Detection and Characterization of Extra-Solar Planets

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ESO Fellow Symposium

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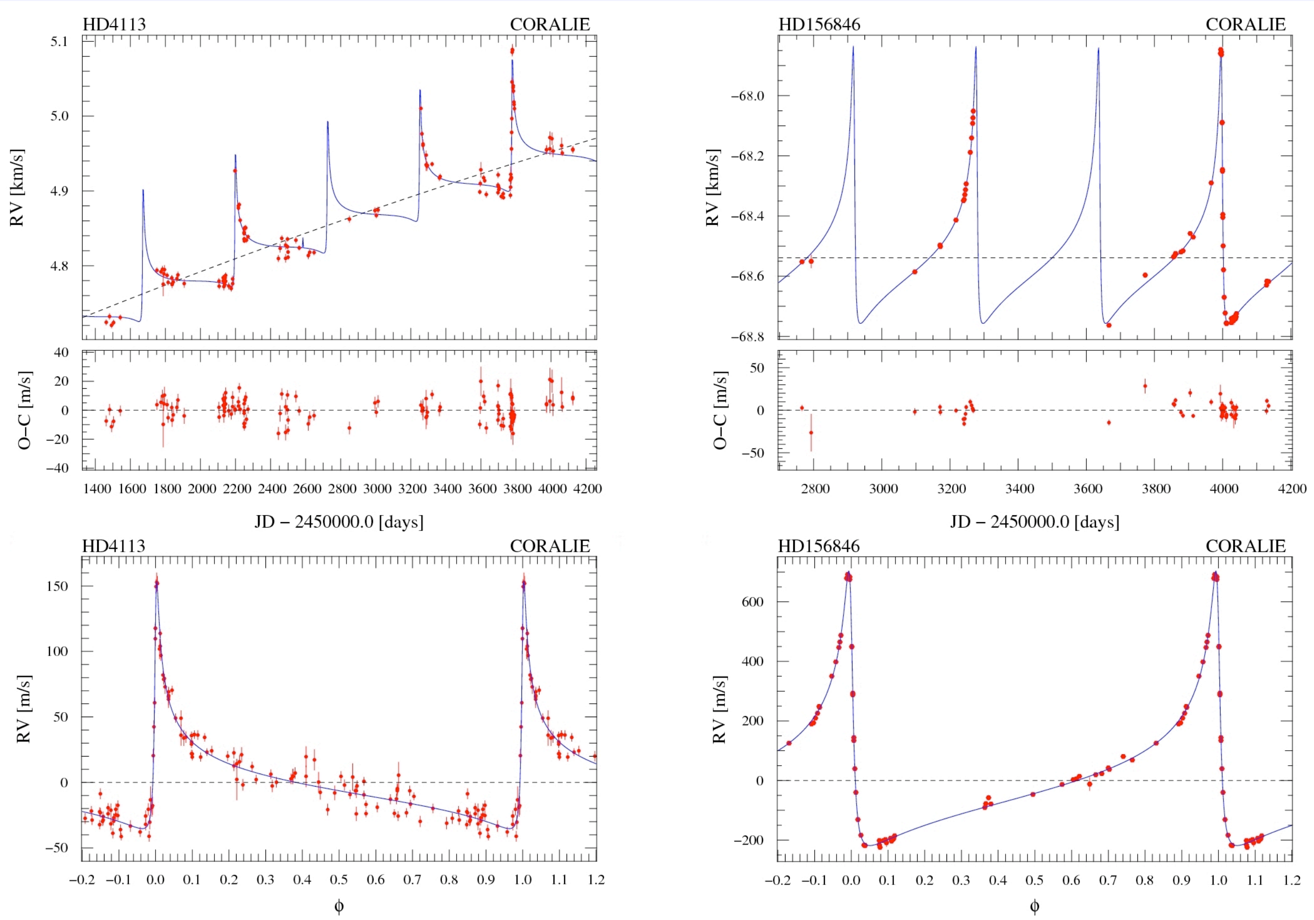
Outline

- **Radial-velocity (RV) planet searches**
- **RV detection bias**
- **Exoplanet population synthesis**

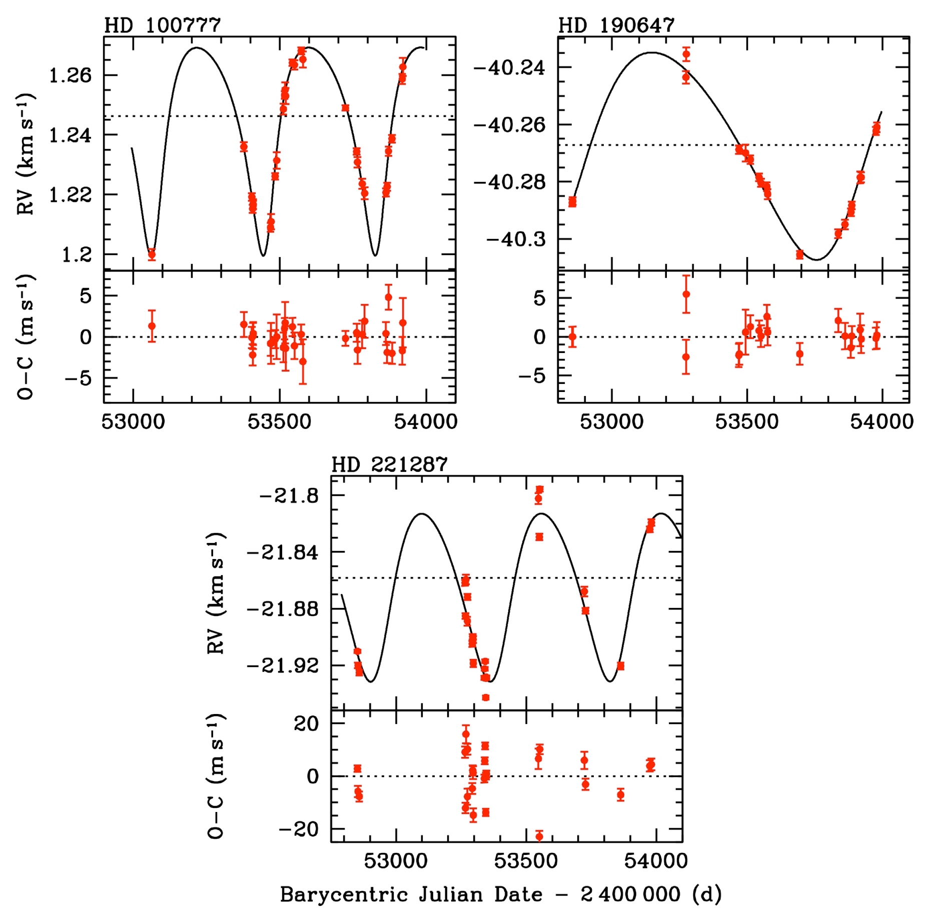
Coralie Planet Search



Tamuz et al. 2007, A&A in press

- **Started in 1998**
- **CORALIE echelle spectrograph @ La Silla 1.2-m Swiss Telescope**
- **Volume limited sample of 1650 Solar-type stars**
- **Also searching for planets around field and open-cluster giants**
- **Instrument recently refurbished : 5 times more efficient and expected improved RV precision**
- **Precision : $\simeq 2\,\mathrm{m\,s}^{-1}$**
- **About 40 exoplanets found so far**
- **CoRoT RV follow-up**
- **superWASP RV follow-up**

HARPS-GTO Planet Search



Naef et al. 2007, A&A 470, 721

- Started in 2003
- HARPS @ La Silla 3.6-m Telescope
- Precision : better than 1 m s^{-1}
- Programmes :
  - ⋆ Extreme RV precision programme. Ex : the μ Arae system, Pepe et al. 2007, A&A 462, 769
  - ⋆ Extension of the CORALIE volume limited sample : 800 additional stars. Ex : HD 212301 b, Lo Curto et al. 2006, A&A 451, 345
  - ⋆ Planets around M-dwarfs : Ex : the Gl 581 system, Udry et al. 2007, A&A 469, L43
  - ⋆ Planets around metal-poor stars : Ex : HD 171028 b, Santos et al. 2007, A&A 474, 647
  - ⋆ RV Follow-up of CoRoT candidates
- 25 exoplanets found so far
- Detected 9 (out of 14) exoplanets with minimal masses below 20 $M_{\rm Earth}$

