

# Exoplanet characterization using ground-based and space-based direct imaging: Application to the SPICES mission and the VLT/NaCo instrument

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Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique



Partenariat Haute résolution Angulaire Sol-Espace

# Outline

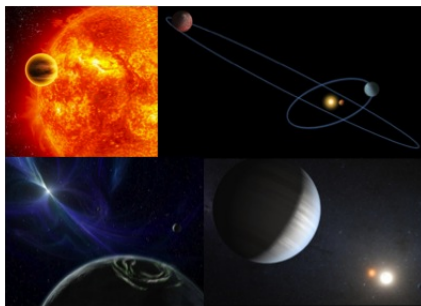
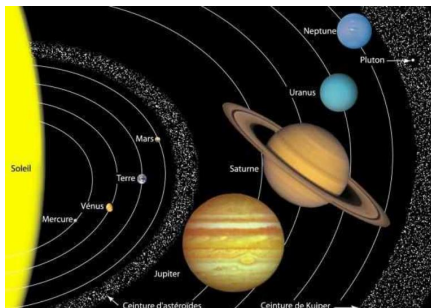
- 1 Context
  - Exoplanets
  - Physical and atmospheric characterization
  - Direct imaging
- 2 Numerical simulations of the performance of the SPICES mission
  - Context and objectives of the study
  - Simulation of the instrument concept
  - Performance in detection
  - Performance in characterization
- 3 Analysis of VLT/NaCo imaging data
  - The VLT/NaCo instrument and the observing program
  - Data reduction
  - ADI sensitivity limits
  - SDI+ADI sensitivity limits
- 4 Conclusions & Prospects
  - Conclusions
  - Prospects

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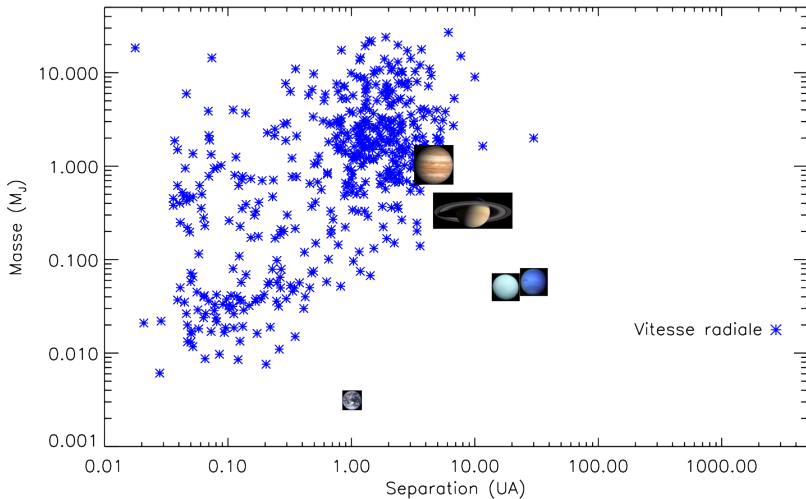
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# Why to study exoplanets ?

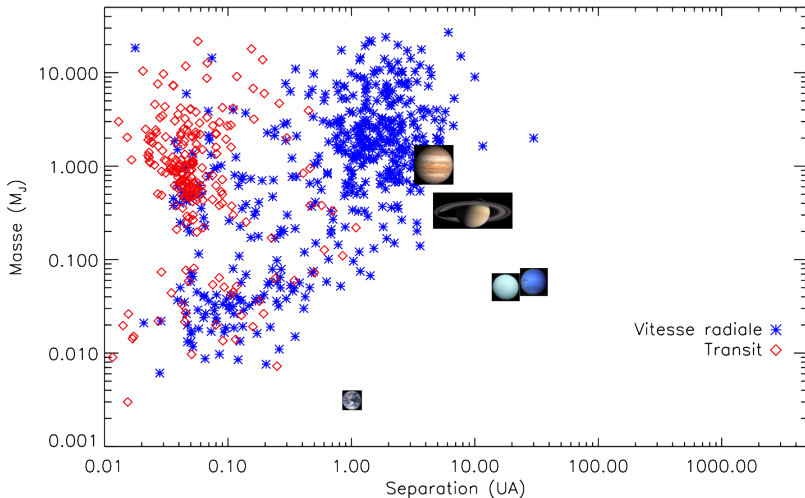
- **Planetary formation and evolution**
  - Before exoplanets → Solar System
  - Since 1995 : hot Jupiters, eccentric planets, pulsar planets, planets in binary systems, super-Earths, etc
- Conditions of emergence and development of **life**
  - habitable zone, biosignatures (Kasting et al. 1993, Des Marais et al. 2002)



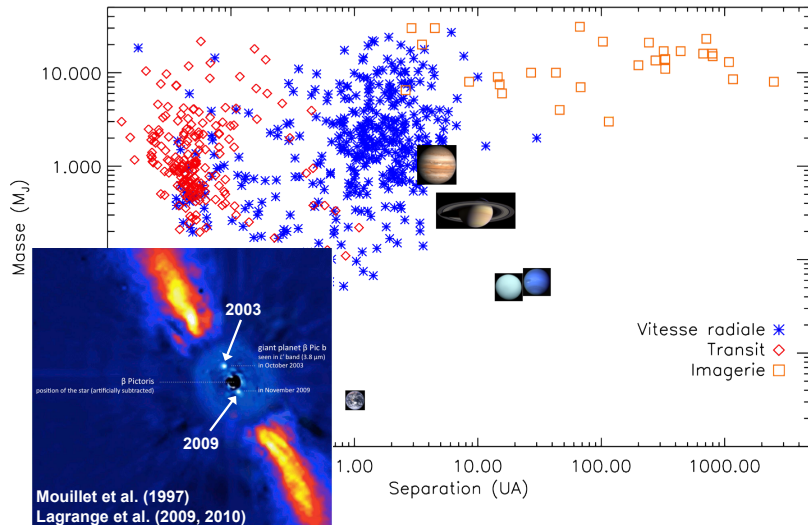
# How to detect exoplanets ?



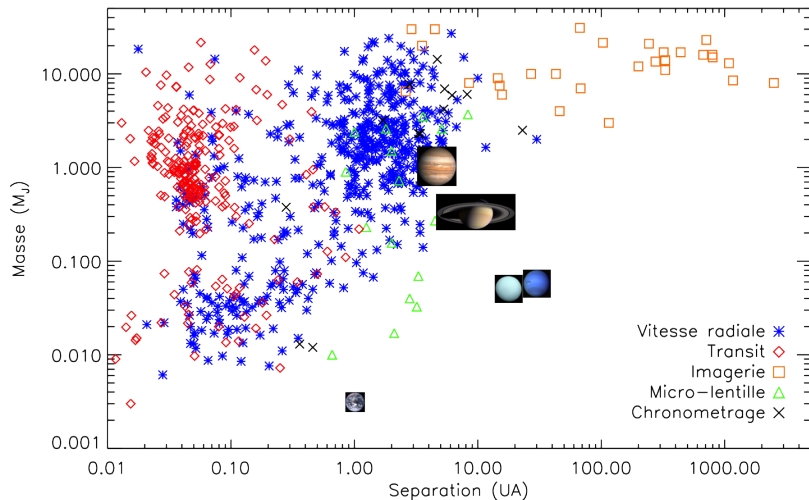
# How to detect exoplanets ?



