HIGH CONTRAST IMAGING WITH EXTREME ADAPTIVE OPTICS

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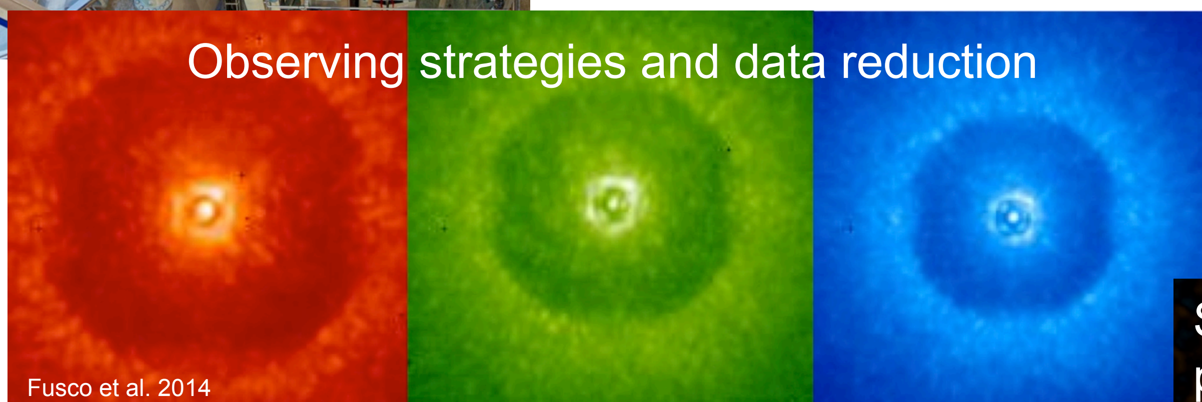
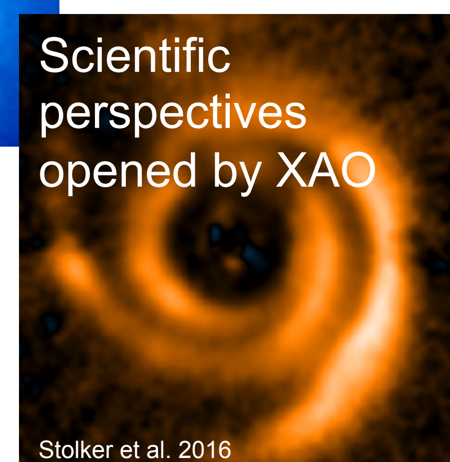
Acknowledgments: D. Mawet, D. Mouillet, A-M. Lagrange, J-L. Beuzit

XAO: from the instrument to the science

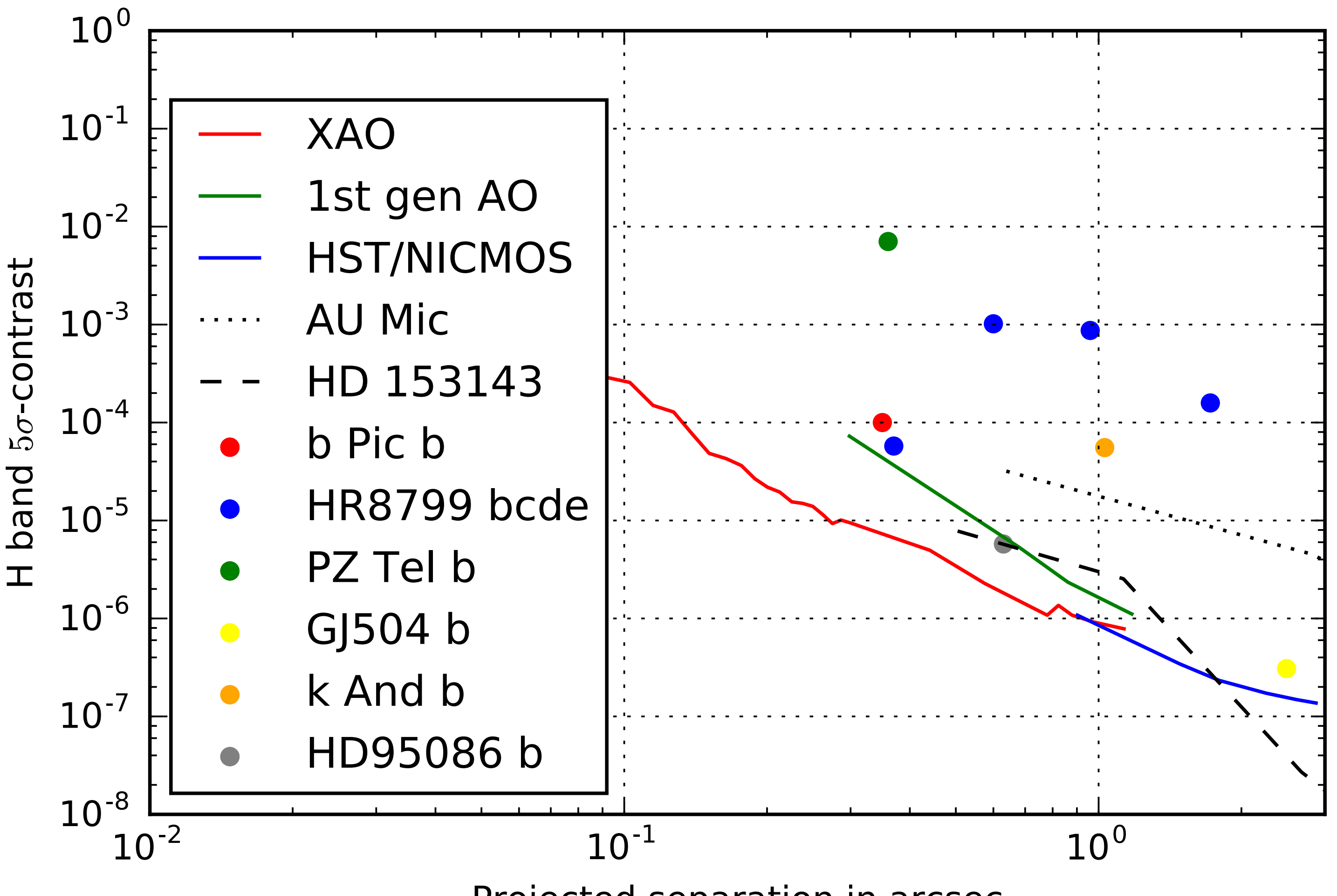




Two requirements:

- High-angular resolution
- High contrast

Short separations and high contrast are the key science drivers



Milli et al. 2016 in press

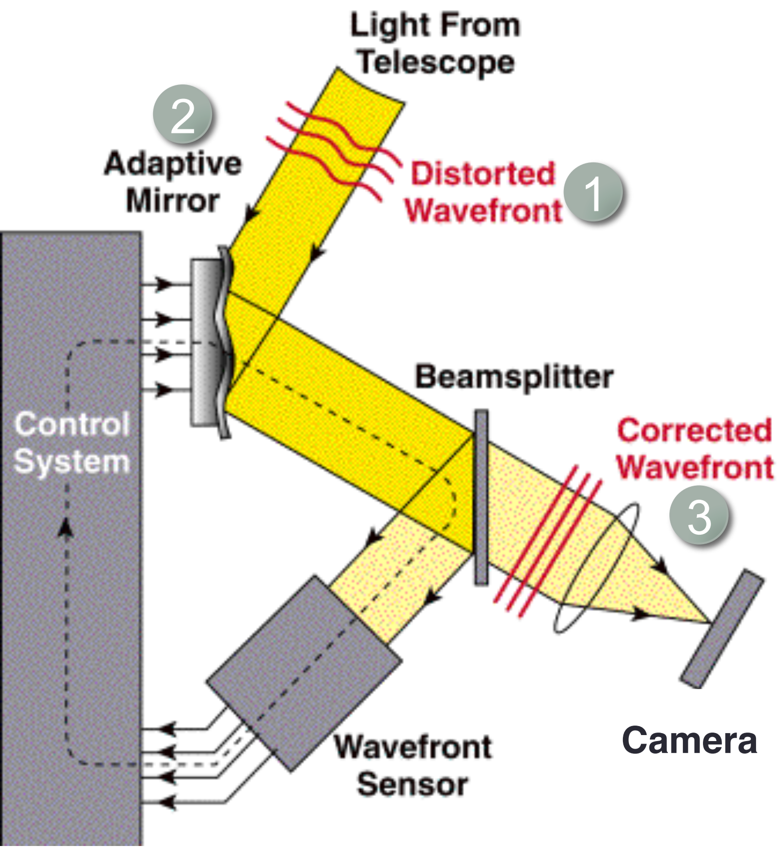
Content

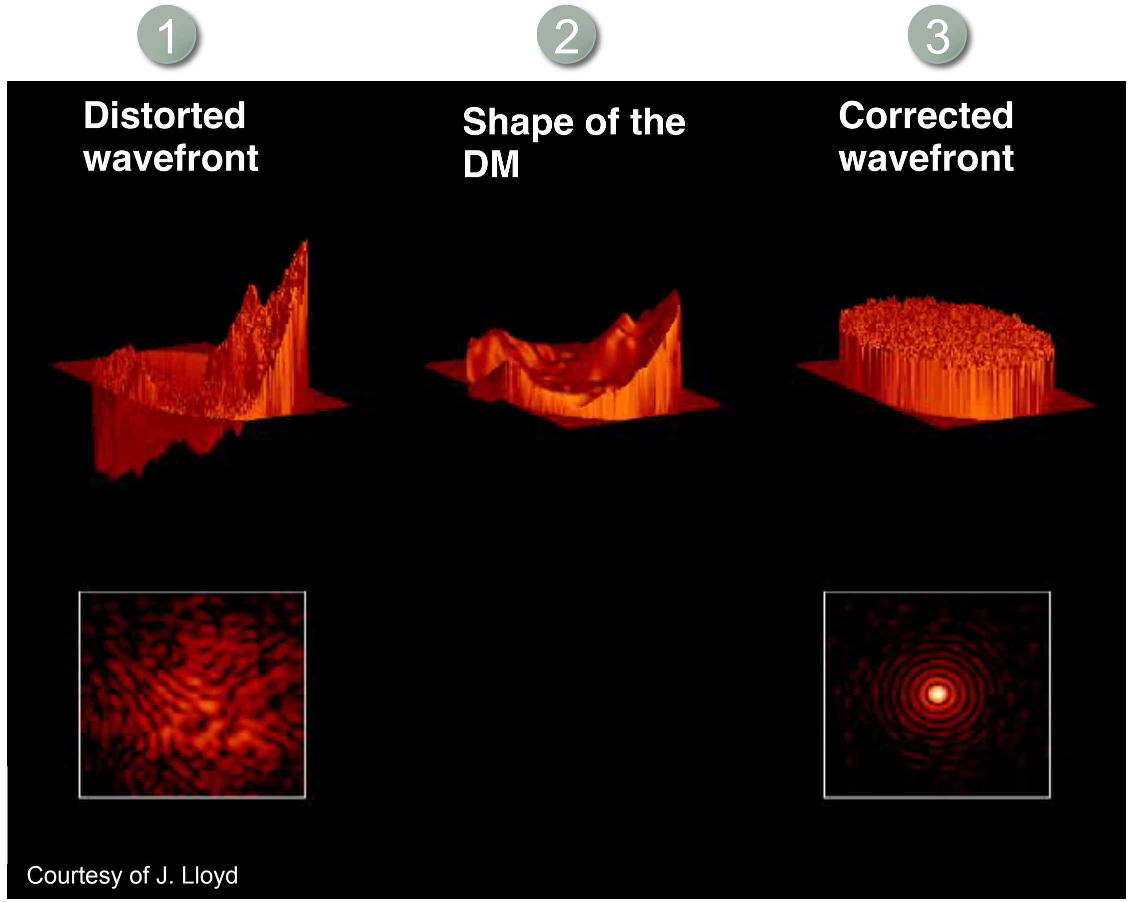
I. **From first gen. to extreme AO instruments**

