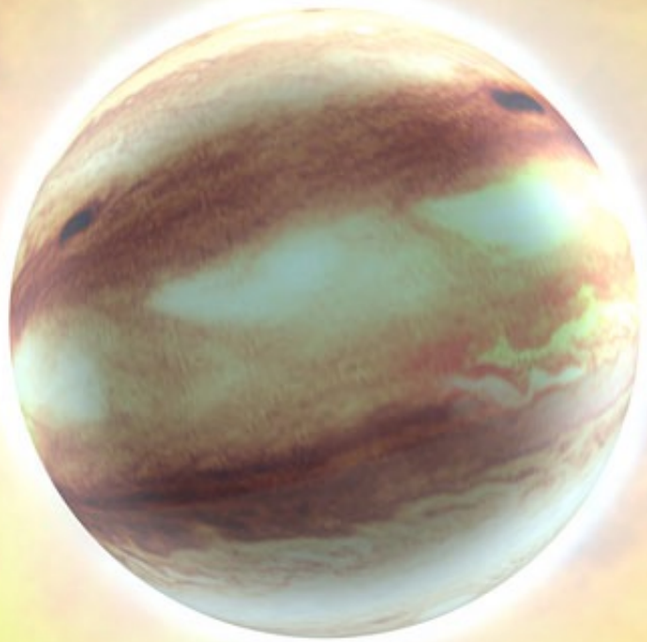
EMIR-RIA, Cadiz, 23-24 Nov, 2017

A GTC/EMIR K-band dayside emission spectrum for the hot Jupiter WASP-43b

Guo Chen

Instituto de Astrofísica de Canarias (IAC)



Collaborators:

E. Palle, L. Nortmann, F. Murgas, H. Parviainien, R. Alonso

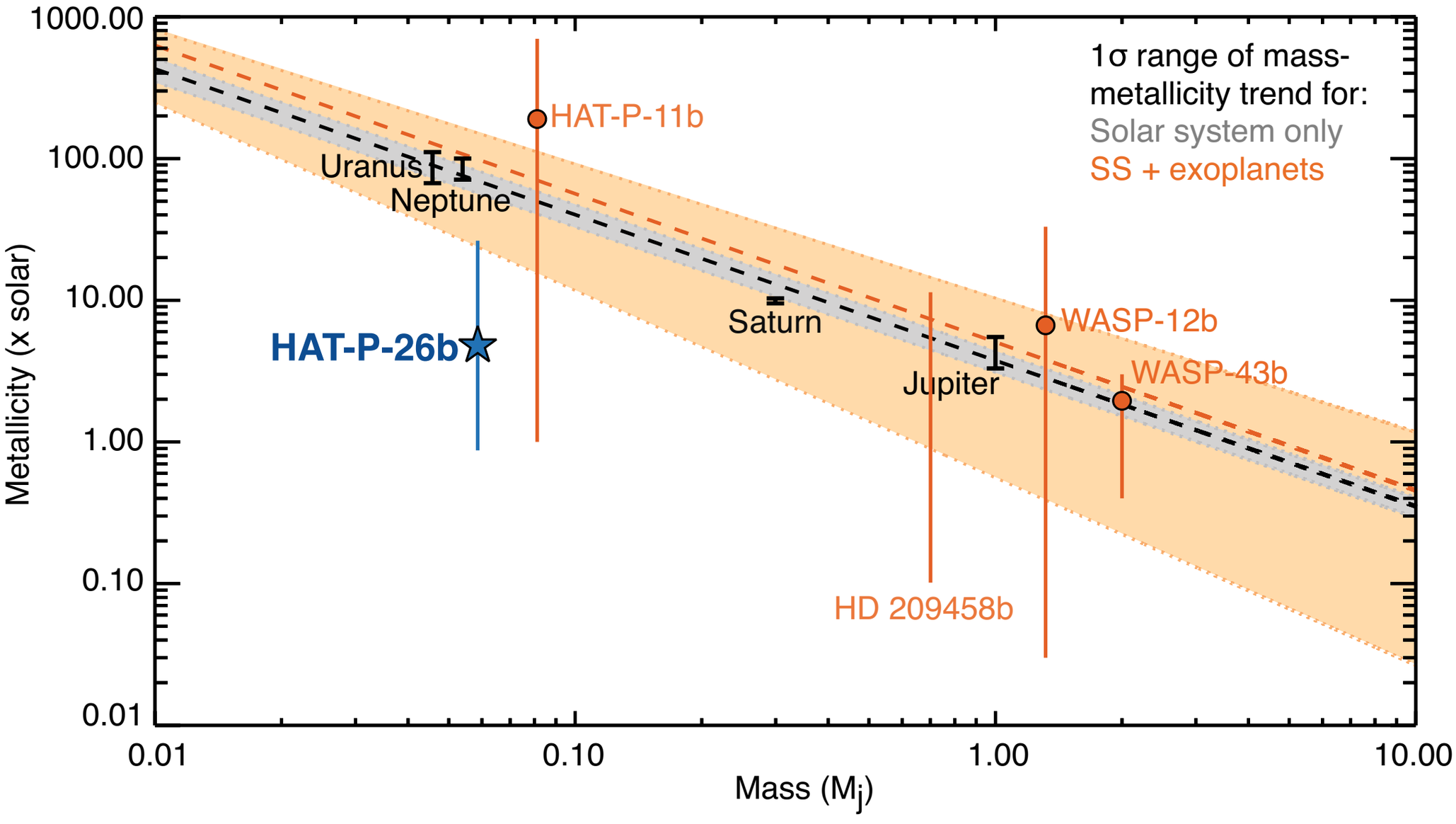
CONCLUSIONS

- GTC/EMIR is able to do precision spectrophotometry!
  - 200 ppm /10 min in K-band
  - 240-450 ppm / 10 min in 30nm channel
  - There is still room to improve with revised observing strategy

- Results of our EMIR science verification program:
  - Thermal emission is detected at 12.6 sigma in the K-band for the hot Jupiter WASP-43b
  - Our measurements indicate a brightness temperature of 1668 ± 32 K at the probed pressure level in the K-band
  - Our K-band emission spectrum shows tentative evidences of CH_4 and CO absorption on top of the water absorption wing

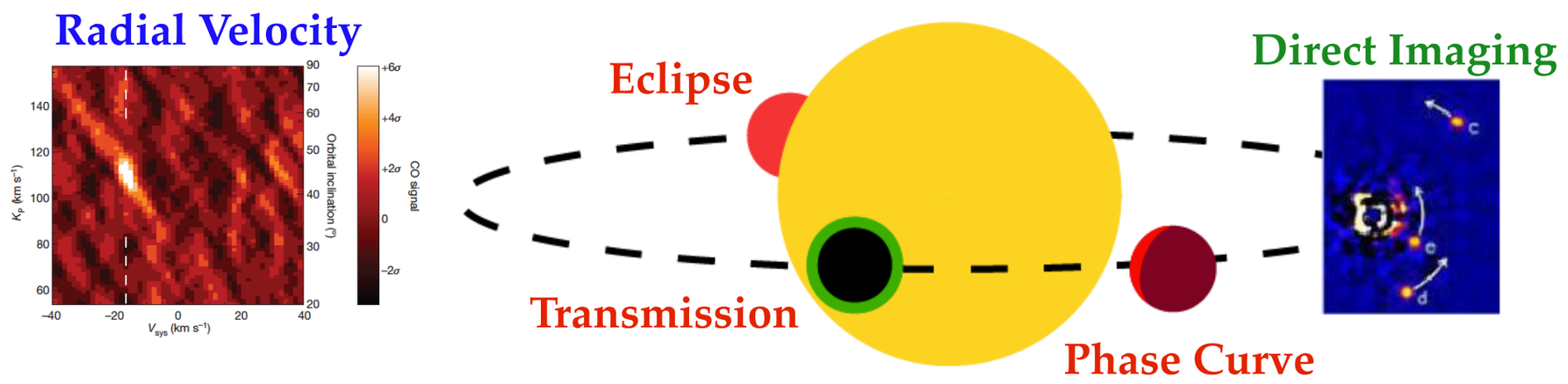
Link Between Planet Atmosphere And Its Origins

- **Metallicity enrichment in planet atmosphere**
  - expected according to core accretion planet formation theory
  - first noted in Solar system giant planets
  - exoplanets generally consistent with this trend



Wakeford+(2017); Kreidberg+(2014a,b); Fraine+(2014); Line+(2016) etc.

Characterization Of Exoplanet Atmospheres

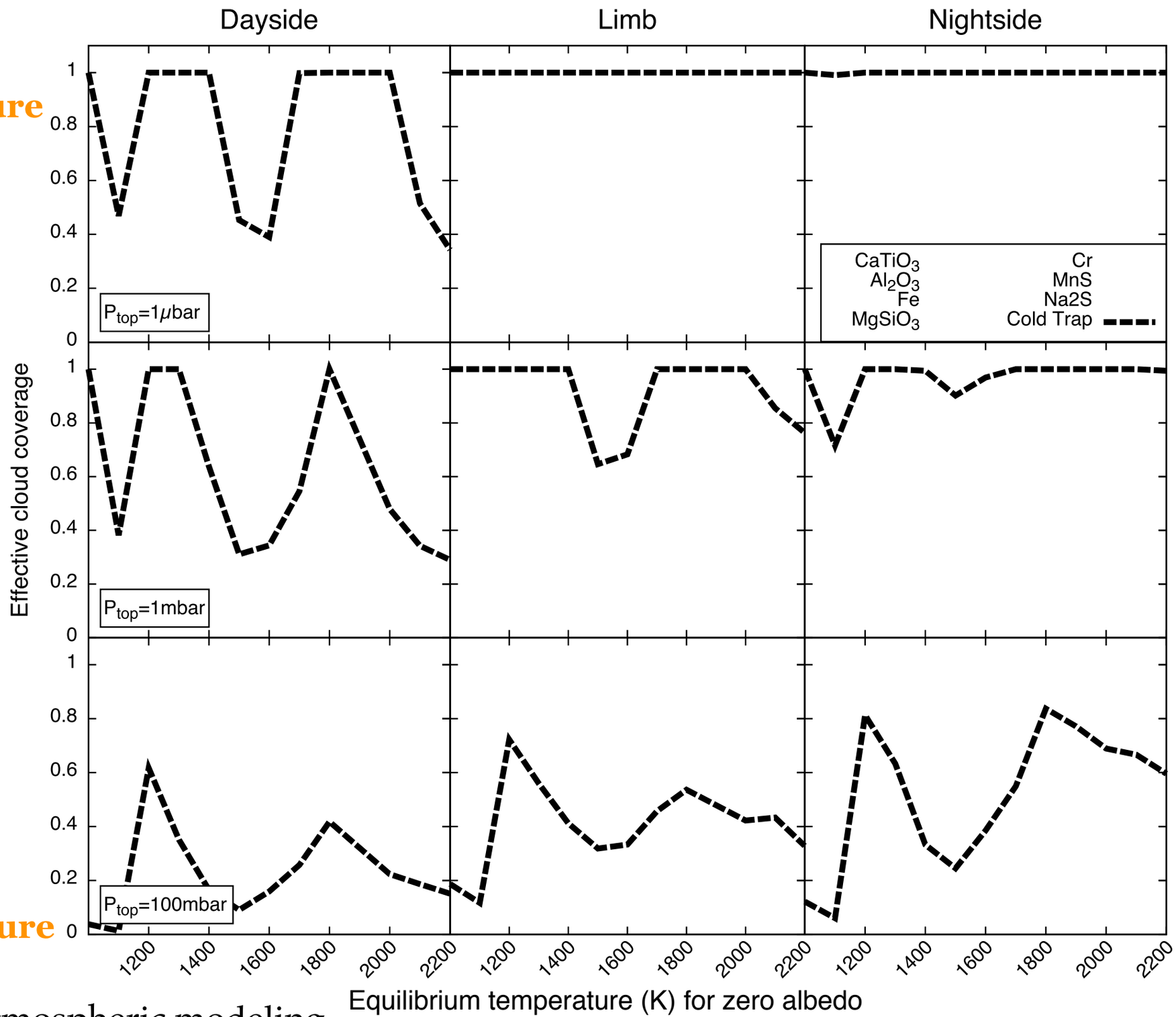


	Direct imaging	Transit	Radial velocity
Planets	Wide separated	Close-in	Close-in
Target brightness	bright	bright	super bright
Planet mass	Yes	Yes	Yes
Planets radius	No	Yes	No
Atmospheric compositions	Yes	Yes	Yes
Clouds/hazes	Yes	Yes	No
Thermal profile	Temperature	Yes	No
Strato-/Thermo-/Exo-spheres	No	S./T./E.	S.
Escape	No	Yes	No
Dynamics/Winds	D.	D./W.	D./W.
Photochemistry	Chemistry	Yes	No

Charbonneau et al. (2002, 2005); Deming et al. (2005); Marois et al. (2008); Snellen et al. (2008); Brogi et al. (2012); Crossfield (2015); etc.

Clouds And Hazes Are Ubiquitous

Lower pressure



Higher pressure

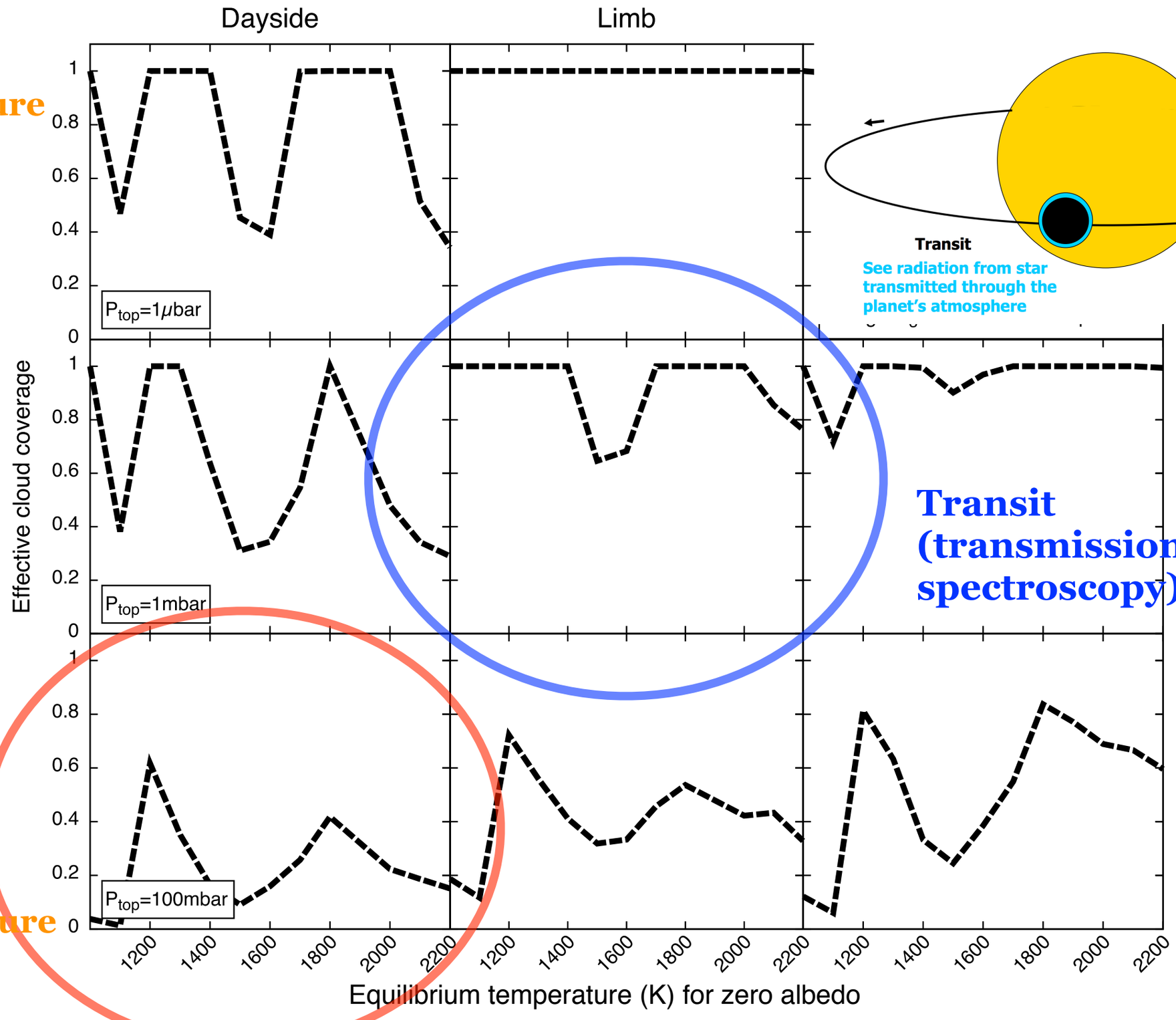
- 3D GCM atmospheric modeling with cold trapping of condensates

