LAST RESULTS ON THE CHARACTERIZATION OF EXOPLANETS AND THEIR STELLAR HOSTS with VEGA/CHARA

Ligi et al. 2016, A&A, 586, A94

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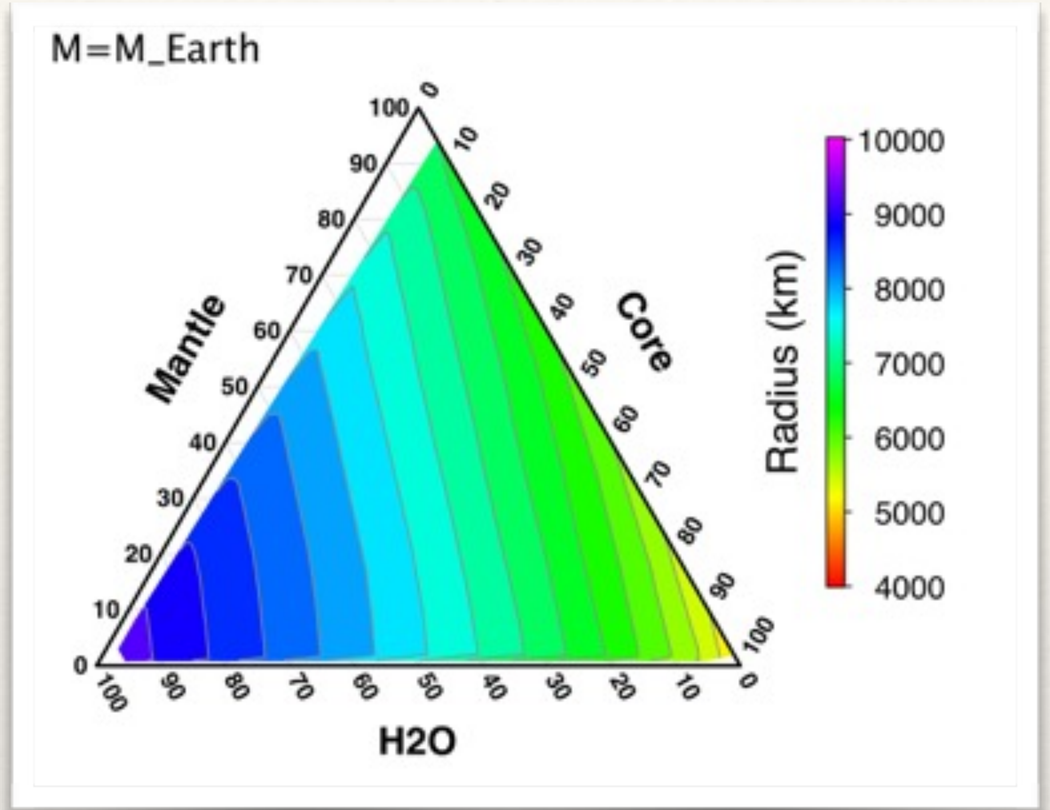
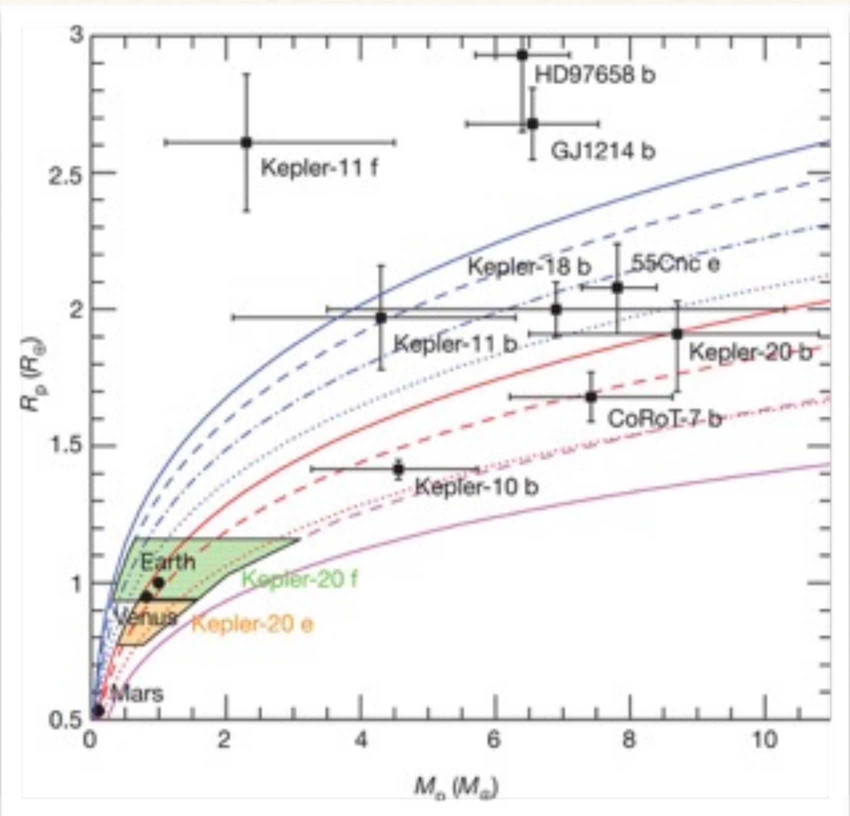
CONTENT

- FROM INTERFEROMETRY TO ANGULAR DIAMETERS
- STELLAR PARAMETERS FROM DIRECT MEASUREMENTS
- STELLAR AGES AND MASSES
- PLANETARY PARAMETERS
- THE CASE OF THE MULTIPLANETARY SYSTEM 55 CNC

INTRODUCTION



Valencia et al. (2006) : δR_p = 2%

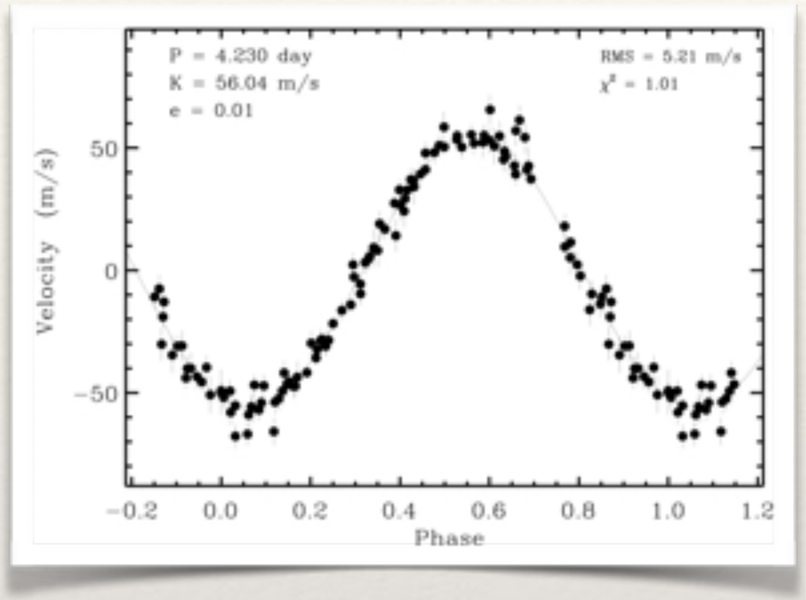


Fressin et al. (2012)

Goal: To obtain exoplanetary parameters accurate enough to constrain their internal structure.

INTRODUCTION

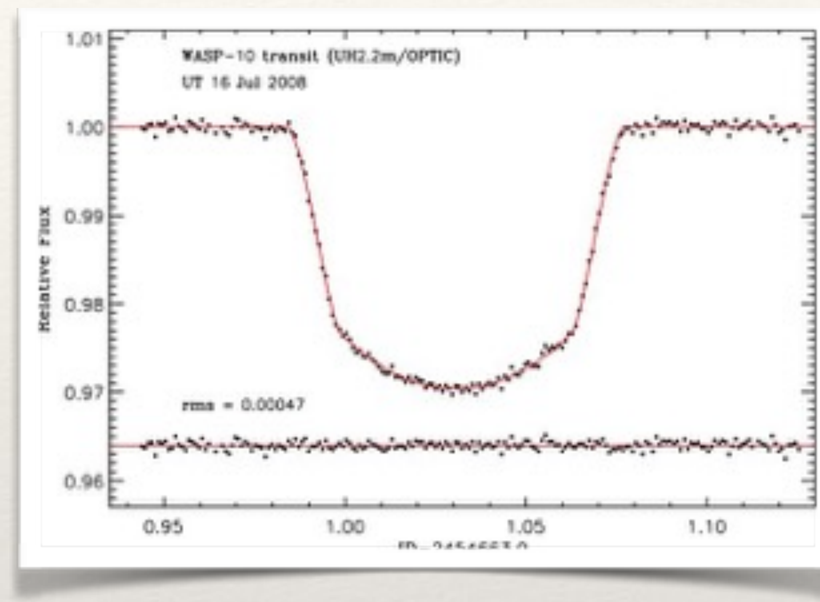
Radial Velocity



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

accuracy on $m_p / M_\star$ << 1%

Transits



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

accuracy on $R_p / R_\star$ << 1%

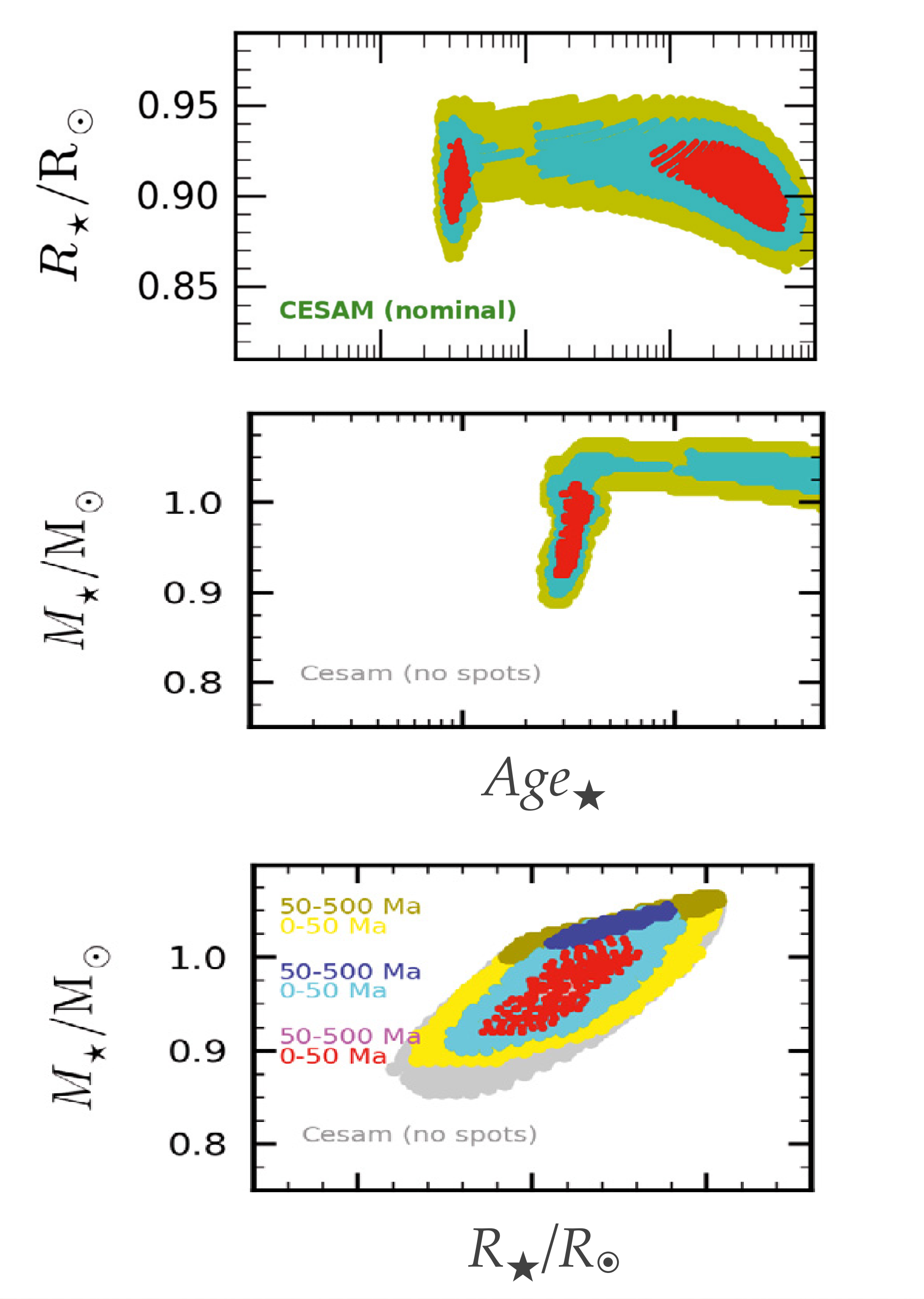
m_p and R_p depend on $M_\star$ and $R_\star$. However, $\delta R_\star \approx 5\%$ and $\delta M_\star \approx 10\%$.

