

Near-Infrared Imaging and Characterization of HD 95086 b with the Gemini Planet Imager



Raphaël Galicher

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Observatoire de la Côte d'Azur

2014 June 17th

Outline

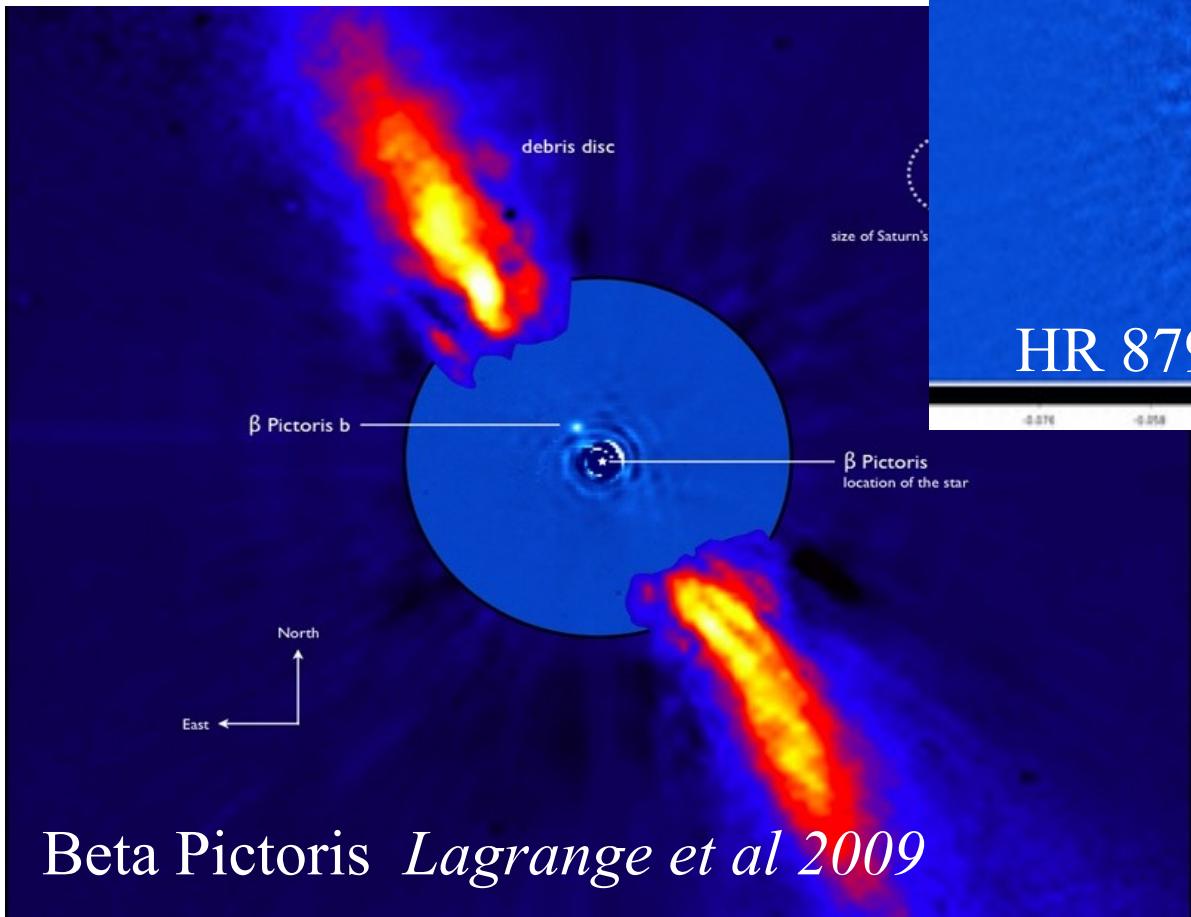
Why direct imaging?

How direct imaging?

The Gemini Planet Imager instrument

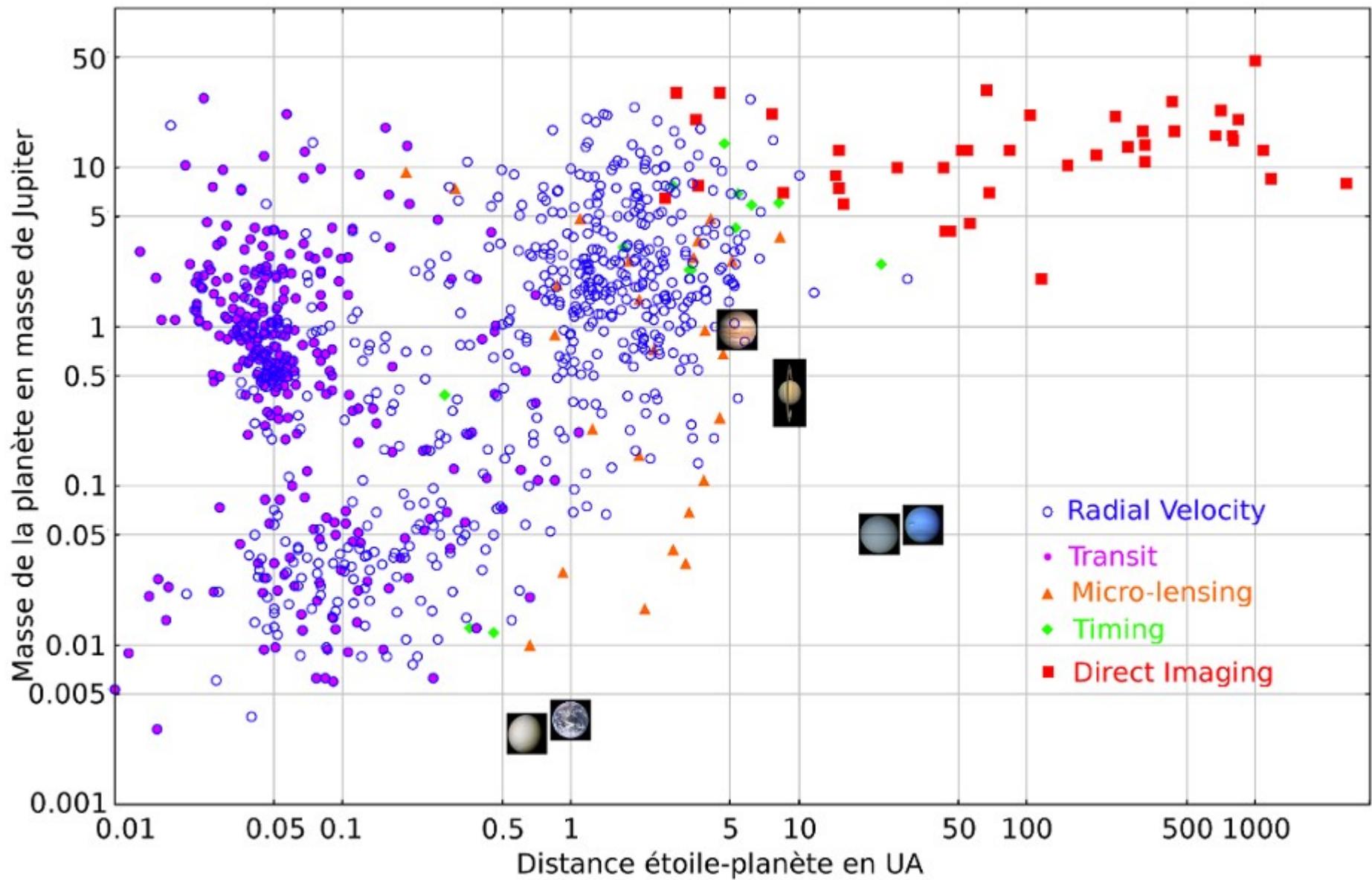
HD 95086 b

Planet-planet & planet-disk interactions



Beta Pictoris *Lagrange et al 2009*

1795 exoplanets today



Formation models and planet frequency

- Planets at $a < 5\text{AU}$

$$\text{freq} \propto \text{Mass}^\delta a^\beta$$

$$\delta = -1.31 \pm 0.20$$

$\beta = -0.61 \pm 0.15$ Cumming *et al.*, 2008

Depends on stellar metallicity and stellar mass, etc.

→ RV+transits

- Planets at $a > 5\text{AU}$

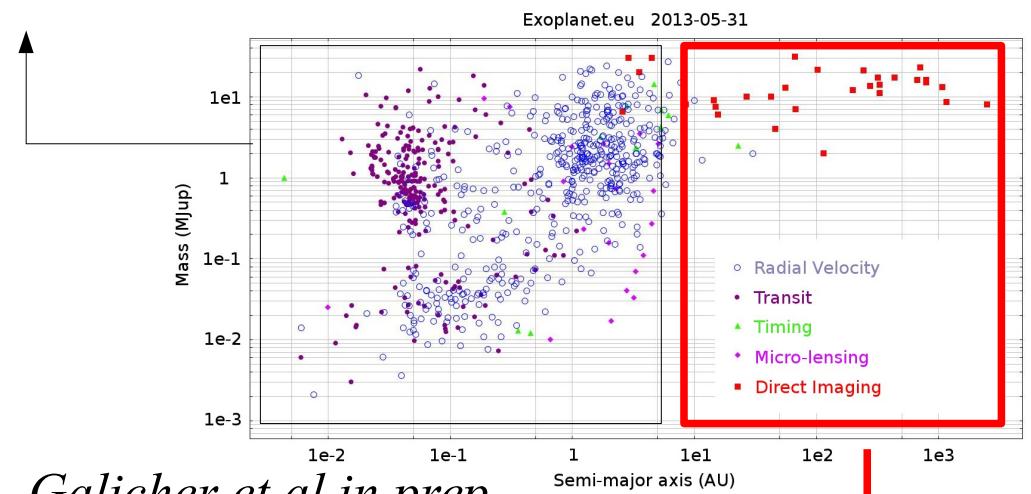
$$\text{freq} = ?$$

Lafrenière *et al.*, 2007

Chauvin *et al.*, 2010 Vigan *et al* 2012, Galicher *et al* in prep

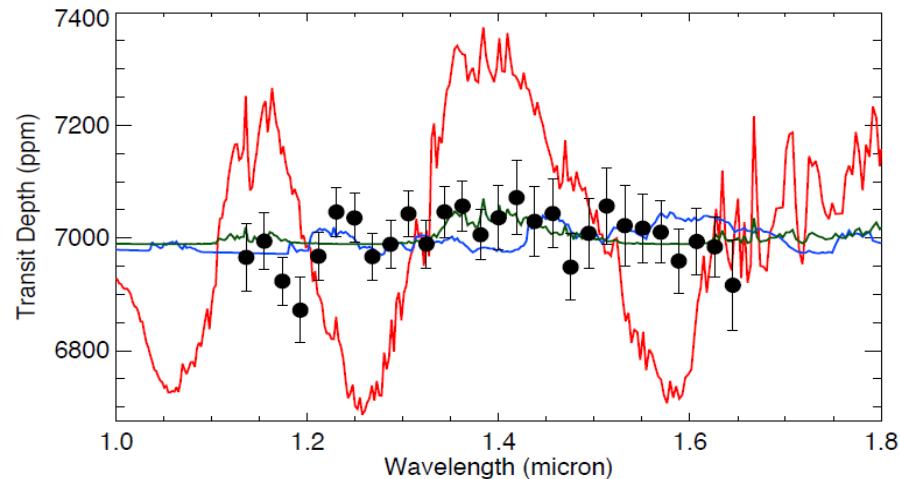
→ Need of detections

→ direct imaging



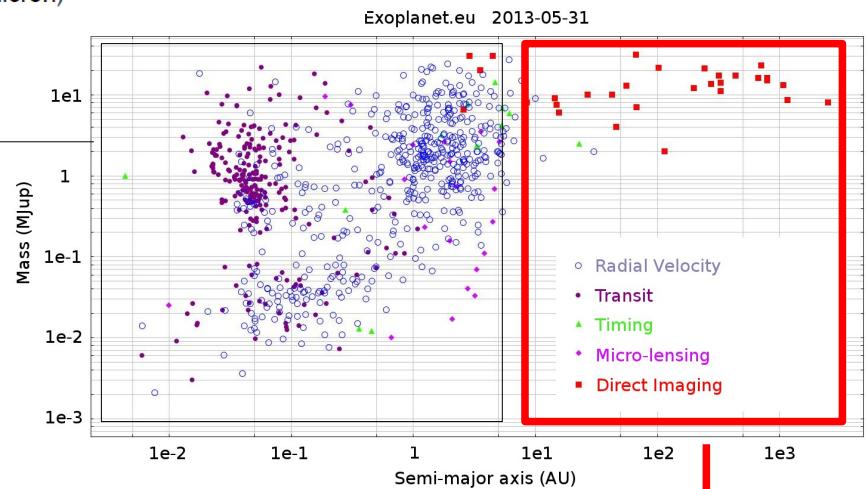
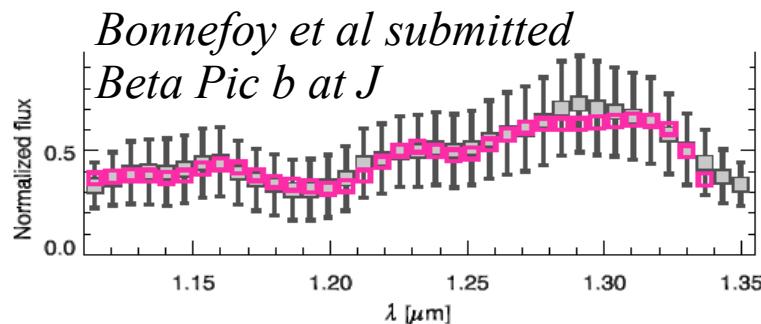
Exoplanetary atmospheres and spectra

- $a < 1\text{AU}$
→ transits



Knutson et al 2014

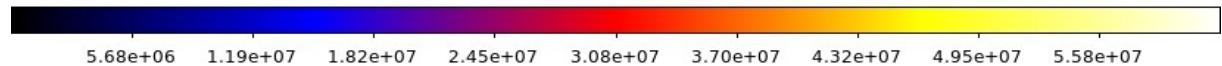
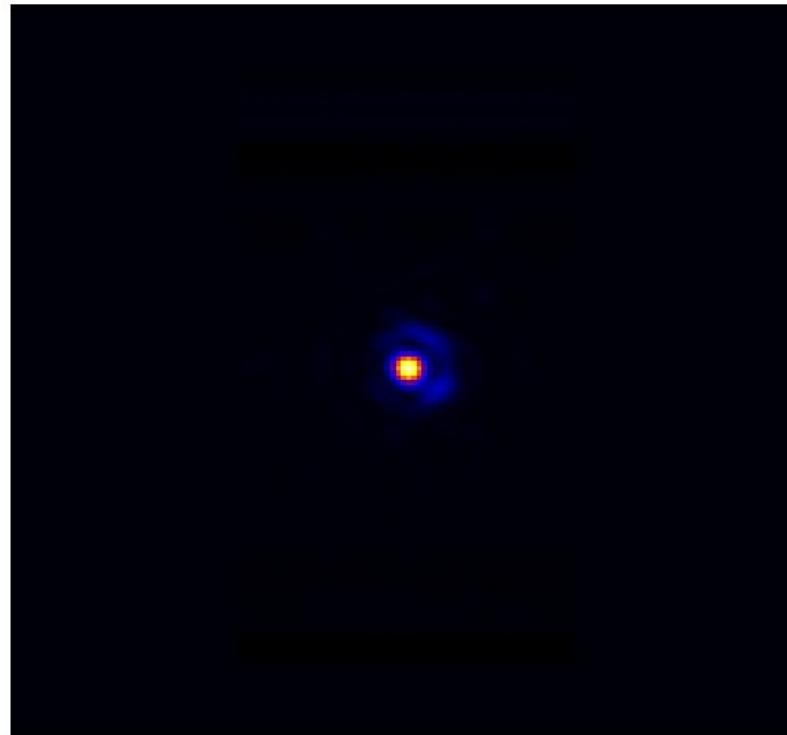
- $a > 5\text{AU}$
→ direct imaging



