Direct exoplanet detection and characterisation from high resolution spectroscopy

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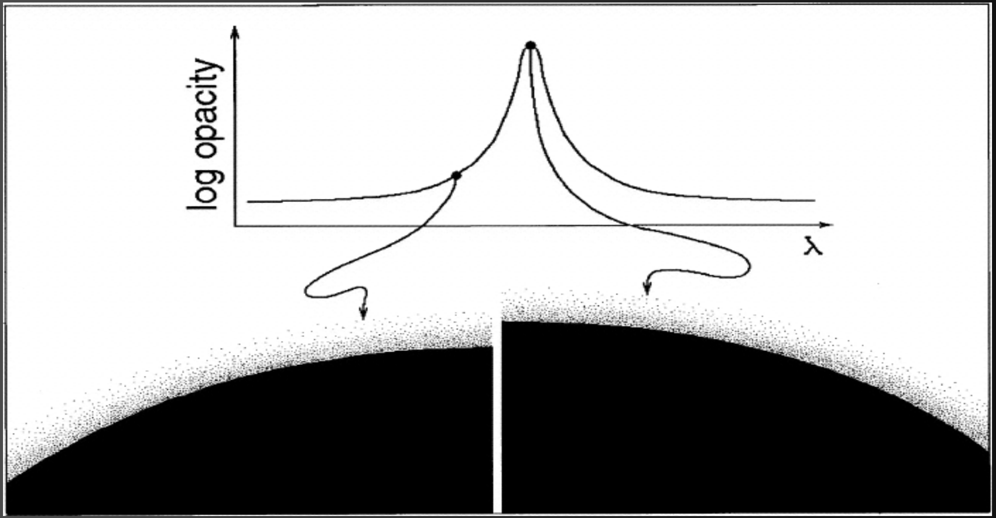
Transit Spectroscopy

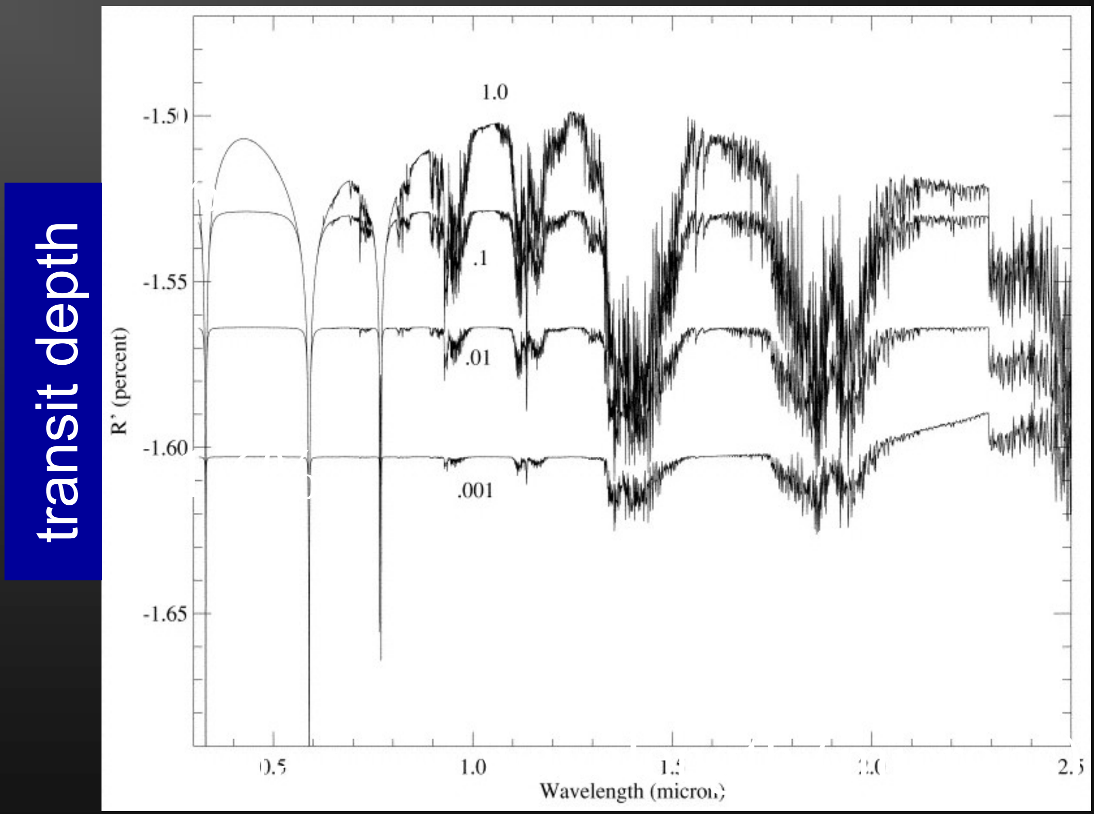
Molecules or objects absorb stellar light passing through atmosphere

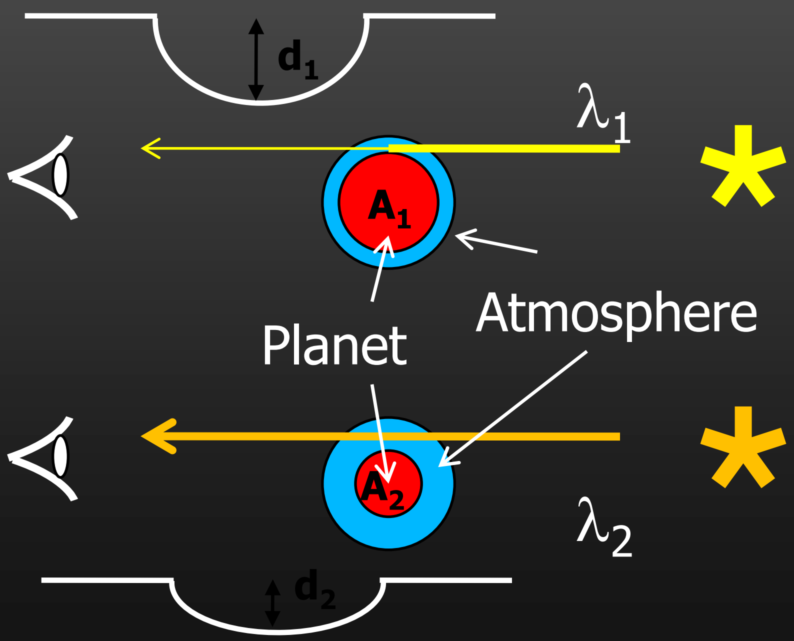
- more opaque at λ_1 than λ_2

→ effective area and radius of planet appears larger ($A_1 > A_2$)