# How to detect exoplanets ?

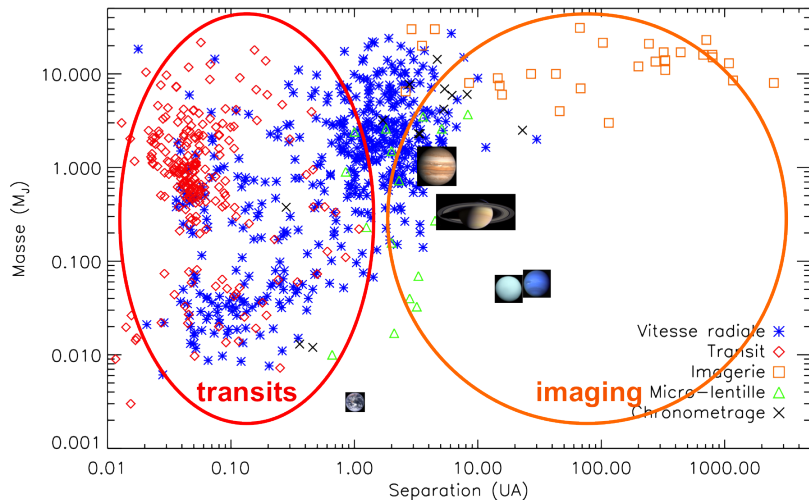


# How to detect exoplanets ?





# How to detect exoplanets ?

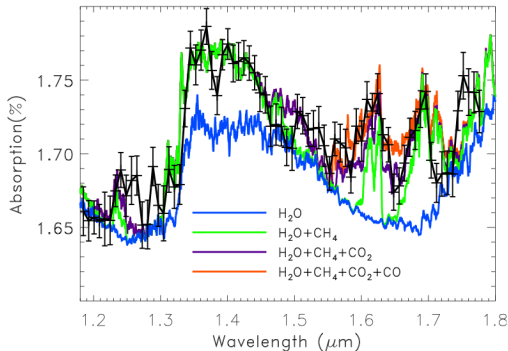
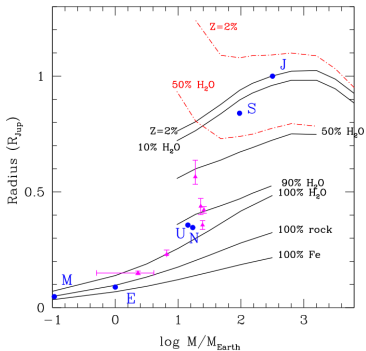


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# Physical and atmospheric characterization

- **Physical** characterization
  - Mass, orbital period, eccentricity, inclination, radius, density
- **Atmospheric** characterization
  - Spectrophotometry → temperature, molecules, vertical structure (clouds, hazes), escapement

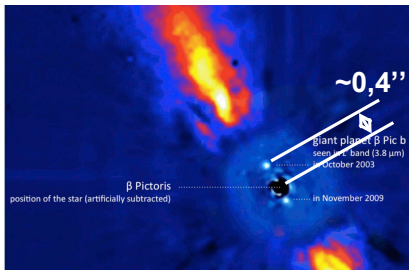


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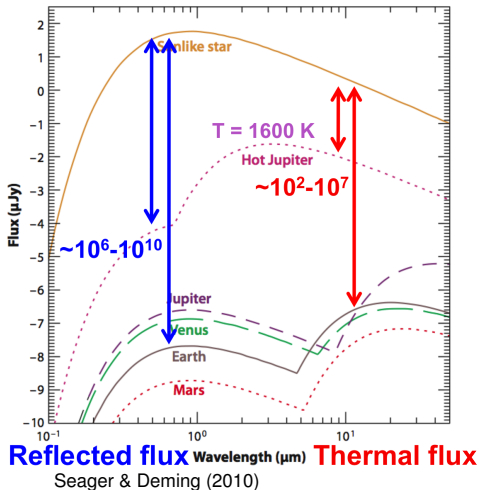
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# Direct imaging

- High contrast @ small angular separation



Theoretical resolution of a telescope:  $\lambda/D$   
 $D=8 \text{ m} \ \& \ \lambda=3.8 \ \mu\text{m} \ \longrightarrow \ \sim 0.1''$

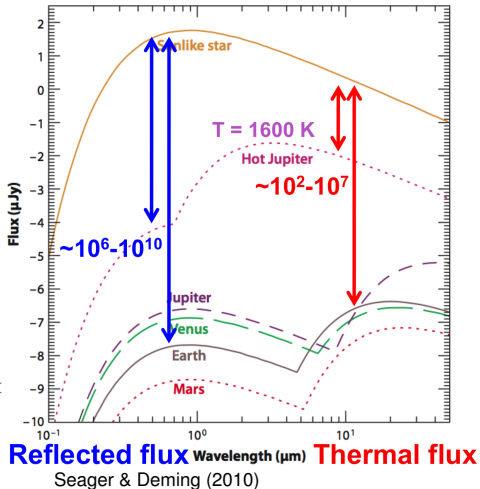
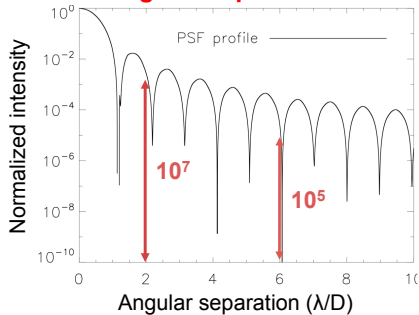


Mouillet et al. (1997), Lagrange et al. (2009, 2010)

# Direct imaging

- High contrast @ small angular separation

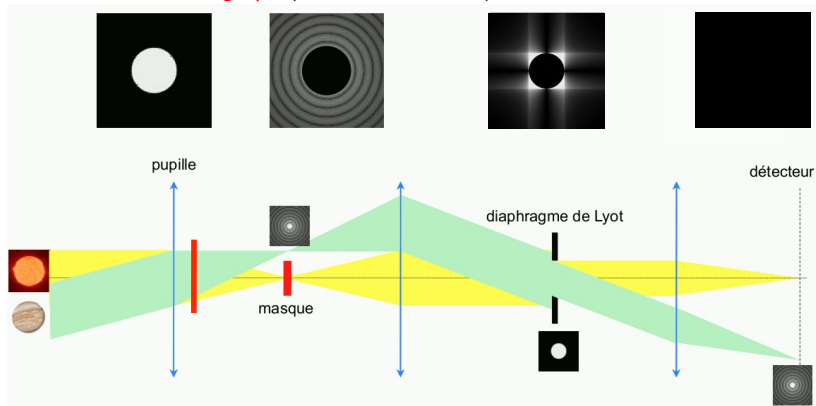
**Diffraction**  $\rightarrow I_{\text{star}}/I_{\text{planet}}$  depends on their angular separation



# Photon noise

## • Coronagraphy

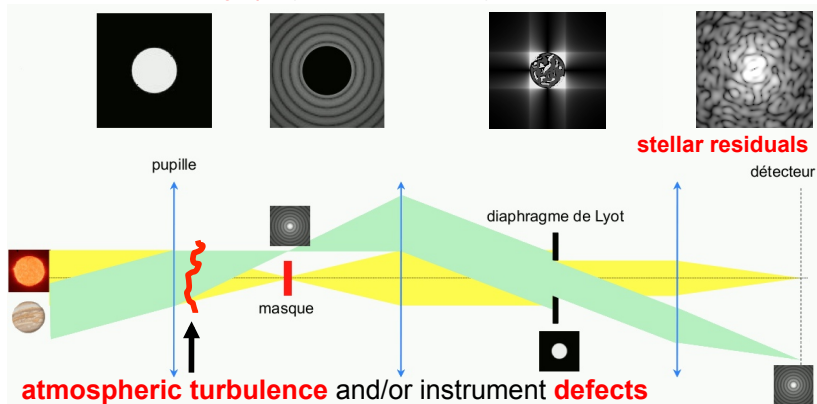
- amplitude coronagraphs, **phase coronagraphs**, apodizers, occultors
- **four-quadrant phase mask** (Rouan et al. 2000)
- **vortex coronagraph** (Mawet et al. 2005)