Direct imaging: telescope + detector

Flux ratio 10^4 to 10^{10}
Separation < 0.5 arcsec

→ Only star is detected

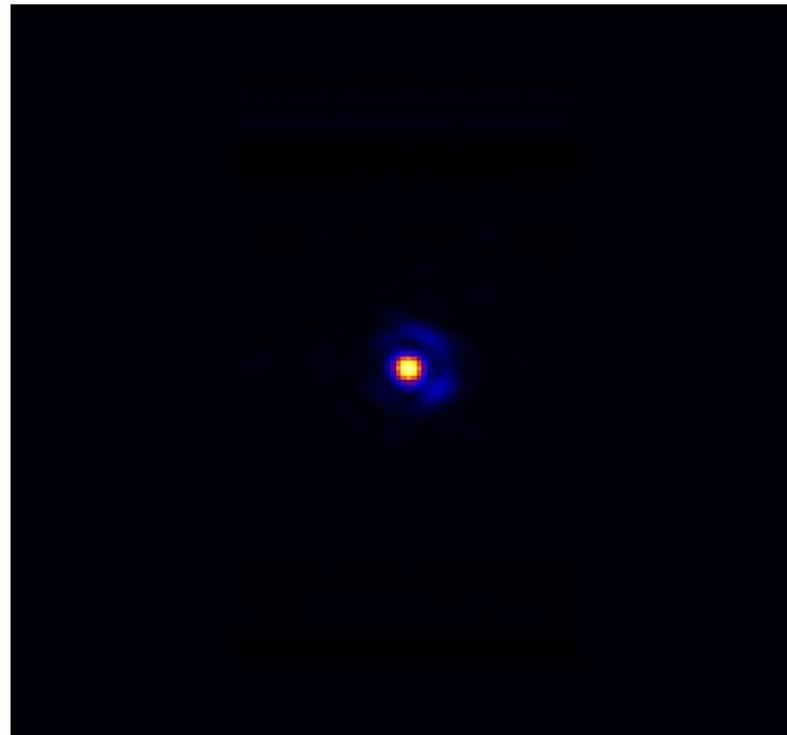


Direct imaging: telescope + detector

Flux ratio 10^4 to 10^{10}

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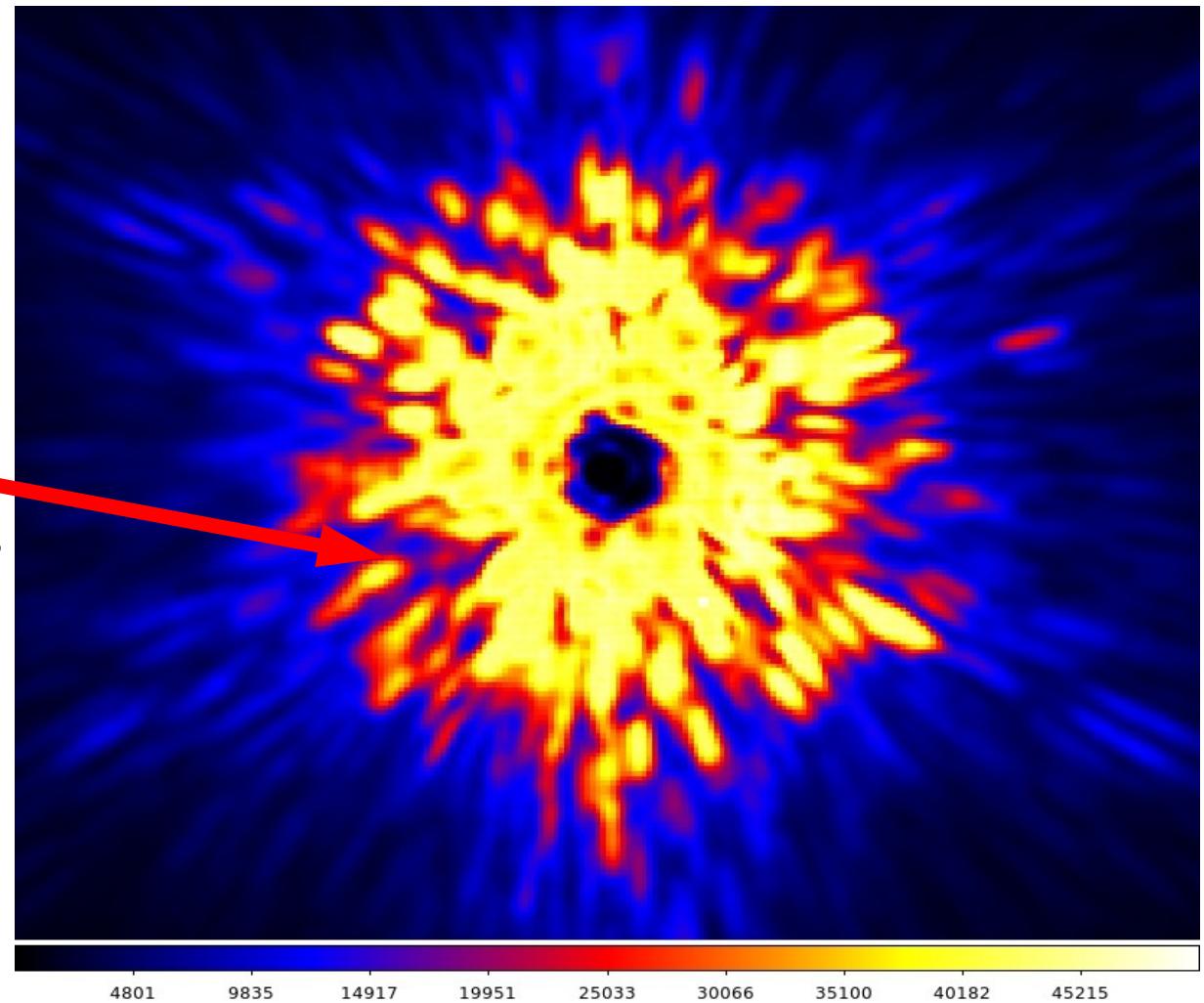
→ Only star is detected



→ coronagraphs

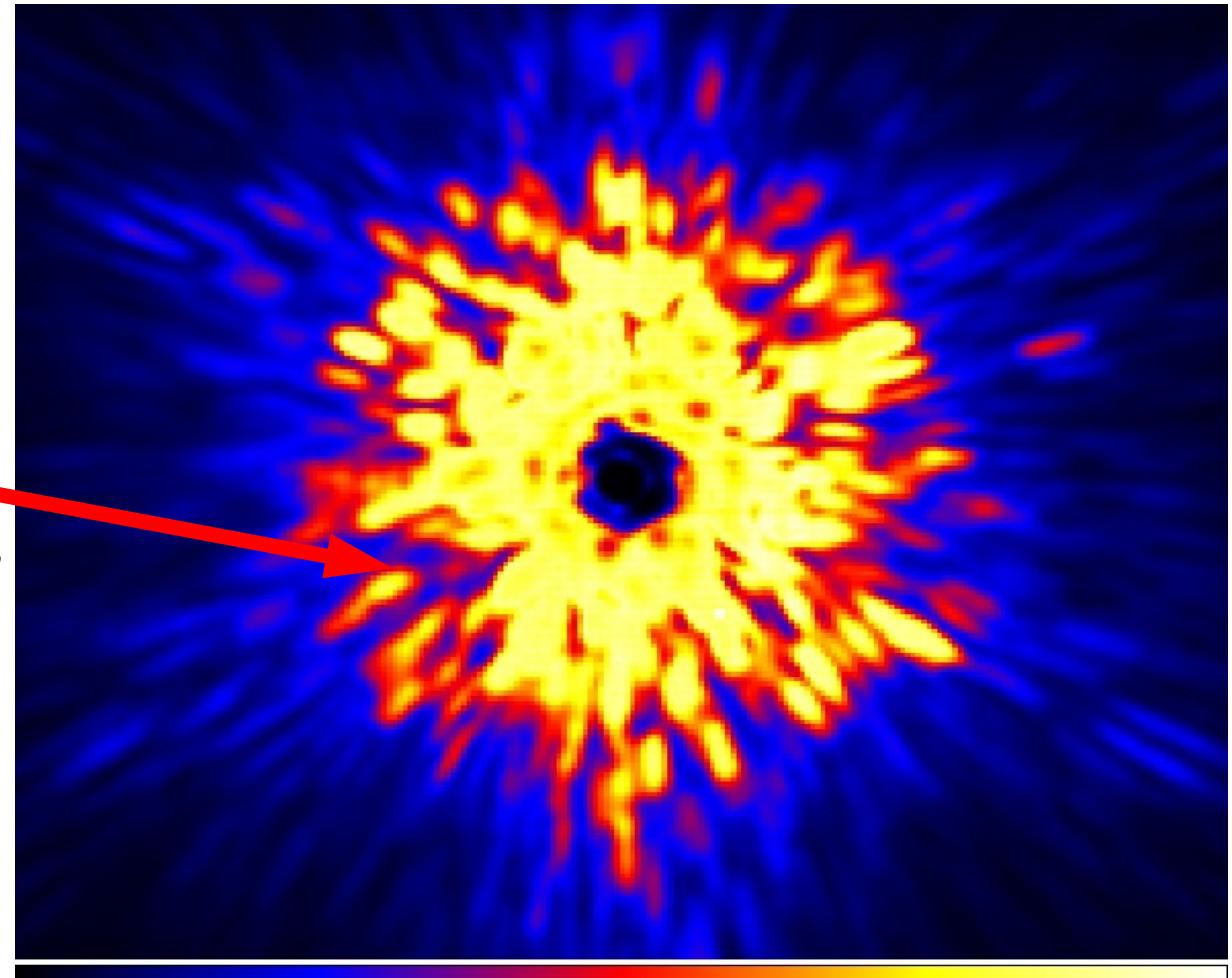
Direct imaging with coronagraphs

Attenuated starlight
but speckles
induced by aberrations



Direct imaging with coronagraphs

Attenuated starlight
but speckles
induced by aberrations



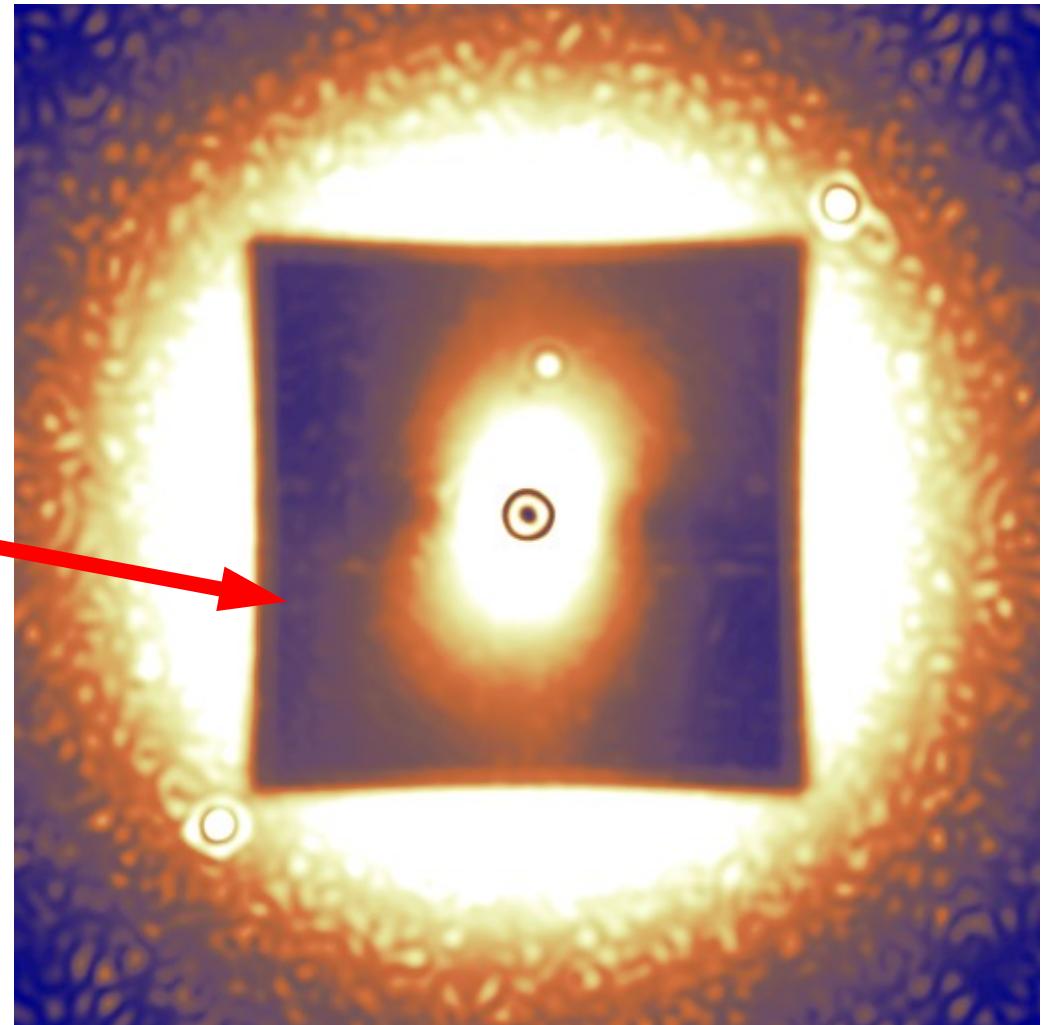
→ correction of aberrations

Direct imaging with deformable mirrors

Correction of aberrations
(deformable mirror)

Dark hole

Attenuation of speckles
but still some of them

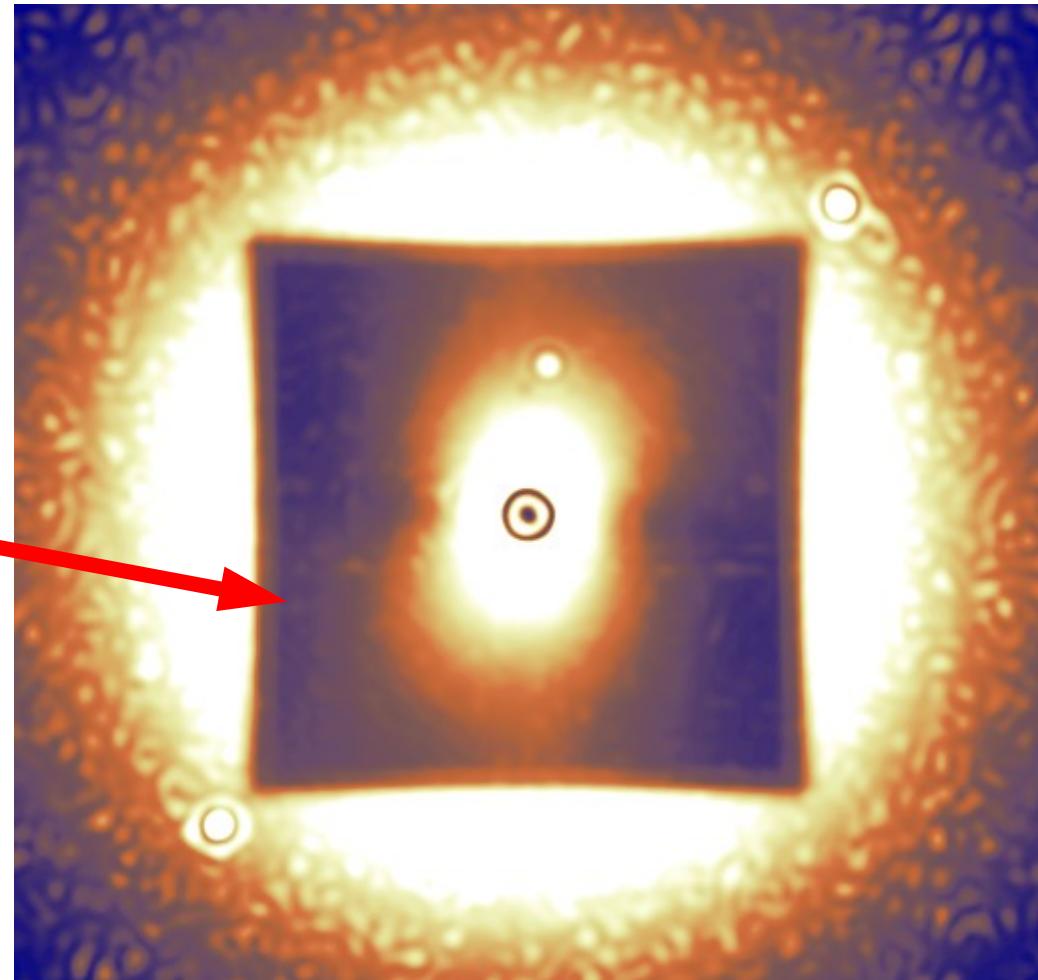


Direct imaging with deformable mirrors

Correction of aberrations
(deformable mirror)

