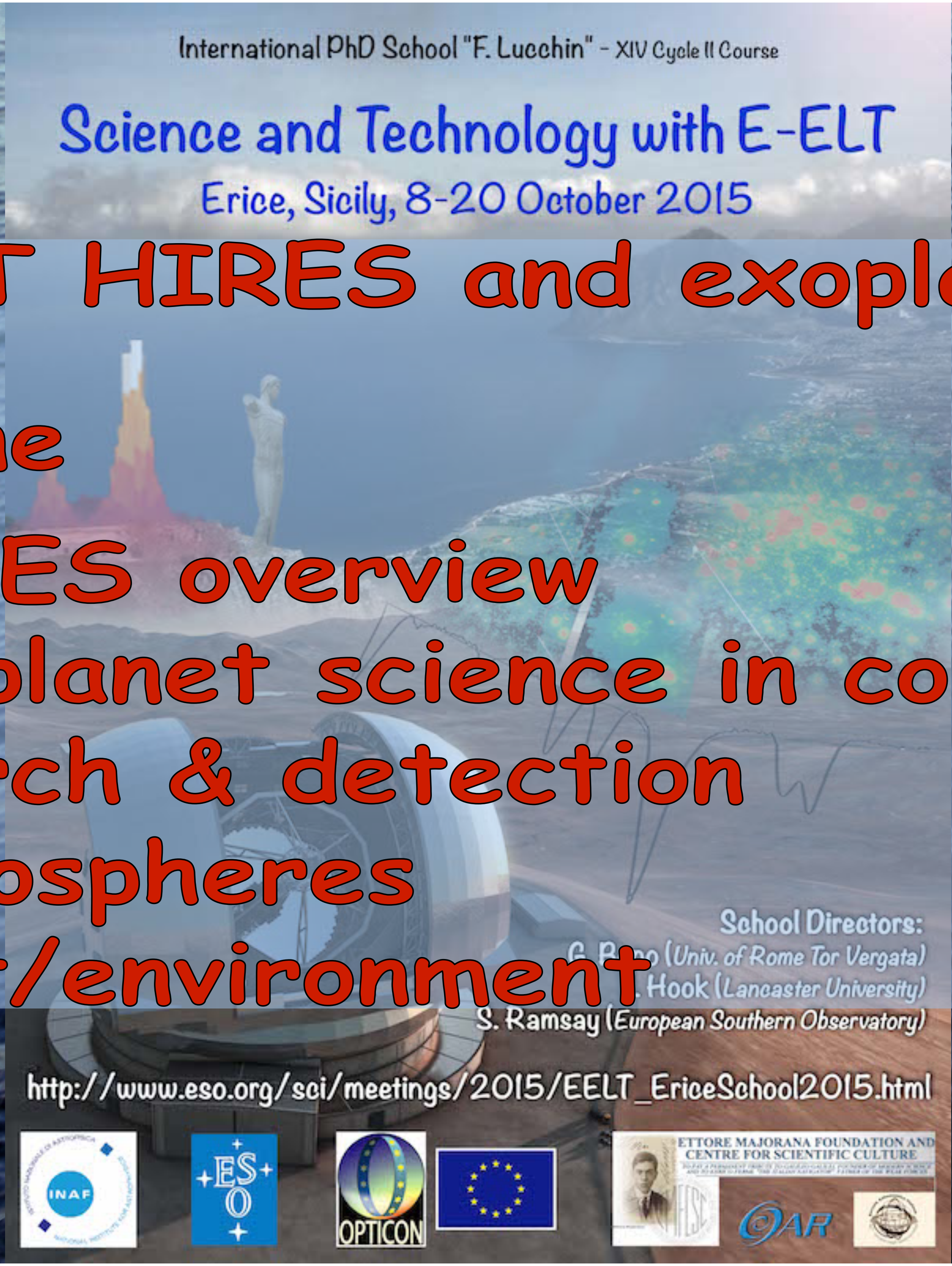
E-ELT HIRES and exoplanets

Livia Origlia - INAF - Bologna, Italy



E-ELT HIRES and exoplanets

Outline

- HIRES overview
- exoplanet science in context
- search & detection
- atmospheres
- host/environment

E-ELT HIRES: the Project

followed the Phase A studies of CODEX (PI L. Pasquini) & SIMPLE (PI L. Origlia) and the new E-ELT instrument roadmap

- International Consortium
  - **Italy** INAF lead technical institution, A. Marconi PI
  - **Chile** (L. Vanzi, Pontificia Universidad Catolica+)
  - **France** (F. Bouchy, Laboratoire d'Astrophysique de Marseille+)
  - **Germany** (K. Strassmeier, Leibniz-Inst. for Astrophysics Potsdam+)
  - **Portugal** (N. Santos, Institute of Astrophysics and Space Sciences)
  - **Spain** (R. Rebolo, Instituto de Astrofisica de Canarias+)
  - **Sweden** (N. Piskunov, Uppsala University+)
  - **Switzerland** (S. Udry, Observatoire de Genève+)
  - **United Kingdom** (R. Maiolino, University of Cambridge+)
- Interested:
  - **Brazil** (J. Renan de Madeiros, Theoretical and Experimental Physics of the Natal University)
  - **Denmark** (J. Fynbo, Niels Bohr Institute Copenhagen +)
  - **Poland** (A. Niedzielski, Nicolaus Copernicus University Toruń +)

E-ELT HIRES: the science cases

HIRES white paper: http://arxiv.org/abs/1310.316v2

RfI-Annex 2: Science Case by ESO+PST

live science cases

- solar system
- exo-planets
- star formation & proto-planetary disks
- stellar astrophysics
- stellar populations & Galactic archaeology
- pristine intergalactic medium & cosmic web
- galaxy evolution
- massive black-holes
- cosmology & fundamental constants
- …
- the unknown

E-ELT HIRES: science top level requirements

- **target sizes & spatial resolution:**
  - mostly point sources (stars, exo-planets, QSOs) or moderately extended (~1" galaxies) ➔ seeing/GLAO PSF
  - sub-structures at ~10mas scale (CS disks): DL in K
  - point sources in very crowded fields: ~DL PSF
- **spectral range & coverage in one exposure:**
  - as wide as possible (e.g. as blue as practical to K)
  - simultaneous 0.37-2.45 micron highly desirable for complete line diagnostics & redshift coverage
- **spectral resolution(s) & multiplexing:**
  - R>=100k + single obj ➔ exo-planets & chemical evol (stars, IGM)
  - R~10k +10 obj ➔ stellar pops, galaxy evolution, IGM tomography
  - R~100k + IFU/MOS at ~DL (IR) → CS disks, dense stellar fields
- **stability & accuracy:** ~0.1% PSF+flatfield, 10 cm s^{-1} $night^{-1}$

E-ELT HIRES: a multipurpose instrument with key science cases

how to meet science requirements while minimizing instrument complexity and associated risks?

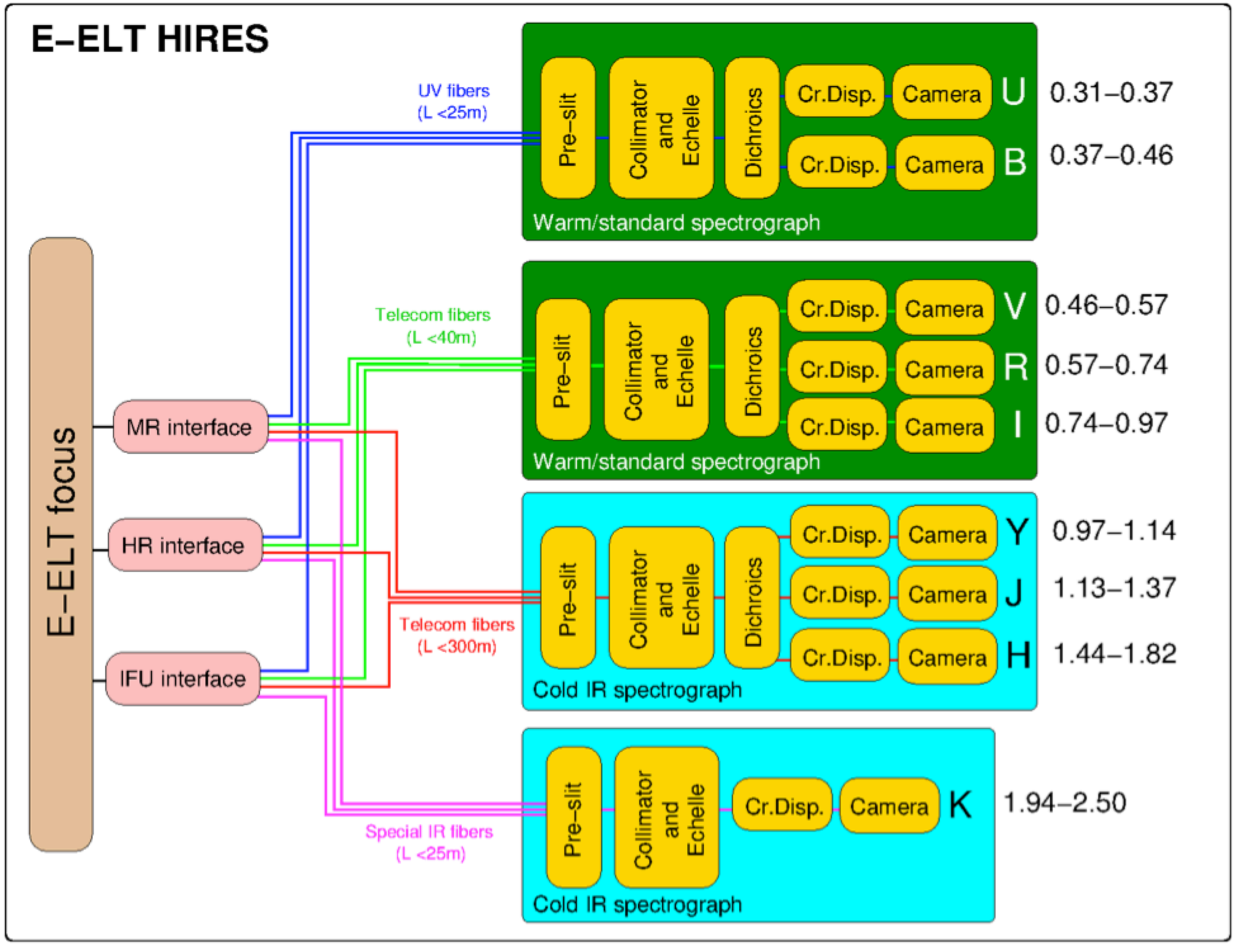
highly modular concept ➔ independent modules

if needed, it can be de-scoped/deployed in sequential stages, starting from high-priority/baseline modules and upgraded with time, depending on budget & resources

it minimizes risks associated with technical issues of individual modules during the construction and afterwards when in operation

more flexibility/options for location and interface at the telescope

E-ELT HIRES: the modular concept



4 independent fiber-fed modules (i.e. spectrometers) optimized over 4 spectral ranges (UB, VRI, YJH, K)

