Shaping the E-ELT – February 25th, 2013, Garching

Exoplanetology with EELT-CAM & IFU

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IPAG
Institut de Planétologie
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de Grenoble

cnrs
advancing the frontiers

Outline

Observing New Worlds

I- Exoplanets

- Techniques & Results
- Open questions

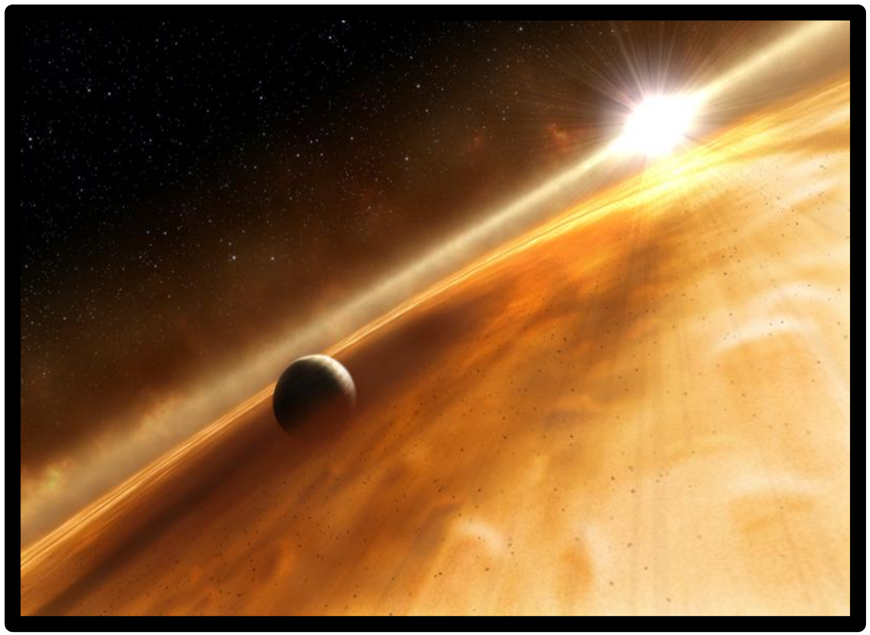
II- E-ELT CAM & IFU perspectives

- Exoplanetology at the E-ELT era
- Science drivers & Instrumental Requirements

I- Introduction
Observing New Worlds

Exo-Planets/exo-Biology **paradigm**

- Stellar Formation (Initial Conditions)
- Formation & Physics of EPs
- Architecture & Evolution
- Favorable conditions for Life
- Exo-Biology & Bio-Signatures



(Planetary formation – Artist's view)

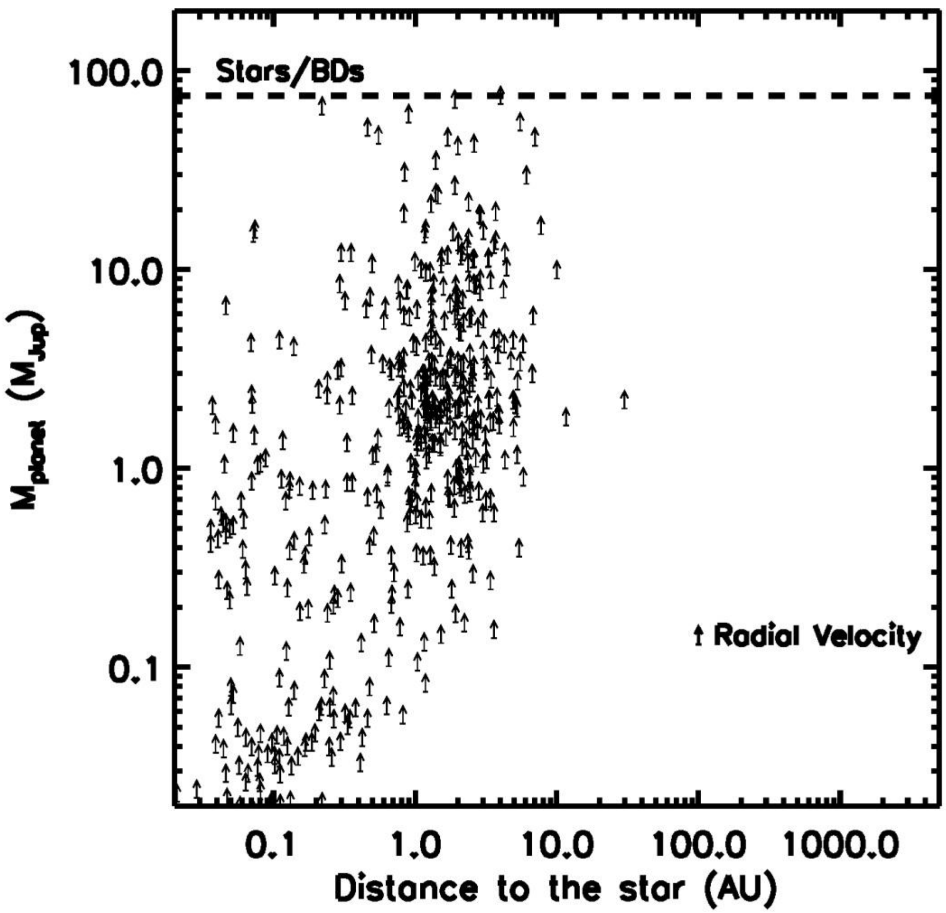
I- Introduction
Techniques & Key-Results

✱ Radial Velocity

. Indirect technique: Doppler shift
(low-activity stars)

. Orbital & Physical properties:
> M_p.sin(i), P, e, a, ω & T_0
> Spin-Orbit Alignment
> Architecture & Stability
> exo-Earths & Habitable Zone

Dumusque et al. 12, Bonfils et al. 11



http://exoplanet.eu/

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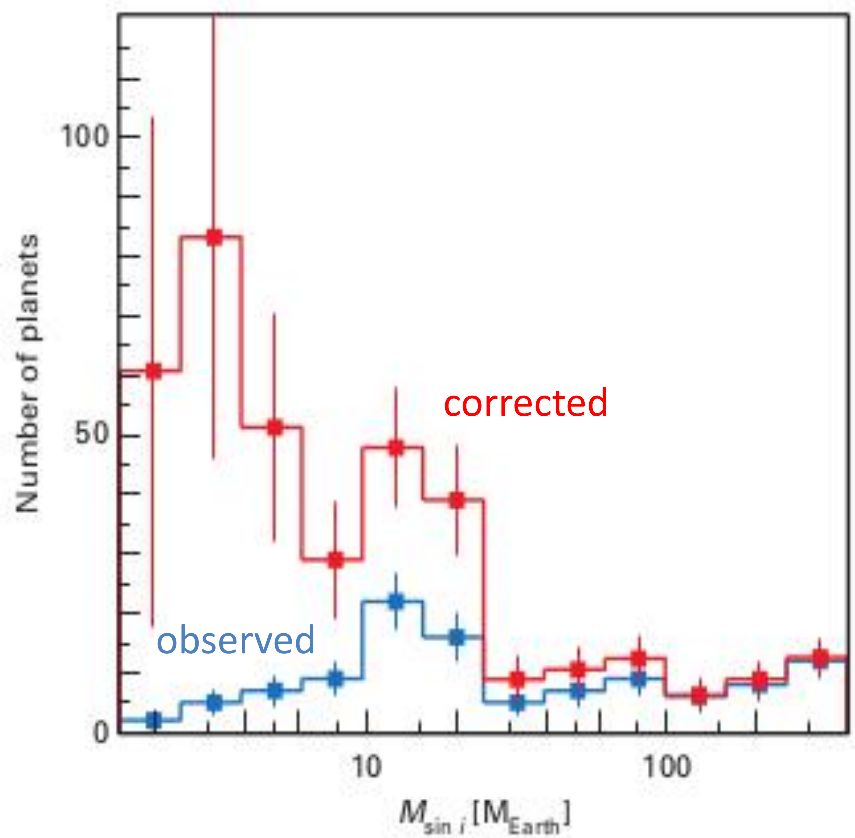
> exo-Earths & Habitable Zone
Dumusque et al. 12, Bonfils et al. 11

. Statistics: more than 800 exoplanets
> Occurrence down to Super-Earths
> Mass/Orbital distributions
> Planetary host dependence:
(Fe/H, alpha-element, SpT, binarity…)
Udry & Santos 07



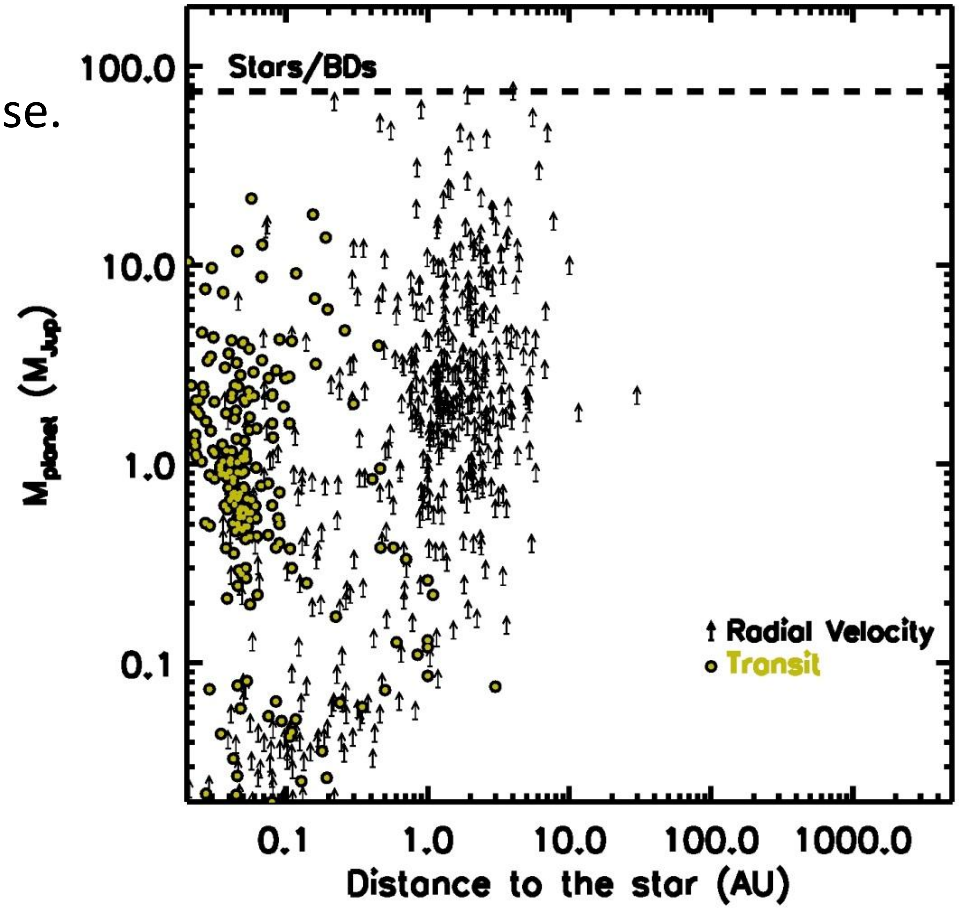
Exoplanet Mass distribution,
Mayor et al. 11