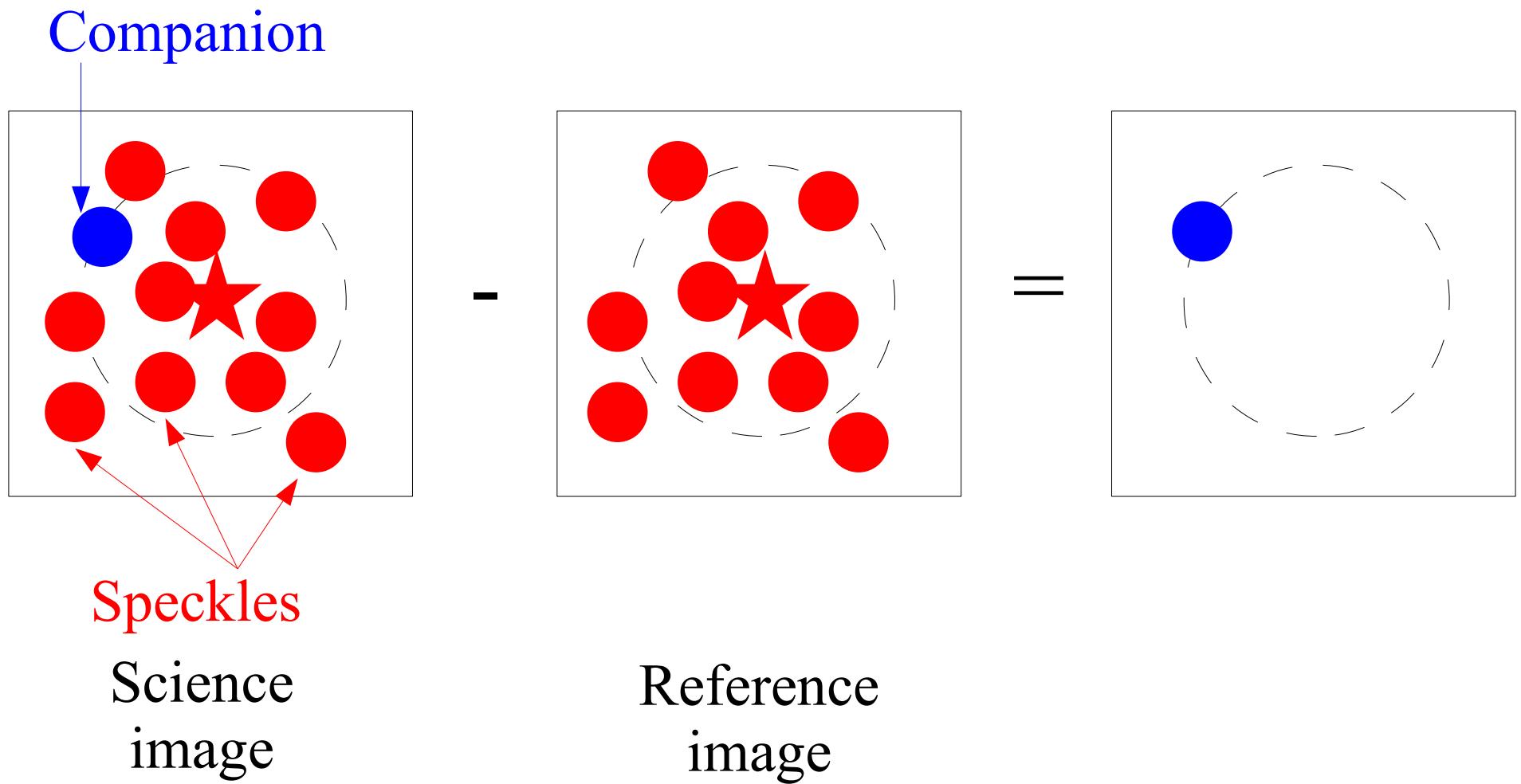
Dark hole

Attenuation of speckles
but still some of them



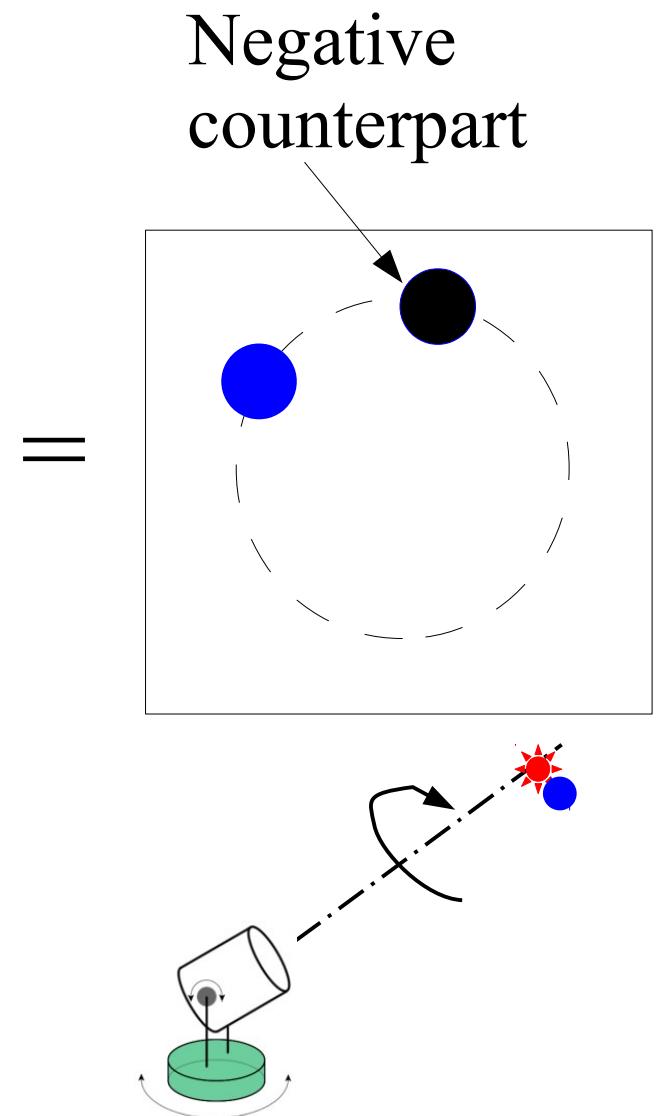
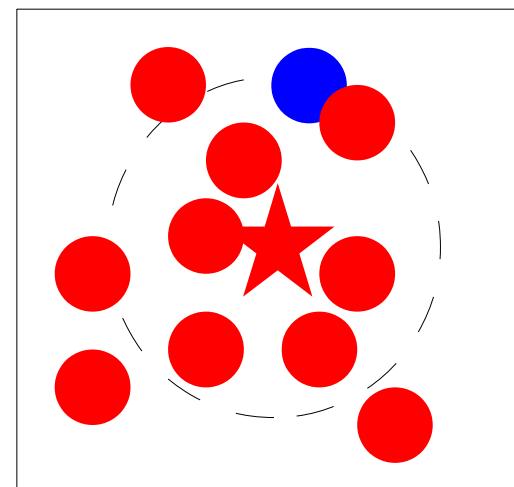
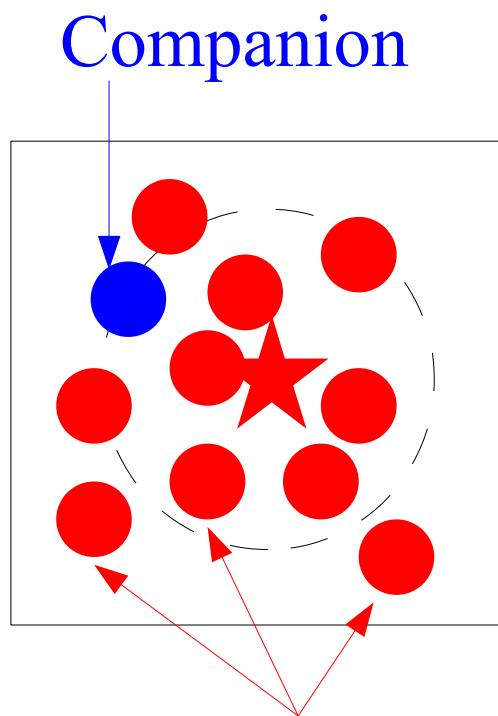
Differential imaging

Principle of differential imaging



Angular differential imaging = ADI

Marois et al 2006



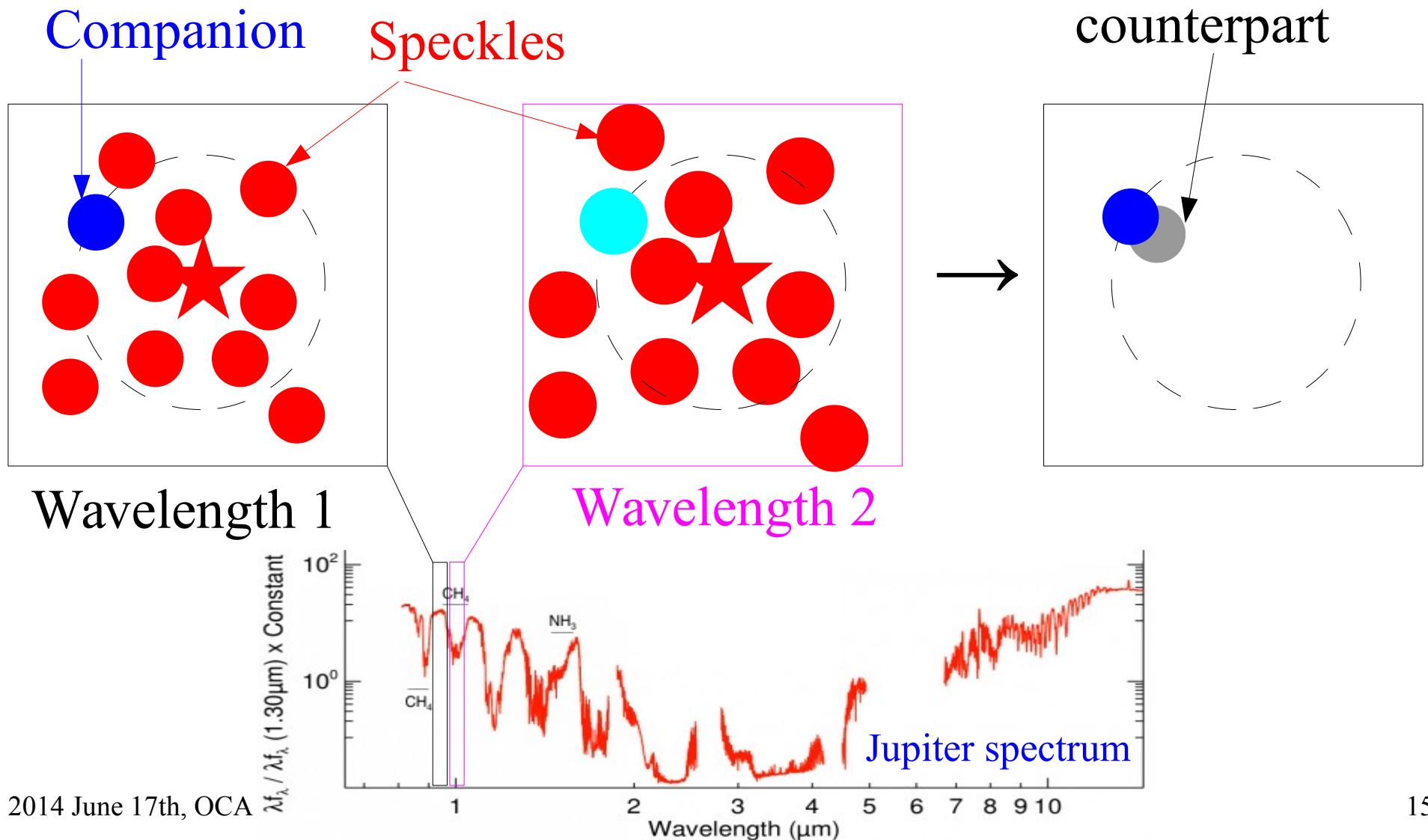
Field of view
Orientation 1

Field of view
Orientation 2

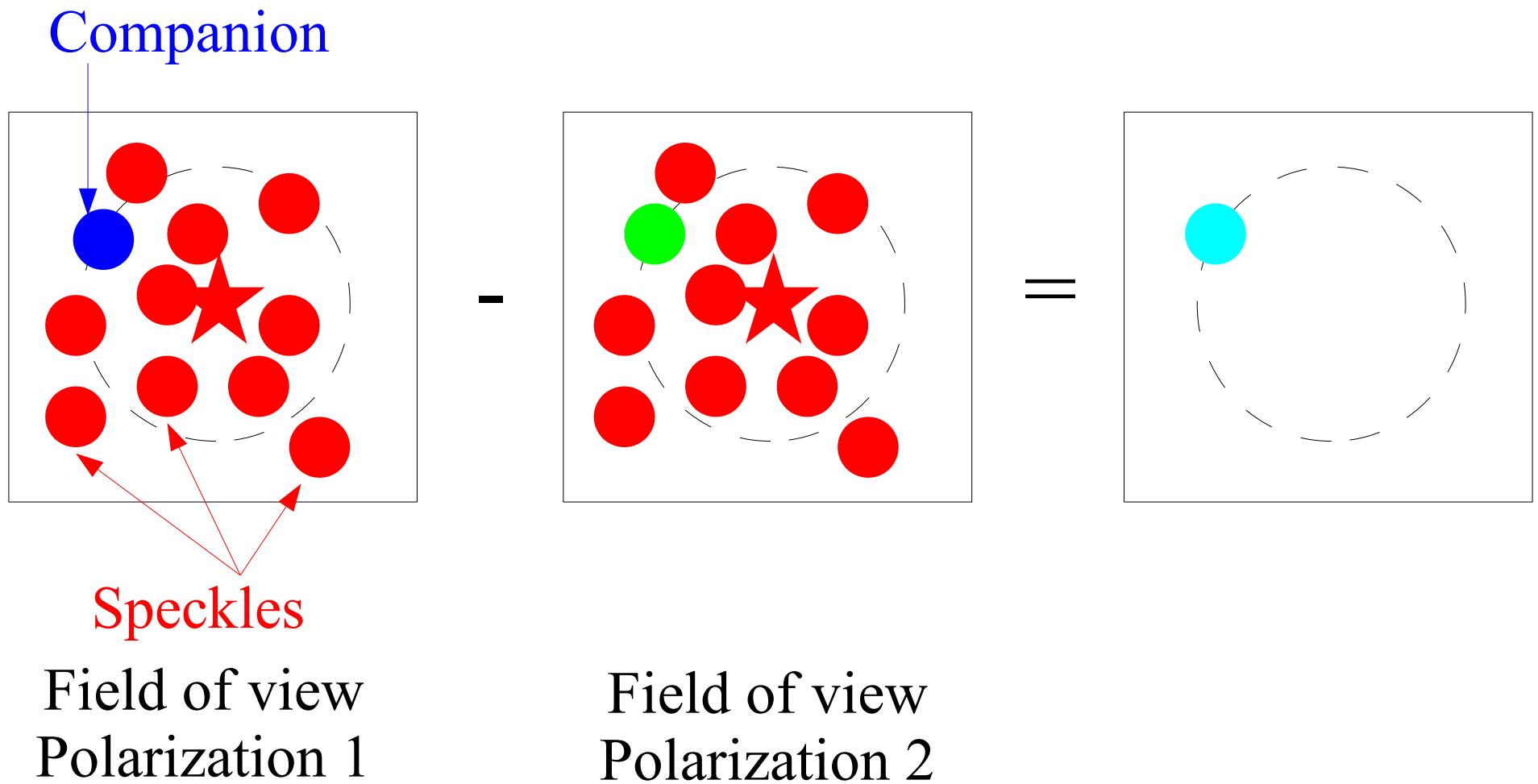
Simultaneously spectral differential imaging

Racine et al 1999

= SSDI

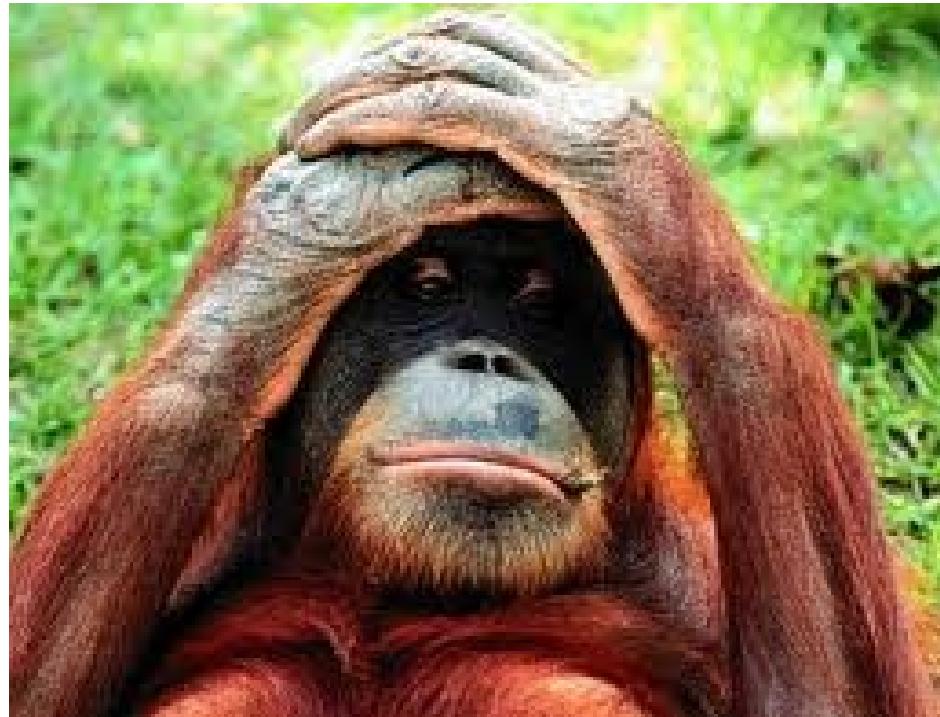


Polarimetry differential imaging



Murikami et al 2006

Combine all these techniques?



