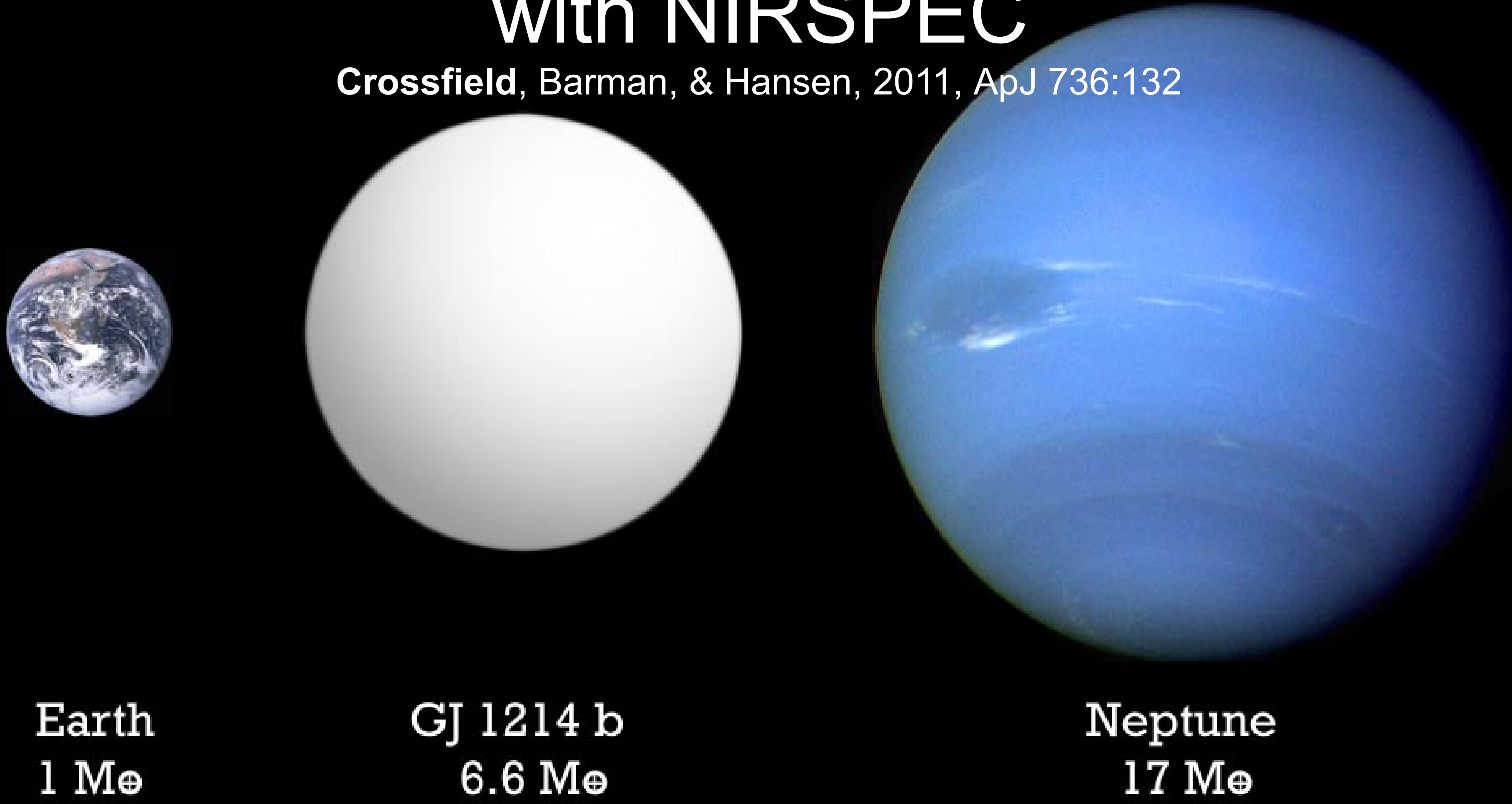
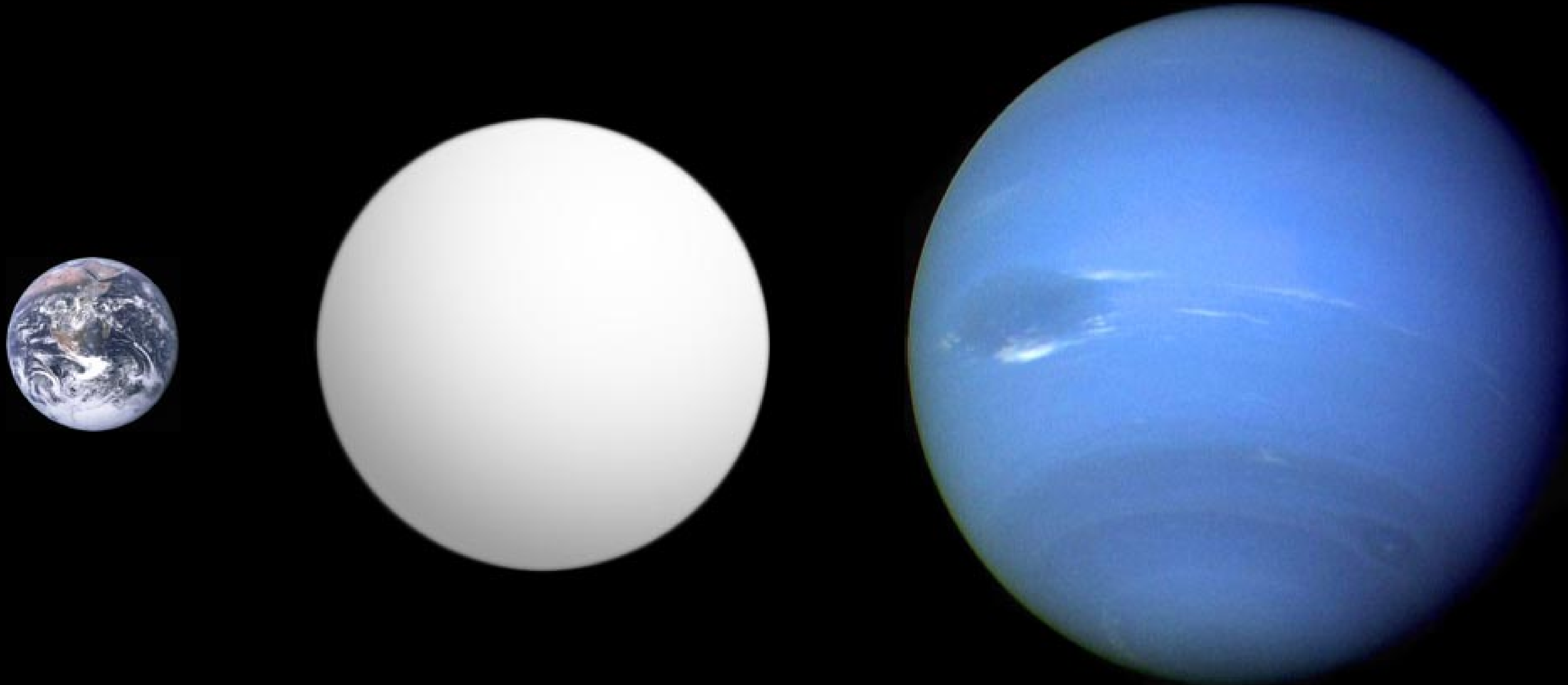
Unraveling the Mystery of GJ1214b with NIRSPEC

Crossfield, Barman, & Hansen, 2011, ApJ 736:132



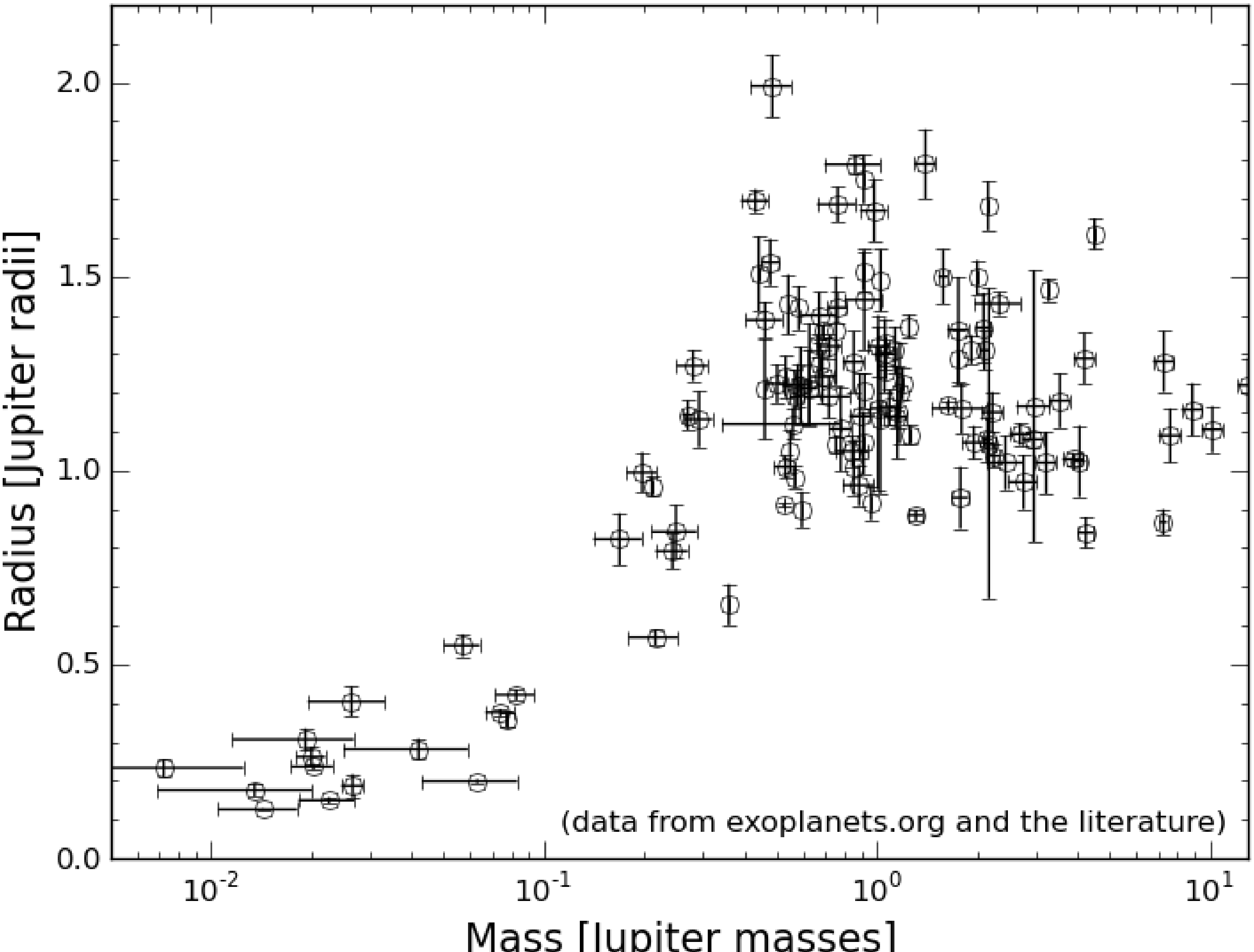
Keck Science Meeting
CIT, Pasadena, 23 Sep 2011

