INTASTE

combining INTerferometry and ASTeroseismology: a new insight on Exoplanet characterisation

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Marie Skłodowska-Curie/AstroFIt2 Fellow

AstroFIt2 Meeting
Roma - October 23rd

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Osservatorio Astronomico di Brera INAF

Astro FIt 2 Astronomy Fellowships in Italy

FROM THE FORMATION TO THE CHARACTERISATION OF EXOPLANETS

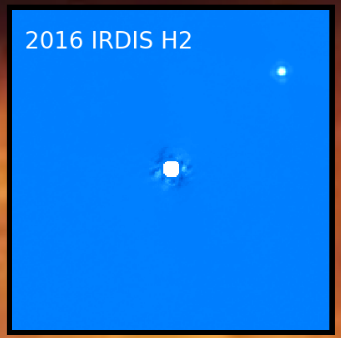
Planetary formation: 2 scenarios

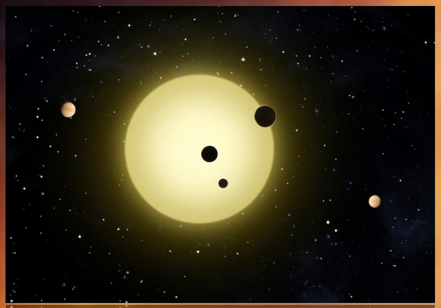
Gravitational instability

- Giant planets, large separation (> 50 au)

Core Accretion

- Rocky planets
- Giant planets close to the star (<50 au)

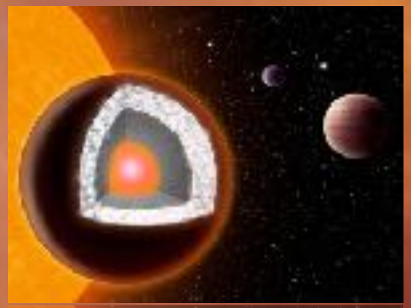


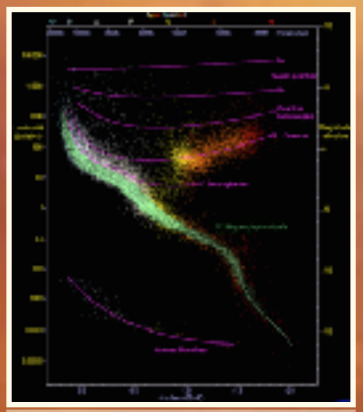


Physical properties

m_p, R_p, ρ_p

Composition, habitability





$R_\star$, $M_\star$, $\rho_\star$

T_{eff}, $L_\star$, abundances

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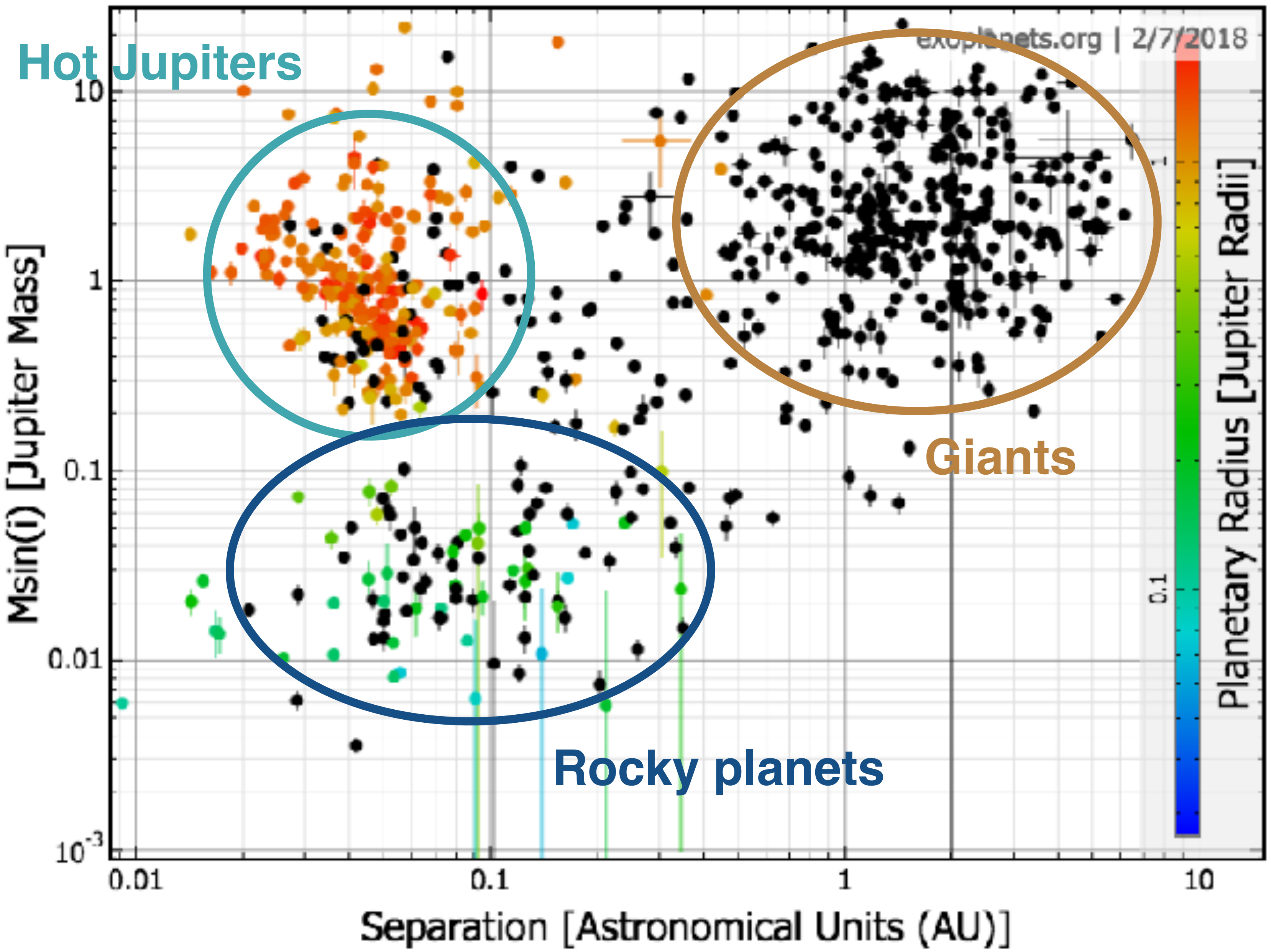
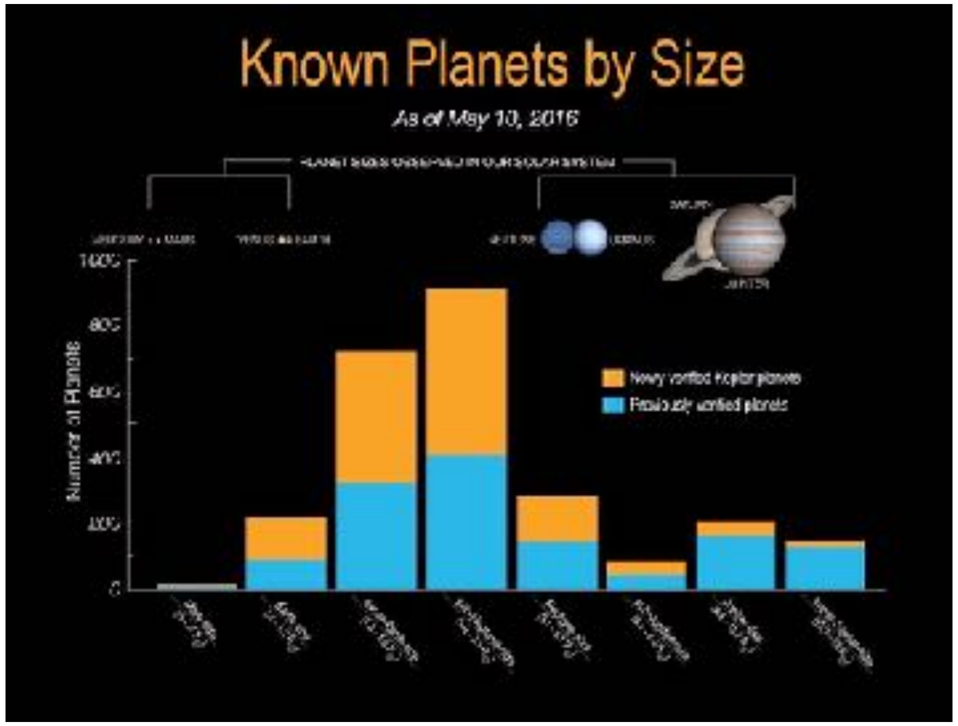


- 3 groups of exoplanets
- instrumental bias?

A majority of Super-Earths and mini-Neptunes



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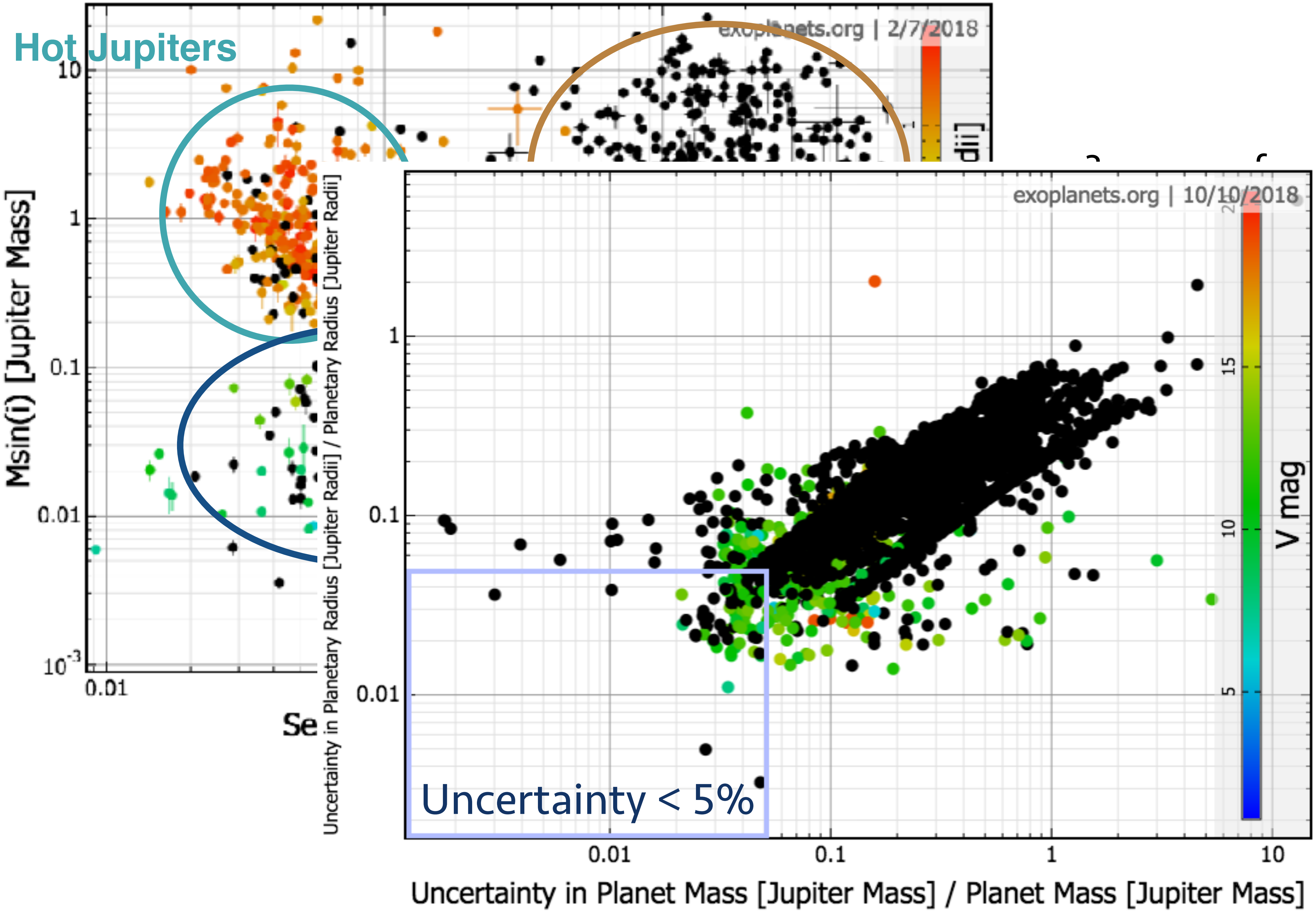
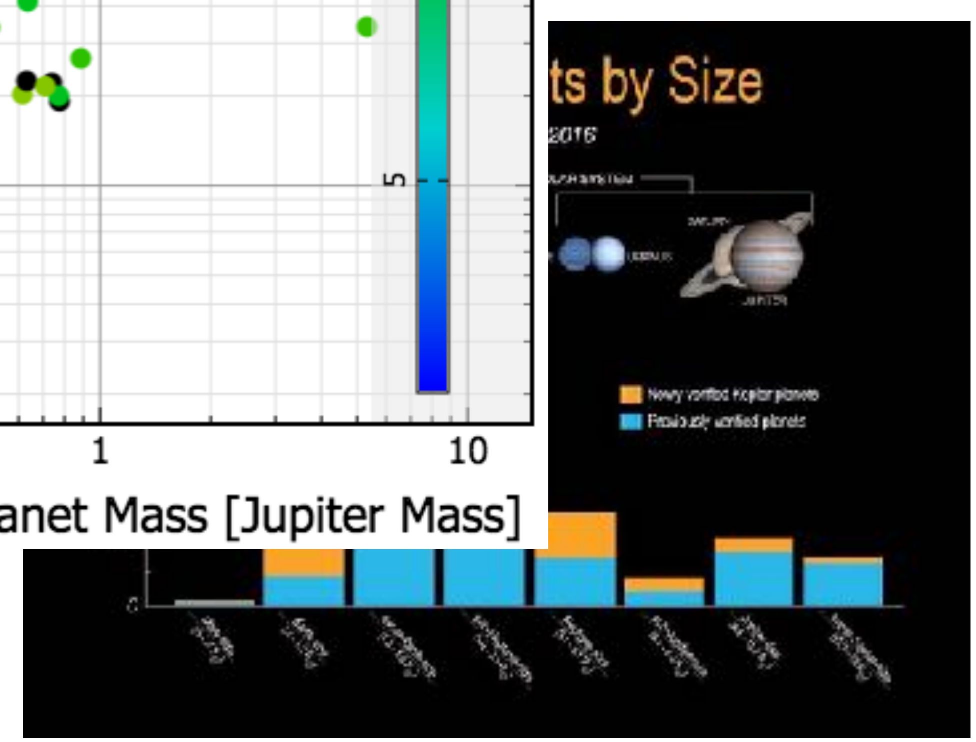


oplanets
ias?

