Post-processing for high contrast imaging

Example of inverse problem approaches: ANDROMEDA and MEDUSAE

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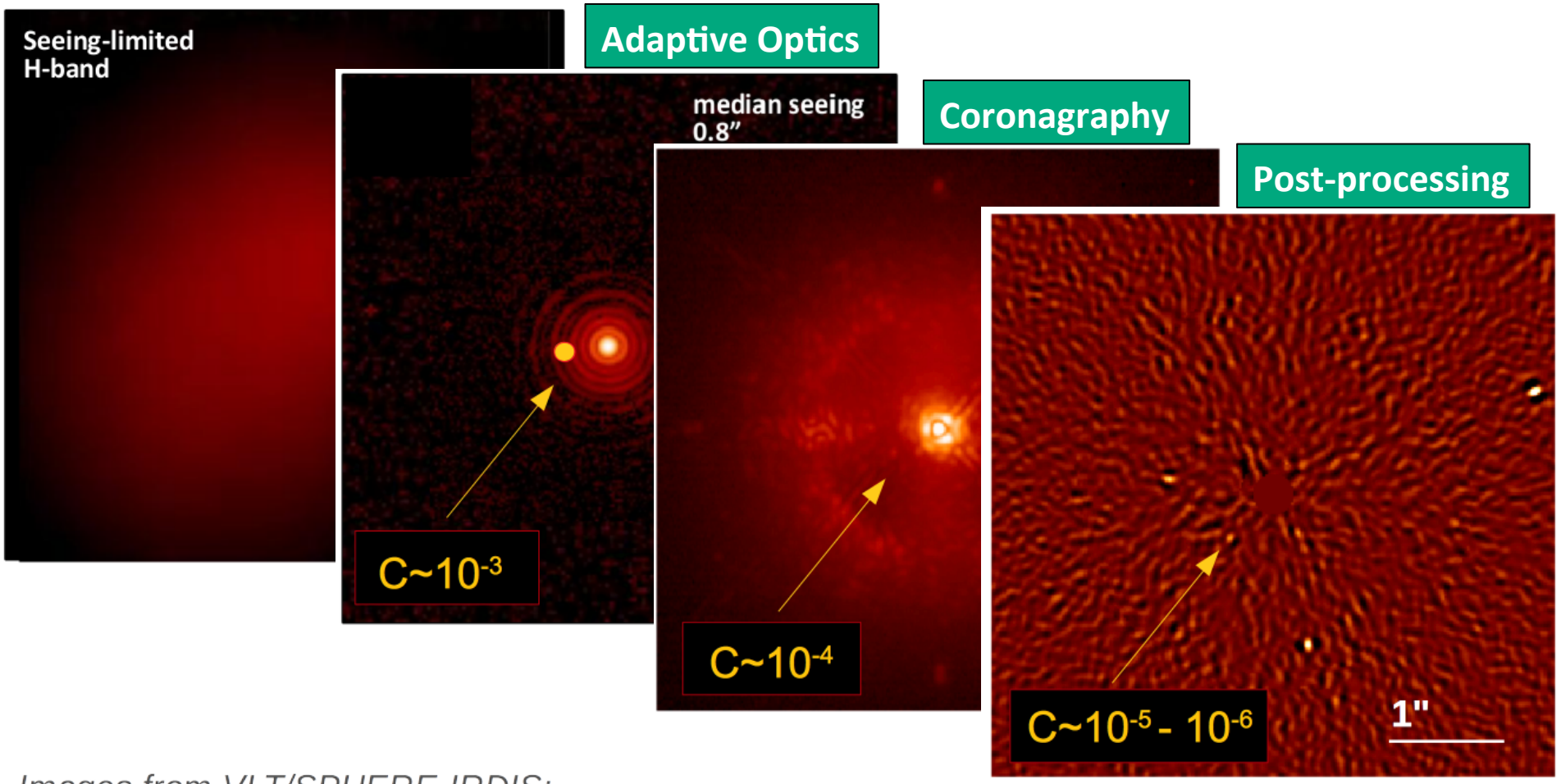
W. Brandner (MPIA)

High contrast imaging

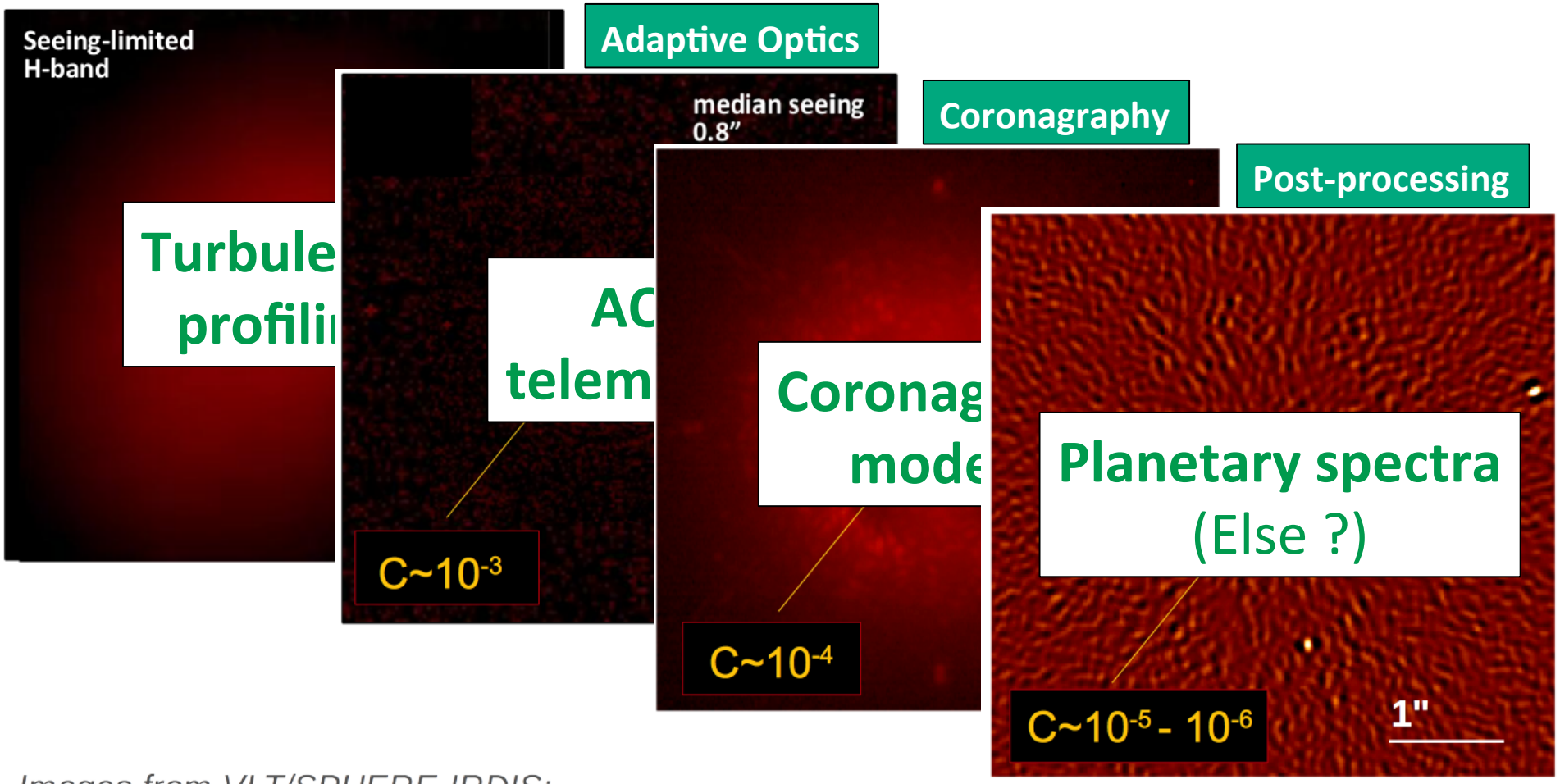
The three ingredients for high-contrast imaging (HCI)
Today reaching contrast of **10^{-6}** contrast at **500 mas**, in infrared