Radial-velocity detection bias : Numerical simulations

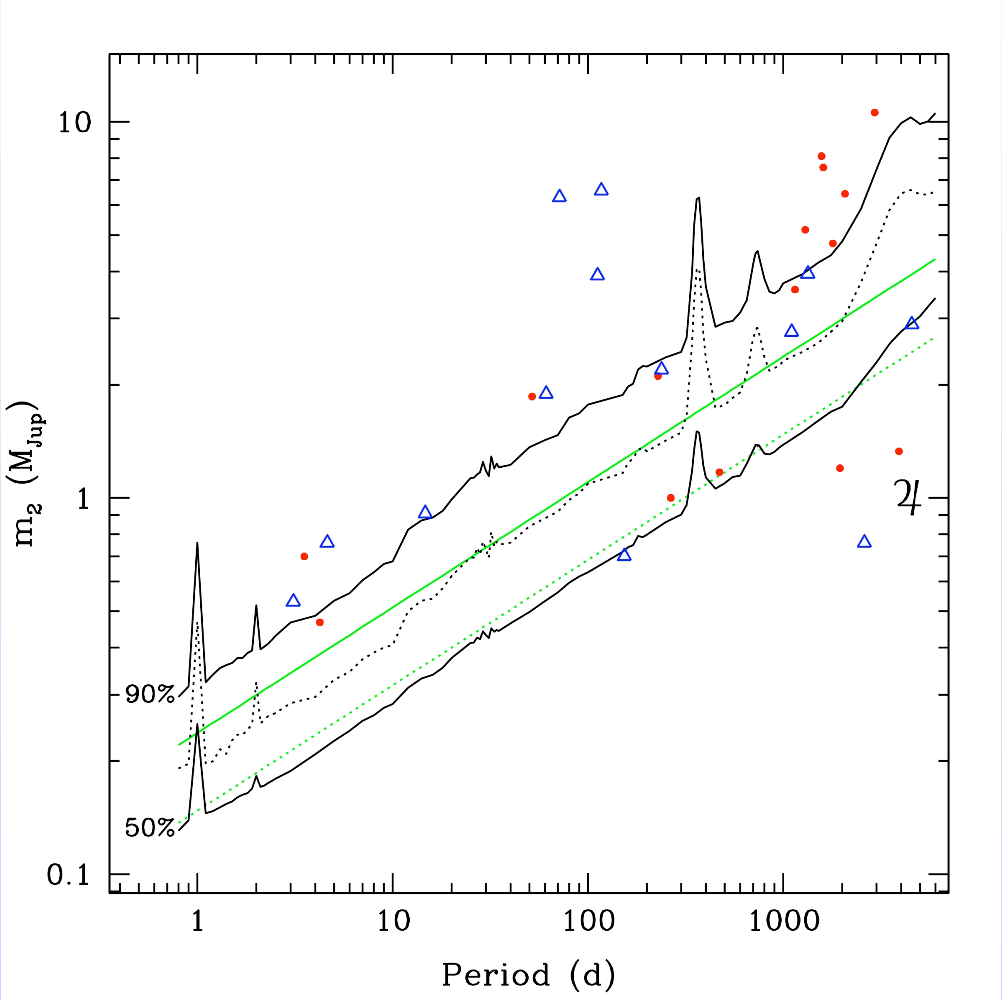
- Grid in the m_2 versus P diagram (more than 5000 grid points)
  - $0.8 \leq P \leq 40\,000$ days
  - $1\ \mathrm{M}_{\mathrm{Earth}} \leq m_2 \leq 40\ \mathrm{M}_{\mathrm{Jup}}$

- For each grid points, 50 000 random orbits are simulated
- The simulations account for :
  - all the error sources : photonic and non-photonic (such as stellar-activity induced jitter, instrument systematics)
  - the stellar sample properties (masses, colours, metallicities, rotation etc...)
  - Random inclination of the orbital planes → probability density $\propto \sin i di$
  - Orbital eccentricities
  - Real measurement timing

- A detection test is made for each of the 50 000 simulated orbits : test based on χ^2 probability

- Fraction of orbits passing the test = Detection probability for this grid point

Radial-velocity detection bias : Results



Exoplanet population synthesis : foreword

- A Bern (W. Benz, C. Mordasini & Y. Alibert) – ESO (D. Naef) collaboration

- Same approach as the pioneer work of Ida & Lin : ApJ 604, 388 (2004) & ApJ 626, 1045 (2005)

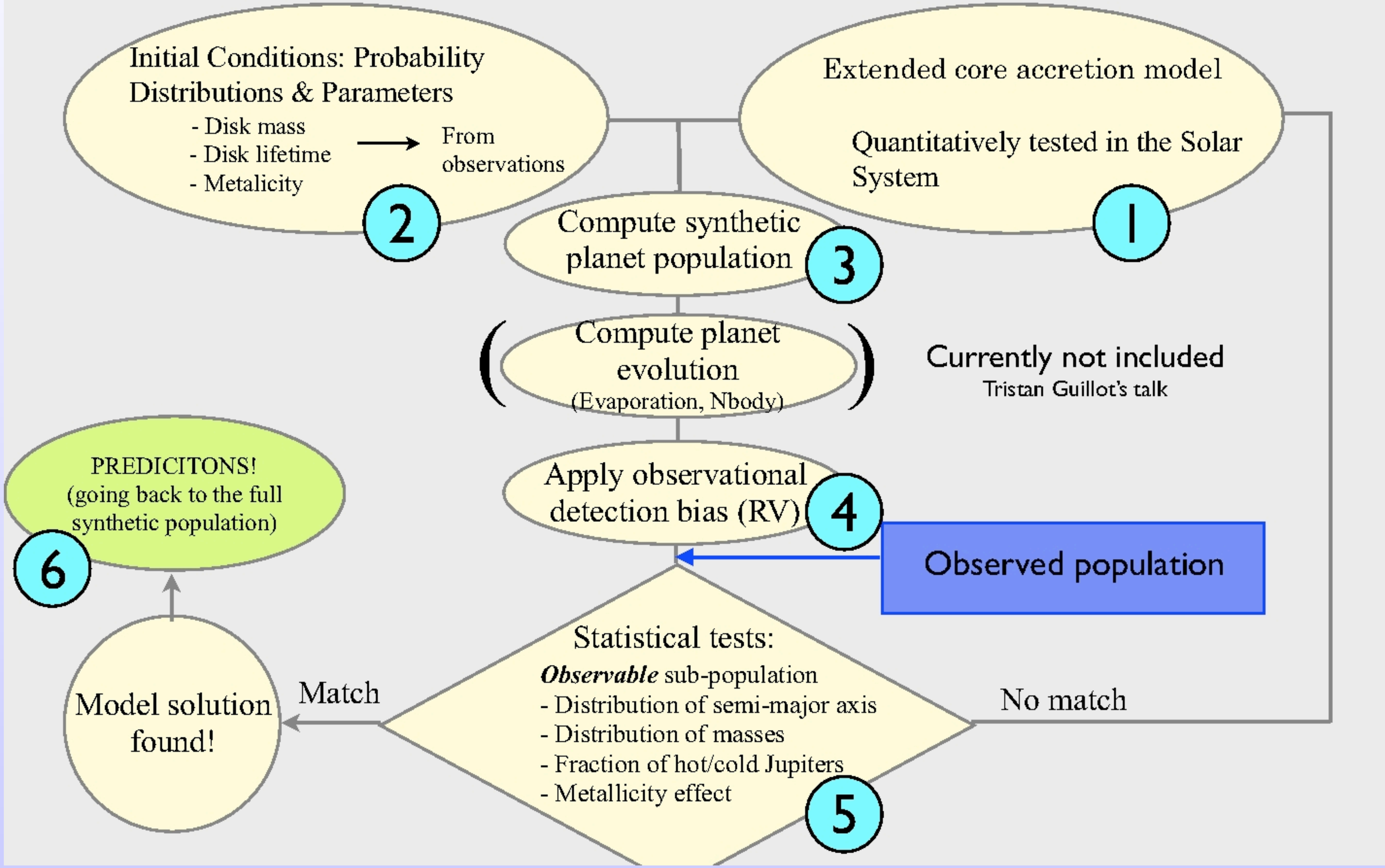
- Preliminary/intermediate results already presented in several conference papers : Benz et al. (2006,2007) & Mordasini et al. (2006, 2007)

- Final results to be published (hopefully) soon in Mordasini, Alibert, Benz & Naef (A&A paper(s) in prep.)

