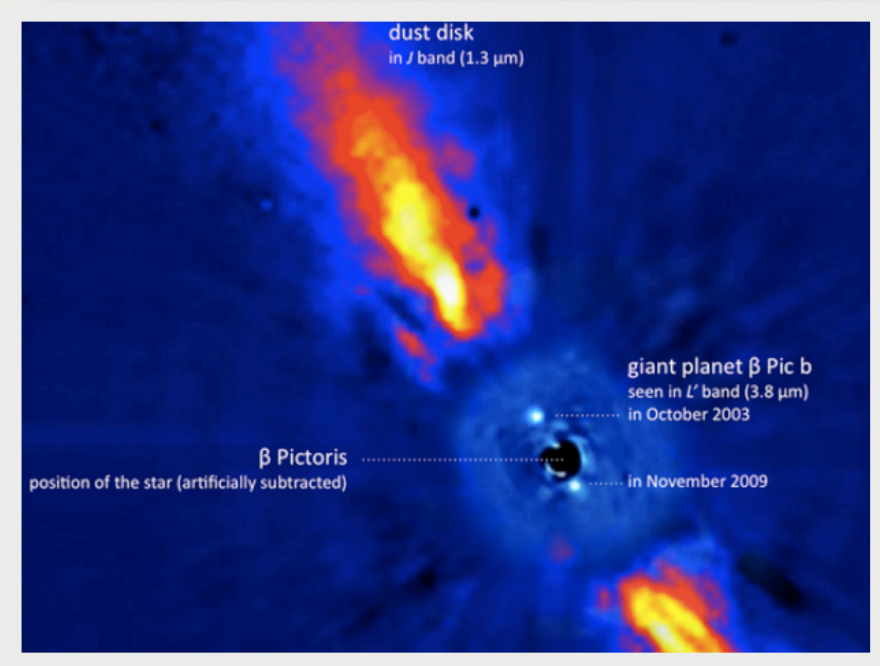
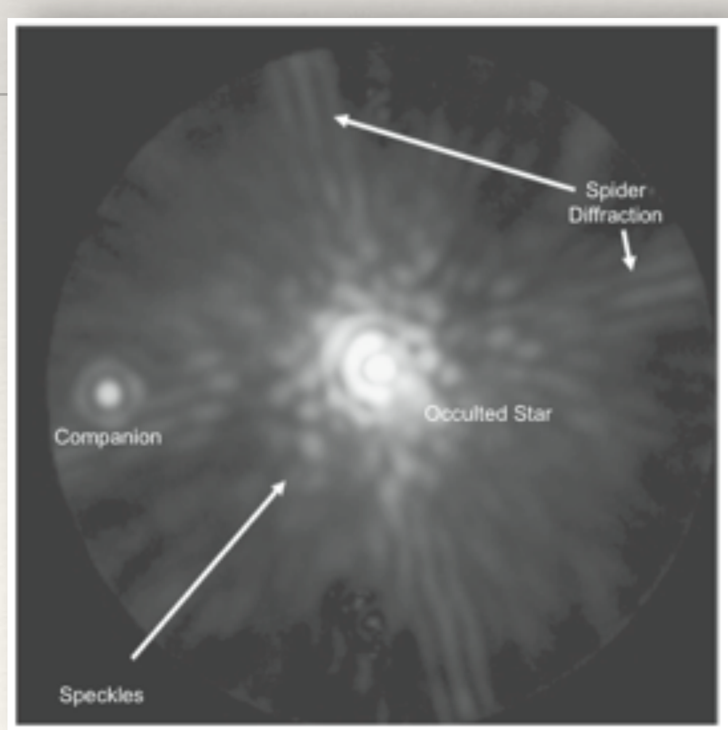



*R. Claudi - INAF - Astronomical Observatory of Padova*

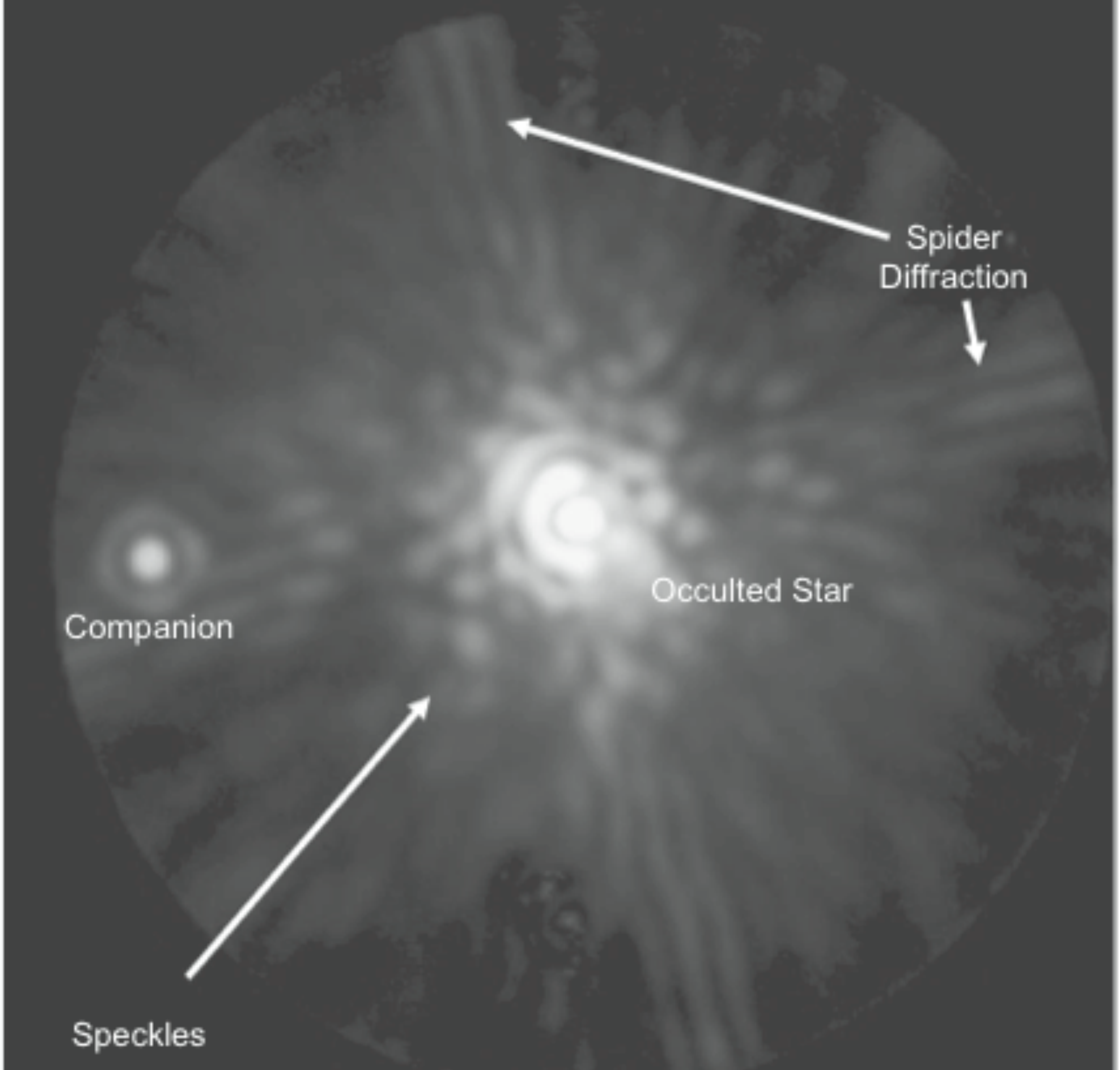
# DIRECT IMAGING OF EXTRASOLAR PLANETS

## V: SPECKLE SUPPRESSION




*1st ADVANCED SCHOOL OF EXOPLANETARY SCIENCE*
*METHODS OF DETECTING EXOPLANETS*
*MAY 25-29, 2015 - VIETRI SUL MARE (SA)*

# Speckle Suppression


Spider
Diffraction
Companion
Occulted Star
Speckles

Plane A: $\psi_A = Ae^{i\varphi}$ if $\varphi$ is small

$$\psi_A = A(1+i\varphi)$$

Plane C: $\psi_C = \psi_A \otimes \overline{M} = (A(1+i\varphi)) \otimes \overline{M}$

$$\psi_C = A \otimes \overline{M} + Ai\varphi \otimes \overline{M}$$

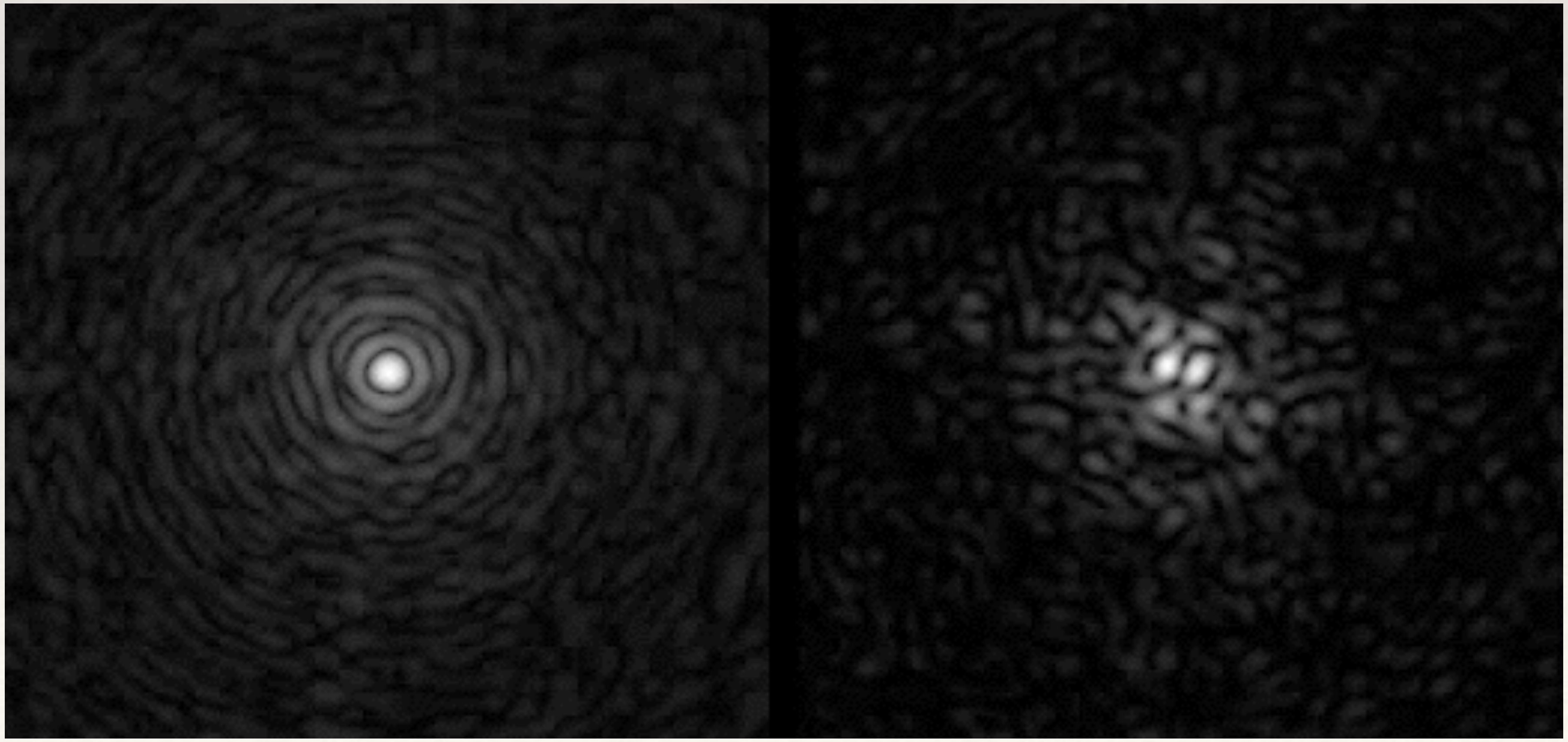
Plane A: $\psi_A = Ae^{i\varphi}$ if $\varphi$ is small

$$\psi_A = A(1 + i\varphi)$$

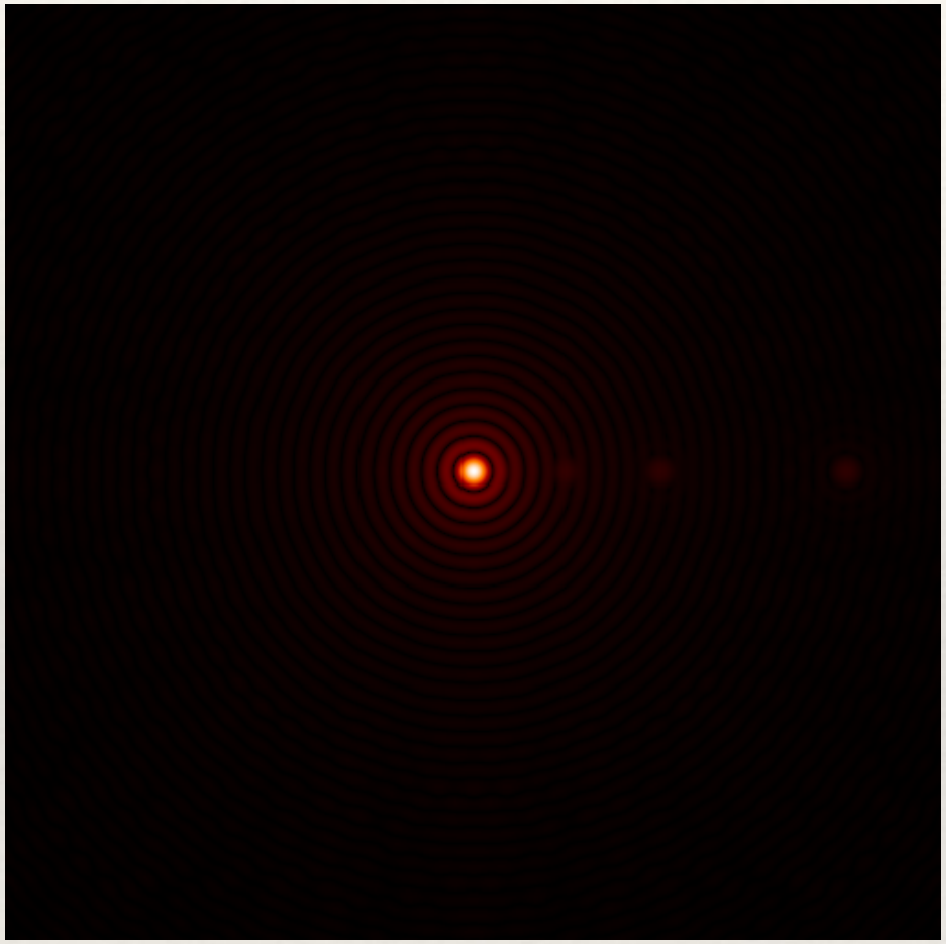
Plane C: $\psi_C = \psi_A \otimes \overline{M} = (A(1 + i\varphi)) \otimes \overline{M}$

$$\psi_C = A \otimes \overline{M} + Ai\varphi \otimes \overline{M}$$

«diffraction» «speckles»



# Enhancing the exposure time the situation is going from bad to worse



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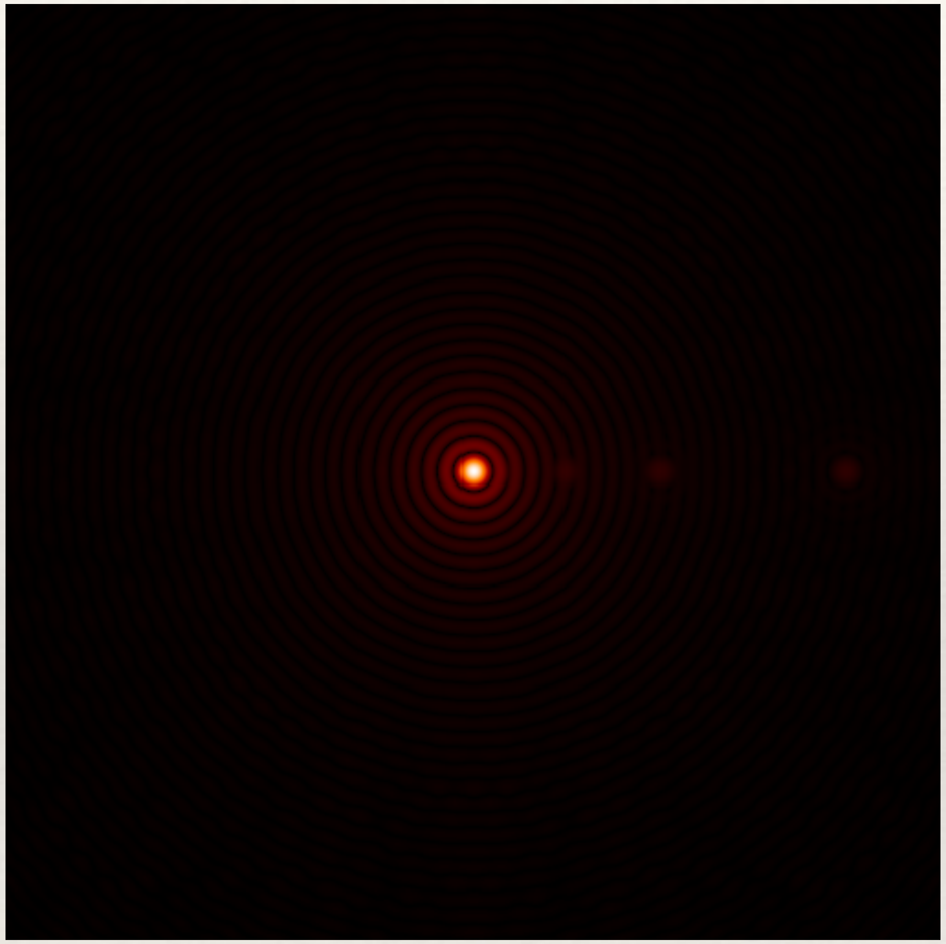
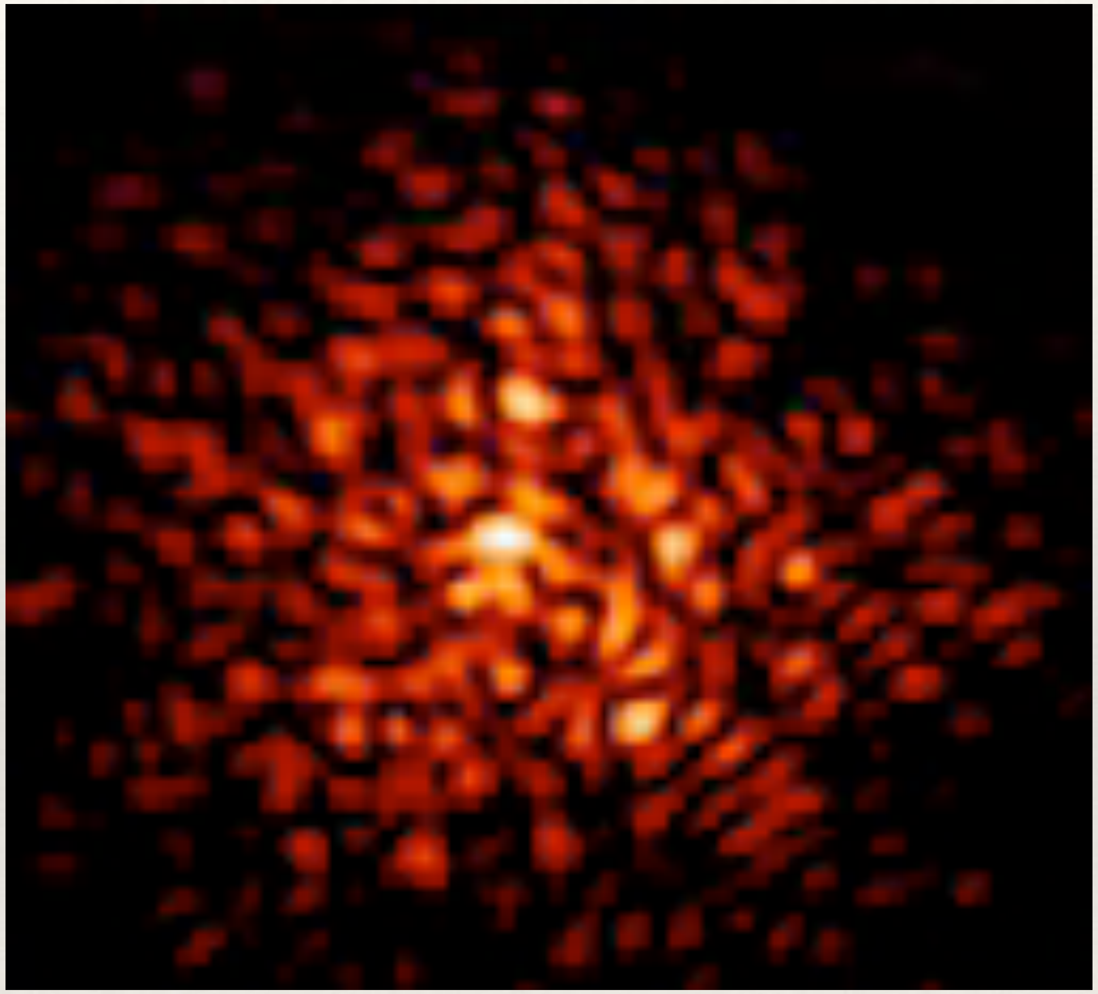




# Solutions? … Differential Imaging

- Principle: calibration of the PSF using one or more reference imaging where the planet signal is either absent or at least displaced
- Various techniques:
  - Temporal stability: PSF subtraction and Angular Differential Imaging (ADI)
  - Chromatic correlation: Spectral Differential imaging (SDI) and Spectral Deconvolution
  - Polarimetric correlation: Polarimetric differential Imaging (DPI)
  - Combination of techniques Principal Component Analysis
- General issue: planet cancellation often limits accuracy of speckle subtraction and regions where it is applicable

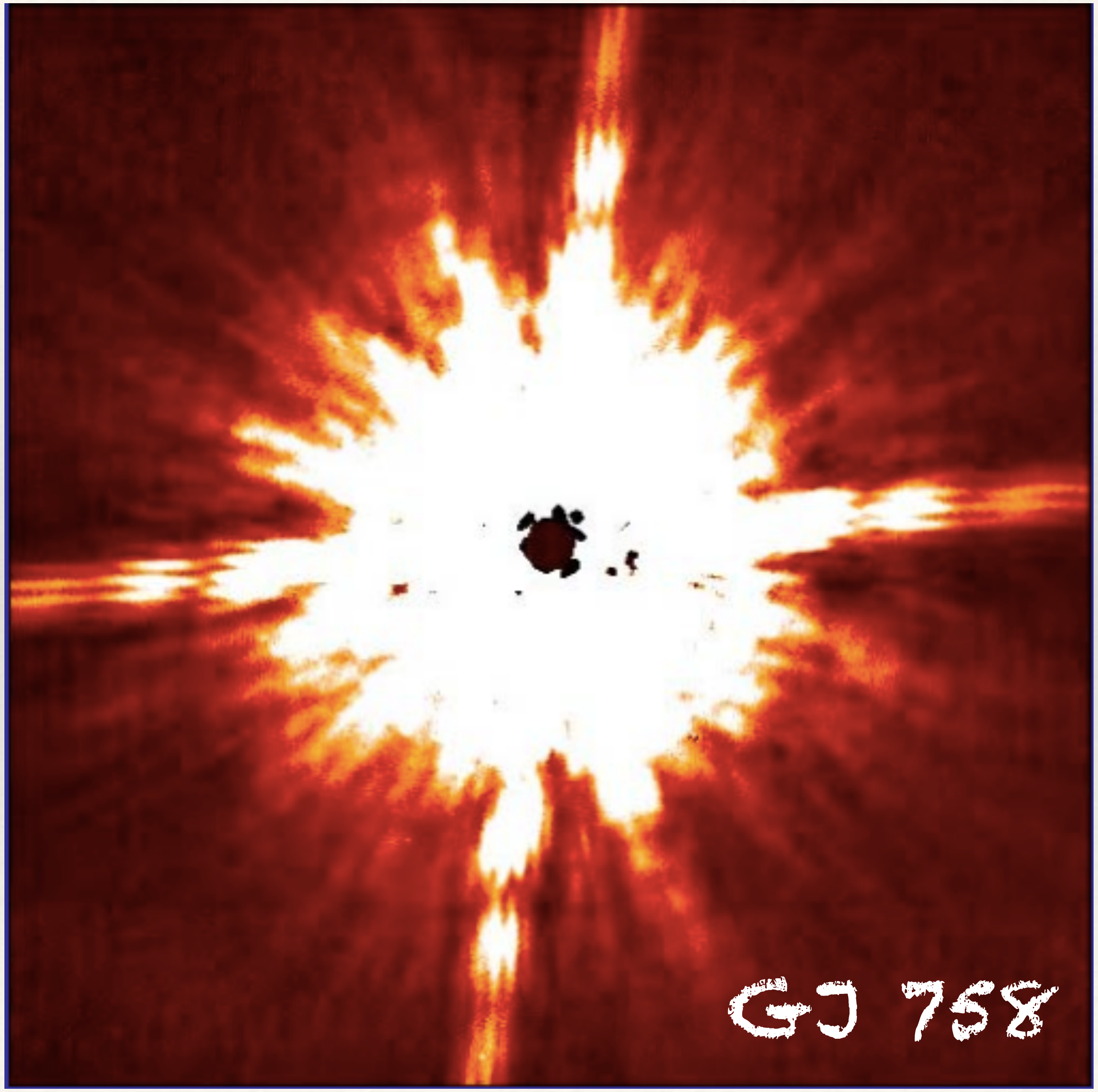
# PSF Subtraction

- PSF subtraction requires observation of a reference target in conditions as similar as possible as those for the program star
- The two PSF's are scaled to a common intensity and then subtracted each other
- It allows detection of faint extended structures: disks, jets
- However, instrument stability usually not good enough in order to make this competitive with other techniques for planet detection

# Angular Differential Imaging

Tutorial by Thalman : http://www.mpia.de/homes/thalmann/adi.htm

Appearance of a typical "good" image
Where is the planet?



