CHEOPS Science Workshop VI

# Investigating the architecture and internal structure of the TOI-561 system planets with CHEOPS, HARPS-N and TESS

Gaia Lacedelli[1,2], T. Wilson, L. Malavolta, M. Hooton,
& many others!

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Osservatorio Astronomico di Padova
INAF Istituto Nazionale di Astrofisica
Università degli Studi di Padova
1222·2022 800 anni

# Investigating the architecture and internal structure of the TOI-561 system planets with CHEOPS, HARPS-N and TESS

G. Lacedelli[1,2*], T. G. Wilson[3], L. Malavolta[1,2], M. J. Hooton[4], A. Collier Cameron[3], Y. Alibert[4,5], A. Mortier[6,7], A. Bonfanti[8], R. D. Haywood[9], S. Hoyer[10], G. Piotto[1,2], A. Bekkelien[11], A. M. Vanderburg[12,13], W. Benz[4,5], X. Dumusque[11], A. Deline[11], M. López-Morales[14], L. Borsato[2], K. Rice[15,16], L. Fossati[8], D. W. Latham[14], A. Brandeker[17], E. Poretti[18,19], S. G. Sousa[20], A. Sozzetti[21], S. Salmon[11], C. J. Burke[12], V. Van Grootel[22], M. M. Fausnaugh[12], V. Adibekyan[20], C. X. Huang[12,23], H. P. Osborn[5,12], A. J. Mustill[24], E. Pallé[25], V. Bourrier[11], V. Nascimbeni[2], R. Alonso[25,26], G. Anglada[27,28], T. Bárczy[29], D. Barrado y Navascues[30], S. C. C. Barros[20,31], W. Baumjohann[8], M. Beck[11], T. Beck[4], N. Billot[11], X. Bonfils[32], C. Broeg[4,5], L. A. Buchhave[33], J. Cabrera[34], S. Charnoz[35], R. Cosentino[18], Sz. Csizmadia[34], M. B. Davies[36], M. Deleuil[10], L. Delrez[22,37], O. Demangeon[20,31], B.-O. Demory[5], D. Ehrenreich[11], A. Erikson[34], E. Esparza-Borges[25,26], H.-G. Florén[17,38], A. Fortier[4,5], M. Fridlund[39,40], D. Futyan[11], D. Gandolfi[41], A. Ghedina[18], M. Gillon[37], M. Güdel[42], P. Gutermann[10,43], A. Harutyunyan[18], K. Heng[5,44], K. G. Isaak[45], J. M. Jenkins[46], L. Kiss[47,48], J. Laskar[49], A. Lecavelier des Etangs[50], M. Lendl[11], C. Lovis[11], D. Magrin[2], L. Marafatto[2], A. F. Martinez Fiorenzano[18], P. F. L. Maxted[51], M. Mayor[11], G. Micela[52], E. Molinari[53], F. Murgas[25], N. Narita[25,54,55], G. Olofsson[17], R. Ottensamer[42], I. Pagano[56], A. Pasetti[57], M. Pedani[18], F. A. Pepe[11], G. Peter[58], D. F. Phillips[14], D. Pollacco[44], D. Queloz[6,11], R. Ragazzoni[1,2], N. Rando[59], F. Ratti[59], H. Rauer[34,60,61], I. Ribas[27,28], N. C. Santos[20,31], D. Sasselov[14], G. Scandariato[56], S. Seager[12,62,63], D. Ségransan[11], L. M. Serrano[41], A. E. Simon[4], A. M. S. Smith[34], M. Steinberger[8], M. Steller[8], Gy. Szabó[64,65], N. Thomas[4], J. D. Twicken[46,66], S. Udry[11], N. Walton[67], J. N. Winn[68]

Lacedelli et al. 2022, accepted in MNRAS

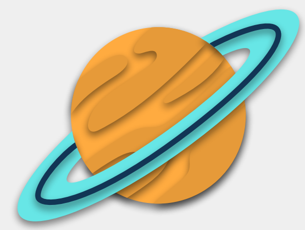
# Exoplanetary characterization
## Multiplanetary systems

### Density

Inner bulk composition

**Rocky or gaseous?**

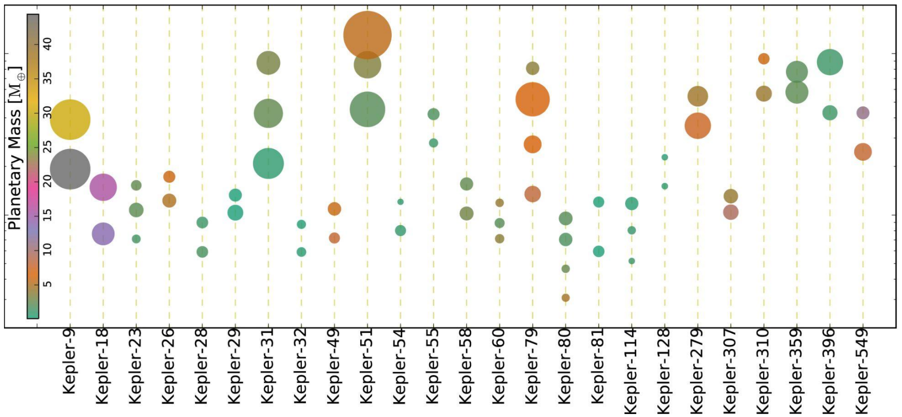
**Atmosphere? Formation & evolution?**



### Comparative planetology

- Comparison of bulk compositions
- Relative planet sizes, masses, and orbital separations
- Mutual inclinations and eccentricities
- ….

*Millholland et al. 2017*



# The TOI-561 system

## The host star

$V = 10.525$ mag

$M_\star = 0.806\ M_\odot$

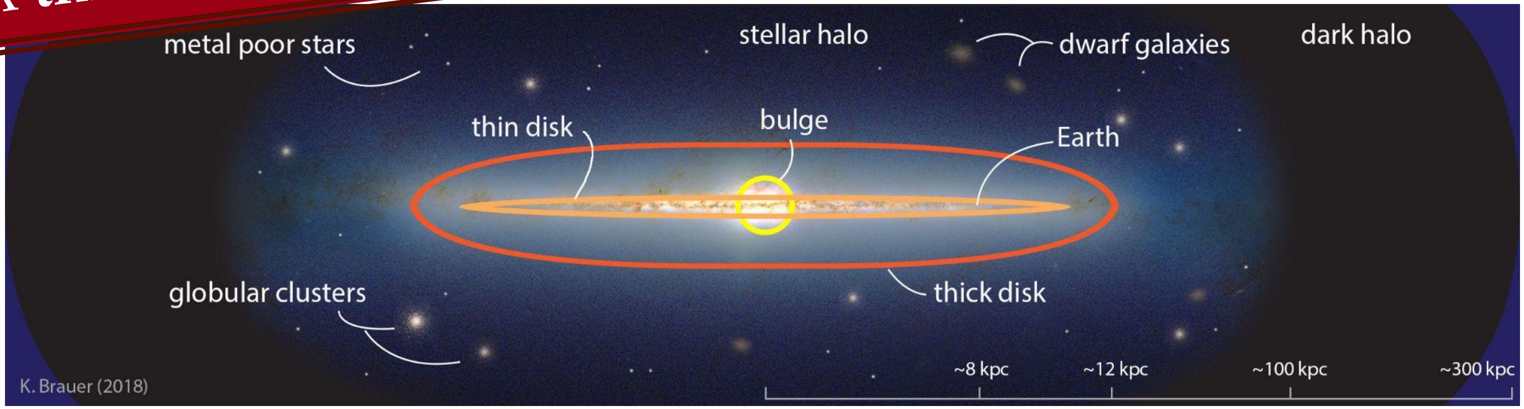
$R_\star = 0.843\ R_\odot$

$T_{eff} = 5327$ K

**CHECKLIST**

- ☑ Old: t ~ 11 Gyr
- ☑ Quiet: $\log R'_{HK} = -5.003$
- ☑ Metal-poor: [Fe/H] = -0.40
- ☑ α-enhanced: [α/Fe] = 0.23
- ☑ High proper motions

**A thick disk star!**



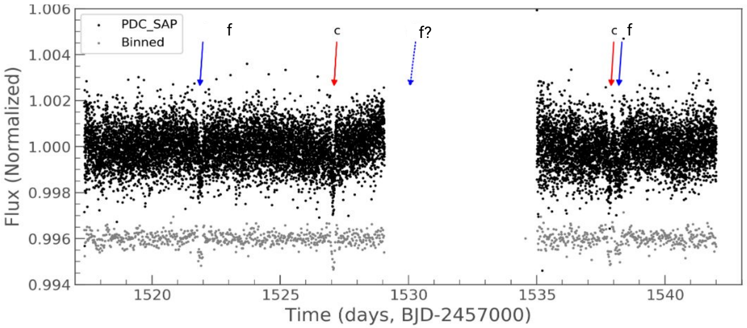

*Credit: Kaley Brauer, MIT*

# The TOI-561 system

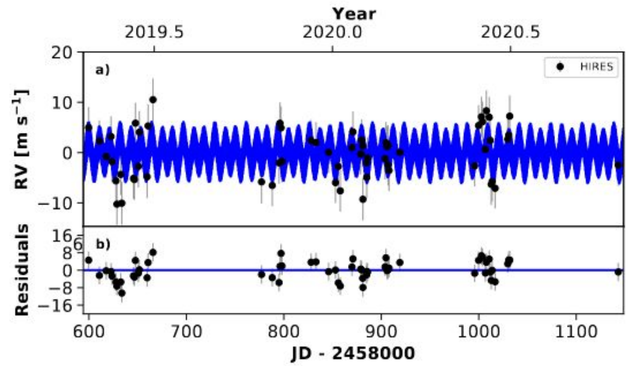
## Literature summary

**WEISS ET AL. 2021**

TESS sector 8




60 HIRES RVs




3 signals identified by the TESS automatic SPOC pipeline

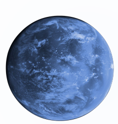
**3-planet scenario**

**TOI-561**: an old, metal poor, **thick disk star**



**TOI-561 b:** a USP super-Earth

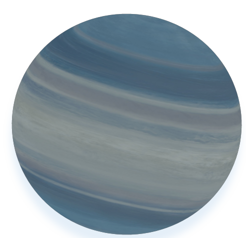
P = 0.44 d
R = 1.45 ± 0.11 $R_\oplus$
M = 3.2 ± 0.8 $M_\oplus$