➔ Obtain stellar parameters with 2% accuracy
➔ Need stellar parameters to determine planetary parameters (*Ligi et al. 2012a*)

INTRODUCTION

3 parameters to be determined from models
➔ 3 free parameters, 3D:

$R_\star$, $M_\star$ and $age_\star$



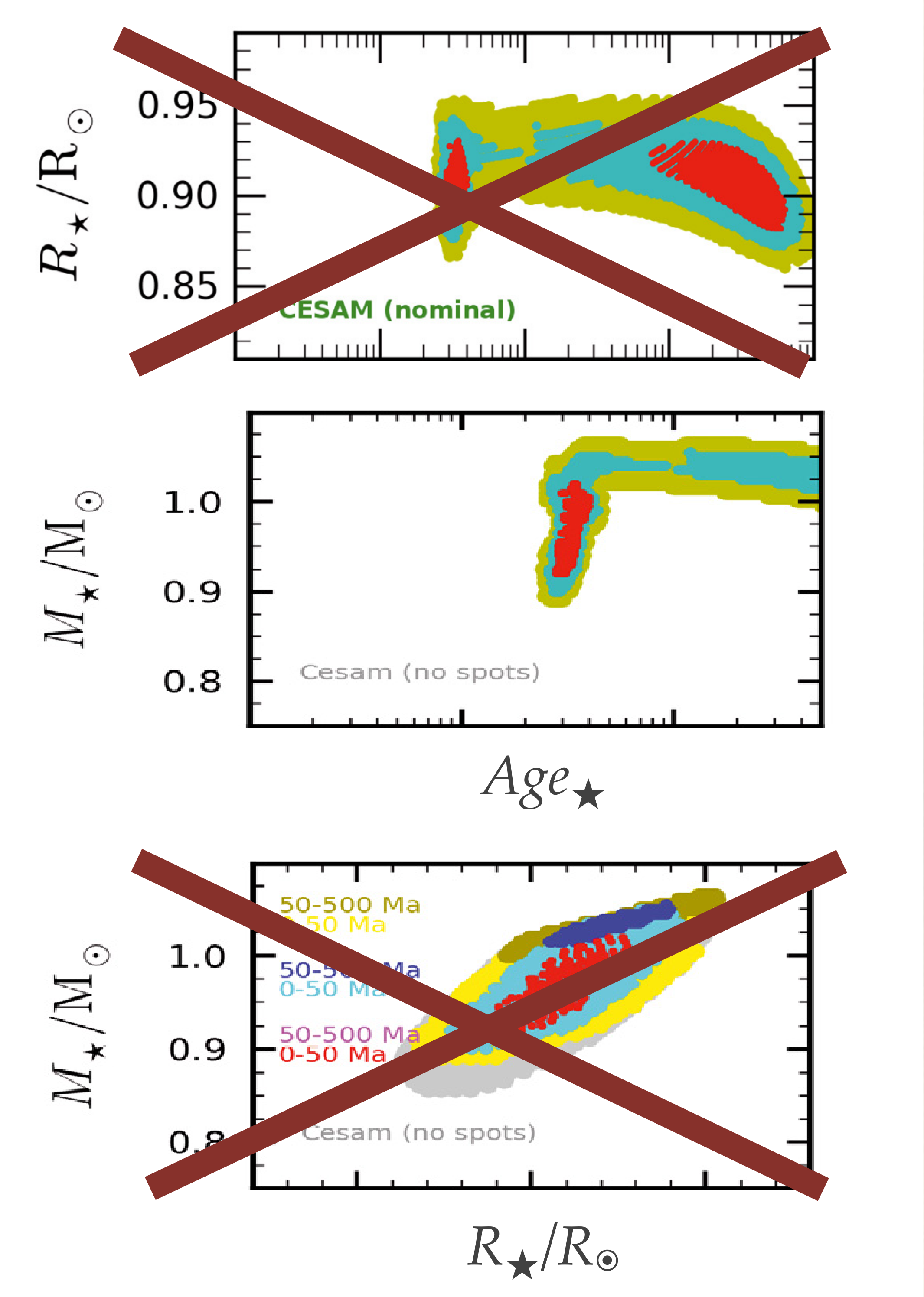
Guillot & Havel (2011)

INTRODUCTION

2 parameters from models:
$M_\star$ and $age_\star$

+ 1 measured parameter: $R_\star$

➔ 2 free parameters, 2D

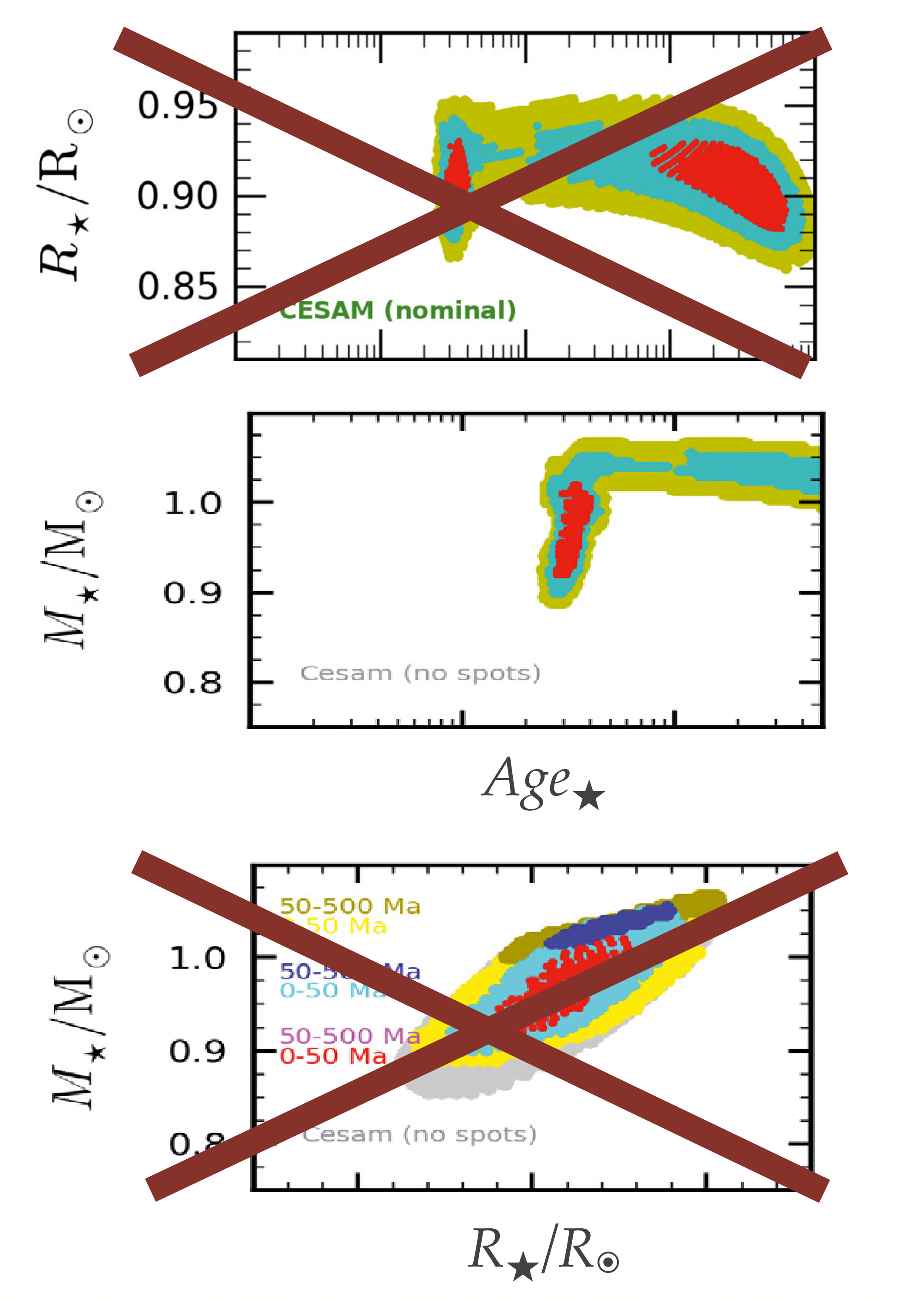


Guillot & Havel (2011)

INTRODUCTION

The radius $R_\star$ is a very important parameter

If we get $R_\star$, we need $T_{eff,\star}$ and $L_\star$ to derive $M_\star$ and age$_\star$



Guillot & Havel (2011)

INTRODUCTION

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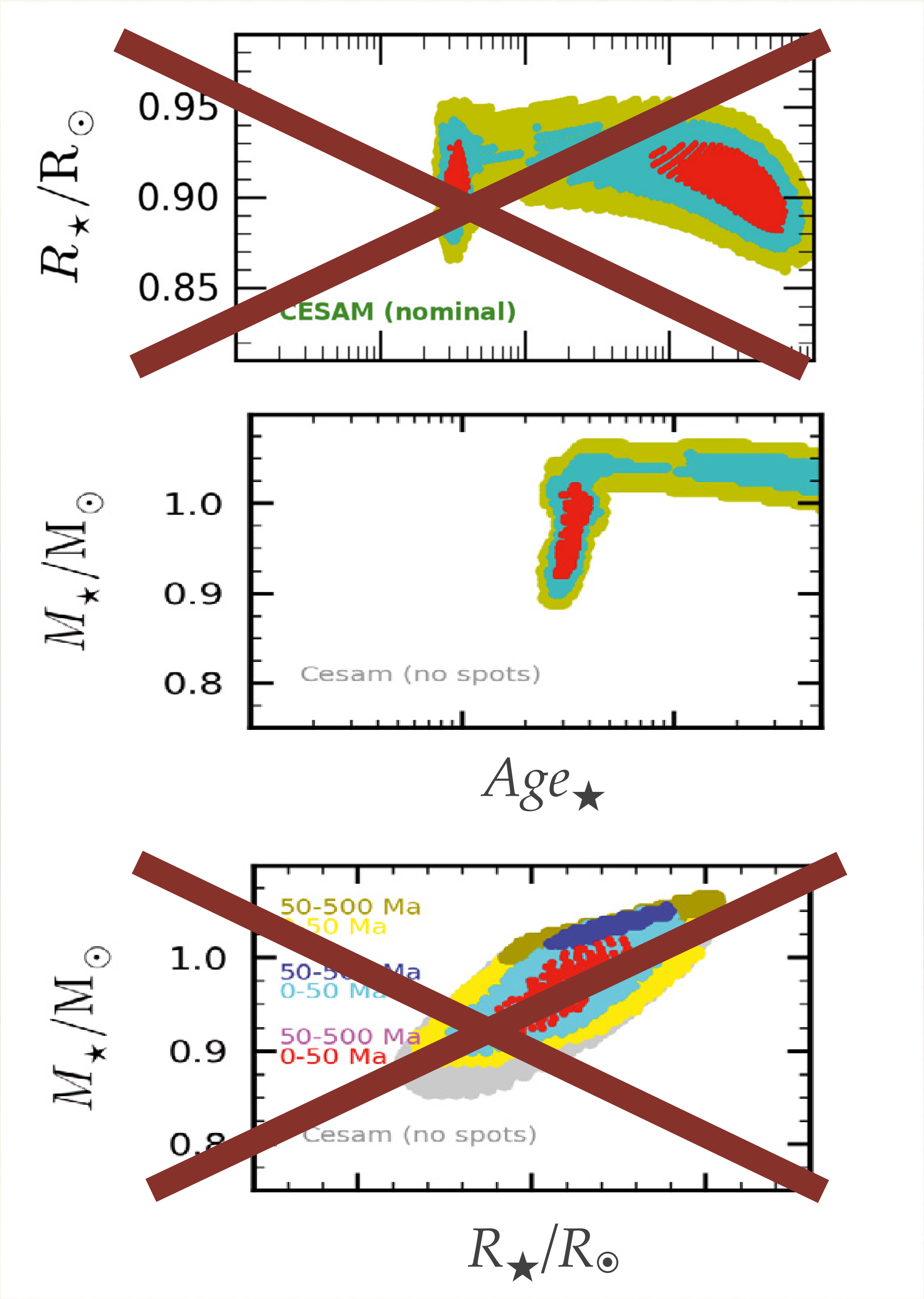
How?