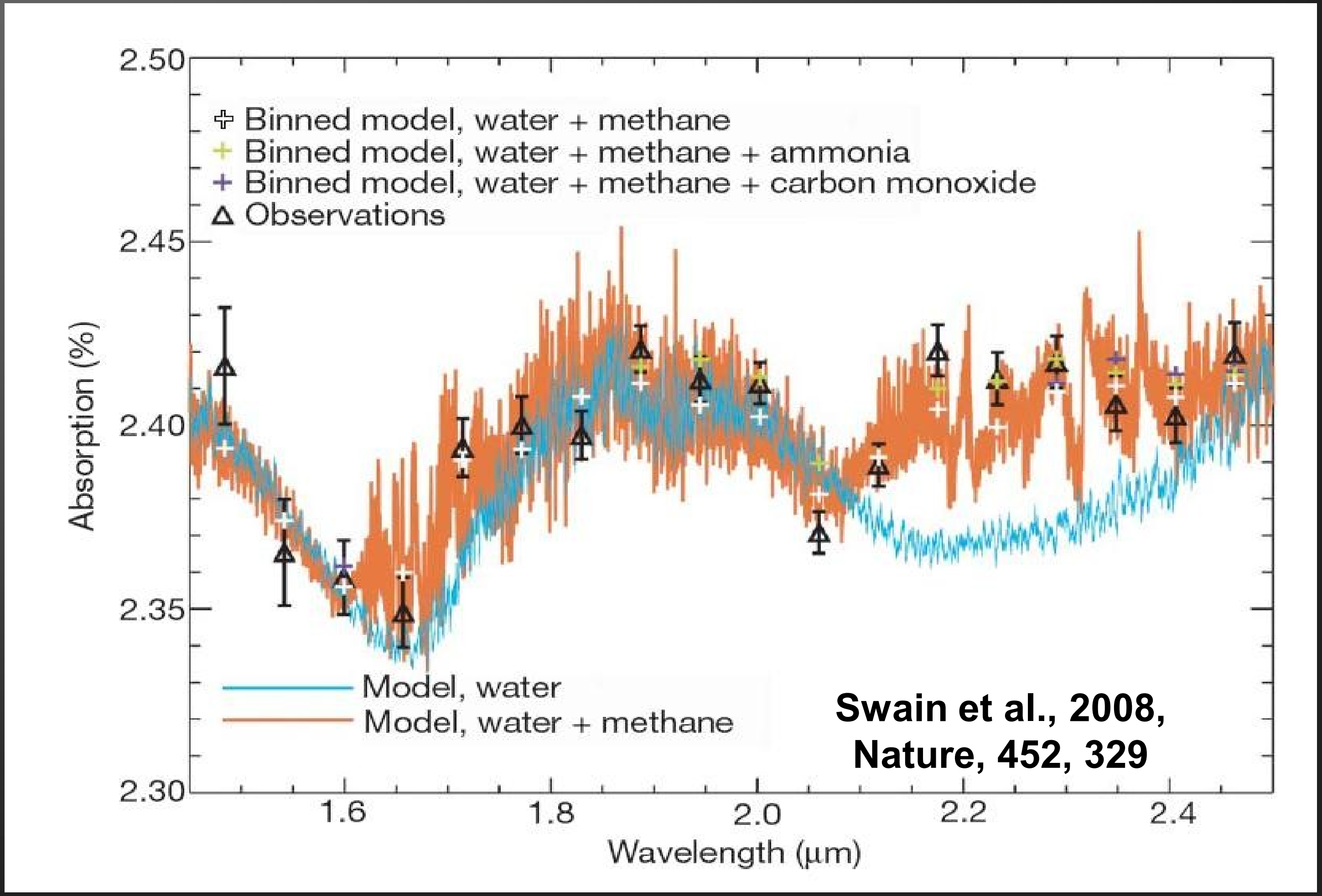
→ transit depth, $d_1 > d_2$







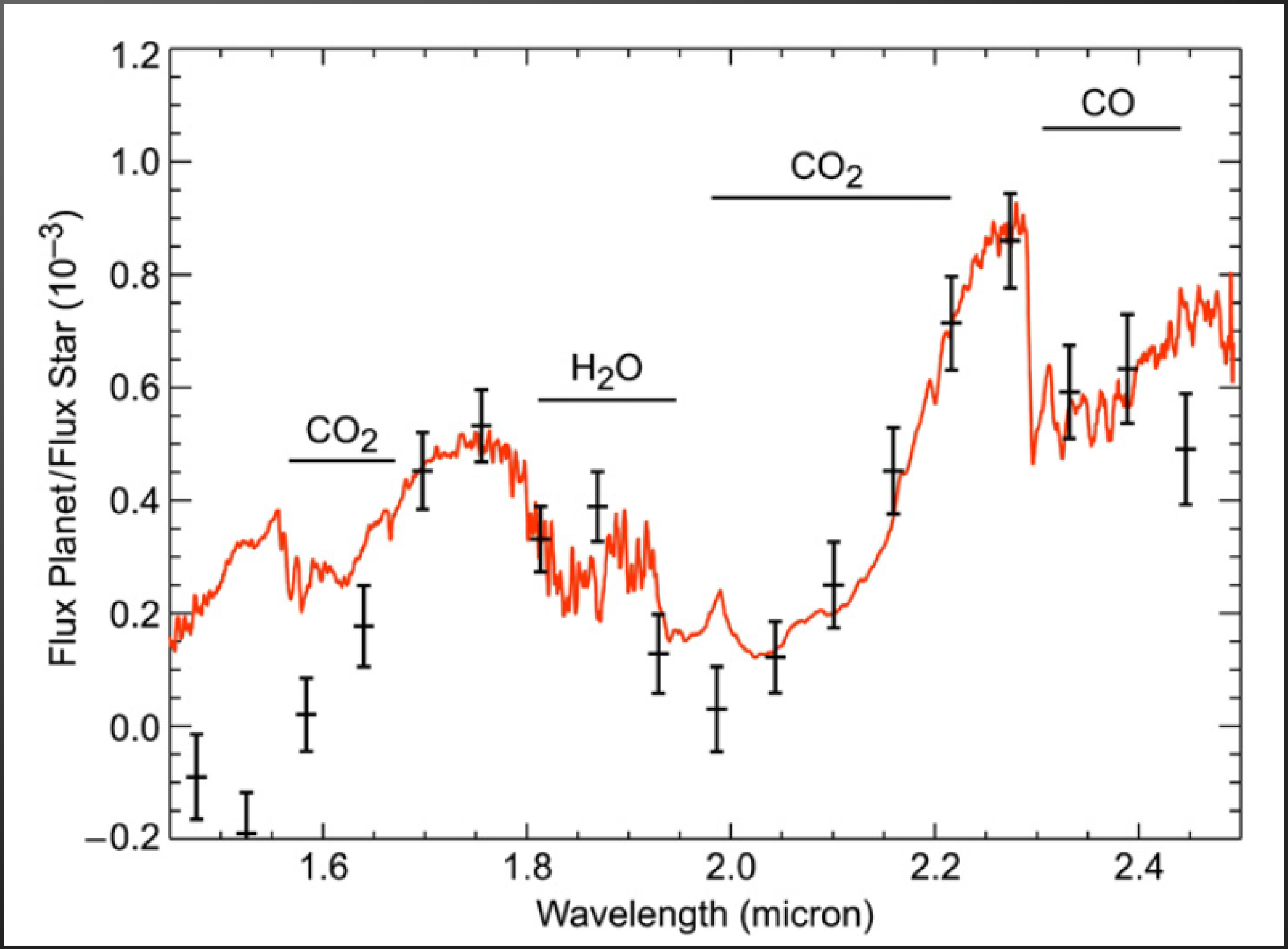
H_2O and CH_4 in atmosphere of HD 189733b



HST/NICMOS transmission spectrum

0.05% amplitude (1/2000) and ~0.01% precision - i.e. 1/10,000

Direct spectrum – Low resolution



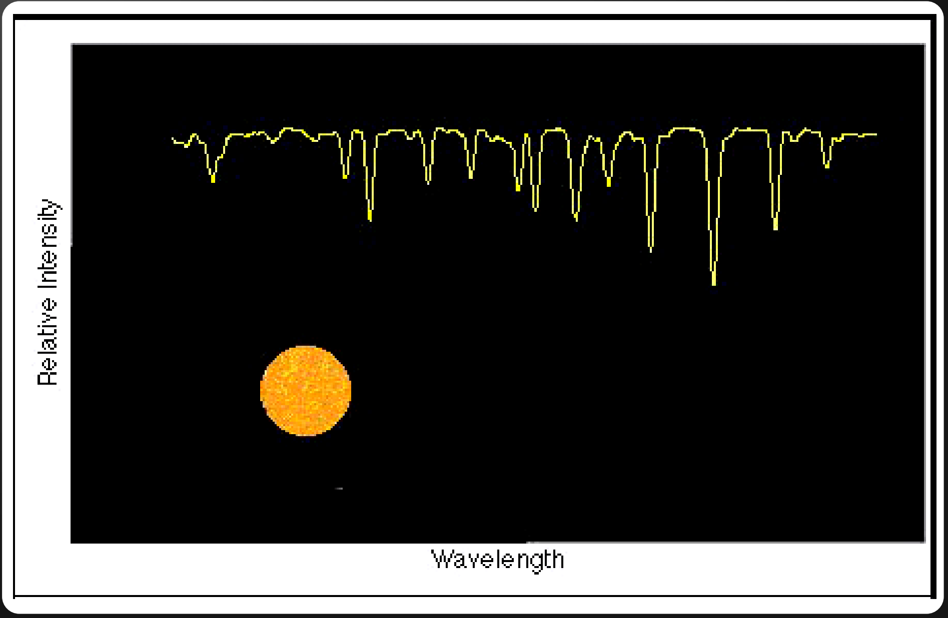
HST/NICMOS secondary eclipse spectrum
1/10,000 precision

Direct near infrared spectroscopic planetary signal (high resolution)

- $F_p/F_* \sim 1/1{,}000$ in the near infrared in the 2.2 μm K band
- Extract the signal from a high resolution spectral timeseries:

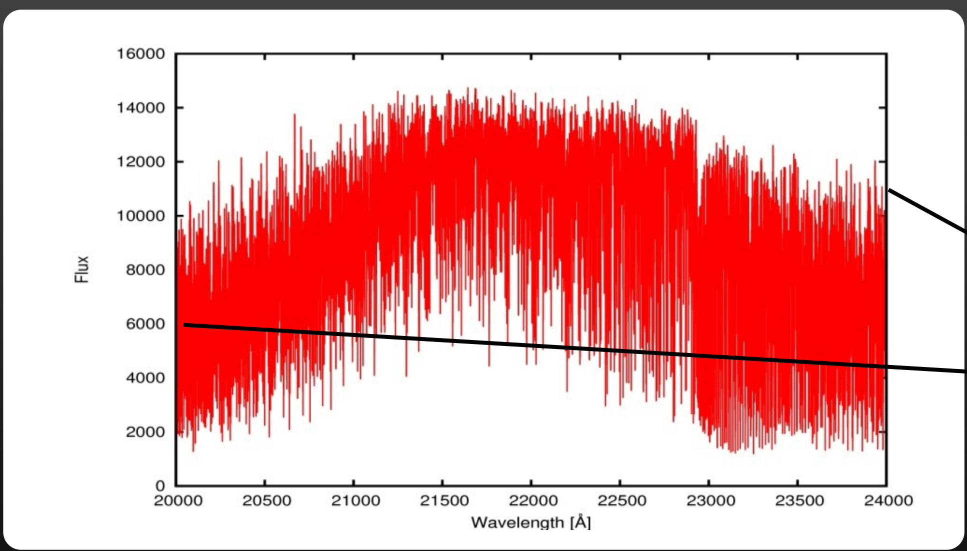
  planetary signature is modeled as a phase dependent spectrum superimposed on an unvarying stellar spectrum

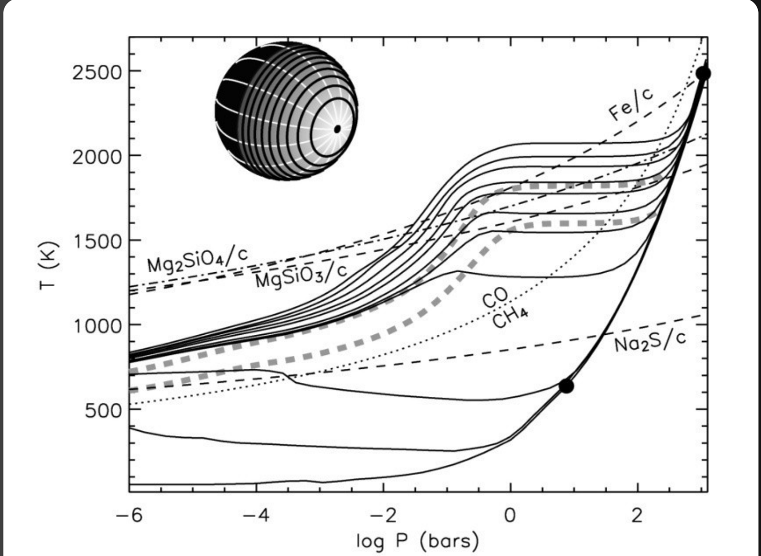
- Least squares deconvolution combines information from thousands of lines
  - Does not require transiting system
  - Contrast ratio determined
  - K_p, hence orbital inclination and planet mass determined
  - Test of model atomic/molecular linelists at high resolution
  - Split data into wavebands to obtain a local SED
  - Optimise the phase function fit to better constrain the energy distribution models



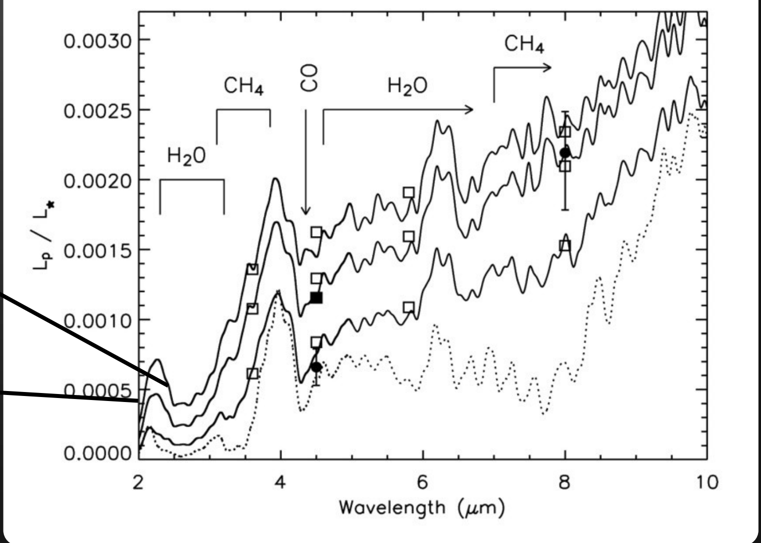
Phase dependent model spectra

- Barman, Hauschildt & Allard, 2005, ApJ, 632, 1132
- pL: Ti, V as solid condensates
  H_2O and CO *absorption*
- pM: TiO, VO opacities absorb incident flux:
  temp. inversion, molecular emission
  H_2O and CO *emission*
- ***Use model linelist to deconvolve a mean line from the spectrum***



