

How do most planets form?

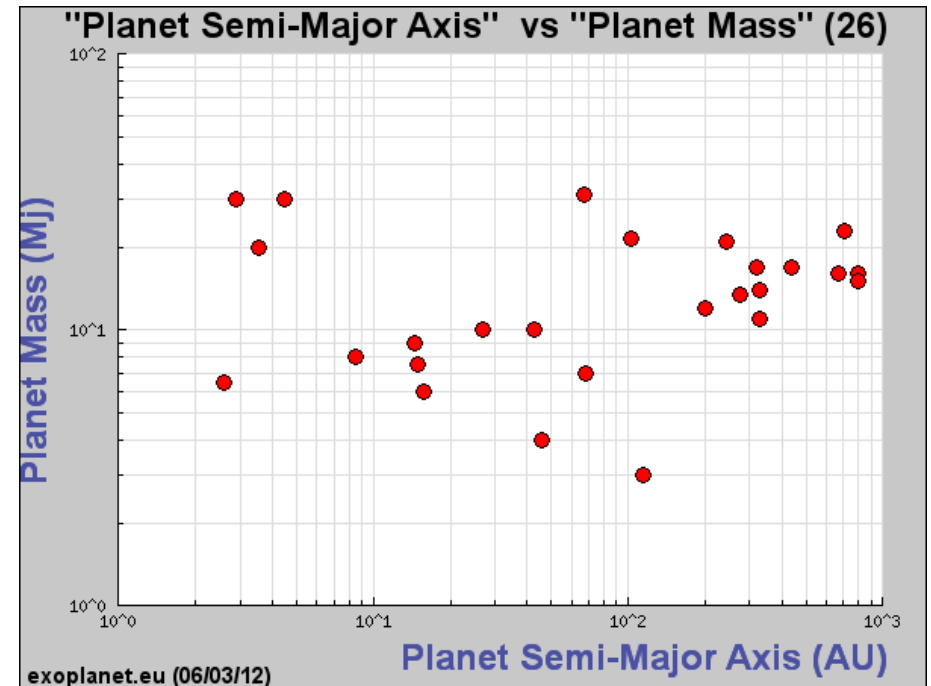
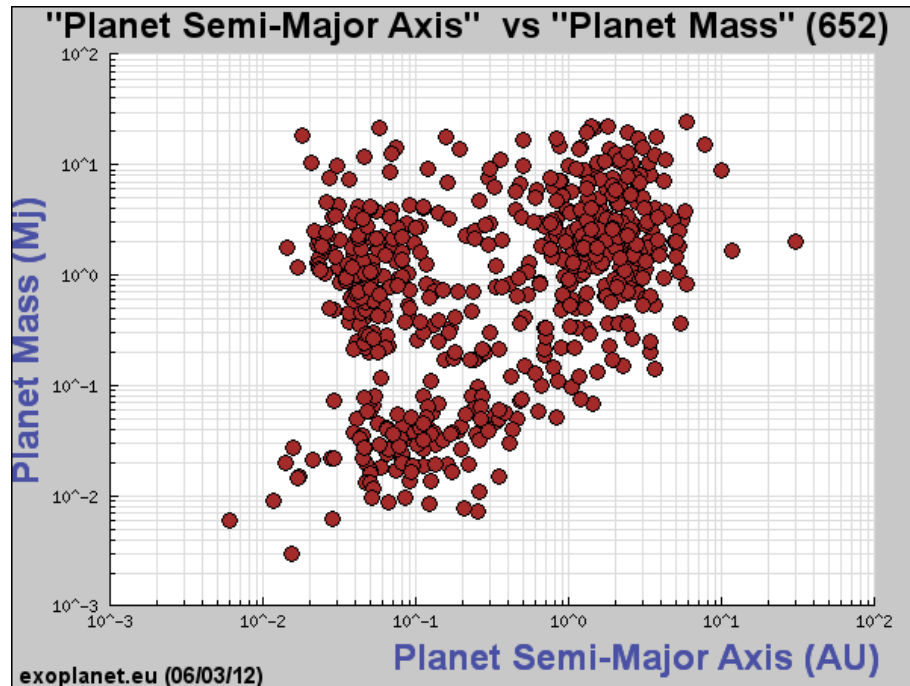
Constraints on disk instability
from Direct Imaging

M. Bonavita

M. Janson, H. Klahr, D. Lafreniere, R. Jayawardhana

Introduction

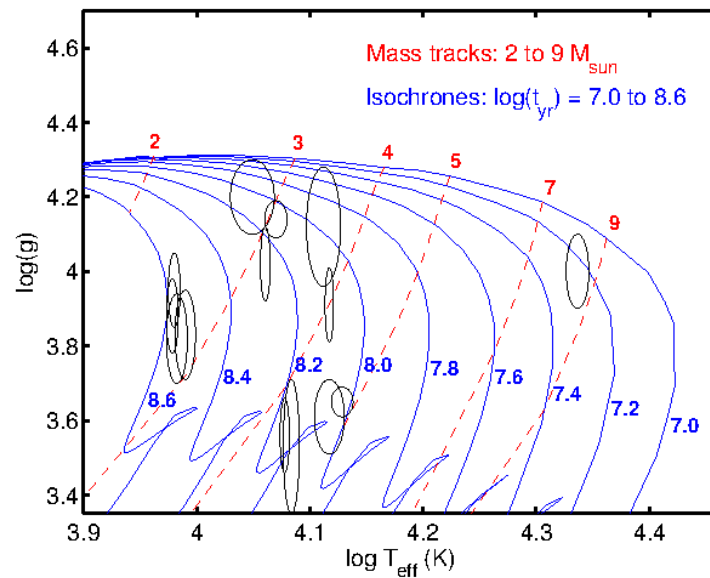
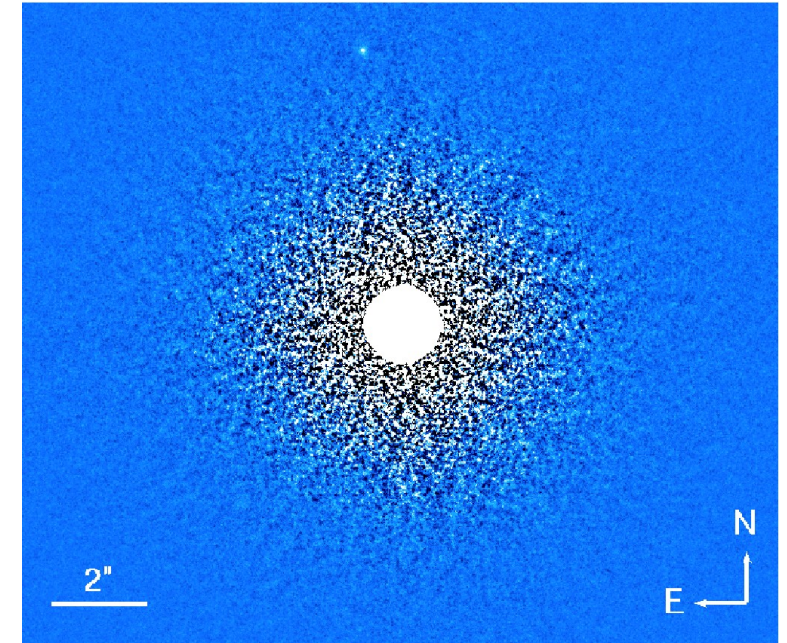
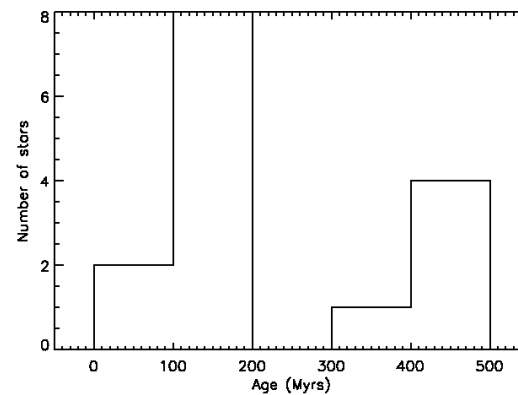
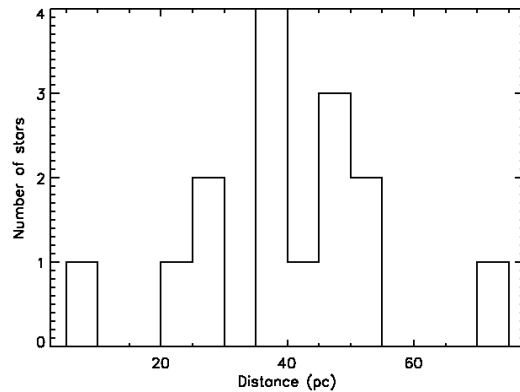
With the many hundreds of planet candidates from radial velocity and more than a thousand putative candidates from transits, the population of close-in (~ 1 AU) exoplanets is starting to be reasonably well characterized down to sub-Jovian masses. Less is known about the wide (>10 AU) population of planets, but the range is starting to be probed with direct imaging.



