

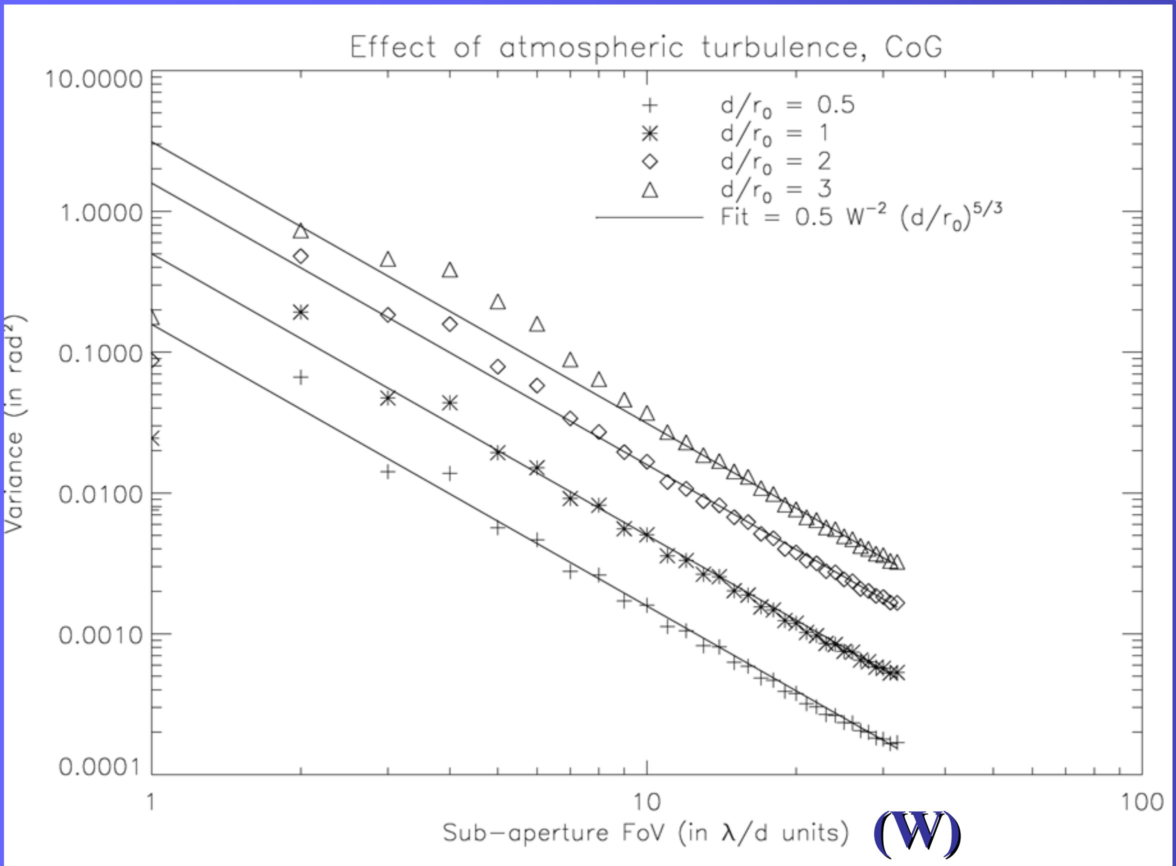
$$\sigma^2_{N_{ph}} = \frac{\pi^2}{2\ln 2}\frac{1}{N_{ph}}\left(\frac{N_T}{N_{samp}}\right)^2\frac{\left(N_T^2+N_w^2\right)^4}{\left(2N_T^2+N_w^2\right)^2 N_w^4} \qquad \sigma^2_{N_r} = \frac{\pi^2}{32(\ln 2)^2}\frac{N_r^2}{N_{ph}^2}\frac{\left(N_T^2+N_w^2\right)^4}{N_{samp}^2 N_w^4}$$

- Correlation

$$\sigma^2_{N_{ph}} = \frac{\pi^2}{2\ln 2}\frac{1}{N_{ph}}\left(\frac{N_T}{N_{samp}}\right)^2 \qquad \sigma^2_{N_r} = \frac{4\pi^2}{N_{samp}^2}\frac{4\delta^2 N_r^2}{N_{ph}^2}$$

Paper: Thomas et al. submitted

Term from atmospherical distortions



Atmospherical turbulence only

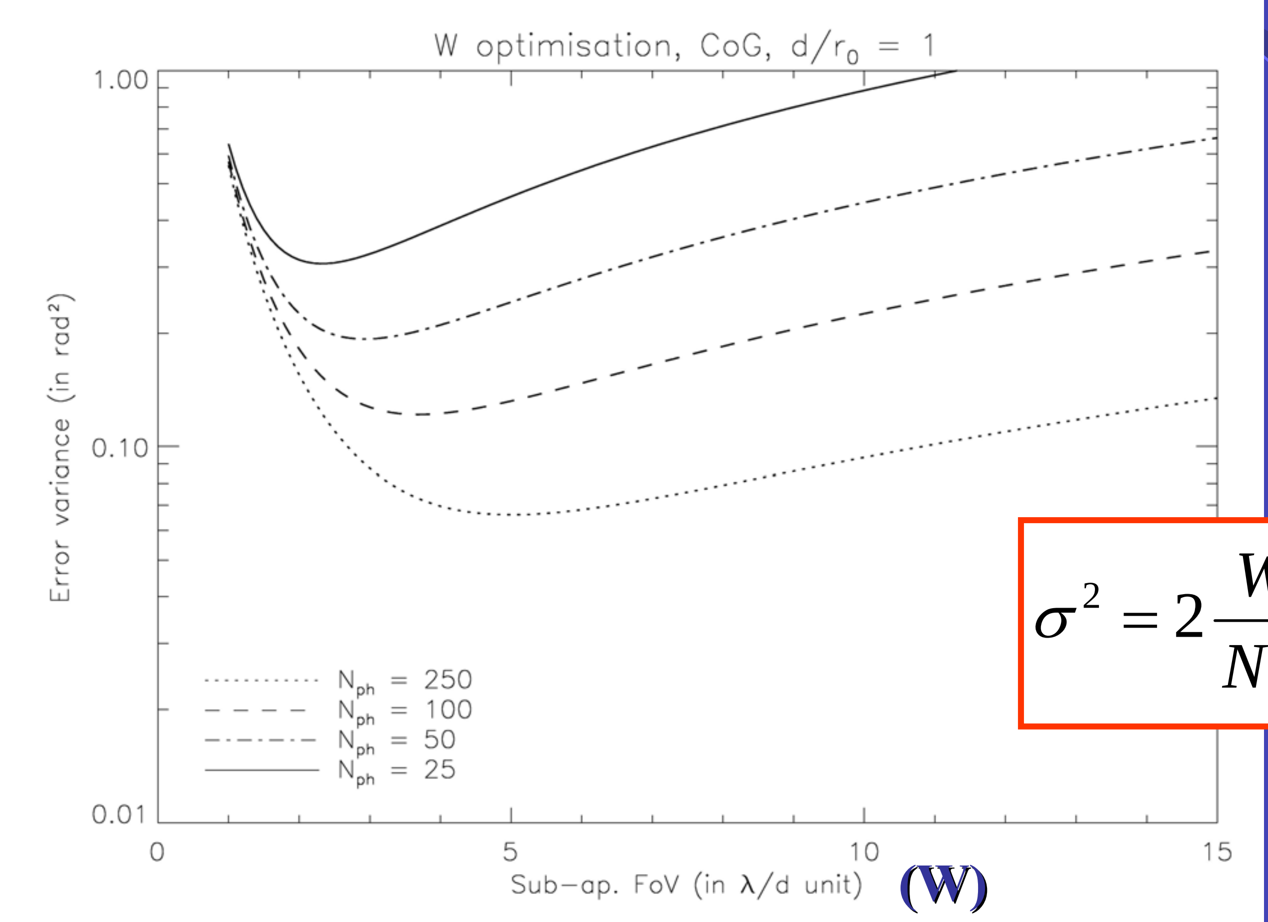
For CoG -correlation

$$\sigma^2_{atm} = 0.5\, W^{-2} \left(d / r_0 \right)^{5/3}$$

For 4Q

$$\sigma^2_{atm} = 0.07 \left(d / r_0 \right)^{5/3}$$

W optimization



(W)

