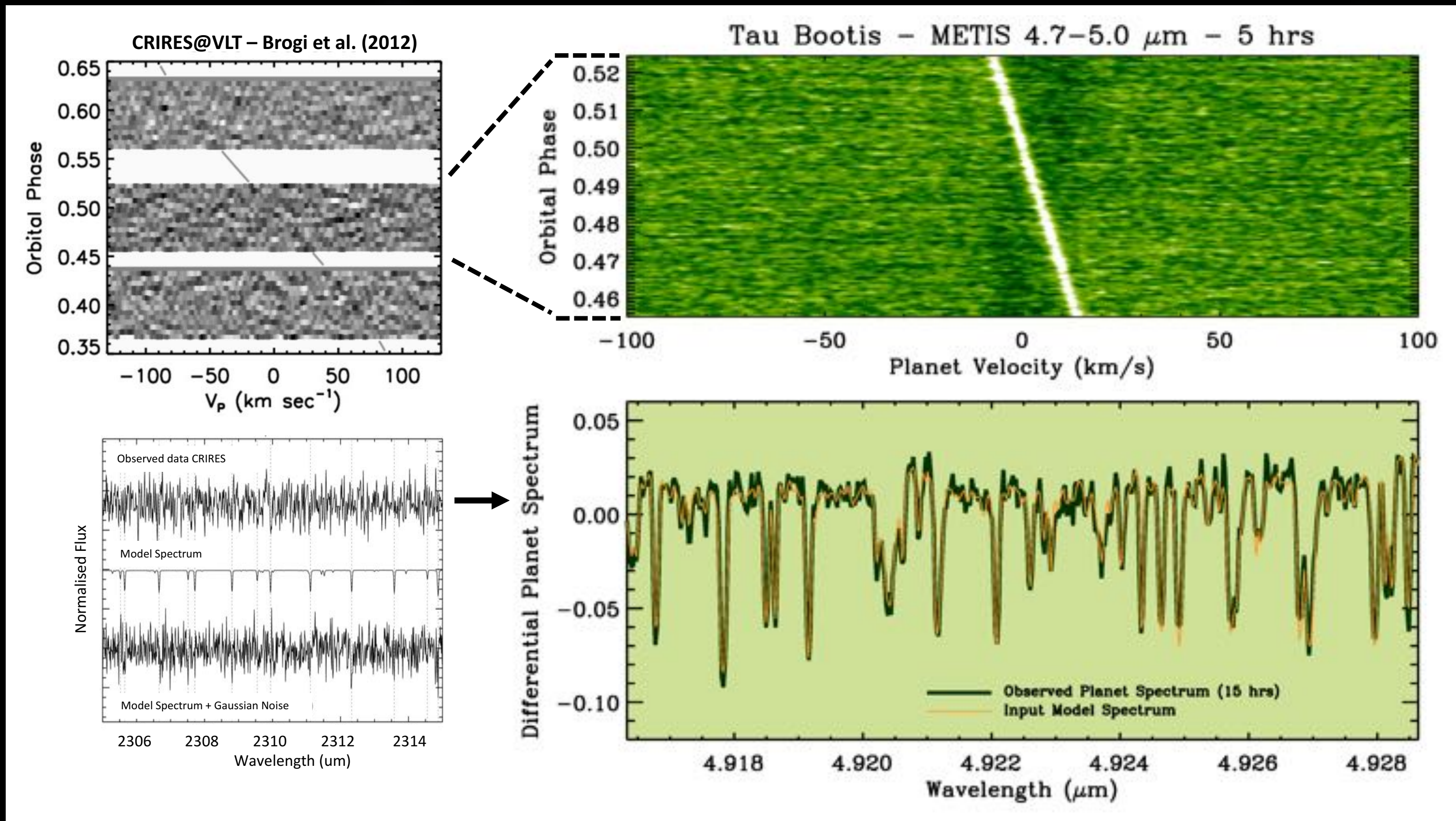
Future directions of high-dispersion spectroscopy of exoplanets – *and beyond*

Ignas Snellen, Leiden University

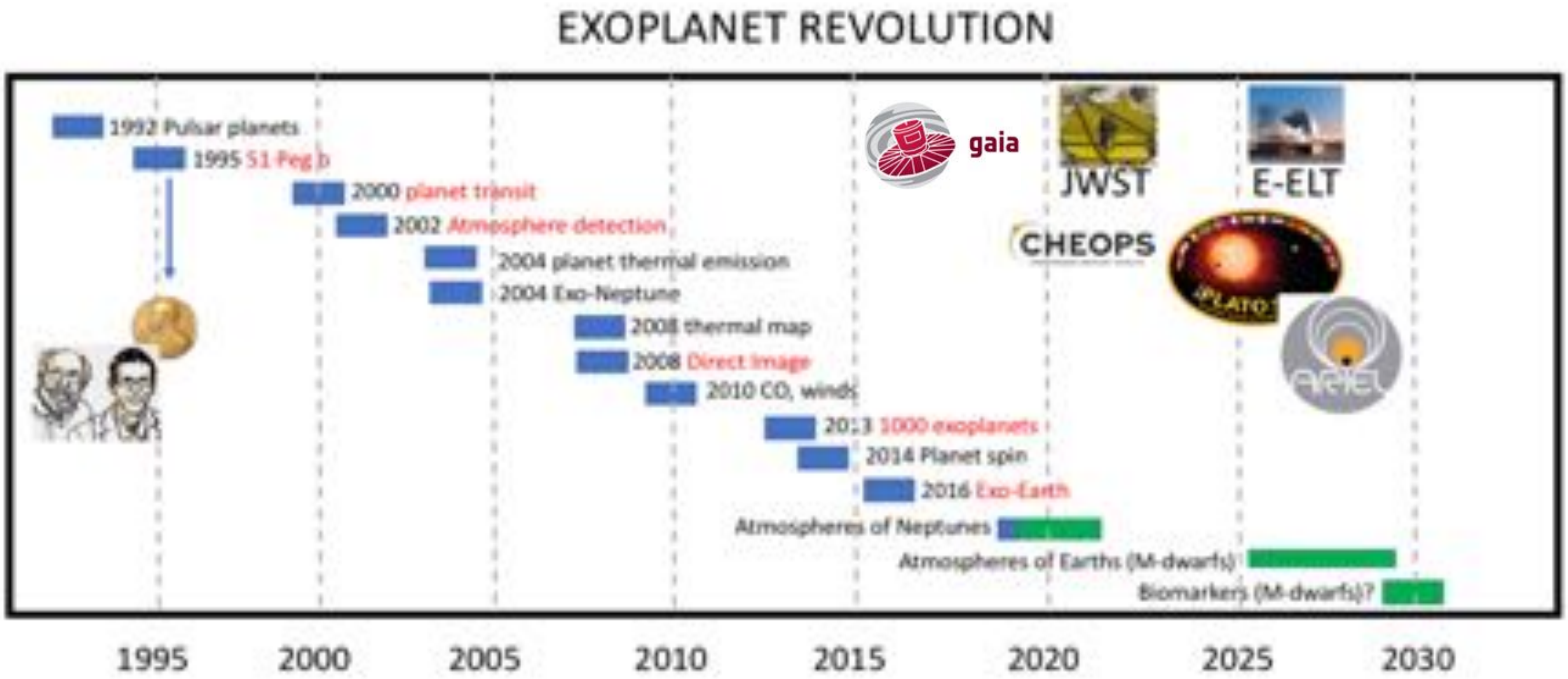


Matteo Brogi, Henriette Schwarz,, Jayne Birkby, Remco de Kok, Simon Albrecht, Remko Stuik, Gilles Otten, Jens Hoeijmakers, Andrew Ridden-Harper, Sebastiaan Haffert, Geert-J. Talens, Javi Alonso, Paul Molliere, Paul Wilson, Patrick Dorval, Dilovan Serindag, Yapeng Zhang, Aurelien Wyttenbach, Aurora Kesseli

Yesterday vs. Today

- Short introduction (Science/Techniques)
- High Resolution Spectroscopy – challenges & prospects
- ESA Voyage: Exoplanet Science 2035 - 2050

A Revolution in Exoplanet Research



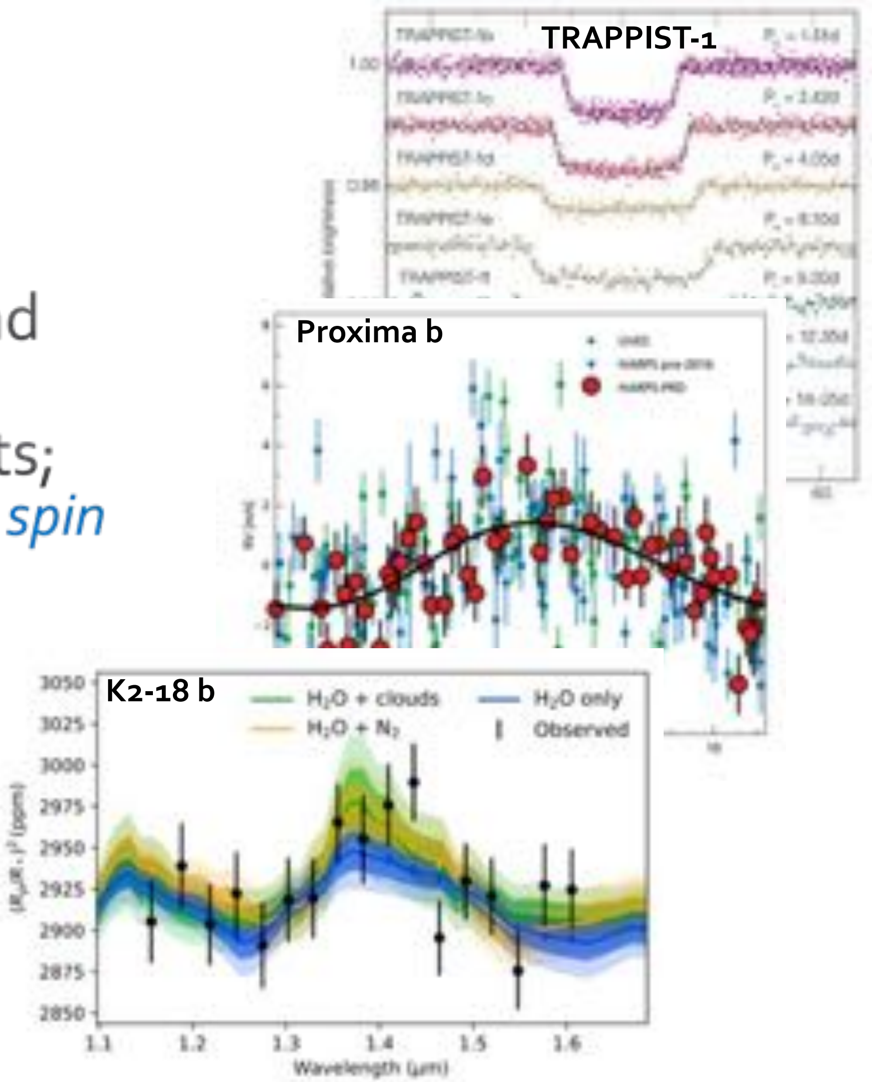
Current Status of Exoplanet Science

What we can do now:

- Find planets down to Earth-size and mass; *around small dwarf stars*
- Characterization of gaseous planets; *molecules, clouds, climate, circulation, spin*

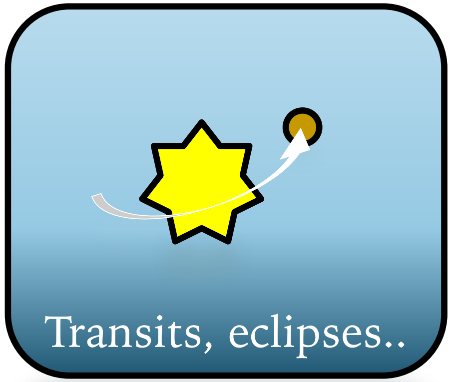
Lessons learned so far:

- Planets are very common; *10% gas-giants, 25% Neptunes, >50% rock*
- Planets show a large diversity; *Hot Jupiters, super-Earths, mini-Neptunes*

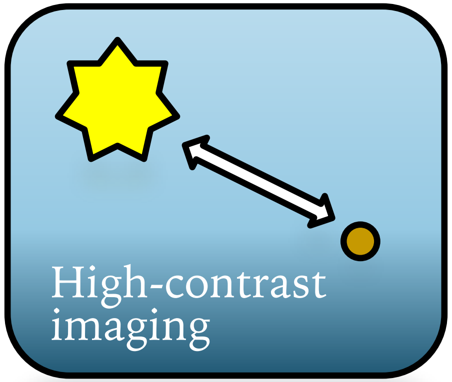


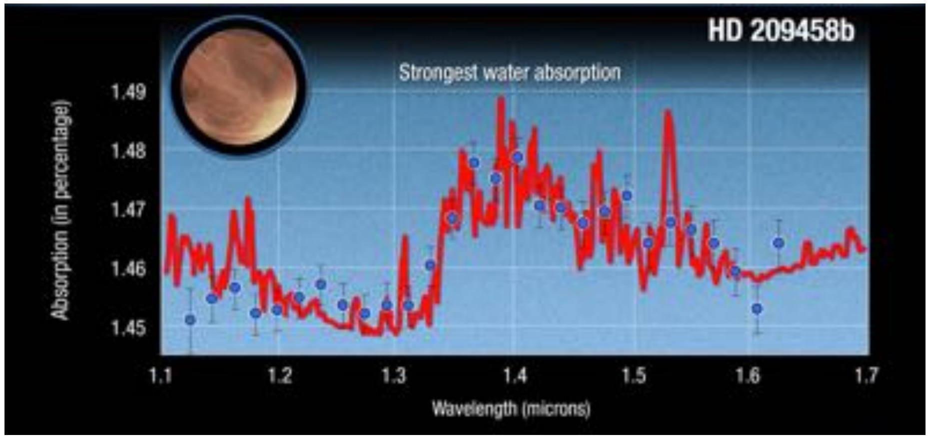
Exoplanet atmosphere observing techniques