Core accretion seems to be the main formation mechanism for close-in planets,
but is that true for the total planet population?

Stellar Samples - I: Massive nearby stars

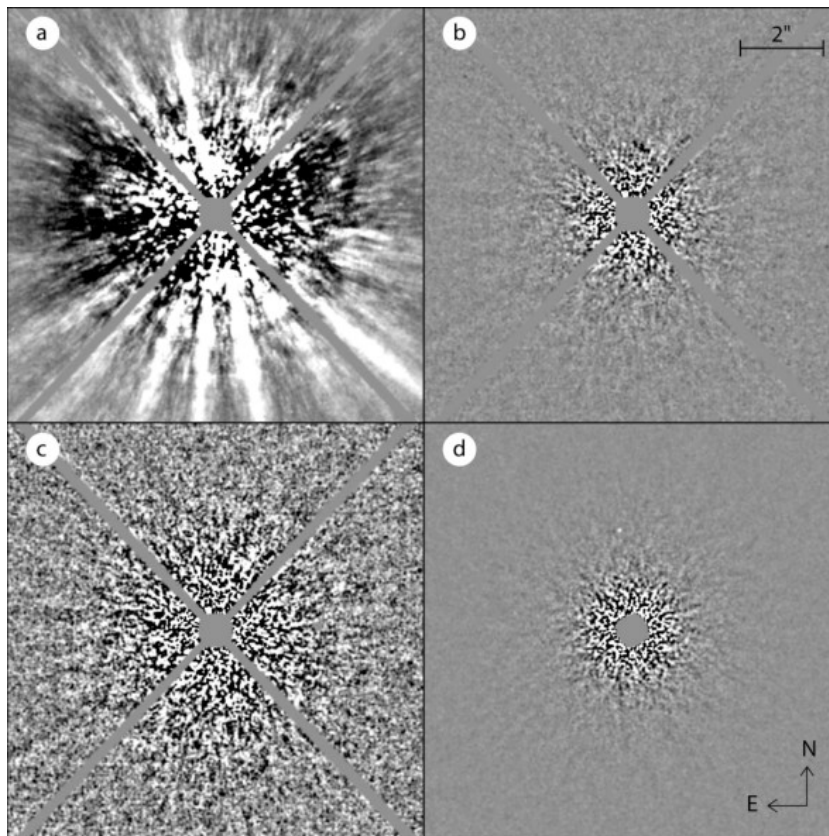
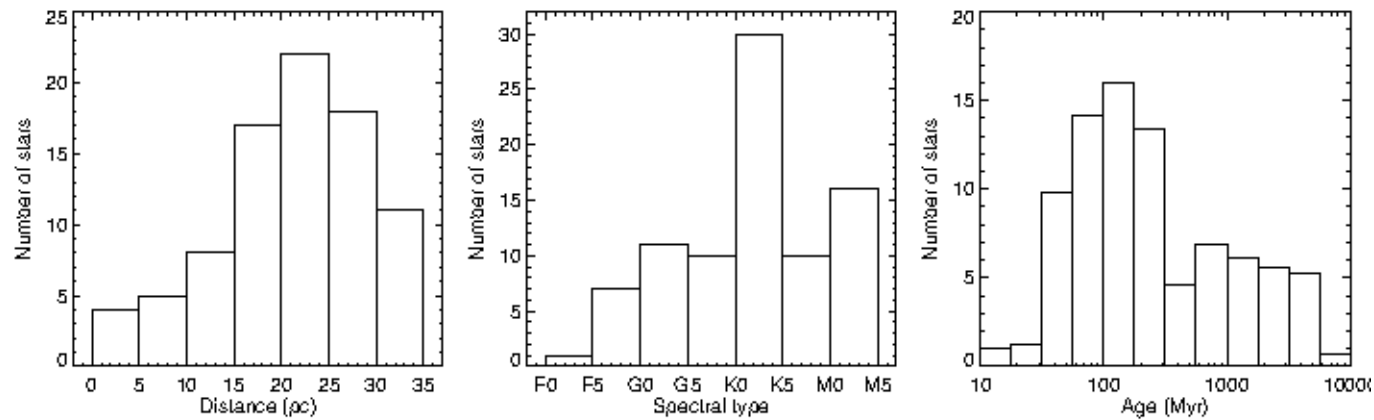
- 15 nearby massive stars (B2–A0)
- 2 White dwarfs
- Altair



Early type stars evolve rapidly with age, so isochronal dating yields their age with good precision

Stellar Samples - II: FGKM stars

➤ 85 nearby stars from the Gemini Deep Planet Survey^{2,3}



² Janson, Bonavita et al. 2012, ApJ, 747, 116

³ Lafreniere et al. 2007 ApJ 670.1367;

Statistical Analysis

MESS code (Bonavita et al. 2012 - See poster S2-P2)

- 10^4 orbits for each point on a grid with 5 AU steps in semi-major axis and $1 M_{\text{Jup}}$ step in Mass
- The orbits are randomly oriented in space, and with a random orbital phase
- Both circular and eccentric case are considered
- Two possible mass distributions
 - a) Uniform over the allowed area
 - b) Uniform along the minimum mass boundary set by Toomre criterion

50 YEARS
1962-2012
Observing Planetary Systems II
Santiago, Chile, March 5-8, 2012

Making a
M.E.S.S.

(Multi-purpose Exoplanet Simulation System)

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Why this MESS?

While there are a wide variety of planet detection surveys with different sensitivities, a global statistical analysis would produce a clear understanding of what we know now and could be used to project how surveys are pursued in the future. In this context it is useful and crucial to learn as much as possible from all of the available data. In addition it is also very important to be able to predict the performances of the forthcoming instruments, not only in terms of number of expected detections, but also in order to understand what parameter space will be explored and the possible synergies between different discovery techniques.

MESS is a Monte Carlo simulation code that allows one to evaluate the completeness of a survey as a function of the detection limits, the target properties, and the chosen parameter distributions. It can be used both for the interpretation of the present results, and to predict what the outcomes of the future instruments would be.

How to make a MESS in few simple steps

(1) Stellar Sample (SS)

The first input of MESS is a sample of target stars (SS), of known properties (mass, radius, temperature, luminosity, distance, age).

(2) Planet Parameter Distributions (PPD)

The characteristics of the targets stars, together with the assumption on the planet parameter distributions (PPD), are used to generate a synthetic planet population (SPP)

$$\frac{dN}{d[M_p \sin i]} \propto [M_p \sin i]^{-\alpha}$$
$$\frac{dN}{da} \propto a^{-\beta}$$

(3) Synthetic Planet Population (SPP)

For each planet in the SPP, the position on the orbit is evaluated according with the orbital parameters and the (real or simulated) date of observation (Fig. 1).

Fig. 1 Position on the FOV of the planets in the SPP

(5) Survey Completeness (SC)

The results of the analysis can be then used to constrain the PPD.

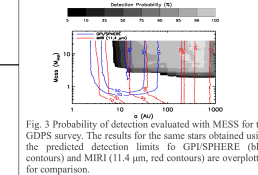


Fig. 3 Probability of detection evaluated with MESS for the GDPS survey. The results for the same stars obtained using the predicted detection limits to GPN sphere (blue contours) and MIRI (11.4 μm, red contours) are overplotted for comparison.

(4) Detection Limits (DL)

Then the properties of the planets are compared to the (real or estimated) detection limits (Fig. 2) to evaluate the survey completeness (Fig. 3).

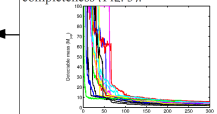


Fig. 2 Minimum mass vs separation for the stars in the GDPS planet sample (Lafreniere et al. 2008).