NIR advanced adaptive optics

Coronagraphs

ADI mode

Integral field spectrometer

Polarimeter

- suppress starlight
- differential imaging
- differential imaging
- differential imaging

Sphere and GPI: direct imaging



PI: Jean-Luc Beuzit



PI: Bruce Macintosh

Objectives: Discovery & Characterization Giant planets orbiting nearby young stars (<100Myr, <50pc)

NIR advanced adaptive optics

Coronagraphs

ADI mode

Integral field spectrometer

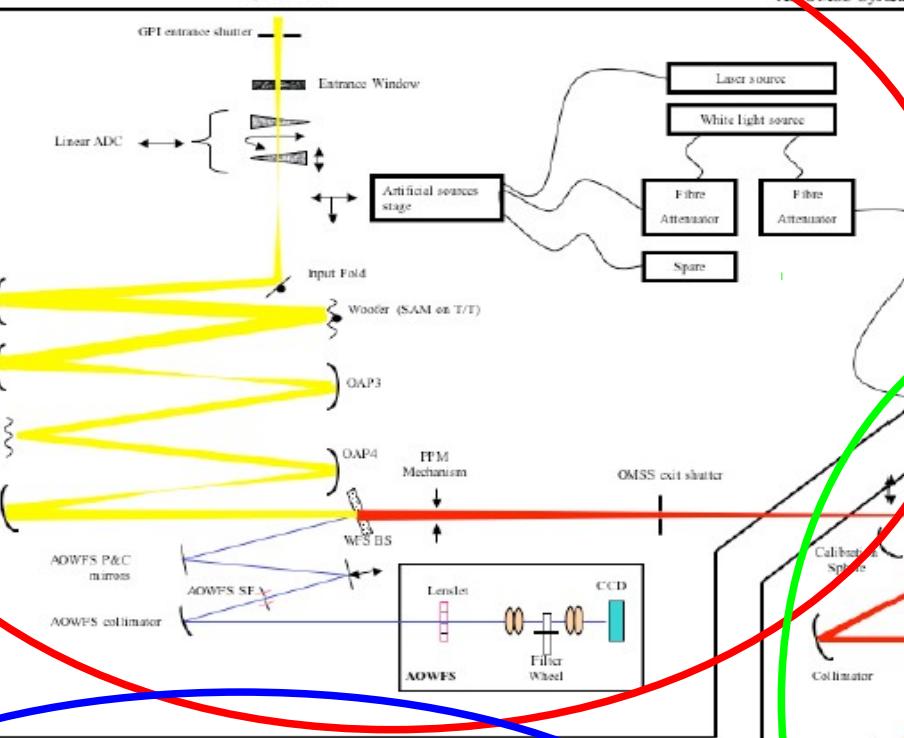
Polarimeter

- suppress starlight
- differential imaging
- differential imaging
- differential imaging



Gemini Planet Imager

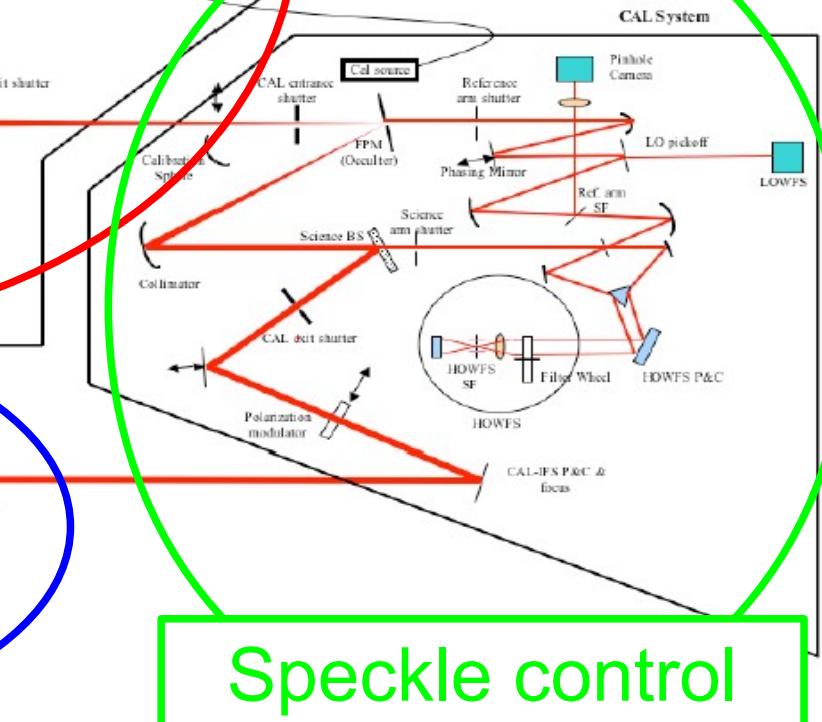
**AO +
coronagraph**



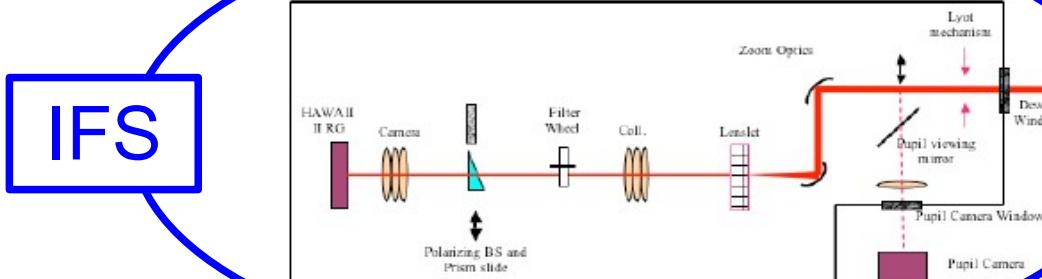
GPI-PROJ-SYS-006
V1.0
Les Saddlemyer
2008-04-21

GPI System Sketch

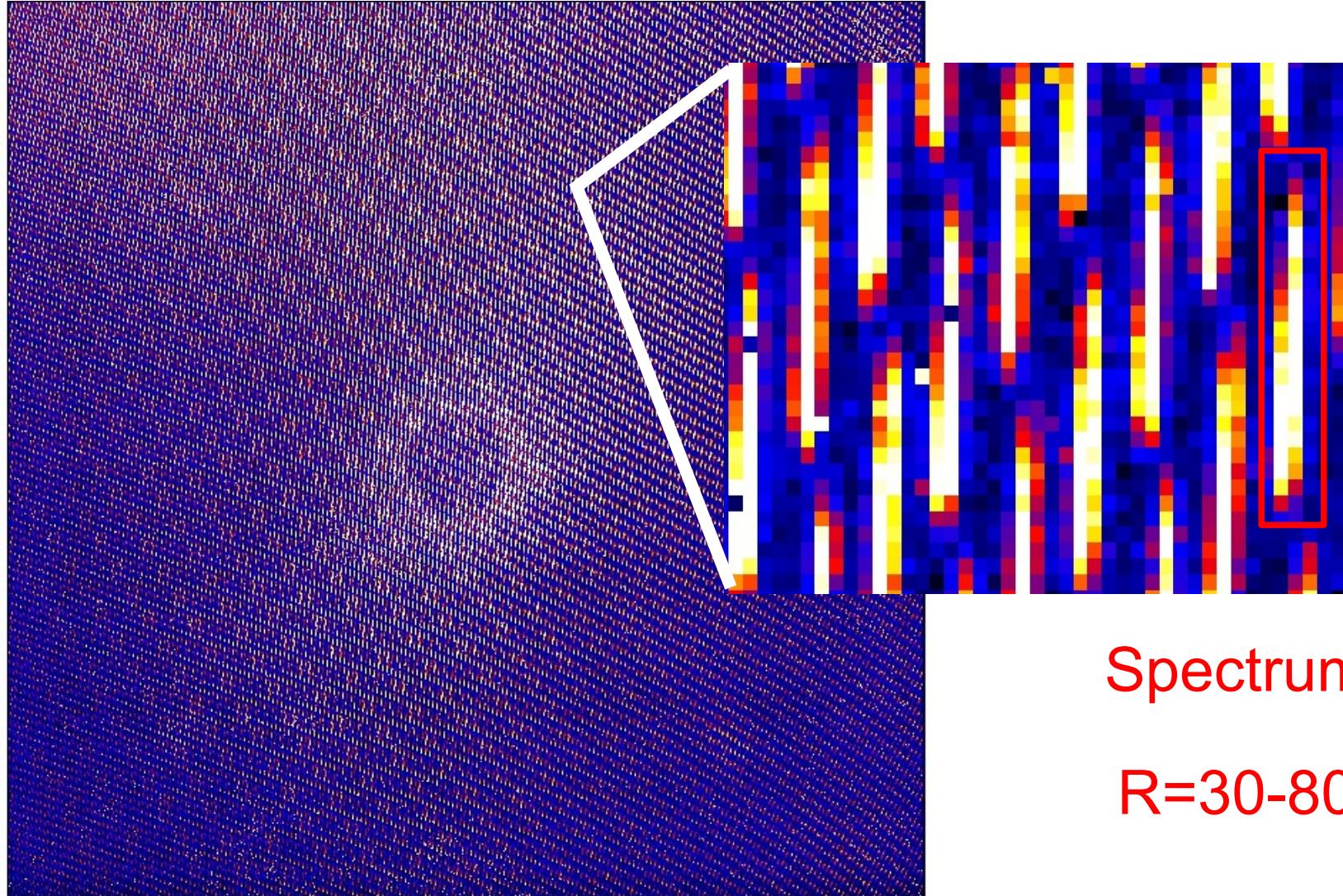
NOTE: Although all components and optics are represented, and in the correct order, sketch is not to scale, and angles on optics are not representative.



