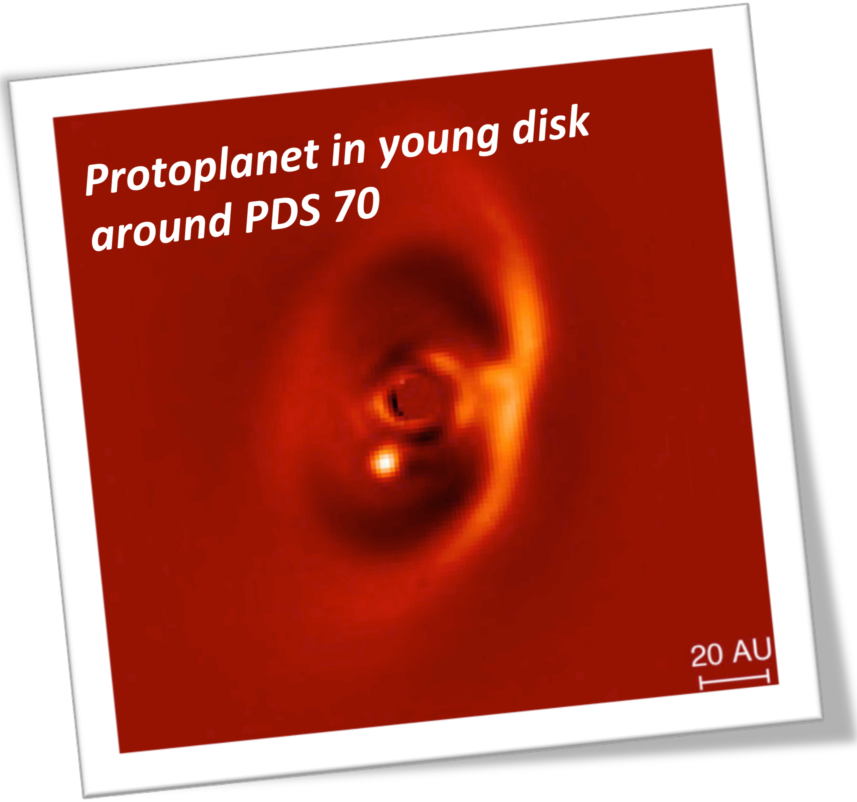
Post-processing techniques for exoplanet and circumstellar disk imaging



Faustine Cantalloube
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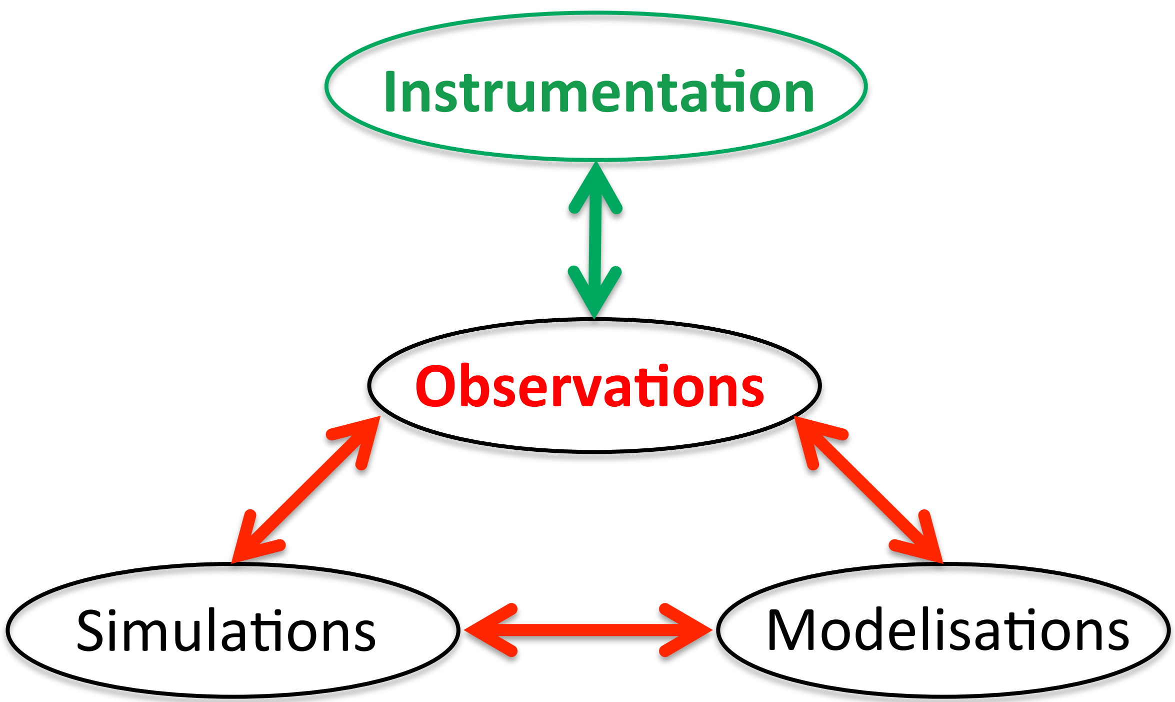
Max Planck Institute for Astronomy, Heidelberg

The “3 questions” about exoplanets

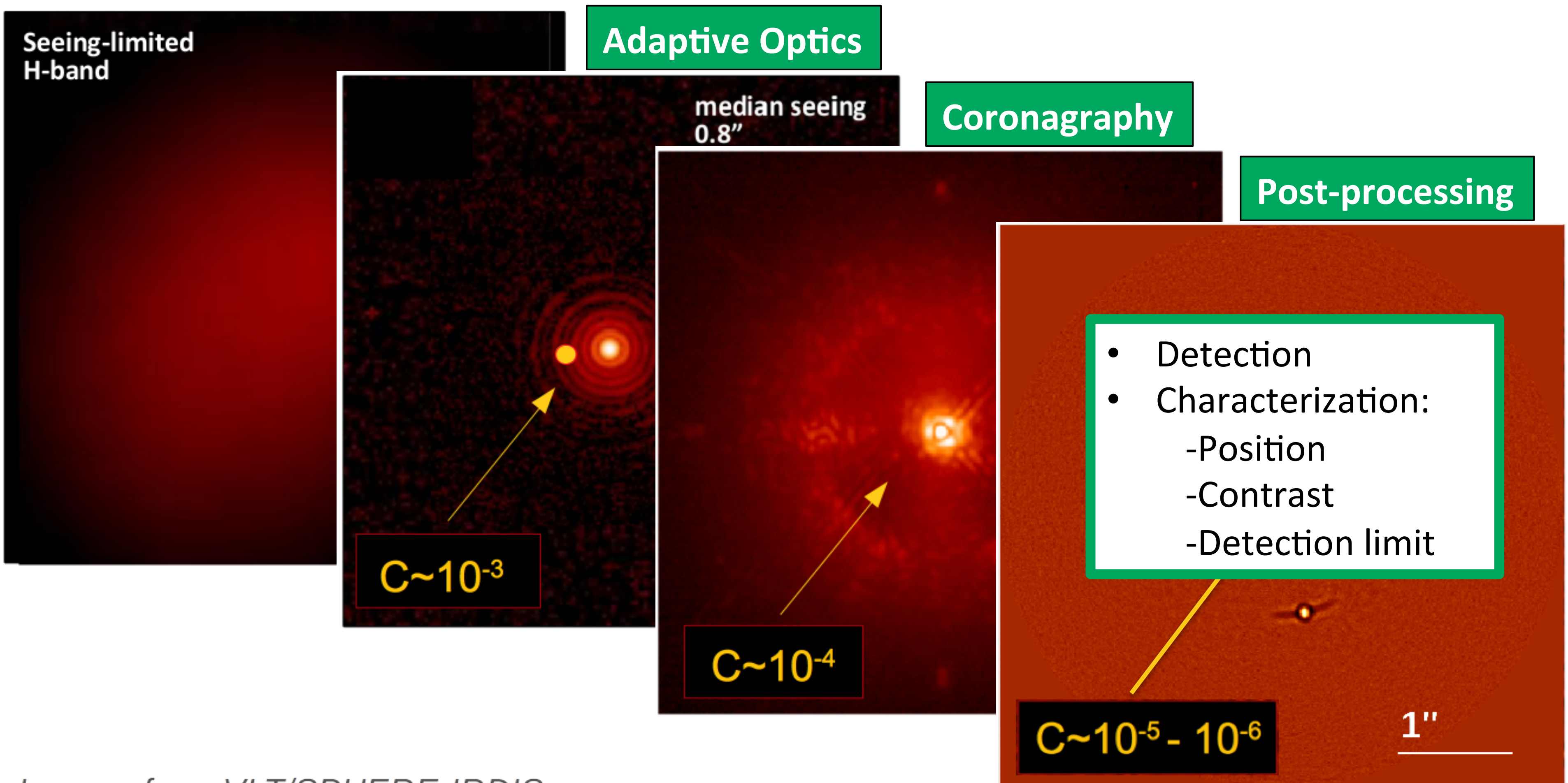
- Planetary **formation**
- **Nature** of exoplanets
- **Dynamical** and **physical evolution** of exoplanets

To address this astronomers have three main pathways:



Post-processing: What we want and why

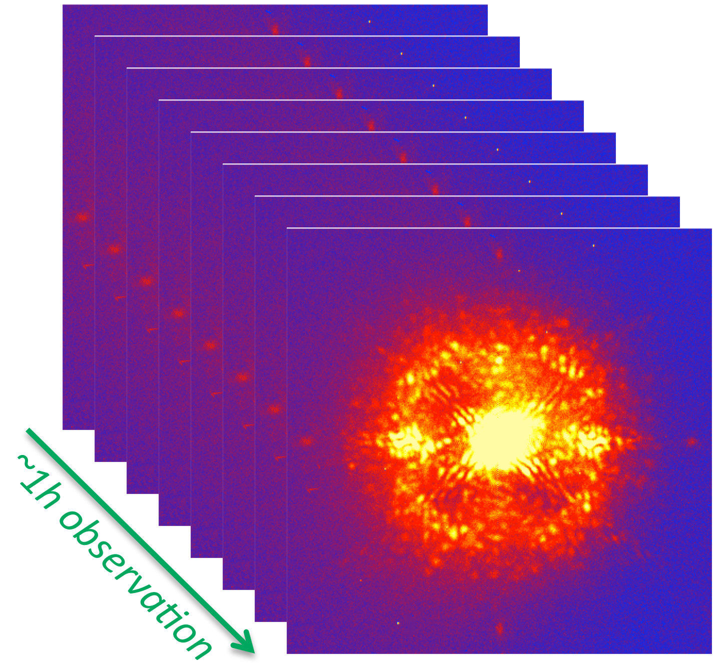
Today reaching contrast of **10^{-6}** contrast at **500 mas**, in infrared



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

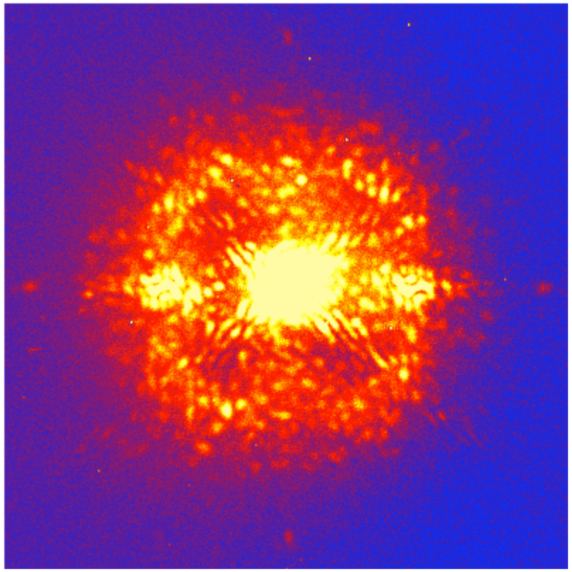
Post-processing:

<u>Basic idea:</u>
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



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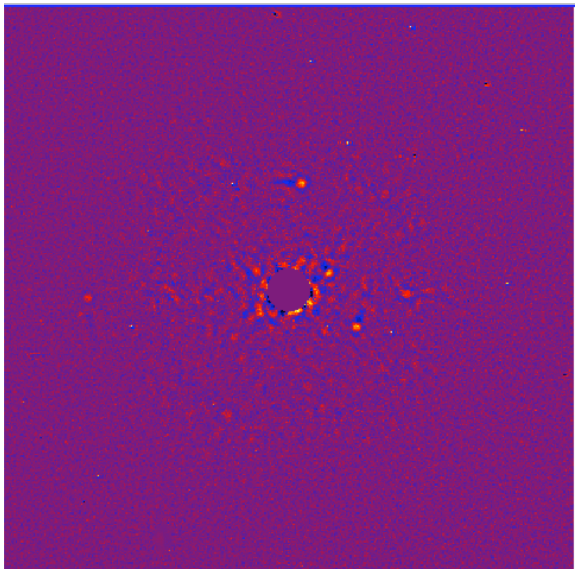
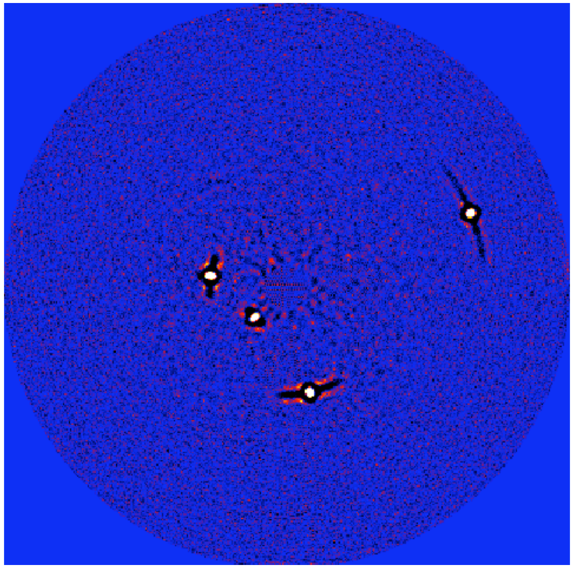