Time differential



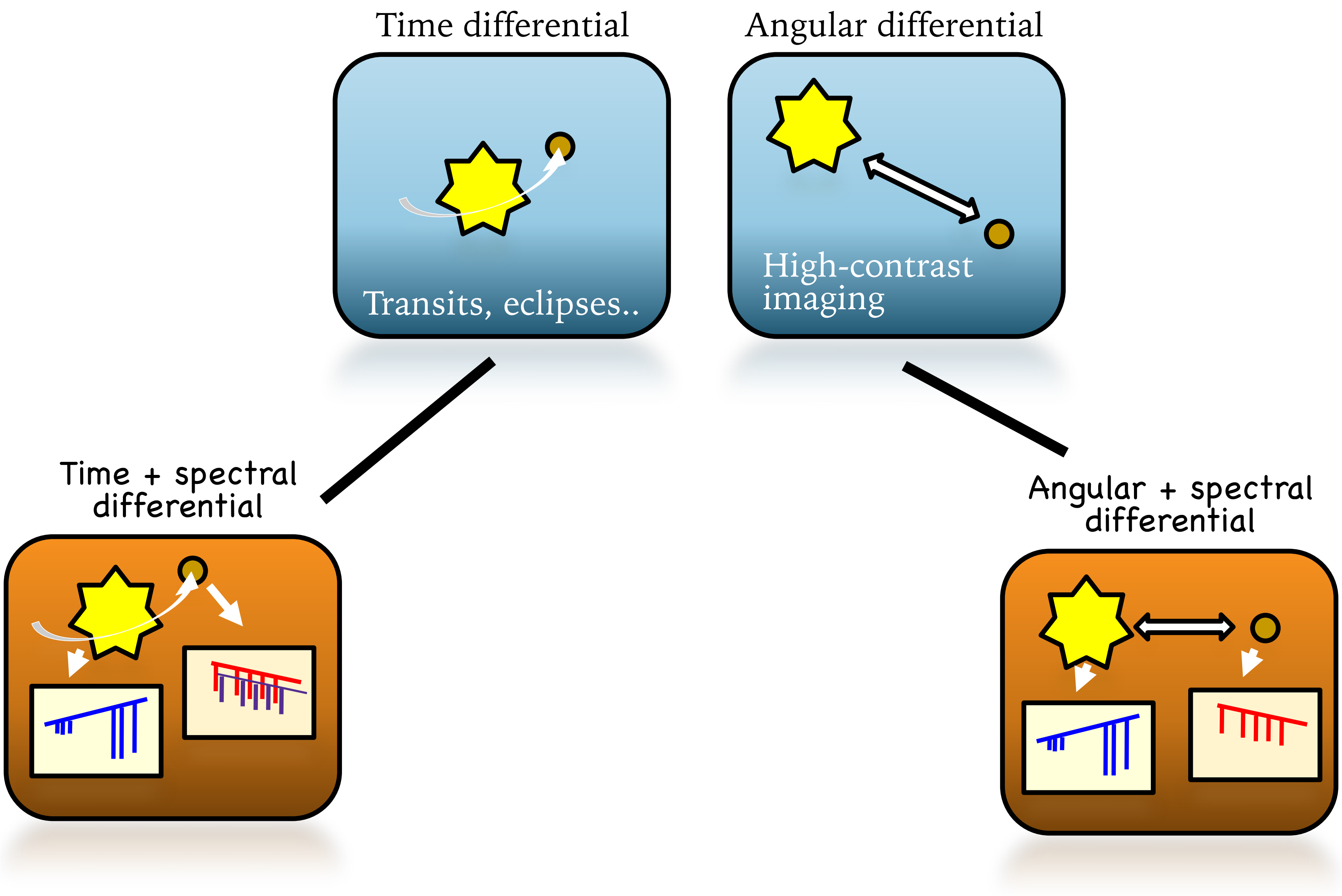
Angular differential

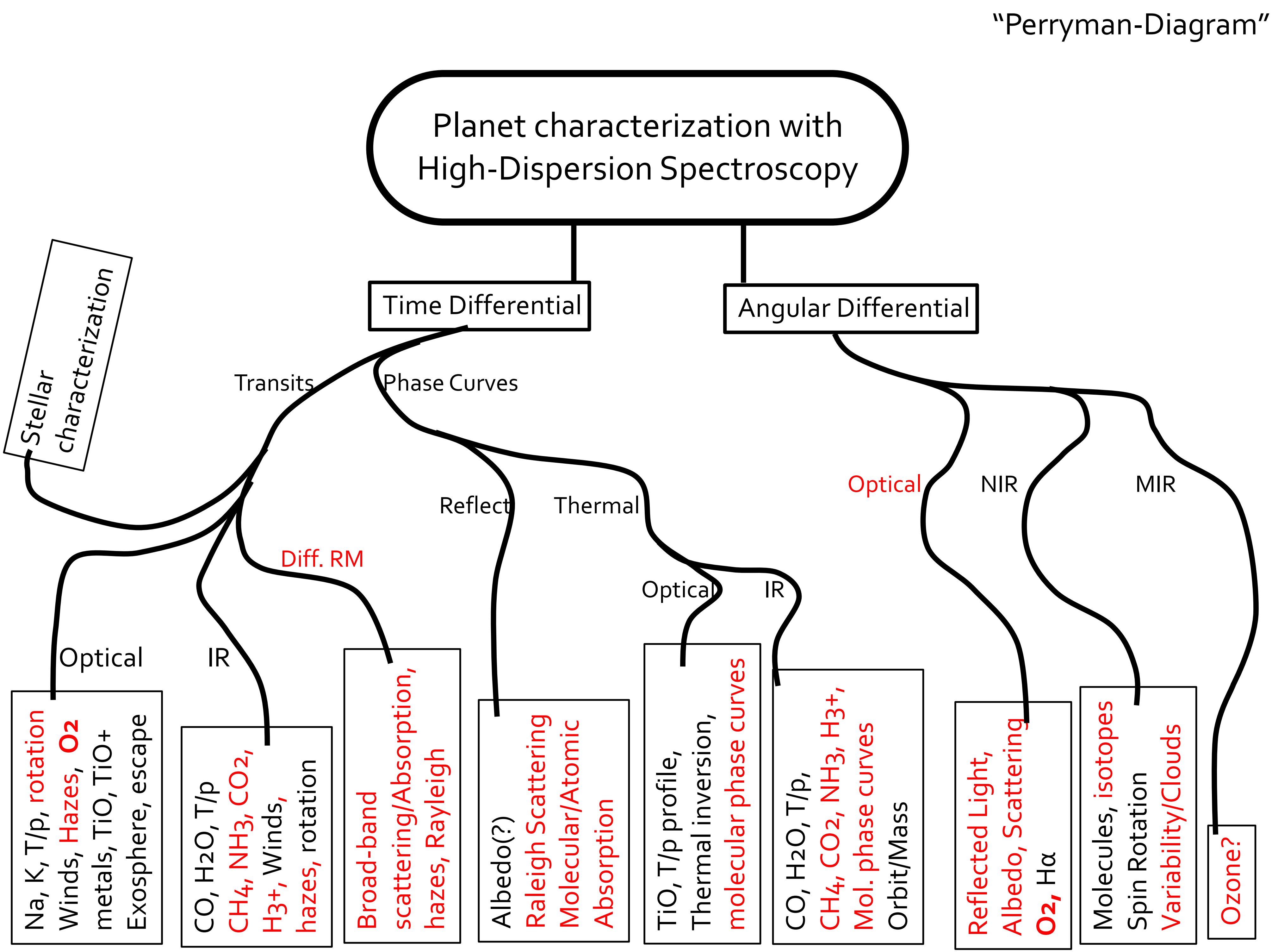




WFC3@HST (Deming et al. 2013)

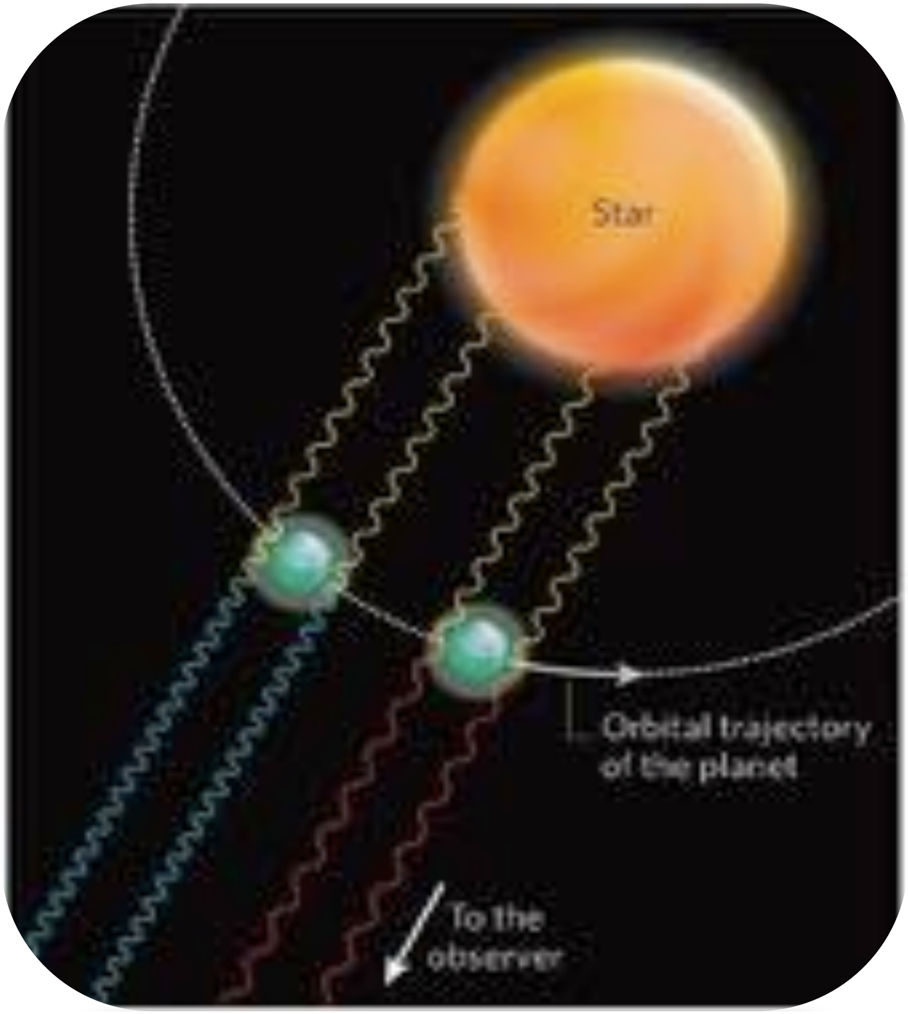
Exoplanet atmosphere observing techniques

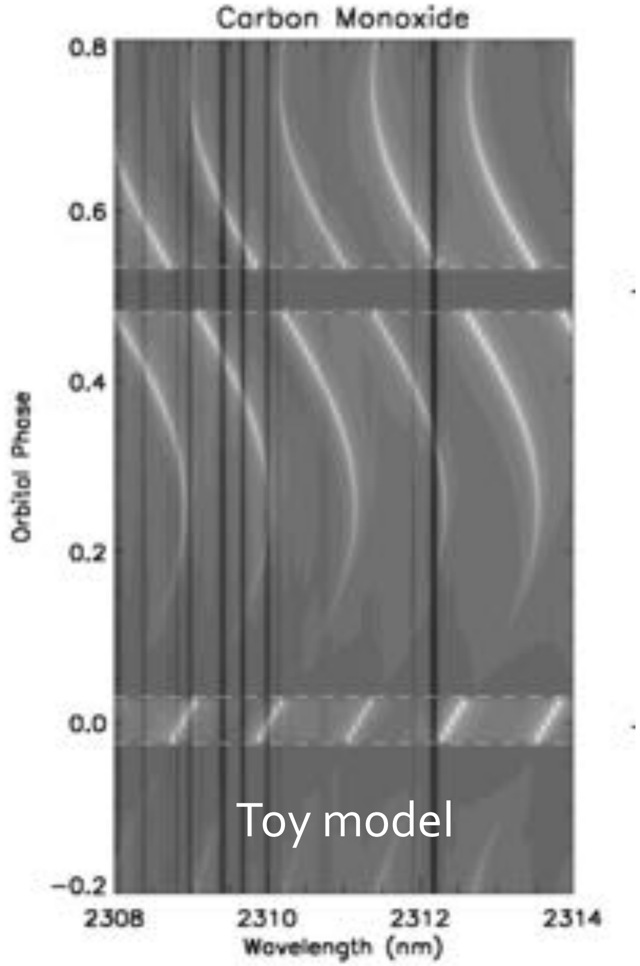



"Perryman-Diagram"
Planet characterization with High-Dispersion Spectroscopy
Time Differential
Angular Differential
Stellar characterization
Transits
Phase Curves
Reflect
Thermal
Diff. RM
Optical
IR
Optical
IR
Optical
NIR
MIR
Na, K, T/p, rotation Winds, Hazes, O2 metals, TiO, TiO+ Exosphere, escape
CO, H2O, T/p CH4, NH3, CO2, H3+, Winds, hazes, rotation
Broad-band scattering/Absorption, hazes, Rayleigh
Albedo(?) Raleigh Scattering Molecular/Atomic Absorption
TiO, T/p profile, Thermal inversion, molecular phase curves
CO, H2O, T/p, CH4, CO2, NH3, H3+, Mol. phase curves Orbit/Mass
Reflected Light, Albedo, Scattering O2, Hα
Molecules, isotopes Spin Rotation Variability/Clouds
Ozone?

