Towards a complete census of planetary system diversity

The role of ground-based observations

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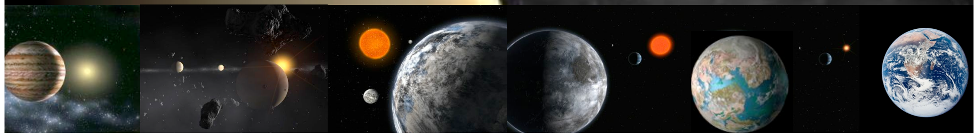
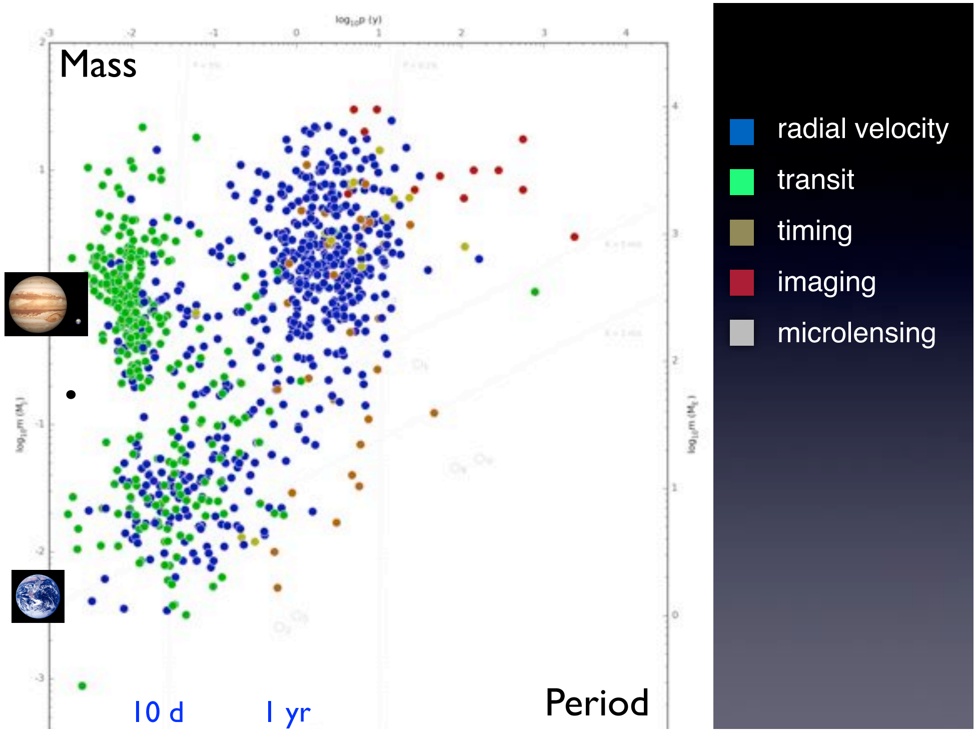




Points to be addressed...

- Radial velocities: from super-Earths to giant planets
  - planet mass distribution, orbital parameters, multi-planet system
  - limitations and challenges
- What we have learned from transits
  - statistics
  - further planet physical properties
  - the future: transits of bright stars
- Planet characterisation
  - Internal structure, atmospheres
- The future: detection of Earth-type planets in the HZ of
  - pushing further: observations, instrumentation
  - a complete census: the synergetic role of radial velocities
  - global coherence

Sucesses

Limitations

Expectations

The role of radial velocity observations

1. Detection (census)
2. Mass estimate, a fundamental param
   - to define the nature of the planet (density, composition)
   - for atmospheric characterization (scale height, gravity)
   - to probe the long term evolution (dynamics)

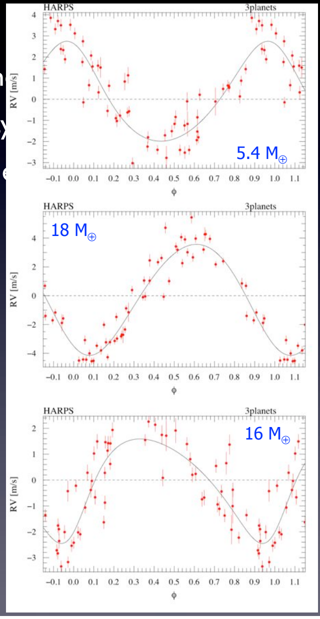
The next step: characterization!

What is characterizing a planet?

- Host star and Orbit → incident stellar flux
- Mass, Radius → mean densitiy, bulk composition
- Atmosphere → scale height, composition
- Age → evolution (dynamics)
- Biosphere → life

The role of radial velocity observations

1. Detection (census)
2. Mass estimate, a fundamental param
   - nature of the "companion" (density
   - atmospheric characterization (scal
   - long term evolution (dynamics)
3. Orbital parameters (architecture)
   - period, separation
   - multiplicity
   - eccentricity
     => dynamics
   - geometry (RM effect)



P_1 = 4.2 days
e_1 = 0.16
m_1 sini = 5.4 $M_\oplus$

P_2 = 38.2 days
e_2 = 0.09
m_2 sini = 18.5 $M_\oplus$

P_3 = 184 days
e_3 = 0.27
m_3 sini = 15.9 $M_\oplus$

Planet detectability with radial velocities

$$k_1 = \frac{28.4\ \mathrm{m\,s^{-1}}}{\sqrt{1-e^2}} \frac{m_2 \sin i}{M_{\rm Jup}} \left(\frac{m_1 + m_2}{M_{\rm Sun}}\right)^{-2/3} \left(\frac{P}{1\ \mathrm{yr}}\right)^{-1/3}$$

Jupiter	@ 1 AU	: 28.4 m s^{-1}
Jupiter	@ 5 AU	: 12.7 m s^{-1}
Neptune	@ 0.1 AU	: 4.8 m s^{-1}
Neptune	@ 1 AU	: 1.5 m s^{-1}
Super-Earth (5 $M_\oplus$)	@ 0.1 AU	: 1.4 m s^{-1}
Super-Earth (5 $M_\oplus$)	@ 1 AU	: 0.45 m s^{-1}
Earth	@ 1 AU	: 0.09 m s^{-1}

The HARPS search for low-mass planets

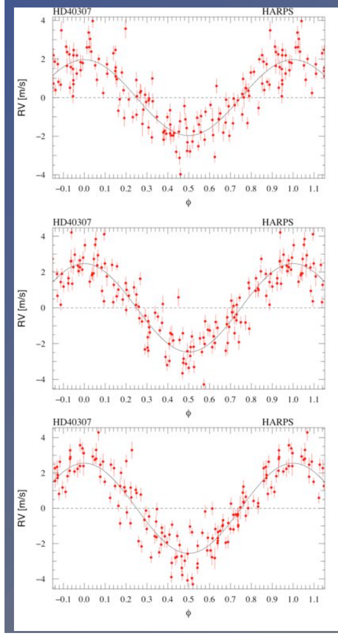
- Sample of ~350 slowly-rotating, nearby solar-type stars, <1m/s precision
- Non active and non evolved stars
- Observations ongoing since 2004
- Focus on low-amplitude RV variations
  - => ~ 50% of HARPS GTO time (265 nights)
  - => + 280 nights over 4 years (-->2013)
  - => + 165 nights over 3 years (2013-->)

ESO-3.6m @ La Silla

HARPS

An emerging population of Hot Neptunes and Super-Earths

Mayor et al. A&A 2009



P_1 = 4.31 days
e_1 = 0.02
m_1 sini = 4.3 $M_\oplus$

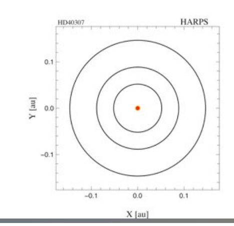
P_2 = 9.62 days
e_2 = 0.03
m_2 sini = 6.9 $M_\oplus$

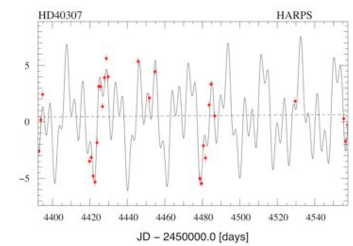
P_3 = 20.5 days
e_3 = 0.04
m_3 sini = 9.7 $M_\oplus$

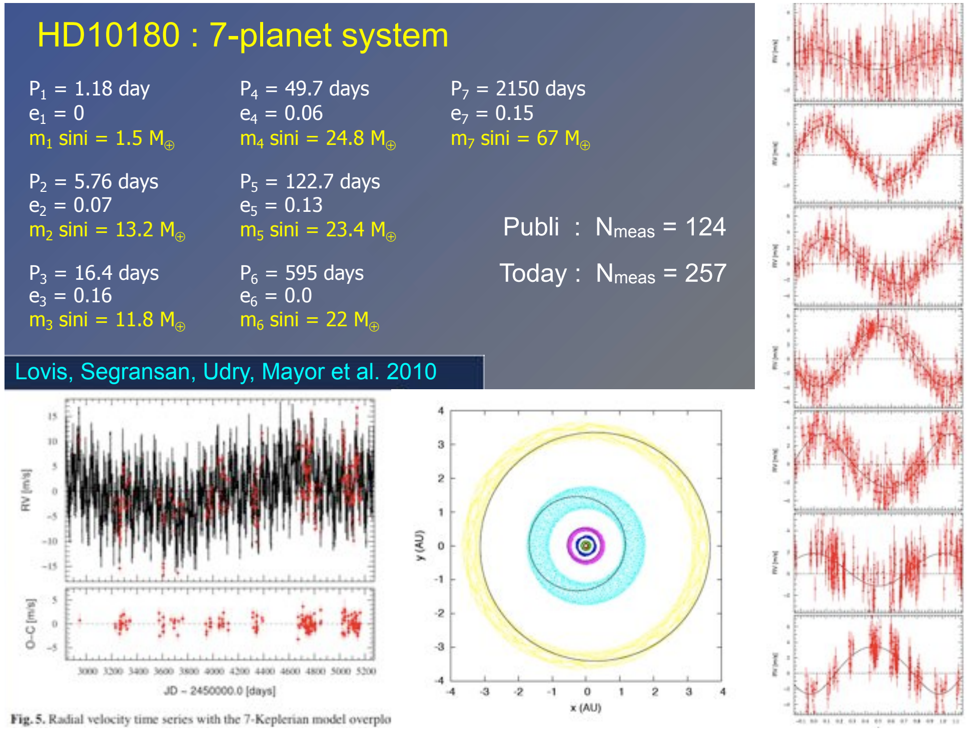
HD 40307
K2 V
Dist 12.8 pc
[Fe/H] = -0.31