The Astrophysical Journal, 641:556–564, 2006 April 10


# ANGULAR DIFFERENTIAL IMAGING: A POWERFUL HIGH-CONTRAST IMAGING TECHNIQUE[1]

Christian Marois,[2,3] David Lafrenière,[2] René Doyon,[2] Bruce Macintosh,[3] and Daniel Nadeau[2]
*Received 2005 October 13; accepted 2005 December 9*

## ABSTRACT

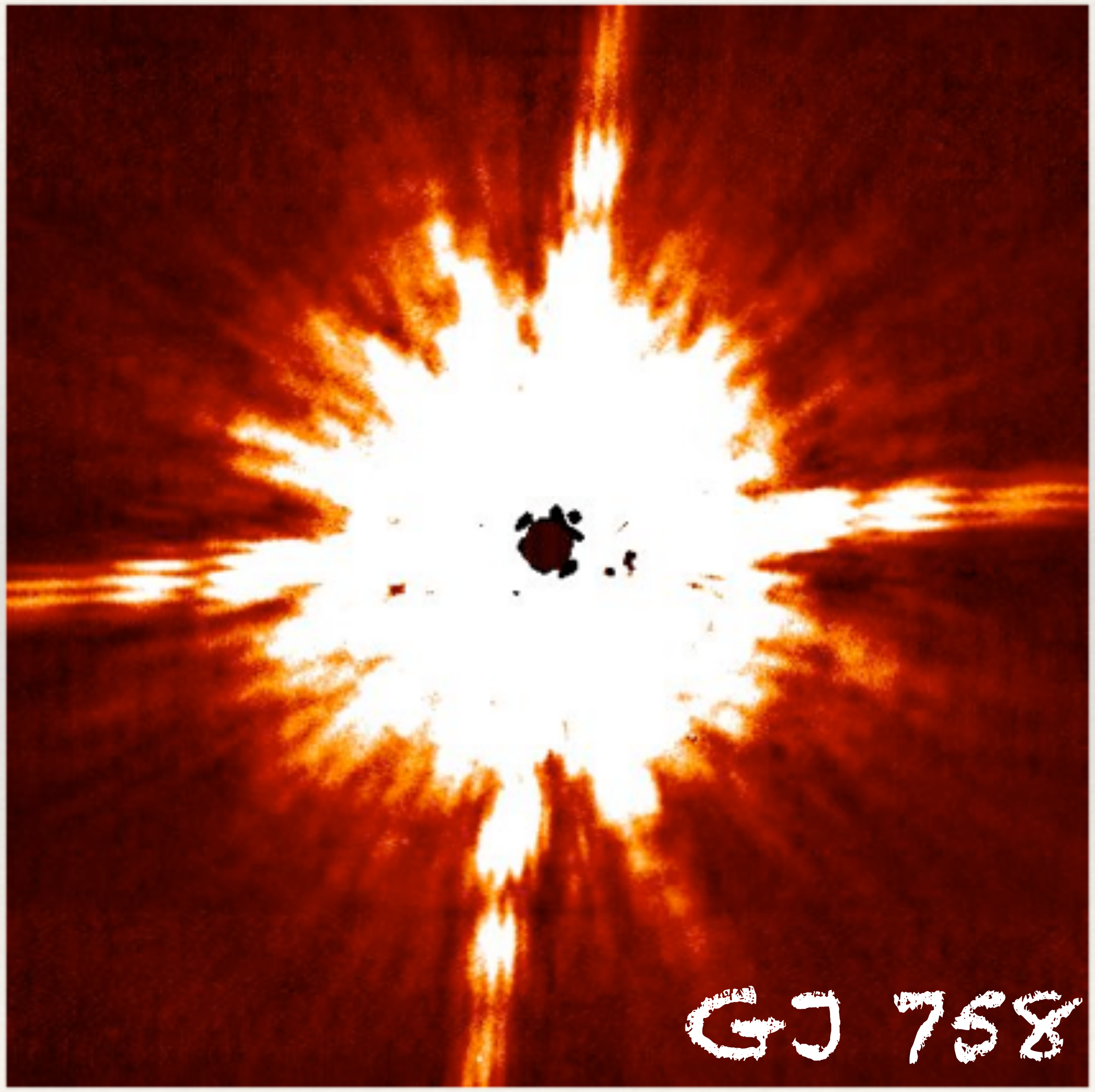
Angular differential imaging is a high-contrast imaging technique that reduces quasistatic speckle noise and facilitates the detection of nearby companions. A sequence of images is acquired with an altitude/azimuth telescope while the instrument field derotator is switched off. This keeps the instrument and telescope optics aligned and allows the field of view to rotate with respect to the instrument. For each image, a reference point-spread function (PSF) is constructed from other appropriately selected images of the same sequence and subtracted to remove quasistatic PSF structure. All residual images are then rotated to align the field and are combined. Observed performances are reported for Gemini North data. It is shown that quasistatic PSF noise can be reduced by a factor ~5 for each image subtraction. The combination of all residuals then provides an additional gain of the order of the square root of the total number of acquired images. A total speckle noise attenuation of 20–50 is obtained for a 1 hr long observing sequence compared to a single 30 s exposure. A PSF noise attenuation of 100 was achieved for a 2 hr long sequence of images of Vega, reaching a 5 $\sigma$ contrast of 20 mag for separations greater than 8″. For a 30 minute long sequence, ADI achieves signal-to-noise ratios 30 times better than a classical observation technique. The ADI technique can be used with currently available instruments to search for $\sim 1 M_{\rm Jup}$ exoplanets with orbits of radii between 50 and 300 AU around nearby young stars. The possibility of combining the technique with other high-contrast imaging methods is briefly discussed.

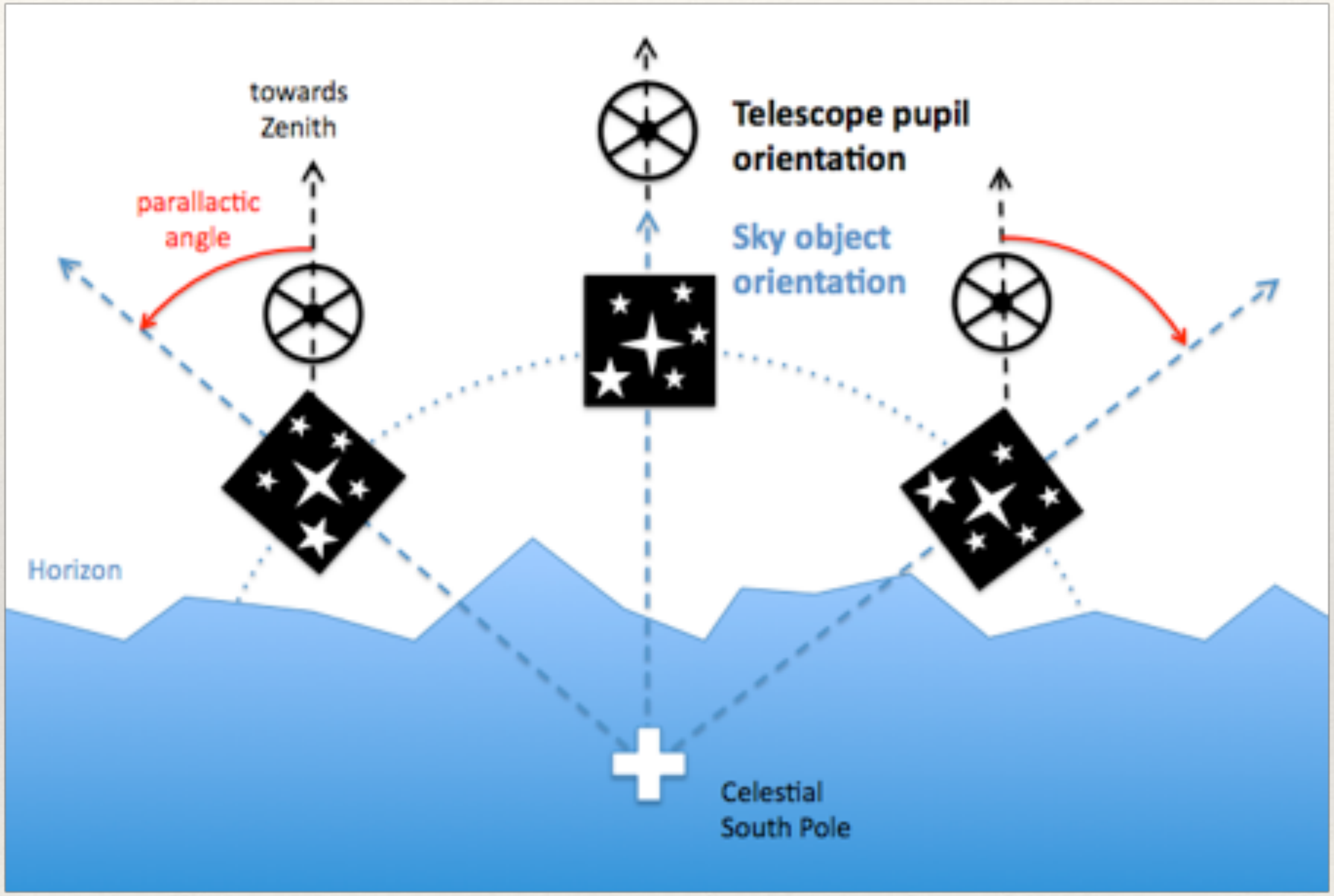
*Subject headings:* instrumentation: adaptive optics — planetary systems — stars: imaging

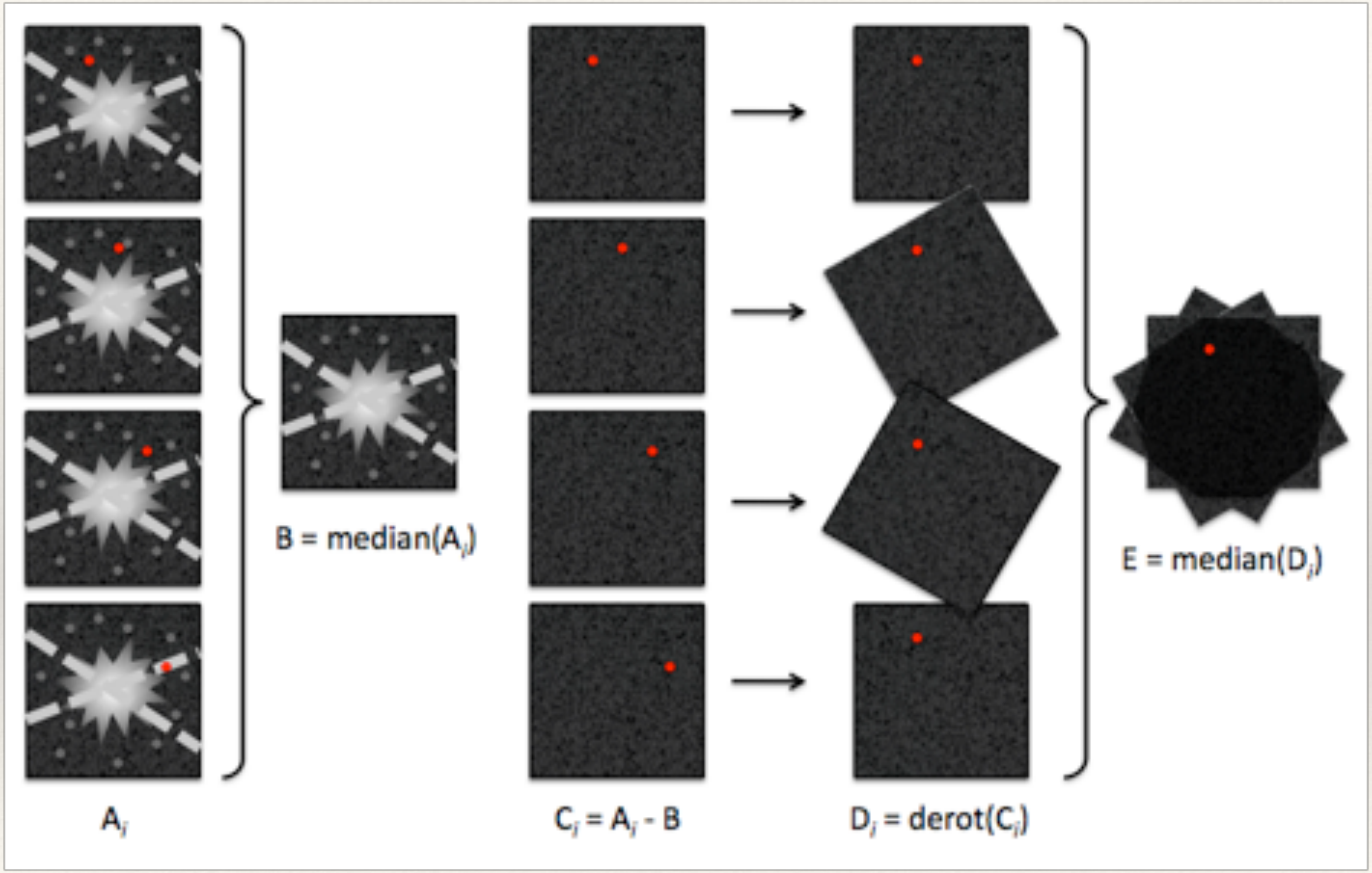
# What's ADI?

## It's a PSF Reference Technique

Observations have shown that for integrations longer than a few minutes, the PSF noise converges to a quasistatic noise pattern, thus preventing a gain with increasing integration time it is thus necessary to subtract the quasistatic noise using a reference PSF.




towards
Zenith
parallactic
angle
Telescope pupil
orientation
Sky object
orientation
Horizon
Celestial
South Pole



B = median($A_i$)
E = median($D_i$)
$A_i$
$C_i = A_i - B$
$D_i$ = derot($C_i$)

Two different ADI methods:

Median of all images taken during the observation

to take the Median of only few images for which the field is rotated at least of 1.5 PSF FWHM

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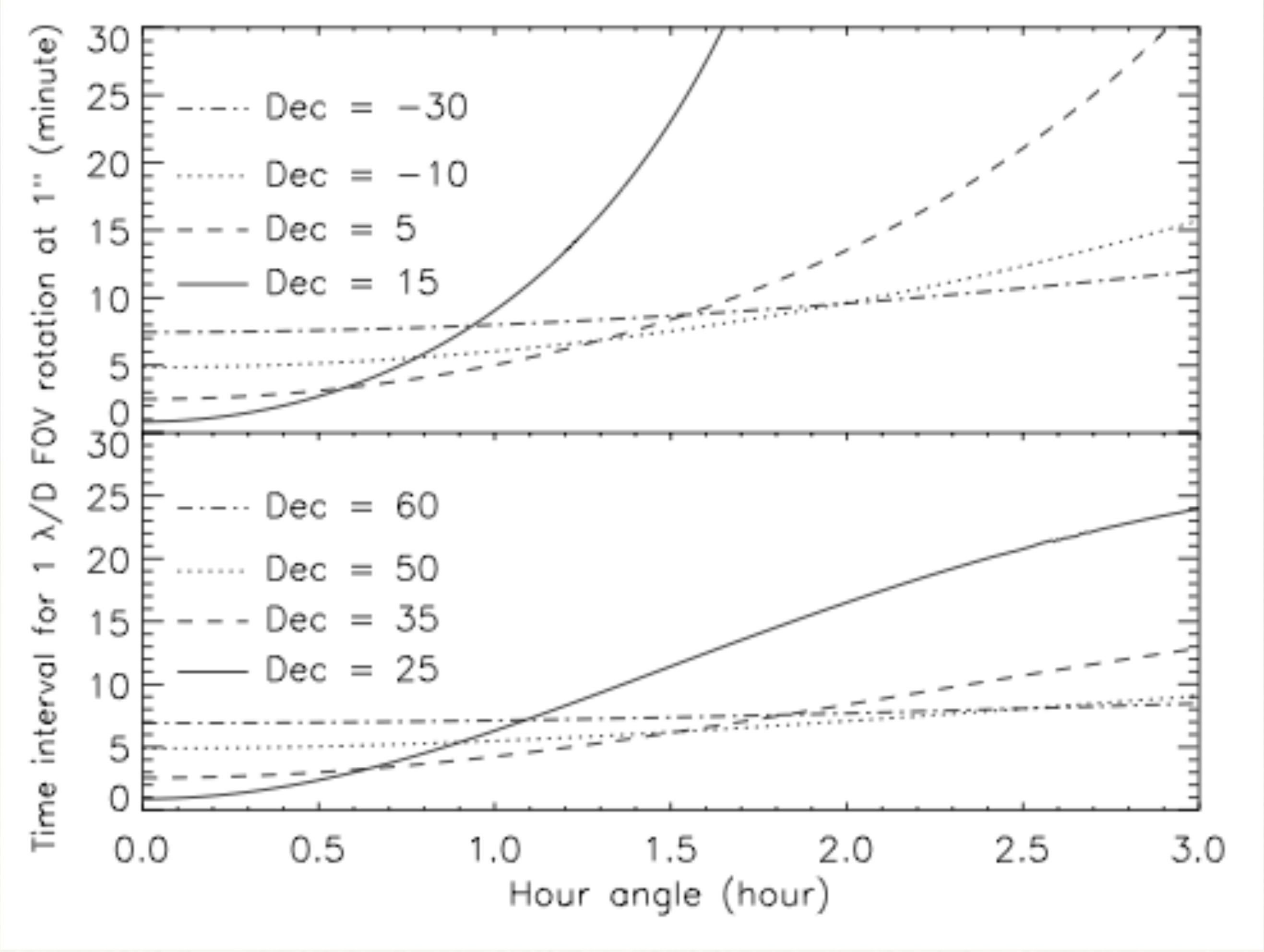
Median of all images taken during the observation

to take the Median of only few images for which the field is rotated at least of 1.5 PSF FWHM

$$\psi = 0.2506 \frac{\cos A \cos \phi}{\sin z}.$$



Two different ADI methods:

Median of all images taken during the observation

to take the Median of only few images for which the field is rotated at least of 1.5 PSF FWHM

