Exo-Abundances Workshop, May 12th – 14th, Grenoble

E-ELT's View of Exoplanetary Atmospheres

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In Collaboration with ESO-PST,
and E-ELT CAM, IFU, MIDIR, MOS, HIRES & PCS consortium

Outline

Exoplanets with the E-ELT

I– The E–ELT project

- Telescope, Discovery Window, Other Projects
- Instrumentation Roadmap

II– Exoplanetary atmospheres

1. MOS transit spectroscopy
2. High–dispersed spectroscopy
3. High–contrast spectroscopy

The E-ELT Project

The Telescope

- **40-m class telescope**: largest **optical-infrared** telescope in the world.
  (GMT = 25m; TMT = 30m)

- **Segmented** primary mirror.

- **Adaptive optics** assisted telescope.

- Diffraction limited performance:
  12mas@K-band
  Wide field of view: 7arcmin.

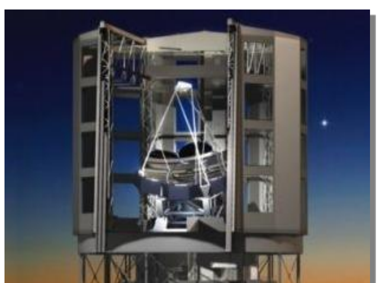
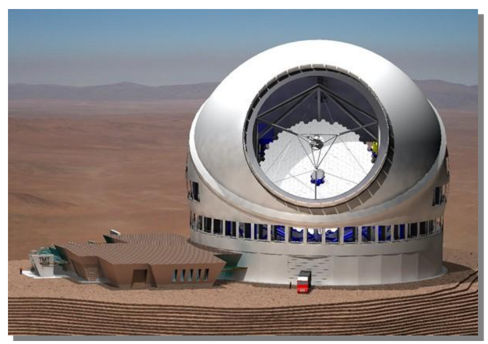
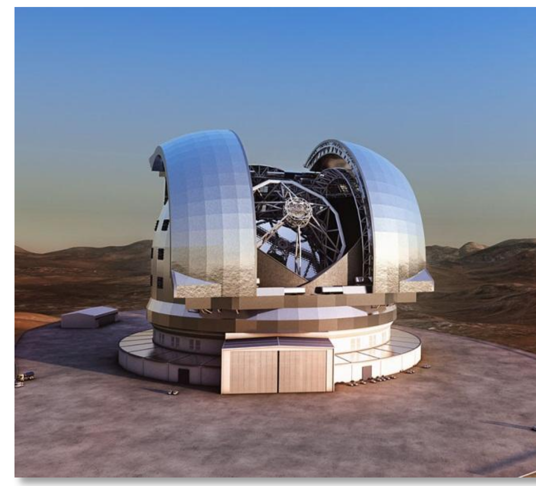
- Mid-latitude site (Amazones/Chile).
  Fast instrument changes.
  VLT level of operations efficiency.

The E-ELT Project

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)**
2 µm	**50mas**	**18mas**	**14mas**	**10mas**	**(JWST: 68mas)**

The E-ELT Project

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, MATISSE, ERIS…***

- ALMA ***(ACA)***

- GAIA

- Cheops

- TESS

- SKA

- JWST

- PLATO, FINESS?

- TMT

- GMT

- E-ELT

The E-ELT Project

Instrument Roadmap

instruments - First Light	AO	Mode	λ (µm)	Resolution	FoV / Sampling	Add. Mode
E-CAM **– 2023**	SCAO, MCAO	- IMG - MRS	0.8 – 2.4	BB, NB 3000	53.0” / 3 mas	Astrometry 40mas Coronography
E-IFU **– 2023**	SCAO, LTAO	- IFU	0.5 – 2.4	4000 10 000 20 000	0.5 1.0” / 4mas 5.0 10.0” / 40mas	Coronography
E-MIDIR – **2024/2028**	SCAO, LTAO	- IMG - MRS - IFU	3 – 13 3 - 13 3 - 5	BB, NB 5000 100 000	18” / 12 mas 0.4” 1.5” / 4 mas	Coronography Polarimetry
E-HIRES - **2024/2028**	SCAO	- HRS	0.37 – 0.71 0.84 – 2.50	200 000 120 000	0.82” 0.027” 0.5”	Polarimetry
E-MOS **- 2024/2028**	 MOAO	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” 2” / 40mas	Multiplex ~ 400 Multiplex ~100 Multiplex ~10 Imaging?
E-PCS **- 2027/2030**	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

SCAO: single-conjugated AO **MCAO:** Multi-Conjugated-AO **LTAO**: Laser-Tomographic AO

MOAO: Multi-Object AO **XAO**: Extreme-AO

The E-ELT Project

instrument Roadmap

- 1st Light instruments

instruments - First Light	AO	Mode	λ (µm)	Resolution	FoV / Sampling	Add. Mode
E-CAM – 2023	**SCAO, MCAO**	**- IMG - MRS**	**0.8 – 2.4**	**BB, NB 3000**	**53.0” / 3 mas**	**Astrometry 40mas Coronography**
E-IFU – 2023	**SCAO, LTAO**	**- IFU**	**0.5 – 2.4**	**4000 10 000 20 000**	**0.5 1.0” / 4mas 5.0 10.0” / 40mas**	**Coronography**
E-MIDIR – 2024/2028	SCAO, LTAO	- IMG - MRS - IFU	3 – 13 3 - 13 3 - 5	BB, NB 5000 100 000	18” / 12 mas 0.4” 1.5” / 4 mas	Coronography Polarimetry
E-HIRES - 2024/2028	SCAO	- HRS	0.37 – 0.71 0.84 – 2.50	200 000 120 000	0.82” 0.027” 0.5”	Polarimetry
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MOAO: Multi-Object AO **XAO**: Extreme-AO

The E-ELT Project
instrument Roadmap

- 2nd Pool instruments

instruments - First Light	AO	Mode	λ (µm)	Resolution	FoV / Sampling	Add. Mode
E-CAM **– 2023**	SCAO, MCAO	- IMG - MRS	0.8 – 2.4	BB, NB 3000	53.0” / 3 mas	Astrometry 40mas Coronography
E-IFU **– 2023**	SCAO, LTAO	- IFU	0.5 – 2.4	4000 10 000 20 000	0.5 1.0” / 4mas 5.0 10.0” / 40mas	Coronography
E-MIDIR **– 2024/2028**	**SCAO, LTAO**	**- IMG - MRS - IFU**	**3 – 13 3 - 13 3 - 5**	**BB, NB 5000 100 000**	**18” / 12 mas 0.4” 1.5” / 4 mas**	**Coronography Polarimetry**
E-HIRES **- 2024/2028**	**SCAO**	**- HRS**	**0.37 – 0.71 0.84 – 2.50**	**200 000 120 000**	**0.82” 0.027” 0.5”**	**Polarimetry**
E-MOS **- 2024/2028**	**MOAO**	**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” 2” / 40mas**	**Multiplex ~ 400 Multiplex ~100 Multiplex ~10 Imaging?**
E-PCS **- 2027/2030**	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

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The E-ELT Project
instrument Roadmap

- XAO instrument

instruments - First Light	AO	Mode	λ (µm)	Resolution	FoV / Sampling	Add. Mode
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E-PCS **- 2027/2030**	**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**

SCAO: single-conjugated AO **MCAO:** Multi-Conjugated-AO **LTAO**: Laser-Tomographic AO

MOAO: Multi-Object AO **XAO**: Extreme-AO

The E-ELT Project

instrument Roadmap

- Various AO Flavors

instruments - First Light	**AO**	**Mode**	**λ (µm)**	**Resolution**	**FoV / Sampling**	**Add. Mode**
E-CAM – 2023	**SCAO, MCAO**	- IMG - MRS	0.8 – 2.4	BB, NB 3000	53.0” / 3 mas	Astrometry 40mas Coronography
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E-HIRES - 2024/2028	**SCAO**	- HRS	0.37 – 0.71 0.84 – 2.50	200 000 120 000	0.82” 0.027” 0.5”	Polarimetry
E-MOS - 2024/2028	**MOAO**	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” 2” / 40mas	Multiplex ~ 400 Multiplex ~100 Multiplex ~10 Imaging?
E-PCS - 2027/2030	**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

SCAO: single-conjugated AO **MCAO:** Multi-Conjugated-AO **LTAO**: Laser-Tomographic AO