IFS

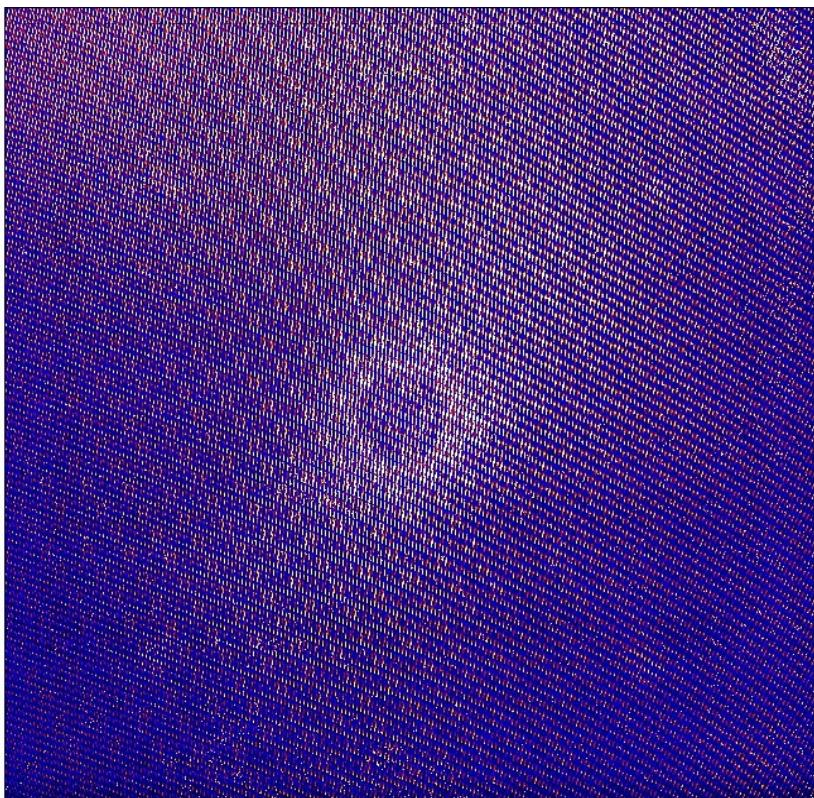


Sphere and GPI raw data

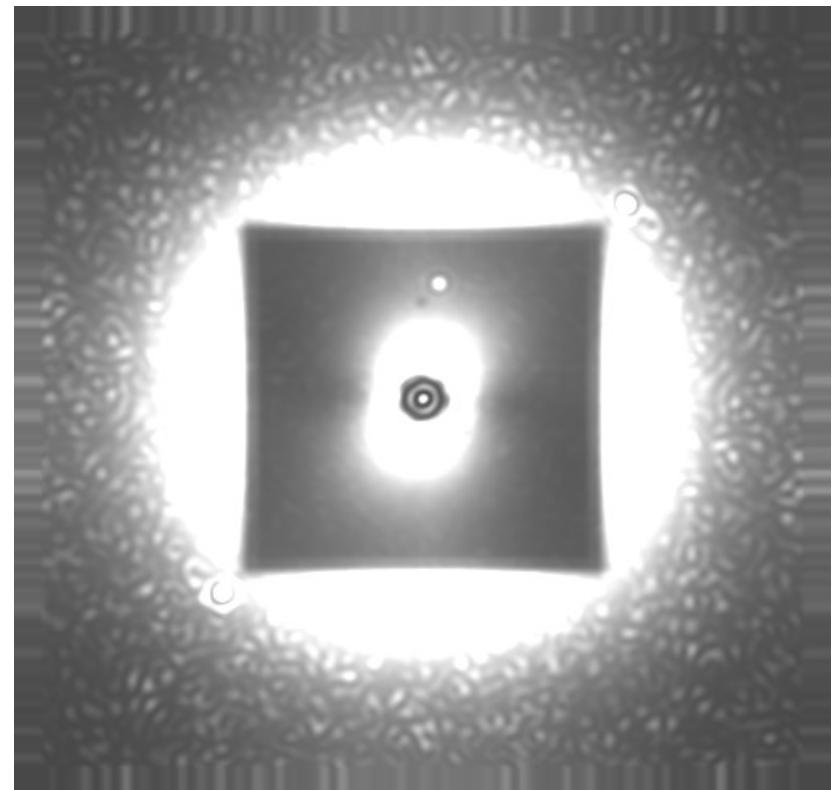




Raw IFS data to spectral datacube



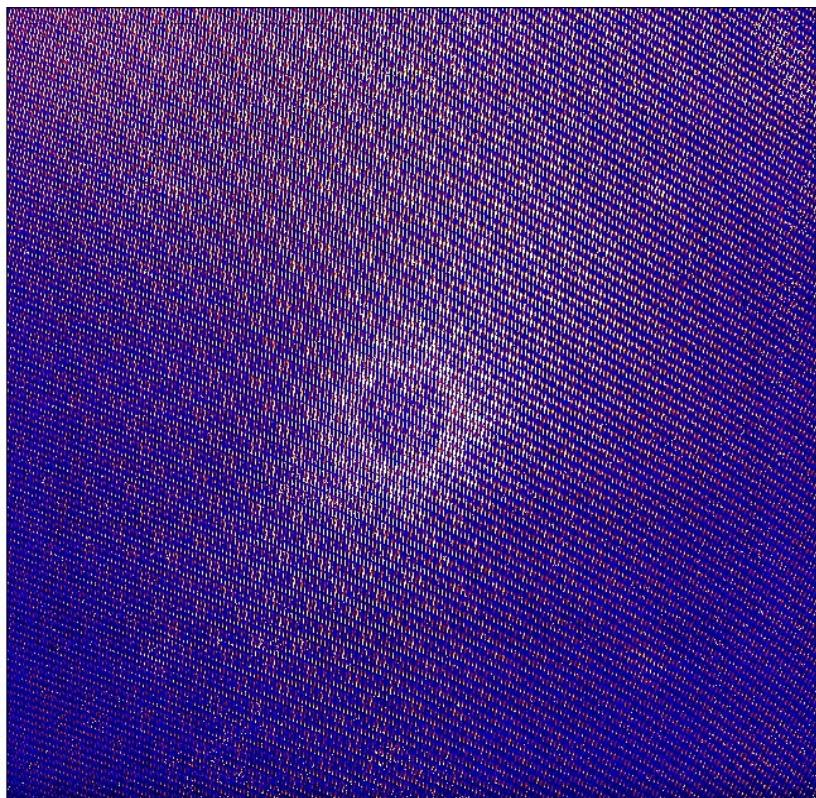
Raw IFS data



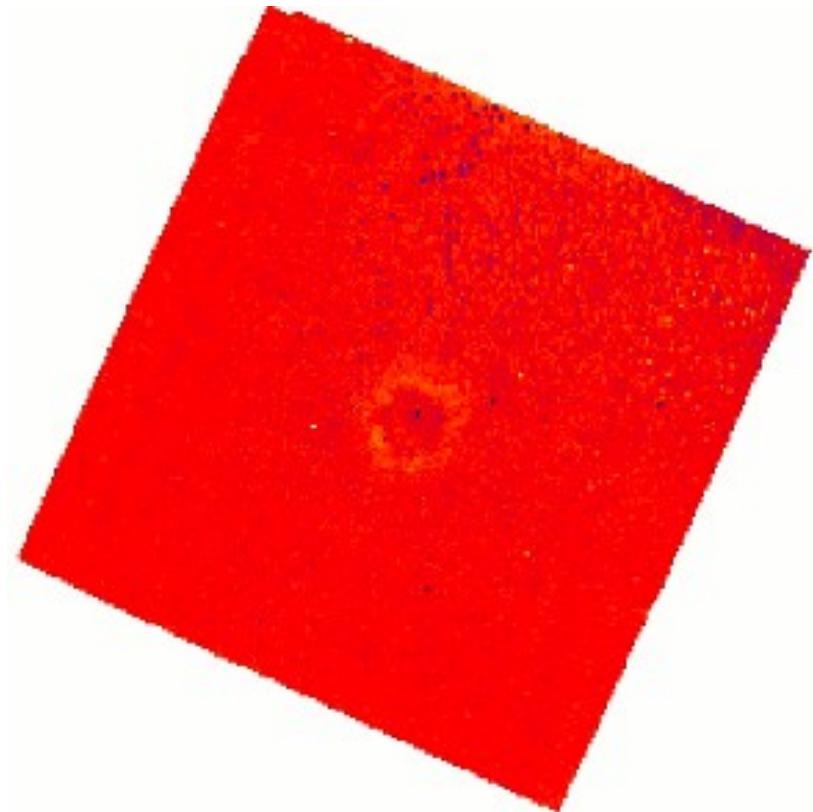
Spectral datacube
Numerical simulation



Raw IFS data to spectral datacube



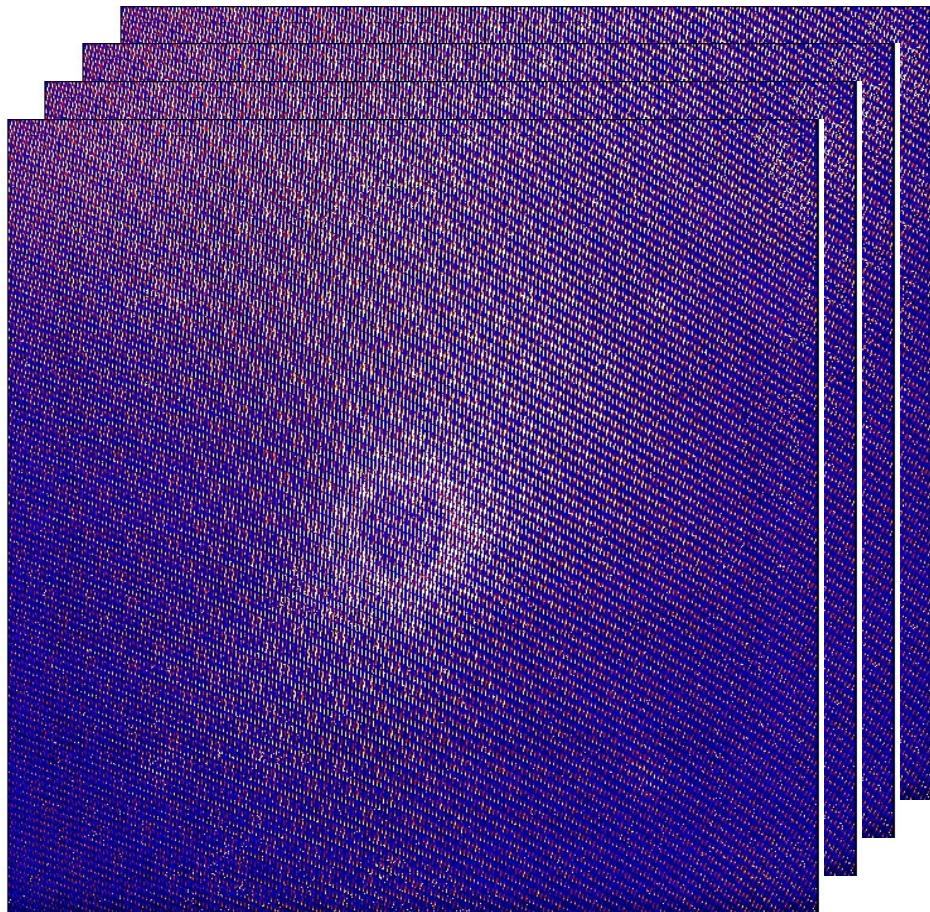
Raw IFS data



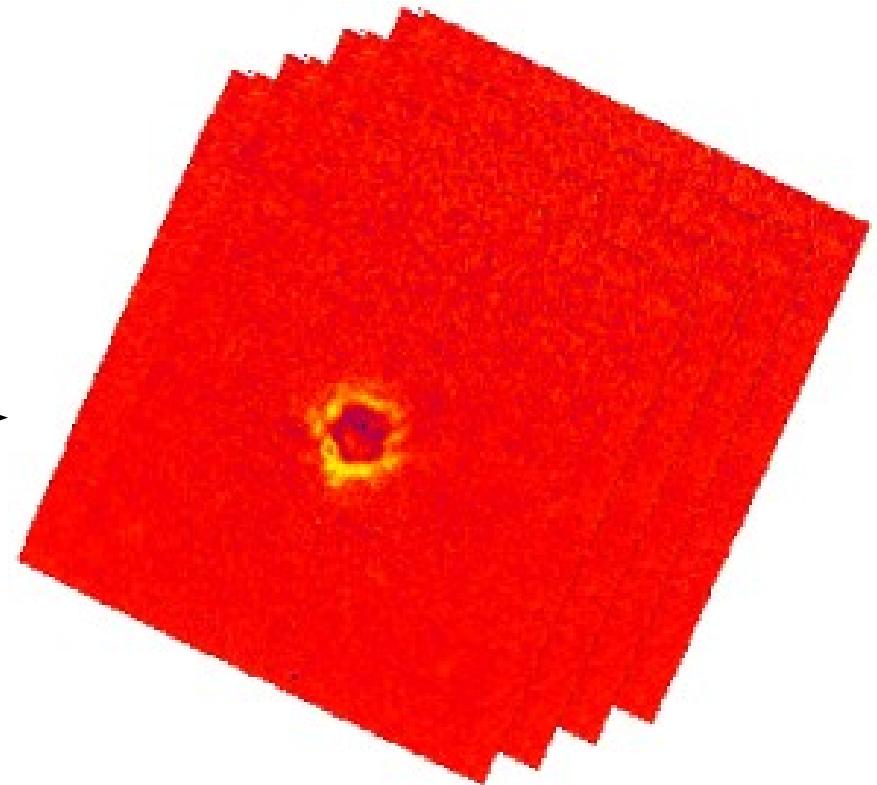
Spectral datacube
Real GPI data



Raw IFS/ADI data to ADI spectral datacube



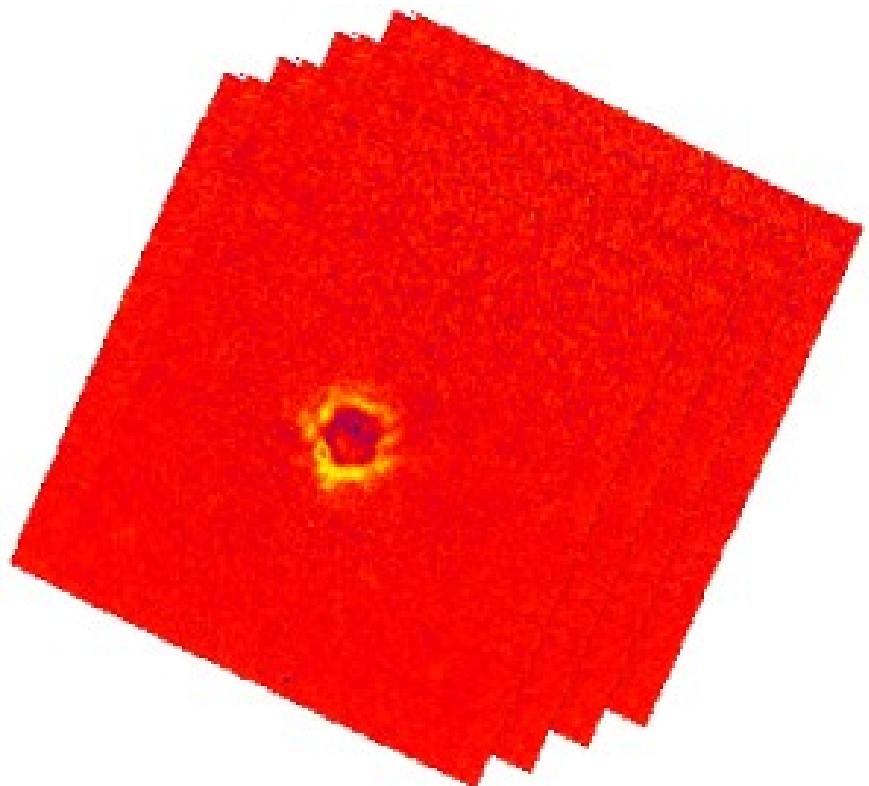
Raw IFS/ADI data



ADI spectral datacube



ADI spectral datacube to reduced data



ADI spectral datacube

Angular and spectral
differential imaging

Best combination of several
100 images

→ **LOCI, KLIP, etc.**
Lafreniere et al 2007
Soummer et al 2012

HD 95086 and GPI data



A8 star (1.6 Sun mass)

Lower Centurus Crux subgroup: 17+/-4Myr

Planet HD 95086 b: 5+/-2MJup at 56 AU *Rameau et al 2013*

Direct image at L'

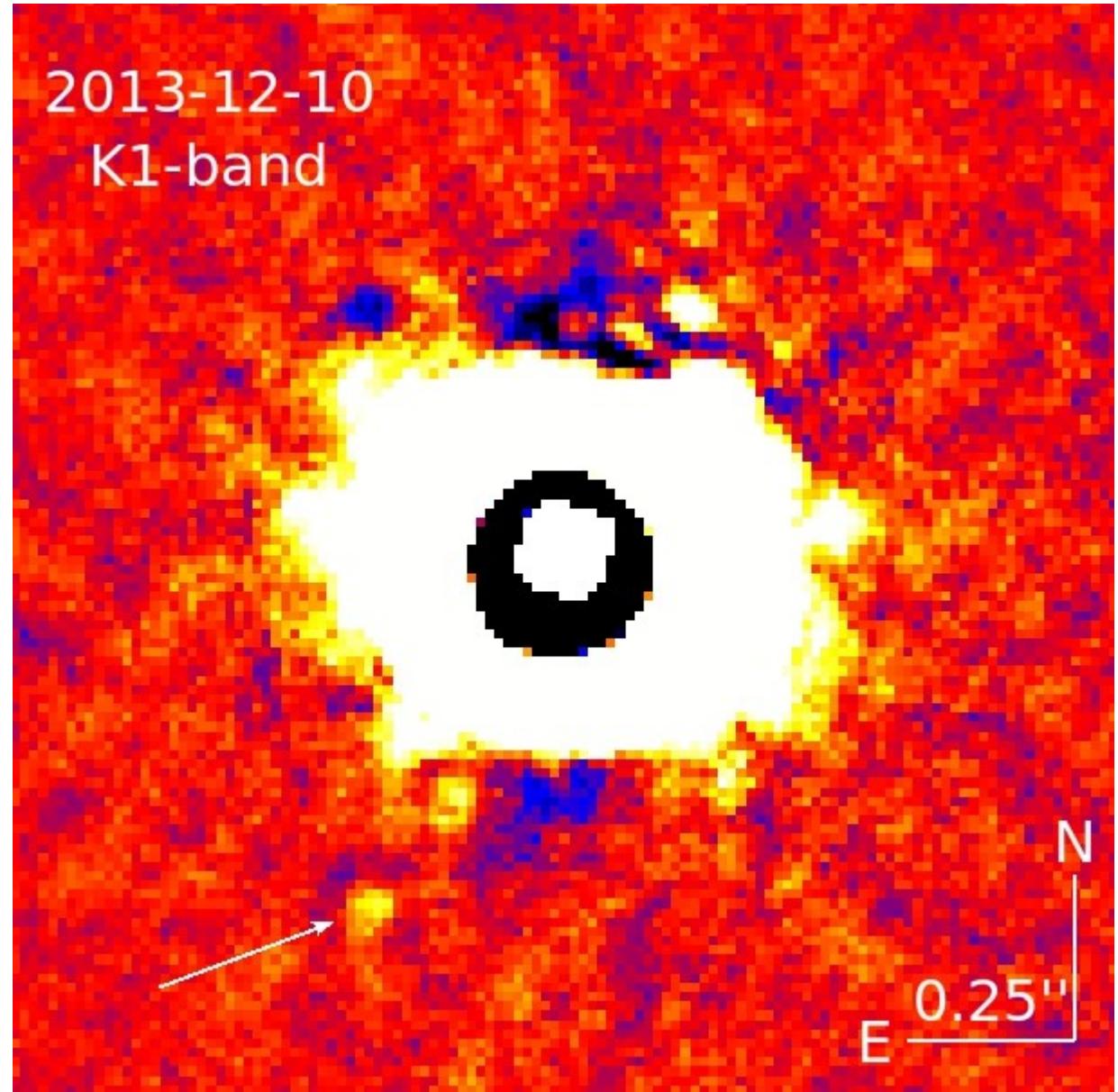
Undetected at K and H

GPI commissioning data at K and H.