# Photon noise

## • Coronagraphy

- amplitude coronagraphs, **phase coronagraphs**, apodizers, occultors
- **four-quadrant phase mask** (Rouan et al. 2000)
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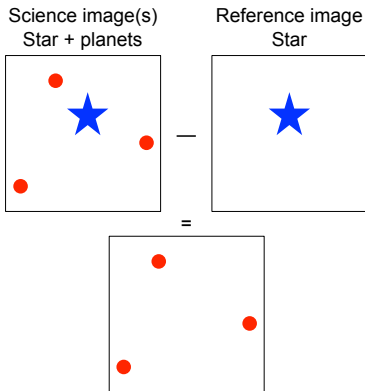




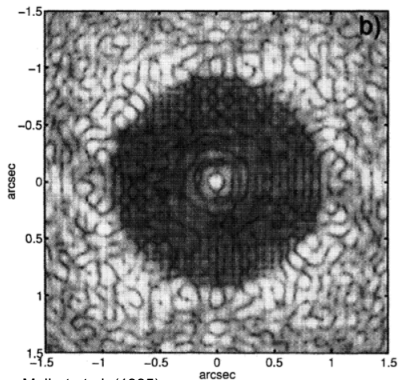
# Speckle noise

- Downstream → **Differential imaging** (Racine et al. 1999, Kuhn et al. 2001, Sparks & Ford 2002, Marois et al. 2006, Baudoz et al. 2006)
- Upstream → **Wavefront control** (Babcock 1953, Malbet et al. 1995)

## differential imaging



## wavefront control



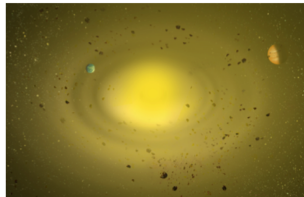
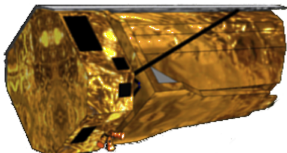
Malbet et al. (1995)

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# Context and objectives of the study

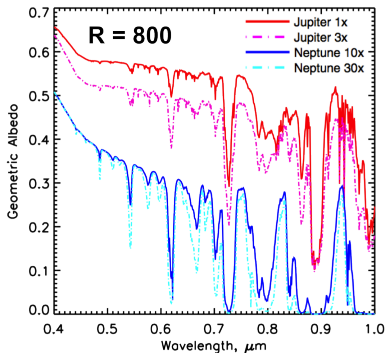
- SPICES (Spectro-Polarimetric Imaging and Characterization of Exoplanetary Systems)
  - 1.5-m visible **coronagraph** - P.I. : A. Boccaletti
  - Proposal for **ESA** Cosmic Vision M3 in 2010
  - **International** consortium of 70 members
  - Spectro-polarimetric analysis of **cold exoplanets** and **circumstellar disks**  
 $\gtrsim 1$  zodi  $\rightarrow$  contrasts  $10^{-9}$ - $10^{-10}$  @  $\sim 0.2''$
- Objectives of the study
  - Top-level requirements
  - **Spectrometric performance**



# Study of performance

- 2 ways for addressing the problem

## Theoretical spectra

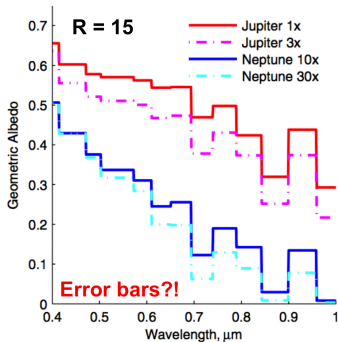


Models from Cahoy et al. (2010)

# Study of performance

- 2 ways for addressing the problem

## Theoretical spectra

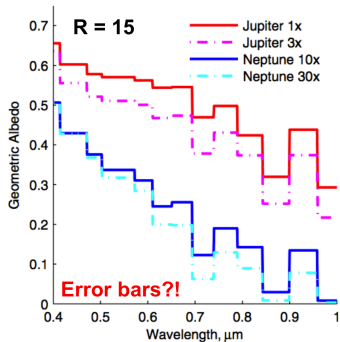


Cahoy et al. (2010)

# Study of performance

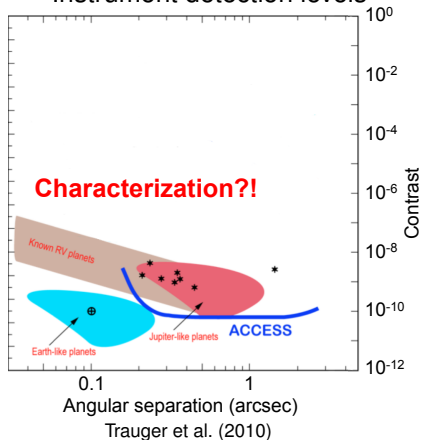
- 2 ways for addressing the problem

## Theoretical spectra



Cahoy et al. (2010)

## Instrument detection levels

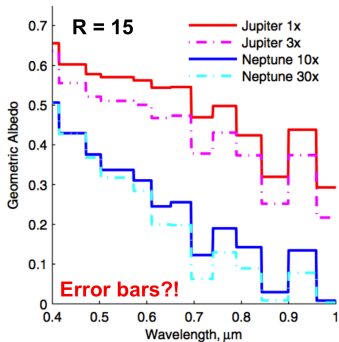


Trauger et al. (2010)

# Study of performance

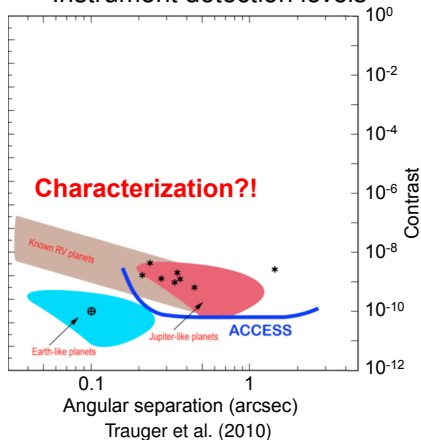
- 2 ways for addressing the problem

## Theoretical spectra



Cahoy et al. (2010)

## Instrument detection levels



Need to **go beyond** these RV two approaches !

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# The beginnings of SPICES...

Telescope  
diameter?

Spectral band?

Optical  
quality?

Speckle  
calibration?

On-axis or off-  
axis telescope?

Integral field  
spectrometer?

Coronagraph?

Deformable  
mirror?

Spectral  
resolution?

# The beginnings of SPICES...

Telescope  
diameter?

**1.5 m**

Spectral band?

Optical  
quality?

Speckle  
calibration?

On-axis or off-  
axis telescope?

Integral field  
spectrometer?

**Yes**

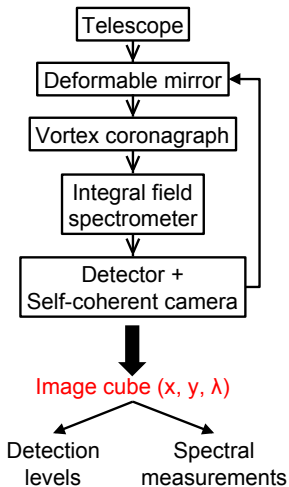
Coronagraph?

