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THE FRENCH AEROSPACE LAB

AO for High Contrast Imaging

From NACO to PCS

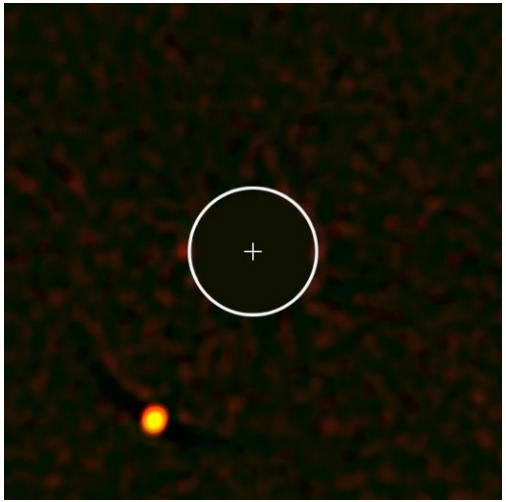
J.-F. Sauvage, WFS workshop @ Porto 2022

High contrast imaging : why, what and how

- Why : Study exoplanet, their atmosphere and their chemical characteristics & clouds content, test the theories of formation, evolution and physics
  - Study protoplanetary dust disks, their composition and dynamics, presence of planet

- What : image the very faint surrounding of a bright source and detect / characterize a companion
  - Flux ratio 10^{-6} @ X00 mas

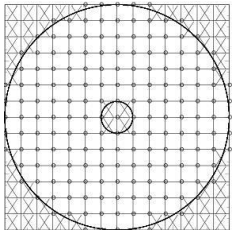
- How : ingredients of High contrast imaging
  - eXtreme Adaptive Optics
  - Coronagraphy
  - Post-processing methods

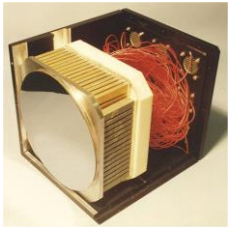


SPHERE reveals its first exoplanet 65426b

Adaptive Optics for High Contrast Imaging, a (*very* very biased) selection

- NAOS-CONICA 2001
  - Vis WFS 14x14, 444Hz, Pitch 58cm
  - High contrast spec : **do what you can with what you have**

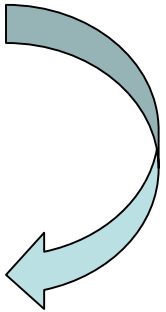




- SAXO-SPHERE 2014
  - Vis Shack Hartmann WFS 40x40, 1400Hz, Pitch 20cm
  - High Contrast spec : « **as deep as you can** » (A good speckle is a dead speckle)

- HARMONI 2028 (hum cough cough)
  - Pyramid WFS 100x100 500Hz, Pitch 50cm
  - High Contrast spec : « **as deep as you can with what you think you will have** »

- PCS : a whole bunch of new challenges
  - ELT is a natural and fundamental challenge : Bigger, more windshake, more flexure, more light obstruction, more segmentation…but 5 times smaller diffraction size, and still the same objective :
  - Science objective has evolved :
    - « as close as you can »
    - « as spectrally resolved as you can »



