Nobelova cena za fyziku 2019: Exoplanety

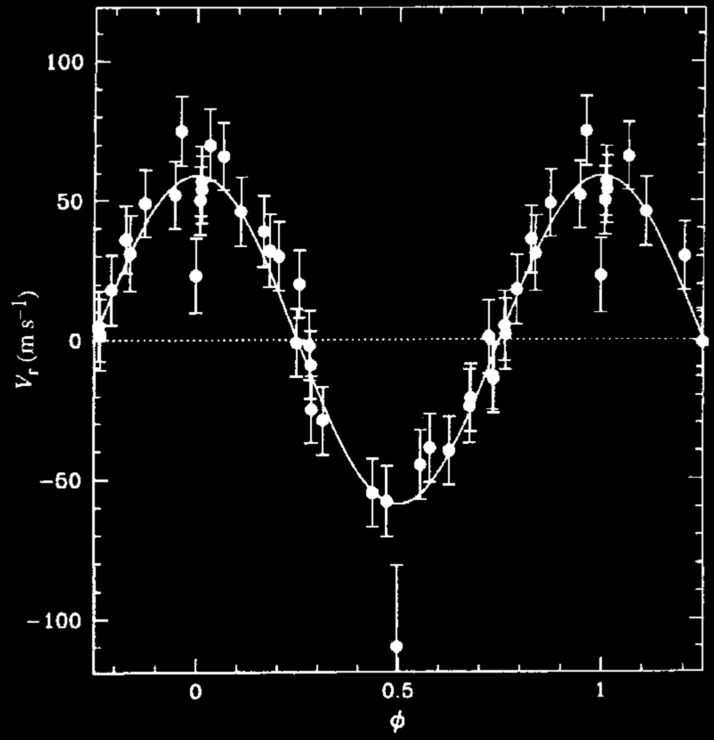

FIG. 4 Orbital motion of 51 Peg corrected from the long-term variation of the γ-velocity. The solid line represents the orbital motion computed from the parameters of Table 1.

5.5 mag
13.7 pc


HAWAII

A Jupiter-mass companion to a solar-type star

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The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.

FOR more than ten years, several groups have been examining the radial velocities of dozens of stars, in an attempt to identify orbital motions induced by the presence of heavy planetary companions[1-5]. The precision of spectrographs optimized for Doppler studies and currently in use is limited to about 15 m s^{-1}. As the reflex motion of the Sun due to Jupiter is 13 m s^{-1}, all current searches are limited to the detection of objects with at least the mass of Jupiter (M_J). So far, all precise Doppler surveys have failed to detect any jovian planets or brown dwarfs.

Since April 1994 we have monitored the radial velocity of 142 G and K dwarf stars with a precision of 13 m s^{-1}. The stars in our survey are selected for their apparent constant radial velocity (at lower precision) from a larger sample of stars monitored for 15 years[6,7]. After 18 months of measurements, a small number of stars show significant velocity variations. Although most candidates require additional measurements, we report here the discovery of a companion with a minimum mass of 0.5 M_J, orbiting at 0.05 AU around the solar-type star 51 Peg. Constraints originating from the observed rotational velocity of 51 Peg and from its low chromospheric emission give an upper limit of 2 M_J for the mass of the companion. Alternative explanations to the observed radial velocity variation (pulsation or spot rotation) are unlikely.

The very small distance between the companion and 51 Peg is certainly not predicted by current models of giant planet formation[8]. As the temperature of the companion is above 1,300 K, this object seems to be dangerously close to the Jeans thermal evaporation limit. Moreover, non-thermal evaporation effects are known to be dominant[9] over thermal ones. This jovian-mass companion may therefore be the result of the stripping of a very-low-mass brown dwarf.

The short-period orbital motion of 51 Peg also displays a long-period perturbation, which may be the signature of a second low-mass companion orbiting at larger distance.

Discovery of Jupiter-mass companion(s)

Our measurements are made with the new fibre-fed echelle spectrograph ELODIE of the Haute-Provence Observatory, France[10]. This instrument permits measurements of radial velocity with an accuracy of about 13 m s^{-1} of stars up to 9 mag in an exposure time of <30 min. The radial velocity is computed

Rozhovor (I)

- **Has it always been a goal to discover a planet?**
- Michel Mayor: No, I was working with CORAVEL on the properties of double stars. Then one day David Latham, then double stars specialist, asked me to confirm the existence of an object of 11 Jupiter-masses orbiting a star in 84 days. We succeeded with CORAVEL and this is when I thought that with a more advanced instrument we should manage to find planets.
- Didier Queloz: When I started my PhD it was clear we were going to develop a much more sensitive instrument than the CORAVEL device. What has allowed us to look for planets is the development of a completely new method: we were able for the first time to simultaneously measure the spectrum of a calibration lamp and that of a star. One could have an accuracy of 10 to 15 m/s on the measurement of radial velocities which was exceptional at that time.

Rozhovor (2)

- **What was your feeling at the sight of the first curve?**
- Michel Mayor: Total disbelief. At that time I was in Hawaii and Didier sent me regular updates on the evolution of the curve. I asked experts around me what they thought, none showed any interest. Such a big planet so close to its star was totally unimaginable.
- Didier Queloz: I could not believe it, I thought there was something not working in the software. I tried to calculate an orbit but knowing nothing, it gave me what I believed being a wacky result. The only one who trusted me, a small PhD student, was Michel Mayor.

Rozhovor (3)

- **When did you start to believe in it?**
- Michel Mayor: I asked Adam Burrows to use his models to see if such a planet could be stable. He then explained to me that up to 2% of the Earth-Sun distance it was possible, yet the distance from 51 Peg b to its star was 5%. Then I thought we were perhaps on the right track.
- Didier Queloz: We were already sure in the spring of 1995, but it was so big, we decided to wait until the reappearance of the star in July. And then yes, we believed in it and we decided to say nothing to anyone.

Rozhovor (4)

- **Was there a race to the planet?**
- Michel Mayor: Not at all. We started to have some doubts in late 1994, but as we did not believe in our measurements we took our time to eliminate all the possibilities that could explain them. Then we waited for the summer of 1995 when the star had reappeared to confirm the observations.
- Didier Queloz: And then we were scared. Afraid that someone else may find it because it seemed too easy. So everything was hidden until the official announcement.

Rozhovor (5)

- **Has your life changed?**
- Michel Mayor: Yes, we have been completely monopolized by journalists.
  At first we thought it was going to calm down quickly enough. Well not at all, with all the new discoveries we have always been much solicited, and this anniversary year it is even more marked.
- Didier Queloz: We learned to handle the media, something we did not know before. My life has not changed very much, except that thanks to Michel I learned how to do research.

cf. Walker etal. (1995)

Observatoire de Haute-Provence

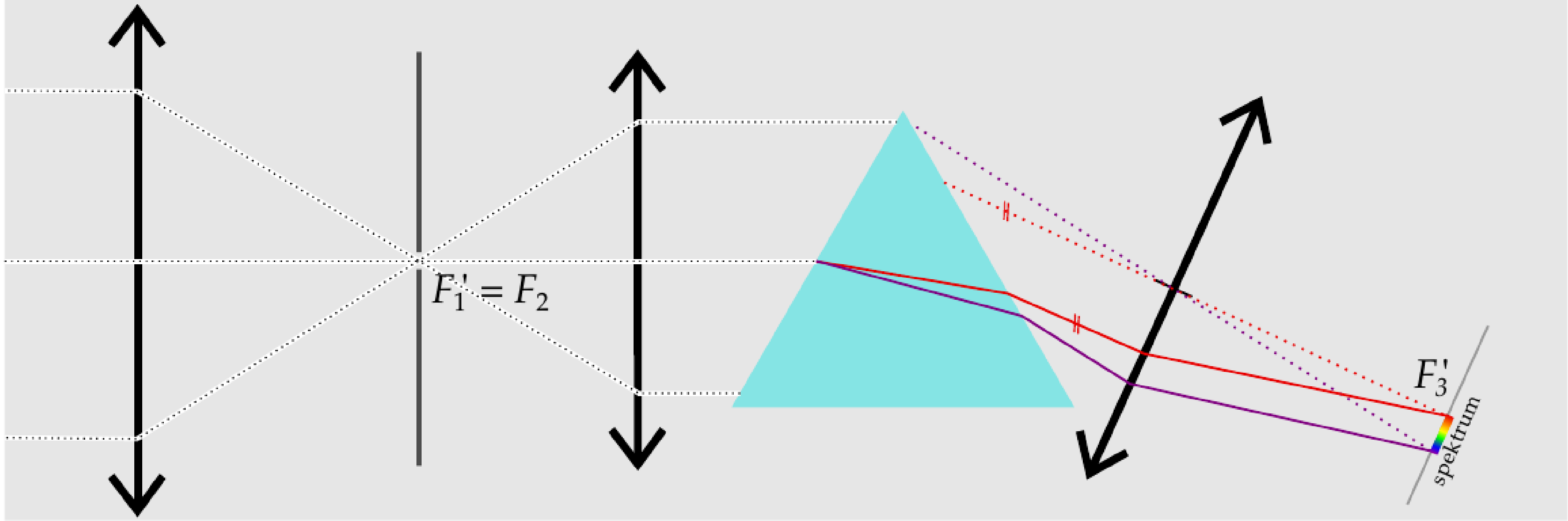
OHP CNRS

En 1995, sur le télescope de 193cm
équipé du spectrographe ELODIE,
Michel Mayor et Didier Queloz
découvraient la première planète
extrasolaire 51 Pegb autour
d'une étoile autre que le Soleil.