Parmentier+ (2016)

Clouds And Hazes Are Ubiquitous

Lower pressure

Higher pressure



Secondary Eclipse

See thermal radiation and reflected light from planet disappear and reappear

Transit

See radiation from star transmitted through the planet's atmosphere

Transit (transmission spectroscopy)

Secondary eclipse (emission spectroscopy)

Parmentier+ (2016)

WASP-43b As A Target Of EMIR Science Verification

- **Host star:**
  - K7V
  - $T_{\rm eff}$: 4400 K
  - $M_{\rm star}$: 0.72 $M_{\rm sun}$
  - $R_{\rm star}$: 0.67 $R_{\rm sun}$

- **Planet:**
  - $T_{\rm eq}$: 1440 K
  - $M_{\rm p}$: 2.03 $M_{\rm Jup}$
  - $R_{\rm p}$: 1.04 $R_{\rm Jup}$
  - log $g_{\rm p}$: 3.67
  - Period: 19.5 hrs

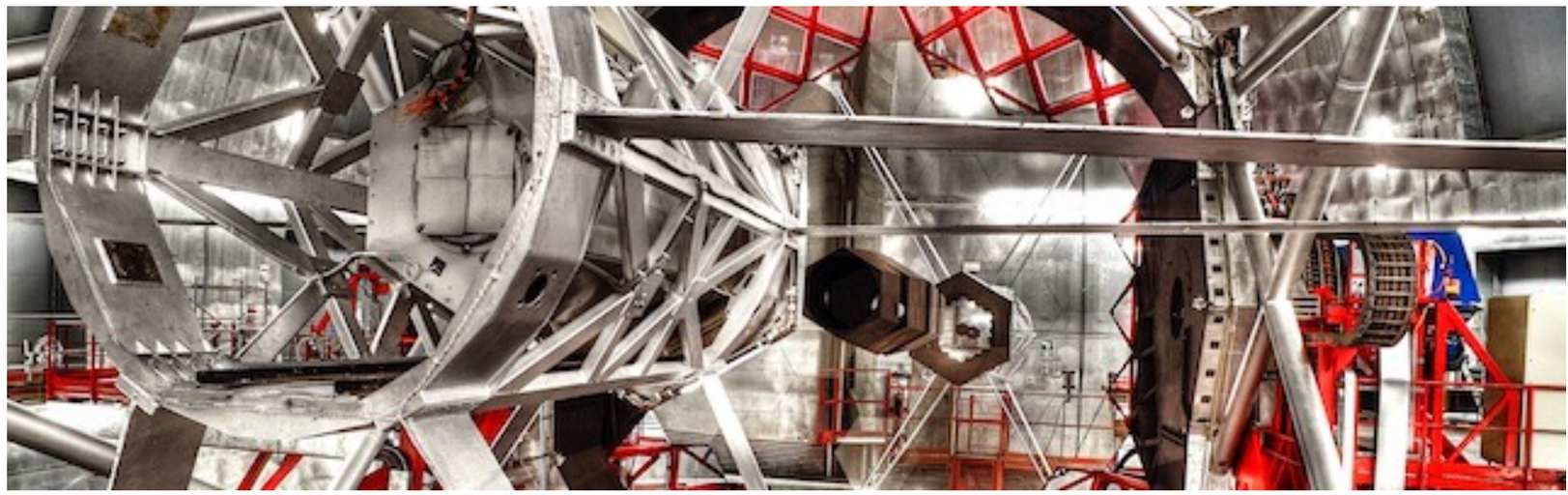
- **Science goals:**
  - to search for thermal emission from dayside atmosphere
  - to constrain abundances of CH_4 and CO
  - to complete the temperature-pressure profile
  - ideal target for a science verification

Ground-based secondary-eclipse observations are very challenging.

Only two succeed in spectroscopy:

- *Magellan/MMIRS on WASP-19b*
  - *Bean et al. (2013)*

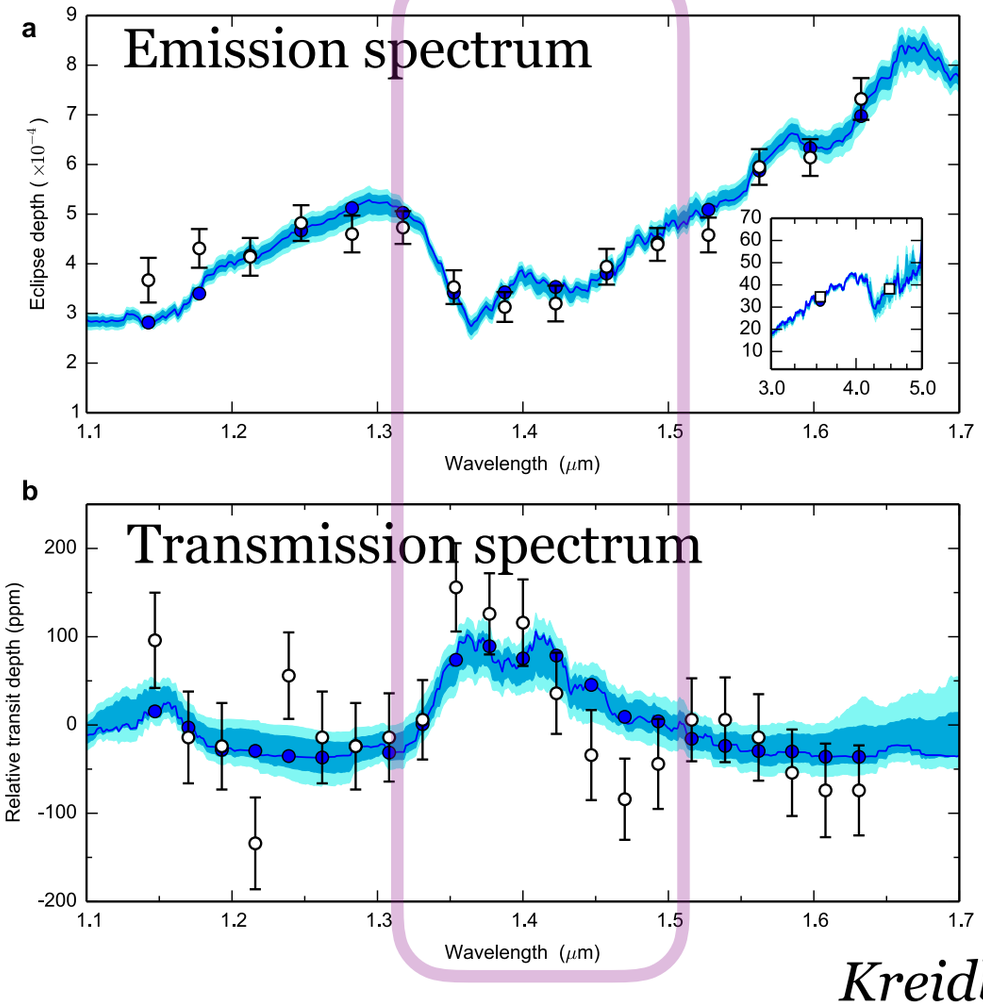
- *LBT/LUCI on KELT-1b*
  - *Beatty et al. (2017)*



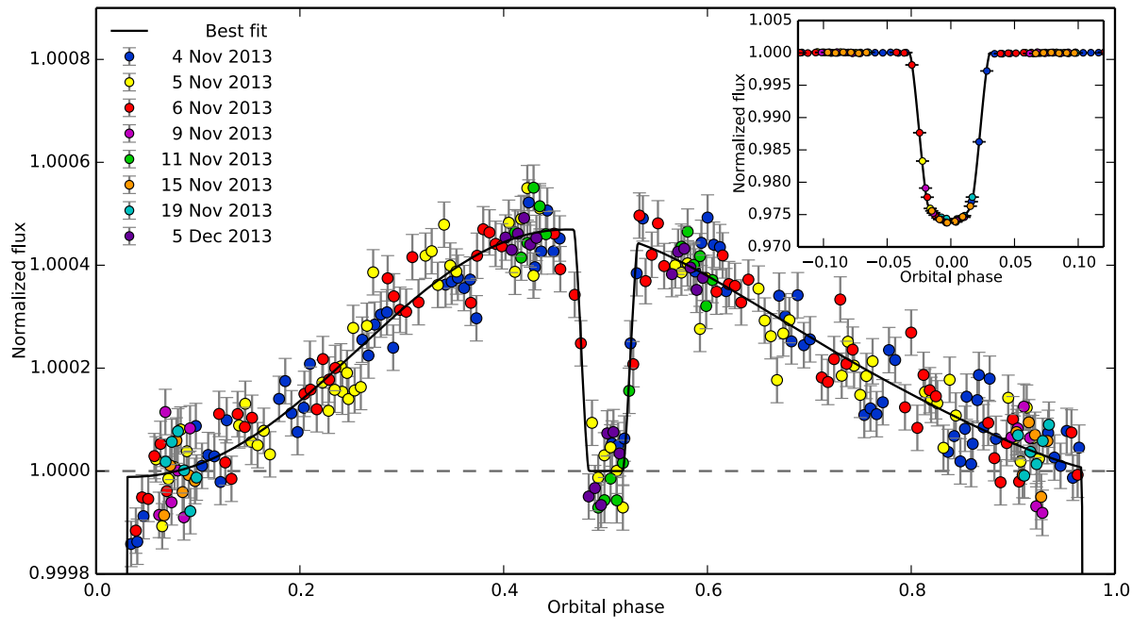
WASP-43b: The Most Extensively Studied Hot Jupiter

- ***HST***:
  - WFC3 1.1-1.7 microns spectroscopy
  - 98 hrs (61 *HST* orbits)
- ***Spitzer***:
  - [3.6] and [4.5] broadband photometry
  - 88 hrs

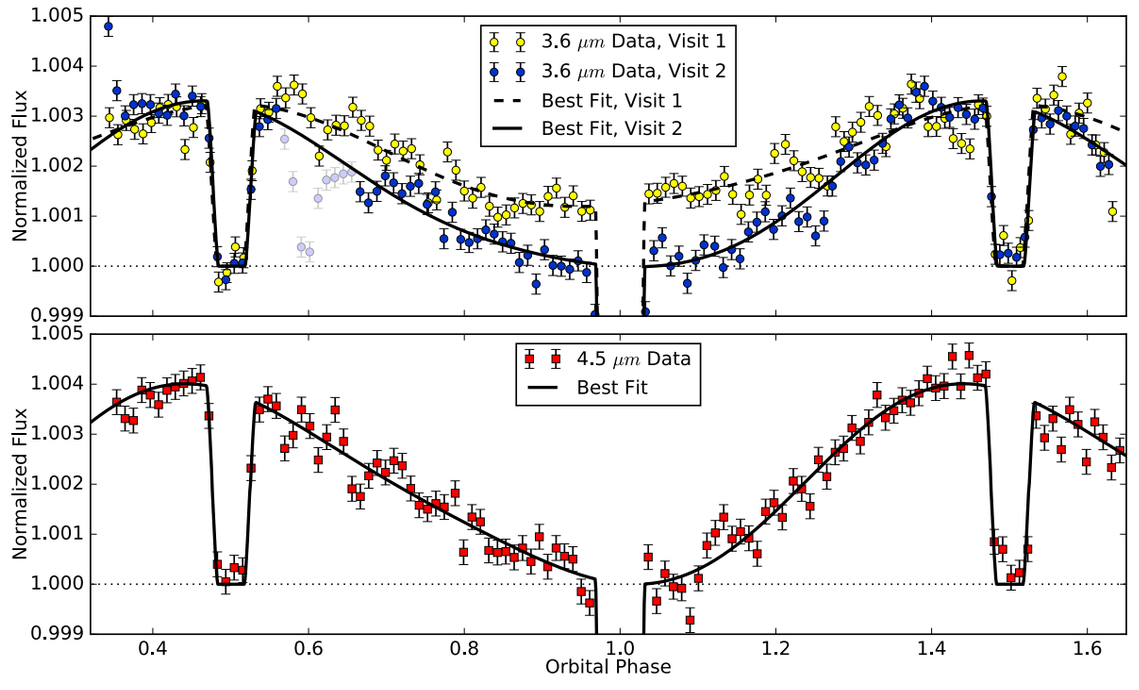
water detection



HST/WFC3 phase curve

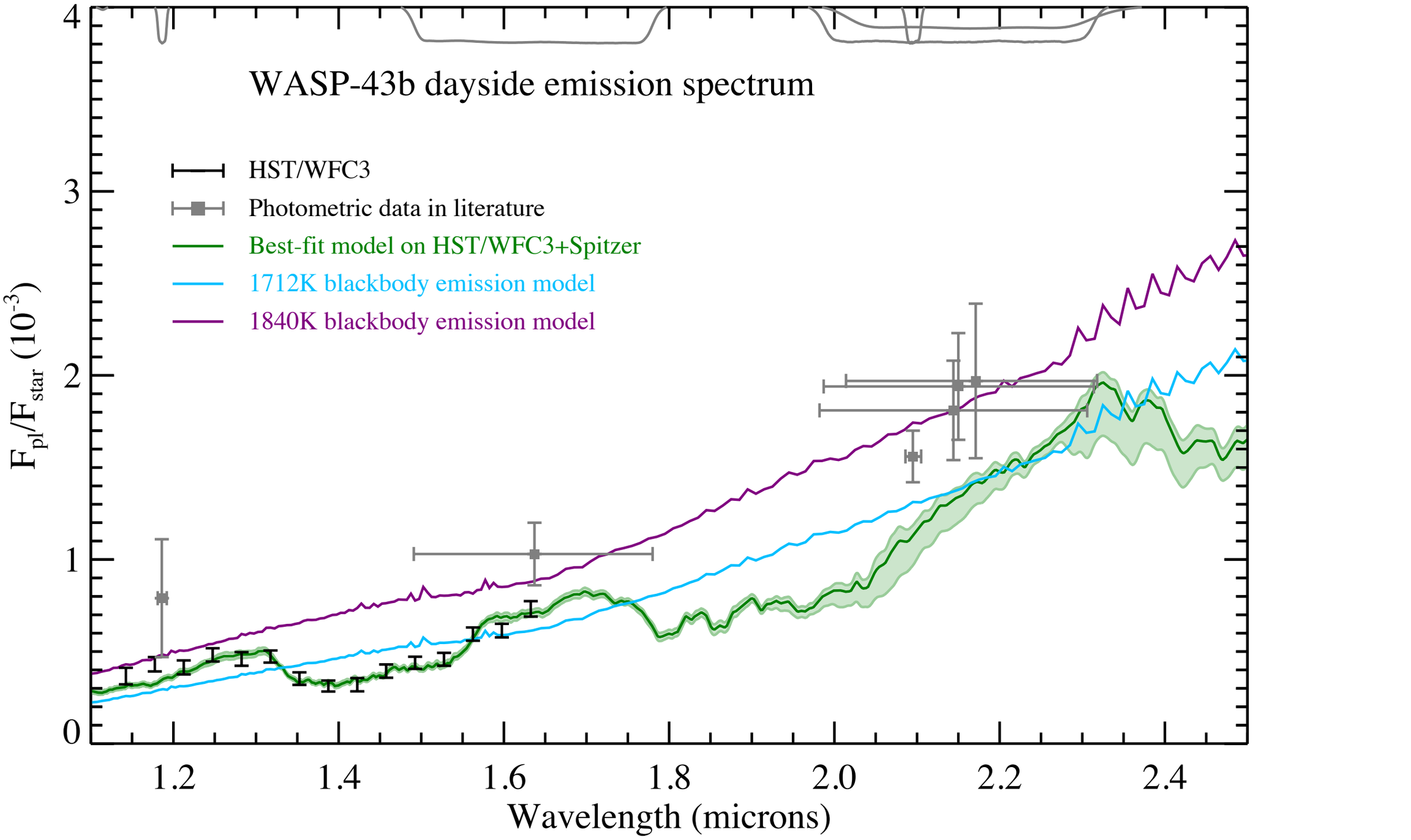


Spitzer [3.6]+[4.5] phase curve



Kreidberg+(2014); Stevenson+(2014,2016); Blecic+(2014)

