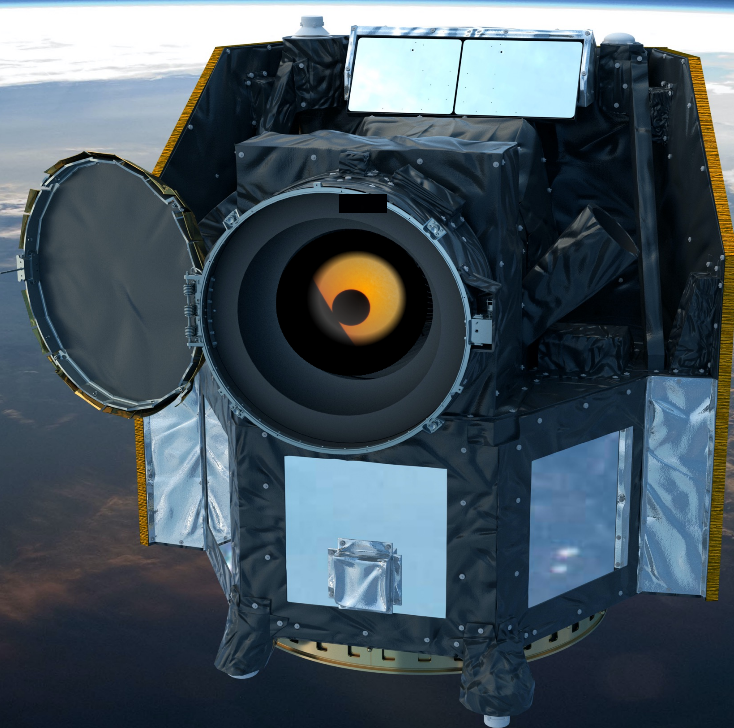
CHEOPS Science Workshop VI • 12th January 2022

Exploring the ν^2 Lupi system with CHEOPS

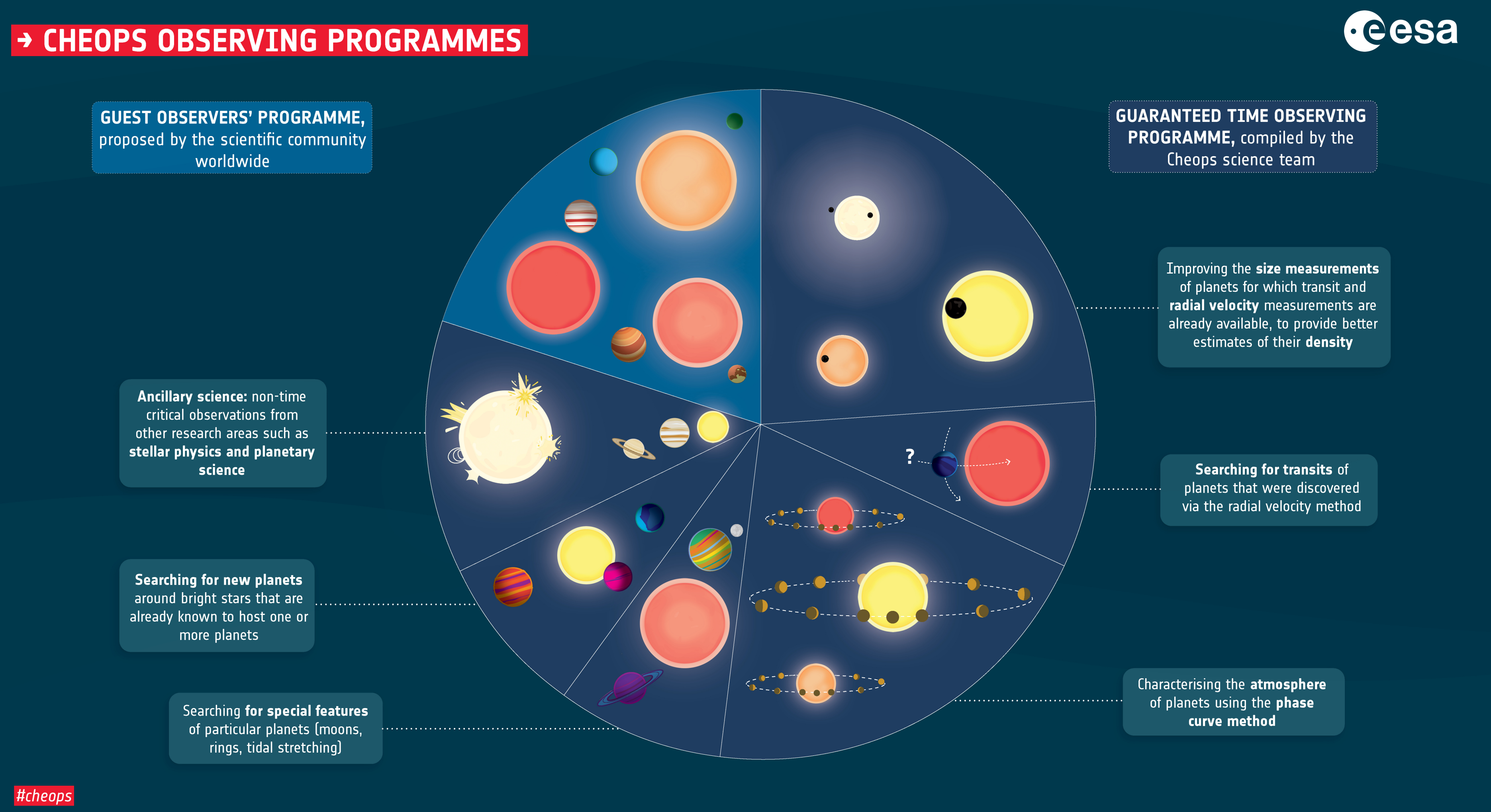
Laetitia Delrez
on behalf of the CHEOPS Consortium



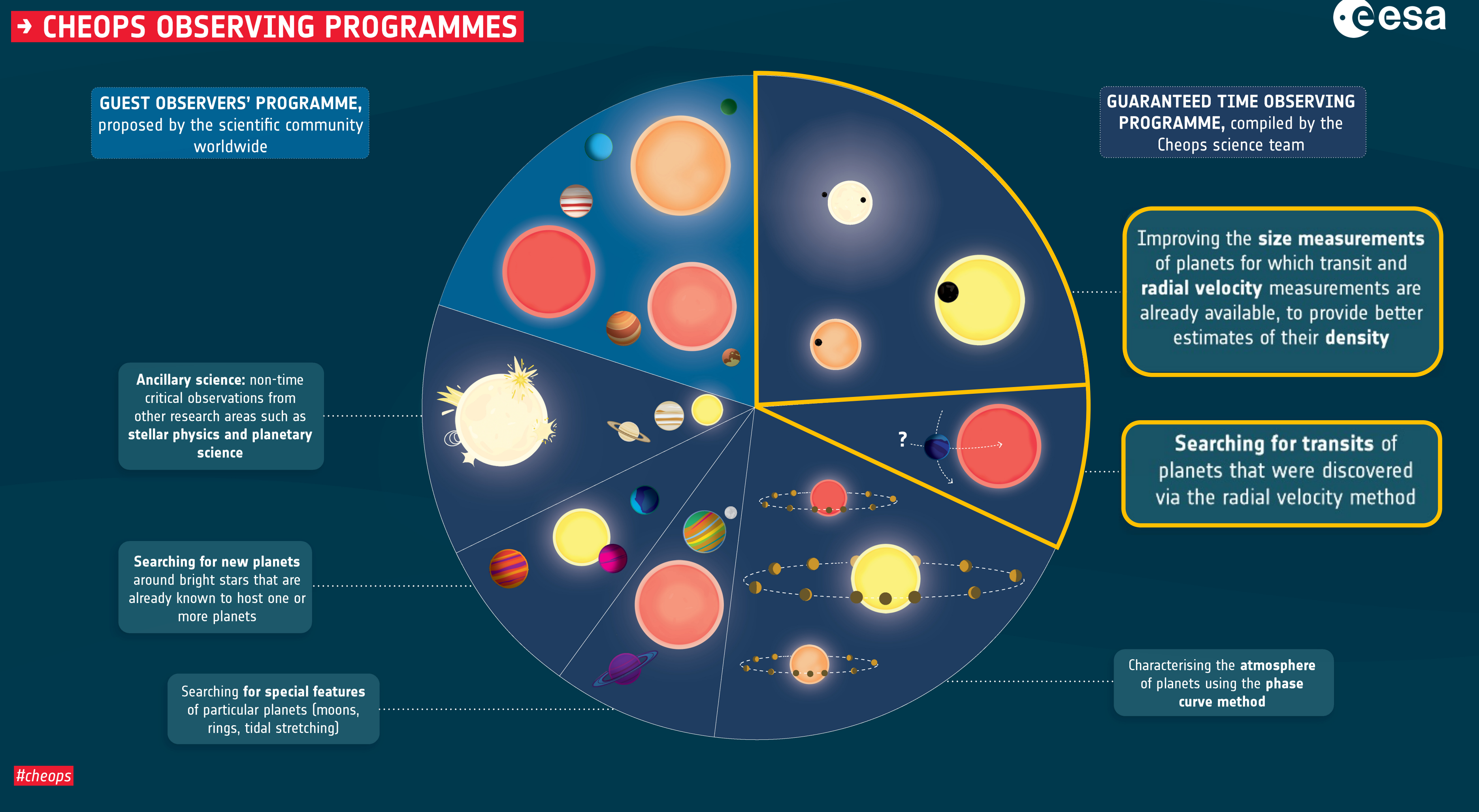
LIÈGE université | fnrs FREEDOM TO RESEARCH

