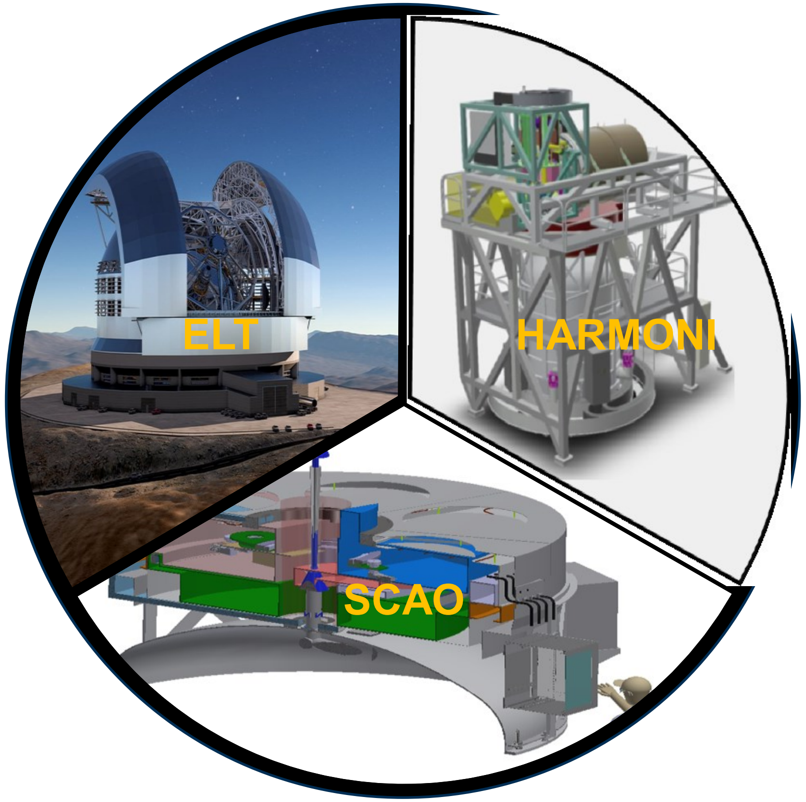
Adaptive Optics for HARMONI – ELT at the diffraction limit

Noah Schwartz

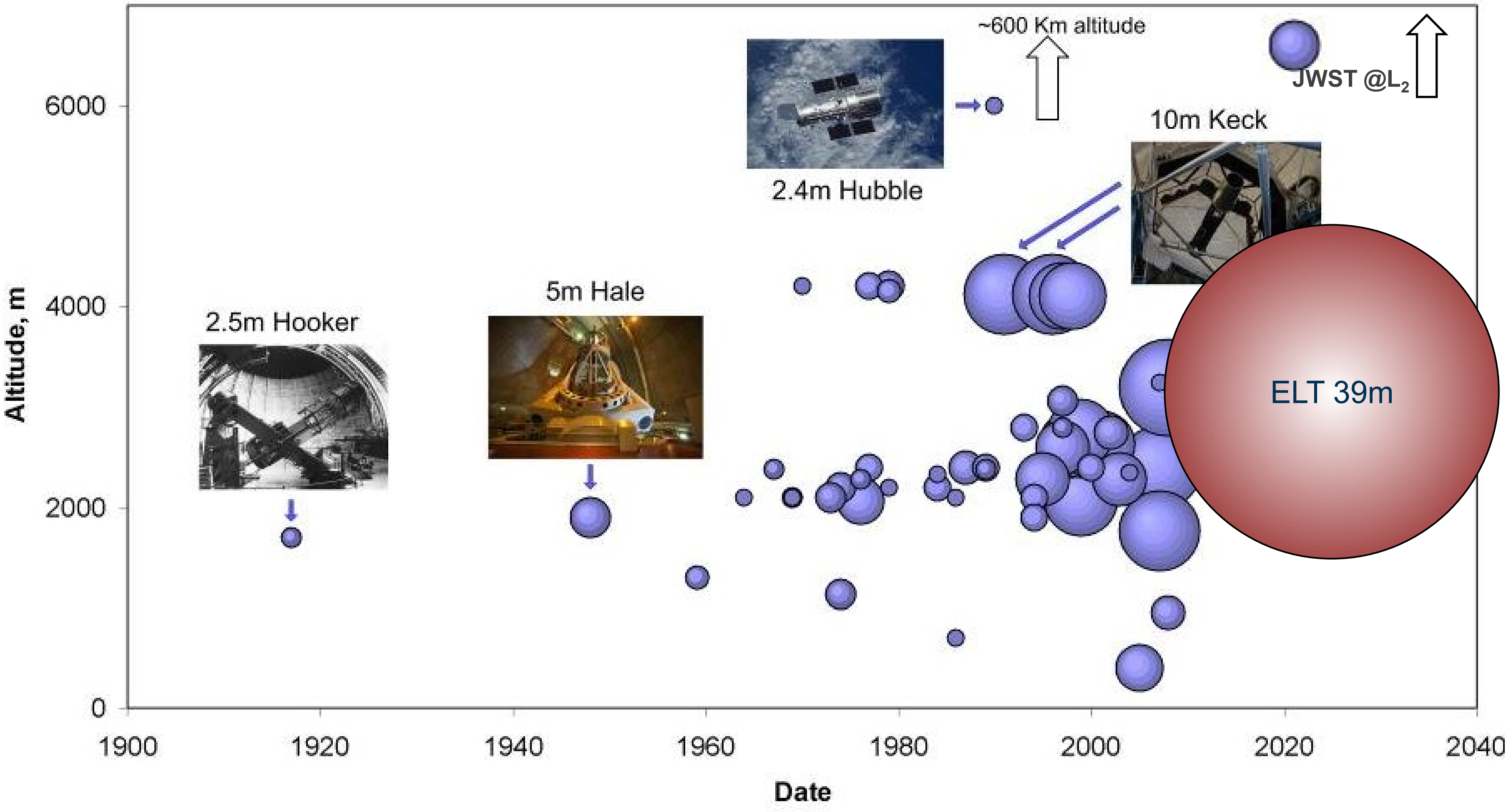
Many thanks to Jean-Francois Sauvage, Fraser Clarke, David Melotte, Benoit Neichel & the HARMONI consortium

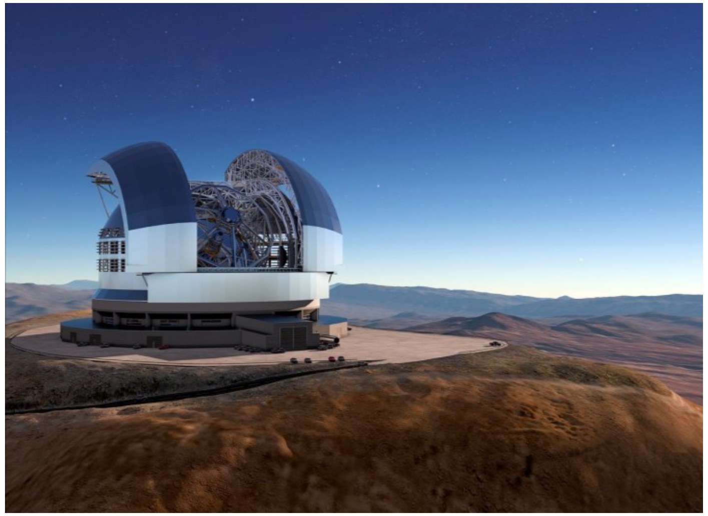
Outline

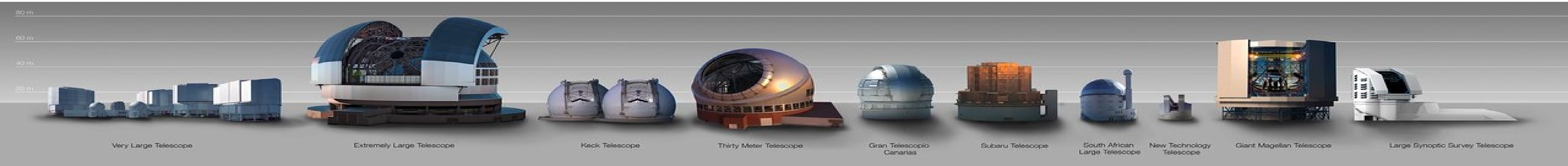


- The Extremely Large Telescope
  - ➢ An Active/Adaptive Telescope
- HARMONI overview
  - ➢ First-light IFU @ELT
- HARMONI AO systems
  - ➢ LTAO, High-Contrast, SCAO
- SCAO with the ELT
  - ➢ Extended Object
  - ➢ Pupil fragmentation

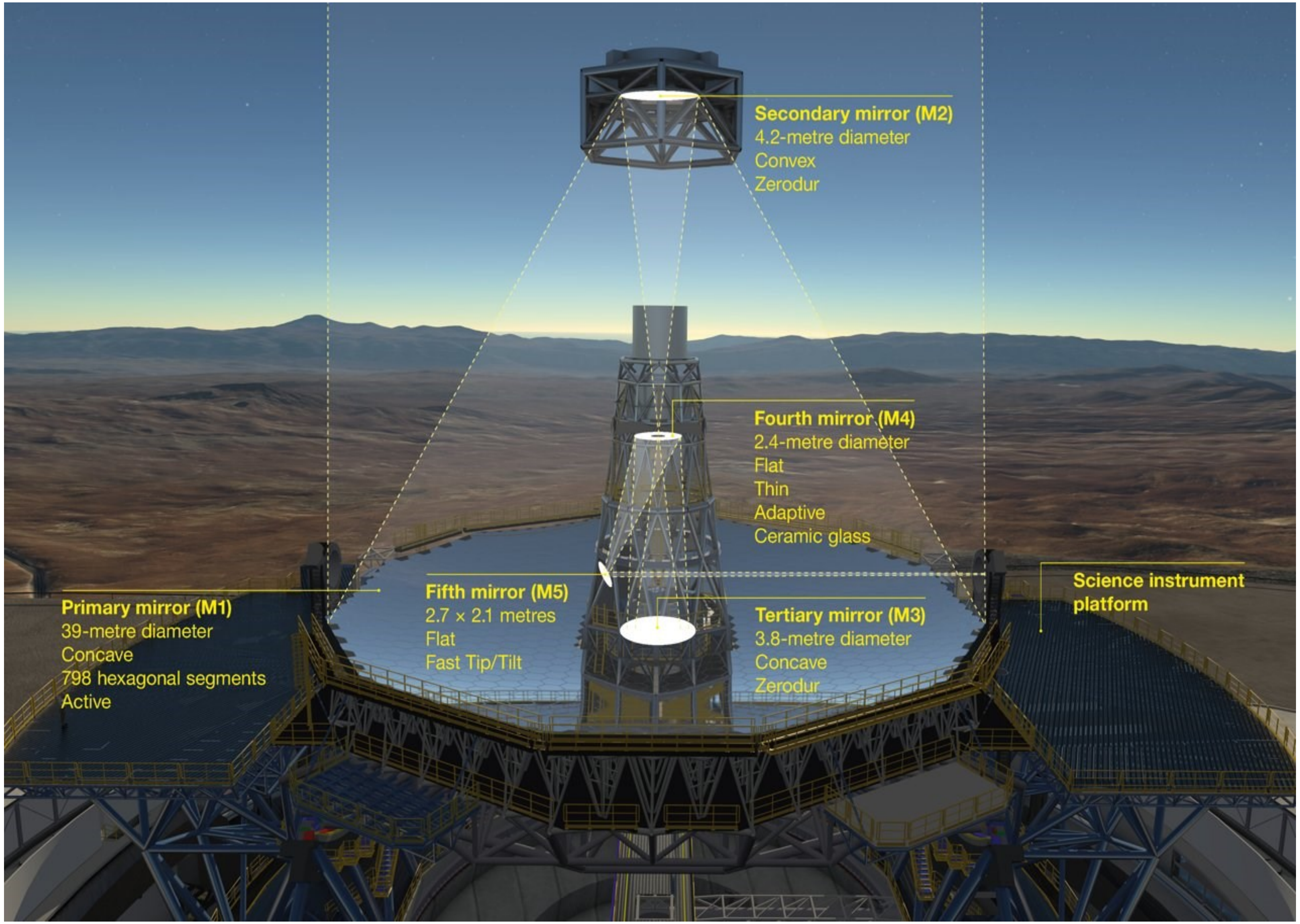
Telescope Mirror Size Progression







World’s largest optical near-IR Telescope



In Numbers

- 39m diameter
  - 798 segments, Ø=1.45m
  - 133 spares
  - 1 to 3 removed each day
- Working from the visible-mid infrared
- Adaptive telescope
  - 5613 fast Voice Coil actuators (400Hz)
- Cost
  - over €1000 million
- First light 2024

