High-contrast Imaging with Differential Imaging

René Doyon

Laboratoire d'Astrophysique Expérimentale

Université de Montréal

Christian Marois (PhD student)

David Lafrenière (PhD student)

René Racine

Daniel Nadeau

+ LAE technical staff

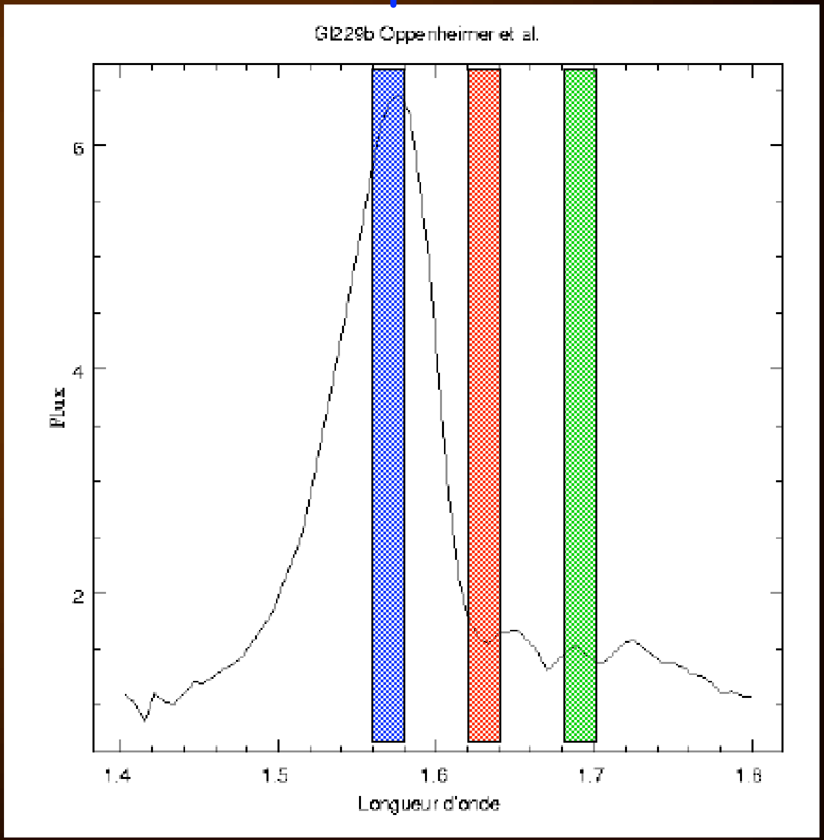
Outline

- Description of differential technique
- TRIDENT (II) performances on CFHT
- Lessons learned with DI
- Laboratory measurements
- Next steps in differential imaging

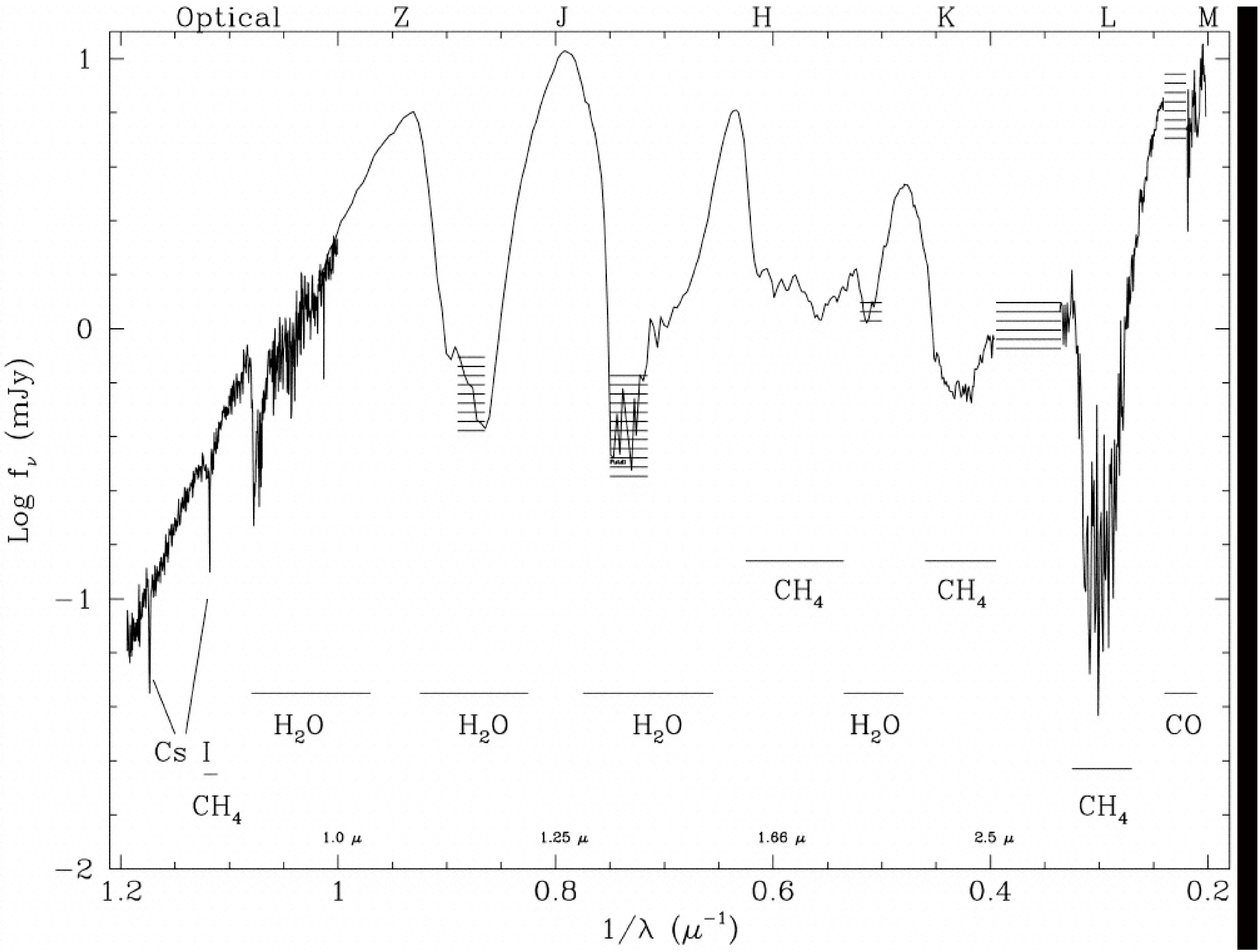
Differential Imaging

- 1^{st} proposed by Smith (1987), rediscovered by Rosenthal etal (1996)
- BDs and giant planets show CH4 absorption at ~1.6 μm but not stars.
- Obtain simultaneous images "on" & "off" the CH4 absorption.
- After proper registration & scaling, image subtraction reveal companion.
- Factor of ~4 contrast
- Significant gain by adding
  a 3^{rd} λ (Marois etal 2000)

Gl229b spectrum



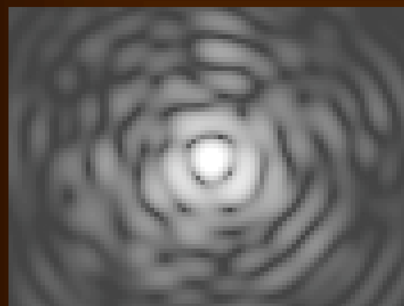
λ_1 λ_2 λ_2



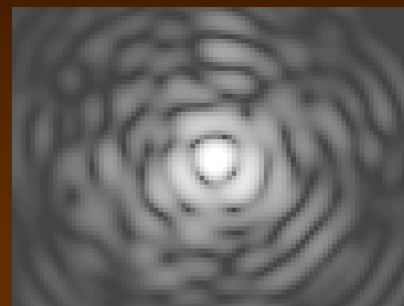
Optical
Z
J
H
K
L
M
Log f_ν (mJy)
1
0
−1
−2
CH_4
CH_4
Cs I
CH_4
H_2O
H_2O
H_2O
H_2O
CO
CH_4
1.0 μ
1.25 μ
1.66 μ
2.5 μ
1.2
1
0.8
0.6
0.4
0.2
$1/\lambda$ (μ^{-1})

Simulation of simple and double difference (Marois etal 2000, PASP, 112,91)

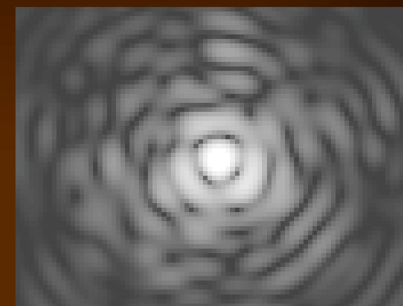
1.57 μm



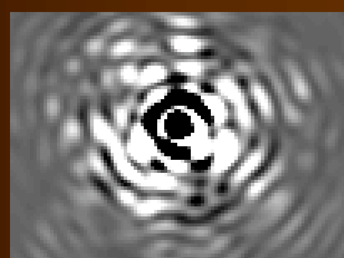
1.625 μm



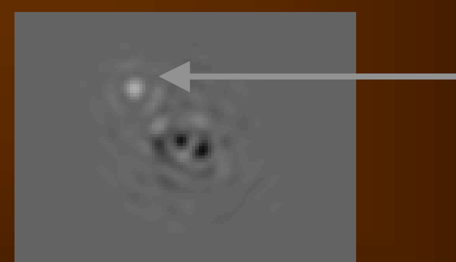
1.68 μm



Small PSF evolution with wavelength



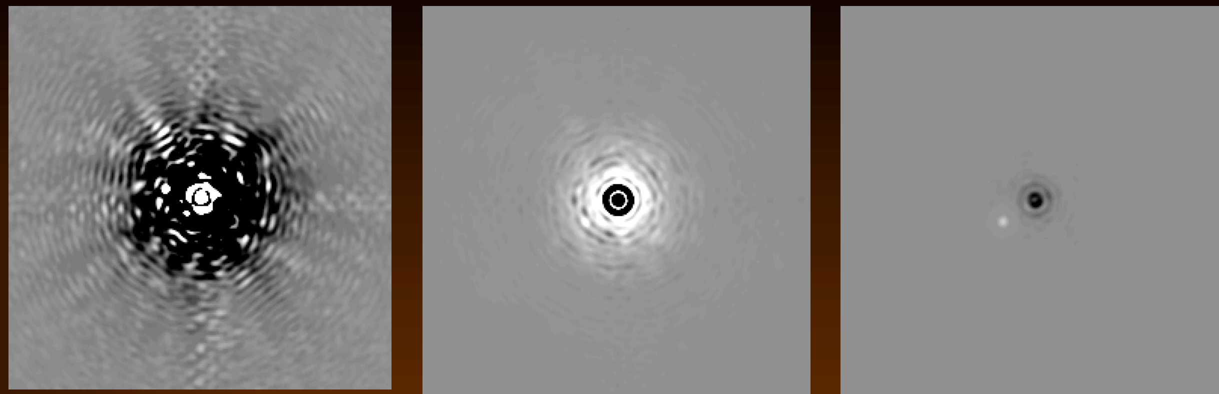
Simple diff.
(λ1-λ2)

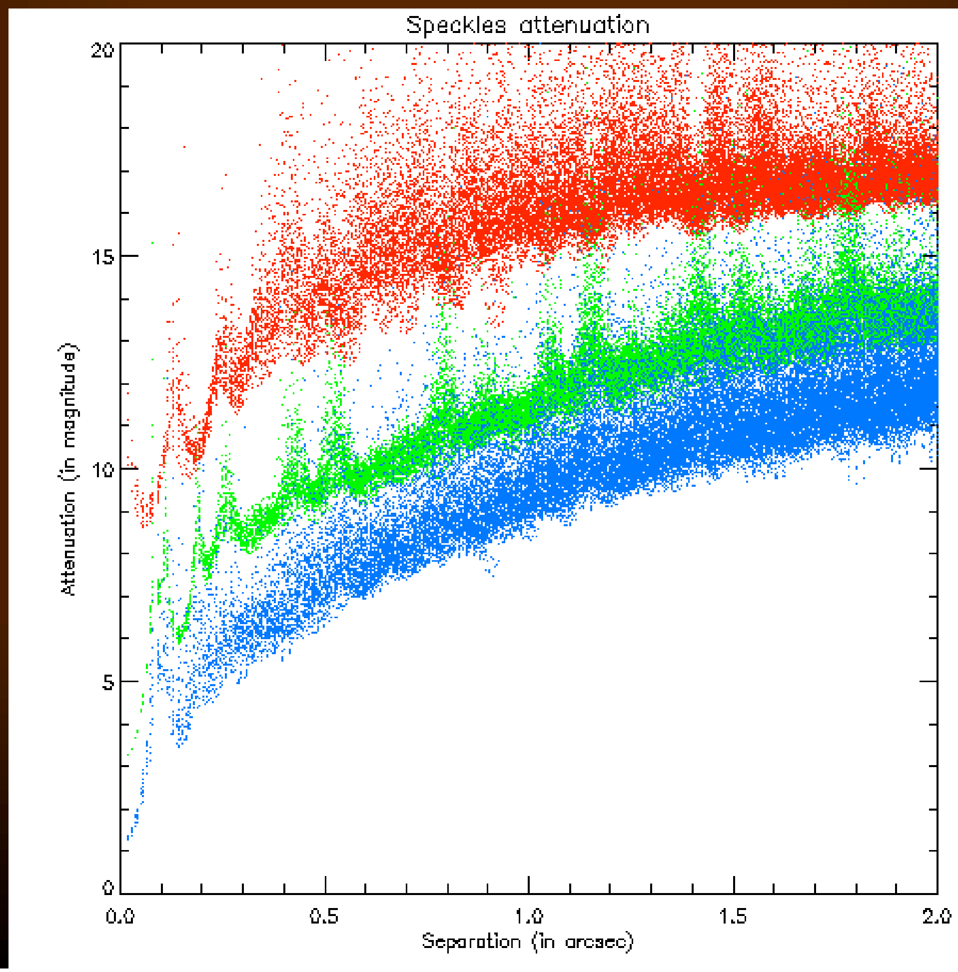


Δm=9

Double diff.
(λ1-λ2) – k (λ1-λ3)