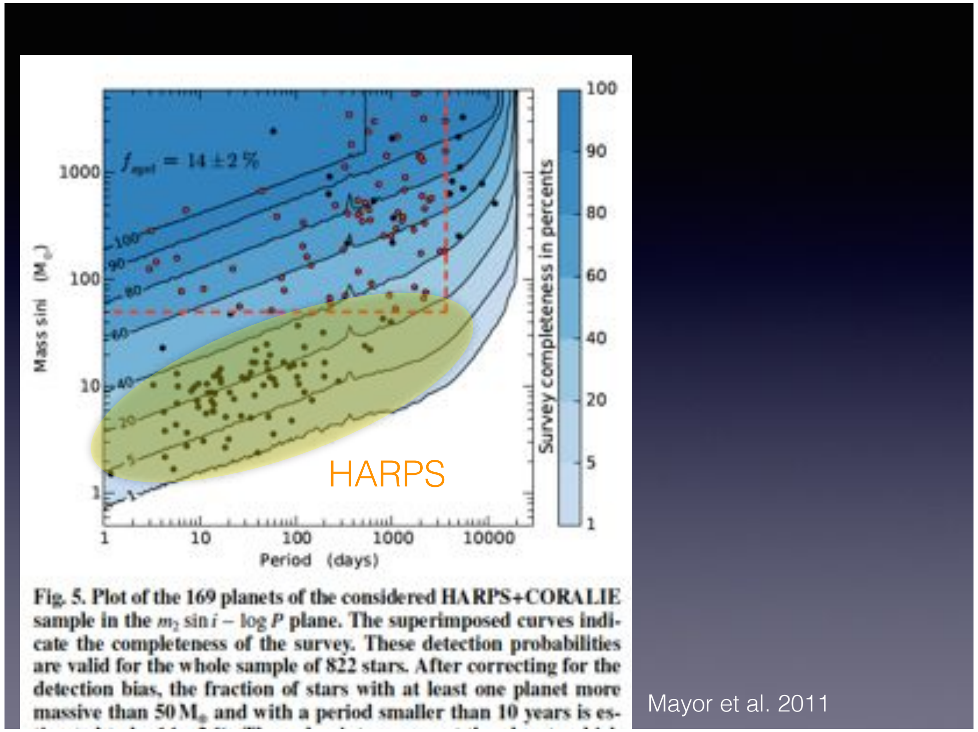
O-C = 0.85 m/s
135 observations

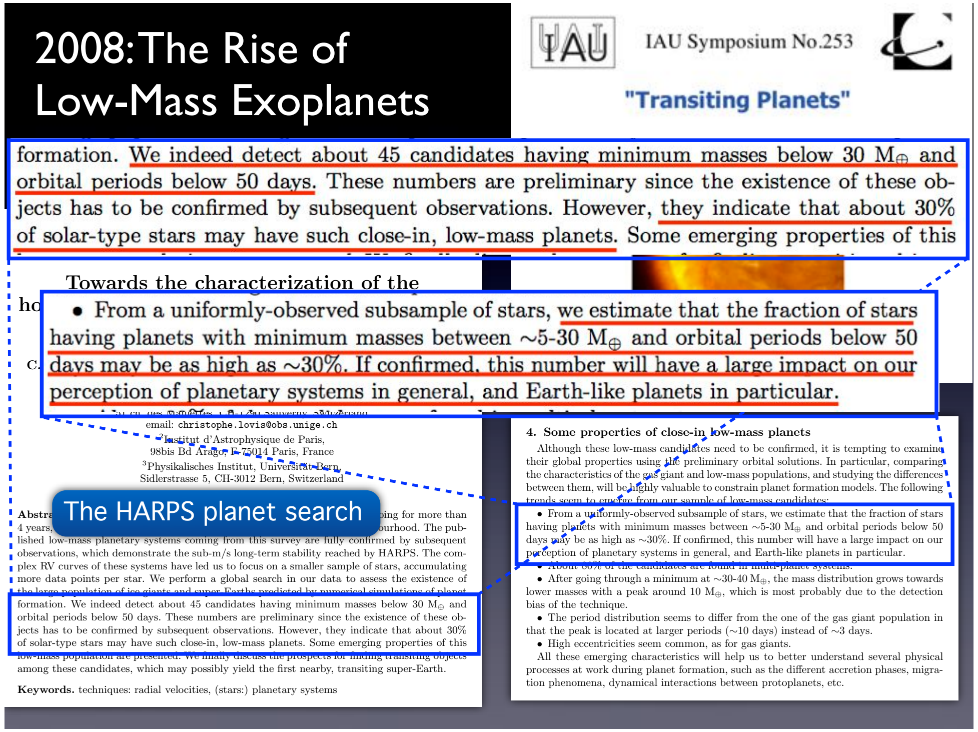
+ drift = 0.5 m/s/y

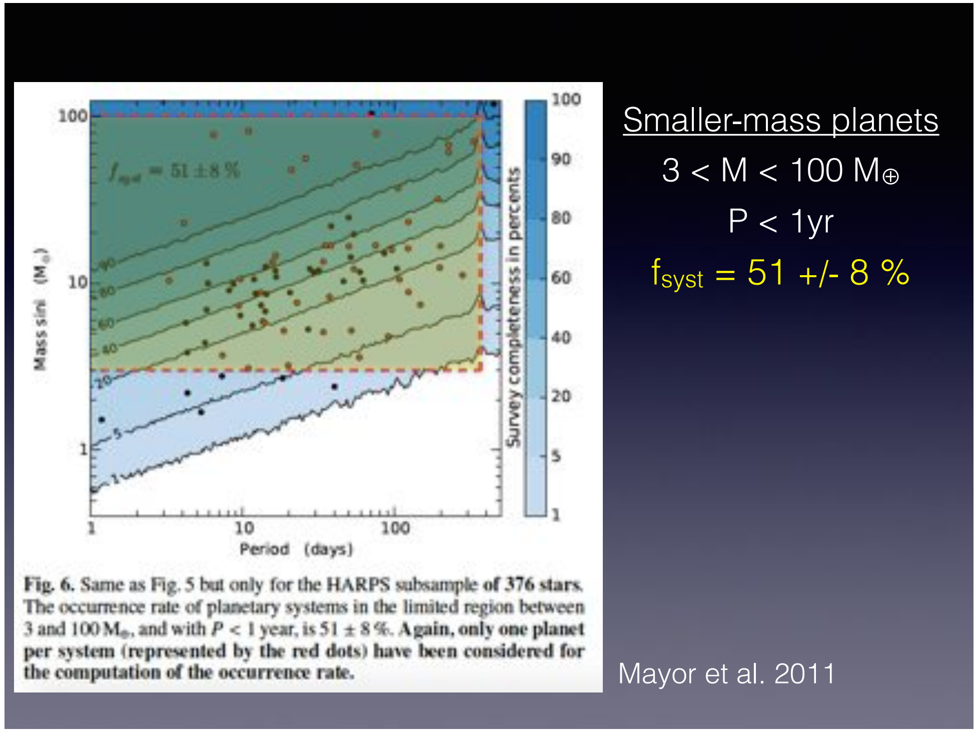




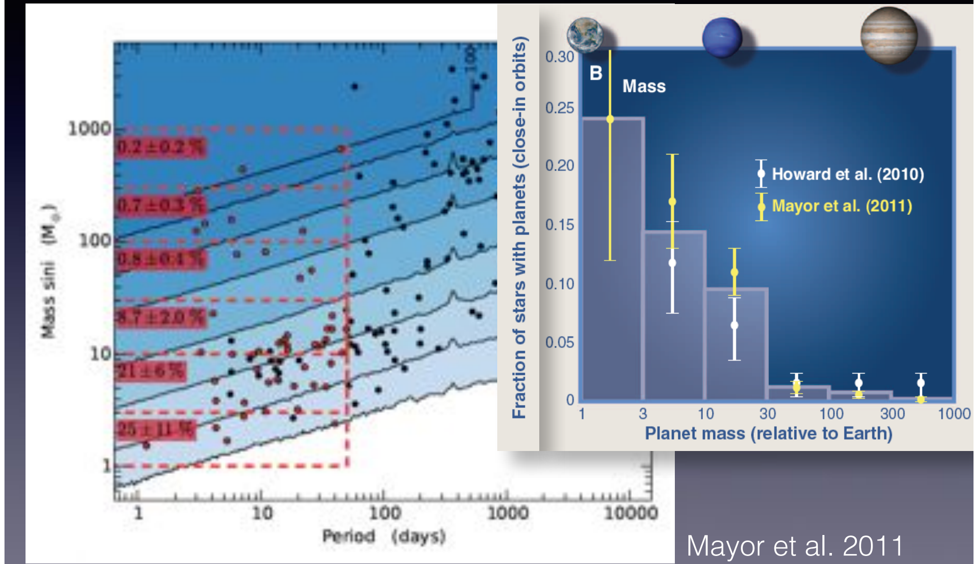

HD10180 : 7-planet system
P1 = 1.18 day
e1 = 0
m1 sini = 1.5 M⊕
P2 = 5.76 days
e2 = 0.07
m2 sini = 13.2 M⊕
P3 = 16.4 days
e3 = 0.16
m3 sini = 11.8 M⊕
P4 = 49.7 days
e4 = 0.06
m4 sini = 24.8 M⊕
P5 = 122.7 days
e5 = 0.13
m5 sini = 23.4 M⊕
P6 = 595 days
e6 = 0.0
m6 sini = 22 M⊕
P7 = 2150 days
e7 = 0.15
m7 sini = 67 M⊕
Publi : Nmeas = 124
Today : Nmeas = 257
Lovis, Segransan, Udry, Mayor et al. 2010
RV [m/s]
O-C [m/s]
JD – 2450000.0 [days]
y (AU)
x (AU)
Fig. 5. Radial velocity time series with the 7-Keplerian model overplo


f_syst = 14 ± 2 %
Mass sini (M_J)
Period (days)
Survey completeness in percents
HARPS
Fig. 5. Plot of the 169 planets of the considered HARPS+CORALIE sample in the m2 sin i – log P plane. The superimposed curves indicate the completeness of the survey. These detection probabilities are valid for the whole sample of 822 stars. After correcting for the detection bias, the fraction of stars with at least one planet more massive than 50 M⊕ and with a period smaller than 10 years is es-
Mayor et al. 2011


