SPHERE

Current performance and future prospects of the extreme-AO instruments SPHERE after 3 years of operations

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Content

1. SPHERE in a nutshell
2. Performance vs atmospheric conditions
3. Limitations and possible improvements

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1. **SPHERE in a nutshell**
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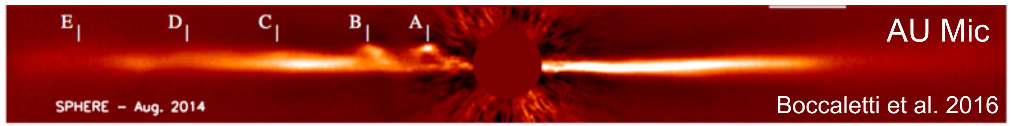
SPHERE: 3 science machines in one

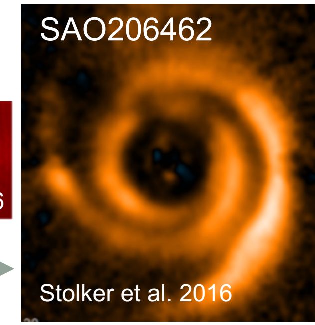
IRDIS: the NIR dual-band (polarimetric) imager

Narrow and broad band filters
"Large" field of view 12"x12"
Polarimetric capabilities

Disk characterization

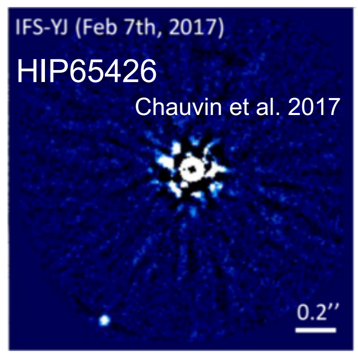


12"

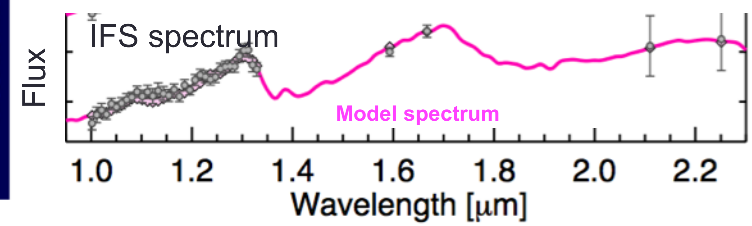


IFS: the NIR integral field spectrograph

Spectral resolution of 30 (Y to H) or 50 (Y to J)
Deepest contrast using the spectral dimension

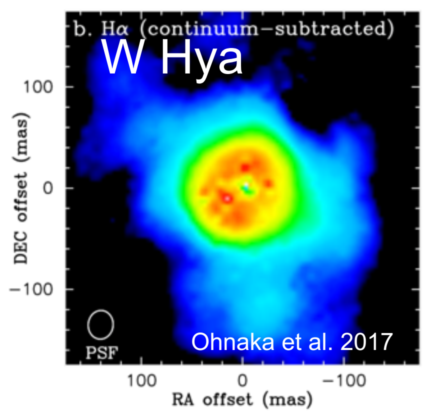


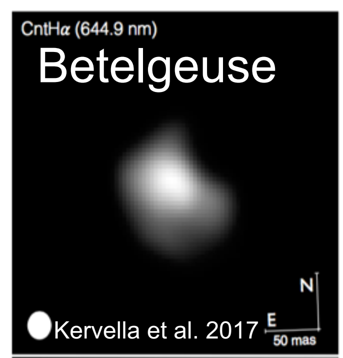
Exoplanet characterization



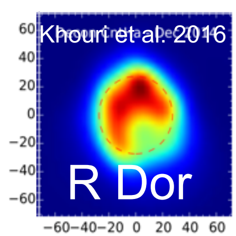
Zimpol: the optical polarimetric imager

Fast switching polarimetry
Highest angular resolution (15mas)