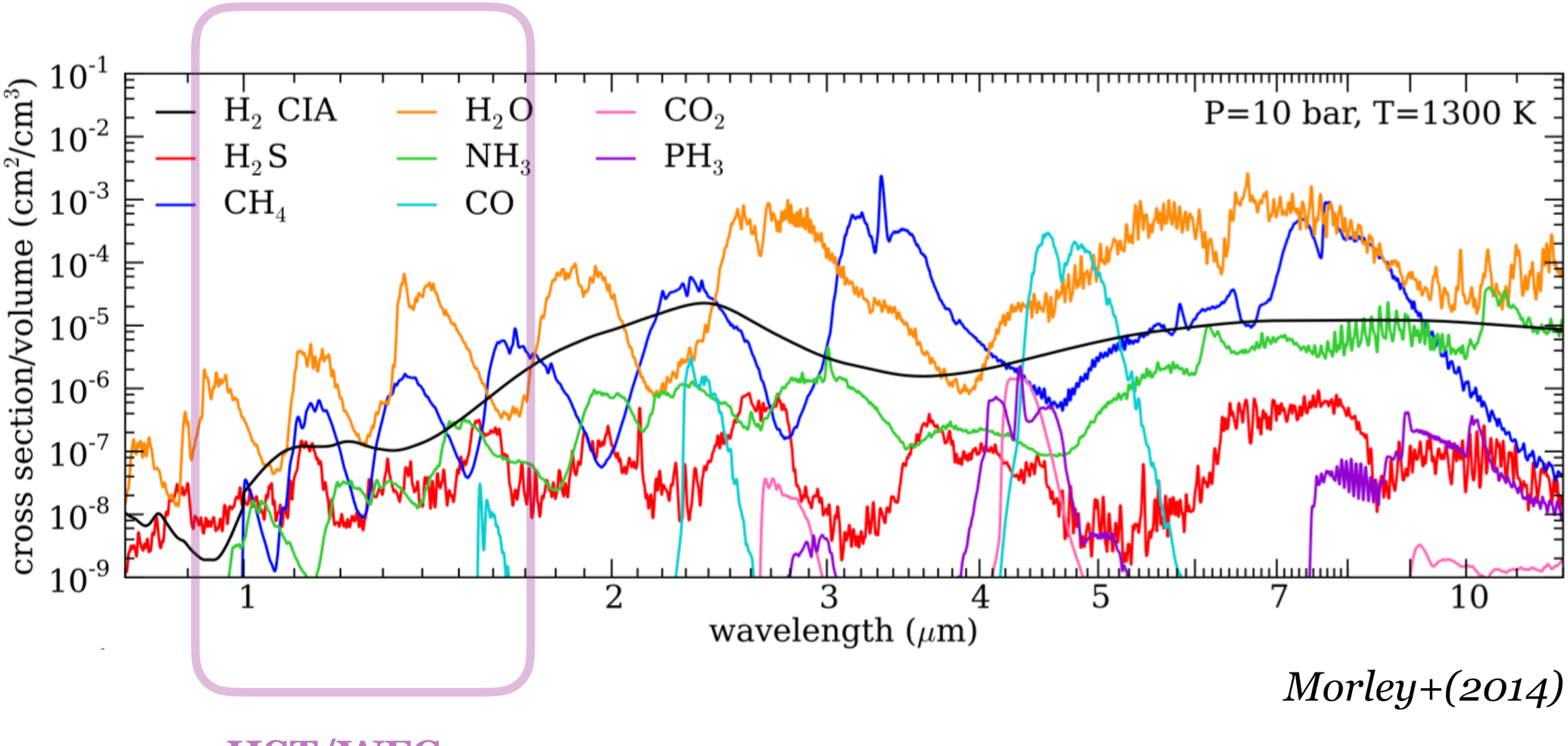
Past Ground-based Secondary-eclipse Observations



- **Consistent with an isothermal atmosphere**
- **But all inconsistent with *HST*/WFC3!**

Gillon+(2012); Wang+(2013); Chen+(2014); Zhou+(2014); Kreidberg+(2014)

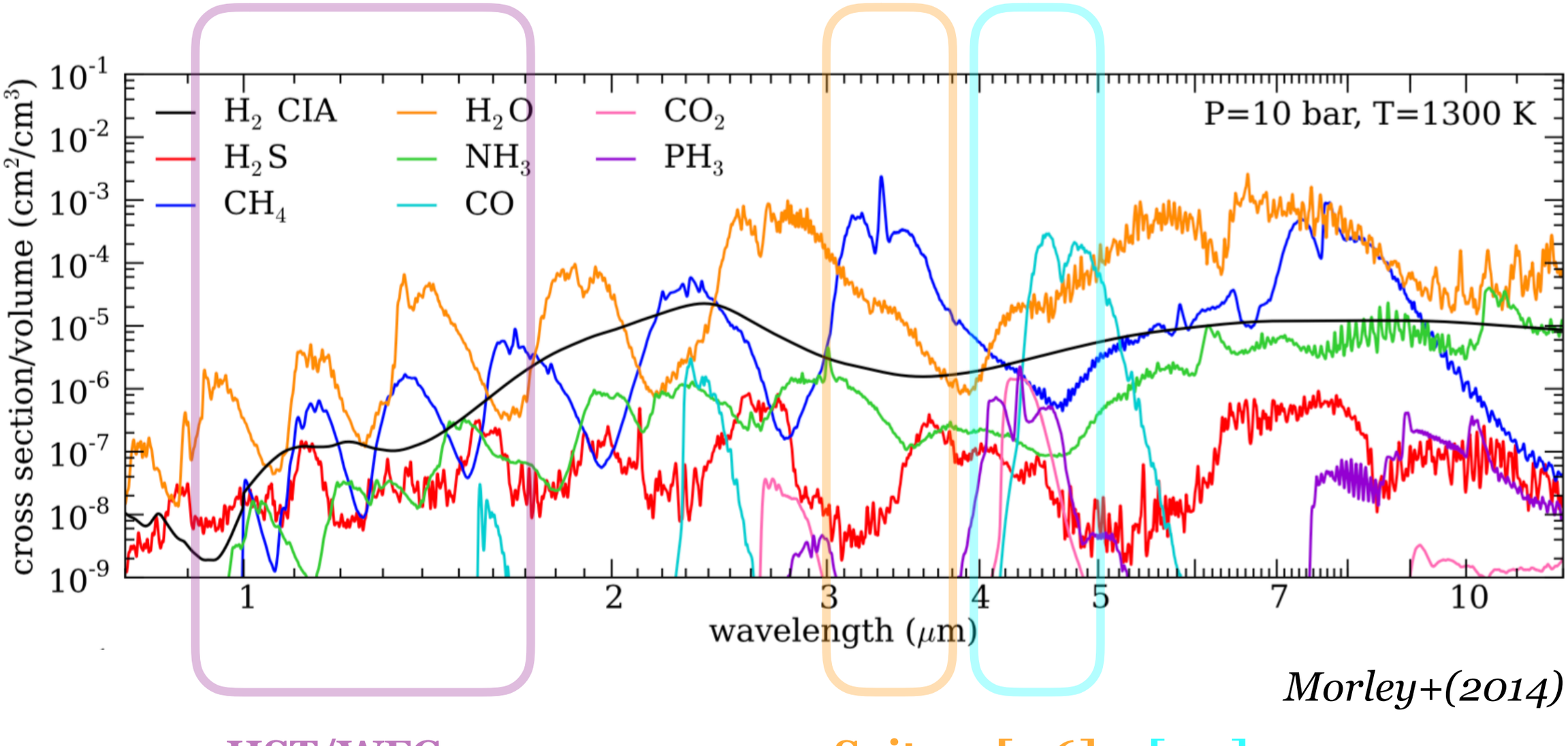
EMIR Can Fill The Gap In The K-band



Morley+(2014)

- ***HST*/WFC3 is dominant by H2O absorption, cannot constrain other molecules**

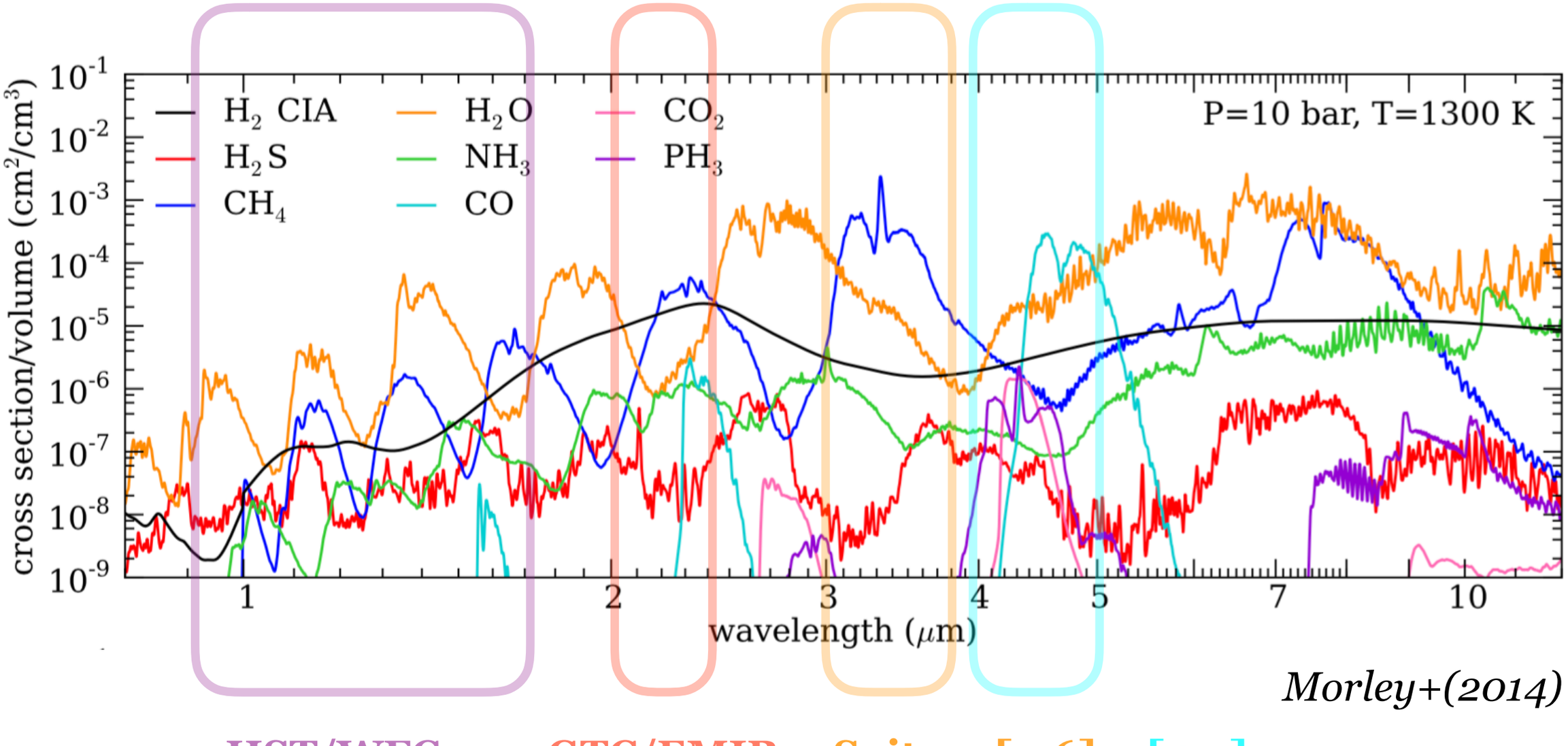
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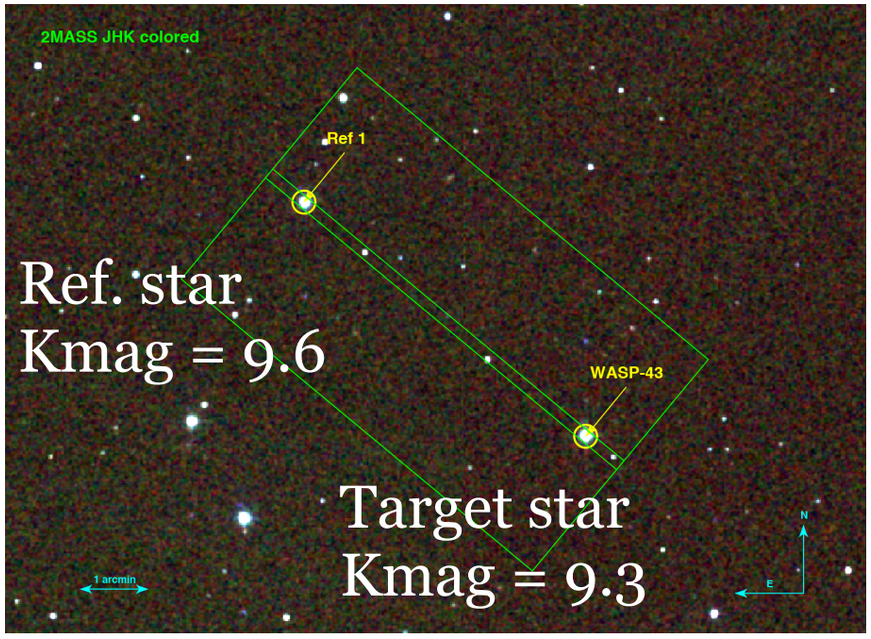
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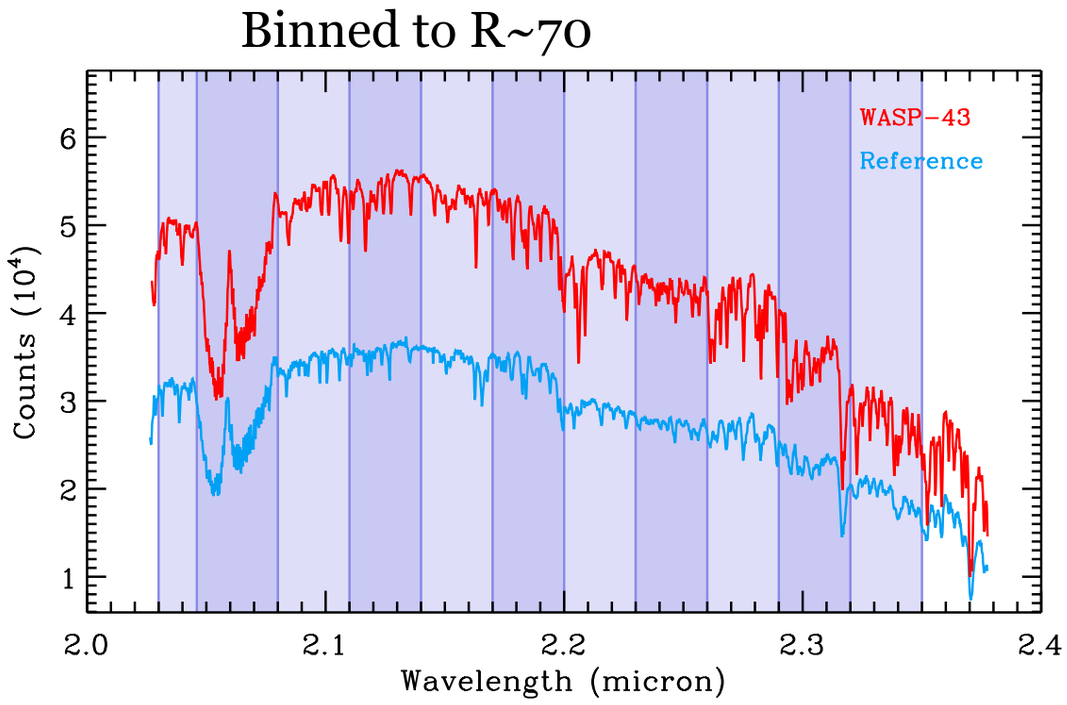


