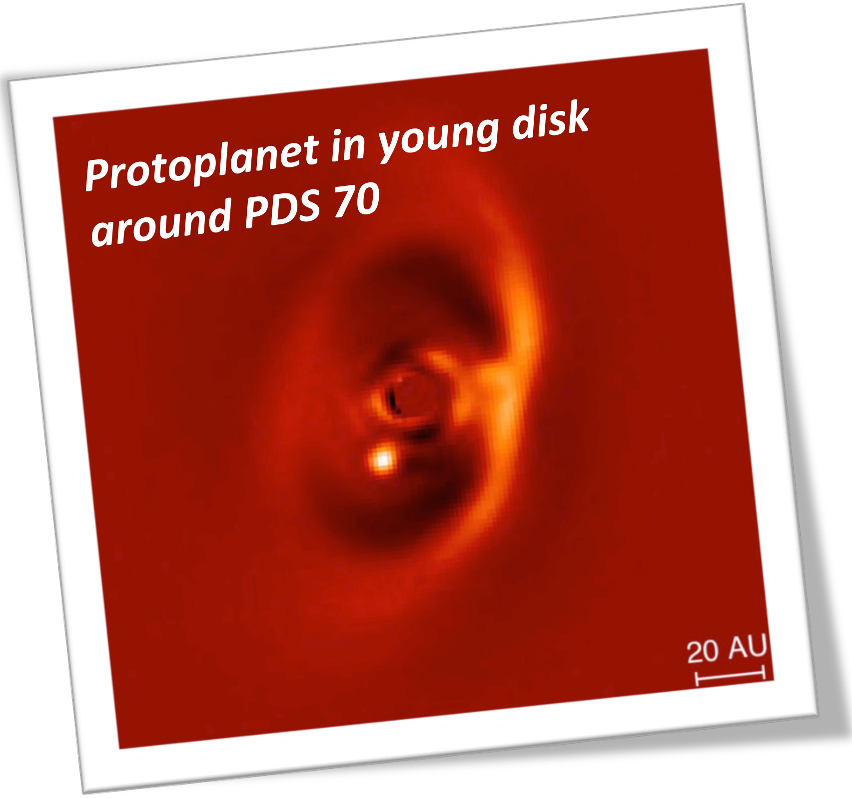
Imaging exoplanets:
The current instruments and their limitations



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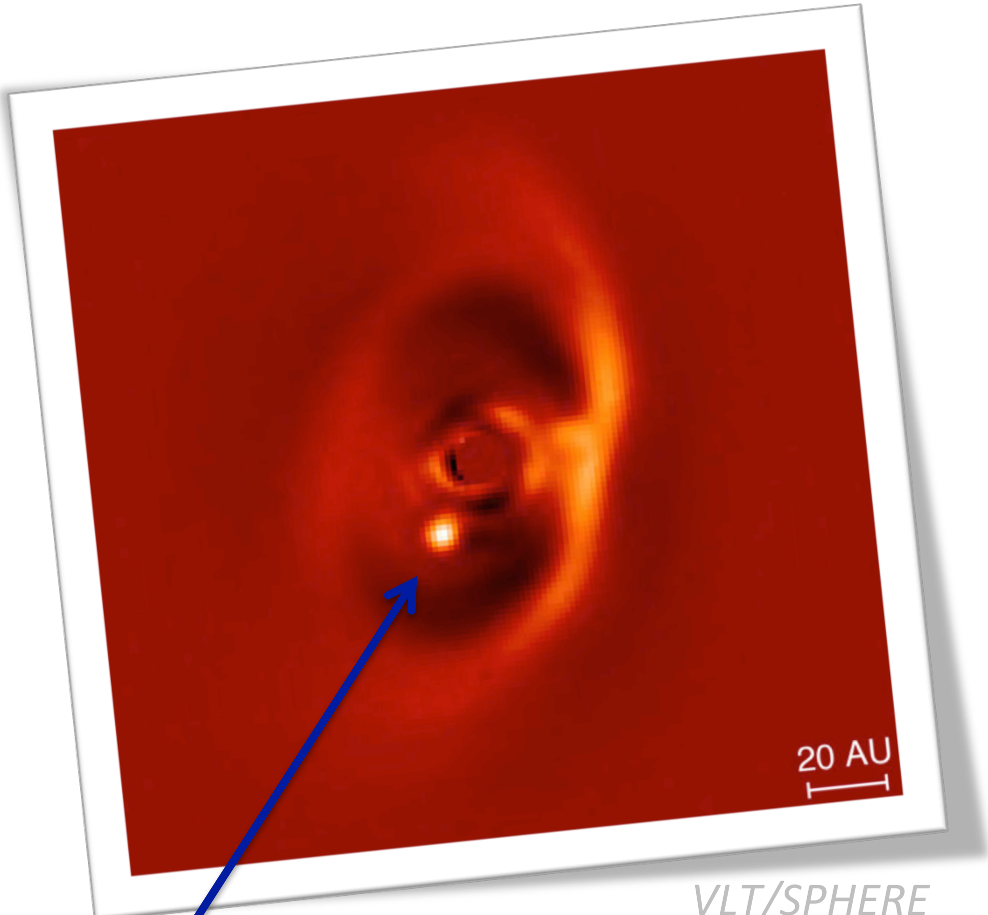
Max Planck Institute for Astronomy, Heidelberg

Heidelberg

Baden-Würtemberg

Germany

What do we get from an image ?



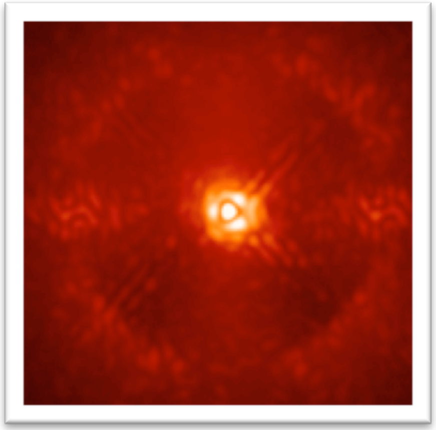
VLT/SPHERE

- Projected **separation** from the host star,
- **Contrast** to the host star,
- **Detection limit** for the data set

What do we infer from an image ?

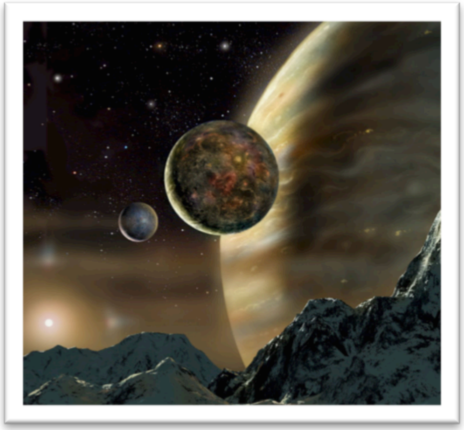
- **Planet parameters:** Mass, radius, temperature, metallicity, surface gravity
- **Planet atmosphere:** clouds, dust, hazes, chemical compounds
- **Dynamics of the system:** orbital parameters, migration, scaterring
- **Statistical survey:** type of companions, link to host star, environment…

-> discriminate between different planetary **formation** and **evolution** models



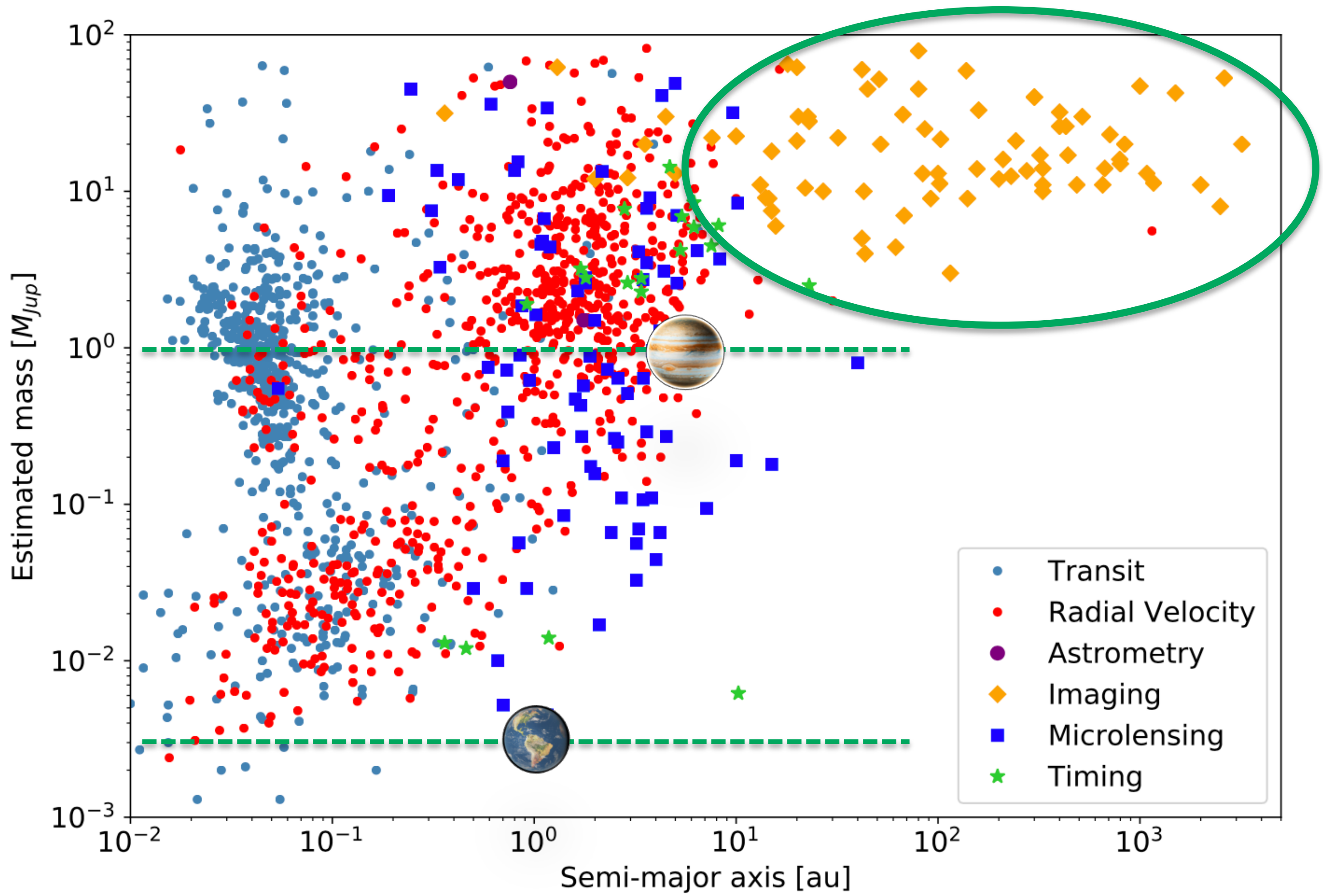
Raw image from
VLT/SPHERE/IFS

Loads of work…



Artistic view
of an exoplanetary system

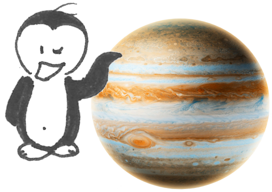
Why do we do exoplanet imaging ?



- **Complementary** to other techniques: young stars, massive and distant planets
- Direct extraction of **spectrum:** atmospheric composition and structures
- Planetary system **architecture:** planet-planet or planet-disk interactions, follow-up…

The challenges of exoplanet imaging

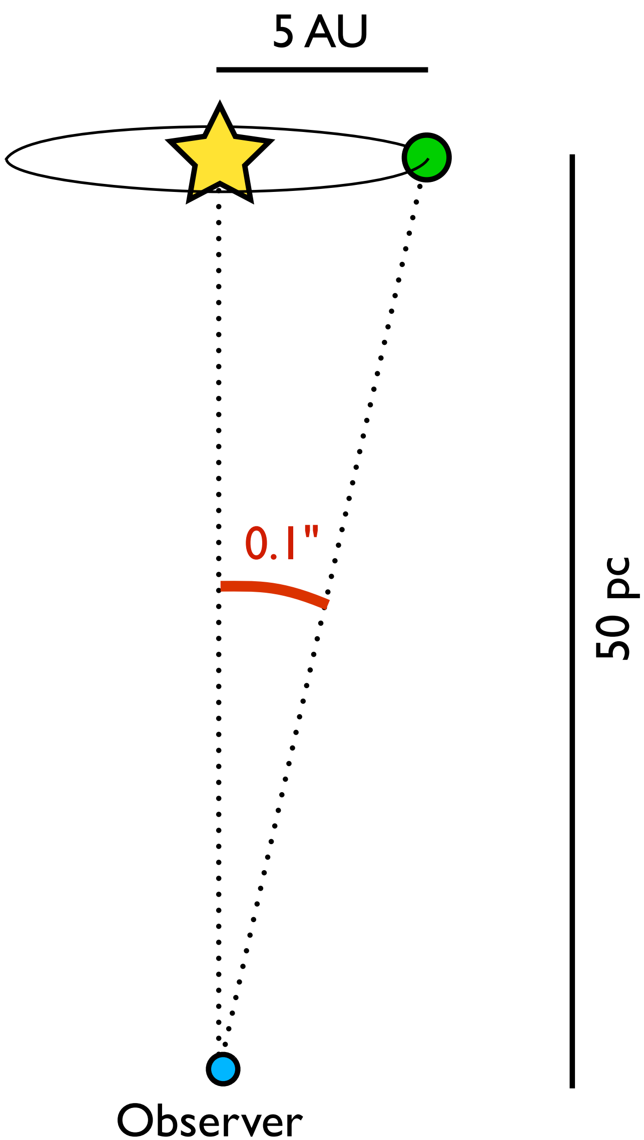
Example of Jupiter



Distance : 5 AU (period 11 years)
→ Observation at 50pc: separation **100 mas**!

Age : 1 billion years old
→ **1 000 000 000** less bright than the Sun!

Note, from Earth:
Moon angular diameter ~ 30 arcmin
Jupiter angular diameter ~ 30 arcsec



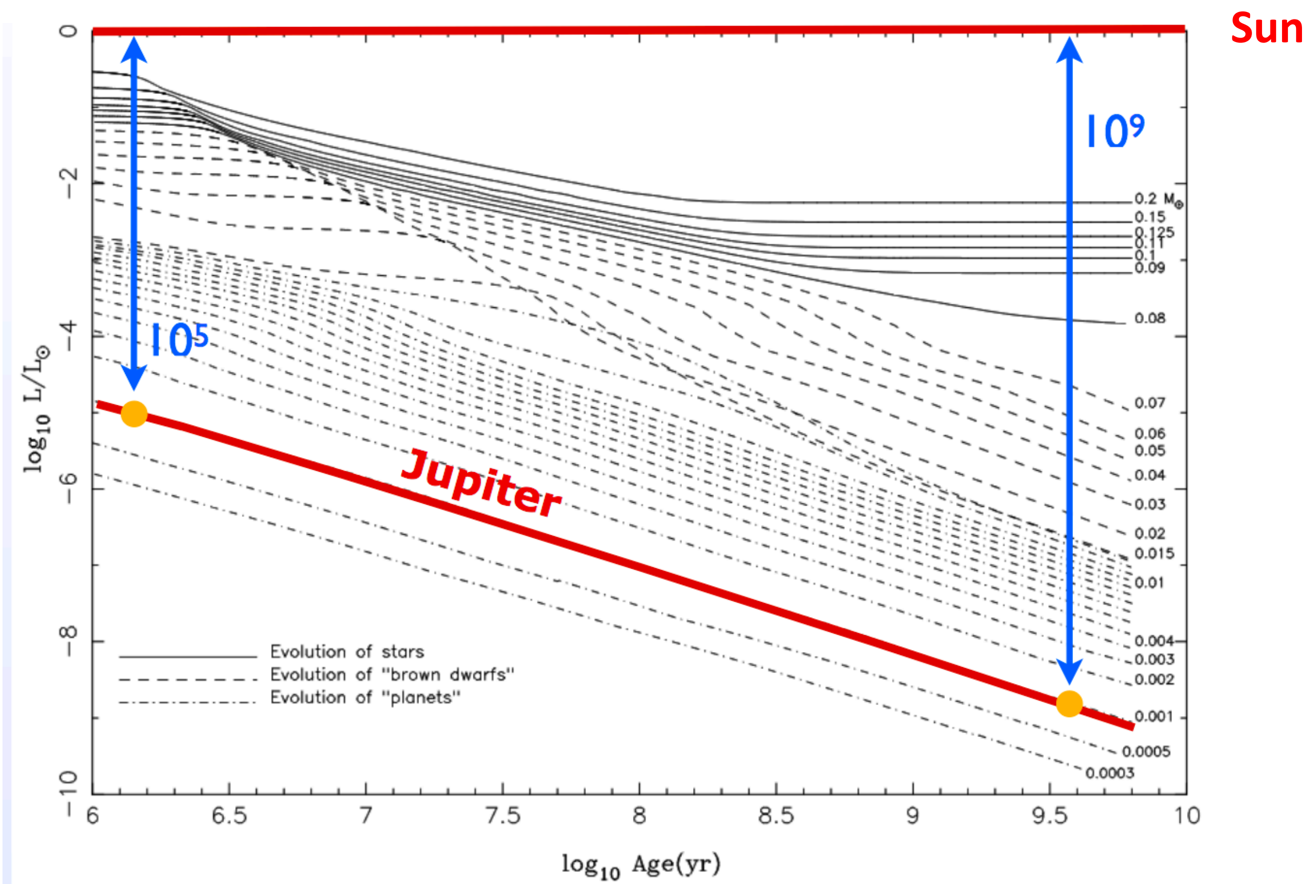
The target stars

High angular resolution and high contrast:

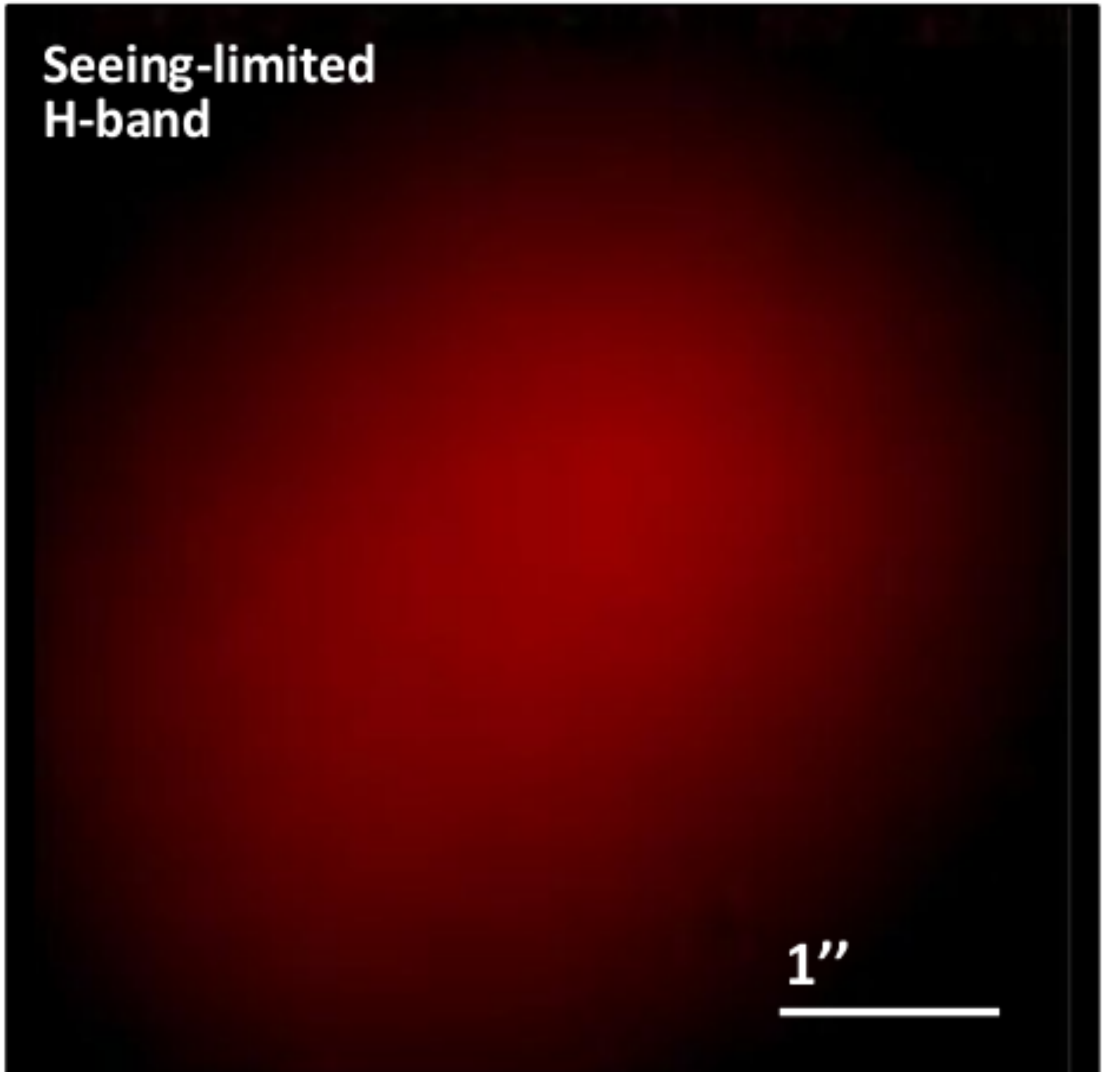
→ Stars close to the Sun

→ Young stars

→ Thermal emission (Infrared)

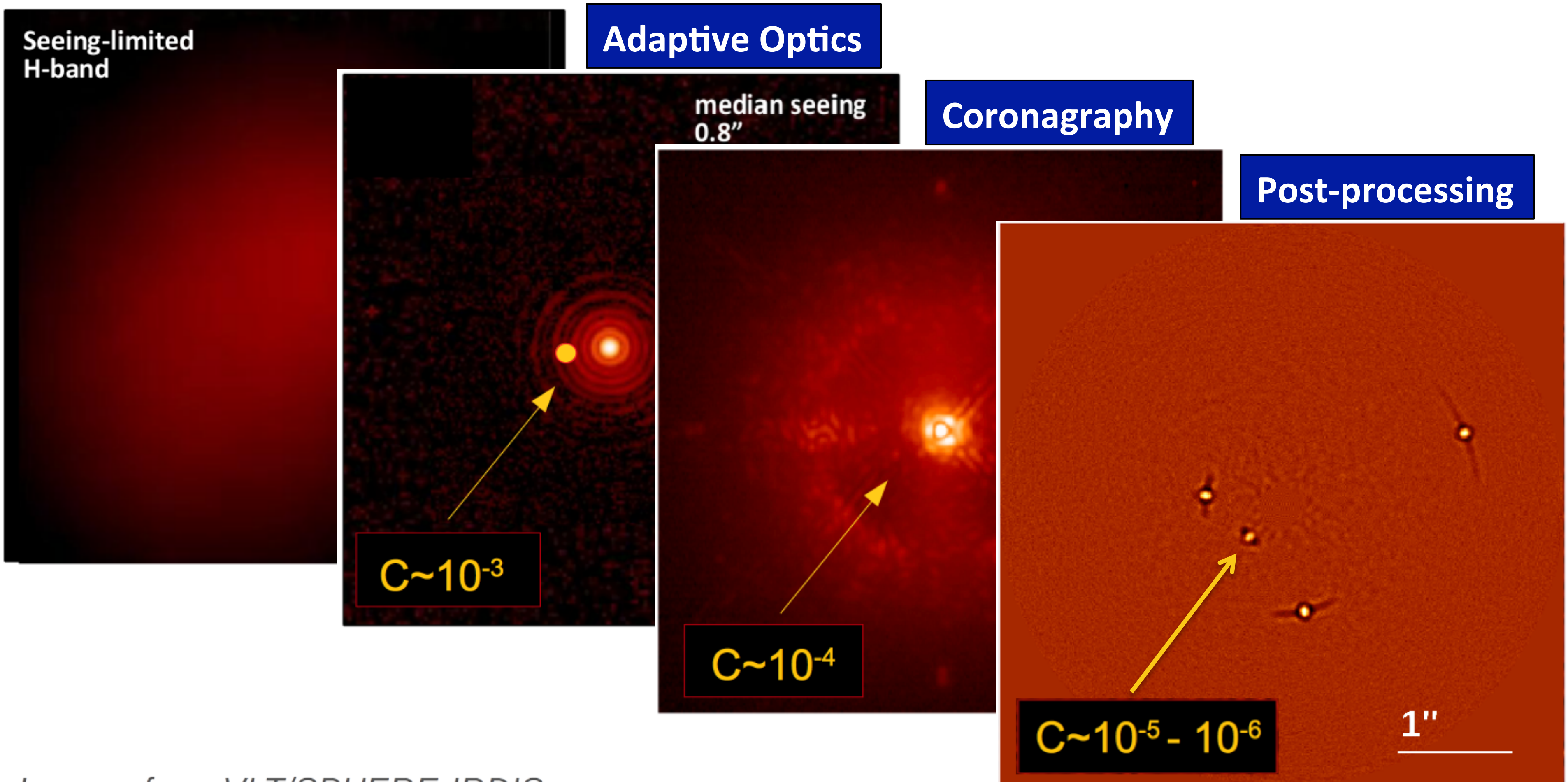


Observing this target with the VLT



The three pillars of high-contrast imaging

Today reaching contrast of **10^{-6}** contrast at **500 mas**, in near-infrared



Images from VLT/SPHERE-IRDIS:
HR8799 in H-band (1.6μm)

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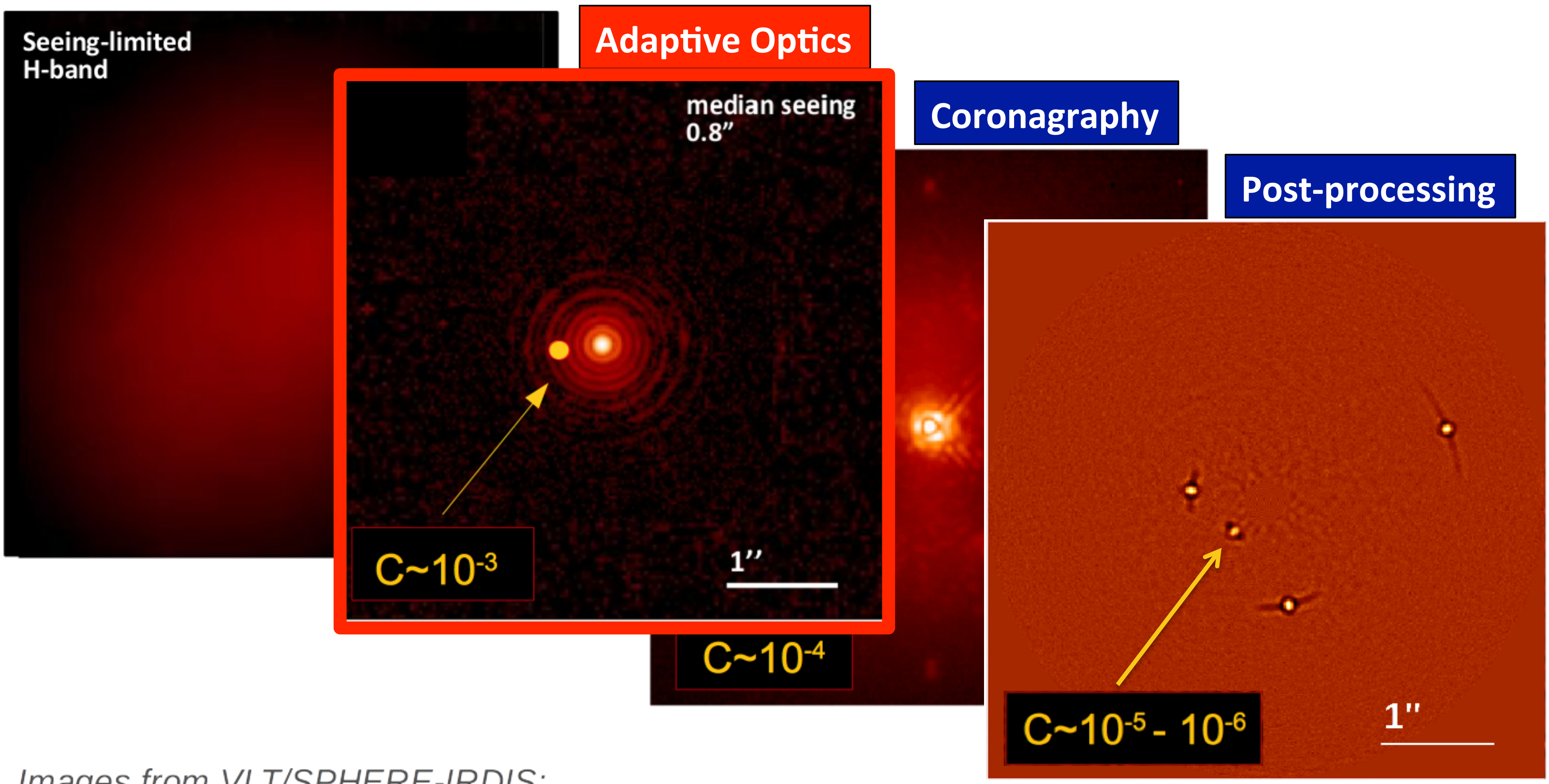
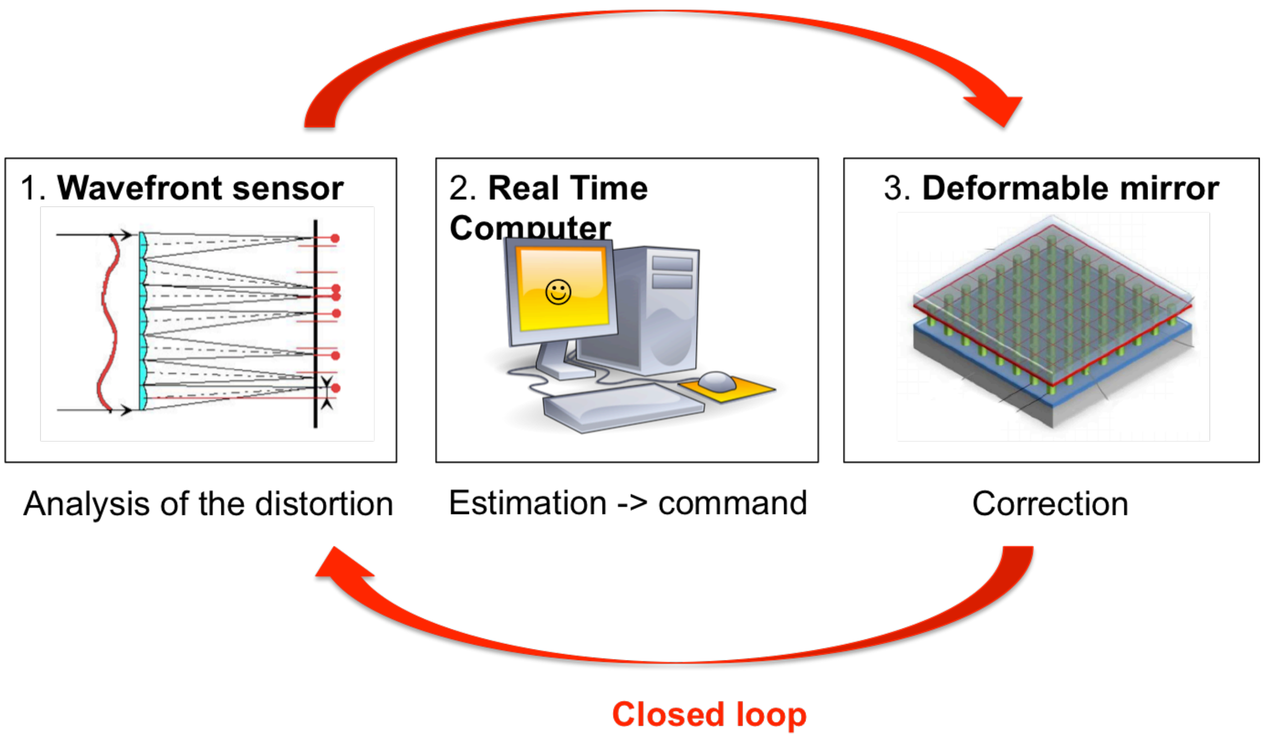
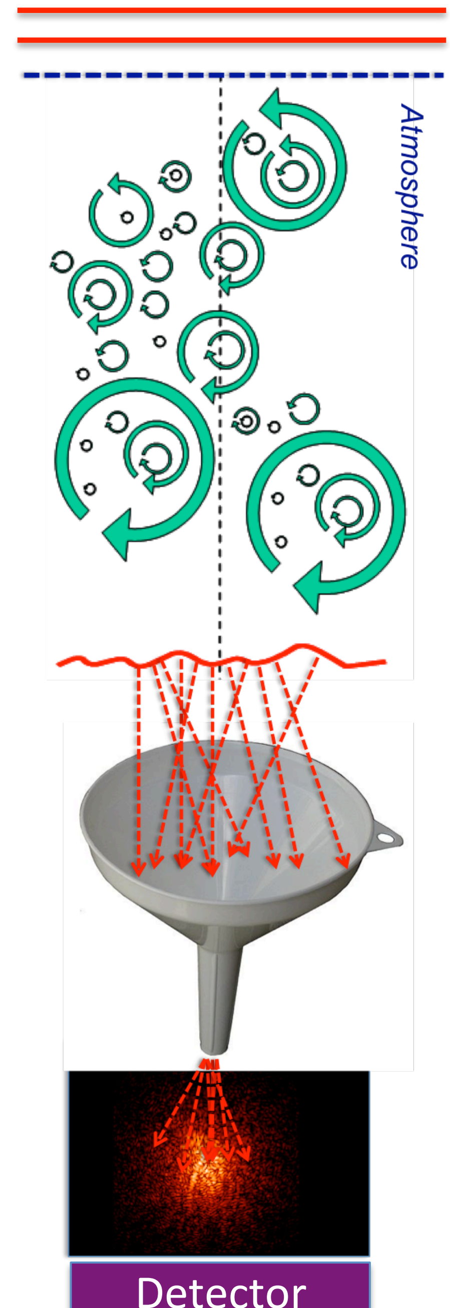