per-Earths
he



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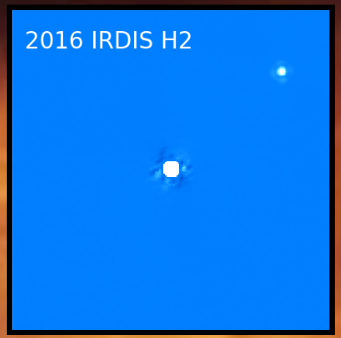

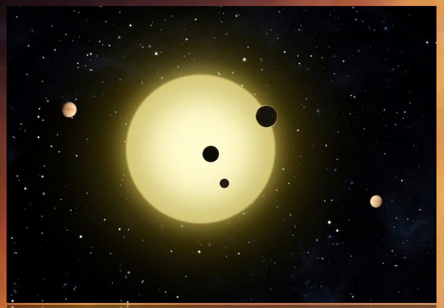

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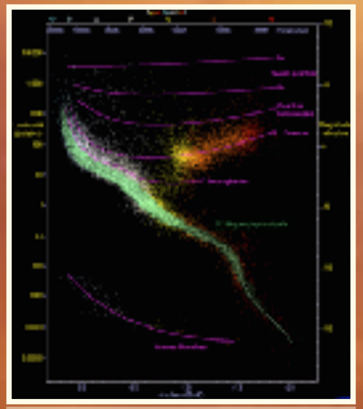

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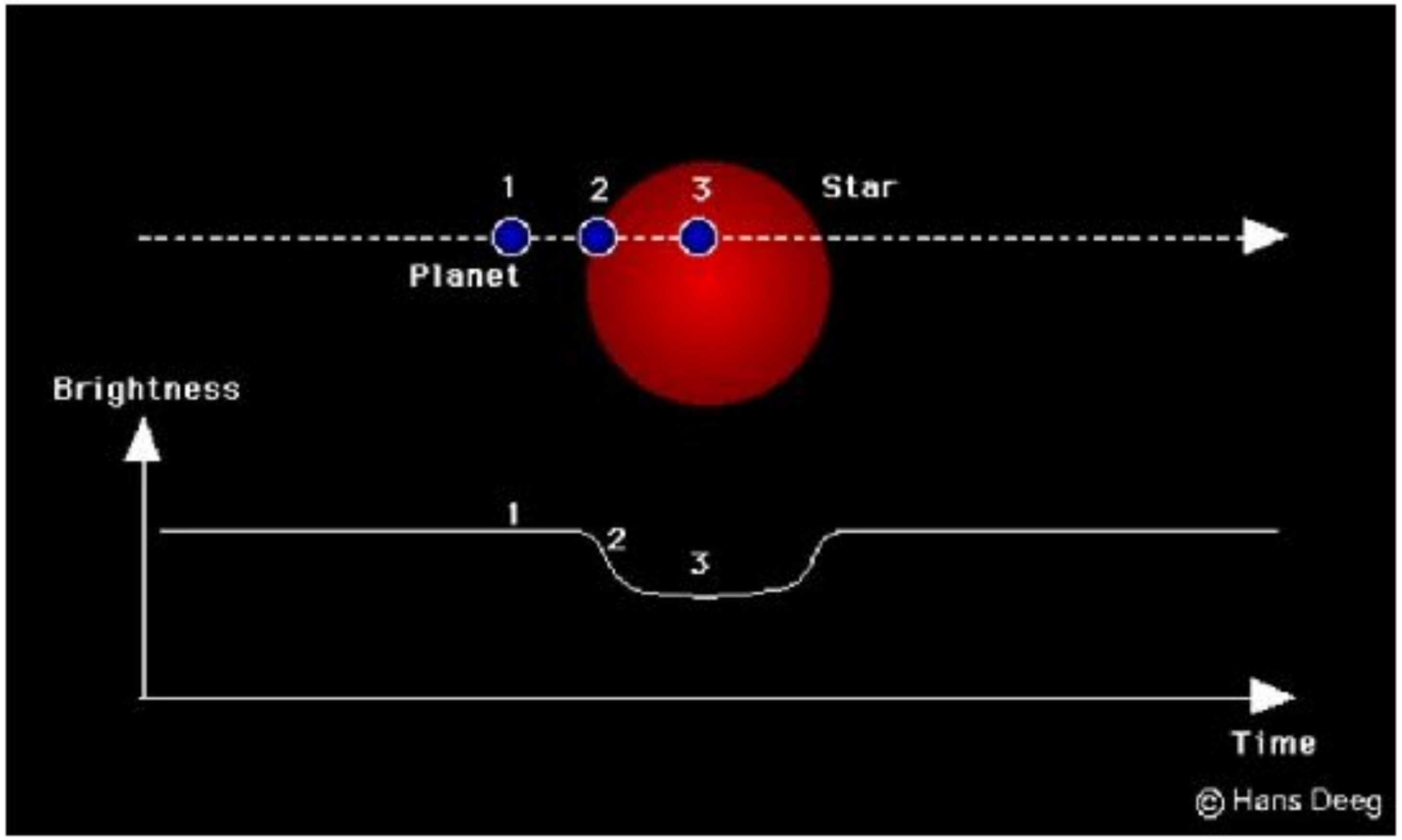

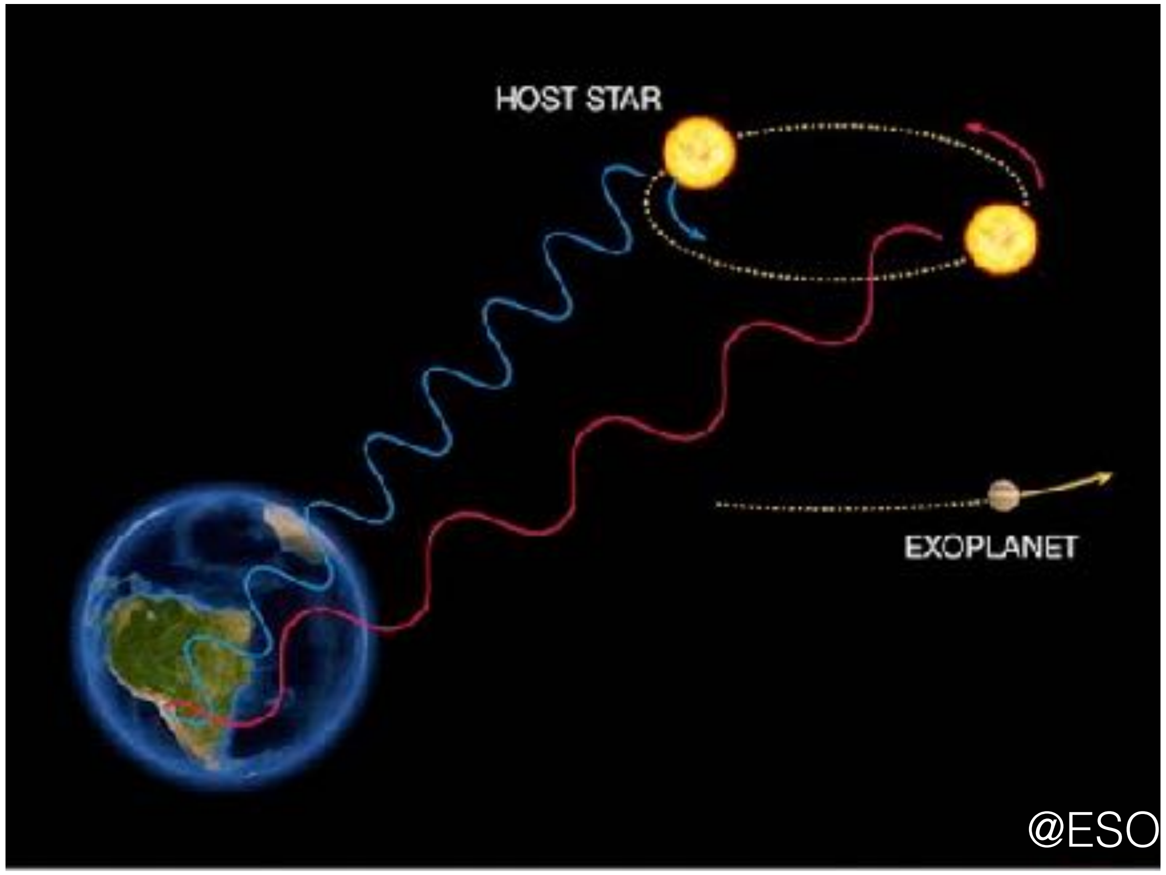

$$\frac{\Delta F}{F} = \left(\frac{R_P}{R_\star}\right)^2$$

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

→ Depend on **R★** and **M★**

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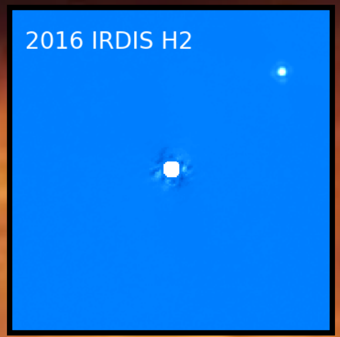

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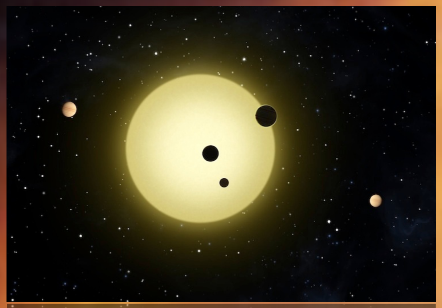

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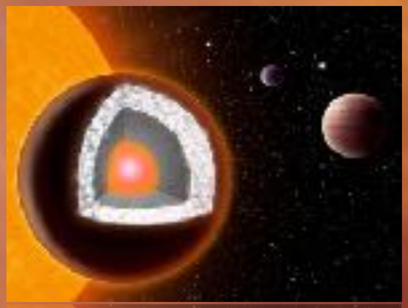

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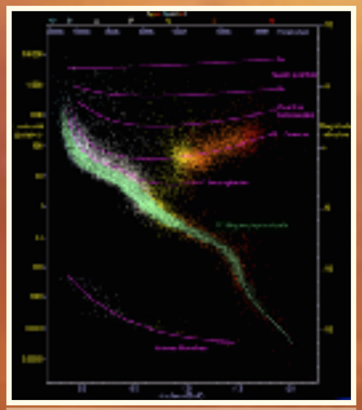

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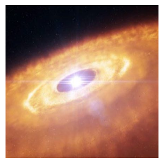
Limitations
- Reserved to bright stars
- Difficult to mix techniques because of stellar properties/ instrumental specificities

High Angular Resolution:
- Interferometry
- Direct imaging

Appropriate for exoplanetary detection and characterisation

OUTLINE



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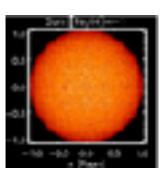
- Getting the most out of it: 55 Cnc

- Formation mechanisms: the challenging case of GJ504



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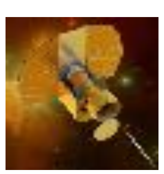
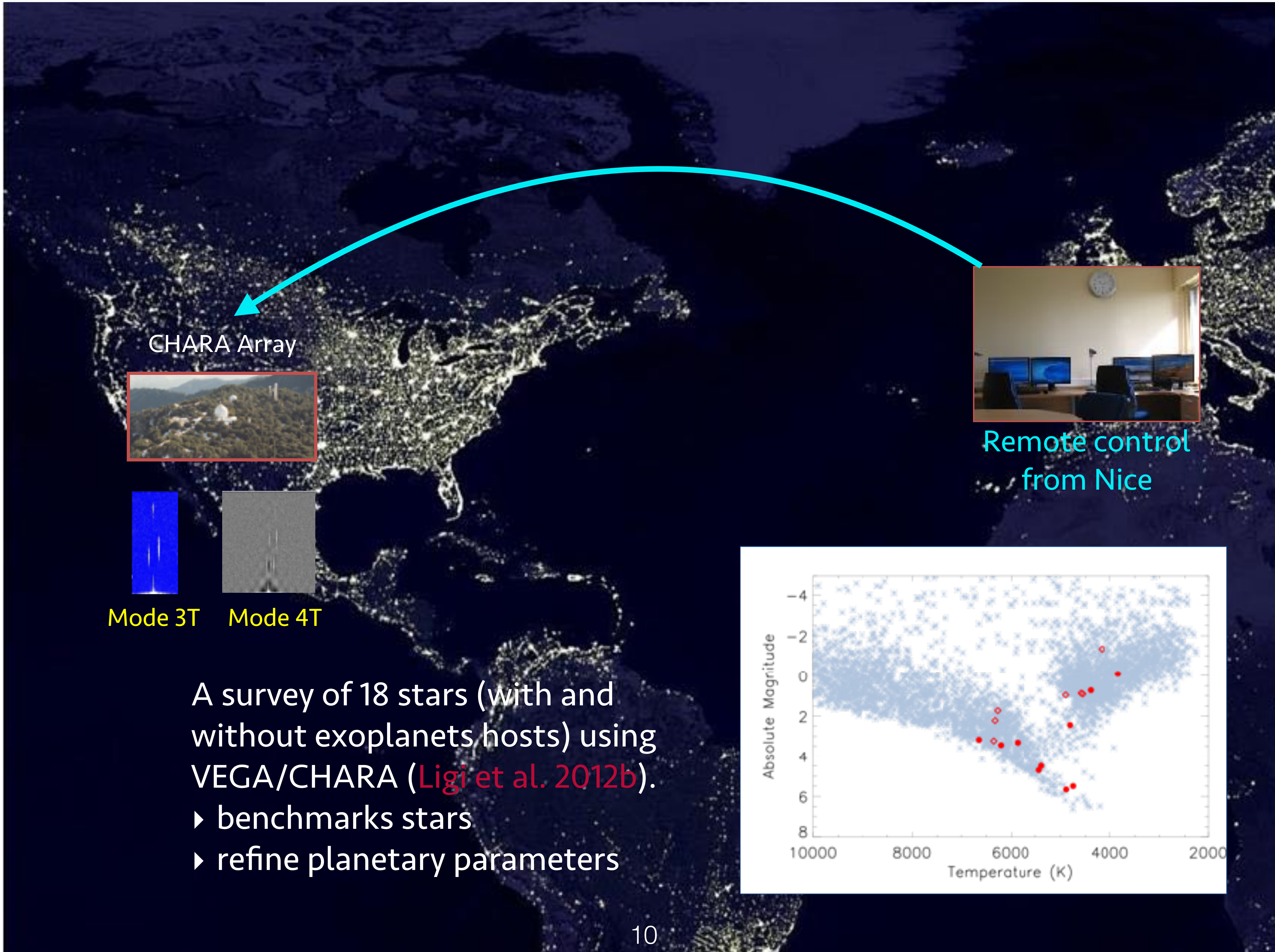


- Conclusion and perspectives

DIRECT MEASUREMENTS OF ANGULAR DIAMETERS



A survey of 18 stars (with and without exoplanets hosts) using VEGA/CHARA (Ligi et al. 2012b).