Simple image Simple difference Double difference



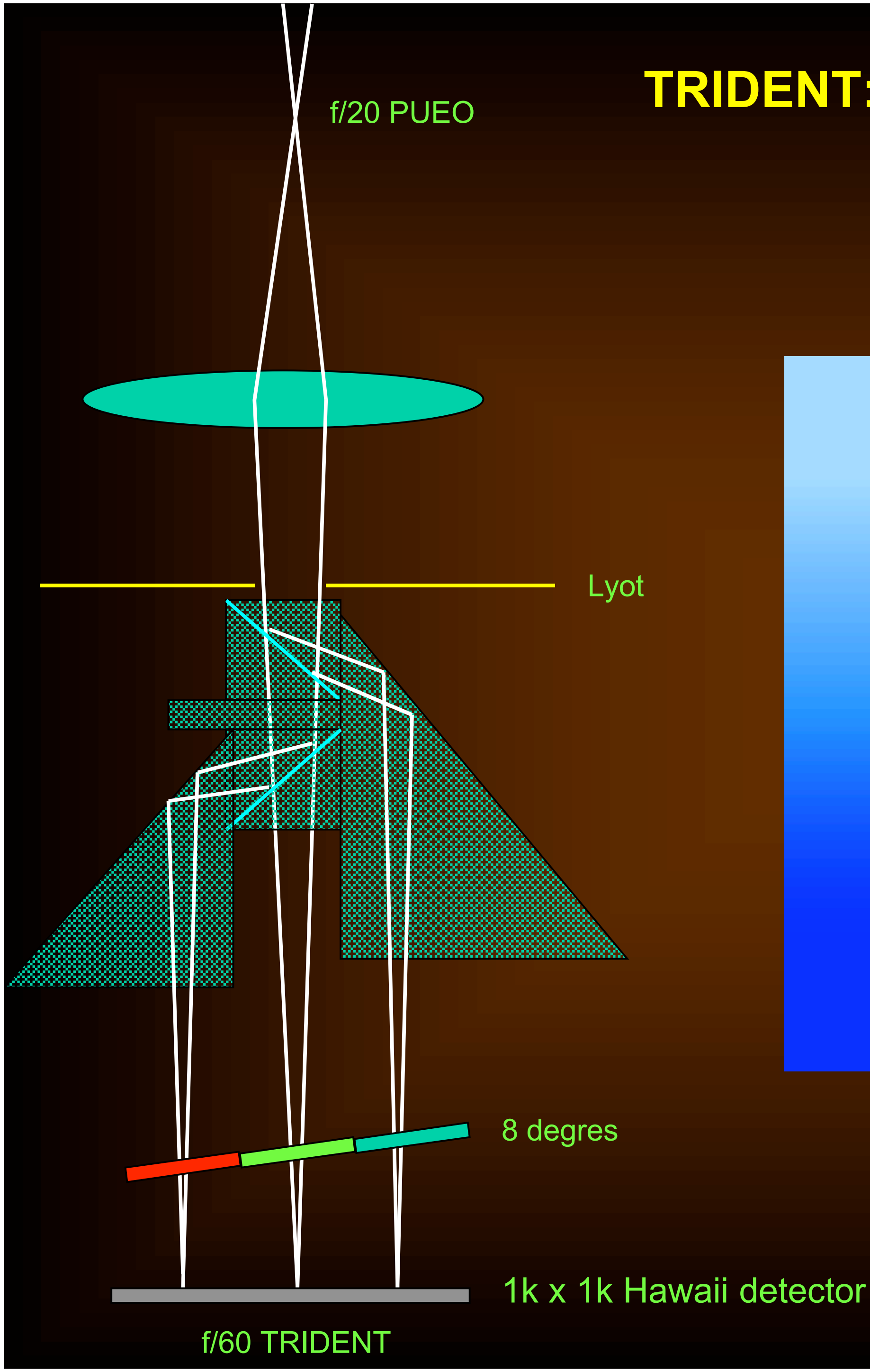


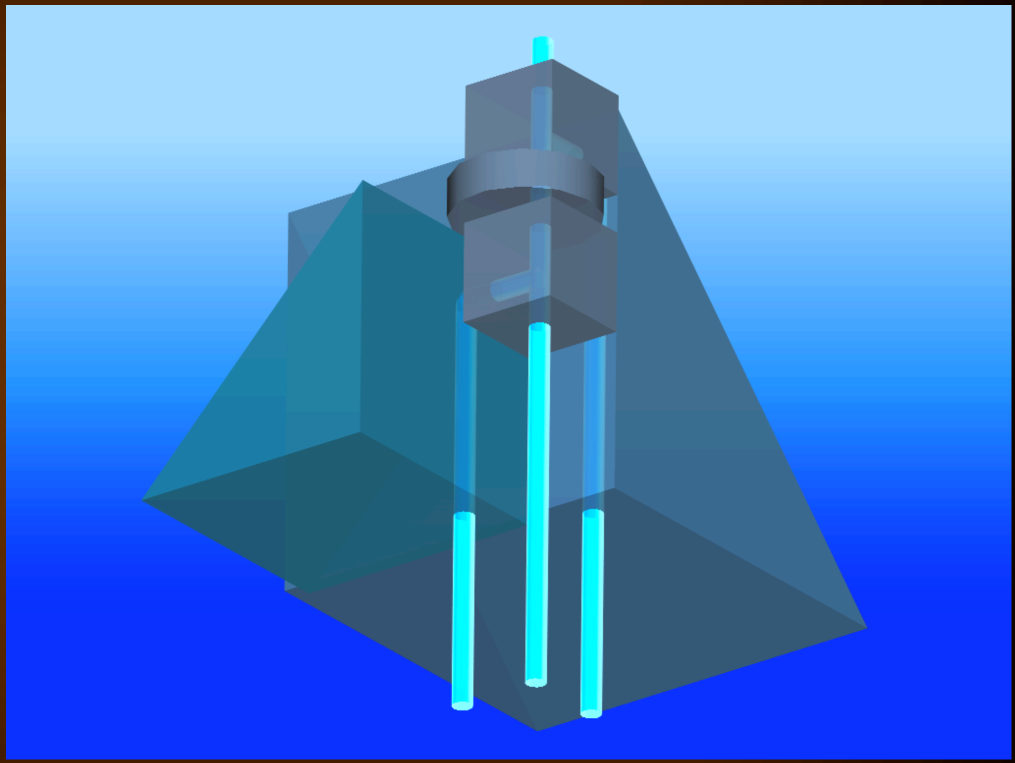
Double difference

Simple difference

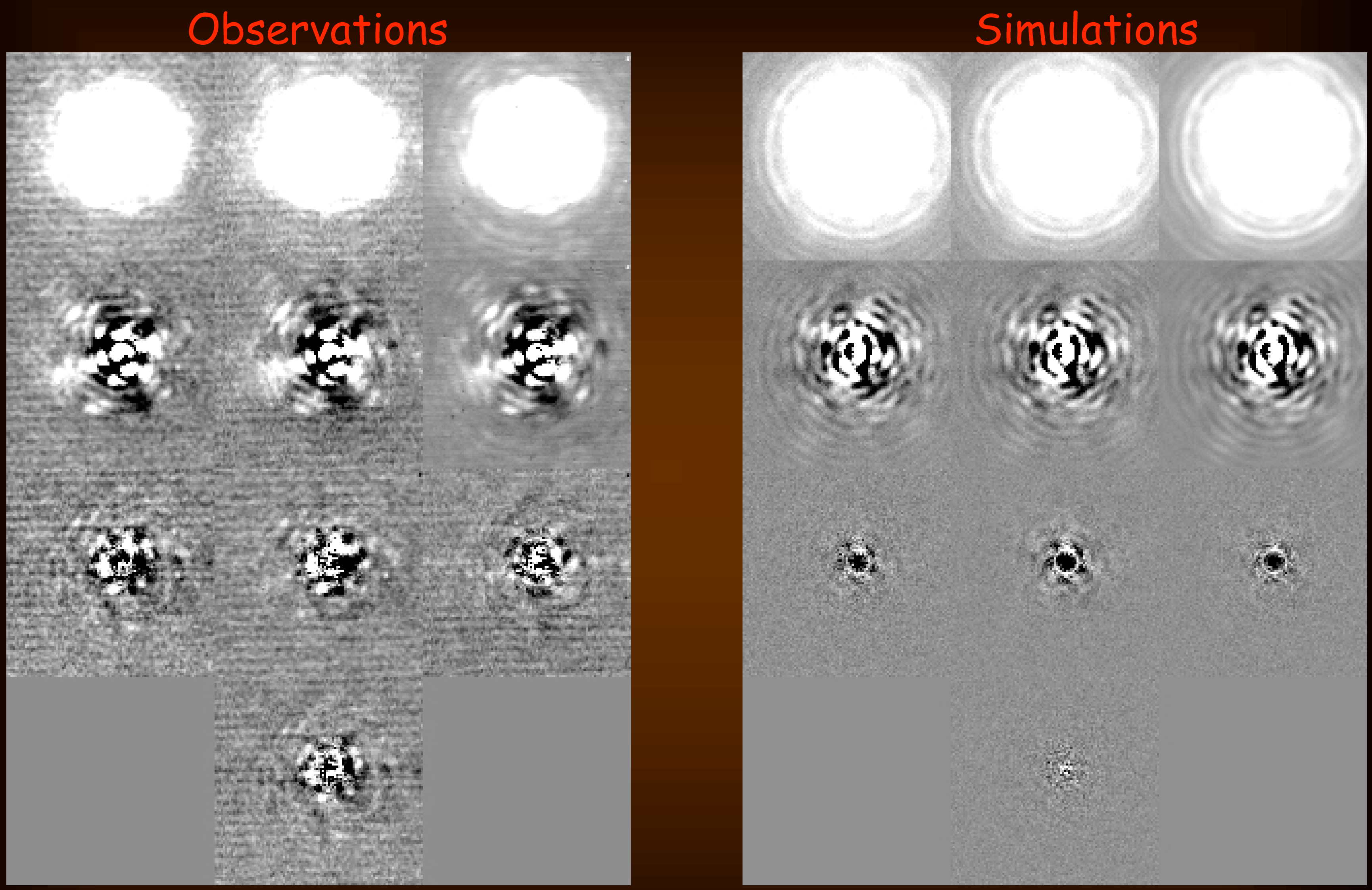
Simple image

TRIDENT: Instrument Concept



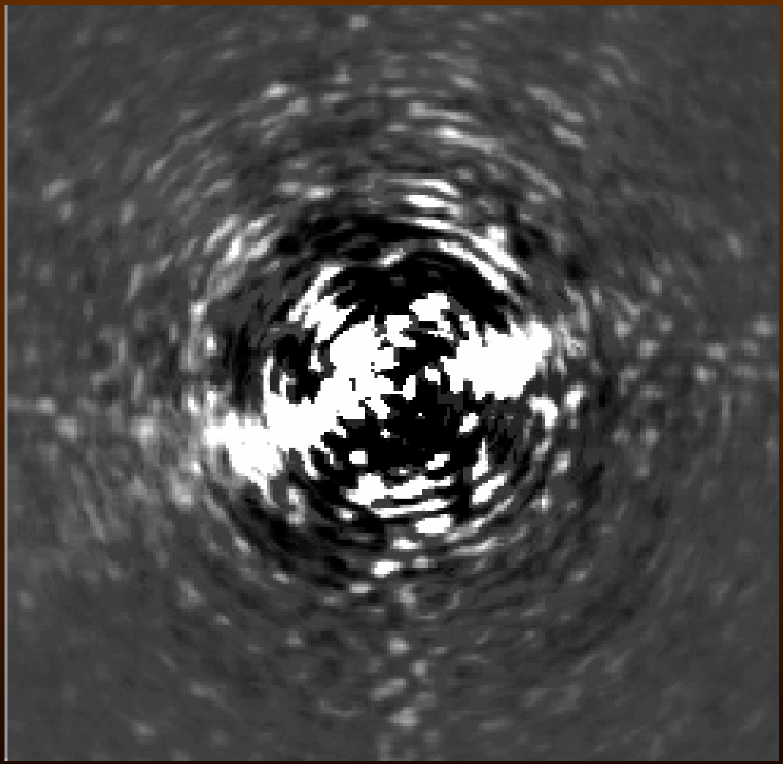


TRIDENT

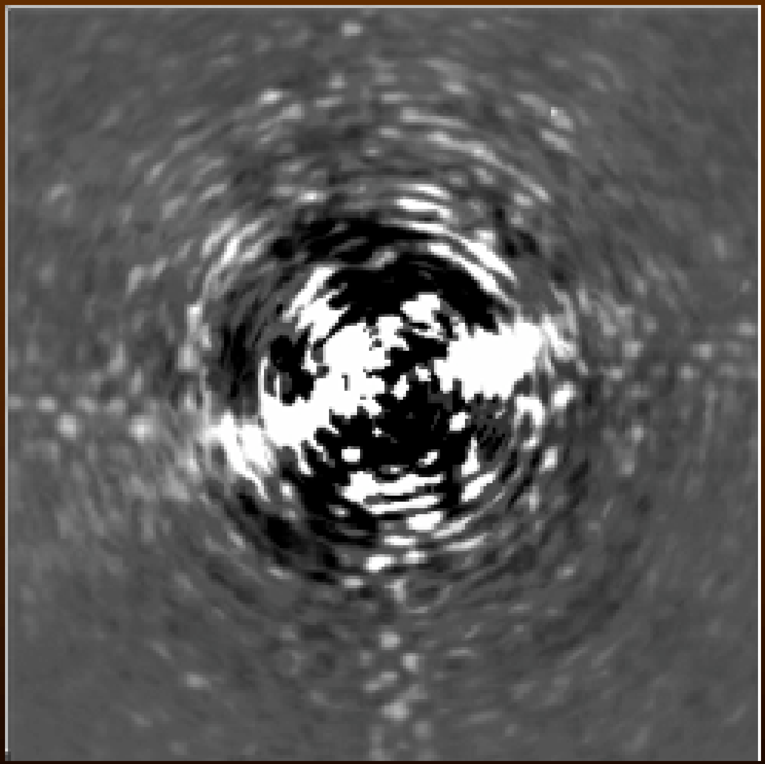


PSF variance *by far* dominated by static aberrations (MSF)

TRIDENT PSF on (1.57 μm)

