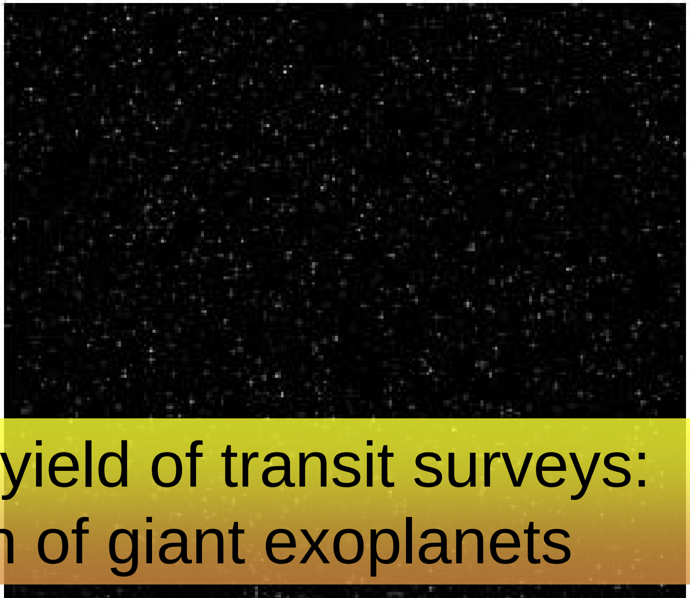
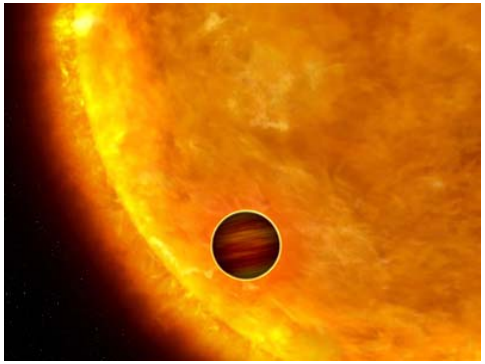
# *Statistical Analysis of Transit Surveys and the Composition of Giant Exoplanets*



I - The CoRoTlux simulator



II - Interpreting the yield of transit surveys:
The composition of giant exoplanets

III - Predictions for CoRoT

# The CoRoTlux simulator

*Tristan Guillot, OCA Nice*
*Francois Fressin, OCA Nice*
*Frédéric Pont, Geneva Obs.*

Aurélien Granier, OCA Nice
Maxime Marmier, Geneva Obs.
Vincent Morello, OCA Nice
Martin Vannier, OCA Nice

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François Bouchy, IAP Paris
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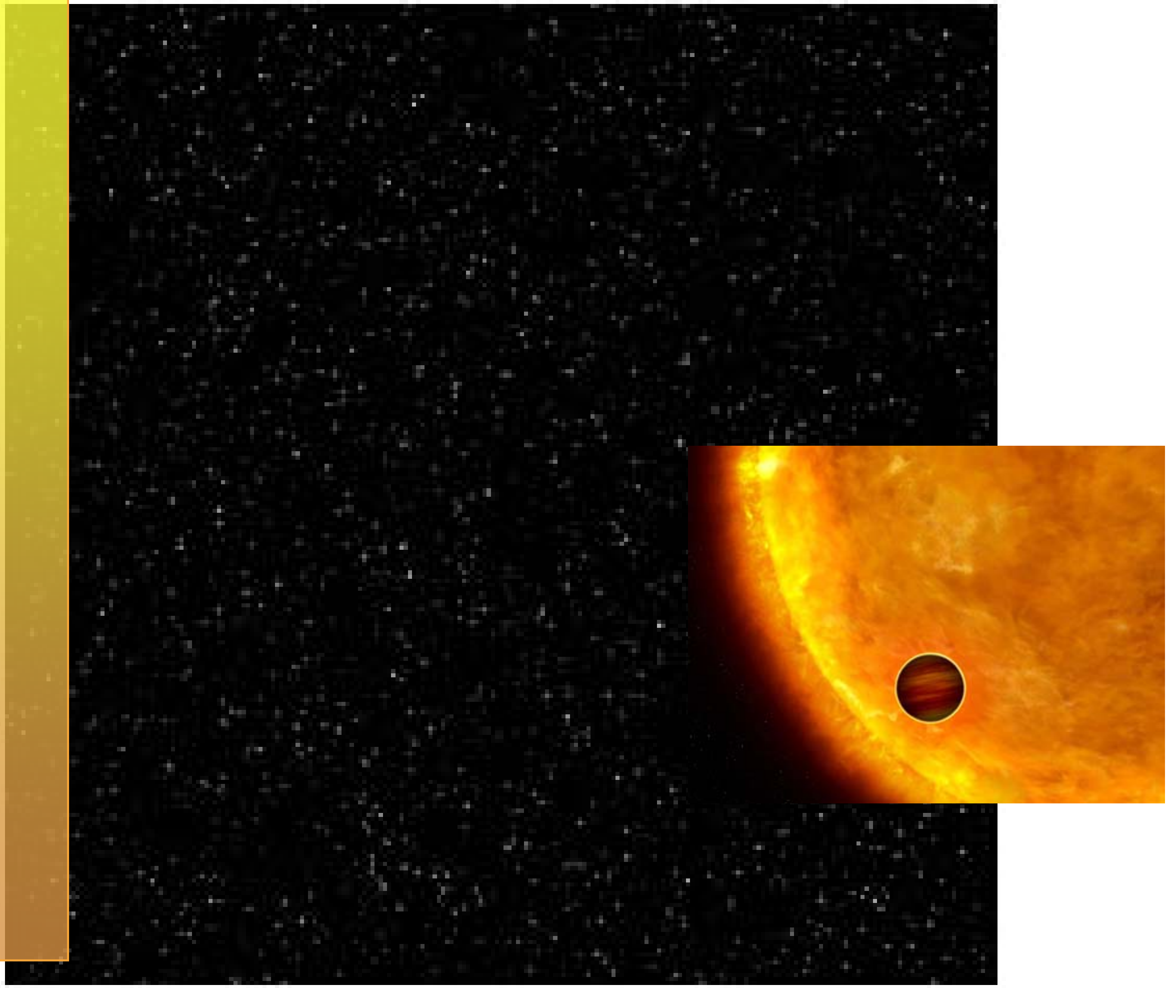
Laurent Jorda, Marseille
Stéphane Lagarde, OCA Nice
Claire Moutou, Marseille
Didier Queloz, Geneva Obs.
Andrzej Udalski, Warsaw Obs.



# Backward Approach

$$\langle N \rangle = \sum_k \underbrace{P_{\mathrm{planet,k}}(M,[\mathrm{Fe/H}],P,r,\ldots)}_{\text{probability of hosting a planet}}\underbrace{P_{\mathrm{transit,k}}(R,P,i)}_{\text{probability planet will transit}}\underbrace{P_{\mathrm{detect,k}}(R,F,r,P\ldots)}_{\text{probability planet will be detected}}$$

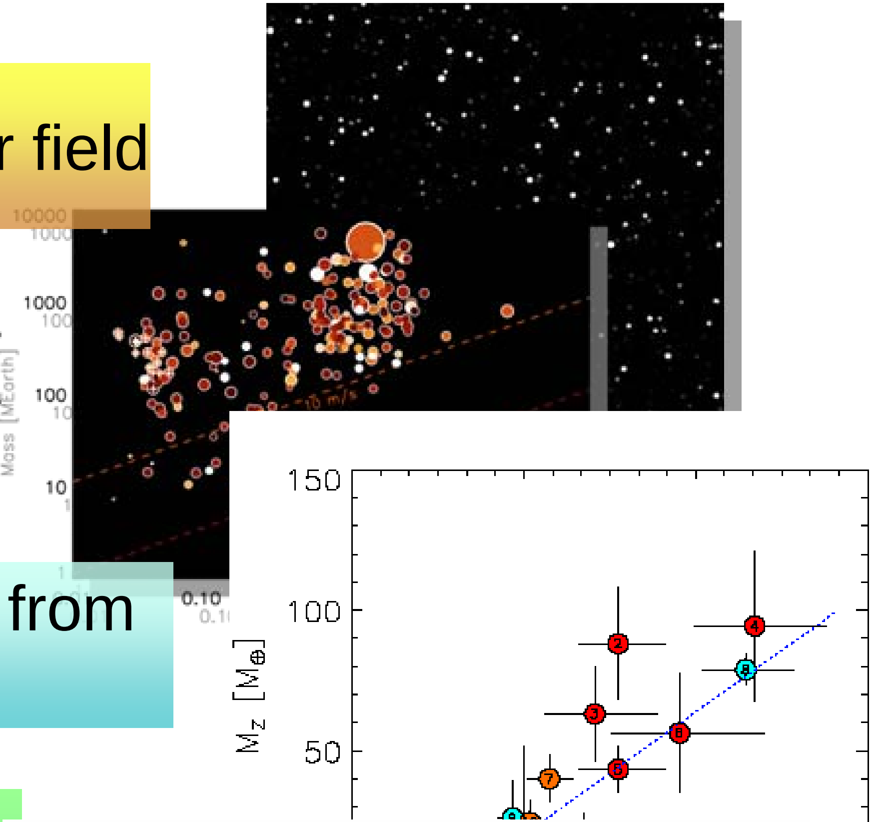
But

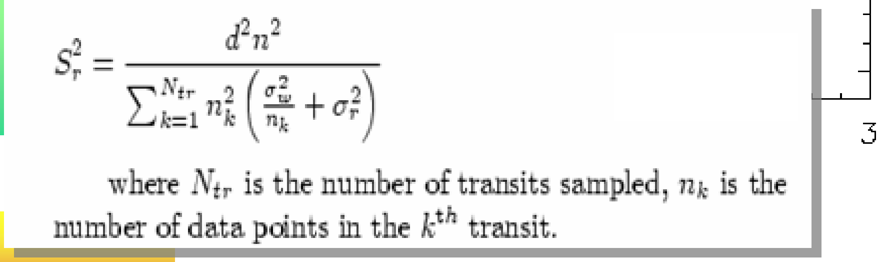
- Monte-Carlo simulation instead of analytical calculation
- Using observing telescopes light curves to help determining noise level and detection probability

I am using OGLE survey as an example

# I - CoRoTlux: method

1. Generate randomly a stellar field
2. Add planetary companions
3. Calculate planetary radii from evolution model
4. Estimate which planets are transiting and detectable
5. Stir & shake. Get results





$$S_r^2 = \frac{d^2 n^2}{\sum_{k=1}^{N_{tr}} n_k^2 \left(\frac{\sigma_w^2}{n_k} + \sigma_r^2\right)}$$

where $N_{tr}$ is the number of transits sampled, $n_k$ is the number of data points in the $k^{th}$ transit.

