CHARACTERISATION OF EXOPLANETARY SYSTEMS WITH HIGH ANGULAR RESOLUTION

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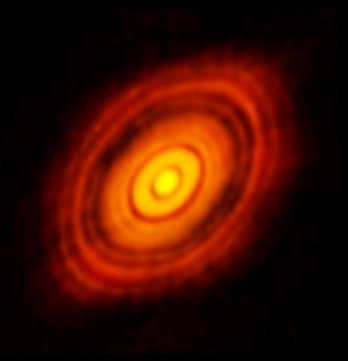
6 Juillet 2018

INTRODUCTION

Planetary formation: 2 scenarios



Gravitational instability

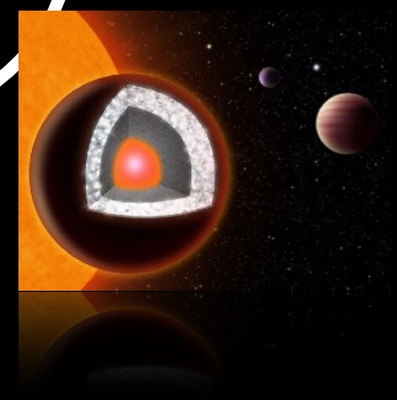
- Giant planets, large separation (> 50 au)

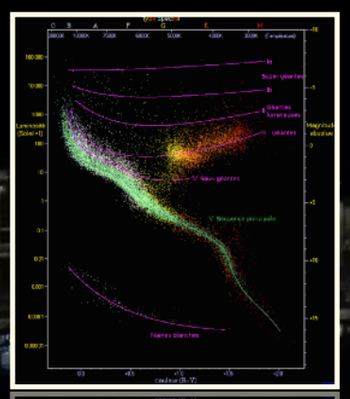
Core Accretion

- 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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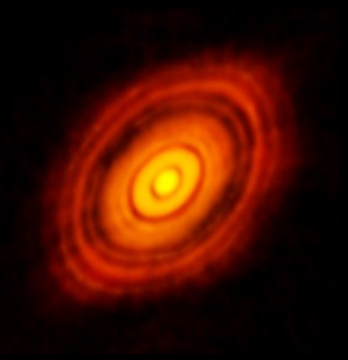

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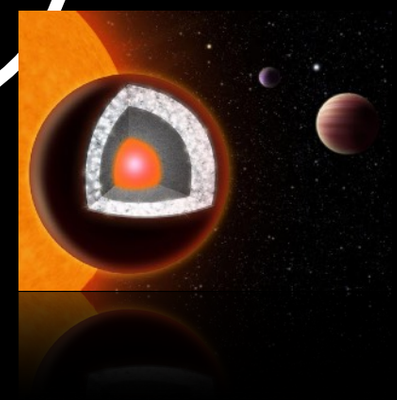

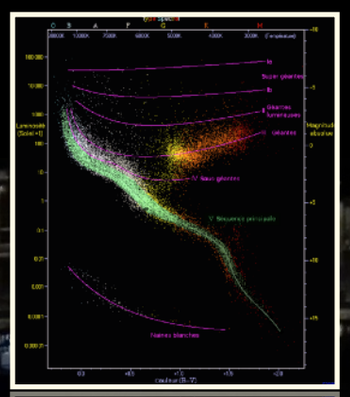

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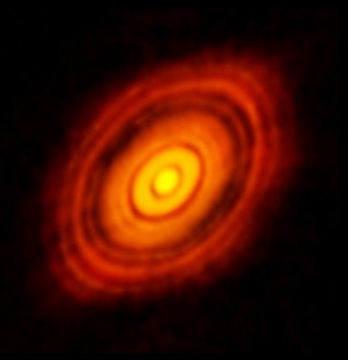

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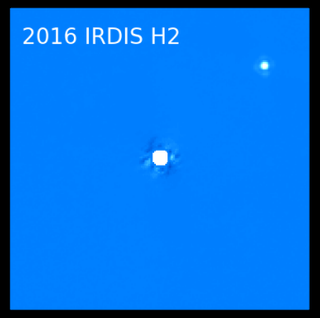

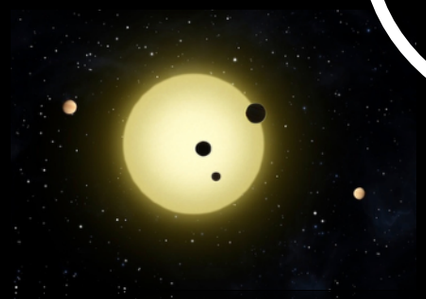

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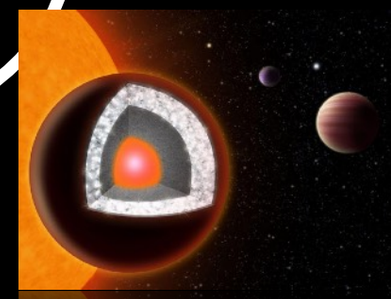

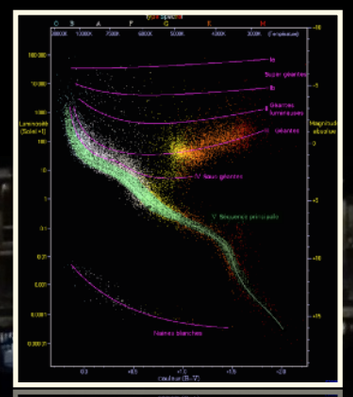

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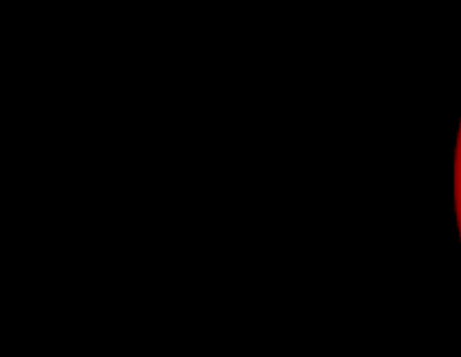
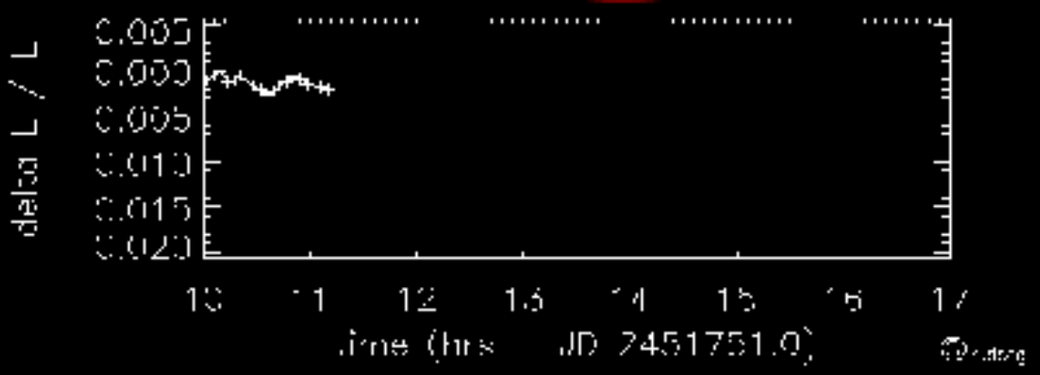
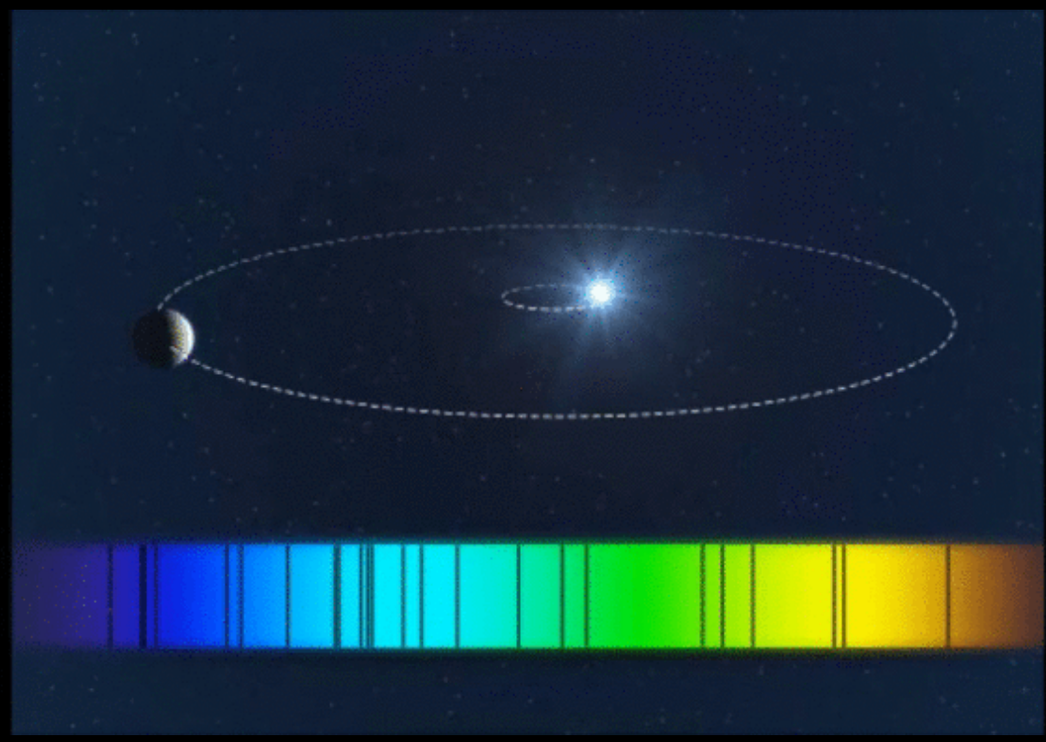




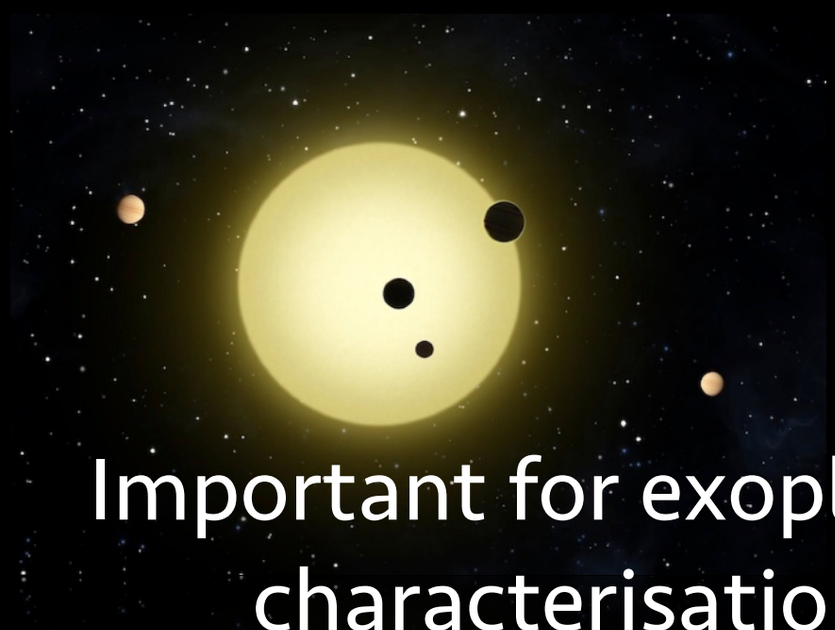


$$\frac{\Delta F}{F} = \left(\frac{R_P}{R_\star}\right)^2$$

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

→ Dependent on **R★** and **M★**

INTRODUCTION



Important for exoplanets characterisation, and in particular for transiting ones

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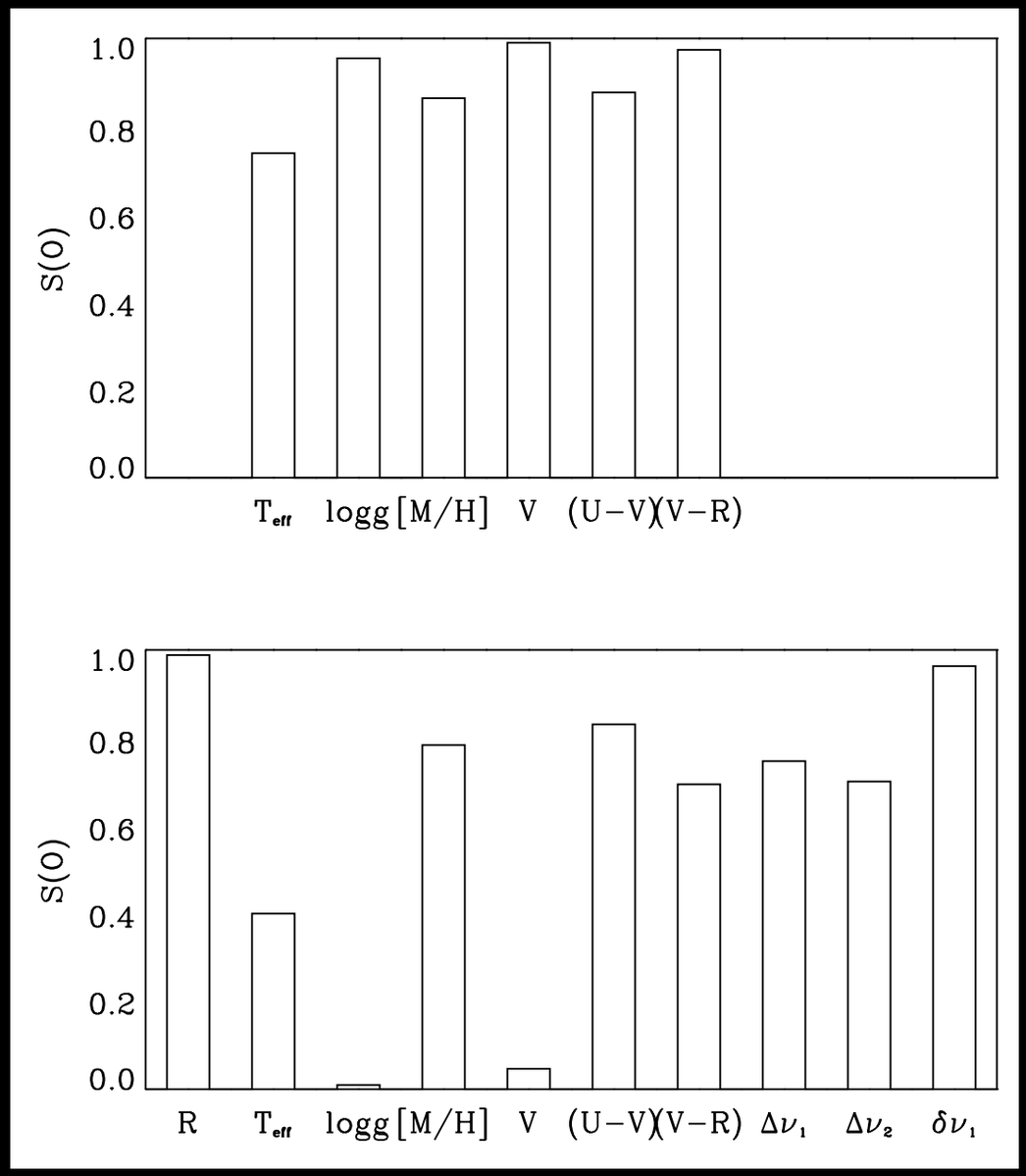

Creevey et al. 2007

And important for stellar characterisation

INTRODUCTION

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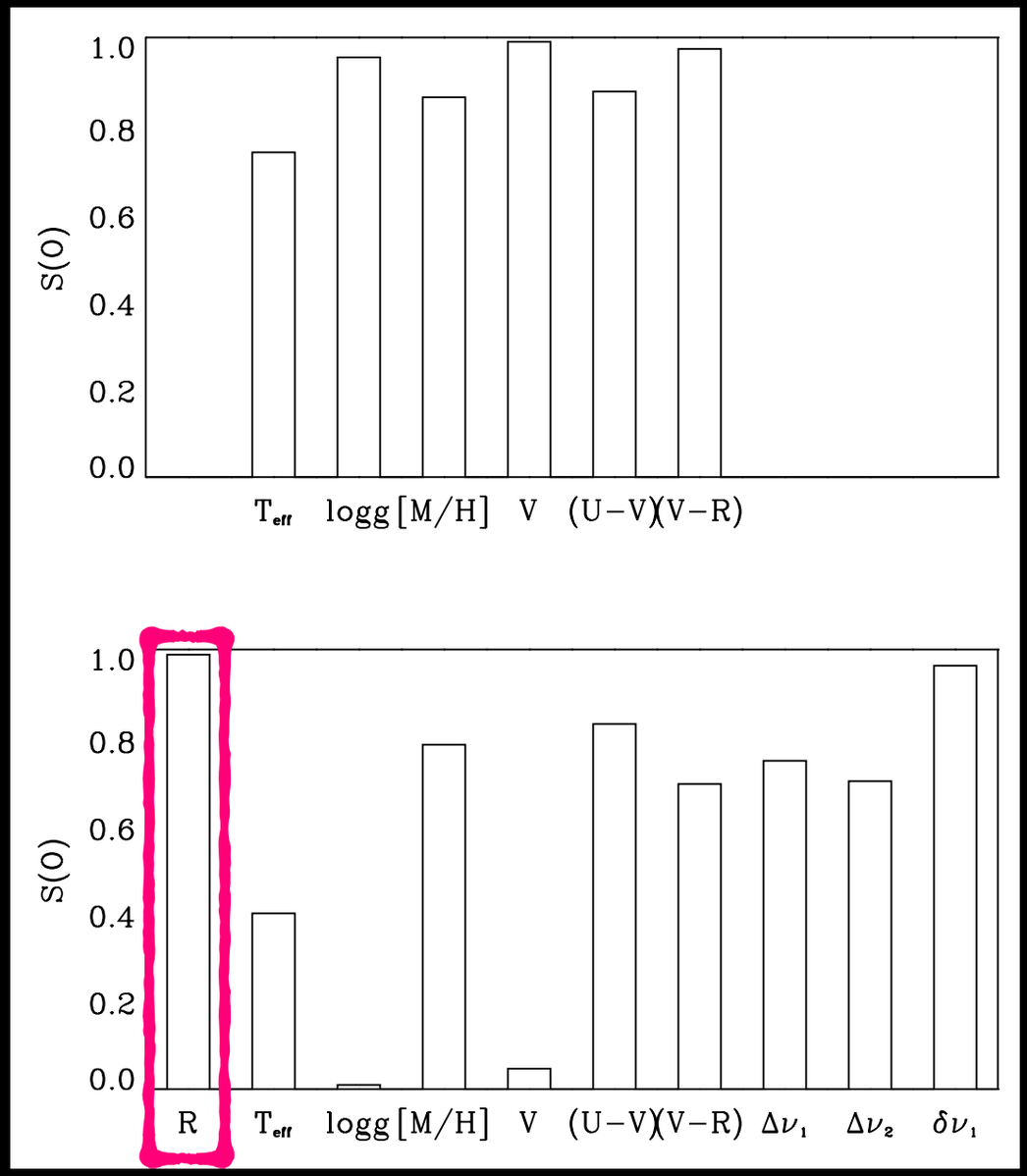