I- Introduction
Techniques & Key-Results

✱ Transit

. (In)direct technique: $1^{ary}/2^{ary}$ eclipse.
(crowded fields)

. Orbital & Physical properties:
> R_*/R_p, M_p, P, a, i, T_0
> Planetary Interiors
> Multiple: Architecture & Stability
> Circumbinary planets
Doyle et al. 11; Balatha et al. 12



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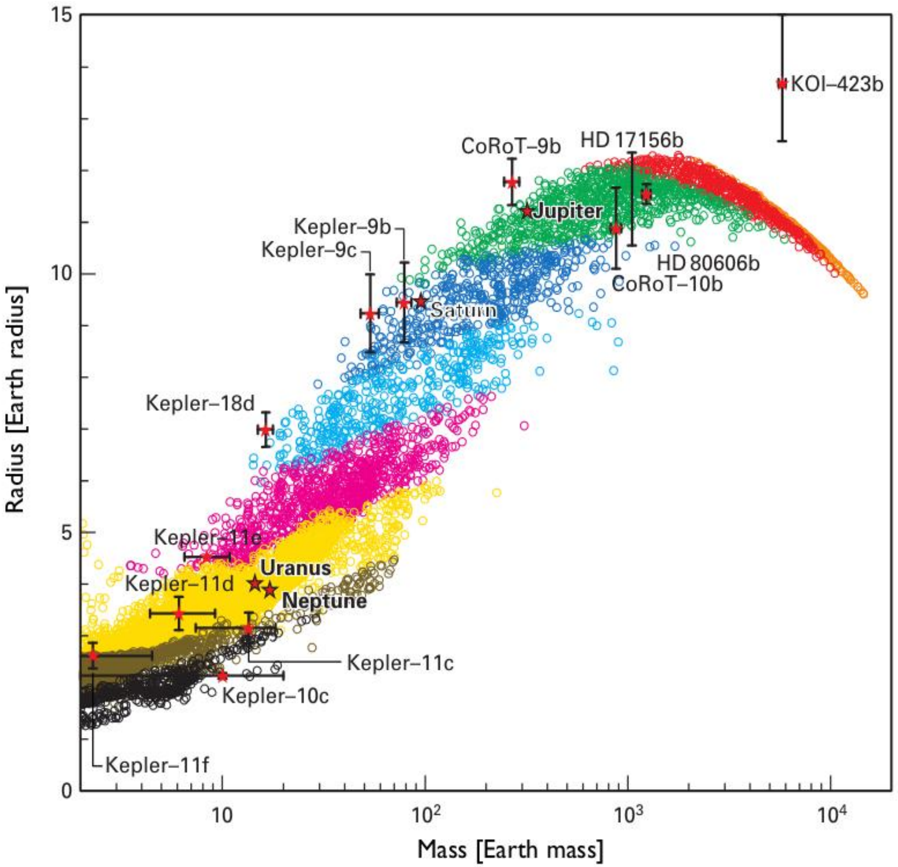

Mordasini et al. 12
(Cora accretion; colors = heavy-elts fraction)

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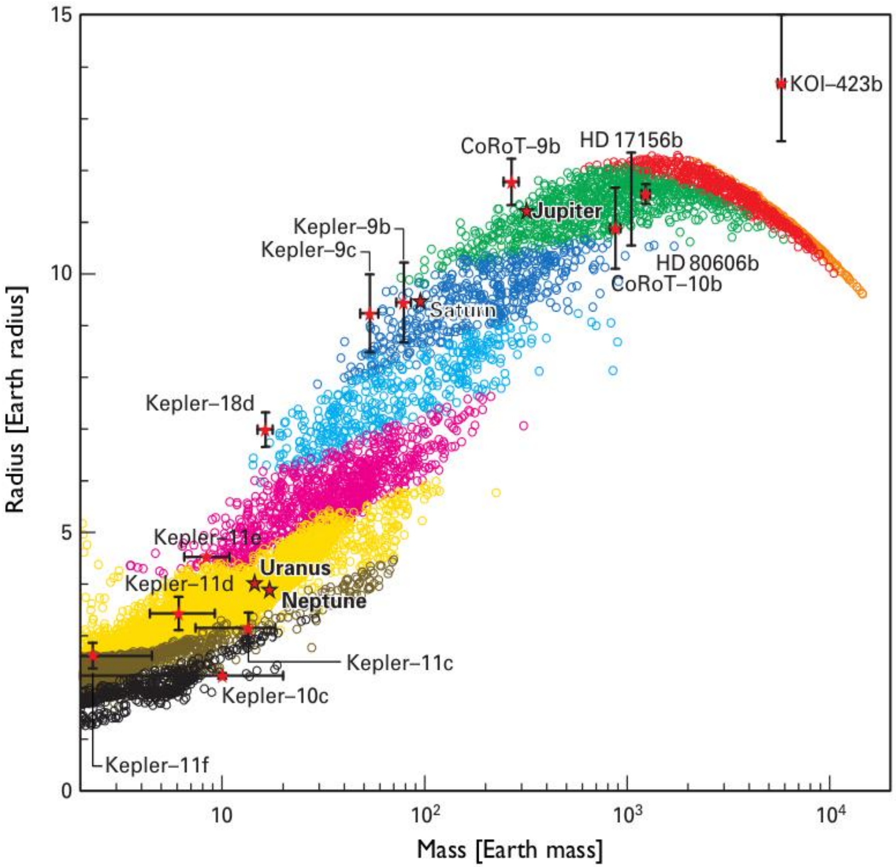
Doyle et al. 11; Balatha et al. 12

. Transmission/emission spectroscopy
> Composition (H2O, CO, NaI, KI... Haze)
> Vertical T-P structure, atmospheric
circulation & evaporation
Swain et al. 08; Desert et al. 12



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I- Introduction
Techniques & Key-Results

✱ μ-lensing

. Indirect technique: Unique Rel. Event (Crowded fields)

. Orbital & Physical properties:

> M_p, M_*, d, P, a (1-5 AU)

> Super-Earths

. Free-floating, wide orbit planets?

Gould et al. 06; Cassan et al. 12

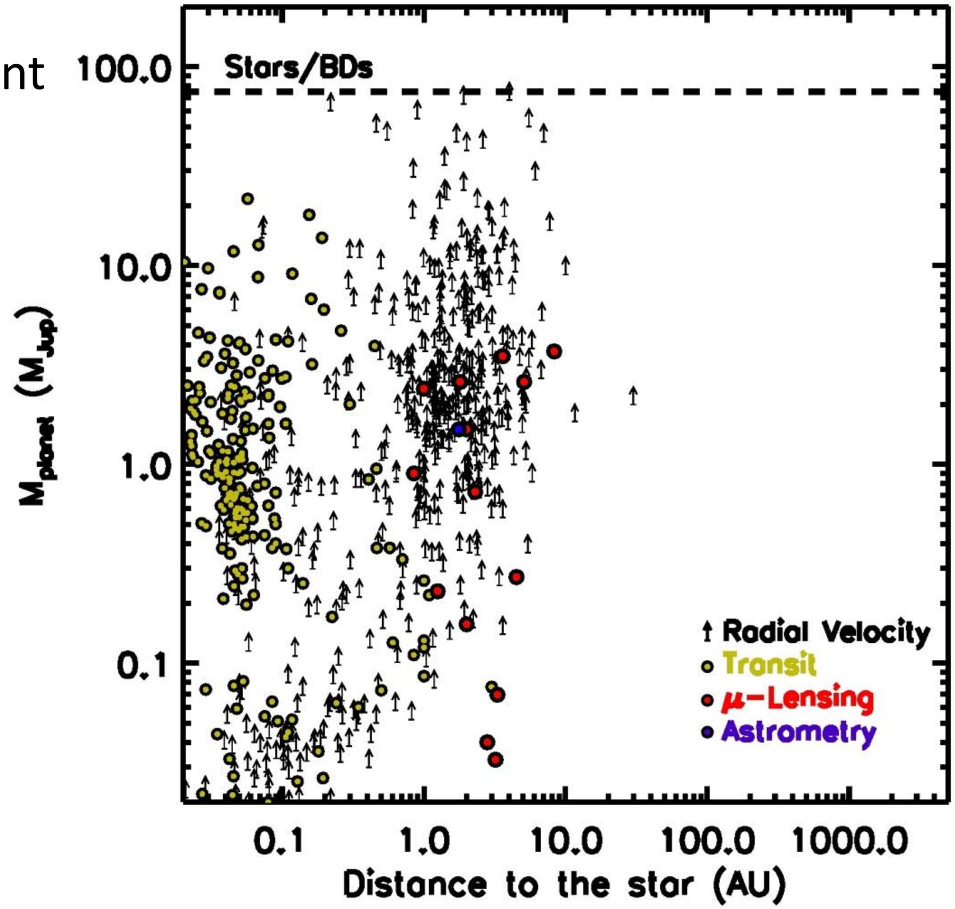
✱ Astrometry

. Indirect technique: Reflex motion (Targets: Nearby stars)