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

Motivations

What information we can use…



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

Outline

Most algorithms widely used today are aiming at **subtracting** the speckle floor
To do so, they only rely on the focal plane images: **no external knowledge** is used

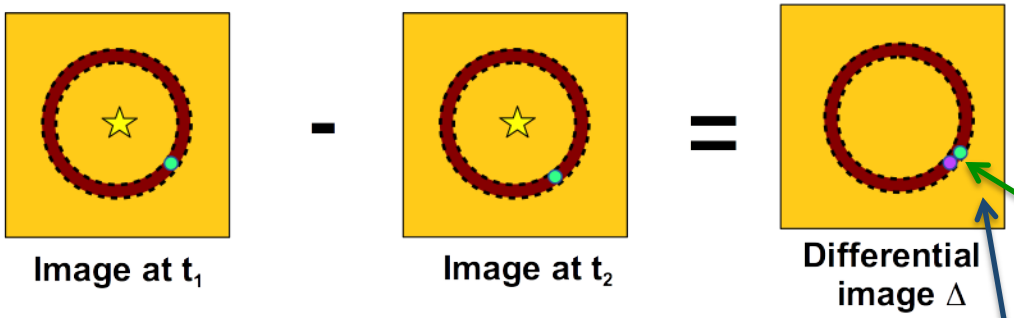
-> How to get further information from the images ?

1- ANDROMEDA

2- MEDUSAE

ANDROMEDA

ADI-based algorithm



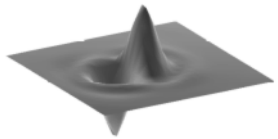
One couple k
chosen by annuli:
→ smallest time interval (t_1-t_2)
→ sufficient signal distance (θ_1-θ_2)

1st step: ADI

→ "Whitens" the speckle noise
→ Specific planet signature

Hypothesis:
Residual noise ***n***
White, **gaussian** and **non-homogeneous**

Model:
Planet signature ***p***
Subtraction of 2 **PSFs**



Unknowns :
- **Initial planet position, r_0**
- **Planet flux, *a***

$$L(r_0,a)\propto\exp\left\{-\frac{1}{2}\frac{\sum_k\sum_r|\Delta(r,k)-a\,p(r,k,r_0)|^2}{\sigma_n^2(r,k)}\right\}$$

2nd step: Maximum Likelihood

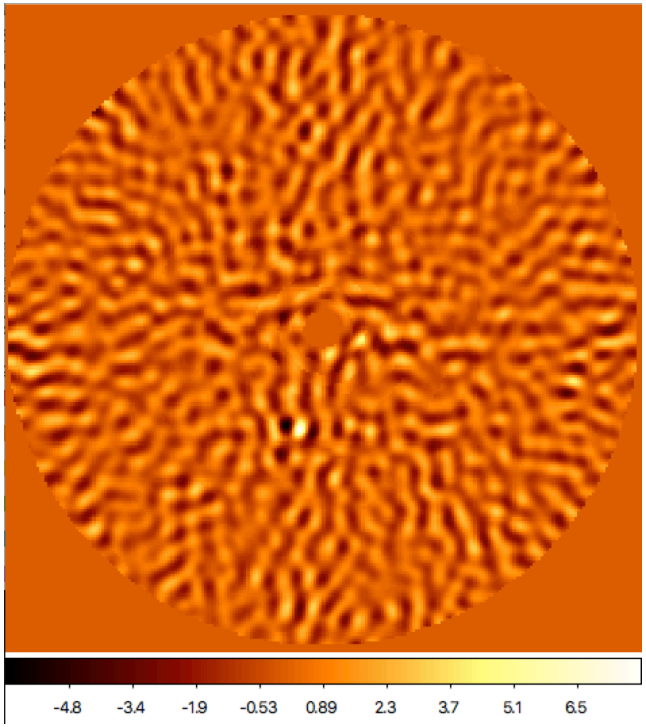
→ Estimation of the flux
→ Provides a detection map

Cantalloube et al. 2015

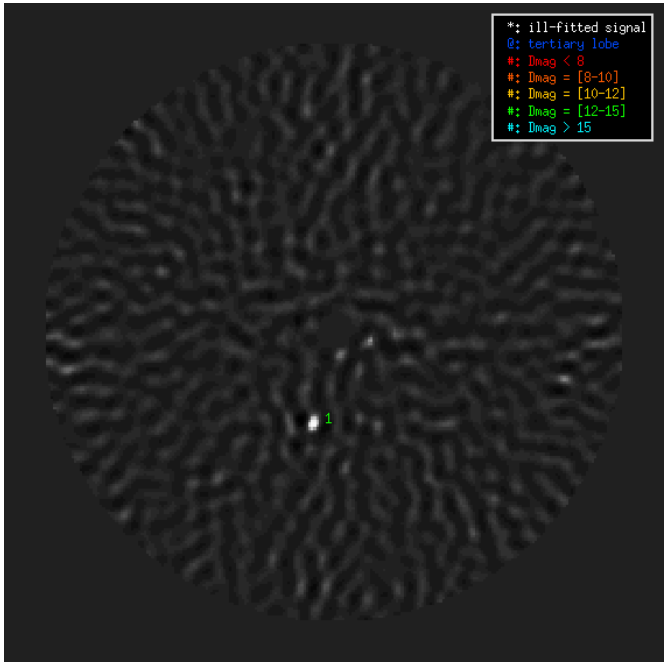
ANDROMEDA

Results (VLT-SPHERE data of 51 Eri)

IRDIS SNR map
Narrow-band K1



Detection map
From ANDROMEDA



This is the **only** signal above 5 sigma !

-> SNR_{51Eri} = 8 sigma

Tested and approved on many HCI instruments (NaCo, SPHERE, NICI, GPI, Keck, LBT…)

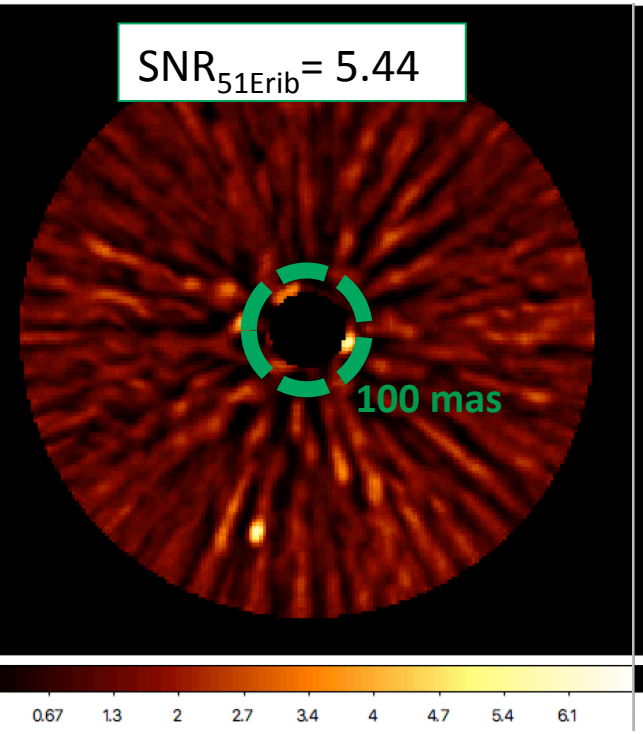
Package_v3.0 available !!!
(IDL), do not hesitate to ask me !