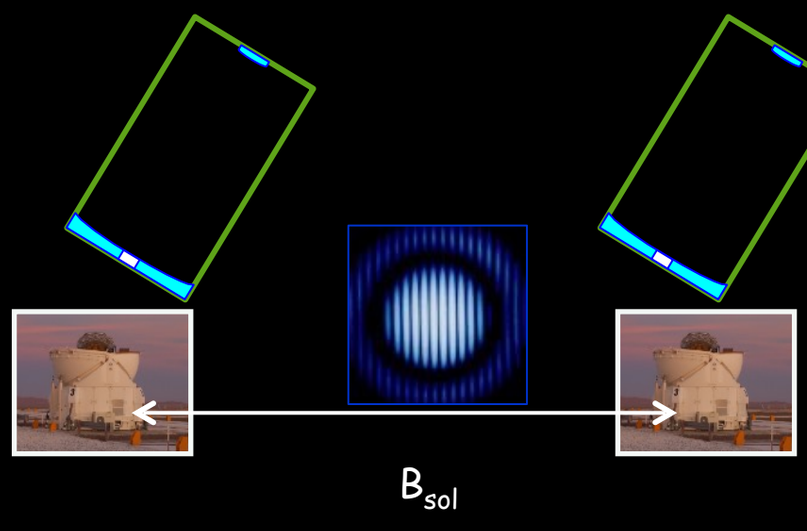
Creevey et al. 2007

→ **interferometry**

And important for stellar characterisation

STELLAR RADIUS WITH INTERFEROMETRY

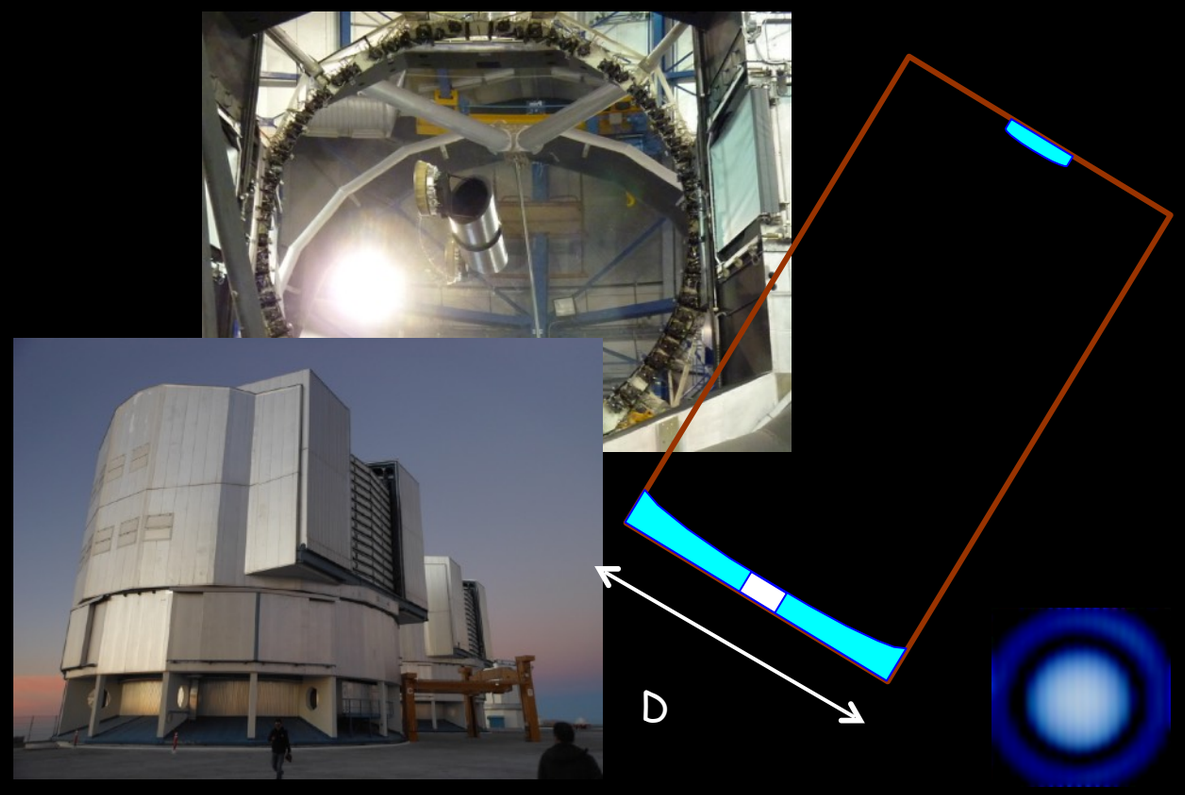
Interferometer



Angular resolution = λ/B

➜ larger resolution
➜ smaller objects

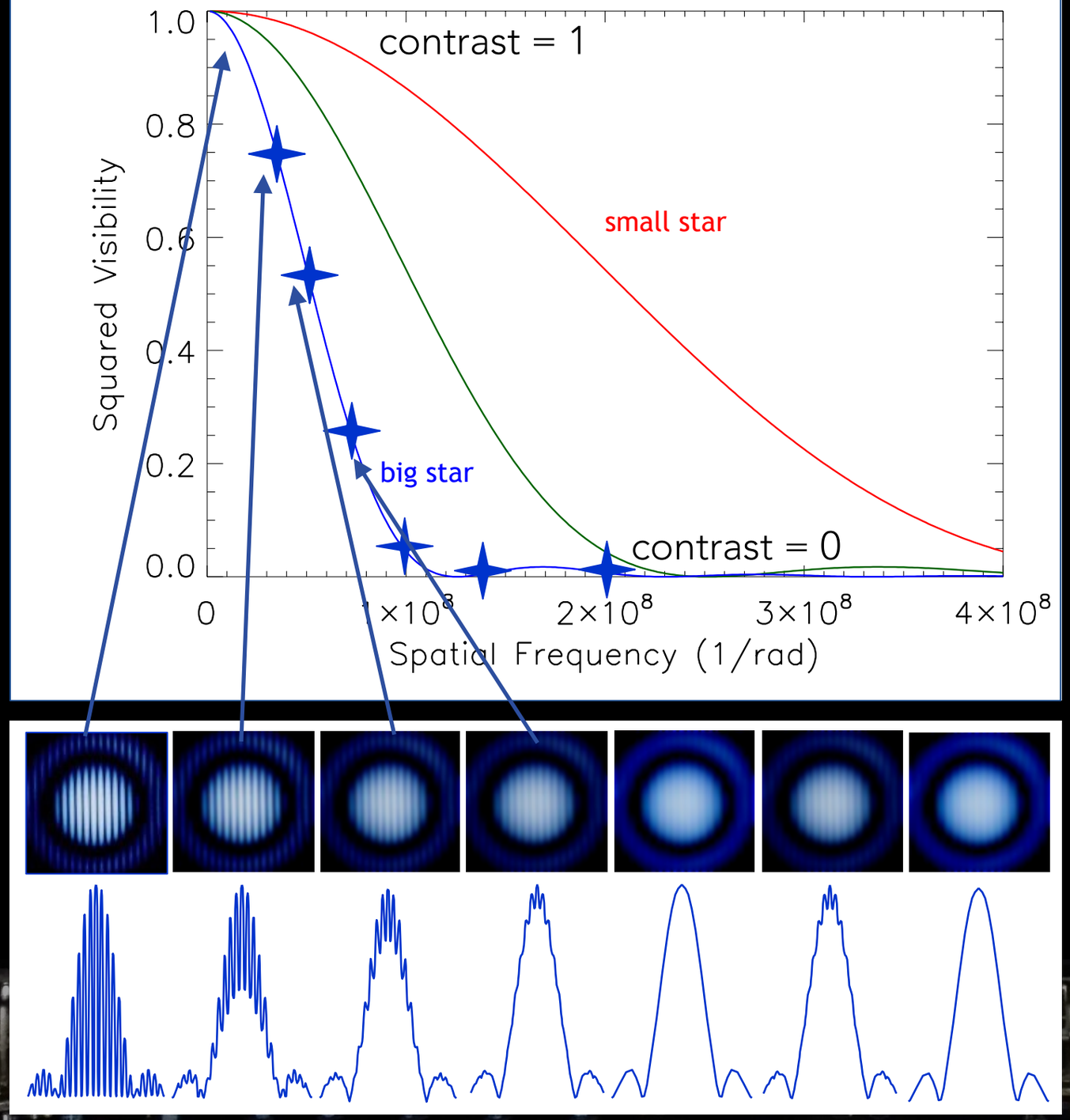
Classical telescope

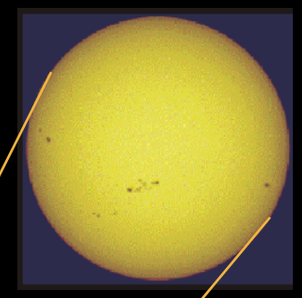


Angular resolution = λ/D

➜ larger sensitivity
➜ more distant objects

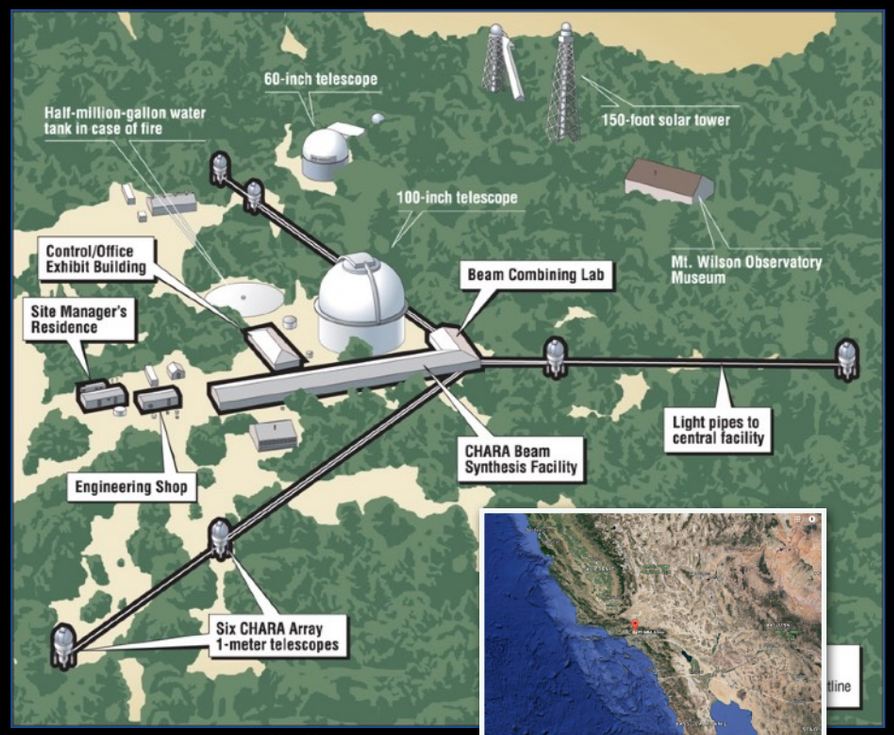
STELLAR RADIUS WITH INTERFEROMETRY





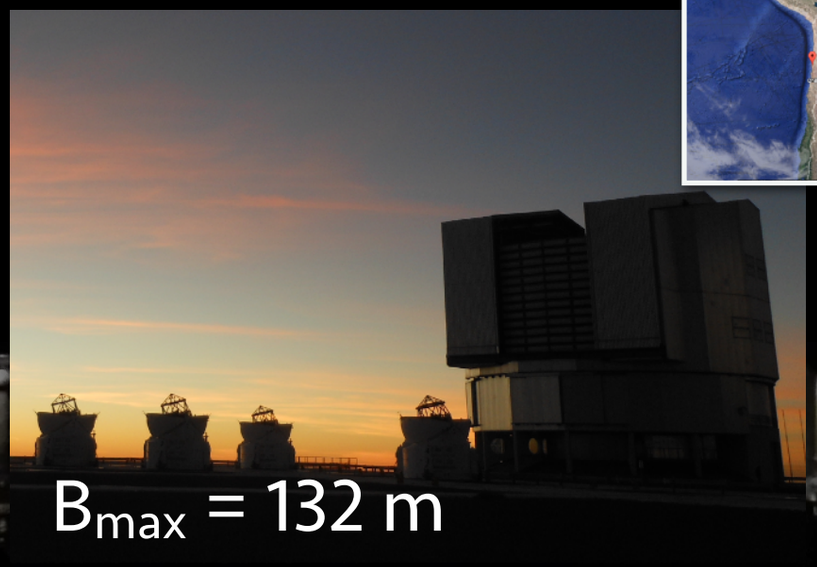
STELLAR RADIUS WITH INTERFEROMETRY

CHARA



B_{max} = 331 m

VLTI

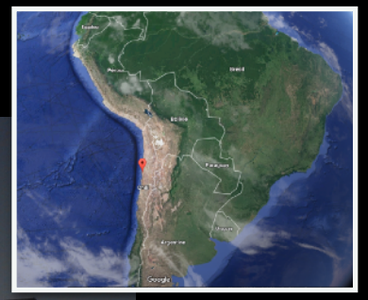


B_{max} = 132 m

SUSI

B_{max} = 167 m

NPOI

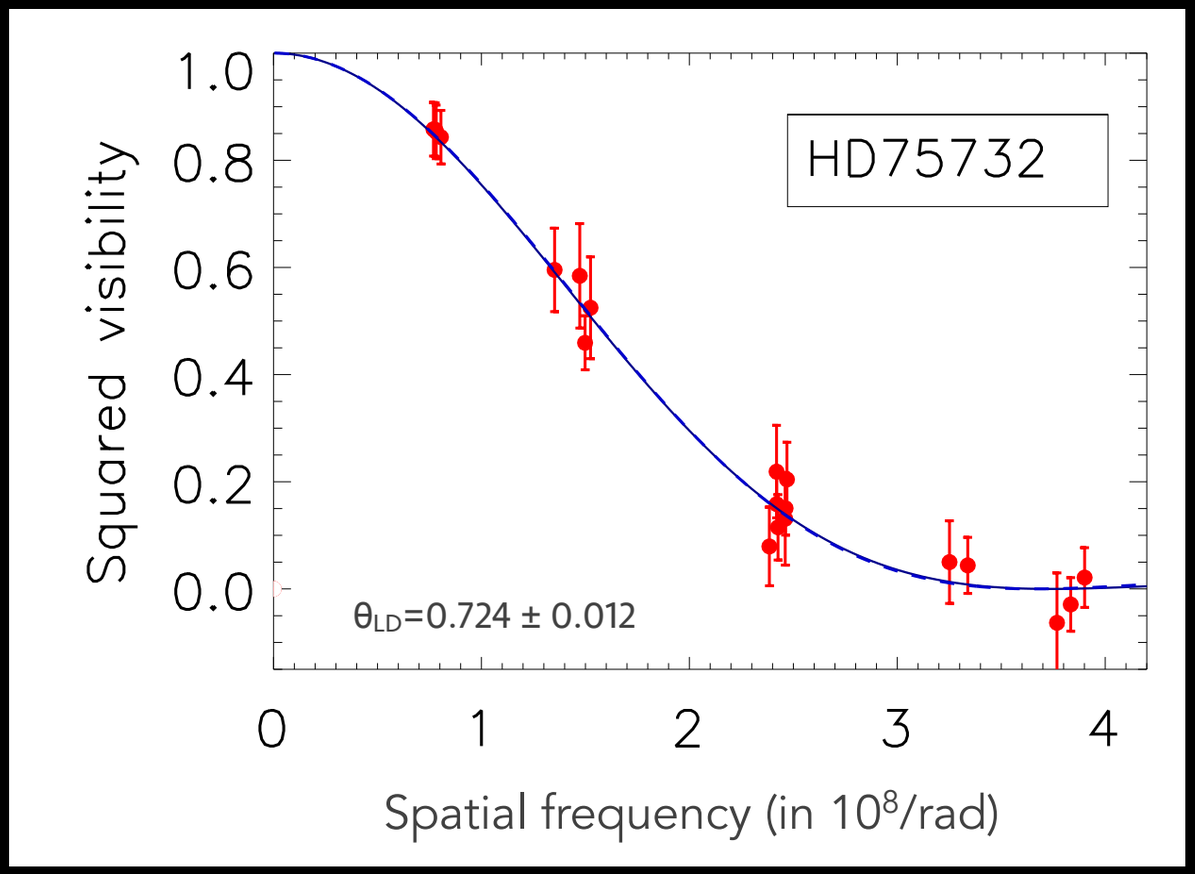


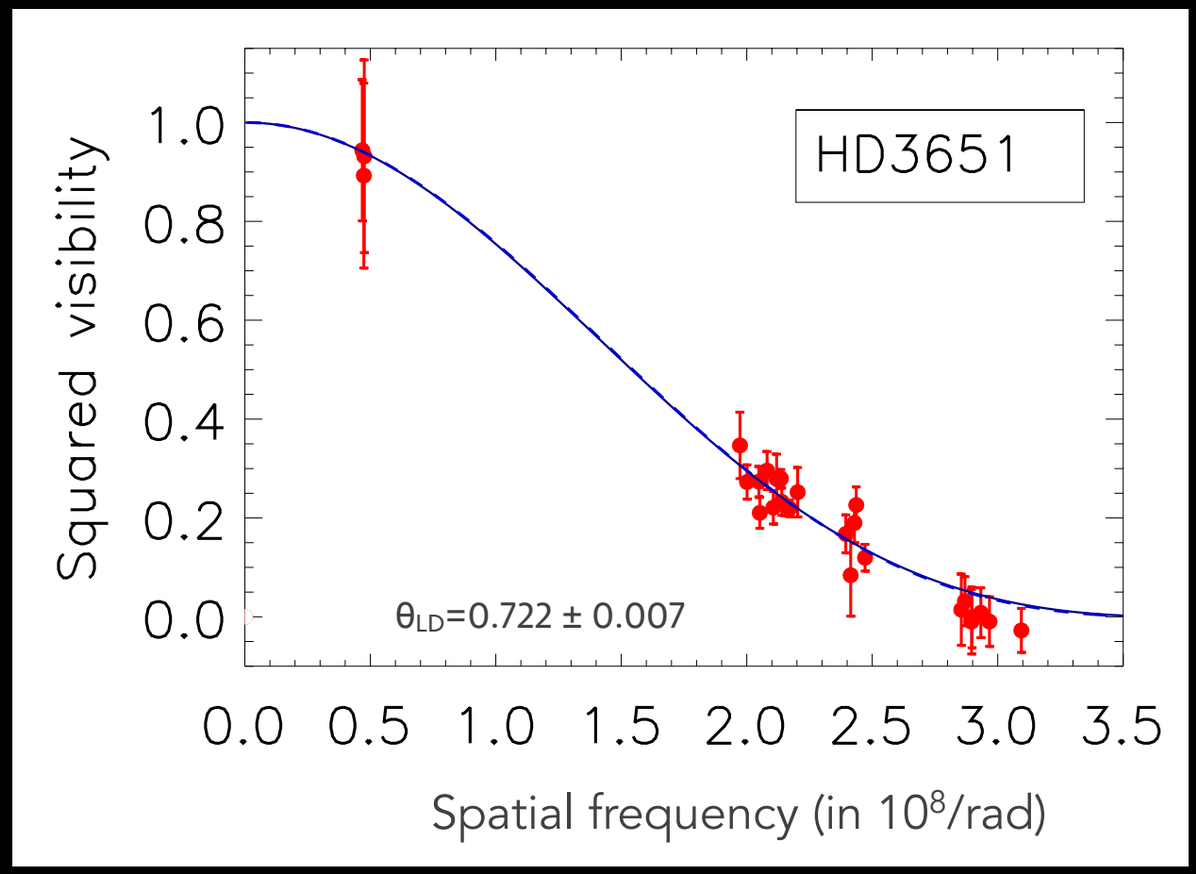
B_{max} = 80 m
(planned 437 m)

STELLAR PARAMETERS FROM INTERFEROMETRY

Interferometric angular diameter → Hipparcos distance

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





Ligi et al. (2012a, 2016)

- Examples of visibility curves from VEGA instrument
  Average accuracy: 1.9 % on diameters (θ_{LD}) and 3% on radii ($R_\star$).