Images from VLT/SPHERE-IRDIS:
HR8799 in H-band (1.6µm)

Adaptive Optics

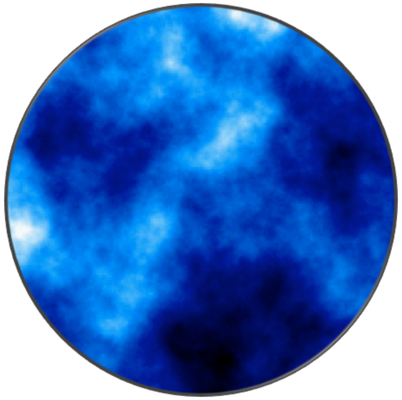
Concept



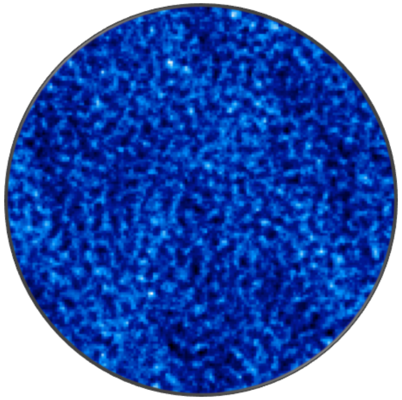


Adaptive Optics

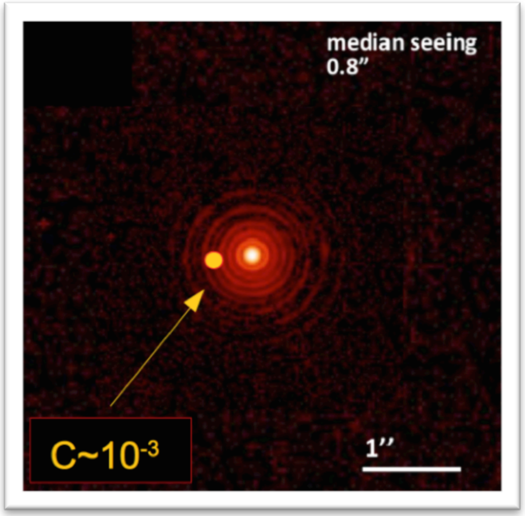
Result



Atmospheric turbulent phase



Realistic AO residual phase



Adaptive Optics

Limitations

But limited:

- Limited spatial sampling of the WFS
- Limited number of photons reaching WFS detector
- Limited number of actuators of the DM

…

The whole system must run as fast as possible

The three pillars of high-contrast imaging

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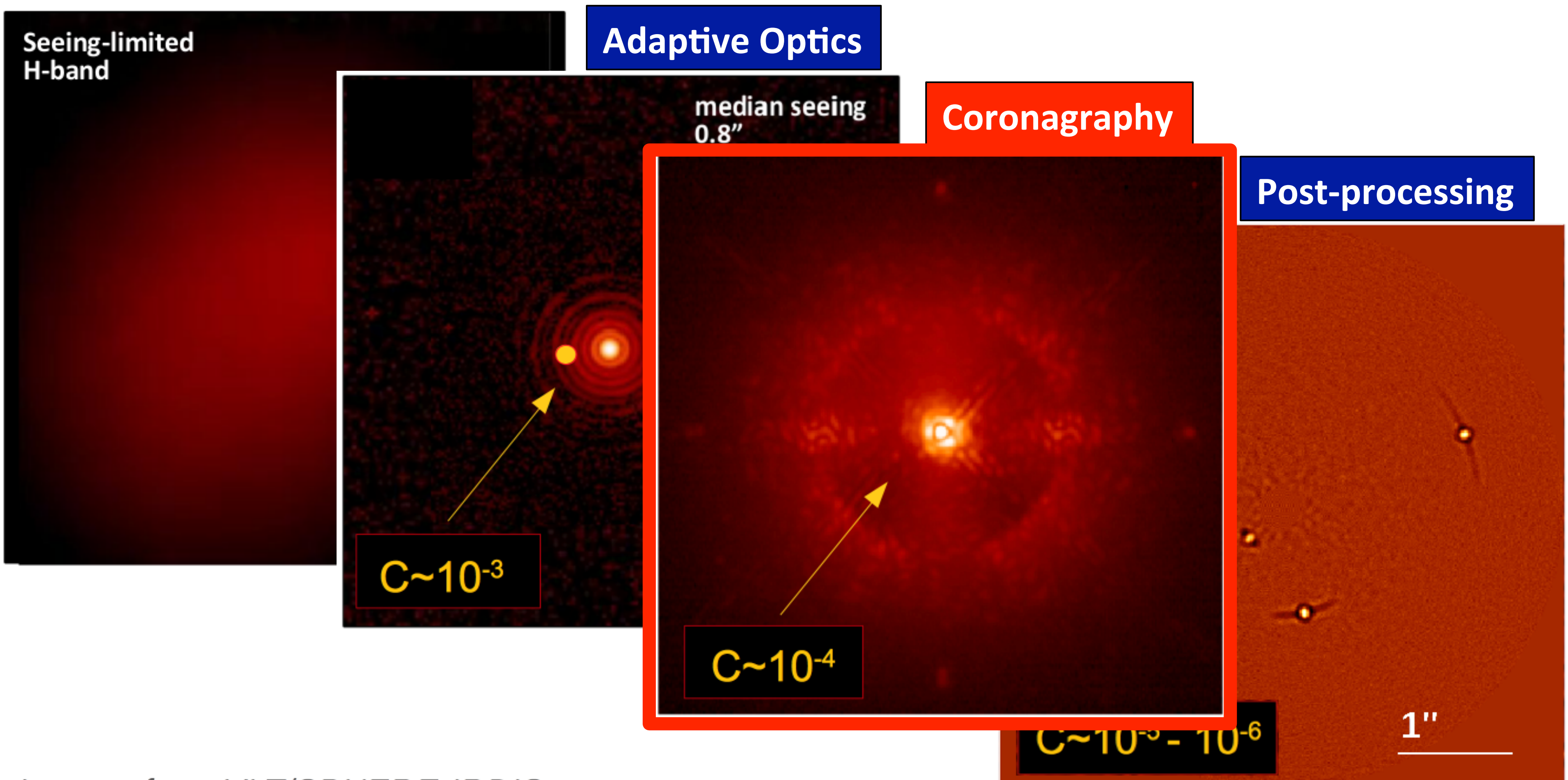
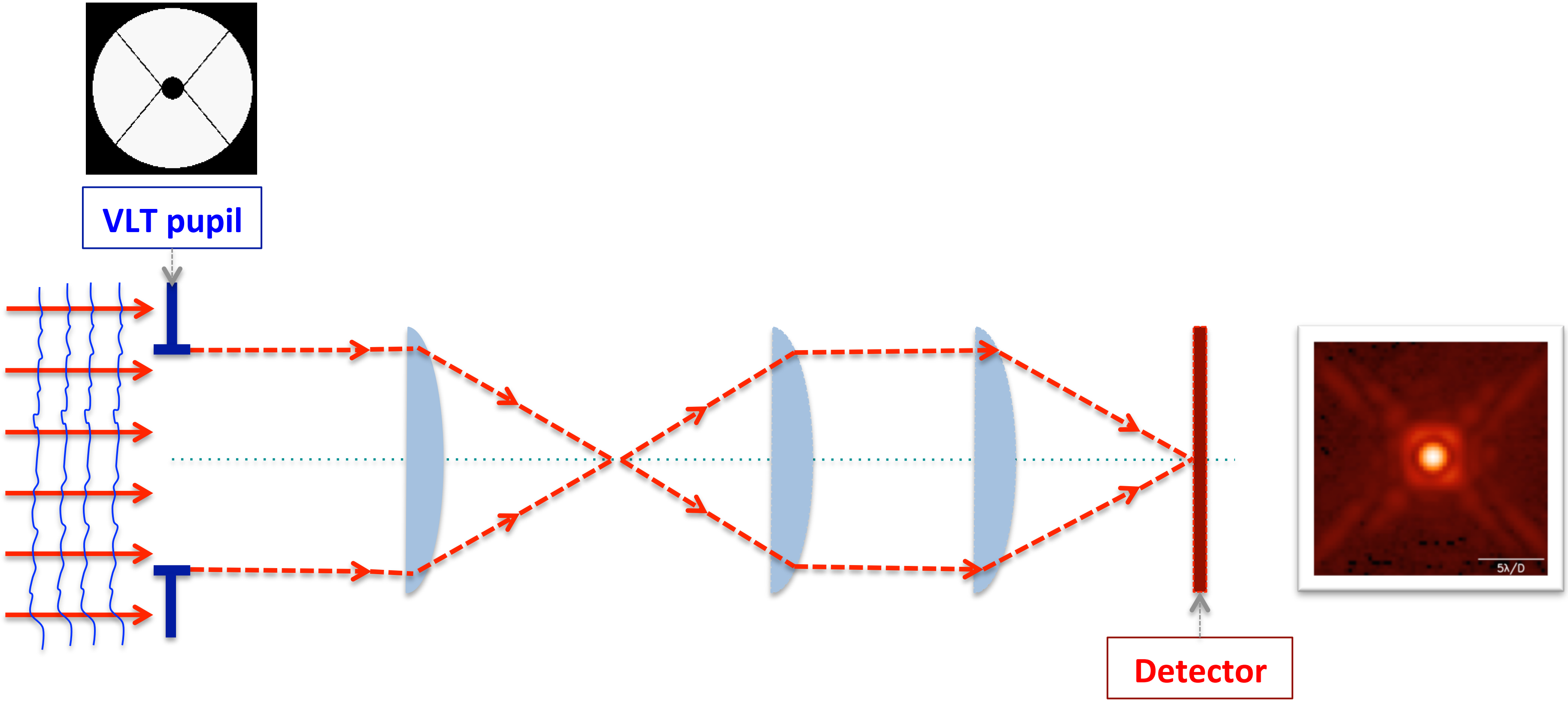


Images from VLT/SPHERE-IRDIS:
HR8799 in H-band (1.6µm)

Coronagraphy

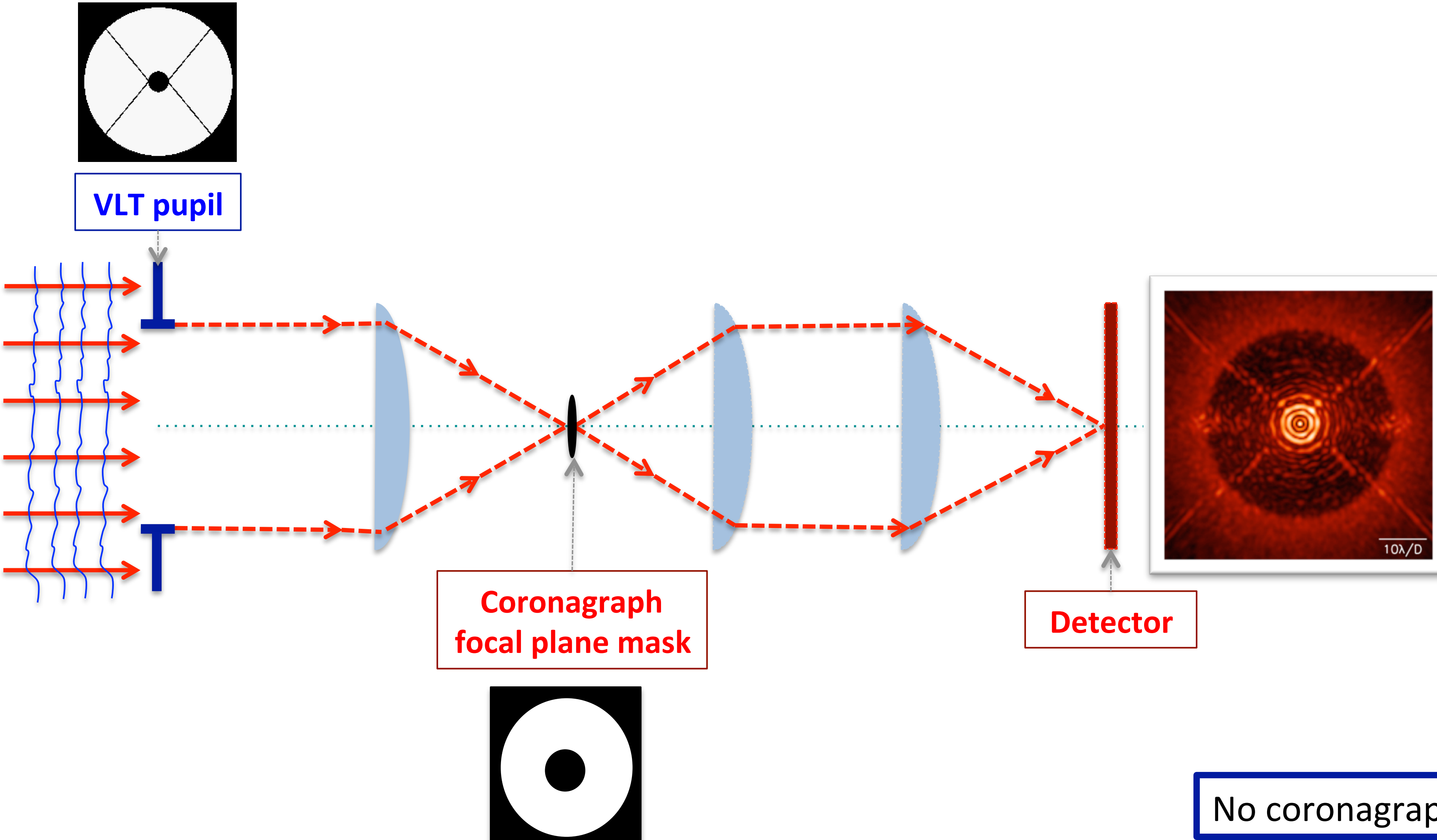
Get rid of the starlight,
while preserving its close environment



