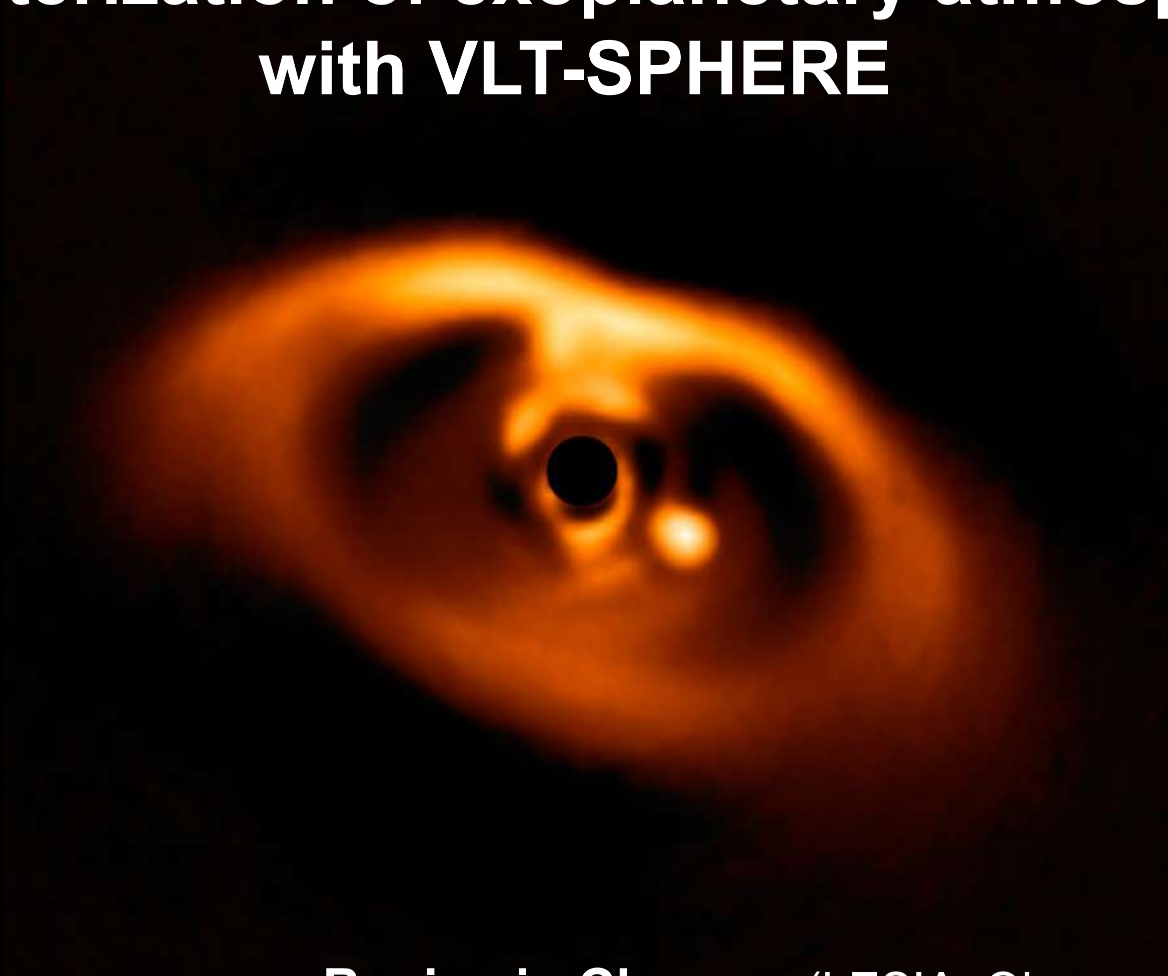
Characterization of exoplanetary atmospheres with VLT-SPHERE



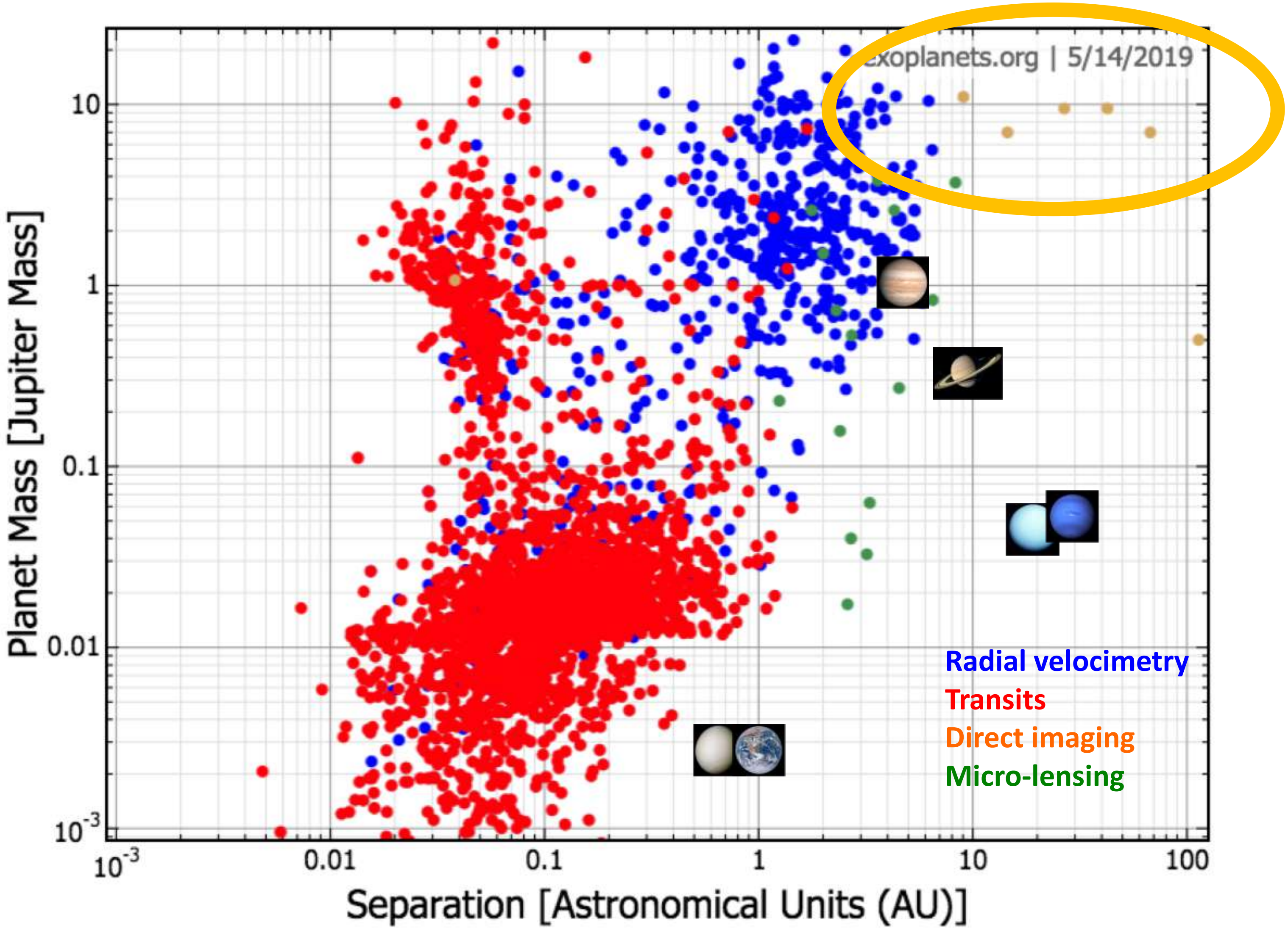
Benjamin Charnay (LESIA, Observatoire de Paris)

with the participation of:
M. Bonnefoy, A. Boccaletti, G. Chauvin, S. Lacour,
M. Nowak **& the SPHERE Consortium**

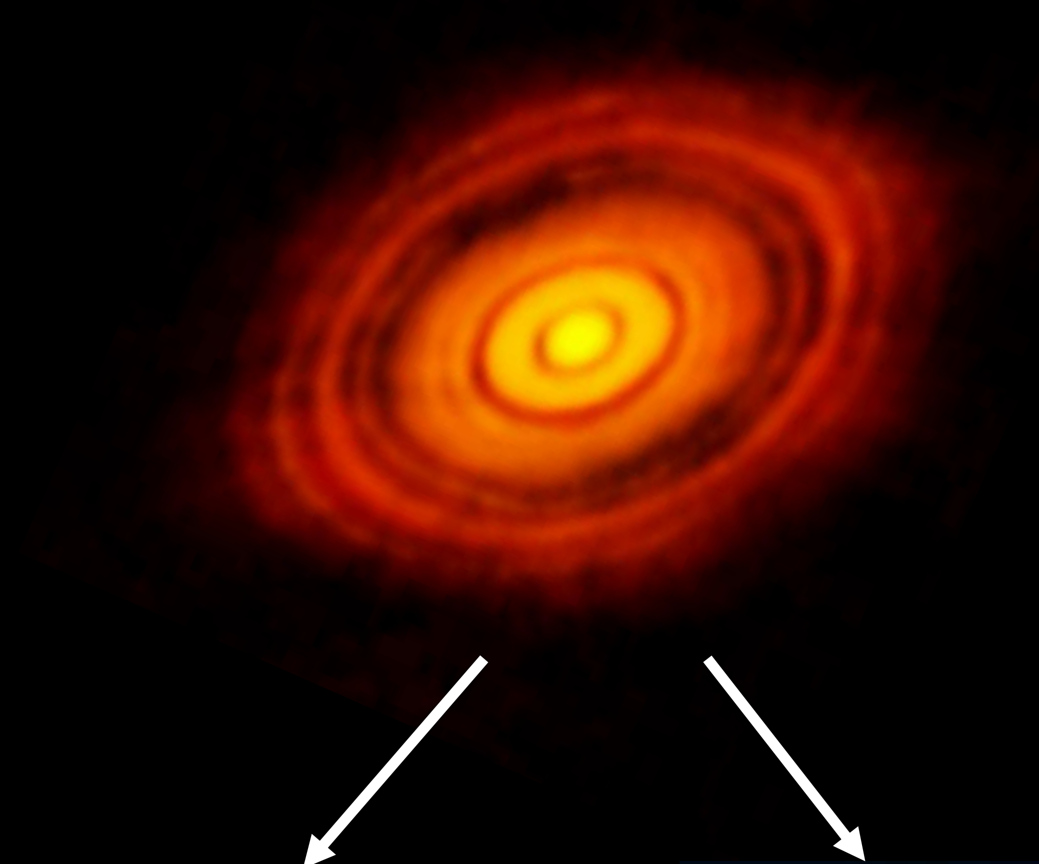
SPHERE
Spectro-Polarimetric
High-contrast
Exoplanet REsearch

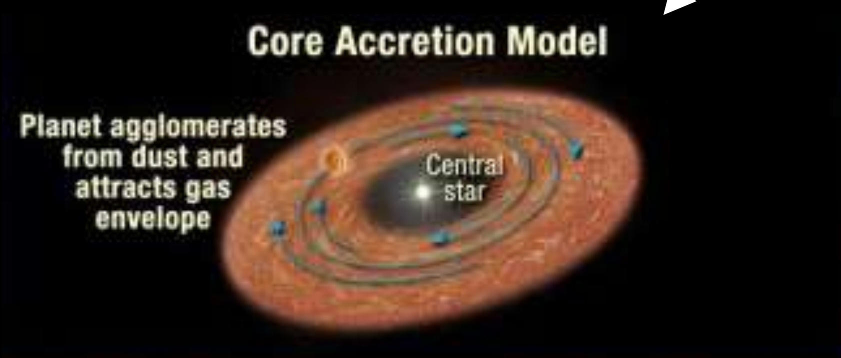
A portrait of the directly imaged planets