. Orbital & Physical properties:

> M_p, P, i, e, a, ω, T_0 (1-5 AU)

Bean et al. 07, 08; Benedict et al. 02, 10
Muterspaugh et al. 10; Sozzetti et al. 10



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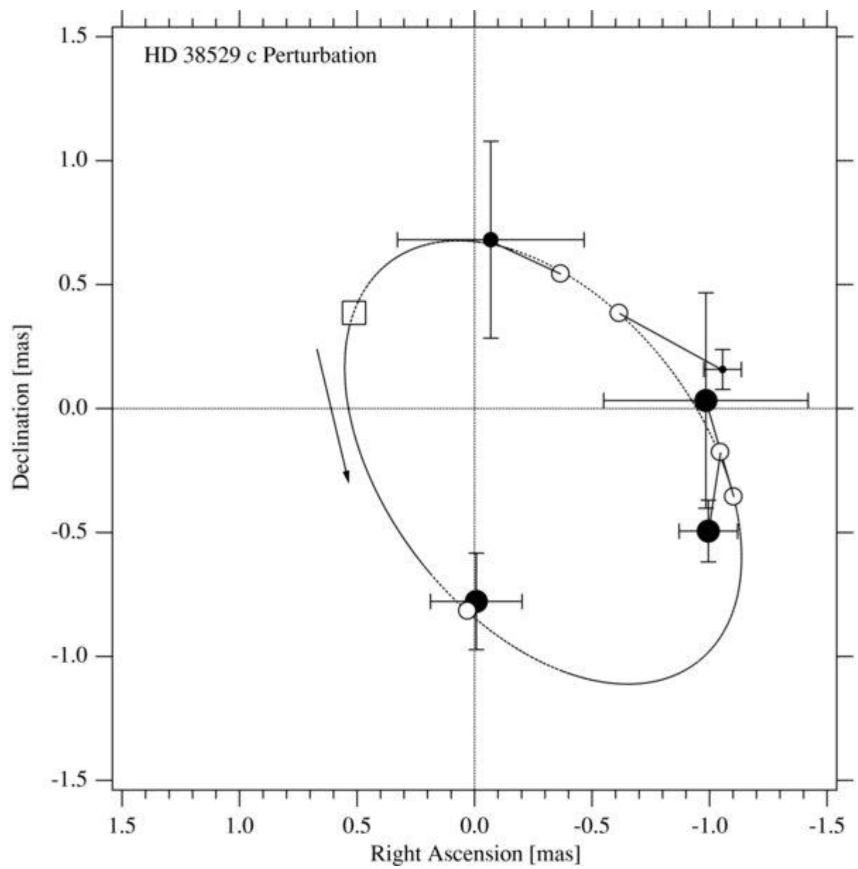


Benedict et al. 10

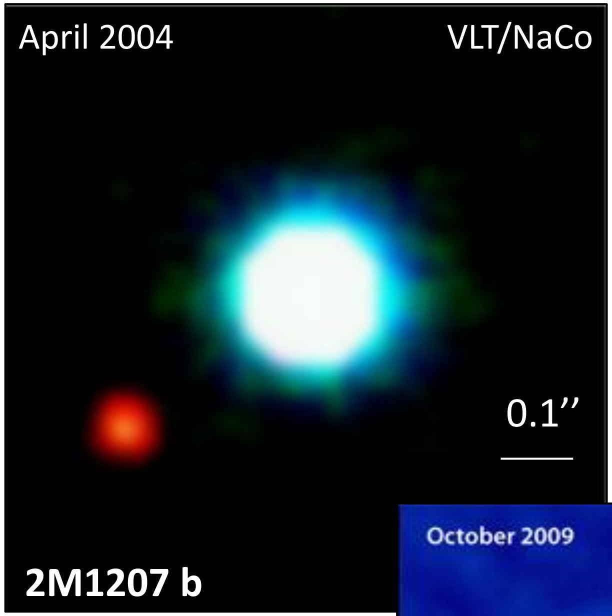
I- Introduction
Techniques & Key-Results

✱ Direct Imaging

. Direct technique: Planet's photons
(Targets: young & nearby stars)

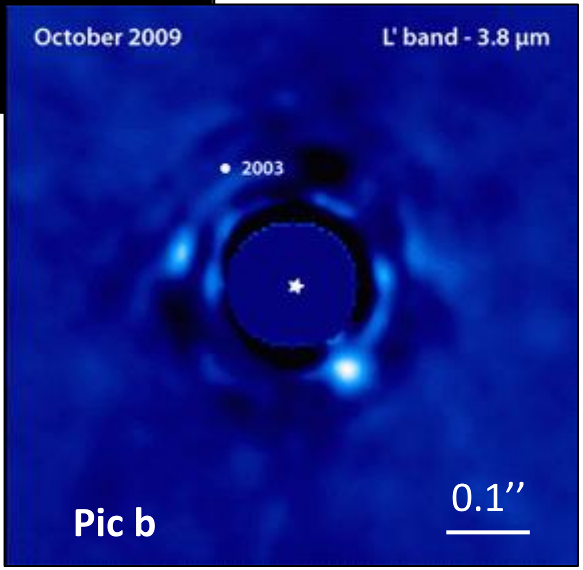
. Orbital & Physical properties
> L, a , e, i, ω, T0
> Giant planets at wide orbits (>10 AU)
> Multiple: Architecture & Stability
> Planet – disk connection
> Gravitational Instability (HR8799)?

Kasper et al. 07; Rameau et al. 13



Chauvin et al. 05

Lagrange et al. 10



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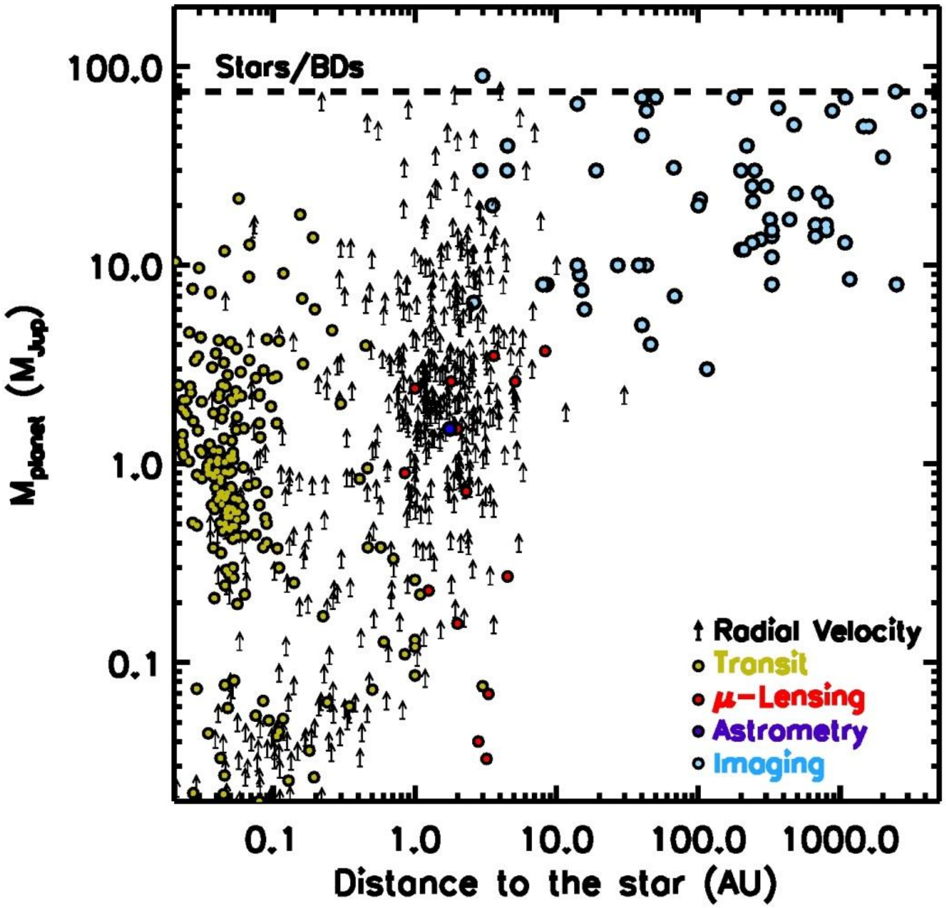

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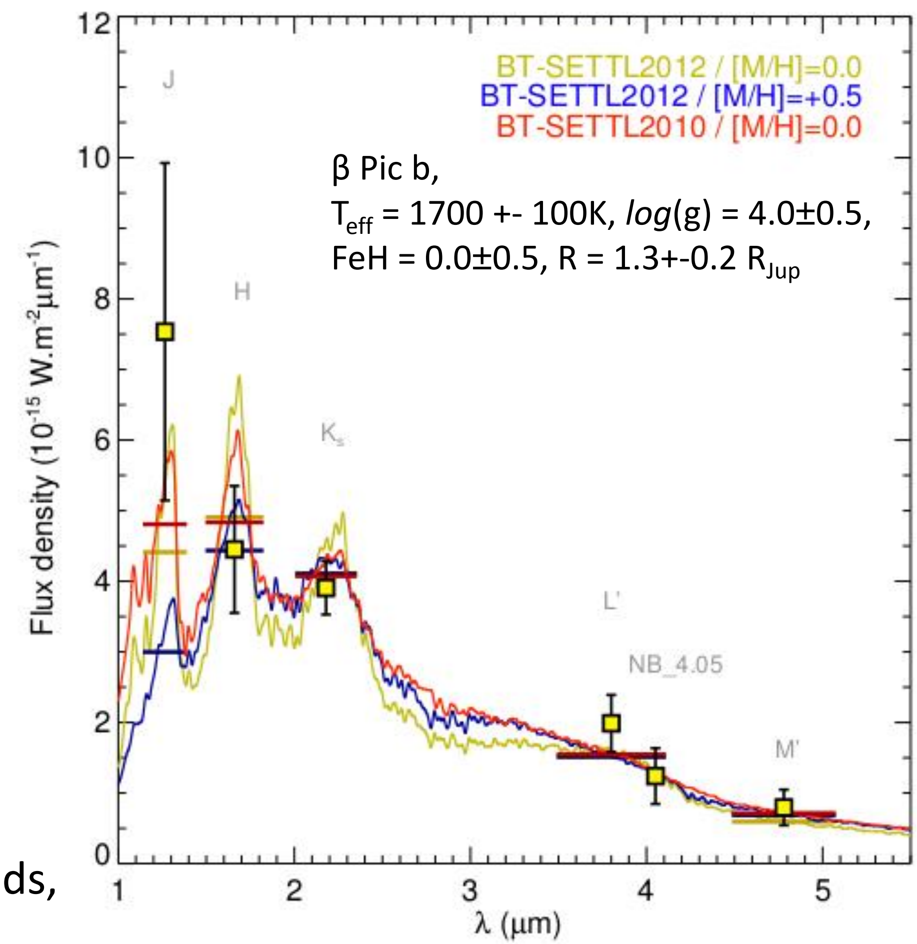
Chauvin et al. 10; Rameau et al. 13