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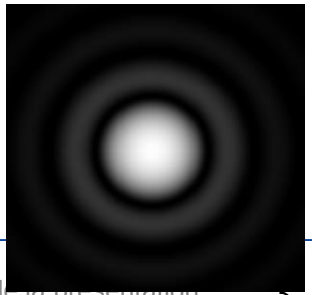
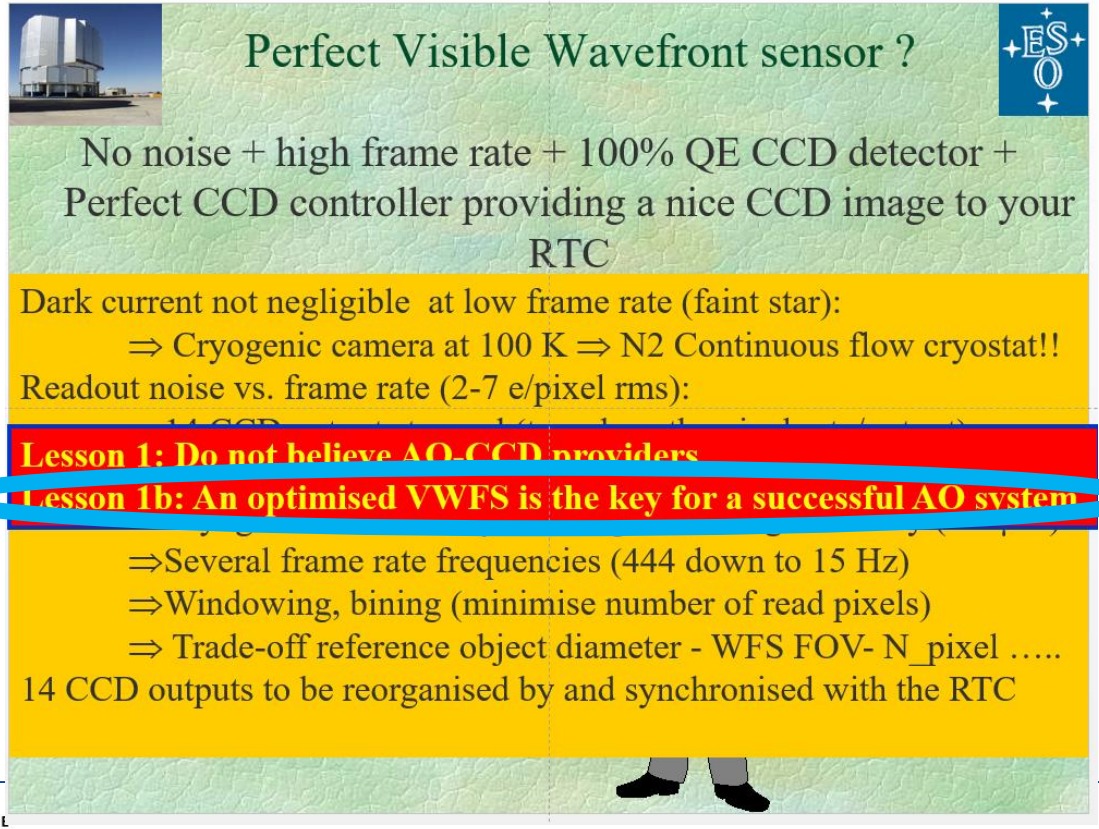
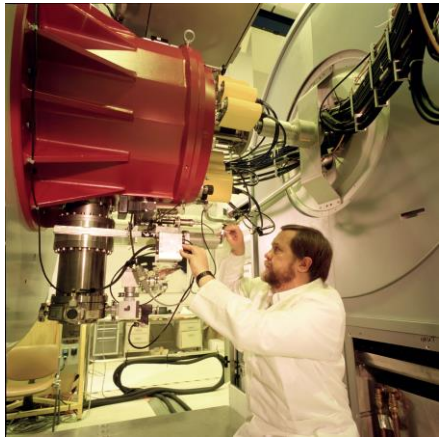
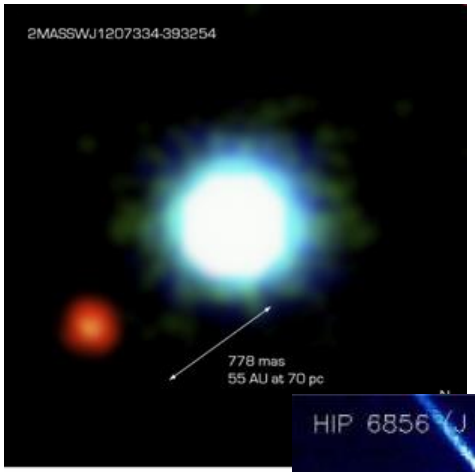


Listen to the wise message from the ~~old~~ … people with experience !!



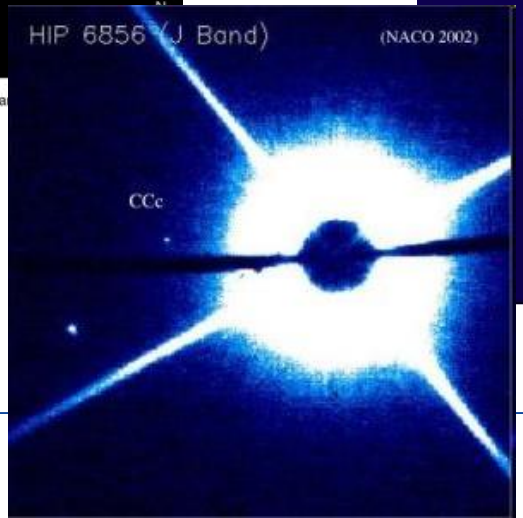


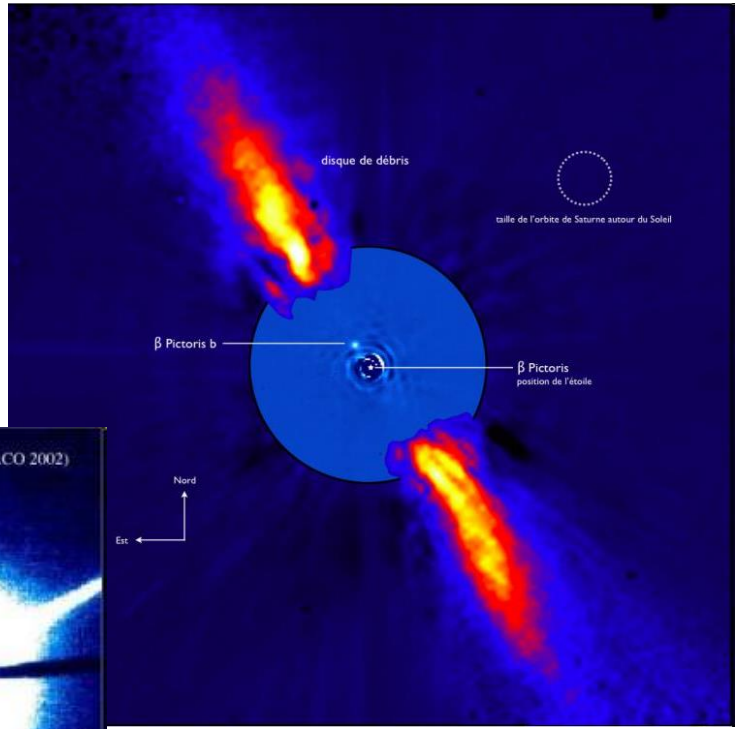
Exoplanet detection with NACO



The Brown Dwarf 2M1207 and its Pla
(VLT/NACO)

