SPHERE

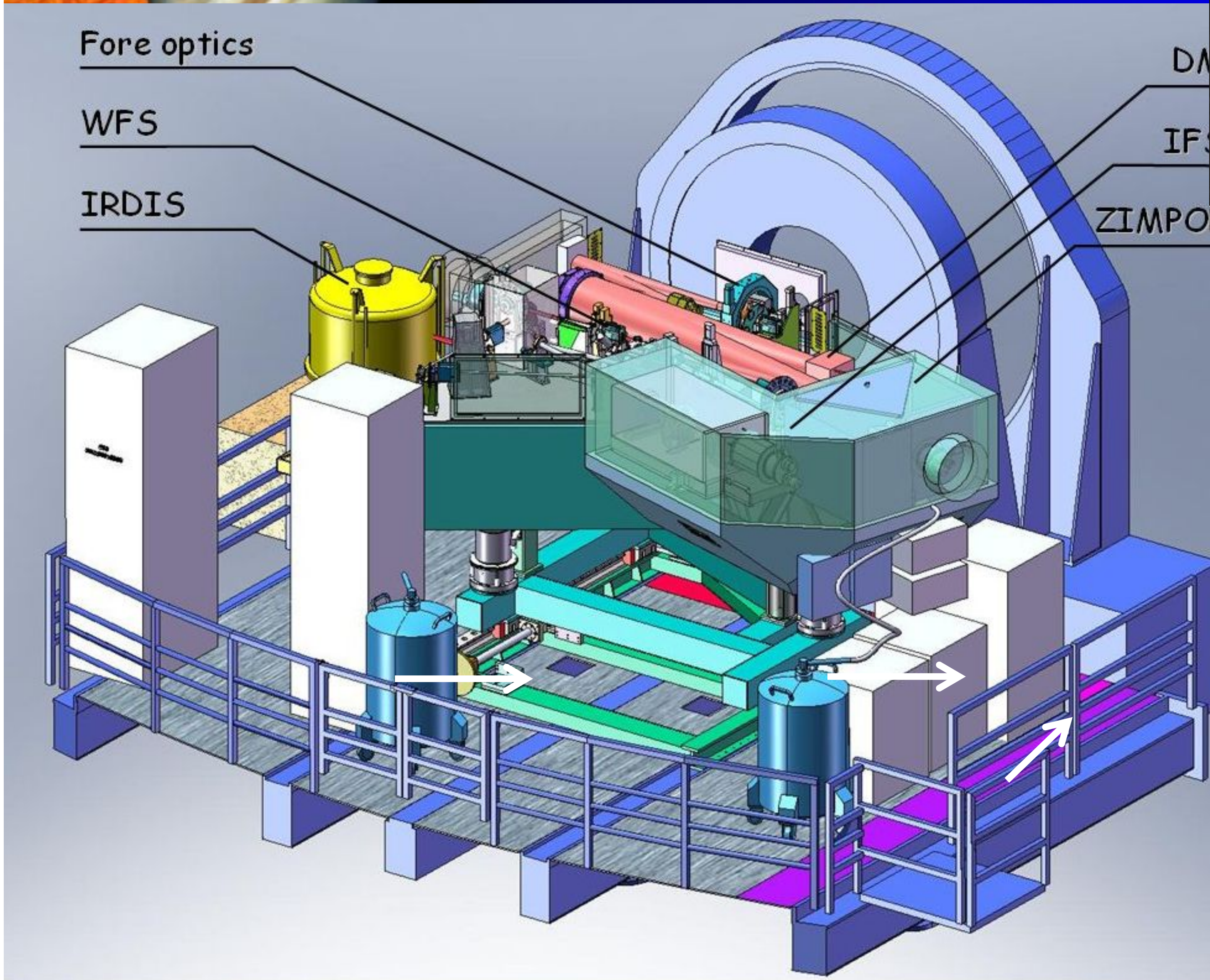
SPHERE:

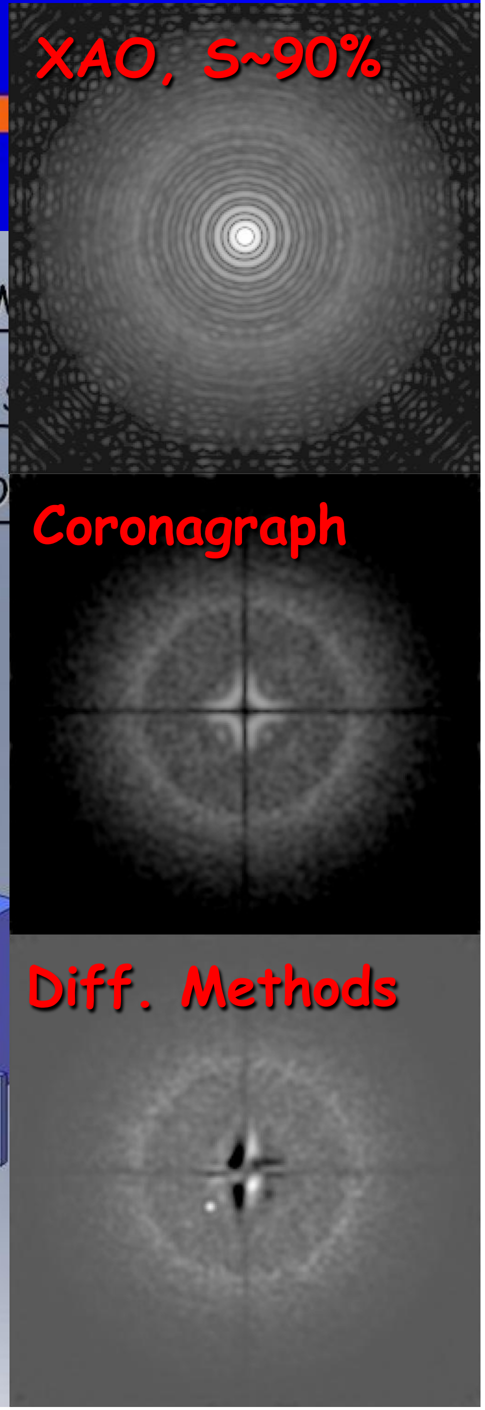
~~Confronting in-lab performance~~

with system analysis predictions

Kjetil Dohlen
SPHERE systems engineer
LAM, Marseille

SPHERE


Fore optics
WFS
IRDIS
D
IF
ZIMPO


XAO, S~90%
Coronagraph
Diff. Methods

SPHERE

System overview

- Integrated system
- Dedicated to high dynamic range imaging
  - Lots of stuff
    - Selectable coronagraphs, Vis and NIR
    - Pupil stabilisation
    - Differential TT control
    - etc
  - But none of the “nice to have” features that classical AO would be tempted to include
    - No field selector
    - No general purpose IR WFS
    - etc