2008: The Rise of
Low-Mass Exoplanets
IAU Symposium No.253
"Transiting Planets"
formation. We indeed detect about 45 candidates having minimum masses below 30 M⊕ and orbital periods below 50 days. These numbers are preliminary since the existence of these objects has to be confirmed by subsequent observations. However, they indicate that about 30% of solar-type stars may have such close-in, low-mass planets. Some emerging properties of this
Towards the characterization of the
• From a uniformly-observed subsample of stars, we estimate that the fraction of stars having planets with minimum masses between ~5-30 M⊕ and orbital periods below 50 days may be as high as ~30%. If confirmed, this number will have a large impact on our perception of planetary systems in general, and Earth-like planets in particular.
The HARPS planet search
4. Some properties of close-in low-mass planets
Keywords. techniques: radial velocities, (stars:) planetary systems

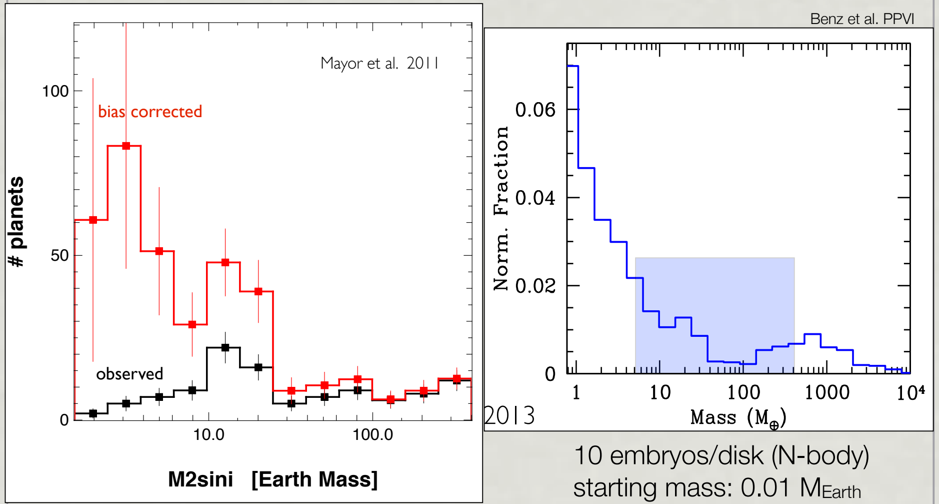

f_syst = 51 ± 8 %
Mass sini (M_J)
Period (days)
Survey completeness in percents
Smaller-mass planets
3 < M < 100 M⊕
P < 1yr
fsyst = 51 +/- 8 %
Fig. 6. Same as Fig. 5 but only for the HARPS subsample of 376 stars. The occurrence rate of planetary systems in the limited region between 3 and 100 M⊕, and with P < 1 year, is 51 ± 8 %. Again, only one planet per system (represented by the red dots) have been considered for the computation of the occurrence rate.
Mayor et al. 2011

Orbital periods < 50 days:
=> increase of f(m) towards low masses



Mayor et al. 2011

Planetary initial mass function



Observed mass function (HARPS)

10 embryos/disk (N-body)
starting mass: 0.01 M_{Earth}

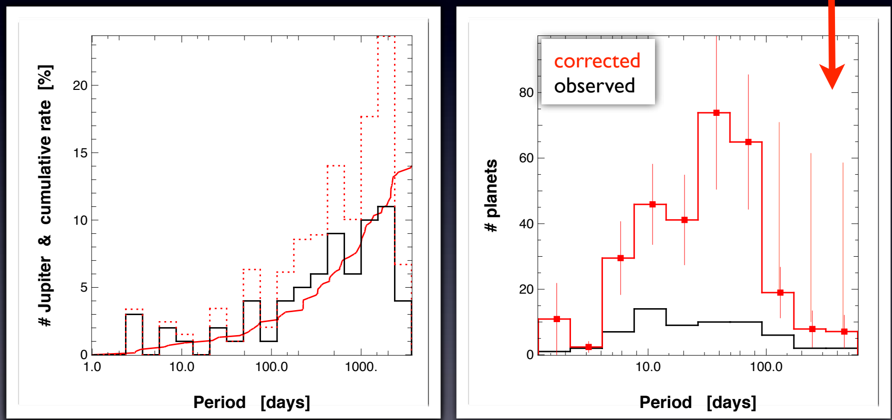
Many low-mass planet - much remains to be discovered.

Period distribution for
Msini < 30 Earth-masses

Detection bias?

Msini > 50 M_{Earth}

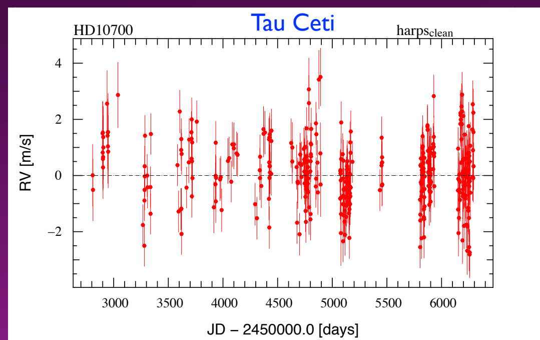
Msini < 30 M_{Earth}



Data analysis challenges => syst. characterisation

1) sampling effects
 - multi-planet systems: all periods need to be covered
 - aliases: 55 Cnc e is the best example (Dawson & Fabrycky 2010)

2) Confidence level
 - different statistical approaches and detection thresholds

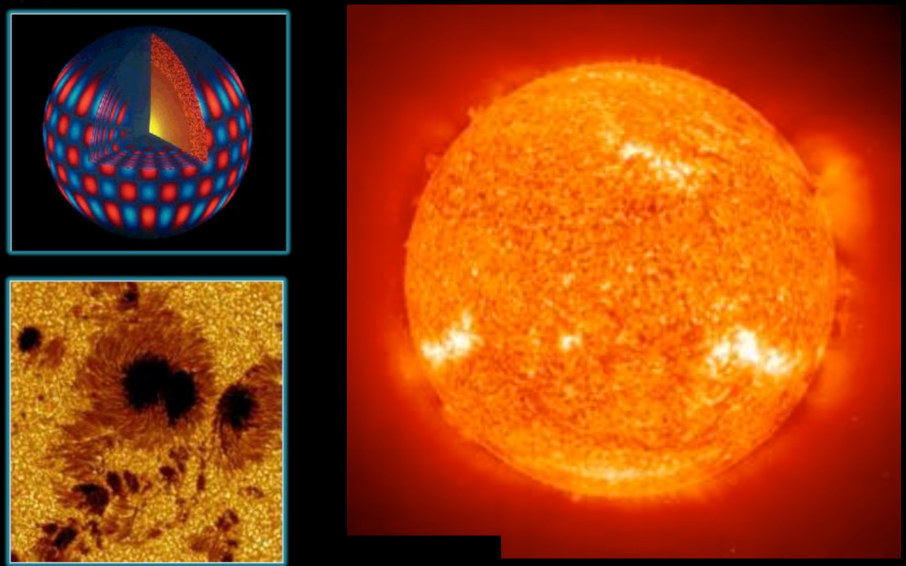


10 years, 375 nights
rms =1 m/s

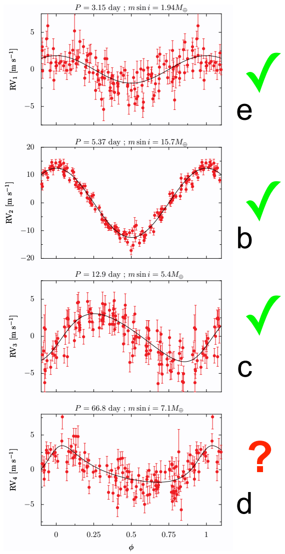
Tuomi et al. 2013
5 planets !
=> two in HZ !!!!

=> none with
our detection threshold

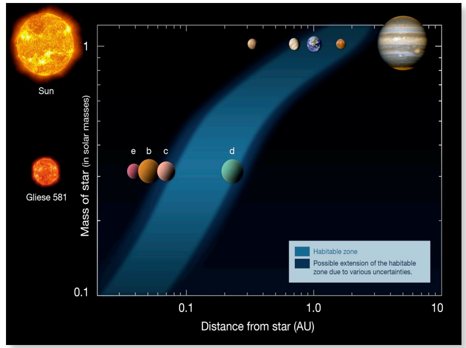
STELLAR INTRINSIC LIMITATIONS



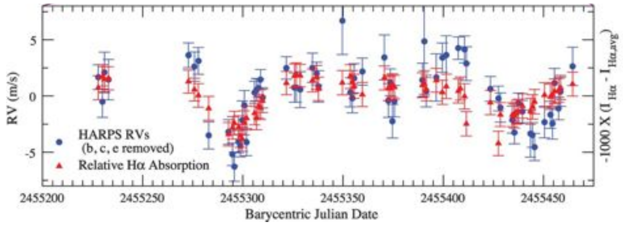
Gl 581 : 4 planets, one in HZ?