$R_\star$ → interferometry

$T_{eff,\star}$ and $L_\star$ → photometry (+ models)

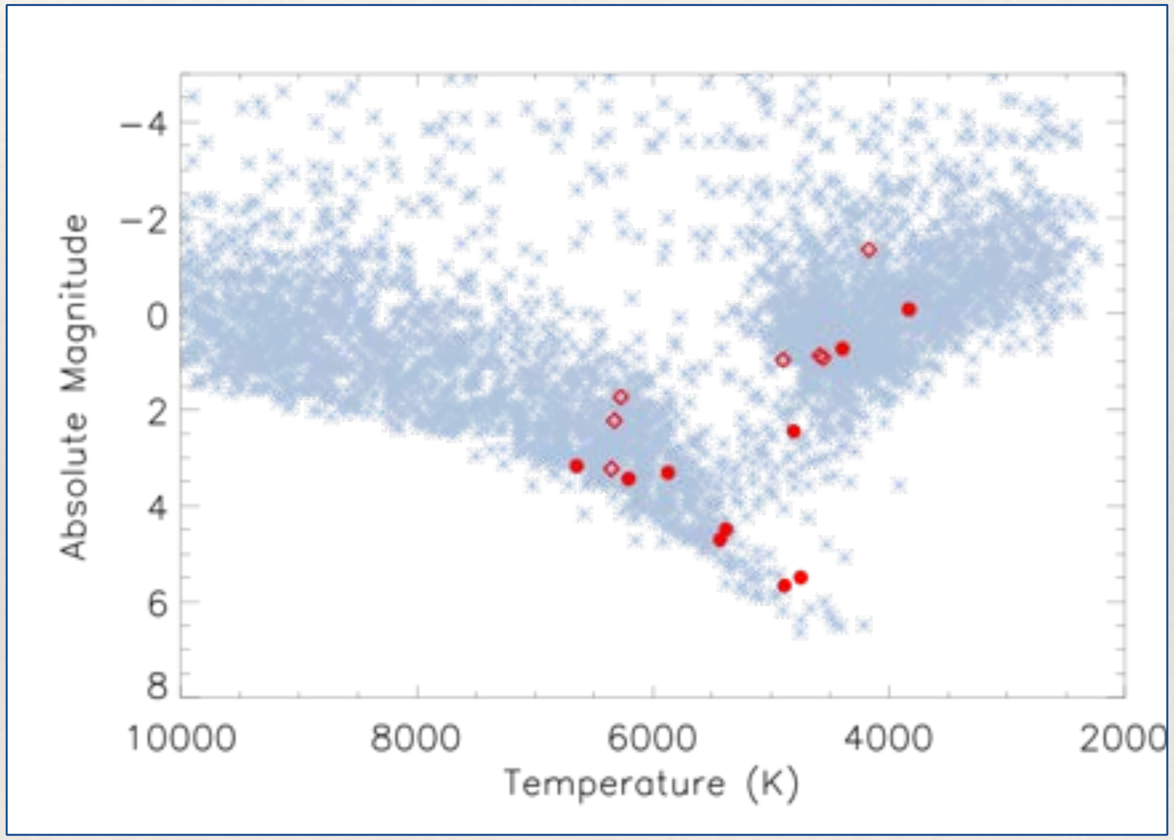
$M_\star$ and age$_\star$ → models



Guillot & Havel (2011)

FROM INTERFEROMETRY TO ANGULAR DIAMETERS

- Selection of exoplanet host stars and potential hosts (*Ligi et al. 2012b, SPIE*):
  - F, G, K
  - 0.3 mas < $\theta_\bigstar$ < 3 mas
  - $m_V < 6.5$ and $m_K < 6.5$
  - -30° < δ < +90°
- Spread over the H-R diagram
- From exoplanet.eu
- Result: 42 accessible stars with VEGA/CHARA.

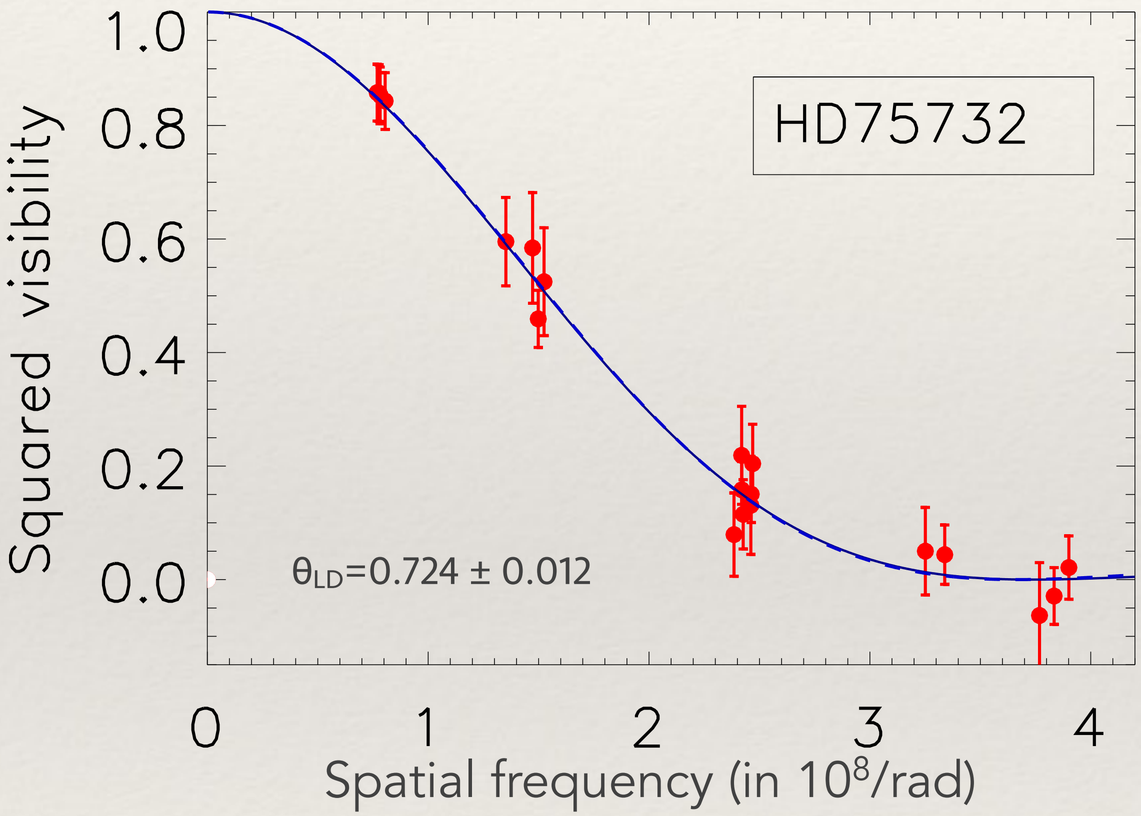


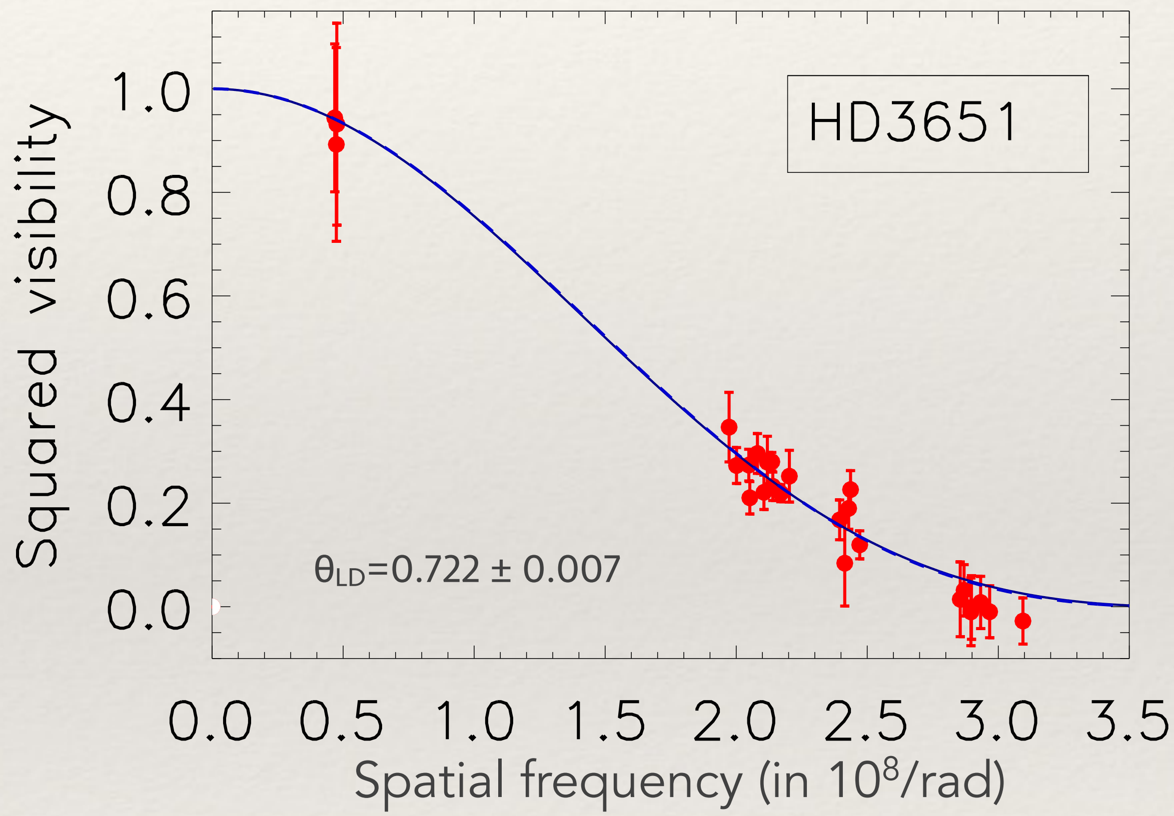
- Final sample:
  - 18 stars
    - 10 exoplanet hosts
  - Observations from 2010 to 2013

STELLAR PARAMETERS FROM DIRECT MEASUREMENTS

RADIUS

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



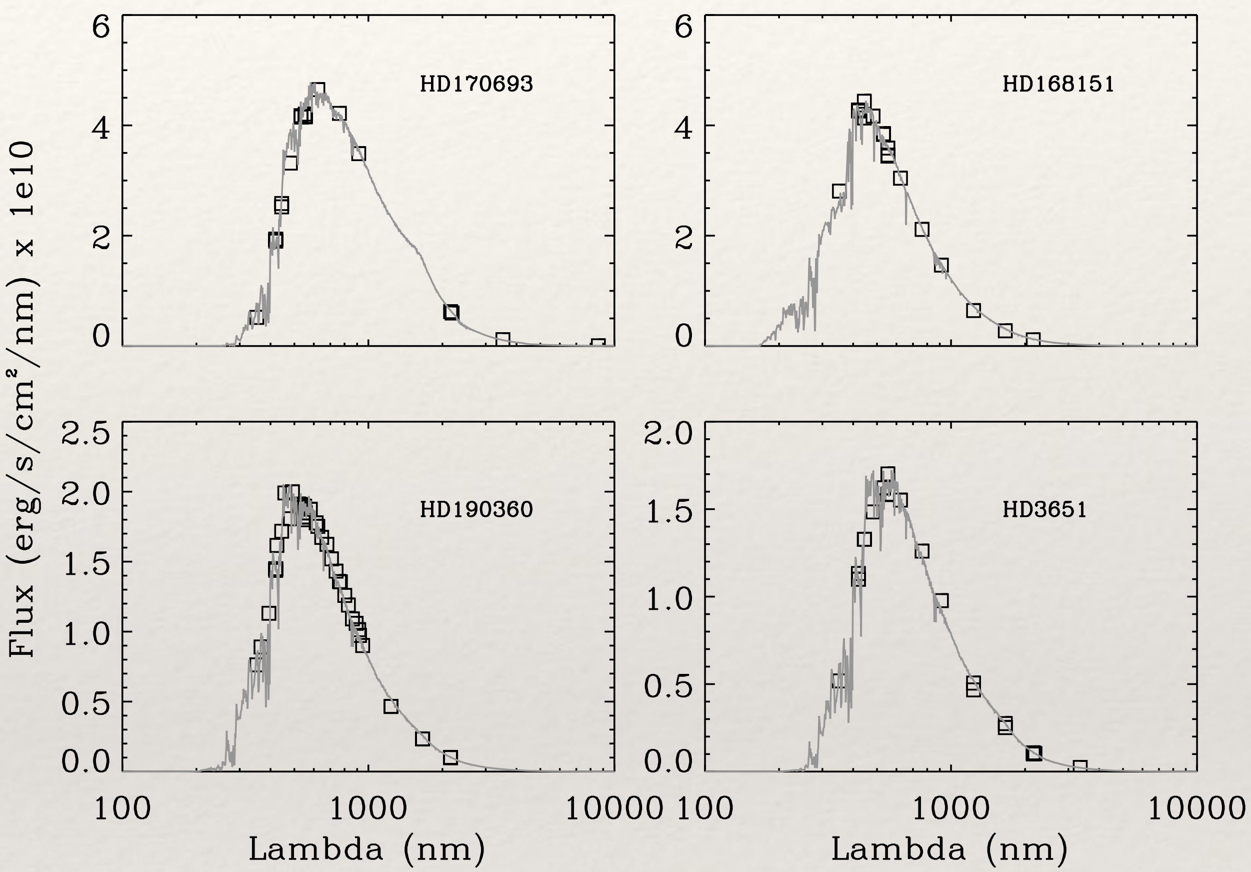


- Examples of visibility curves from VEGA instrument
- Average accuracy: 1.9 % on diameters (θ_{LD}) and 3% on radii ($R_\star$).