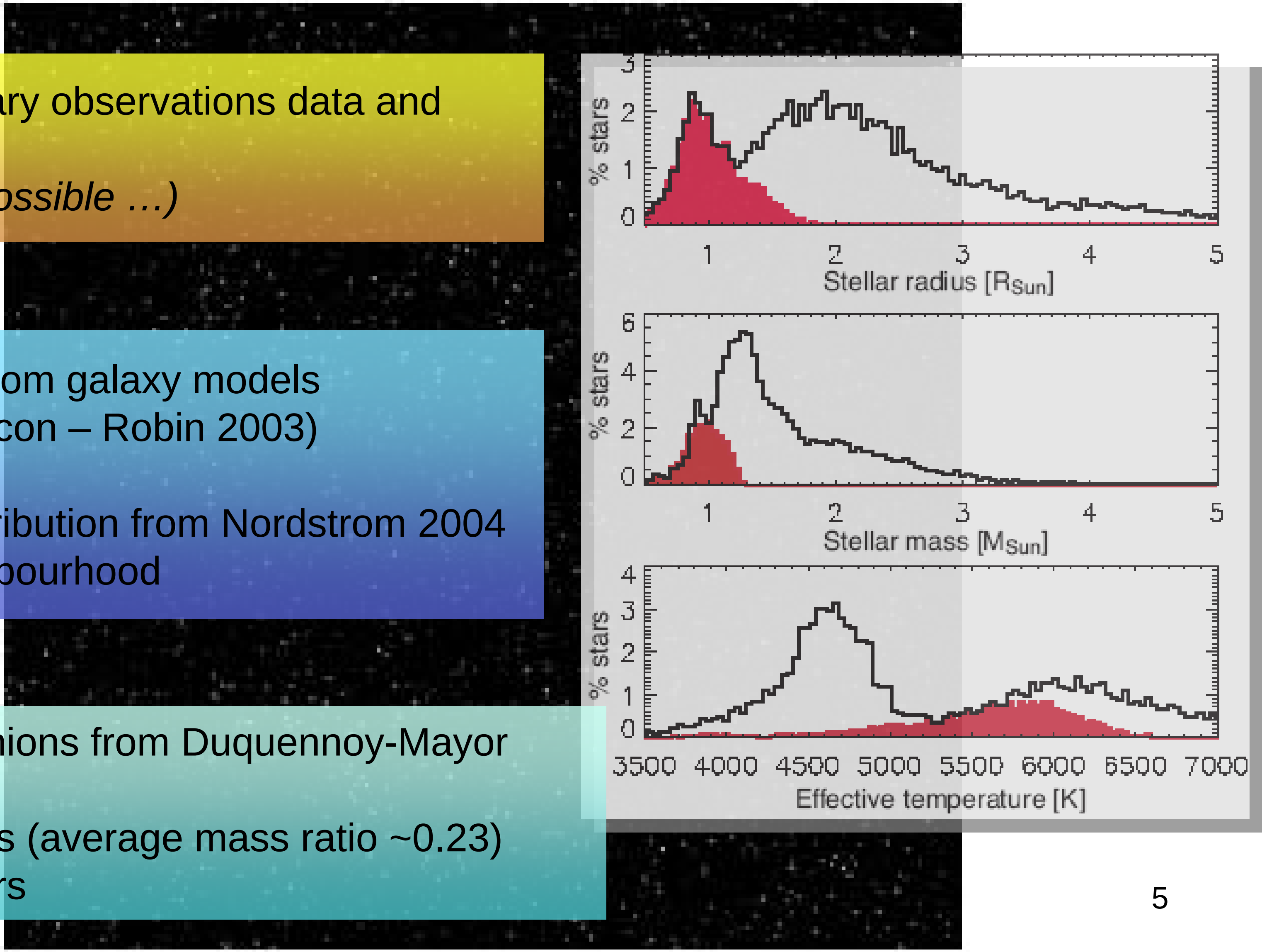
# 1. Generate a stellar field

From preliminary observations data and catalogues
*(as much as possible …)*

Missing data from galaxy models
(mainly Besancon – Robin 2003)

Metallicity distribution from Nordstrom 2004 for solar neighbourhood

Stellar companions from Duquennoy-Mayor 1991:
50 % dual stars (average mass ratio ~0.23)
10 % triple stars



# 2. Giant planetary companions

Probability:

*Metallicity link from Santos 2004*

Mass / Period distribution:

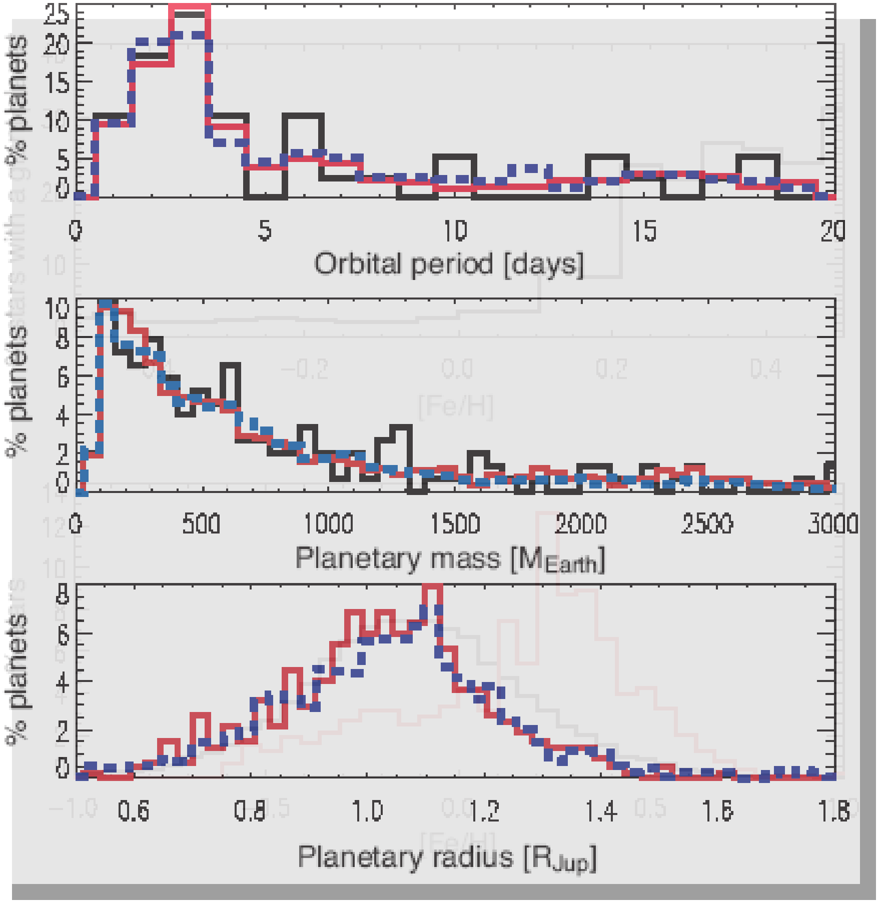
1-From analytical distribution

*Period distribution from Brown 2003*

*Mass distribution from Zucker –Mazhet 2001*

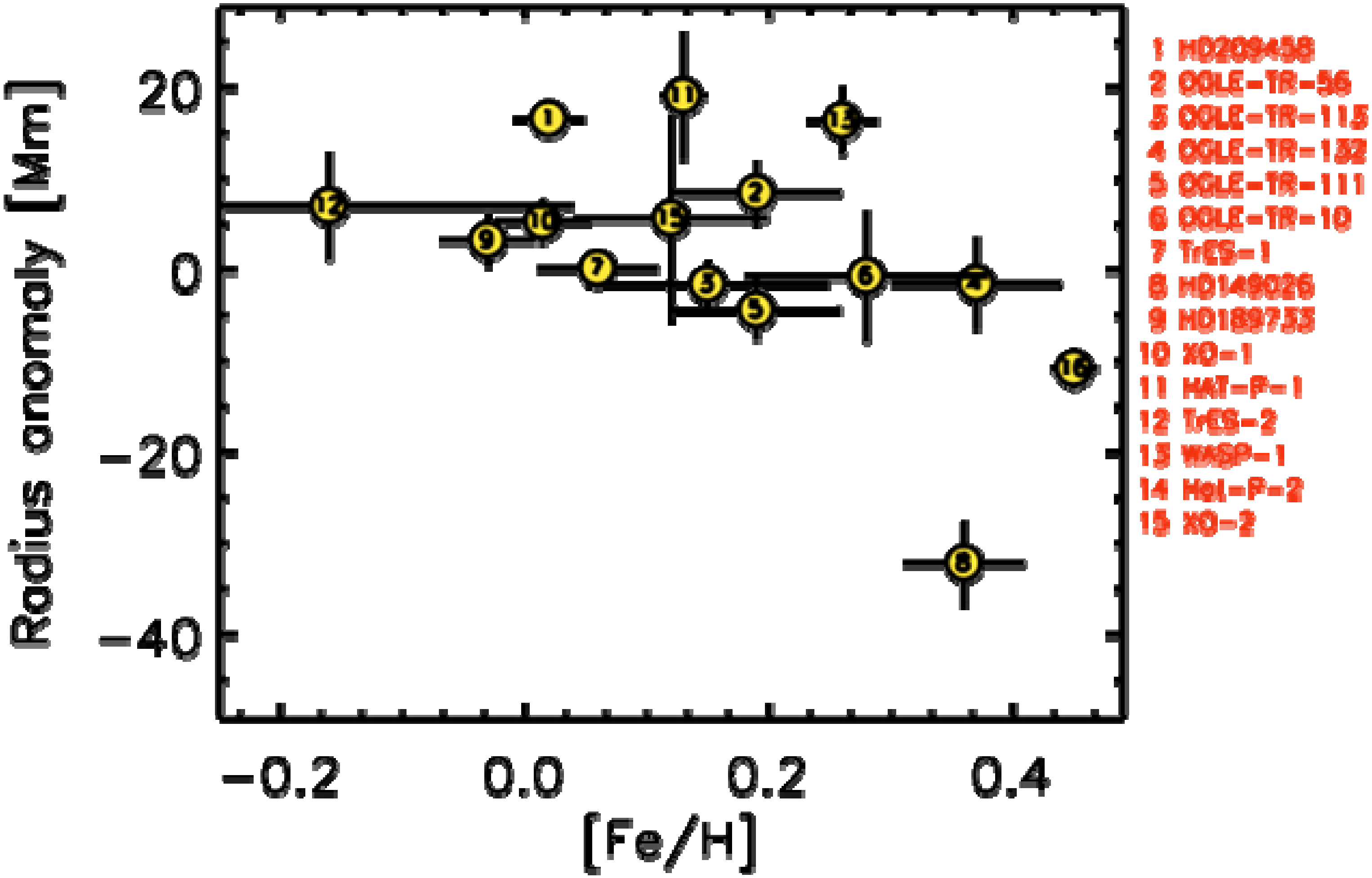
OR

2- Carbon copy of RV planets



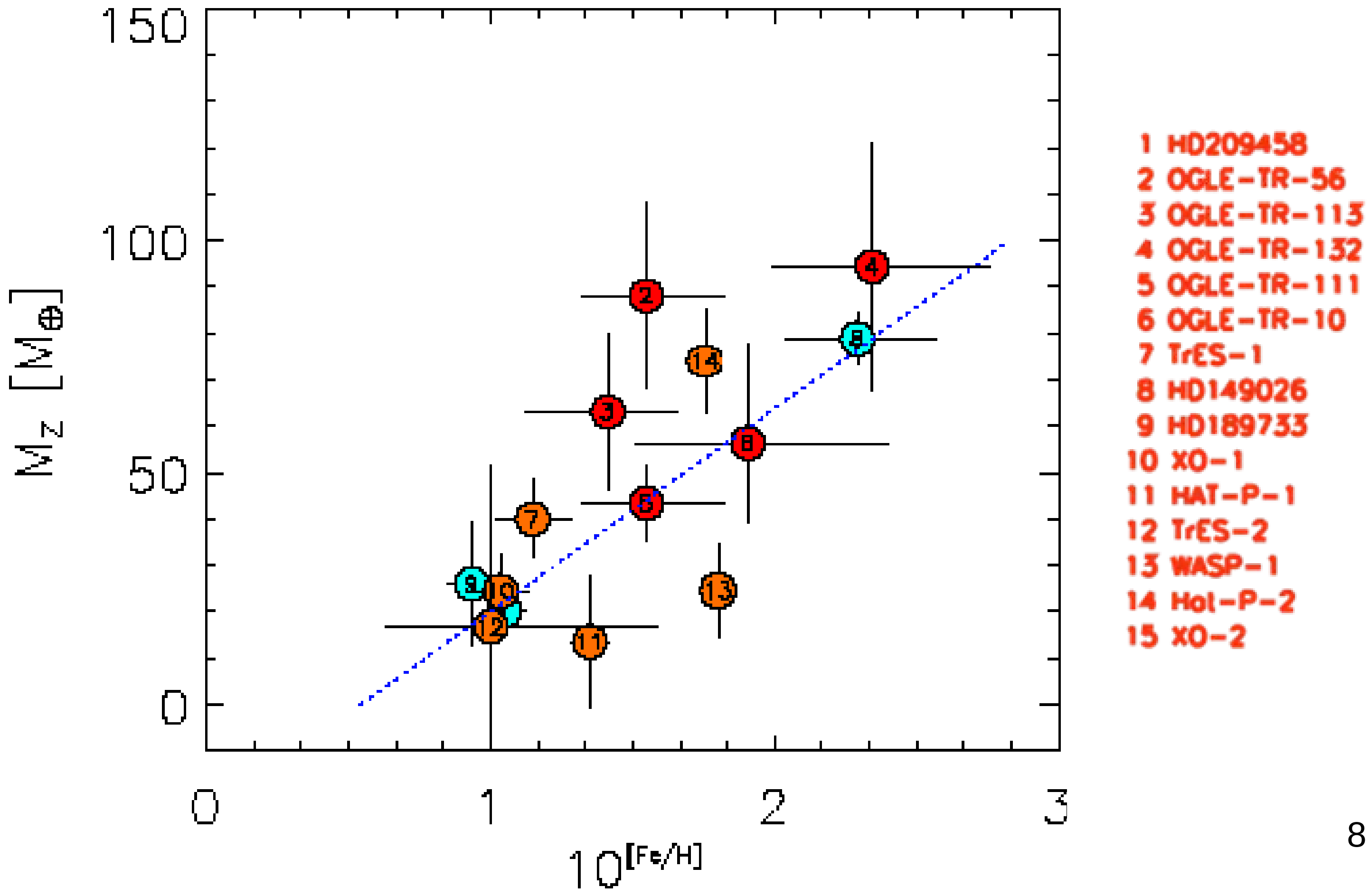
# 3. Planetary radii : Radius anomaly

## A link with host star metallicity – Guillot 2006



# 3. Planetary radii from evolution models

## A link with host star metallicity – Guillot 2006

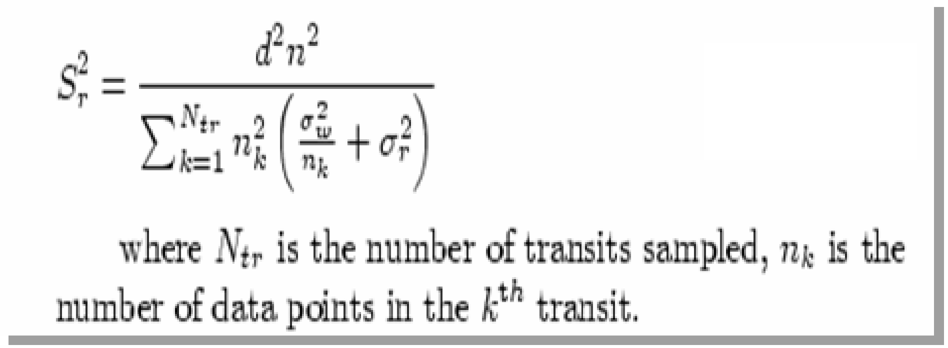


# 4. Detection threshold

- Compute what is transiting (planets & stars), as a function of main and secondary radii, inclination, eccentricity