Cantalloube et al. 2015

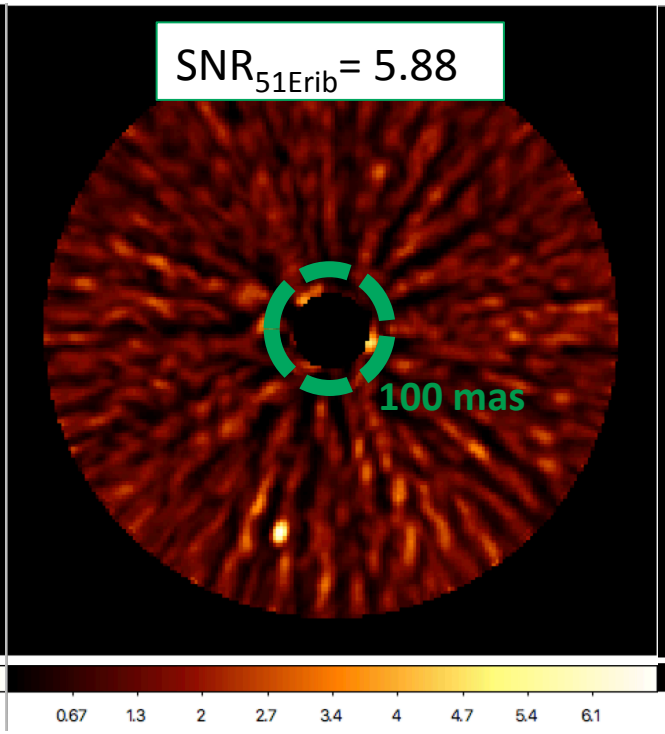
ANDROMEDA

Results (VLT-SPHERE data of 51 Eri)

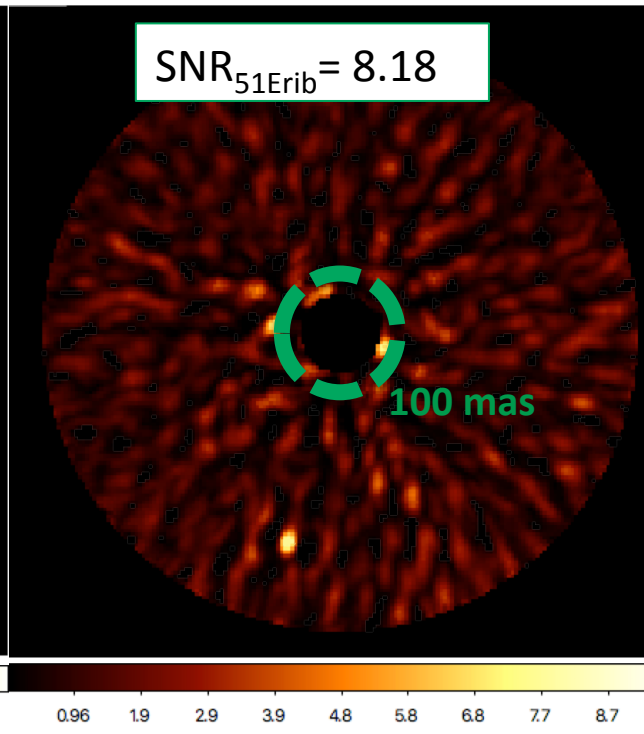
IFS detection map
With **uniform** template



IFS detection map
With **T-dwarf** template



IFS detection map
With its **own** spectrum



Tested and approved on many HCI instruments
(NaCo, SPHERE, NICI, GPI, Keck, LBT…)

Package_v3.0 available !!!
(IDL), do not hesitate to ask me !

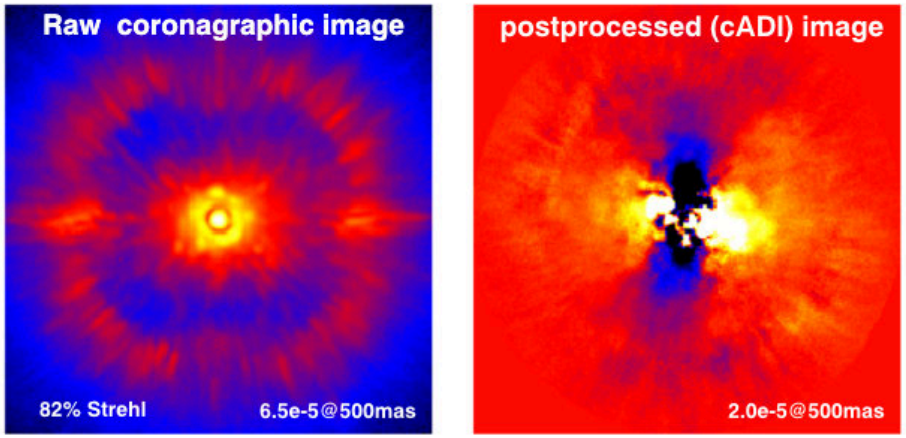
ANDROMEDA

Limitations: The noise is regarded as white and Gaussian …

1- Low spatial frequencies, slowly varying (e.g. due to AO residuals)

→ Ok with high-pass Fourier filtering !

→ Might need to carefully assess the wind driven halo



2- Residuals after the 1st step, are not fully white and Gaussian

→ Empirical correction from what we expect

→ Change the 1st step to a more efficient subtraction

→ Change the maximum-likelihood for the "real" noise distribution

Master thesis
M. Quesnel at MPIA

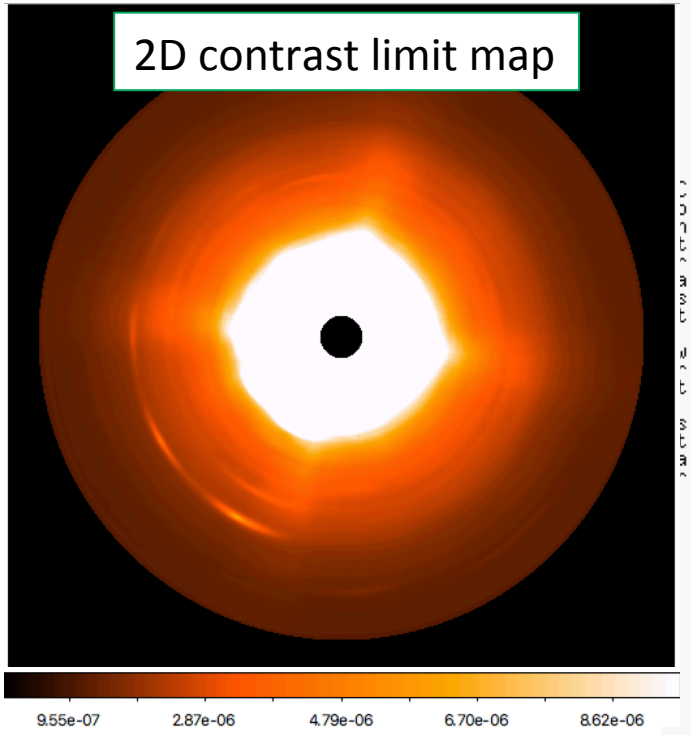
(Pairet et al. in prep)

