Osservatorio Astronomico di Brera INAF

Astro Flt 2 Astronomy Fellowships in Italy

AstroFlt2 Meeting, Roma, October 15th 2019

THE CHARACTERIZATION OF EXOPLANETARY SYSTEMS

From stellar to planetary parameters

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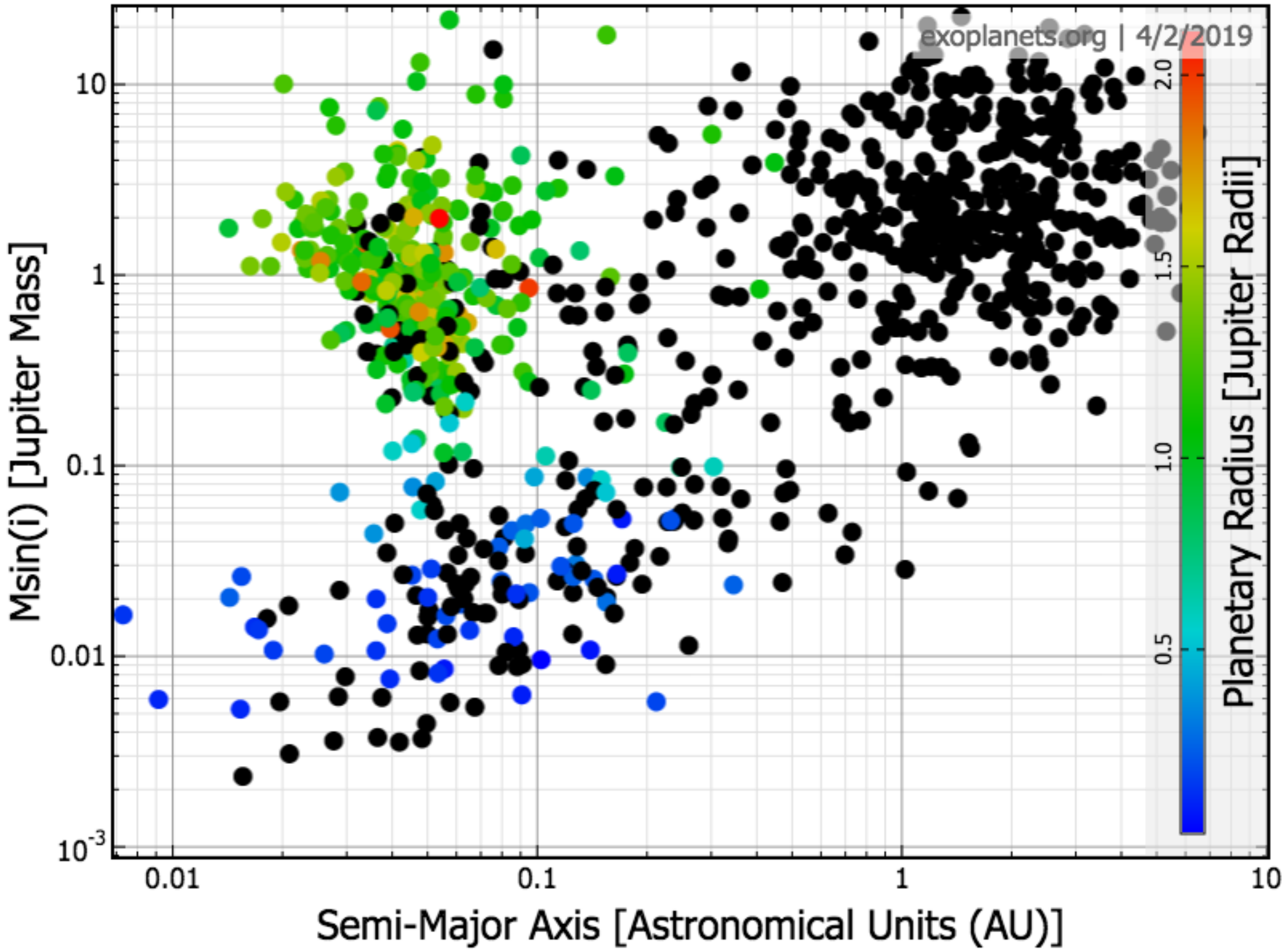
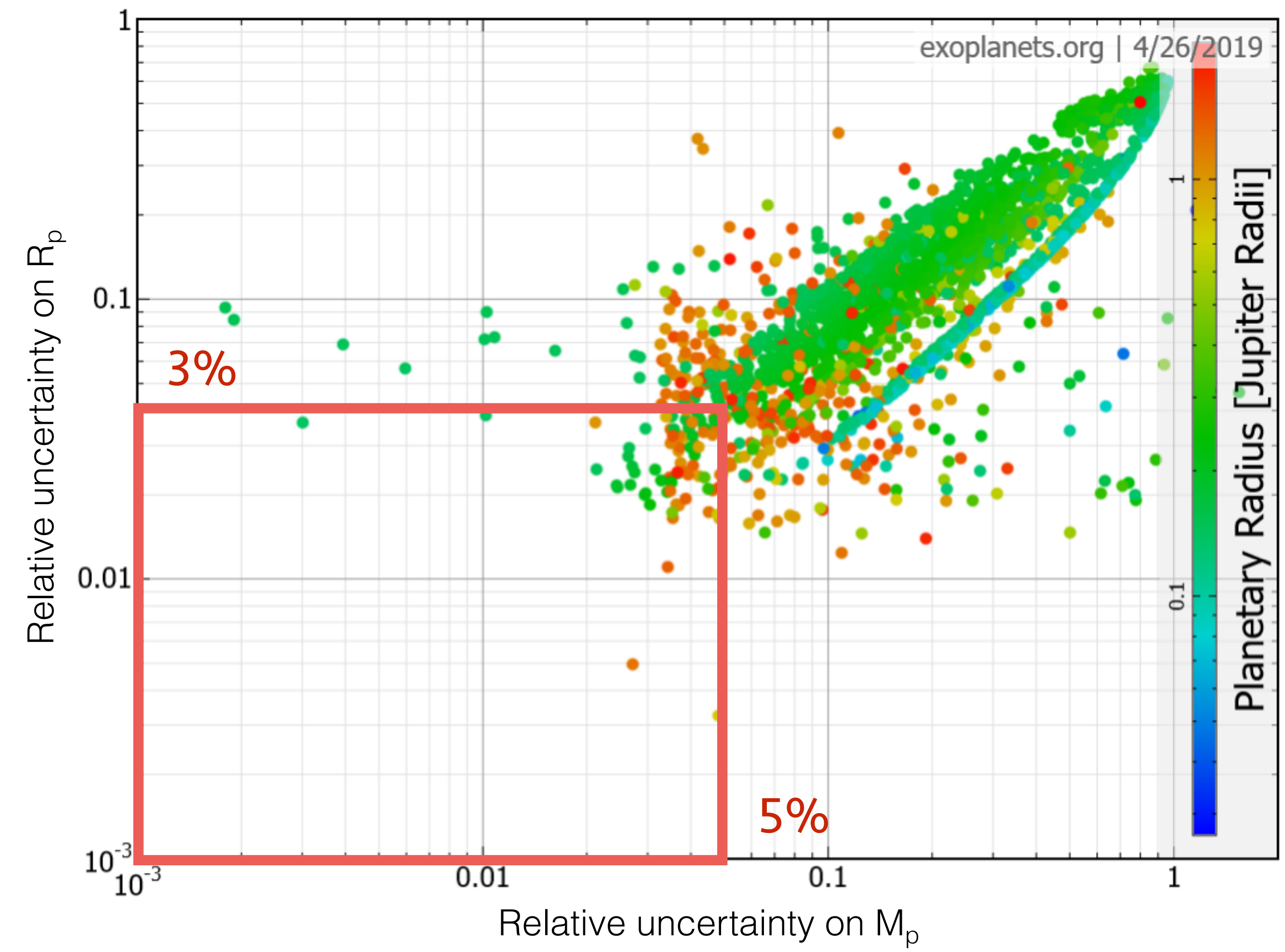
This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement n. 664931

INTRODUCTION





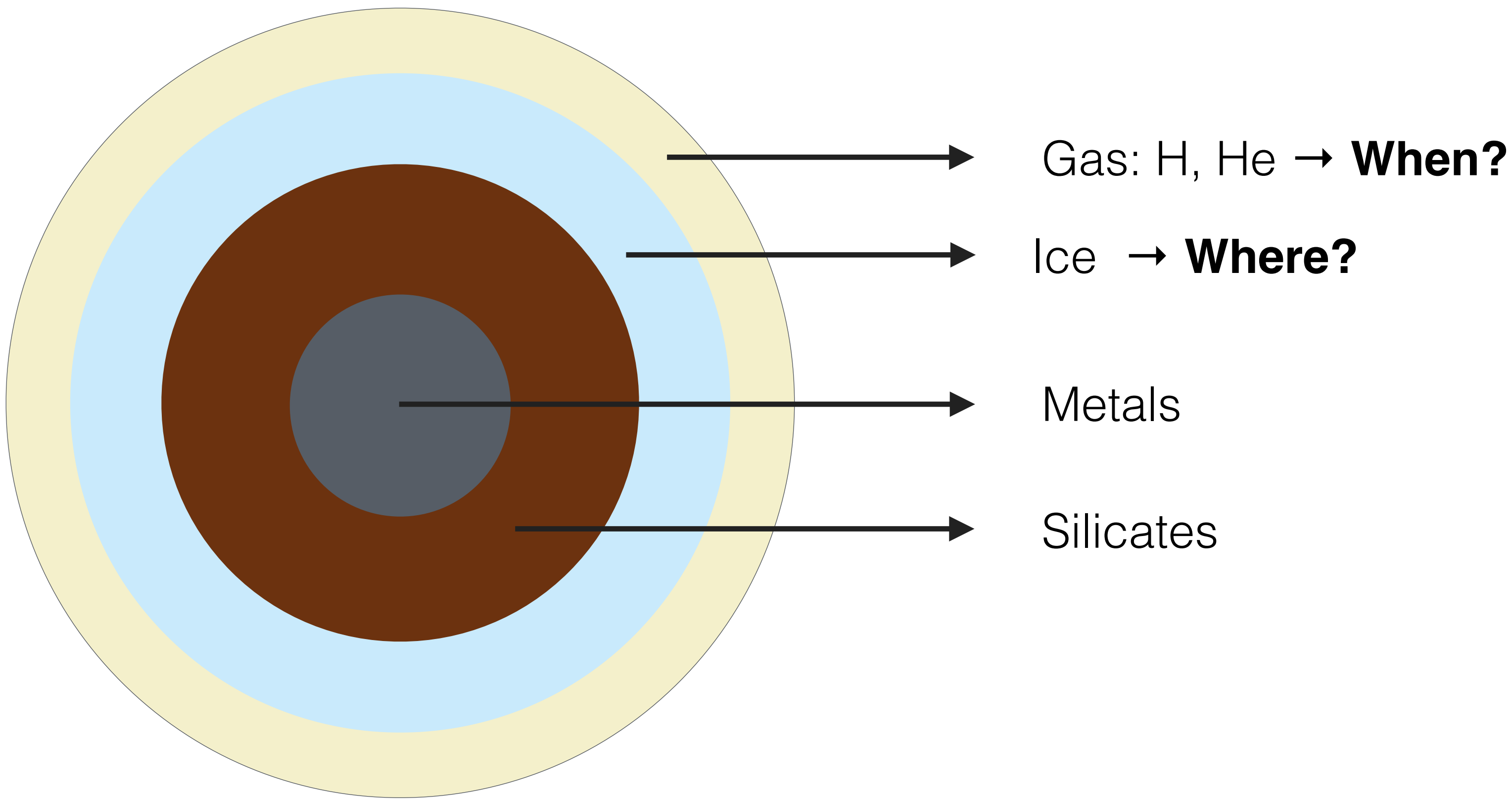
More than 4000 exoplanets known
→ revolution for planet formation theories
→ search for other habitable (habited) worlds.