. High-contrast spectroscopy
> Non-strongly irradiated EGPs
> Low-gravity, composition, non-LTE, clouds,

Bonnefoy et al. 09, 13; Madhusudhan et al . 11



Bonnefoy et al. 13

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II/ EELT-CAM & IFU

Timeline: current/future missions

2012 ***2014*** ***2016*** ***2018*** ***2020*** ***2022*** ***2024*** ***2026*** ***2028***

Ground: Harps N/S, SOPHIE, NaCo, VISIR, CRIRES, WASP…

Space: *Spitzer, Herschel,* Kepler*, CoRoT*

- VLT & VLTI 2nd *& 3rd generation*
PRIMA, K-MOS*, SPHERE, MUSE, ESPRESSO, GRAVITY…*

- ALMA *(ACA)*

- GAIA

- SKA

- Cheops

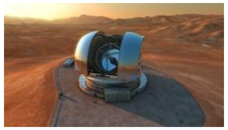
- JWST

- EChO/PLATO?

- TMT

- GMT

- E-ELT

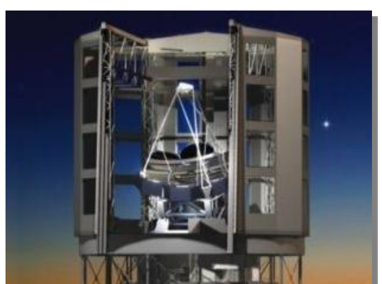


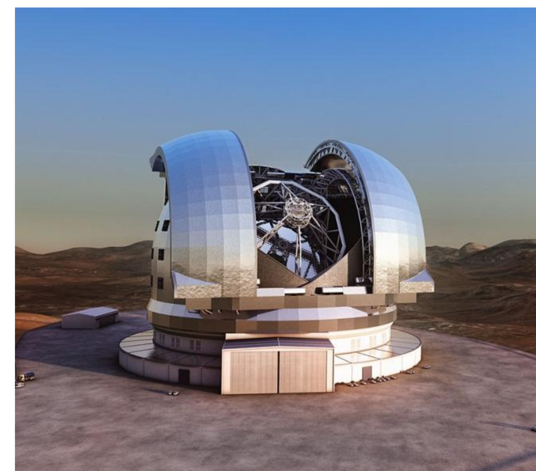
II/ EELT-CAM & IFU

E-ELT & other competitive projects

* **Discoveries by opening a new parameter space**

- Increased Sensitivity
- Spatial resolution (10 mas scale)



	50m2	**400m2**	**600m2**	**1200m2**	**(JWST: 25m2)**
1 µm	**25mas**	**9mas**	**7mas**	**5mas**	**(JWST: 34mas)**

II/ EELT-CAM & IFU

Description & Agenda

Instruments - First Light	**AO**	**Mode**	**λ (µm)**	**Resolution**	**FoV & Sampling**	**Add. mode**
ELT-1: CAM (MICADO) - 2022	**SCAO, MCAO**	**- IMG - MRS**	**0.8 – 2.4**	**3000**	**53.0” / 3 mas**	**Coronography**
ELT-2 IFU (HARMONI) - 2022	**SCAO, LTAO**	**- IFU**	**0.5 – 2.4**	**4000 10 000 20 000**	**0.5*1.0” - 5.0*10.0” / 4 – 40 mas**	**Coronography**
ELT-3: MIR (METIS) - **2024**	SCAO, LTAO	- IMG - MRS - IFU	3 – 13 3 - 5	 5000 100 000	18” / 12 mas 0.4*1.5 / 4 mas	Coronography Polarimetry
ELT-4/5: HIRES (CODEX/SIMPLE) - **2026/2028**	No AO SCAO, MCAO, LTAO	- HRS	0.37 – 0.71 0.84 – 2.50	130 000 130 000	0.82 0.027*0.5	
ELT-4/5: MOS (EAGLE/EVE/ DIORAMA) **- 2026/2028**	No AO, GLAO MCAO	Slits IFUs IFUs	0.37 – 1.4 0.37 – 1.4 0.8 – 2.45	300- 2500 5000 – 30 000 4000 – 10 000	6.8”/ 0.1” 420’ / 0.3” 420’ /	
ELT-X: PCS (EPICS) **- 2025/2030**	XAO	EPOL IFS	0.6 – 0.9 0.95 – 1.65	 125 – 20 000	2.0” / 2.3 mas 0.8“ / 1.5 mas	Coronography Polarimetry

II/ EELT-CAM & IFU

in a nutshell

NIR Imager & Long-slit Spectrograph

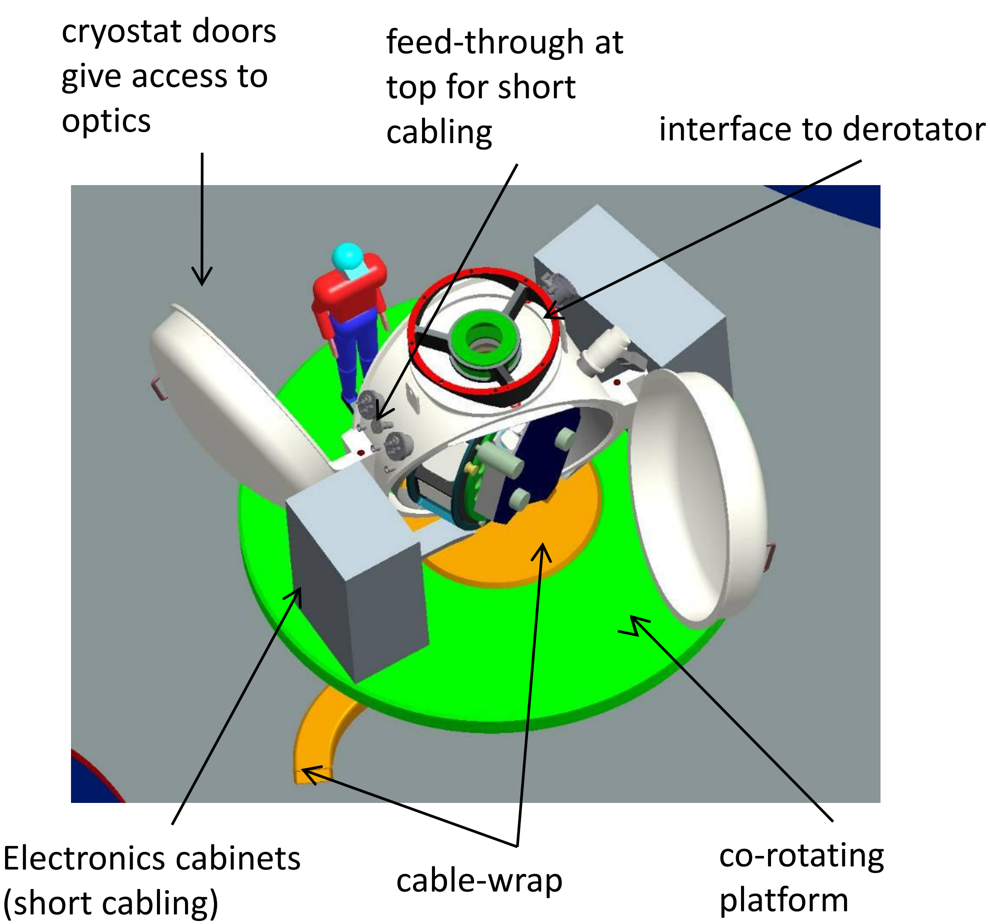
> R. Davies's Talk

AO flavors:
Seeing-limited: no AO & GLAO
Diffraction-limited: SCAO or MCAO

Sensitivity and resolution
6 mas (J-band) to 10 mas (K-band)
up to 0.5/3.0 mag deeper/JWST,
Platescale = 3 and 1.5 mas/pixel
FoV = 53" and 6"