Photon noise and atmospherical turbulence

$$\sigma^2 = 2\frac{W}{N_{ph}} + 0.5\,W^{-2}\left(d/r_0\right)^{5/3}$$

Weak turbulence

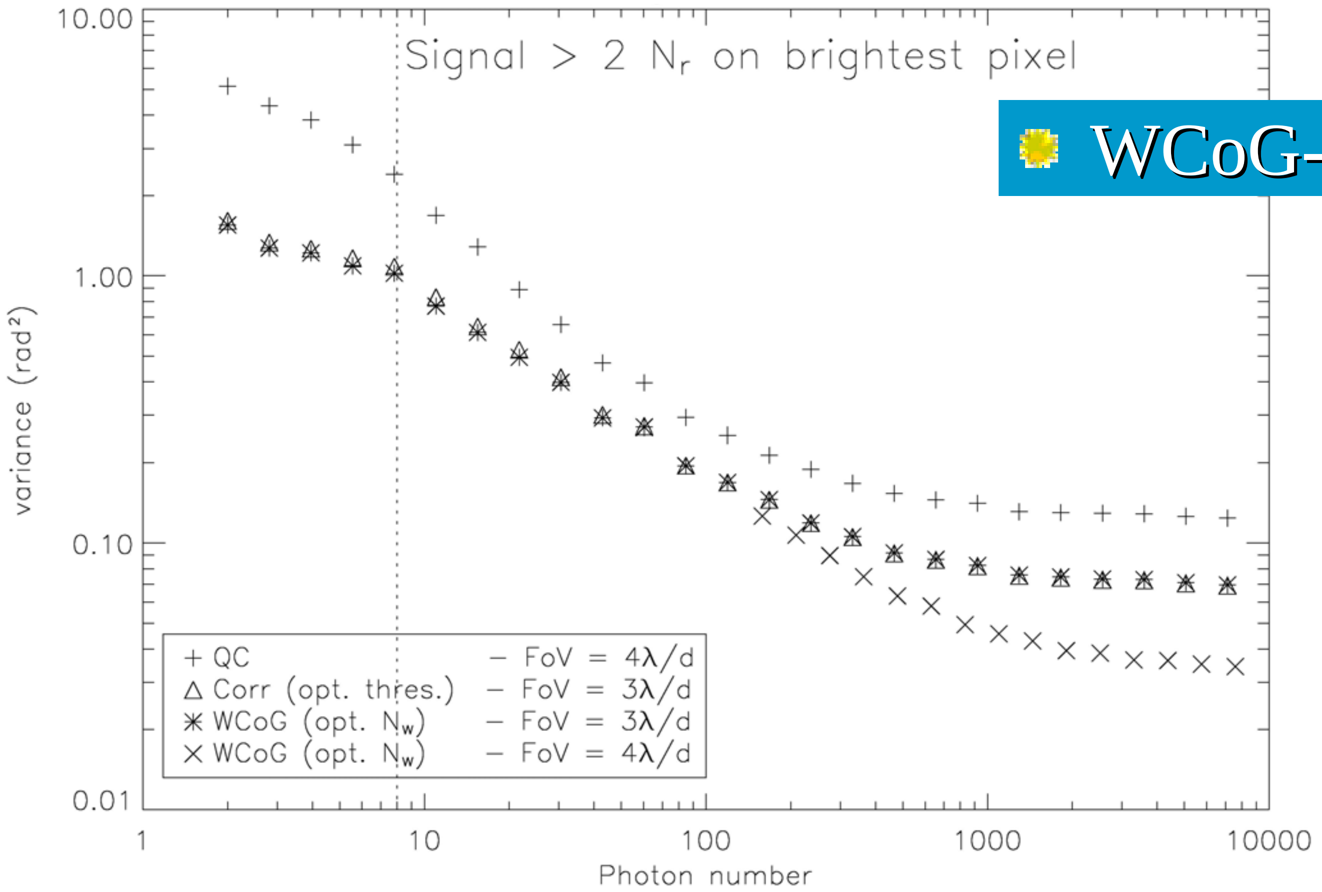
Methods comparison

	Pros	Cons
Thresholding –Windowing	Reduction of noisy pixels	Not robust at low flux
Quad Cell	Robustness and good noise propagation at low flux and high N_r	Response coefficient to adjust and difficult to estimate Non-linear, not precise at high flux
Weigthed windowing	Robustness and good noise propagation	Response coefficient to adjust
Correlation	Independent from the size and shape of the spot	Peak determination Big calculation

By adapting the parameters for each method, it is possible to find the minimum error with the minimum of changes