ESO PR Photo 14a/05 (30 April 2005)



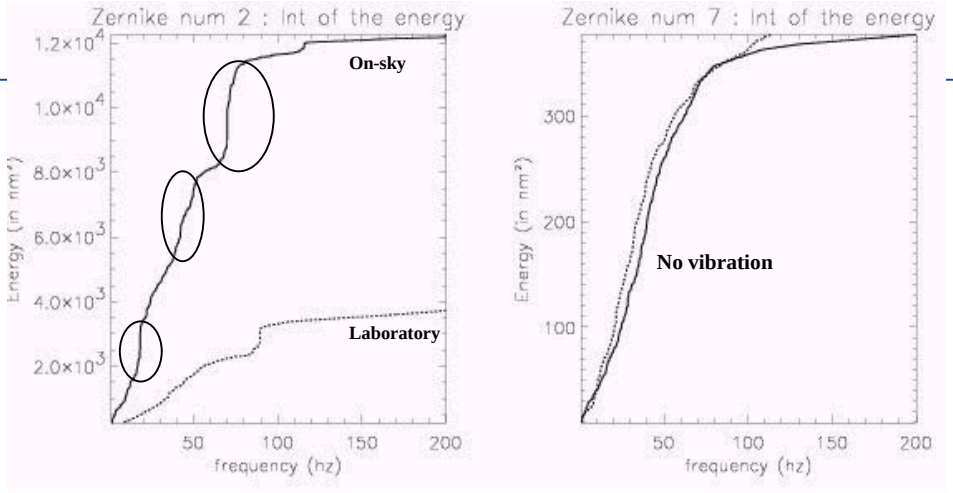


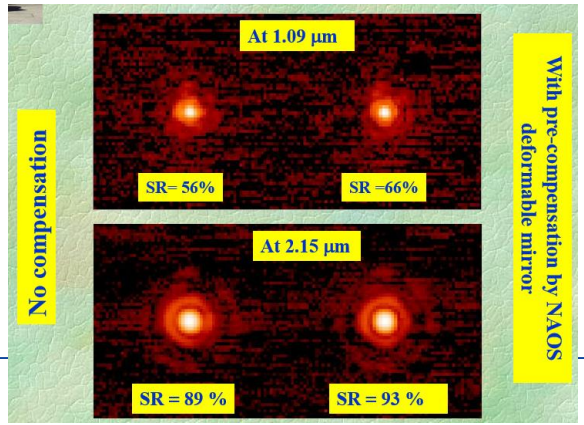
Challenges with NACO

- Strehl Ratio ~50%@K-band

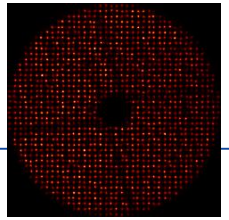
- Strong limitations
  - Vibrations
  - NCPA (maybe LWE)
    - Many optics moving in CP
  - Far too many AO modes (binning + IR/VIS)

- Inputs for the next system (SPHERE)
  - Work on vibration estimation / control
  - Work on NCPA estimation / control
  - Use only 1 binning mode on WFS

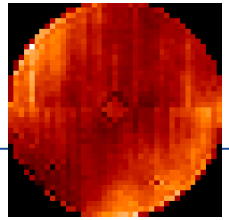




The SPHERE Odyssey



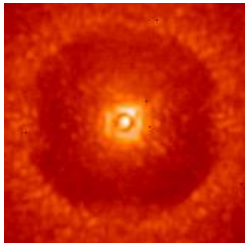
40x40 EMCCD SH WFS

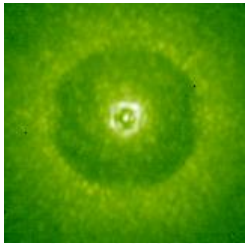


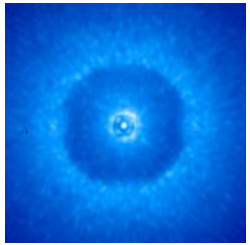
41x41 Piezzo DM

SAXO Real-Time scheme (1200Hz)

- **Tip-Tilt**
  - Kalman predictive control law
- **HODM**
  - Separation from Tip-Tilt
  - Optimised modal gain
  - Garbage collector
  - Anti Wind up







- **SAXO slow control scheme**
  - Differential loop
  - Pupil loop

  0.1 - 1 second
  - AtmMonitor
  - Vibration identification
  - Modal gains optimisation

  1 min
  - Adaptive Spatially filtered SH

  1 Obs
  - NCPA calibration and compensation

  1 day

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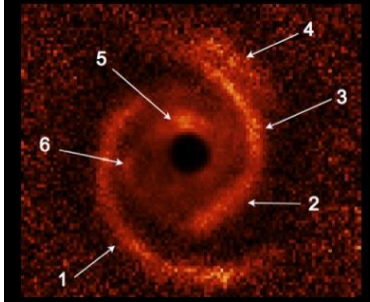
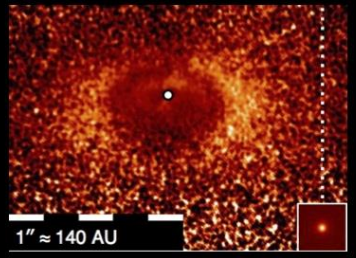
Sphere disk image gallery