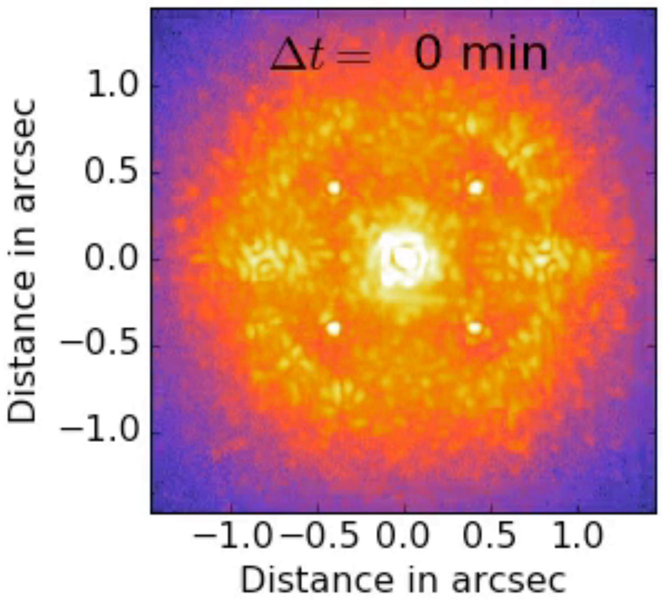


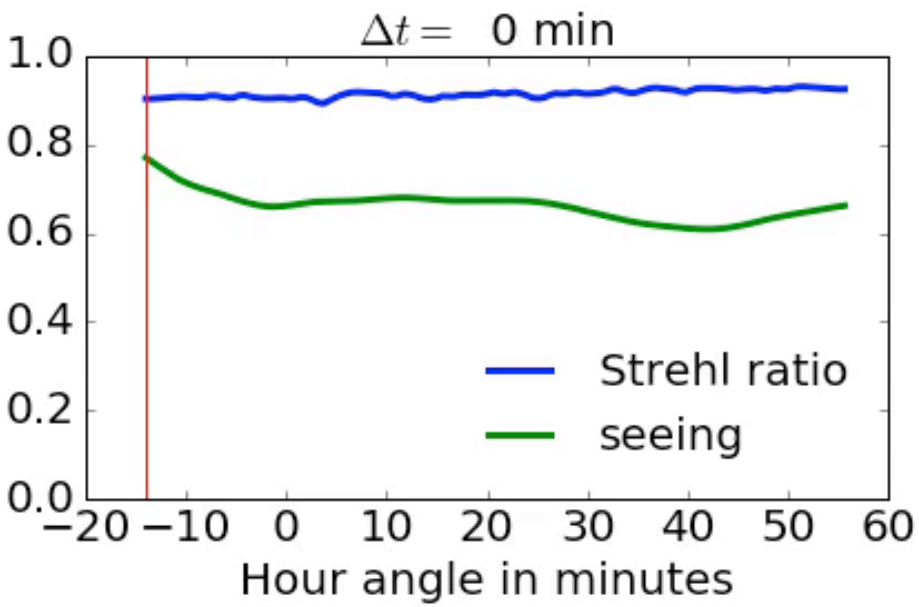


First images of stellar surfaces



Critical prequisite: a stable, high-Strehl point-spread function

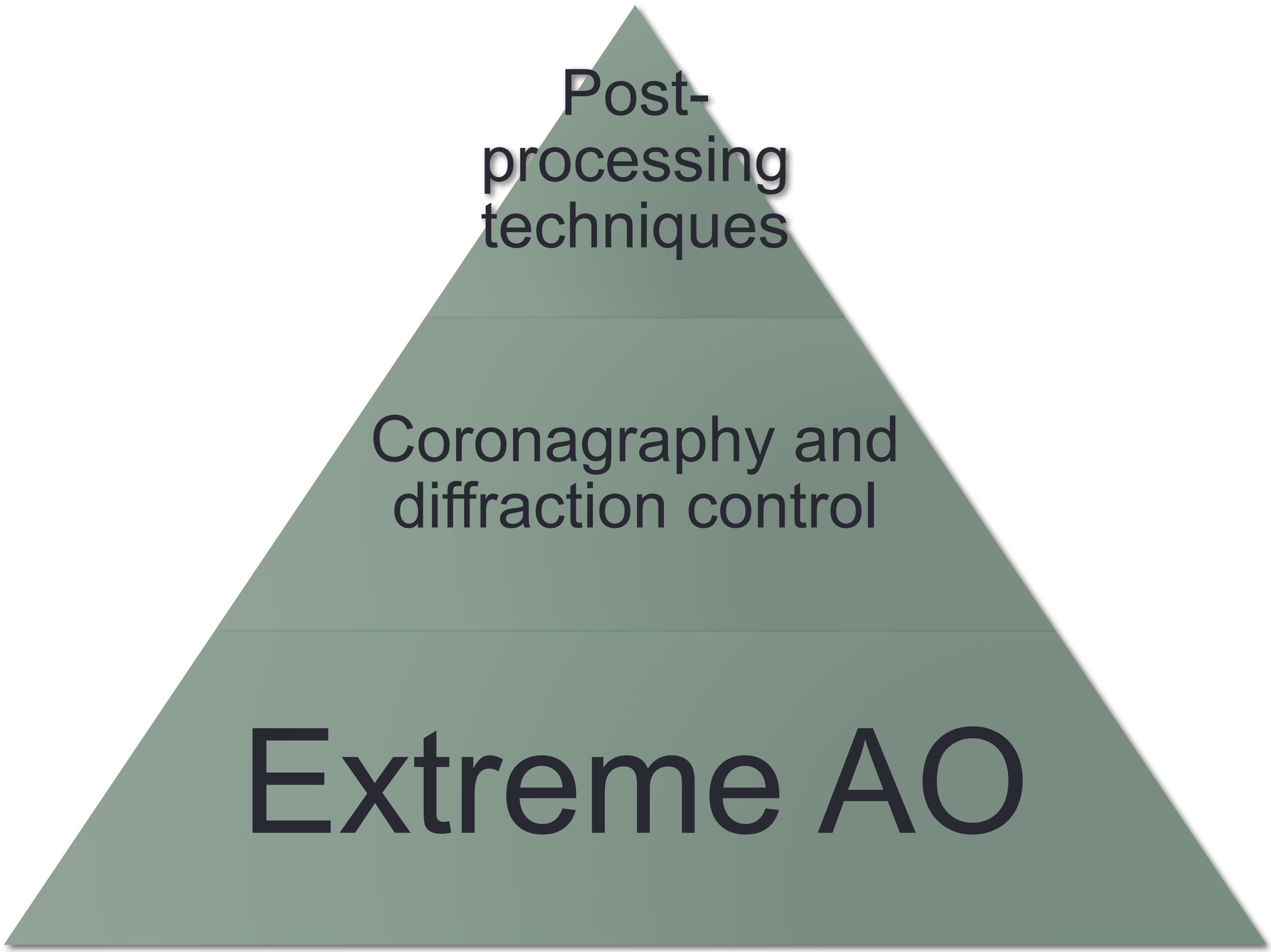


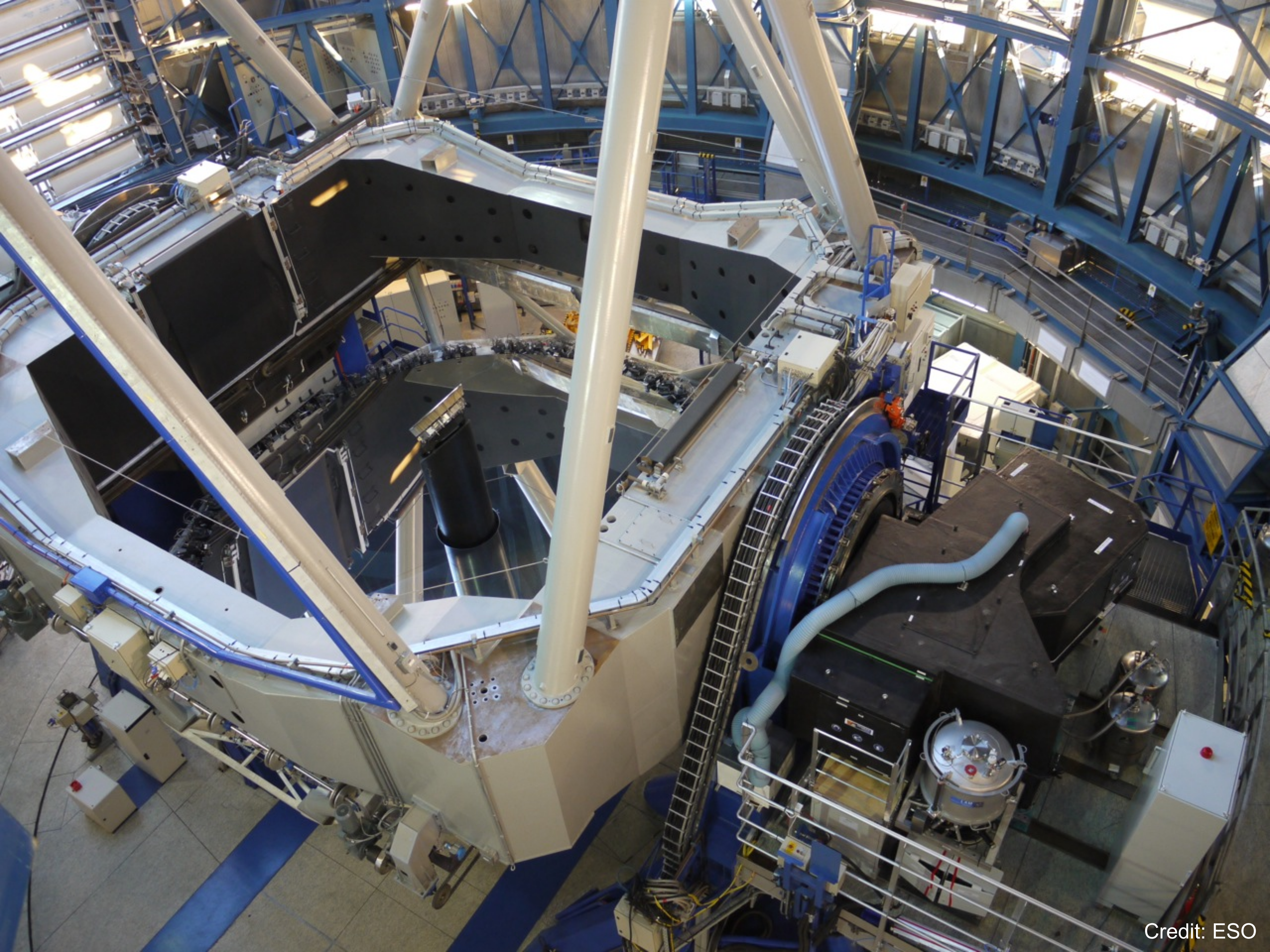


H band image
Apodized Lyot Coronagraph

On-sky observations of a bright star R=5
Stable speckle field
Strehl of ~90%

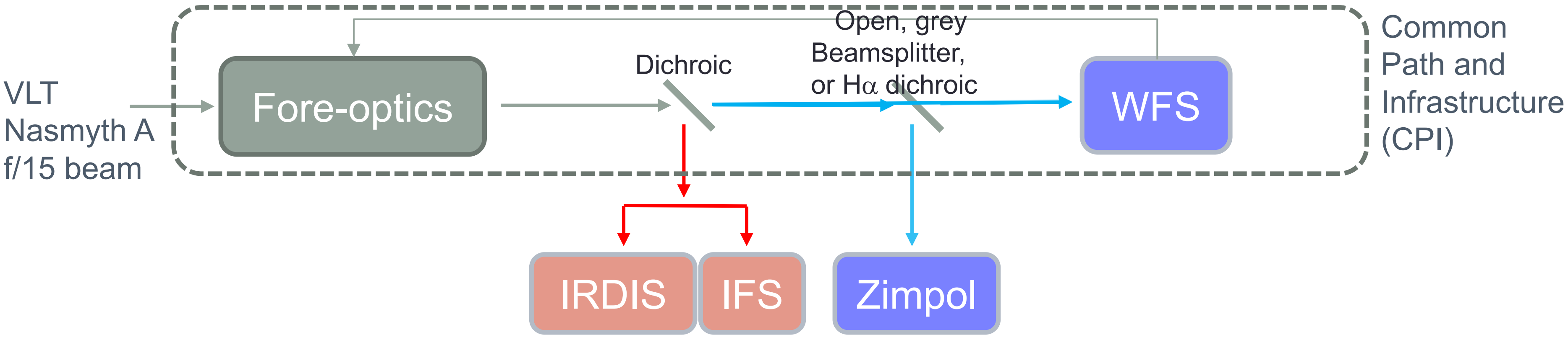
Pillars of high-contrast imaging





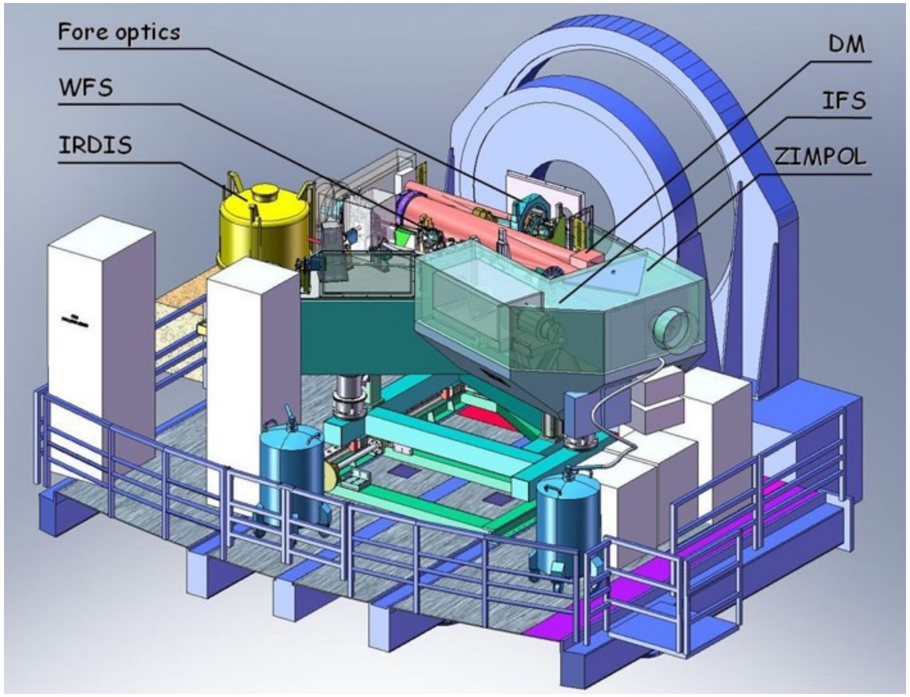
Credit: ESO

The heart of the instrument: CPI



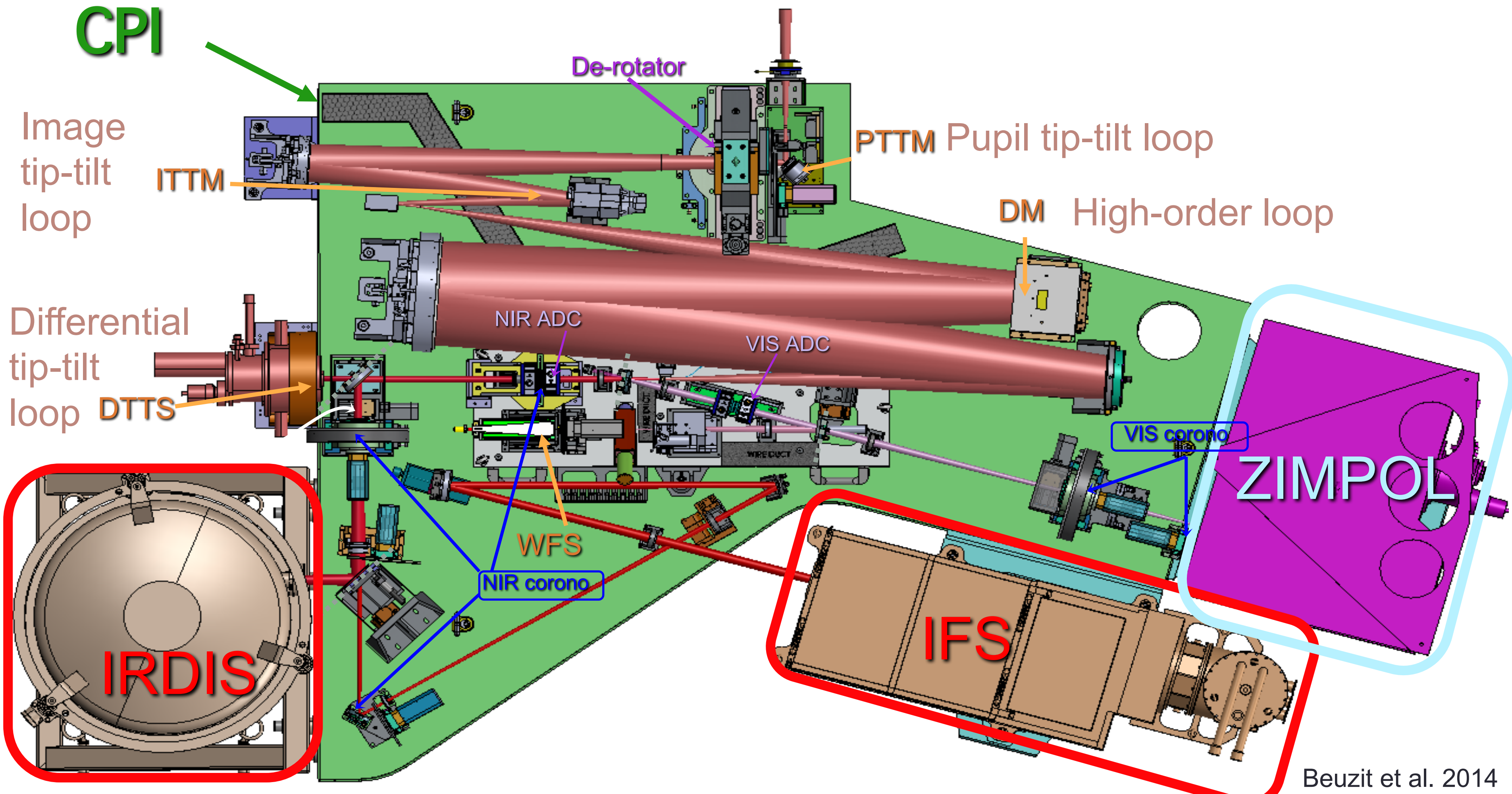
The CPI delivers a corrected beam to IRDIS, IFS and Zimpol and is optimized for thermal and mechanical stability:

- temperature control
- cleanliness control
- active vibration control
- Pupil-stabilization



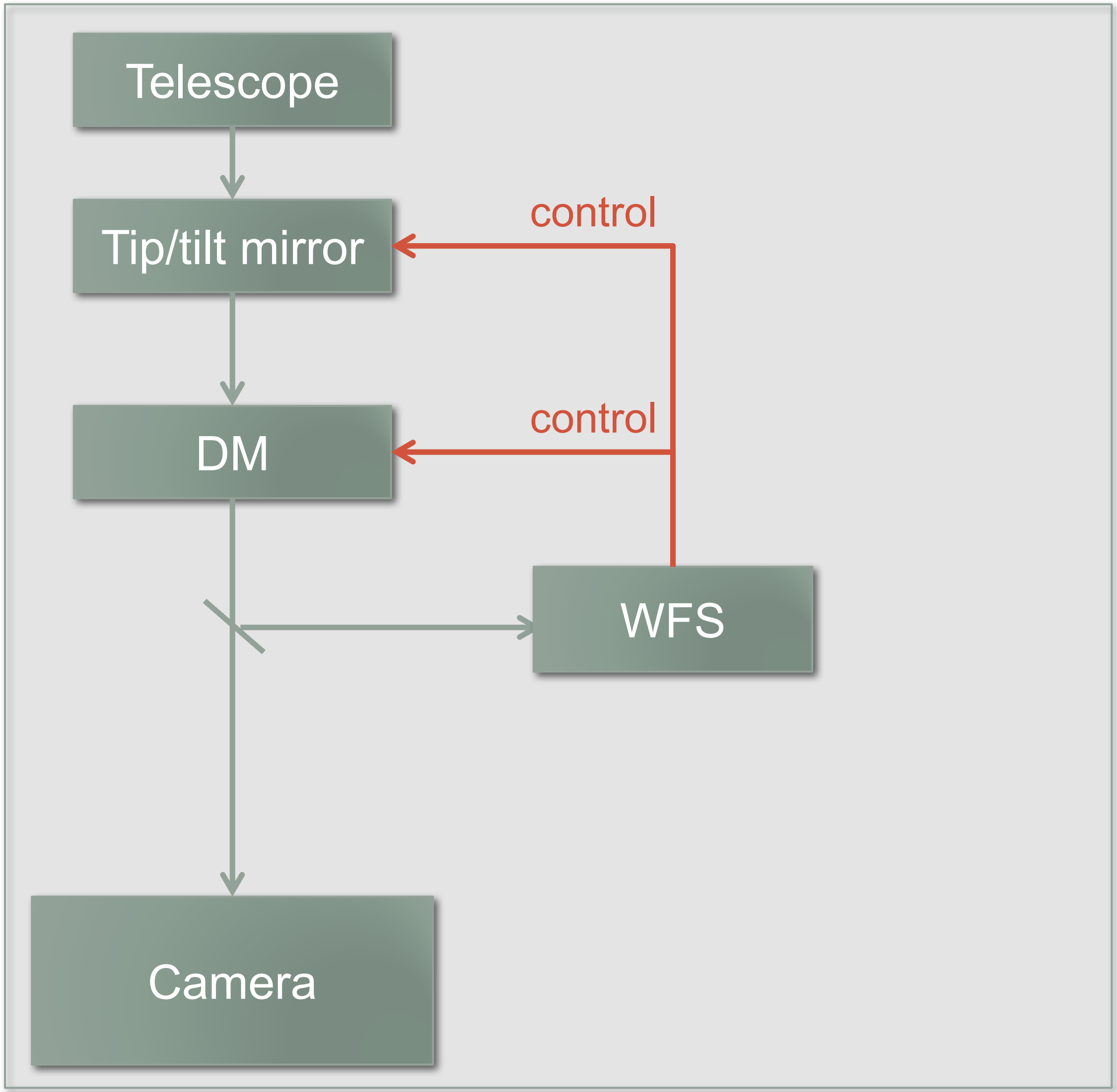
Stability is key

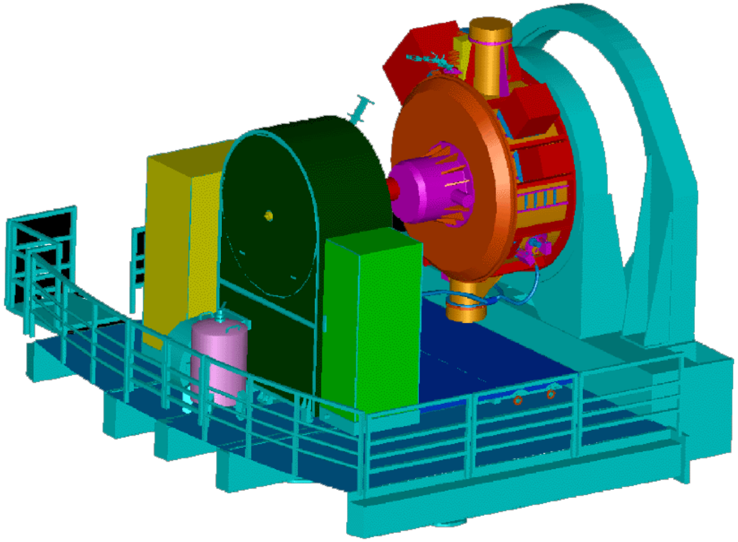
Key components in the CPI



Beuzit et al. 2014

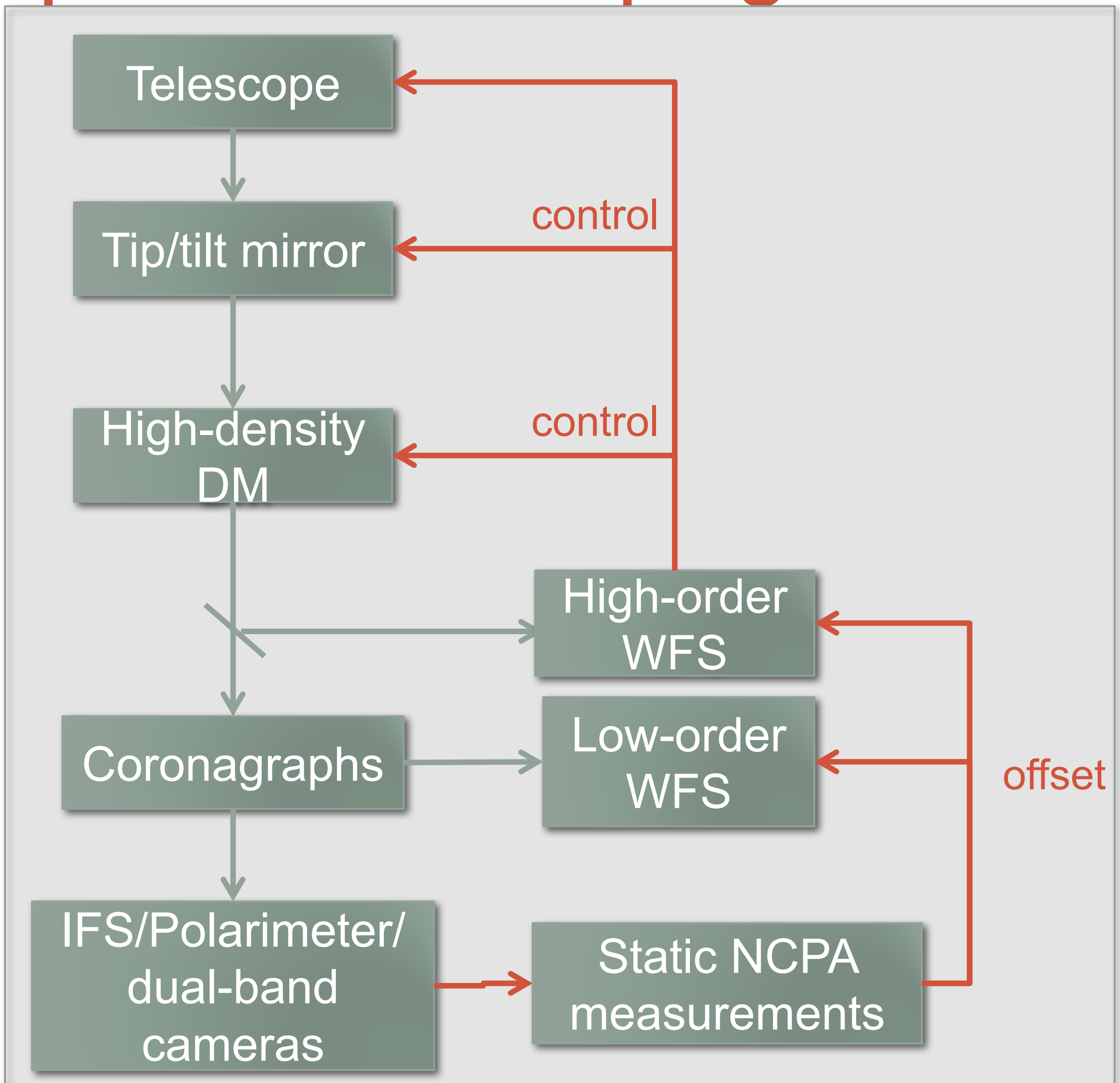
The architecture of 1st generation AO systems