Example 1: Planet Finder

Nyquist, N_r= 0.5 e-, d/r_0=1



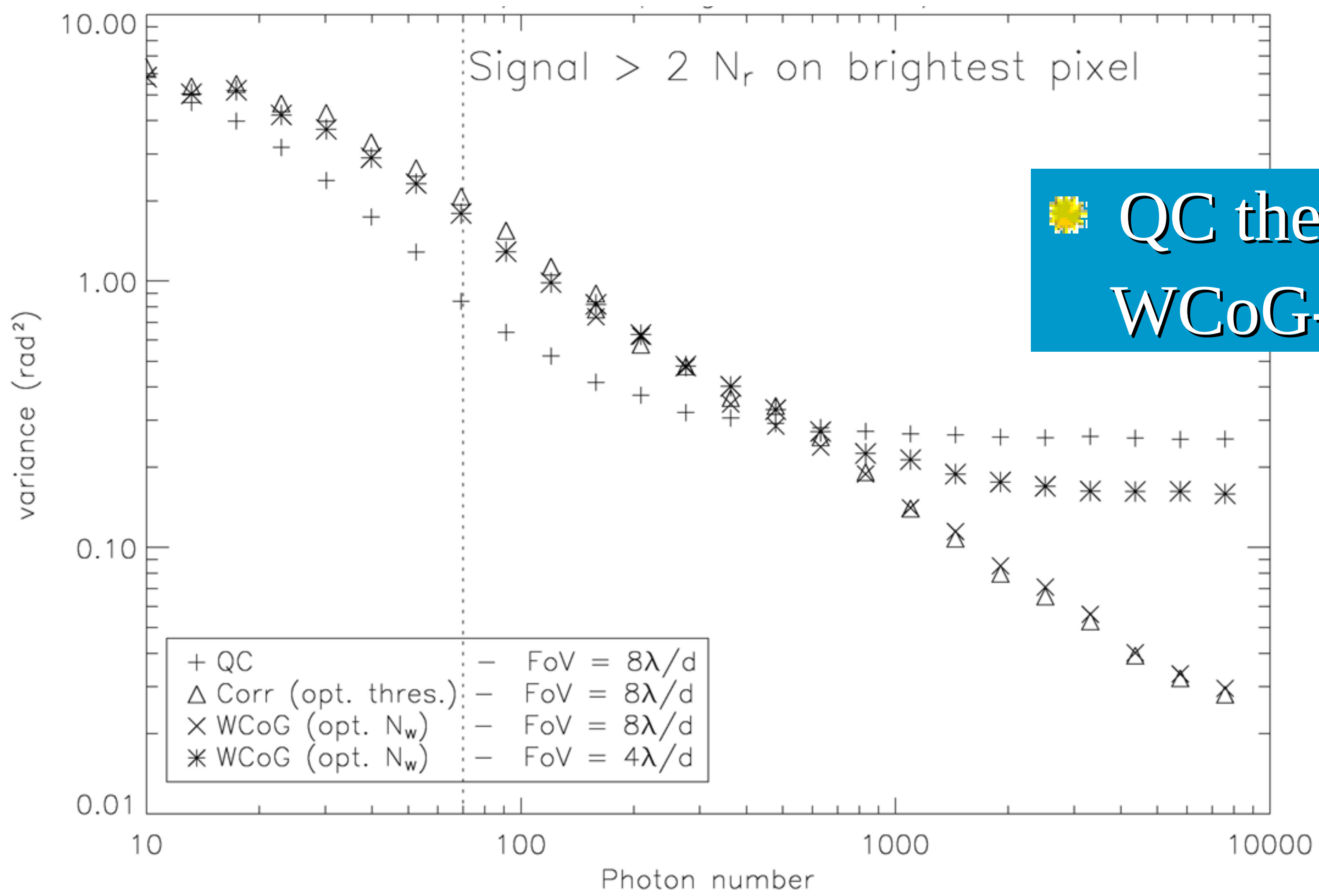
- WCoG-Correlation

SAM WFS

- Shack-Hartmann
  - 10x10 sub-apertures
  - 8x8 pixels per subapertures
  - UV-Visible (100-1100 nm)
- CCD-39 EEV + controler SDSU-III
  - Readout noise = 5.9e$^-$ at 200 Hz
  - Binning capacity (1x1, 2x2, 4x4)

Example 2: SAM

Nyquist/2, N_r = 5 e-, d/r_0=2



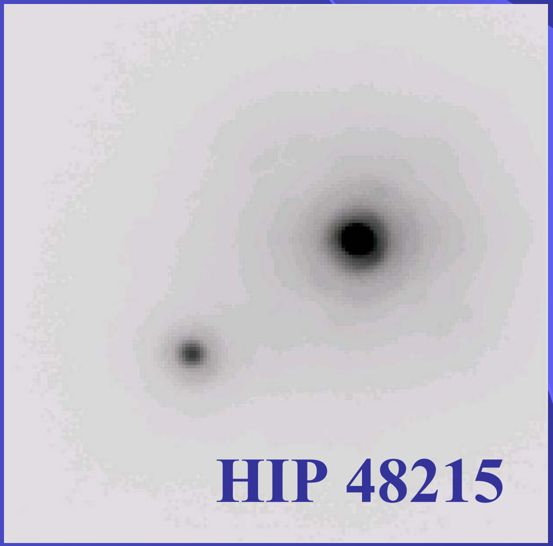
- QC then WCoG-correlation

Conclusions 1

- Adaptive optics wide FoV in the visible
- Study of the main components of SAM
  - TurSim: Development et validation
  - MD: Validation and test of 2 types of mirror
  - Contribution to the optical design
  - Development and use of a prototype
- Theoretical study and simulation of a SH WFS:
  - Definition of an error budget
  - Comparison of different methods of spot position
  - Development of analytical expressions
  - Application to different type of systems

Search for tertiary companions to close spectroscopic binaries

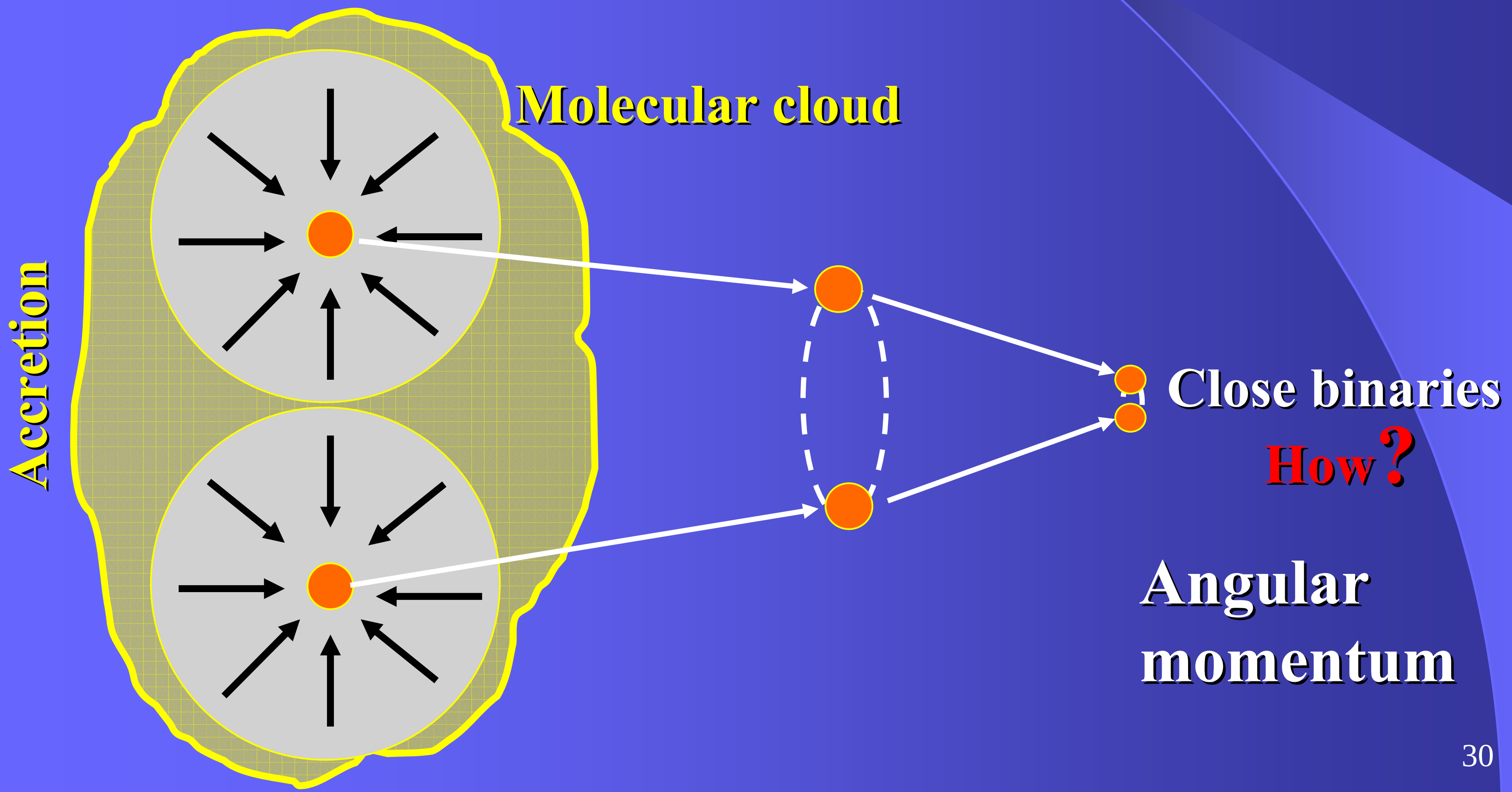
In collaboration with A. Tokovinin, M. Sterzik, S. Udry



Tokovinin A., Thomas S., Sterzik M., Udry S., A&A, 2006

Context

How do we explain the separation of close binaries of a few days?