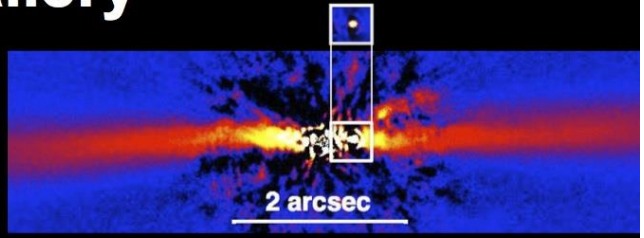
MWC 758
SVT

HD142527
COMM/GTO

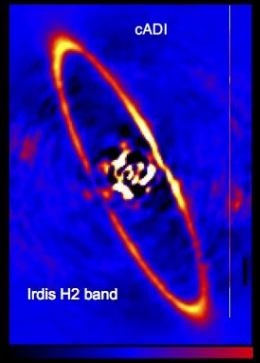


LkCa 15
SVT

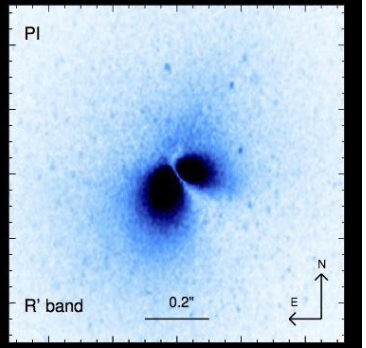
beta Pic



HR4796A
COMM



BP Psc
SVT

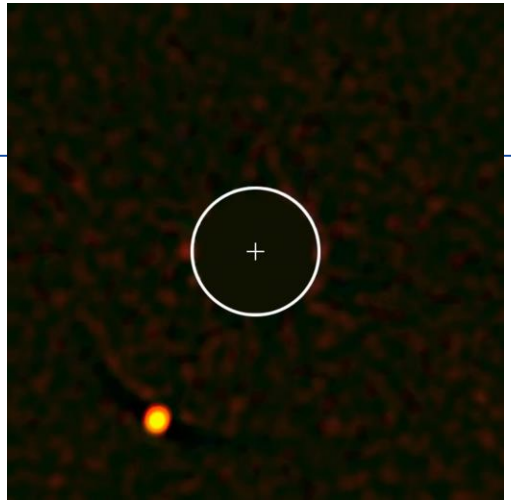


AU Mic
COMM/GTO

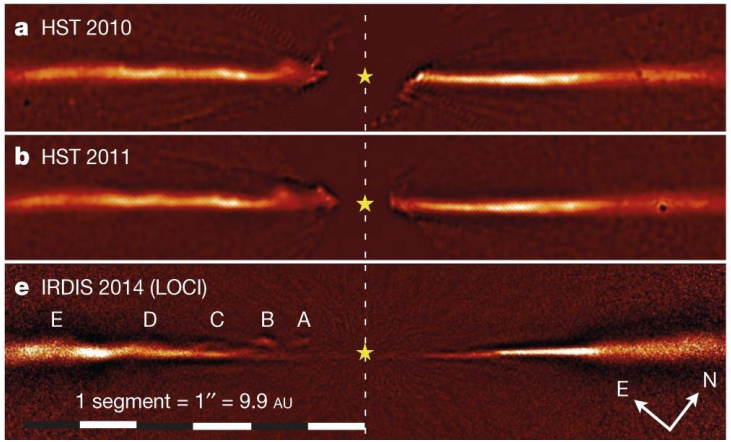
SPHERE also exoplanets

- First exoplanet discovered by SPHERE
  - Warm 1200 deg C
  - 10 x Jupiter
  - Absence of disk dispite the age of the star

- AU microscopii debris disk
  - Edge on
  - Planet discovered in the debris disk
  - Co-existence with the disk, allows to test the mode



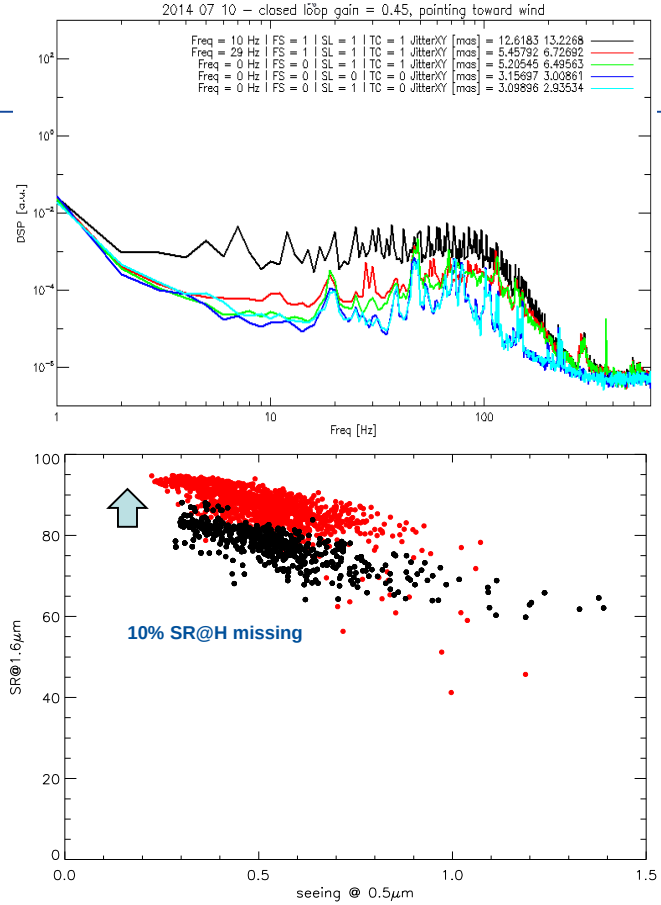
SPHERE reveals its first exoplanet 65426b