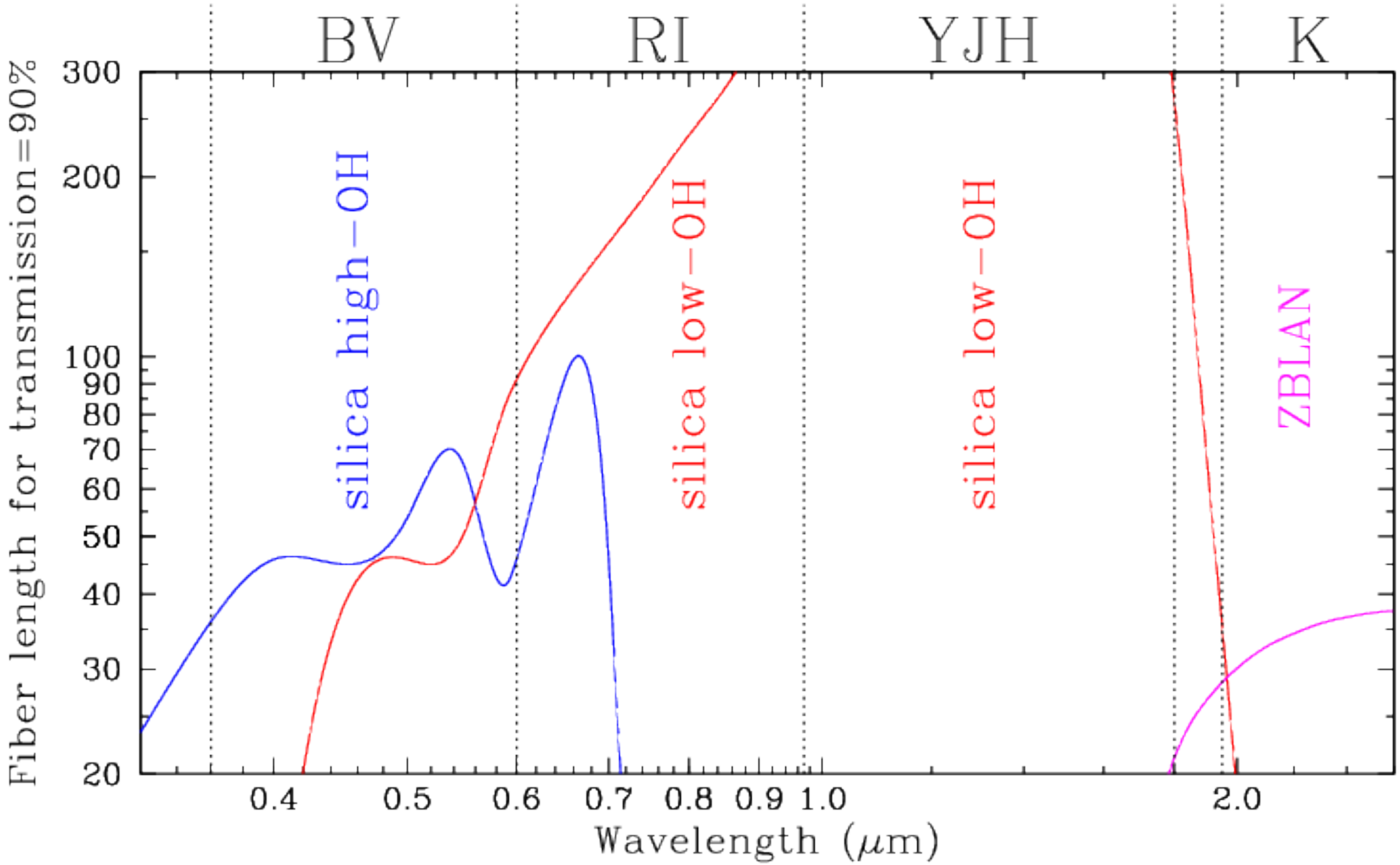
different observing modes are obtained using different and independent groups of fibers feeding each spectrometer

observing mode is selected in the pre-slit (fore-optics) of each module, no change inside the spectrometers.

modules and observing modes may be added or removed following a trade-off study between scientific priorities & tech/cost constraints

E-ELT HIRES: the fiber feeding system

fibers ➔ independent location of each spectrograph on the platform/other rooms



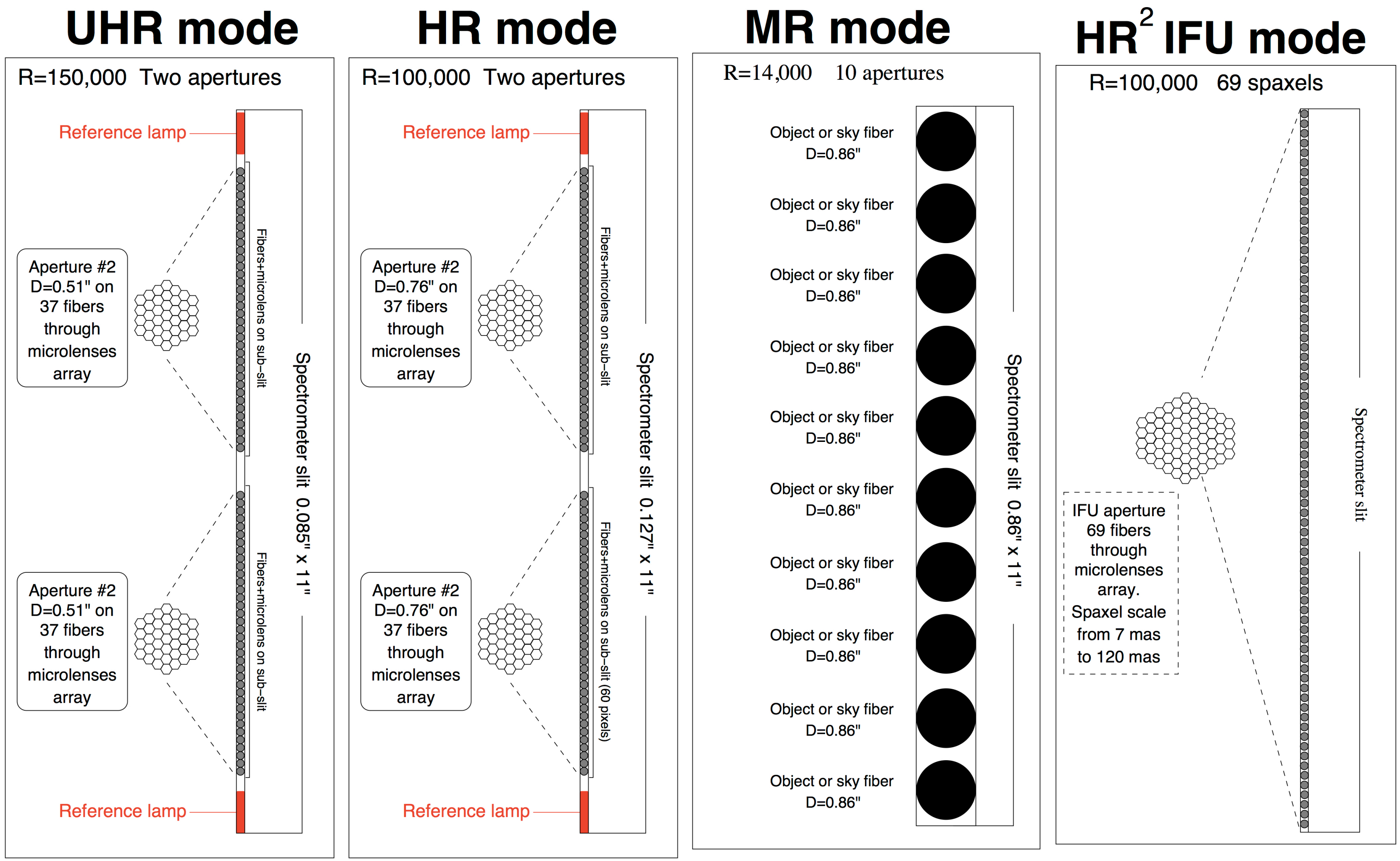
E-ELT HIRES: possible observing modes

seeing/GLAO PSF at the E-ELT $A\Omega$ = constant ➔ $N_{pix} = 160\ (\theta'')^2\ F^2_{camera}$

spreads over many pixels because of the large aperture & the small pix size (15 μm)

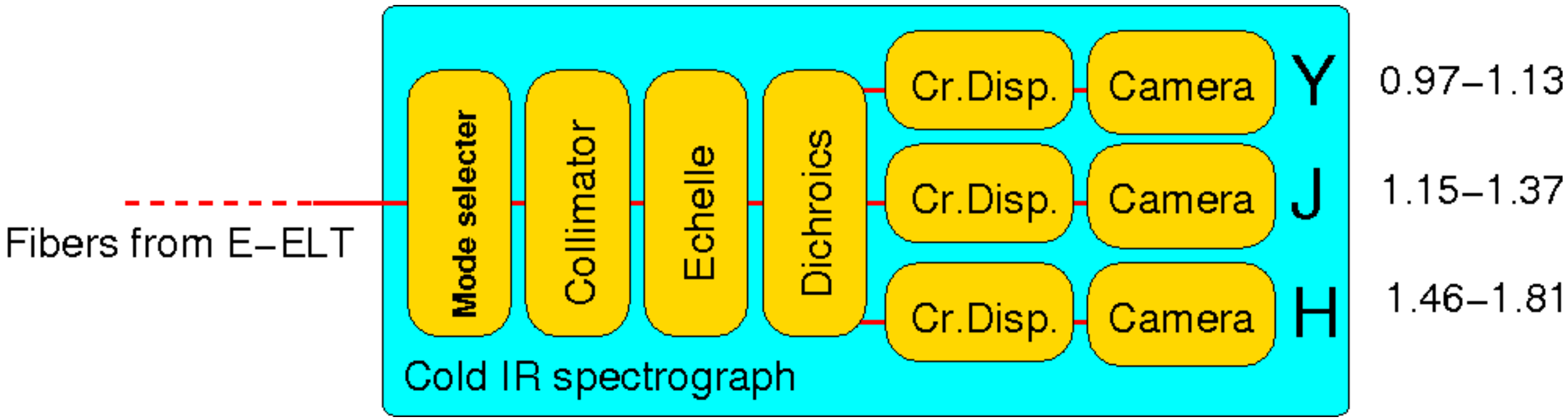
pseudo-slit of 11" along the spatial direction Y, pixels used for slicing (HR) or MOS/IFU

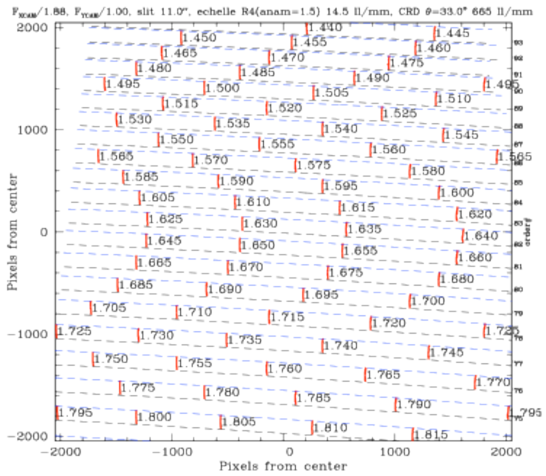
different slit-widths (0.13" at R =100,000) are used to achieve different spec res