The MESS Prediction MODE (PM)

MESS can also be used to evaluate the yield of future instruments, helping to foresee the characteristics of the planet population that will be explored. Fig. 4 shows the results of the application of the tool to EPICS (Kasper et al. 2010), using a sample of ~600 nearby stars.

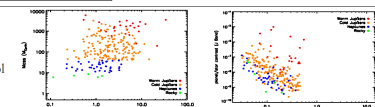


Fig. 4 Mass vs Semi-major Axis (left panel) and planet/star contrast vs separation (right panel) of the planets detectable with EPICS.

To be continued (there's always room for a bigger MESS)...

MESS is an ongoing project! Further versions of the tool are under test or are planned for the near future.

The 1.0 version of MESS is available for download at: <http://messthecode.com/downloads-3/>

The Disk Instability scenario

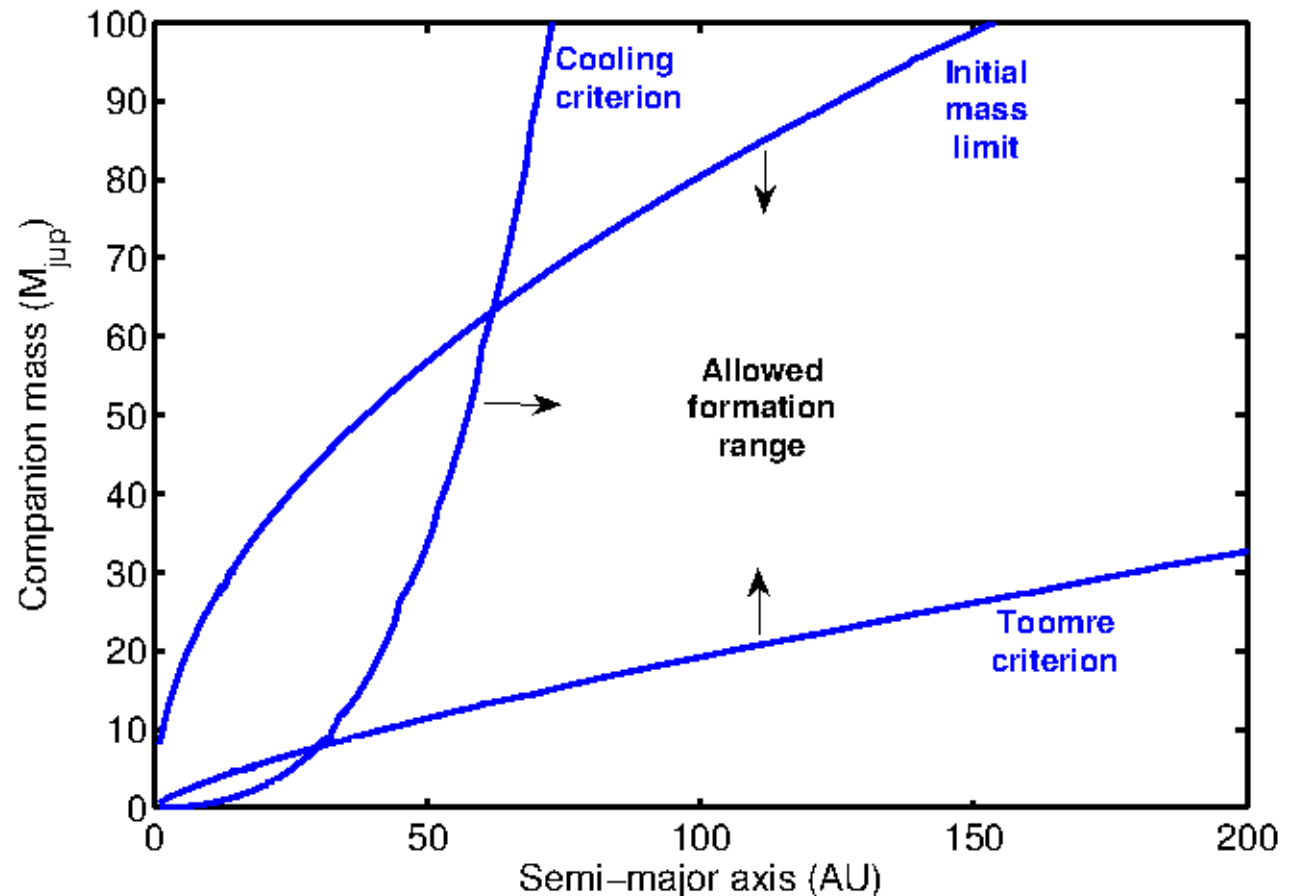
For a fragment in the planet or brown dwarf mass range to form,
The following conditions need to be fulfilled:

✓ Toomre criterion: $Q = \frac{(c_s \kappa)}{\pi G \Sigma} < 1$

✓ Cooling criterion:

$$t_{cool} \propto \frac{E_{th,1} - E_{th,0}}{T_{eff}^4 - T_{irr}^4} < \tau_{orb}$$

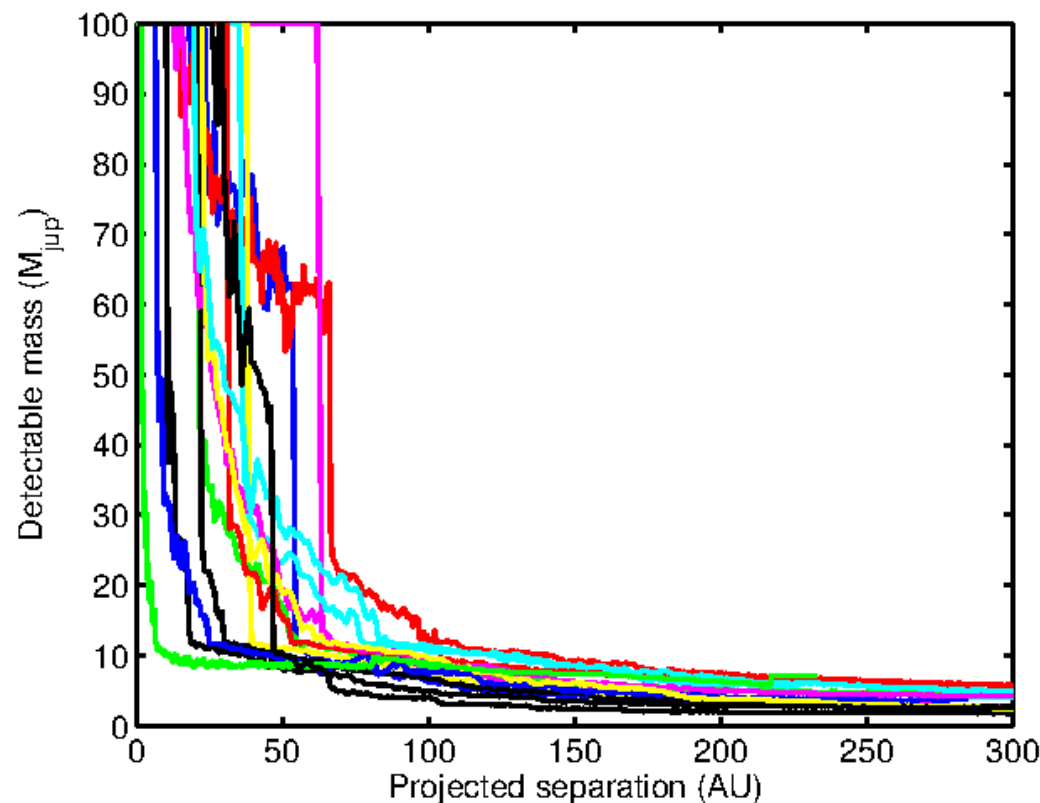
✓ Initial mass limit



Detection Limits

To obtain 5σ brightness contrast limits as a function of the separation:

- 1) Each final image is convolved with Gaussian of the same FWHM
- 2) The standard deviation within a sequence of annuli is assumed as the σ for each corresponding separation
- 3) A minimum mass limit is then obtained from the resulting contrast limit, using evolutionary models (COND/DUSTY).