Fast-moving features in the debris disk around AU Microscopii

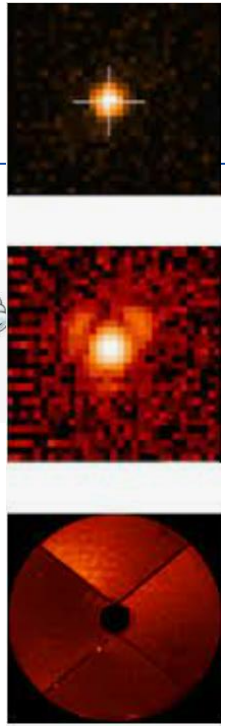
SPHERE challenges : vibrations

- During commissionning 2 - #Performance
- 10 to 15% of SR missing compared to simulation
- AO is not responsible (seen in open-loop & VLTI)
- Large overexcitation of high temporal frequency in Tip-Tilt compared to simulation / AIT
- Not filtered by AO vibration control (10 lines)
- Solved by … switching OFF Telescope Chopping

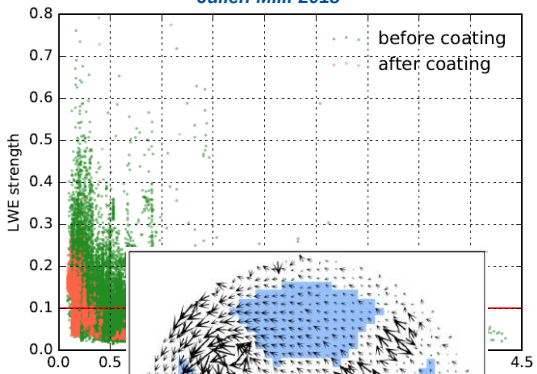


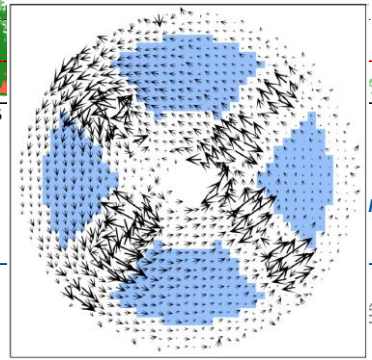
SPHERE challenges : Low Wind Effect

- Challenge
  - Thermo-optical effect seen by SPHERE
  - Related to radiative transfert (cooling) of M2 spiders & surrounding air
  - Responsible for 1µm discontinuous OPD for 1° cooling



Julien Milli 2018





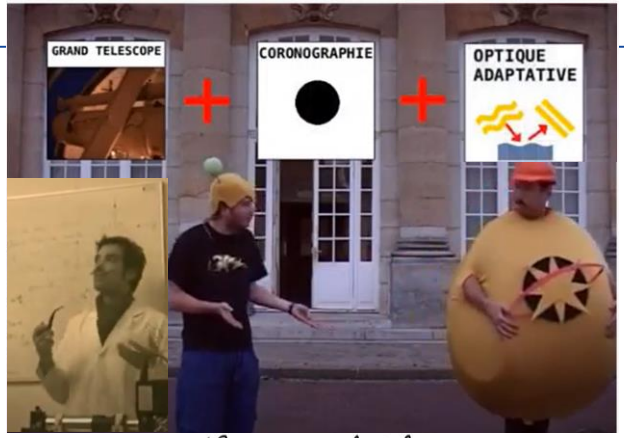
Nicolas Pourré 2022

- Where are we going
  - Re-coating of M2 spiders on UT3
    - Decrease the effect at the root, price of thermal emission
  - AO analysis (Nicolas Pourré, Gravity+)
  - VLT modelization
  - Echange between consortia for ELT instruments

SPHERE challenges : NCPA compensation

- « NCPA compensation with AO is very simple » (Jeff, 2007)
  - Put a reference source at entrance of AO
  - Close the AO loop
  - Measure NCPA seen by the science with your favorite tool
  - Modify reference slopes of AO and you're done !

- NCPA in practice becomes highly complicated (…Jeff, 2014)
  - Take a first measurement of NCPA from entrance to science, with a given pupil shape and source profile
  - Subtract a second measurement from coronagraph to science, with another pupil shape and source profile
  - The DM has dead actuators
  - Observe on-sky with another pupil shape and source profile…nothing has improved…surprised ?



