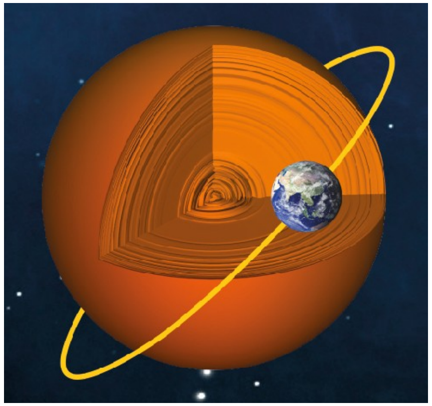
The space photometry revolution

CoRoT3-KASC7 joint meeting

HD 97658 and its super-Earth

Spitzer & MOST transit analysis and seismic modeling of the host star



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M. Gillon (U. Liege), D. Valencia (U. Toronto), N. Madhusudhan (U. Cambridge), D. Dragomir (UC Santa Barbara), and the Spitzer team

1. Introducing HD 97658 and its super-Earth

The second brightest star harboring a transiting super-Earth

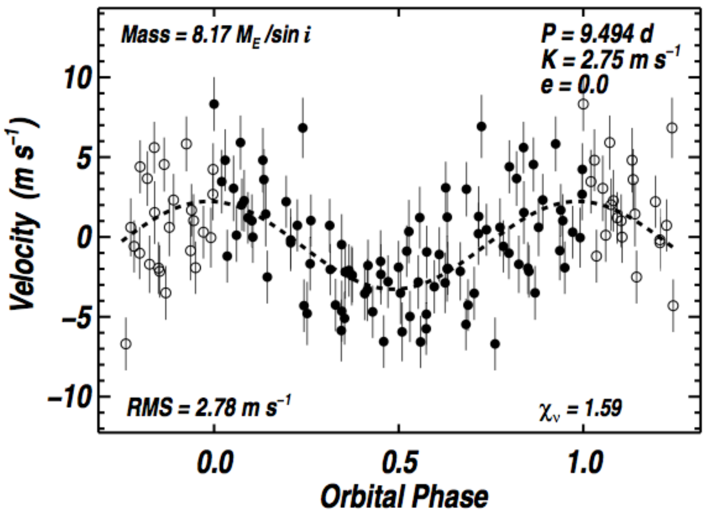
HD 97658 (V=7.7, K=5.7)

- T_{eff} = 5170 ± 50 K (Howard et al. 2011)
- [Fe/H] = -0.23 ± 0.03 ⇒ ~ Z
- d = 21.11 ± 0.33 pc ; from Hipparcos (Van Leeuwen 2007)

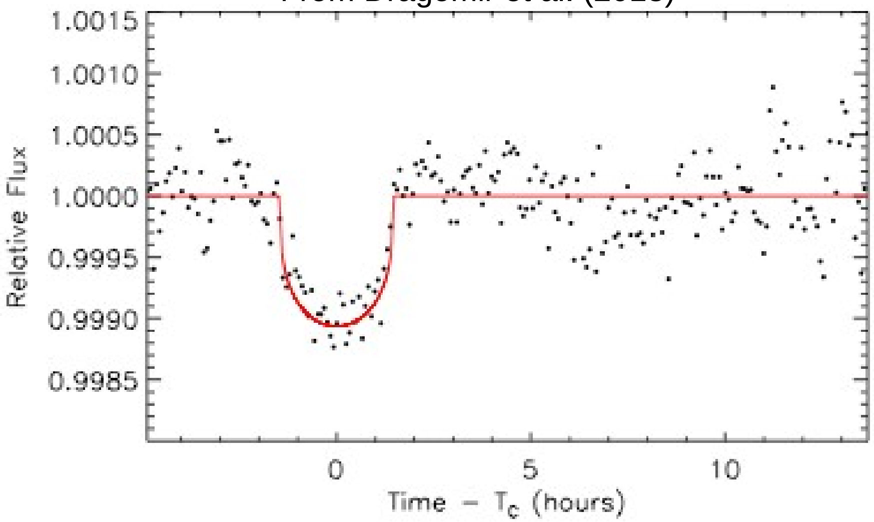
HD 97658 b, a transiting super-Earth

- Discovery by Howard et al. (2011) from Keck-Hires RVs:
  - $M_P \sin i = 8.2 \pm 1.2\ M_{earth}$
  - $P_{orb} = 9.494 \pm 0.005$ d
- Transits discovered by Dragomir et al. (2013) with *MOST*: $R_P = 2.34 \pm 0.18\ R_{earth}$

