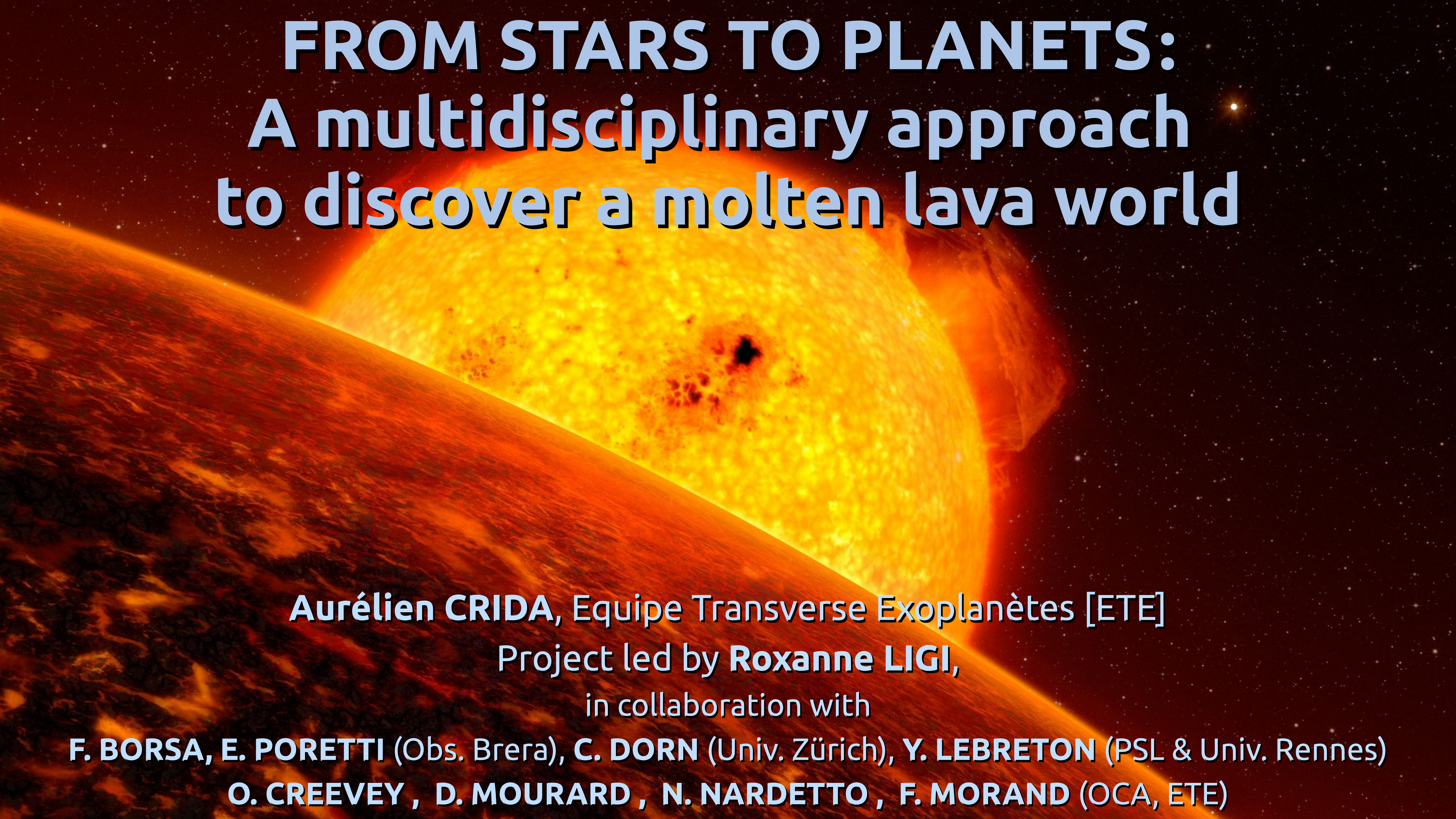


FROM STARS TO PLANETS: A multidisciplinary approach to discover a molten lava world

Aurélien CRIDA, Equipe Transverse Exoplanètes [ETE]

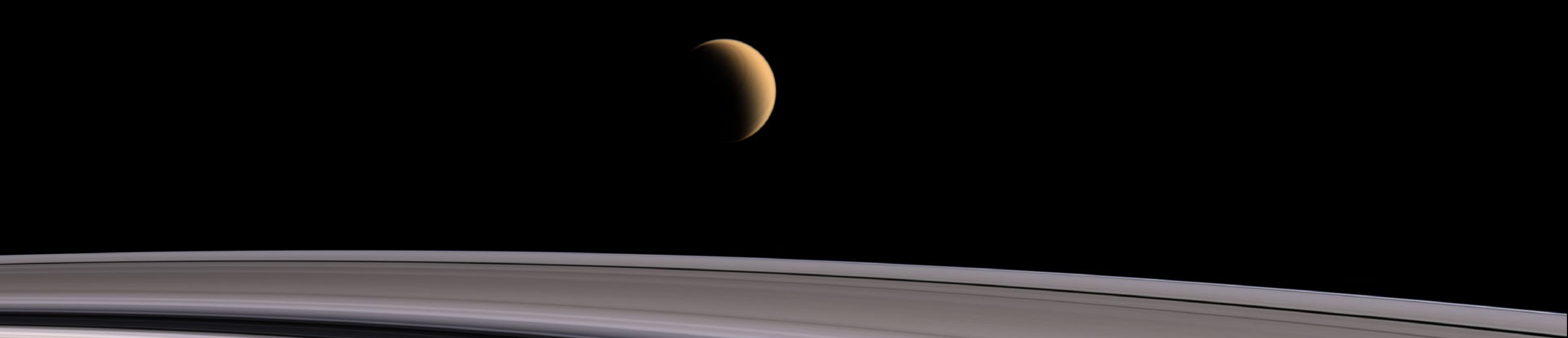
Project led by **Roxanne LIGI**,

in collaboration with

F. BORSA, E. PORETTI (Obs. Brera), **C. DORN** (Univ. Zürich), **Y. LEBRETON** (PSL & Univ. Rennes)

O. CREEVEY , D. MOURARD , N. NARDETTO , F. MORAND (OCA, ETE)

Les anneaux de Saturne sont-ils vraiment jeunes ?



Une *perspective*.

Crida, Charnoz, Hsu, Dones :

<u>Are Saturn's rings really young ?</u>

Soumise à Nature le 13/4, décision éditoriale en cours...

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Perspectives

Perspective articles are intended to provide a forum for authors to discuss models and ideas from a personal viewpoint. They are more forward looking and/or speculative than Reviews and may take a narrower field of view. They may be opinionated but should remain balanced and are intended to stimulate discussion and new experimental approaches.

Aurélien CRIDA, Journée Lagrange 25/4/2019

Les anneaux de Saturne sont-ils vraiment jeunes ?

nature astronomy

PERSPECTIVE

https://doi.org/10.1038/s41550-019-0876-y

Are Saturn's rings actually young?

Aurélien Crida[1,2]*, Sébastien Charnoz[3], Hsiang-Wen Hsu[4] and Luke Dones[5]

Spectacular results from Cassini's Grand Finale have provided constraints on the characteristics and evolutionary processes of Saturn's rings. These results have been interpreted as proof that the rings are much younger than the Solar System, dramatically changing our view of the origin of the whole Saturnian system and attracting the attention of scientific media outlets. But we should keep in mind that the age of the rings has not actually been measured (which is impossible per se) but rather is inferred. Here, we put these latest results into perspective and we point out that the young-rings hypothesis has some unsolved problems. Other interpretations, compatible with rings as old as the Solar System, are still possible.

To clarify the debate, it may be useful to start by defining three different ages. First, the ring formation age is the time elapsed from their formation until now. This is the one we wish to constrain. Second, the age of the structures observed in the rings (the Cassini division, various gaps, waves and plateaus) is the time age (see below), this mass is actually consistent with the expected dynamical evolution of primordial, massive rings. Interactions between the ice blocks that constitute the rings lead to an outward transfer of angular momentum, resulting in the spreading of the rings. This can be modelled by a viscosity in a sheared fluid[6].

Une *perspective*.

Crida, Charnoz, Hsu, Dones :

<u>Are Saturn's rings really young ?</u>

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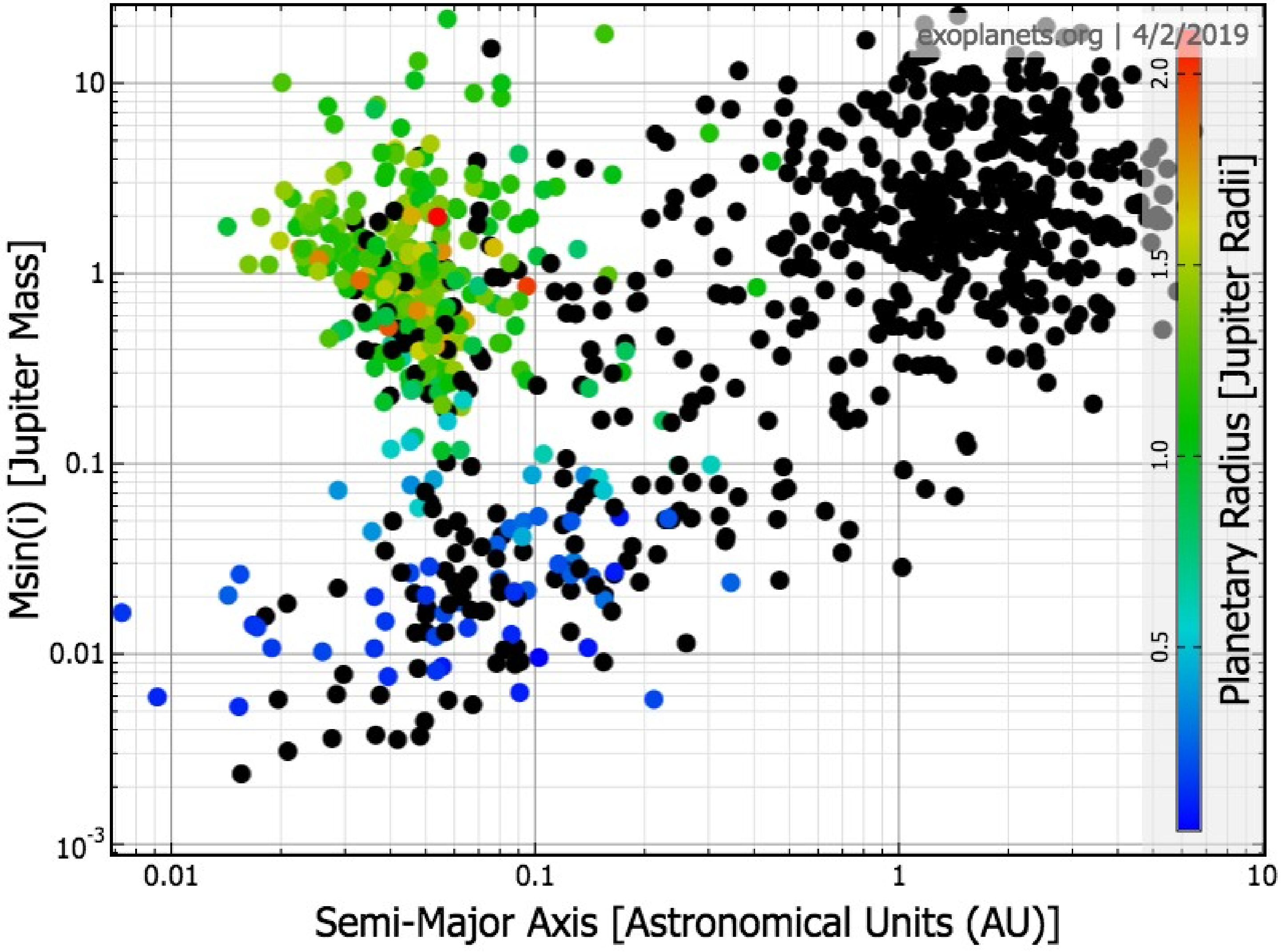
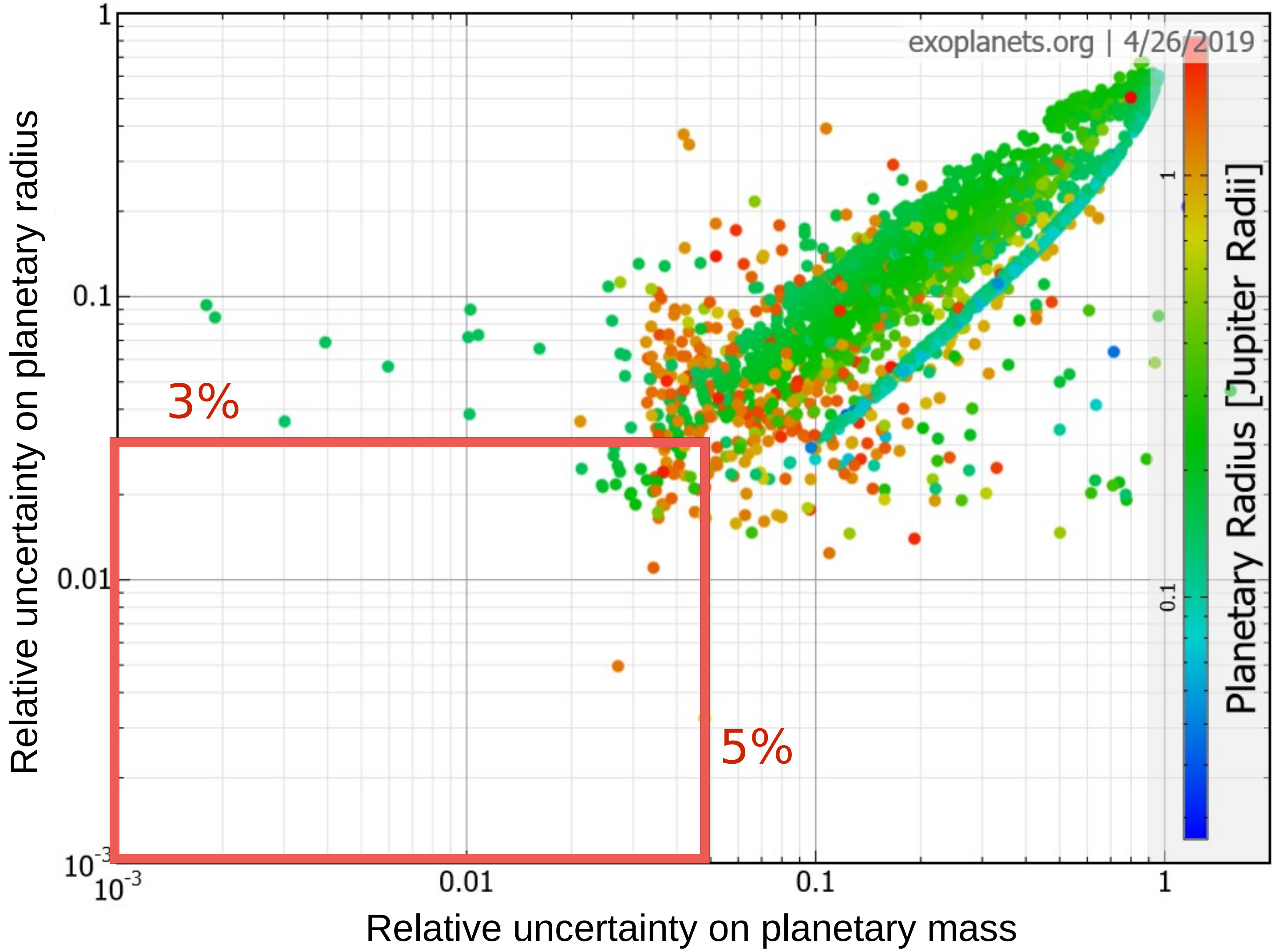
INTRODUCTION