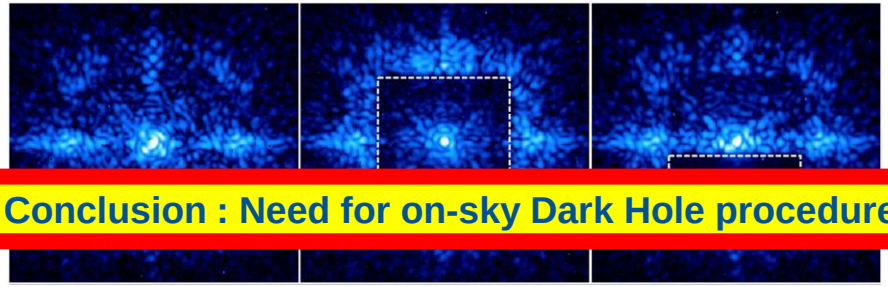
SPHERE today : dark hole on sky

- Monitoring nanometric evolution of SPHERE NCPA

Conclusion : internal turbulence is limiting the internal performance
This will become an issue for SPHERE+
~~Quasi-static~~ aberrations

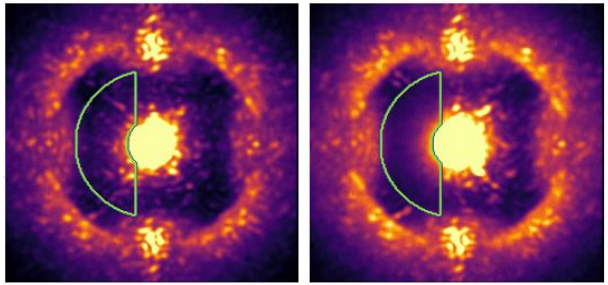
Arthur Vigan, SPHERE NCPA calibration 2022

- Performing Dark Hole on SPHERE



Conclusion : Need for on-sky Dark Hole procedures

Axel Pottier, Dark hole on SPHERE 2020



Axel Pottier, Dark hole on SPHERE 2022 (prep)

After SPHERE, Pyramid times…

XAO
Predictive CC
Super-Resolution
Unmodulated P
Petalometer

- A question of concept maturity

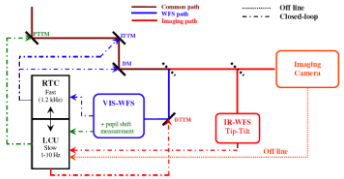
PAPYRUS

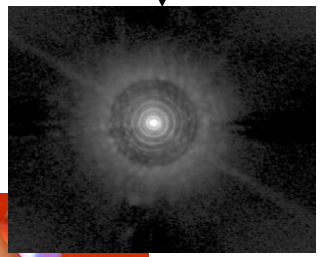
2001 2004 2008 2010 2014 2015 2022 2028 20XX

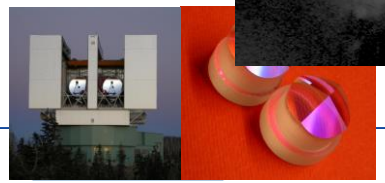
NACO → Vibration control, NCPA, WCOG → SPHERE KO → SPHERE FDR → SPHERE 1st → Feedback TEL → HARMONI KO → RISTRETTO → HARMONI 1st → ANDES → PCS

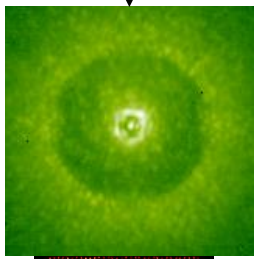
FLAO 1st

Feedback TEL









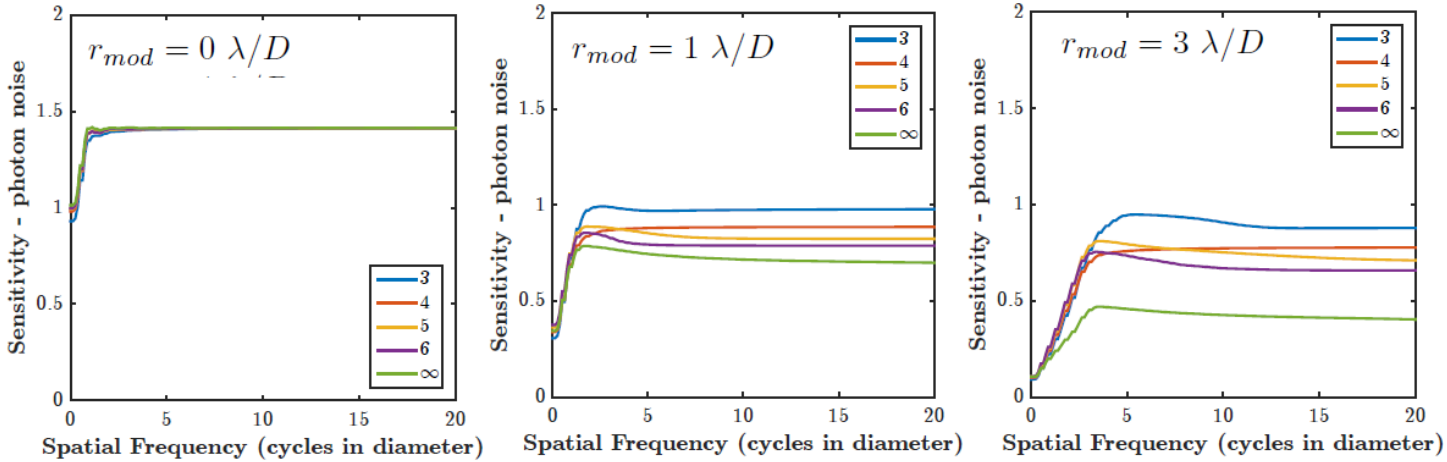
Basic Pyramid
Modulation 3
Chromatisme correction
Coupled to Low Order Loop