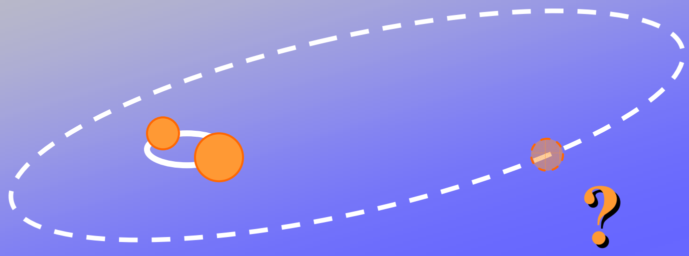


Close binaries formation

- Idea: *orbital shrinkage*
- Magnetic breaking or disk breaking…
- Evolution like Kozai cycle (Kozai 1962)

Hypothesis: deposition of the angular momentum in a tertiary component

Existence = Melo et al. 2001, Simulations: Sterzik et al. 2003



Eggleton 2001,
Kiseleva-Eggleton, 2004

Question:

Are tertiaries needed in the SBs formation?

Are all SBs part of a multiple system?

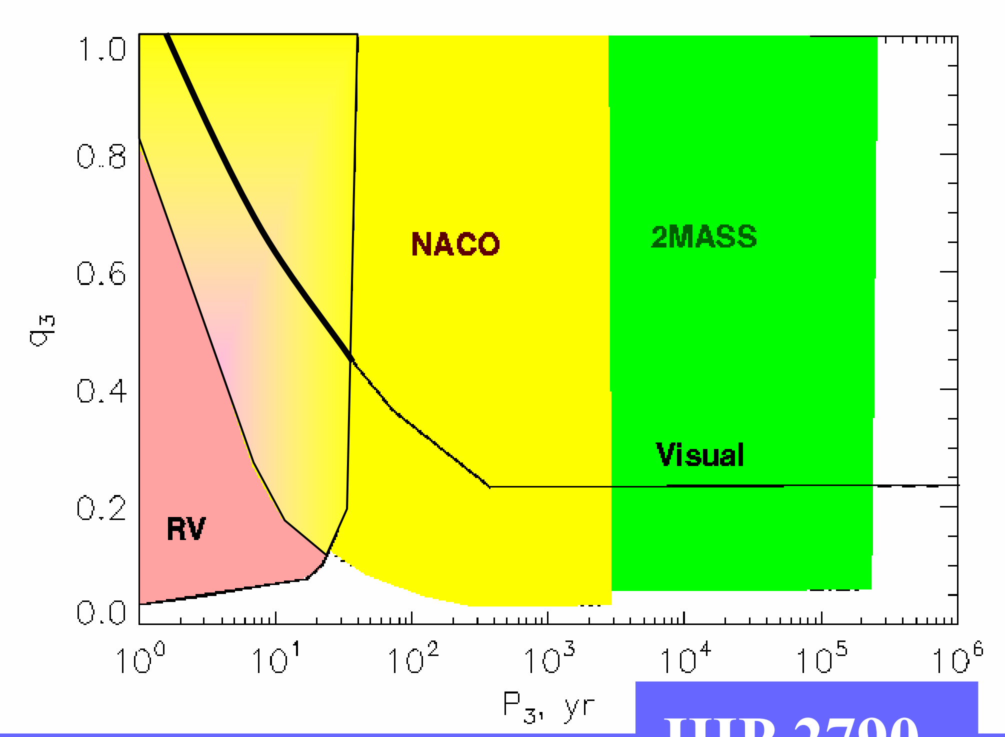
Tertiary detection

Sample

- Close < 100pc (Hipparcos)
  larger separations
- Periods [1j – 30j]
- CORALIE, Batten et al. (1989), recent paper
- Dwarfs from 0.4 to 1.7 M.

(more numerous, close, not too bright and sharp lines.)

Technics



HIP 2790
30pc, G8V

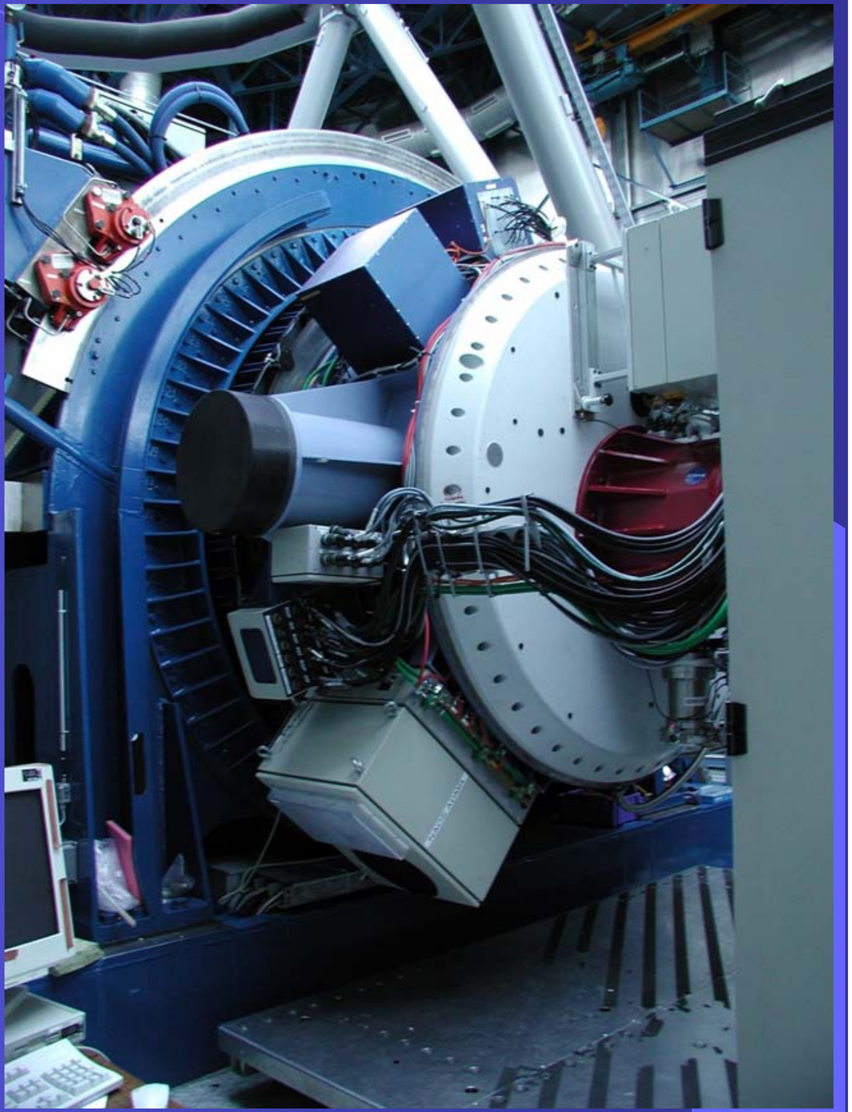
165 SBs in 161 systems

NACO: AO on Yepun (VLT4)