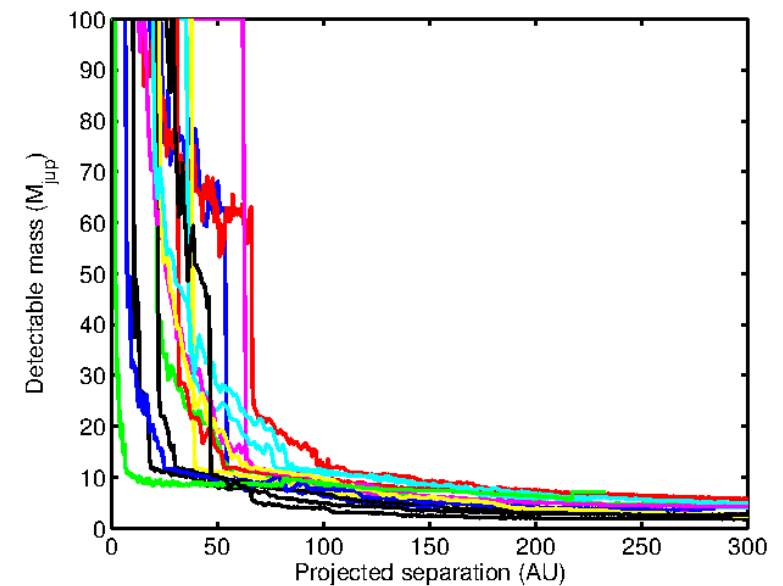
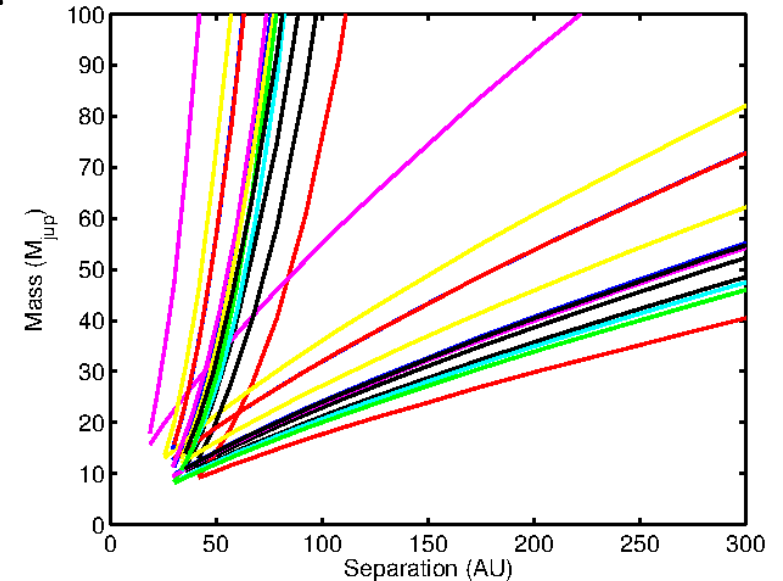


Results - Ia: Massive Stars - B2-A0 sample

Detection Probabilities

Target	Det. Prob. Circular Uniform (%)	Det. Prob. Eccentric Uniform (%)	Det. Prob. Circular Minimum (%)	Det. Prob. Eccentric Minimum (%)
Alpheratz	90.6	88.8	77.4	76.1
41 Ari	90.3	90.0	80.6	80.8
Algol	91.3	87.7	71.5	69.2
Bellatrix	52.6	54.3	64.5	64.7
Elnath	90.8	89.9	87.4	87.4
β CMi	92.6	91.9	84.0	84.2
30 Mon	97.0	96.9	84.5	84.0
θ Hya	98.6	98.4	96.7	96.0
Regulus	91.1	82.7	89.8	80.7
γ Crv	99.3	99.2	99.4	99.3
109 Vir	99.0	98.8	97.5	97.3
β Lib	96.3	96.1	86.0	86.4
ϵ Her	94.6	94.5	75.3	76.0
Vega	86.8	79.7	82.6	75.1
λ Aql	94.1	93.6	86.4	86.5
Sample mean	91.0	89.5	84.2	82.9

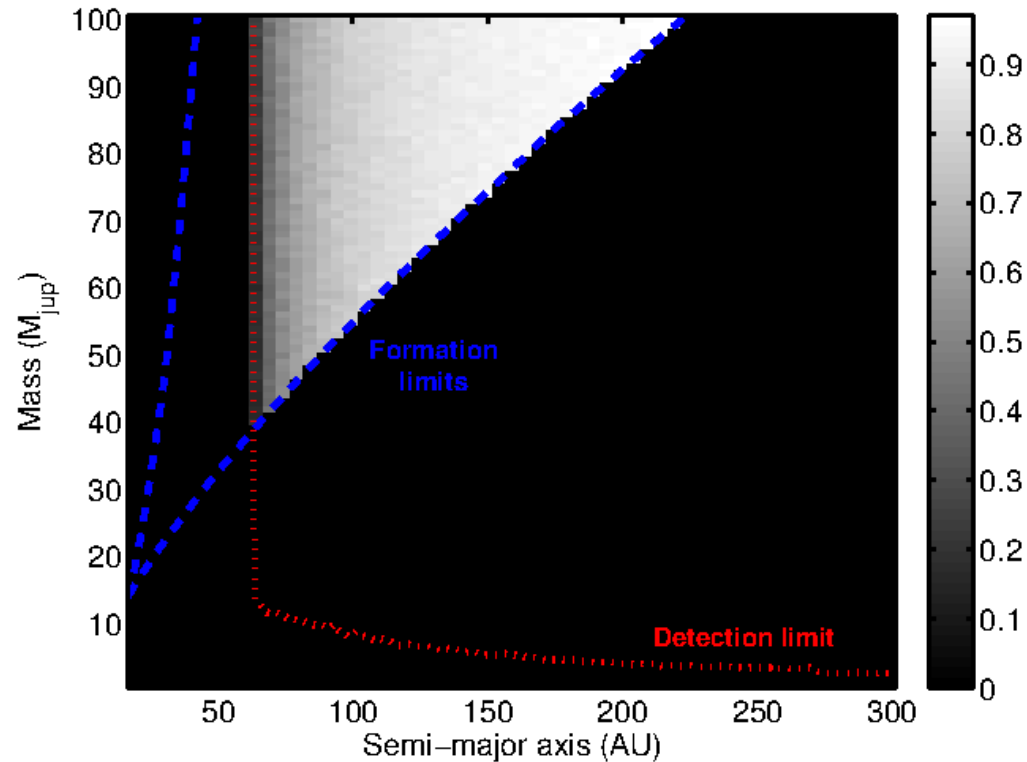
Typical detection probabilities obtained: 80–90%



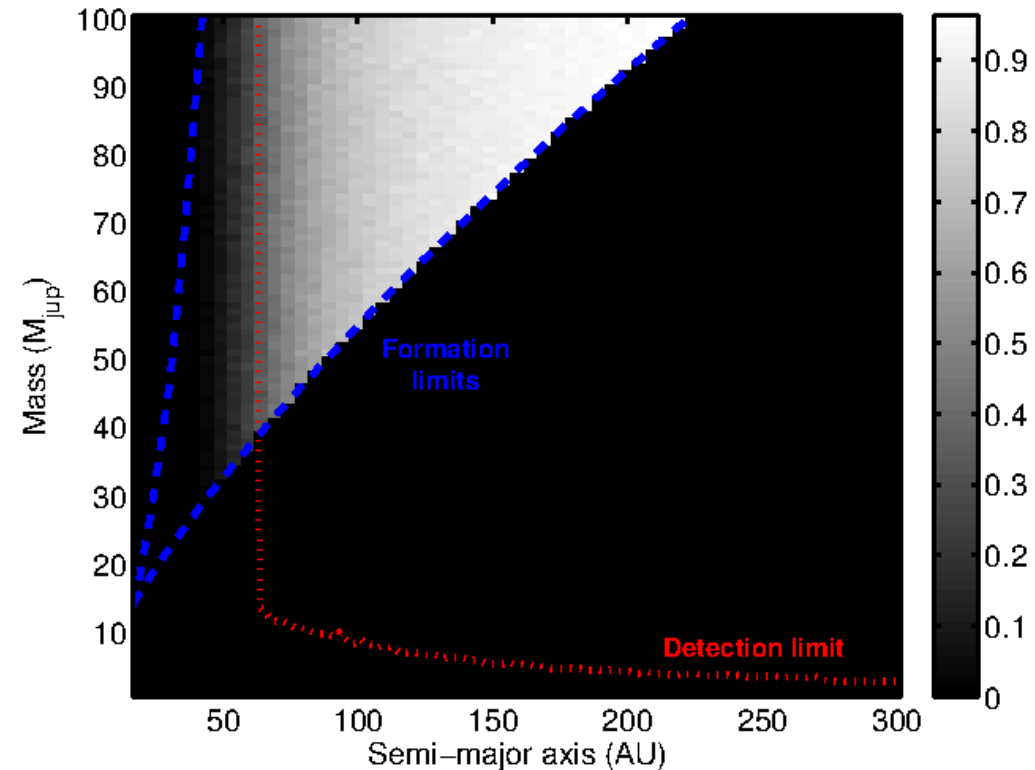
At 99.9% confidence, less than 27.4%–30.1% of these stars forms companions with mass $< 100 M_{\text{jup}}$ within 300 AU through disk instability.