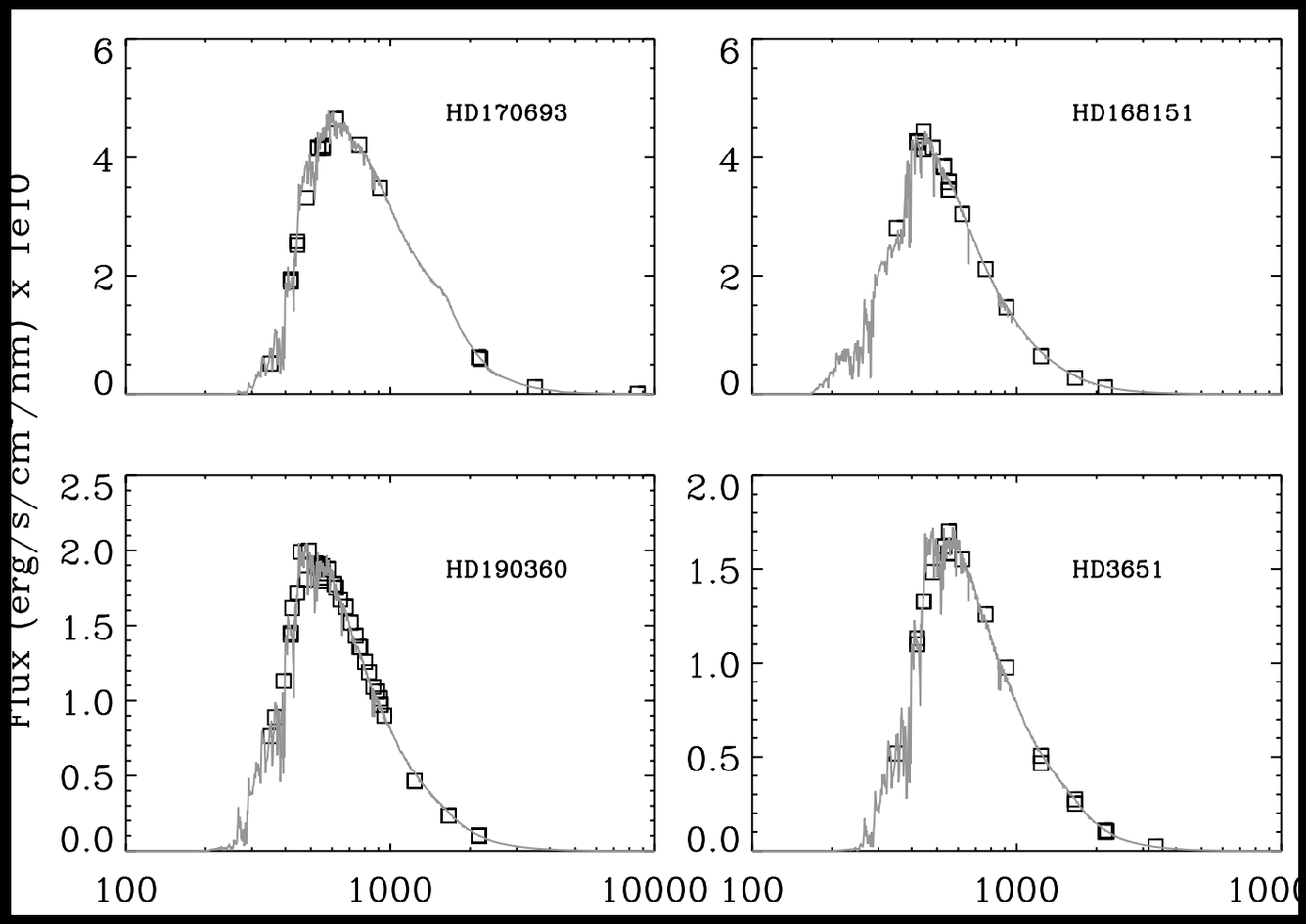
STELLAR PARAMETERS FROM INTERFEROMETRY

Photometry from VizieR Photometry Viewer

Fit from BASEL library spectra

Take into account log(g), Av, [Fe/H]

Average accuracy on $T_{eff,\star}$: 57K in average



SED

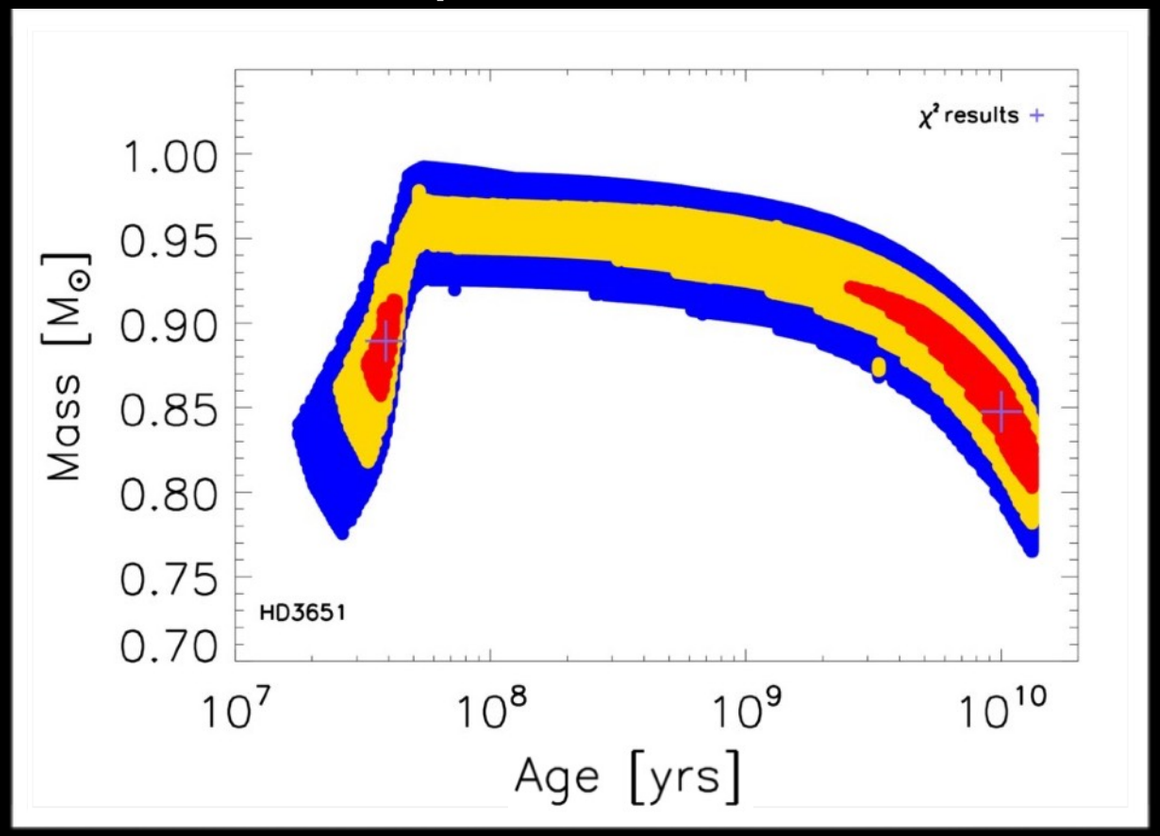
$$T_{\mathrm{eff},\star} = \left(\frac{4 \times F_{\mathrm{bol}}}{\sigma_{\mathrm{SB}} \theta_{\mathrm{LD}}^2} \right)^{0.25}$$

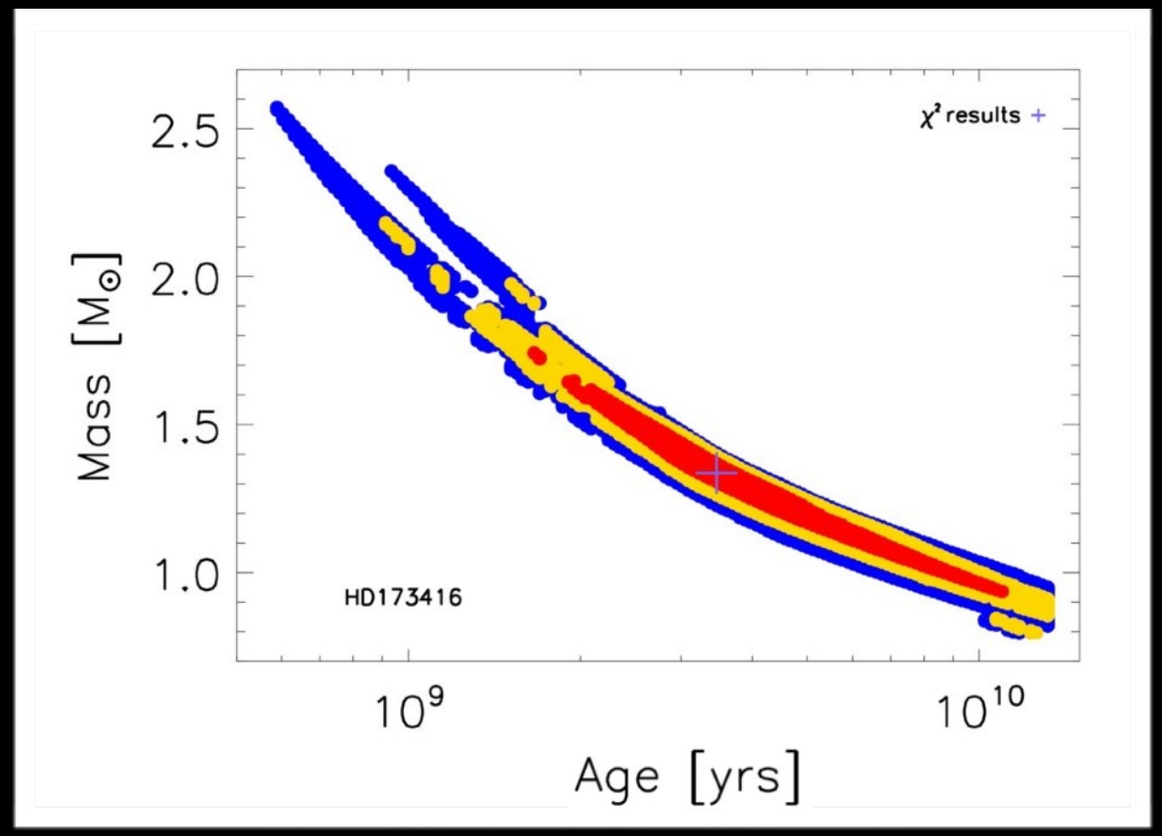
$$L_\star = 4\pi d^2 F_{\mathrm{bol}}$$

Interferometric angular diameter

STELLAR PARAMETERS FROM INTERFEROMETRY

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

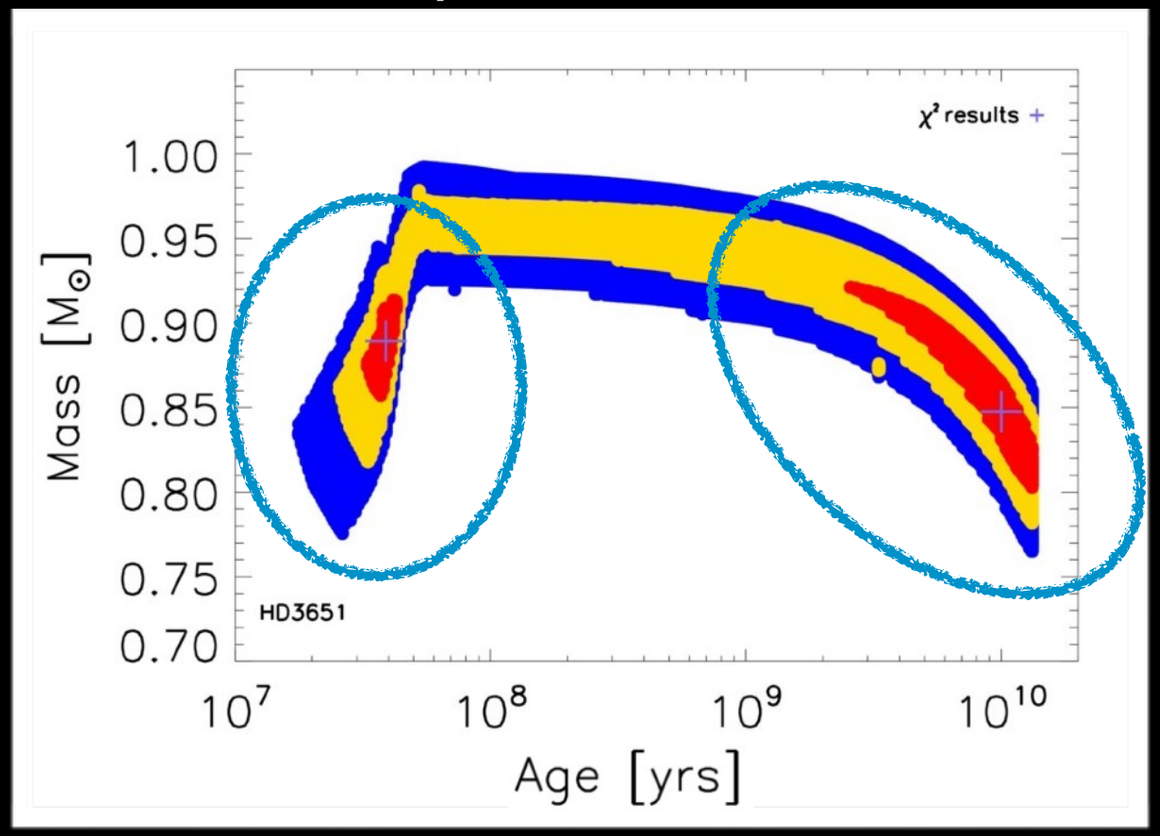


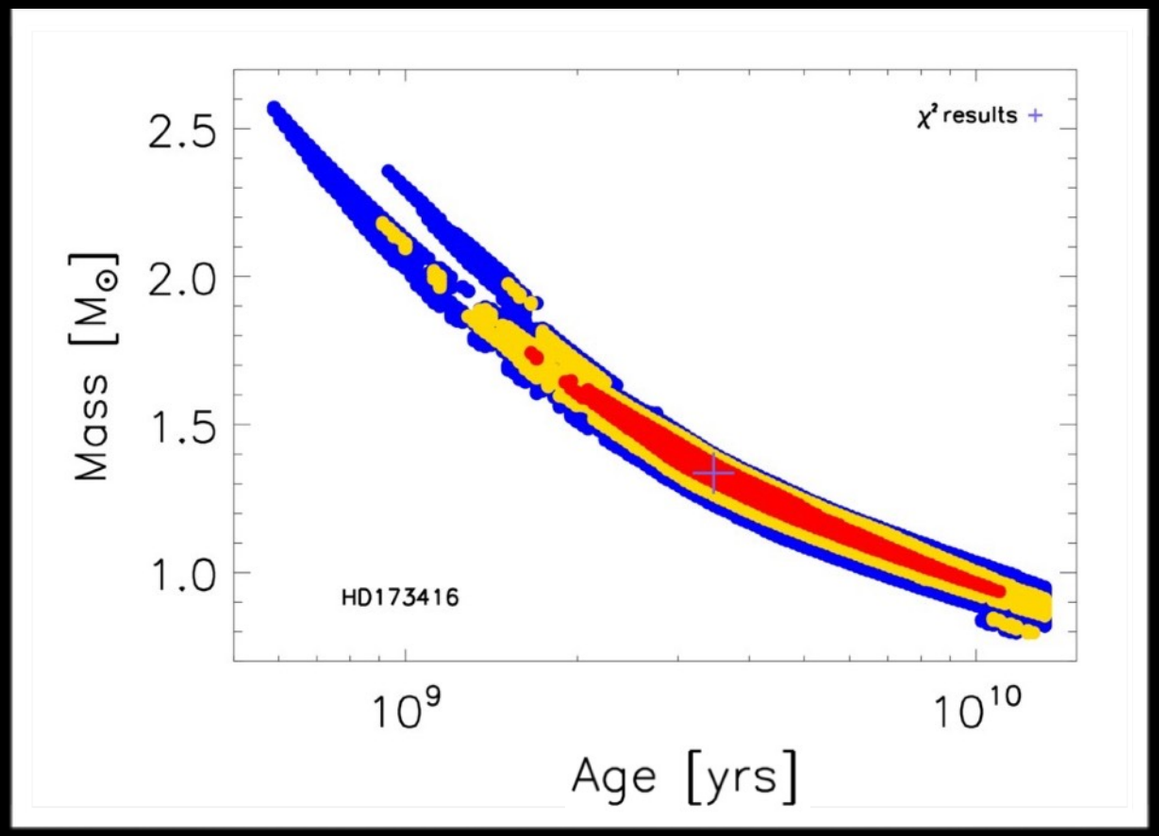


- This corresponds to the approximate likelihood map in the ($M_{\star}$, $age_{\star}$) for which each term of the equation $\chi^2 = \frac{(L - L_\star)^2}{\sigma_{L_\star}{}^2} + \frac{(T_{\rm eff} - T_{\rm eff,\star})^2}{\sigma_{T_{\rm eff,\star}}{}^2} + \frac{([{\rm M/H}] - [{\rm M/H}]_\star)}{\sigma_{[{\rm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

STELLAR PARAMETERS FROM INTERFEROMETRY

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



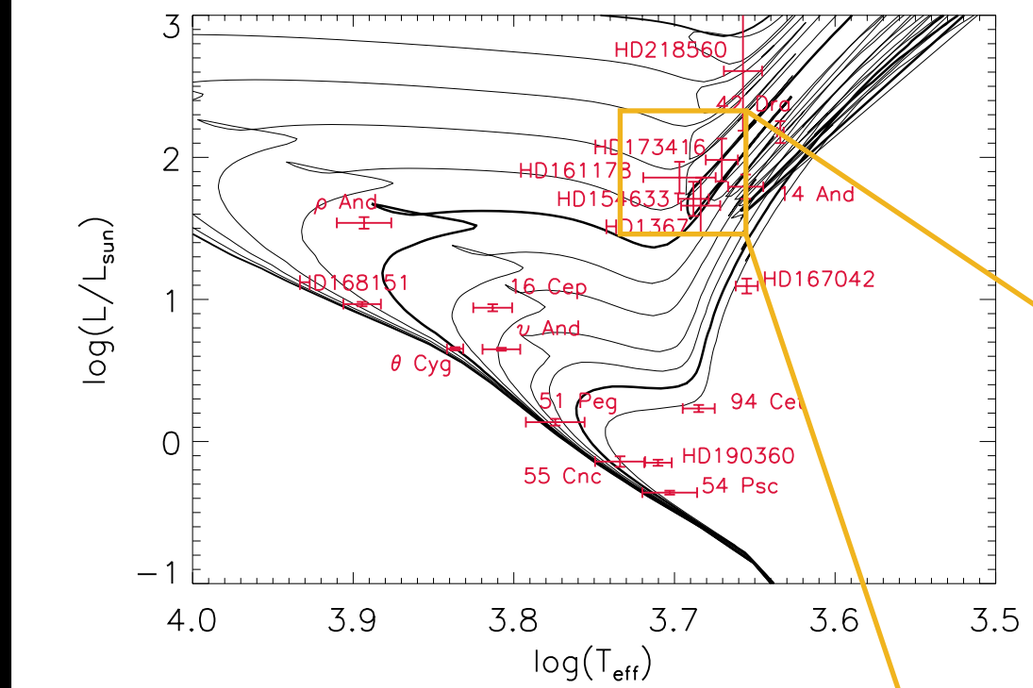


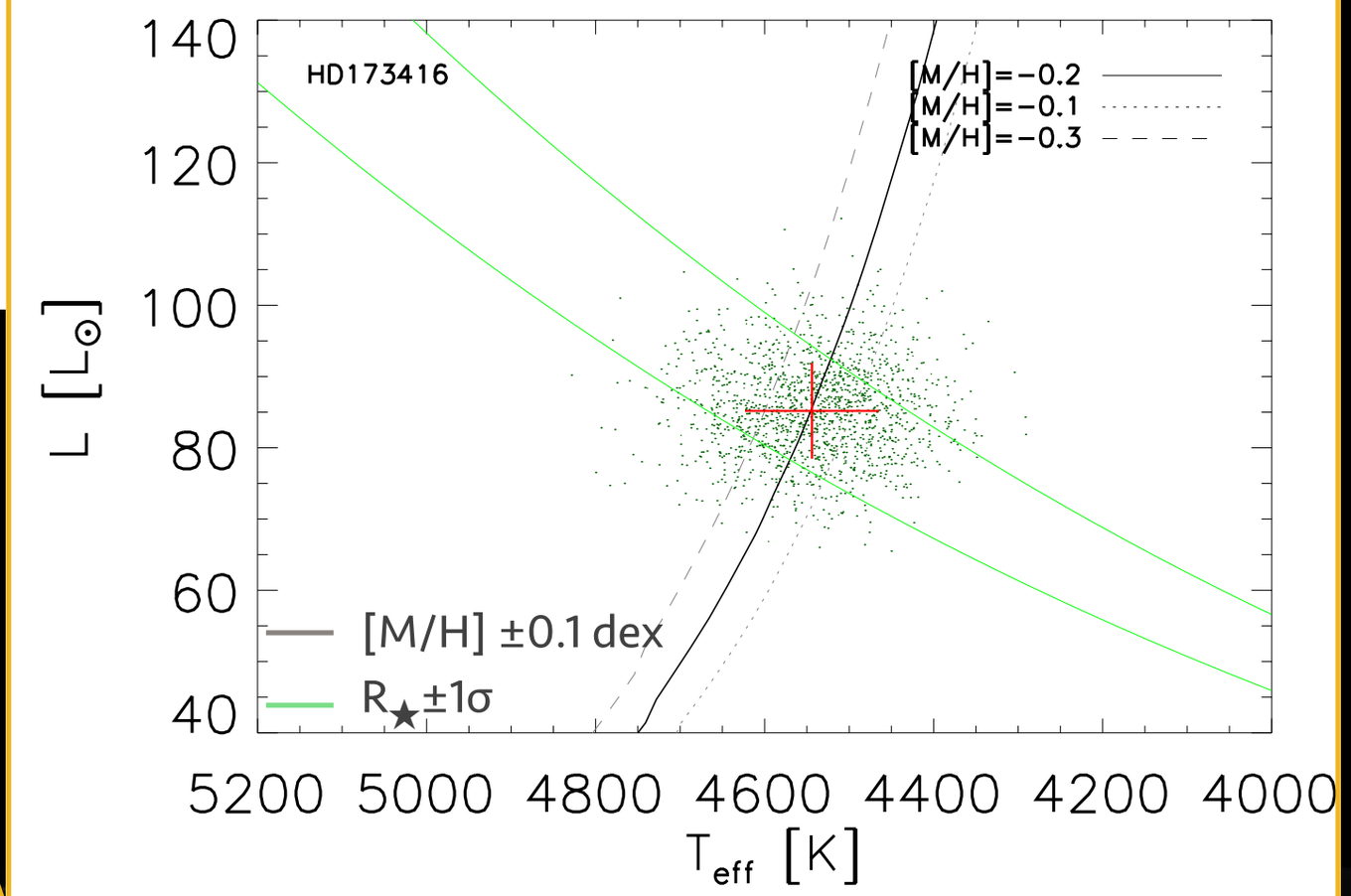
- $\mathcal{L}$ shows 2 different peaks for many MS stars:
  an old solution: > 400 Myrs
  a young solution: < 400 Myrs

→ Need additional stellar properties (gyrochronology, chromospheric activity, Lithium abundance...) to validate the age.