MOAO: Multi-Object AO **XAO**: Extreme-AO

The E-ELT Project

instrument Roadmap

- Science Priority / **Exoplanetary Atmospheres**

instruments - First Light	**AO**	**Mode**	**λ (µm)**	**Resolution**	**FoV / Sampling**	**Add. Mode**
E-CAM – 2023	SCAO, MCAO	- IMG - MRS	0.8 – 2.4	BB, NB 3000	53.0” / 3 mas	Astrometry 40mas Coronography
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E-PCS - 2027/2030	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

Low   Medium   High

Outline

Exoplanets with the E-ELT

I– The E–ELT project

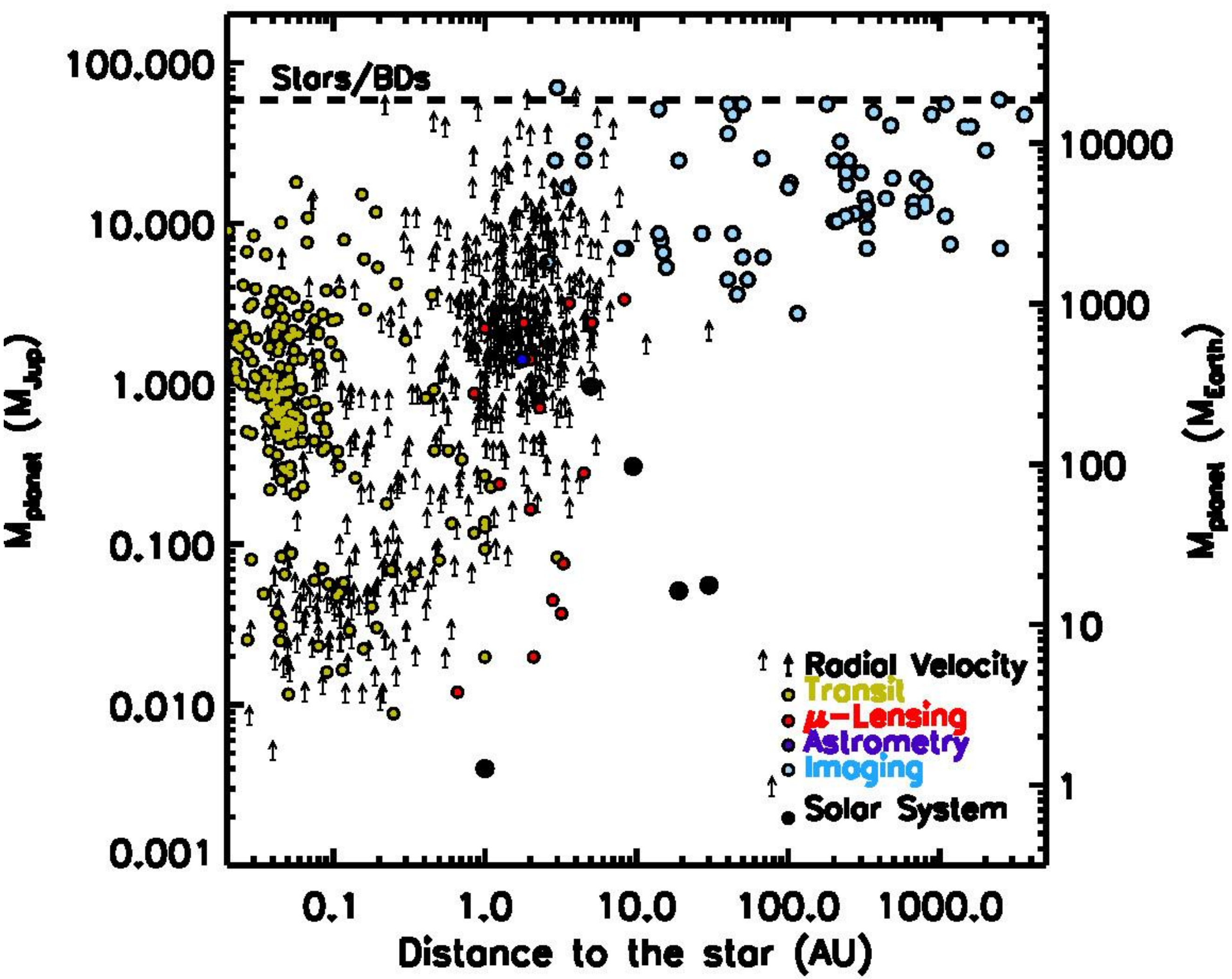
- Telescope, Discovery Window, Other Projects
- instrumentation Roadmap