No coronagraph

Coronagraphy

Get rid of the starlight,
while preserving its close environment



No coronagraph

Coronagraphy

Get rid of the starlight,
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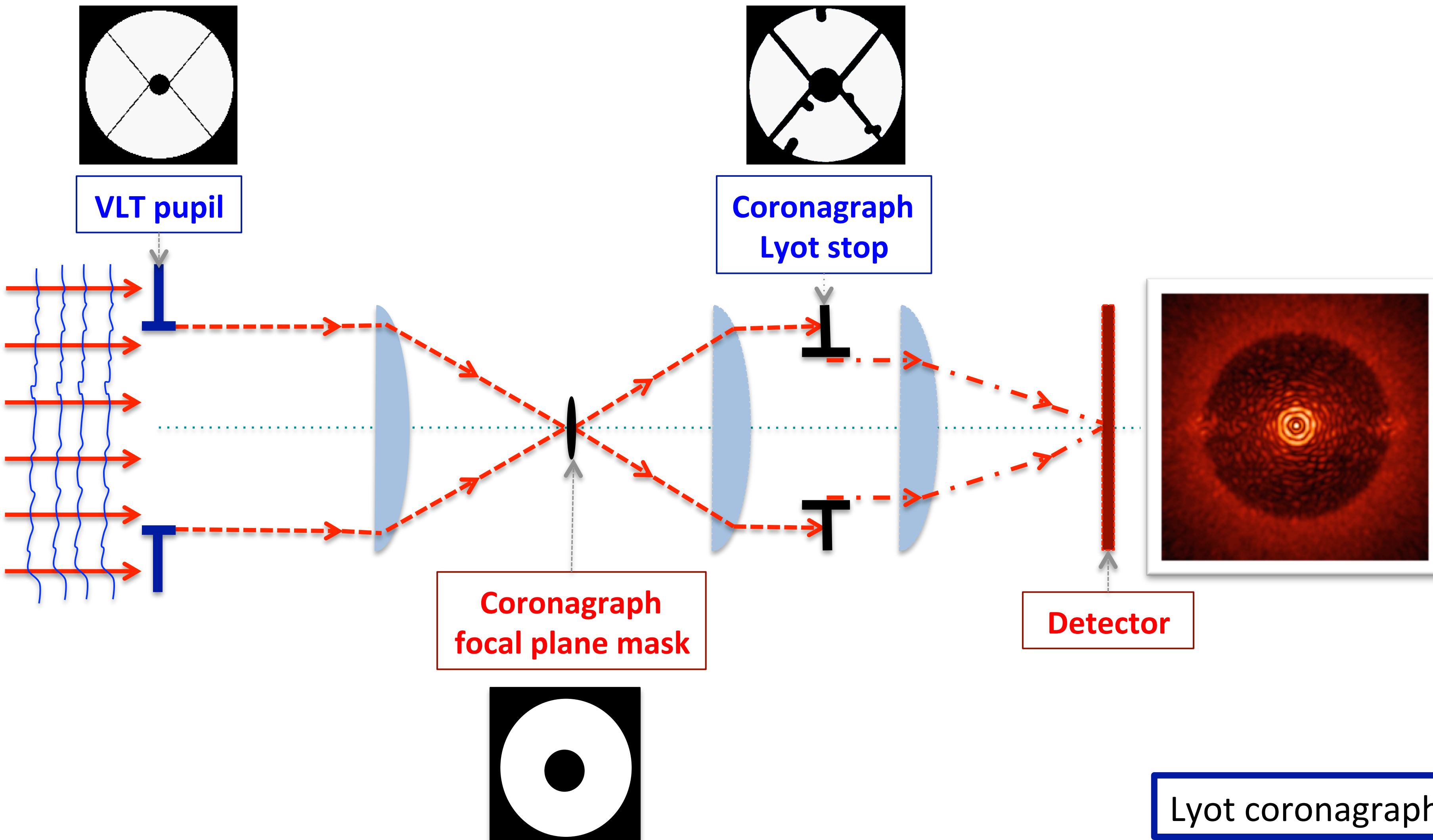
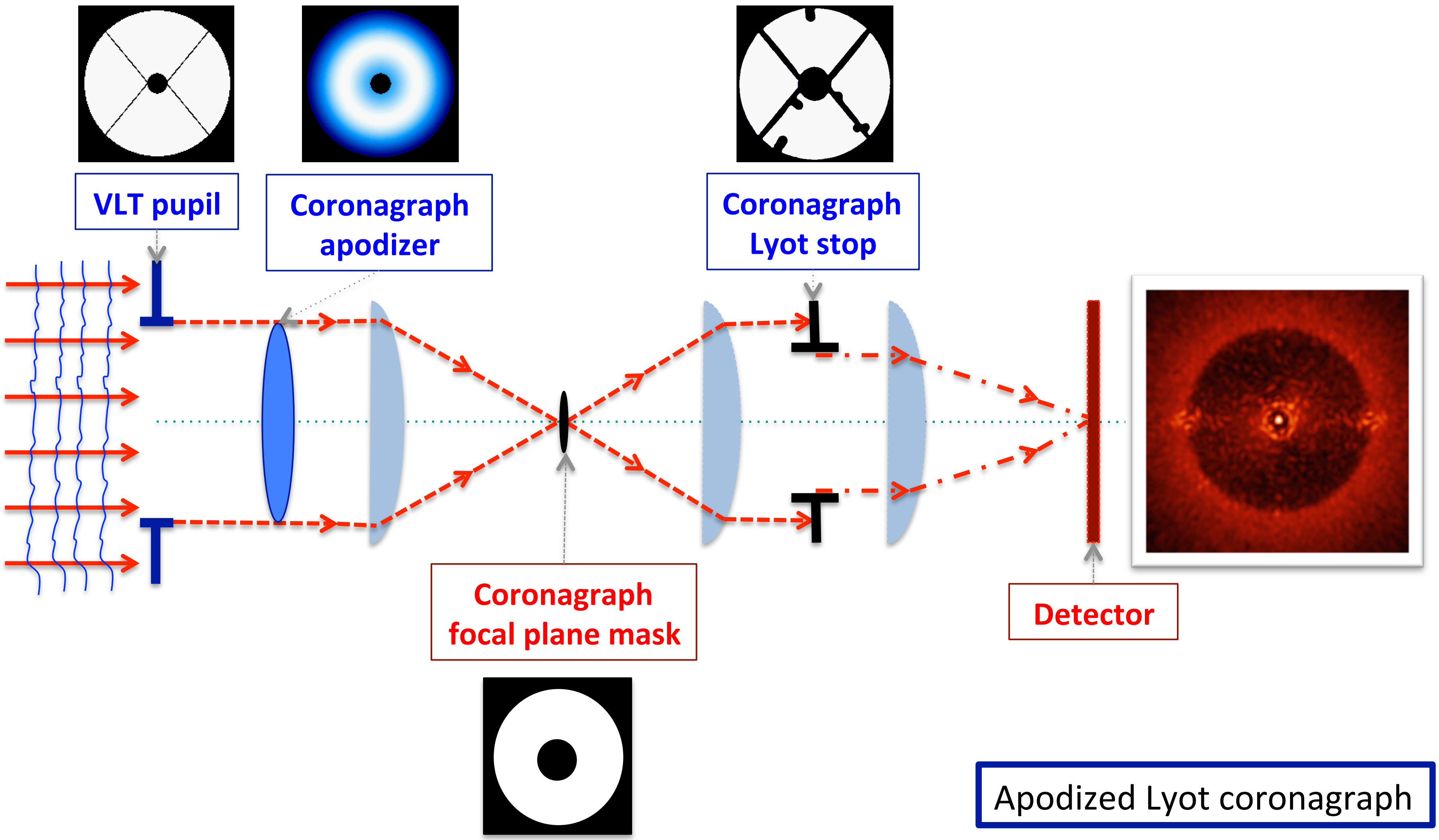


Lyot coronagraph

Coronagraphy

Get rid of the starlight,
while preserving its close environment



Apodized Lyot coronagraph

Coronagraphy

Limitations

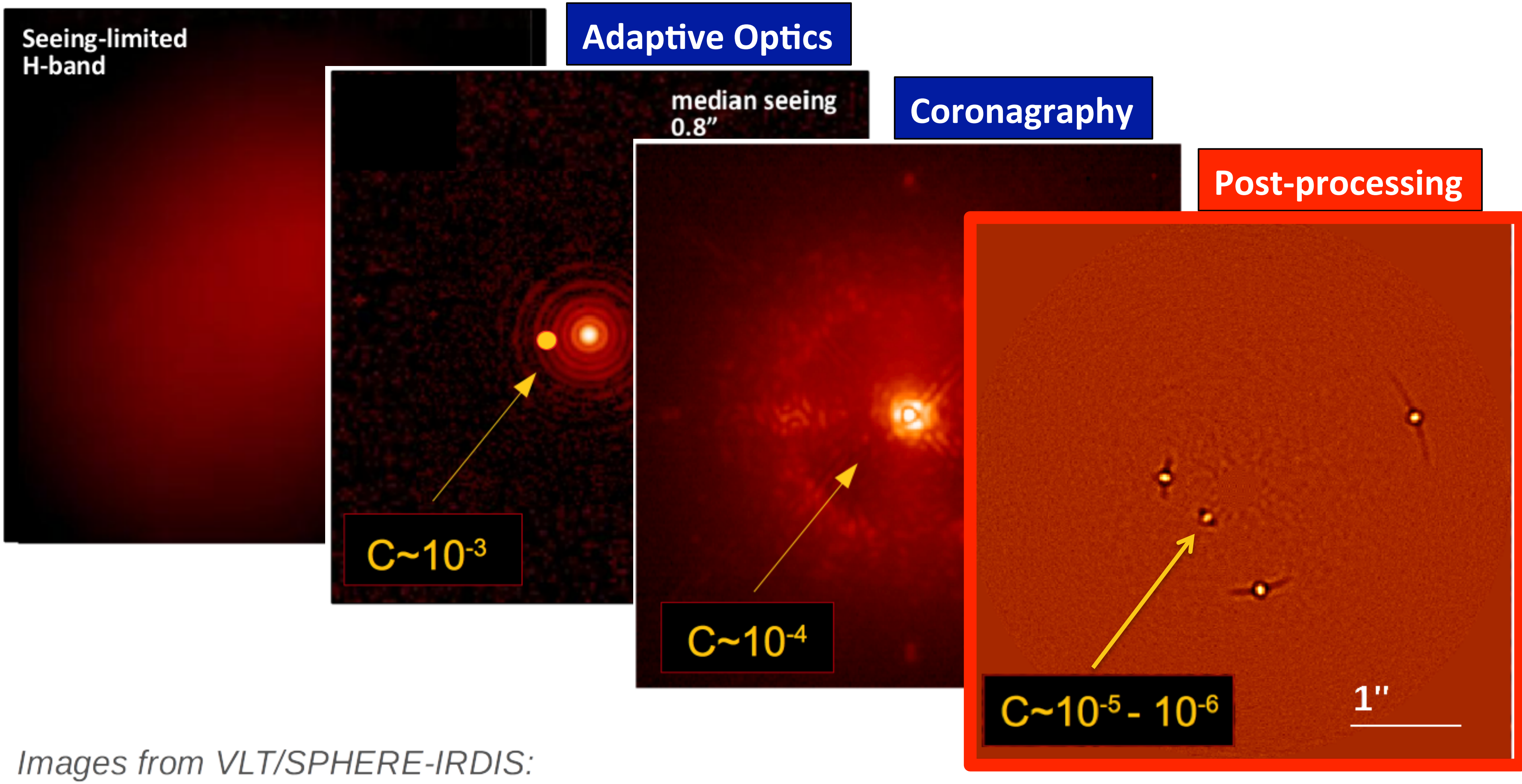
But limited:

- Sensitivity to jitter
- Spectral bandwidth
- Throughput close to the star

The coronagraph must have small inner working angle

The three pillars of high-contrast imaging

Today reaching contrast of **10^{-6}** contrast at **500 mas**, in near-infrared

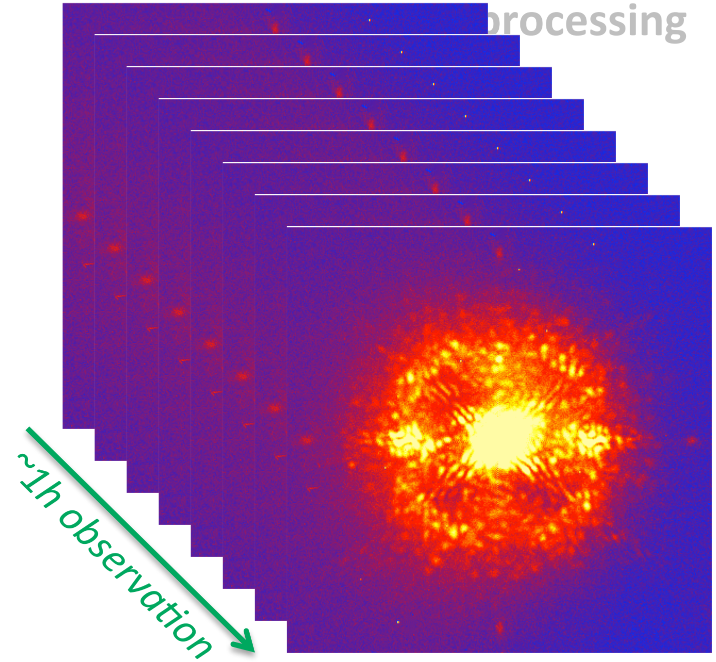


Images from VLT/SPHERE-IRDIS:
HR8799 in H-band (1.6µm)

Post-processing

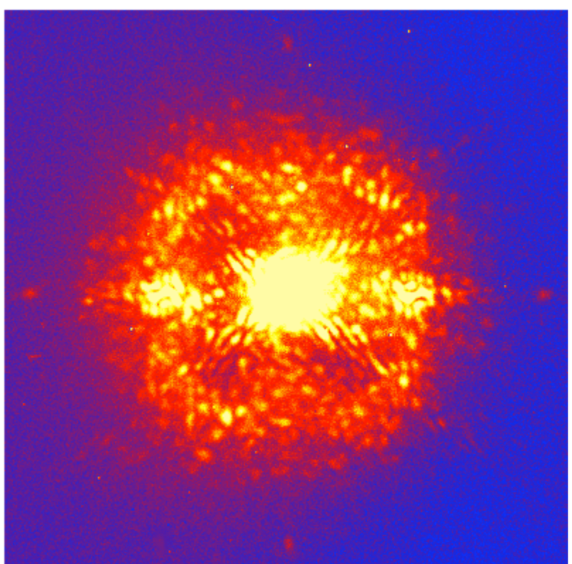
Principle

Find a **different** behavior between
the speckles and the astrophysical signals.
→ **Exploit this <u>diversity</u> to recover the signal**

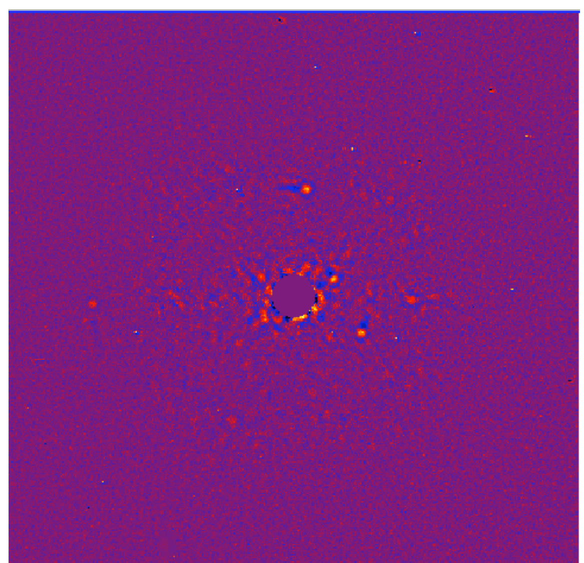


Today, all are based on **differential imaging**:

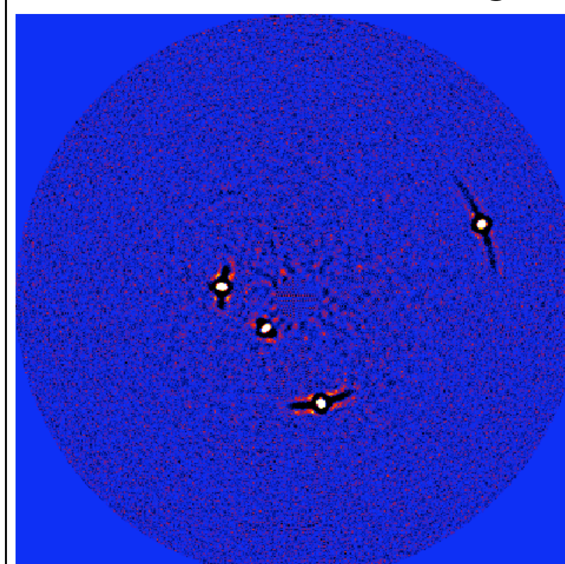
1. **Estimate** the star image



2. **Subtract** it to the image



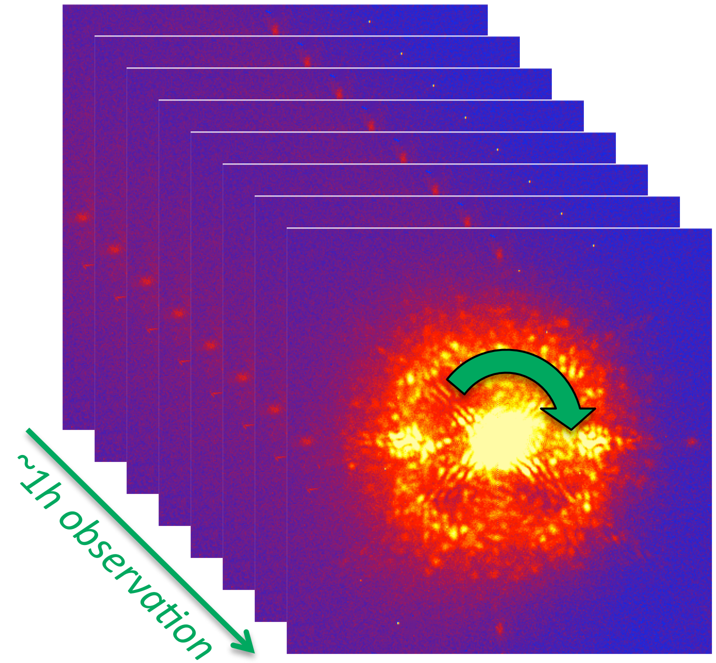
3. **Combine** all the images



Post-processing

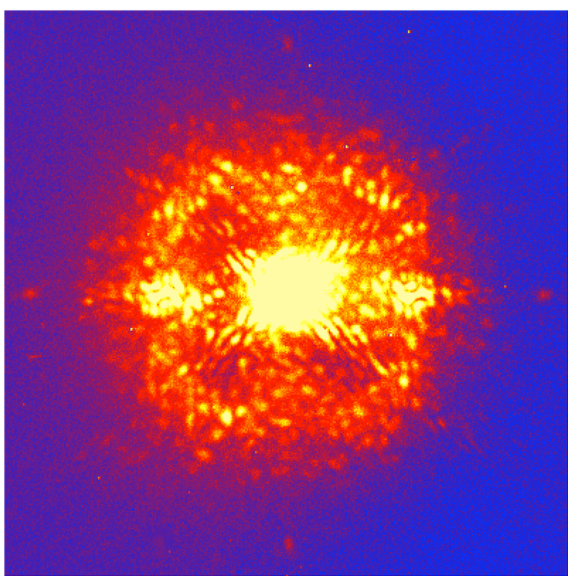
Angular differential imaging (ADI)