esa

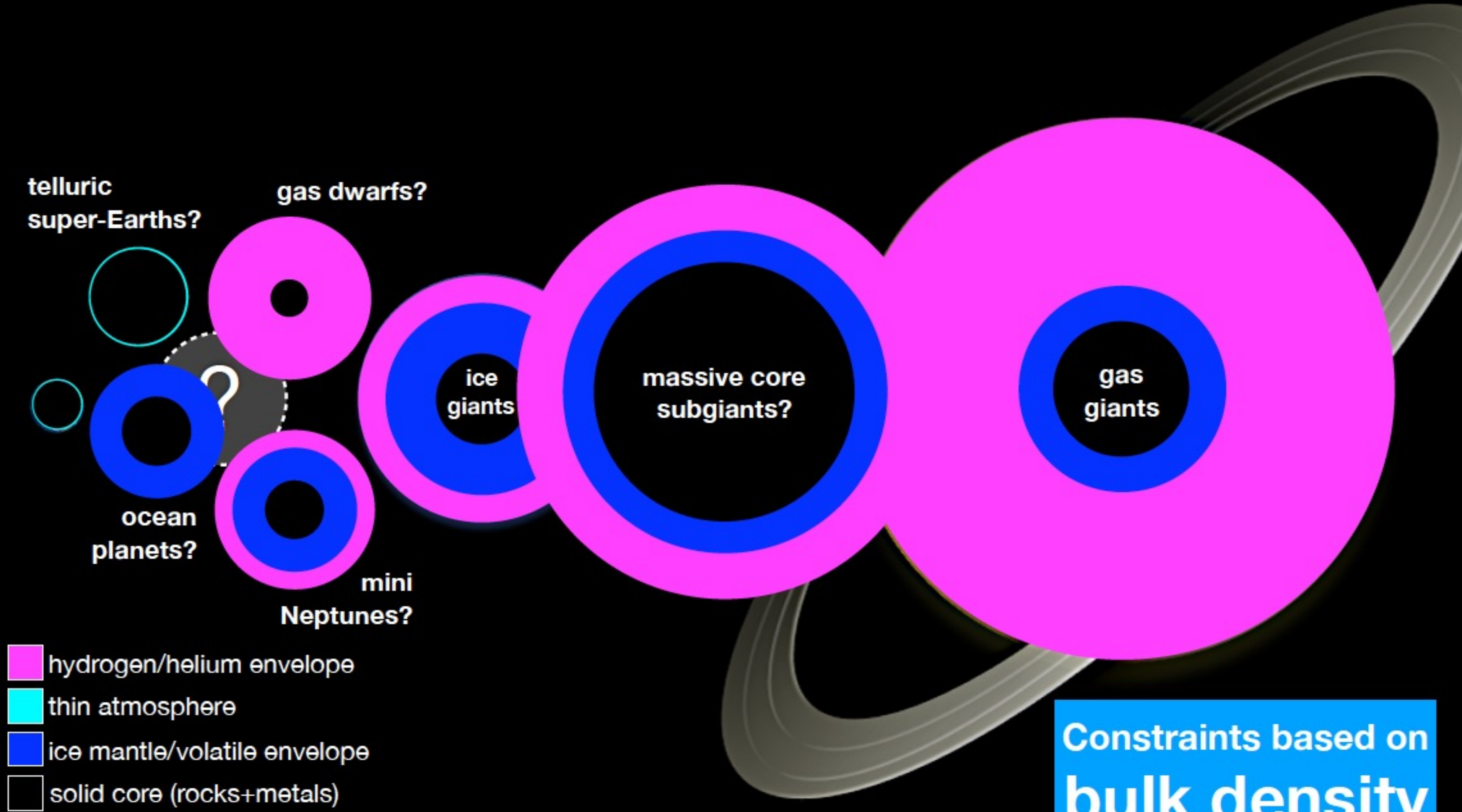
CHEOPS Science



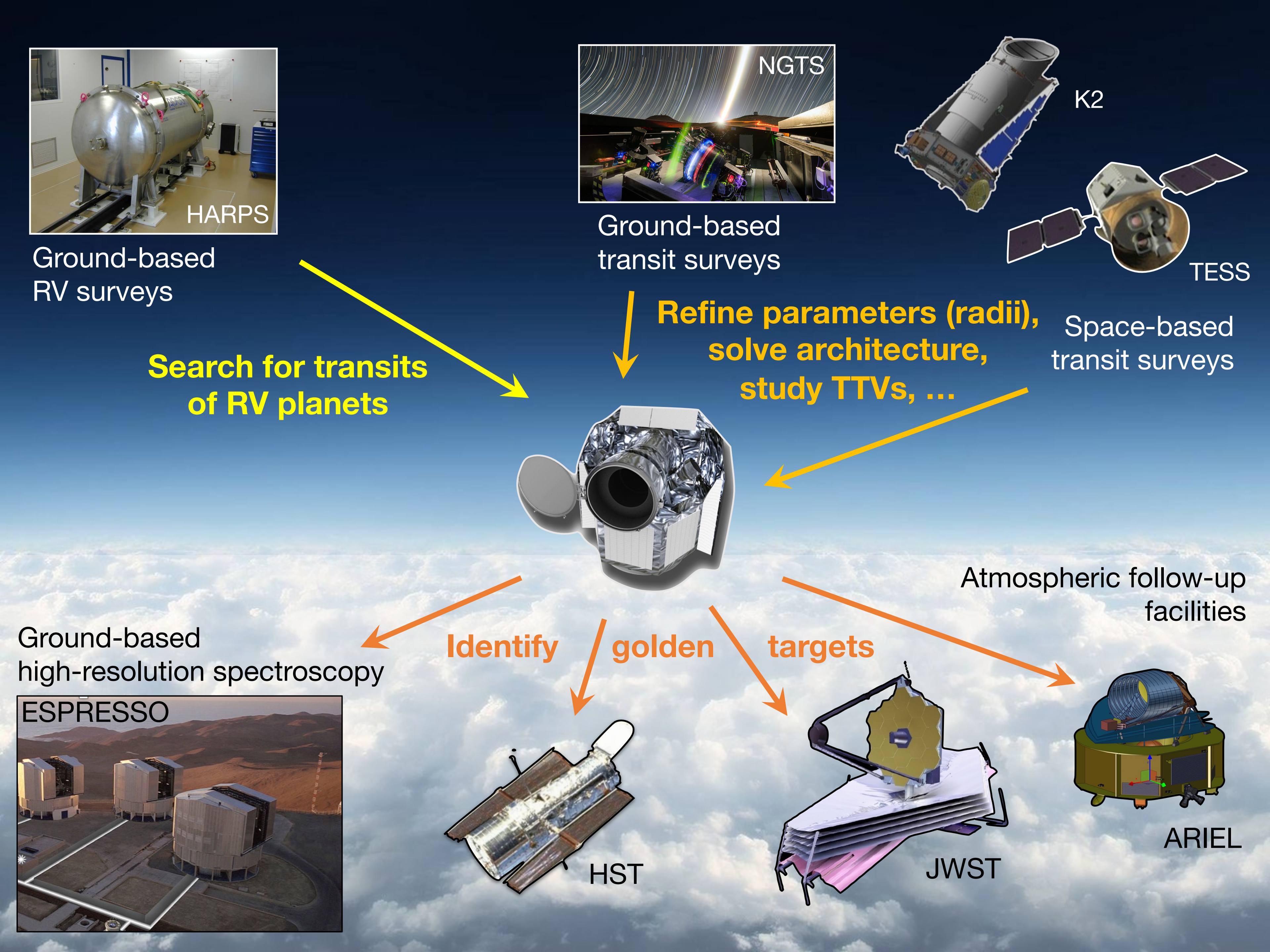
CHEOPS Science



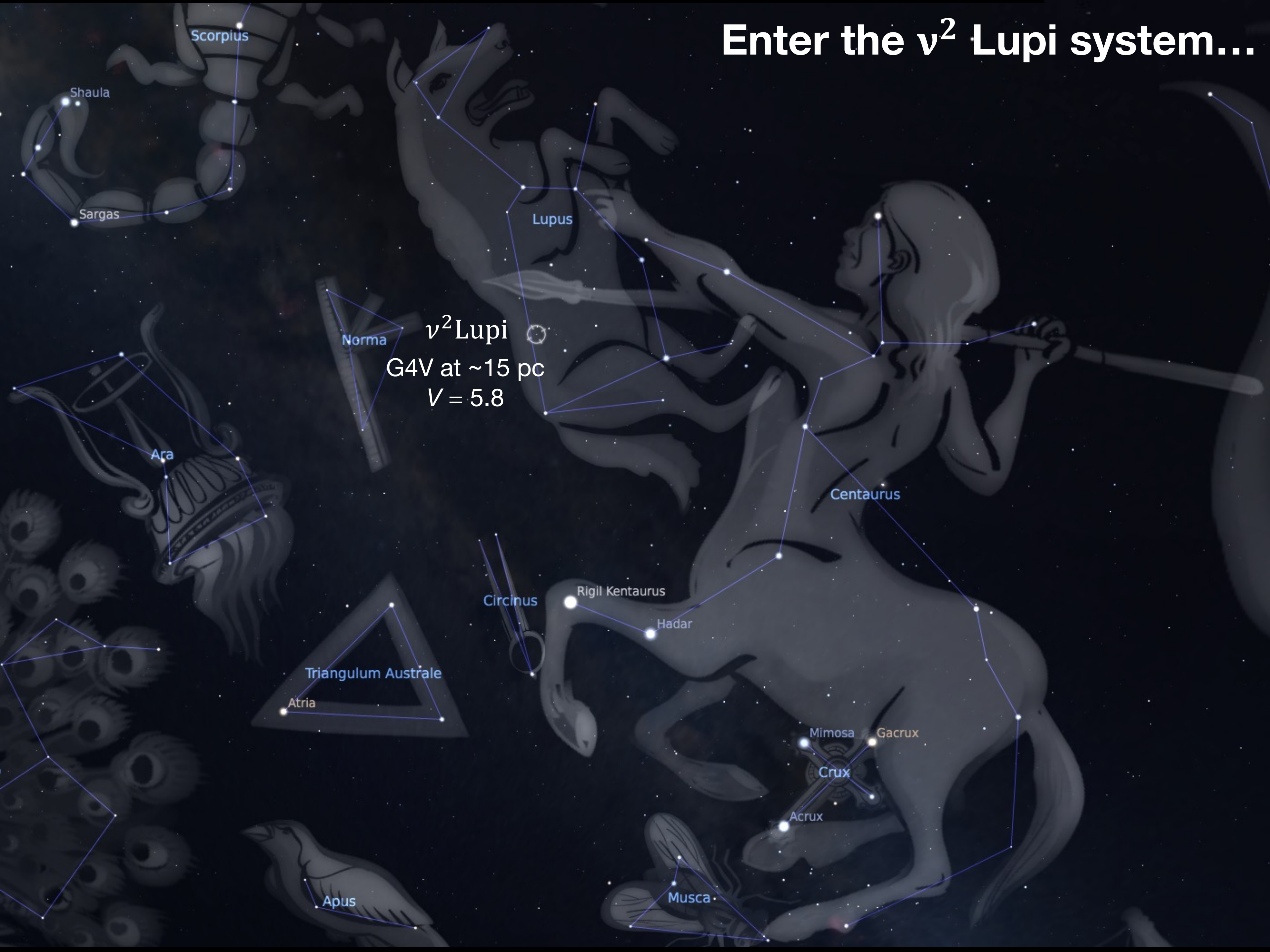
What are exoplanets made of?