3. **Combine** all the images



Current post-processing:

Different type of diversities can be used:

- Reference (RDI): *many people*
- Binary (BDI): *Rodigas et al. 2015*
- Polarimetric (PDI): *Kuhn et al. 2001*
- Spectral (SDI): *Close et al. 2005*
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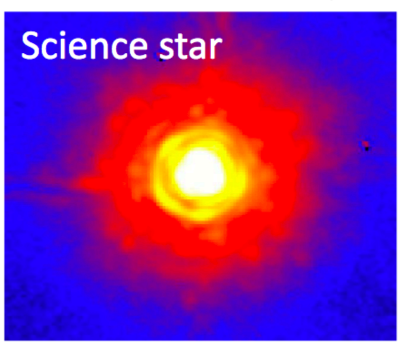
Requires:

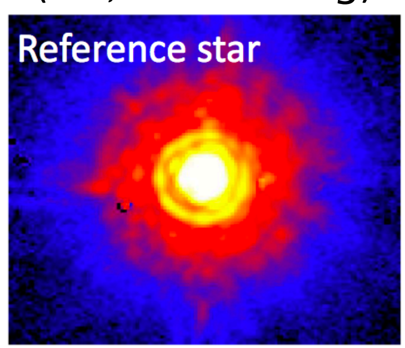
- A close star,
- Same brithness,
- Same spectral type

HD 142527
(F6, K=4.98mag)



−

HD 181296
(A0, K=5.01mag)



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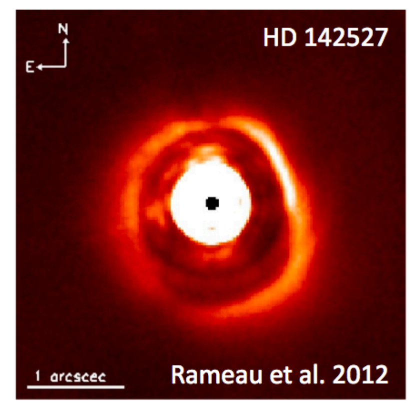

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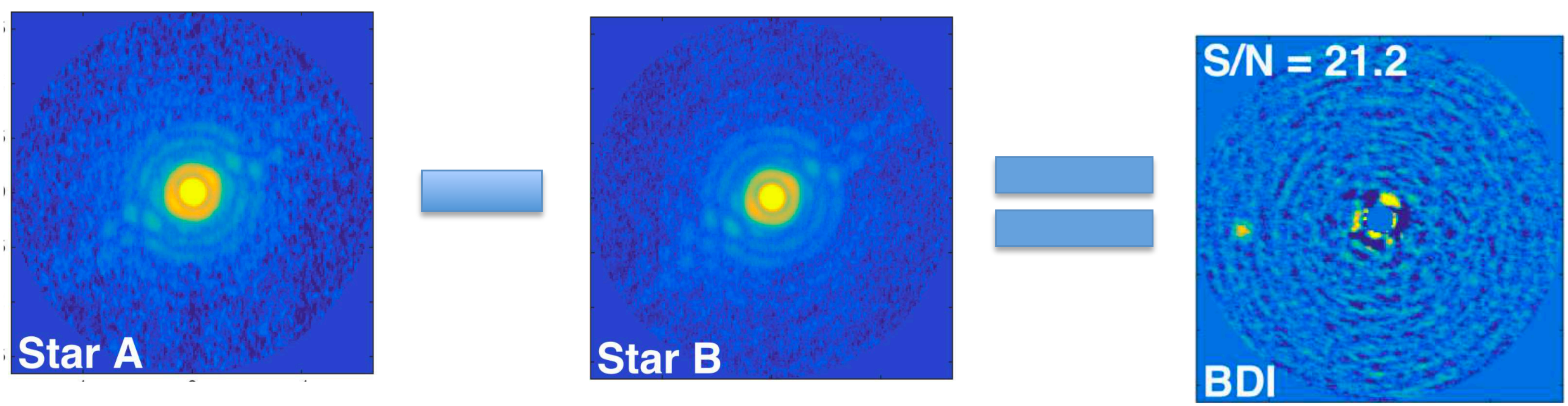
Requires:

- A visual binary star

HD 37551 visual binary

Distance: about 4”



Injected companion

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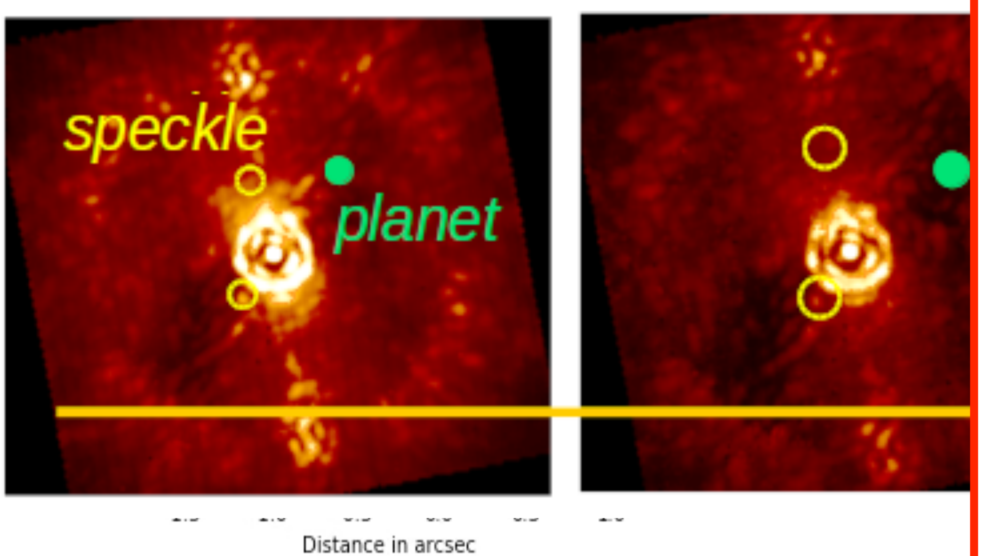
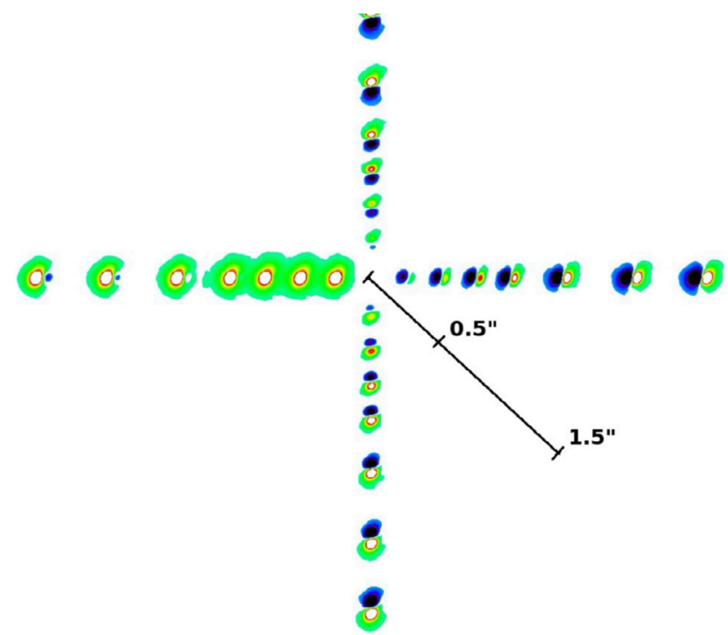
Assumes:

- Fraunhoffer

$$h^{\lambda_2}\left(\frac{\lambda_2}{\lambda_1}\,\mathbf{r}\right) = \left(\frac{\lambda_1}{\lambda_2}\right)^2 . \, h^{\lambda_1}(\mathbf{r})$$



- Limited at close separation
- OR absorption feature needed



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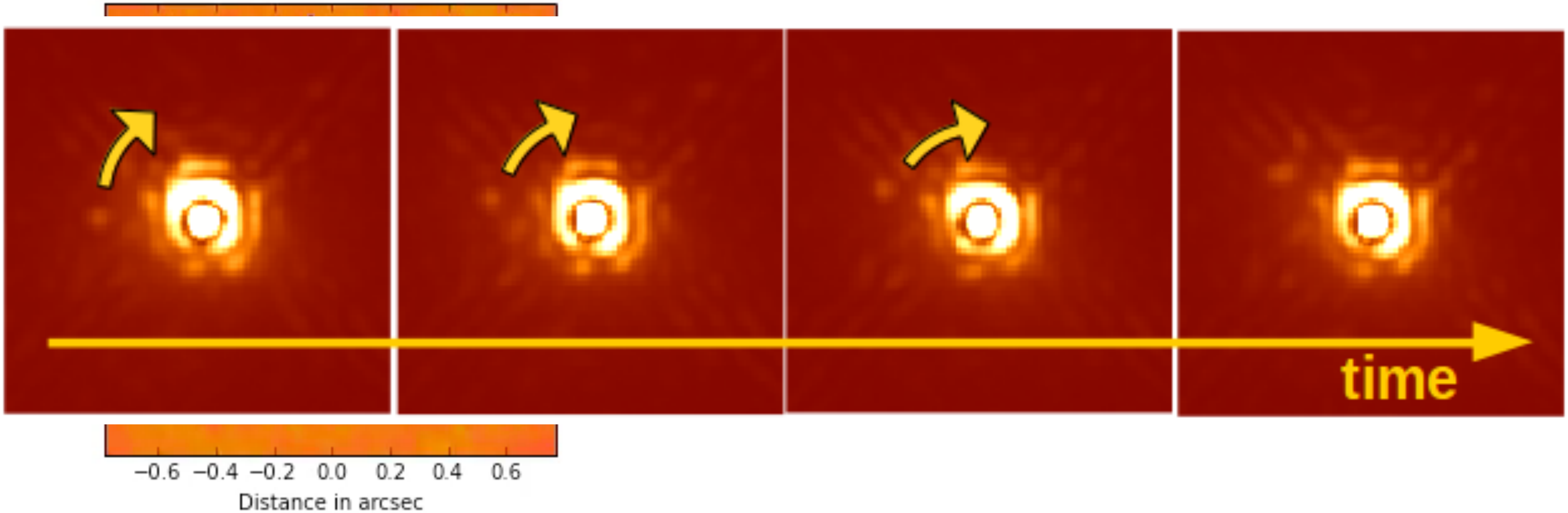
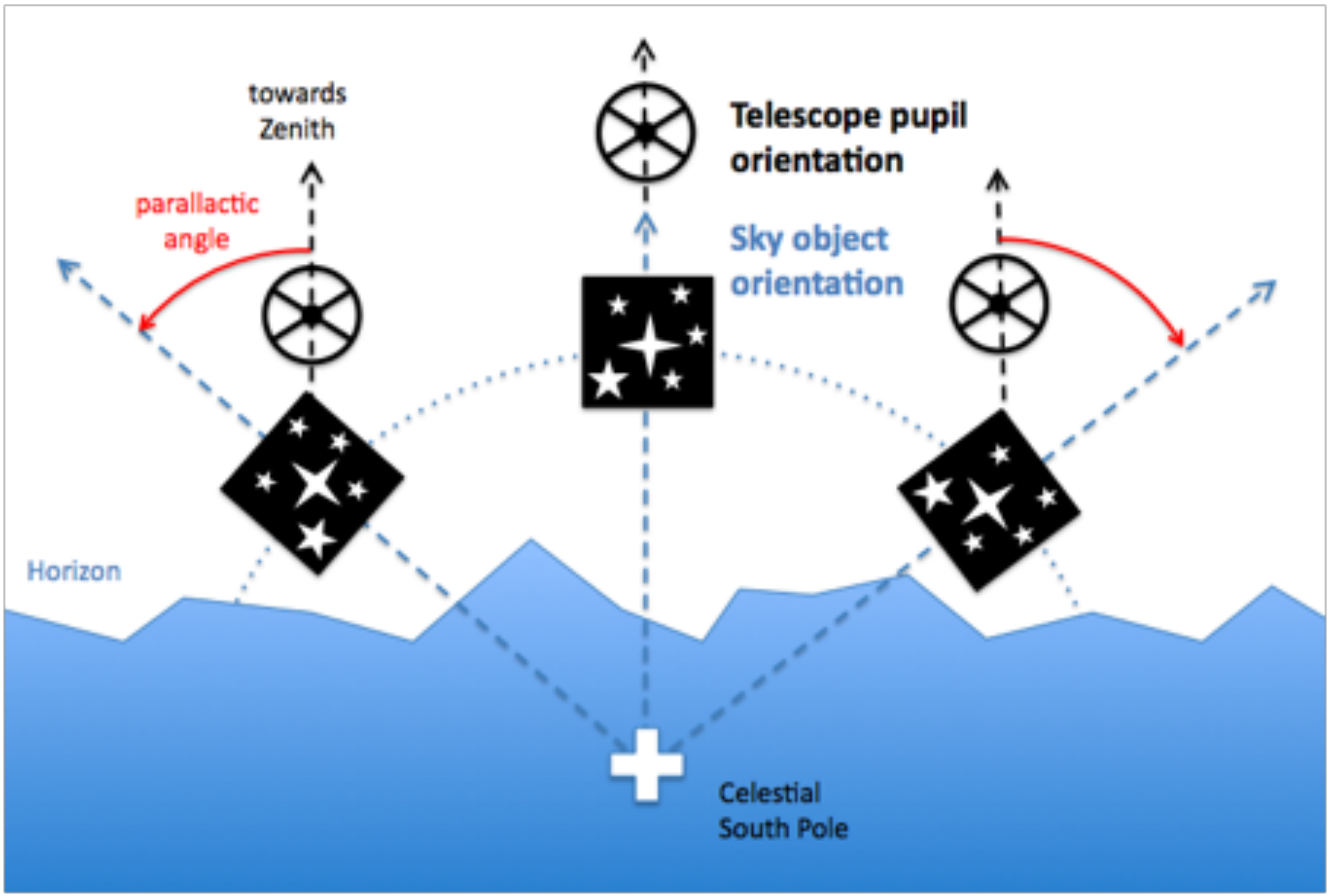