**Vortex**

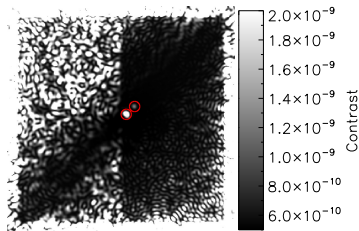
Deformable  
mirror?

Spectral  
resolution?

# Numerical model of the instrument



- ✓ Aberrations
- ✓ Chromaticity
- ✓ Planet(s)
- ✓ Zodiacal light
- ✓ Exo-zodiacal cloud (Zodipic library)
- ✓ Perfect estimation of aberrations
- ✓ Projection onto deformable mirror
- ✓ Photon noise
- ✓ Read-out noise
- ✓ Response of the detector pixels



Maire, Galicher, et al. 2012

# Top-level requirements (contrasts $10^{-9}$ – $10^{-10}$ @ $\sim 0.2''$ )

Telescope diameter?

**1.5 m**

Spectral band?

**0.45 – 0.9  $\mu\text{m}$**

Optical quality?

**Aberrations 15 nm rms**

Speckle calibration?

**Yes  $\rightarrow$  Self-coherent camera**

On-axis or off-axis telescope?

**Off-axis telescope**

Integral field spectrometer?

**Yes**

Coronagraph?

**Vortex**

Deformable mirror?

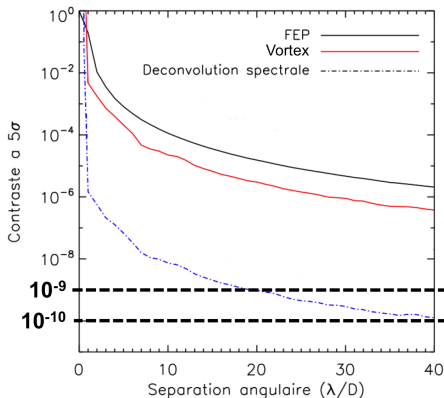
**Oui  $\rightarrow$  64 $\times$ 64**

Spectral resolution?

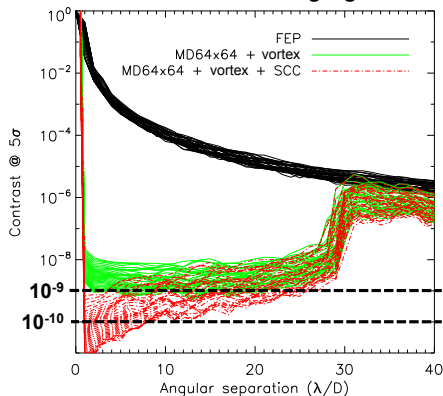
**50**

# Wavefront control ?

## Spectral deconvolution



## Wavefront control + differential imaging

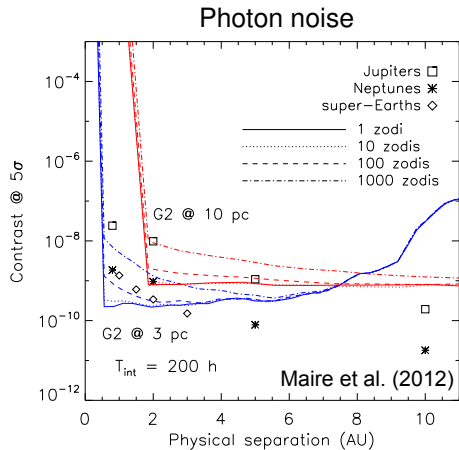
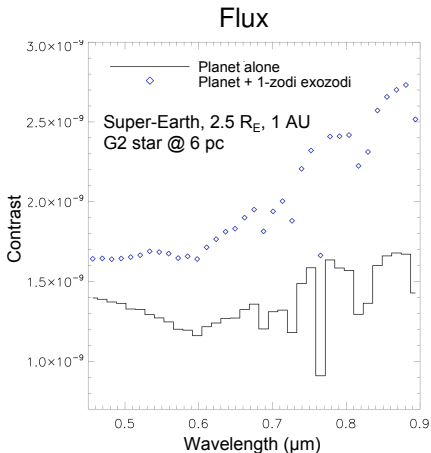


- Only combination **vortex + deformable mirror + differential imaging** satisfies **SPICES'** requirements

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# Sensitivity to the intensity of the exo-zodiacal cloud



- Calibration exo-zodiacal cloud flux even for 1 zodi  $\rightarrow$  hypothesis **perfect calibration** (to the precision imposed by photon noise)
- SPICES' targets  $\rightarrow$  **a few 10-zodi** clouds

# Thermal flux vs. reflected flux

- **Thermal** flux  $\rightarrow$  model  $\sim$  independent of star-planet separation
- **Reflected** flux  $\rightarrow$  **structure** depends on star-planet separation
- **Planet models** for **discrete** separations and a **solar-type star**  $\rightarrow$  flux conservation for other stellar types



5 AU



1.5 AU



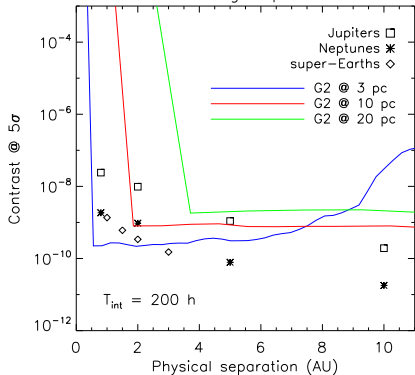
- 1-AU Earth models  $\rightarrow$  flux  $\propto$  albedo/separation<sup>2</sup> between 1–3 AU



# Sensitivity to stellar type

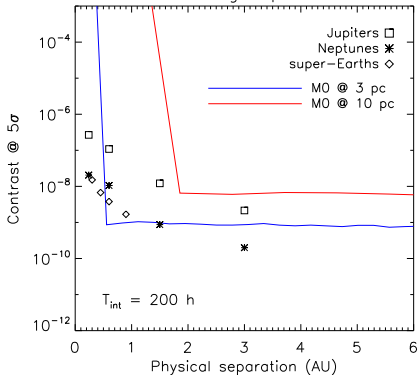
## Type G2

$\lambda$ -averaged profiles



## Type M0

$\lambda$ -averaged profiles



Maire et al. (2012)

- G2 stars  $\lesssim 10 \text{ pc}$   $\rightarrow$  24 G stars
- M0 stars  $\lesssim 7.5 \text{ pc}$   $\rightarrow$   $\sim 100$  M stars

([simbad.u-strasbg.fr](http://simbad.u-strasbg.fr))

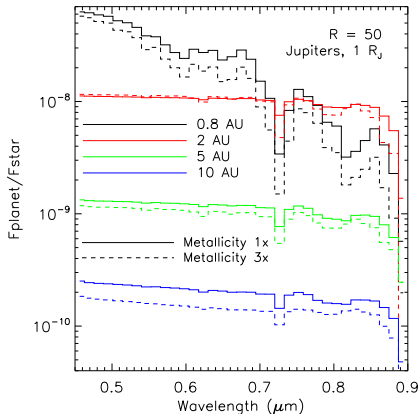
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# Characterization criterion

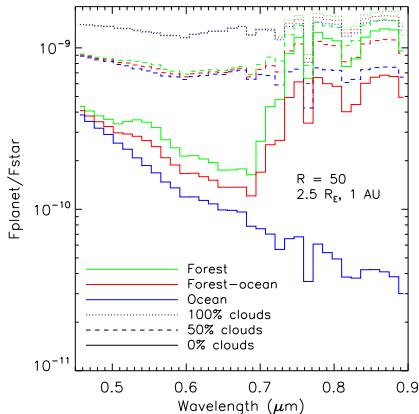
- Signal-to-noise ratio for which differences between 2 planetary spectra detected @ N times the measured noise ?