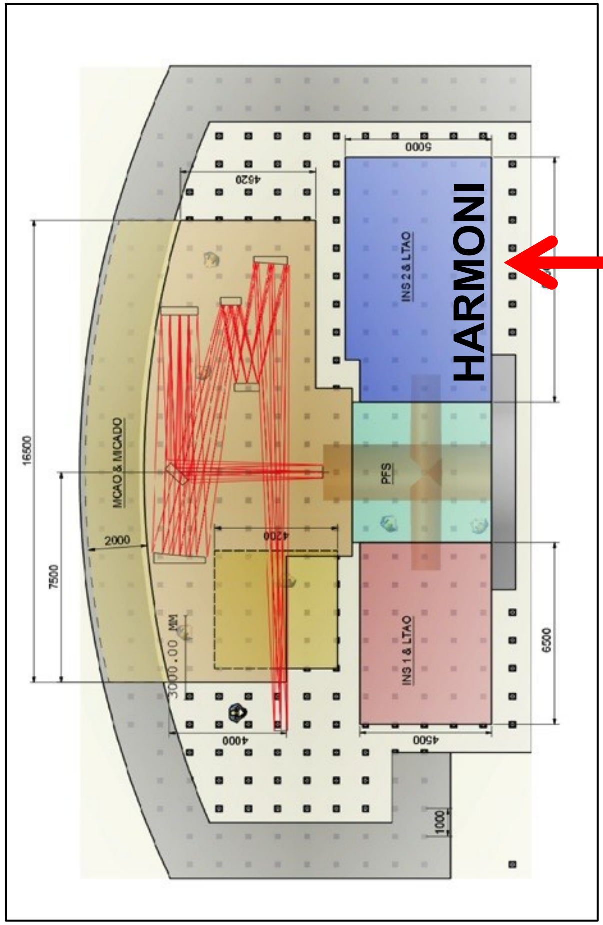
ELT Countdown

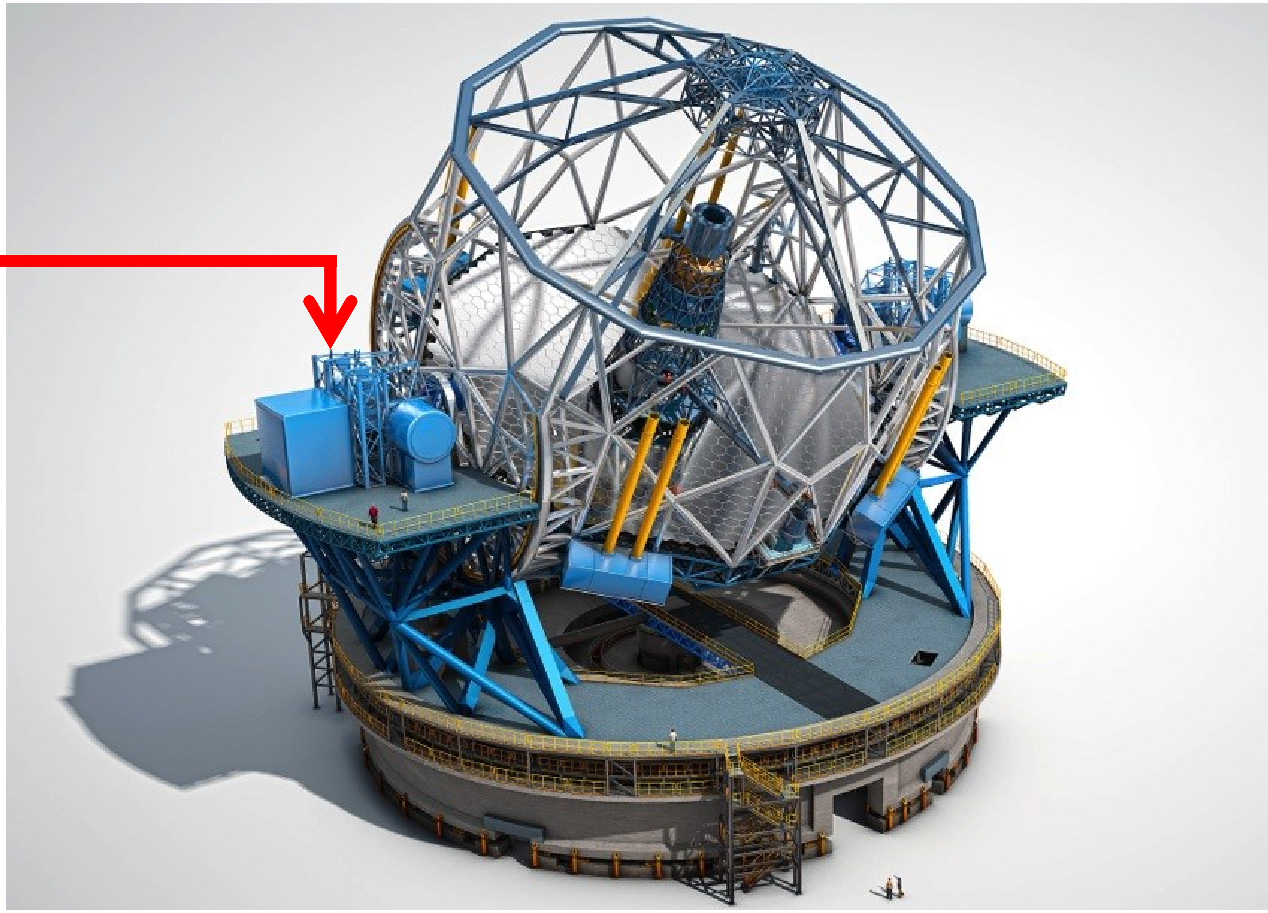
ELT First Light Sunset In

2055	16	53
Days	Hours	Minutes

HARMONI

HARMONI: High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph



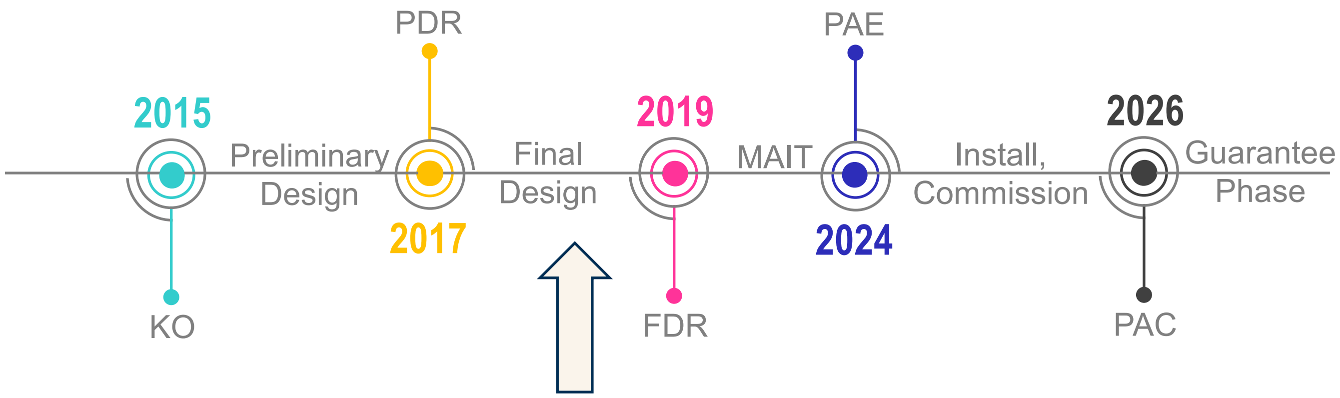


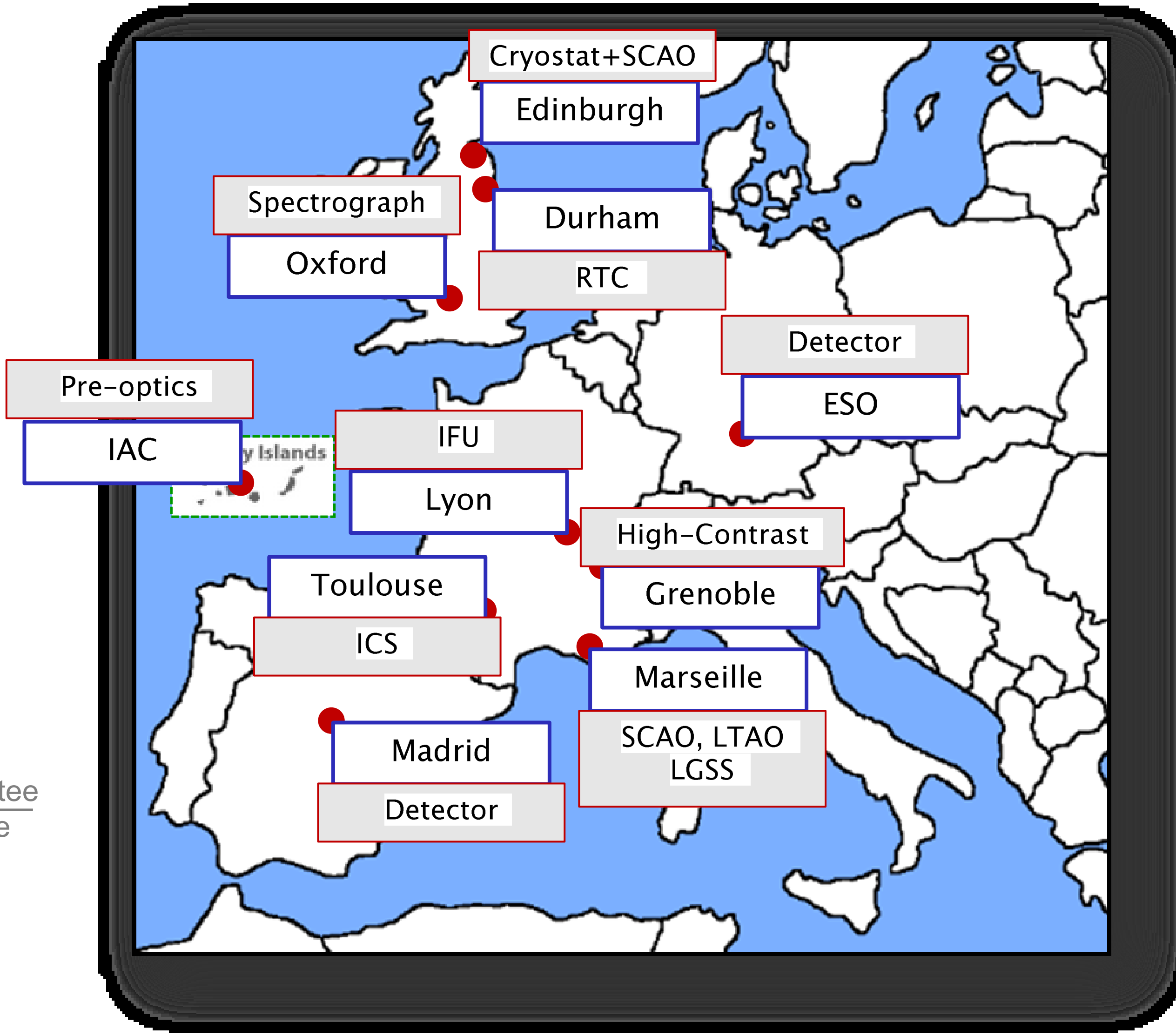
Project Overview

Countries involved
- UK-France-Spain-ESO project

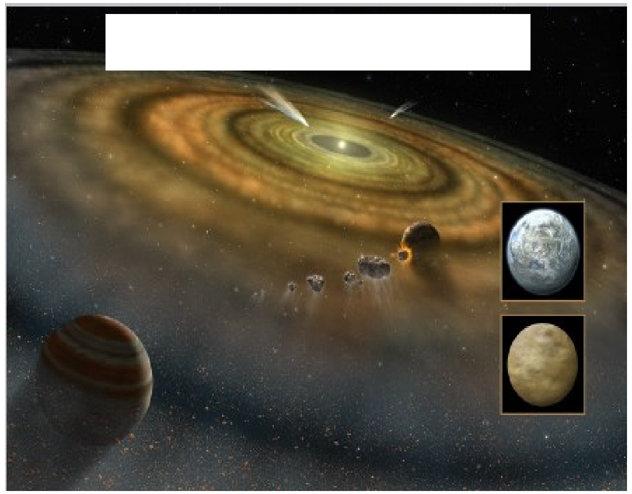
Overall Effort
- ~450FTE
- ~32M€ hardware

Duration
- 9 year for main design & build phase





HARMONI Science Cases



Solar system bodies

Strehl Ratio

acterization

of known planets

The physics of
high redshift galaxies

From first light to the
earliest galaxies

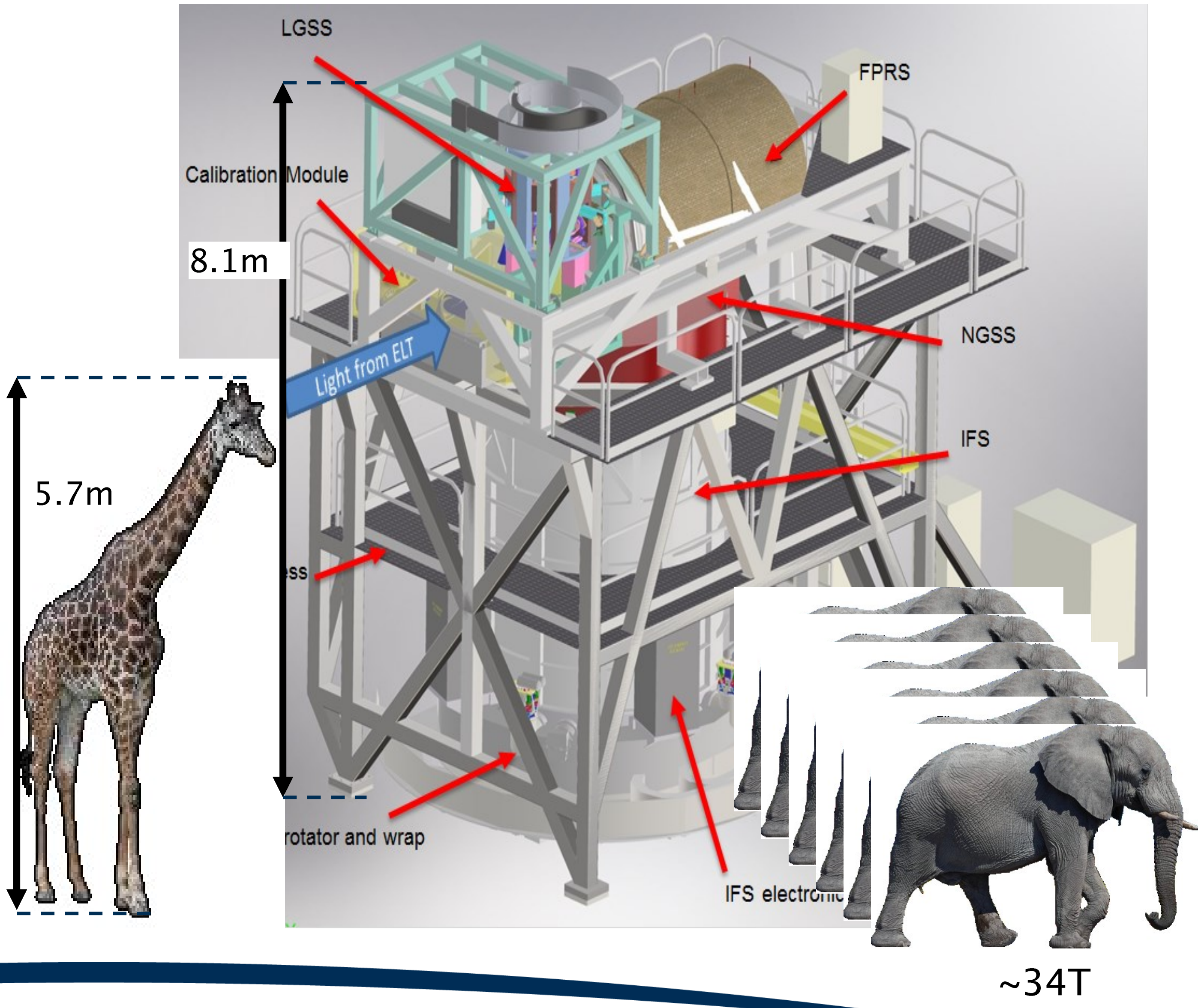
SCAO

LTAO

Sky Coverage at South Galactic Pole

HARMONI – General Overview

- First light general purpose Integral Field Spectrograph for ELT
  - Work horse instrument
  - Early ‘highlight’ science on key objects/projects
  - Low technology risks
- V-band to K-band (0.47-2.45μm) spectra coverage
- R = 3500, 7000, 18000 resolutions
- 60, 20,10 & 4mas pixel scales
- Work with NoAO/SCAO/LTAO correctior
- 204x152 pixel field of view (31000 spaxe image slicer)
  - Eight Hawaii-4 detectors
  - Four Optical CCDs