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EMIR Observing Summary

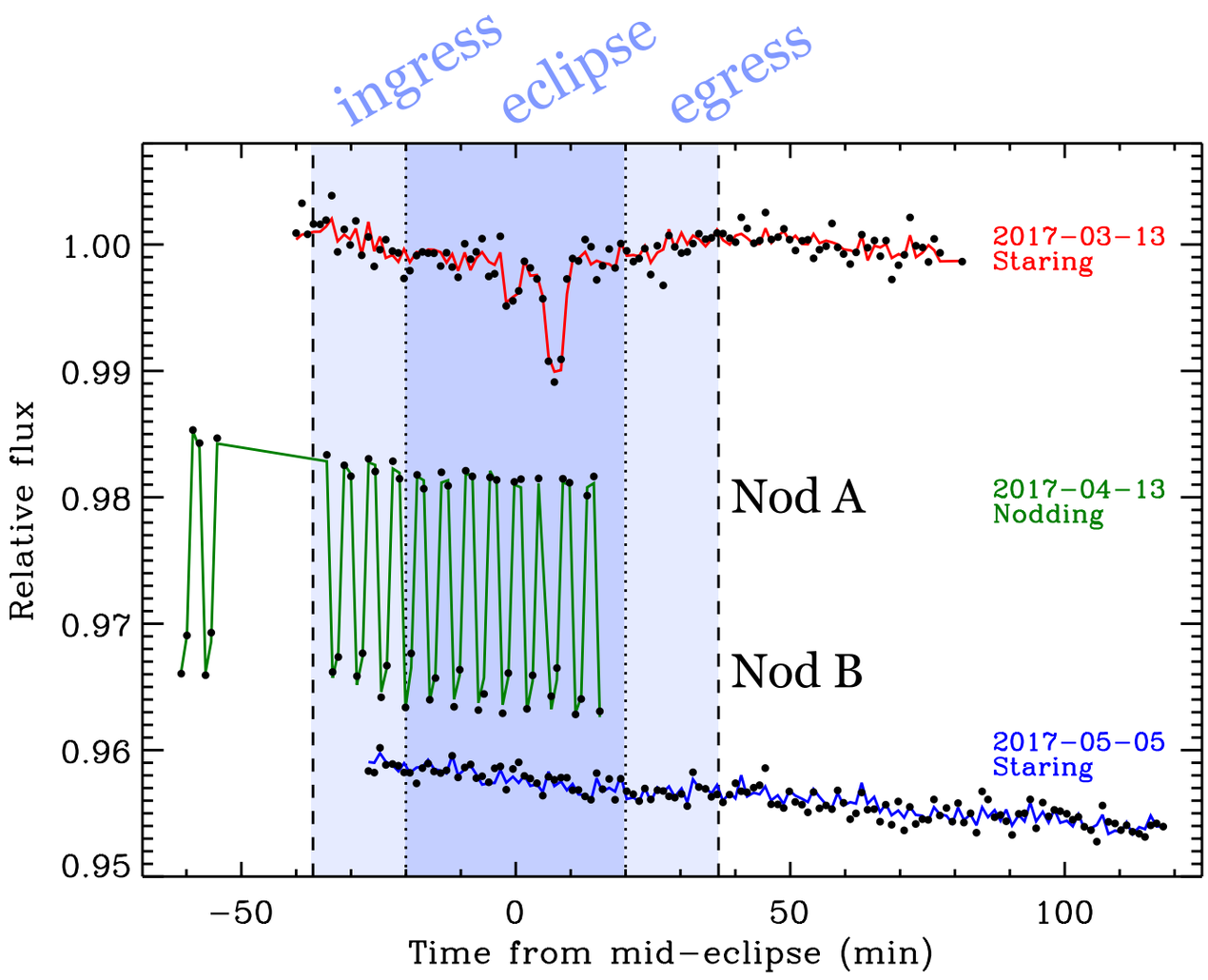




	Eclipse 1	Eclipse 2	Eclipse 3
Night	2017-03-13	2017-04-13	2017-05-05
Observing mode	Stare	Nod	Stare+Nod
Slit width	10“	10“	10“
Read mode	RAMP-30, CDS-10, **RAMP-60**, CDS-15	**RAMP-60**	**RAMP-60**
Transit coverage	Full (little pre-transit)	Partial	Partial
Usable science time	2.0 hrs	0.9 hrs	2.4 hrs
Comments	Highly variable seeing	Stopped due to thick clouds	Started in twilight

Chen+ (2017, in prep)

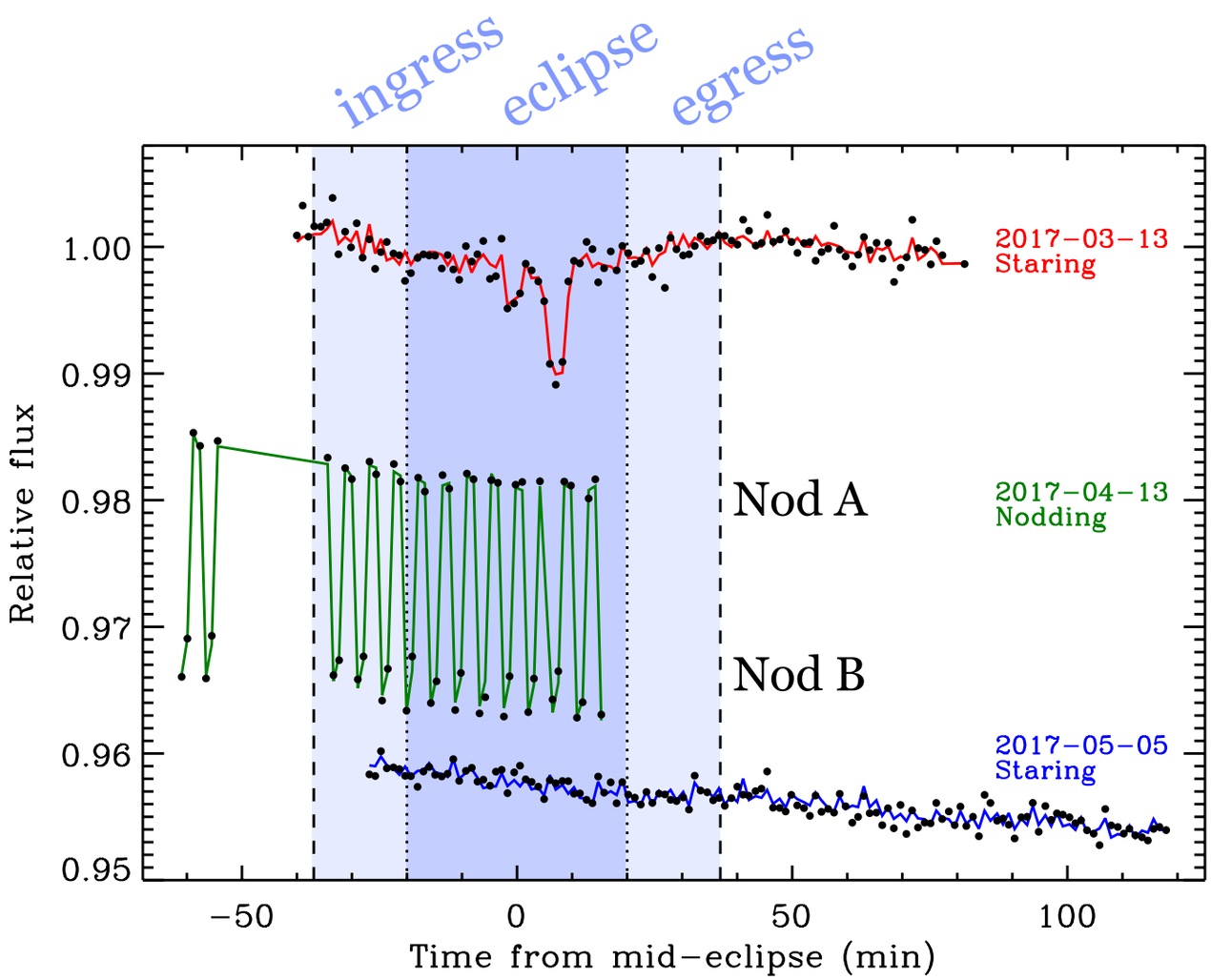
WASP-43b: White-color Light Curves



- **Major systematics:**
  - Ramp effect
  - Pixel dependency
    - seeing variation
    - position shifts
  - CSU background
  - Little pre-transit constraint

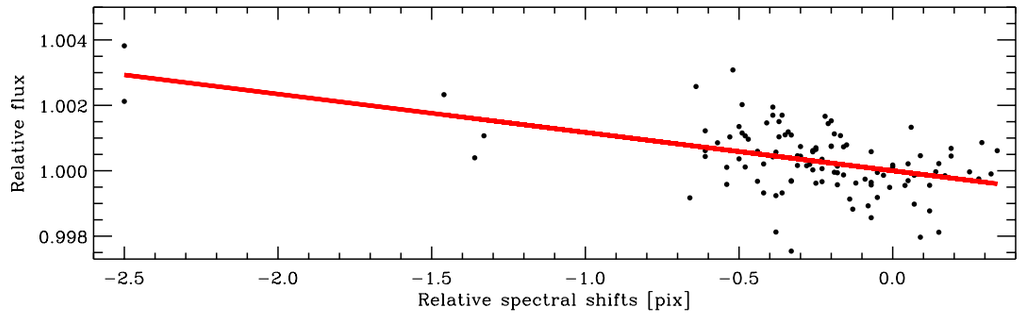
Chen+ (2017, in prep)

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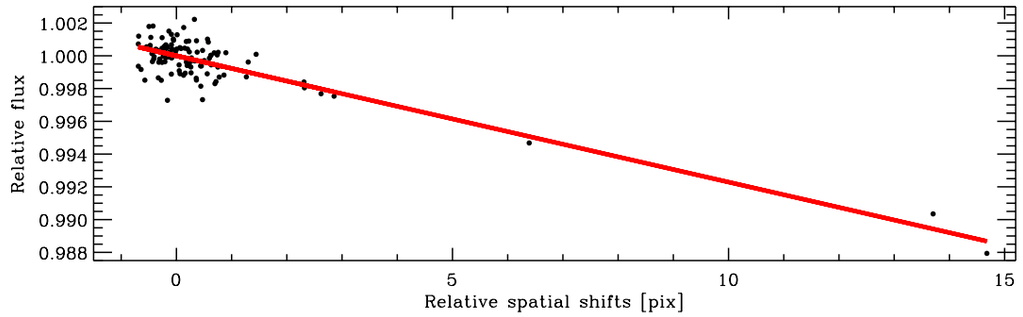


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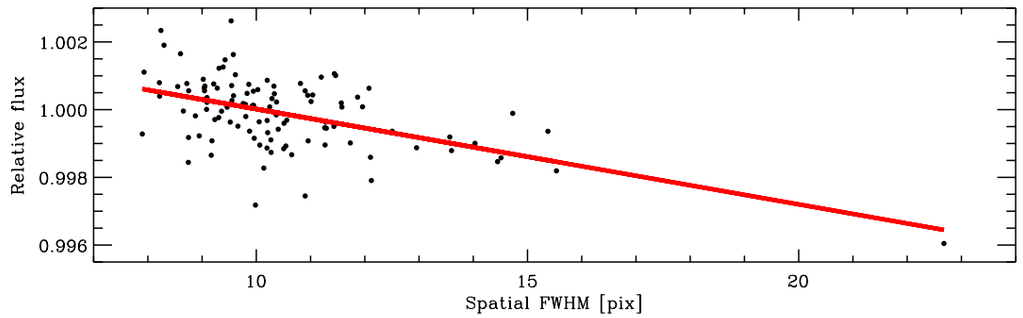
Flux v.s. X shifts