Imaged planets are massive and far from their host star

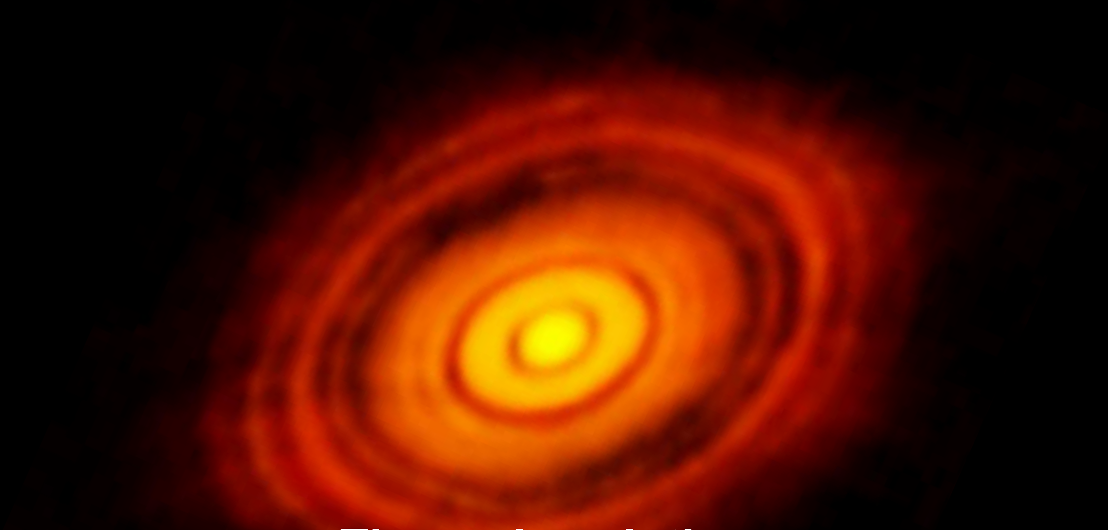


Giant planet formation

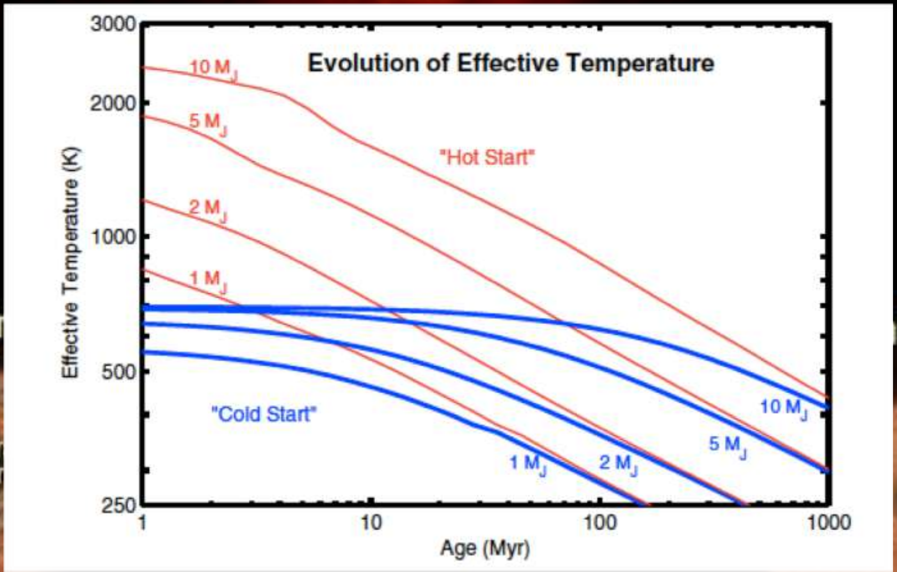


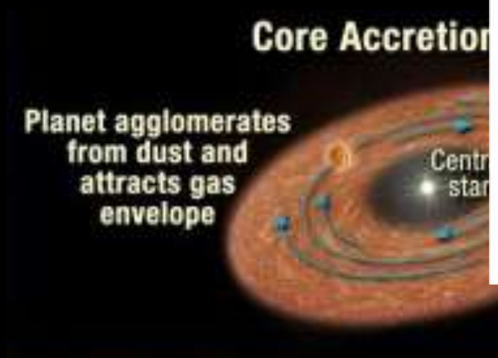


Atmospheres as probes of planetary formation



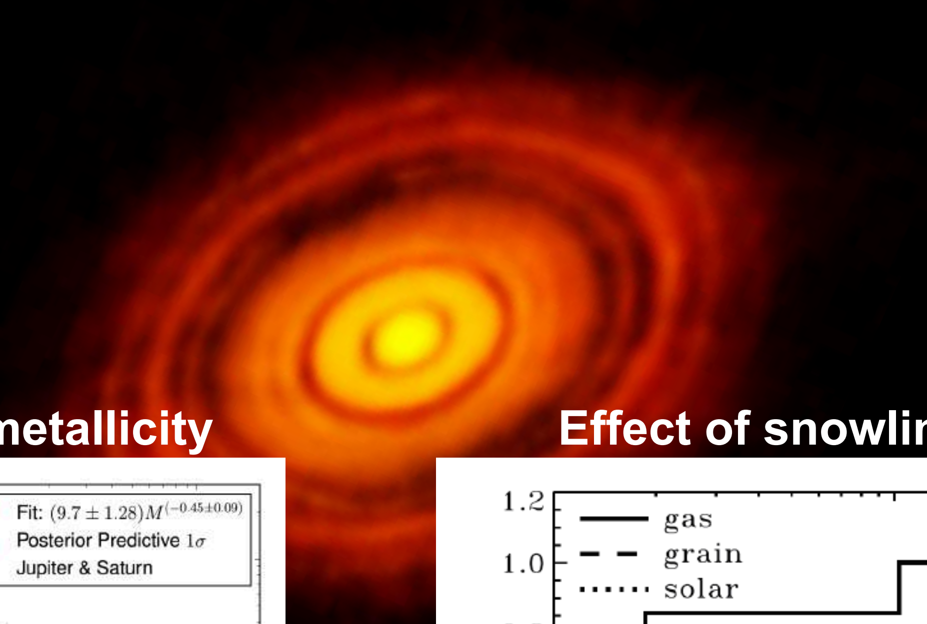
Thermal evolution



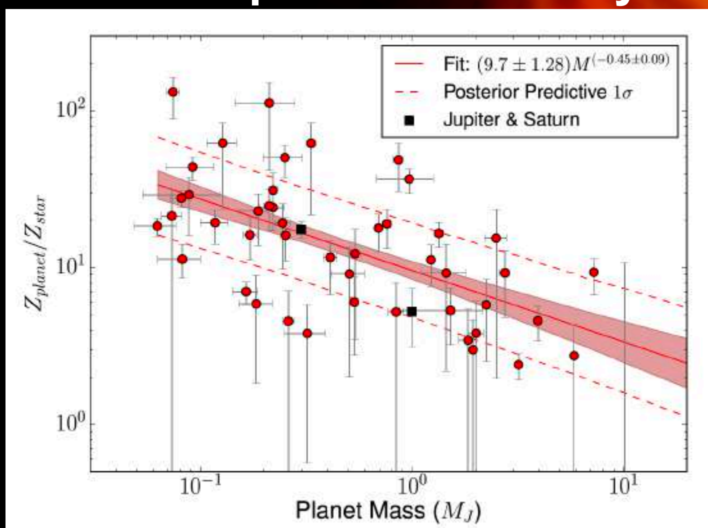


Spiegel & Burrows (2012)

Atmospheres as probes of planetary formation

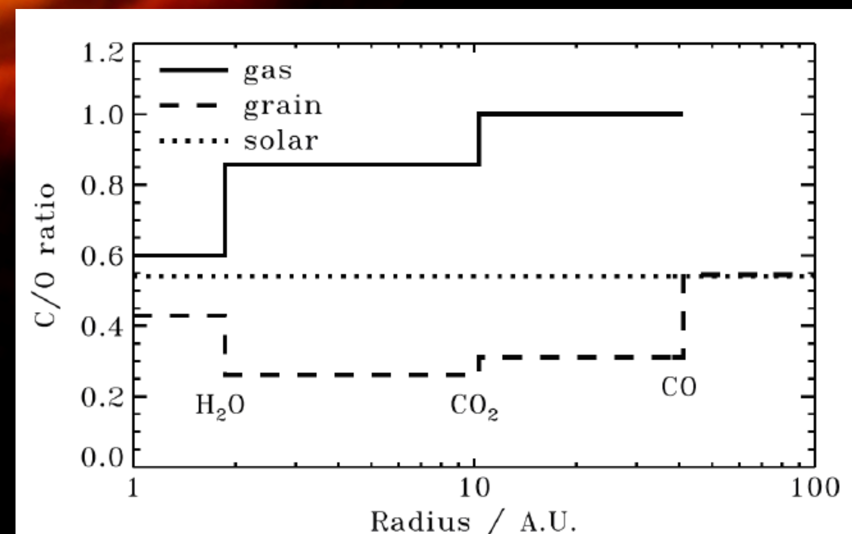


Atmospheric metallicity



Thorngren et al. (2016)

Effect of snowlines on C/O



Öberg al. (2011)

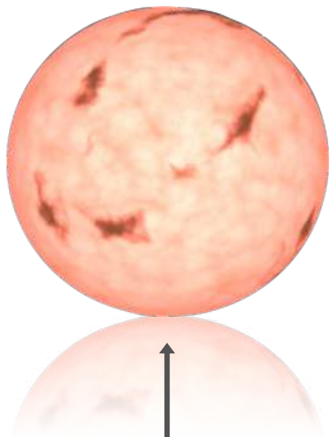
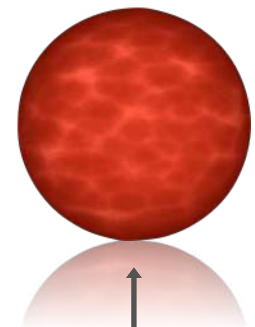
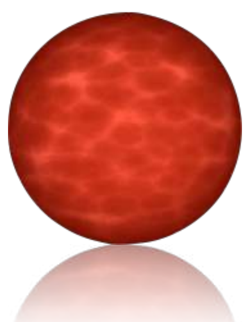
Luminosity and radius
Atmospheric composition
(metallicity, C/O,…)

↔

Formation mechanism
& interior

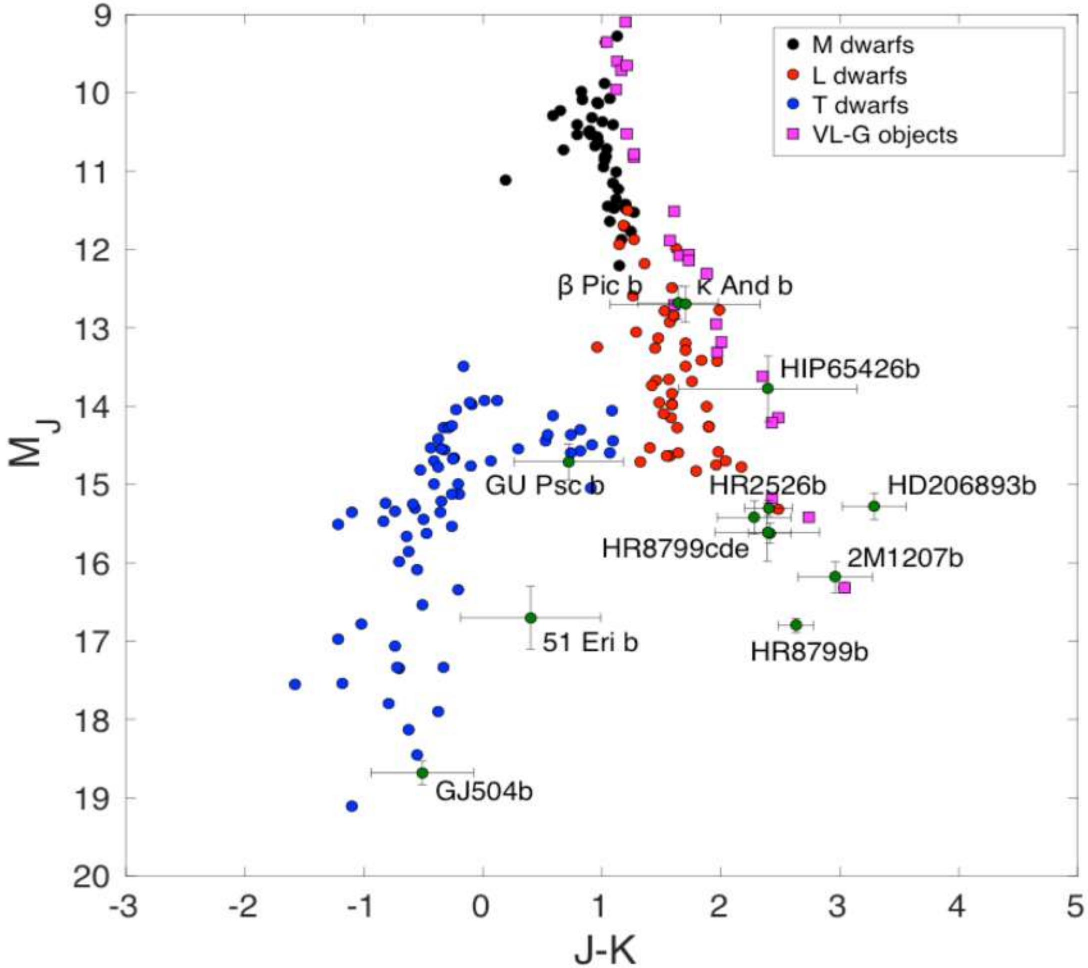
Comparison brown dwarfs vs imaged giant planets