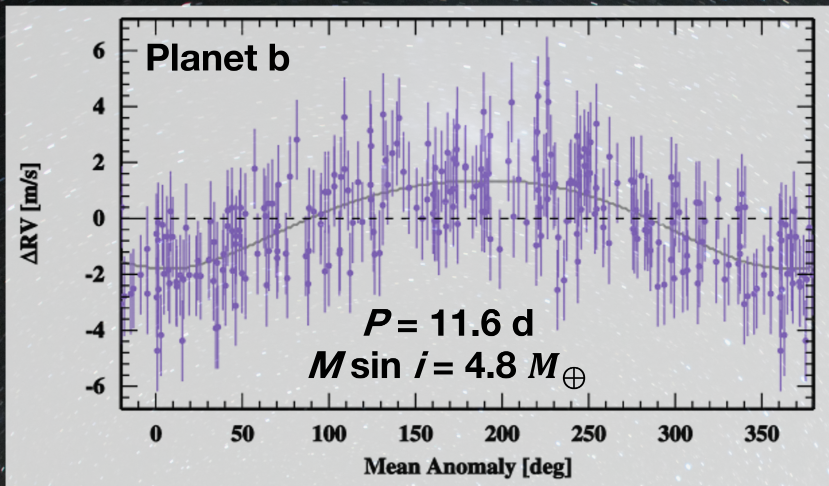
Constraints based on **bulk density**

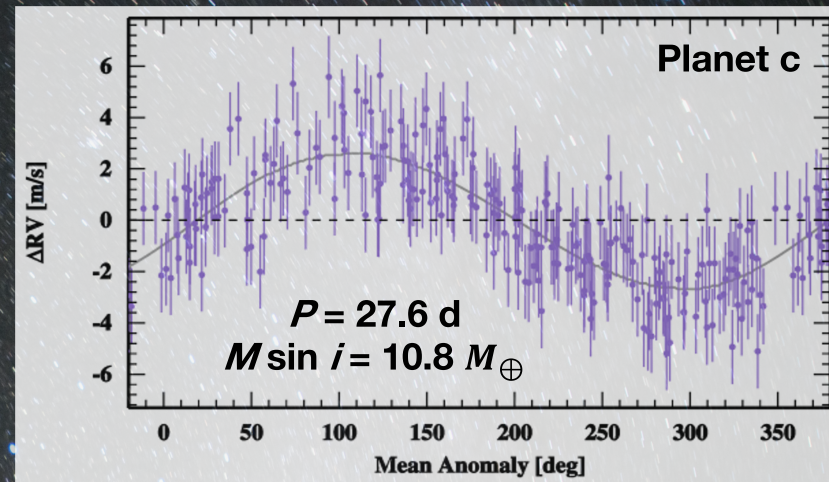

HARPS
Ground-based
RV surveys
NGTS
Ground-based
transit surveys
K2
TESS
Space-based
transit surveys
Search for transits
of RV planets
Refine parameters (radii),
solve architecture,
study TTVs, ...
Atmospheric follow-up
facilities
Ground-based
high-resolution spectroscopy
ESPRESSO
Identify
golden
targets
HST
JWST
ARIEL