SPHERE

System overview

- Present here some optical aspects of system analysis and performance prediction

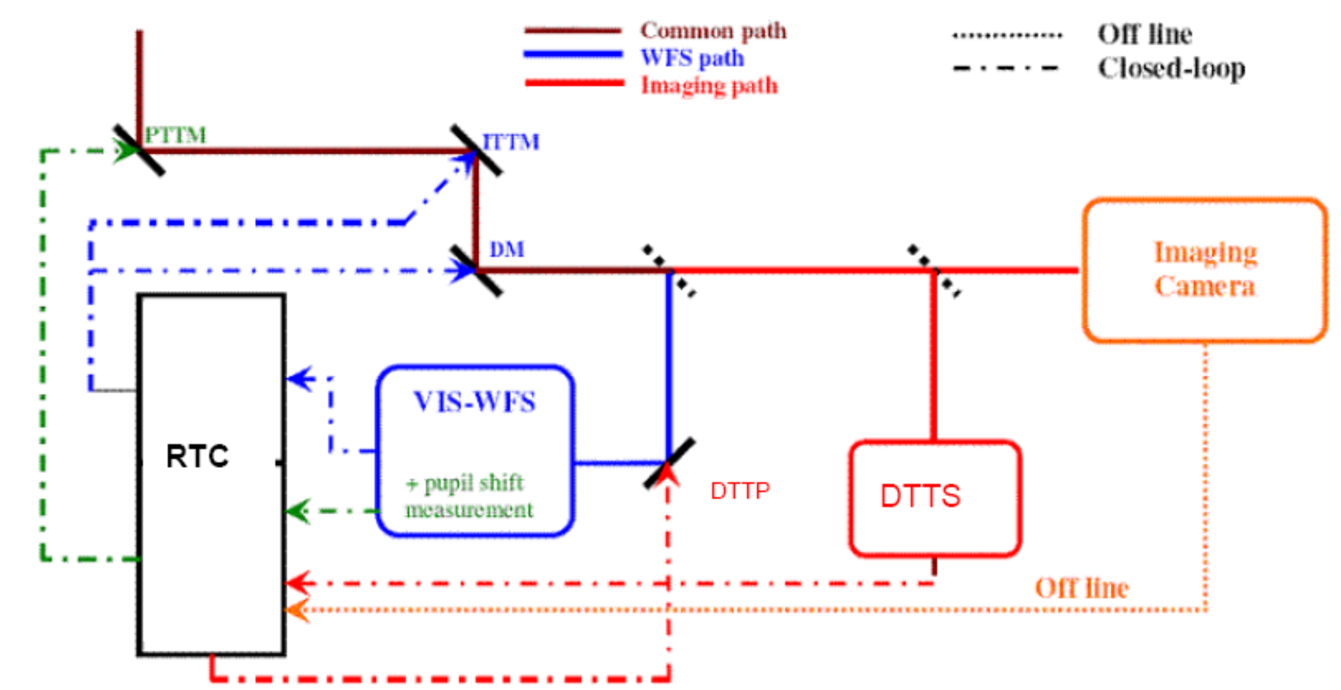
- In reality the system includes far more
  - Tribute to a large group of people working on all aspects, opto-mechanical design and integration to motor control, instrument software, and data reduction

- Consortium with participants from labs all across Europe, ESO, and several industrial companies