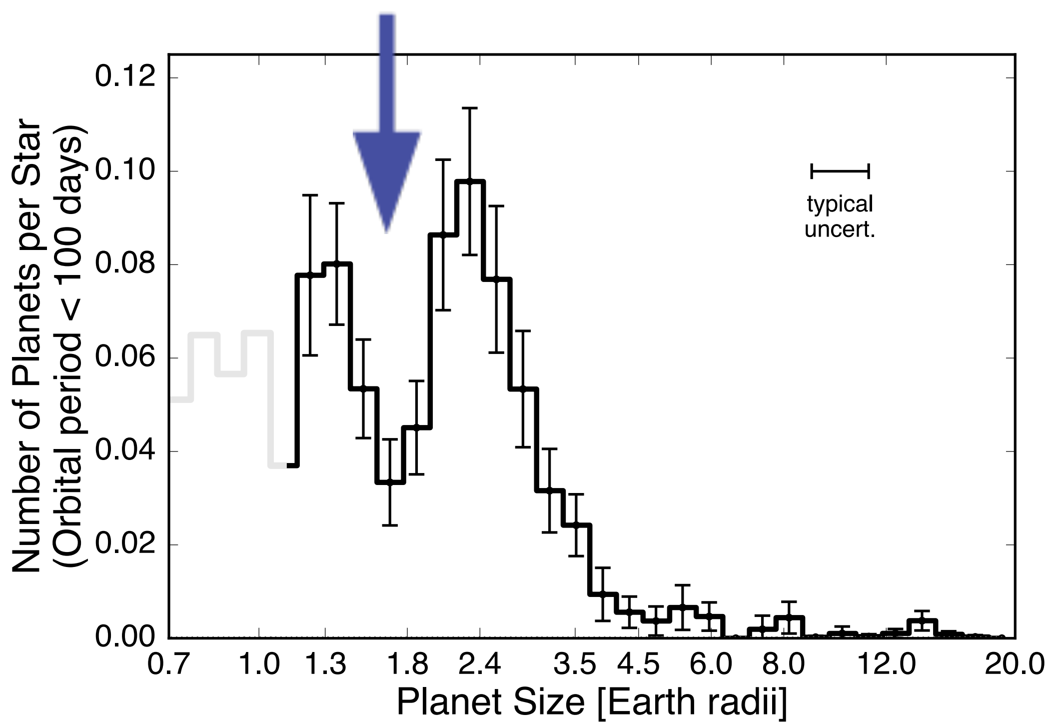
Relative uncertainty on planetary parameters (mass & radius) generally huge.
→ difficulty in characterizing the exoplanets.

INTRODUCTION

Formation?
Habitability? →
Diversity?

Need 3-5% precision on M_p and R_p to infer the internal structure of a planet, and thus constrain its nature and origin.





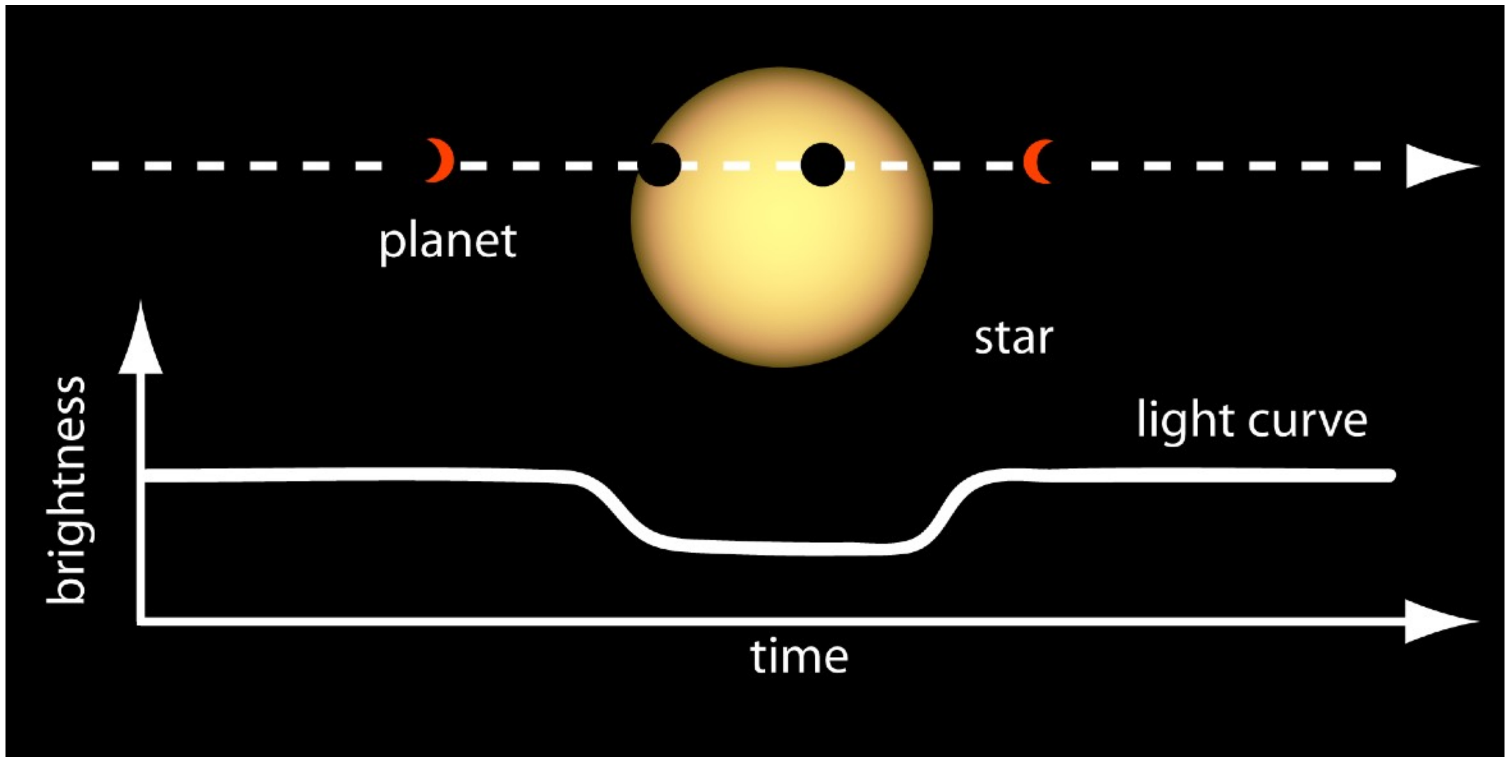
Fulton et al. (2017)

Dorn et al. (2015)
Valencia et al. (2007)
CHEOPS Redbook
PLATO Science Managment Plan (2017)

Ex: The « evaporation valley » or « Fulton gap » observed in the distribution of planetary radii.
→ Super-Earths ≠ Mini-Neptunes ?

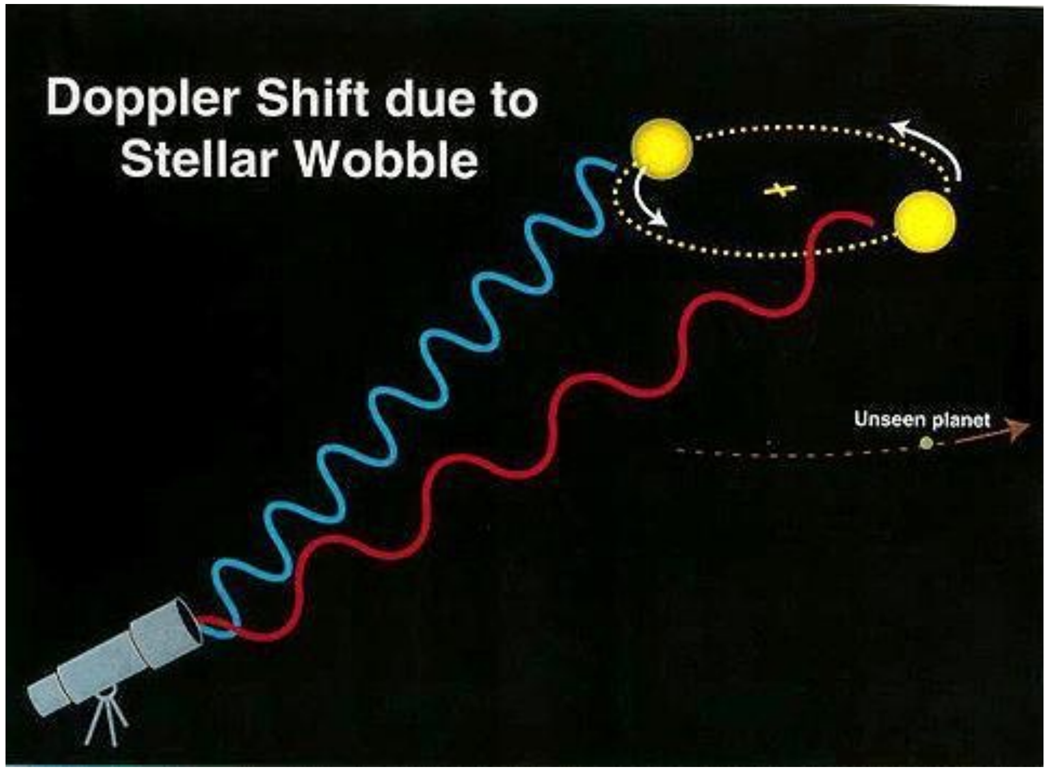
INTRODUCTION

Transit method



$$\frac{\Delta F}{F} = \left(\frac{R_P}{R_\star}\right)^2$$

Radial velocity measurements



$$\frac{(m_p \sin i)^3}{(M_\star + m_p)^2} = \frac{P}{2\pi G} K^3 (1-e)^{3/2}$$

→ R_p and M_p depend critically on **$R_\star$** and **$M_\star$**

In many cases, these ratios are better known than the stellar parameters. Often, the stellar mass and radius are derived through stellar evolution models.
→Precise, but questionable accuracy (see later)...