II– Exoplanetary atmospheres

1. MOS transit spectroscopy (transmission MRS)
2. High–dispersed spectroscopy (HDS)
3. High–contrast spectroscopy (HCS)

State-of-art

Exoplanets Detection

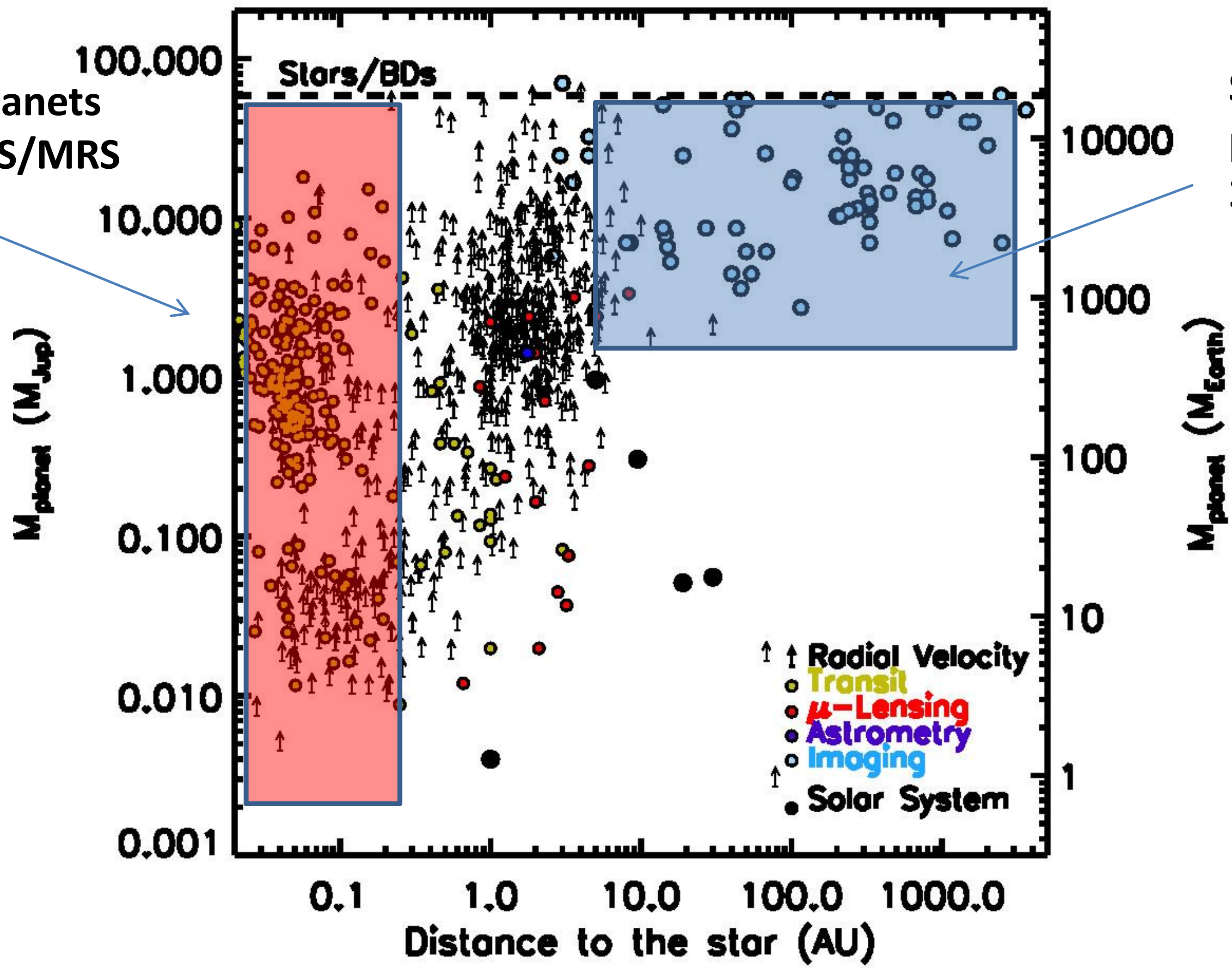


State-of-art

Exoplanets characterization

Strongly Irradiated planets
1. Transit LRS/MRS
2. HDS

Self-luminous planets
3. HCS



E-ELT Science Cases

1. MOS Transit spectroscopy

E-ELT MOS, MOSAIC consortium

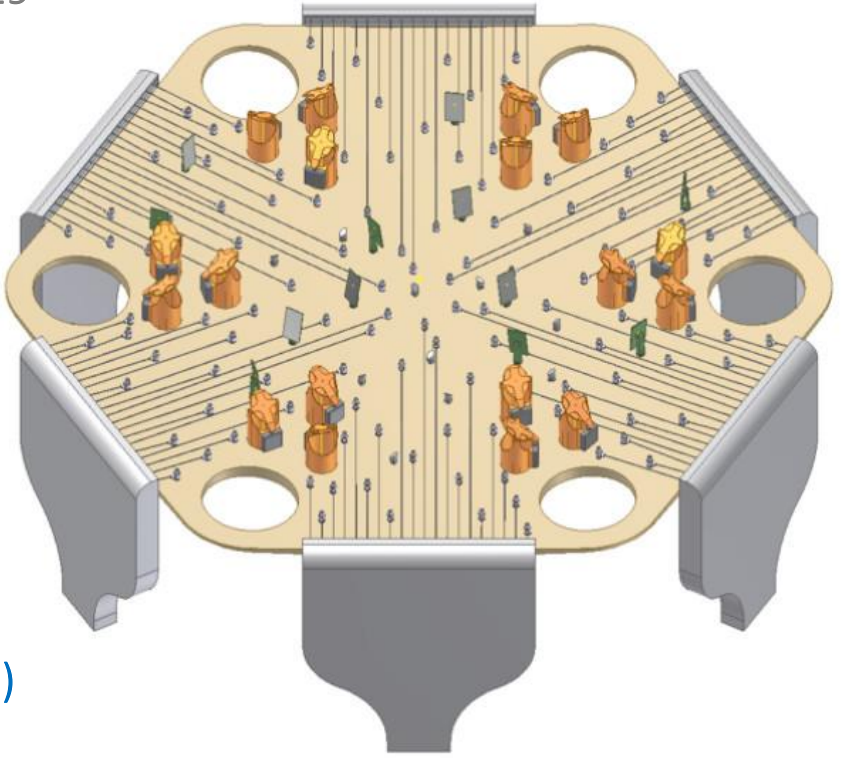
Evans et al. 2013, White paper, arXiv1303.0029

Patrol field = 7’

Spectral range = 0.4 – 2.45 µm

Resolution = 4000 – 30 000

- High multiplex mode (N> 100)
- High definition mode (MOAO, 90 mas)



ESO Top-Level-Requirements (TLRs):

Transmission spectroscopy of Super-Earths

Use of several reference stars (10th mag)

Targets: M dwarfs (Habitability)

Photometric accuracy = 10-5 (Goal 10-6)

Search for bio-signatures (O2, O3, CH4, CO2…)

E-ELT Science Cases

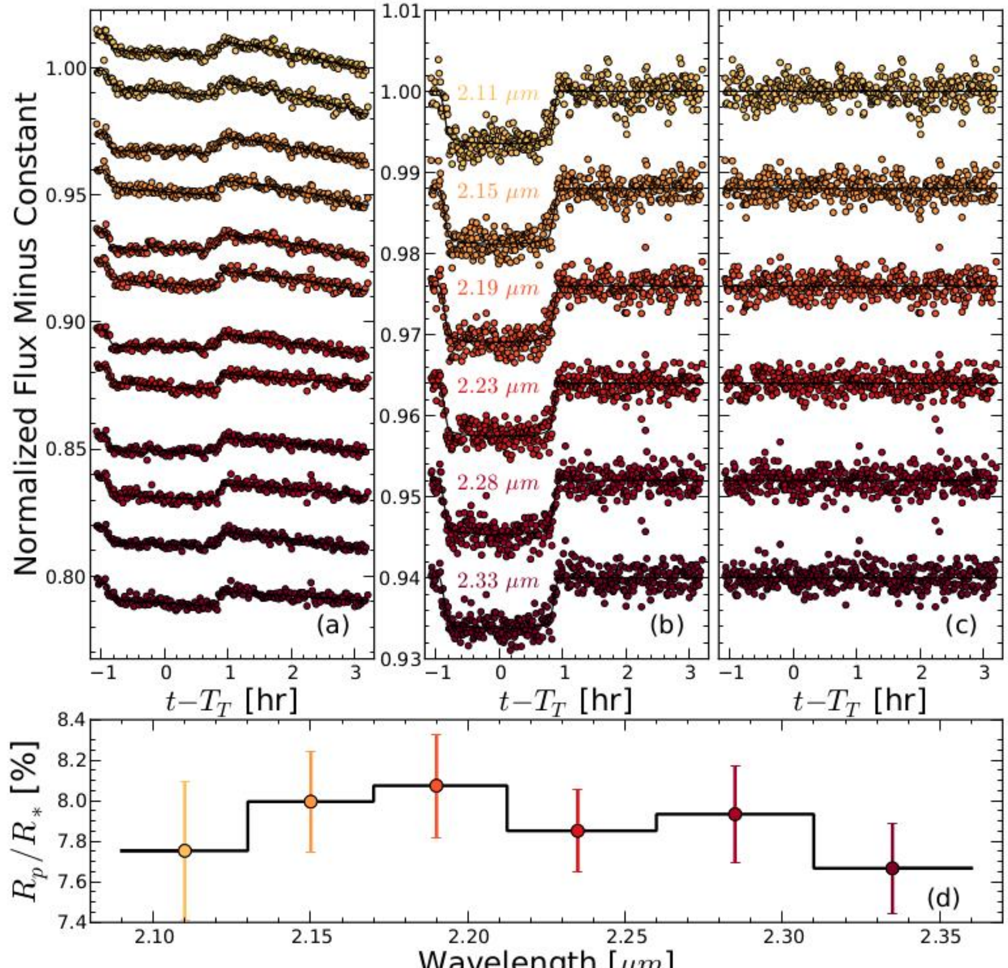
1. MOS Transit spectroscopy

GJ3470b

a new ~800 K,
low-density ice giant
(discovered at IPAG!)

MOS Transmission spectroscopy
Keck/MOSFIRE
FoV = 6’ x 6’; Reference stars
Spectral range= 2.0 – 2.4 µm
Resolution = 3500 (OH lines)
10^{-4} photometric precision