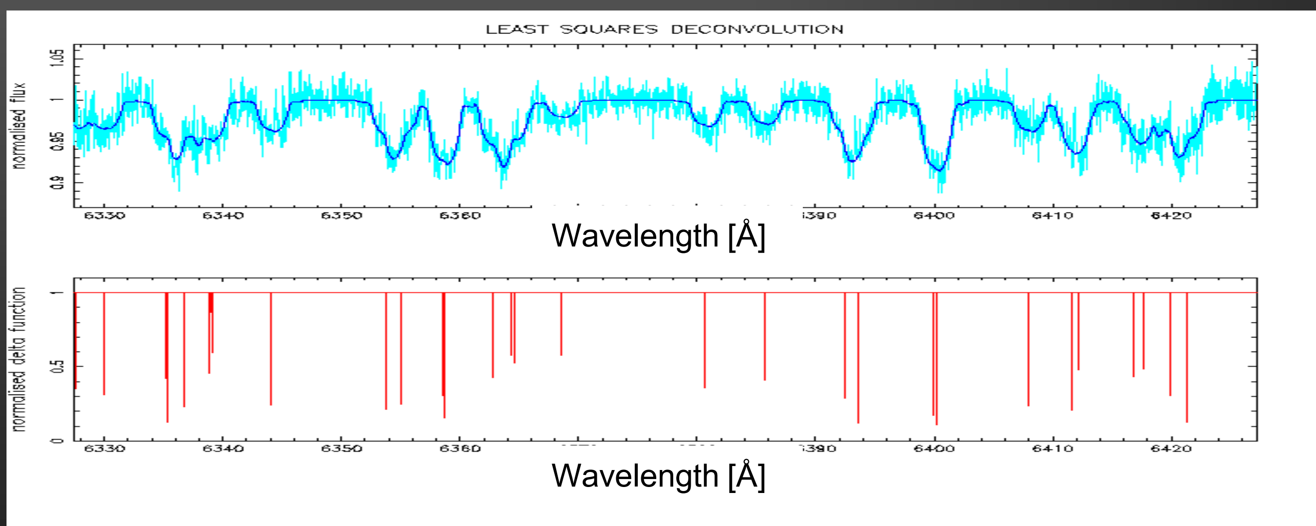


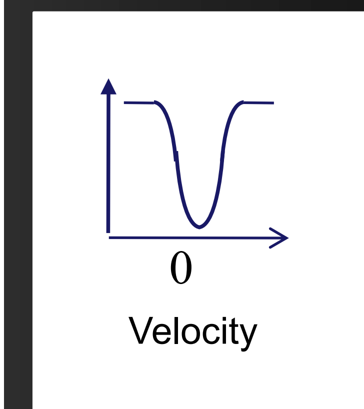
Barman, Hauschildt, Allard (2005, ApJ, 632, 1132)



Deconvolution

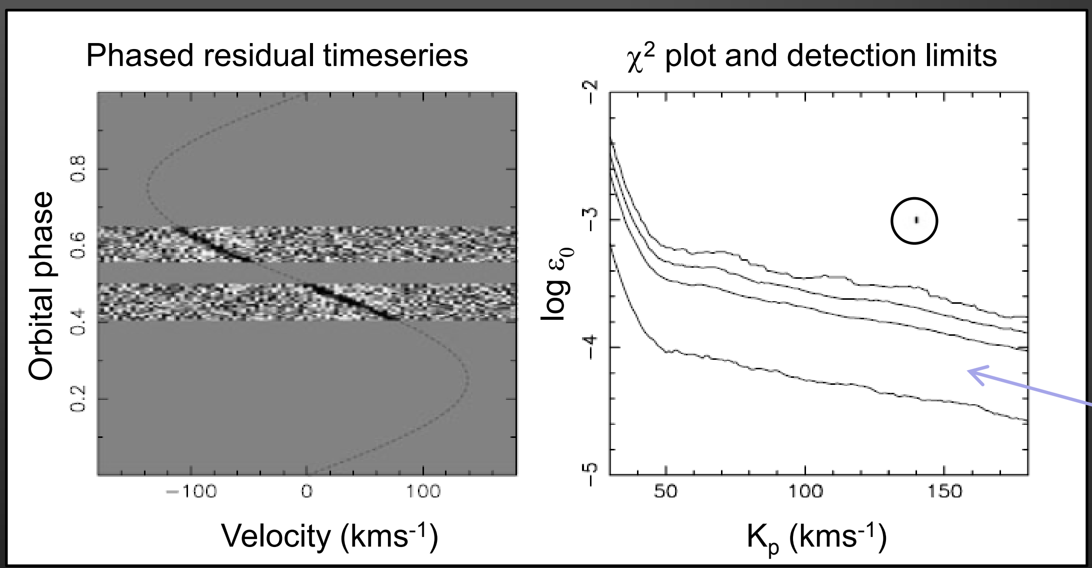
- S/N in a single observed spectrum is typically a few hundred
- Several hundred to several thousand lines in a typical spectrum
  - Use *model spectrum linelist* to perform a least squares deconvolution of a *mean line profile* from the observed spectra ***after removal of stellar/telluric lines***
- Boosts the S/N ratio by a factor depending on the number of lines
  Gain factor of several up to a few x10 gain





Modeling/detecting a planet

- Sinusoidal RV motion of the planet is modeled with model profile scaled according to orbital phase
- Since inclination is generally unknown run model for pairs of velocity amplitude, K_p, and maximum planet/star brightness, ε_0, and measure improvement in χ^2 for combination of ε_0 vs K_p

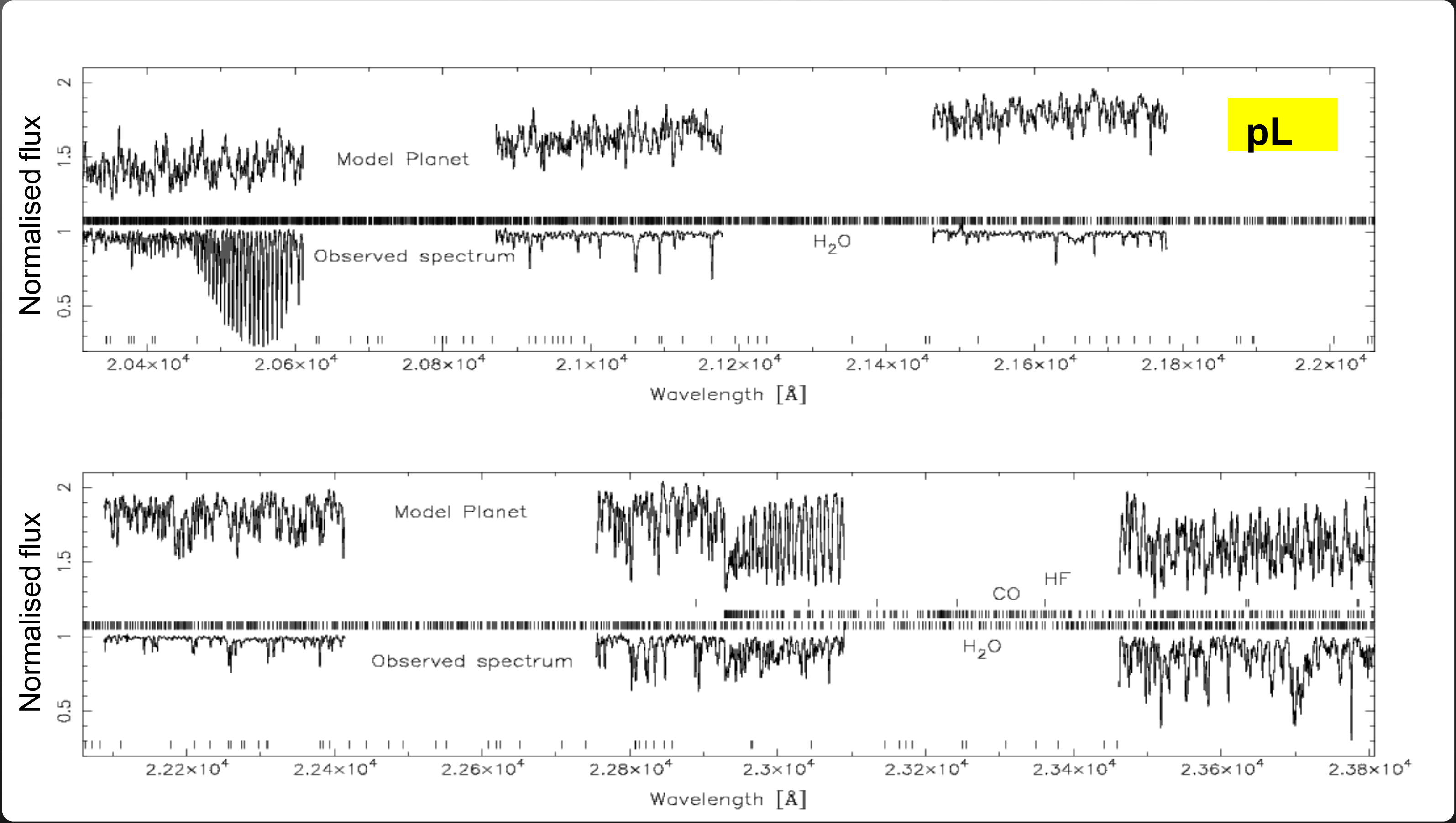


99.9%, 99%, 95.4%, 68.3% confidence levels

- Test significance of the result by randomising the order of spectra within each night and re-performing the search as above. By using several thousand randomised data sets, we can plot confidence levels for detected enhancements in χ^2.