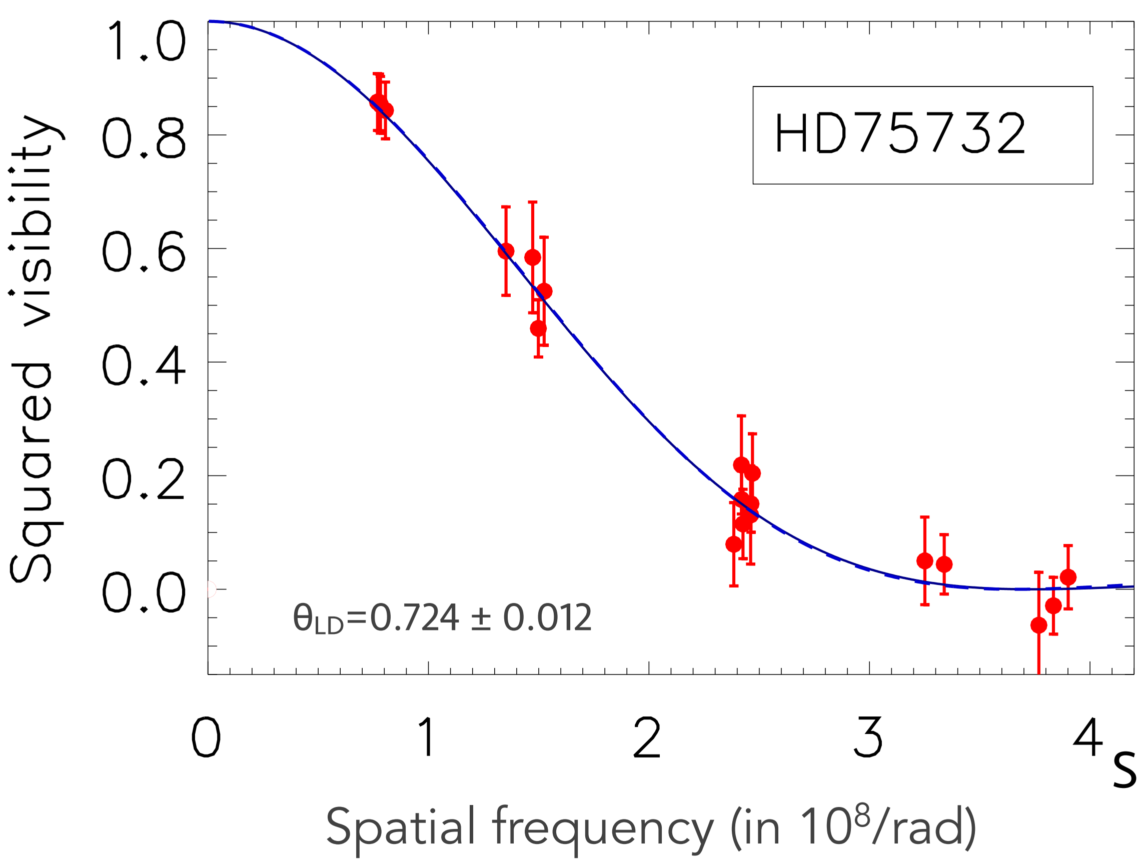
- benchmarks stars
- refine planetary parameters

DIRECT MEASUREMENTS OF ANGULAR DIAMETERS

Interferometric angular diameter

Hipparcos+*Gaia* distance

$$R_{\star[R_\odot]} = \frac{\theta_{\mathrm{LD[mas]}} \times d_{\mathrm{[pc]}}}{9.305} .$$



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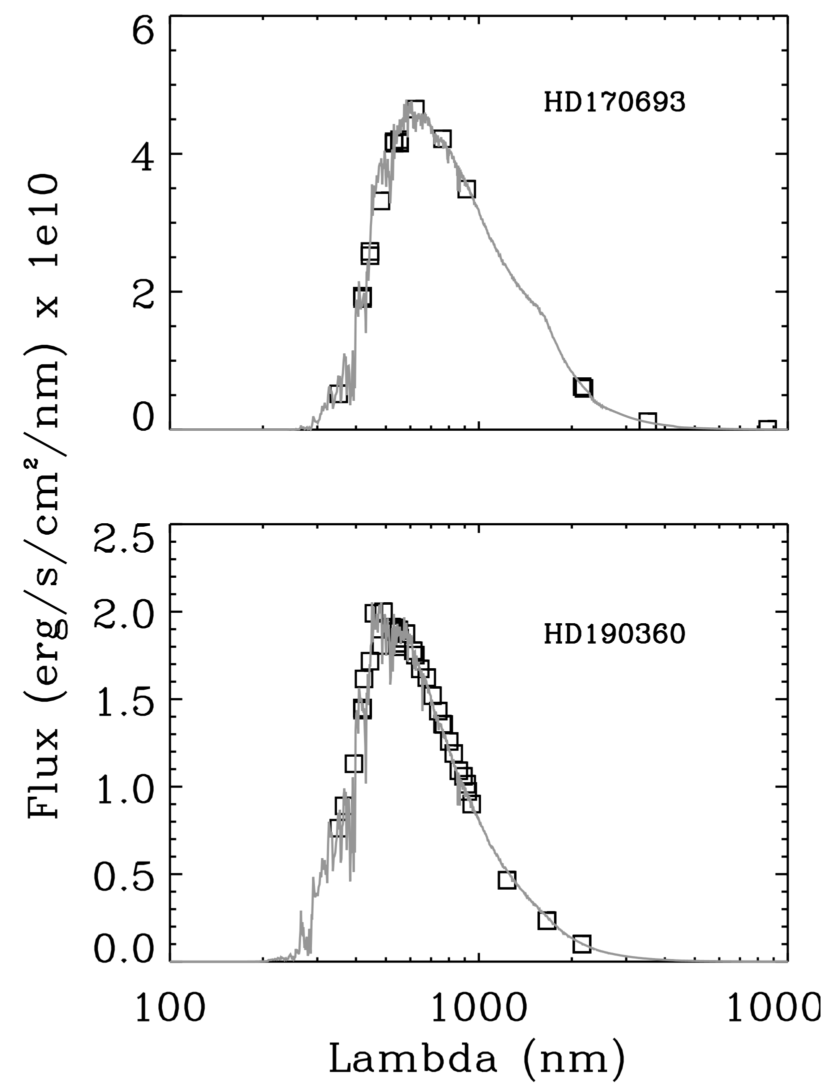


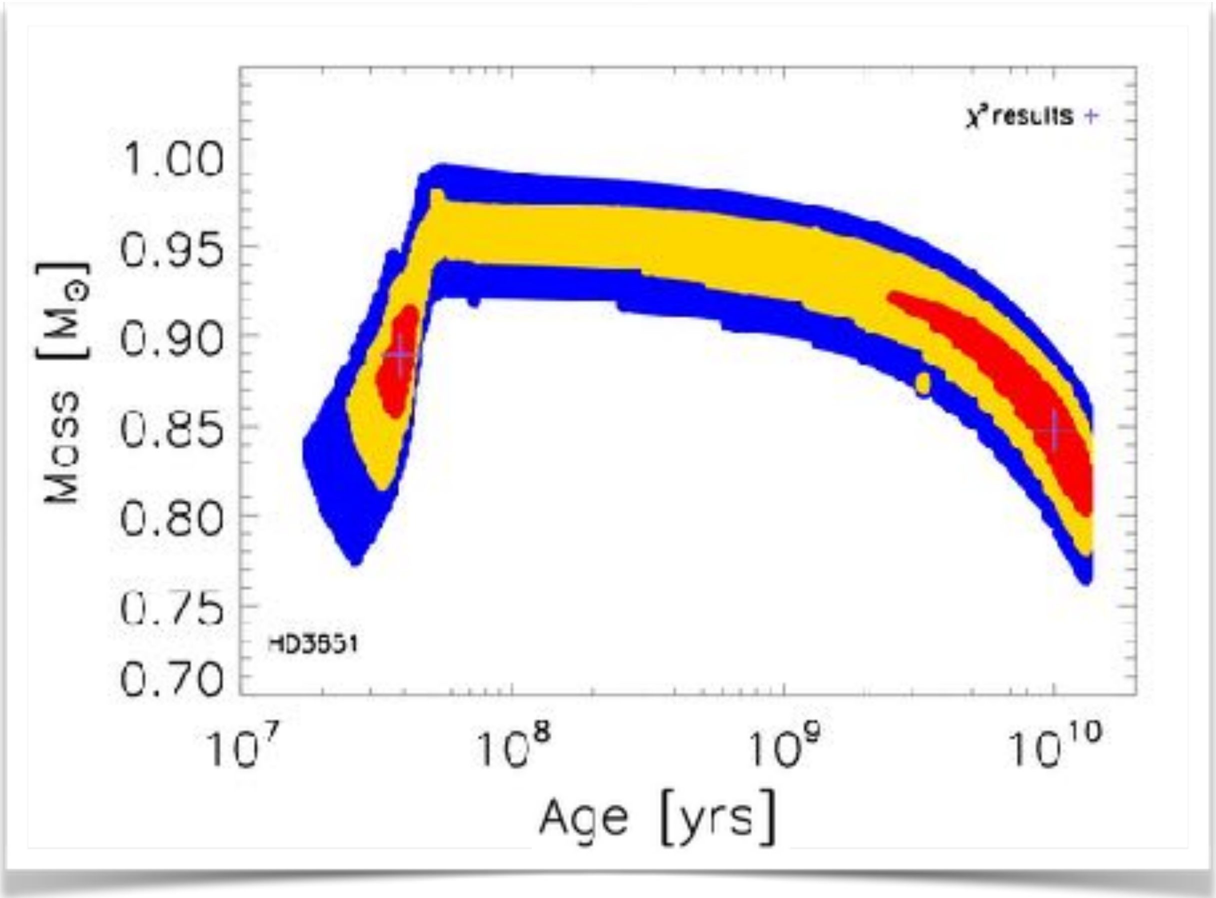
$$T_{\mathrm{eff},\star} = \left(\frac{4 \times F_{\mathrm{bol}}}{\sigma_{\mathrm{SB}} \theta_{\mathrm{LD}}^2}\right)^{0.25} \Rightarrow L_\star = 4\pi d^2 F_{\mathrm{bol}}$$

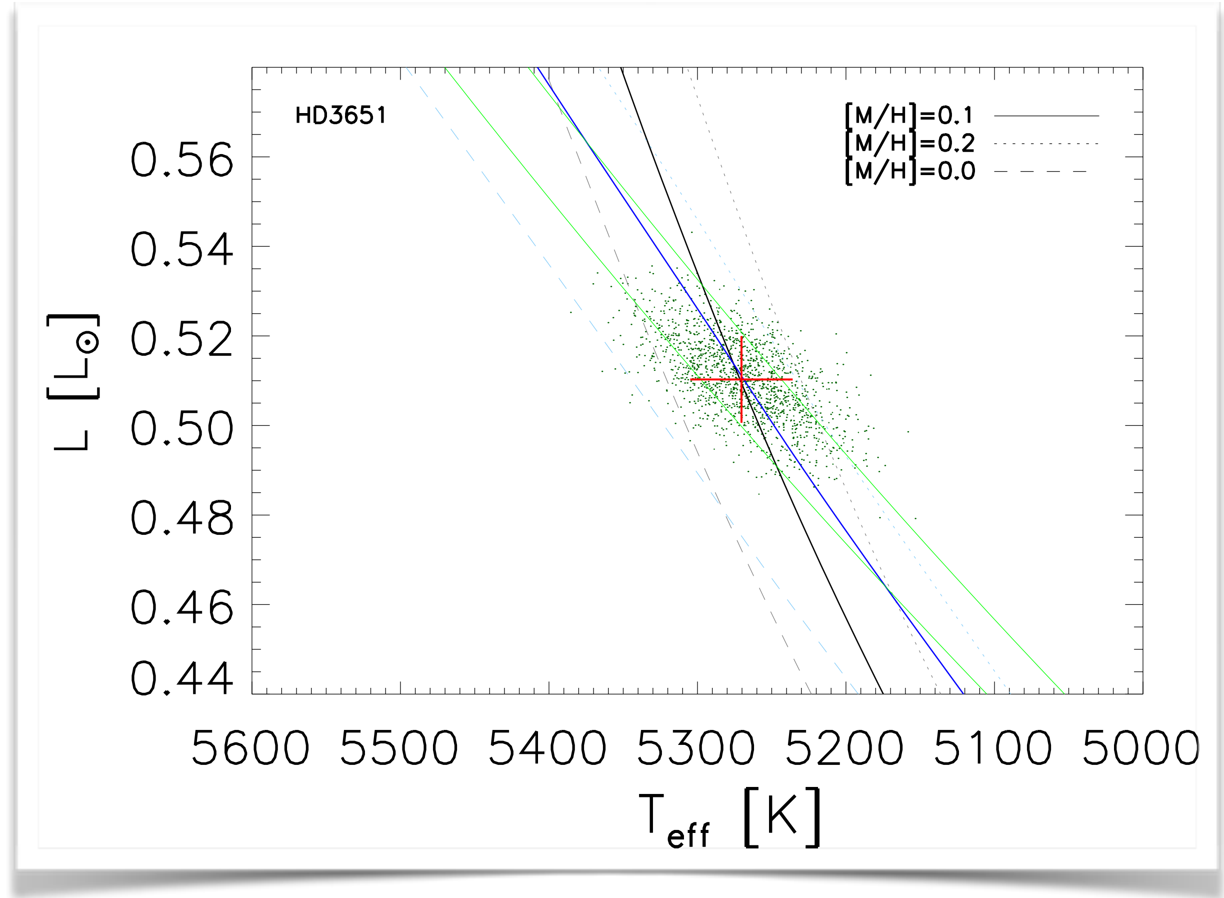
Interferometric angular diameter

Ligi et al. (2012a, 2016)

DETERMINATION OF STELLAR MASSES AND AGES

Method: Interpolation of PARSEC stellar models (*Bressan et al. 2012*).