## Jupiters



Models from Cahoy et al. (2010)

## Super-Earths



Models from Stam (2008)

## Characterization criterion

- Signal-to-noise ratio for which differences between 2 planetary spectra detected @ N times the measured noise ?

**N = 10**

Planet	Parameter	<b>SNR<sub>r</sub></b>
Jupiter	0.8/2 AU	<b>15</b>
Jupiter 0.8 AU	metallicity 1/3×	<b>30</b>
Jupiter 2 AU	metallicity 1/3×	<b>30</b>
Jupiter 5 AU	metallicity 1/3×	<b>30</b>
Neptune	0.8/2 AU	<b>15</b>
Neptune 0.8 AU	metallicity 10/30×	<b>30</b>
Neptune 2 AU	metallicity 10/30×	<b>25</b>
Forest Earth	0/50/100% clouds	<b>25</b>
Ocean Earth	0/50/100% clouds	<b>25</b>
Clear Earth	0/50/100% forests	<b>12</b>
50% cloudy Earth	0/50/100% forests	<b>30</b>
Cloudy Earth	0/50/100% forests	<b>220</b>

## Characterization criterion

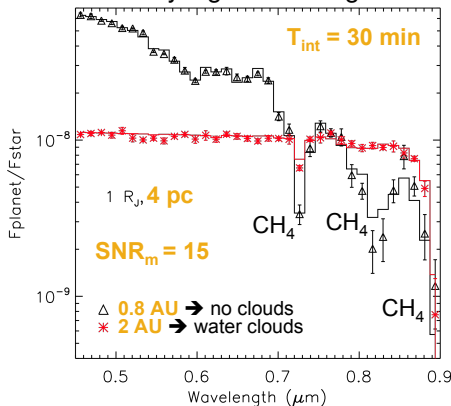
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Forest Earth	0/50/100% clouds	<b>25</b>
50% cloudy Earth	0/50/100% forests	<b>30</b>
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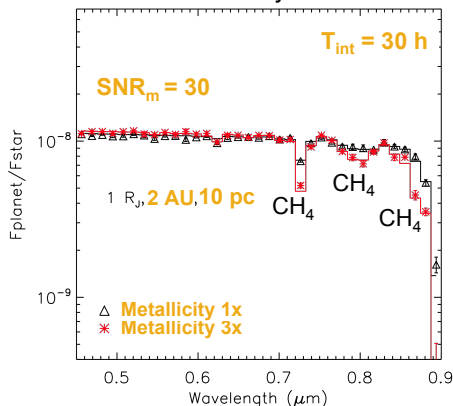
# Gas giant planets

## Rayleigh scattering



Maire et al. (2012)

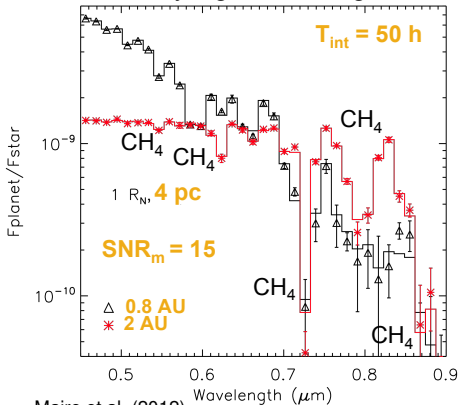
## Metallicity



- Measurements for all G2-star systems **angularly separated**

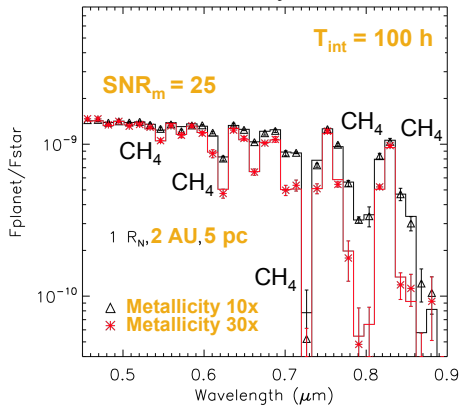
# Ice giant planets

## Rayleigh scattering



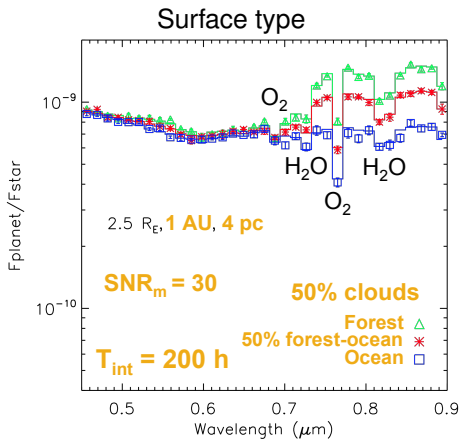
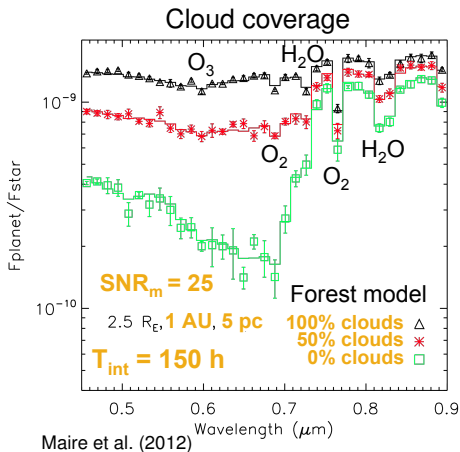
Maire et al. (2012)

## Metallicity



- Rayleigh scattering measured for **all targets angularly separated**
- Metallicity enhancement  $\geq 3$  analyzed for **targets  $\lesssim 6 \text{ pc}$**

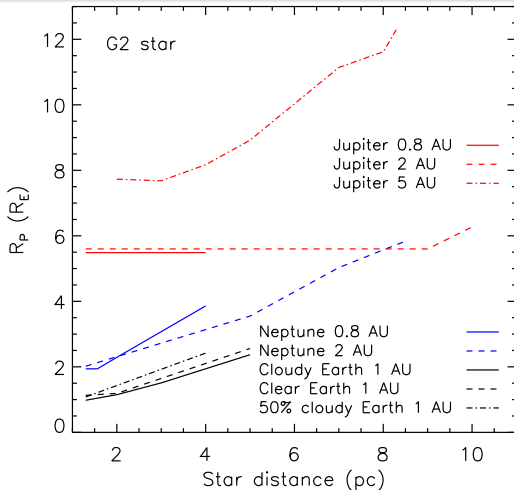
# Super-Earths @ 1 AU



- Clouds of forest planets  $\rightarrow$  all targets angularly separated
- Surface of 50%-cloudy planets  $\rightarrow$  distances  $\leq 4$  pc



# Potential targets



Maire et al. (2012)

- G2 stars  $\leq 10$  pc  $\rightarrow$  24 G stars (simbad.u-strasbg.fr)
- All stellar types  $\rightarrow$   $\sim$ 300 stars