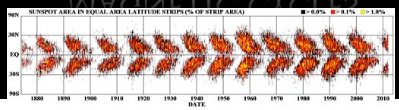
(Udry et a. 2007, Mayor et al. 2009)

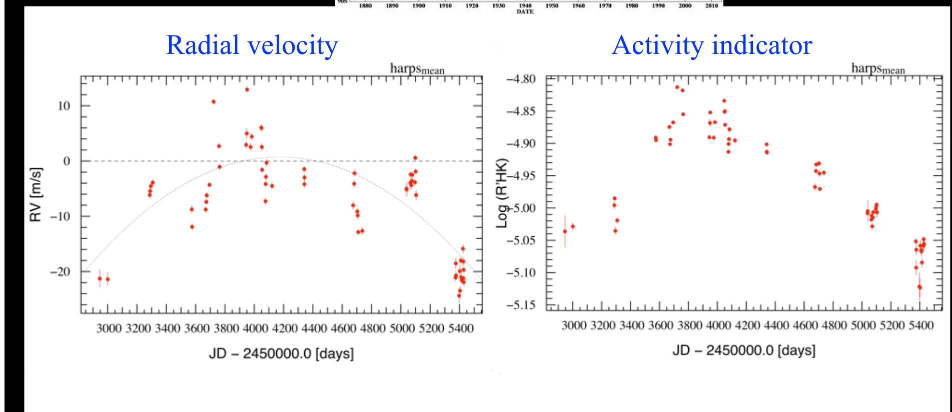


Robertson et al. 2014



MAGNETIC CYCLES





HARPS: >30% of low-activity stars show magnetic cycles

- Impact on parameter estimate
- derived architecture
- Importance of diagnostics

Challenge of finding small planets in noisy data

- Multi-planet systems: superposition of signals
  => sample various time scales
- Sampling effects:
  => need to cut aliases
- Data analysis, confidence level
  => need to increase signal to noise
- Stellar effect
  => beat down the noise by brute force averaging
  => develop diagnostics
  (hope in the modelling of the stellar signal)

=> large number of observations needed (N>100-150)

HD 85512 b (Pepe et al. 2011)
P = 58.4 days, m2sini= 3.6 M Earth
185 measurements

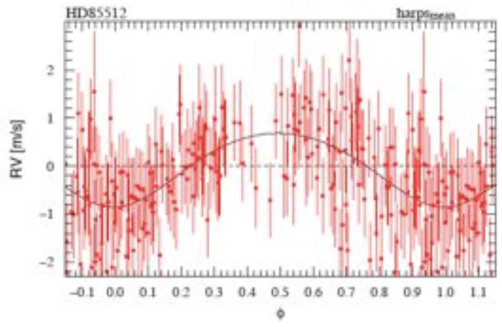
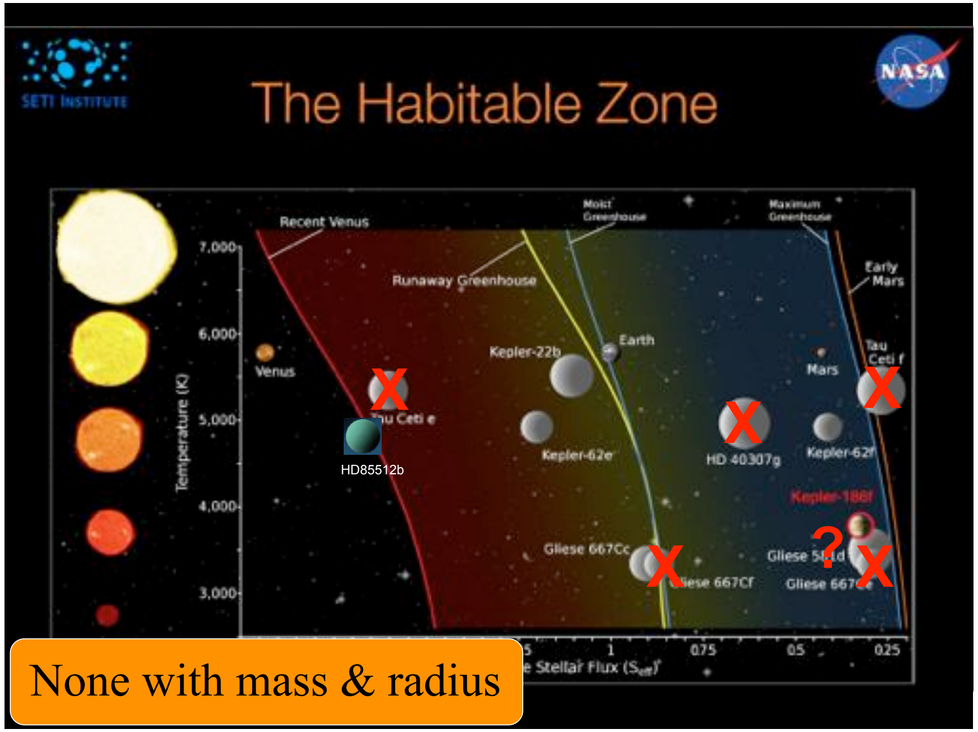


Fig. 13. Phase-folded RV data of HD 85512 and fitted Keplerian solution. The dispersion of the residuals is 0.75 m s^{-1} *rms*.



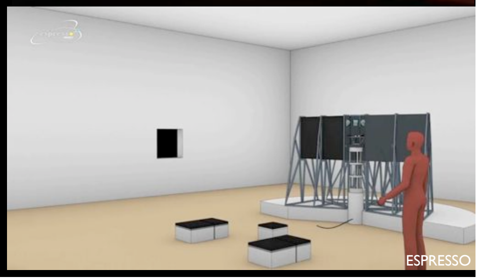
ESPRESSO on ESO VLT

«**E**chelle **SP**ectrograph for **R**ocky **E**xoplanets and **S**table **S**pectroscopic **O**bservations»

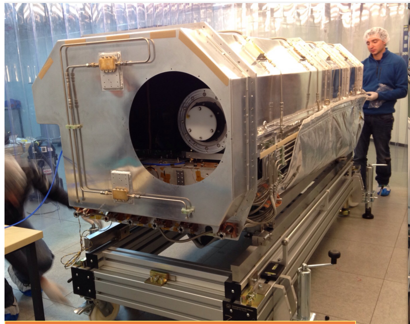
- Ultra-stable spectrograph for the VLT
- R=120'000
- visible: blue + red arms
- can use any of the UTs (coudé train)

- Consortium : CH, Italy, Portugal, Spain
- FDR in June 2013
- On the sky : 2017

- Precision in RV : < 10 cm/s
- Goal :Very low-mass planets



ESPRESSO: integration=>end 2016, vacuum tank in Geneva



One front End

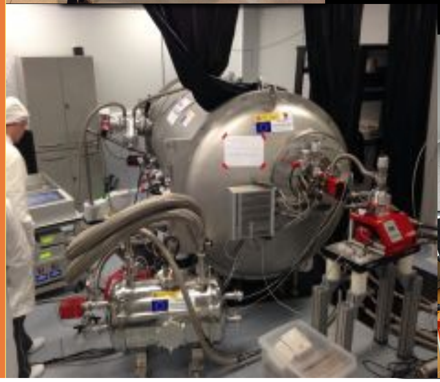
Two spectrographs

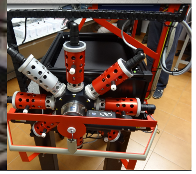
Two vacuum tanks

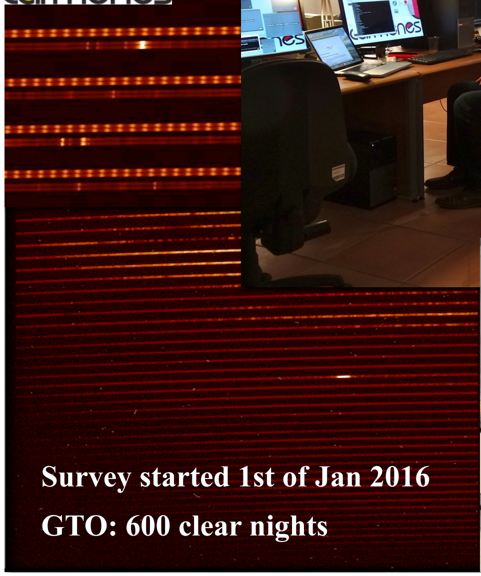
Two Cal-Units
(Fabry Perot)

CARMENES:

- 10 institutes in Spain, Germany, (+CAHA)
- 3.5m telescope on Calar Alto (Spain)
- VIS+NIR channels fibre-fed (hexagonal fibres)
- Δλ = 550-1700 nm
- R=82'000
- Calibration: Fabry Perot
- GTO time 600 clear nights





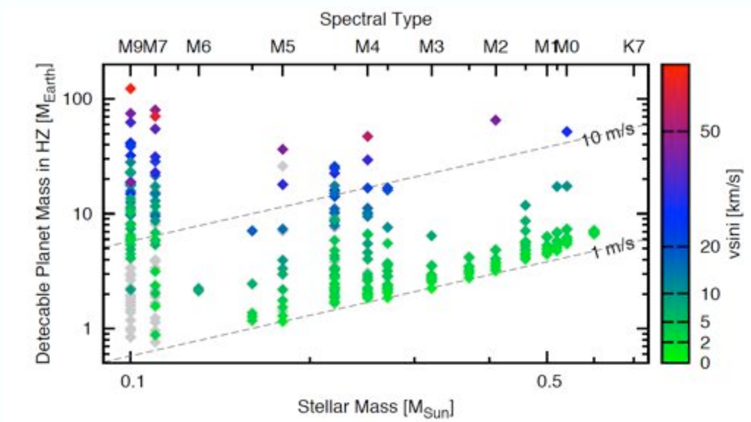


Survey started 1st of Jan 2016

GTO: 600 clear nights

Expectations:

- Sample: 362 M0V - M6V stars (mainly M3-M4).
- 60 RVs per star, >200 RVs of most interesting 100 stars.
- Simulations: ~ 80% detection rate
- including high rate of multiple planets (60%)
- Most planets with masses 3-7 M_{Earth}, some with 1 M_{Earth}.