Consistent with a rocky composition

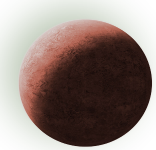
**TOI-561 c:** a gaseous mini-Neptune

P = 10.78 d
R = 2.90 ± 0.13 $R_\oplus$
M = 7.0 ± 2.3 $M_\oplus$



**TOI-561 f:** a mini-Neptune

P = 16.3 d
R = 2.32 ± 0.16 $R_\oplus$
M = 3.0 [-1.9, +2.4] $M_\oplus$

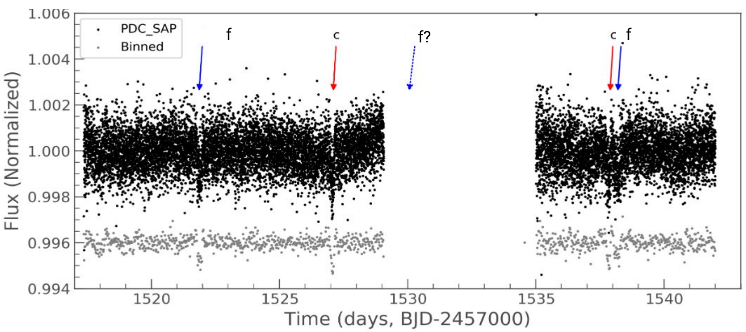


Mass consistent with zero

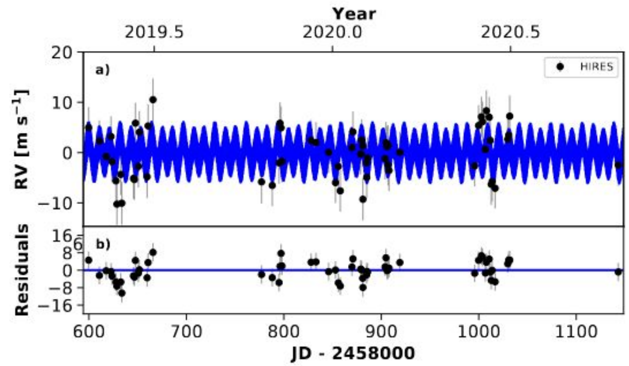
# The TOI-561 system
## Literature summary

**WEISS ET AL. 2021**

**TESS sector 8**




**60 HIRES RVs**




3 signals identified by the TESS automatic SPOC pipeline

**3-planet scenario**

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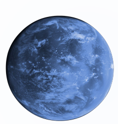

Consistent with a rocky composition

**TOI-561 c:** a gaseous mini-Neptune

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R = 2.90 ± 0.13 $R_\oplus$
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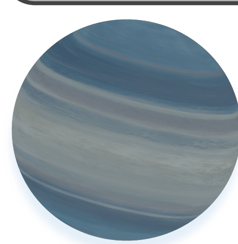


~~TOI-561 … a … e~~

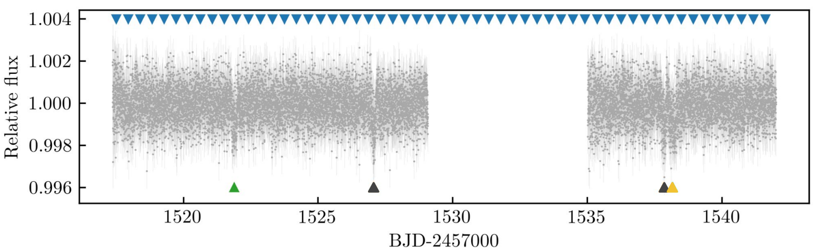
~~P = 16.3 … R = 2 … M … 1.9, +2…~~

Mass consistent with zero

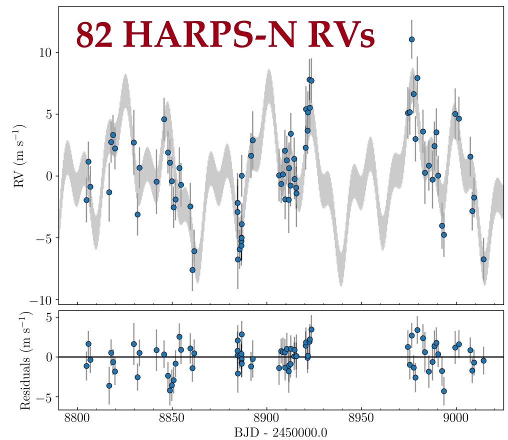
# The TOI-561 system
## Literature summary

**LACEDELLI ET AL. 2021**

**TESS sector 8**



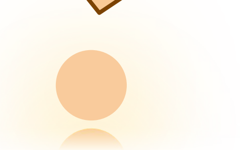

+




- Different $T_{dur}$
- No 16 d signal in RVs
- Dynamical analysis

**4-planet scenario**

**TOI-561**: an old, metal poor, **thick disk star**



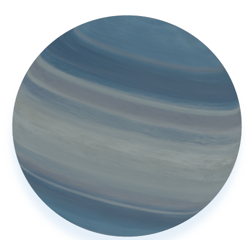
**TOI-561 b:** a USP super-Earth

P = 0.44 d
R = 1.42 ± 0.07 $R_\oplus$
**M = 1.59 ± 0.36 $M_\oplus$**

The lowest density USP planet known to date!

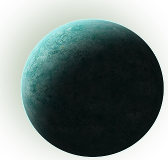
**TOI-561 c:** a gaseous mini-Neptune

P = 10.78 d
R = 2.88 ± 0.10 $R_\oplus$
M = 5.4 ± 1.0 $M_\oplus$



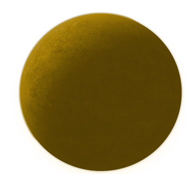
**TOI-561 d:** a mini-Neptune

P = 25.62 d
R = 2.53 ± 0.13 $R_\oplus$
M = 11.9 ± 1.3 $M_\oplus$



**TOI-561 e:** a(nother) mini-Neptune

P = 77.23 d
R = 2.67 ± 0.11 $R_\oplus$
M = 16.2 ± 1.3 $R_\oplus$

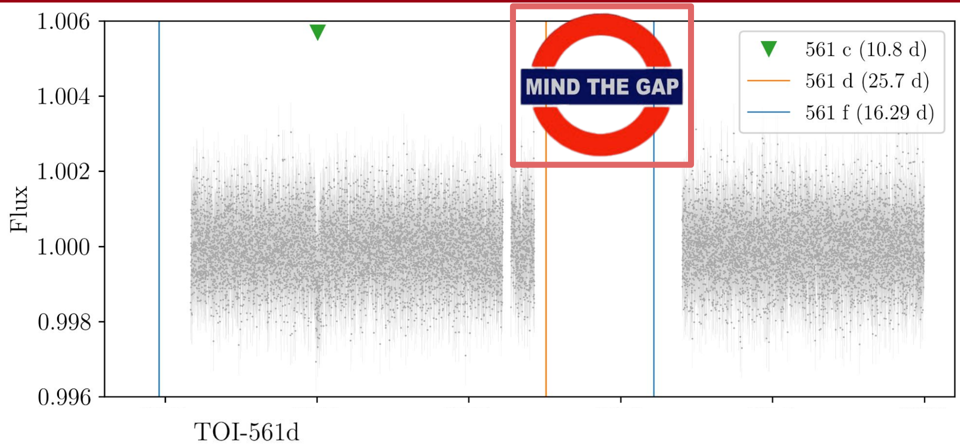


**Two single-transit** planets with significant mass and radius determination

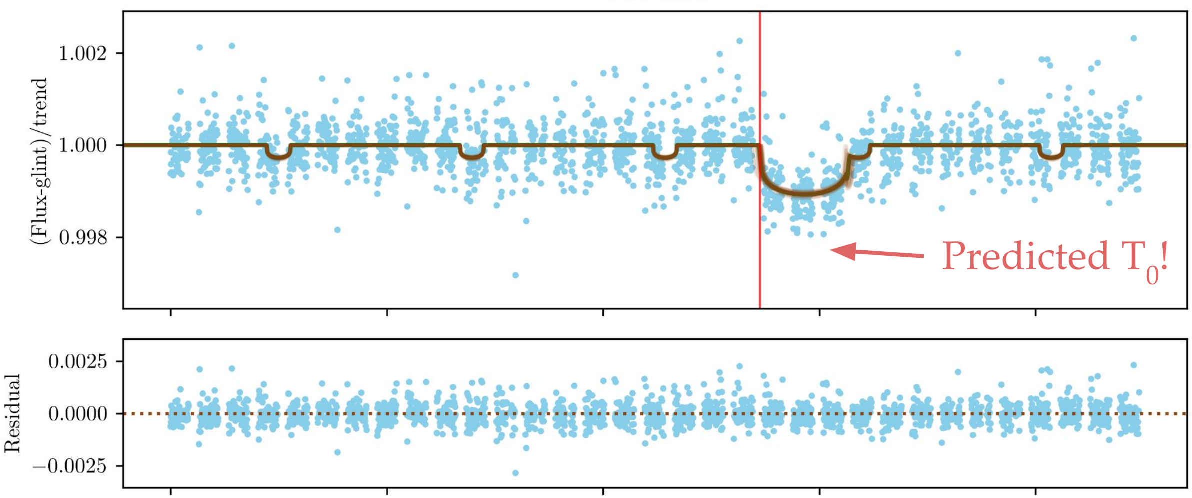
# The TOI-561 system

## CHEOPS/HARPS-N collaboration

**TESS S35**
Feb/March 2021




Successful **CHEOPS** observation in April 2021 thanks to updated ephemeris!