Results - Ib: Massive Stars - Bellatrix

Circular case



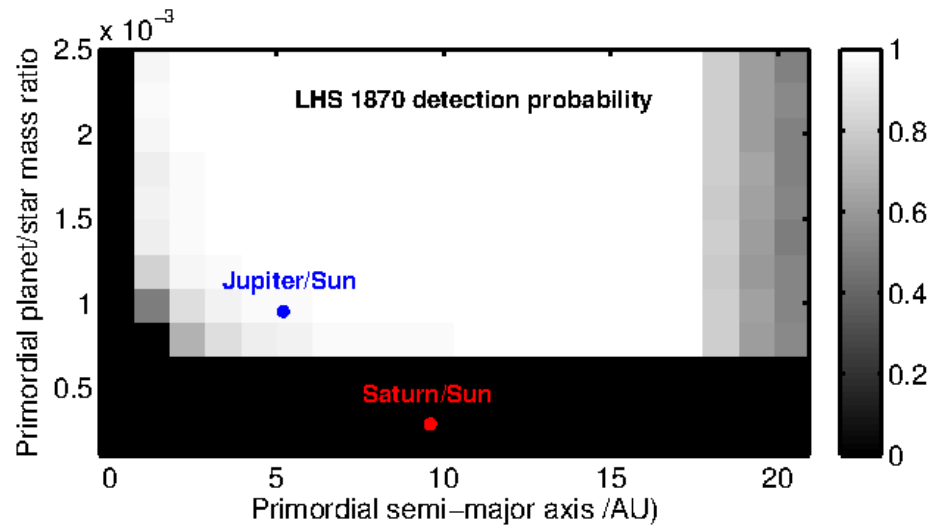
Eccentric case



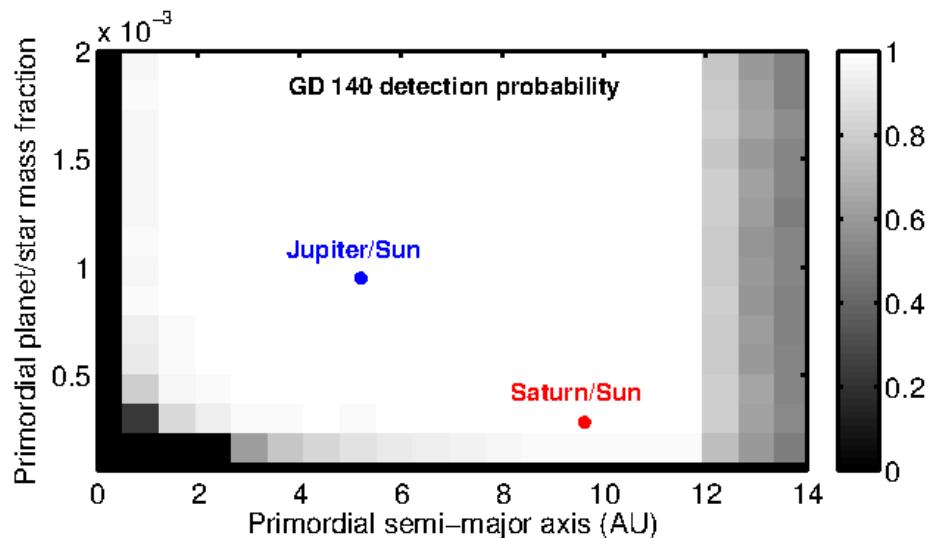
- ◆ Most of the syntetic planets are undetectable (probability less than 80%)
- ◆ Large difference between circular/eccentric case

Results - Ic: White dwarfs

- x No formation limits assumed
- x Total ages including estimated main-sequence lifetime and post-main-sequence cooling time (Burleigh et al. 2002).



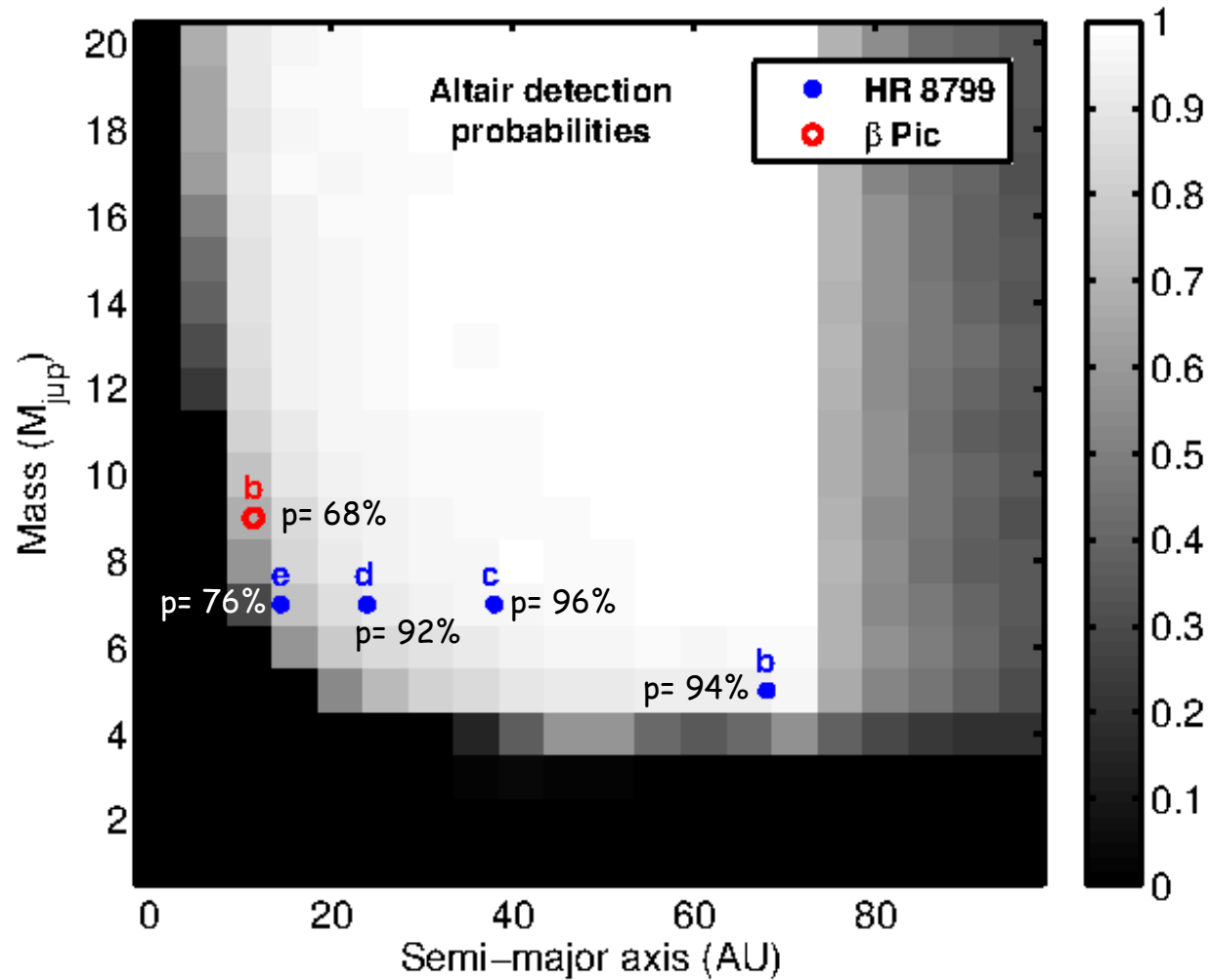
Main-sequence mass = $3.1 M_{\text{Sun}}$
White dwarf mass = $0.66 M_{\text{Sun}}$
Age = 700 Myrs



Main-sequence mass = $6.3 M_{\text{Sun}}$
White dwarf mass = $0.9 M_{\text{Sun}}$
Age = 250 Myrs

Results - Id: Altair

Age = 250-500 Myrs (Suarez et al. 2005)



Results - II: GDPS Stars

These stars are still in the Hayashi contraction phase when the planets form.
The evolution of the stellar luminosity with age is very fast.