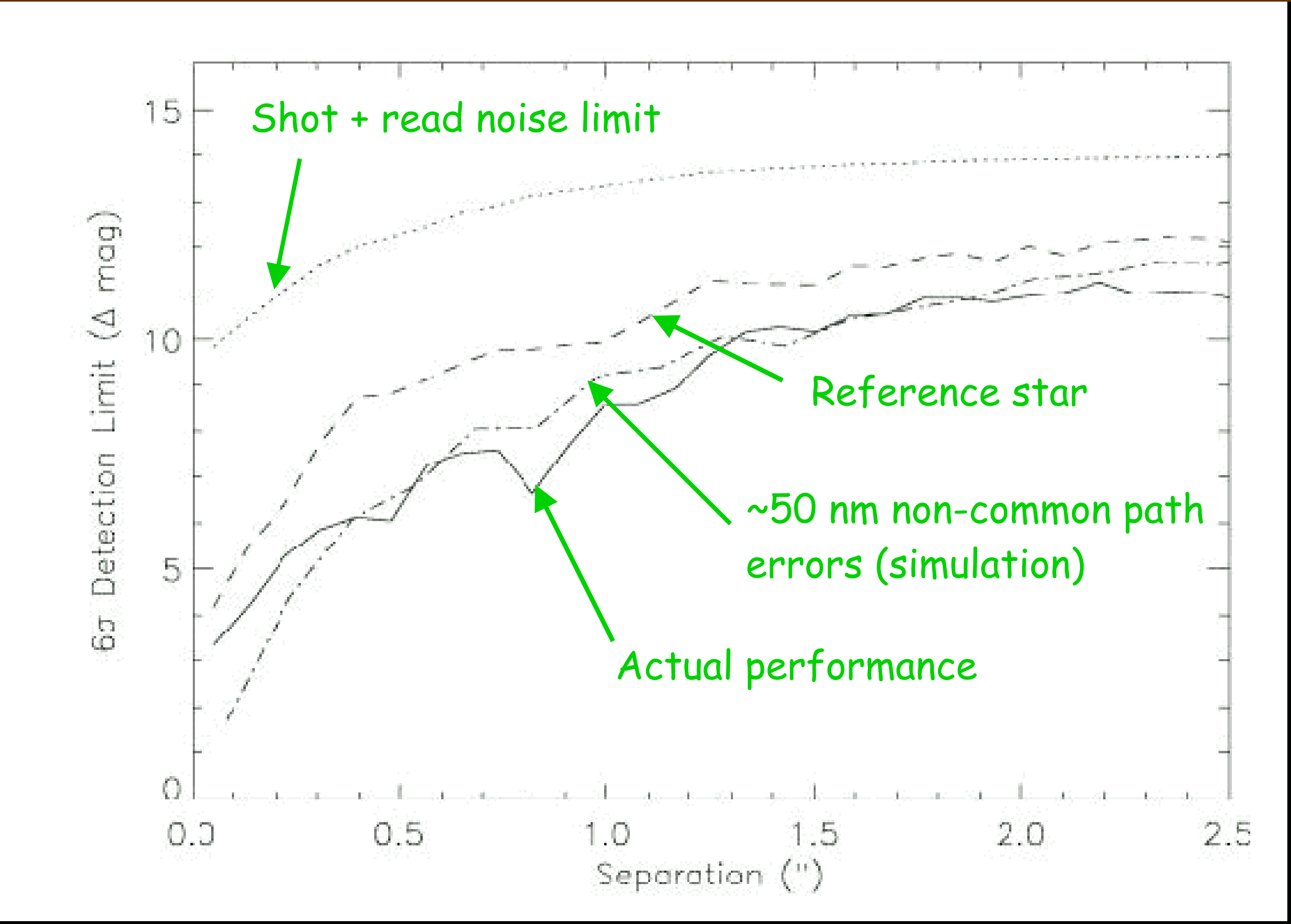


15 mins

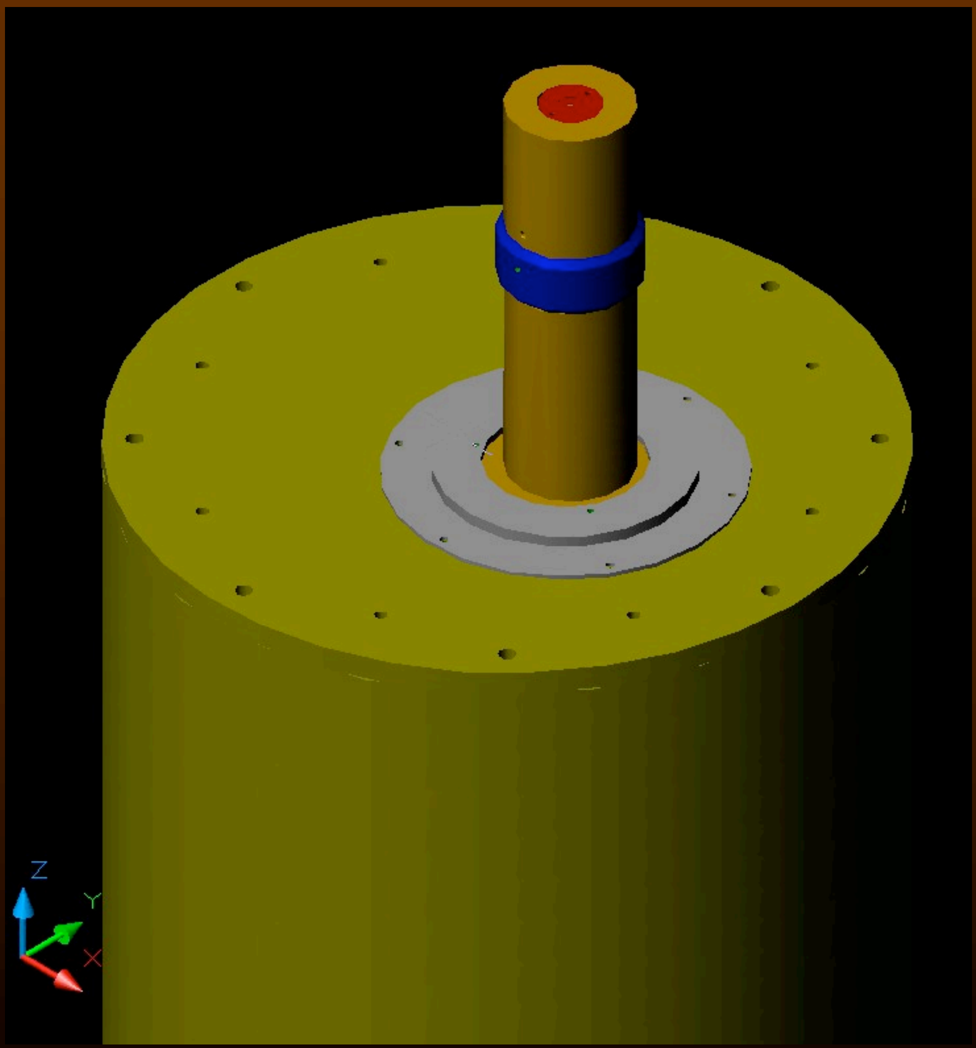


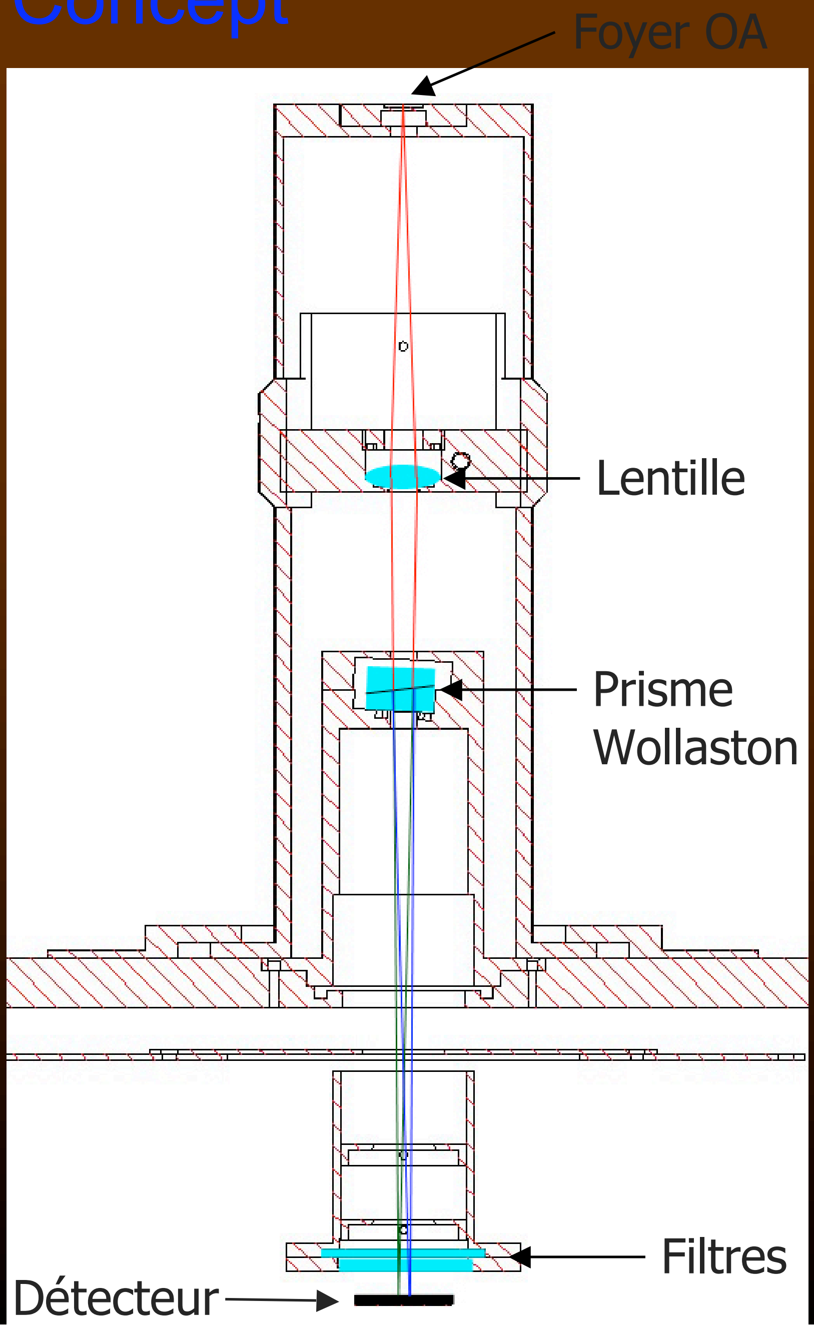
60 mins

TRIDENT performance