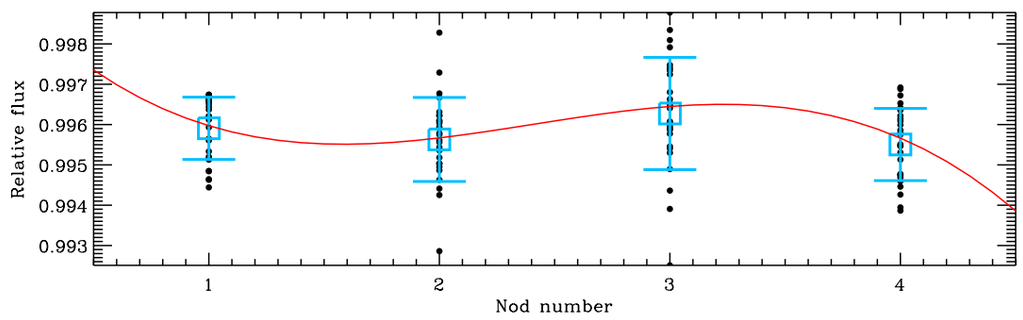
Flux v.s. Y shifts



Flux v.s. FWHM



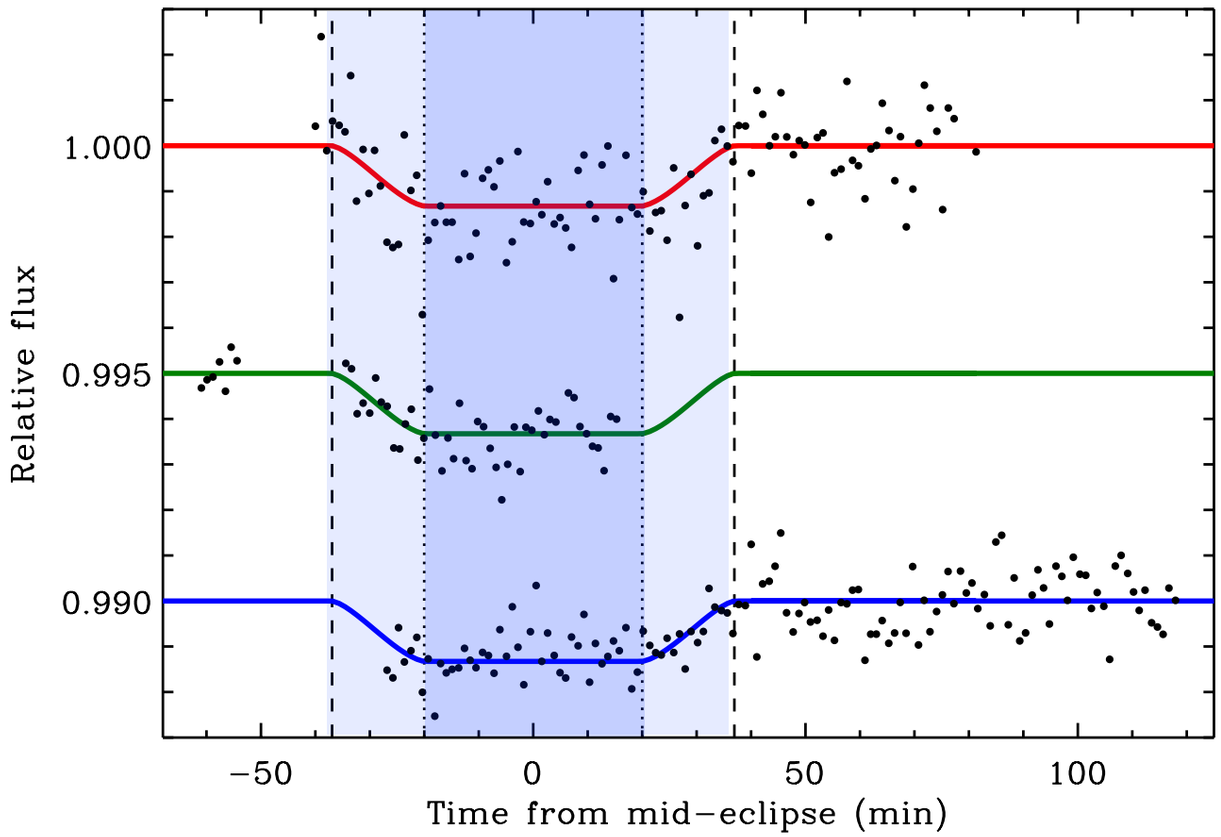
Flux v.s. Nod number

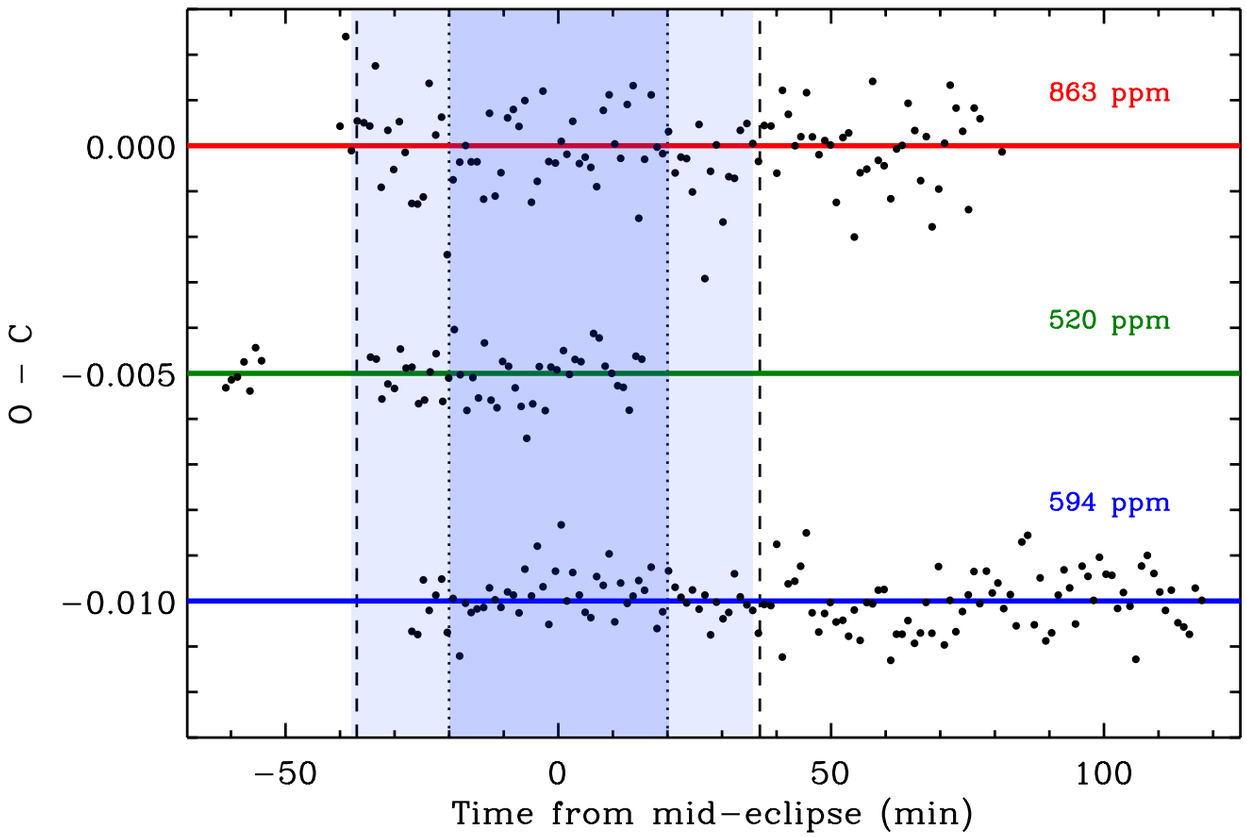


Chen+ (2017, in prep)

WASP-43b: Systematics Corrected

- **Light curves of individual nights and their best-fit residuals**

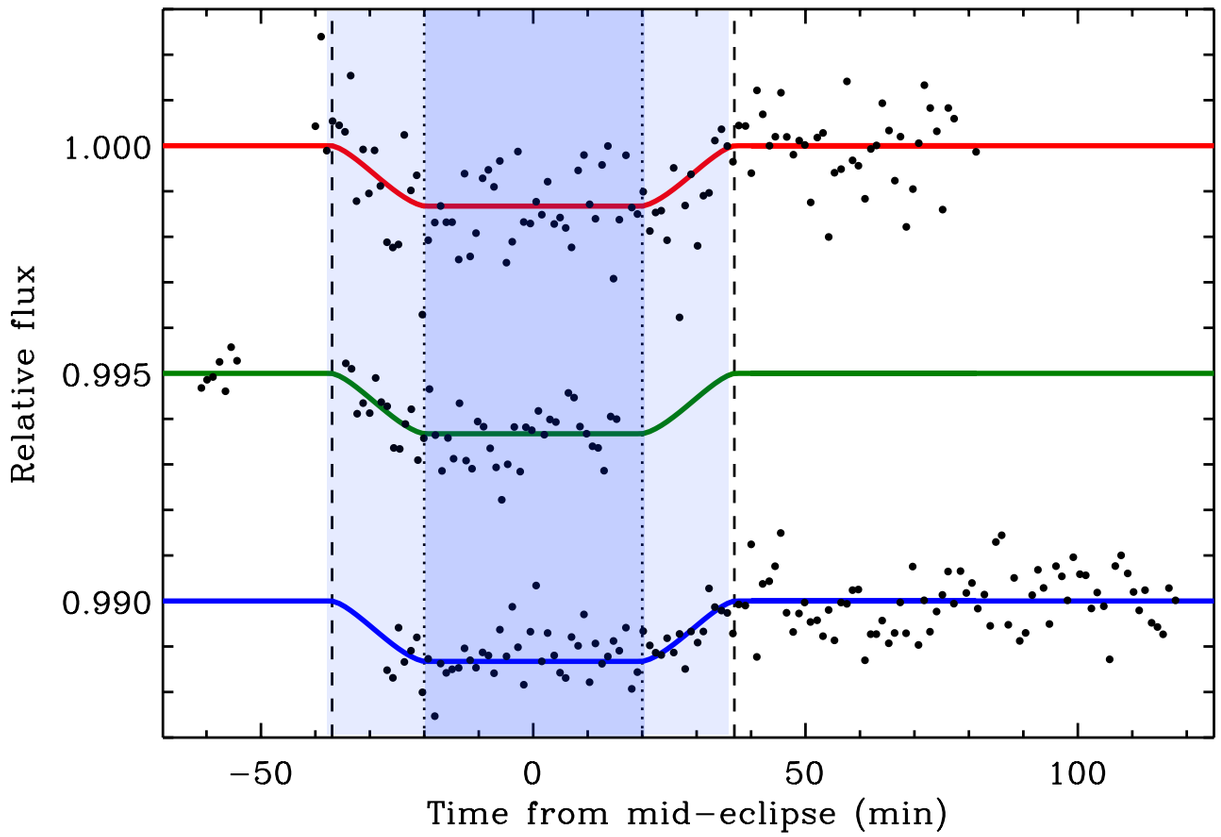


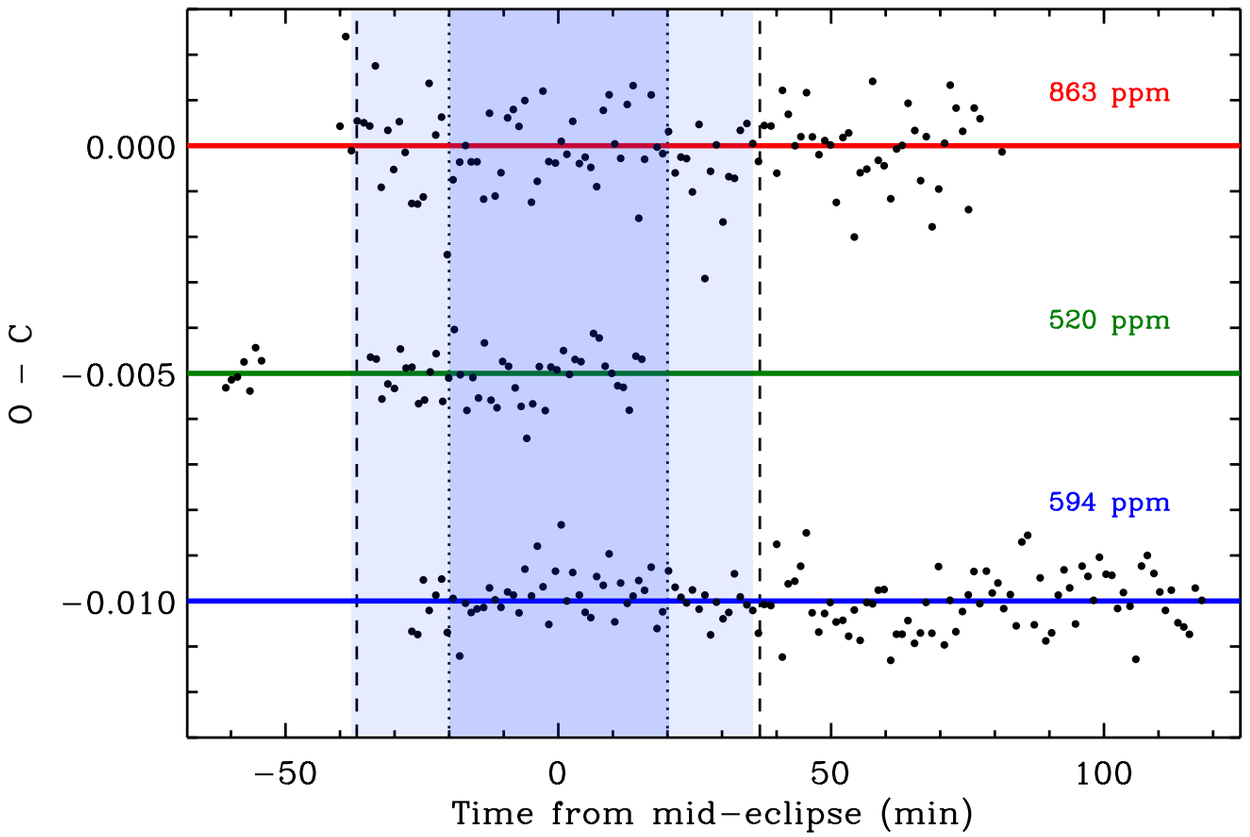


Chen+ (2017, in prep)

