Post-processing techniques for high-contrast imaging

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Outline

1. Motives and Challenges
2. Post-Processing techniques
3. Data analysis good practices
4. Prospects / developments

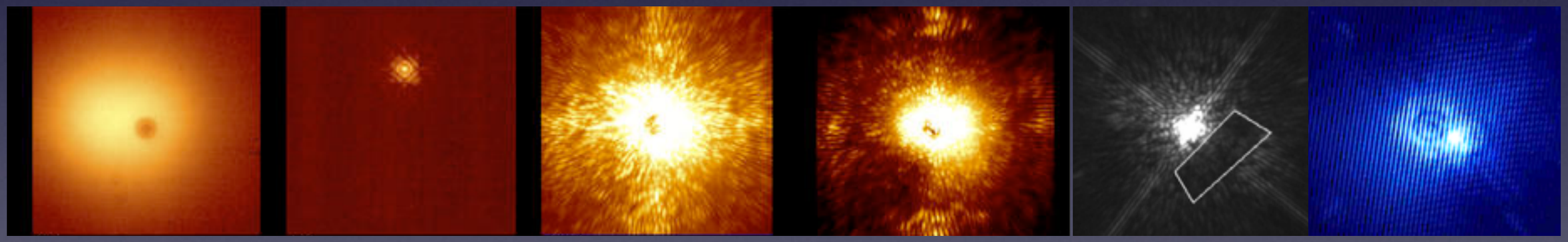
1. Motives & Challenges

High-contrast imaging instruments

Technical steps to optimize starlight suppression

(Ground-based tel.)

Telescope — AO system — Coronagraph — Low-Order WFS/C — Wavefront Shaping — Science Camera

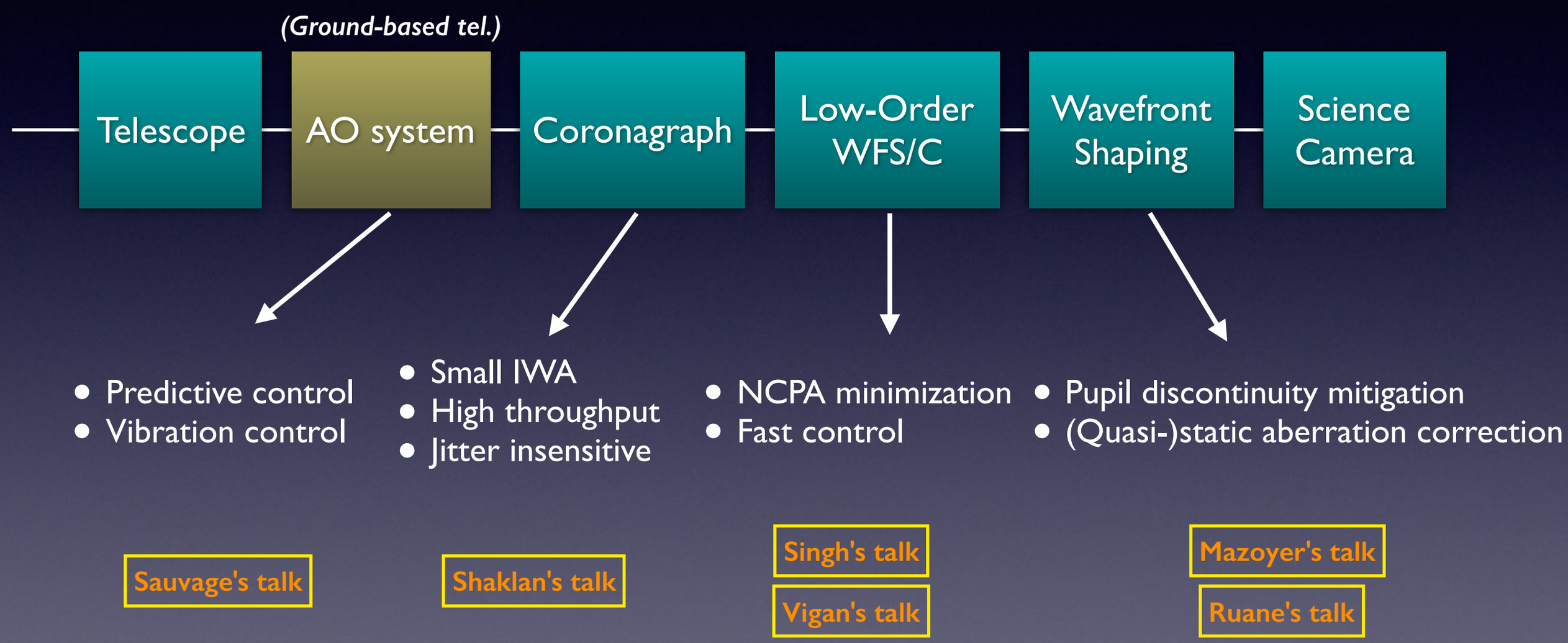


Credit: R. Oppenheimer *Bottom et al. (2016)* *Perrin et al. (2014)*

Contrast gain: x 5-10 x 5-10 x 3-5

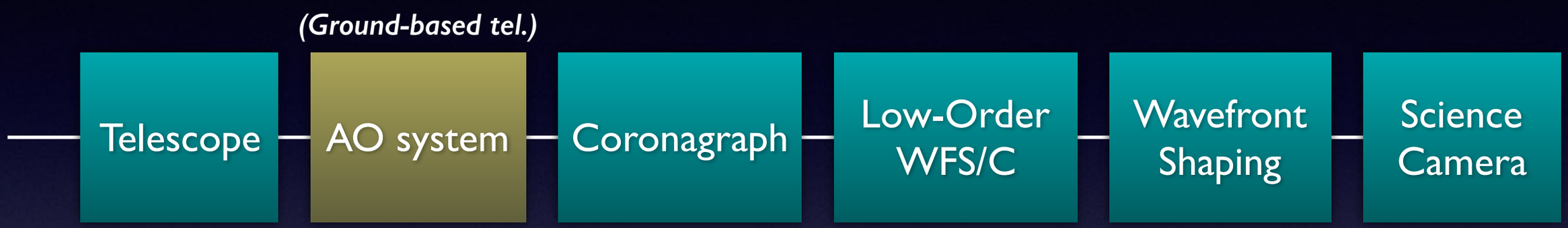
High-contrast imaging instruments

Very active fields of research



High-contrast imaging instruments

Typical raw contrast limits at 5 λ/D



Ground-based tels	HST	Future space missions
~ 10^{-3} - 10^{-4}	~ 10^{-2}	~ 10^{-8} - 10^{-9}

High-contrast imaging instruments

Typical raw contrast limits at 5 λ/D

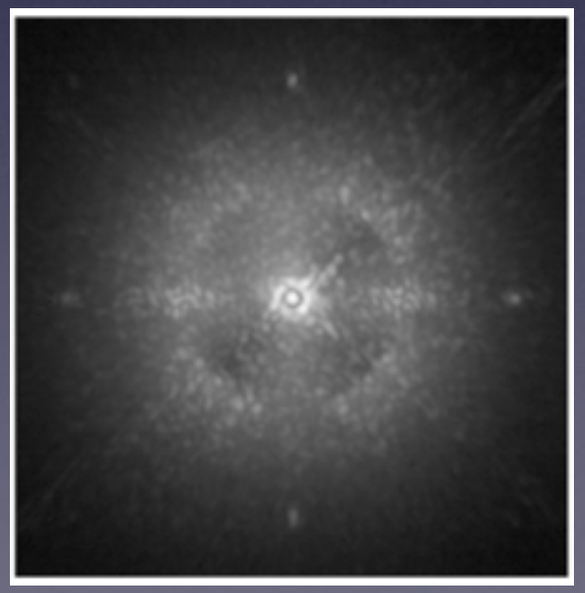
(Ground-based tel.)

No matter how well the instrument is designed, there will always be residual starlight in the science image

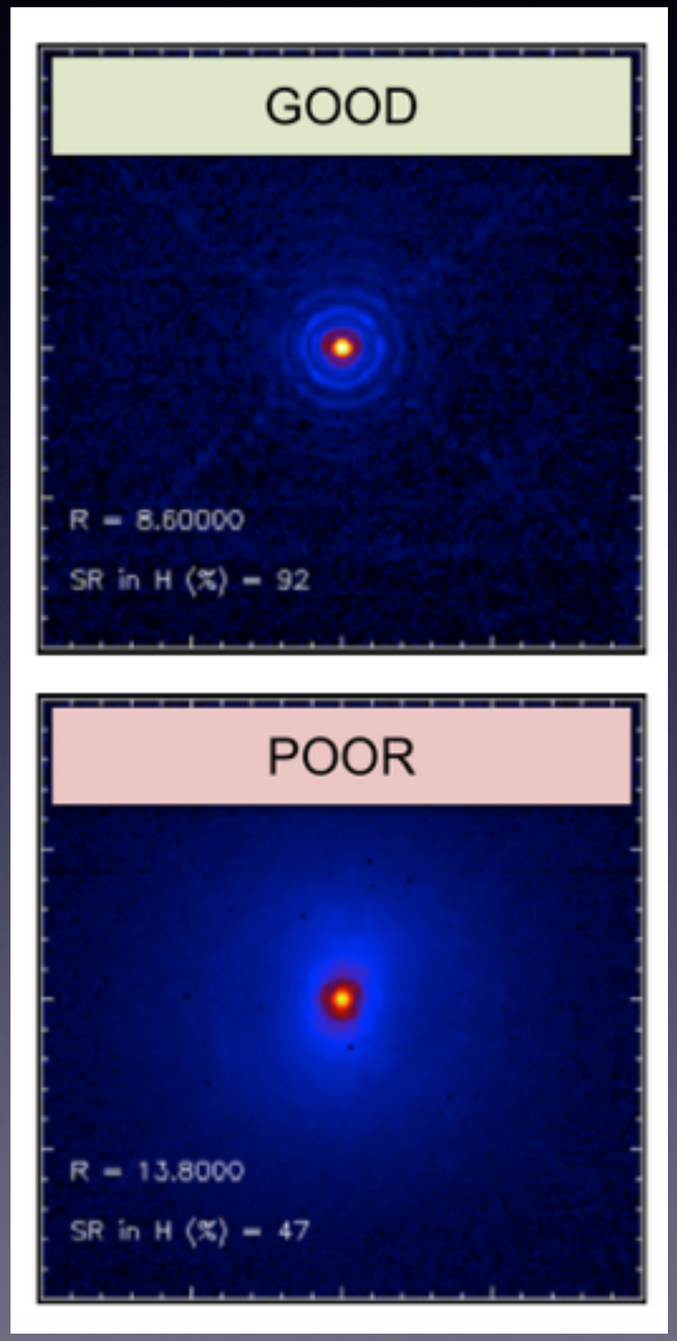
Speckle temporal variations

Fast speckles

- t < exposure time
- AO residual
- Average on a large Halo
- Can be subtracted or filtered out



SPHERE manual

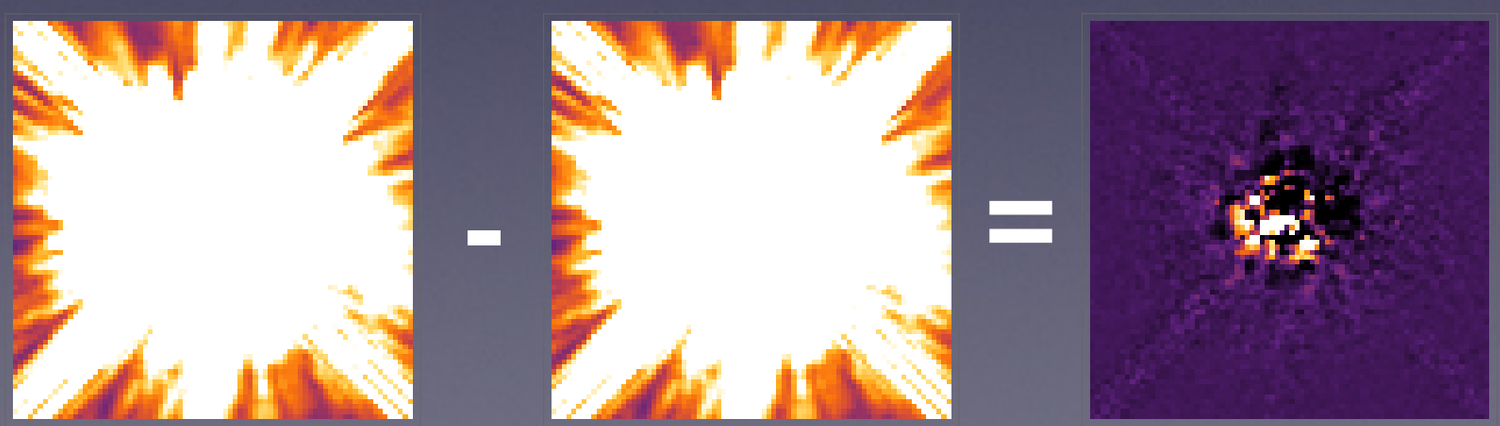


Speckle temporal variations

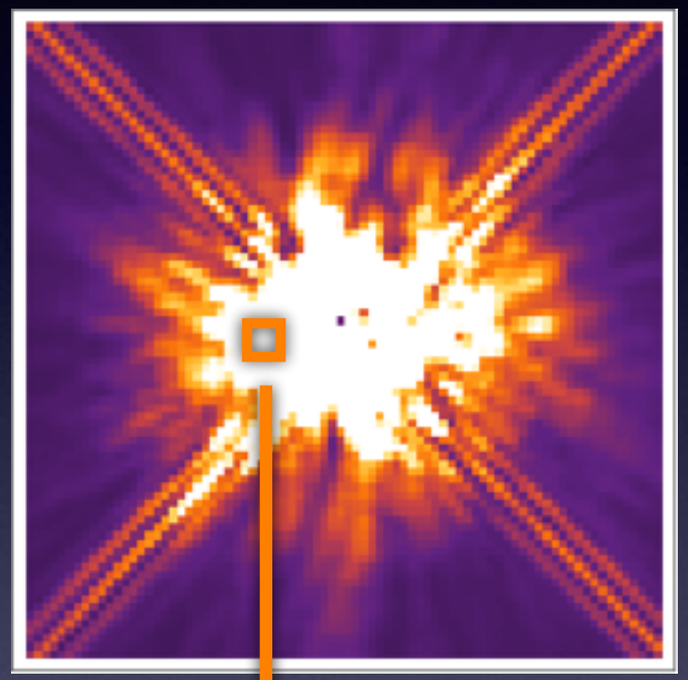
Quasi-static speckles

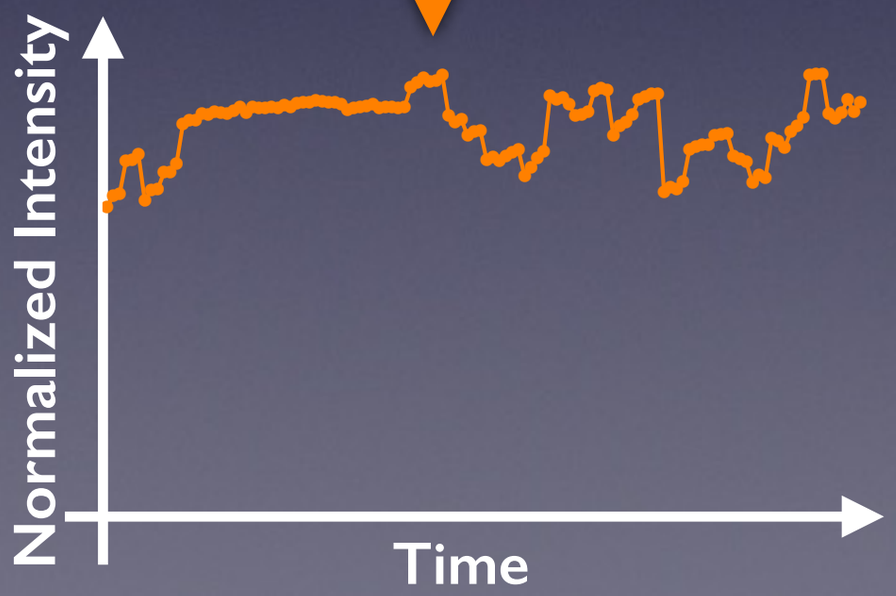
- t ~ exposure time
- instrumental deformations
- Worse lifetime possible