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# The VLT/NaCo instrument

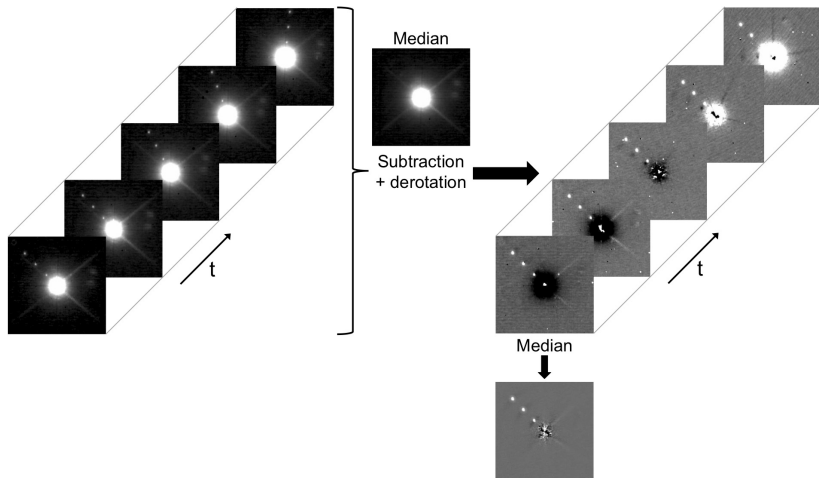
- **NaCo**  $\rightarrow \geq 2001$ 
  - **Adaptive optics** NAOS + **IR camera** CONICA
  - Imaging, spectroscopy, etc + spectral filters
  - **Exoplanets** :
    - ✓ **four-quadrant phase mask** (FQPM)
    - ✓ **angular & spectral differential imaging** (ADI & SDI)
      - $\rightarrow$  modes combined in **SPHERE** (2013)



- 1 - Detect **young giant planets** ( $\lesssim 200$  Myr) around **nearby** stars ( $\lesssim 25$  pc)
- 2 - Prepare **analysis** and **interpretation** of SPHERE **SDI data**

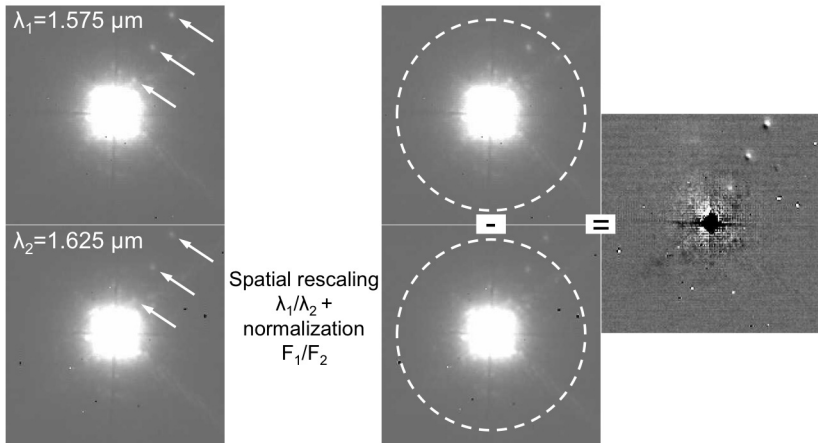
# ADI (Marois et al. 2006)

- Differential imaging = subtract image of the star alone
- Angular = **rotation** of field of view



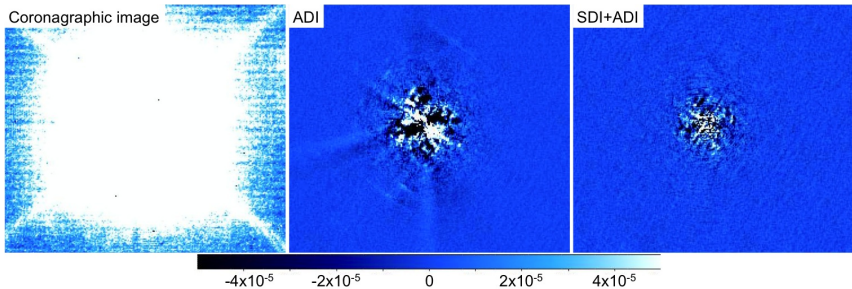
# SDI (Racine et al. 1999)

- Differential imaging = subtract image of the star alone
- Spectral = **differences** star-planet spectra  $\rightarrow$  planet = cold object  $\rightarrow$  CH<sub>4</sub> bands  $\sim 1.6 \mu\text{m}$  for  $T \lesssim 1300 \text{ K}$



# Why to combine FQPM+SDI+ADI ?

- Search for faint companions close to stars
  - Photon noise → coronagraphy
  - Speckle noise → differential imaging
  - ADI limitation : speckles non static
  - One solution :
    - 1 SDI → “fast” + “slow” speckles
    - 2 ADI → “slow” speckles

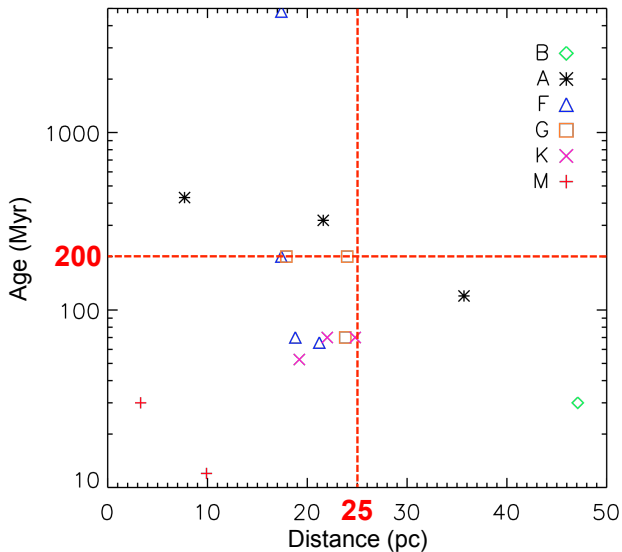


3 - Search for close-in planets →  $\sim 5-10$  AU

# Outline

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  - Performance in characterization
- 3 **Analysis of VLT/NaCo imaging data**
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  - **Data reduction**
  - ADI sensitivity limits
  - SDI+ADI sensitivity limits
- 4 **Conclusions & Prospects**
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# Sample properties



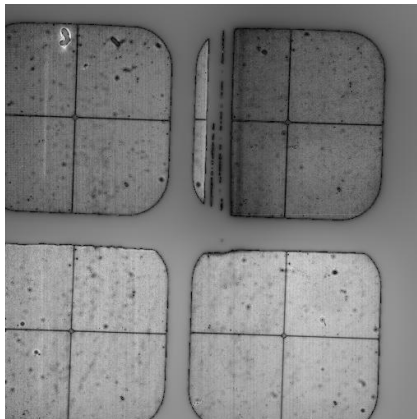


# Data reduction pipeline

- Pre-processing
  - Bad pixels
  - Transmission optical elements
  - Selection
  - Co-addition
  - Sky background
  - Selection
  - Separation  $\lambda$
  - Recentering
- Differential imaging
  - SDI algorithm
  - ADI algorithm
  - Detection levels
  - Attenuation off-axis point sources

# Data reduction pipeline

- Pre-processing
  - Bad pixels
  - **Transmission optical elements**
  - Selection
  - Co-addition
  - Sky background
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# Data reduction pipeline

- Pre-processing
    - Bad pixels
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    - Selection
    - Co-addition
    - Sky background
    - Selection
    - Separation  $\lambda$
    - Recentering
  - Differential imaging
    - SDI algorithm
    - ADI algorithm
    - Detection levels
    - Attenuation off-axis point sources
- 2-step selection
- 1 - Adaptive optics loop (partially) open
  - 2 - Flux statistics

# Data reduction pipeline

- Pre-processing

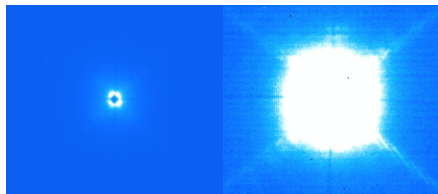
- Bad pixels
- Transmission optical elements
- Selection
- Co-addition
- Sky background
- Selection
- Separation  $\lambda$
- **Recentering**