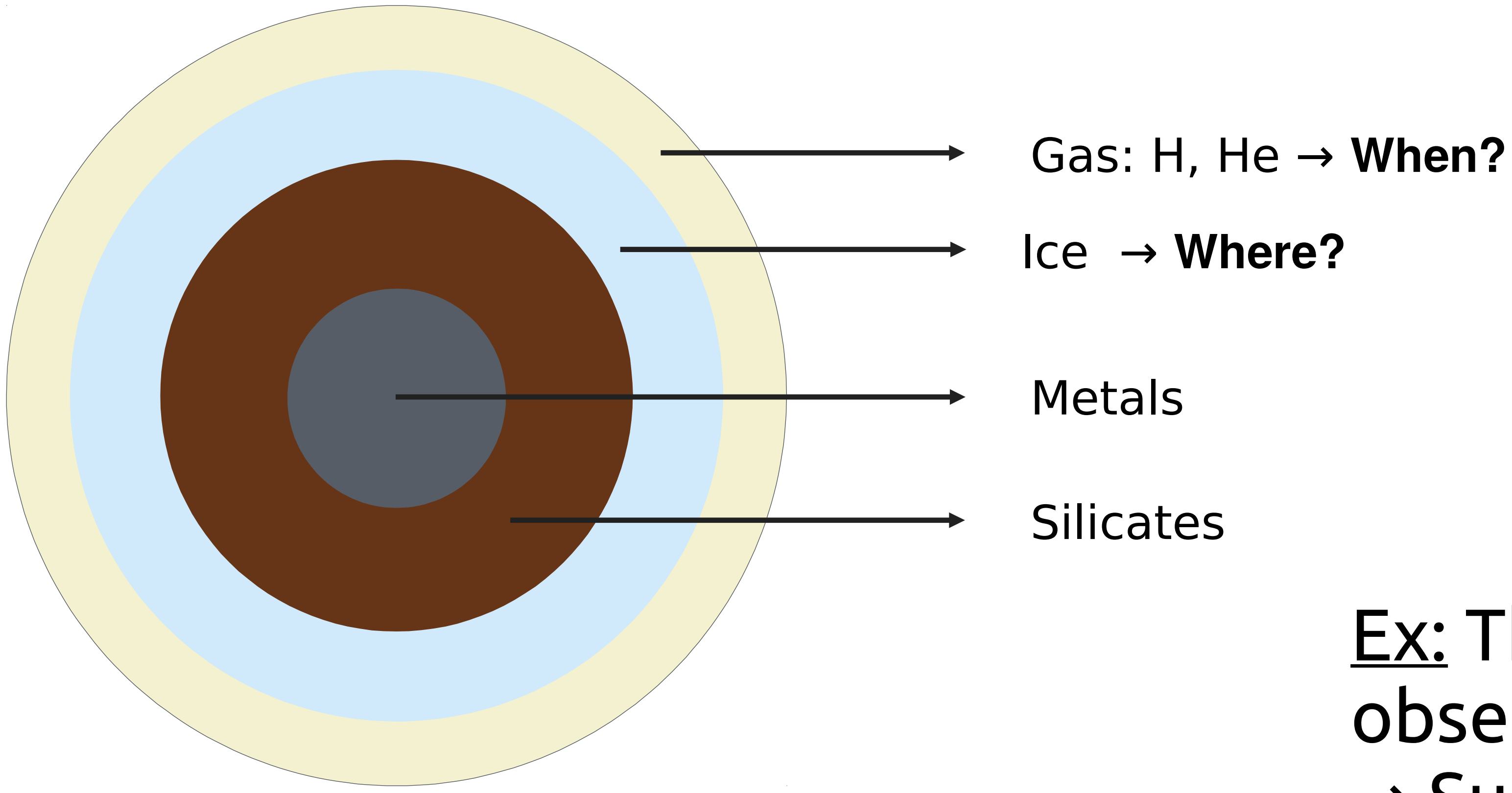


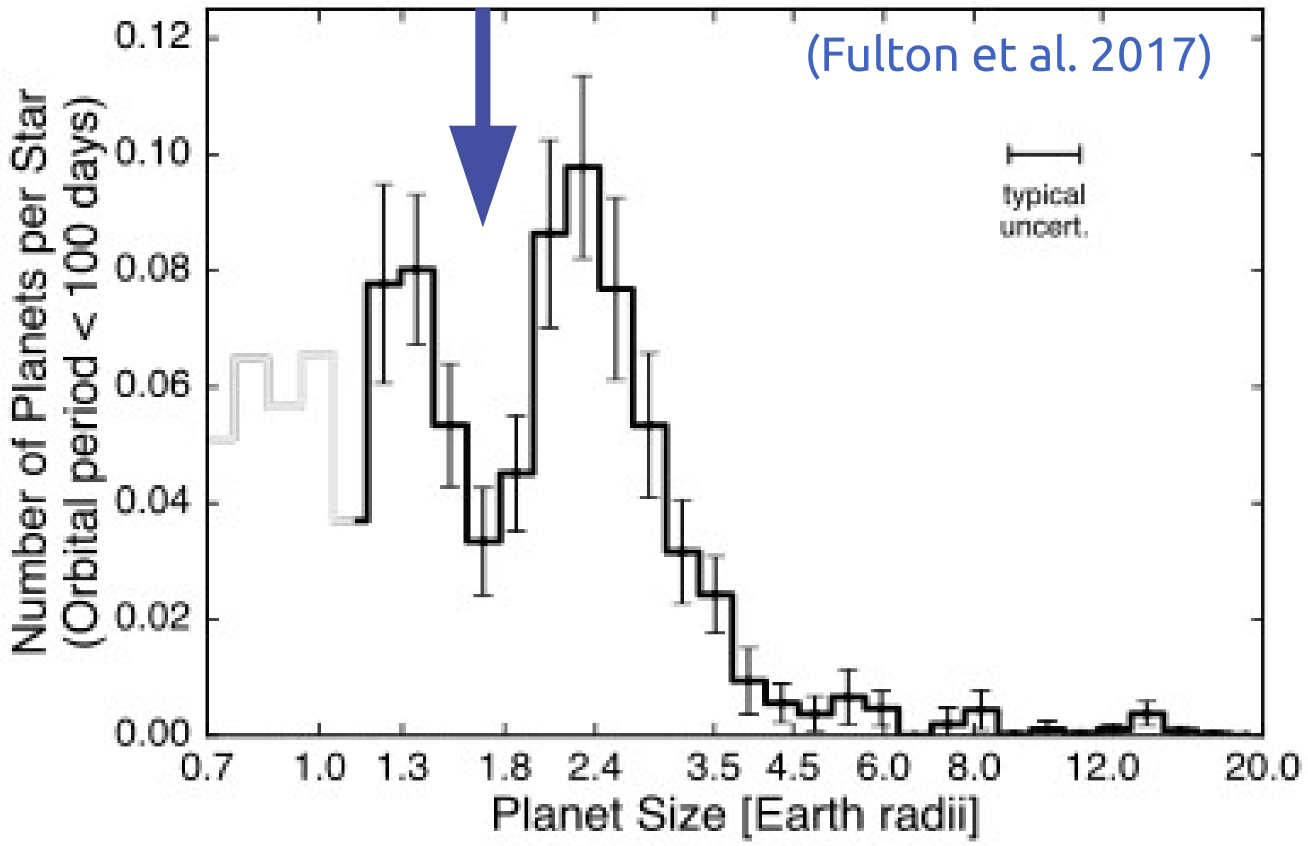
More than 4000 exoplanets known
→ revolution for planet formation theories
→ search for other habitable (habited) worlds.

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

INTRODUCTION

Formation ? Habitability ? Diversity of the population ?
→ Need 3-5 % precision on mass and radius to infer the internal structure of a planet, and thus constrain its nature and origin.