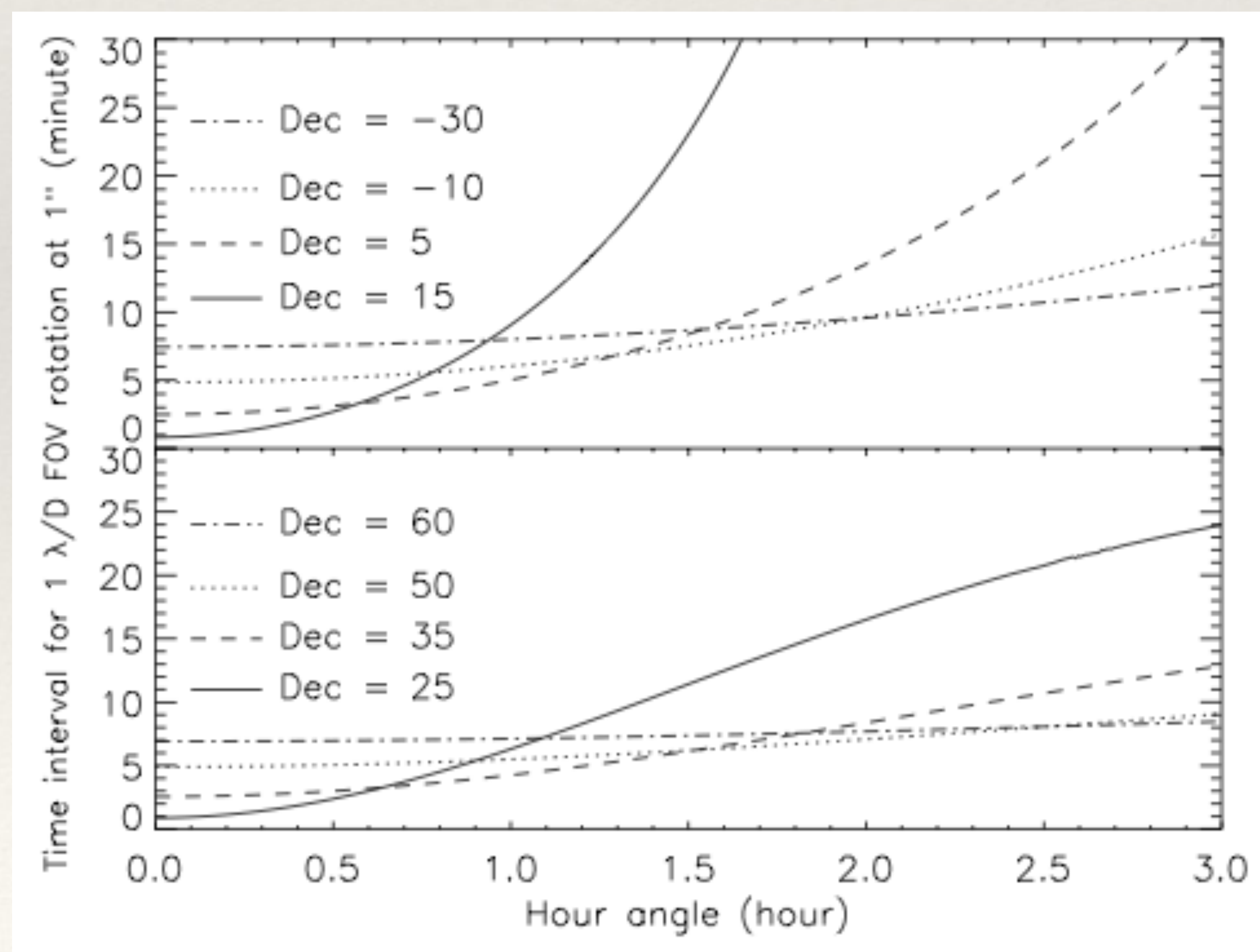
Telescope Latitude

Rotation Rate

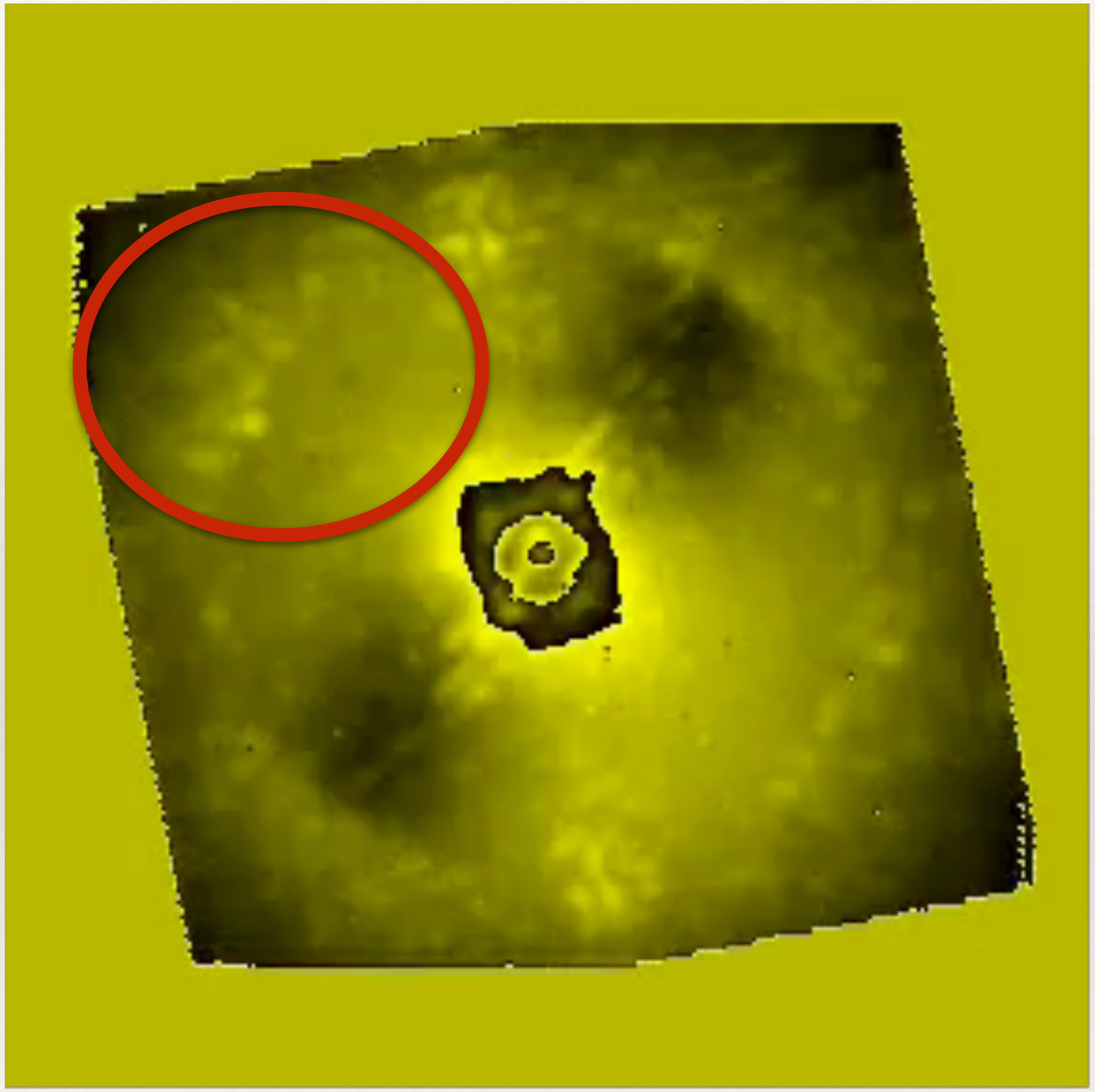
Target Azimuth

$$\psi = 0.2506 \frac{\cos A \cos \phi}{\sin z}.$$

Zenith Distance

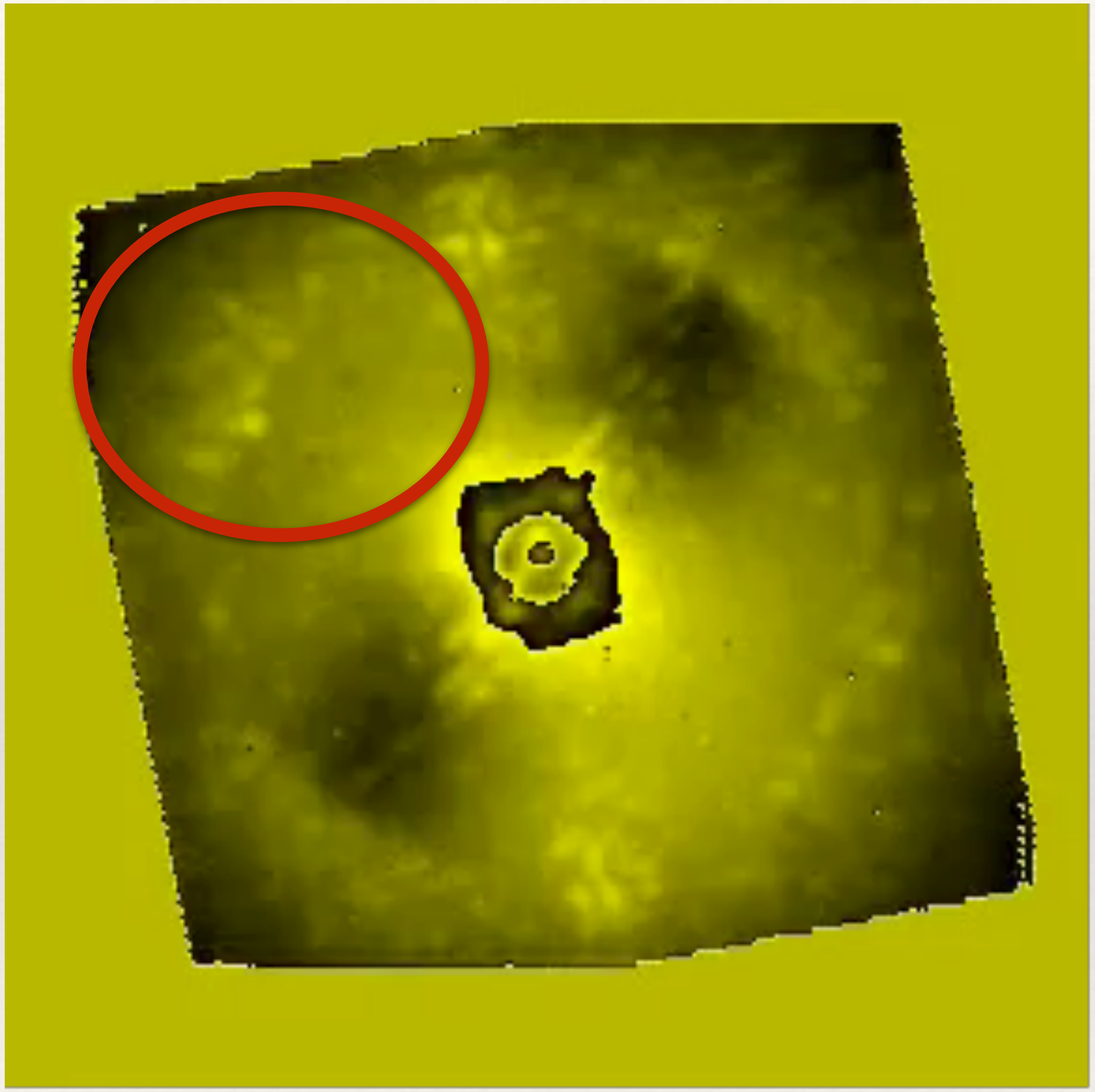


- To avoid cancellation of the planet signal, field rotation should be enough to move its image by at least $\lambda/D$
- Need to consider the rotation law: maximum field rotation near passage at meridian and for objects close to zenith careful planning of the observations
- Typical values may be ~30-60 degree/hr10 minutes yield 5-10 degrees ~ 0.1-0.2 radians    ADI applicable from ~5-10 $\lambda/D$ (~0.2-0.4 arcsec for H-band observations), depending on target
- Most efficient ADI require aggressive techniques which weigh more observations taken at shortest time distance: some cancellation, to be properly evaluated using simulated fake planets



ADI exploits the fact that the field and the pupil rotate with respect to each other

In pupil stabilized mode, most speckles are caused by instrumental artifacts and are locked up in the pupil plane, whereas the object of interest, a companion or a disk, will rotate as the field rotates



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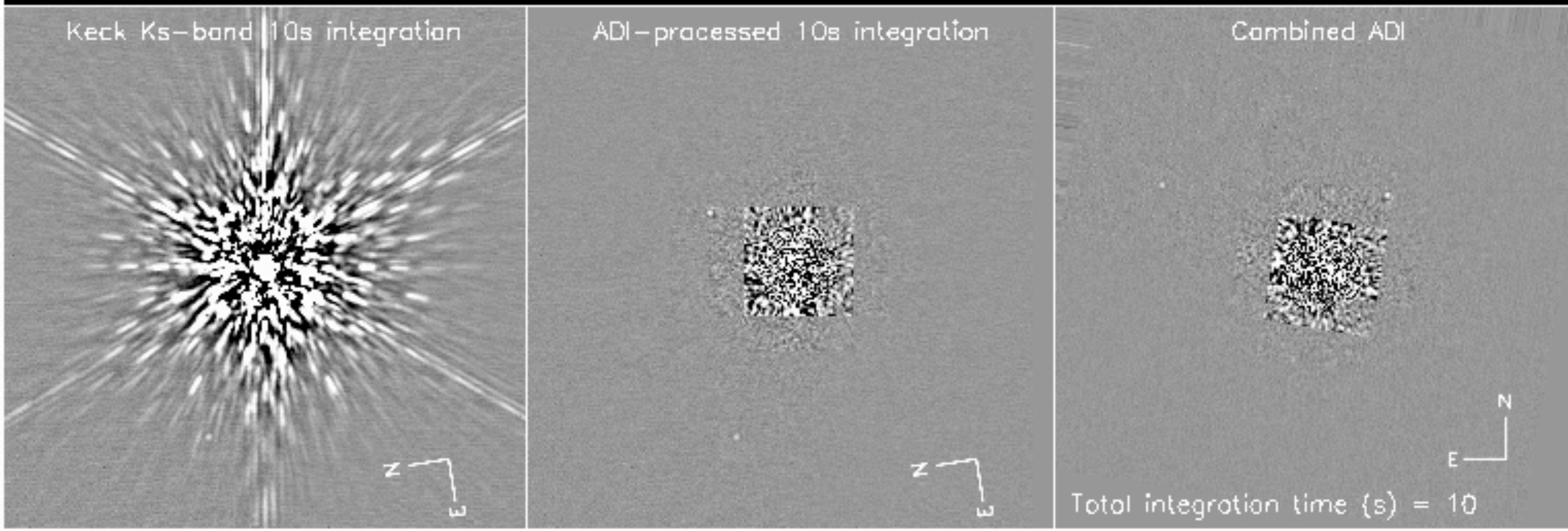
# Angular Differential Imaging (ADI)



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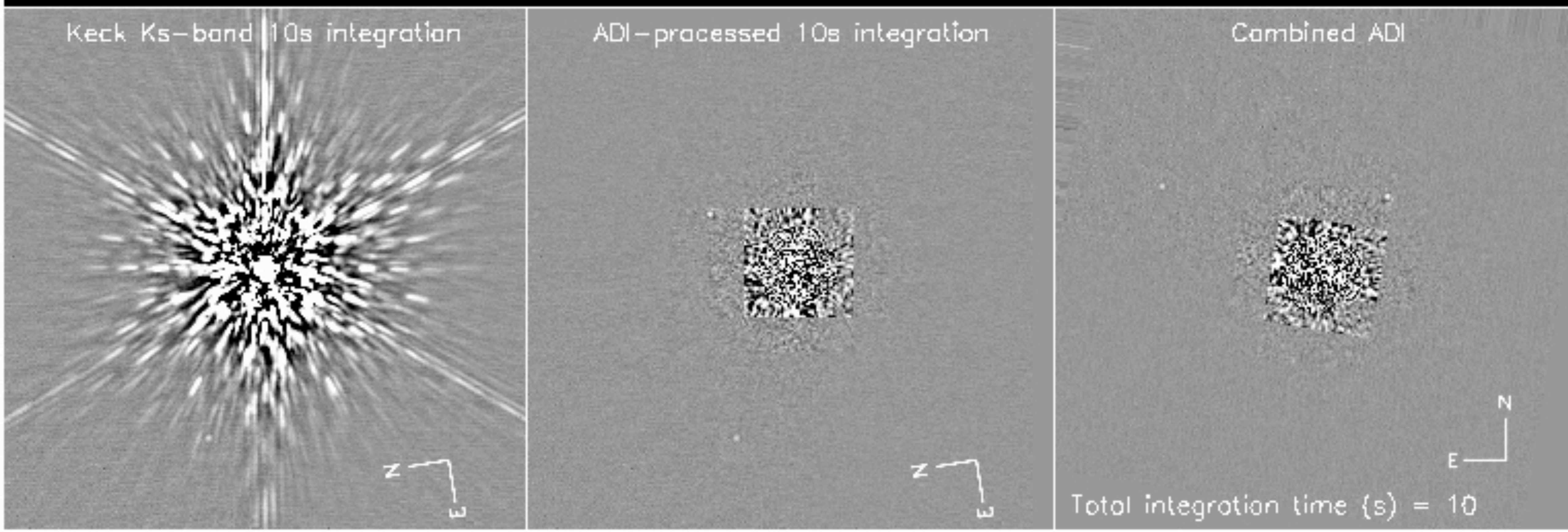

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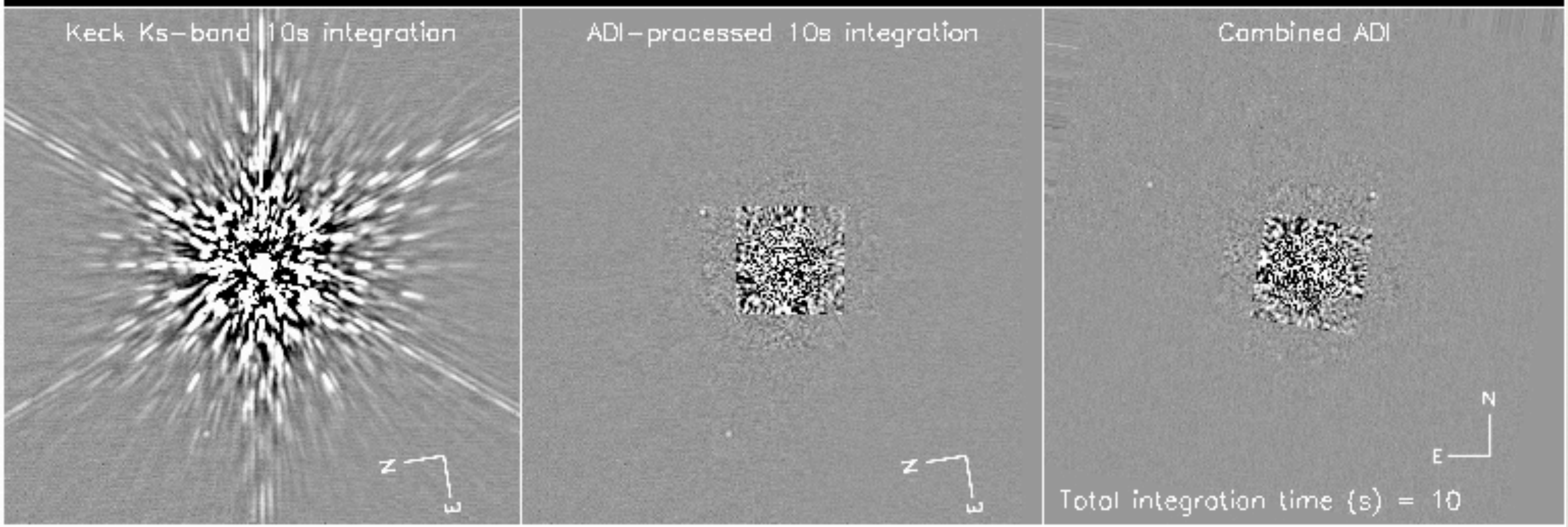

ADI The ADI technique attenuates the PSF noise in two steps,

(1) by subtraction of a reference image to remove correlated speckles and

(2) by the combination of all residual images after FOV alignment to average the residual noise.

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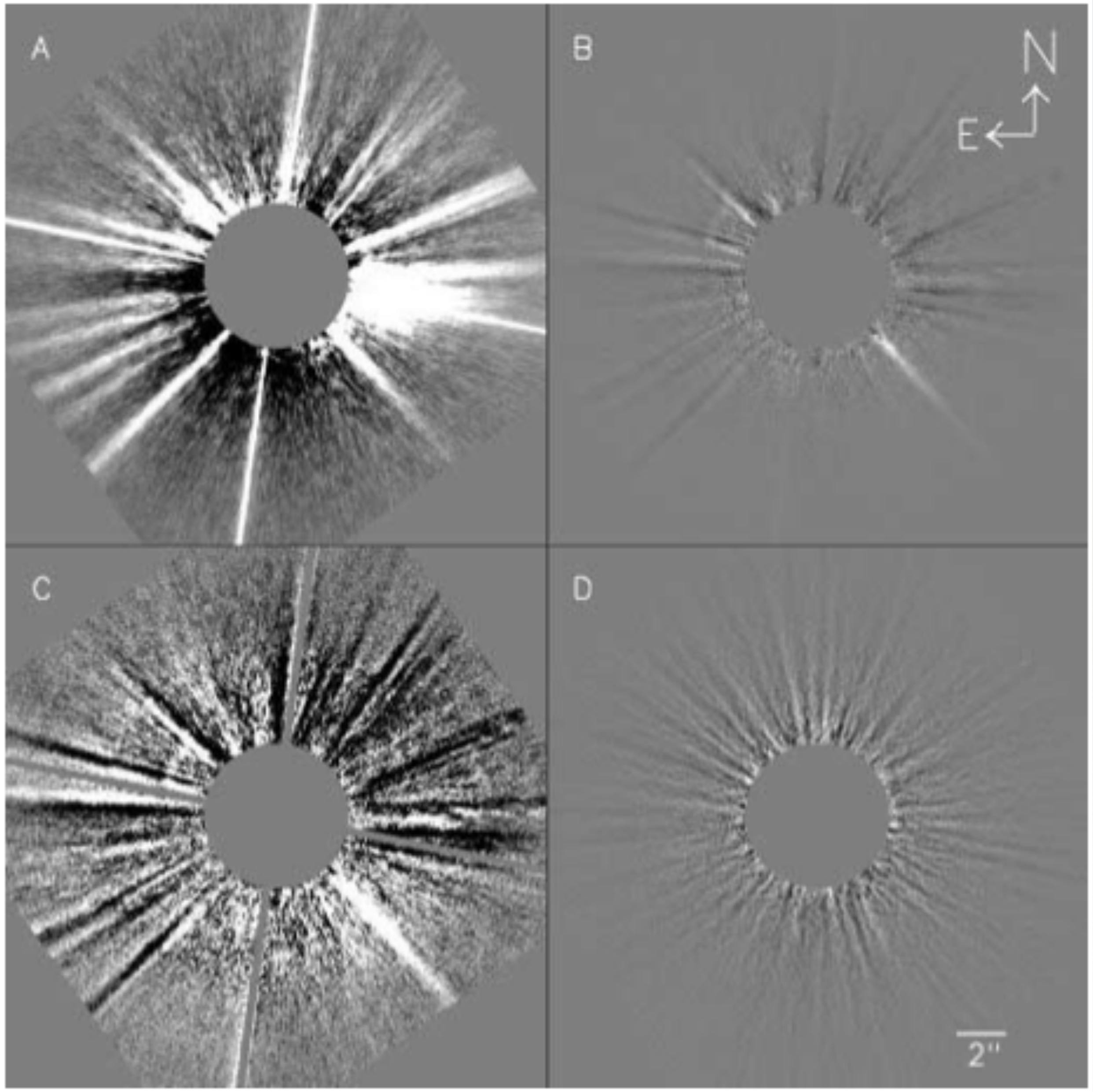

ADI The ADI technique attenuates the PSF noise in two steps,

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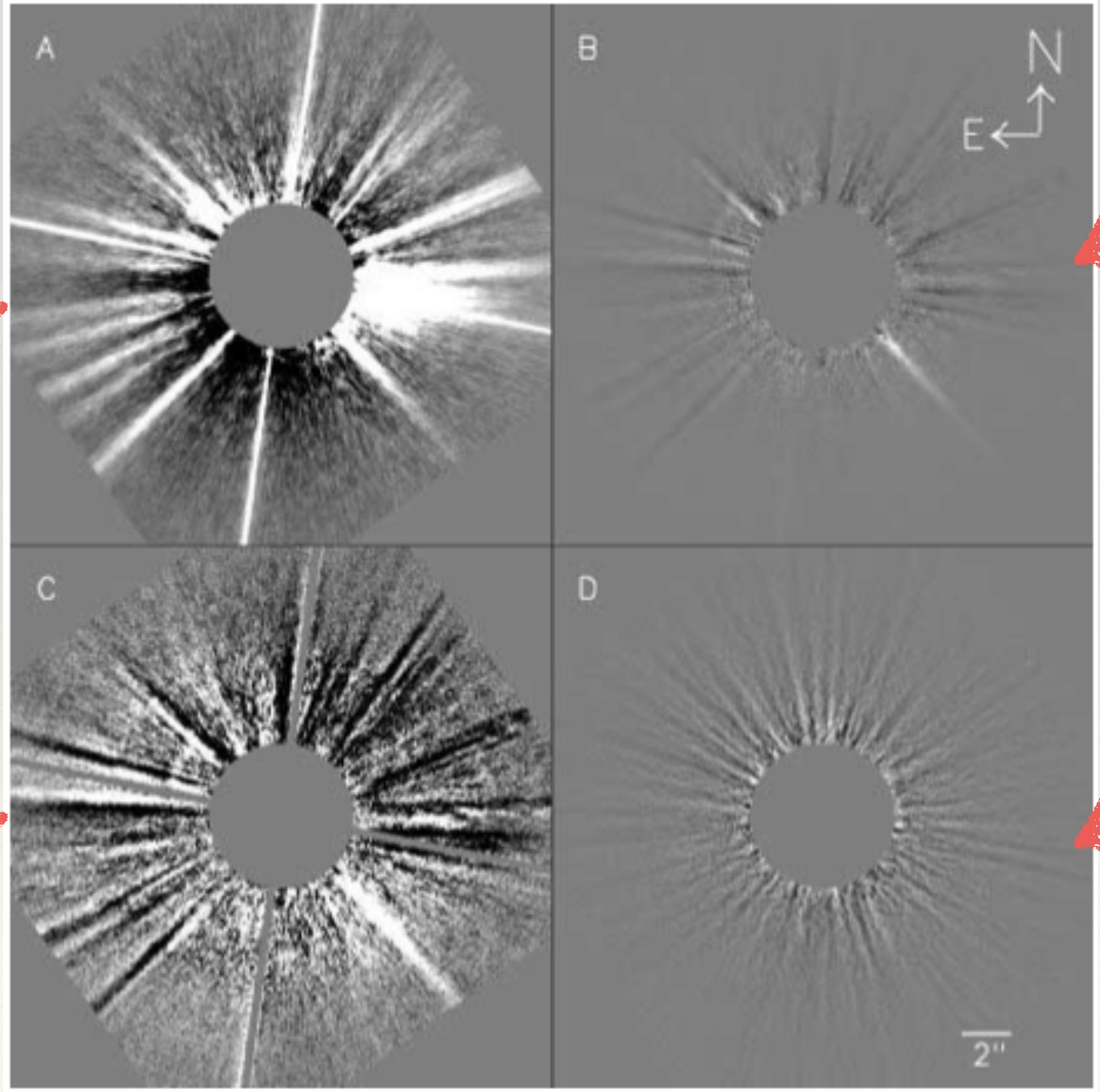
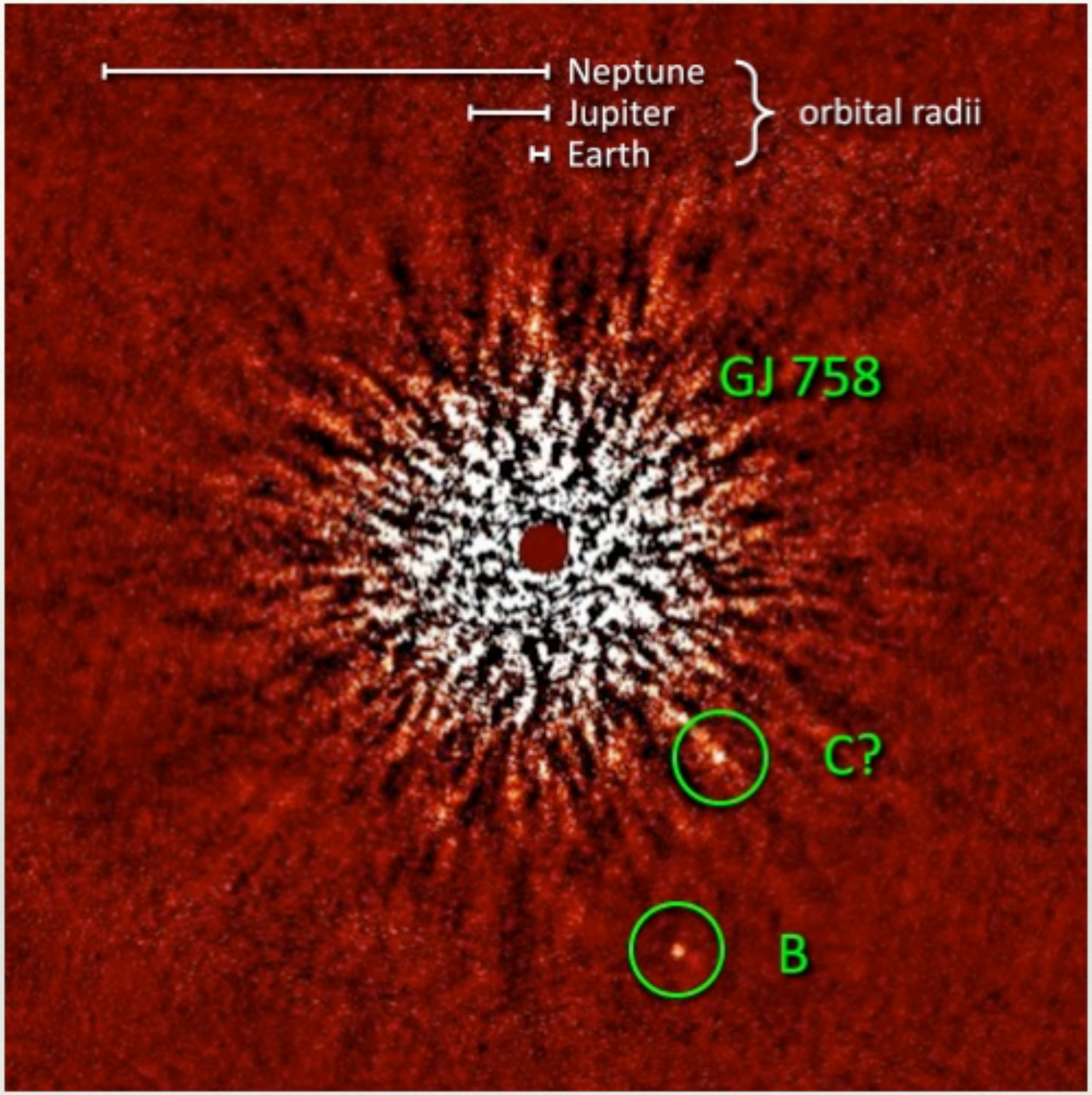
After FF, Bad Pixels Distorsion and azimuthally symmetric profile reduction

Same of B with higher cuts




Single ADI difference image

Final combination of all ADI differences




GJ 758 and companions: Thalmann et al. 2009, ApJ Letters

# Limits of ADI

Time evolution of speckle pattern: in most instrument lifetime of instrumental speckles is ~10 minutes (see e.g. Martinez et al. 2012 A&A, 541, A136)

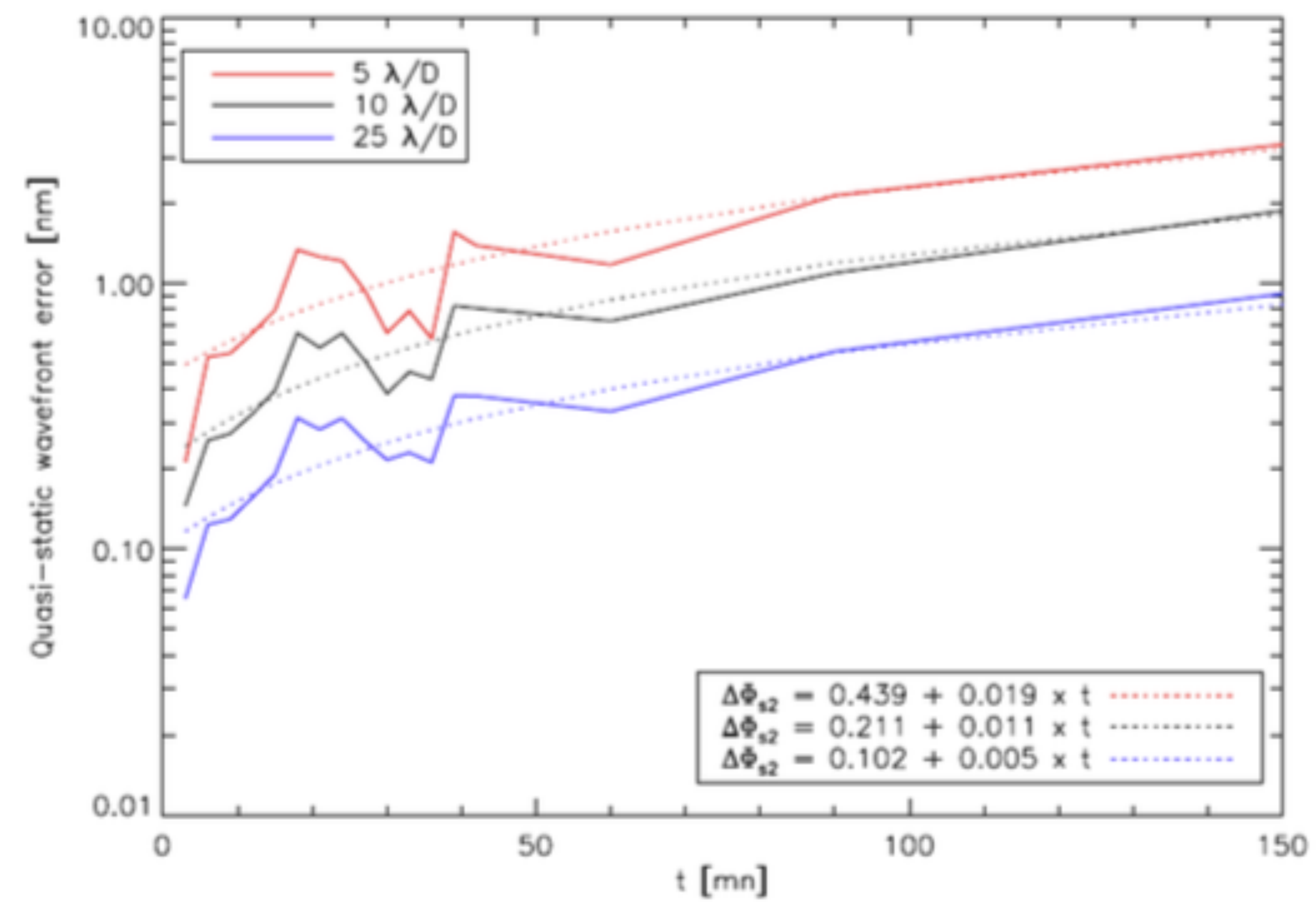



**Fig. 5.** Time variability of wavefront error due to quasi-static speckles, evaluated at various angular separations (observational data).