Time-differential high-dispersion spectroscopy

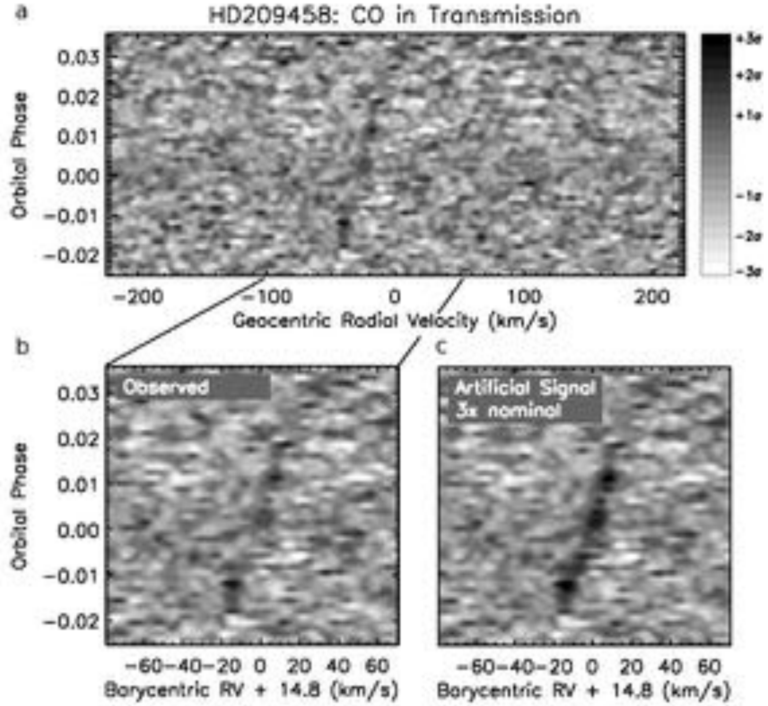
- At R=100,000 molecular bands are resolved in tens of individual lines
- Strong doppler effects due orbital motion of the planet (up to >150 km/s).
- Moving planet lines are distinguished from stationary telluric + stellar lines





CRIRES@VLT

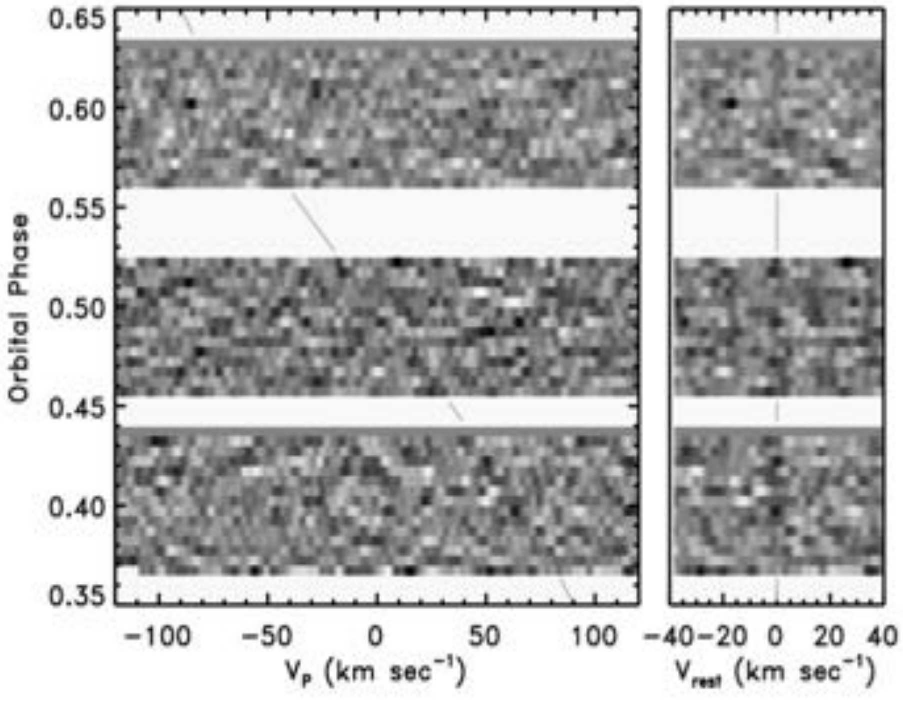
Transmission

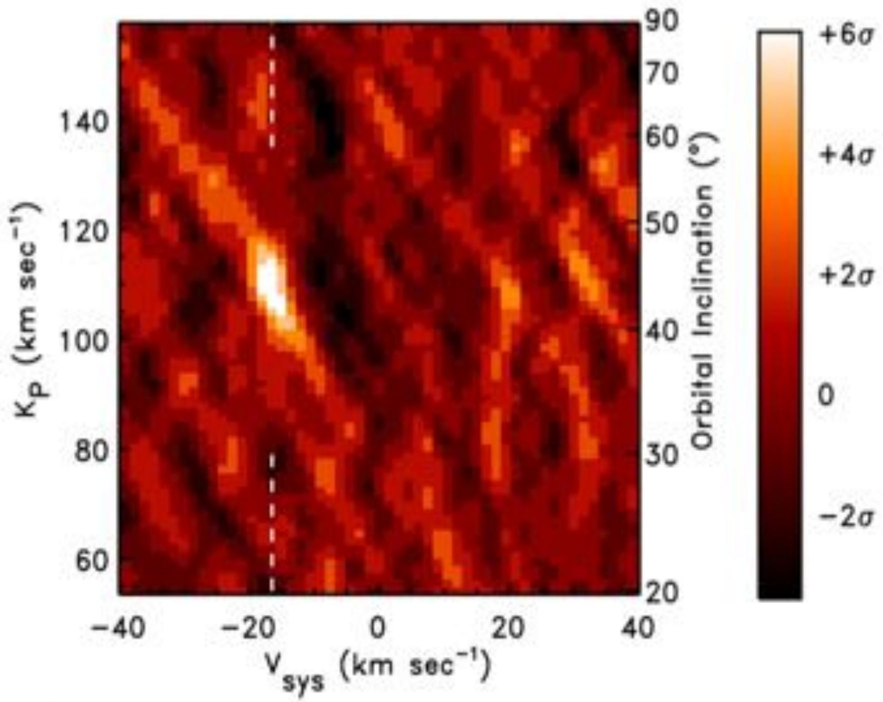


Transmission spectroscopy of CO at 2.3 um
Of HD209458b (Snellen et al. 2010)

Emission spectroscopy of CO of tau Bootis
(Brogi et al. 2012)

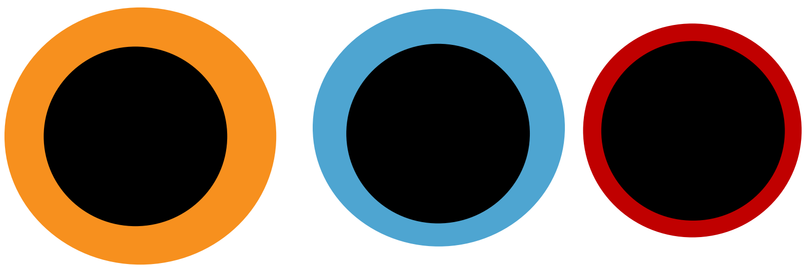
Dayside emission

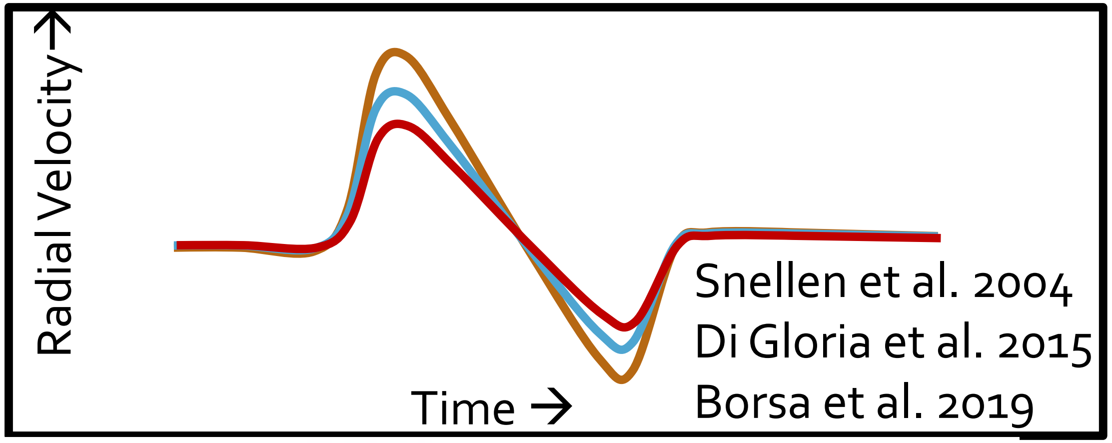


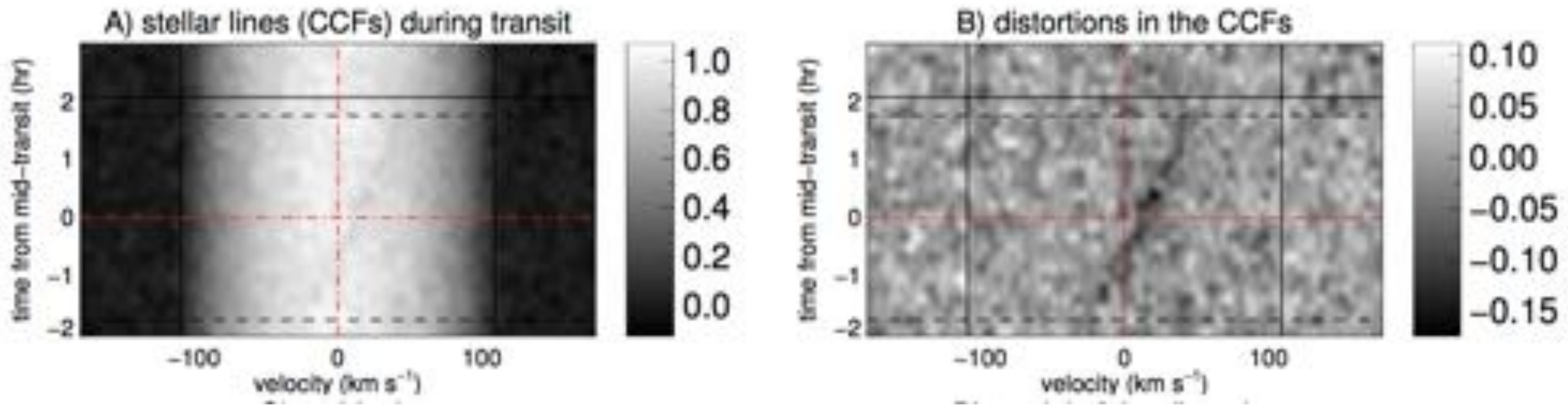


Differential RM effect during transit

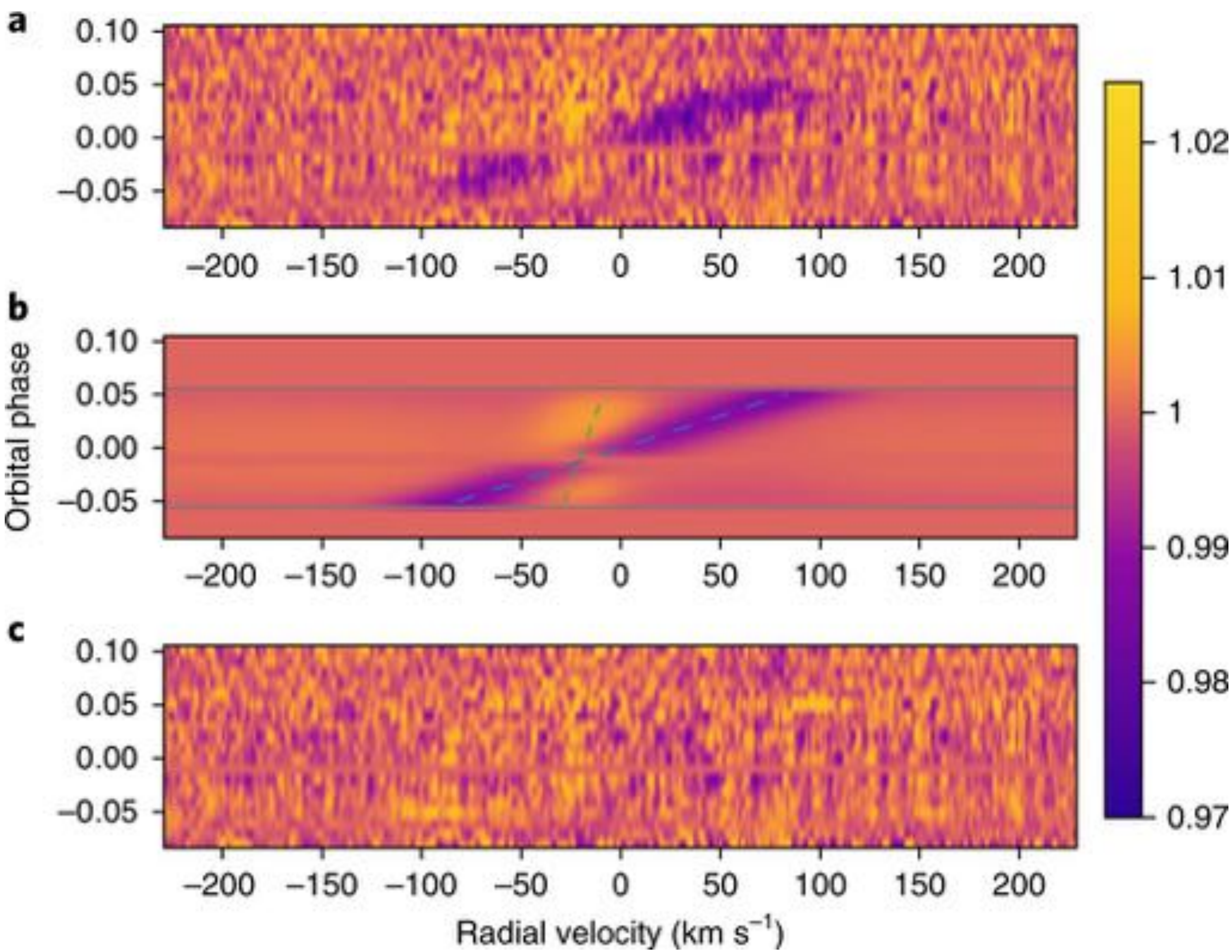
- Amplitude of Rossiter McLaughlin Effect depends on planet size
- Size of planet influenced by absorption of atmosphere
- E.g. for Rayleigh Scattering effects