The speckle field is ~ stable in time
the planetary signal rotates at a deterministic speed
→ **Exploit of the <u>pupil traking mode</u>**



Temporal median (cADI)
Linear combination (LOCI)
PCA (KLIP / PynPoint)

1. **Estimate** the star image



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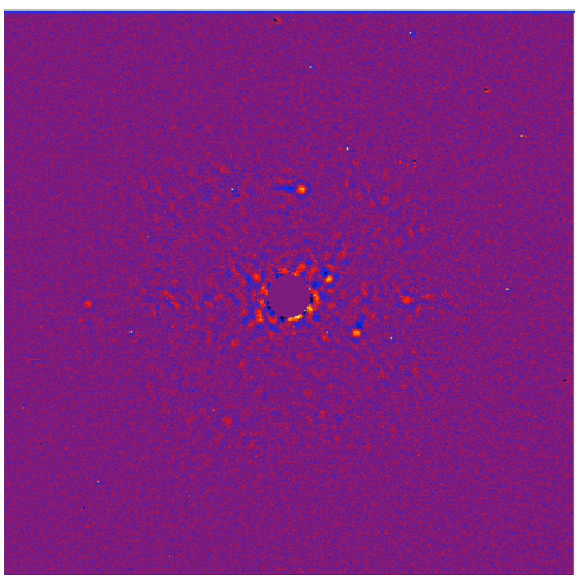

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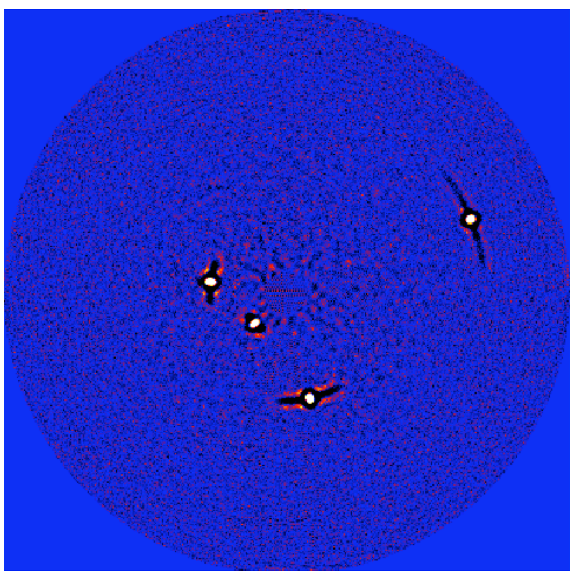


Post-processing

Three families

1: "speckle subtraction"

Differential imaging techniques alone

Visual detection
+ post-characterization

…Improvements…:
Pairet et al. 2018
Bottom et al. 2017
Bonse et al. 2019
…

2: "Match-filtering"

Use the expected pattern of the planet as a model
+ inverse problem approach

Automatic detection
+ characterization

ANDROMEDA
Cantalloube et al., 2015

FMMF
Ruffio et al., 2017

PACO
Flasseur et al., 2018

3: "Machine learning"

Use the massive sample of images
+ neural network

Only detection
Not mature yet

SODINN
Gomez-Gonzales et al., 2017

Post-processing

Limitations

But limited:

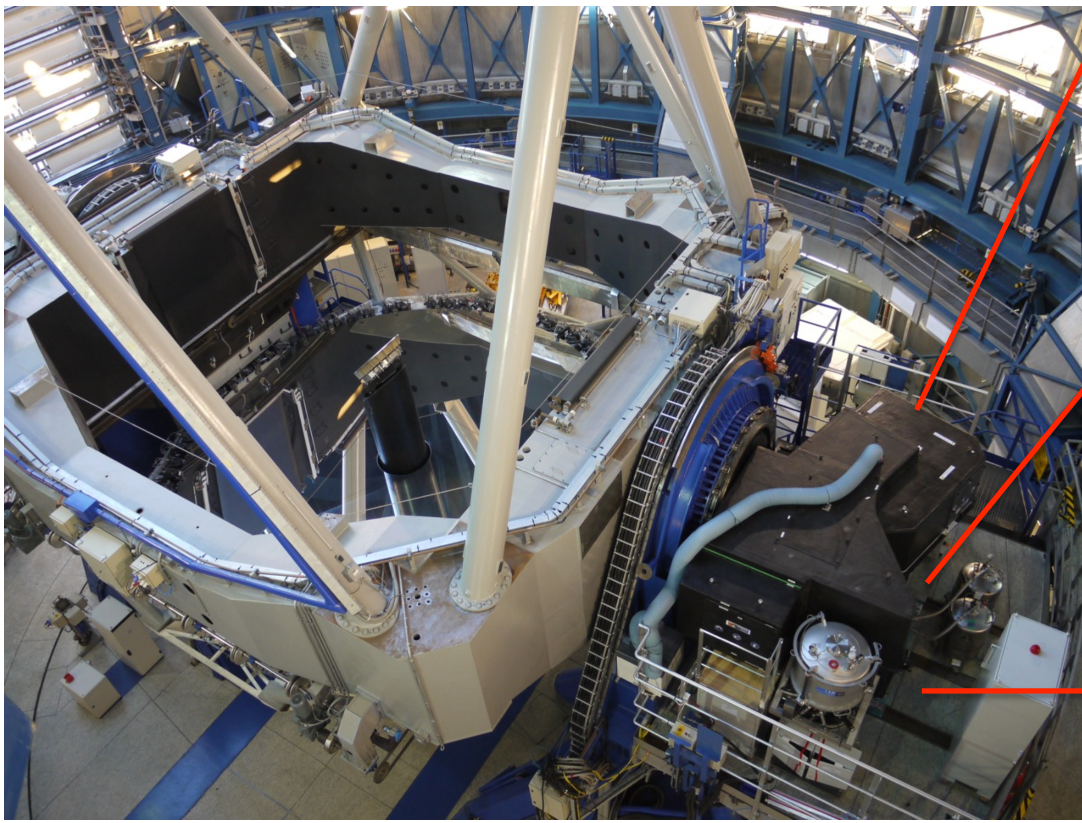
- Speckle field estimate is not perfect
- Not suited for extended features
- Not really robust to temporal errors*

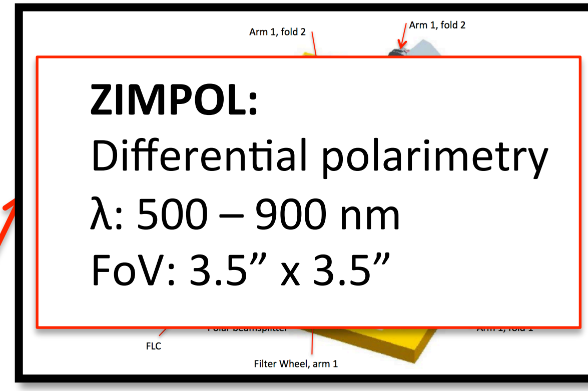
We are missing knowledge about the instrument…

The SPHERE instrument

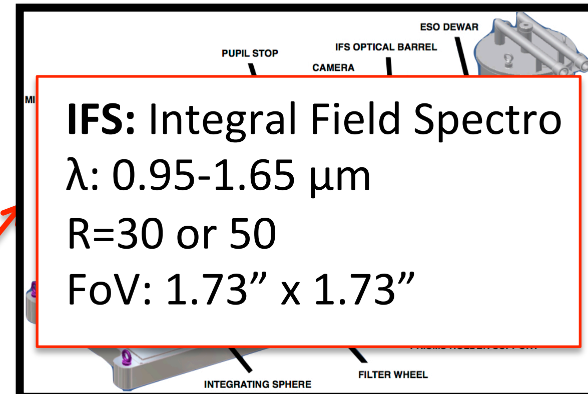
Commissioned in May 2014

- One common path instrument: AO + coronagraph
- Three subsystem instruments

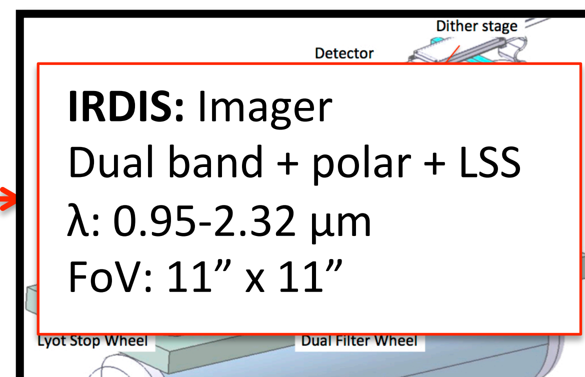




ZIMPOL:
Differential polarimetry
λ: 500 – 900 nm
FoV: 3.5” x 3.5”

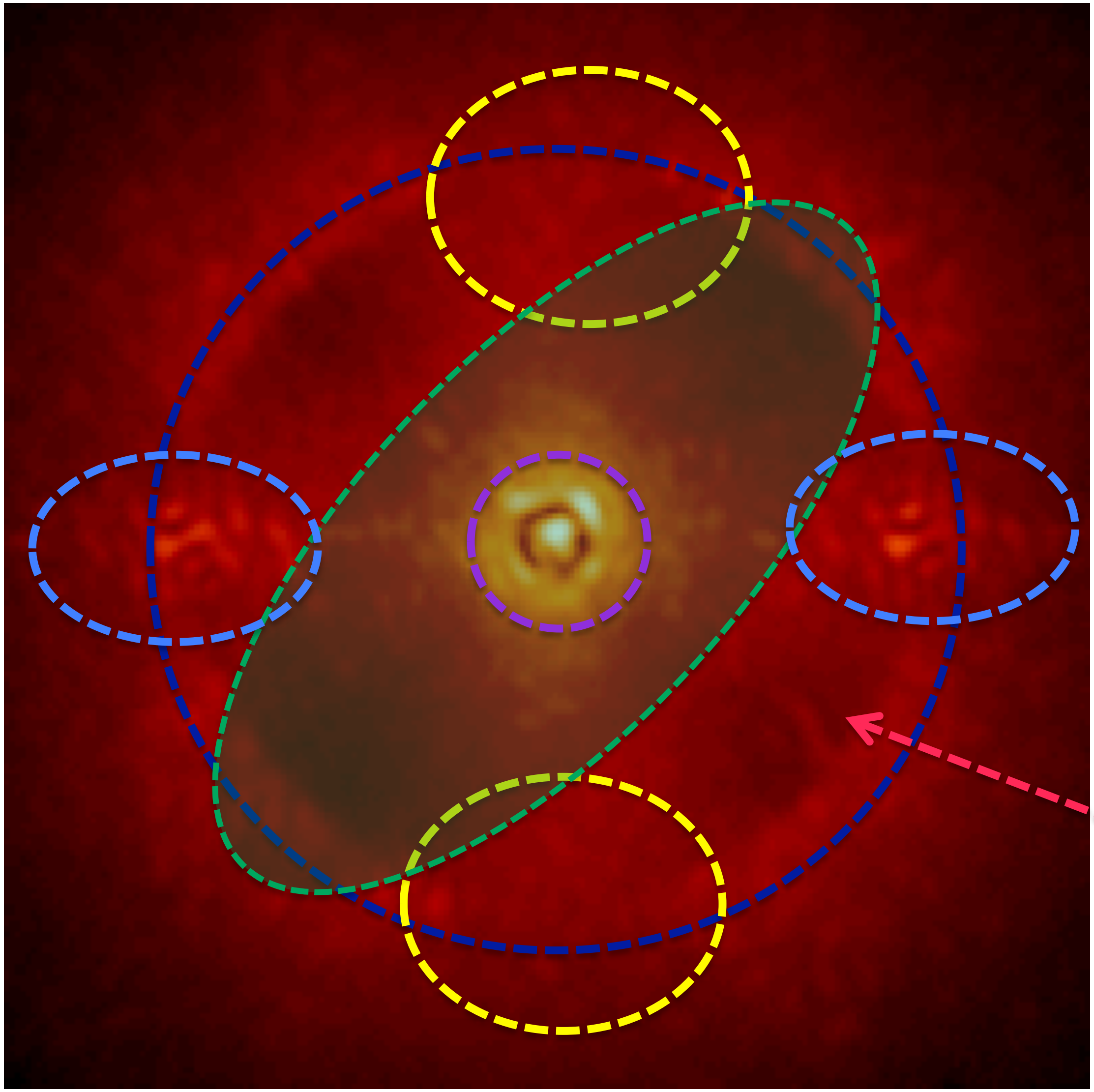


IFS: Integral Field Spectro
λ: 0.95-1.65 µm
R=30 or 50
FoV: 1.73” x 1.73”

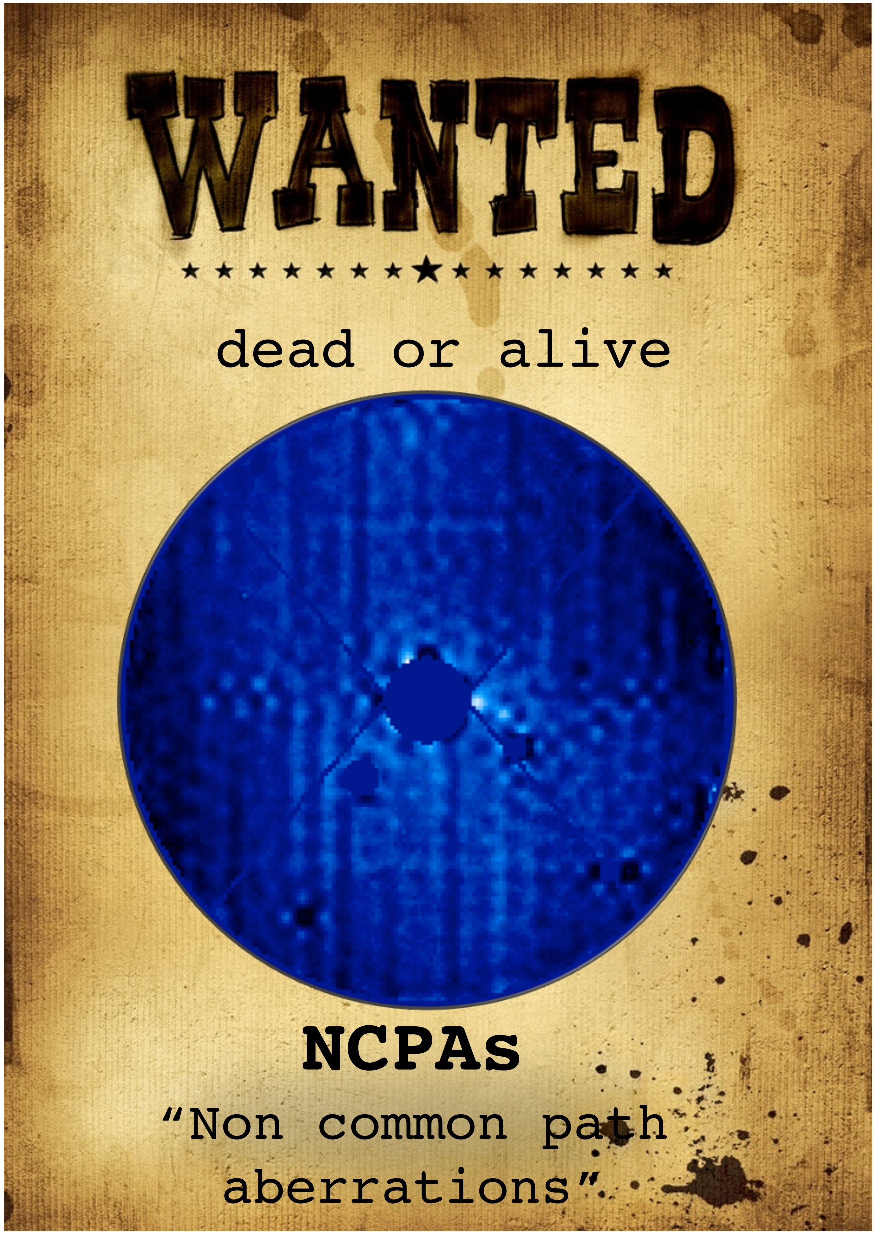


IRDIS: Imager
Dual band + polar + LSS
λ: 0.95-2.32 µm
FoV: 11” x 11”