- This corresponds to the approximate likelihood map in the ($M_\star$, $age_\star$) for which each term of the equation $\chi^2 = \frac{(L - L_\star)^2}{\sigma_{L_\star}{}^2} + \frac{(T_{\rm eff} - T_{\rm eff,\star})^2}{\sigma_{T_{\rm eff,\star}}{}^2} + \frac{([{\rm M/H}] - [{\rm M/H}]_\star)}{\sigma_{[{\rm M/H}]_\star}{}^2}$ is less than 1, 2, 3 (red, yellow, blue, resp.).

- Then, least squares to give a value.
- generally 2 distinct solutions for main sequence stars (degeneracy).

Ligi et al. (2012a, 2016)

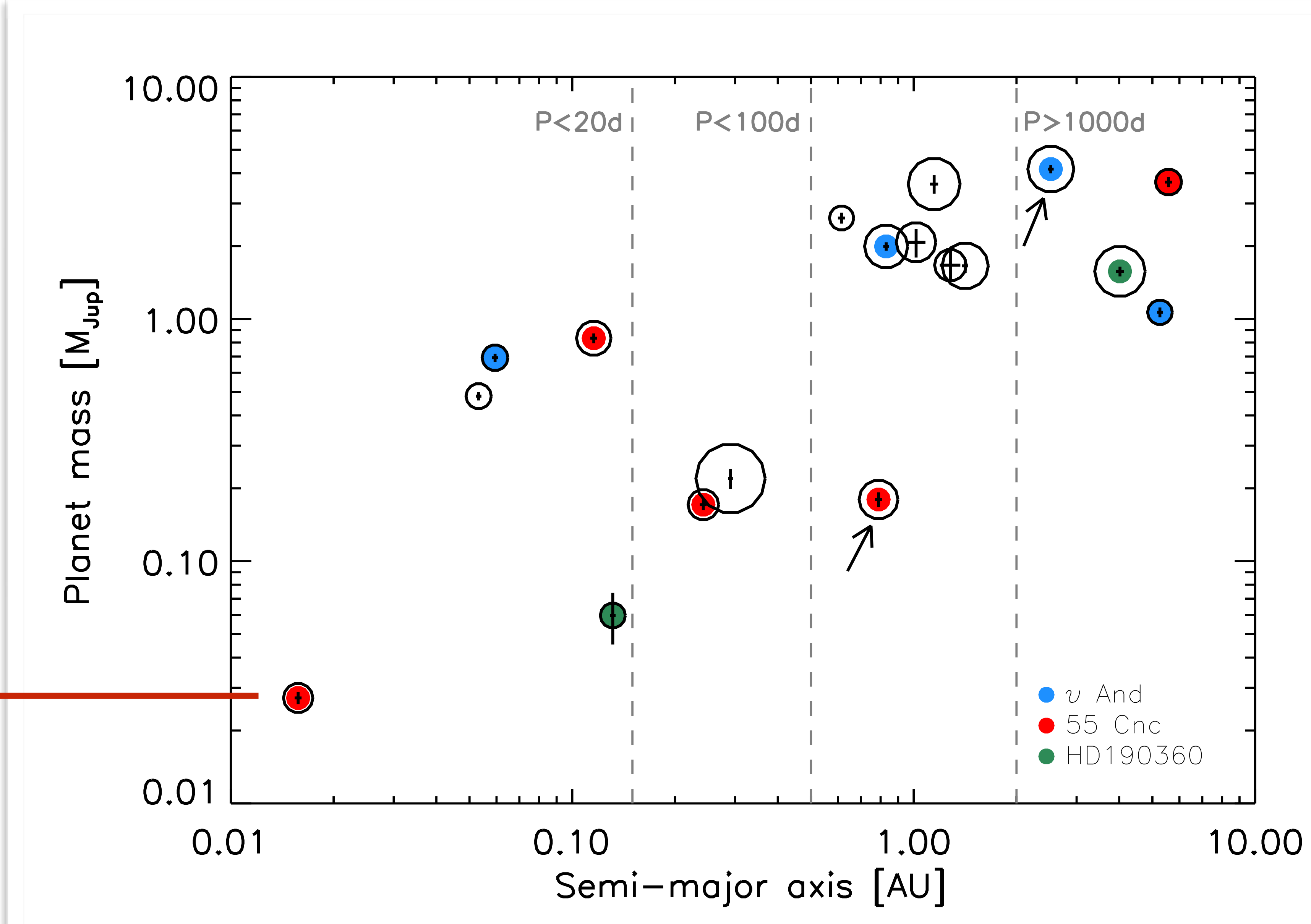
FROM STELLAR PARAMETERS TO EXOPLANET PROPERTIES

New robust determinations:

- semi-major axis *a*,
- habitability zone,
- $m_p \sin(i)$

Decrease the uncertainties for 18 exoplanets

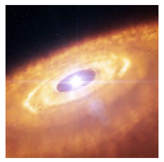
Transiting exoplanet 55 Cnc e



→ Better description of exoplanetary population

Ligi et al. (2012a, 2016)

OUTLINE



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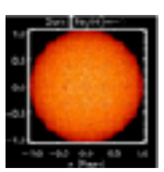

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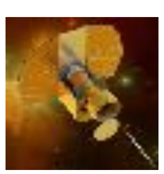

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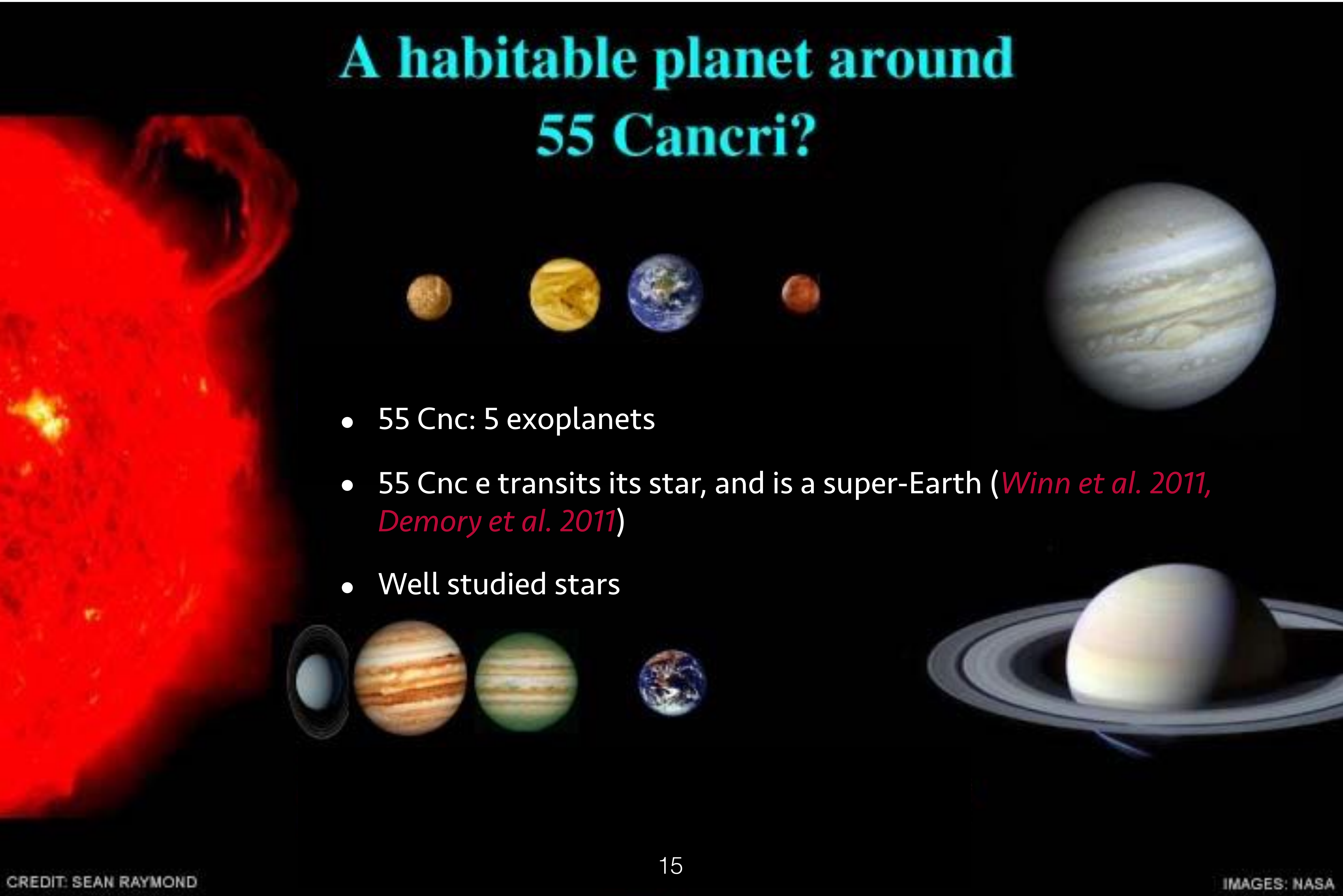
55 CNC AND ITS TRANSITING EXOPLANET



- 55 Cnc: 5 exoplanets
- 55 Cnc e transits its star, and is a super-Earth (*Winn et al. 2011, Demory et al. 2011*)
- Well studied stars

55 CNC AND ITS TRANSITING EXOPLANET

Stellar Results

Transit duration: $T=2R_\star/a\Omega$
Period: $P = 2\pi/\Omega$

→

$P/T^3 = (\pi^2 G/3)\,\rho_\star$
measure of stellar density $\rho_\star$ **(Maxted et al. 2015, Seager & Mallén-Ornelas 2003)**

Measure of $R_\star$ by interferometry → $M_\star=(4\pi/3)R_\star{}^3\rho_\star$ **(Ligi et al. 2016)**

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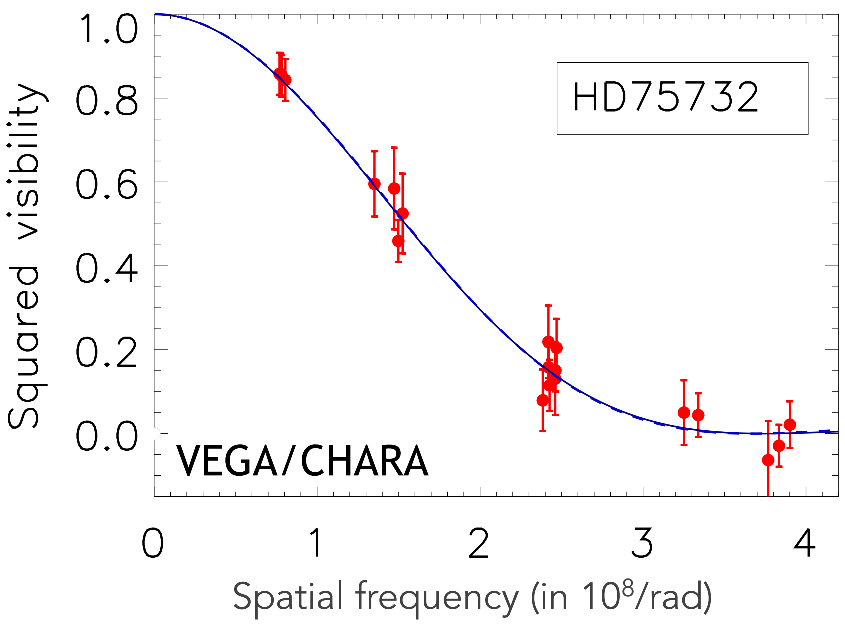

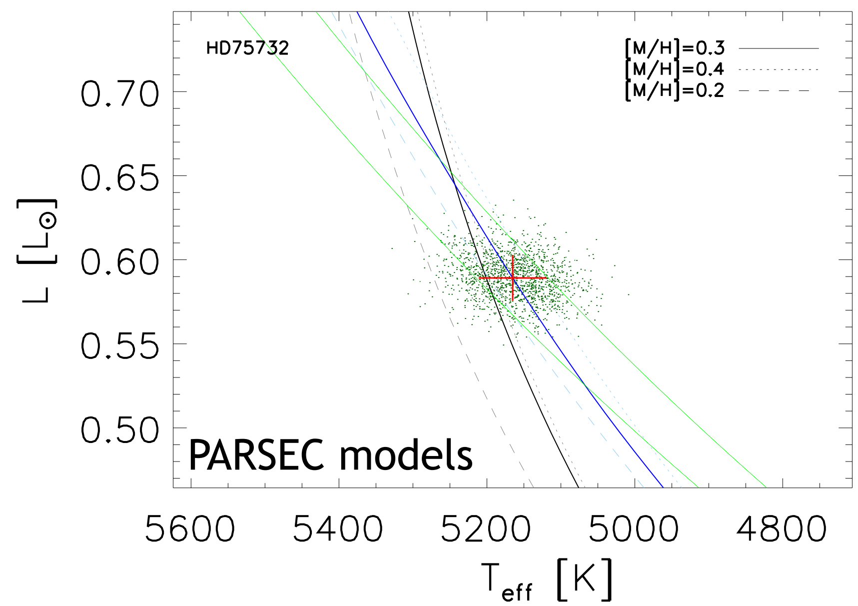

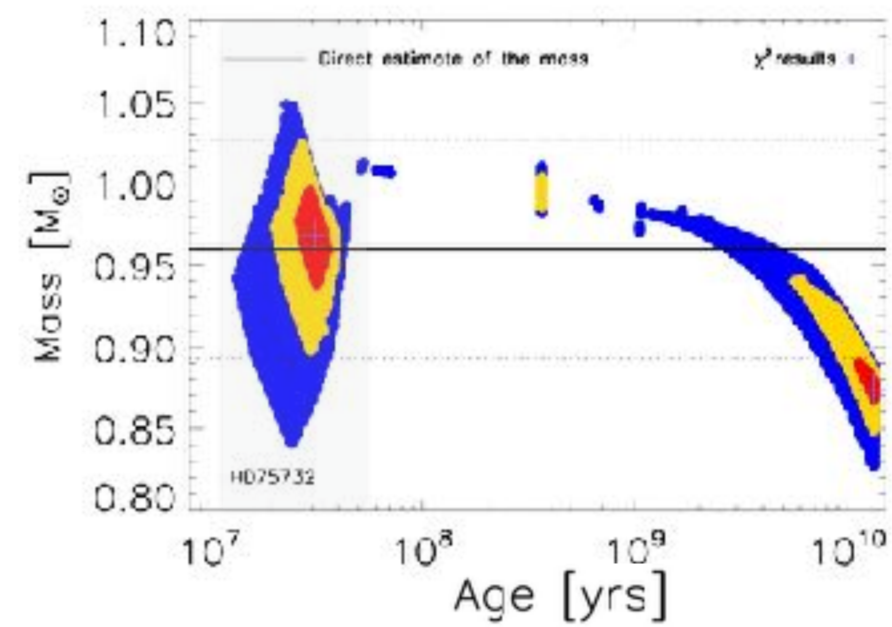

- From isochrones: 2 solutions
  - **Young solution**: $M_\star = 0.968 \pm 0.018\ M_\odot$, 30.0 ± 3.028 Myrs
  - **Old solution**: $M_\star = 0.874 \pm 0.013\ M_\odot$, 13.19 ± 1.18 Gyrs
- Using the stellar density + interferometric radius: $M_\star = 0.96 \pm 0.067\ M_\odot$