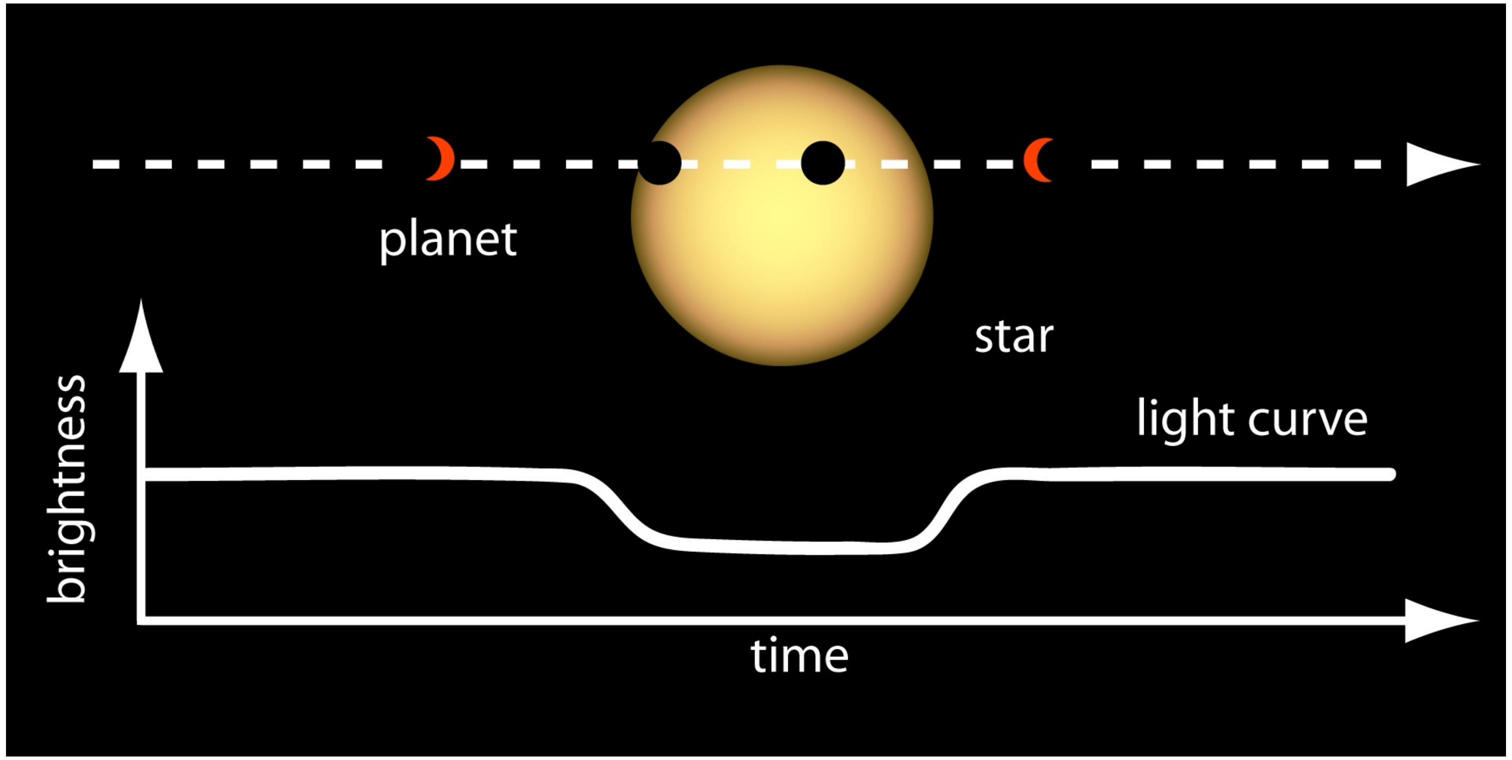




<u>Ex:</u> The « evaporation valley » or « Fulton gap » observed in the distribution of planetary radii.
→ Super-Earths ≠ Mini-Neptunes ?

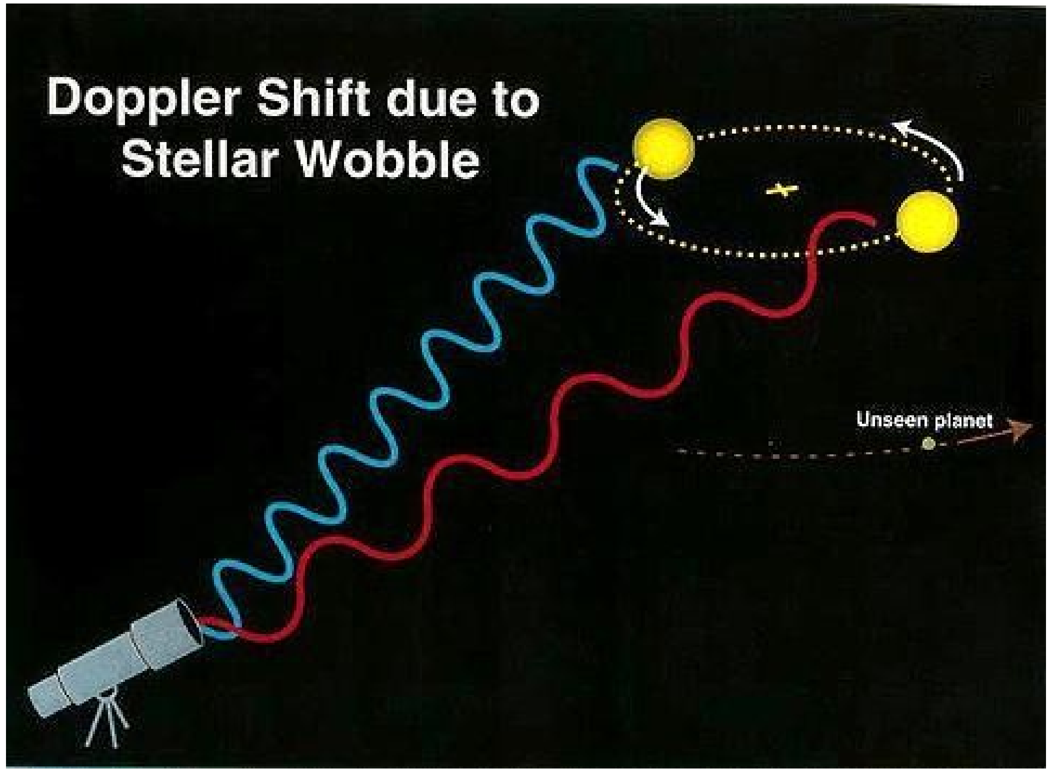
INTRODUCTION

Transit method



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

Radial velocity method



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

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

In many cases, the 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)...

Our method / Outline :

0) Use existing transit and radial velocity data.

1) Measure the stellar diameter by interferometry (<2% precision).

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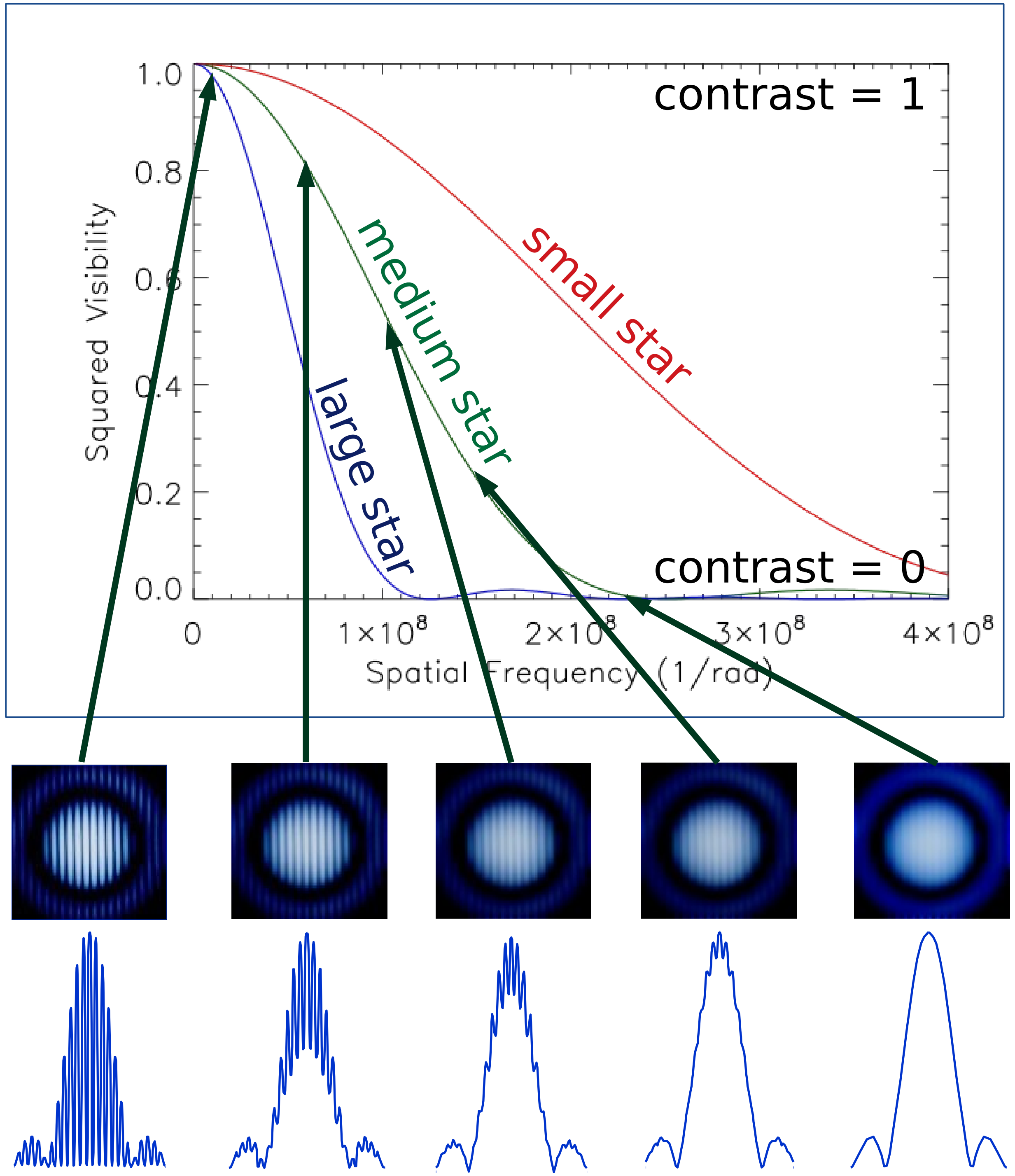
1) Interferometry – principles



Observe a star with two 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.

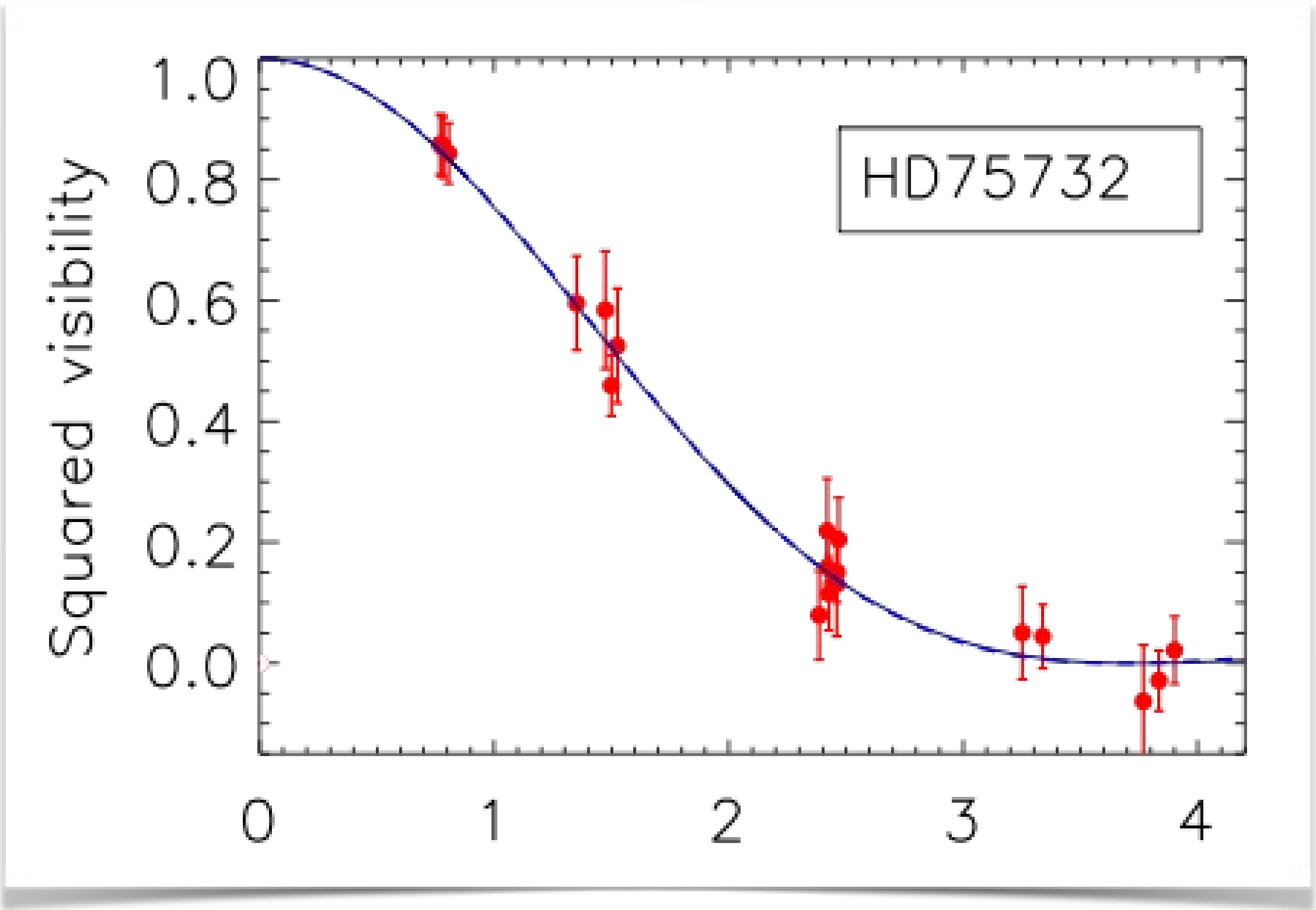
<u>Stellar radius:</u> $R_\star = \theta/2\pi$. (π = parallax)