- Differential imaging

- SDI algorithm
- ADI algorithm
- Detection levels
- Attenuation off-axis point sources

## Recentering criterion

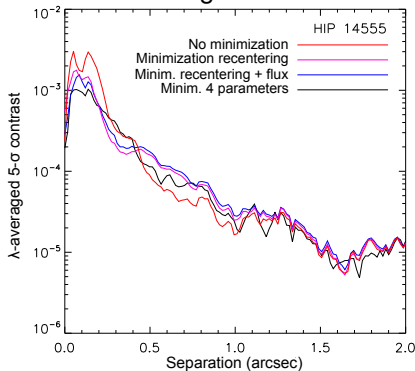
- **Thresholding**
- Calculation zone shape
- Telescope spiders



# Data reduction pipeline

- Pre-processing
  - Bad pixels
  - Transmission optical elements
  - Selection
  - Co-addition
  - Sky background
  - Selection
  - Separation  $\lambda$
  - Recentring
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## SDI algorithms

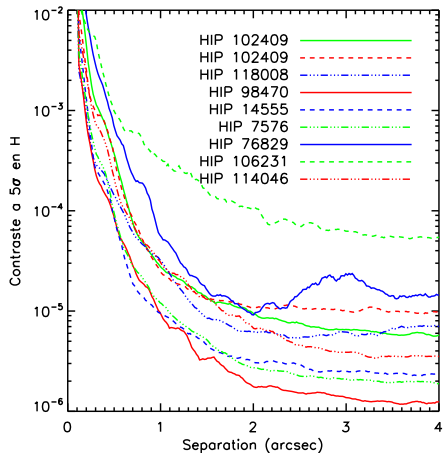
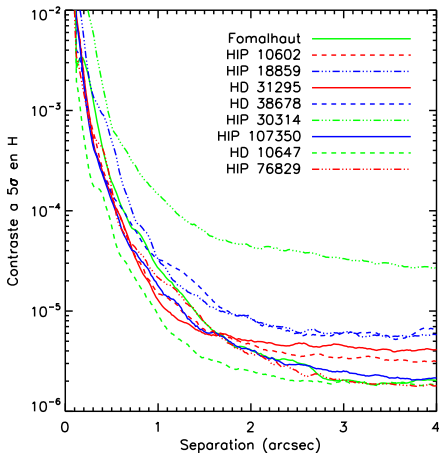


No minim. → slightly better perfs @ 0.5–1''

# Outline

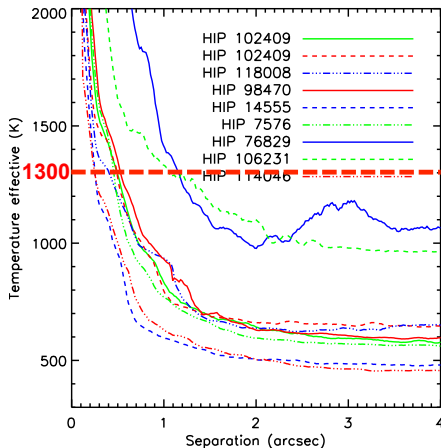
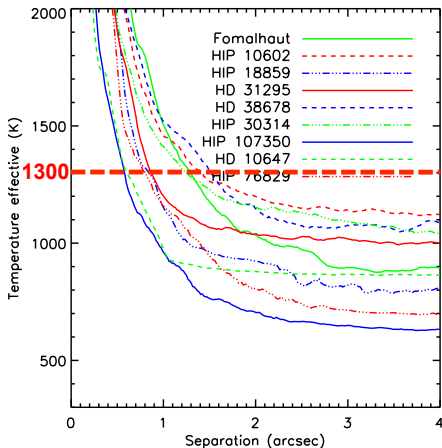
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# 5- $\sigma$ detection levels



ADI-attenuation corrected

# Effective temperature of detectable companions

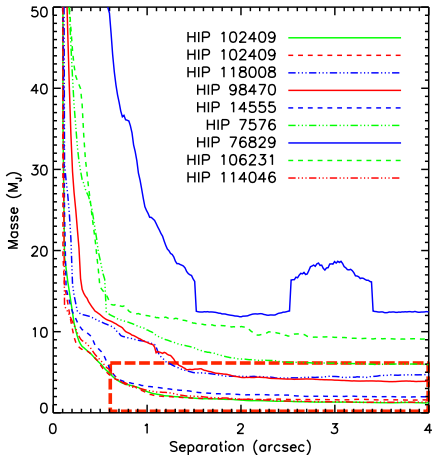
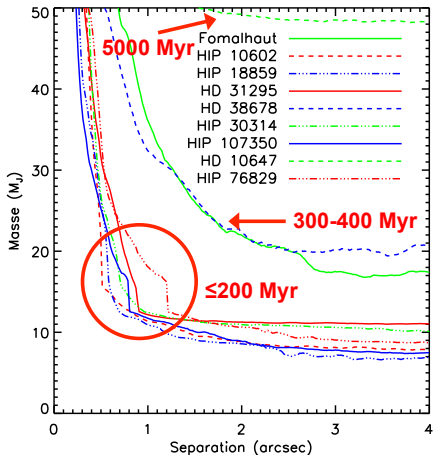


BT-SETTL models (Allard & Freytag 2010)

$T < 1300$  K for all stars (0.3–1.5'')  $\rightarrow$  ok for SDI

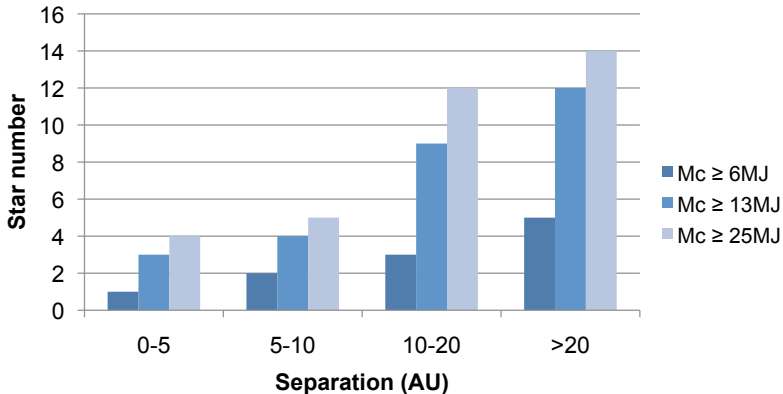


# Mass of detectable companions



BT-SETTL models (Allard & Freytag 2010)

# Companion mass vs. separation



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# Difficulties of the interpretation of SDI fluxes

$$F_{\text{SDI}} = F_1 - F_2 \times \alpha \times \phi \quad (\text{J. Rameau, Master thesis})$$

$F_1$  : residual flux in image filter 1

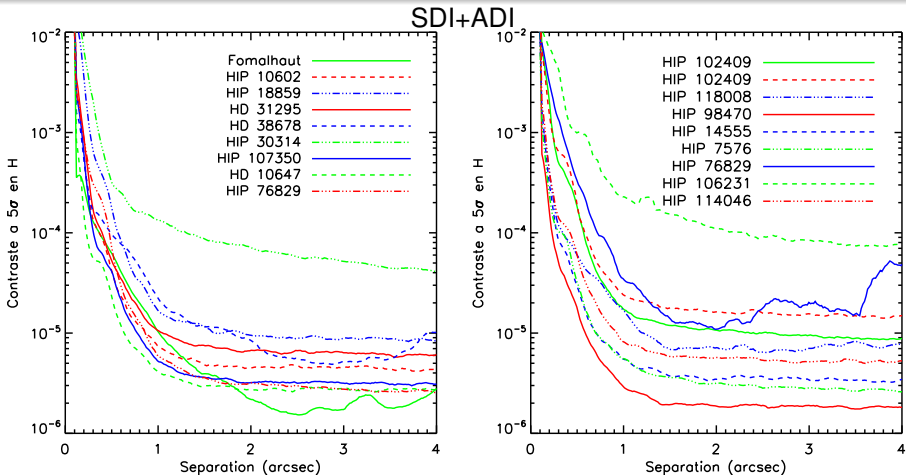
$F_2$  : residual flux in image filter 2