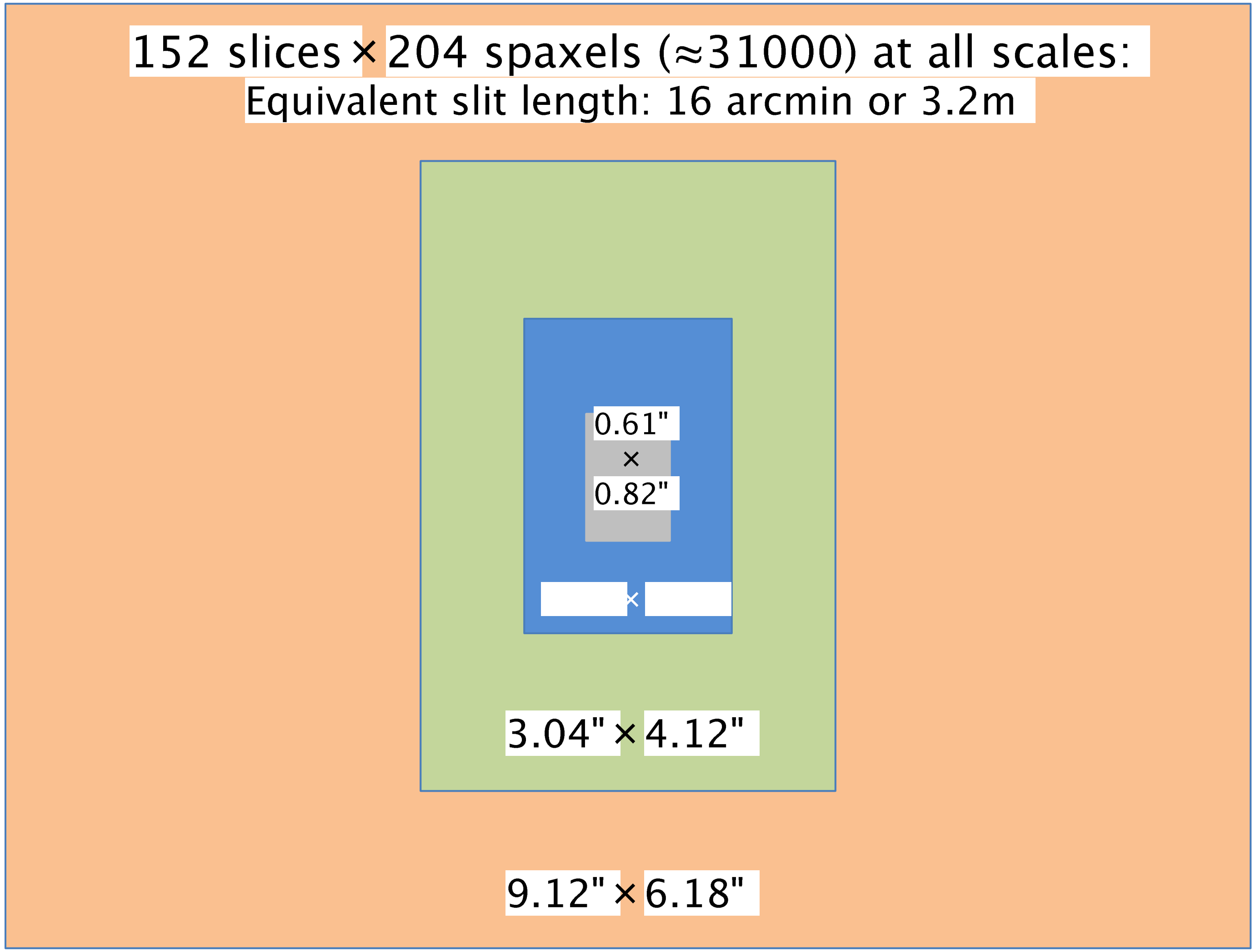
Field of View and Spaxel Size

60mas × 30mas — For non-AO & visible observations

20 mas — For optimal sensitivity (faint targets)

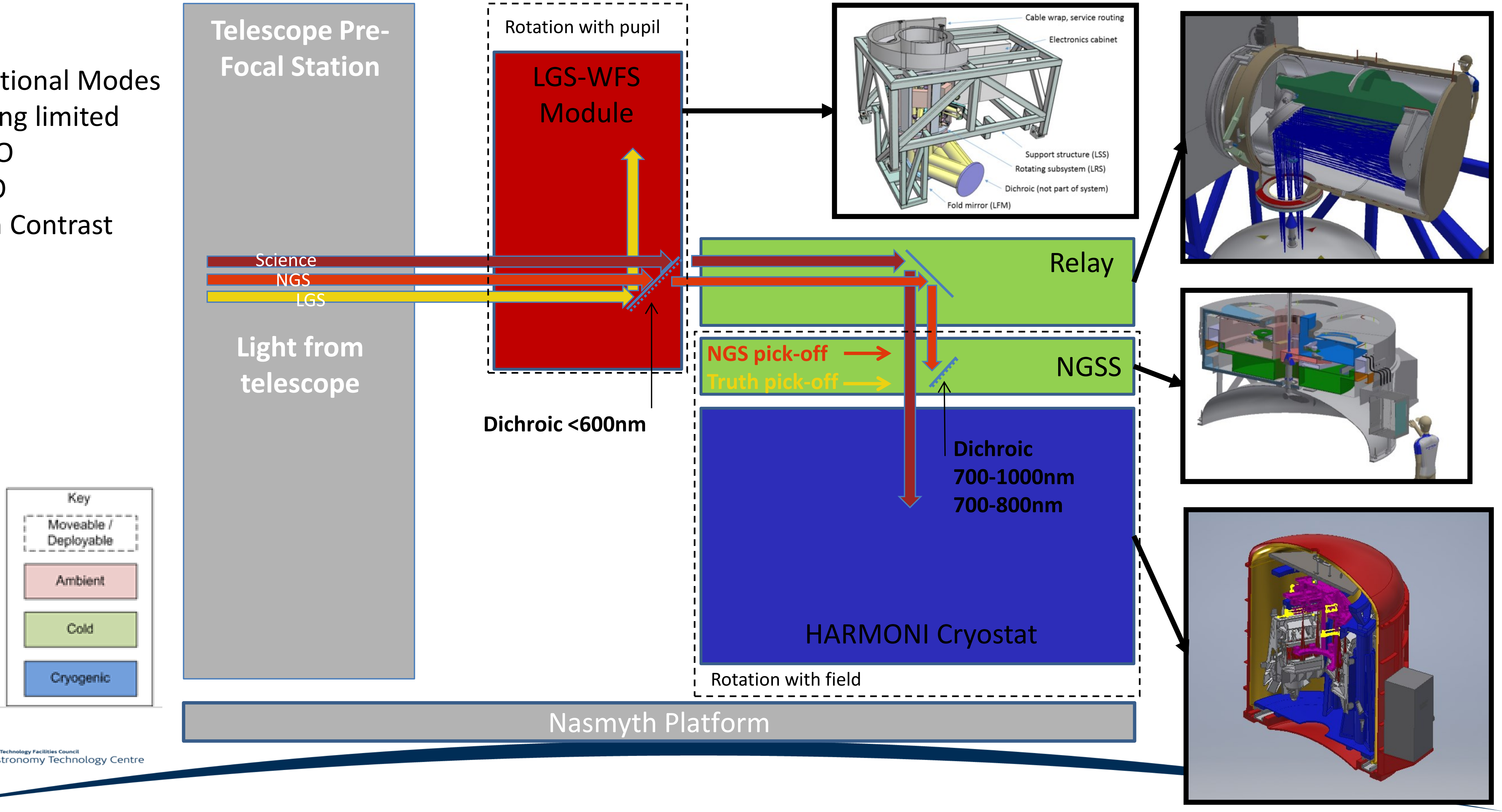
10 mas — Best combination of sensitivity and spatial resolution

4 mas — Best spatial resolution (diffraction limited)



HARMONI, SCAO & LTAO implementation

Operational Modes
+ Seeing limited
+ SCAO
+ LTAO
+ High Contrast

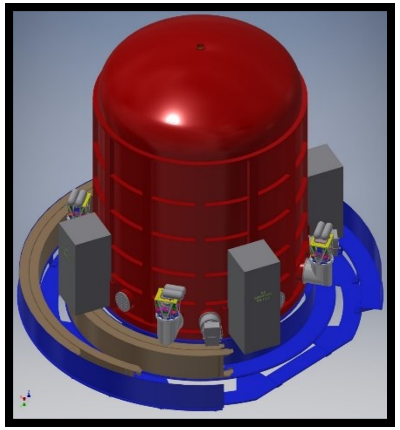


HARMONI Architecture PBS

- HARMONI breaks down into three main areas

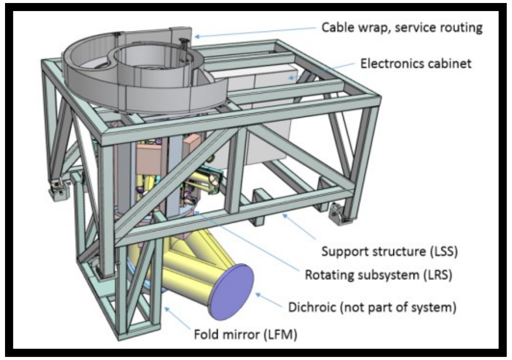
"Science Instrument"

- Integral Field Spectrograph
  - Pre-optics
  - IFU
  - Spectrographs
  - Cryostat



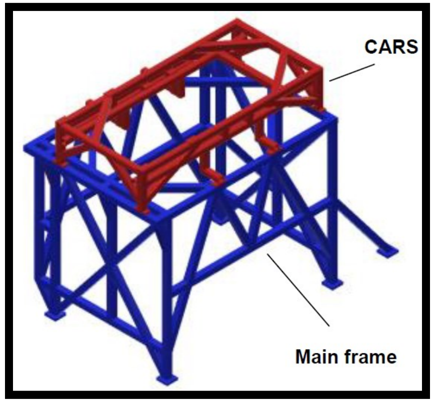
"Wavefront Sensors"

- LTAO LGS/NGS
- SCAO
- High contrast module
- Secondary Guiding



"Supporting Systems"

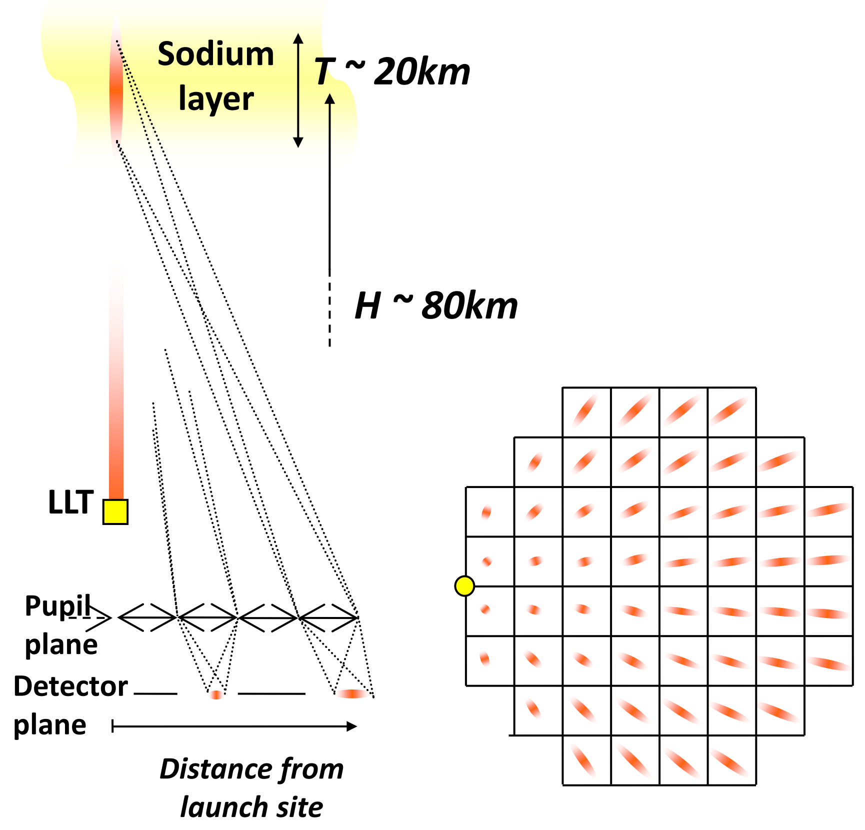
- Mechanical Structures
- Control Systems
- Calibration
- Software
- Data flow
- Etc etc



Laser Tomography AO

- Top-level requirements
  - **Peak Performance** (SR = 50% @2.2µm & Sky Coverage = 10% @SGP)
    - Drives the LGS (High-Order correction)
  - **Good Performance** (SR = 30% @ 2.2µm & Sky Coverage = 75% @SGP)
    - Drives the NGS (Low-Order correction)
    - Open-loop DM to correct for off-axis NGS star
- Driving criteria: number of detector pixels
  - Options to mitigate truncation under investigation
  - Potential alternative camera design identified