USING STELLAR DENSITY AND ANGULAR DIAMETERS

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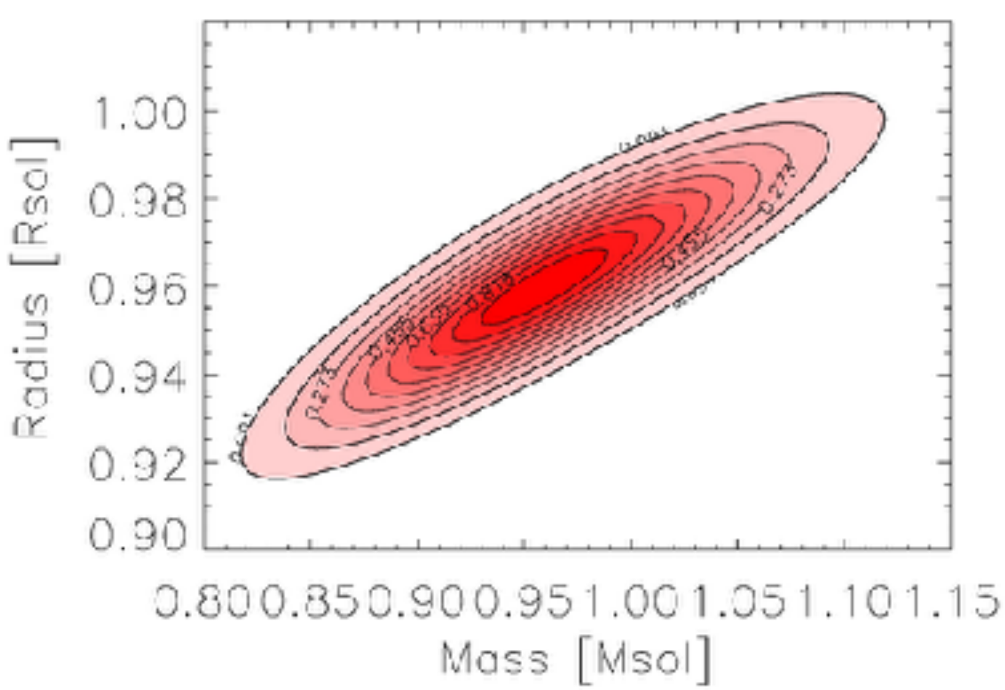
From the PDF of $R_\star$ and $\rho_\star$,
analytic joint PDF of $M_\star$ - $R_\star$.

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

→ Strong correlation: 0.995!
(Crida, Ligi et al. 2018a,b)
→ Different $M_\star$ than von Braun et al. (2011) based on isochrones.



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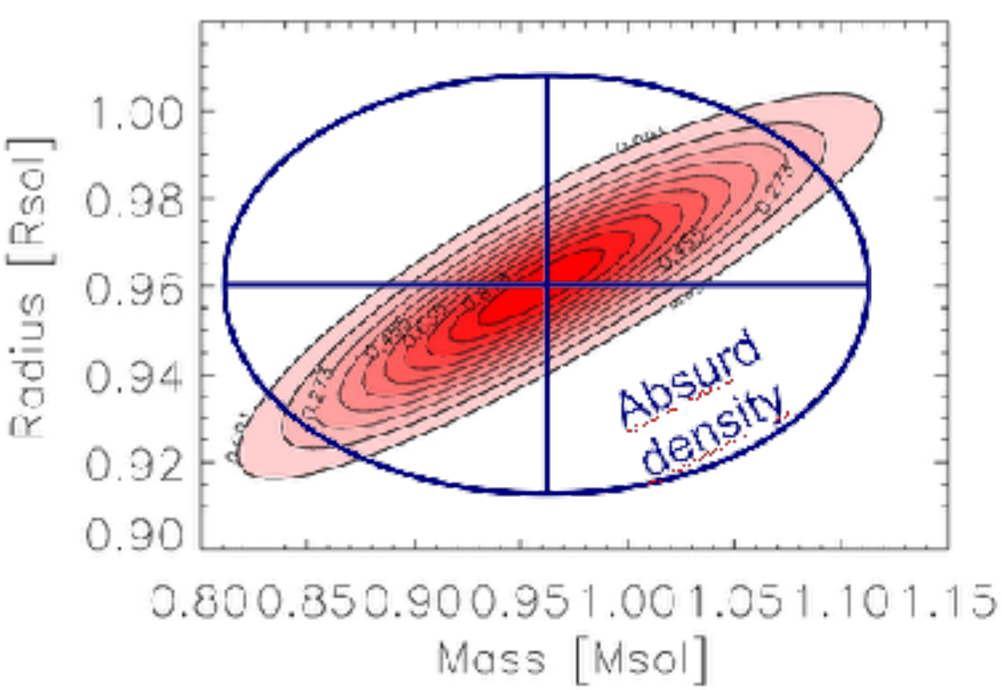
Taking the values of $R_\star$ and $M_\star$ from Ligi et al. (2016), one gets the large, wrong blue ellipse.



USING STELLAR DENSITY AND ANGULAR DIAMETERS

Planetary Results

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$\rightarrow$

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Measure of $R_\star$ by interferometry $\rightarrow$ $M_\star = (4\pi/3) R_\star^3 \rho_\star$ **(Ligi et al. 2016)**

Transit light curve:
$R_p = R_\star \times \sqrt{TD}$

RV measurements:
$m_p \sin(i) = M_\star K (P/2\pi G M_\star)^{1/3}$

sin(i)

R_p

m_p

ρ_p

Some calculation to decrease the error bar...

$$\rho_p = \frac{3^{1/3}}{2\pi^{2/3} G^{1/3}} \rho_\star^{2/3} R_\star^{-1}\, T D^{-3/2}\, P^{1/3}\, K\, (1-e^2)^{1/2}$$

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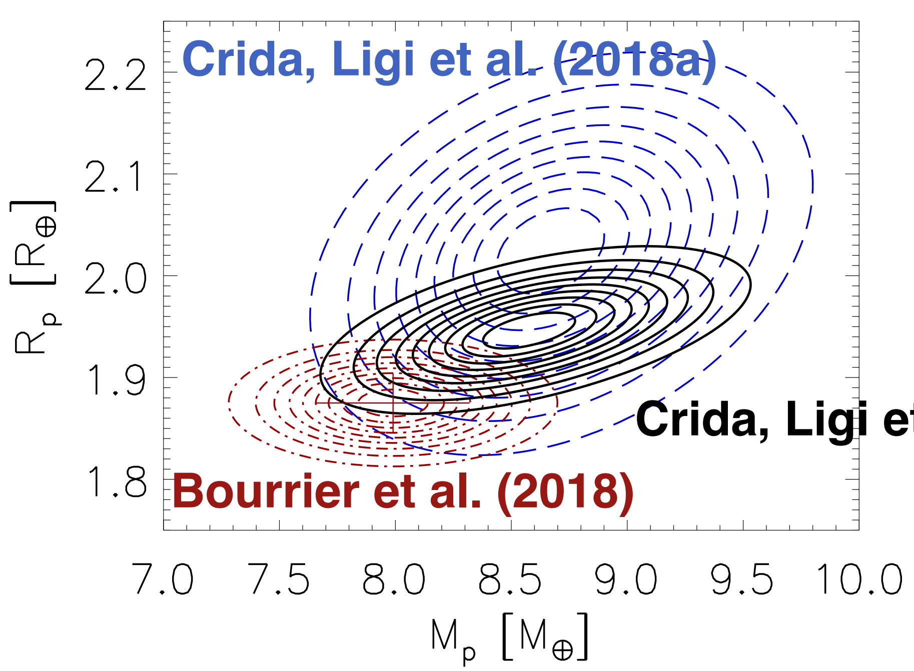
→ Joint PDF of m_p-R_p



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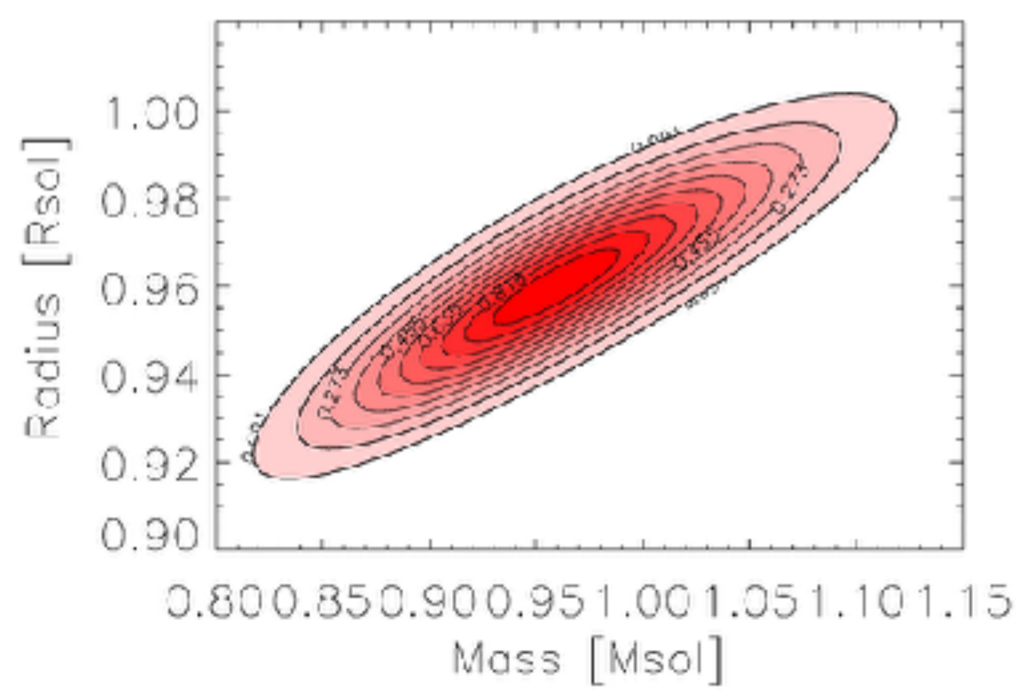

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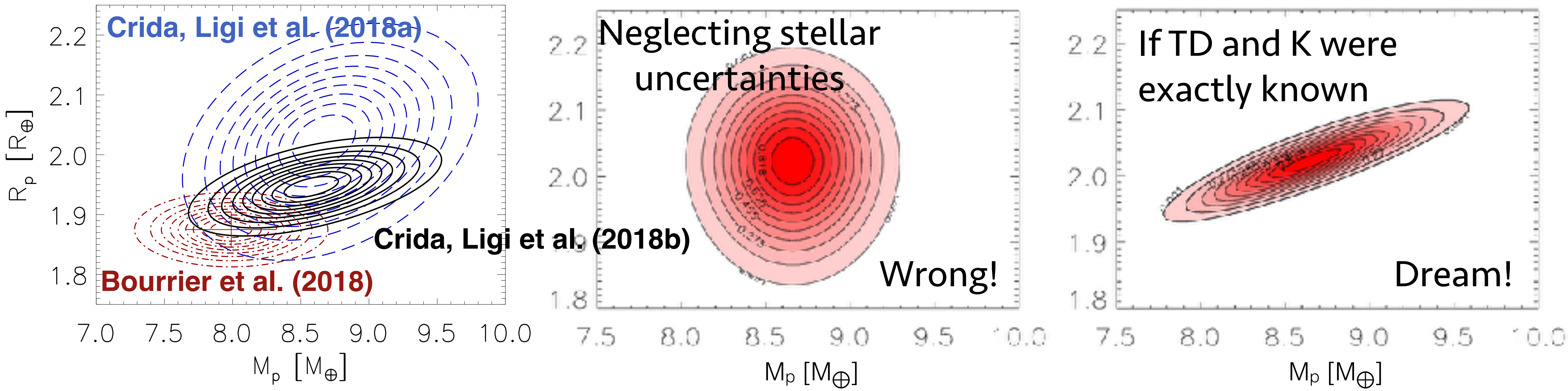
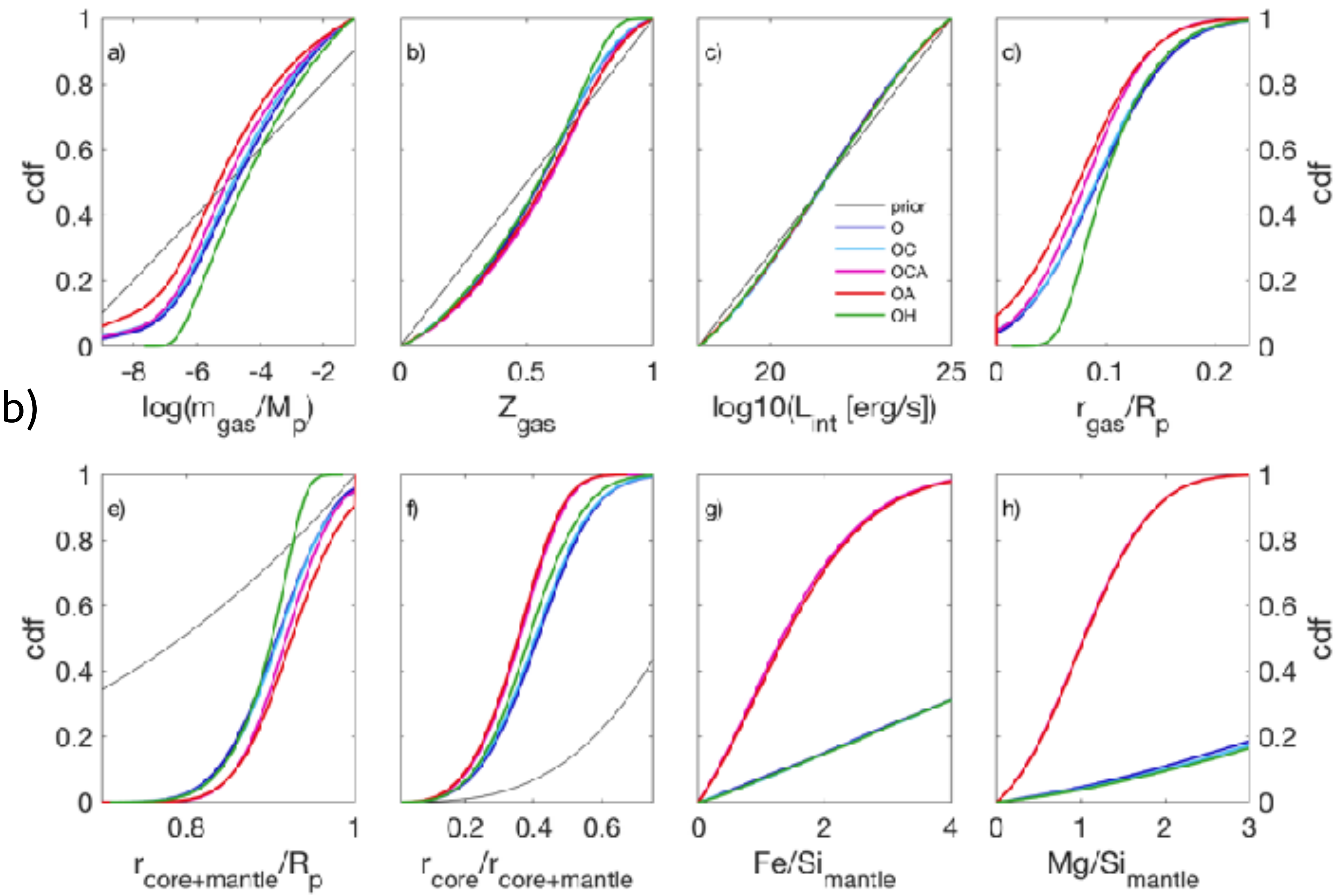