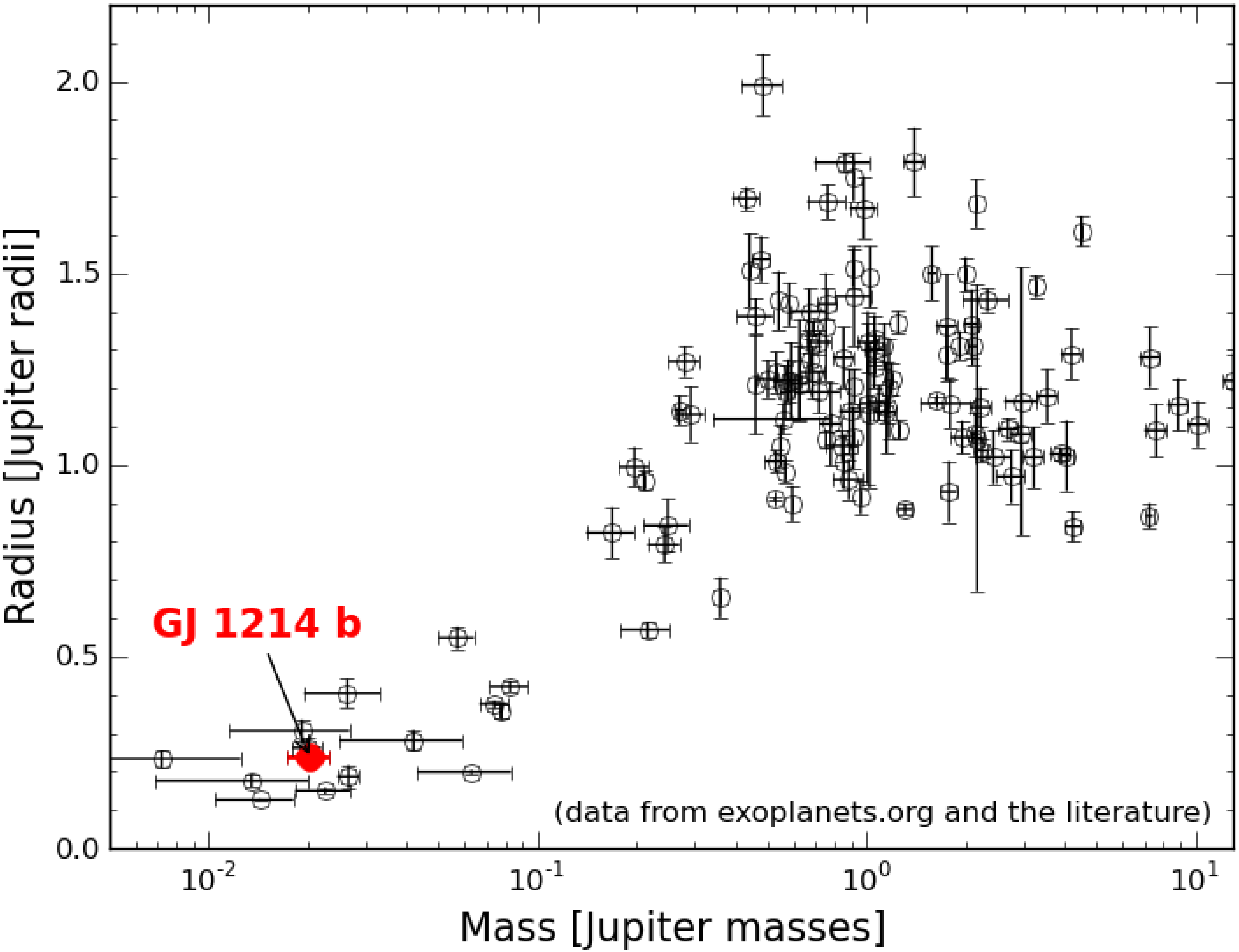


Earth
1 M⊕

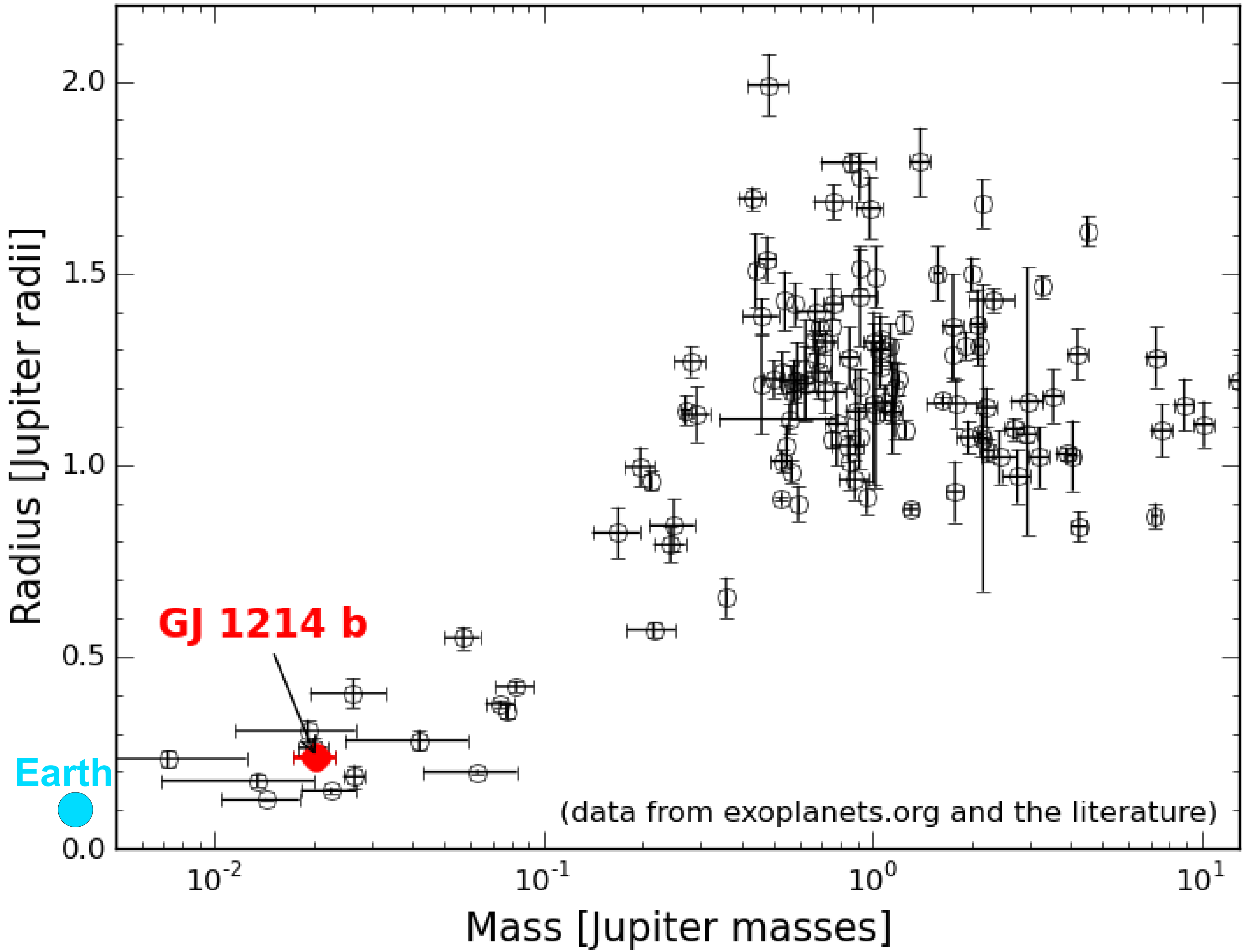
GJ 1214 b
6.6 M⊕

Neptune
17 M⊕

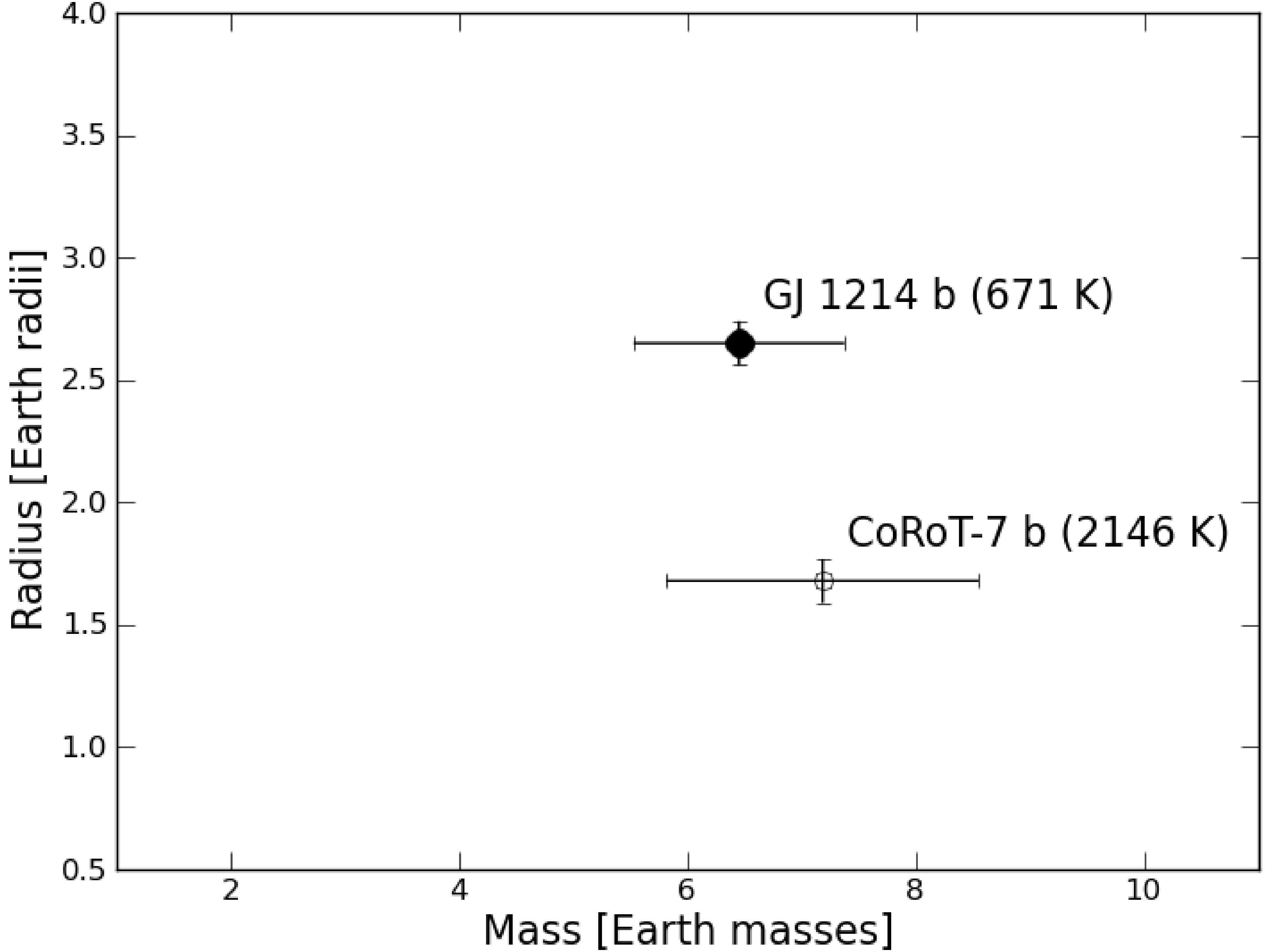

2.0
1.5
1.0
0.5
0.0
Radius [Jupiter radii]
10^{-2}
10^{-1}
10^{0}
10^{1}
Mass [Jupiter masses]
(data from exoplanets.org and the literature)



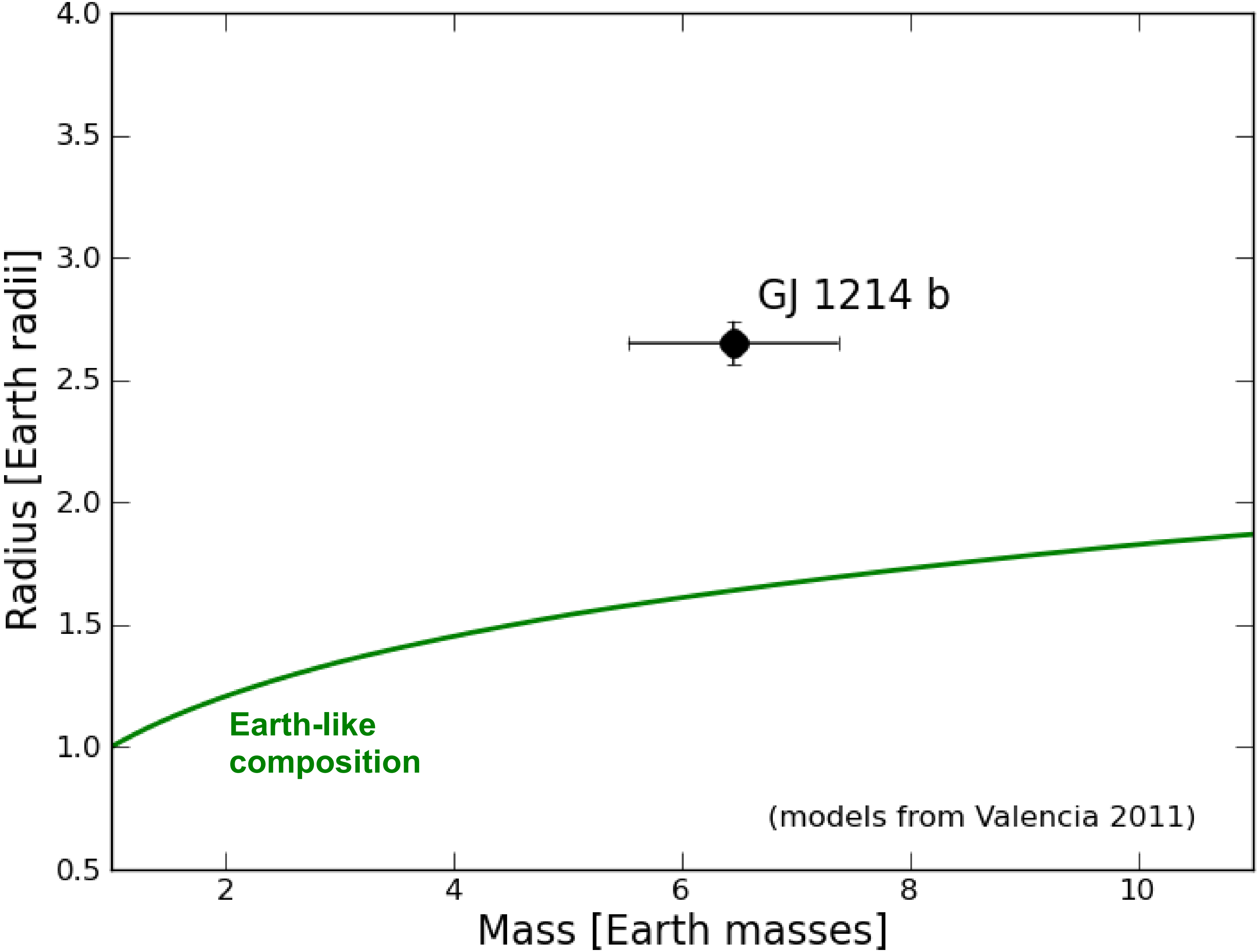
GJ 1214 b
Radius [Jupiter radii]
Mass [Jupiter masses]
(data from exoplanets.org and the literature)
0.0
0.5
1.0
1.5
2.0
10^{-2}
10^{-1}
10^{0}
10^{1}