II. Observing strategy and data processing

III. Perspectives opened by the XAO instruments

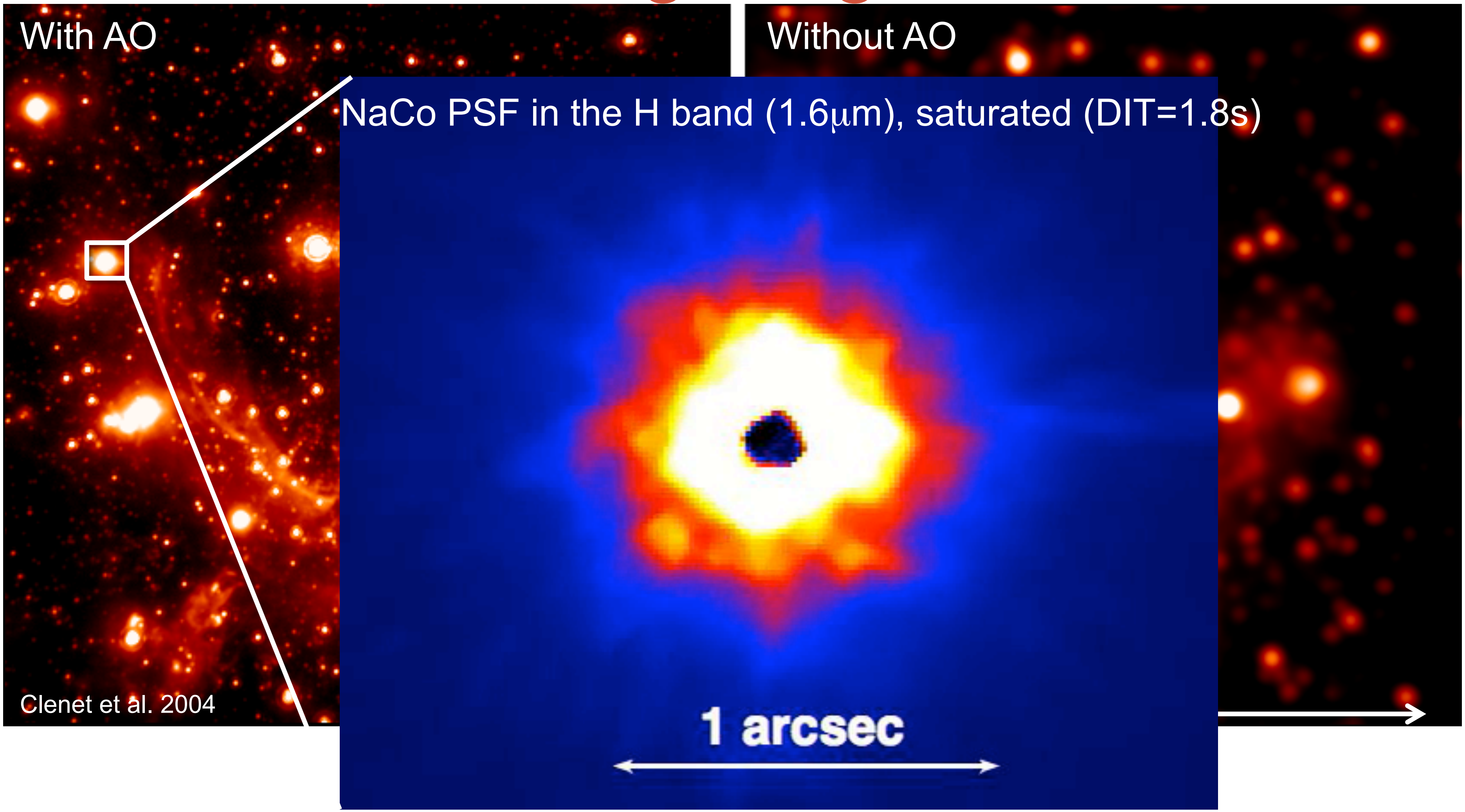
The fundamental components of AO



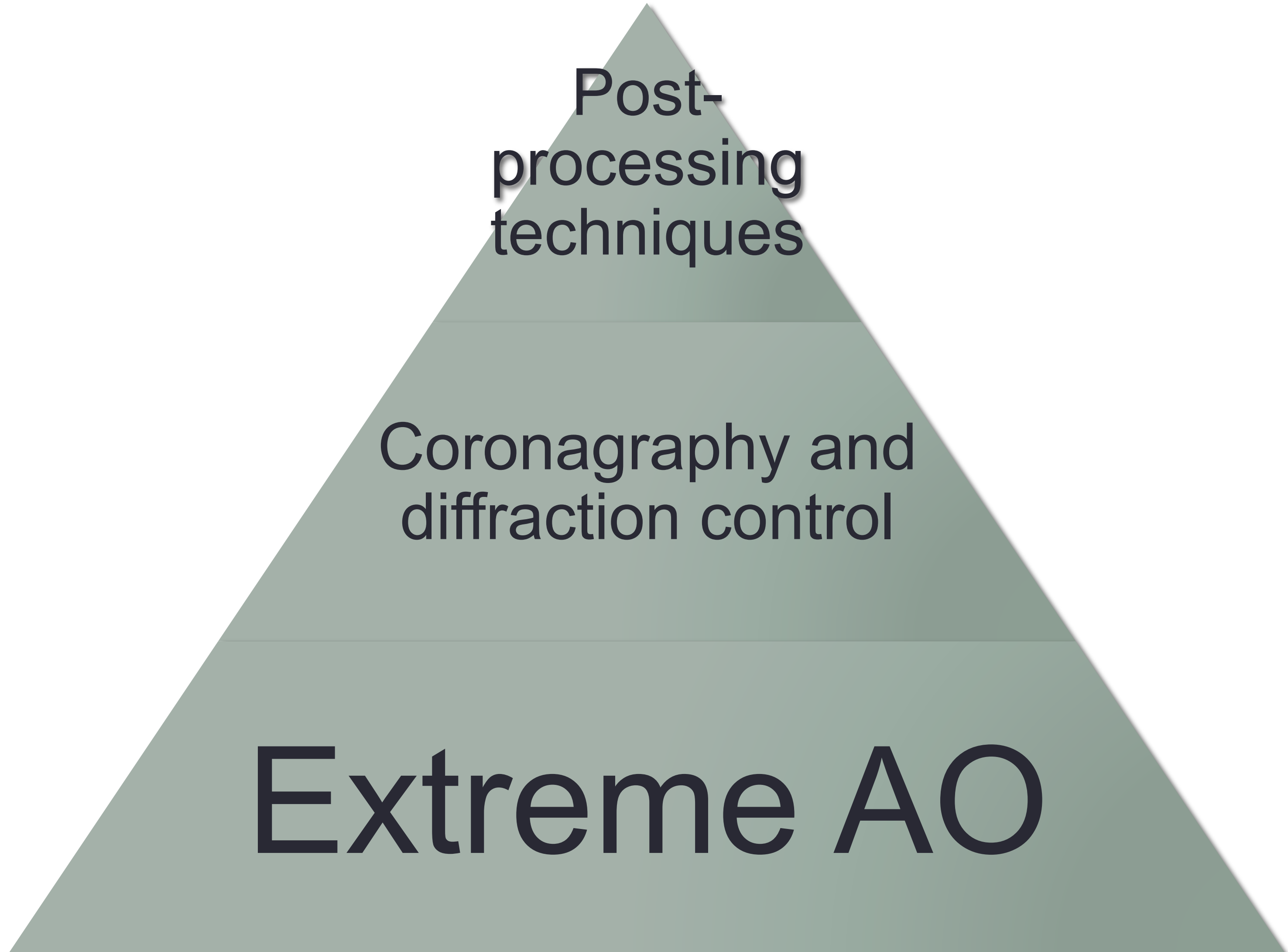


Performance indicator: $$Sr \approx \exp\left(-\sigma_{\varphi}^{2}\right)$$

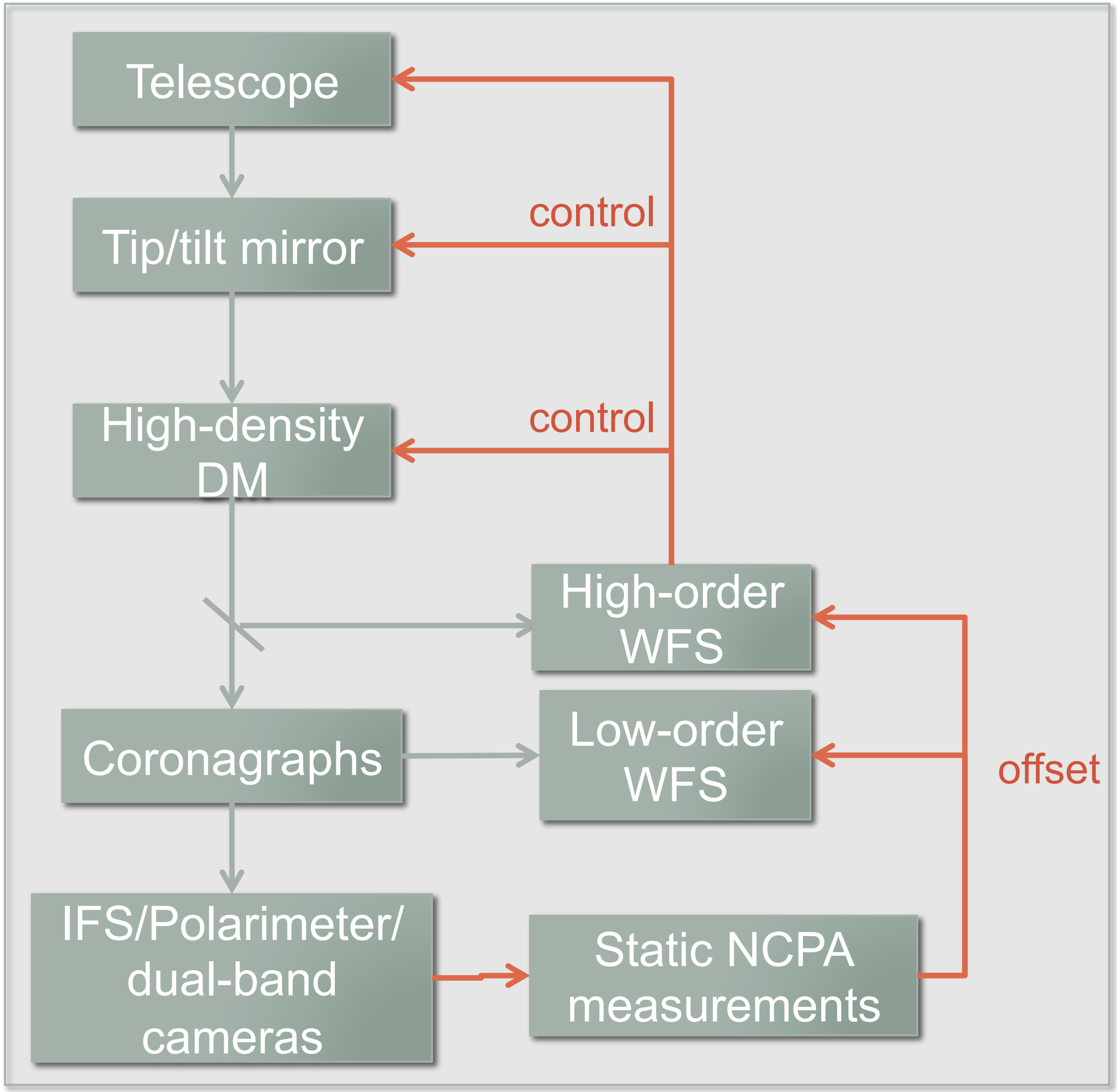
The challenge: high contrast



2nd generation of high-contrast imagers



A similar architecture and a few critical tweaks



1st gen AO on steroids:

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

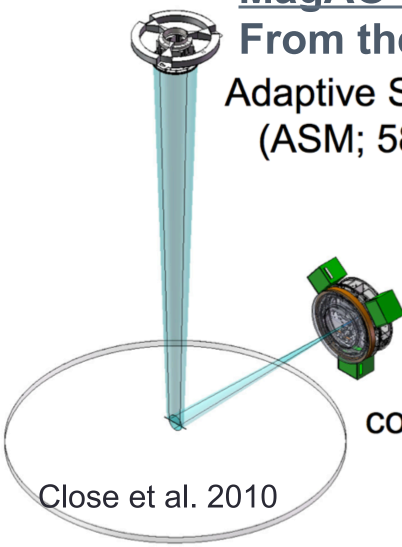
Critical tweaks:

- Low-order WFS and calibration strategy for Non-Common Path Aberrations (NCPA) fully built-in.
- High-quality optics (ADC, derotator)
- Optimized for mechanical and thermal stability

The XAO family

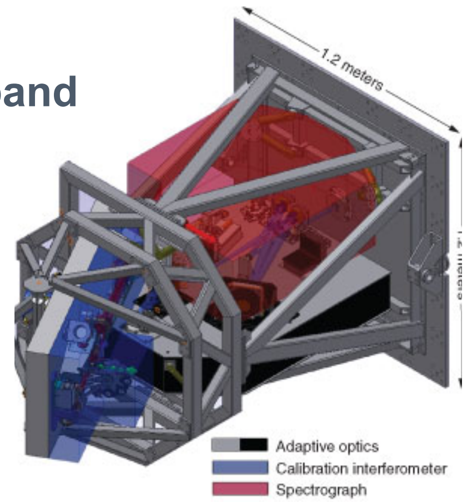
MagAO (Clay telescope)
From the visible to the M band

Adaptive Secondary Mirror
(ASM; 585 actuators)



Pyramid
WFS 378
modes
controlled at 1KHz

Close et al. 2010

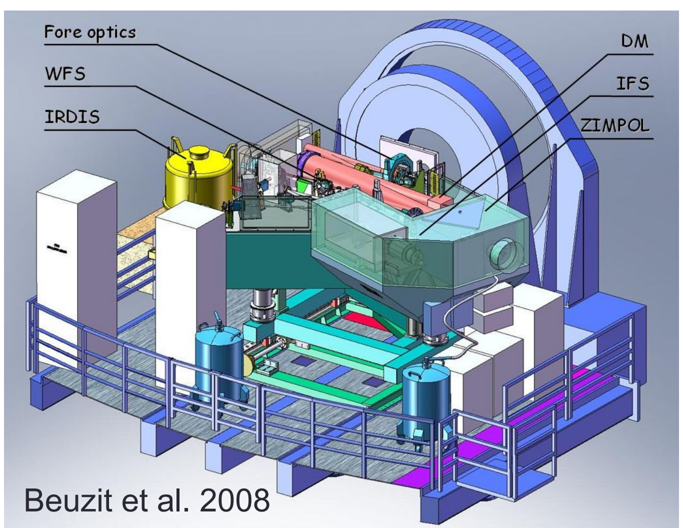


Macintosh et al. 2014

GPI (Gemini South)
a compact and light
Cassegrain instrument

MEMS DM of 4096 act.
Interferometric calibration
unit for NCPA compensation
Shack Hartmann WFS at
2.5kHz

Talk K. Follette



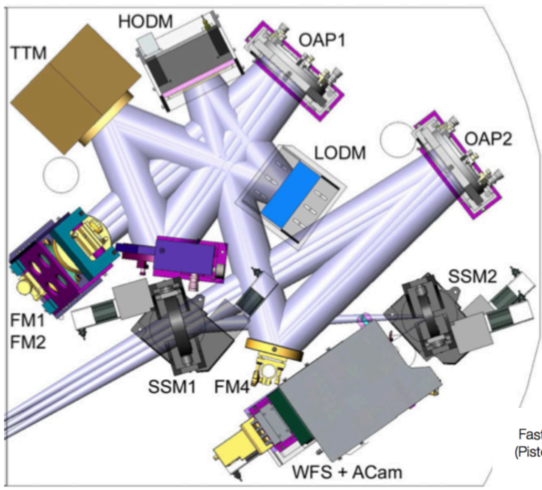
Beuzit et al. 2008

SPHERE (VLT)
A heavy stable Nasmyth instrument
With 3 sub-instruments IRDIS, IFS
Zimpol

Piezoelectric DM of 1377 actuators
Shack Hartmann WFS 40x40 at 1.4kHz
Off-line phase diversity for NCPA calibration

The XAO family: northern instruments

P3K- P1640 (200" Hale telescope, Palomar)

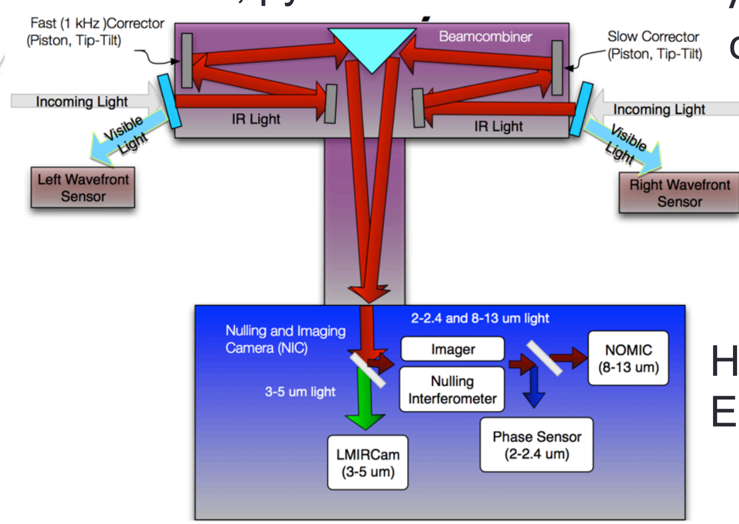


Dekany et al. 2013

3388 actuators
Shack
Hartmann
WFS at 2kHz

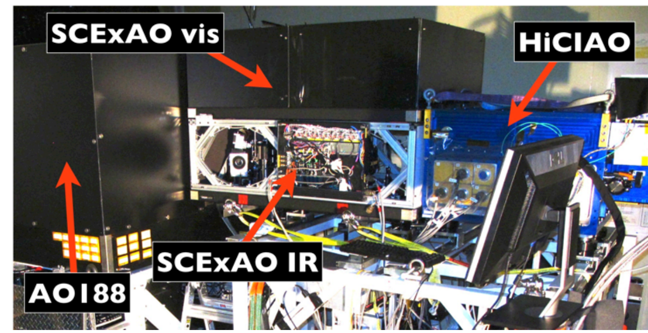
FLAO - LBT(I)