Precision astrometry
<40 μas over 1' in one epoch
10 μas/yr after 3/4 years

Wide coverage spectroscopy
0.8-2.5 μm simultaneously
at R~5000-10000



II/ EELT-CAM & IFU

in a nutshell

VIS-NIR Integral Field Spectrograph

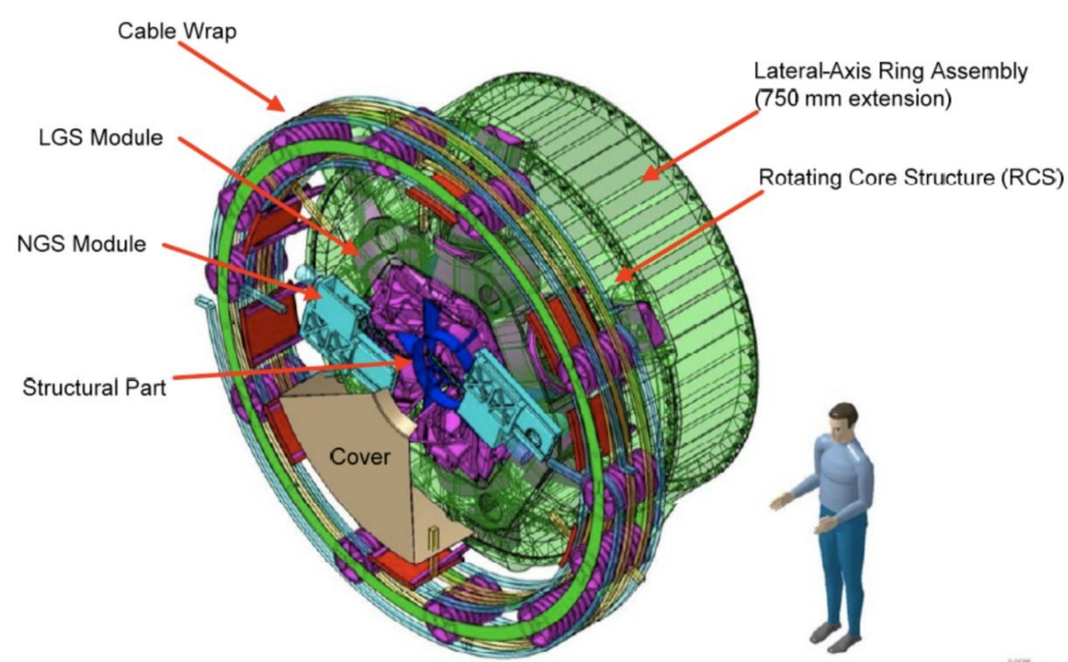
> N. Thatte's Talk

AO flavors:
Seeing-limited: no AO or GLAO
Diffraction-limited: SCAO, LTAO (?)

IFU concept:
Image slicer/splitter (SINFONI-like)
New *no amorph* design

Sensitivity and resolution
6 mas to 10 mas (J, K-band resp.)
Platescale = 40, 20, 10 & 4 mas/pixel
FoV: 10×5” to 1.0”×0.5”

Spectral resolution
Various setting 0.5 – 2.5 µm
R = 4 000, 10 000 & 20 000



II/ EELT-CAM & IFU

Drivers for Exoplanetology

a/ High-Precision Astrometry

b/ High-Contrast Imaging

& Spectroscopy

II/ EELT-CAM & IFU

Drivers for Exoplanetology

a/ High-Precision Astrometry

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II/ EELT-CAM & IFU

a/ High-Precision Astrometry

* The GAIA Legacy (2013 – 2018)

Exo-Jupiter, 5 AU, @10pc, G = 500 µas
Exo-Earth, 1 AU, @10 pc, G = 0.3 µas
Exo-Saturn, 1 AU, @10pc, M = 50 µas
Exo-Neptune, 0.5AU, @10pc, L = 10 µas

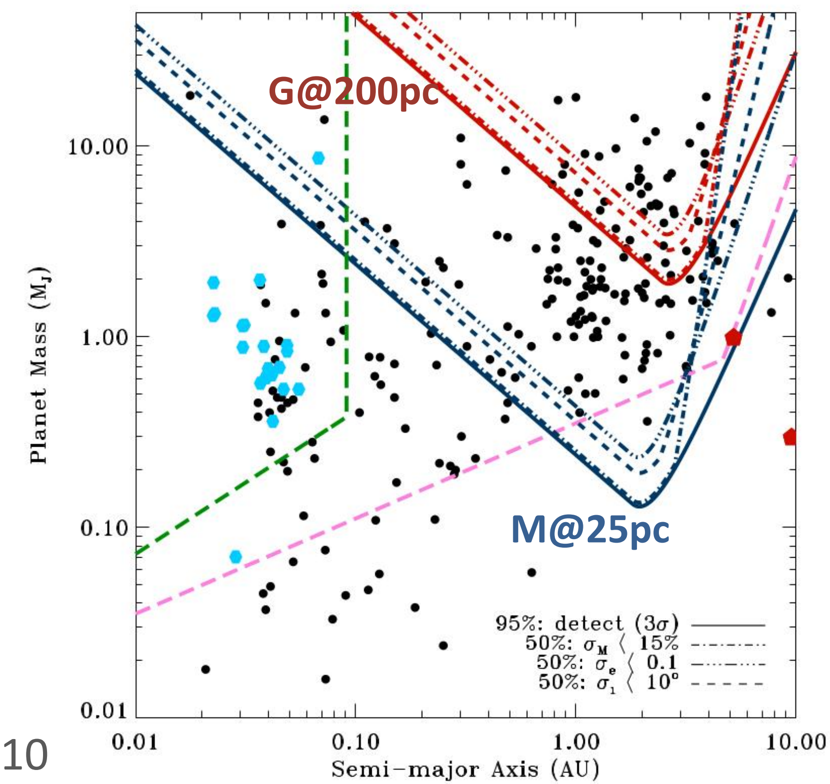
GAIA Perfomances (eom):

Bright (6 < V < 13) : **10 µas**
Faint (V = 15) : 10 - 30 µas
VF (V = 20) : 100 – 300 µas

Exoplanet Programme:

Volume limited < 200 pc survey
AFGK to early-M dwarfs,
> 10^4 EGPs expected btw 2 – 4 AU
Sozzetti 12

But less performant for very-low mass stars



Lattanzi & Sozzetti 10

II/ EELT-CAM & IFU

a/ High-Precision Astrometry

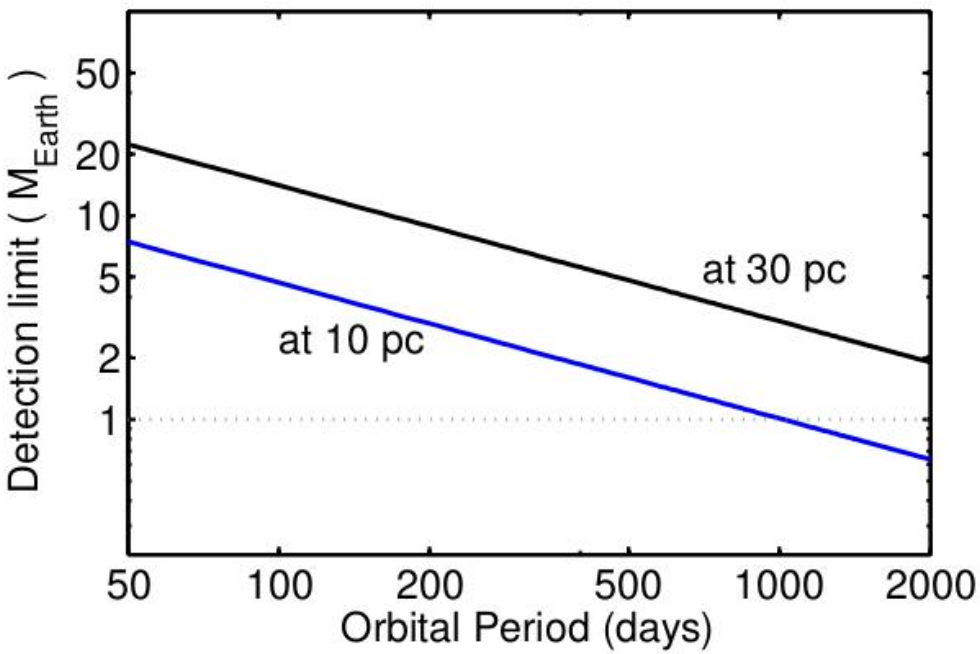
* Exoplanets around late-M, L, T and Y dwarfs

FORS2 heritage, Lazorenko et al. 11
Fov = 4.2’, 0.1”/pix, no AO
Astrometric precision = 100 µas
PALTA survey of L, T & Y stars/BDs
Sahlmann et al. 11, 13 (in prep)

CAM: FoV = 53”, 3 mas/pix, no AO,
Availability of reference stars (>10)
Expected precision = **5 - 10 µas/meas**

Exoplanet: Minimum detectable mass
Primary = 0.06 M_{sun}
30 meas. over the full orbit

Minimum Detectable Mass (3σ)



Sahlmann, Queloz 12, priv. comm.

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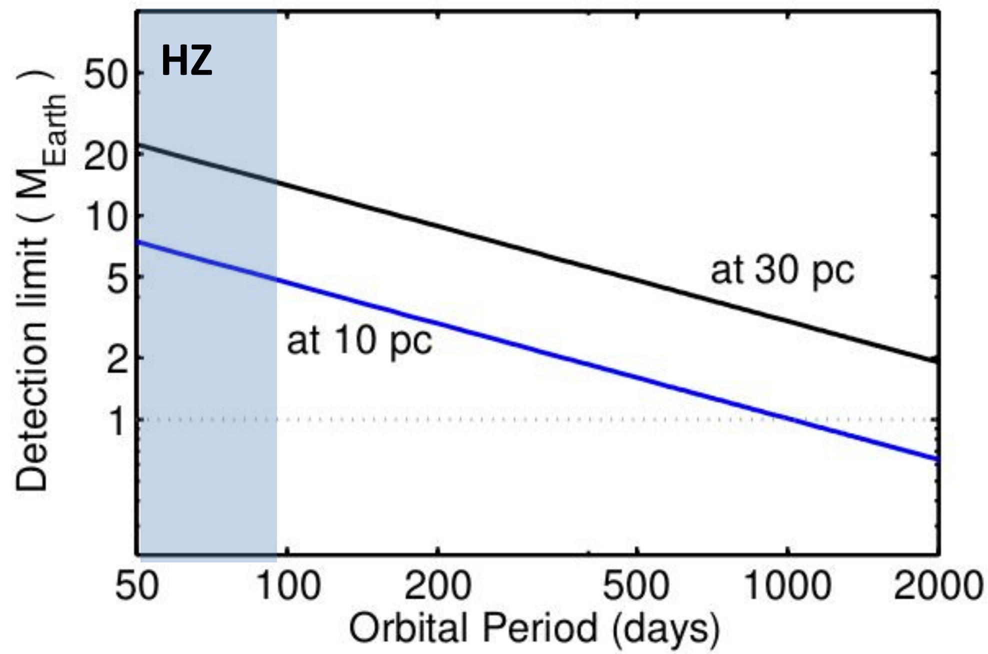