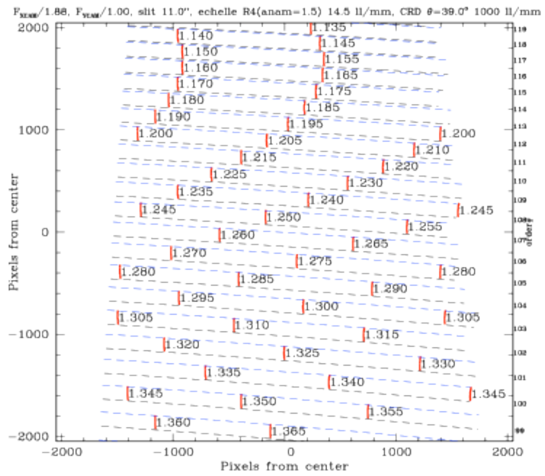


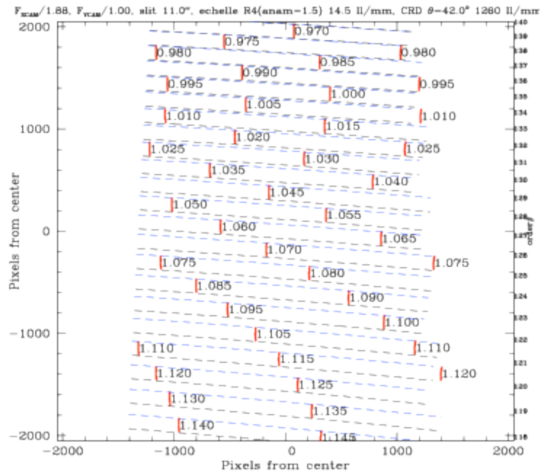
HIRES YJH module: cross dispersed spectral format

spectral format is fixed, the same for all observing modes









H 1.45-1.81 μm
orders 74-93

J 1.16-1.38 μm
orders 99-119

Y 0.97-1.14 μm
orders 118-140

exoplanet science

e.g.

2015ARA&A..53..409	Winn, Joshua N.; Fabrycky, Daniel C.	**The Occurrence and Architecture of Exoplanetary Systems**
2012ARA&A..50..411	Gaudi, B. Scott	**Microlensing Surveys for Exoplanets**
2012ARA&A..50..211	Kley, W.; Nelson, R. P.	**Planet-Disk Interaction and Orbital Evolution**
2010ARA&A..48..631	Seager, Sara; Deming, Drake	**Exoplanet Atmospheres**
2007ARA&A..45..397	Udry, Stéphane; Santos, Nuno C.	**Statistical Properties of Exoplanets**
2003ARA&A..41..429	Kasting, James F.; Catling, David	**Evolution of a Habitable Planet**
2002ARA&A..40..103	Hubbard, W. B.; Burrows, A.; Lunine, J. I.	**Theory of Giant Planets**
1998ARA&A..36..507	Woolf, Neville; Angel, J. Roger	**Astronomical Searches for Earth-Like Planets and Signs of Life**
1998ARA&A..36...57	Marcy, Geoffrey W.; Butler, R. Paul	**Detection of Extrasolar Giant Planets**

main lines of investigation

- **search and detection**
  dedicated surveys/telescopes/instruments from ground and space
- **characterization of their atmosphere**
  structure, chemical composition, weathering etc.
- **characterization of their host/environment**
  star properties and activity, star-planet-disk interaction, etc.
- **architecture, formation and evolution**
  population studies, theory

exoplanet science: the context in the E-ELT era

2017: CHEOPS CHaracterising ExOPlanet Satellite

search for transits by means of ultra-high precision photometry on bright stars hosting planets
http://www.cosmos.esa.int/web/cheops

2018: JWST

proto-planetary systems, exoplanet atmospheres (**e.g. Beichman+, 2014 PASP 126,1134**)
http://www.jwst.nasa.gov

2018: TESS The Transiting Exoplanet Survey Satellite

two-year all-sky transit survey of the solar neighborhood, monitoring of more than 500,000 stars, it will identify planets ranging from Earth-sized to gas giants, around a wide range of stellar types and orbital distances.
http:tess.gsfc.nasa.gov/

2024: PLATO PLAnetary Transits and Oscillations of stars

- photometric monitoring of a large number of bright stars for the detection of planetary transits, with emphasis on planets orbiting in the habitable zone.
- asteroseismology for the determination of stellar masses, radii, and ages.

http://sci.esa.int/plato/

2025: ARIEL The Atmospheric Remote-Sensing Infrared Exoplanet Large-survey

candidate ESA M4 mission

1m-class telescope and a spectrometer covering the 1.95-7.8 micron band + photometric bands in the Visible and in the near-IR to continuously observe (3.5 yrs operations) exoplanets transiting their host Star and monitor the stellar activity, measure the albedo and detect clouds.
http://ariel-spacemission.eu

exoplanets: search & detection

http://exoplanet.eu/catalog.php

normally searched around bright stars ➔

normally not necessary a large telescope aperture

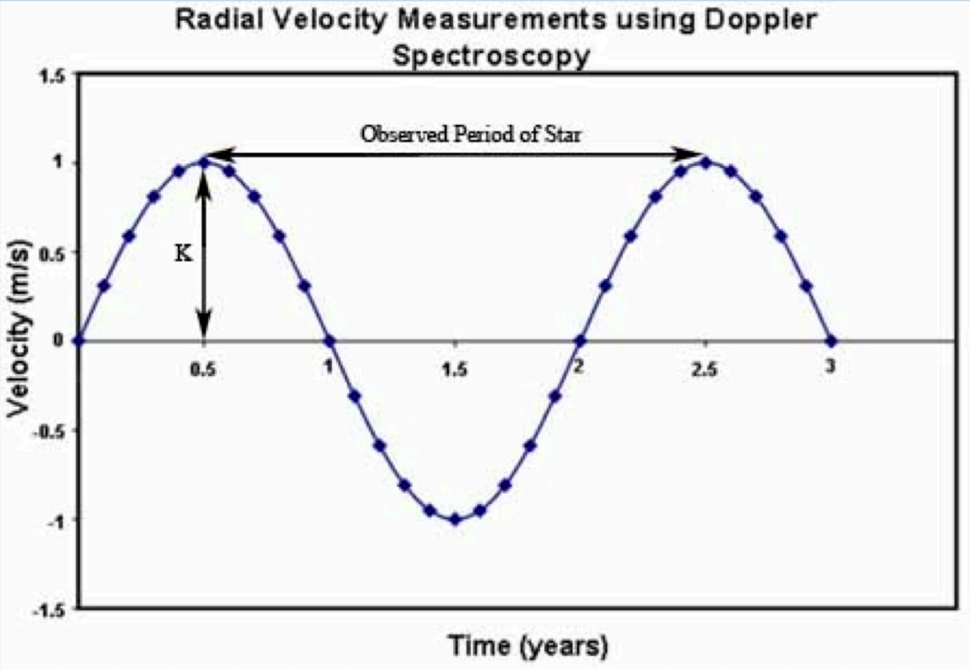
BUT

- **high performance/optimized instruments**
- **large amount of telescope time ➔ dedicated surveys/telescopes**

detection techniques

- **astrometric:** changes in the proper motion of the host star
- **photometric:** changes in the luminosity of the host star (planet transit)
- **spectroscopic:** changes in the RV of the host star (Doppler shift)
- **microlensing:** changes in the light curve of the host star
- **direct imaging**

E-ELT HIRES and exoplanets: detection



$$K = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{M_p \sin i}{(M_p + M_*)^{2/3}} \frac{1}{(1-e^2)^{1/2}} \text{ m/s}$$

P : orbital period

M_p : planet mass

i : inclination of the planet orbit to the line perpendicular to the line-of-sight

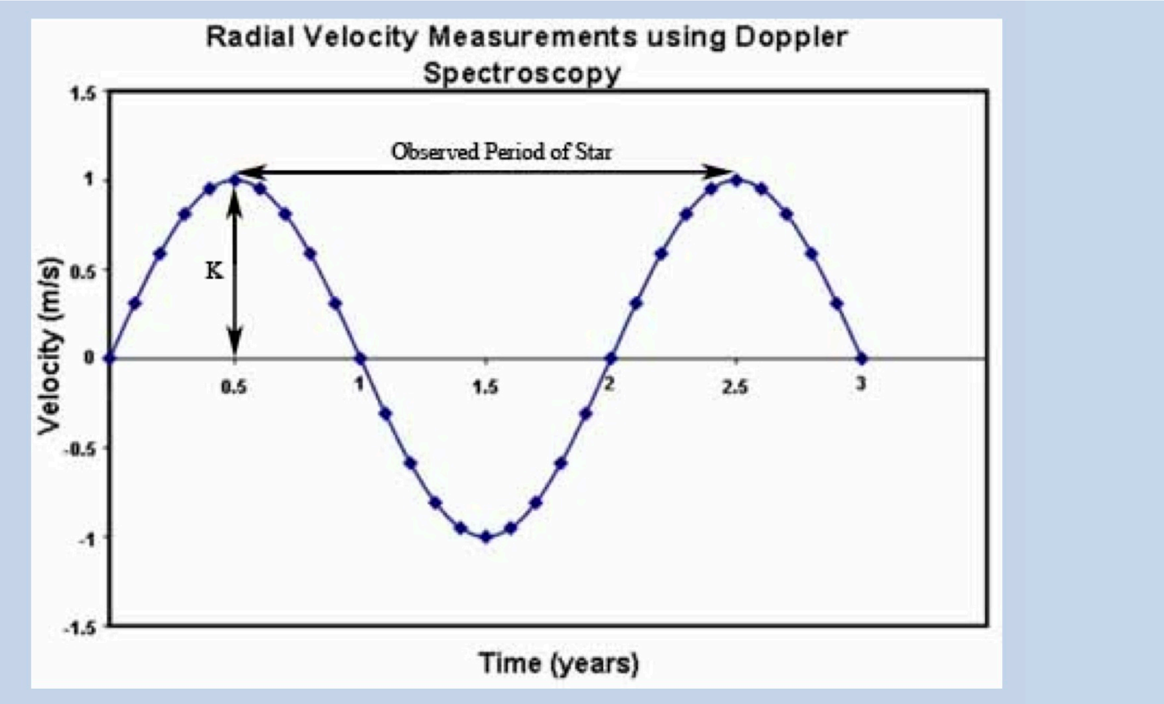
M_* : stellar mass

e : orbit eccentricity

Rossiter-McLaughlin effect
the shape of the RV curve depends on the *angle* *i*

$K_{Earth} \sim 0.08$ m s^{-1} $K_{Jupiter} \sim 12$ m s^{-1} $K_{Neptune} \sim 0.28$ m s^{-1}

E-ELT HIRES and exoplanets: detection



σ (RV) ~ FWHM × $(s/n)^{-1}$ × $(N_{lines})^{-0.5}$ [m s^{-1}]

- FWHM → high spectral resolution
- $(s/n)^{-1}$ → high spectral quality
- $(N_{lines})^{-0.5}$ → wide spectral coverage in a single exposure