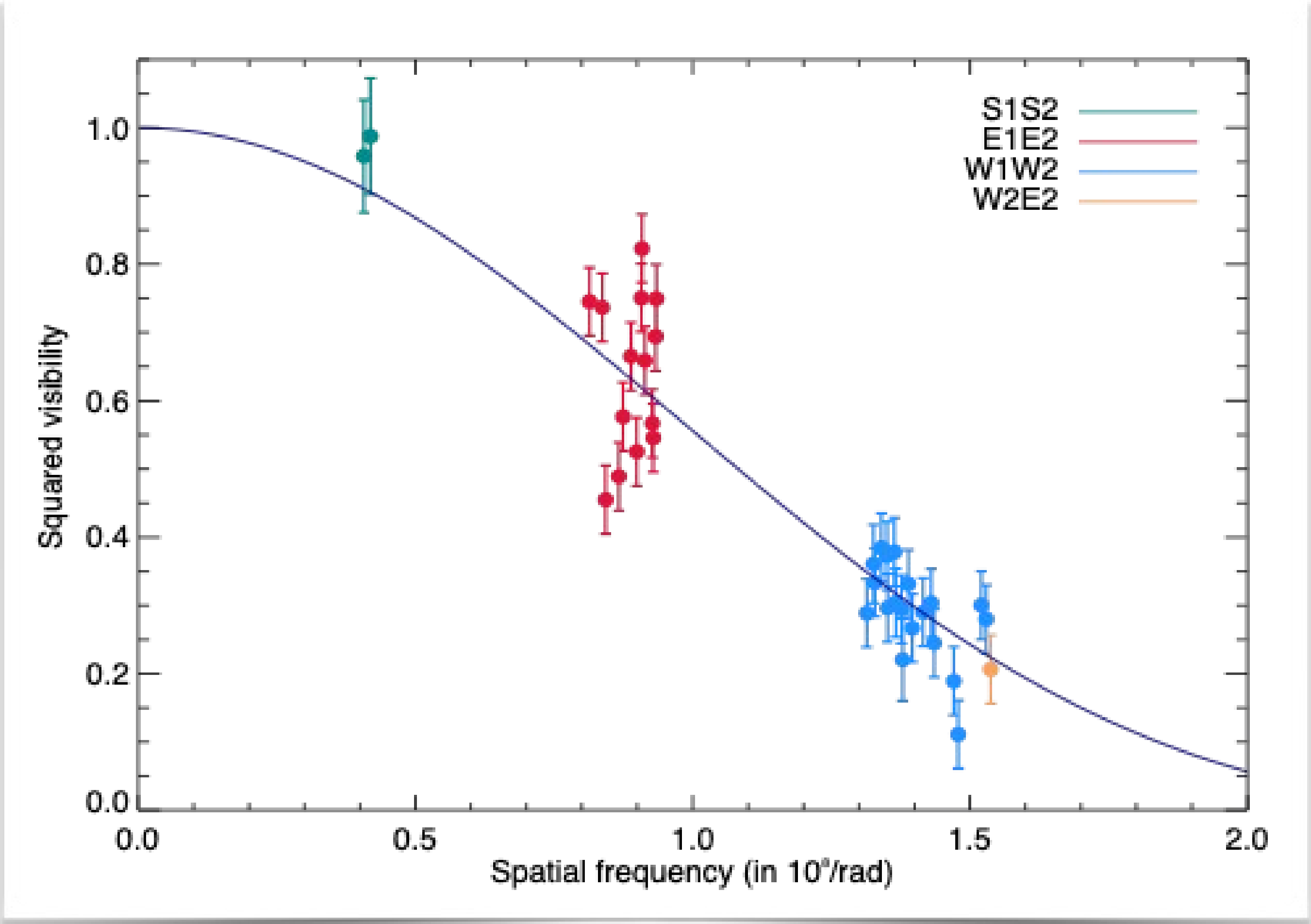
<u>Probability Density Function *f*:</u>

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

1) Interferometry – results

We (R. Ligi, F. Morand, D. Mourard, N. Nardetto) used the VEGA/CHARA instrument at Mount Wilson in California, piloted in remote from Calern, on 2 transiting exoplanet host stars: 55 Cnc (aka HD75732) and HD219134.

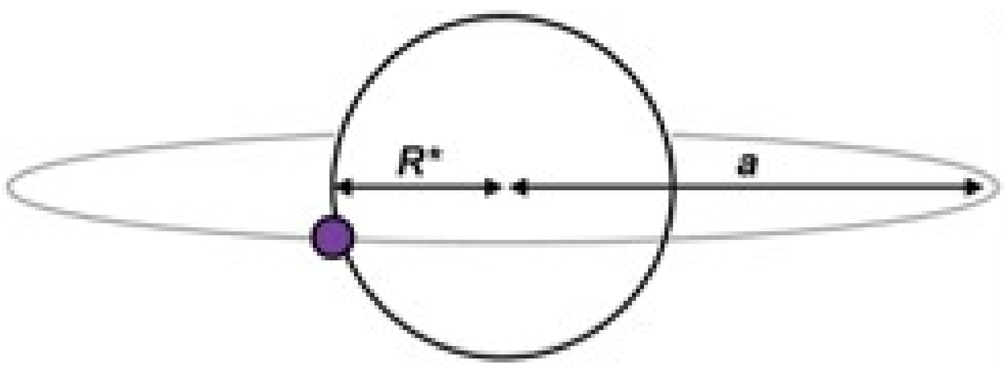


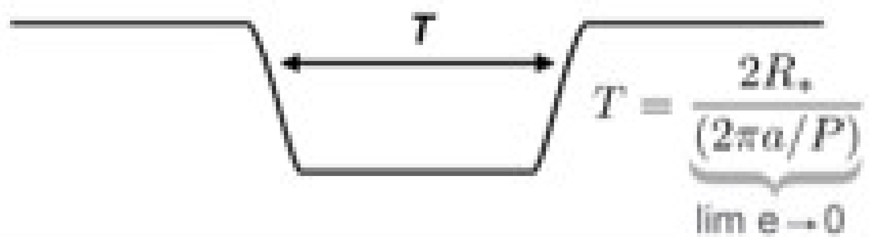


55 Cnc: $\theta = 0.724 \pm 0.012$ mas
$\rightarrow R_\star = 0.960 \pm 0.018\ R_\odot$ (Ligi + 2016)

HD219134: $\theta = 1.035 \pm 0.021$ mas
$\rightarrow R_\star = 0.726 \pm 0.014\ R_\odot$ (Ligi+ 2019)

2) Stellar density





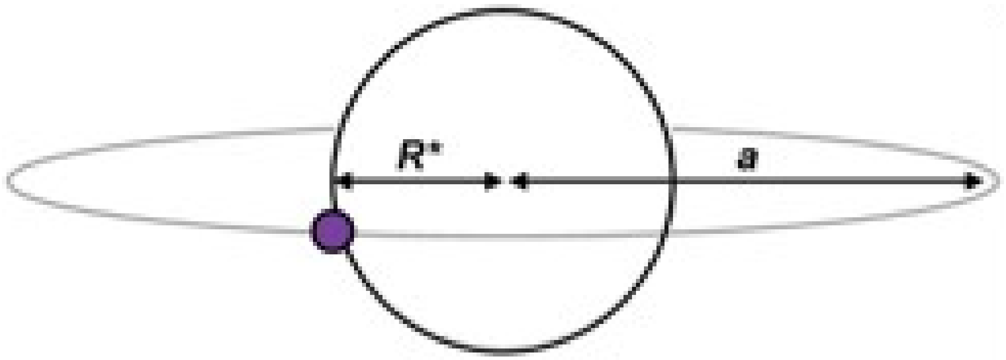
<u>Kepler's 3rd law :</u> $P^2 = (4\pi^2/GM_\star)a^3$.

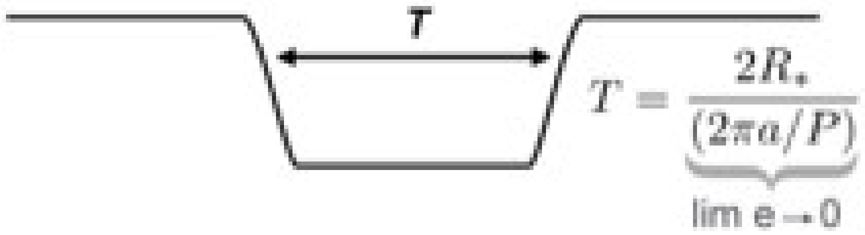
<u>Transit duration</u>: $T = 2R_\star/v$, where $v = 2\pi a/P$.