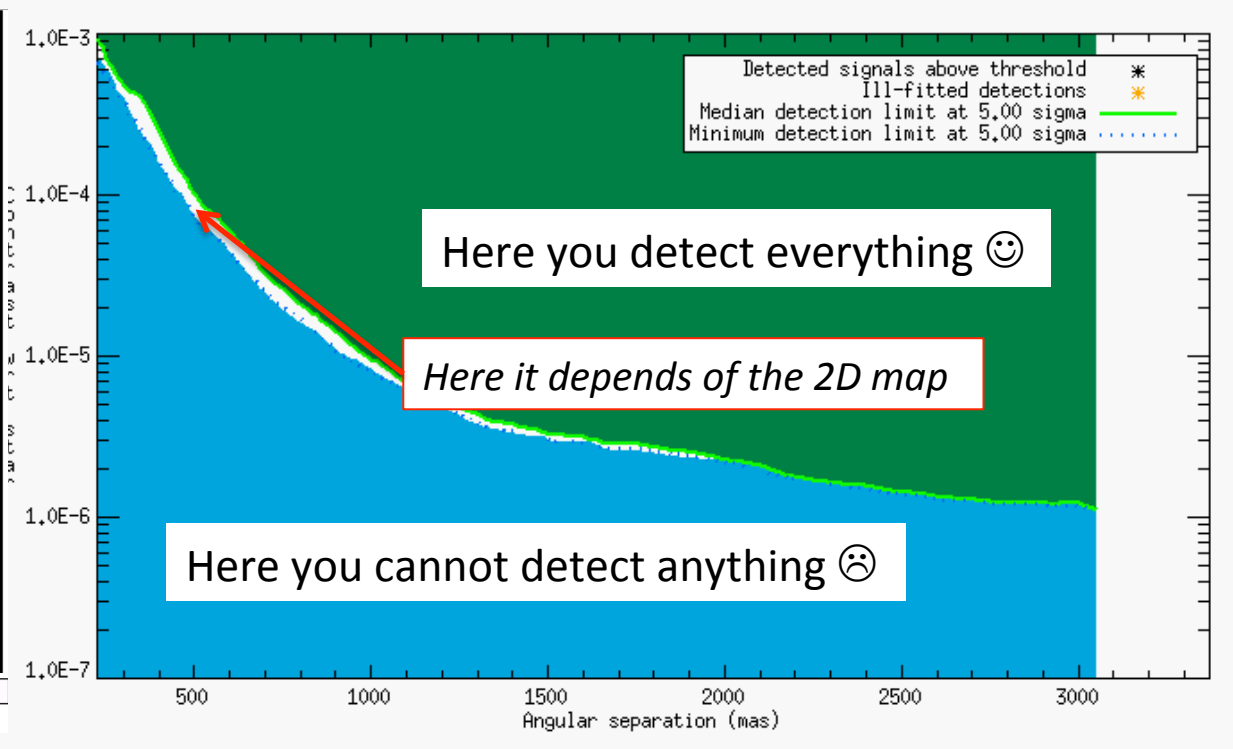
ANDROMEDA

The detection limits – contrast curves

$$SNR = \frac{\hat{a}(r_0)}{\sigma(\hat{a}(r_0))}$$

H_0: The 1-sigma contrast limit at that position
H_1: The 1-sigma uncertainty on the contrast estimation

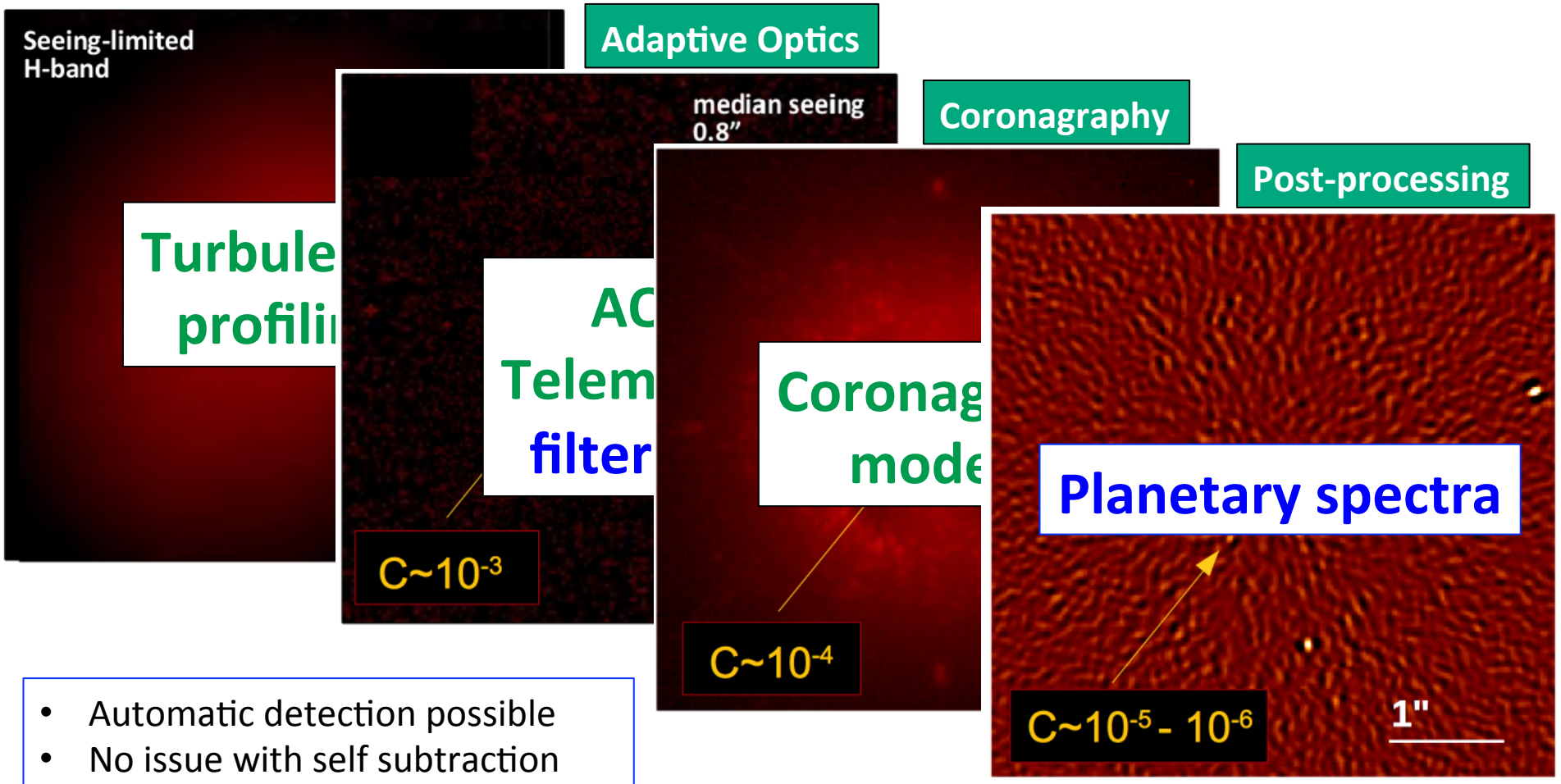




Note: it **doesn't** sort FPF and TPF but it is a **by-product** of the method, linked with PFA !
On top of that, sorting of the detected signals on morphological and flux criteria

Motivations

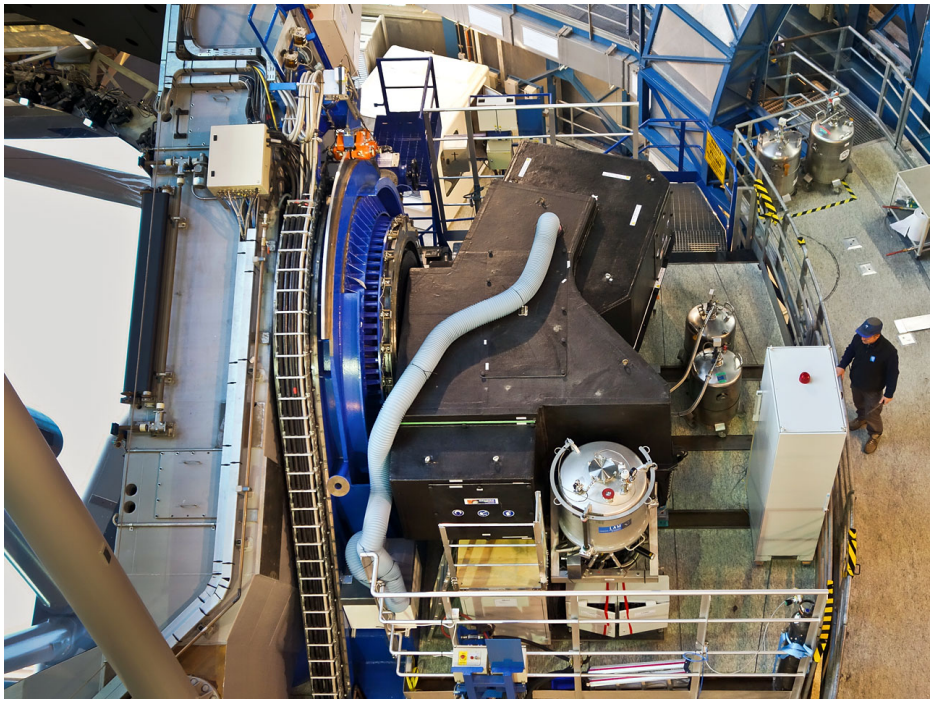
What information ~~we can use…~~ we used for ANDROMEDA



- Automatic detection possible
- No issue with self subtraction
- Contrast curves are a by-product

And it runs fast !