R=100k i.e. FWHM=3×10^3 m s^{-1}, s/n~1000, N_{lines}=1000 → σ(RV) ~0.1 m s^{-1}

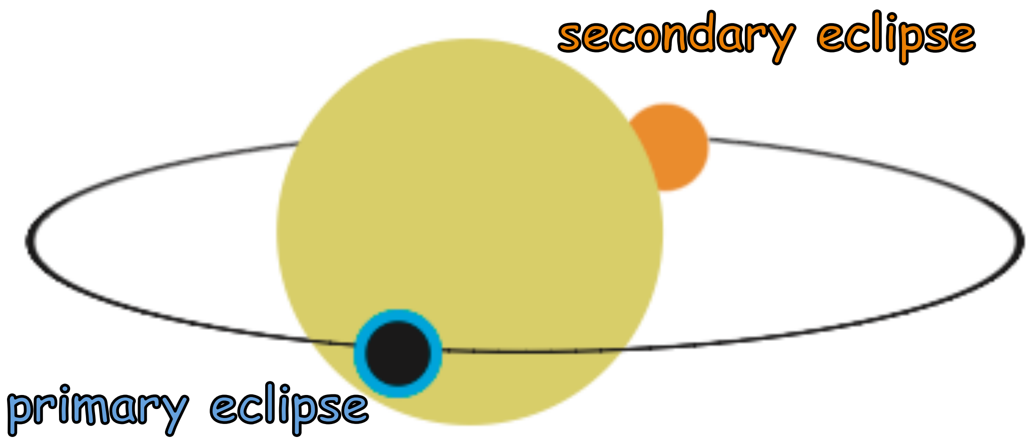
exoplanets: atmospheres

Seager & Drake 2010, ARA&A,48,631

techniques

direct imaging: currently limited to big, bright, young, or massive planets located far from their stars

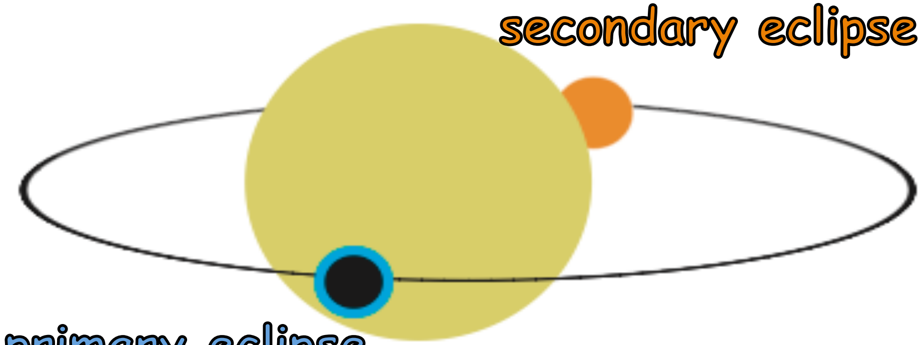
during a transit: the planet passes in front of the parent star as seen from Earth
probability ~ R_*/a, where R_* is the stellar radius and a is the semi-major axis



As the **planet passes in front of the star**, starlight drops by the amount of the planet-to-star area ratio. If the size of the star is known, the planet size can be determined. During transit, some of the starlight passes through the planet atmosphere, picking up some of its spectral features.
A **planetary transmission spectrum** can be obtained by dividing the star+planet spectrum during transit by the star alone spectrum (taken before and/or after transit).

Planets on circular orbits that pass in front of the star **also disappear behind the star. Just before the planet goes behind the star, planet and star can be observed together.**
The luminosity drop during secondary eclipse depends on the relative sizes of the planet and star and their relative brightness.
The **flux spectrum of the planet** can be derived by subtracting the flux spectrum of the star alone (during secondary eclipse) from the flux spectrum of the star+planet (just before and after secondary eclipse).
The planet flux gives information on its atmospheric **composition** and **temperature gradient** (at **IR** wavelengths) or **albedo** (at **visible** wavelengths).

exoplanets: atmospheres



secondary eclipse: dayside planet spectrum

contrast ~ $L_p(\lambda) / L_*(\lambda)$ ➔ higher at longer wavelengths

primary eclipse: nightside spectrum ➔ transmission spectroscopy

line depth diluted by geometric cross-section

$$\sigma = \Sigma_{atm} / \Sigma_{star} = 2 \pi R_p H_{atm} / \pi R_*^2$$

H_{atm} = planet atmosphere scale height ➔ from ~10 to 10^4 km

σ ➔ from ~ a few 10^{-3} (hot Jupiters) to a few 10^{-7} (Earth-like) around Sun-like

exoplanets: atmosphere diversity **Seager & Drake 2010, ARA&A,48,631**

relative abundances of rock-ice-gas

In the **Solar System**, there is a definite relationship between the relative abundances of rock-ice-gas and planet mass: **small** planets (**$M \leq 1\ M_\oplus$**) are **rocky**, **intermediate** planets (~**15–17 $M_\oplus$**) are **icy**, and **larger** planets are predominantly **gaseous**. Whether or not exoplanets also follow this pattern is one of the most significant questions of exoplanet formation, migration, and evolution.

- **H and He rich** atmospheres

Planetary atmospheres that predominately contain both H and He in approximately cosmic proportions. In our Solar System these include the **giant and ice giant planets**.

- **outgassed** atmospheres **H-rich + some molecular gas (**H_2, H_2O, and CH_4 or CO)

  e.g. hot Jupiters (~ 1000 K)

- **outgassed** atmospheres **CO_2 or N_2 rich**

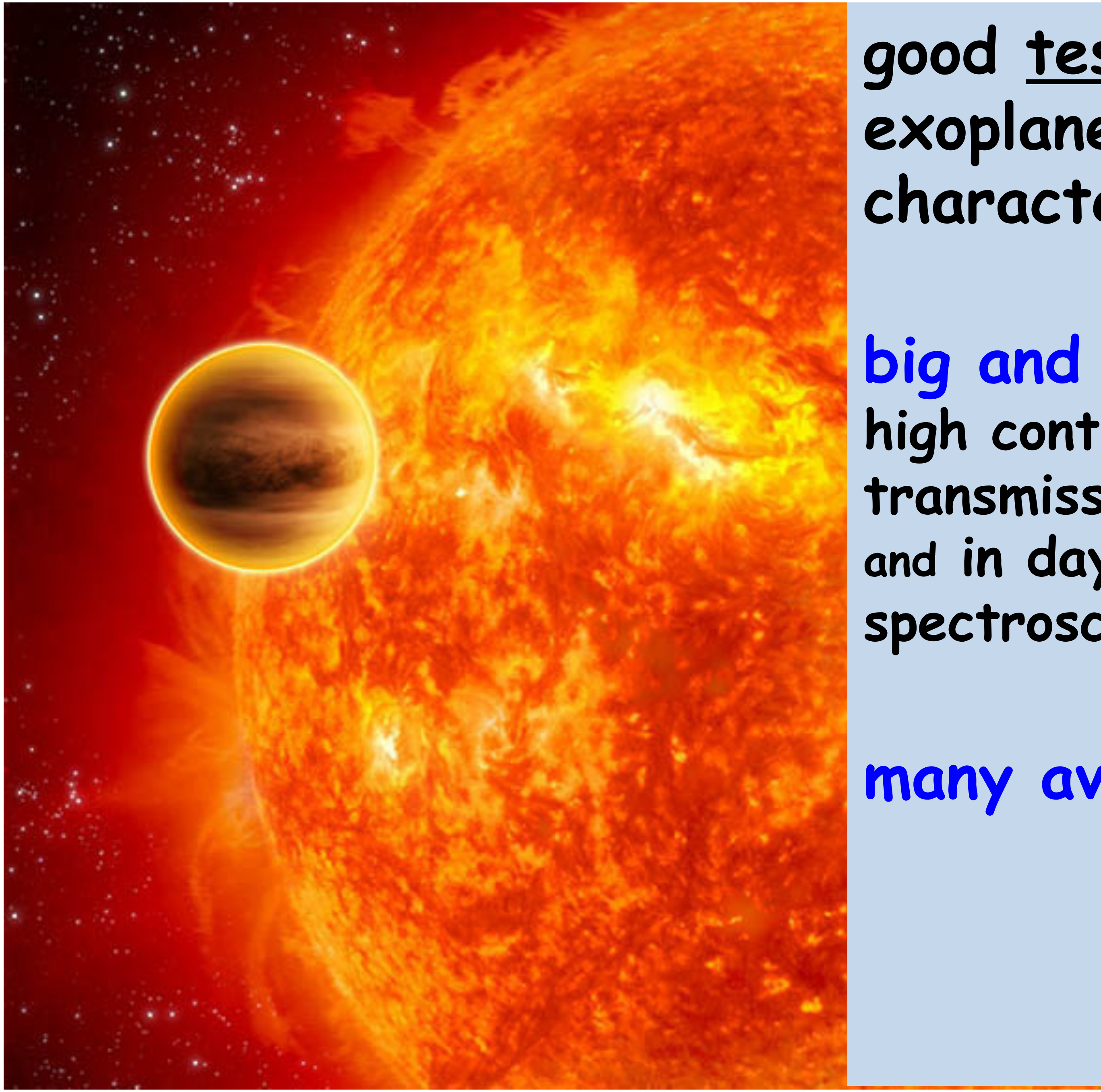
  (have lost H and He, signs of H_2O can be indicative of a liquid water ocean)

  On Earth, CO_2 dissolved in the ocean, sequestered in limestone sedimentary rocks, leaving N_2 as dominant atmospheric gas.

- **hot super Earth** atmospheres **lacking volatiles**

  With atmospheric temperatures well over 1,500 K, hot Earths or super Earths will have lost not only H but also other volatiles such as C, N, O, and S. The atmosphere would then be composed of silicates enriched in more refractory elements such as Ca, Al, and Ti .

exoplanets: Hot Jupiter atmospheres



good test cases for exoplanet atmosphere characterization

big and hot ➔
high contrast both in transmission (large R_p & H_{atm}) and in dayside (large R_p and T) spectroscopy

many available

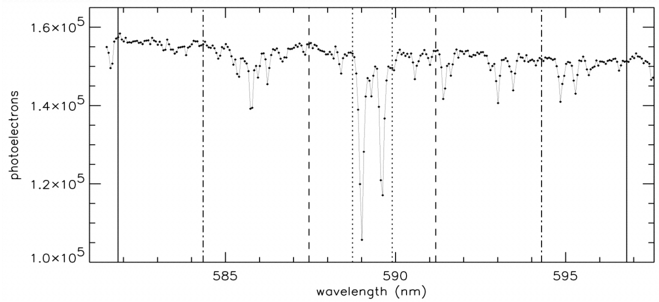
exoplanets: Hot Jupiter atmospheres

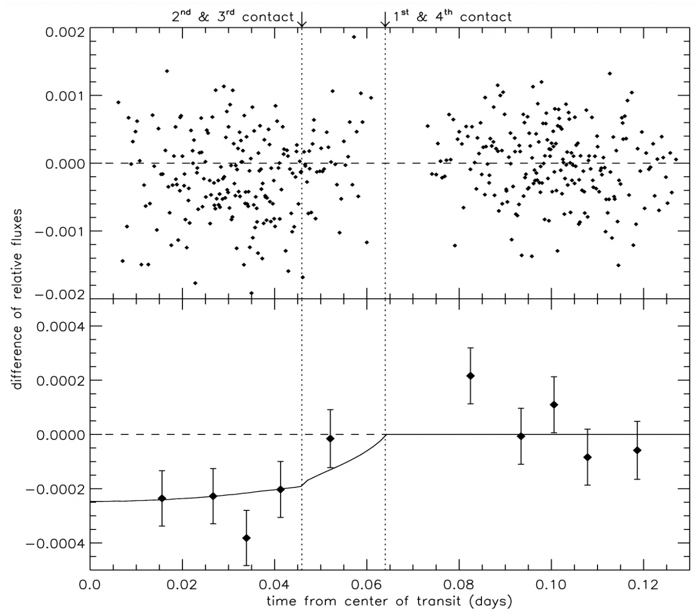
HD 209458b and HD 189733b – the iconic Hot Jupiters