Objectives: 1/ Characterize HD 95086 b

2/ Test our data reduction pipelines (for Sphere)

HD 95086 b

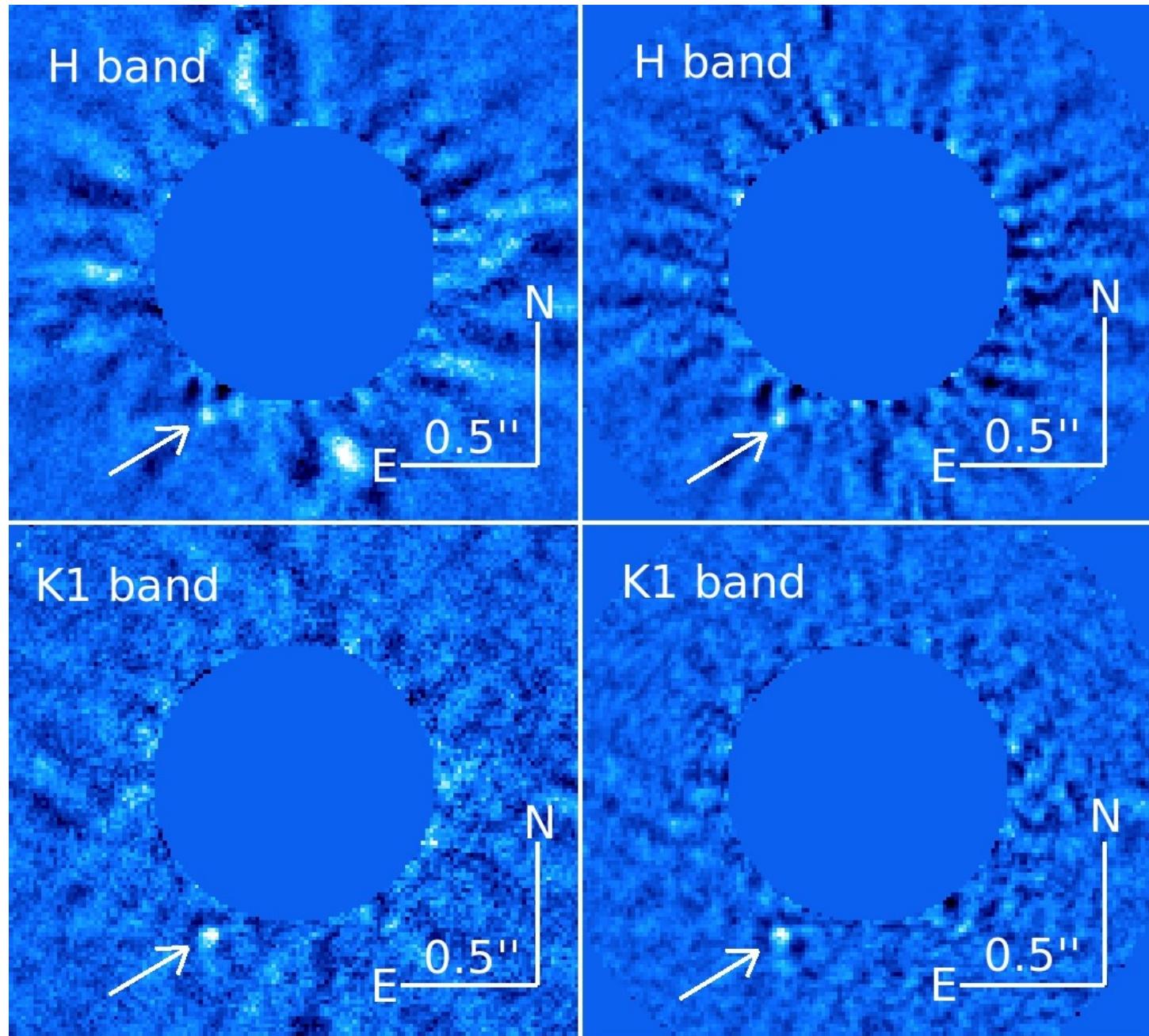


HD 95086 b

6 independent
pipelines

1st detections at
H and K bands

Galicher et al 2014



HD 95086 b positions and magnitudes

GPI data

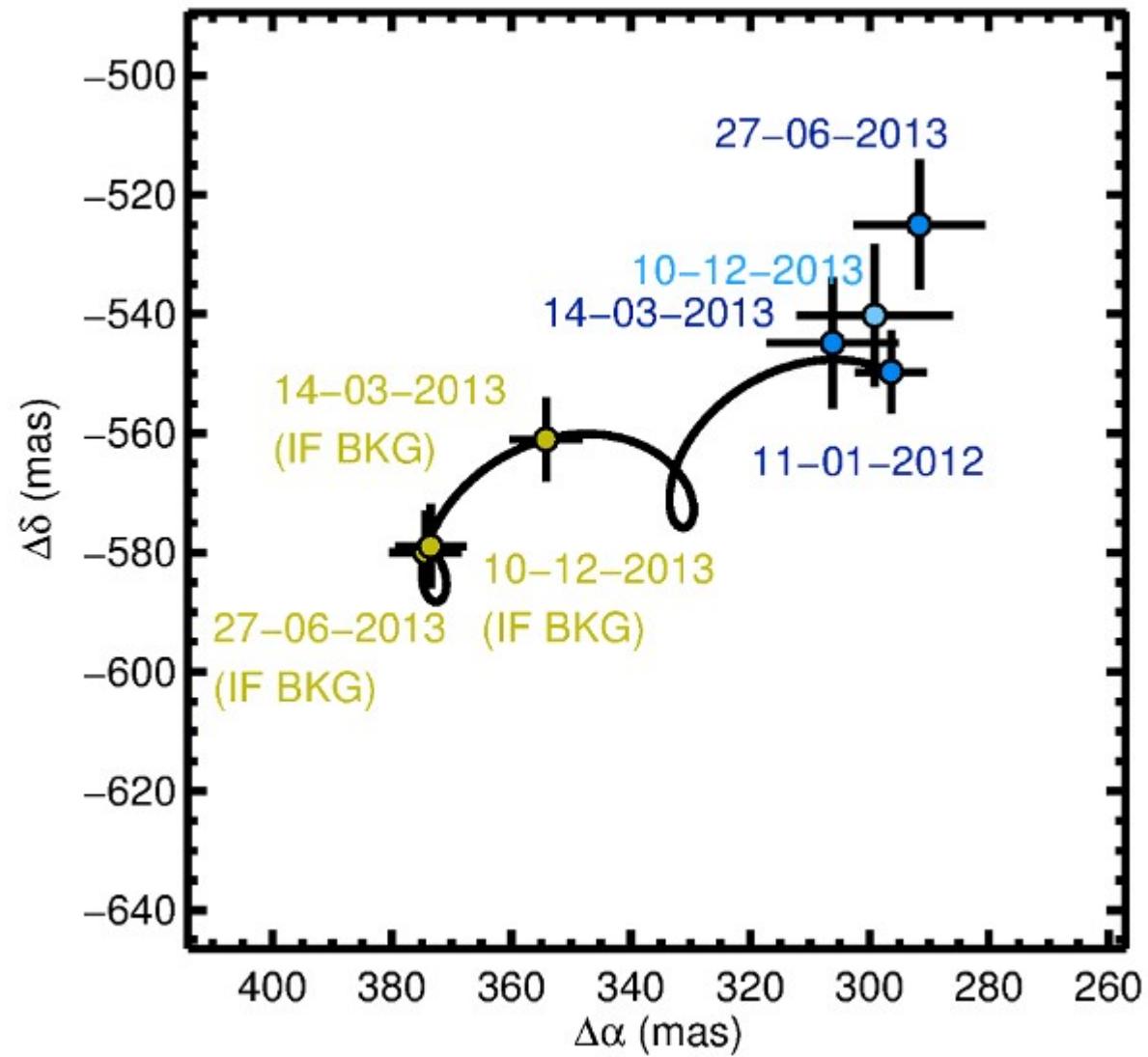
Date	Filter	Sep (mas)	PA($^{\circ}$)	Δm
2013/12/11	H	633 ± 17	150.6 ± 1.7	13.1 ± 0.9
2013/12/10	K ₁	623 ± 15	151.4 ± 1.5	12.1 ± 0.5
2013/03/24	L'	626.1 ± 12.8	150.7 ± 1.3	9.71 ± 0.56
2012/01/11	L'	623.9 ± 7.4	151.8 ± 0.8	9.79 ± 0.40
2012/01/11	L'	623.9 ± 7.4	151.8 ± 0.8	$9.48 \pm 0.19*$

NaCo data

Galicher et al 2014

HD 95086 b astrometry w.r.t its star

Confirmation of
planet status



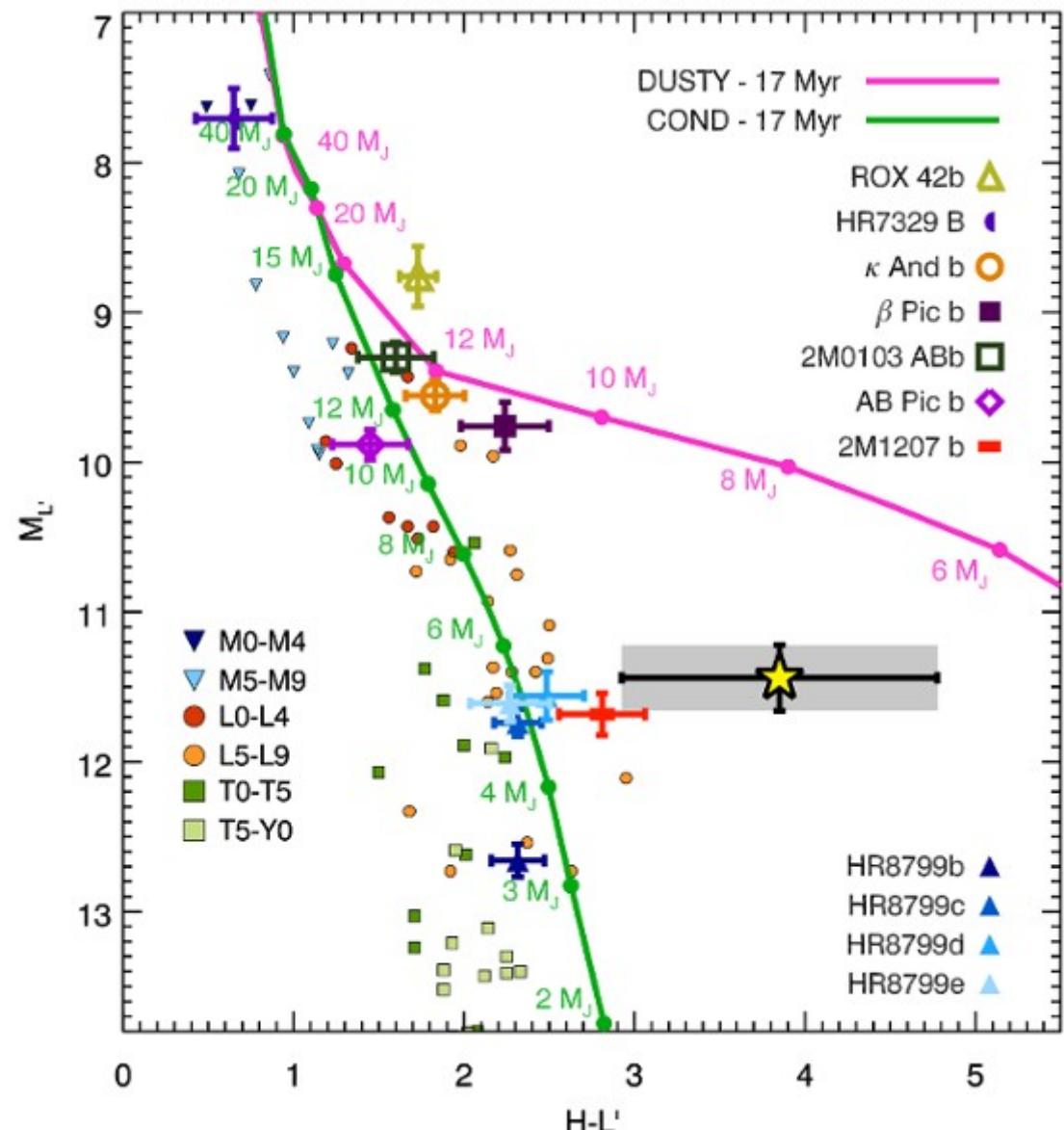
Galicher et al 2014

HD 95086 b, brown dwarfs, exoplanets

Red color

→ high content of photospheric dust

→ reduced surface gravity



Galicher et al 2014

HD 95086 b: atmosphere models

BT-SETTL *Allard et al 2012*

600 K < Teff < 1,500 K

3.5 dex < log g < 4.5 dex

LESIA *Baudino et al 2014*

900 K < Teff < 1,500 K

2.1 dex < log g < 4.5 dex

Conclusion

600 K < Teff < 1,500 K

2.1 dex < log g < 4.5 dex

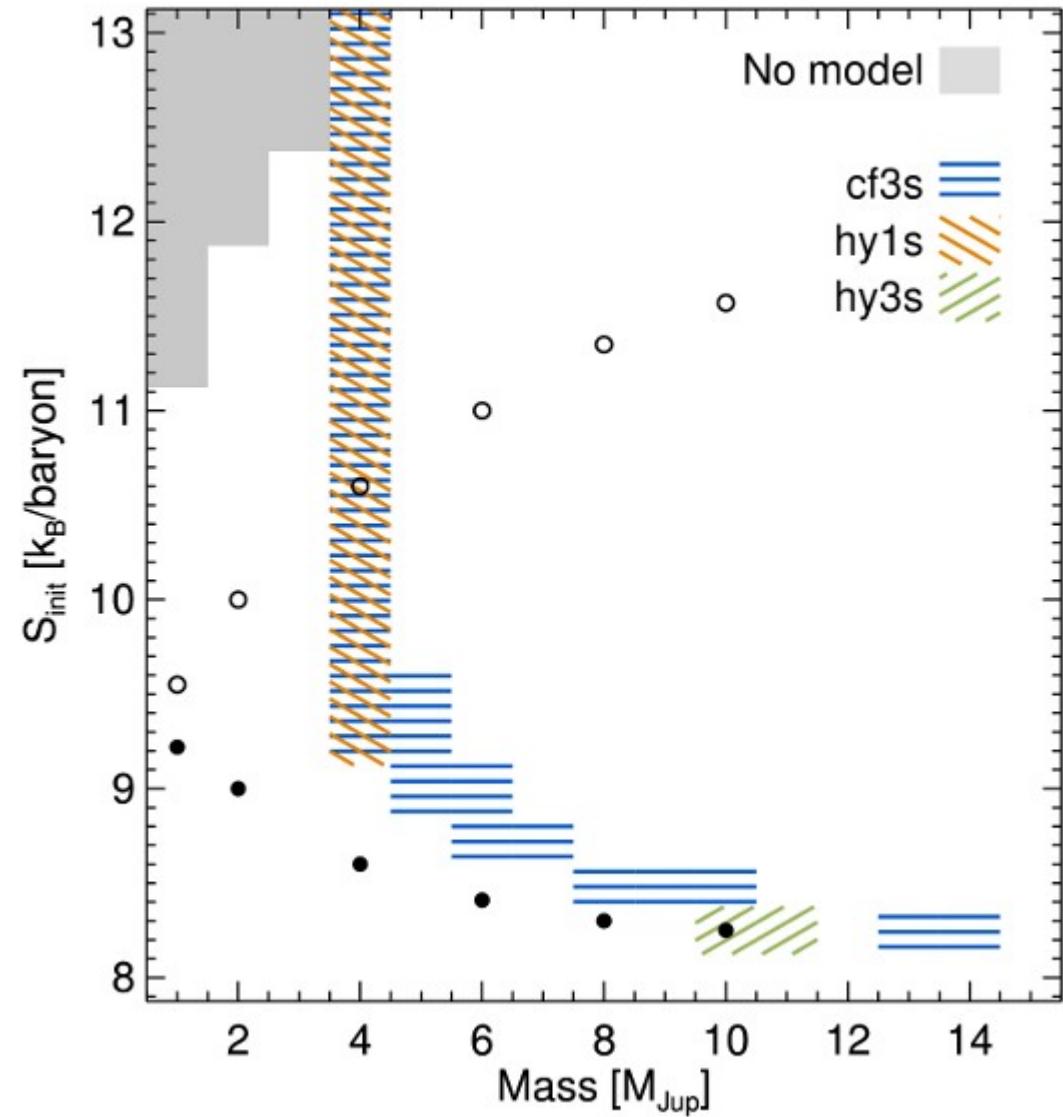
Galicher et al 2014

HD 95086 b: evolutionary models

Hot-start models and L' mag
COND/DUSTY
Mass = 5+/-2 Mjup

Warm-start models
Mass = 4 to 14 Mjup
 $S_{\text{init}} = 8 \text{ to } 13 k_B / \text{baryon}$

Galicher et al 2014



Conclusions

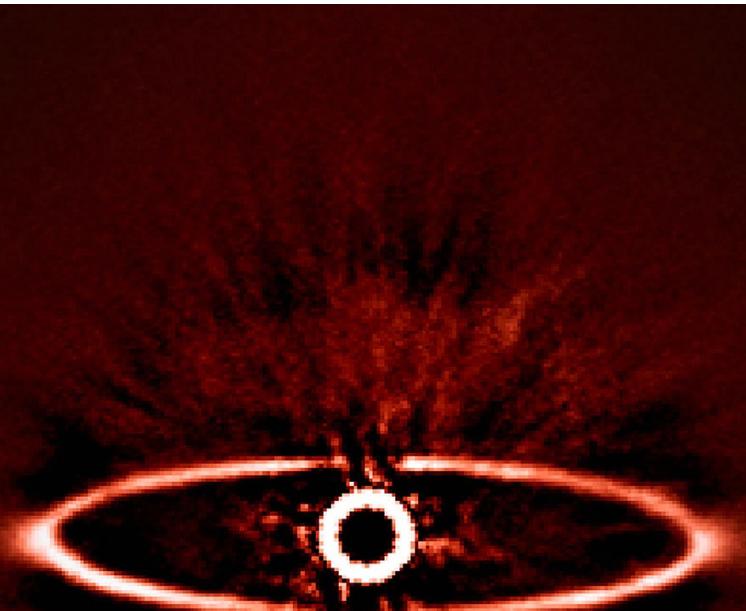
Direct imaging: planets at > few AUs → frequency
 → atmosphere