55 CNC E: INTERNAL COMPOSITION

Input :
Original data mp
Correl. mp-Rp (0.30)
Hypothetical corr. (0.85)
Abundances

Model by Dorn et al. (2017a,b)

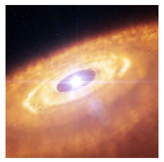
Results :
A → composition of the mantle
C → gas layer
H → could rule out pure solid composition



OCA case: our best constrains on all the parameters.

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

OUTLINE



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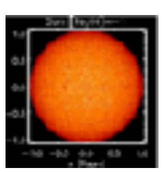

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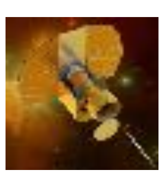


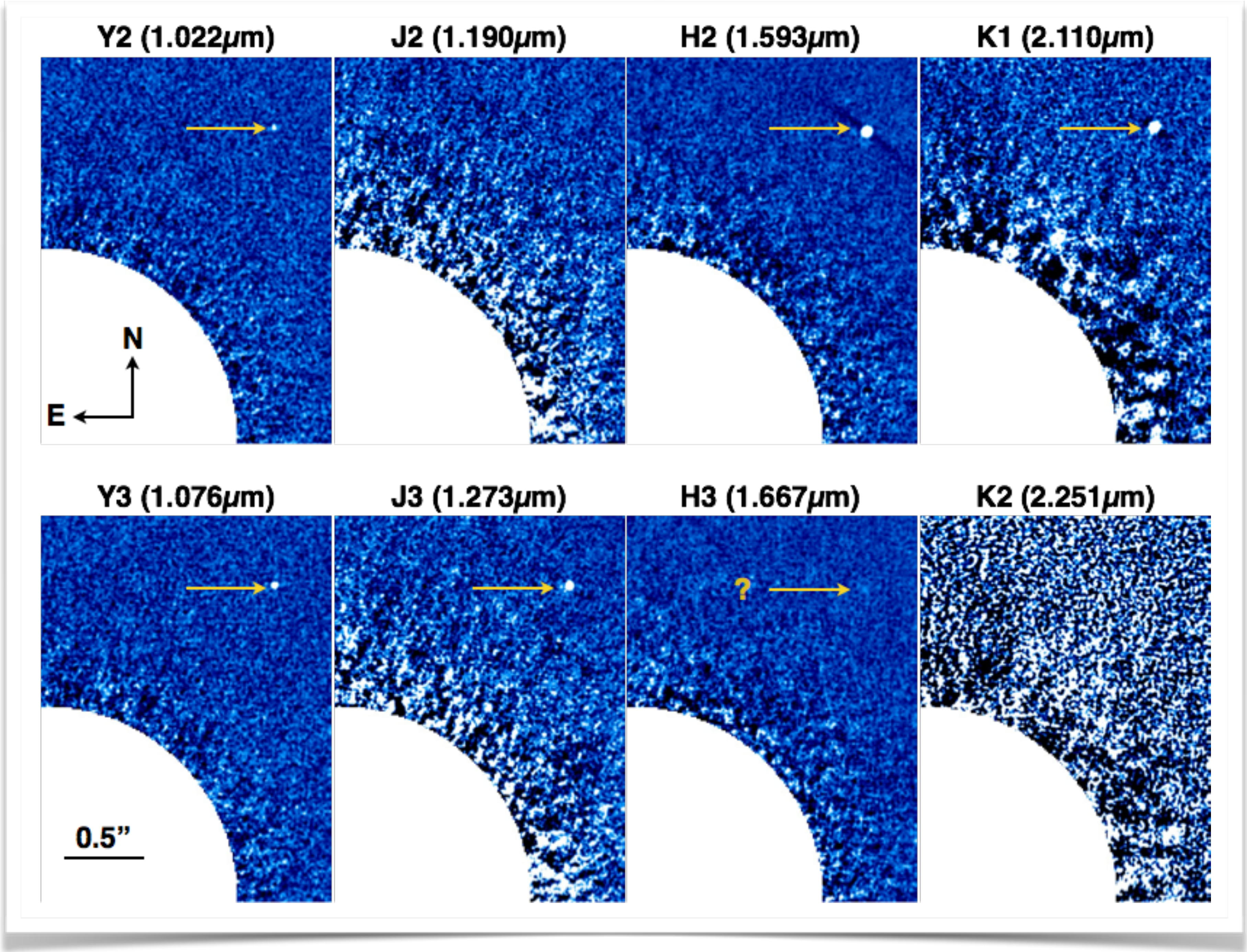
- Conclusion and perspectives

COMBINING INTERFEROMETRY AND ASTEROSEISMOLOGY: THE SYSTEM OF GJ504

GJ504
G0V bright star
High metallicity
High activity

One companion detected
at 43.5 au (SEEDS survey)
First jovian planet resolved around a solar-type star

Mass of the companion?
Strongly depends on the age of the star!



IRDIS & IFS images (SPHERE/VLT), SHINE survey
Bonnefoy, [...], Ligi et al. (2018)

A COMPANION MASS DEPENDING ON THE STELLAR AGE

Kazuhara et al. (2013)
➔ 4 M_{Jup}, 160 Myr
(rotational period, activity)

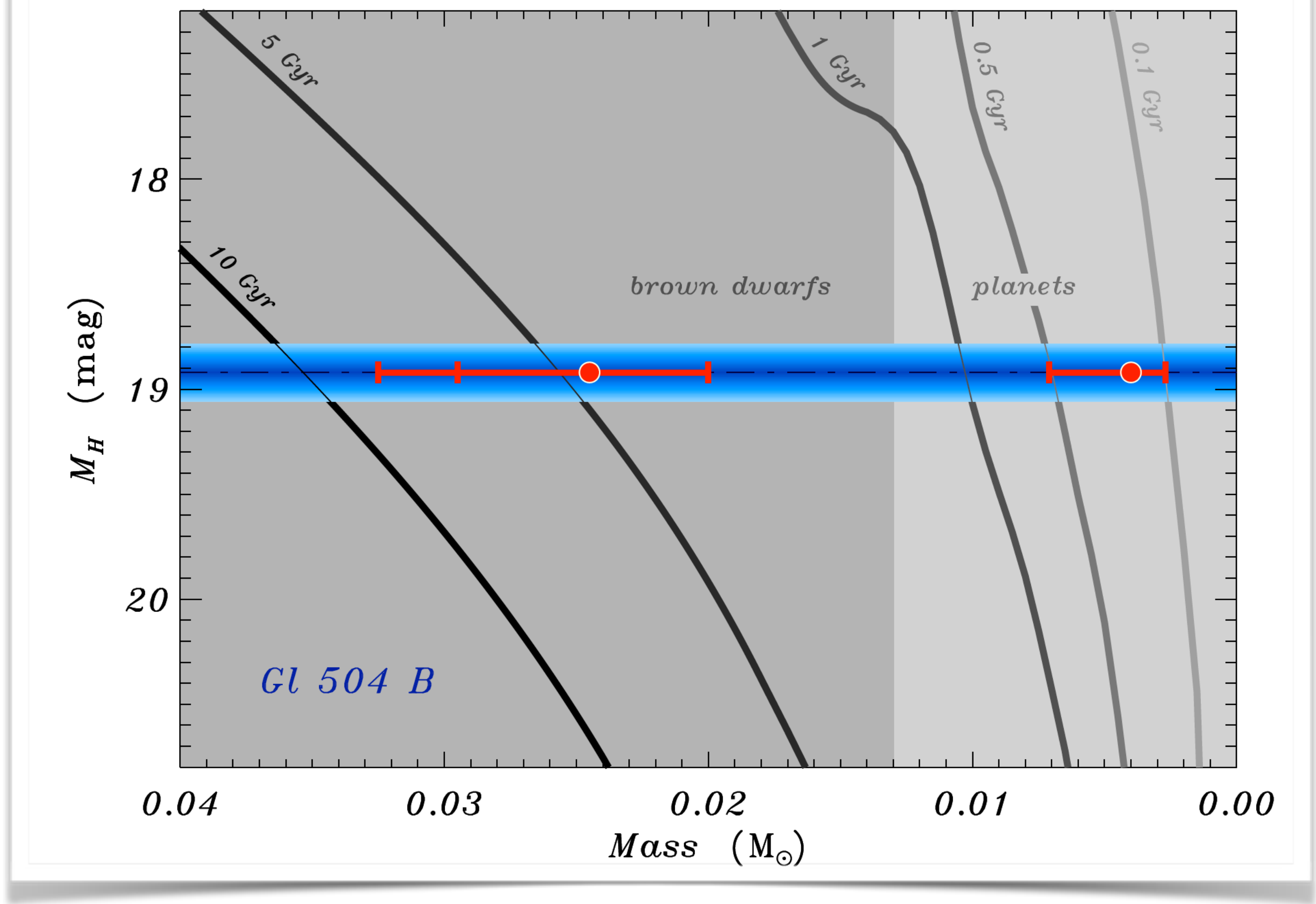
Fuhrmann & Chini (2015)
➔ 25 M_{Jup}, 4.5 Gyr
(high-resolution spectroscopy)

d'Orazi et al. (2017)
➔ BD, 2.5 Gyr
(differential spectroscopy)

Bonnefoy et al. (2018.)
➔ 1.3 Mjup (21 Myr) or
23 Mjup (4 Gyr)
(isochronal age)

~25 M_{Jup} ↑ 4.5 Gyr (Fuhrmann & Chini 2015)

~4 M_{Jup} ↑ 160 Myr (Kuzuhara et al. 2013)



Fuhrmann & Chini (2015)

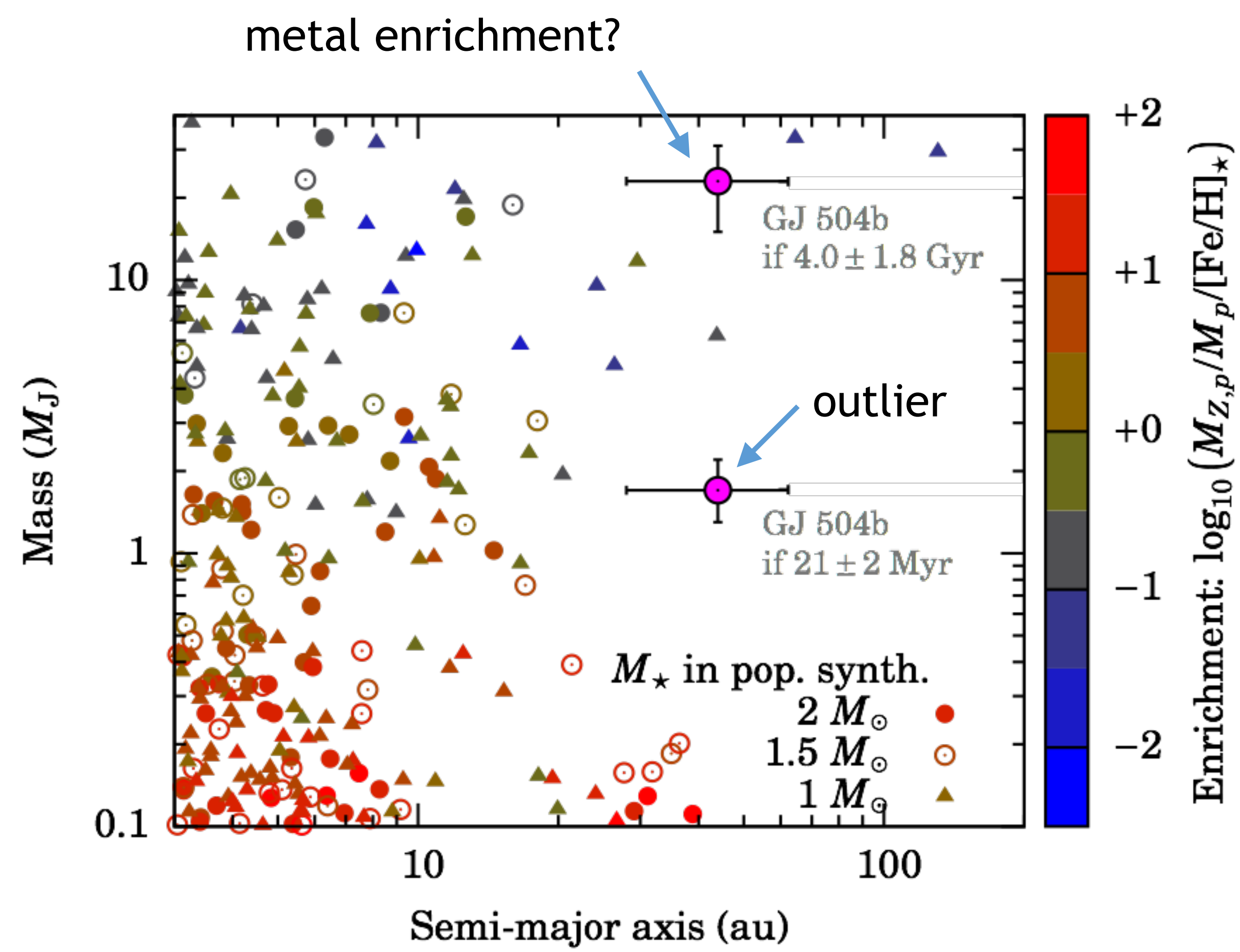
A COMPANION MASS DEPENDING ON THE STELLAR AGE

Different masses call different formation mechanisms:

Brown Dwarf + old system:
Gravitational instability + inward migration

Planet + young system:
Core accretion but challenging given the system properties

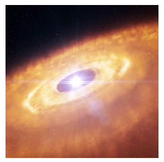
In both cases, the companions is in a « desert »!