STELLAR PARAMETERS FROM DIRECT MEASUREMENTS

BOLOMETRIC FLUX AND LUMINOSITY

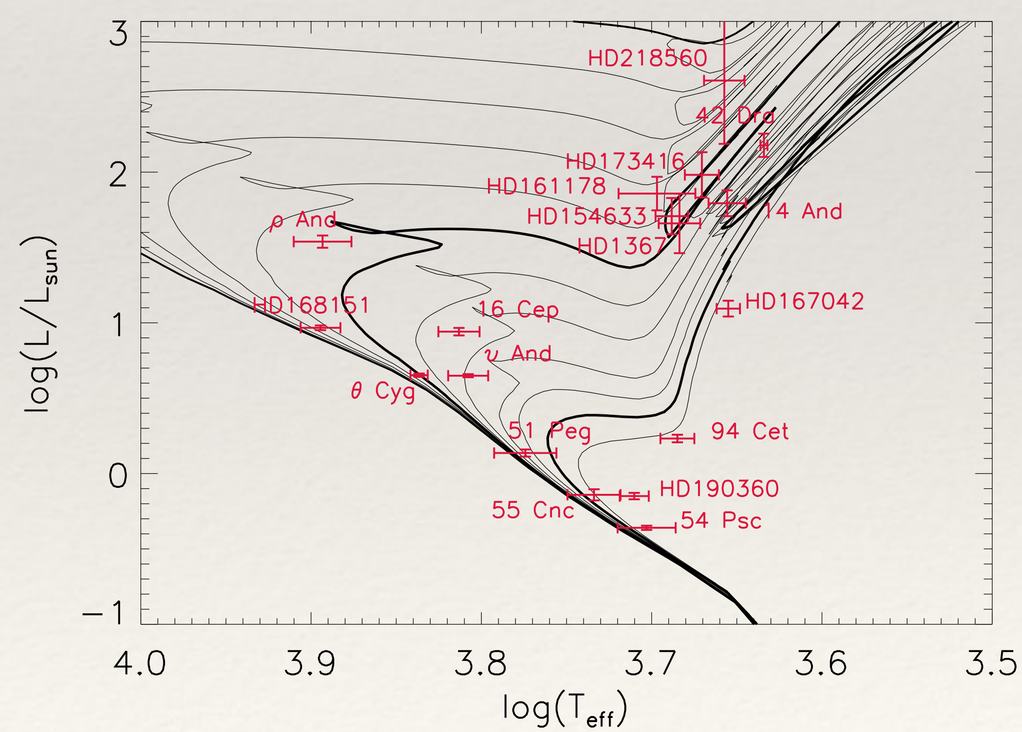
- Photometry from VizieR Photometry Viewer
- Fit from BASEL library spectra
- Take into account log(g), Av, [Fe/H]
- Average accuracy on $T_{\mathrm{eff},\star}$: 57K in average



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

STELLAR MASSES AND AGES

- Recall: why deriving stellar mass and ages?
  - Provide benchmark stars to stellar physicists (also applies to non host stars, see O. Creevey's talk)
  - Better understand planetary formation, age of the planetary system
  - Derive planetary parameters



STELLAR MASSES AND AGES

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    (also applies to non host stars, see O. Creevey's talk)
  - Better understand planetary formation, age of the planetary system
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- Masses and ages usually derived from models
  (if no exception case like binaries…)
- We used PARSEC stellar models (*Bressan et al. 2012*).

STELLAR MASSES AND AGES

- Method: Interpolation
  - Separation between 2 points of an isochrone are < $\sigma T_{eff,\star}$ and < $\sigma L_{\star}$
  - Step in log(age$_{\star}$) are 0.01 from 6.6 to 10.13
  - [M/H] goes from 0.5 to -0.8 in steps of ~0.015 (not always the case!)

- Best fit (least square): minimizing the quantity

$$\chi^2 = \frac{(L - L_\star)^2}{\sigma_{L_\star}{}^2} + \frac{(T_{\rm eff} - T_{\rm eff,\star})^2}{\sigma_{T_{\rm eff,\star}}{}^2} + \frac{([\mathrm{M/H}] - [\mathrm{M/H}]_\star)}{\sigma_{[\mathrm{M/H}]_\star}{}^2}$$

→ $M_\star$, age$_\star$? Not that easy...

STELLAR MASSES AND AGES

Recipe to produce a simplified map of $\mathcal{L}$ in the ($M_\star$, $age_\star$) plane

- Likelyhood function $\mathcal{L}$: probability of getting the observed data for a given set of stellar parameters (see *Pont & Eyer 2004, Jørgensen & Lindegren 2005*)
  - Easy to express as a function of observables: $L_\star$, $T_{eff,\star}$, $[M/H]_\star$
  - Less easy to express as a function of the physical parameters: $age_\star$, $M_\star$

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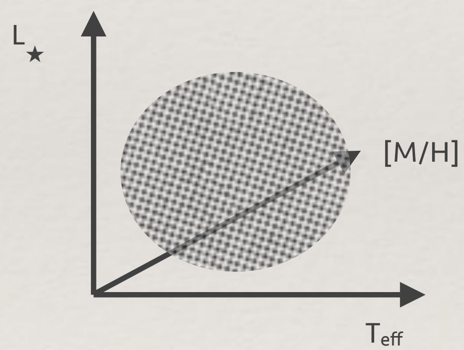

$$\chi^2 = \underbrace{\frac{(L - L_\star)^2}{\sigma_{L_\star}{}^2}}_{<1,2,3} + \underbrace{\frac{(T_{\rm eff} - T_{\rm eff,\star})^2}{\sigma_{T_{\rm eff,\star}}{}^2}}_{<1,2,3} + \underbrace{\frac{([\rm M/H] - [\rm M/H]_\star)}{\sigma_{[\rm M/H]_\star}{}^2}}_{<1,2,3}$$

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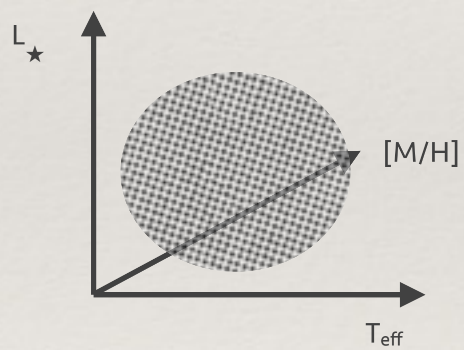

→ Least square: ($M_\star$, age$_\star$)

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STELLAR MASSES AND AGES

Recipe to produce a simplified map of $\mathcal{L}$ in the ($M_\star$, age$_\star$) plane

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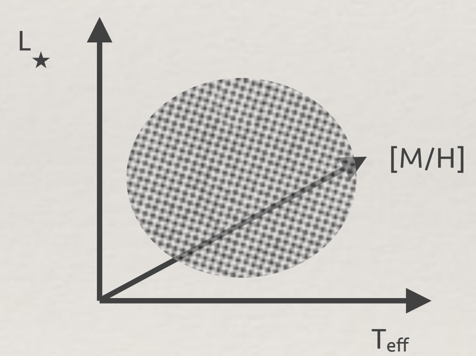

Least square:
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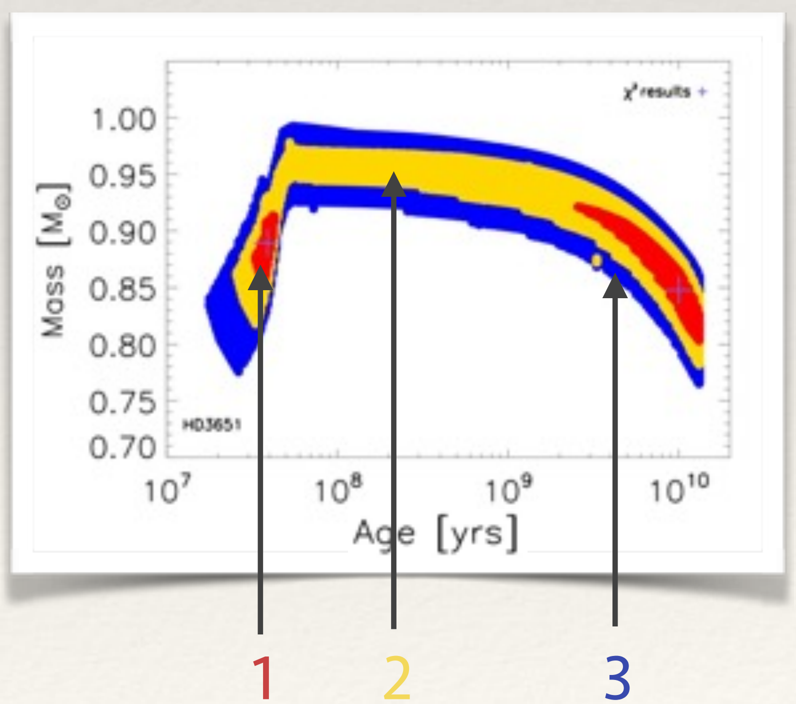