(TESS tica FFIs + new **HARPS-N** data set)

62 RVs in Nov 20-June 21
(**144** total RVs)

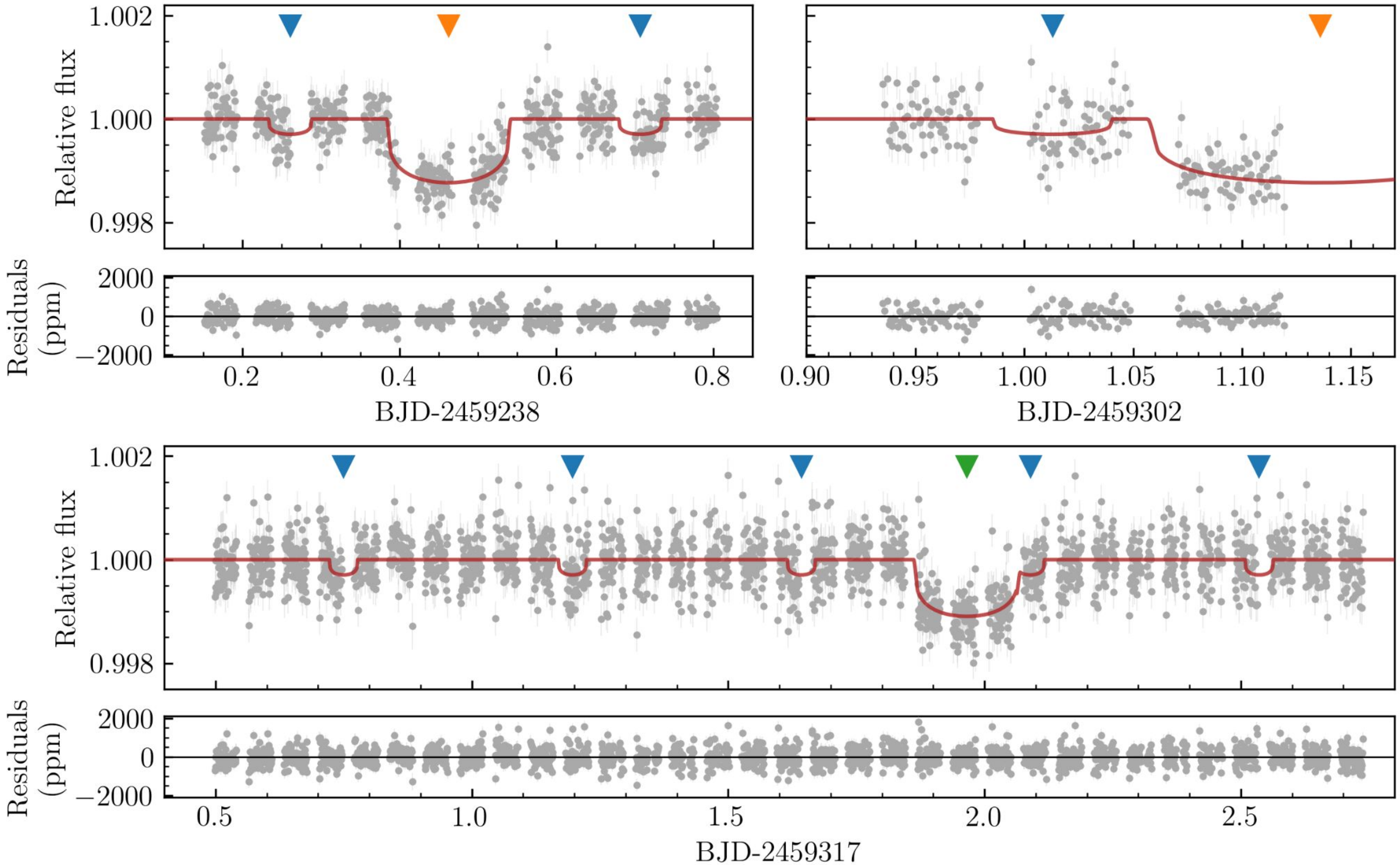
Nice confirmation of the 25 d period planet and witness of a successful **CHEOPS/HARPS-N collaboration!**

# The TOI-561 system
## CHEOPS observations

**TOI-561 b** ⇒ P = 0.45 d
8 transits

**TOI-561 c** ⇒ P = 10.8 d
1 + ½ transit

**TOI-561 d** ⇒ P = 25.7 d
1 transit

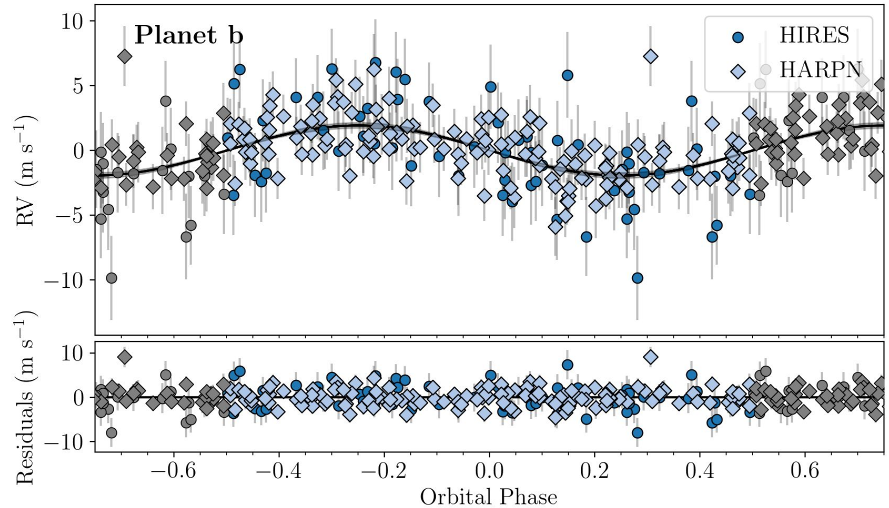


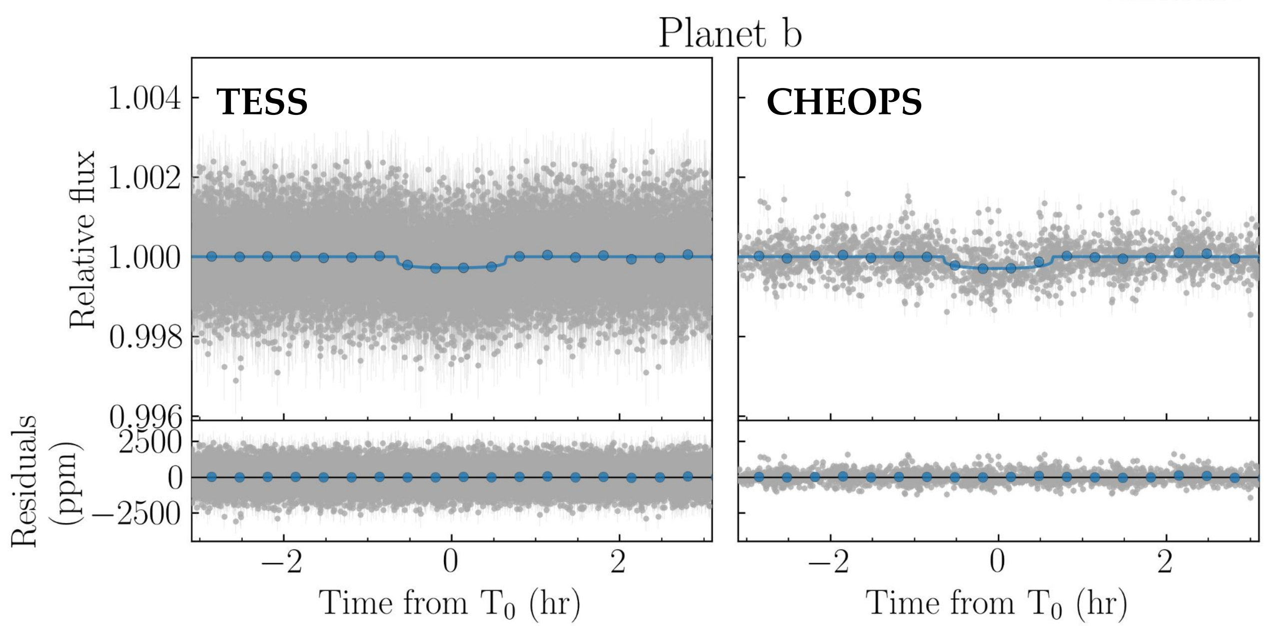
# The TOI-561 system

## Planetary properties

**TOI-561 b**

| | |
|---|---|
| Period | 0.44657 d |
| Radius | 1.425 ± 0.037 $R_\oplus$ **(2.6%)** |
| Mass | 2.00 ± 0.23 $M_\oplus$ **(11.5%)** |
| Density | 3.8 ± 0.5 g $cm^{-3}$ |