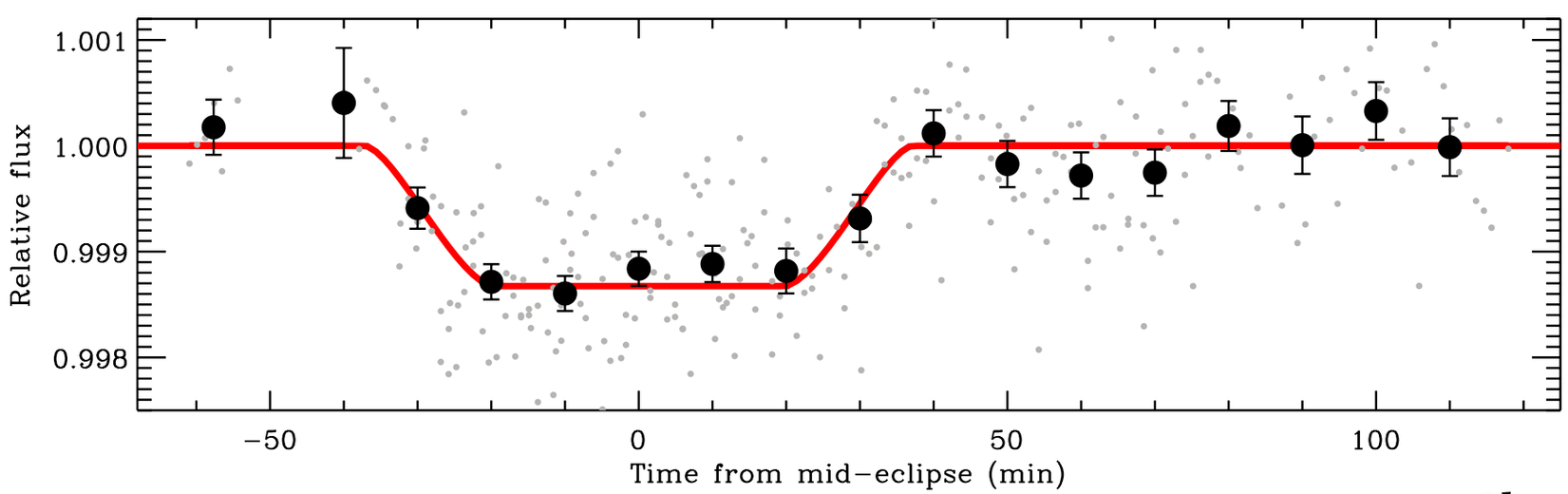
WASP-43b: Systematics Corrected

- **Light curves of individual nights and their best-fit residuals**





- **Phase-folded light curve of three nights and binned into 10 min**

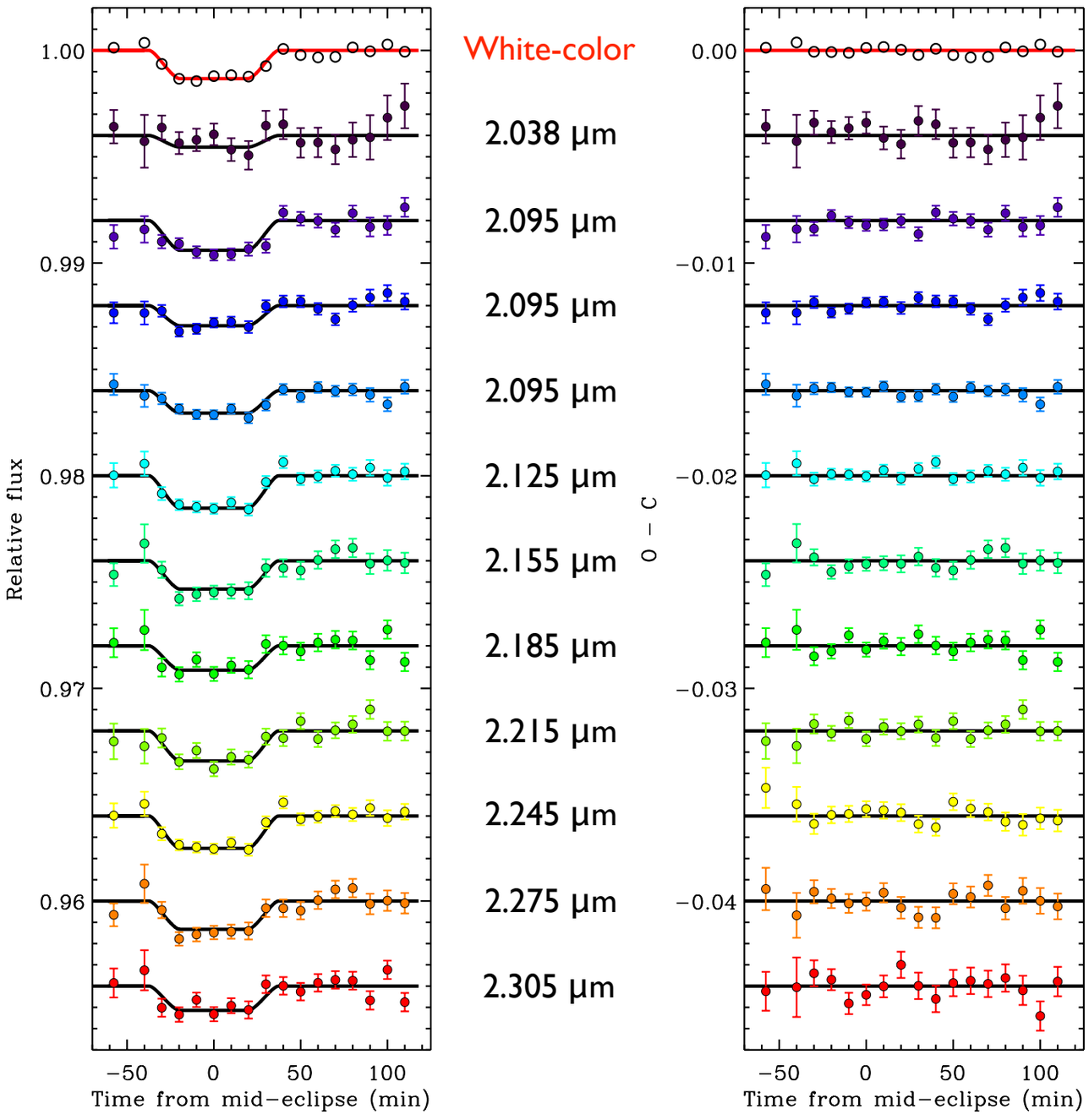


RMS
196 ppm / 10 min

Chen+ (2017, in prep)

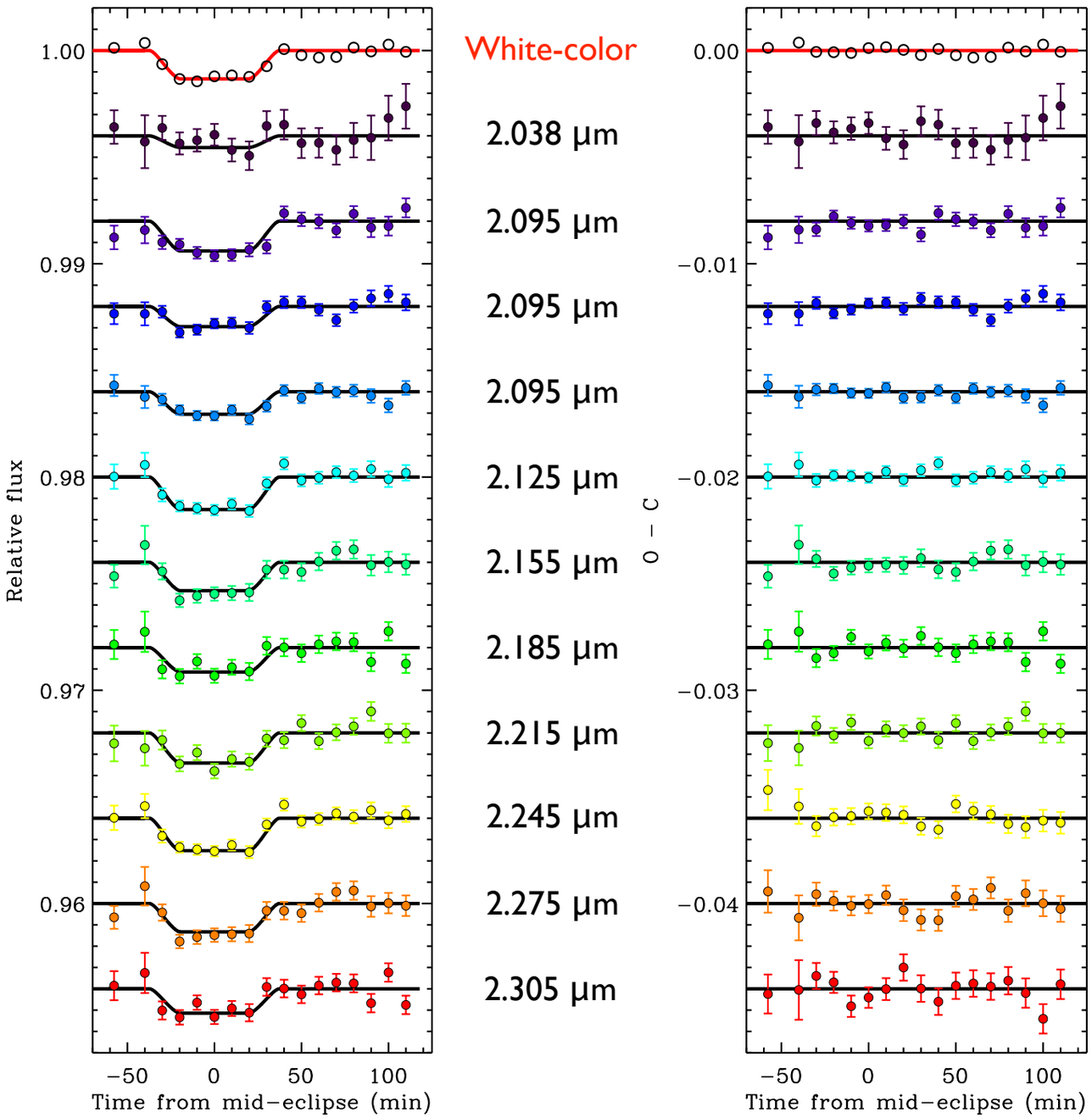
WASP-43b: Spectral Light Curves

- **GTC/EMIR (Chen+2017, in prep)**
  - 1 full + 2 partial eclipses (5.4 hrs)
  - binned in 10 min:
    - 240-450 ppm per 30nm channel

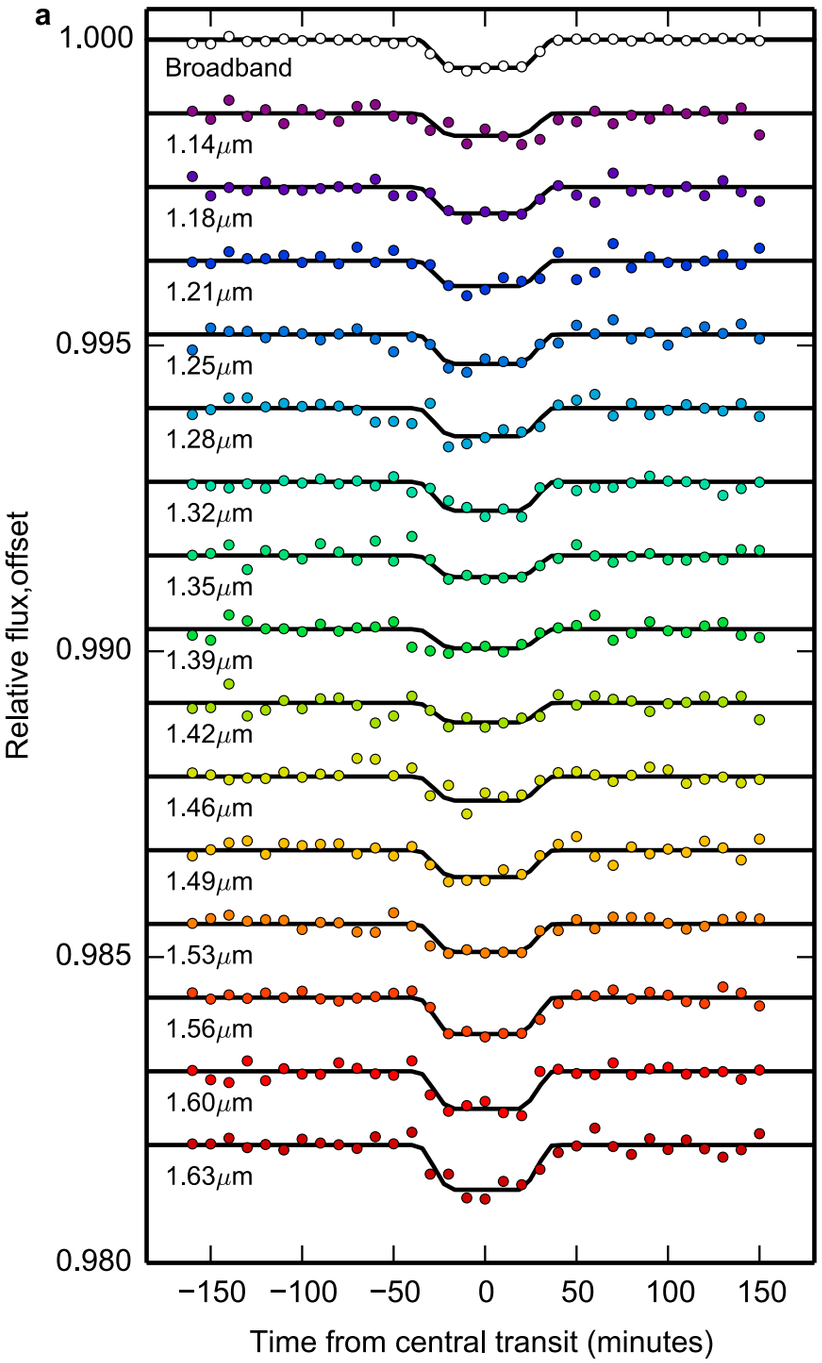


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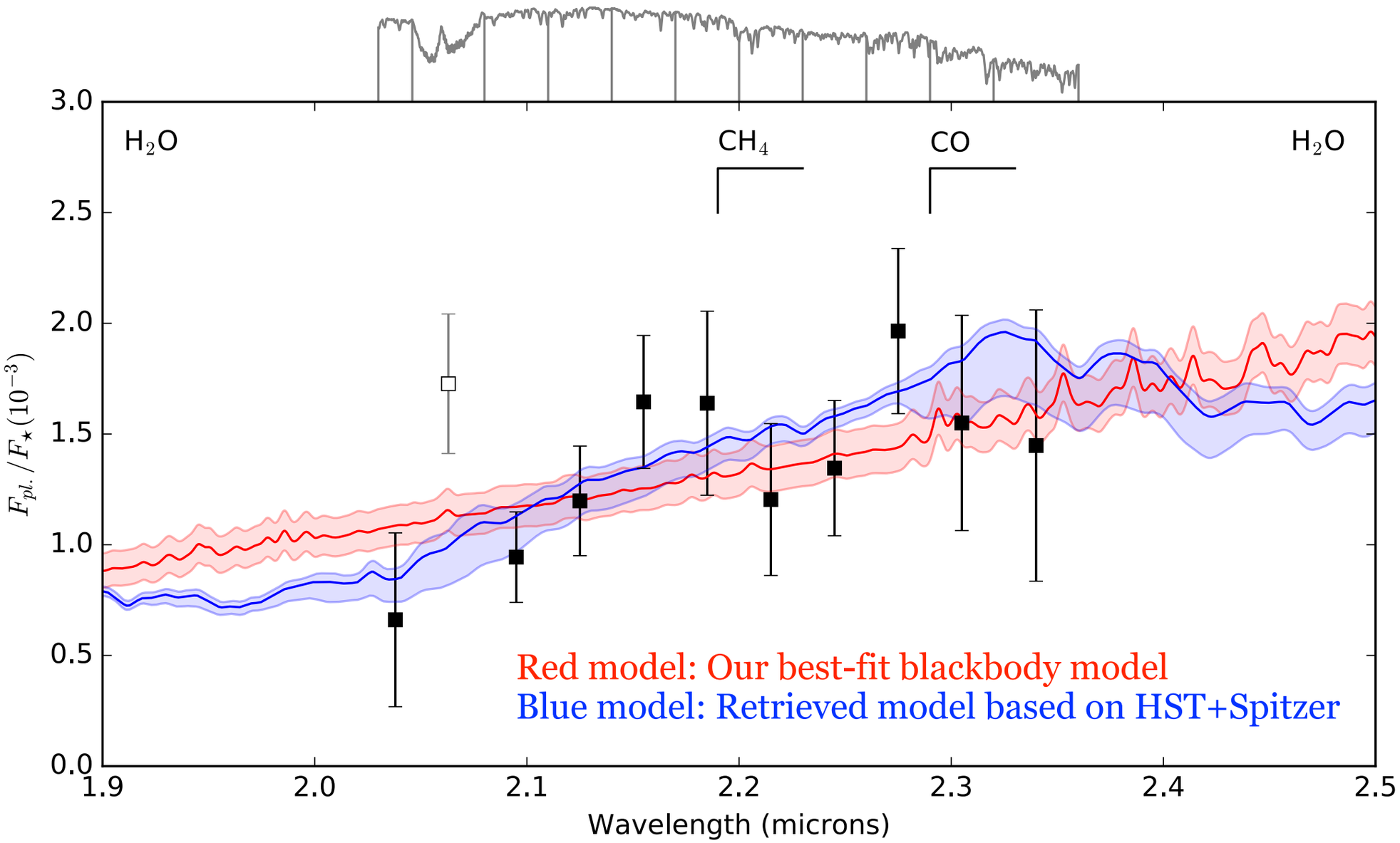