Bonnefoy, […], Ligi et al. (2018)

We need the age of the system to unravel the mass of GJ504 b!
→ **Asteroseismology**: several proposals submitted (HARPS-N, ESPRESSO)

OUTLINE

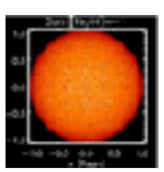


- Introduction: from the formation to the characterisation of exoplanets

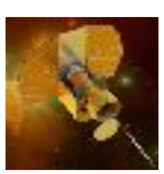
- Characterisation of exoplanetary systems with interferometry

- Getting the most out of it: 55 Cnc

- Formation mechanisms: the challenging case of GJ504



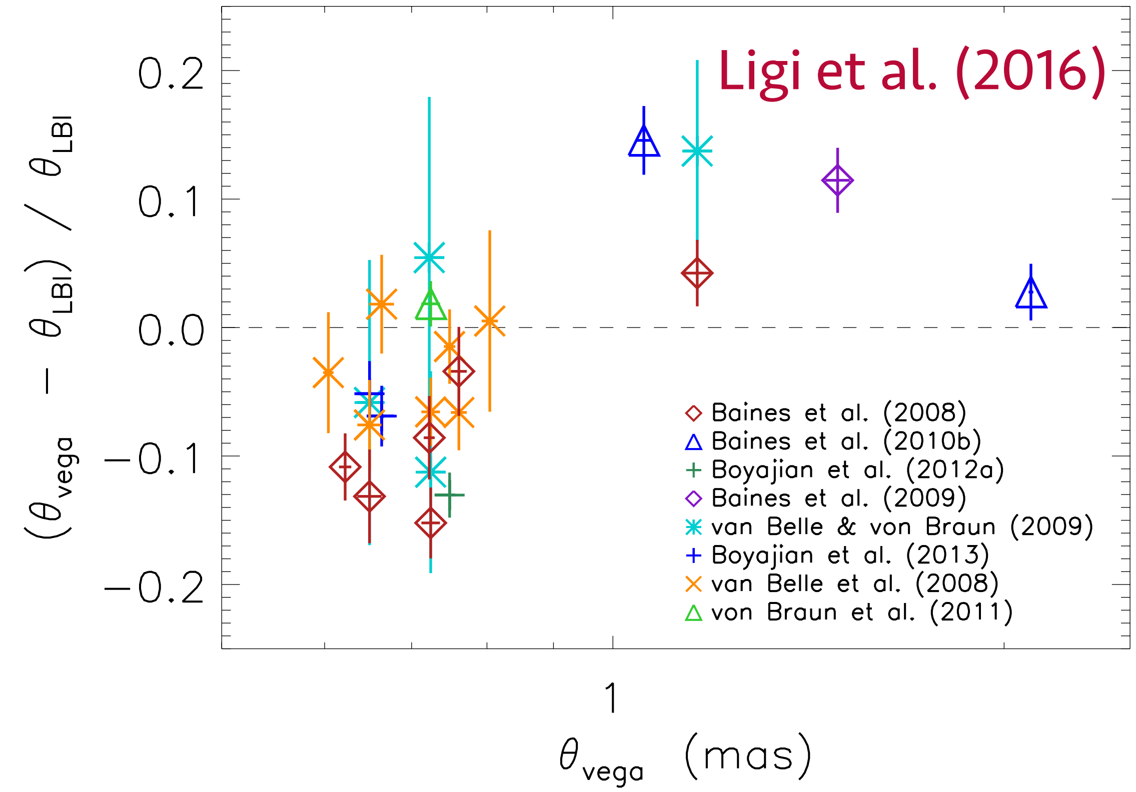
- Some limitations in interferometric measurements

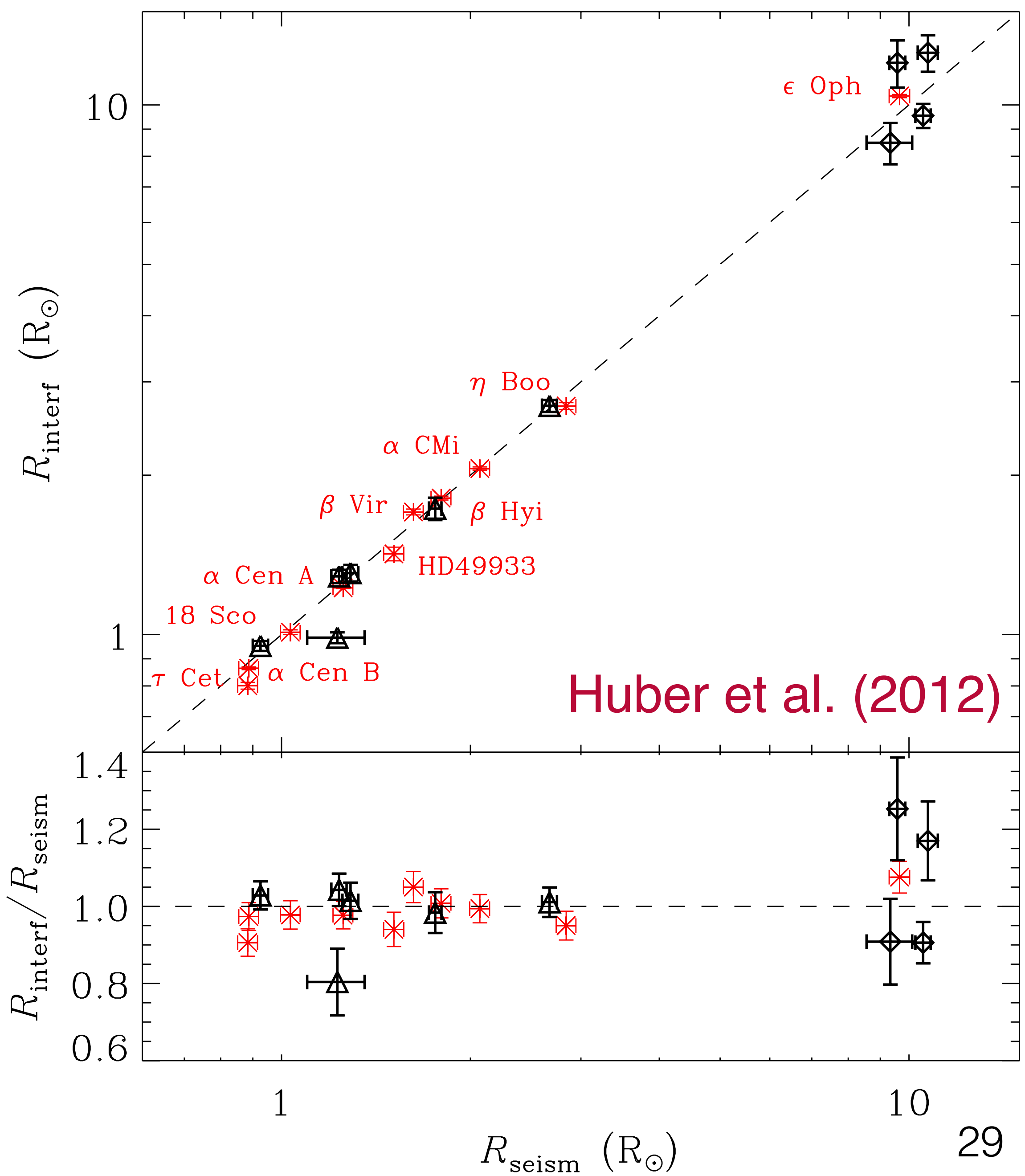


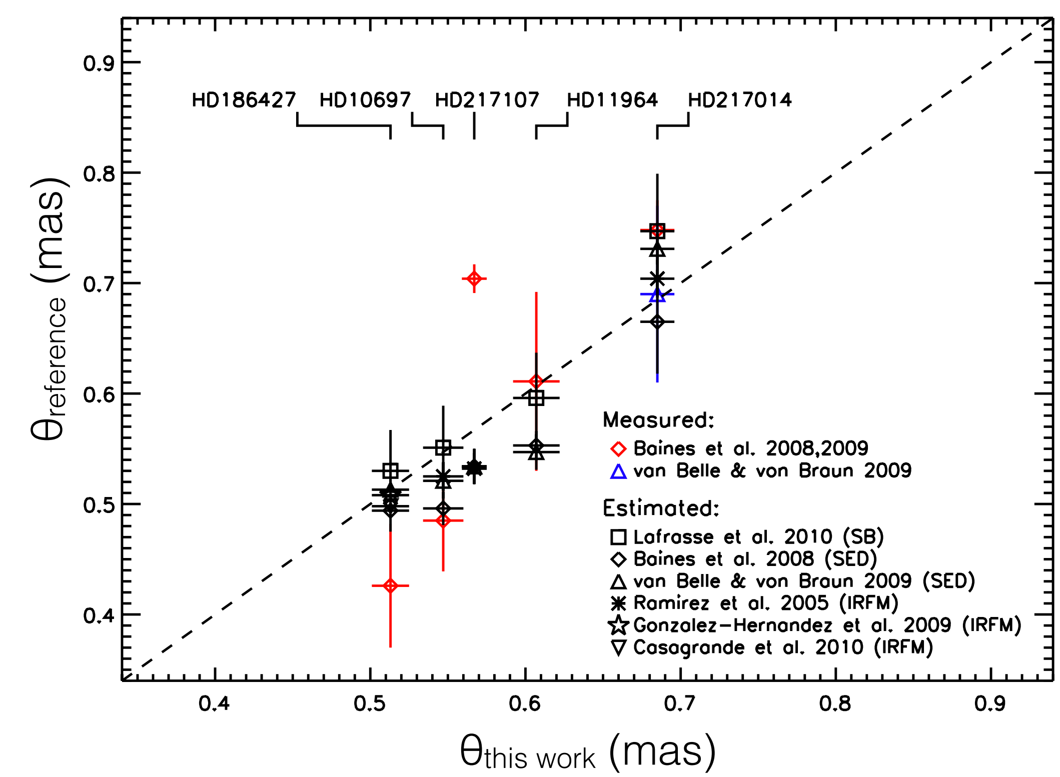
- Conclusion and perspectives

DISCREPANCIES BETWEEN MEASUREMENTS

- Between interferometric measurements from different instruments
- Between direct and indirect measurements
- Between interferometric and asteroseismic radii







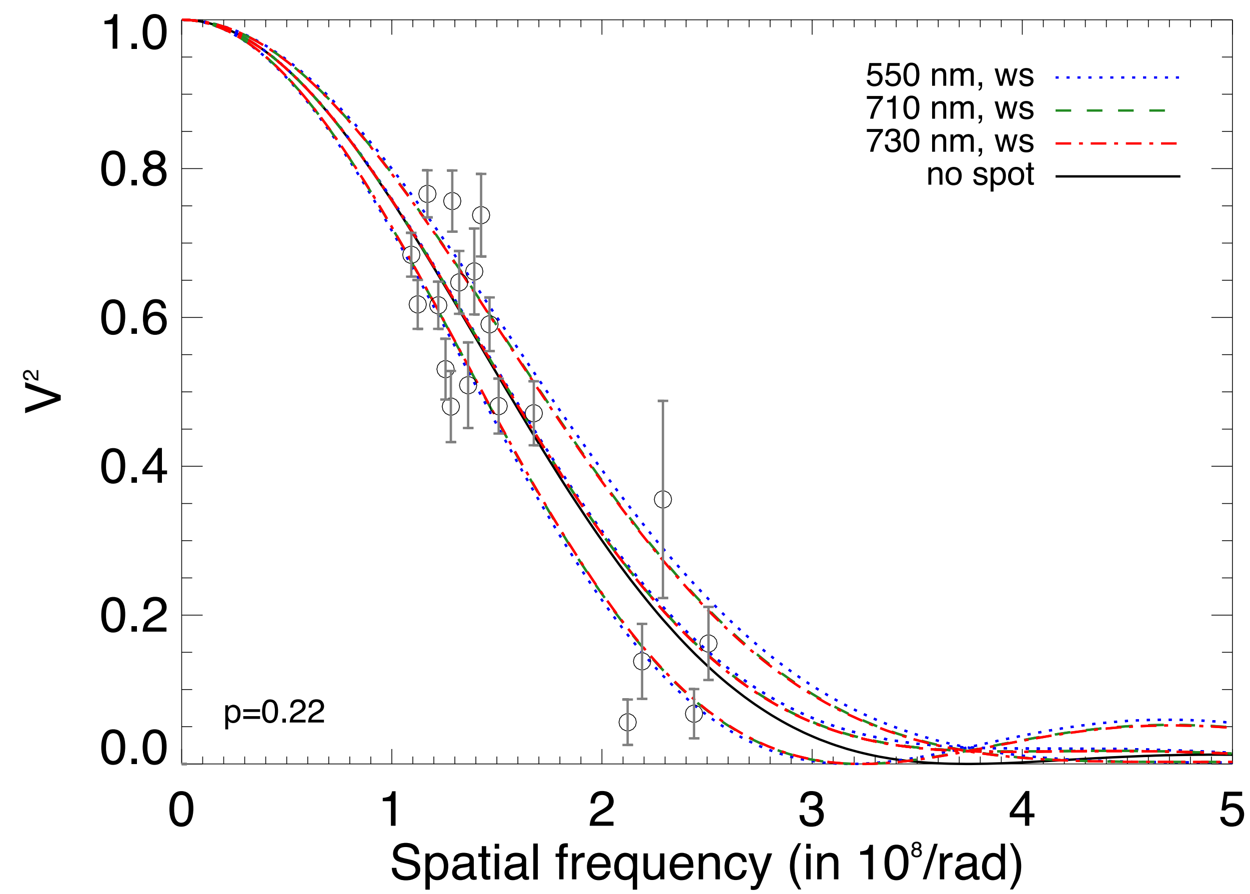
Boyajian et al. (2013)