*N.B.* All analyses carried out with **PyORBIT** by L. Malavolta

# The TOI-561 system
## Planetary properties

**TOI-561 b**

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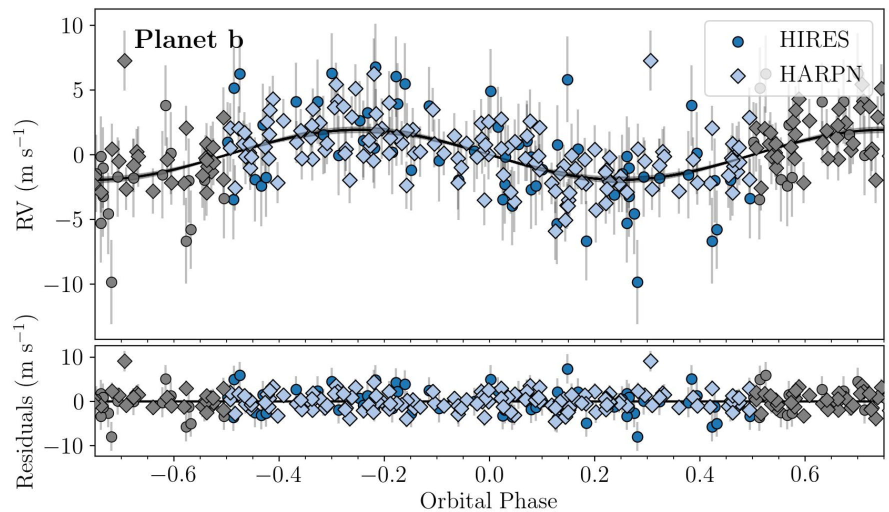
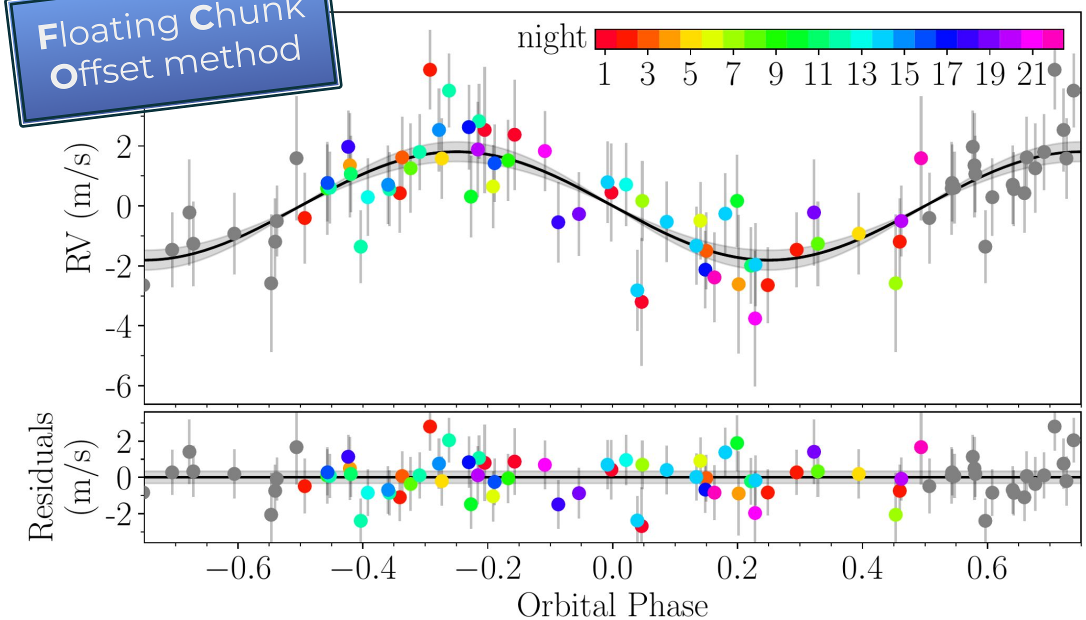



Floating Chunk Offset method



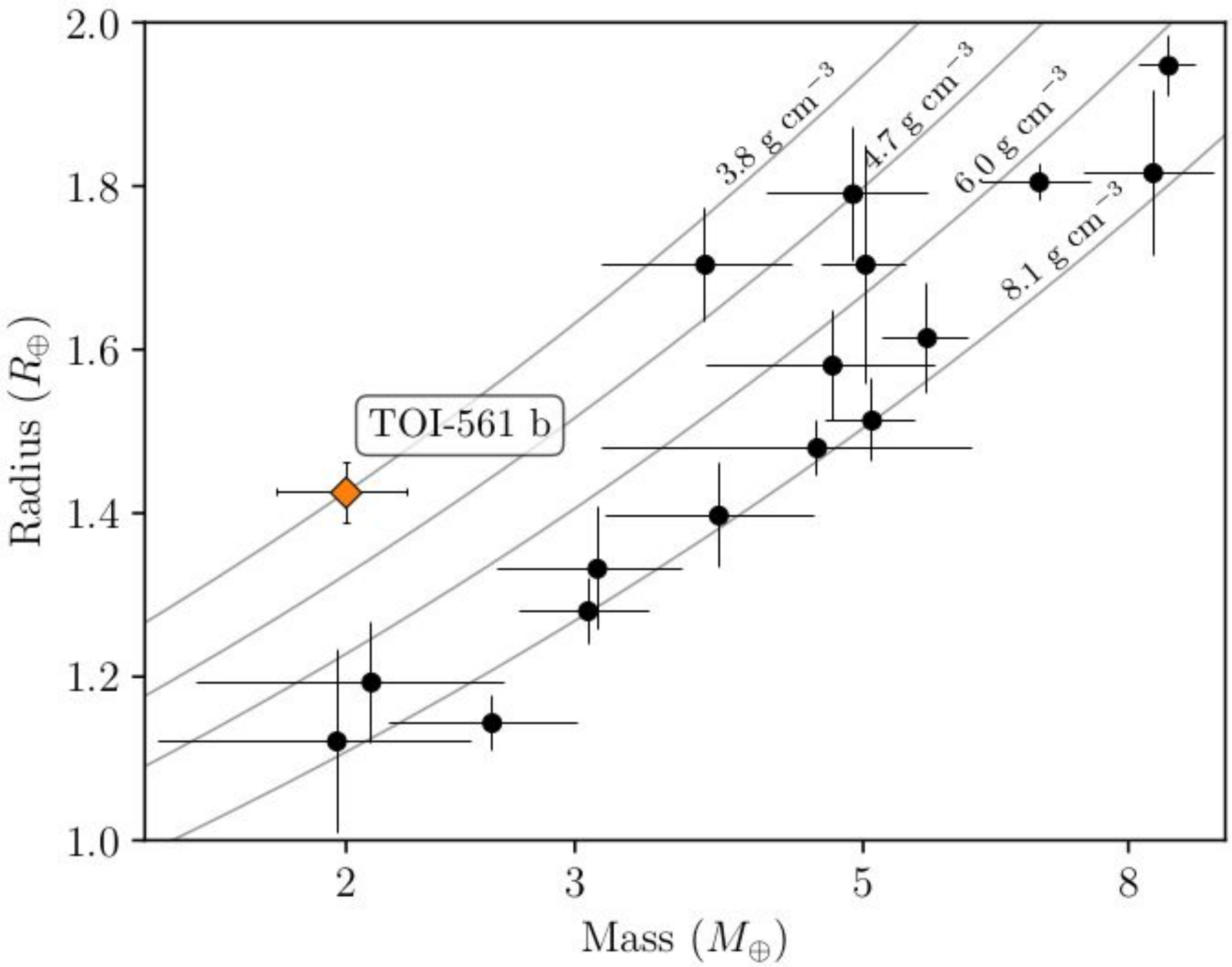

**FCO** method on 22 total HARPS-N nights

$M_b = 1.86 \pm 0.33\ M_\oplus$

Yes, it is really the lowest density USP!