… How to use more information from the instrument up to the image formation…

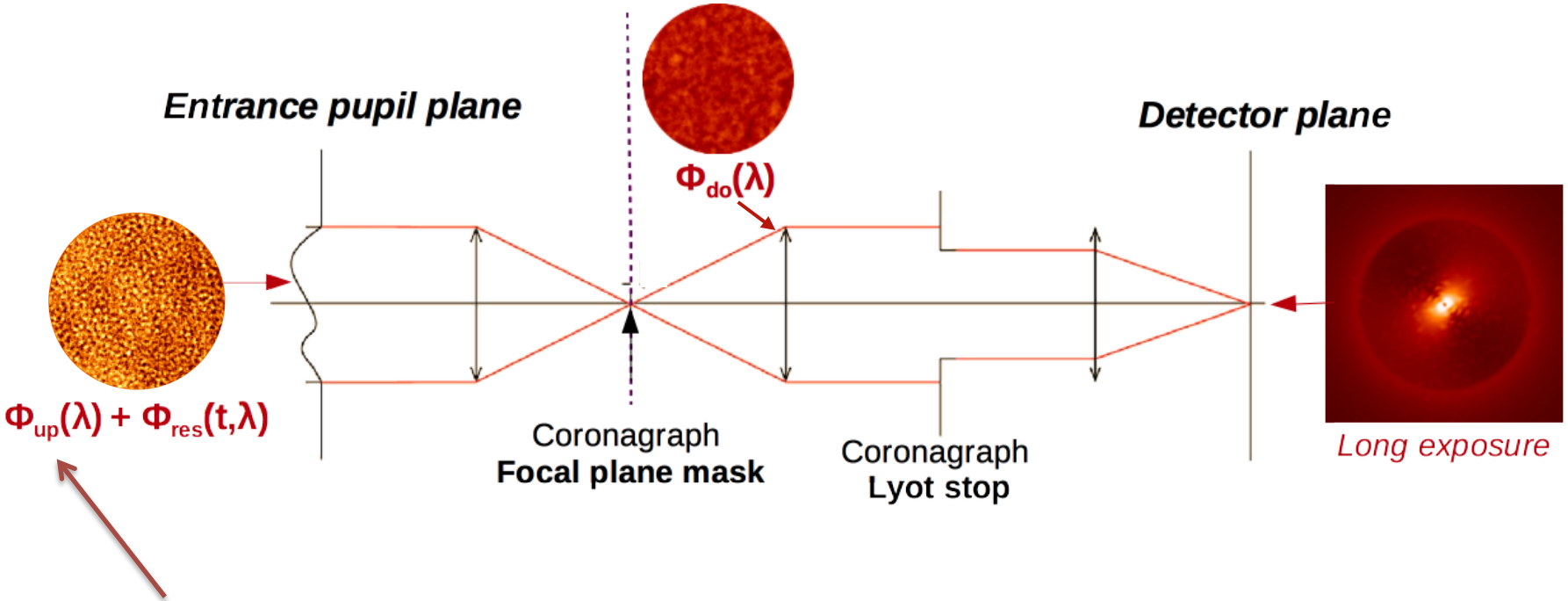


VLT/SPHERE (Beuzit/ESO)

MEDUSAE

Using a model of the high-contrast imager !

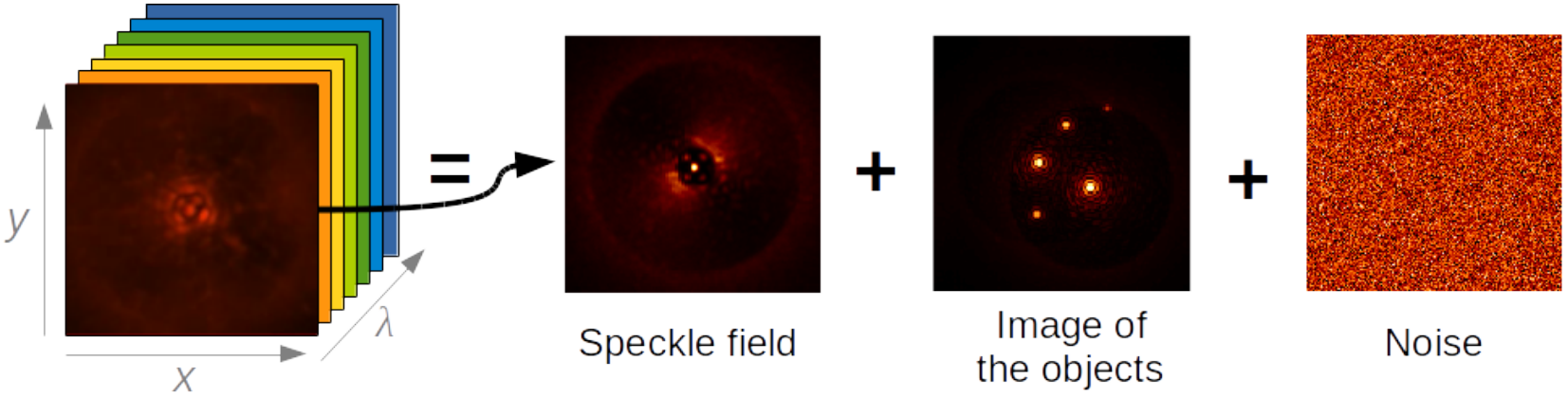
Most image processing today rely on an **empirical** estimation of the PSF reference
MEDUSAE relies on **theoretical** knowledge about the instrument



Only δ_{up} and the star flux are estimated from the data

MEDUSAE

Using spectral diversity to estimate the quasi-statics aberrations



$$J\left(\delta_{up}, o, f^{star}\right) = \sum_{\lambda}\sum_{\alpha} \frac{1}{2\sigma^2_{\lambda,\alpha}} \left| i_{\lambda,\alpha} - m_{\lambda,\alpha}\left(\delta_{up}, o, f^{star}\right)\right|^2 + R_{object}(o) + R_{f^{star}}\left(f^{star}\right)$$

Image model

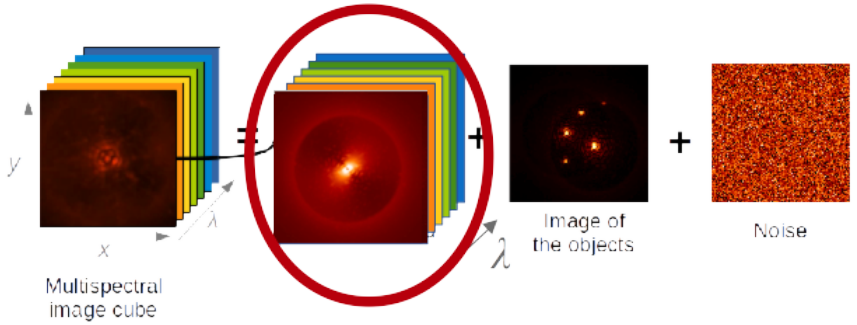
Bayesian framework

Iterative procedure until J reaches a minimum

$$m_{\lambda,\alpha} = f^{star} \times h^{c}\left(\delta_{up}\right) + o \times h^{nc}\left(\delta_{up}\right)$$

MEDUSAE

Speckle field estimation



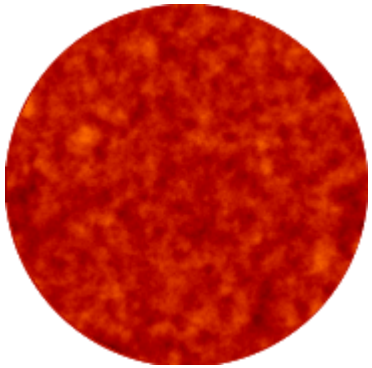
Focal plane

AO residual phase structure function

$\mathbf{D}_{\varphi\text{-}res}$

To be estimated…

Pupil plane

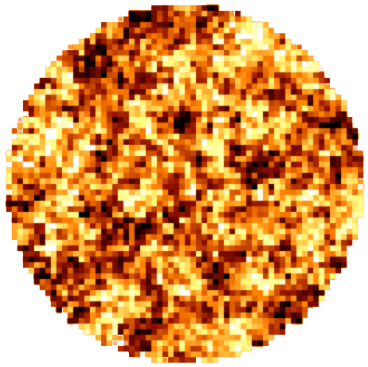


Downstream (after corona) Optical path difference

$\boldsymbol{\delta}_{do}$

To be measured…

Pupil plane



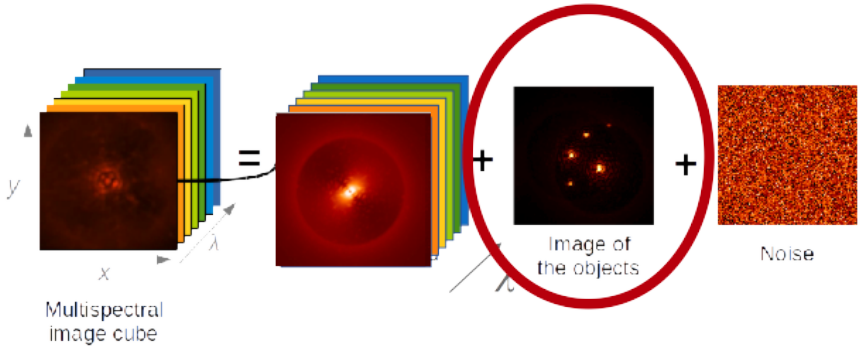
Upstream (before corona) Optical path difference