# Spectral Differential Imaging SDI

PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC, 111:587–594, 1999 May


## Speckle Noise and the Detection of Faint Companions

RENÉ RACINE
Observatoire du Mont Mégantic and Département de Physique, Université de Montréal, Montréal, PQ H3C 3J7, Canada; and Université Laval, Sainte-Foy, Quebec, PQ G1K 7P4, Canada; racine@astro.umontreal.ca

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AND

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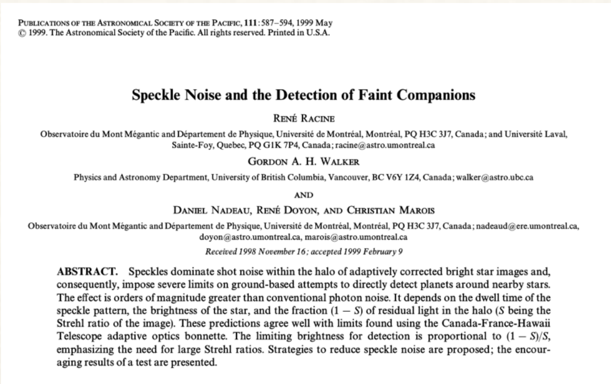
*Received 1998 November 16; accepted 1999 February 9*

**ABSTRACT.** Speckles dominate shot noise within the halo of adaptively corrected bright star images and, consequently, impose severe limits on ground-based attempts to directly detect planets around nearby stars. The effect is orders of magnitude greater than conventional photon noise. It depends on the dwell time of the speckle pattern, the brightness of the star, and the fraction $(1 - S)$ of residual light in the halo ($S$ being the Strehl ratio of the image). These predictions agree well with limits found using the Canada-France-Hawaii Telescope adaptive optics bonnette. The limiting brightness for detection is proportional to $(1 - S)/S$, emphasizing the need for large Strehl ratios. Strategies to reduce speckle noise are proposed; the encouraging results of a test are presented.

# Spectral Differential Imaging SDI



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**Speckle Noise and the Detection of Faint Companions**

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Gordon A. H. Walker
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and
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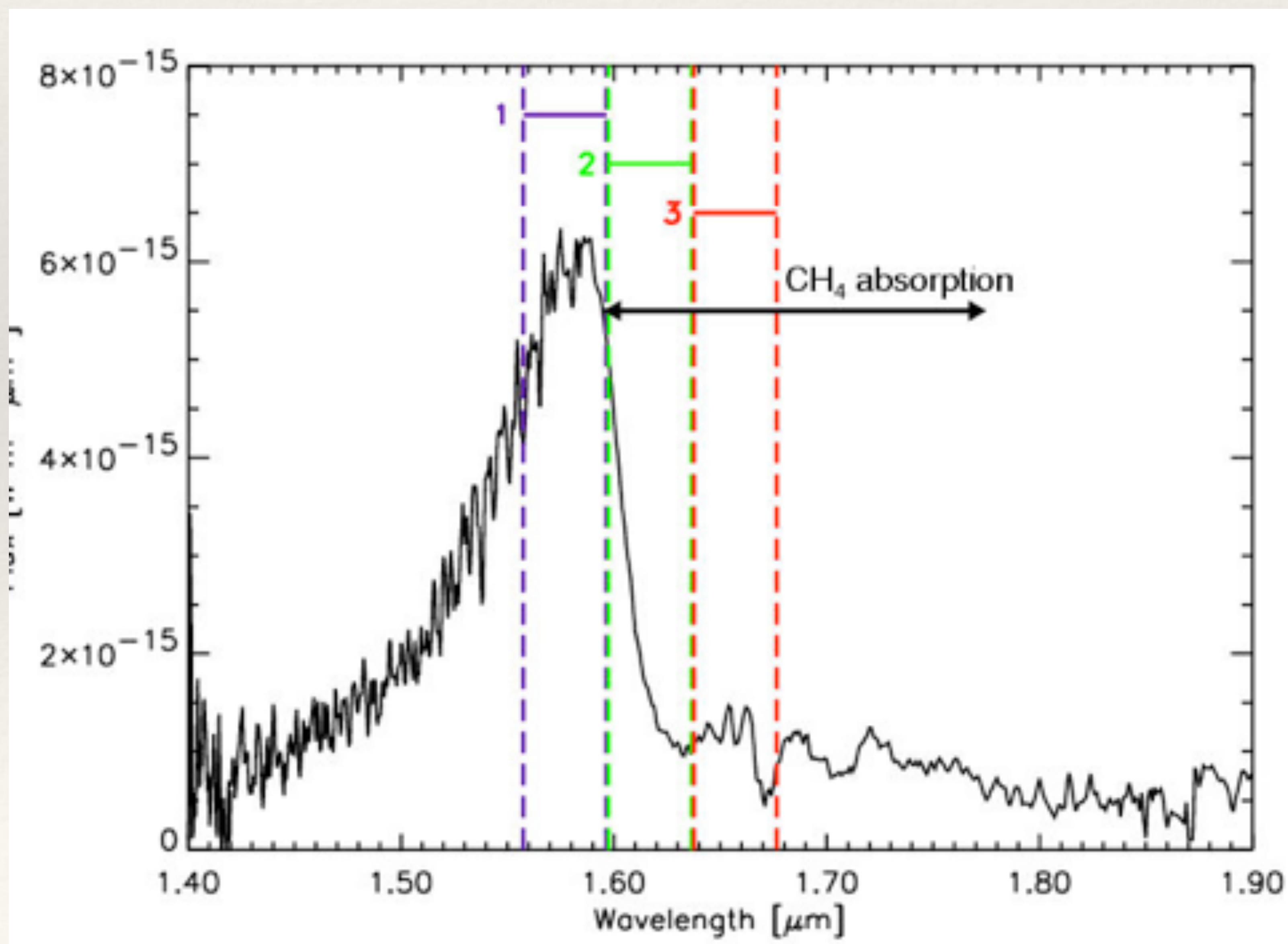
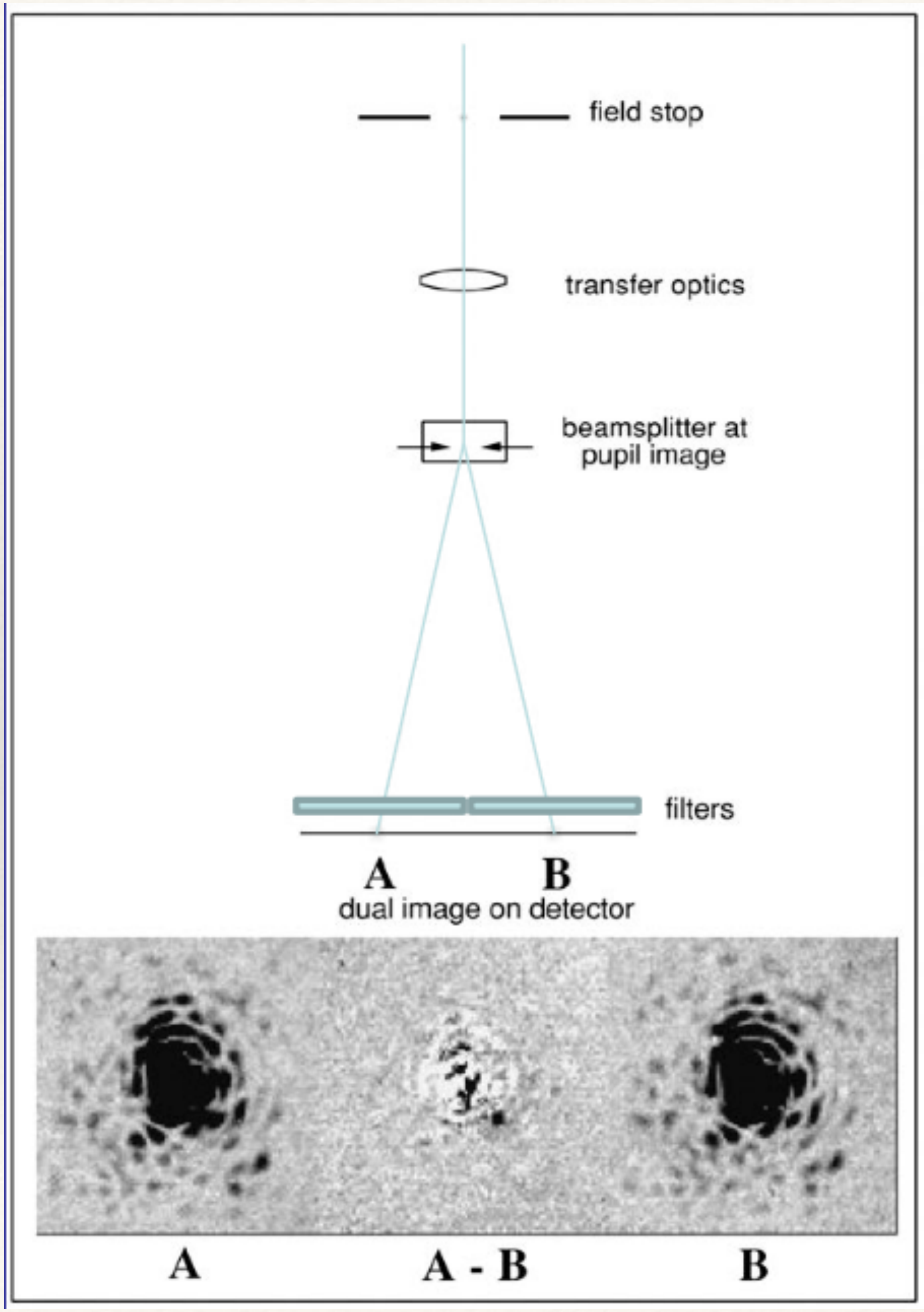
The spectra of cool planets are thought to be dominated by strong methane bands.

This is true for Jupiter and Saturn, as well as for T-type BDs

The planet image will be absent/present in two or more adjacent bands in/out methane bands



# Spectral Differential Imaging SDI




Residuals pattern due to:

- ☑ Dependence of Speckles on wavelength
- ☑ Changes in optical path

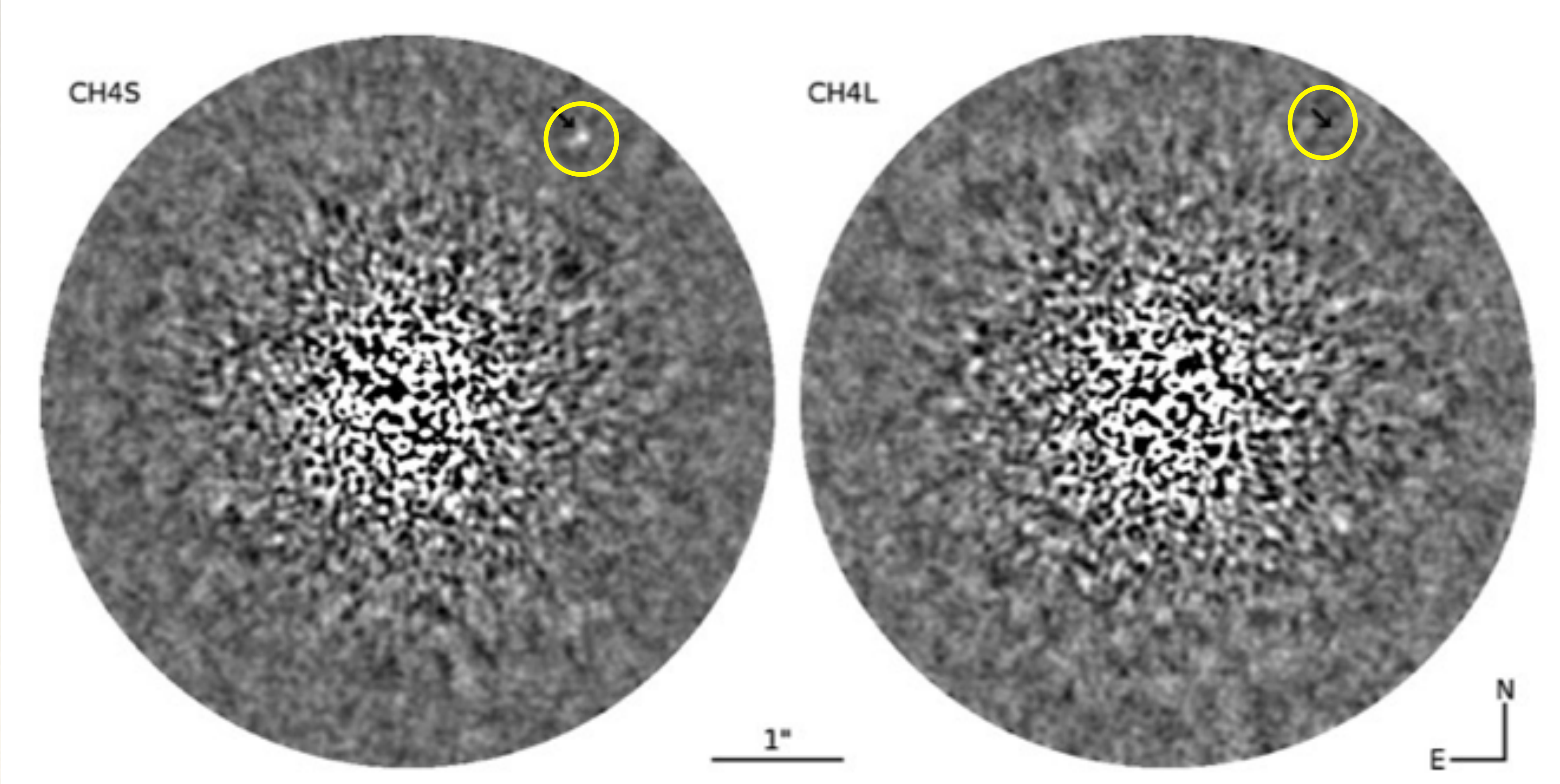
Racine et al., 1999

# Spectral Differential Imaging SDI

The planet image will be absent/present in two or more adjacent bands in/out methane bands

Differentiating these images, we may hope to cancel the speckle pattern and show the planet

GJ 504 b, Janson et al. 2013



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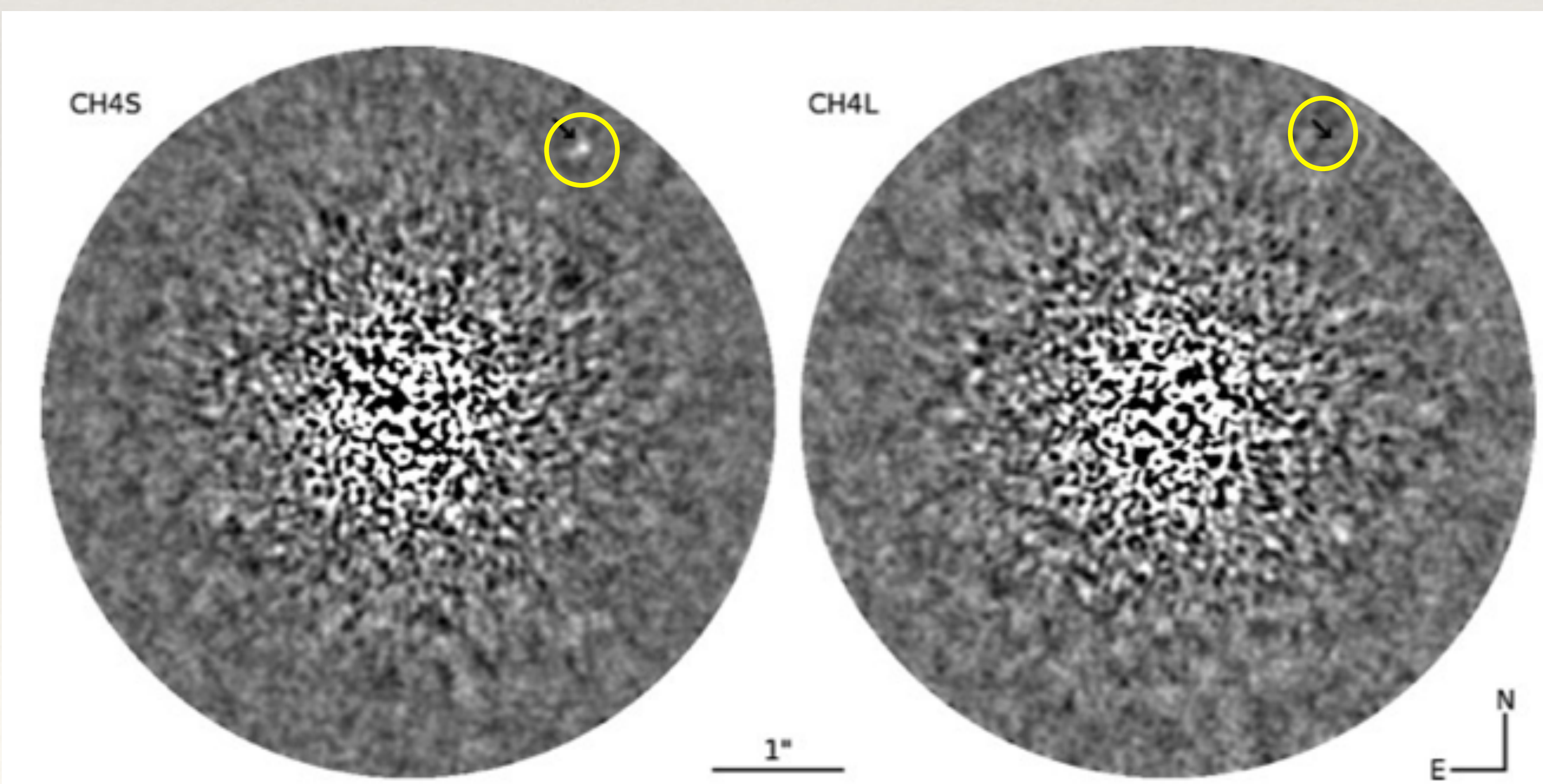