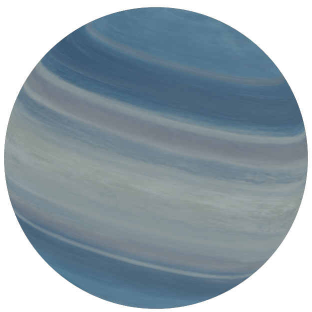
# The TOI-561 system

## USP planets

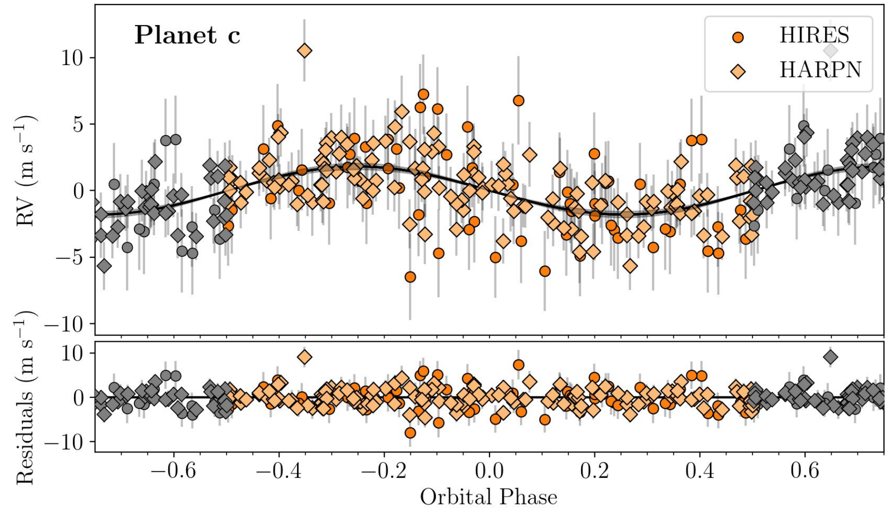


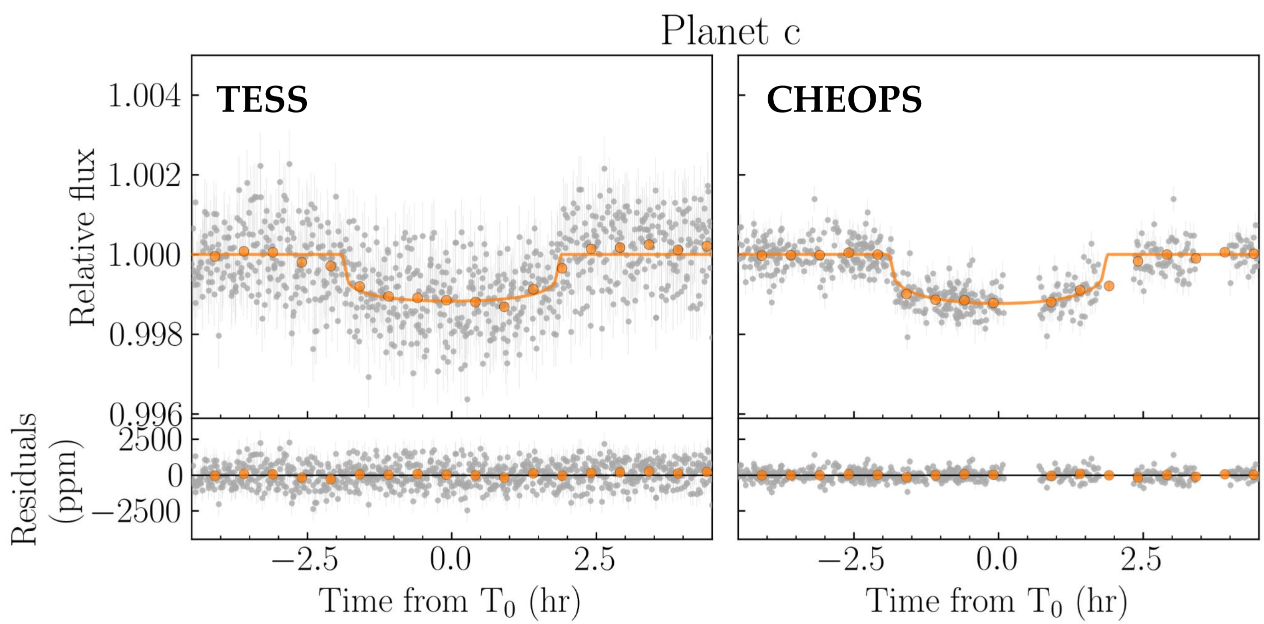
# The TOI-561 system
## Planetary properties

**TOI-561 c**



| | |
|---|---|
| Period | 10.778831 d |
| Radius | 2.91 ± 0.04 $R_\oplus$ **(1.8%)** |
| Mass | 5.39 ± 0.69 $M_\oplus$ **(12.8%)** |
| Density | 1.2 ± 0.2 g cm$^{-3}$ |

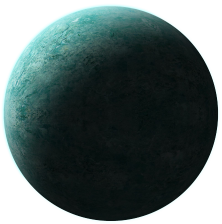


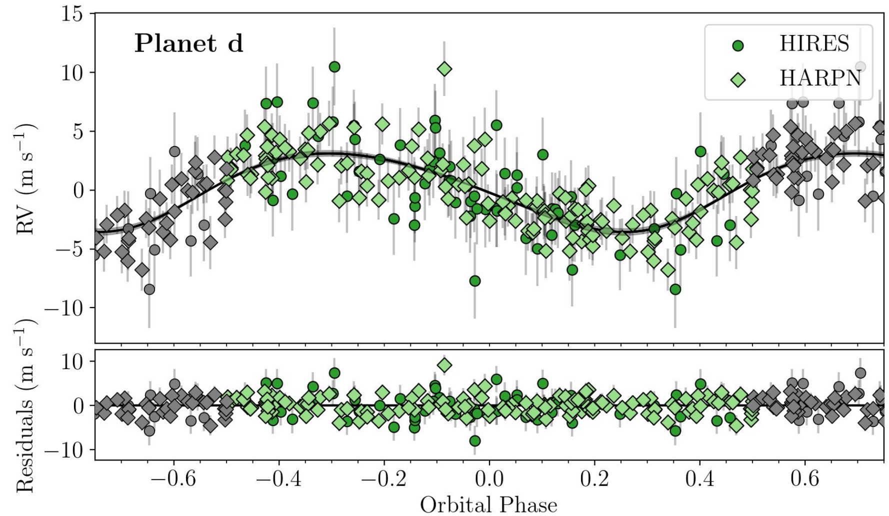
# The TOI-561 system

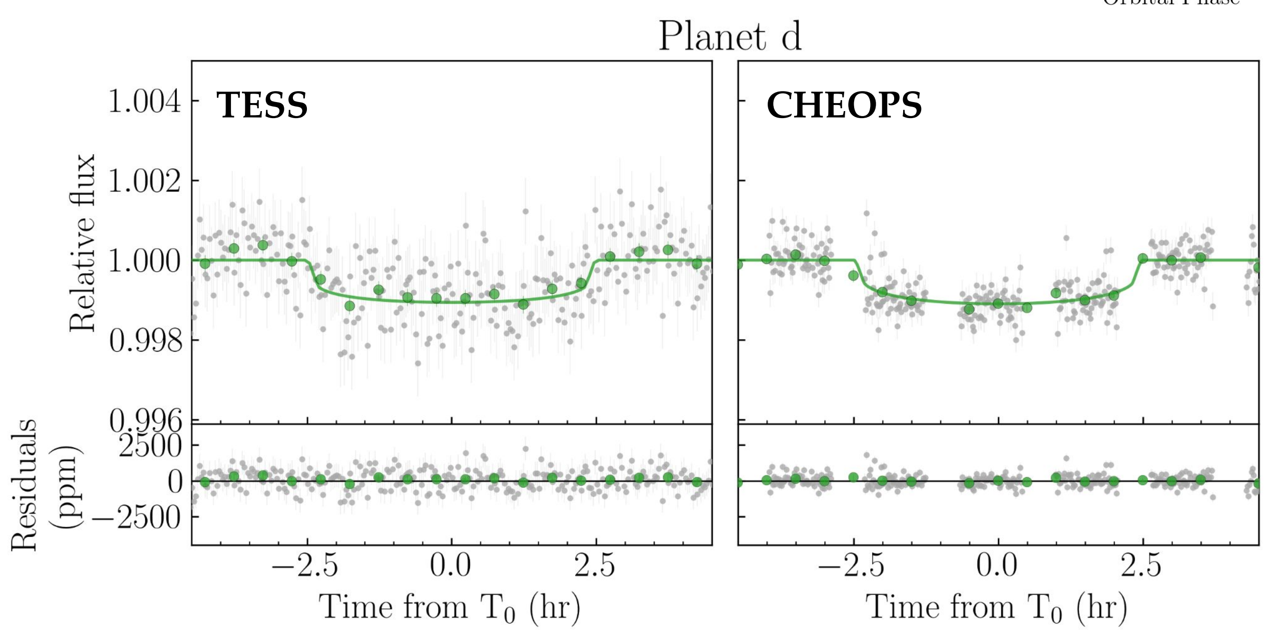
## Planetary properties

**TOI-561 d**



| Period | 25.7124 d |
|---|---|
| Radius | 2.82 ± 0.07 $R_\oplus$ **(2.5%)** |
| Mass | 13.2 ± 1.0 $M_\oplus$ **(7.6%)** |
| Density | 3.2 ± 0.3 g cm$^{-3}$ |