- Next slides kindly provided by C. Mordasini (from his talk at the JENAM meeting, Aug. 2007)

Population synthesis: Principle (& Talk outline)

In general, extra-solar planets do not constrain planet formation models much on an individual basis. It is the properties of the population as a whole that does!



Initial Conditions: Probability Distributions & Parameters
- Disk mass
- Disk lifetime
- Metalicity

→ From observations

②

Extended core accretion model

Quantitatively tested in the Solar System

①

Compute synthetic planet population ③

(Compute planet evolution (Evaporation, Nbody))

Currently not included
Tristan Guillot's talk

Apply observational detection bias (RV) ④

Observed population

Statistical tests:

Observable sub-population
- Distribution of semi-major axis
- Distribution of masses
- Fraction of hot/cold Jupiters
- Metallicity effect

⑤

No match

Match

Model solution found!

PREDICITONS!
(going back to the full synthetic population)

⑥

Linking Initial Cond. and End-Products: Core Accretion Formation Model II

- Model structure ("Extended core accretion model")

1) "Standard" core accretion model (Pollack et al. 1996) for core and envelope growth
but....

$\tau_{\text{migration}} \leq \tau_{\text{formation}} \approx \tau_{\text{disk evolution}}$

→ extend model to include in a self consistent way:

2) Disk evolution
(1+1 D) α-disk with photoevaporation (Papaloizou & Terquem 1999)

3) Type I and type II planetary migration
(Lin & Papaloizou 1986; Ward 1997; Tanaka et al. 2002)

- Basic assumptions

1) Only one embryo per disk, no systems !!

2) Formation followed only until the disk disappears: Evolution after disk dispersal (Terrestrial planets, Ice giants) not included !!

3)No eccentricity, planets are on circular orbits !!

4) Planets migrate until the disk disappears: no particular stopping mechanism !!

Population Synthesis: Initial conditions

Some can be constrained by observations, some from theoretical arguments and
some are just “educated” guesses.

- Four Monte Carlo Variables with Probability Distributions:

  1. Dust-to-gas ratios: Constrained by observed Stellar Metallicities
  2. Gas surface densities: Constrained by observed Disk Masses
  3. Photoevaporation rates: Constrained by observed Disk Lifetimes
  4. Initial location of embryo in the disk

- Parameters (fixed for one synthetic population)

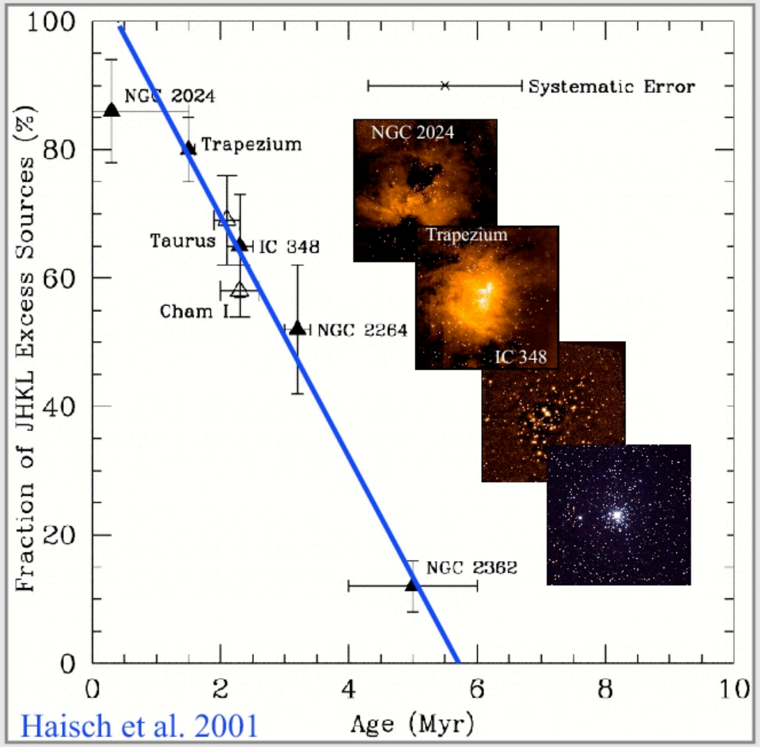
  - Type I migration rate reduction factor F_1
  - Disk viscosity parameter α (0.01)
  - Initial mass of seed embryo (0.6 M_{Earth})
  - Planetesimal size (R=100 km)
  - Planetesimal properties (Density, Strength, etc.)
  - Stellar mass (0.5, 1.0, 1.5 M_{Sun})
  - Scaling of disk mass with stellar mass ($\propto M_{star}$, $\propto M_{star}^{1.2}$)

Probability Distribution III: Disk Lifetime

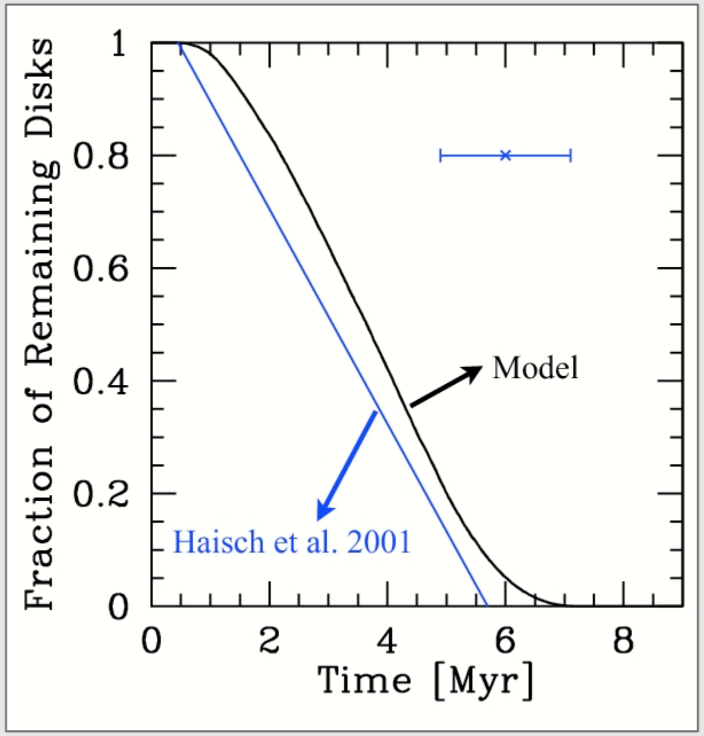
L-band (3.4 μm) photometry:
- excess caused by μ-sized dust @ ~900K

- Disk photoevaporation rate
- Viscosity parameter (α) (fixed)