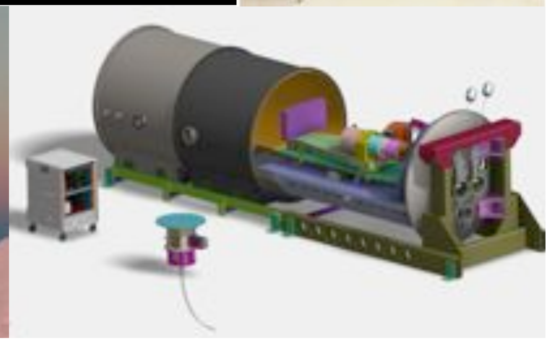
SPIRou: a spectropolarimeter for the CFHT in the NIR

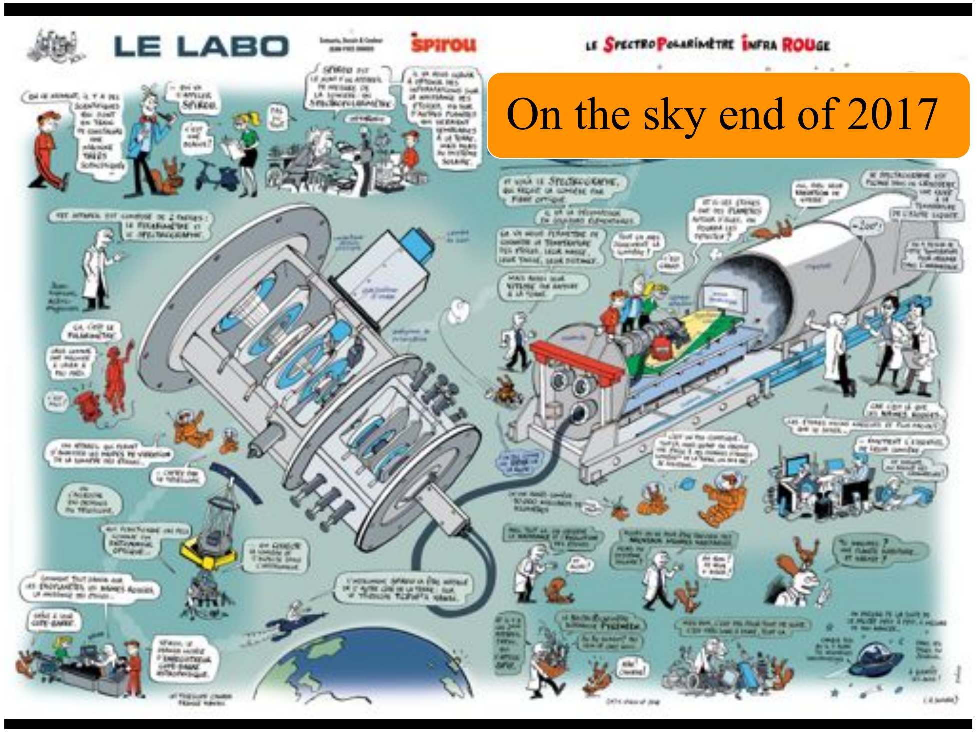
0.98 - 2.35 μm (Y, J, H, K bands)

SPIRou cryostat

SCIENCE:

- search for habitable worlds around M stars
- follow up of space missions
- atmosphere characterisation
- stellar characterisation, magnetic field





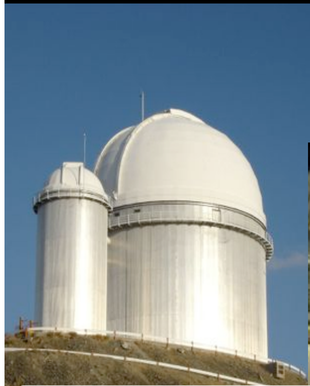
On the sky end of 2017

Brazil - Can - CH - F - P - S - UK

A red arm for HARPS on the 3.6m/ESO

SCIENCE:
- search for habitable worlds around M stars
- follow up of space missions (TESS, PLATO)
- atmosphere characterisation

CONTEXT:
- Large GTO (>700 nights)
- No harm on HARPS + simultaneous use
- TESS => quickly on the sky (=> 2019)
- ESO policy: 3.6m “dedicated” to exoplanets, 2025+



Contract being signed with ESO

Ground based Transit surveys of Giant Planets: past successes and future challenges

Successful “classical” programmes

HATNET

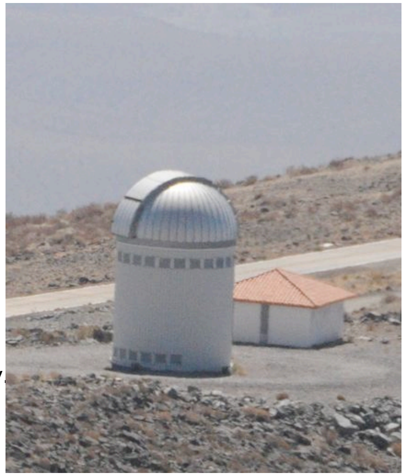
Programs that have discovered TEP’s include:

HATNET 56 Planets
OGLE
QATAR
TRES
WASP
XO

Multi station
Including HATN-11b, 13b, 2b
Many interesting objects
Excellent survey

Successful “classical” programmes

OGLE



Programs that have discovered TEP’s include:

HATNET 56 Planets
OGLE 8 Planets
QATAR
TRES
WASP
XO

Not actually an ESP facility but designed
For similar measurements and 1.2x1.2deg fov.
Includes OGLE-TR-56b - very short period
Planet, microlensing planets

Successful “classical” programmes

QATAR

Programs that have discovered TEP’s include:

HATNET 56 Planets
OGLE 8 Planets
QATAR 2 Planets
TRES
WASP
XO

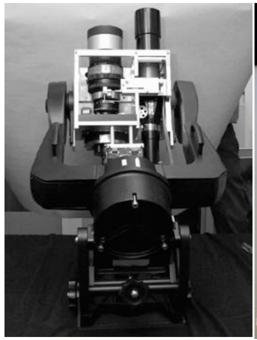
Fainter, redder targets….

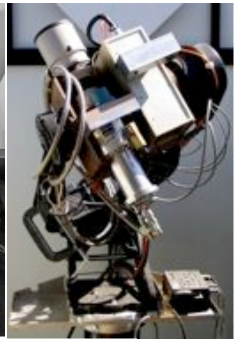
Successful “classical” programmes

Programs that have discovered TEP’s include:

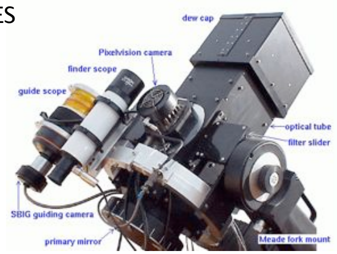
HATNET 56 Planets
OGLE 8 Planets
QATAR 2 Planets
TRES 5 Planets
WASP
XO

Included STARE
Pioneering survey





TRES



Successful “classical” programmes

XO

Programs that have discovered TEP’s include:

HATNET 56 Planets
OGLE 8 Planets
QATAR 2 Planets
TRES 5 Planets
XO 5 Planets
WASP

XO-2 - wide binary with gas giants orbiting each component

Successful "classical" programmes

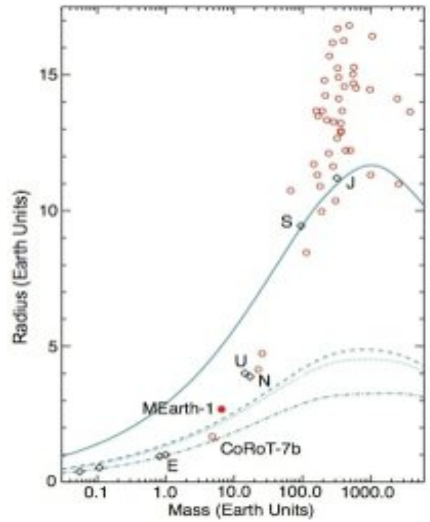
Programs that have discovered TEP's include:

HATNET 56 Planets
OGLE 8 Planets
QATAR 2 Planets
TRES 5 Planets
XO 5 Planets
WASP 106 Planets

Factory TEP discovery
=> WASP-150b

Successes

1) Diversity and Inflation

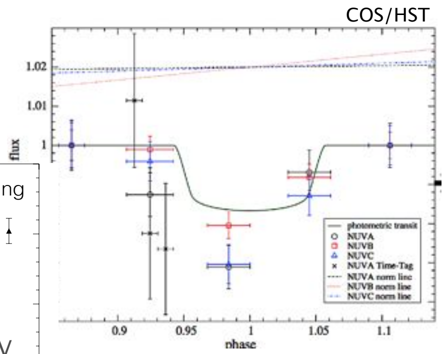


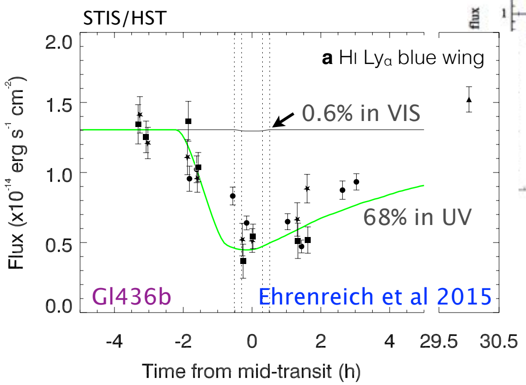
Successes

1) Diversity and Inflation

2) Evaporation

e.g. WASP-12b Fossati et al 2010



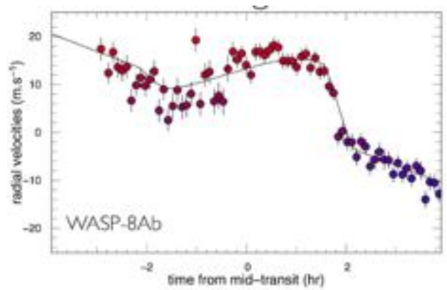


Successes

1) Diversity and Inflation

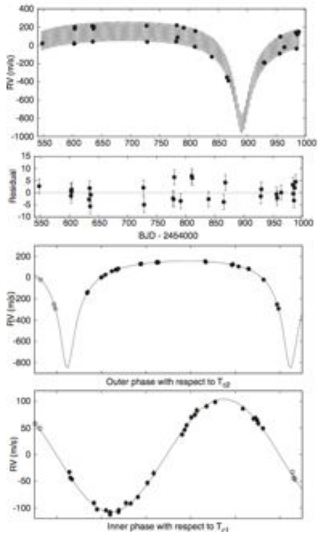
2) Evaporation

3) RMs and scattering/migration



Successes

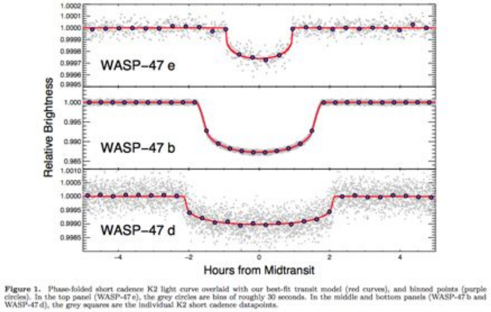
1) Diversity and Inflation
2) Evaporation
3) RMs and scattering/migration
4) Long period massive companions