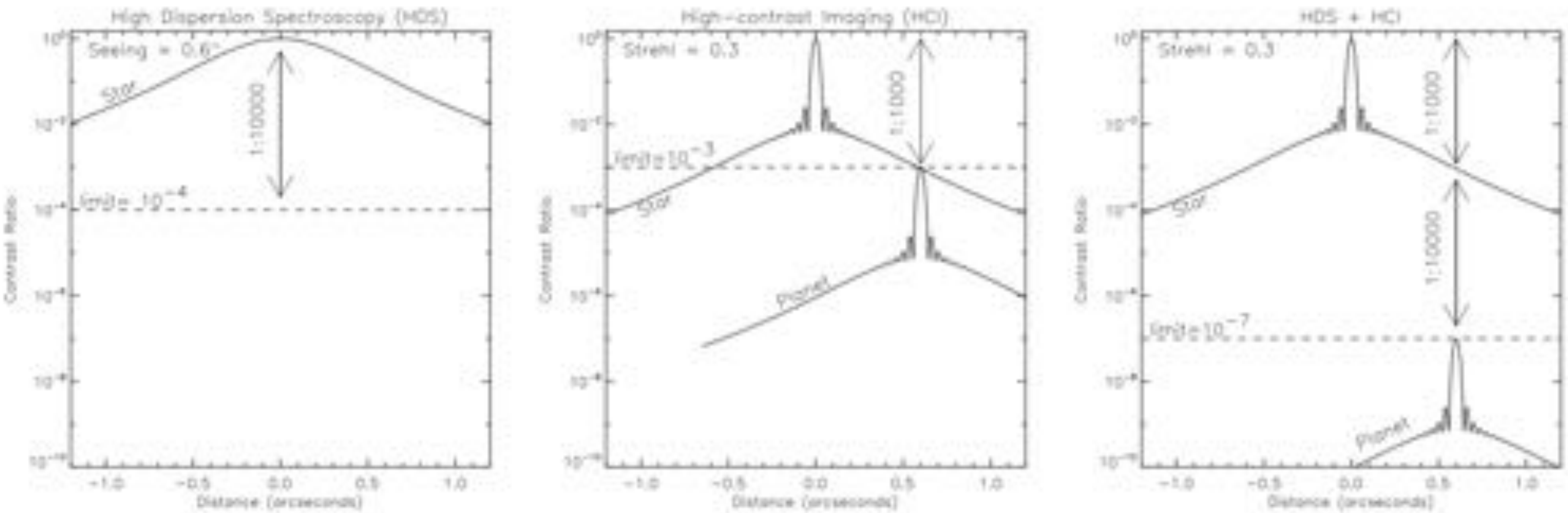
Model line shapes for fast rotating stars



Fei Yan & Henning 2018 - Halpha in Kelt-9b

Angular-differential high-dispersion spectrocopy

HDS+HCI

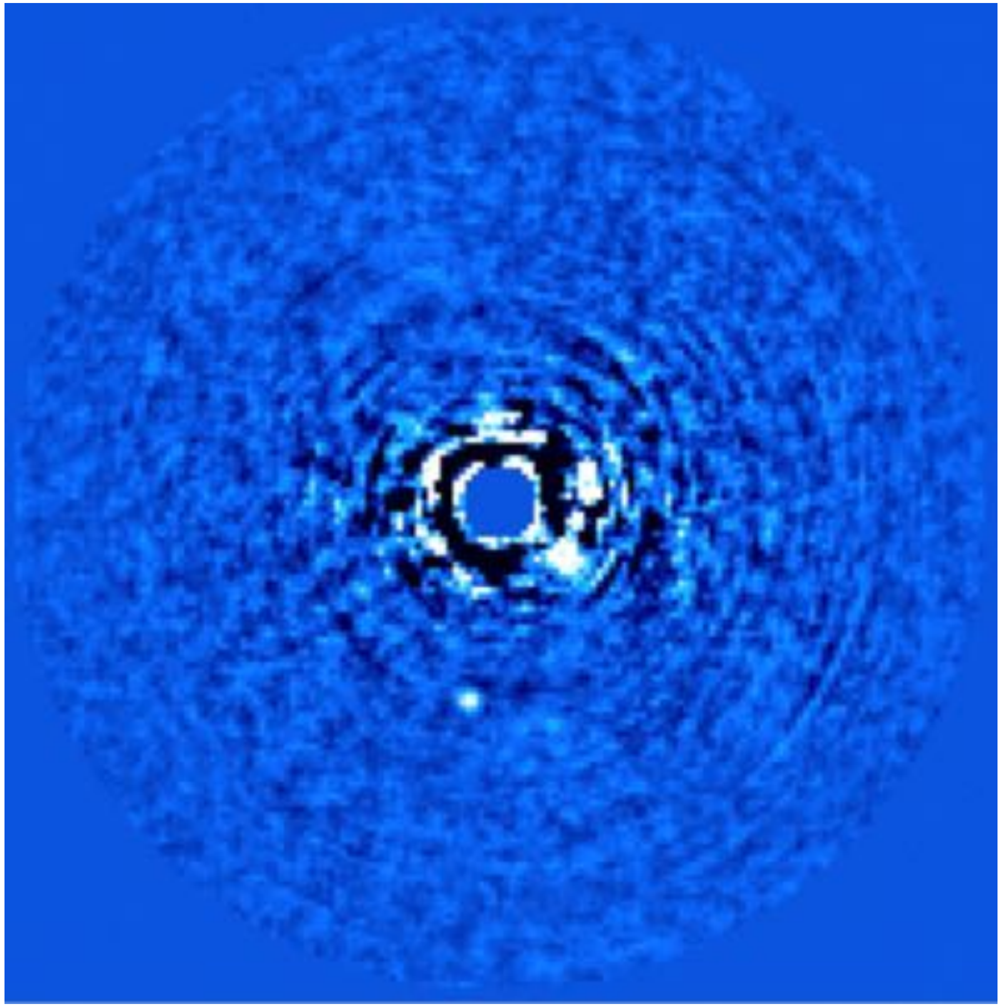


$$S/N = \frac{S_{\text{planet}}}{\sqrt{S_{\text{star}}/K + \sigma_{\text{bg}}^2 + \sigma_{\text{RN}}^2 + \sigma_{\text{Dark}}}} \sqrt{N_{\text{lines}}},$$

Sparks & Ford 2002
Riaud & Schneider 2007
Snellen et al. 2015

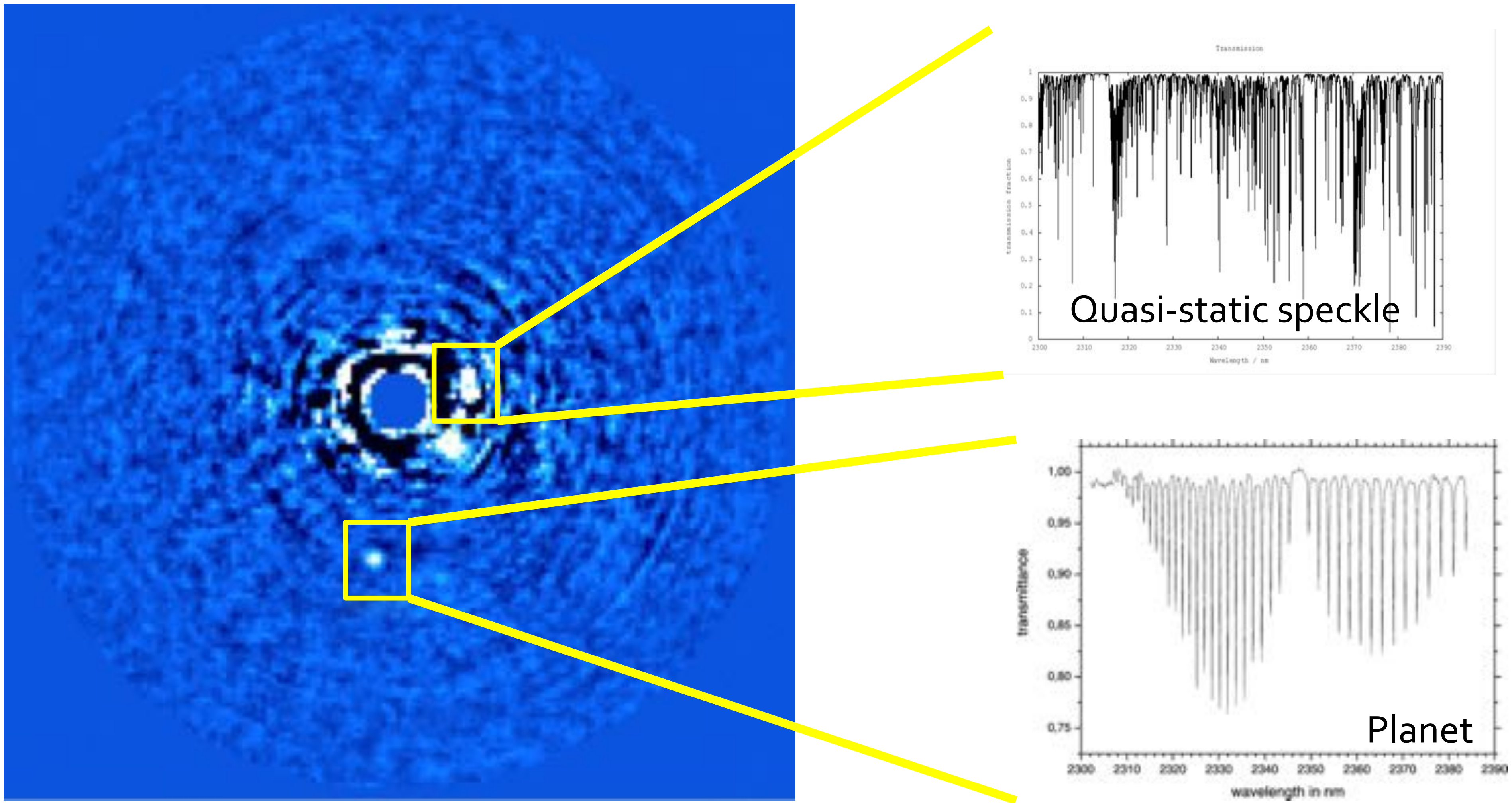
Angular-differential high-dispersion spectrocopy