} Disk lifetime



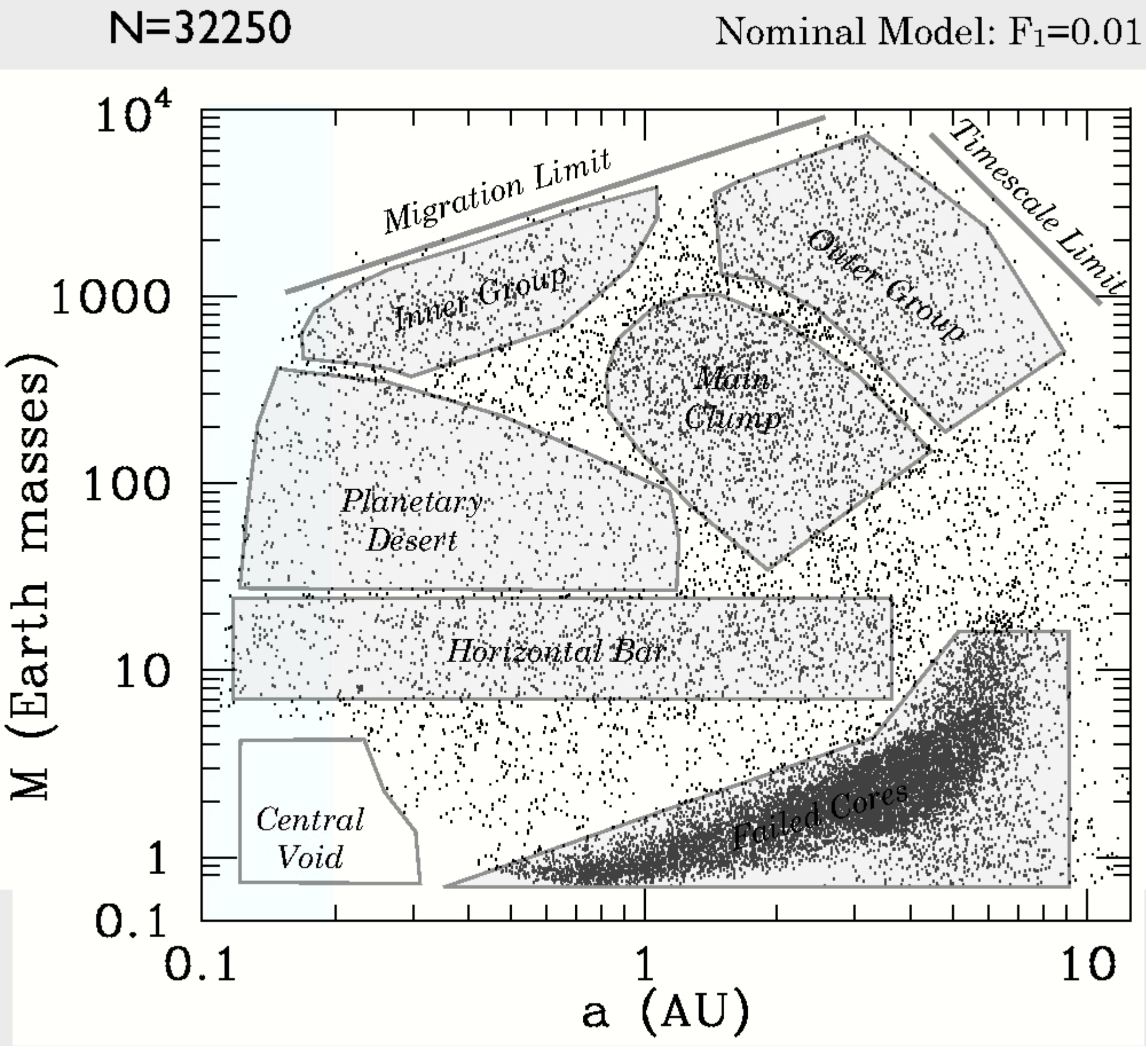
Haisch et al. 2001



Giant planets must form within 4-6 Myr

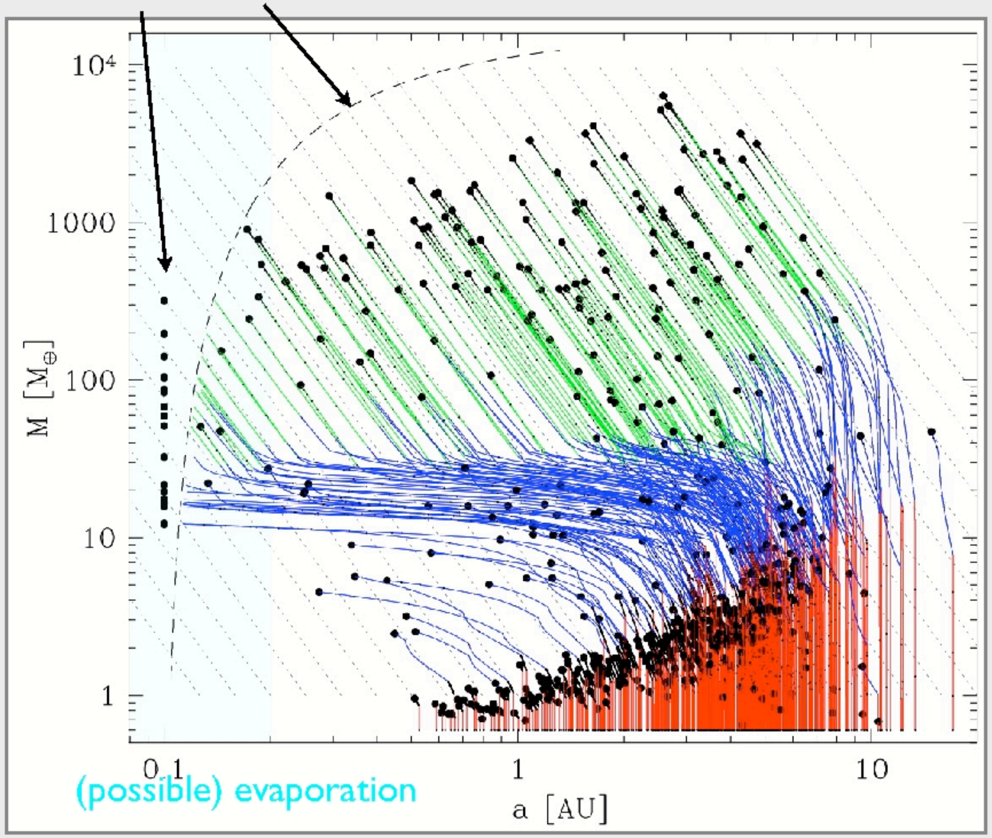
Adjust the distribution of photoevaportion rates to obtain a distribution of lifetimes of the synthetic disks that is compatible to the observed disk lifetime distribution.

Synthetic Population: a-M (around G stars)



- *Indeed, just the variation of the IC produces very, very different planets.*
- *Many low mass planets (Failed cores)*
- *Horizontal bar: Migrating cores to form Hot Neptunes*
- *Main Clump at 1-2 AU, Jovian Mass*
- *Planetary desert (Ida & Lin 2004): not so empty & outer boundary at 1 AU*
- *Migration limit: M_{max} increases with a out to 3 AU (Udry et al. 2003)*
- *Absence of very massive planets far out (Timescale limit)*
- *Absence of M<5 & a<0.2 (central void). Late time formation could fill it.*
- *Separation of types in a/m (Inner, outer group)*

Population synthesis literally: Planetary evolution tracks



Reached inner boarder of computational disk

(possible) evaporation

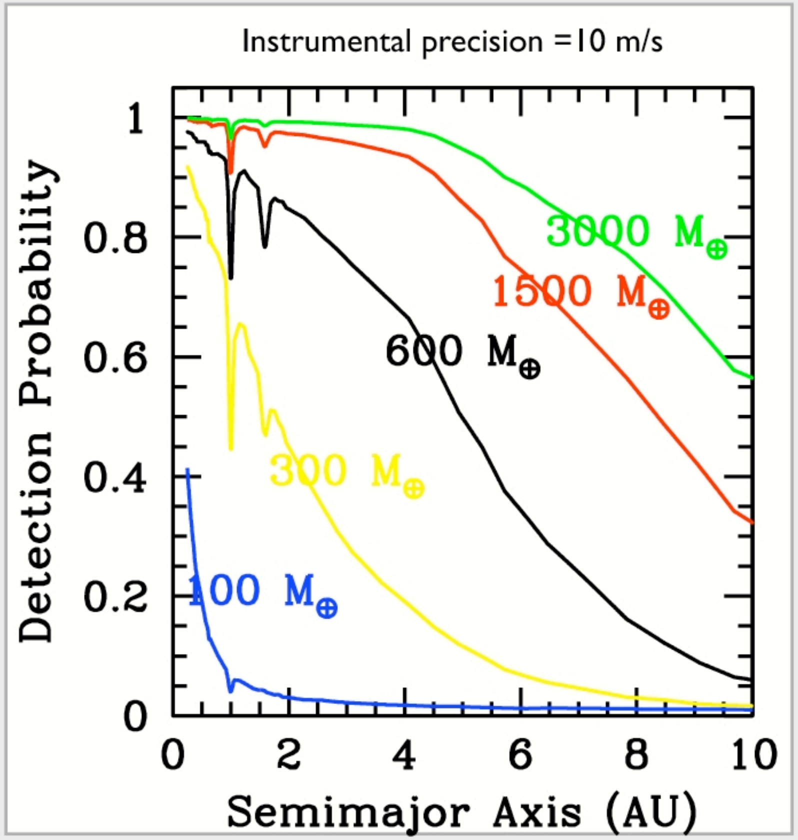
M_{star}=1 M_{sun}
Nominal Model: F_I=0.01