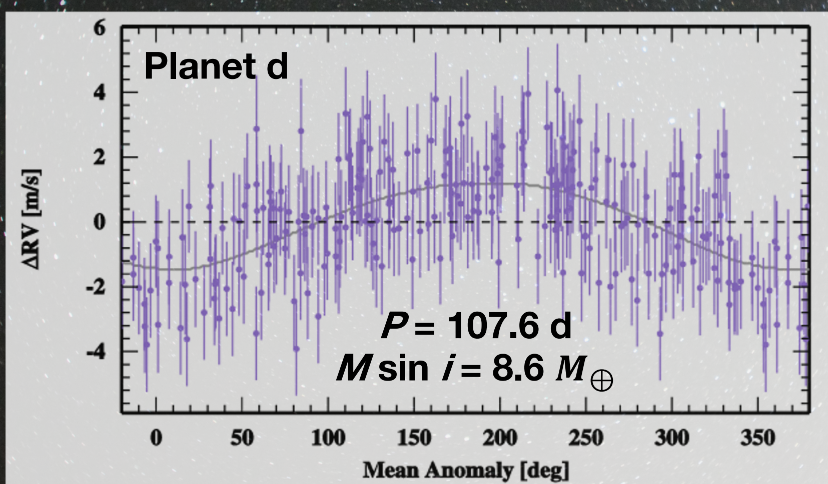
Enter the ν^2 Lupi system…



Three low-mass planets detected with HARPS

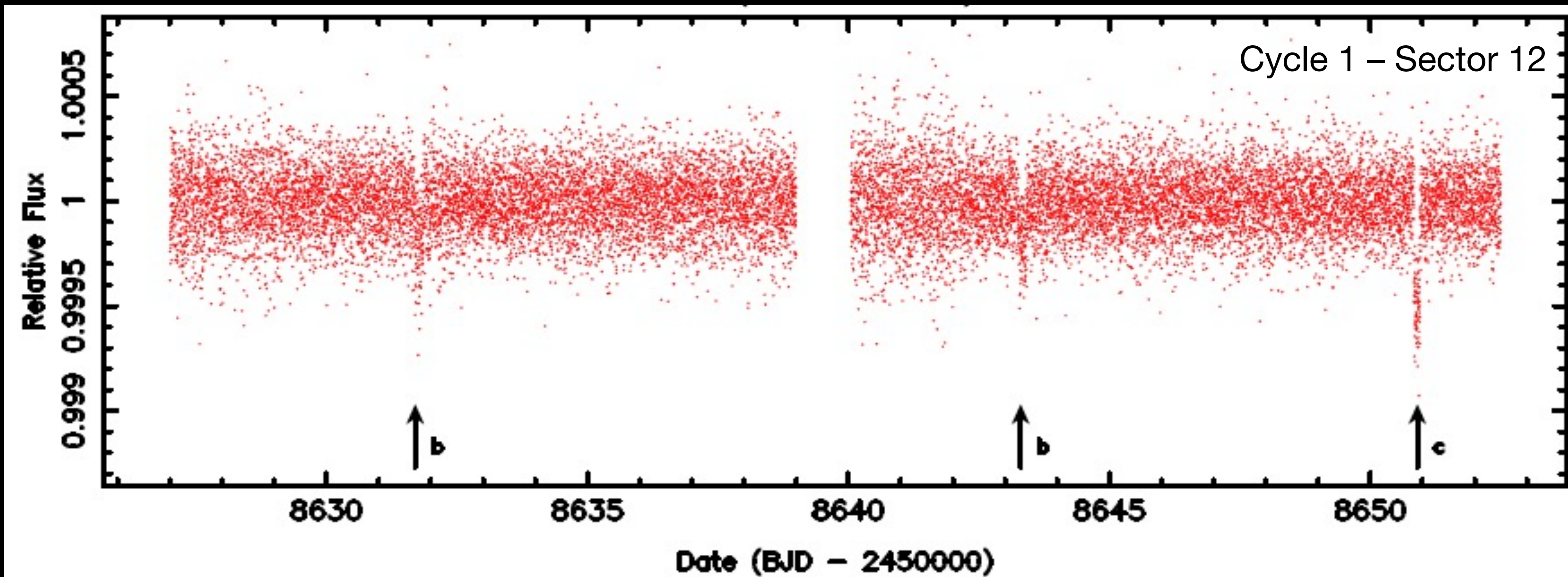


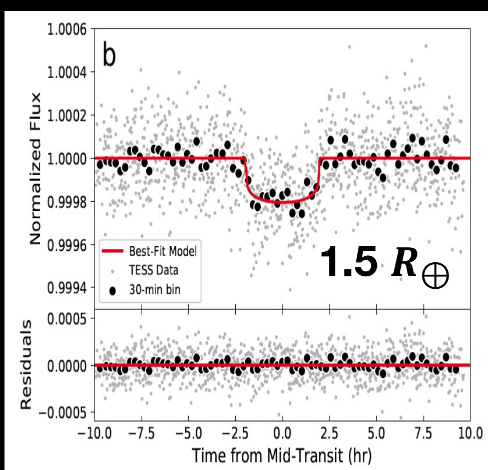


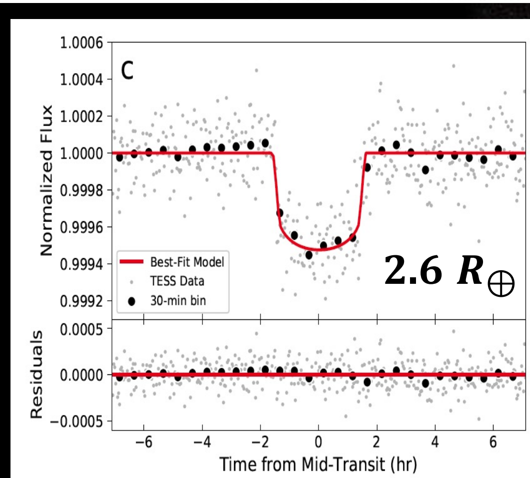


Udry+ 2019

Planets b and c caught in transit with TESS



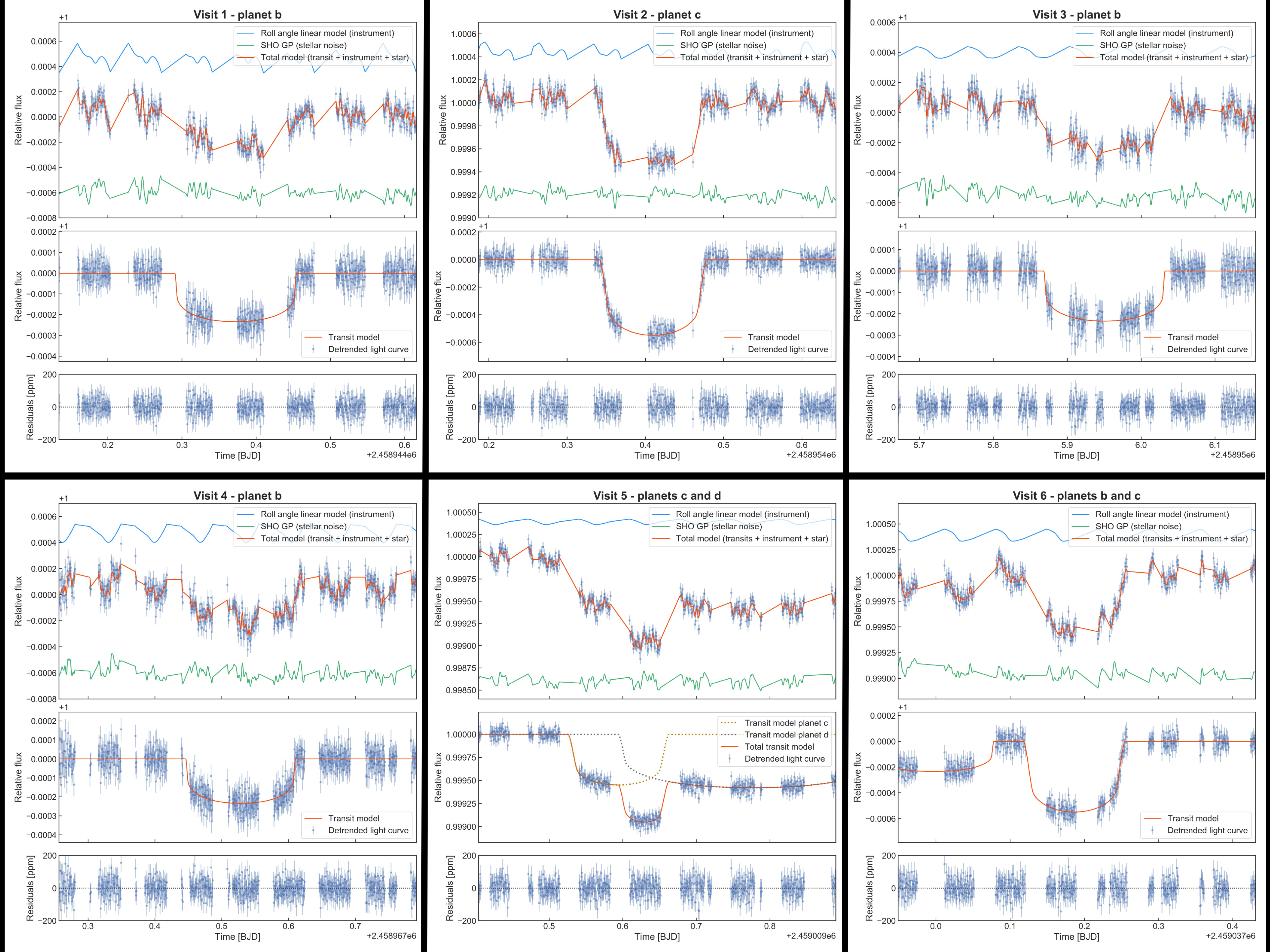




Planet d?

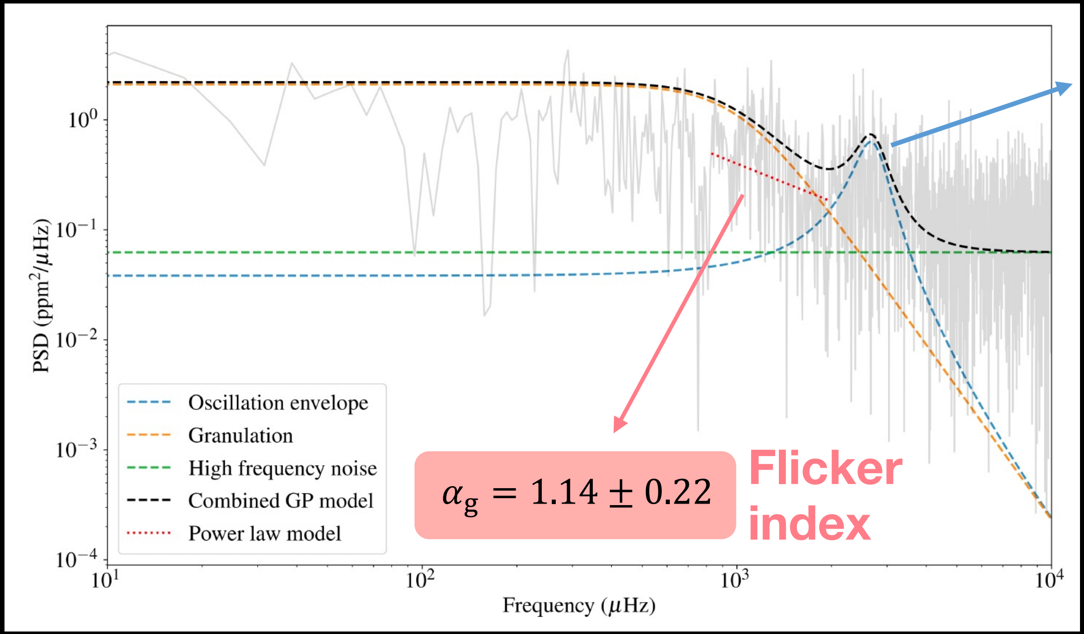
TESS did not cover any inferior conjunction

Kane+ 2020 (note: reobserved during Sector 38 – two more transits of b and one more of c)



Visit 1 - planet b
Roll angle linear model (instrument)
SHO GP (stellar noise)
Total model (transit + instrument + star)
Transit model
Detrended light curve
Relative flux
Residuals [ppm]
Time [BJD]
+2.458944e6
Visit 2 - planet c
Roll angle linear model (instrument)
SHO GP (stellar noise)
Total model (transit + instrument + star)
Transit model
Detrended light curve
Relative flux
Residuals [ppm]
Time [BJD]
+2.458954e6
Visit 3 - planet b
Roll angle linear model (instrument)
SHO GP (stellar noise)
Total model (transit + instrument + star)
Transit model
Detrended light curve
Relative flux
Residuals [ppm]
Time [BJD]
+2.45895e6
Visit 4 - planet b
Roll angle linear model (instrument)
SHO GP (stellar noise)
Total model (transit + instrument + star)
Transit model
Detrended light curve
Relative flux
Residuals [ppm]
Time [BJD]
+2.458967e6
Visit 5 - planets c and d
Roll angle linear model (instrument)
SHO GP (stellar noise)
Total model (transits + instrument + star)
Transit model planet c
Transit model planet d
Total transit model
Detrended light curve
Relative flux
Residuals [ppm]
Time [BJD]
+2.459009e6
Visit 6 - planets b and c
Roll angle linear model (instrument)
SHO GP (stellar noise)
Total model (transits + instrument + star)
Transit model
Detrended light curve
Relative flux
Residuals [ppm]
Time [BJD]
+2.459037e6

Characterization of the stellar signal



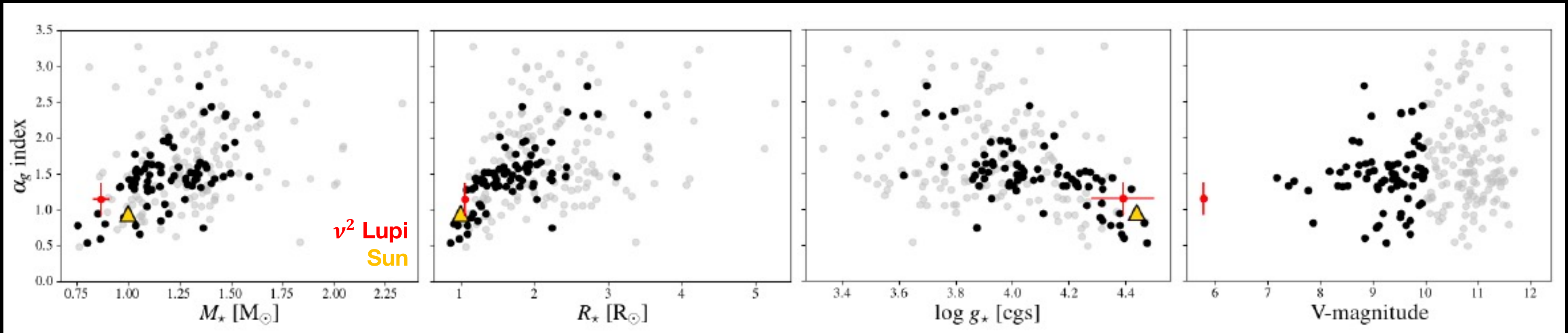
$\alpha_g = 1.14 \pm 0.22$

Flicker index

Frequency at maximum power

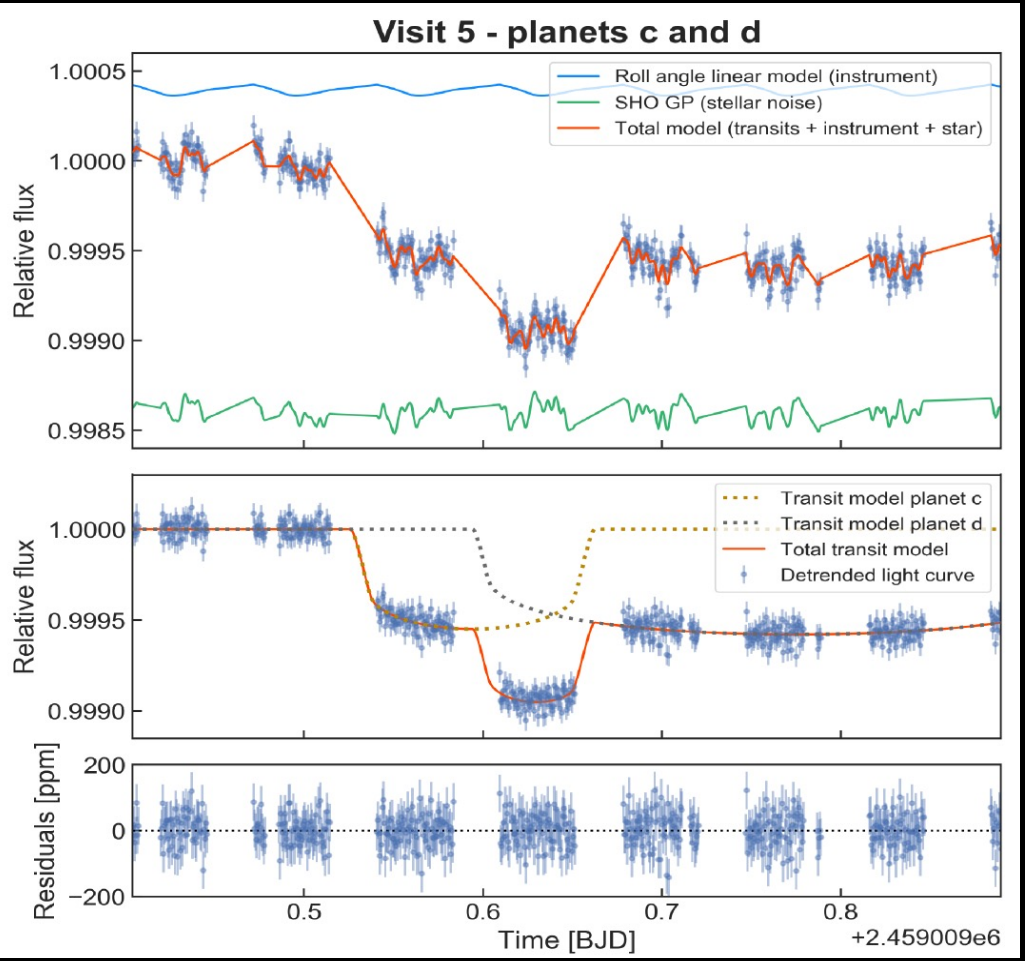
$\nu_{max} = 2710 \pm 77$ μHz

First asteroseismic measurement with CHEOPS !



