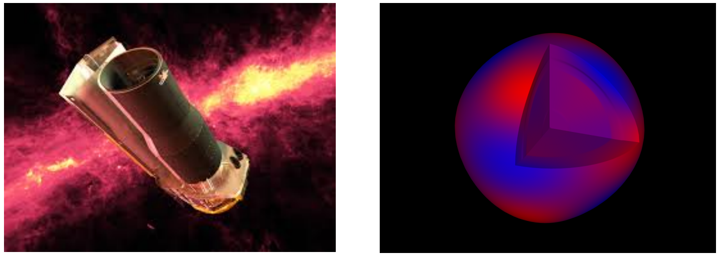
International Francqui Symposium
What asteroseismology has to offer to astrophysics

HD 97658 and its super-Earth

Spitzer transit analysis and seismic modeling of the host star



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Outline

- ✓ Introducing HD 97658, the 2nd brightest star harboring a transiting super-Earth
- ✓ Stellar evolution modeling of HD 97658
- ✓ Spitzer transit light curve analysis
- ✓ Global analysis of RVs, Spitzer and MOST photometry
- ✓ Discussion:
  - ✓ HD 97658b, a key super-Earth
  - ✓ What asteroseismology can bring to HD 97658
- ✓ Conclusion & Prospects

1. HD 97658, the 2nd brightest star harboring a transiting super-Earth

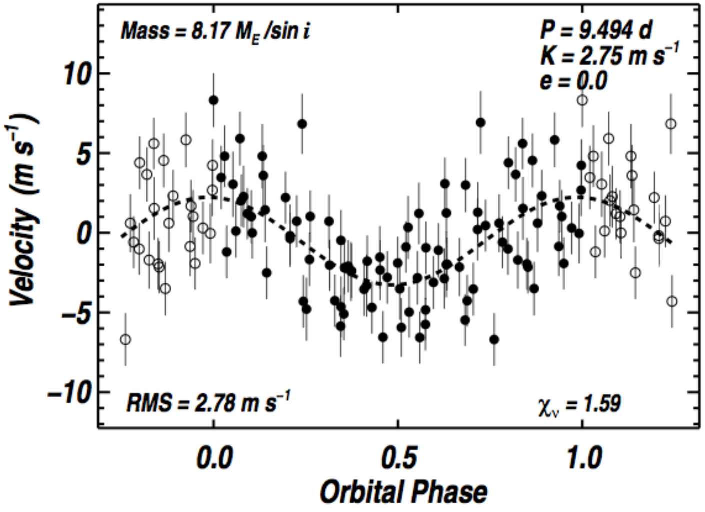
HD 97658 (V=7.7, K=5.7), a K1-type star

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

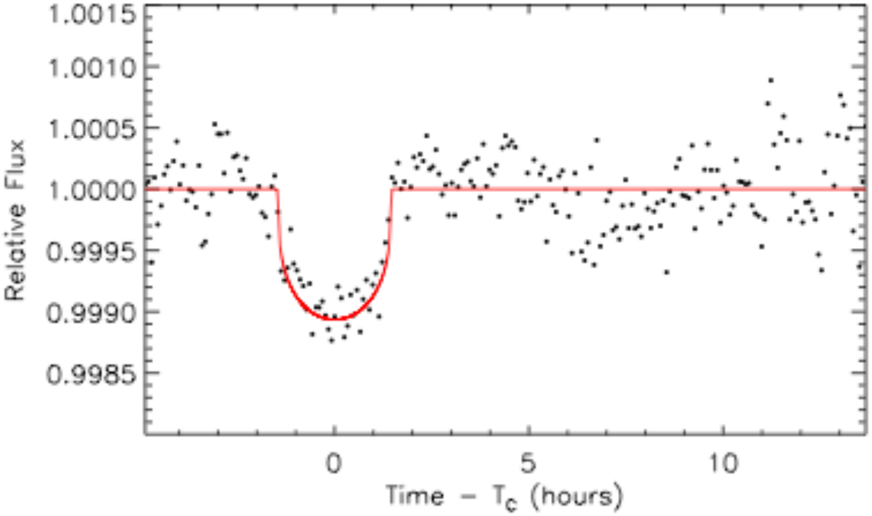
HD 97658 b, a transiting super-Earth

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

From Howard et al. (2011)