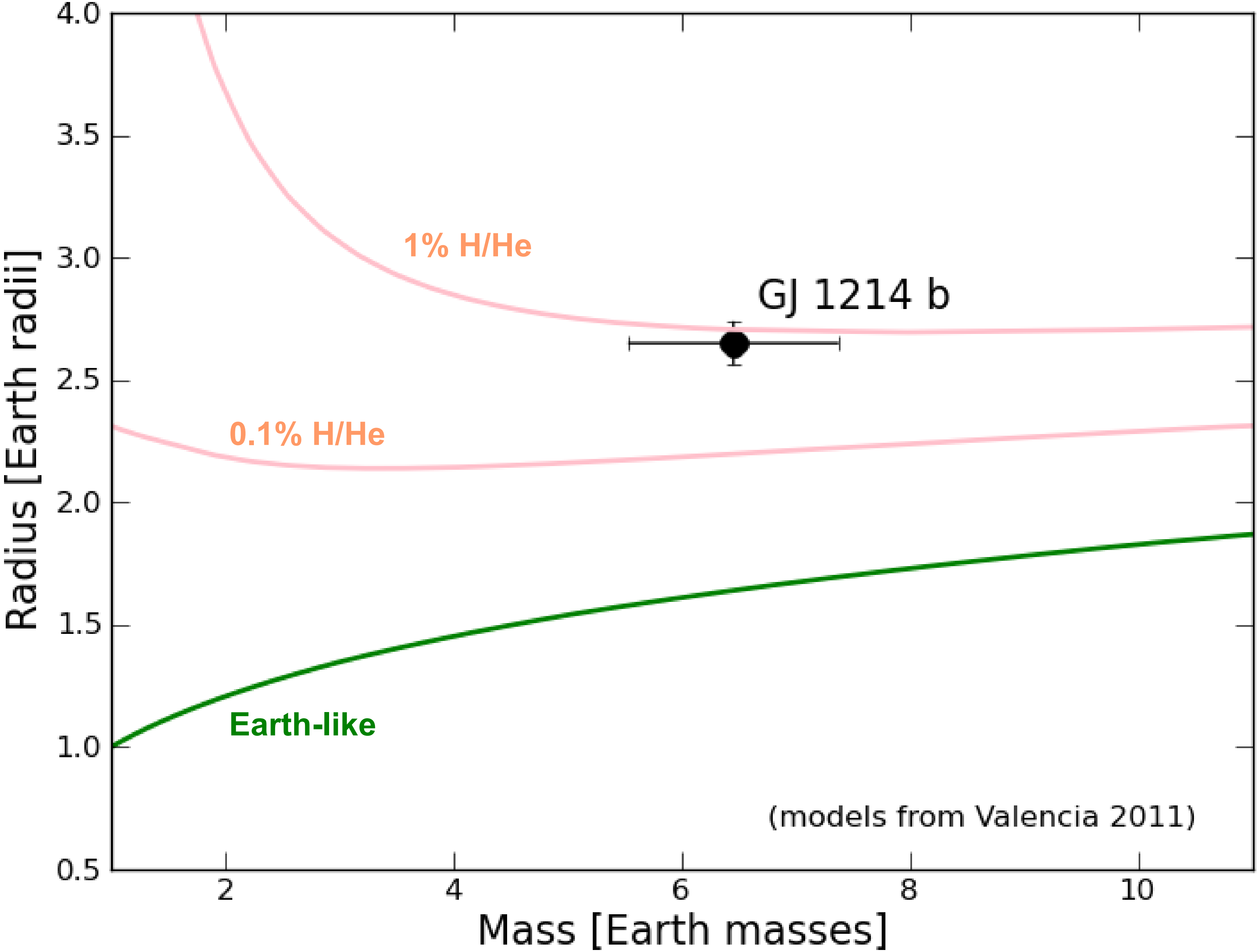
Radius [Jupiter radii]
Mass [Jupiter masses]
2.0
1.5
1.0
0.5
0.0
10^{-2}
10^{-1}
10^{0}
10^{1}
GJ 1214 b
Earth
(data from exoplanets.org and the literature)

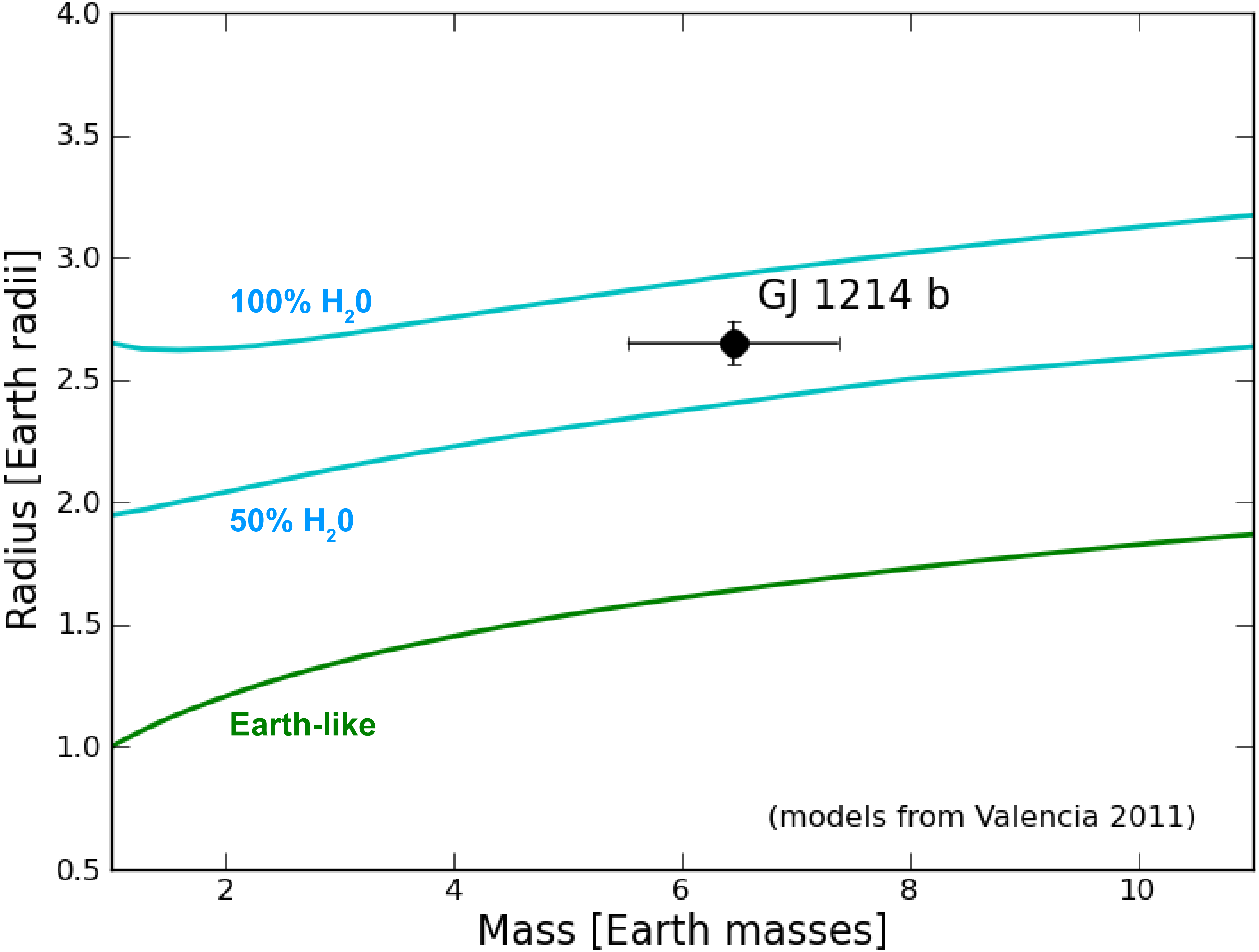


GJ 1214 b (671 K)
CoRoT-7 b (2146 K)
Radius [Earth radii]
Mass [Earth masses]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
2
4
6
8
10

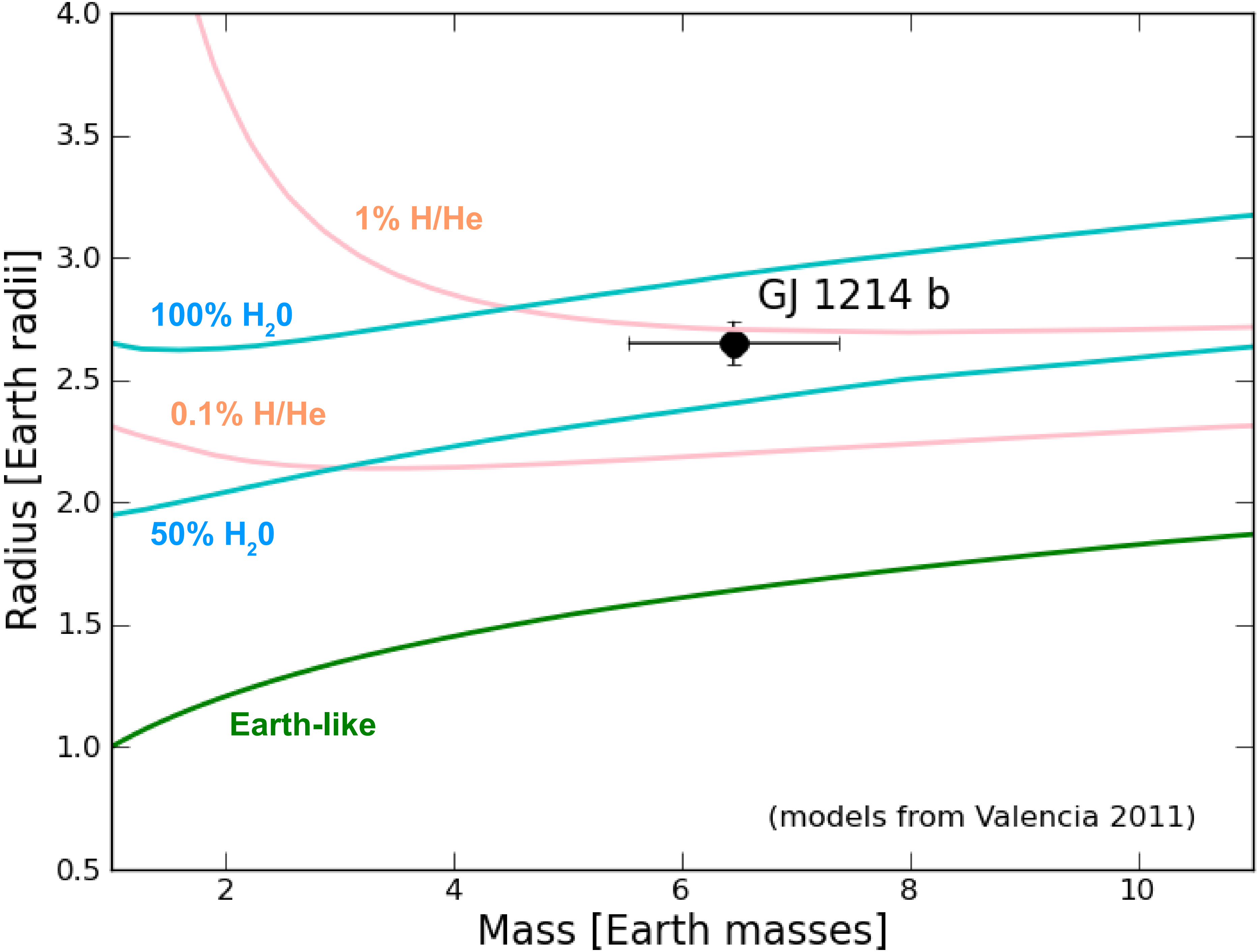


4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
Radius [Earth radii]
GJ 1214 b
Earth-like
composition
(models from Valencia 2011)
2
4
6
8
10
Mass [Earth masses]