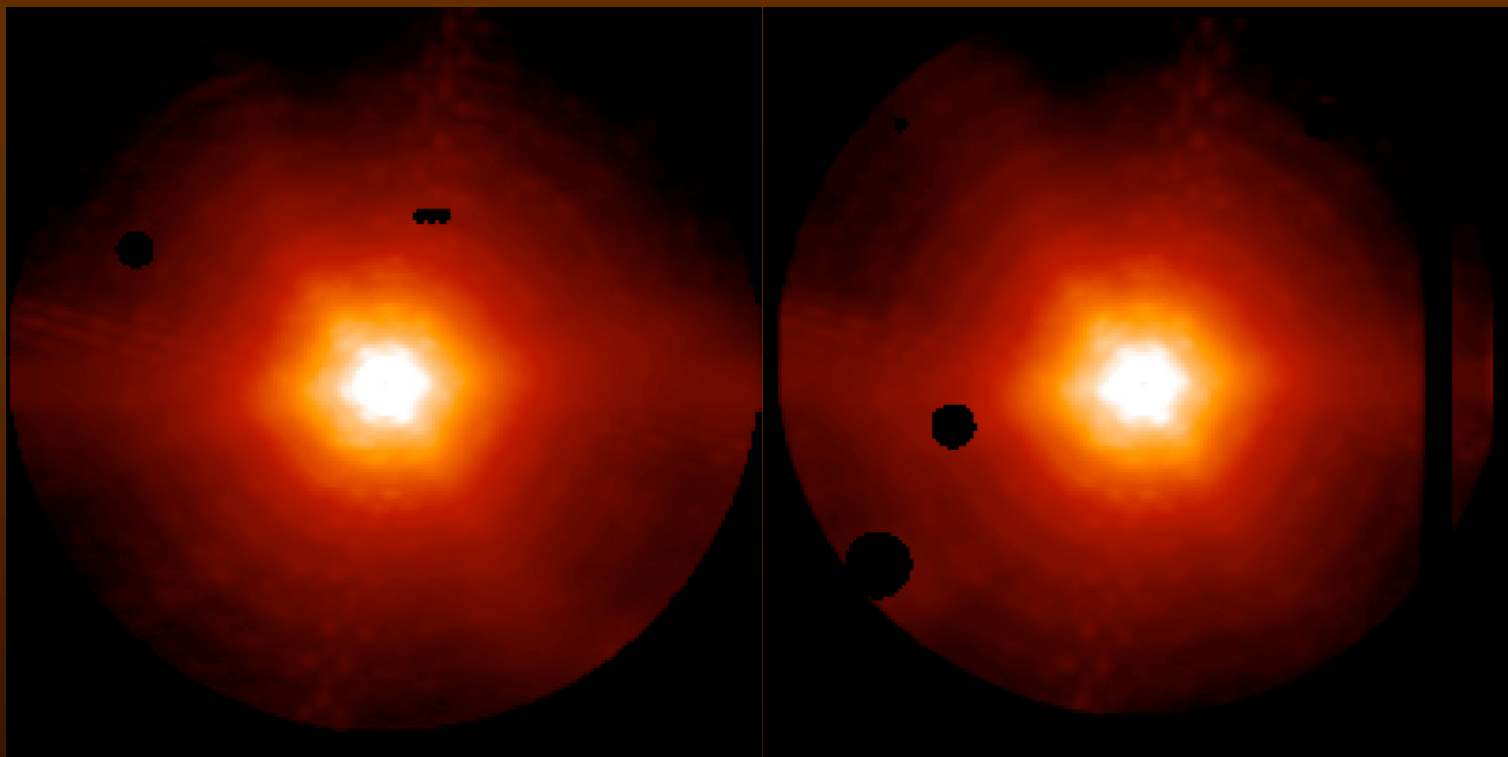


TRIDENT II - Concept

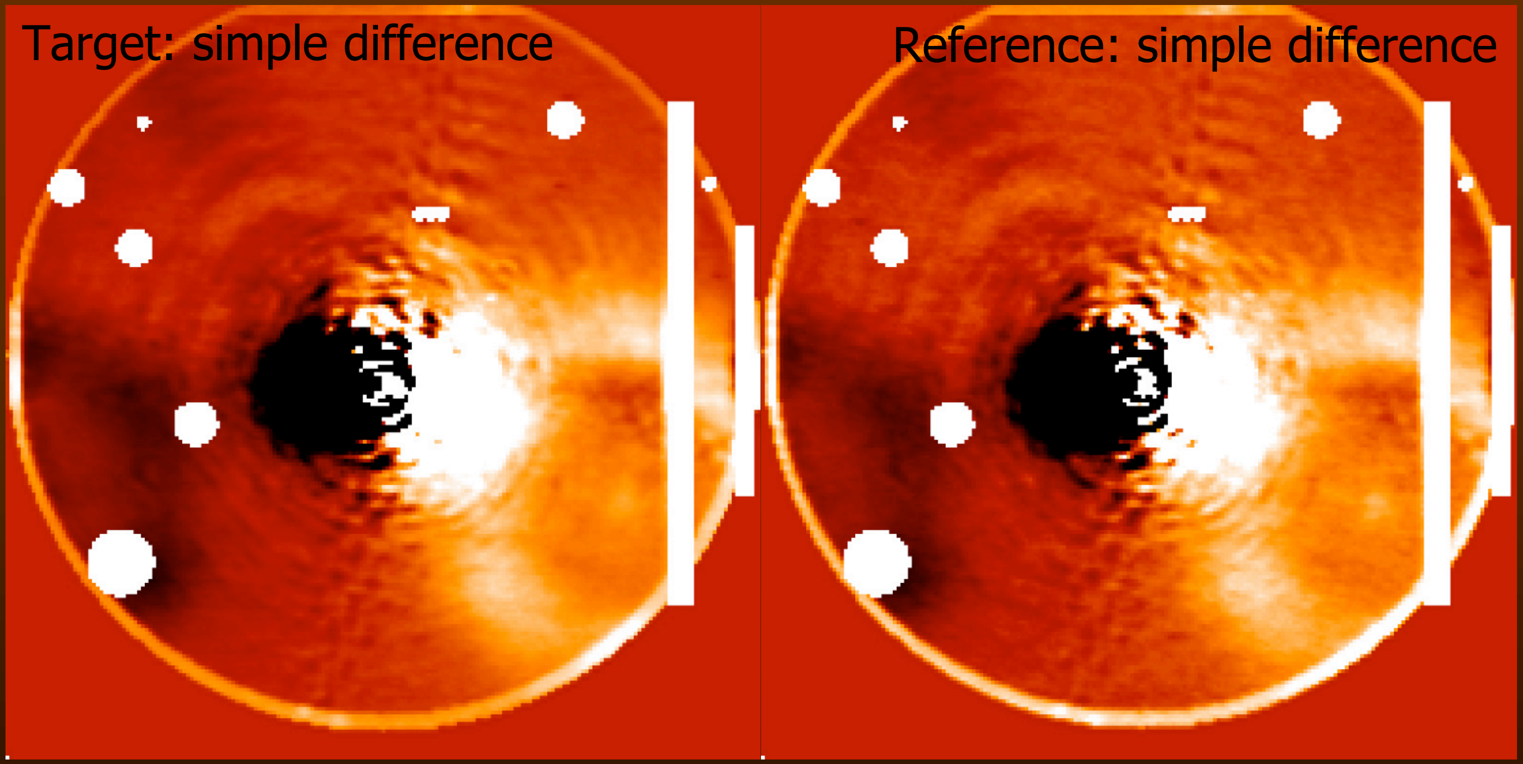




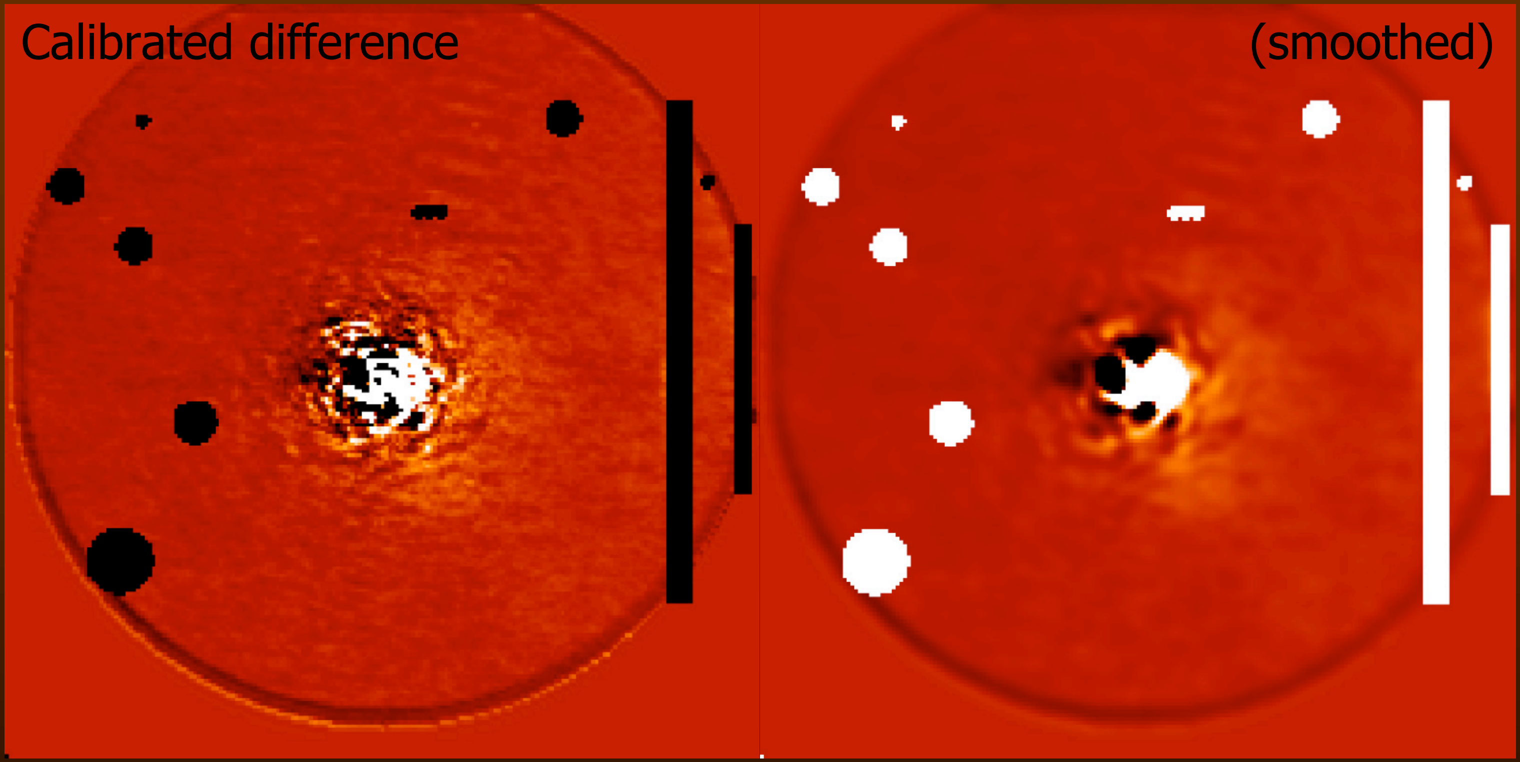
Typical TRIDENT-II data (saturated core)