1,93 m
Cassegrain
f/15
1958

SOPHIE
fiber-fed
spectrograph

Spektrograf je přístroj, kterým světlo rozkládáme na spektrum. Při pozorování Slunce **první čočkou** vytvoříme jeho obraz v první ohniskové rovině. Úzkou **štěrbinou** vybereme tu část Slunce, kterou chceme studovat. Rozbíhavý svazek za štěrbinou změníme **druhou čočkou** na rovnoběžný; ten necháme dopadnout na **hranol**. Za hranolem máme rovnoběžný svazek fialový a jiný rovnoběžný červený. V rovnoběžném svazku ale nikdy obraz nevznikne, pročež máme **třetí čočku**, která vytvoří sbíhavý svazek, potažmo ostré **spektrum** ve druhé ohniskové rovině.

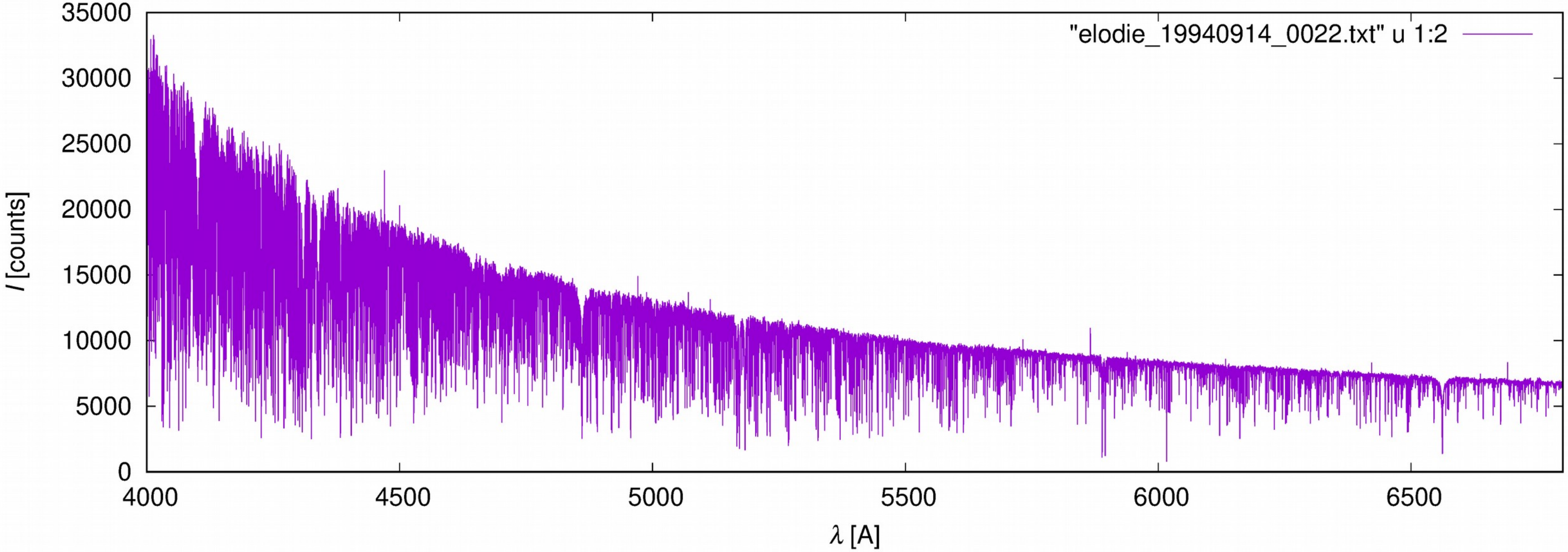


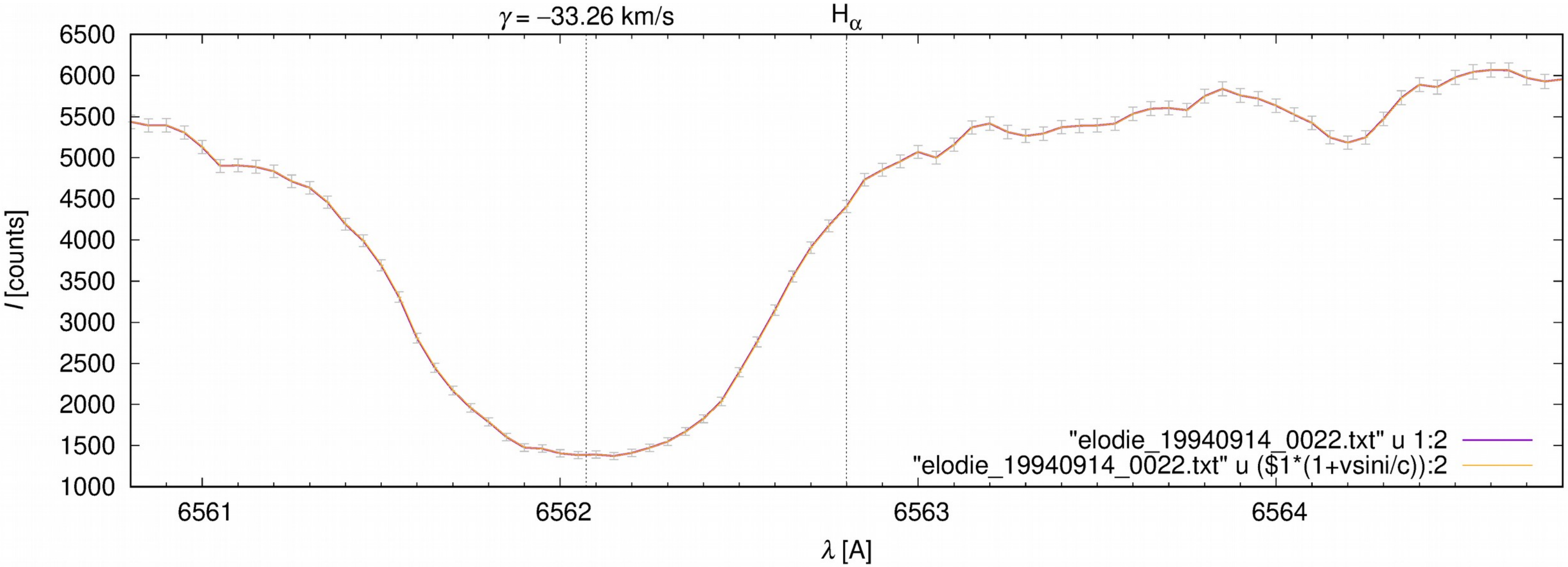
Ve spektru jsou vidět i ostatní barvy v tomto pořadí: červená, oranžová, žlutá, zelená, modrá, fialová.

ELODIE

- **echelletový spektrograf**, mřížka + cross-disperser
- λ = 390-682 nm, 67 řádů
- $R = \lambda/\Delta\lambda = 42\,000$
- CCD 1024 × 1024 pxl; tj. až 0,004 nm/pxl
- 2 o. vlákna, scrambling
- současná kalibrace Th-Ar
- tepelná stabilizace
- 5000 spektrálních čar
- Baranne etal. (1996)

51 Peg
Th-Ar
echelle
spectrum


"elodie_19940914_0022.txt" u 1:2
I [counts]
λ [A]
0
5000
10000
15000
20000
25000
30000
35000
4000
4500
5000
5500
6000
6500


$\gamma = -33.26$ km/s
H_α
"elodie_19940914_0022.txt" u 1:2
"elodie_19940914_0022.txt" u ($1*(1+vsini/c)):2
I [counts]
λ [A]
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
6561
6562
6563
6564

Stabilita, stabilita, stabilita

- drift nulového bodu (dle 87 *)
- RV systému, $\gamma = 33{,}26$ km/s ≠ konst.?
- změny RV oscilacemi na *?

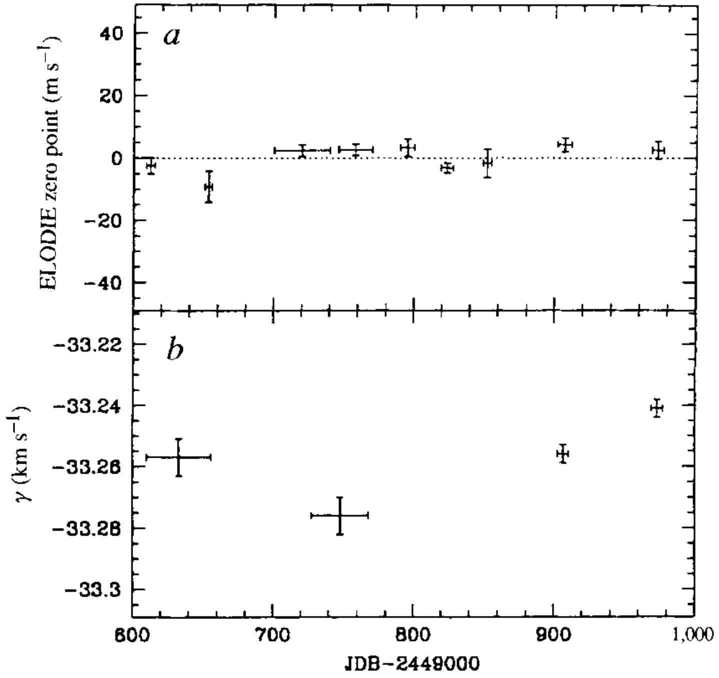


FIG. 3 *a*, ELODIE zero point computed from 87 stars of the sample having more than two measurements and showing no velocity variation. No instrumental zero point drift is detected. *b*, Variation of the γ-velocity of 51 Peg computed from the orbital fits displayed in Fig. 2. Considering the long-term stability of ELODIE this perturbation is probably due to a low-mass companion.

Křivka RV

- pozorované spektrum *vs.* vhodný vzor: **kroskorelace** $f(v_r)$, průměr z 5000 čar

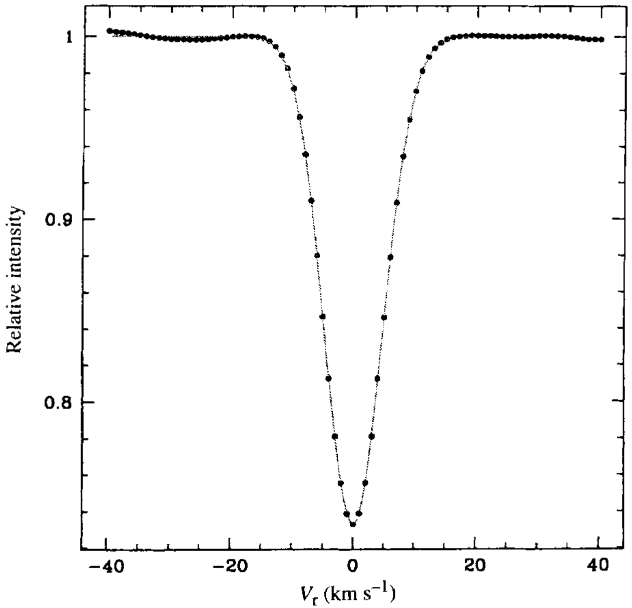
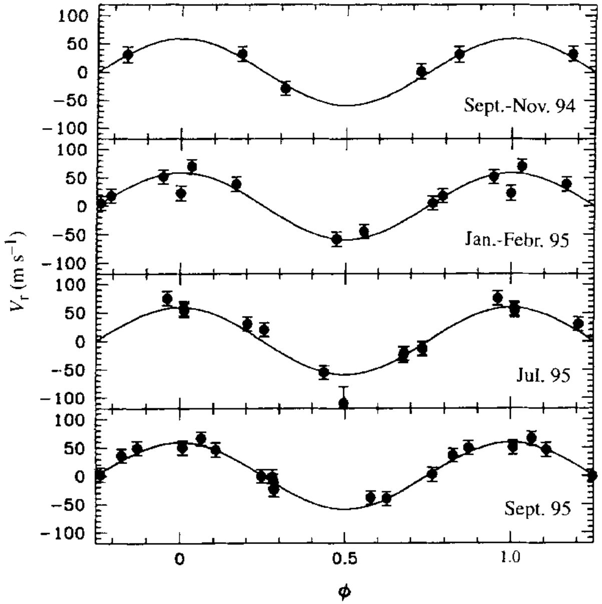


FIG. 1 Typical cross-correlation function used to measure the radial velocity. This function represents a mean of the spectral lines of the star. The location of the gaussian function fitted (solid line) is a precise measurement of the Doppler shift.



fáze

FIG. 2 Orbital motion of 51 Peg at four different epochs corrected from the γ-velocity. The solid line represents the orbital motion fitted on each time span with only the γ-velocity as a free parameter and with the other fixed parameters taken from Table 1.

Orbitální parametry

- neznámý sklon i, pouze $v_1 \sin i$; excentricita $e < 0{,}09$
- funkce hmoty $f \equiv m_2^3/(m_1 + m_2)^2 \cdot (\sin i)^3 = K_1^3 P/(2\pi G)$

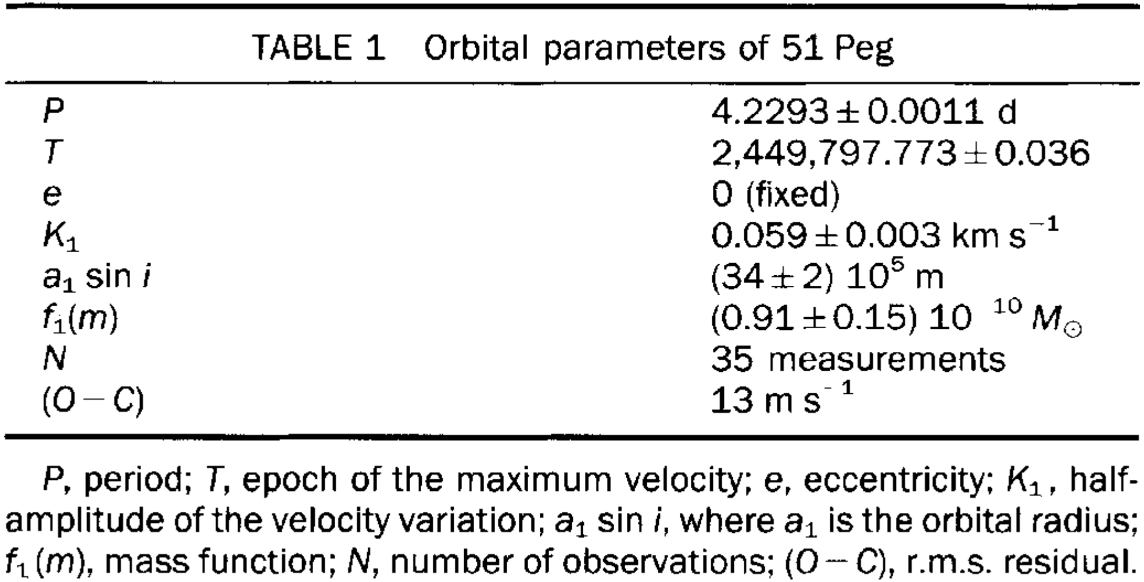


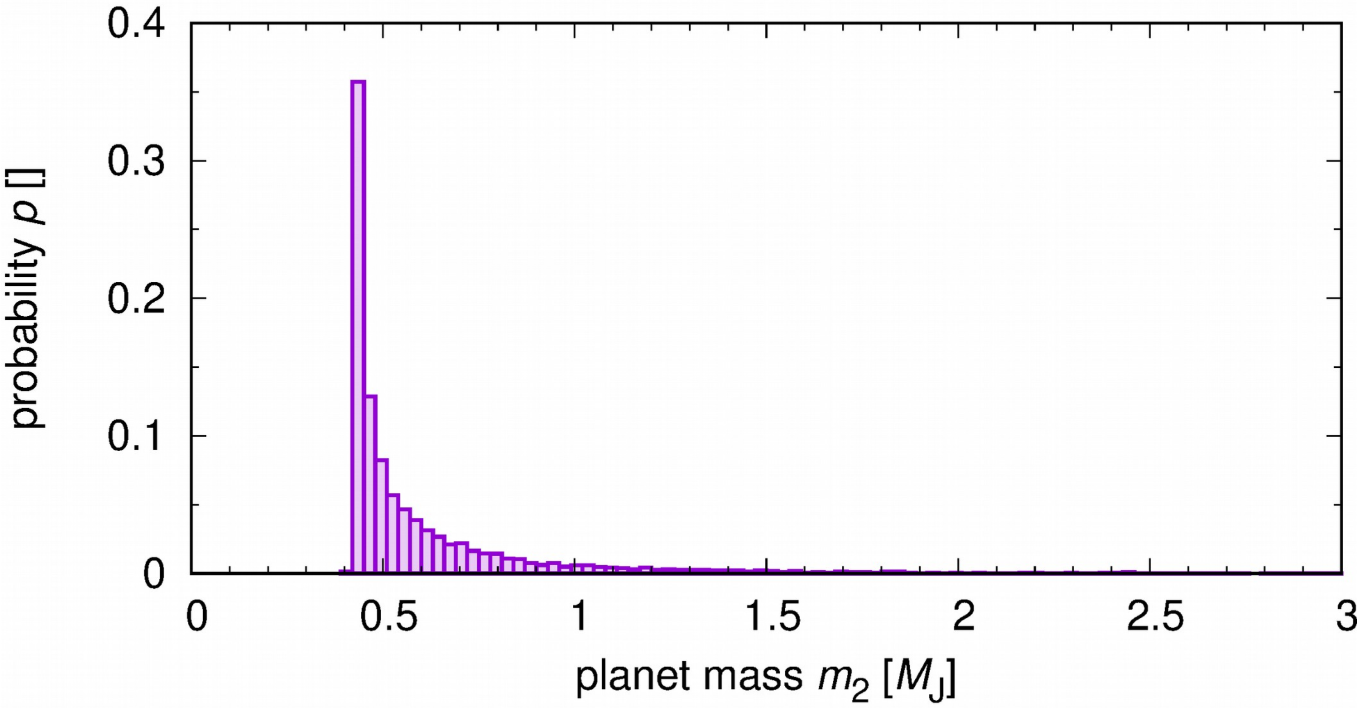
TABLE 1 Orbital parameters of 51 Peg

P	4.2293 ± 0.0011 d
T	$2{,}449{,}797.773 \pm 0.036$
e	0 (fixed)
K_1	0.059 ± 0.003 km s^{-1}
$a_1 \sin i$	$(34 \pm 2)\ 10^5$ m
$f_1(m)$	$(0.91 \pm 0.15)\ 10\ ^{10}\ M_\odot$
N	35 measurements
$(O - C)$	13 m s^{-1}

P, period; T, epoch of the maximum velocity; e, eccentricity; K_1, half-amplitude of the velocity variation; $a_1 \sin i$, where a_1 is the orbital radius; $f_1(m)$, mass function; N, number of observations; $(O - C)$, r.m.s. residual.

Hmotnost m_2

- náhodné rozdělení *i*, resp. sin *i* → rozdělení m_2; observační nedostatečnost (bias)



Další objevy...

- 2. exoplaneta **47 UMa b** (Butler & Marcy 1996)
- 3. exoplaneta **70 Vir b** (Marcy & Butler 1996)

⋮

- 1. systém **υ And A b, c, d** (Butler etal. 1999)
- 1. tranzitující **HD 209458 b** (Henry etal. 2000; Charbonneau etal. 2000)

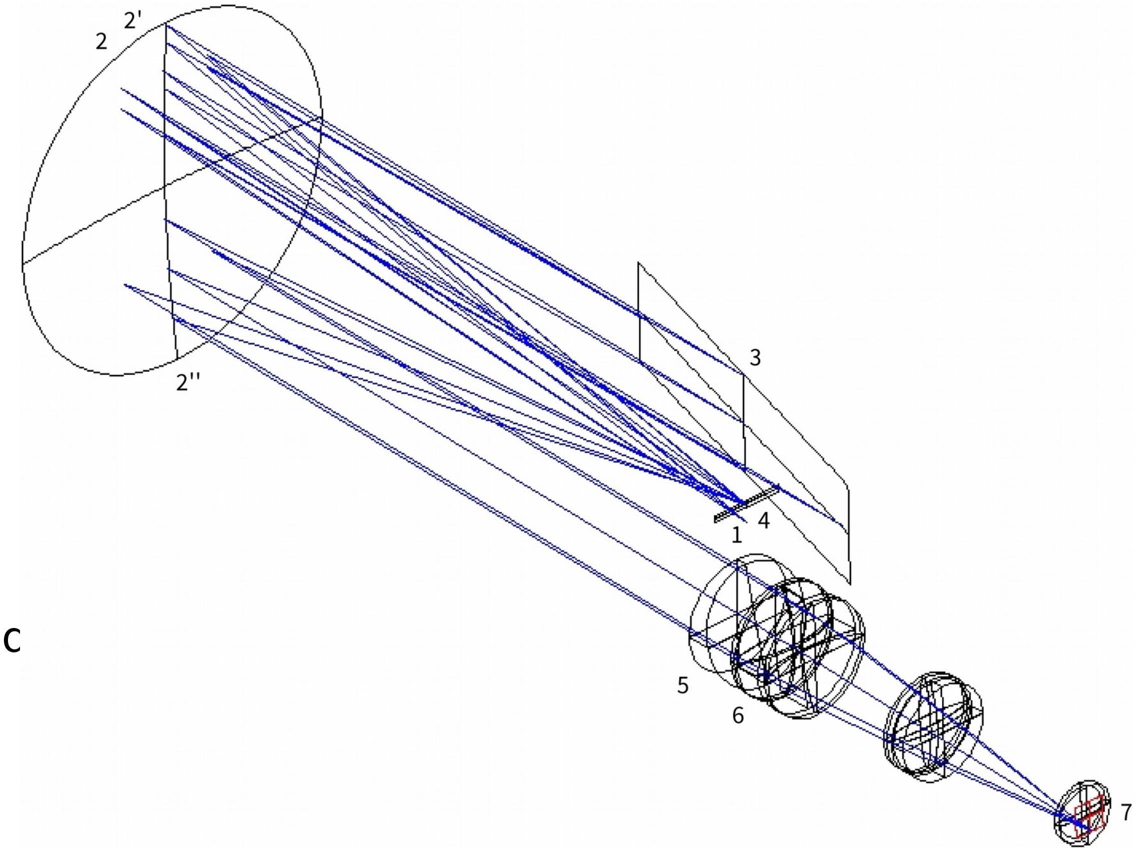
⋮

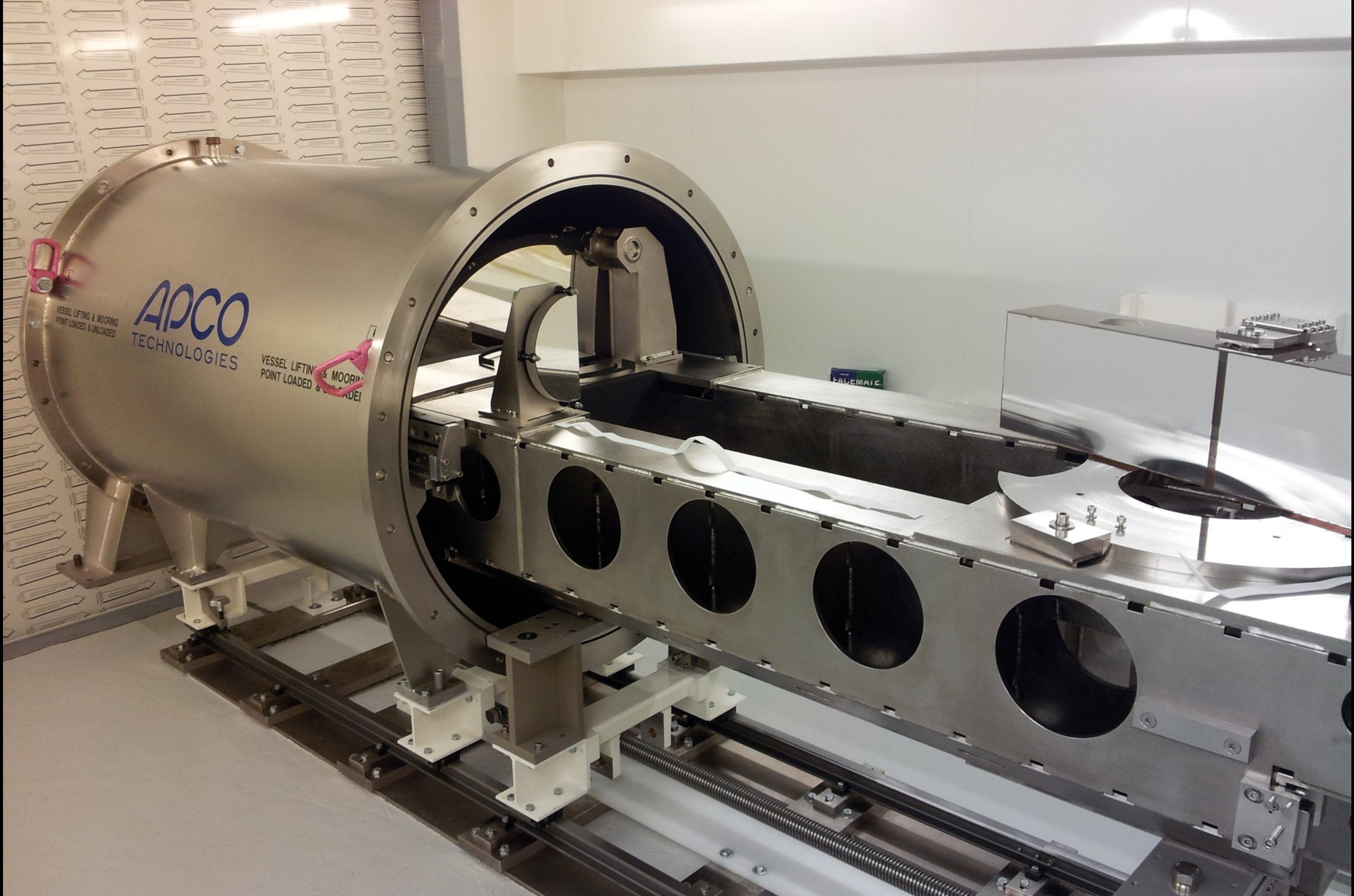
& A. Wolszczan?

- exoplanety o. **PSR B1257+12** (Wolszczan & Frail **1992**)
- neutronová *, resp. pulsar 6,2 ms
- P = 98,2 a 66,6 d; a = 0,47 a 0,36 au; M > 2,8 a 3,4 M_E
- perturbace a 3. planeta M = 0,02 M_E (Wolszczan 1994)
- 3 další pulsary

HARPS

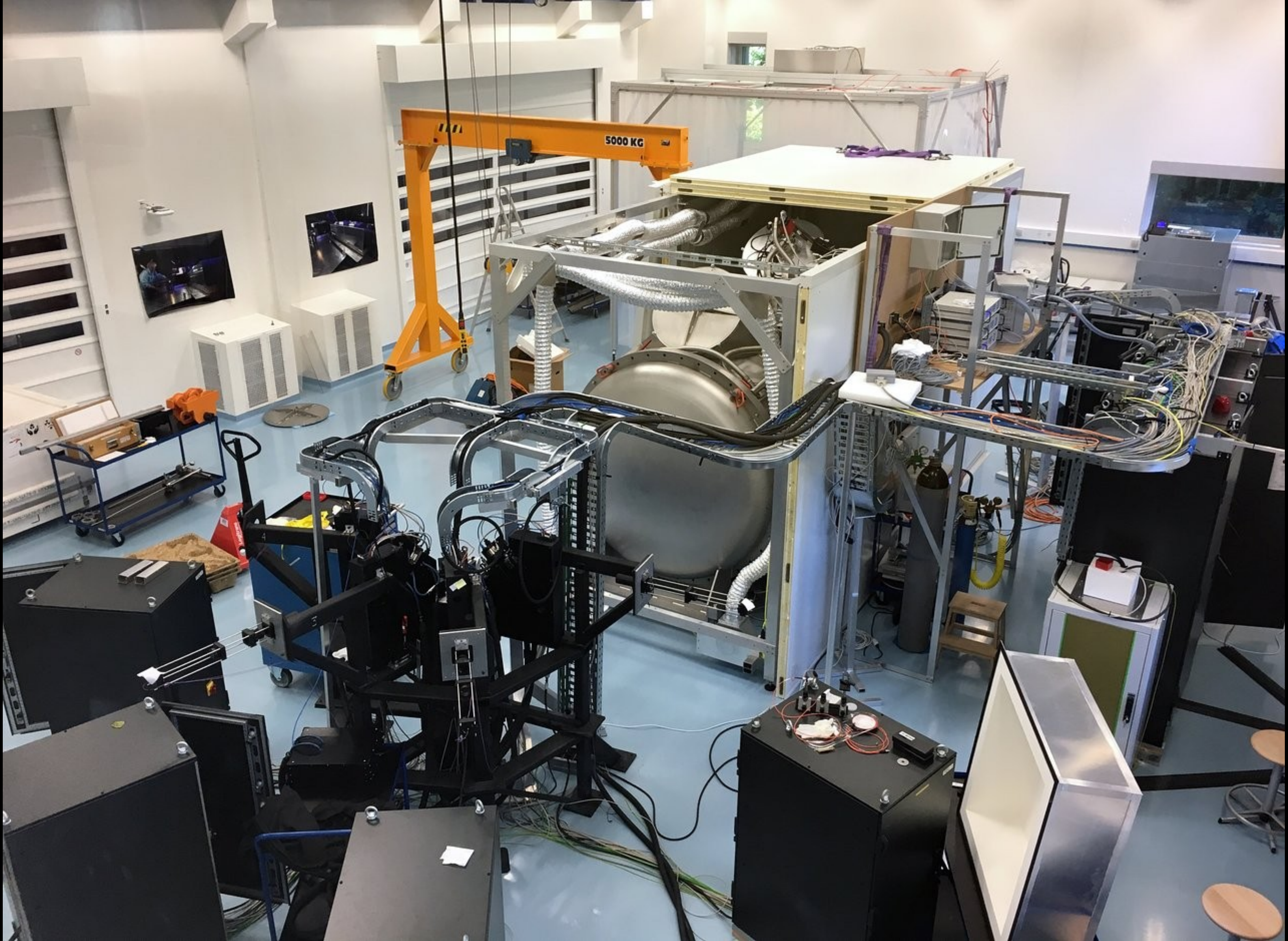
- vakuová komora, $P = 1$ Pa, fluktuace n
- stabilita 290 ± 0,001 ± 0,01 K
- CCD kryostat 148 ± 0,02 K; dilatace čipu
- λ = 398-691 nm, 68 řádů
- $R = 120\,000$
- $D = 3{,}6$ m
- observatoř La Silla, též La Palma
- $\sigma_{RV} = 0{,}3\ (0{,}6)$ m/s
- Mayor etal. (2003)

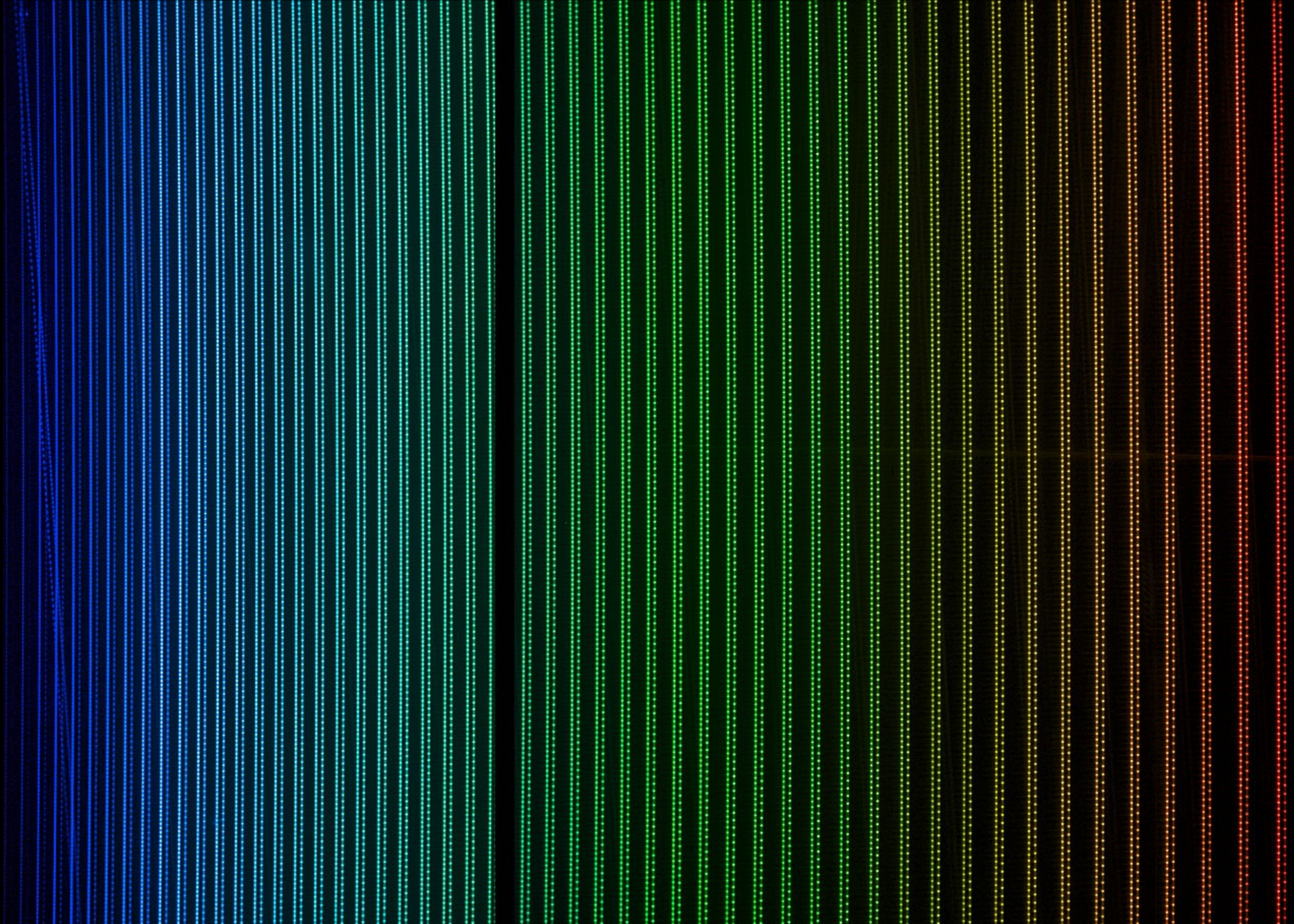



APCO
TECHNOLOGIES
VESSEL LIFTING & MOORING
POINT LOADED & UNLOADED
VESSEL LIFTING & MOORING
POINT LOADED & UNLOADED

ESPRESSO

- λ = 380-788 nm, $R = \lambda/\Delta\lambda$ = 140 000, φ = 1,0", η = 11 %, V ~ 17 mag
- kalibrace Th-Ar, Fabry-Pérot, Laser Frequency Comb
- cylindrická optika tvarující pupilu (slicer)
- dichroické zrcadlo, 2 optimalizované kamery
- 4 dalekohledy VLT, nekoherentní ohnisko
- σ_{RV} = 10 cm/s
- cf. $v_{\mathrm{kepl}} = [G\,(M+m)/r\,]^{1/2}$, $v_2 = v_{\mathrm{kepl}}\, m/(M+m)$ = 9 cm/s


5000 KG

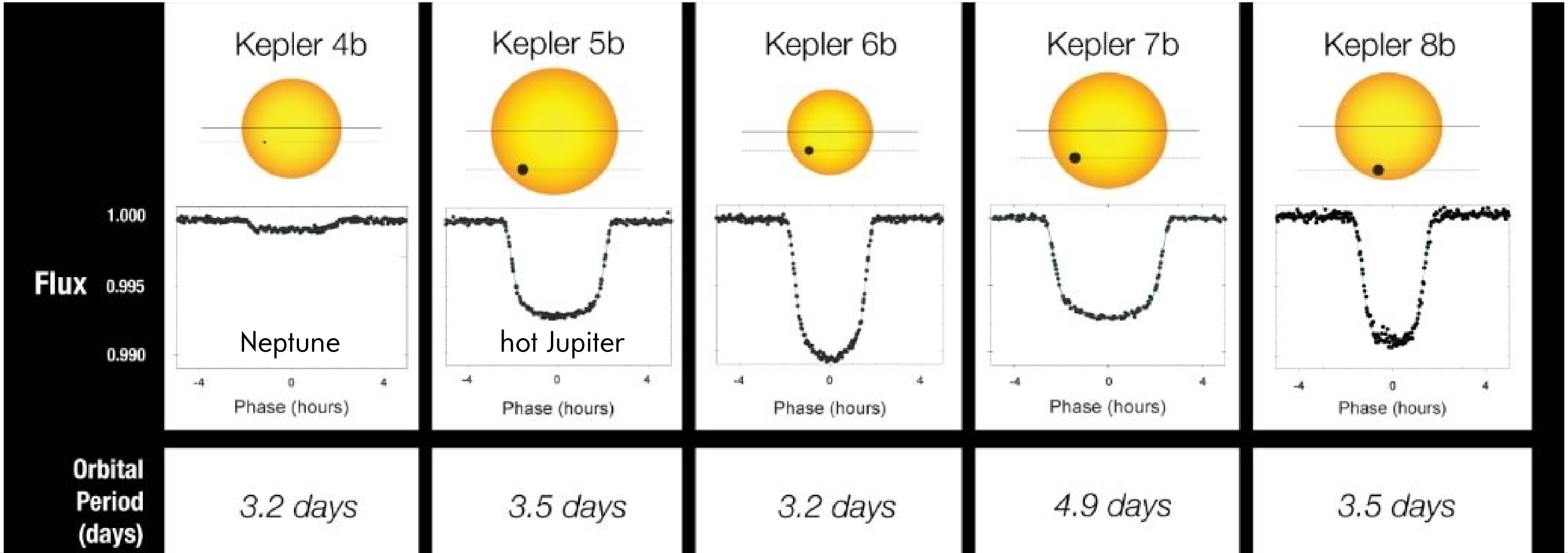


9. 5. 2016

Tranzity

- CoRoT, **Kepler**, **TESS**, CHEOPS, PLATO, …
- $V = 12$ mag, $t_{\mathrm{exp}} = 30$ min, $\boldsymbol{\Phi} = 5{,}2 \cdot 10^{-14}$ W m^{-2}, $E_{\gamma} = 3{,}6 \cdot 10^{-19}$, QE = 85 %, $\eta = 1{,}4$ ADU e.$^{-1}$, $S^* = 214000000$ ADU, $N^* = (S^*)^{1/2} = 17000$, $S^*/N = 12000$, $\boldsymbol{\sigma} = \mathbf{80}$ **ppm**

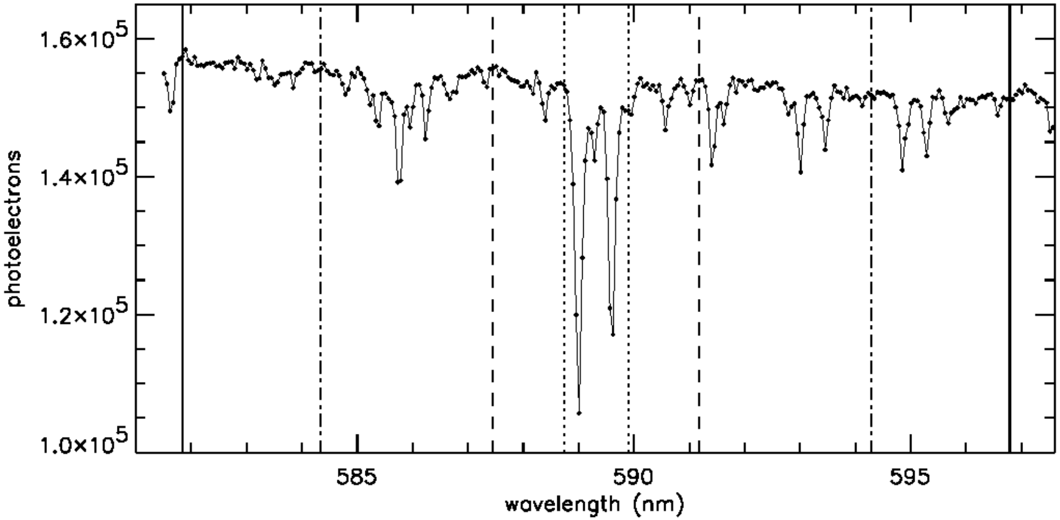
Borucki etal. (2010)

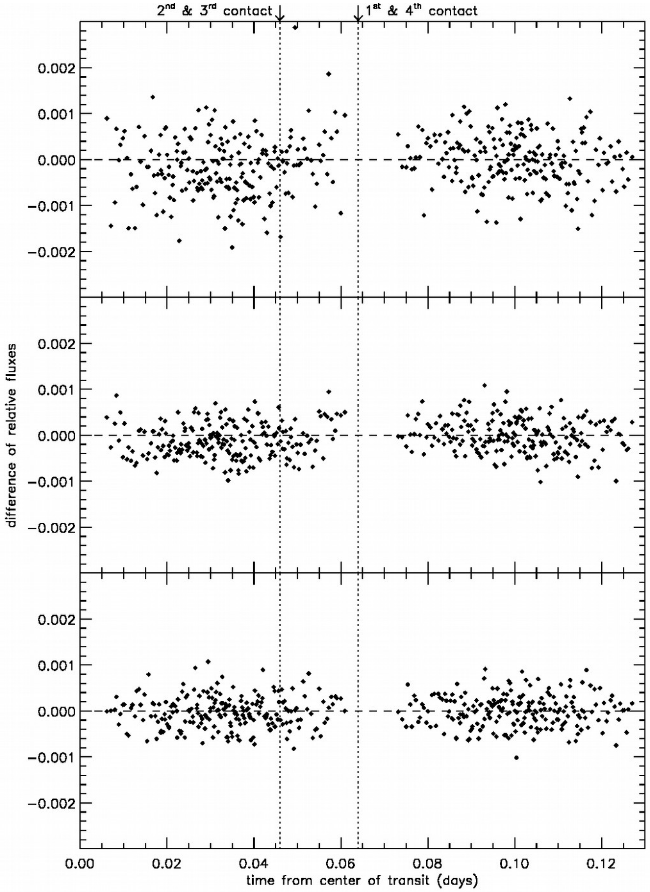


$R^* = 1\,R_{\odot}$, $\pi R^2/[\pi R^{*2}] = \sigma$, $R = 1\,R_{\oplus}$

Transmisní spektroskopie

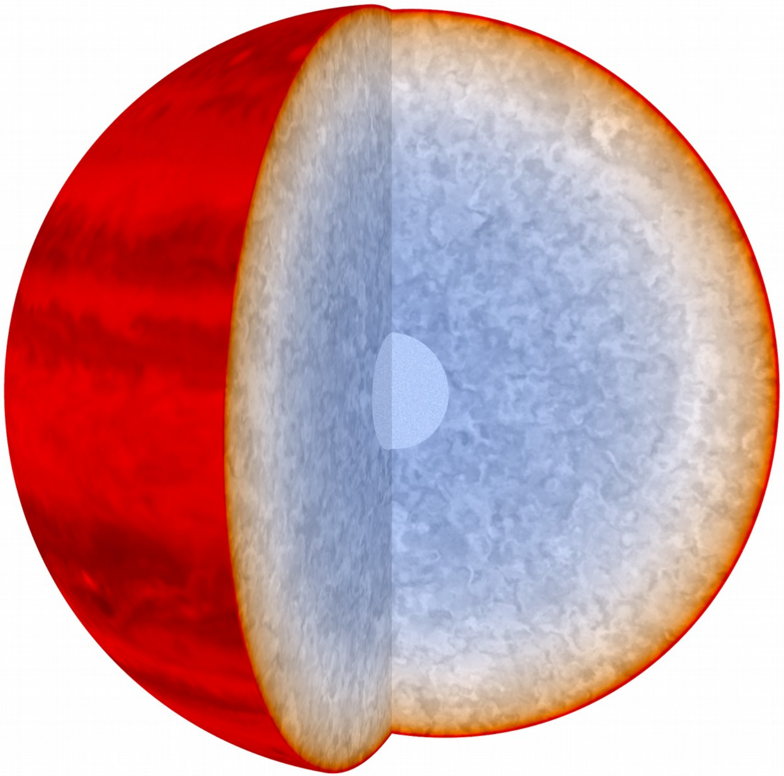
- HD 209458 b, $P = 3{,}52$ d, $M = 0{,}69\ M_J$ (Charbonneau etal. 2002 .. Sanchez-Lopez etal. 2019)
- detekce: C, CH_4, CO, CO_2, H, H_2, H_2O, HCN, He, K, Mg, NH_3, **Na** (i.e. $(2{,}3 \pm 0{,}6) \cdot 10^{-4}$), O I, O_2, TiO, VO





Typy planet

- trpasličí (cf. Vernazza etal. 2019)
- protoplanety? (Měsíc, Merkur, Mars)
- terestrické
- ledové obry
- **plynné obry**
- super Země
- mini Neptuny
- horké Jupitery
- pulsarovské
- interstelární
- nafouknuté
- hnědí trpaslíci



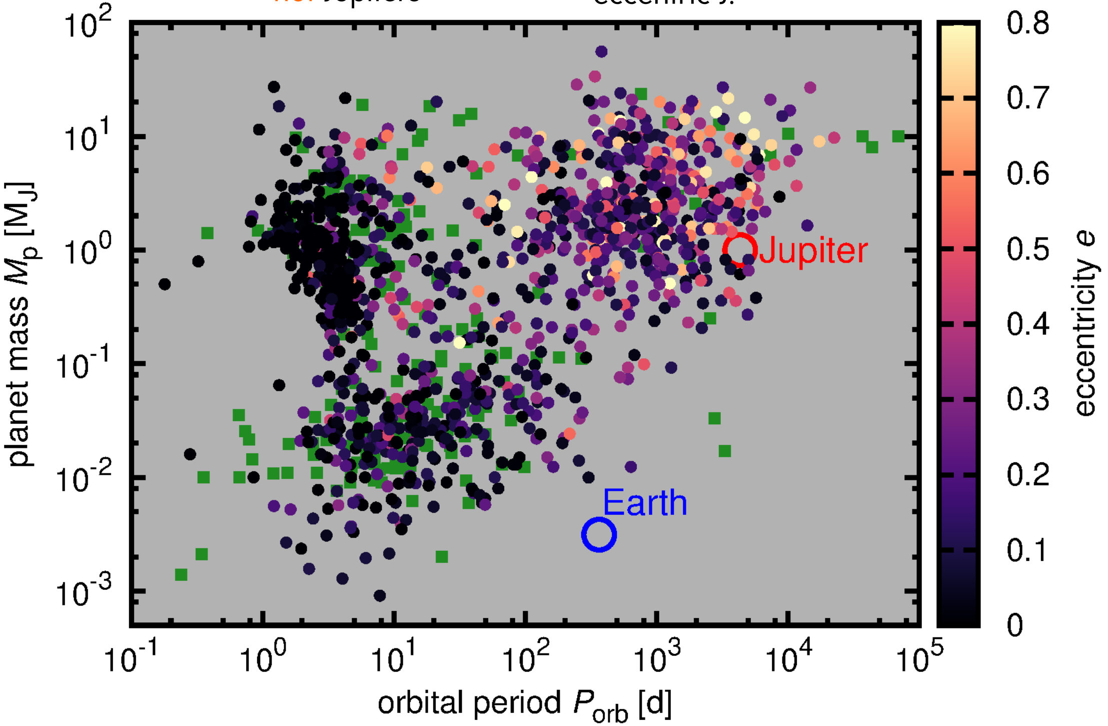
Statistika exoplanet

- hmotnost *vs.* orbitální perioda *vs.* excentricita; 1400 exoplanet; vzdálenost *!

hot Jupiters

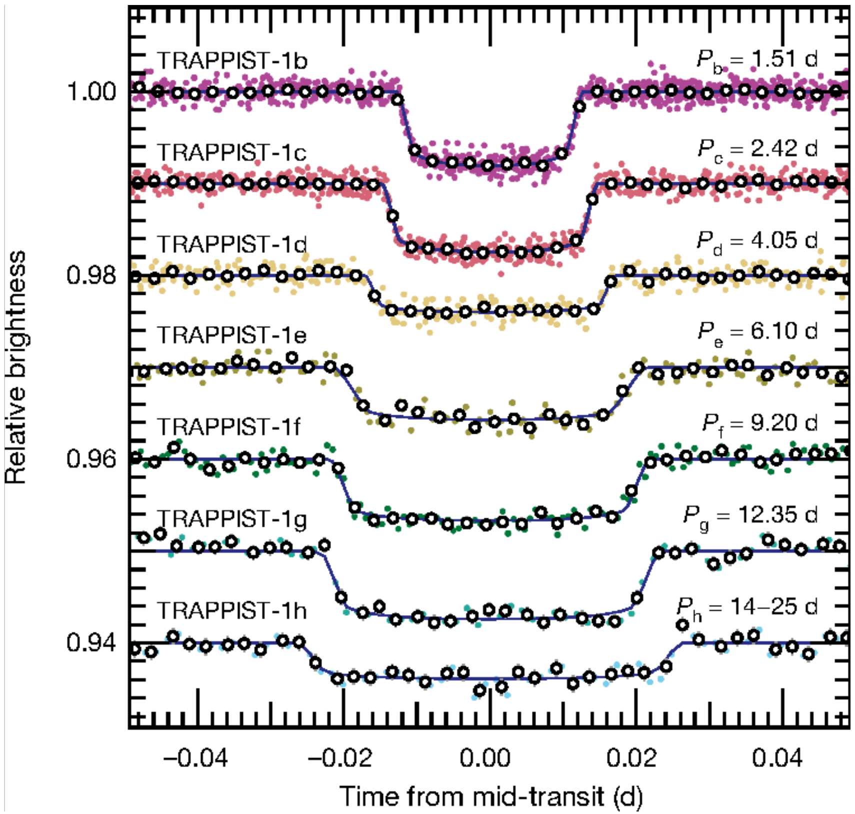
eccentric J.

mini-Neptunes
super-Earths



Červení trpaslíci a jejich planety

- Gillon etal. (2016, 2017) & D. Q.
- **7 planet** (TRAPPIST-1 b-h; Aqr)
- větší kontrast, $L^* = 0{,}08\ L_\odot$, $R^* = 1\ R_\mathrm{J}$ (!)
- $P = 1{,}51,\ 2{,}42,\ 4{,}04,\ 6{,}06,\ 9{,}1,\ 12{,}35$ a ? dní
- skoro rezonanční řetězec 8/5, 5/3, 3/2, 3/2, 4/3
- silný signál **TTV** (1 planeta → celý systém)
- $a = 0{,}011\text{-}0{,}062$ au; $R = 0{,}77\text{-}1{,}15\ \mathrm{R}_\oplus$; $M = 0{,}33\text{-}1{,}16\ \mathrm{M}_\oplus$
- slapy → vázaná rotace; slapový ohřev
- formování →, migrace ←?



“Údolí smrti”

- Fulton etal. (2017)
- spektroskopie * → T_{eff}, log g, …
- zpřesnění R^*, L^*
- chybějící mini-Neptuny, $R \sim 1{,}8\ R_\oplus$
- fotœvaporace?
- jádra mini-Neptunů asi $< 1{,}5\ R_\oplus$?