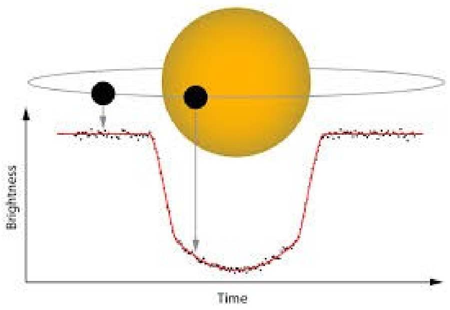
From Howard et al. (2011)



From Dragomir et al. (2013)



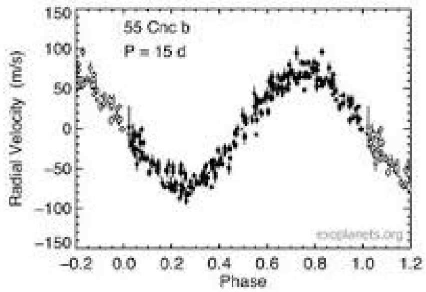
2. Modeling the host star HD 97658



Transits

$$R_p \propto R_*$$

$$M_p \propto M_*^{2/3}$$



Radial velocities

+ the **age** of the star is the best proxy for the age of its planets

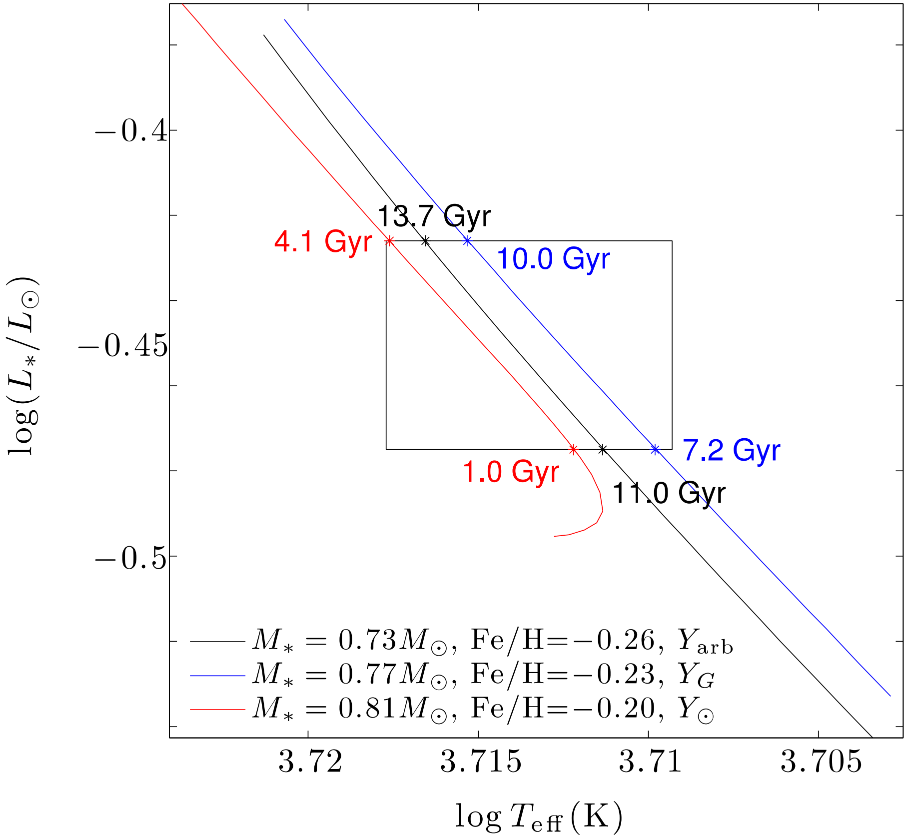
(Sun: 4.57 Gyr, Earth: 4.54 Gyr)

- With Asteroseismology: T. Campante, V. Van Eylen's talks
- Without Asteroseismology: stellar evolution modeling

2. Modeling the host star HD 97658

- d = 21.11 ± 0.33 pc, V = 7.7 ⇒ $L_* = 0.355 \pm 0.018\ L_{sun}$
- $+T_{eff}$ from spectroscopy: $R_* = 0.74 \pm 0.03\ R_{sun}$
- Stellar evolution code CLES (Scuflaire et al. 2008)

⇒ M_*, age with T_{eff}, [Fe/H] and L_* as inputs (with 1σ uncertainties)



α_{MLT}=1.8; no overshooting

Mixture AGSS09

CEFF EoS

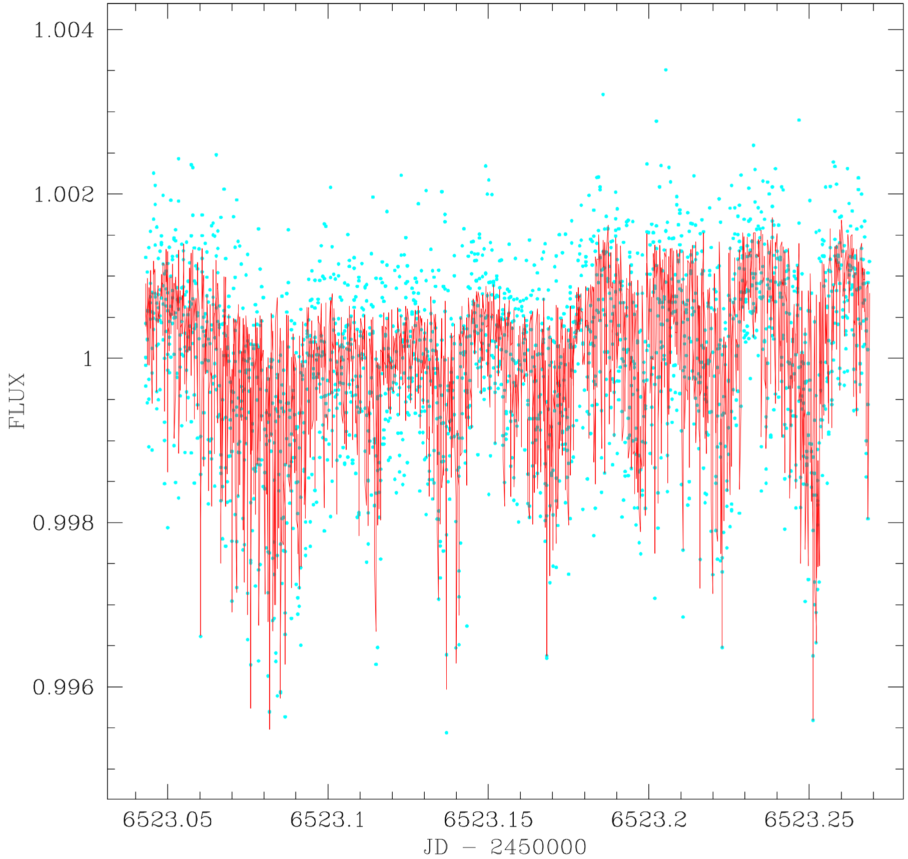
Opacities OPAL05+Ferguson06

Several Y_{ini}

- $M_* = 0.77 \pm 0.05\ M_{sun}$
- No constrain on age

3. Spitzer observations

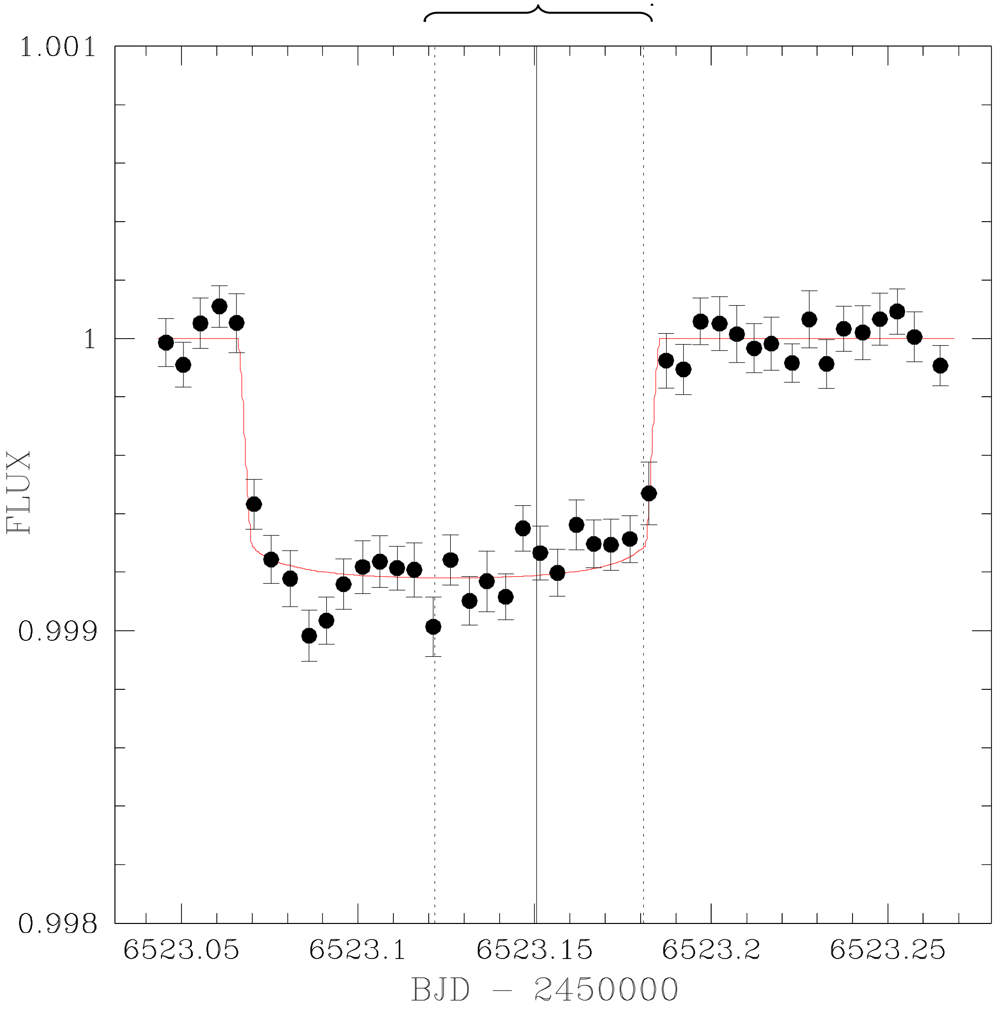
- « Warm » Spitzer IRAC camera at 4.5µm
- As part of the program to search transits for low-mass planets found in RV
  (Programs 60027 and 90072, PI M. Gillon)
- 6h-long lightcurve acquired on Aug 10, 2013 after MOST's ephemeris



Blue dots: raw data
Red curve: photometric model
(= Spitzer systematics)

3. Spitzer observations

MOST transit window (17 orbits after)



Spitzer fully confirms, within 1σ, the MOST ephemeris

4. The MCMC method to characterize HD 97658b

I used Monte-Carlo Markov Chain (MCMC) code of Gillon et al. (2012), with jump parameters (those for which the chain is varying):

•With uniform prior distribution: mid-transit time T_0, transit depth dF, transit width W, P_{orb},…

•With Gaussian prior distribution: stellar mass M_* ($0.77\pm0.05\ M_s$), luminosity ($0.355\pm0.018\ L_s$), T_{eff} (5170 ± 50 K) and metallicity ([Fe/H]=-0.23 ± 0.03)

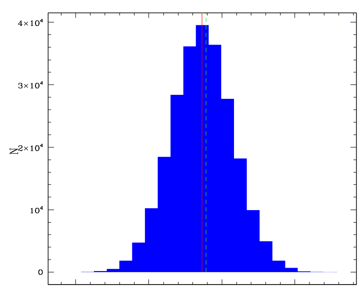
Jump parameters ⇒ model to compare to data through a merit function

$$Q_n^2 = \sum_{k=1}^{l} \frac{(\nu_k - \mu_k)^2}{\sigma_{\nu_k}^2} + \sum_j \frac{(P_{n,j} - P_{0,j})^2}{\sigma_{P_{0,j}}^2}$$

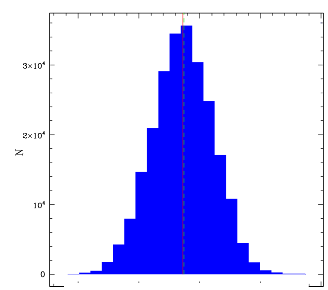
data model

penalty for jump parameter with Gaussian prior

- Results: Probability Density Functions (PDFs) for each jump parameter + for derived parameters: planet mass, radius,…



stellar mass



transit depth

5. Global MCMC analyses of RVs, Spitzer and MOST

171 Keck-Hires RVs + 1 Spitzer transit + 3 MOST transits

Parameter	Symbol	Value	Unit
Jump parameters			
Jump parameter, uniform prior			
Transit depth, *Spitzer*	dF	773 ± 42	ppm
Transit width	W	0.1187 ± 0.0012	days
Mid-transit time-2450000	T_0	$6523.12540^{+0.00060}_{-0.00056}$	BJD_TDB
Impact parameter	$b' = a \cos i / R_*$	$0.35^{+0.13}_{-0.21}$	R_*
Orbital period	P	$9.4903^{+0.0016}_{-0.0015}$	days
Derived planet parameters			
Planet radius (at 4.5μm)	R_P	$2.247^{+0.098}_{-0.095}$	$R_\oplus$
Planet mass	M_P	$7.55^{+0.83}_{-0.79}$	$M_\oplus$
Planet density	ρ_P	$3.90^{+0.70}_{-0.61}$	g cm^{-3}
Planet surface gravity	$\log g_P$	$3.166^{+0.059}_{-0.061}$	
Orbital inclination	i	$89.14^{+0.52}_{-0.36}$	deg
Orbital semi-major axis	a	$0.080^{+0.0017}_{-0.0018}$	AU
Orbital eccentricity	e	$0.078^{+0.057}_{-0.053}$	
Argument of the periastron	ω	71^{+65}_{-63}	deg
RV orbital semi-amplitude	K	$2.73^{+0.26}_{-0.27}$	m/s

Just a word about the uncertainties

Host star:

-3% on R_*

-8% on M_*

→

+ Spitzer & Keck RVs systematics

Planet:

-5% on Rp

-11% on Mp

CHEOPS: uncertainties on planet will come from the star

PLATO and asteroseismology: star + planet < 5%

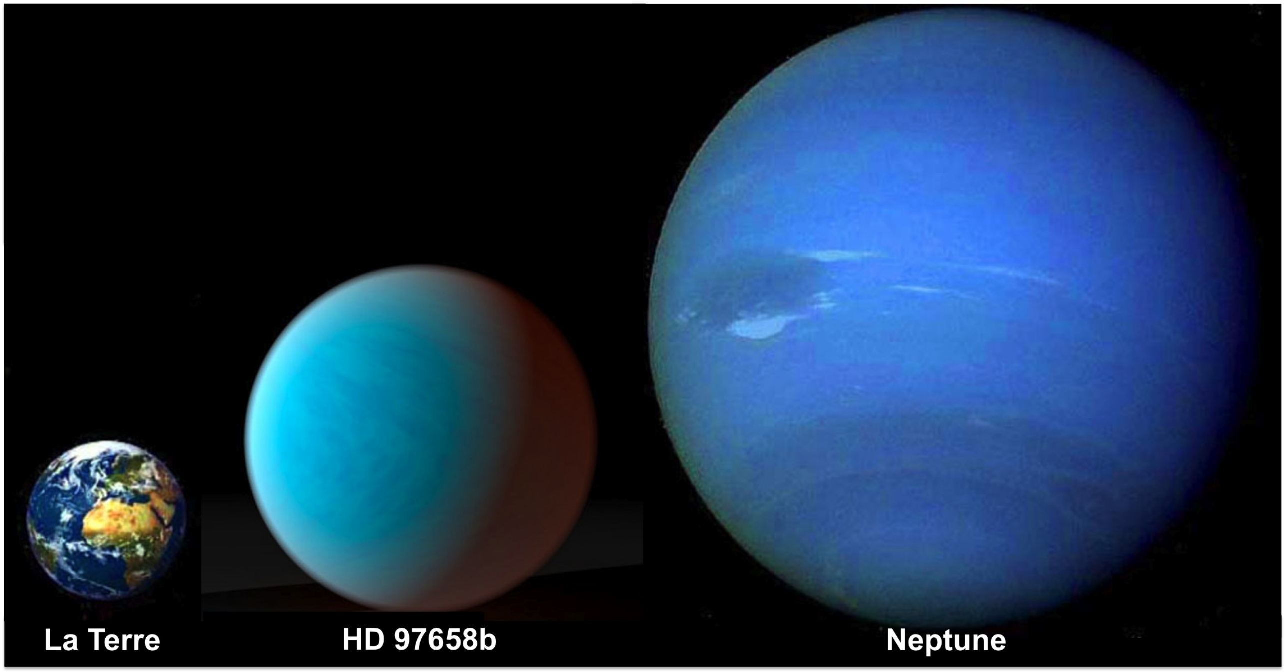
Note: Dragomir et al. (2013), with the same MOST light curves:

$R_P = 2.34 \pm 0.18\ R_{earth}$ (8%)

BUT they used spectroscopic log g and not L_* from Hipparcos

6. HD 97658b, a key object for super-Earth characterization

« True » super-Earth, water-world, mini-Neptune, dwarf gas planet ?



6. HD 97658b, a key object for super-Earth characterization

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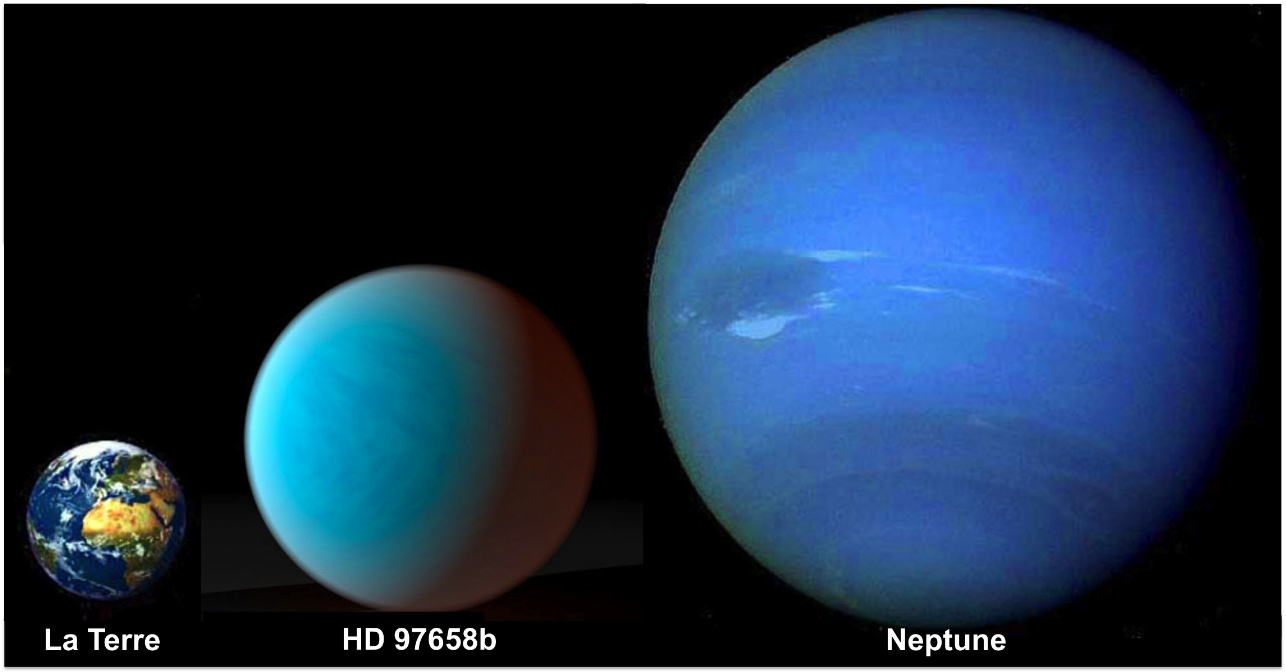


$$\left.\begin{array}{l} R_P = 2.247^{+0.098}_{-0.095}\ R_{earth} \\ M_P = 7.55^{+0.83}_{-0.79}\ M_{earth} \end{array}\right\} \Rightarrow \quad \rho_P = 3.90^{+0.70}_{-0.61}\ \ \mathrm{g\ cm^{-3}}$$

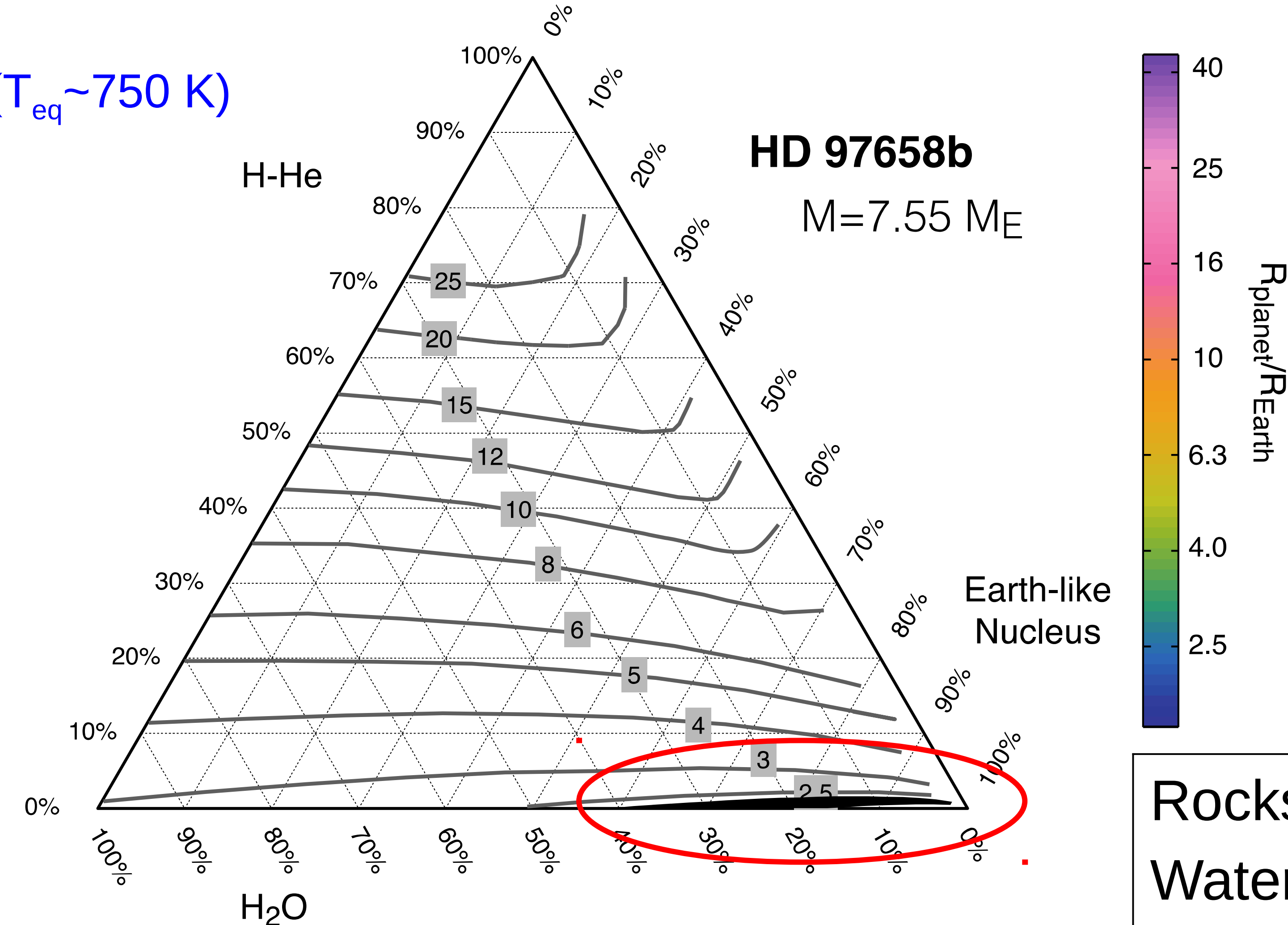
$(\rho_{Earth} = 5.5\ \mathrm{g\ cm^{-3}})$

$(\rho_{Jupiter} = 1.3\ \mathrm{g\ cm^{-3}})$

6. HD 97658b, a key object for super-Earth characterization

Internal composition (D. Valencia)

(T_{eq}~750 K)



(in mass)

Rocks > 60%

Water+Ices 0-40%

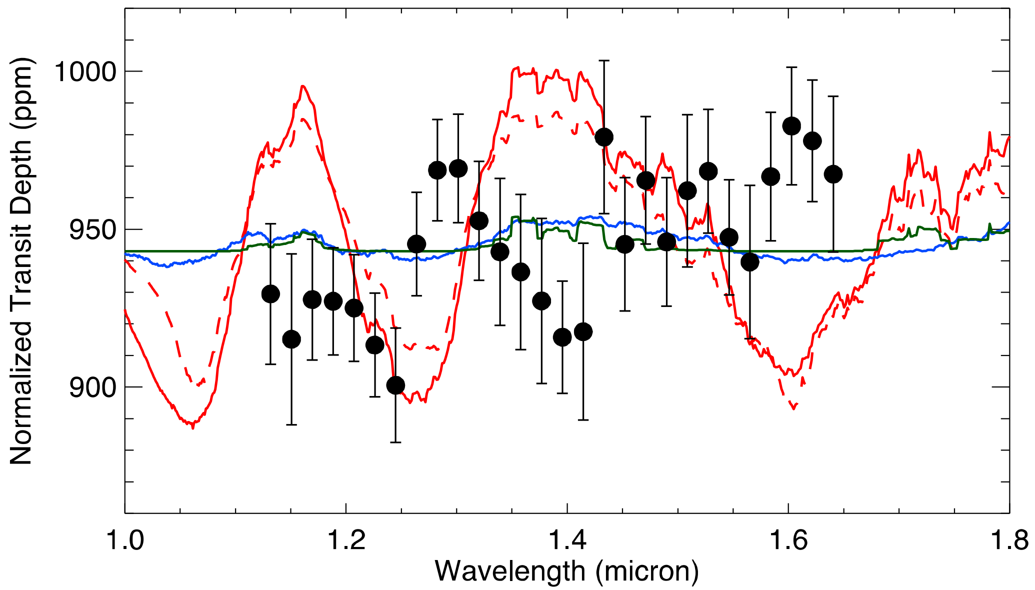
H-He 0-2%

Ices: methanie-ammonia

6. HD 97658b, a key object for super-Earth characterization

Planet atmosphere (H. Knutson)