OUTLINE

0. Use existing transit and radial velocity data.

I. Stellar diameters with interferometry

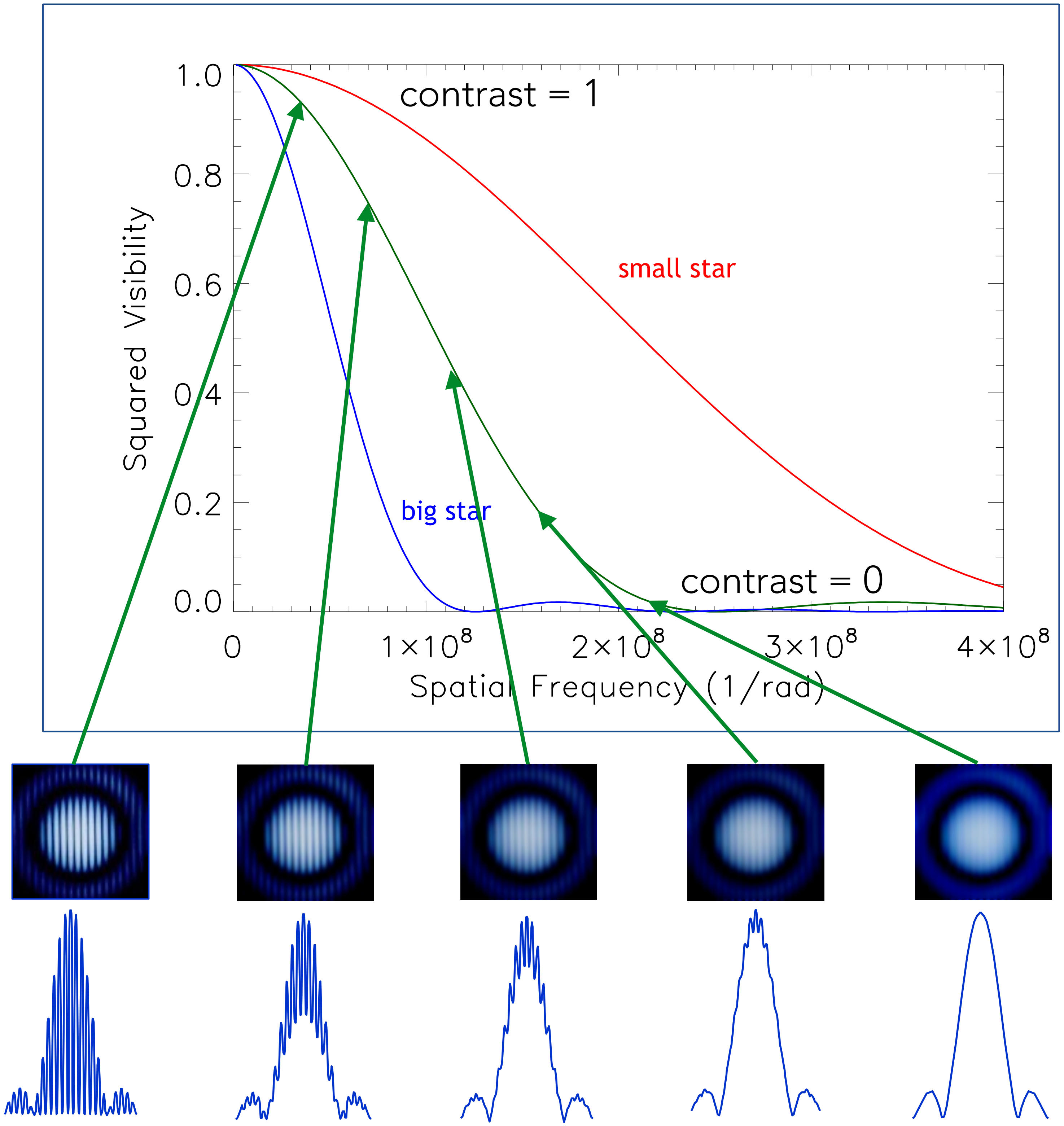
II. Stellar density from the transit light-curve

III. Probability Density Function of $R_\star$ and $M_\star$, independently of stellar models

IV. Exoplanetary radius and mass R_p and M_p , and planetary properties

V. Conclusions and perspectives

I. INTERFEROMETRY: PRINCIPLES



Observation of a star with 2 or more telescopes, and combine the light from the two apertures
→ interference fringes.

Point source → contrast = 1 (Young).

Extended source → several fringe patterns which don't overlap exactly → contrast < 1, depends on telescope separation (baseline).

⟹ Measuring the contrast gives directly the angular diameter of the star, θ.

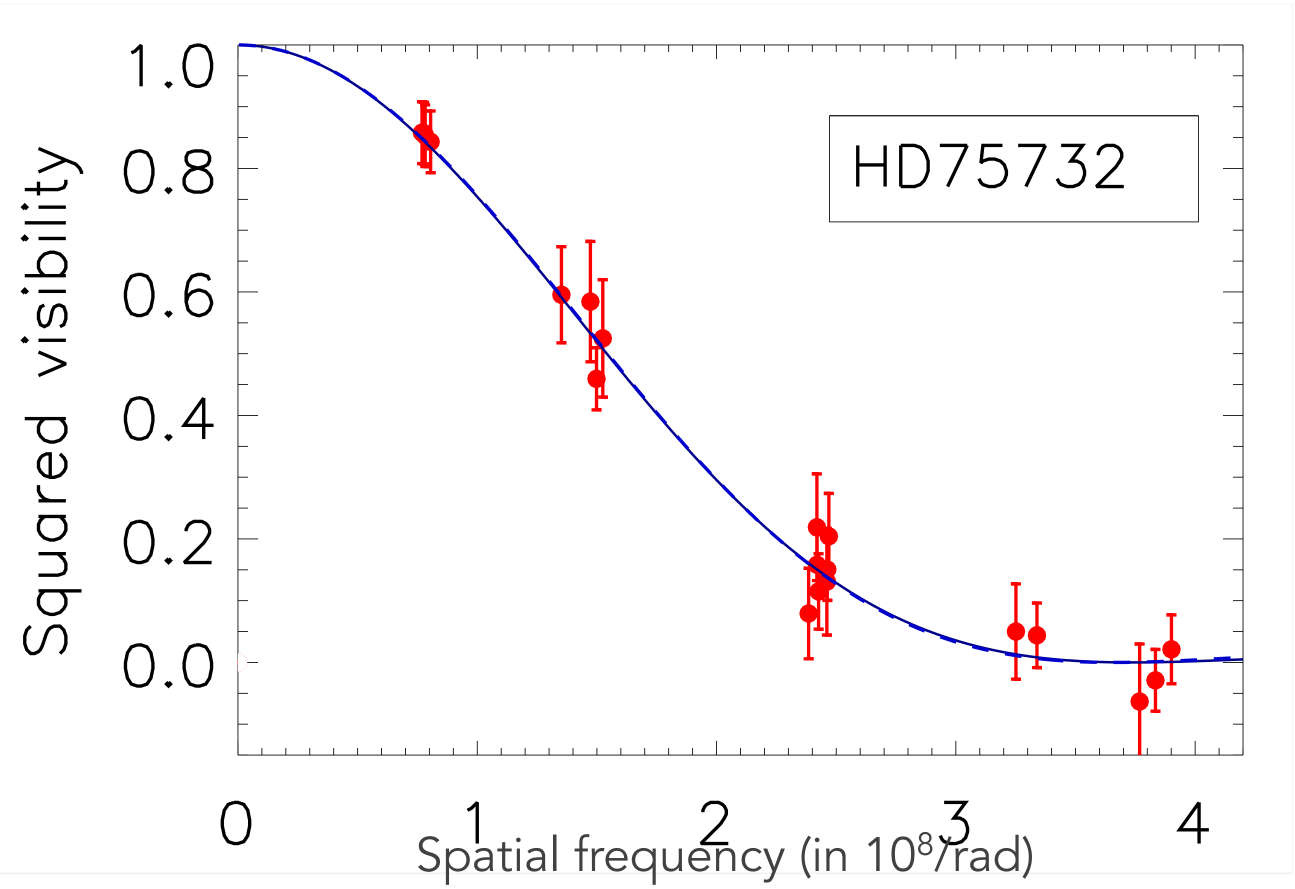
Stellar radius: $R_\star = \theta/2\pi$. (π = parallax)

Probability Density Function f :

$$f_{R_\star}(R) = \frac{R_0}{R^2} \int_0^\infty t\, f_\pi\left(\frac{R_0\, t}{R}\right) f_\theta(t)\, \mathrm{d}t$$

I. INTERFEROMETRY: RESULTS

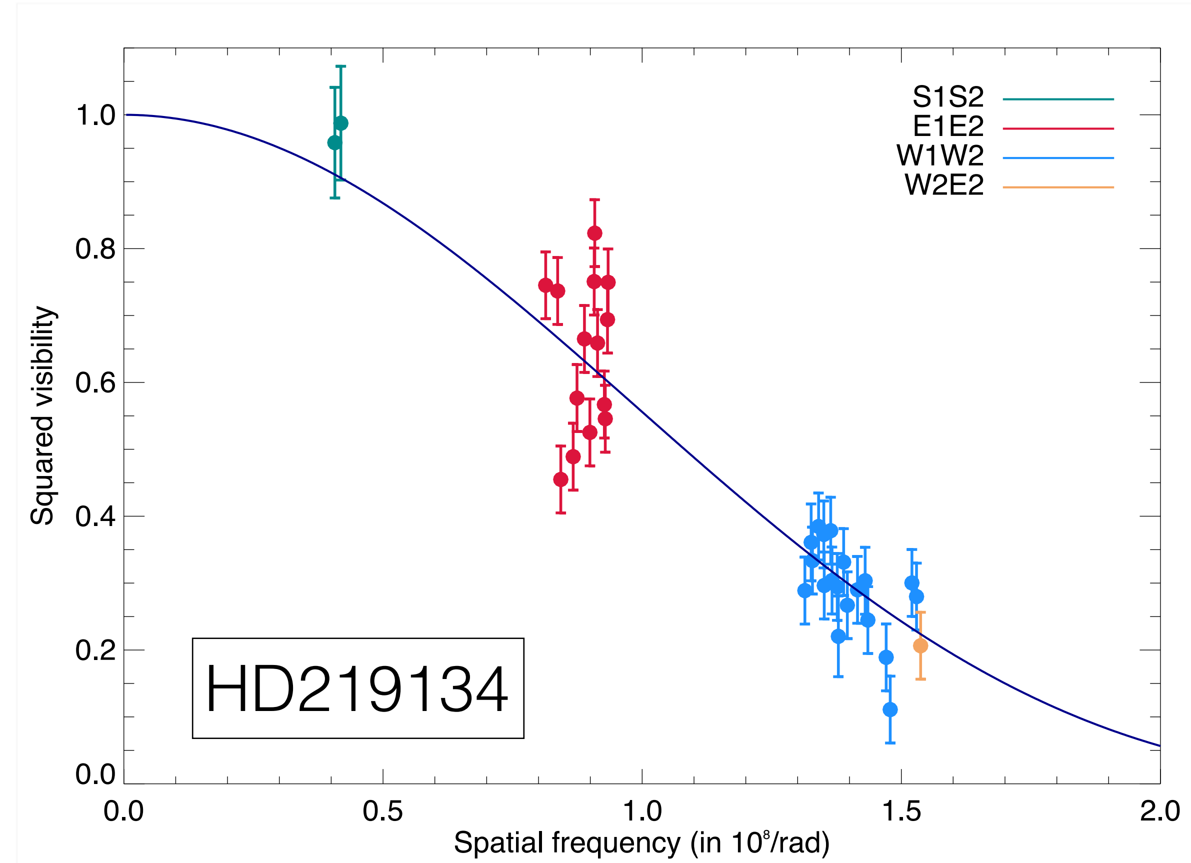
Angular diameter measured with the VEGA/CHARA interferometer, for two stars hosting transiting exoplanets: 55 Cnc and HD219134.