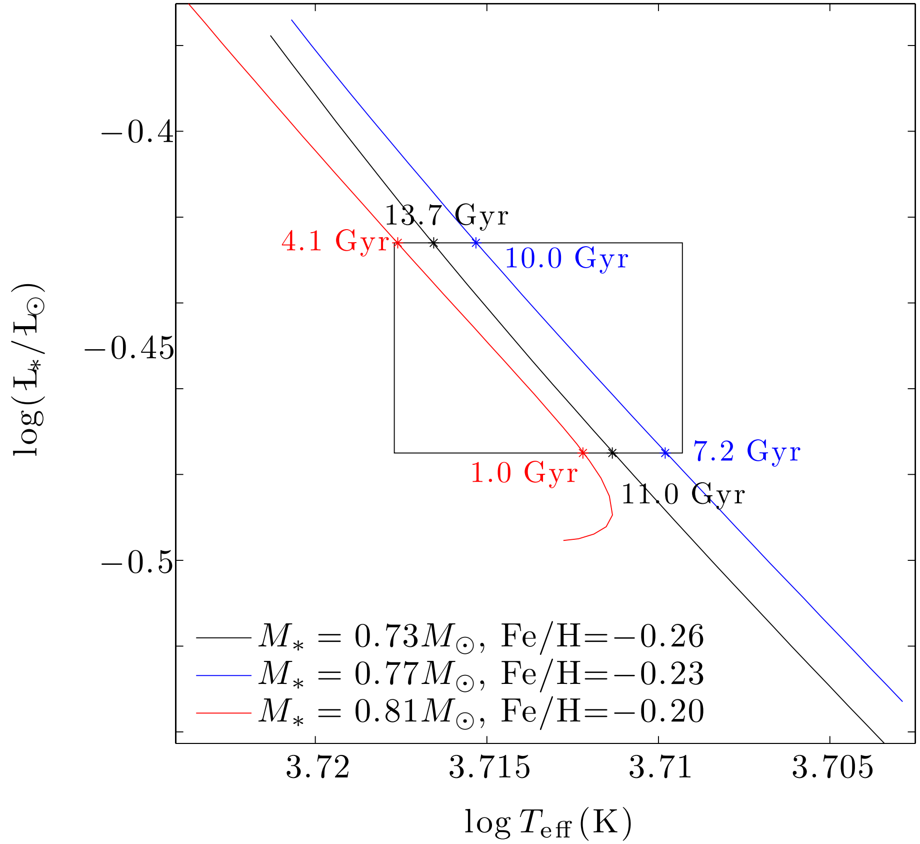
From Dragomir et al. (2013)



2. HD 97658 stellar evolution modeling

- 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)



$M_* = 0.77 \pm 0.05\ M_{sun}$

No constrain on age

(1-14 Gyr….)

3. The MCMC method to characterize HD 97658b

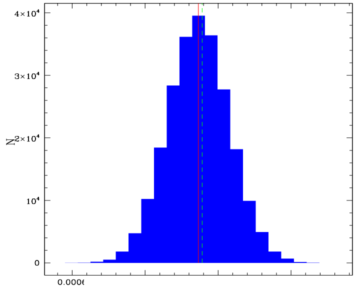
I used Monte-Carlo Markov Chain (MCMC) code of Gillon et al. (2012), with jump parameters (those for which the chain is varying):

- With uniform prior distribution: mid-transit time T_0, transit depth dF, transit width W, orbital period P,…
- 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)

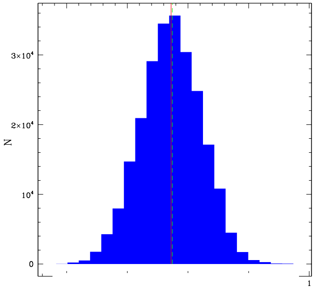
Jump parameters ⇒ model to compare to data through a merit function

$$Q_n^2 = \sum_{k=1}^{l} \frac{(\underset{\substack{\uparrow\\ \text{data}}}{\nu_k} - \underset{\substack{\uparrow\\ \text{model}}}{\mu_k})^2}{\sigma_{\nu_k}^2} + \underbrace{\sum_{j} \frac{(P_{n,j} - P_{0,j})^2}{\sigma_{P_{0,j}}^2}}_{\text{penalty for jump parameter with Gaussian prior}}$$