$\alpha$  : intensity rescaling

$\phi$  : attenuation due to spatial rescaling

- Dependence on spectral properties of planets  $\rightarrow$  **synthetic planets** for estimating **sensitivity limits**
- SDI photometry for  $M \gtrsim 10 M_J \rightarrow$  **non applicable to all stars**
- Optimistic hypothesis  $F_2 \ll F_1 \rightarrow$  **optimal performance**

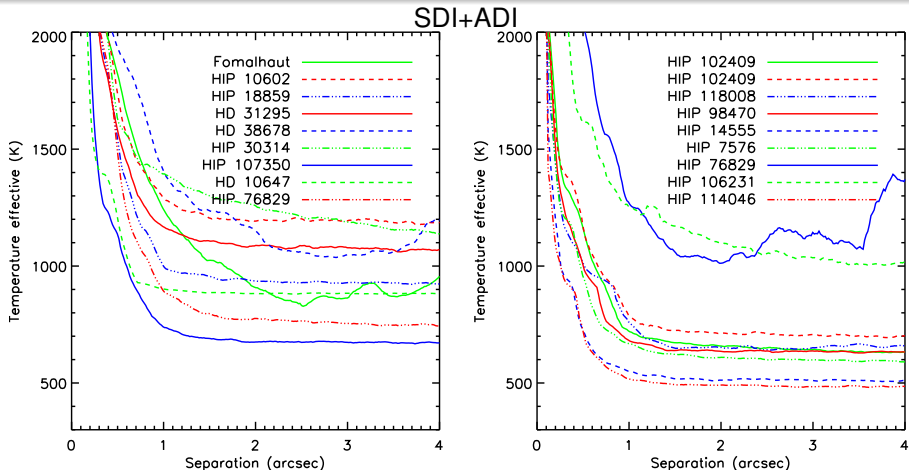
# 5- $\sigma$ detection levels



BT-SETTL models (Allard & Freytag 2010)

- $\leq 0.4''$  : contrasts / 5–10  $\rightarrow$  magnitude gain 1.8–2.5
- $\sim 1''$  : contrasts / 3–4  $\rightarrow$  magnitude gain 1.2–1.5

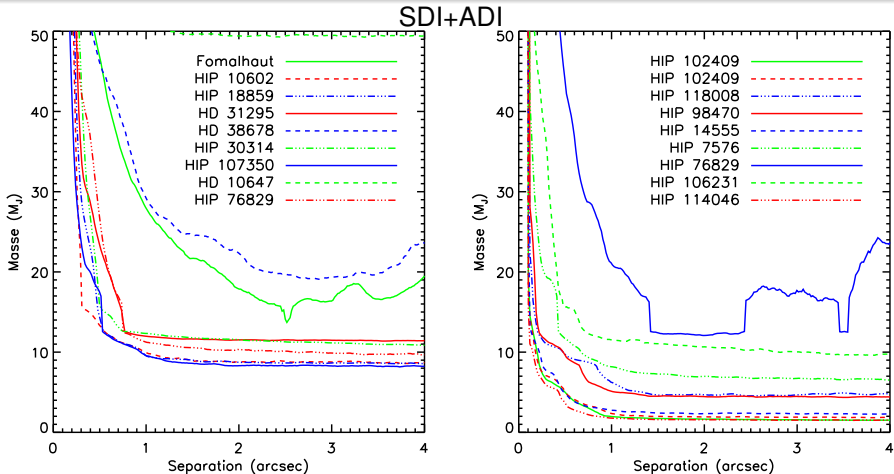
# Effective temperature of detectable companions



BT-SETTL models (Allard & Freytag 2010)

- $\sim 0.45''$  :  $T \leq 1300$  K for **50%** targets vs. **22%** in ADI
- $\sim 1''$  :  $T \leq 1300$  K for **85%** targets vs. **66%** in ADI

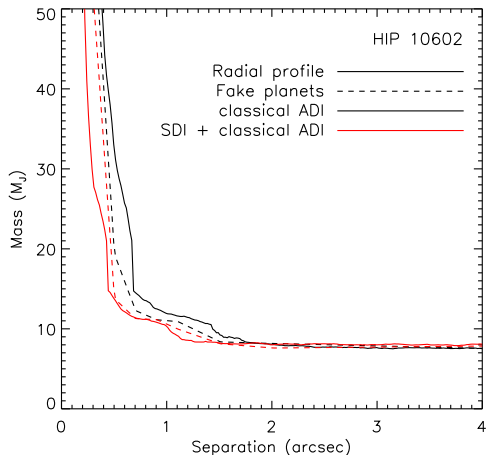
# Mass of detectable companions



BT-SETTL models (Allard & Freytag 2010)

- $\sim 0.45''$  : angular resolution **gain 0.3–0.35''**
- $M = 13 M_J \lesssim 0.8''$  vs.  $\lesssim 1.25''$  for stars  $\leq 200$  Myr

# Real performance of SDI+ADI processing



DUSTY models (Chabrier et al. 2000)

- SDI+ADI gain **smaller** wrt optimistic hypothesis



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# Conclusions

- Science performance of the SPICES mission Maire et al. (2012), A&A
  - **Top-level specifications** of the critical subsystems
  - **Characterization** performance : **SNR = 25–30** for R = 50
    - Exoplanetology possible for **~300** planetary systems
    - Characterization **Jupiters**  $\sim 0.25\text{--}7$  AU
    - **Molecule** CH<sub>4</sub>, **Rayleigh scattering**, **metallicity** enhancement  $\geq 3$
    - Characterization **super-Earths**  $\sim 0.25\text{--}2$  AU
    - **Molecules** H<sub>2</sub>O, O<sub>2</sub>, O<sub>3</sub> + **vegetation** ( $\lesssim 50\%$  clouds) + **ocean**
- Analysis of VLT/NaCo FQPM+SDI+ADI imaging data
  - No detections of companions
  - **Contribution** to reduction pipeline
  - **ADI** detection limits  $\rightarrow 10^{-4}\text{--}10^{-5}$  @  $0.5\text{--}1''$   $\rightarrow 25\text{--}10 M_J$  @  $5\text{--}10$  AU
  - **SDI+ADI** detection limits  $\rightarrow$  need **different analysis**

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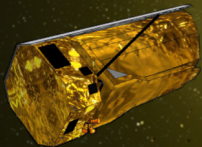
# Prospects

- Space coronagraphic telescope
  - Preparation **next ESA calls for proposals** (2013/2014 ?)
  - Improvement **numerical model** of the instrument
  - **Other science cases** (planet polarimetry, circumstellar disks)
  - **Other projects** (TPF-C, 50-cm telescope Canada)
- Ground-based imaging instruments
  - **SDI+ADI detection limits** of **all stars**
  - **Different ADI algorithms** (LOCI, KLIP)
  - **Statistical** analysis → constraints on **properties** of long-period planets
  - Stars from SPHERE catalog

Merci

Thank you

Obrigada



Gracias

Dank u

谢谢