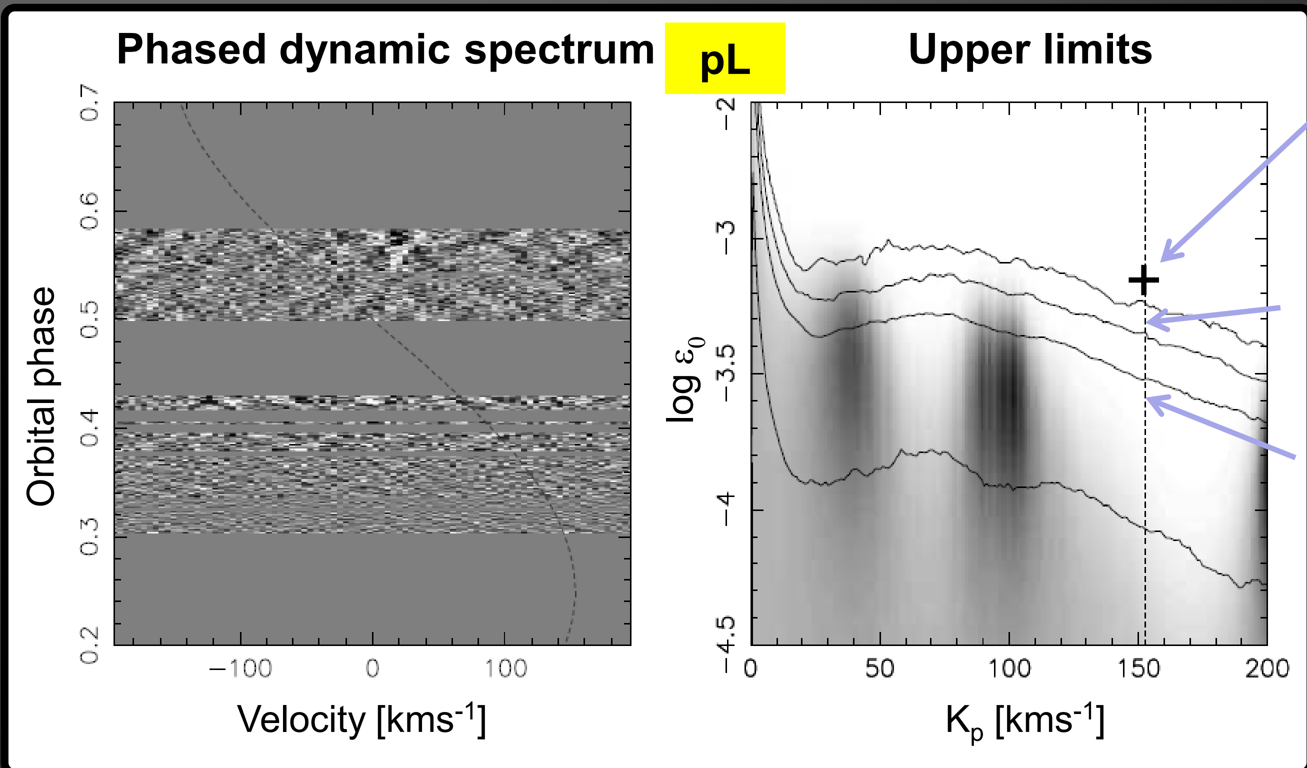
HD 189733b

- SpT=K1-2V, P=2.21 d, a=0.031 AU, K_p = 153 km/s
- 2.0 μm– 2.4 μm at R ~ 25,000



2008 Results: HD 189733b

Keck – 14/06/08 & 21/06/08 - R ~ 25,000



predicted planet

No planet detection

99.9% : log ε_0 = -3.2 (1/1698)

95.4% : log ε_0 = -3.5 (1/3388)

2006 data published in Barnes, Barman, Prato, Segransan, Jones, Leigh, Collier Cameron, Pinfield, 2007, MNRAS, 382, 473

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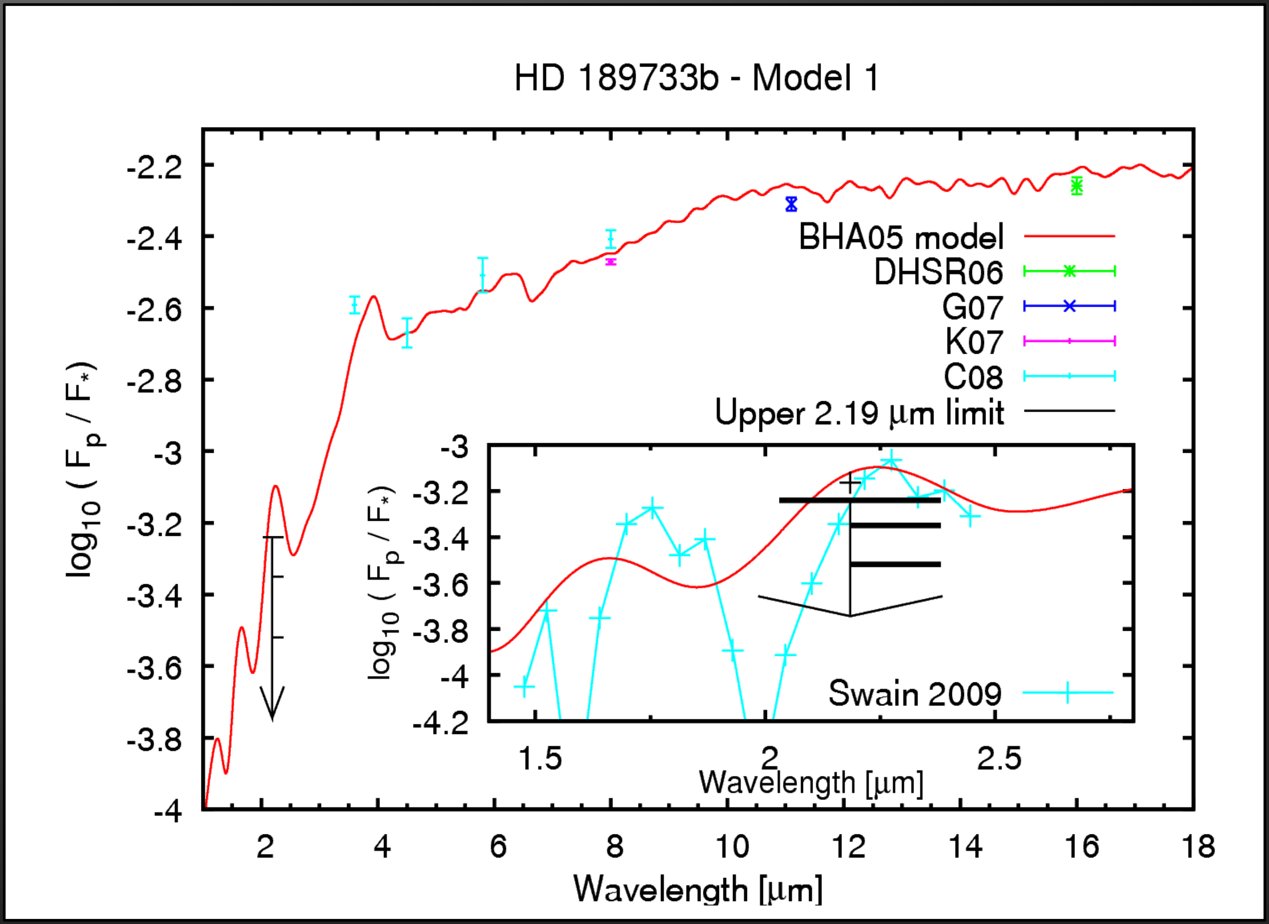
HD 189733b SED

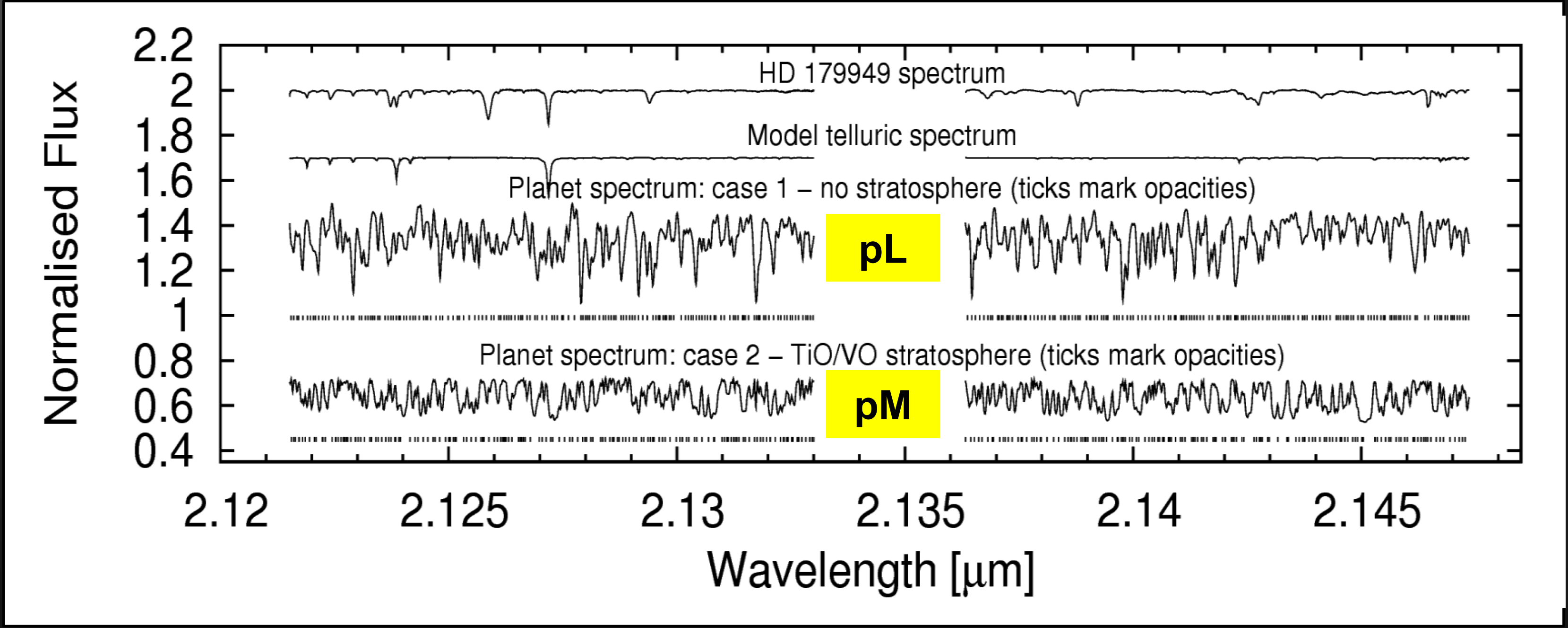


Deming, Seager, Richardson & Harrington (DHSR06), 2006, ApJ, 644, 560
Grillmair et al. (G07), 2007, ApJ, 658, L115
Knutson et al. (K07), 2007, 447, 183
Charbonneau et al. (C08), 2008, astro-ph (arXiv:0802.0845v2)