SPHERE

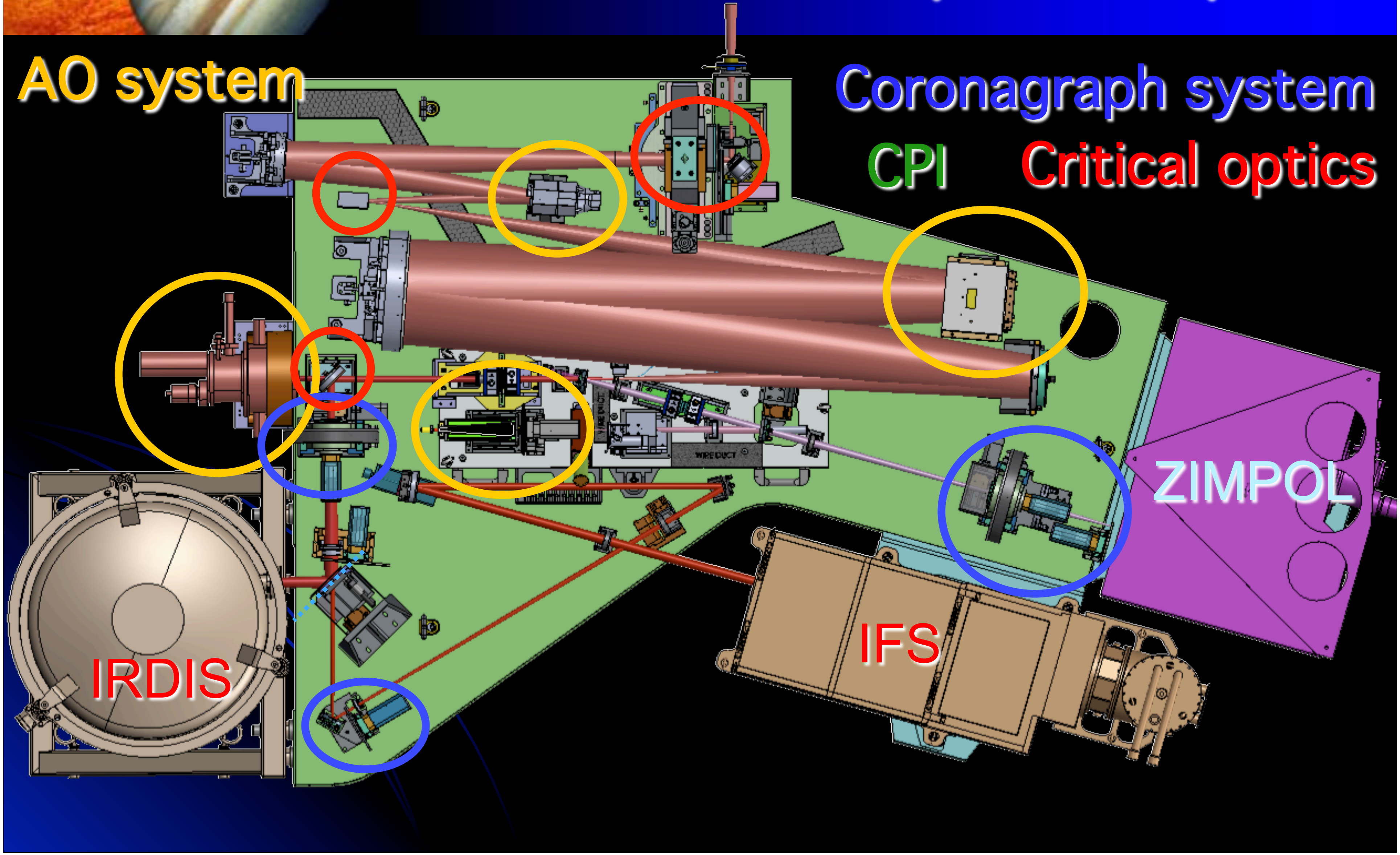
Adaptive optics features

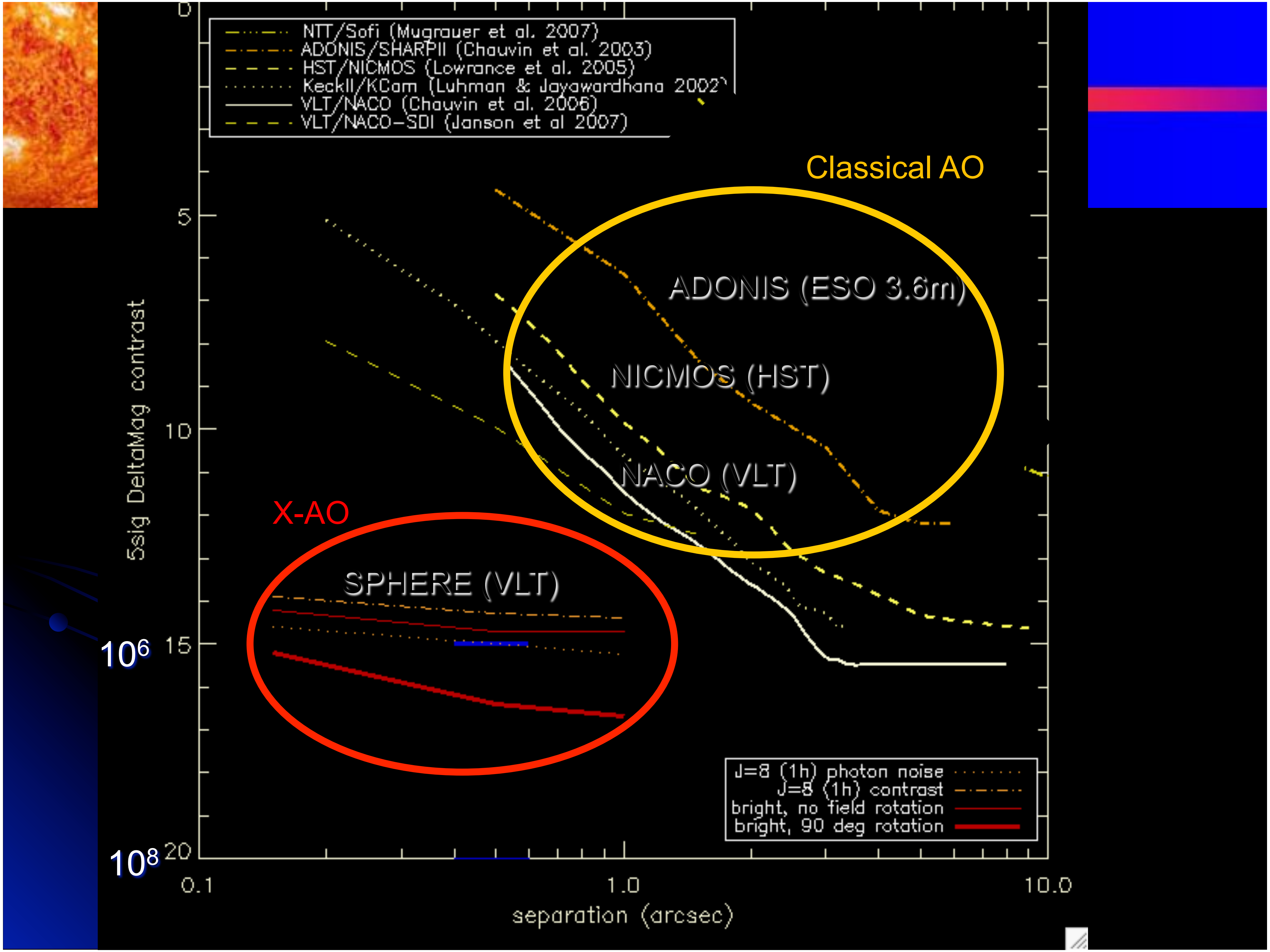
- Image stability essential for the coronagraphic PSF
  - Differential atmospheric dispersion
  - Thermo-mechanical drift
- Differential TT sensor implemented
- NCPA calibration
  - Phase Diversity algorithm
  - Minimizes aberrations in the coronagraph plane
  - Corrects at least 55 Zernike modes (up to about 4c/pup)