Two sets of formation limits for each star:

L1: earlier formation, higher luminosity

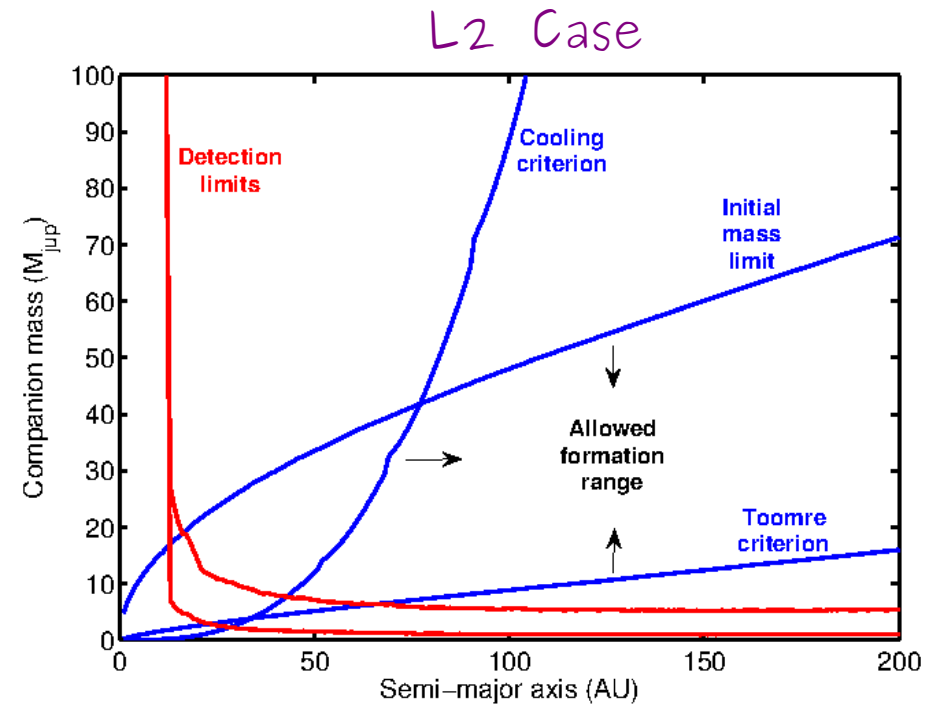
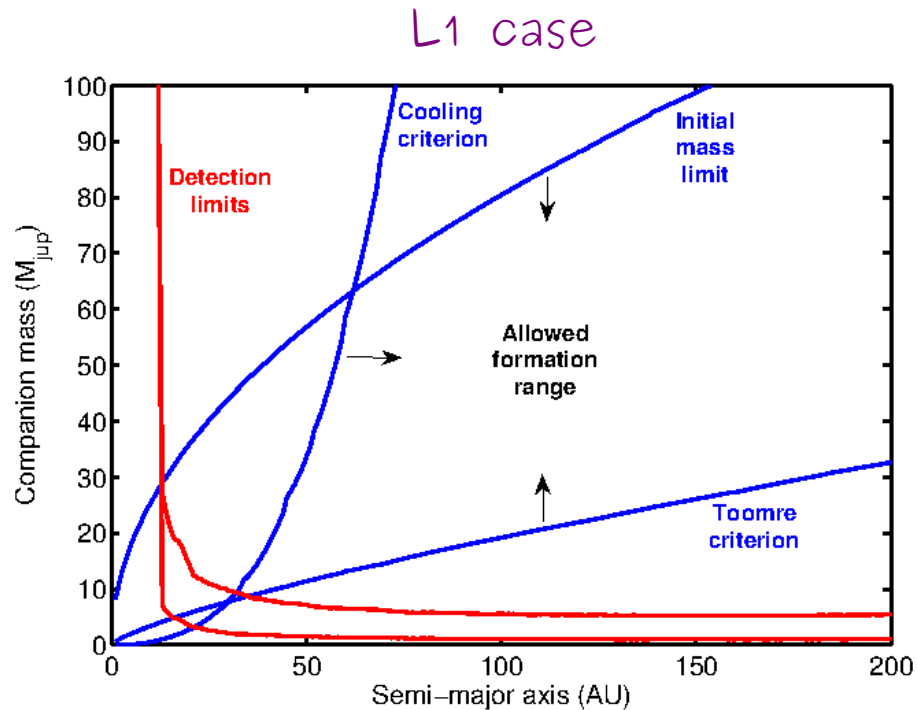
L2: later formation, lower luminosity

Also, for most of the targets the uncertainties on the age are very high

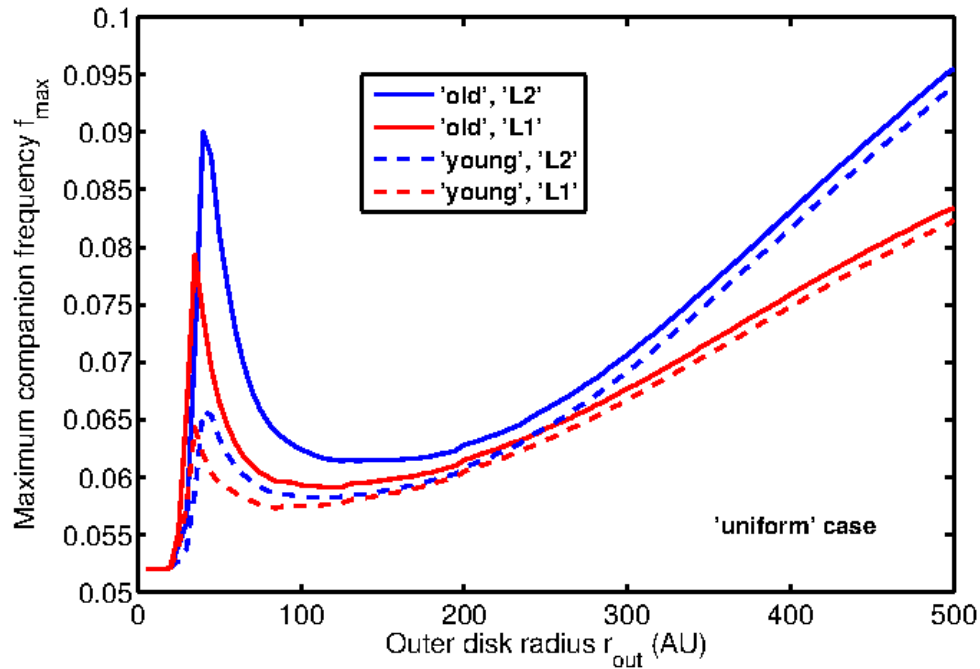
Two sets of detection limits for each star:

D1: young case, lower mass limit

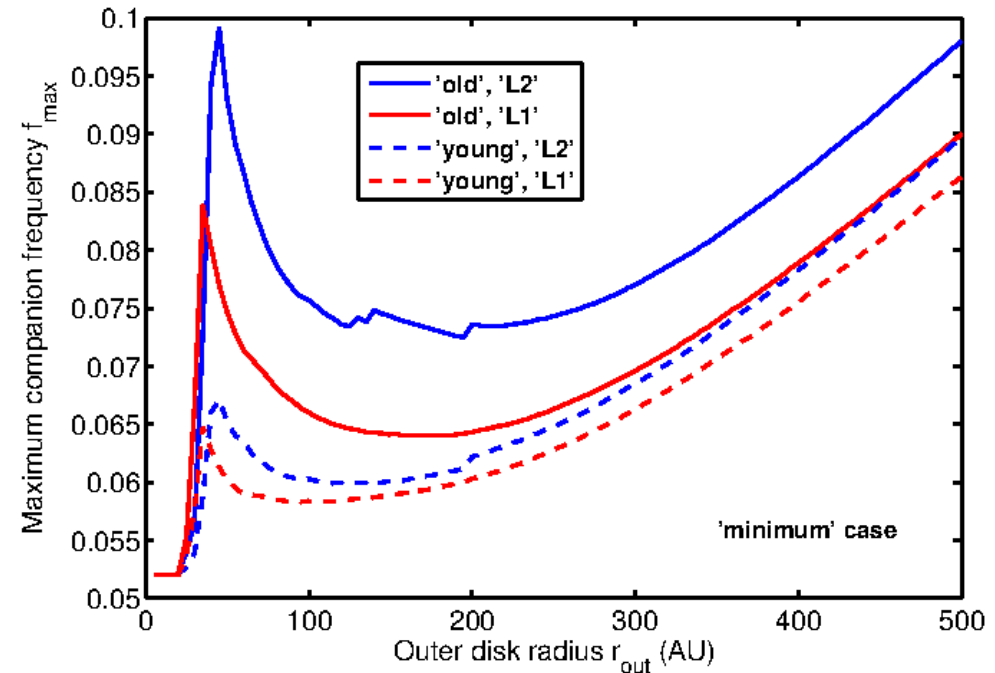
D2: old age, higher mass limit



Uniform case



Minimum case

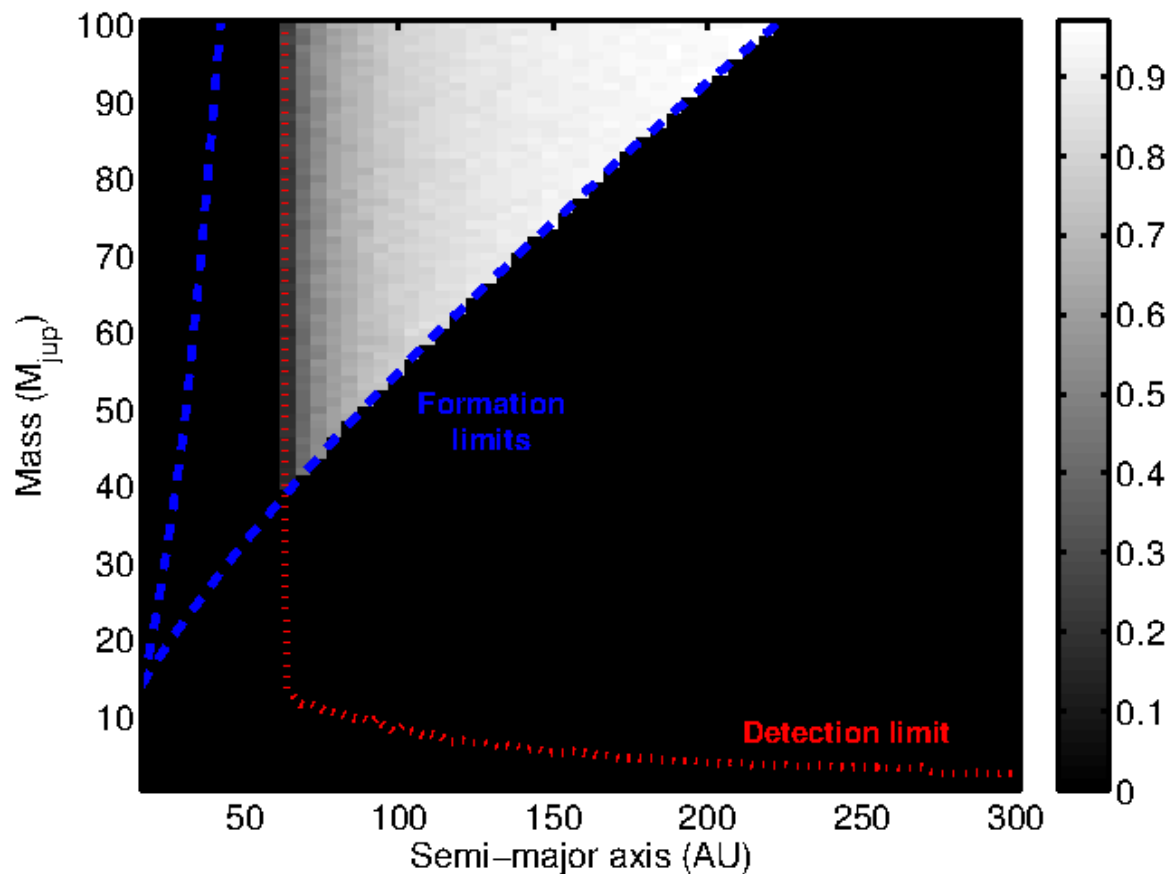


For any outer disk radius below 500 AU,
 f_{\max} is always lower than 9.9% at 99% confidence!

Conclusions

- Less than 32% of B2–A0 stars form and retain in-situ companions within 300 AU through disk instability at 99% confidence
- Less than 9.99 % of FGKM stars form and retain in-situ companions within 500 AU through disk instability at 99% confidence

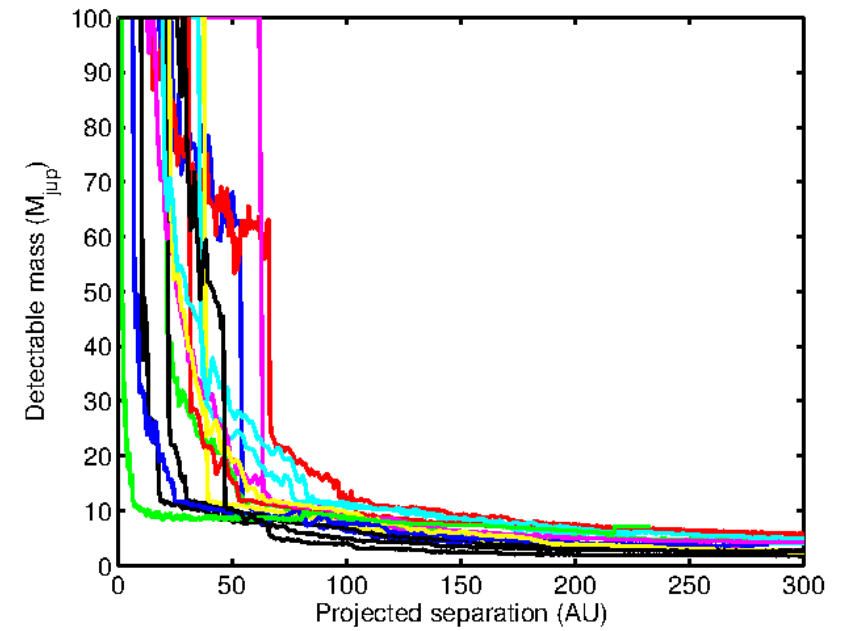
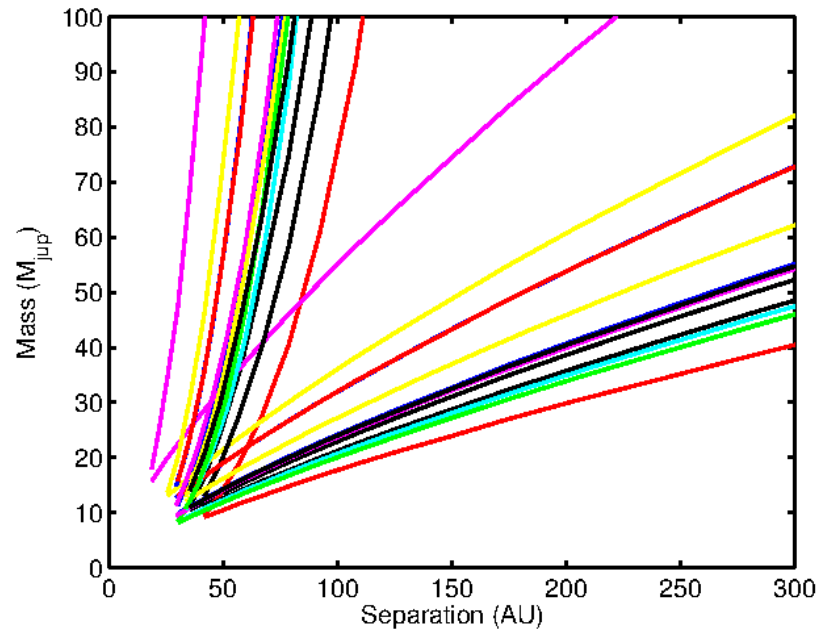
The value of the mass of the generated planet is compared to the detection limit at the corresponding projected separation, And a **detection probability map** is finally obtained.