- $M_\star$ and $age_\star$ are not independent
- Clear negative correlation for the old solution

STELLAR PARAMETERS FROM INTERFEROMETRY





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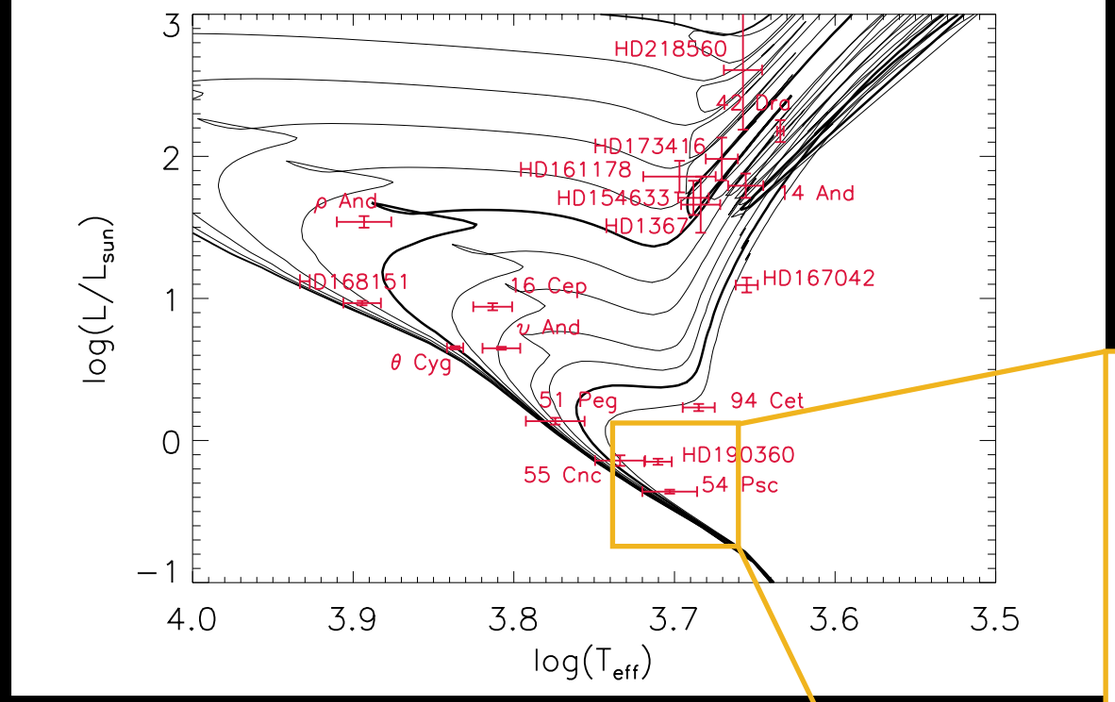
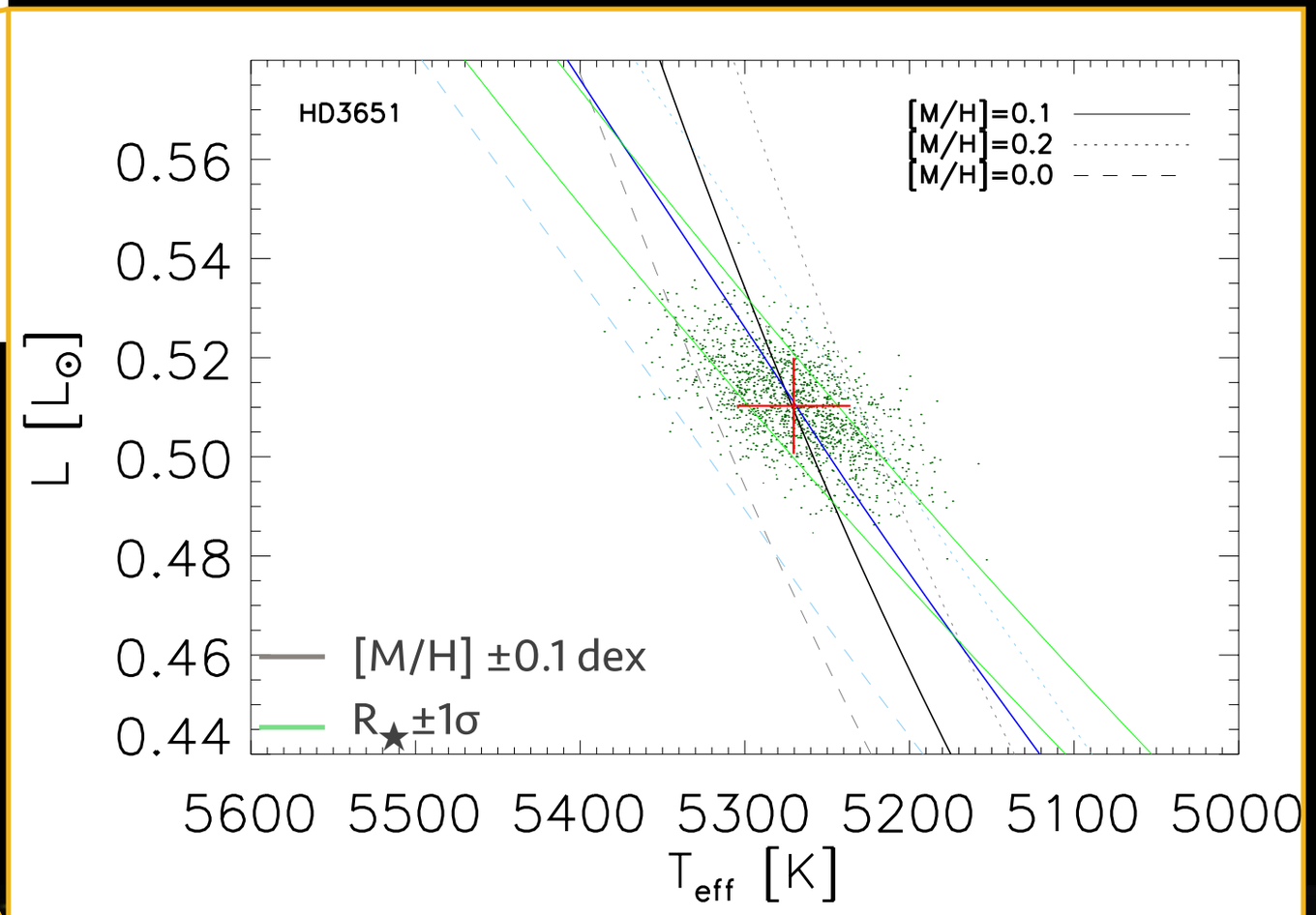


Accuracy on ages: ~ Myrs and Gyrs



Average accuracy on masses:

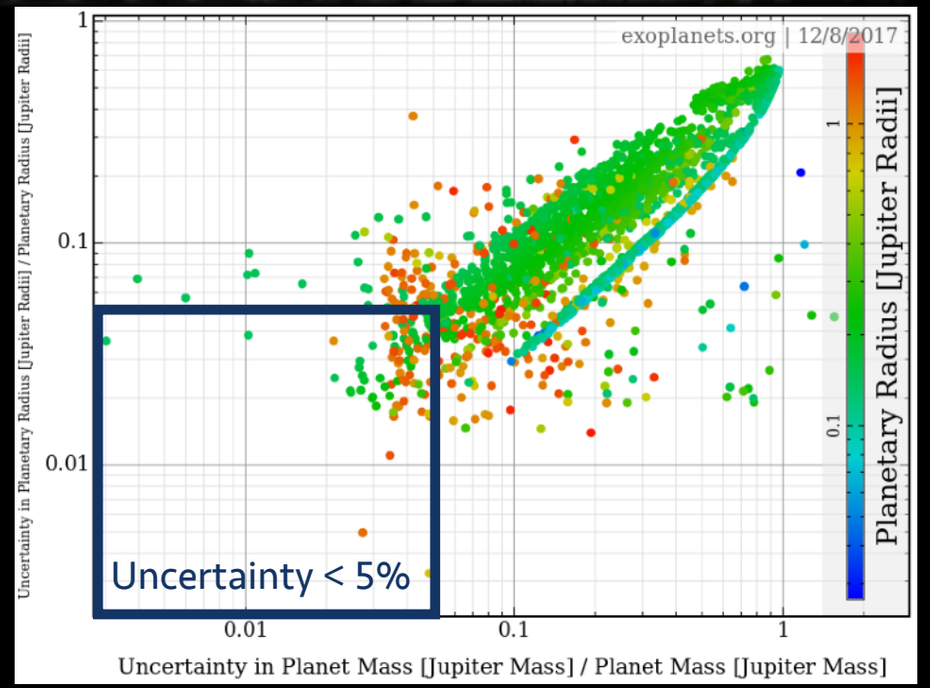
- 7.6% for old solutions
- 10% for young solutions

PLANETARY PARAMETERS

Usually: Radial Velocity (RV) detections

Thus we obtain $m_p \sin(i)$ from RV and stellar masses:

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



Habitable Zone (HZ) (*Jones et al. 2006*) $\propto L_\star / T_{eff,\star}^{\ 2}$

Semi-major axis $\propto M_\star^{\ 1/3}$

→ New estimations of HZ, semi-major axis (au) and $m_p \sin(i)$ from our measurements.

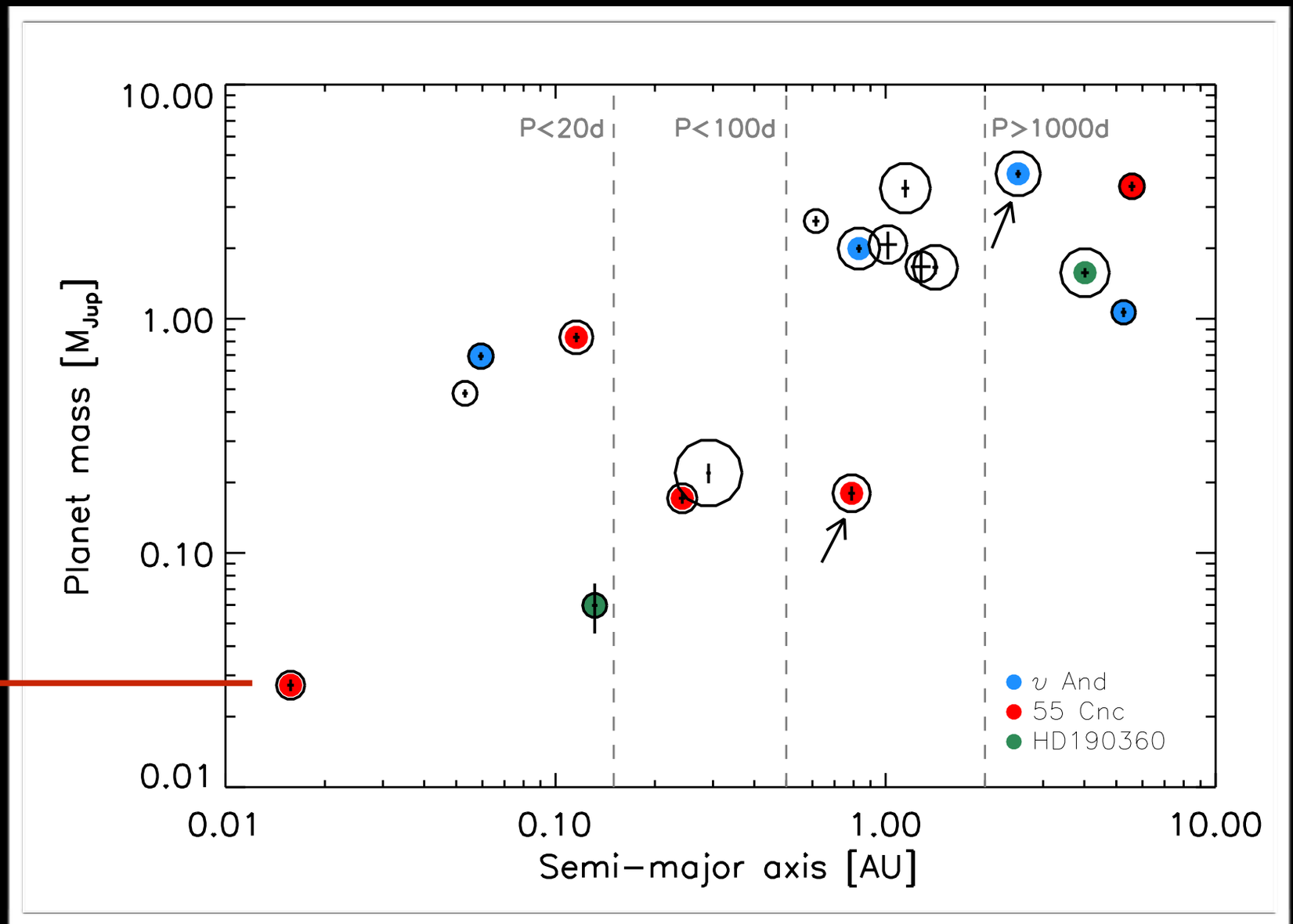
PLANETARY PARAMETERS

New robust determinations:

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

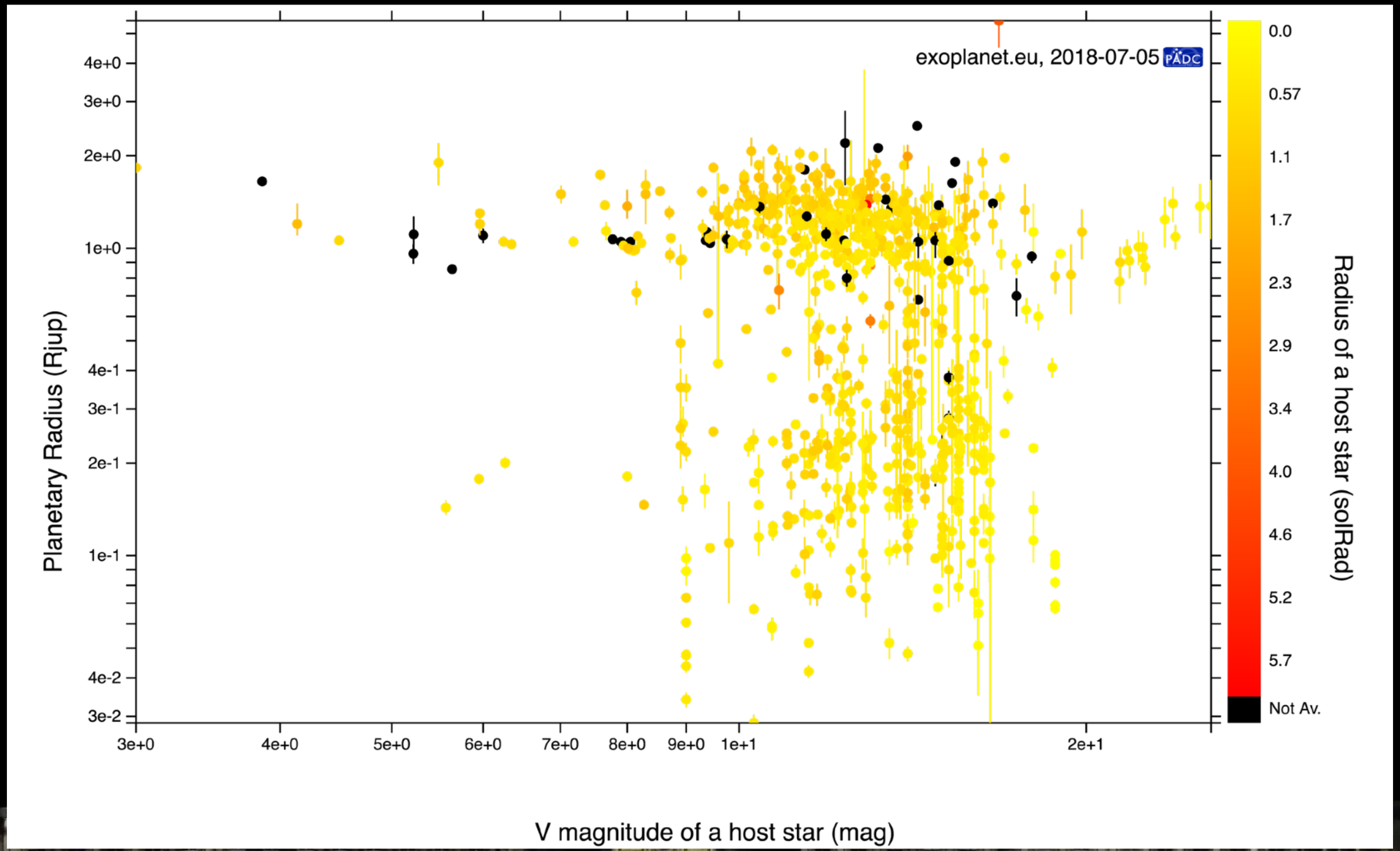
Decrease the uncertainties for 18 exoplanets

Transiting exoplanet 55 Cnc e (See talk of A. Crida)



Ligi et al. (2012a, 2012b, 2016)

THE FUTURE: TESS, PLATO, CHEOPS...