Delrez+ 2021, work by S. Sulis

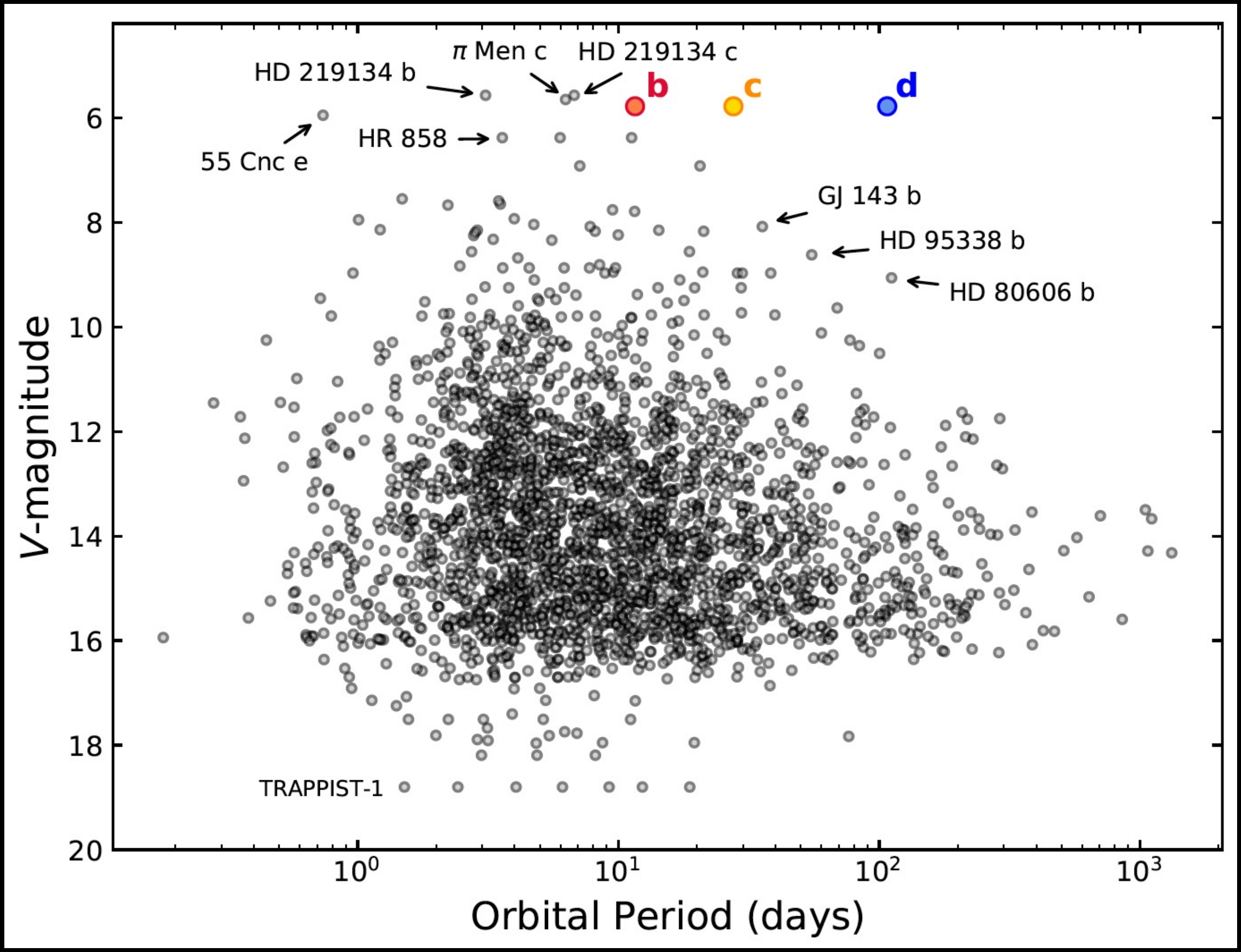
An unexpected transit-like flux drop during the fifth CHEOPS visit



Occurred at 1.3σ of an inferior conjunction of planet d (based on the HARPS RVs)

Delrez+ 2021

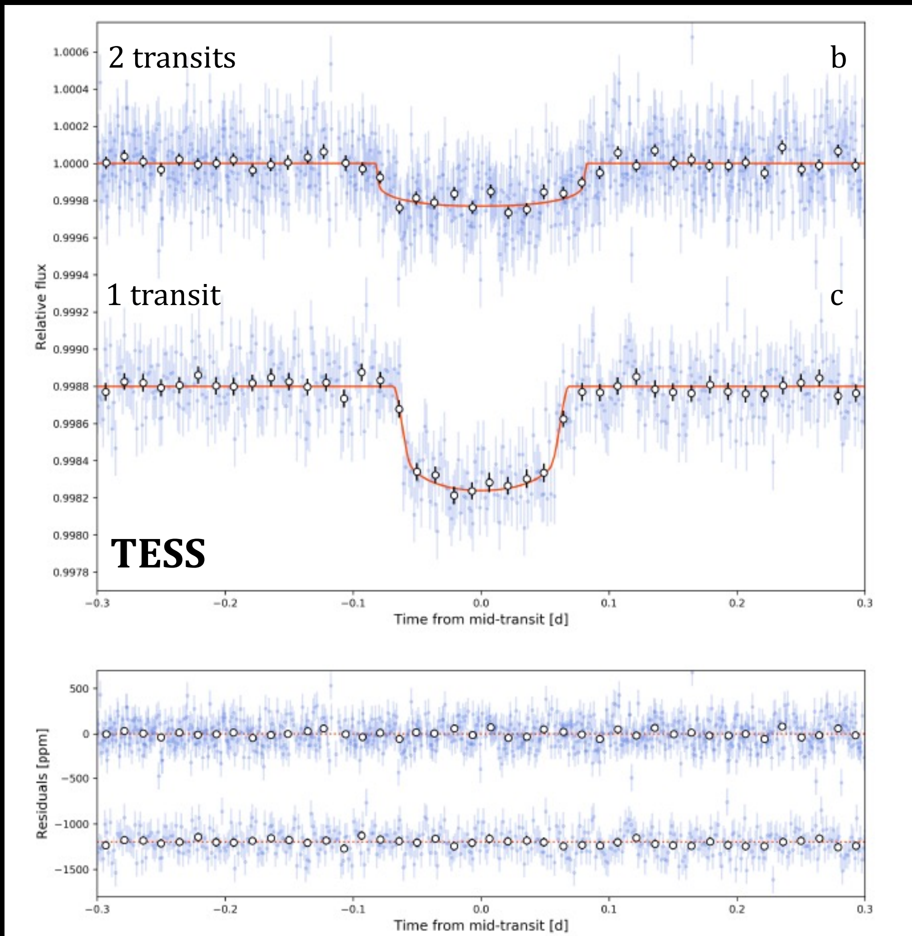
ν^2 Lupi d: the first long-period planet detected to transit a naked-eye star

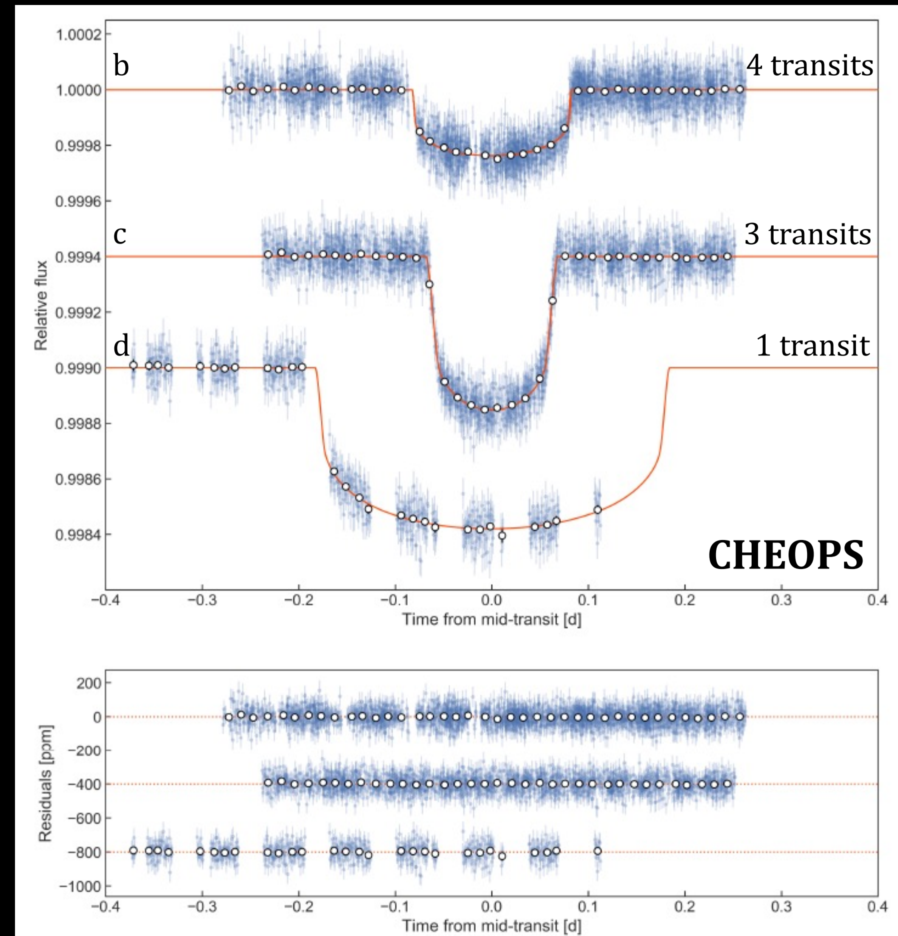


Delrez+ 2021

Comparison between TESS and CHEOPS

Phase-folded detrended light curves





Typical RMS of the individual light curves :