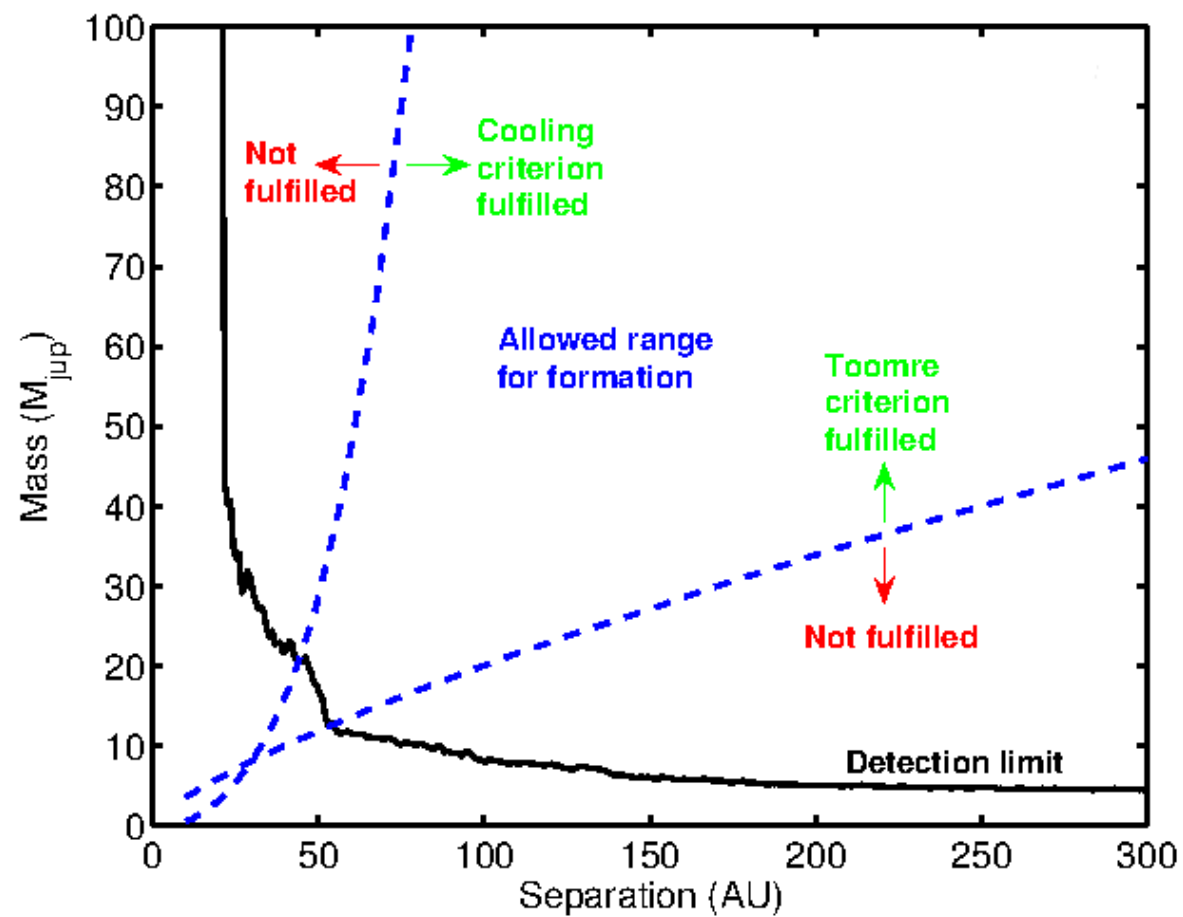


If the result of the survey is a null detection, the probability of detecting no companions, assuming f as a value of the expected frequency is given by

$$P = \prod_i 1 - fp_i$$

Results – I: Massive Stars





Effect of migration

ADI Image processing

1. A sequence of many exposure of the target is taken, with the instrument rotator OFF
2. A reference image is created and subtracted from the target images
3. The residual images are then rotated to align their FOV and co-added

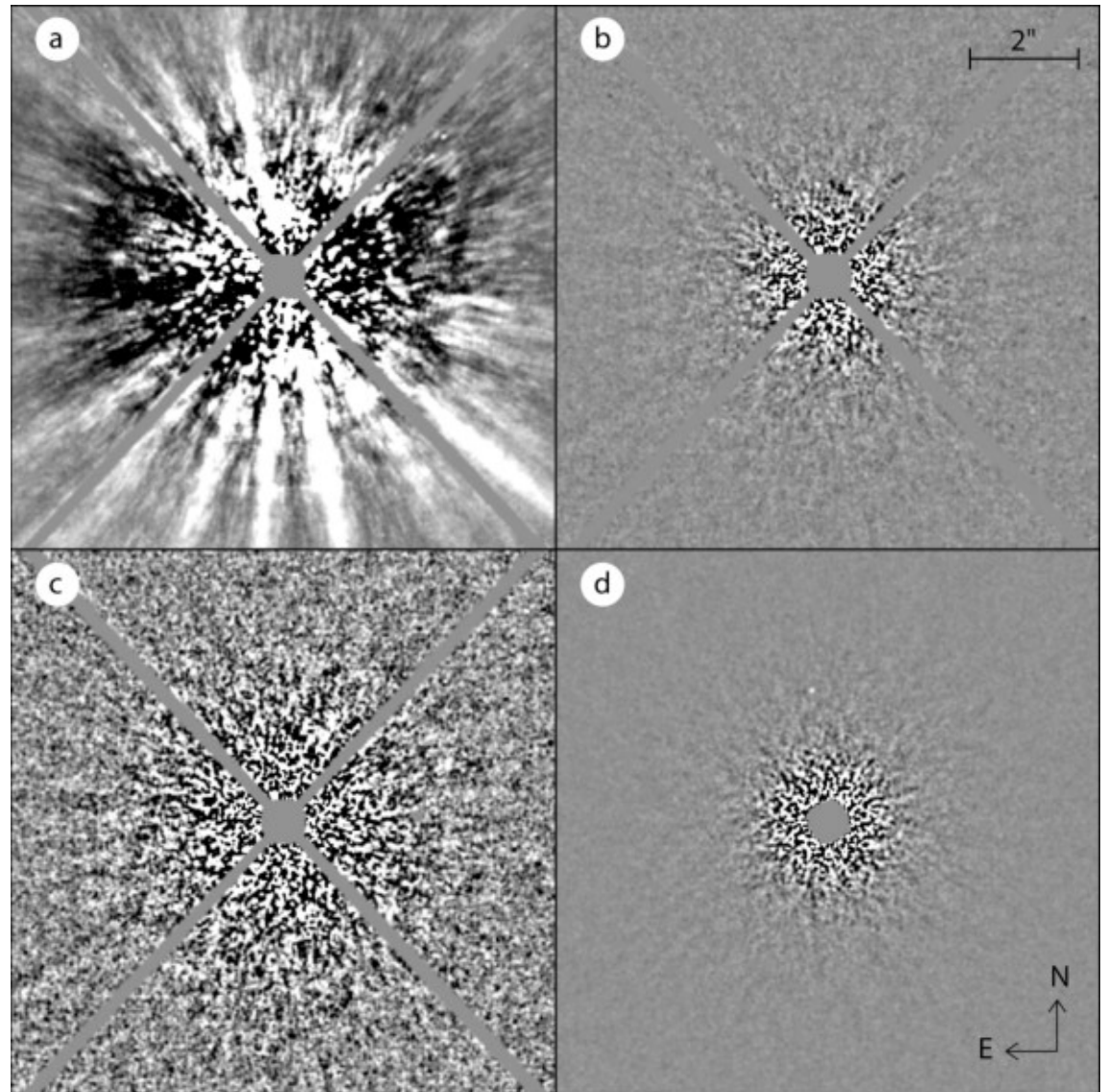


Figure from Lafreniere et al. 2007 ApJ 670.1367

Proposed planet formation scenarios:

- *Core accretion*: tiny clumps of dust stick together to create solid cores of rock, which either accumulate a thick atmosphere and become gas giants or do not, becoming rocky planets like earth
- *Gravitational instability*: planets form as the disk of gas and dust that surround the stars breaks up