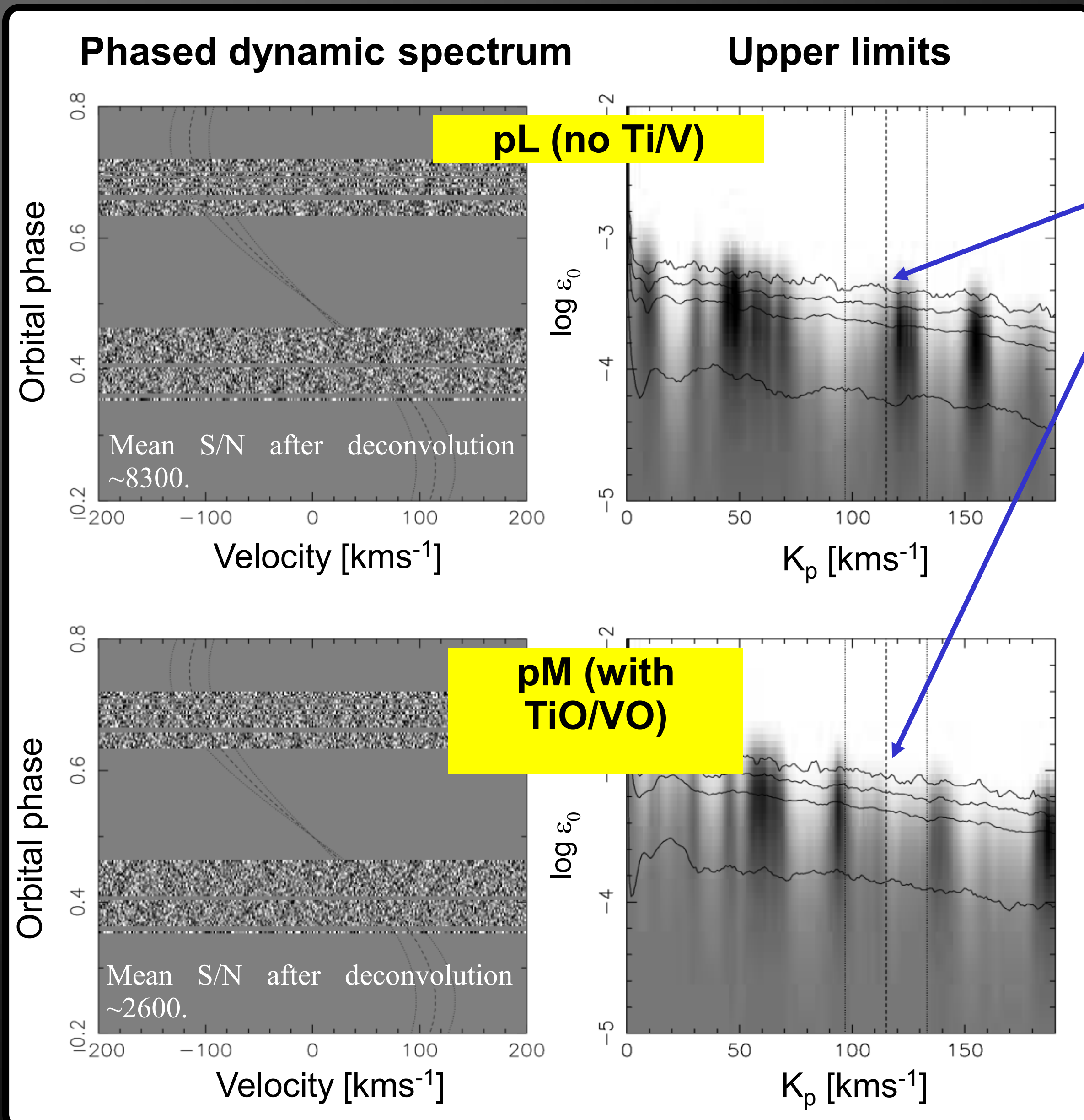
HD 179949b

Barnes, Barman, Jones, Leigh, Collier Cameron, Barber, Pinfield, 2008, MNRAS, 390, 1258

- SpT = F8V, P = 3.09 d, a = 0.045 AU
- CRIRES/VLT on 26th Jul and 2nd Aug 2007
- 46 + 27 spectra (coadded groups of 4) in excellent conditions < 10% humidity and ~0.5” seeing
- *Spectral coverage 2.122 μm– 2.175 μm at R ~ 50,000*



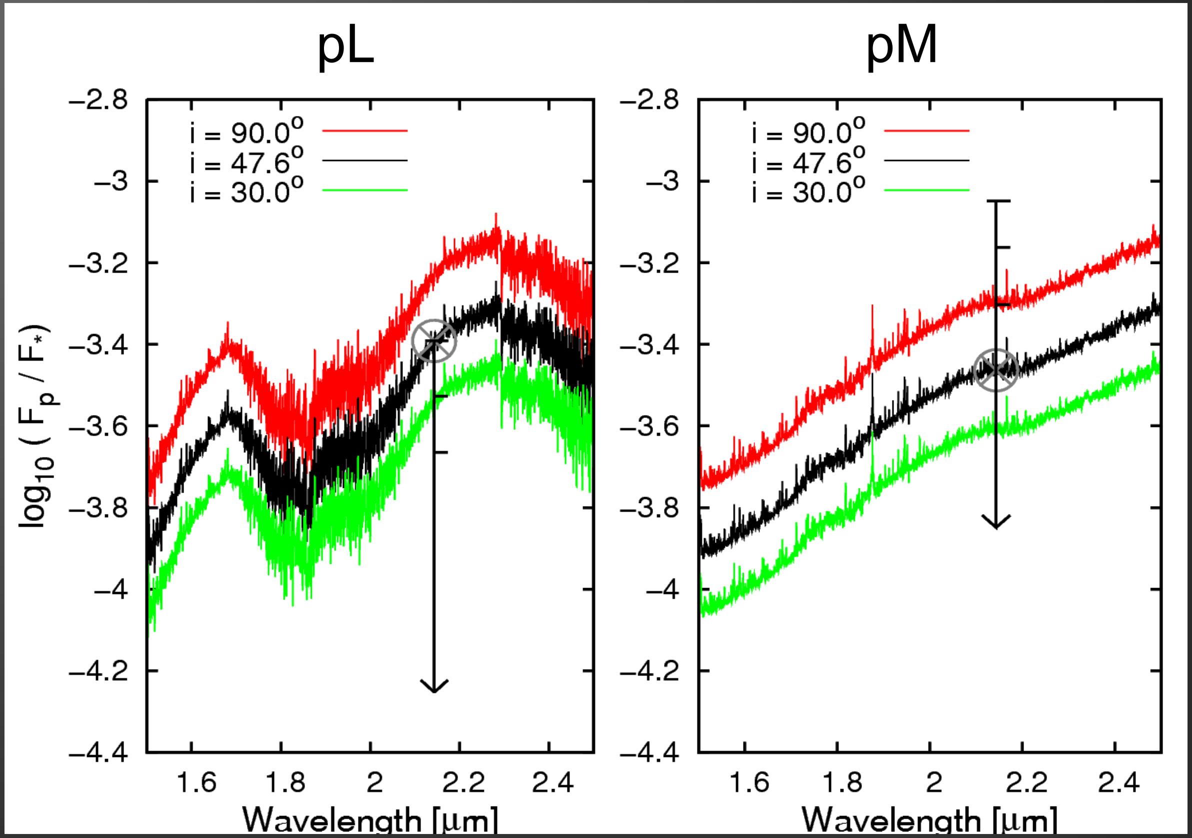
HD 179949b



Note relative significance between models

N.B. no planet at $\hat{K}_p$ = 115 kms^{-1}.

Results: HD 179949b



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Summary

For Hot Jupiter atmospheres

- HD 189733b: We can rule out the pL atmosphere where atomic species such as Ti and V have "rained out" resulting in an atmosphere dominated by H_2O and CO absorption
  - For a 99.9% signal to appear as a 68.3% signal, line depths must be weaker by a factor of ~4.5 → T-P profile incorrect?
- HD 179949b: The unknown orbital inclination introduces a further degree of freedom into the interpretation of the results
  - reject pL atmosphere
  - more observations needed to enable detection or rejection of the pM atmosphere scenario where a high altitude absorbing species results in formation of a stratosphere, pushing many H_2O transitions into emission

Summary

- Spectrum vs deconvolution linelist mismatches assessed using H_2O spectra
  - deconvolution is robust i.e. detection ability relatively insensitive to 250 K temeprature mismatch
  - Absolute calibration is sensitive to linelist mismatch

- Effects explored not sufficient to explain lack of detection – at least for HD 189733b
- Exploration metallicity, temperature effects, mismatches on emergent planet spectrum – e.g. molecular abundances

M dwarfs

- For G-K dwarfs, close orbiting giant planets:
  - H,J,K band of order $F_p/F_* = 1/1000 – 1/10000$
  - 4-24 mm – contrasts of order $F_p/F_* = 1/100 – 1/1000$
- What about M dwarfs?
  - Lower contrast ratios…
  - …but lower irradiation and heating for parent star

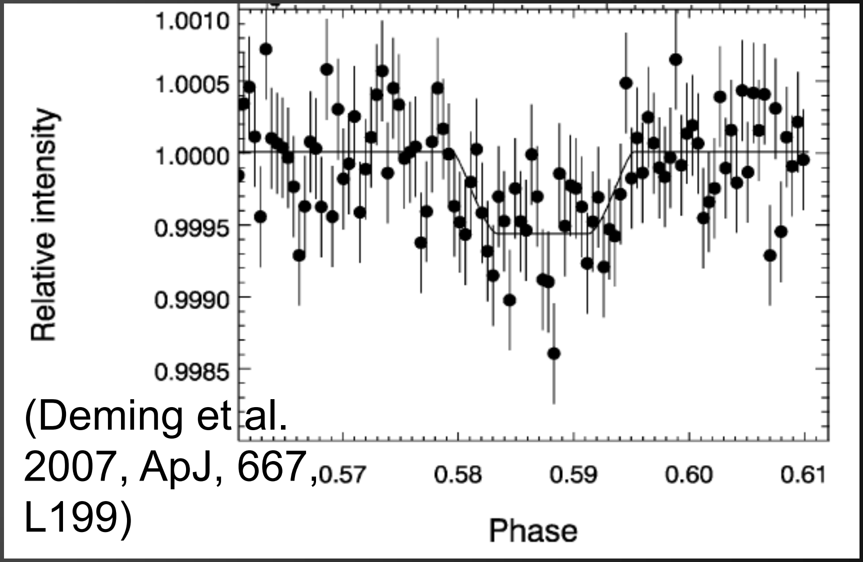
GJ 436b

- M2.5V @ d = 10.2 pc
- I = 8.24, J = 6.9, H = 6.3, K = 6.1
- 8 μm eclipse amplitude