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Availability of reference stars (>10)
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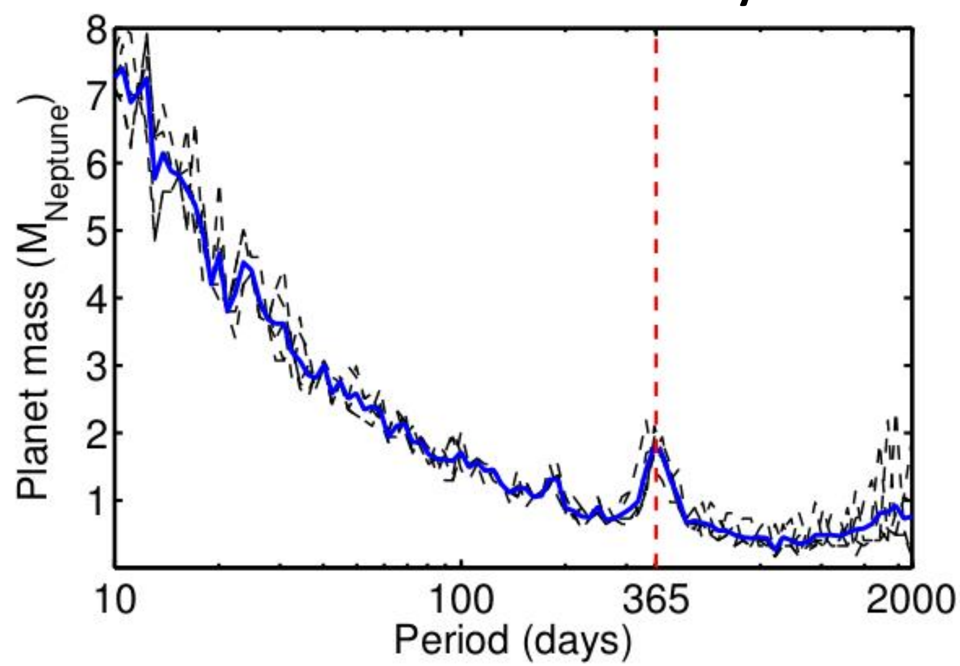
Exoplanet: Campaign detection limit
Primary = 0.06 M_{sun}
30 meas. over 3 yrs (10 meas./semester)
1 measurement = 0.5h, i.e 1.7n/target over 3 yrs

Detectable Limit over 3 yrs



Sahlmann, Queloz 12, priv. comm.

II/ EELT-CAM & IFU

Drivers for Exoplanetology

a/ High-Precision Astrometry

b/ High-Contrast Imaging

& Spectroscopy

II/ EELT-CAM & IFU

b/ High-Contrast Imaging & Spectroscopy

* Characterizing known EGPs

Context:

- Observed/Predicted Contrast for Giant Planets (H-band)

Bpic b, 8 M_{Jup}, 12 Myr, 19.3pc, A5V	**10^{-4}** at 0.4" (8 AU)
Young 1 M_{Jup}, 50 Myr, 20pc, G2V	**10^{-7}** at 0.5" (10 AU)
Cold 1 M_{Jup}, 0.5 Gyr, 20pc, G2V	**10^{-9}** at 0.5" (10 AU)

- Giant Planet Imagers: VLT/SPHERE and GPI (2013); JWST (2018)

NaCo performances (H-band):	**10^{-5}** at 0.5"
SPHERE performances (H-band):	**10^{-6}** at 0.1", **10^{-7}** at 0.5"

- GAIA (2018): 10^4 planetary systems (including young stars at less than 200 pc)

II/ EELT-CAM & IFU
b/ High-Contrast Imaging & Spectroscopy

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CAM & IFU: Characterizing systems with known Giant Planets

BUT, should achieve contrast performances: **10^{-7}-10^{-8} at 0.1-0.5”**
for ***photometric***, ***astrometric*** and ***spectroscopic*** characterization

II/ EELT-CAM & IFU

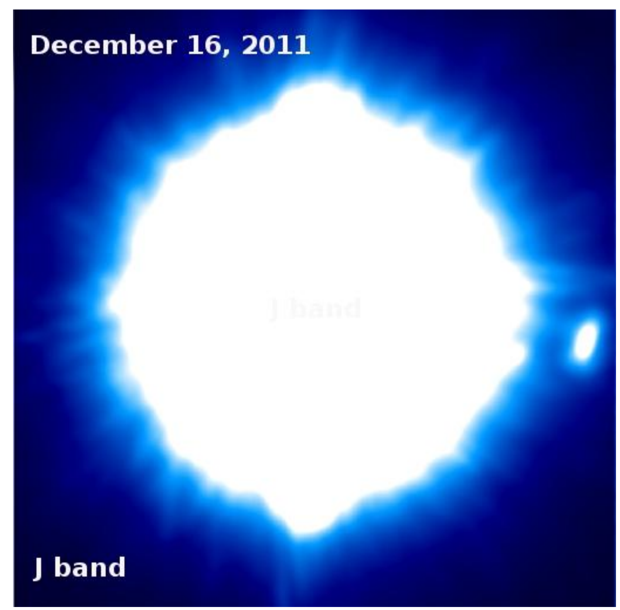
b/ High-Contrast Imaging & Spectroscopy

★ Characterizing known EGPs

Goal: 10^{-7}-10^{-8} at 0.1-0.5”

Instrumental requirements:

1. High, stable diffraction-limited AO correction:
   > **SCAO** (70-80% Sr in K-band, bright sources)
2. Stellar halo suppression:
   > Occultation / Apodizer / Coronagraph (CLC, ALC, AGPM)
3. Quasi-statics speckles calibration:
   > differential imaging (ADI, SDI)
   > NCPA corrections



1“ (i.e 19AU@19pc)

II/ EELT-CAM & IFU

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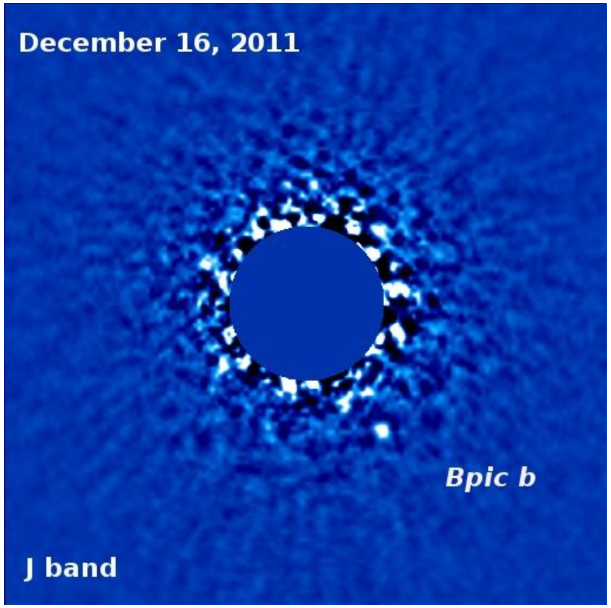

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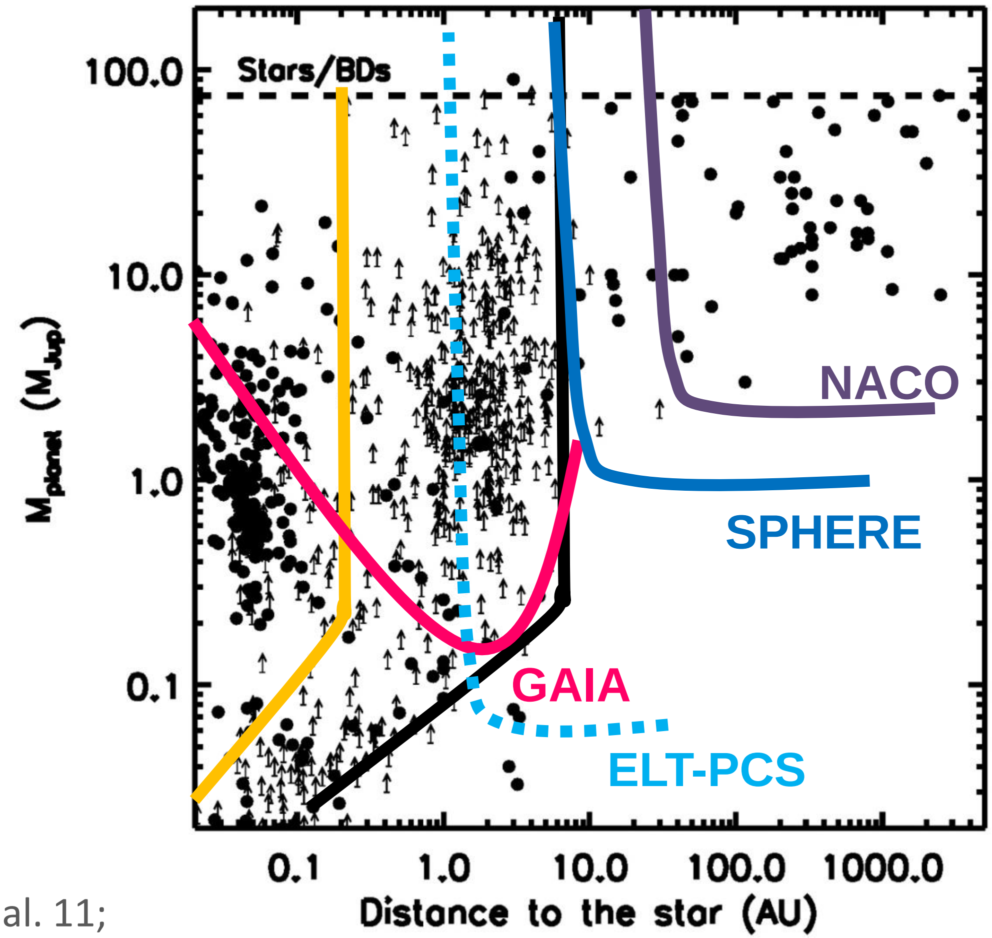
II/ EELT-CAM & IFU