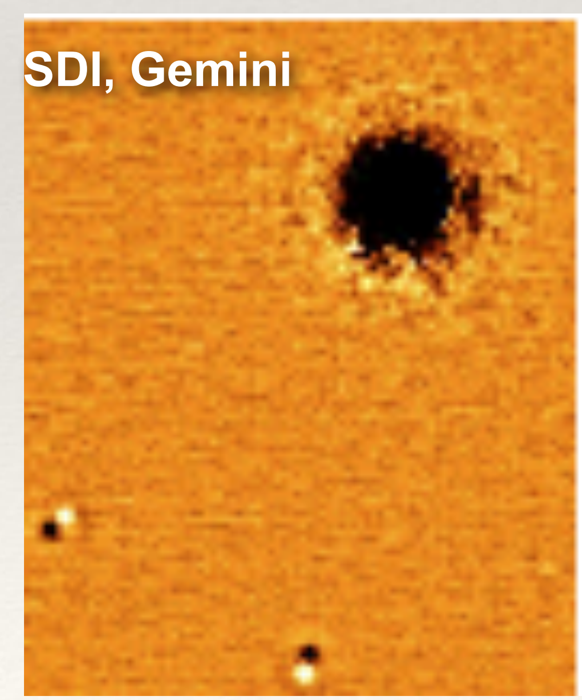

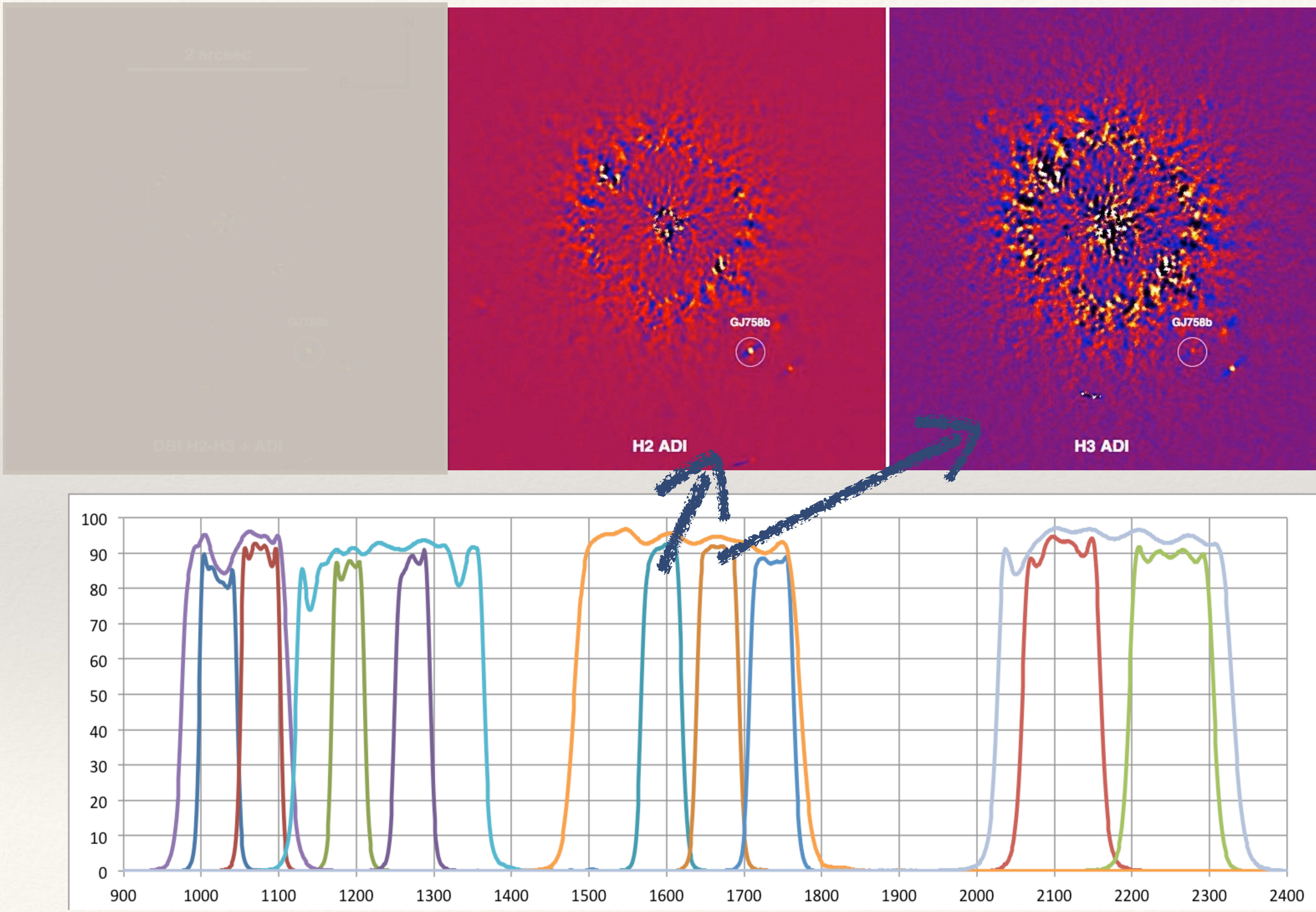
GJ758b
H2 ADI
GJ758b
H3 ADI
100
90
80
70
60
50
40
30
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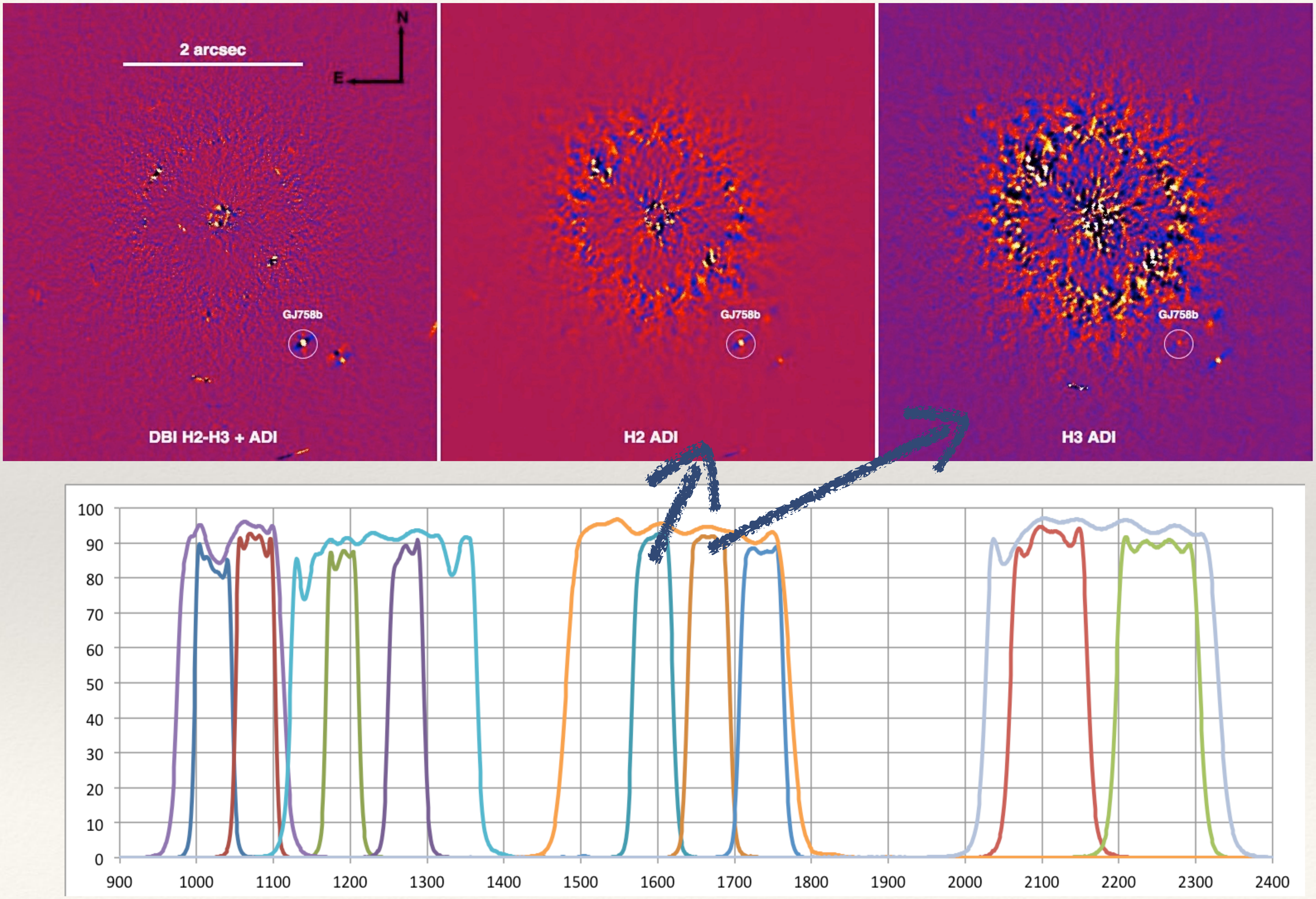
2 arcsec
N
E
GJ758b
DBI H2-H3 + ADI
GJ758b
H2 ADI
GJ758b
H3 ADI
100
90
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50
40
30
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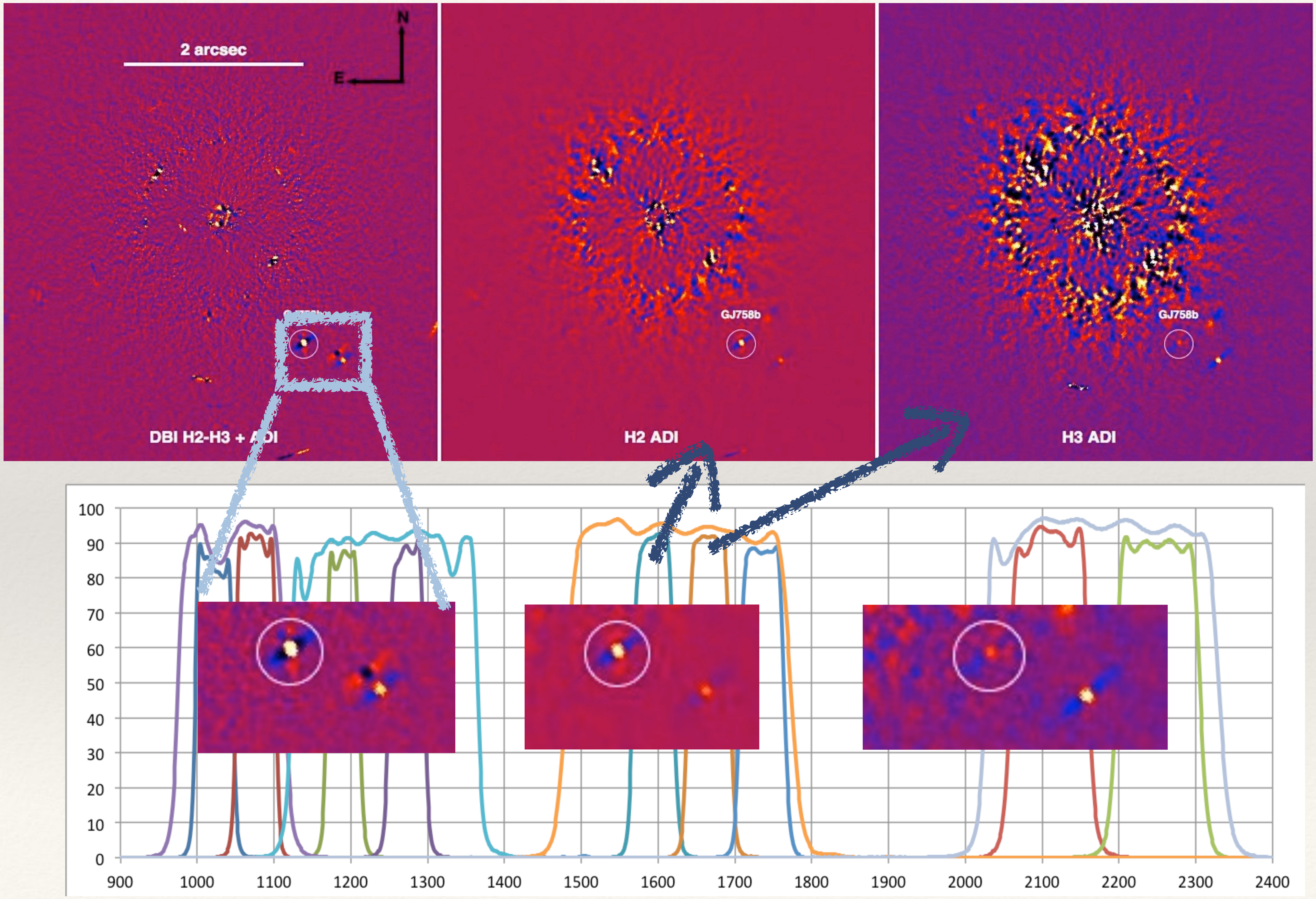

2 arcsec
N
E
GJ758b
DBI H2-H3 + ADI
H2 ADI
H3 ADI
100
90
80
70
60
50
40
30
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0
900
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1200
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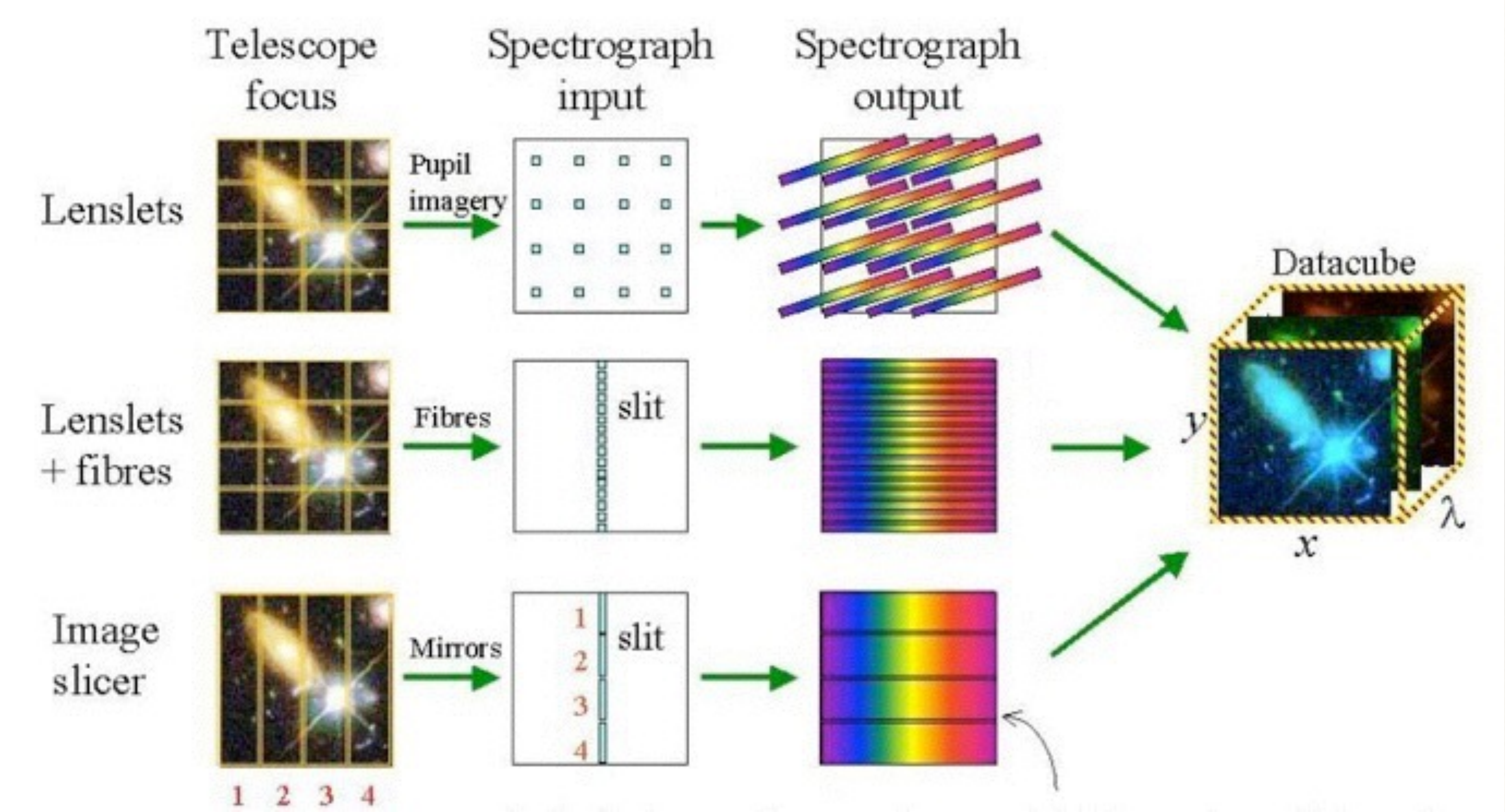
# Spectral Differential Imaging evolution: using IFS

# Spectral Differential Imaging evolution: using IFS



# IFS Concept

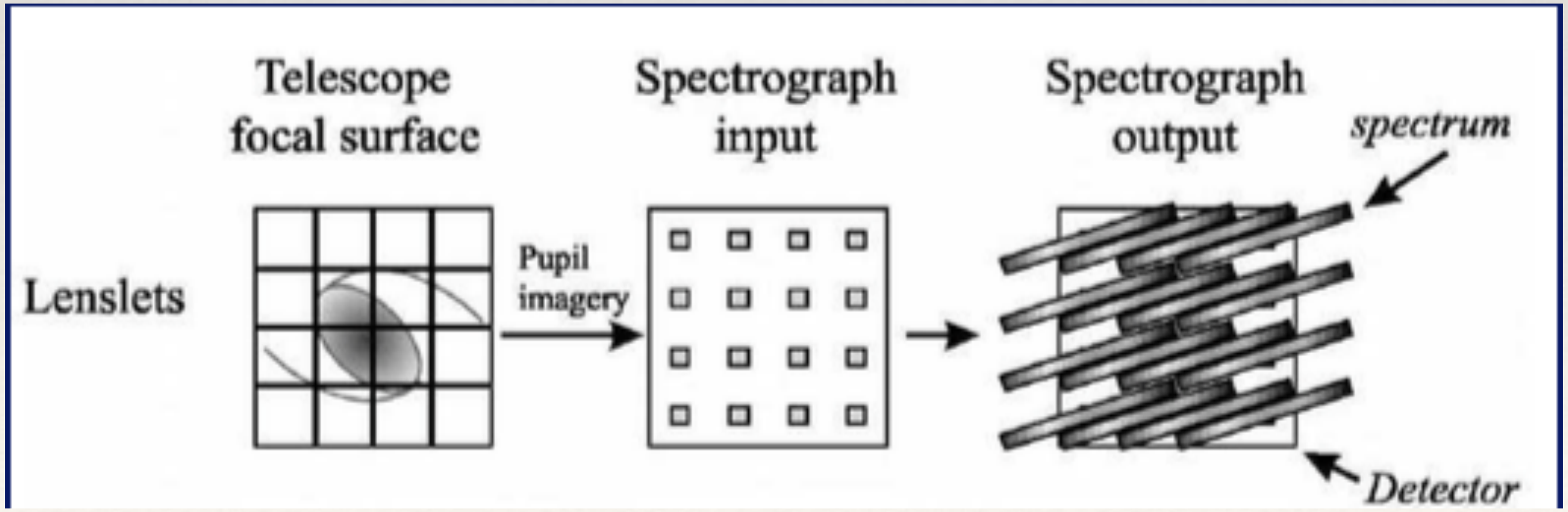
Lenslet Integral Field Spectrographs

– Simpler to realize

– Worst use of detector

– Re-imaging of pupil (TIGRE) Simpler realization (each lenslet is a simple lens)  Higher cross talk due to diffraction and interference between lenslets

– Re-imaging of focal plane (BIGRE)




Allington - Smith et al., 2001

# IFS Concept

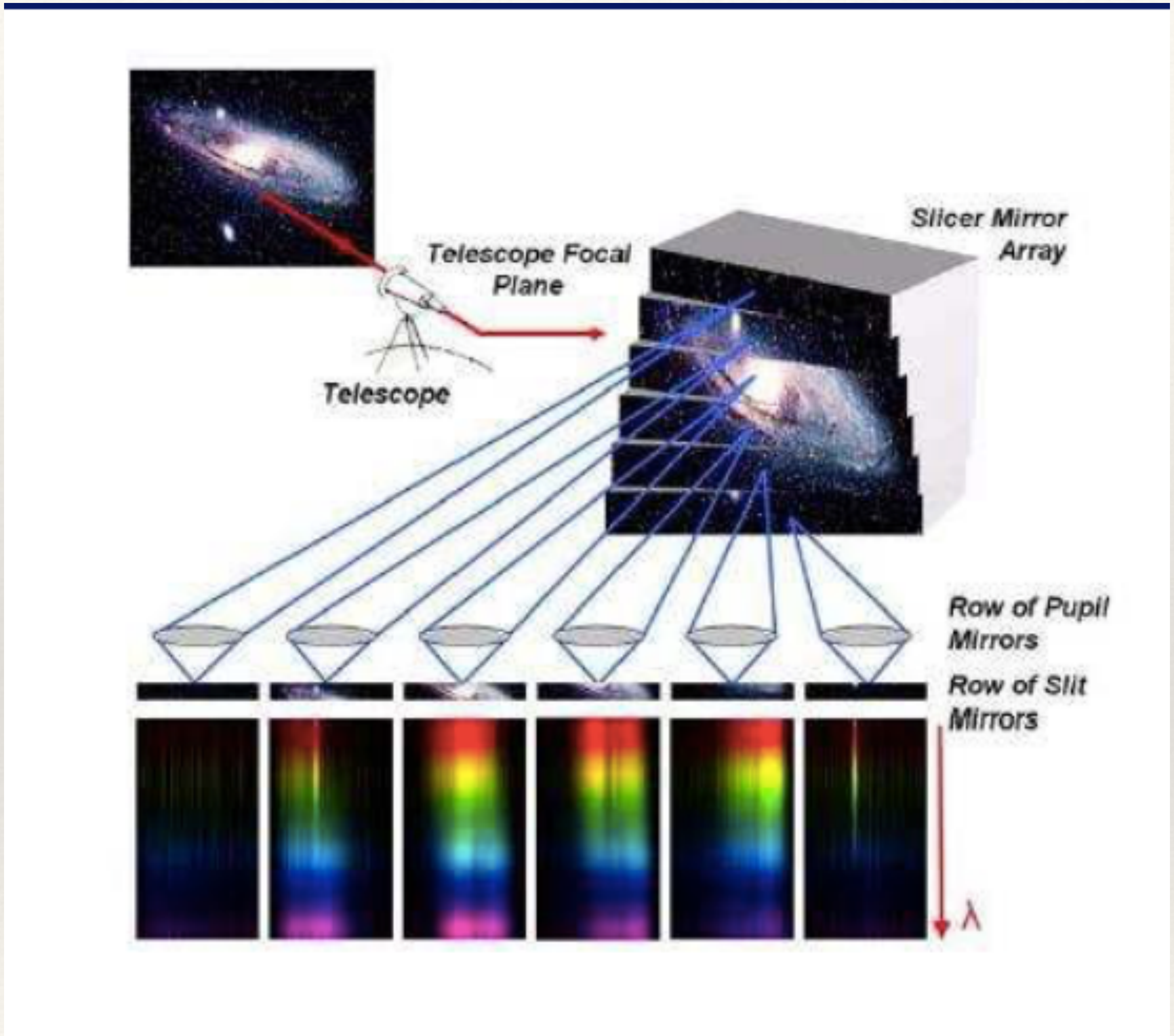



Image Slicer Spectrograph

More Complex Instrument

Best use of detector

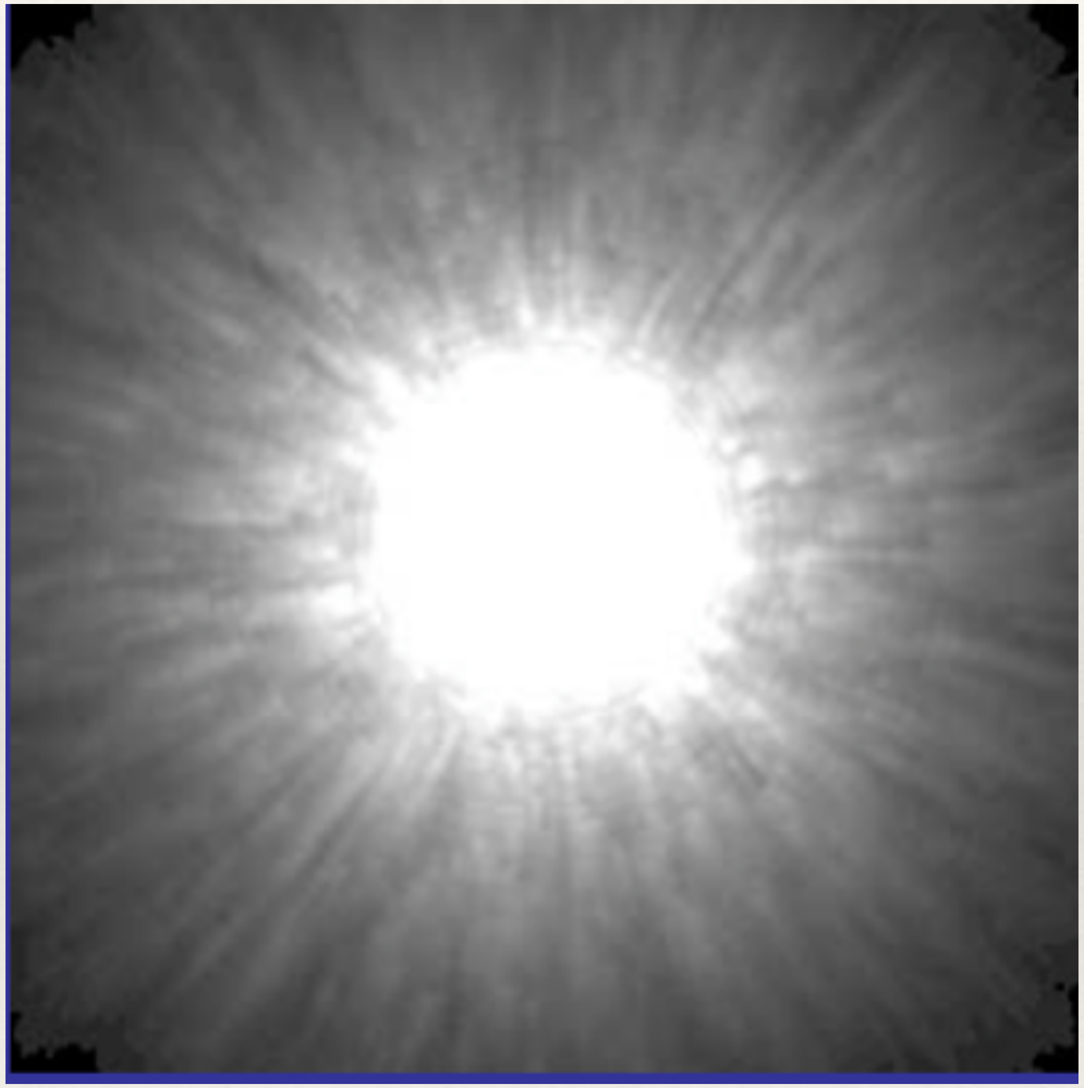
Prieto &Vives, 2006

# Chromatic correlation of speckles

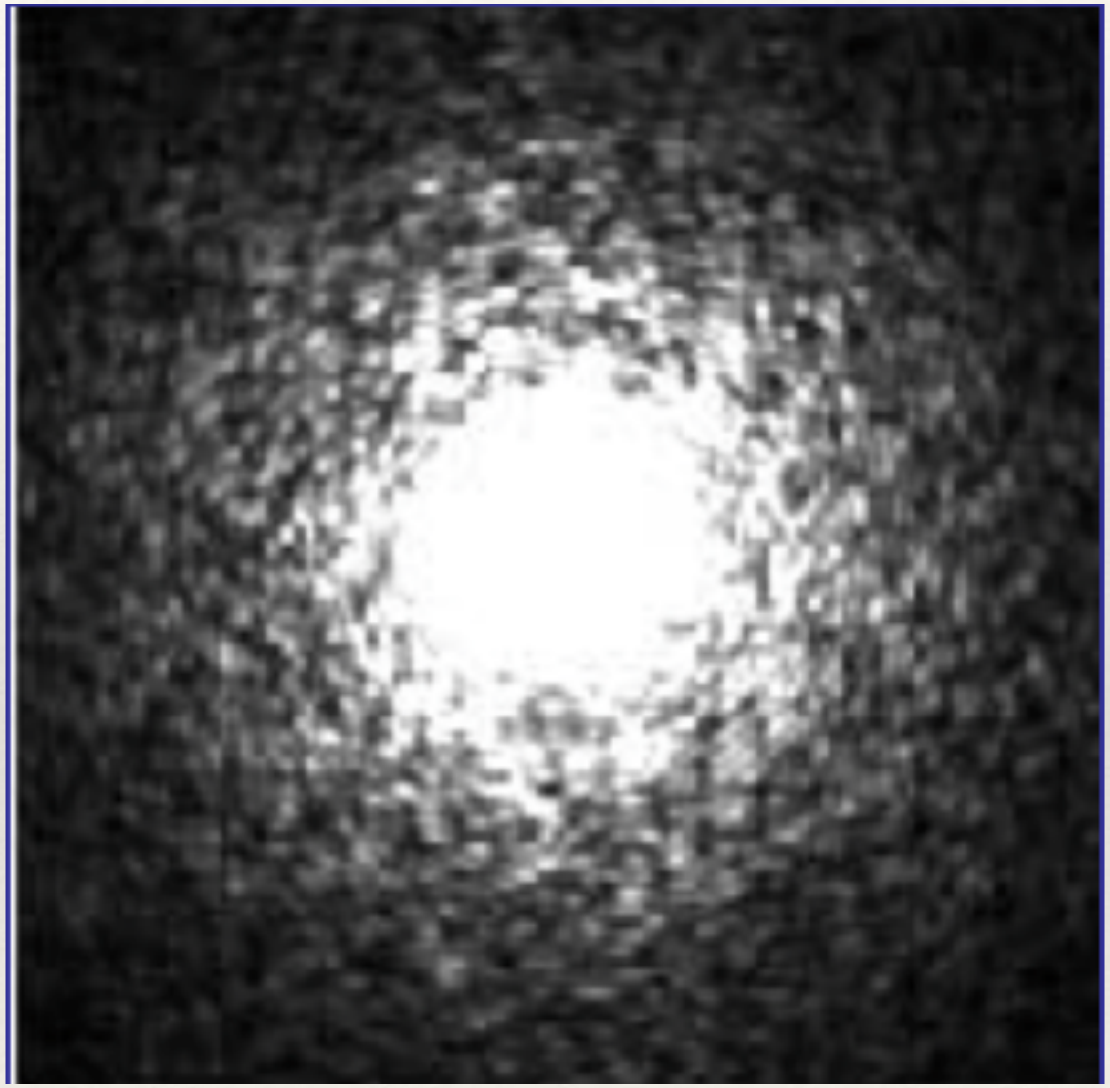
- ☑ Speckles are due to diffraction and interference
- ☑ Their separation from star center should scale with wavelength
- ☑ Since separation of planet images is independent on wavelength, it is possible to separate speckle signal from the planet one and remove it if images at different wavelengths are acquired (e.g. using an integral field spectrograph)