  (5.7 ± 0.8) x 10^{-4} - i.e. 1/1750
- c.f. 8 μm HD 189733b eclipse

  amplitude with 1/300 (6x lower contrast)

Secondary eclipse



(Deming et al. 2007, ApJ, 667, L199)

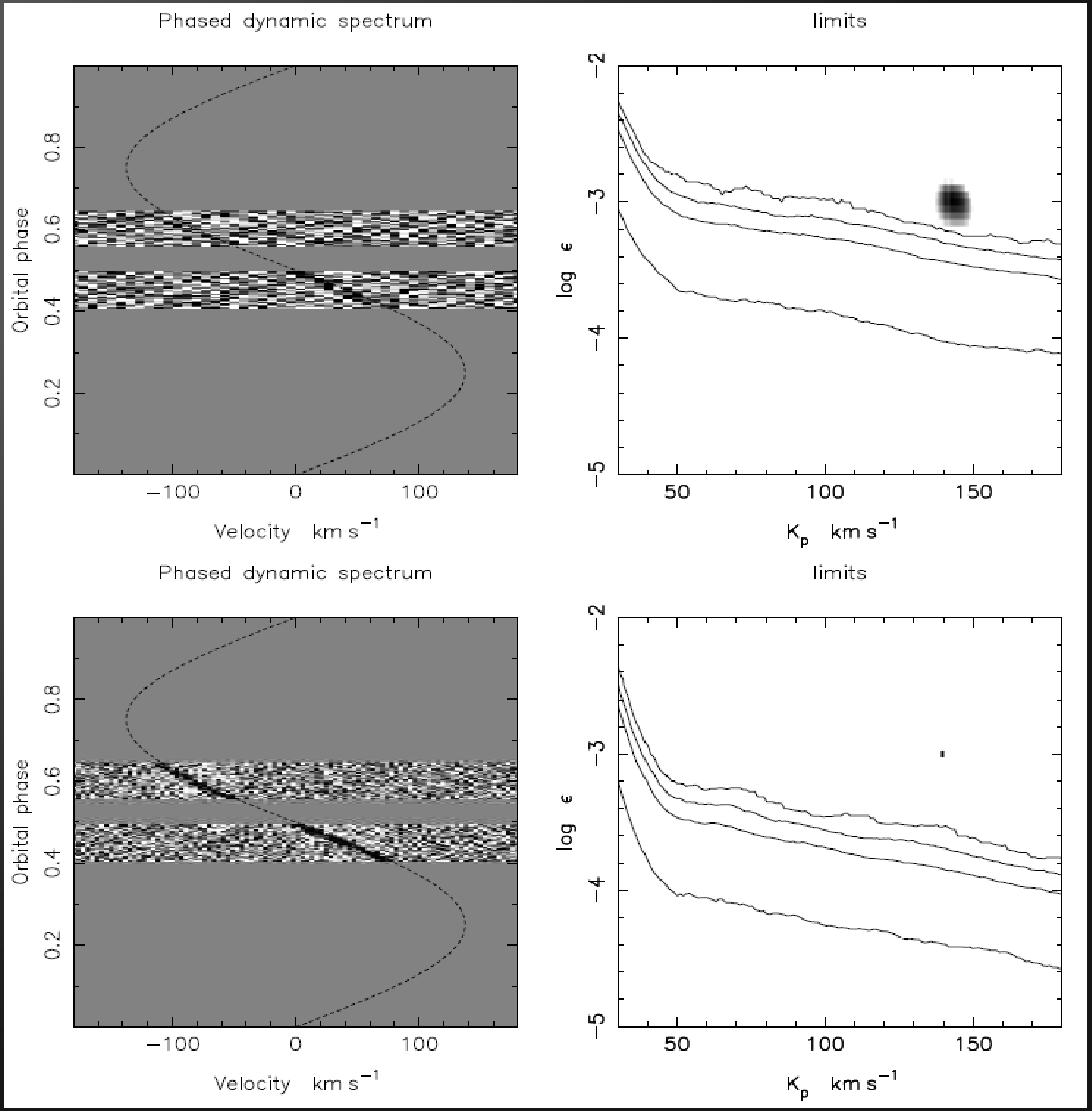
- Scaling Swain et al. HD 189733b dayside H&K band flux ratios, expect approx GJ 436b ratios of:
  - H band F_p/F_* ~ 1/11000
  - K band F_p/F_* ~ 1/7000

High res. NIR sensitivities

- K band
- Keck/NIRSPEC coverage
- S/N = 300
- 50 spectra per night

- Spectral resolution
  Top: R ~ 20,000
  Bottom: R ~ 40,000

- 99% confidence level
  $F_p/F_* \sim 2,000$ (R 20,000)
  $F_p/F_* \sim 5,000$ (R 40,000)



High res. NIR sensitivities for M dwarf planets

- Multiorder cross-dispersed spectrograph encompassing 1-2.5 μm region (3x wavelength simulated K band coverage)
- Good seeing conditions and multi-frame exposures enable S/N = 600 to be achieved with Keck (2x simulated sensitivity), obtaining 100 spectra per night (2x simulated sensitivity)
- Two nights observing → detection:
  - K band: $F_p/F_* = 5000.2\sqrt{2} = 14{,}000$ @ 99% conf.
  - J,H,K band combined $F_p/F_* \times \sqrt{3} = 24{,}000$ @ 99% conf.
- M dwarf stars are good targets for cross-dispersed high resolution spectroscopic studies

Close orbiting Neptune planets around M2.5V stars could be detected and characterised (GJ 436 K mag ~ HD 189733)

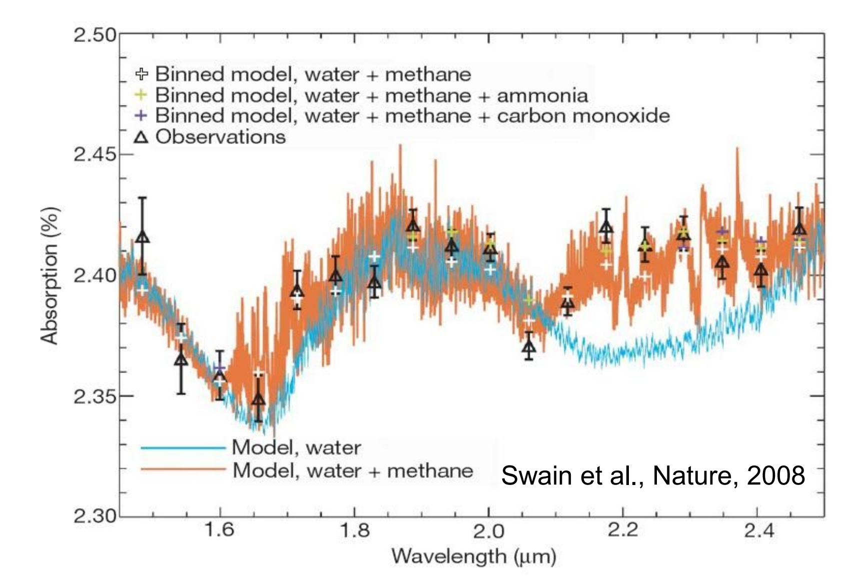
What can we achieve with low-res.?

Direct and transmission spectroscopy

- Reproduction of recent Swain et al. HST/NICMOS results with JWST will enable fainter objects to be probed.
- Eclipse depth equivalent to HD 189733b:

  - 0.2 $M_\odot$ star transiting Neptune radius (0.82 R_{Nep}) planet
  - 0.1 $M_\odot$ star transiting Earth radius (0.8 $R_\oplus$) planet

- Based on aperture alone, an additional 2 mags in will enable objects with H and K mags of ~8 to be studied with the same precision as HD 189733b.
- 1/2500 precision would enable H_2O detection for H/K = 9-10



Swain et al., Nature, 2008

Conclusions

- Prospects for ground based high resolution spectroscopic characterisation studies of M dwarfs looks promising

  - 42m E-ELT will give gain (over 8m tels.) of 3.6 mags for same time allocation enabling study of K~10 systems

- Low resolution: transmission and direct spectroscopy studies:

  - 6.5m JWST will enable space based precision to probe K~10 systems

  i.e. M3.0 to 46 pc, M5.0 to 20pc, M7.0 to 10.5pc

  Among 100 closes stars:

  GJ 1156, M5.0V @ 6.5 pc - K = 7.6

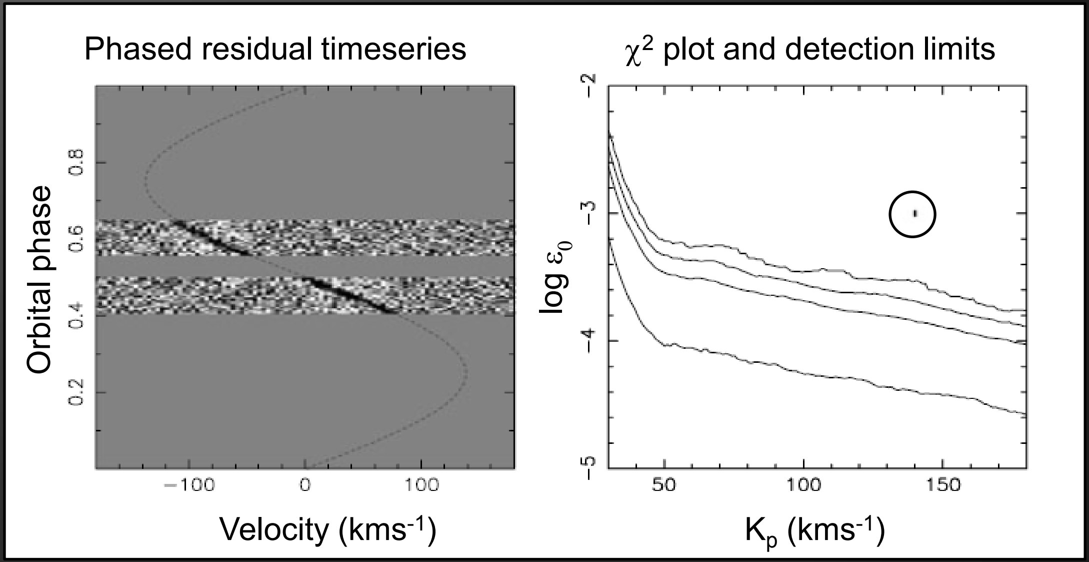
  LHS 2090, M6.0V @ 6.4 pc - K = 8.4

  LHS 3003, M7.0V @ 6.3 pc - K = 8.9

The End

Modeling/detecting a planet

- Sinusoidal RV motion of the planet is modeled with model profile scaled according to orbital phase
- Since inclination is generally unknown run model for pairs of velocity amplitude, K_p, and maximum planet/star brightness, ε_0, and measure improvement in χ^2 for combination of ε_0 vs K_p



- Test significance of the result by randomising the order of spectra within each night and re-performing the search as above. By using several thousand randomised data sets, we can plot confidence levels for detected enhancements in χ^2.