→ $P/T^3 = (\pi^2 G/3)\,\rho_\star$ (Seager & Mallén-Ornelas 2003)

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

2) Stellar density





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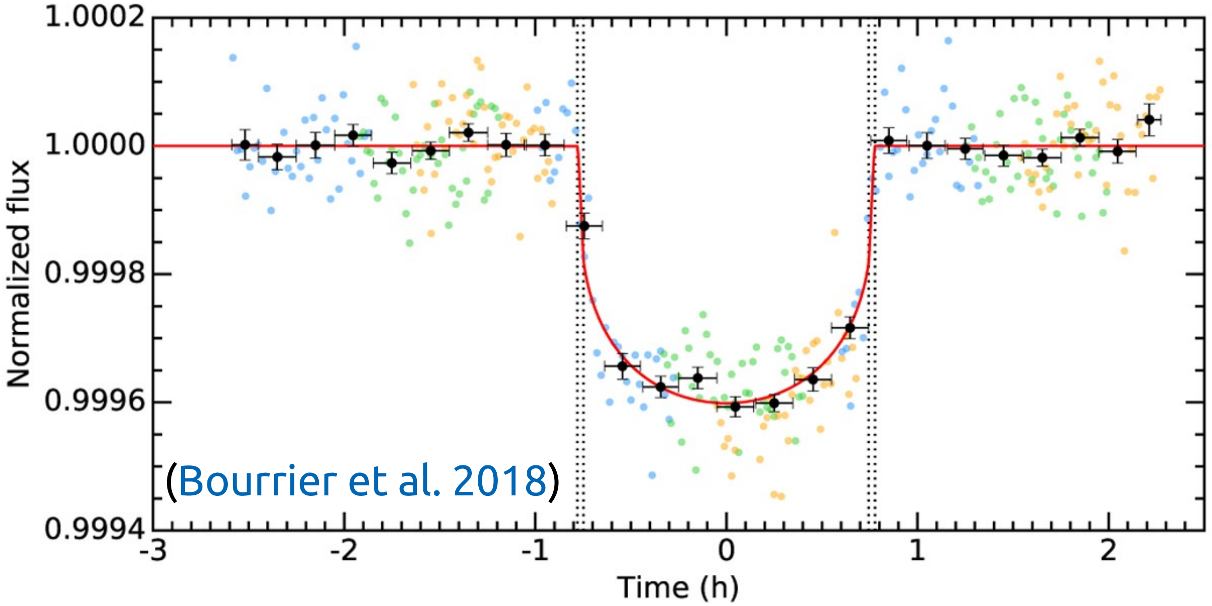
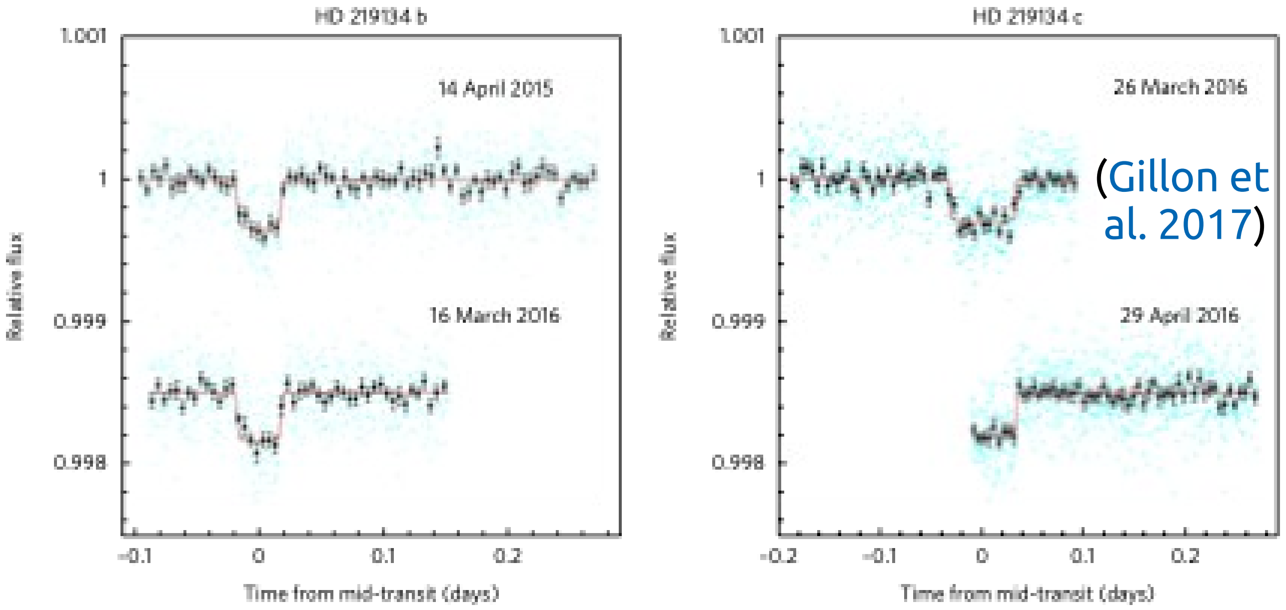
A fine transit light-curve allows to *measure* the density of the host star!

55 Cnc: $\rho_\star = 1.079 \pm 0.005\ \rho_\odot$ (Crida+ 2018) ; HD219134: $\rho_\star = 1.82 \pm 0.19\ \rho_\odot$ (Ligi+ 2019)



(Bourrier et al. 2018)



(Gillon et al. 2017)

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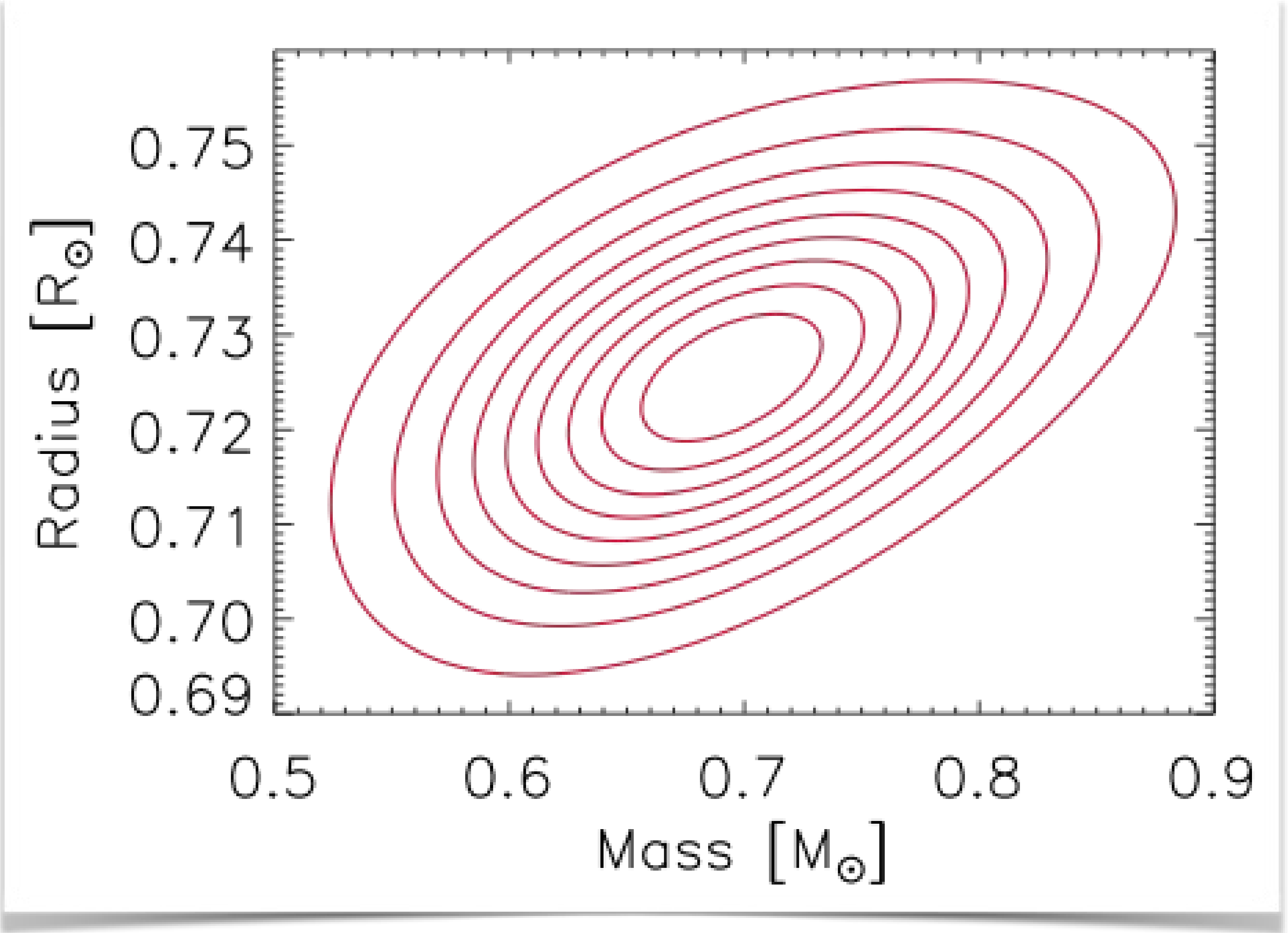
3) Mass and Radius of the stars

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

$M_\star$ 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

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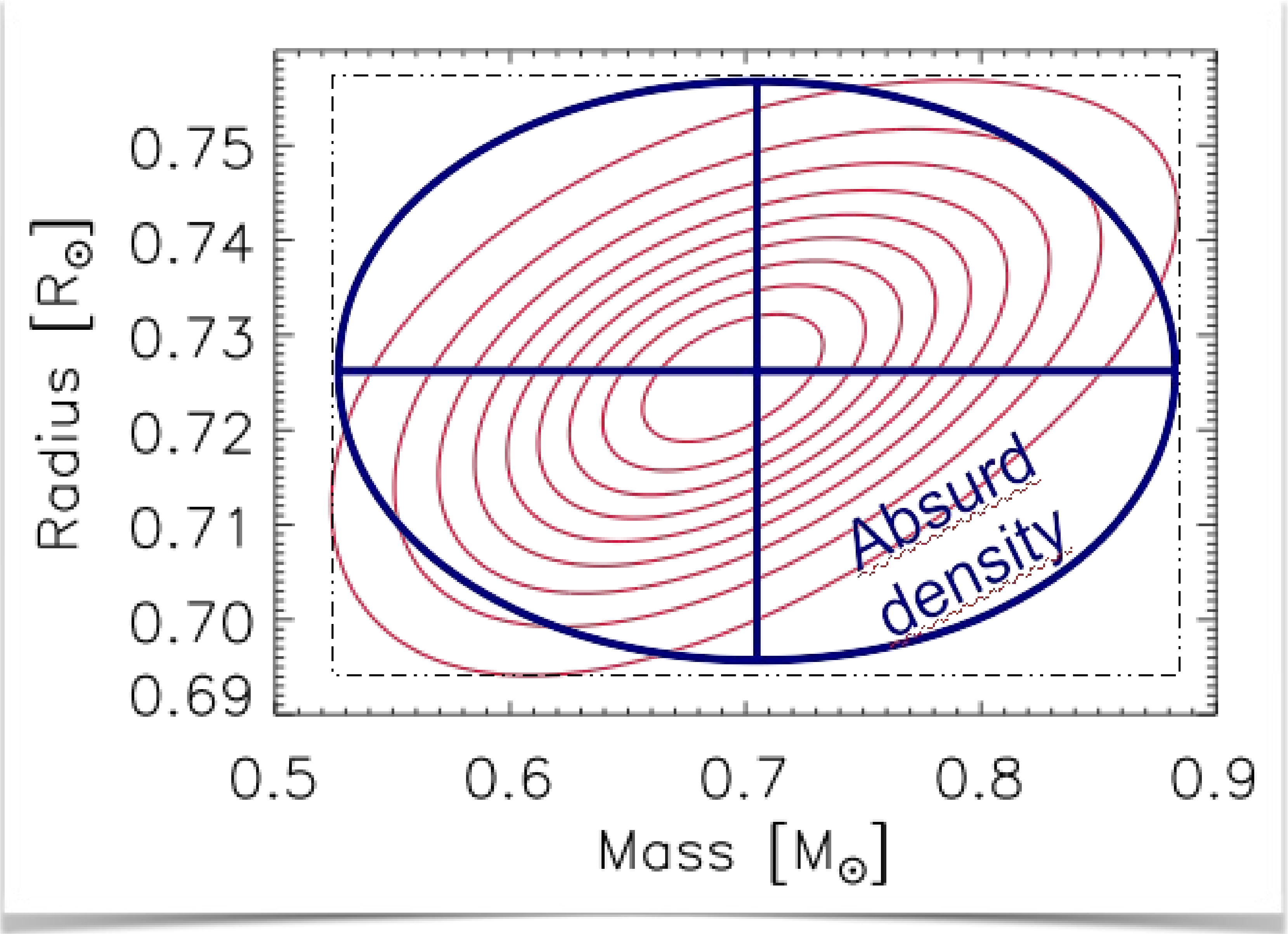