Example of NaCo

2nd generation: minimizing (quasi) static speckles or keeping them as stable as possible



<u>1st gen AO on steroids:</u>

- High density DM
- Spatially-filtered, high frequency, low-noise WFS

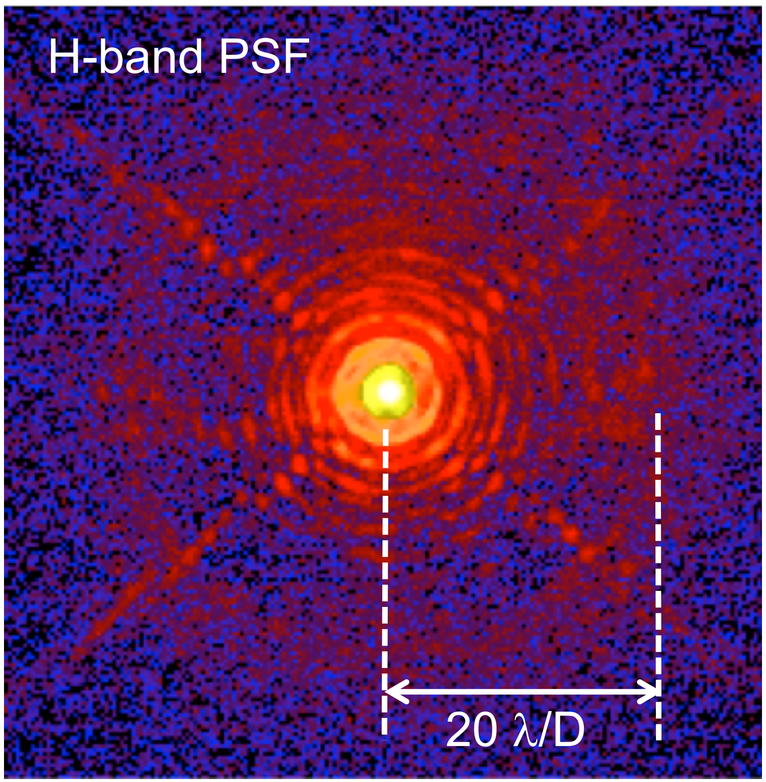
<u>Critical tweaks:</u>

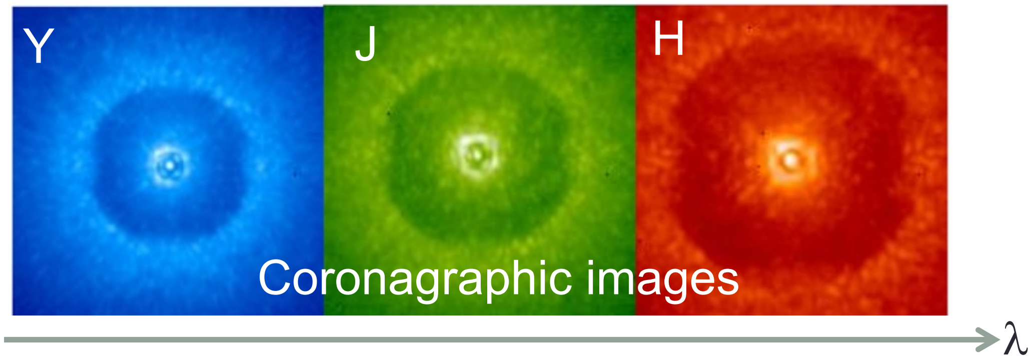
- Low-order WFS (1-10Hz)
- Pupil loop (1-10Hz)
- High-quality optics (ADC, derotator are critical)
- Optimized for mechanical and thermal stability
- Vibrations identifications (every min)
- Modal gains optimisations (every min)

The contrast is the new performance indicator

- High-density DM: 1377 actuators
  41x41 piezoelectric from CILAS
- High-density, fast low-noise WFS
  40x40 SH-WFS: EMCCD 1.4 kHz, RON < 1e-

>90% Strehl reached on bright targets

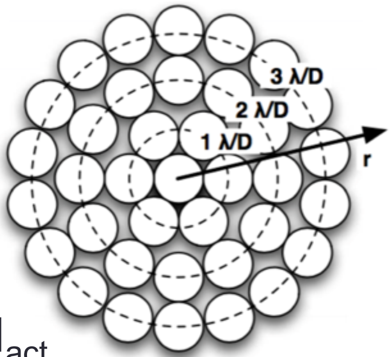




Typical contrast of 10^{-4} in the well-corrected radius

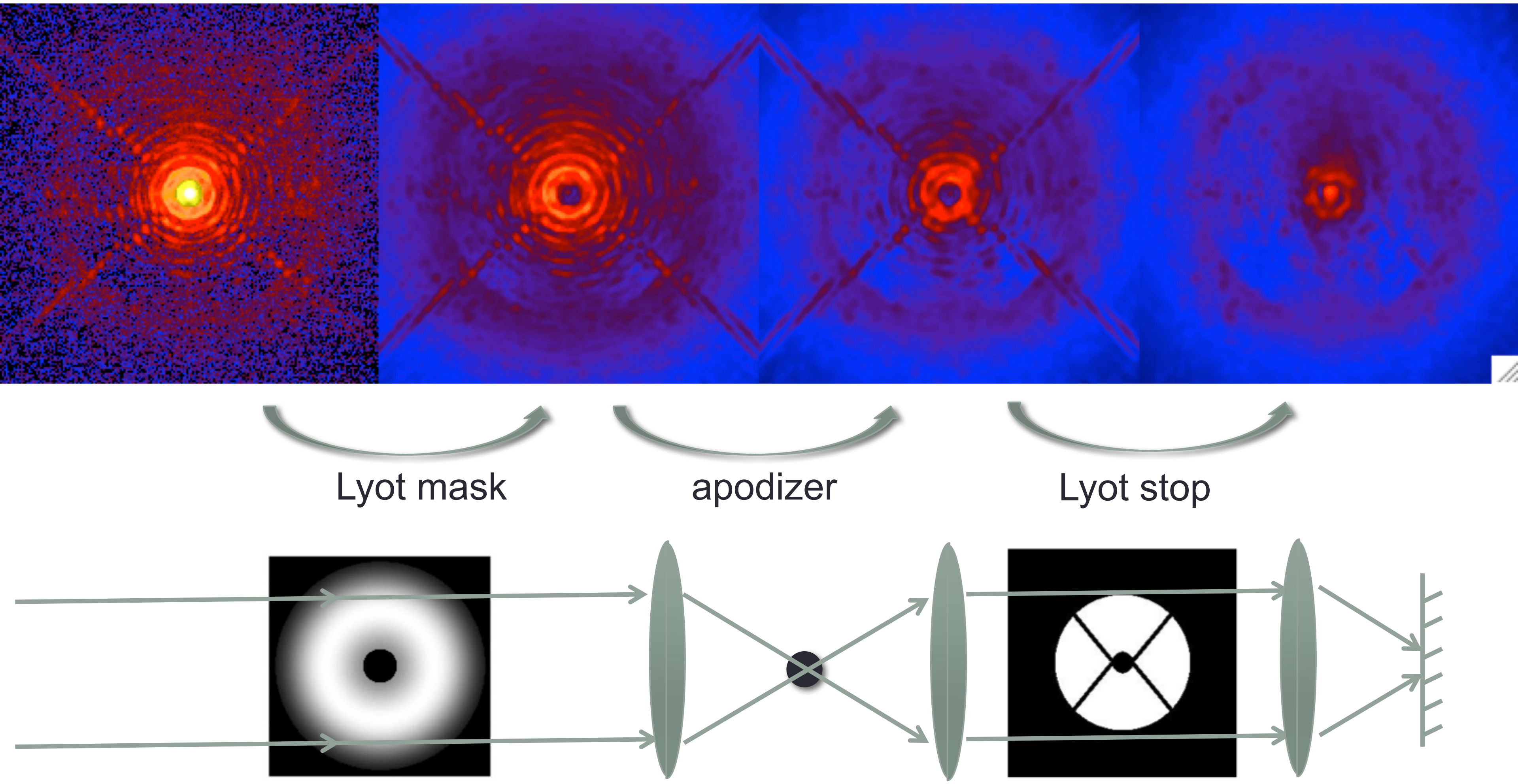
Raw contrast = I_{max} / I_{σ}

Well approximated by $(1-Sr)/N_{act}$

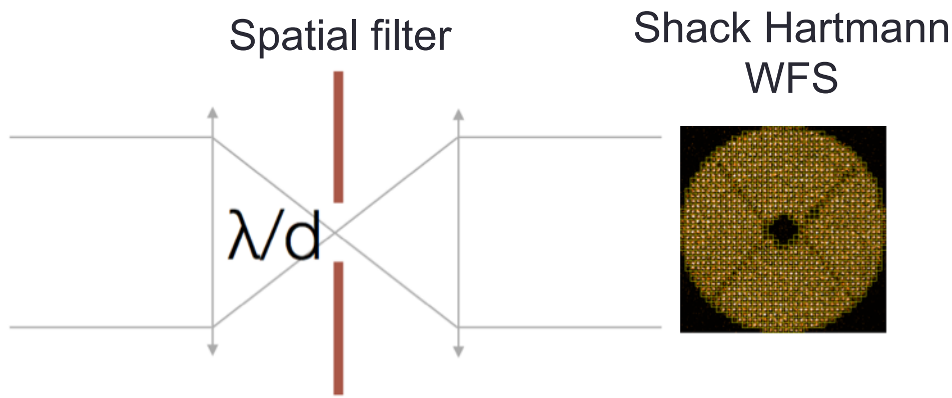


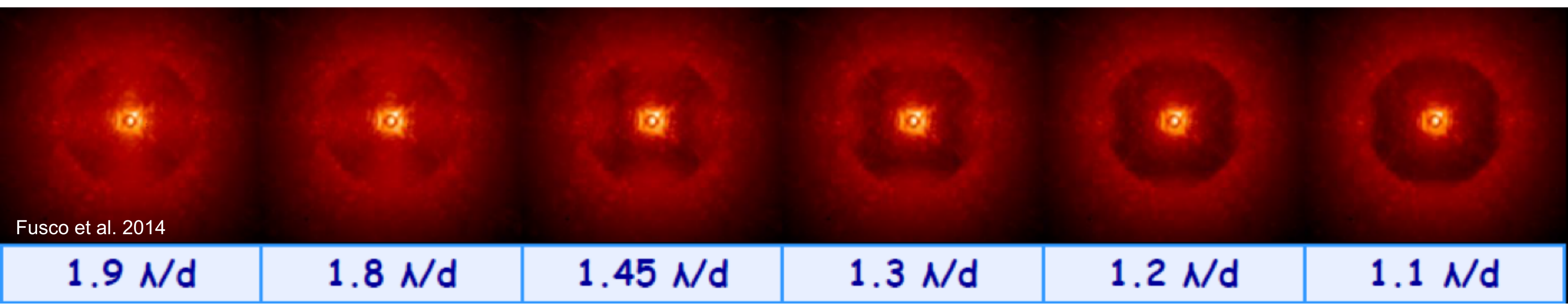
Serabyn et al. 2007

Diffraction control with pupil apodization



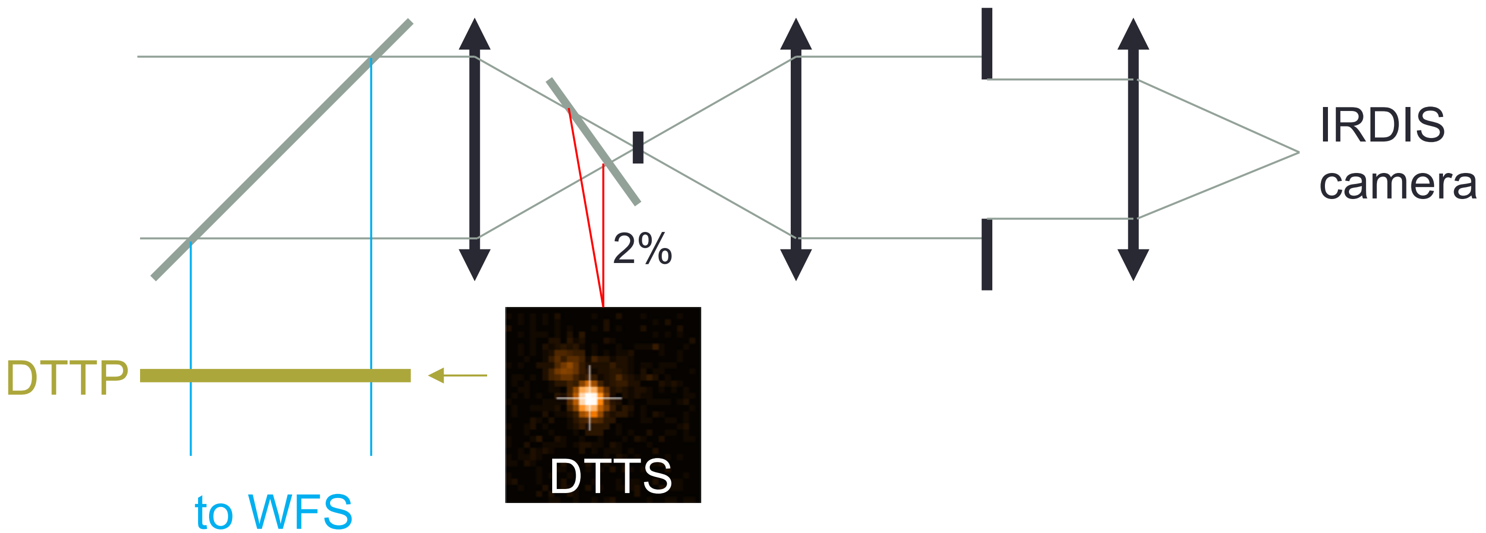
Minimizing aliasing with a spatially-filtered Shack Hartmann WFS





Spatial filter progressively closed

Low order wavefront sensing



Control of low-order aberrations is critical for optimal coronagraphic rejection.