HDS+HCI

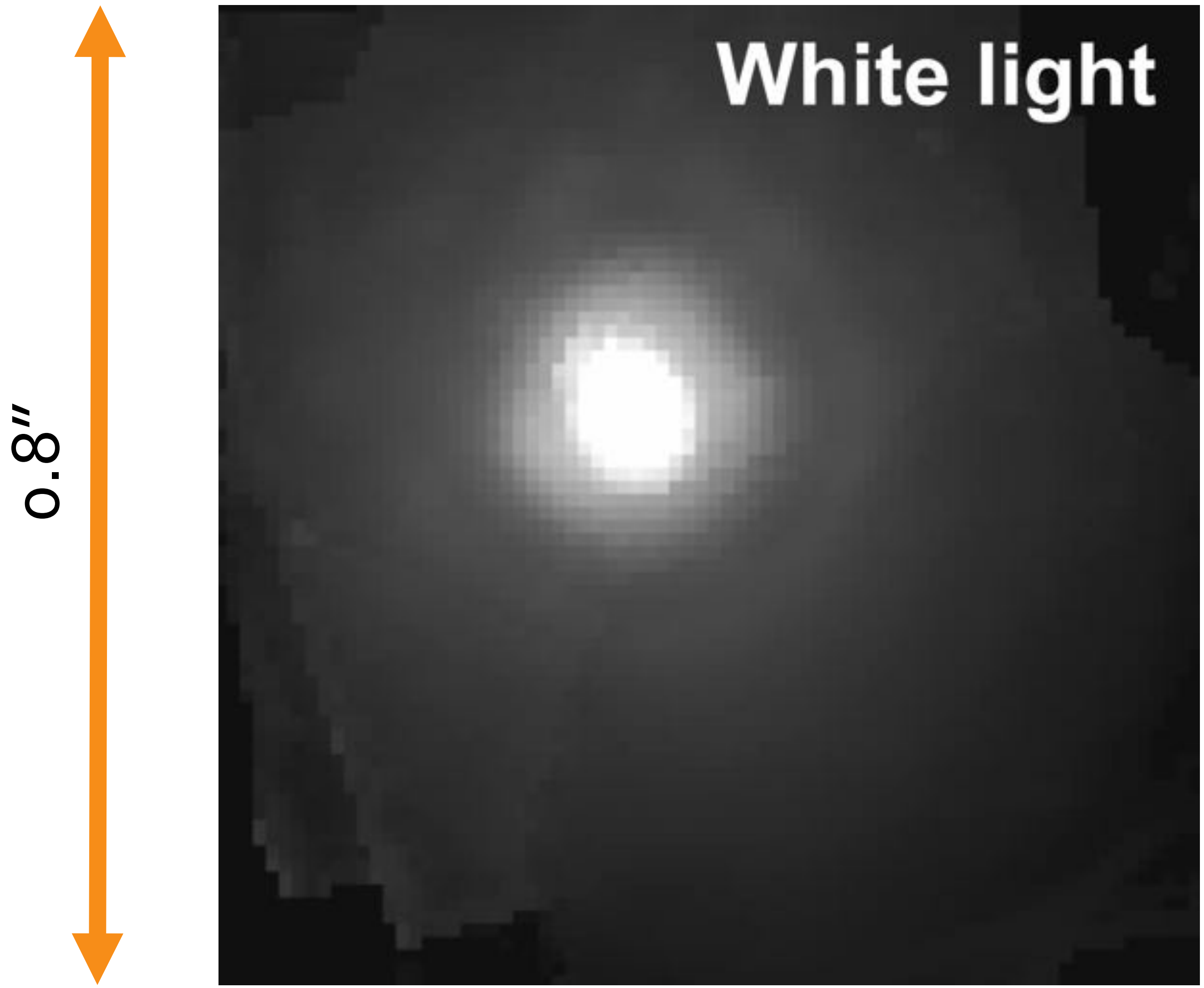


Angular-differential high-dispersion spectrocopy

HDS+HCI



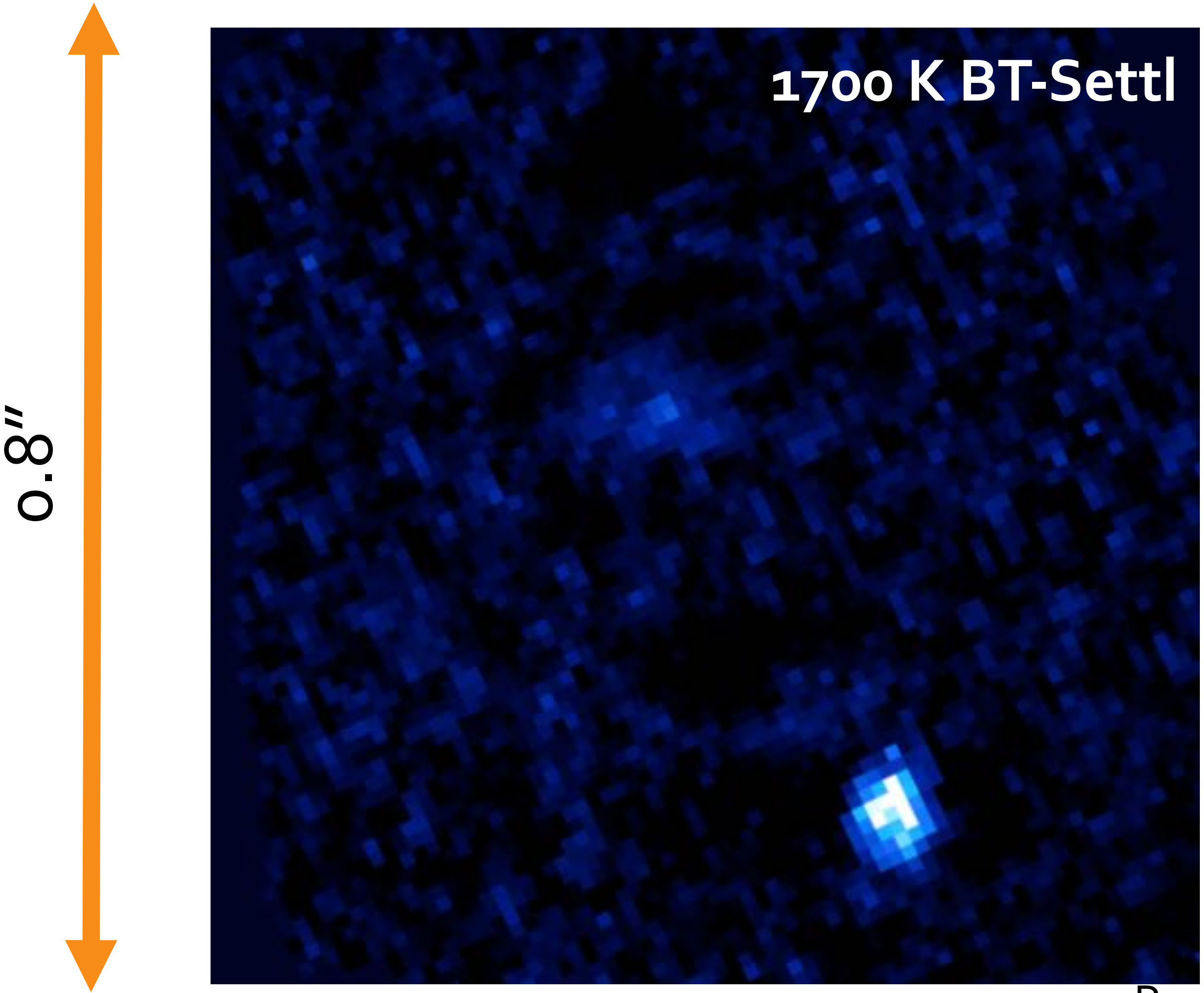
Low spectral resolution Beta Pictoris with SINFONI (R=4000)



Hoeijmakers et al. 2018

Raw contrast = 250

Low spectral resolution Beta Pictoris with SINFONI (R=4000)

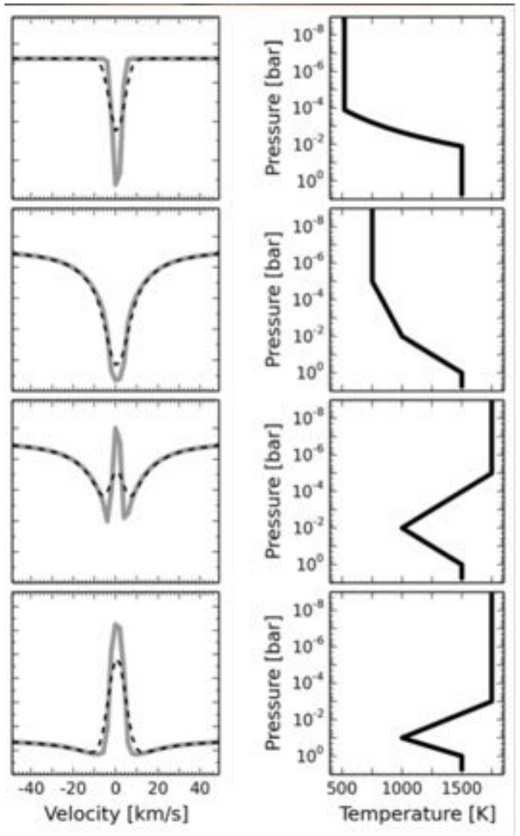


Hoeijmakers et al. 2018

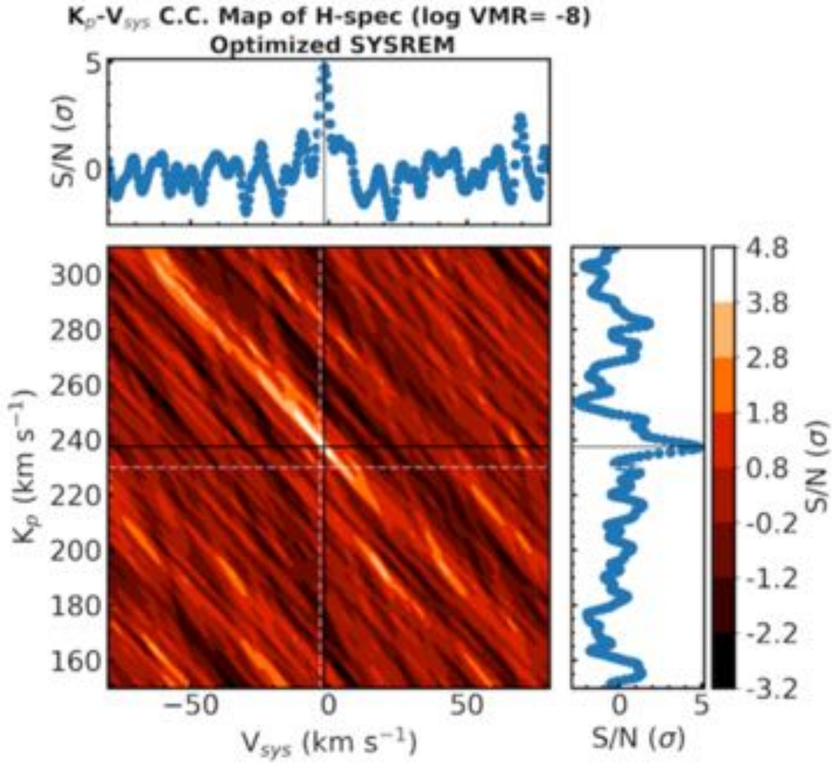
Raw contrast = 250
Final contrast = 100,000

What interesting stuff can be probed?

- **Molecular and Atomic Abundances**
- **Atmospheric temperature structure**



Schwarz et al. 2015



TiO in emission in WASP-33 (Nugroho et al. 2017)
Direct proof of **thermal inversion**

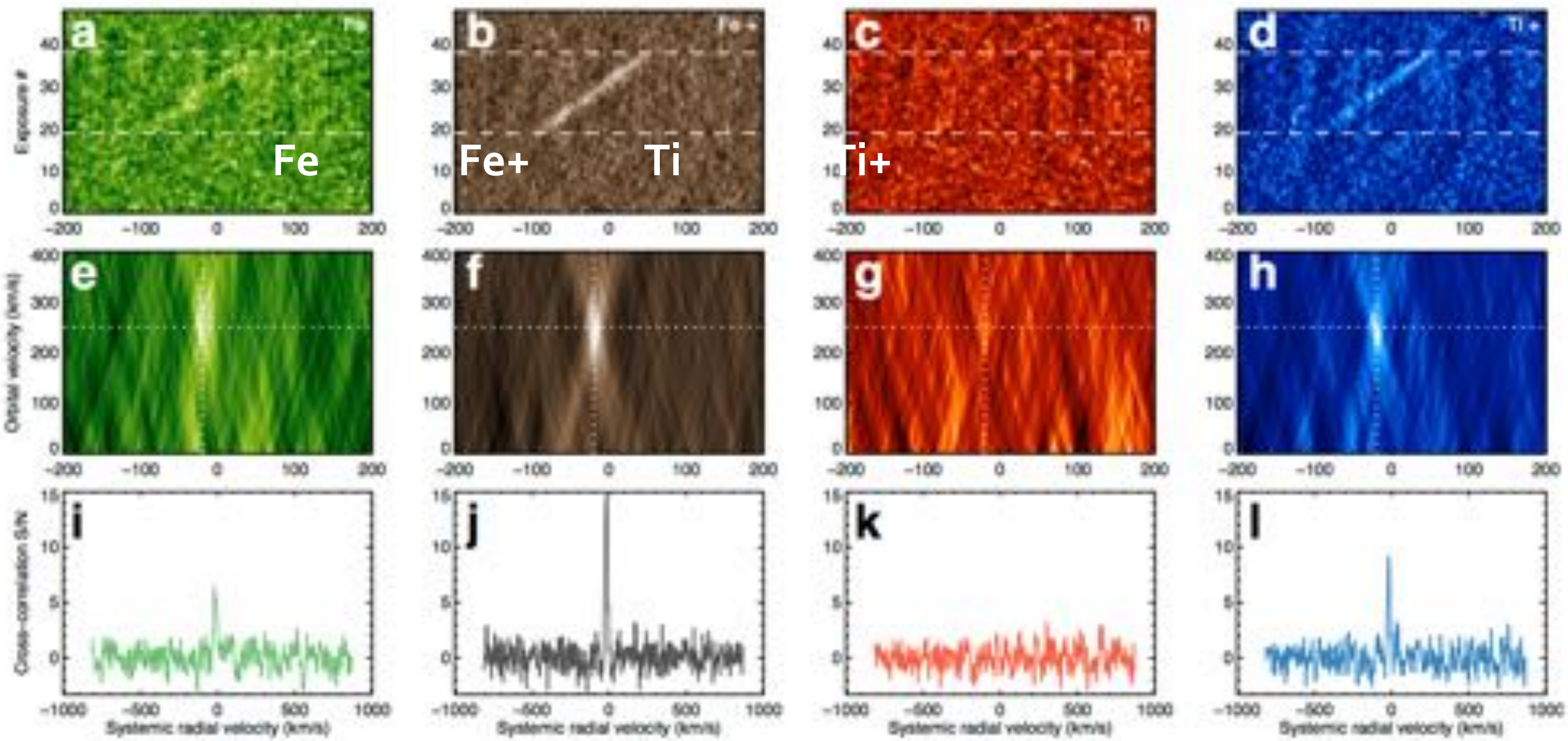
As function of orbital Phase → morning, afternoon, evening, and nightside spectra!

LETTER

https://doi.org/10.1038/s41586-018-0401-y

Atomic iron and titanium in the atmosphere of the exoplanet KELT-9b

H. Jens Hoeijmakers[1,2], David Ehrenreich[1], Kevin Heng[2]*, Daniel Kitzmann[2], Simon L. Grimm[2], Romain Allart[1], Russell Deitrick[2], Aurélien Wyttenbach[1], Maria Oreshenko[2], Lorenzo Pino[1], Paul B. Rimmer[3,4], Emilio Molinari[5,6] & Luca Di Fabrizio[5]



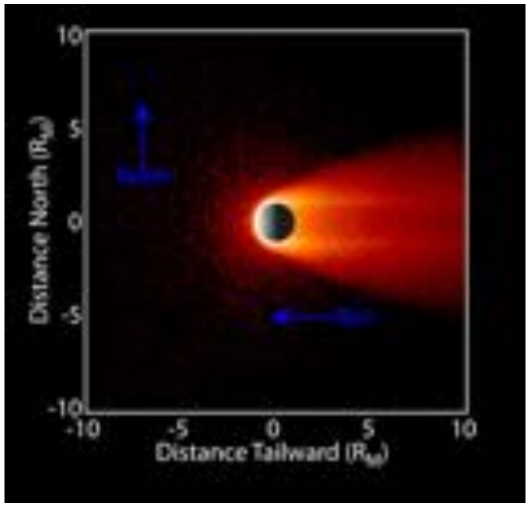
What interesting stuff can be probed?

- **Winds, Circulation & Rotation**
  Winds as function of altitude; equatorial jets; global circulation (climate); spin rotation; tidal locking

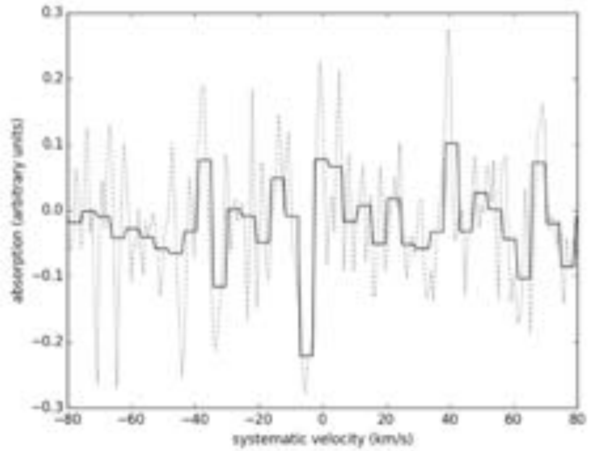
- **Exospheres**
  Understanding the evolution of atmospheres – atmospheric escape – interaction with their host stars (hot Jupiters to terrestrial planets)