Ligi et al. (2016)

$\theta = 0.724 \pm 0.012$ mas

$R_\star = 0.960 \pm 0.018\ R_\odot$



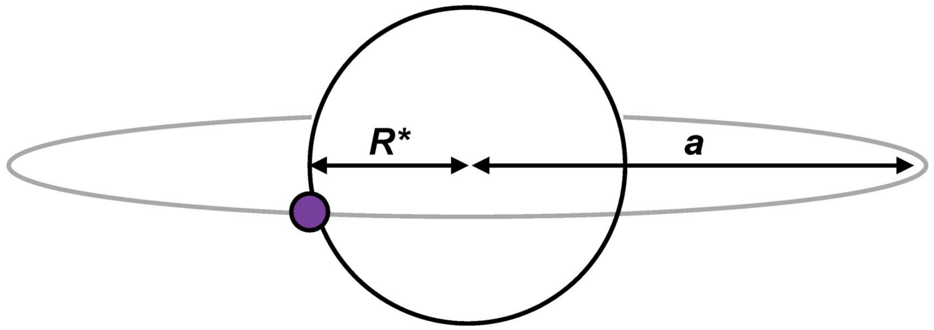
Ligi et al. (2019)

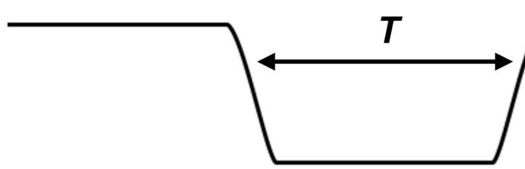
$\theta = 1.035 \pm 0.021$ mas

$R_\star = 0.726 \pm 0.014\ R_\odot$

II. STELLAR DENSITY

Transit duration





$$T = \underbrace{\frac{2R_*}{(2\pi a/P)}}_{\lim e \to 0}$$

3rd Kepler law

$$\frac{P^2}{4\pi^2} = \frac{a^3}{G\,(M_* + M_p)} \simeq \frac{a^3}{GM_*}$$

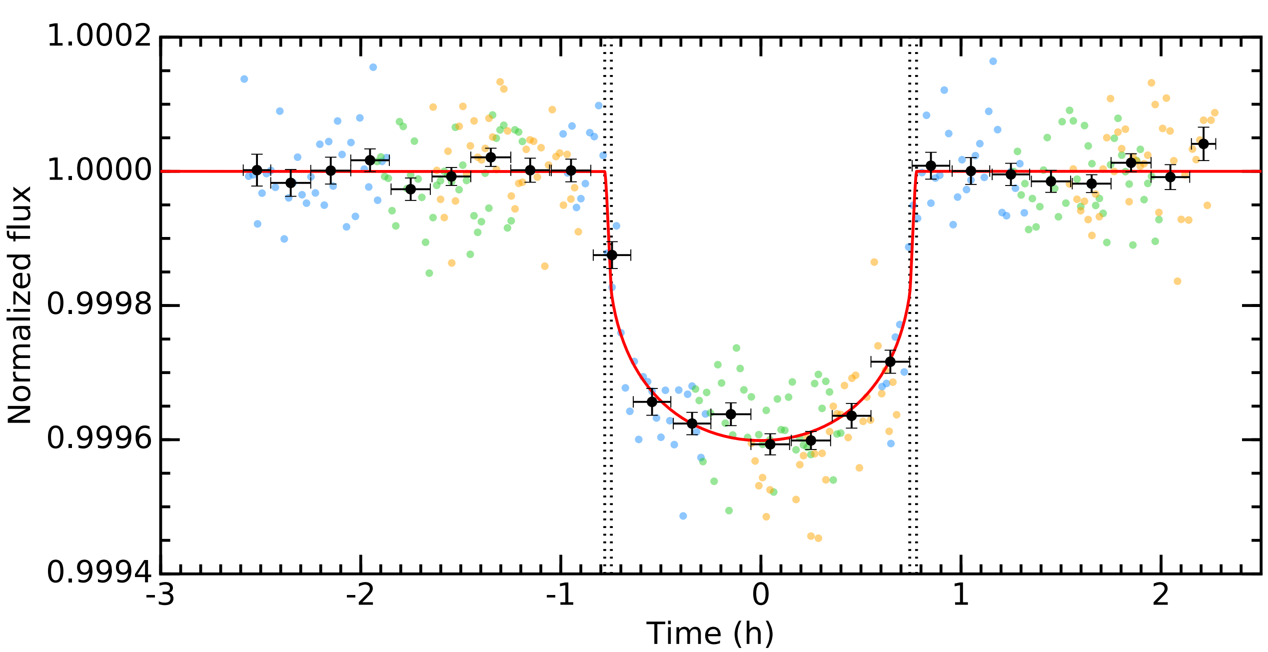
$$\rightarrow P/T^3 = (\pi^2 G/3)\ \rho_\star$$

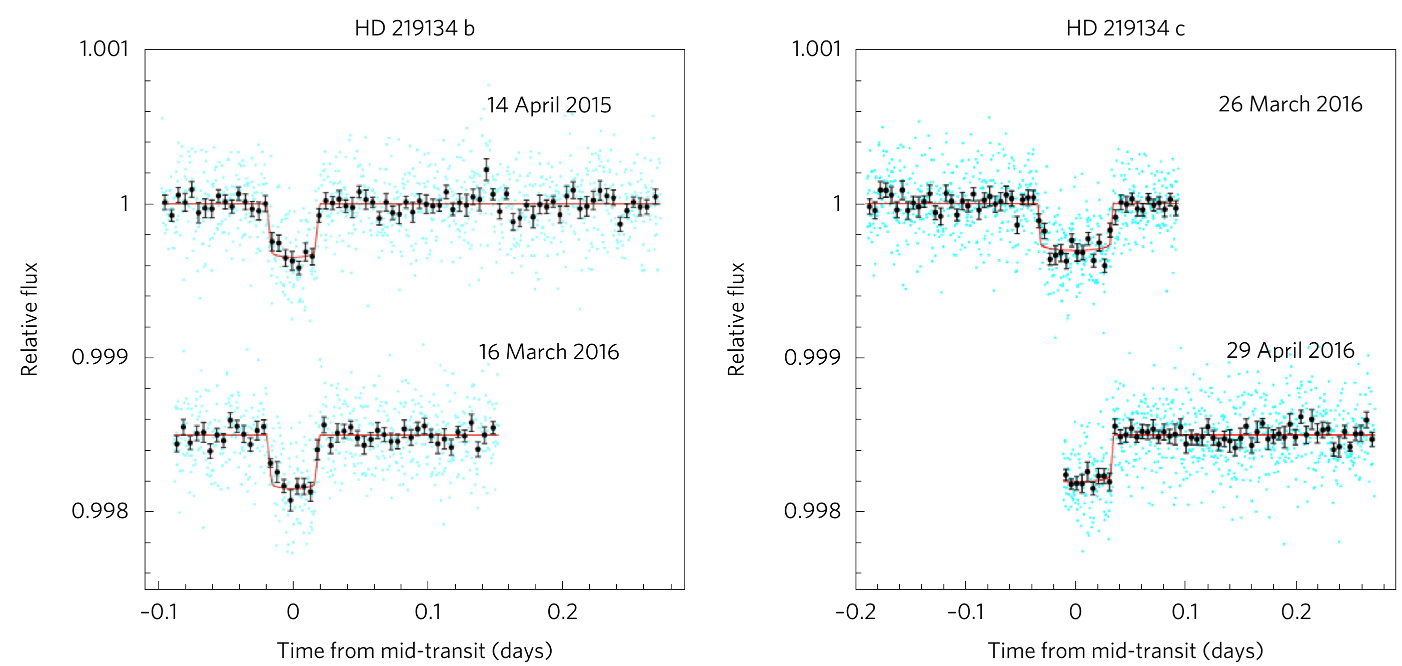
(Seager & Mallén-Ornelas 2003)

A fine transit light-curve allows to *measure* the density of the host star!

55 Cnc: $\rho_\star = 1.079 \pm 0.005\ \rho_\odot$ (Crida, Ligi et al. 2018)

HD219134: $\rho_\star = 1.82 \pm 0.19\ \rho_\odot$ (Ligi et al. 2019)





Bourrier et al. (2018)

Gillon et al. (2017)