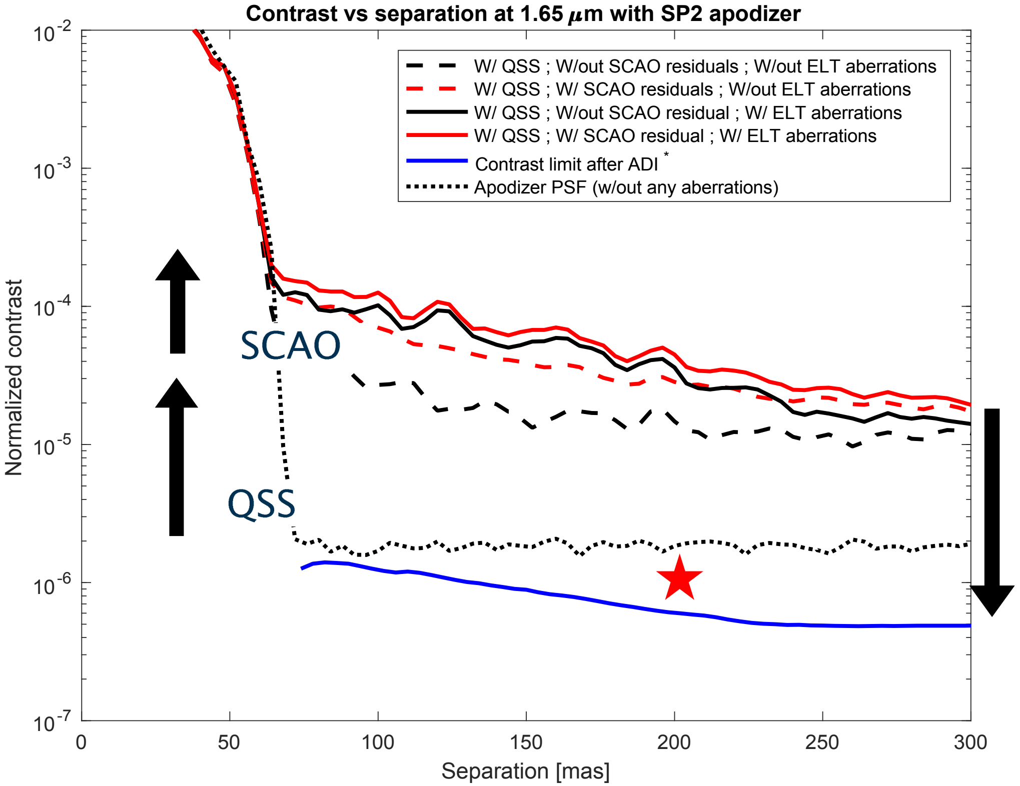
Low sky coverage (1%)	High sky coverage (50-90%)
Best Performance (Diffraction limited)	High-performance



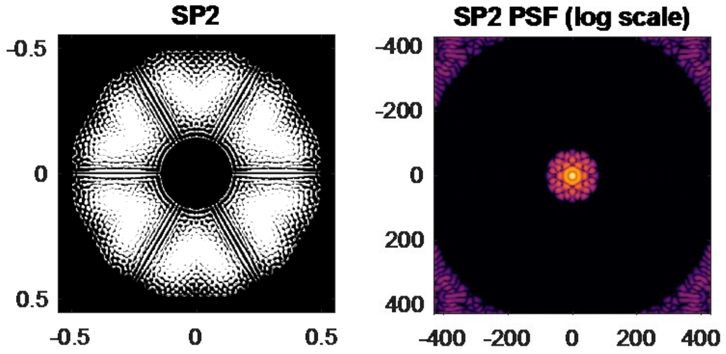
High-Contrast Module

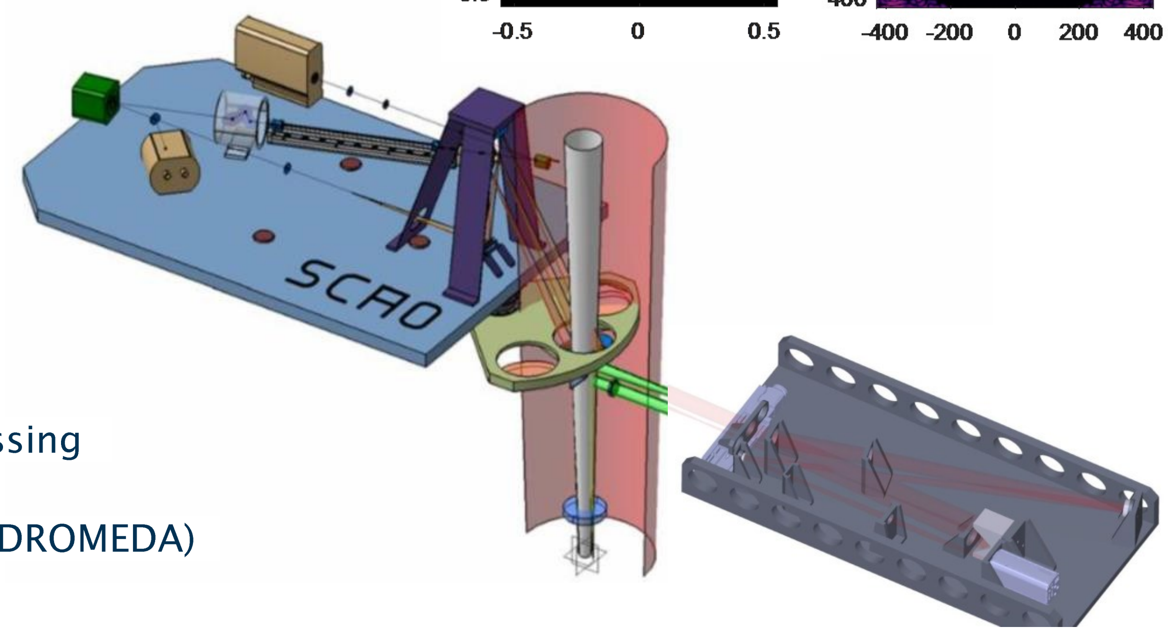
High Contrast Requirements

- Spectral characterization of young Jupiters around nearby stars in H & K bands at R=3000-20000, with **a 10^{-6} contrast at 200mas**.
- Takes benefit from SCAO correction



SP2 apodizer
10^{-6} contrast
70 mas in H
100 mas in K





processing

Po(ANDROMEDA)

HARMONI SCAO module

High-Order WFS

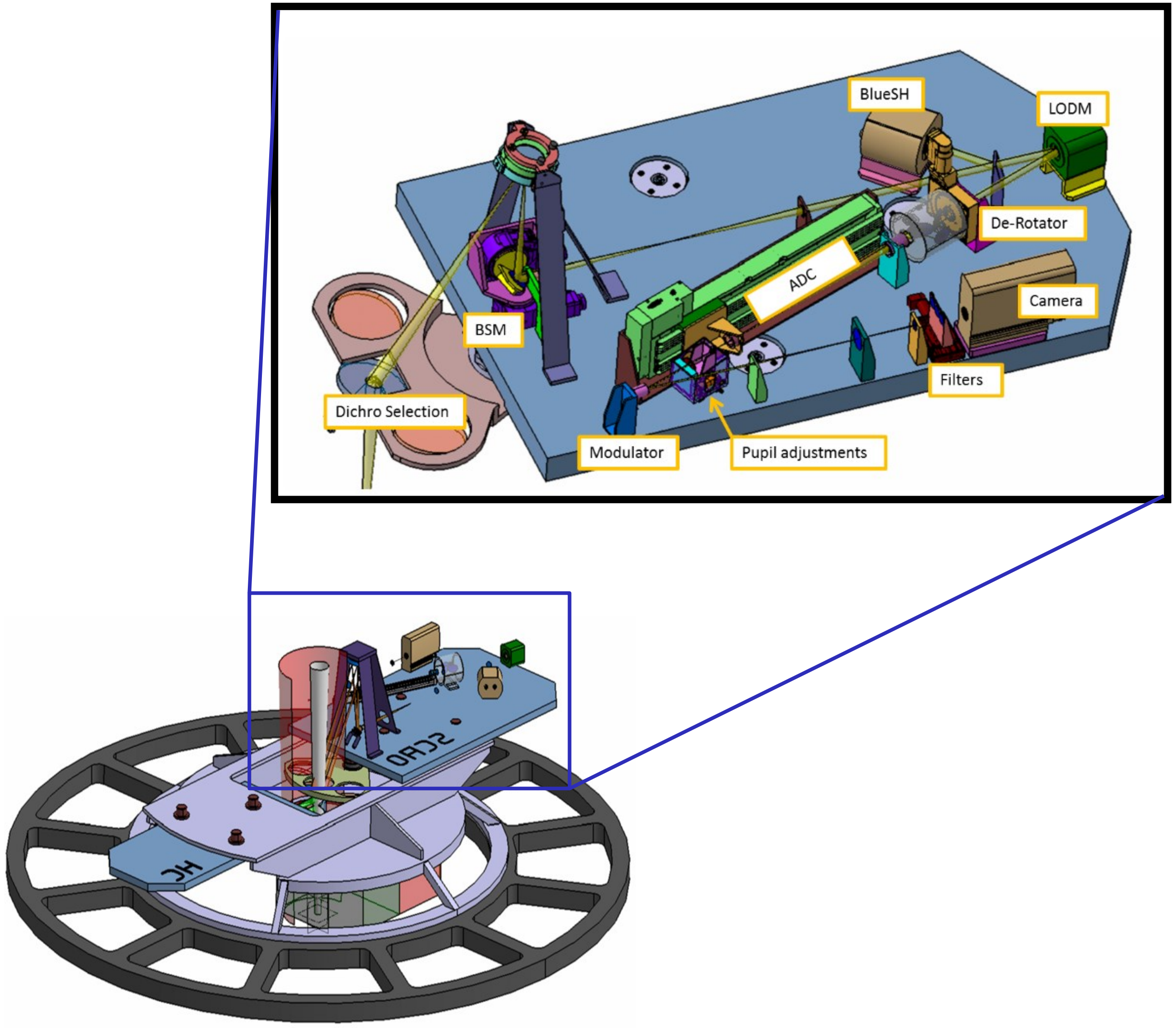
- Pyramid + $OCAM^2$ camera @500Hz
- 700-800nm or 700-1000nm

Low Order Loop

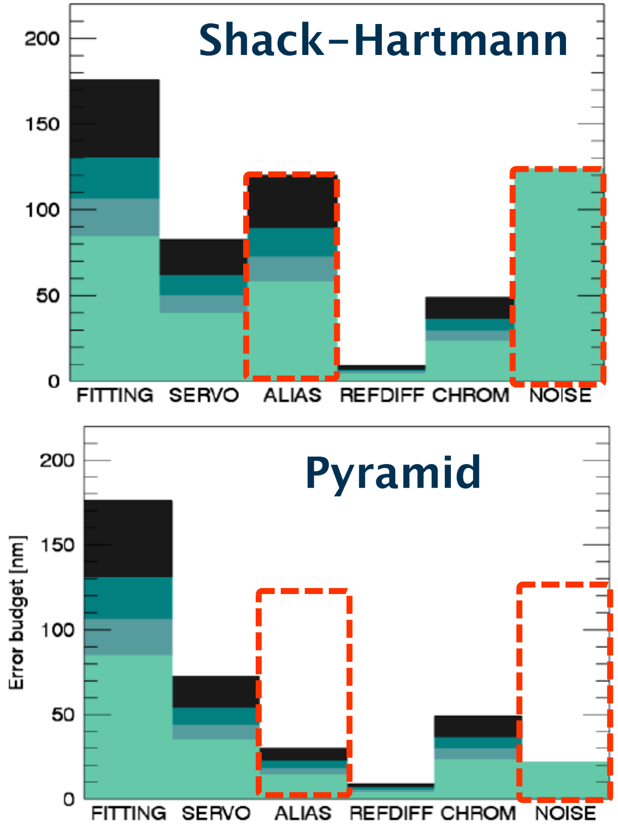
- LODM (13x13 actuators)
- Low order Shack-Hartmann
  - 650nm, 10nm bandwidth,1s rate
- Differential tip-tilt stabilisation
- NCPA low order compensation

SCAO active components

- Object selection mirror: 15 arcsec radius
- ADC, Derotator (K-mirror)
- Pupil adjustment loop
  - Control of shift / rotation / distortions



SCAO Wavefront Sensing



Pure turbulence compensation

- Error dominated by DM fitting
- Better CCD camera available
- Less aliasing

Pyramid WFS

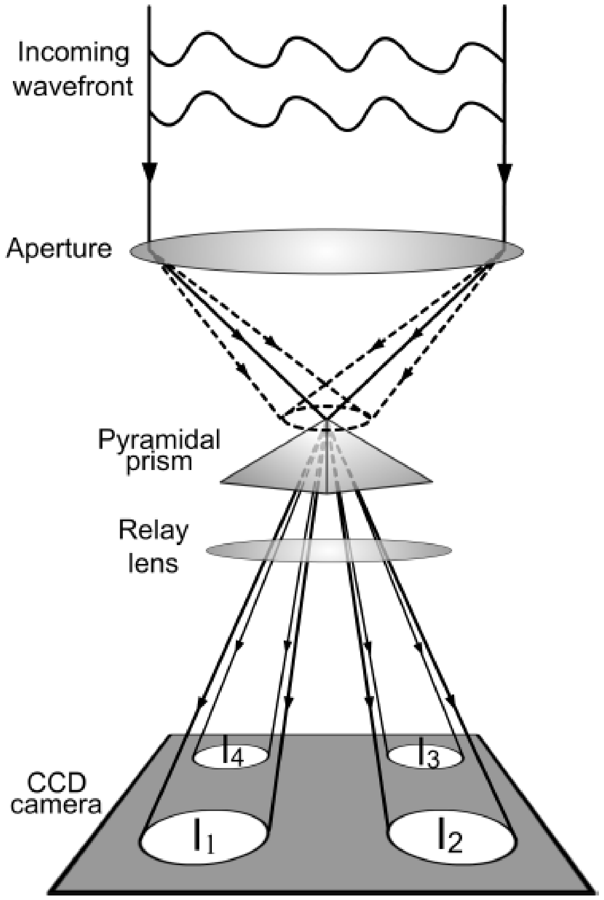
- 4-sided prism (oscillating), re-imaging optics & camera
- Splits light into 4 regions (intensities) that are recombined to measure wavefront.