# Speckles Chromatism

Integrated Light (0.7-1.0 $\mu$m)



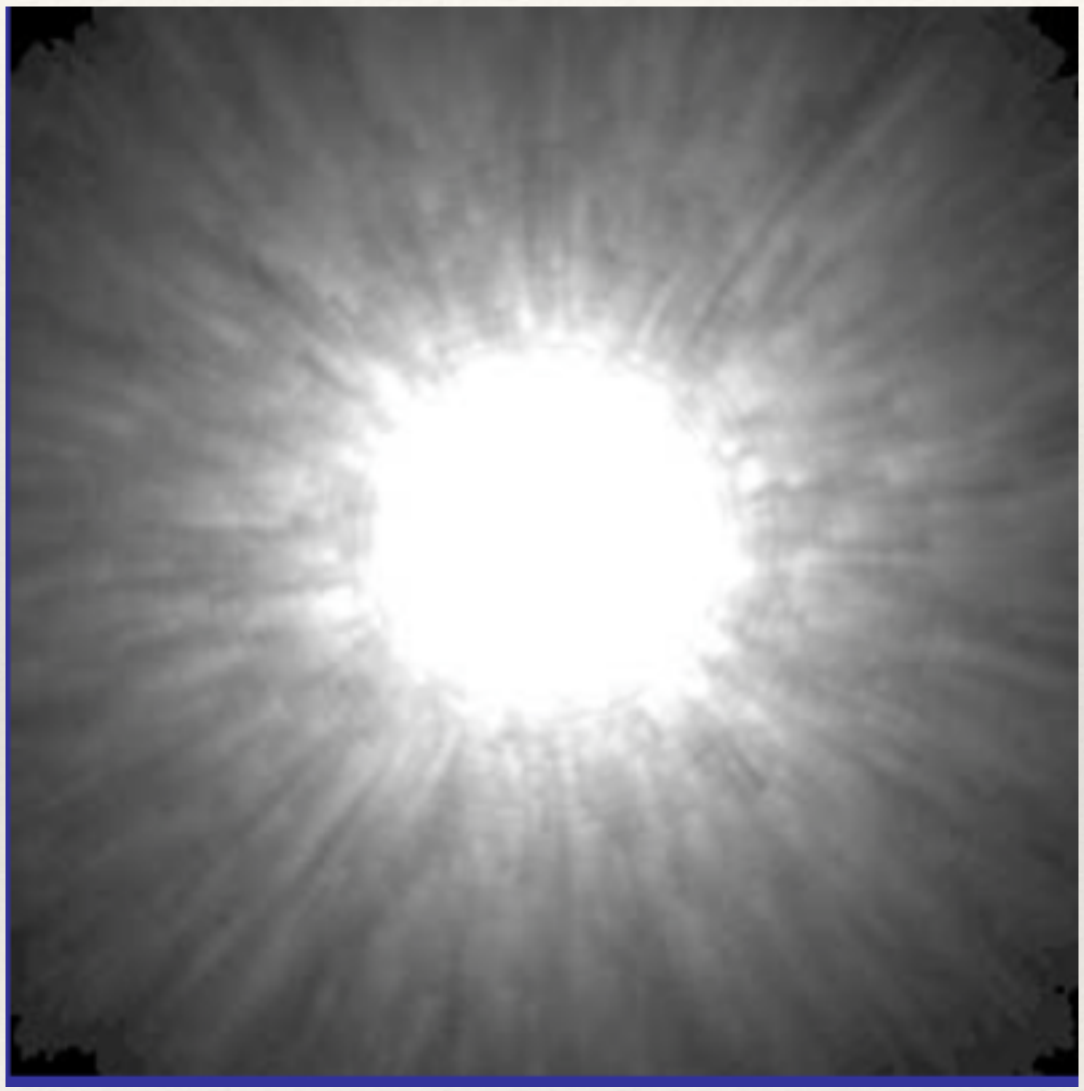
0.7 $\mu$m



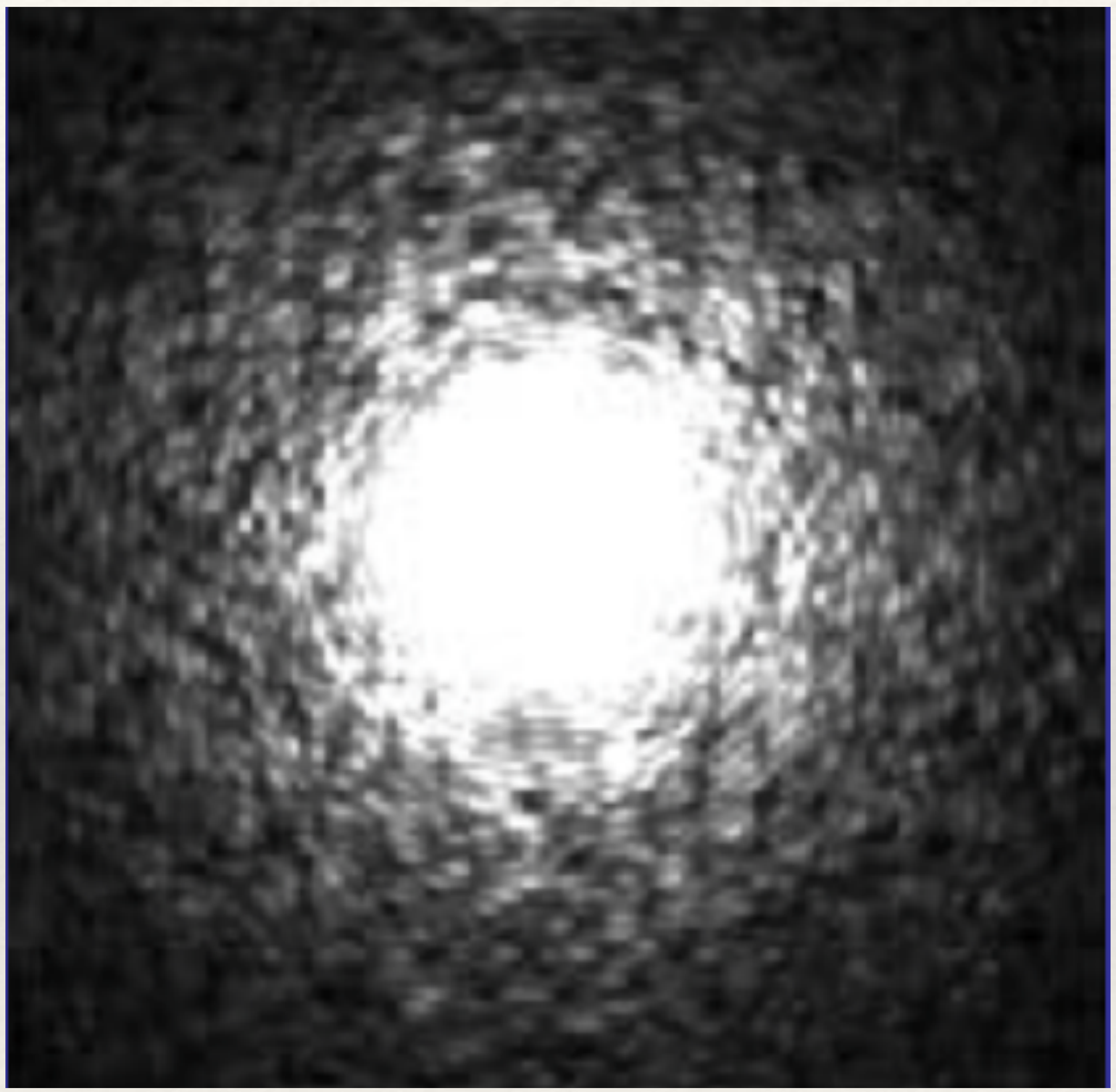
Sparks and Ford, 2002, ApJ, 578, 543

# Speckles Chromatism

Integrated Light (0.7-1.0 $\mu$m)



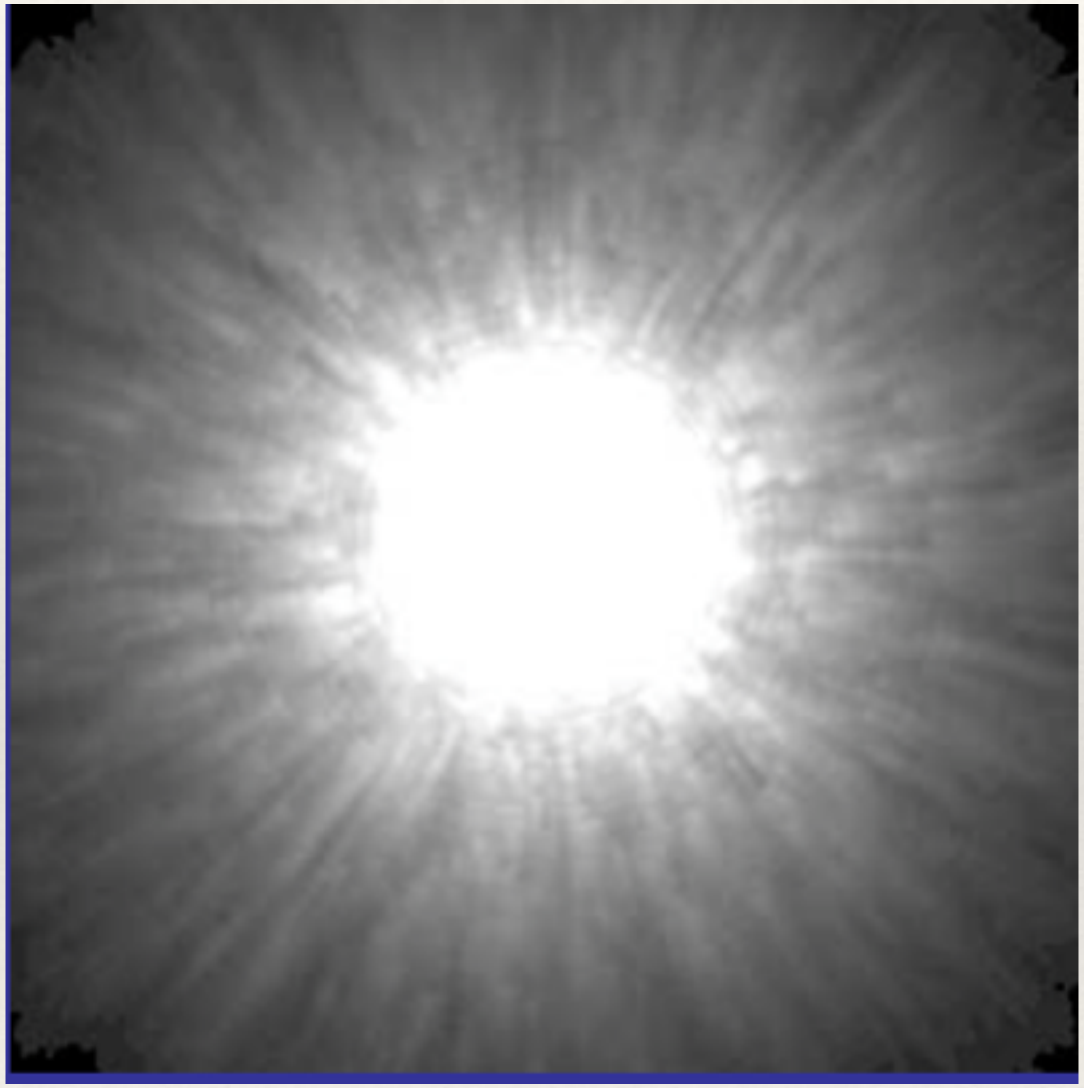
0.76 $\mu$m



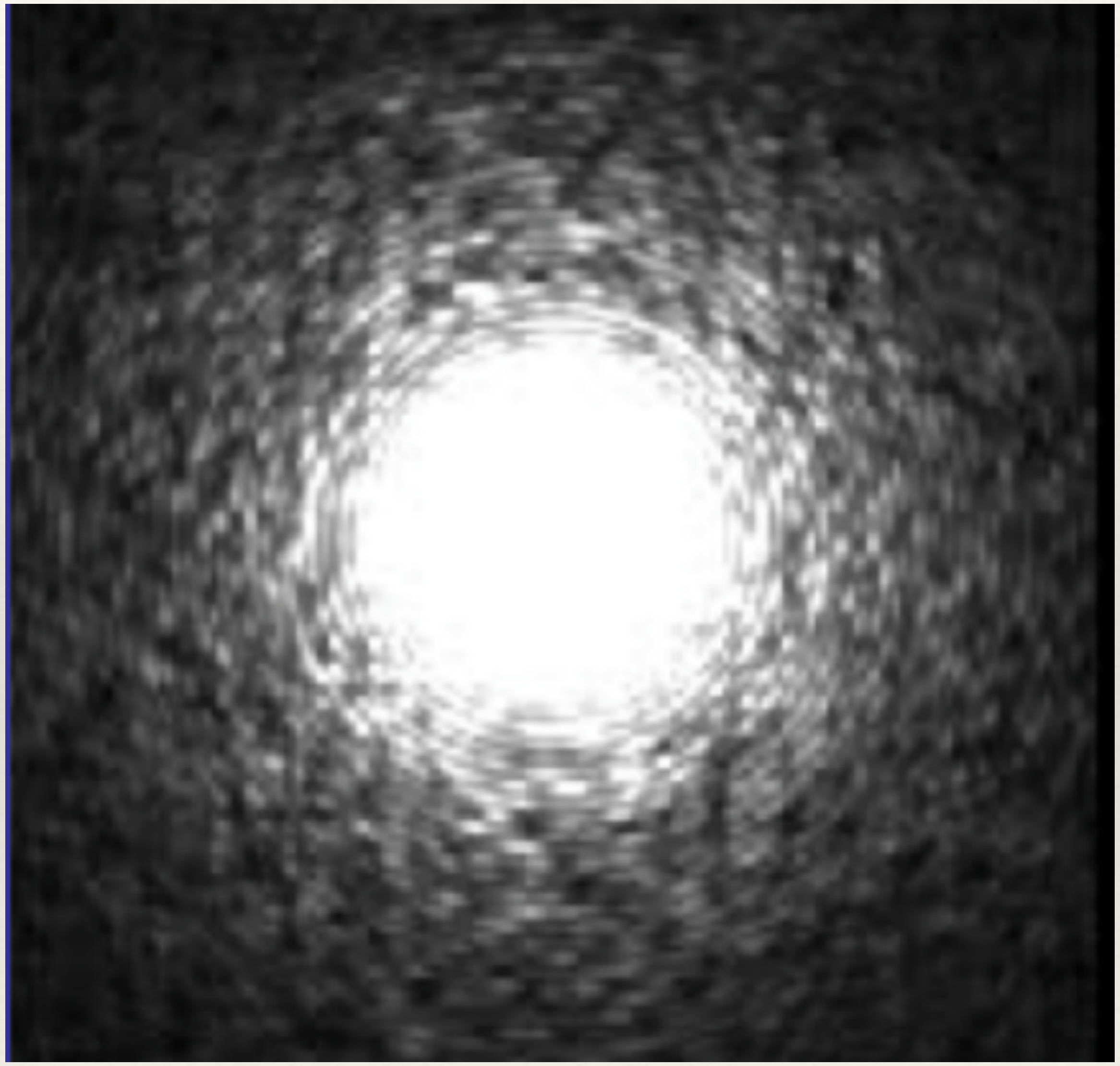
Sparks and Ford, 2002, ApJ, 578, 543

# Speckles Chromatism

Integrated Light (0.7-1.0 $\mu$m)



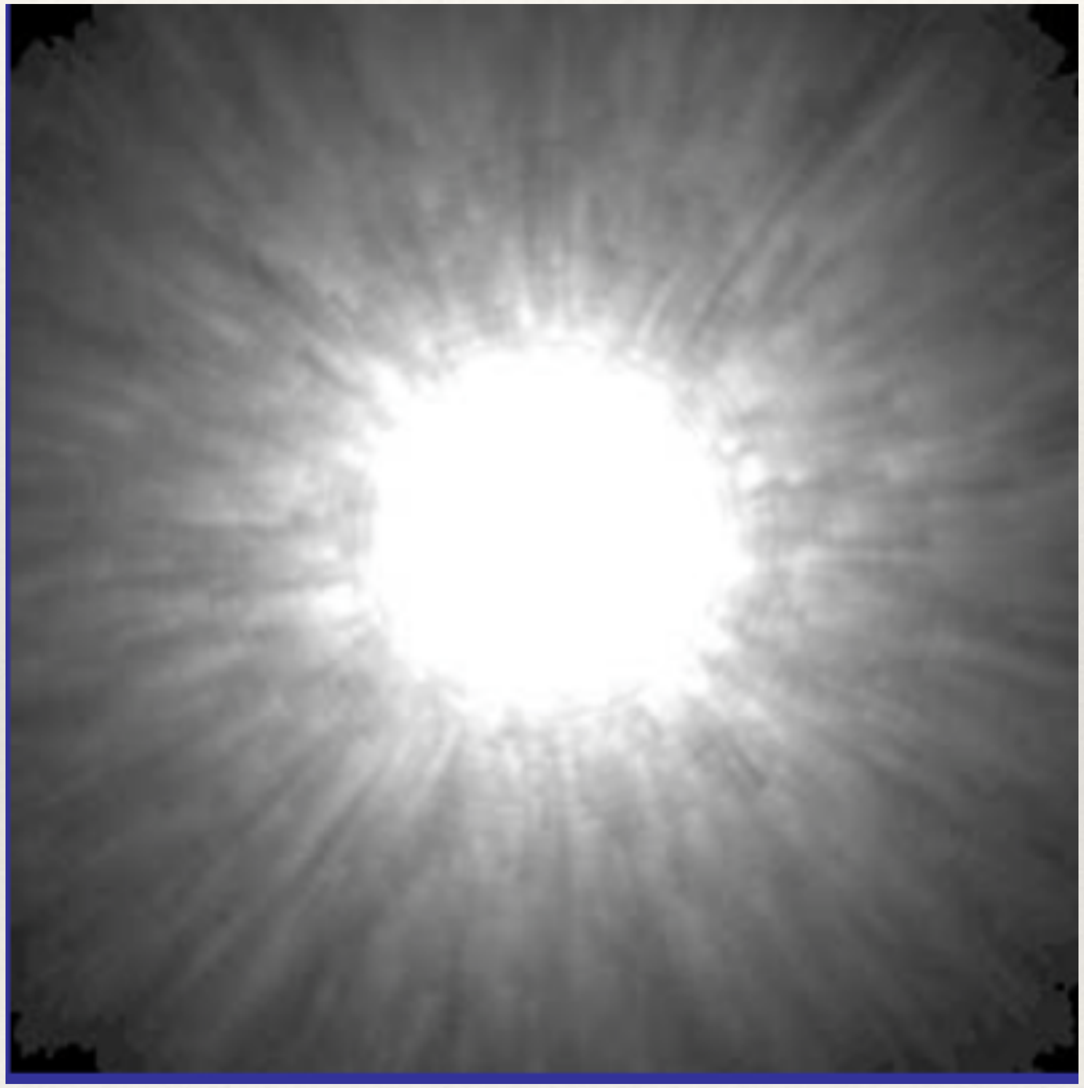
0.84 $\mu$m



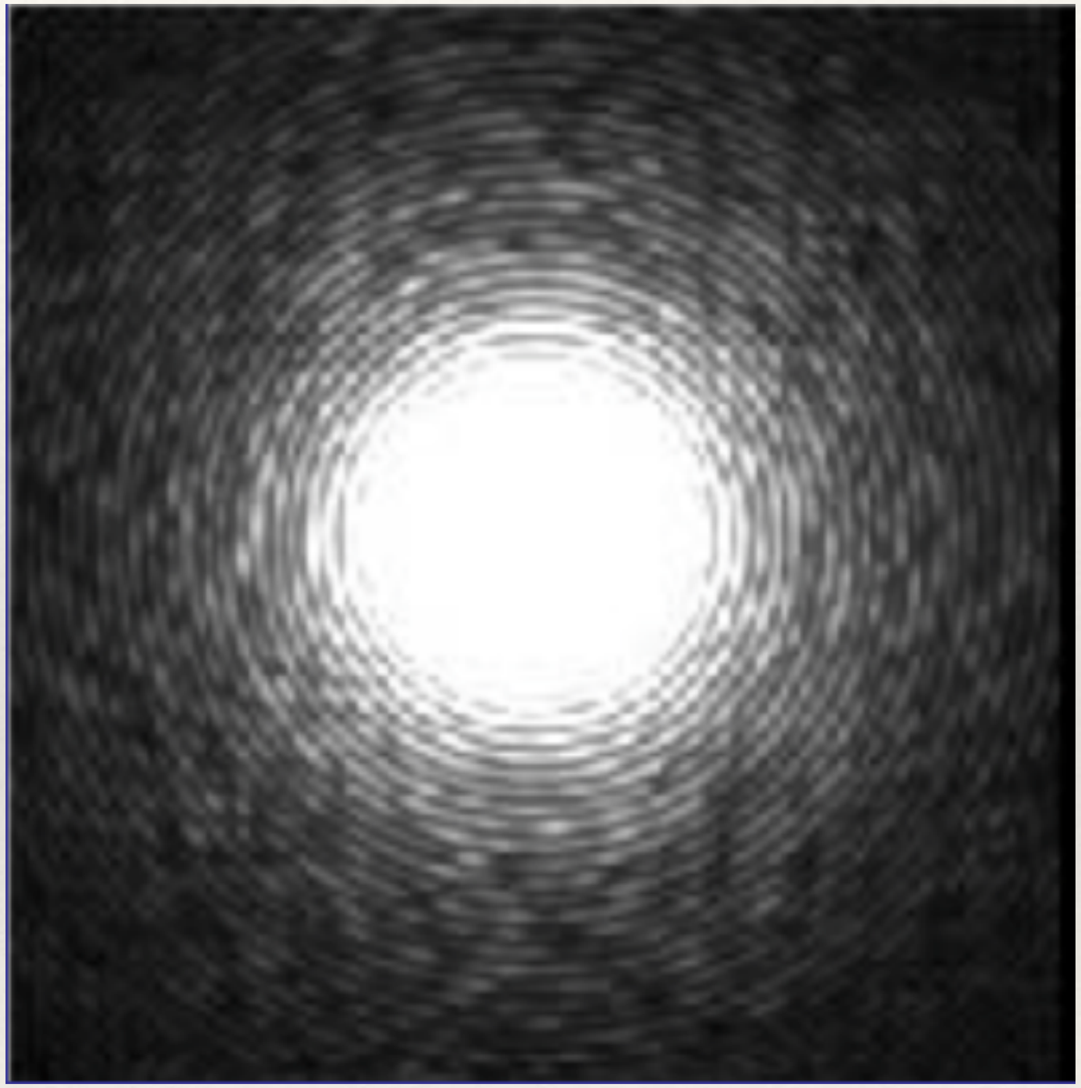
Sparks and Ford, 2002, ApJ, 578, 543

# Speckles Chromatism

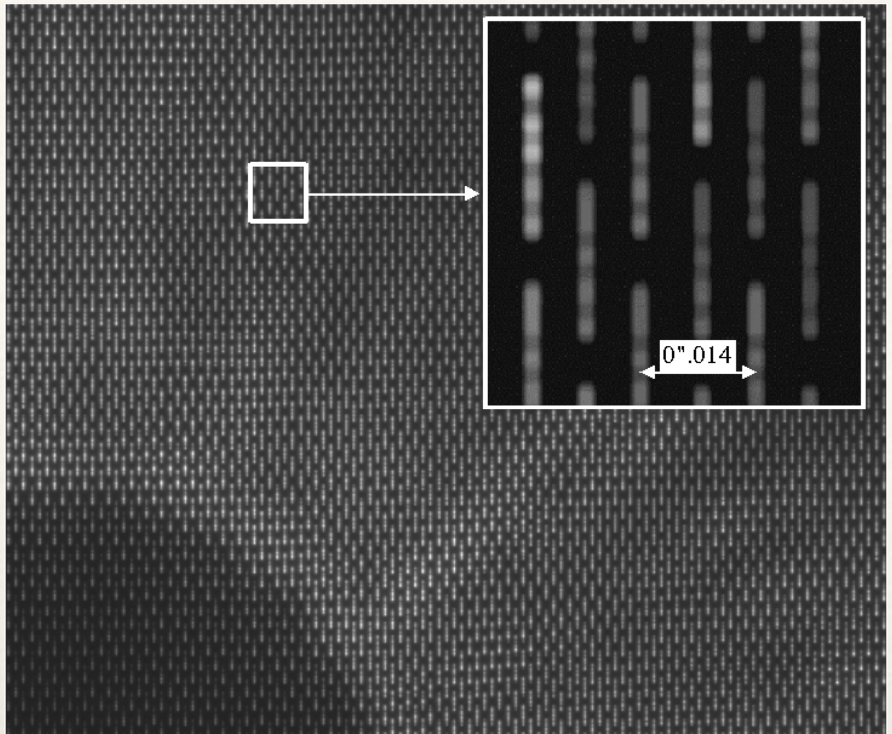
Integrated Light (0.7-1.0 $\mu$m)