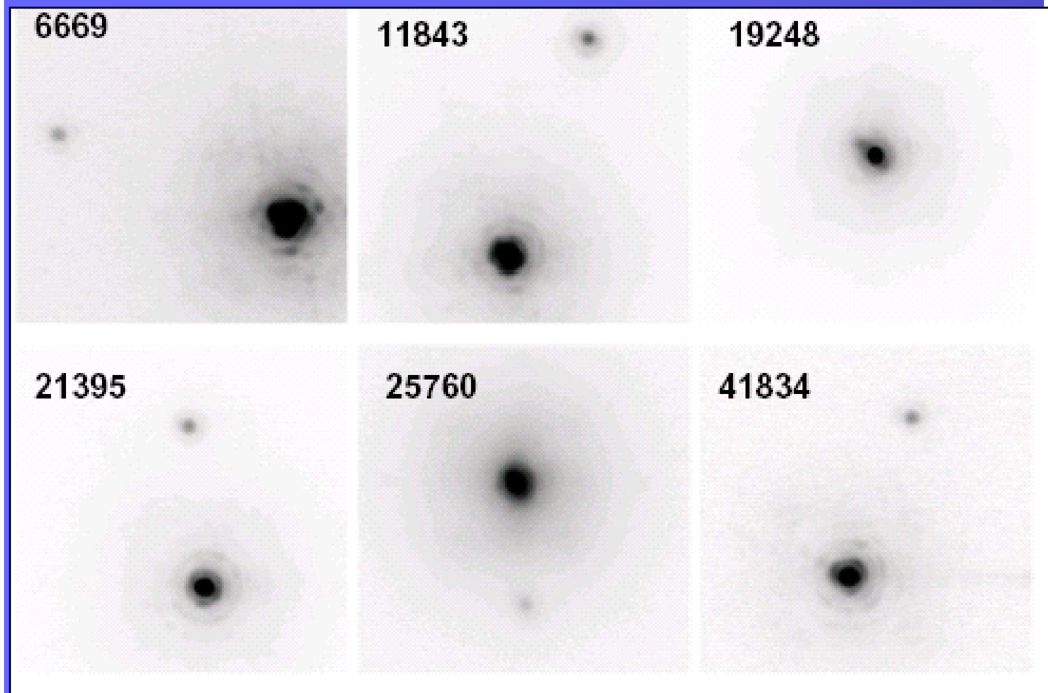
- NACO: Imagery, polarimetry, spectroscopy, coronography
- λ = 1-5 µm.
- R ~ 50% in K band with a reference star of V=12

- 2 runs: Novembre 2004 and July 2005
- Band K + bands J H for some of Nov.
- 72 objects observed + 2 calibrators

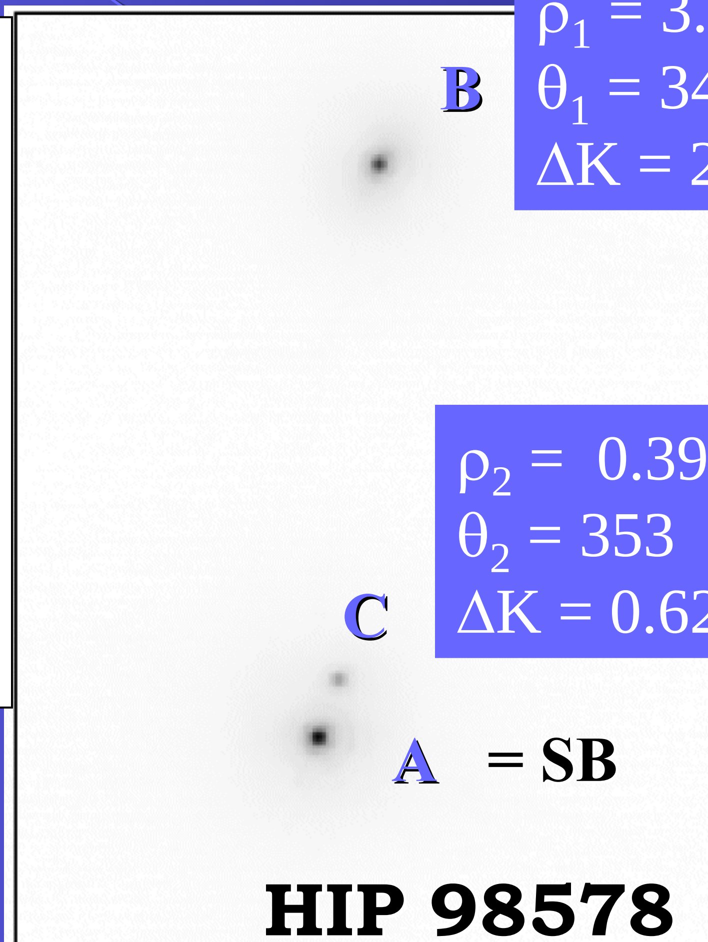
⇒ 1pixel = 13.30 mas



Example of companions



Representative narrow-band images FoV = 2'' x 2''

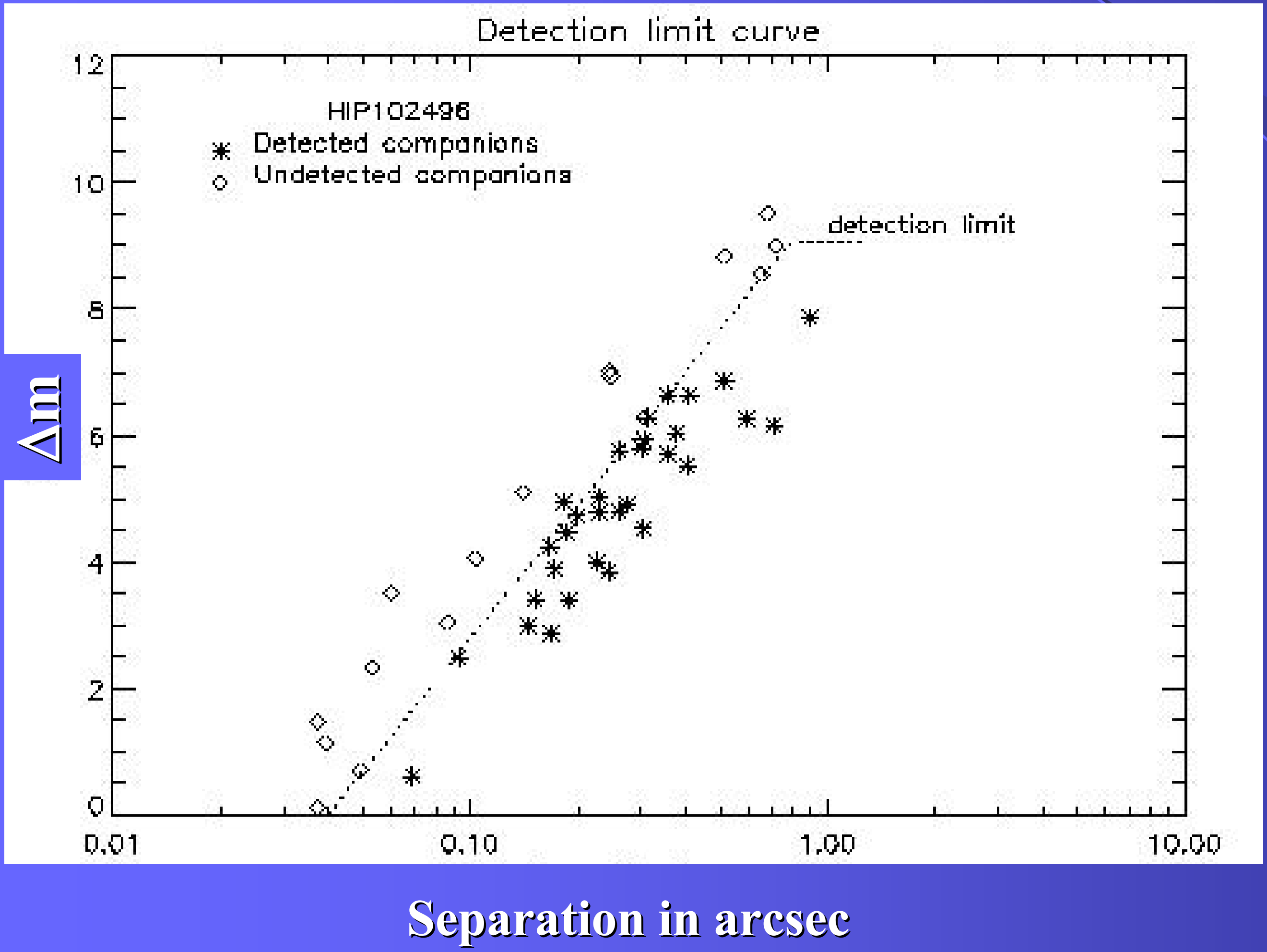


Data reduction

- **Regular data reduction, package Eclipse**
- **DAOPHOT procedure: fitting of the image with the primary.**
- **PSF extraction**