Crossfield et al. 2013



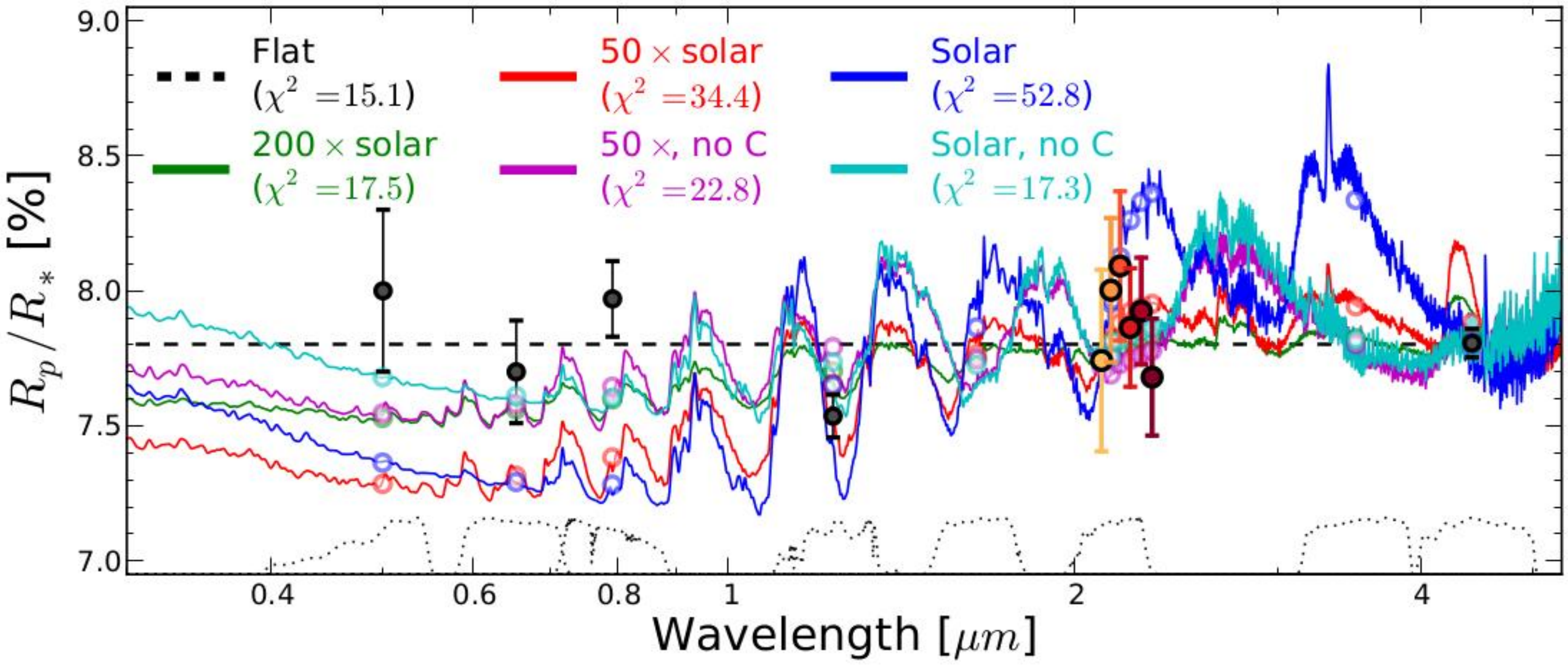
E-ELT Science Cases

1. MOS Transit spectroscopy

GJ3470b

a new ~800 K,
low-density ice giant
(discovered at IPAG!)

Crossfield et al. 13; Fukui et al. 13;
Demory et al. 13; Ehrenreich et al. 14
GJ3470b's transmission spectrum looks flat!
Suggests hazes and/or disequilibrium chemistry



E-ELT Science Cases

2. High-dispersed spectroscopy

E-ELT HIRES,

Maiolino et al. 13, White paper,
Seeing-limited (SCAO? IFU?)
Slit-spectroscopy; FoV < 0.8”
Spectral range = 0.4 – 2.45 µm
Resolution = 120 000 – 200 000

ESO TLRs:
Dayside/Transmission HDS of Giant, icy to telluric planets
Molecules: CO, CO2, H2O, CH4, even O2 (0.76 and 1.27 µm)
Line contrast of 10-5

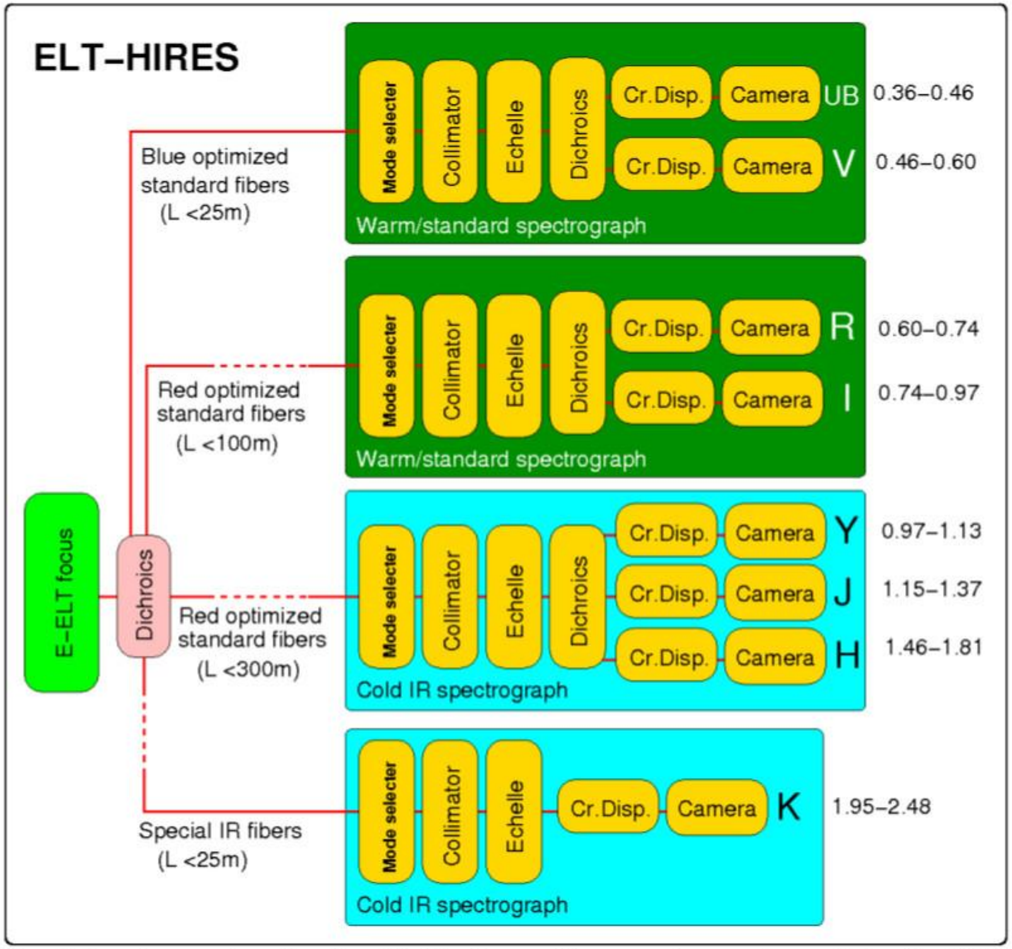
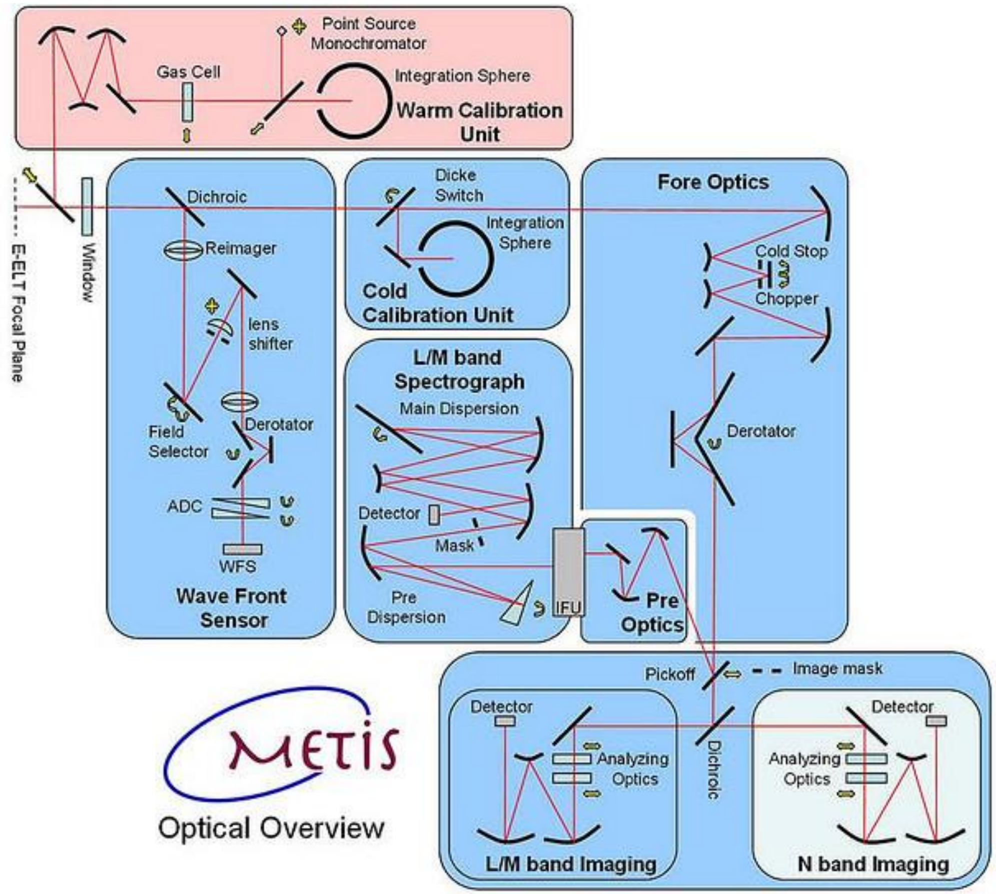


Fig.A1. Possible scheme showing the distribution of the spectroscopic modules for HIRES.