CoRoT, *Kepler*
>3000 exoplanets discovered

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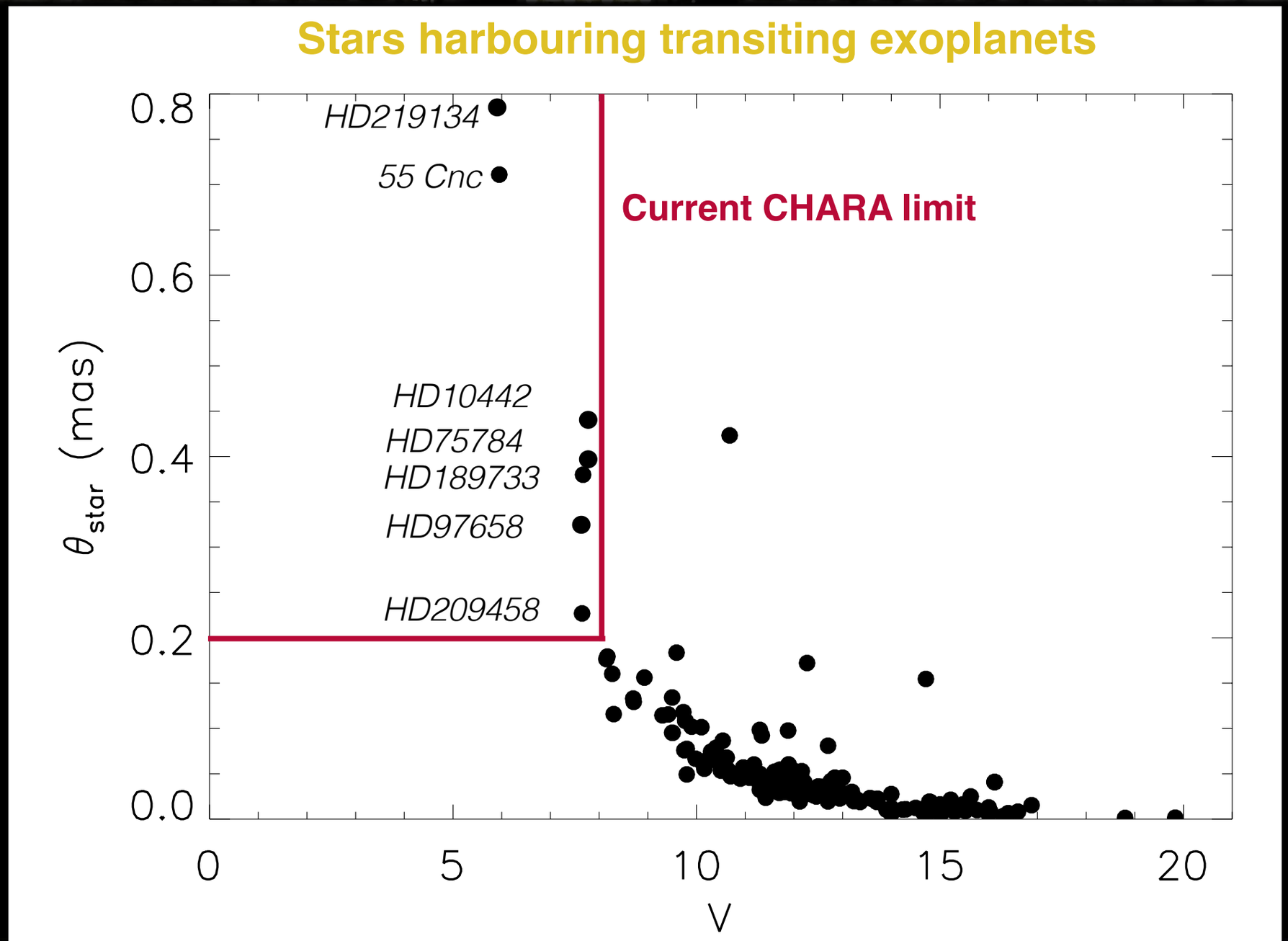

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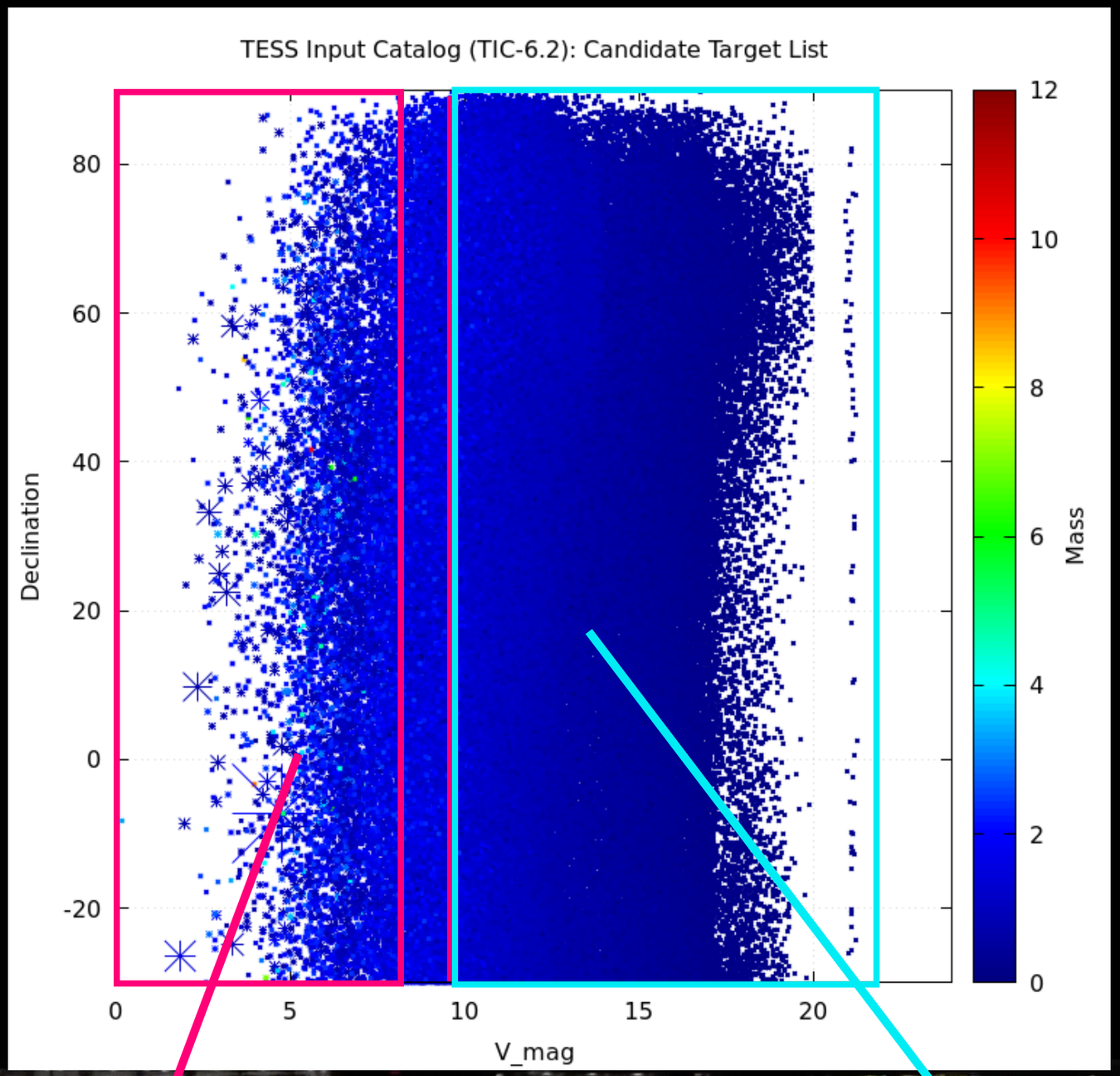
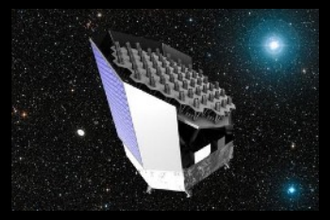


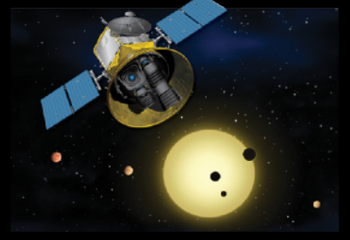
PLATO



4-11 mag

solar type stars

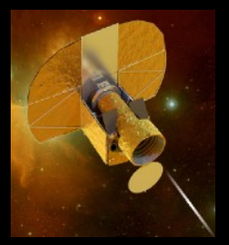
TESS



4-12 mag

F5 to M5

CHEOPS



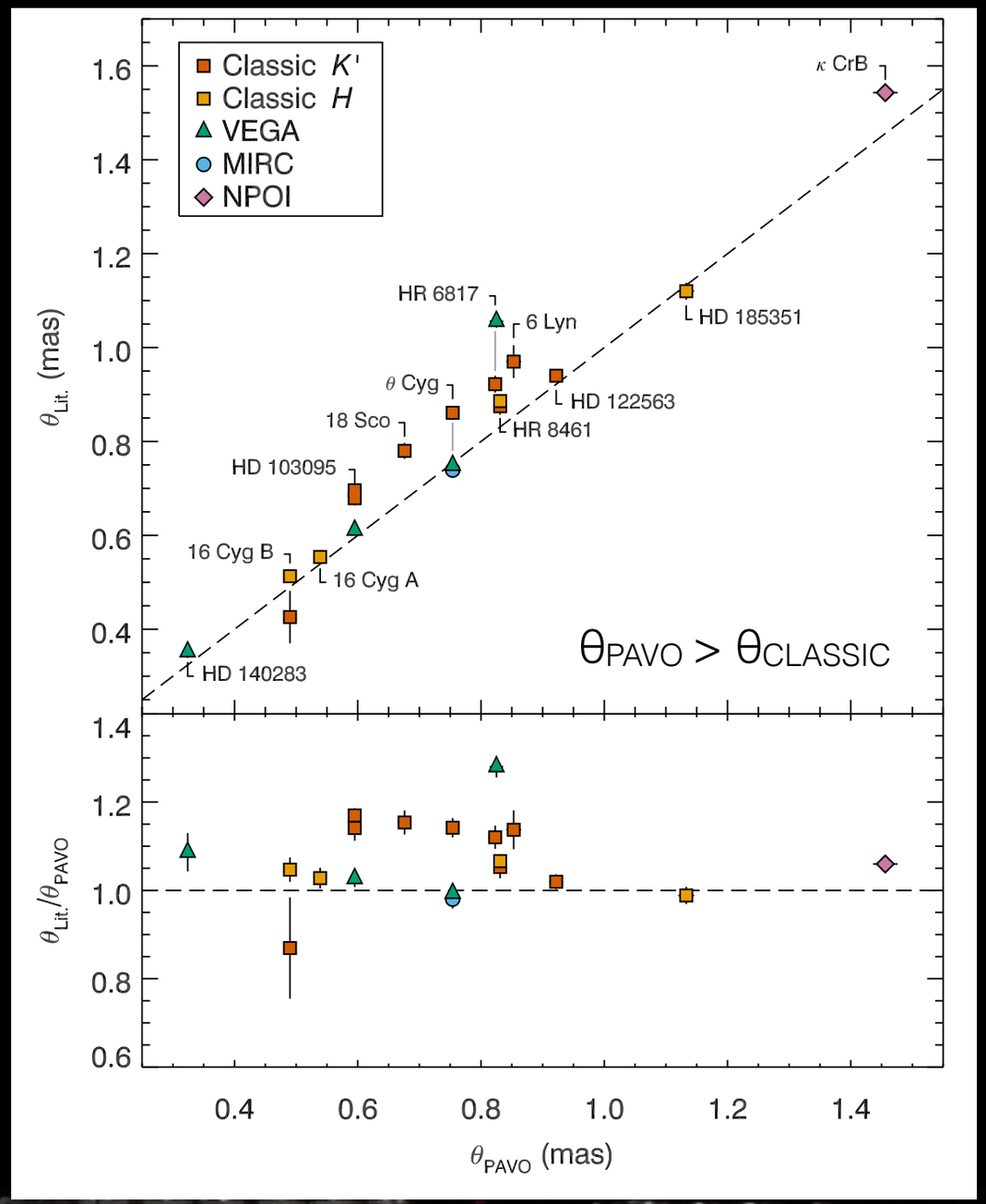
V<12 mag

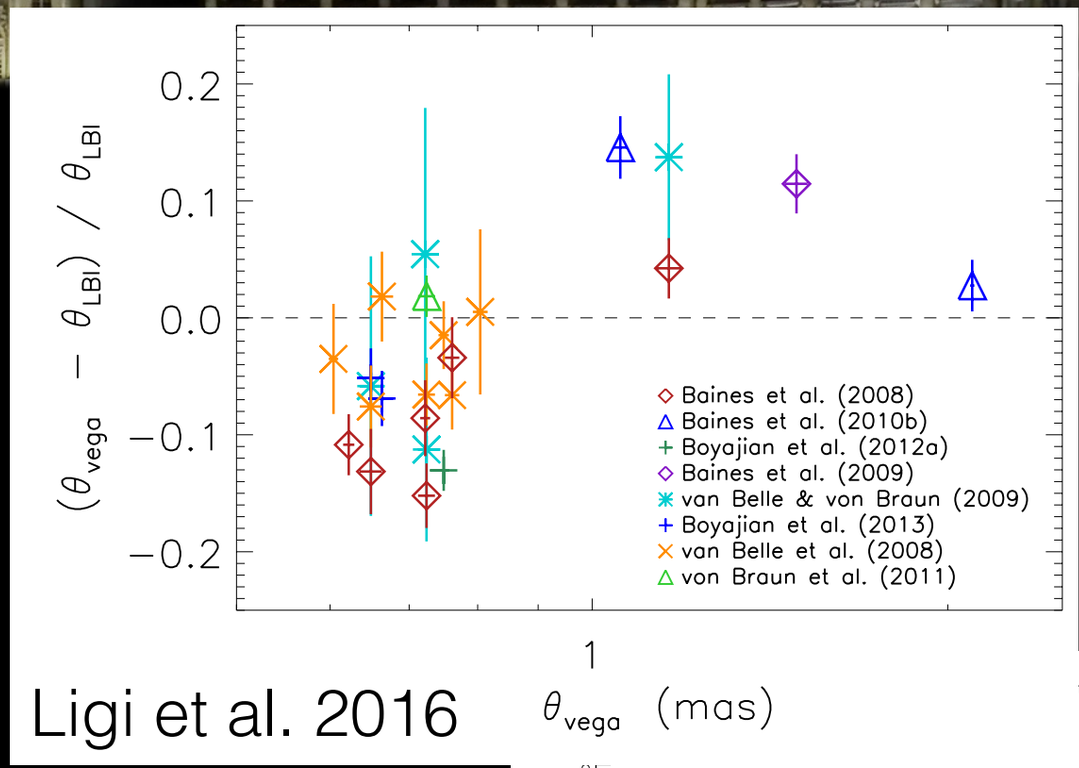
Known host stars

Direct measurements

Indirect measurements

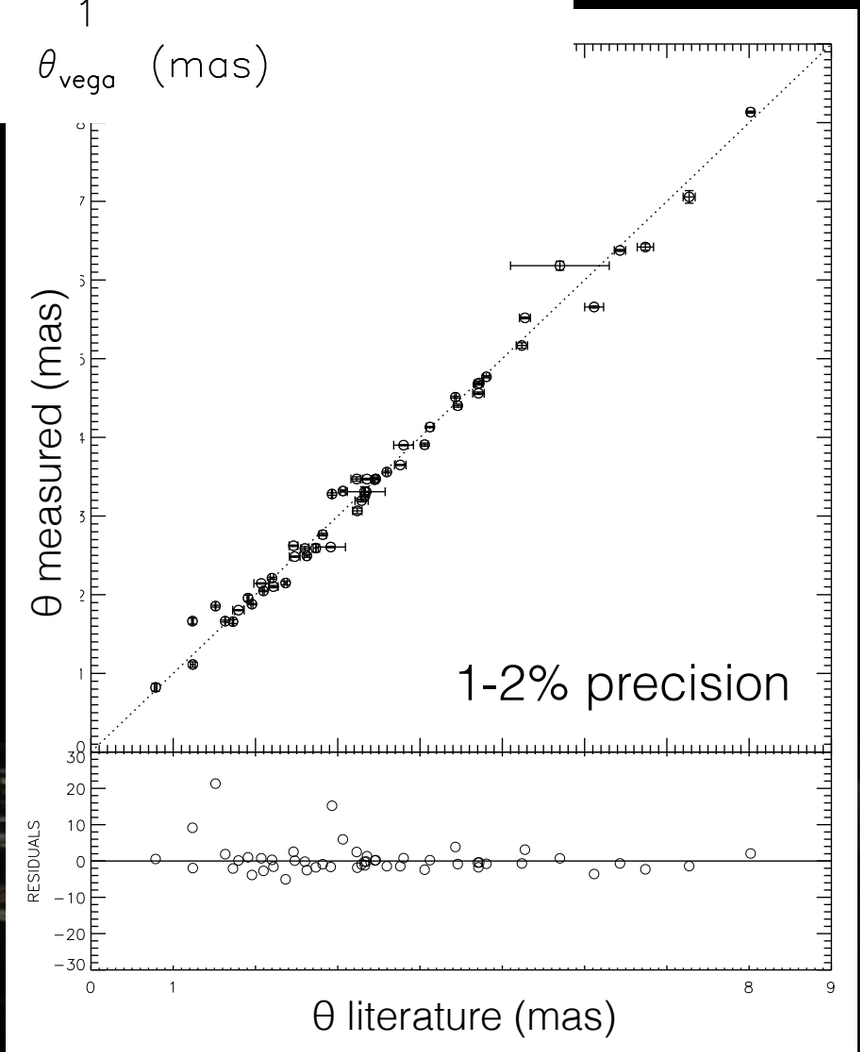
SOME LIMITATIONS: COMPARISON BETWEEN MEASUREMENTS





Ligi et al. 2016

4% discrepancy (median)



White et al. 2018

Baines et la. 2018

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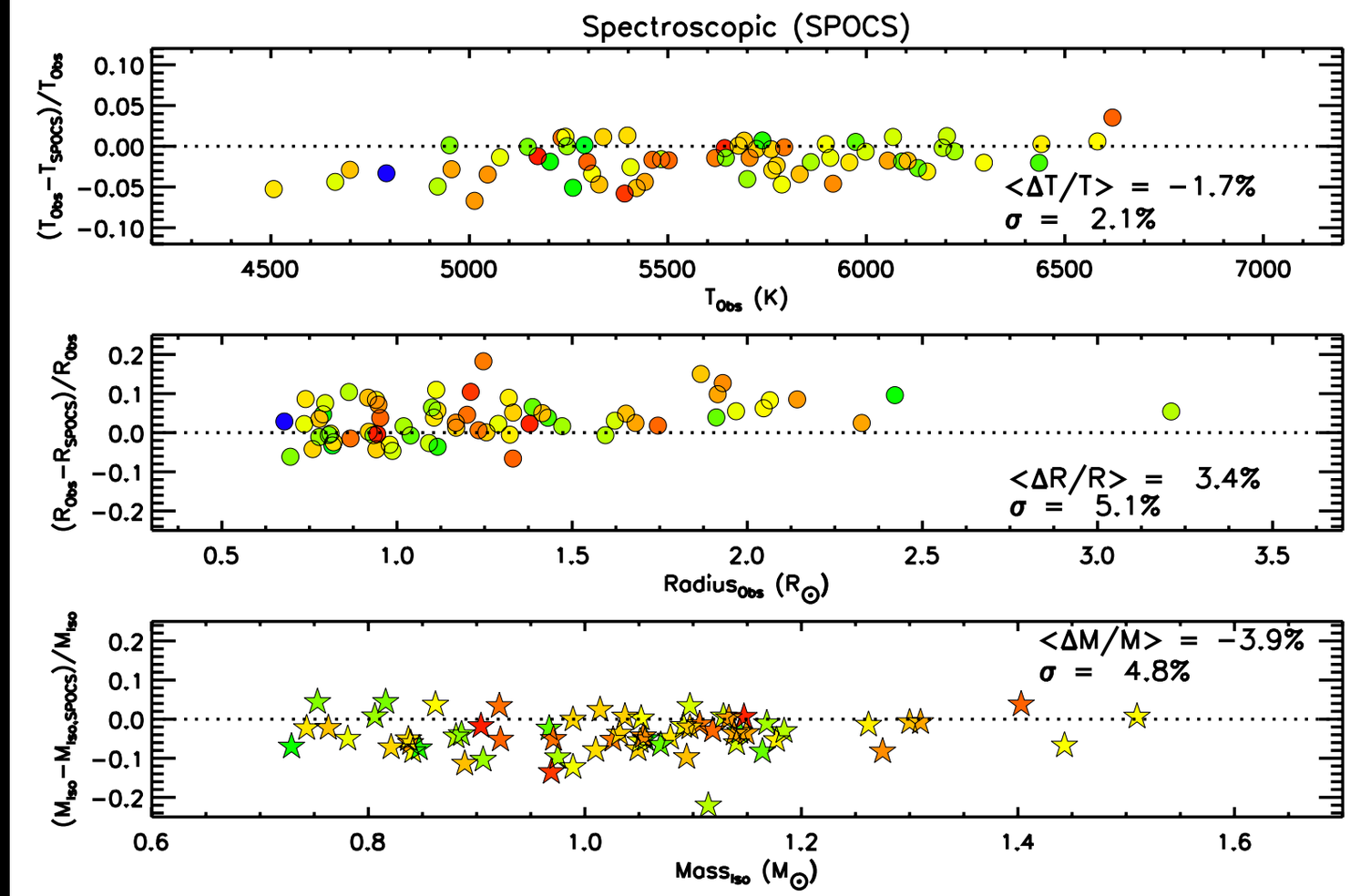
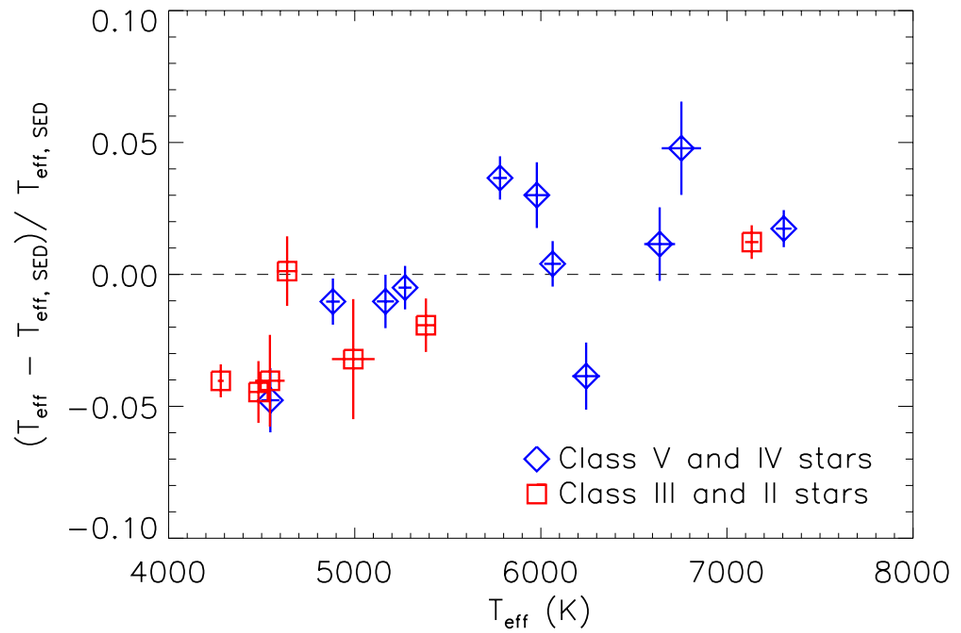
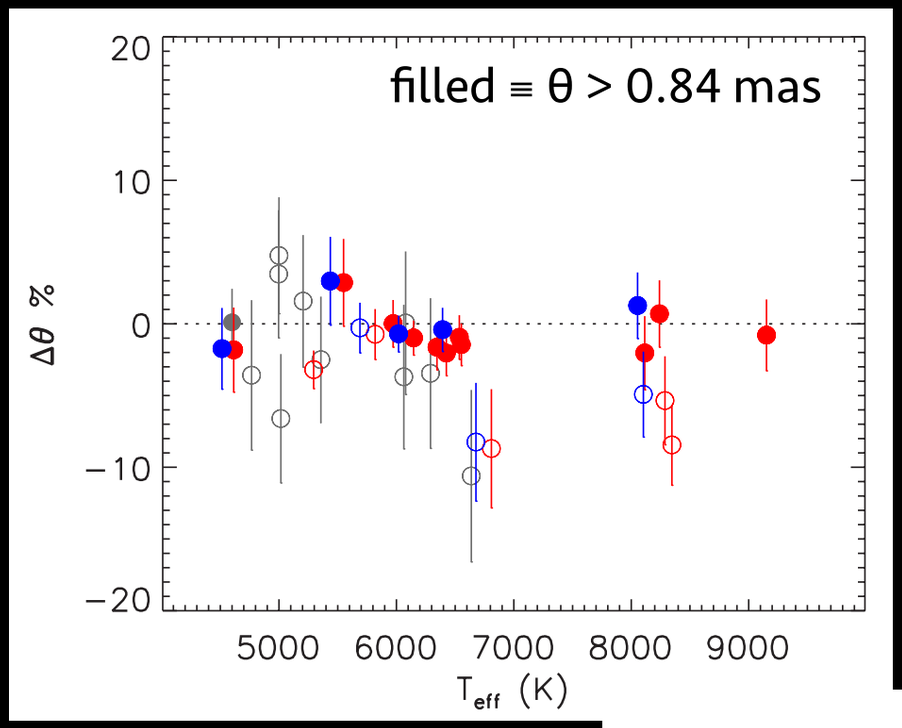