<u>first detections of planet atmospheres</u>

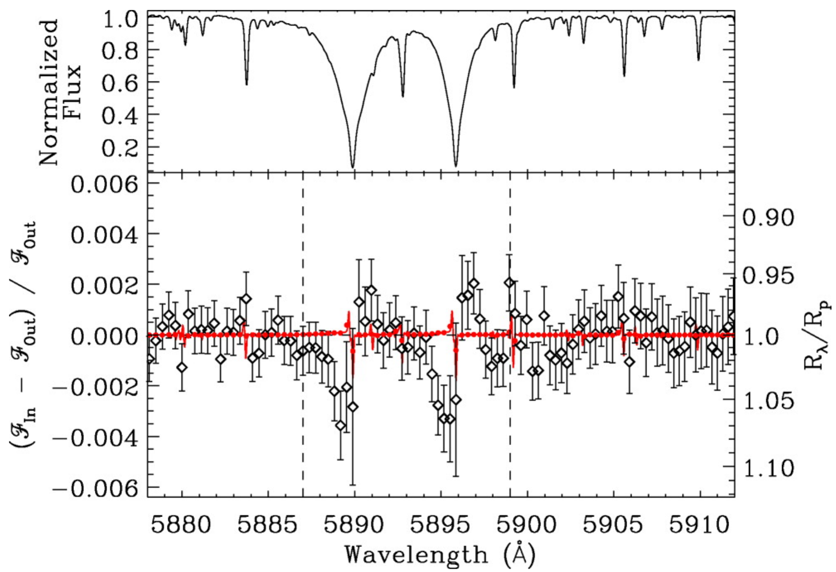
HD 189733b
Charbonneau+ 2002, ApJ 568,377
HST-STIS R~5500

atomic Na (589.3 nm)





HD 189733b
Redfield+ 2008, ApJ 673,87
HET-HRS R~60000



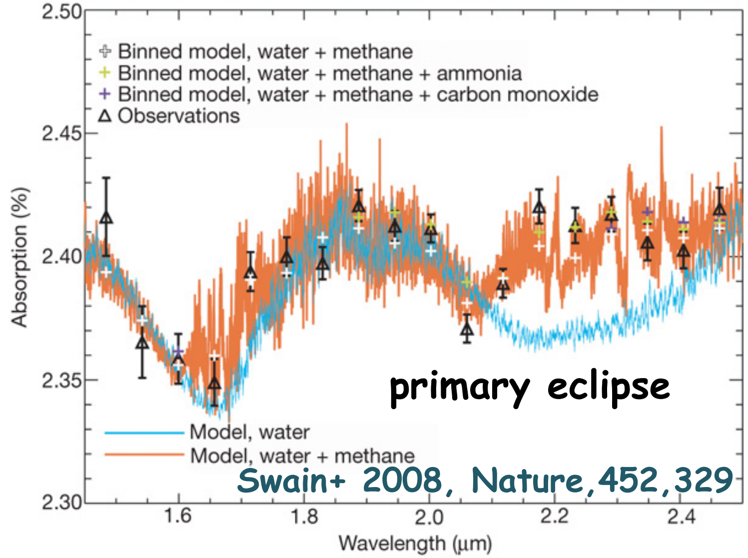
exoplanets: Hot Jupiter atmospheres

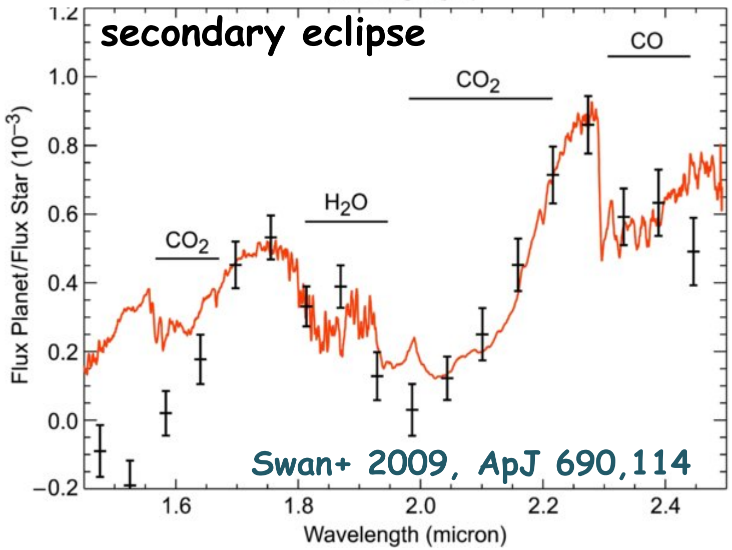
HD 209458b and HD 189733b – the iconic Hot Jupiters

<u>first detections of planet atmospheres</u>

molecules with NICMOS-HST

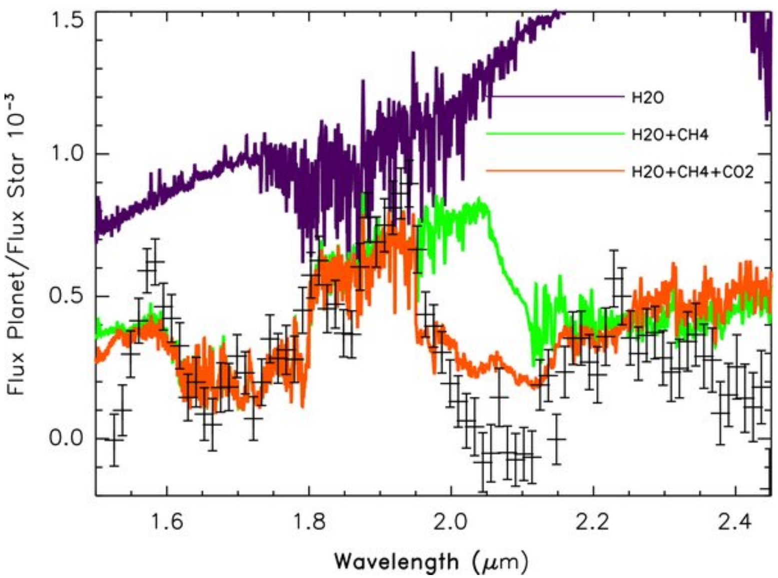
HD 189733b





HD 209458b - secondary eclipse

Swain+ 2009, ApJ 704,1616



exoplanets: Hot Jupiter atmospheres

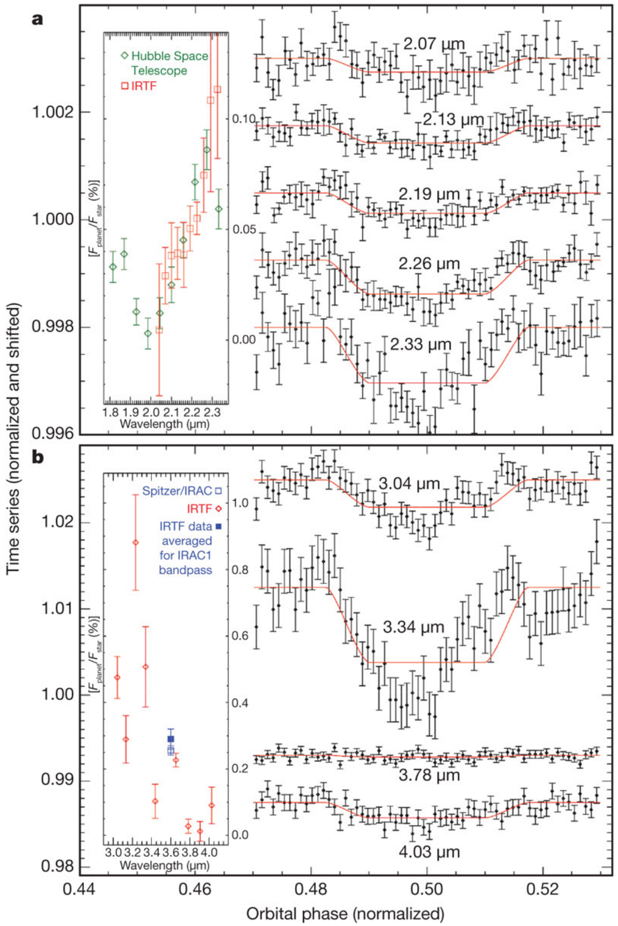
HD 209458b and HD 189733b – the iconic Hot Jupiters

first detections of planet atmospheres

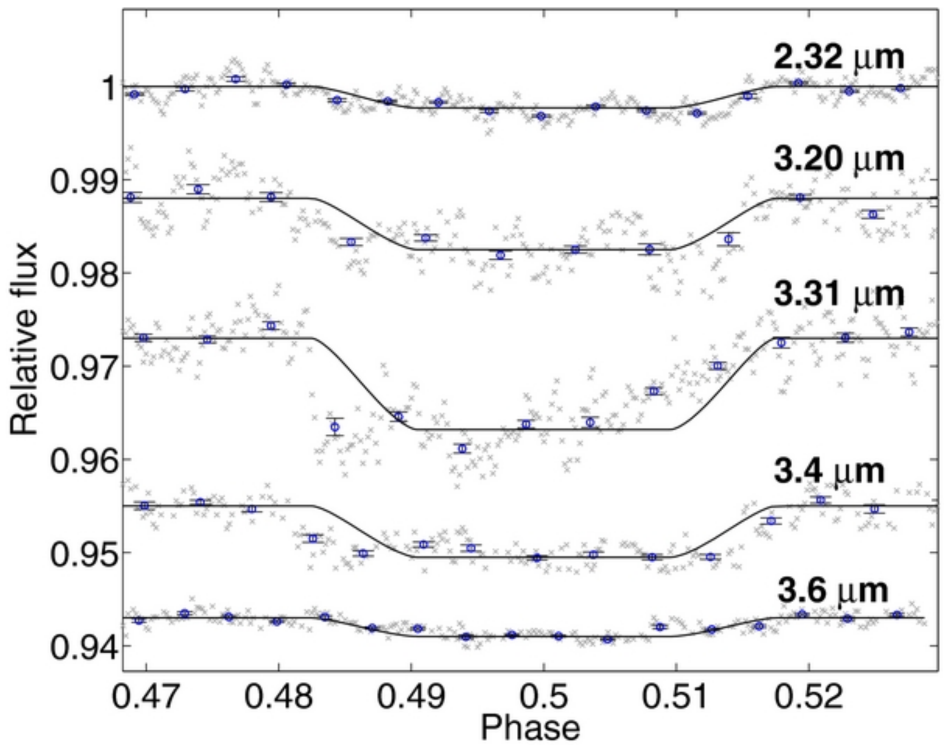
molecules from the ground: CO_2,H_2O,CO,CH_4