- ***Position error* = 0.5 mas if $\Delta m<3^m$ and 5 mas if $\Delta m=5^m$**
- ***rms magnitude difference error* = 0.02^m if $\Delta m<3^m$ and 0.05^m if $\Delta m=5^m$**

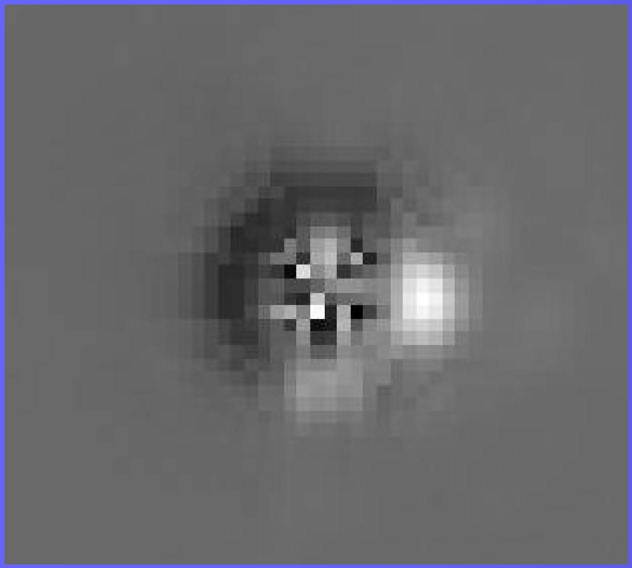
Detection limit



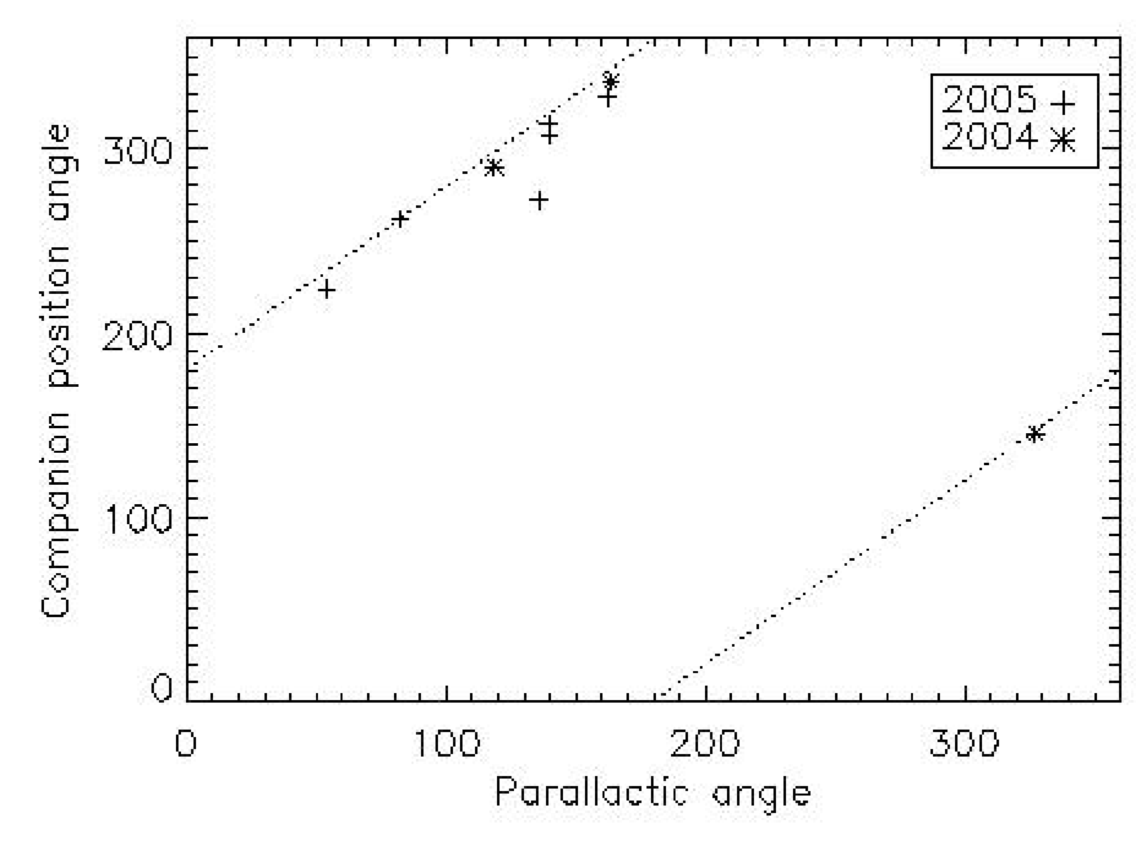
- 3σ detection from $I(r,\theta)$
- Check with simulation
- Model

False detections

$\rho = 0.1''$, $\Delta m = 3$



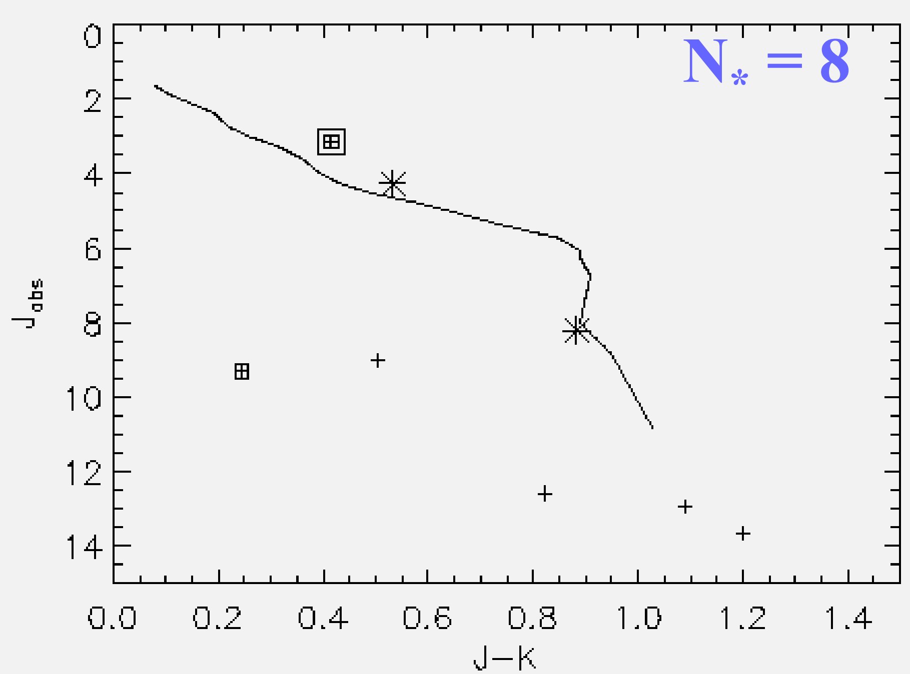
HIP86289



Search for wider companions

2MASS

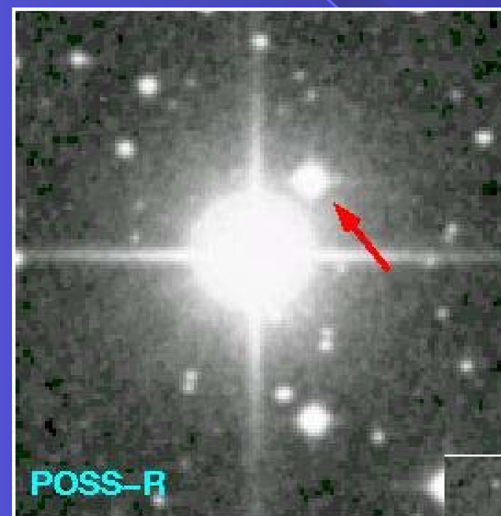
1. Extract data, ρ<2’
2. Plot CMD (*J*, *J-K*)
3. Select candidates < 0.2^m from the main sequence