Type I migration
(Analytical rate reduced by F_I)

Type II migration
(Disk dominated)

Type II migration
(Planet dominated, when mass of planets becomes comparable to local disk mass)

Synthetic detection bias I: Radial Velocity


Instrumental precision =10 m/s

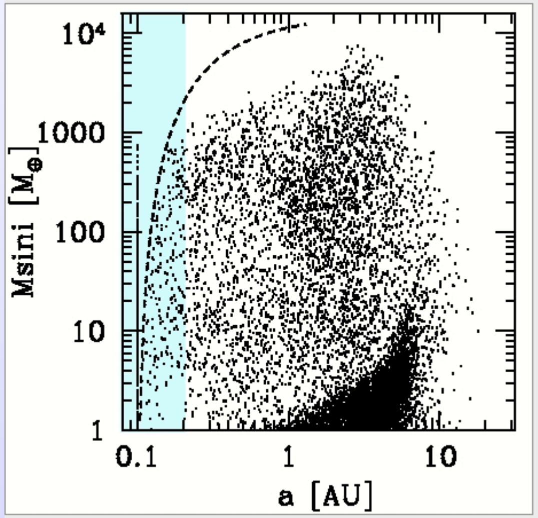
Naef et al. 2004

Includes effects of
- Orbital eccentricity
- Stellar metallicity
- Stellar rotation rate
- Stellar jitter
- Actual measurement schedule

Real RV detection probabilities are significantly lower than estimated from a simple comparison of the RV amplitude induced by the planet and the instrumental precision!

Statistical assessment I:
Kolmogorov-Smirnov test 2D a-Msini

Full synth. population



M_{star}=1 M_{sun}
Nominal Model (best statistic results): F_1=0.01

"Observe" 10 yrs at 10 m/s

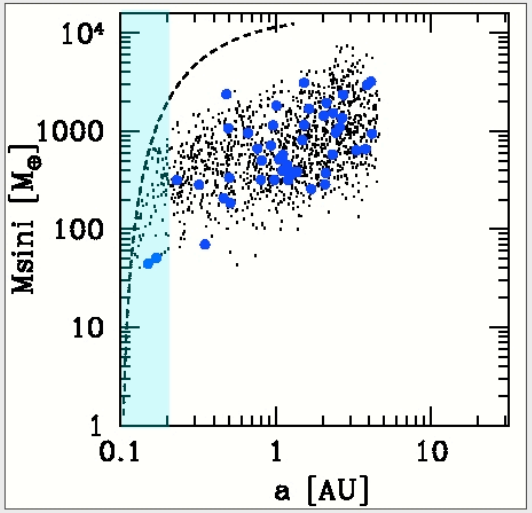
- Tip of the iceberg!!!
- Overall detection probability: 6.1 - 8.4 % (as obs.)

&

Observational comp. sample

- 0.8 < M_{star} < 1.2
- e < 0.6
- One planet / star
- Single host stars
- K>10 m/s

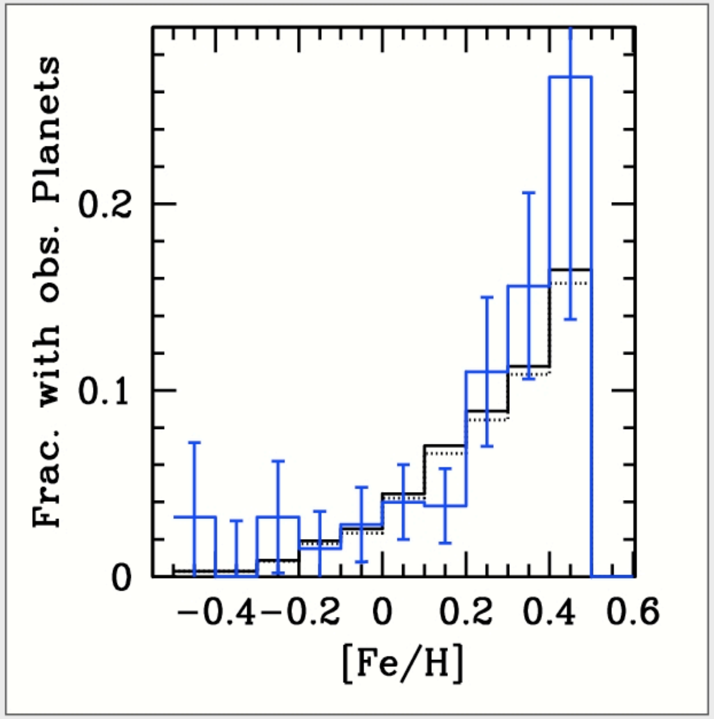
Observable sub-population



KS a-Msini: 54%

- *The extended core accretion model is a reasonable match to RV data*

Statistical assessment III: "Metallicity effect"



cf. also Santos et al. 2004, 2005

Blue: Observation (Fischer & Valenti 2005)
Black: Observable synthetic planets

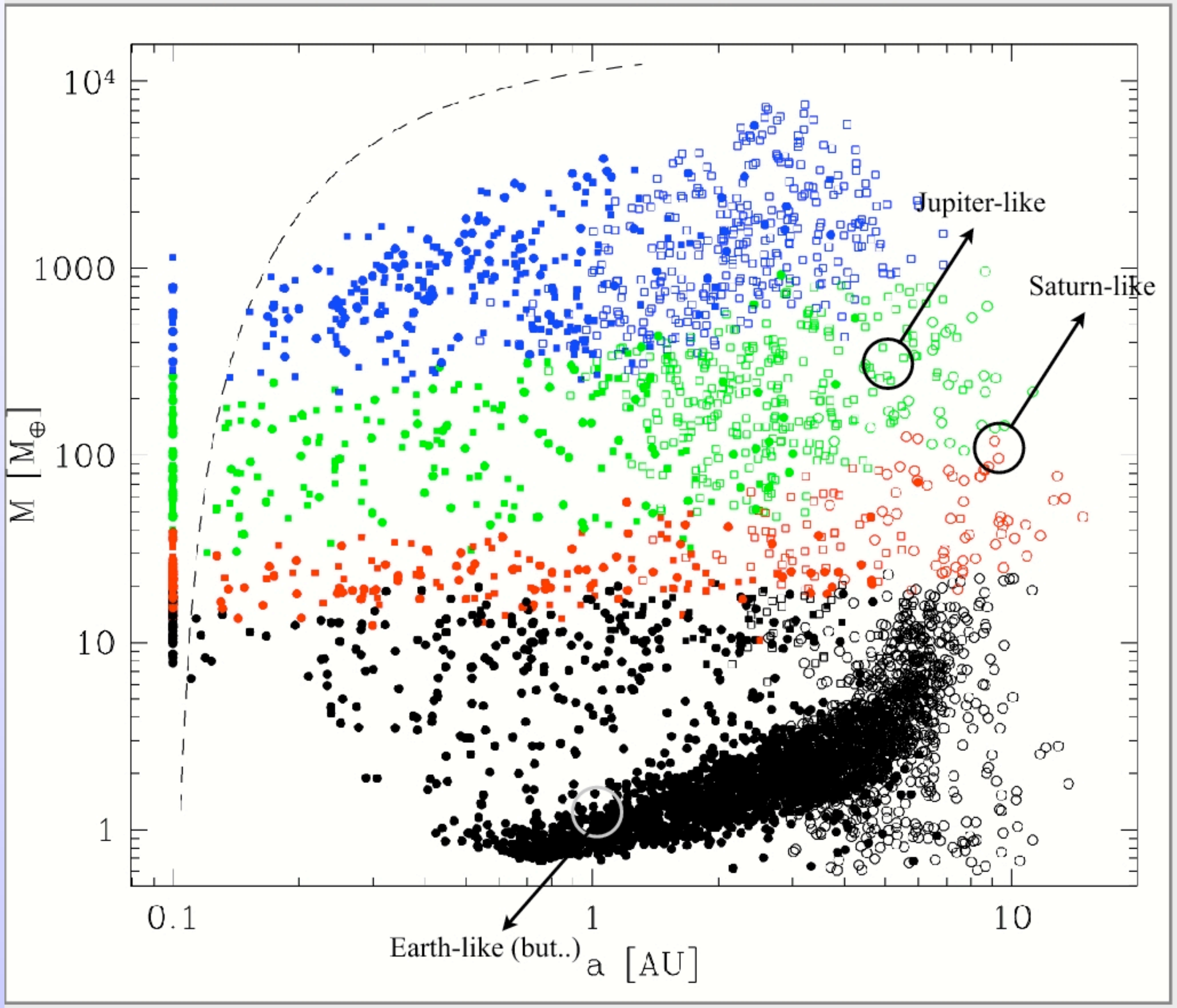
Large metallicity effect on RV detections