DISCREPANCIES BETWEEN MEASUREMENTS

- Between interferometric measurements from different instruments
- Between direct and indirect measurements
- Between interferometric and asteroseismic radii

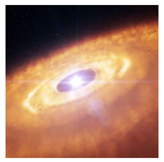
Possible causes

- Calibrators?
  → verification in the sample (on-going)
- Stellar activity?
  → comparison with 3D models (coll. A. Chiavassa; planned)



GJ504, Bonnefoy et al. (2018) using COMETS code (Ligi et al. 2015)

OUTLINE



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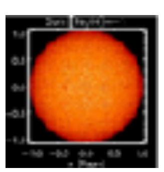

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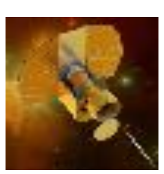
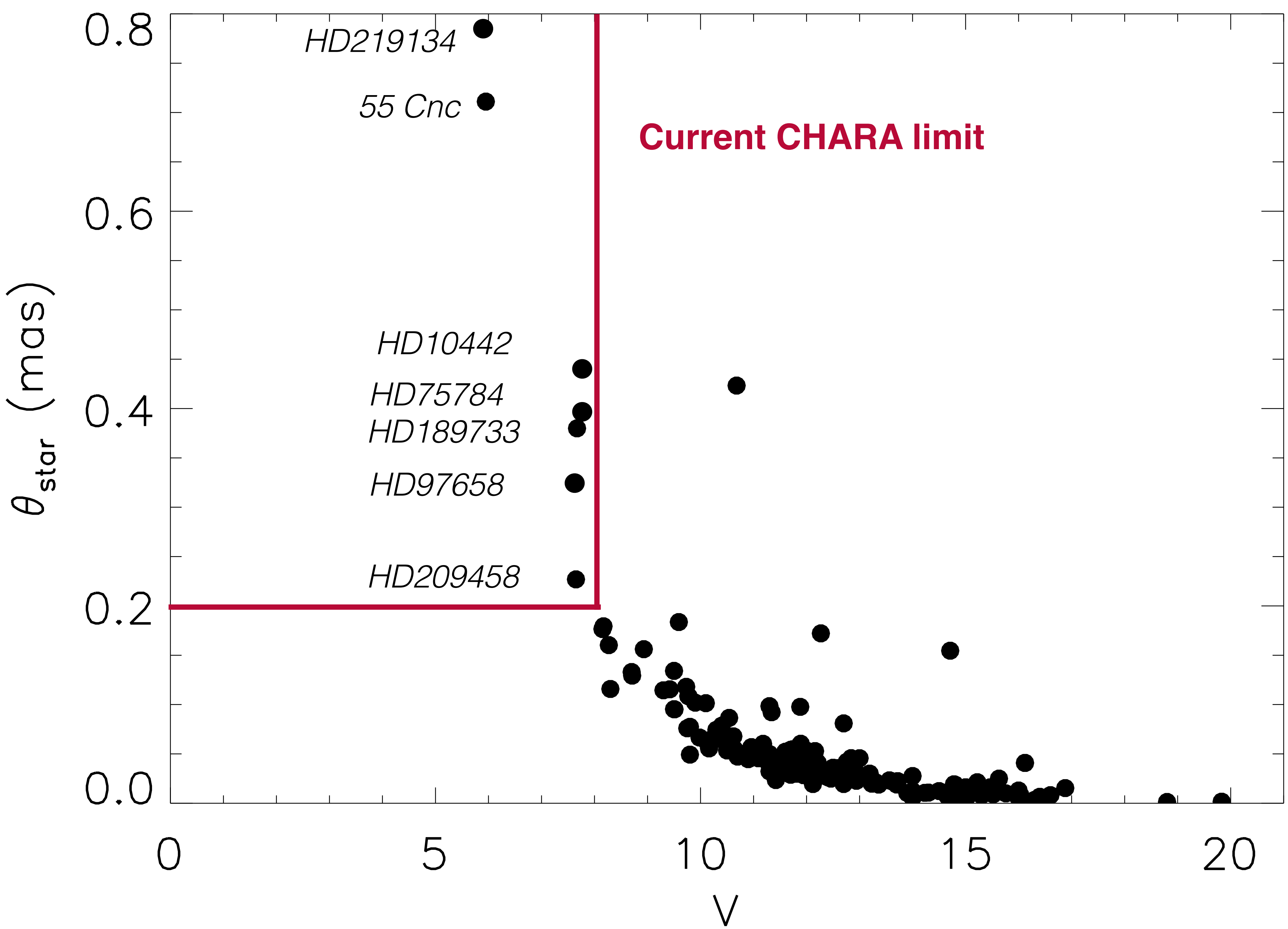


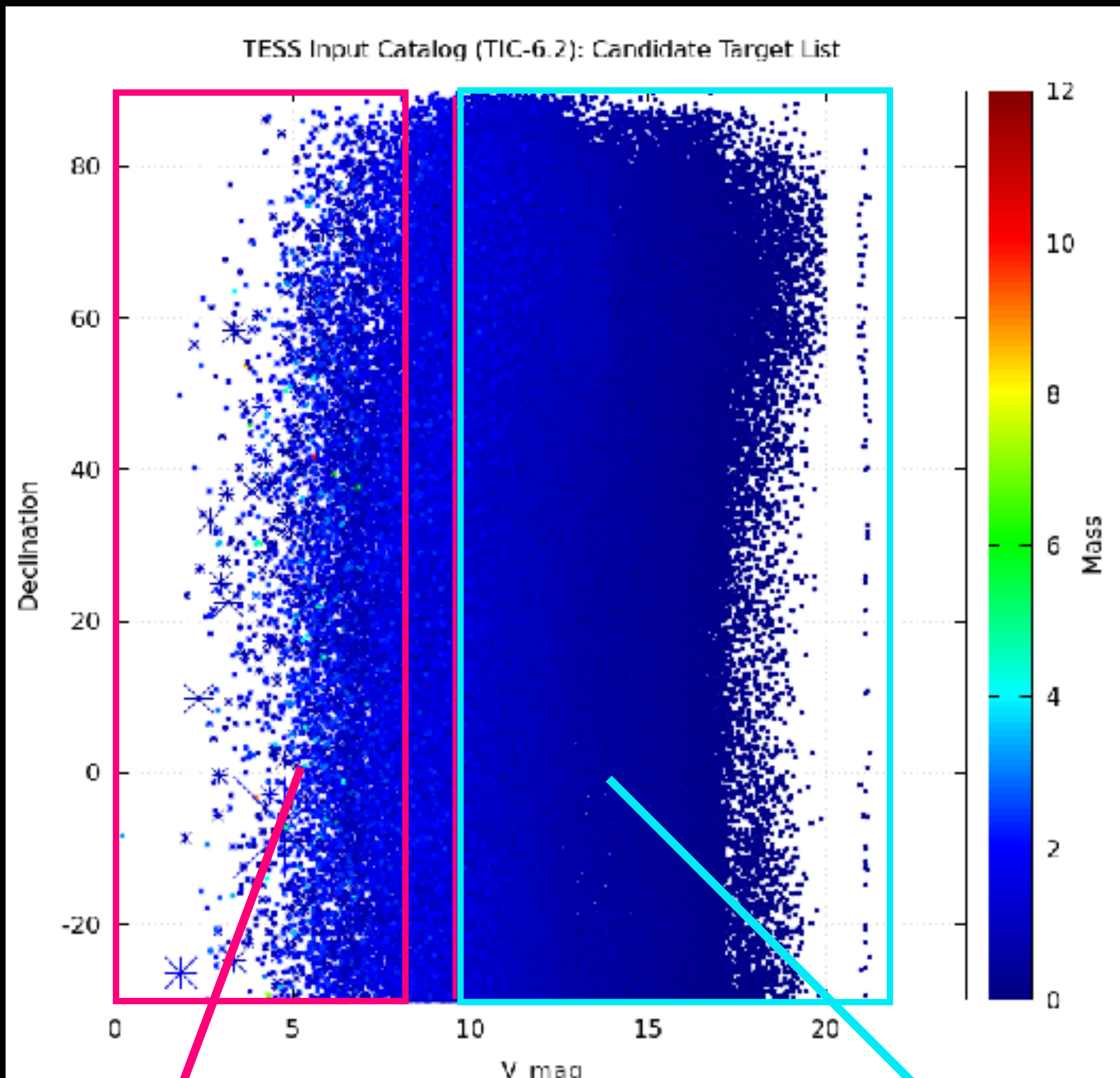
- Conclusion and perspectives

INTERFEROMETRY FOR FAINTER STARS

Stars harbouring transiting exoplanets



FUTURE AND ON-GOING WORK



PLATO

4-11 mag

solar type stars

TESS

4-12 mag

F5 to M5

CHEOPS

V<12 mag

Known host stars

Direct measurements

Indirect measurements

FUTURE AND ON-GOING WORK

Investigation of transiting exoplanets (same model as 55 Cnc)

- Better characterisation of exoplanetary population
- Keys for planetary formation

Investigation on the limitations of the radius determination

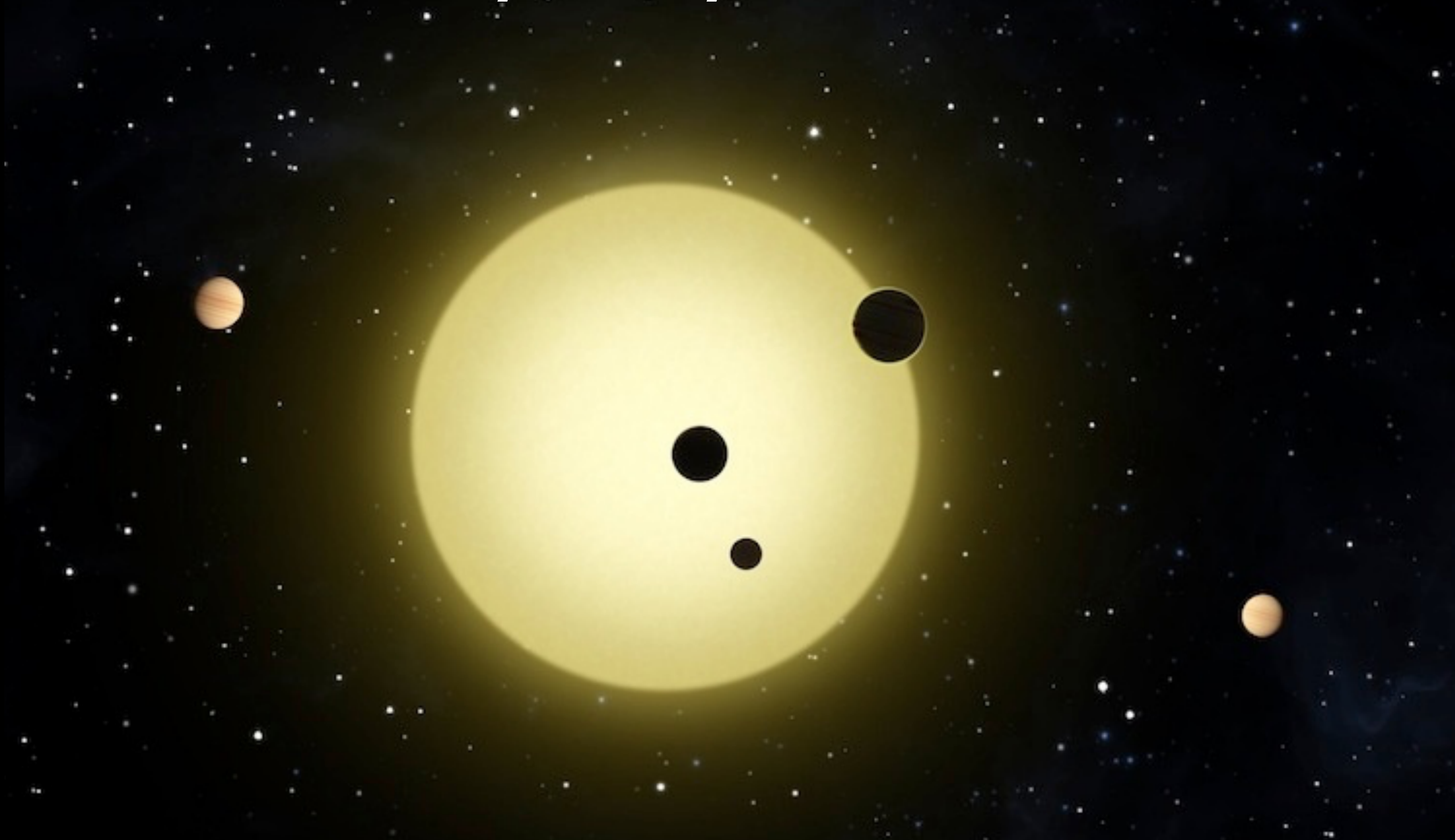
- stellar activity
- bias in the calibrators

Combination of asteroseismology and interferometry

- for individual targets (e.g. GJ504, TESS targets)
- for larger samples (discrepancies)
- testing radius determination: asteroseismology from photometry/spectroscopy, interferometry

…

Thank you for your attention!



INTASTE

combining INTerferometry and ASTeroseismology: a new insight on Exoplanet characterisation