Advantages over Shack-Hartmann

- Potential for increases sensitivity
- Less aliasing
- Modulation for adjusting linear range for different condition at the cost of sensitivity
- (see later on pupil segmentation)

Disadvantages

- Variable gain
- Non-linear behaviour



Credit: Iu. Shatokhina

Global SCAO Performances

Requirements

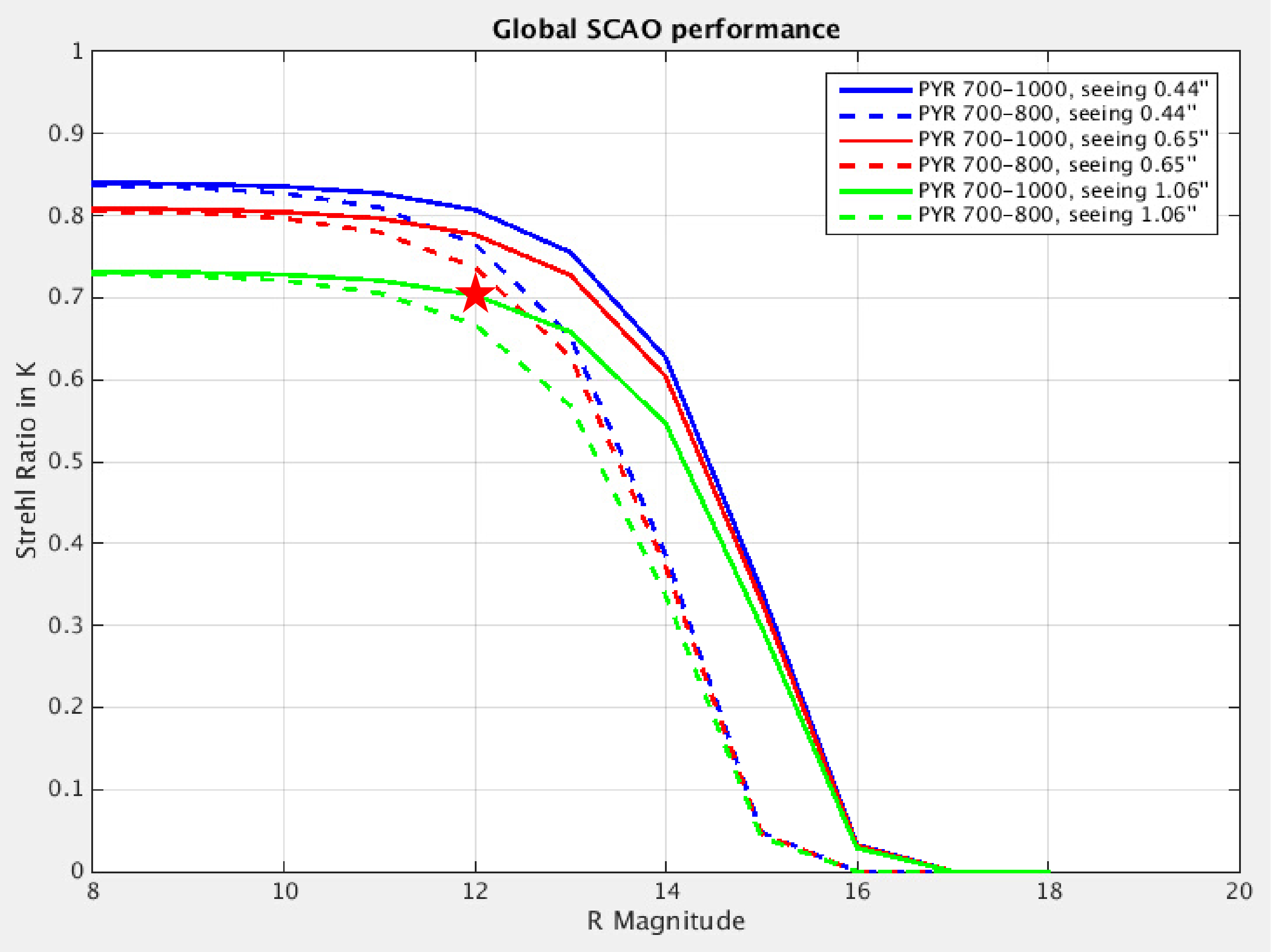
- Strehl Ratio @ K-band > 70%
- Medium seeing 0.65’’
- Magnitude R=12

Results at PDR

- Spec. reached with small margin
- Effects taken into account
  - Atmospheric turbulence
  - Instrument contributions
    - Island + NCPA residuals
  - Telescope contribution
    - Static contribution
    - Dynamic contribution (excl. Low-Wind Effect & Vibrations)

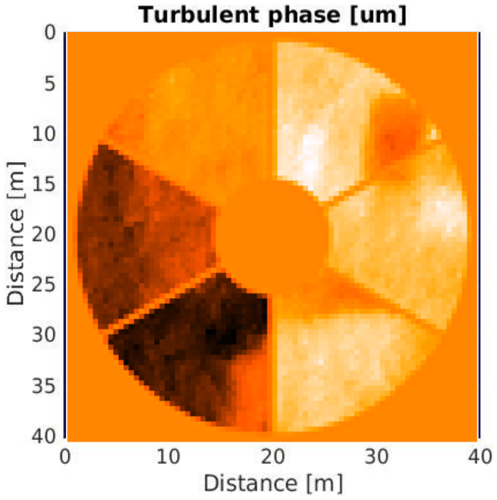
Good performance on faint M stars

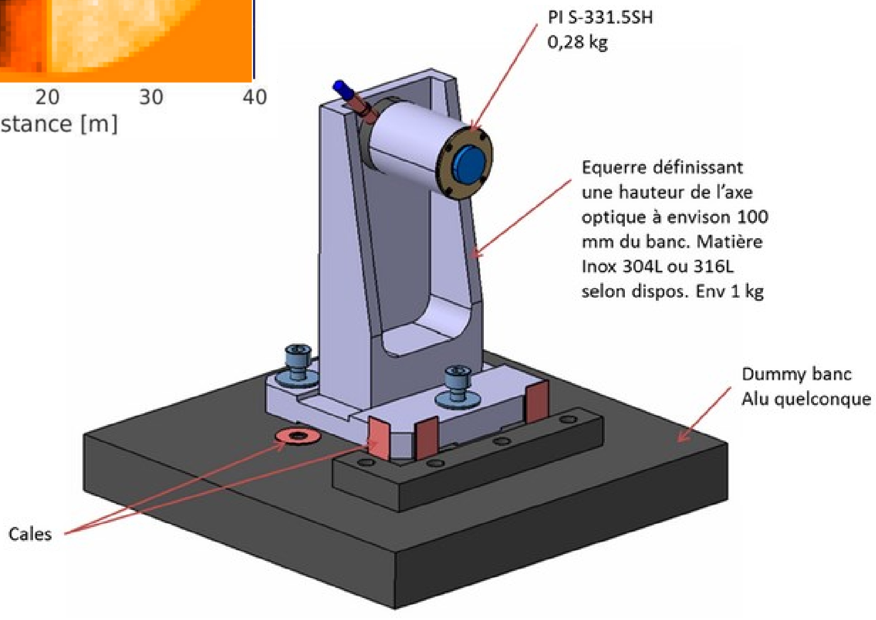
- Compatibility with HC module



Ongoing work: SCAO

- **Extended object performances**
  - Ongoing study
  - OK for bright objects
- **Telescope and Instrument issues**
  - Islands effect
    - ➔ Solution developed for HARMONI-SCAO
  - Low-wind Effect
    - ➔ Ongoing study
- **Prototyping**
  - Cold tests of Modulator / OSM
  - Verify fast tip-tilt in -20°C environment
  - Verify Object selection mirror absolute precision
- **Laboratory evaluation work (bench)**
  - Analyse the Pyramid sensitivity
  - Investigate optimal correction vs. seeing condition
  - Demonstrate NCPA correction for high-orders





Ongoing work: Extended Object

Studied impact of object

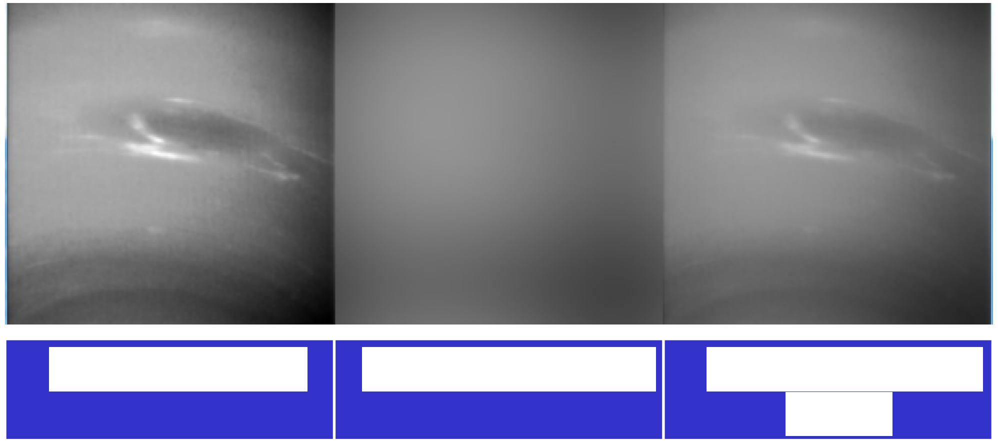
- Size, Flux, Structure

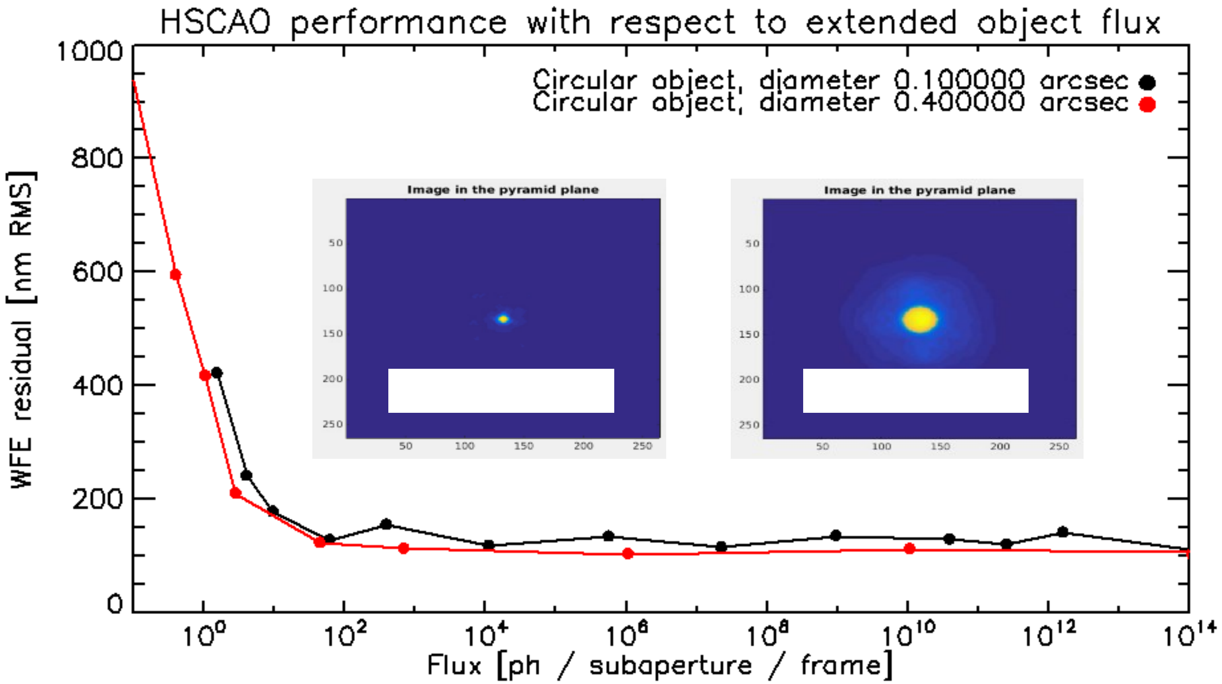
Simplified (Mini-ELT) configuration

- 10m telescope
- Mini M4 mirror (hexagonal)

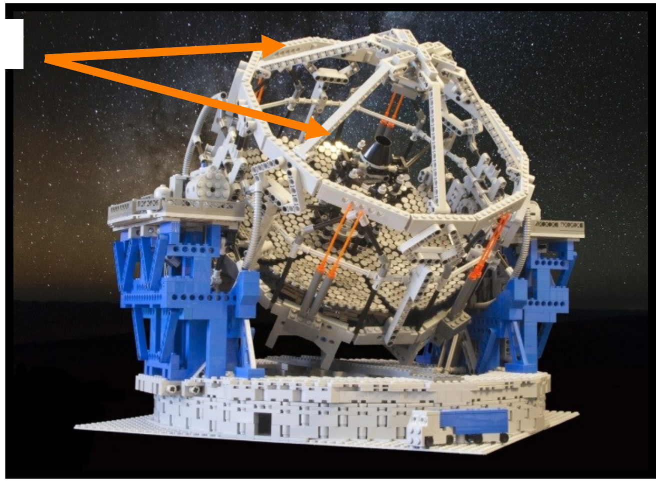
Performance vs. flux

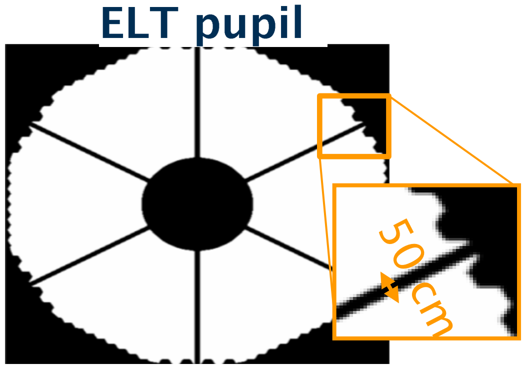
- Little impact of object size from 0.1 to 0.4 arcsec
- Validated down to very faint flux
- Only depends on the total number of photons in the WFS
- Structured object: additional tip-tilt residual