E-ELT Science Cases

2. High-dispersed spectroscopy



E-ELT MIDIR,

Brandl et al. 12, SPIE, 8446, 1

SCAO in VIS or NIR

- IMG: Spectral range = 2.9– 13 µm
  slit-spectroscopy
  Resolution = 4000
- IFU: Spectral range = 2.9 – 5.5 µm
  Resolution = 100 000

ESO TLRs:

Dayside/Transmission HDS of Giant & icy planets

Molecules: CO, CO2, CH4, H2O, NH3 can be probed btw 2.9 and 5.4 µm

E-ELT Science Cases

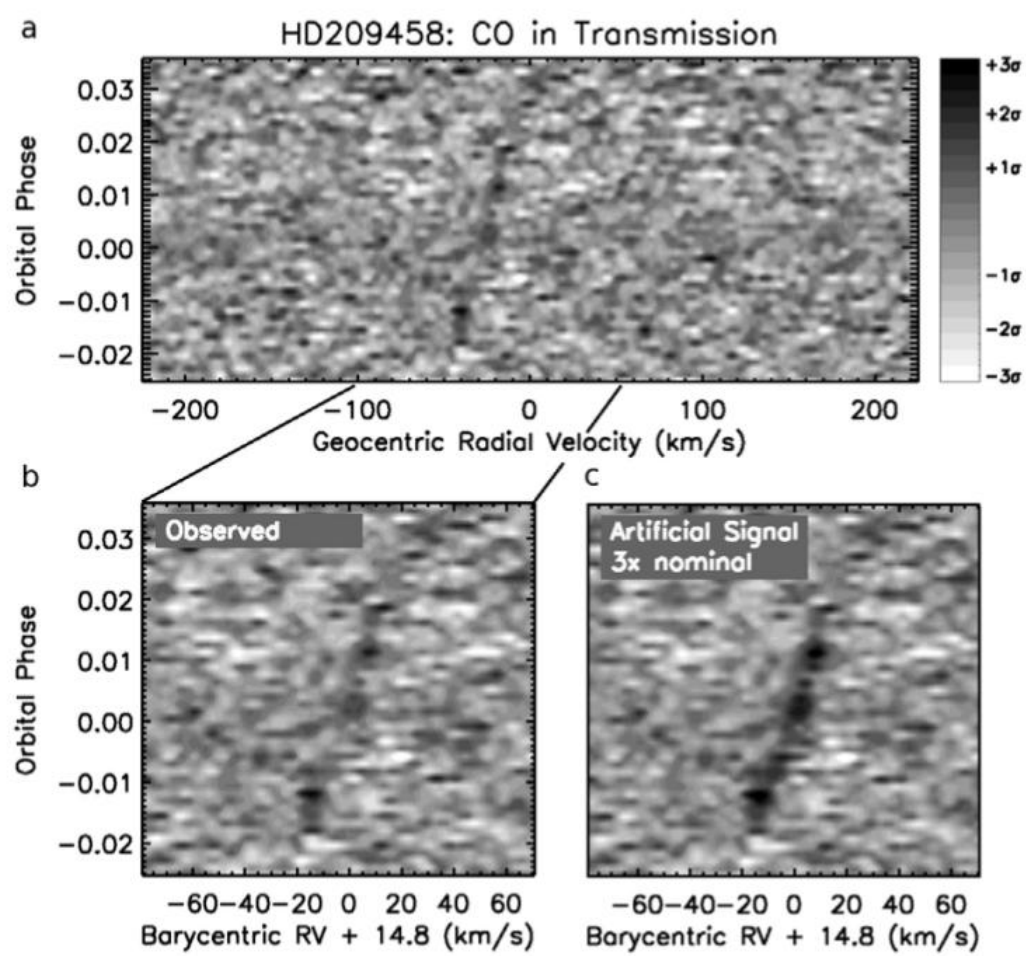
2. High-dispersed spectroscopy

HD209458b

Hot Jupiter, Teq ~ 1300K
0.64 M_{Jup}, P = 3.4 days

VLT/CRIRES observations
Resolution = 100 000
Spectral coverage = 2.29-2.35 µm

Absorption lines from CO at 2.3 µm seen In transmission.
Orbital motion, absolute mass and high-altitude winds observed
Snellen et al. 10



E-ELT Science Cases

2. High-dispersed spectroscopy

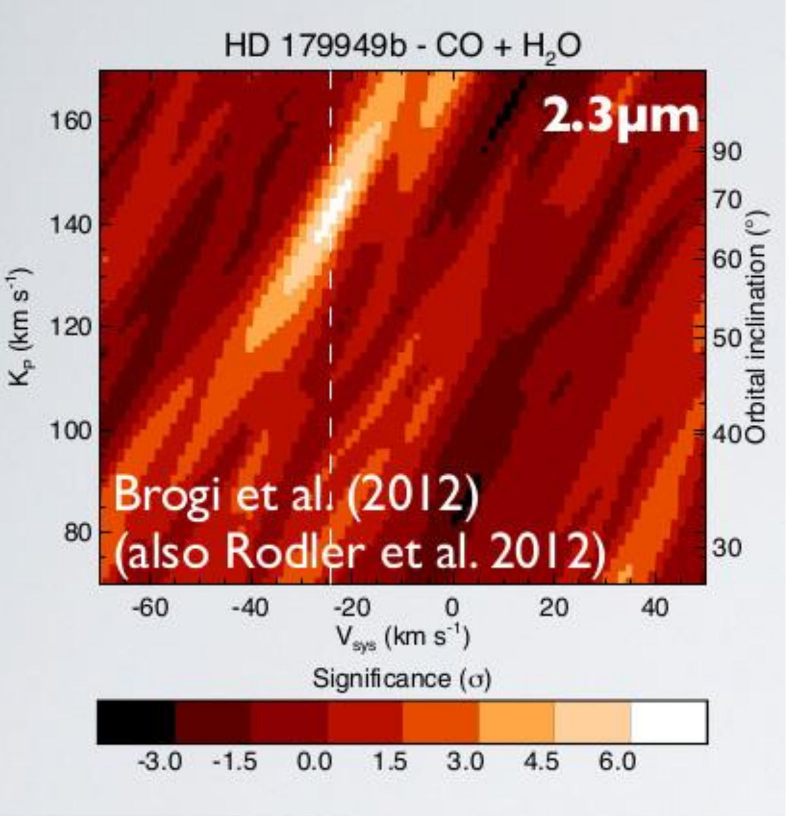
Non-transiting planets

Dayside of the planet seen in CO, H2O…

VLT/CRIRES observations
Resolution = 100 000
Spectral coverage = 2.29-2.35 µm

Systems:
- 51 Peg, Brogi et al. 13;
- τ Boo, Brogi et al. 12
- HD179949, Brogi et al. 14