Toward fast / Unmod Pyramid
NCPA correction
Predictive control

GSC – Pyramid
Unmod Pyramid
Chromatisme

Pyramid : the road to sensitivity

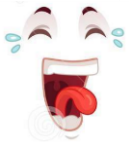
- P-WFS is naturally a more photon-sensitive sensor than Shack-Hartmann
  - Sensitivity increases with absence of modulation

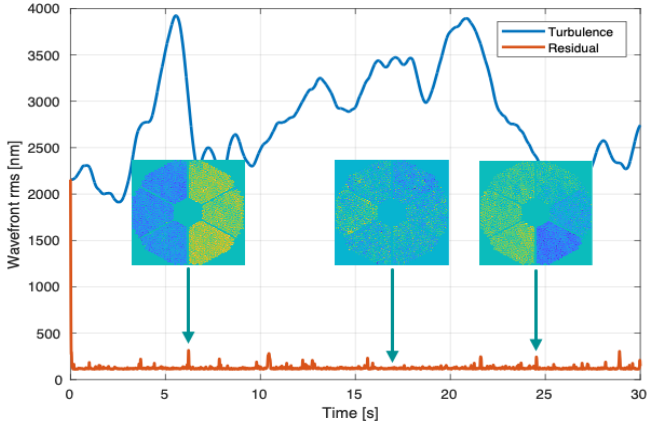


Vincent Chambouleyron, 2020

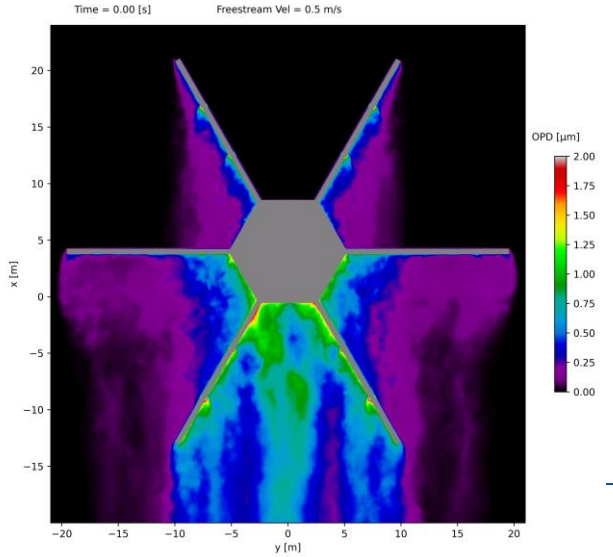
1st generation AO on ELT

- Challenge: the telescope spiders
  - Large spiders + AO generate incoherent sub-telescopes
    - AO struggles to avoid this phasing error (« islands »)
  - Large spiders generate additionnal wave-front errors
    - Large
    - Dynamic
    - Discontinuous





Charlotte Bond, Islands on HARMONI, Petal day (ESO) 2022

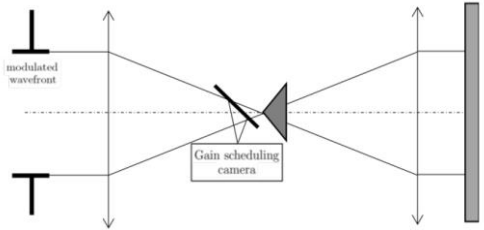


Ron HolzLohner, Low Wind Effect on ELT (SPIE 2022)

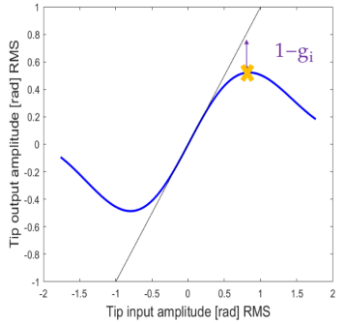
WFS toward ELT-PCS : Where to go

- The graal of non-modulated pyramid
  - Pyramid … or Fourier-filtering WFS
  - Sensitive to discontinuities
  - Sensitive to photons
  - Also impossible to bootstrap and operate

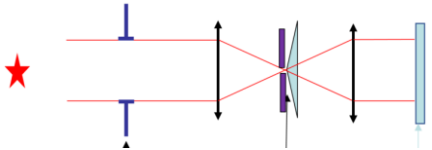
- Options
  - Improve dynamics of FF-WFS
  - Use Gain Sensing Camera as a dual sensor for Pyramid
    - Optical gains
    - (Quasi-Static) aberrations monitoring
    - & much more
  - Use Pyramid (or FF…) as a second stage, unmodulated if possible
  - Use color information in FF-WFS
  - Use data fusion between AO – Science - Monitoring