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



stellar mass



transit depth

4. Spitzer transit light curve analysis

- « 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

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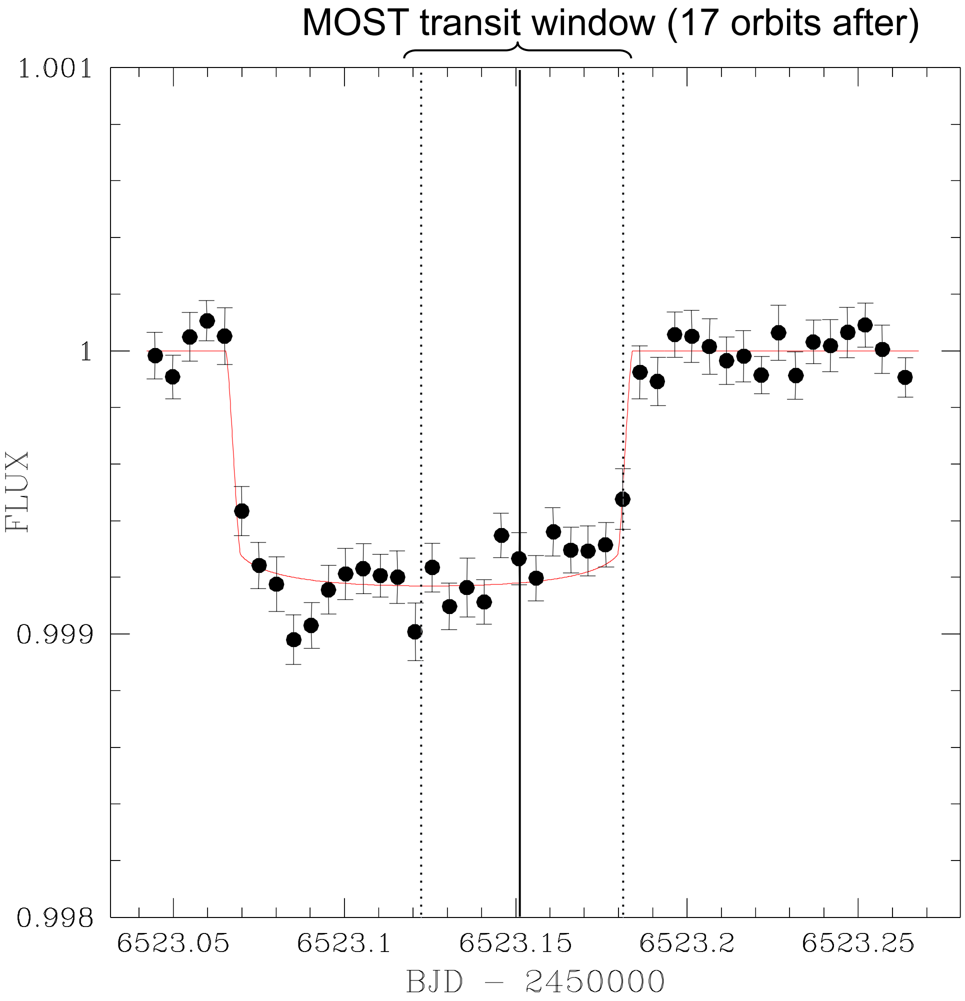


Spitzer mid-transit time:

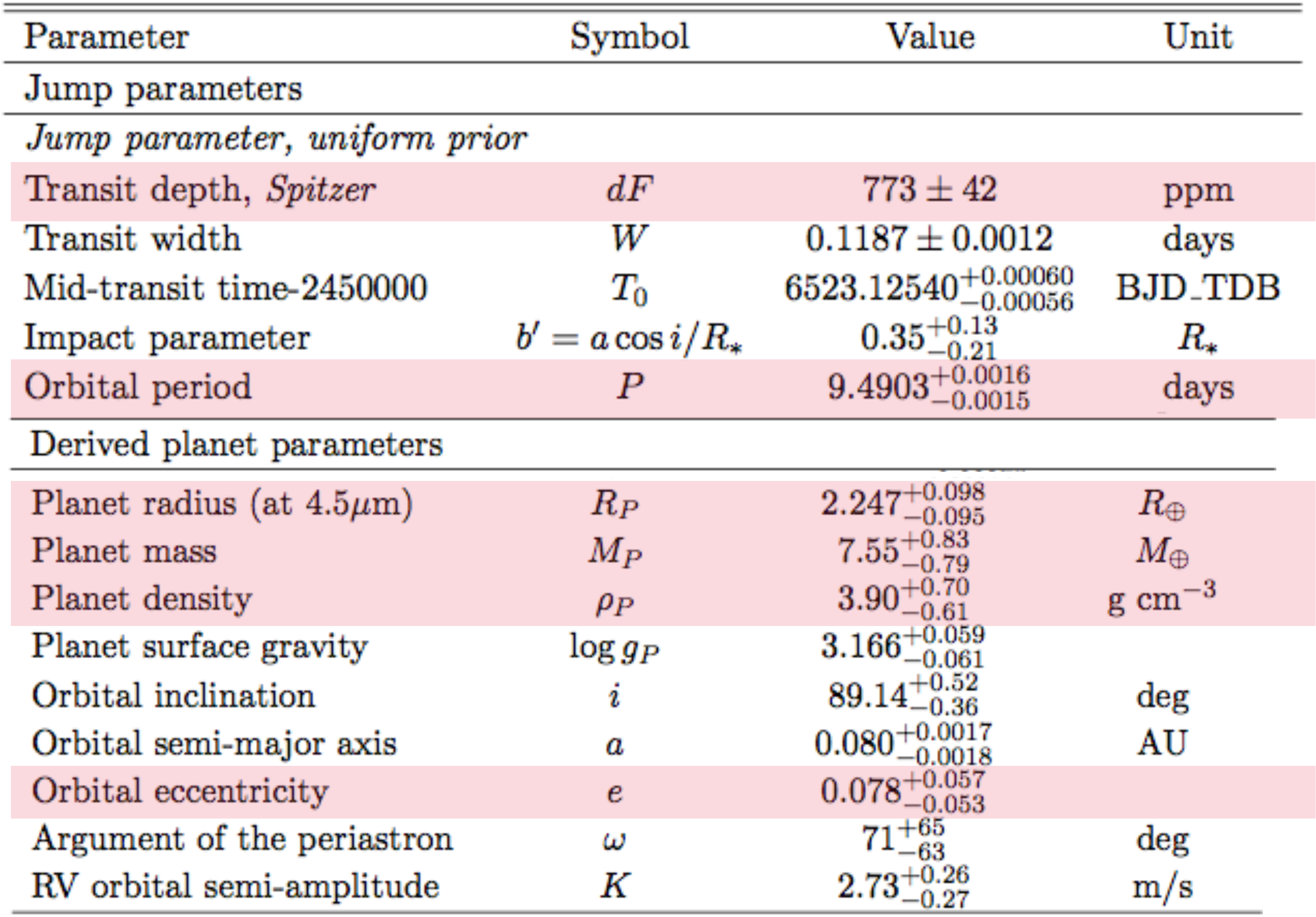
$T_0 = 6523.12544^{+0.00062}_{-0.00059}$

(BJD-2450000)

Spitzer fully confirms, within 1σ, the MOST ephemeris

5. Global MCMC analyses of RVs, Spitzer and MOST

a. 171 Keck-Hires RVs + Spitzer photometry

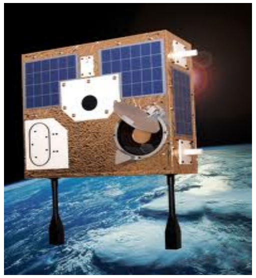


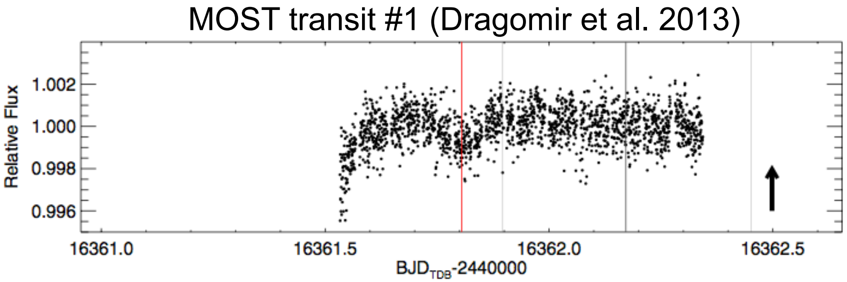
Parameter	Symbol	Value	Unit
Jump parameters			
Jump parameter, uniform prior			
Transit depth, *Spitzer*	dF	773 ± 42	ppm
Transit width	W	0.1187 ± 0.0012	days
Mid-transit time-2450000	T_0	$6523.12540^{+0.00060}_{-0.00056}$	BJD_TDB
Impact parameter	$b' = a \cos i / R_*$	$0.35^{+0.13}_{-0.21}$	R_*
Orbital 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