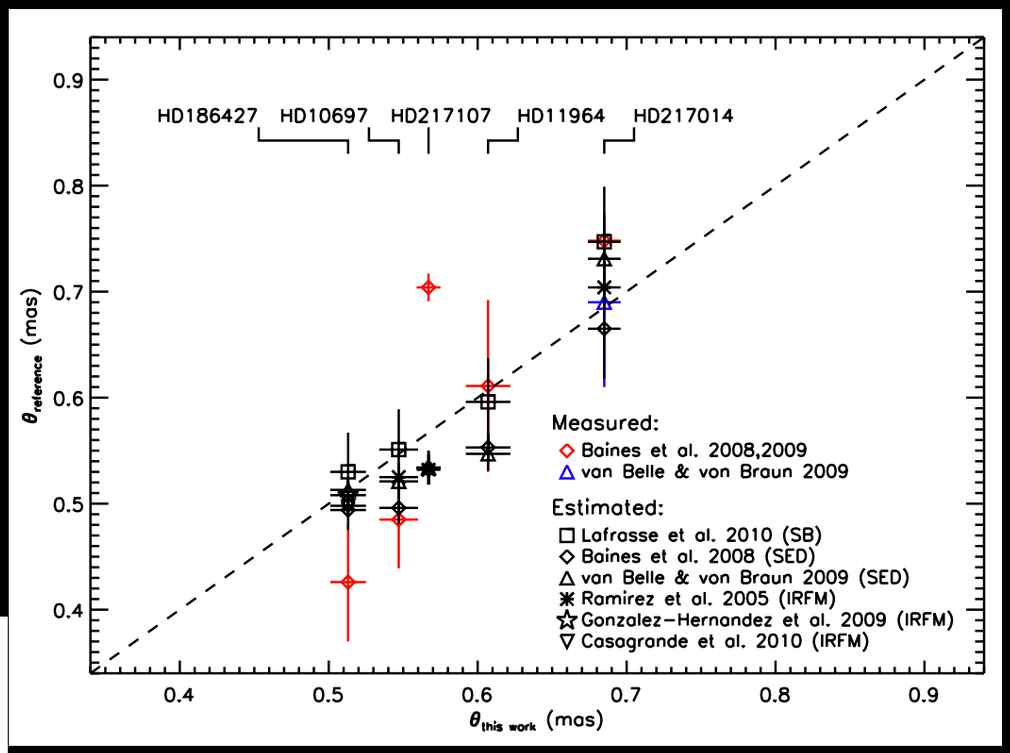
Boyajian et al. 2013



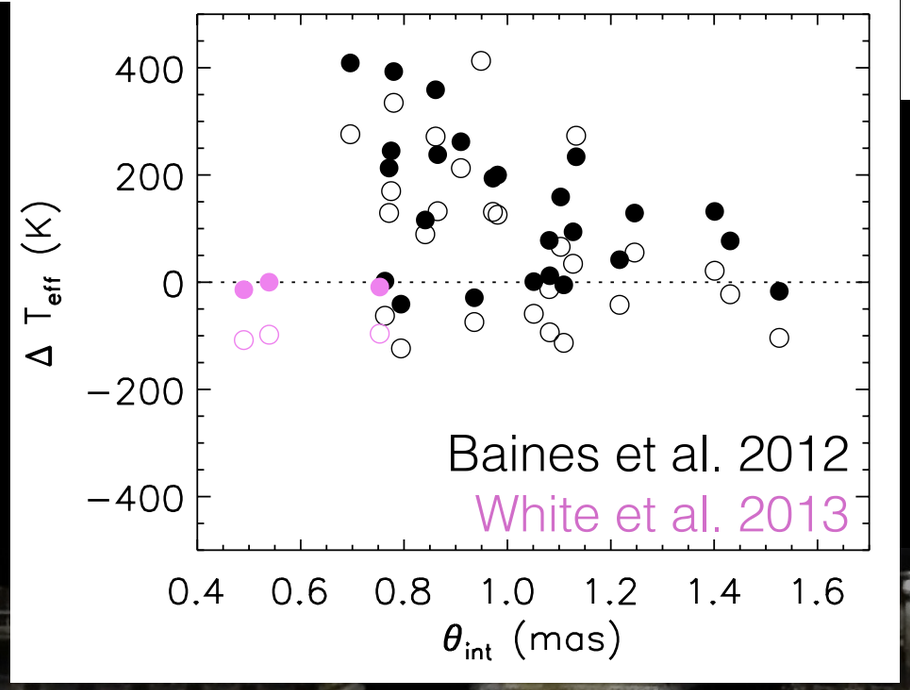
Ligi et al. 2016

EMPIRICAL RELATIONS



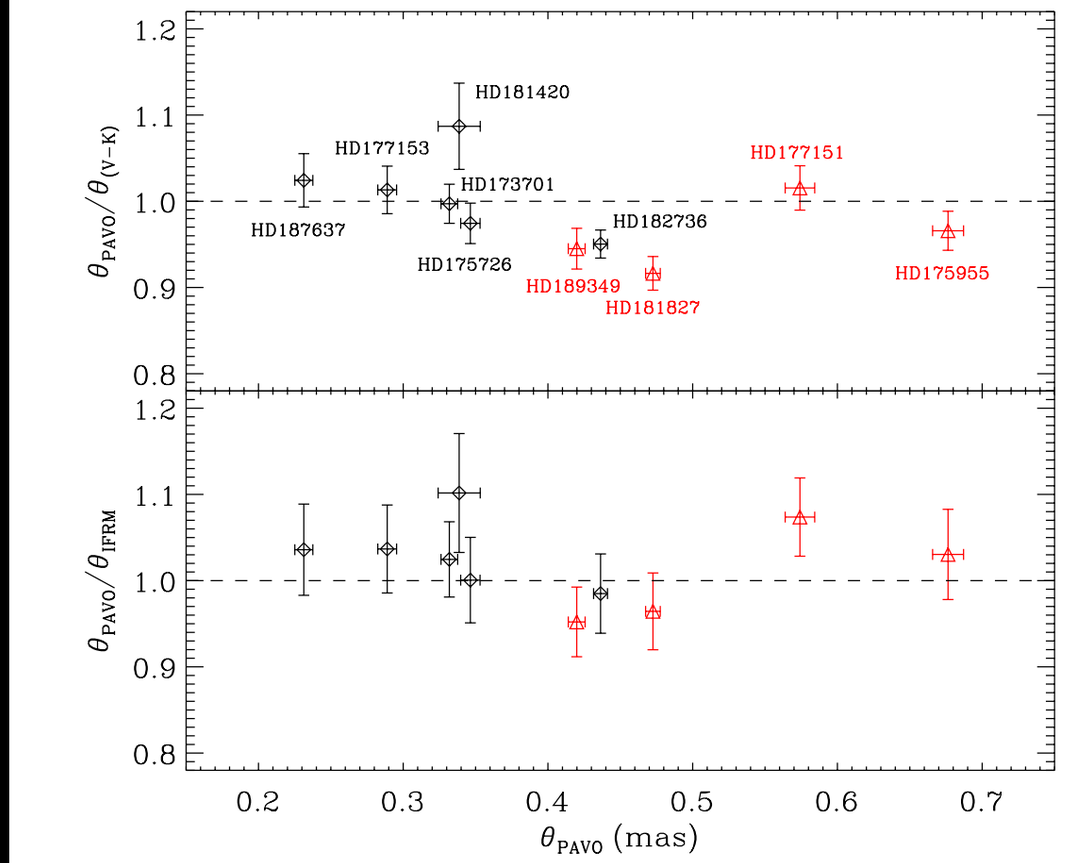


Boyajian et al. 2013

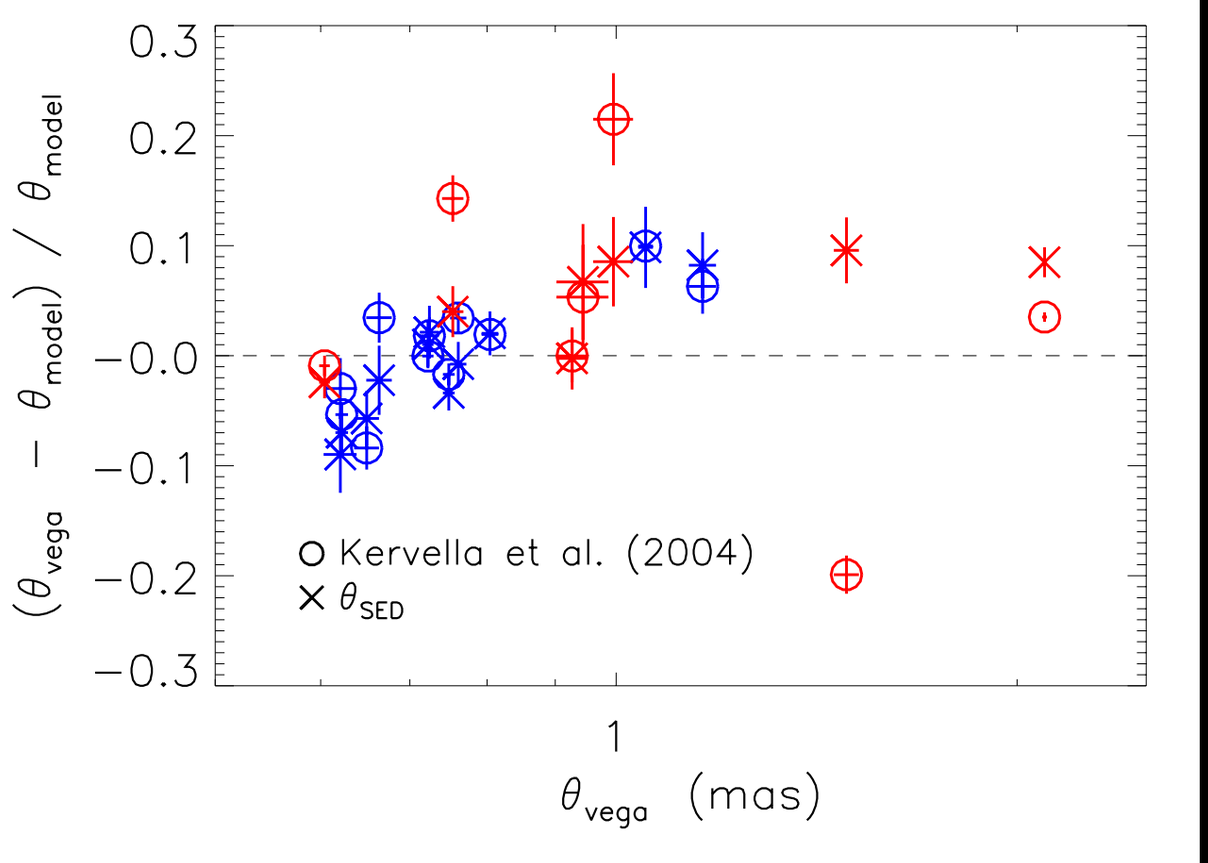


Cassagrande et al. 2014

EMPIRICAL RELATIONS



Huber et al. 2012

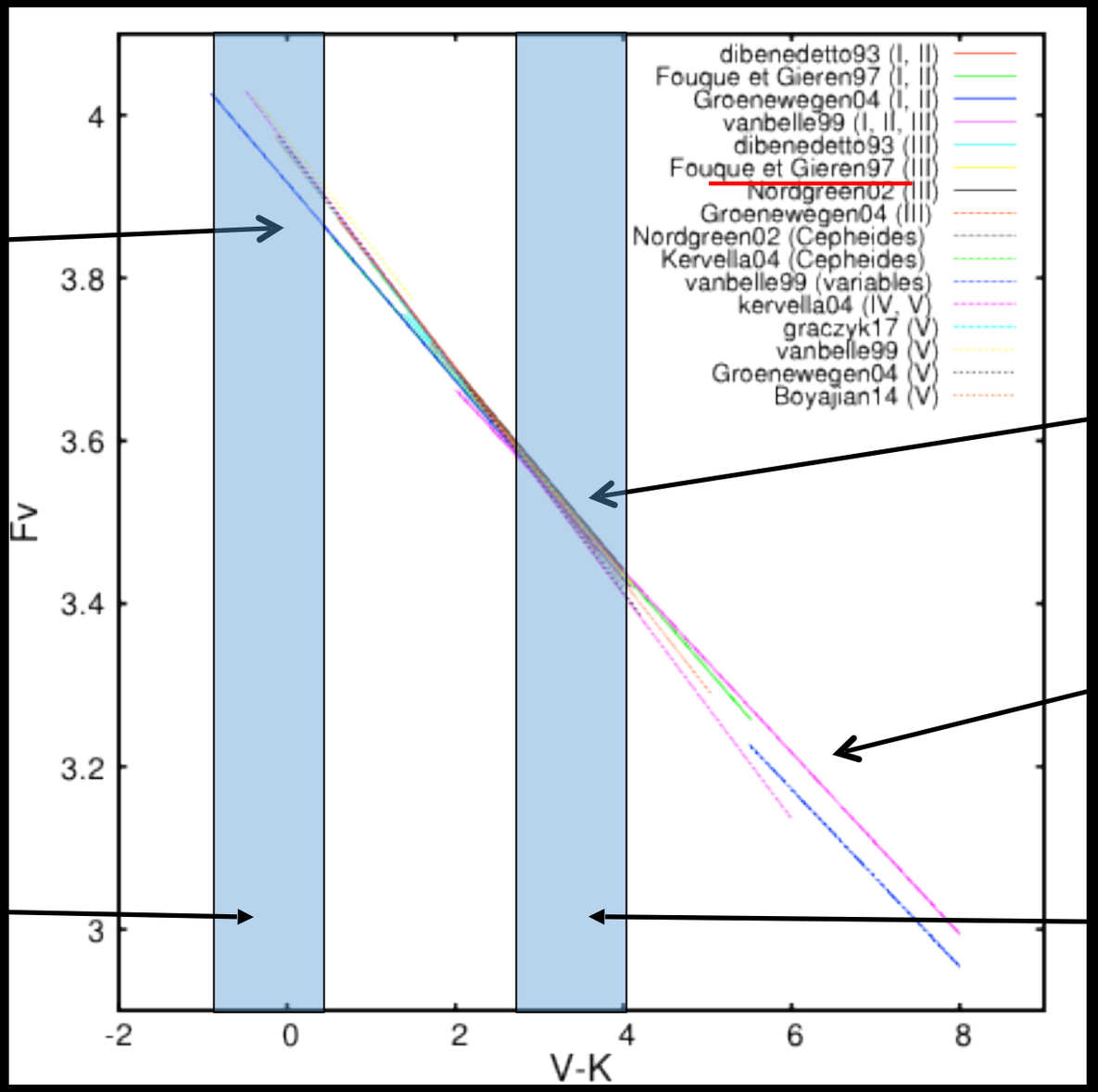


Ligi et al. 2016

EMPIRICAL RELATIONS

Surface-brightness color relation (SBCR) - NARDETTO HDR 2017

relations not precise (7%) and inconsistent (8%)



1. $S_V = V - 5\log\theta_{LD} = \sum a_k (V-K)^k$
2. $F_V = 4.2207 - 0.1 S_V = \alpha + \beta(V-K)$
3. $\log\theta_{LD} = d_1 + c_1 1(V-K) - 0.2V$
4. $\theta_{LD}(V=0) = 10^{A+B(V-K)}$
5. $\Phi_V = \frac{\theta}{9.305 * 10^{\frac{-V}{5}}} = \sum z_k (V-K)^k$

2% precision

precise (1-2%) but inconsistent (6%) relations

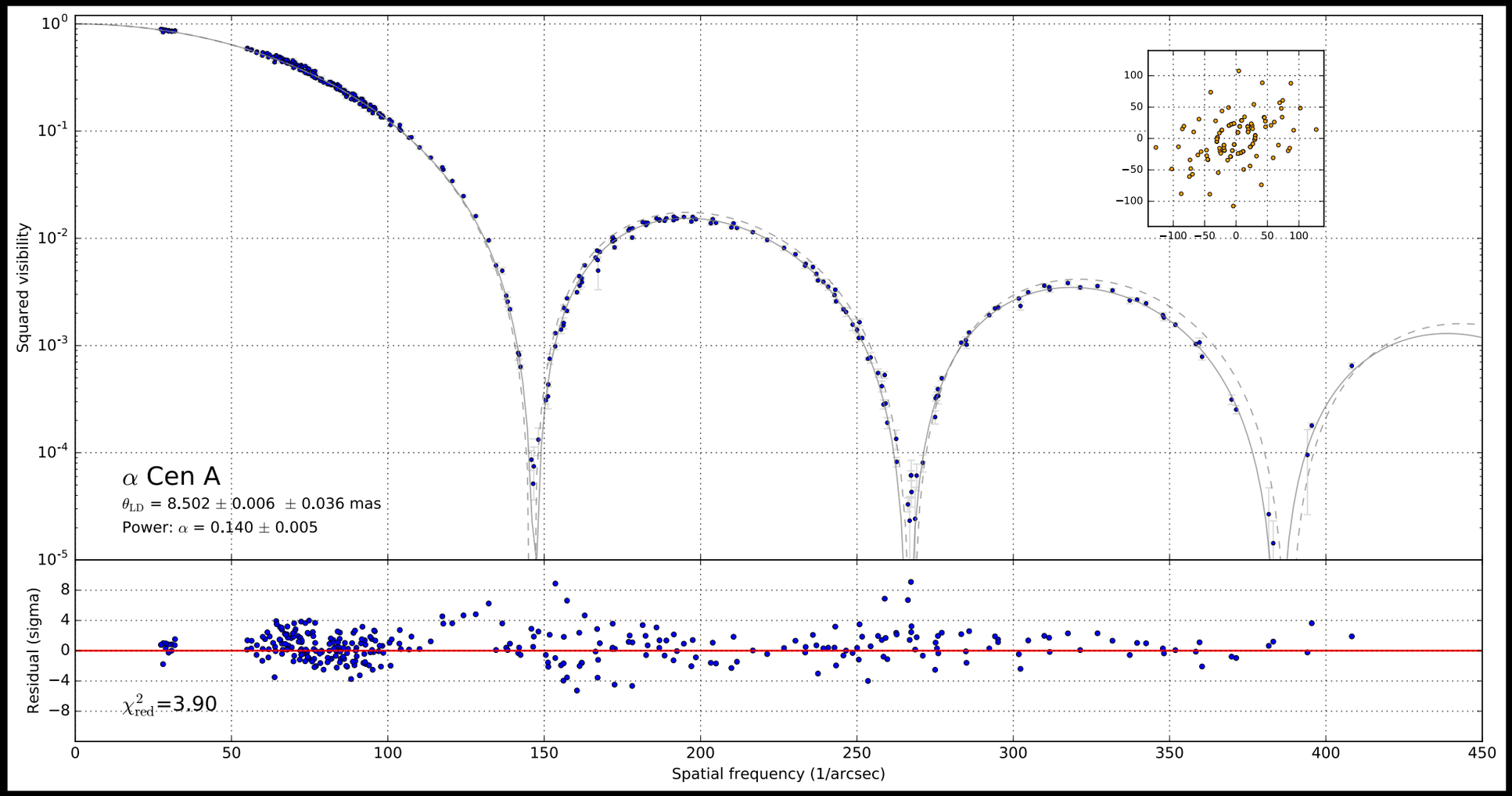
Useful for eclipsing binaries and early types (M31/M33)