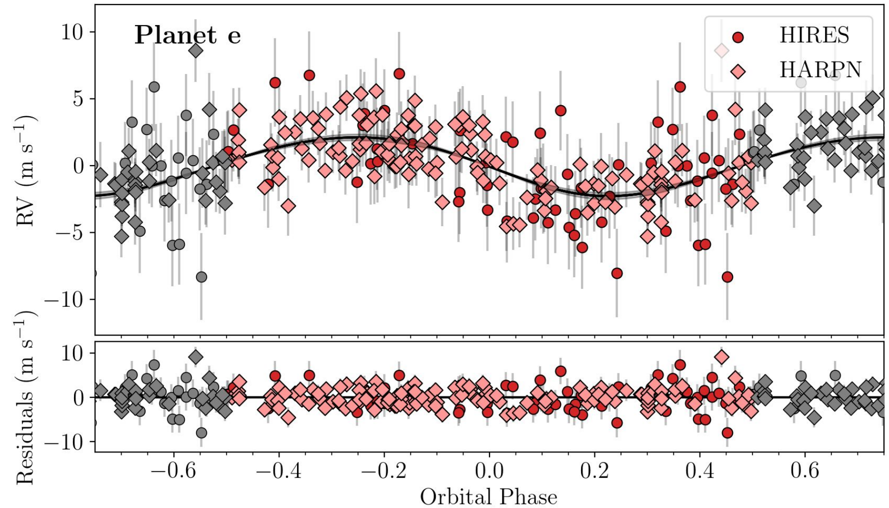


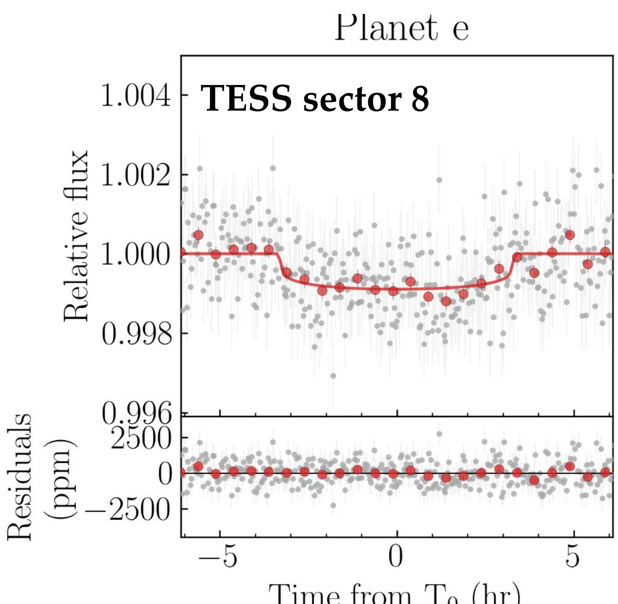



# The TOI-561 system
## Planetary properties

**TOI-561 e**

| | |
|---|---|
| Period | 77.03 d |
| Radius | $2.55 \pm 0.13\ R_\oplus$ (**5.1%**) |
| Mass | $12.6 \pm 1.4\ M_\oplus$ (**11.1%**) |
| Density | $4.2 \pm 0.8$ g cm$^{-3}$ |



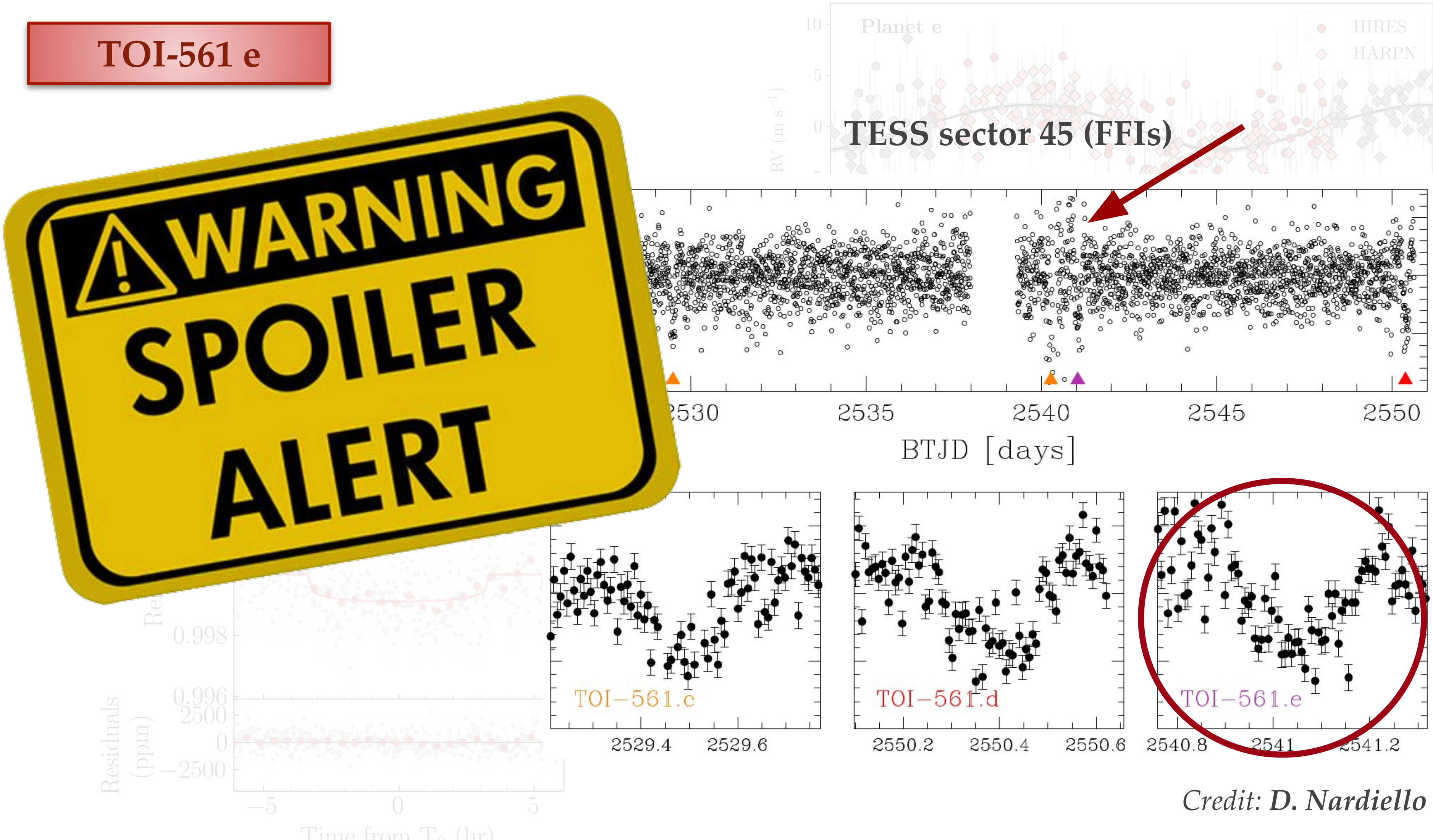




No CHEOPS observations
(**yet… But scheduled for the 2022 observing season!**)

↓

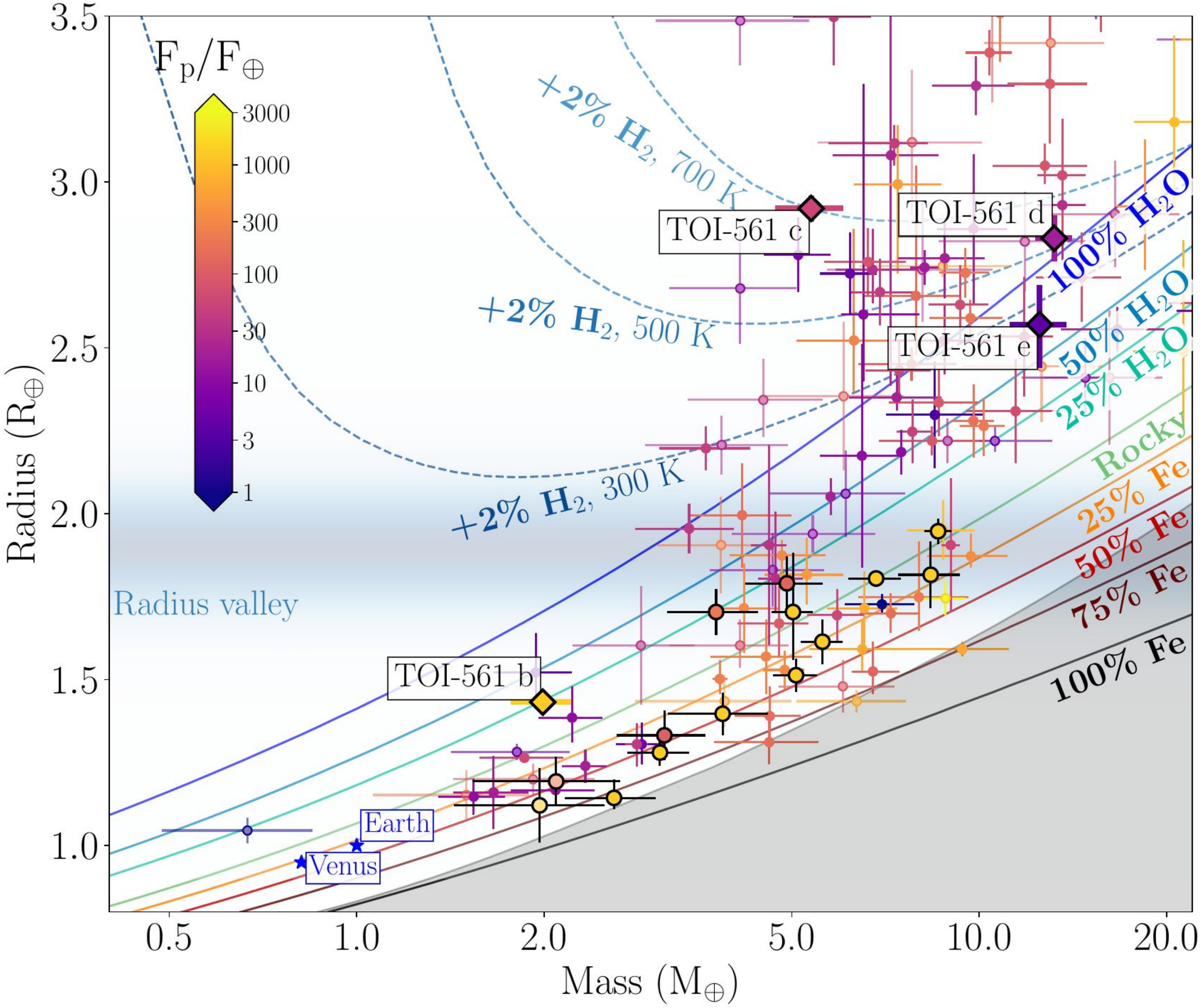
Lower radius precision

# The TOI-561 system
## Planetary properties




*Credit:* ***D. Nardiello***

# The TOI-561 system
## Mass-radius diagram



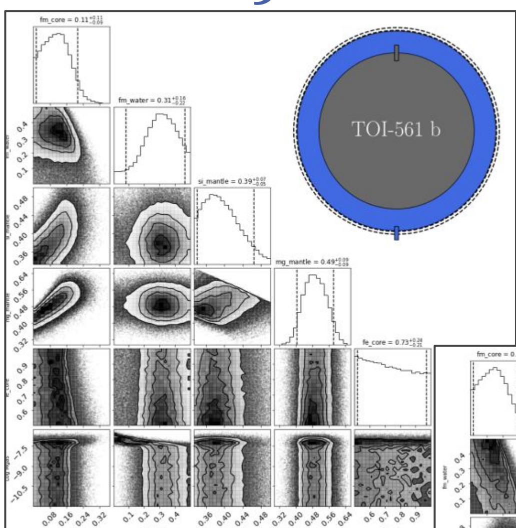
# The TOI-561 system
## Internal structure modelling