dayside spectrum of HD 189733b with IRTF-SpeX at low resolution

Swain+ 2010; Nature 463,637



Waldmann+ 2012 ApJ 744,35



M_p=1.14 M_J R_P=1.14 R_J P=2.21857

a=0.03142 AU e=0.0041 i=85.51°

exoplanets: Hot Jupiter atmospheres

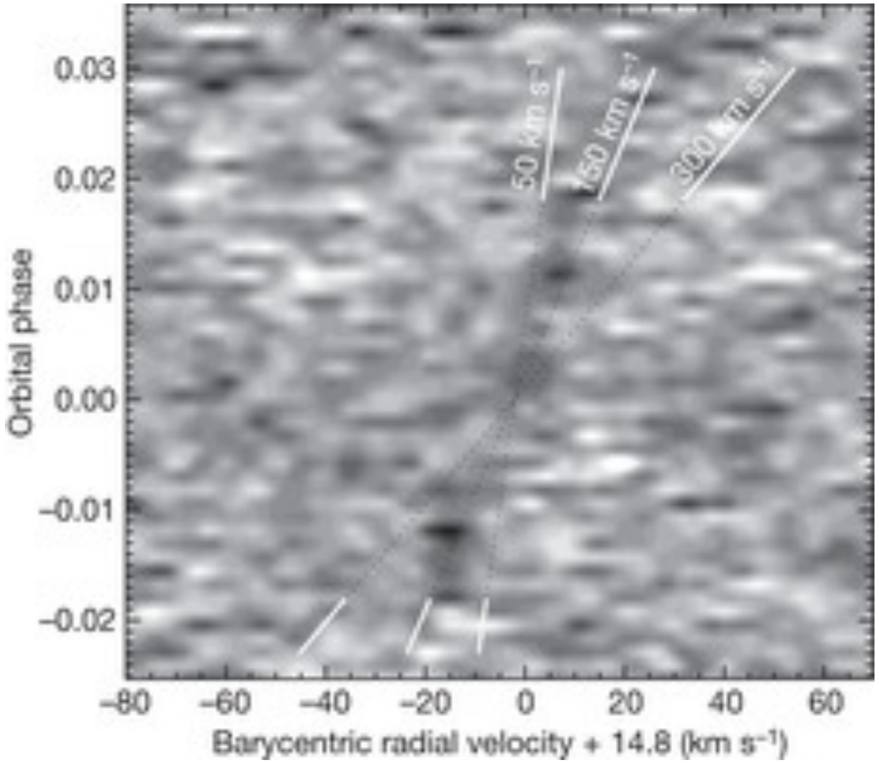
HD 209458b and HD 189733b – the iconic Hot Jupiters

<u>first detections of planet atmospheres</u>

molecules from the ground: *CO*

nightside spectrum of HD 209458b with VLT-CRIRES at R=100,000

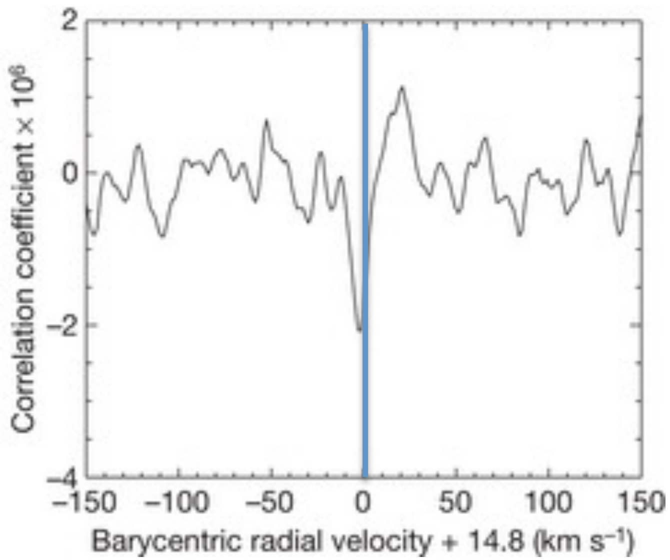
Snellen+ 2010; Nature 465,1049



✓planet orbital velocity (140 km s^{-1}) and absolute mass (0.64 ± 0.09 M_{Jup})

✓mass of the star (1.00+/-0.22 M_o)

✓blueshift (2 km/s) ➔ high altitude winds



M_p=0.69 M_J R_P=1.38 R_J P=3.52472

a=0.04747 AU e=0.0082 i=86.59°

exoplanets atmospheres: the future

2010 ARA&A..48..631 Seager, Sara; Deming, Drake

*At the present time there is a great divide between the hot Jupiter exoplanets that we can study observationally and the **super Earths that we want to study but which are not yet accessible**.*

secondary eclipse: dayside planet spectrum ➔

contrast ~ $L_p(\lambda) / L_*(\lambda)$ ➔ Earths very low contrast ...

primary eclipse: nightside spectrum ➔ transmission spectroscopy

$$\sigma = \Sigma_{atm} / \Sigma_{star} = 2 \pi R_p H_{atm} / \pi R_*^2$$

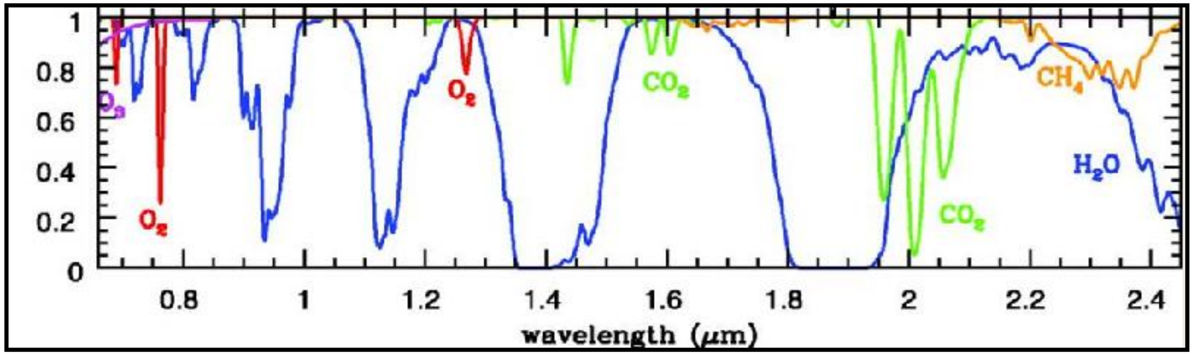
[super]Earths: H_{atm} ➔ from ~10 to 100 km

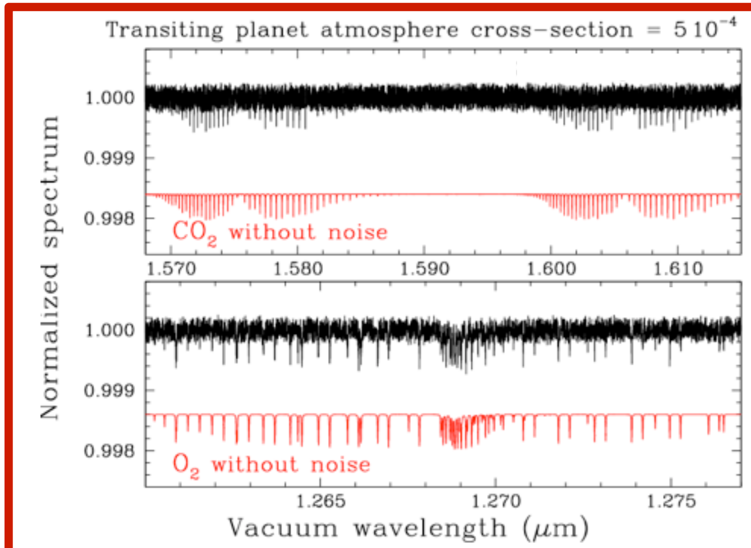
σ ➔ 10^{-6} – 10^{-5} around M dwarfs ($R_* \sim 0.3$ ➔ $0.1\ R_{sun}$)

very high s/n ➔ large aperture telescopes

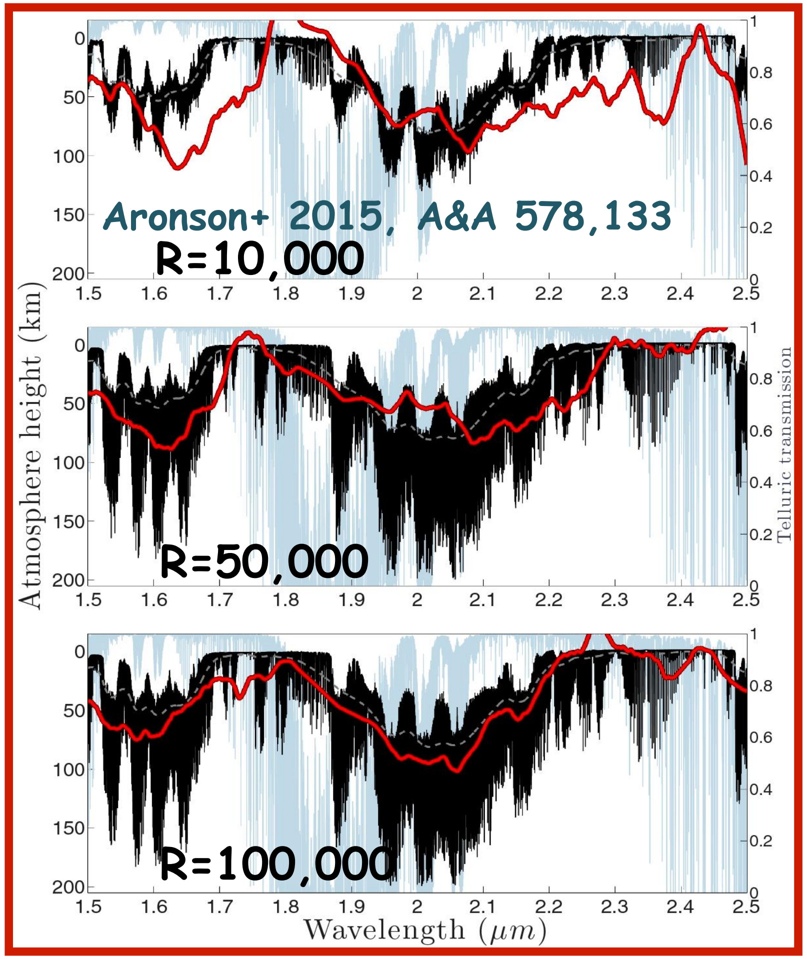
from the ground also high spectral resolution (R~100,000) to disentangle telluric/stellar/planet spectrum ➔ ELT-class telescopes