Current post-processing:
Angular differential imaging (ADI)



Possible with an alt-az mount

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
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Use the massive sample of images
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Only detection
Not mature yet

SODINN
Gomez-Gonzales et al., 2017

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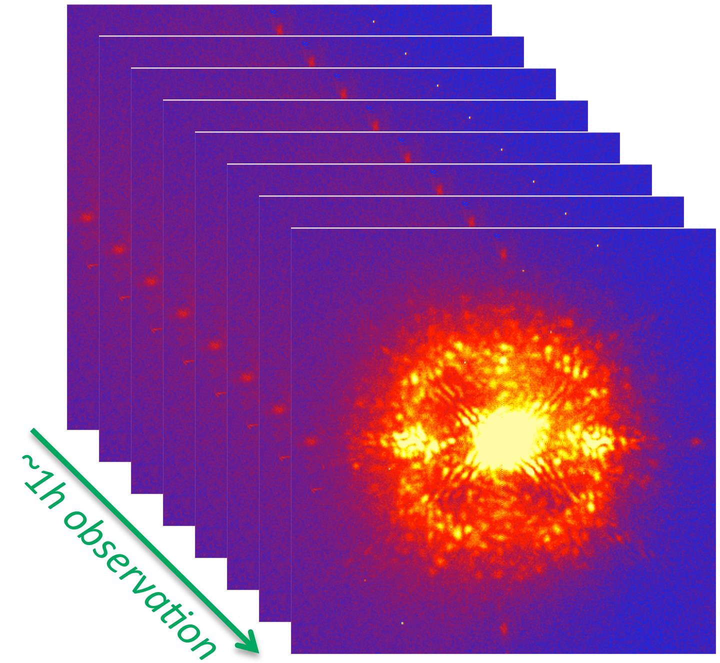

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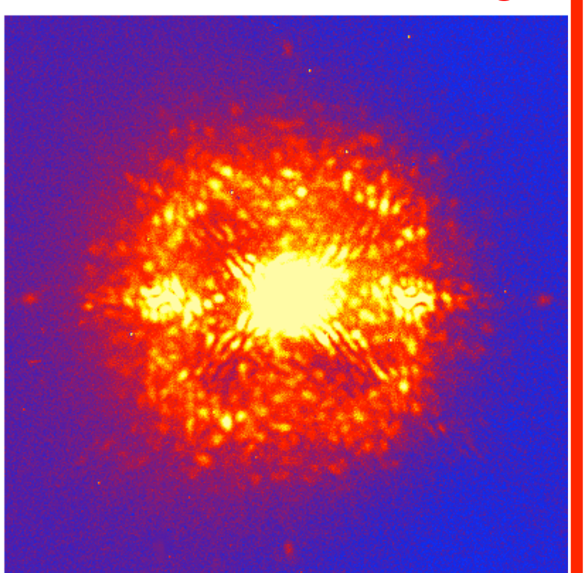

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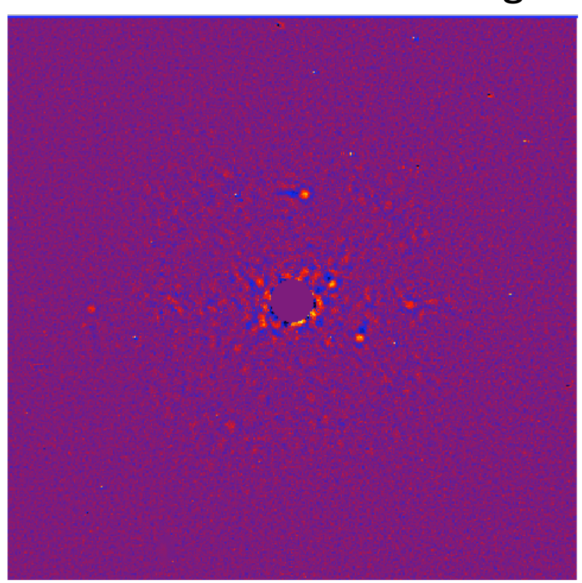

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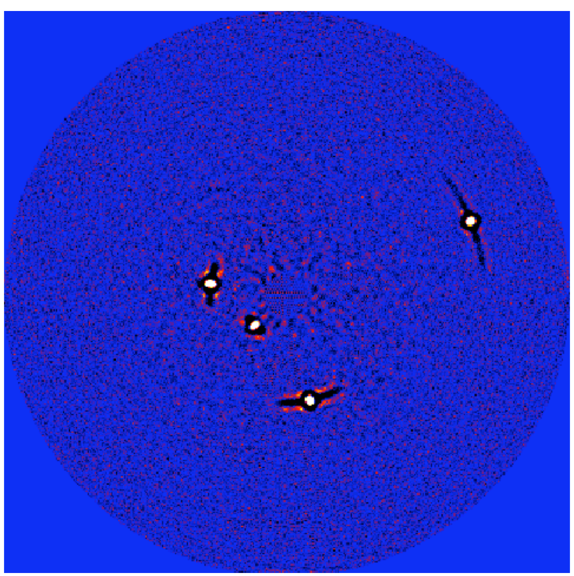
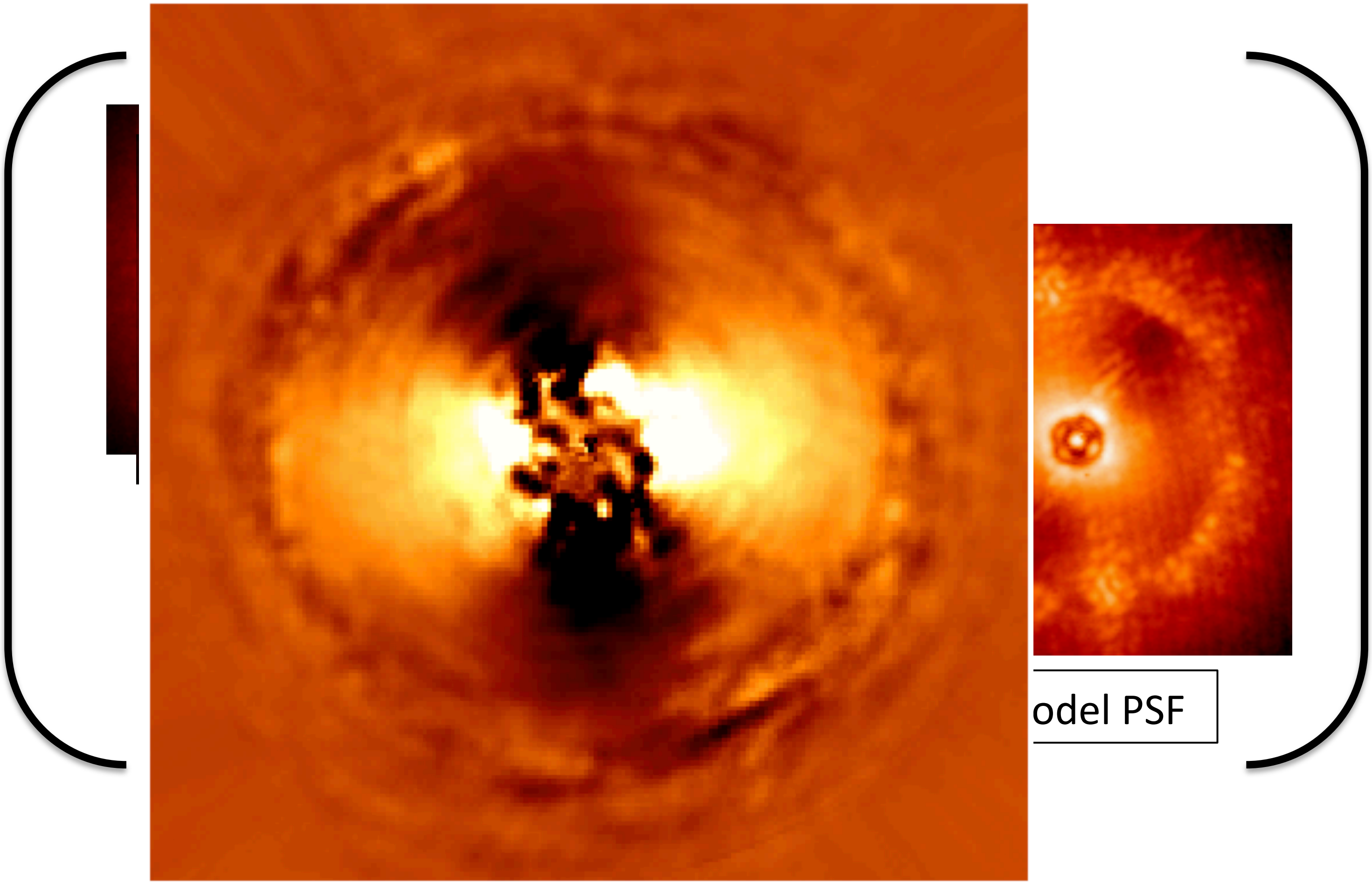