A differential tip/tilt control loop located close to the coronagraphic focus keeps the NIR jitter below 3.5mas

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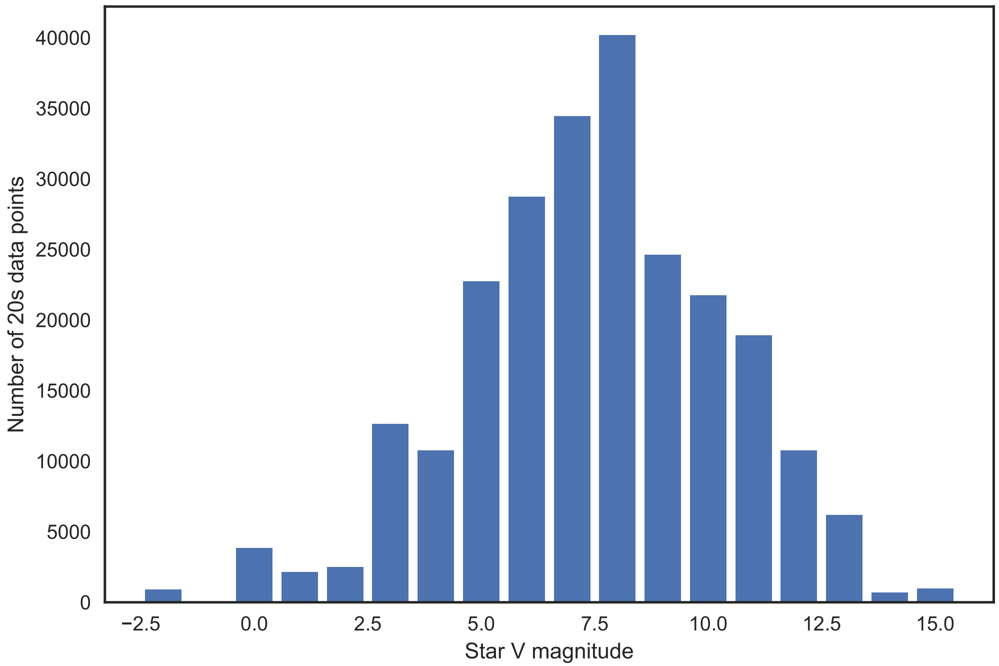
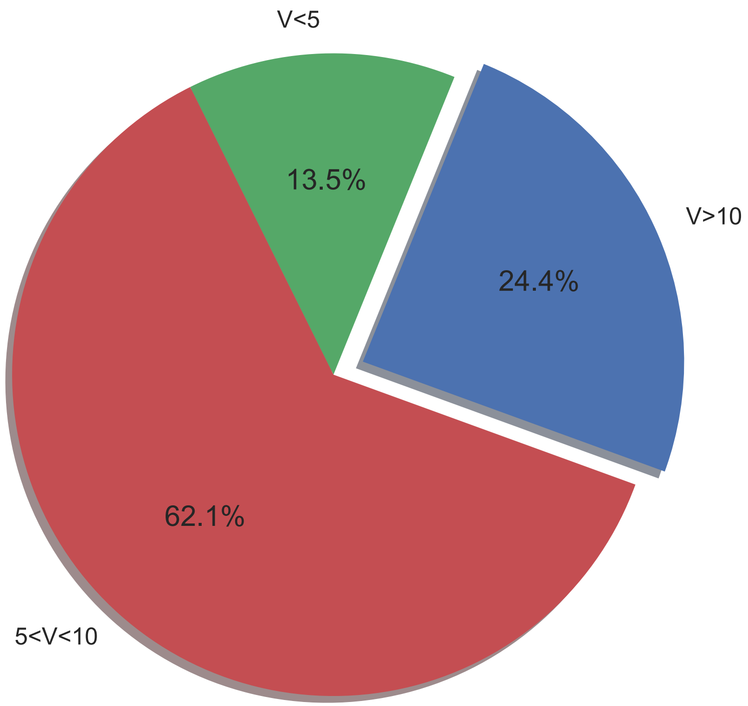
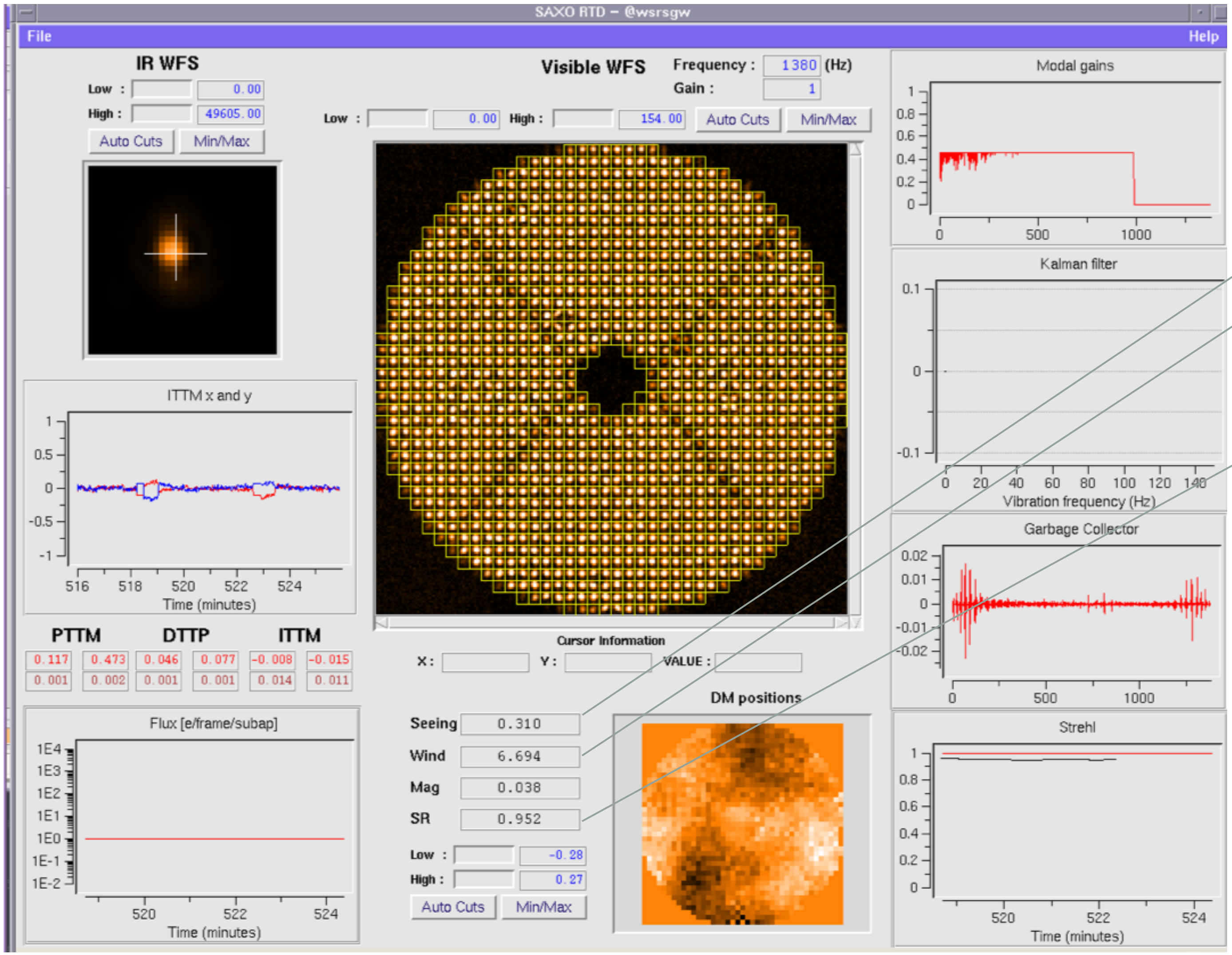
Data used and sample definition





- All AO telemetry data from January 1st 2015 to May 1st 2017 when IFS and/or IRDIS are used (all visible light sent to the WFS)
- 200 000 data points (20s average each) over 465 nights or more than 1000 stars

Performance and atmospheric parameters estimators

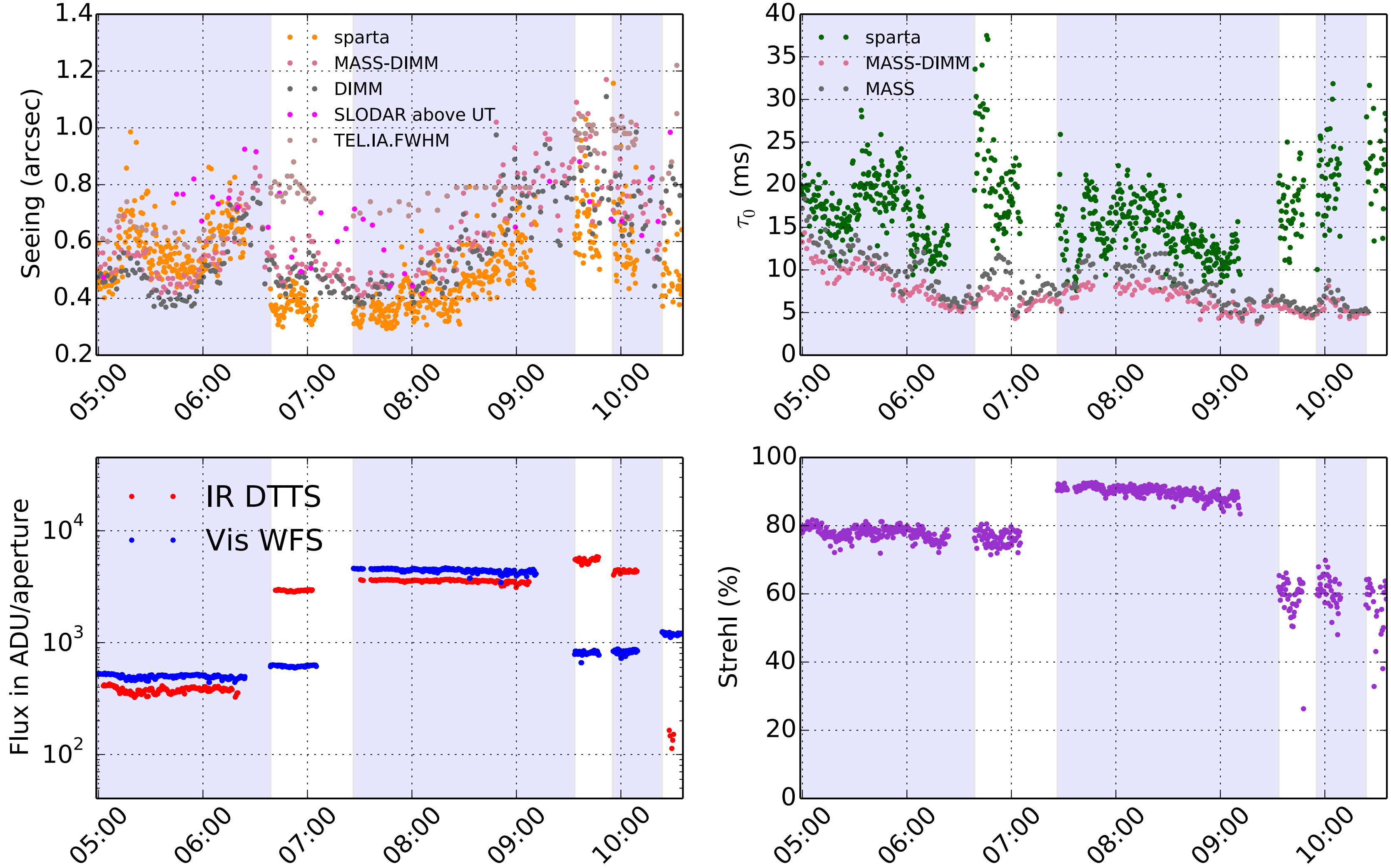


SPHERE RTC saves systematically every 20s:

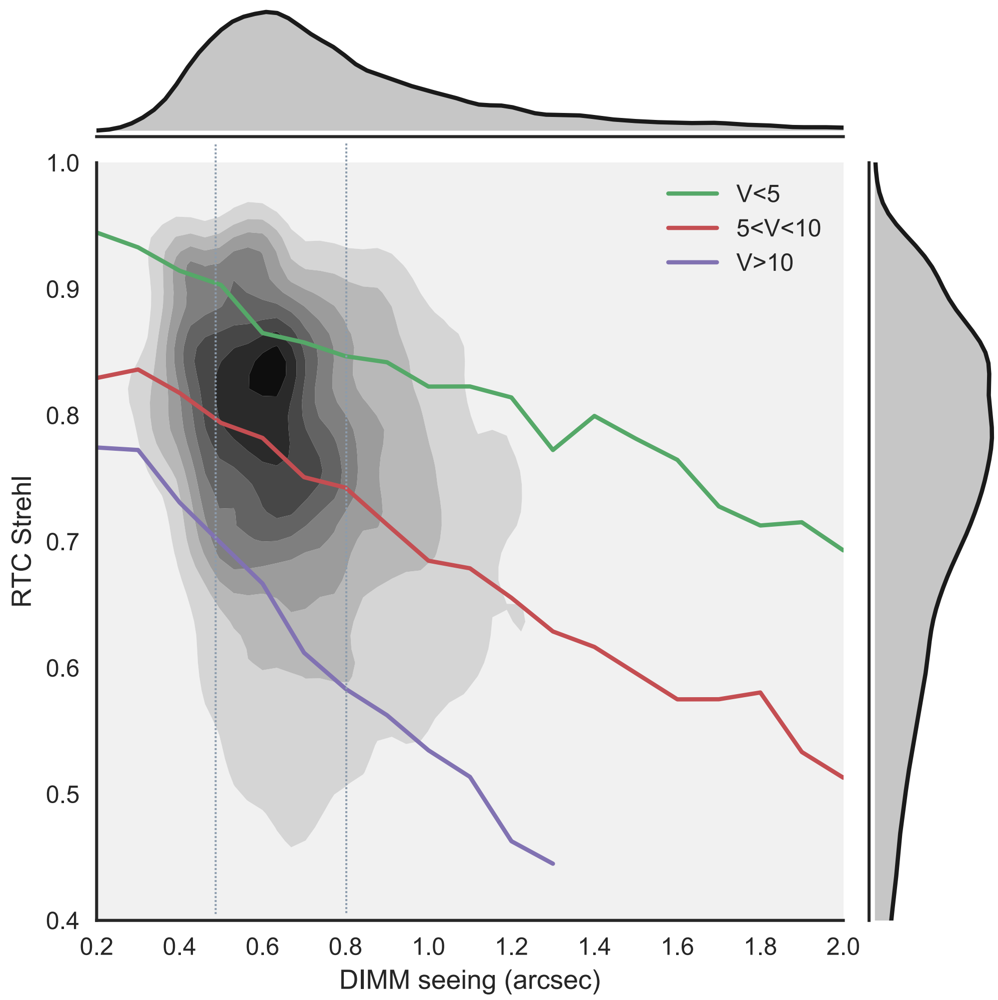
- Seeing (or r_0) at 500nm
- Coherence time (or equivalent velocity) at 500nm
- H band Strehl