Adaptive seconday mirror of 672 act., pyramid WFS



Hinz et al. 2001,
Esposito 2010

SCexAO (Subaru, Mauna Kea)



Guyon et al. 2010

AO188 upstream with MEMS DM of 1000 act., pyramid WFS

Talk
J.Lozi, T.
Currie

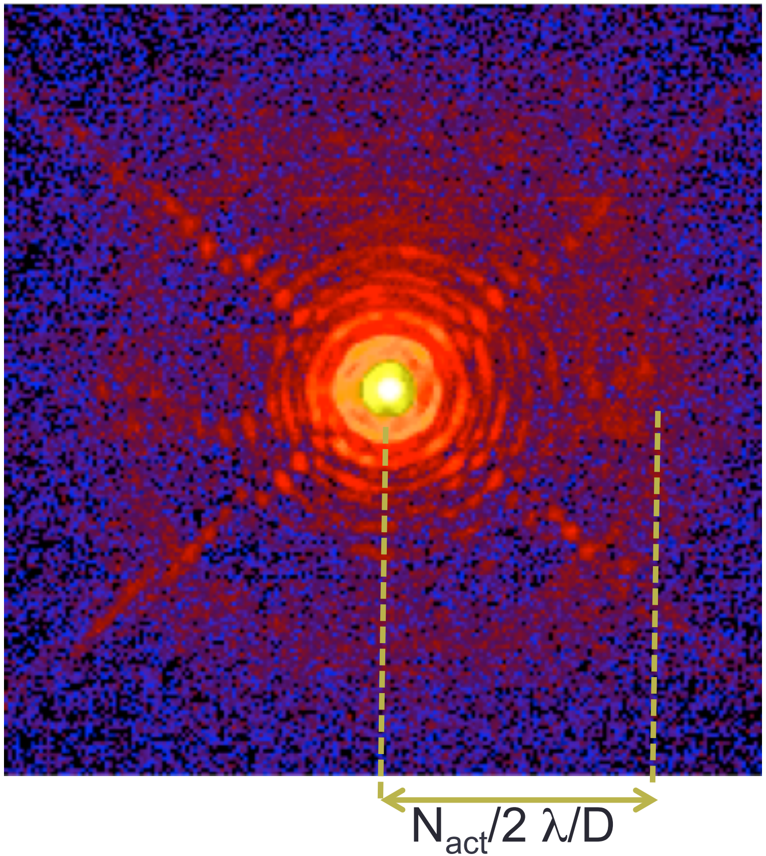
The contrast is the new performance indicator

- High-density DM
- High-density, faster WFS

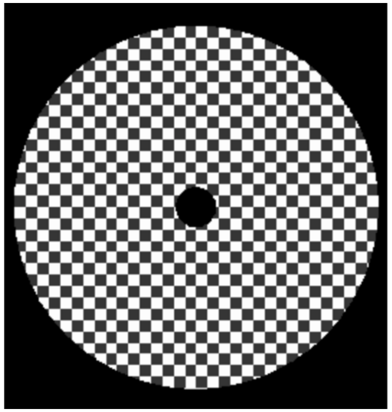
90% Strehl reached: almost the theoretical diffraction limit

Contrast ≈ $(1\text{-}Sr) / N_{act}^2$

(Serabyn et al. 2007)



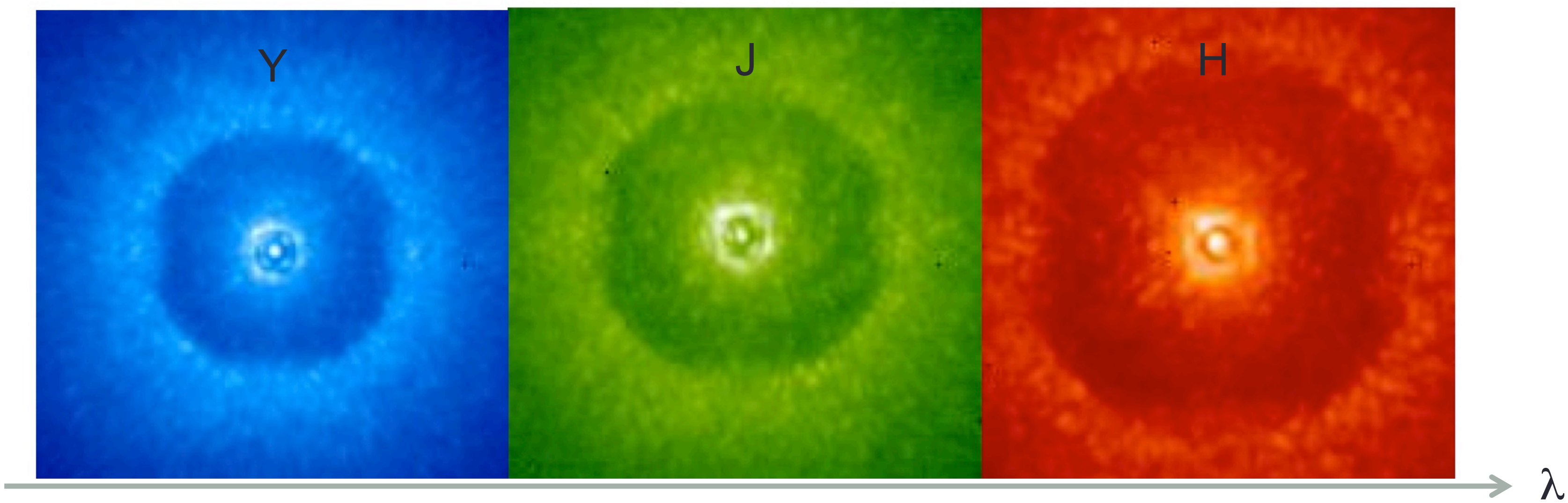
With $N_{act} \times N_{act}$ we can correct up to $N_{act}/2$ cycles / pup

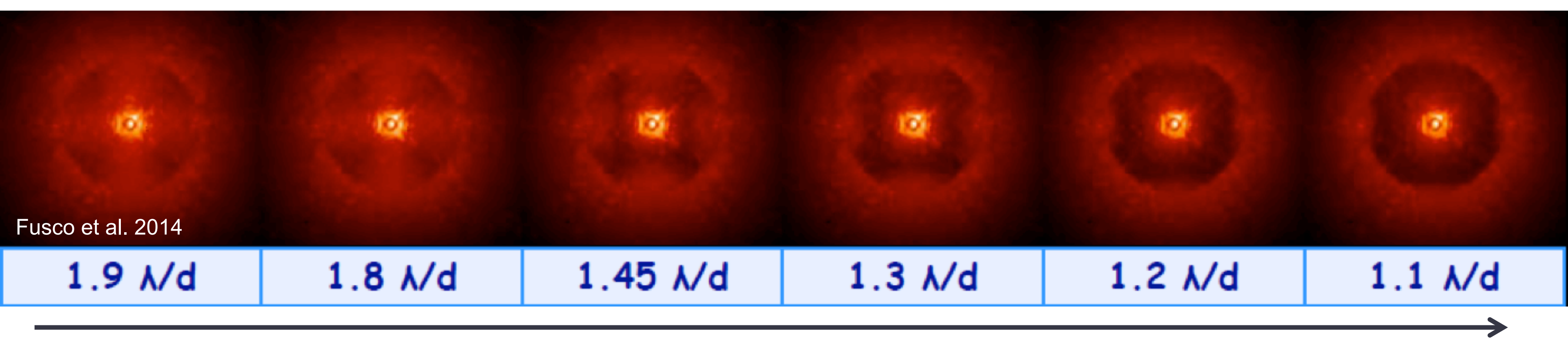


Highest spatial frequency obtainable

Results: deep coronagraphic images

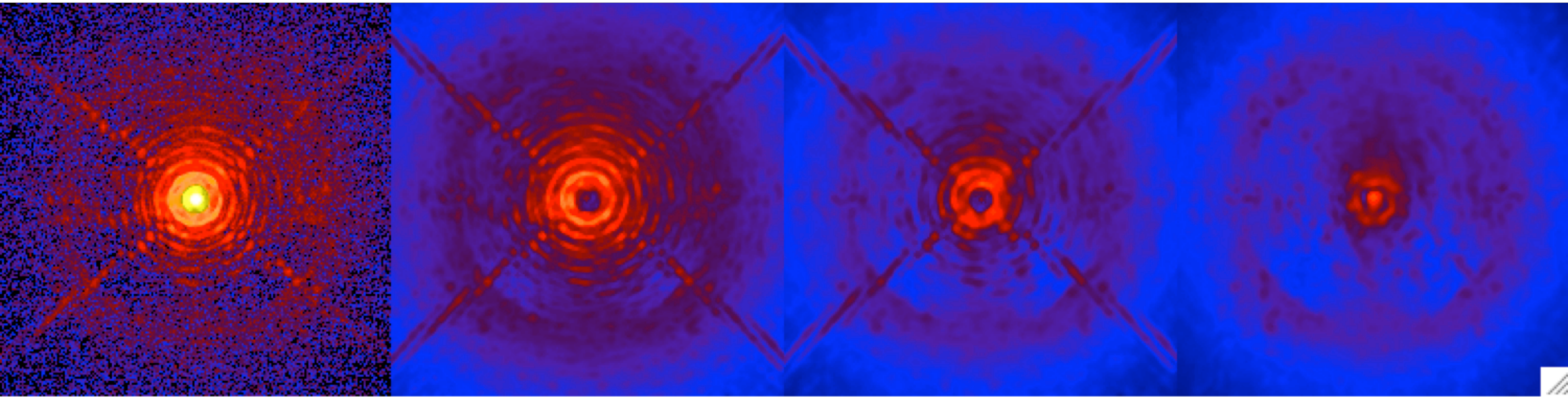
"Coronagraphic dark hole", example of SPHERE / Irdis