Current post-processing:
1- Classical ADI

Estimate of the star = temporal **median** of the sequence

Σ rot



Current post-processing:
2- LOCI based algorithms

Estimate of the star = **local linear combination** of the images

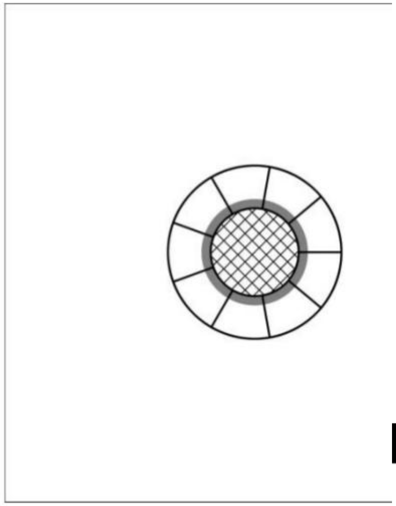
r to be estimated

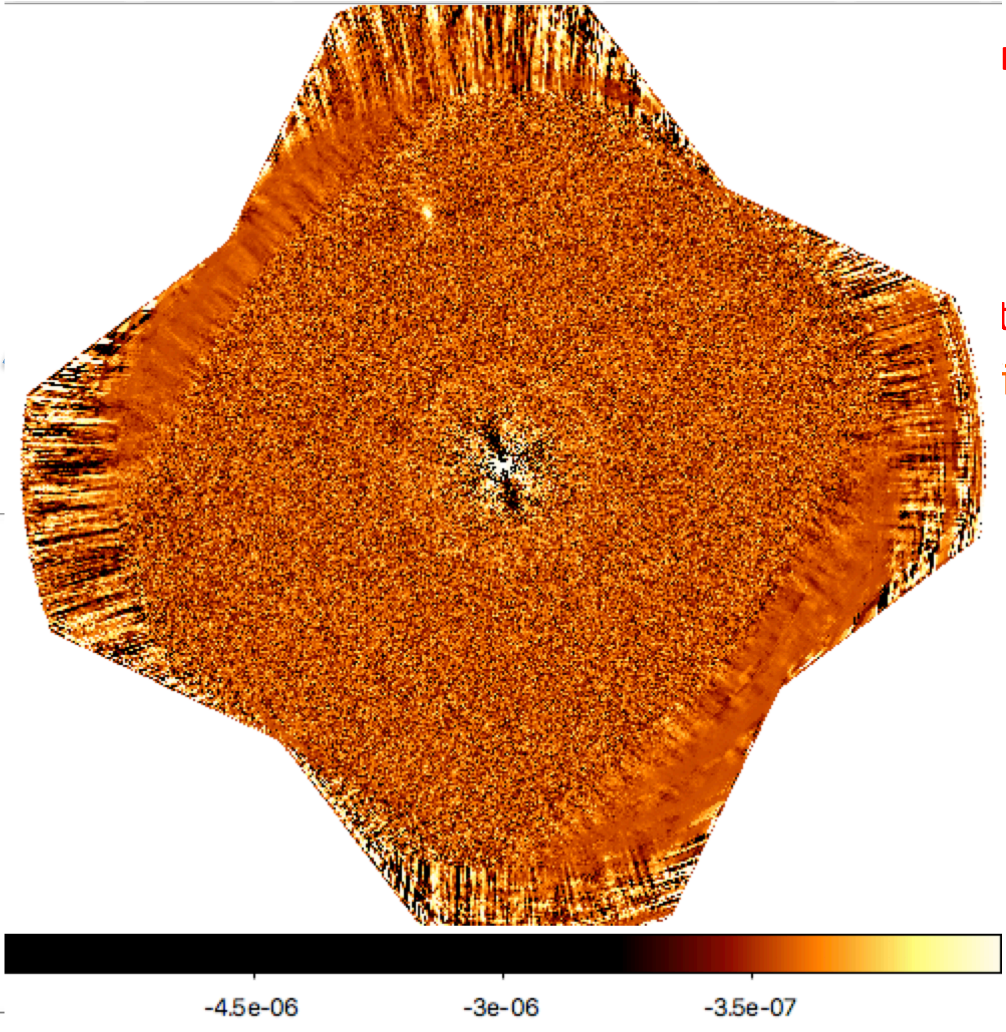
Min(σ_{res}^2) = Min

t of the images

icients

All the

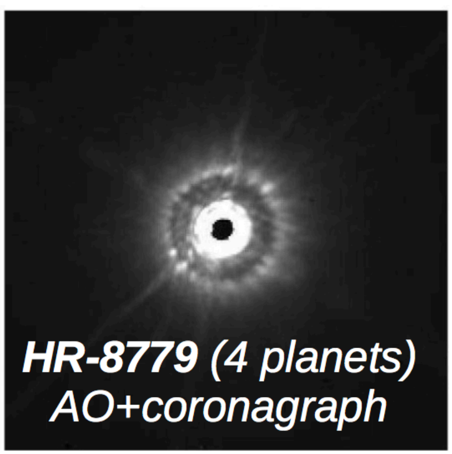


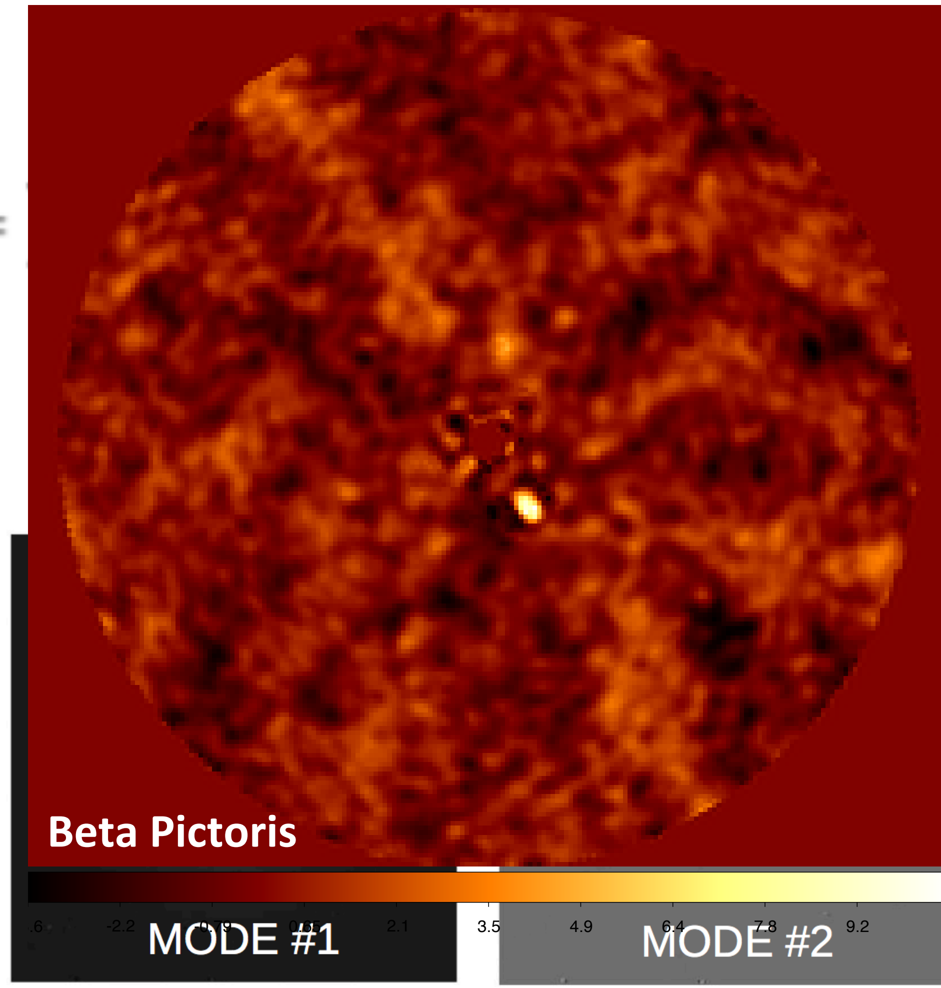


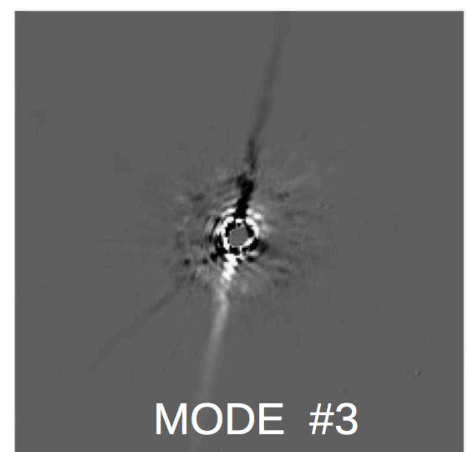
Current post-processing:
3- PCA-based algorithms

Estimate of the star = **linear combination** of the images decomposed on orthogonal basis

$I(\vec{x}) =$ $(\vec{x})\ d\vec{x}.$







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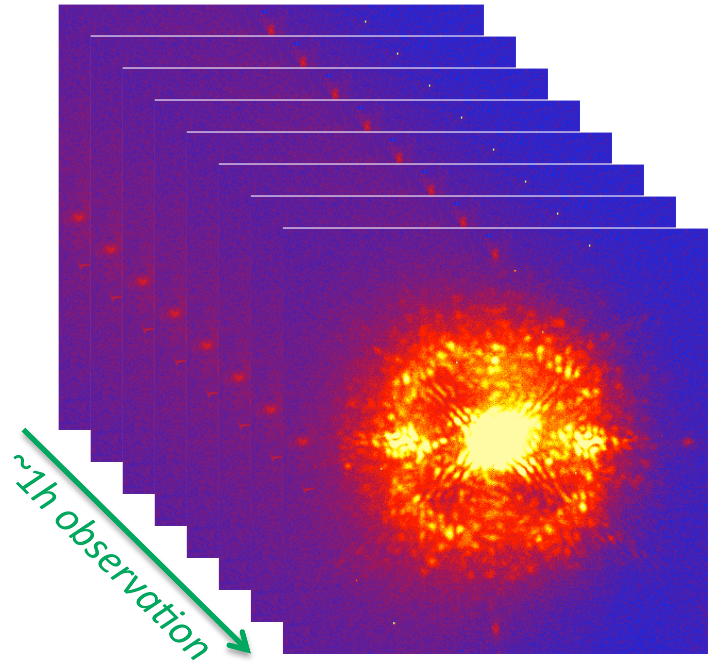
Astrometry Photometry

Post-processing:



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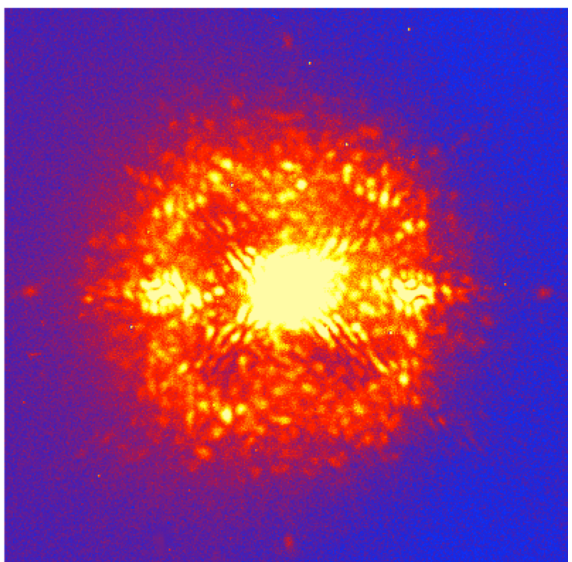

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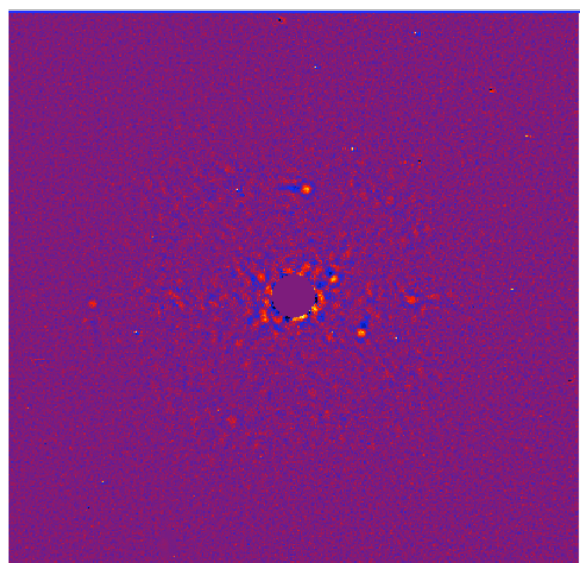

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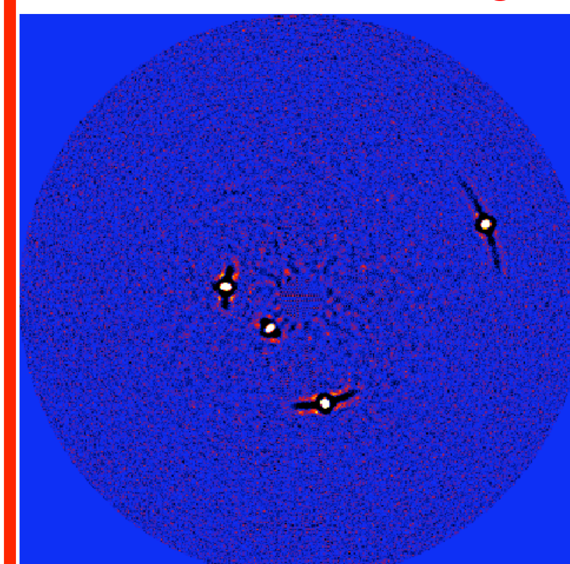


STIM-map

Method

- Take into account the **"real" residuals** distribution (after a PCA)
- **Bound this distribution** to reject the null hypothesis (no companions) H_0 (and therefore accept H_1)
- Empirical and analytical proof, submitted to MNRAS: *Pairet et al. 2018*

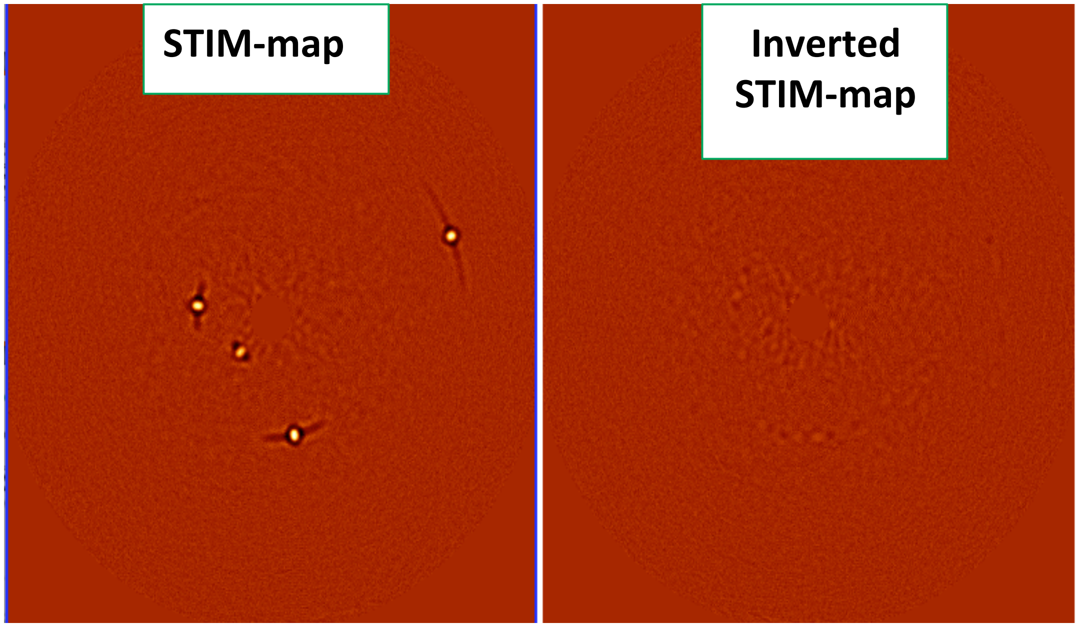
INPUT: The cube of subtracted images
→ The cube is then **combined**, using the **temporal information**