SPHERE

Optical lay-out

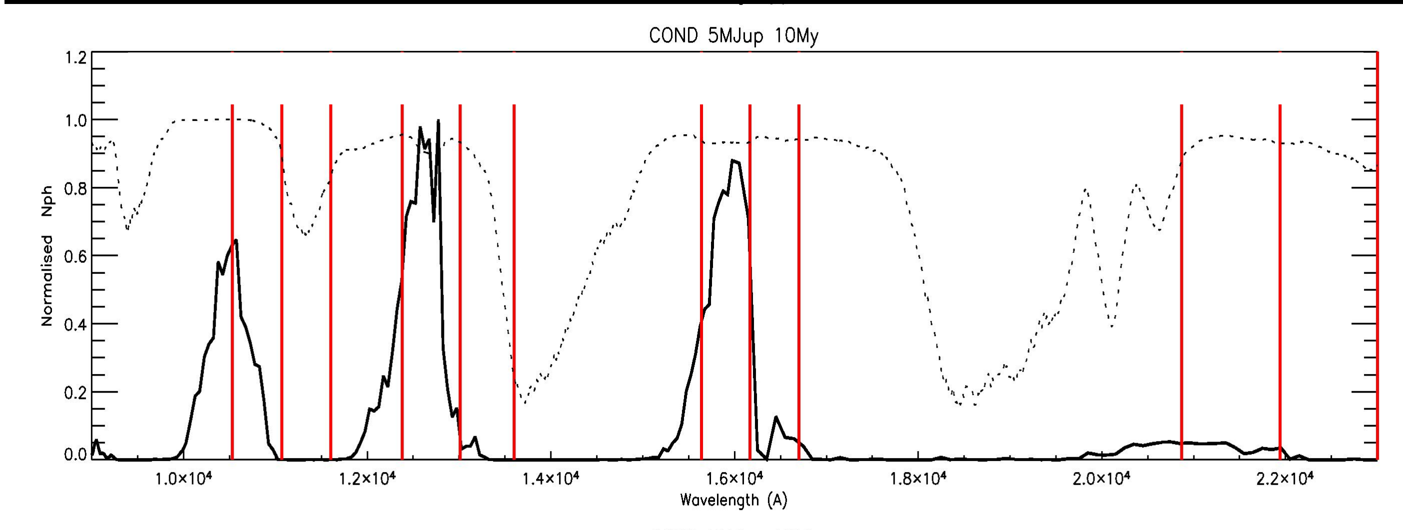




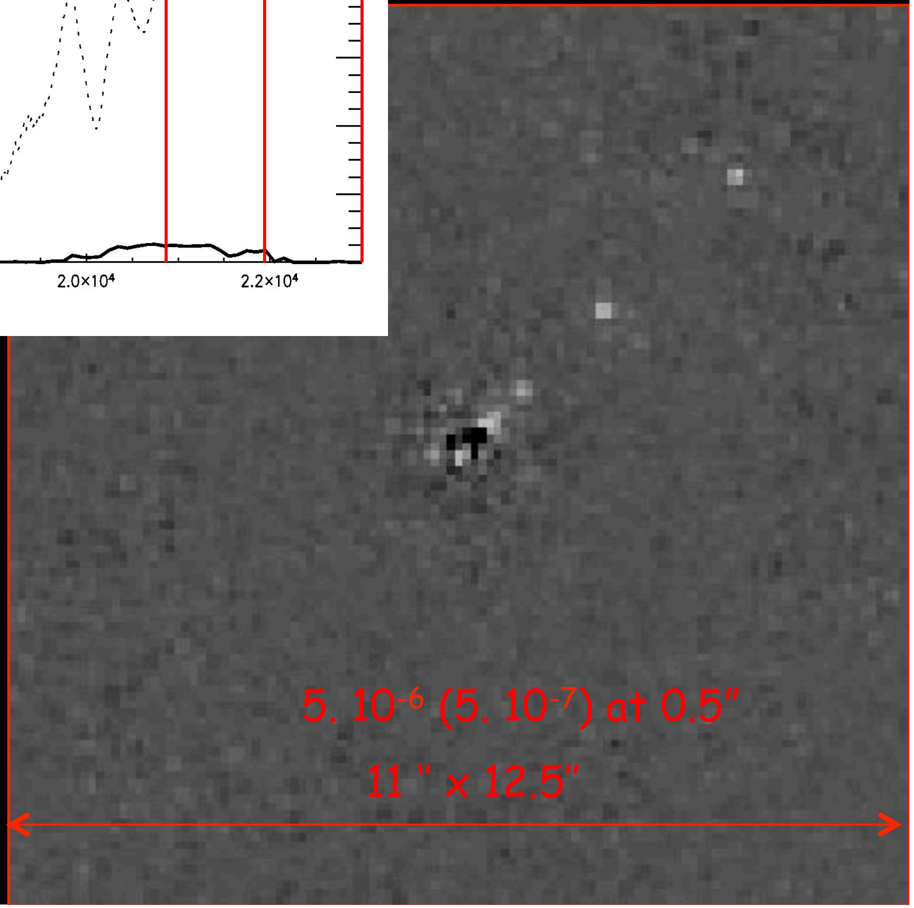
NTT/Sofi (Mugrauer et al. 2007)
ADONIS/SHARPII (Chauvin et al. 2003)
HST/NICMOS (Lowrance et al. 2005)
KeckII/KCam (Luhman & Jayawardhana 2002)
VLT/NACO (Chauvin et al. 2006)
VLT/NACO-SDI (Janson et al 2007)
Classical AO
ADONIS (ESO 3.6m)
NICMOS (HST)
NACO (VLT)
X-AO
SPHERE (VLT)
5sig DeltaMag contrast
5
10
15
20
10^6
10^8
0.1
1.0
10.0
separation (arcsec)
J=8 (1h) photon noise
J=8 (1h) contrast
bright, no field rotation
bright, 90 deg rotation