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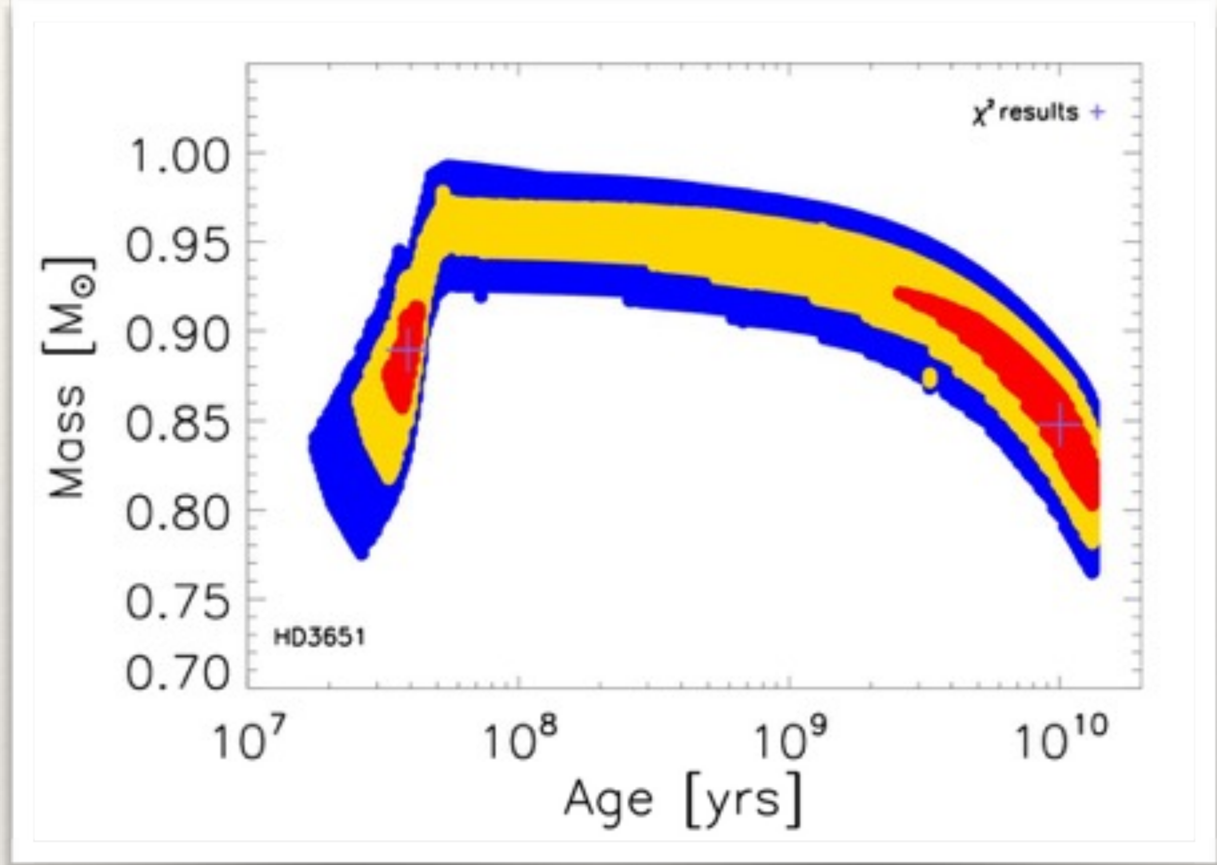
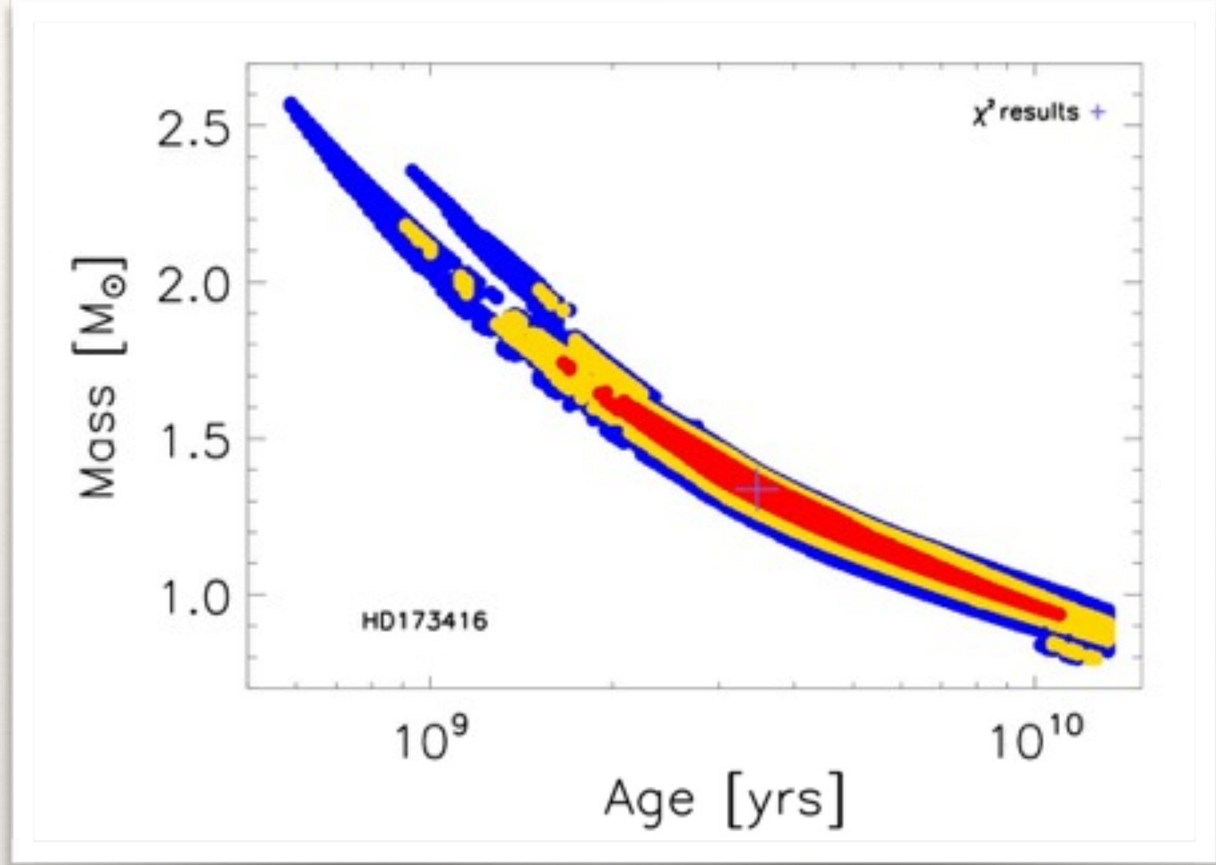
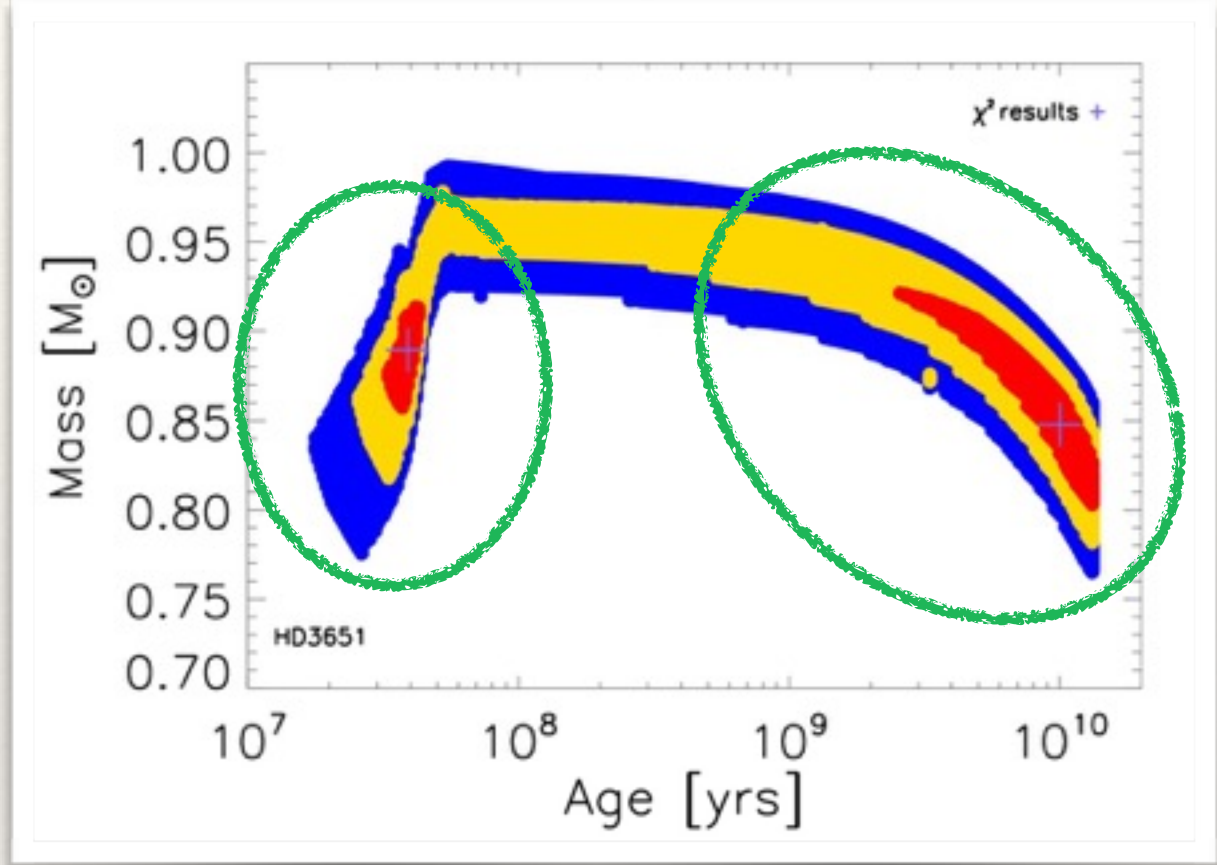
STELLAR MASSES AND AGES

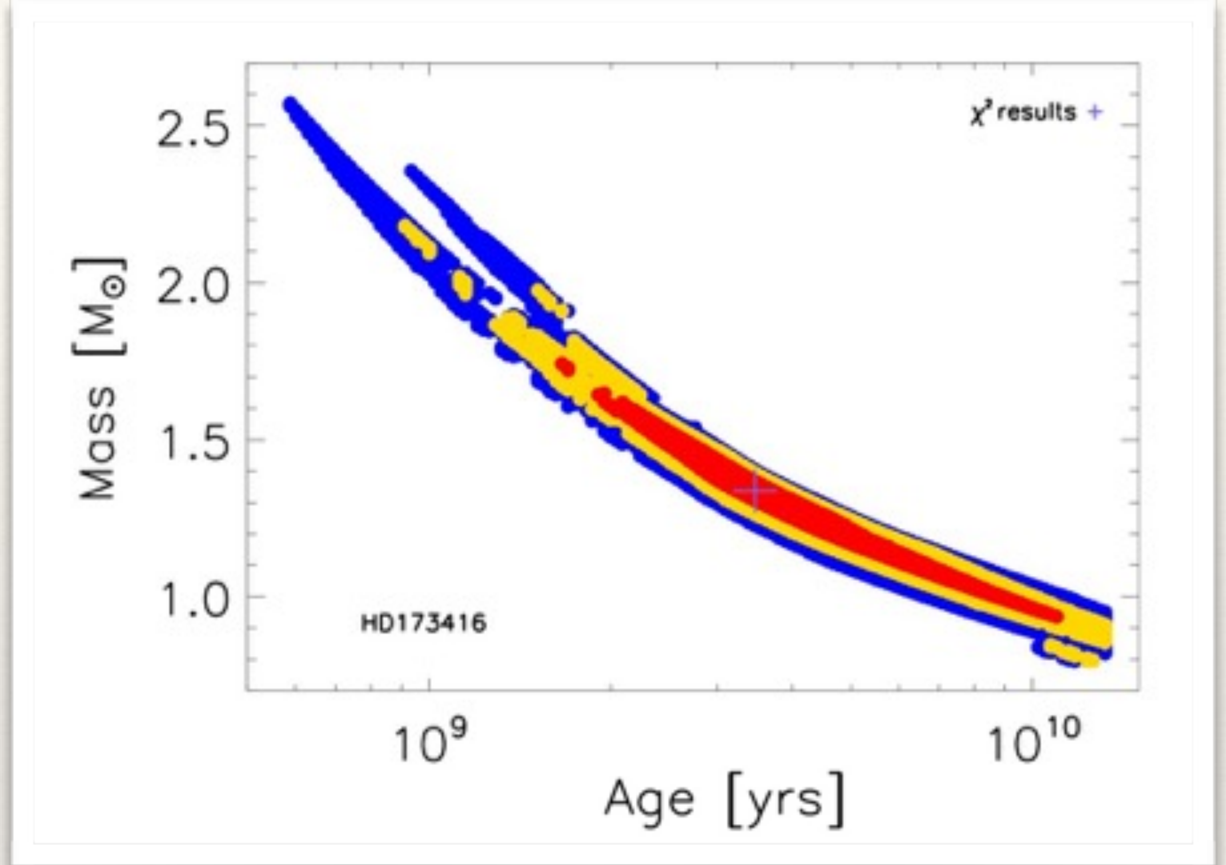




- This corresponds to the approximate likelyhood map in the ($M_\star$, age$_\star$) for which each term of the equation $\chi^2 = \frac{(L - L_\star)^2}{\sigma_{L_\star}{}^2} + \frac{(T_{\rm eff} - T_{\rm eff,\star})^2}{\sigma_{T_{\rm eff,\star}}{}^2} + \frac{([{\rm M/H}] - [{\rm M/H}]_\star)}{\sigma_{[{\rm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