- **HST/WFC3 (Kreidberg+2014)**
  - 5 eclipses (32 hrs)
  - binned in 10 min:
    - 120 ppm per 35nm channel



WASP-43b: K-band Emission Spectrum With EMIR

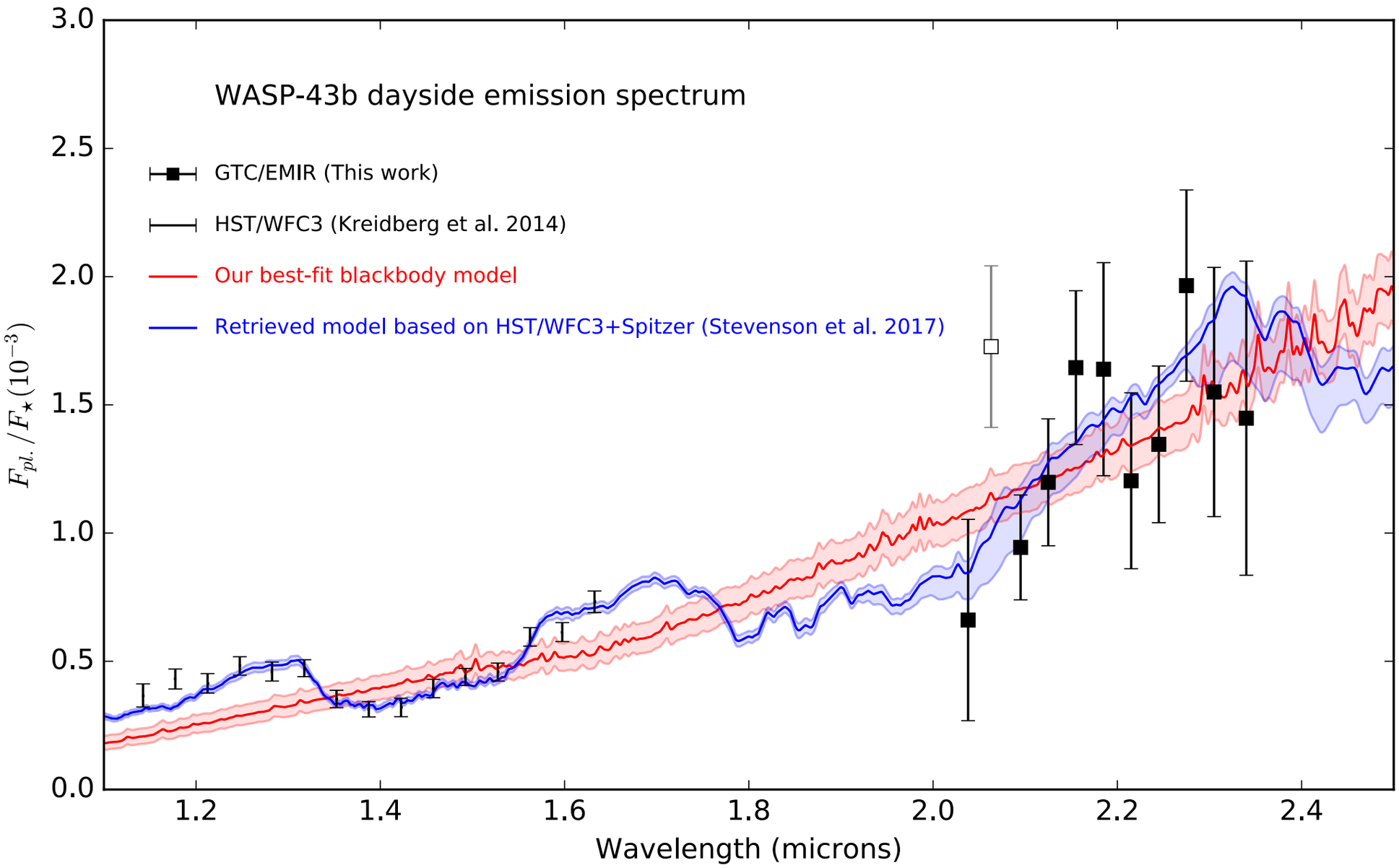
- **Results from our EMIR measurements:**
  - Thermal emission is detected at 12.6 sigma
  - K-band brightness temperature: 1668 ± 32 K
  - Tentative evidences of CH_4 and CO



Chen+ (2017, in prep)

WASP-43b: K-band Emission Spectrum With EMIR

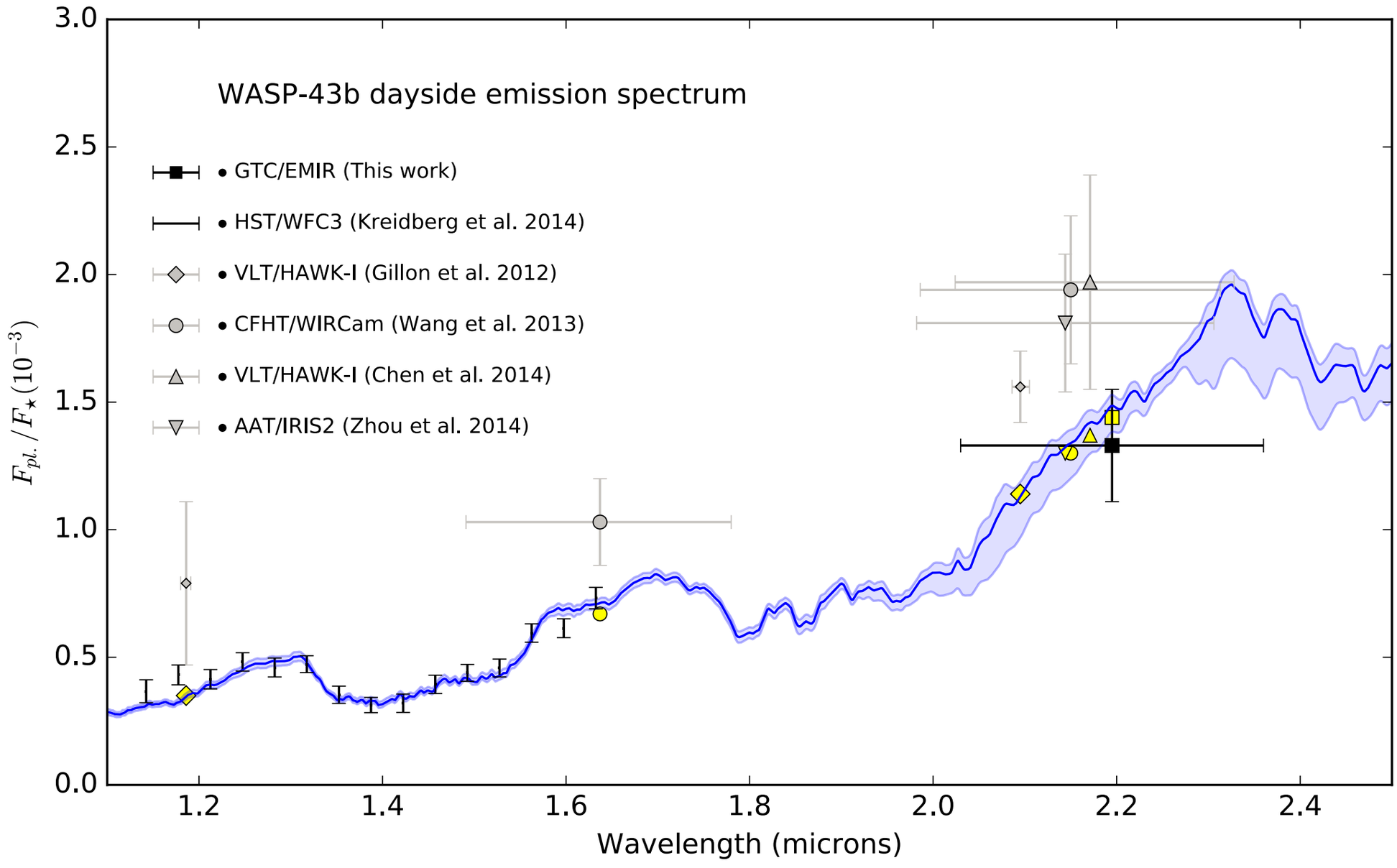
- **Consistent with *HST*/WFC3 measurements**
  - Our error bars are dominated by red noise
    - accounted by Gaussian process



Chen+ (2017, in prep)

WASP-43b: K-band Emission Spectrum With EMIR

- **Compared to past ground-based secondary-eclipse observations:**
  - Our results are physically reasonable
  - Literature photometric results are all biased to higher values
    - their error bars are highly likely underestimated



Chen+ (2017, in prep)

CONCLUSIONS

- GTC/EMIR is able to do precision spectrophotometry!
  - 200 ppm /10 min in K-band
  - 240-450 ppm / 10 min in 30nm channel
  - There is still room to improve with revised observing strategy

- Results of our EMIR science verification program:
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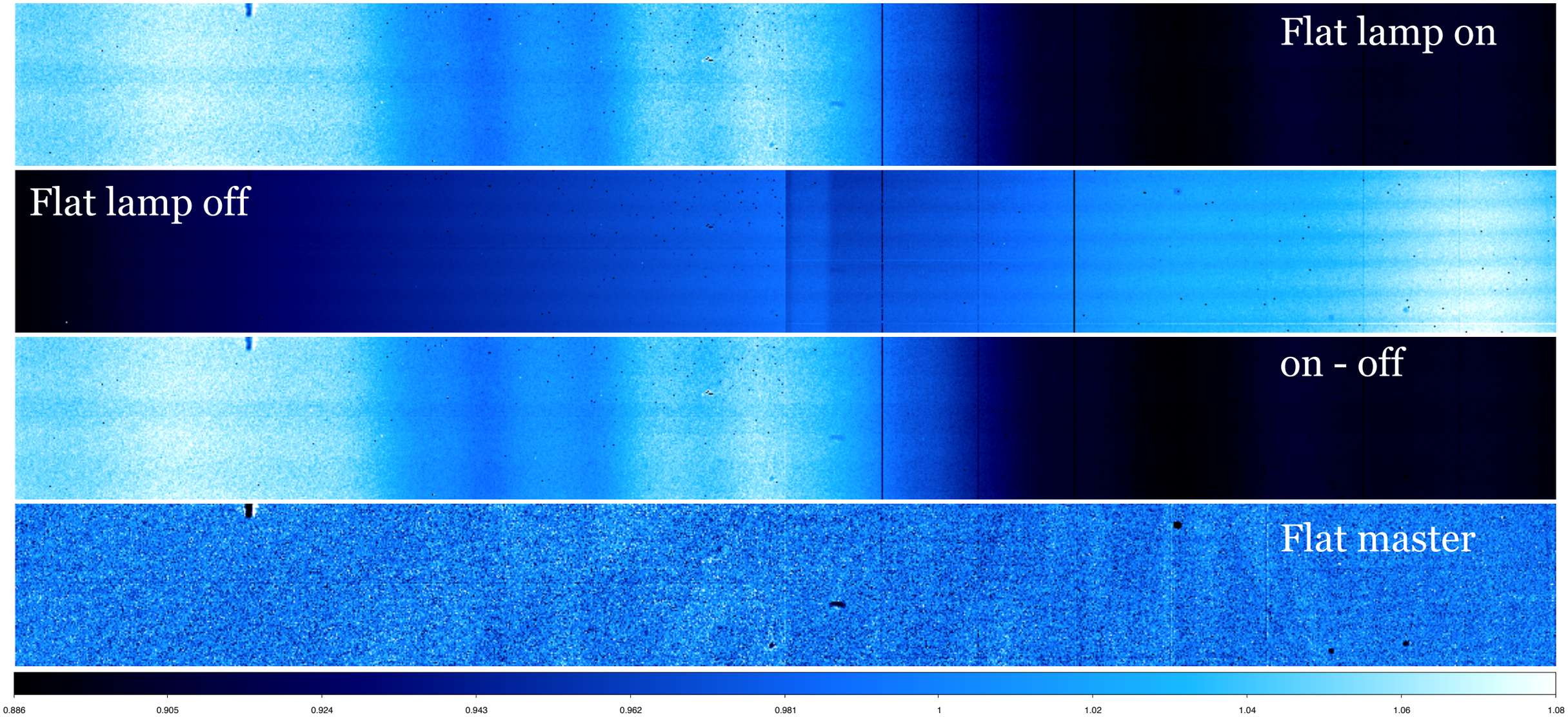
Gracias!

Thank you for your attention!

:)

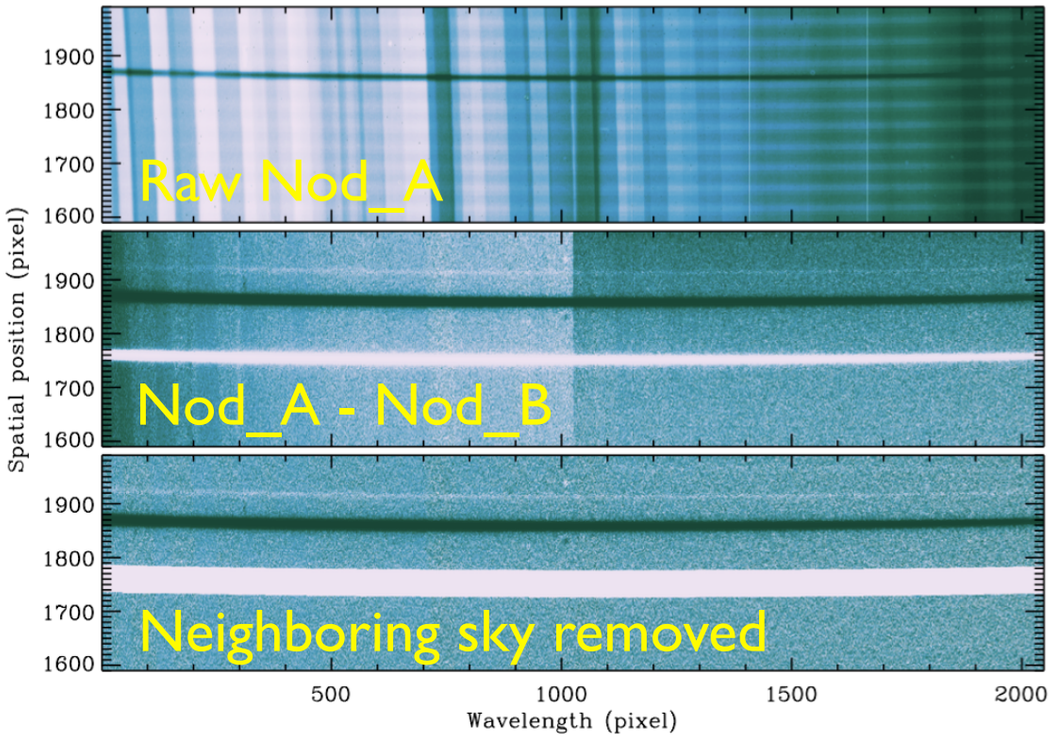
Spectral Flats

- **Spectral flats with 10″-wide slit**
  - Lamp on/off to remove CSU pattern
  - This flat correction does reduce the pixel-to-pixel variation