Threshold considering red noise – *From Pont 2006*

$S_r = 9$ as threshold



$$S_r^2 = \frac{d^2 n^2}{\sum_{k=1}^{N_{tr}} n_k^2 \left(\frac{\sigma_w^2}{n_k} + \sigma_r^2\right)}$$

where $N_{tr}$ is the number of transits sampled, $n_k$ is the number of data points in the $k^{th}$ transit.

Observation windows

*Real observation Julian dates from light curves*

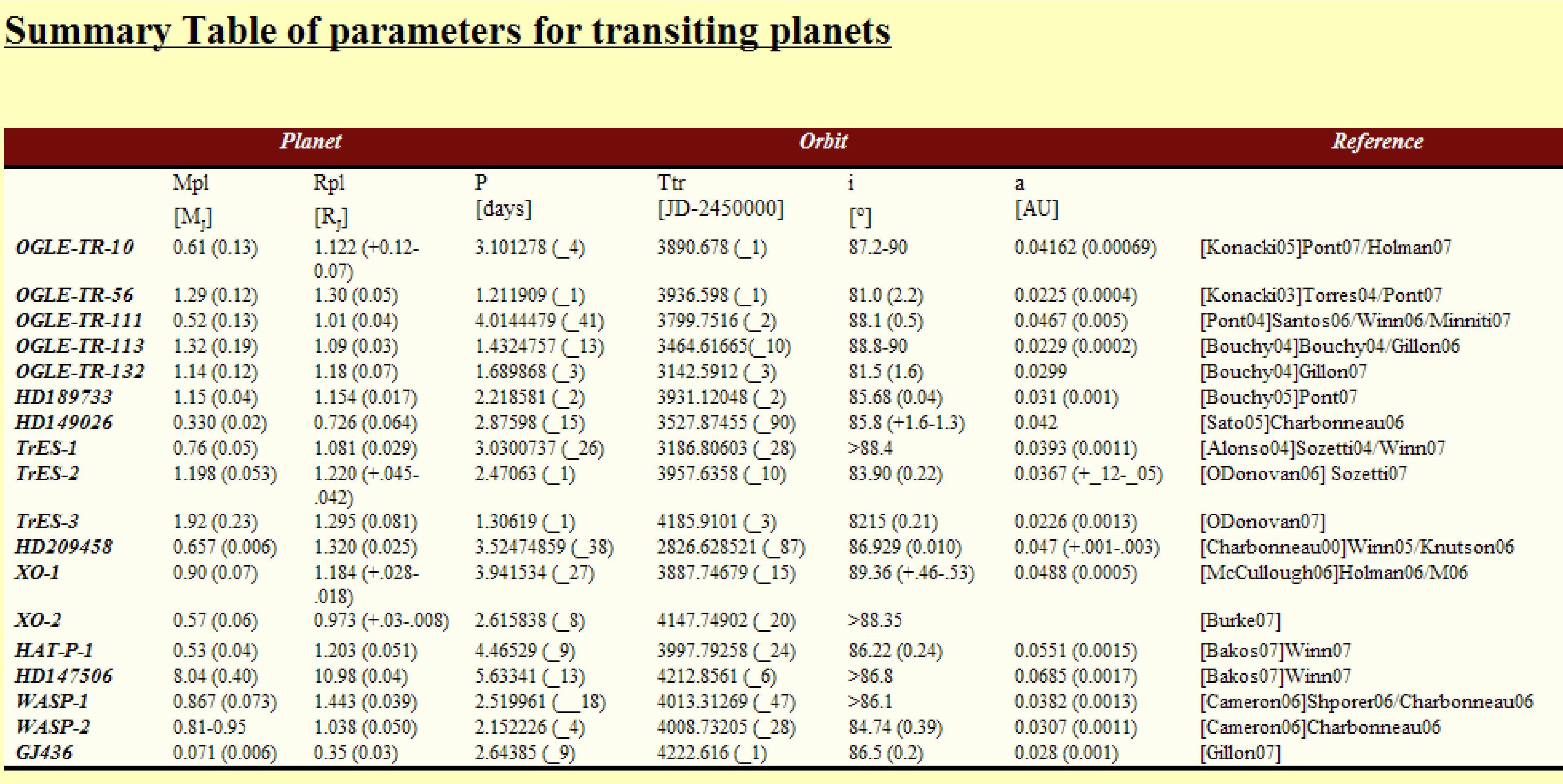
White noise level

*extrapolated from telescope calibration stars flux*

Red noise level

*extracted from the analysis of the light curves*

# Referenced transiting planets



**Summary Table of parameters for transiting planets**

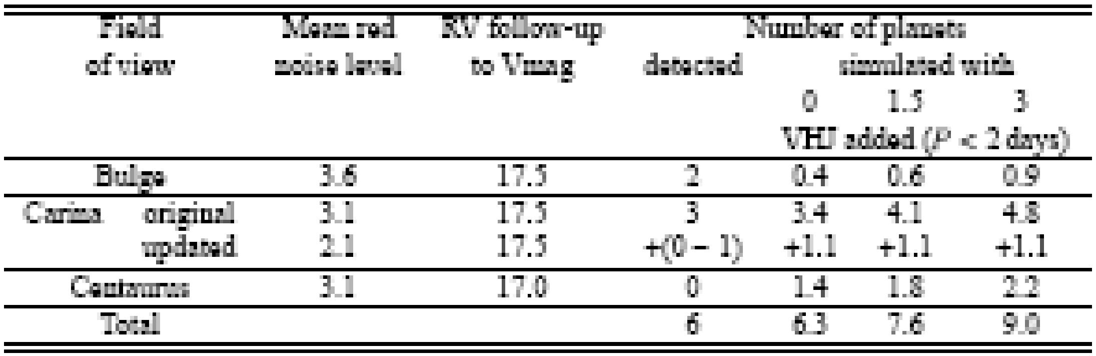
| | *Planet* | | | *Orbit* | | | *Reference* |
|---|---|---|---|---|---|---|---|
| | Mpl $[M_J]$ | Rpl $[R_J]$ | P [days] | Ttr [JD-2450000] | i [°] | a [AU] | |
| ***OGLE-TR-10*** | 0.61 (0.13) | 1.122 (+0.12-0.07) | 3.101278 (_4) | 3890.678 (_1) | 87.2-90 | 0.04162 (0.00069) | [Konacki05]Pont07/Holman07 |
| ***OGLE-TR-56*** | 1.29 (0.12) | 1.30 (0.05) | 1.211909 (_1) | 3936.598 (_1) | 81.0 (2.2) | 0.0225 (0.0004) | [Konacki03]Torres04/Pont07 |
| ***OGLE-TR-111*** | 0.52 (0.13) | 1.01 (0.04) | 4.0144479 (_41) | 3799.7516 (_2) | 88.1 (0.5) | 0.0467 (0.005) | [Pont04]Santos06/Winn06/Minniti07 |
| ***OGLE-TR-113*** | 1.32 (0.19) | 1.09 (0.03) | 1.4324757 (_13) | 3464.61665(_10) | 88.8-90 | 0.0229 (0.0002) | [Bouchy04]Bouchy04/Gillon06 |
| ***OGLE-TR-132*** | 1.14 (0.12) | 1.18 (0.07) | 1.689868 (_3) | 3142.5912 (_3) | 81.5 (1.6) | 0.0299 | [Bouchy04]Gillon07 |
| ***HD189733*** | 1.15 (0.04) | 1.154 (0.017) | 2.218581 (_2) | 3931.12048 (_2) | 85.68 (0.04) | 0.031 (0.001) | [Bouchy05]Pont07 |
| ***HD149026*** | 0.330 (0.02) | 0.726 (0.064) | 2.87598 (_15) | 3527.87455 (_90) | 85.8 (+1.6-1.3) | 0.042 | [Sato05]Charbonneau06 |
| ***TrES-1*** | 0.76 (0.05) | 1.081 (0.029) | 3.0300737 (_26) | 3186.80603 (_28) | >88.4 | 0.0393 (0.0011) | [Alonso04]Sozetti04/Winn07 |
| ***TrES-2*** | 1.198 (0.053) | 1.220 (+.045-.042) | 2.47063 (_1) | 3957.6358 (_10) | 83.90 (0.22) | 0.0367 (+_12-_05) | [ODonovan06] Sozetti07 |
| ***TrES-3*** | 1.92 (0.23) | 1.295 (0.081) | 1.30619 (_1) | 4185.9101 (_3) | 8215 (0.21) | 0.0226 (0.0013) | [ODonovan07] |
| ***HD209458*** | 0.657 (0.006) | 1.320 (0.025) | 3.52474859 (_38) | 2826.628521 (_87) | 86.929 (0.010) | 0.047 (+.001-.003) | [Charbonneau00]Winn05/Knutson06 |
| ***XO-1*** | 0.90 (0.07) | 1.184 (+.028-.018) | 3.941534 (_27) | 3887.74679 (_15) | 89.36 (+.46-.53) | 0.0488 (0.0005) | [McCullough06]Holman06/M06 |
| ***XO-2*** | 0.57 (0.06) | 0.973 (+.03-.008) | 2.615838 (_8) | 4147.74902 (_20) | >88.35 | | [Burke07] |
| ***HAT-P-1*** | 0.53 (0.04) | 1.203 (0.051) | 4.46529 (_9) | 3997.79258 (_24) | 86.22 (0.24) | 0.0551 (0.0015) | [Bakos07]Winn07 |
| ***HD147506*** | 8.04 (0.40) | 10.98 (0.04) | 5.63341 (_13) | 4212.8561 (_6) | >86.8 | 0.0685 (0.0017) | [Bakos07]Winn07 |
| ***WASP-1*** | 0.867 (0.073) | 1.443 (0.039) | 2.519961 (__18) | 4013.31269 (_47) | >86.1 | 0.0382 (0.0013) | [Cameron06]Shporer06/Charbonneau06 |
| ***WASP-2*** | 0.81-0.95 | 1.038 (0.050) | 2.152226 (_4) | 4008.73205 (_28) | 84.74 (0.39) | 0.0307 (0.0011) | [Cameron06]Charbonneau06 |
| ***GJ436*** | 0.071 (0.006) | 0.35 (0.03) | 2.64385 (_9) | 4222.616 (_1) | 86.5 (0.2) | 0.028 (0.001) | [Gillon07] |