Useful for eclipsing binaries and late-type stars (LMC/SMC)

Courtesy D. Mourard

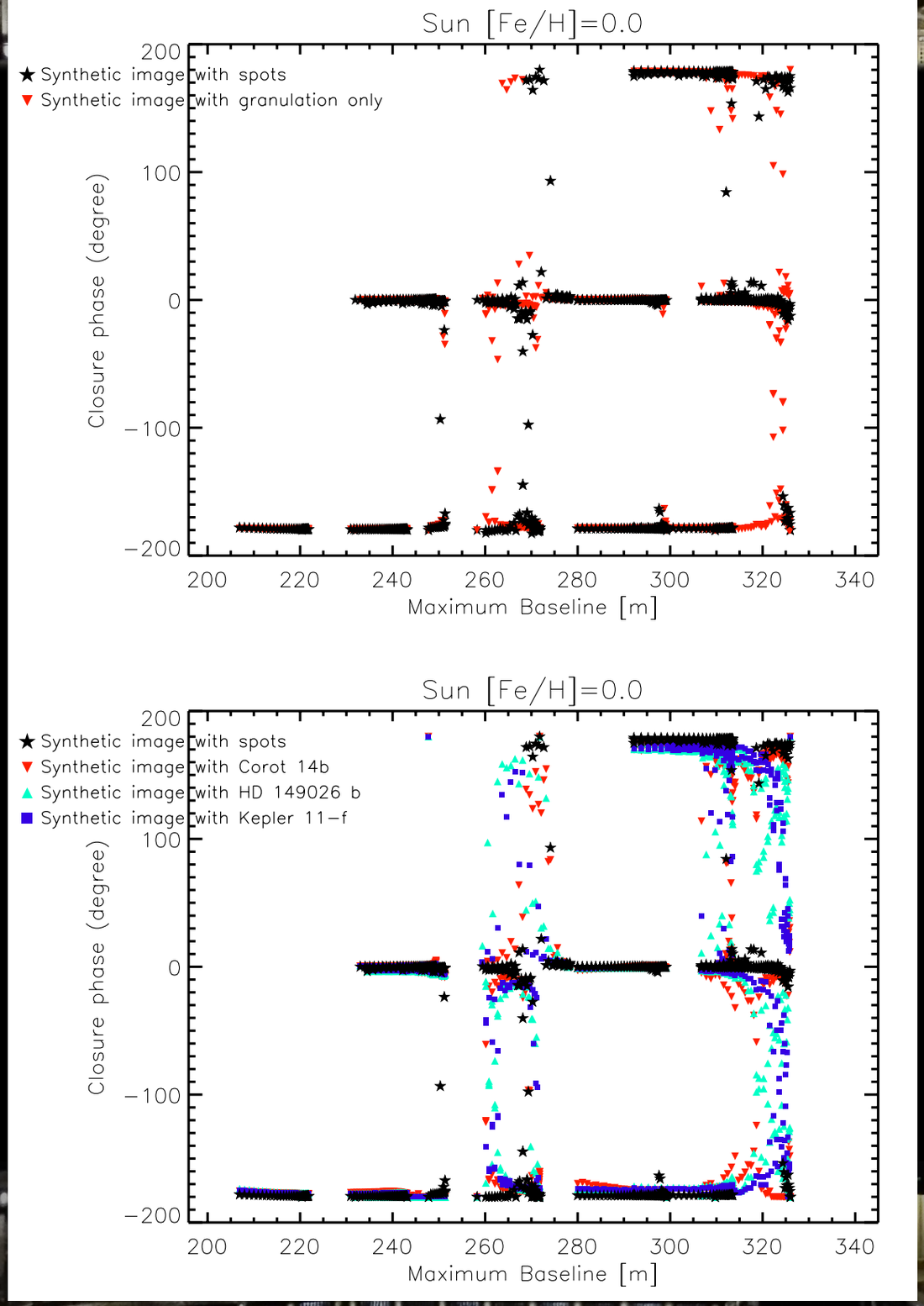
SOME LIMITATIONS: LIMB-DARKENING

α Cen A with Pionier/VLTI

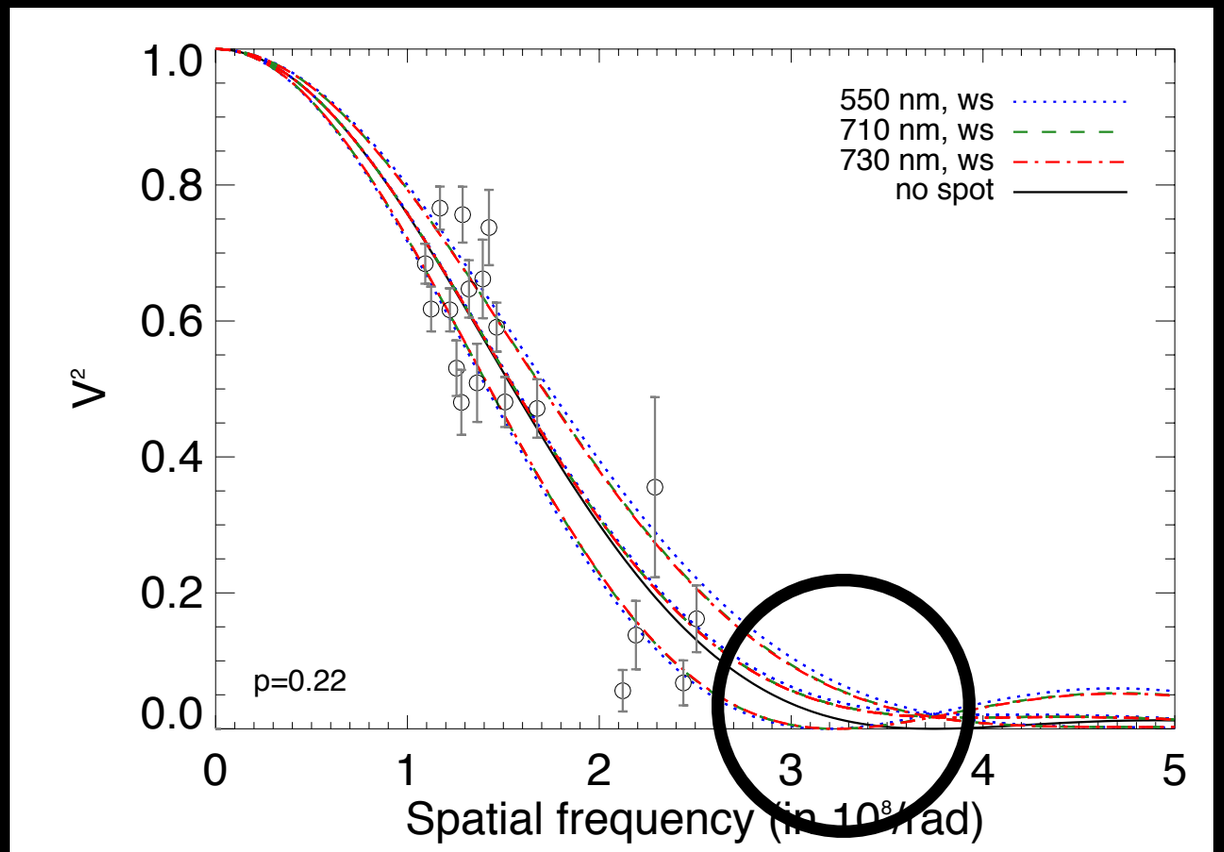


Kervella et al. 2017

SOME LIMITATIONS: STELLAR ACTIVITY



Chiavassa et al. 2014



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

Effects of spots on the visibility curve could change the diameter.

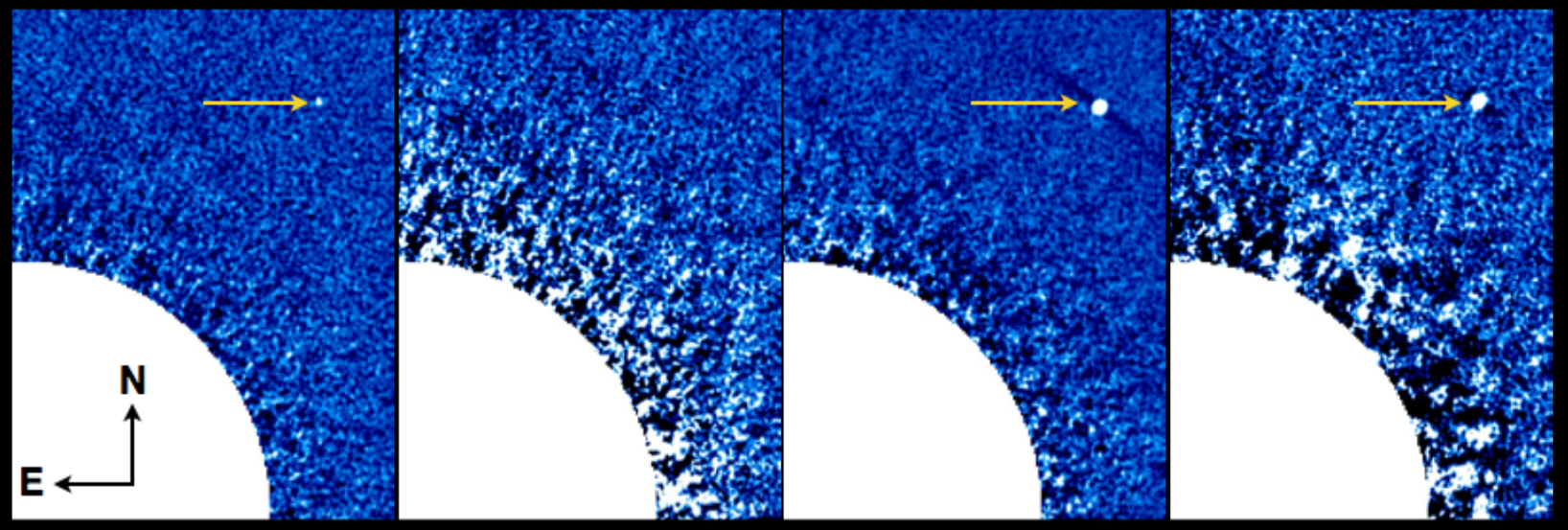
MIXING TECHNICS: THE EXAMPLE OF GJ504

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 et al. 2018

MIXING TECHNICS: THE EXAMPLE OF GJ504

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

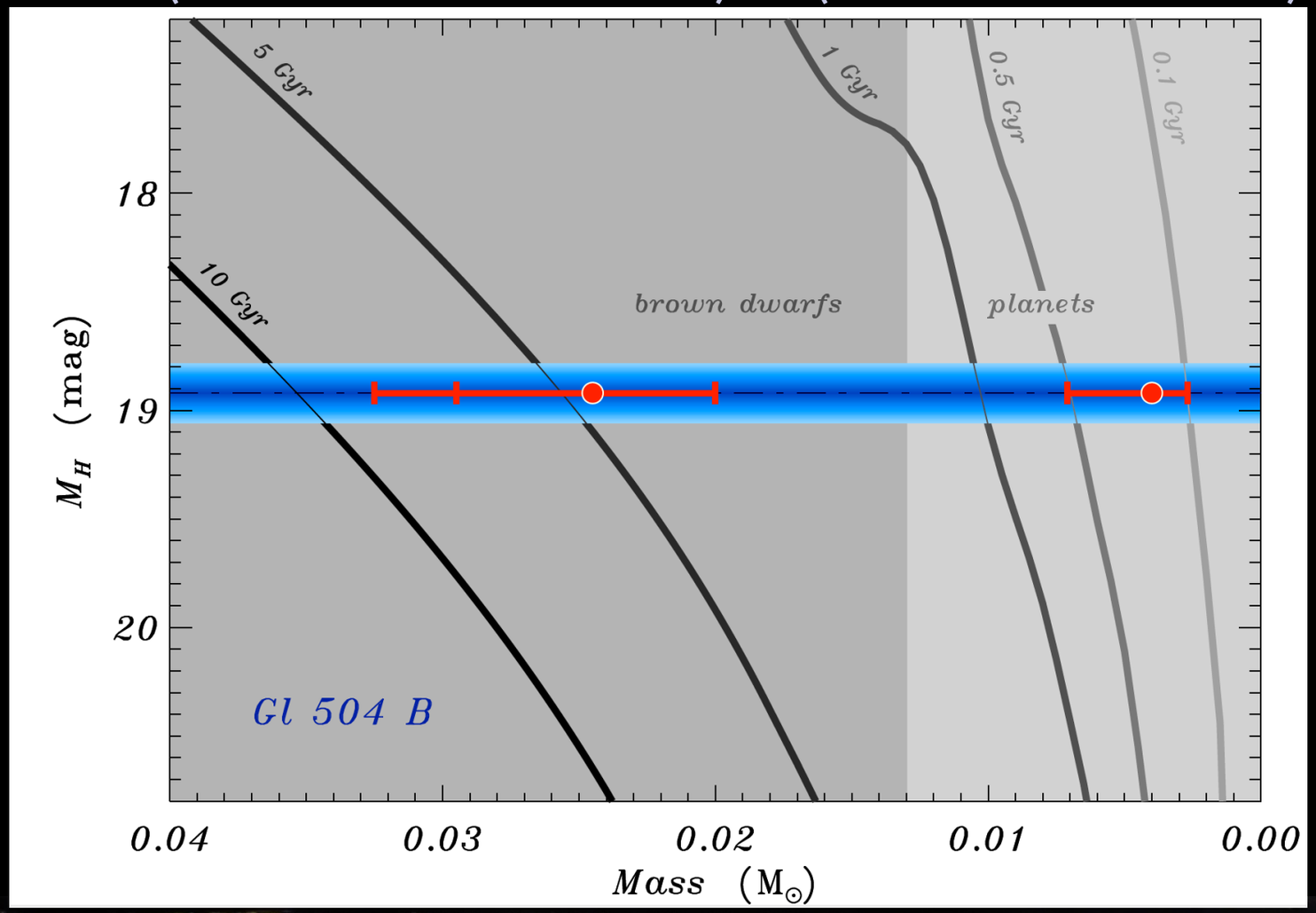
Fuhrmann & Chini (2015)
➔ 25 M_{Jup}, 4.5 Gyr
(high-resolution spectroscopy)

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)

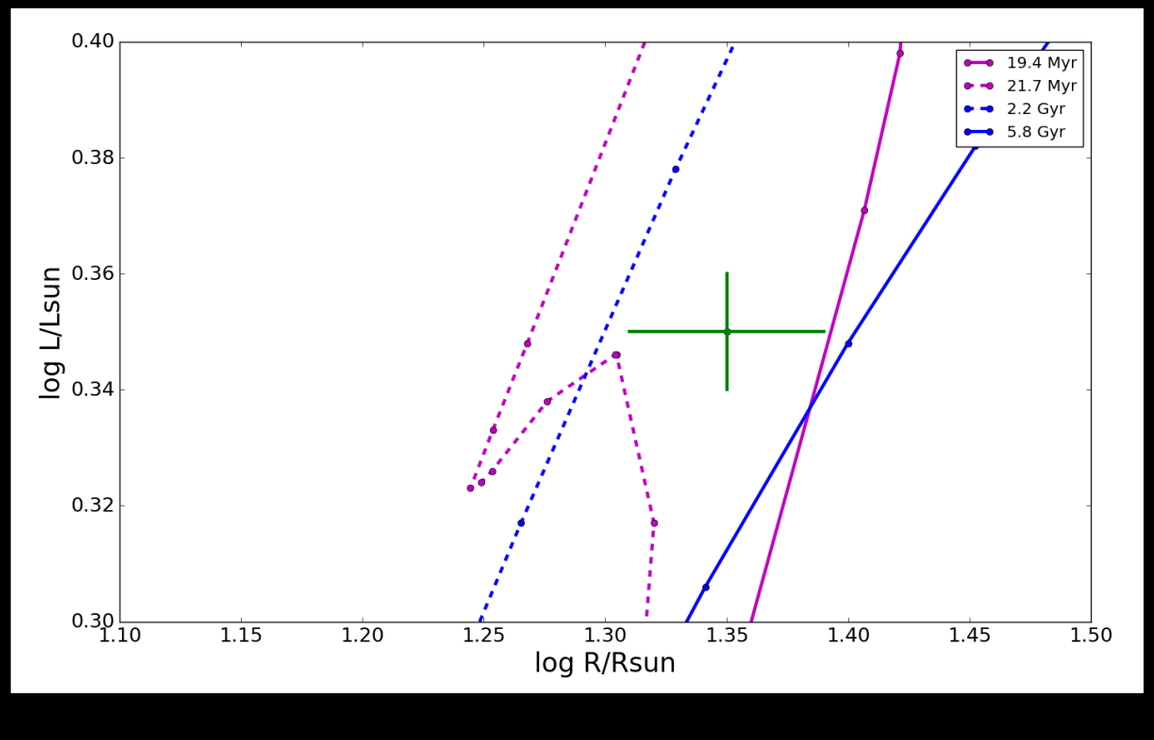
~25 M_{Jup} ↑ 4.5 Gyr (Fuhrmann & Chini 2015)

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



Fuhrmann & Chini (2015)

MIXING TECHNICS: THE EXAMPLE OF GJ504



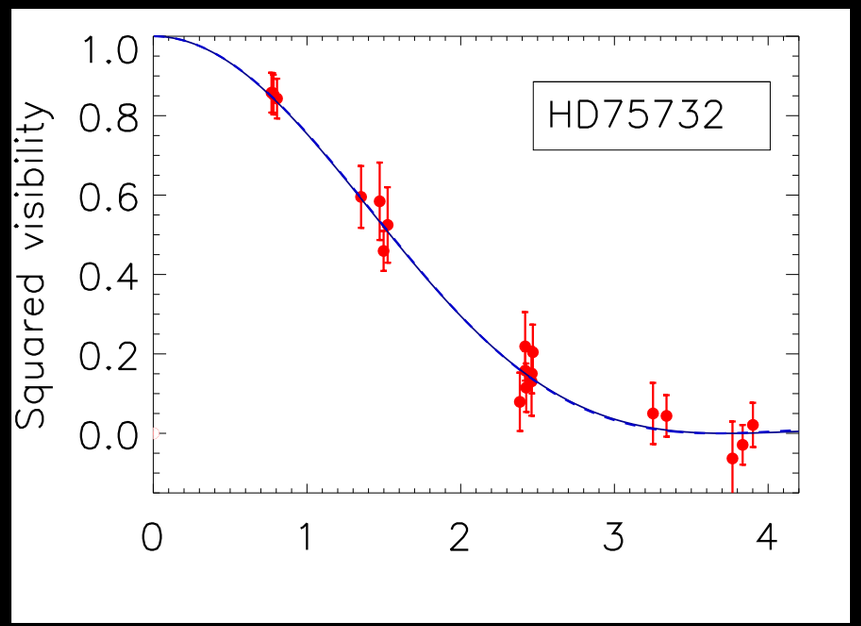
Interferometric measurements
to refine the isochronal age:
VEGA/CHARA: 0.71±0.02 mas