Differential Imaging
is not enough



HST - NICMOS F160W



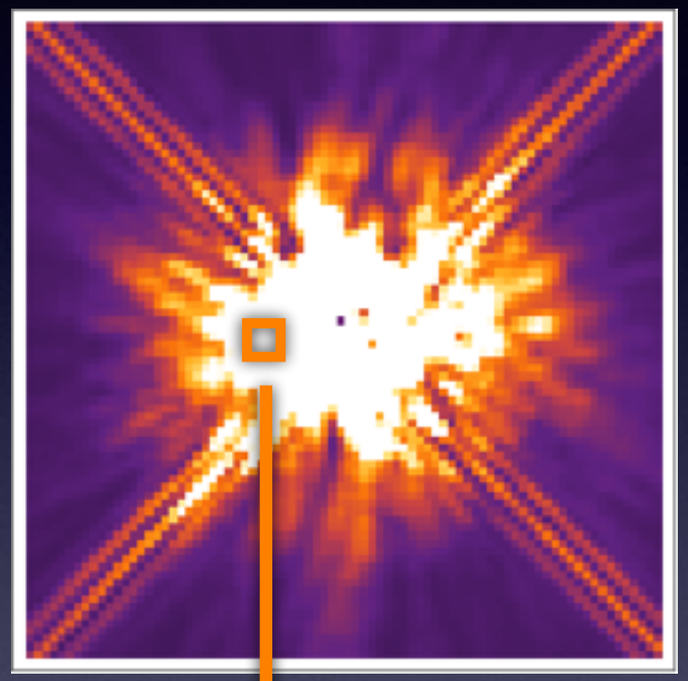


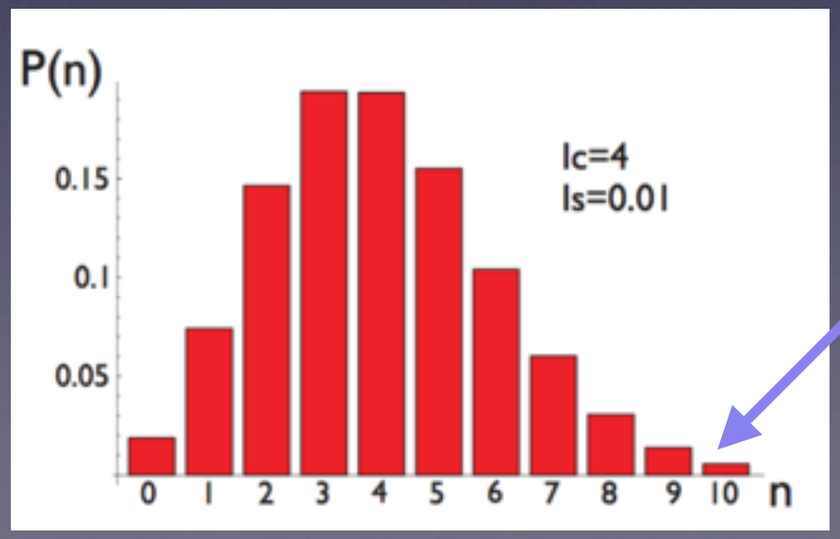
Speckle temporal variations

Quasi-static speckles

- Quasi-static speckles:
  - instrumental deformations
  - t ~ exposure time
  - Worse lifetime possible
  - Follow a modified Rician distribution

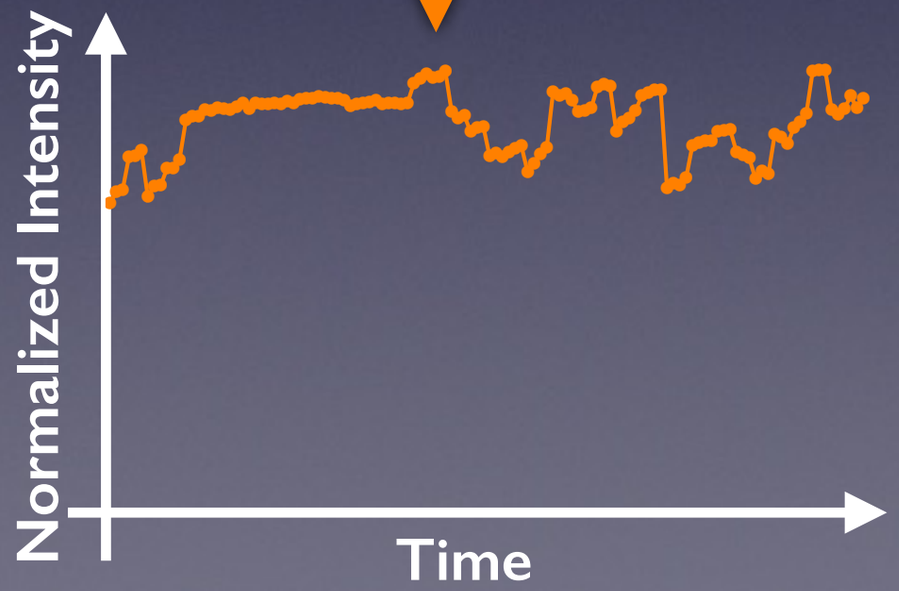
HST - NICMOS F160W





Long tail:
Mimic planets

Soummer & Aime 2004
Soummer et al. 2007
Marois et al. 2008



Motives & Challenges

Take-home messages

Fundamental limit to differential imaging : Instrument stability
Post-processing always helps improving detection limits

Speckle variation are hard to predict
On-going efforts to use models for post-processing

State-of-the art:

100% of current post-processing methods use data itself
to build empirical models from many speckle noise realizations

2. Post-processing techniques

2. Post-processing techniques

cADI
rADI
smartADI
ASDI
ADI
BDI
ODI
Pynpoint
DBI
PCA
SSDI
S4
KLIP
LLSG
RDI**
MRDI
RDI*
TLOCI
LOCI
MLOCI
dLOCI
PDI
SDI

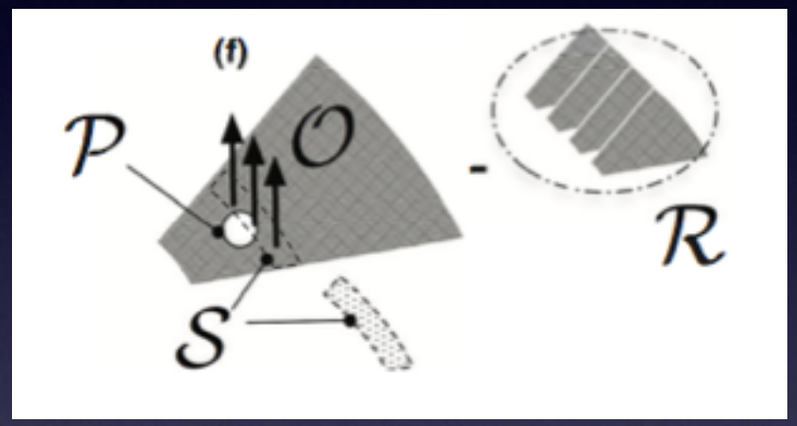
* Roll Differential Imaging
** Reference star Differential Imaging

How to sort that out?

PSF template(s)

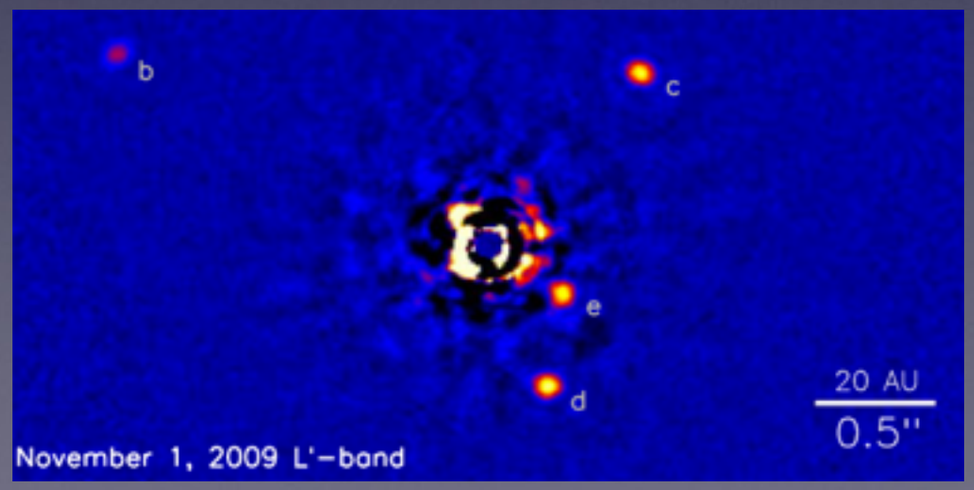
Post-processing algorithm

+



Pueyo et al. 2012

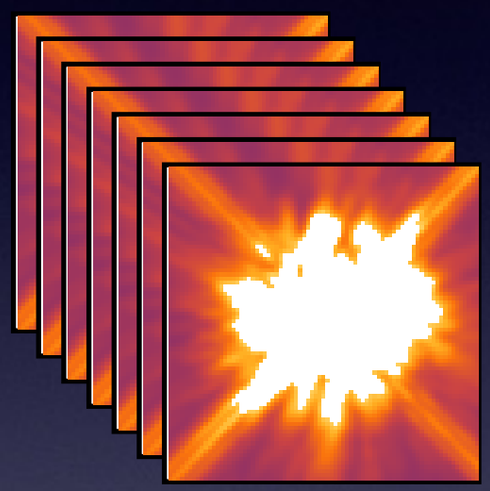
PSF subtraction

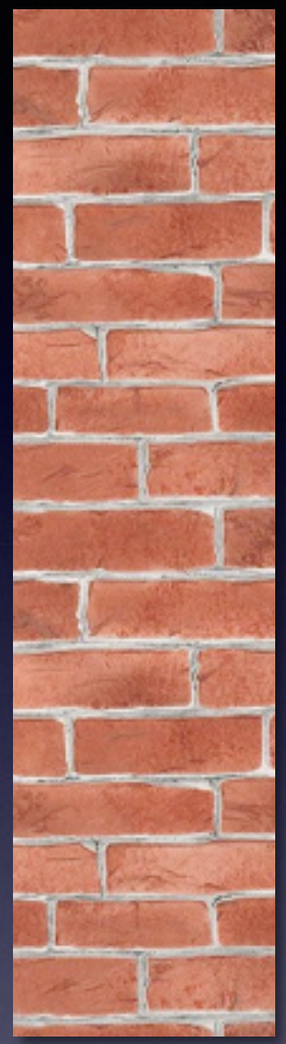


Marois et al. 2010

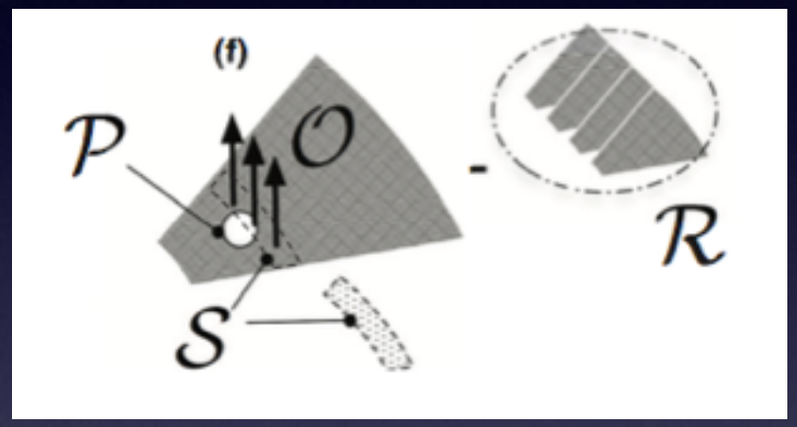
How to sort that out?

PSF template(s)



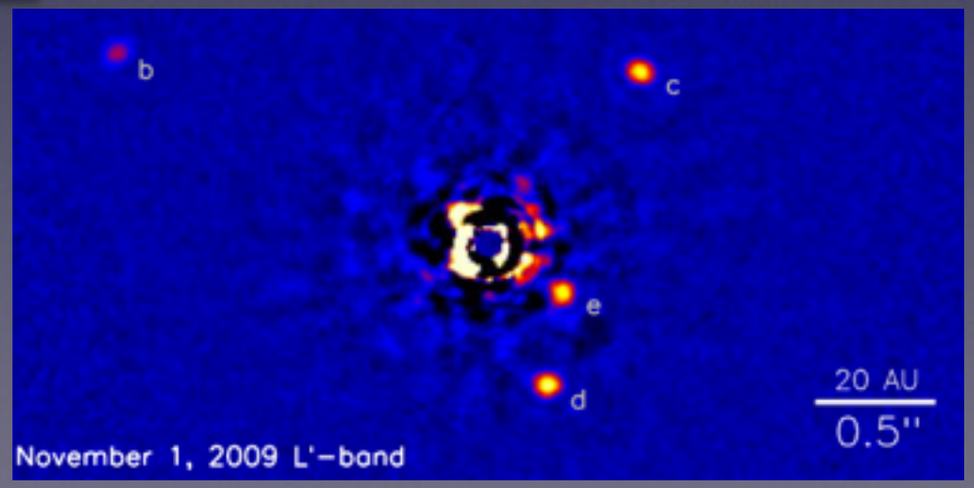


Post-processing algorithm



Pueyo et al. 2012

PSF subtraction



Marois et al. 2010

How to sort out?