From Pont’s

**Summary Table of parameters for transiting planets**

# II – CoRoTlux results interpretation: Giant planets in the OGLE field

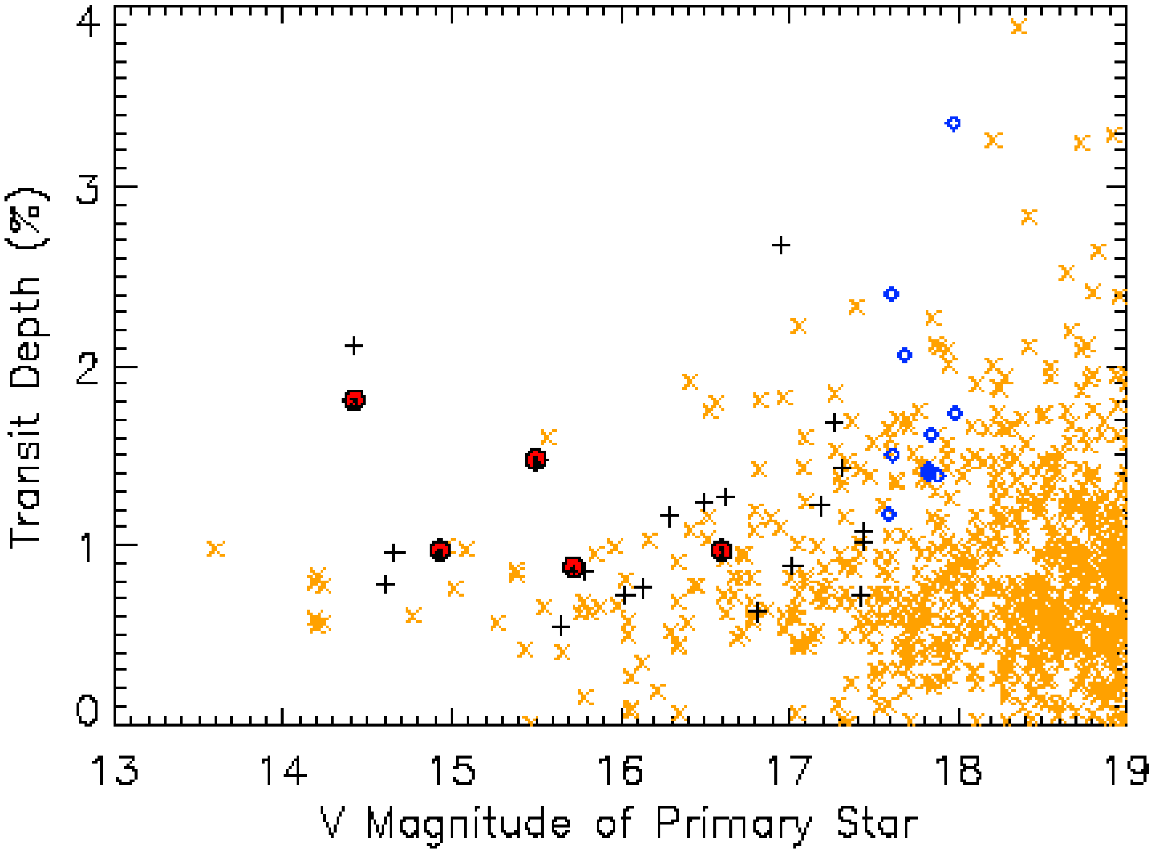
## 1. Quantitative analysis



| Field of view | | Mean red noise level | RV follow-up to Vmag | Number of planets | | | |
|---|---|---|---|---|---|---|---|
| | | | | detected | simulated with | | |
| | | | | | 0 | 1.5 | 3 |
| | | | | | VHJ added ($P < 2$ days) | | |
| Bulge | | 3.6 | 17.5 | 2 | 0.4 | 0.6 | 0.9 |
| Carina | original | 3.1 | 17.5 | 3 | 3.4 | 4.1 | 4.8 |
| | updated | 2.1 | 17.5 | +(0 – 1) | +1.1 | +1.1 | +1.1 |
| Centaurus | | 3.1 | 17.0 | 0 | 1.4 | 1.8 | 2.2 |
| Total | | | | 6 | 6.3 | 7.6 | 9.0 |

## 2. Characterization: planet (M, R, P) as a function of star (M, R, [Fe/H])

# Quantitative information from OGLE analysis



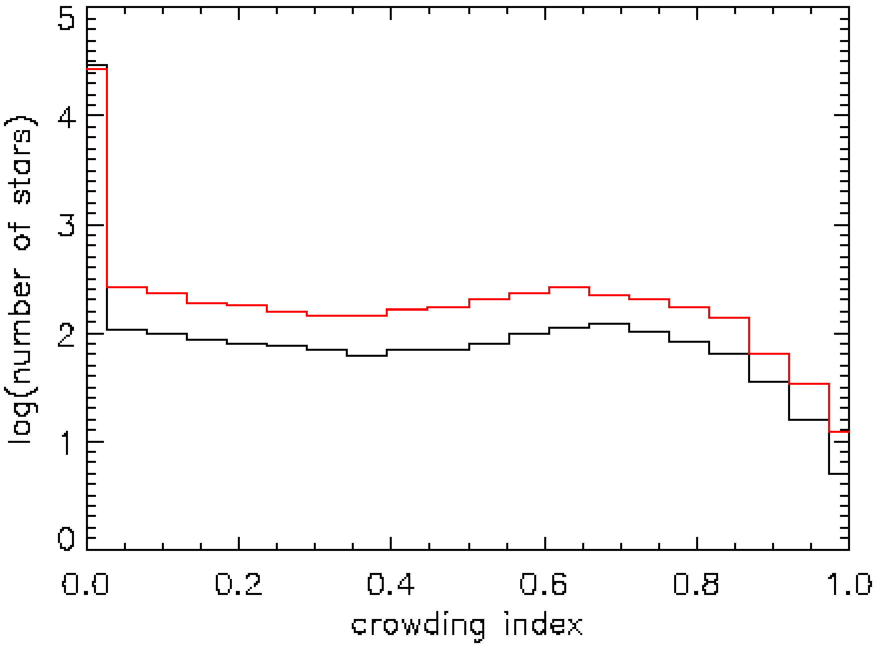
**+: detection**

**o: unconfirmable detection**

**x: missed detection**

**o: real OGLE planets**

# Quantitative information from OGLE analysis: Red noise understanding



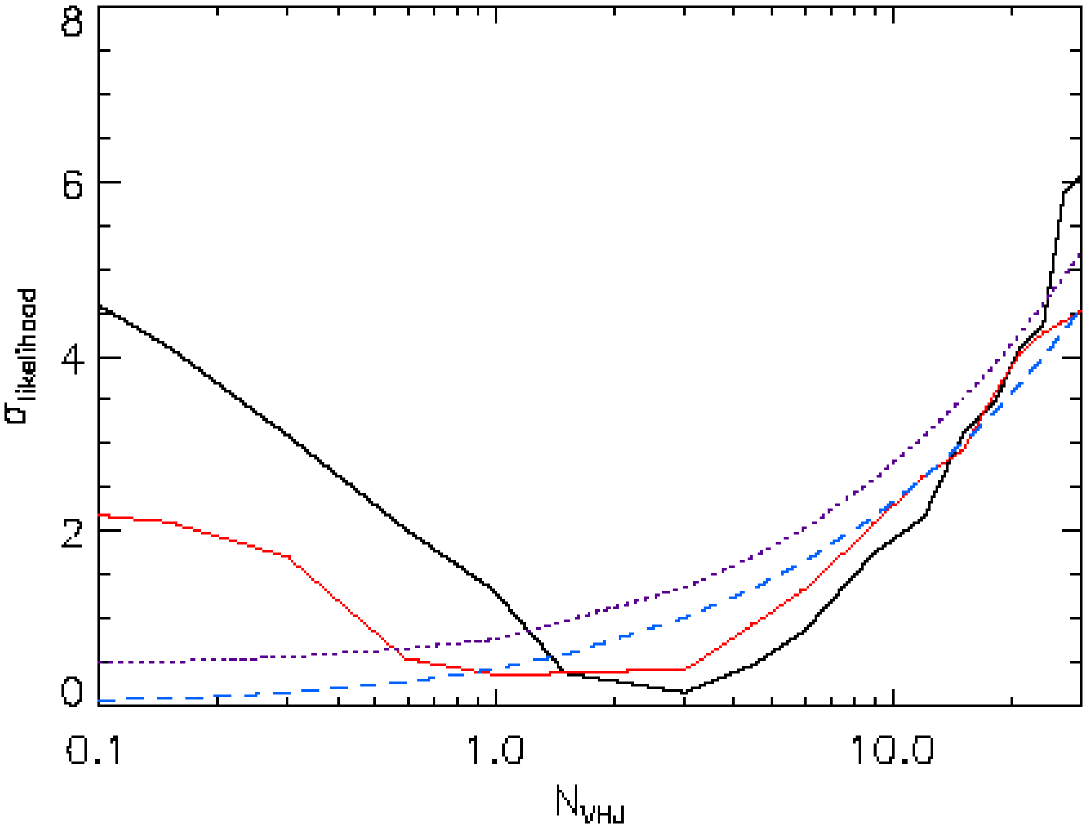
Bulge field $\sigma_r$ = 3.6 mmag

Carina field $\sigma_r$ = 3.1 mmag

⇒ $\sigma_r = 2.6 + I_{Crowding} \times 0.4$ mmag - for OGLE

⇒ A fraction of the red noise level is a function of crowding

# Quantitative information from OGLE analysis

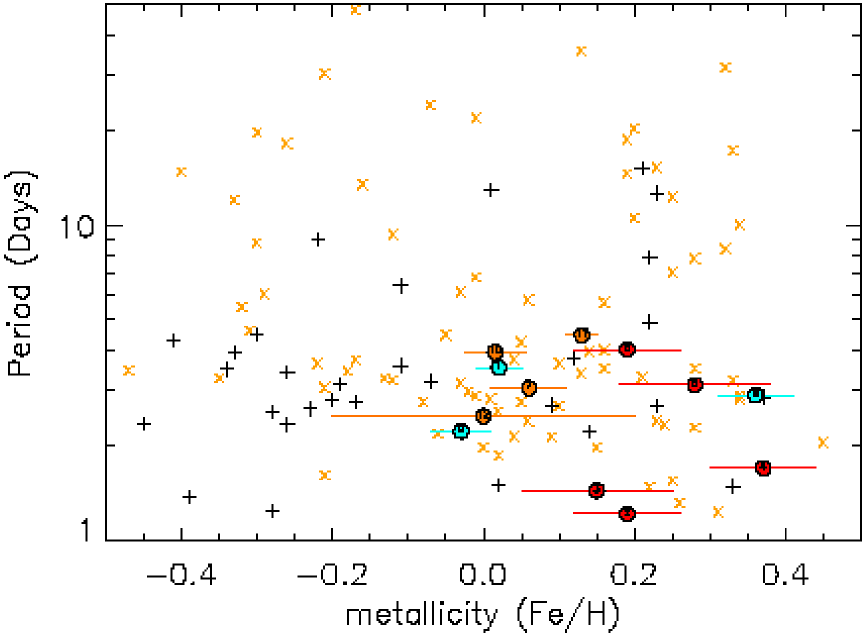


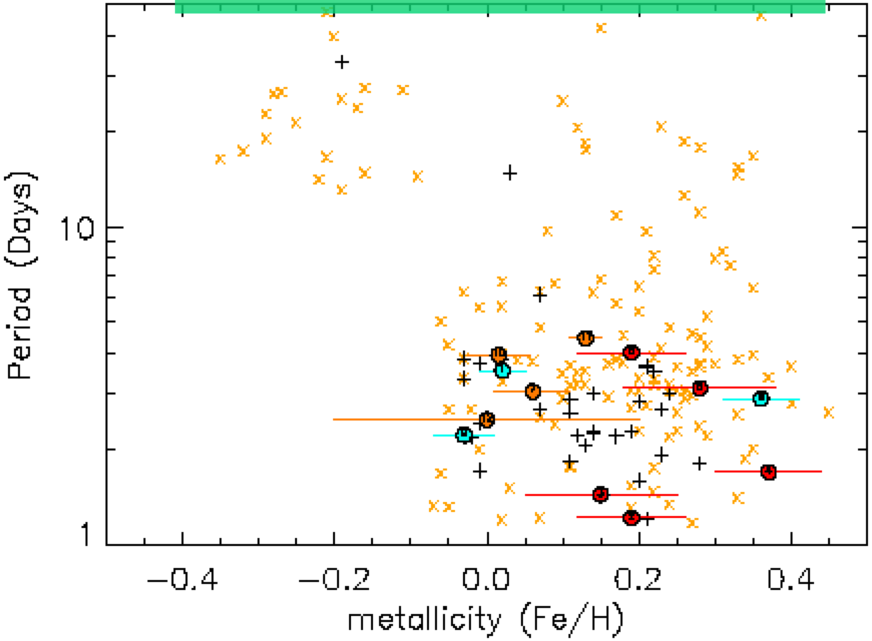
=> VHJ (1 to 2 days) ~8 times less frequent than HJ (2 to 5 days)