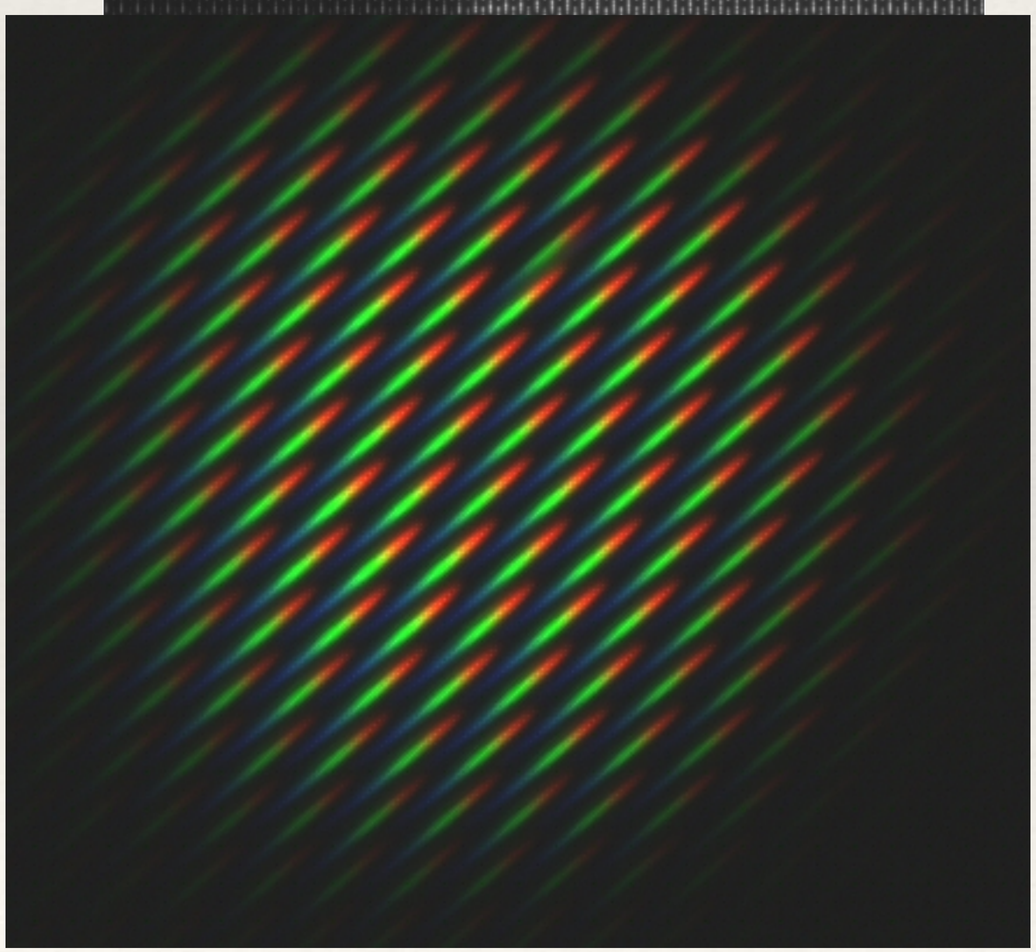


1.0 $\mu$m



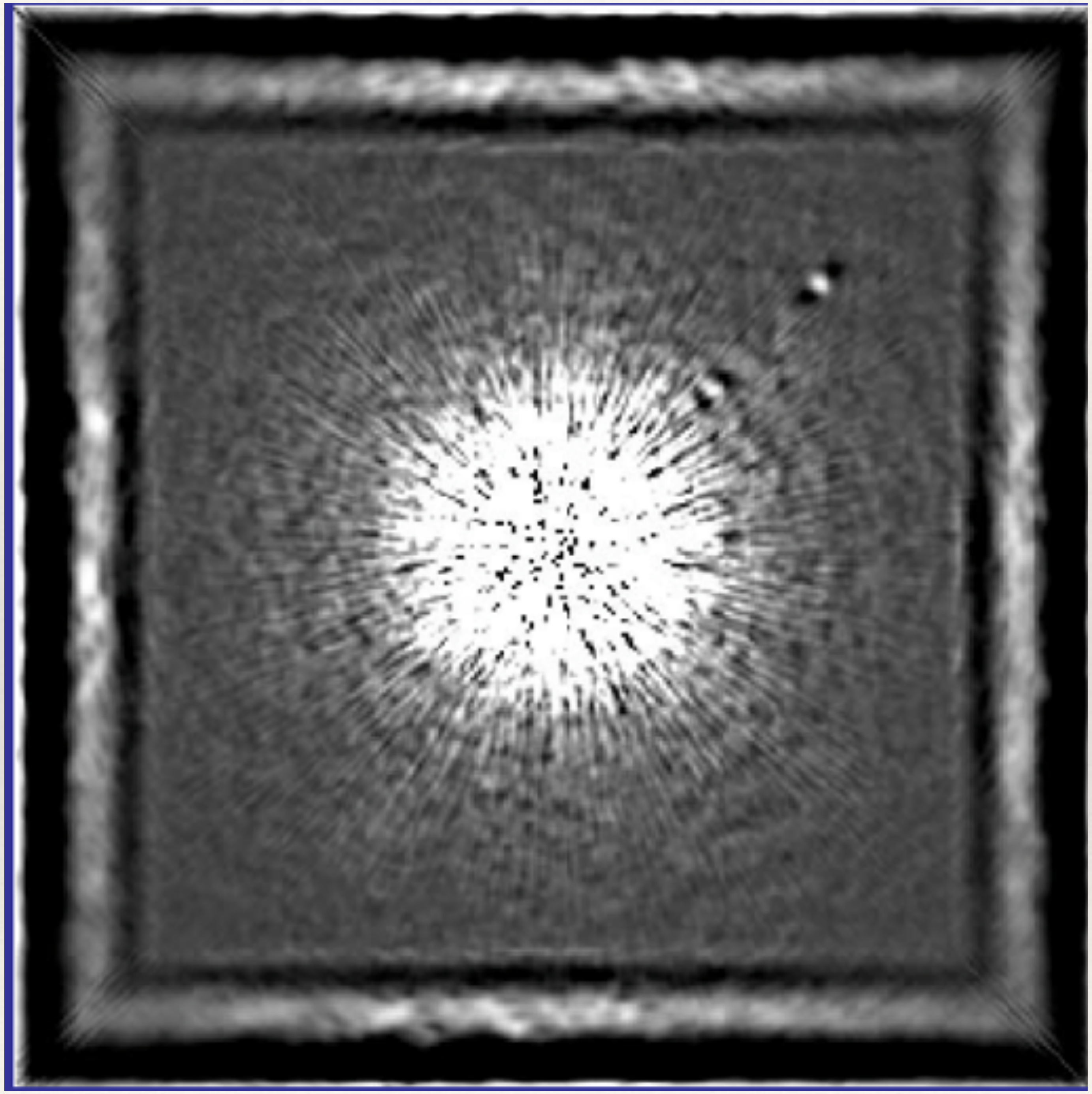
Sparks and Ford, 2002, ApJ, 578, 543



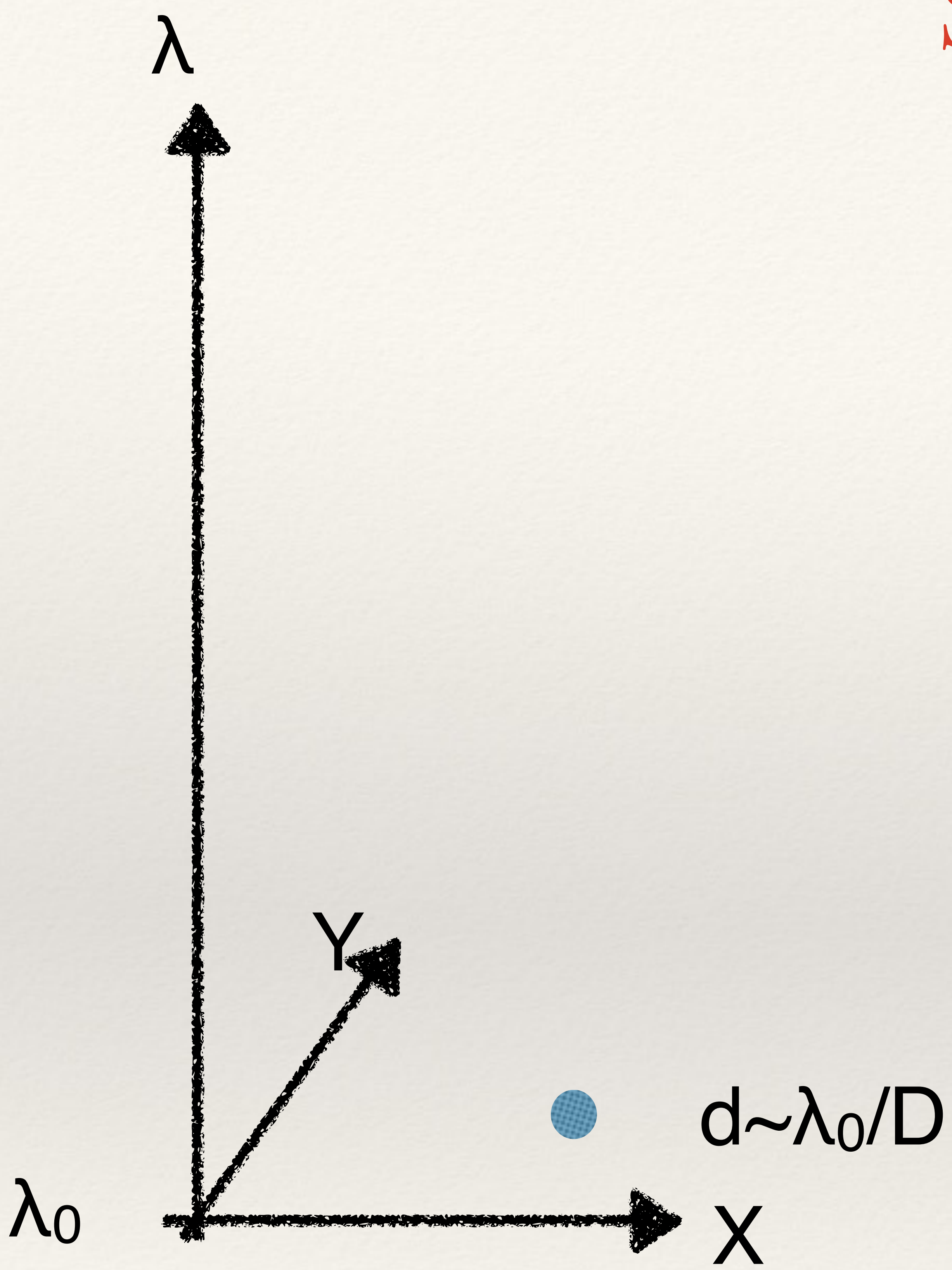
Construction of a Data Cube with a number of "monochromatic" images equal to the number of spectral resolution element in each spectra obtained by means of an Integral Field Spettrograph