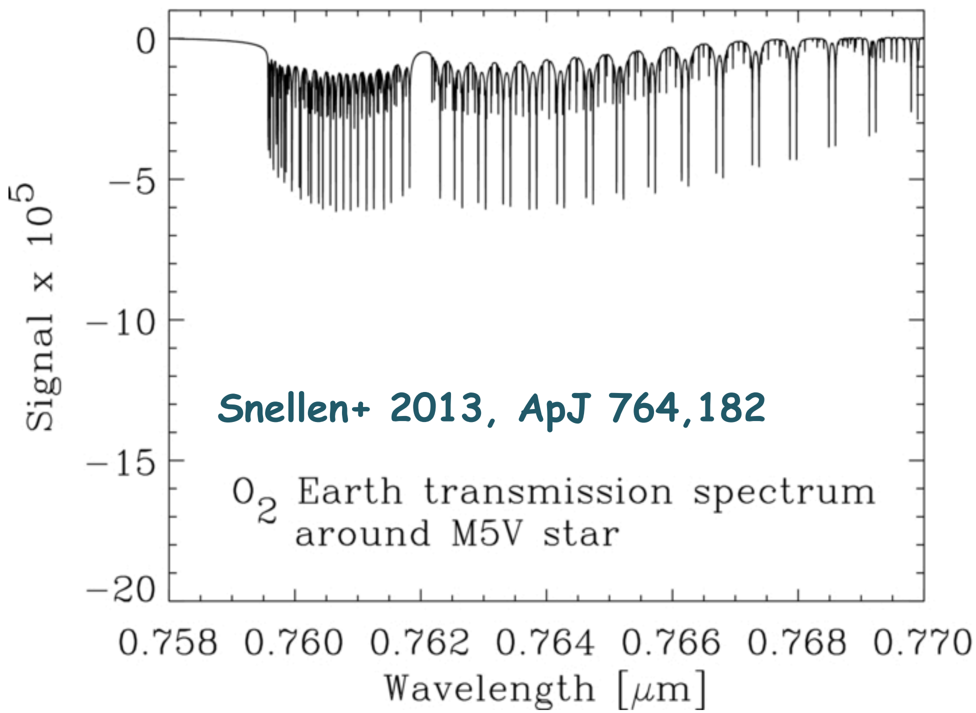
E-ELT HIRES and exoplanets: atmosphere simlulations





E-ELT SIMPLE Phase A study (2010)

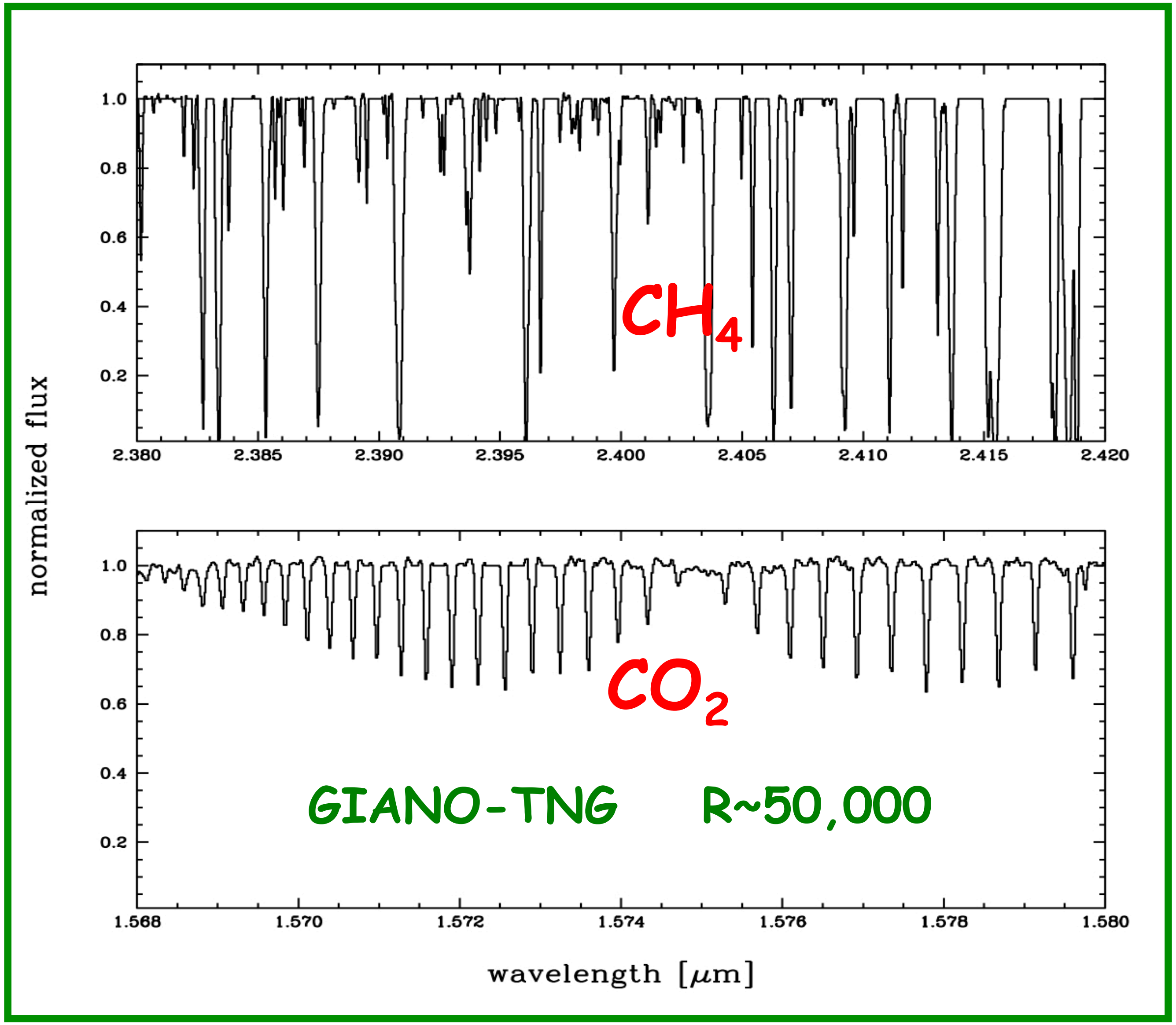




Snellen+ 2013, ApJ 764,182

E-ELT HIRES and exoplanets

observed high resolution telluric spectrum



E-ELT HIRES and exoplanets: atmospheres

hot Jupiters and other giant planets ➔ ARIEL and JWST

some mini-Neptunes/superEarths ➔ JWST

intensive obs of 1-2 Earth-like ➔ JWST

HIRES
detailed characterization of virtually any kind of planet atmosphere, from hot Jupiters to rocky/[super]Earths

- chemistry (possible bio-signatures)
- orbital velocity
- structure and weather

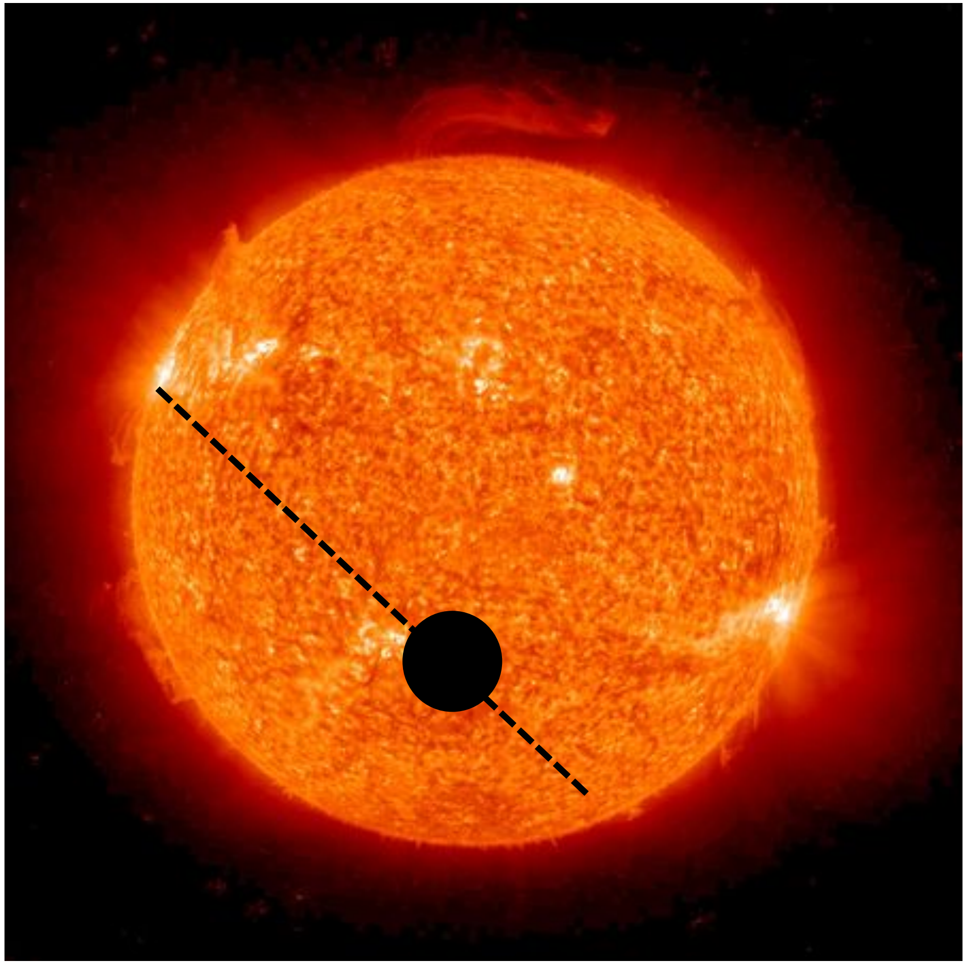
Habitable Zone: surface temperatures consistent with liquid water

Earth-like planet atmospheres in the HZ is a frontier/challenge for any instrument ➔ HIRES can attempt that around late M dwarfs with observations of the many transits occurring in a few years

E-ELT HIRES and exoplanets: host star characterization

metallicity, **structure** (3D, granulation, oscillations etc.), **rotation**, **variability** (pulsations etc.), **activity** (spots, convection, magnetic etc.)