Linelist / Spectrum mismatch tolerance

Simulation: Simple absorption spectra – T=1250K - to generate fake planet at known contrast ratio into 2008 HD 189733b data set

(1a) Recover planet by modifying line positions according to:

75% of transitions known experimentally (strongest)

25% of lines are experimental of which:

- 49% are known to within 0.1cm-1 (R~45,000 at 2.2 μm)
- 91% are known to within 0.3cm-1 (R~15,000 at 2.2 μm)

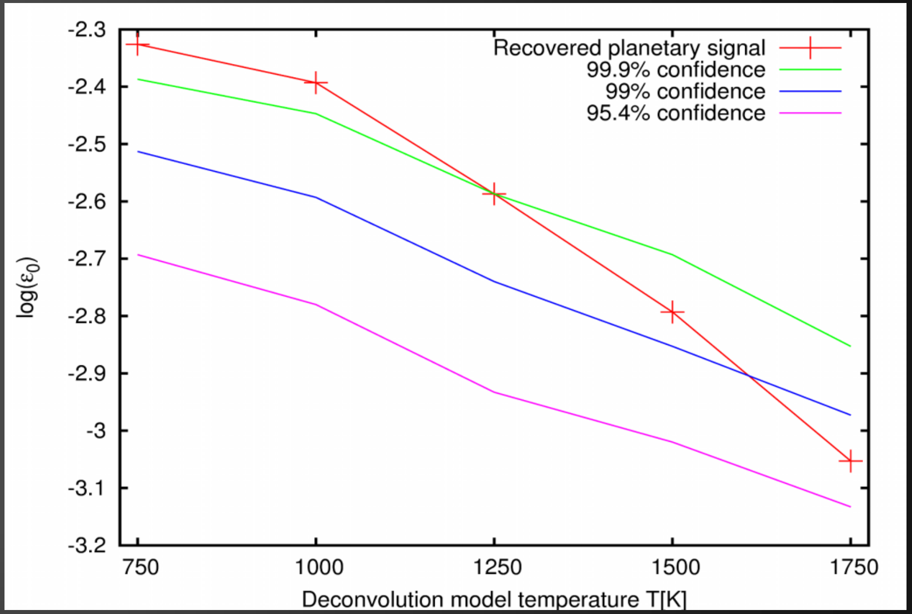
(1b)

Linelist / Spectrum mismatch tolerance

(2) Recover T = 1250 K planet using T=750 K – 1750 K linelists

- T = 750 K – signif. @ 114%

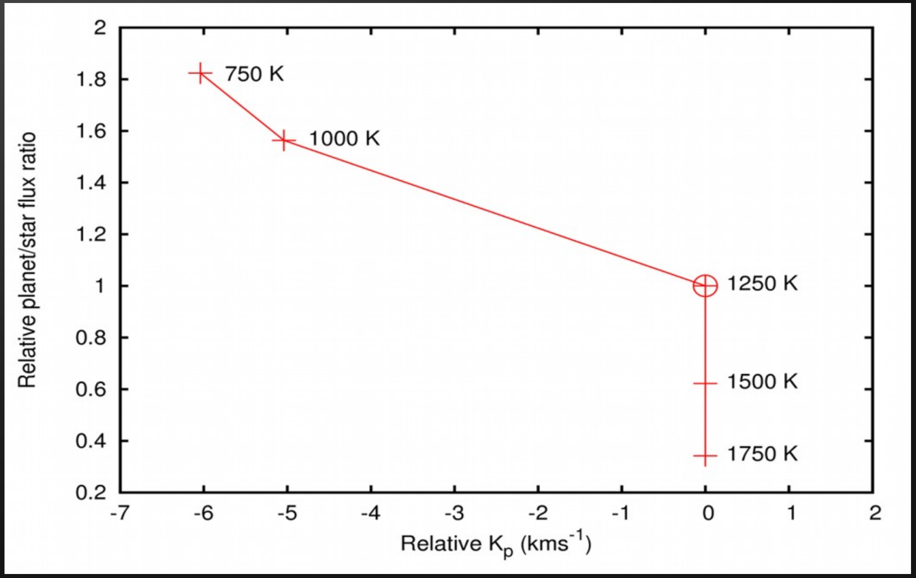
- T =1750 K – signif @ 63%



Planet/star flux ratio

- T = 750 K overest. by 180%

- T = 1750 K underest. by 35%



(250 K model temperature inaccuracy → ~ 50% error on contrast ratio)

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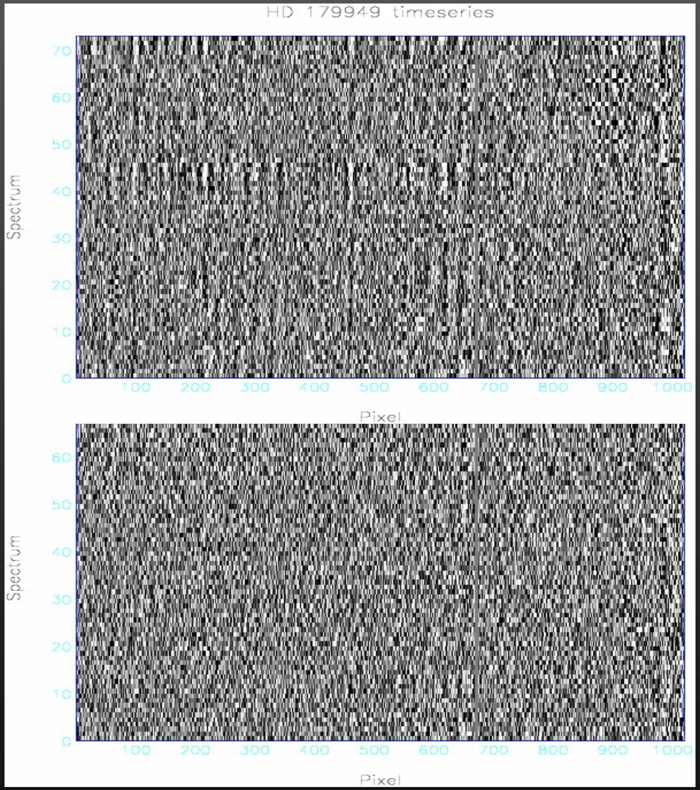
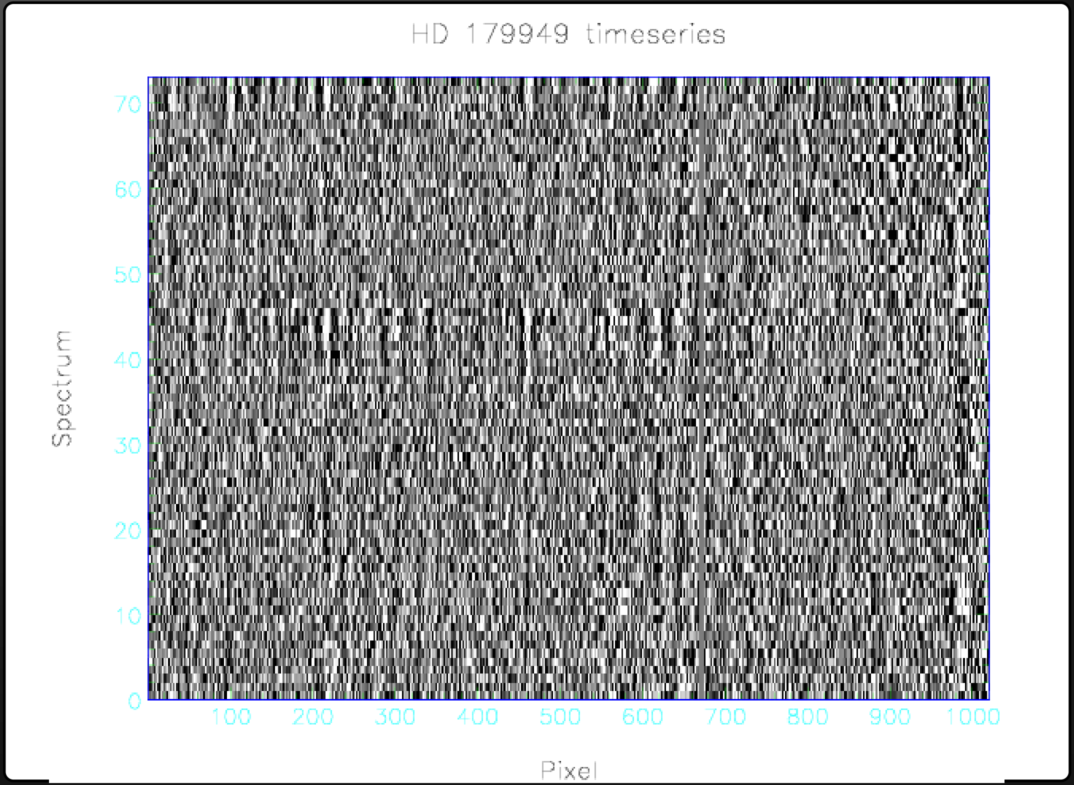
Modeling the planetary motion

- High S/N average spectrum is scaled, shifted and subtracted from each spectrum in turn in order to remove stellar spectrum + tellurics
  - Residuals contain only a planetary absorption spectrum (not removed by mean spectrum subtraction due to radial velocity changing from spectrum to spectrum during motion of the planet in its orbit)
- Remaining trends moved using principal components analysis





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Phase dependency of model

- Planetary time dependent variations
  - Doppler shift of the spectrum due to relative orbital position of planet
  - Phase dependent flux ratio f_p/f_* which is dependent on the atmospheric physics and heating due to the parent star