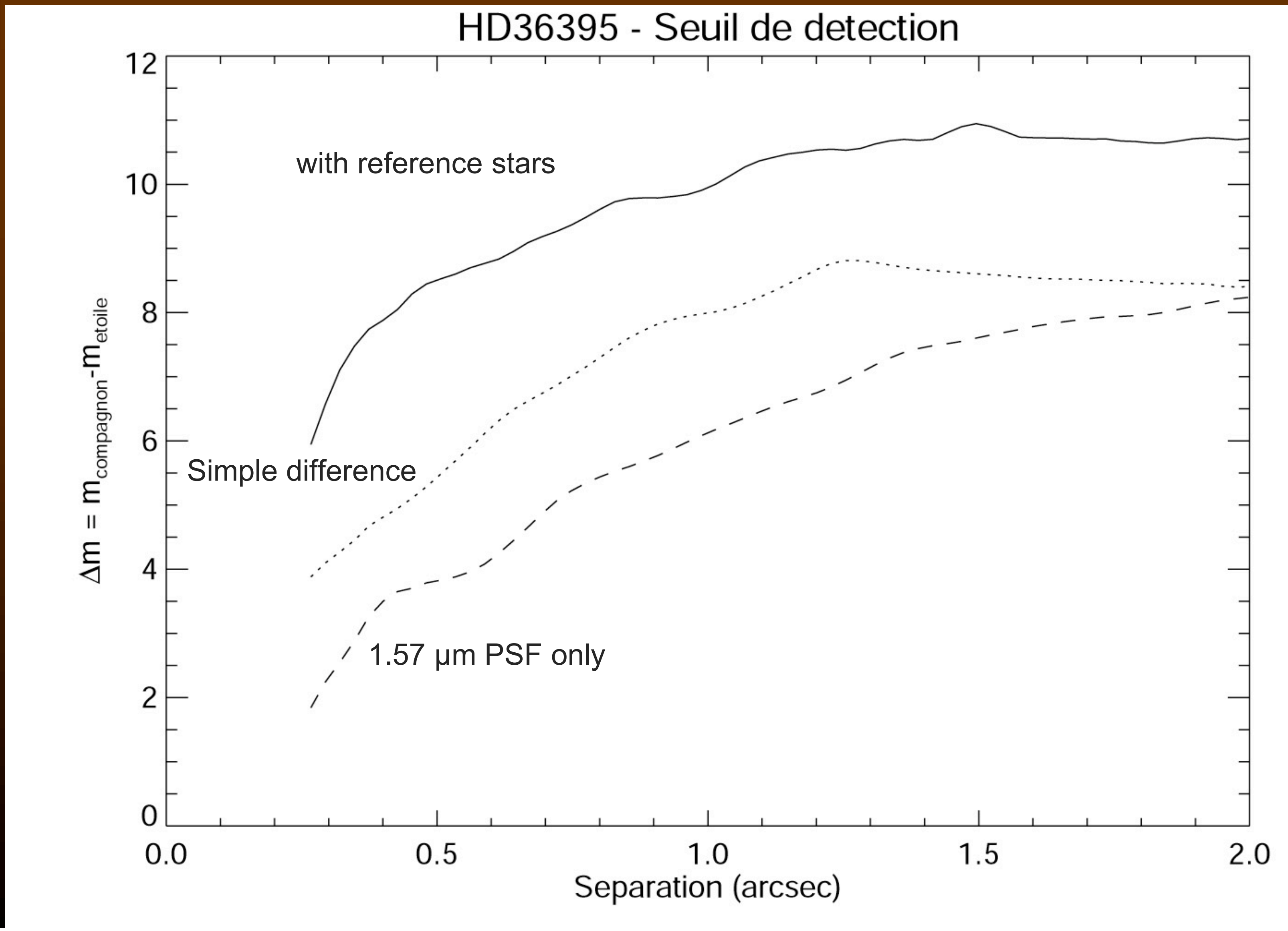
Typical TRIDENT-II data (saturated core)



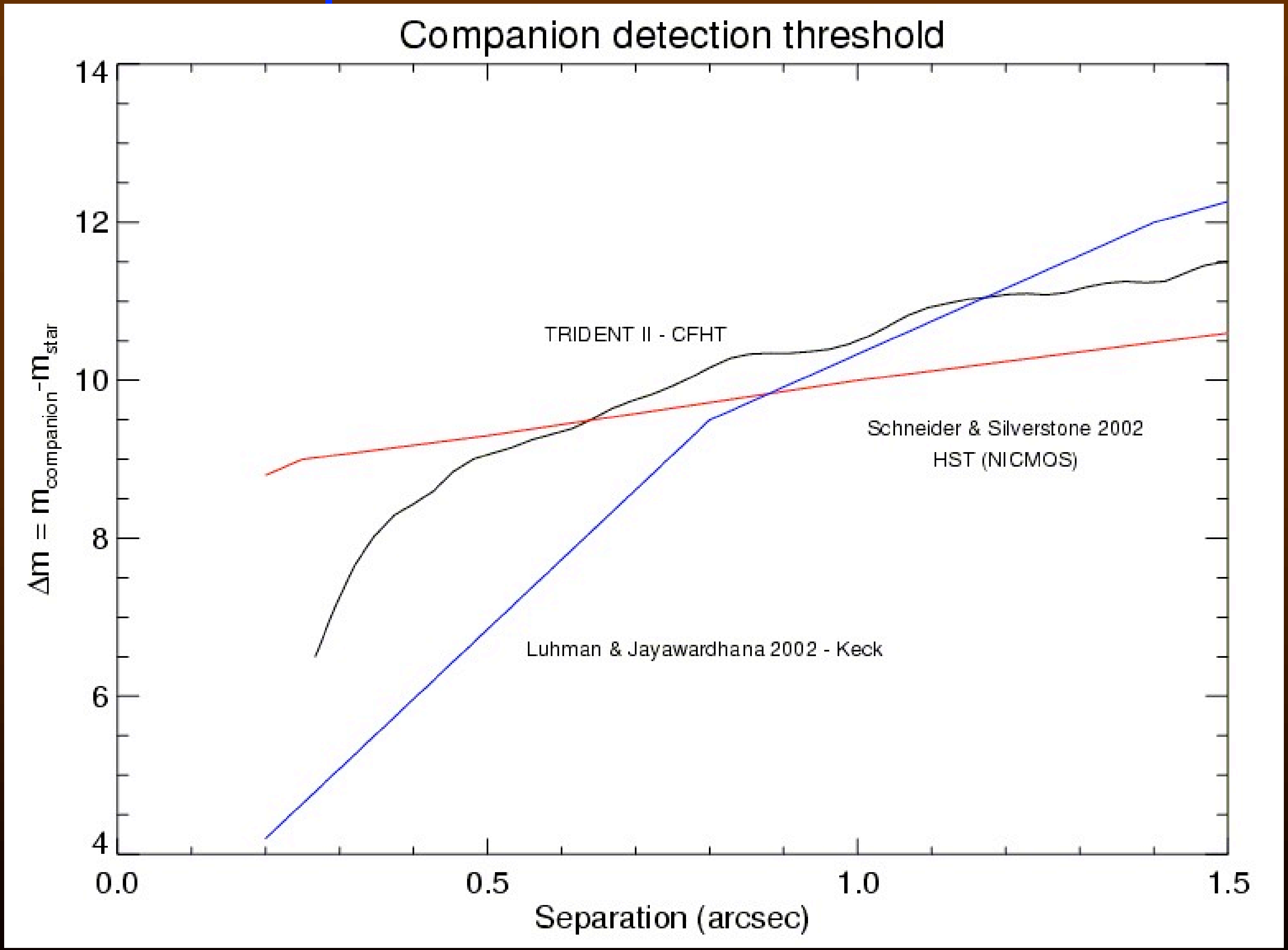
Typical TRIDENT-II data (saturated core)