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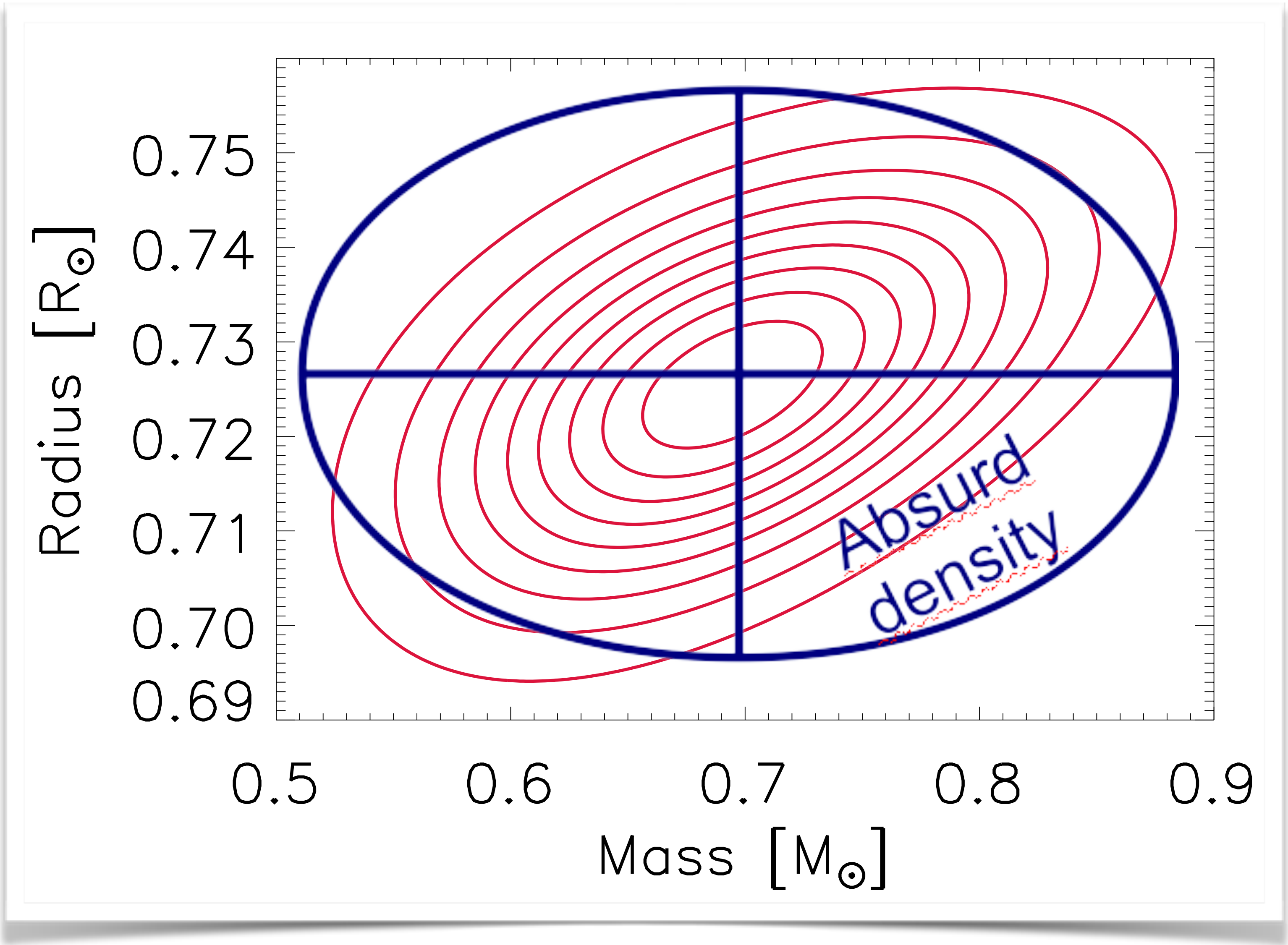
III. STELLAR MASS AND RADIUS

$$M_\star = (4\pi/3) R_\star^3 \rho_\star \quad \rightarrow \quad \mathcal{L}_{MR\star}(M,R) = \frac{3}{4\pi R^3} \times f_{R_\star}(R) \times f_{\rho_\star}\left(\frac{3M}{4\pi R^3}\right)$$

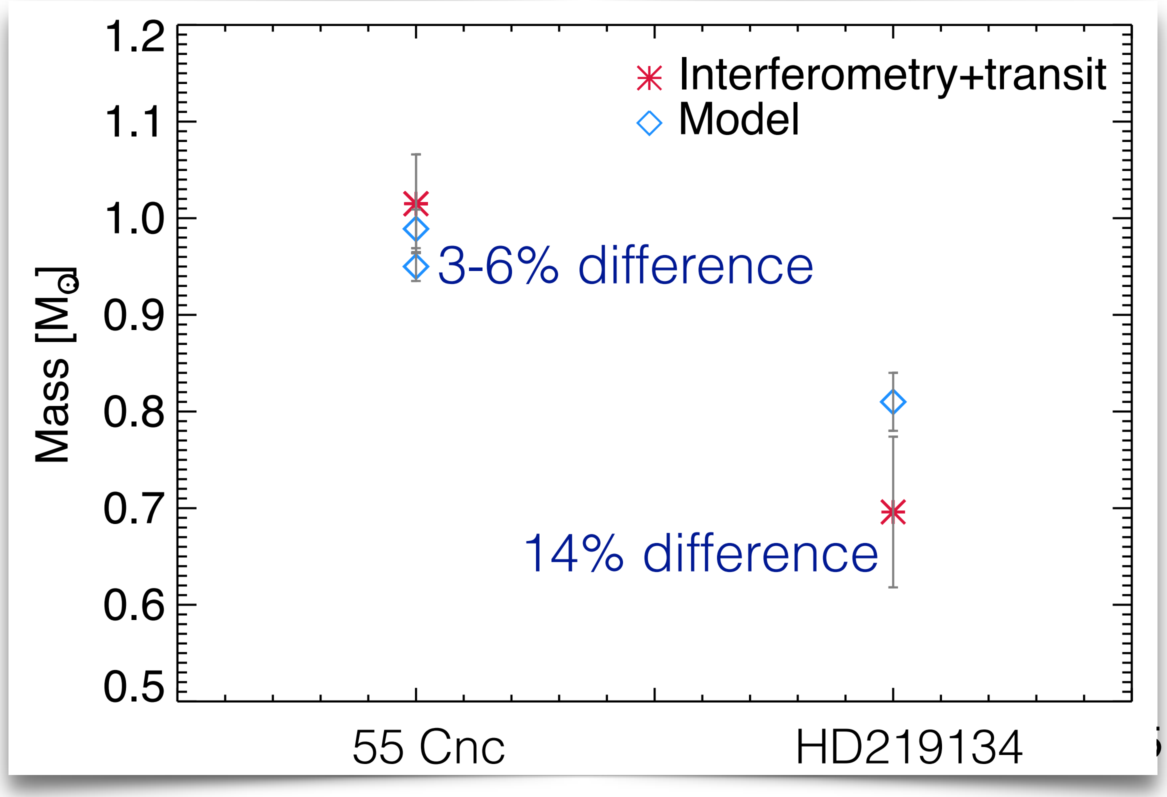
$M_\star$ being an explicit function of $R_\star$, they are not independent, but correlated.

Ex: HD219134: level curves of the joint PDF.
Correlation ($M_\star$ - $R_\star$) = 0.46



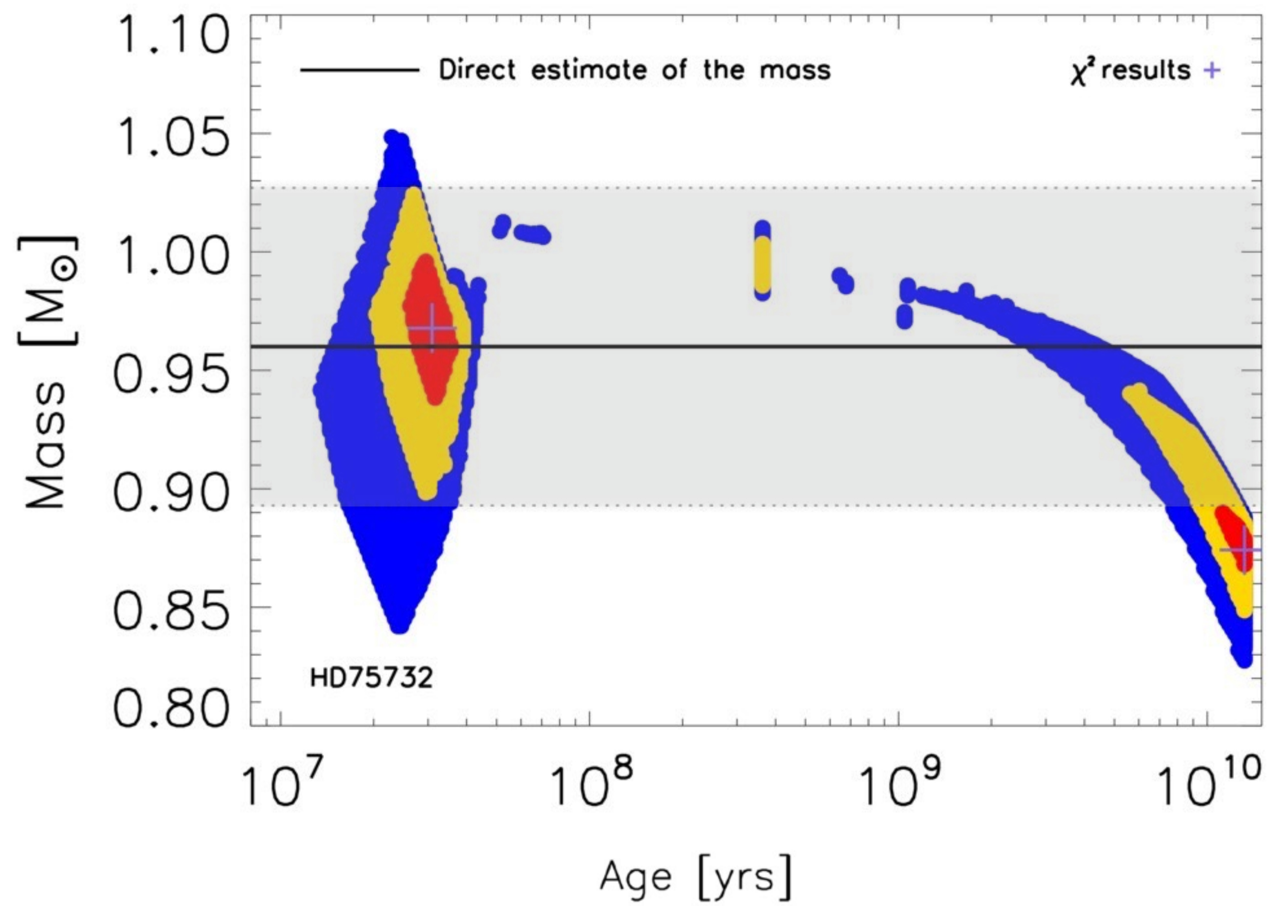
Ligi et al. (2019)

III. STELLAR MASS AND RADIUS



Comparison with Stellar models:

Provide a small error bar = internal error of the model.