Pynpoint

c-ADI

ASDI

BDI

S4

PCA

rADI

temp ADI s)

Po DBI rocessing algor KLIP

smart-ADI

ODI

SSDI

LSSG

RDI**

PDI

SDI

MRDI

RDI*

TLOCI

LOCI

MLOCI

DLOCI

* Roll Differential Imaging
** Reference star Differential Imaging

How to sort that out?

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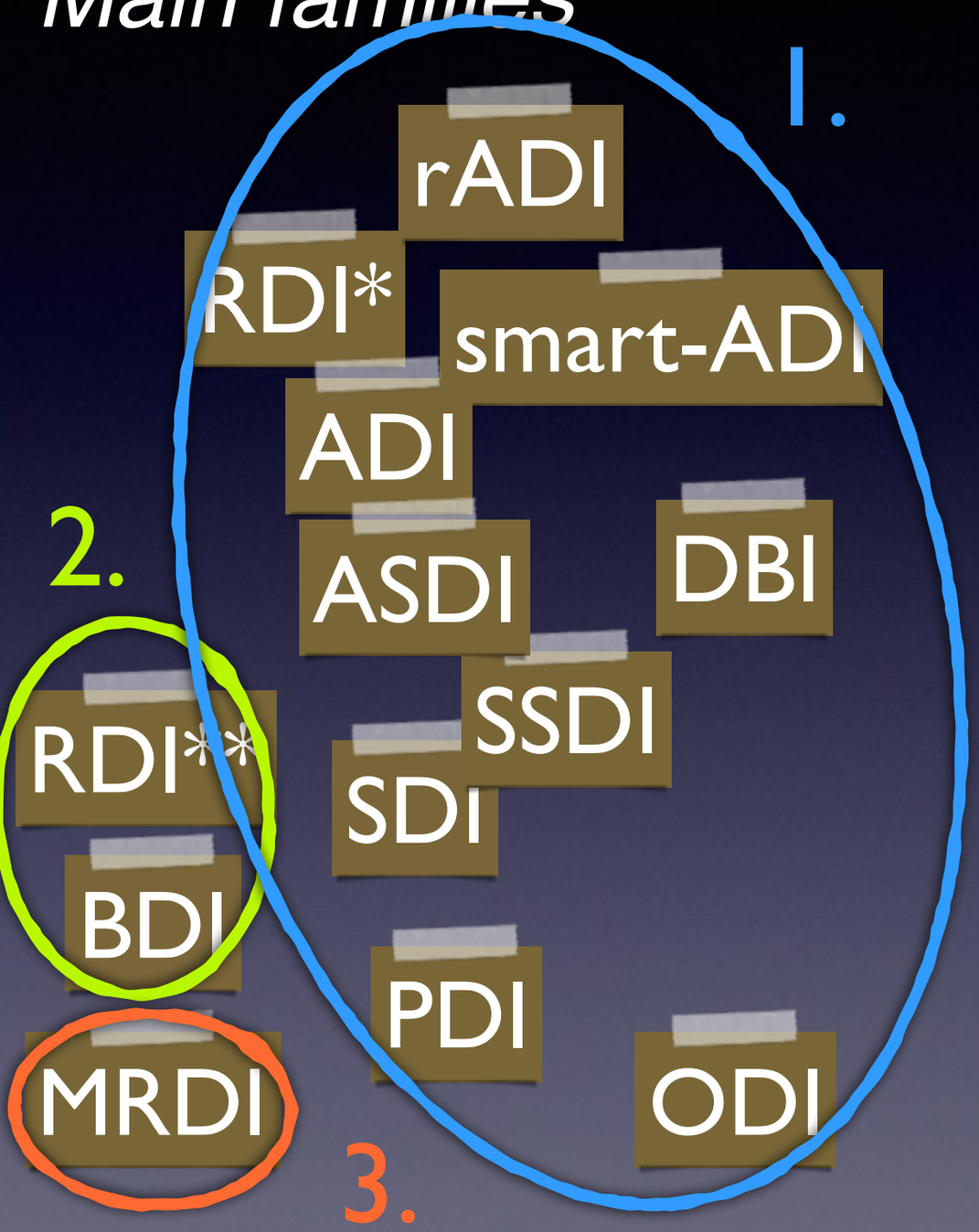
PSF Template(s)

Main families



1. Uses the Science Target
   - Needs some diversity
   - Induces self-subtraction
   - No chromatic artifacts

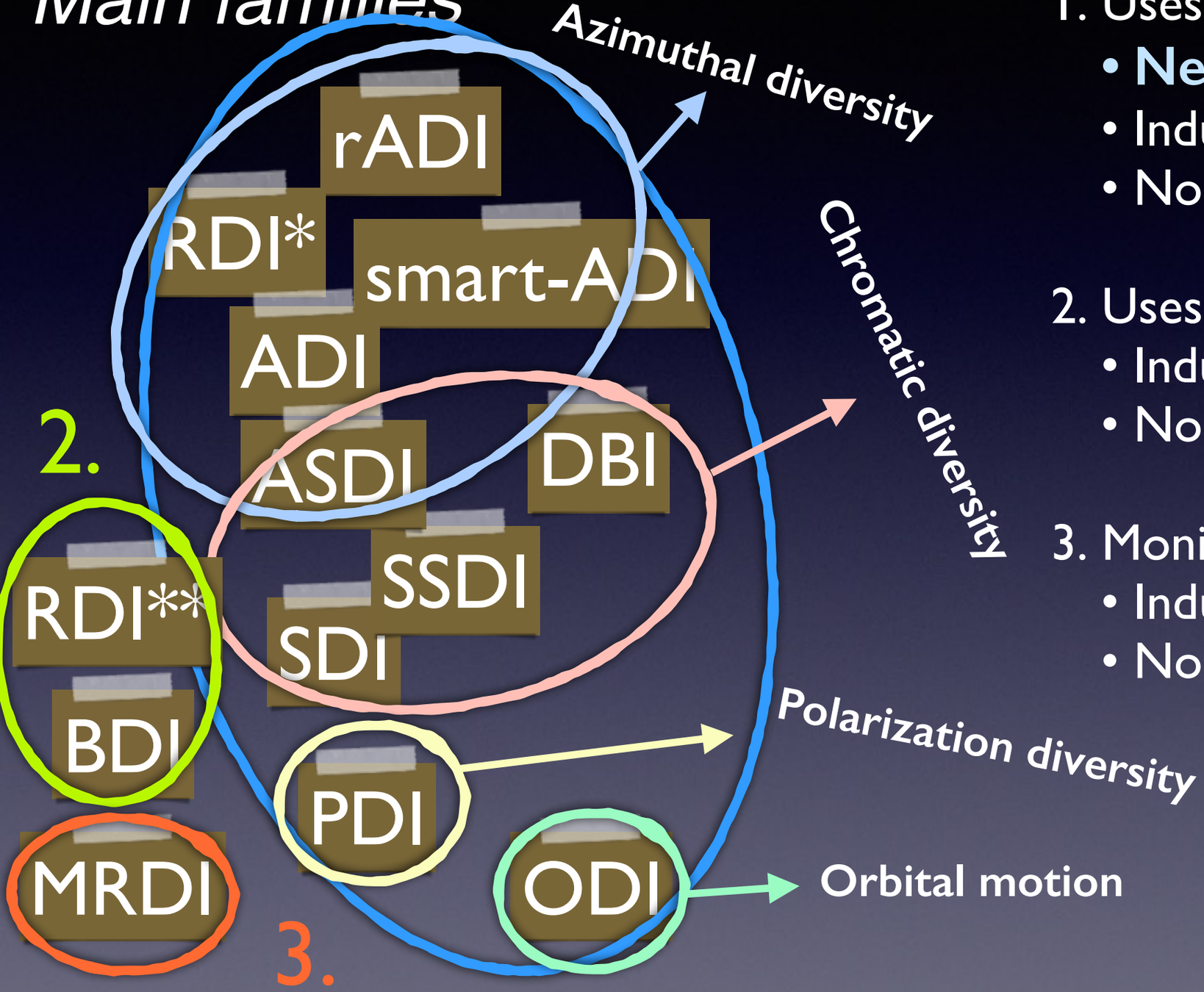
2. Uses a Reference Star
   - Induces chromatic artifacts
   - No self-subtraction

3. Monitors the instrument PSF
   - Induces chromatic artifacts
   - No self-subtraction

* Roll Differential Imaging
** Reference star Differential Imaging

PSF Template(s)

Main families



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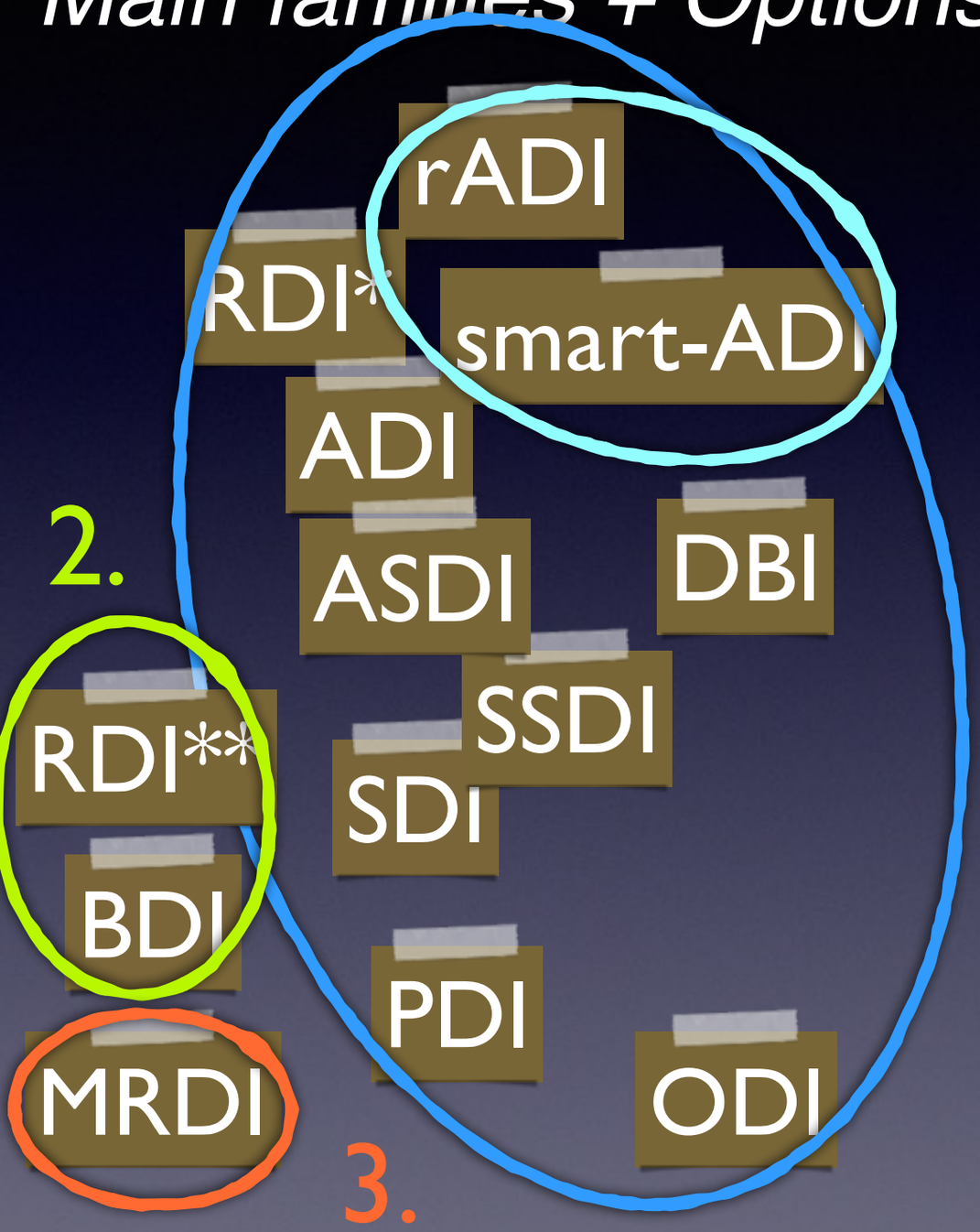
** Reference star Differential Imaging

PSF Template(s)