- **Surface Sputtering & disintegrating planets**

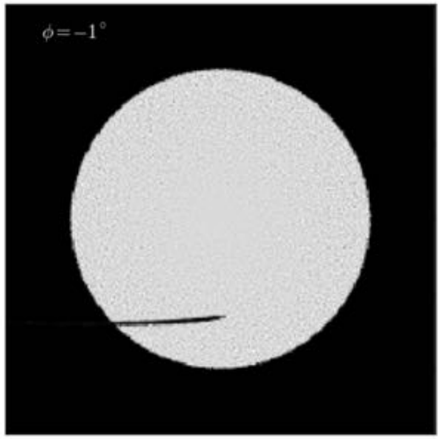
Na & Ca+ tails of planet Mercury



55 Cnc e: Ca+?? [Ridden-Harper et al. 2016]

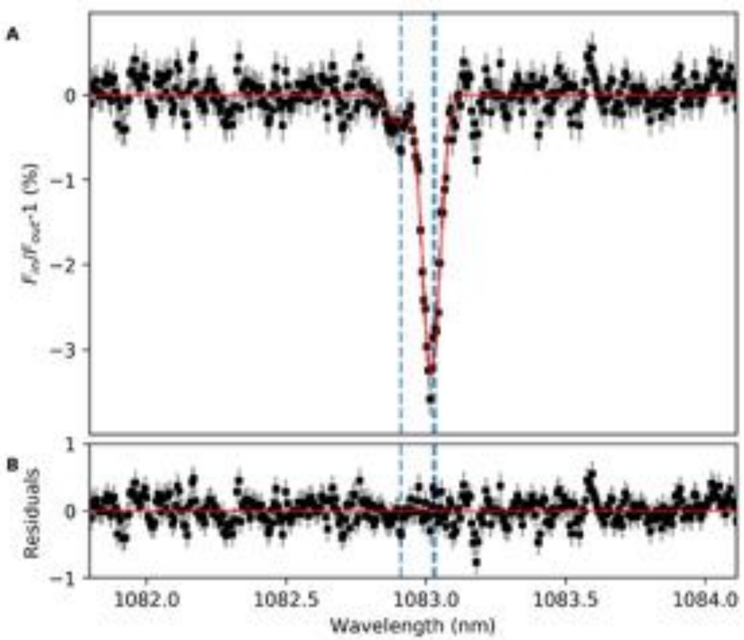


Ridden-Harper – PhD thesis

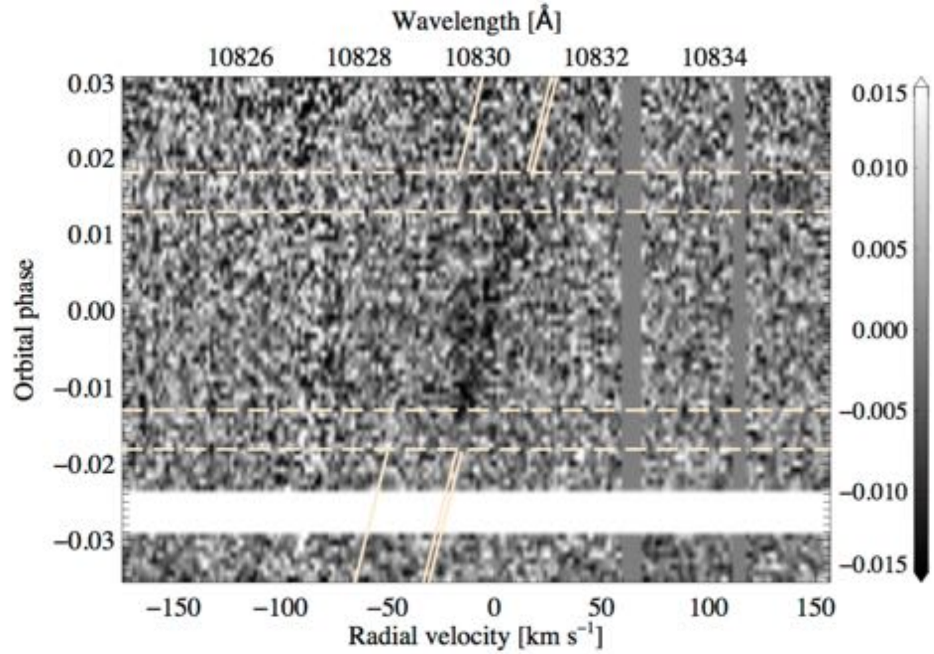


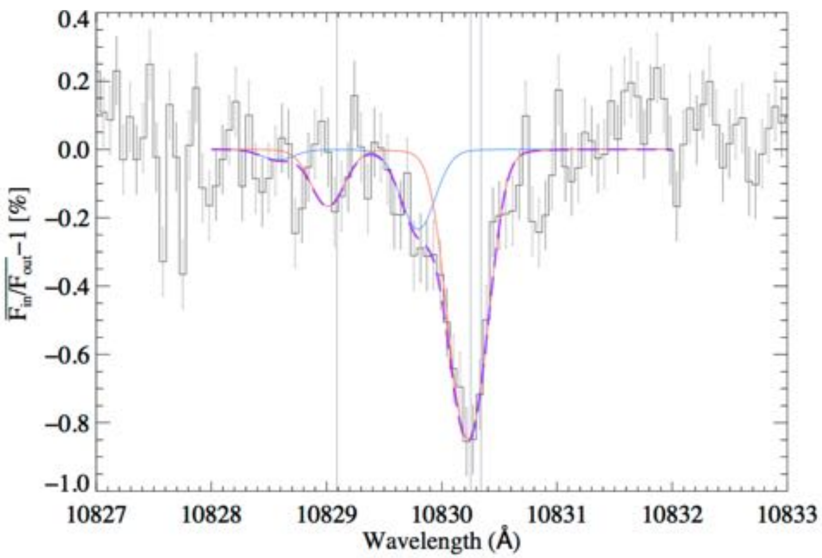
Evaporating atmospheres in helium with CARMENES

Nortmann et al. ***Science***, 2018
CARMENES spectrograph – WASP-69b



Alonso Floriano et al. 2019





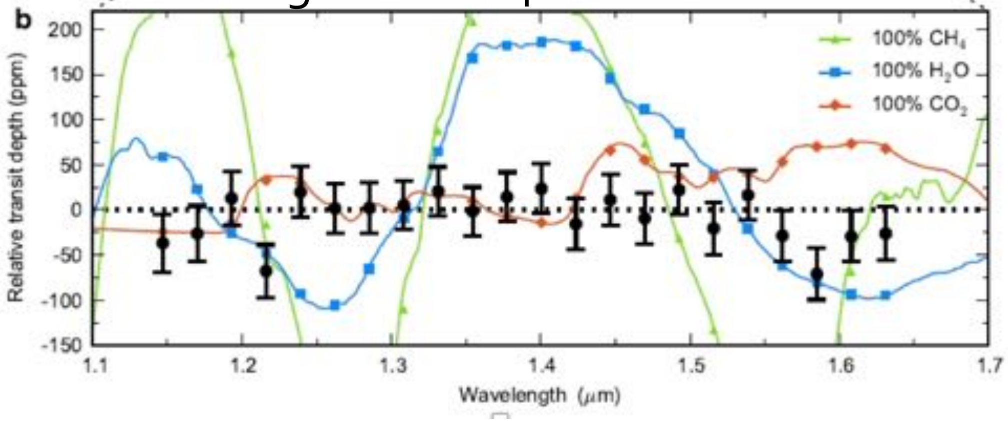
Also: Oklopcic & Hirata 2018; Spake et al. 2018; Salz et al. 2018; Allart et al. 2018; 2019)

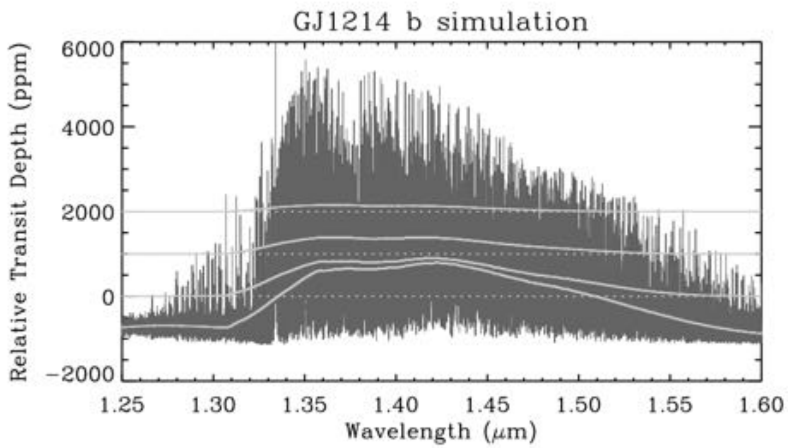
What interesting stuff can be probed?

- **Clouds, hazes, scattering processes**

HDS in transmission probes effectively higher up in the atmosphere – probe molecular absorption above the clouds?

Kreidberg et al. 2014





- **Isotopes and Isotopologues** [Paul; Ian]

New way to probe the origin and evolution of planets and their atmosphere? Accretion history – history of atmospheric escape

Molliere & Snellen 2018:

- 13C/12C is easy, and should soon be doable (but not so interesting?)
- HDO/H2O is very interesting and maybe in reach of 10m class telescopes
- D/H (HDO, CH3D) is great for METIS@ELT. Even D/H for Proxima b

Astronomy & Astrophysics manuscript no. isos
January 7, 2019
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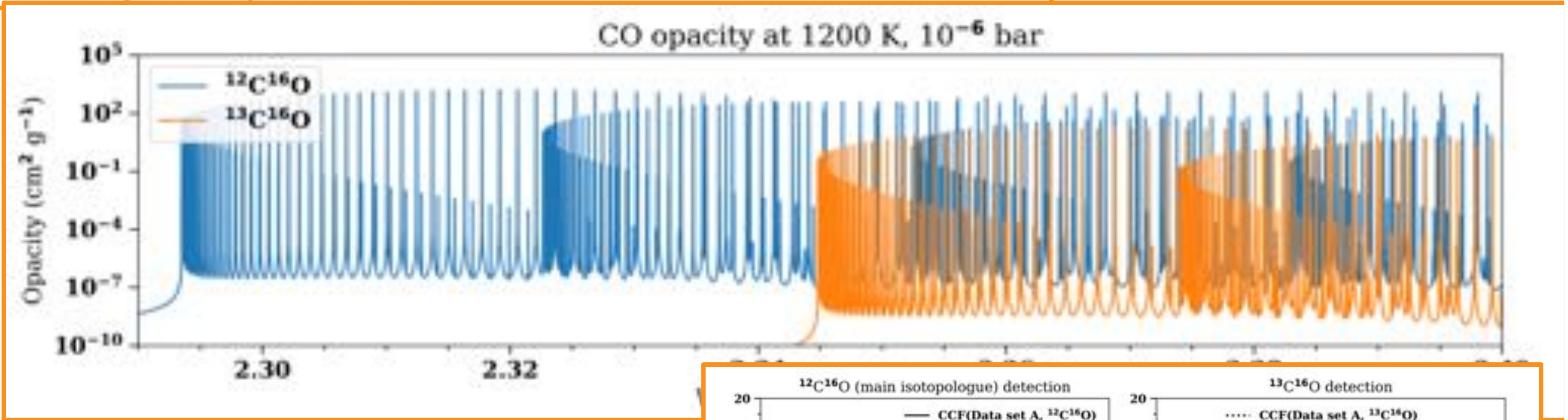
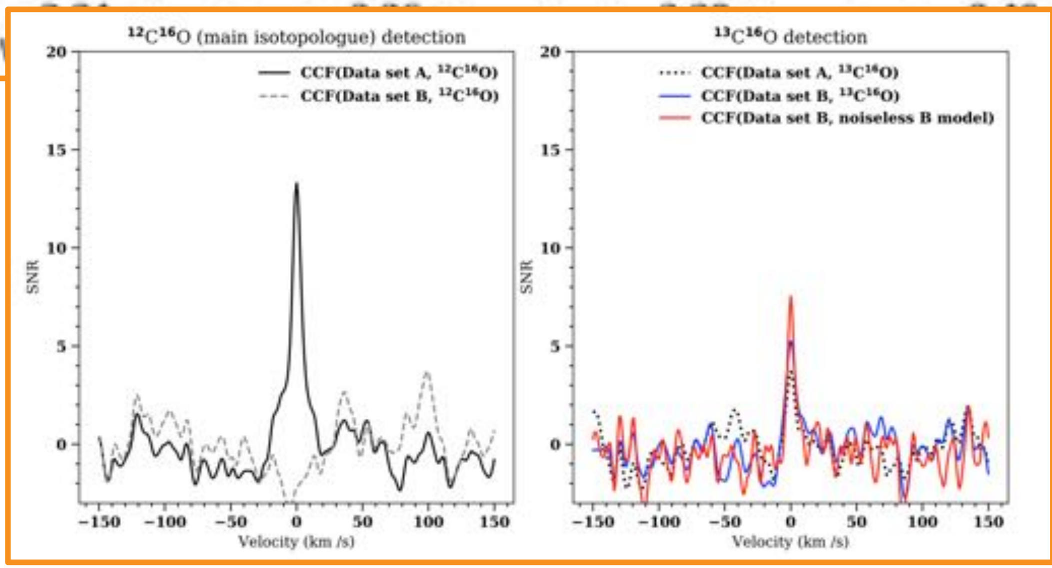
Detecting isotopologues in exoplanet atmospheres using ground-based high-dispersion spectroscopy

P. Mollière[1] and I.A.G. Snellen[1]

Leiden Observatory, Leiden University, Postbus 9513, 2300 RA Leiden, The Netherlands

Received 31 August 2018 / Accepted 19 December 2018





How can we achieve progress?

1. Easier Targets!
   Think Kelt-9b; WASP-189b; MASCARA 1b&2b; TESS

2. Better algorithms – [e.g. Machine Learning – Chloe Fisher et al]
   "SYSREM gets rid of all the red noise, but removes half of my planet signal"

3. Better models
   your observations are only as good as your model → your model is only as good as your line list

4. Combine HDS with low-resolution information

5. Wider instantaneous wavelength range
   more lines give more signal [GIANO; CARMENES; SPIROU; CRIRES+]

6. More stable instruments and detectors

7. Better Throughput with new instrument concepts

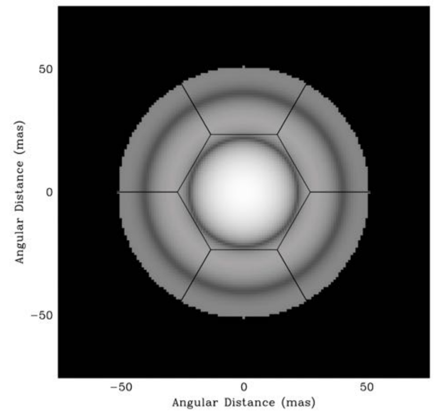
How can we achieve progress?

9. Purpose-built instrumentation for HDS+HCI

SPHERE & ESPRESSO; SPHERE & CRIRES+; **LEXI (PhD thesis S. Haffert)**

Proxima b: $F_p/F_* \sim 2 \times 10^{-7}$ at $2\lambda/D$ @ 0.75 µm

- SPHERE XAO upgrade
- vAPP coronagraphy
- ESPRESSO IFU mode
- ESPRESSO fiber injection upgrade



Reflected light in 30 nights

O2 in 60 nights

[Lovis et al. 2017]

Technology development

- CRIRES+ (Vigan+)
- SCExAO + IRD (Subaru JP)
- MagAO-X + RHEA (Magellan USA)
- Keck Planet Imager + Characterizer

How can we achieve progress?