# Distribution vs Metallicity for close-in planets

Unbiased model

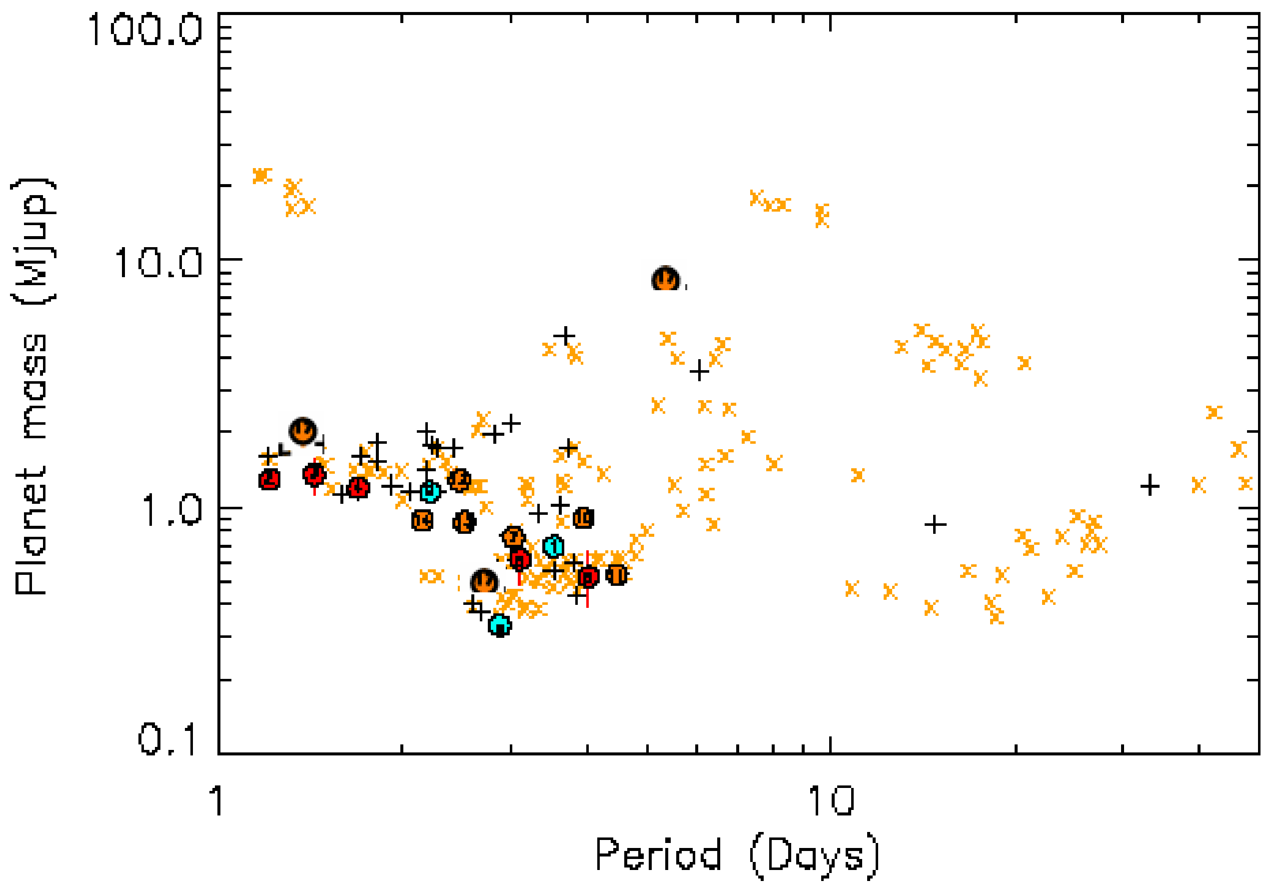
No close-in planet for [Fe/H] less than -0.1





=> The metallicity bias is even stronger for close-in planets

# Mass-period diagram

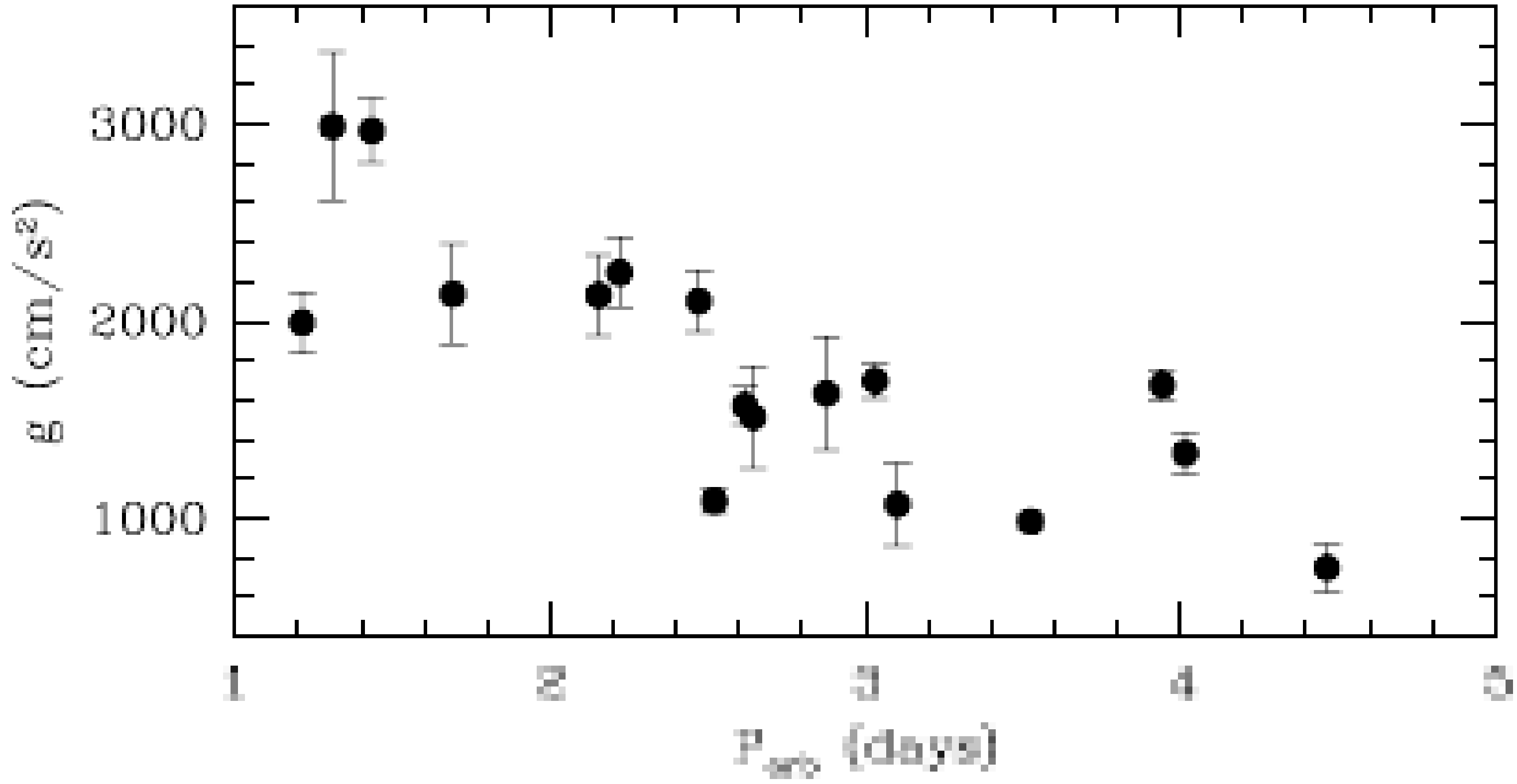


⇒ Agreement between transits and RV

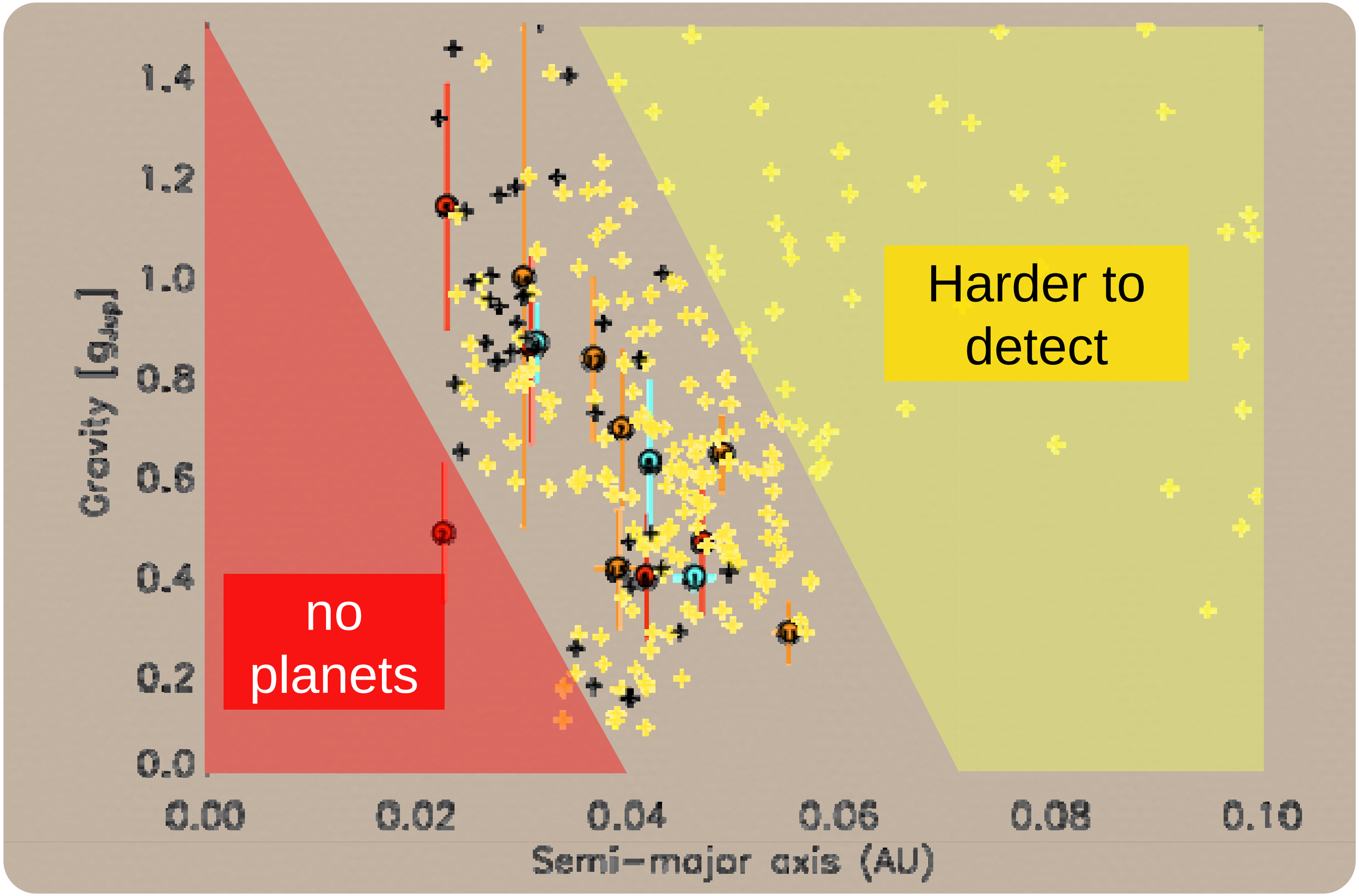
⇒ No very close-in low mass giant planet ?