Hubble Space Telescope WFC3 (19 bandpasses in 1.1-1.6 μm)



Knutson et al. (2014)
ArXiv1403.4602

Excluded: • Cloud-free solar and 50x solar composition atmosphere (red)

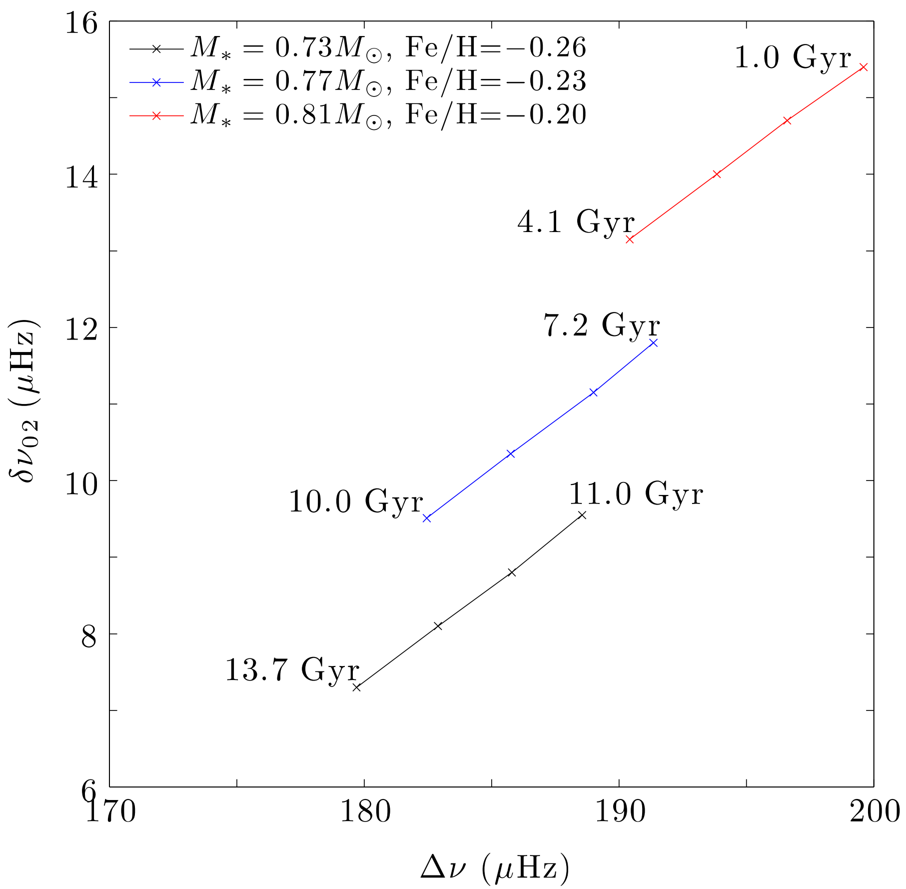
Possibilities: • Water atmosphere (blue)

(2σ…) • Solar composition atmosphere with cloud/hazes at 1 mbar (green)

7. What asteroseismology can bring to HD 97658

- I computed oscillation adiabatic properties of stellar (consistent) models that respect the T_{eff}, L_*, [Fe/H] observational constraints
- Large separations $\Delta\nu=\nu_{n+1,0} - \nu_{n,0}$ and small separations $\delta\nu=\delta\nu_{02}=\nu_{n,0} - \nu_{n-1,2}$ are given here at their ν_{max}'s (where the observed pulsation spectrum is expected to be)

C-D diagram



α_{MLT}=1.8; no overshooting

Several Y_{ini}

~1 μHz accuracy on Δν and $\delta\nu_{02}$ will help to get better stellar mass & age

8. Conclusion & Prospects

Conclusion:

HD 97658b is a key transiting super-Earth

- HD 97658b is an intermediate density super-Earth ⇒ composition of such objects ? (internal composition ? Volatiles ? Thick atmosphere ?)
- Orbiting a bright star (V=7.7,K=5.7) ⇒ very important for future atmospheric characterization (JWST,…)
- Formation of such a planet ?
- Characterizing the host star (mass, radius, age) is essential

Future observations:

- Coming: 3 more transits with Spitzer (PI D. Dragomir)
- GAIA ⇒ very accurate distance, luminosity, and stellar radius (but not sufficient to have Y_{ini} and α_{MLT})
- CHEOPS & TESS: Accurate planet radius in visible
- Asteroseismic observations to improve the stellar mass and age ⇒ we need PLATO !