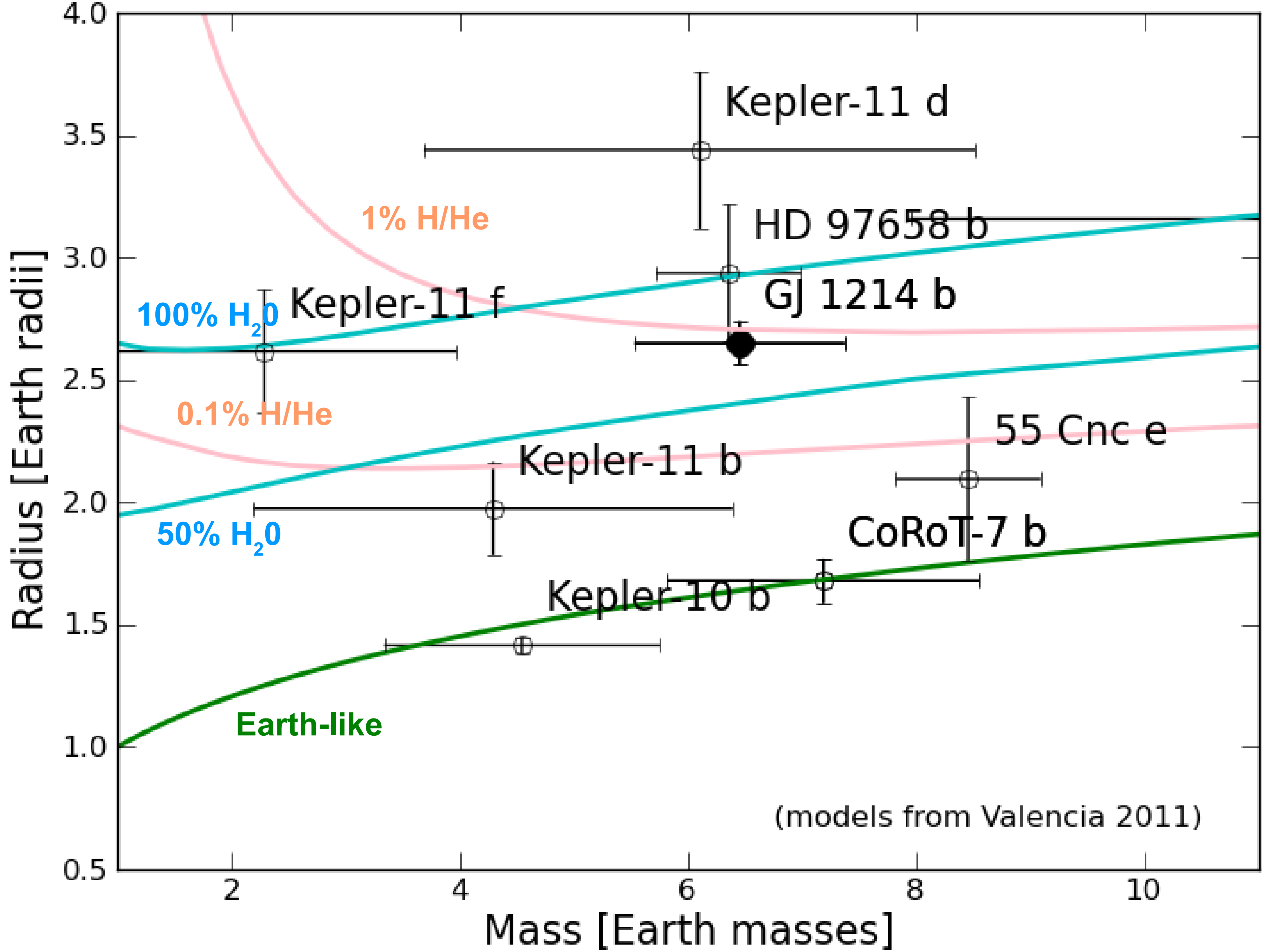

4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
2
4
6
8
10
Radius [Earth radii]
Mass [Earth masses]
1% H/He
GJ 1214 b
0.1% H/He
Earth-like
(models from Valencia 2011)



100% H_20
GJ 1214 b
50% H_20
Earth-like
(models from Valencia 2011)
Radius [Earth radii]
Mass [Earth masses]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
2
4
6
8
10

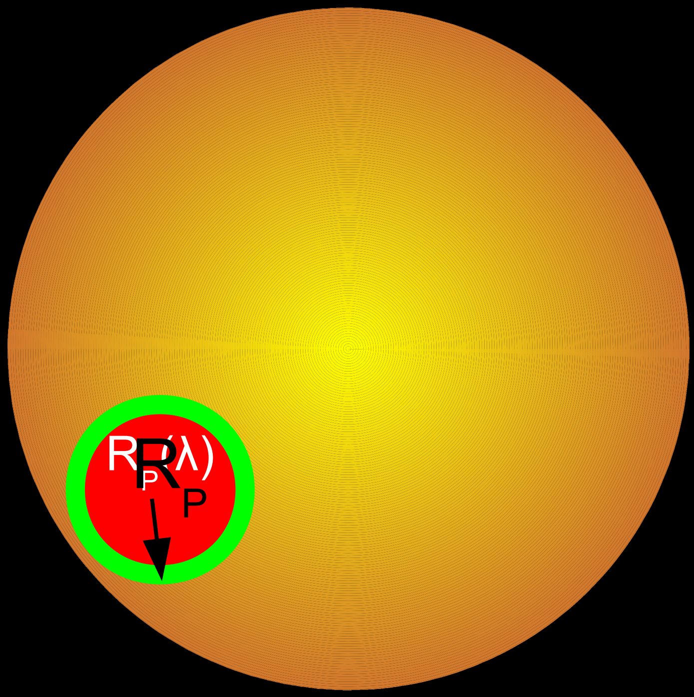


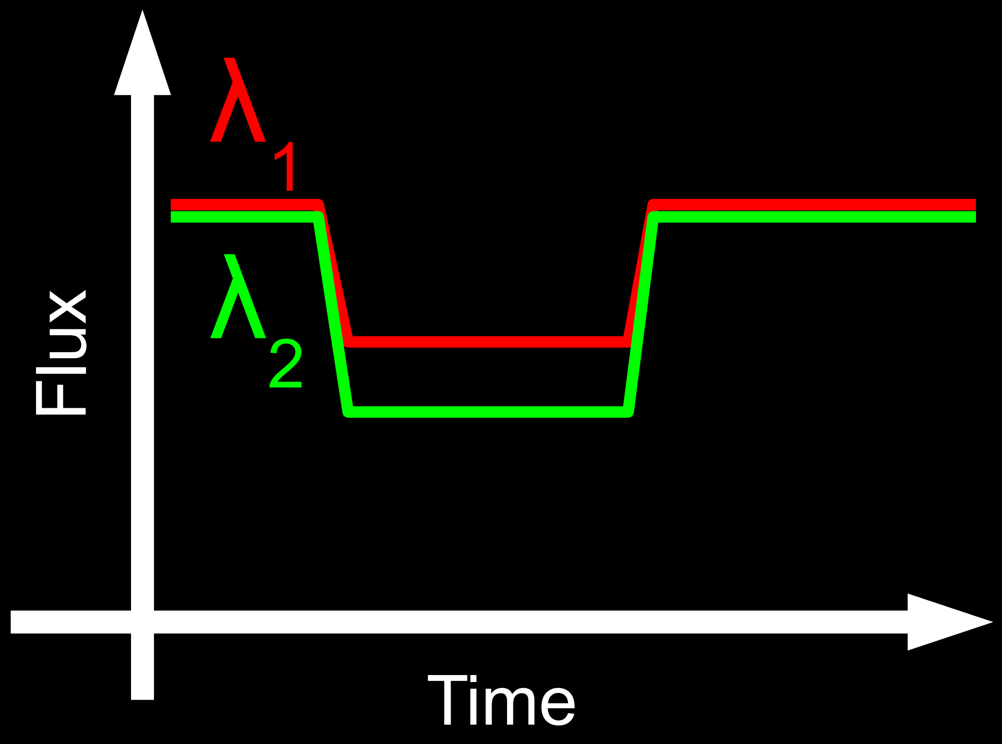
Radius [Earth radii]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
1% H/He
100% H_20
GJ 1214 b
0.1% H/He
50% H_20
Earth-like
(models from Valencia 2011)
2
4
6
8
10
Mass [Earth masses]

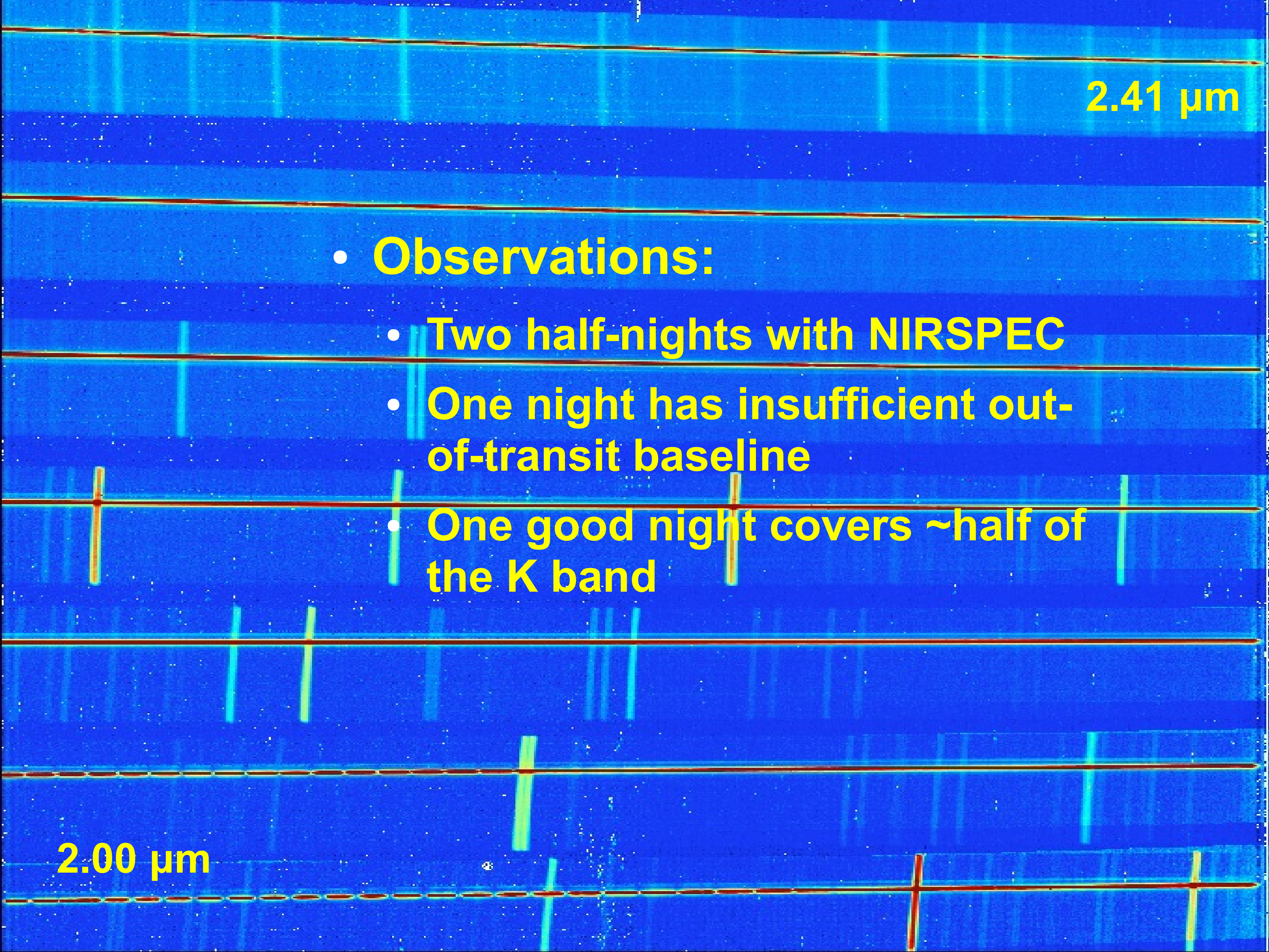


Kepler-11 d
1% H/He
HD 97658 b
GJ 1214 b
Kepler-11 f
100% H2O
0.1% H/He
55 Cnc e
Kepler-11 b
50% H2O
CoRoT-7 b
Kepler-10 b
Earth-like
(models from Valencia 2011)
Radius [Earth radii]
Mass [Earth masses]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
2
4
6
8
10