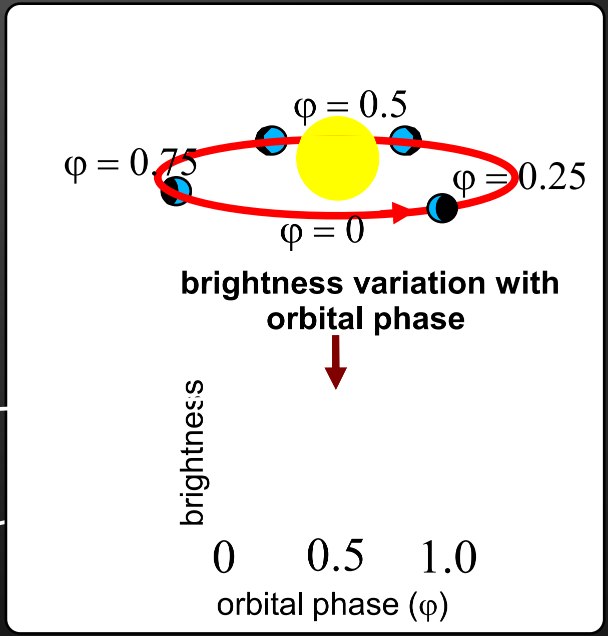
$$\epsilon(\alpha,\lambda)=\frac{f_p(\alpha,\lambda)}{f*(\lambda)}=\epsilon_0(\lambda)g(\alpha,\lambda)$$

$$\alpha=\sin(i)\cos(\phi)$$

α = phase angle

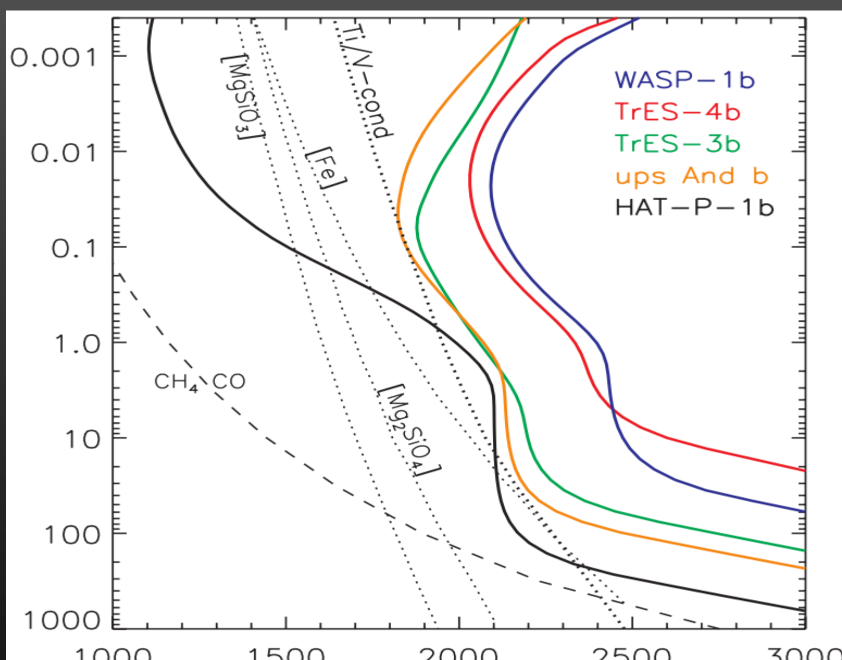
$\varepsilon_0(\lambda)$ = maximum planet/star flux ratio at φ=0.5

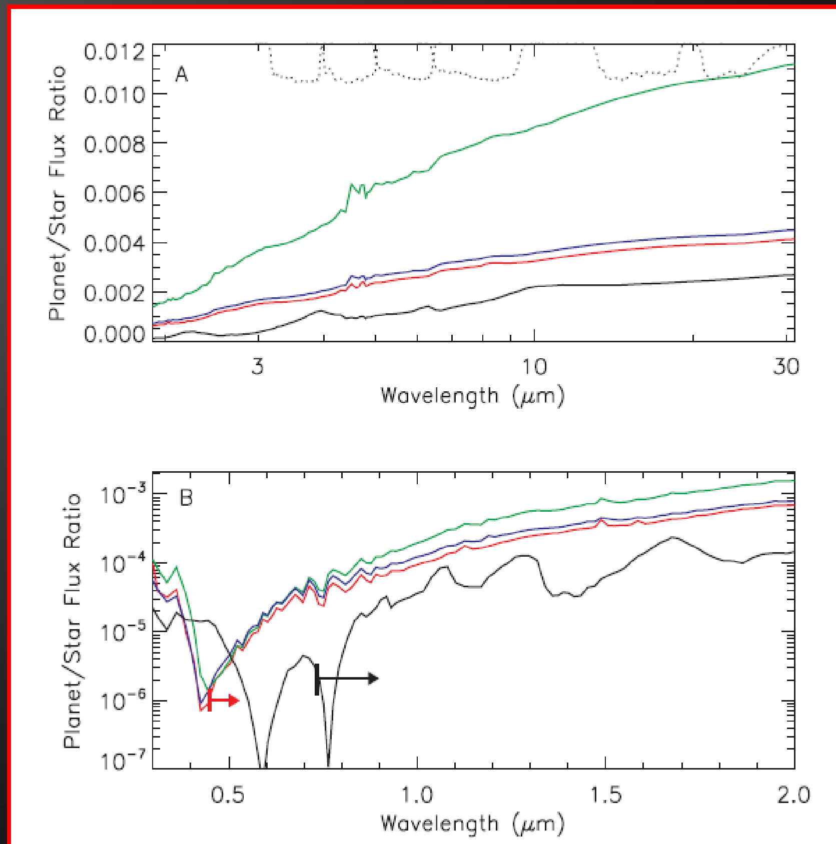
g = phase function



Hot Jupiter models - A stratosphere?

- Stratospheric absorber included in models by Burrows, Budaj & Hubeny (2008, ApJ, 678, 1436):
  - constant opacity at λ = 0.42 - 1.0 μm below a given pressure (0.03 bars).
- TiO and VO give similar (Fortney et al., 2008, ApJ, 678, 1419) effects which result in a temperature inversion





Fortney et al. (2008)

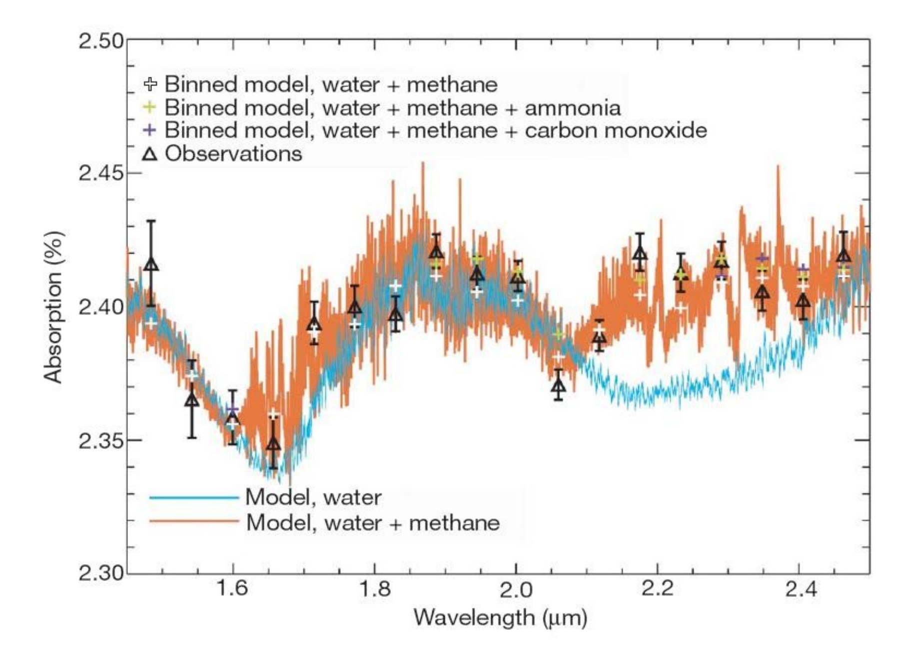
So where are the planets?

- Devil is in the systematics – tellurics are the major concern and have to be dealt with carefully
  - BUT: Principal components analysis can move residuals, but at some level the sensitivity is compromised

HOWEVER: With the HD 189733b and HD 179949b data, we have achieved sensitivities at which a planet should be visible

- For HD 189733b no detection at 2σ level if
  - Line depths modified by 70%
  - Wavelength postns. uncertain by 20%
- Are model opacities precise at high res.?
  - 90% opacities with 0.3 cm^{-1} (factor 3)
  - 49% within 0.1 cm^{-1} (factor 1.4)

(BT2, Barber, Tennyson, Harris, Tolchenov, 2006, 368, MNRAS, 1087)

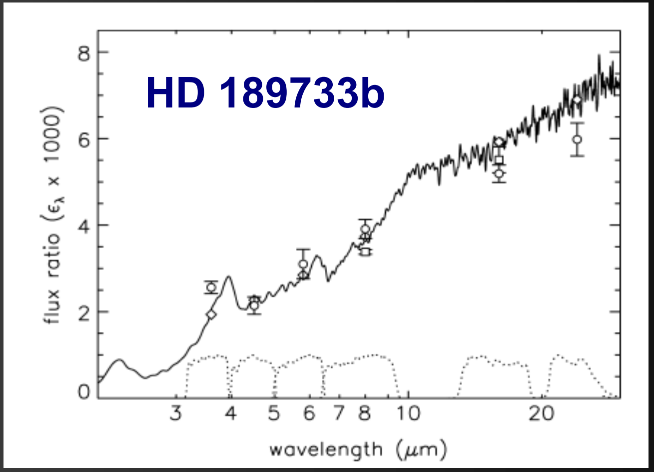


Swain, Gautam & Tinetti 2008, Nature, 452, 329

Two classes of irradiated atmospheres?

pL: Cooler – Ti, V as solid condensates

- absorb radiation deeper in atmosphere
- atmospheric dynamics will more readily redistribute energy leading to cooler day sides, warmer night sides and phase shifts in thermal emission lightcurves
- e.g. HD 189733b TrES-1

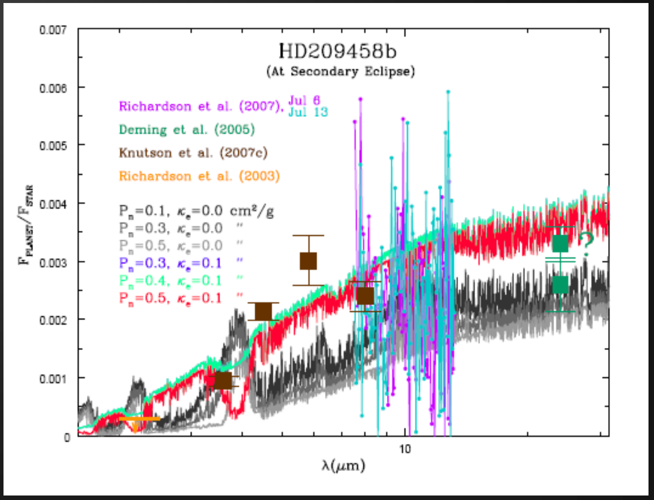


Barman 2008, ApJ, 676, 61

pM: Hot - TiO, VO opacities absorb incident flux: hot stratospheres, molecular emission

- Peaks/troughs evened out
- Contrast ratio increased telluric window regions where weak absorption features instead appear in emission - search for emission features?

e.g. HD 209458b, Ups And b & probably HD 179949b



Burrows et al. 2008, ApJ, 668, L171