Imaged planets are young ⇒ low surface gravity

	BROWN DWARF	PLANET
t=1 Myr	 M=65 M_{Jup} T_{eff}=3550 K log g=3.5	 M=6 M_{Jup} T_{eff}=2000 K log g=3.5
t=1 Gyr	 T_{eff}=2000 K log g=5.3	 T_{eff}=400 K log g=4.2

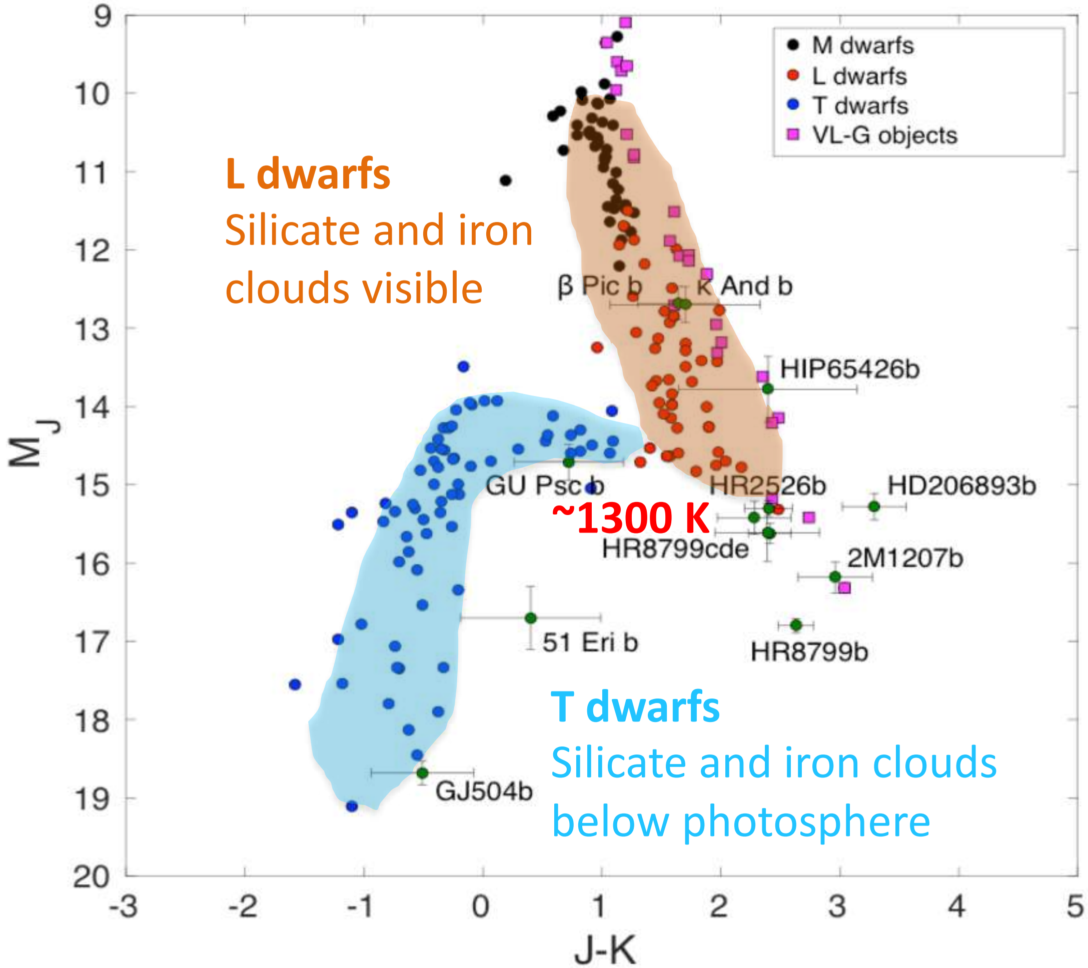
Photometry of brown dwarfs and young giant exoplanets

The LT transition



Photometry of brown dwarfs and young giant exoplanets

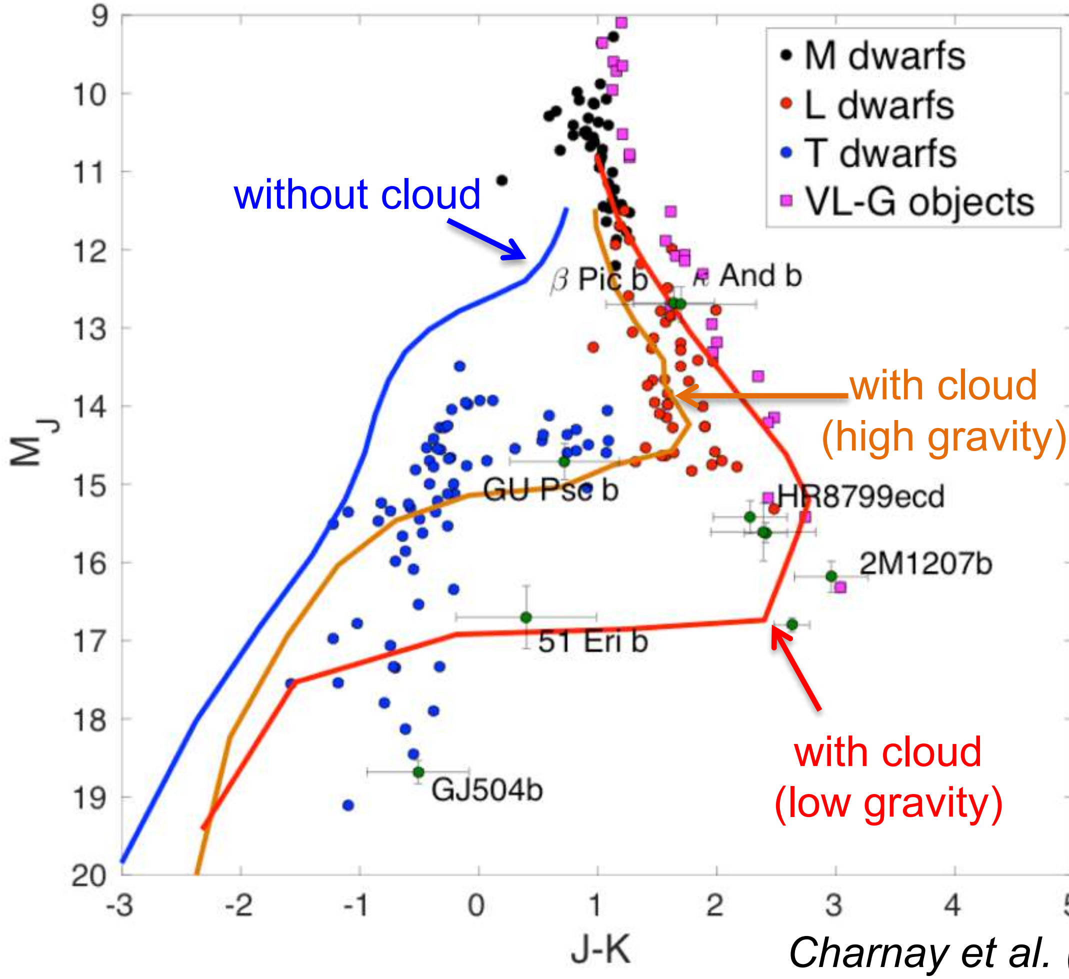
The LT transition



Photometry of brown dwarfs and young giant exoplanets

The LT transition

Model 1D Exo-REM

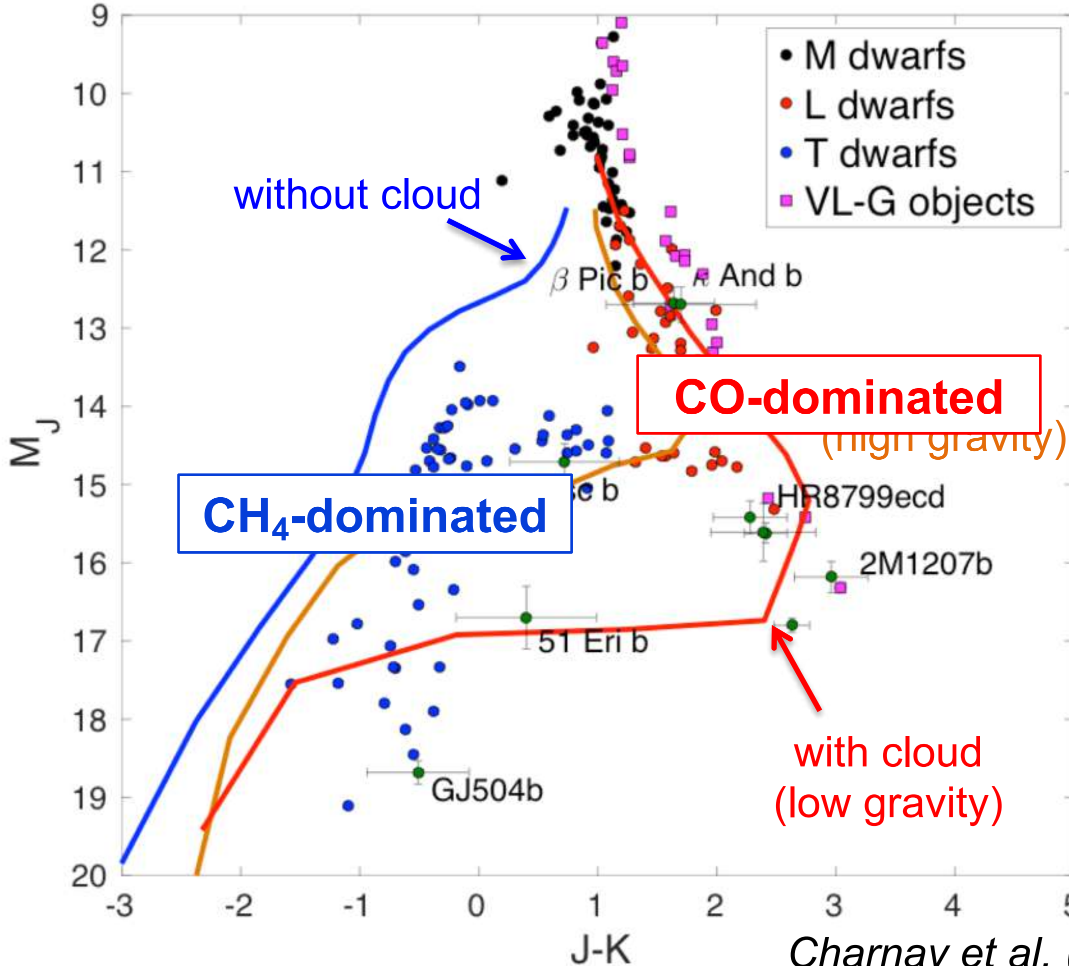


Charnay et al. (ApJ 2018)