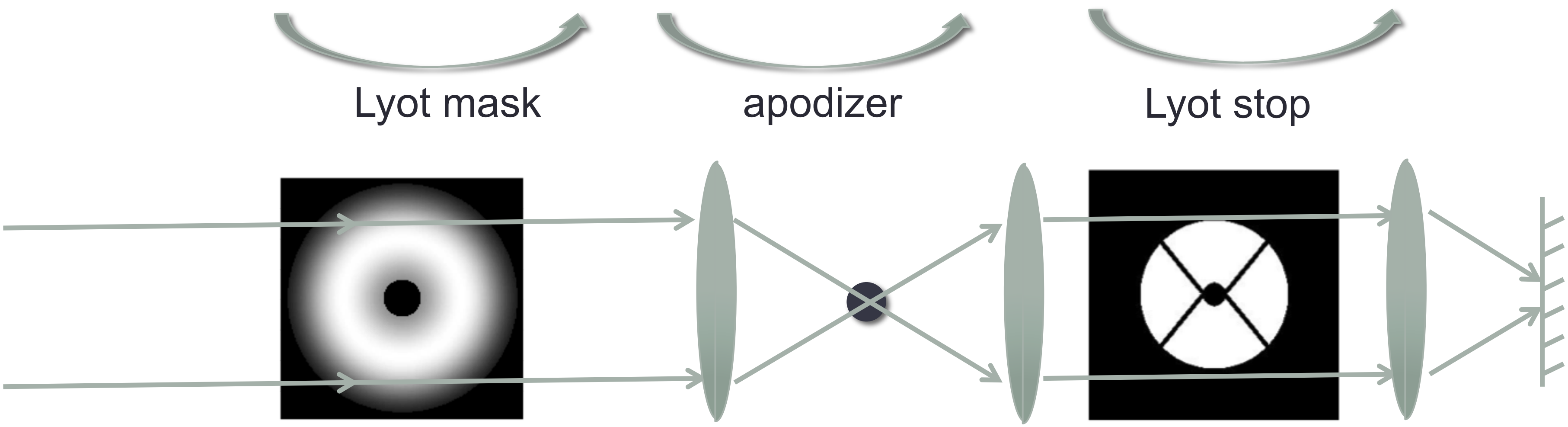




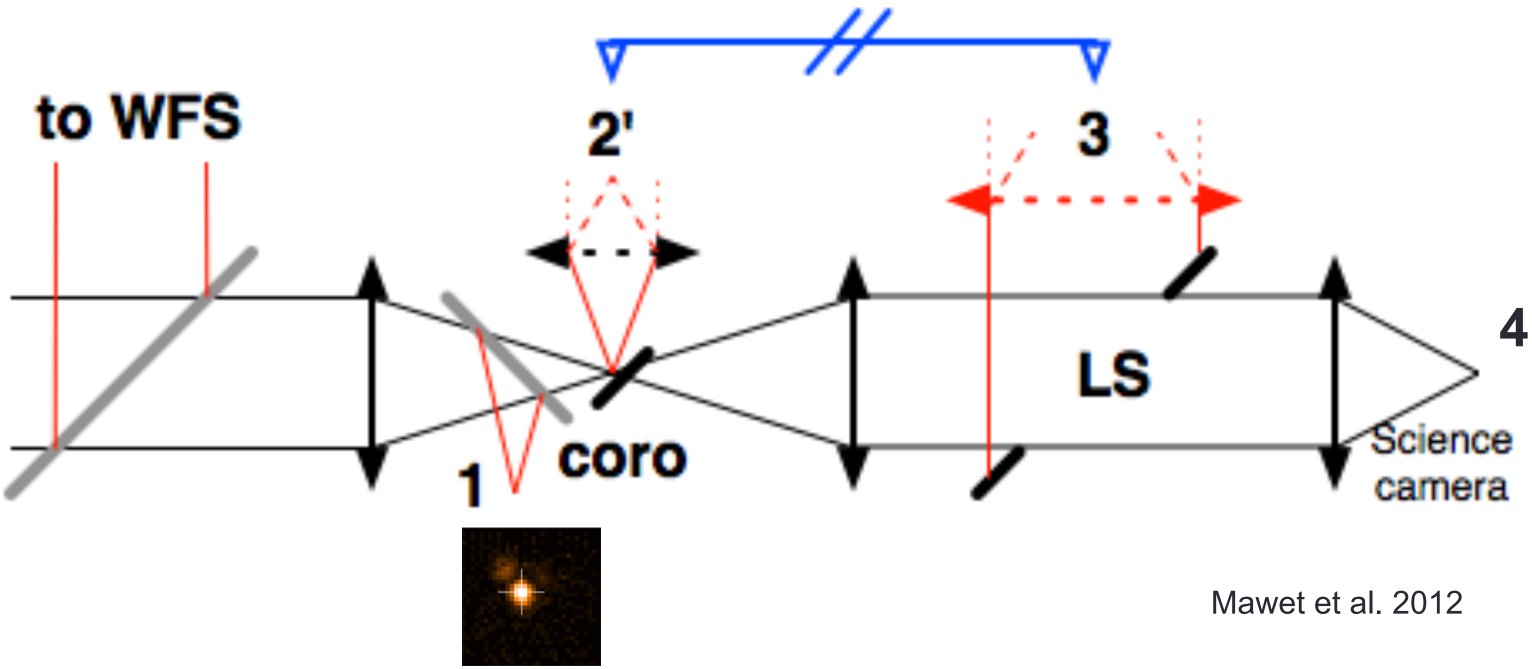
Spatial filter progressively closed

Diffraction control with pupil apodization





Low order wavefront sensor and correction of NCPA

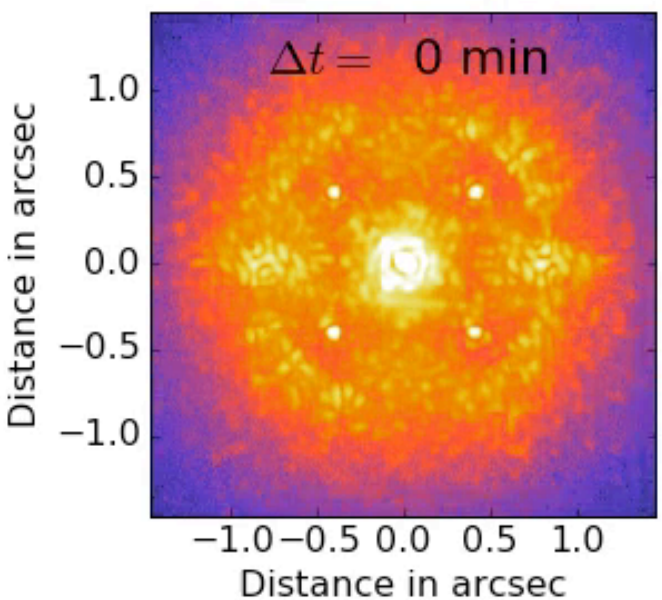


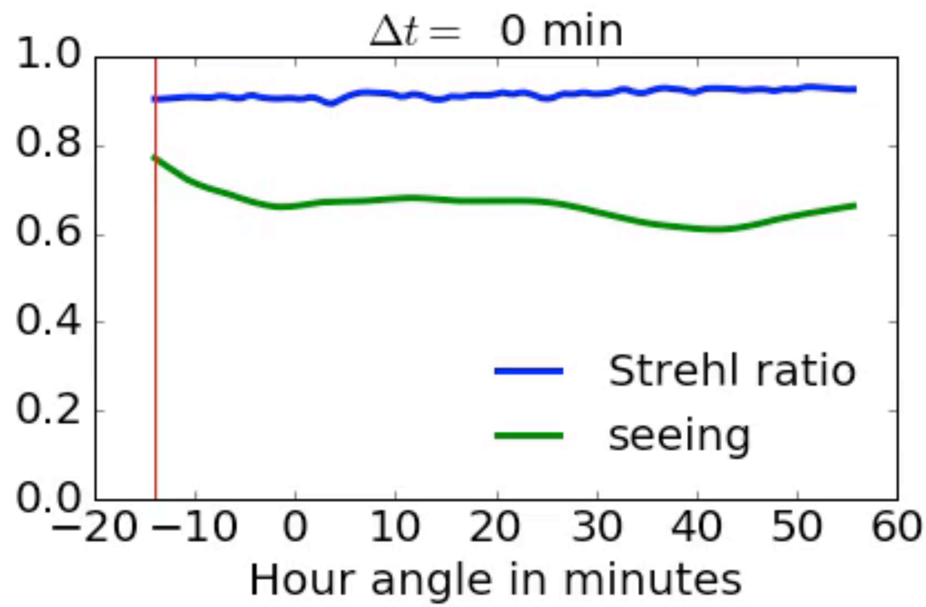
Mawet et al. 2012

Non-common path aberrations (NCPA) can be calibrated downstream from the WFS beam splitter:

- Either by dedicated calibration systems (1,2,3) OR
- Directly from the science camera, using phase diversity techniques (4)

Summary: on-sky performance





Stable speckle field
Strehl of 90% on a bright star R=5
Disk of HR4796 visible in the raw images

Content

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How to decouple the stellar halo from an astrophysical object ?

