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

How do most planets form?

Constraints on disk instability from Direct Imaging

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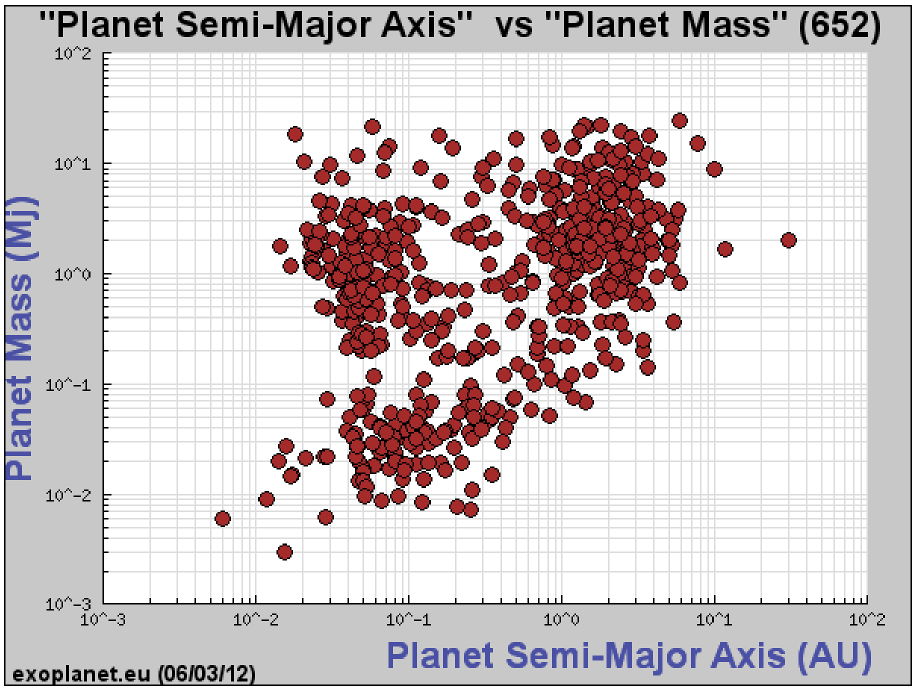
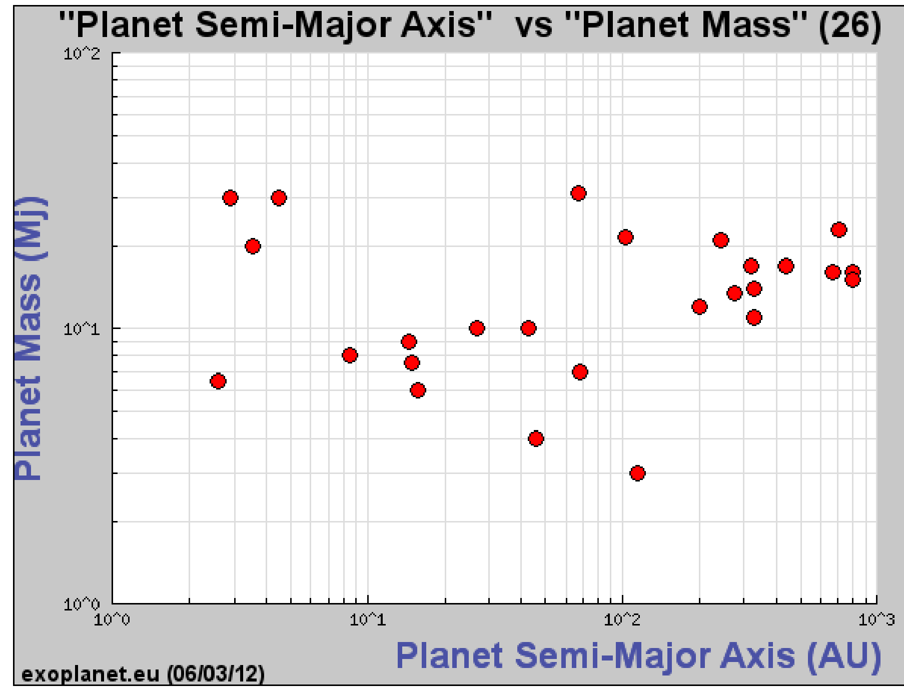
Introduction

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.

