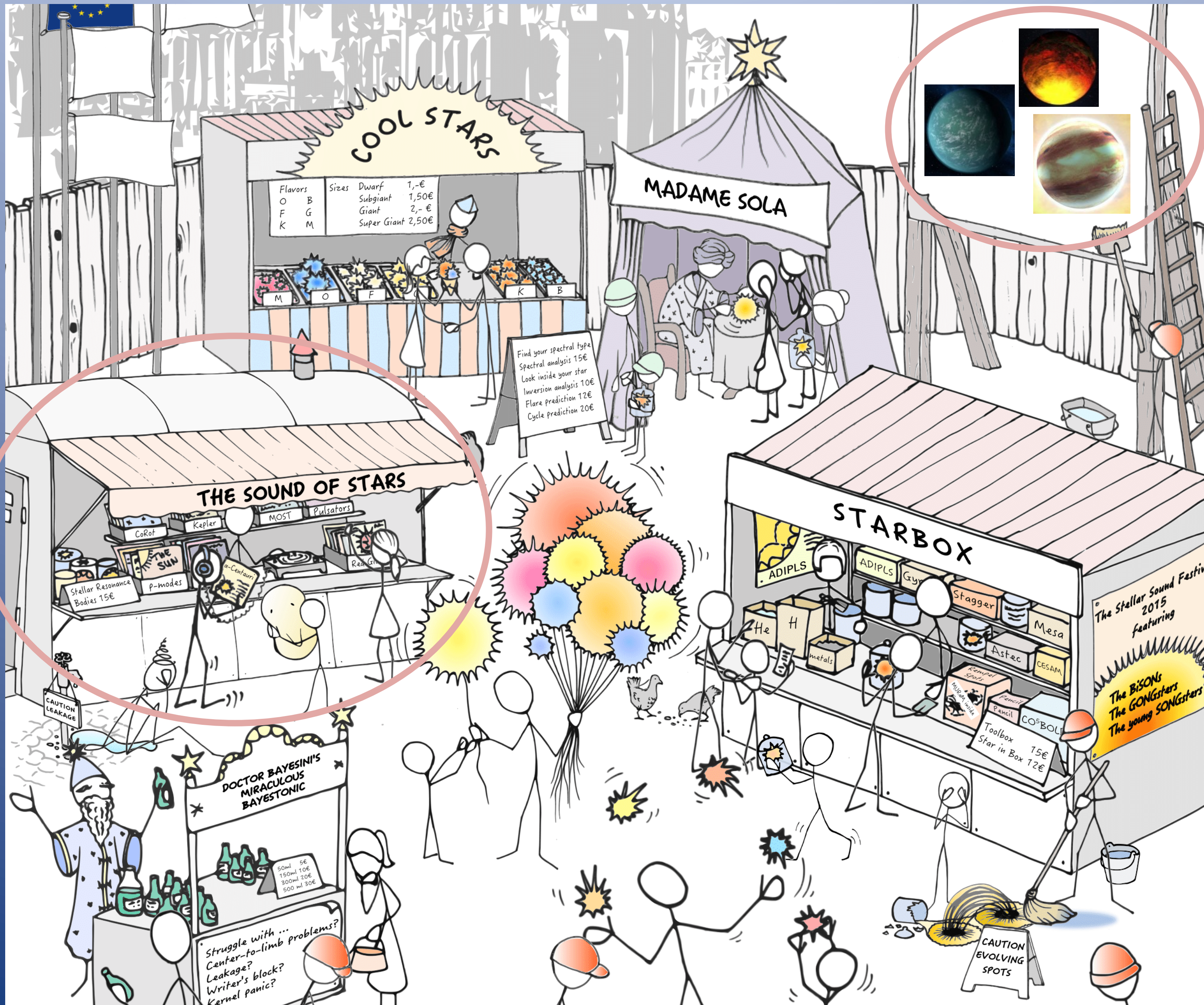
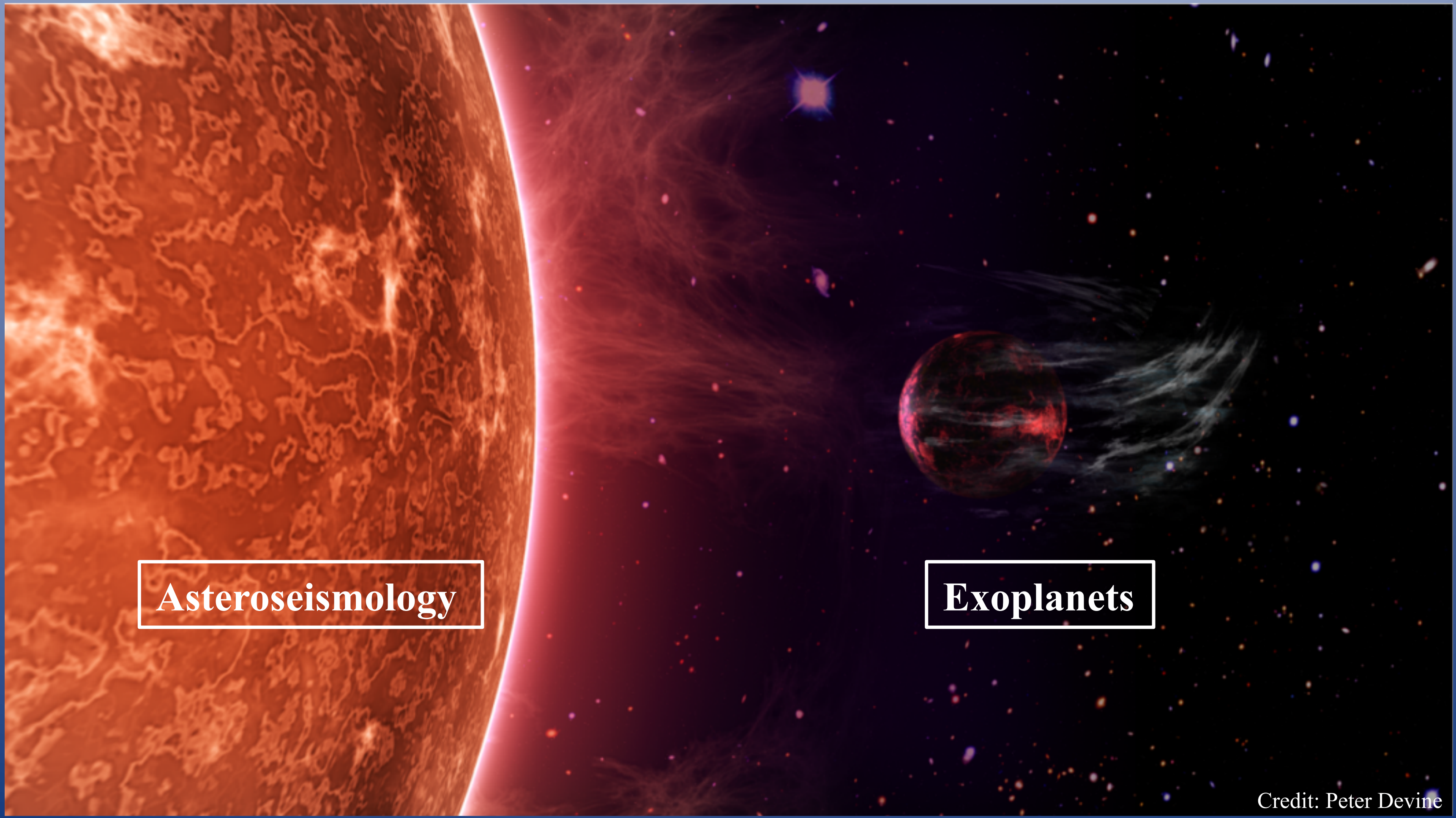
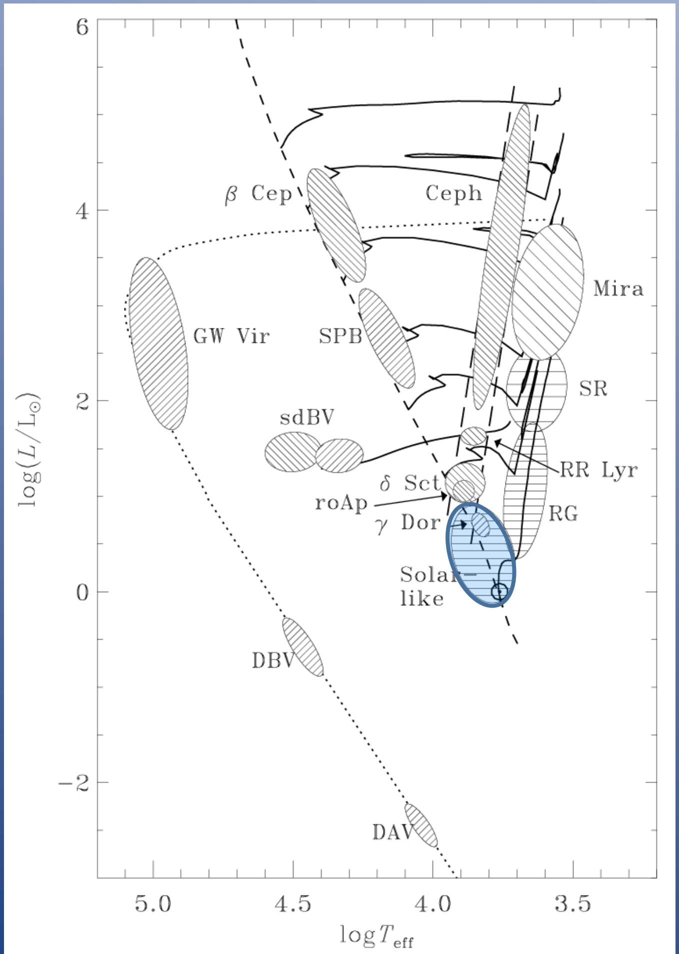
Credit: http://www.spaceinn.eu/wp-content/uploads/2015/05/poster_helas7_2015.pdf and NASA



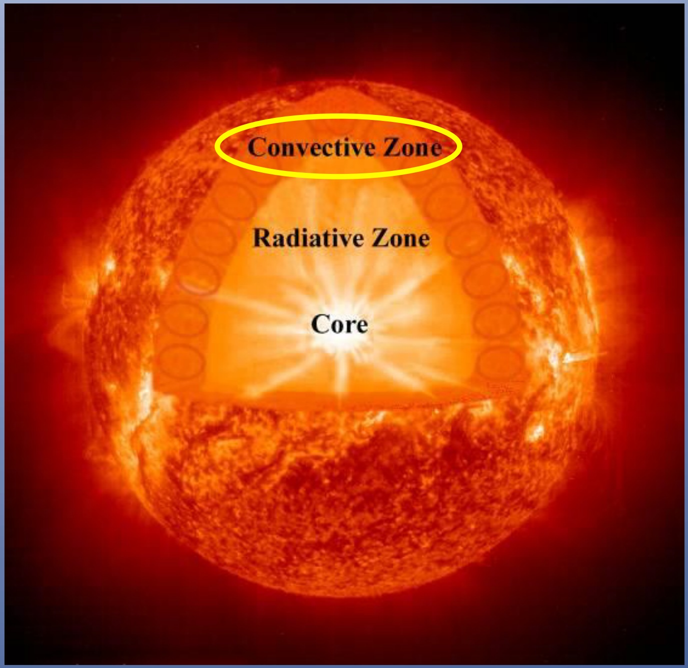
Exoplanet properties using asteroseismology

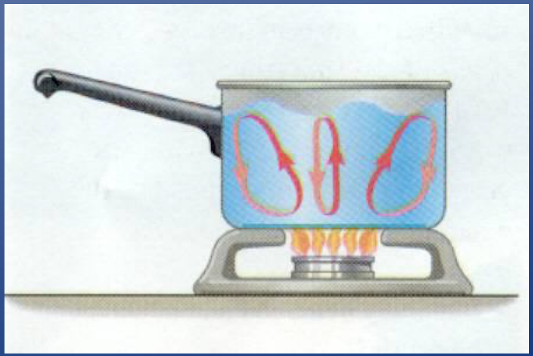


Introduction to asteroseismology

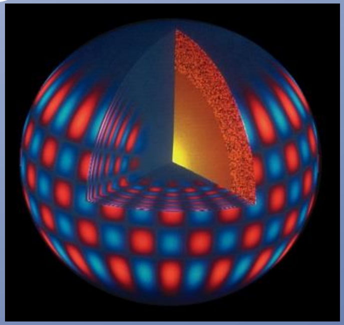


Christensen-Dalsgaard, 2012

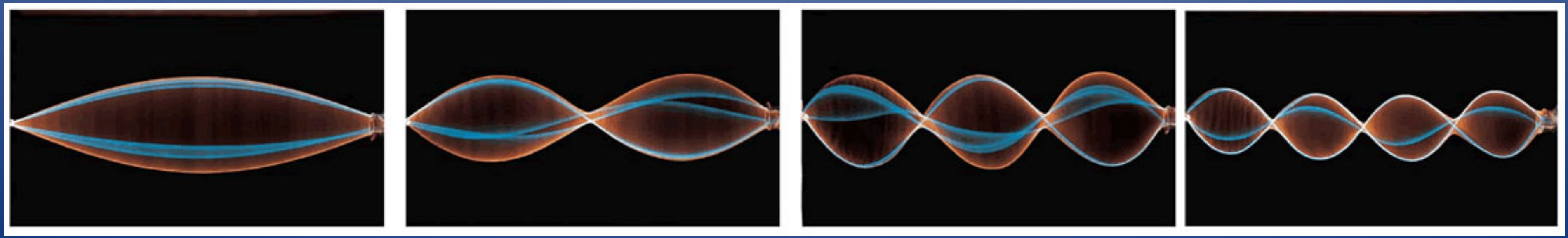




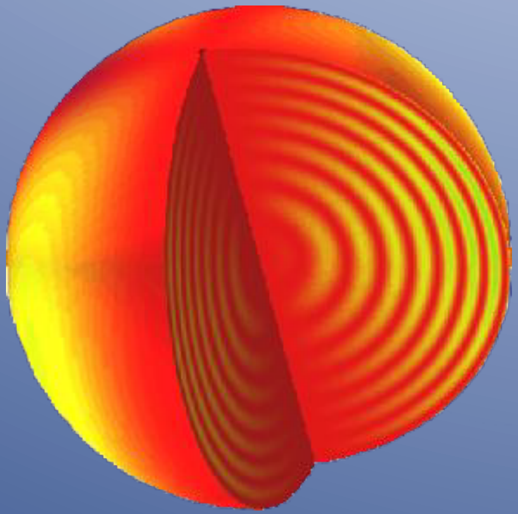
Standing waves on a string



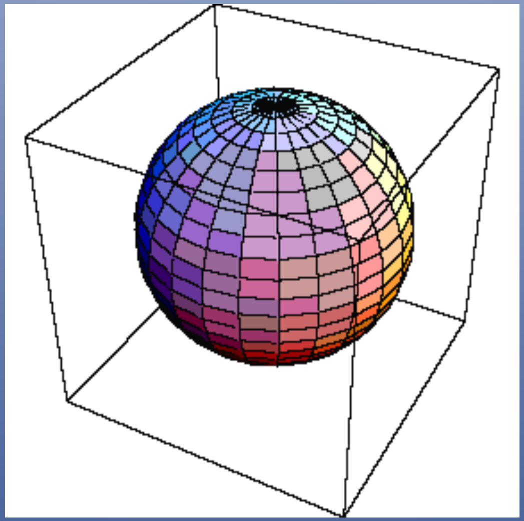
- Eigenmodes of the string:
  - Standing wave, string fixed in both ends.
  - $L = n\lambda/2 \Leftrightarrow \lambda = 2L/n \Leftrightarrow \nu = nc/2L$.
  - Infinite number of eigenmodes with increasing frequency.