Bayesian approach assuming a fully-differentiated 4-layers model:

**[Core + Mantle] + Water layer + H/He envelope**

*Work by Y. Alibert*

### TOI-561 b

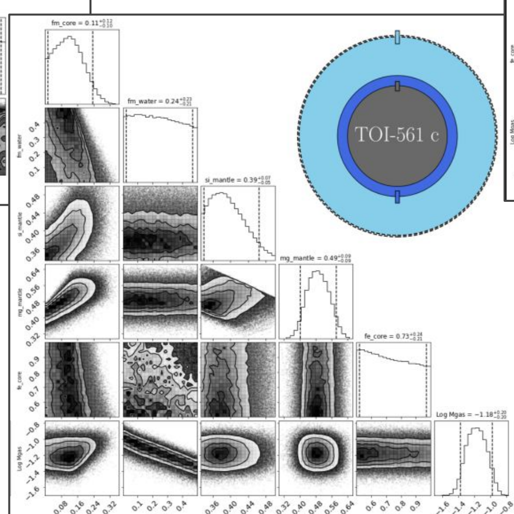



$M_{H_2O} = 31^{+16}_{-22}$ wt%

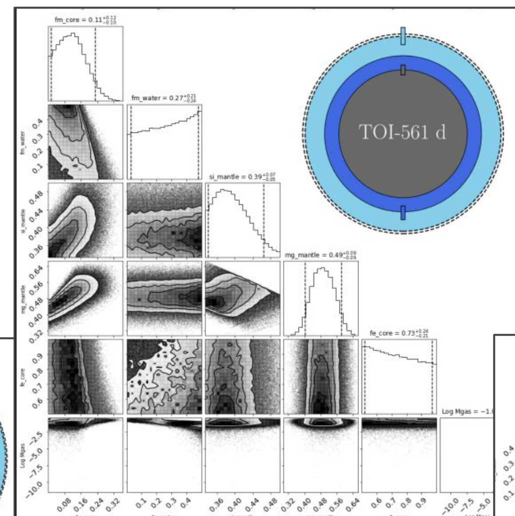
### TOI-561 c

$M_{gas} = 1.3^{+0.8}_{-0.4}$ wt%

$M_{H_2O} = 24^{+23}_{-21}$ wt%




### TOI-561 d



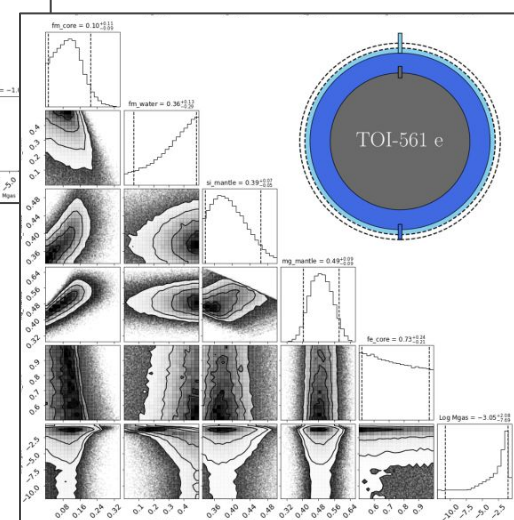

$M_{gas} = 0.8^{+1.0}_{-0.5}$ wt%

$M_{H_2O} = 27^{+21}_{-24}$ wt%

### TOI-561 e

$M_{gas} < 0.9$ wt%

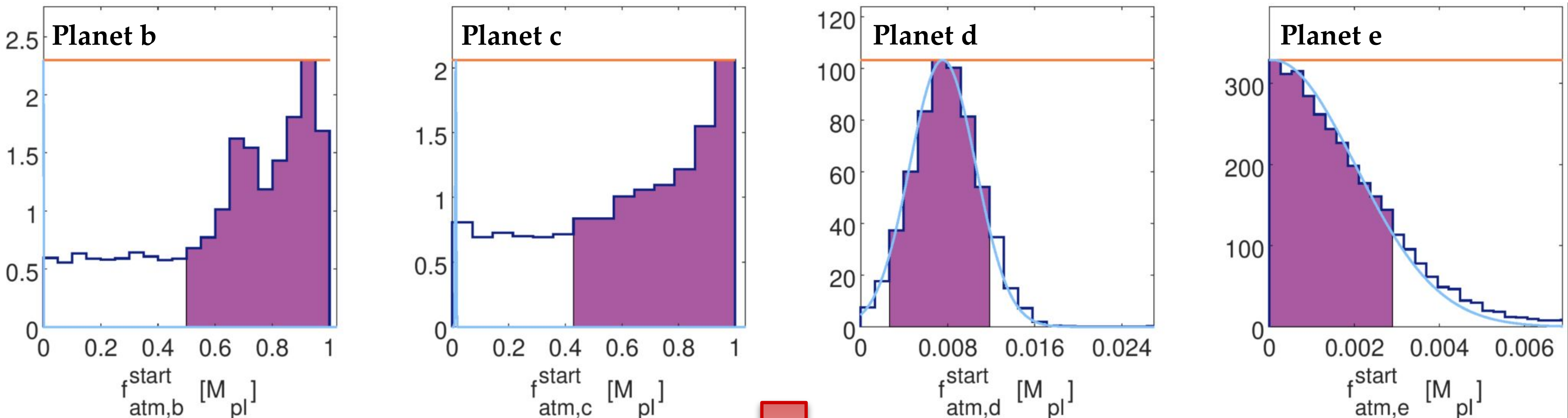
$M_{H_2O} = 36^{+13}_{-29}$ wt%



# The TOI-561 system
## Atmospheric evolution modelling

Bayesian approach (PASTA code, Bonfanti at al. 2021) to compute the atmospheric content at the dispersal of the protoplanetary disk:

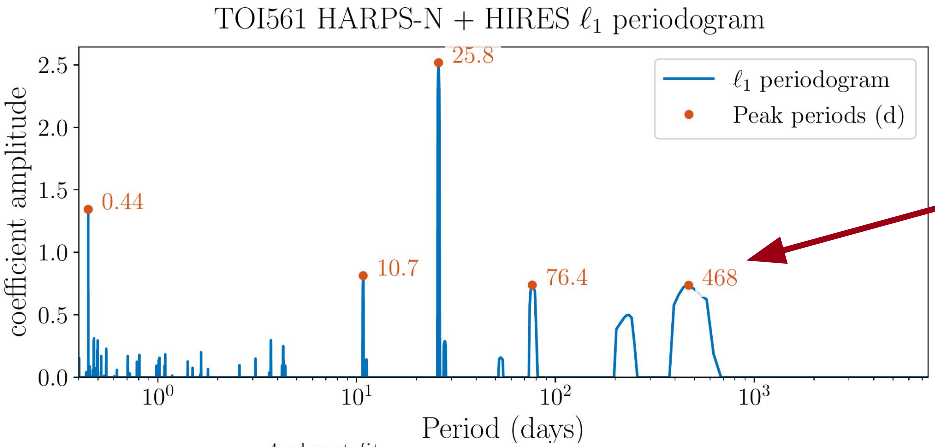
*Work by A. Bonfanti & L. Fossati*



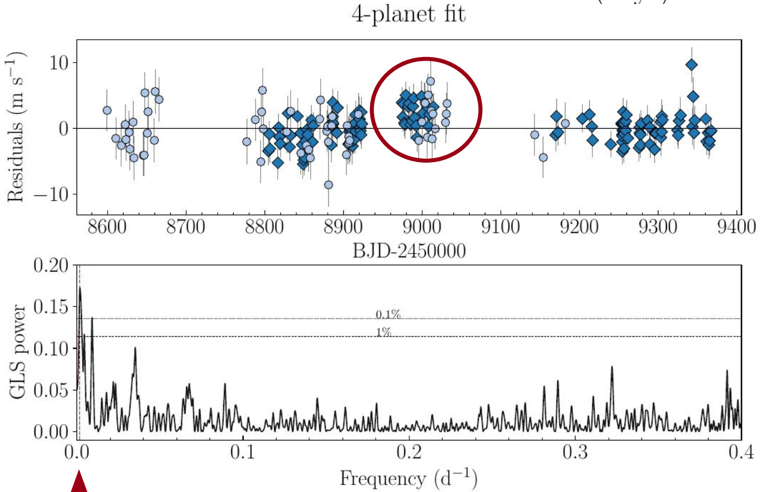

Planets b and c underwent strong envelope loss, while planets d and e did not experience strong atmospheric escape