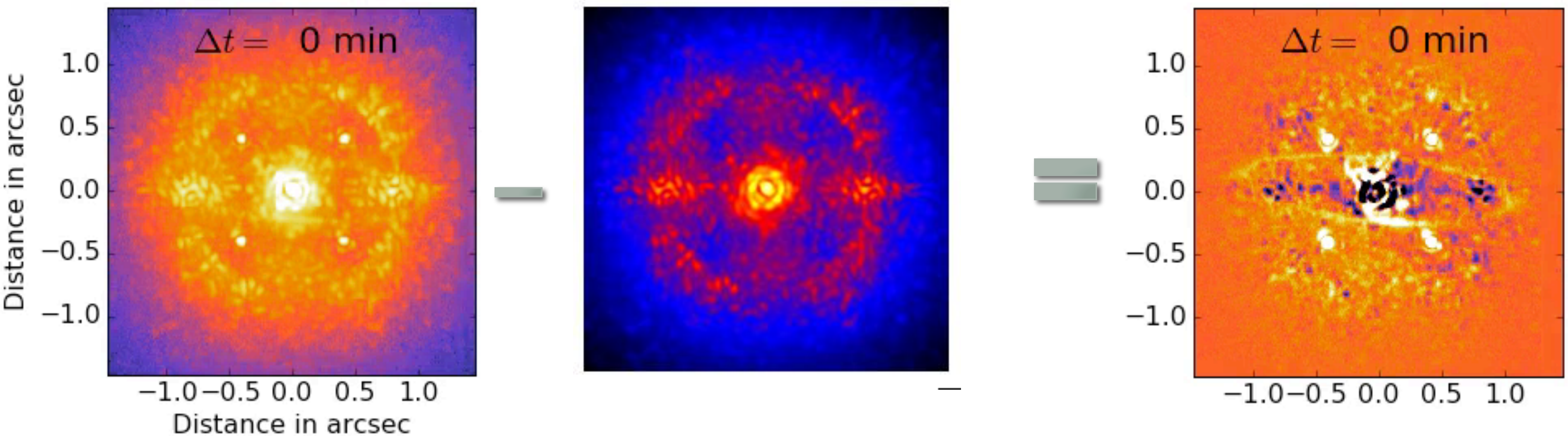
Angular differential Imaging (ADI)

Reference star differential imaging (RDI)

Polarimetric Differential Imaging (PDI)

Spectral differential imaging (SDI)

Angular differential imaging



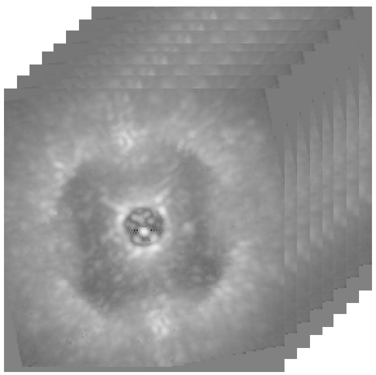
Pupil-stabilized sequence of coronagraphic images

Median of the sequence

2 challenges: - how to build the optimal reference coronagraphic image ?
- how does the coronaphic image evolve over time ?

Angular differential Imaging (ADI)	Reference star differential imaging (RDI)	Polarimetric Differential Imaging (PDI)	Spectral differential imaging (SDI)

Optimally combining the images to subtract the halo

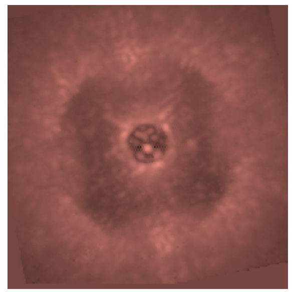


I_n

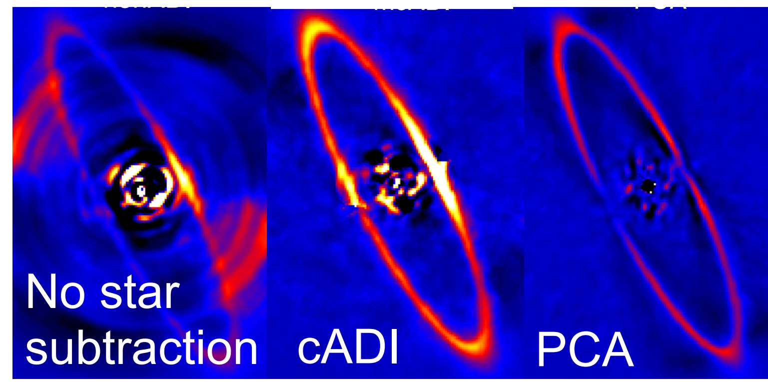
I_1

Library of coronagraphic images

$$\sum_{i=1}^{n} \alpha_i I_i$$



Reference image to subtract from the science images



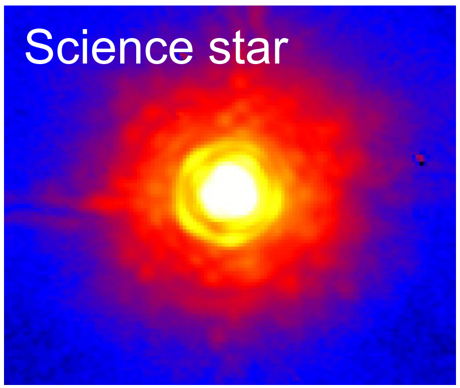
Milli et al. recommended for publication

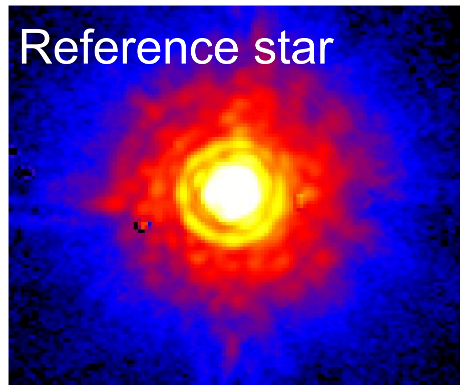
- LOCI: linear combination of images to minimize the noise (Lafrenière et al. 2007)
- PCA : orthogonalisation of library of images that is restrained to the first modes (Soummer et al 2012, Amara et al. 2012)
- Sparse Decomposition / Low rank approximation (Gomez et al. 2016)

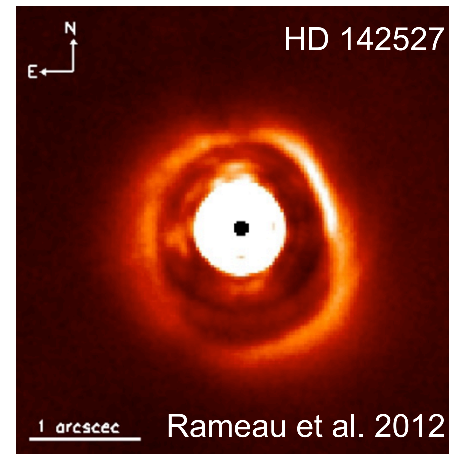
Poster 1

Angular differential Imaging (ADI)	Reference star differential imaging (RDI)	Polarimetric Differential Imaging (PDI)	Spectral differential imaging (SDI)

Reference star differential imaging







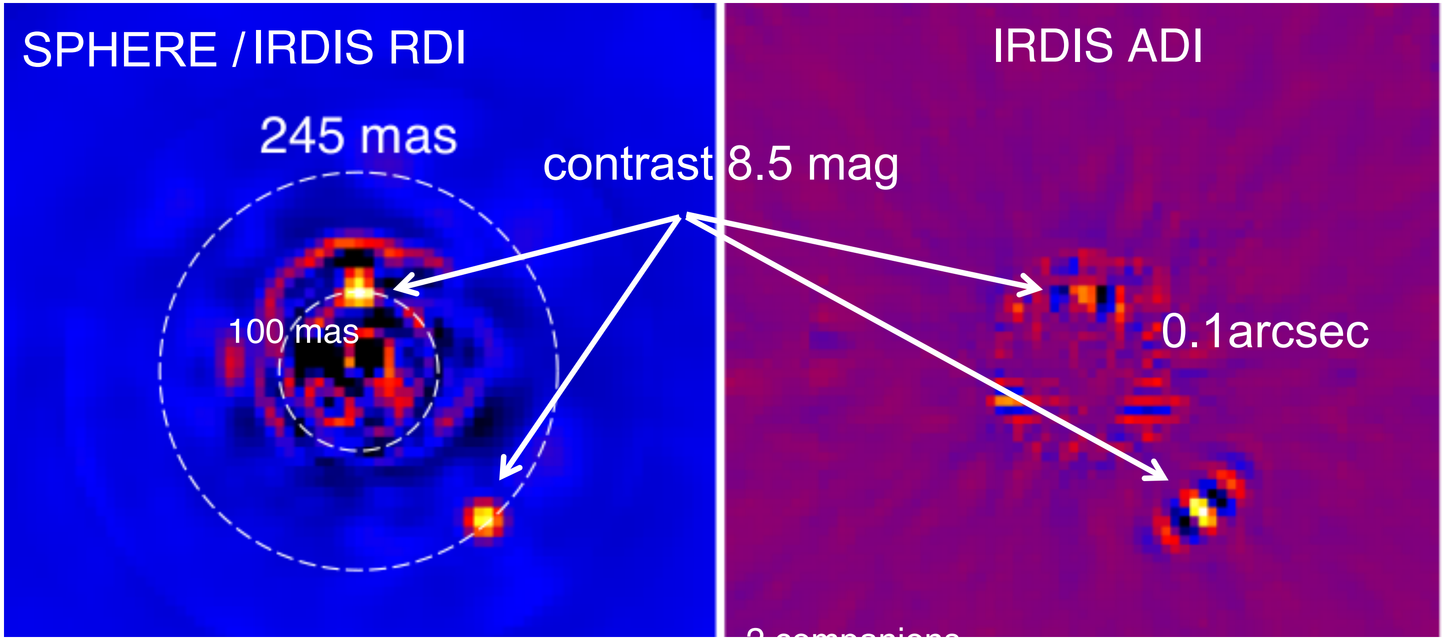
Angular differential Imaging (ADI)

Reference star differential imaging (RDI)

Polarimetric Differential Imaging (PDI)

Spectral differential imaging (SDI)

RDI beats ADI in some conditions



7º rotation (0.4 λ/D at 0.1 arcsec)

Angular differential Imaging (ADI)

Reference star differential imaging (RDI)

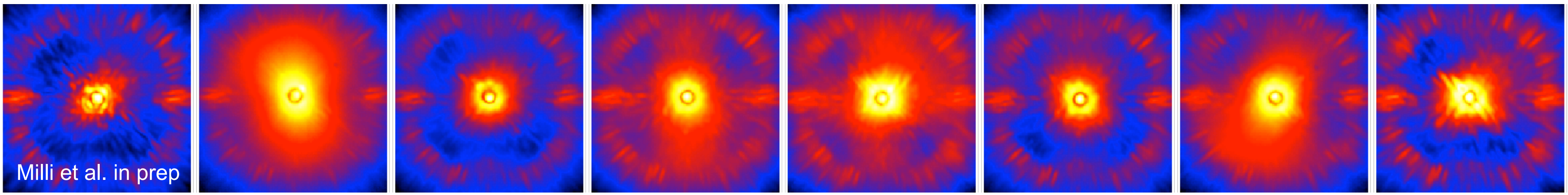
Polarimetric Differential Imaging (PDI)