We also queried the ASM (Astronomical Site Monitor) for independent seeing and coherence time measurements

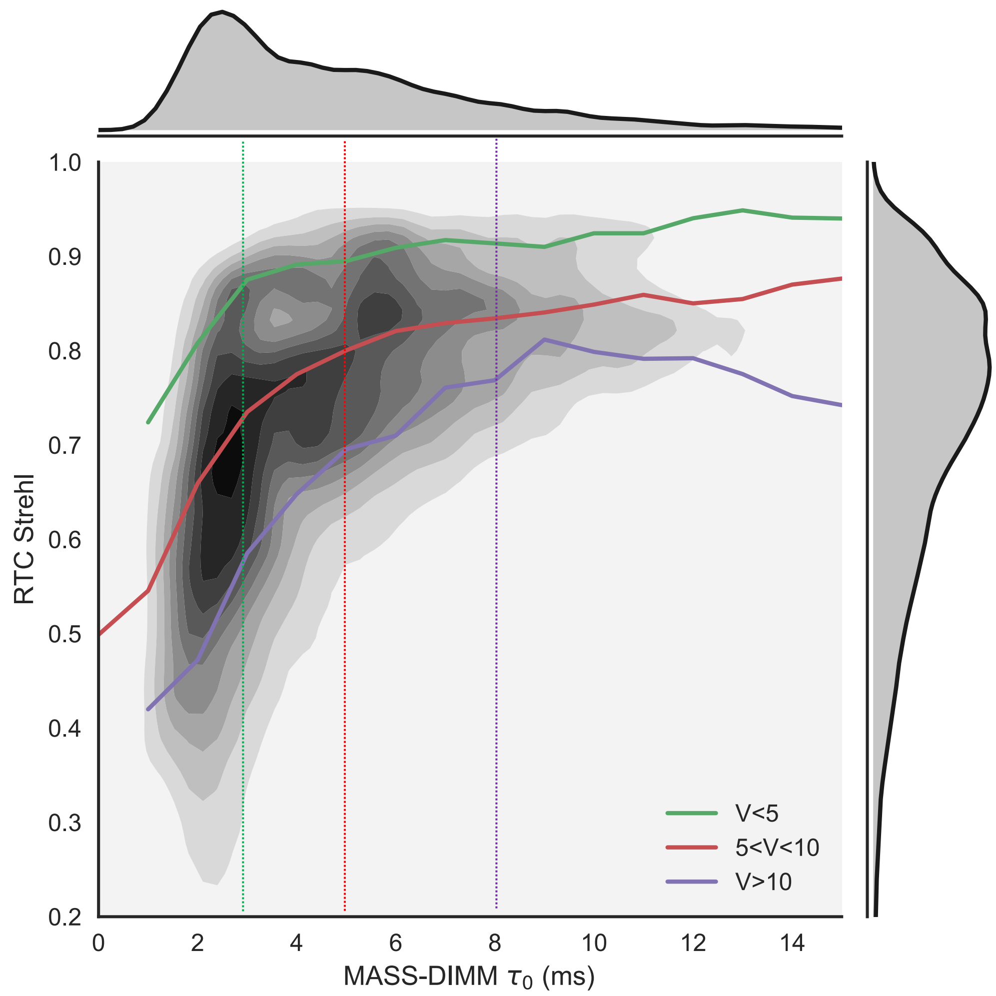
Typical example for a night



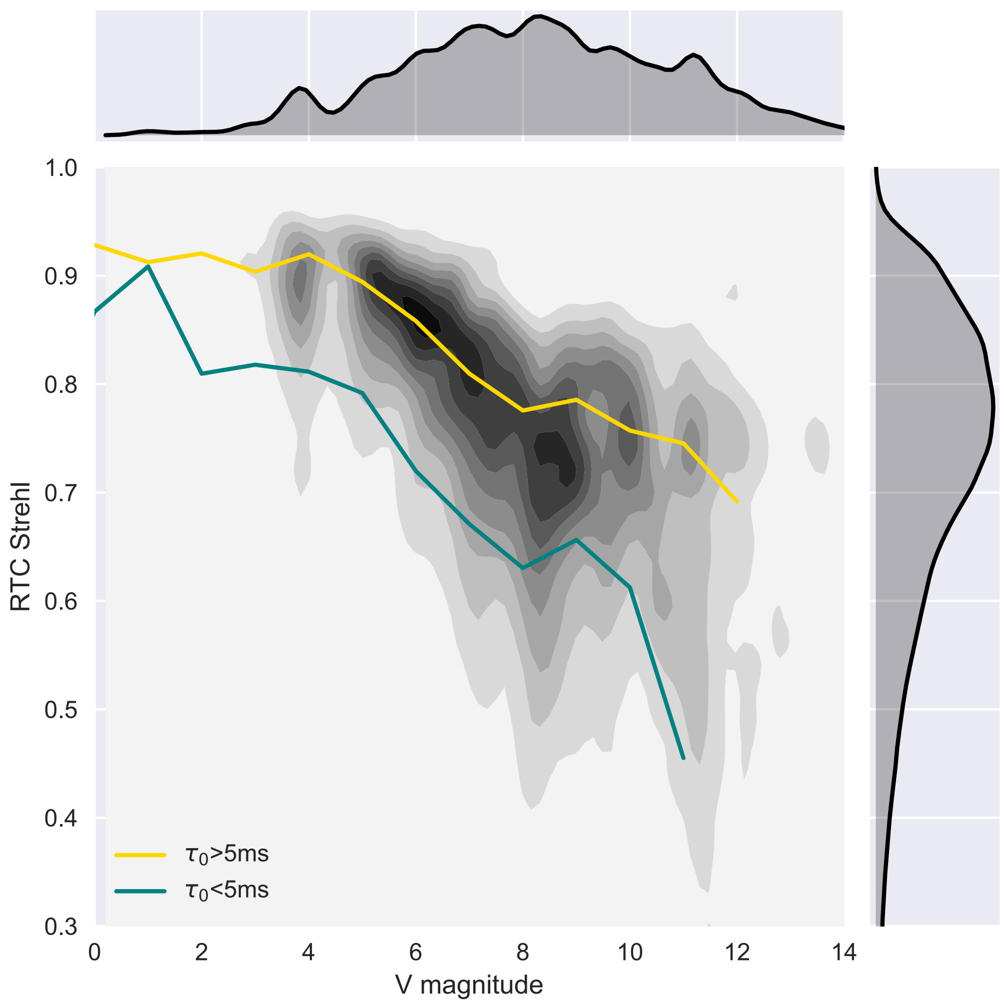
Strehl and seeing dependency



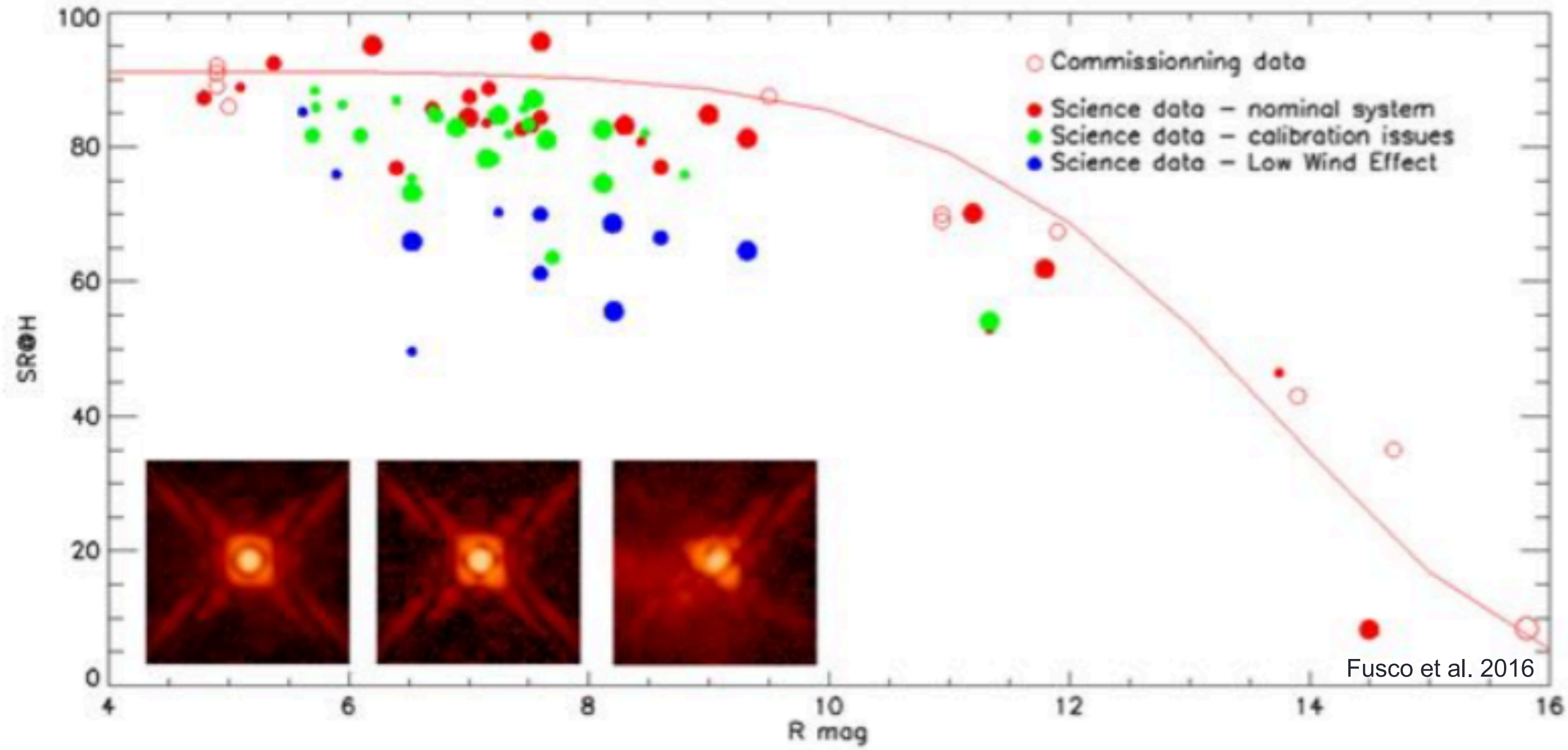
Strehl and coherence time dependency



Strehl and magnitude dependency



Expected Strehl vs magnitude

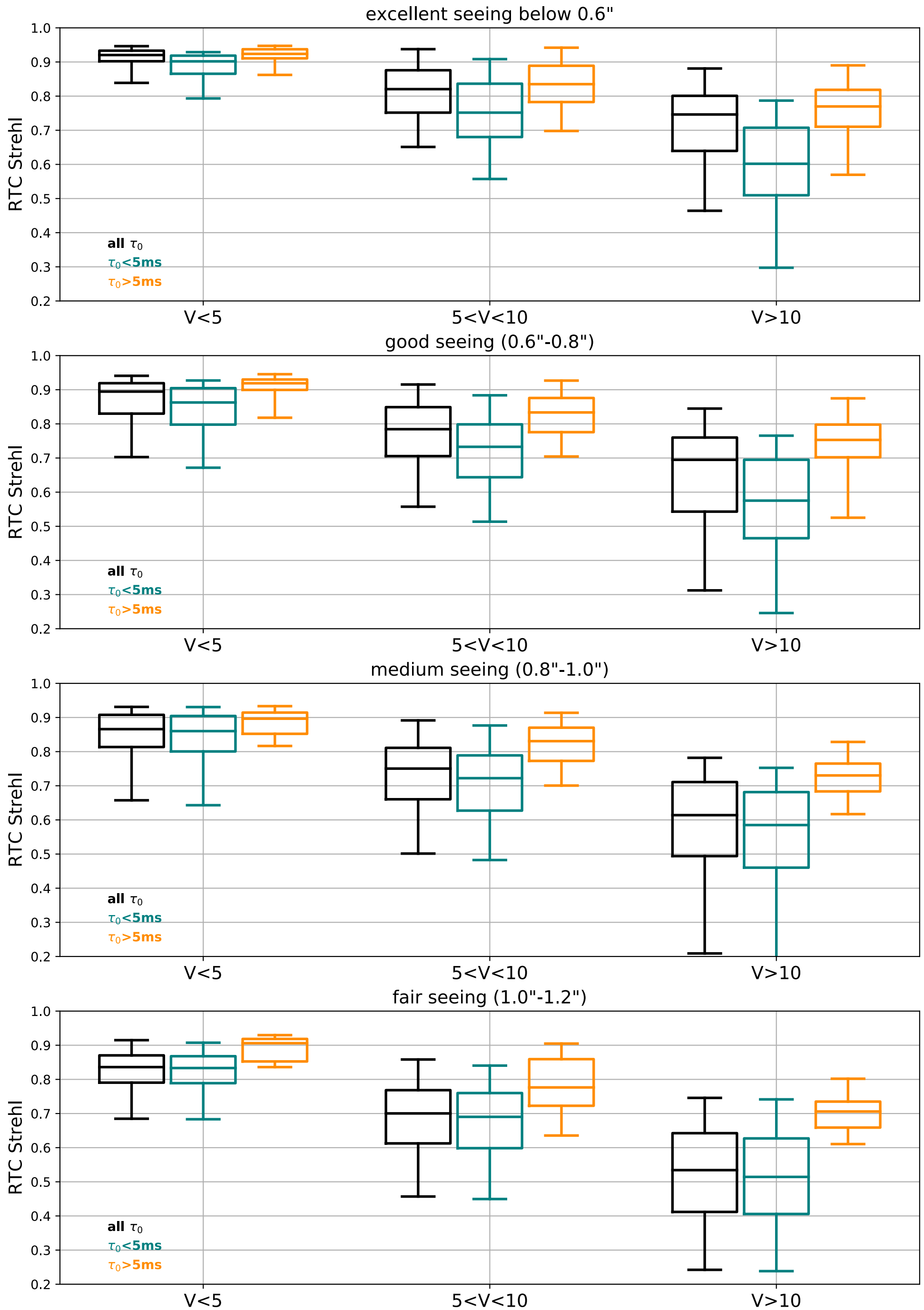


Differences currently investigated.
Suspects: calibration issues, biases in RTC estimations