We measure: $M_\star = 1.015 \pm 0.051\ M_\odot$

For 55 Cnc

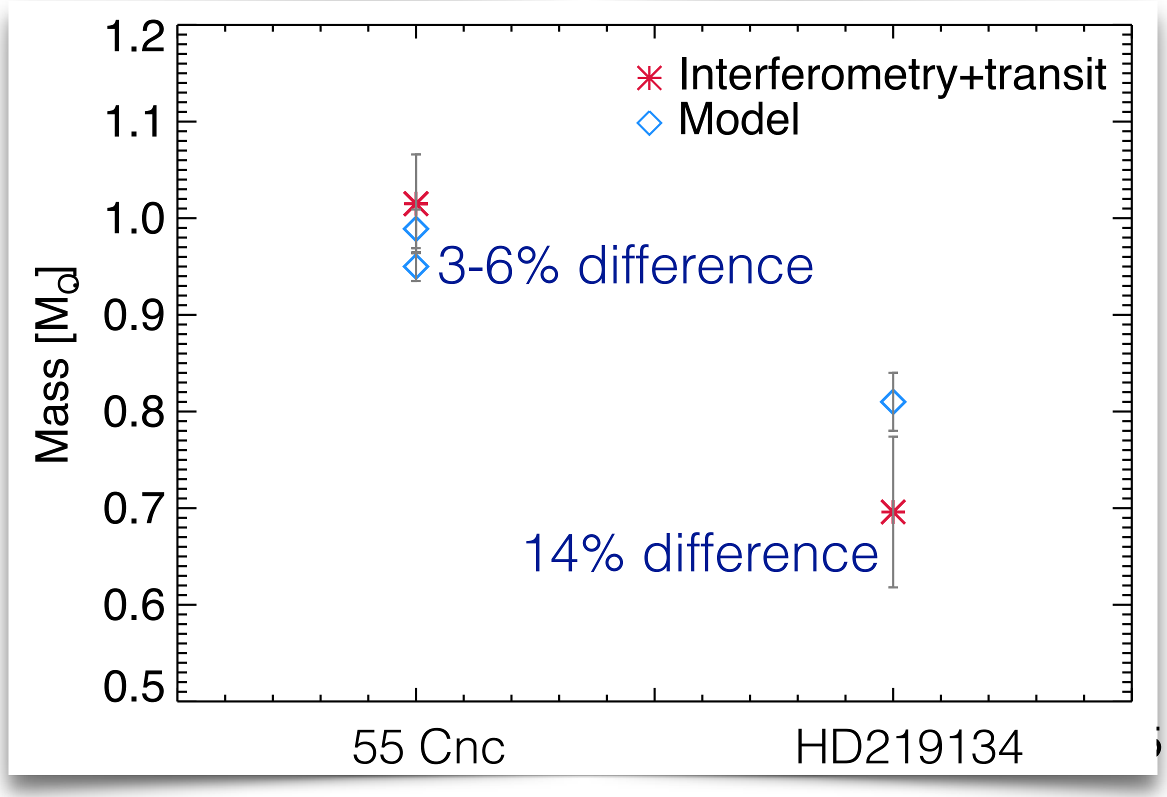
Fit ($L_\star$, T_{eff}) → $M_\star$, $R_\star$, age.

From BASTI isochrones: 2 solutions

- **Young solution**: $M_\star = 0.968 \pm 0.018\ M_\odot$, 30.0±3.028 Myrs
- **Old solution**: $M_\star = 0.874 \pm 0.013\ M_\odot$, 13.19±1.18 Gyrs

Ligi et al. (2016, 2019)
Crida, Ligi et al. (2018a,b)

III. STELLAR MASS AND RADIUS



Comparison with Stellar evolution models:

Provide a small error bar = internal error of the model.

But depend on many (unknown?) parameters: He initial abundance, solar mixture, metalicity, rotation, magnetic field, external boundary condition, mixing length ...

For HD219134

- We measure $M_\star = 0.696 \pm 0.078\ M_\odot$ and $\rho_\star = 1.82 \pm 0.19\ \rho_\odot$
- Models with different input physics give:

$M_\star = 0.755$ to $0.810 \pm 0.04\ M_\odot$

(or 0.719 with large initial Helium abundance),

and $\rho_\star = 1.96 - 2.09 \pm 0.22\ \rho_\odot$.

We rather use our **measurements**.

We may lose in precision, but we gain in accuracy!

Ligi et al. (2016, 2019)
Crida, Ligi et al. (2018a,b)

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IV. MASS AND RADIUS OF THE PLANET 55 CNC e

$$f_p(M_p, R_p) \propto \iint \exp\left(-\frac{1}{2}\left(\frac{K(M_p, M_\star) - K}{\sigma_K}\right)^2\right)$$ ← RV measurements

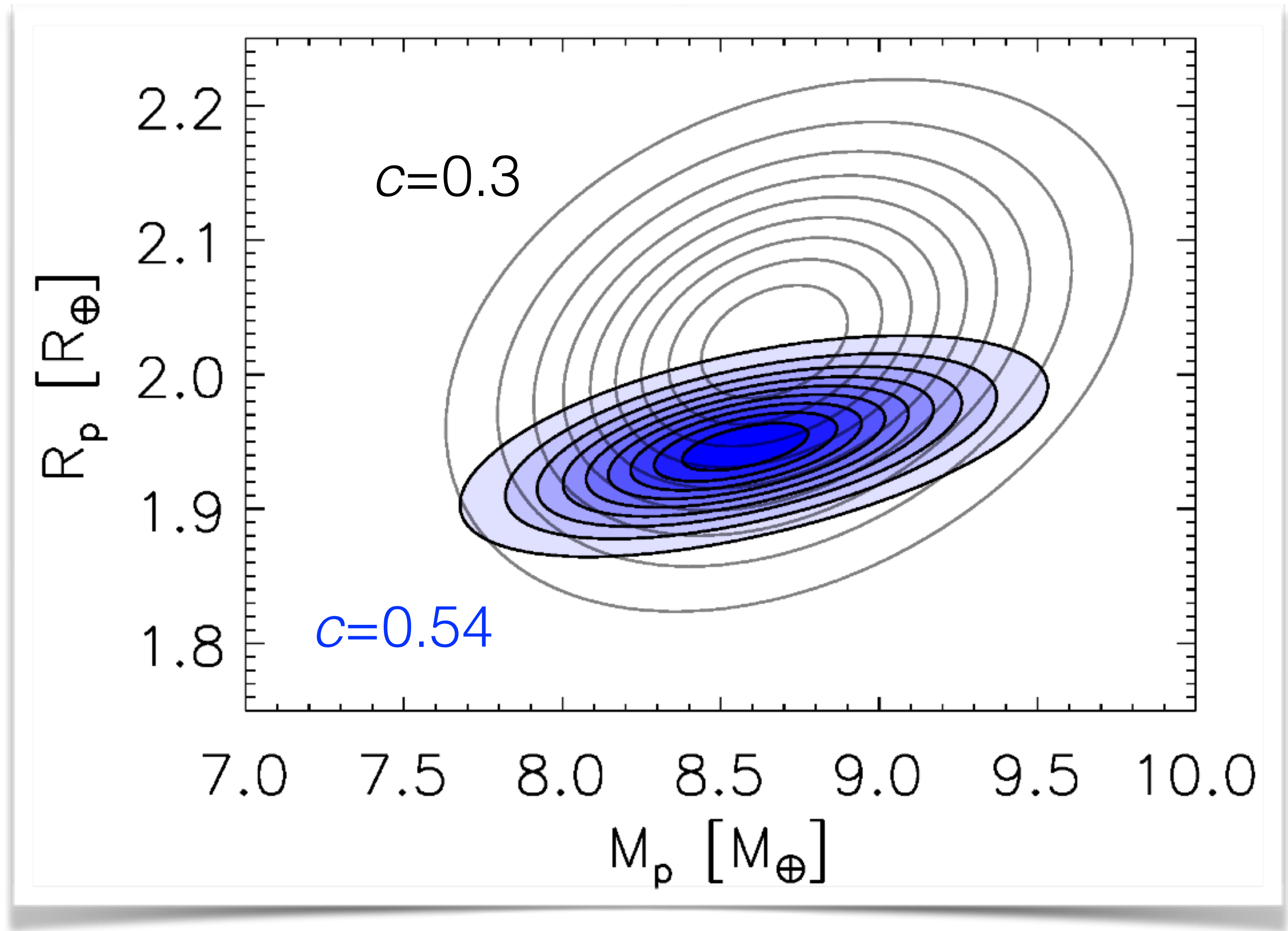
$$\times \exp\left(-\frac{1}{2}\left(\frac{\Delta F(M_p, M_\star) - \Delta F}{\sigma_{\Delta F}}\right)^2\right)$$ ← transit measurements

$$\times \mathcal{L}_{MR\star}(M_\star, R_\star)\, \mathrm{d}M_\star\, \mathrm{d}R_\star\ .$$

55 Cnc e

White: our first estimate, with Hipparcos parallax + poor transit light-curve. Correlation: 0.3.
→ ρ_p =1.06±0.13 $\rho_\oplus$

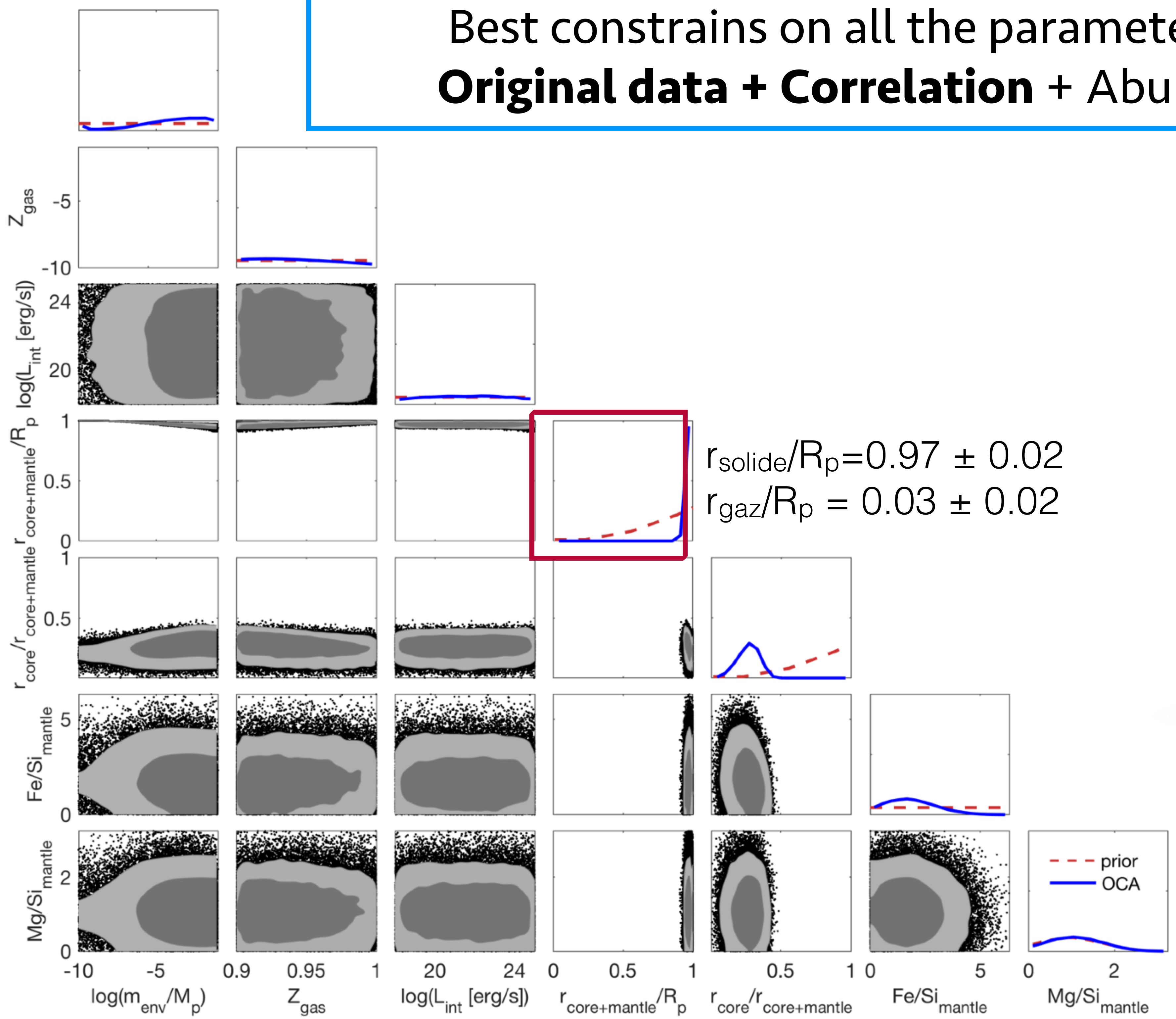
Blue: our second estimate, with Gaia parallax + refined HST light-curve and radial velocity. Correlation: 0.54.
→ ρ_p =1.164±0.062 $\rho_\oplus$ = 6421±342 kg.m^{-3}