Transmission spectroscopy: probes atmospheric composition via $R_P(\lambda)$

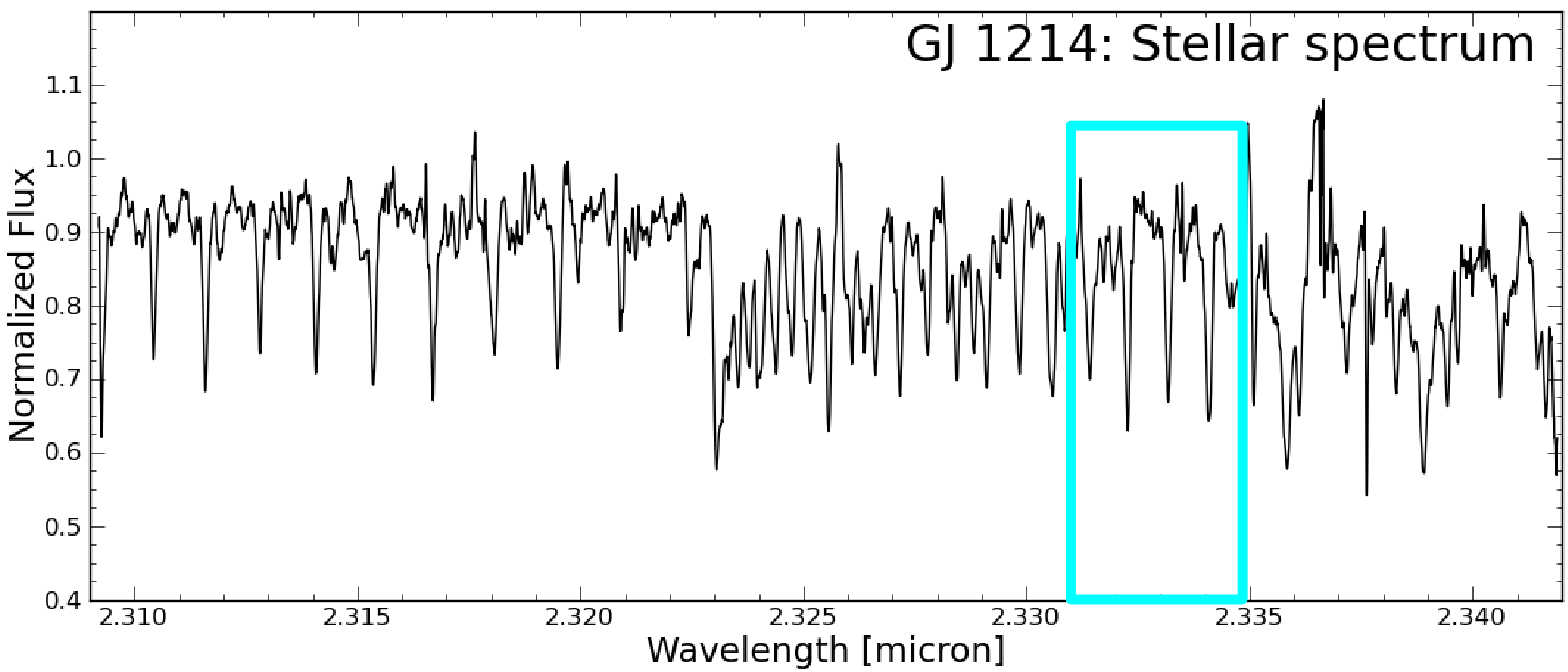




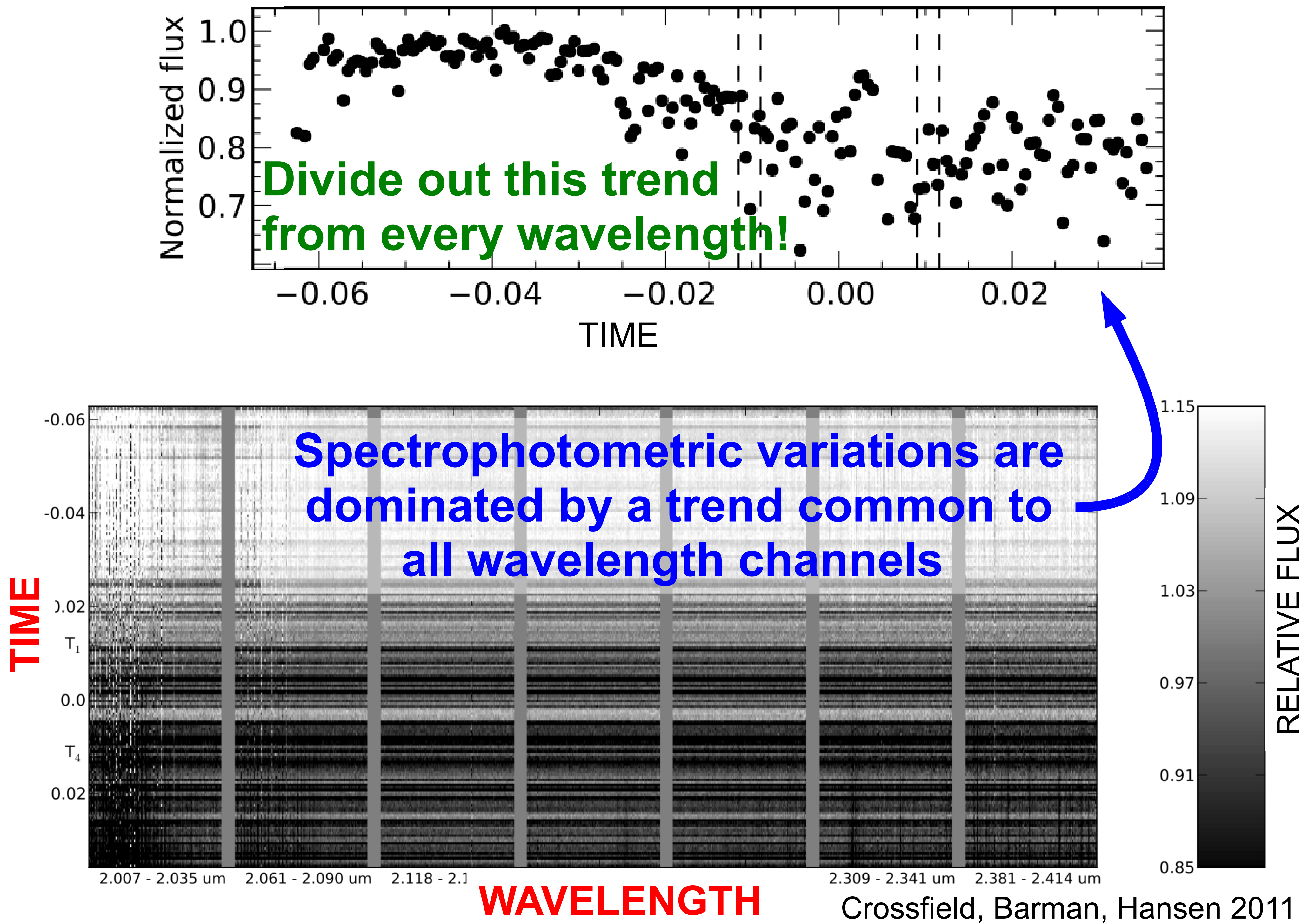


- **Observations:**
  - **Two half-nights with NIRSPEC**
  - **One night has insufficient out-of-transit baseline**
  - **One good night covers ~half of the K band**

We get a high S/N spectrum of this K=8.8 M dwarf:

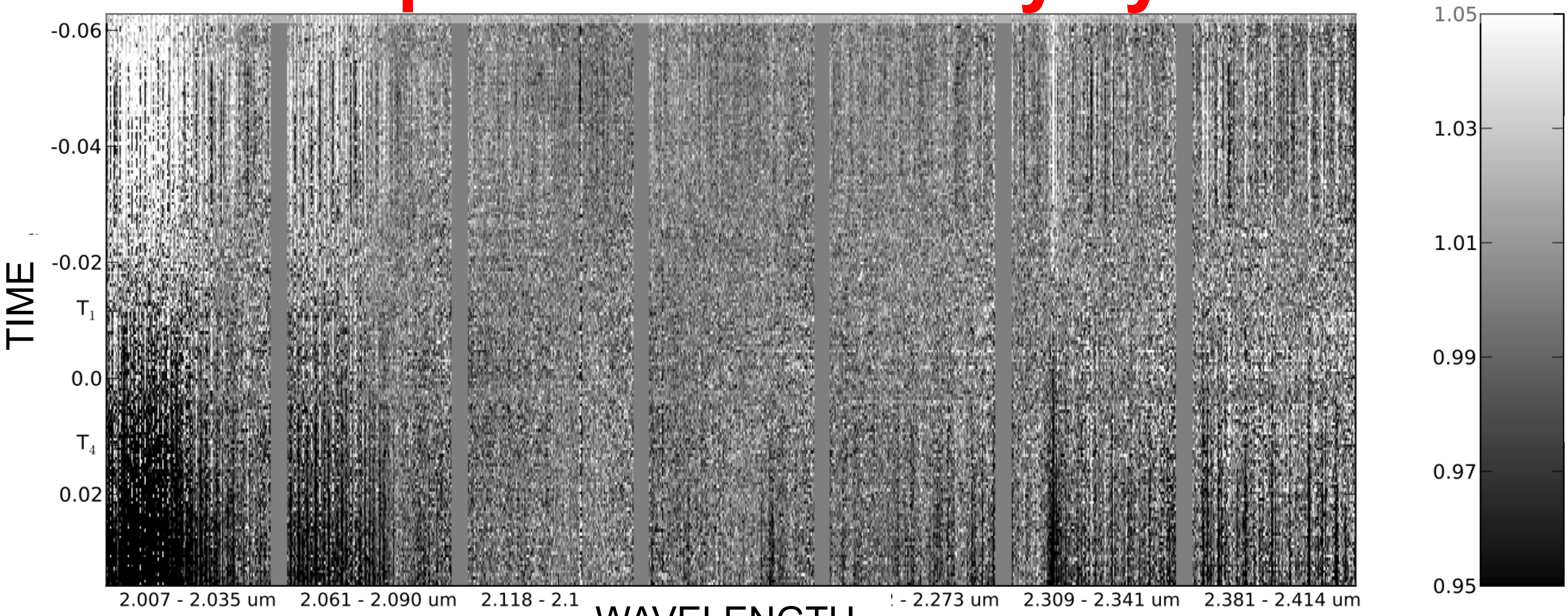


Crossfield, Barman, Hansen 2011


Normalized flux
1.0
0.9
0.8
0.7
Divide out this trend
from every wavelength!
−0.06
−0.04
−0.02
0.00
0.02
TIME
-0.06
-0.04
0.02
T1
0.0
T4
0.02
TIME
Spectrophotometric variations are
dominated by a trend common to
all wavelength channels
1.15
1.09
1.03
0.97
0.91
0.85
RELATIVE FLUX
2.007 - 2.035 um
2.061 - 2.090 um
2.309 - 2.341 um
2.381 - 2.414 um
WAVELENGTH
Crossfield, Barman, Hansen 2011

Removing common-mode variations leaves differential transit signal:

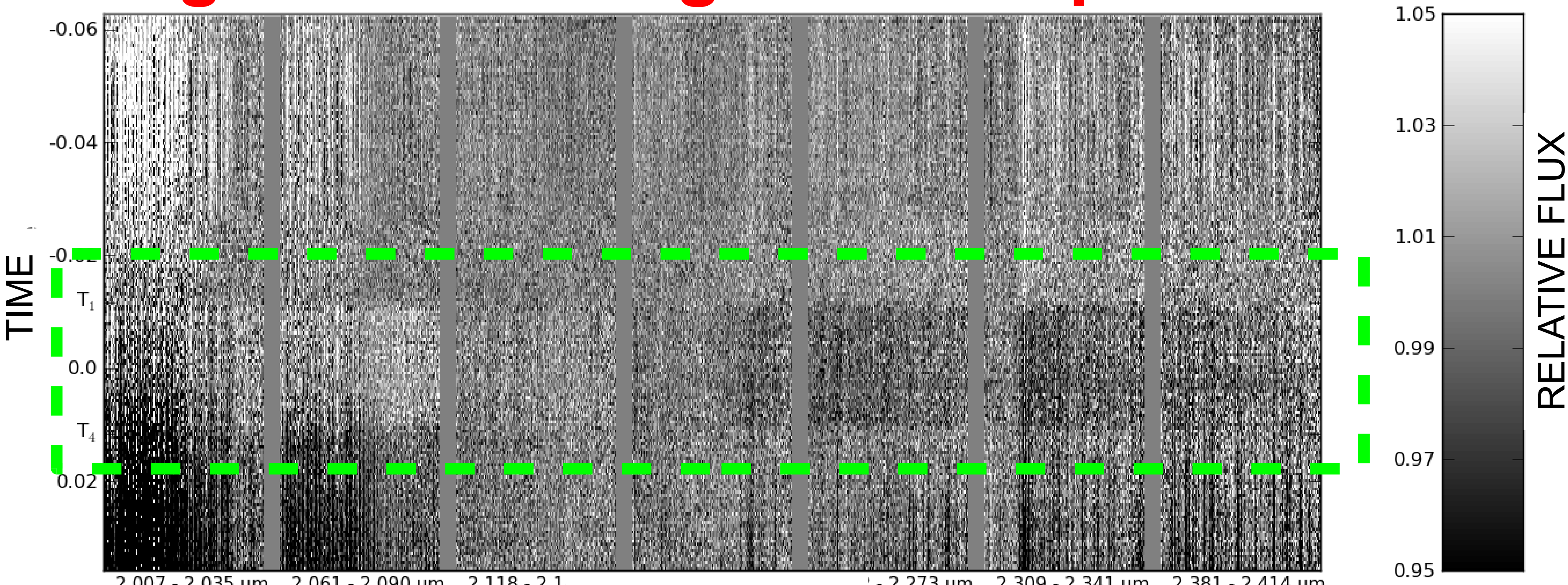
Observed data: no residual transit spectrum visible by eye



Crossfield, Barman, Hansen 2011

Removing common-mode variations leaves differential transit signal:

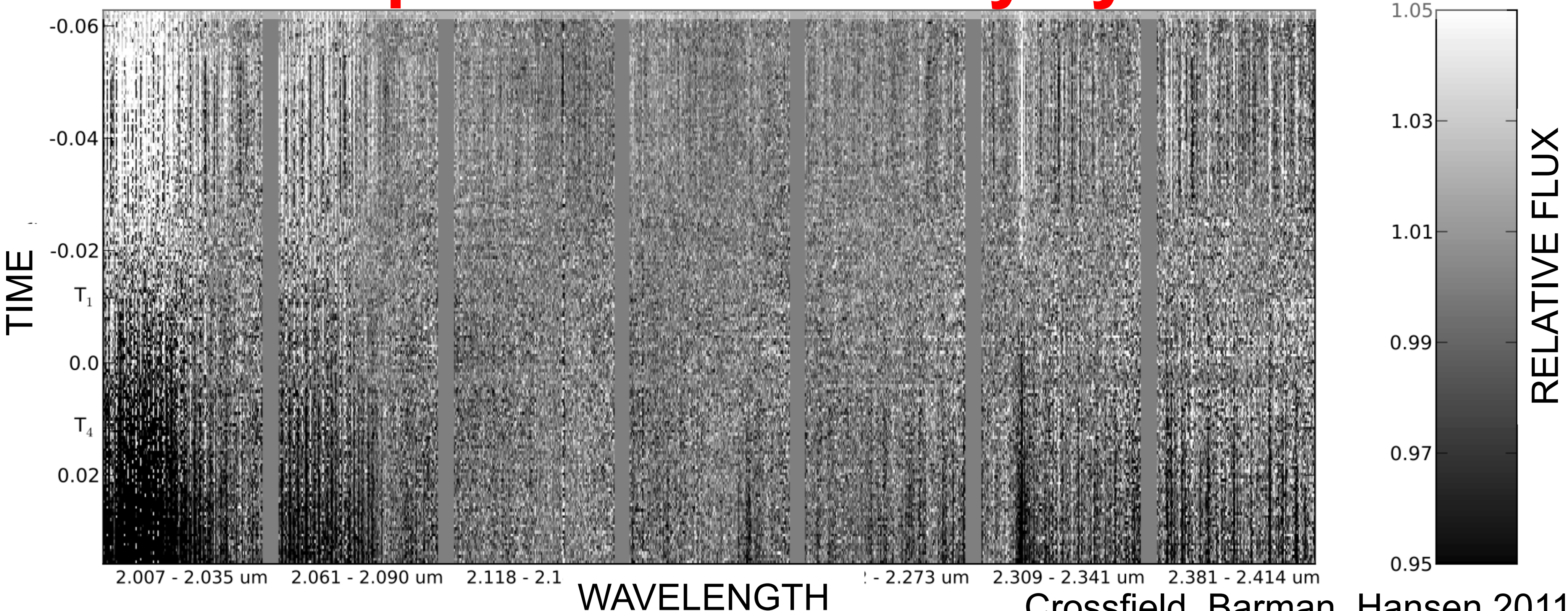
Simulated observation: transit signal 10x stronger than expected



Crossfield, Barman, Hansen 2011

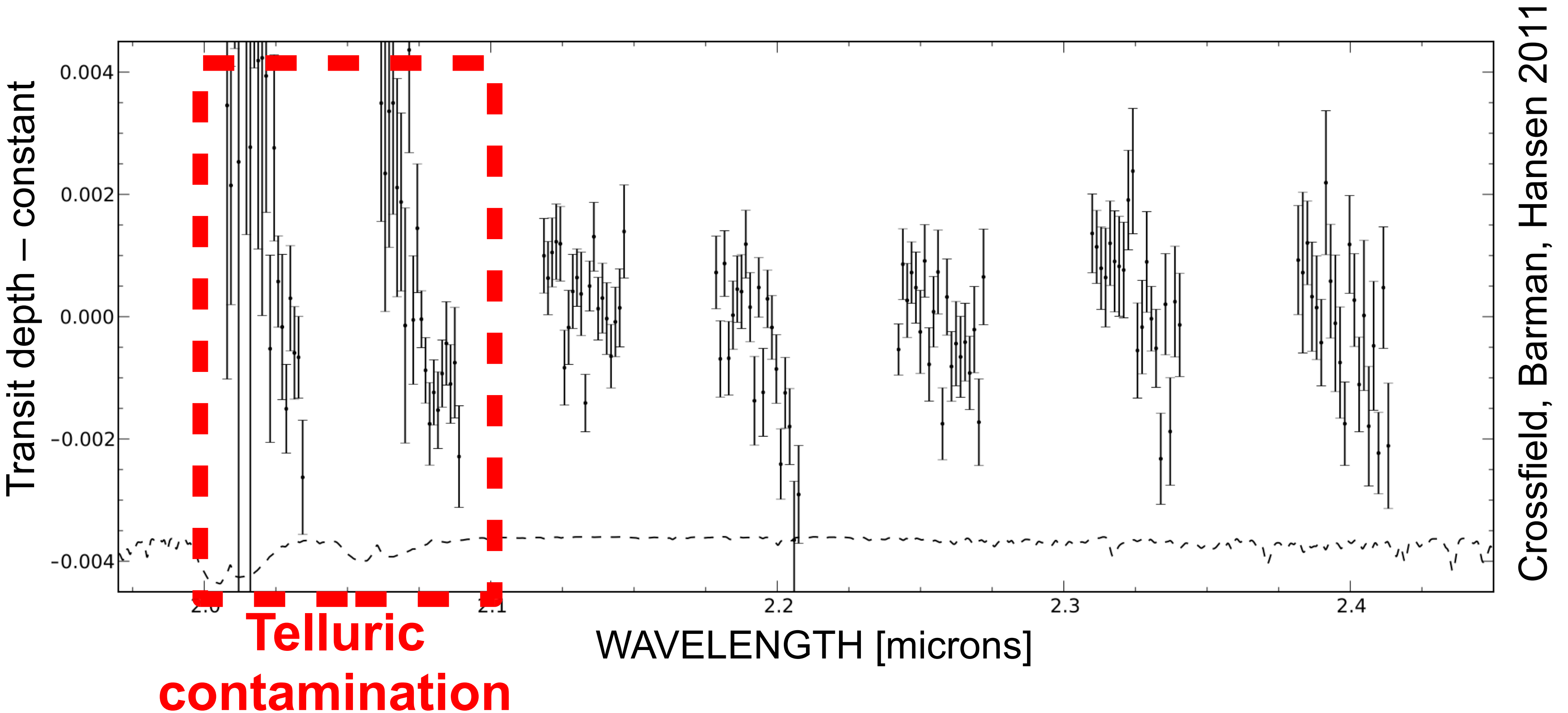
Removing common-mode variations leaves differential transit signal:

Observed data: no residual transit spectrum visible by eye



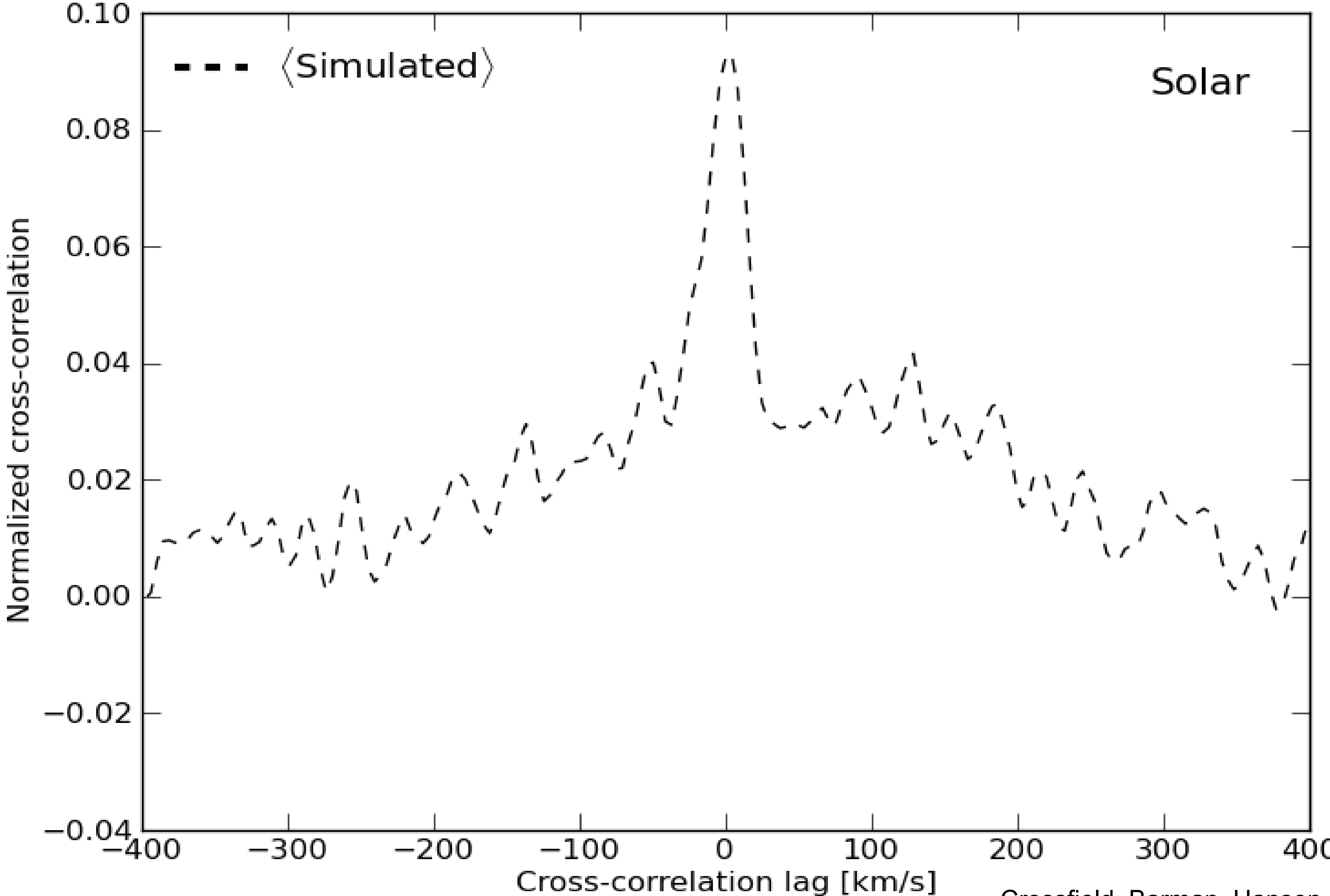
Crossfield, Barman, Hansen 2011

Initial transmission spectrum of GJ1214b:

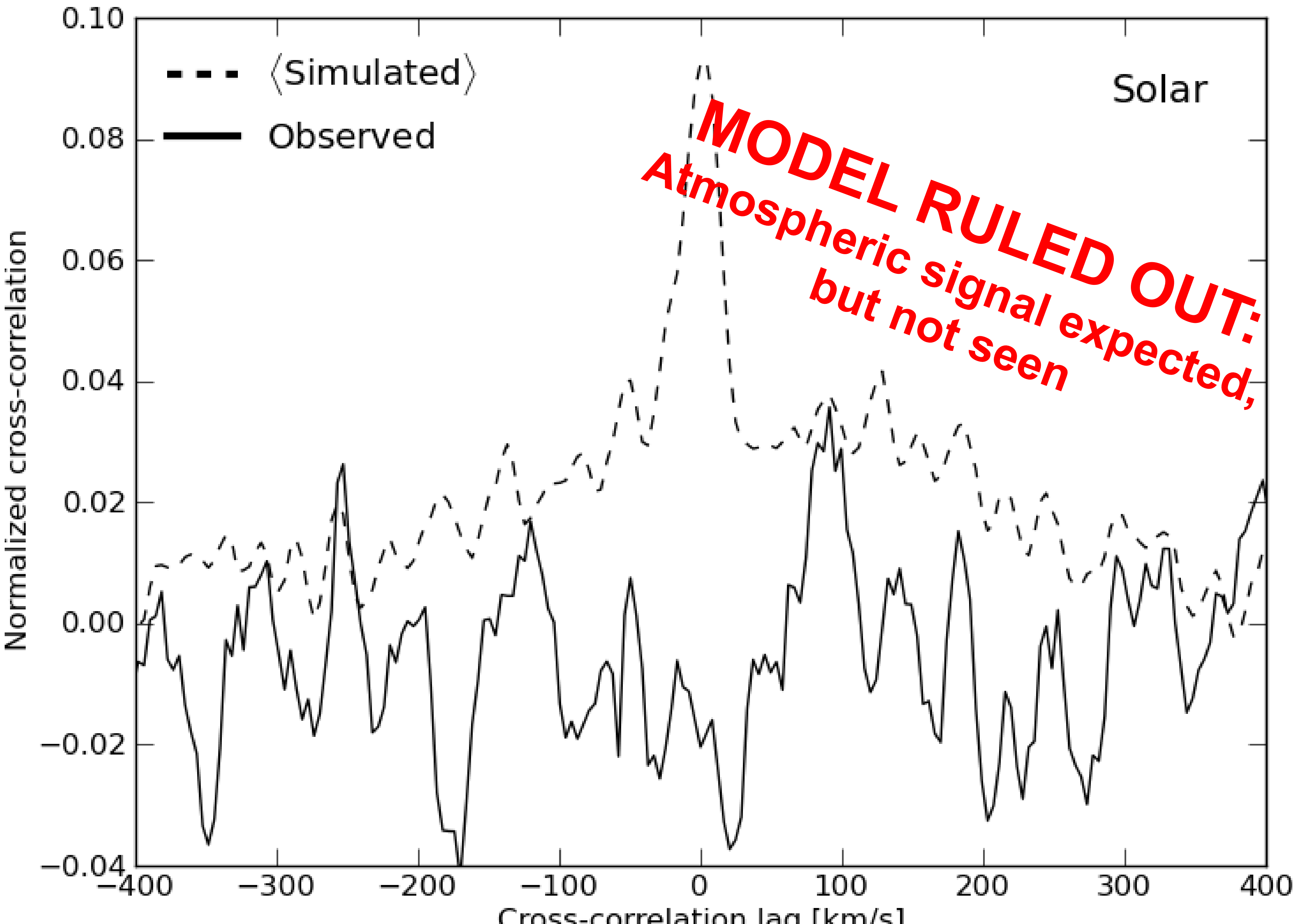


We cross-correlate this spectrum with models to confirm or rule out atmospheric compositions