# A Gravity-Orbital Distance Correlation?

## (Noyes 2006)



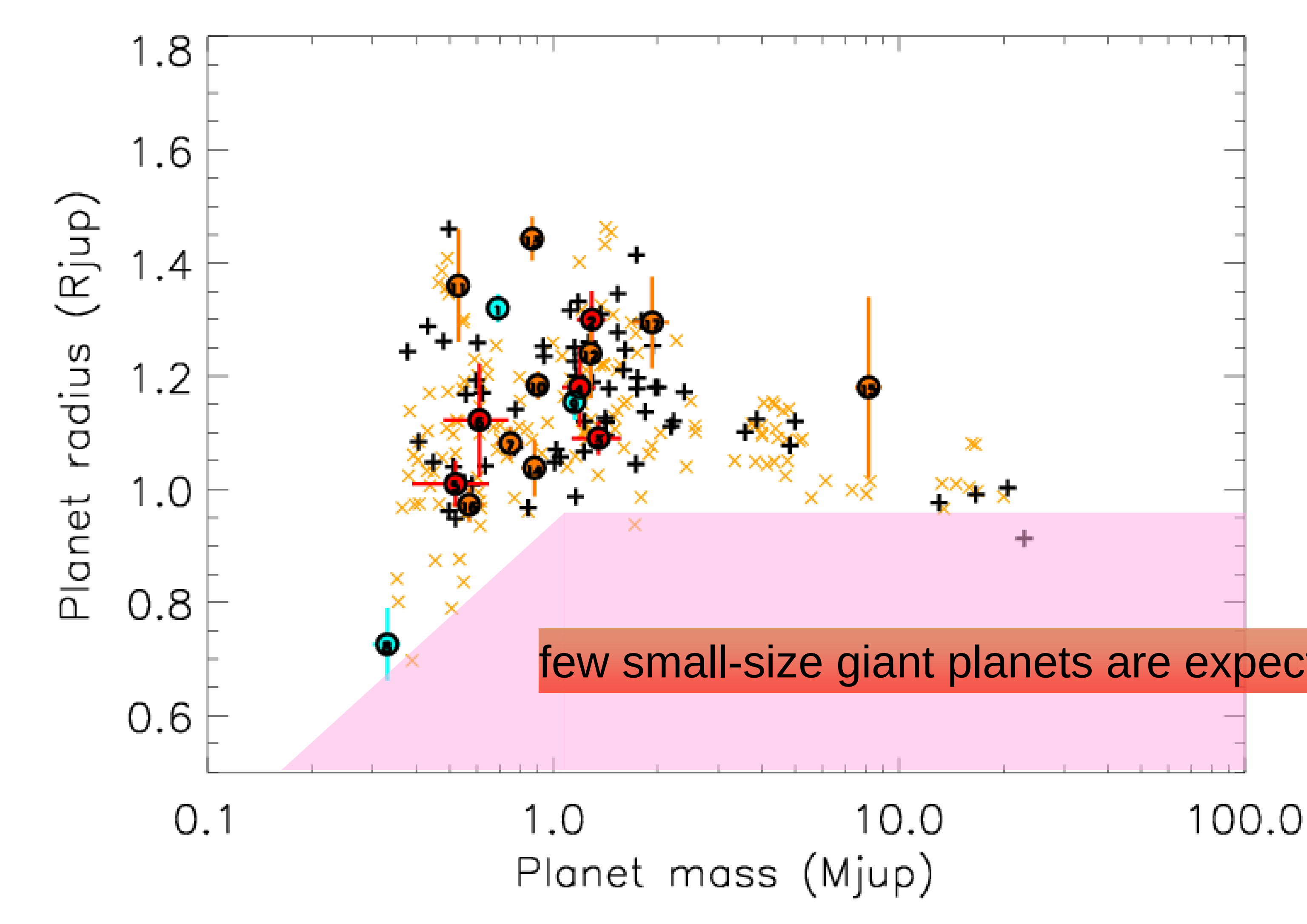
# A Gravity-Orbital Distance Correlation?



Harder to detect

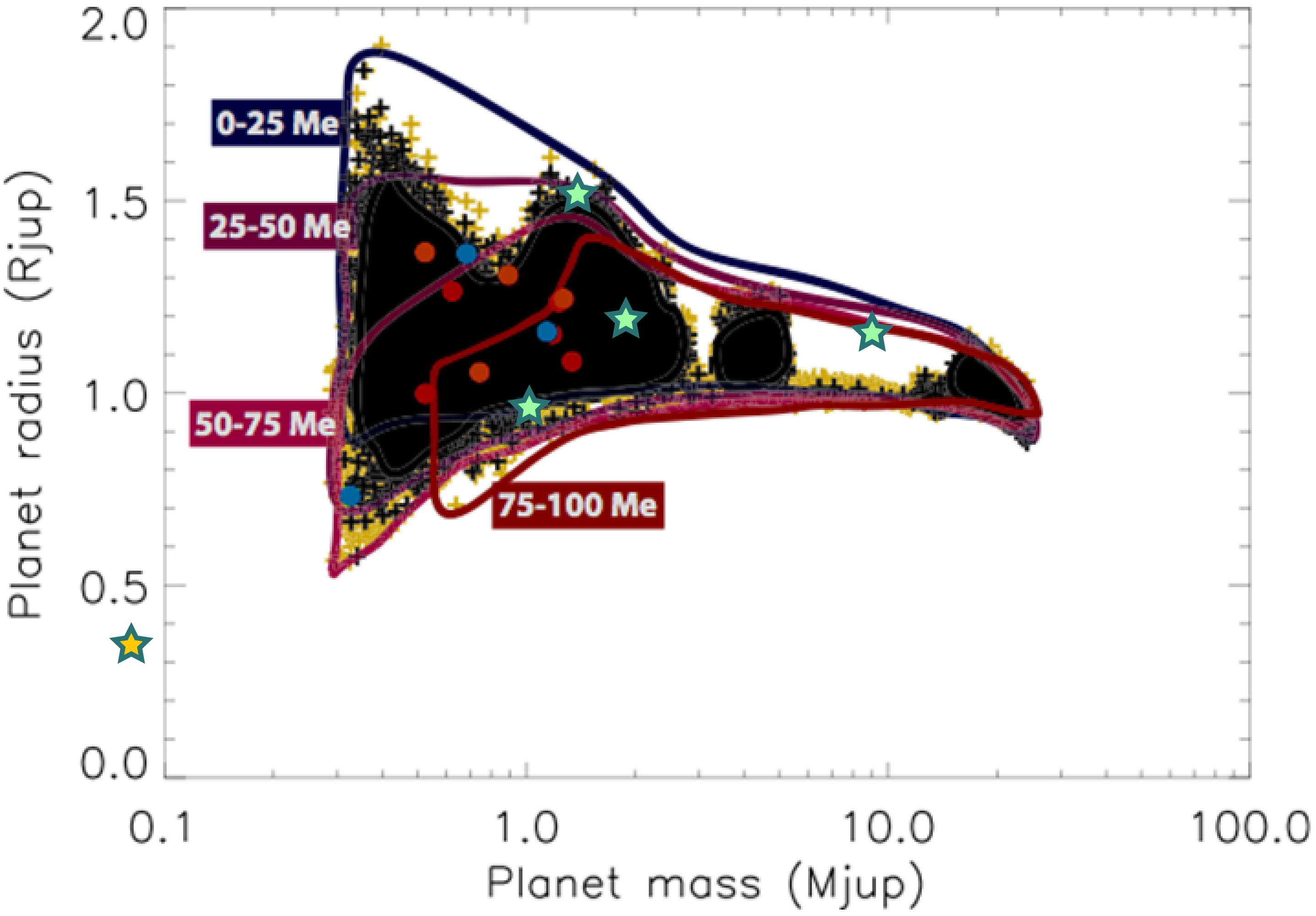
no planets

# Mass-radius diagram for transiting planets

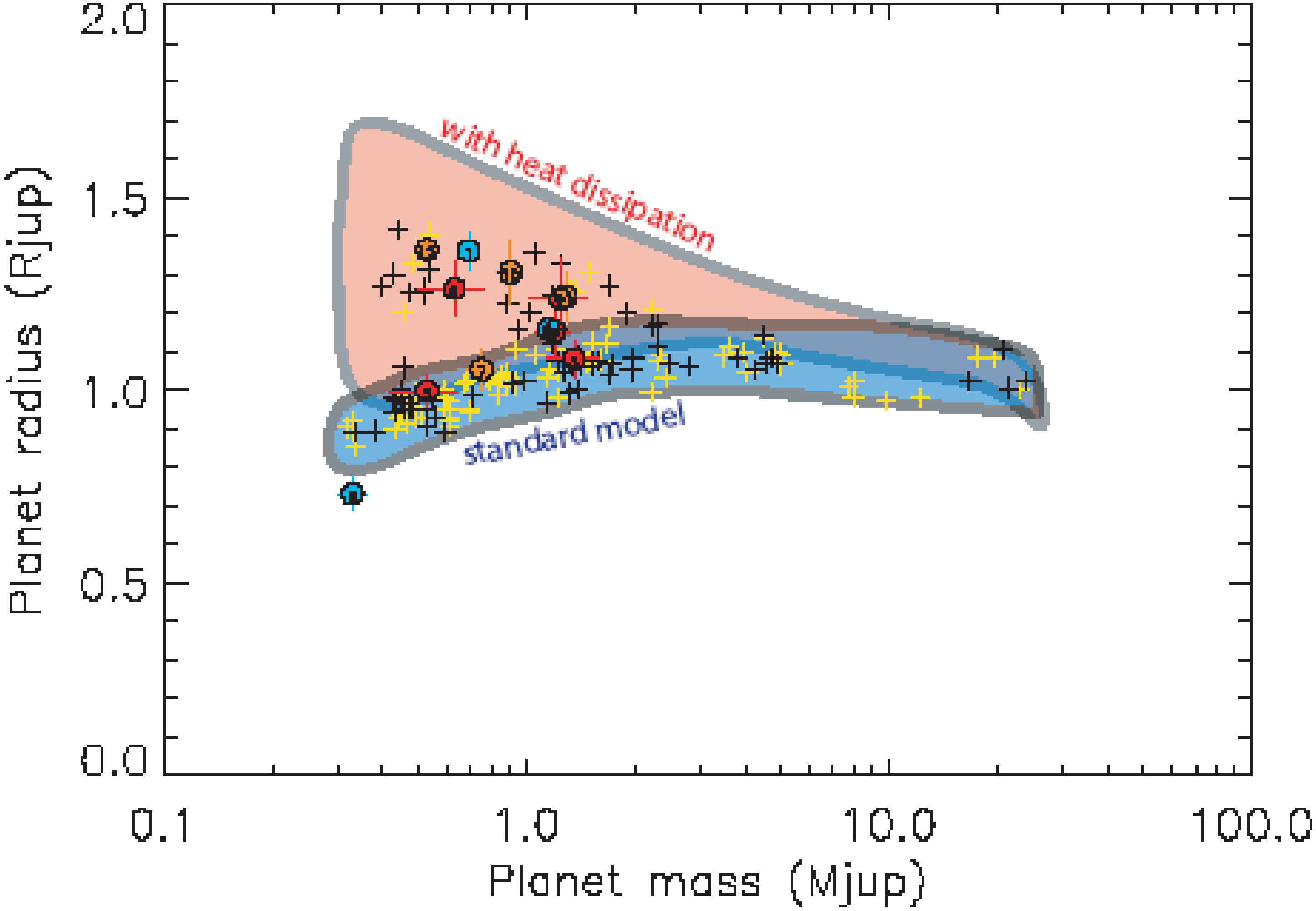


few small-size giant planets are expected

# Mass-radius diagram for transiting planets



# Mass-radius diagram for transiting planets



# III – Predictions for CoRoT yield: Full observation campaign

1 initial run (60 days)

5 long runs (150 days)
> 3 runs towards Galactic center field
> 2 runs towards Anti-center

5-10 short runs (21 days)

Total of ~170.000 stars observed

# Predicting the yield of CoRoT: ingredients for CoRoTlux

Stellar Distribution

- *From preliminary observations*

*(referenced in CoRoT - EXODAT database -*
*from INT telescope wide field camera observations - La Palma)*

Planet distribution

- Giant planets
  - *As for OGLE*
- Small planets (preliminary)
  - *Distribution from Ida & Lin 2005*
  - *Log distribution in mass*