~80 ppm / 10 minutes
~30 ppm / 1 hour

~15 ppm / 10 minutes
~6 ppm / 1 hour

Delrez+ 2021

Comparison between TESS and CHEOPS

Parameters	*TESS* (+RVs)	*CHEOPS* (+RVs)	Global analysis (*TESS*+*CHEOPS*+RVs)
Planet b			
$R_p/R_\star$	$0.01323^{+0.00075}_{-0.00074}$	$0.01439^{+0.00040}_{-0.00041}$	$0.01428^{+0.00036}_{-0.00038}$
R_p ($R_\oplus$)	1.527 ± 0.090	1.661 ± 0.055	$1.648^{+0.052}_{-0.051}$
b ($R_\star$)	$0.38^{+0.15}_{-0.22}$	$0.48^{+0.09}_{-0.16}$	$0.47^{+0.09}_{-0.16}$
W (hours)	$4.25^{+0.25}_{-0.34}$	$3.95^{+0.14}_{-0.08}$	$3.940^{+0.103}_{-0.064}$
T_0 ($\mathrm{BJD_{TDB}} - 2,450,000$)	$8631.7723^{+0.0036}_{-0.0050}$	$8944.3718^{+0.0016}_{-0.0026}$	$8944.3724^{+0.0015}_{-0.0019}$
P (days)	$11.57748^{+0.00103}_{-0.00124}$	$11.57822^{+0.00045}_{-0.00061}$	$11.57795^{+0.00009}_{-0.00014}$
e	$0.098^{+0.076}_{-0.064}$	$0.066^{+0.058}_{-0.045}$	$0.076^{+0.047}_{-0.046}$
Planet c			
$R_p/R_\star$	$0.0249^{+0.0012}_{-0.0010}$	$0.02551^{+0.00055}_{-0.00051}$	$0.02527^{+0.00046}_{-0.00050}$
R_p ($R_\oplus$)	$2.87^{+0.14}_{-0.13}$	$2.944^{+0.084}_{-0.079}$	$2.918^{+0.074}_{-0.077}$
b ($R_\star$)	$0.874^{+0.012}_{-0.013}$	0.876 ± 0.010	0.873 ± 0.010
W (hours)	3.24 ± 0.11	$3.242^{+0.041}_{-0.038}$	$3.254^{+0.039}_{-0.033}$
T_0 ($\mathrm{BJD_{TDB}} - 2,450,000$)	$8650.8959^{+0.0013}_{-0.0012}$	$8954.40959^{+0.00067}_{-0.00070}$	$8954.40987^{+0.00051}_{-0.00054}$
P (days)	$27.5911^{+0.0029}_{-0.0034}$	$27.59255^{+0.00045}_{-0.00048}$	27.59220 ± 0.00011
e	$0.038^{+0.042}_{-0.027}$	$0.022^{+0.027}_{-0.016}$	$0.022^{+0.026}_{-0.015}$

Delrez+ 2021

Comparison between TESS and CHEOPS

Parameters	*TESS* (+RVs)	*CHEOPS* (+RVs)	Global analysis (*TESS*+*CHEOPS*+RVs)
Planet b			
$R_p/R_\star$	$0.01323^{+0.00075}_{-0.00074}$	$0.01439^{+0.00040}_{-0.00041}$	$0.01428^{+0.00036}_{-0.00038}$
$R_\mathrm{p}\ (R_\oplus)$	1.527 ± 0.090	1.661 ± 0.055	$1.648^{+0.052}_{-0.051}$
$b\,(R_\star)$	$0.38^{+0.15}_{-0.22}$	$0.48^{+0.09}_{-0.16}$	$0.47^{+0.09}_{-0.16}$
W (hours)	$4.25^{+0.25}_{-0.34}$	$3.95^{+0.14}_{-0.08}$	$3.940^{+0.103}_{-0.064}$
$T_0\ (\mathrm{BJD_{TDB}} - 2,450,000)$	$8631.7723^{+0.0036}_{-0.0050}$	$8944.3718^{+0.0016}_{-0.0026}$	$8944.3724^{+0.0015}_{-0.0019}$
P (days)	$11.57748^{+0.00103}_{-0.00124}$	$11.57822^{+0.00045}_{-0.00061}$	$11.57795^{+0.00009}_{-0.00014}$
e	$0.098^{+0.076}_{-0.064}$	$0.066^{+0.058}_{-0.045}$	$0.076^{+0.047}_{-0.046}$
Planet c			
$R_p/R_\star$	$0.0249^{+0.0012}_{-0.0010}$	$0.02551^{+0.00055}_{-0.00051}$	$0.02527^{+0.00046}_{-0.00050}$
$R_\mathrm{p}\ (R_\oplus)$	$2.87^{+0.14}_{-0.13}$	$2.944^{+0.084}_{-0.079}$	$2.918^{+0.074}_{-0.077}$
$b\,(R_\star)$	$0.874^{+0.012}_{-0.013}$	0.876 ± 0.010	0.873 ± 0.010
W (hours)	3.24 ± 0.11	$3.242^{+0.041}_{-0.038}$	$3.254^{+0.039}_{-0.033}$
$T_0\ (\mathrm{BJD_{TDB}} - 2,450,000)$	$8650.8959^{+0.0013}_{-0.0012}$	$8954.40959^{+0.00067}_{-0.00070}$	$8954.40987^{+0.00051}_{-0.00054}$
P (days)	$27.5911^{+0.0029}_{-0.0034}$	$27.59255^{+0.00045}_{-0.00048}$	27.59220 ± 0.00011
e	$0.038^{+0.042}_{-0.027}$	$0.022^{+0.027}_{-0.016}$	$0.022^{+0.026}_{-0.015}$

Consistent and CHEOPS significantly more precise

(higher photometric precision but also more transits)

Delrez+ 2021

Comparison between TESS and CHEOPS

Parameters	*TESS* (+RVs)	*CHEOPS* (+RVs)	Global analysis (*TESS*+*CHEOPS*+RVs)
Planet b			
$R_p/R_\star$	$0.01323^{+0.00075}_{-0.00074}$	$0.01439^{+0.00040}_{-0.00041}$	$0.01428^{+0.00036}_{-0.00038}$
R_p ($R_\oplus$)	1.527 ± 0.090	1.661 ± 0.055	$1.648^{+0.052}_{-0.051}$
b ($R_\star$)	$0.38^{+0.15}_{-0.22}$	$0.48^{+0.09}_{-0.16}$	$0.47^{+0.09}_{-0.16}$
W (hours)	$4.25^{+0.25}_{-0.34}$	$3.95^{+0.14}_{-0.08}$	$3.940^{+0.103}_{-0.064}$
T_0 ($\mathrm{BJD_{TDB}} - 2,450,000$)	$8631.7723^{+0.0036}_{-0.0050}$	$8944.3718^{+0.0016}_{-0.0026}$	$8944.3724^{+0.0015}_{-0.0019}$
P (days)	$11.57748^{+0.00103}_{-0.00124}$	$11.57822^{+0.00045}_{-0.00061}$	$11.57795^{+0.00009}_{-0.00014}$
e	$0.098^{+0.076}_{-0.064}$	$0.066^{+0.058}_{-0.045}$	$0.076^{+0.047}_{-0.046}$
Planet c			
$R_p/R_\star$	$0.0249^{+0.0012}_{-0.0010}$	$0.02551^{+0.00055}_{-0.00051}$	$0.02527^{+0.00046}_{-0.00050}$
R_p ($R_\oplus$)	$2.87^{+0.14}_{-0.13}$	$2.944^{+0.084}_{-0.079}$	$2.918^{+0.074}_{-0.077}$
b ($R_\star$)	$0.874^{+0.012}_{-0.013}$	0.876 ± 0.010	0.873 ± 0.010
W (hours)	3.24 ± 0.11	$3.242^{+0.041}_{-0.038}$	$3.254^{+0.039}_{-0.033}$
T_0 ($\mathrm{BJD_{TDB}} - 2,450,000$)	$8650.8959^{+0.0013}_{-0.0012}$	$8954.40959^{+0.00067}_{-0.00070}$	$8954.40987^{+0.00051}_{-0.00054}$
P (days)	$27.5911^{+0.0029}_{-0.0034}$	$27.59255^{+0.00045}_{-0.00048}$	27.59220 ± 0.00011
e	$0.038^{+0.042}_{-0.027}$	$0.022^{+0.027}_{-0.016}$	$0.022^{+0.026}_{-0.015}$

Best constraints

Ephemeris refinement: uncertainty in 2022 = 15.1 / 4.8 min for b / c (vs 140 / 164 min previously)