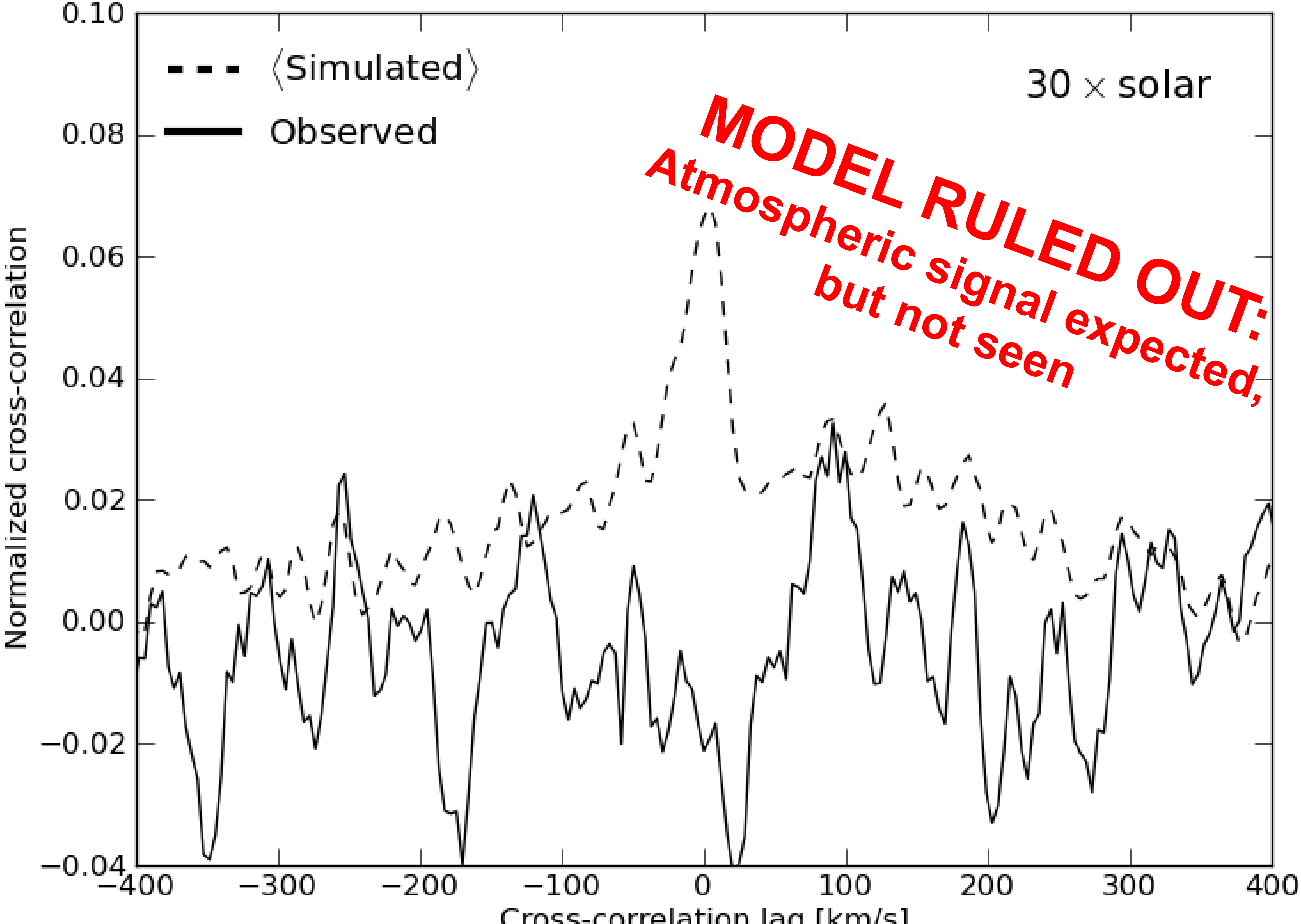
Model cross-correlation can detect the ensemble of lines in a spectrum:



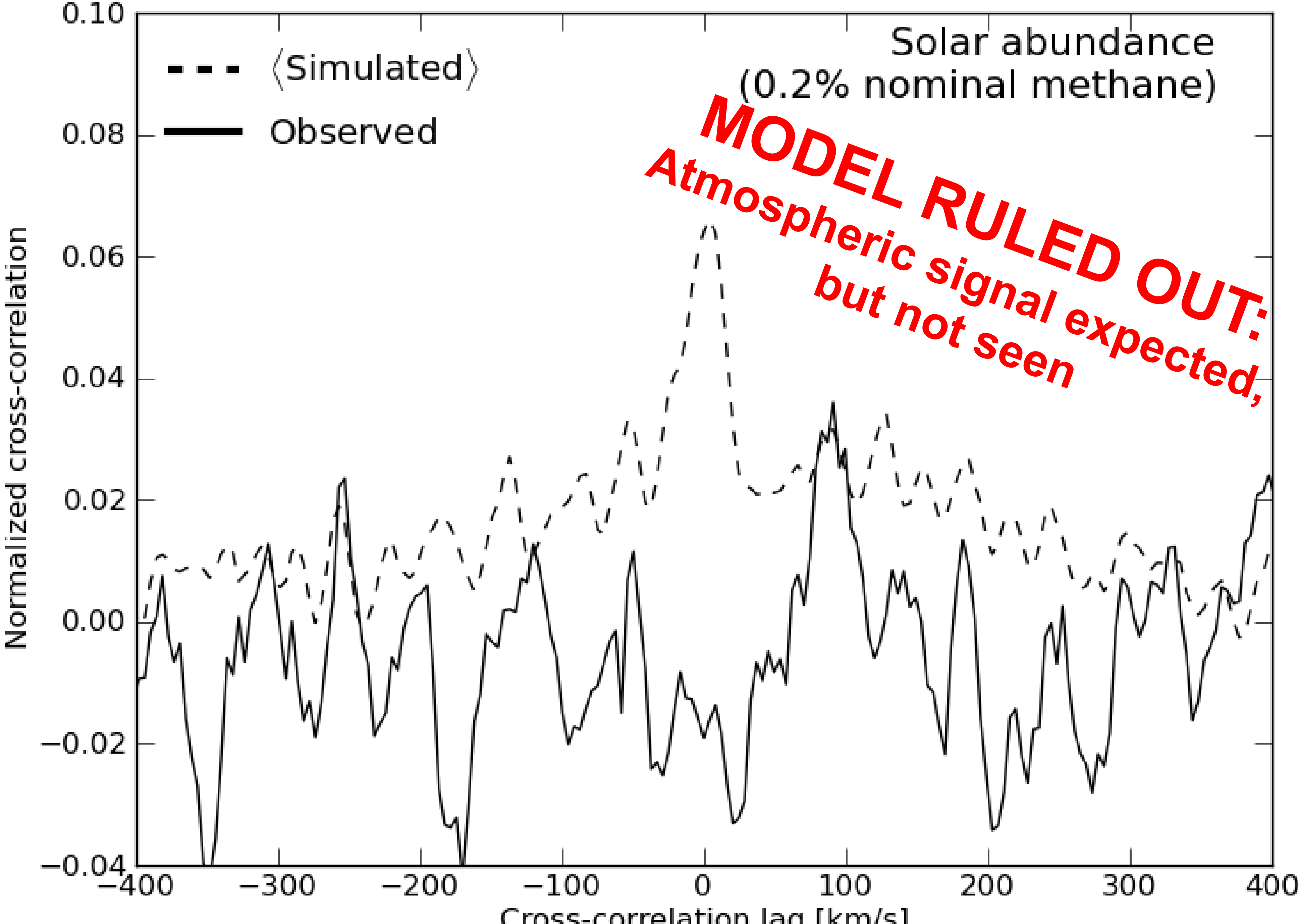
Crossfield, Barman, Hansen 2011



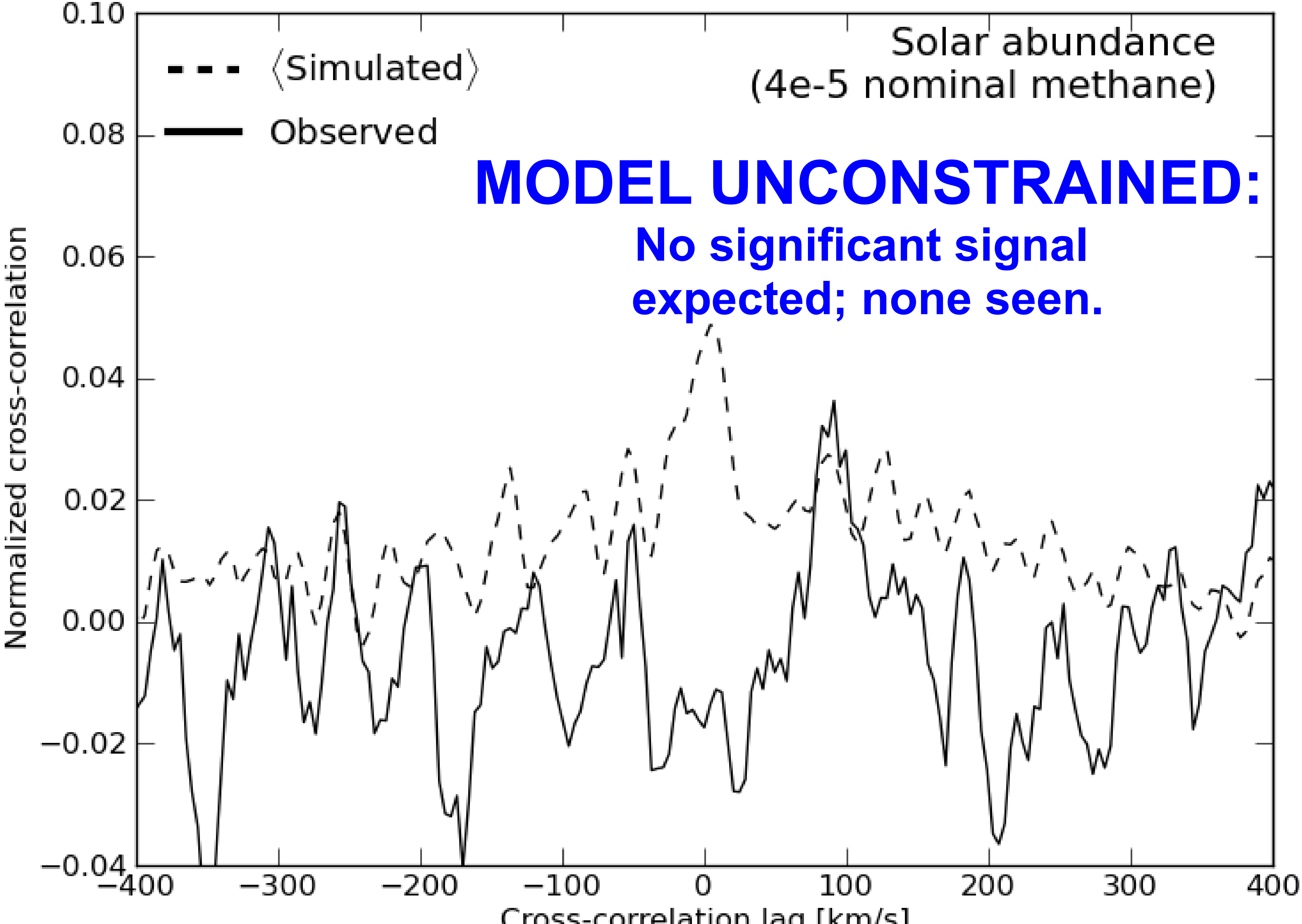
Crossfield, Barman, Hansen 2011



Crossfield, Barman, Hansen 2011



Crossfield, Barman, Hansen 2011



Crossfield, Barman, Hansen 2011

Our Results

We rule out hydrogen-dominated atmospheres in or near chemical equilibrium:

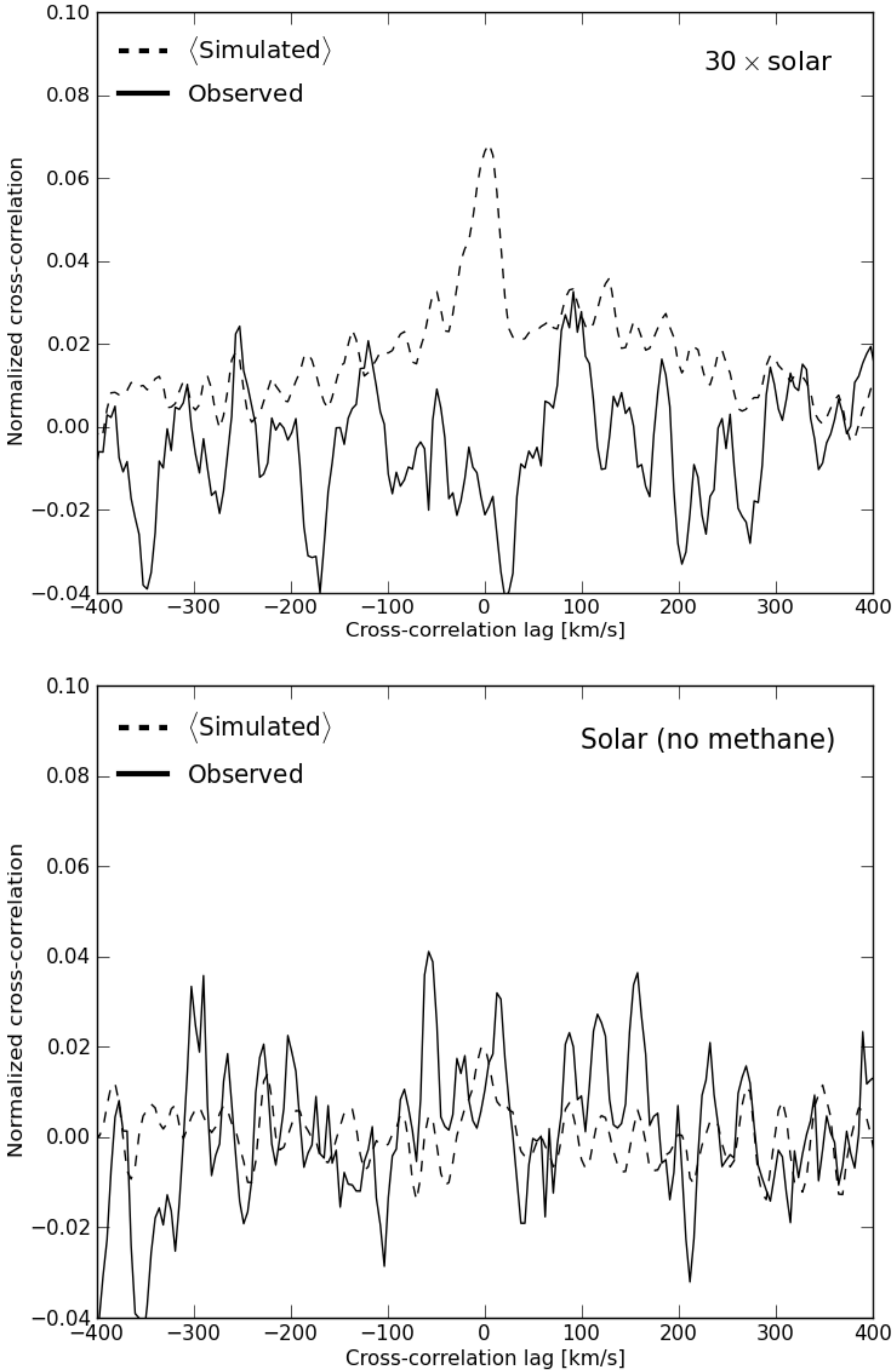
Solar, 10x solar, 30x solar abundances with mild-to-no methane depletion

We cannot constrain atmospheres with flatter spectra:

H-dominated (Low carbon, substantial methane depletion)

Hazes/clouds

Low scale height (high mean molecular weight: e.g., H_2O)



Crossfield, Barman, Hansen 2011

Other results also agree (mostly) on a flat, featureless spectrum:

Bean+2011: 0.8-1.0 um spectrum; flat

Desert+2011: Spitzer/IRAC CH1+2; flat

Croll+2011: NIR photometry, $R_K > R_J$ (>4σ)

Bean+(1109.0582): 0.6-1.0 um + JHK; flat.

Berta+(in prep): 1.1-1.65 um spectrum; flat.

Conclusions

GJ 1214b has a flat transmission spectrum, meaning the planet either:

--Is covered in opaque clouds, OR

--Has a high mean molecular weight atmosphere (e.g., H_2O)

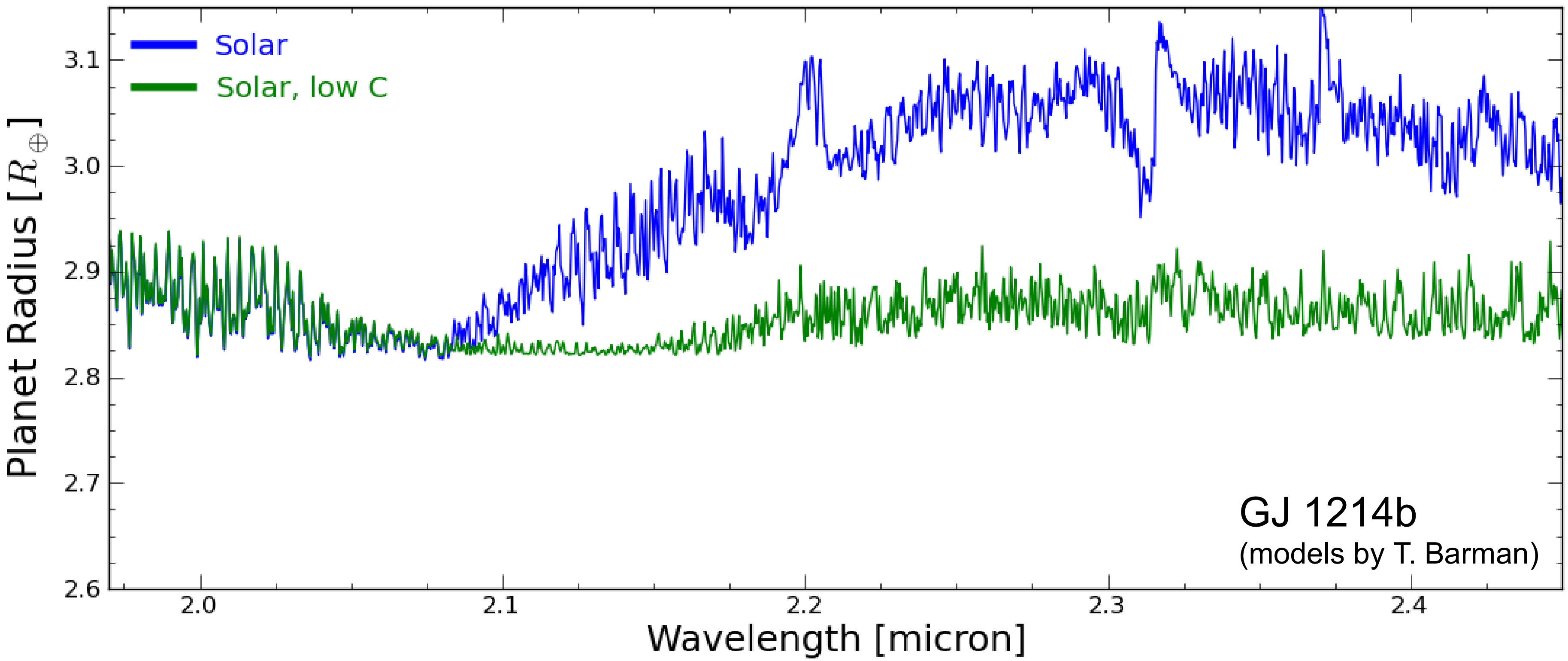
If a 'water' world, GJ 1214b likely formed beyond the snow line and migrated inward without accreting substantial H_2/He

NIRSPEC-like instruments can constrain exoatmospheres, and multi-object spectrographs like MOSFIRE (see Bean+2011) are poised to do even better.

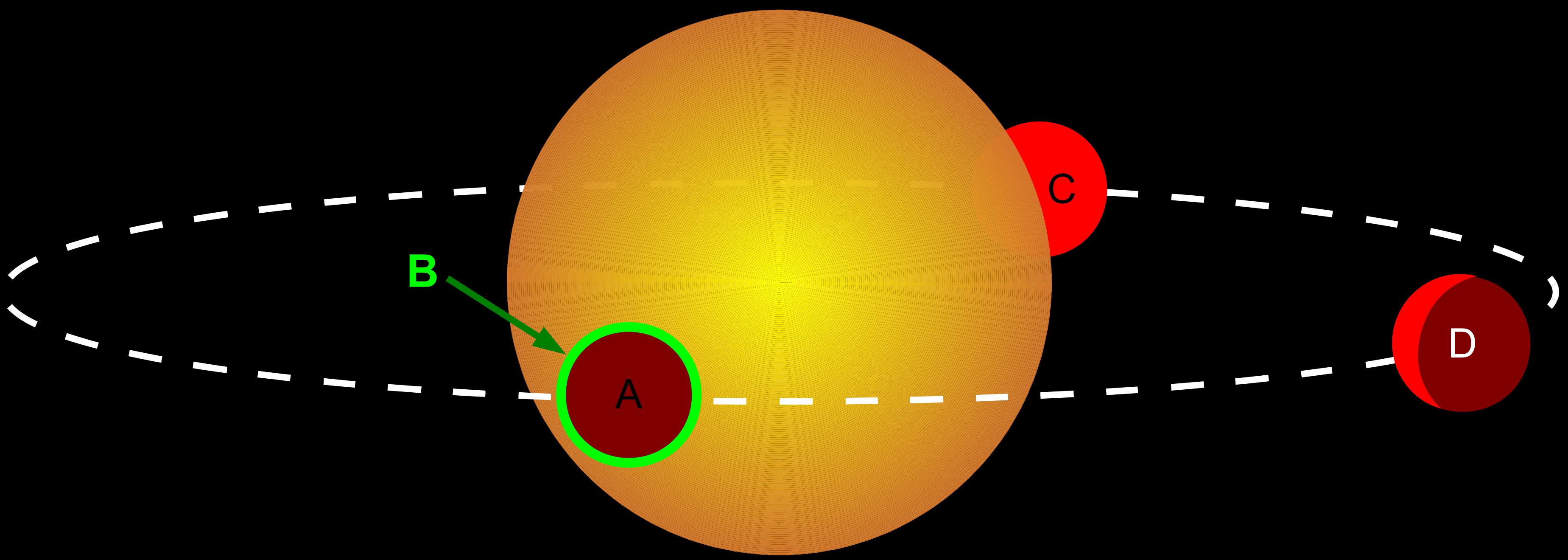
Backup:

- Simulations and time-offset extractions to estimate uncertainties inherent in data
  - Estimation of non-detection confidence

Transmission spectra can constrain atmospheric composition:



Several techniques can characterize exoplanet atmospheres:

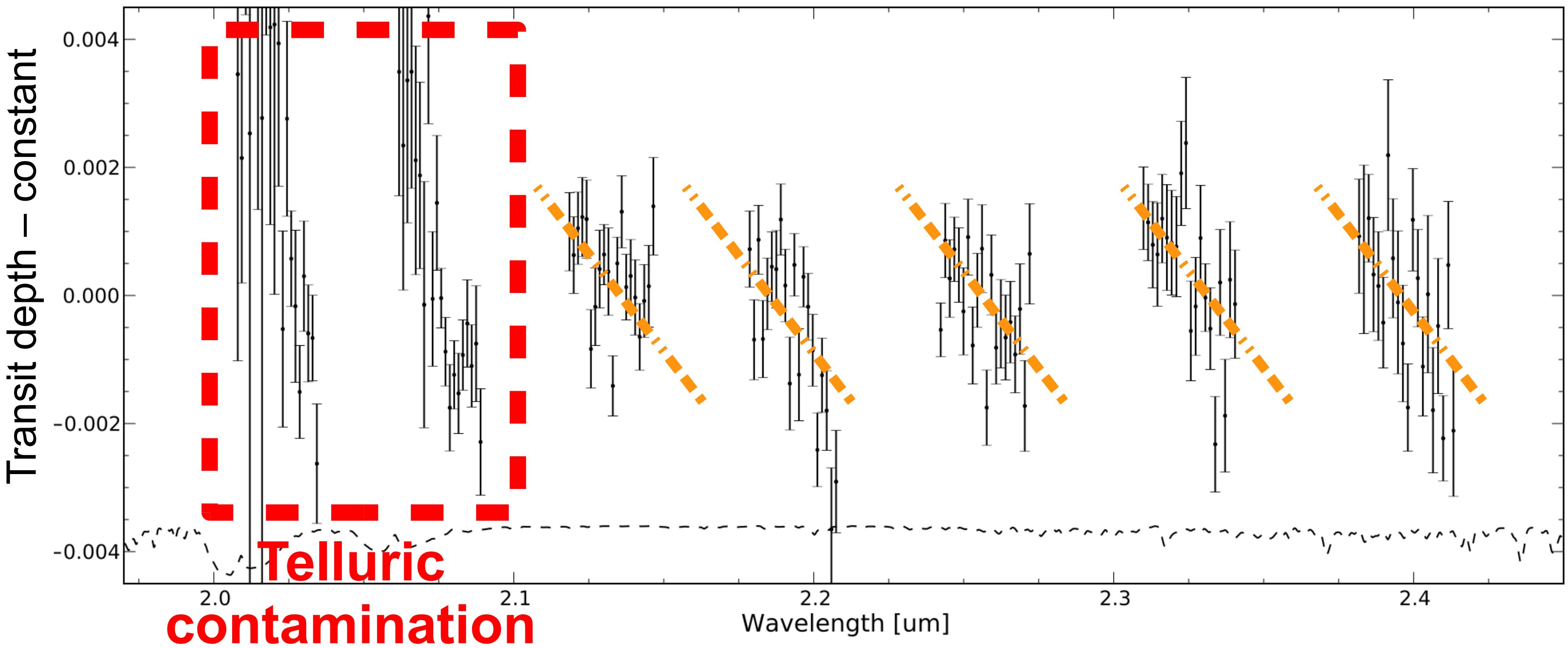


	Method:	Signal scales as:
(A)	Transit	(Rp / Rs)^2
(B)	Transmission	(Tp Rp / Mp) (Rp / Rs)^2
(C)	Eclipse	Tp / Ts (Rp / Rs)^2
(D)	Phase curve	ΔTp/Ts (Rp / Rs)^2

Fit a transit model to each wavelength channel:

$$f'_{i\lambda} = f_{0\lambda} e^{b_\lambda a_i} (1 + d_\lambda r_i) \left(1 + \sum_{j=1}^{J} c_{j\lambda} v_{ji}\right)$$

Initial transmission spectrum of GJ1214b:



BUT: Tilt should not affect spectral features on the narrowest scales