Quantum numbers

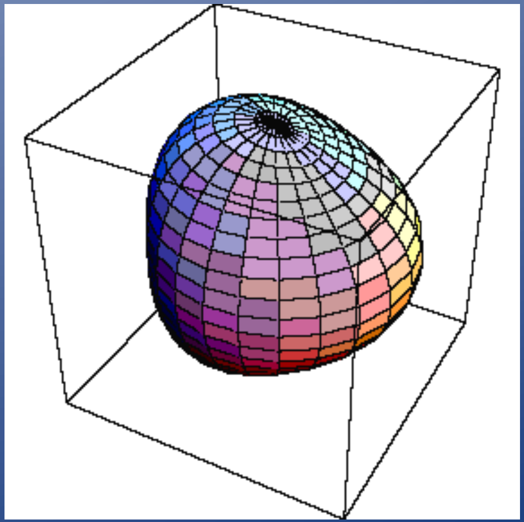


n=18 and l=|m|=2



l=1, m=0

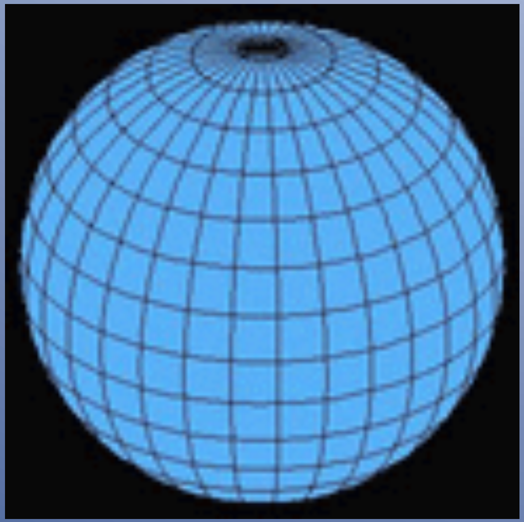
l=3, |m|=1



http://astro.phys.au.dk/KASC/seismology/seism.html

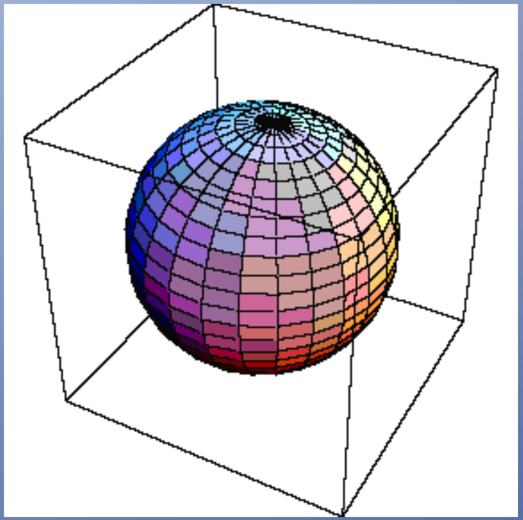
http://www.physics.usyd.edu.au/~bedding/animations/visual.html

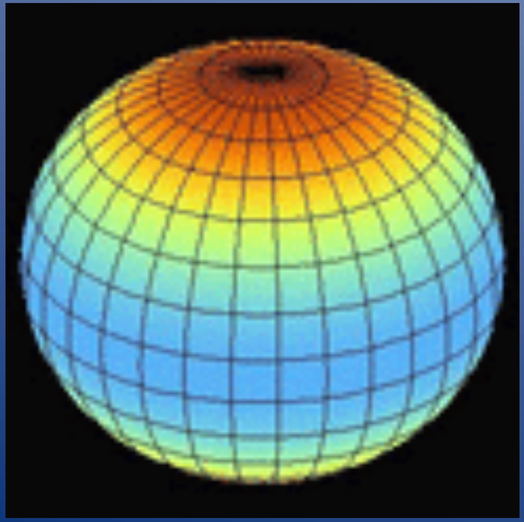
Quantum numbers, quiz



l=0, m=0

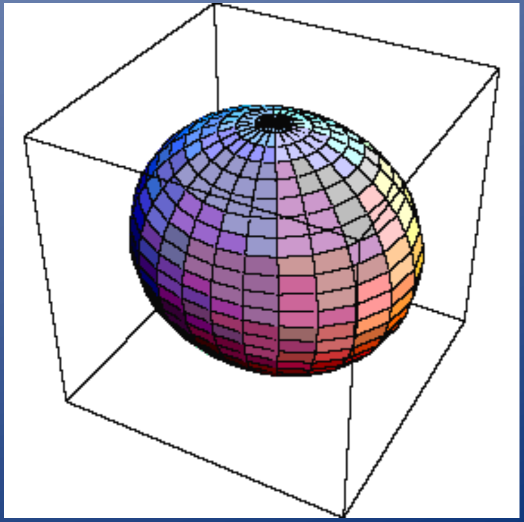
l=1, $|m|$=1



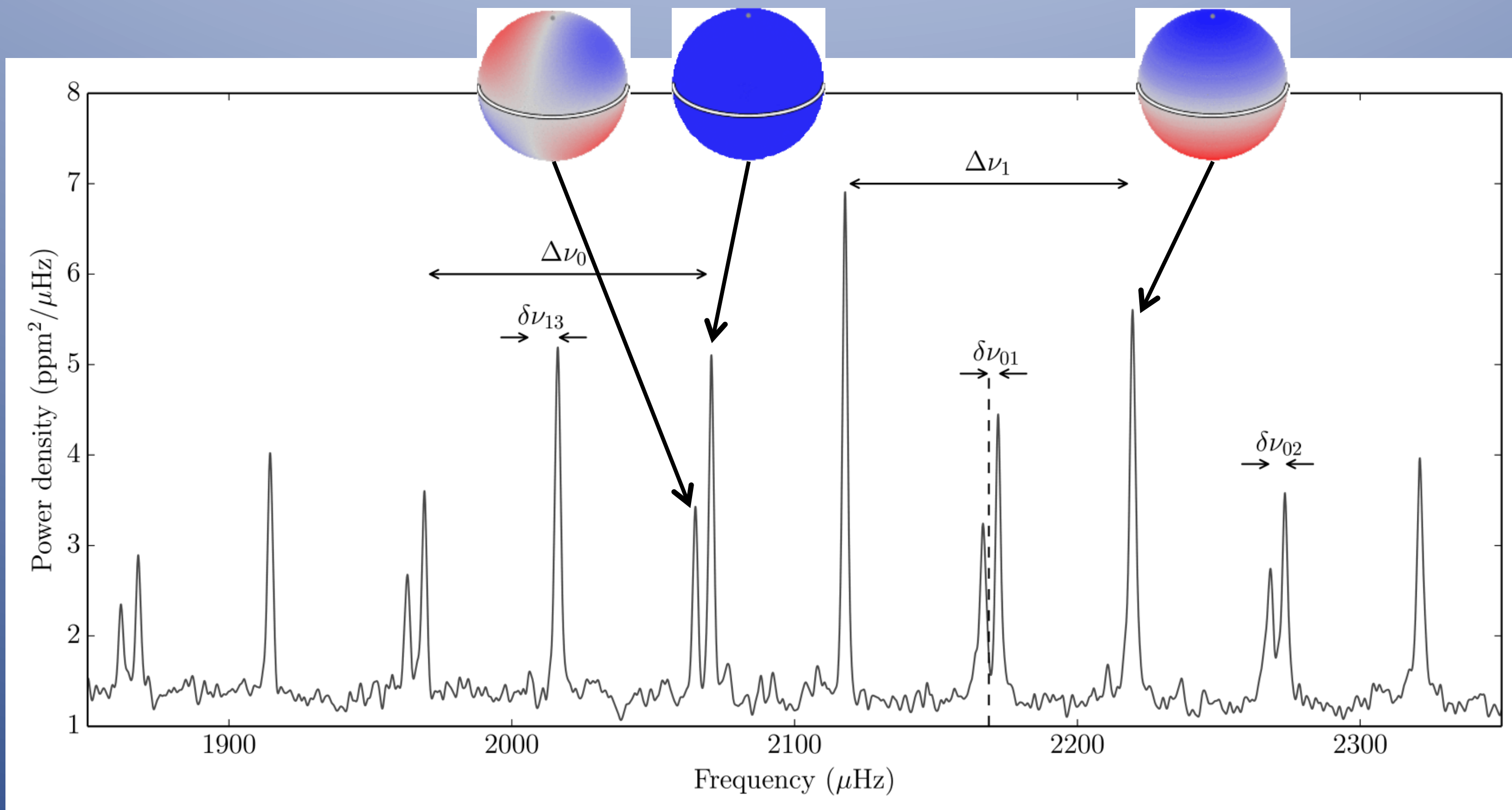


l=2, m=0

l=2, $|m|$=2



The asymptotic relation



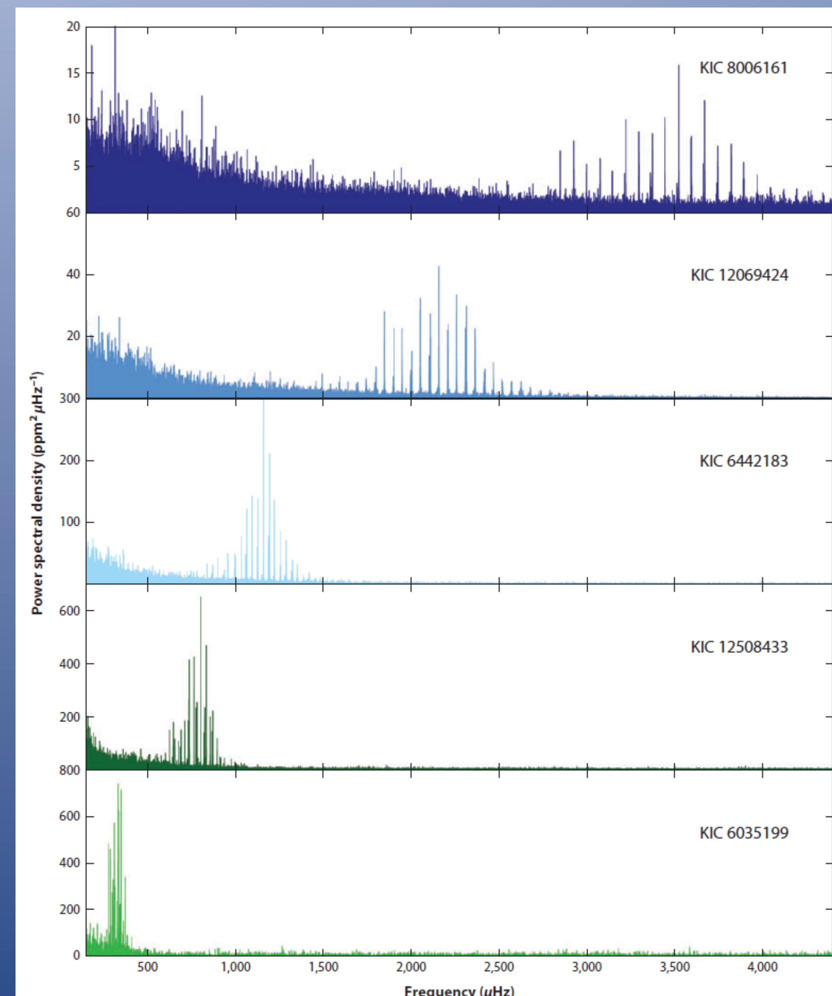
KIC 1129542616 as observed by *Kepler*

- $\nu_{n,l} = \Delta\nu\left(n + \frac{l}{2} + \varepsilon\right) - l(l+1)D_0$, $\delta\nu_{02} = \frac{1}{6} D_0$.

Scaling relations

- $\Delta\nu \propto \sqrt{\rho}$.
- $\nu_{max} \propto g\, T_{eff}^{-1/2}$.

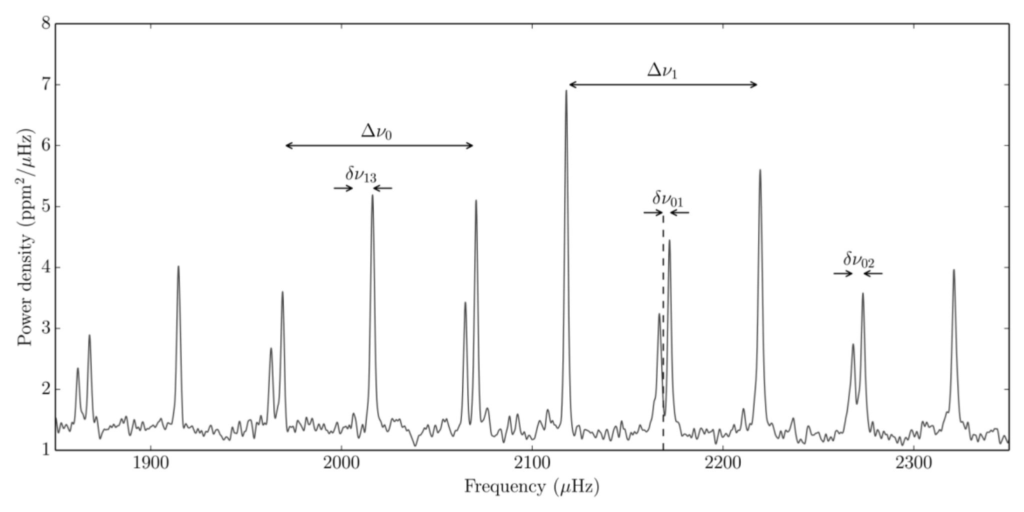
- As a star evolves:
  - $\Delta\nu$ decreases.
  - ν_{max} decreases.