Main families + Options



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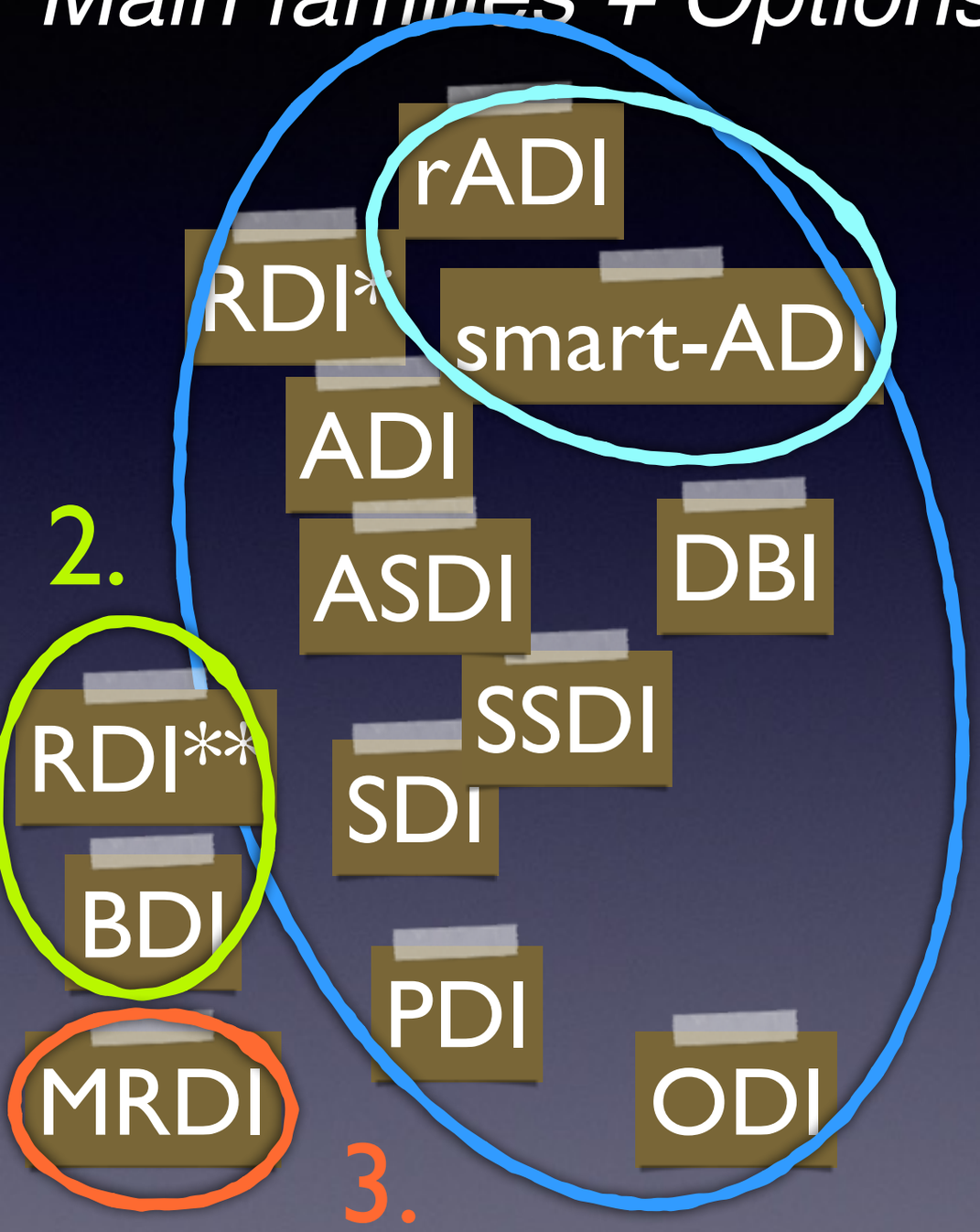
+ Frame selection

* Roll Differential Imaging
** Reference star Differential Imaging

PSF Template(s)

Main families + Options



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3. Monitors the instrument PSF
   - Induces chromatic artifacts
   - No self-subtraction

+ Frame selection

- exclusion angle
- exclusion bandpass
- frame correlation

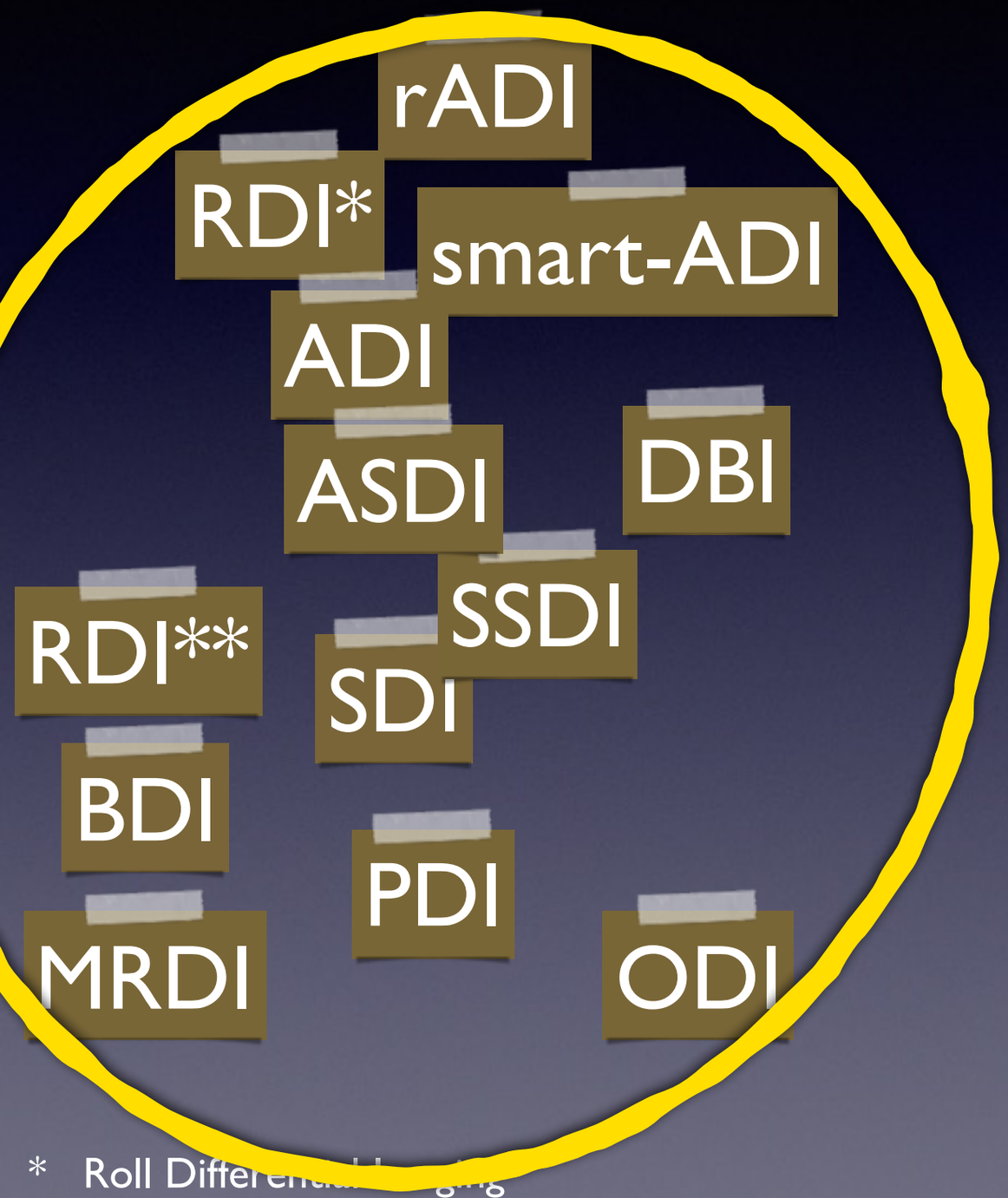
Not Specific to ADI!

* Roll Differential Imaging

** Reference star Differential Imaging

PSF Template(s)

Main families + Options



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** Reference star Differential Imaging

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3. Monitors the instrument PSF
   - Induces chromatic artifacts
   - No self-subtraction

+ Frame selection

+ Union of several methods

- ADI + SSDI
- SDI + RDI
- etc.

PSF Template(s)

Take home messages

No optimal rule, depends on practical reasons, instrument stability...

Do the best you can to assemble a PSF library while:

- having a sample representative of the speckle noise in the science data
- limiting self-subtraction impact

Post-processing algorithm

c-ADI

Pynpoint

KLIP

PCA

S4

TLOCI

MLOCI

LOCI

LSSG

DLOCI

Post-processing algorithm

Main families

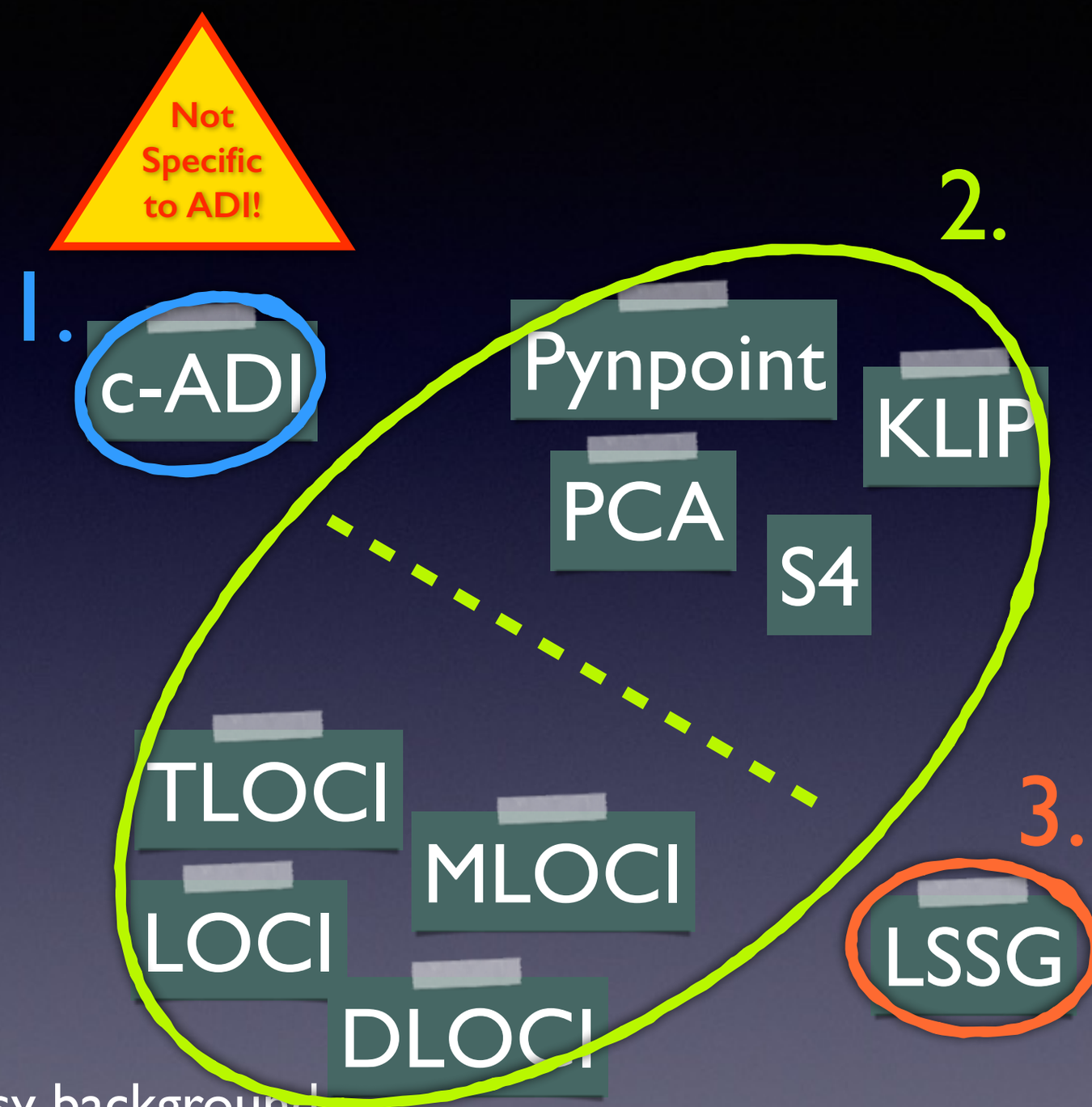
1. Classical subtraction (mean / median)
   - independent of the astro signal
   - don't account for speckle variations

2. Solve the least-square problem:

$$\min_{\{c_k\}} ||T - \sum_k^K c_k R_k||^2$$

R_k = reference images : LOCI-type
R_k = eigen-images : PCA-type

3. Low-rank + Sparse decomposition
   - Isolate a moving object on a fixed noisy background
   - join identification, rather than PSF subtraction



Post-processing algorithm

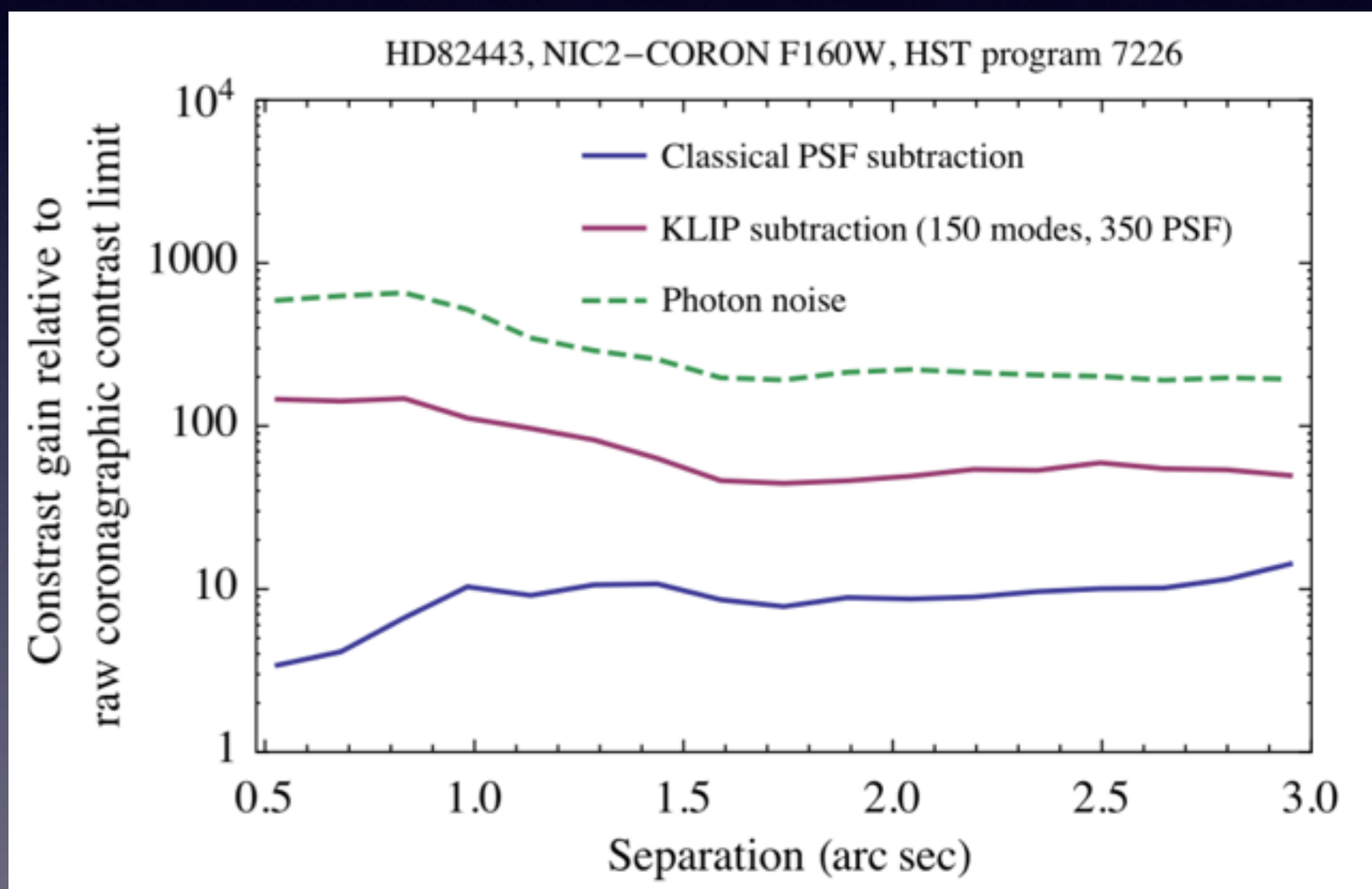
Main characteristics

Method	Applies to any PSF library	Locally optimizable	Over-subtraction Free	Disk friendly
Classical (mean / median)	√	X	√	√
LOCI & PCA & derivatives	√	√	X	√
LSSG	**X (ADI/SDI)**	√	X	X

Post-processing algorithm

Performances

Depends on the speckle noise statistics!