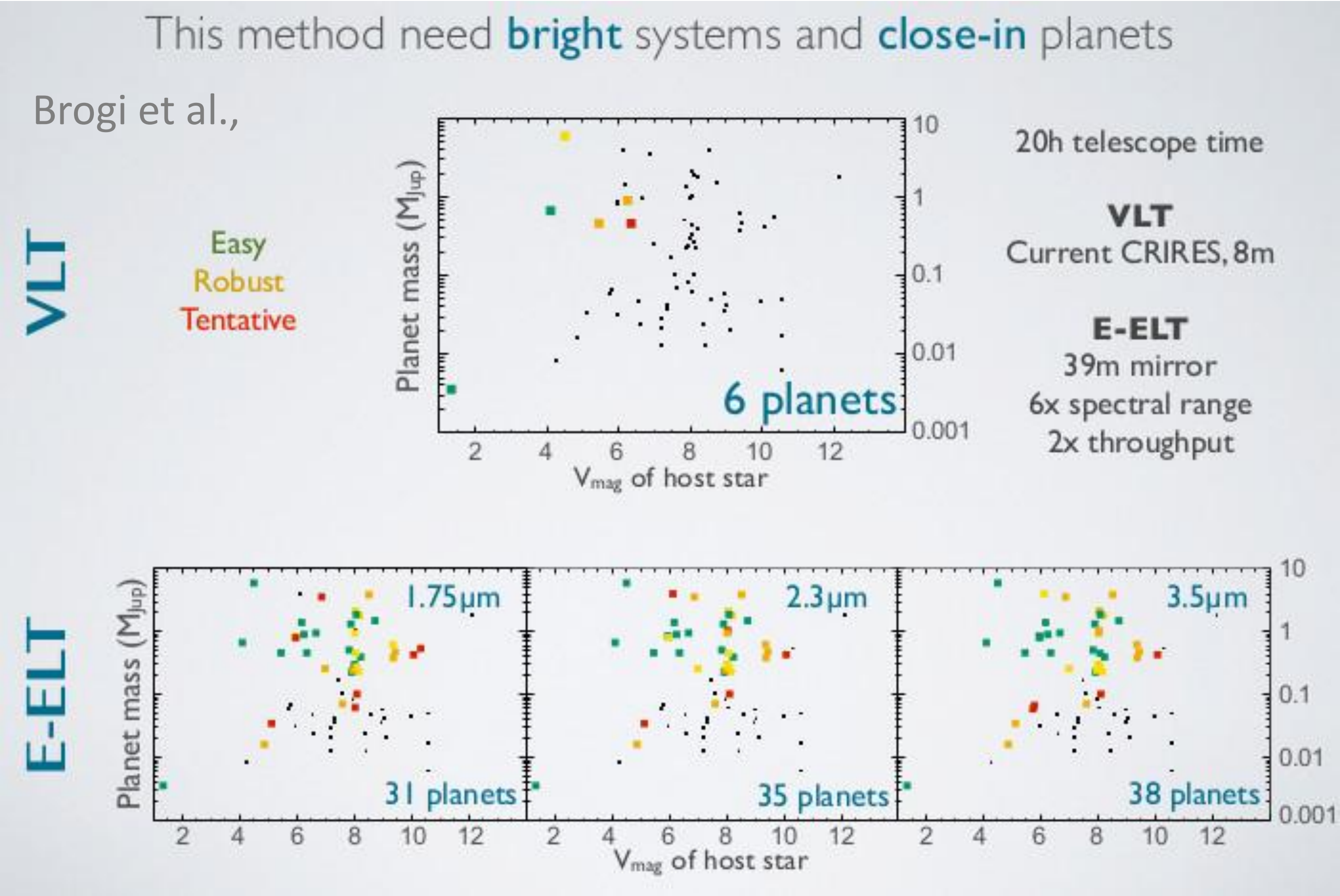
Results:
- CO, H20 molecular detections
- Mass, inclination
- Bulk atmospheric thermal structure
- Atmospheric circulation, phase curves, C/O ratios



E-ELT Science Cases

2. High-dispersed spectroscopy

Non-transiting planets (dayside spectroscopy)

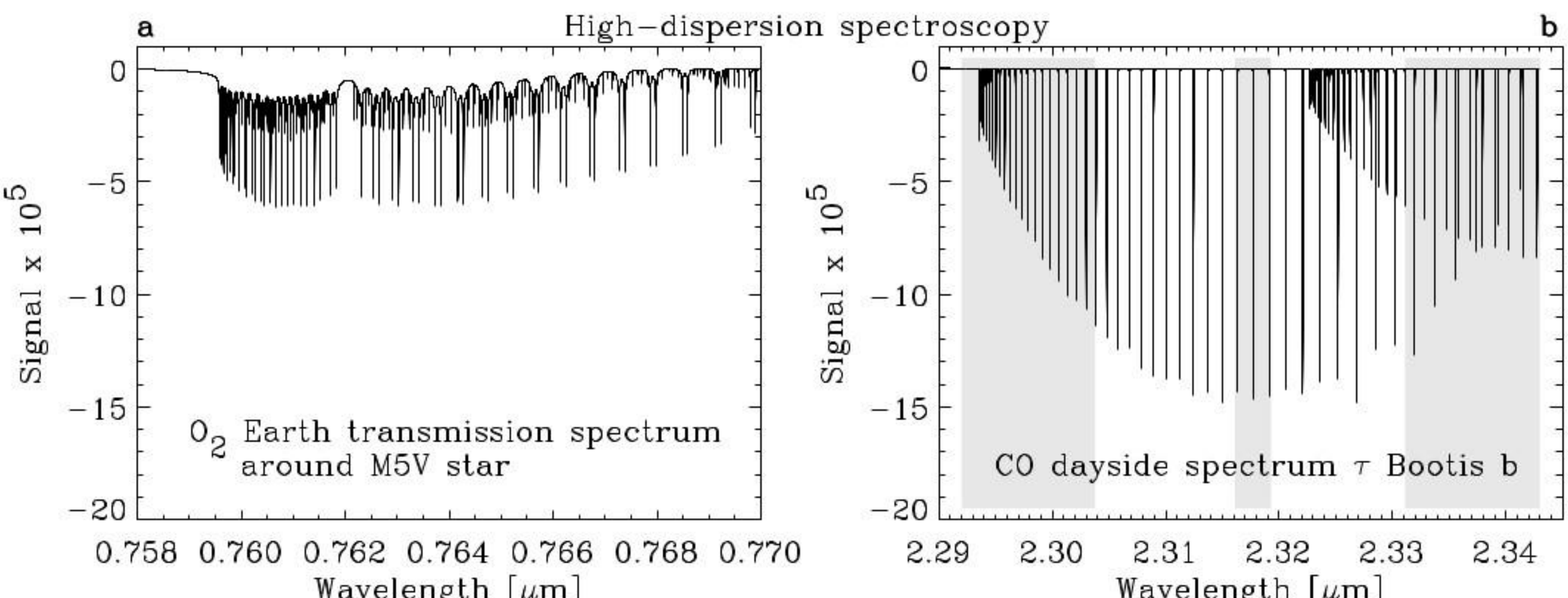


E-ELT Science Cases

2. High-dispersed spectroscopy

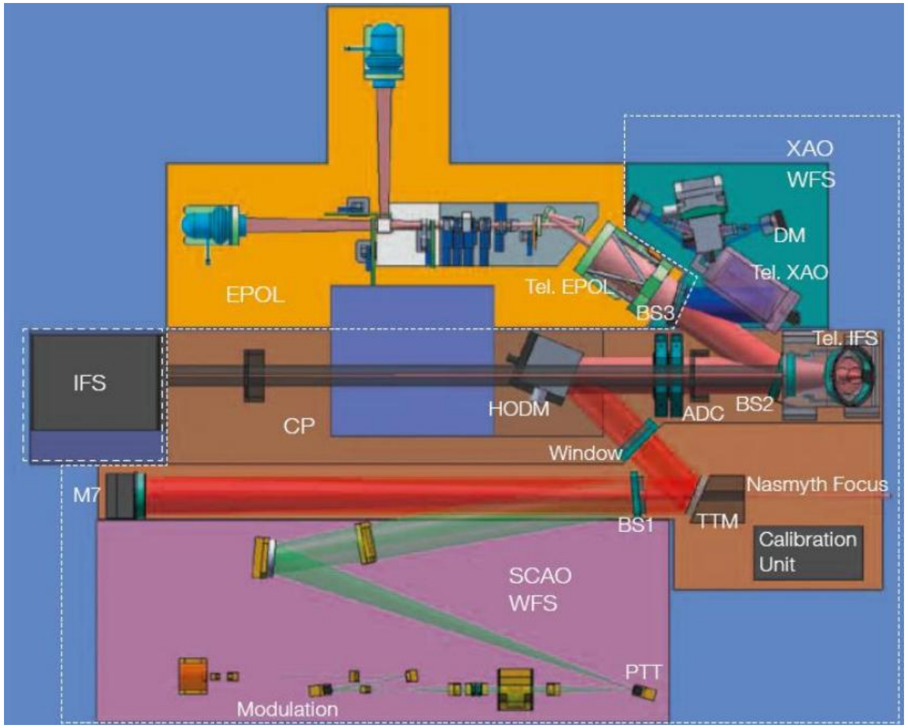
Finding extraterrestrial life (Snellen et al. 13)

- Simulated O2 **transmission signal** for an Earth-twin transiting an M5 dwarf star.
- Signal 2-3 lower than the CO signal detected by Brogi et al. (2012).
- challenge comes from the expected faintness of the nearest late M-dwarf with a transiting Earth-twin >> need to cumulate several transits



E-ELT Science Cases
3. High-Contrast spectroscopy

E-ELT PCS,
Kasper et al. Proc. SPIE arXiv:1207.0768



SPHERE-like concept (Phase A)
1. XAO: Atmospheric turbulence
2. Diffraction Pattern
3. Quasi-static instrumental aberrations

- NIR IFS: 950-1650 nm,
  0.8″ FoV, 2.33 mas/px
  R = 125, 1400, 20.000
- EPOL: Vis IMG:
  600-900 nm, 2″ FoV, 1.5 mas/px
  Vis polarimetry