5. Global MCMC analyses of RVs, Spitzer and MOST

b. 171 Keck-Hires RVs + Spitzer + MOST photometry

MOST: broadband visible light, 3 full transiting light curves





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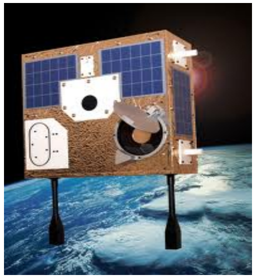
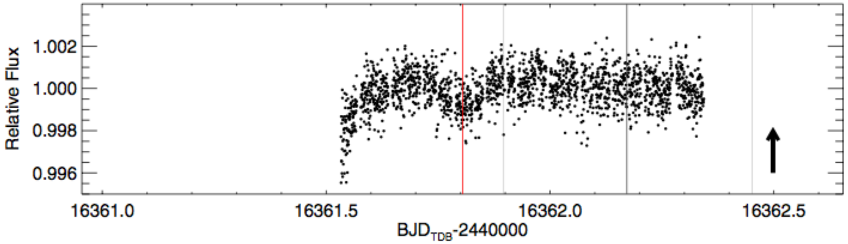




MOST transit #1 (Dragomir et al. 2013)

- $dF_{MOST} = 949^{+81}_{-75}$ ppm ⇒ $R_P = 2.49^{+0.14}_{-0.13}\ R_{earth}$ (visible)
- $dF_{Spitzer} = 773 \pm 42$ ppm ⇒ $R_P = 2.247^{+0.098}_{-0.095}\ R_{earth}$ (4.5 µm)

✓ MOST unknown instrumental or reduction pipeline effects ?

✓ True ? (planet atmosphere with Rayleigh scattering)

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

$R_P = 2.34 \pm 0.18\ R_{earth}$

BUT they used $L_* = 0.30 \pm 0.03\ L_{sun} \Rightarrow R_* = 0.70 \pm 0.03\ R_{sun}$, too small !

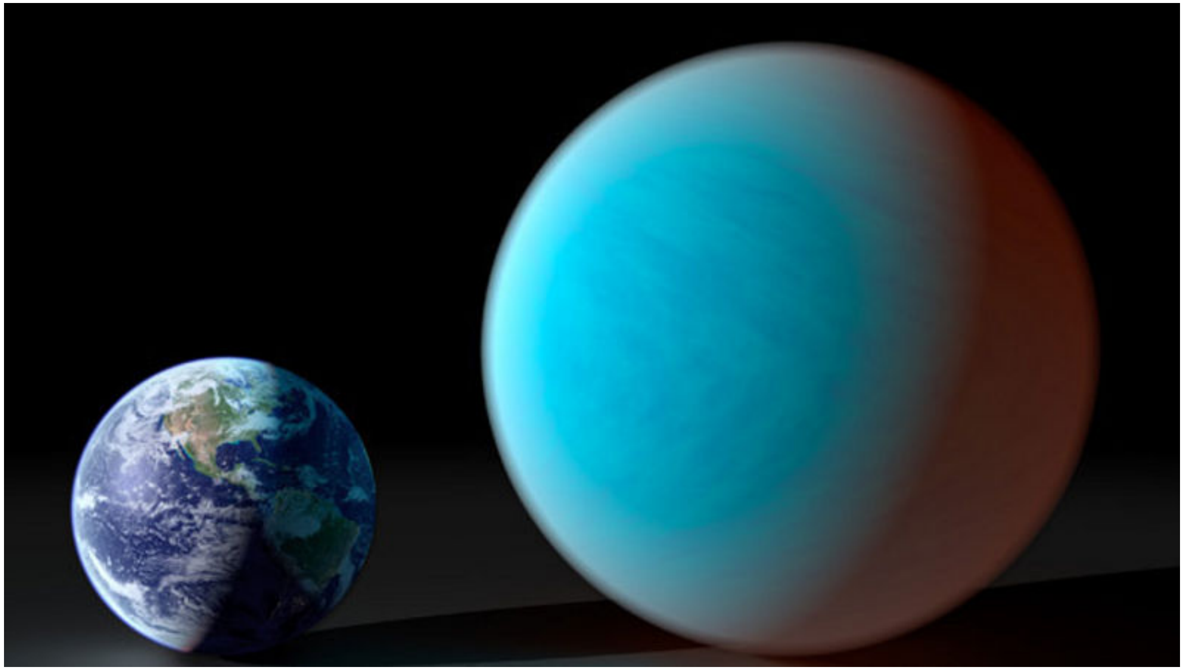
6. HD 97658b, a key object for super-Earth characterization

a. Internal composition (D. Valencia)