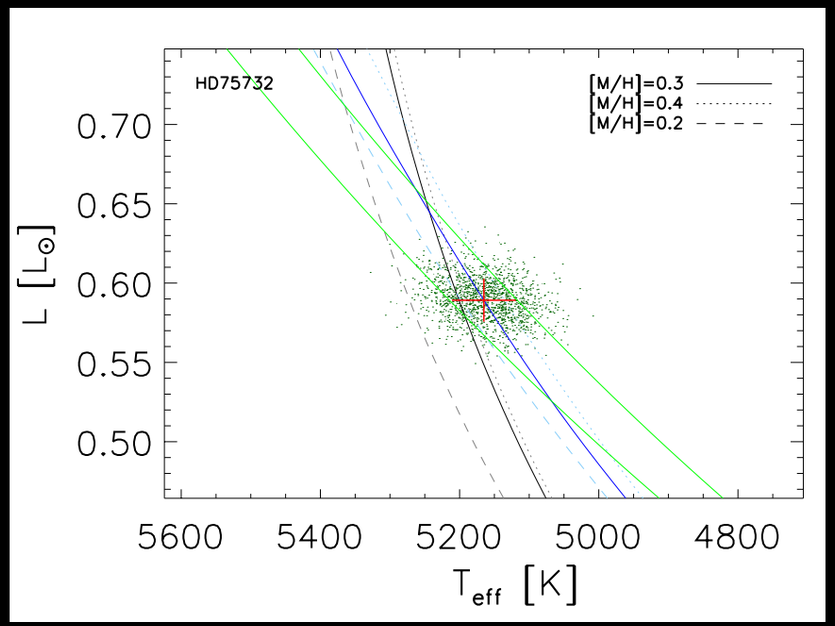
But still compatible with **2 isochronal ages**:
21±2 Myr
4.0±1.8 Gyr

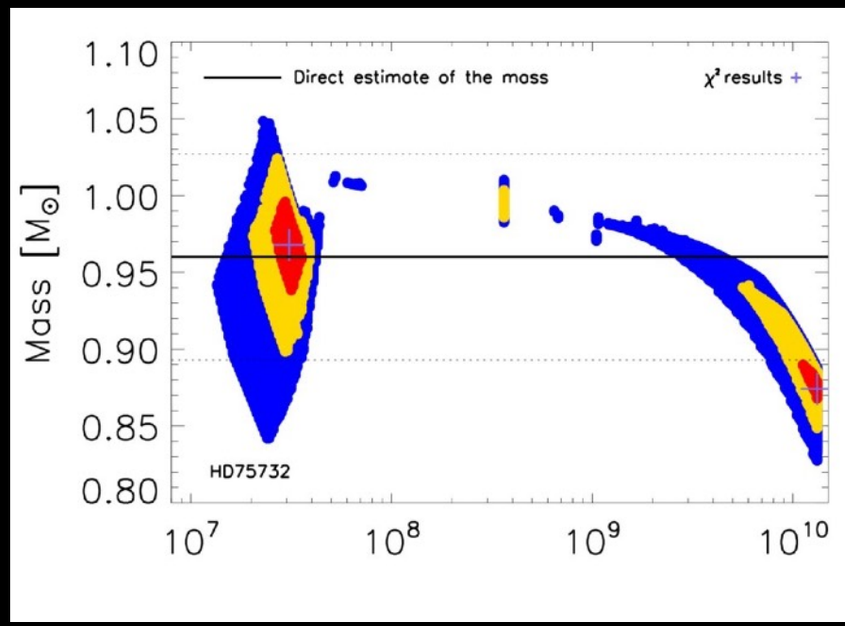
- Scatter in the $T_{eff,\star}$ determination, thus the age.
- GJ504 A is an active, rapid rotator, thus spots can be found at its surface.
  ➔ Effects of spots? Could affect $L_\star$ and $T_{eff,\star}$

Results:
- Due to the dispersion of the interferometric measurements, spot should not affect the measured angular diameter.
- Possible spots either too small (p=7%) or too big (p=22%) to be compatible with the bias in $T_{eff,\star}$.

COMPARING MODELS AND MEASUREMENTS: THE EXAMPLE OF 55 CNC







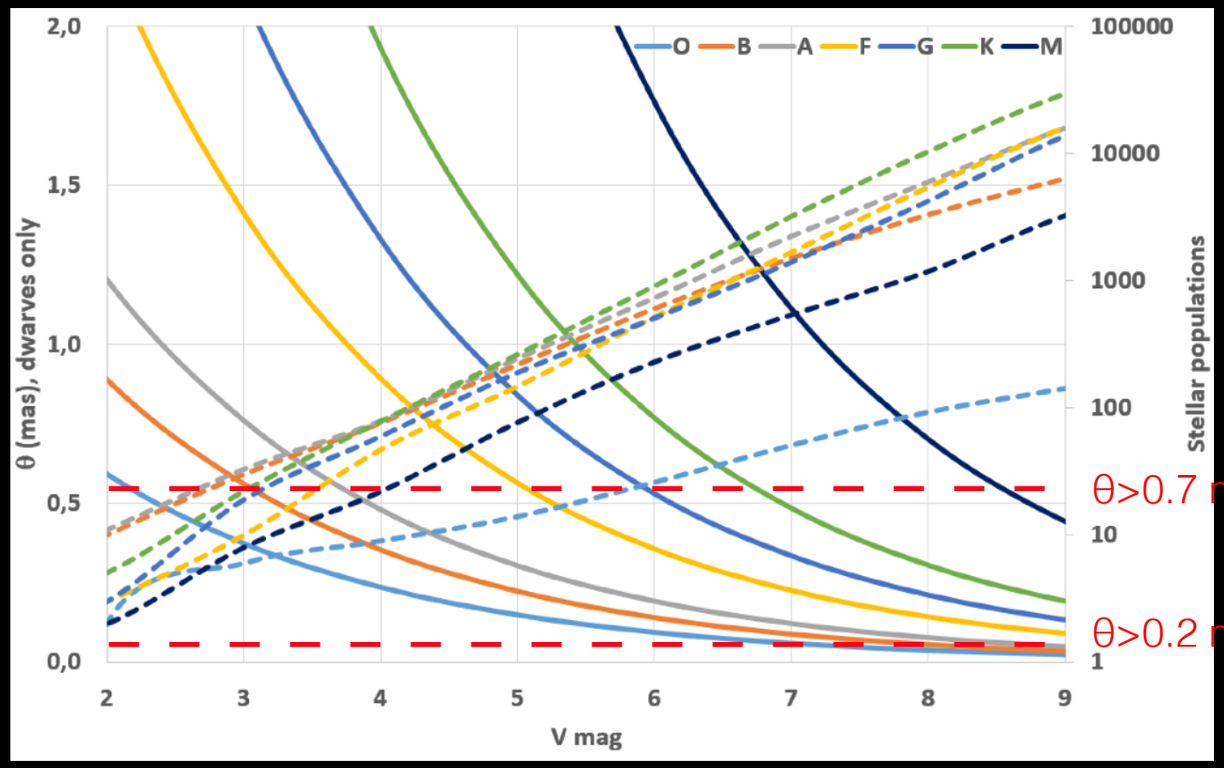
See talk A. Crida

- Using the stellar density + interferometric radius: **$M_\star$ = 0.96 ± 0.067 $M_\odot$**

- Still, different parameters in the model → different, inconsistent masses for the young solution: CES2MO (Lebreton & Goupil 2014) gives $M_\star$ from

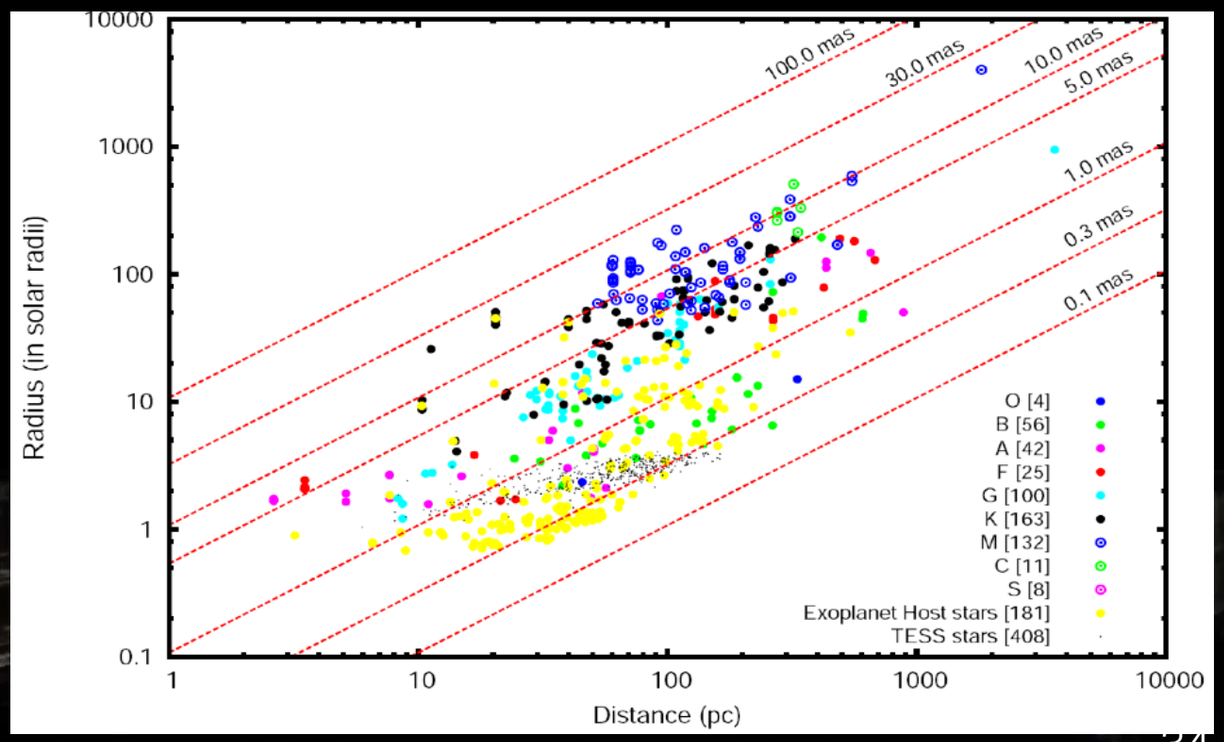
0.950 ± 0.015 to 0.989 ± 0.020 $M_\odot$

THE SPICA PROJECT

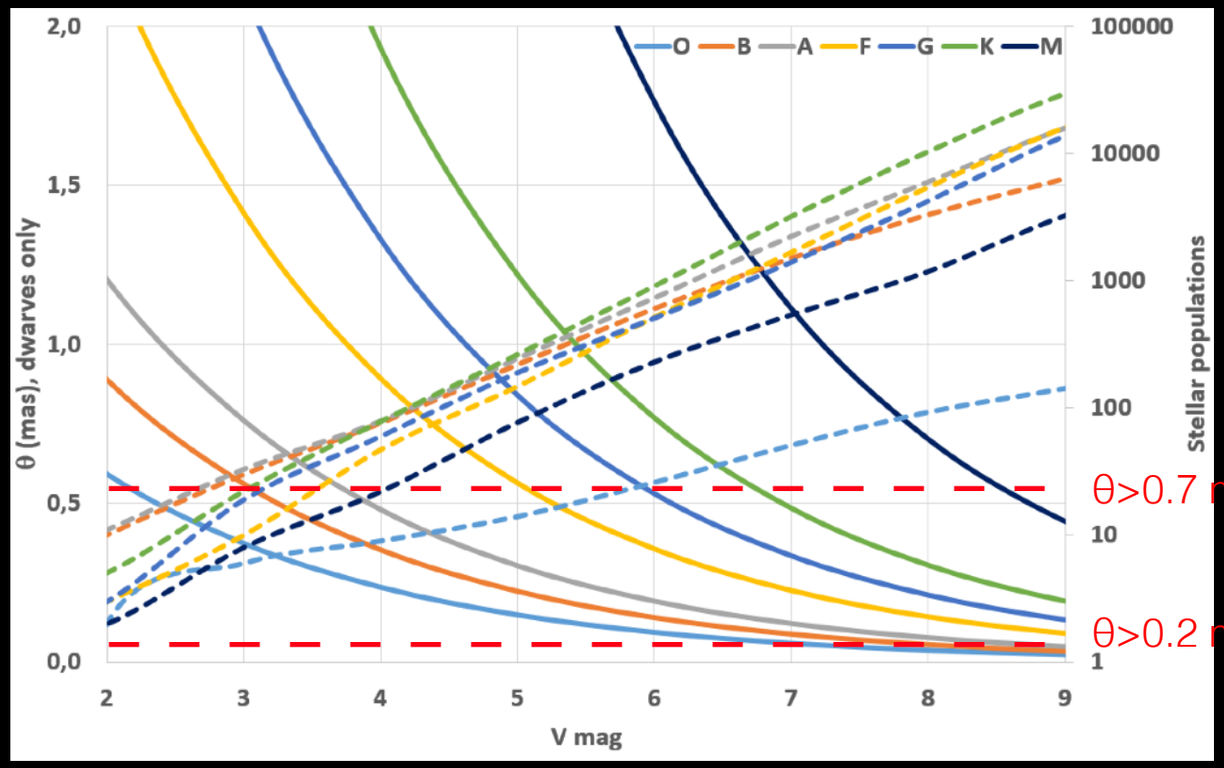


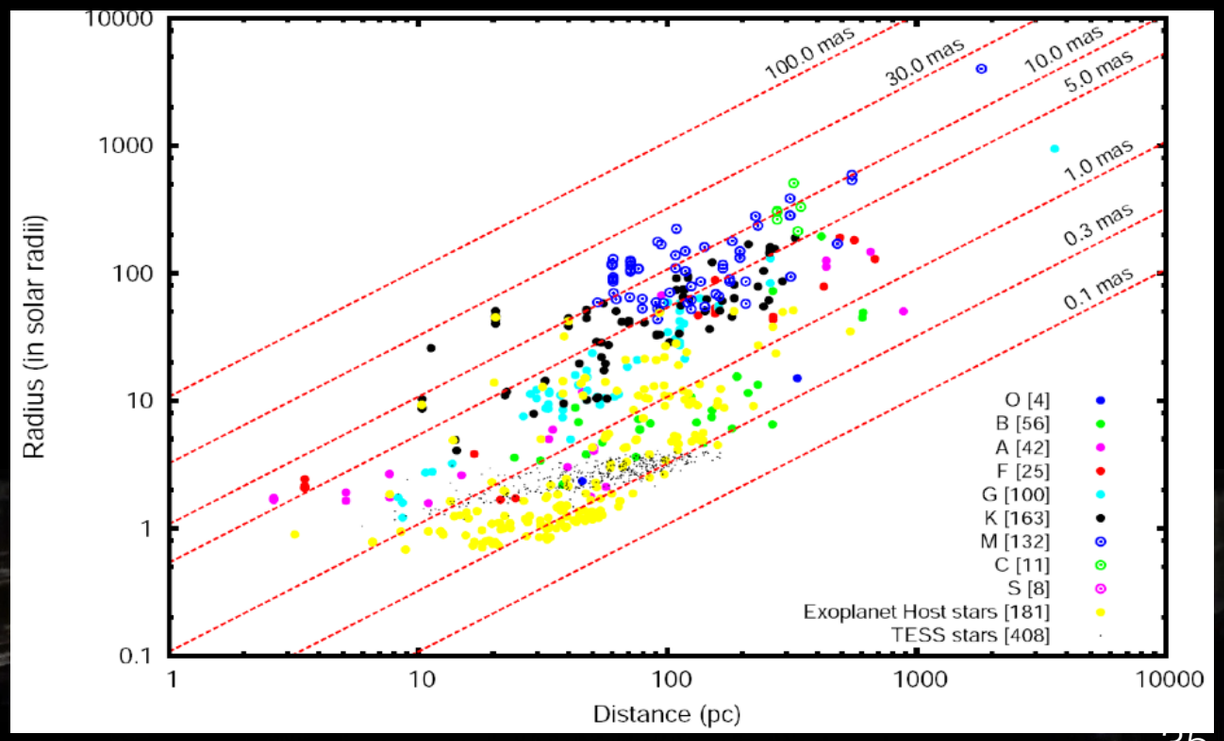
A large program for:

- interferometric measurements of angular diameters of stars compatible with PLATO/TESS/CHEOPS →**brights stars**
  (mag~8, then 9)
- improving SBC relations→ **faint stars**
- imaging stellar surfaces → **effects of activity, rotations…**



THE SPICA PROJECT





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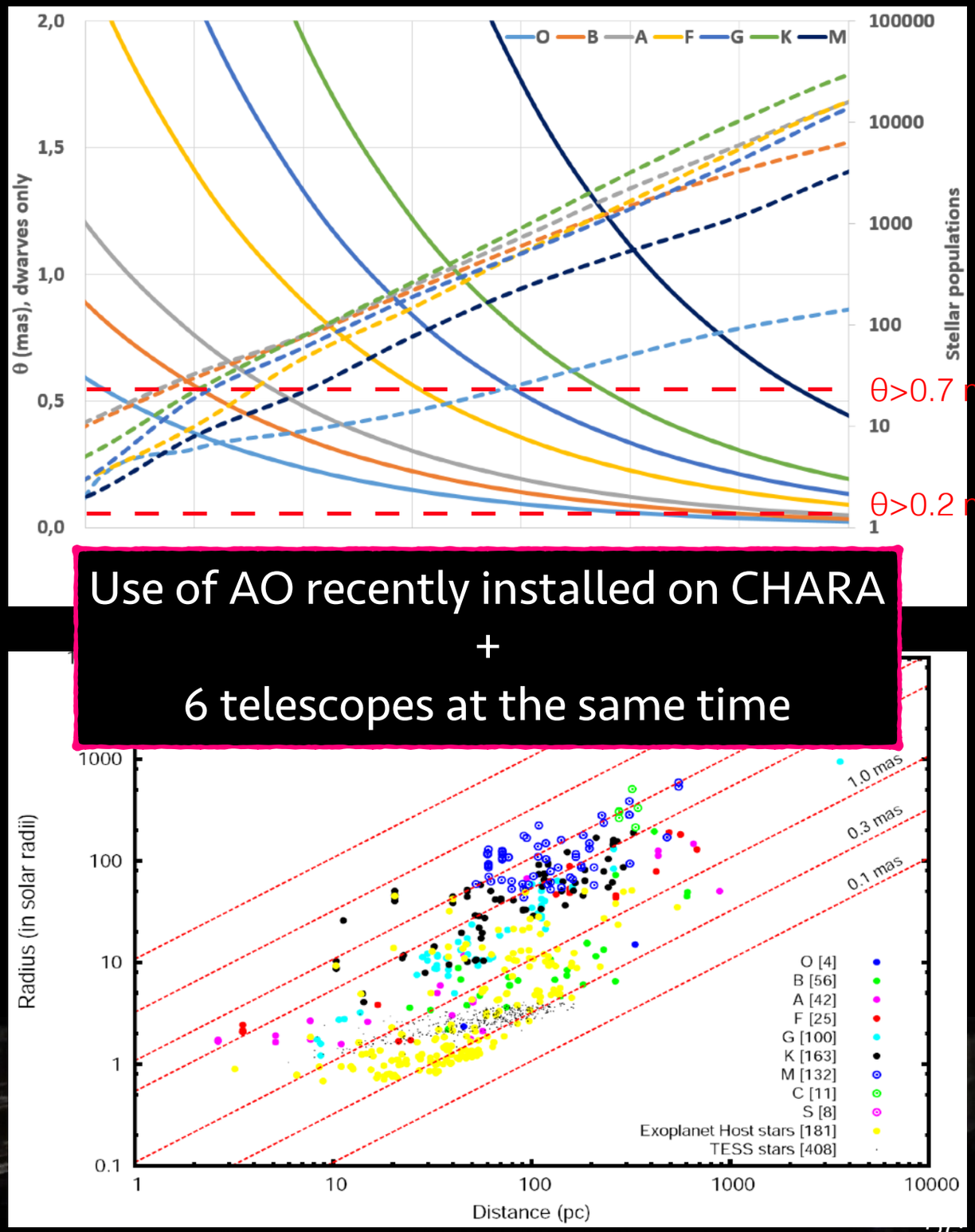
Requirements:

- Coverage of class I-V and spectral types OBAF + K-IV/V et M-IV/V
- Host stars ans seismic stars
- Expected to measure the limb-darkening
- Taking into account stellar activity
- Precision of ~1% on diameters and SBC relations

THE SPICA PROJECT



Use of AO recently installed on CHARA
+
6 telescopes at the same time

A large program for:

- interferometric measurements of angular diameters of stars compatible with PLATO/TESS/CHEOPS →**brights stars**
  (mag~8, then 9)
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CONCLUSION

Often, many techniques needed to characterise an exoplanetary system
Interferometry brings information at several levels (radius, age…)

In the (near) future…
More targets accessible with high angular resolution
Complementarity between instruments/spatial missions

➔ Better characterisation case by case: composition, habitability.
➔ Better global view: link between planetary parameters and formation mechanisms
➔ Characterisation of faint stars will become possible (refine empirical relations)

THANK YOU FOR YOUR ATTENTION!