STELLAR MASSES AND AGES

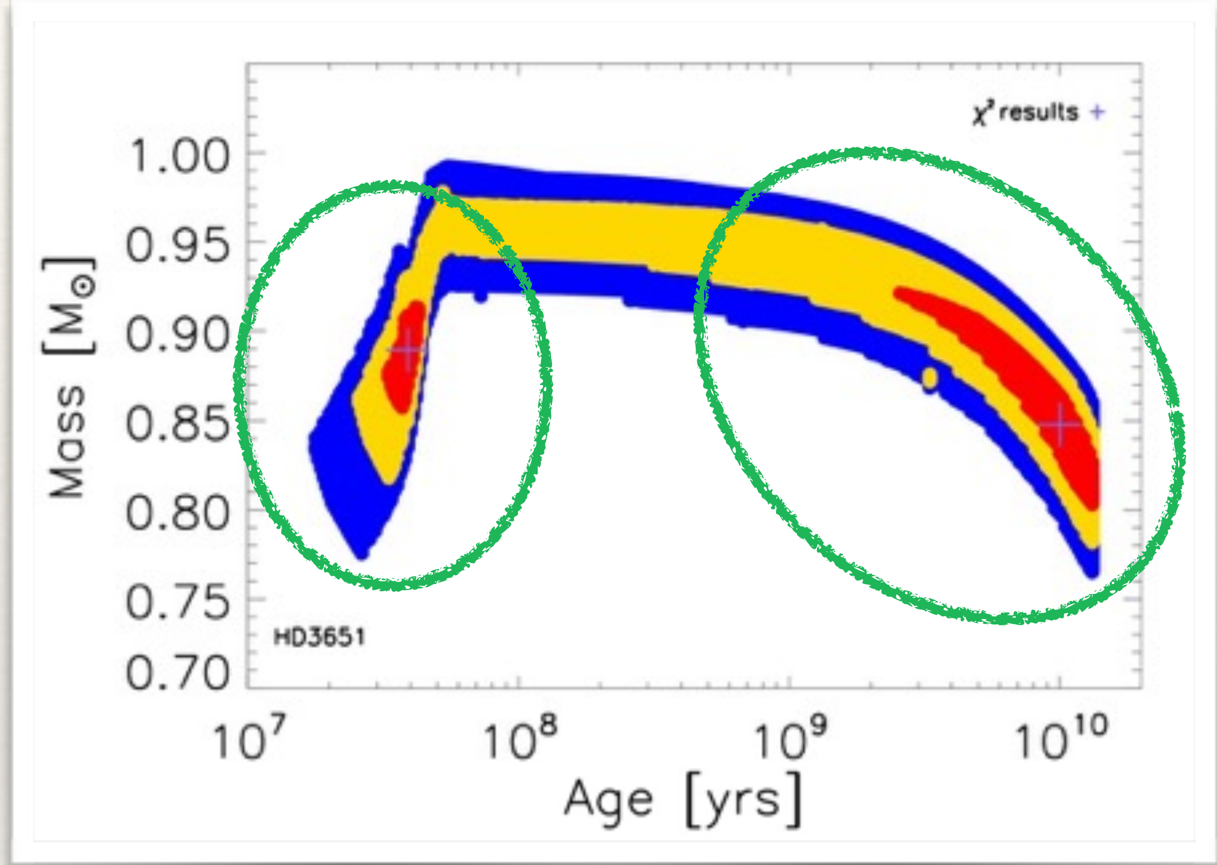


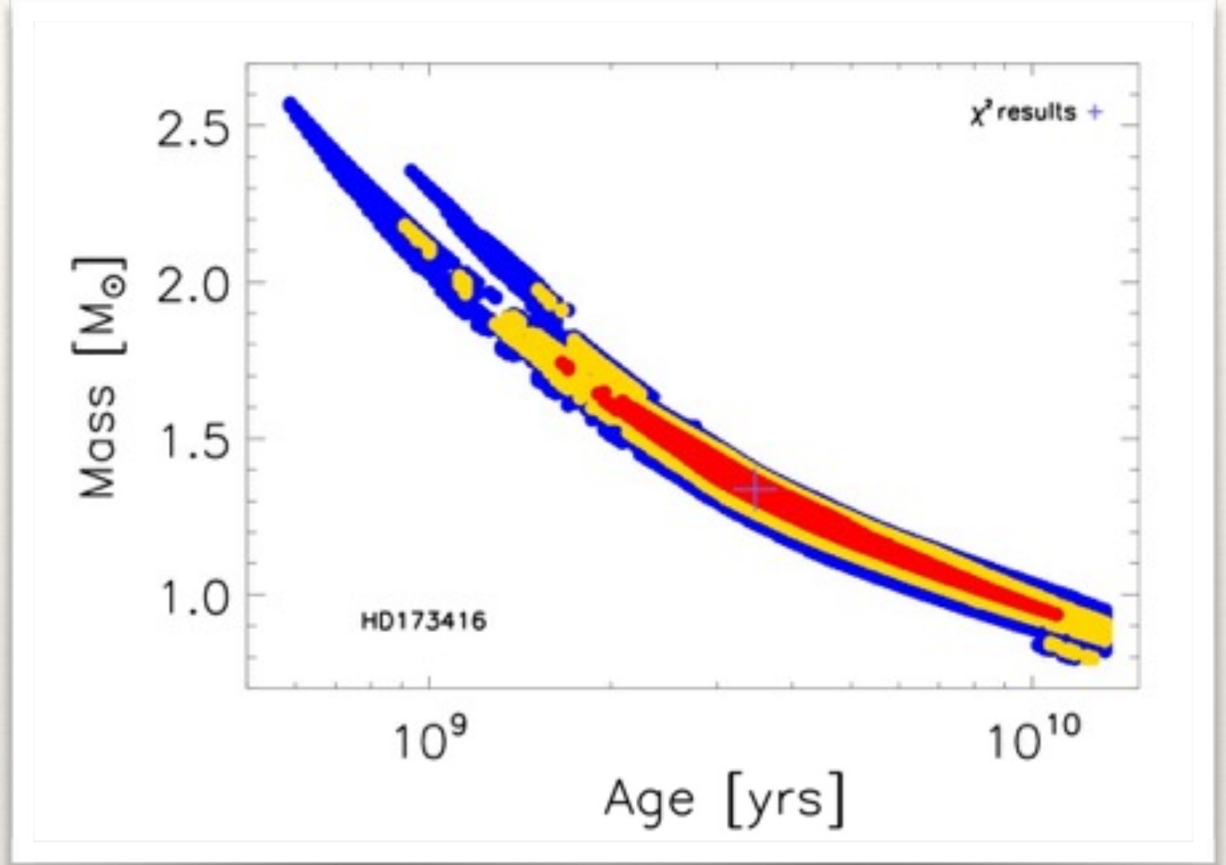


- $\mathcal{L}$ shows 2 different peaks for many MS stars:
  - an old solution: < 400 Myrs
  - a young solution: > 400 Myrs

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

STELLAR MASSES AND AGES





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

STELLAR MASSES AND AGES

How to calculate the error on ages and masses? Not easy.

- Monte-Carlo method?
  - Bias on ages and masses but not on errors (see *Jørgensen & Lindgren 2005*)
- Independent Gaussian sets of $T_{eff,\star}$ and $L_\star$?
  - Erase the correlation between $T_{eff,\star}$ and $L_\star$
  - Large cloud of points

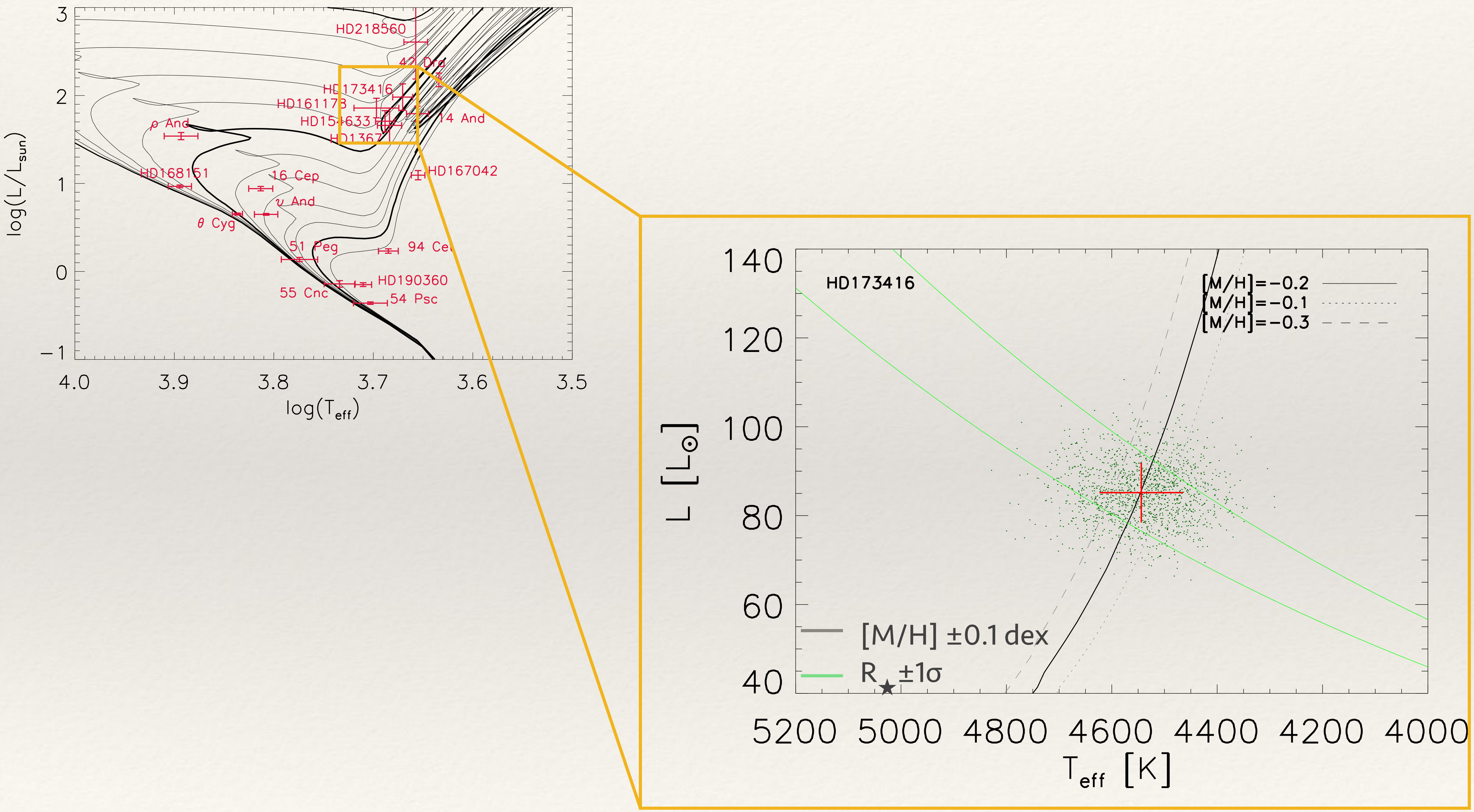
STELLAR MASSES AND AGES

How to calculate the error on ages and masses? Not easy.

Instead:

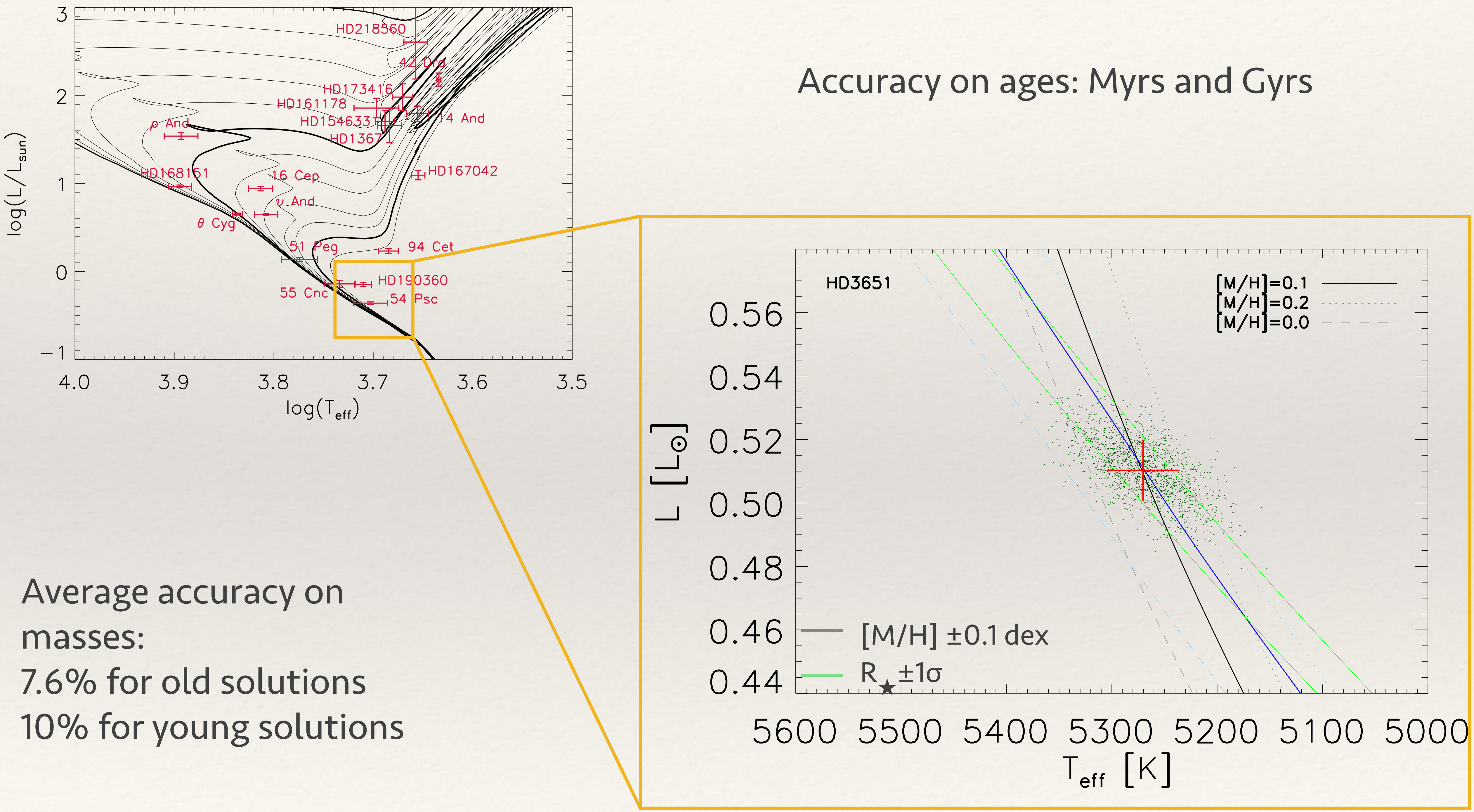
- 1500 quadruplets $\{F_{bol}, d, \theta, [M/H]\}$ (independent random Gaussian variables)
- Combine them into triplets $\{L_\star, T_{eff,\star}, [M/H]_\star\}$
- Apply the least square procedure → 1500 $\{M_\star, age_\star\}$ pairs
- Compute the standard deviation of the masses and ages = errors

STELLAR MASSES AND AGES



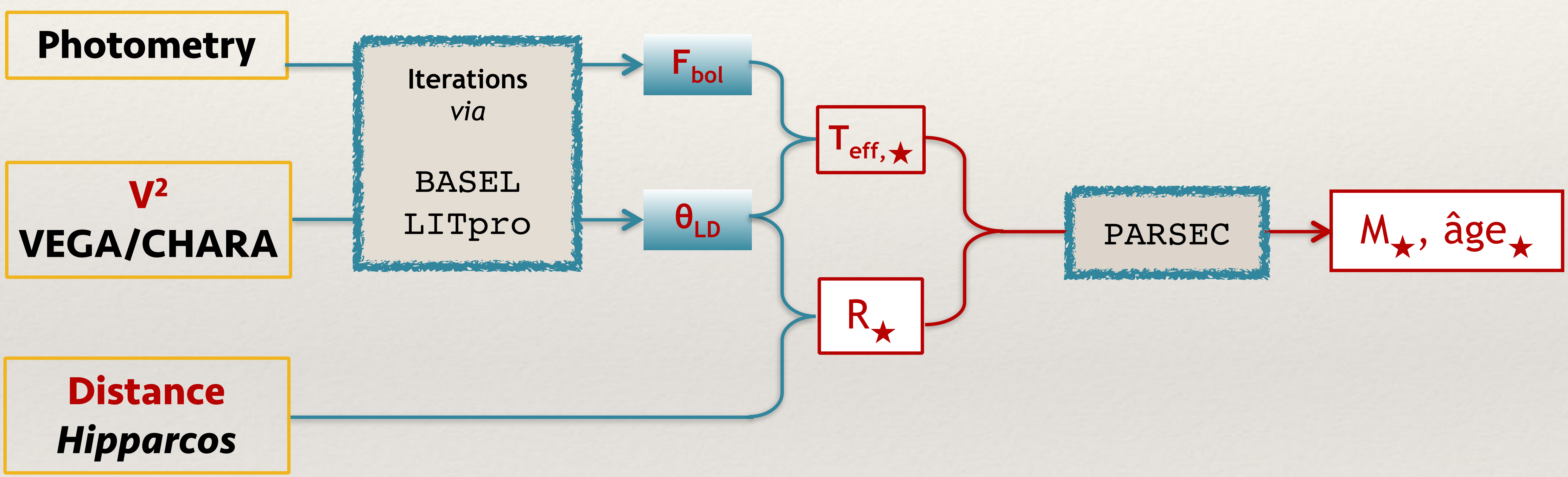
STELLAR MASSES AND AGES

Accuracy on ages: Myrs and Gyrs



Average accuracy on masses:
7.6% for old solutions
10% for young solutions

STELLAR MASSES AND AGES



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PLANETARY PARAMETERS

- Usually: Radial Velocity (RV) detections
- Thus we obtain $m_p$sin(i) from RV and stellar masses:

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

- Habitable Zone (HZ) (*Jones et al. 2006*) $\propto L_{\star}/T_{\mathrm{eff},\star}^{2}$
- Semi-major axis $\propto M_{\star}^{1/3}$

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

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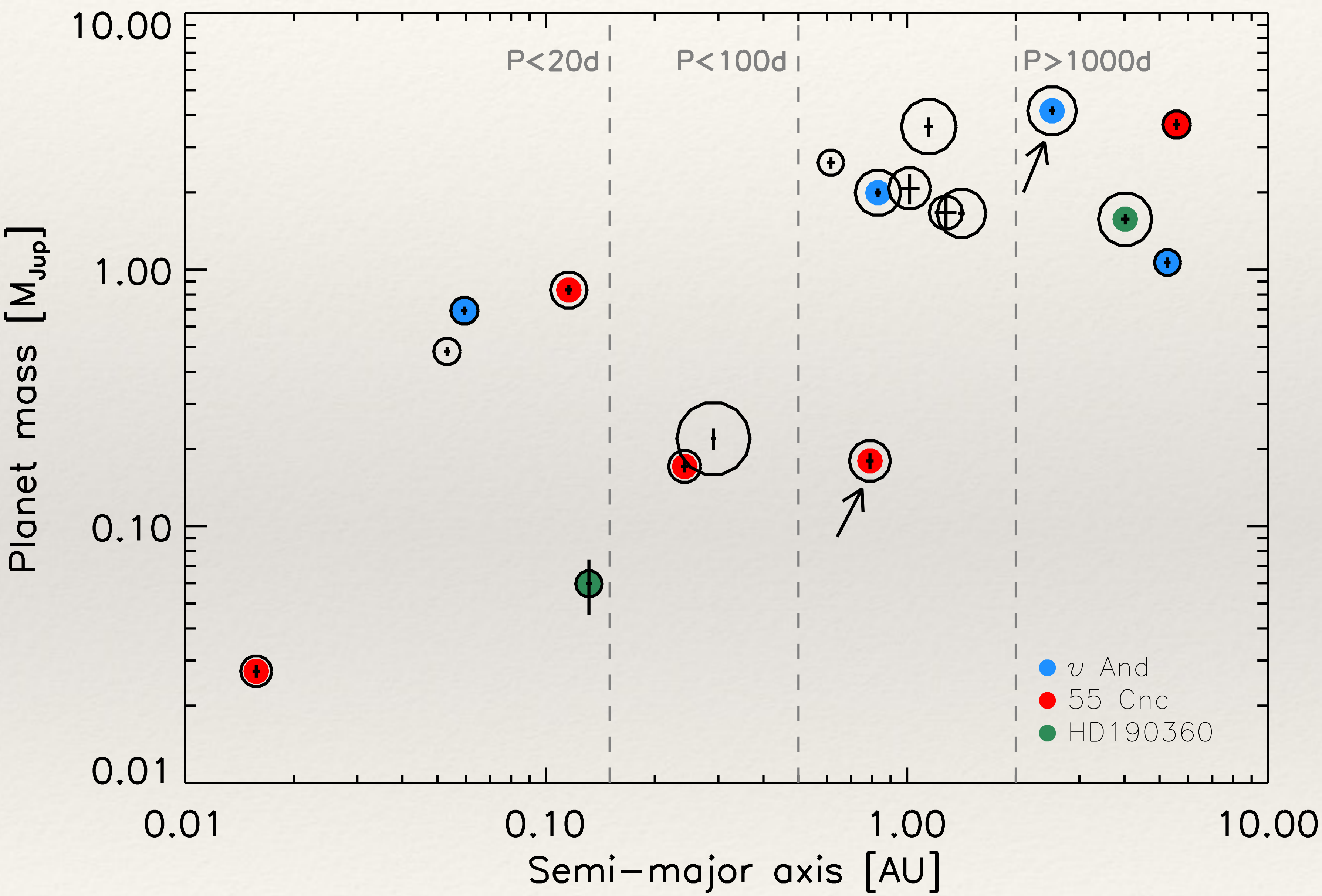
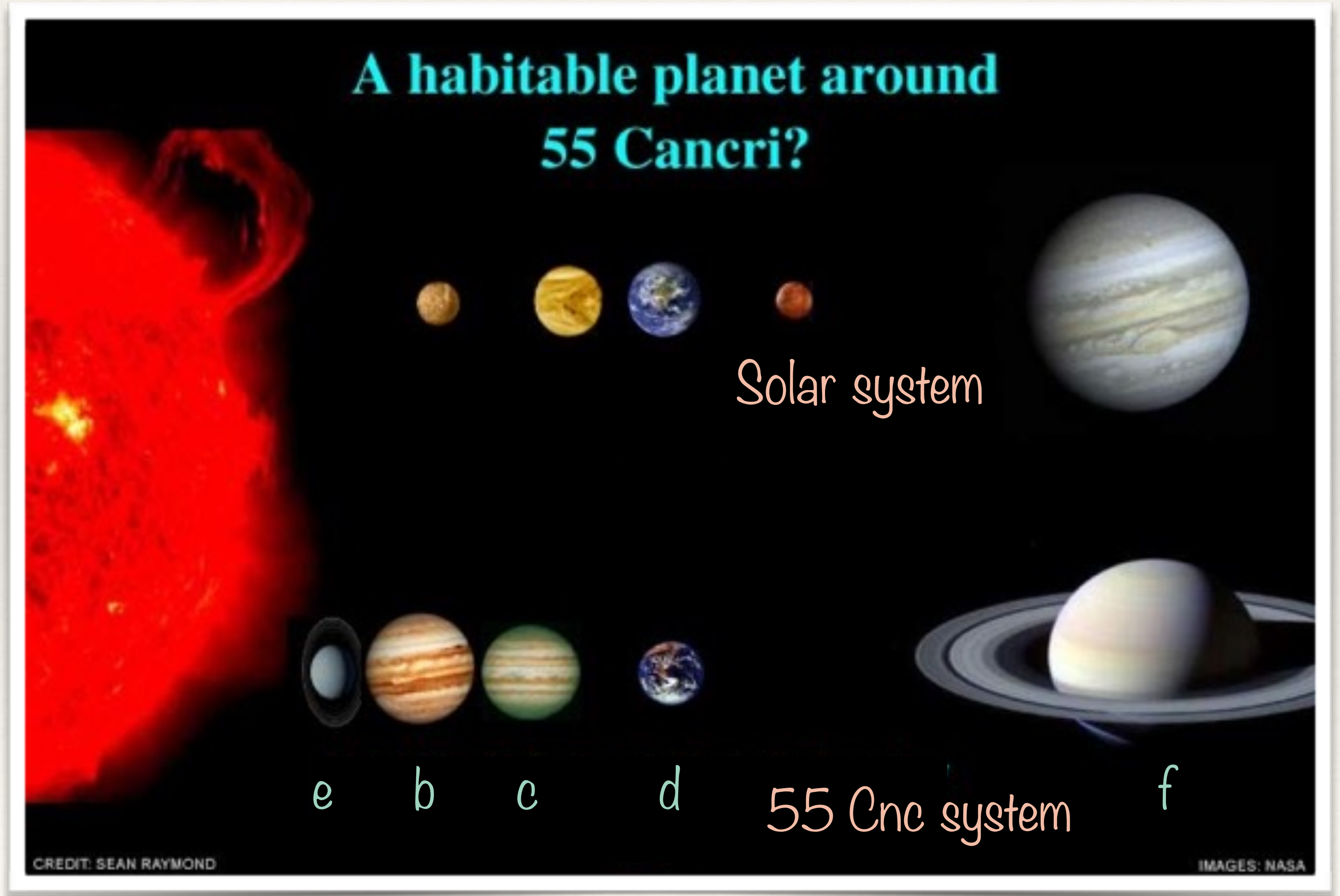