HAT-P-13b/c Bakos et al

Successes

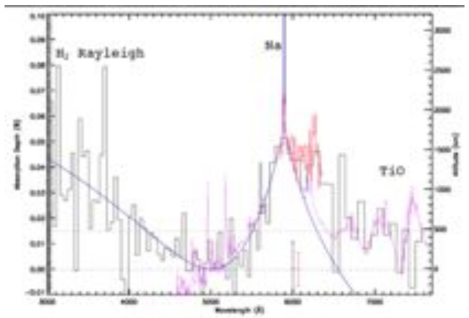
1) Diversity and Inflation
2) Evaporation
3) RMs and scattering/migration
4) Long period massive companions
5) Terrestrial companions



Becker et al

Successes

1) Diversity and Inflation
2) Evaporation
3) RMs and scattering/migration
4) Long period massive companions
5) Terrestrial companions
6) Atmospheres: clouds, etc

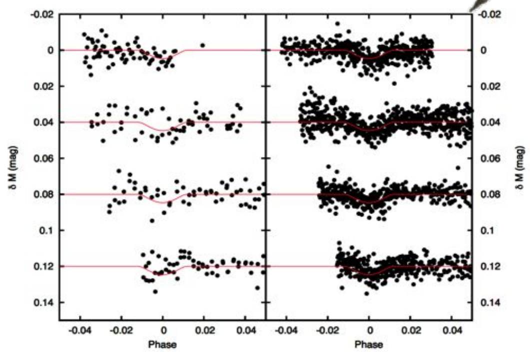


Sing et al.

Improvements to SWASP

(WASP-S currently surveying extremely wide fields)

Stabilized focus
Several years of data
currently being reduced.



Other fun targets coming: WASP-150b 5mmag, 7.7Mj , R~0.3-0.4Rj
ΔMj, ΔRj < 10%, e~0.4

Push to smaller stars: HATS

Another excellent survey from Bakos et al

3 sites: Chile, Namibia, Australia, operational since 2010

Smaller fov, fainter stars
12 Planets

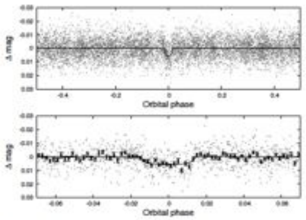


FIG. 1.— Unbinned instrumental r band light curve of HATS-7 folded with the period $P = 3.1853150$ days resulting from the global fit described in Section 3. The solid line shows the best-fit transit model (see Section 3). In the lower panel we zoom-in on the transit; the dark filled points here show the light curve binned in phase using a bin-size of 0.002.

So far highlight is HATS-7b (Bakos et al), 8b (Baylis et al) – Super-Neptunes

Depths are 0.5-1%. HATNET/WASP have few similar depth objects

Push to smaller stars: MEarth

First pointed survey.
Telescopes with smart observational strategy.

Targets one at a time.

Designed to look at M dwarfs (aiming for M5)

Science Driver: small planets in the HZ.

GJ1214 b : Charbonneau et al. 2009 ($M=6.5M_\oplus$, $R=1.6R_\oplus$) follow-up: HARPS
GJ1132 b : Berta-Thompson et al. 2015 ($M=1.6M_\oplus$, $R=1.2R_\oplus$) follow-up: HARPS-N

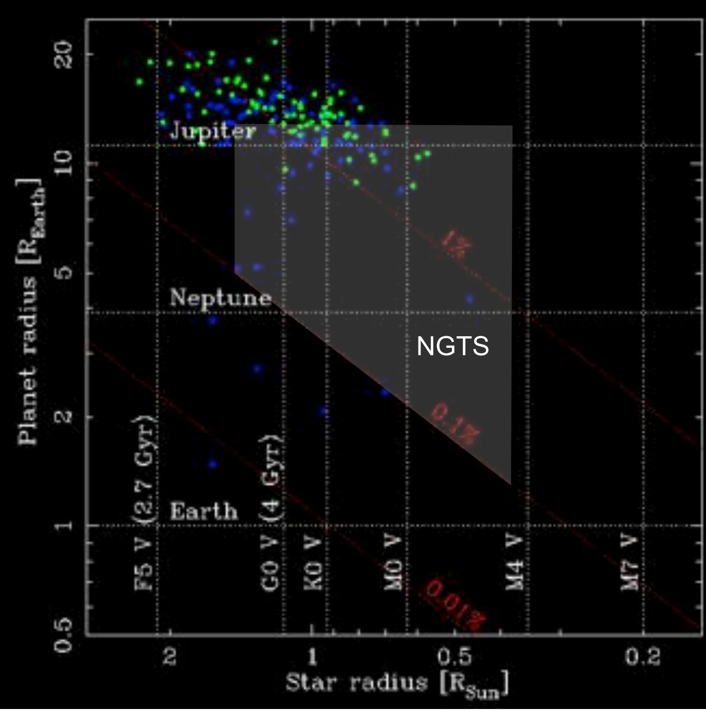
Fantastic for atmosphere follow-up observations in IR (JWST) but haze/clouds

NGTS
NEXT-GENERATION TRANSIT SURVEY

Push to smaller planets

12 x 20cm f/2.8 telescopes
independent mounts,
back-illuminated, deep-depletion CCDs
100 sqr deg FoV (equivalent to Kepler);
sub-millimag precision

University of Warwick
University of Lecicester
University of Belfast
University of Cambridge
DLR Berlin
University of Geneva

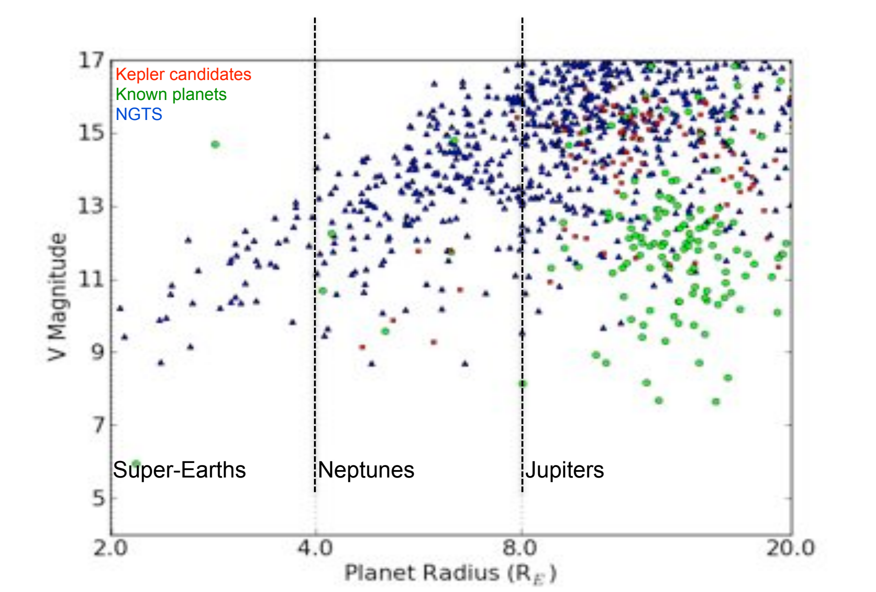


Transit discovery space

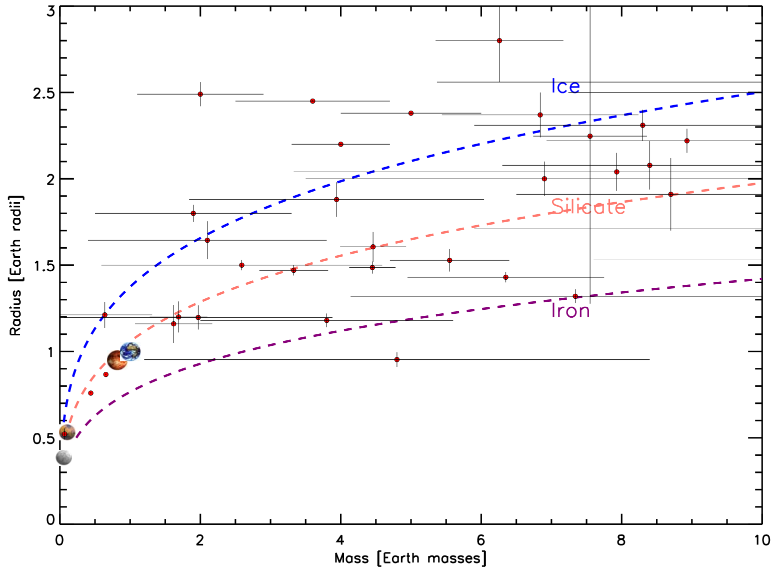
Follow-up machine for TESS candidates V>13