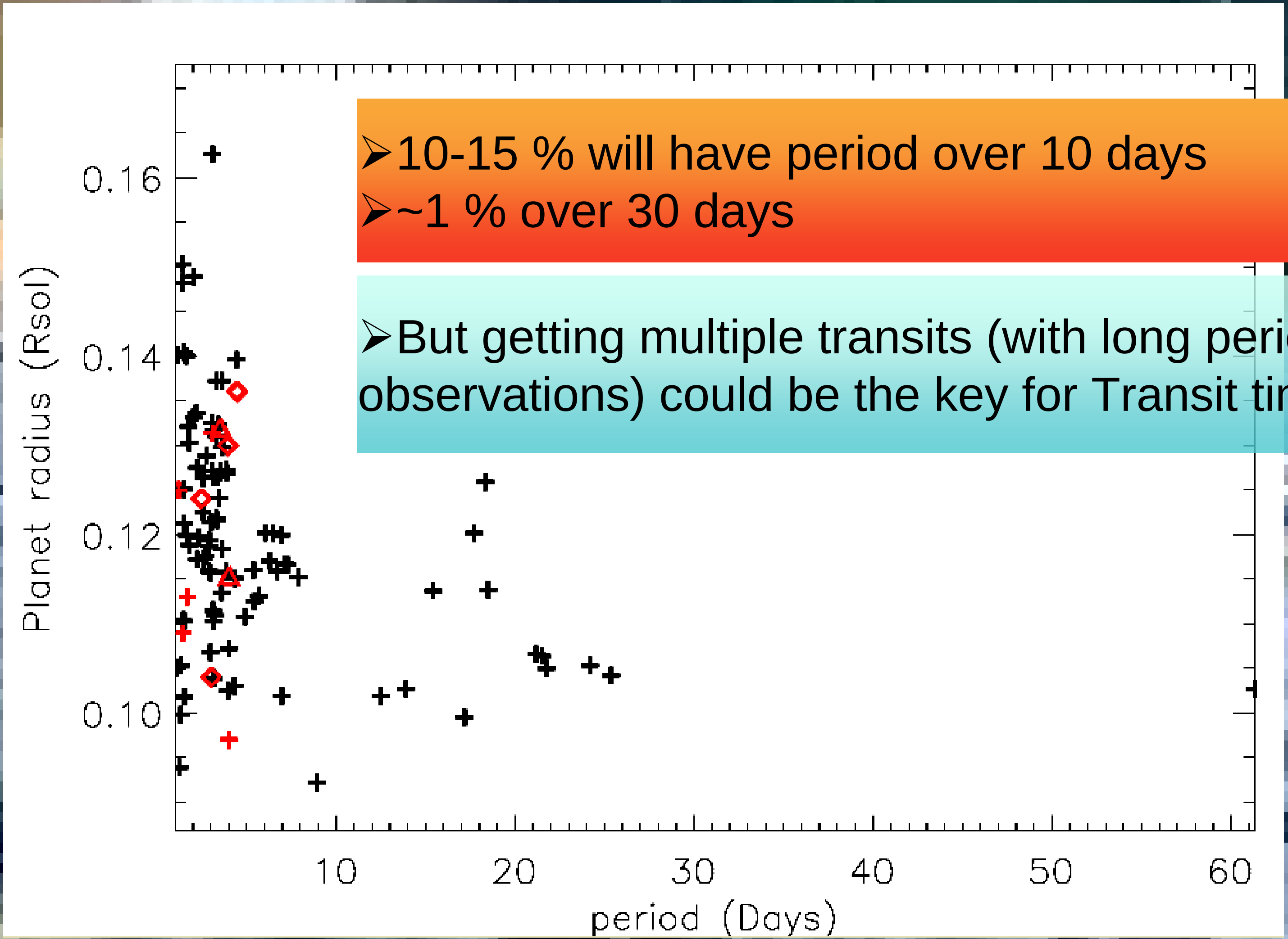
- *To be replaced by Alibert model*
- *Evolution model for Hot Neptunes*

Photometric precision : red noise level

- 0.5 mmag from official initial chart
- 2.1 mmag from CoRoT blind tests (0.5 after detrending)
- ~1 mmag for partially detrented real light curves

# Predicting the yield of CoRoT

## Giant planets



- 10-15 % will have period over 10 days
- ~1 % over 30 days

- But getting multiple transits (with long period observations) could be the key for Transit timing finds

# Predicting the yield of CoRoT:
## *False transits*

(Just for 0.5 % and deeper events):

| Galactic Center field | |
|---|---|
| Grazing eclipse | 11 |
| Low mass companion | 17 |
| Background eclipse | 38 |
| Triple star | 7 |

| Anticenter field | |
|---|---|
| Grazing eclipse | 9 |
| Low mass companion | 18 |
| Background eclipse | 29 |
| Triple star | 7 |

Total for CoRoT
(10 short runs & 5 long runs)

| | |
|---|---|
| Grazing eclipse | 93 |
| Low mass companion | 159 |
| Background eclipse | 245 |
| Triple star | 54 |
| *Total of false transits* | *~550* |

# Predicting the yield of CoRoT: Complete survey Yield

~80 Hot Jupiter (0.3+ Mjup) – majority from short runs
- > 10-15 % with period more than 10 days
- > ~1 % with period more than 30 days

~550 False transits to discriminate (just for 0.5+ % events)
- > using light-curves, colour information
- > ground-based follow-up

~25 ‘Small planets’ (10 to 100 earth masses)
majority from long runs

# *Earths – Super-Earths ?*
# *Unanswered questions …*

-What is the exact sub-millimag red noise level of CoRoT ?

-Is stellar variability the ultimate limit of transit search ?

-What is the distribution of short period terrestrial planets ?

-Will we ‘dig’ as far considering the expected number of false transits at this phot

-If thresh

-What lie

-Does Harry Potter survive ?

~2 earth radius detections <u>possible</u>
but their number is tricky to estimate

~1 earth radius planets detections
‘<u>highly lucky</u>’

# Conclusion: simulating transit surveys

- Predict the yield of surveys (~100 planets for CoRoT)
- Estimate the number of false transits
  - discreditable in light curve
  - requiring RV follow-up (and how long)
  - couldn’t be confirmed
- Optimize the optimal settings for future surveys

- Test planetary formation/evolution models
- Understand planets distribution as a function of stellar characteristics
- Constrain formation, evaporation, migration conditions and limits

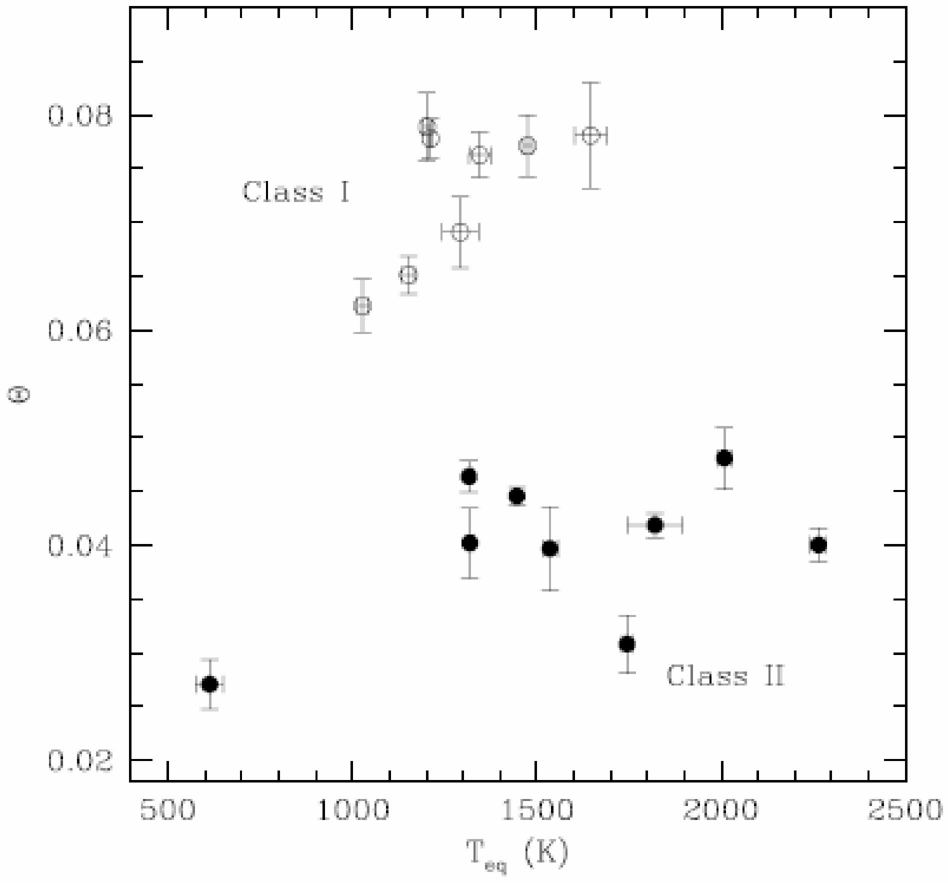


Fig. 3.— If we replace the gravity with the Safronov number Θ, we find that there are now two clear groups at fixed equilibrium temperature $T_{eq}$, apart from two outliers discussed in the text. We label them as 'Class I' (open points) and 'Class II' (solid points).

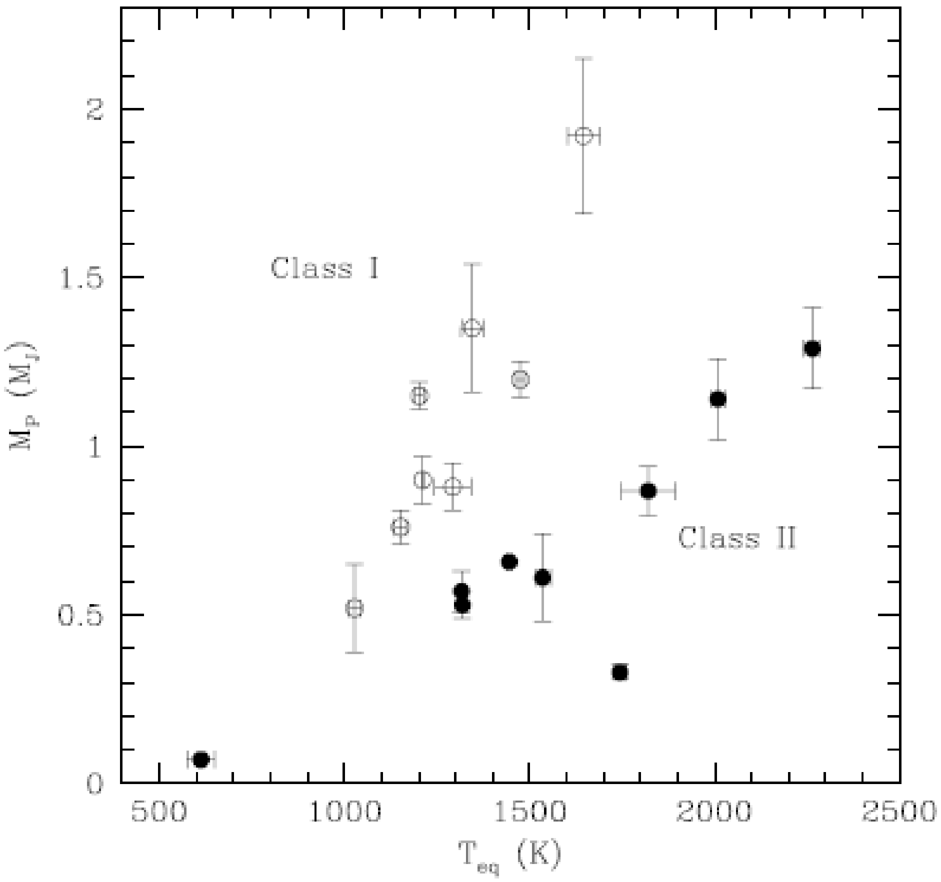
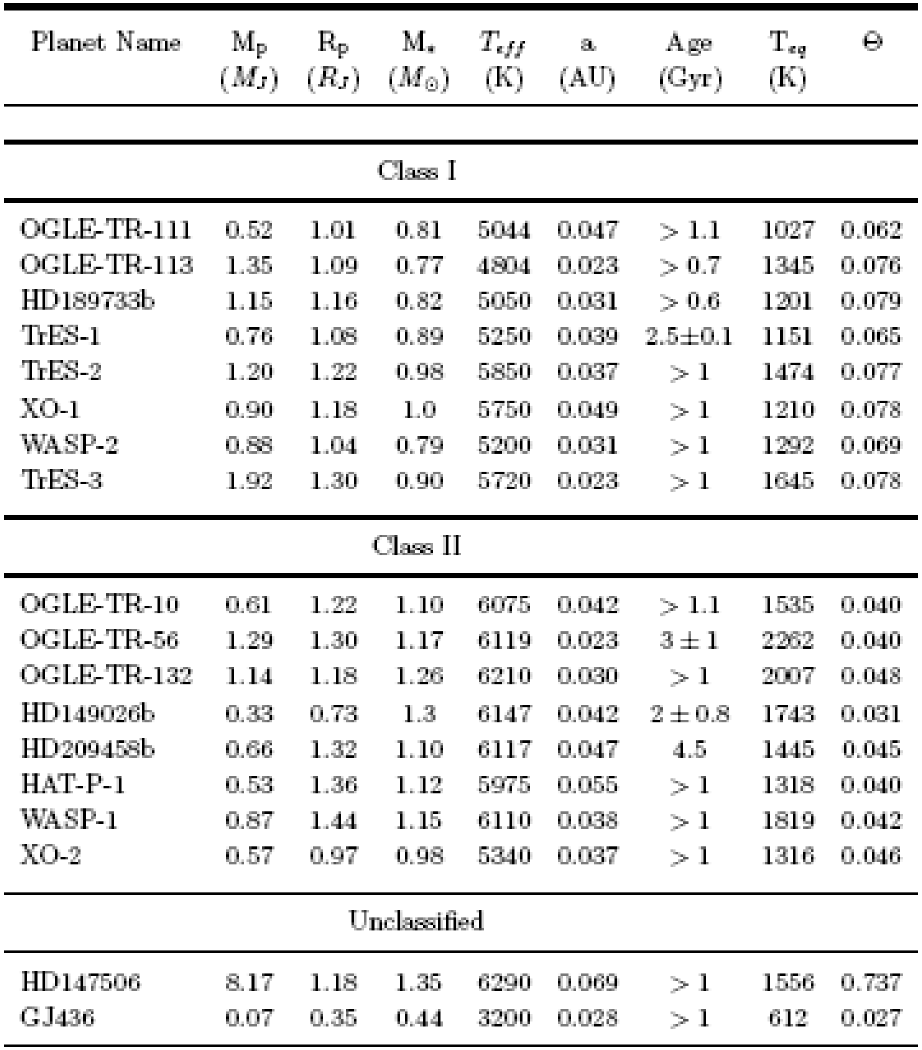