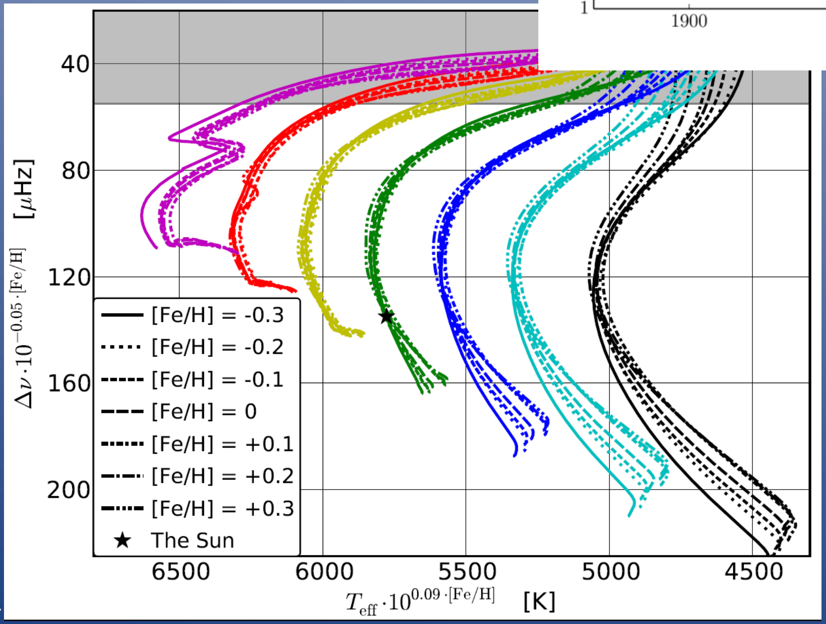
Chaplin and Miglio, 2013

Modelling

- Detailed modelling



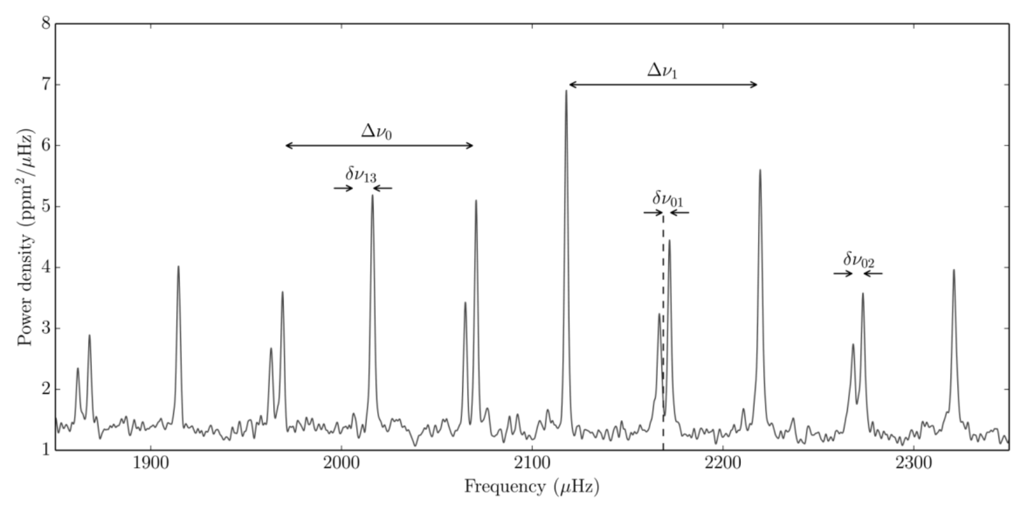
- Grid-based modelling



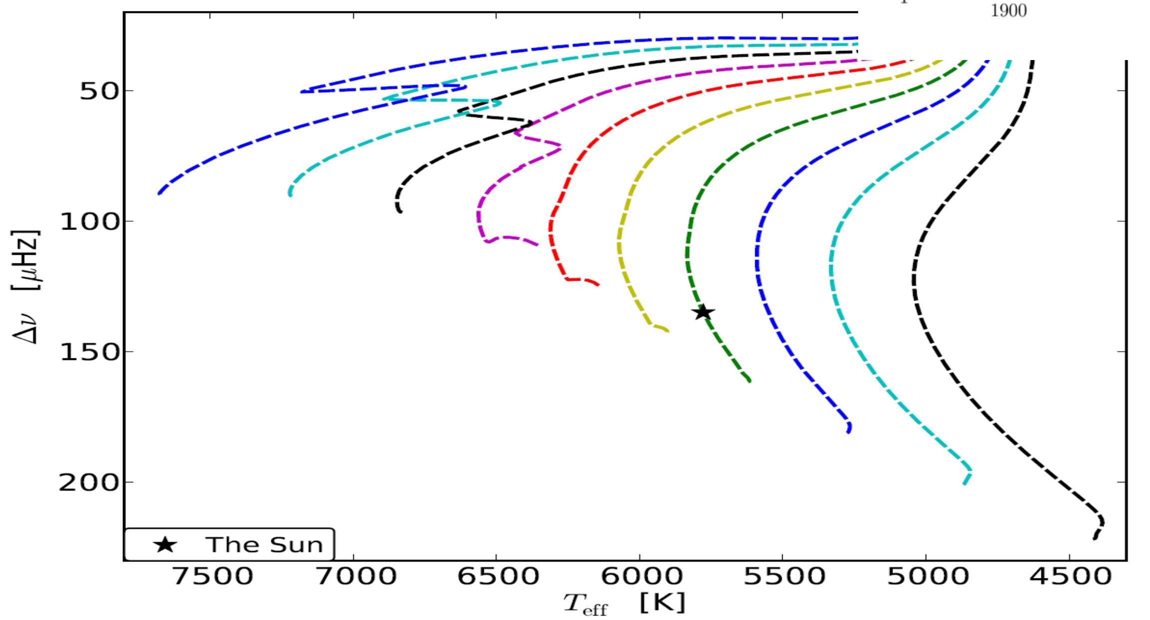
Lundkvist et al., 2014

Modelling

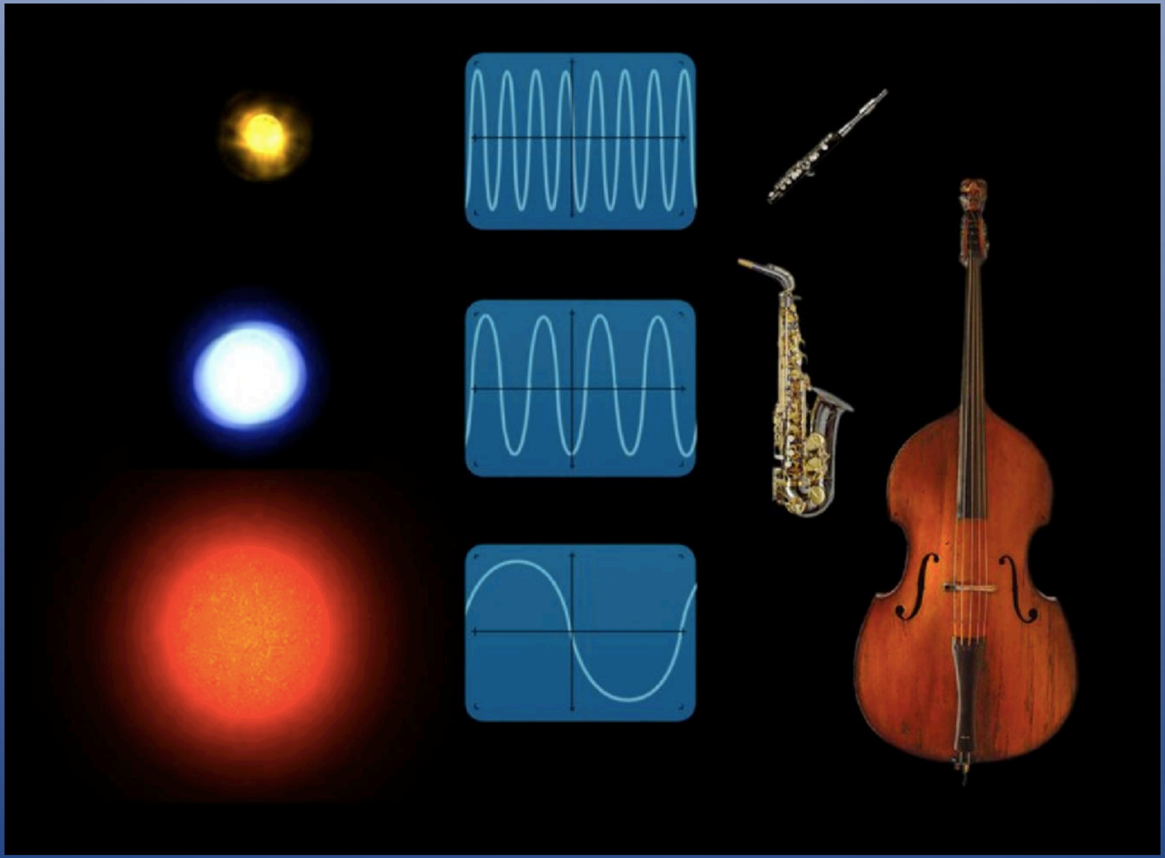
- Detailed modelling



- Grid-based modelling

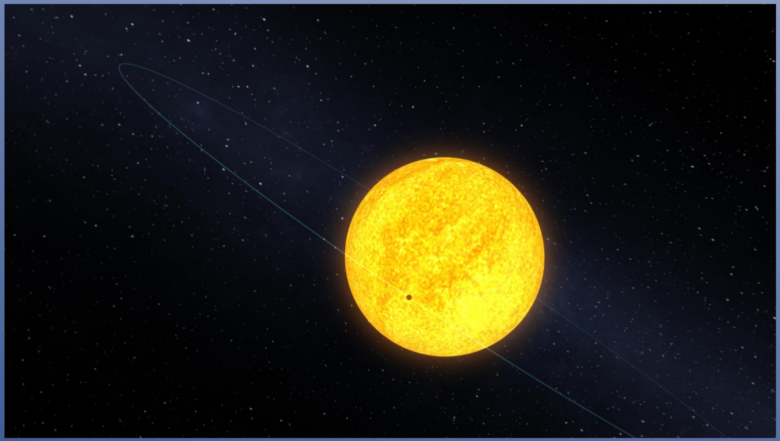


Music of the stars

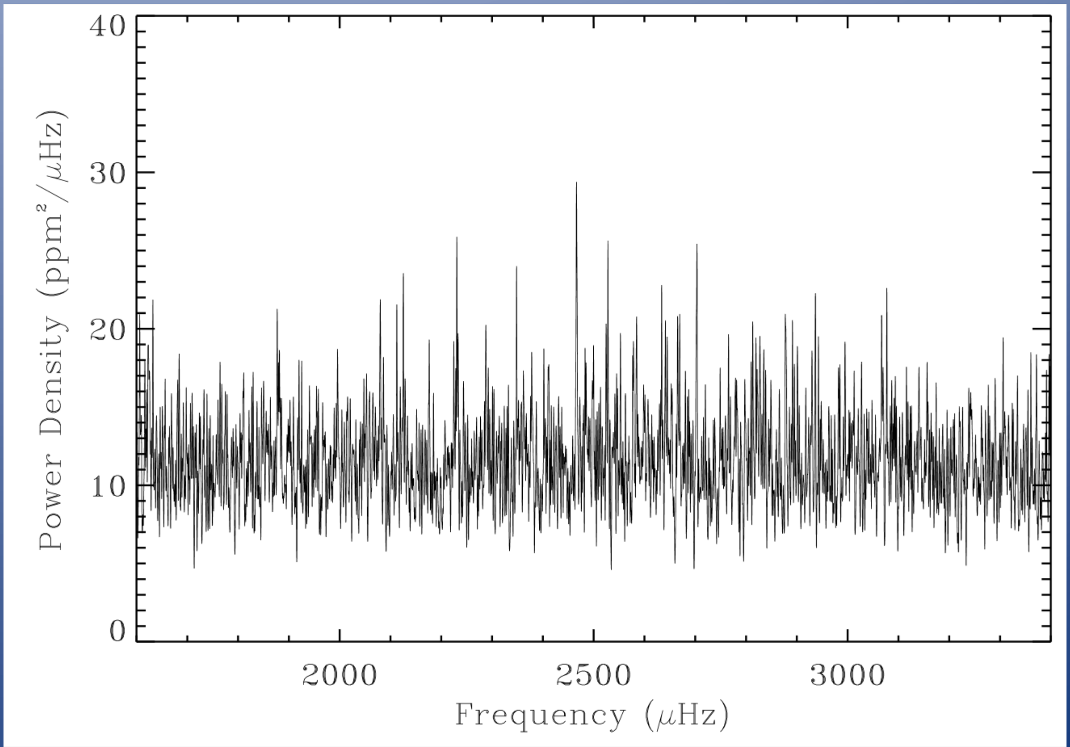


Kepler-10

- Hosts the first rocky planet found by *Kepler*.



http://www.nasa.gov/mission_pages/kepler/multimedia/images/kepler10b_images.html



http://kasoc.phys.au.dk/kepler10/

Batalha et al. (2011)

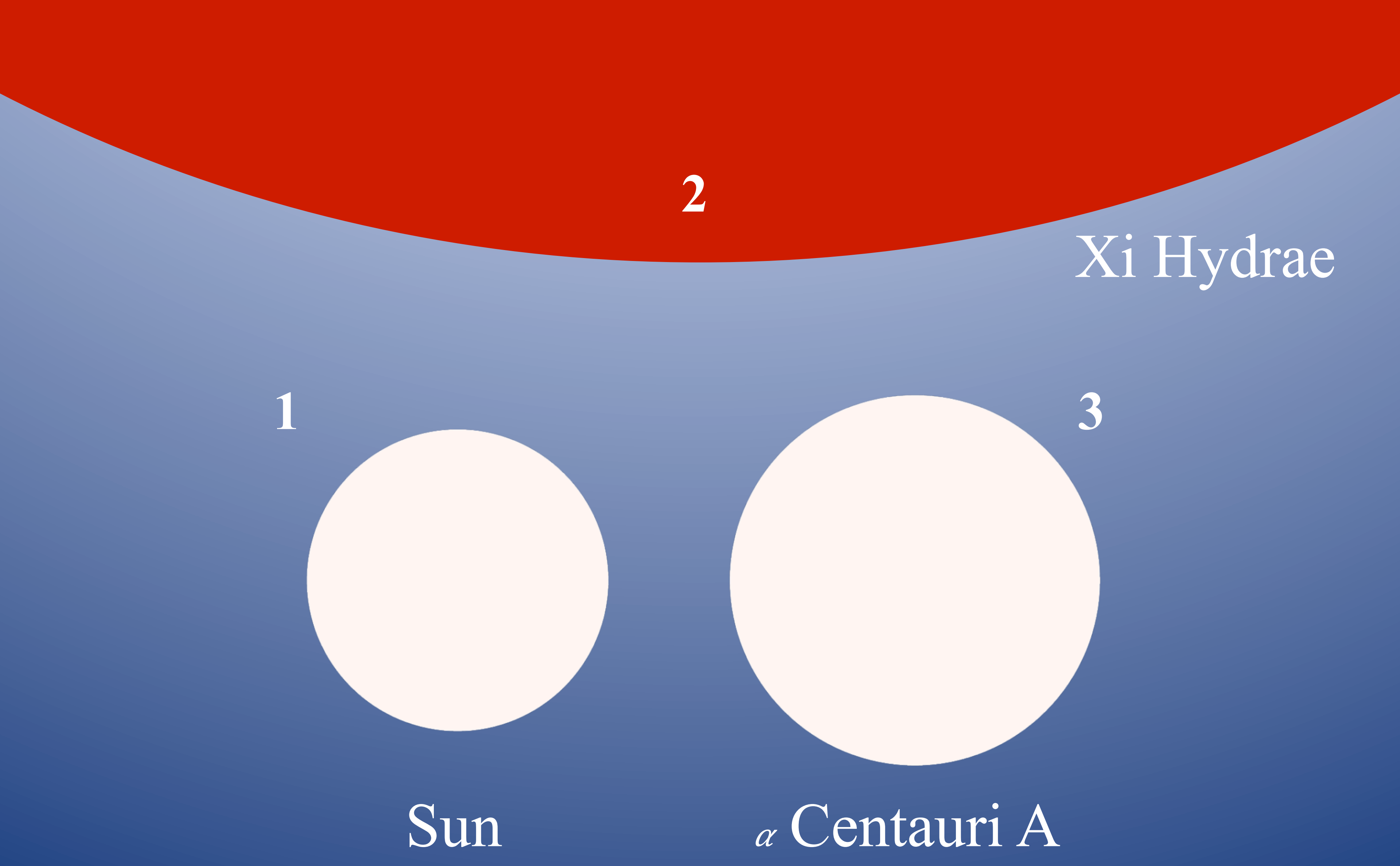
Music of the stars

- 3 examples

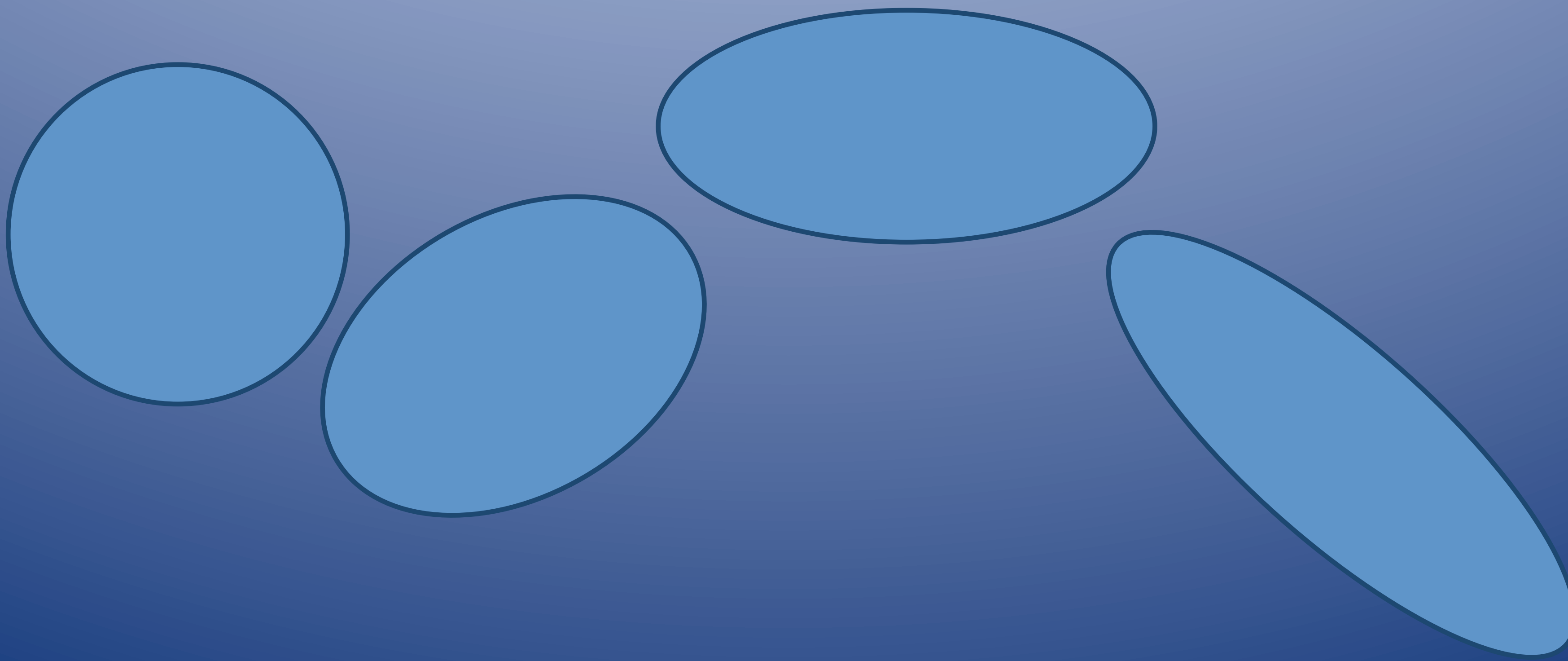
2

1

3

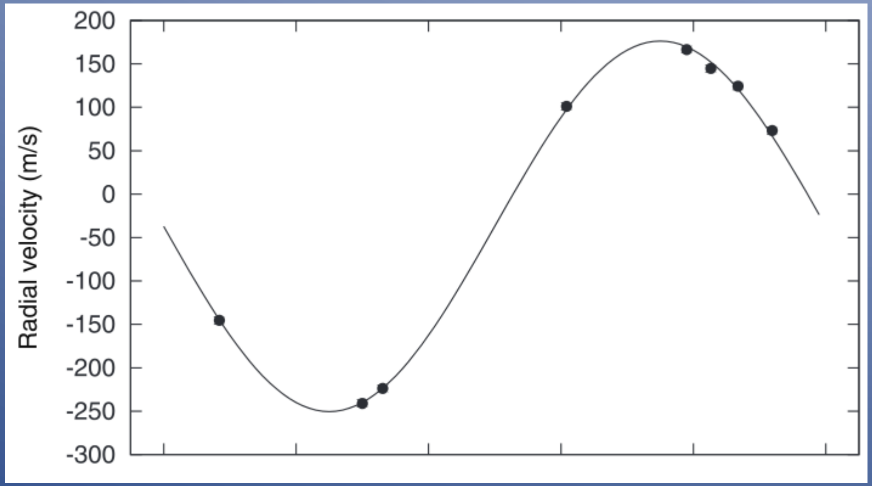

2
Xi Hydrae
1
3
Sun
α Centauri A

Asteroseismology & exoplanets -eccentricities

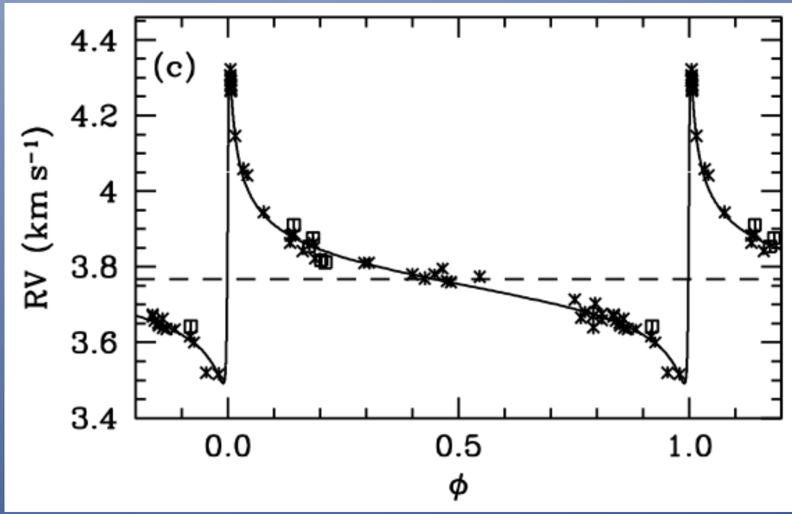


RV measurements of eccentricity

- HAT-P-7b: e = 0
- HD 80606b: e = 0.927



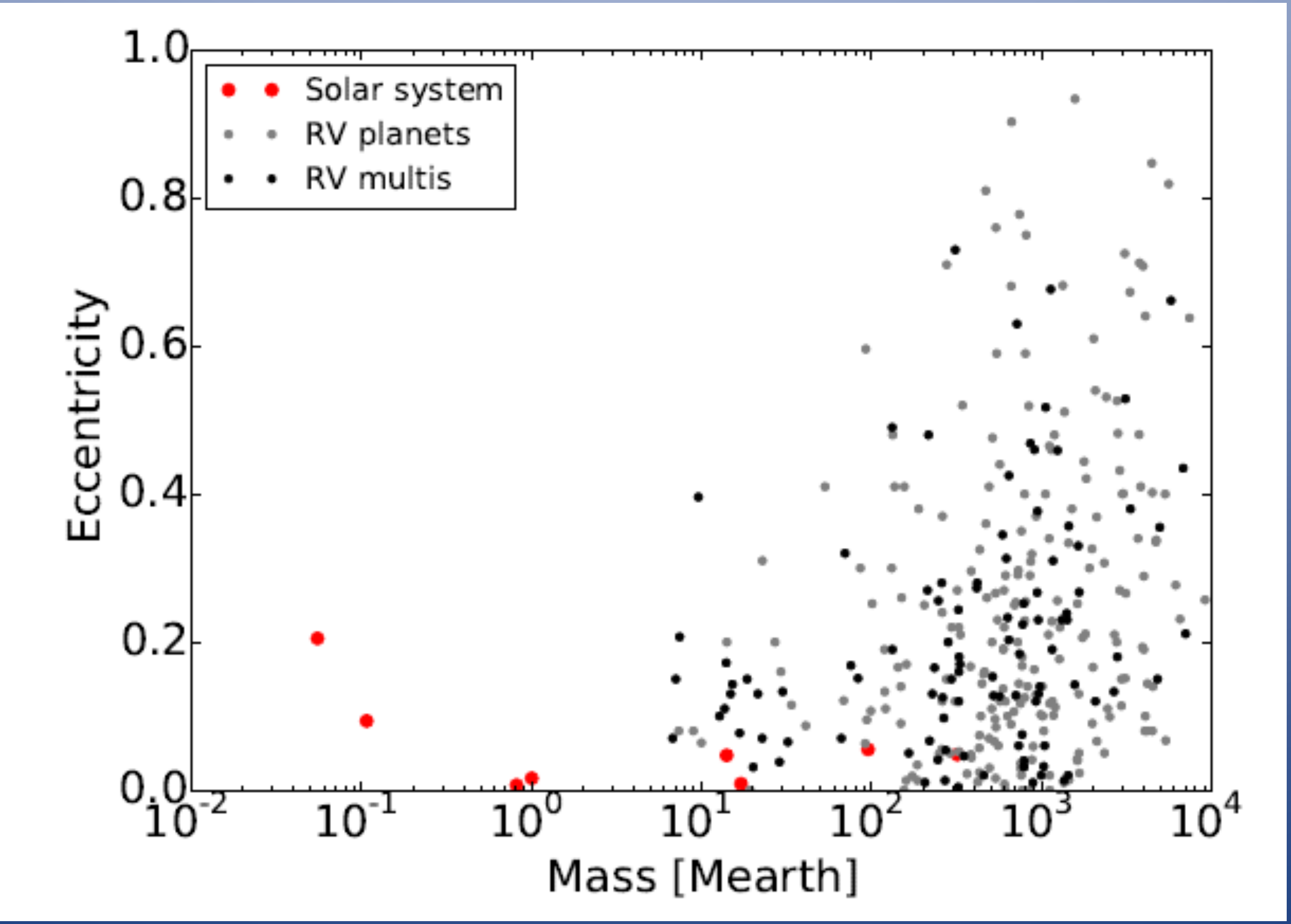
Pál et al. (2008)



Naef et al. (2001)

Signal is km/s.

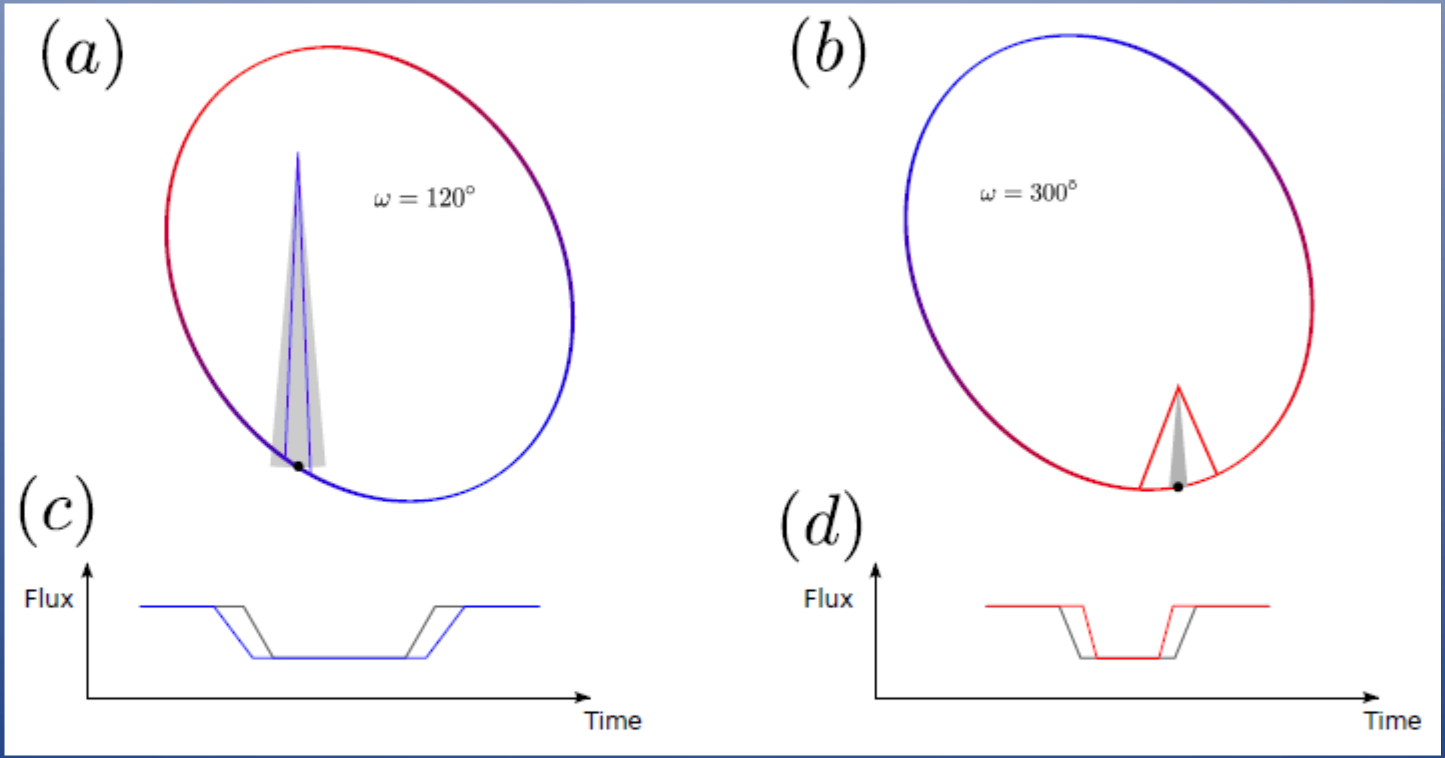
Exoplanet eccentricities (RV)



Vincent Van Eylen, KASC8 presentation

Eccentricity of exoplanets without RV

- Transit durations (stellar mean density).



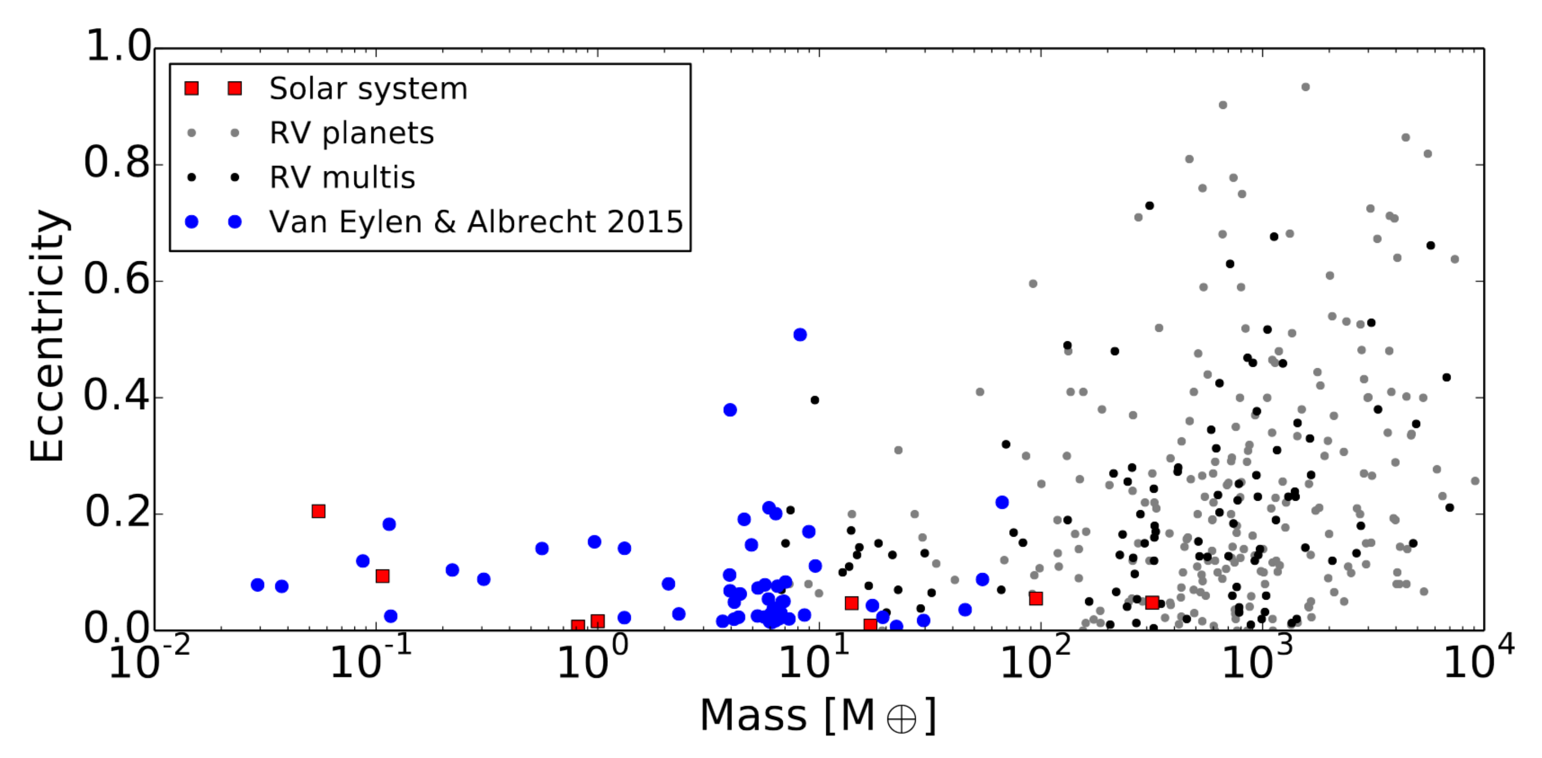
Van Eylen and Albrecht (2015)

Eccentricity of exoplanets without RV

- Circular orbit, full star crossing: $x=2R_*$ and $v=2\pi a/P$ $\Rightarrow T=x/v=2PR_*/2\pi a \propto R_*/a$.
- K3: $P^2=4\pi^2 a^3/G(M_\mathrm{p}+M_*)$, meaning: $M_* \approx 4\pi^2 a^3/GP^2$ $\Leftrightarrow \rho_{*,\mathrm{tr}} \approx 4\pi^2 a^3/GP^2 \; 3/4\pi R_*^3 = 3\pi/GP^2 \; (a/R_*)^3$.
- Can also get ρ_* from asteroseismology.

Results

- Van Eylen and Albrecht (2015): 74 planets (in 28 systems).

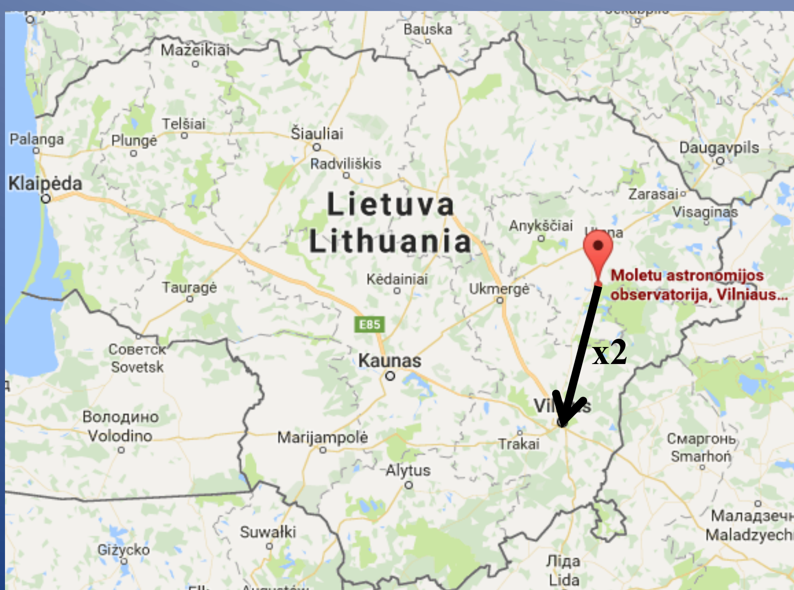


Asteroseismology & exoplanets - precise exoplanet properties

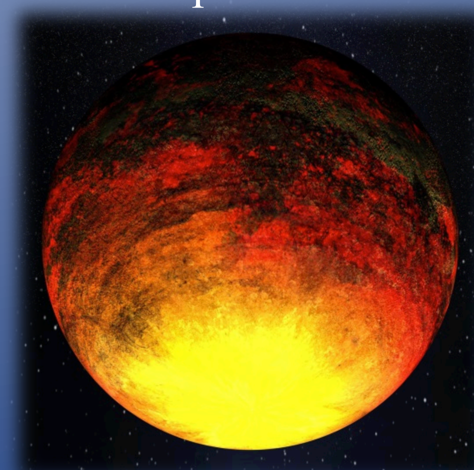
The 2-planet system Kepler-10

Period (days)	Radius ($R_\oplus$)	$T_{day,max}$ (K)	Age (Gyr)
0.8374912 ± 0.0000003	1.46 ± 0.02	3316 +52/-56	10.41 ± 1.36

Fogtmann-Schulz et al. (2014)

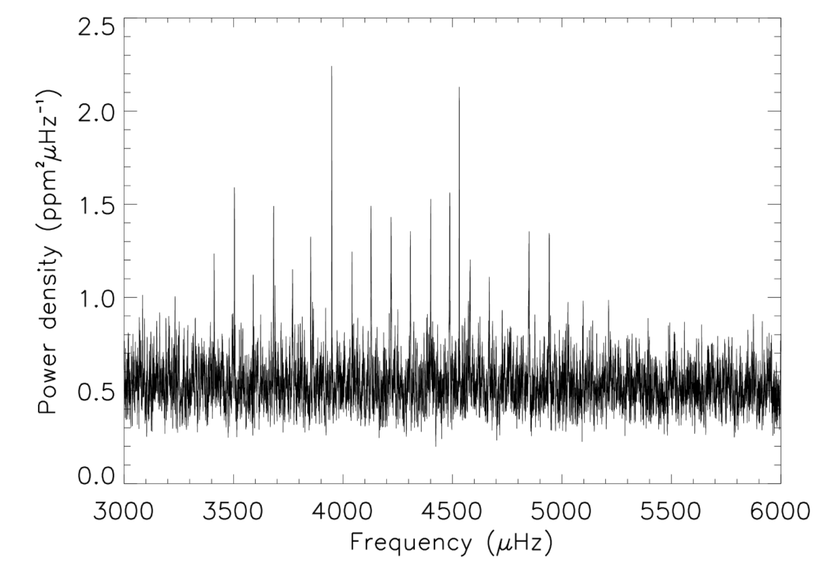


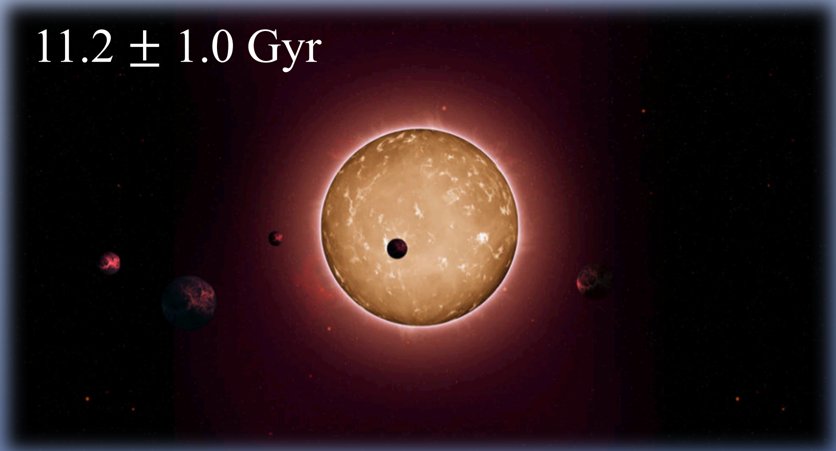
Kepler-10b



Credit: NASA/Kepler Mission/Dana Berry

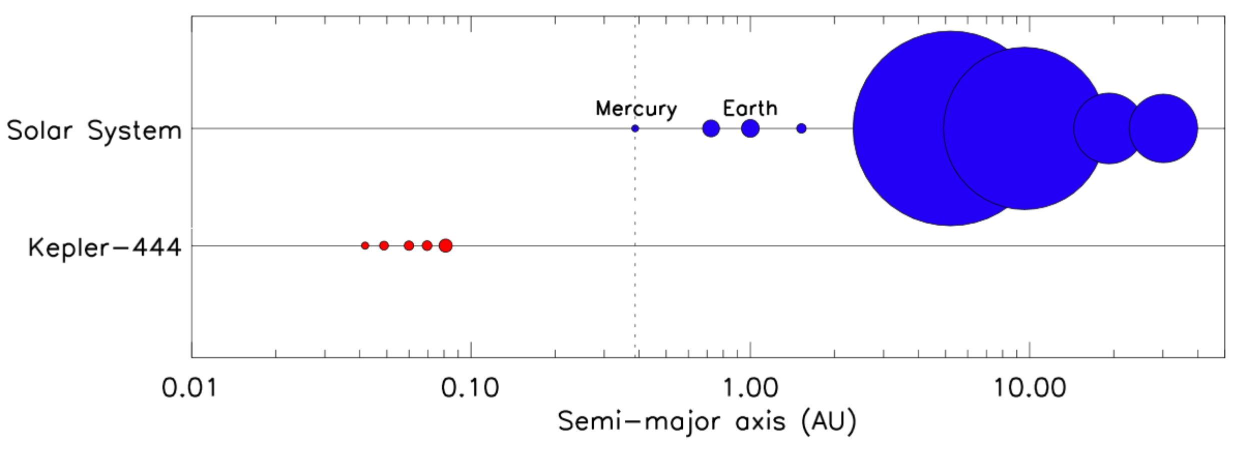
The 5-planet system Kepler-444





Credit: Tiago Campante/Peter Devine

Campante et al. (2015)



nature COMMUNICATIONS

ARTICLE

Received 7 Sep 2015 | Accepted 1 Mar 2016 | Published 11 Apr 2016 DOI: 10.1038/ncomms11201 OPEN

Hot super-Earths stripped by their host stars

M.S. Lundkvist[1,2], H. Kjeldsen[1], S. Albrecht[1], G.R. Davies[1,3], S. Basu[4], D. Huber[1,5], A.B. Justesen[1], C. Karoff[1,6], V. Silva Aguirre[1], V. Van Eylen[1], C. Vang[1], T. Arentoft[1], T. Barclay[7,8], T.R. Bedding[1,5], T.L. Campante[1,3], W.J. Chaplin[1,3], J. Christensen-Dalsgaard[1], Y.P. Elsworth[1,3], R.L. Gilliland[9], R. Handberg[1], S. Hekker[1,10], S.D. Kawaler[11], M.N. Lund[1,3], T.S. Metcalfe[1,12], A. Miglio[1,3], J.F. Rowe[7,13], D. Stello[1,5], B. Tingley[1] & T.R. White[1,14]

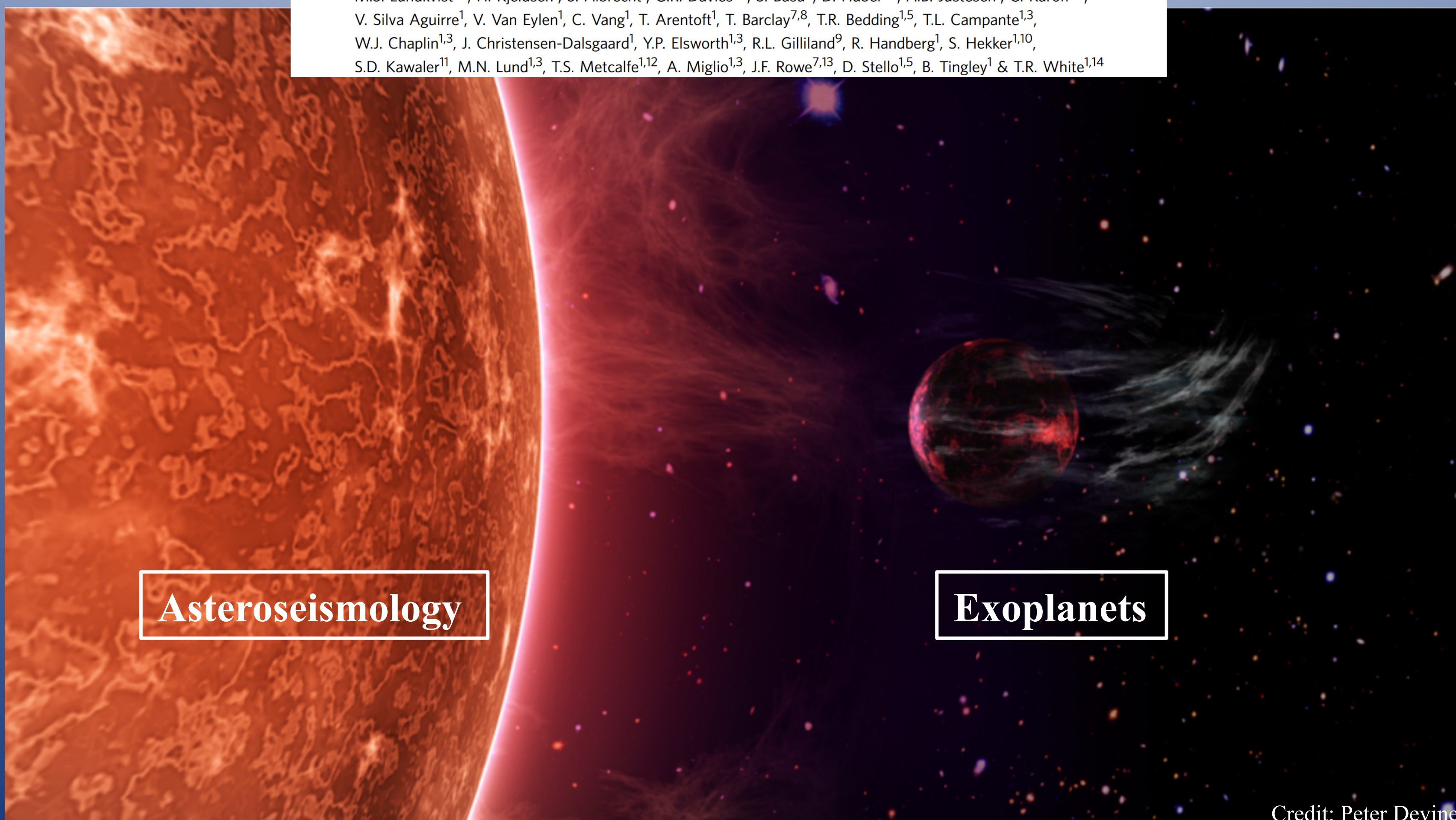
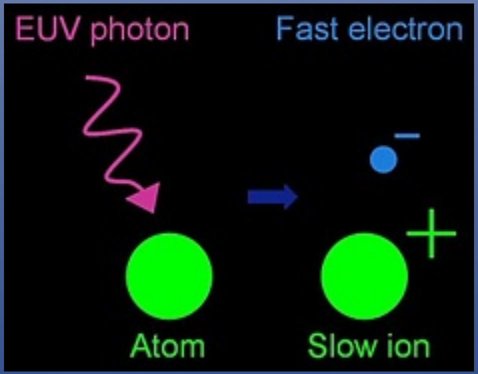


Photo-evaporation

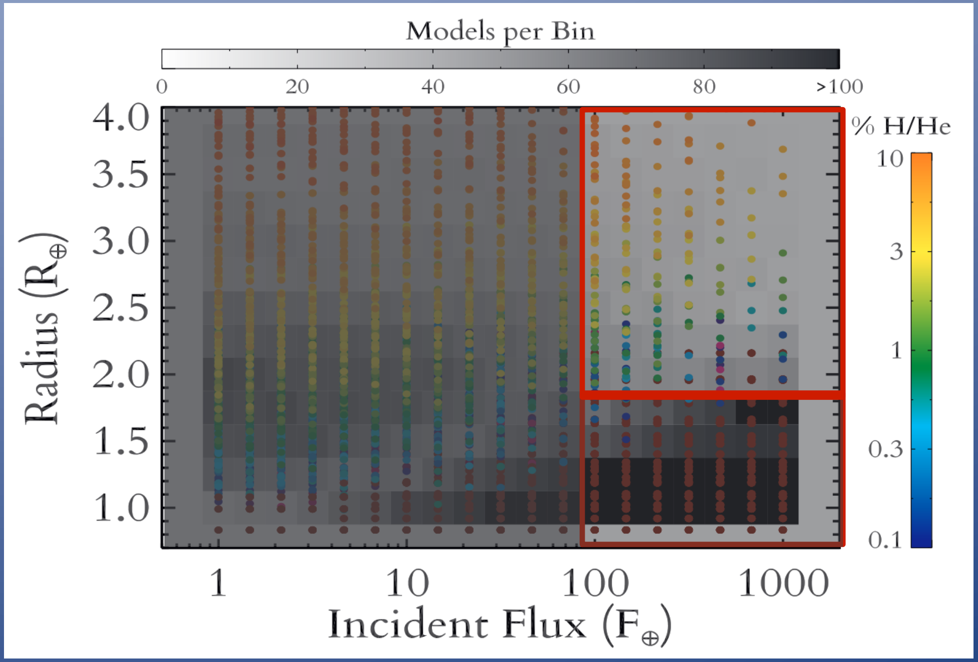
- EUV or X-ray photons photoionize atomic H.
- Produces significant heating.
- This can lead to mass loss, in particular of a large amount of H /He.



http://www.einlightred.tue.nl/projects/euv/index_en.html

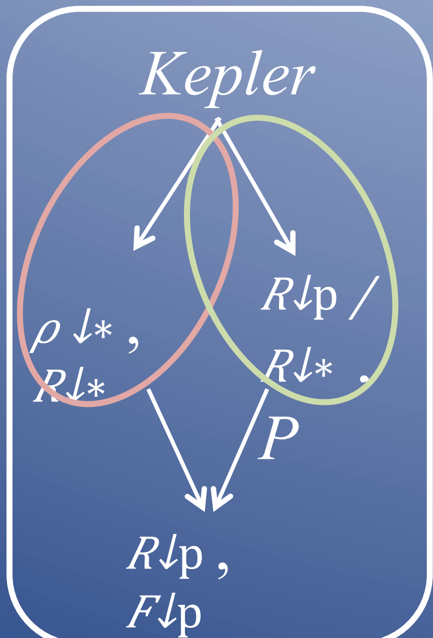
Background

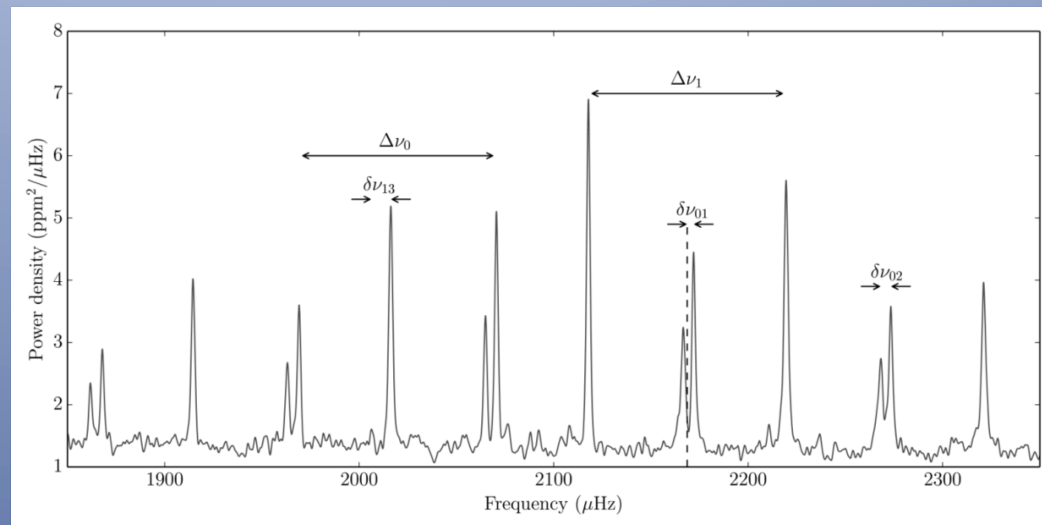
- Models predict stripping of envelope by photo-evaporation.
- $F > 100\ F_{\oplus}$ and $1.8 < R/R_{\oplus} < 4.0$: missing.
- $F > 100\ F_{\oplus}$ and $R < 1.8\ R_{\oplus}$: over-abundant.
- Asteroseismology is essential.



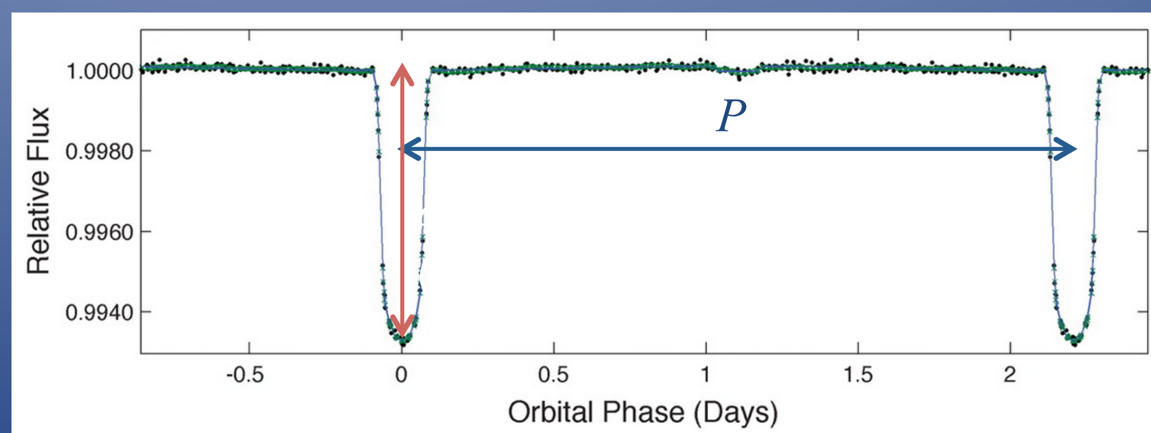
Lopez and Fortney (2013)

Planetary radius and incident flux



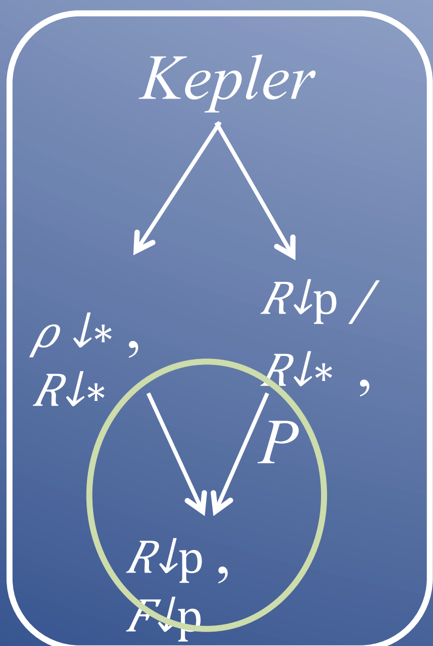


KIC 1129542616 as observed by *Kepler*



HAT-P-7, Borucki et al. (2009)

Planetary radius and incident flux



- Radius:

$$R_p = (R_p / R_*) R_* .$$

- Incident flux:

$$F_p / F_\oplus = (\rho_* / \rho_\odot)^{-2/3} (P / 1\,\mathrm{yr})^{-4/3} (T_{\mathrm{eff},*} / T_{\mathrm{eff},\odot})^{4} .$$

The incident flux

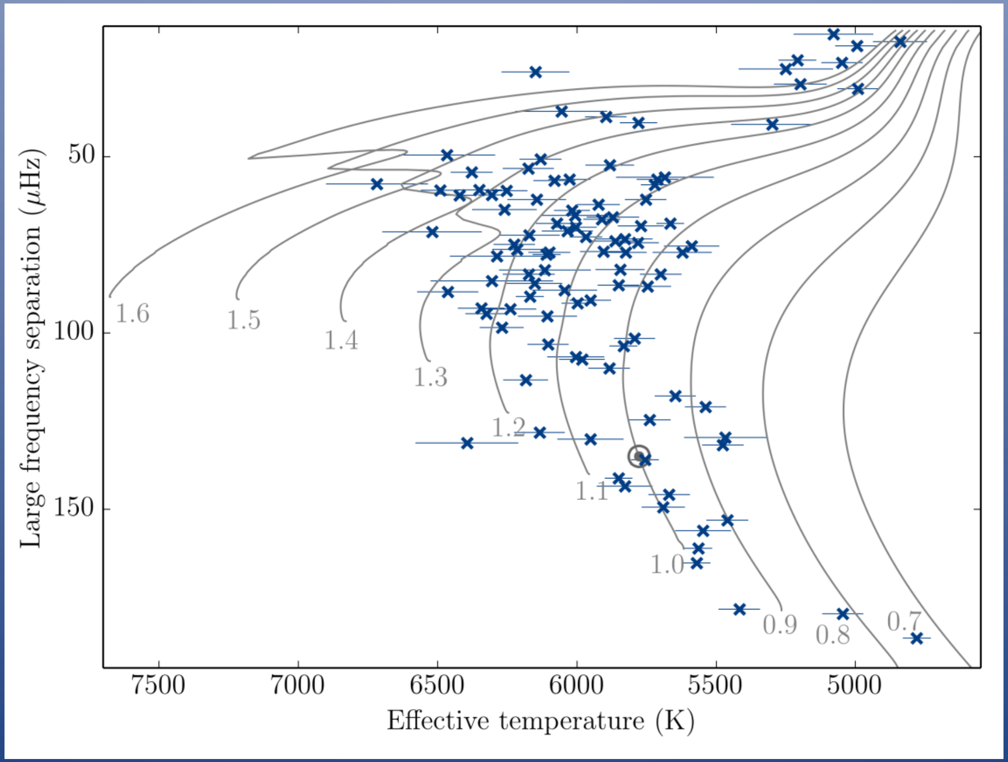
- For a circular orbit: $F_\mathrm{p} = L/4\pi a^2$ } $F_\mathrm{p} \propto R^2/a^2 \; T_\mathrm{eff}^4$
- $L = 4\pi R_*^2 \, T_\mathrm{eff}^4$
- K3: $P^2 \propto a^3/M_* \Leftrightarrow a^2 \propto (M_* P^2)^{2/3}$

$$\Rightarrow F_\mathrm{p} \propto R^2 T_\mathrm{eff}^4 / M^{2/3} P^{4/3} \propto (R^3/M)^{2/3} \, P^{-4/3} \, T_\mathrm{eff}^4$$

$$\propto \rho_*^{-2/3} \, P^{-4/3} \, T_\mathrm{eff}^4 \, .$$

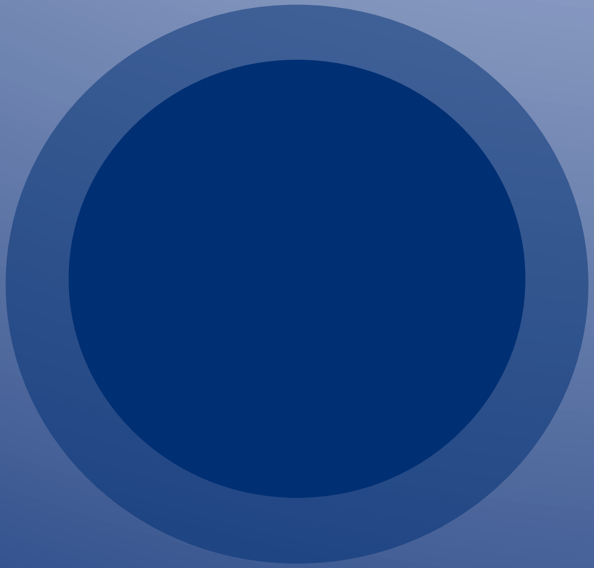
The asteroseismic host star sample

- 102 confirmed and candidate exoplanet host stars brighter than 13.5 mag with SC data.

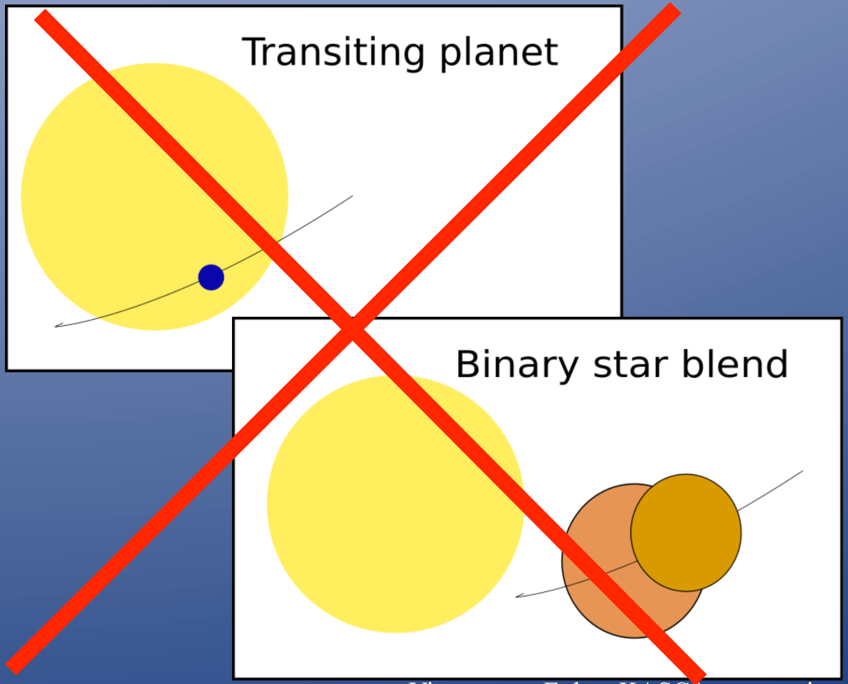


Vetting of the exoplanet sample

- Uncertain radius



- Astrodensity profiling

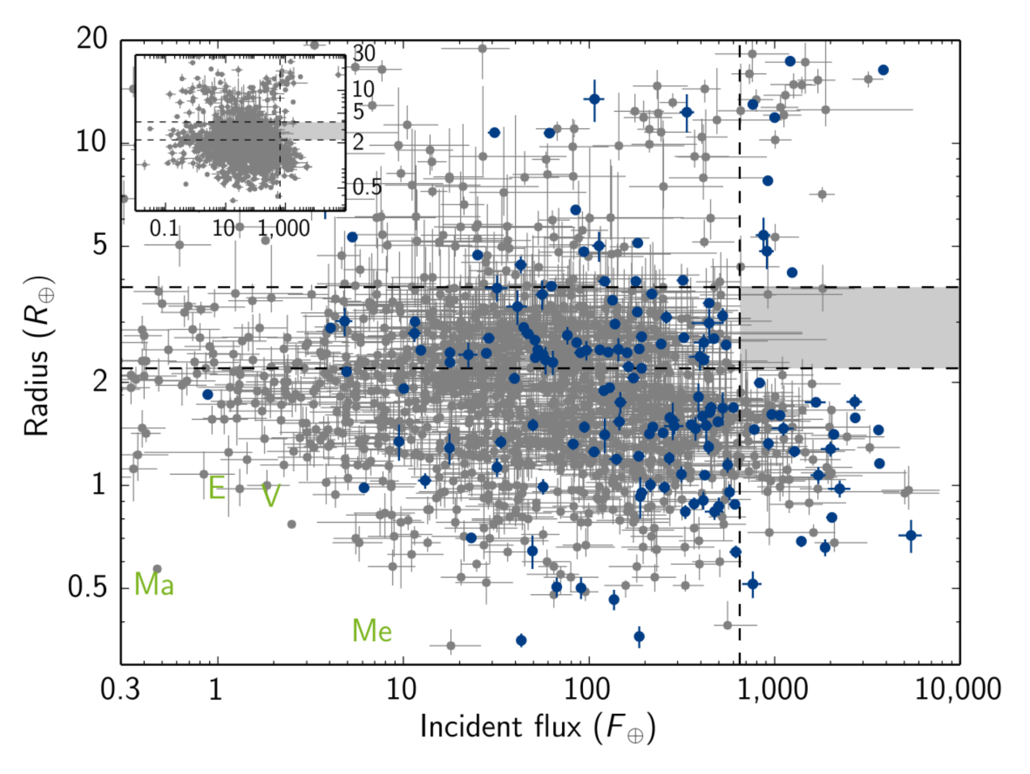


Vincent van Eylen, KASC8 presentation

The radius-flux diagram

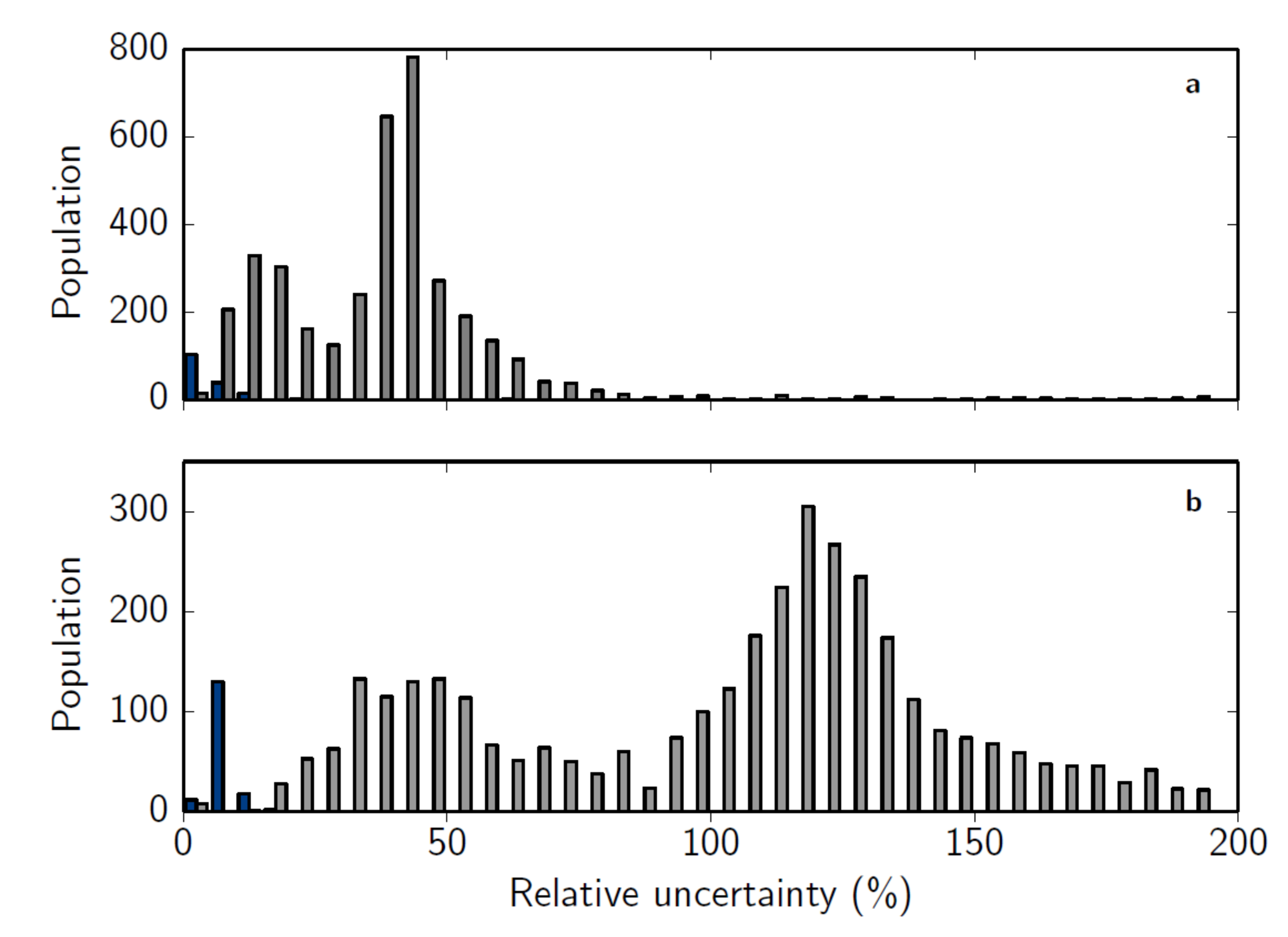
- Empty region: $F > 650\ F_\oplus$ and $2.2 < R/R_\oplus < 3.8$.

⇨ The hot-super-Earth desert.



Hot exoplanets with $R < 2.2\ R_\oplus$ are likely rocky.

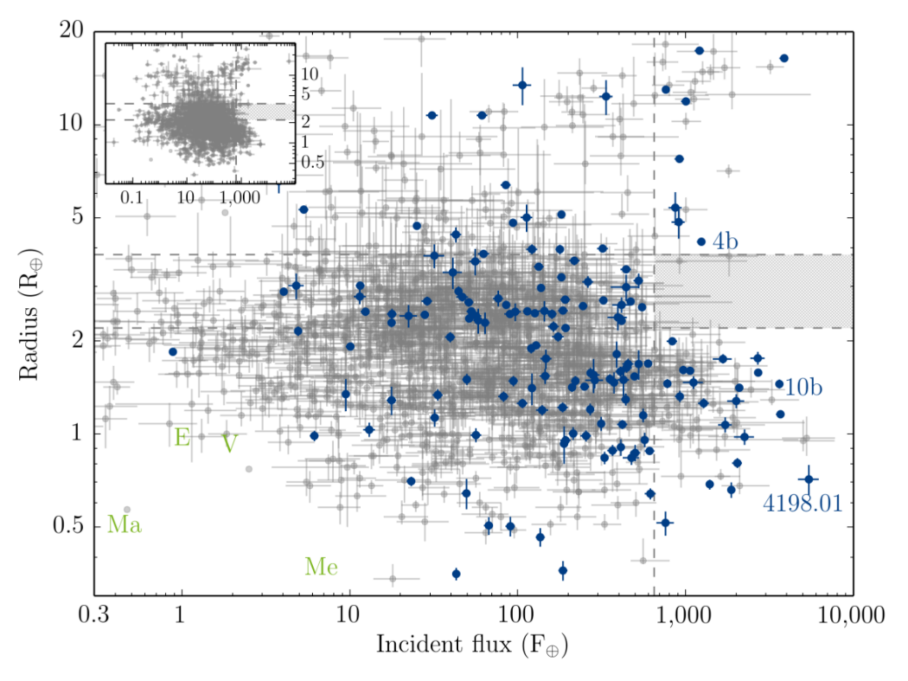
Uncertainties



Selection effects and false positives

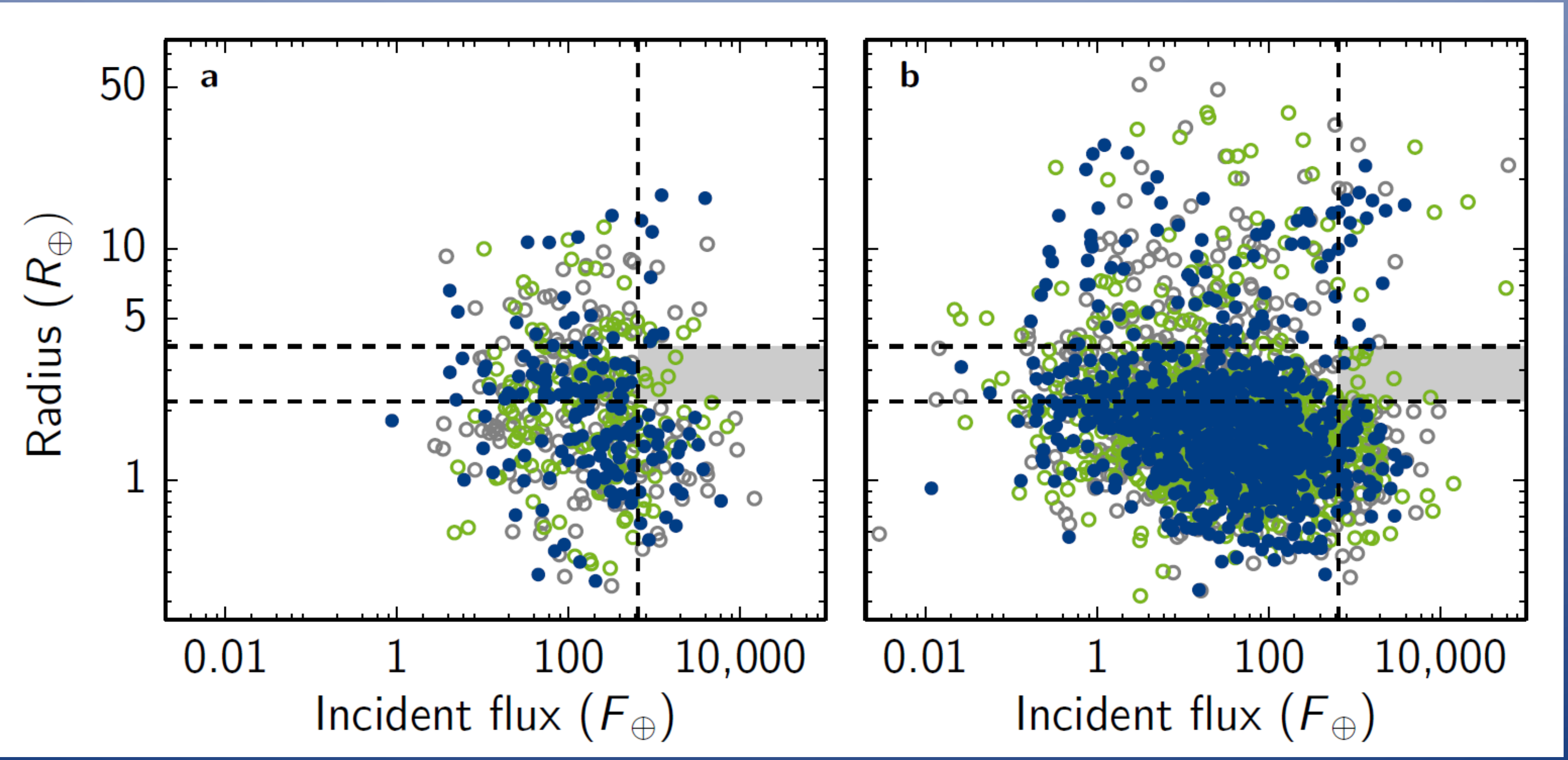
- Selection effects:
  - Detection sensitivity (miss: low R, low F planets).
  - Short-cadence data (miss: high R, low F planets).
- False positives:
  - Removed %'s according to Fressin et al (2013).

⇨ Neither affect the desert.

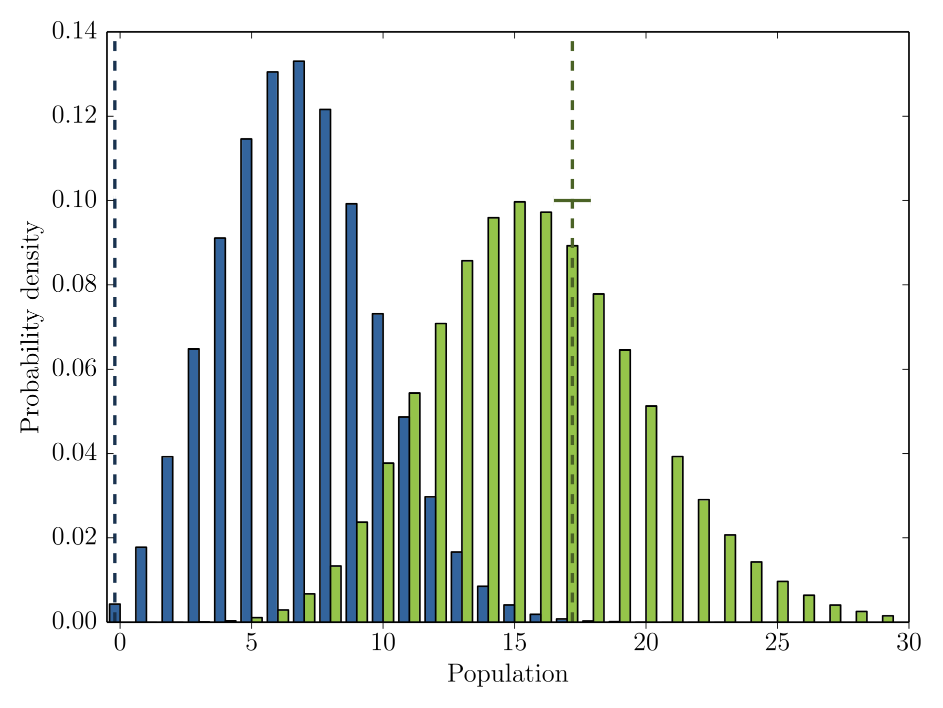


Significance – the Gaussian Mixture Model (GMM)

- Good agreement.



Significance - results



- Observed number in the desert: 0 ± 0.04 .

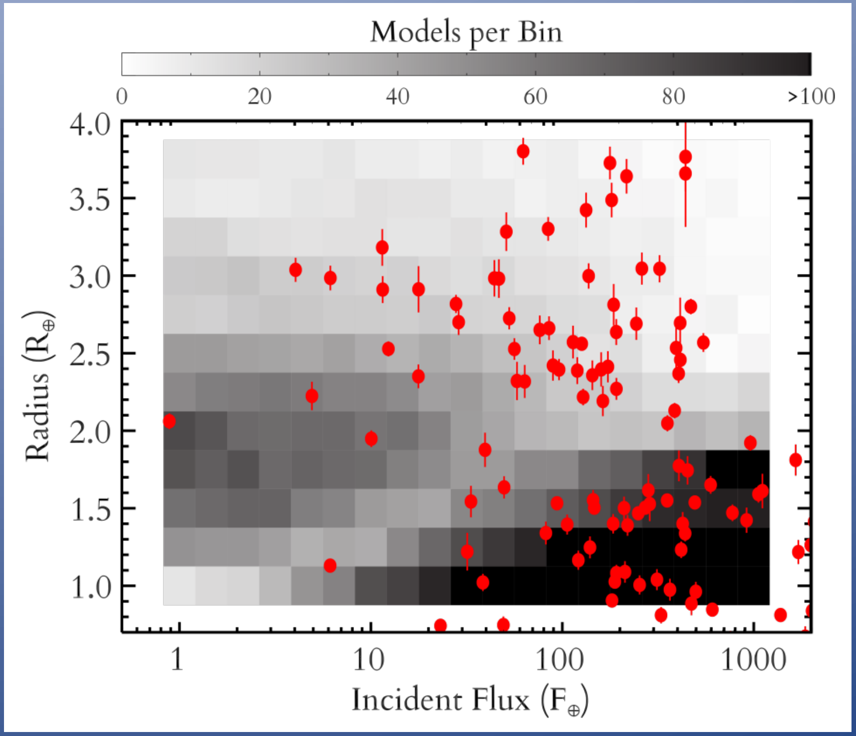
⇒ Less than 0.4% of the simulations return 0 planets in the desert.