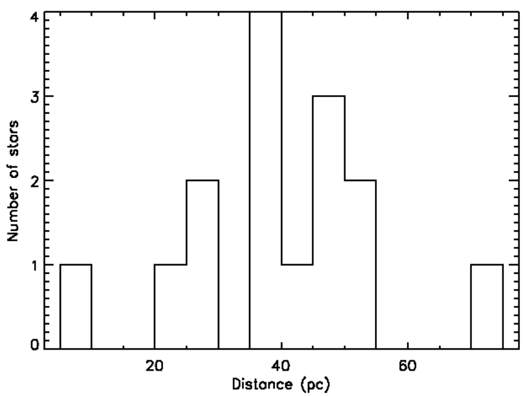


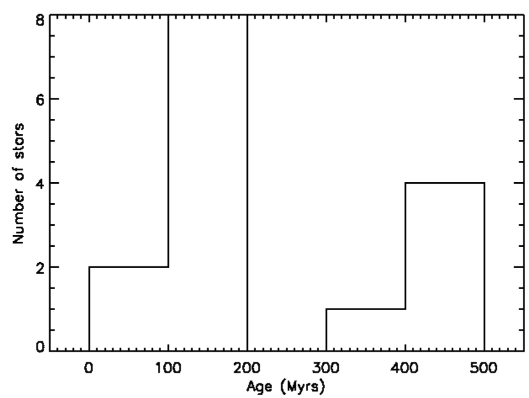


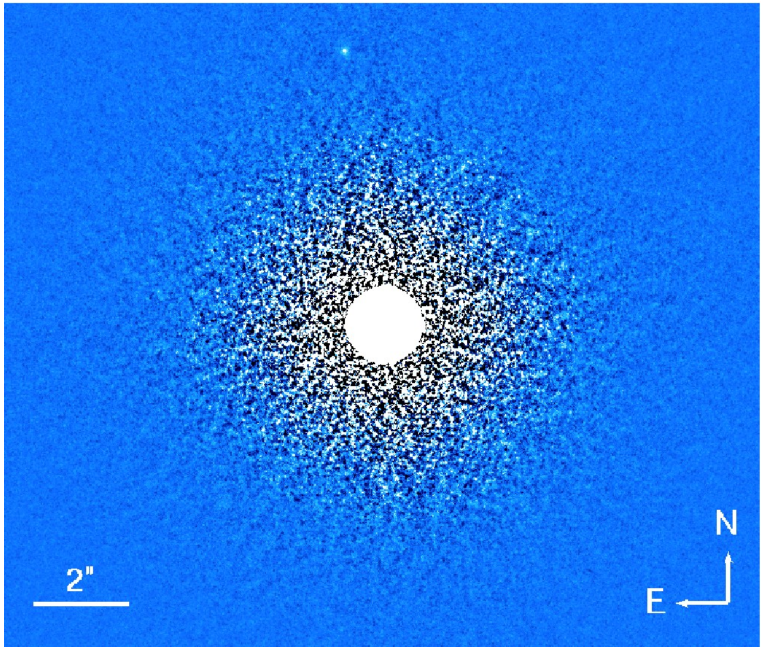
Core accretion seems to be the main formation mechanism for close-in planets, but is that true for the total planet population?

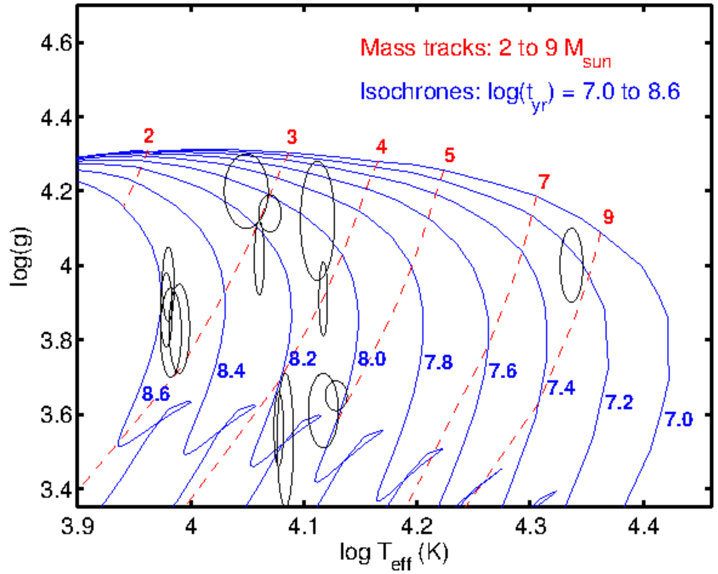
Stellar Samples – I: Massive nearby stars

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







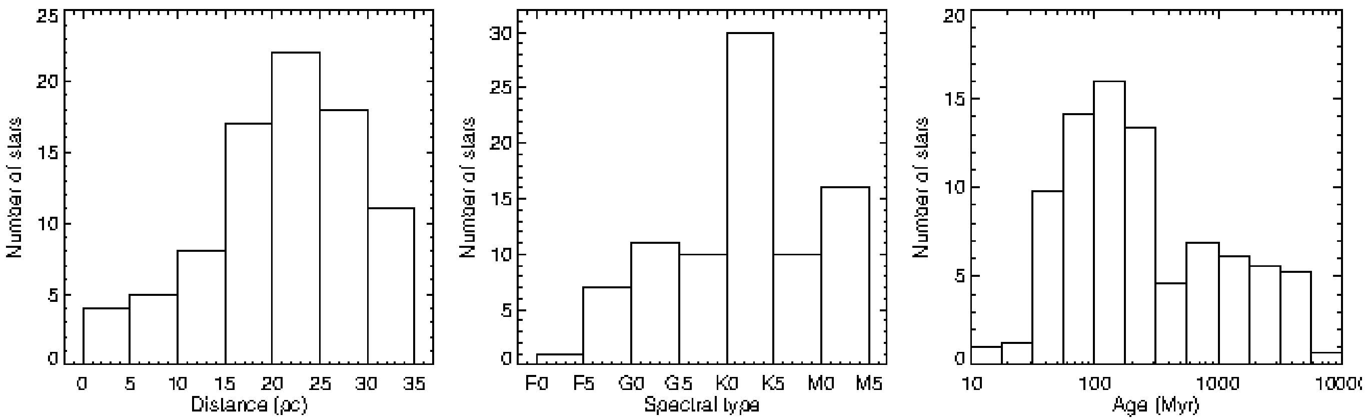


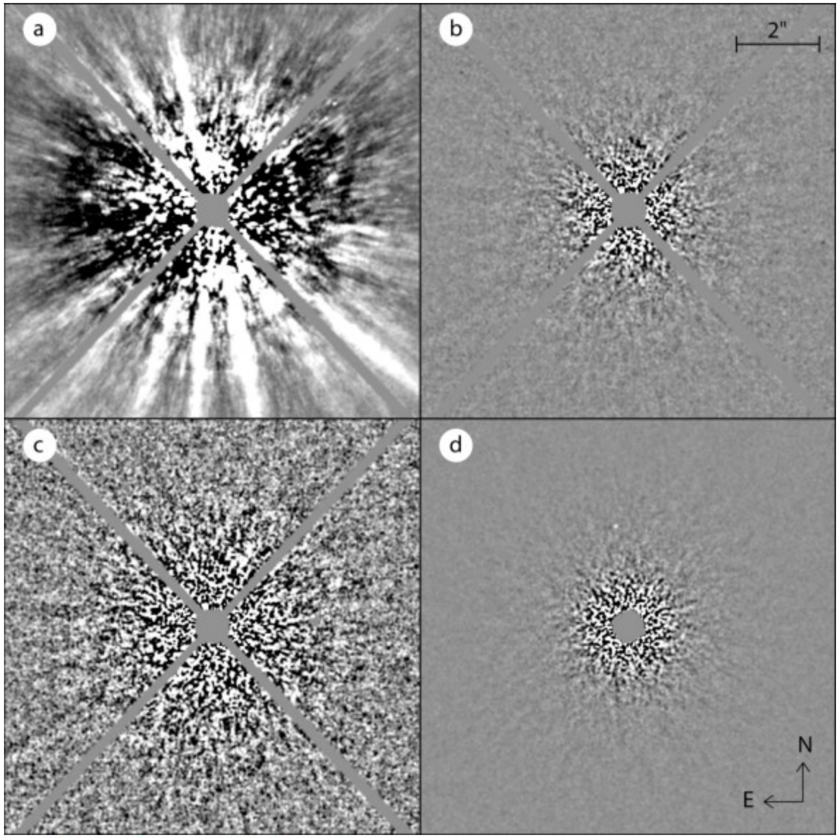
Early type stars evolve rapidly with age, so isochronal dating yields their age with good precision