- Metal rich systems tend to produce more massive planets
- Radial velocity method favors massive objects

Predictions II: Internal Composition (G stars)

rocky planetesimals accreted
100% ● ● ● ●
> 50% ■ ■ ■ ■

icy planetesimals accreted
100% ○ ○ ○ ○
> 50% □ □ □ □



M_{star}=1 M_{sun}
Nominal Model (best statistic results): F_1=0.01

$M_{env} / M_{heavy} > 10.0$

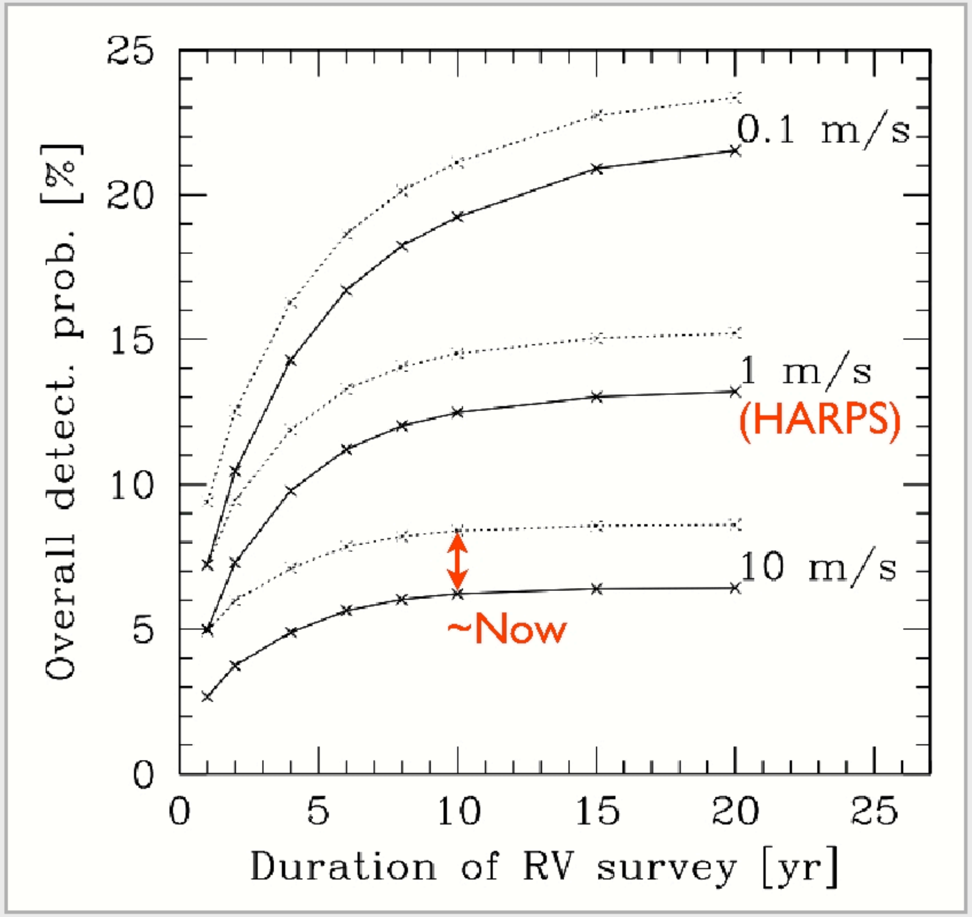
$1.0 < M_{env} / M_{heavy} \leq 10.0$

$0.1 < M_{env} / M_{heavy} \leq 1.0$

$M_{env} / M_{heavy} \leq 0.1$

- *Clear Horizontal Stratification in M_{env}/M_{heavy}*
- *(Partial) vertical separation in ice fraction (no empty symbols<0.5 AU, but some filled squares)*

Predictions VII: Yields of RV surveys



M_{star}=1 M_{sun}
Nominal Model: F_1=0.01

The higher the RV precision, and the longer the survey, the higher the yield.

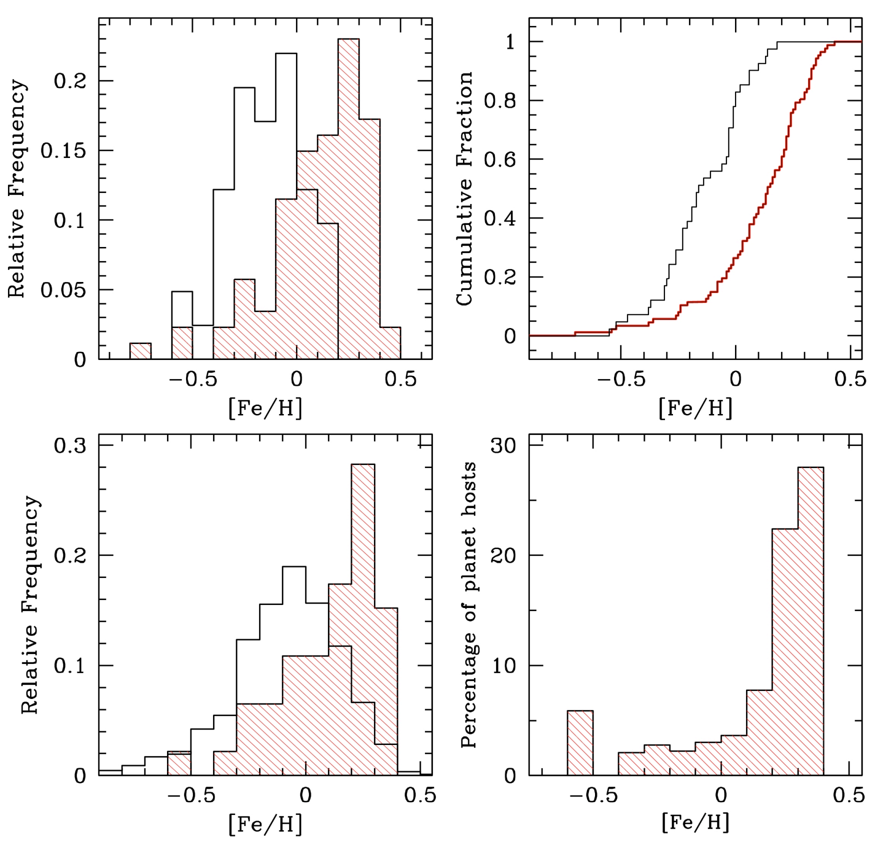
- *Leveling off after 10-20 yrs*
- *10 yrs at 10 m/s: 6-8%, as observed (Naef et al, Butler et al)*

Values for 0.1 m/s: Lower limits (model incompleteness)