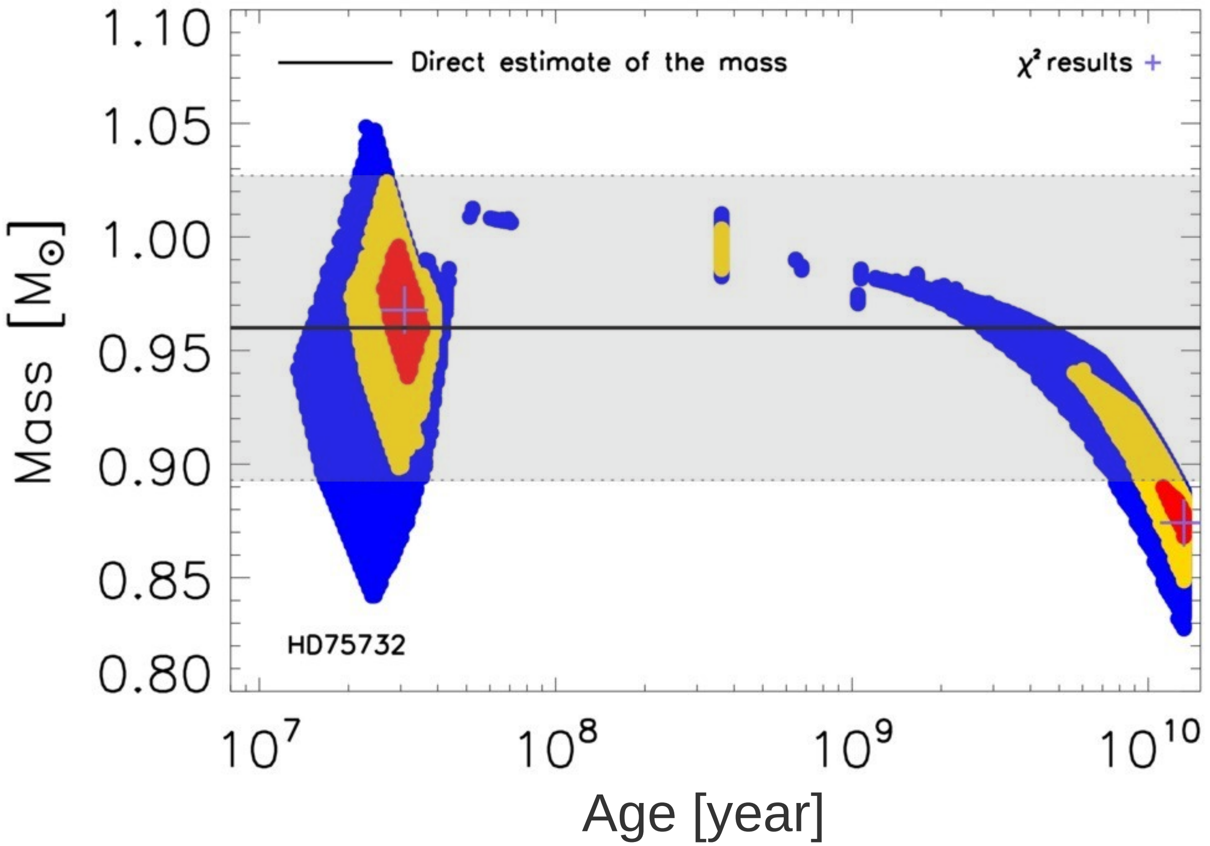
Ex: HD219134: level curves of the joint PDF.
Correlation ($M_\star$ - $R_\star$) = 0.46

3) Mass and Radius of the stars

Comparison with stellar models:

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

55 Cnc:



2 solutions: young and old.
+ Mass – age degeneracy (Ligi+ 2016).

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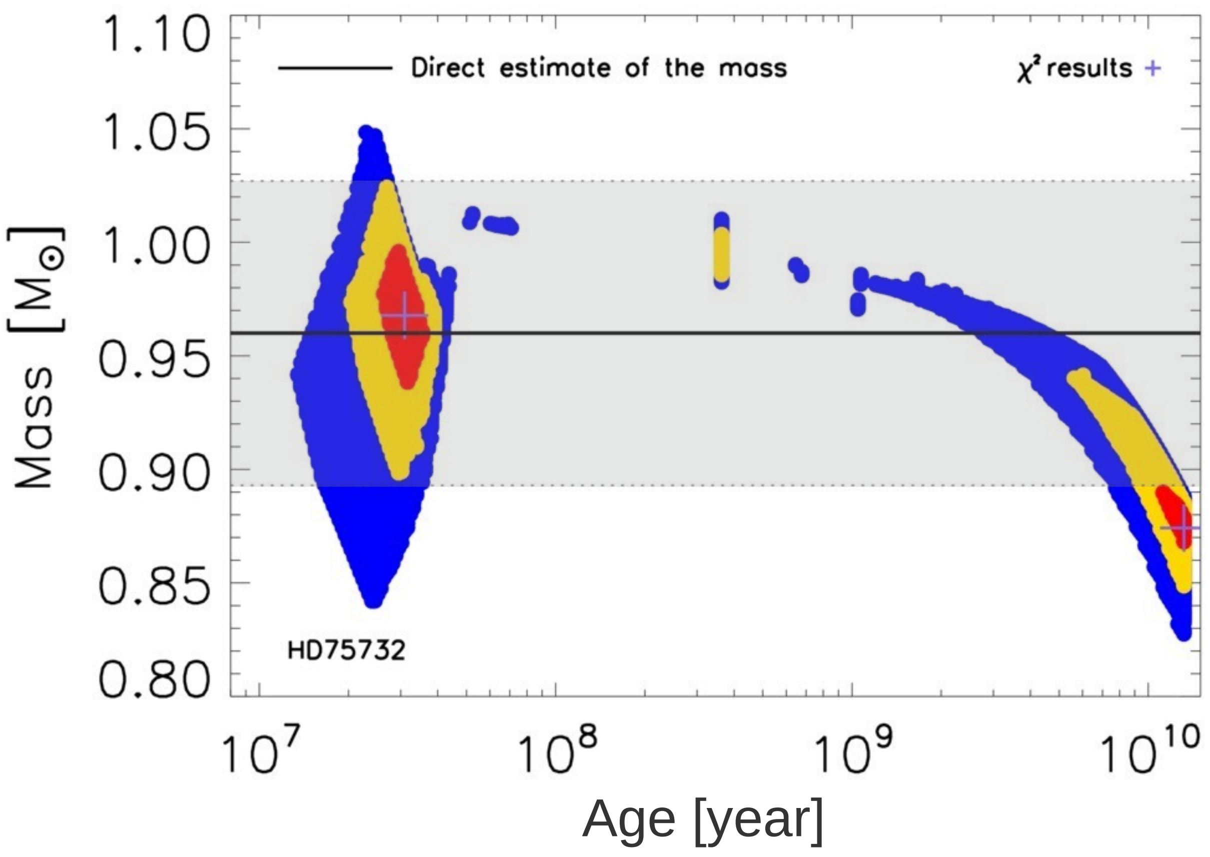

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Stellar evolution models:

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 ± 0.078 $M_\odot$; $\rho_\star$ = 1.82 ± 0.19 $\rho_\odot$.

Models with different input physics give $M_\star$ = 0.755 to 0.810 ± 0.04 $M_\odot$ (or 0.719 with large initial Helium abundance), and $\rho_\star$ = 1.96 – 2.09 ± 0.22 $\rho_\odot$.

3) Mass and Radius of the stars

Conclusion:

Stellar evolution models are great to understand stellar physics and/or stellar populations.

They are not adapted to derive the parameters of 1 given star of unknown other parameters.
The small uncertainty is only the internal one, and neglects the external source of error.

We rather use our **measurements**.

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

Stellar evolution models:

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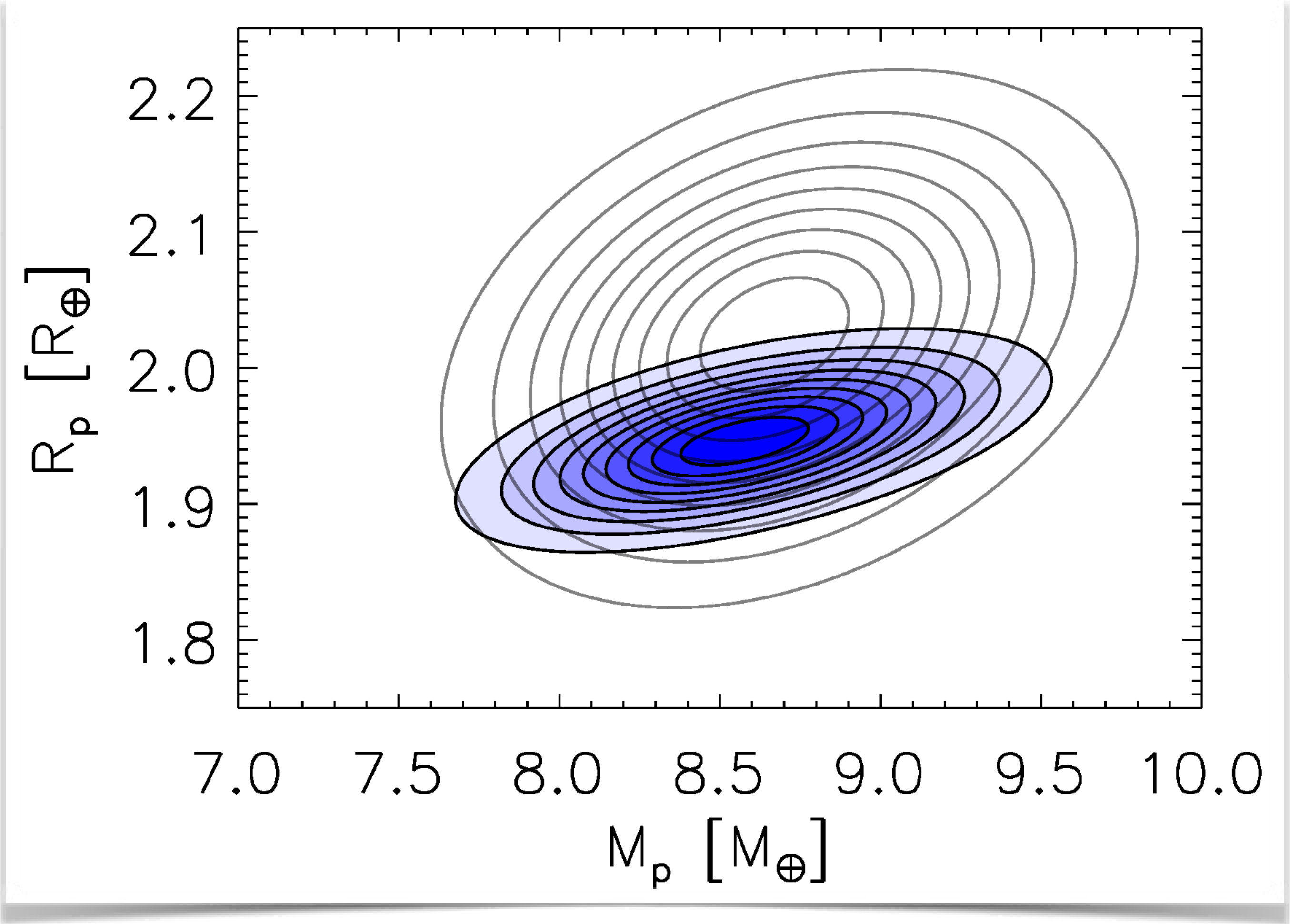
4) Mass and Radius of the planet 55 Cnc e

$$f_p(M_p,R_p) \quad \propto \quad \iint \exp\left(-\frac{1}{2}\left(\frac{K(M_p,M_\star)-K}{\sigma_K}\right)^2\right) \times \exp\left(-\frac{1}{2}\left(\frac{\Delta F(M_p,M_\star)-\Delta F}{\sigma_{\Delta F}}\right)^2\right) \times f_{MR\star}(M_\star,R_\star)\,\mathrm{d}M_\star\,\mathrm{d}R_\star$$

55 Cnc e:



White: our first estimate, with Hipparcos parallax + poor transit light-curve.

Correlation: 0.3

→ $\rho_p = 1.06 \pm 0.13\ \rho_\oplus$.

Blue: our second estimate, with Gaia parallax + refined HST light-curve and radial velocity.