Debes et al. 2016

Contrast gain:

PCA

Classical

x 10-20

Raw data

x 5-10

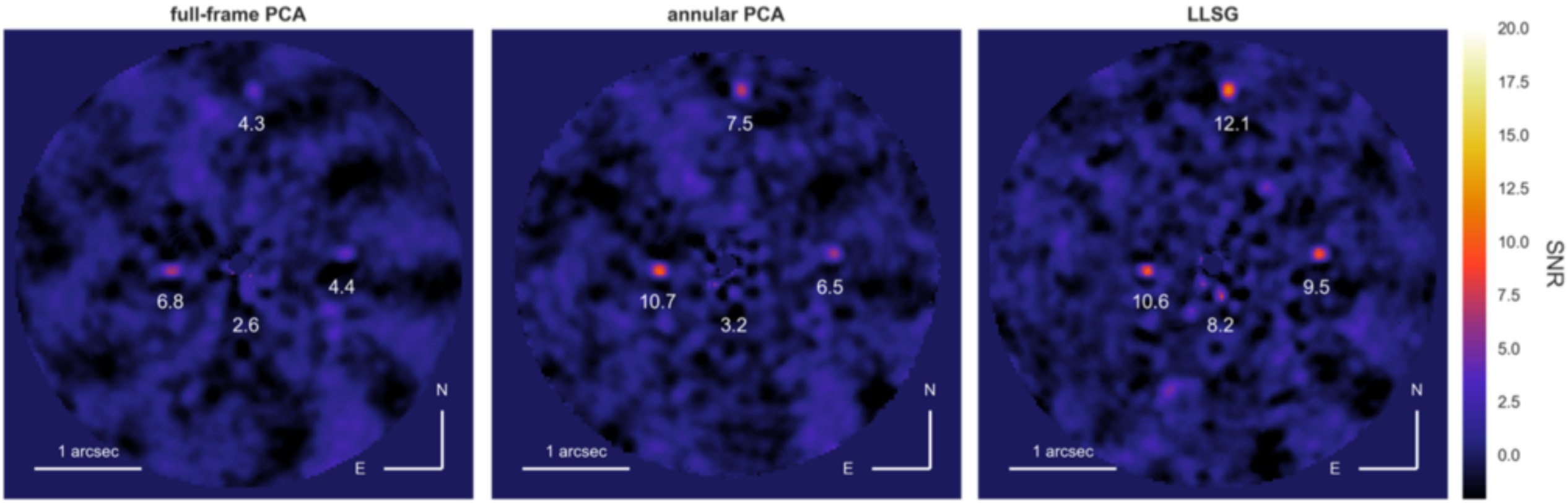
Post-processing algorithm

Performances

Contrast gain:

Locally optimized :
x 1.5 - 2

LLSG vs PCA
x 1 - 2.5

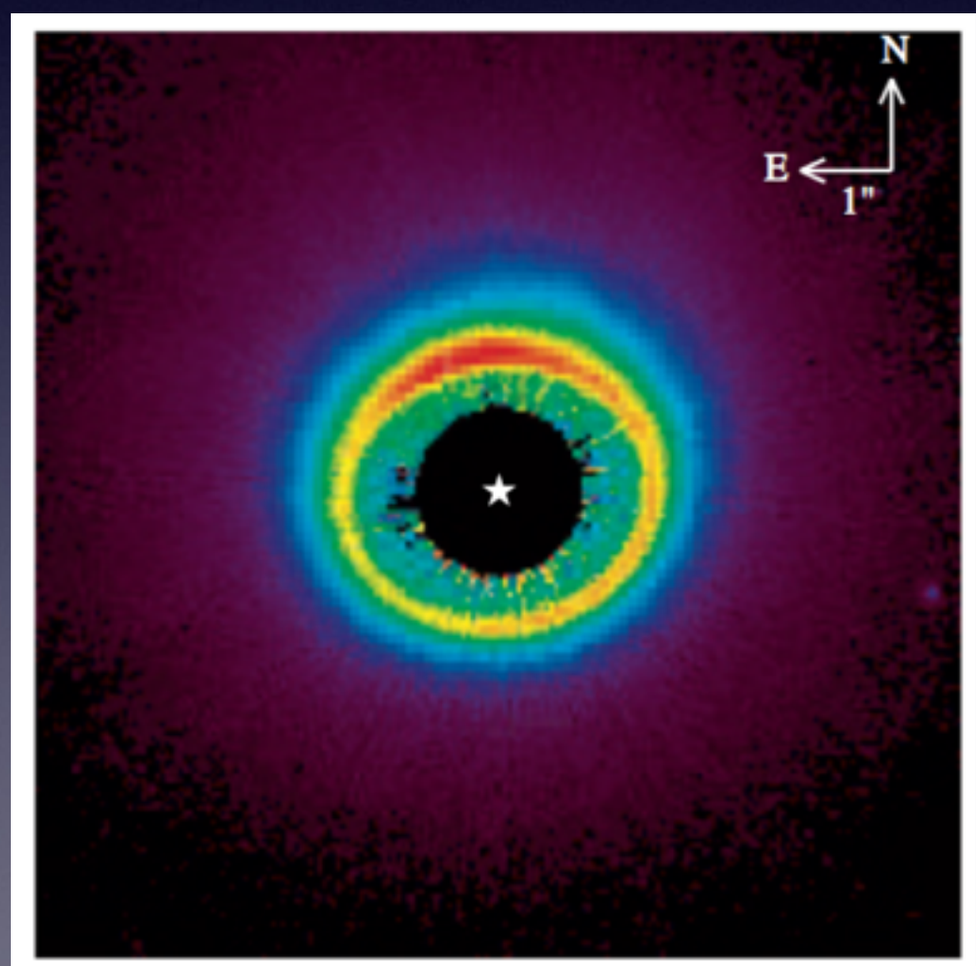


Gomez Gonzalez et al. 2016

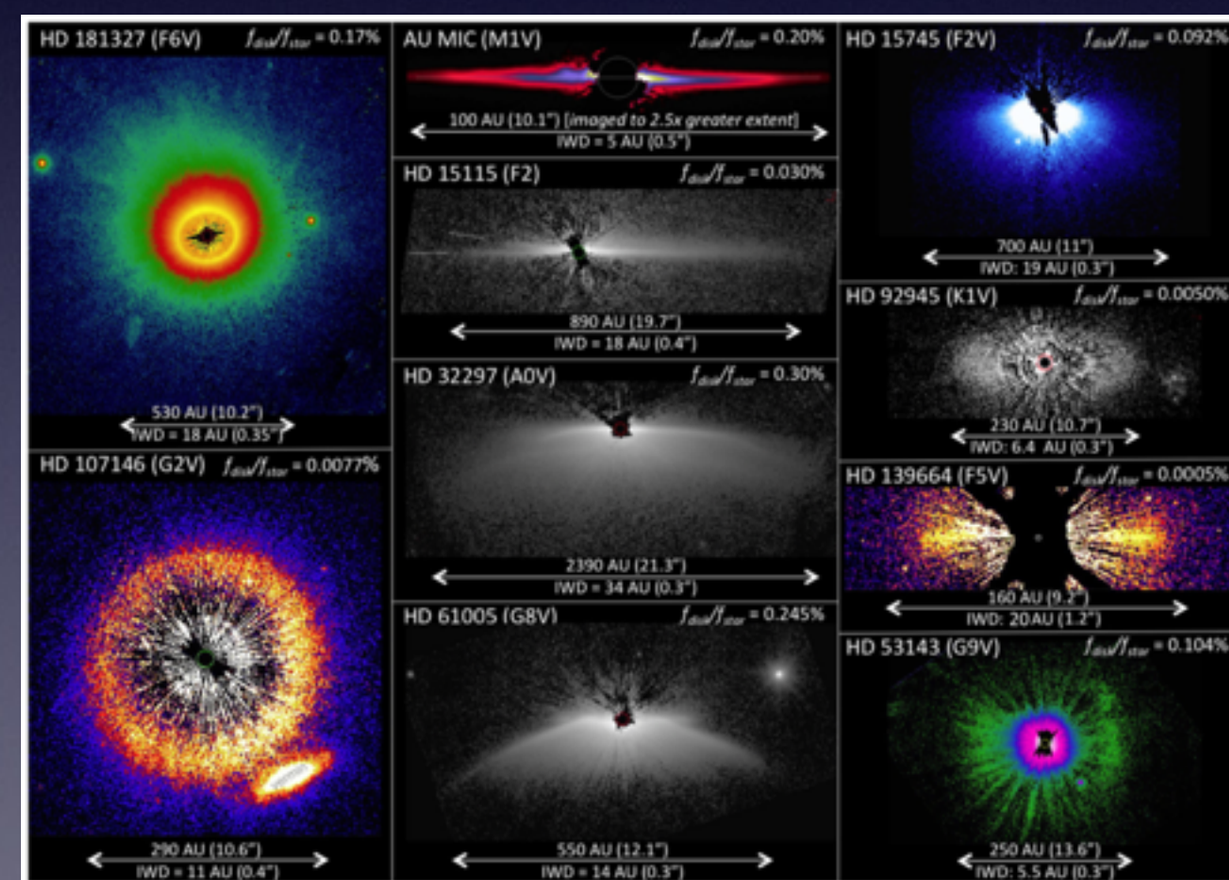
Post-processing algorithm

Some results

RDI + Classical algorithm :
Great for disk imaging



Stark et al. 2014



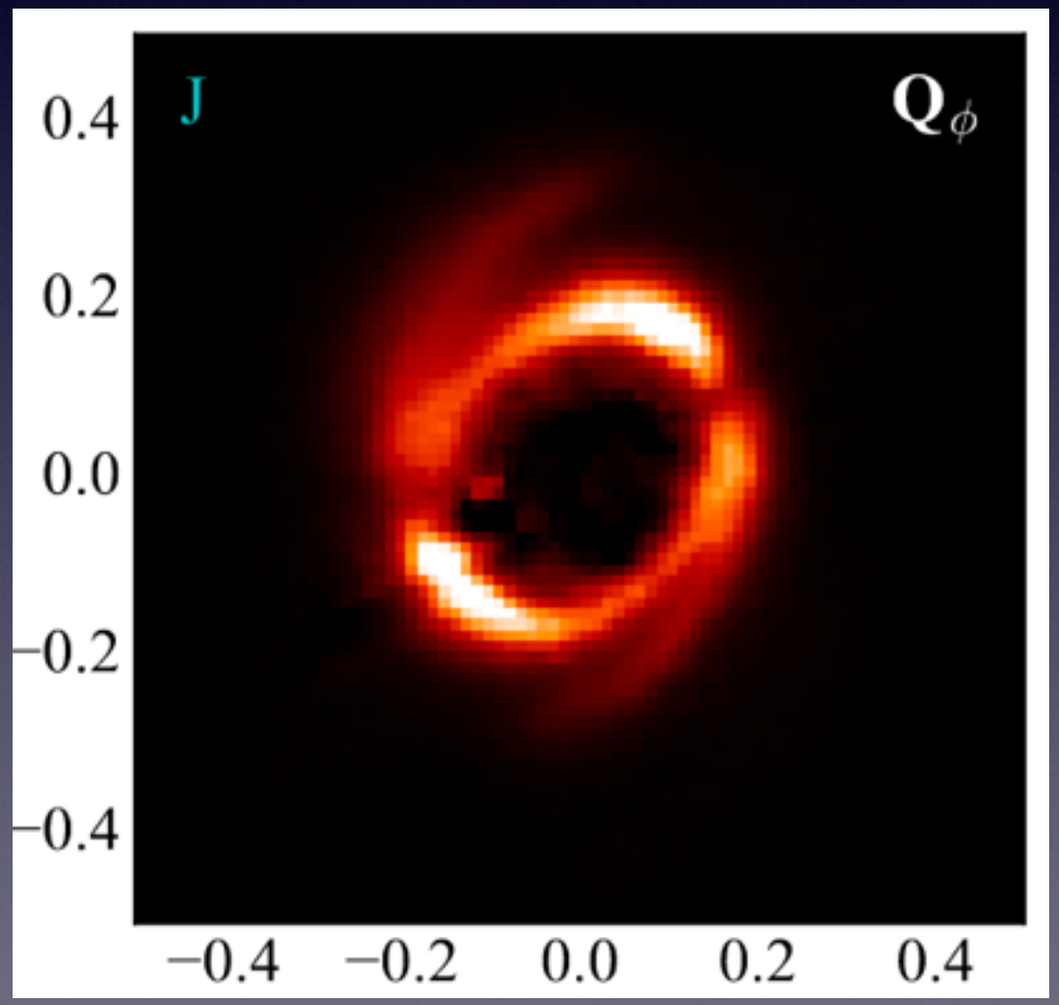
Schneider et al. 2014

HST-STIS

Post-processing algorithm

Some results

PDI + Classical algorithm :
Great for disk characterization



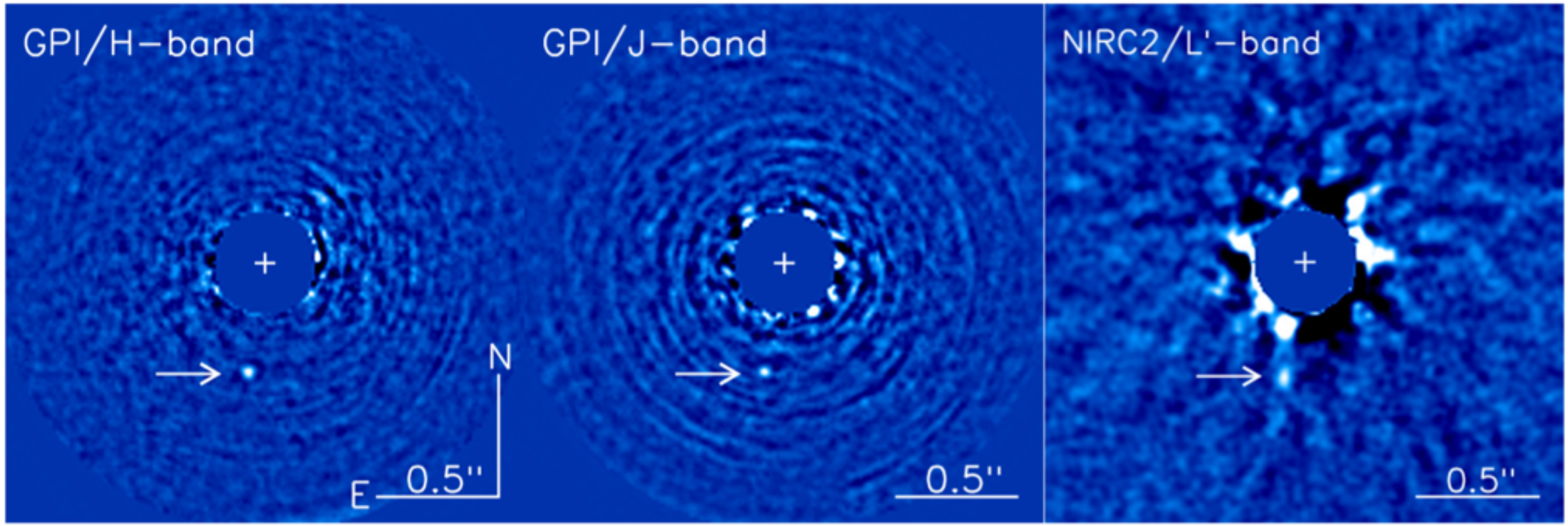
Benisty et al. 2016

VLT-SPHERE

Post-processing algorithm

Some results

ADI-SDI + PCA/LOCI :
Great for planet detection



Macintosh et al. 2015

3. Data Analysis
Good practices

Forward Modeling

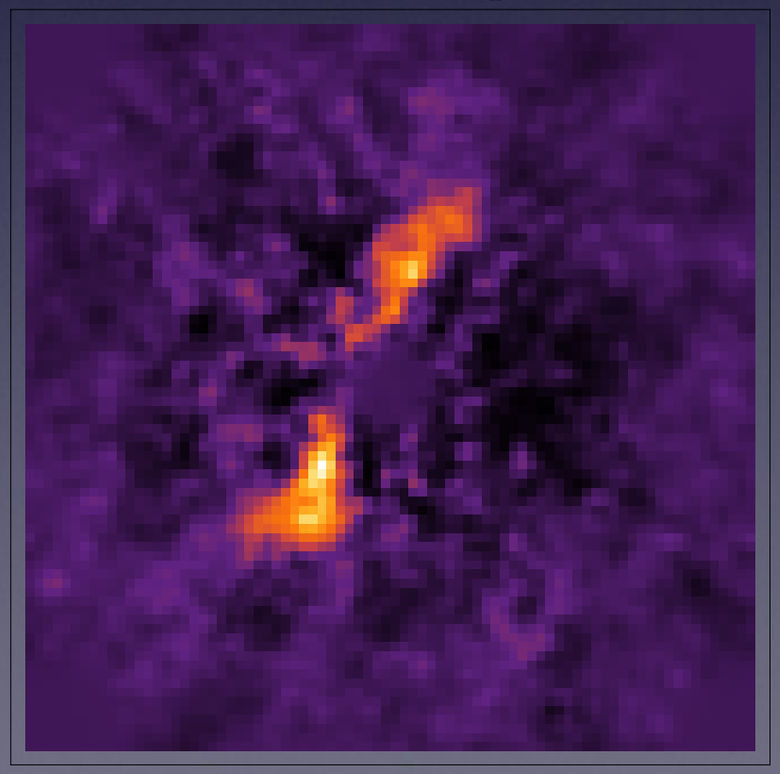
Post-processing artifacts

Self-subtraction &/or over-subtraction:

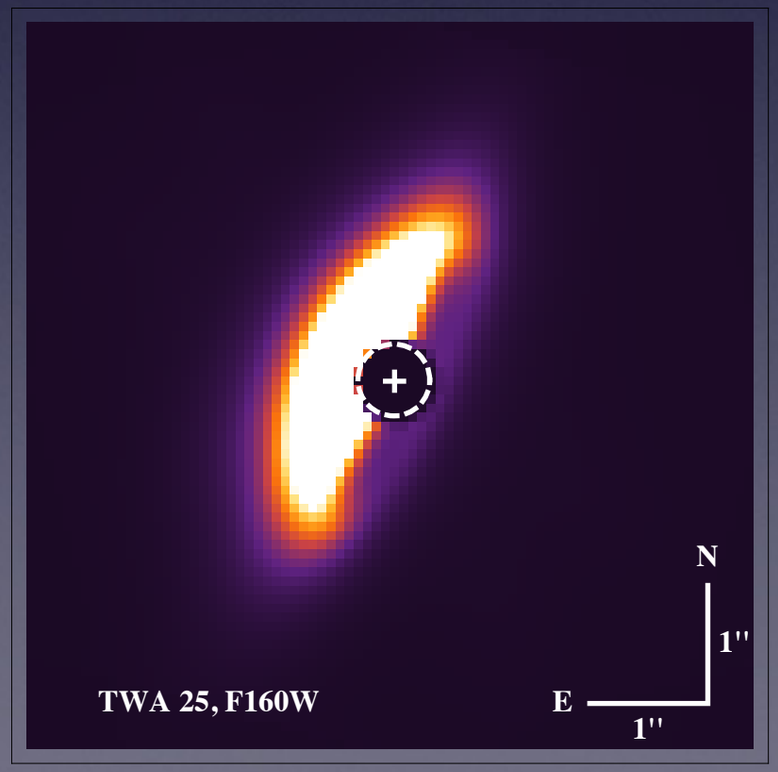
Affects both:

- Astrometry / morphology
- Photometry

Disk image



Disk model

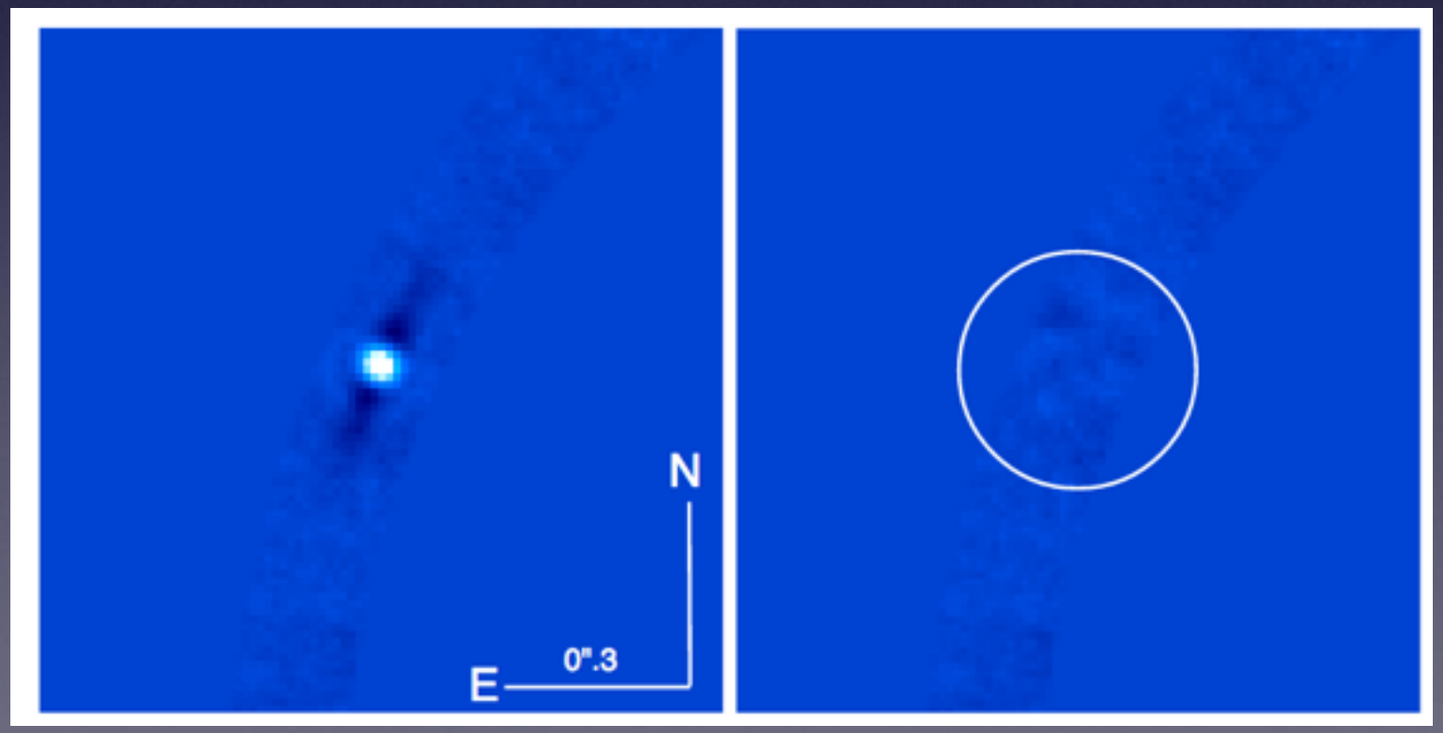


Choquet et al. 2016

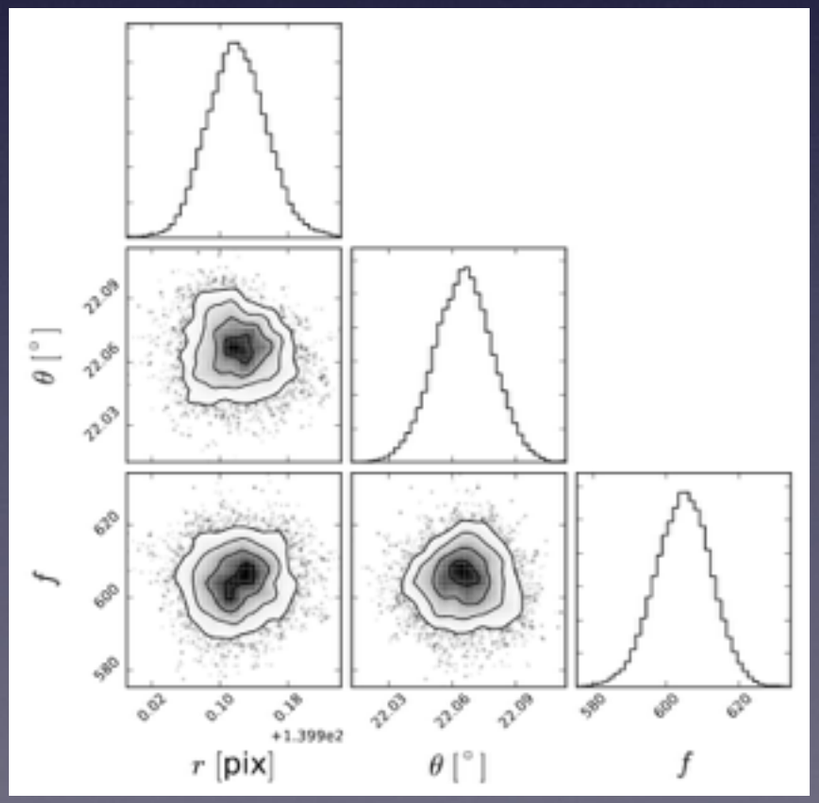
Forward Modeling

Negative model injection (brute force)

- Inject models of the object in the raw data
- Re-reduce the data
- Measure the residuals
- Repeat for many different models (grids, MCMC...)