SPHERE

Spectral differential imaging



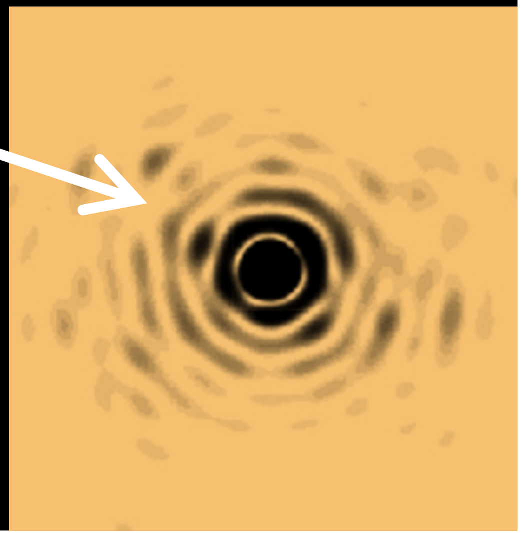
- Speckles scale with wavelength but the pattern remains mostly constant
- How constant?
- Which performance criterion?



SPHERE

Imaging theory: Fraunhofer approximation

- Assuming all optics in the pupil plane
- Image is Fourier transform of the pupil
- For small aberrations, PSF essentially described by three terms
  - The Airy pattern
  - The wavefront Power Spectral Density (PSD)
  - A cross term: Pinned Speckles
- A perfect coronagraph removes the Airy pattern and the Pinned Speckles
- Left with the PSD

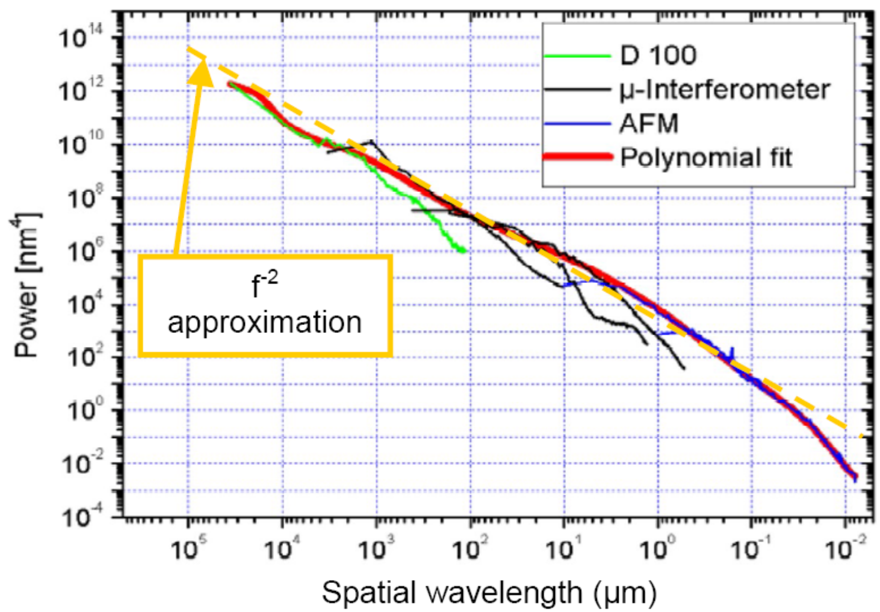


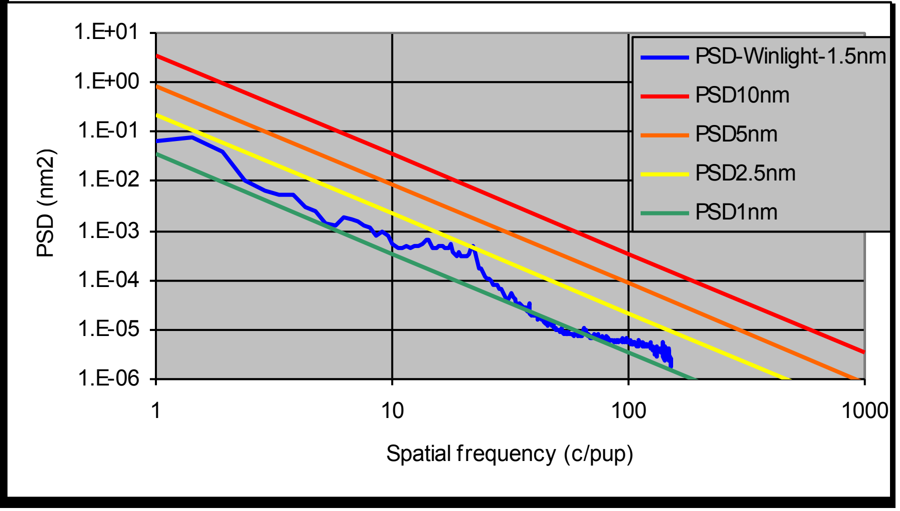
SPHERE

Optics description: PSD

- Residual speckles ~ PSD
  - Proportional to $(WFErms)^2$
  - Hence related to Strehl ratio…
- PSD characterizes error distribution over spatial frequencies
  - Expected speckle intensity at different points in the FOV
  - Exactly what we need
- But cumbersome to use and difficult to communicate
- Good optics tends to follow a $1/f^2$- law
  - Use as working assumption and make budget based on WFErms
  - To account for AO correction and NCPA calibration, define three different budgeting bands:

    Lo – Mid - Hi





SPHERE

PSD model vs AO imaging simulation

- Budget considers assumed azimuthally averaged PSDs for each optical surface
- Total budget obtained by summing individual PSDs
- Provides input to an adaptive optics simulator based on CAOS (eg. Carbillet et al 2008)
  - Takes into account instrumental effects that are not described by the simple PSD model
  - Coronagraph decenter, pupil misalignment, atmospheric residuals, etc
- PSD budget allows optical design trade-offs and fixing optics manufacturing specs

SPHERE

Role of AO in the PSD budget

- AO corrects common-path instrumental aberrations
  - Filter the PSD up to f_{Mid} = 20c/pup
- But adds non-common path aberrations to the science beam
- Calibrate these aberrations using Phase-Diversity
  - Filter the PSD up to f_{Lo} = 4c/pup
- Calibration is not efficient for time variable aberrations
  - Rotating elements (ADCs)
  - Beam shift effects

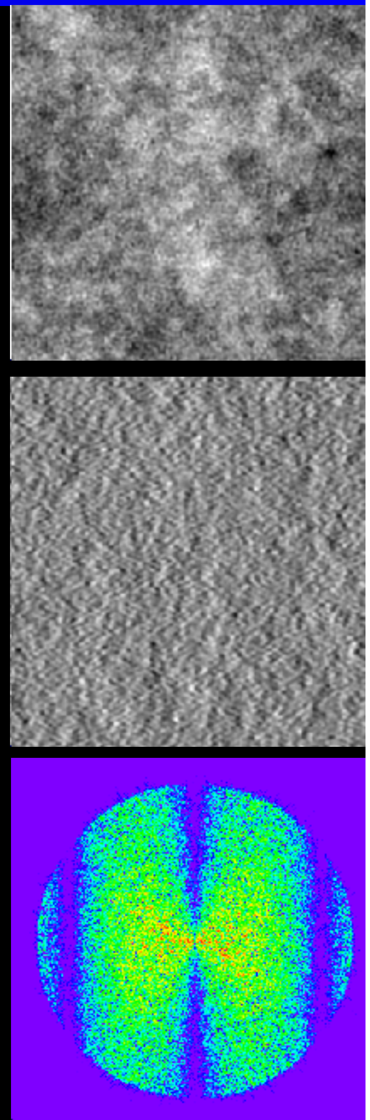
SPHERE

Out-of-pupil aberrations: Beam shift

- Due to atmospheric dispersion, the visible beam (WFS) does not see the same aberrations as the NIR science beam
- Residual error is the difference between two identical phase screens shifted by a fraction $\delta p/d$
- For spatial frequencies $f \ll \delta p/d$, the PSD of the difference is approximately:

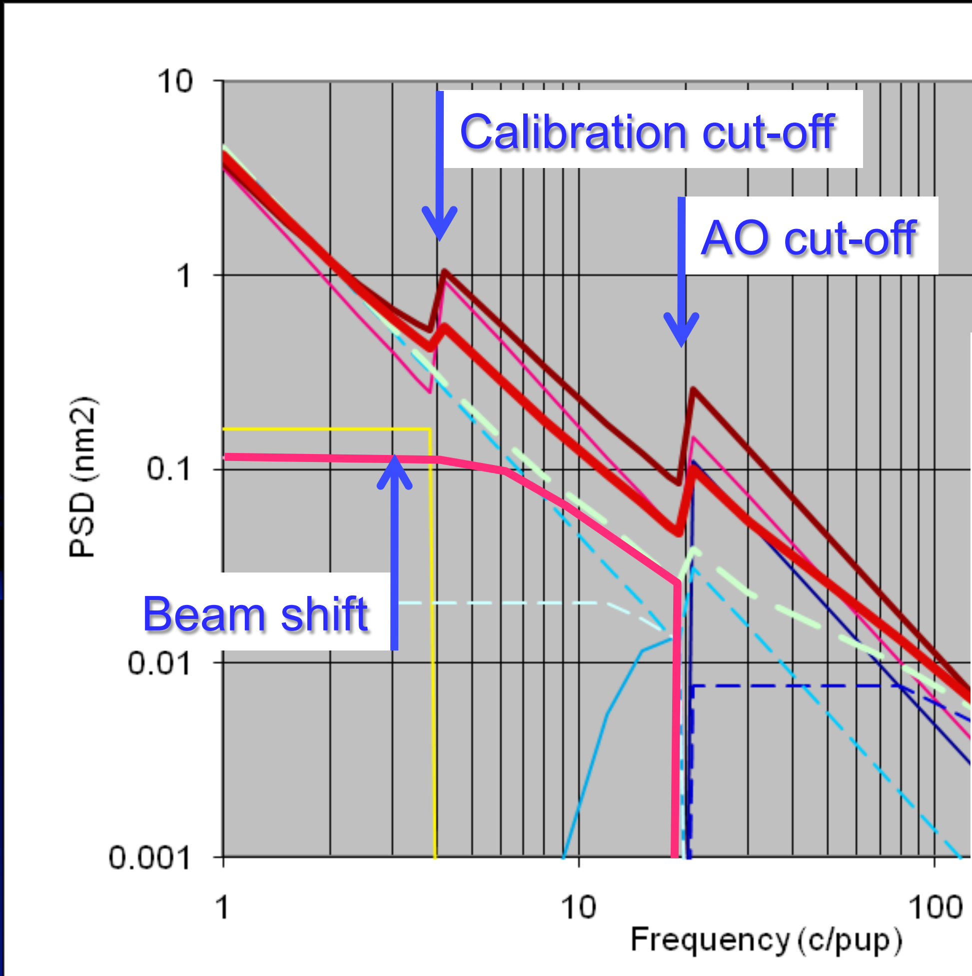
$$\Delta PSD = \left(\frac{2\pi f \delta p}{d}\right)^2 PSD$$