Summary

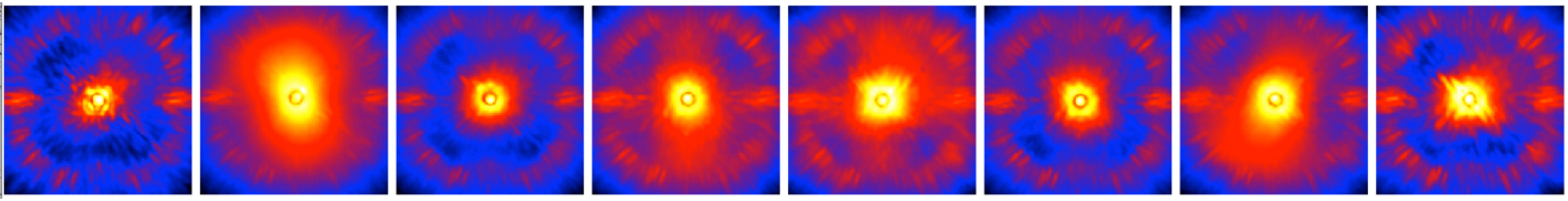
At first order: Strehl = f (τ_0, ε, R_{mag})

Currently the coherence time cannot be constrained for service mode observations → we are working on that to guarantee higher data quality

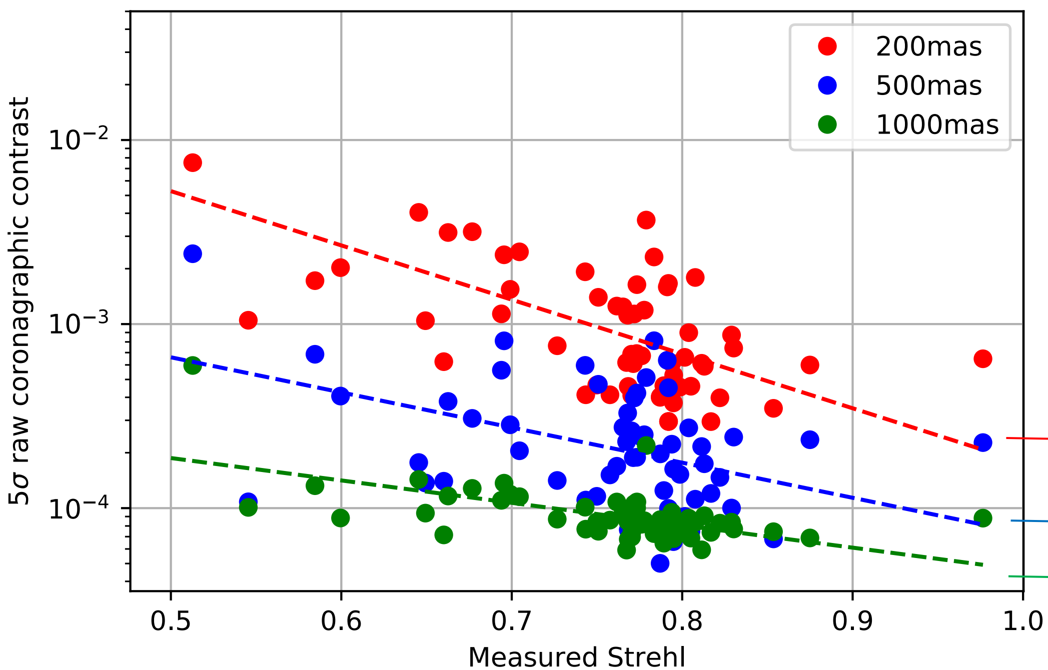


Milli et al. 2017 submitted

From Strehl to raw contrast



Reduced sample of stars used for this analysis (SHARDDS survey)



Analysis done on a reduced sample of 55 stars from R=5 to 11. Work on a larger sample pending pipeline developments

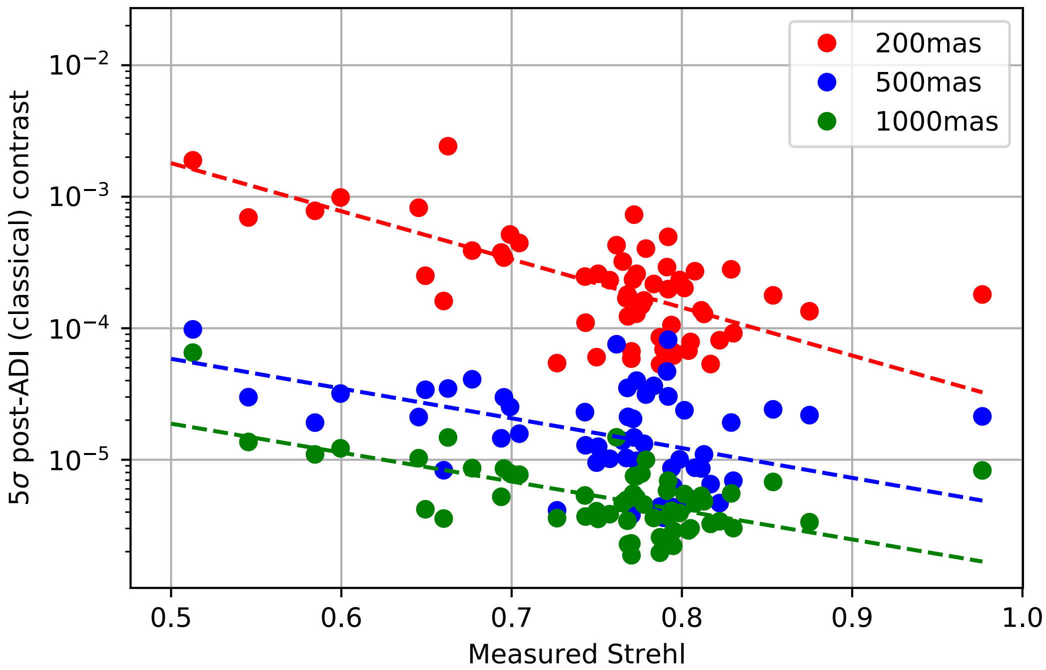
Main noise contributors

Temporal bandwidth error $\alpha\ \tau_0^{-5/3}$

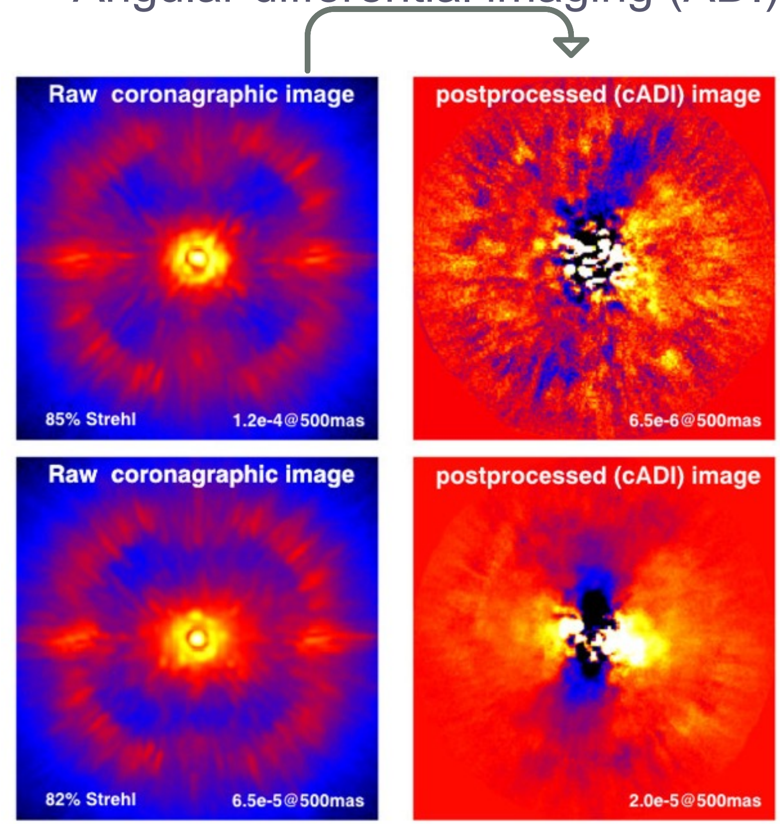
aliasing (+ measurement noise)

Fitting error $\alpha\ r_0^{-5/3}$

From Strehl to final contrast after post-processing (ADI)

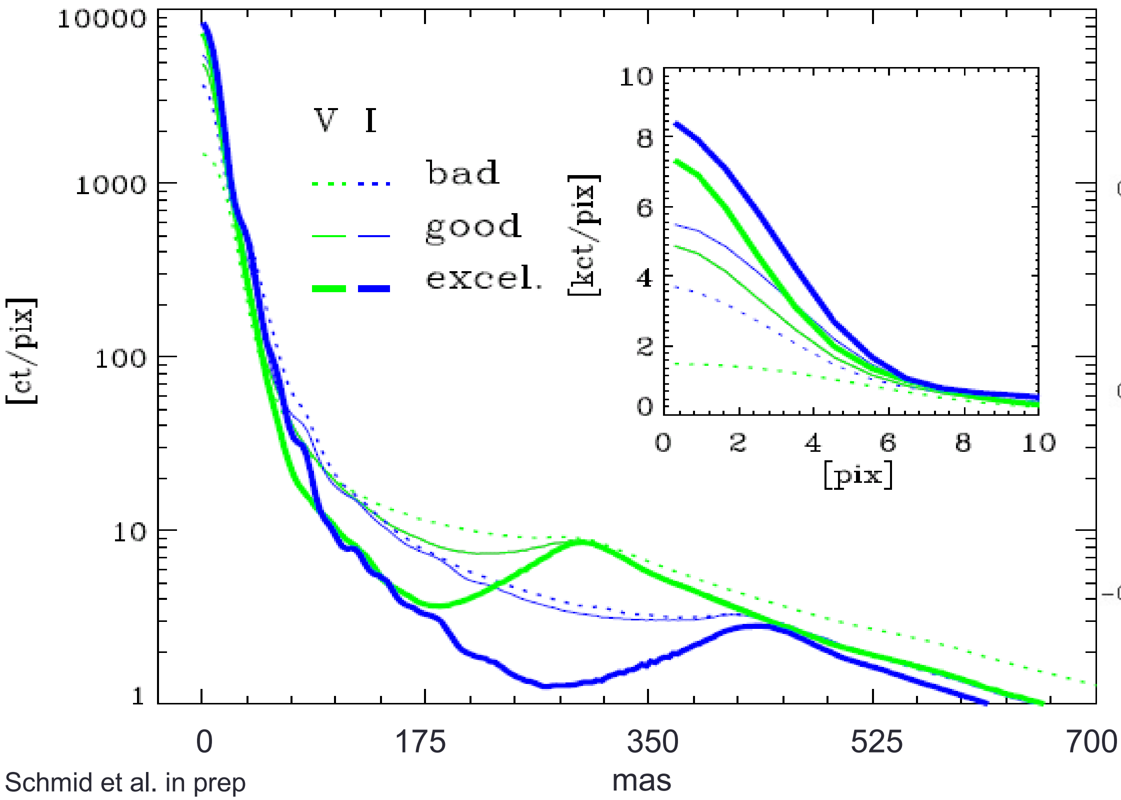


Angular differential imaging (ADI)

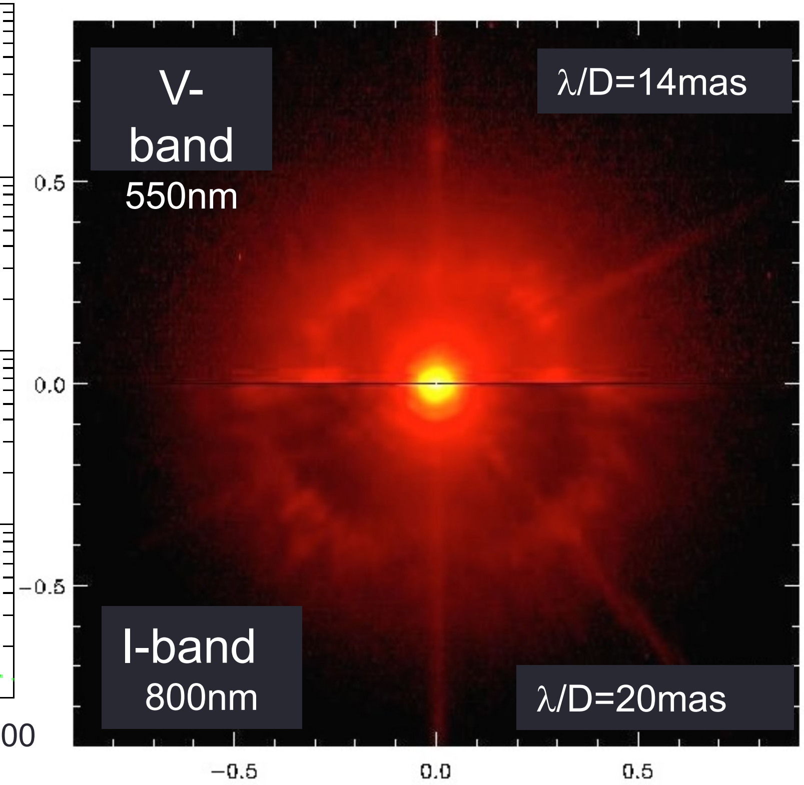


Factor ~20 gained in post-processing, dependent on temporal stability and parallactic angle rotation
Influence of the Strehl still visible

Zimpol PSF in the optical



Schmid et al. in prep



Much stronger dependence on atmospheric parameters in the optical

Very high contrast obtained in polarimetry for deep exposures in good conditions: 10^{-7}

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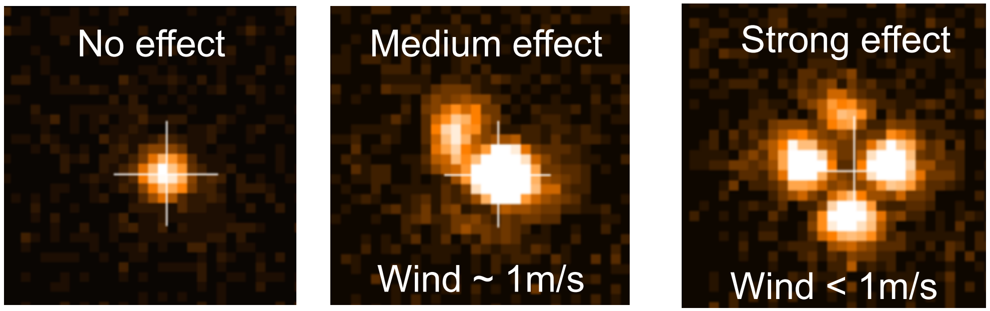
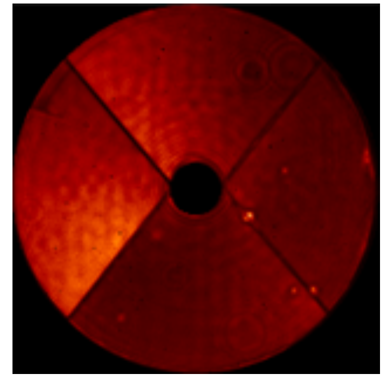
Low-wind effect: a contrast killer