[1] Janson, Bonavita et al. 2011 ApJ, 736, 89

Stellar Samples - II: FGKM stars

- 85 nearby stars from the Gemini Deep Planet Survey[2,3]



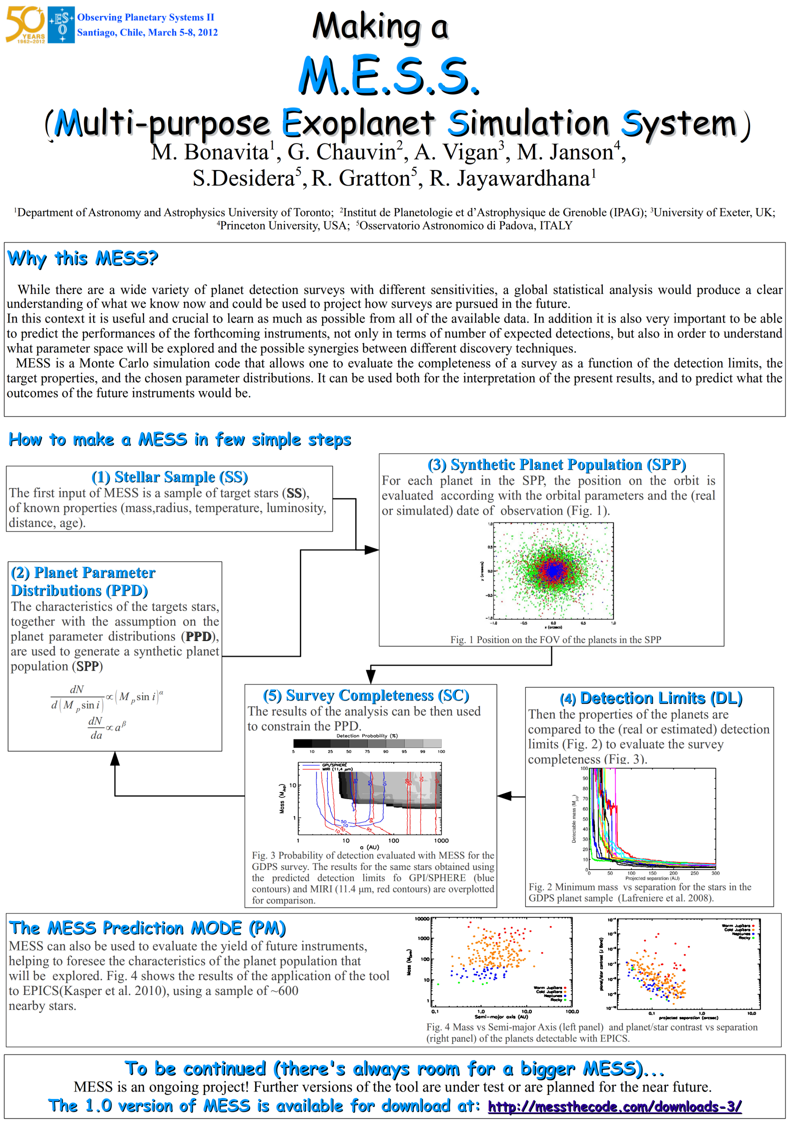


[2] Janson, Bonavita et al. 2012, ApJ, 747, 116
[3] Lafreniere et al. 2007 ApJ 670.1367;

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_{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