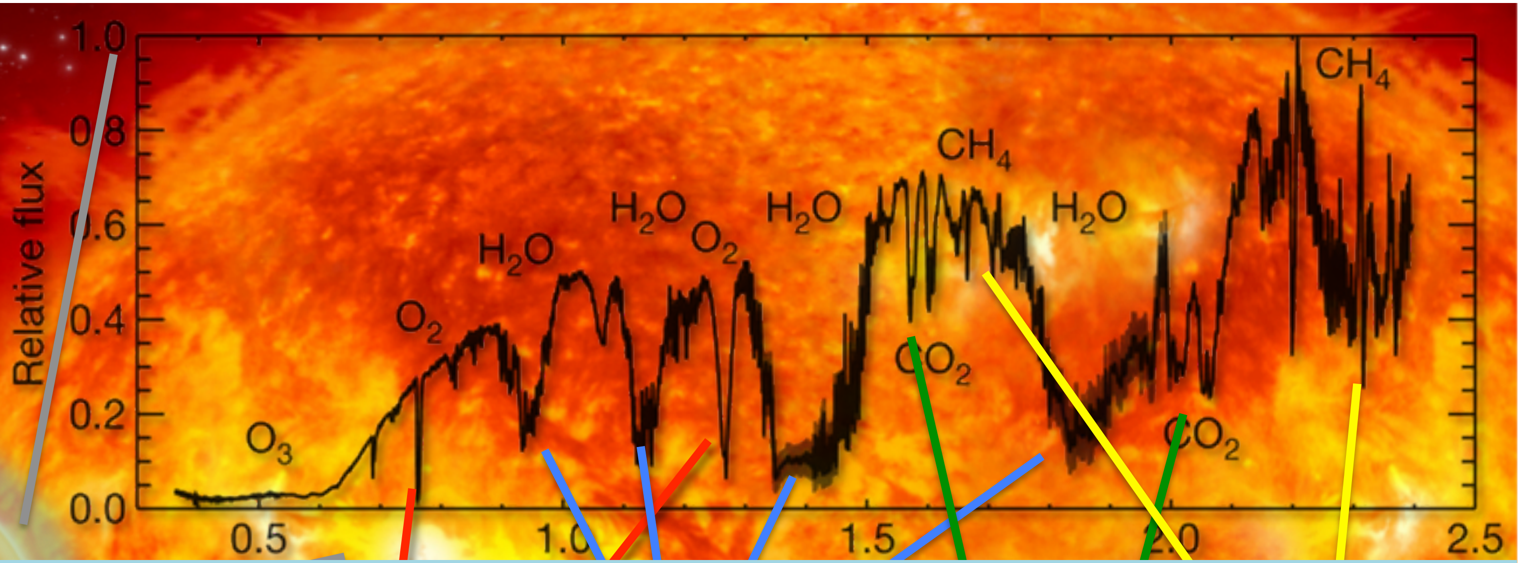
very high spectral resolution and high signal-to-noise mandatory



full characterization of **M-dwarfs**

- challenging for the current generation of high resolution spectrographs at 8-10m class telescopes
- **HIRES** will provide it simultaneously with the planet transit observations

HIRES:
exo-planets



transit spectroscopy

atmospheres (red-IR) and host star (blue-IR) characterization

high spectral resolution critical

- ➢ **to disentangle stellar/planetary/telluric spectrum** and cancel contamination/ systematics
- ➢ **to combine hundreds of molecular lines & boost the SNR**
- ➢ **to use individual lines to measure planet orbital velocity & high altitude winds**

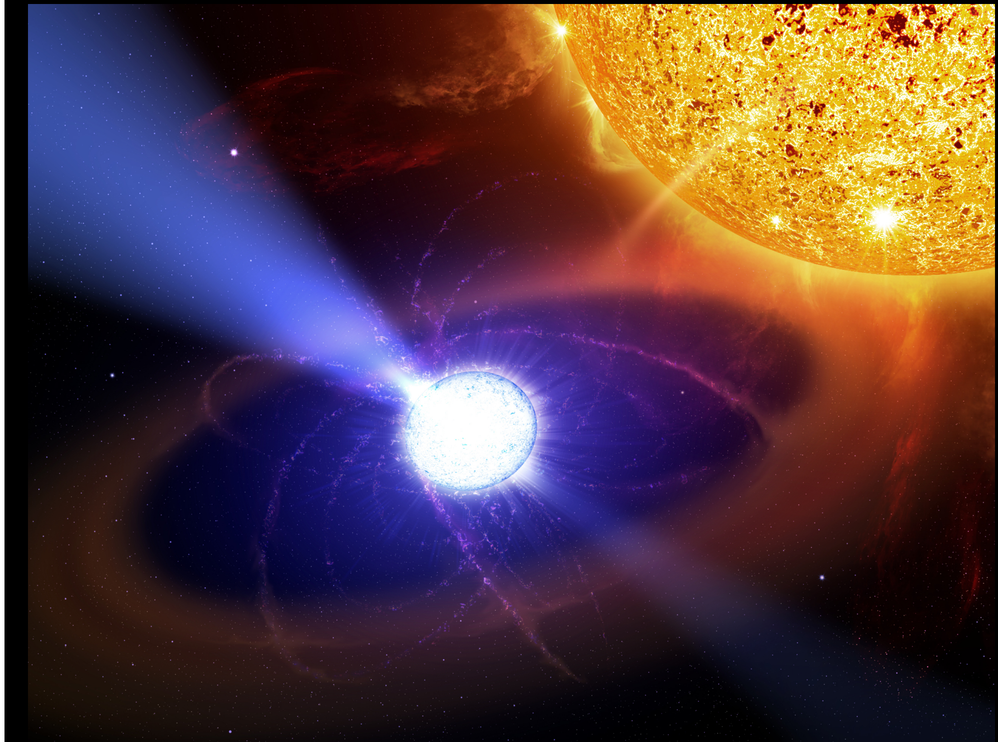
E-ELT critical

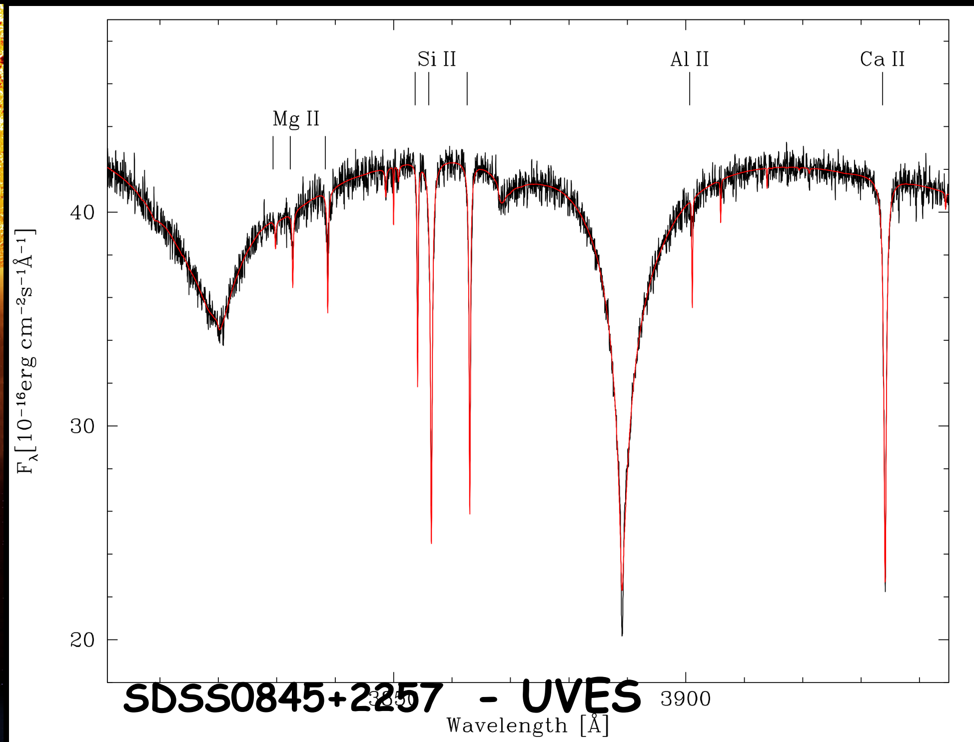
- ➢ **to get very high SNR in relatively short (e.g. transit duration) exposures**

red-IR critical

- ➢ **to study transiting planets around M dwarfs (highest planet/star contrast)**
- ➢ **to measure (bio-markers?) molecules like O_2, H_2O, CO, CO_2, CH_4**

metal polluted white dwarfs & planet debris





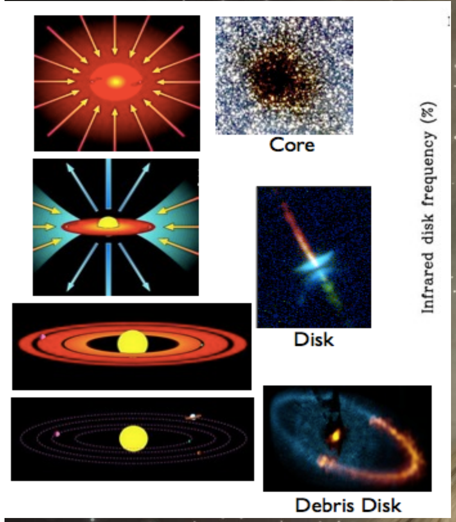
high spectral resolution critical

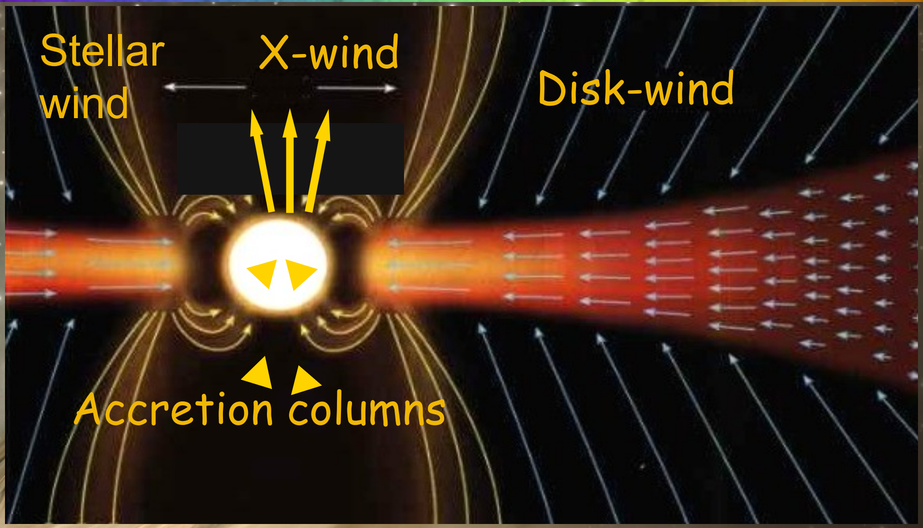
- to measure the faint metallic lines

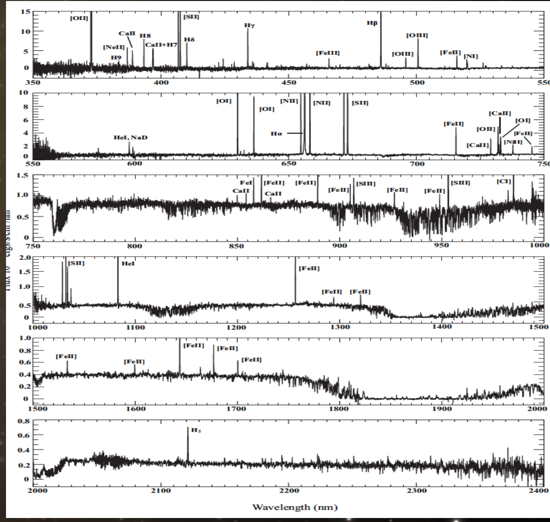
E-ELT critical

- faint stars
- new environments: Solar neighbohrs → MW

star/disk/planet formation







high spectral and spatial resolution and E-ELT critical

- to trace the innermost disk/wind/jet regions where planet formation should occur
- new environments: Solar neighbohrs → MW

IR critical

- for AO correction
- to study highly reddened SF regions
- for atomic and molecular wind/disk/jet line diagnostics