H band PSF (DTTS images)

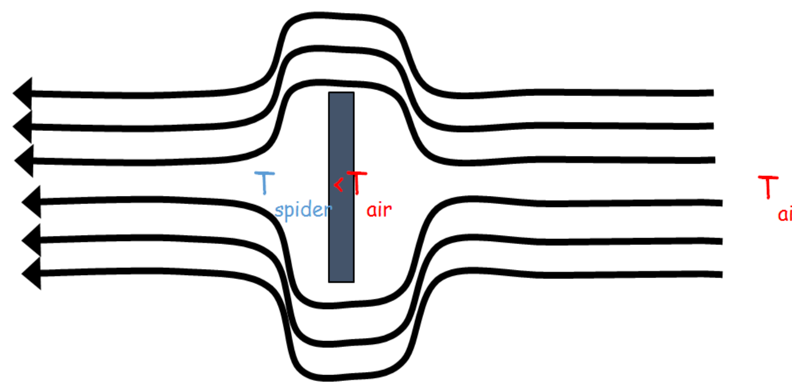


Phase map, using the Zernike phase mask
(N'Diaye 2013)

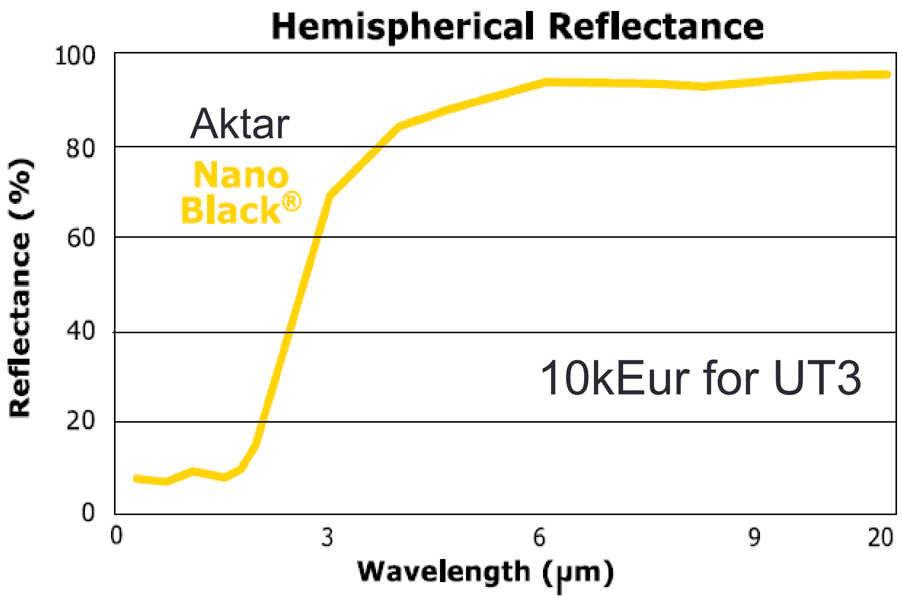


Combination of piston, tip and tilt on each pupil segment

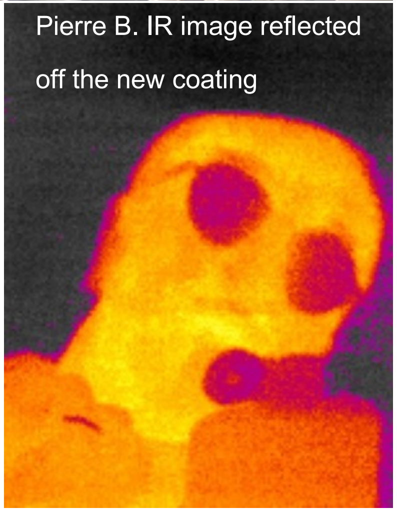
- Occurrence ~16% of time during the best conditions
- Many actions tried without success: fewer/more corrected modes, dome ventilation on, different SH centroidings, disabling subpupils, different pointing…
- Physical explanation based on temperature sensors and simulations: $T_{spider} < T_{air}$ due to radiative cooling to the colder night sky → air cools →change in refractive index
- DM can correct it but the WFS does not measure it → active correction difficult



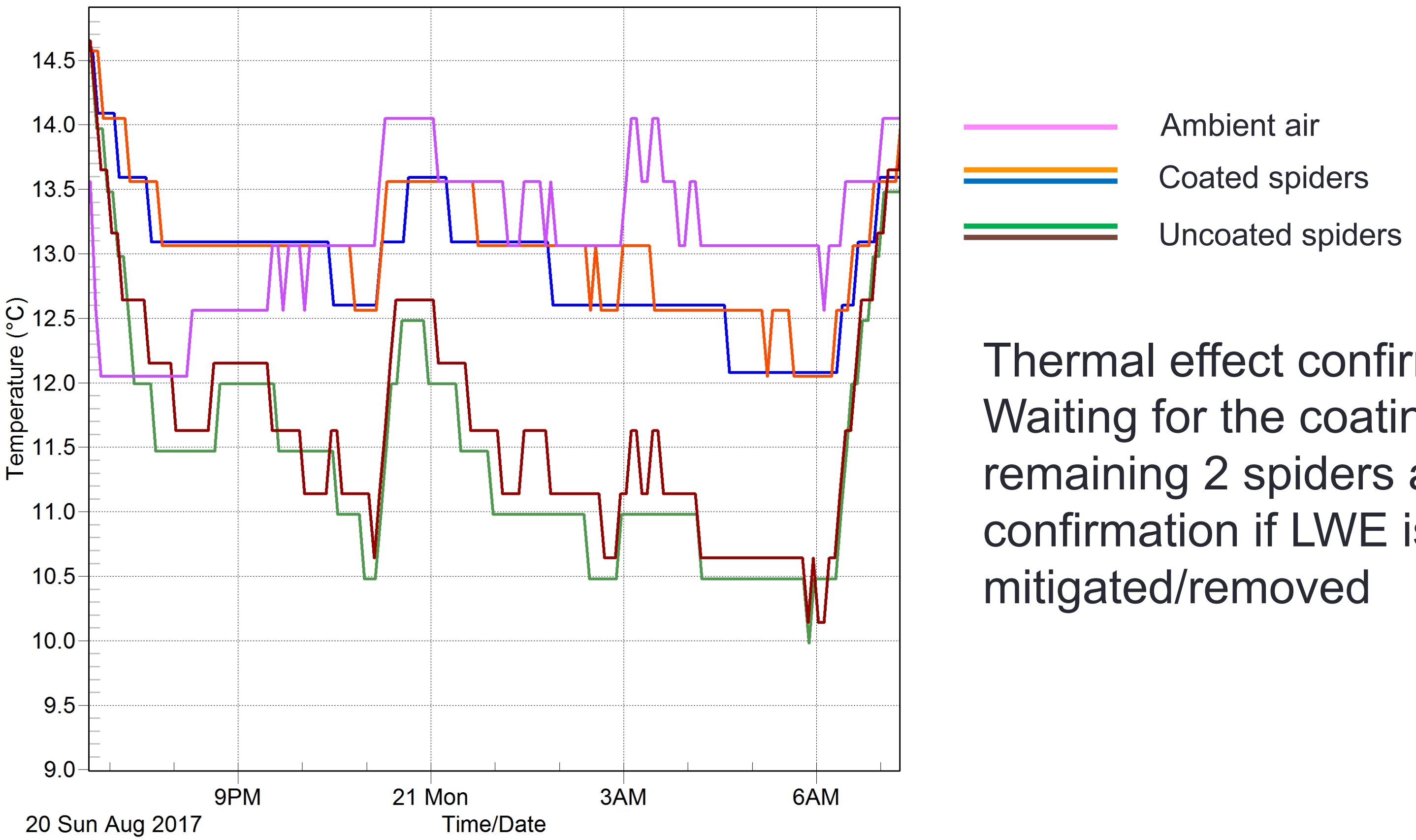
Low wind effect: passive correction



- Black in optical/NIR (low scatter), white in MIR, $\varepsilon \sim 10\%$ (low emission)
- Has trouble to radiate at room temperature →Structure maintains ambient temperature



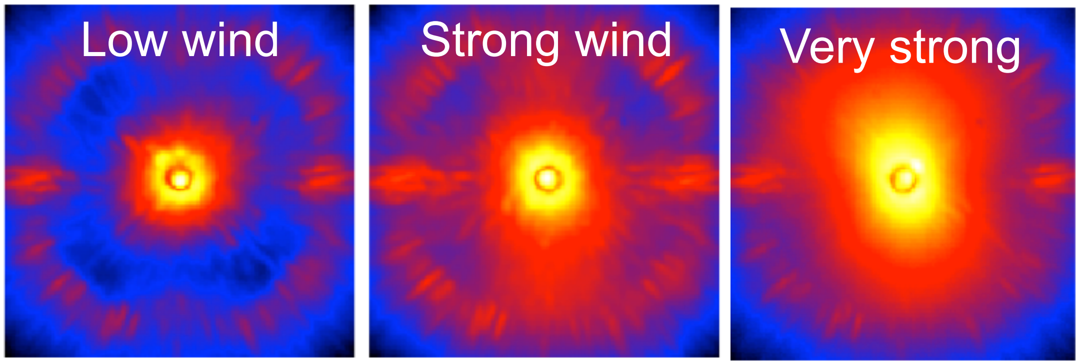
Low wind effects: promising results



Thermal effect confirmed
Waiting for the coating of the remaining 2 spiders and confirmation if LWE is mitigated/removed

If successful, the piders of UT4 (adaptive telescope with MUSE-GALACSI, HAWK-I GRAAL and soon ERIS) might be recoated too.

Turbulence residuals from temporal bandwidth error

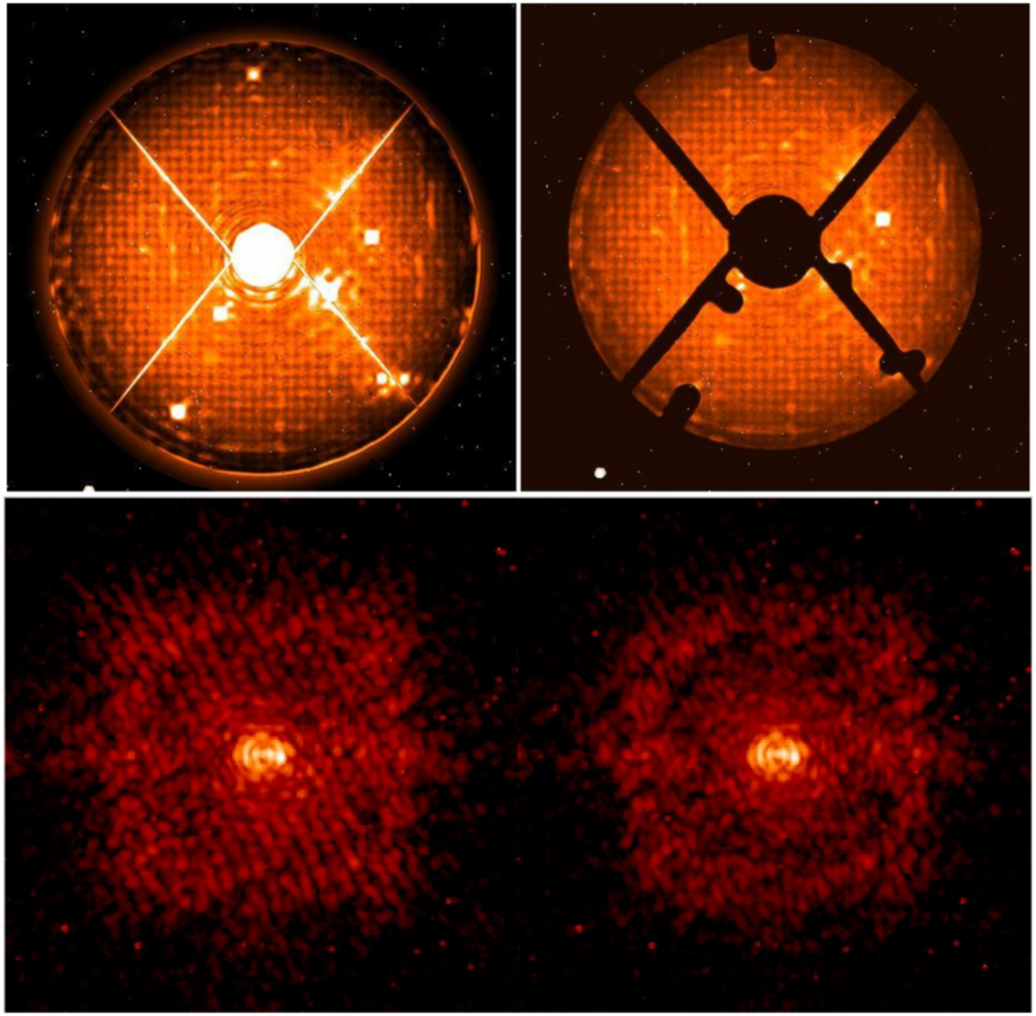


Wind = equivalent wind, most of the time driven by altitude wind at ~12km (jet stream)

<u>Solutions</u>

- Improve post-processing strategies: PSF reconstruction techniques
- Upgrade the SPHERE AO system:
  - Increase AO loop frame rate: faster WFS (2-3kHz), faster RTC, DM ok.
  - Improve control laws: gains adapted to wind behavior (cf GPI)
  - Improve WFS sensitivity

A new DM for SPHERE

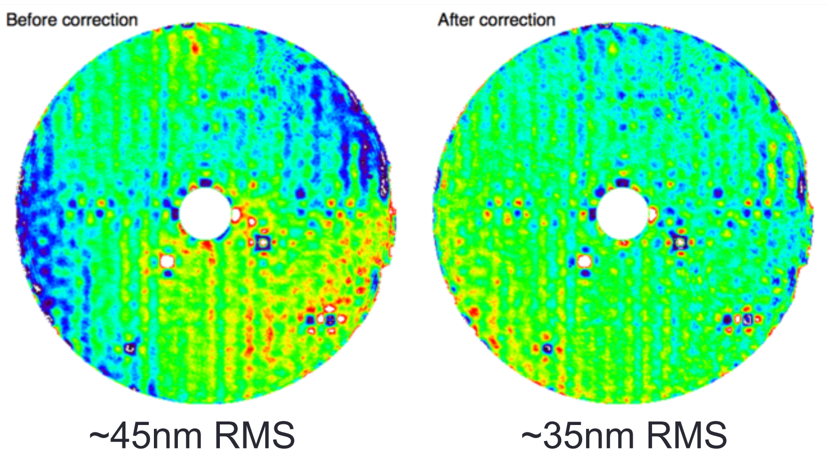


- 17 dead or slowly responding actuators (7 seen through the Lyot stop useful aperture)
- Stable situation since the start of operations
- CILAS proposes a replacement of the DM, discussions are on-going to secure funding by the SPHERE consortium