# SDI exploiting Speckles Chromatism

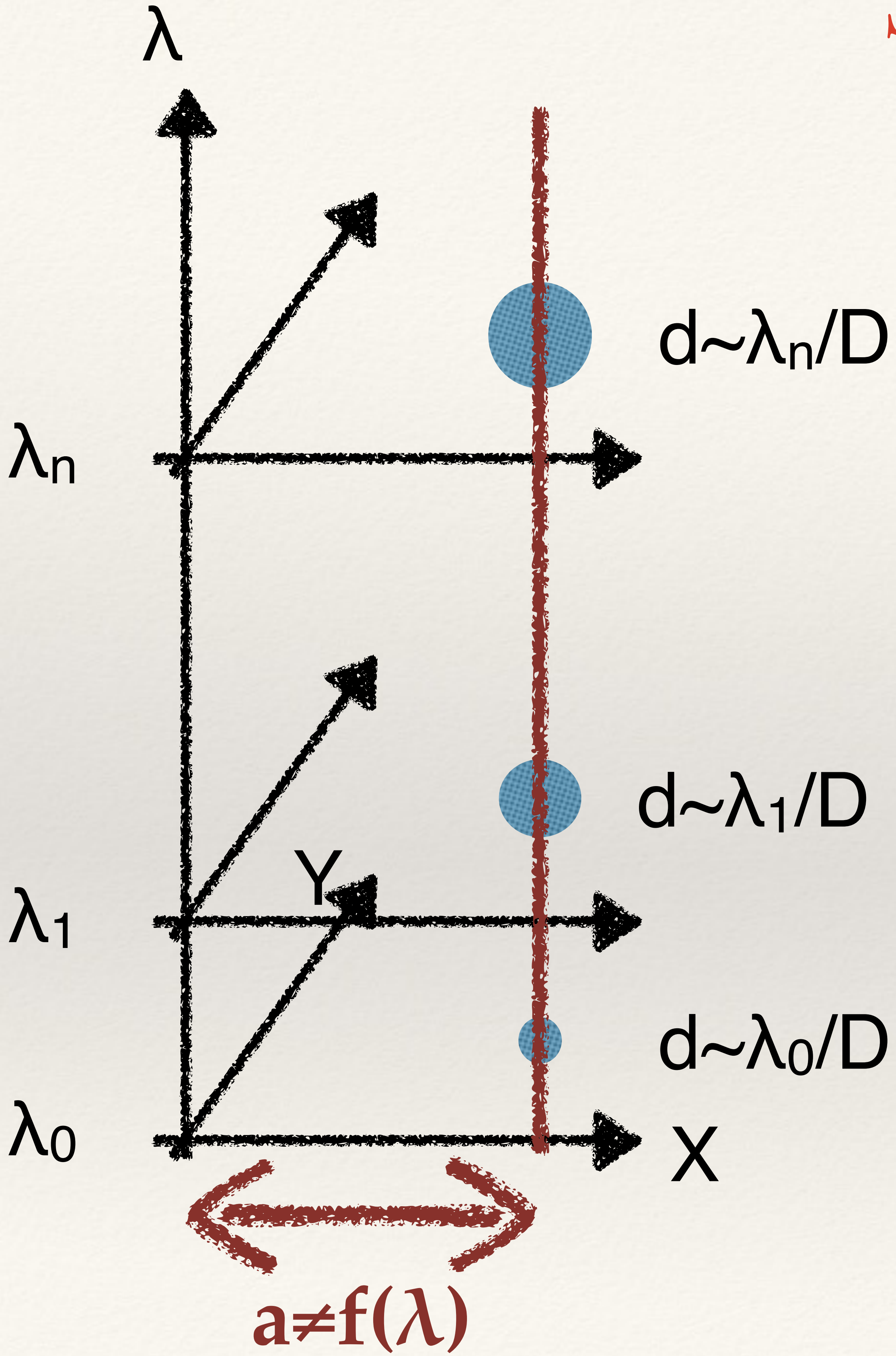


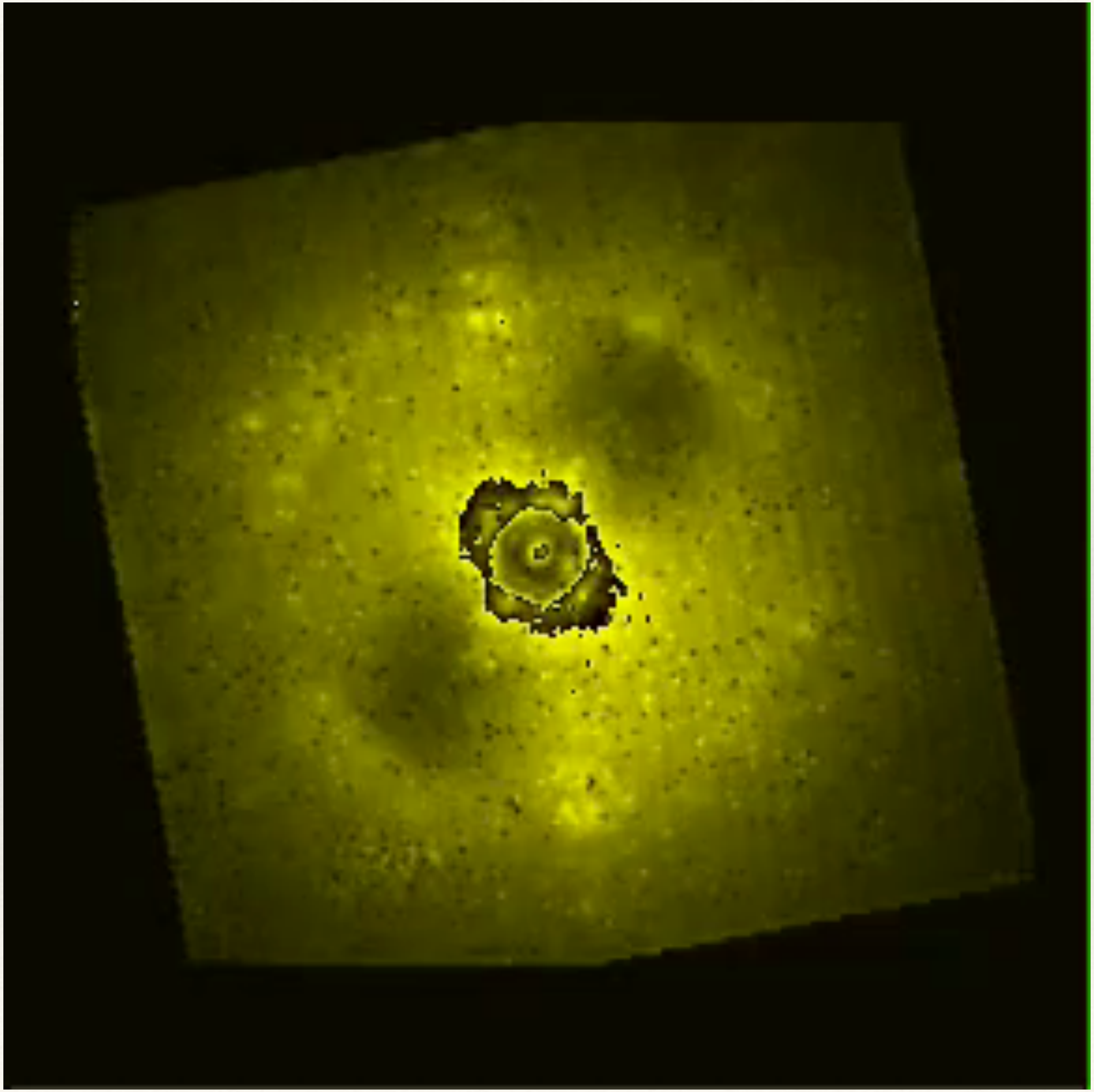
Sparks and Ford, 2002, ApJ, 578, 543

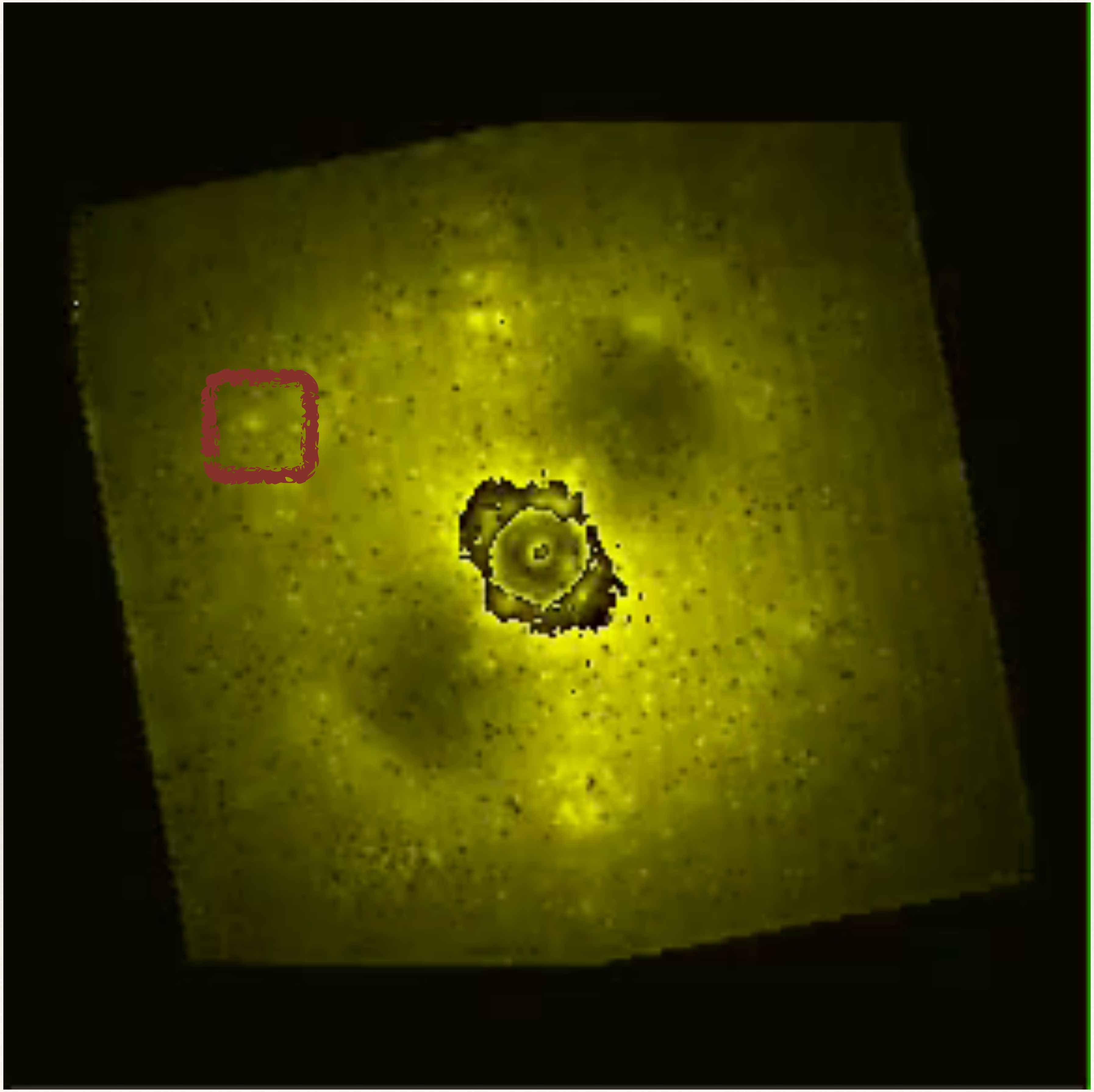
# Speckles Deconvolution



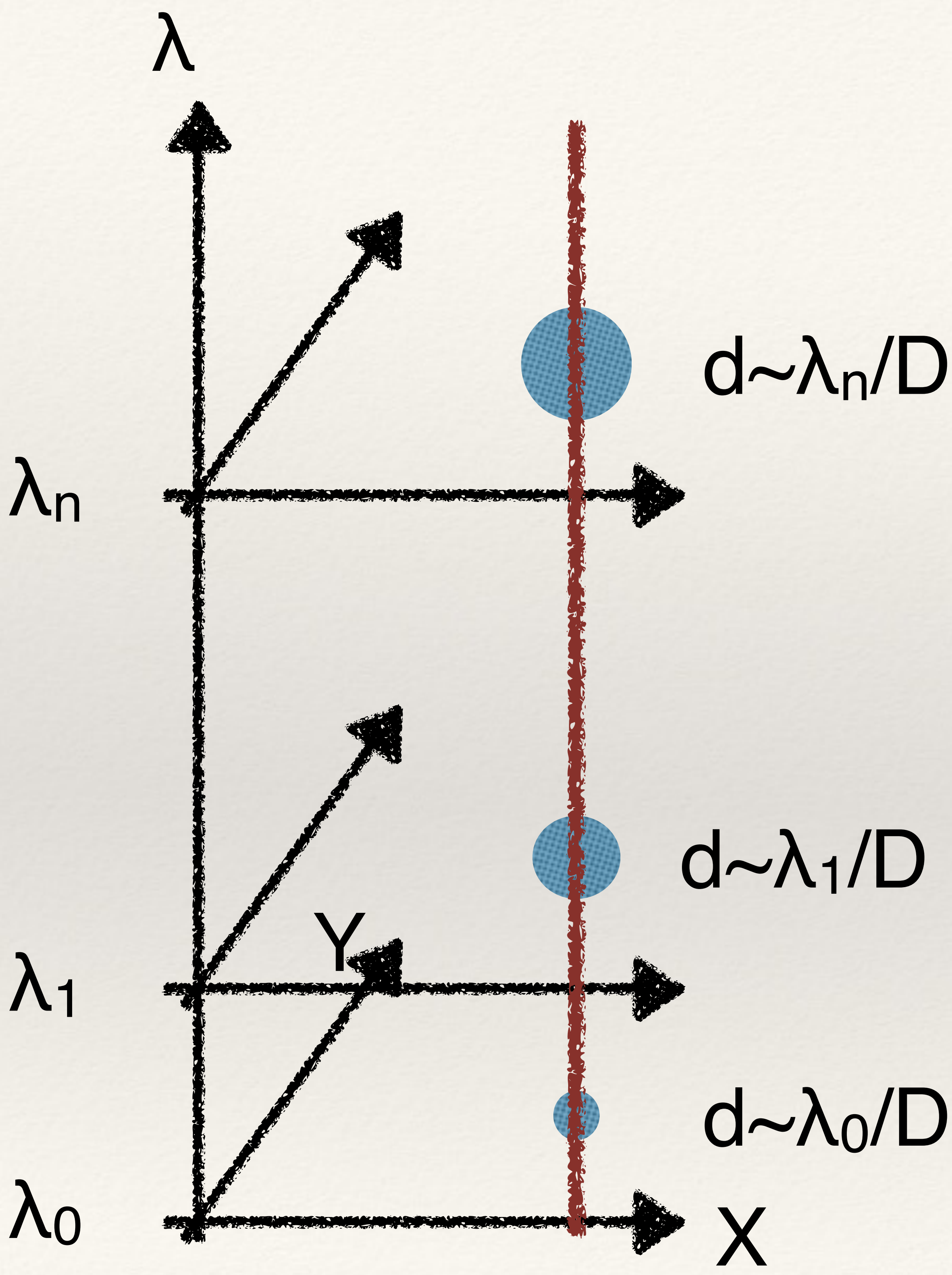
# Speckles Deconvolution



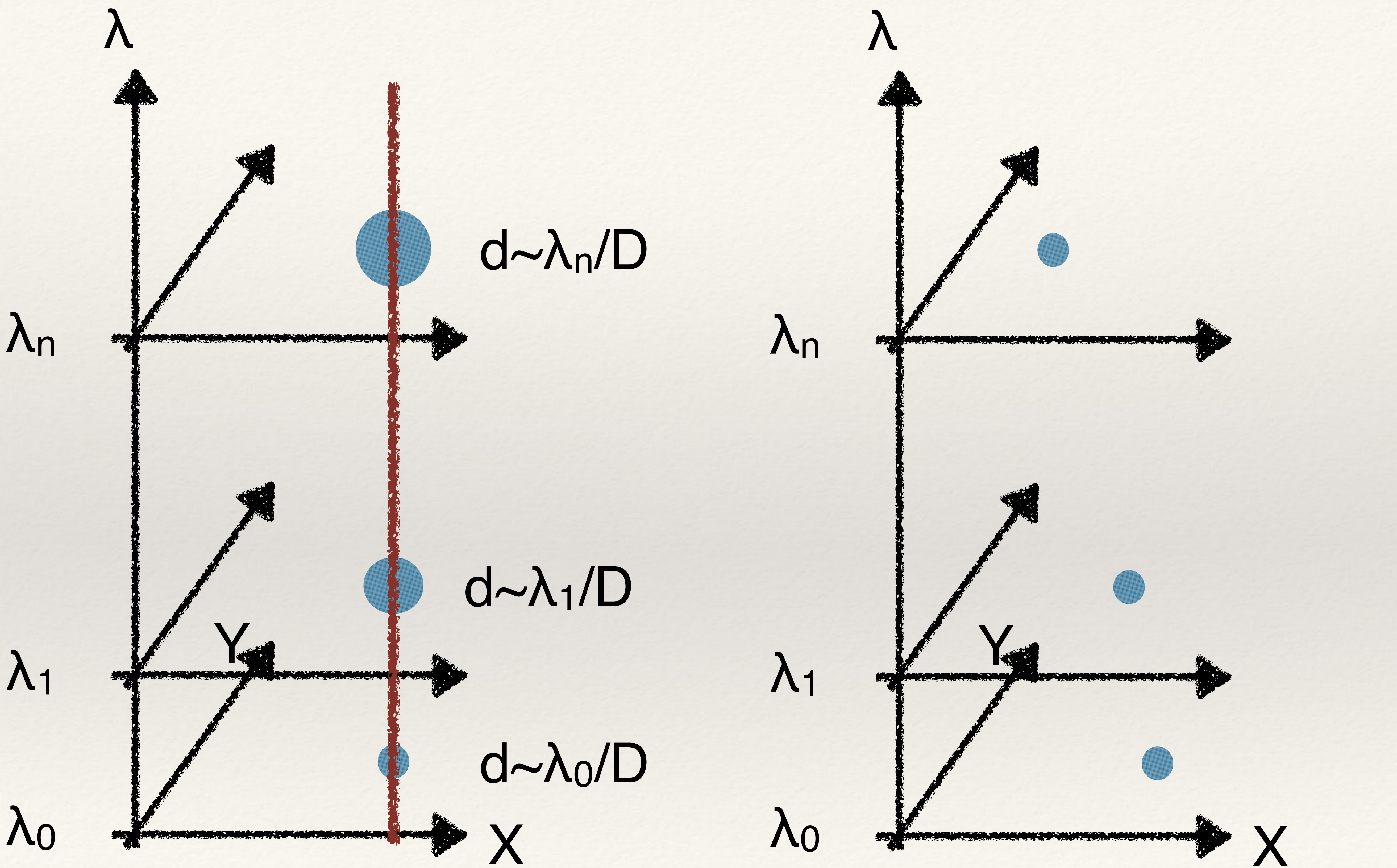




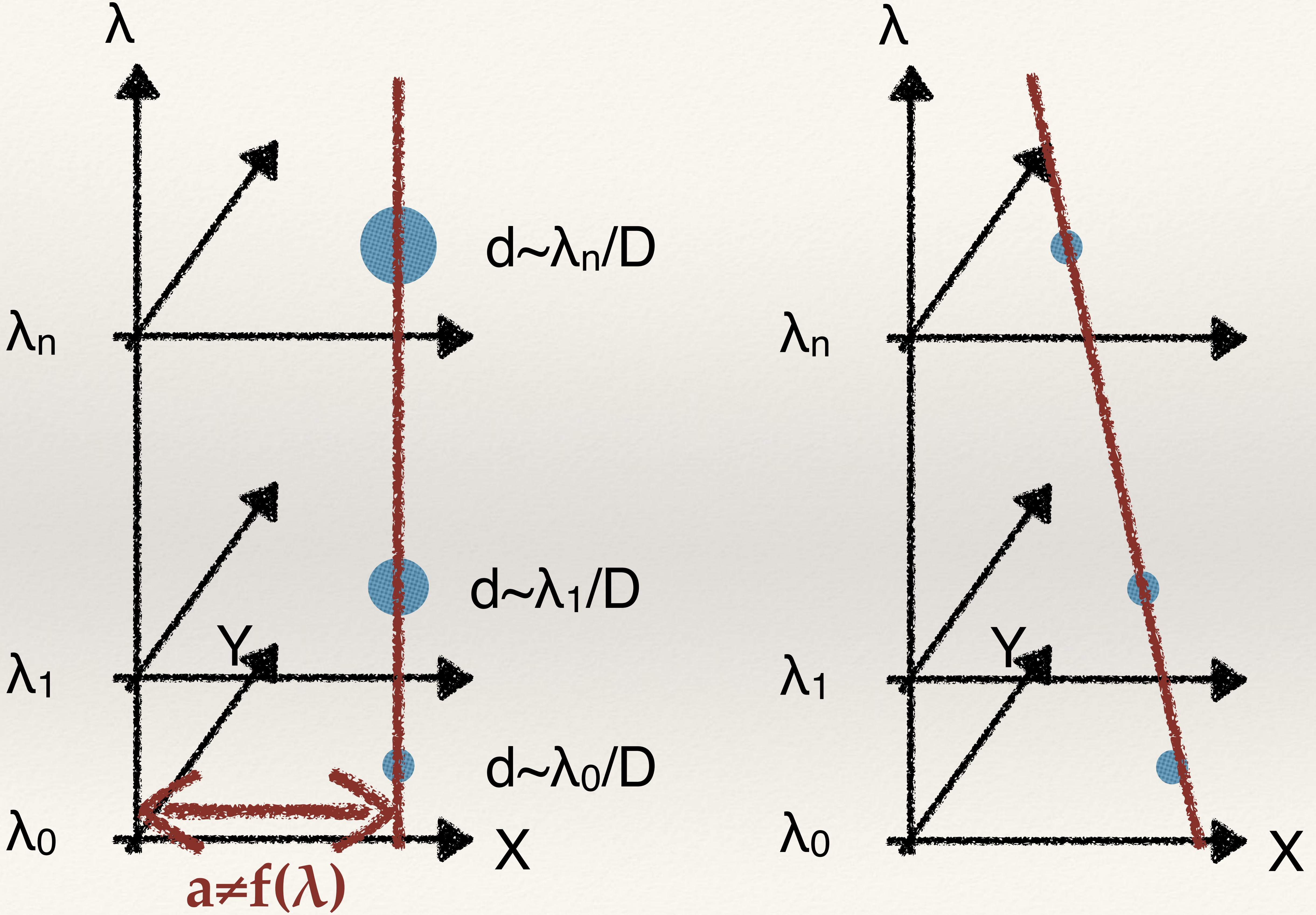
# Speckles Deconvolution



# Speckles Deconvolution



# Speckles Deconvolution



# Speckles Deconvolution

- Speckle deconvolution is applicable when the planet image does not extend over the whole observed spectrum
- There is a minimum separation from the star where this occurs (bifurcation radius)

$$r = 2\,\varepsilon 1.22(\lambda_0/D)\,[\lambda_1/\lambda_2 - \lambda_1)]$$

where $\lambda_0$, $\lambda_1$ and $\lambda_2$ are mean, minimum and maximum wavelength and $\varepsilon$ is a factor ~1 that takes into account how many points are actually needed to provide a good estimate of the local background

Thatte et al., 2007, MNRAS, 379, 1229

# Bifurcation Radius for Diff. Telescopes

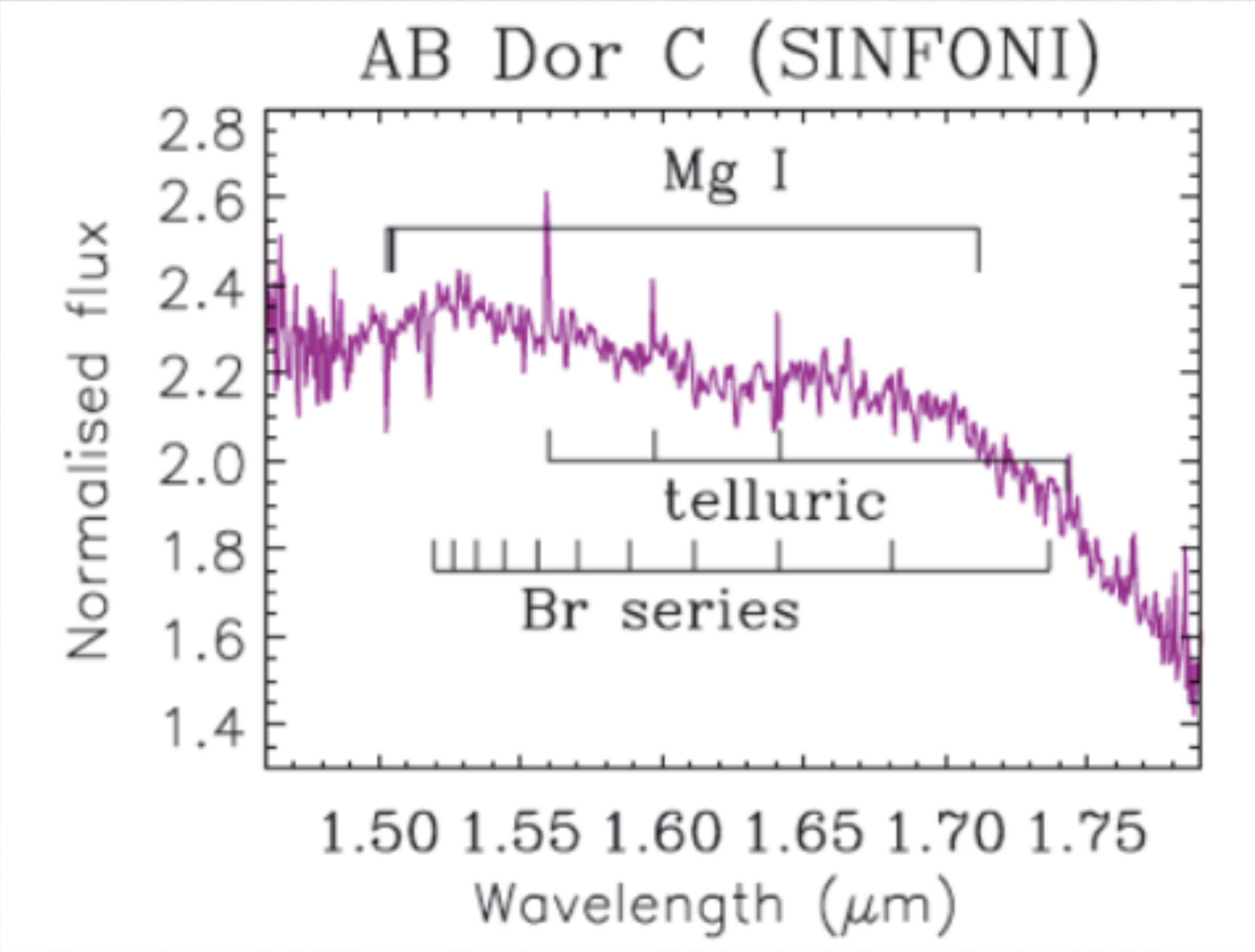
| Band | $\lambda_{min}$ | $\lambda_{max}$ | r (arcsec) | r (arcsec) |
|---|---|---|---|---|
| Telescope | | | VLT | E-ELT |
| Y-J | 0.95 | 1.35 | 0.18 | 0.039 |
| H | 1.45 | 1.80 | 0.45 | 0.095 |
| K | 1.95 | 2.45 | 0.58 | 0.122 |
| Y-J-H | 0.95 | 1.80 | 0.10 | 0.022 |
| H-K | 1.45 | 2.45 | 0.19 | 0.040 |
| Y-J-H-K | 0.95 | 2.45 | 0.07 | 0.015 |

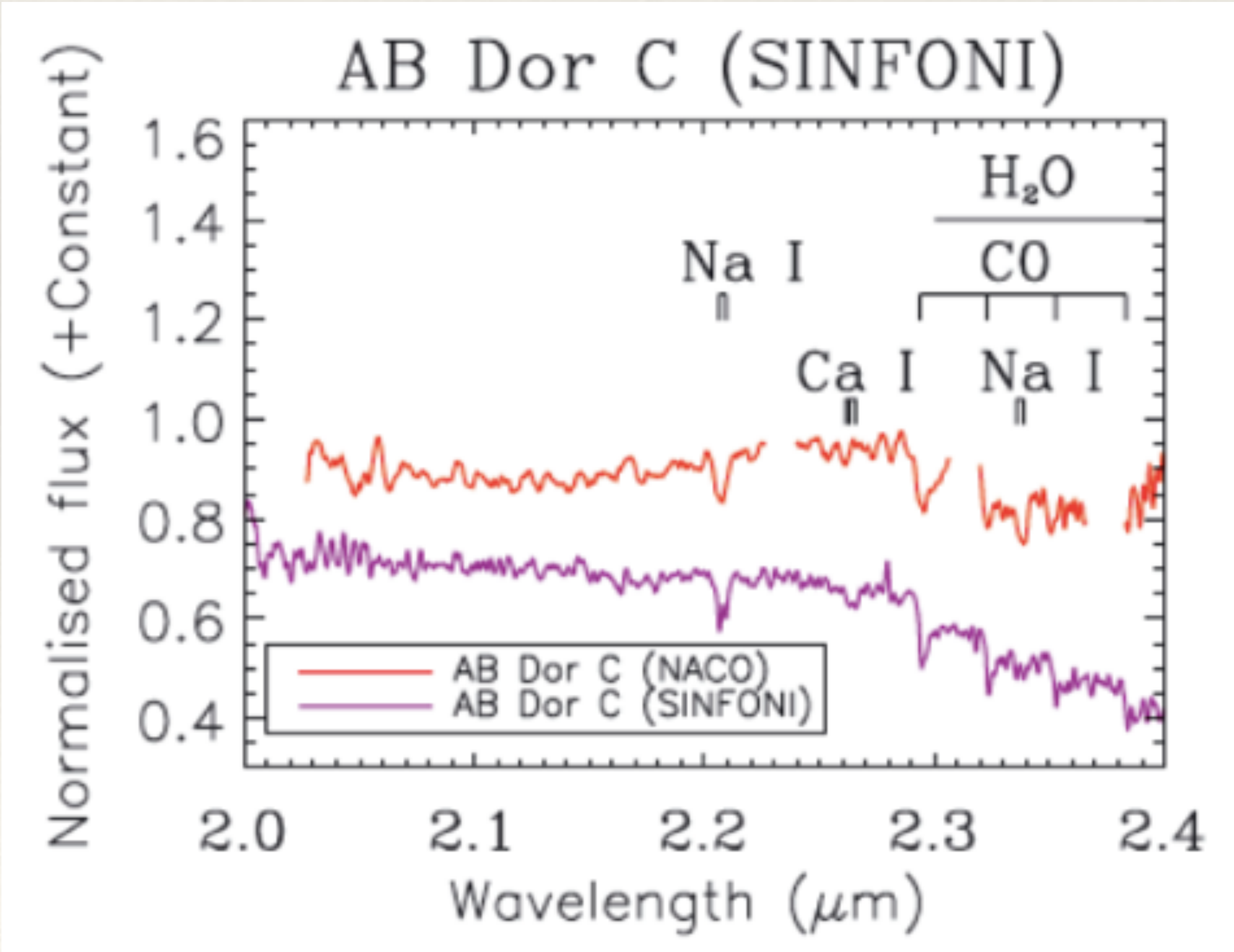
# Very Interesting …

On the contrary of SDI, speckle deconvolution does not depend on the planet spectrum….

## so

it is extracted from the data cube …

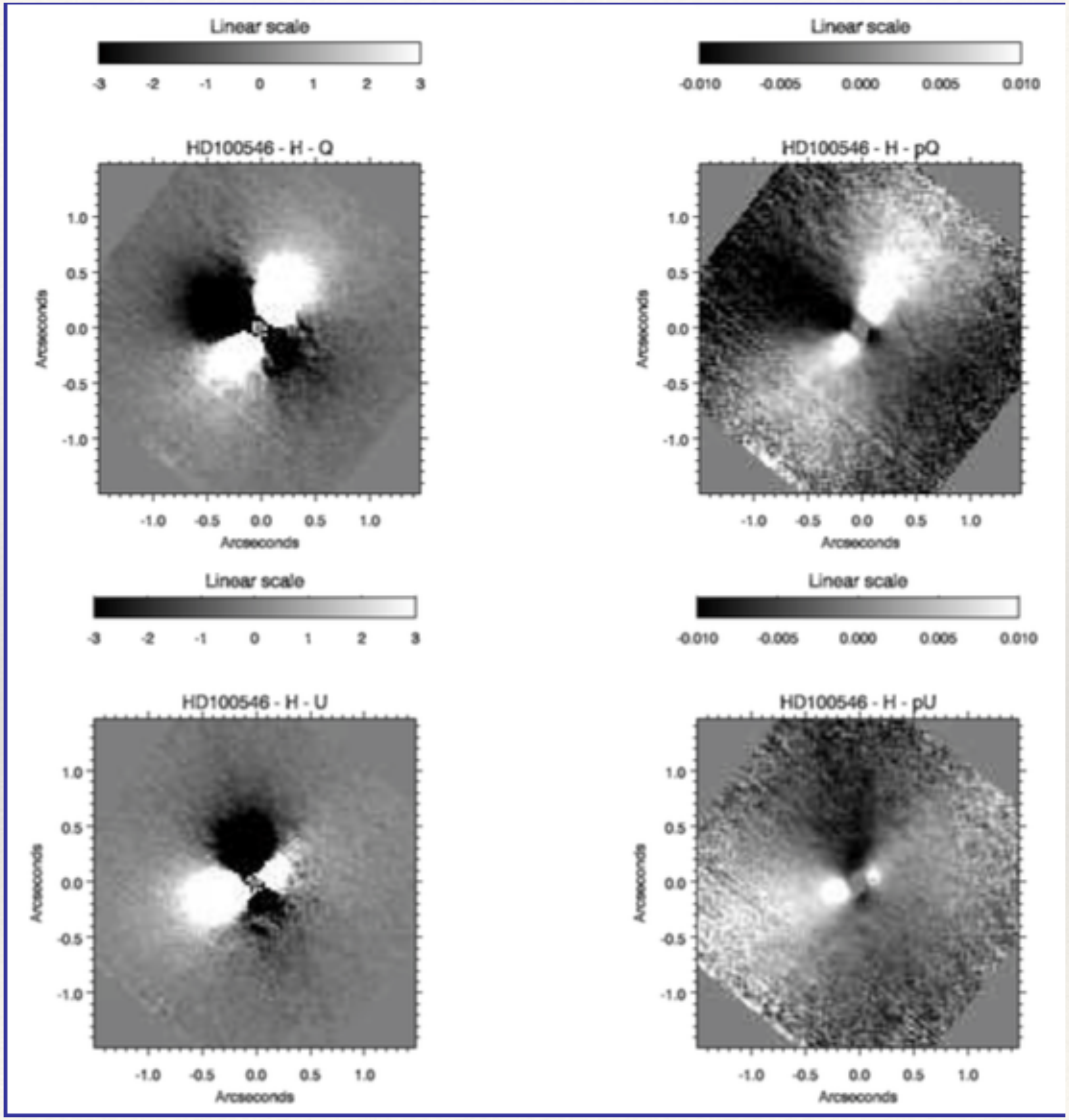


# PDI: Polarimetric Differential Imaging

- Speckles are usually assumed to be independent of polarization
- Speckles may then be cancelled by differentiating images obtained in different polarization modes
- If light from the source (planet) is polarized, it is not completely canceled and can be detected
- Planets are expected to be polarized only if they shine by reflected light
- PDI very useful for disks
- ZIMPOL: an extremely sensitive DPI instrument (see SPHERE description) – Essentially, photon noise limited

# PDI for disks



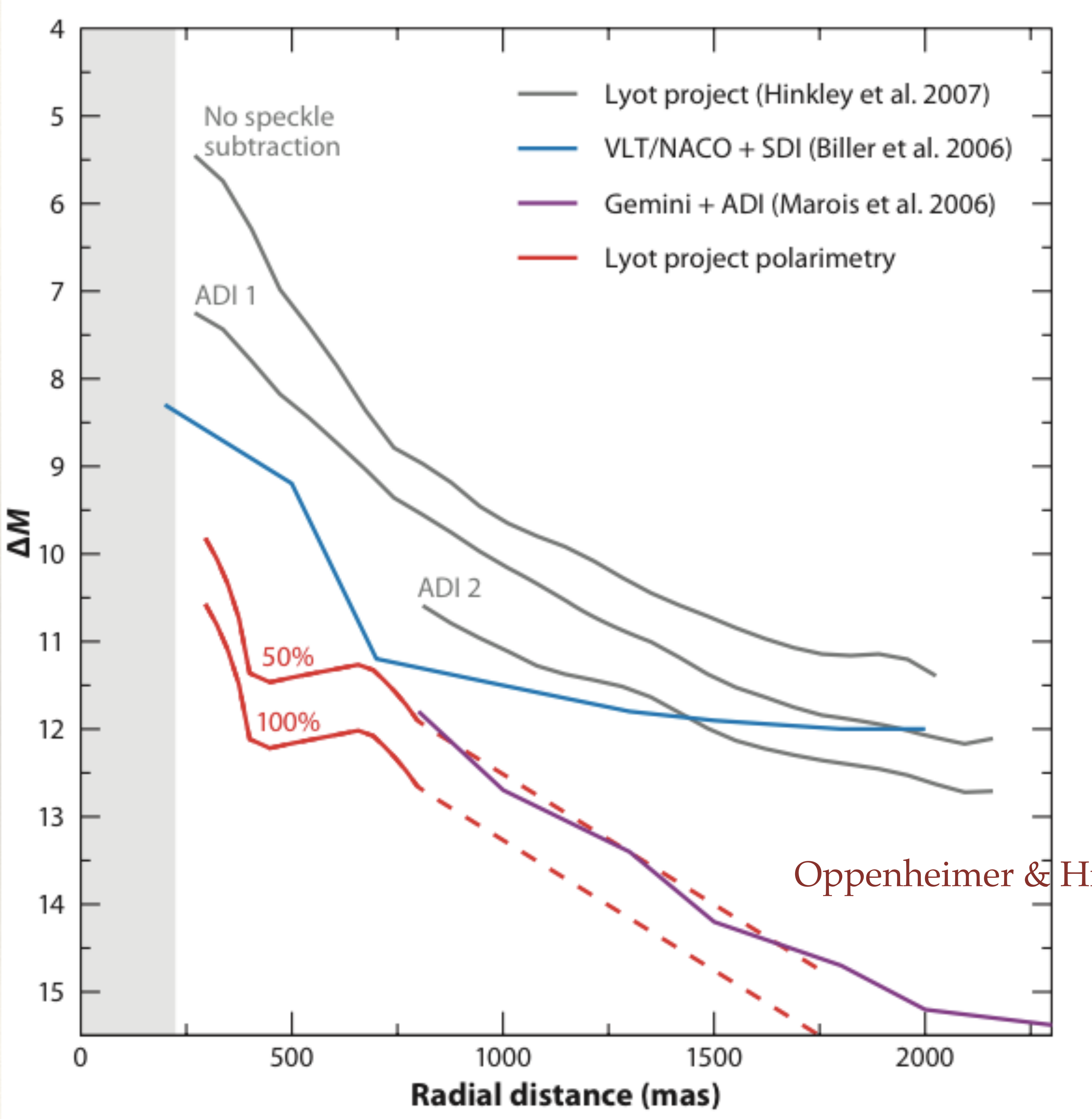

Quanz et al. 2011, ApJ 738, 23

# PCA, T-LOCI etc.

- Some differential image techniques can be coupled to improve contrast:

e.g. ADI with speckle deconvolution or spectral differential imaging or polarimetric differential imaging

- This can be obtained in a single step using Principal Component Analysis (PCA)
- Alternatively, other algorithms can be used (e.g. T-Loci)




Oppenheimer & Hinkley, 2009