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

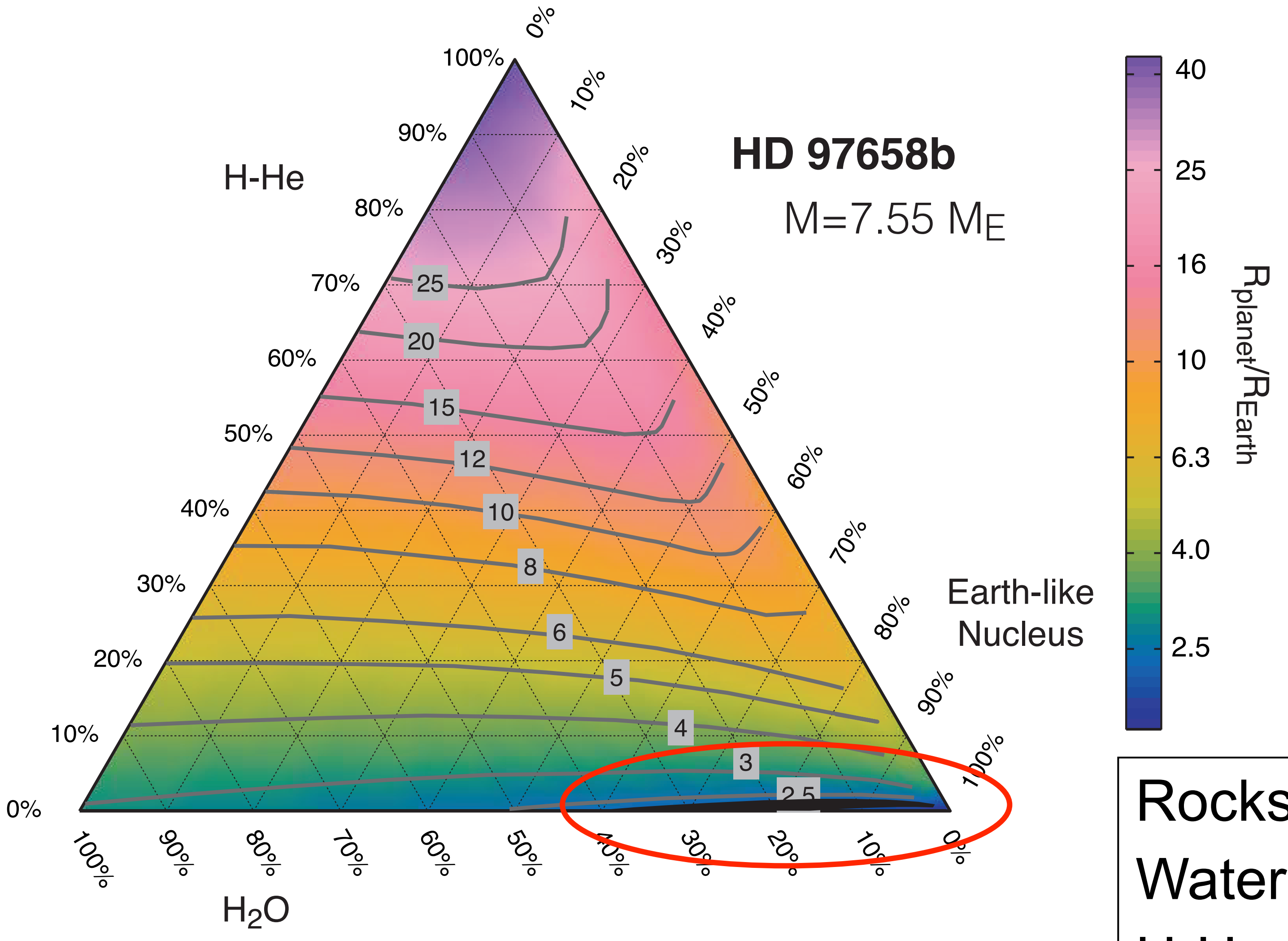
$(\rho_{Earth} = 5.5\ \mathrm{g\ cm^{-3}})$

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



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

Ternary diagram (T_{eq}~750 K)