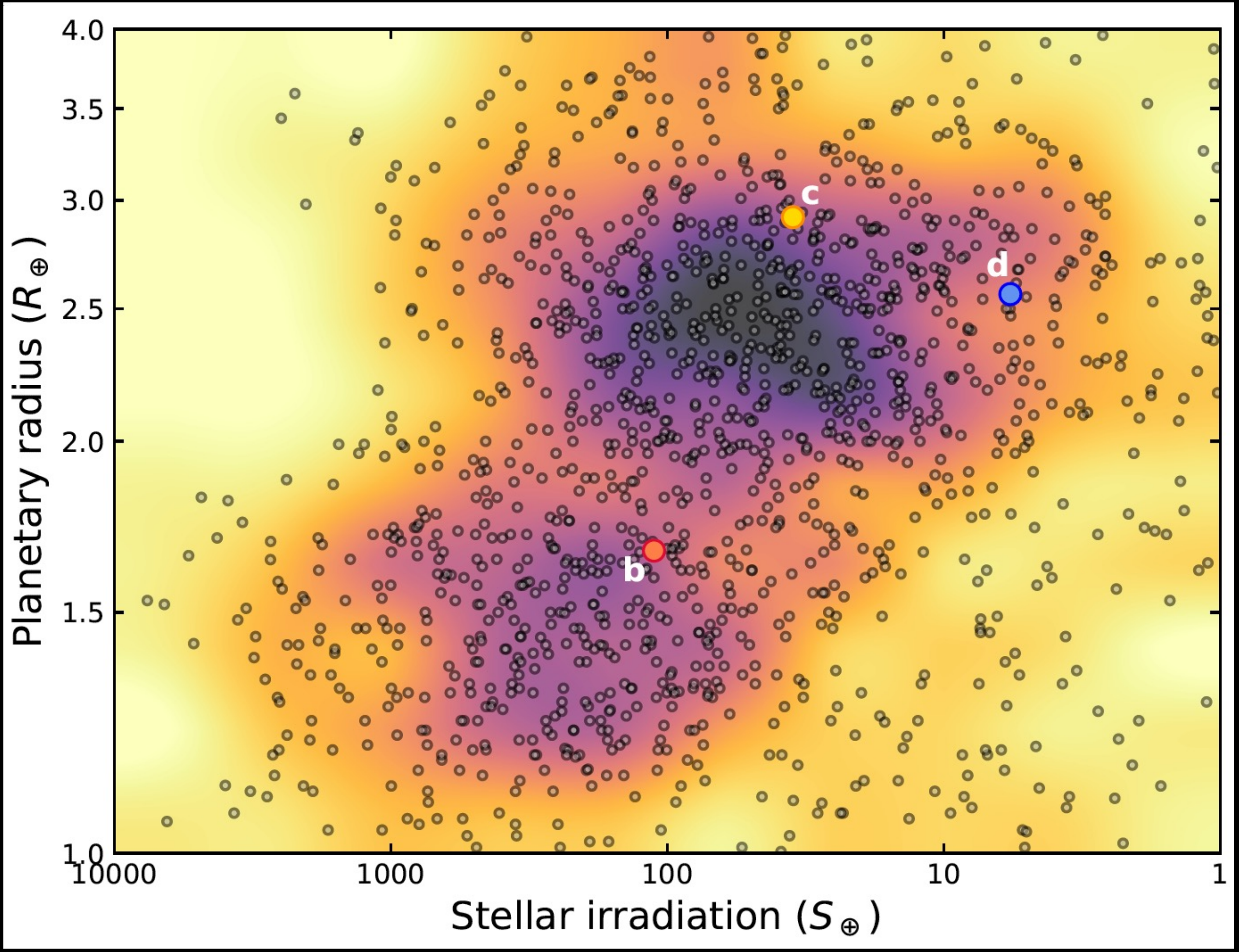
Delrez+ 2021

A system straddling the radius valley

$R_b = 1.664 \pm 0.043\ R_\oplus$
(2.6%)

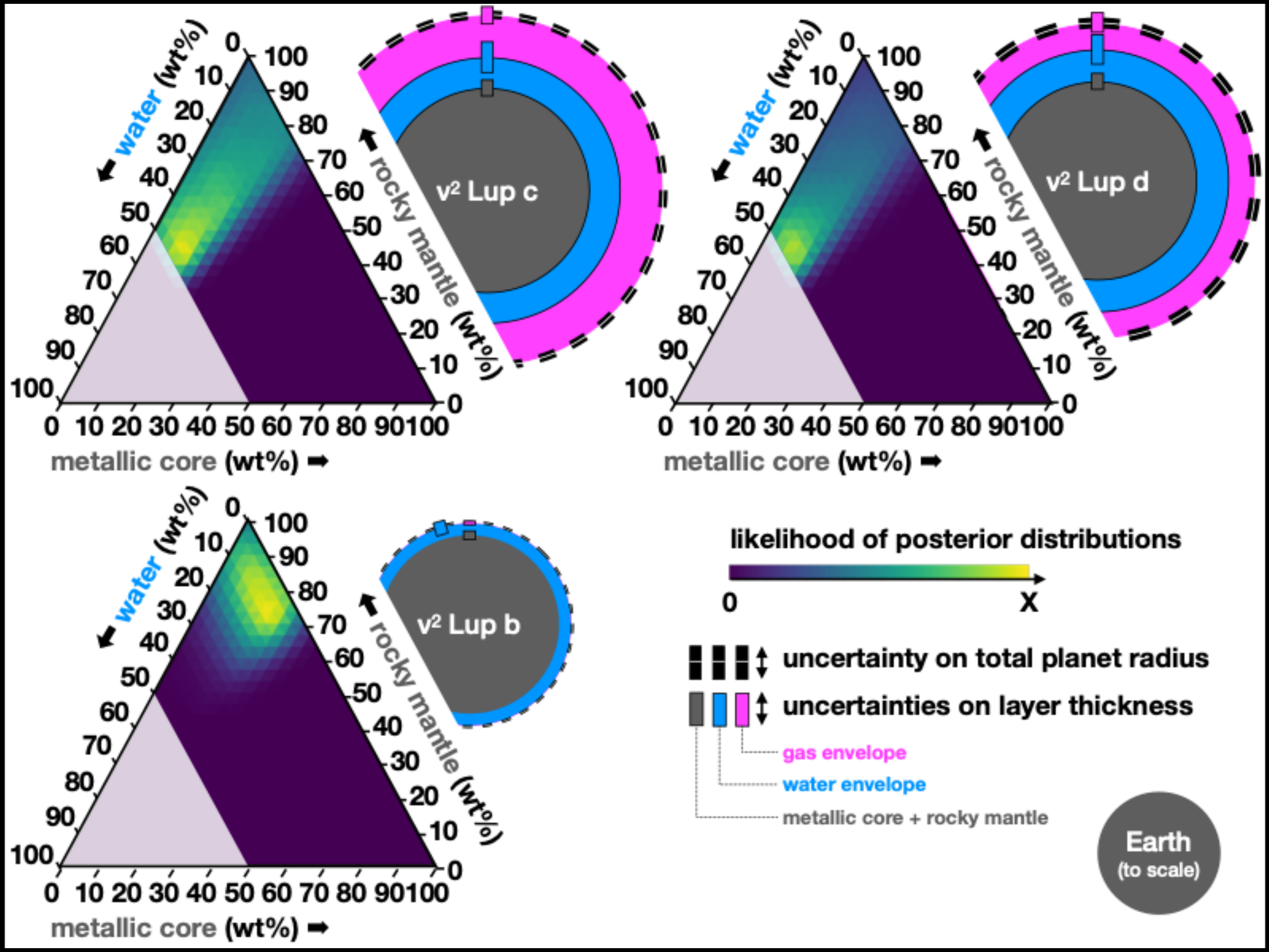
$R_c = 2.916^{+0.075}_{-0.073}\ R_\oplus$
(2.6%)

$R_d = 2.562^{+0.088}_{-0.079}\ R_\oplus$
(3.4%)



Delrez+ 2021

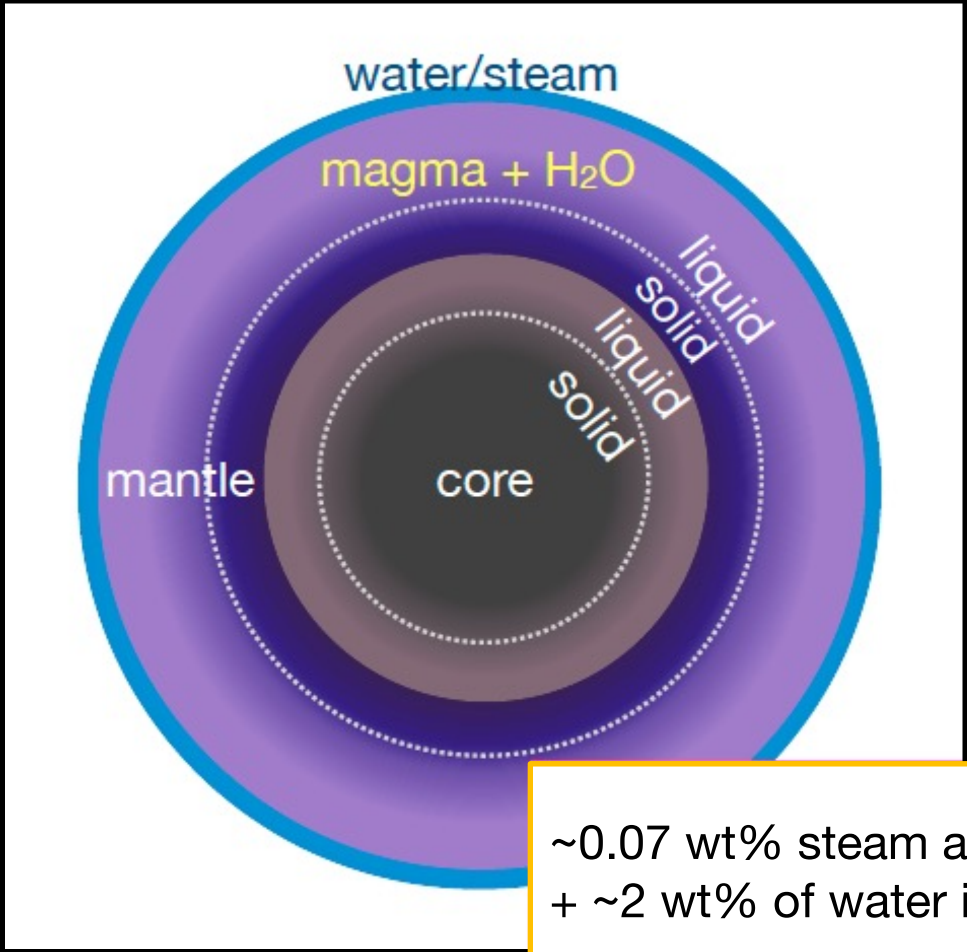
Internal structures



Planet b: bare core (no gas), mostly rocky
Planets c and d: small H/He envelopes (≲1% in mass)
and large water fractions (formed beyond the ice line?)