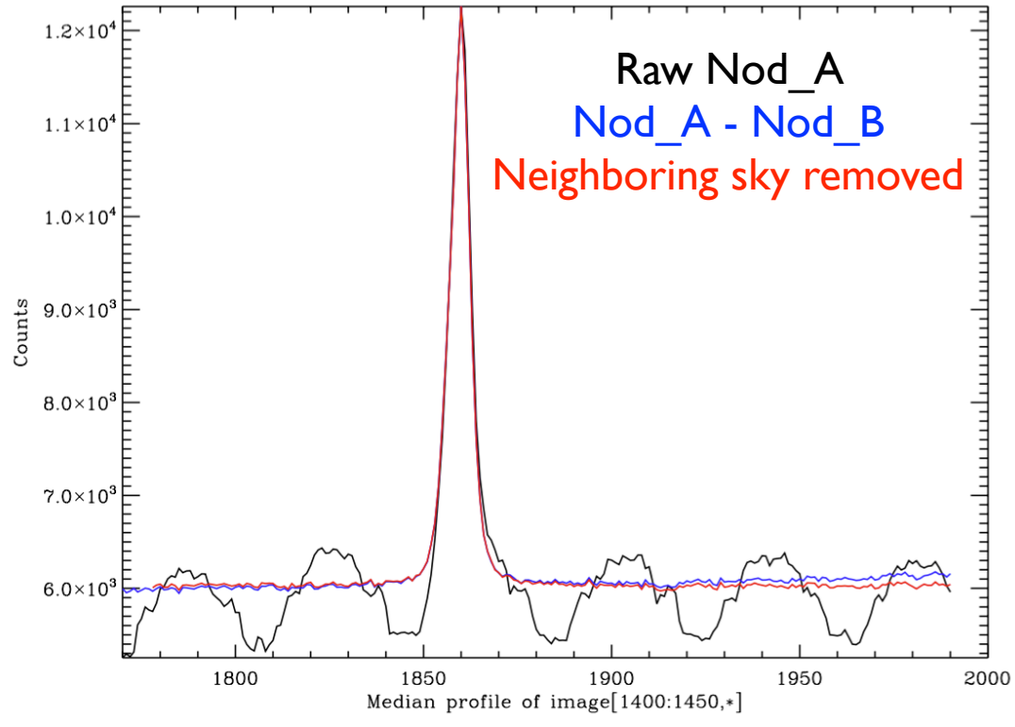


CSU BACKGROUND PATTERNS

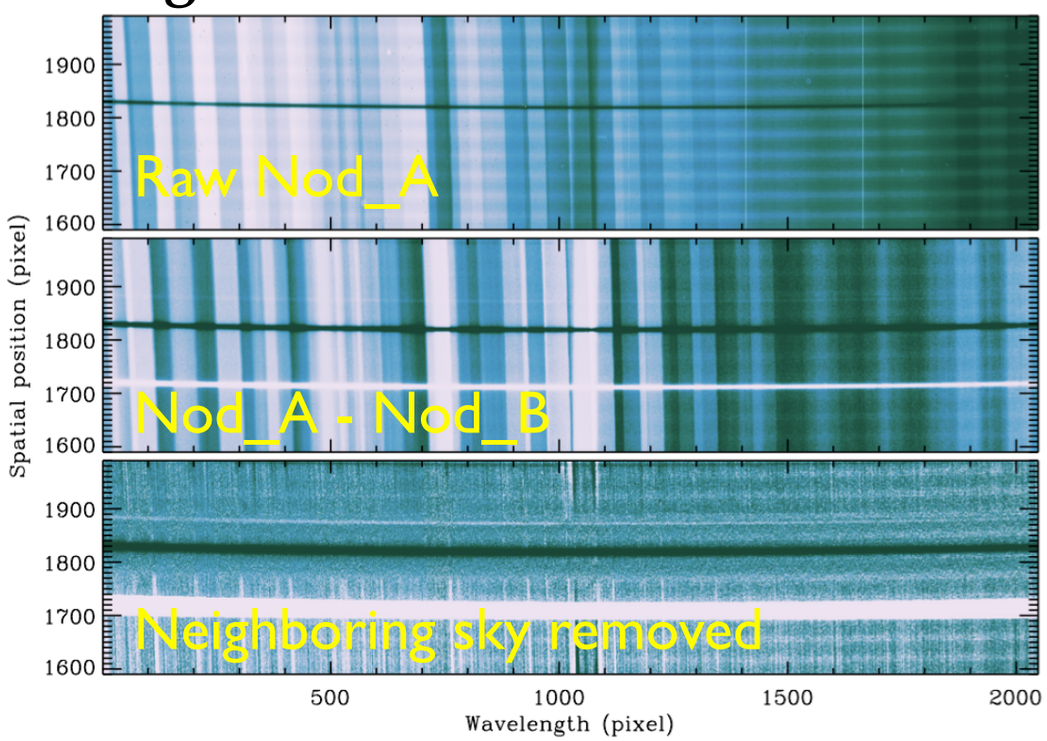
- **Image reduction of Nod observation**

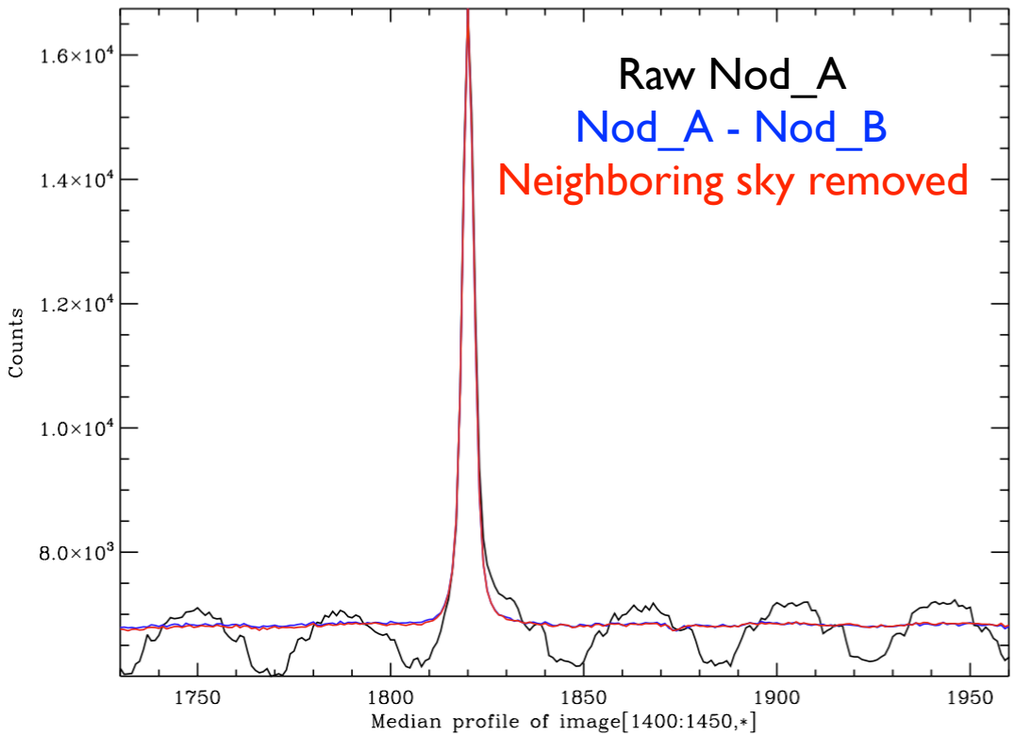


Sky is constructed in wavelength space and transformed back to pixel space for subtraction.



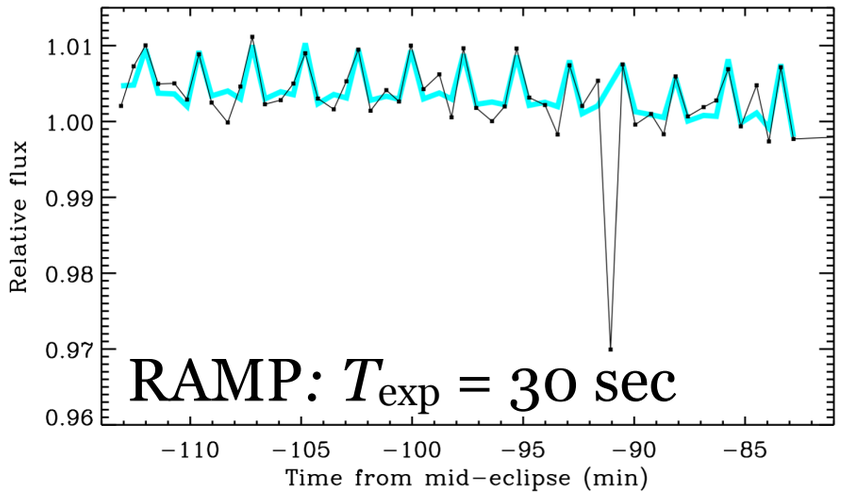
- **Image reduction of Stare+Nod observation**

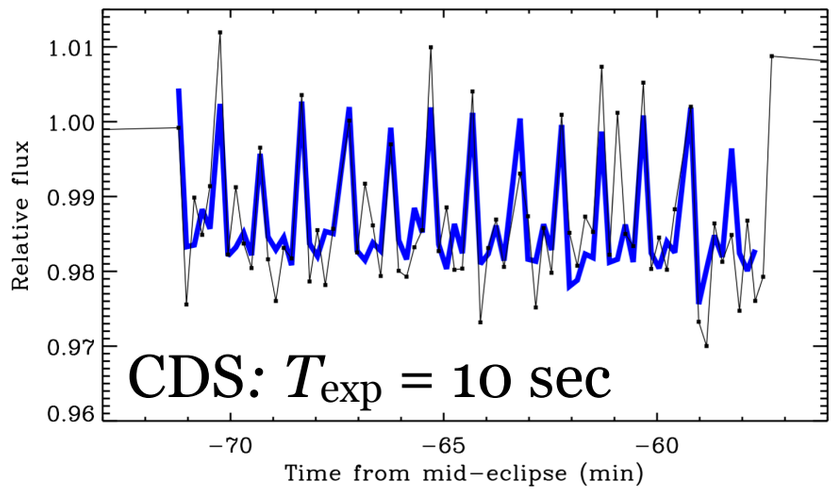


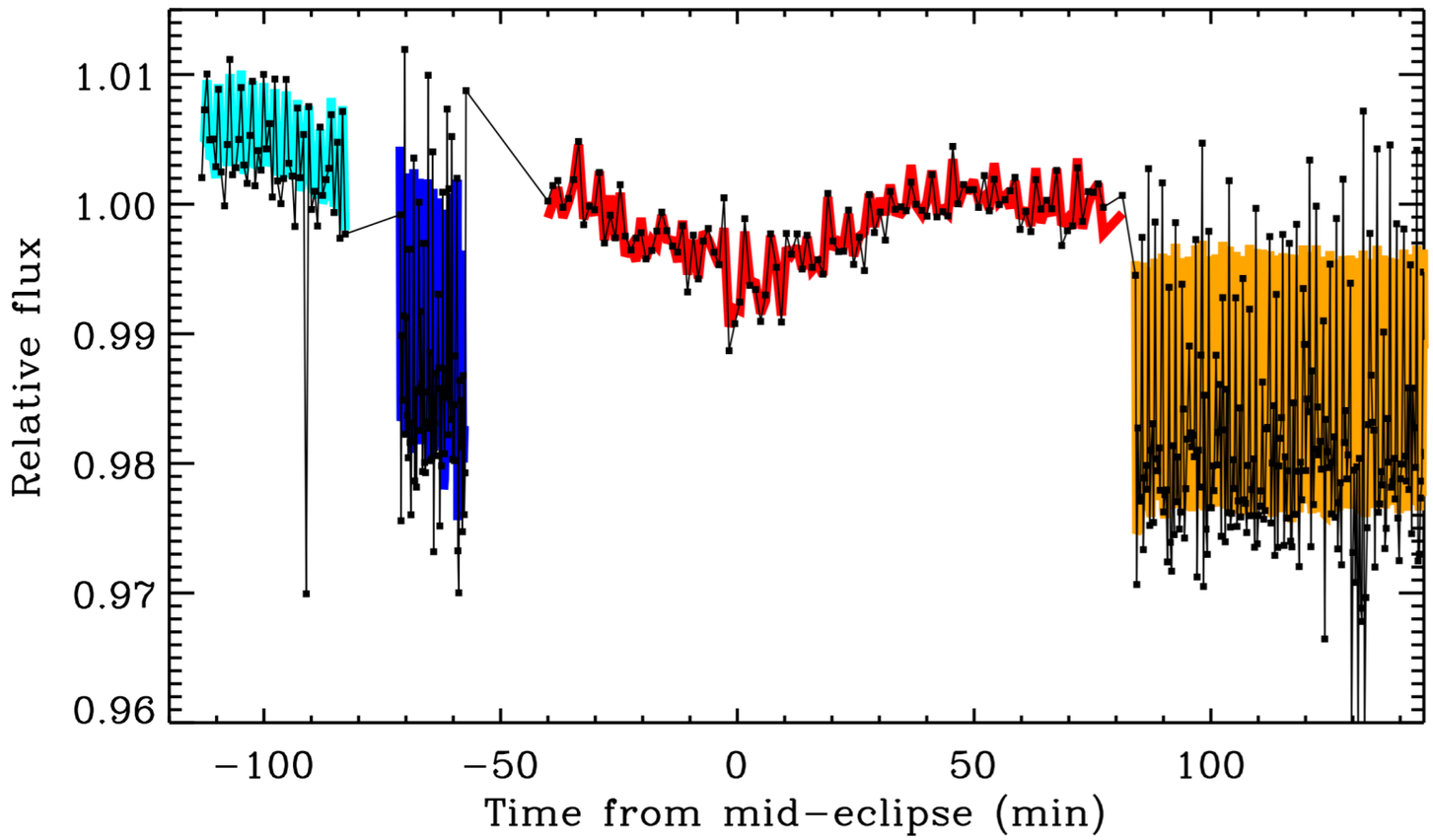


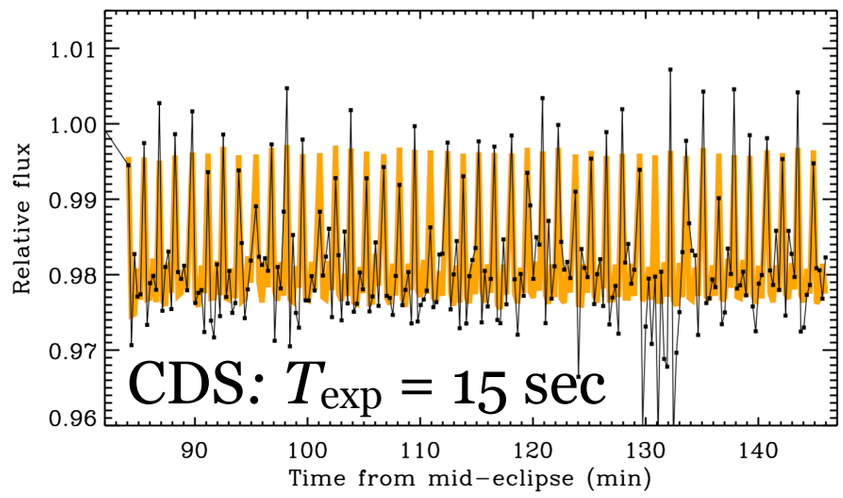
Comparison Between Different Read Modes

- **Stick to one read mode through the whole observation:**
  - Relative flux level might differ in different modes
  - Complicated systematics with more modes:
    - Ramp effects could differ
    - Sky contribution changes









Slit Failure In Arc Lamp Measurements