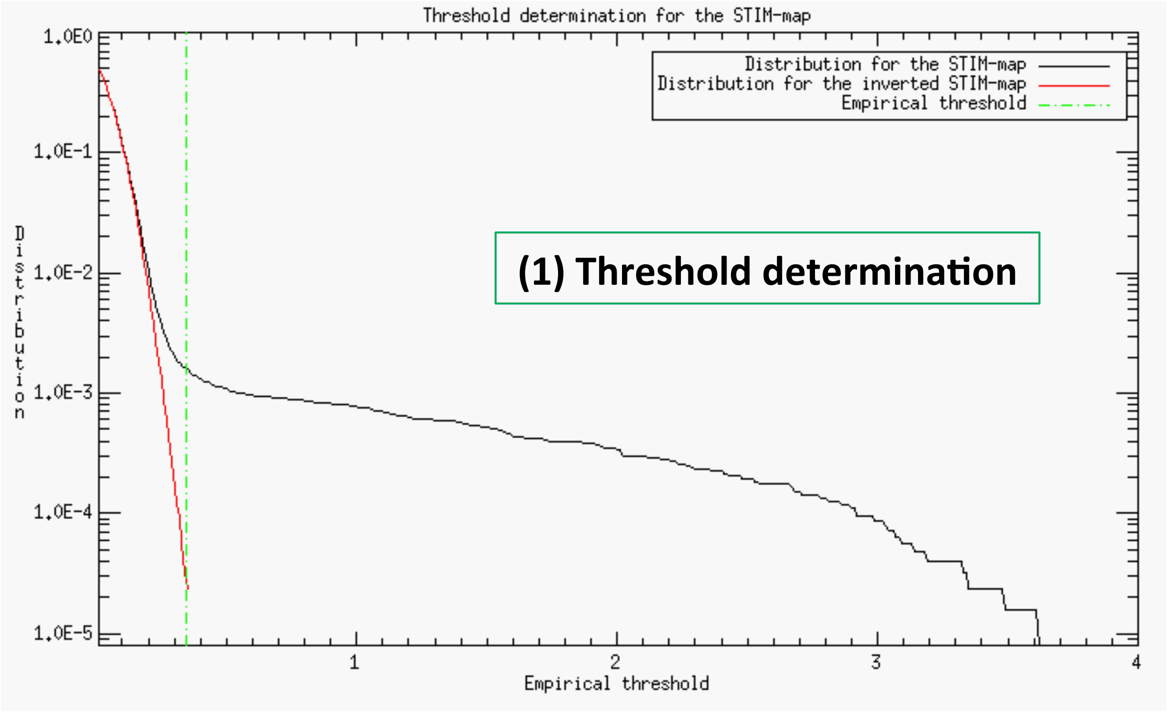
$$d_g = \frac{\hat{\mu}_g}{\hat{\sigma}_g}$$

The paper is now on ArXiv:
https://arxiv.org/pdf/1810.06895.pdf

STIM-map

Automatique detection





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ANDROMEDA: inverse problem approach

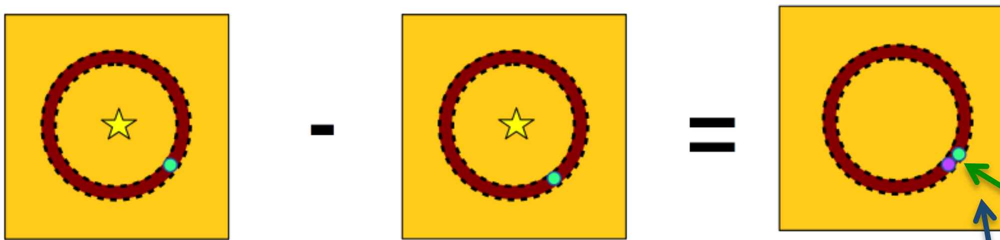


Image at t_1 Image at t_2 Differential image Δ

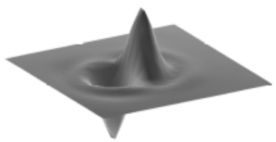
One couple k
chosen by annuli:
→ smallest time interval $(t_1 - t_2)$
→ sufficient signal distance $(\theta_1 - \theta_2)$

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**

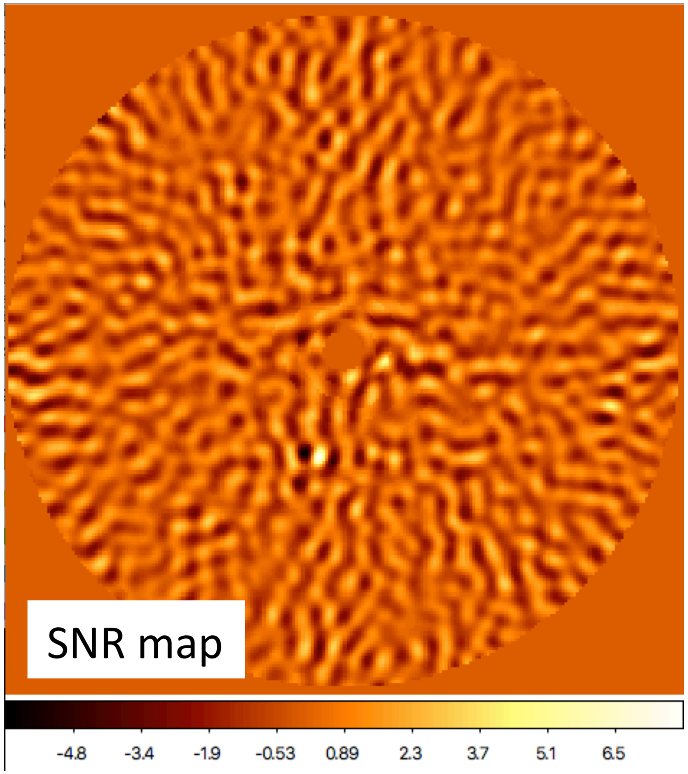
$$J(r_o, a) = \sum_{\boldsymbol{r},k} \frac{|\Delta(\boldsymbol{r},k) - a\ \boldsymbol{p}(\boldsymbol{r},k;\boldsymbol{r}_0)|^2}{2\,\sigma_n^2(r)}$$

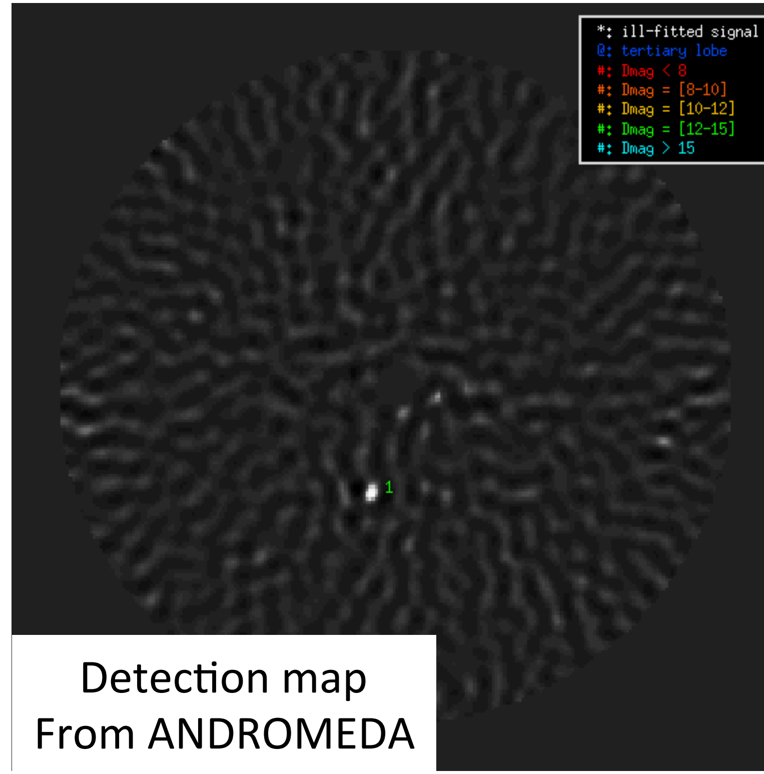
2nd step: Maximum Likelihood

→ Estimation of the flux
→ Provides a detection map

ANDROMEDA: inverse problem approach

Detection maps





This is the **only** signal above 5 sigma !
-> SNR_{51Eri} = 8 sigma

Advantages:

- Very quick
- Direct characterization
- Automatic detection
- One user-parameters

Disadvantages:

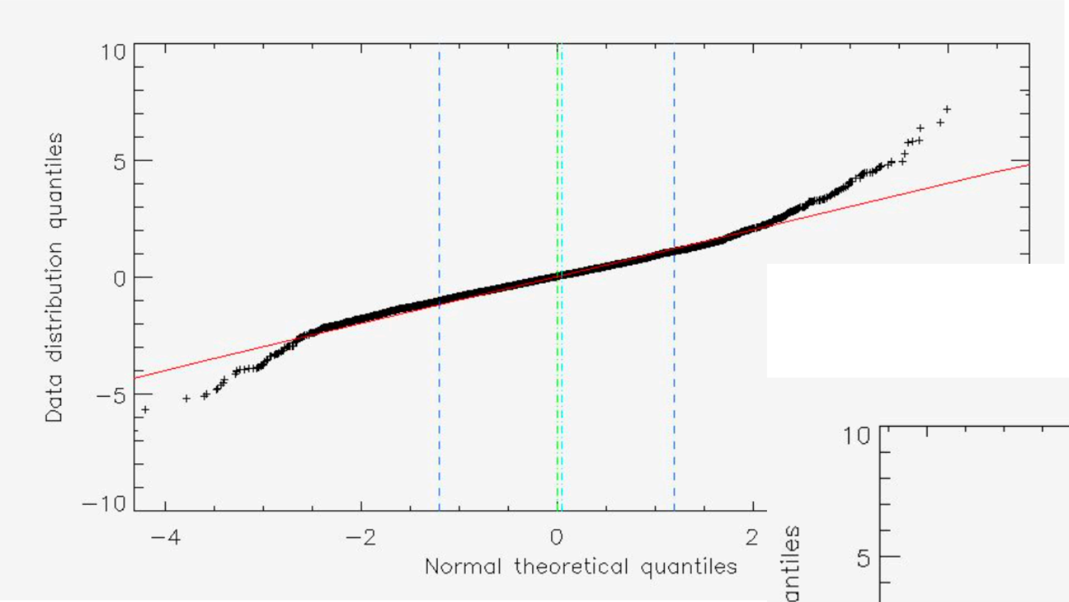
- Requires a post-normalization

Cantalloube et al., 2015

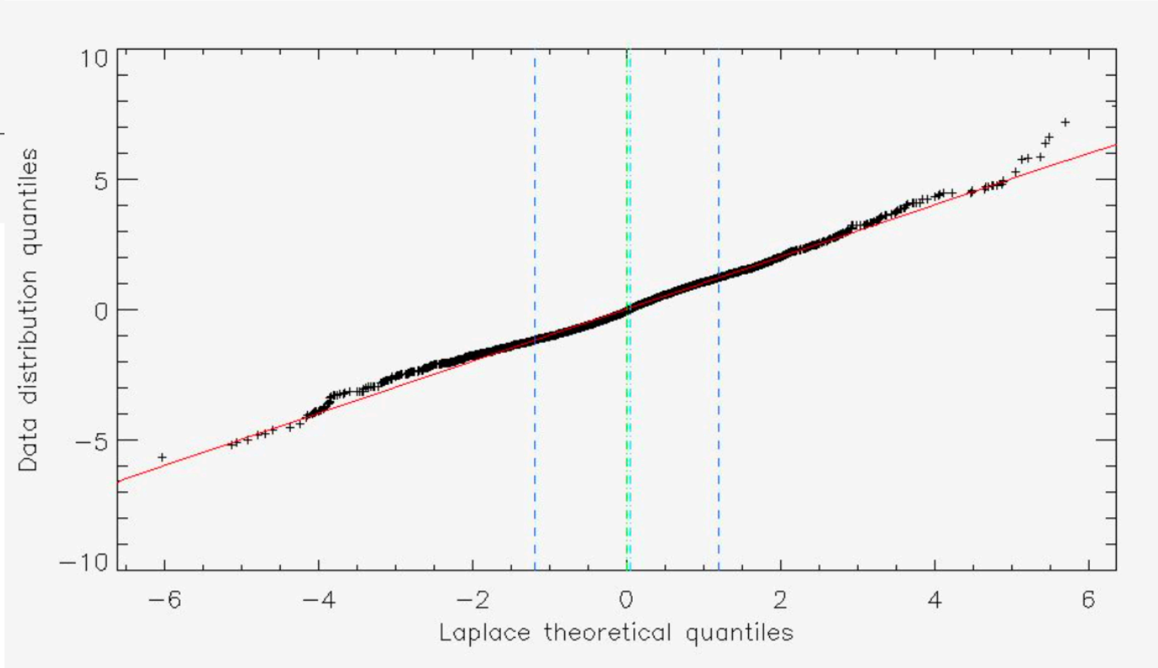
ANDROMEDA: inverse problem approach

Modifying the MLE using an L1-norm

Gaussian distribution:



Laplacian distribution:



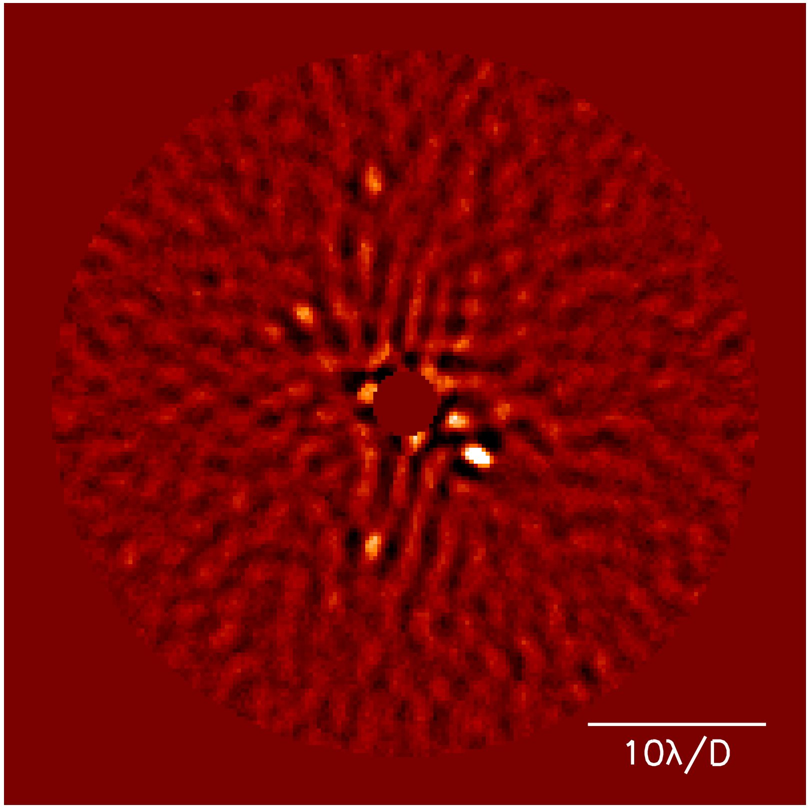
ANDROMEDA: inverse problem approach

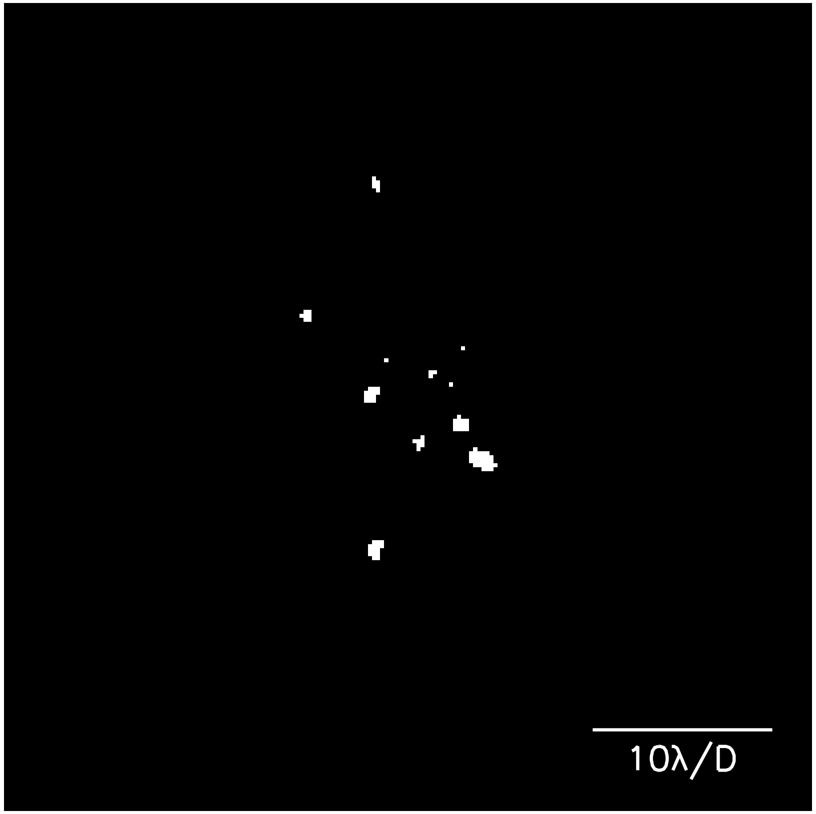
Modifying the MLE using an L1-norm

- **L2-norm**:
  - Hypothesis: white and **Gaussian** noise
  - Likelihood: $$L(r_0, a) \propto exp\left(-\frac{1}{2}\left\|\frac{\Delta(r,k) - a\,p(r,k;r_0)}{\sigma_\Delta(r)}\right\|_2^2\right)$$
  - **Analytical** solution
- **L1-norm**:
  - Hypothesis: white and **Laplacian** noise
  - Likelihood: $$L(r_0, a) \propto exp\left(-\left\|\frac{\Delta(r,k) - a\,p(r,k;r_0)}{b_\Delta(r)}\right\|_1\right)$$
  - **Numerical** solution: Least absolute deviation approach

ANDROMEDA: inverse problem approach

Detection maps with the L1-norm





Advantages:
- Better accuracy
- Smaller error
- Better sensitivity
- No user-parameters

Disadvantages:
- Longer computation time
- Residuals close to the axis

Cantalloube et al., in prep

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The caveats

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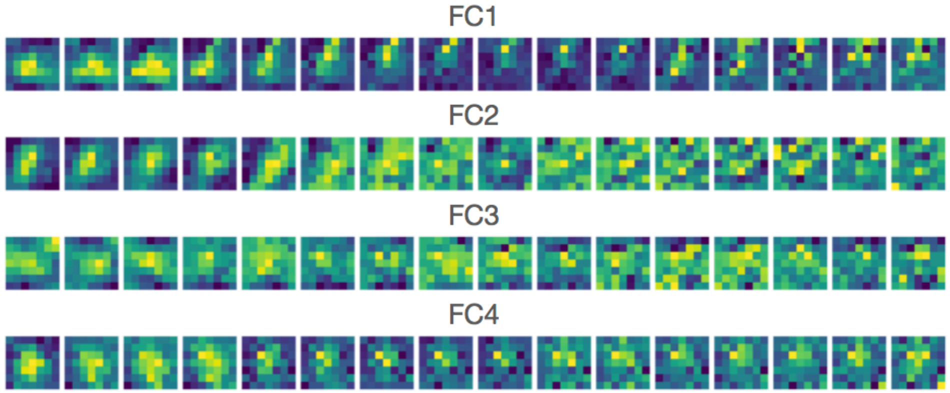
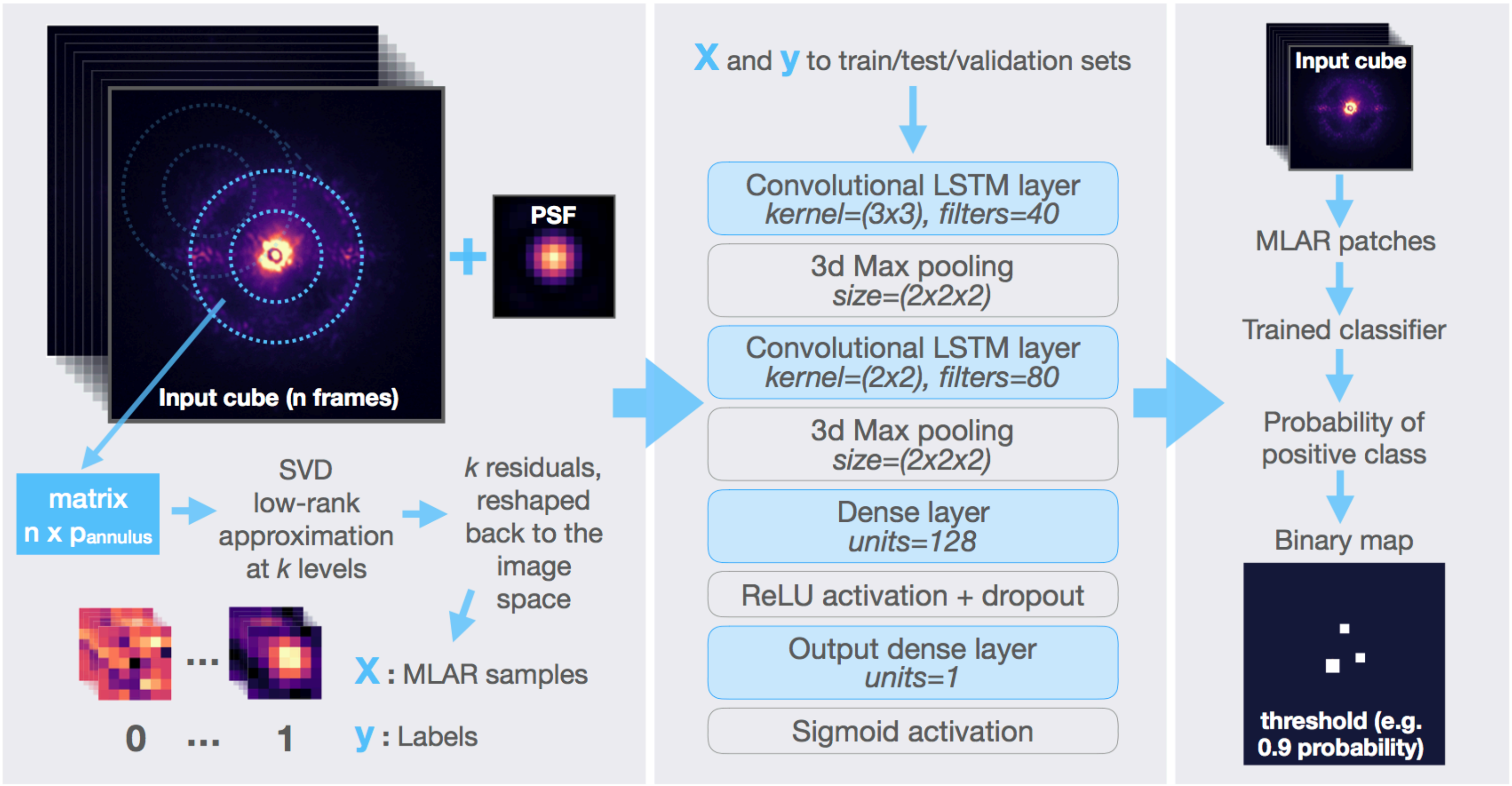
Machine learning (SODINN)



After an ADI processing

Classifier H_0 vs H_1 based on deep neural network

Trained on fake companions injected

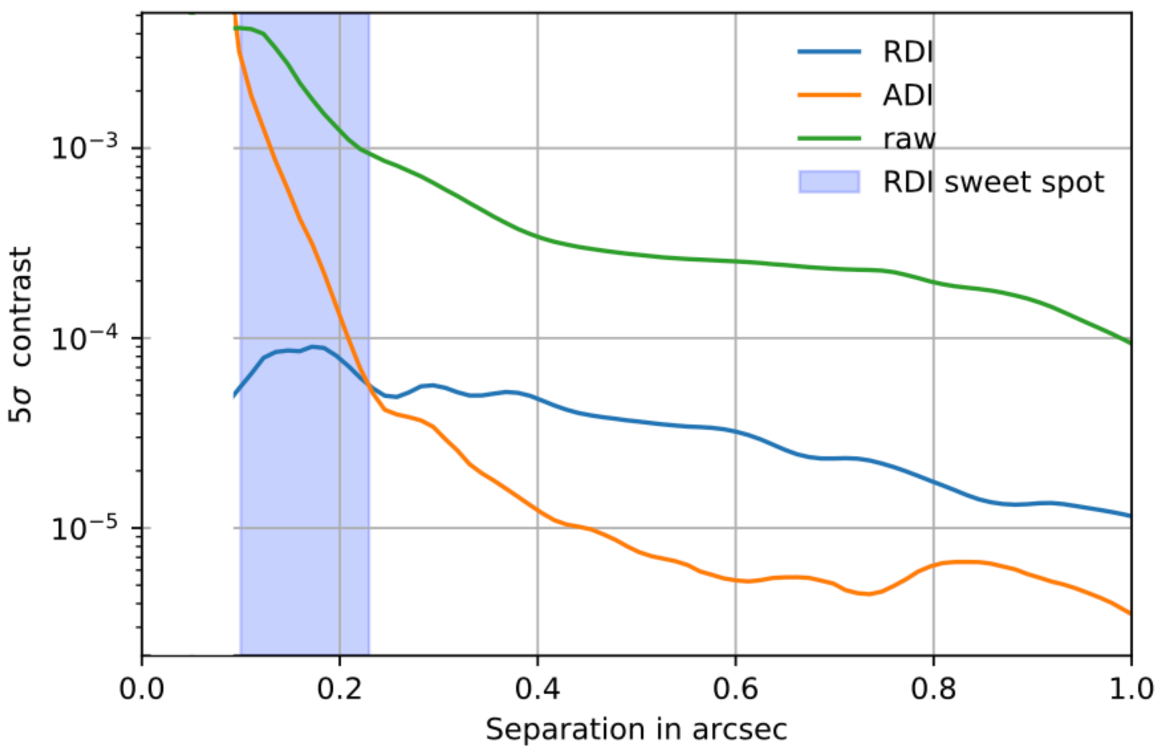


Gomez et al., 2017

Post-processing

New RDI techniques using libraries of images

- Large number of images available as references in the archive
- No additional observing time required to observe a reference star
- No sidereal timing constraints compared to ADI