TRIDENT-II performance



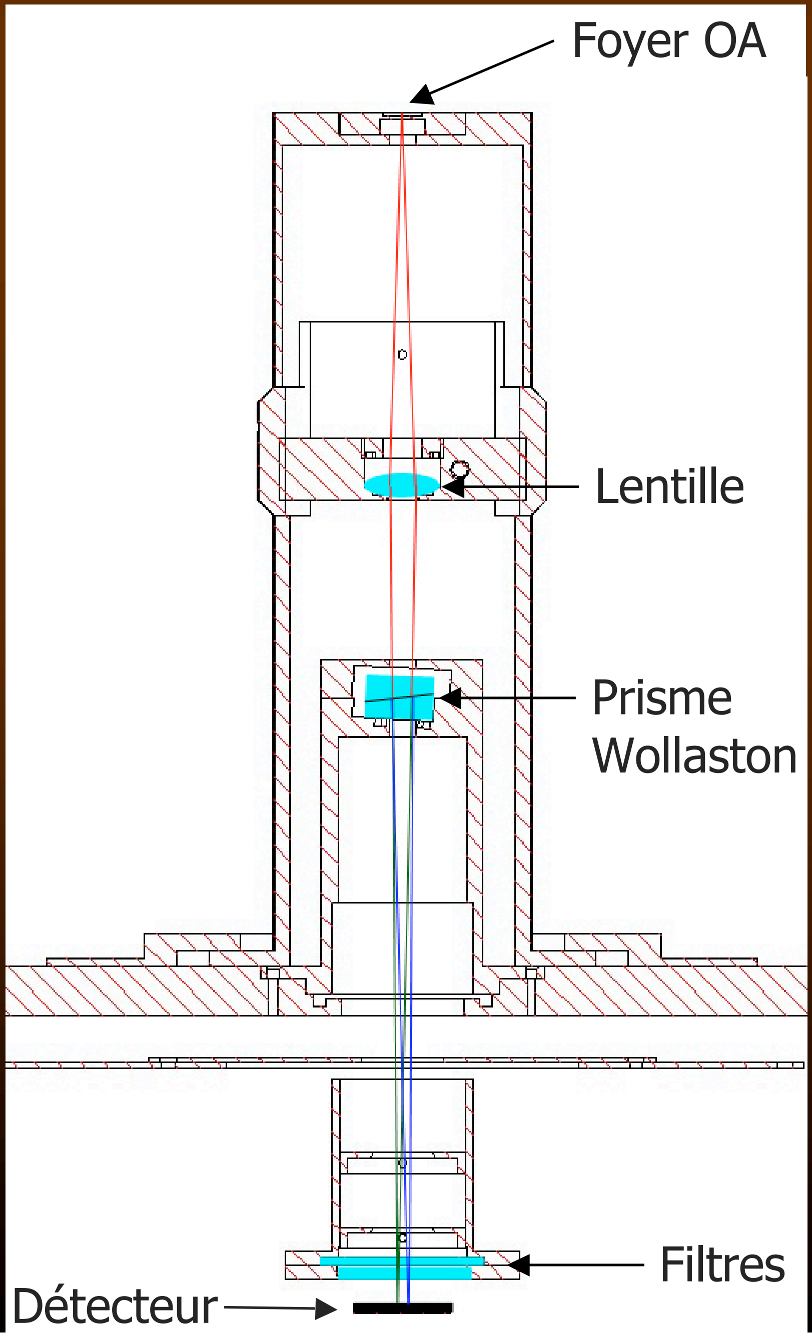
TRIDENT performance vs Keck and HST



Lessons learned with TRIDENT on CFHT

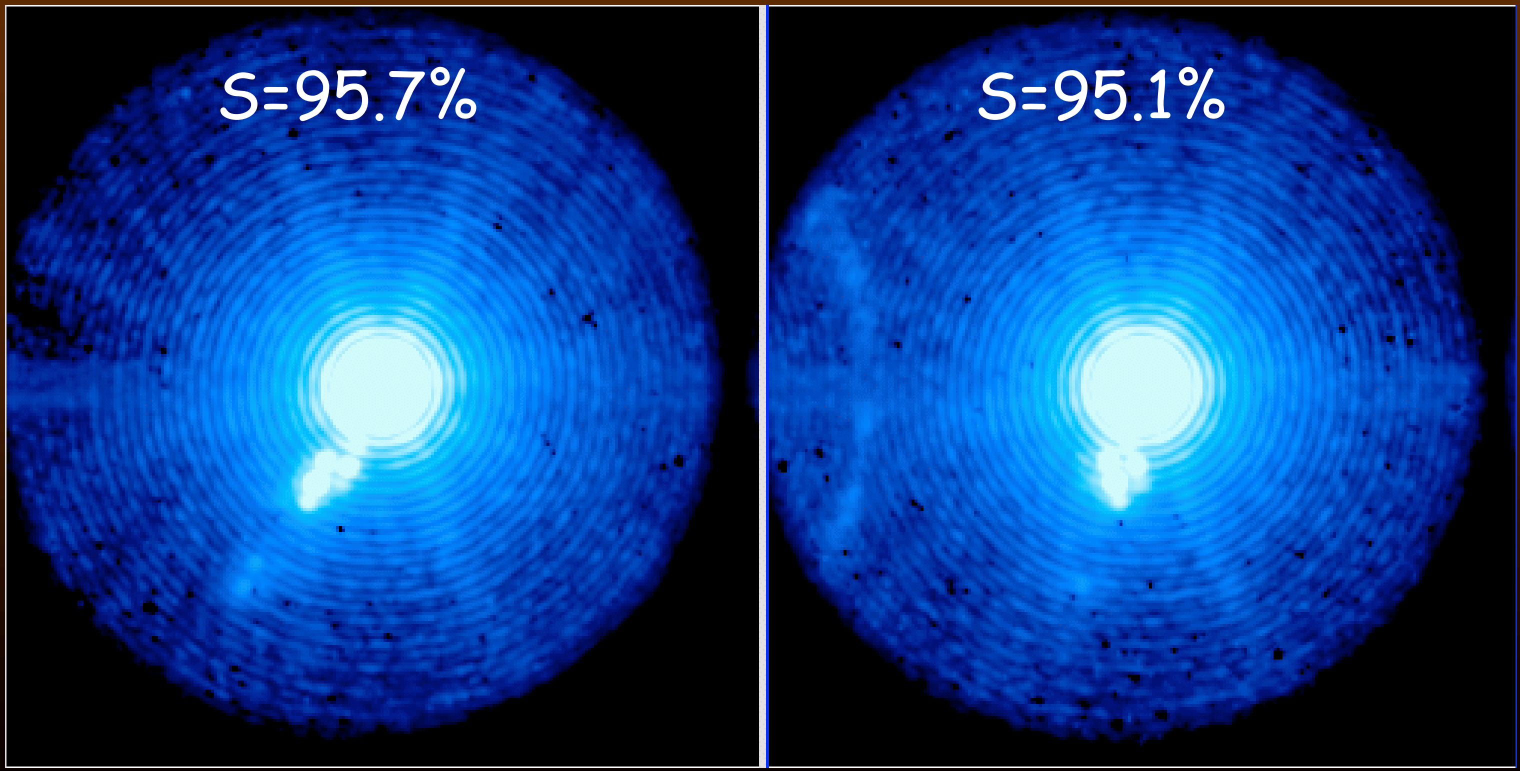
- Differential imaging works … but not quite as good as originally predicted.
- Quasi-static aberrations are long-lived and by far dominate the variance of the PSF
  - Requires more than two λs for efficient suppression and/or reference star calibration
- Atmospheric speckles play an important role only close to the core
  - Dual-imaging enough for atmospheric speckle suppression
- Performance strongly limited by non common-path aberrations. Differential aberrations must be kept below λ/100 (@ 630 nm)
- Static aberrations must be included in simulations.
- Results so far: ~70 nearby stars (G, K, M) surveyed and no detection.

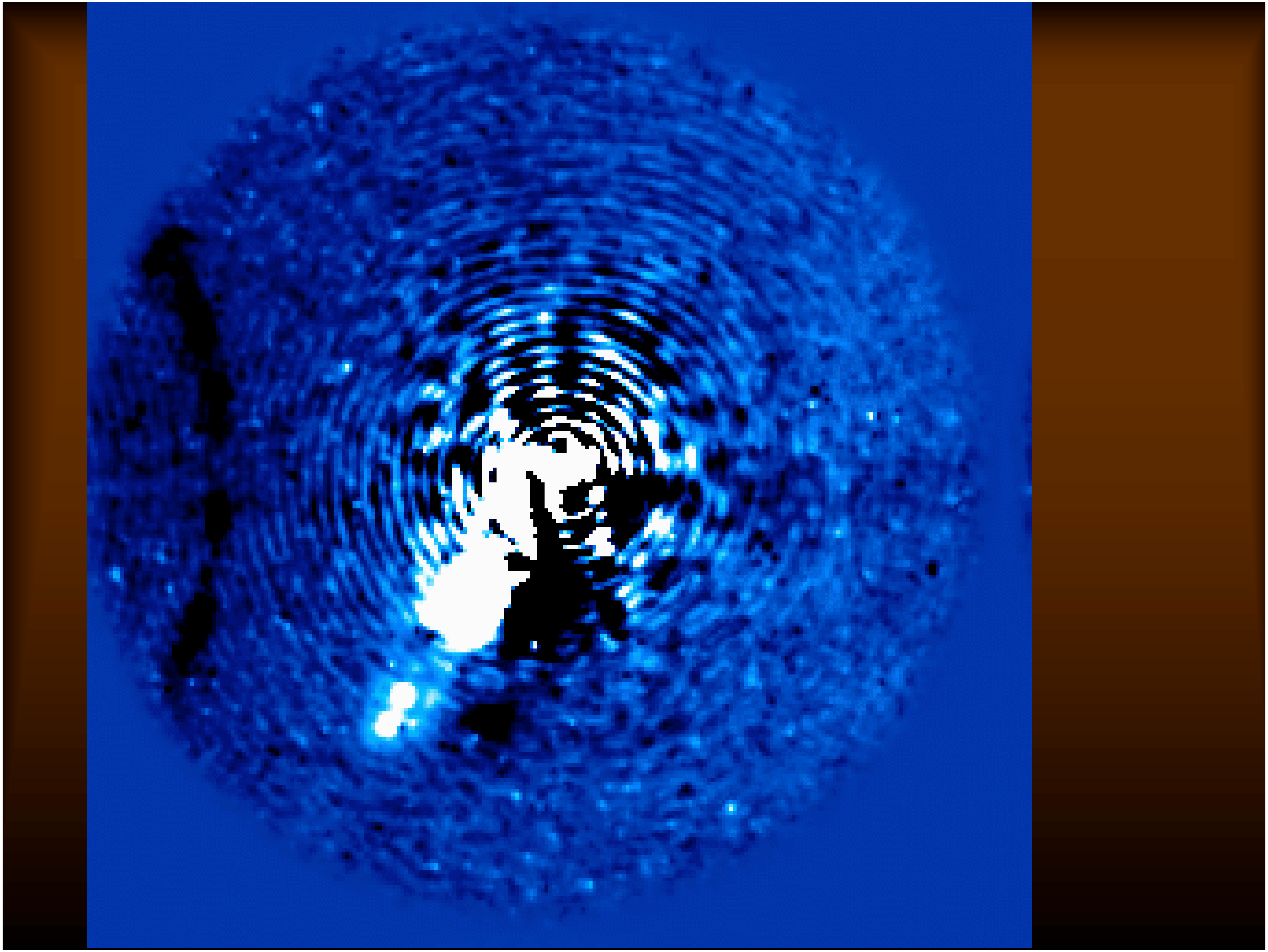
Laboratory tests

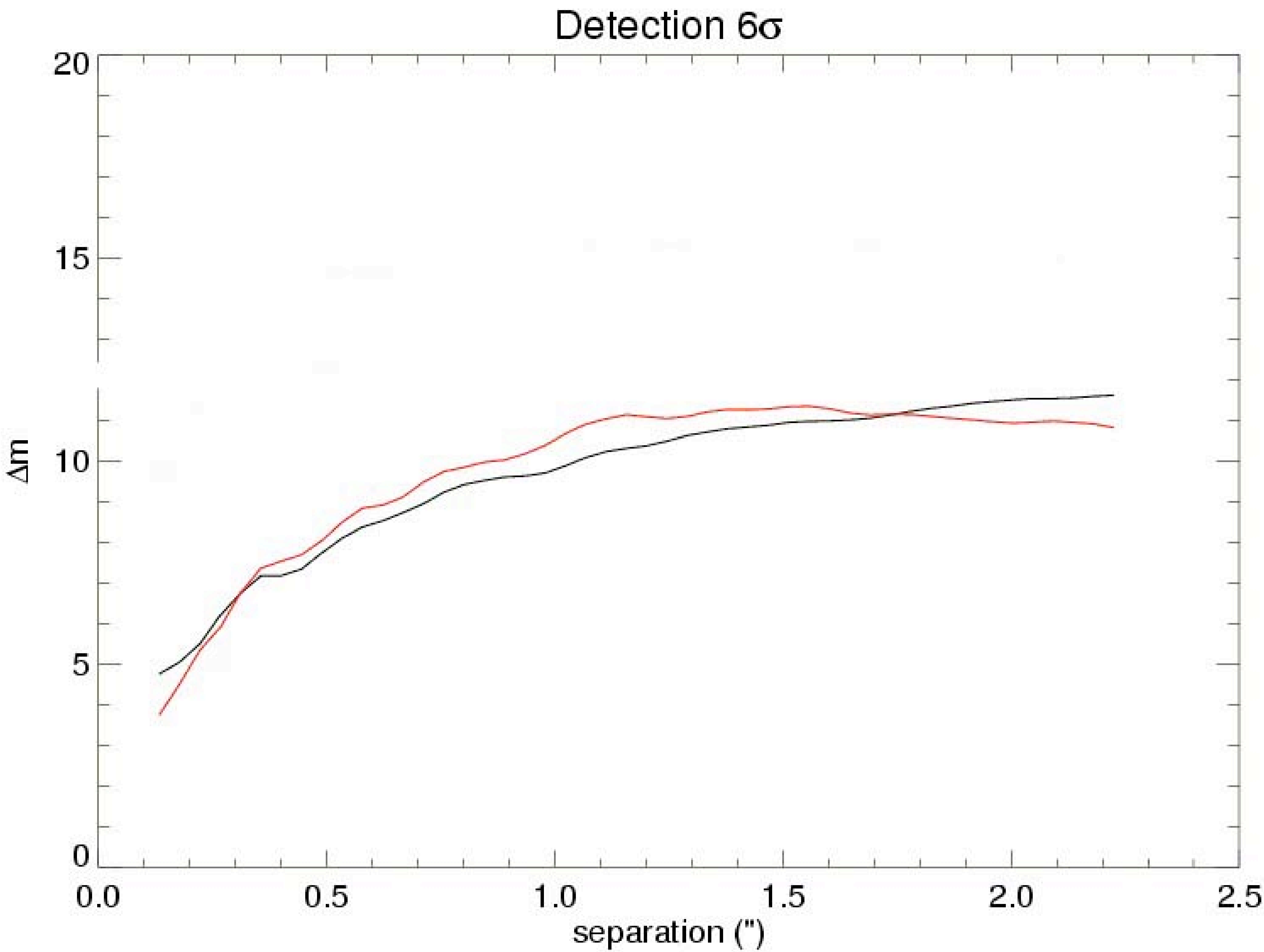


Laboratory tests

Simultaneous iso-chromatic PSFs taken with a Wollaston prism





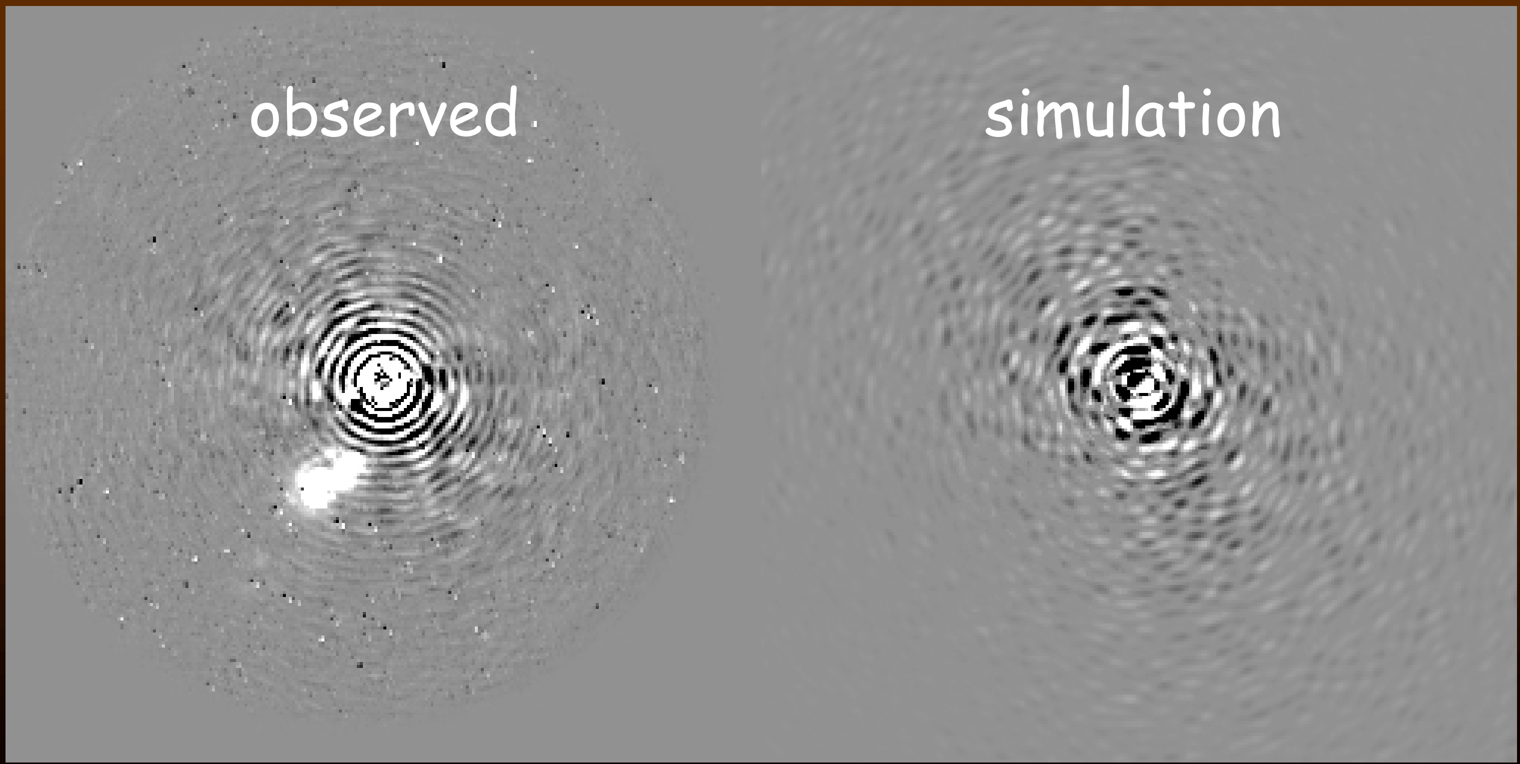


Detection 6σ
Δm
separation (")
20
15
10
5
0
0.0
0.5
1.0
1.5
2.0
2.5

Laboratory tests

Effect of displacing one PSF by 0.5 pixel

(pupil "shearing" of ~1/1000)