Spectral differential imaging (SDI)

A promising strategy: library-based RDI

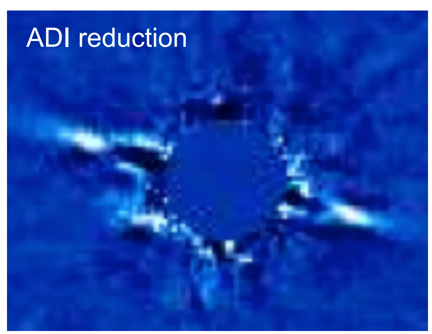
Talk E. Choquet

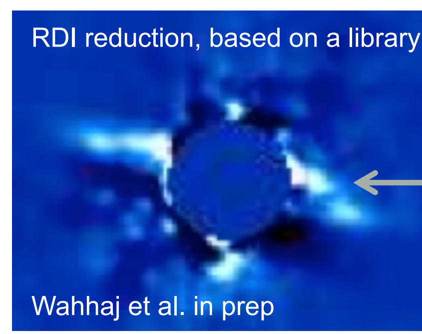
- Technique inspired by HST which has a stable PSF (Soummer et al. 2012)
- Library of stars observed in different conditions with the same setup:



- Pilot study on-going called SHARDDS program to search for debris disks
- New detection based on RDI

Poster 6

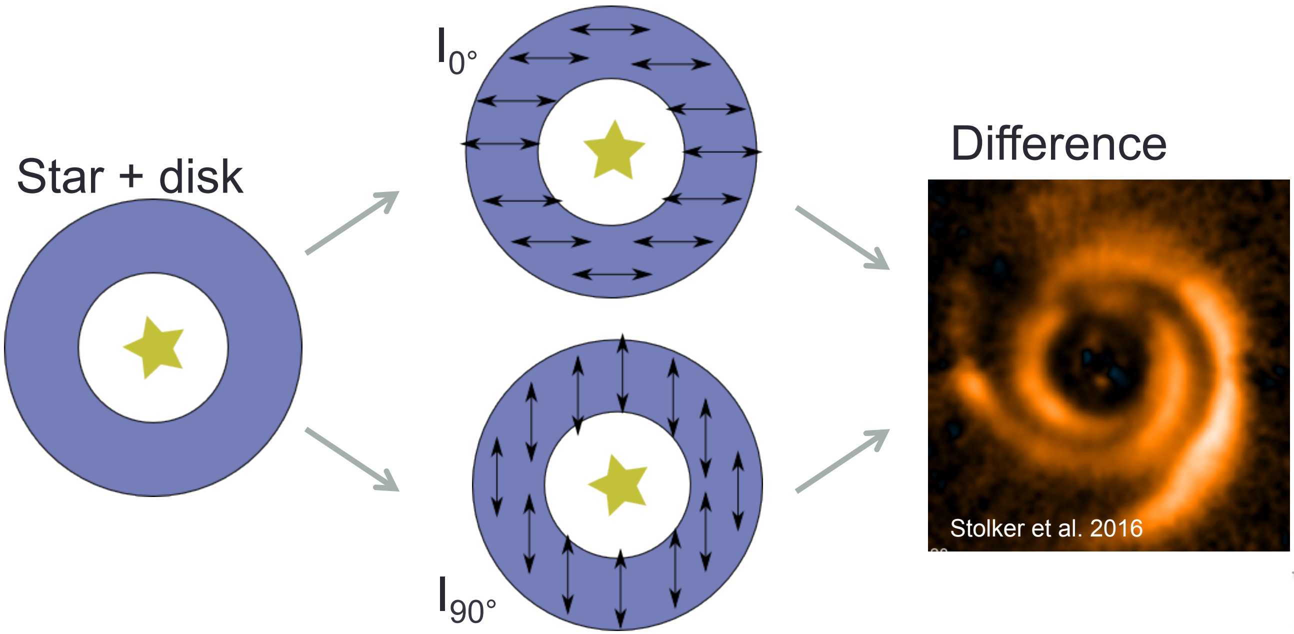




More disk signal retrieved in RDI

Angular differential Imaging (ADI) | Reference star differential imaging (RDI) | Polarimetric Differential Imaging (PDI) | Spectral differential imaging (SDI)

Polarimetric differential imaging

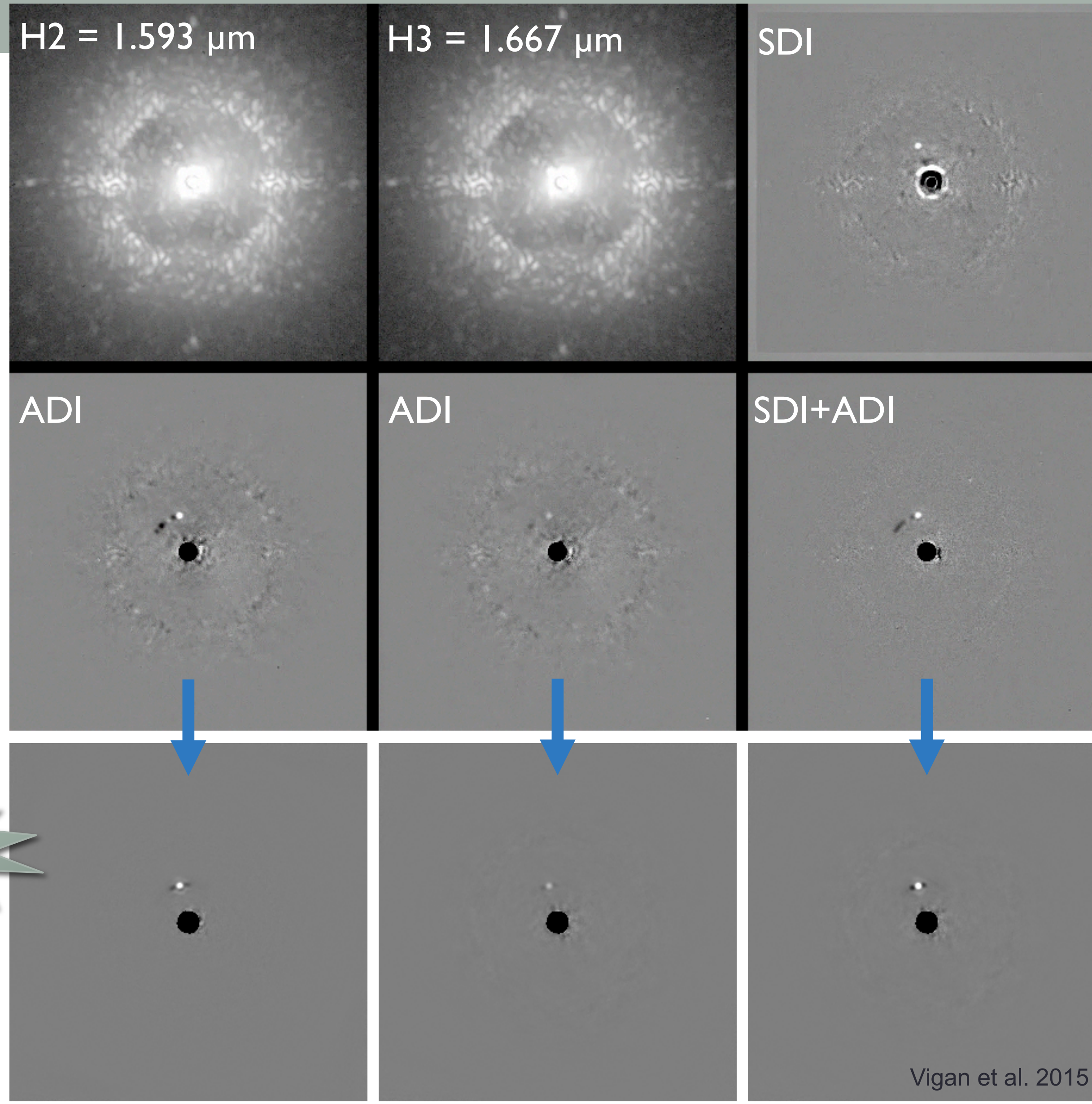


Talk H. Avenhaus

- Instantaneous subtraction
- Calibration of the instrumental polarization and differential aberrations is required

Angular differential Imaging (ADI)	Reference star differential imaging (RDI)	Polarimetric Differential Imaging (PDI)	Spectral differential imaging (SDI)

Combining the spectral dimension: ADI + SDI



Talk M. Langlois

- Dual-band imaging
- IFS

Angular differential Imaging (ADI) | Reference star differential imaging (RDI) | Polarimetric Differential Imaging (PDI) | Spectral differential imaging (SDI)

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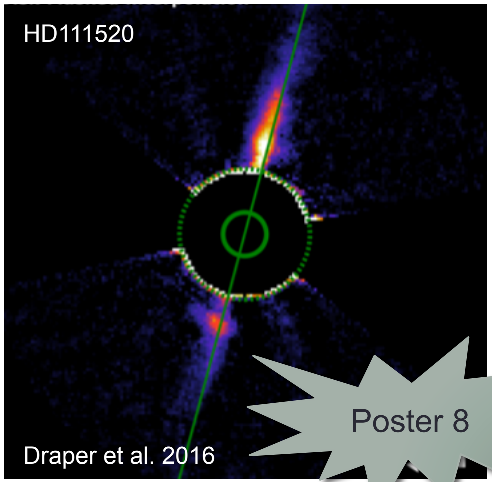
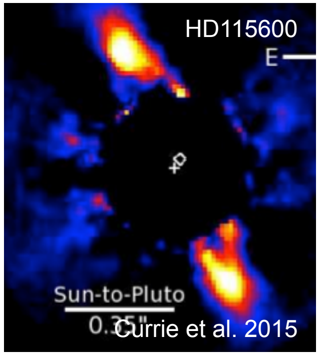
III. **Perspectives opened by the XAO instruments**