Vincent Chambouleyron, Gain Sensing Camera 2021



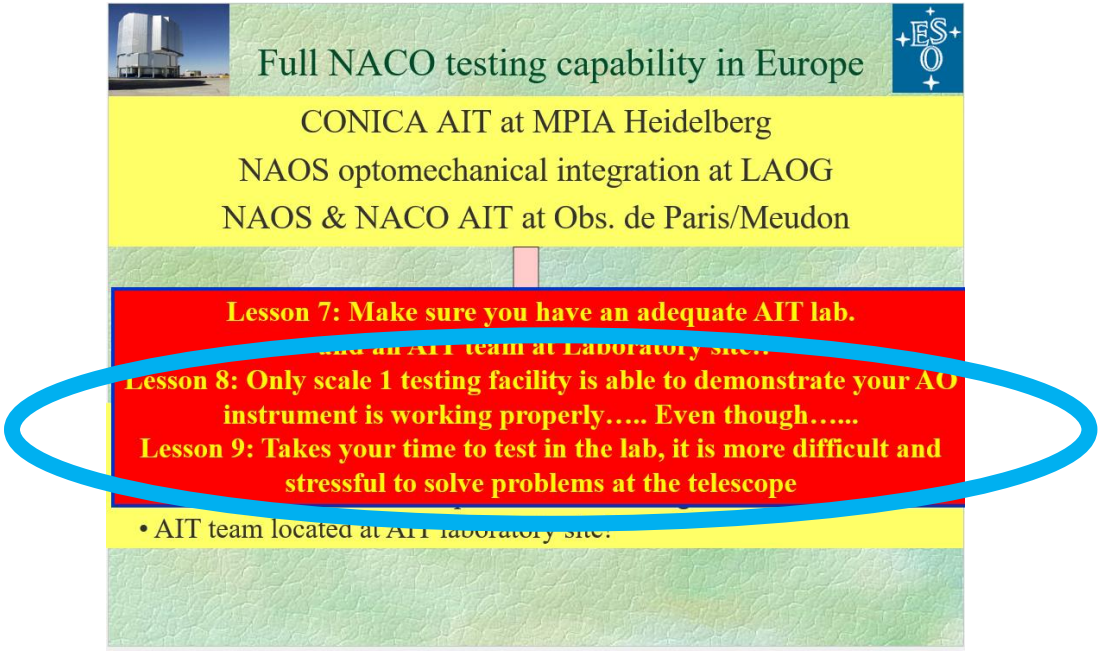
Mahawa Cisse, Phase-shifted Z mask (This conf)



Nicolas Levraud, Spatial filter for pyramid (This conf)

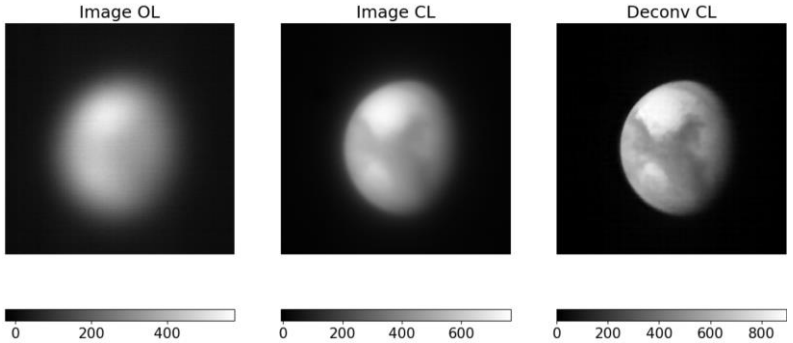
And more PhDs to come !!

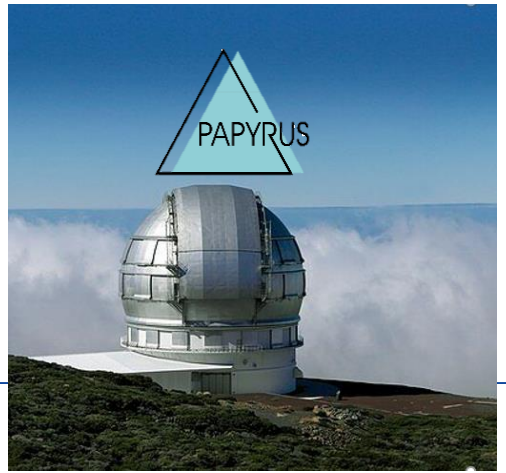
How to deal with these challenges…the return of experience



Need for scale 1 testing facility

- Large telescope is required
  - There is no ELT prototype obviously
  - But there are a lot of 10m telescopes
- Large & open access is required
  - « Testing » is the realm of long time, tens or more nights / year
- Options ?
  - PAPYRUS @ OHP (R. Fetick)
    - Operation & performance of pyramid-WFS
    - Playing with Low-Wind / Petal / Phasing,
    - Testing Pyramid (MP ; NMP ; FP) / Zernike (Z1 ; Z2 ; PS-Z) / No limit
  - VLT / Subaru / Keck .. are very busy observatories
    - Still, we don't need a Nasmyth / Cassegrain / Science focus… Just a star somewhere in a focal plane
    - Is there, somewhere at Paranal or elsewhere, a guide probe far away from science that could be dedicated to AO testing ?
  - Projects on large telescope
    - Objective Grantecan





- AO4ELT7 in Avignon
- June 2023