The Disk Instability scenario

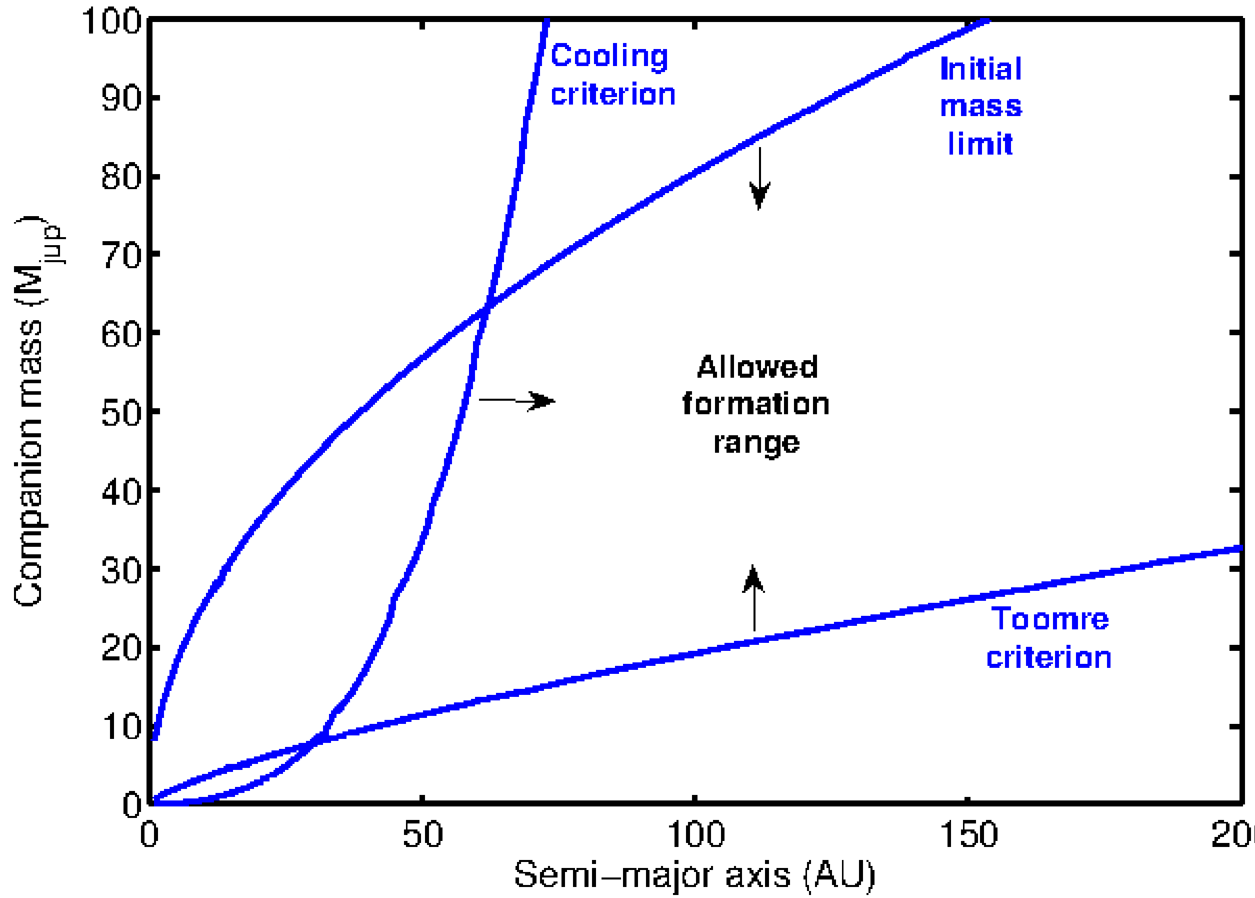
For a fragment in the planet or brown dwarf mass range to form,
The following conditions need to be fulfilled:

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

✔ Cooling criterion:

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

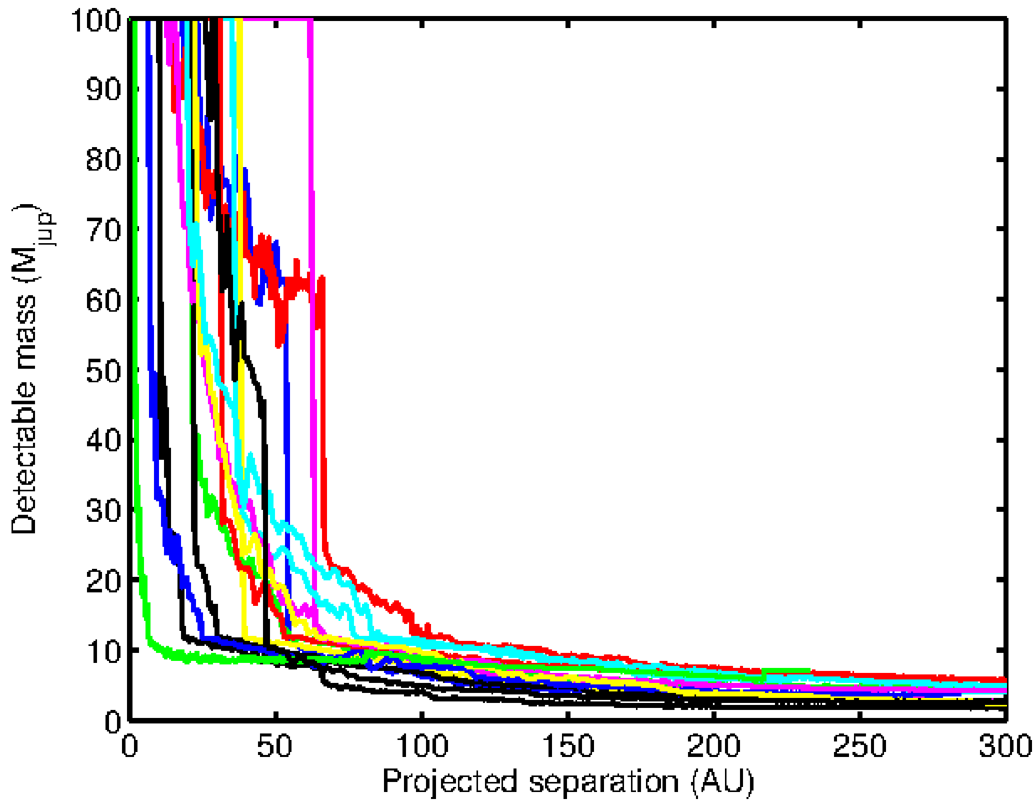
✔ Initial mass limit



Detection Limits

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

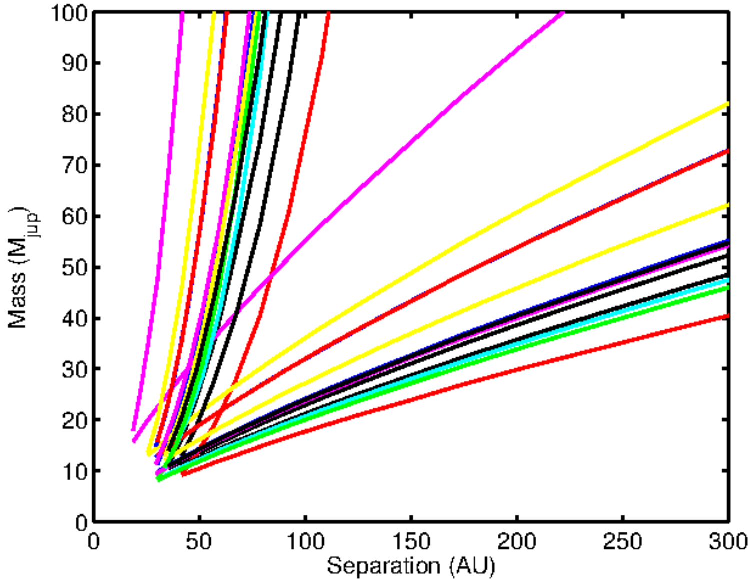
1) Each final image is convolved with Gaussian of the same FWHM
2) The standard deviation within a sequence of anuli is assumed as the σ for each corresponding separation
3) A minimum mass limit is then obtained from the resulting contrast limit, using evolutionary models (COND/DUSTY).