10. Bigger Telescopes!

NAS Exoplanet Science Strategy Report 2018:

Finding: GMT and TMT, equipped with high-resolution optical and infrared spectrographs, will be powerful tools for studying the atmospheres of transiting and non-transiting close-in planets, and have the potential to detect molecular oxygen in temperate terrestrial planets transiting the closest and smallest stars.

ELT: First-light instrument METIS will have a R=100,000 IFU (L & M)

HIRES will be *the* HDS instrument in the optical/NIR

Atmospheric characterization of temperate rocky planets around nearby M-dwarfs, including possible biomarker gases

Beyond Ground-based High-res spectroscopy

Context: Long-term planning of ESA

- Scientific program relies on long-term planning of its priorities

- **Horizon 2000** (1983)

  → Cassini-Huygens; Rosetta; Herschel; Planck

- **Horizon 2000+** (1994)

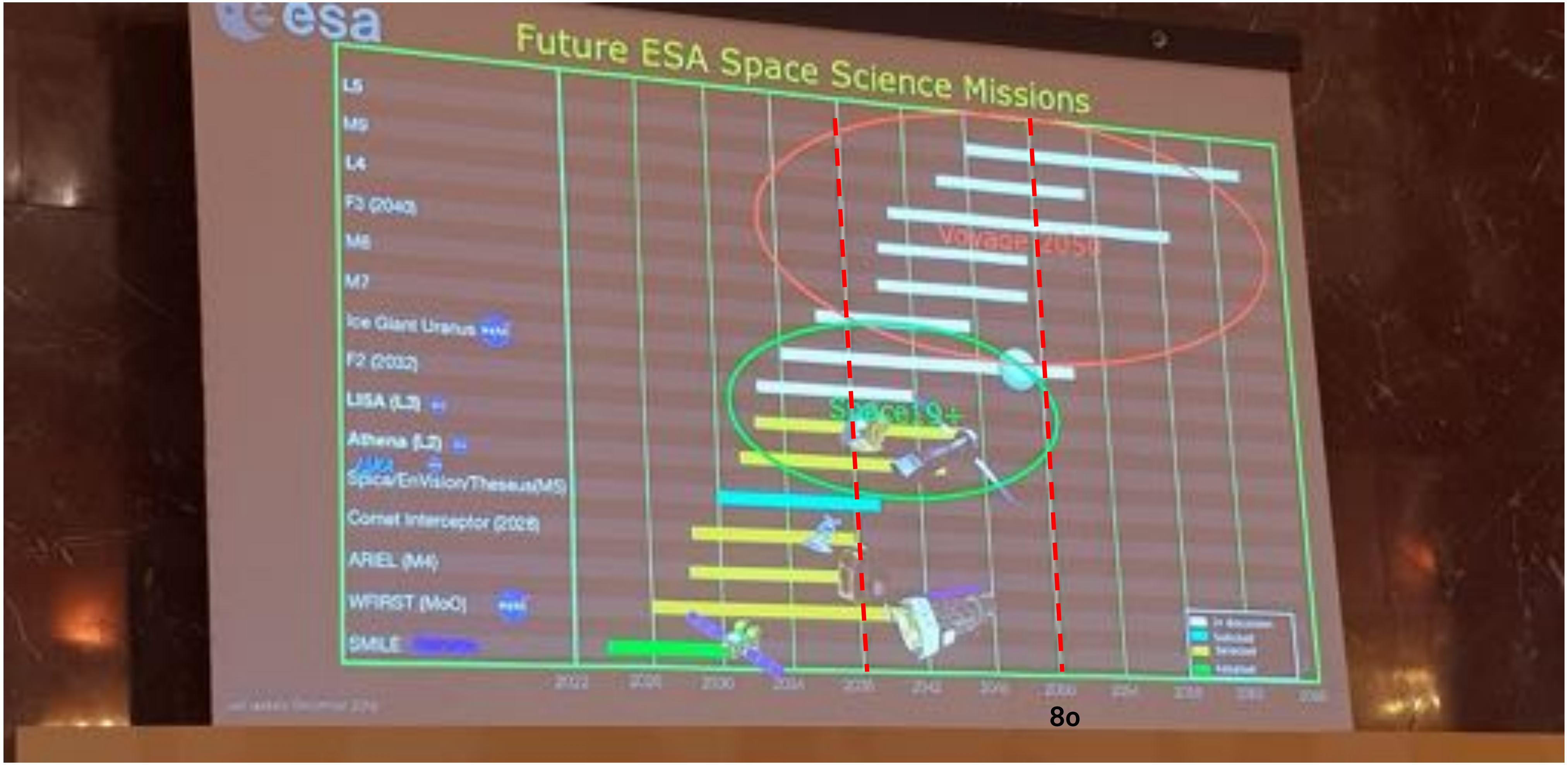
  → Gaia; BepiColombo; JWST

- **Cosmic Vision** (2004)

  → Juice; Athena; LISA (CHEOPS; Euclid; PLATO; ARIEL)

- **Voyage 2050** (now!) **** 2035 – 2050 period ****

Goal: *select research areas for 3 L-class missions (~1 Geuro)*
identify high-impact science themes for M-missions
identify science themes for investment in long-term tech development


esa
Future ESA Space Science Missions
L5
M5
L4
F3 (2040)
M6
M7
Ice Giant Uranus
F2 (2032)
LISA (L3)
Athena (L2)
Spica/EnVision/Theseus(M5)
Comet Interceptor (2028)
ARIEL (M4)
WFIRST (MoO)
SMILE
Voyage 2050
Space 19+
80

The Process

- Call for white papers (August 2019)
- Selection of senior committee
- Supported by topical teams
- *Workshop – last October*
- Interactions with topical teams (next 6-months)
- Recommendations from topical teams to senior committee
- Final recommendation of senior committee to SPC(?)/Directorate

Senior committee

Linda Tacconi (Chair)
Max Planck Institute for Extraterrestrial Physics,
Garching, Germany

Chris Arridge (Co-Chair)
Lancaster University,
United Kingdom

Alessandra Buonanno
Max Planck Institute for Gravitational Physics,
Potsdam, Germany

Mike Cruise
Retired,
United Kingdom

Olivier Grasset
University of Nantes,
France

Amina Helmi
University of Groningen,
The Netherlands

Luciano Iess
Sapienza University of Rome,
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Eiichiro Komatsu
Max Planck Institute for Astrophysics,
Garching, Germany

Jérémy Leconte
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France

Jorrit Leenaarts
Stockholm University,
Sweden

Jesús Martín-Pintado
Spanish Astrobiology Center (CAB),
Madrid, Spain

Rumi Nakamura
Space Research Institute,
Austrian Academy of Sciences, Austria

Darach Watson
University of Copenhagen
Denmark


Topical Team Membership
Solar/Plasma
B. Lavraud
J. DeKeyser
I. DeMoortel
L. Fletcher
D. Fontaine
R. Harrison
H. Nilsson
J. Soucek
F. Valentini
Solar System
F. Abernethy
B. Charnay
M. El-Maarry
J. Flahaut
C. Freissinet
A. García Muñoz
A. Genova
B. Langlais
M. Massironi
A. Mura
G. Tobie
J. Trigo-Rodriguez
Star/Galaxy Evolution
K. Caputi
L. Labadie
S. Mathis
L. Wang
A. Quirrenbach
A. Vallenari
L. Buchhave
E. Choquet
A. Santerne
F. van der Tak
X. Luri
H. Cegla
Extreme Universe
A. DeRosa
J. Gair
R. Kotak
G. Nelemans
A. Petiteau
Cosmology/Fund. Phys
S. Ettori
P. de Bernardis
P. Natoli
C. de Rham
T. Sotiriou

White papers

- ~100 white papers submitted – 32 presented at workshop
  Solar system science: 25
  Sun & Plasma Physics: 15
  Galaxies/cosmology: 14
  High-Energy/Xrays: 12
  Fundamental Physics/GW: 8
Exoplanets/Planet@Starformation: 15

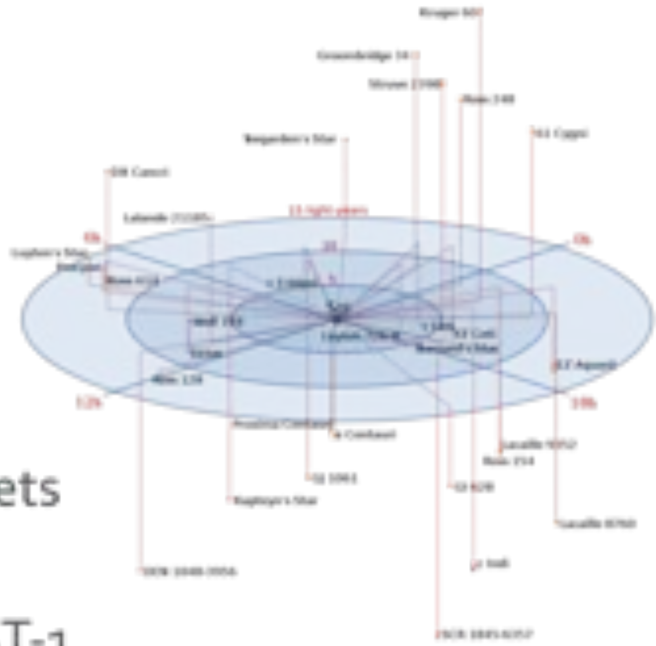
E.g.:
Snellen; Snik; Kenworthy; de Boer; Miguel; Kreidberg; Keller (+60 et al.):
Detecting life outside our solar system with a large **high-contrast-imaging mission**

Sascha Quanz et al.:
Atmospheric characterization of terrestrial exoplanets in the mid-infrared: biosignatures, habitability & diversity [**Nulling Interferometer**]

Exoplanets: What to expect 2020 – 2035?

- Great new observatories: JWST (2021) & Extremely Large Telescopes (2026)
- NASA TESS; WFIRST; **ESA Gaia; CHEOPS (2019); PLATO (2026); ARIEL (2028)**

Likely Status - 2035:



- Nearby transiting planet population unveiled
- Local planet M-dwarf population known
- Twin-Earths around Sun-like stars still challenging

- In-depth statistical data on hot/warm gaseous planets
- First atmospheric studies of few Earths/M-dwarfs
- Atmospheric constituencies of Proxima-b/TRAPPIST-1
- **Atmospheric characterization of twin-Earths around sun-like stars, out of reach**

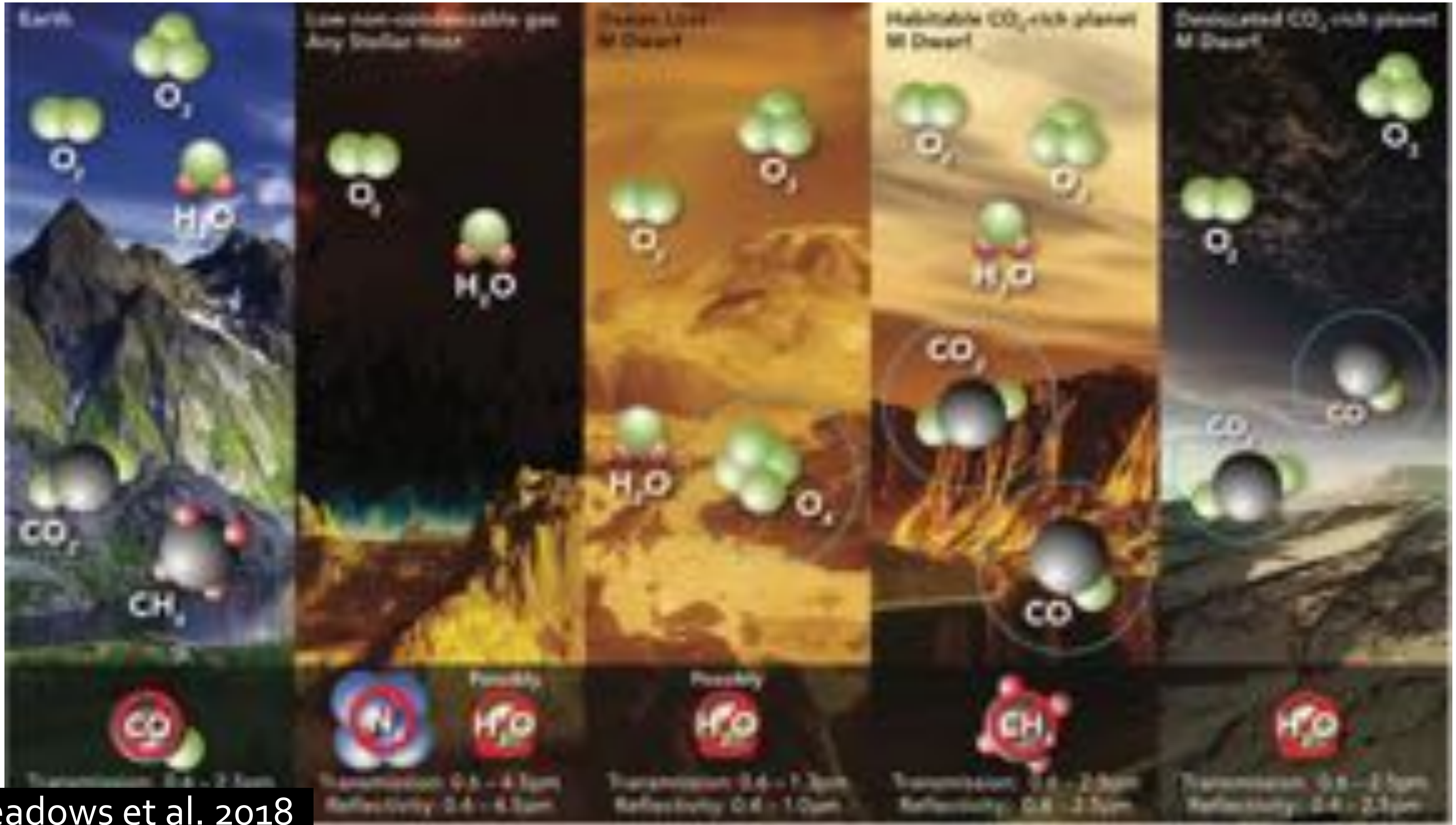
Exoplanet science drivers in 2035 and beyond

- Planetary architectures around Sun-like stars
- Atmospheres of the wide diversity of planets
- Climates + physical/chemical processes & Geology
- Main constituencies of temperate-rocky-planet:
  - N_2/CO_2 dominated atmospheres?
  - H_2O present?
  - $O_2 – CH_4$ Biomarker gases present?
  - Biomarker gases due to biotic or abiotic processes?