HD 95086 b: 1st detection at H and K

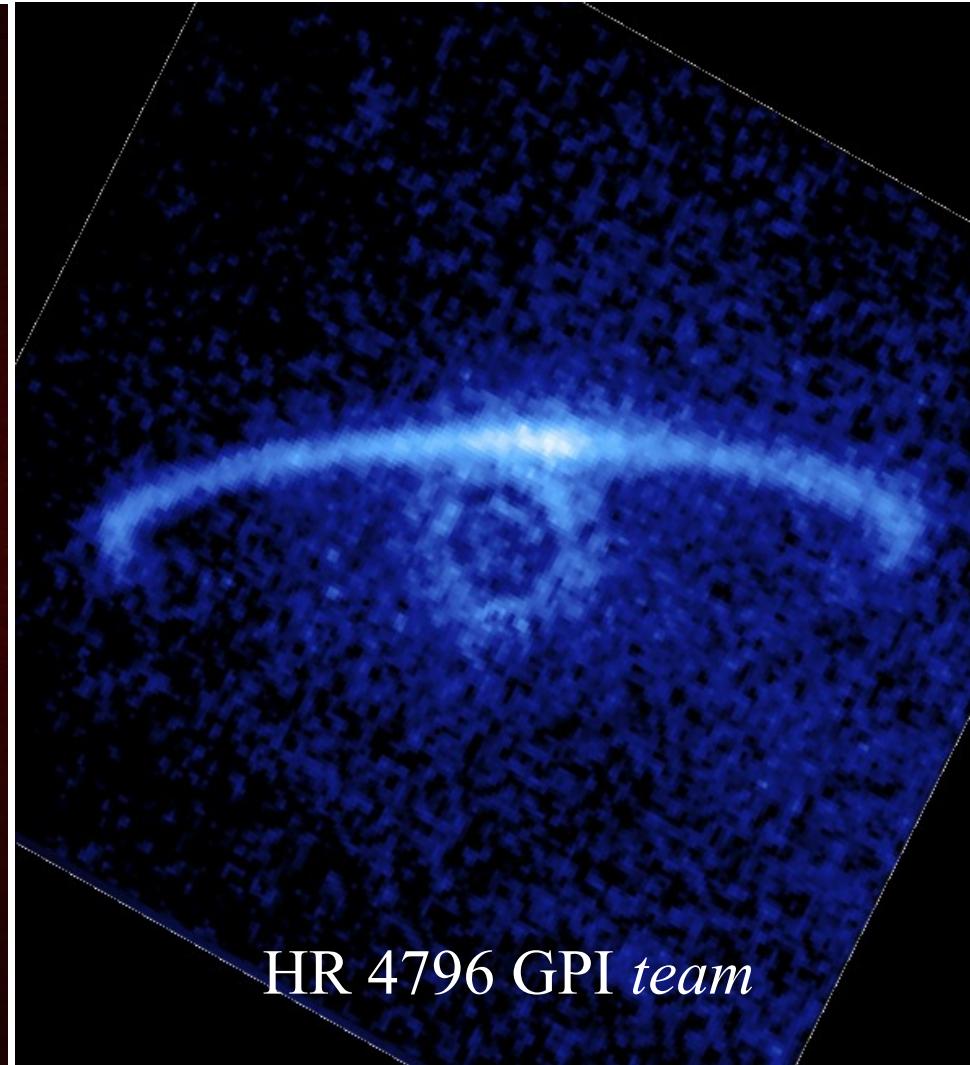
- dust in the atmosphere and low surface gravity
- $600\text{K} < \text{Teff} < 1,500\text{ K}$
- $2.1 < \log g < 4.5$
- Hot-start models: $5+/-2\text{ Mjup}$
- Warm-start models: 4 to 14 Mjup
 - $8.5 \text{ to } 13\text{ k}_\text{B}/\text{baryon}$

Dedicated instruments: GPI (Gemini) ; SPHERE (VLT)

Thank you

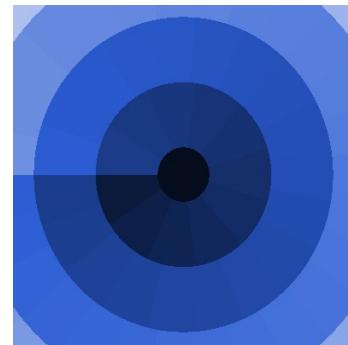
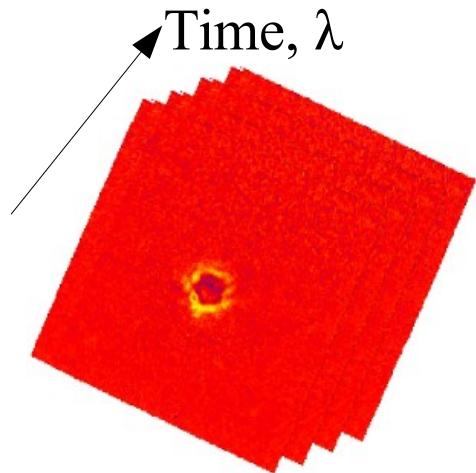


HR 4796 *SPHERE team*



HR 4796 *GPI team*

LOCI : Locally Optimized Combination of Images

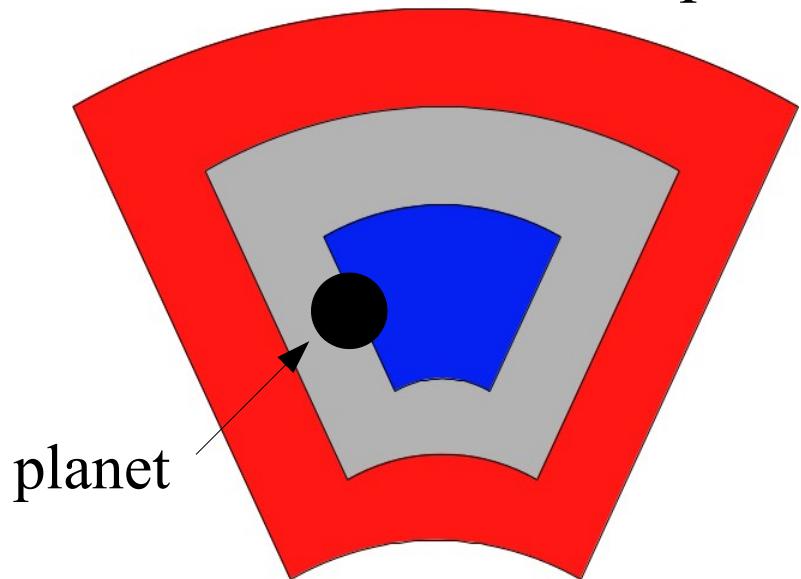


$$\chi_i^2 = \sum_{\text{pix}} |S_{\text{ec}_i} - \sum_j \alpha_{i,j} S_{\text{ec}_j}|^2$$

j for planet self-subtraction < x %

Minimization \rightarrow SVD $\rightarrow \alpha_{i,j}$

Speckles are temporally and spatially correlated



- Blue: S_{ec_i} = sec of interest
- Red: where χ_i^2 is minimized
- Grey: Not used

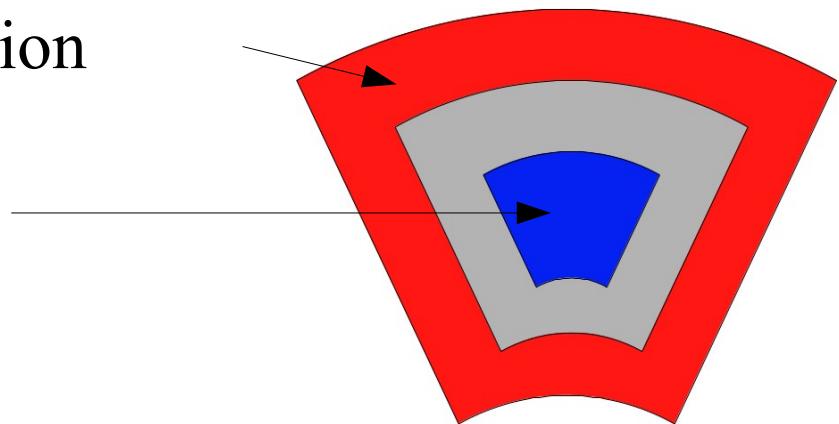
Marois et al 2008, 2010

LOCI parameters

g = min planet motion between image and references

$r_{opt,1}, r_{opt,2}, \theta_{opt,1}, \theta_{opt,2}$ = optimizing region

$r_1, r_2, \theta_1, \theta_2$ = region of interest

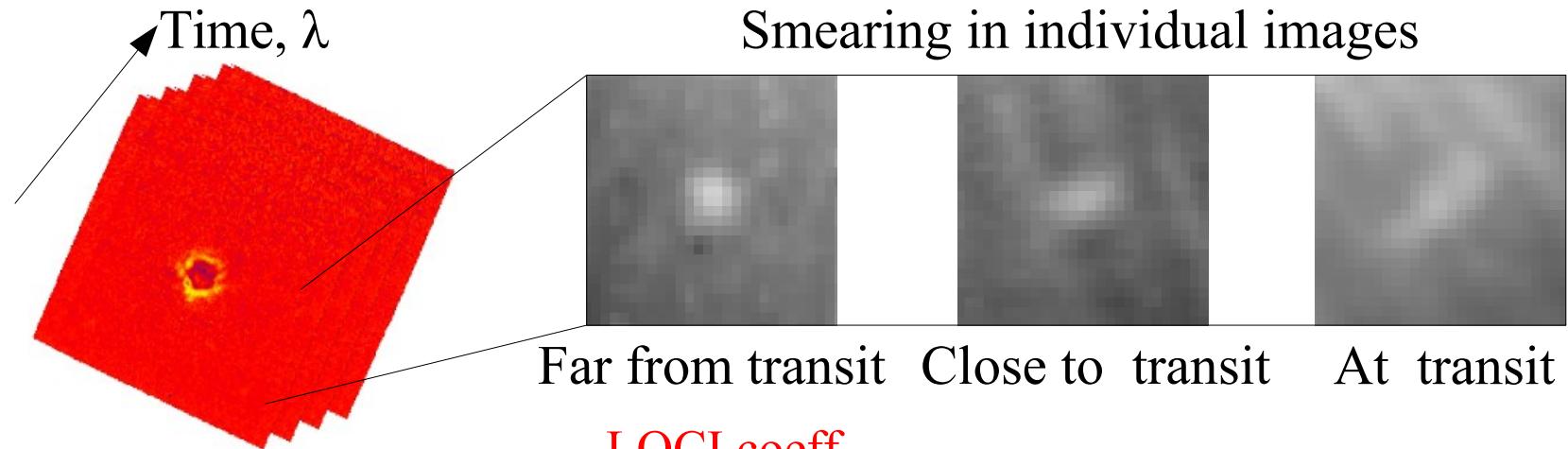


N = max nb of references

SDI = ADI+SDI at the same time with a LOCI algorithm (NICI data)

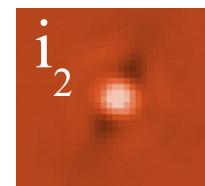
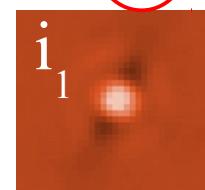
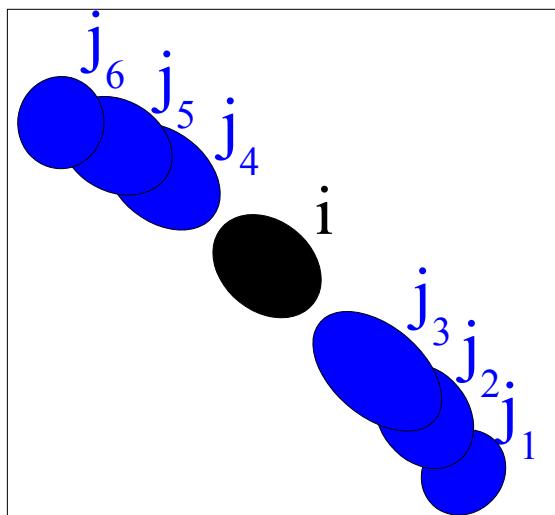
$Arch$ = can use an archive of reference images (mainly for HST data)

LOCI : off-axis image formation



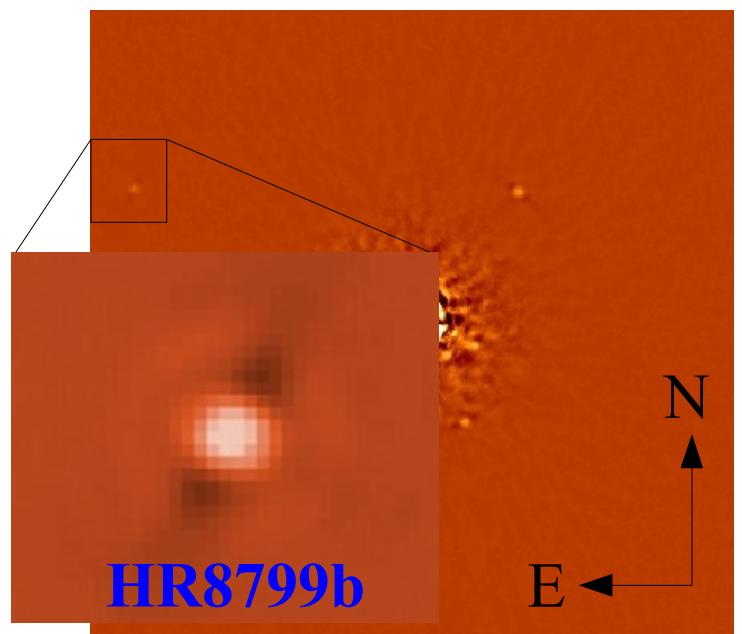
$$\text{Speckle Res}_i = \text{Sec}_i - \sum_j \alpha_{i,j} \text{Sec}_j$$

LOCI coeff



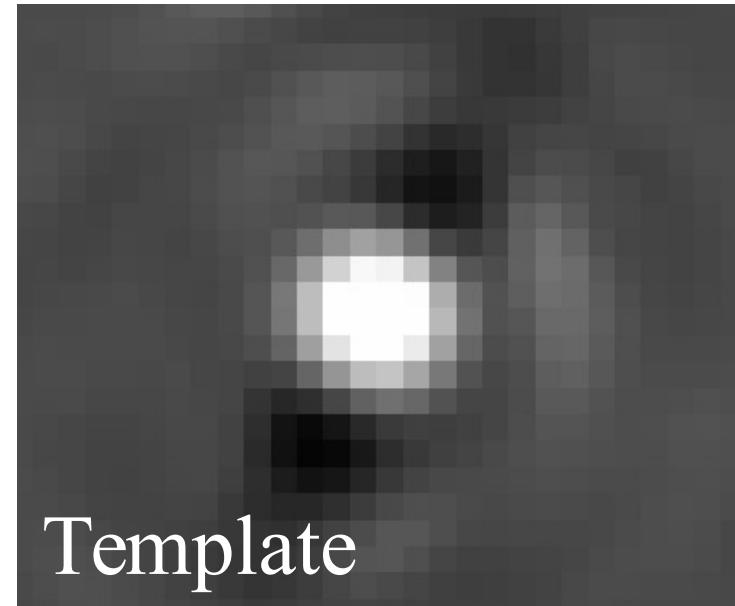
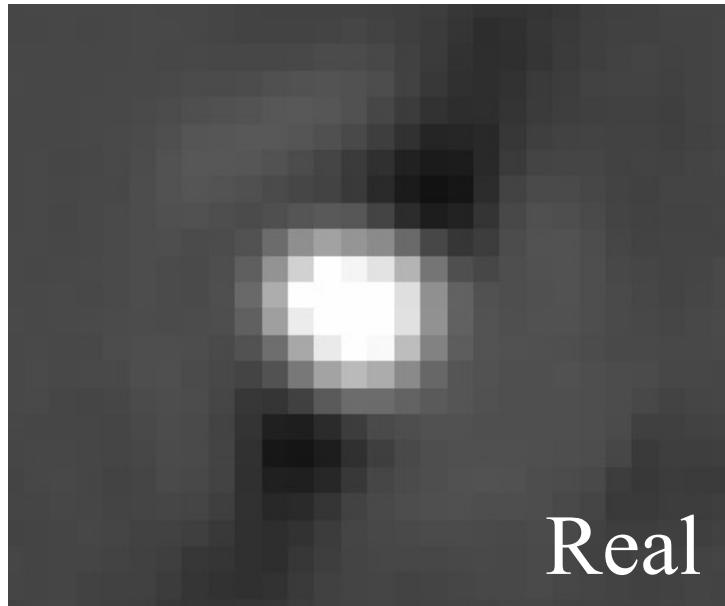
...