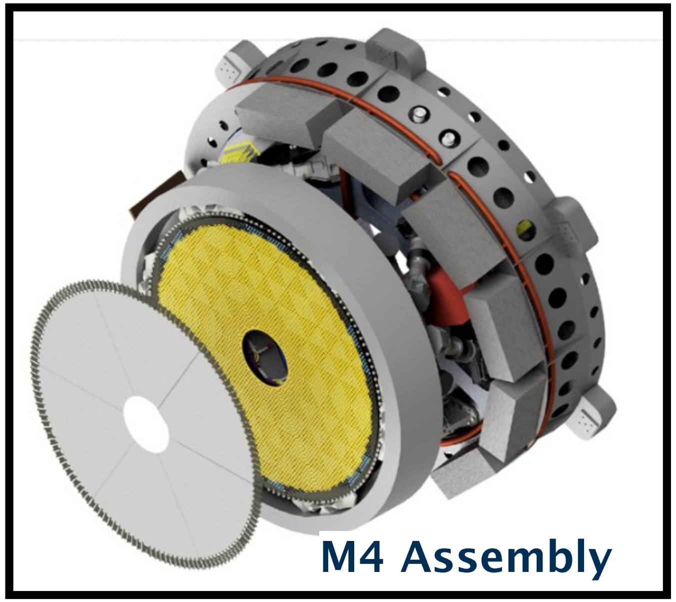
Pupil Segmentation

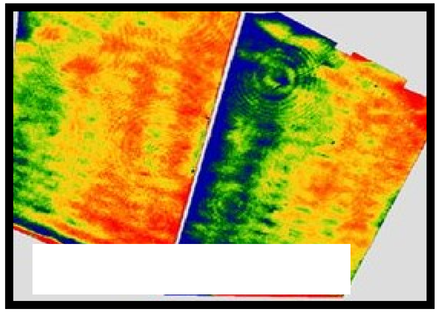




Support struts (aka spiders)

- Six 50 cm wide spiders (>r0 @ λ_{WFS})
- Creates discontinuities in pupil
- Obscure entire lines of sub-apertures on the SCAO Pyramid WFS





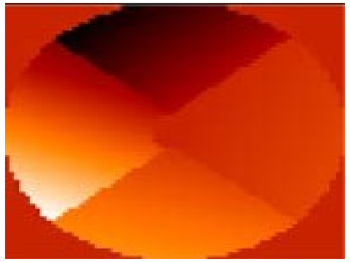
High-order wavefront control M4 (DM)

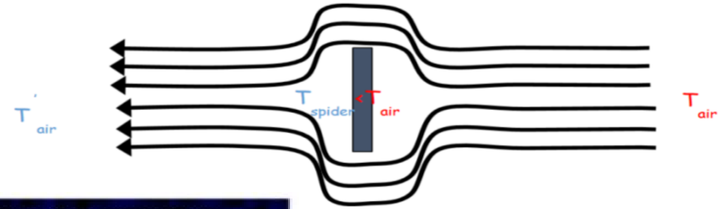
- Segmented thin shell made of 6 discontinuous petals (segments)
- Matching the 6 spiders geometry
- Common reference body

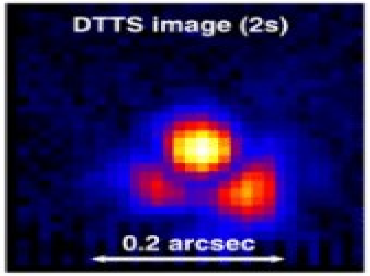
Impact of Pupil Segmentation

Low-Wind Effect

- Combination of Piston, Tip, Tilt
- Telescope induced effect
  - Created by radiative cooling of the telescope spiders
- Strength depends on the <u>height</u> of the spiders
- Vary slowly over time

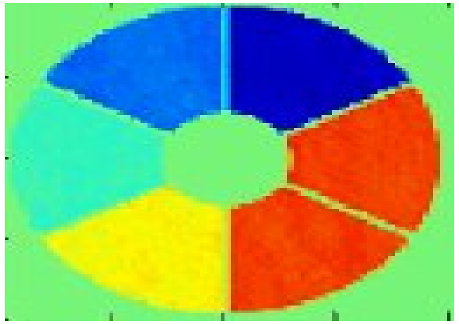


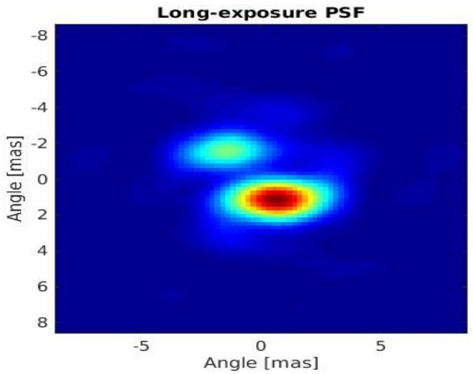




Island effect

- Differential Pistons (ΔP)
- Created by the AO loop itself
  - ΔP undergo amplification during the inversion / reconstruction
  - True for any badly seen modes such as waffle
- Strength depends on the <u>width</u> of the spiders
- Vary at loop frequency





Low Wind Effect

Assumptions

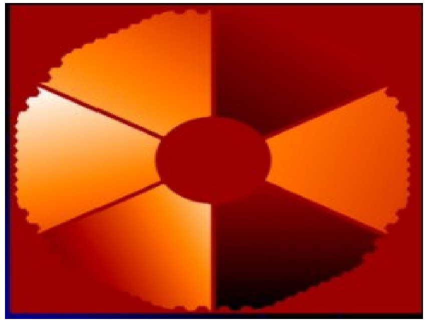
- ELT spiders will use same VLT-UT3 coating
- Rule of thumb
  - Reduction of 1/5th of residual LWE
  - Spiders height 5x larger than VLT
  - ➔ LWE residual around 800nm PV

Impact on performance

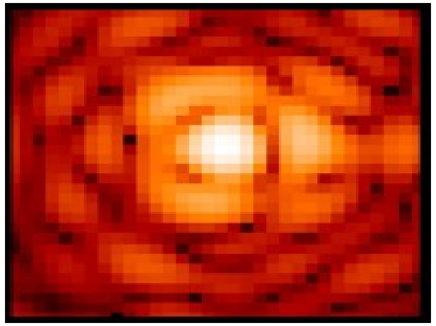
- Impacts SCAO and LTAO
- Visible on SCAO and up to 20mas boxes

Conclusion at PDR

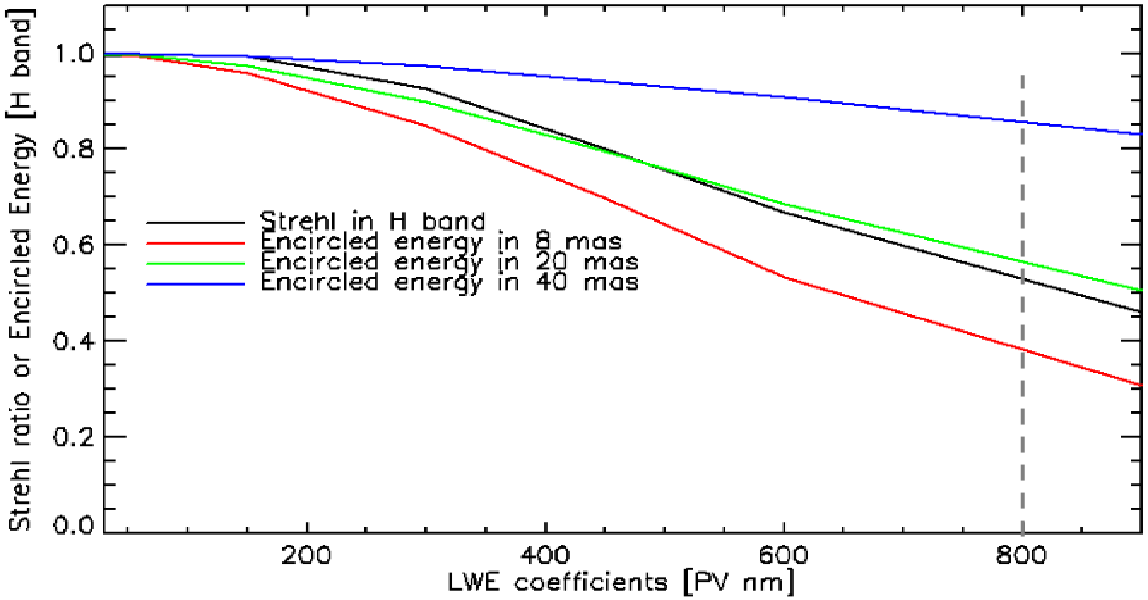
- Additional correction on top of spider coating
- Interaction with Island Effect



LWE pattern simulated on ELT pupil



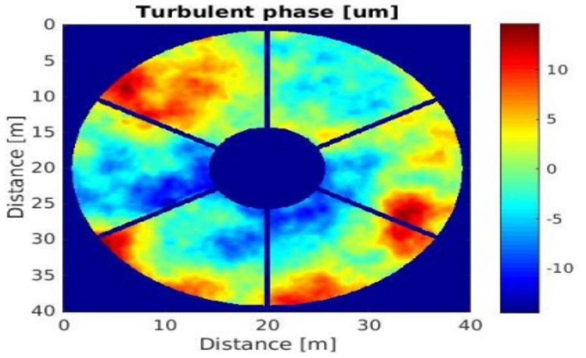
H band PSF

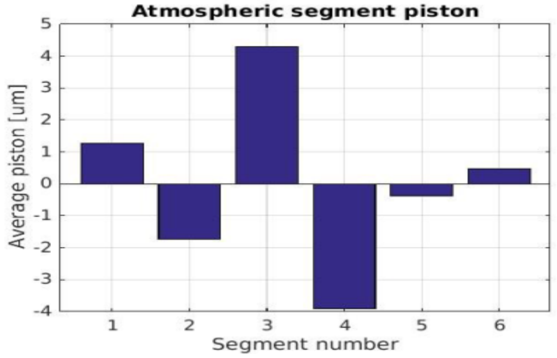


Island Effect: Atmospheric turbulence

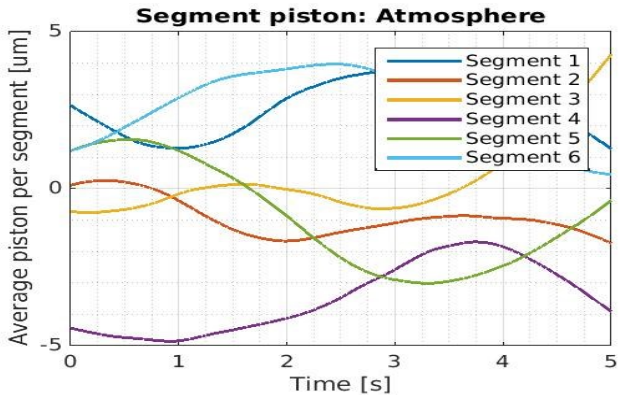
Differential Piston

- The atmosphere produces differential piston between the segments



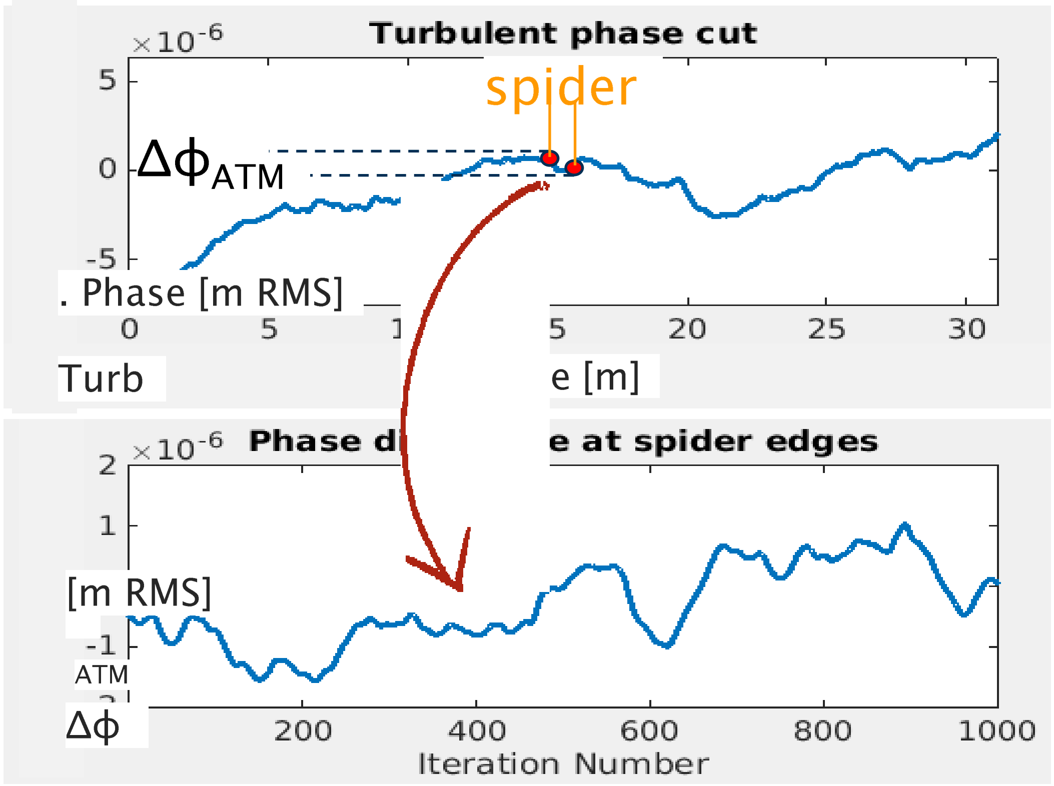


- Variation are slow (seconds), driven by wind speed



Phase across spiders

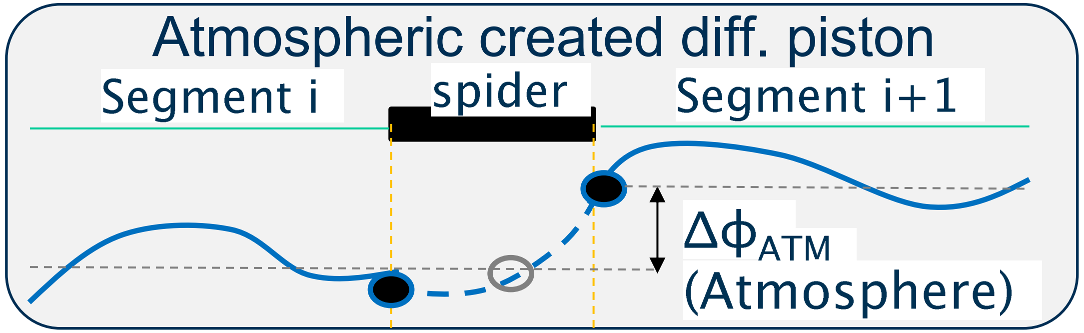
- Large phase jumps across spider
- r0 (<20cm) << spider width (50cm)
- Loss of spatial coherence