$\boldsymbol{\delta}_{up}$

MEDUSAE's business

MEDUSAE

Object map estimation



Object deconvolution:

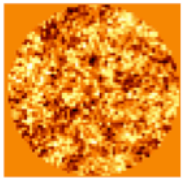
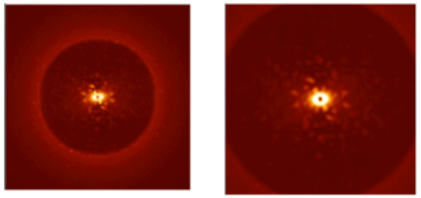
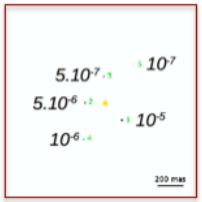
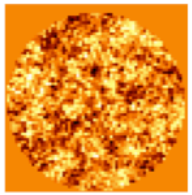
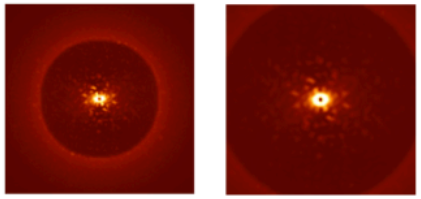
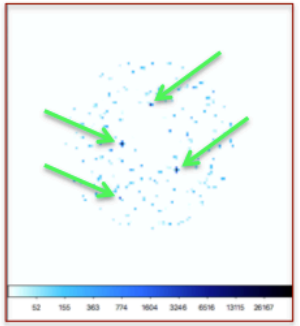
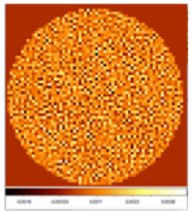
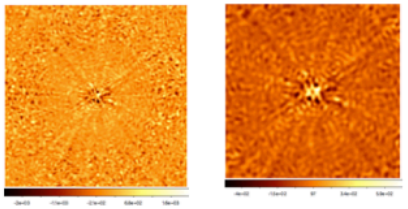
-Non-myopic

-Maximum a Posteriori

MEDUSAE

Results (1) Concept and minimization strategy:

Model for coronagraphic images: *Sauvage et al. 2010 (JOSA)*
Demonstration of the concept: *Ygouf et al. 2012 (A&A)*
Improvement of the strategy: *Cantalloube et al. 2017 (AO4ELT)*

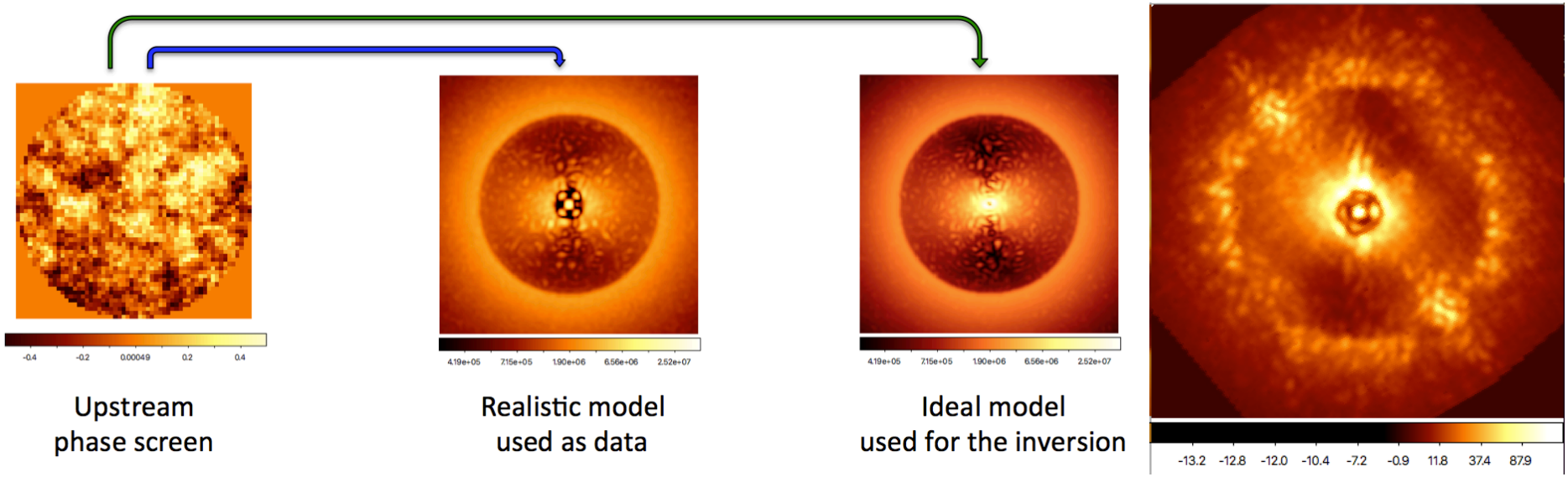
	Upstream phase (30nm rms)	**Speckle field** (at 950 nm and 1647 nm)	**Object map** (5 planets)
Simulated data:			
Estimation with 6 wavelengths (950 -> 1650nm)			
Difference:			

→ Ideally, we can reach a contrast of **5.10^{-7} at ~300mas**

MEDUSAE

Results (2) Adaptation to real data from SPHERE-IFS:

Test on realistic simulations: *Cantalloube et al. 2017 (AO4ELT)*
Implementation of a realistic coronagraph model: *Cantalloube et al. 2018 (SPIE)*



Upstream phase screen

Realistic model used as data

Ideal model used for the inversion

Simulated images at 967nm

SPHERE-IFS image

MEDUSAE

Short term work plan

1- To reach a higher IWA (>3 lambda/D) need a refined coronagraphic model
-> Analytical model of a realistic coronagraph (O. Herscovisci-Schiller et al. 2017)

2- To make it work we need to deal with the AO-residual phase signature
-> on-going work with LAM, IPAG, ESO and Leiden

CONCLUSION

Inverse problem approaches for HCI post-processing

Not only a speckle subtraction:

-ANDROMEDA models the expected planetary signature

-MEDUSAE models the whole instrument aberrations

MEDUSAE-like methods need to be developed along **the instrument conception**:

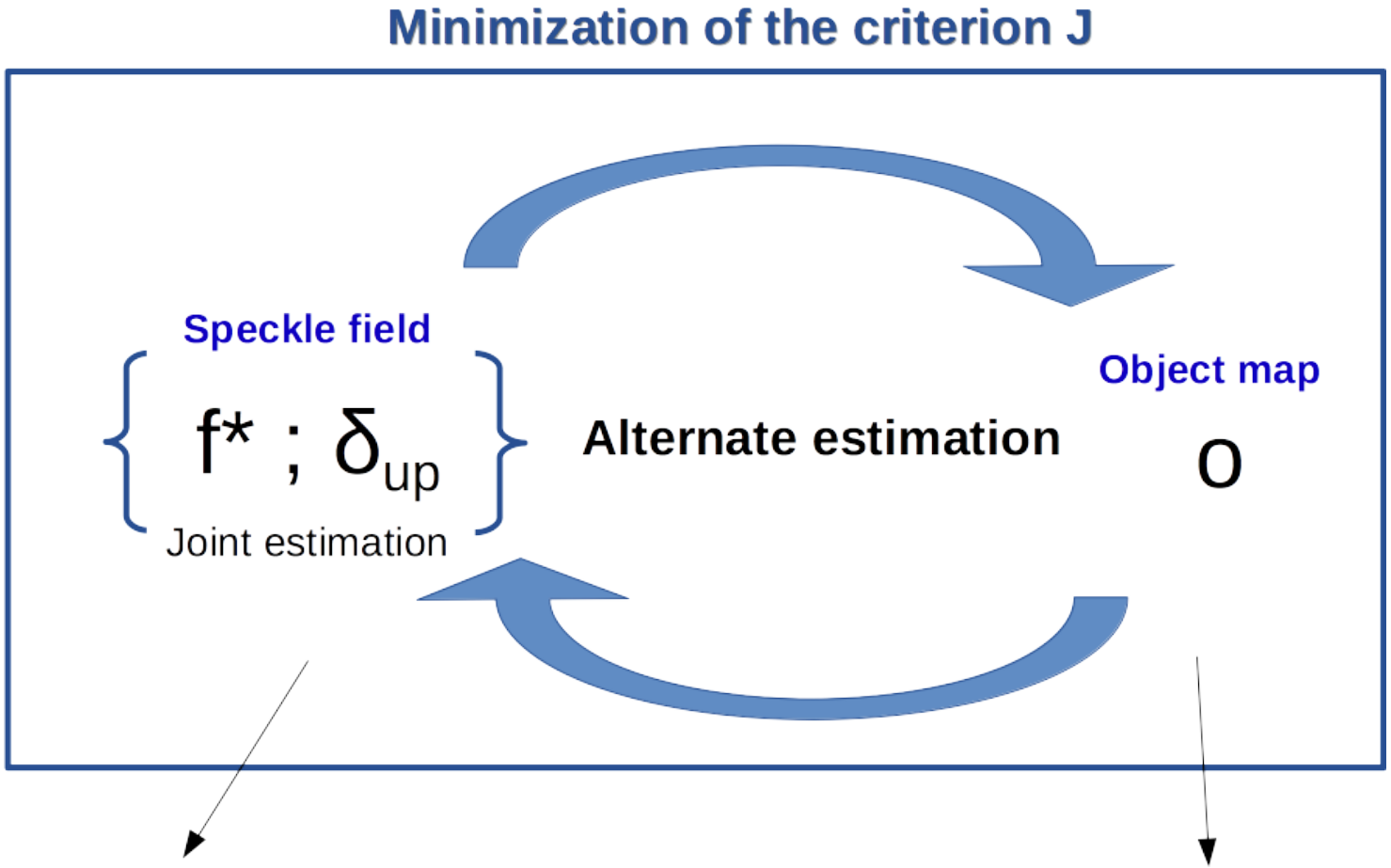
- precise model of the instrument,
- specific calibration procedures,
- bring regularization terms.

-> Talk by M. Ygouf !