- Observed number below the desert: 17 ± 0.7 .

⇒ Not statistically significant (note selection effects).

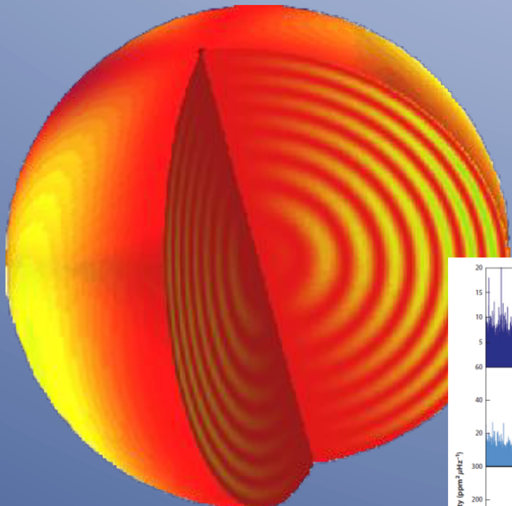
Improved transit properties

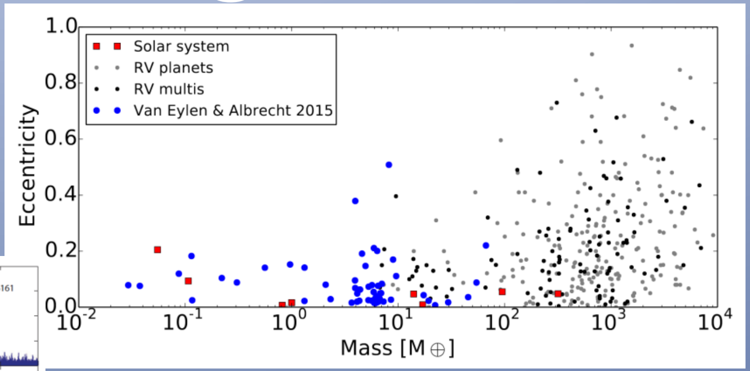
- Re-analysis of 139 planets mostly from the seismic sample.
- Bimodal distribution in radius with a minimum at $R_p \sim 2 R_\oplus$.
- Caused by a transition in composition?

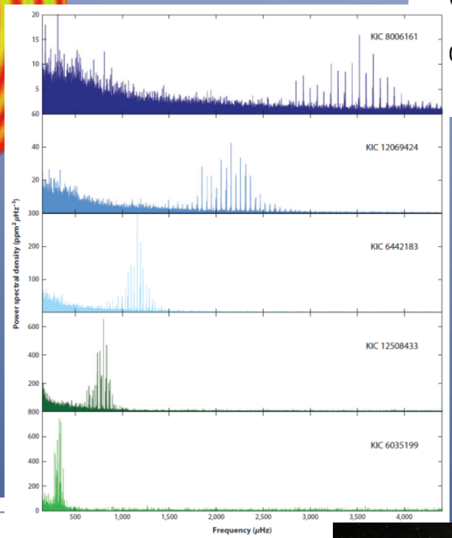


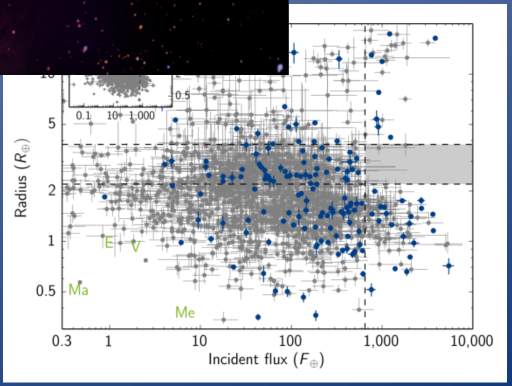
Master thesis C. Agentoft (2016)

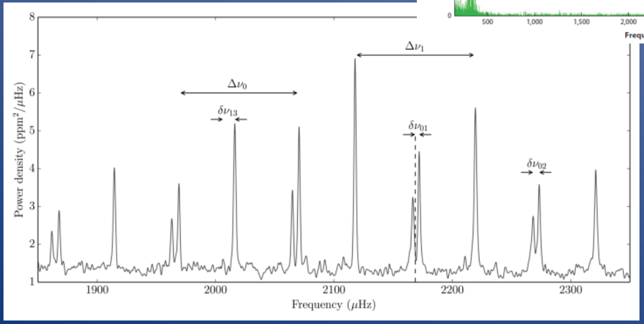
Take-home messages/summary









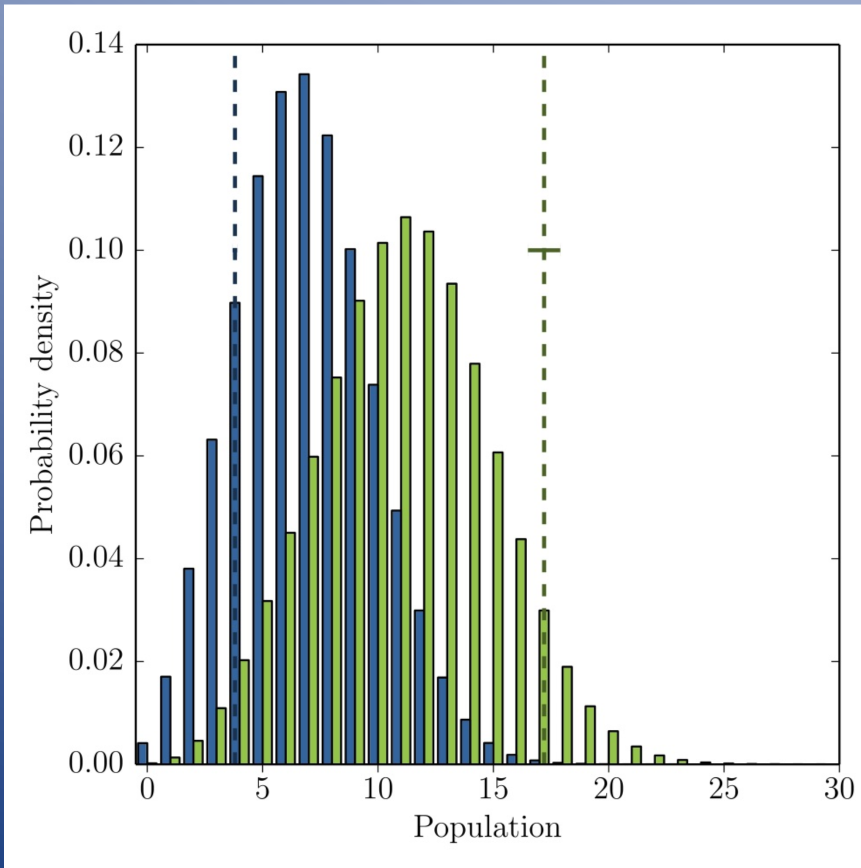


Conclusion

- We have detected a hot-super-Earth desert, which is consistent with expectations of photo-evaporation from theory.
- This will be an added constraint for models of the evolution of planetary systems.
- Planets with R < 2.2 $R_{\oplus}$ are probably rocky (since they do not appear to evaporate).

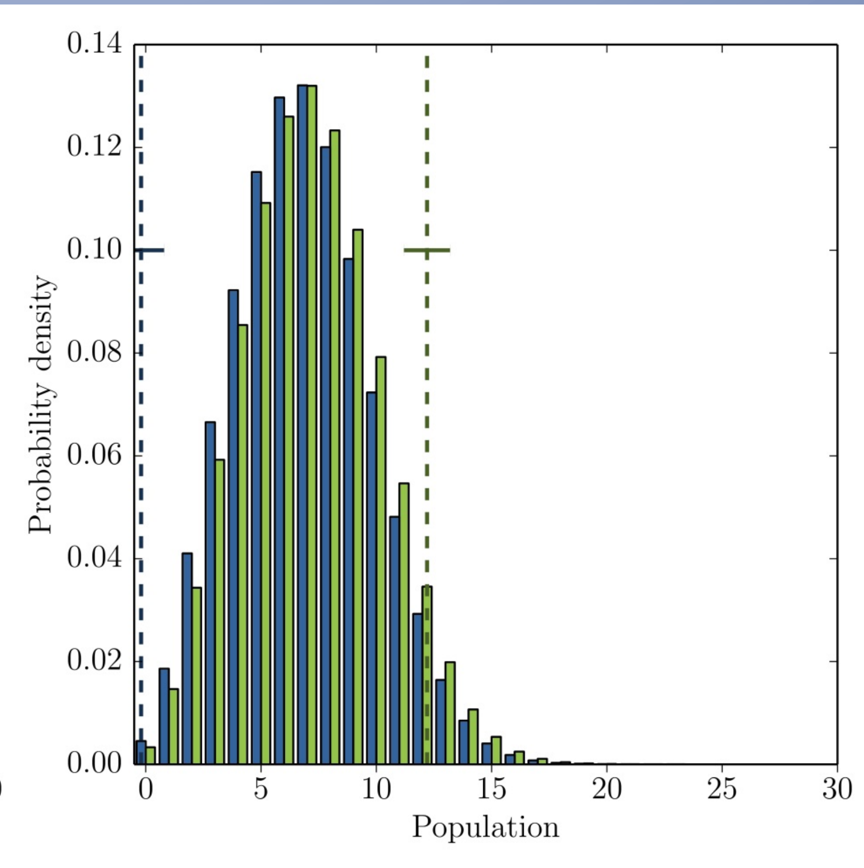
Significance – other regions

$F > 650\ F_{\oplus}$ and $2.2 < R/R_{\oplus} < 10$



Desert not significant

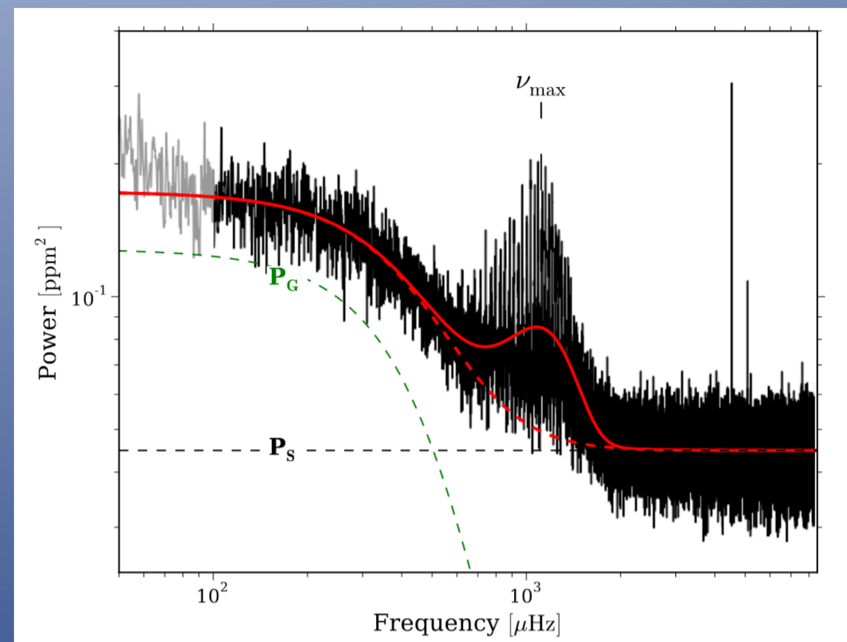
$F > 1000\ F_{\oplus}$ and $2.2 < R/R_{\oplus} < 10$



Desert significant, bus less

The granulation background

- Important to model correctly.
- Harvey (1985): $B(\nu)=\sum_{i=0}^{4} \frac{A_i}{1+(2\pi\nu\tau_i)^{b_i}} + B_0$.

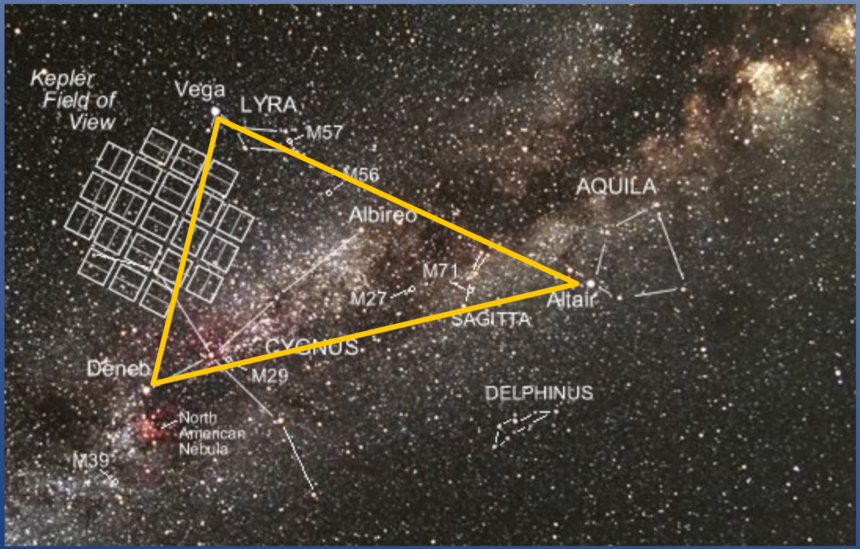


Lund et al. (2014)

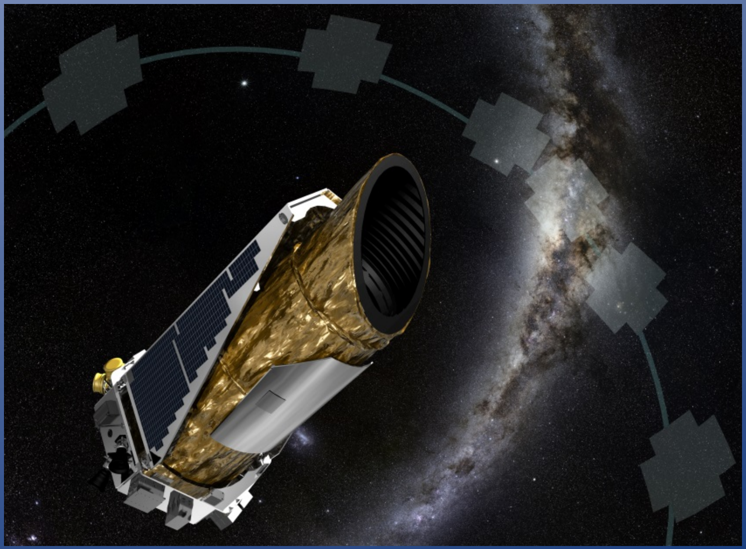
Kepler and K2

- Observed for 4 years.
- More than 100.000 stars and 2326 confirmed planets.

- Observing changing fields along the ecliptic.
- 47 confirmed planets.



http://kepler.nasa.gov/Science/about/targetFieldOfView/



http://www.nasa.gov/content/kepler-multimedia