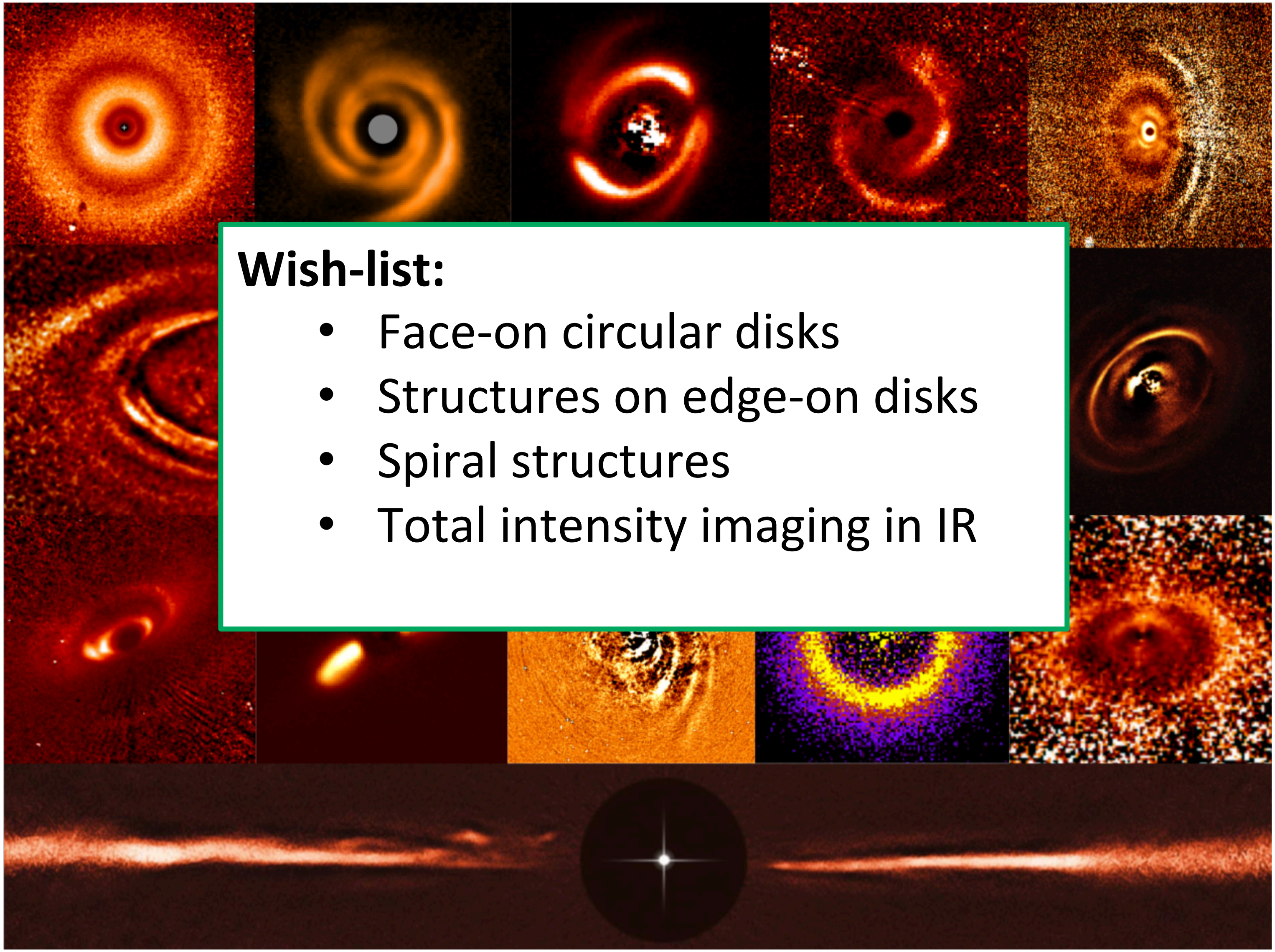


Pending questions:
- Frame selection ?
- Number of frames ?
- Frame correlation ?

SPHERE High-Angular Resolution Debris Disk Survey (SHARDDS led by J. Milli)
55 targets (~20 000 frames)
40min on source for each target with large field rotation

Courtesy, J. Milli (ESO)

Extended sources



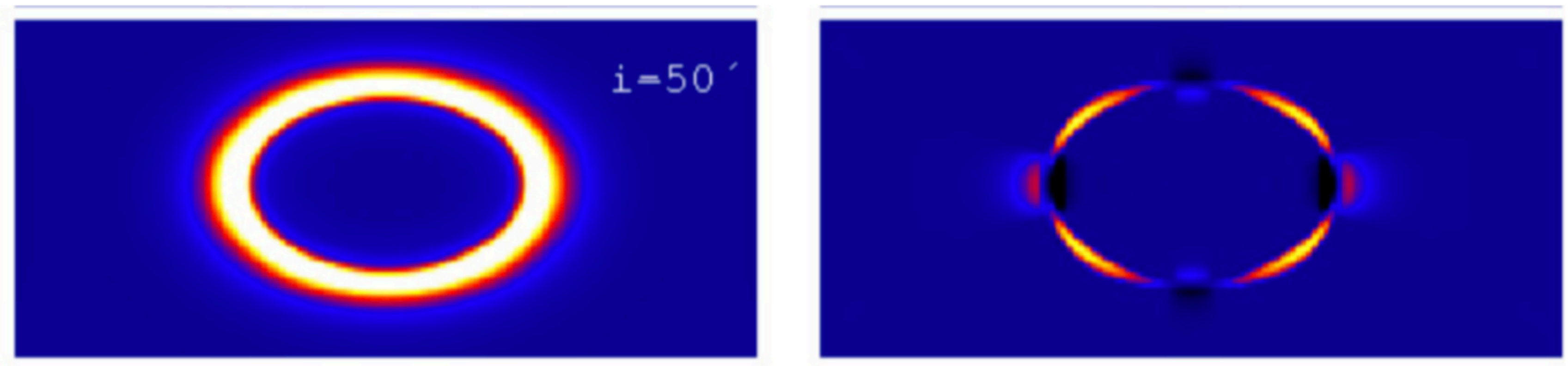
Wish-list:

- Face-on circular disks
- Structures on edge-on disks
- Spiral structures
- Total intensity imaging in IR

Garuffi et al., 2017

Extended sources

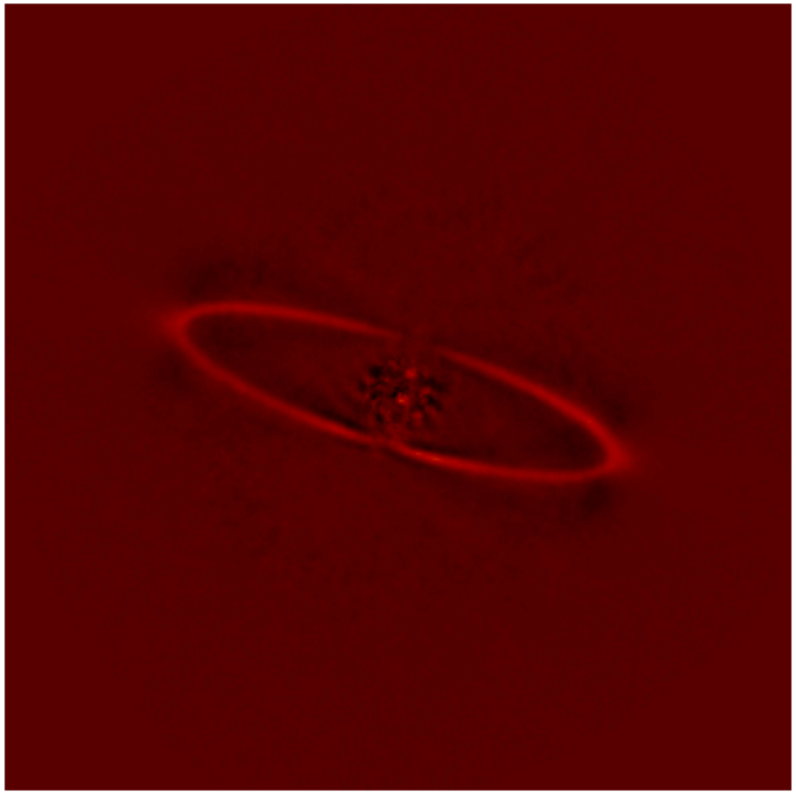
Case circular face-on → disappears
Case edge-on → remains with separation bias

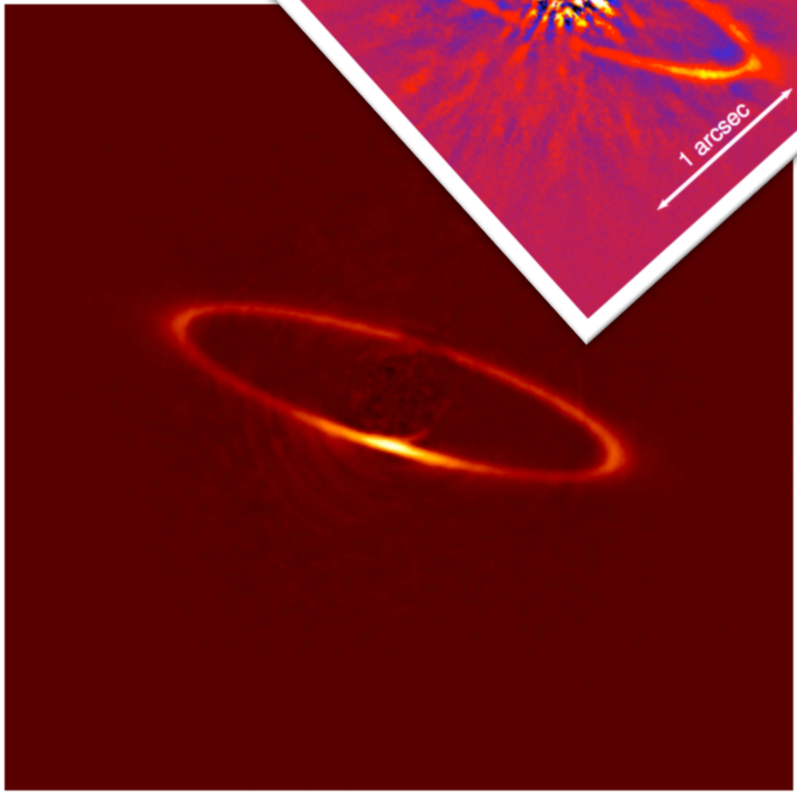


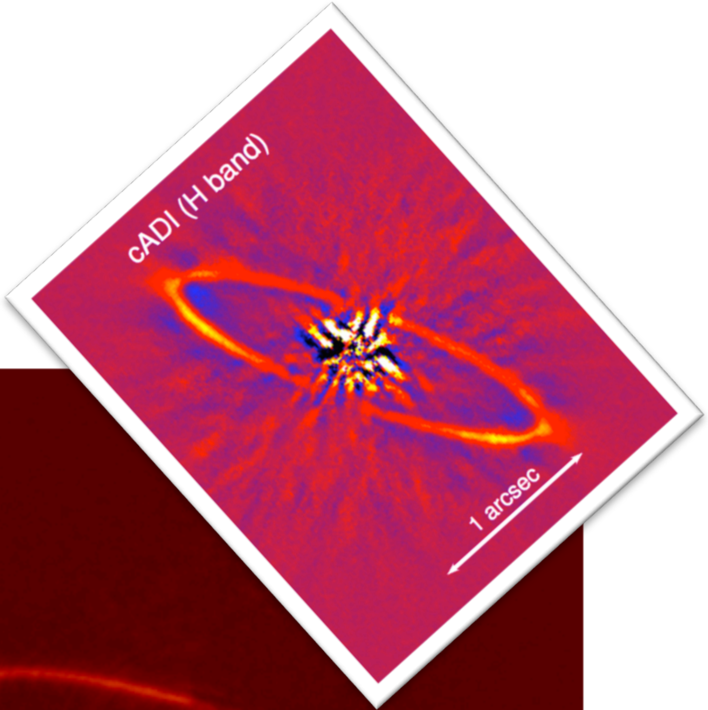
Milli et al., 2012

Imaging disks:

Iterative procedure

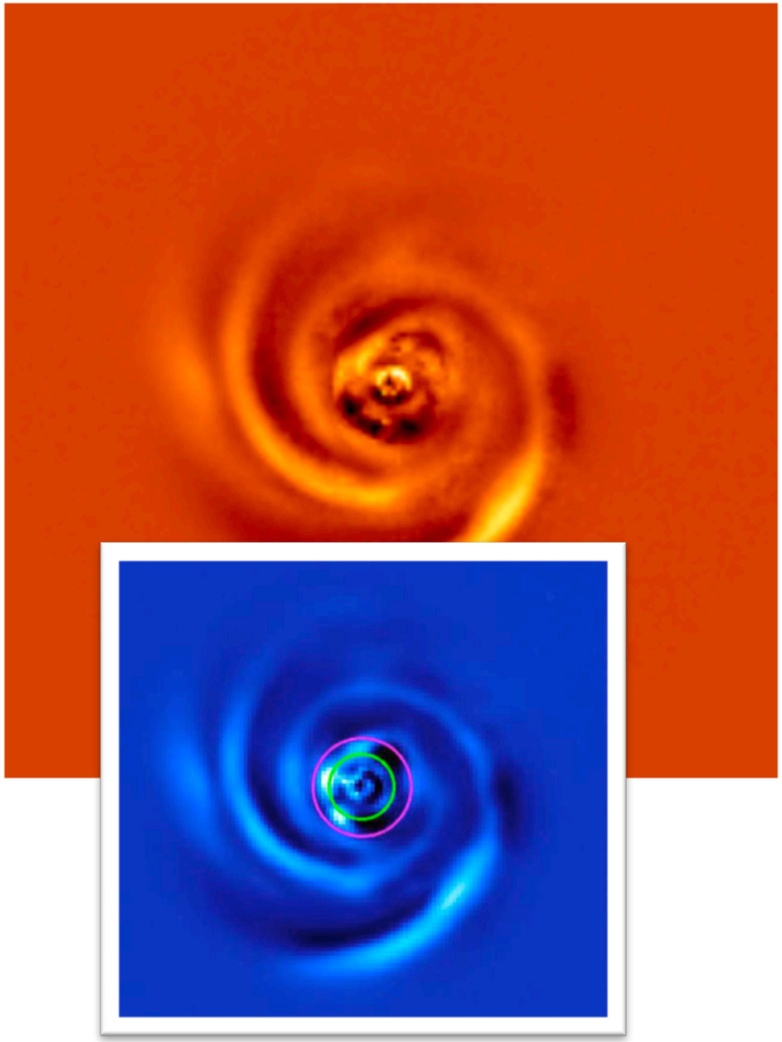


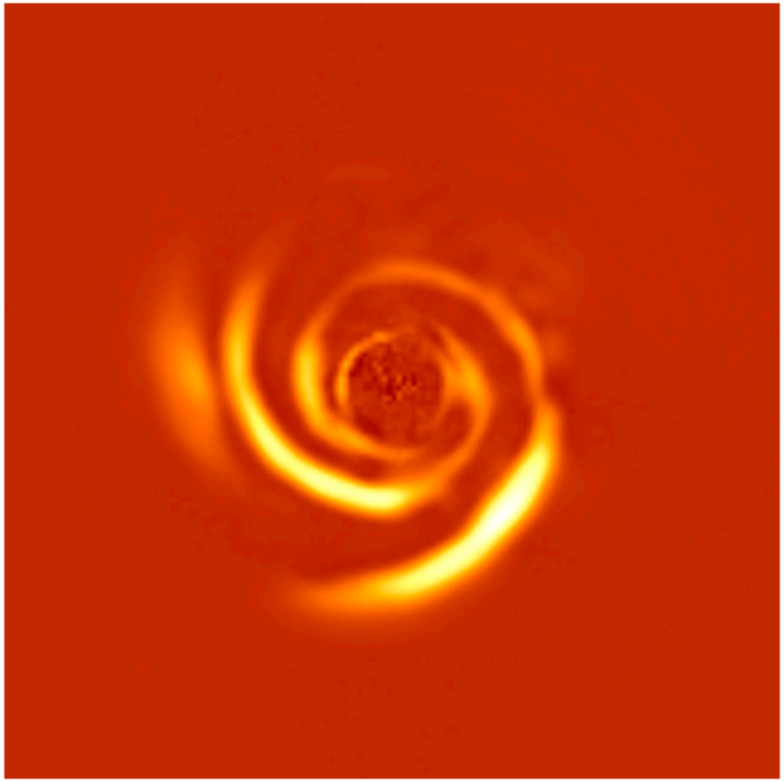




Pairet et al., 2018

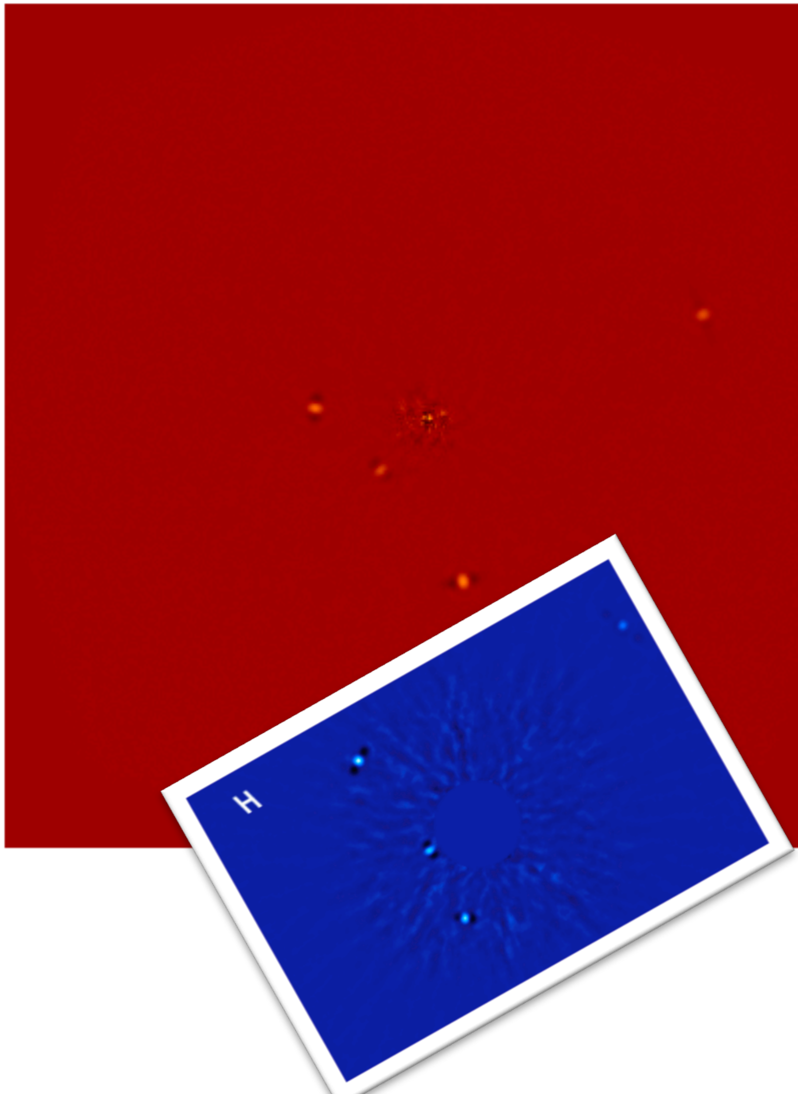
Imaging disks:
Iterative procedure

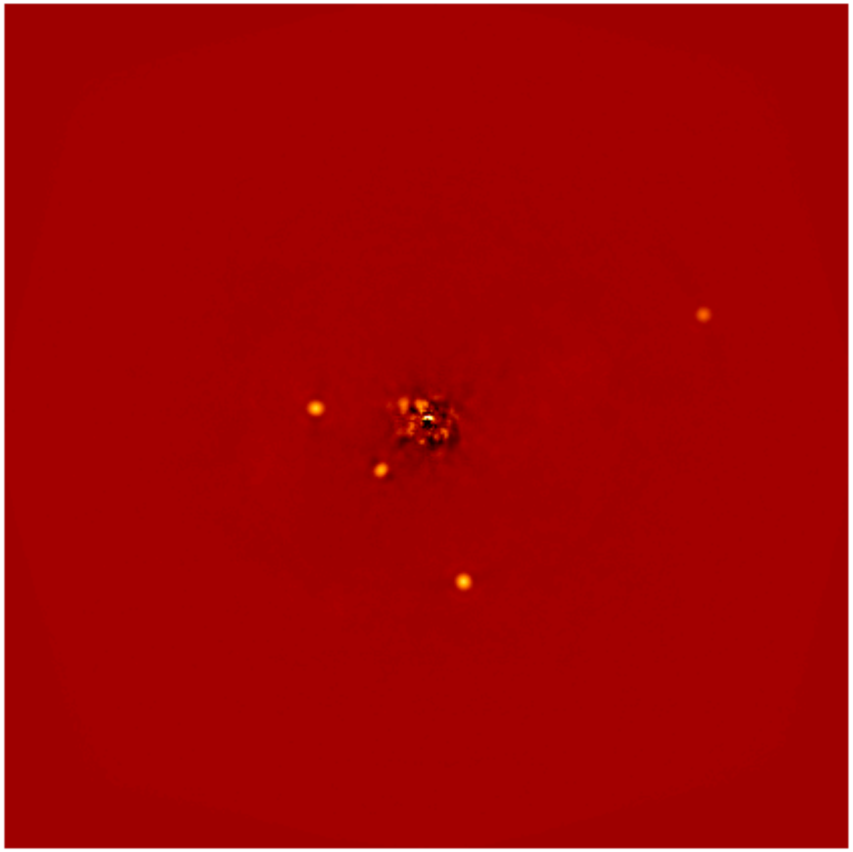




Pairet et al., 2018

Imaging disks:
Iterative procedure

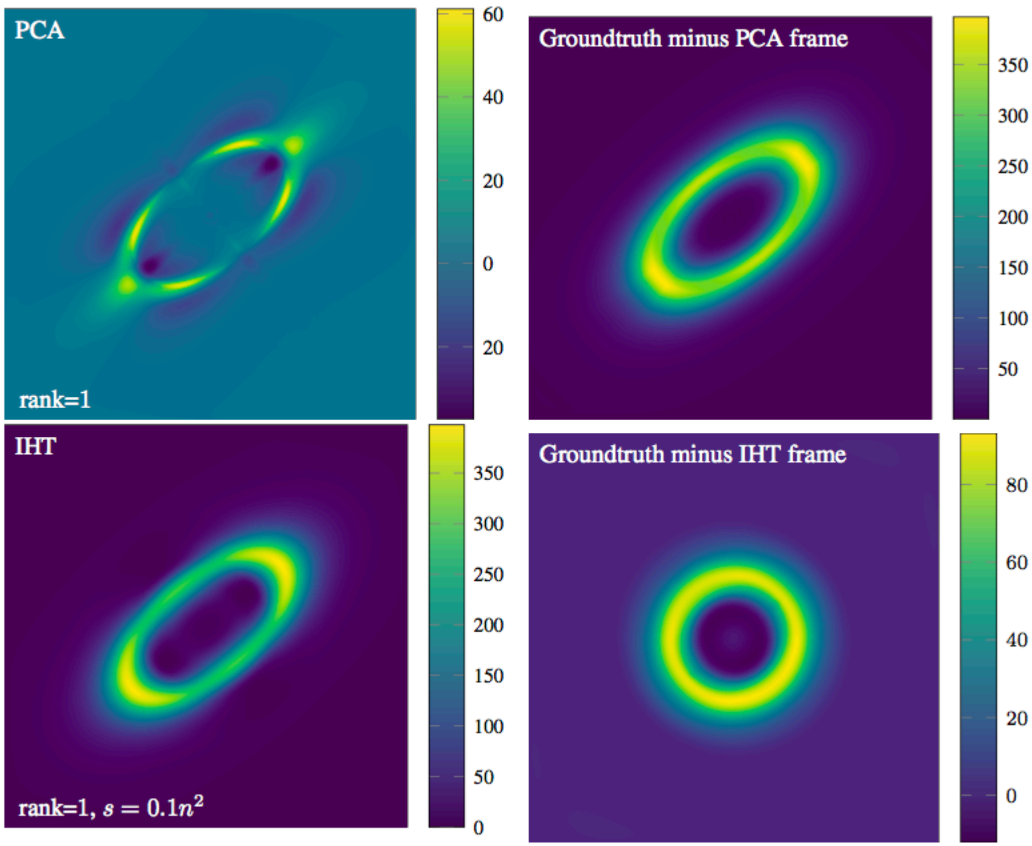




Pairet et al., 2018

Imaging disks:
Inverse problem approach

Unmixing signals with wavelet filtering and iterative approach
IHT: Iterative hard thresholding



On injected disk (GRATER):
-> residual structure to be identified

On-going work with
Université Catholique de Louvain

Pairet et al., in prep.

Conclusion

Post-processing are essential but:

- Robust/unsupervised detection
- Extended objects
- Detection limits

Other perspectives:

- Using different diversities
- Adding the instrument model
- Using meta-data