Developing such methods is also important to **re-process** archival data

Summary of MEDUSAE's strategy

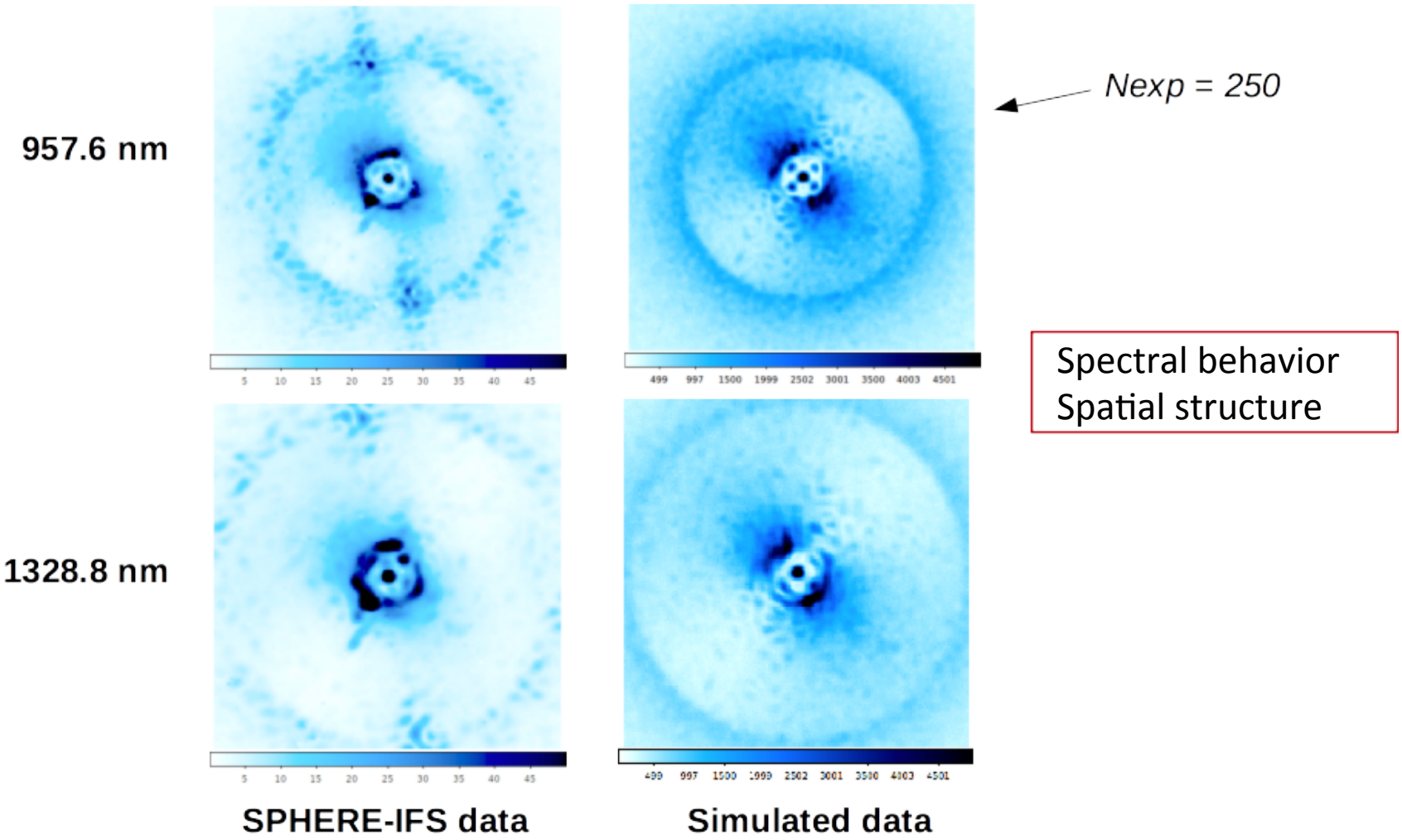
Ygouf et al. 2013



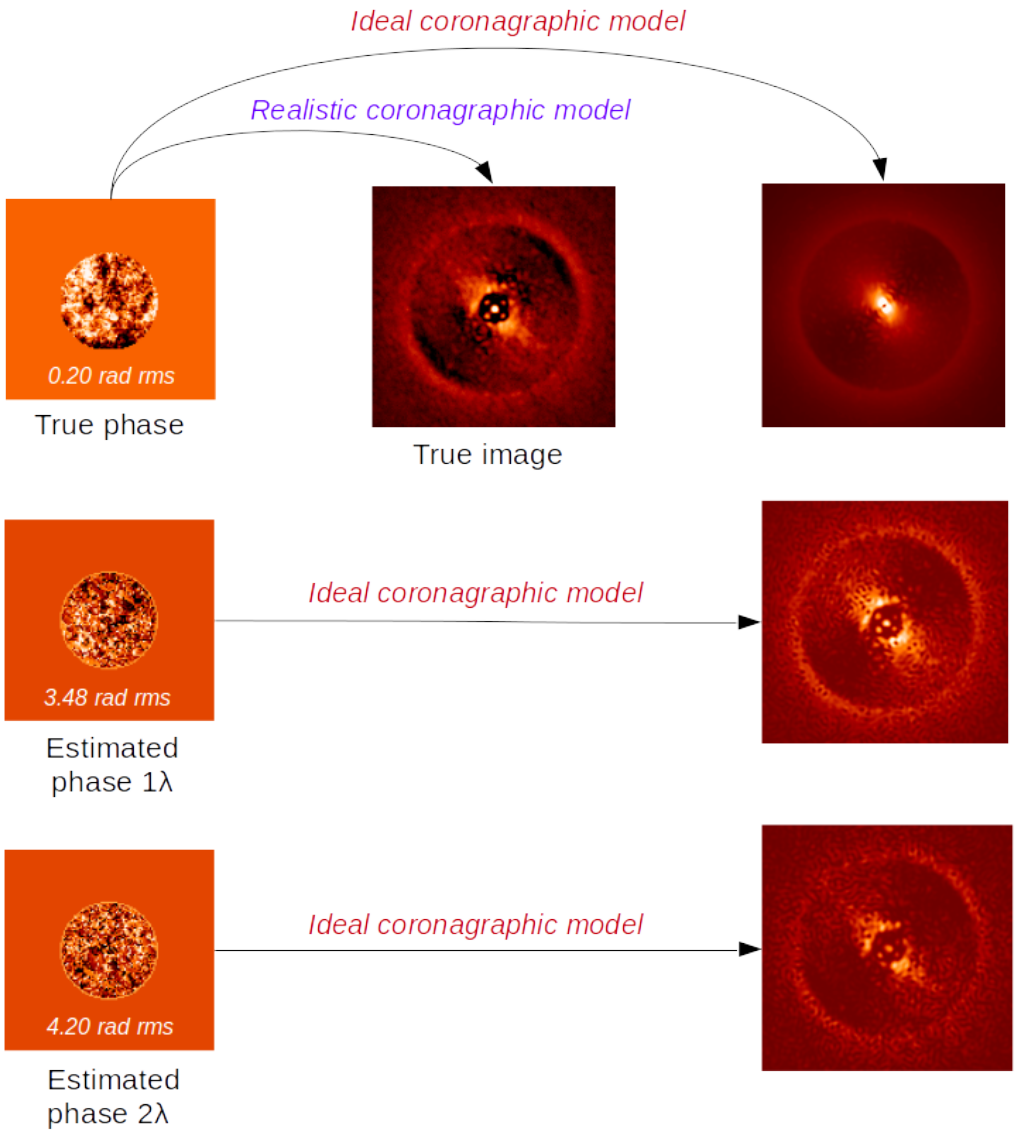
Speckle field (fixed object)
→ Local descent: analytical gradients expression

Object estimation (fixed speckle field)
→ Non-myopic deconvolution

Simulation of SPHERE-like images



MEDUSAE on SPHERE-like images



MEDUSAE

Almost there… but…how to estimate the $D_{\varphi\text{-}res}$

The action levers we have:

- **Atmospheric profiling:**
  r_0, L_0, wind speed and direction, $Cn^2(h)$
- **AO Telemetry:**
  DM or WFS slopes -> inside the AO correction zone
- **Focal plane image:**
  Fitting directly on the images via minimization

The tools we have:

- Theory (books) for direct model
- Spatial power spectrum approach (PAOLA)
- E2E AO-simulations approach (OOMAO, YAO, SOAPY, DASP, COMPASS etc.)
- Dictionary of data (e.g. machine learning)

MEDUSAE

Almost there… but…how to estimate the $D_{\varphi\text{-}res}$

Goal: Extract directly the essential parameters to estimate $D_{\varphi\text{-}res}$

- -The Fried parameter
- -The wind direction
- -The wind speed

In an easy and cheap way (in terms of memory) via post-processing

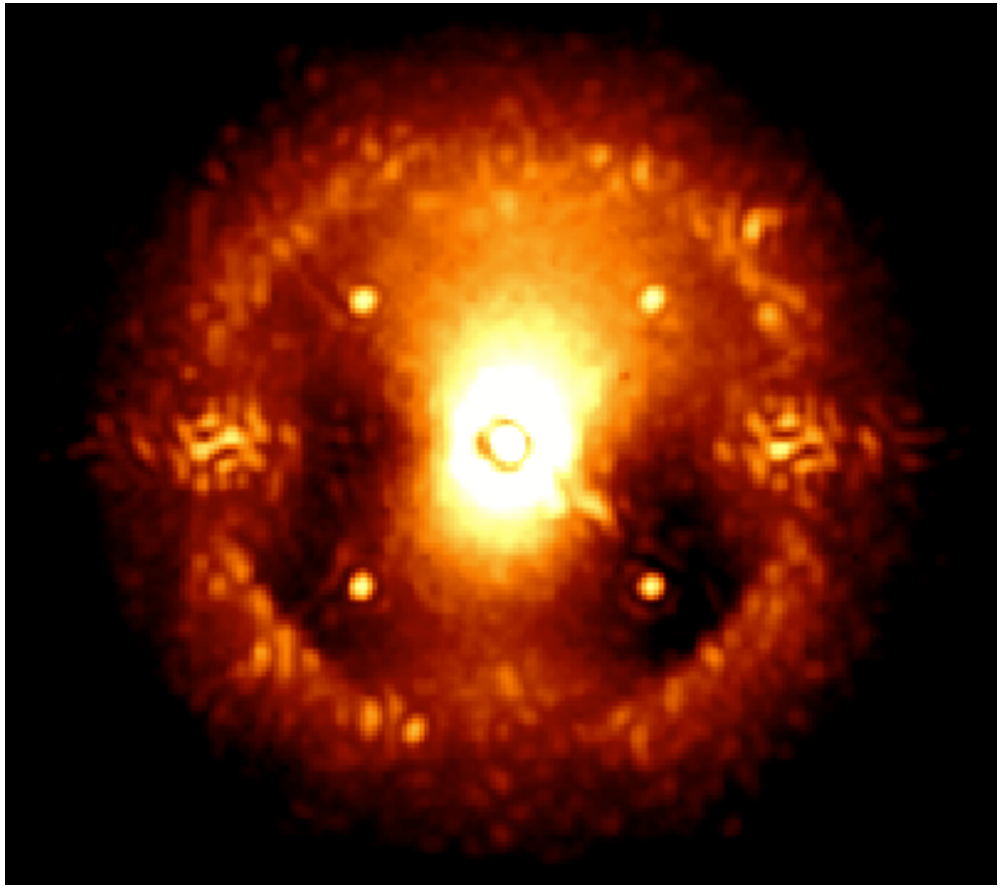
We do not want to play on controllers (such as predictive control)

Complexity / cost ↓

Solution#1: Direct model from the profiling data
Solution#2: Adapted filtering
Solution#3: Fitting on the focal plane image(s)
Solution#4: Using telemetry data
Solution#5: Via inverse problem (requires model+regul)

Open issues

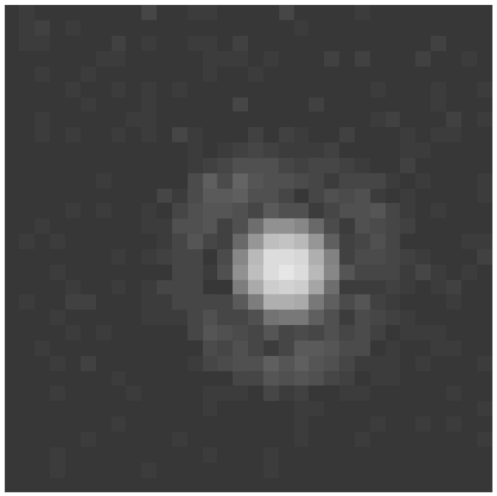
The halo is not centro-symmetric…



GJ 504 with VLT/SPHERE in H2 band
(I purposely stretched the colorbar)

Origin:

- Certainly due to the centering of the coronagraph (not in DTTS)
- Dome seeing ?
- Ground Layer ?
- Chromatic effect ?



DTTS detector image
H-band <- 10% from the science beam
Spatial resolution: