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Current and Future Observational Opportunities and Challenges:

Ground: IRTF, Keck, ELT, TMT

2009 Sagan Exoplanet Summer workshop

Dr. P. Deroo

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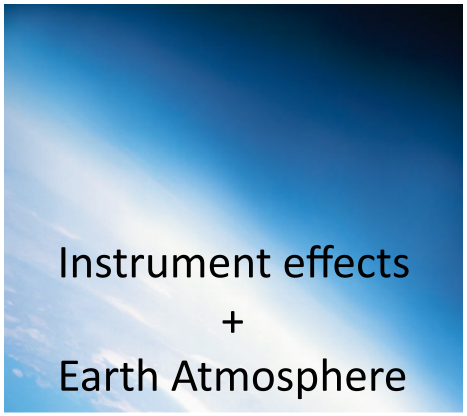
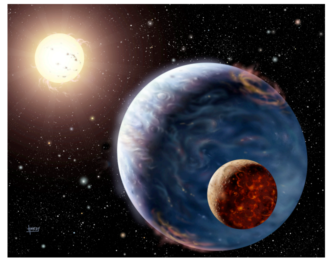
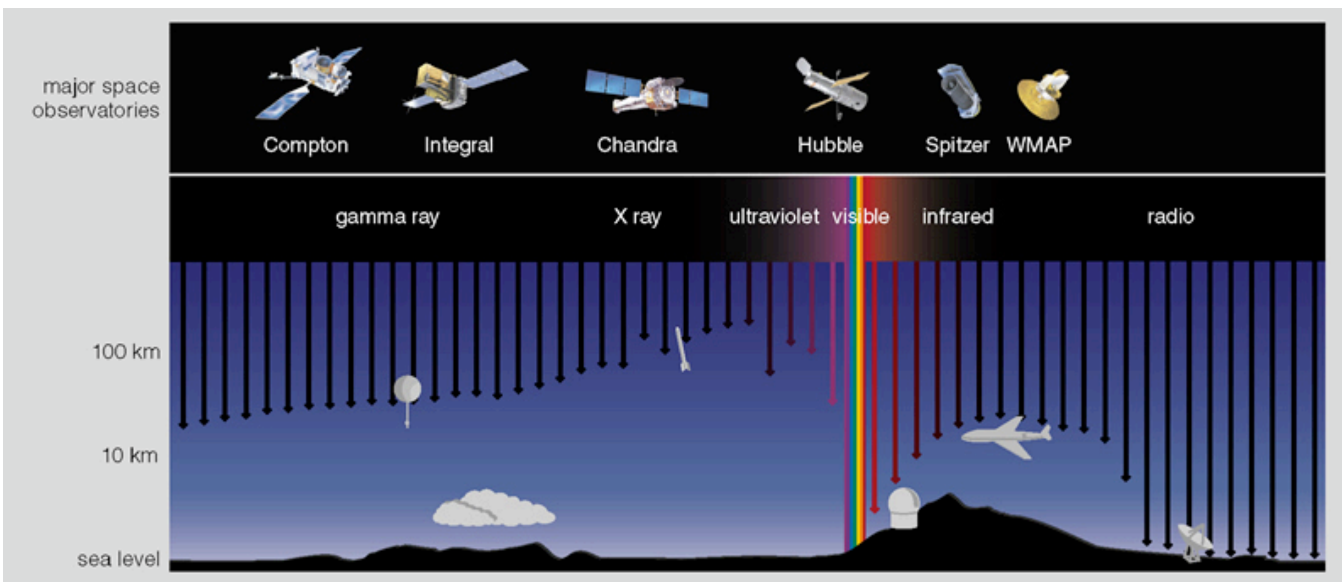
Ground versus space:







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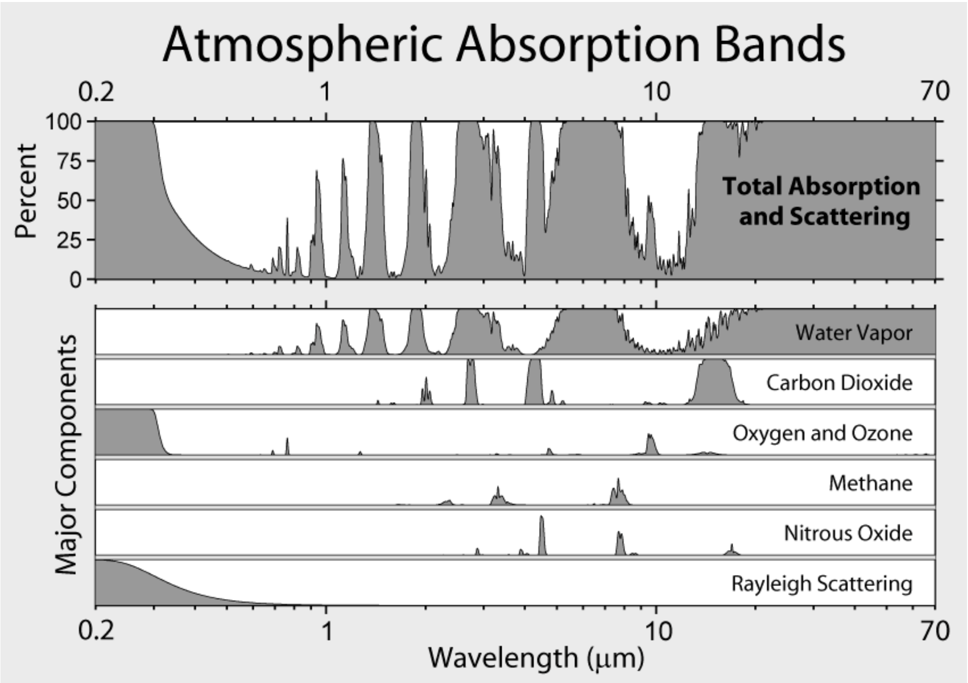
Earth atmosphere:

- Limits wavelength range: optical – near-IR
- Variable absorption and emission
- Introduces wave front phase errors and scintillation



Optical ~ extinction roughly smooth function
IR ~ NOT smooth function
Extinction ~ airmass

Earth atmosphere influence is **irregular** and **impossible to estimate a priori** at the level of extra-solar planet sensitivity (but see also predictive AO).

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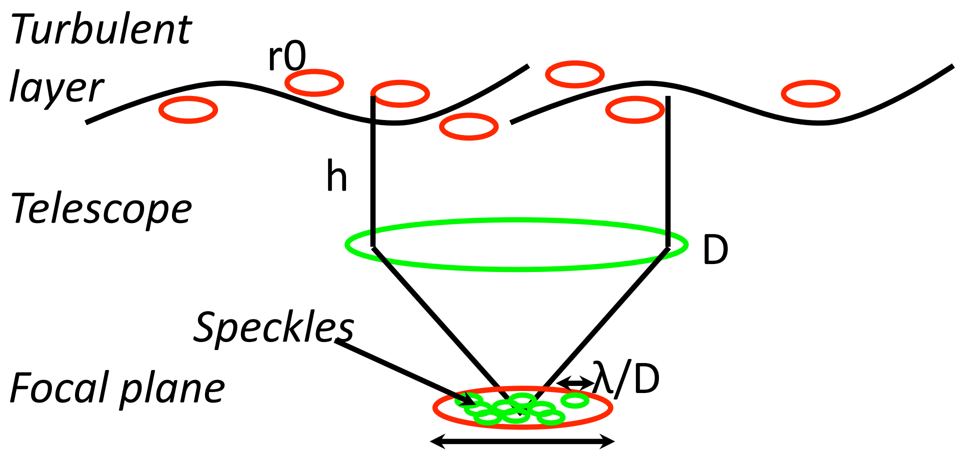
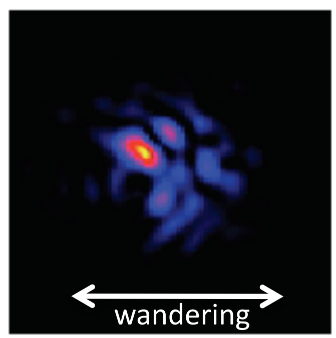
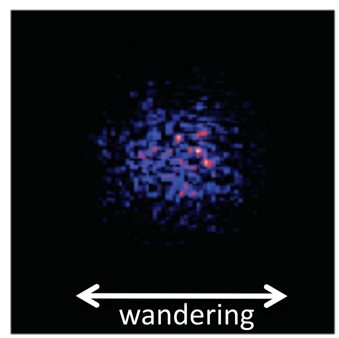




D = 2 m



D = 8 m

- Scintillation
- Wandering of the PSF
- Speckles

Earth atmosphere influence is **irregular** and **impossible to estimate a priori** at the level of extra-solar planet sensitivity (but see also predictive AO).

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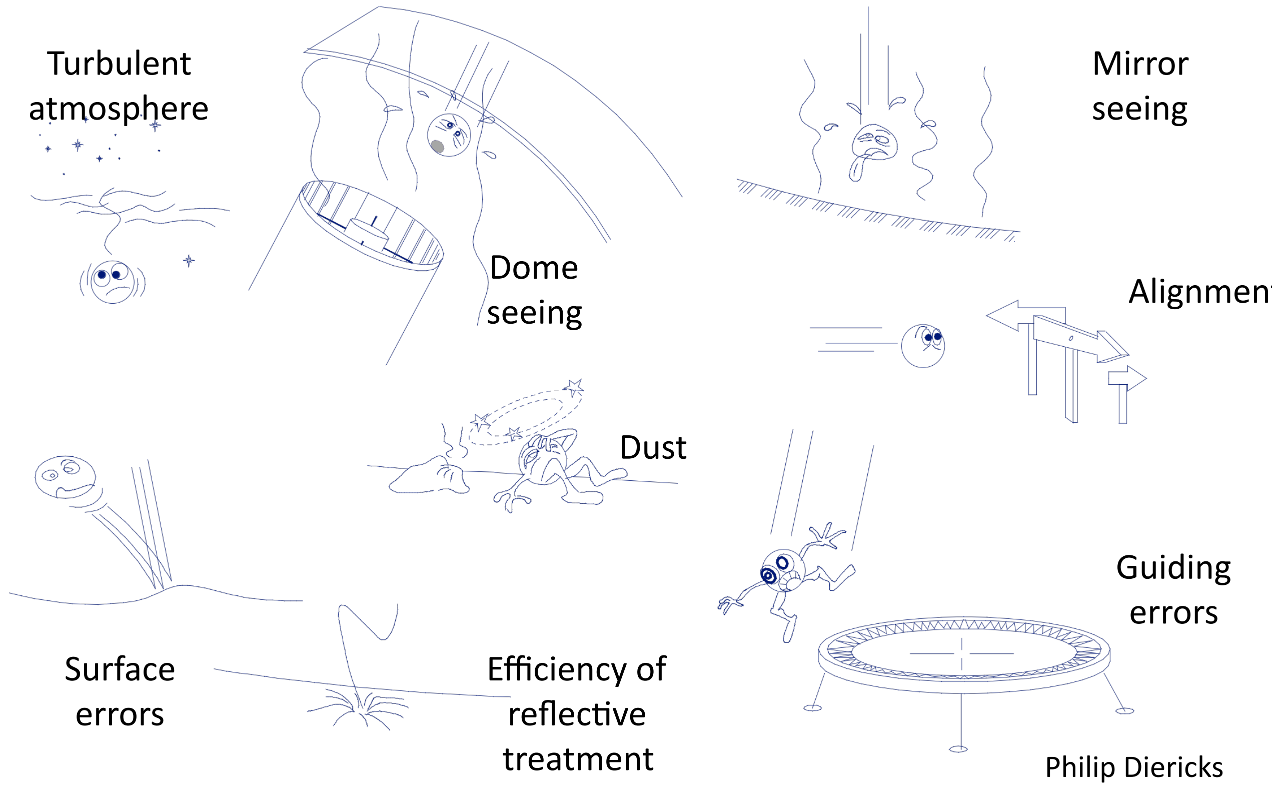
But also: The life of a photon in the telescope



Ground based challenge: Correct for the Earth atmosphere ***and*** tackle the same problems as for space based observations

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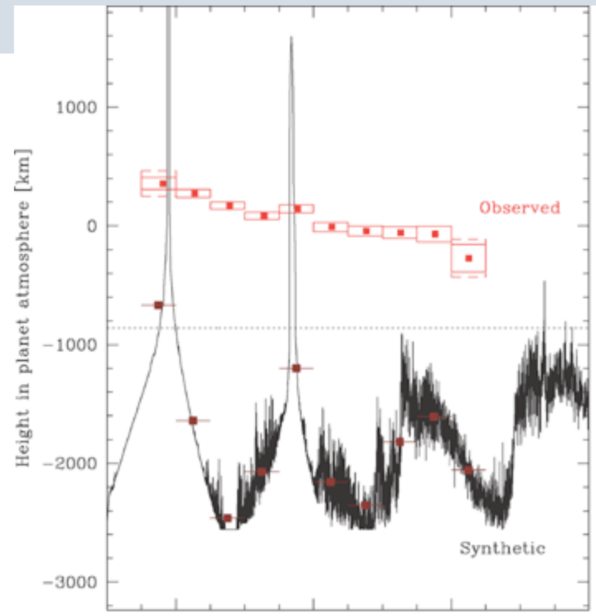
Eclipse spectro-photometry

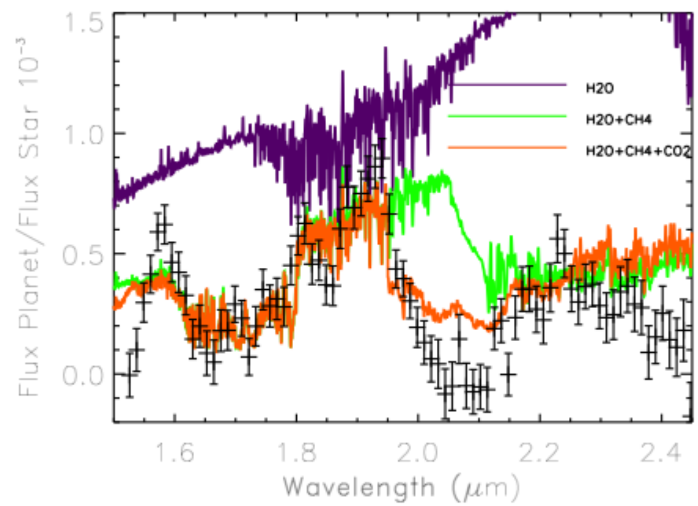
Science case:

- Optical:
  - Timing, radius, …
  - Presence of Hazes
  - Atomic absorptions
  - …
- Near- Infrared:
  - Molecules! H_20, CH_4, CO, CO_2
  - Temp-Pressure profile
  - primary and secondary eclipse: localized knowledge!
  - …

AND ground based observations make exoplanet characterization accessible to the general community/public



Pont et al. 2008



Swain et al. 2009

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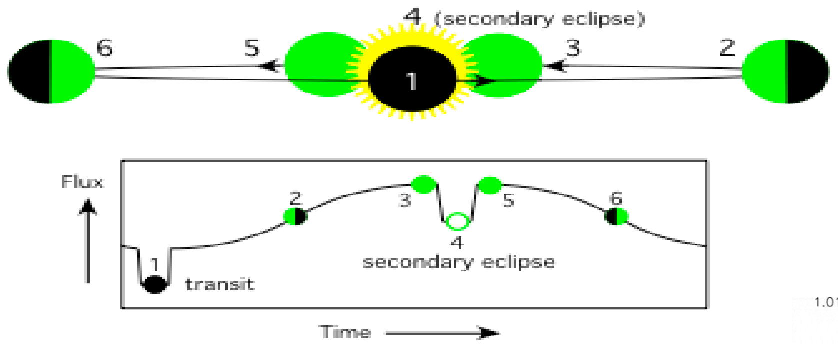
Eclipse spectro-photometry



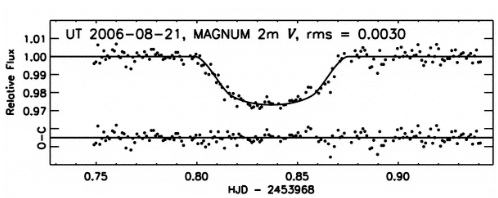
Primary eclipse

Optical & IR

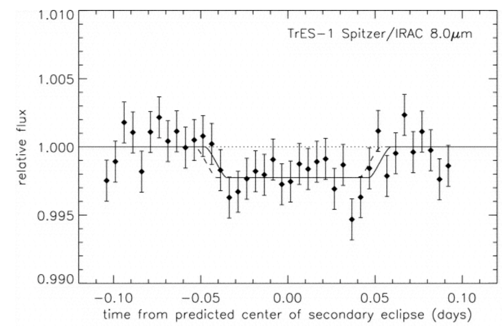
Secondary eclipse

Infrared

Winn et al. 2007



Charbonneau et al. 2005

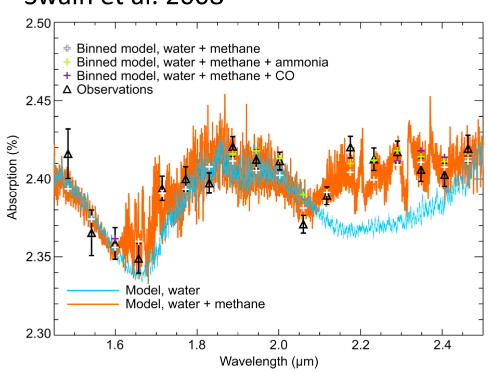


1 %

0.1 %

Correct the Earth atmosphere + instrument effects to this level (optimistic)

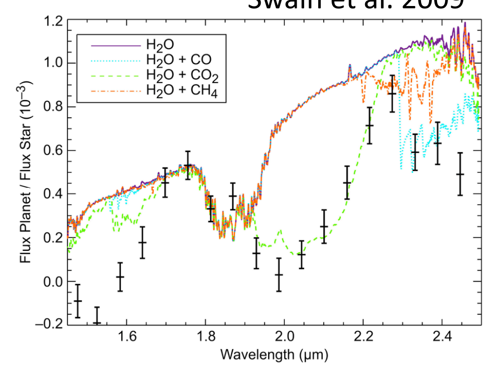
Swain et al. 2008



0.02 %

0.02 %

Swain et al. 2009



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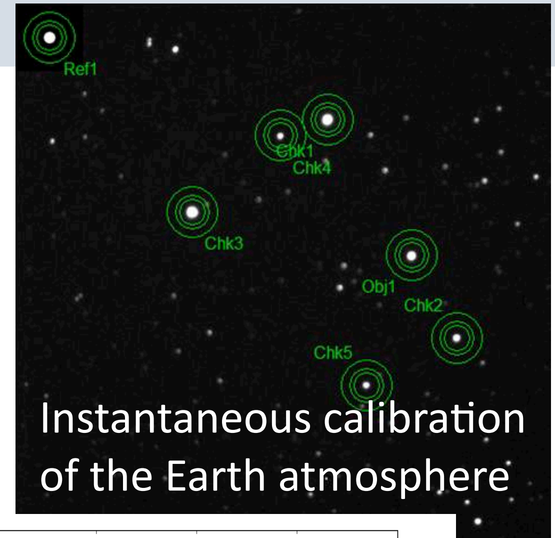
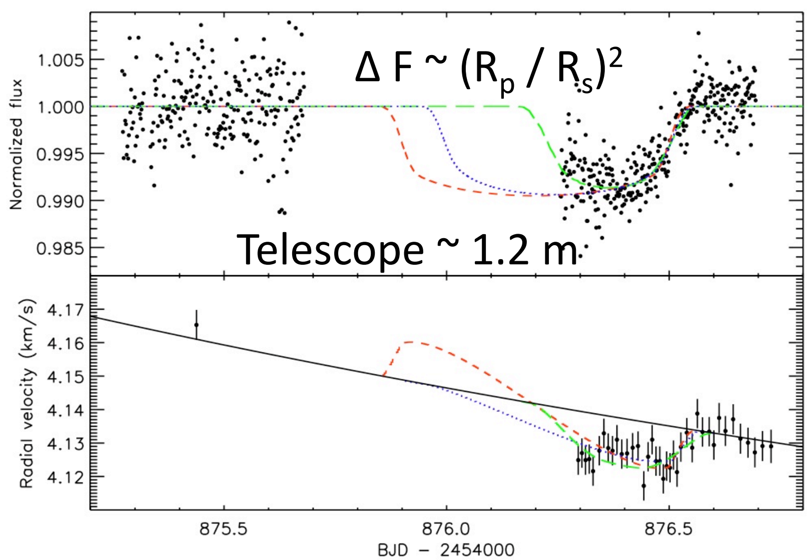
Transit photometry

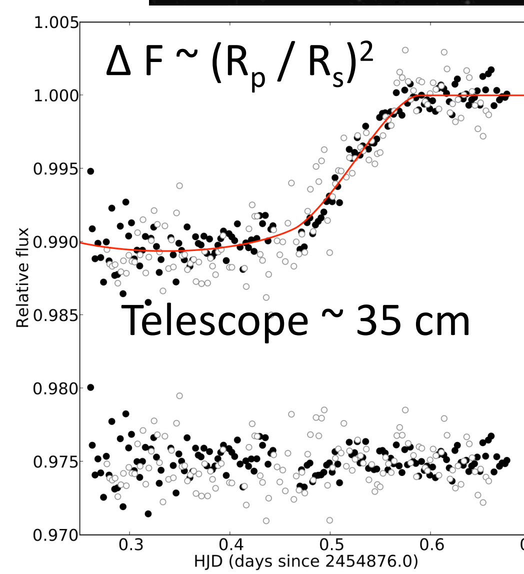


Biggest success from the ground

R_{planet}, M_{planet}, Rossiter-McLaughlin, clues to interior structure and astmospheric energy balance, timing can be used to detect presence of moons, mean stellar density, … (see e.g. “The transit light curve project; Winn et al.)



Moutou et al. 2009



Fossey et al. 2009

See talk by M. Lopez-Morales

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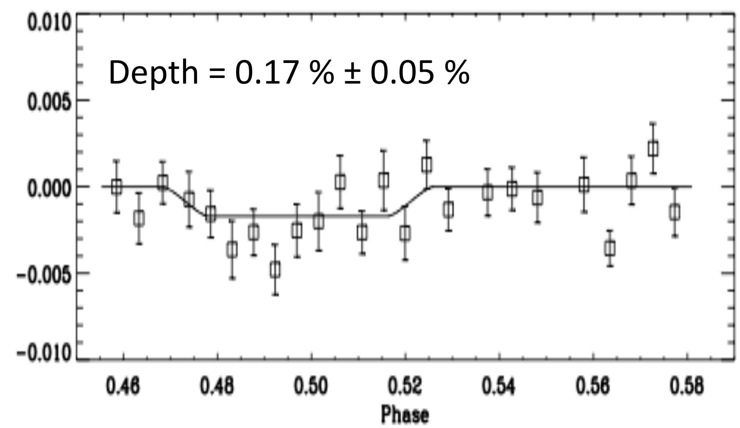
Occultation photometry

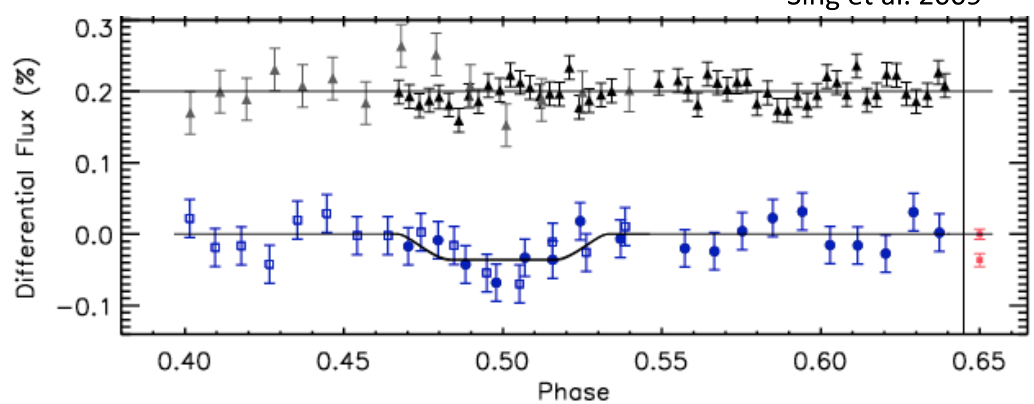
Transit photometry: 1E-2 ⟷ Secondary eclipse: 1E-3

- Successful detection of two very hot planets
  - K-band:
    - 1 % = typical photometric reliability using standard techniques while the photon noise < 1d-3
    - 0.05 % (Snellen & Covino 2007) by avoiding systematic effects (random jitter offsets, short exposure time)
  - Z-band:
    - Relative photometry; detrending based on position, seeing, airmass
    - Scatter close to the Poison limit

Snellen & Covino et al. 2007



Sing et al. 2009



Depth = 0.0363% ± 0.0091 %

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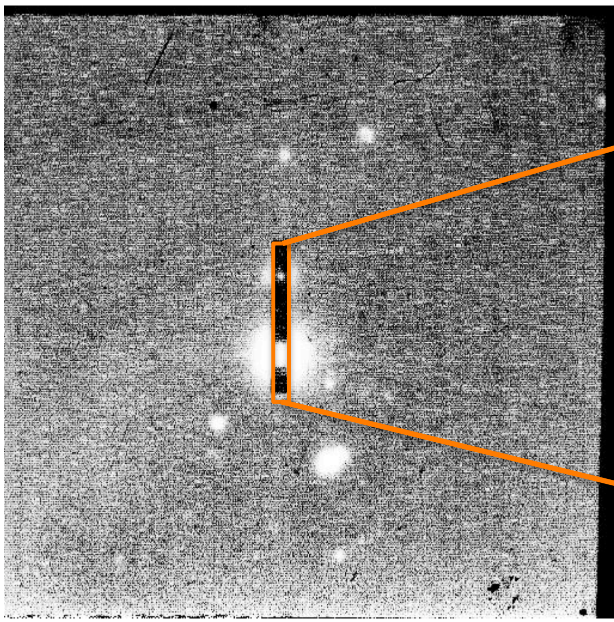
Spectroscopy

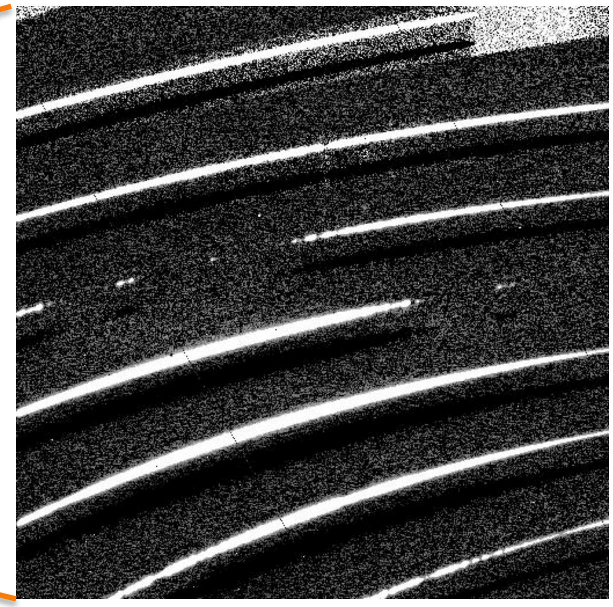
Transit photometry: 1E-2 ⟷ Spectroscopy: 2E-4

And: a slit



Flux ~ seeing

Relative photometry?



Observing/calibration strategies:

- Spectral differential
- Relative spectro-photometry
- New calibration algorithms
- Improved instrumentation

+ Enhanced post-observing analysis

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Spectral differential spectroscopy

Detection of Na D line from the ground

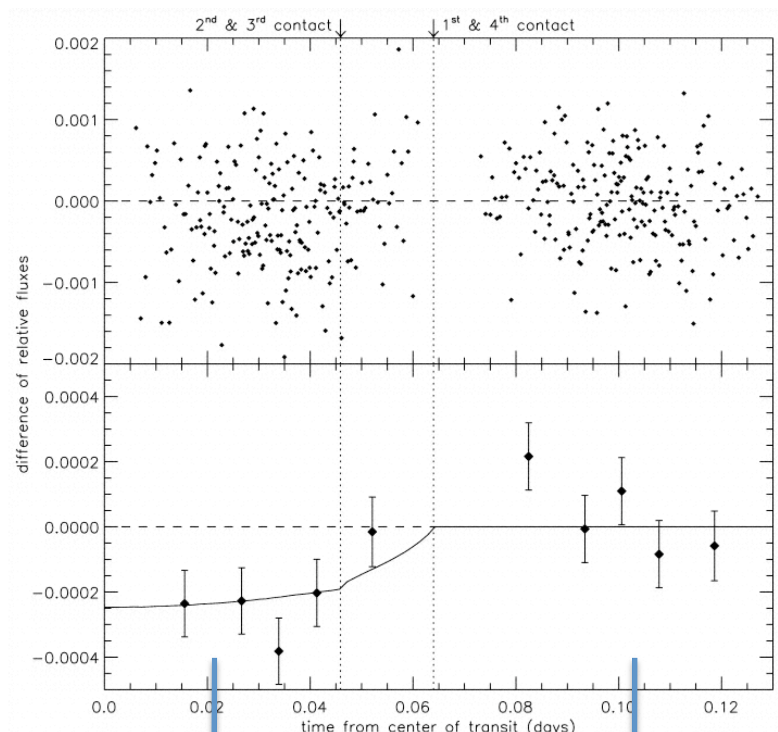
Echelle spectrograph on 8 m

in 3 Å band ~ few times 10^{-4}

However: Upper limits of 1% - 0.1% linked to instrument and Earth atmospheric effects

- Bundy & Marcy 2000: Keck – HIRES
- Moutou et al. 2001: UVES - VLT
- Winn et al. 2004: Subaru - HDS
- Narita et al. 2005: Subaru – HDS

Signal ~ 2d-4 – 1d-3



Charbonneau et al. 2002

Ground: different airmass, telluric, night, instable instrument

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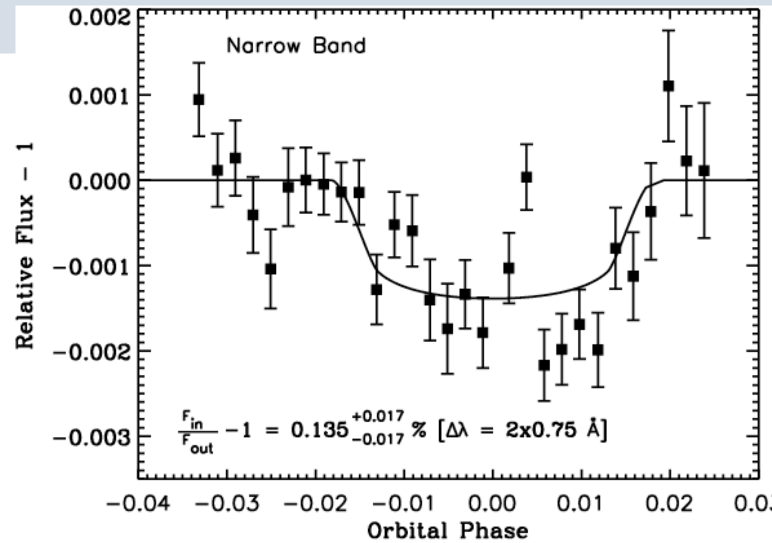
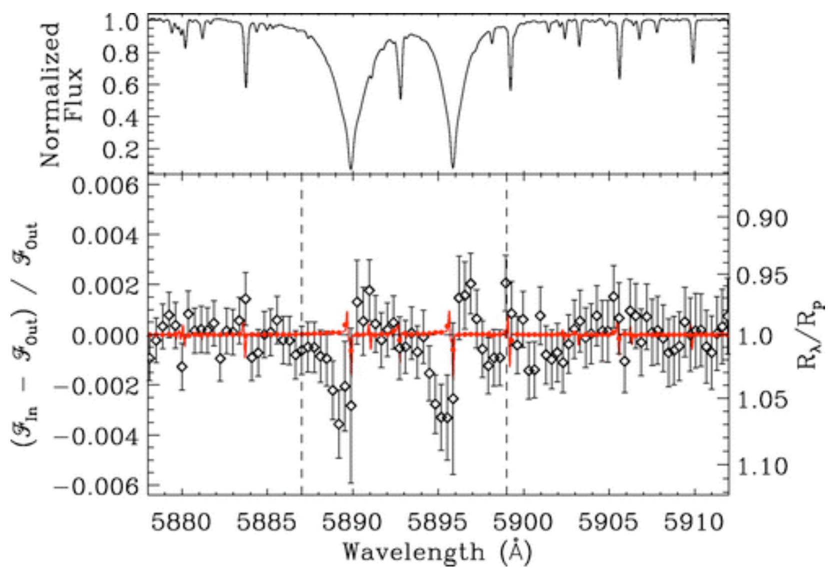
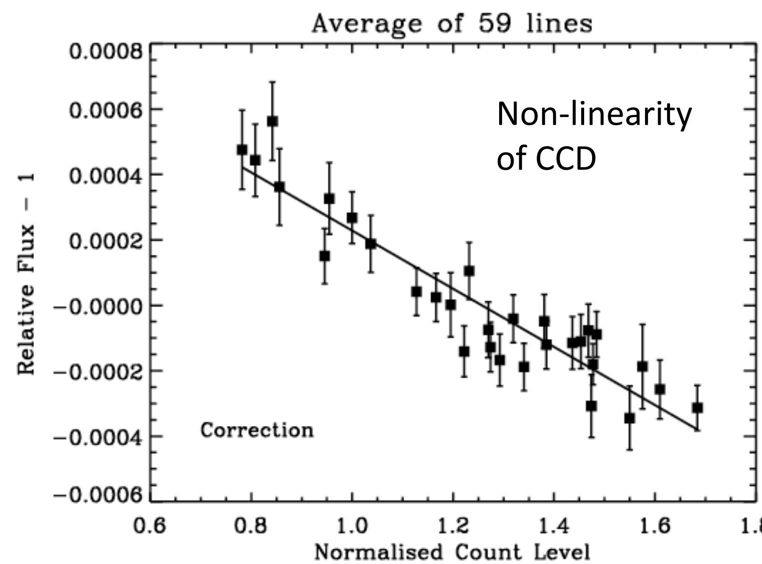
Spectral differential spectroscopy

- Success by enhanced calibration of the instrument and atmospheric effects:
  - equivalent width of Na D lines is not sensitive variations in seeing and variations of the spectral lines due to Rossiter-McLauglin effect
  - Characterization of non-linearity of the CCD
- Success by measuring 11 different transits





Redfield et al. 2008; HD 189733b; 9.2 m HET



Snellen et al. 2008; HD 209458b; Subaru

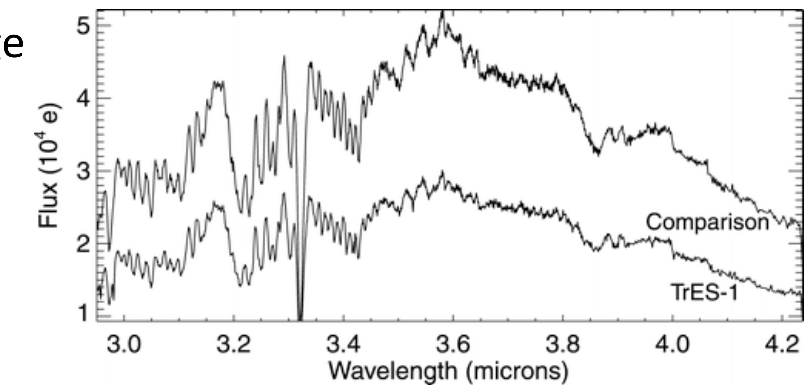
Relative spectro-photometry

- Relative spectroscopy between simultaneously acquired spectra

Variations:
- 10-20% correlated with λ change
- factor 2-3: moving in-out of slit
- non-linearity variations

-> 0.15 % detection sensitivity

Two stars in the slit



Knutson et al. 2007; Tres-1; Gemini

- MOS technology: possible breakthrough

Late 2010

KMOS

VLT

Spring 2010

MOSFIRE

Keck

now

GMOS

Gemini

“Standard” eclipse spectroscopy

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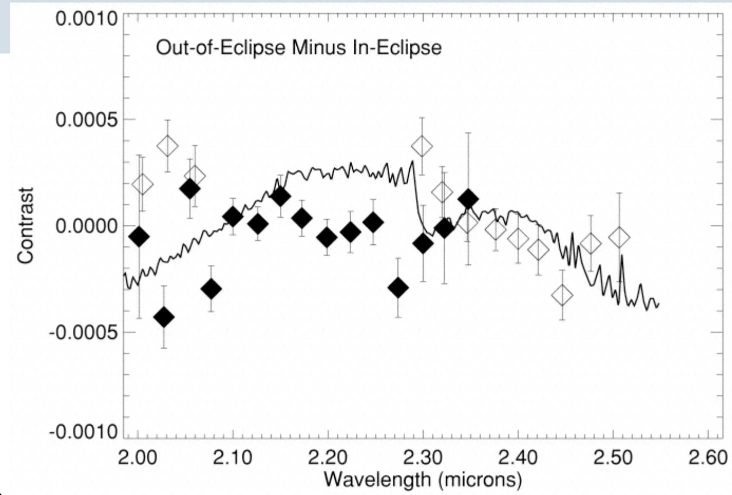
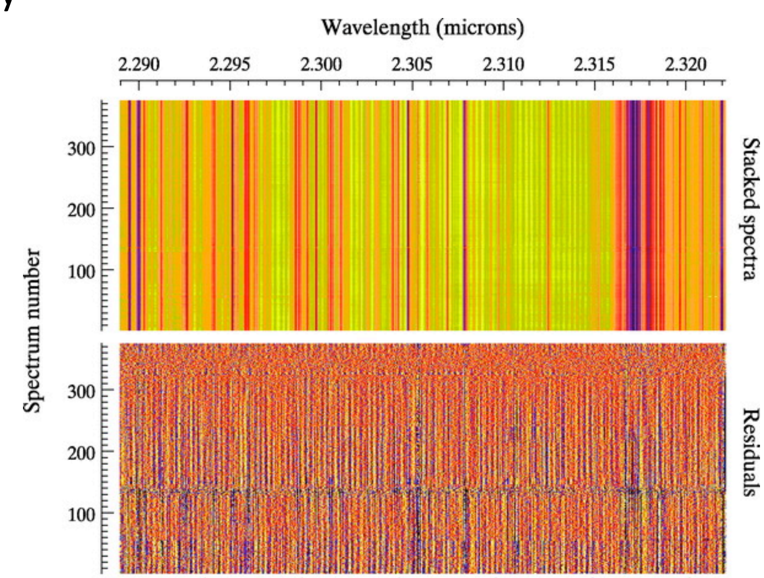
Strong limits have been set on transmission and emission spectra:

- Calibration of the instrument is being challenged : Previously unknown instrument effects are almost always encountered
- Optimum observing strategies depend strongly on prior knowledge of instrument behavior; re-observing is often necessary
- Telluric variability is a severely limiting factor; the task is to probe molecules present in both the Earth and exoplanet atmosphere
- Accurate error analysis is of the utmost importance to establish limits



Richardson et al. 2003



Deming et al. 2005

Other methods explored

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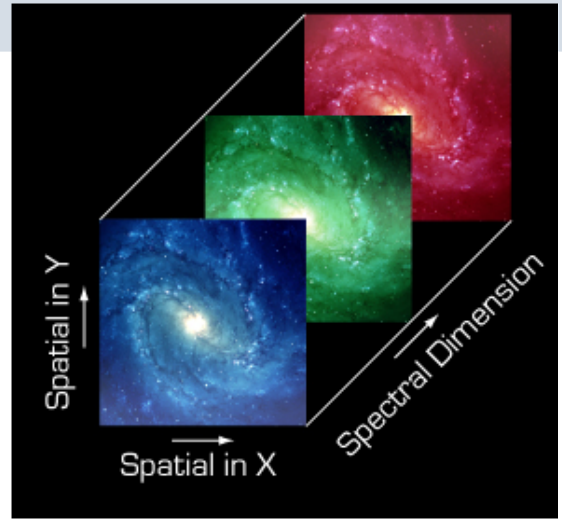
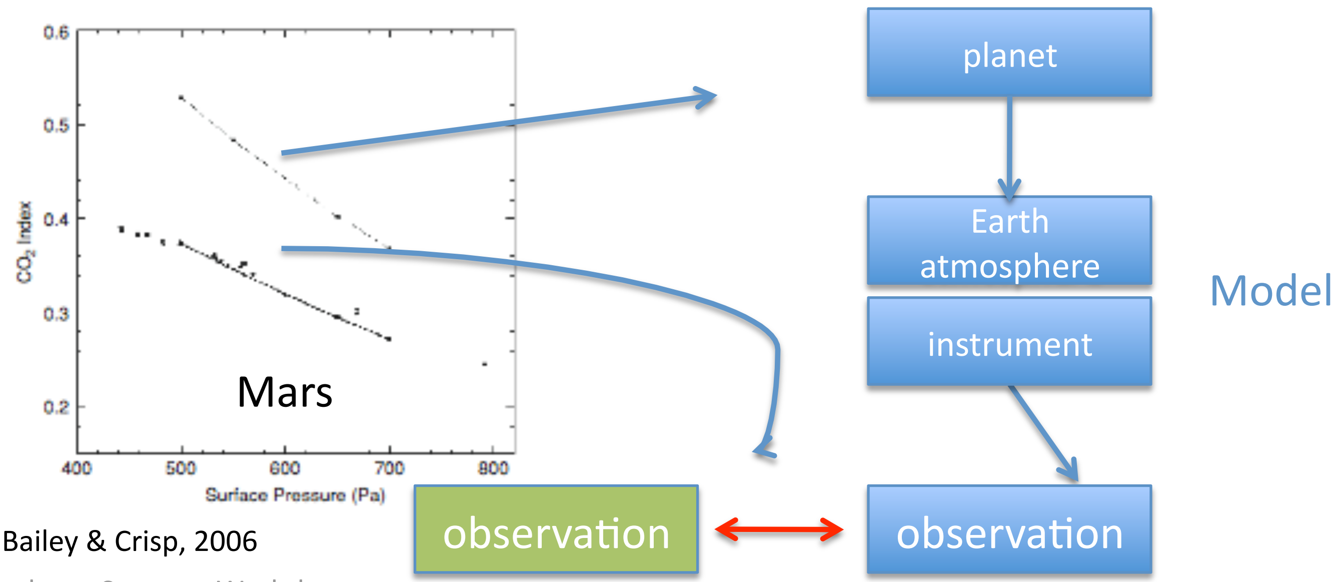
- Integral field spectroscopy: no slit, larger duty cycle, instantaneous notion of the earth atmosphere
- Extreme spectral resolution allows to disentangle lines coming only from the exoplanet (CRIRES, ELT/TMT)
- Doppler shift in emission of exoplanets (NIRSPEC/Keck)
- Forward modeling of the Earth-atmosphere effect





Chamberlain, Bailey & Crisp, 2006

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Conclusions

- Exoplanet spectro-photometry from the ground is possible!
  - Transits are measured routinely
  - Differential spectroscopy in the optical is demonstrated
  - Secondary eclipses have been measured
  - Near-IR spectroscopy is reaching the required accuracy
- Ground based eclipse measurements require non-standard calibrations
  - Systematics in instrument and Earth atmosphere effects dominate (the photon noise is not always relevant!)
  - The instrument is never understood at the required level
  - Multiple tries on the same instrument are often necessary
- The deployment of MOS, IFU, larger telescopes could make Exoplanet spectroscopy service mode observing (☺)