Rotation
→
+ median



LOCI : photometry/astrometry

- 1/ Off-axis source cube (positions and smearing)
- 2/ LOCI using the already calculated $\alpha_{i,j}$ → template
- 3/ Fit the template to the real image

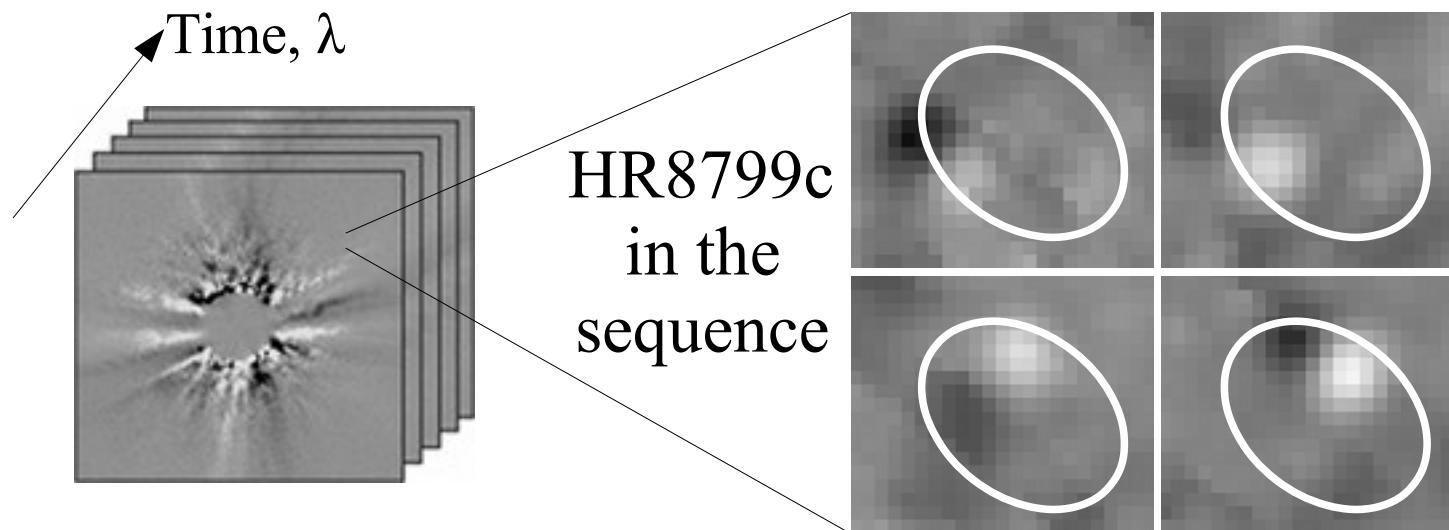


Astrometric errors include errors on the PSF
Photometric errors + star flux variations in unsat data

LOCI : global shift

1/ degrades the contrast

2/ biases astrometry/photometry



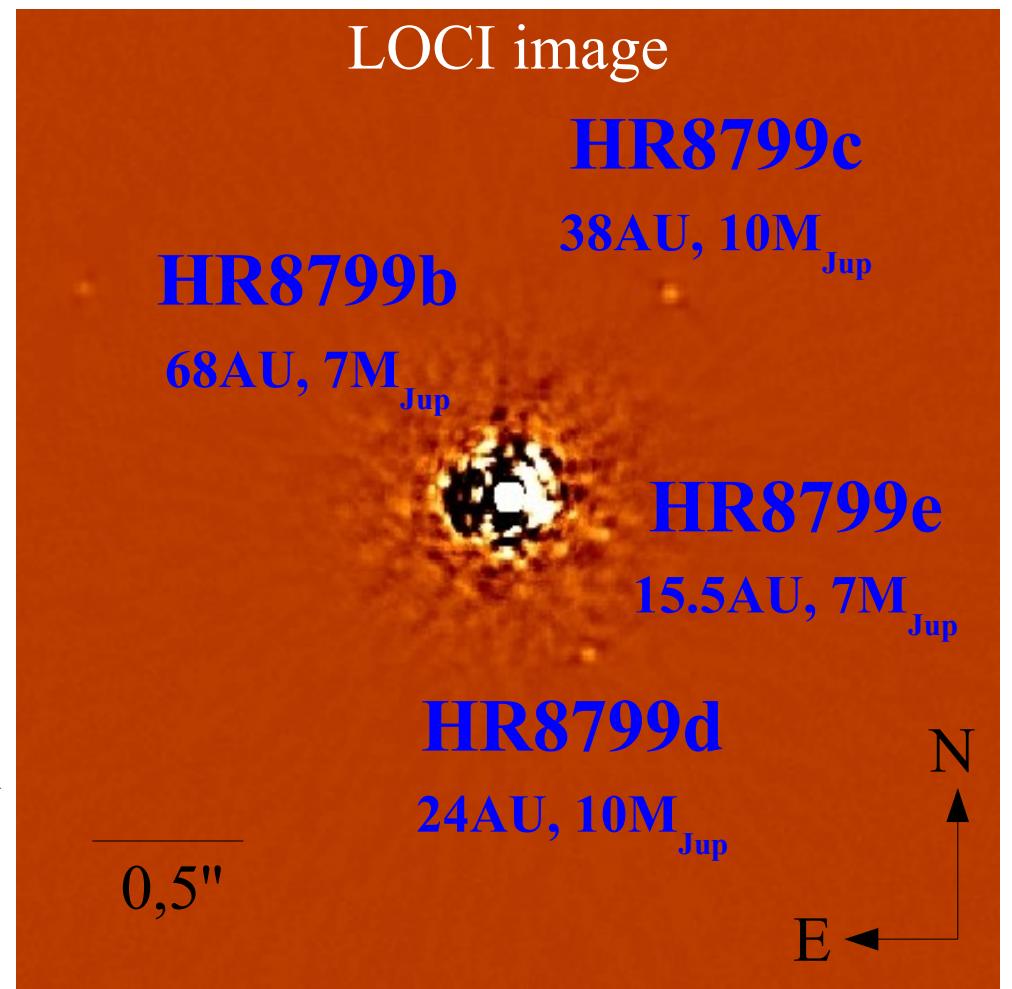
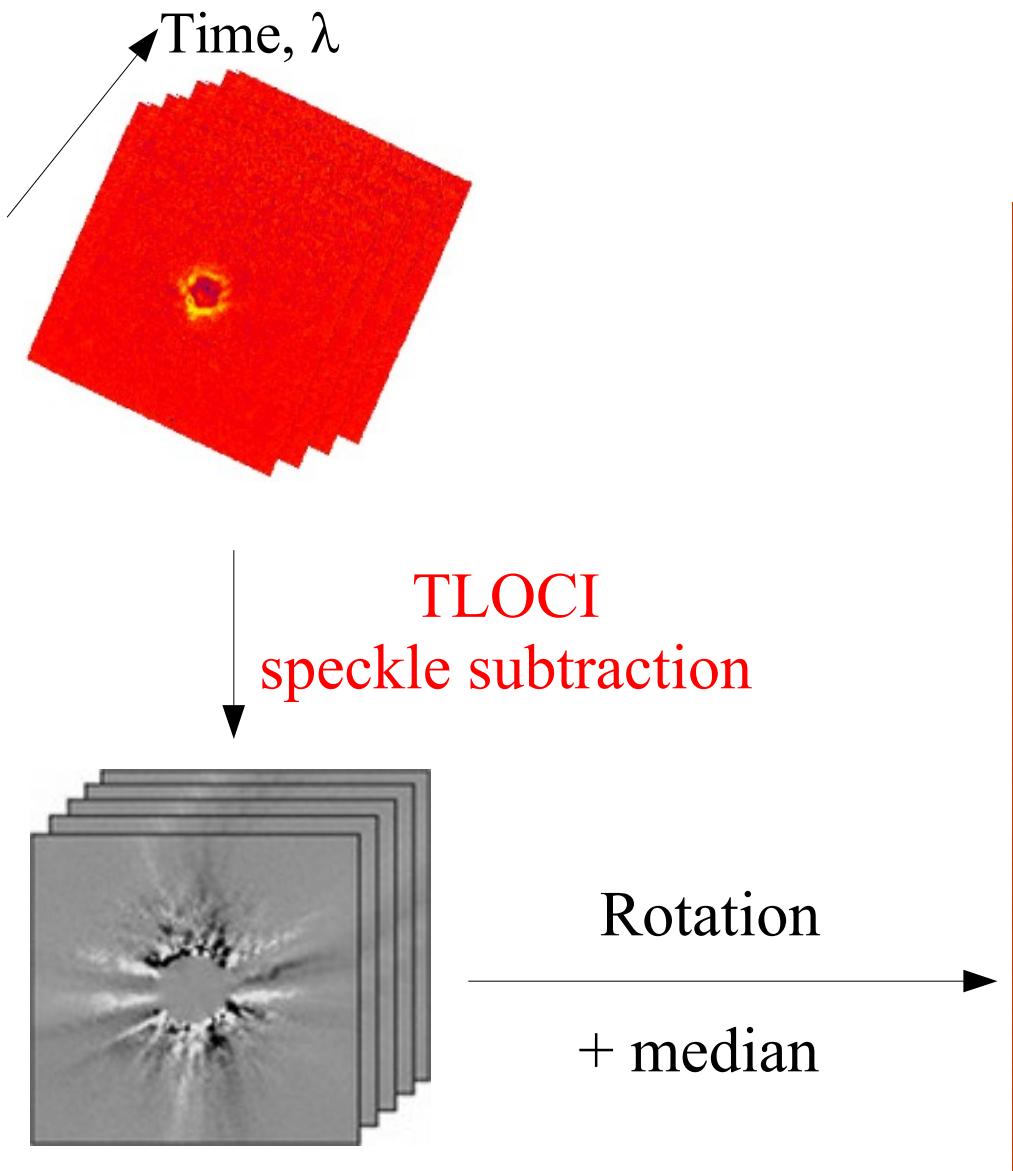
Maximizing off-axis source flux :

1/ Δx et Δy du cube

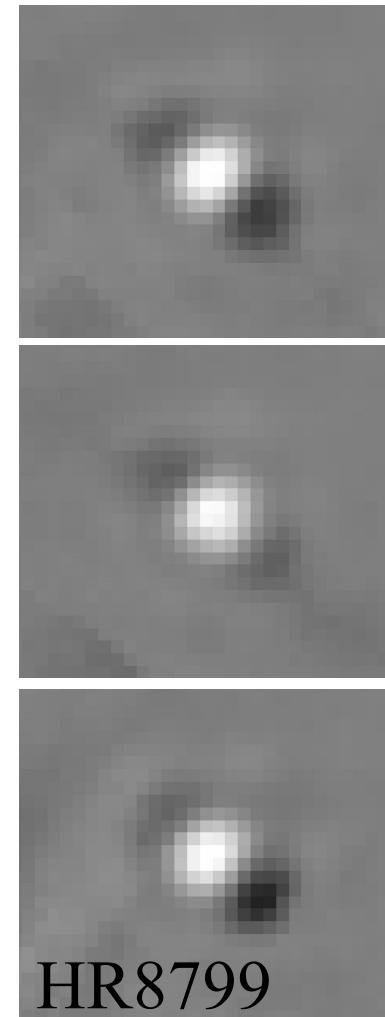
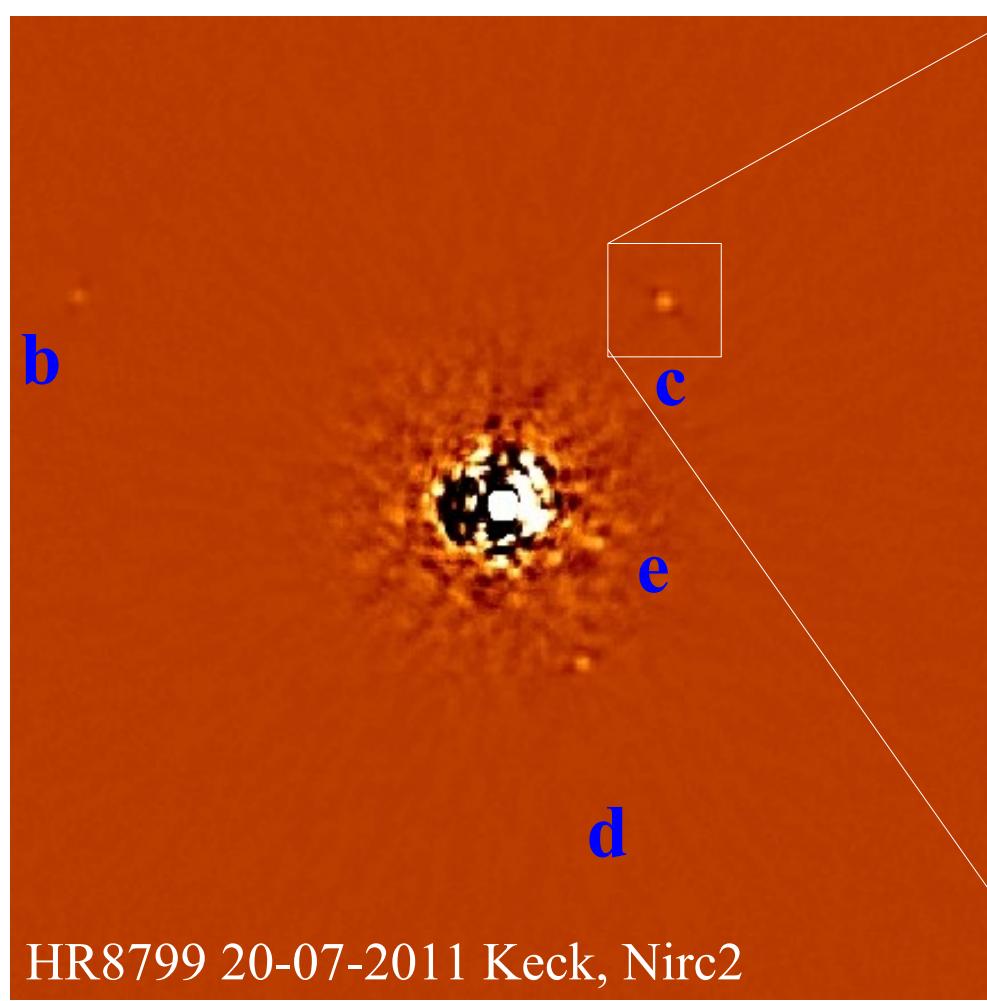
2/ offsets on telescope latitude and header sidereal time

TLOCI/SOSIE

Marois et al. 2010



TLOCI : off-axis image biases !



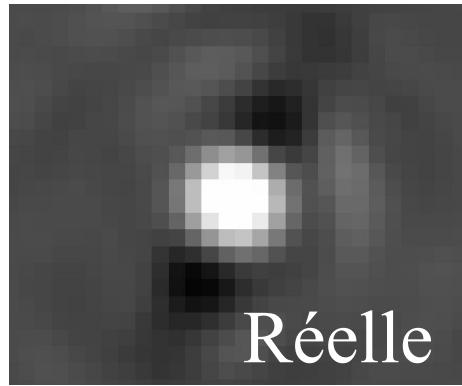
Same sequence
but
different
TLOCI
parameters

TLOCI => biased photometry and astrometry !

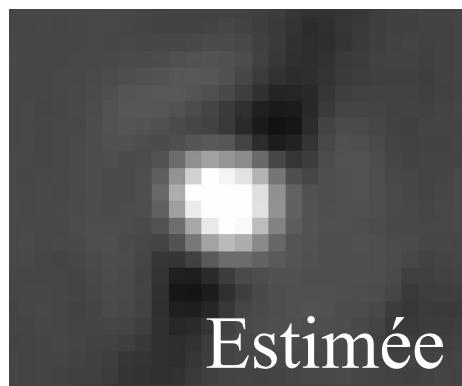
Photométrie et astrométrie avec ADI/SSDI/LOCI

Galicher et al, 2011

Idée :



Réelle



Estimée