b/ High-Contrast Imaging & Spectroscopy

* CAM & IFU Contrast Performances



Star 50 Myr at 20pc

Mesa et al. 11;
Kasper et al. 10; Lattanzi & Sozzetti 10

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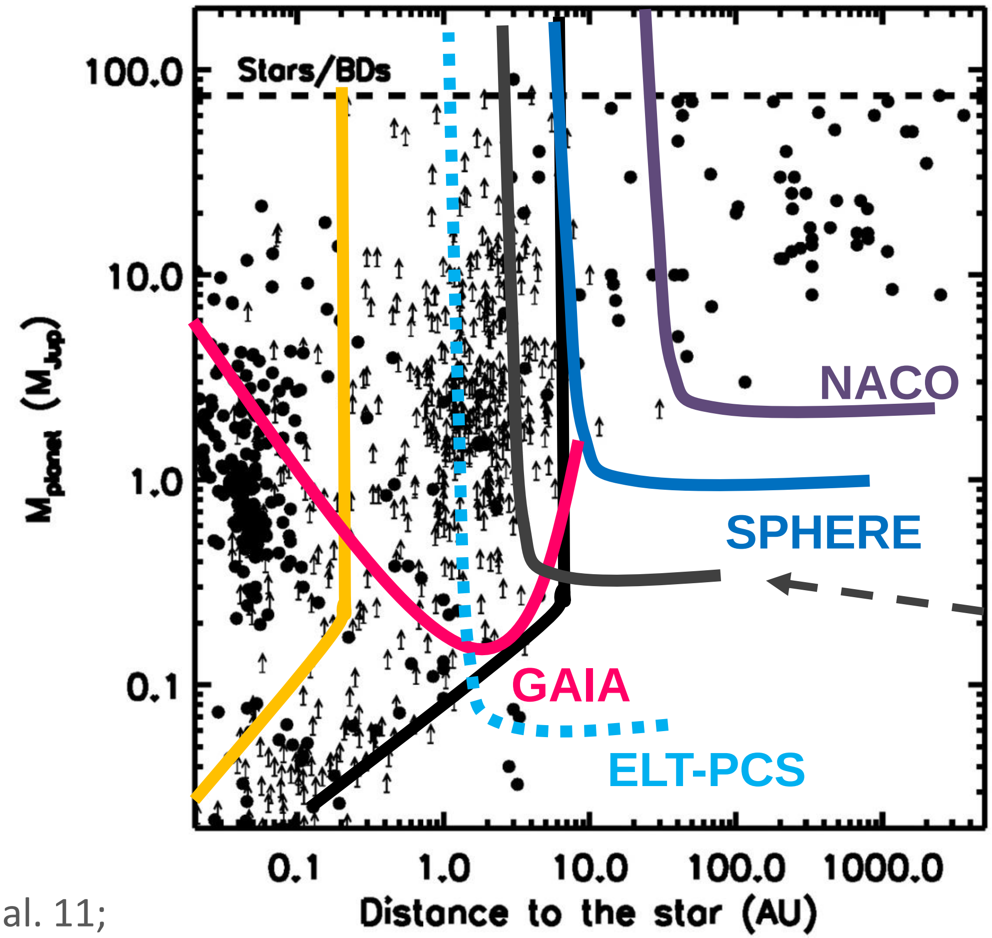

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II/ EELT-CAM & IFU

b/ High-Contrast Imaging & Spectroscopy

★ 1/3 Mass-Luminosity Relation

Dynamical Mass:

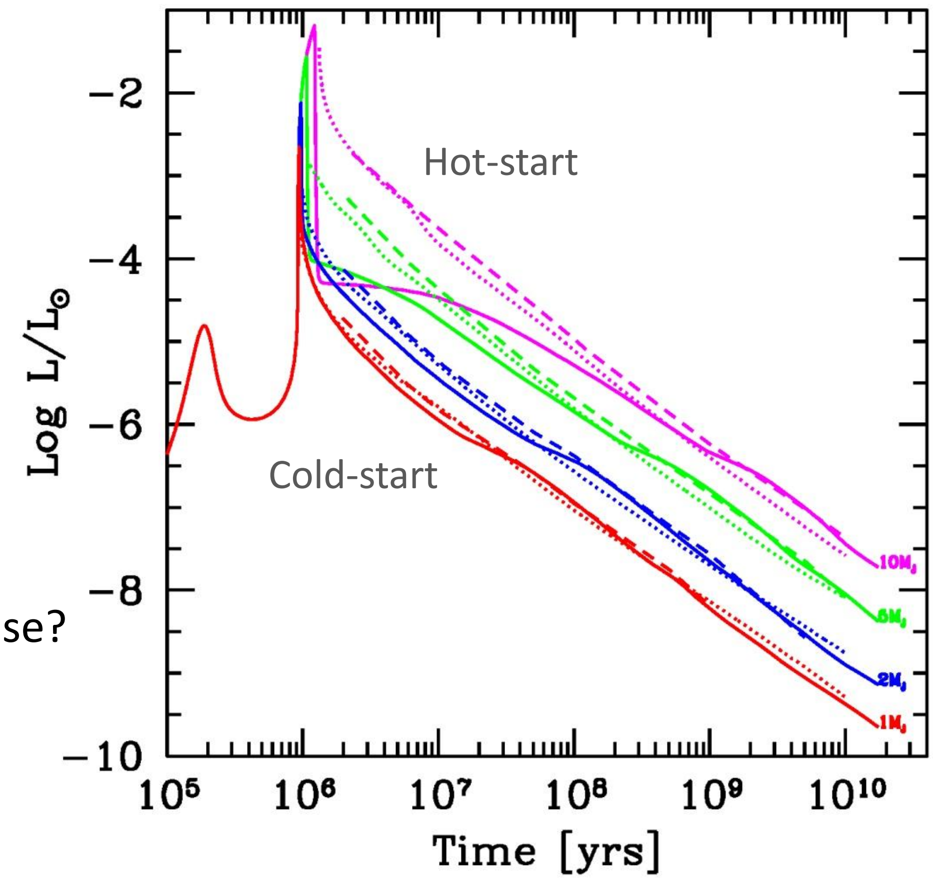
. not directly measured in Imaging
. Combined with GAIA, RV (*activity*)

Calibrating formation
& evolutionary models

. not-calibrated at young ages

. Role of initial conditions (Formation)
(Baraffe et al. 03; Burrows et al. 03)

. Gas-accretion Evolution
> Energy lost during the gas-accretion phase?
(Marley et al. 07; Fortney et al. 08)



Mordasini et al. 12

II/ EELT-CAM & IFU
b/ High-Contrast Imaging & Spectroscopy

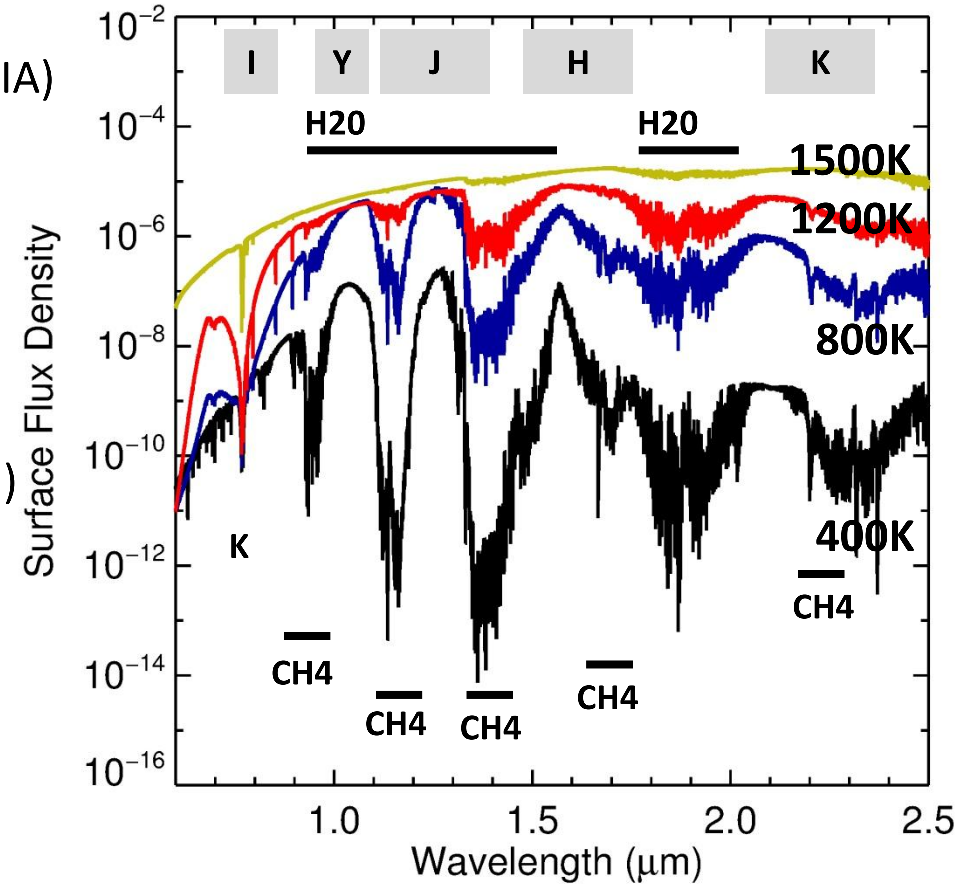
✱ 2/3 Giant planet atmospheres

Composition & chemistry
Molecules (H20, CH4, NH3, FeH, H2-CIA) & Atomic (K, Al, Na…) lines

- Cloud Formation/Sedimentation
- Cloud saturation
- Molecular opacities
- Non-equilibrium chemistry
- Fraction of heavy-elements
- Variability (Atmosphere circulation)

Physical, properties
T_{eff} , *log*(g) and [Fe/H]

> Formation mechanism signature, over-abundance for CA?