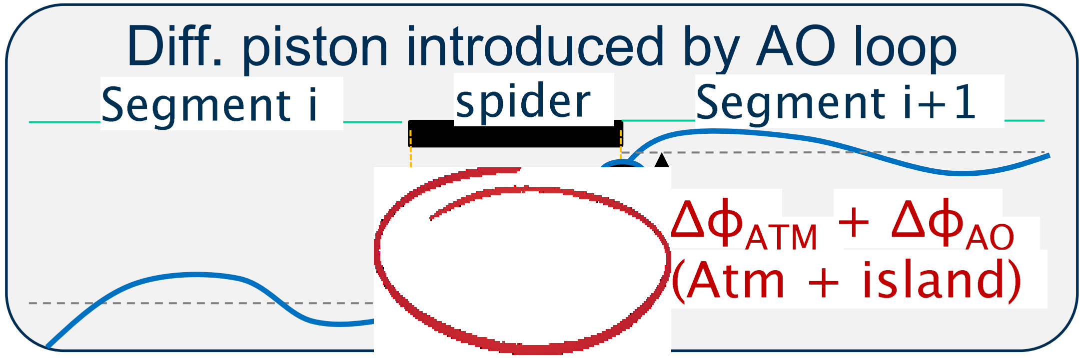


Island Effect: Atmospheric turbulence

Island Effect

- Differential piston
  - Not well sensed by the P-WFS
  - Additional term injected by AO loop
- $\Delta\phi_{ATM}$ and $\Delta\phi_{AO}$
  - Of the same order of magnitude
  - Difficult to disentangle





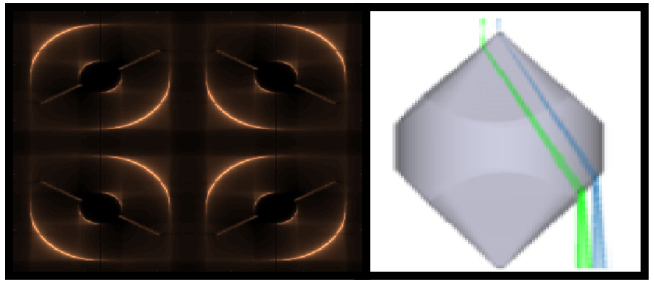
Requirements (HARMONI)

- Provide a <u>simple/robust solution</u>
  - Correct atmospheric differential pistons ($\Delta\phi_{ATM}$)
  - While preventing any island effect build-up ($\Delta\phi_{AO}$)
- SCAO error budget study
  - <u>$\Delta\phi_{AO}$ < 70nm RMS</u> of additional diff. piston (in quadrature)

Island Effect: Potential solutions

Using PYR-WFS only

- PYR can measure diff. piston
  - Need small modulation
  - Careful selection of valid signal
- Large gaps of 50cm
  - Little actual signal
  - Limited capture range $\pm\lambda_{WFS}/4$
- Alternative designs
  - 2 Pyramids at $\neq\lambda_{WFS}$ (see GMT)
  - Sense at longer wavelength
  - Signal extrapolation



Reconstruction

Solution 1

- Filtering out all differential piston
- Also removes atmospheric contributions

Solution2

- Regularisation: relying on priors to smooth the DM commands
- Best correction possible (if model well tuned!)
- No complete recovery is possible without adding complementary measurements
- Work in progress!

$$s_\alpha = G\varphi + \eta$$
$$\varphi = R s_\alpha$$

Pairwise Edge Actuator Coupling

Correction concept

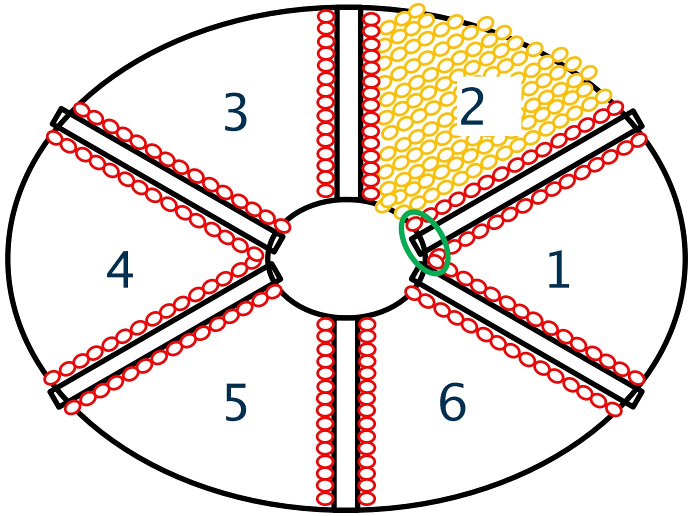
- Good performance w/o spiders & w/ continuous DM
- Cannot change spiders physical properties…
- Can we change DM behaviour?

Approach details

- Pairwise coupling of edge actuators
- Common reference body gives absolute position of the 6 DM petals
- Harder (but not impossible) for the DM to produce a segment piston

Limitations

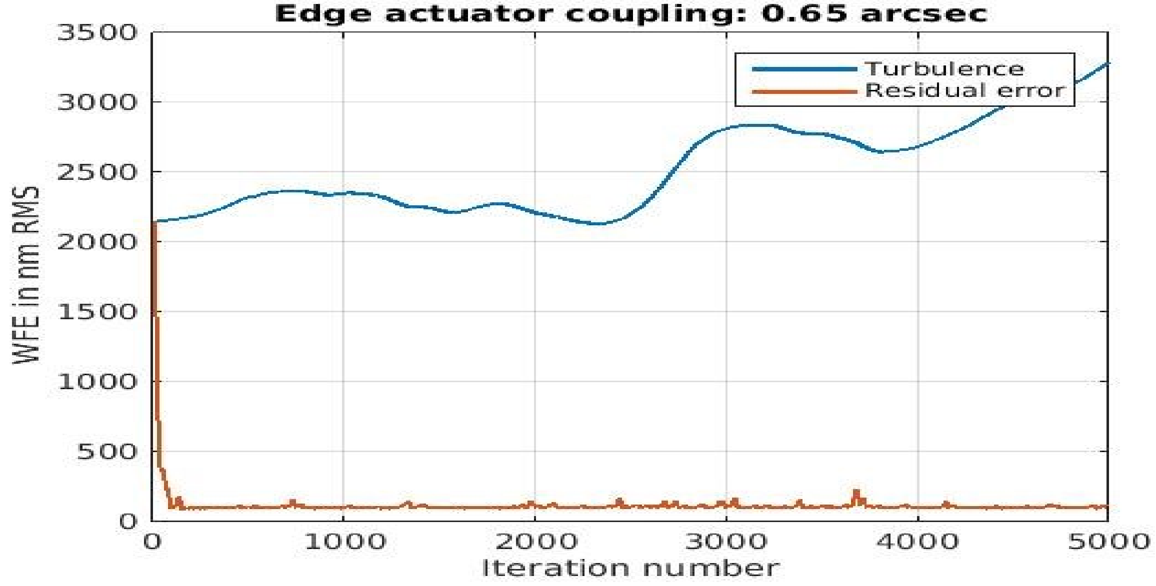
- We loose in actuators count (162 DoF): negligible
- Complex coupling with Low-Wind Effect?

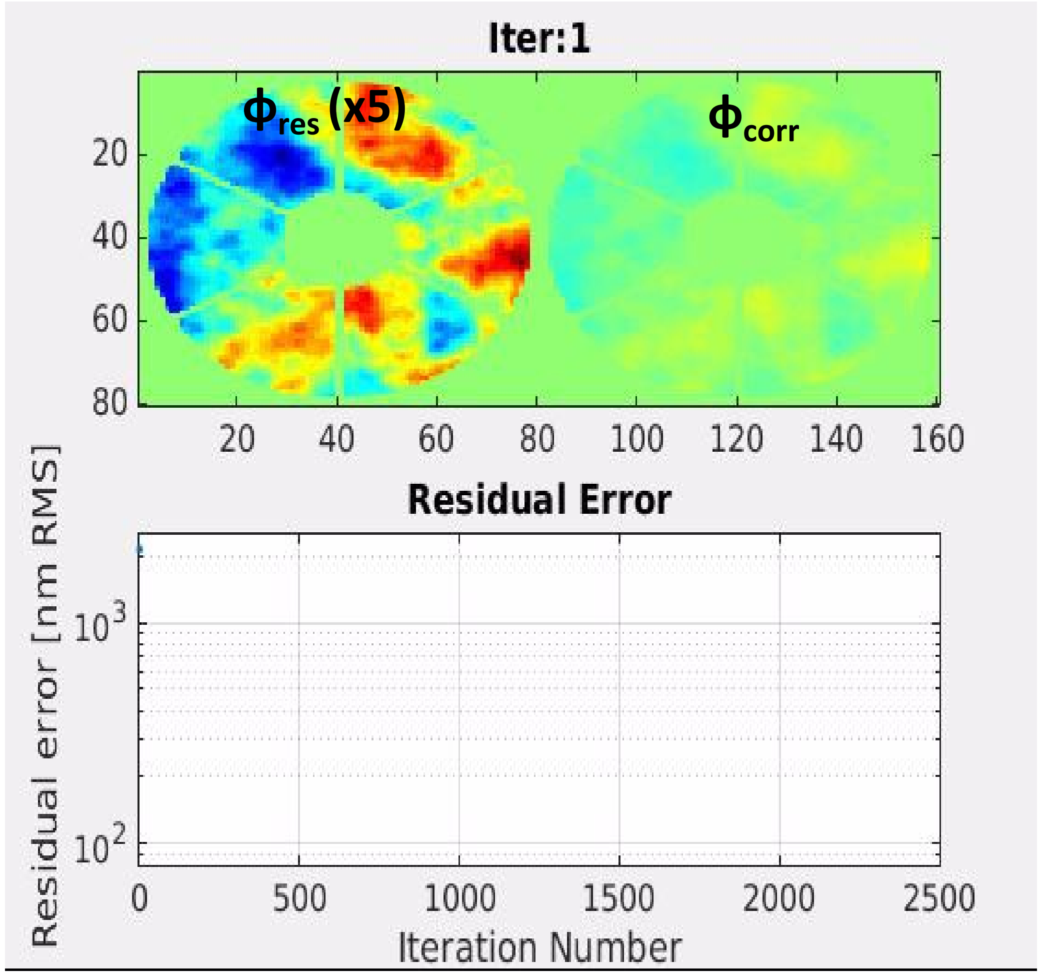


Edge Actuator Coupling (EAC)

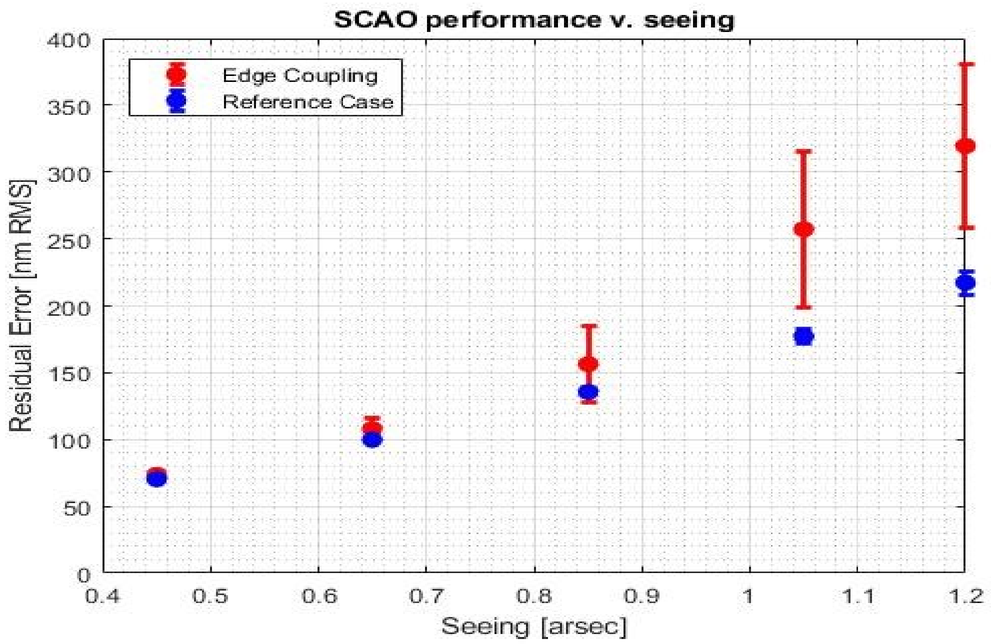
General overview

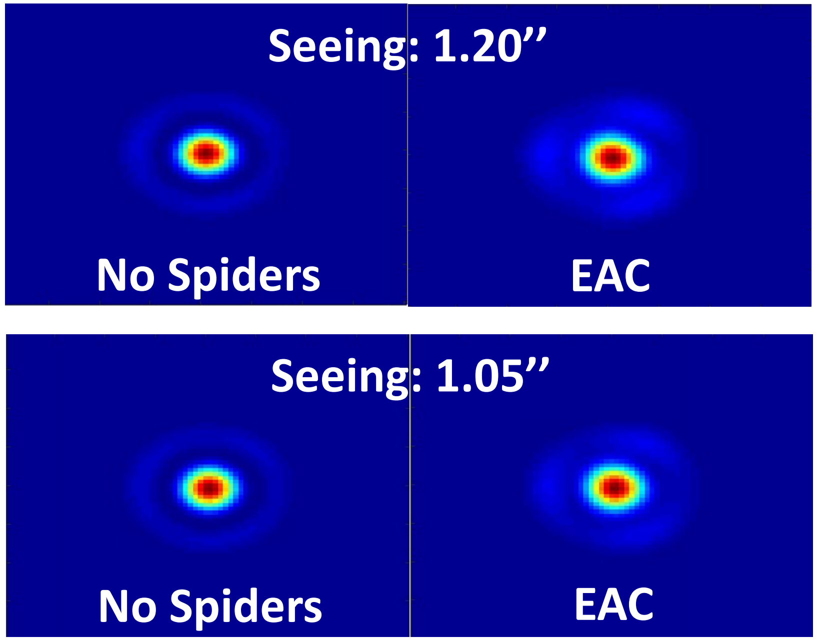
- Good average performance
  - ➢ 107 nm RMS (at 0.65'' seeing)
  - ➢ **35 nm RMS of island effect**
- Good stability
  - ➢ Min 100 nm & max 140 nm





Edge Actuator Coupling: Seeing





- Good performance even for strong seeing
  - ➢ To be compared to microns of uncorrected islands!!!
- Same simulation conditions for reference & EAC cases
  - ➢ Modulation between 3, 5λ/D depending on seeing
  - ➢ Between approx. 4000 & 5000 modes controlled depending on seeing
  - ➢ Scalar optical gain for all modes

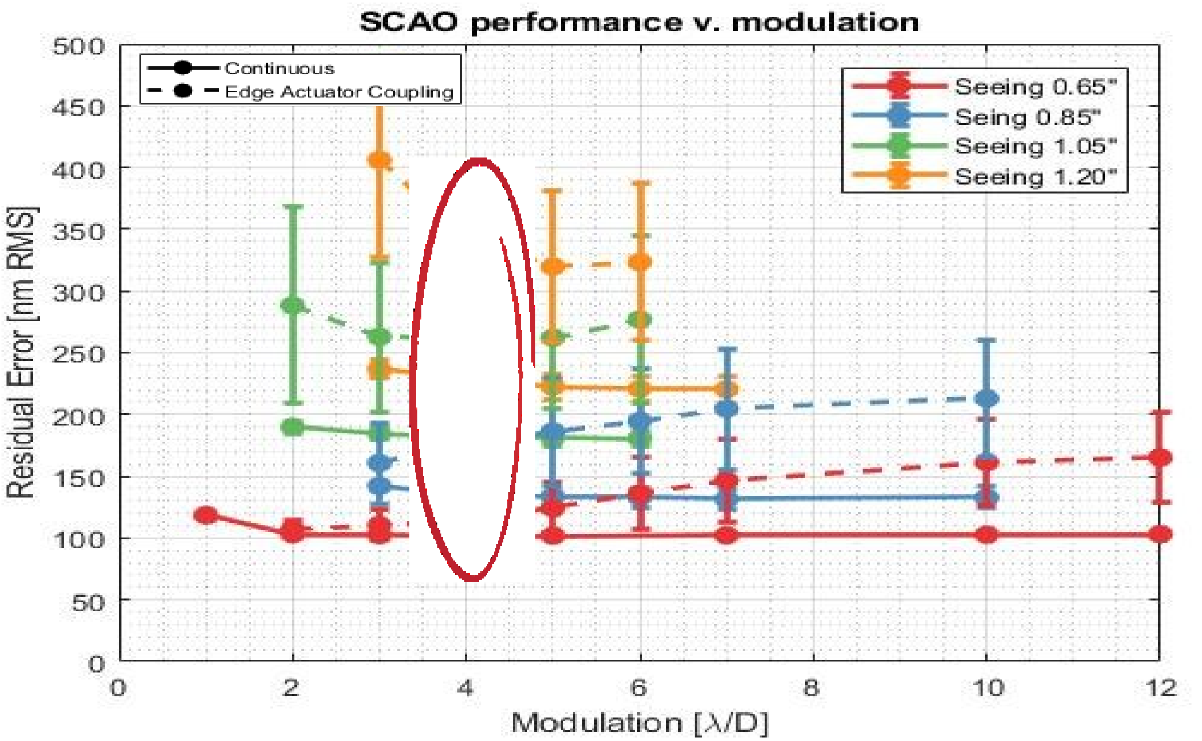
Edge Actuator Coupling: Modulation

Impact of modulation

- Need to keep modulation low for the sensing of differential pistons
- Need to increase modulation in strong turbulence

Modulation choice: 4λ/D

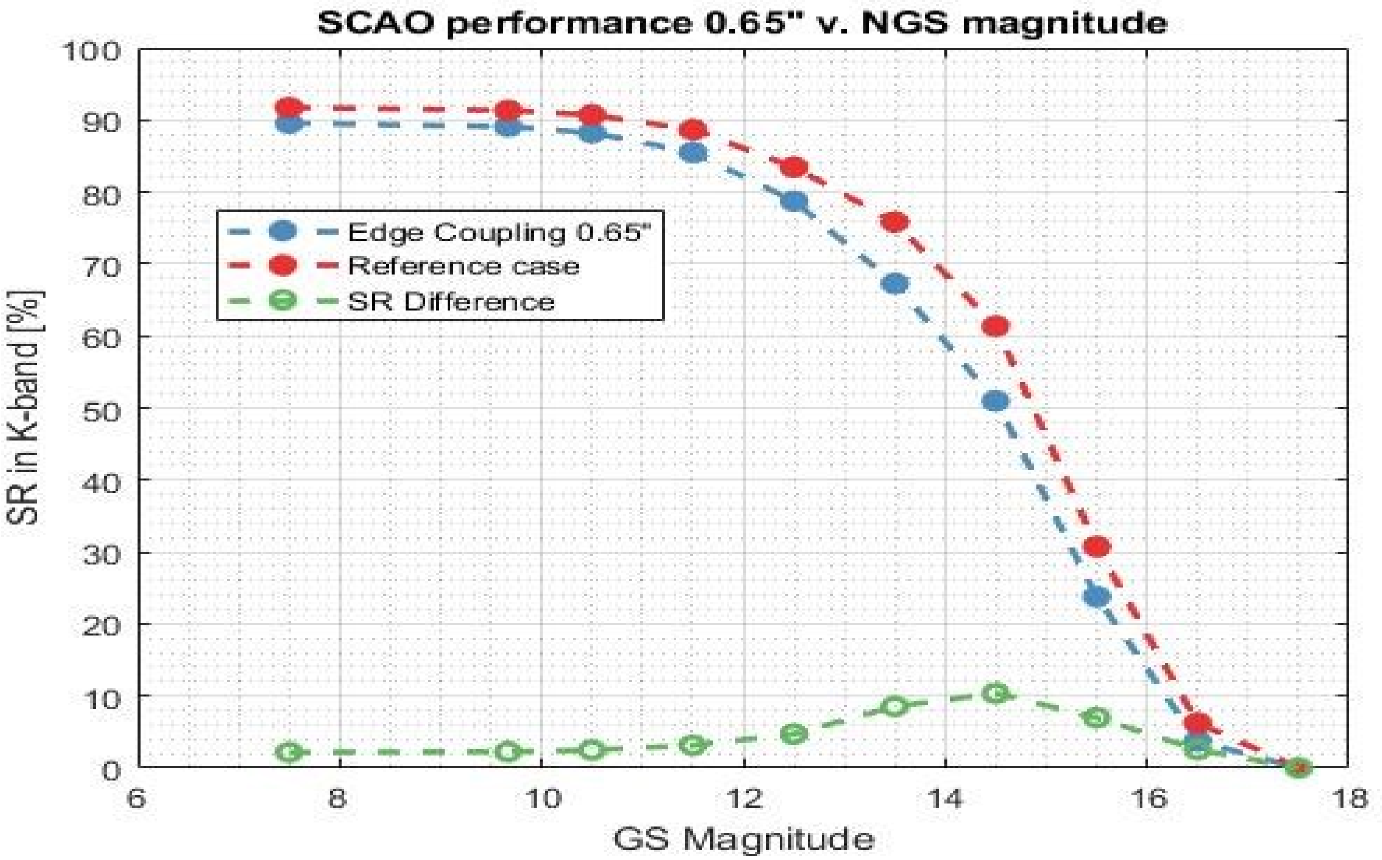
- One modulation for all seeing
- Only rising the residual error from 107 to 114 nm RMS at 0.65″
- 50 nm RMS dedicated to Island Effect



EAC: Guide Star Magnitude

Minimal performance loss as a function of GS magnitude

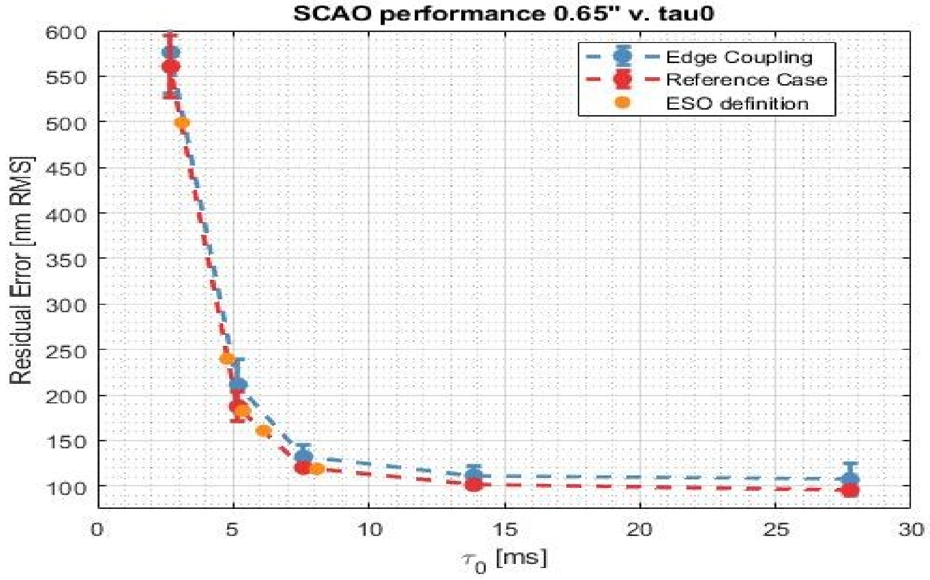
- ➢ Pure AO corrected atmosphere
- ➢ No-binning, no loop frequency optimisation



EAC: Wind speed & Sensing wavelength

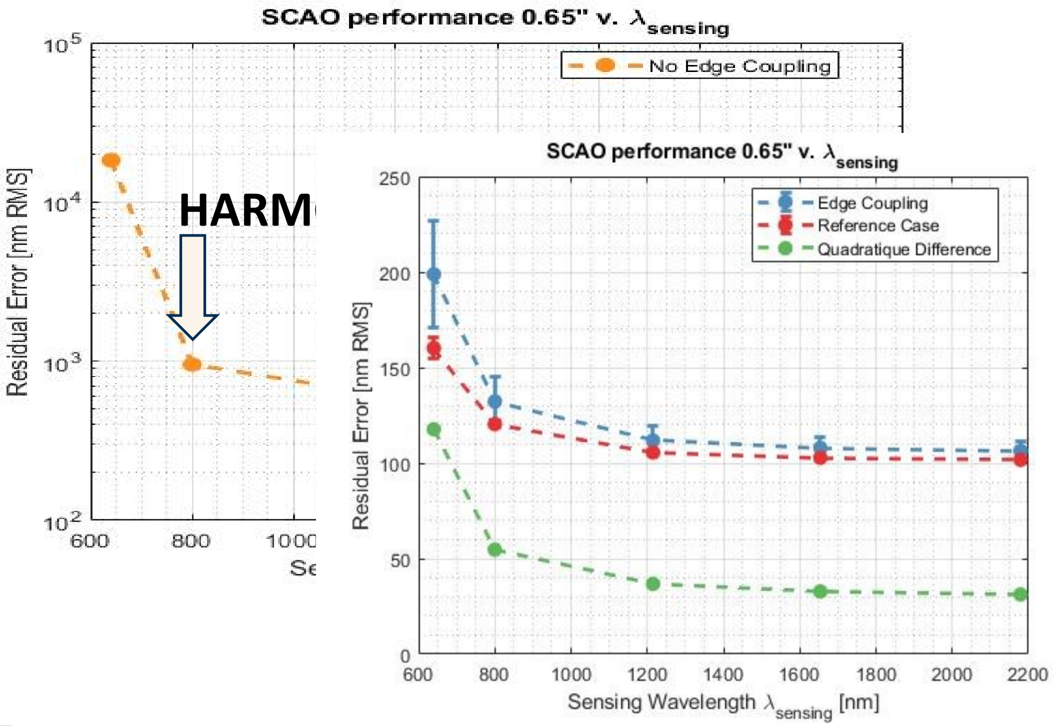
Impact of varying wind speed

- Fitting-limited performance
  - ➢ SCAO performance limited by the DM fitting error
  - ➢ Temporal errors have limited impact on performance
- EAC doesn't introduce any additional error



Impact of sensing wavelength

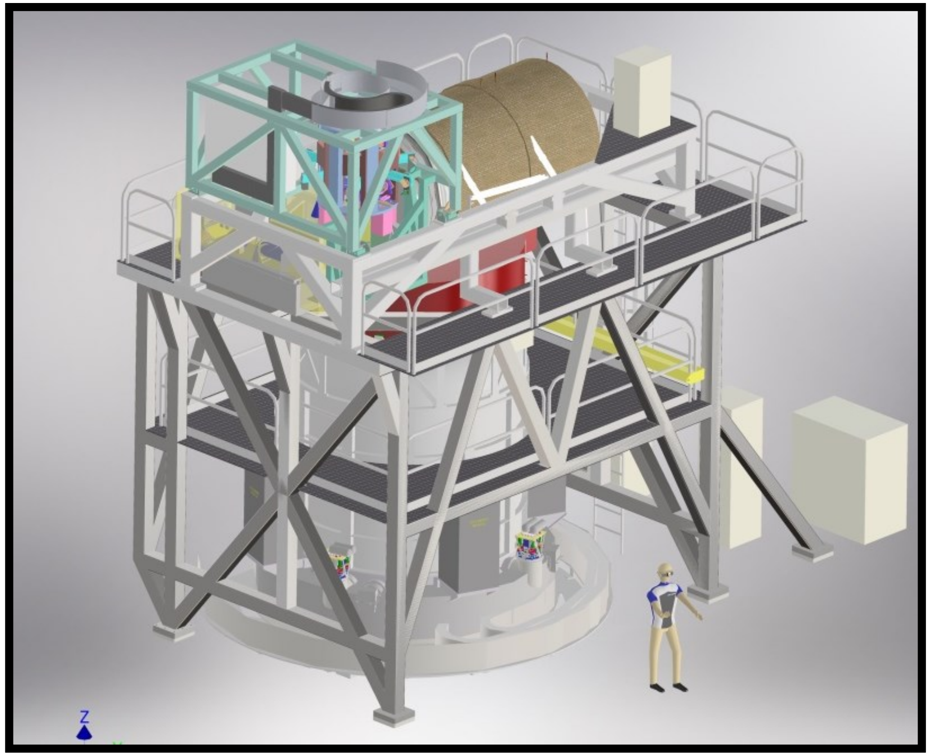
- Break of spatial coherence across the gap (0.5m)
- Correction in the visible more challenging than IR



Conclusions

Adaptive Optics

- Key elements & issues investigated for PDR
  - Robust Island Effect mitigation solution
- Main objective for FDR
  - Validate key AO components
  - Demonstrate complete AO loop including all AO and other components.



HARMONI

- FDR started in July 2018
  - Prototyping / design activities have begun in earnest
- First light in 2024 with ELT first light