Ongoing developpments

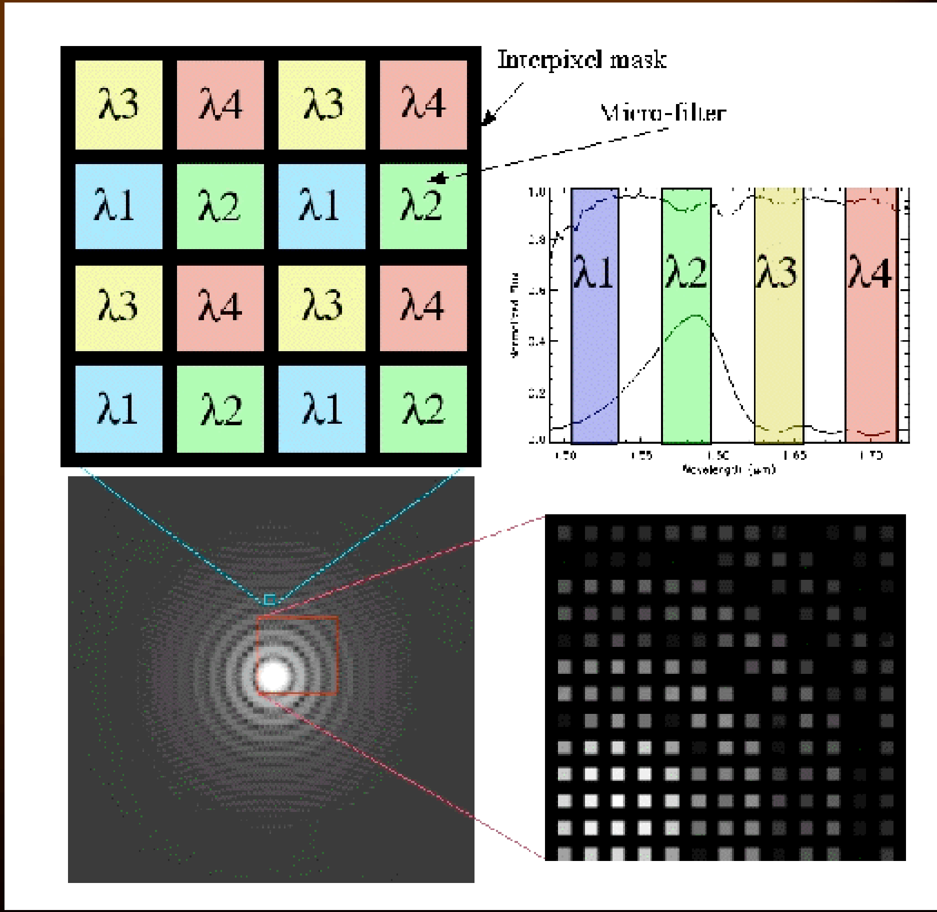
- Dual-beam polarimetry (disks)
  - With rotary _ wave plate (2003B proposals in)
- Study DI in conjonction with a coronagraph
  - Requires a high-S AO system with an ADC
- Study "self-calibrating" differential imaging technique
  - Tunable filters (single or dual channels)
  - IFU (micro-pupil type, e.g. OSIRIS, NIFS)
  - Multi-Color Detector Arrays

Differential Imaging with a Multi-Color Detector Array (MCDA)

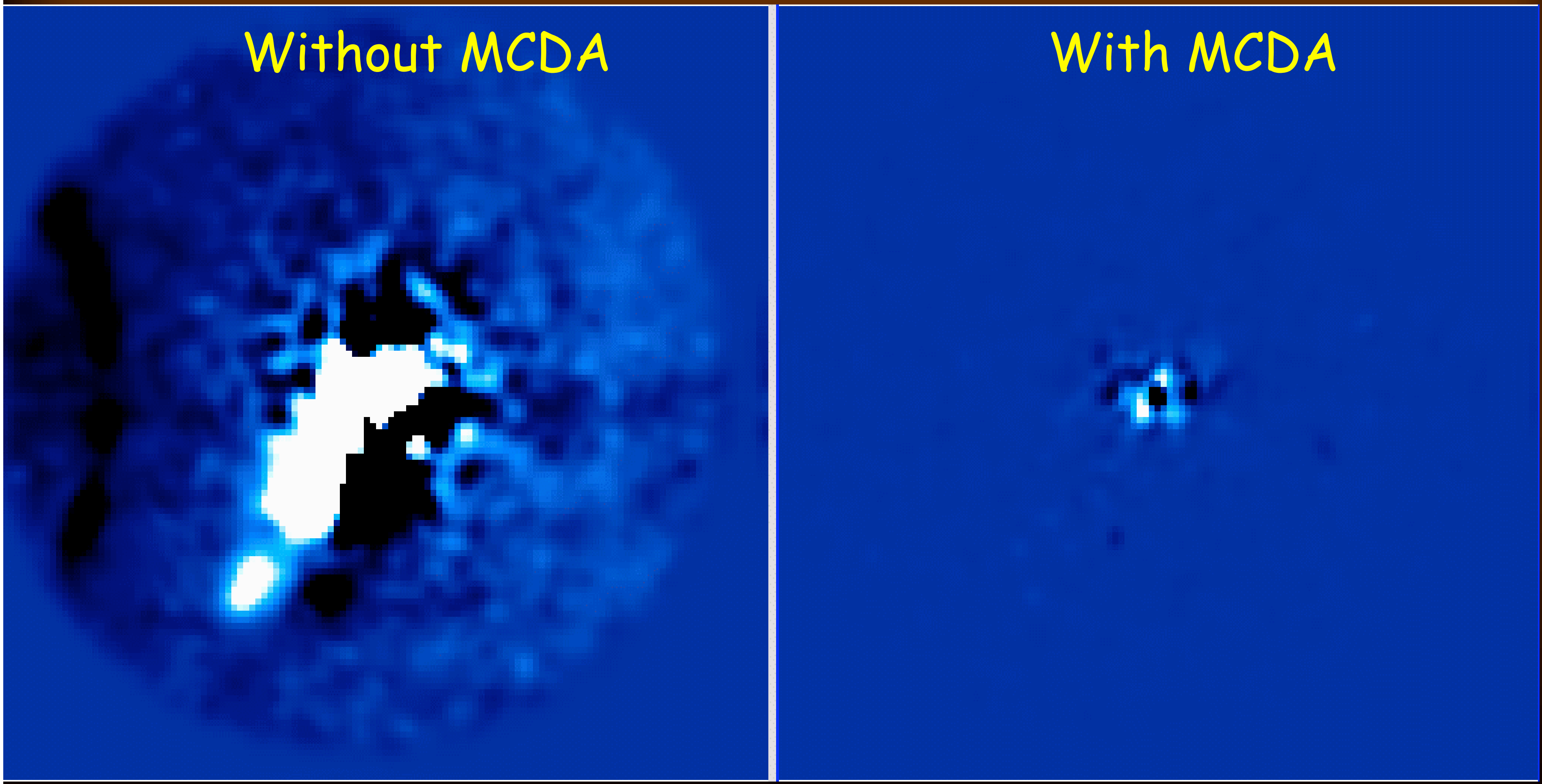
$\lambda/4D$ PSFs, $\lambda_i/2D$, i=1,2,3,4

Advantages

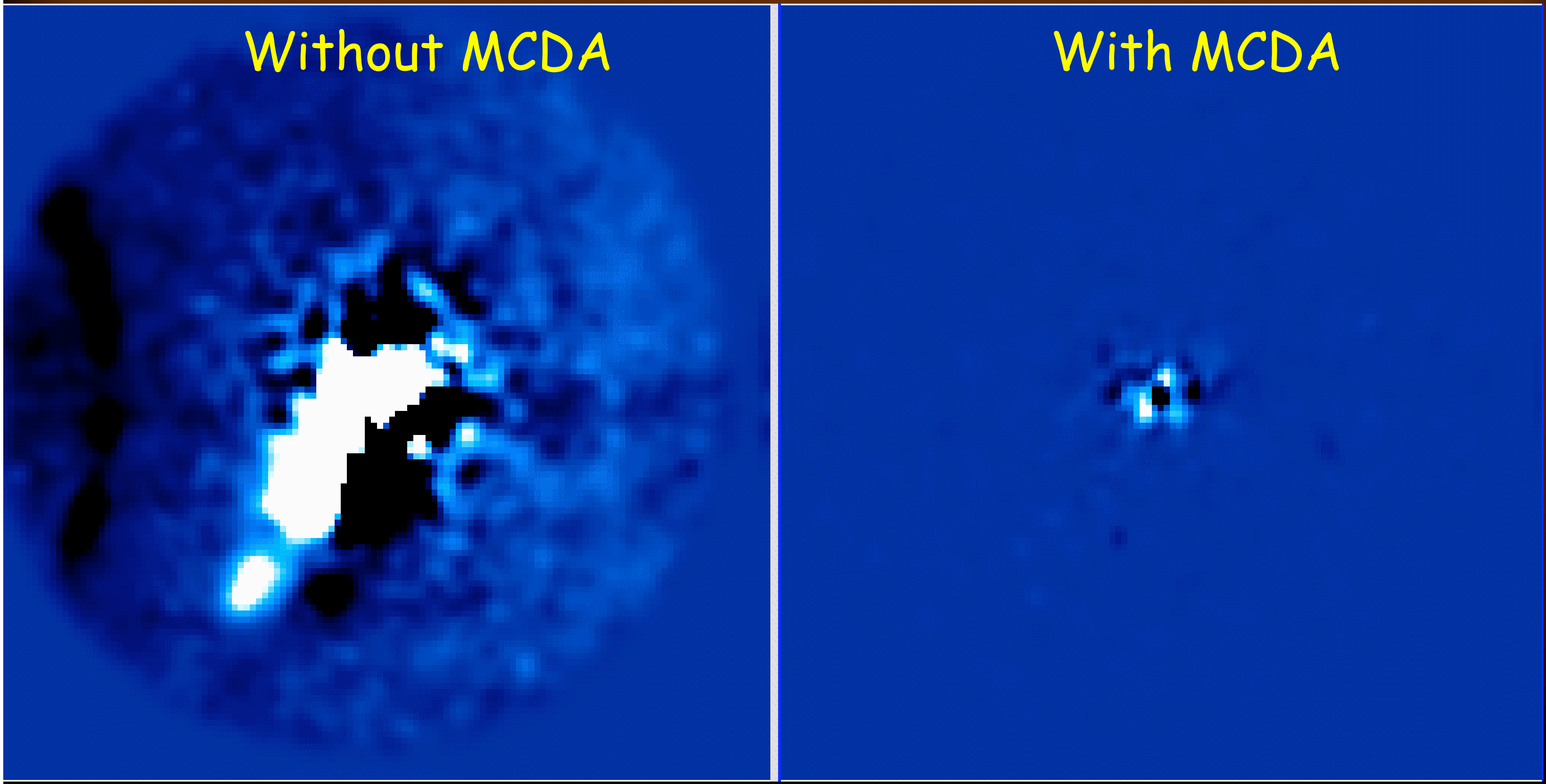
- Perfect PSP correlation
- Large FOV: 20"x20" with 1Kx1K at 1.6 μm (CFHT)
- Simple implementation (standard reimaging optics)
- Micro-filters could be replaced by micro-polarizers
- Can also be used as "broad band" imager by summing all λ