Updated from Wheatley et al. 2014

Prediction: ~40 RV-confirmable super-Earths and ~230 Neptune for bulk composition

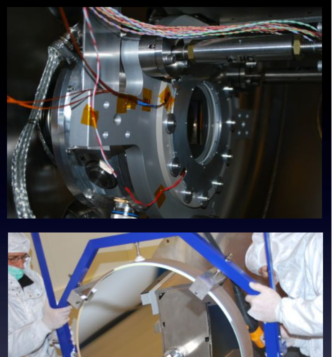


Diversity: Important to have better error bars



(Courtesy H. Rauer)

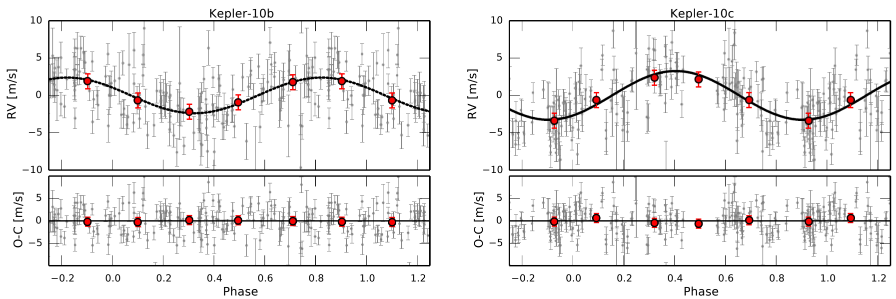
HARPS-N



Consortium

- Geneva Observatory (Head),
- CfA, Harvard University,
- INAF-TNG,
- University of St. Andrews,
- University of Edinburgh,
- Queens University Belfast

HARPS-N Radial Velocity Measurements



Kepler-10b

P = 0.84 d
R = 1.47 $R_\oplus$
M = 3.33 $M_\oplus$ 15% on mass
density= 5.8 g/cm^3

Kepler-10c

P = 45.3 d
R = 2.35 $R_\oplus$
M = 17.2 $M_\oplus$ 11% on mass
density= 7.1 g/cm^3

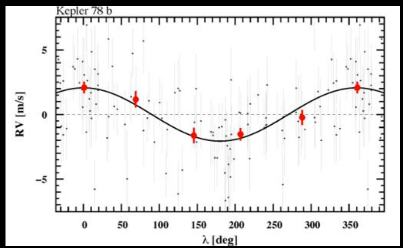
Kepler-78 b

Sanchis-Ojeda et al. 2013

P = 8.5 hours !

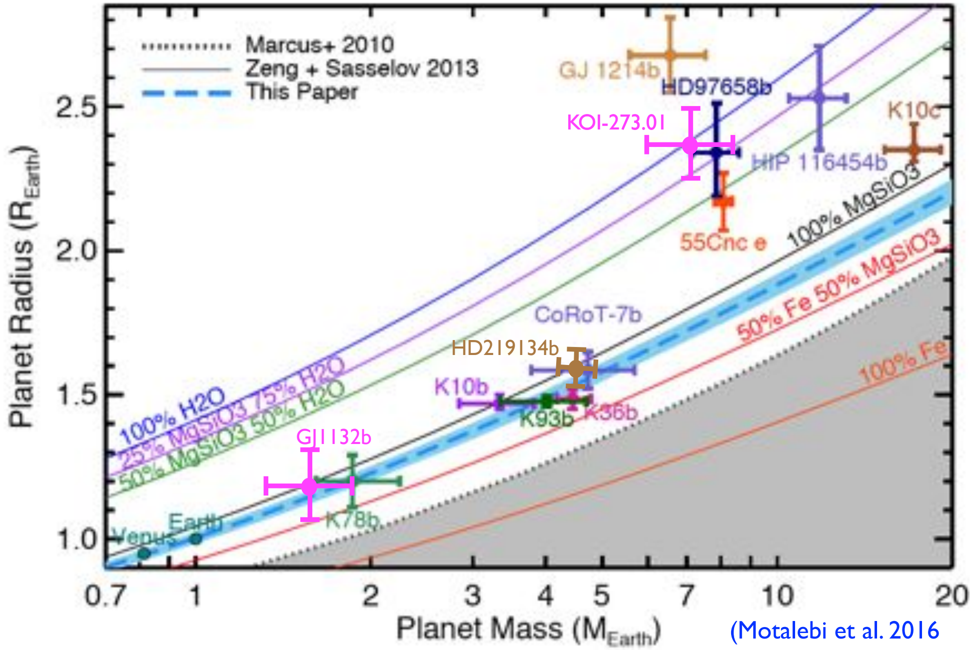
Final Results

Statistical parameter	Mass [$M_\oplus$]	Radius [$R_\oplus$]	Density [g cm^{-3}]
Mode	1.86	1.173	5.57
Median	1.91	1.194	6.13
68.3% confidence interval	1.61 – 2.24	1.084 – 1.332	4.26 – 8.59
99% confidence interval	1.17 – 3.00	0.942 – 1.584	2.34 – 14.29



Pepe et al. 2013
Howard et al. 2013

P_1 = 0.35 day
K = 1.9 m/s
$m_1 \sin i$ = 1.86 $M_\oplus$



(precision on the mass < 20%)

(Motalebi et al. 2016 updated from Dressing et al. 2015)

HD219134

V=5.5

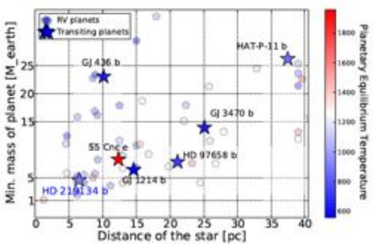
The HARPS-N Rocky Planet Search

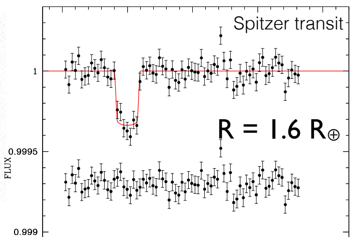
I. A transiting rocky planet in a system of super-Earths at 6.5 pc from the Sun *

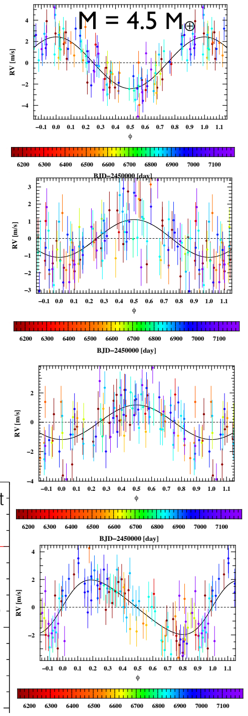
F. Motalebi[1], S. Udry[1], M. Gillon[2], C. Lovis[1], D. Segransan[1], L. Buchhave[3,4], B. Demory[5], L. Malavolta[6], C. Dressing[3], D. Sasselov[3], K. Rice[7], D. Charbonneau[3], D. Collier Cameron[8], D. Latham[3], E. Molinari[9,10], F. Pepe[1], L. Affer[11], A. Bonomo[12], R. Cosentino[9], X. Dumusque[3], P. Figueira[13], A.F.M. Fiorenzano[9], S. Gettel[3], A. Harutyunyan[9], R. D. Heywood[8], J. Johnson[3], E. Lopez[7], M. Lopez-Morales[3], M. Mayor[1], G. Micela[11], A. Mortier[8], V. Nascimbeni[6], D. Philips[3], G. Piotto[6], D. Pollacco[14], D. Queloz[1,4], A. Sozzetti[12], A. Vanderburg[3], and C. A. Watson[15]

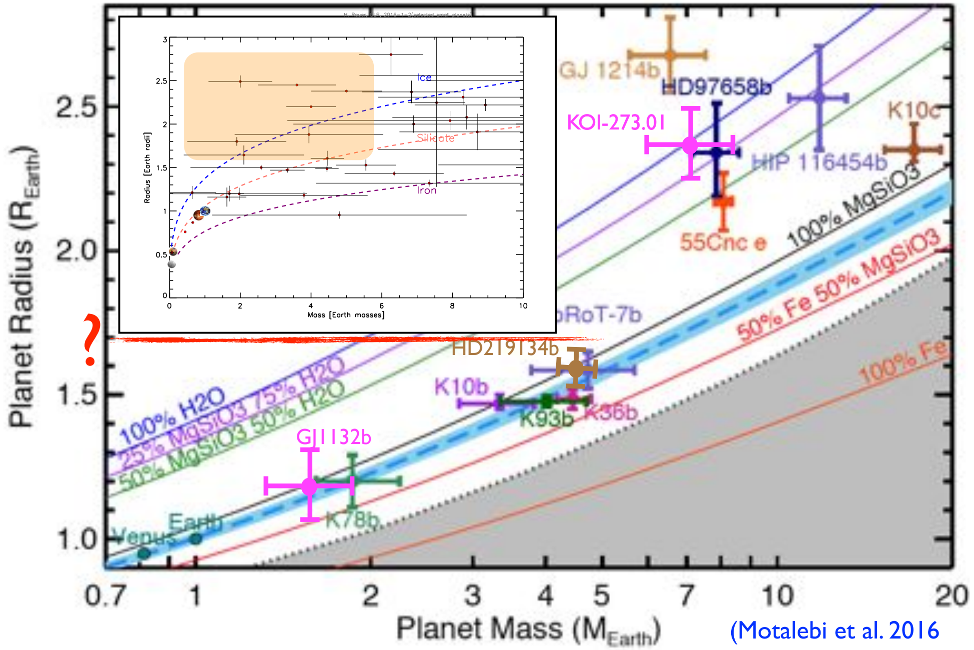
Orbital solution and planet inferred parameters for the four-Keplerian model (K4) of the system around HD 219134.