Photometry of brown dwarfs and young giant exoplanets

The LT transition

Model 1D Exo-REM



Charnay et al. (ApJ 2018)

Alternative explanation:

Thermochemical instabilities producing reddening for L dwarfs

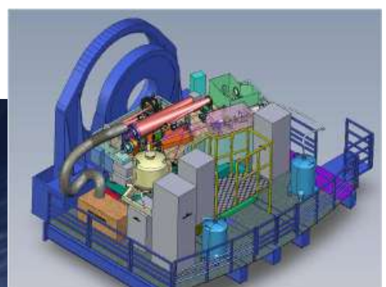
Tremblin et al. (2016, 2017)

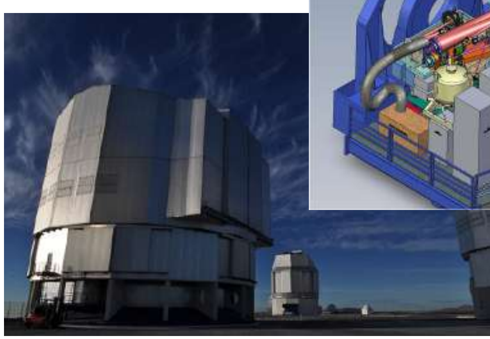
Current facilities for direct imaging

SPHERE
Spectro-Polarimetric High-contrast Exoplanet REsearch

European Consortium, VLT

- IR Camera
- IR spectrograph
- Visible highprecision polarimeter





US, Gemini South

IR spectrograph

Japan, Subaru

- IR Camera
- IR spectrograph

US, Chile

Visible Camera

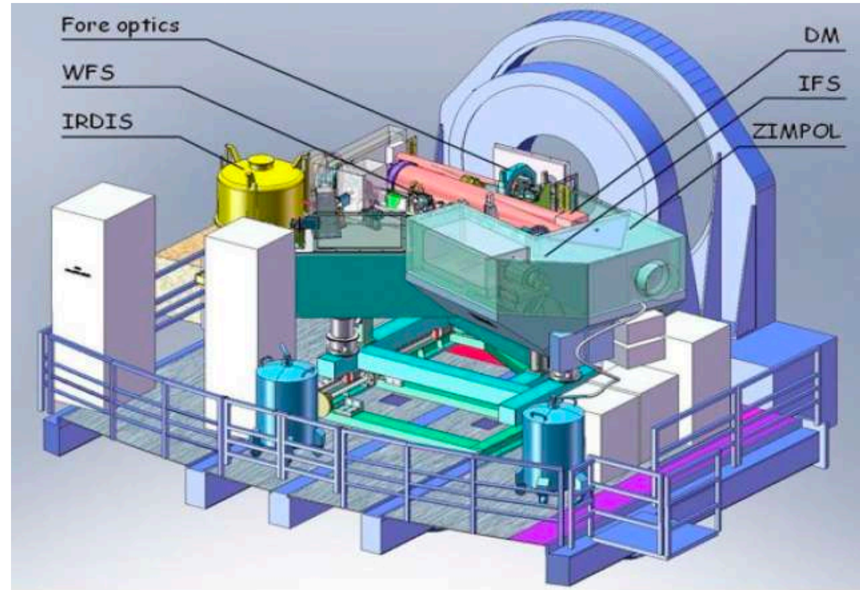
VLT-SPHERE

SPHERE
Spectro-Polarimetric
High-contrast
Exoplanet REsearch

1st light: May 4th, 2014
Operations: Feb. 2015

VLT-SPHERE

- **Contrast (planet/star) $\leq 10^{-5}$**
- **Combine Ex-AO and advanced coronography**
- **GTO: 260 nights over 5 years**
- **SHINE Program** (200 nights): survey for exoplanets of 400-600 young stars (< 800 Myrs, R mag < 11.5)

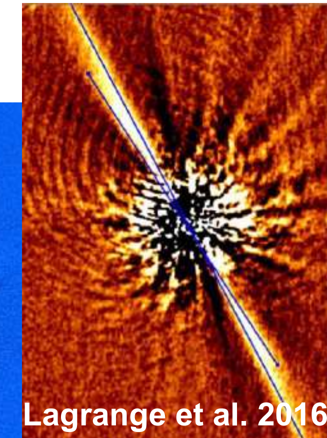


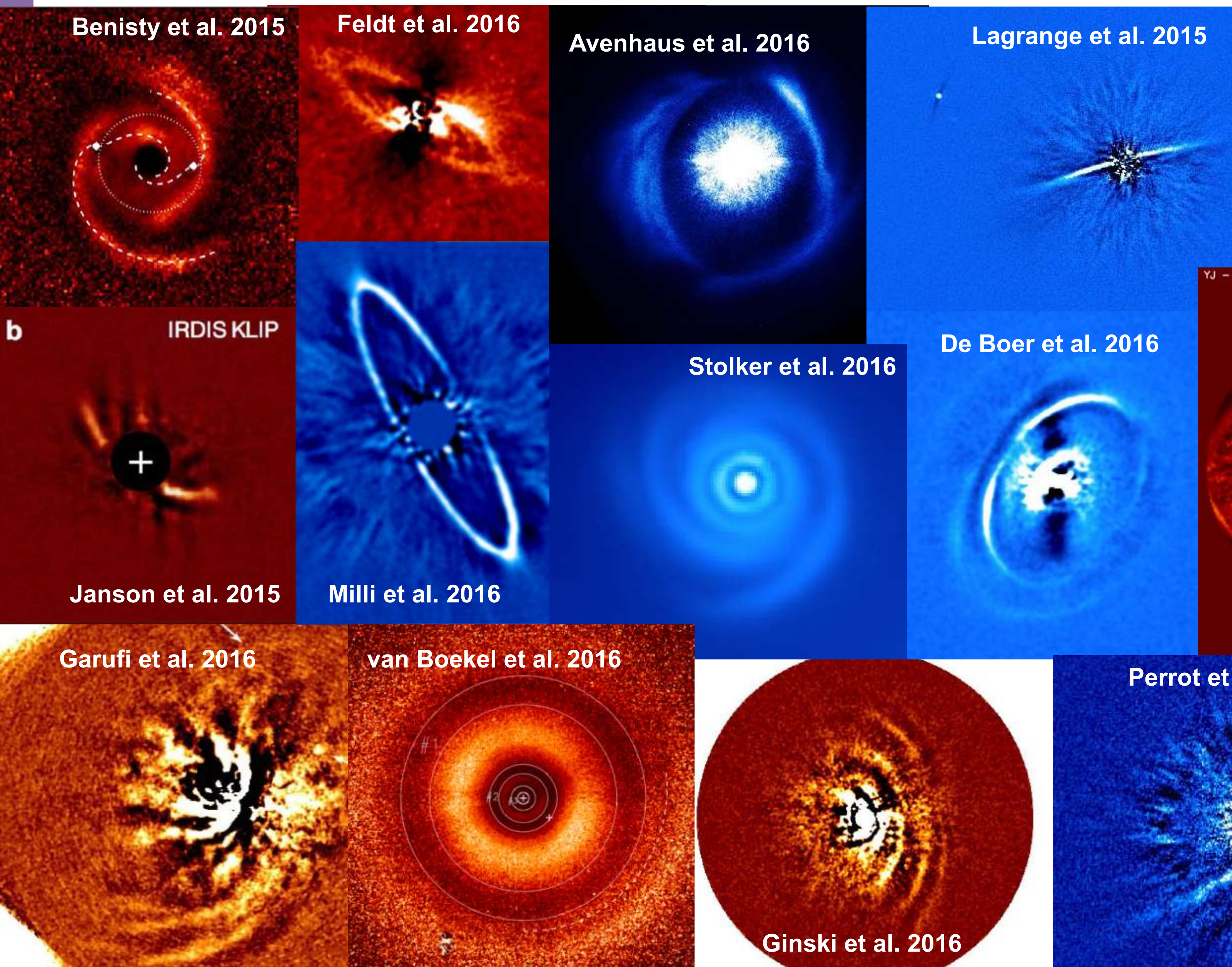
Beuzit et al. (2008, 2019)

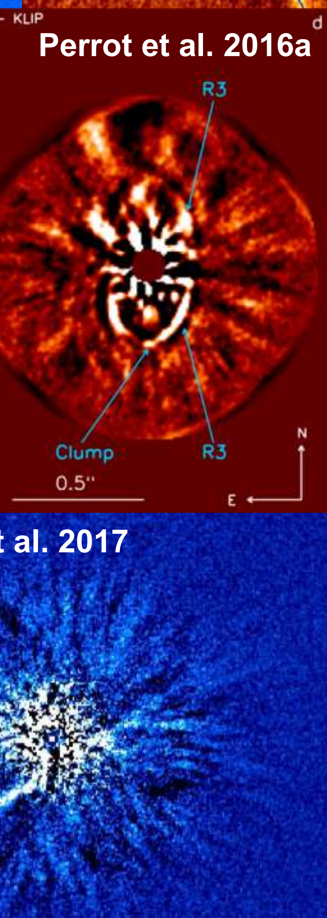
	IFS	IRDIS	ZIMPOL
FOV	1.73" x 1.73"	11" x 11"	3.5"x3.5"
SPECTRAL RANGE	0.95- 1.65 µm: YJH	0.95-2.32 µm: YJHK	500 - 900 nm
SPECTRAL CHANNELS	39	2	2
POLARIMETRY	X	√	√

VLT-SPHERE

Harvest of disks

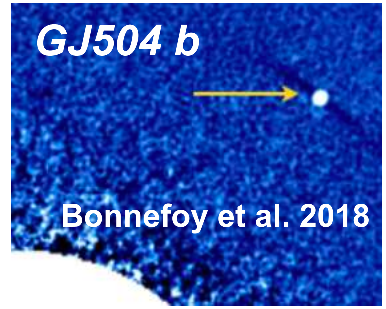


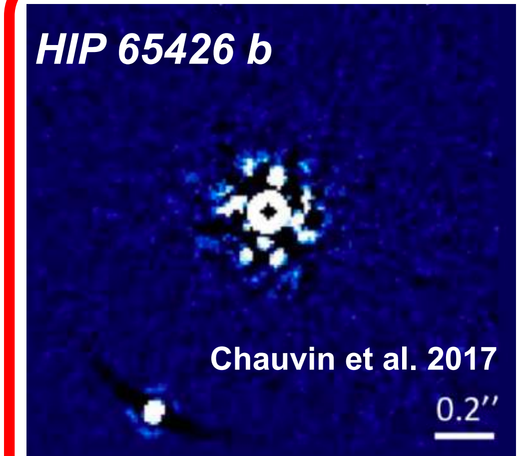


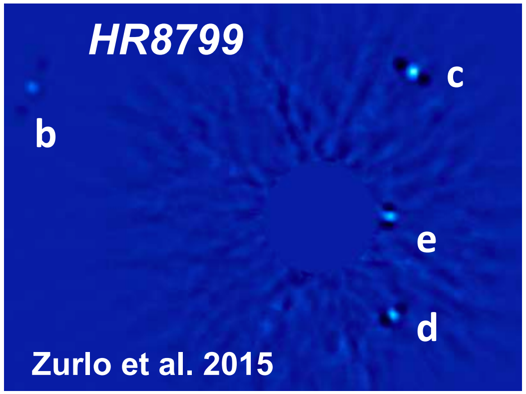


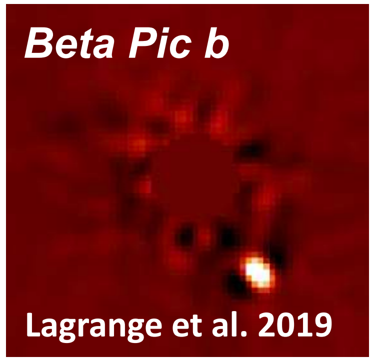
VLT-SPHERE

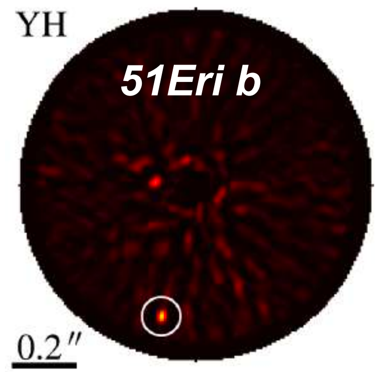
2 new planets
Characterization of several YGP & BD