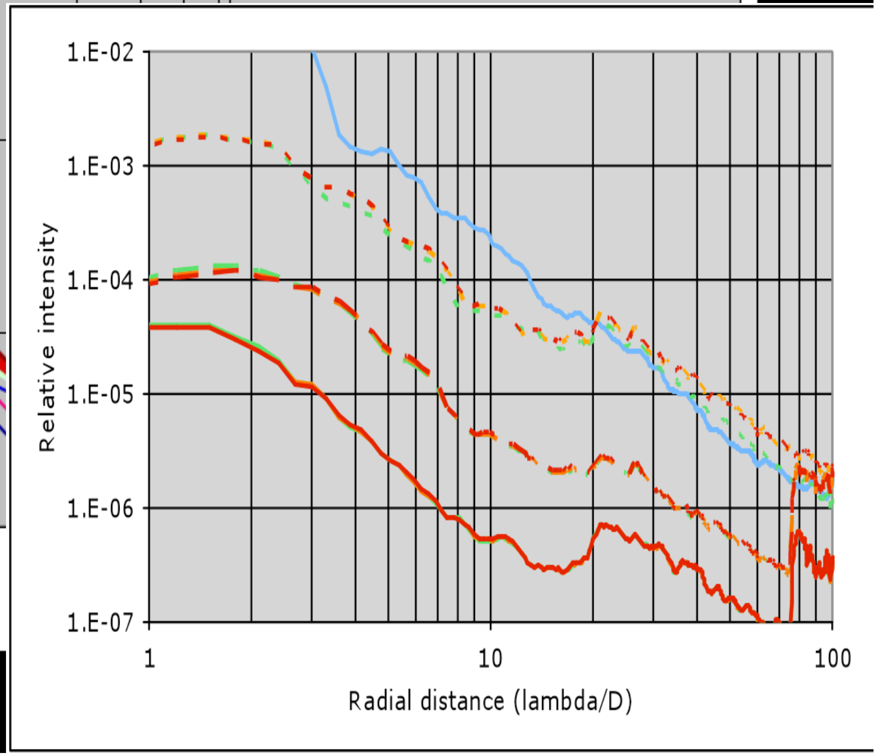
- For our $1/f^2$ model, the result is a constant
- *Affects* mirrors upstream of the dichroic close to image planes:
  - PTTM, Derotator, TM2
- Budgeting these items allowed to fix minimum out-of-image distances for these optics.



SPHERE

Resulting PSD budget





SPHERE

Differential aberrations

- What is the residual after spectral differential imaging?
  - Chromatic speckle evolution
    - Higher order PSF terms
  - Differential aberrations between imaging channels (Cavarroc 2006)

$$\Delta I \propto PSD_{Fore}\,\sigma_{Diff}$$

  - Introduces differential aberrations as important parameter in the budget
- Good balance of various effects is found with WFEdiff = 10nm
  - Set as spec for IRDIS
- Nearly negligible effect found for WFEdiff = 5nm
  - Set as goal
- As-built budget indicates that we are very close to goal
- Confirmed by Phase diversity measurements

SPHERE

Out-of-pupil aberrations: Fresnel effect

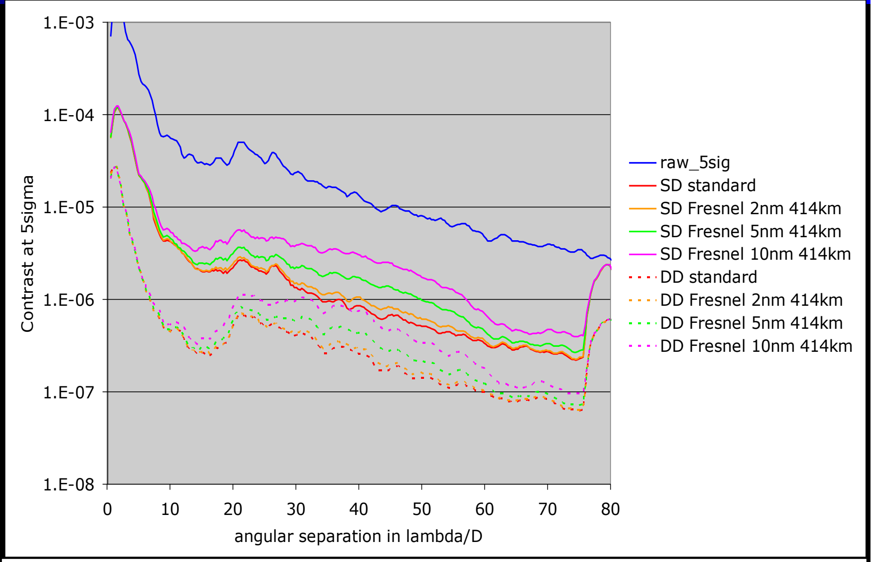
- Treated by Marois et al in 2006
  - Propagation to the pupil plane transforms phase errors into amplitude according to Talbot
  - Depends on wavelength and spatial frequency
- Note that in the case of an ideal coronagraph, an out-of-pupil phase screen alone is OK
- Problem is that a cross term appears when mixing with an in-pupil screen

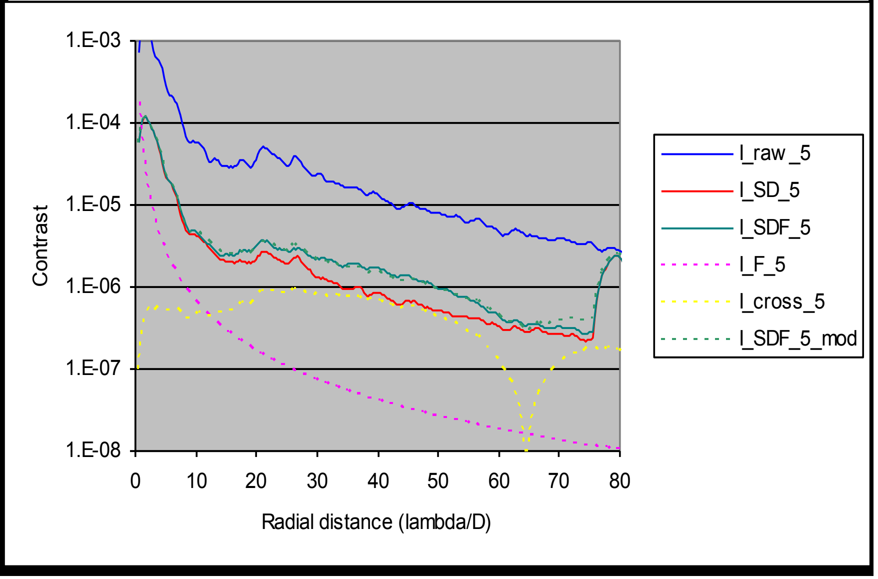
$$I_{SD}^{F} = I_{SD} + \sqrt{I_{Raw} I_{OutPup}} \sin(\pi \Delta N_T)$$