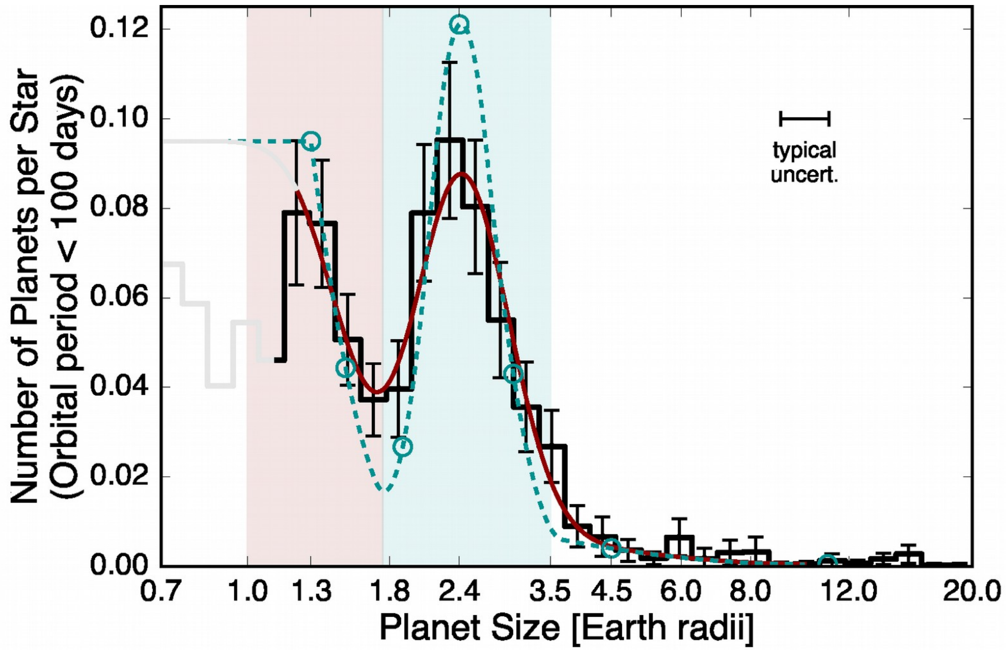


FIG. 7.— *Top:* Completeness-corrected histogram of planet radii for planets with orbital periods shorter than 100 day
in the bin amplitudes are calculated using the suite of simulated surveys described in Section C. The light gray region of t
radii smaller than 1.14 $R_\oplus$ suffers from low completeness. The histogram plotted in the dotted grey line is the same distri
radii uncorrected for completeness. The median radius uncertainty is plotted in the upper right portion of the plot. *Botto*
panel with the best-fit spline model over-plotted in the solid dark red line. The region of the histogram plotted in light gre
in the fit due to low completeness. Lightly shaded regions encompass our definitions of “super-Earths” (light red) and
(light cyan). The dashed cyan line is a plausible model for the underlying occurrence distribution after removing the sme
uncertainties on the planet radii measurements. The cyan circles on the dashed cyan line mark the node positions and
spline fit described in §4.2.

Paralaxy * a planet

- Berger etal. (2018)
- 177 911 * dle Gaia DR2
- zpřesnění poloměrů * (8 %) → planet
- potvrzení údolí, pro $\Phi > 200\ S$
- potvrzení pouště, pro $\Phi > 10^3\ S$
- 8 + 30 planet nalezených v tzv. "optimistické obyvatelné zóně" ($R < 2\ R_\oplus$; $0{,}25\ S < \Phi < 1{,}5\ S$)

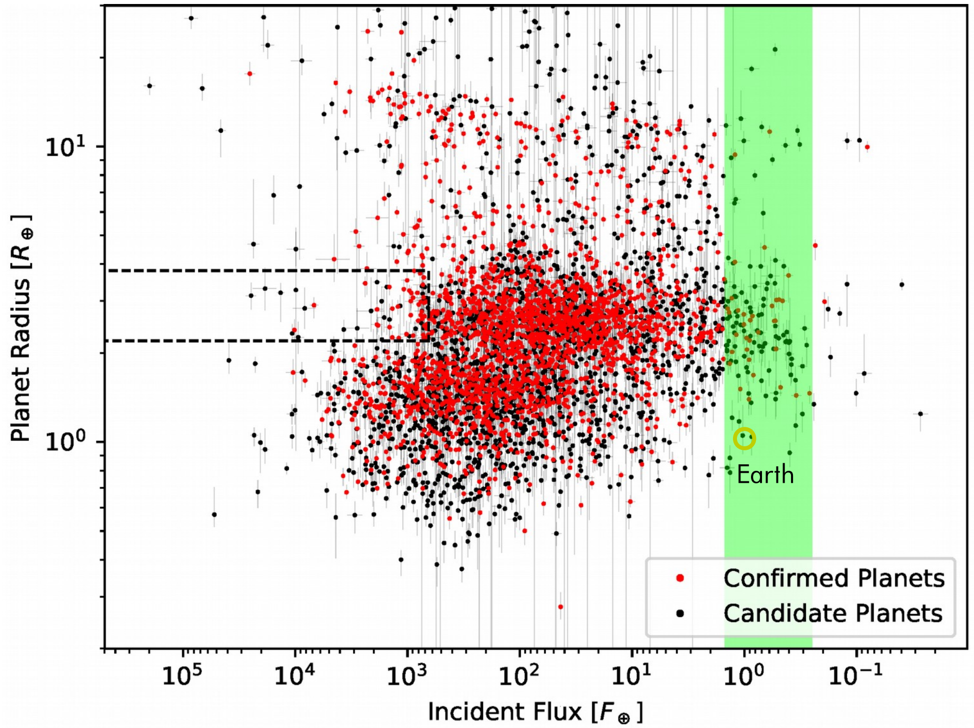
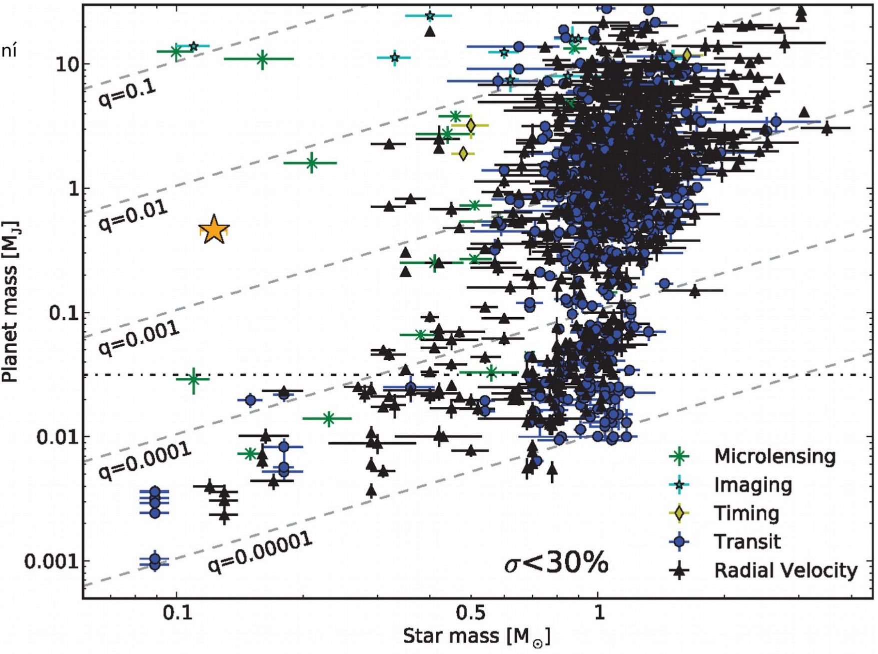


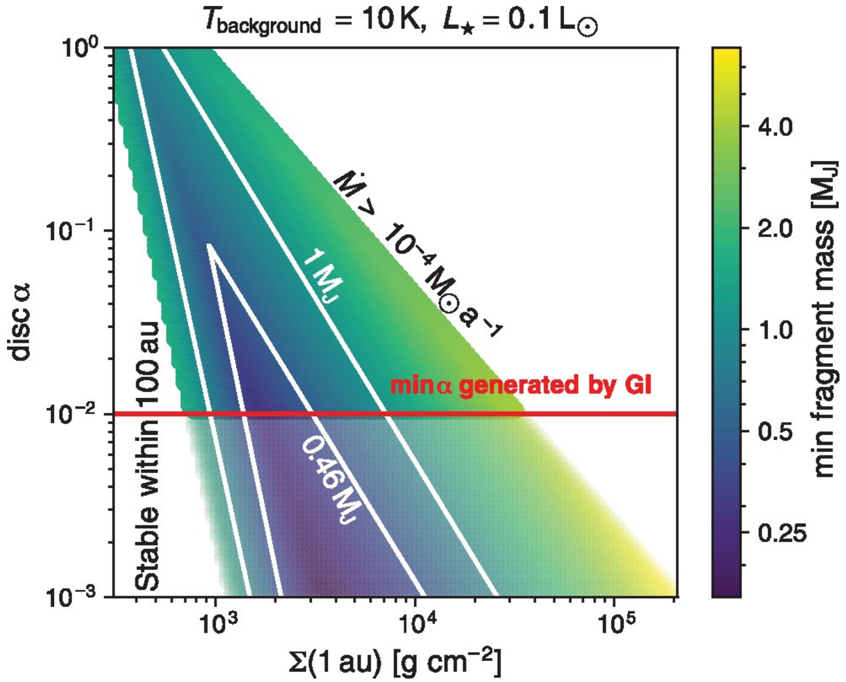
Figure 9. Planet radius versus incident flux for *Kepler* exoplanets. Red and black dots are confirmed and candidate exoplanets, respectively. We also plot our asymmetric error bars in transparent gray. The dashed line box represents the extension of the super-Earth desert identified in Lundkvist et al. (2016), while the green bar indicates the approximate optimistic habitable zone for FGK stars as detailed in Kane et al. (2016).

Extrémní planety

- Morales etal. (2019); GJ 3512; sp. M5.5, $M = 0{,}12\ M_\odot = 12\ M_J$
- $P = 204$ d; $M > 0{,}46\ M_J$; $e = 0{,}43$ ← gravitační nestabilita disku? interakce planet?

mikročočkování





povrchová hustota vs. viskozita vs. hmotnost fragmentu

Protoplanetární disky

(Andrews etal. 2018; Avenhaus etal. 2018)

- interferometr ALMA (sub-mm, radio) *vs.* adaptivní optika VLT/SPHERE (V, NIR)