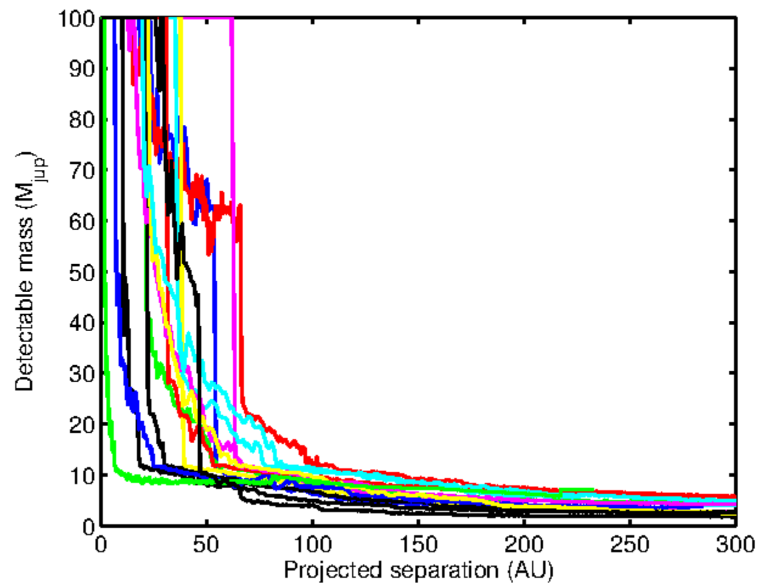


Results - Ia: Massive Stars - B2-A0 sample

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



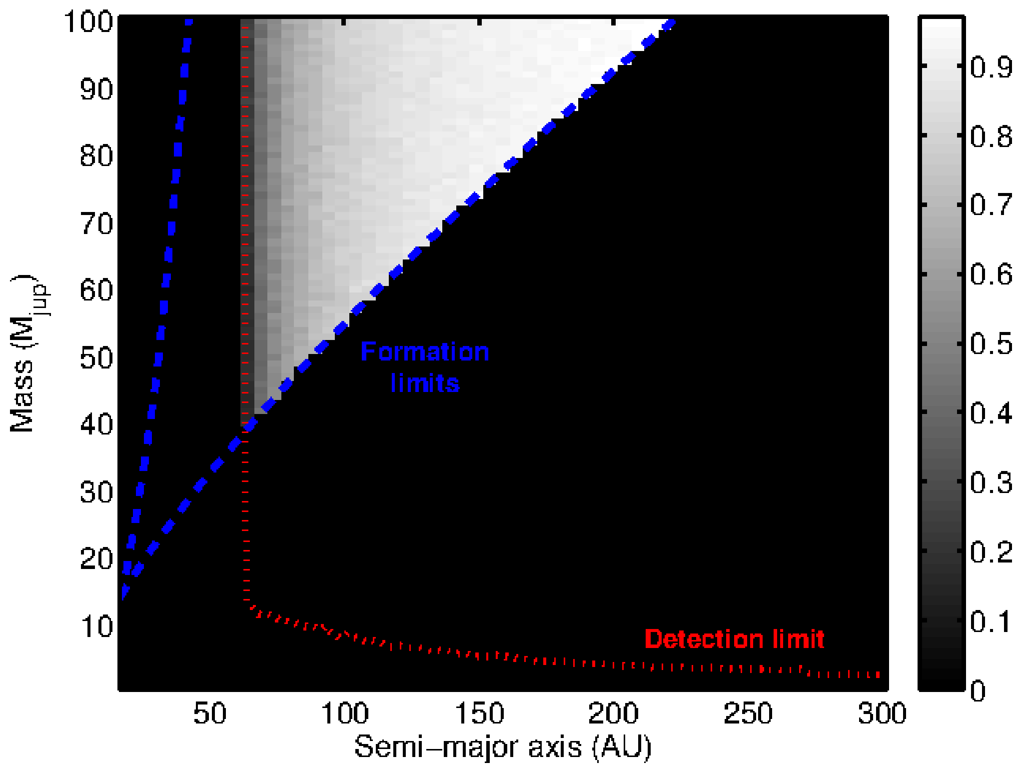


Typical detection probabilities obtained: 80-90%

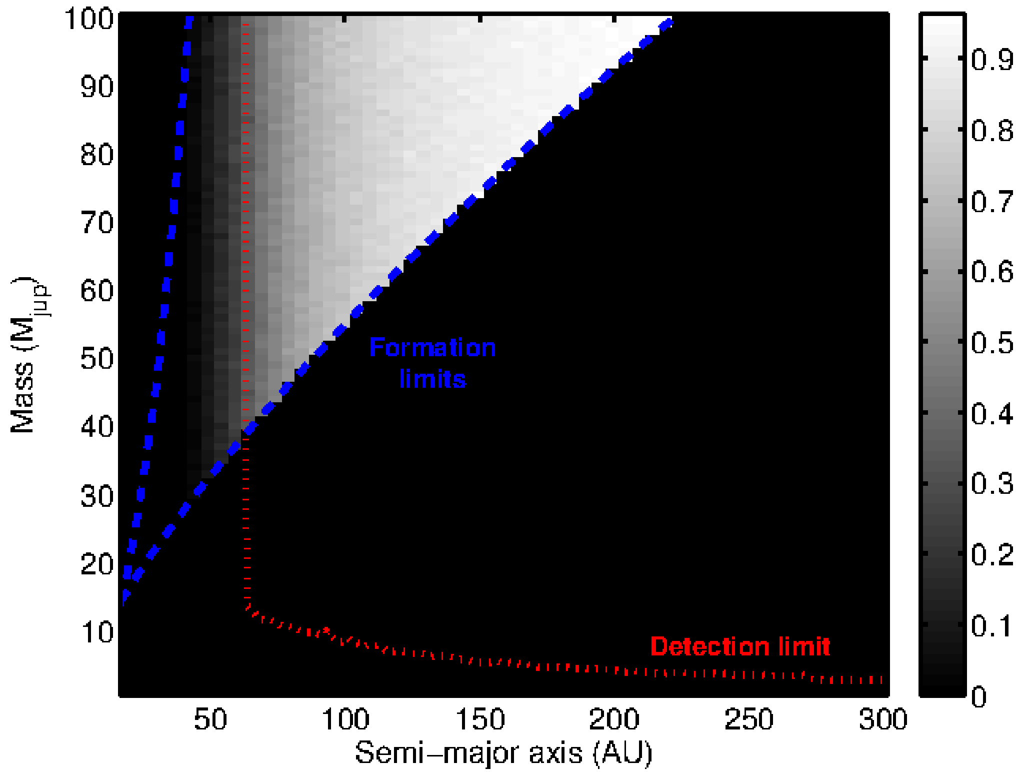
At 99.9% confidence, less than 27.4%-30.1% of these stars forms companions with mass < 100 M_{jup} within 300 AU trough disk instability.