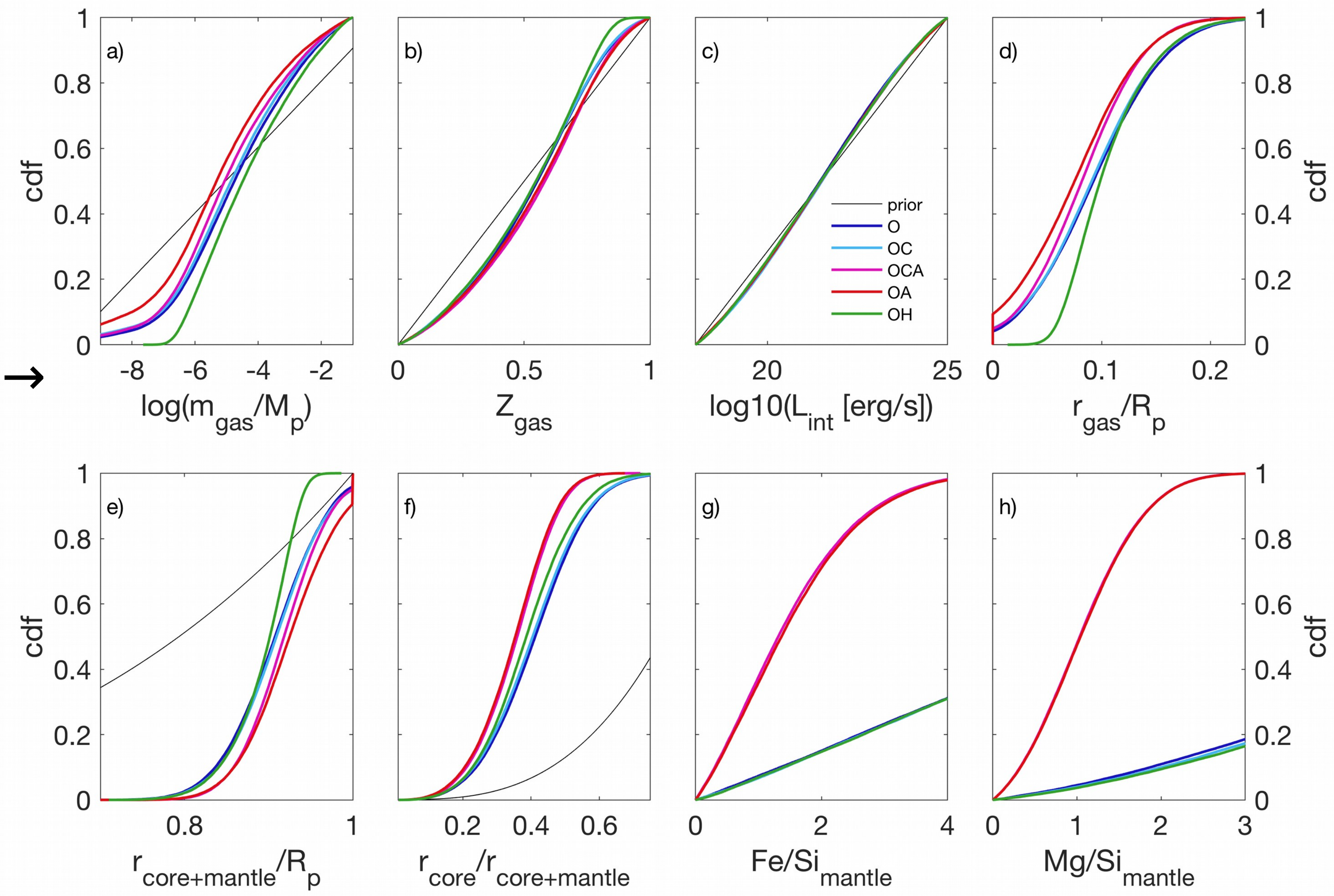
Correlation: 0.54.

→ $\rho_p = 1.164 \pm 0.062\ \rho_\oplus = 6421 \pm 342$ kg.m^{-3} .

4) Infer the planets' properties: 55 Cnc e

Input:
Original data M_p
Correl. M_p-R_p (0.30)
Hypothetical corr. (0.85)
Abundances

Model by Dorn et al. (2017a,b) →

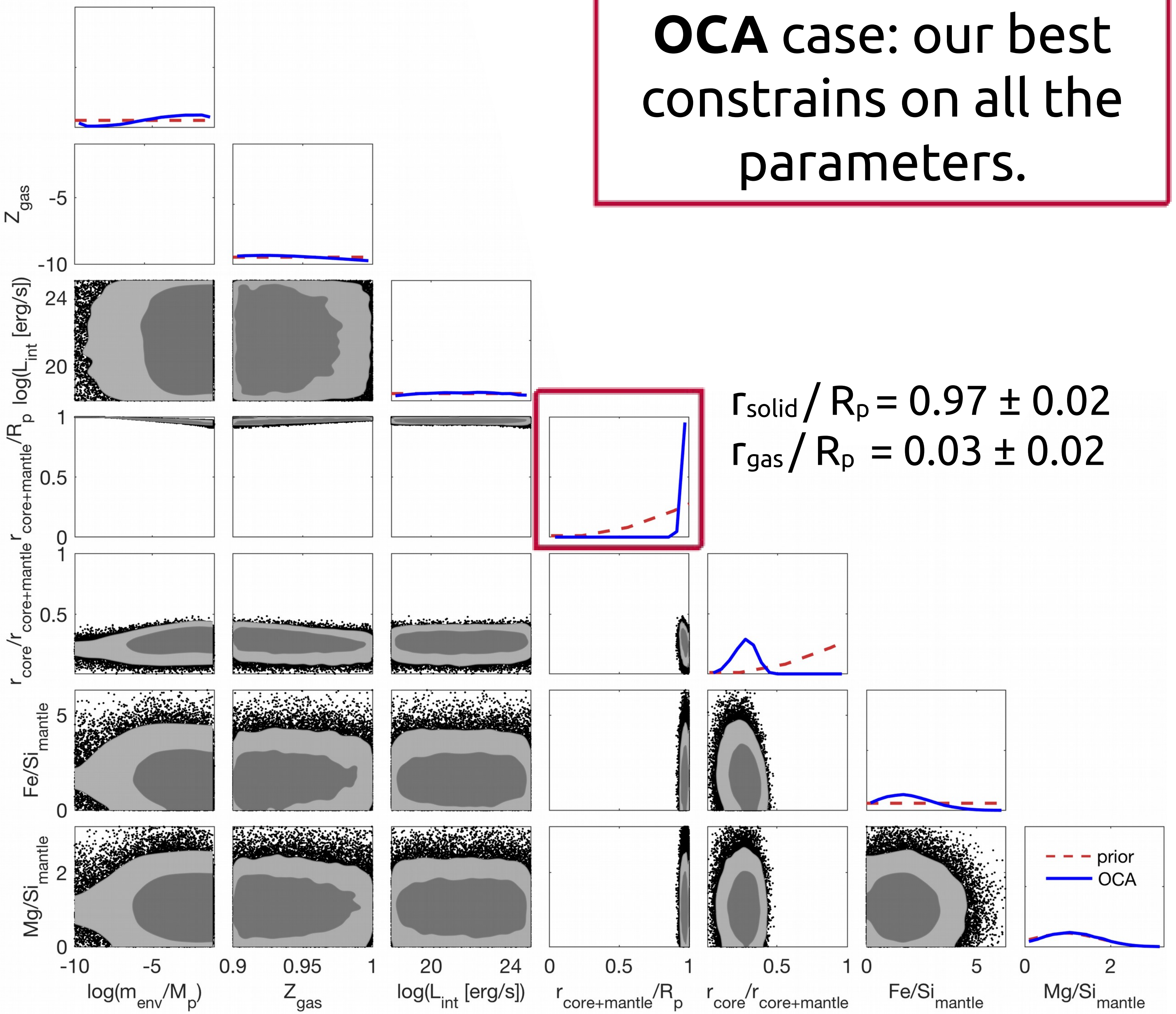


Results:
A → composition of the mantle
C → gas layer
H → could rule out pure solid composition

4) Infer the planets' properties: 55 Cnc e

OCA case: our best constrains on all the parameters.

$r_{solid} / R_p = 0.97 \pm 0.02$
$r_{gas} / R_p = 0.03 \pm 0.02$



Atmosphere thickness = **3% of R_p**

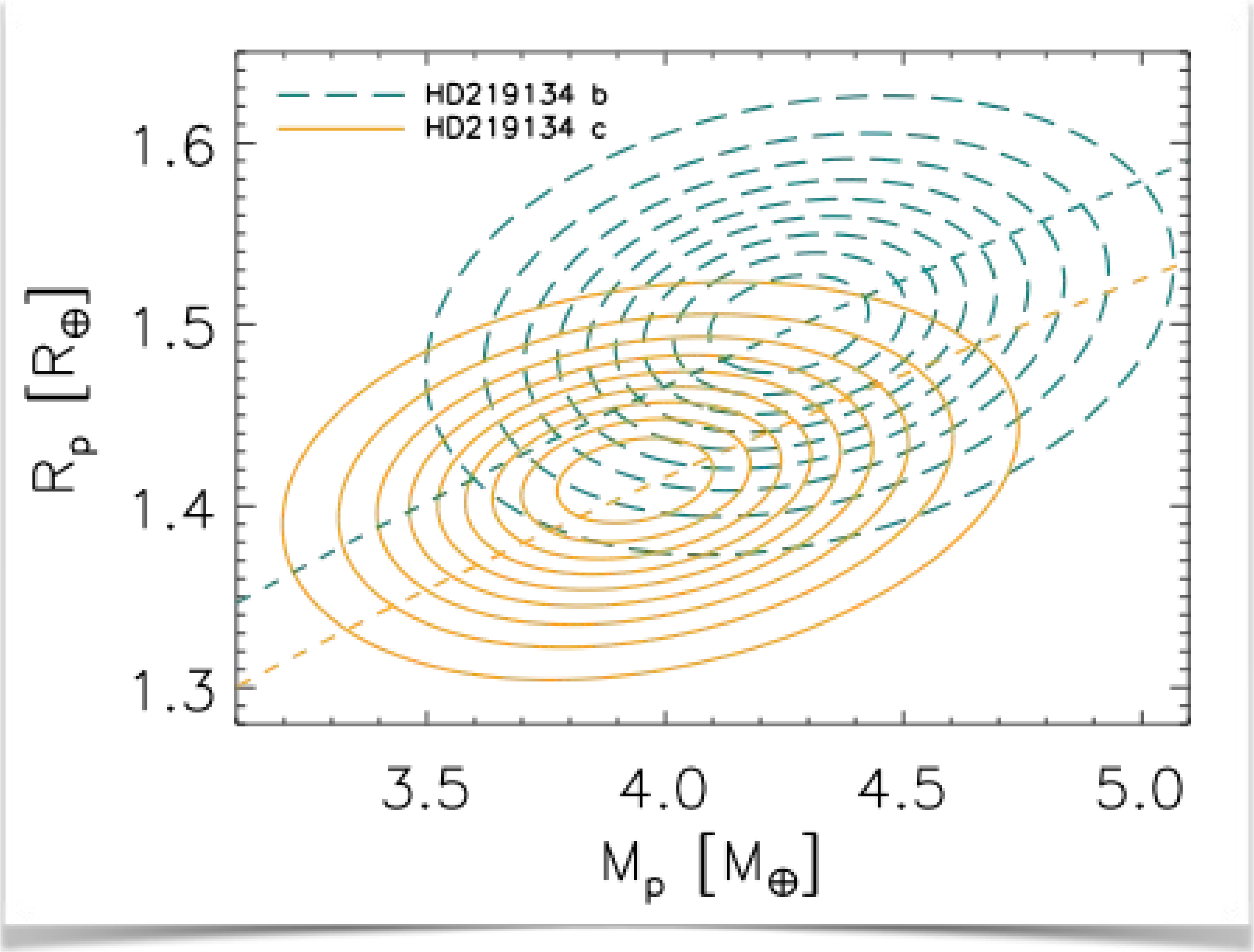
➔ not a good target for transmission spectroscopy

➔ chemistry of the interior non necessarily carbon-rich

4) Mass and Radius of HD219134's planets

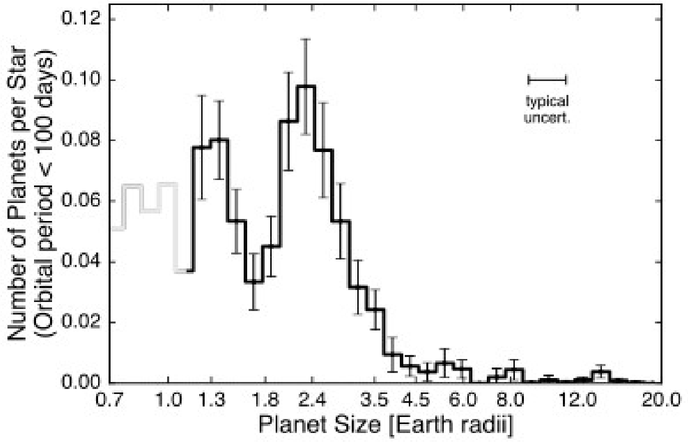
$$f_p(M_p, R_p) \propto \iint \exp\left(-\frac{1}{2}\left(\frac{K(M_p, M_\star) - K}{\sigma_K}\right)^2\right) \times \exp\left(-\frac{1}{2}\left(\frac{\Delta F(M_p, M_\star) - \Delta F}{\sigma_{\Delta F}}\right)^2\right) \times f_{MR\star}(M_\star, R_\star)\, \mathrm{d}M_\star\, \mathrm{d}R_\star$$

HD219134 b & c:



	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

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



4) 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 two times 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 ?