Conclusions

- The progress in characterizing both the initial conditions for planet formation as well as finding more and more extrasolar planets has made a new test for theoretical models possible:
  - The comparison of synthetic populations and the real extrasolar planet population.
- Improved/extended core accretion models allow such quantitative tests with observations (gravitational instability model does not)
  - The whole population of detected planets can be used to constrain the models
    - No more model tuning for a specific case...
    - Fully exploit the observational investment !
- Improved/extended core accretion models *do* reproduce *many* observed properties & correlations in a *quantitative* significant way with *one* synthetic population at *one* time.
  - (Finally, hopefully) a certain convergence of theory and observations
- Improved/extended core accretion models can be used to predict future observations
  - Theory can feed back on the design of future instruments

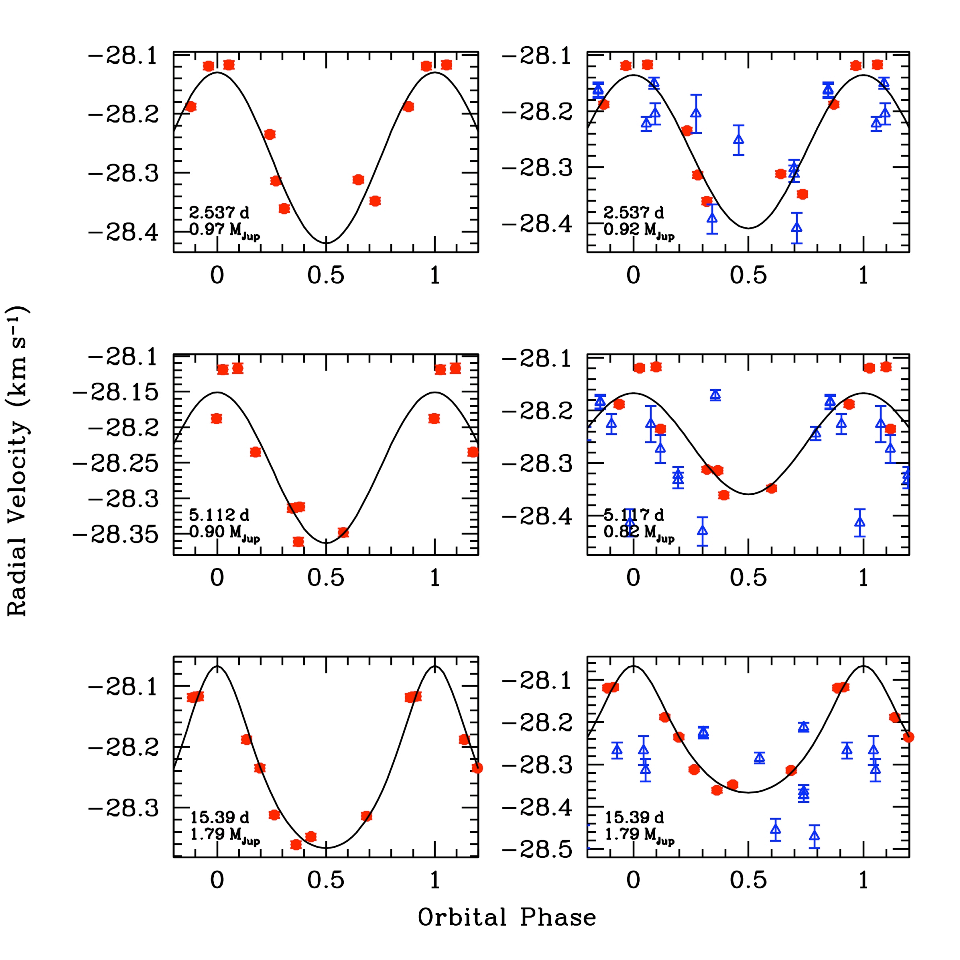
Why searching for planets in open clusters ?



Santos et al. 2004, A&A 415, 1153

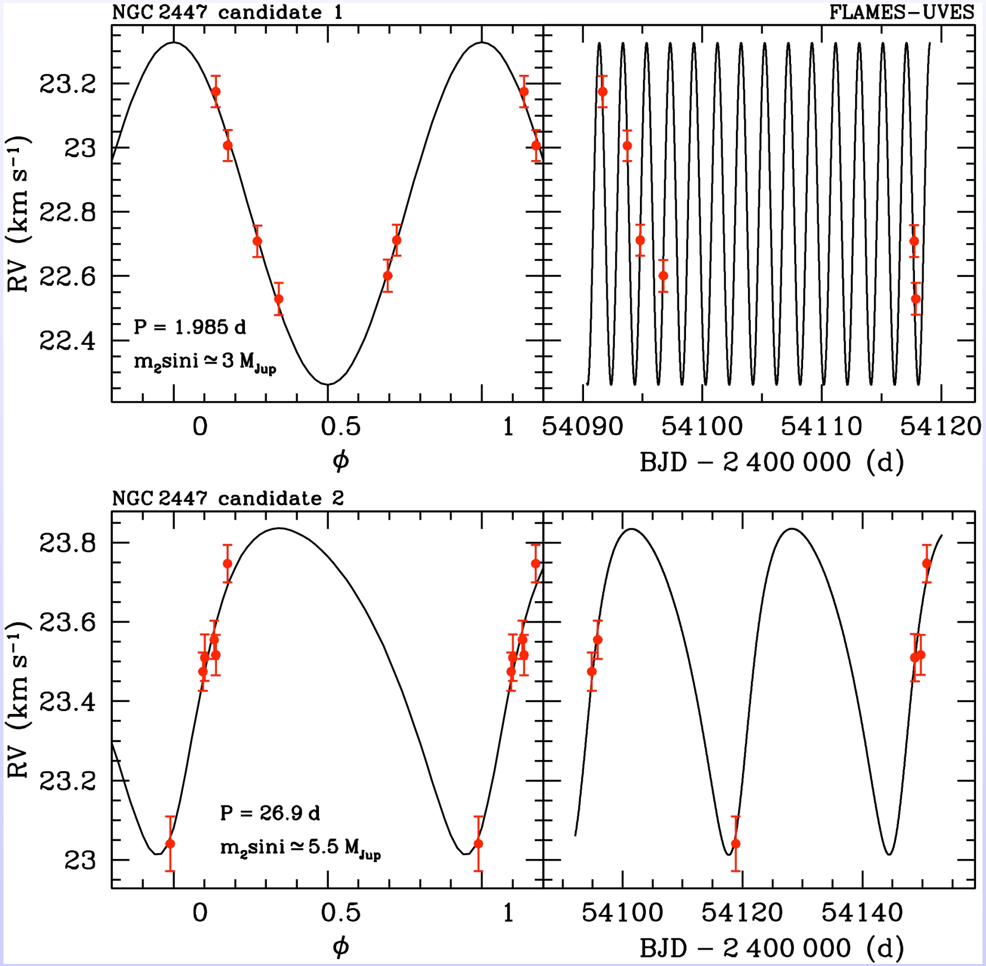
- Stars (only ?) form in clusters/associations → if field stars host planets, planets should also be found around cluster stars
- Open cluster : uniform stellar populations
- Age and metallicities are well defined and more or less constant within a cluster
- Mass = the only stellar evolution parameter → possibility to study the impact of stellar mass on planet caracheristics
- Is the [Fe/H] effect seen for field stars (cf. Santos et al. 2004) hosting planets also present in open clusters ?
- Unlike in the field, masses of evolved stars can be precisely estimated in clusters → possibility to search for planets around stars with higher (and well known determined) masses.
- To date, only 3 planets (or low-mass brown dwarfs) in open clusters are known : They orbit the giant stars ϵ Tau (Sato et al. 2007), NGC 2423 No 3 and NGC 4349 No 127 (Lovis & Mayor 2007). All 3 detected with the RV method.
- Many transit searches in open clusters. So far, no detection ! → ”cheap” but inefficient method (too few stars, largely underestimated systematics, ...)