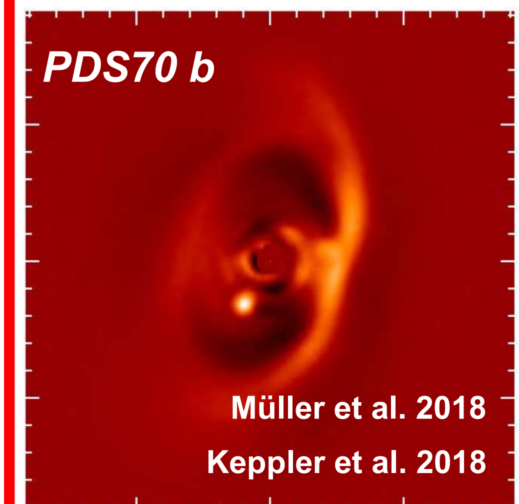


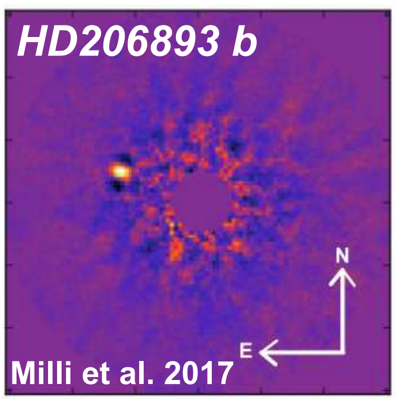


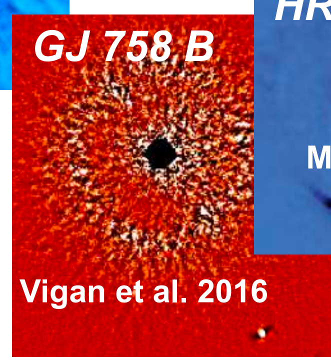


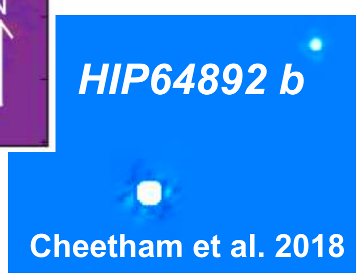


Samland et al. 2017



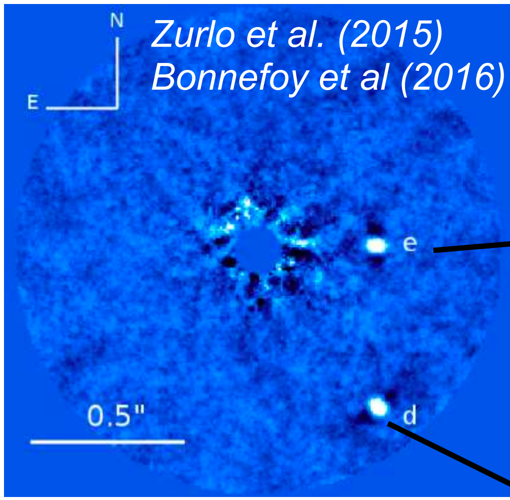


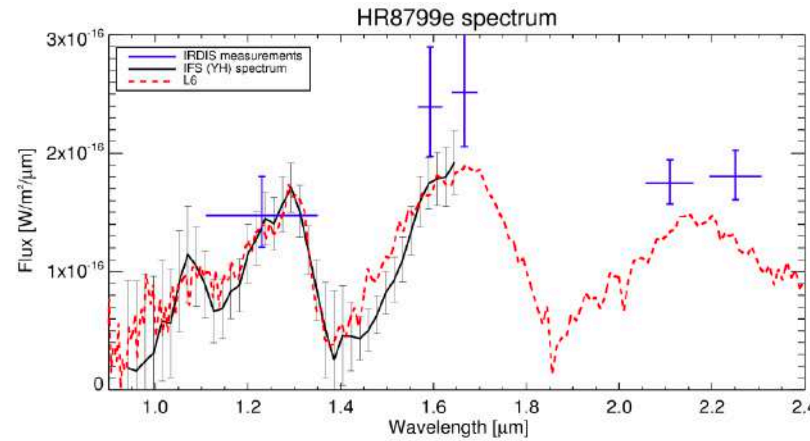


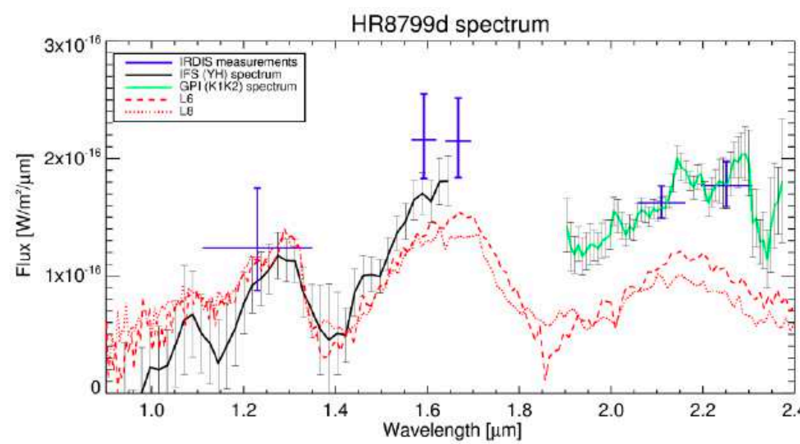


Exploring the L/T transition

The HR8799 system







HR8799 de:

Age ~ 30 Myr

Distance = 16/24 au

Masse ~ 7 M_{jup}

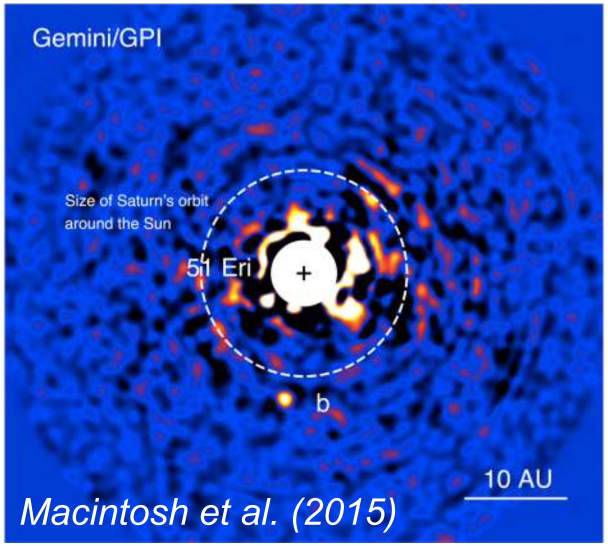
T_{eff} ~ 1100-1200 K

Empirical fitting:

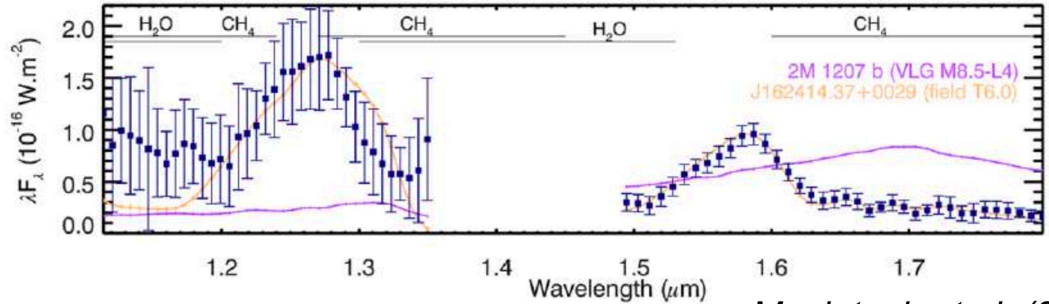
- Best SED fitting for L6-L7 dwarf (delayed LT transition)
- Additionnal reddening is needed for K band

Exploring the L/T transition

51 Eri b

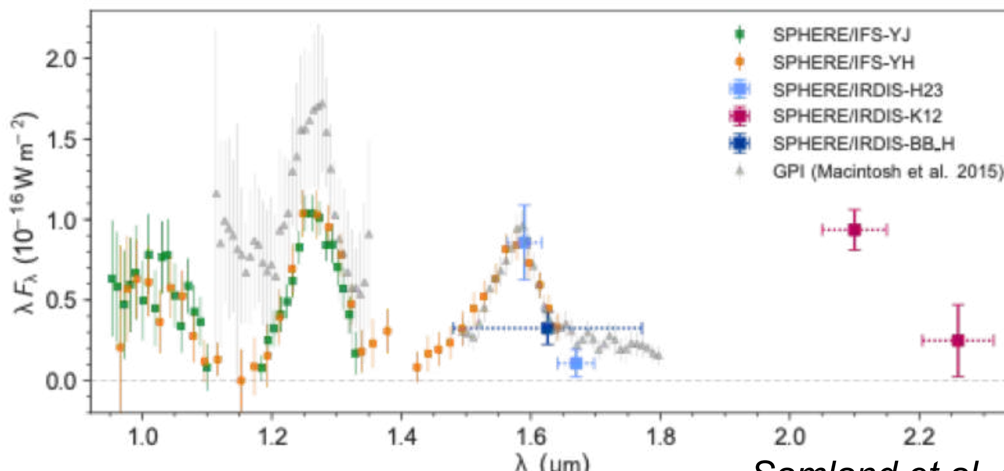


GPI spectrum: 1.13-2.19 µm / R = 35 (J) to 83 (K)



Macintosh et al. (2015)

SPHERE: R~30/50 IFS spectra up to 1.64 µm
+ H and K band photometry



Samland et al. (2017)

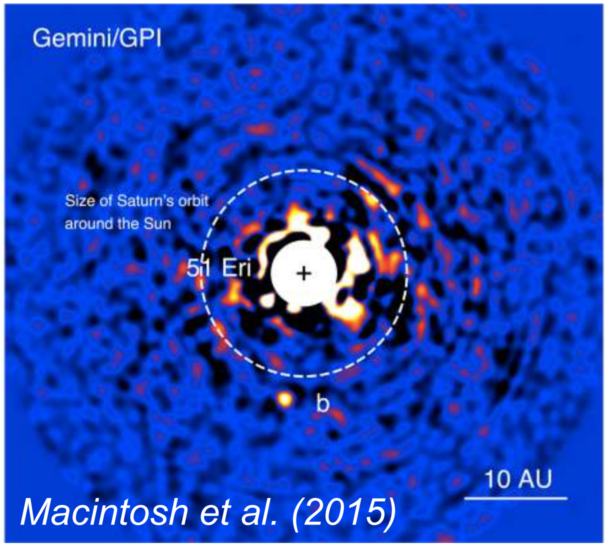
51 Eri b:
Age ~ 20 Myr
Distance : 14 au
Masse ~ 2 M_{Jup}
T_{eff} ~ 600-750 K

Photometric and spectral Fitting:

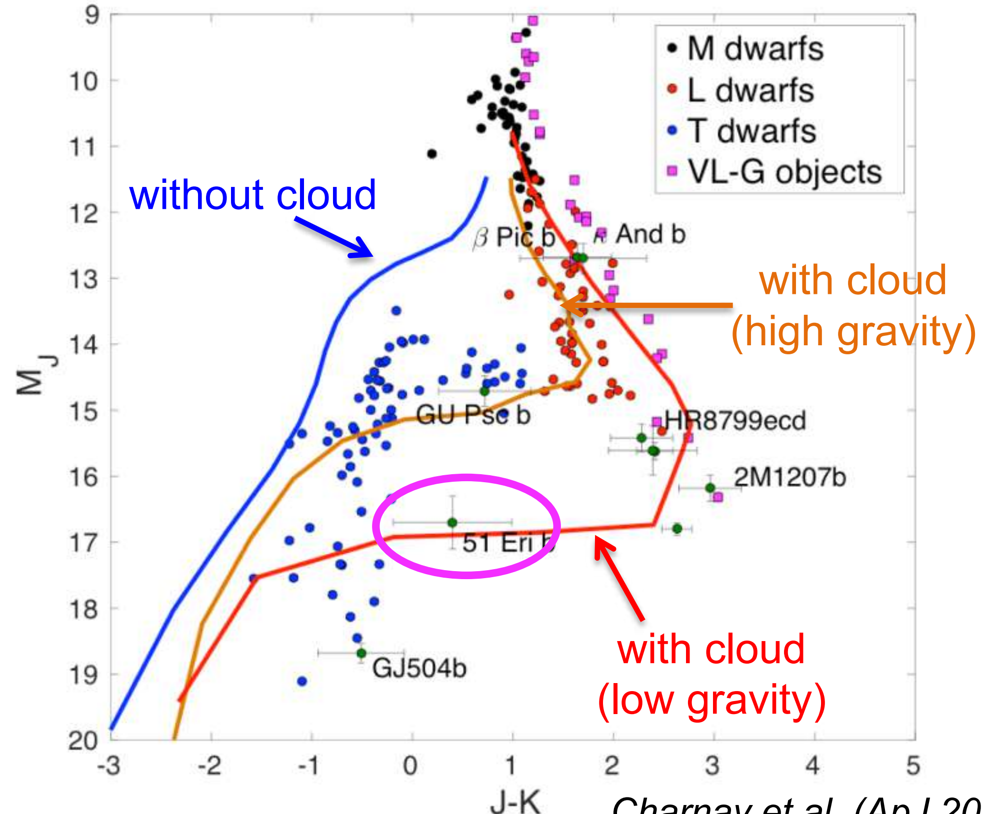
- T-type object (CH_4-dominated)
- Additionnal reddening by cloud needed

Exploring the L/T transition

51 Eri b



51 Eri b:
Age ~ 20 Myr
Distance : 14 au
Masse ~ 2 M_{Jup}
T_{eff} ~ 600-750 K



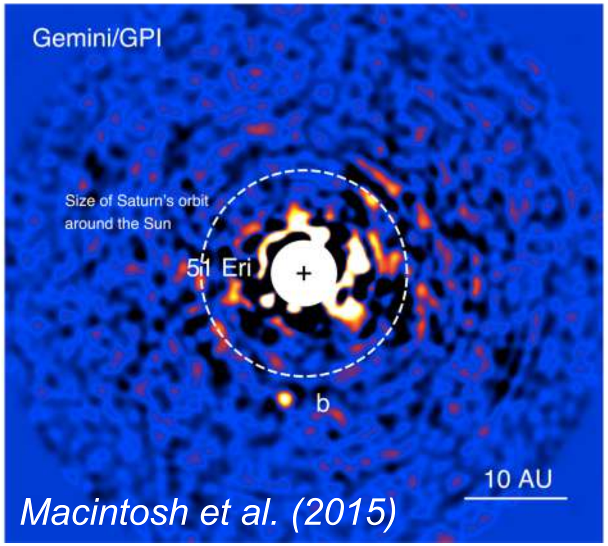
Charnay et al. (ApJ 2018)

Photometric and spectral Fitting:

- T-type object (CH_4-dominated)
- Additionnal reddening by sulfide clouds or transitioning LT object at low gravity

Exploring the L/T transition

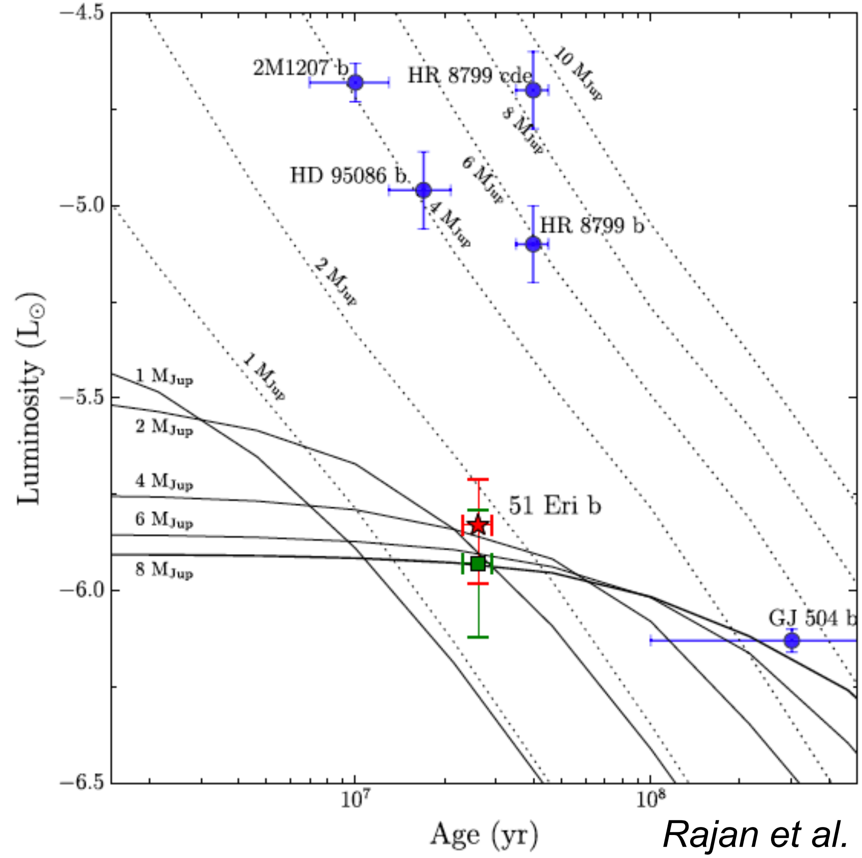
51 Eri b



Macintosh et al. (2015)

<u>51 Eri b:</u>
Age ~ 20 Myr
Distance : 14 au
Masse ~ 2 M_{Jup}
T_{eff} ~ 600-750 K

Luminosity evolution

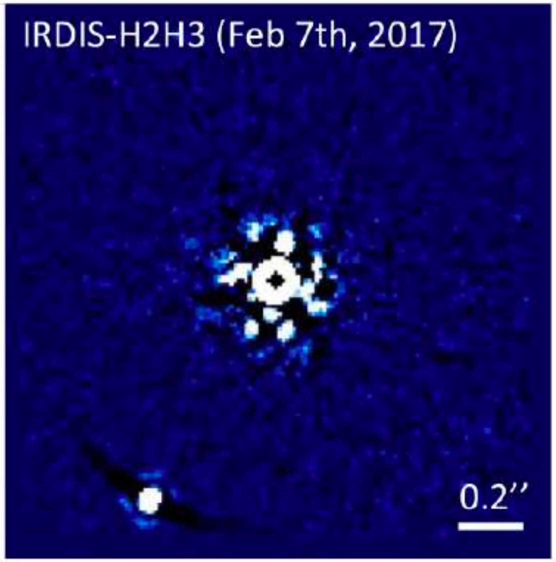


Rajan et al. (2017)

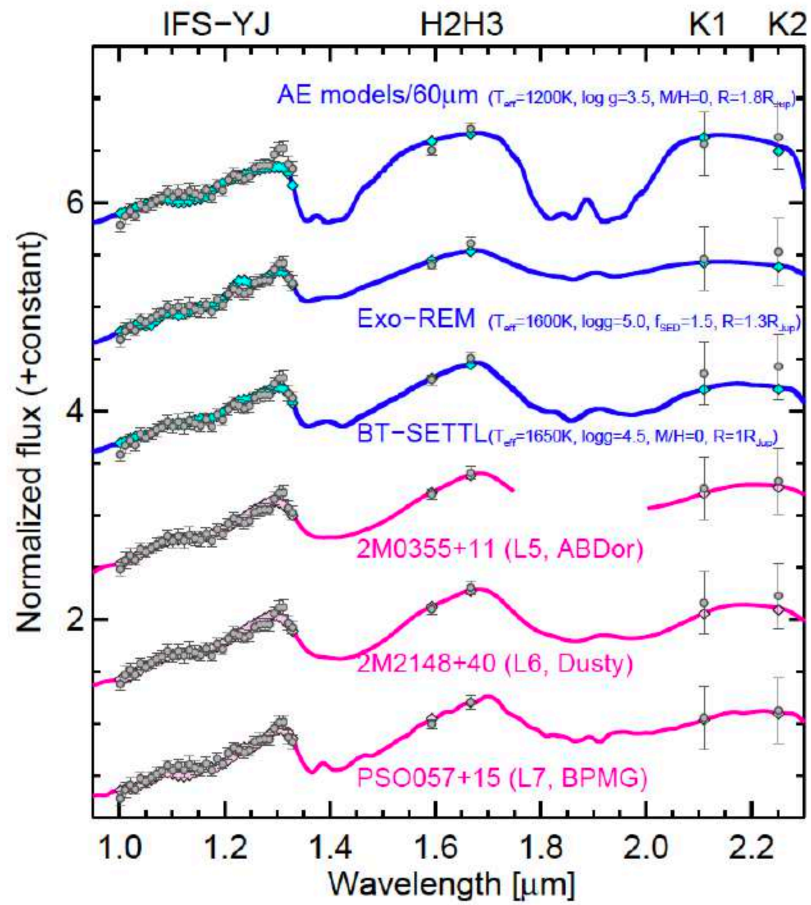
<u>Thermal evolution:</u>
Compatible with a "hot-start » (2 M_{jup})
and a "cold-start" (>2M_{jup})
⇒ need astrometric mass estimations (Gaia)

New planets

HIP65426 b



Chauvin et al. (2017)