Prelim. ESO TLRs:
LRS/MRS of giant, icy and telluric planets
in reflected/emitted light
>> 10-9 contrast required for super-Earths imaging

E-ELT Science Cases

3. High-Contrast «Low-Res» spectroscopy

Beta Pic b

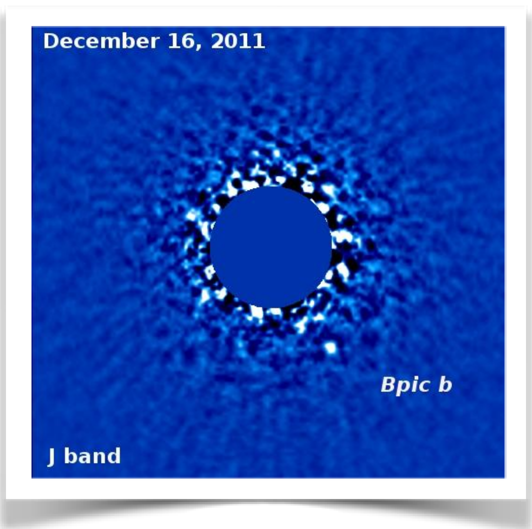
8 – 13 M_{Jup} planet, 9 AU;

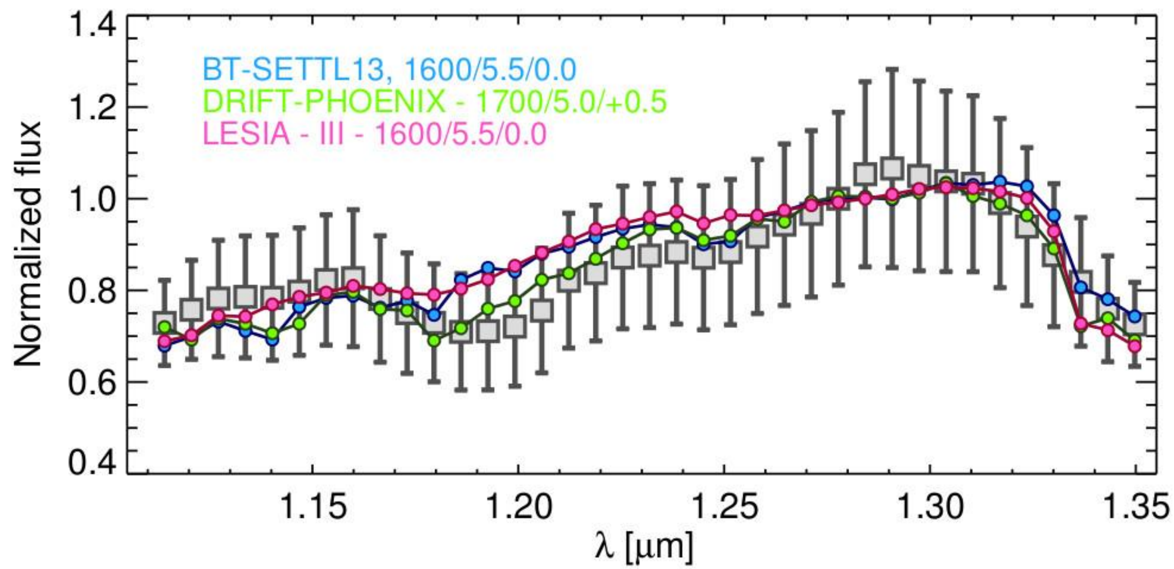
T_{eff} = 1650 +- 150K, *log*(g) = 4.0±0.5 and R = 1.3+-0.2 R_{jup} (Bonnefoy et al. 13)

>> Access the broad molecular absorptions (here H2O)…

GPI IFS observations in J-band, Res = 50

Bonnefoy et al. 14



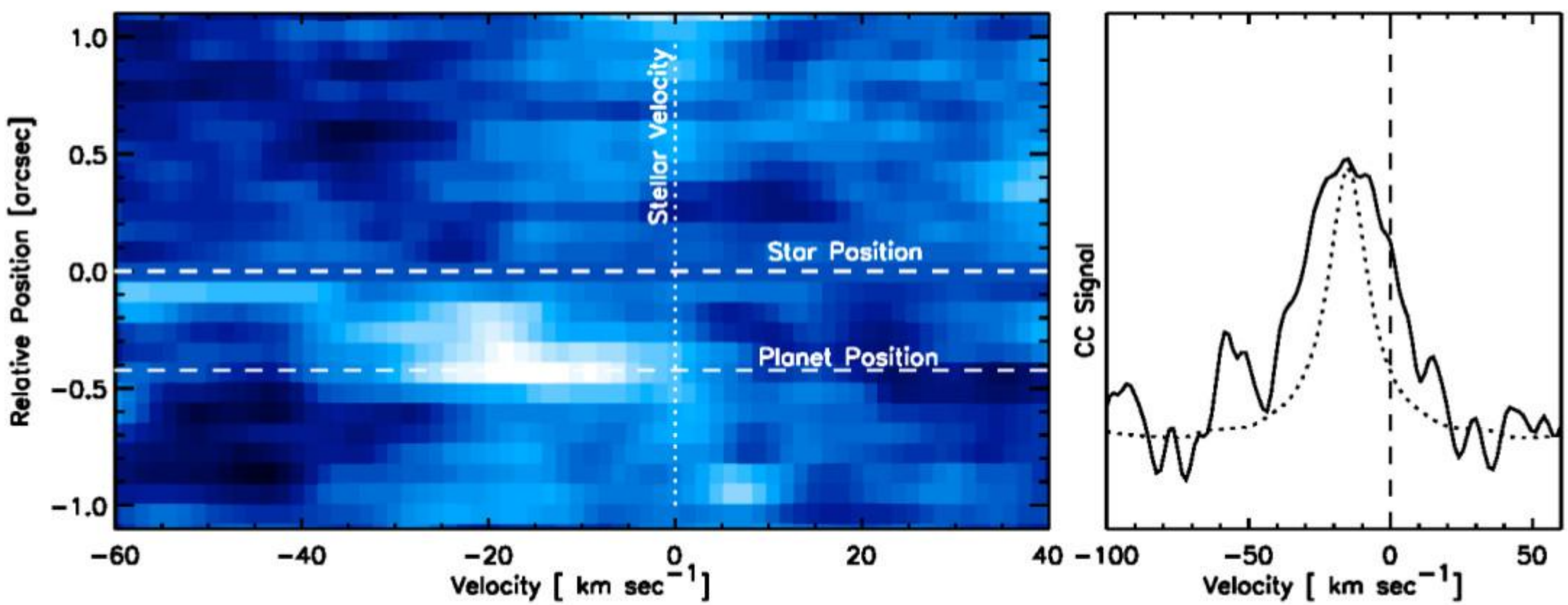


E-ELT Science Cases

3. High-Contrast « High-Res » spectroscopy

Beta Pic b

VLT/CRIRES, Res. = 100 000; 2.303-2.331 µm
CO line at 2.3µm **spatially resolved;** Rotational broadening of 25+-3 km/sec
Planet rotation of 8.1+-0.1 hrs
Snellen et al. 14, arXiv:1404.7506

