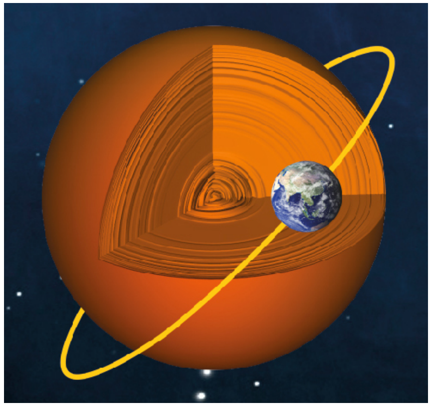
The space photometry revolution

CoRoT3-KASC7 joint meeting

HD 97658 and its super-Earth

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



Valerie Van Grootel
(University of Liege, Belgium)

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

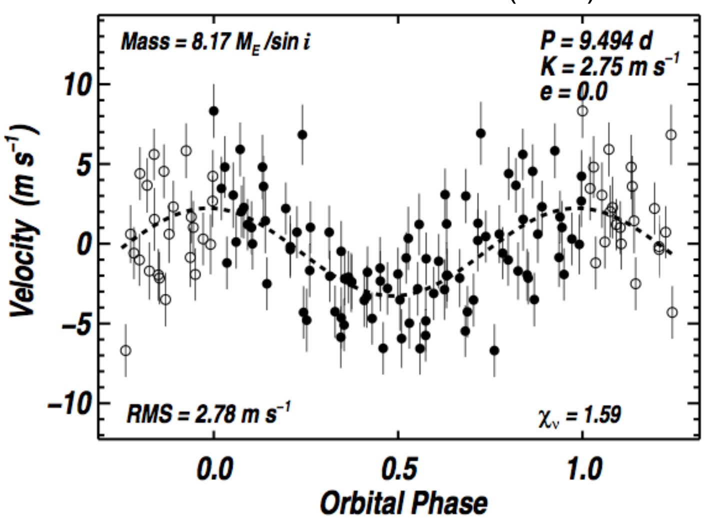
HD 97658 (V=7.7, K=5.7)

- 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)

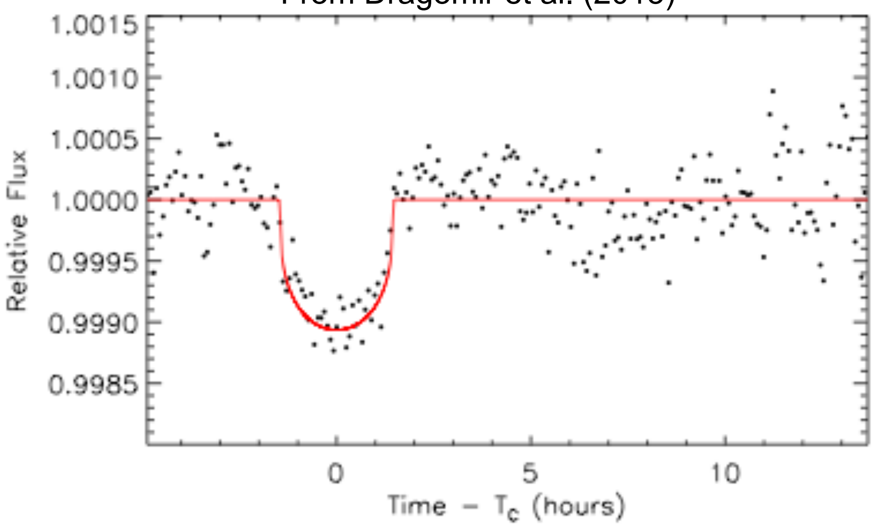
HD 97658 b, a transiting super-Earth

- 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*: $R_P = 2.34 \pm 0.18\ R_{earth}$

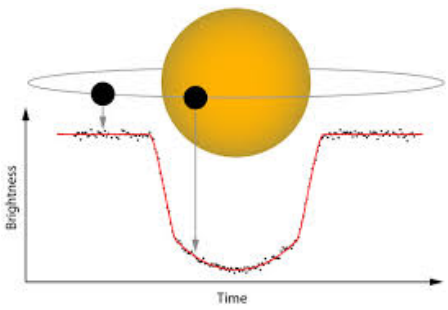
From Howard et al. (2011)



From Dragomir et al. (2013)



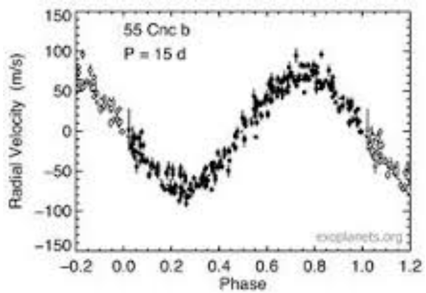
2. Modeling the host star HD 97658



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

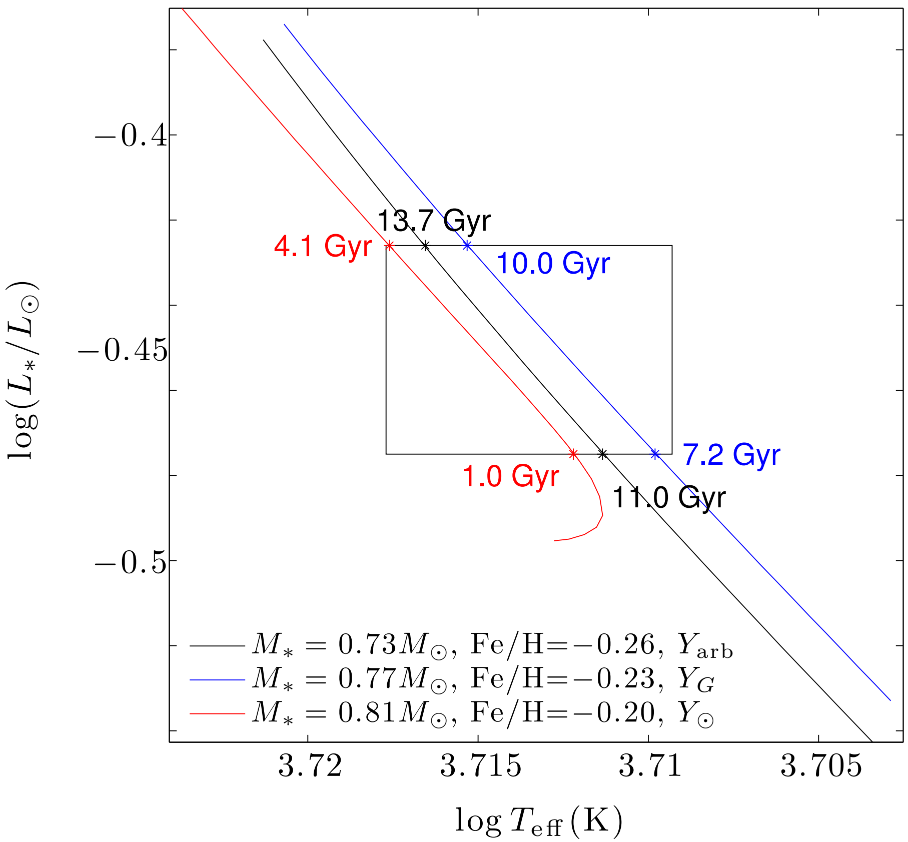
(Sun: 4.57 Gyr, Earth: 4.54 Gyr)

- 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

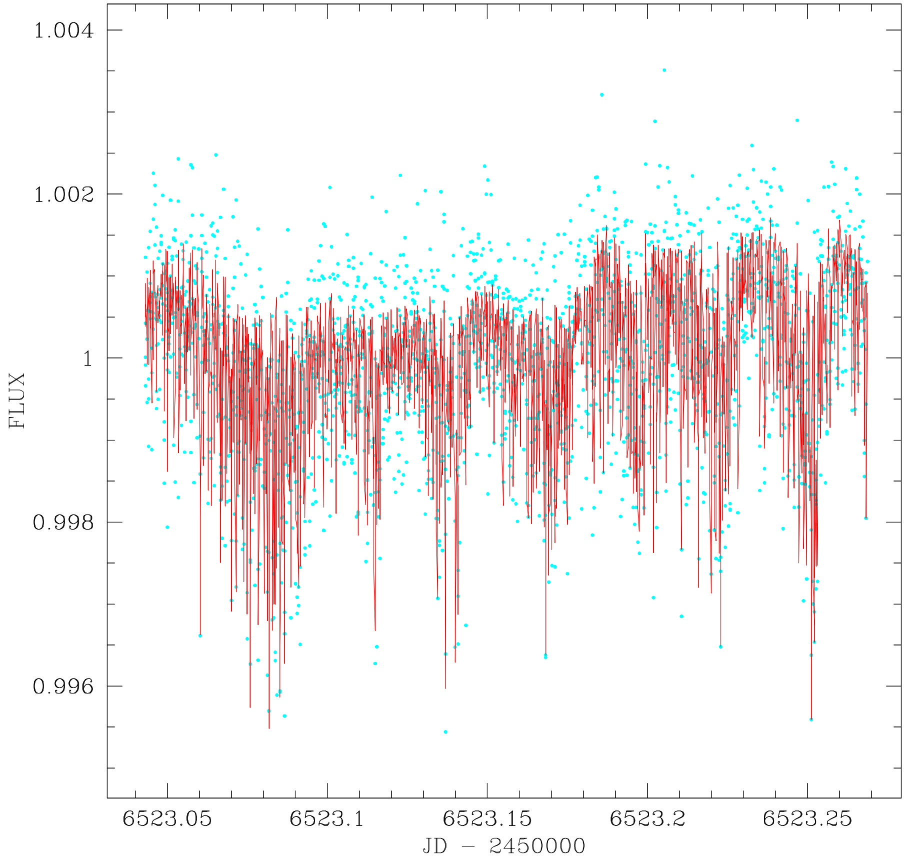
Opacities OPAL05+Ferguson06

Several Y_{ini}

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

3. Spitzer observations

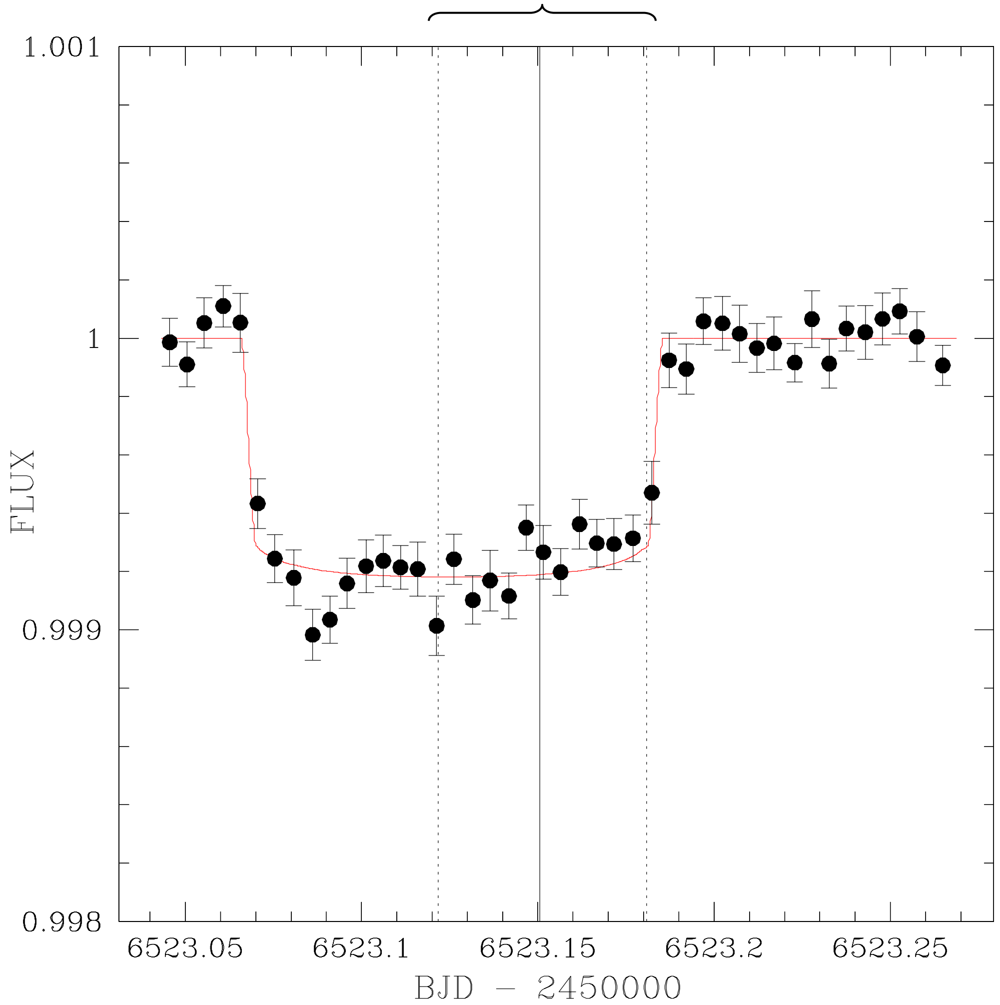
- « Warm » Spitzer IRAC camera at 4.5µm
- As part of the program to search transits for low-mass planets found in RV
  (Programs 60027 and 90072, PI M. Gillon)
- 6h-long lightcurve acquired on Aug 10, 2013 after MOST's ephemeris



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±0.05 M_s), luminosity (0.355±0.018 L_s), T_{eff} (5170±50 K) and metallicity ([Fe/H]=-0.23±0.03)

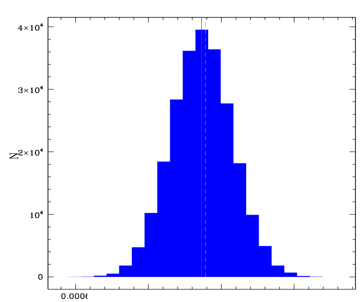
Jump parameters ⇒ model to compare to data through a merit function

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

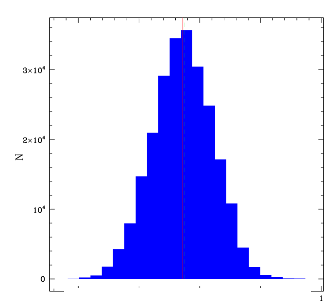
data (ν_k) model (μ_k)

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

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

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%

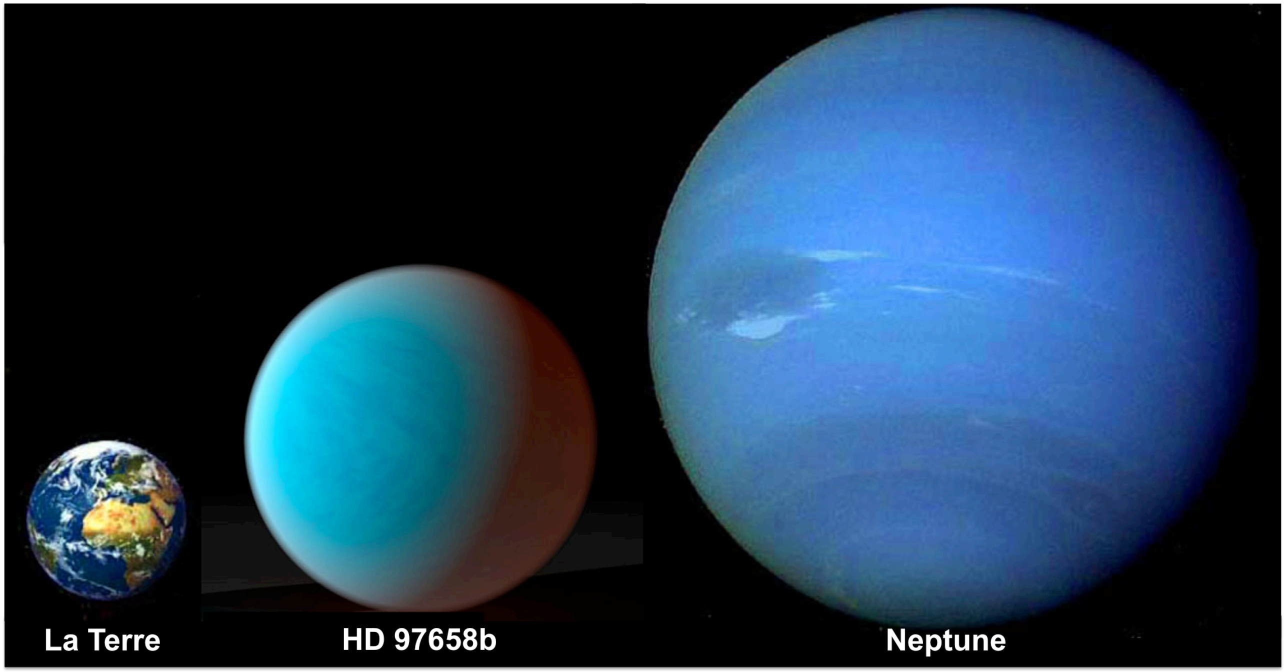
Note: Dragomir et al. (2013), with the same MOST light curves:

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

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

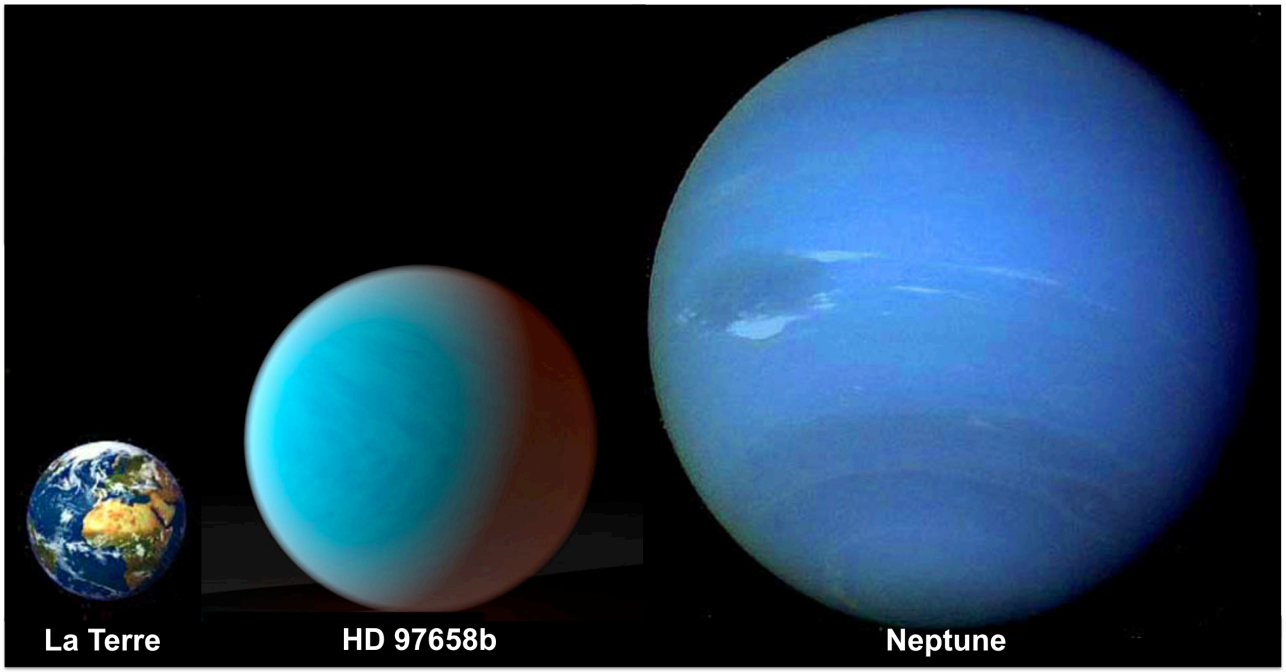
6. HD 97658b, a key object for super-Earth characterization

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



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

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



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

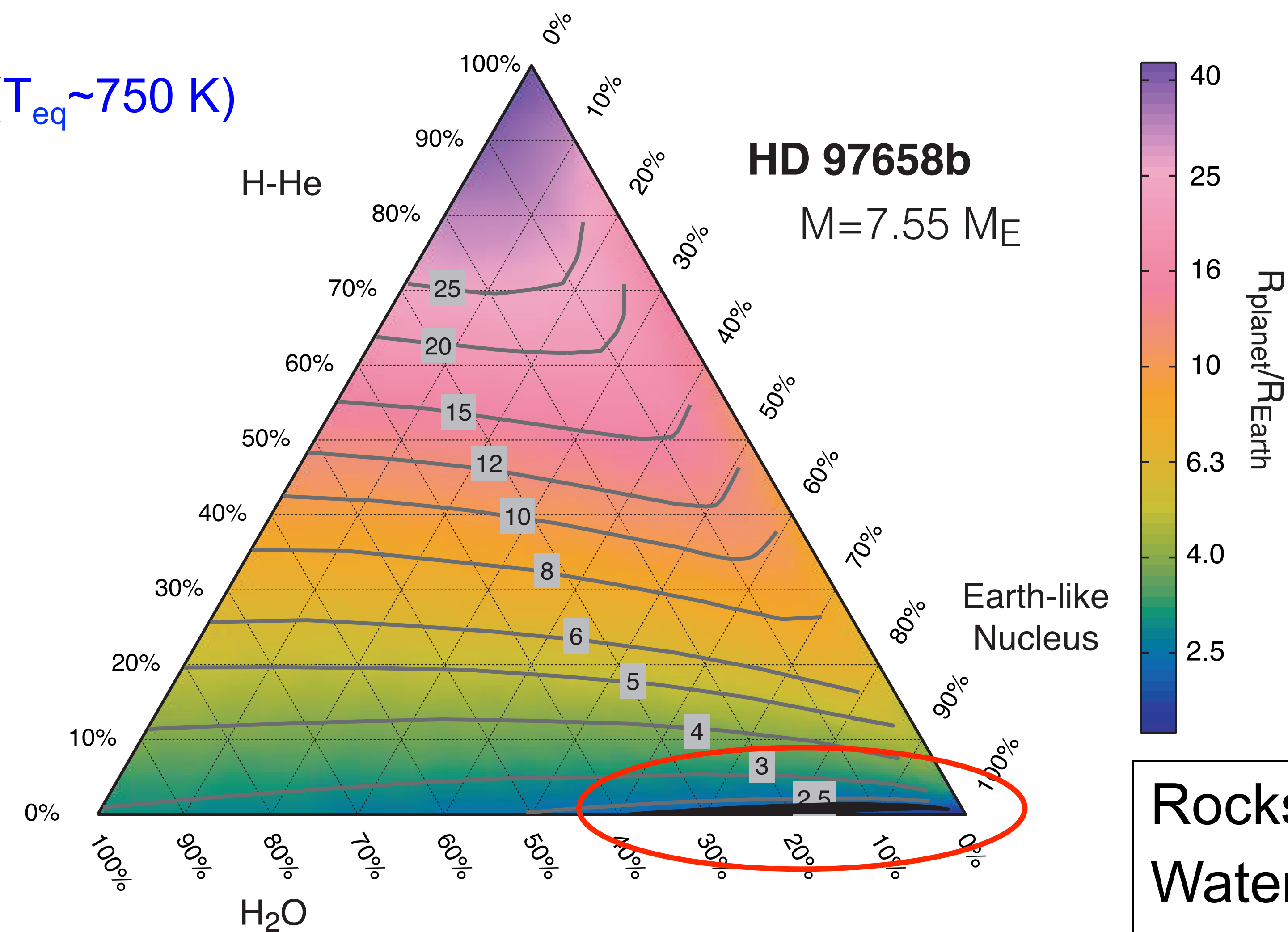
(ρ_{Earth} = 5.5 g cm^{-3})

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

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

Internal composition (D. Valencia)

(T_{eq}~750 K)



Ices: methanie-ammonia

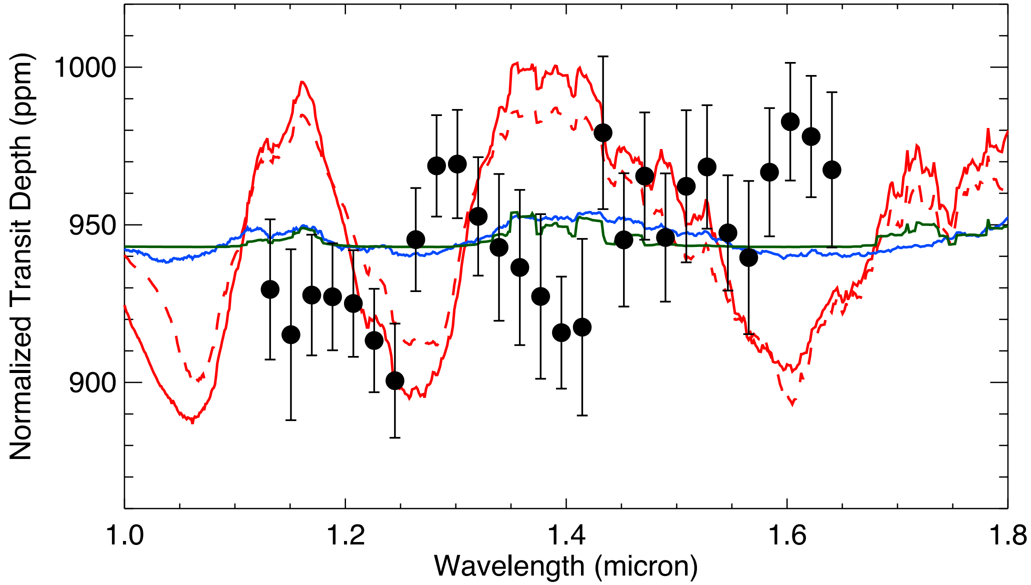
(in mass)

Rocks > 60%
Water+Ices 0-40%
H-He 0-2%

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

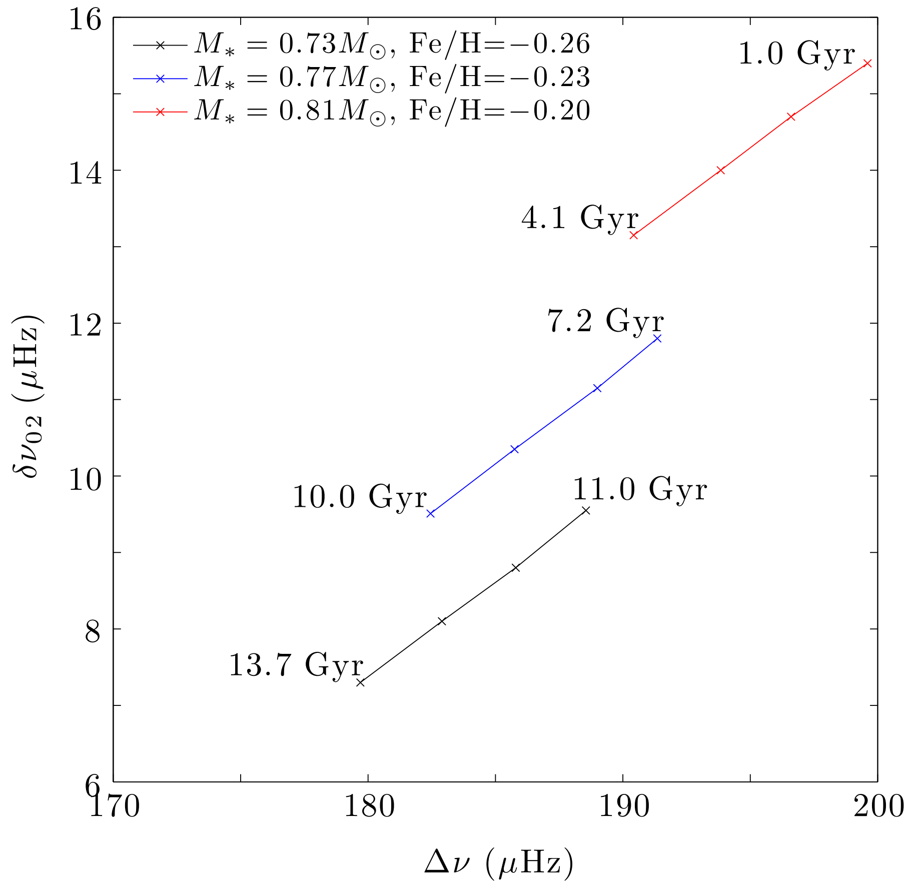
Excluded:
- Cloud-free solar and 50x solar composition atmosphere (red)

Possibilities: (2σ…)
- Water atmosphere (blue)
- 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 $\Delta\nu$ 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})
- Asteroseismic observations to improve the stellar mass and age knowledge ? ⇒ we need PLATO !