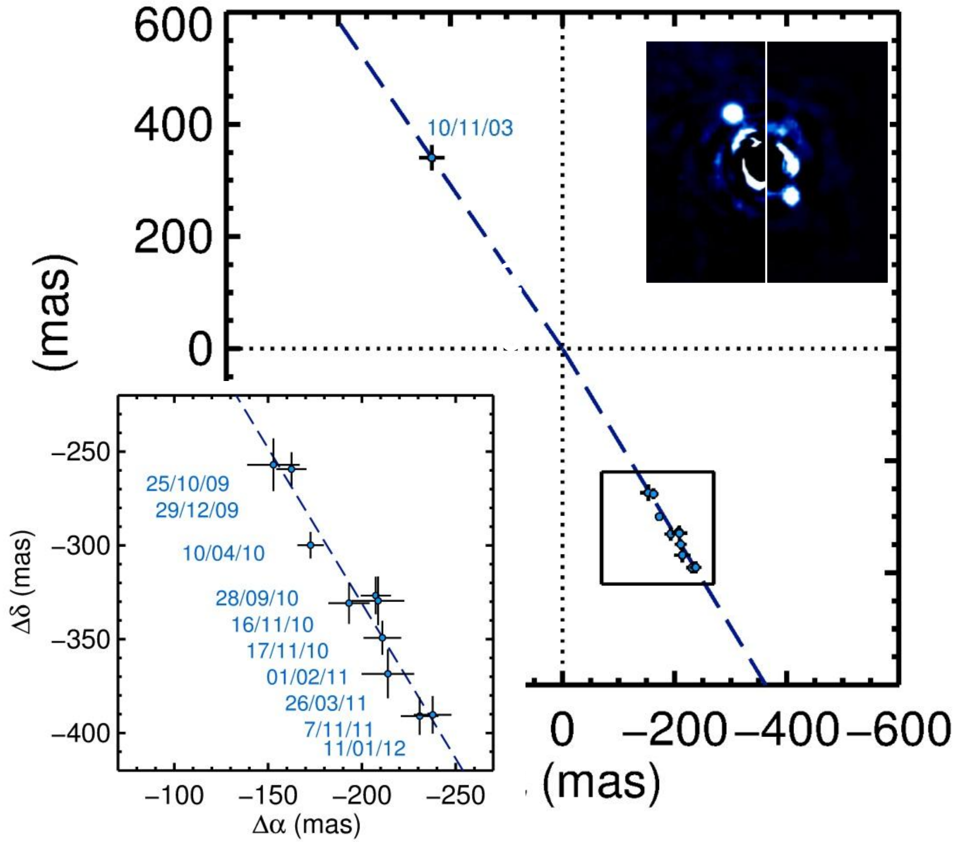
II/ EELT-CAM & IFU
b/ High-Contrast Imaging & Spectroscopy

★ 3/3 Architecture of planetary systems

Exoplanet's revolution
β Pic b,
P = 17 - 21 yrs; a = 8 - 10 AU
e < 0.17; i = 88.5 +- 1.5 deg
Ω = 212.5 +- 1.5 deg

Planet – Planet Interactions
Dynamical stability and resonances

Planet – disk connection
β Pic b in the inner warped disk
at the origin of the warp
Lagrange et al. 12



Chauvin et al. 12

II/ EELT-CAM & IFU

b/ High-Contrast Imaging & Spectroscopy

★ 3/3 Architecture of planetary systems

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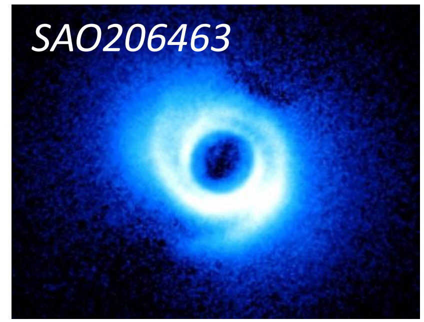
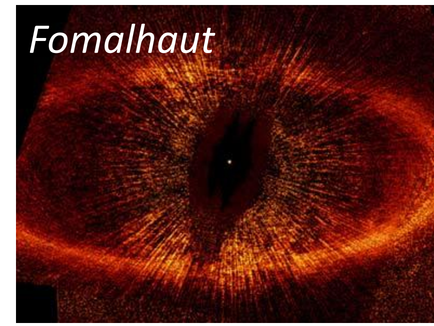
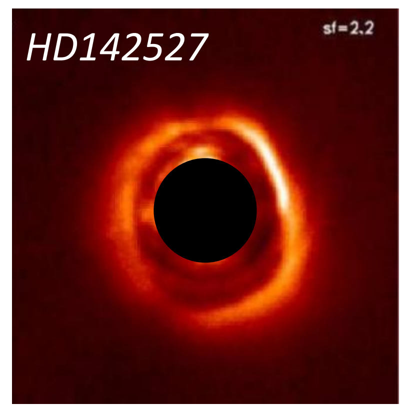
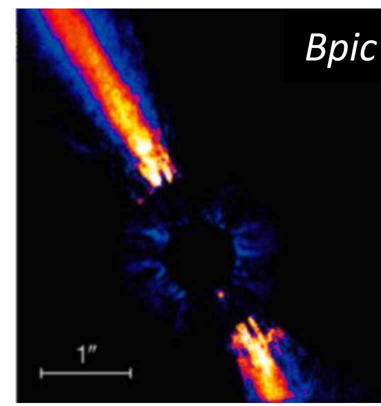


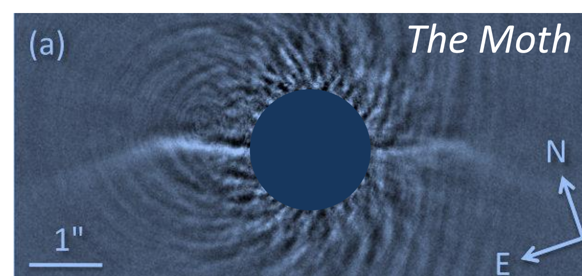


Planet – Planet Interactions
Dynamical stability and resonances





Planet – disk connection
β Pic b in the inner warped disk
at the origin of the warp
Lagrange et al. 12



Grady et al. 12; Kalas et al. 04;
Rameau et al. 12; Lagrange et al. 12;
Buenzli et al. 10

Conclusions

Exoplanetology with EELT- CAM & IFU: YES!

2022, a rich context for exoplanets

(HARPS N/S, SPHERE, GAIA, Cheops, ESPRESSO...)

- 10^4 planetary systems (< 200 pc) in astrometry
- Population of wide orbit planets probed by SPHERE, GPI

Definitively, CAM & IFU more for Giant Planet Characterization

a/ **High-precision astrometry** around VLMs (late-M, L, T and Y-types)

b/ **High-contrast Imaging & Spectroscopy** of known systems

- Mass – Luminosity relation (overlap GAIA & RV)
- Atmosphere of self-luminous giant planets
- Planetary system architecture and stability

BUT, important requirements:

Goals: - Astrometric precision = 5 - 10 µas/measurement

- Contrast = 10^{-7}-10^{-8} at 0.1-0.5"

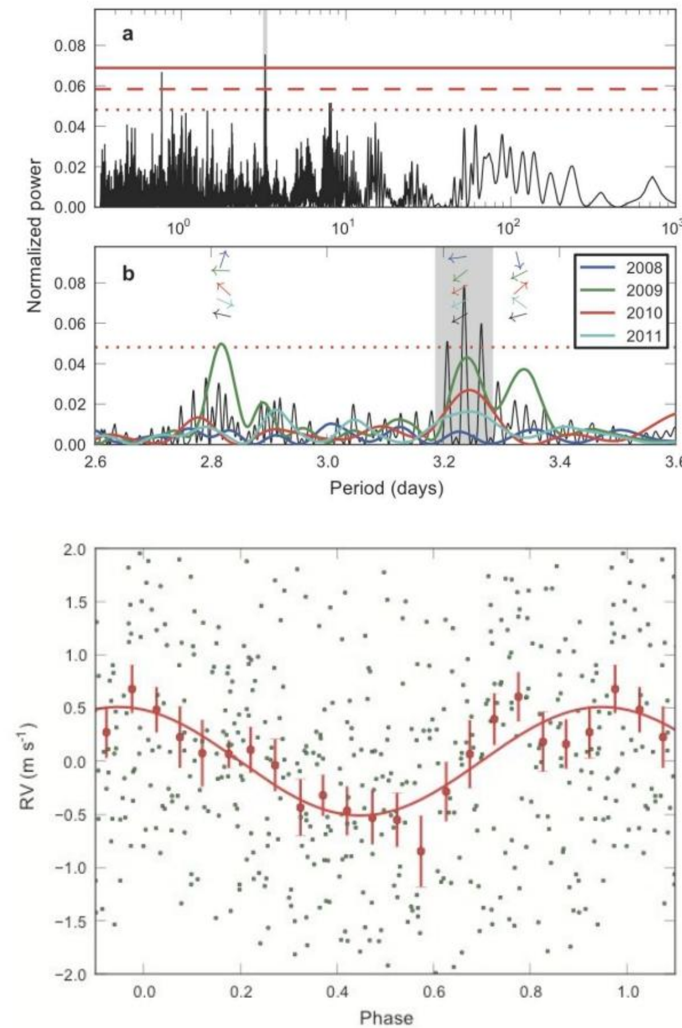
I- Introduction
Techniques & Key-Results

✱ Radial Velocity

. Indirect technique: Doppler shift
(low-activity stars)

. Orbital & Physical properties:
> M_p.sin(i), P, e, a, ω & T_0
> Spin-Orbit Alignment
> Architecture & Stability
> exo-Earths & Habitable Zone

. Statistics: more than 800 exoplanets
> Occurrence down to Super-Earths
> Mass/Orbital distributions
> Planetary host dependence:
(Fe/H, alpha-element, SpT, binarity…)
Udry & Santos 07



α Cen Bb, 1.13 M_{Earth}, 3.24 days,
Dumusque et al. 12