THE MULTIPLANETARY SYSTEM 55 CNC

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



THE MULTIPLANETARY SYSTEM 55 CNC

- Well studied star
- Photometry (transit) + the direct estimate of $R_\bigstar$ (this work)

  → direct estimate of R_p

- *Maxted et al. (2015)* measured the stellar density $\rho_\bigstar$ of 55 Cnc from photometry:

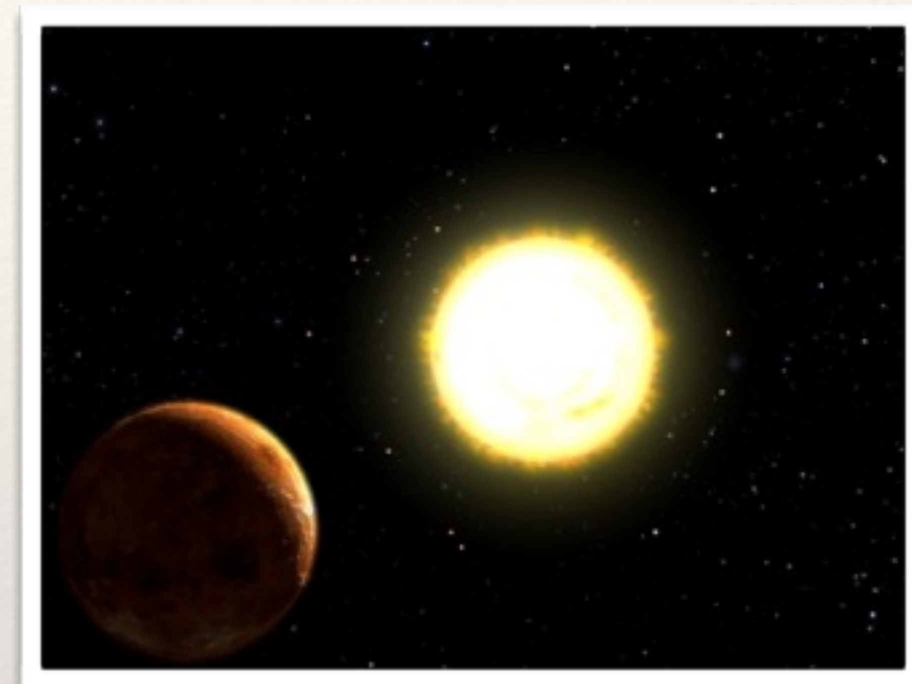
$$\rho_\star = \frac{\breve{P}}{T^3}\frac{3}{\pi^2 G}$$

→ $R_\bigstar + \rho_\bigstar$ = direct estimate of the stellar mass!

→ direct estimate of m_p

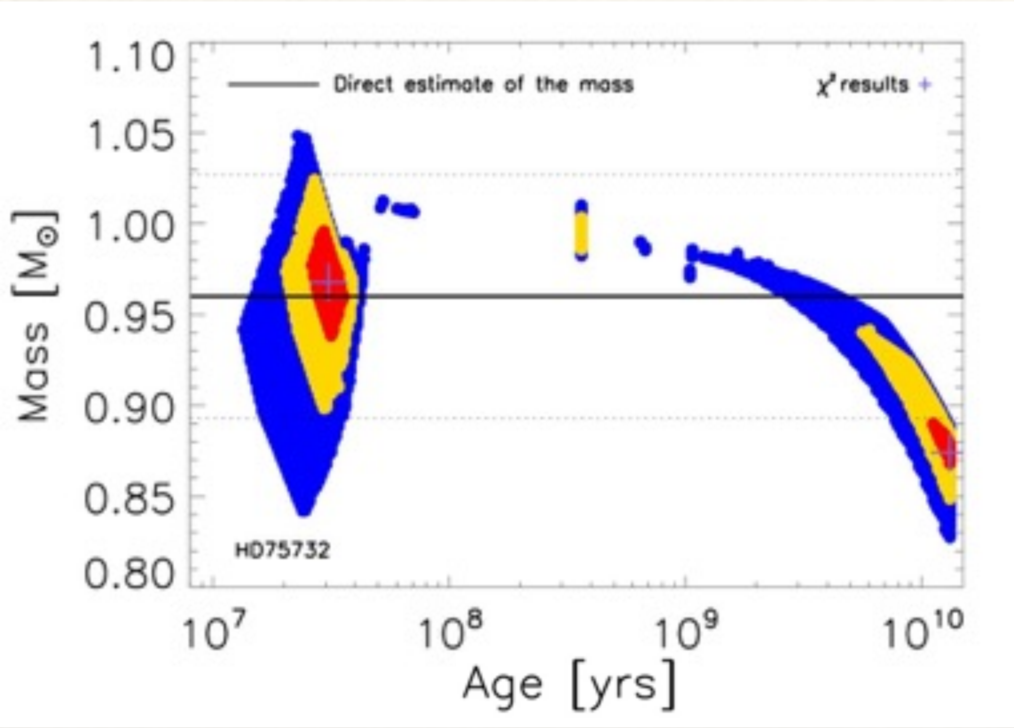
- Direct estimate of the planetary density!

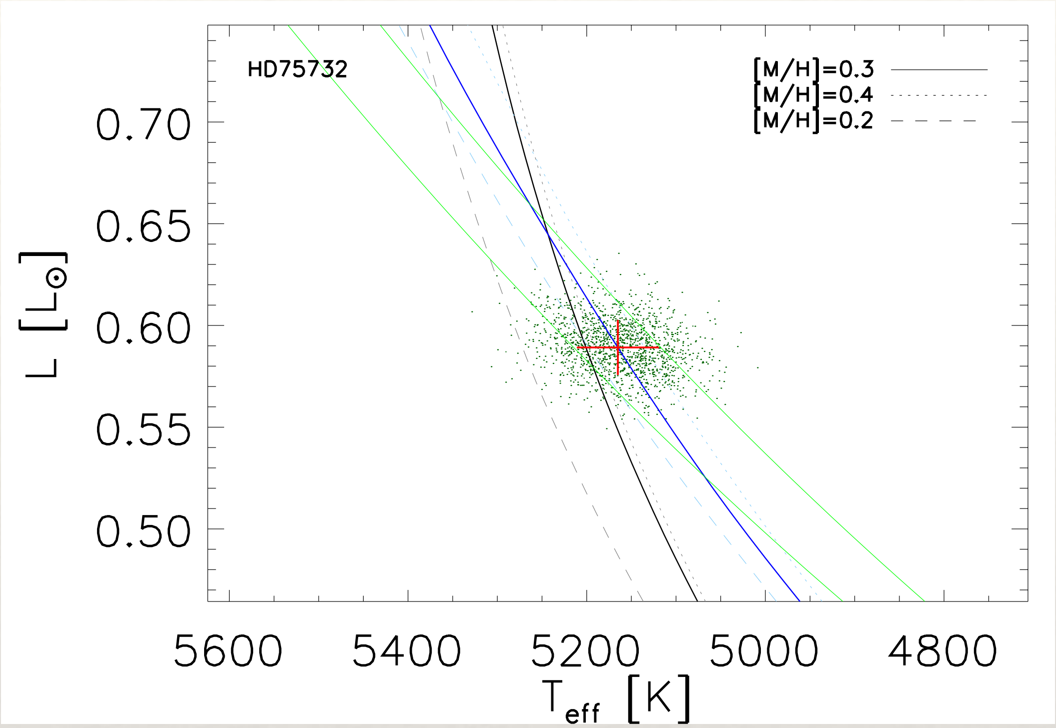
$$\rho_p = \frac{3^{1/3}}{2\pi^{2/3}G^{1/3}}\rho_\star^{2/3}\, R_\star^{-1}\, T D^{-3/2}\, P^{1/3}\, K\,(1-e^2)^{1/2}$$



THE MULTIPLANETARY SYSTEM 55 CNC

Stellar Results



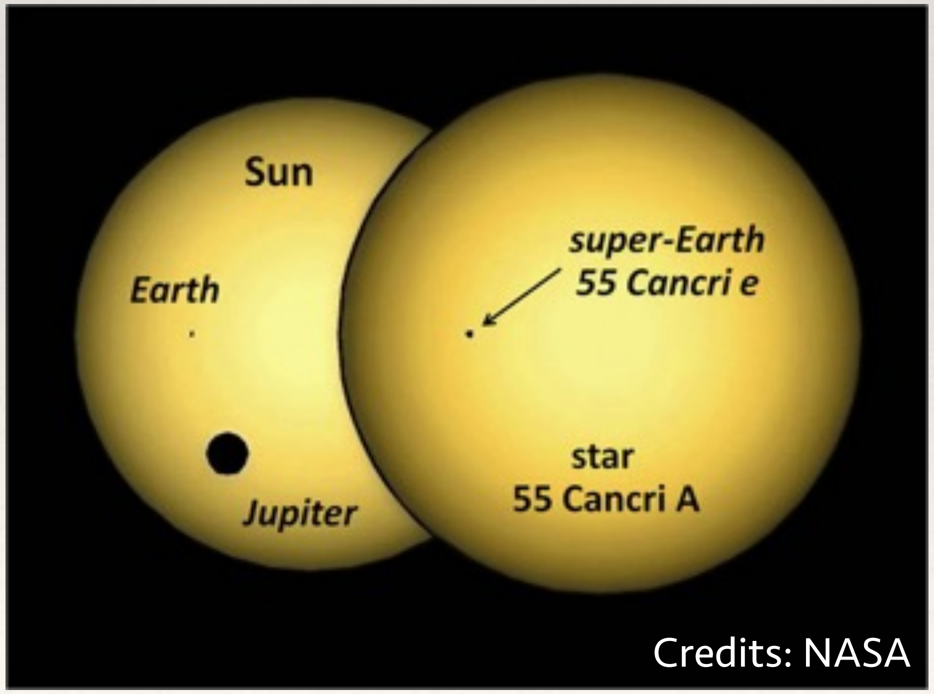


- Using the stellar density: $M_\star = 0.96 \pm 0.067\ M_\odot$
- From isochrones:
  - Young solution: $M_\star = 0.968 \pm 0.018\ M_\odot$, 30.0 ± 3.028 Myrs
  - Old solution: $M_\star = 0.874 \pm 0.013\ M_\odot$, 13.19 ± 1.18 Gyrs

THE MULTIPLANETARY SYSTEM 55 CNC

Planetary results

Planet	a [au]	$m_p \sin(i)$ [M_{Jup}]
b	0.1156 ± 0.0027	0.833 ± 0.039
c	0.2420 ± 0.0056	0.1711 ± 0.0089
d	5.58 ± 0.13	3.68 ± 0.17
e	0.01575 ± 0.00037	8.66 ± 0.50* $M_\oplus$
f†	0.789± 0.018	0.180 ± 0.012



Credits: NASA

55 Cnc e	
R_p [$R_\oplus$]	$2.031^{+0.091}_{-0.088}$
M_p [$M_\oplus$]	8.631 ± 0.495
ρ_p [$g.cm^{-3}$]	$5.680^{+0.709}_{-0.749}$

- Super-Earth
- All stellar parameters come from direct measurements
  - better accuracy
- Better accuracy on the density:
  - compared to *Winn et al. (2011)* and *Demory et al. (2011)* ~25% → 12%
  - error on ρ_p dominated by error on TD.
  - 55 Cnc e has a terrestrial density!

TOWARD A BAYESIAN APPROACH

- Add hypothesis on the distribution of the parameters:
  ➔ add a « prior » to the distribution
- Take into account the physics of the parameters
- In the case of 55 Cnc
  ➔ « prior » on $M_\star$ and $age_\star$

CONCLUSIONS

- Direct observables (especially the radius) are necessary to improve the accuracy of stellar ages and masses.
- In any case, the estimation of the error is very important, and can be obtained with MC.
  - Bayesian approach to be compared to interpolation.
- Taking [M/H] it into account increases the error on $M_\star$ and $age_\star$, but leads to more realistic results.

CONCLUSIONS

- Stellar parameters are needed to derive planetary parameters.
- Direct stellar density gives a direct estimates of stellar masses (ex.: 55 Cnc).
  - Extend to HD189733, HD209458…
- 55 Cnc system
  - new estimation of stellar masses and ages
  - new and more accurate estimations of planetary radius, mass and density for the transiting planet 55 Cnc e.


Thank you!