Crida, Ligi et al. (2018a,b)

IV. PLANETS PROPERTIES: 55 CNC e

Best constrains on all the parameters with
Original data + Correlation + Abundances



$r_{solide}/R_p = 0.97 \pm 0.02$
$r_{gaz}/R_p = 0.03 \pm 0.02$

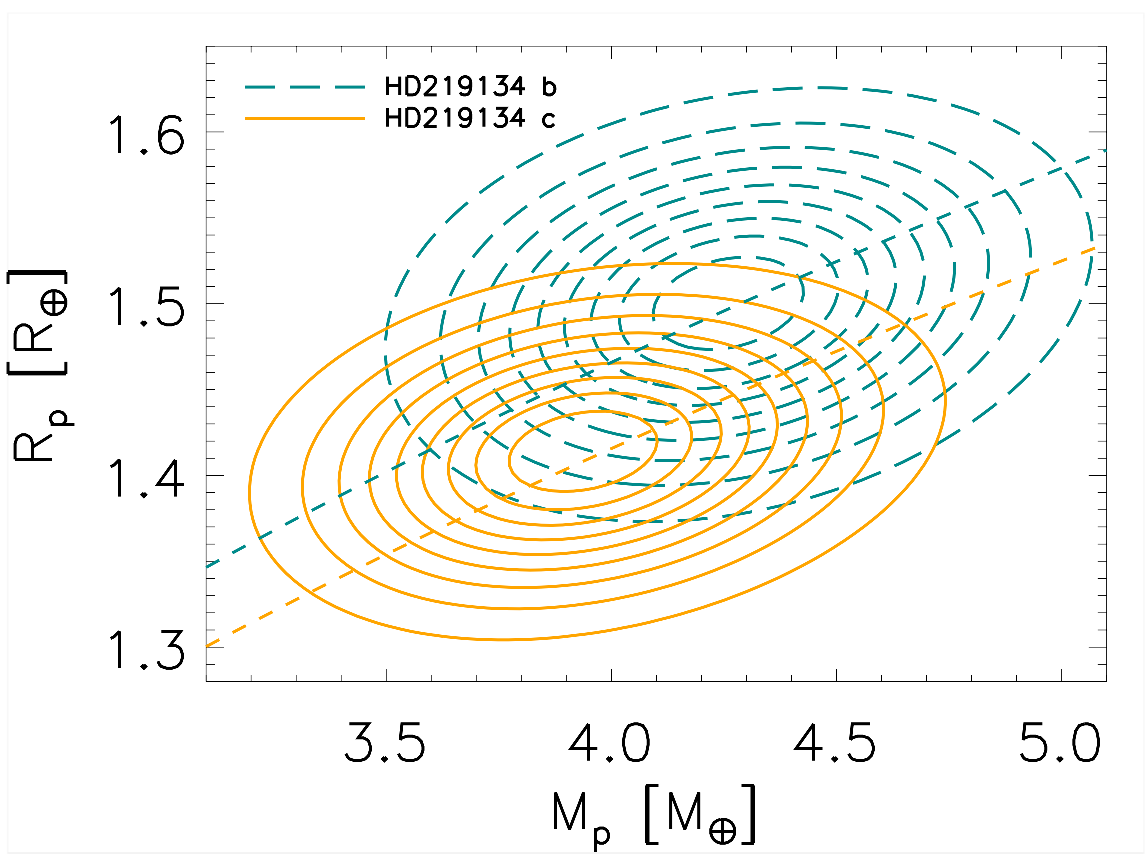
Atmosphere thickness
= **3% of R_p**

➔ not a good target for transmission spectroscopy

➔ chemistry of the interior non necessarily carbon-rich

Crida, Ligi et al. (2018a,b)

IV. MASS AND RADIUS OF HD219134'S PLANETS

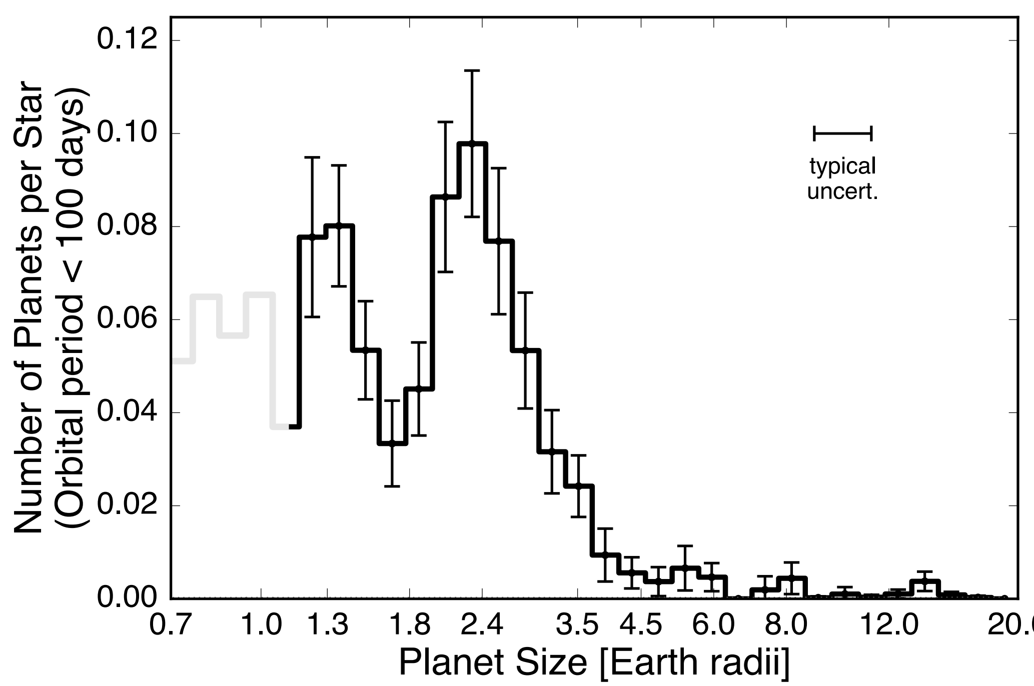


Smaller planets than previous estimates

→ These new radii put the planets on the small side of the evaporation valley, while they were thought in the gap.

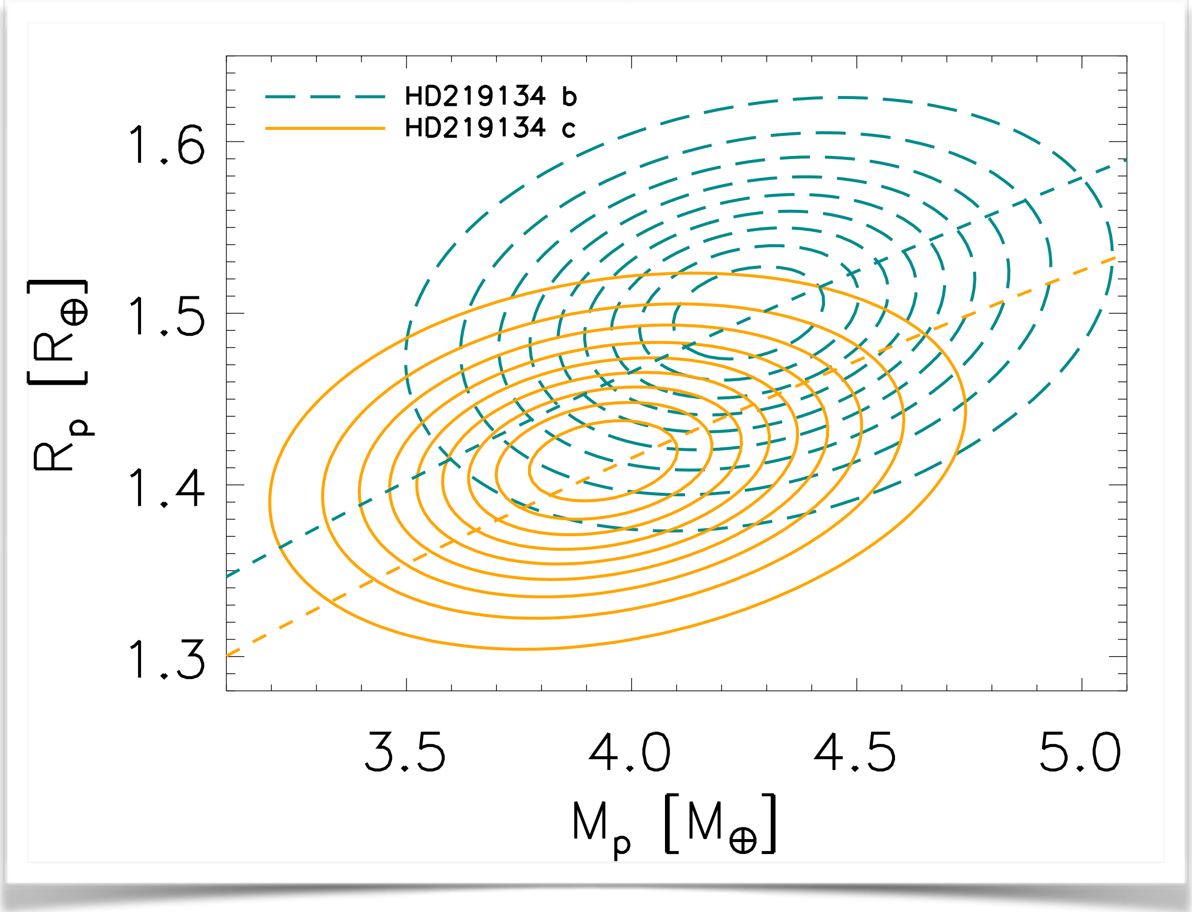
	PLANET B	PLANET C
Radius [$R_\oplus$]	1.50 ± 0.06	1.41 ± 0.05
Mass [$M_\oplus$]	4.27 ± 0.34	3.96 ± 0.34
Density [$\rho_\oplus$]	1.27 ± 0.16	1.41 ± 0.17
Corr. (M_p - R_p)	0.22	0.23

Ligi et al. (2019)



Fulton et al. (2017)

IV. PLANETS PROPERTIES: HD219134 b & c



ρ_b/ρ_c = 0.905 ± 0.131 (0.95 for Venus/Earth)
→ 50 % chance that their densities differ more than 2× more than those of Venus and Earth…

The more massive one (b) is the less dense.
→ Different core/mantle ratio ? Thick gas envelope ? Enrichment in refractory elements ?