<u>Biosignature</u>: *an effect of biological activity on its environment, detectable at interstellar distances*

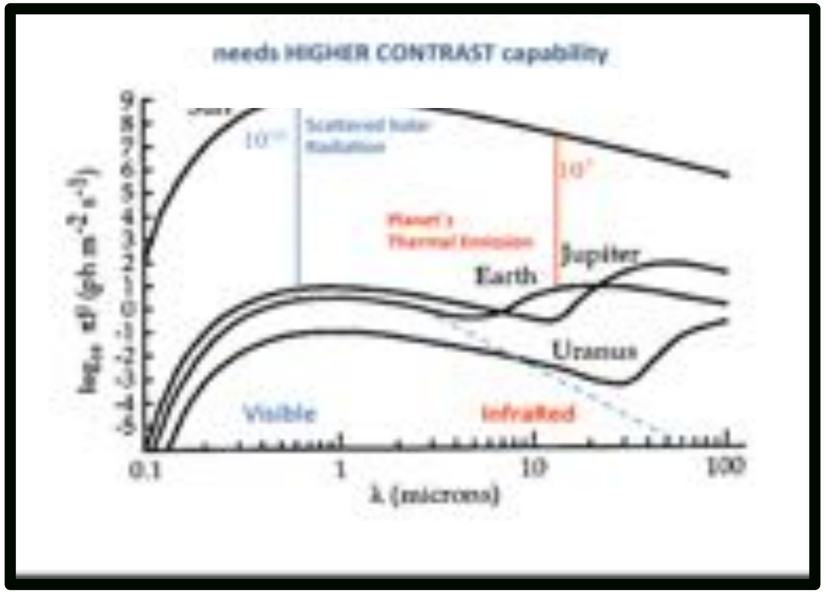
<u>Requirements:</u> *Surface ocean? geological activity? magnetic field?*

Life detection will always require understanding of evolutionary and geophysical context of a planet



Meadows et al. 2018

Challenges



→ Transits too infrequent and signal too small
→ Contrast too large for ground-based telescopes

Solutions

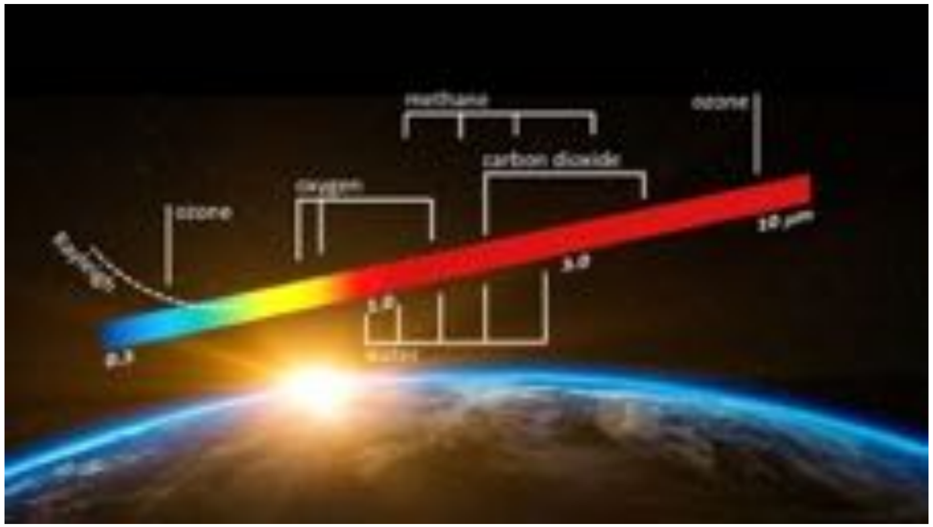
1. Large High-Contrast-Imaging Telescope [LUVOIR/HabEx/ESA-alone]
2. IR Space Interferometer (*talk*: Sasha Quanz)
3. Potential others: starshade + ground-based telescopes [*wp*: Janson]

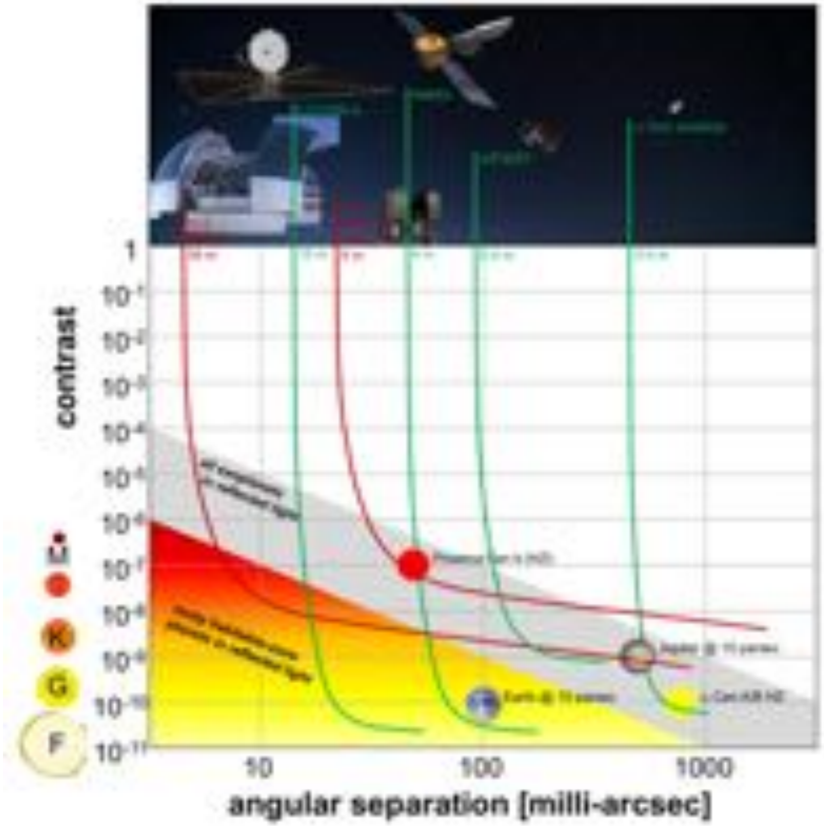
ESA should be able to make an educated decision in 10 yrs
Start a European development program for technology validation <u>now</u>

Requirements for a HCI Space Mission

- A contrast of 10^{-10} at an IWA of 80 -100 m.a.s.[a]
- Wavelength range covering the optical and NIR
- Sufficient Spectral Resolution for molecular detections
- Light Collecting Power + mission life time = # planetary systems

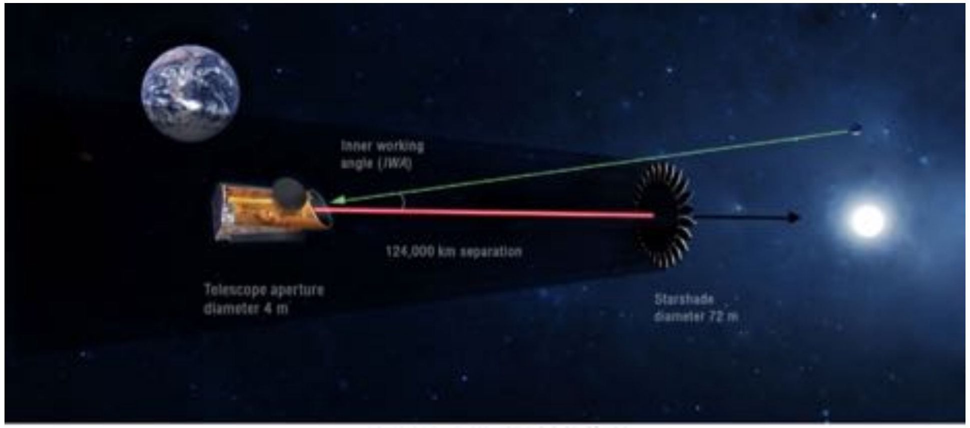
[a] depends on λ / starshade

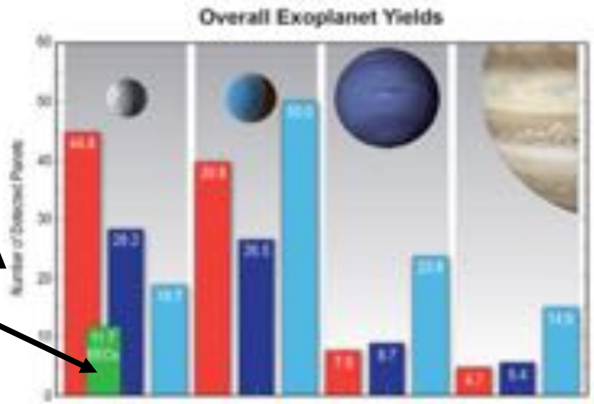




Current NASA studies

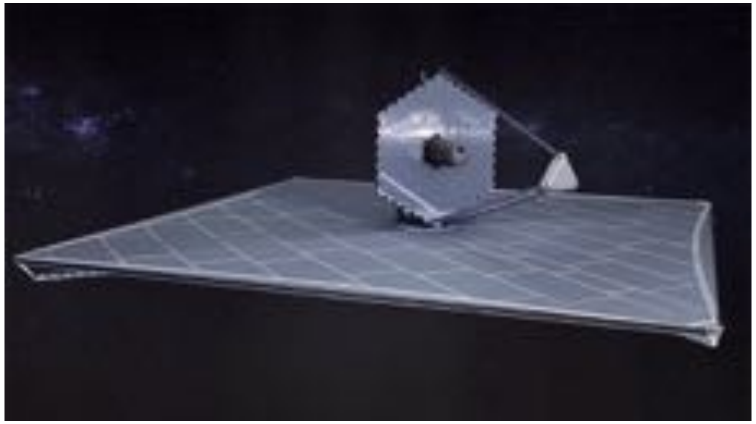
Habitable Exoplanet Observatory
4m Telescope + External Occulter





4-30 EA

Large UV/Optical/IR Telescope - LUVOIR
8m & 16m aperture



Planet yield:
[10 – 55] & [20 – 110] Earth Analogs

General-purpose observatory

ESA stand-alone mission?

NASA **WFIRST** is the only HCI mission (as tech demonstrator).
Opportunity for **full science+technology demonstrator** mission?

Bridge the gap between young-Jupiter and Earth-analog science

3-meter ESA HCI telescope:

- Jupiter analogs out to 50 lyr
- Dozen(s) of sub-Neptunes
- Down to rocky planets

The road ahead – central message & recommendations

ESA should be able to make an educated decision in 10 yrs
Start a European development program for technology validation now

A technological and science development path for Europe

- Testbeds for technology demonstration for HCI in space
- Increase TRL of specific technologies and subsystems
- Possible opportunity for full science+technology demonstrator mission?

European Expertise areas [*wp Sect. 5.5*]

Large space telescopes
Adaptive Optics
Coronagraphy
Wavefront sensing
System design
Spectroscopy
Polarization techniques
Detectors
Astrophotonics
Data-reduction techniques

A census of support from the Exoplanet community

Belgium
Michaël Gillon (University of Liège)
Anne-Lise Maire (University of Liège)

Denmark
Lars Buchhave (DTU Copenhagen)
Simon Albrecht (Aarhus University)

France
Anne-Marie Lagrange (Grenoble University)
Mamadou N'Diaye (Obs. Cote d'Azur)
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Pierre Baudoz (Observatoire de Paris)
Elsa Huby (Observatoire de Paris)
Anthony Boccaletti (Observatoire de Paris)
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Germany
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Roy van Boekel (MPIA Heidelberg)
Ralf Launhardt (MPIA Heidelberg)

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The Netherlands
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Jos de Boer (Leiden University)
Ignas Snellen (Leiden University)
Yamila Miguel (Leiden University)
Jayne Birkby (University of Amsterdam)
Michiel Min (SRON)
Daphne Stam (Technical University Delft)
Pieter de Visser (SRON)
Jean-Michel Désert (University of Amsterdam)
Christoph Keller (Leiden University)

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Kevin Heng (University of Bern)
Brice-Olivier Demory (University of Bern)

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Mark Claire (University of St. Andrews)
Beth Biller (University of Edinburgh)
Christiane Helling (University of St. Andrews)
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Tim Lenton (University of Exeter)
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Ignasi Ribas (ICE Barcelona)
Enric Palle (IAC Tenerife)

United States of America
Laura Kreidberg (Harvard University)
Olivier Guyon (University of Arizona; HabEx)
Bertrand Mennesson (NASA JPL; HabEx)
Christopher Stark (STSCI; HabEx/LUVOIR)
Victoria Meadows (Washington; LUVOIR)
Scott Gaudi (Ohio State University; HabEx)
Garreth Ruane (Caltech)

Thoughts, considerations, politics, strategies… (exoplanets)

- Exoplanet community showed a united front during workshop
- Main aim: - get exoplanets selected as one of the L1-themes
  - start tech development program
- Tension between visionary thinking "big and bold" and "cost caps"
- Most solar-system talks mentioned exoplanets
- ESA seems very willing to contribute to a HabEx/LUVOIR mission, if NASA selects this.
- *By default*, such contribution is probably not exoplanet related
- Could an ESA L-class mission (pride/flagship) be a contribution to something much bigger, or rather not?
- Is there too much dependence on US Decadal Process?
- Are we aiming too high with LUVOIR/HabEx (think TPF/Darwin)…

Thoughts, considerations, politics, strategies… (exoplanets)

- Interaction expected between topical teams and white paper leads
- Plan: convey message that there is also life in exoplanet science without LUVOIR/HabEx *(pun intented)*
- An ESA-alone direct-imaging mission is a real option: sub-HabEx

→ ARIEL surveys gas-giant Jupiters and Neptunes, few super-Earths(?)

→ ESA Direct Imaging mission (3m) surveys sub-Neptunes & Super-Earths, few Earths

→ Pre – LUVOIR → Earths in habitable zones

Reflected light	HabEx (4m)	3m ESA	2m ESA
Jupiters	25	10	3
Neptunes	40	15	5
Super-Earths	100	40	12
Rocky planets	100 (10)	40 (4)	12 (1)

- In the end, such mission could well merge again with LUVOIR/HabEx