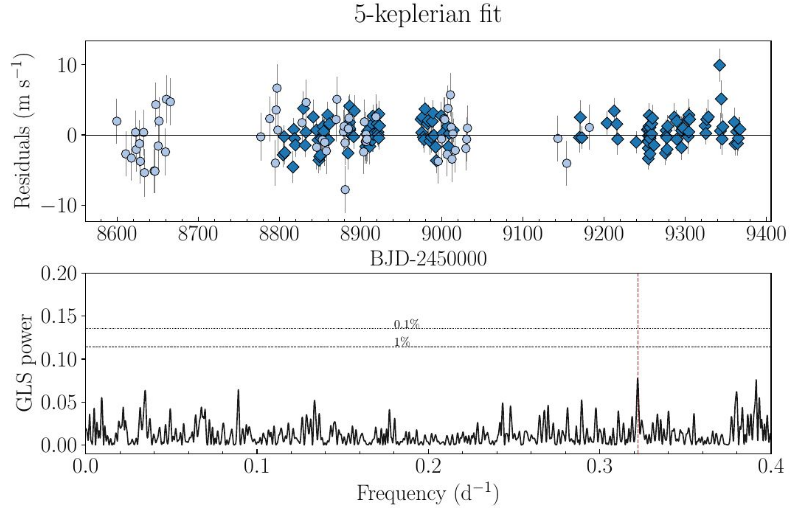
# The TOI-561 system

## An additional signal




Clear detection of the **4 planetary signals** + an additional, broad long-period peak




5-keplerian model strongly favoured by Bayesian Evidence ($\Delta \ln Z = 19$)

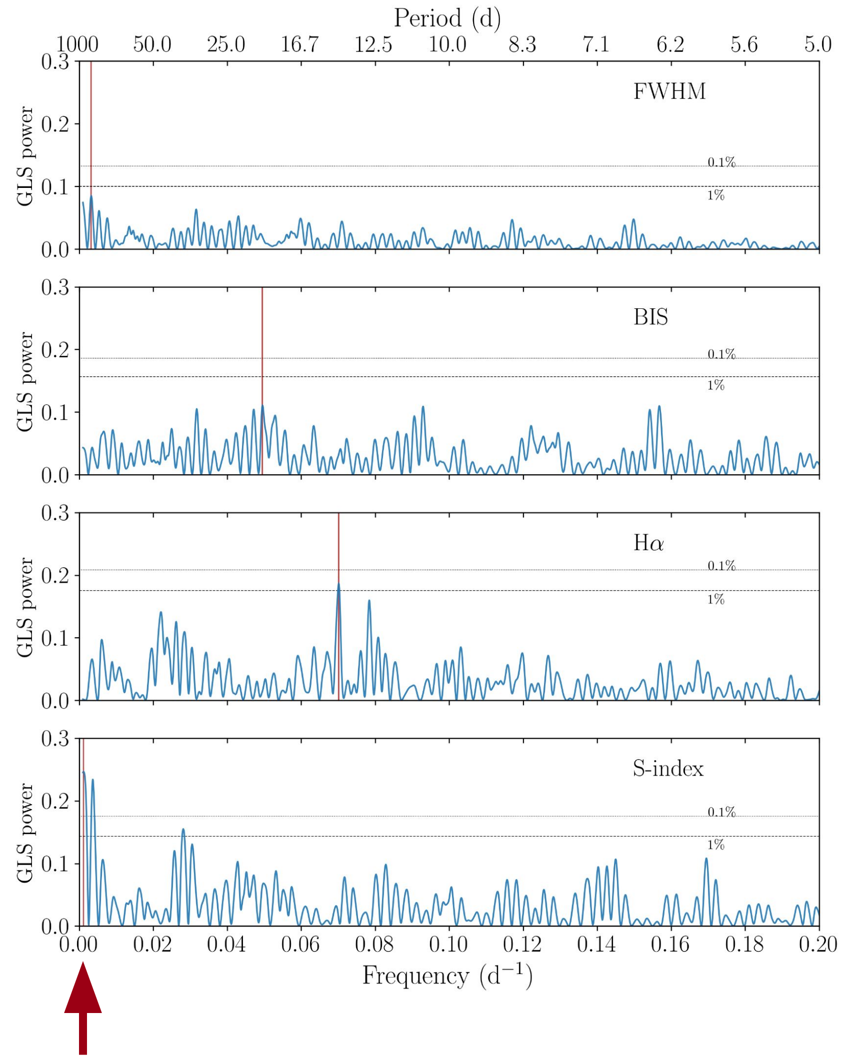
# The TOI-561 system
## An additional signal

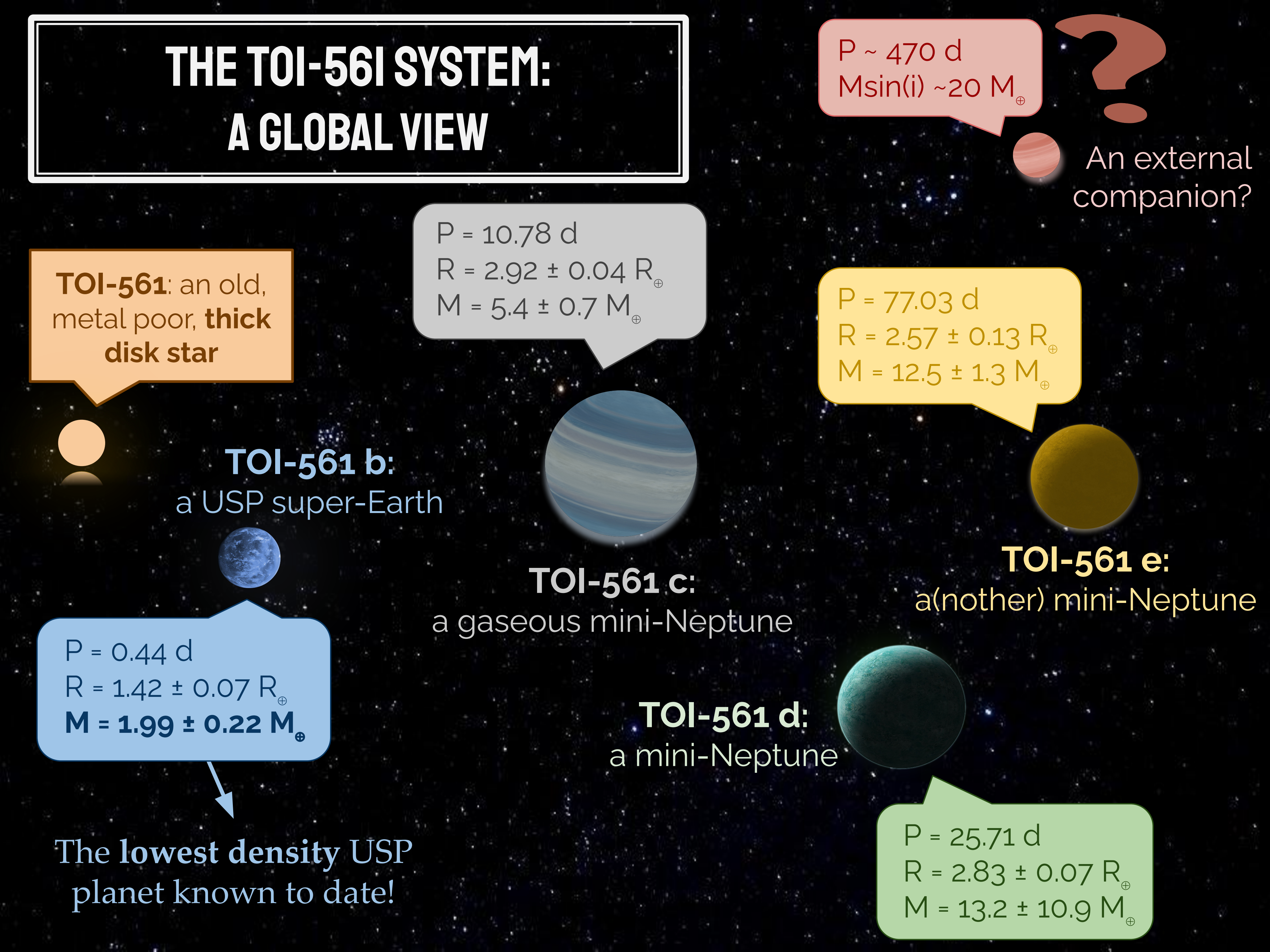
### What is it?

- ➢ $P_5$ = 473 [-25, +36] d
- ➢ $K_5 = 1.94 \pm 0.27$ m $s^{-1}$
- ➢ **Stellar** origin ⇒ magnetic fields (S-index low-frequency peak)
- ➢ **Planetary** origin ⇒ Found in SCALPELS independent analysis (not a CCF shape-driven signal)

5-keplerian fit, with the 5th keplerian both compliant with a planetary companion or a stellar signal

Activity indices periodograms




THE TOI-561 SYSTEM:
A GLOBAL VIEW
P ~ 470 d
Msin(i) ~20 M⊕
An external companion?
TOI-561: an old, metal poor, thick disk star
P = 10.78 d
R = 2.92 ± 0.04 R⊕
M = 5.4 ± 0.7 M⊕
P = 77.03 d
R = 2.57 ± 0.13 R⊕
M = 12.5 ± 1.3 M⊕
TOI-561 b:
a USP super-Earth
TOI-561 c:
a gaseous mini-Neptune
TOI-561 e:
a(nother) mini-Neptune
P = 0.44 d
R = 1.42 ± 0.07 R⊕
M = 1.99 ± 0.22 M⊕
TOI-561 d:
a mini-Neptune
P = 25.71 d
R = 2.83 ± 0.07 R⊕
M = 13.2 ± 10.9 M⊕
The lowest density USP planet known to date!