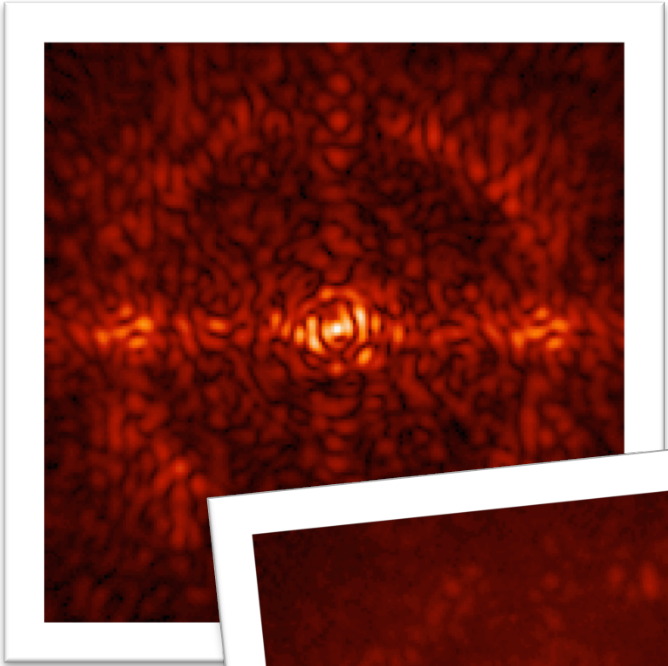
Then real life…

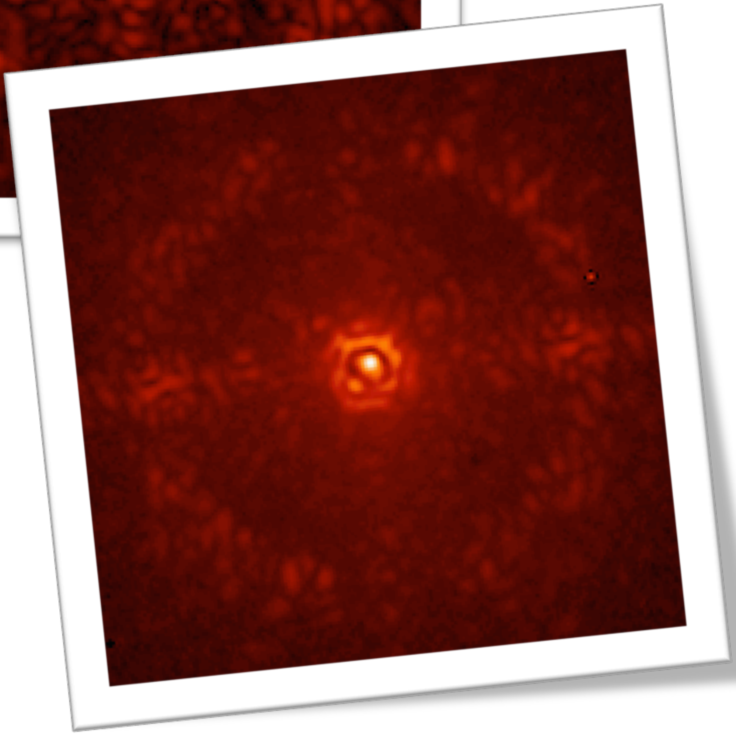


The contrast killer #1



Responsible for "**quasi-statics speckles**"





The contrast killer #1

NCPAs: Origin and solutions

Origin:

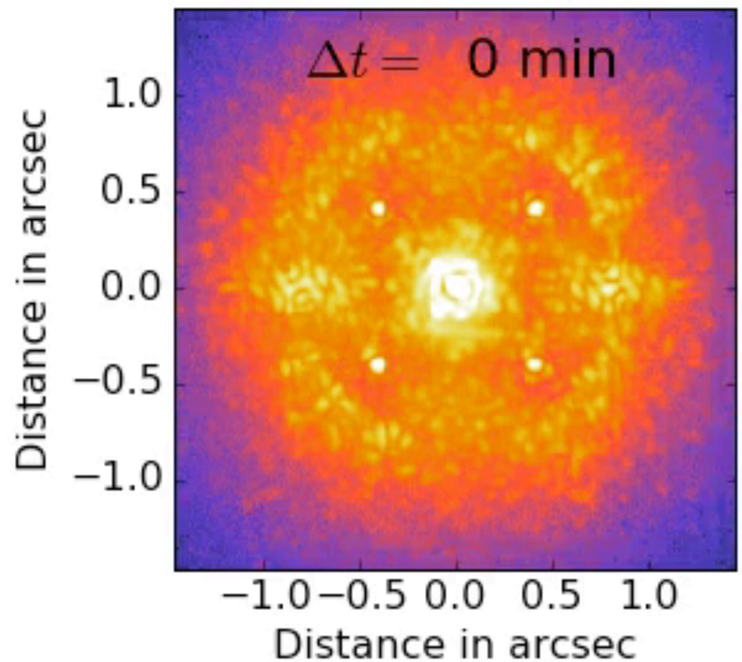
Any **optical aberration** not corrected by the AO or not in the science arm

- Internal turbulence
- Temperature changes,
- Pressure changes,
- Gravitational bent,
- …

Quasi-statics speckles are the problem:

-**Too slow:** Cannot be averaged in a halo

-**Too fast:** Cannot be calibrated



The contrast killer #1

NCPAs: Origin and solutions

Origin:

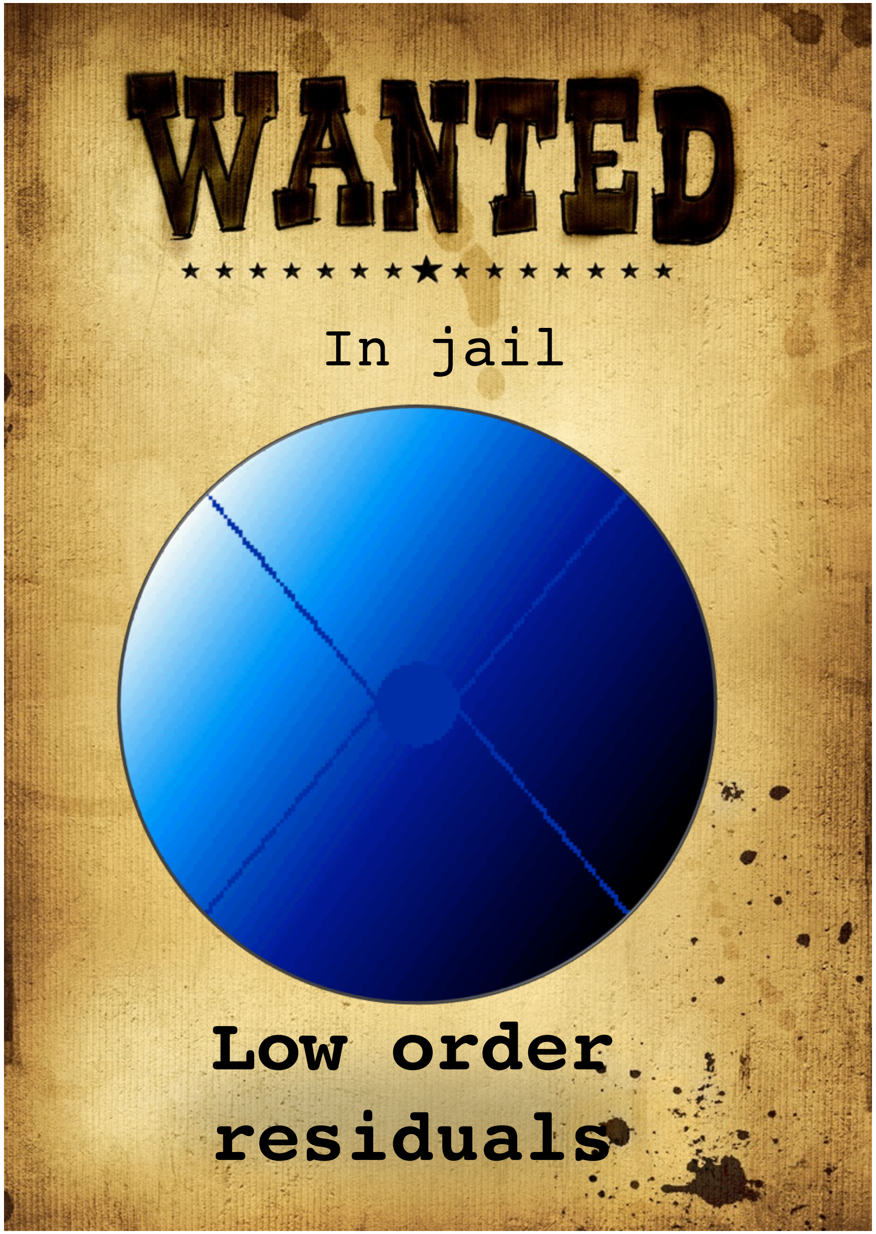
Any **optical aberration** not corrected by the AO or not in the science arm

- Internal turbulence
- Temperature changes,
- Pressure changes,
- Gravitational bent,
- …

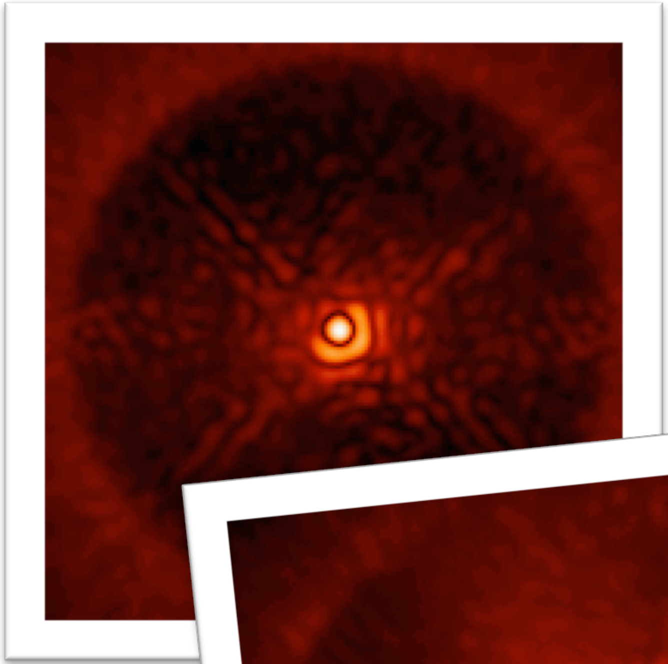
Mitigation:

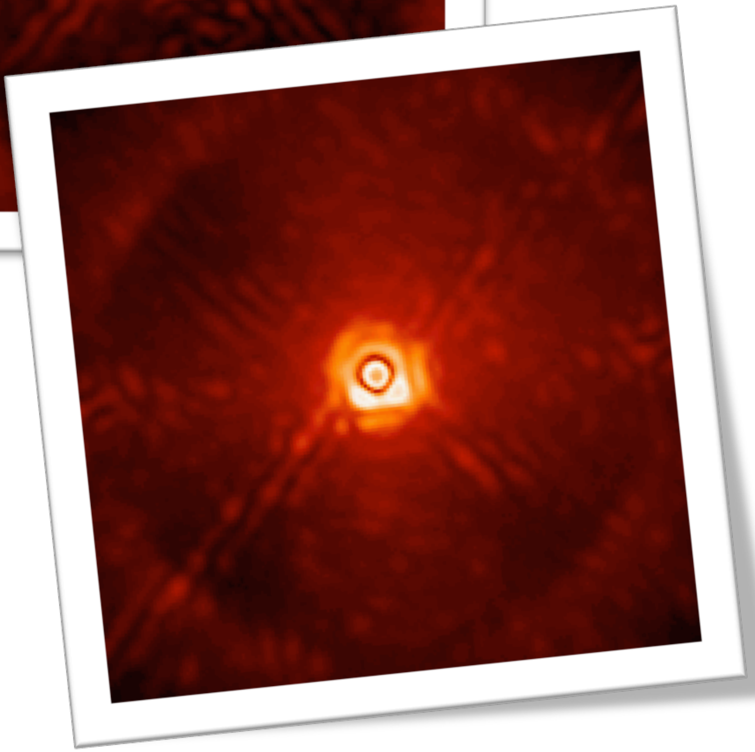
- **Off-line software solutions**: post-processing techniques
- **Hardware solutions**: ZELDA, Focal plane sensing (VVC, vAPP)
- **On-line software solution**: COFFEE, EFC, PSI…
- **Heavy hardware solutions:** SCC

The contrast killers #2



Responsible for **starlight leakage**





The contrast killer #2

LOR: Origin and solutions

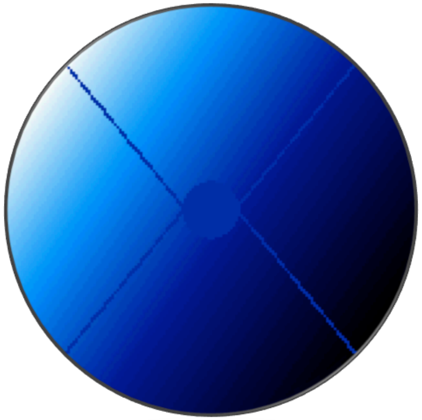
Origin:

- Atmospheric post-AO residuals: ~ 0.06 mas
- Vibrations: ~ 100 mas
- Atmospheric dispersion residuals: ~ 0.16 mas
- Differential thermal/mechanical effect: ~ 0.20 mas

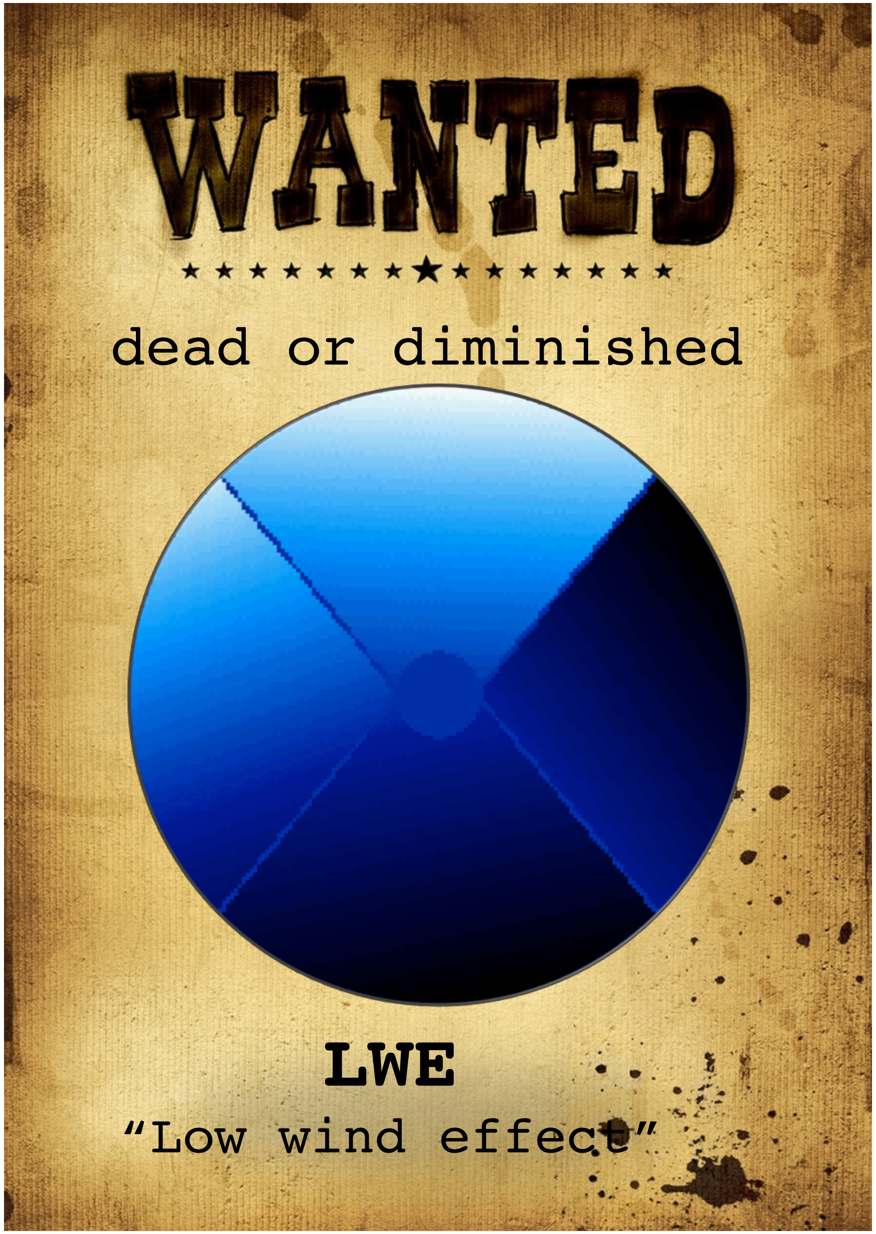
Mitigation:

- **Coronagraphic device**: pupil plane coronagraph
- **On-line solution**: using the waffle mode
- Control solution: differential tip-tilt sensor (DTTS) - goal < 0.2mas

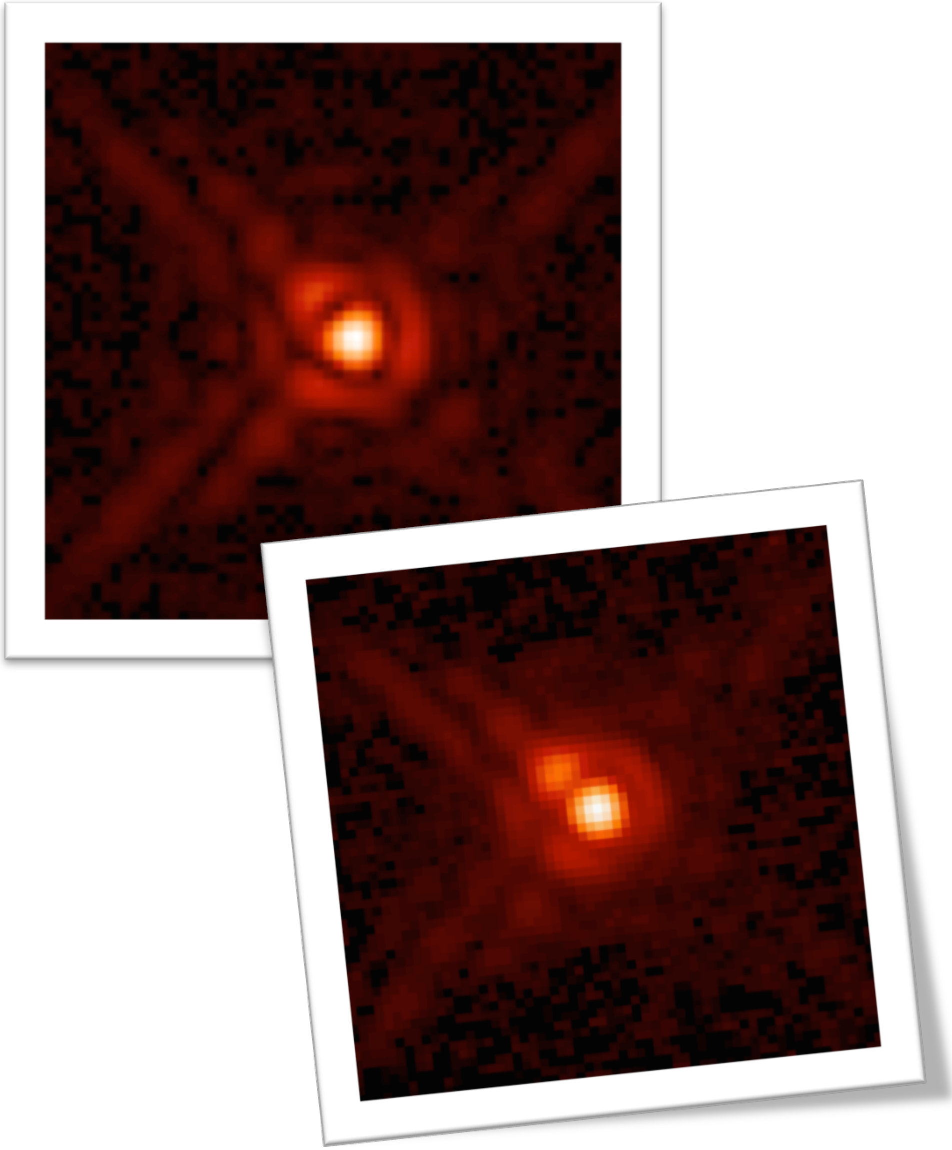
Baudoz et al., 2018



The contrast killers #3



Responsible for “**Mickey Mouse effect**”



The contrast killer #3

LWE: Origin and solutions

Origin:

The spider legs are **colder** than the ambiant air;
Around each fragment it creates layer of air of **different** refraction index;
It provokes **a differential piston-tip-tilt** in each fragment.

Mitigation:

- **Software solutions**: but instrument-dependent
- **Active solutions** (spiders heating, ventilation): too invasive
- **Passive solution**: low emissivity coating

The contrast killer #3

LWE: Origin and solutions and results

<u>Origin:</u>
The spider legs are **colder** than the ambiant air;
Around each fragment it creates layer of air of **different** refraction index;
It provokes **a differential piston-tip-tilt** in each fragment.

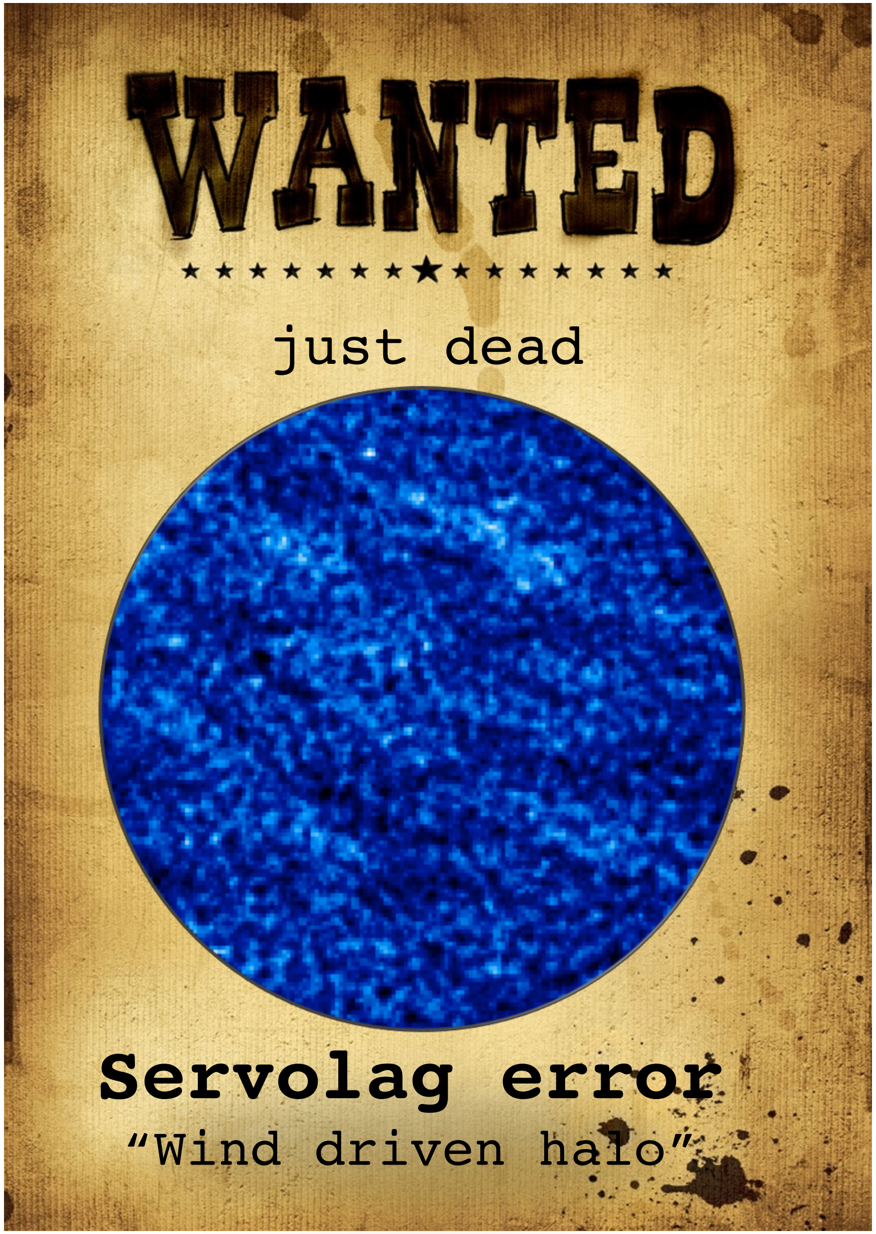
<u>Mitigation:</u>

- **Software solutions**
- **Active solution**
- **Passive solution !**

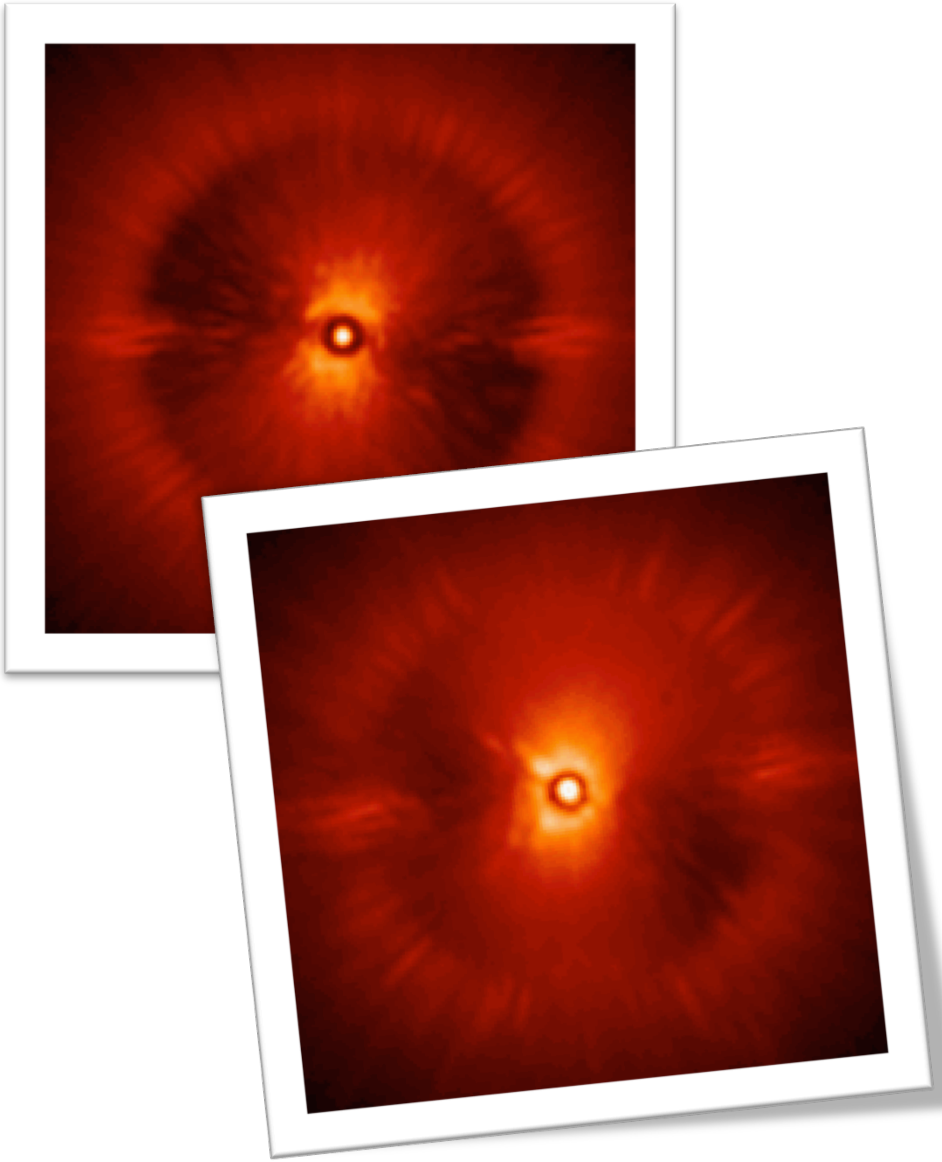
On VLT/UT4 (SPHERE):
Occurrence from 18% to 3% !

Milli et al., 2018

The contrast killers #4



Responsible for the **“Wind driven halo”**



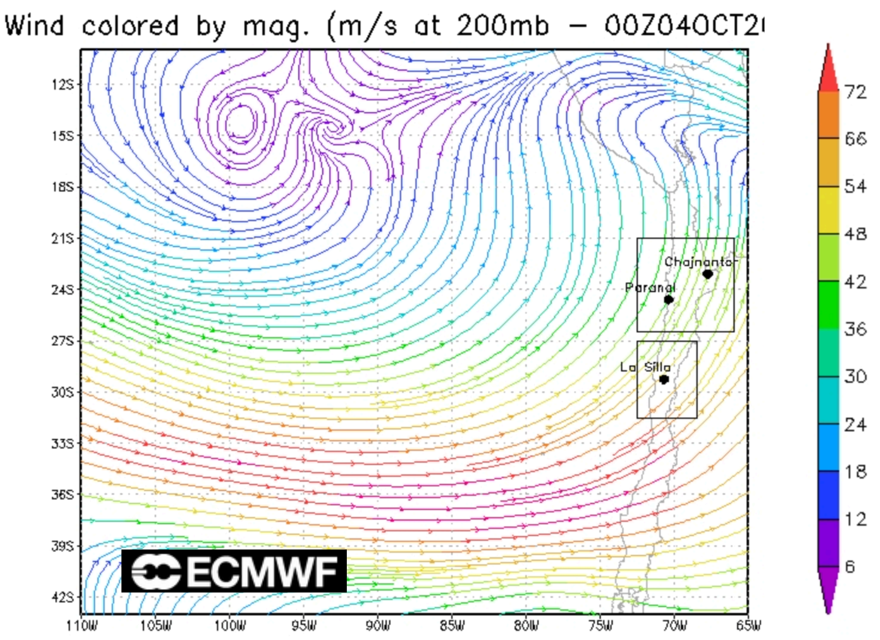
The contrast killer #4

WDH: Origin and solutions

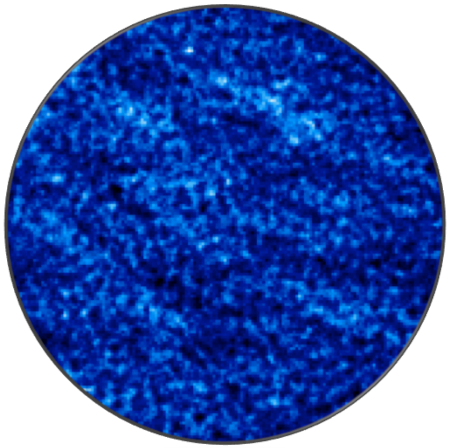
Origin:

AO-servolag (temporal bandwidth errror) **vs** turbulence speed

The **jetstream** layer (12km, 20 to 50m/s!) is responsible for it



jetstream wind forecast



The contrast killer #4

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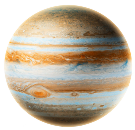
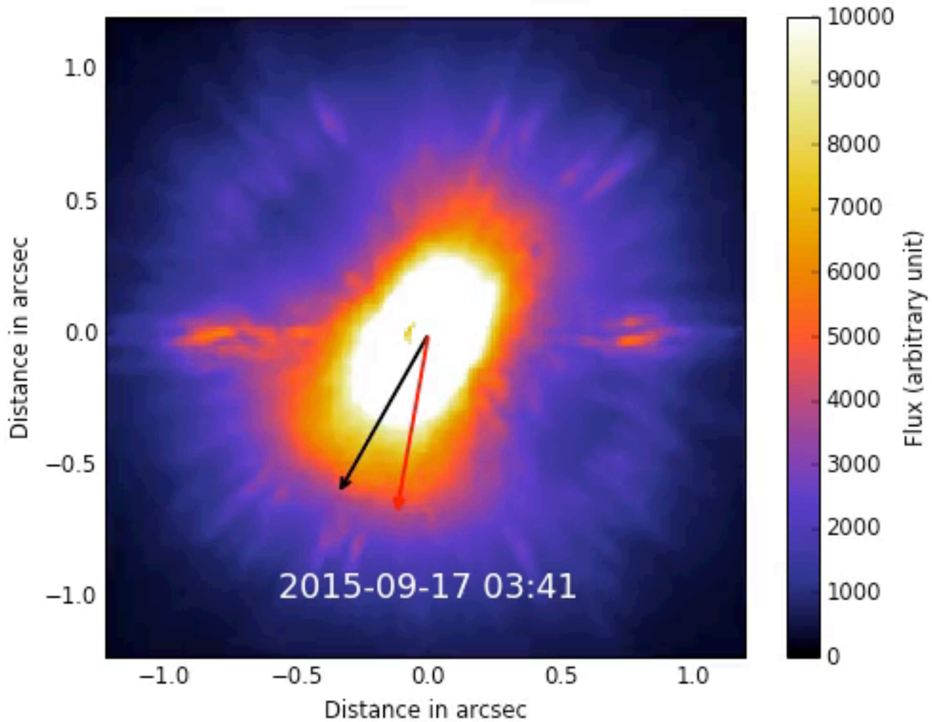
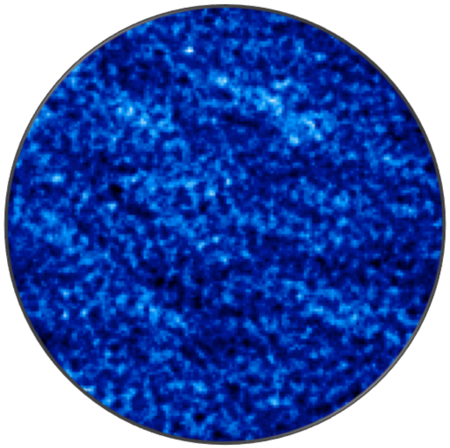




Movie from SHARDDS (SPHERE-IRDIS − Broadband H):

Red arrow: ground layer

Black arrow: jet stream layer



The contrast killer #4

WDH: Origin and solutions

<u>Origin:</u>

AO-servolag (temporal bandwidth errror) **vs** turbulence speed
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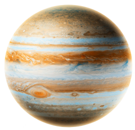
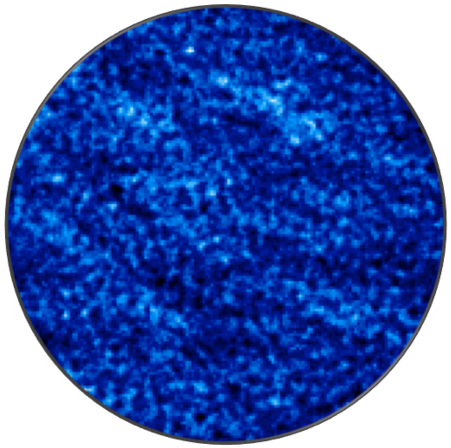


<u>Mitigation:</u>

- **Faster AO**
- **Predictive control for the AO**
- **Post-processing: on-going work !**



What's next

Upgrade of SPHERE ?