Bower et al. (2019): a molten mantle is 25% less dense than a solid one. Could HD219134b be partially molten ?

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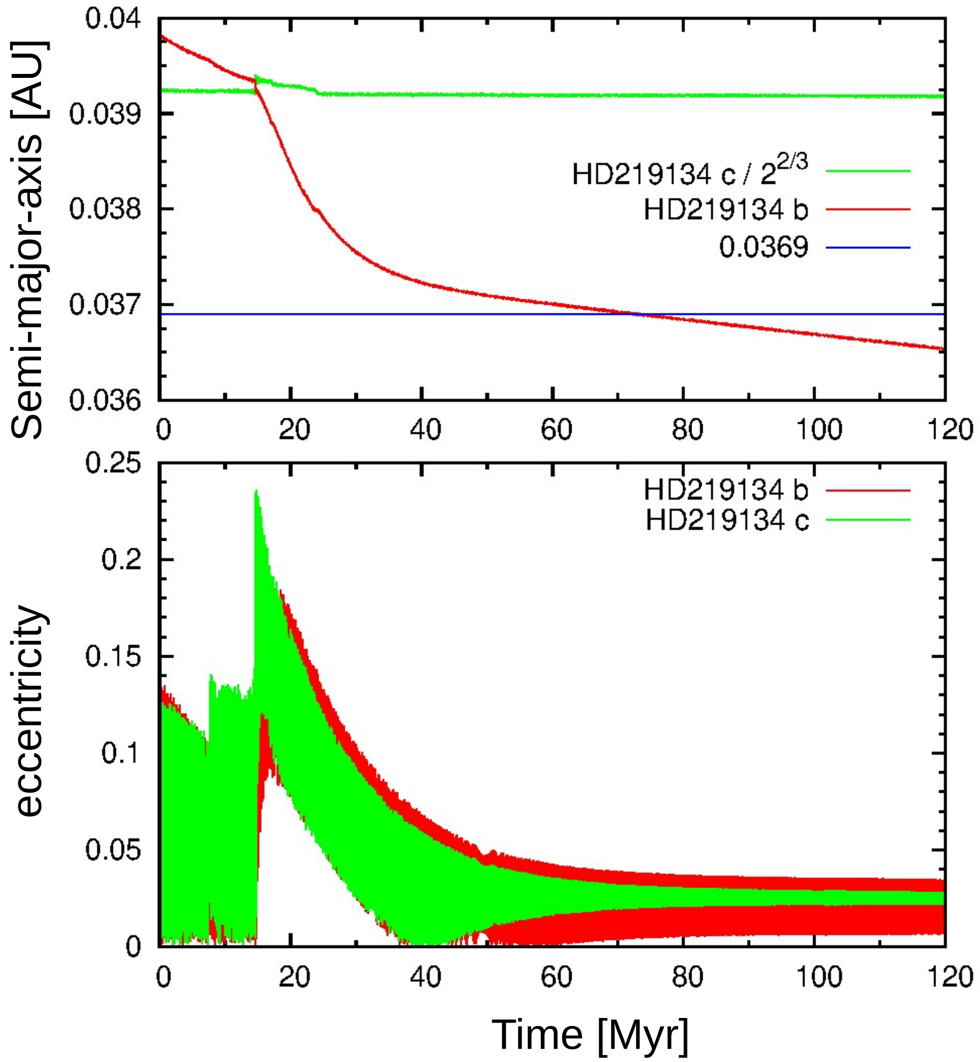


Tidal heating from the host star dissipates energy and circularizes the orbit.
→ Sustainable energy source if and only if the eccentricity is pumped by other planets (ex: Io).

$$\dot{E} = \frac{21}{2}\frac{k_2}{Q}\frac{(\omega R_p)^5}{G}e^2$$

<u>N-body simulations of the system:</u>

e_b oscillates between 0.005 and 0.037.
→ tidal heating up to 100 times more than Io!

HD219134c: less tidal heating than Io (because further from the star).

4) Planets' properties: HD219134 b & c

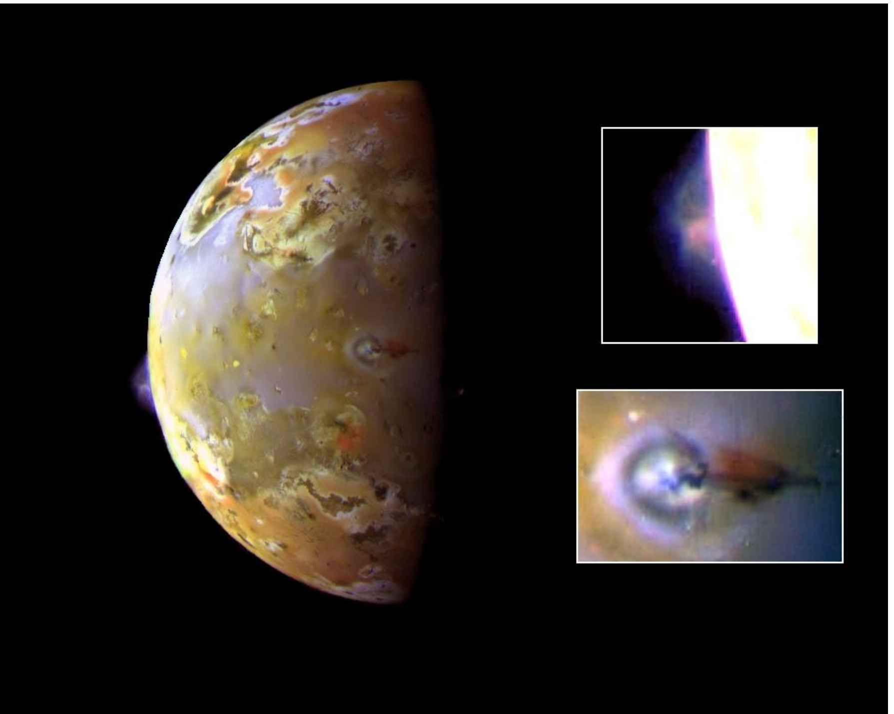
$\rho_b/\rho_c = 0.905 \pm 0.131$

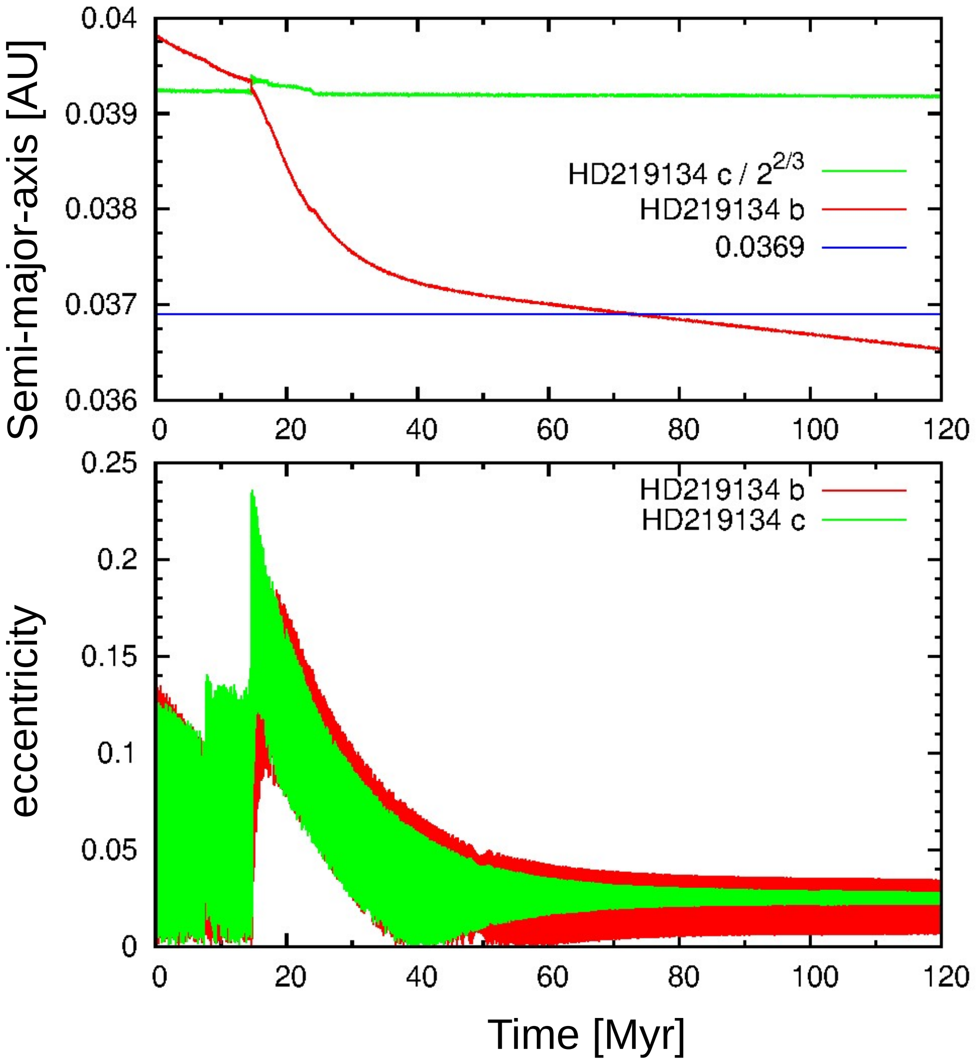
$$\dot{E} = \frac{21}{2}\frac{k_2}{Q}\frac{(\omega R_p)^5}{G}e^2$$

<u>Conclusion</u>

N-body simulations of the system show that planet b's eccentricity is excited despite not measurable.

Assuming a dissipation (k_2/Q) 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.





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CONCLUSIONS & PERSPECTIVES

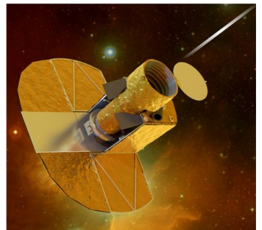
OK, « *Discovery of a molten lava world* » was more a catchy title than a real thing.

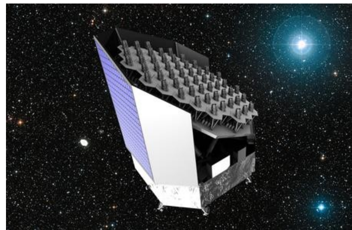
Nonetheless, our method combining interferometry with transit light-curve to measure the radius and mass of stars is powerful:

- characterization of transiting exoplanets, independently of stellar models

- benchmark stars for testing stellar models

TESS, CHEOPS, & PLATO are going to discover plenty of transiting exoplanets in front of bright stars, accessible by interferometry (1^{st} release of TESS: already 7 planets around 4 four stars accessible with VEGA, if in northern hemisphere) + SPICA/CHARA will push the limits of interferometry → promising future for this method…





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Crida, Ligi, Dorn, Lebreton (2018, ApJ + RNAAS)

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