  - The sin term includes the differential Talbot order:

$$\Delta N_T = \frac{h}{L_T} \frac{\Delta\lambda}{\lambda} \qquad L_T = \frac{2\Lambda^2}{\lambda} = \frac{2(D/f)^2}{\lambda}$$

- "Bulge " appears, peaking at $\Delta N_T = 0.5$
- CAOS simulations confirm this simple model
  - To avoid the bulge within the AO corrected area, need h<2000km
  - Most critical surface in SPHERE is DTTS BS: h=420km
  - Specified and manufactured to 5nm rms

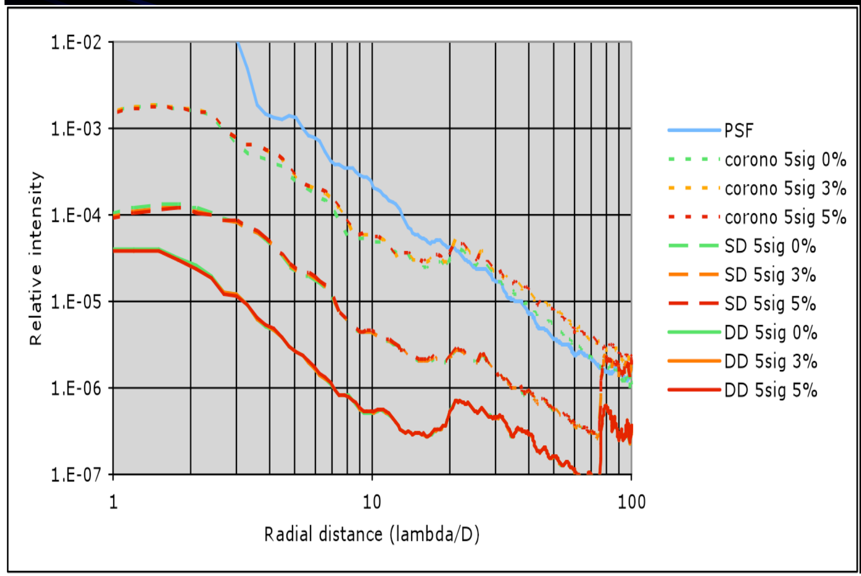


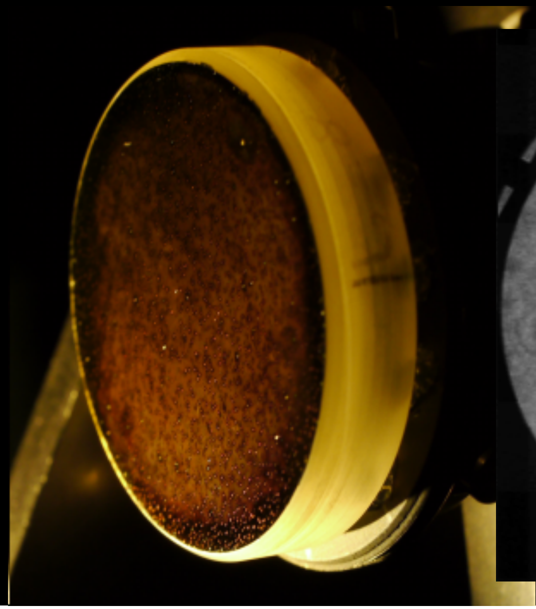


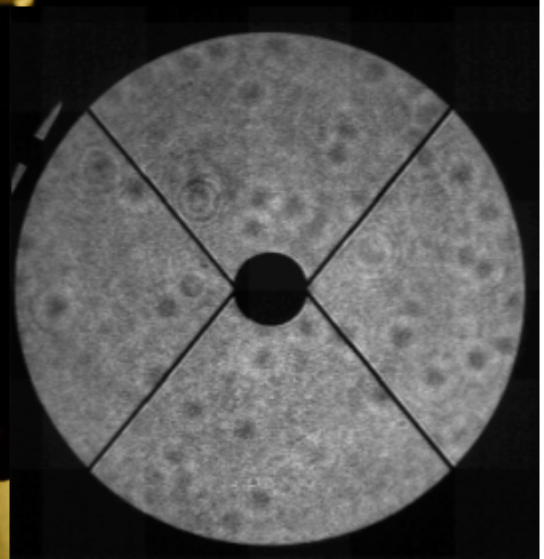
SPHERE

Transmission non-uniformity

- By simulations established that this is not very critical
- Assume a total budget of 5% rms variation
  - Insignificant performance reduction
  - Allocate 0.5% to each instrument optics (not measured)
  - Leave 4.5% to the telescope optics (not measured)
- Should be OK
- ... if it wasn't for degradation of mirrors occurring since a few weeks







SPHERE

Conclusions

- WFE budget elaborated in terms of PSD
  - Accounts for numerous instrumental effects such as beam shift etc
  - As-built budgets are conforming with design
  - Differential aberrations at goal spec
- Feeds into performance simulations
  - CAOS software package
  - Module for Fresnel effect implemented
- Predicted double difference performance in the NIR compatible with goal specs
  - 10-5 at 0.1"
  - 5. 10-7 at 0.5"
- Main current high-risk item: Mirror coatings

SPHERE