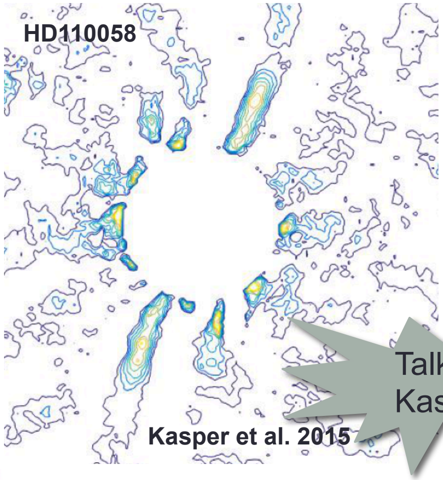
Increasing the statistics with new discoveries of faint and compact disks

Great harvest of new debris disks in the Sco-Cen association

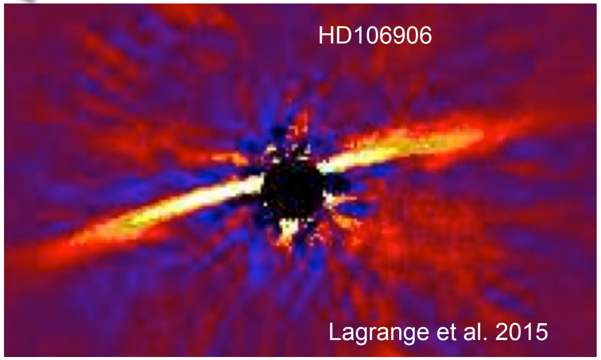


Poster 8



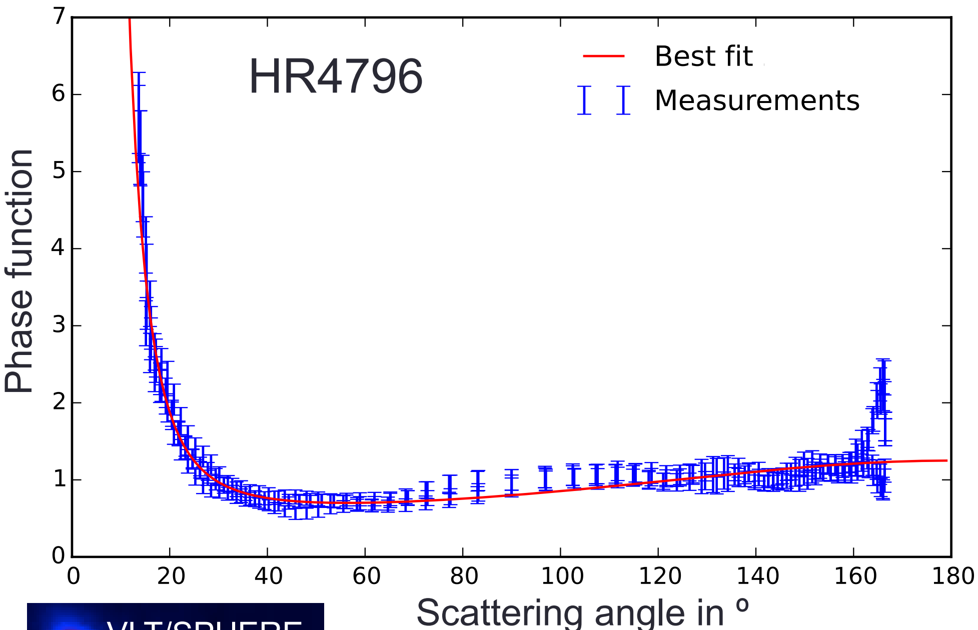


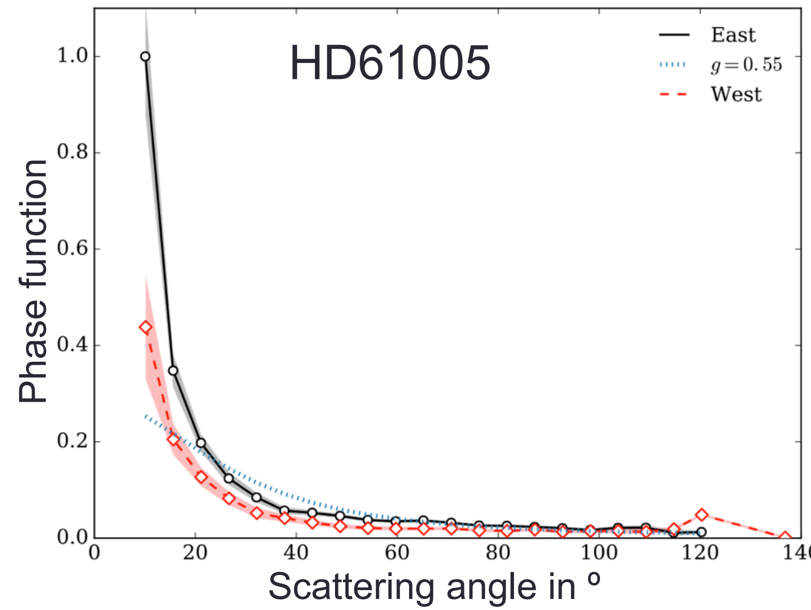
Talk M. Kasper

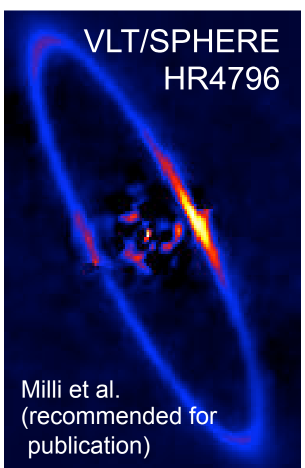


The number of debris disks resolved in scattered light doubled in 3 years

Revealing the dust physical properties

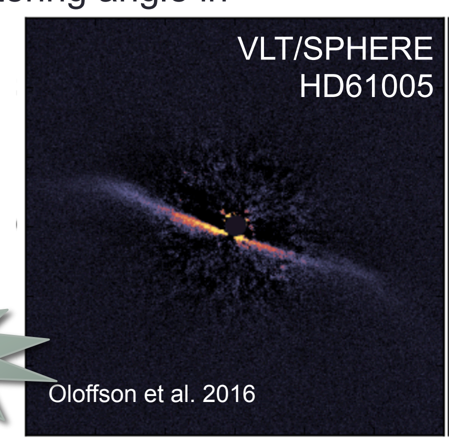




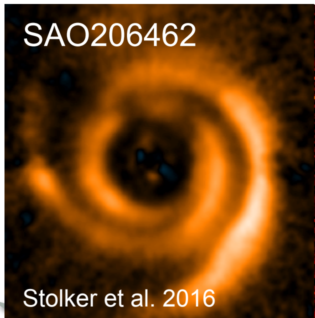


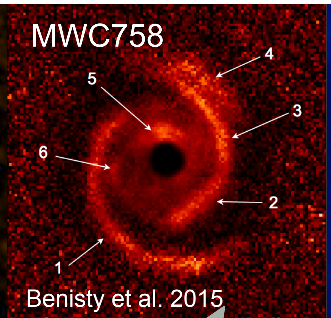
The dust phase function is
a powerful diagnostic tool to investigate
the particle shape and sizes

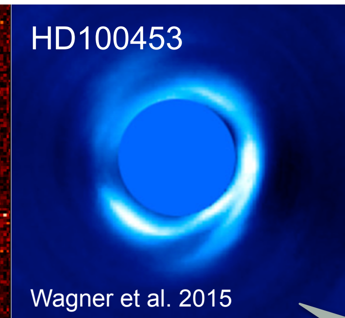
Talk J. Oloffson

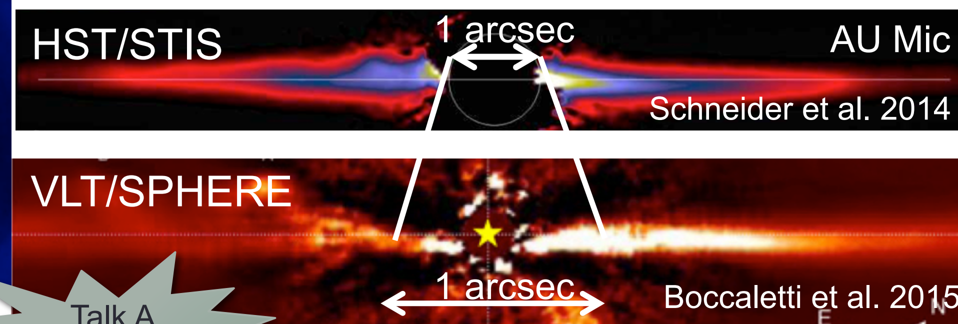


Revealing morphological details









Talk P. Pinilla

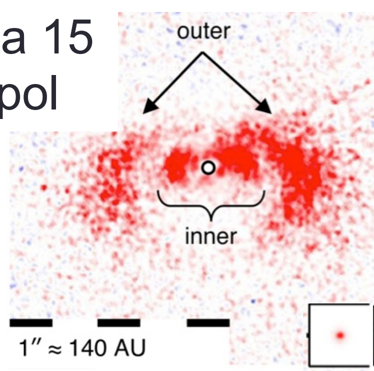
Poster 2

Talk A. Boccaletti

Shadows and time variability are now discernable thanks to the amount of details provided by XAO

Exquisite resolution with visible AO

LkCa 15
Zimpol



Thalmann et al. 2015

SPHERE / Zimpol, ScexAO / Vampires, MagAO / VisAO

Resolution of 15mas in the V band
50% Strehl in R on bright stars R<7

Conclusions

- XAO systems are designed to beat both atmospheric speckles and quasi-static instrumental speckles by integrating calibration strategies

- They yielded spectacular observations of disks now to be tested against planetary formation theories

- New challenges:
  - Better control of low-order aberrations for improved coronagraphic rejection
  - Improved sensitivity to faint target
  - Higher-rejection coronagraphs
  - Some unexpected obstacles: dead actuators, vibrations, aberrations unseen by the WFS in the absence of wind

Magellan / Mag AO
Alpha Centauri
4"
Hale / P1640
Gemini / GPI
Subaru / SCexAO
VLT / SPHERE