Faster, closer, deeper, fainter

Proposed new hardware:

AO:
- New DM with less dead actuators
- Faster DM + loop + detector
- More sensitive WFS
- Predictive control

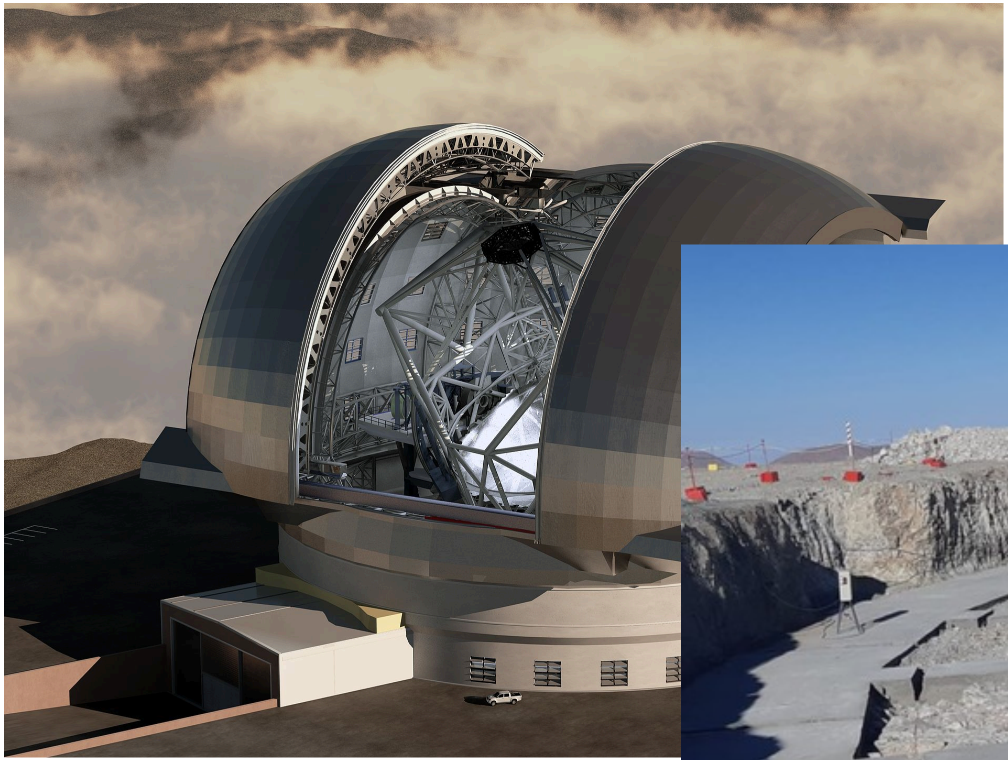
Coronagraph:
- Transparent focal plane mask
- Pupil plane
- Active NCPAs control

Subsystems:
- High spectral resolution
- Coupling with other instruments (CRIRES+, ESPRESSO)
- Lucky imaging techniques

On-going action for ESO proposition

What's next

ELT instrumentation



As of December 2018

What's next

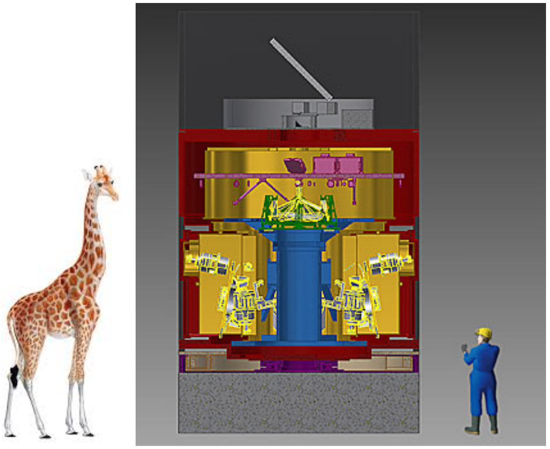
ELT instrumentation

Three instruments foreseen for first light in 2030:

→ They all have a high contrast mode !

METIS

Mid-infrared
E-ELT Imager and
Spectrograph

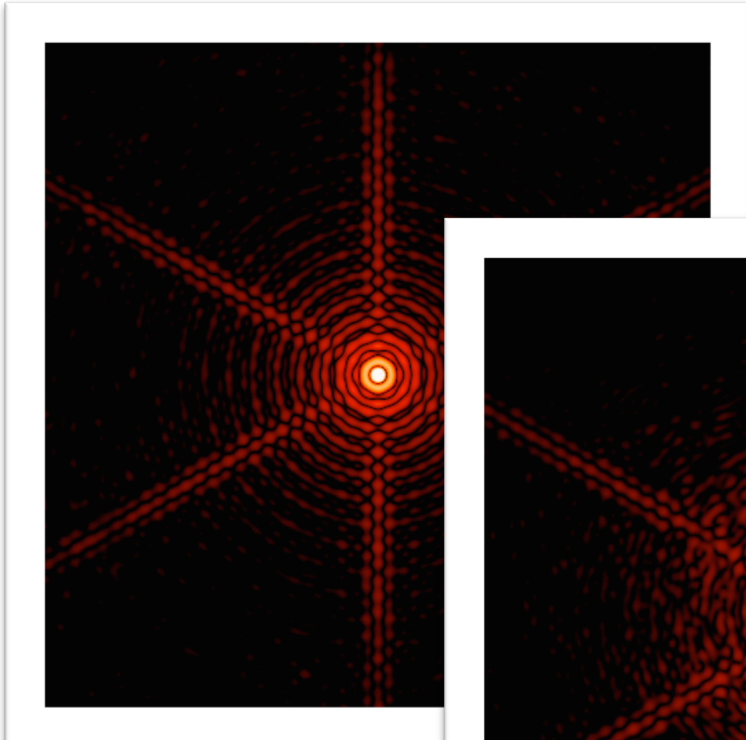


HARMONI

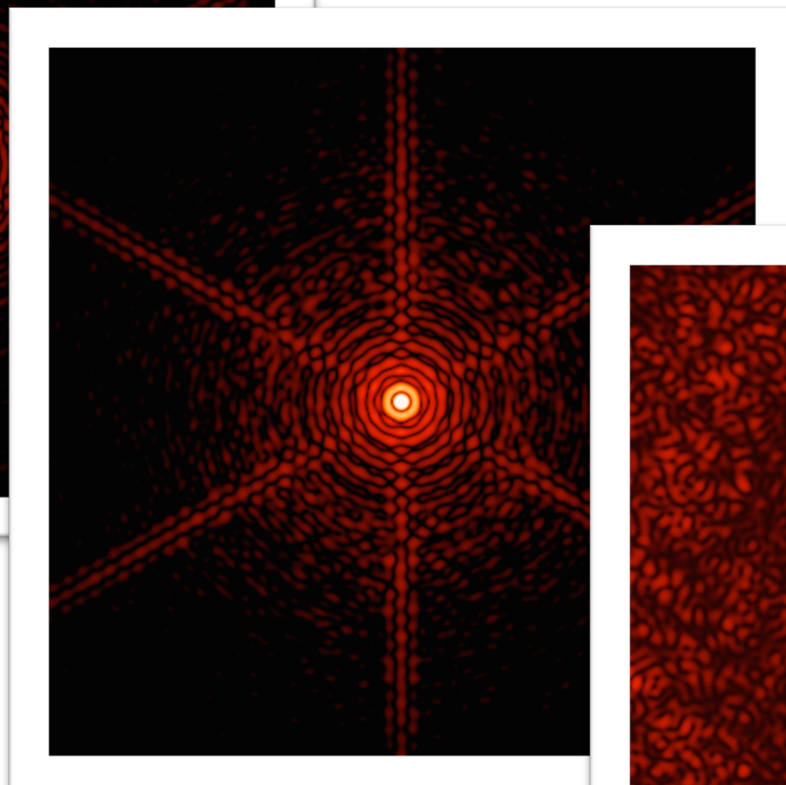
MICADO

What about ELT instruments …

METIS end-to-end simulations

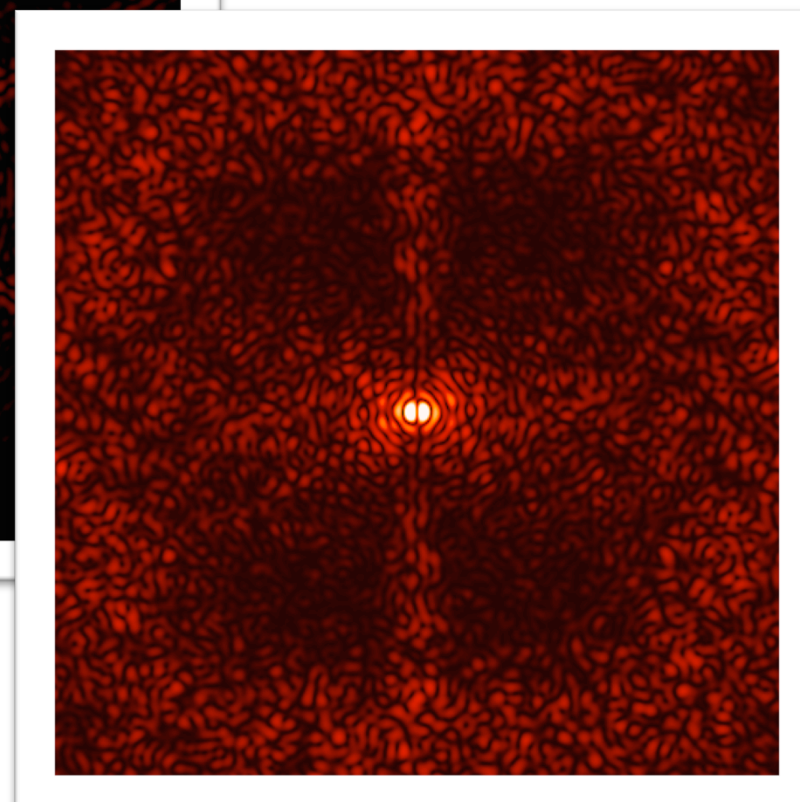


Diffraction only



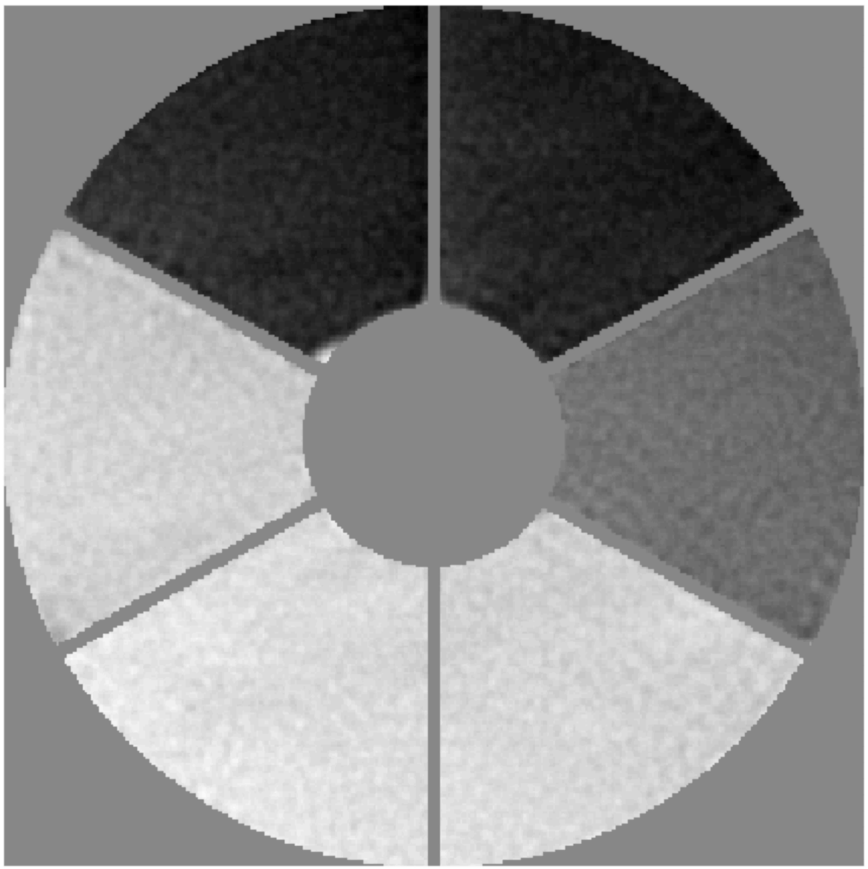
Diffraction + AO residuals

Coronagraphic image…



What about ELT instruments …

The infamous "**Island effect**" due to pupil fragmentation:
This is a different origin from low wind effect or atmospheric piston !
But same effect on the PSF…



METIS end-to-end simulations

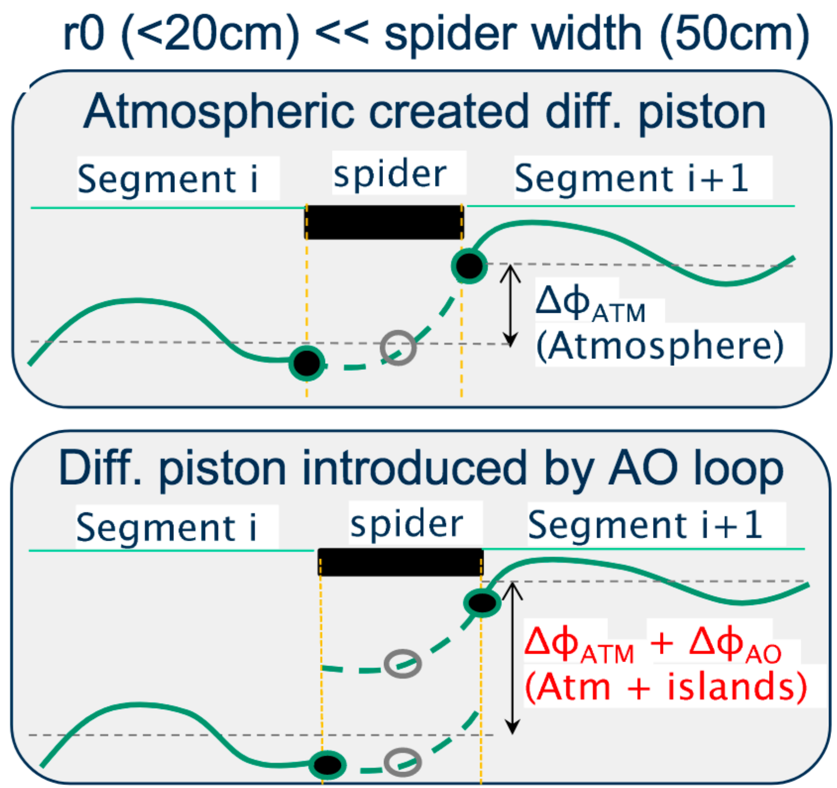


Illustration N. Schwarz (UK-ATC)

What about ELT instruments …

… Still a lot of work …

High-contrast imaging is a very specific regim
Understanding instruments such as SPHERE is key for ELT design

Conclusions:

Imaging exoplanets …

- bring precious info
- require specific instrumentation
- require specific post-processing techniques
- makes us discover things we ignored
- is definitely fun !

Thank you !