	PLANET B	PLANET C
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Density [$\rho_\oplus$]	1.27 ± 0.16	1.41 ± 0.17
Corr. (M_p - R_p)	0.22	0.23

Bower et al. (2019): a molten mantle is 25% less dense than a solid one. Could HD219134 b be partially molten ?

Ligi et al. (2019)

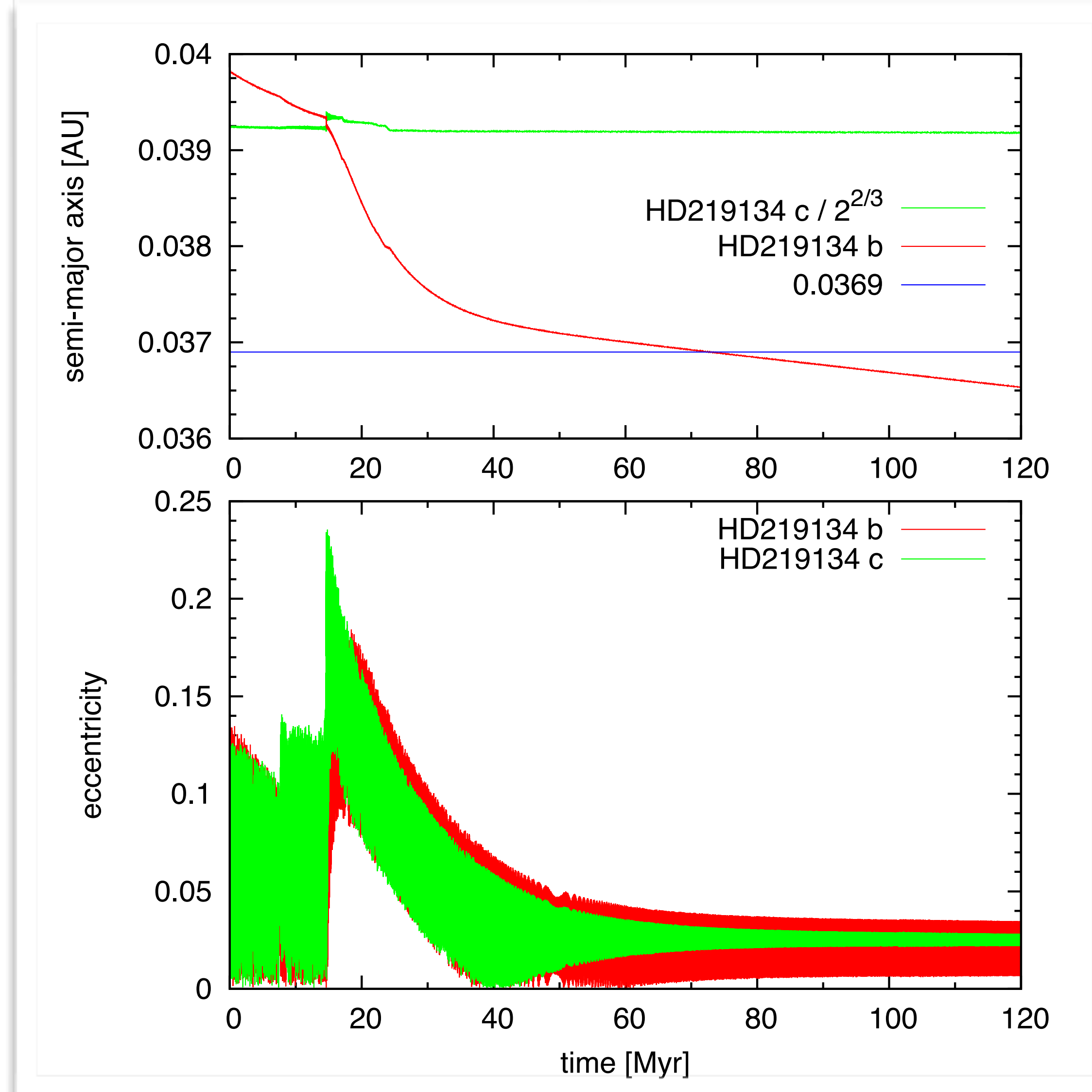
IV. PLANETS PROPERTIES: HD219134 b & c

Tidal heating from the host star dissipates energy and circularizes the orbit.

→ Sustainable energy source if and only if the eccentricity is pumped by other planets (ex: Io).

N-body simulations of the system:
e_b oscillates between 0.005 and 0.037.

→ tidal heating up to 100 times more than Io!
HD219134 c: less tidal heating than Io (because further from the star).



Conclusion

→ N-body simulations: planet b's eccentricity is excited despite not measurable.

→ Assuming a dissipation inside this planet equivalent to that of Earth, this strongly suggests that this planet could be at least partially molten, explaining its lower density than its neighbor HD219134 c, even if they have identical composition.

Ligi et al. (2019)

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V. CONCLUSION AND PERSPECTIVE

Stellar parameters

- Should be precise and accurate: **$R_\star$, $\rho_\star$, and $M_\star$ directly determined + correlations**
- Direct determination diverges from models → Direct impact on planetary parameters

Planetary interiors

- 55 Cnc e:
  Tiny atmosphere (3% of R_p)
  Non necessarily carbon-rich interior

  → thanks to very precise transit parameters + correlations

- HD219134 b and c:
  Validation of the Super-Earths natures
  High molten fraction of the mantle of planet b to explain its lower density

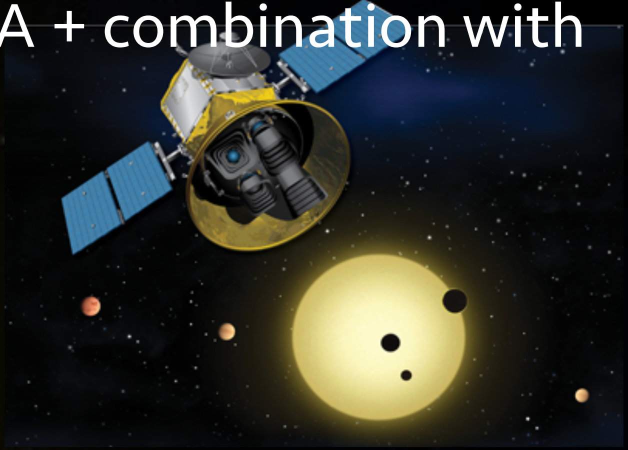
  → need more accuracy on the transit parameters to confirm the different densities in general.

V. CONCLUSION AND PERSPECTIVE

In the near future…

- Measurements of 4 stars with VEGA/CHARA and analysis with the same method: expect some new planetary parameters!

- Measurement of TESS targets for next semester with VEGA/CHARA + combination with **asteroseismology**! (NOAO proposal; PI Ligi)



In the future…

- Member of the CHARA/SPICA project (Leader of the WP « Exoplanets hosts »)

  - On the CHARA array, 6T interferometer, mag limit = 9 → **many targets ahead!**

- The future spatial missions TESS, CHEOPS, PLATO will provide plenty of new bright stars hosting transiting exoplanets

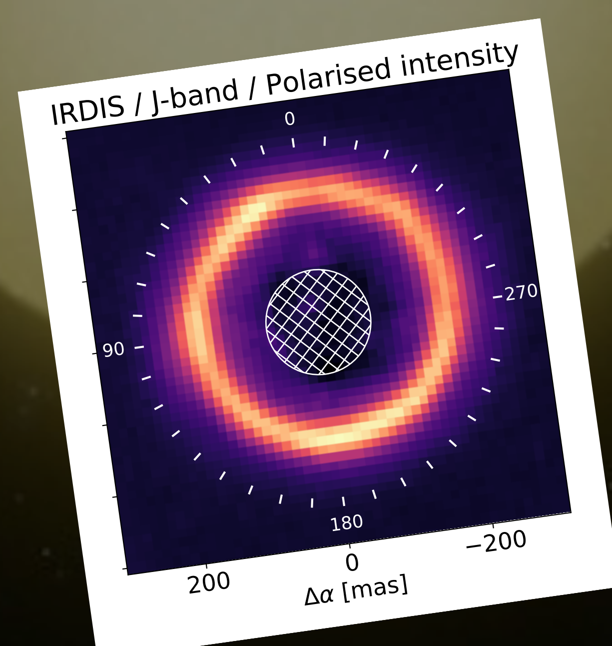
  ➡ Insights on stellar masses (measurements *vs* models) → calibrations of stellar models

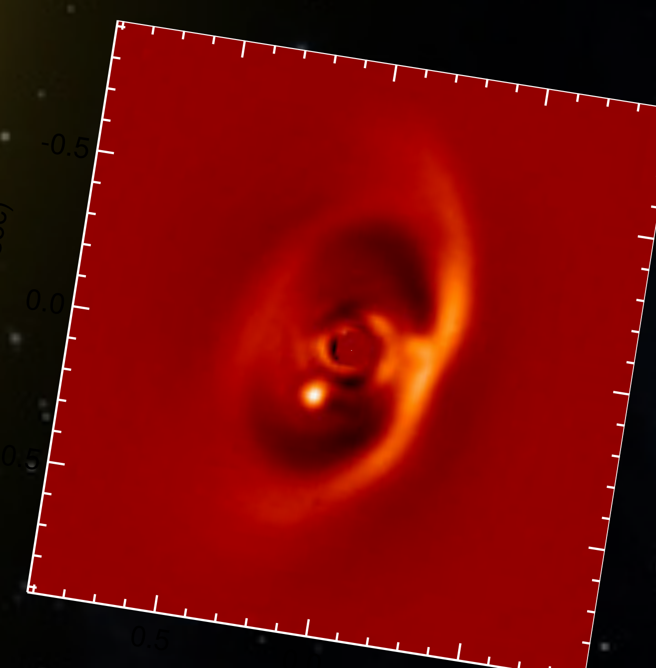
  ➡ Refine population of exoplanets → confirmation (or not) of planetary formation theories, discovery of new rocky planets habitable for life?

V. CONCLUSION AND PERSPECTIVE

And also direct imaging for exoplanets detection…

- New data on HD169142 with SPHERE/VLT (Ligi et al. 2018a; Gratton, Ligi et al. 2019 + Media INAF)
- Proposal SPHERE/VLT on the follow-up of TESS targets (1 accepted, 1 submitted; PI Desidera): detection of false-positives (see Ligi et al. 2018b)
- Member of the DSHARP project: search of planets in disks with SPHERE
- Member of the GAPS project: detection and follow-up of exoplanets with RV





THANK YOU FOR YOUR ATTENTION

AstroFIt2 Meeting, Roma, October 15th 2019

Roxanne LIGI

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement n. 664931