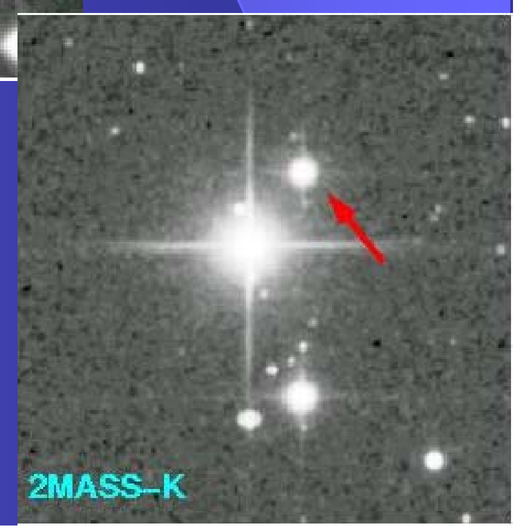


2 physical companions

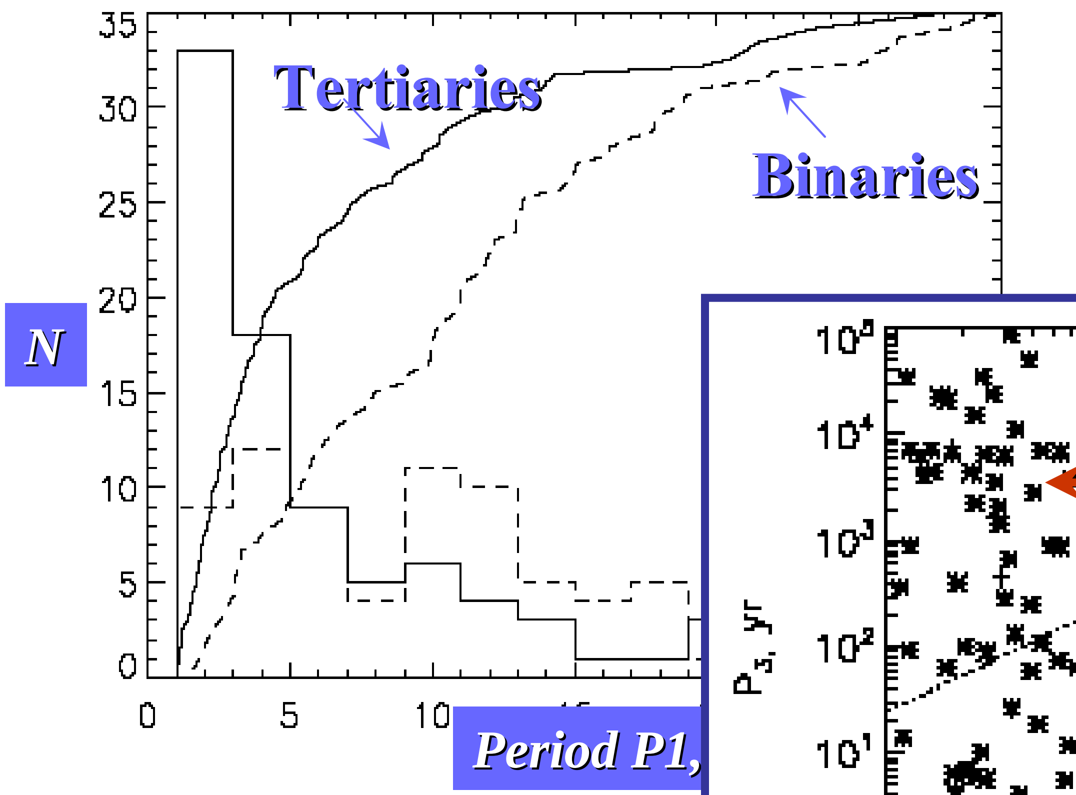
POSS:

Palomar Observatory Sky Survey

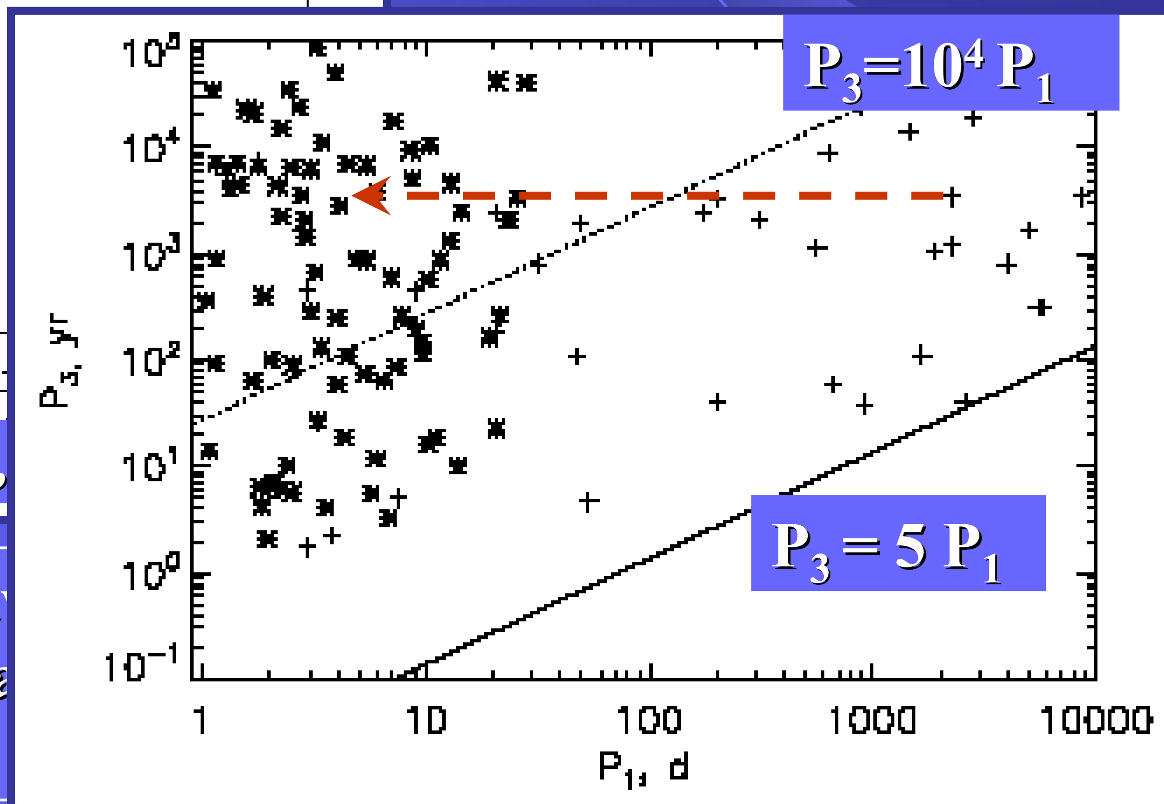




Period distribution



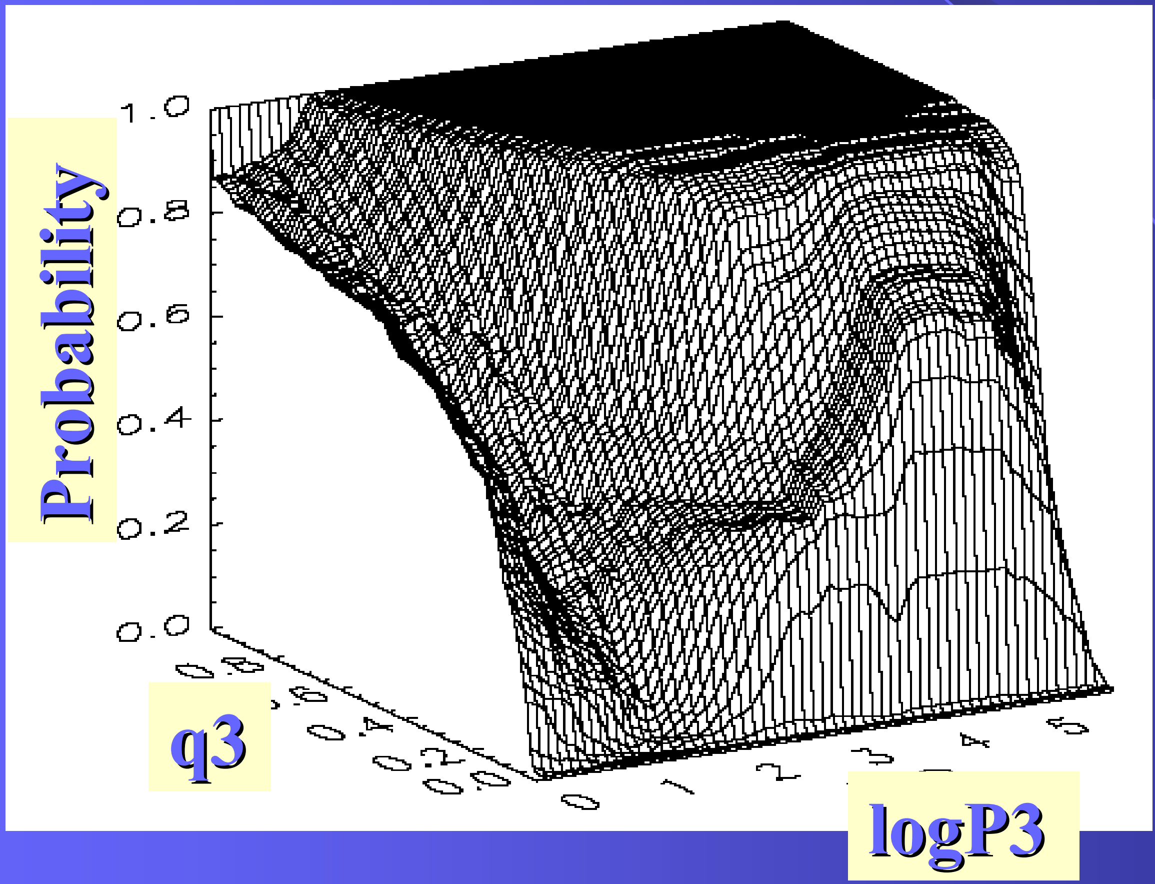
+ MSC catalog (Tokovinin,1997)
∗ Our observations



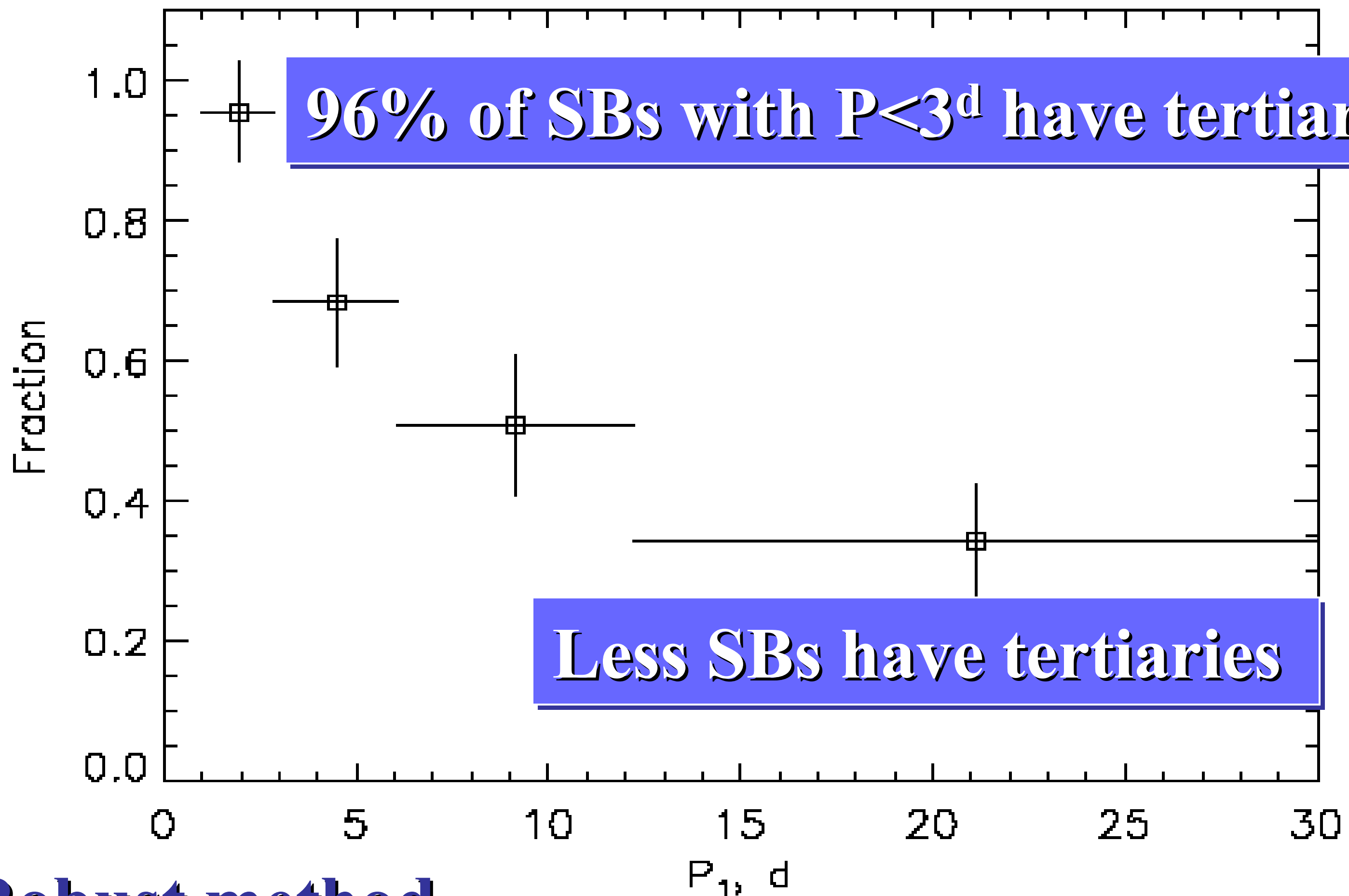
SBs with a tertiaires hav
significatively larger fra
systems with $P_1<10^d$

Correction for incomplete detection

- *Correction done by maximum likelyhood*



Fraction of tertiary vs SB's period



96% of SBs with $P<3^d$ have tertiaries

Less SBs have tertiaries

Robust method

Conclusions 2

- Tertiary fraction depends on the period P_1 of the SBs
  - For $P_1<3^d$, almost all SBs $\in$ multiple systems
  - If P_1 is bigger, $\exists$ pure SBs. Tertiary frequency < one of solar type systems
- Different period distribution between triple and binaries
- Same mass distribution
- No relation between P_1 and P_3
- Most massive component = closest one

- $\exists$ pure SBs $\Rightarrow$ no Kozai cycle

Hyp: accretion, disk braking.

SBs could have lost their tertiaries.

Perspectives

- Implementation of GLAO systems
- 1st generation of AO for the ELTs
- Follow-up of the WFS study in the case of a laser guide star

- Problem of SBs is only partially resolved
- Other science: Brown dwarf formation, Herbig AeBe star formation.

MERCI A TOUS