Model		K4+ $\mathcal{N}(0, \sqrt{\sigma_i^2 + s^2})$			
		HD 219134 b	HD 219134 c	HD 219134 d	HD 219134 e
P	[days]	3.0937 ± 0.0004	6.765 ± 0.005	46.78 ± 0.16	1190^{+379}_{-34}
K	[m/s]	2.33 ± 0.24	1.09 ± 0.26	1.94 ± 0.29	4.46 ± 0.52
λ_0	[deg]	82 ± 8	295 ± 20	98 ± 16	206^{+3}_{-45}
T_t	[BJD-2400000]	57126.7001 ± 0.001	57129.46 ± 0.45		
$\sqrt{e}.\cos(\omega)$		0.05 ± 0.19	0.17 ± 0.26	−0.43 ± 0.18	0.21 ± 0.23
$\sqrt{e}.\sin(\omega)$		−0.11 ± 0.21	−0.03 ± 0.31	0.03 ± 0.21	−0.35 ± 0.24
e		$0.00^{+0.13}_{-0.00}$	$0.00^{+0.26}_{-0.00}$	0.32 ± 0.14	0.27 ± 0.11
ω		undefined	undefined	143 ± 33	288 ± 45
$m_{pl} \sin i$	[$M_\oplus$]	4.46 ± 0.47	2.67 ± 0.59	8.67 ± 1.14	62 ± 6
a	[AU]	0.0382 ± 0.0003	0.064 ± 0.001	0.234 ± 0.002	$2.14^{+0.43}_{-0.02}$



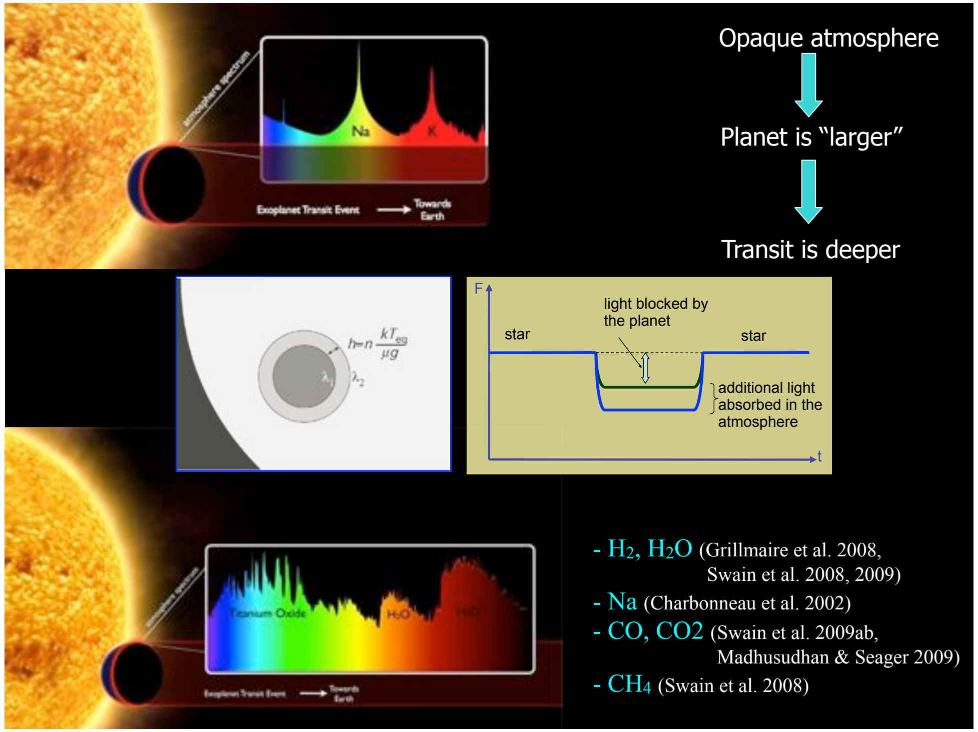


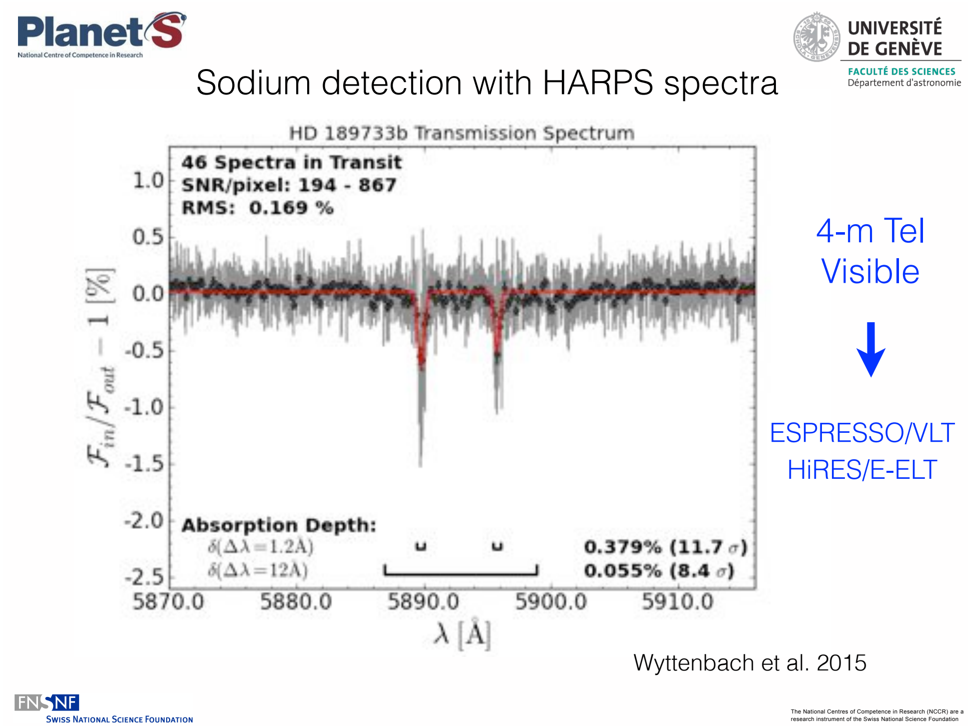


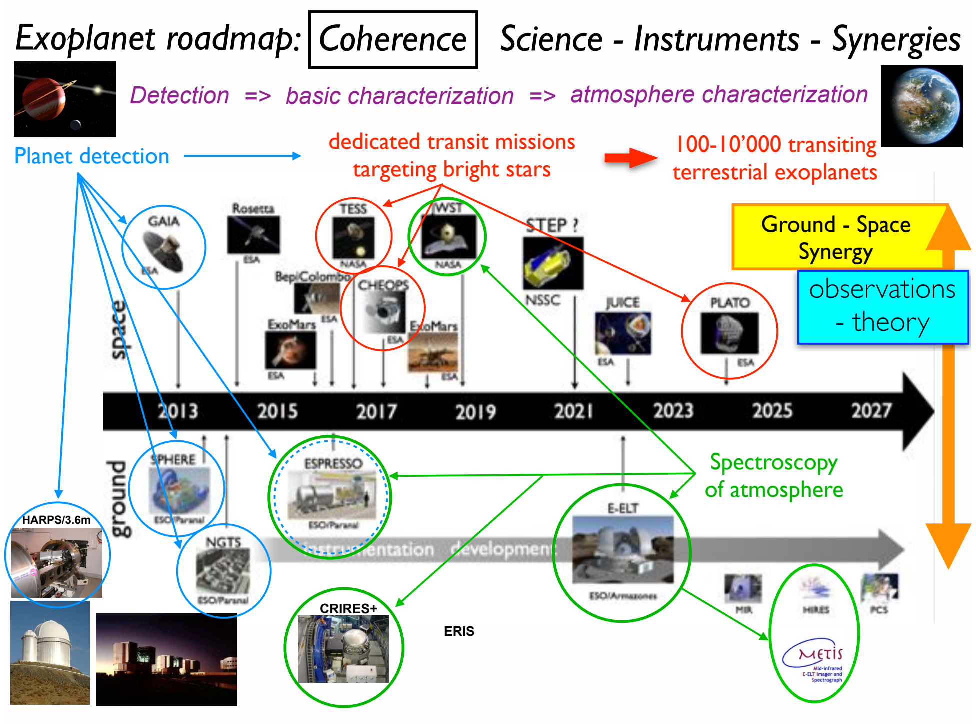


(precision on the mass < 20%)

(Motalebi et al. 2016 updated from Dressing et al. 2015)


Opaque atmosphere
Planet is "larger"
Transit is deeper
Na
K
Exoplanet Transit Event
Towards Earth
star
light blocked by the planet
star
additional light absorbed in the atmosphere
Titanium Oxide
- H_2, H_2O (Grillmaire et al. 2008, Swain et al. 2008, 2009)
- Na (Charbonneau et al. 2002)
- CO, CO2 (Swain et al. 2009ab, Madhusudhan & Seager 2009)
- CH_4 (Swain et al. 2008)


PlanetS
UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département d'astronomie
Sodium detection with HARPS spectra
HD 189733b Transmission Spectrum
46 Spectra in Transit
SNR/pixel: 194 - 867
RMS: 0.169 %
Absorption Depth:
$\delta(\Delta\lambda=1.2Å)$ 0.379% (11.7 σ)
$\delta(\Delta\lambda=12Å)$ 0.055% (8.4 σ)
$\mathcal{F}_{in}/\mathcal{F}_{out} - 1$ [%]
λ [Å]
4-m Tel Visible
ESPRESSO/VLT
HiRES/E-ELT
Wyttenbach et al. 2015
FNSNF
Swiss National Science Foundation


Exoplanet roadmap: Coherence Science - Instruments - Synergies
Detection => basic characterization => atmosphere characterization
Planet detection
dedicated transit missions targeting bright stars
100-10'000 transiting terrestrial exoplanets
Ground - Space Synergy
observations - theory
GAIA
Rosetta
TESS
JWST
STEP ?
BepiColombo
CHEOPS
ExoMars
NSSC
JUICE
PLATO
space
2013
2015
2017
2019
2021
2023
2025
2027
ground
SPHERE
ESPRESSO
HARPS/3.6m
NGTS
E-ELT
Spectroscopy of atmosphere
instrumentation development
CRIRES+
ERIS
MIR
HIRES
PCS
METIS


Thank you