Results – Ib: Massive Stars – Bellatrix

Circular case



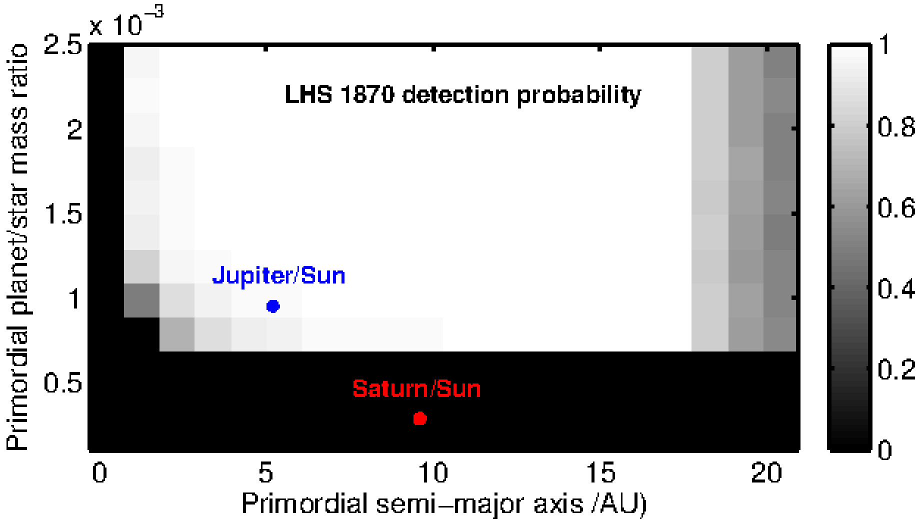
Eccentric case



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

Results – Ic: White dwarfs

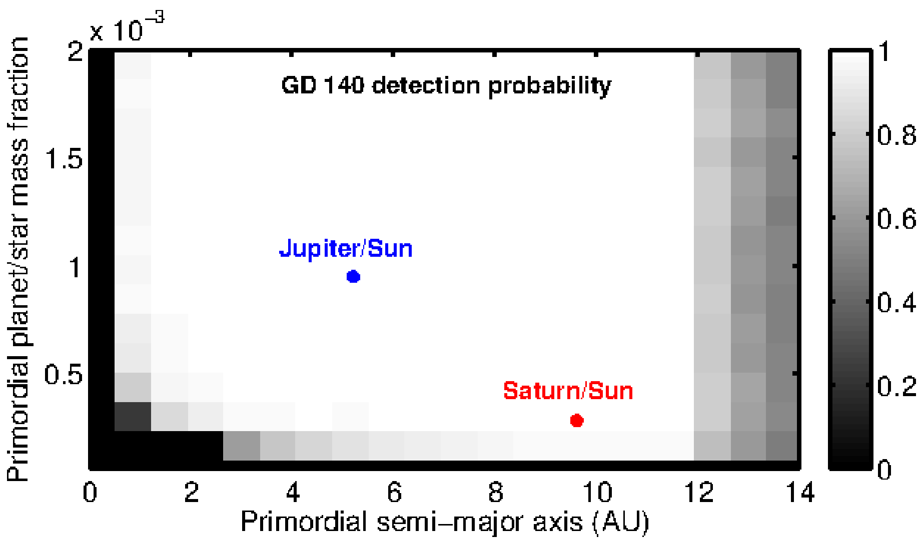
- No formation limits assumed
- Total ages including estimated main-sequence lifetime and post-main-sequence cooling time (Burleigh et al. 2002).