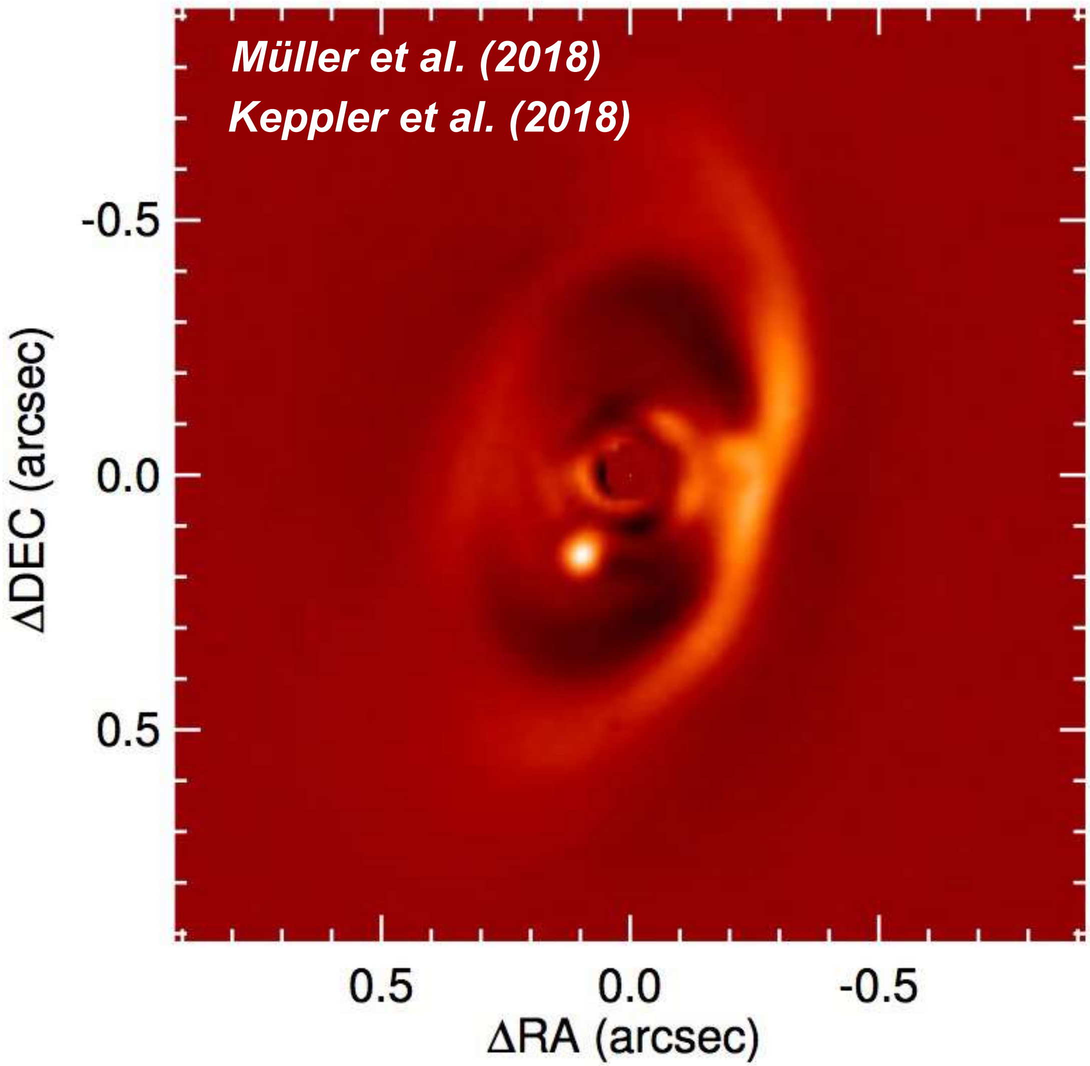


HIP65426 b:
Age = 14 ± 4 Myr
Distance ~ 100 au
Masse ~ 6-12 M_{Jup}
T_{eff} ~ 1600 K

Spectral fitting:
- Mid-L spectral type
(intermediate between β Pic b & HR8799bcde)
- Reddening by thick cloud

New planets

PDS 70 b protoplanet



Star:

- 0.7 $M_\odot$
- 5.4 ± 1 Myr
- 113 ± 0.5 pc

Disk:

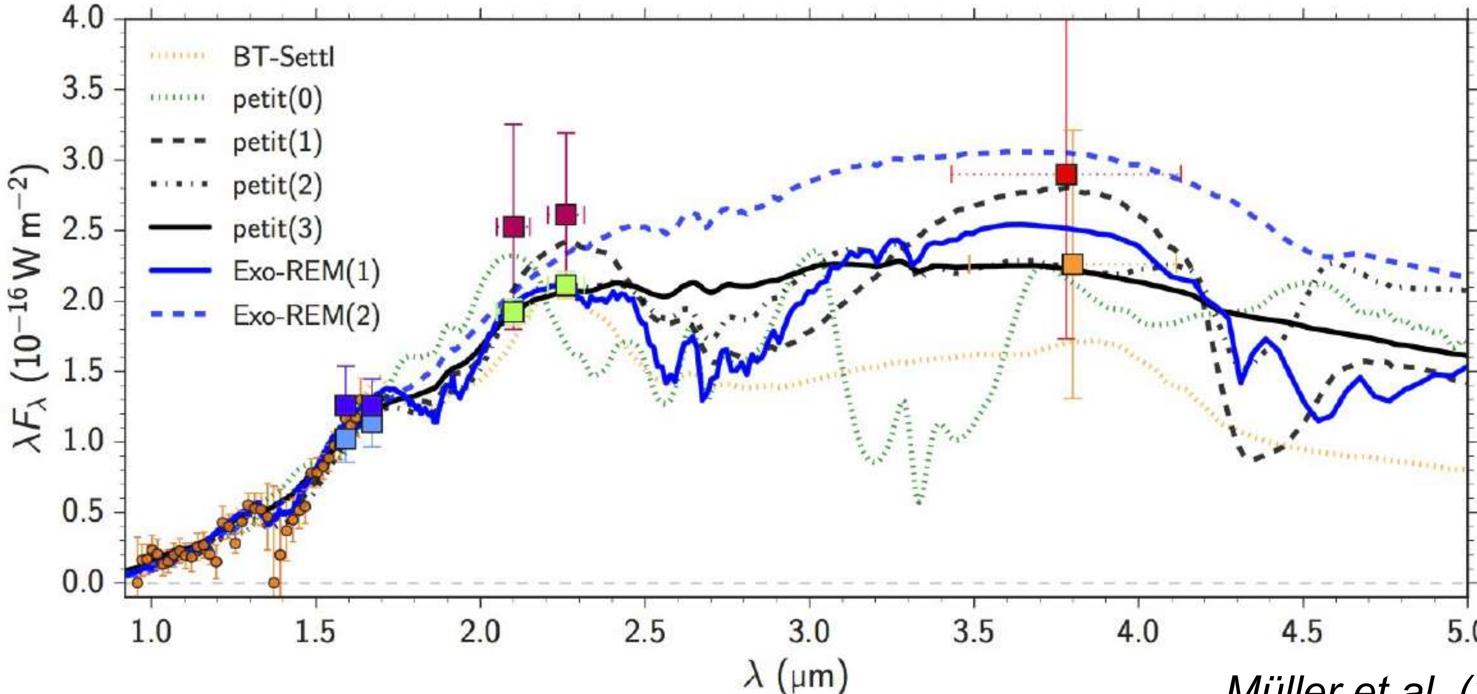
- 65 au gap
- gas and dust (transition disk)

Candidate:

- Co-moving / 4 years
- 5-10 M_{Jup}
- 22 au orbit
- red colors

New planets

PDS 70 b protoplanet



Müller et al. (2018)

<u>PDS 70 b:</u>
Age ~ 5 Myr
Distance : 22 au
T_{eff} ~ 1050-1600 K
Gravity: log(g) ≤ 3.5
Radius ~ 1.4-**3.7** R_{Jup}

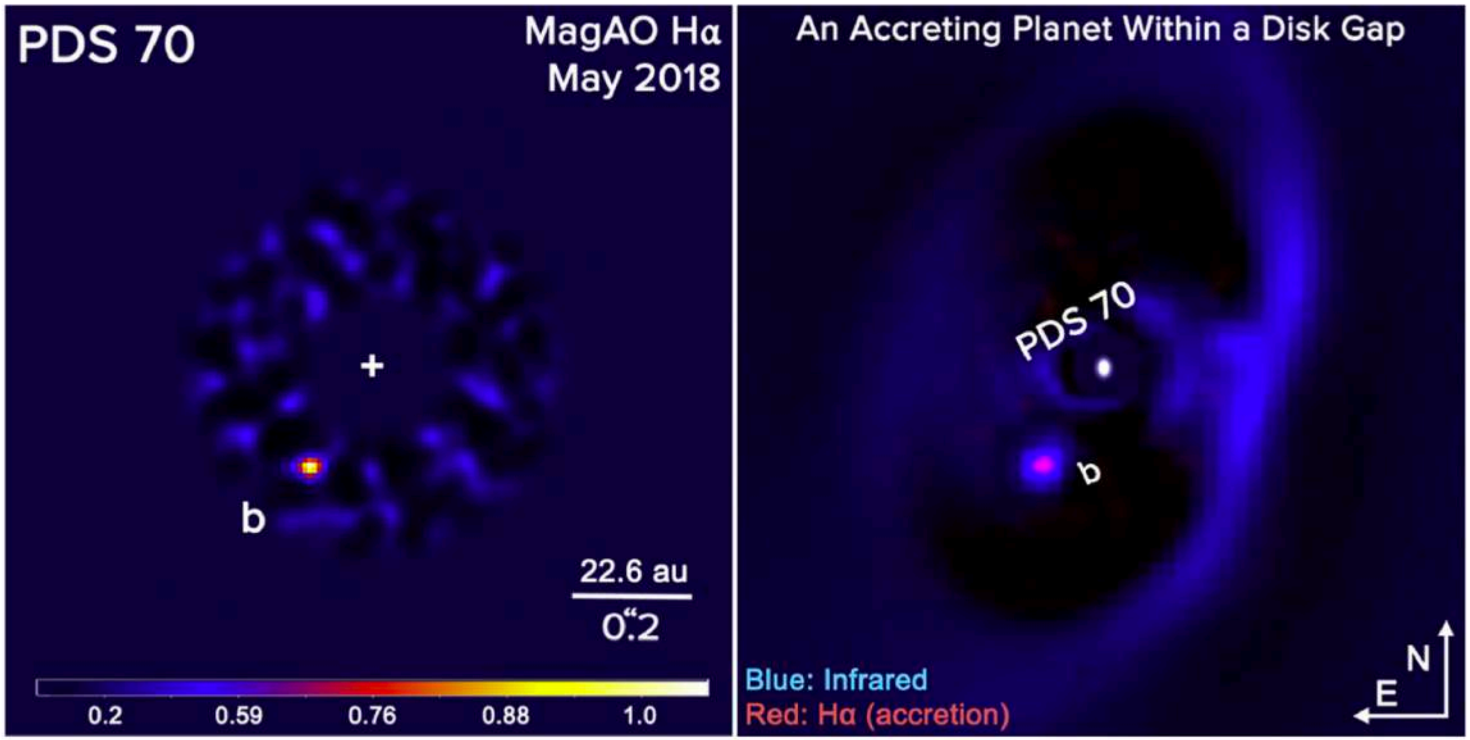
Models with clouds & very low gravity

Large radius ⇒ physical ?

(accretion, absorption/emission from circumplanetary disk ?)

New planets

PDS 70 b protoplanet



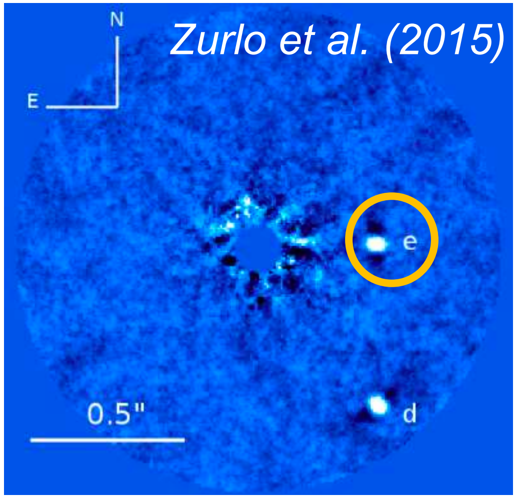
Wagner et al. (2018)

Hα luminosity ⇒ Accretion of hydrogen

$(\dot{M} = 10^{-8\pm1} M_{Jup} yr^{-1})$

Atmospheric characterization with GRAVITY/VLTI

HR8799 e



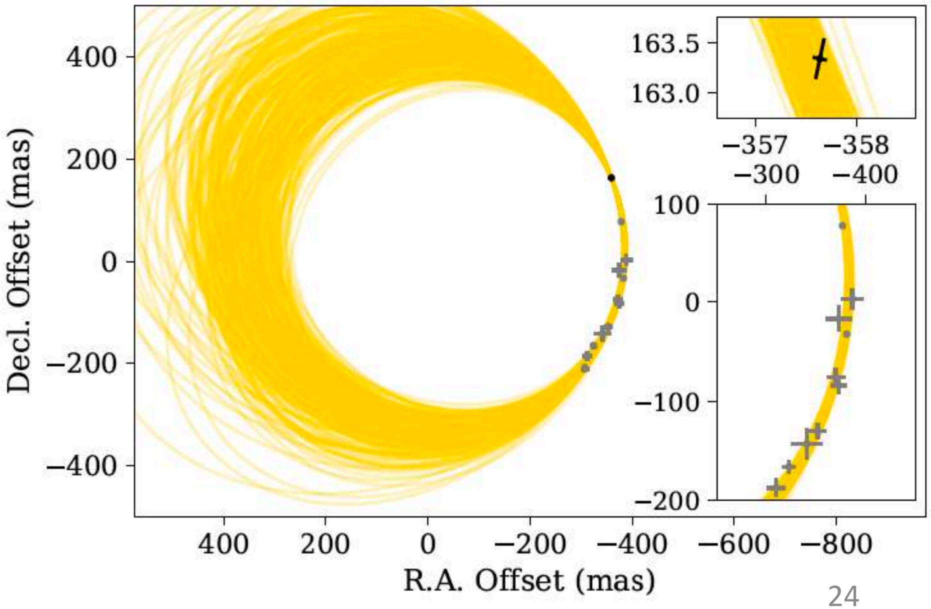
eso1905 — Science Release

GRAVITY instrument breaks new ground in exoplanet imaging

Cutting-edge VLTI instrument reveals details of a storm-wracked exoplanet using optical interferometry