Delrez+ 2021, work by Y. Alibert and J. Haldemann, based on Dorn+ 2015, 2017

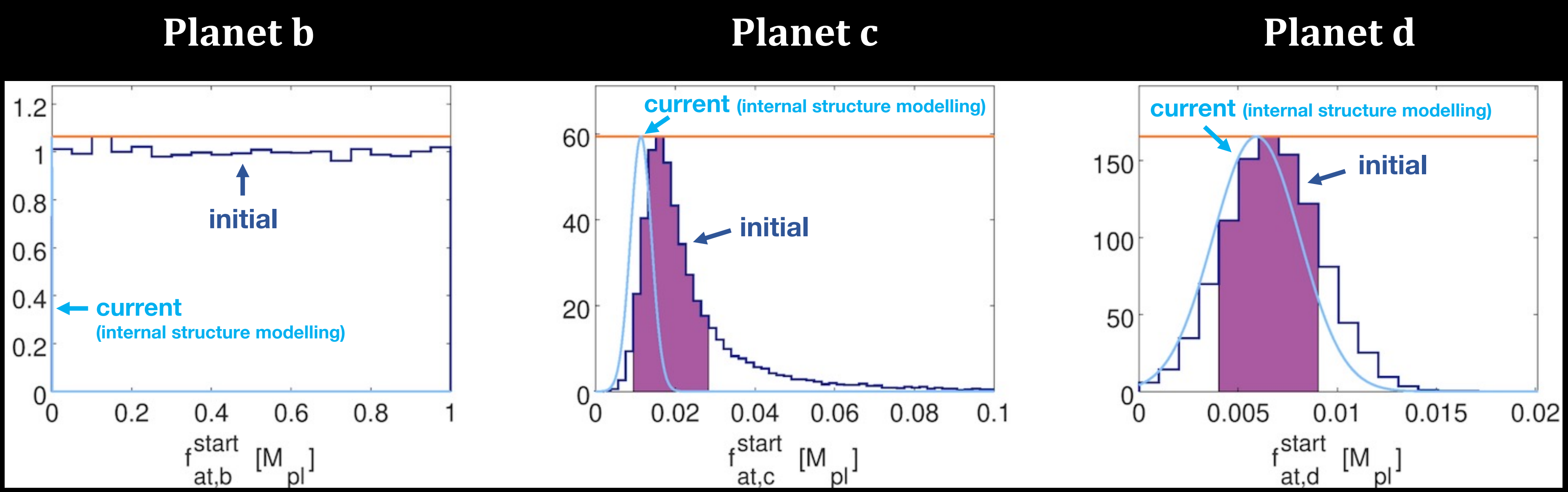
Alternative interior model for planet b



~0.07 wt% steam atmosphere
+ ~2 wt% of water in magma ocean

Lichtenberg & Dorn 2021 (see also poster by C. Dorn)

Evolution of the atmospheric mass fraction



Planet b:
completely lost its primary atmosphere at some unknown point in time

Planets c and d:

- weakly affected by mass loss → low gas content of primordial origin
  → did not reach the critical mass
- core mass and gas-to-core ratio for two objects *in the same system*
  → important anchor for formation models of sub-critical planets

Delrez+ 2021, work by L. Fossati and A. Bonfanti, based on Kubyshkina+ 2019

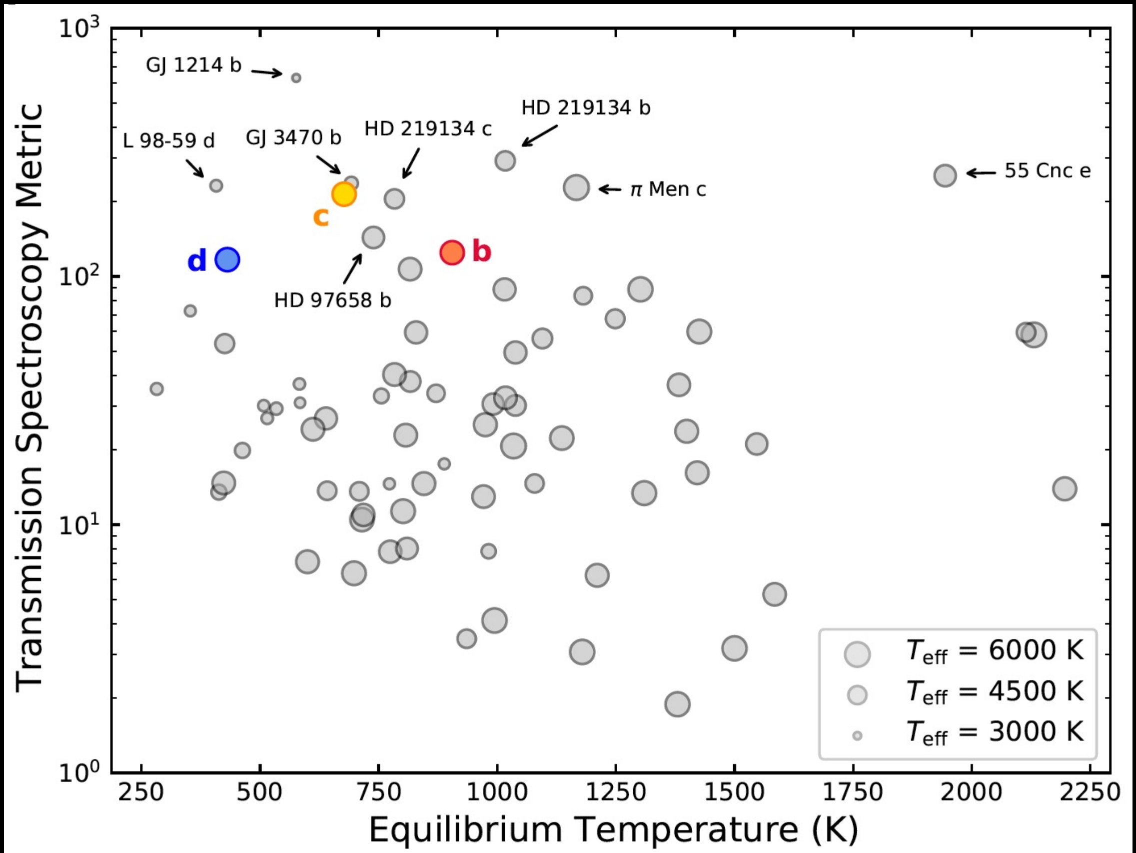
Potential for atmospheric characterization

Transmission spectroscopy metric of Kempton+ 2018

$$TSM \propto \frac{R_p^3 T_{eq}}{M_p R_s^2} 10^{\frac{-m_J}{5}}$$

ν^2 Lupi d is the best target so far for studying the atmosphere of a mildly irradiated small planet around a Sun-like star

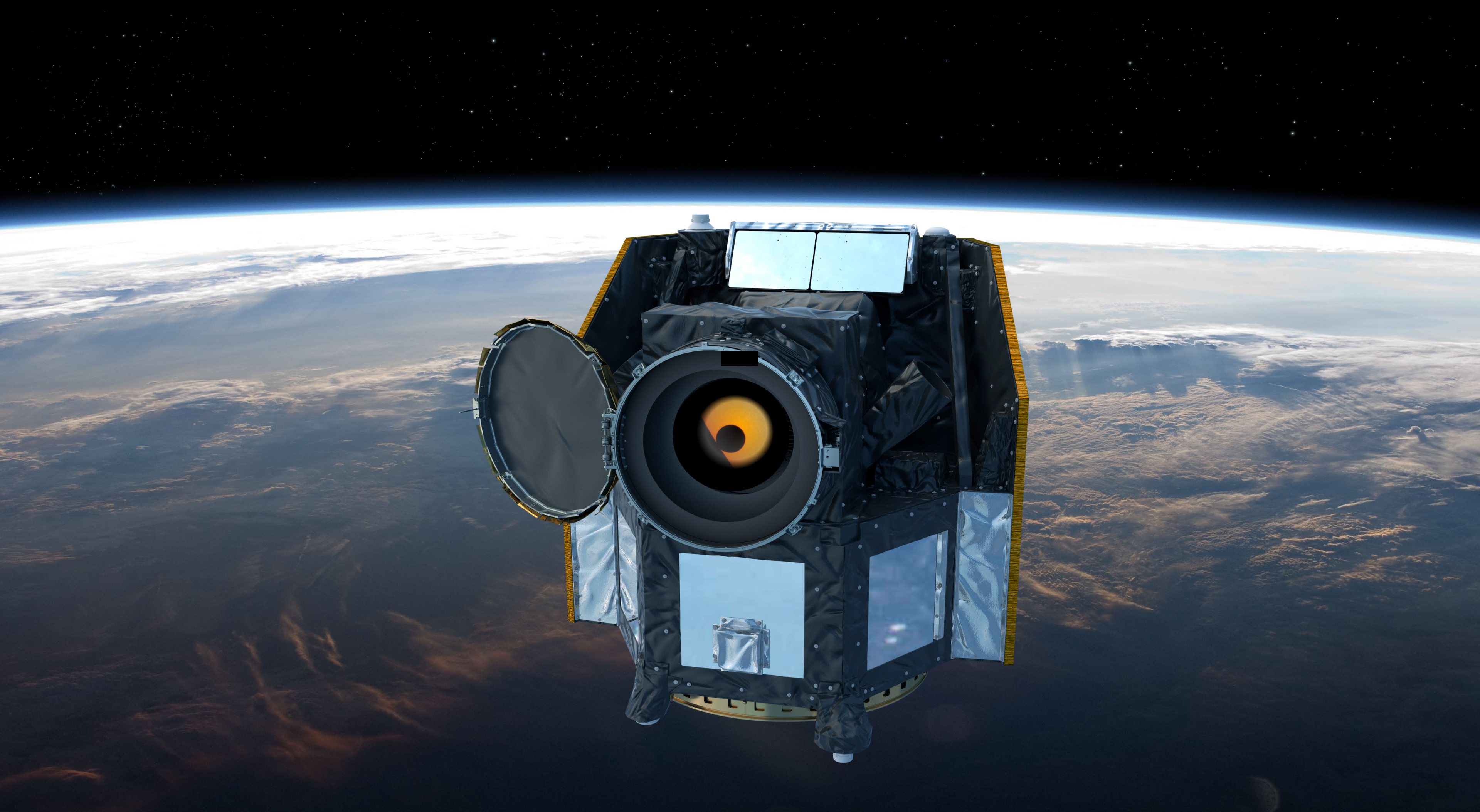
Exoplanets with well constrained masses and radii (<4 $R_\oplus$)



Ongoing program with HST (PI: D. Ehrenreich) to study the atmospheric escape of the three planets in the FUV

Delrez+ 2021

Stay tuned for more results!



Thanks to the CHEOPS team