Fig. 5.— Planet masses plotted against equilibrium temperatures. The two classes of planet both appear to obey an approximately linear relation with $T_{eq}$, but with slopes different by almost a factor of 3.

$$\Theta = \frac{1}{2}\left(\frac{V_{esc}}{V_{orb}}\right)^2 = \frac{a}{R_p}\frac{M_p}{M_*},$$

Vesc : escape velocity from the surface of the planet

Vorb : orbital velocity of the planet



| Planet Name | $M_p$ ($M_J$) | $R_p$ ($R_J$) | $M_*$ ($M_\odot$) | $T_{eff}$ (K) | a (AU) | Age (Gyr) | $T_{eq}$ (K) | $\Theta$ |
|---|---|---|---|---|---|---|---|---|
| | | | | Class I | | | | |
| OGLE-TR-111 | 0.52 | 1.01 | 0.81 | 5044 | 0.047 | $> 1.1$ | 1027 | 0.062 |
| OGLE-TR-113 | 1.35 | 1.09 | 0.77 | 4804 | 0.023 | $> 0.7$ | 1345 | 0.076 |
| HD189733b | 1.15 | 1.16 | 0.82 | 5050 | 0.031 | $> 0.6$ | 1201 | 0.079 |
| TrES-1 | 0.76 | 1.08 | 0.89 | 5250 | 0.039 | $2.5 \pm 0.1$ | 1151 | 0.065 |
| TrES-2 | 1.20 | 1.22 | 0.98 | 5850 | 0.037 | $> 1$ | 1474 | 0.077 |
| XO-1 | 0.90 | 1.18 | 1.0 | 5750 | 0.049 | $> 1$ | 1210 | 0.078 |
| WASP-2 | 0.88 | 1.04 | 0.79 | 5200 | 0.031 | $> 1$ | 1292 | 0.069 |
| TrES-3 | 1.92 | 1.30 | 0.90 | 5720 | 0.023 | $> 1$ | 1645 | 0.078 |
| | | | | Class II | | | | |
| OGLE-TR-10 | 0.61 | 1.22 | 1.10 | 6075 | 0.042 | $> 1.1$ | 1535 | 0.040 |
| OGLE-TR-56 | 1.29 | 1.30 | 1.17 | 6119 | 0.023 | $3 \pm 1$ | 2262 | 0.040 |
| OGLE-TR-132 | 1.14 | 1.18 | 1.26 | 6210 | 0.030 | $> 1$ | 2007 | 0.048 |
| HD149026b | 0.33 | 0.73 | 1.3 | 6147 | 0.042 | $2 \pm 0.8$ | 1743 | 0.031 |
| HD209458b | 0.66 | 1.32 | 1.10 | 6117 | 0.047 | 4.5 | 1445 | 0.045 |
| HAT-P-1 | 0.53 | 1.36 | 1.12 | 5975 | 0.055 | $> 1$ | 1318 | 0.040 |
| WASP-1 | 0.87 | 1.44 | 1.15 | 6110 | 0.038 | $> 1$ | 1819 | 0.042 |
| XO-2 | 0.57 | 0.97 | 0.98 | 5340 | 0.037 | $> 1$ | 1316 | 0.046 |
| | | | | Unclassified | | | | |
| HD147506 | 8.17 | 1.18 | 1.35 | 6290 | 0.069 | $> 1$ | 1556 | 0.737 |
| GJ436 | 0.07 | 0.35 | 0.44 | 3200 | 0.028 | $> 1$ | 612 | 0.027 |

$$\Theta = \frac{1}{2}\left(\frac{V_{esc}}{V_{orb}}\right)^2 = \frac{a}{R_p}\frac{M_p}{M_*},$$

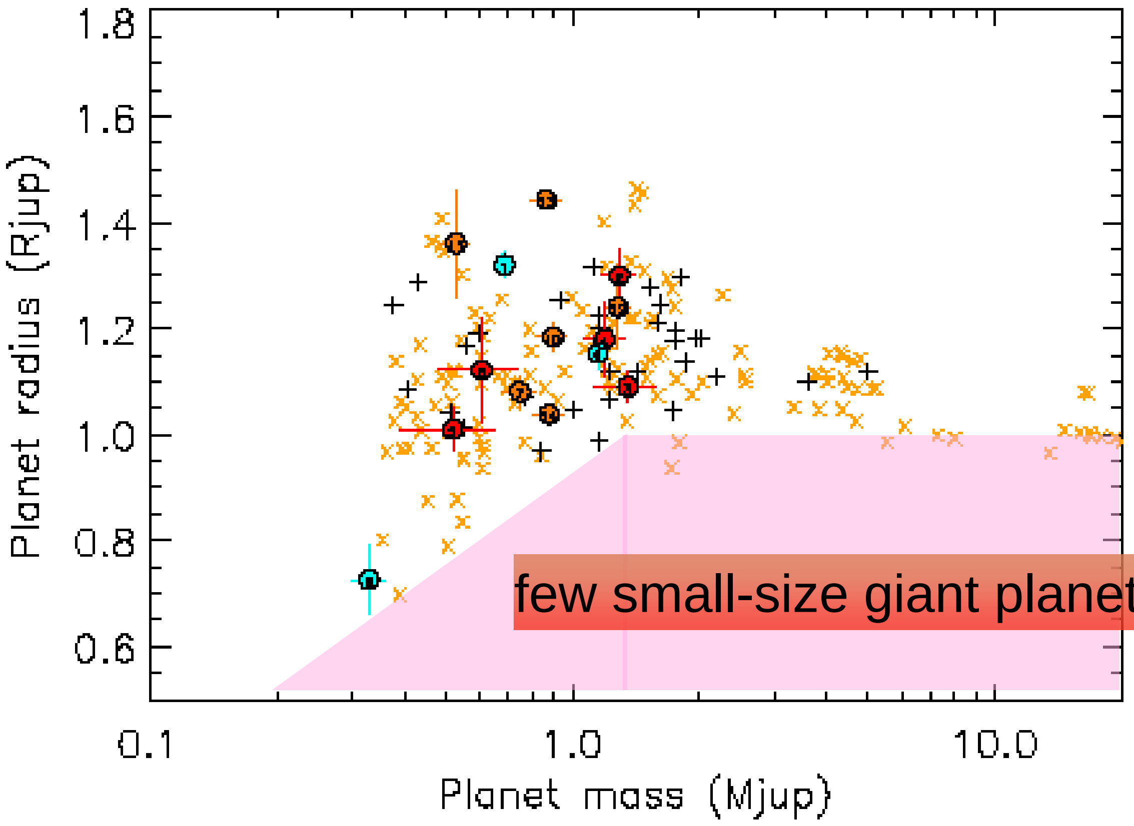
Vesc : escape velocity from the surface of the planet

Vorb : orbital velocity of the planet

1 - Safronov number, which essentially measures the efficiency with which a planet scatters other bodies, plays an important role in determining when a planet halts its migration.

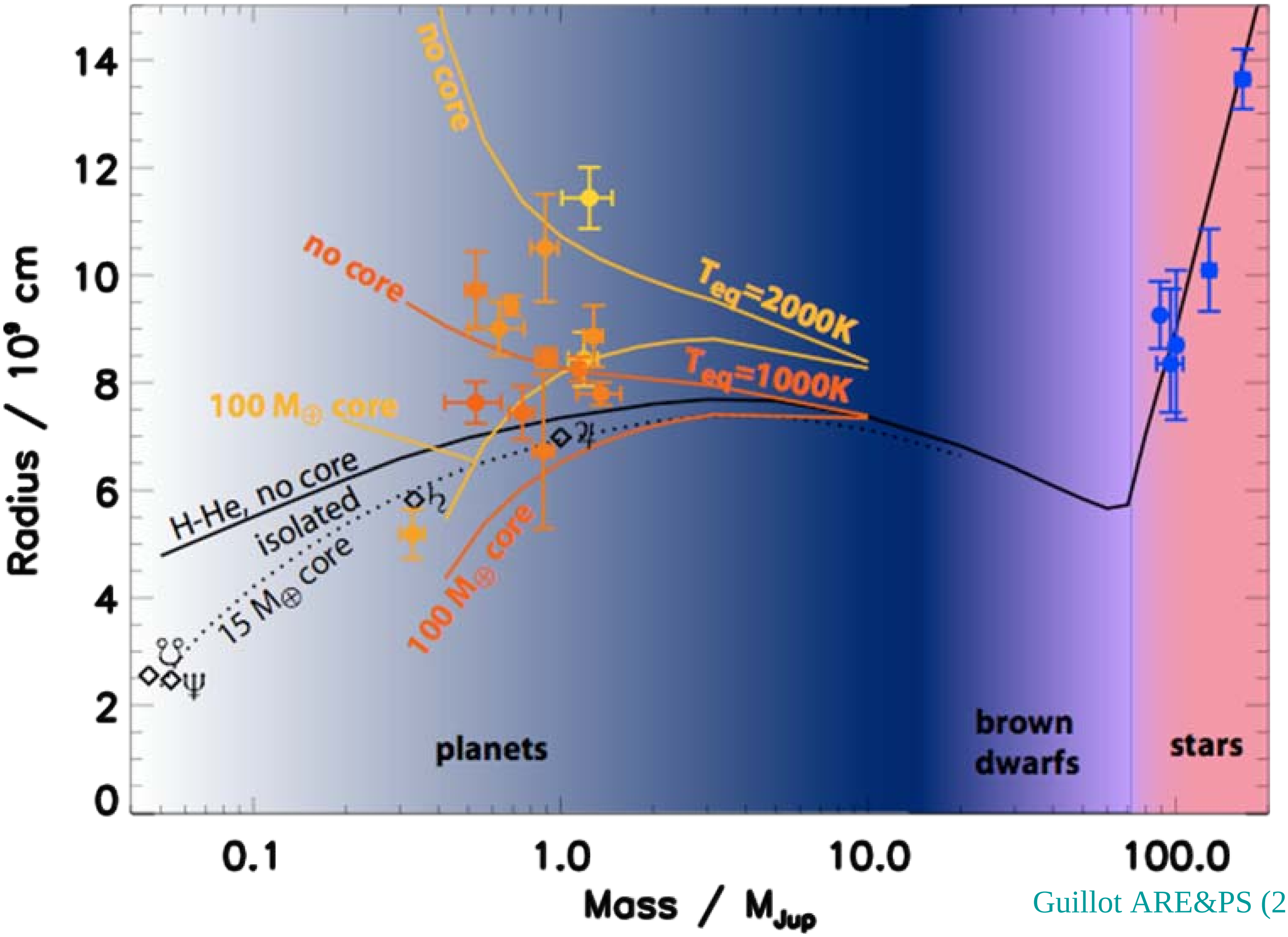
2 - difference in  is a consequence of the fact that some of the planets have lost a markedly larger fraction of their mass through some form of evaporation. This scenario requires that many of the Class II planets lose  50–60% of their initial mass.

# Mass-radius diagram for transiting planets



few small-size giant planets are expected

# Mass-radius relations



Guillot ARE&PS (2005)