Searching for planets in Open clusters : NGC 6253



- A **Geneva** (D. Queloz, PI) – **ESO** (C. Melo, D Naef) – **Porto** (N.C. Santos) collaboration
- Radial-velocity search using **FLAMES**@VLT & **HARPS**@La Silla 3.6-m Telescope
- **NGC 6253** : an **old** (5 Gyr) **super metal-rich** ([Fe/H]=0.36, i.e. 2.3 times Solar) open cluster
- Old cluster → non-active stars → **precise** RVs easier to obtain
- Metal-rich cluster → expected **high** fraction of stars with planets
- Several planets **candidates** identified using FLAMES data
- Limited RV precision of FLAMES → follow-up with HARPS mandatory to get reliable orbital solution
- HARPS follow-up of the best candidates started and still ongoing

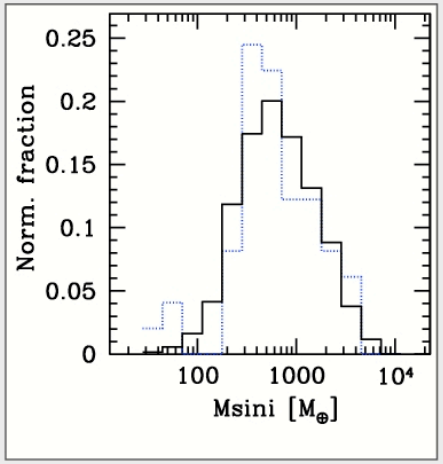
Searching for planets in Open clusters : NGC 2447 & NGC 6134



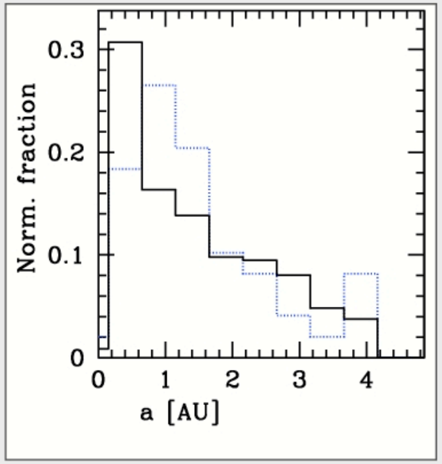
- A **Concepción** – **ESO** (D Naef, C. Melo, M. Sterzik) – **Geneva** collaboration
- PI : W. Gieren
- Radial-velocity search using **FLAMES**@VLT & (hopefully) **HARPS**@La Silla 3.6-m Telescope
- Clusters ages and metallicites well **complement** the programme on NGC 6253 :
  - ⋆ **NGC 2447** : age ≃390 Myr – [Fe/H]=0.03
  - ⋆ **NGC 6134** : age ≃930 Myr – [Fe/H]=0.18
- Intial target selection using photometry from the **Warsaw** 1.3-m Telescope (i.e. the OGLE telescope) @ Las Campanas
- Cluster **memberships** checked for both clusters and **binaries** idendified with FLAMES-GIRAFFE
- FLAMES-UVES RV follow-up of cluster members started in NGC 2447, several planet **candidates** identified but require a HARPS follow-up
- FLAMES-UVES RV follow-up in NGC 6134 not started yet

Statistical assessment II:
KS tests 1D Msini, a, [Fe/H]

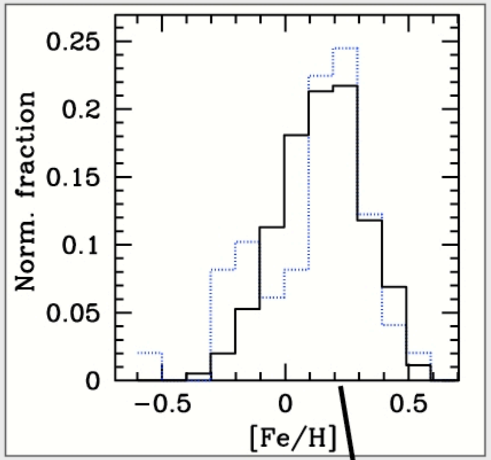
Mass Msini: KS 92%



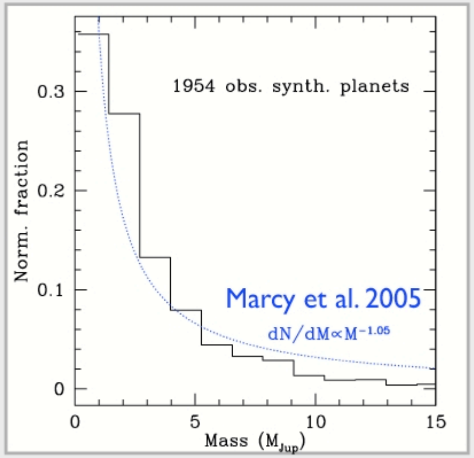
Semi. axis: KS 33%



[Fe/H]: KS 30%



Clear shift to higher Fe/H

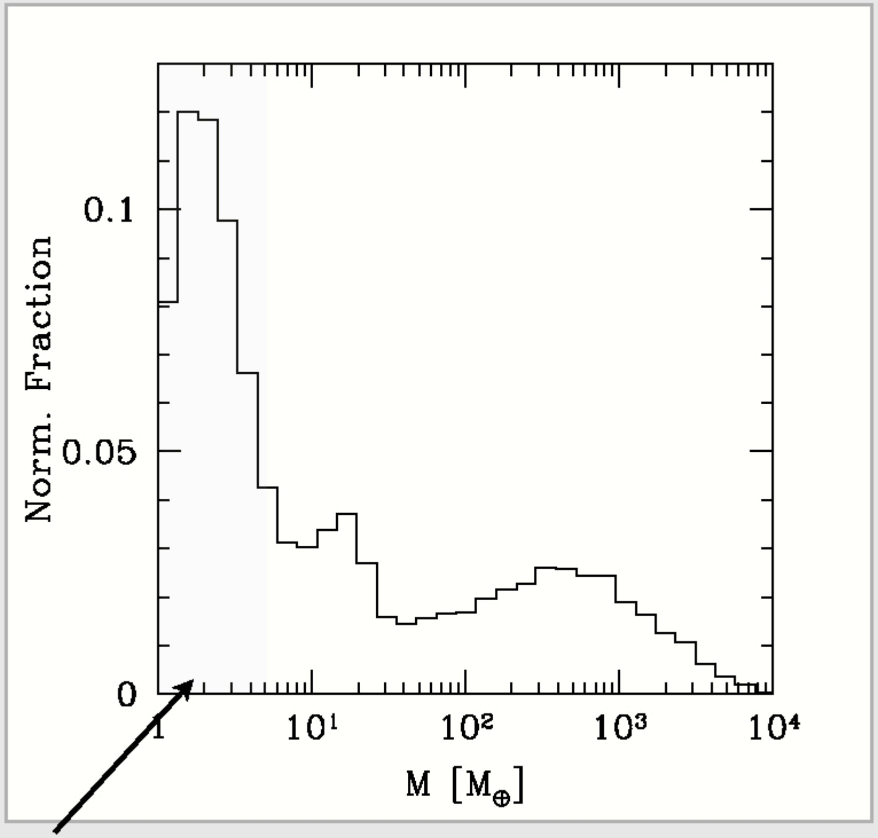


Blue lines: Observational comparison sample
Black lines: Observable synthetic sub-population

The mass distribution is better reproduced than the semi-major axis and [Fe/H| distribution

→ Migration model?
→ N-body interactions?
→ Too simplistic planetesimal disk model? (Kornet et al. 2005)

Predictions IV: Planetary IMF (around G stars)



Model incompleteness

M_{star}=1 M_{sun}
Nominal Model: F_1=0.01

Type	Range [$M_\oplus$]	%
Terrestrial	1-5	50.2
Super-Earth	5-10	7.6
Neptune	10-20	8.2
Intermediate	20-100	9.5
Jovian	100-500	12.2
Super-Jupiter	500-4323	11.8
D-Burning Pl.	>4323	0.5

1 $M_J \approx$ 318 $M_\oplus$

-Complex structure, dominated by low mass planets
→Consistent w. non-detection of Jupiters around 90-95%.
-Overall largest planetary mass: 4 planets(of 32250) w. 25-35 M_J