Wertz et al. 2016

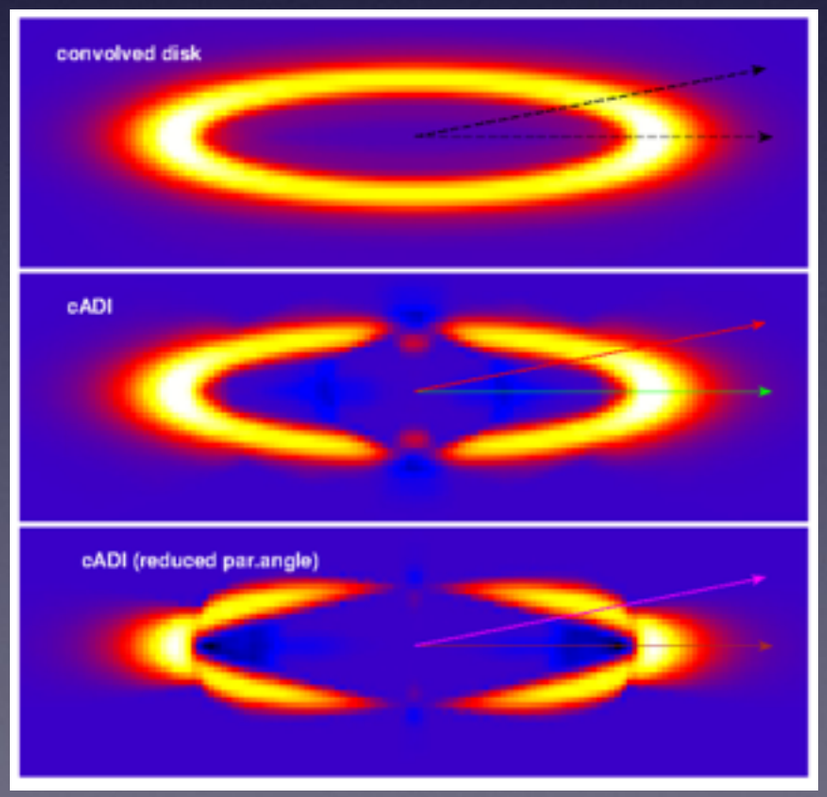


Forward Modeling

Analytical way

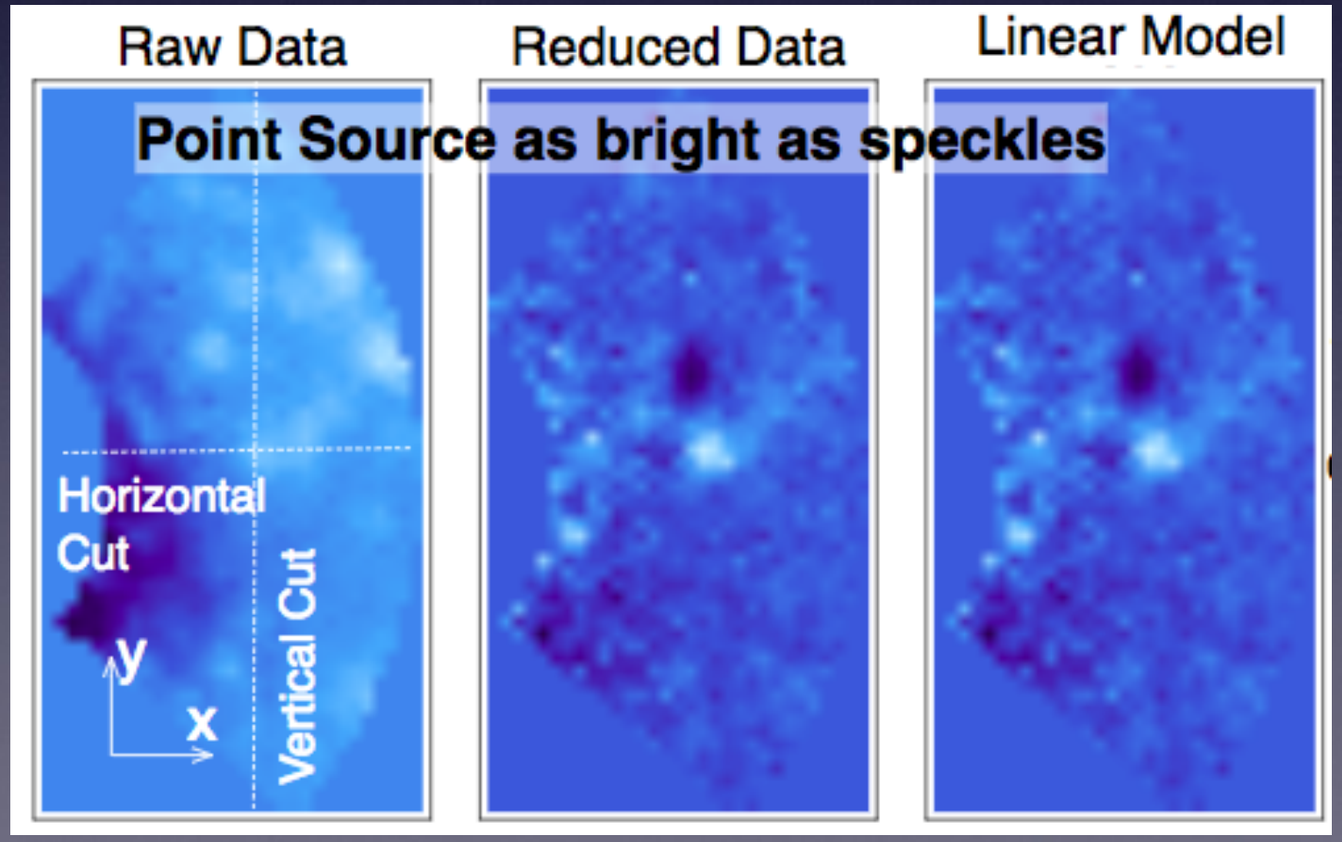
- Measure the effect of post-processing on the model
- Without re-processing the data for each model

Mean PSF subtraction:



Milli et al. 2012

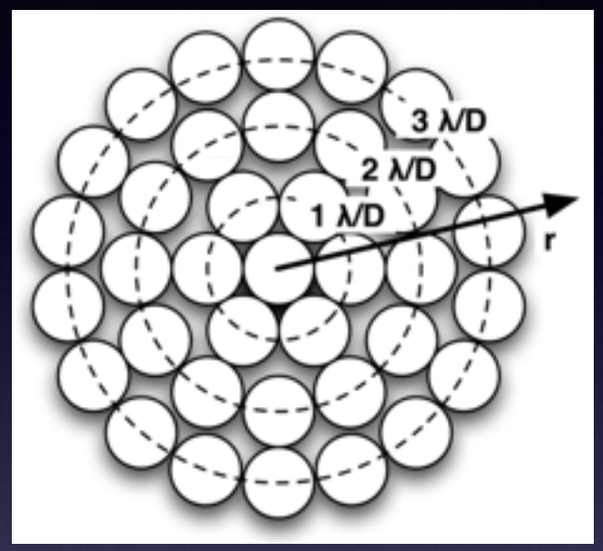
KLIP - FM

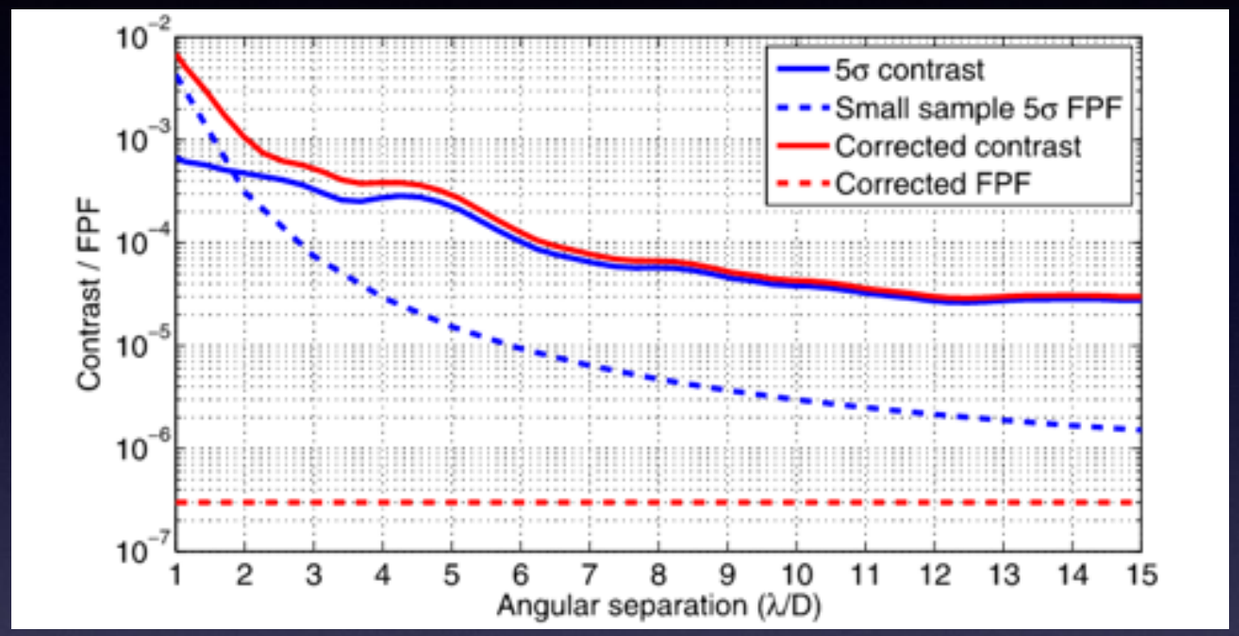


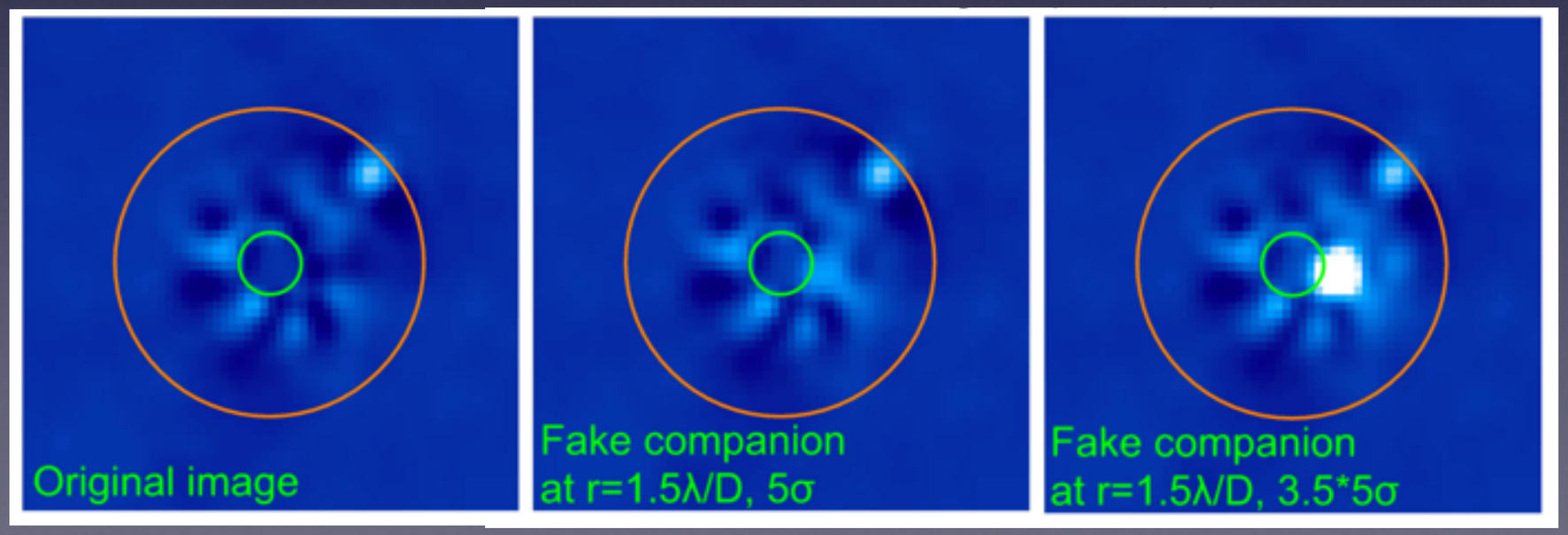
Pueyo 2016

Small sample statistics

Affects confidence limits



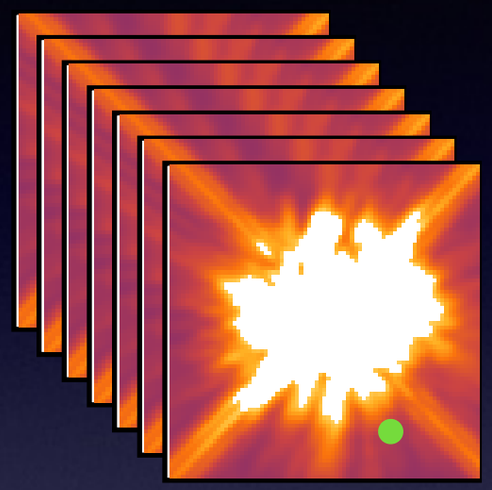




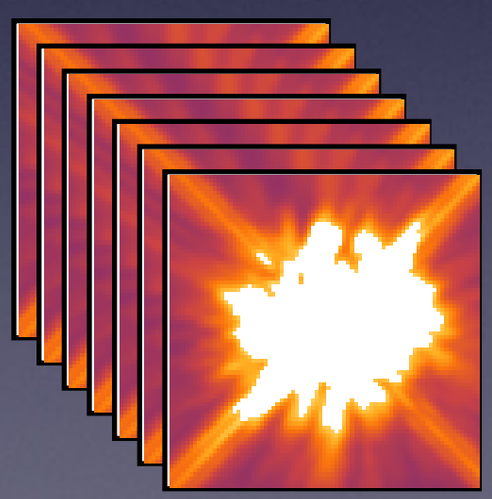
Mawet et al. 2014

Completeness of a detection method

Receiver Operating Characteristics (ROC)



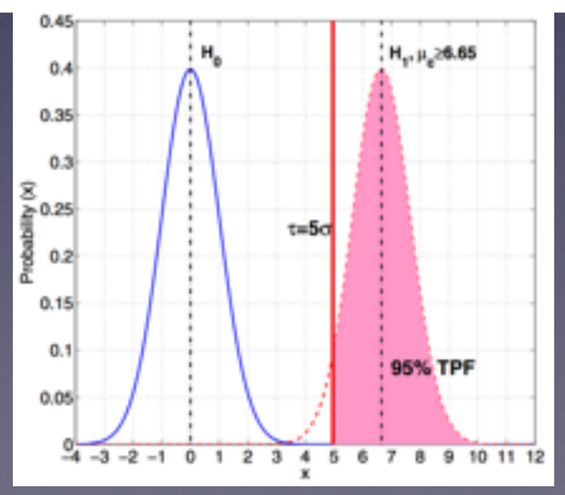
Fake planet injected



Control sample

Reduce

Classifier (significance threshold τ)