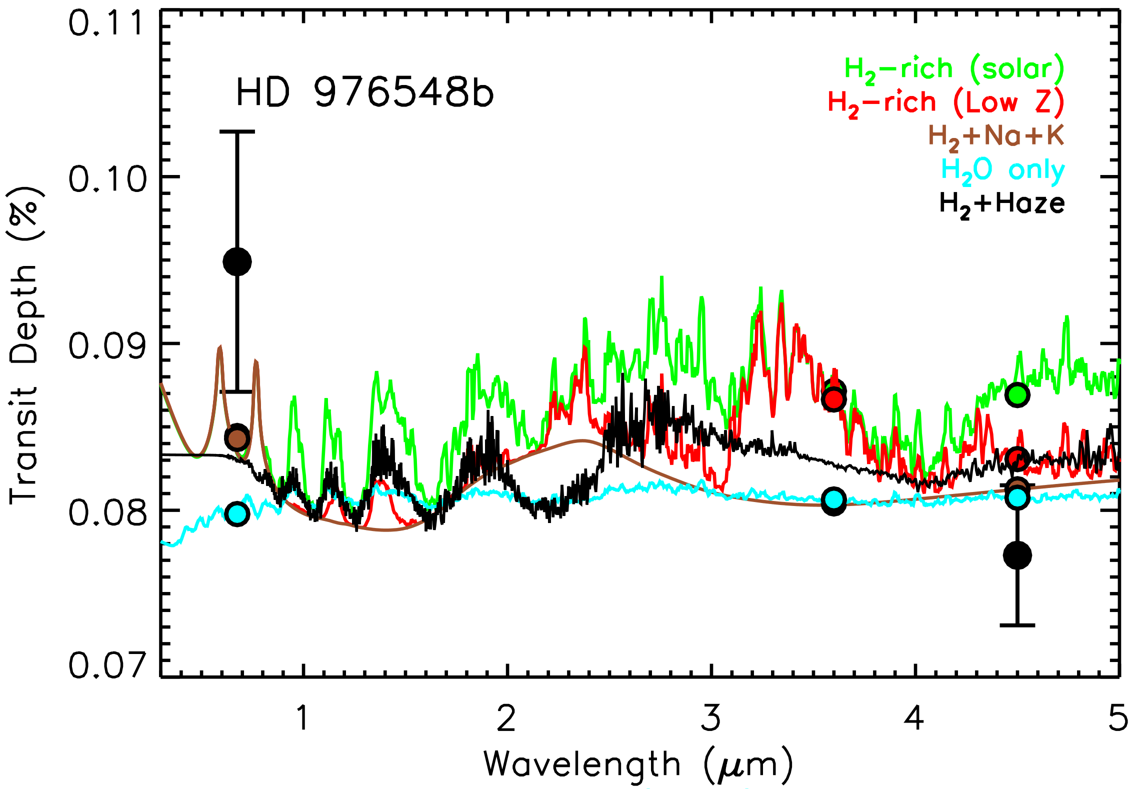
Rocks > 50%

Water 0-40%

H-He 0-2%

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

b. Planet atmosphere modeling (N. Madhusudhan)



Excluded:

- Water-rich atmosphere (blue)
- Cloud-free solar composition atmosphere (green)
- thick opaque clouds (flat spectrum)

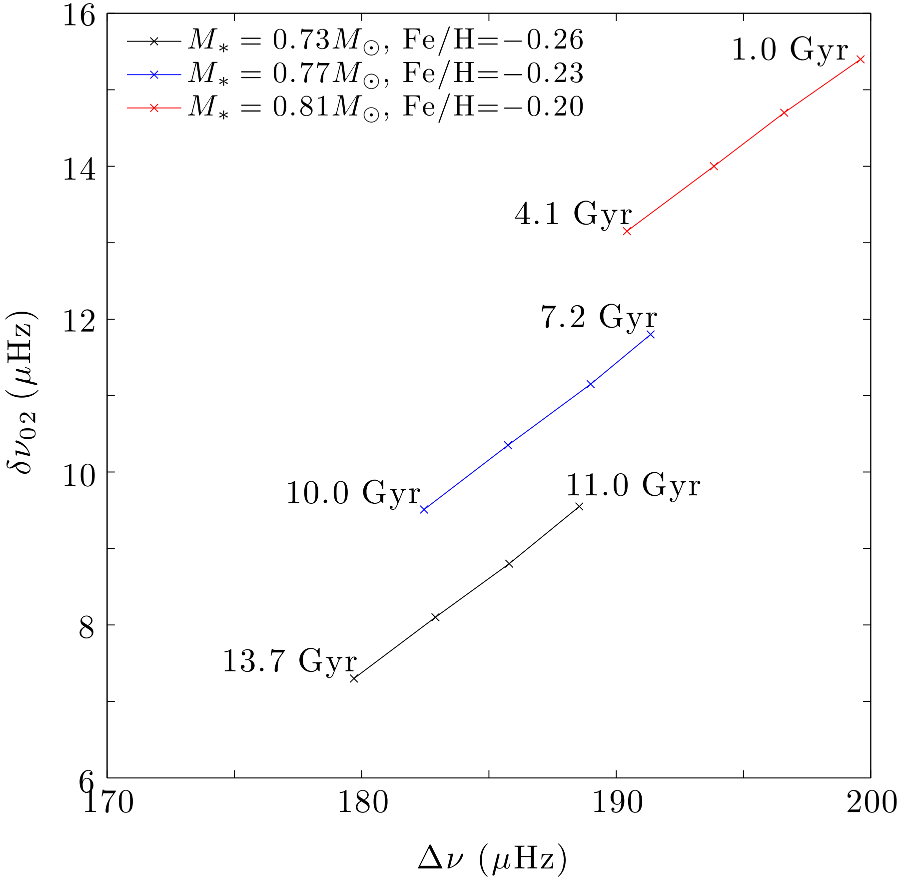
Possibilities:

- low metallicities atmospheres (red and brown): H_2-rich, low Z (O (solar)/50) or H_2+Na+K only
- H_2-rich atmosphere with haze (black)

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



Even a ~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

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

Future observations:

- Coming: 6 more transits with Spitzer (PI D. Dragomir) and transmission spectroscopy for atmospheric characterization with Hubble/WFC3 IR (PI H. Knutson)
- GAIA ⇒ very accurate distance, luminosity, and stellar radius (but not sufficient)
- Asteroseismic observations to improve the stellar mass and age knowledge ?

TESS, CHEOPS, PLATO 2.0 ?

2. HD 97658 stellar evolution modeling

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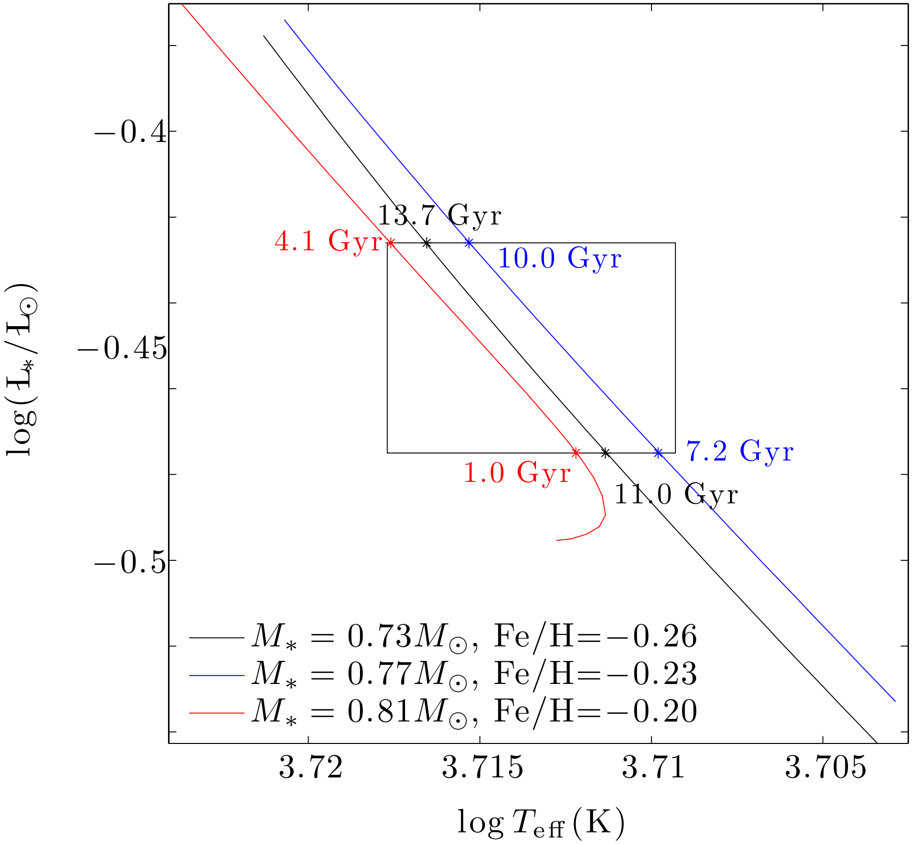

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(1-14 Gyr….)