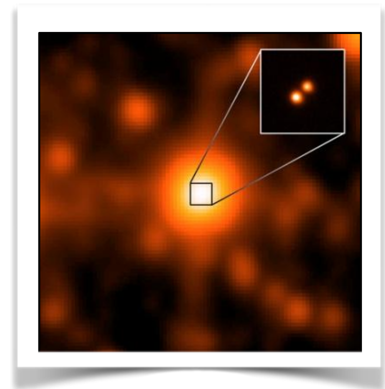


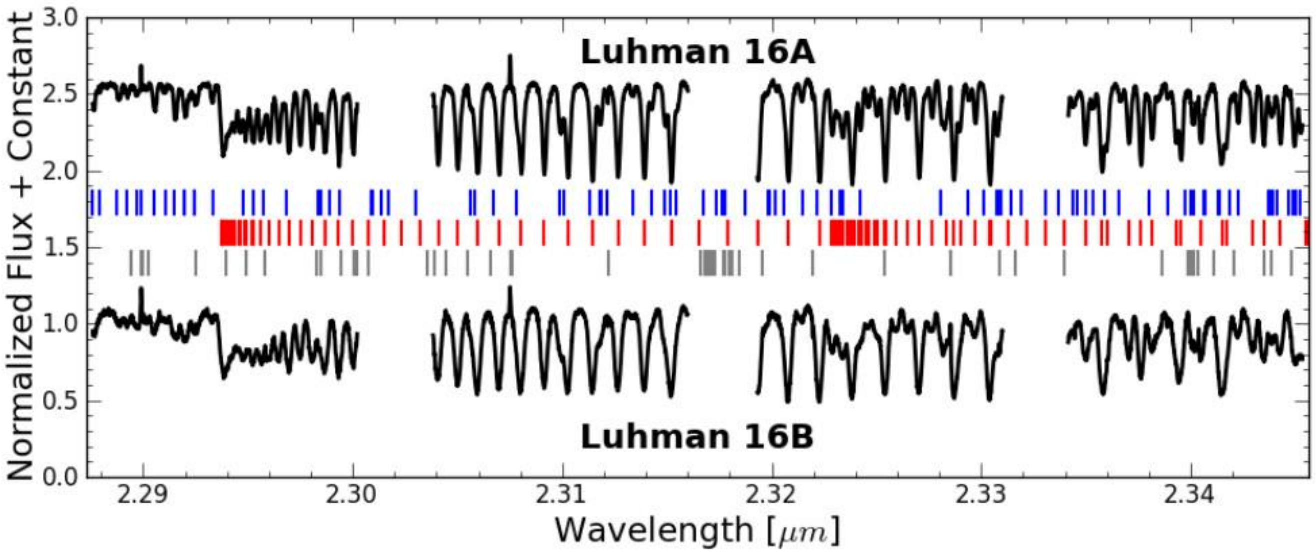
E-ELT Science Cases

3. High-Contrast « High-Res » spectroscopy

Luhman 16 AB, Cloud Mapping

VLT/CRIRES, Res = 100 000,
2.288—2.345 µm, CO and H2O lines
Luhman 16 B, 2 pc, Rotation 4.9hrs
spectroscopic variability
Doppler imaging
Crossfield et al. 14





E-ELT Science Cases

3. High-Contrast « High-Res » spectroscopy

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VLT/CRIRES, Res = 100 000,
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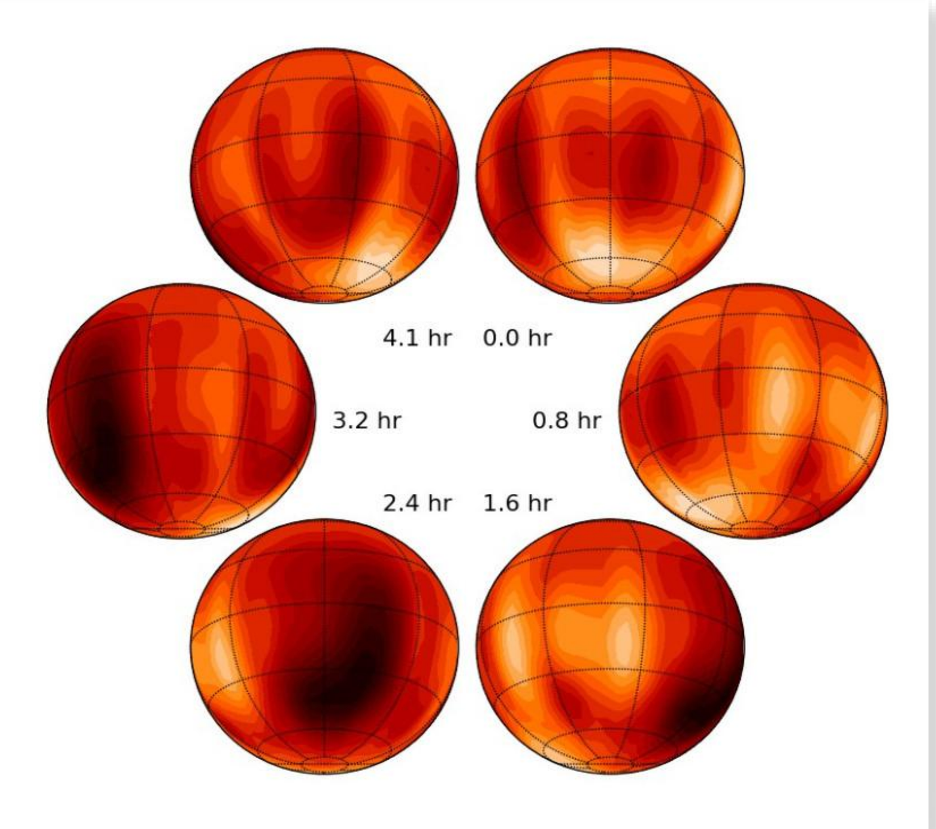


Exciting perspectives:
- E-MIDIR and new PCS concept?
- Molecules: CO, CH4, H2O, NH3

Cloud mapping of various species
Atmospheric circulation & winds

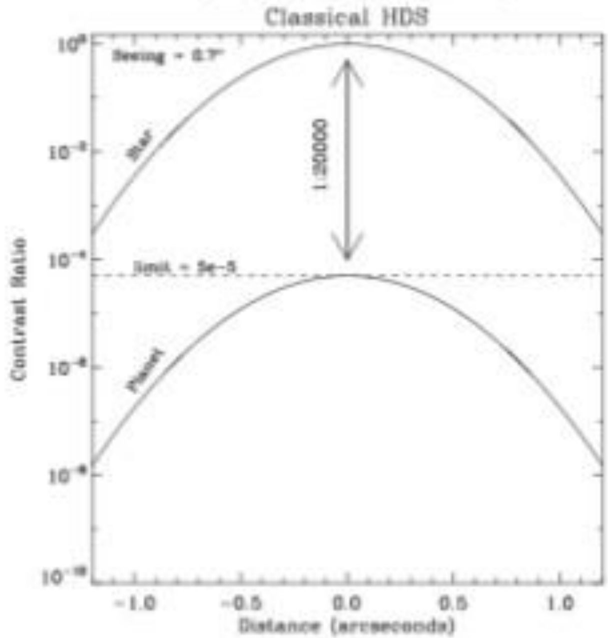
E-ELT Science Cases

3. High-Contrast « High-Res » spectroscopy

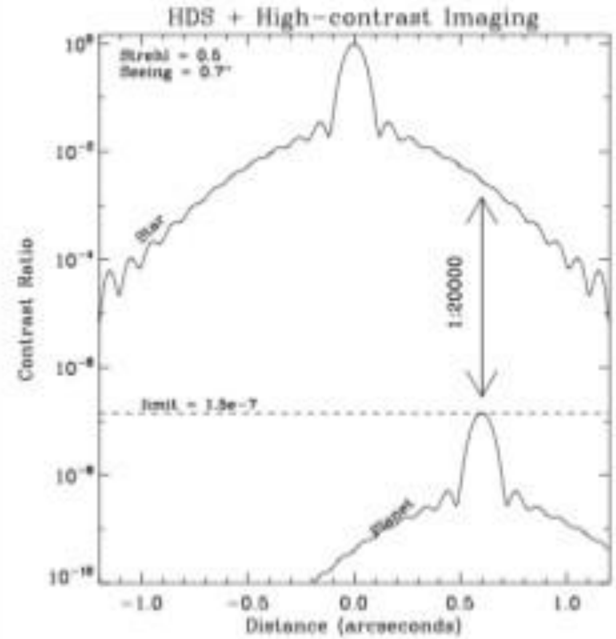
Ultimate perspective: XAO + HDS

- Combining HDS + HCS to probe Earth-like planets with the E-ELT
- Powerful technique, capable to characterize rocky planets in HZ?
  >> Reflected light (10-9 contrast)

Classical HDS



HDS + HCI



Conclusions

Exoplanetology with the EELT

2024, a rich context for exoplanets
(HARPS N/S, SPHERE, GPI, GAIA, Cheops, ESPRESSO, JWST...)

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

E-ELT, a machine for exoplanet's characterization (Atmospheres)

Main techniques/instruments:

- MRS Transmission spectroscopy (E-MOS)
  Goal of 10-6 photom. accurracy for bio-signatures around M dwarfs
- HDS in Transmission/Dayside of Giant, icy to telluric planets (E-HIRES, E-MIDIR); 10-5 contrast for O2 (1.26um)
- HCS of reflected lights of Giant (to super Earths, 10-9) (PCS)
  >> HCS(XAO) + HDS: powerful technique for reaching 10-9 contrast for detection of bio-signatures (PCS, MIDIR…)