Mawet et al. 2014

True Positive rate
False Negative rate

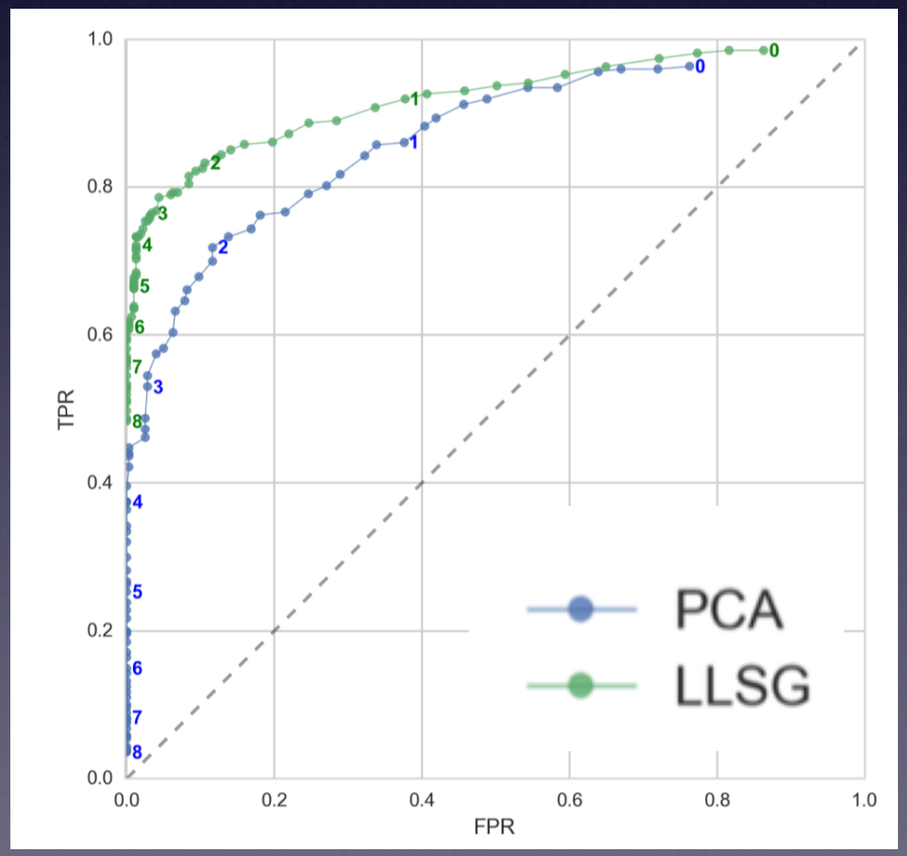
True Negative rate
False Positive rate

Completeness of a detection method

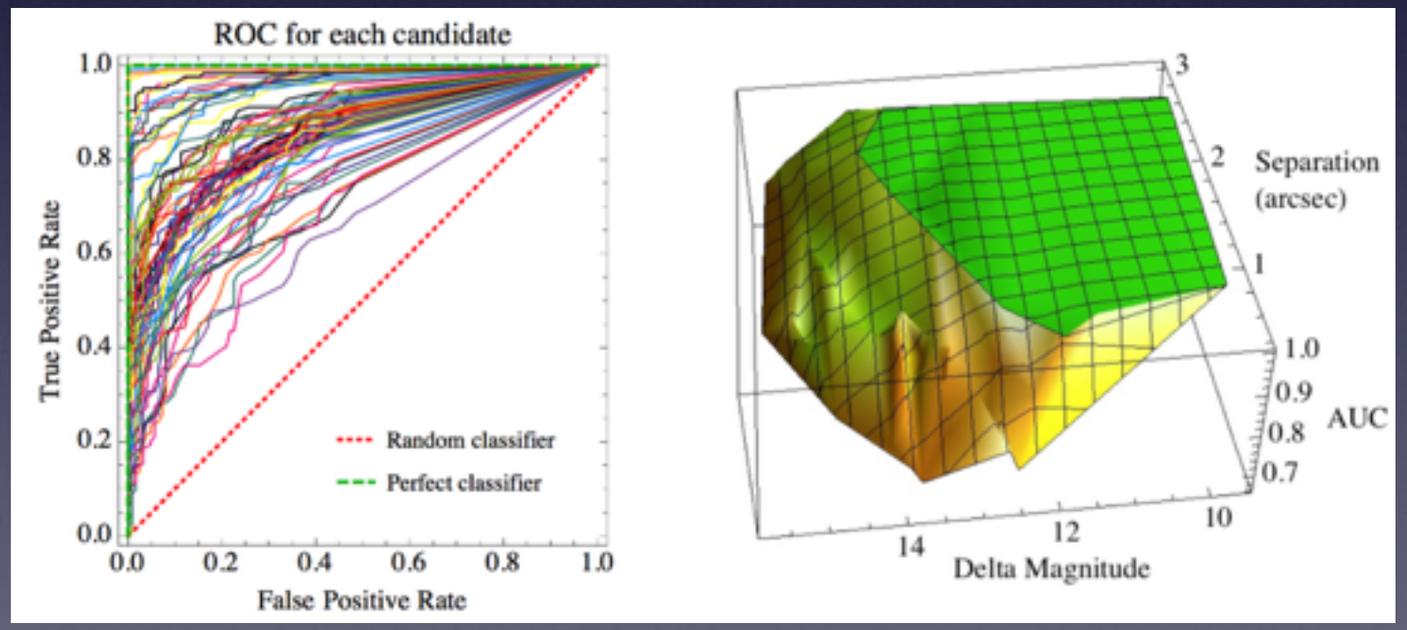
Receiver Operating Characteristics (ROC)

To compare :
- Reduction methods
- Classifiers

To measure the confidence level and sensitivity as a function of separation and contrast



Gomez Gonzalez et al. 2016



Choquet et al. 2014

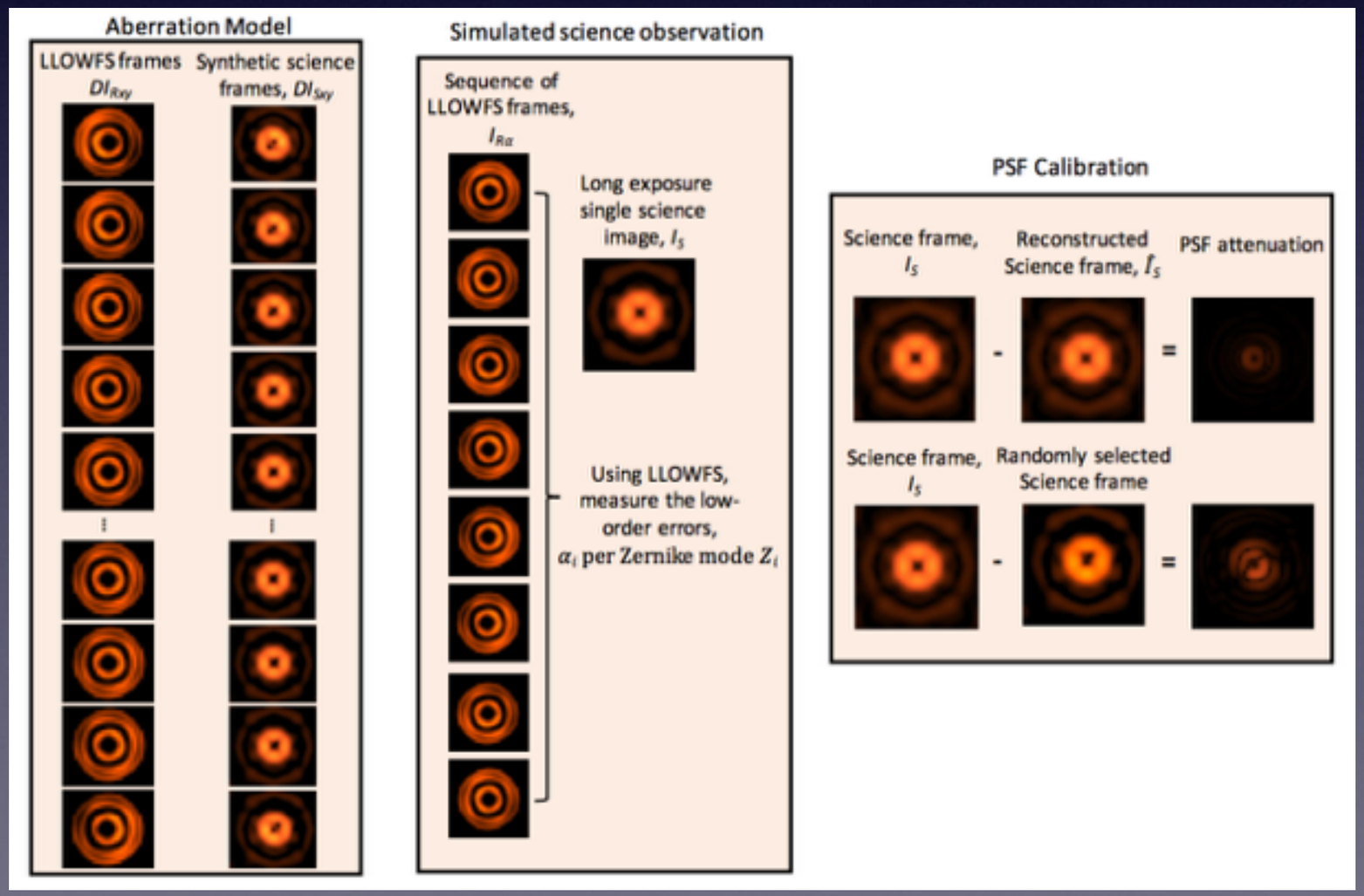
4. Prospects

Modeling the instrument

Using WFS and LOWFS telemetry

Train the post-processing by:

- creating a {LOWFS + science image} dictionary *in advance*
- use the real-time LOWFS telemetry to complete the PSF library



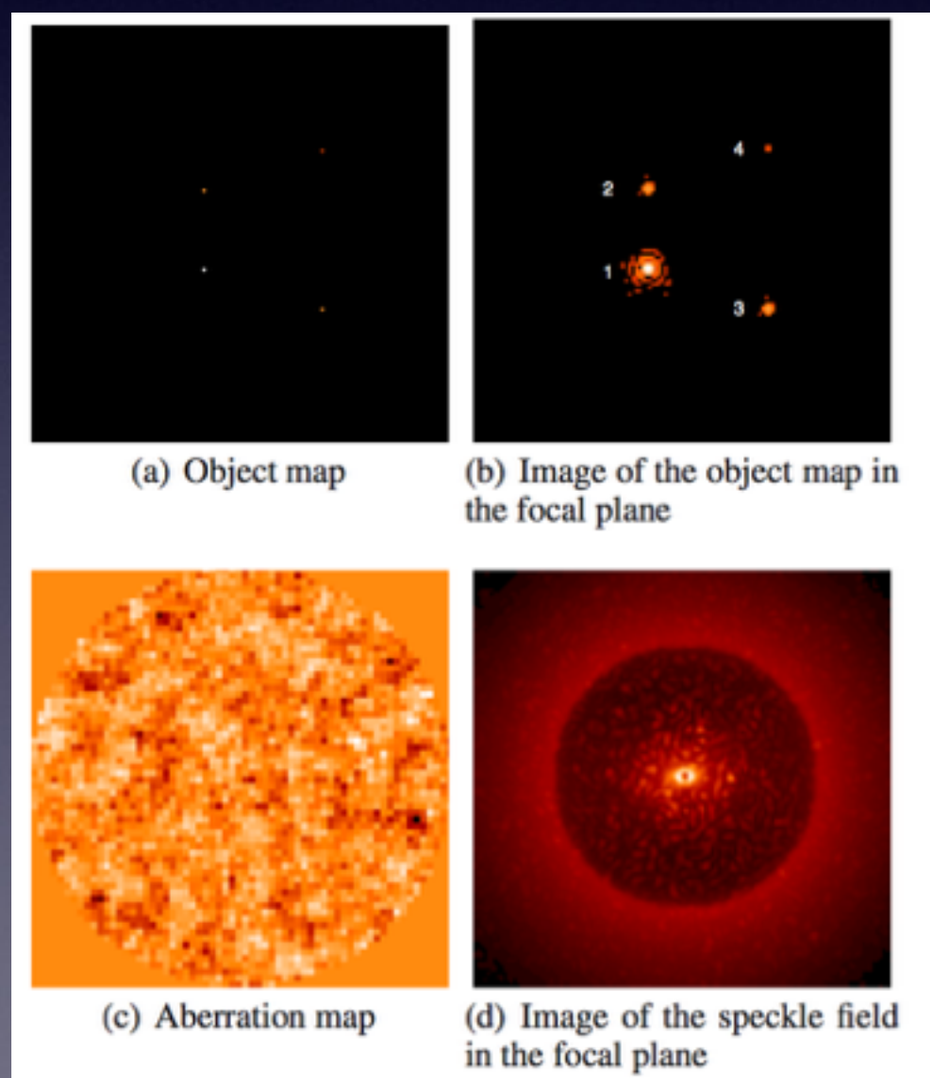
Singh et al. 2016

Modeling the instrument

Parametric modeling of the aberrations and signal

Use a Bayesian approach on SDI data to decompose them into:

- Instrument aberrations (using a model of the system)
- Astrophysical signal

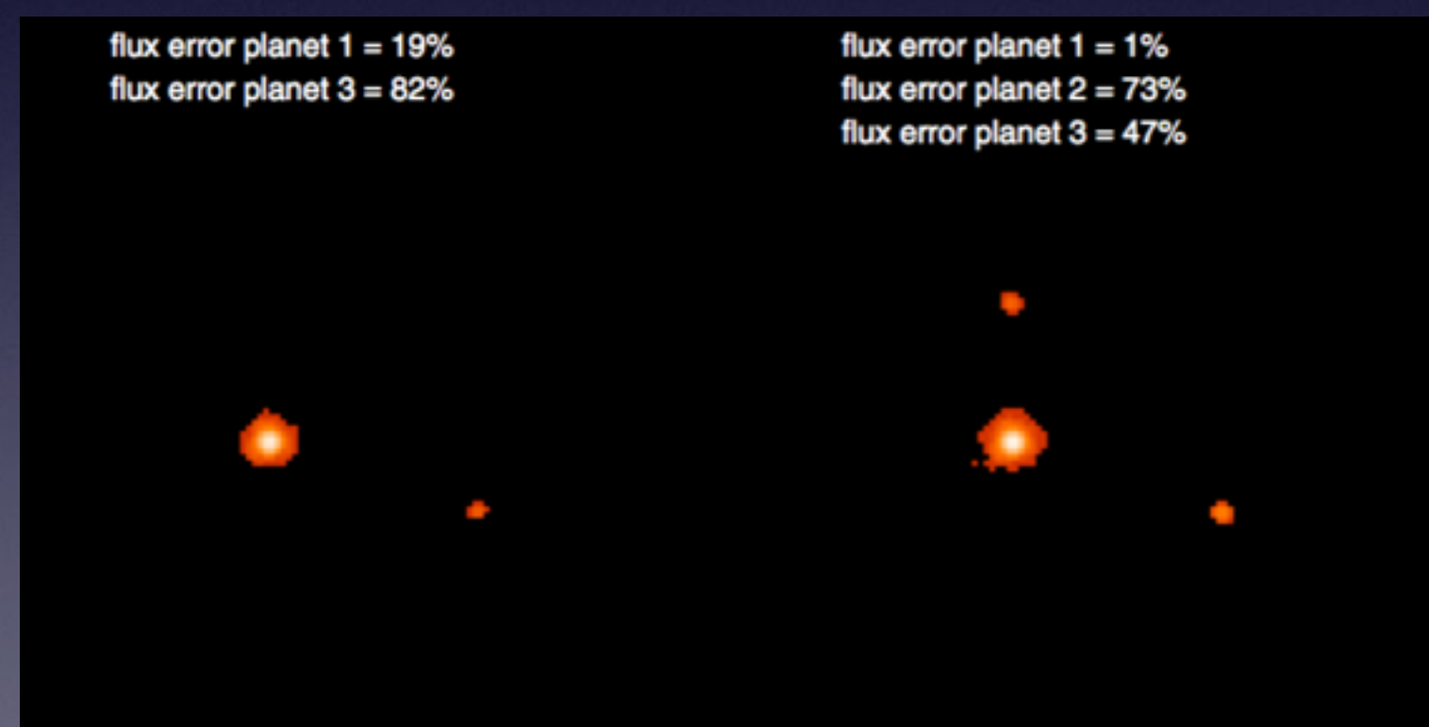


(a) Object map

(b) Image of the object map in the focal plane

(c) Aberration map

(d) Image of the speckle field in the focal plane



Ygouf et al. 2016

Conclusion & Take-home messages

- Instrument stability (speckle noise) limits Differential Imaging
- Advance post-processing algorithms are needed to push detection limits

- Post-processing will play a major role in the planet yield of WFIRST, Habex, LUVOIR