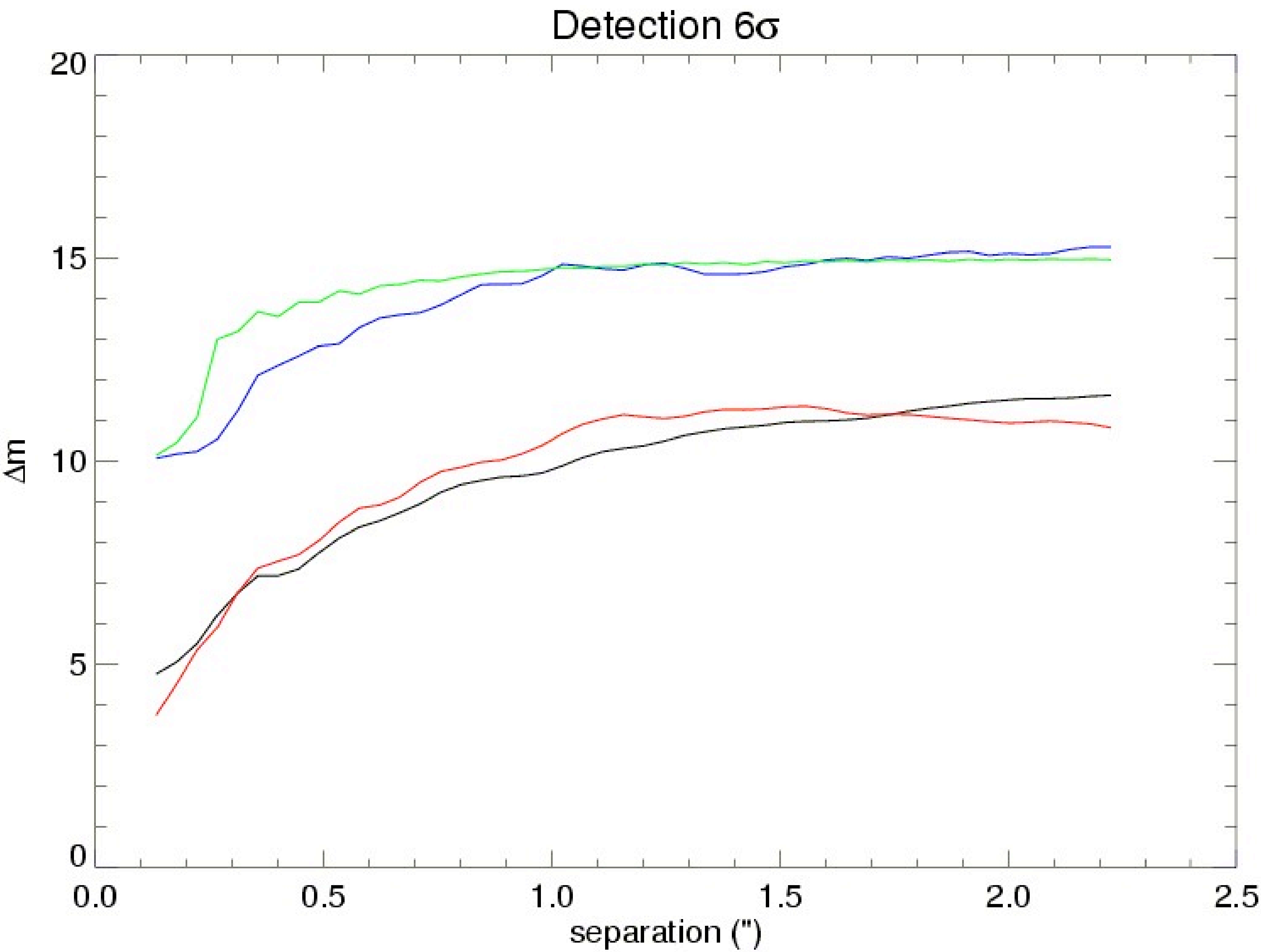


Empirical validation of MCDA



Empirical validation of MCDA




Detection 6σ
20
15
10
5
0
Δm
0.0
0.5
1.0
1.5
2.0
2.5
separation (")

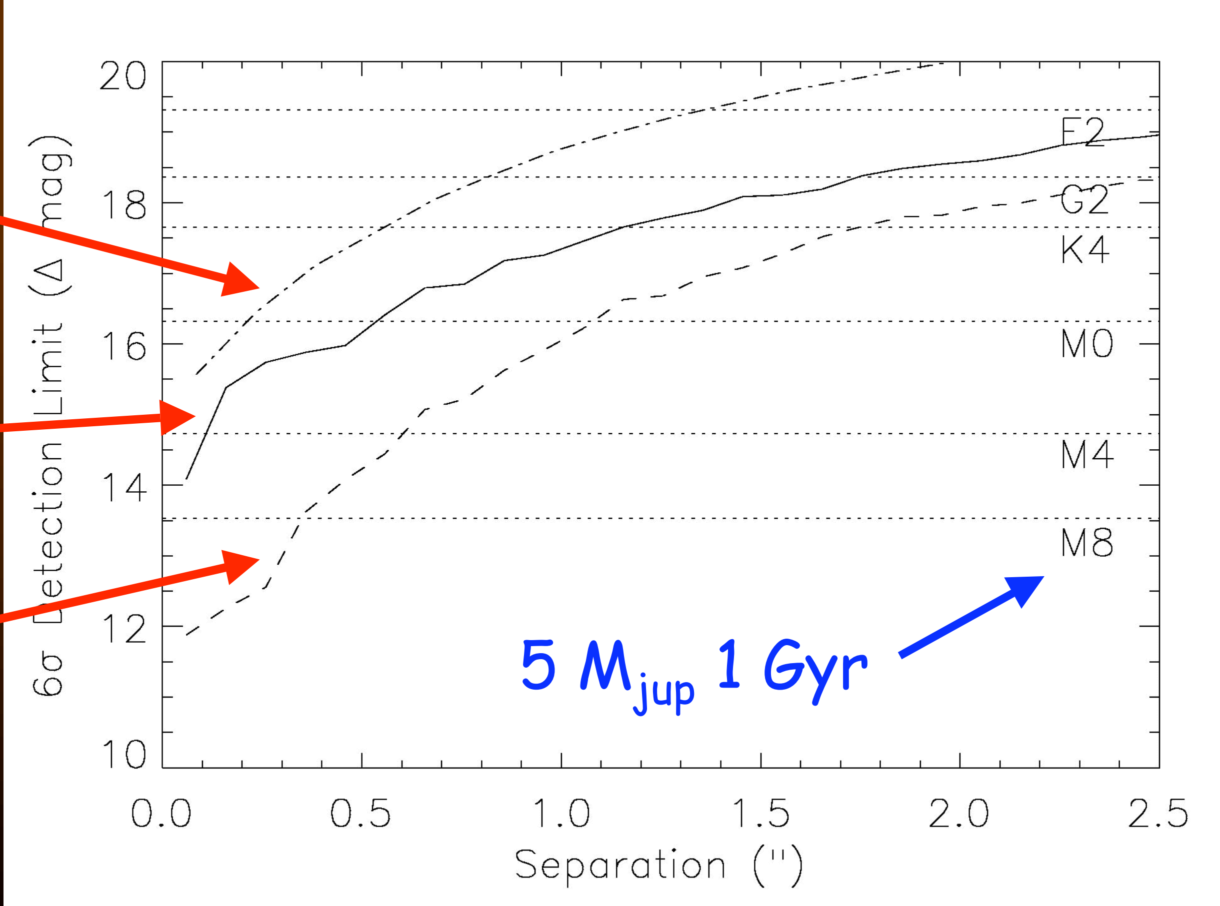
Performance of PUEO-NUI + MCDA

ΔH 6σ 10^5 sec, shot noise limited, no coronagraph

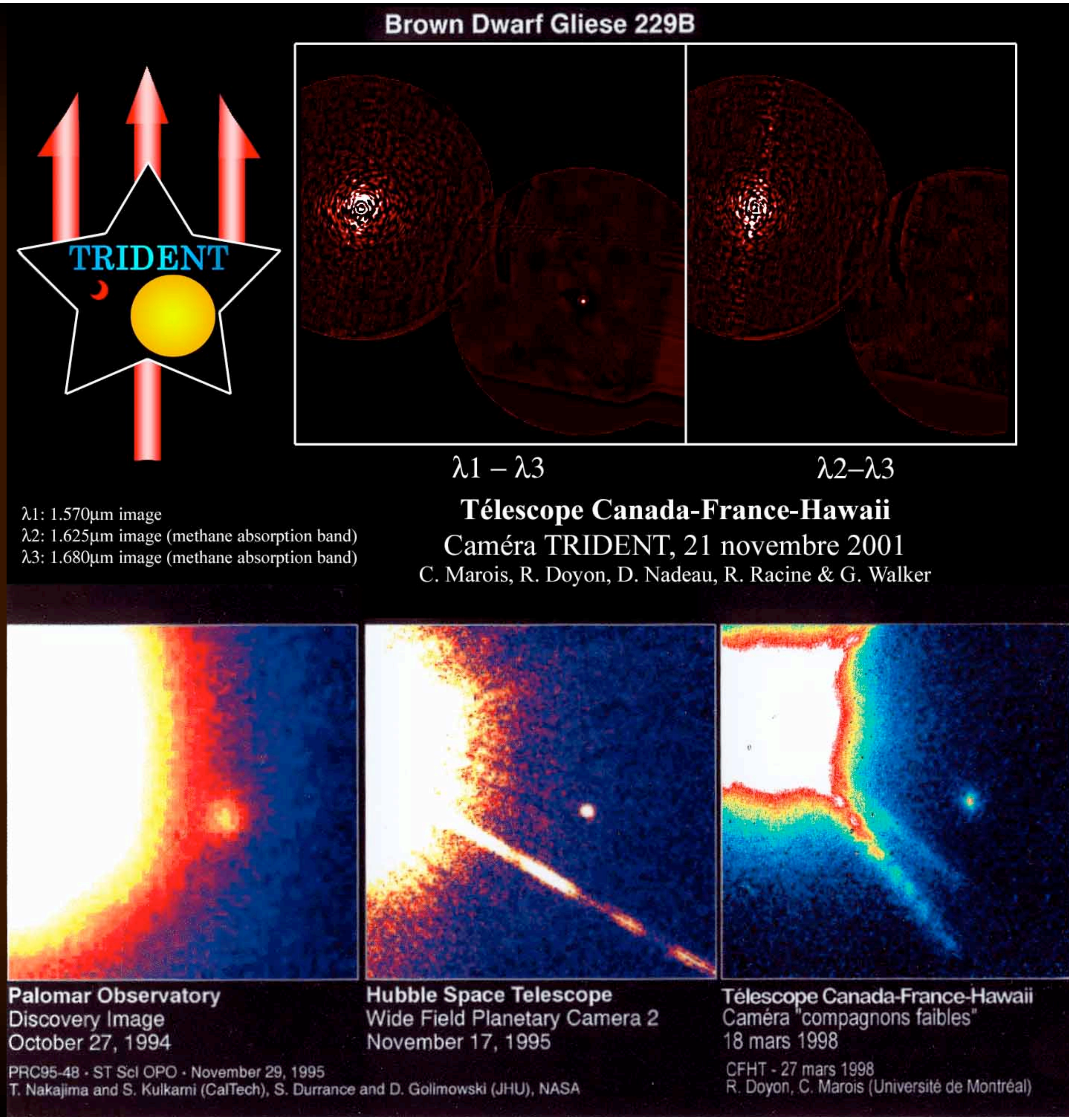
8m N_{eff}=75

CFHT N_{eff}=50

CFHT N_{eff}=9



5 M_{jup} 1 Gyr


Brown Dwarf Gliese 229B
TRIDENT
λ1 – λ3
λ2–λ3
λ1: 1.570µm image
λ2: 1.625µm image (methane absorption band)
λ3: 1.680µm image (methane absorption band)
Télescope Canada-France-Hawaii
Caméra TRIDENT, 21 novembre 2001
C. Marois, R. Doyon, D. Nadeau, R. Racine & G. Walker
Palomar Observatory
Discovery Image
October 27, 1994
Hubble Space Telescope
Wide Field Planetary Camera 2
November 17, 1995
Télescope Canada-France-Hawaii
Caméra "compagnons faibles"
18 mars 1998
PRC95-48 · ST ScI OPO · November 29, 1995
T. Nakajima and S. Kulkarni (CalTech), S. Durrance and D. Golimowski (JHU), NASA
CFHT - 27 mars 1998
R. Doyon, C. Marois (Université de Montréal)