27 March 2019

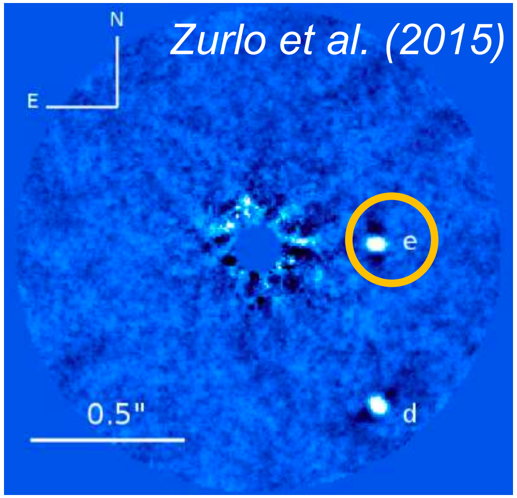
➡ **Very accurate astrometry (0.1 mas)**
Non-coplanar orbit



GRAVITY Collaboration, Lacour et al. (2019)

Atmospheric characterization with GRAVITY/VLTI

HR8799 e



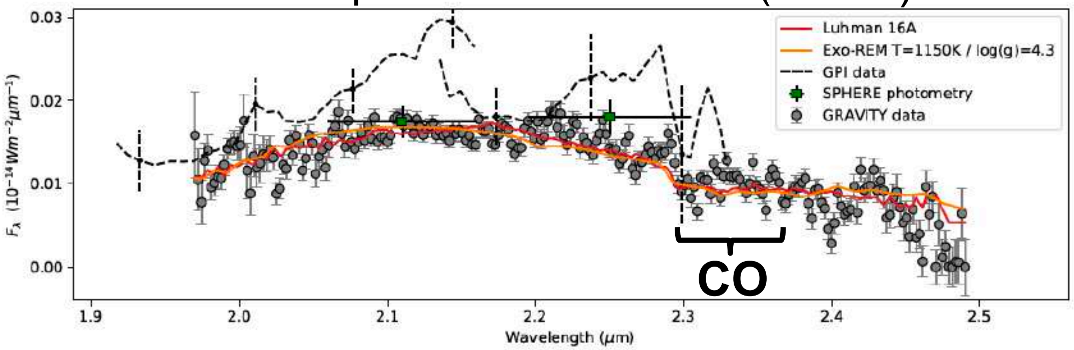
eso1905 — Science Release

GRAVITY instrument breaks new ground in exoplanet imaging

Cutting-edge VLTI instrument reveals details of a storm-wracked exoplanet using optical interferometry

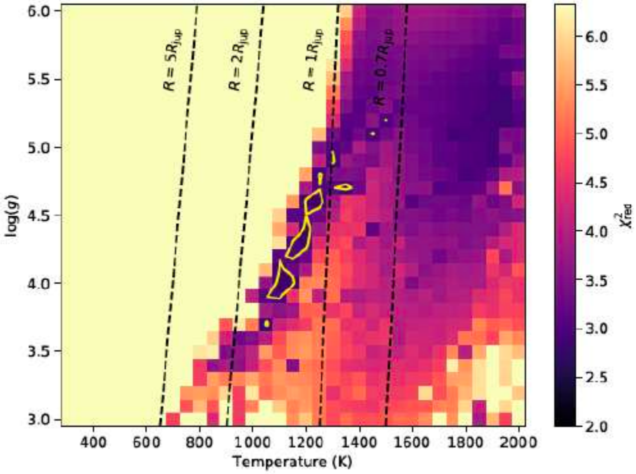
27 March 2019

K spectrum of HR8799e (R=500)



GRAVITY Collaboration, Lacour et al. (2019)

Fitting with Exo-REM

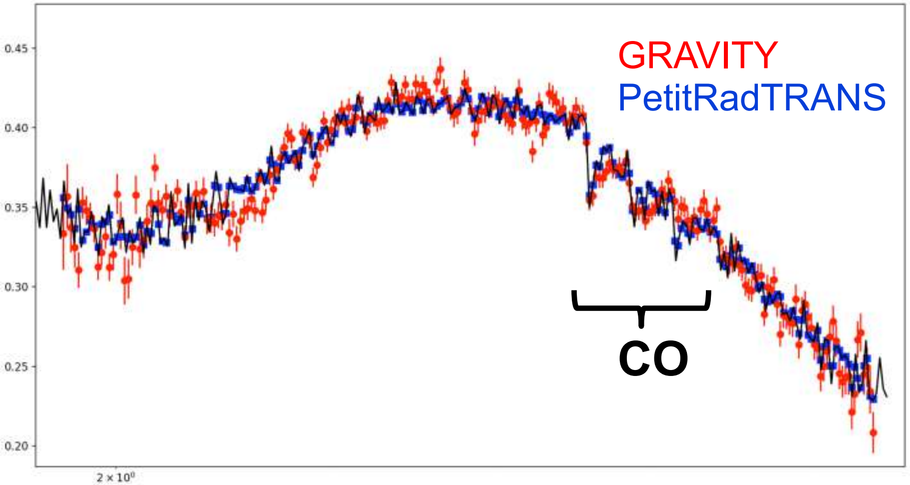


T_{eff}~1150 K with thick clouds
CO dominated ⇒ chemical disequilibrium

Atmospheric characterization with GRAVITY/VLTI

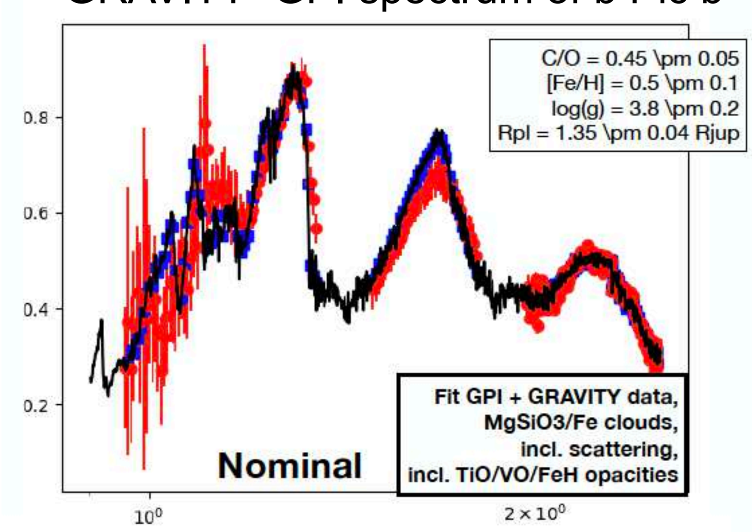
β Pictoris b

GRAVITY spectrum of b Pic b



Nowak et al. (in prep)

GRAVITY+GPI spectrum of b Pic b



➡ **Access to C/O in the K band (substellar value)**

Complementarity with SPHERE & GPI
Preparation for futures observations (JWST, ELTs)

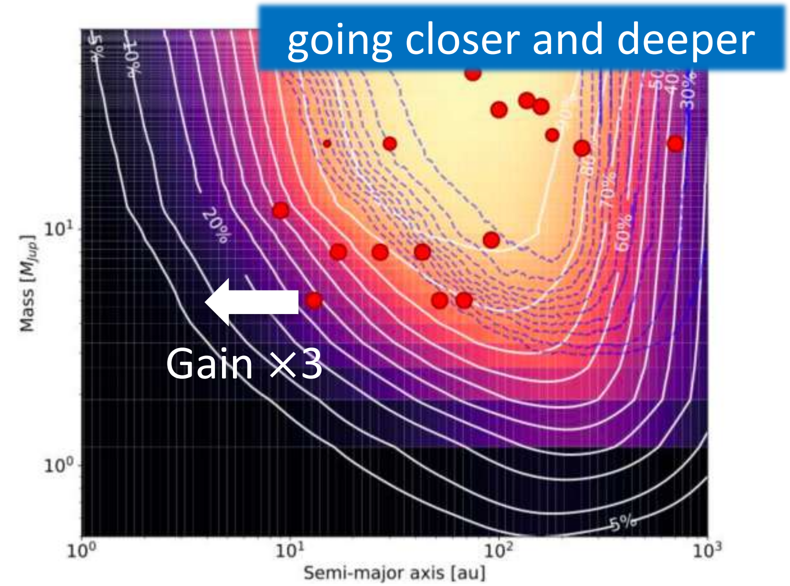
Futur improvements: SPHERE+

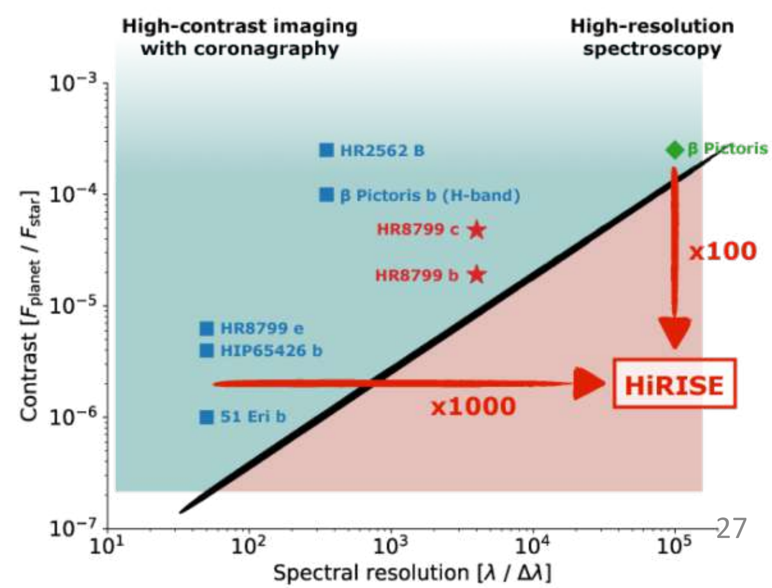
➢ **Decreasing inner working angle:**
XAO (DM) 1 kHz ⇒ 3kHz

➢ **Looking at fainter stars (ex Taurus):**
Wavefront Sensing : Pyramid in the IR
⇒ gain ~2 mag (G, M stars)

➢ **Medium Resolution:**
new spectrograph SPHERE
(for detection + characterization)

➢ **High Resolution:**
characterization by coupling with CRIRES+
(Project HiRISE, PI: A. Vigan)





Take-home messages

- **5 years since first light from SPHERE**
(>80 refereered publications on young giant planets, disks and solar system bodies)

- **2 new exoplanets**, including PDS 70 b, a unique case to test models of planetary formation and planet-disk interactions

- With other high-constrast instruments, **catalogue of young giant planets**

- Young giant exoplanets appear more cloudy than field brown dwarfs
(same issue for transiting exoplanets)

- To measure molecular abundances in cloudy atmospheres, we need:
    1) longer wavelength (JWST, ARIEL)
    2) medium/high resolution (GRAVITY, ELTs, SPHERE+)

Young companions **(Courtesy G. Chauvin)**