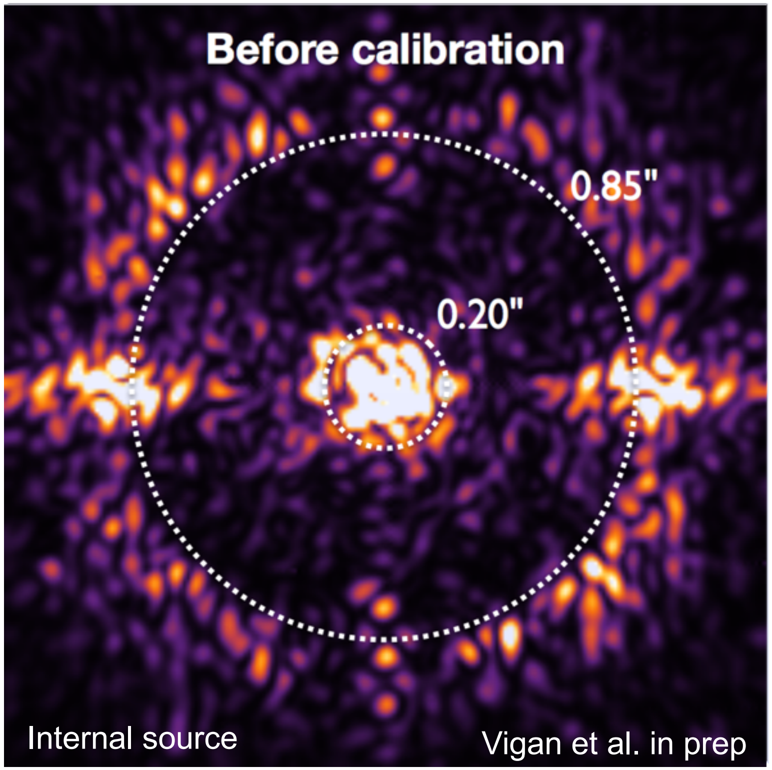
Dead actuators are contrast killers

Non-common path aberrations

Concept: measure NCPA offline using the Zernike phase mask (N'Diaye et al. 2013) and compensate via differential reference slopes



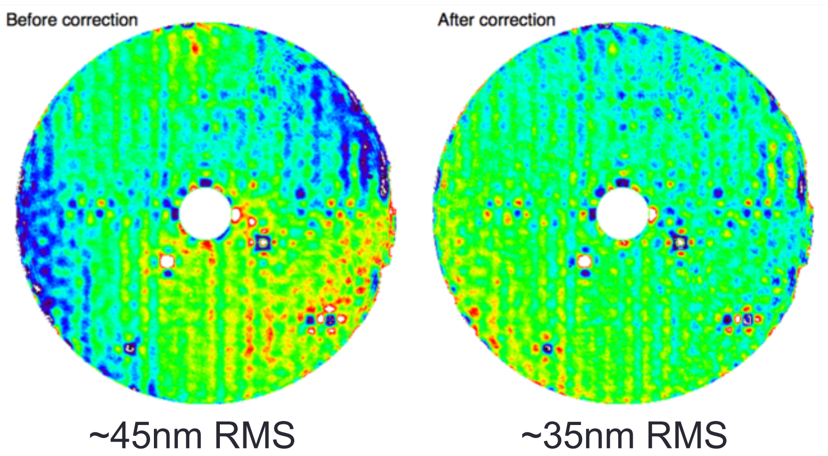
N'Diaye et al. 2016



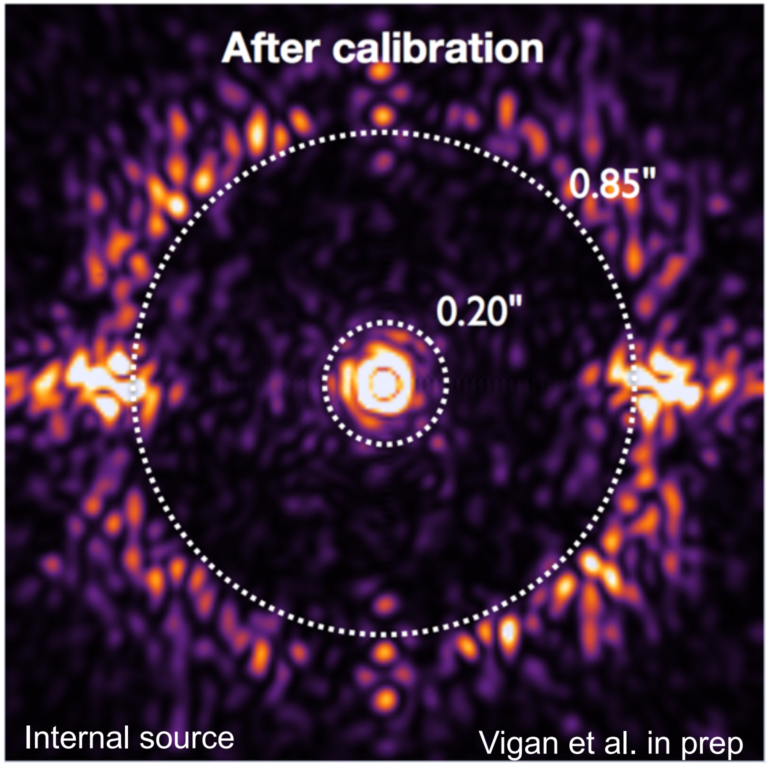
- Improvements by 10 in contrast at 0.2" on internal source
- Results on-sky disappointing in March 2017, but new tests requested early 2018 to implement it in the daily calibration of SPHERE

Non-common path aberrations

Concept: measure NCPA offline using the Zernike phase mask (N'Diaye et al. 2013) and compensate via differential reference slopes



N'Diaye et al. 2016



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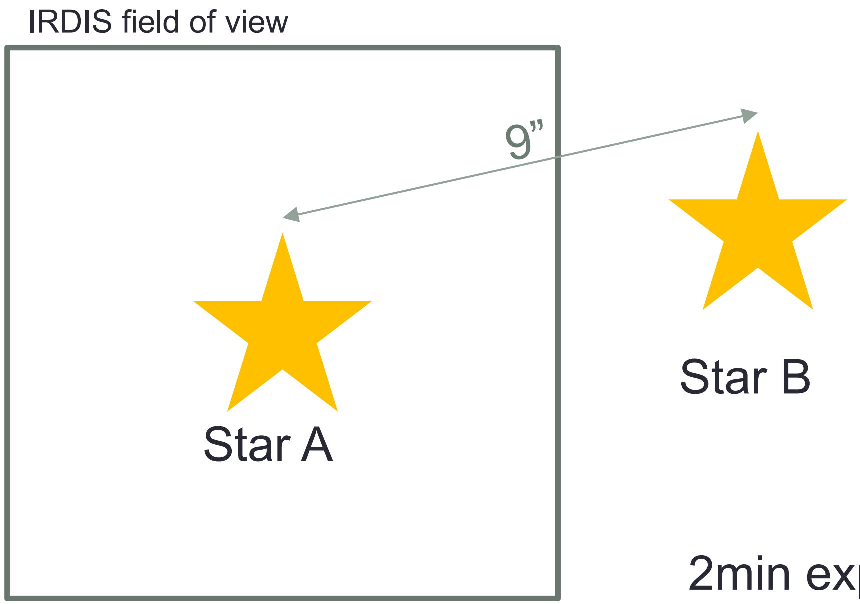
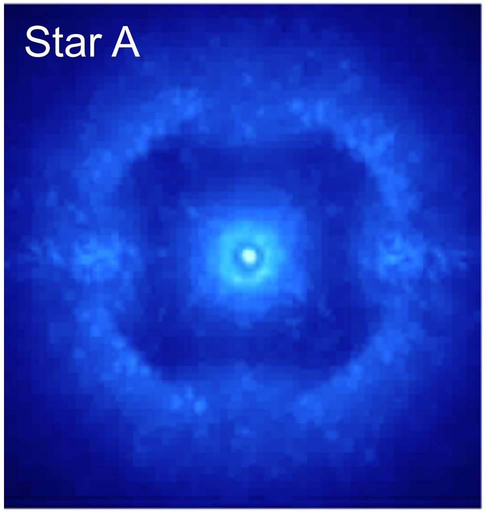
Star hopping: higher contrast at short separation



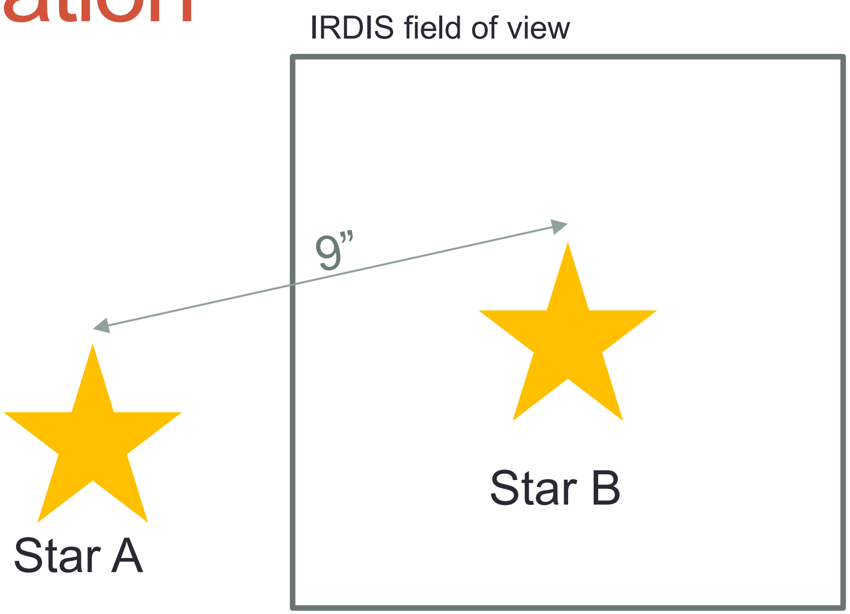


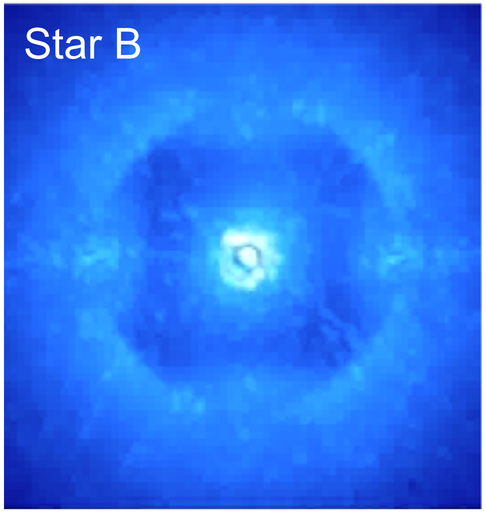
2min exposure on star A

Pantoja et al. in prep, Girard et al. in prep

- Goal: hop from one star to another to beat speckle decorrelation
- Offered in service mode in a first implementation (AO optimisation skipped), faster hopping using combined telescope offset for 2 stars < 10' tested
- To be implemented next year

Star hopping: higher contrast at short separation





5s later: AO loop closed on B
2min exposure on star B

Pantoja et al. in prep, Girard et al. in prep

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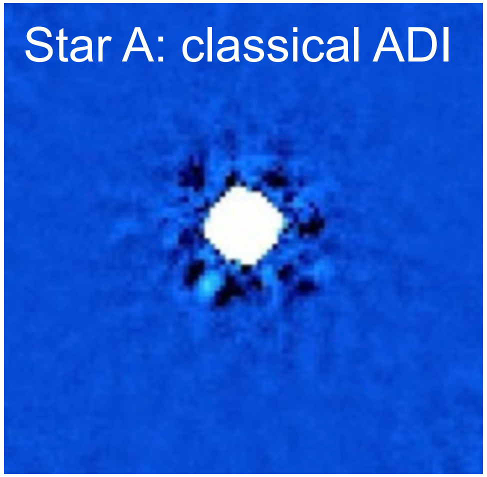
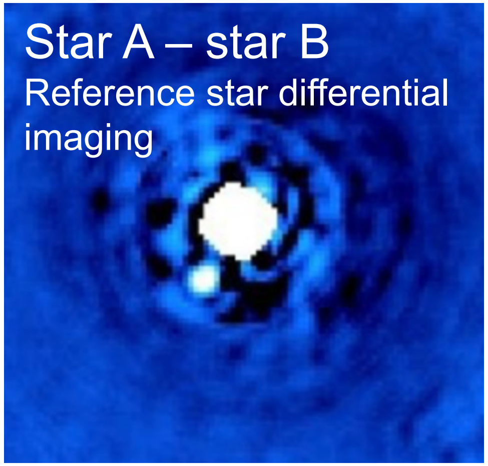
- To be implemented next year

Star hopping: higher contrast at short separation

Star hopping gives a contrast twice better at 100mas





Fake companion of contrast 10^{-4} at 160mas

Pantoja et al. in prep, Girard et al. in prep

- Goal: hop from one star to another to beat speckle decorrelation
- Offered in service mode in a first implementation (AO optimisation skipped), faster hopping using combined telescope offset for 2 stars < 10’ tested
- To be implemented next year

Smaller inner-working angle coronagraph

Context

Currently, no small IWA coronagraph offered (smallest APLC has a radius of 72.5mas, 4QPM have disappointing performance)

Parameter space from 1λ/D to 3λ/D scientifically very interesting

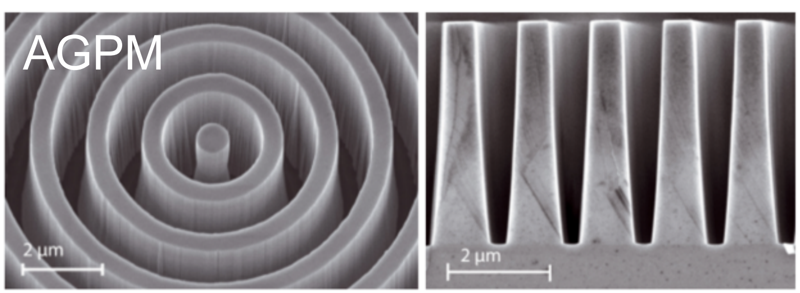
1 free slot in the coronagraphic filter wheel

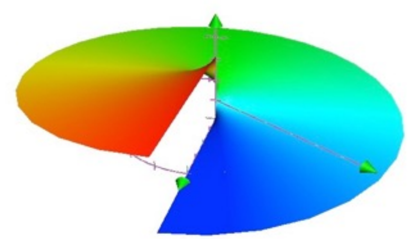
On going-project:

Understand poor performance of 4QPM

Confirm the scientific potential of a vortex on SPHERE (simulations on-going by E. Huby)

Choose a technology (AGPM, LCP, vAPP), wavelength, apodiser…





Conclusions and perspectives

- SPHERE fully working within specifications after 3 years, and operations are smooth
- Performance analysis highlight the critical influence of coherence time
- Many challenges and on-going
  - Low wind effect mitigation
  - NCPA compensation
  - Higher-rejection coronagraph
- Upgrade proposal being prepared to improve the performance of the AO system
- Prospects of fiber coupling with CRIRES+ or ESPRESSO for high-resolution spectroscopy