Main-sequence mass = 3.1 M_{Sun}

White dwarf mass = 0.66 M_{Sun}

Age = 700 Myrs



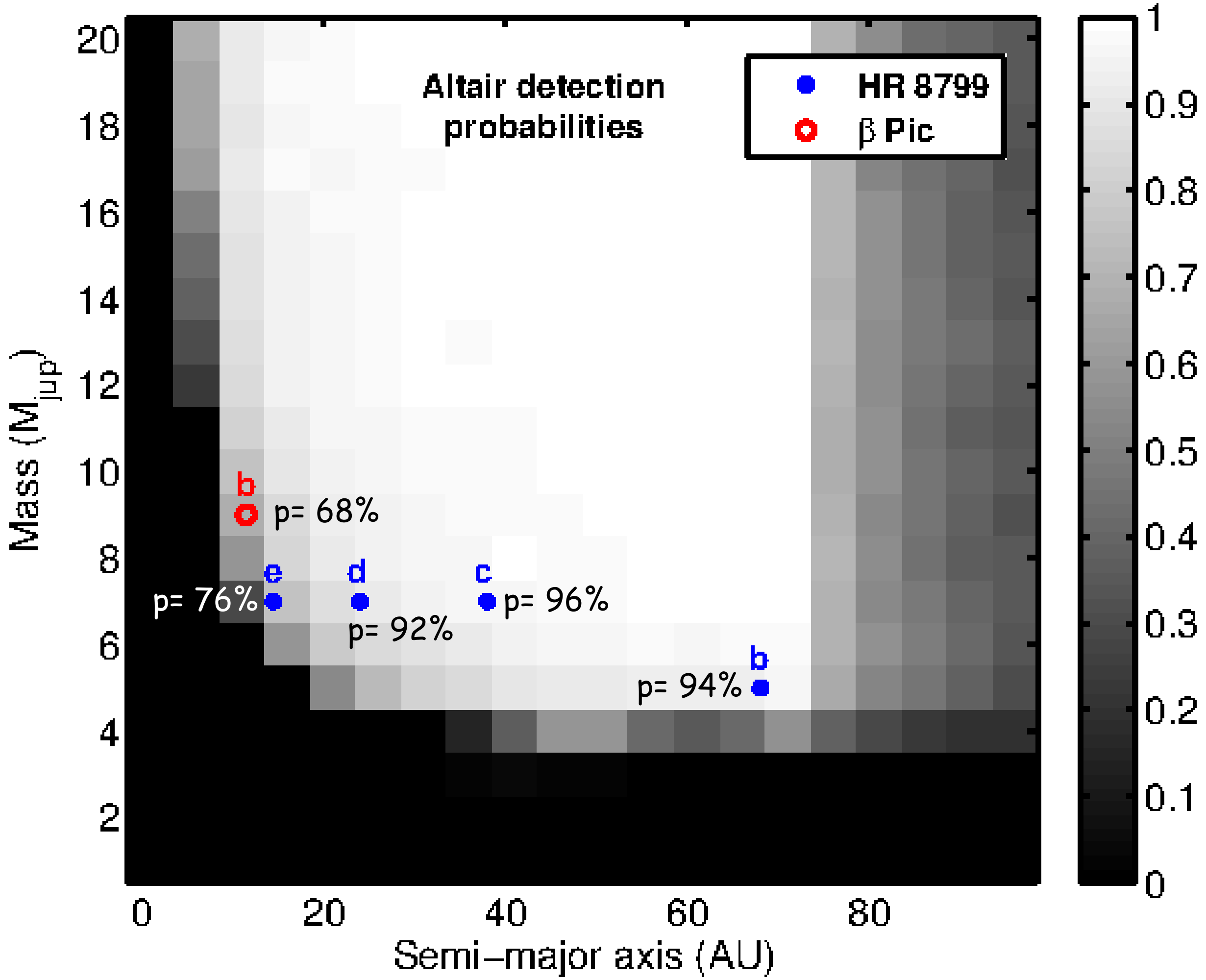
Main-sequence mass = 6.3 M_{Sun}

White dwarf mass = 0.9 M_{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

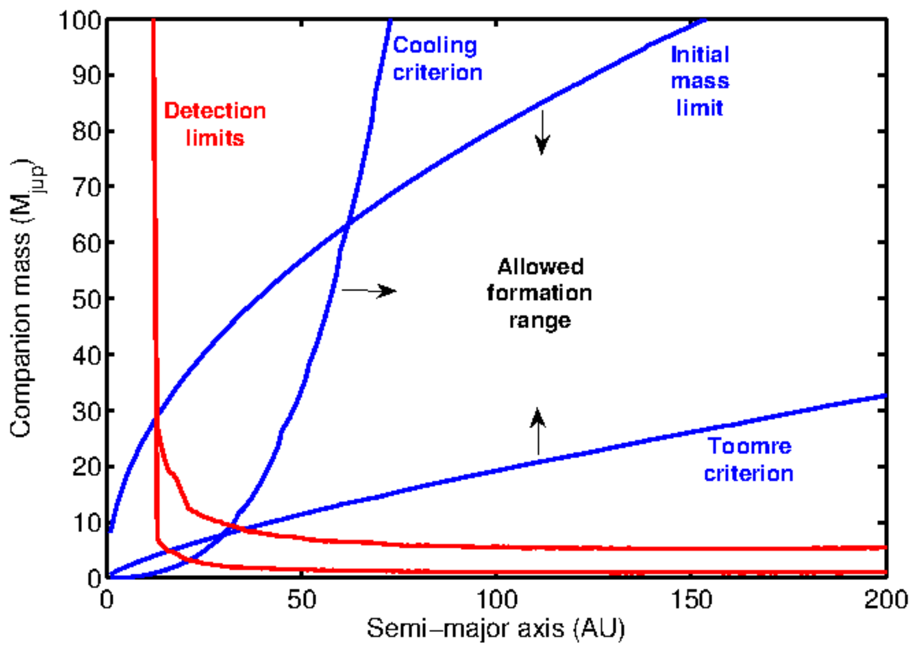
Also, for most of the targets the uncertainties on the age are very high

Two sets of detection limits for each star:

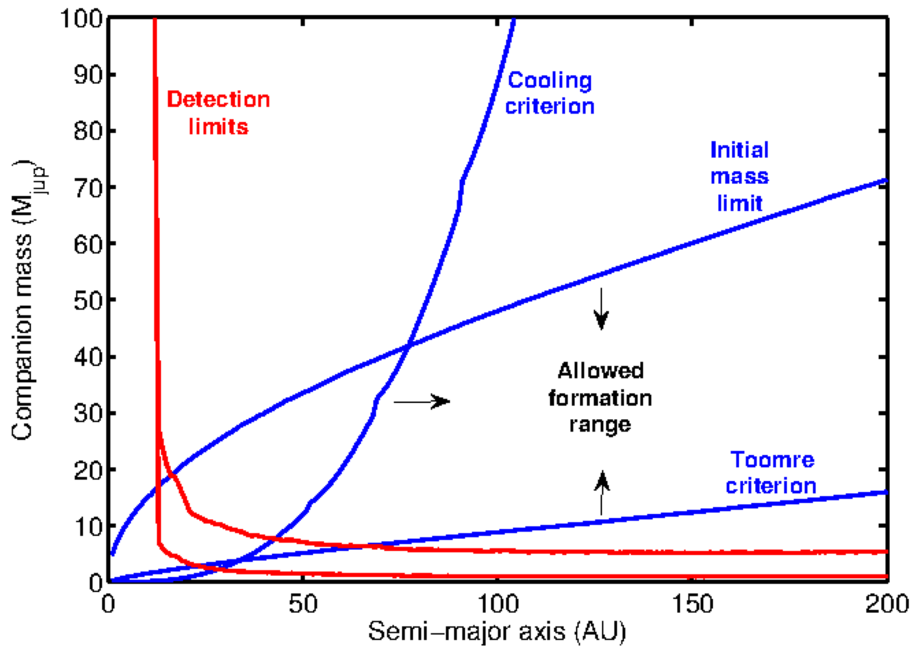
D1: young case, lower mass limit

D2: old age, higher mass limit

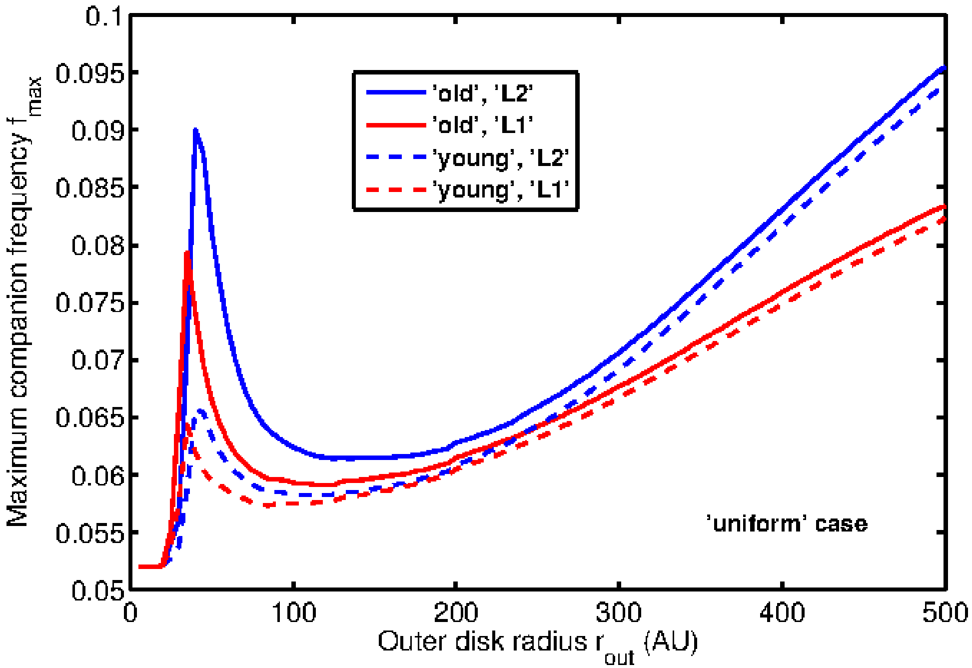
L1 case



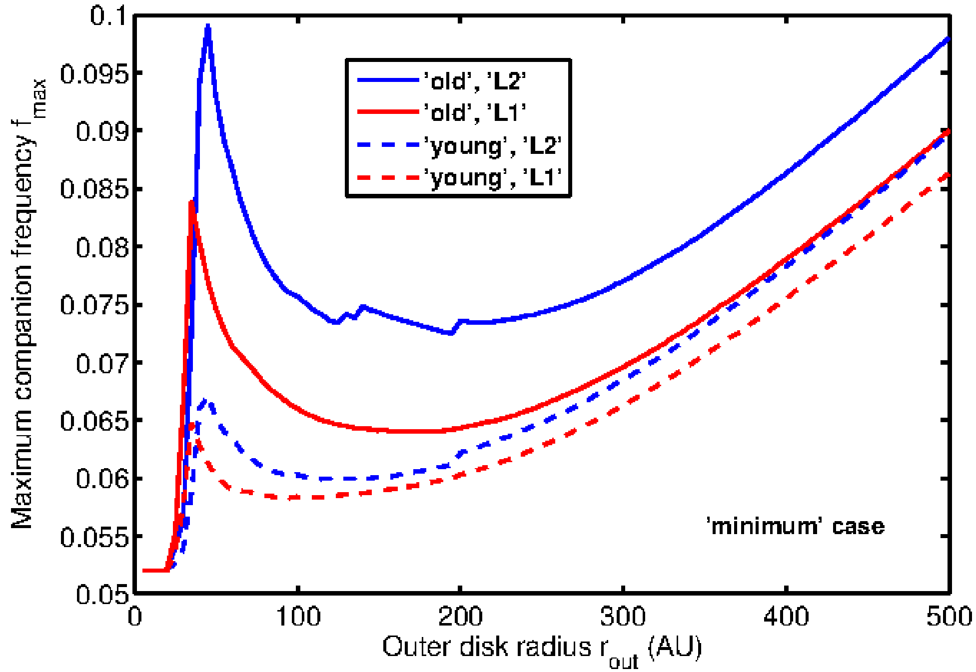
L2 Case



Uniform case



Minimum case



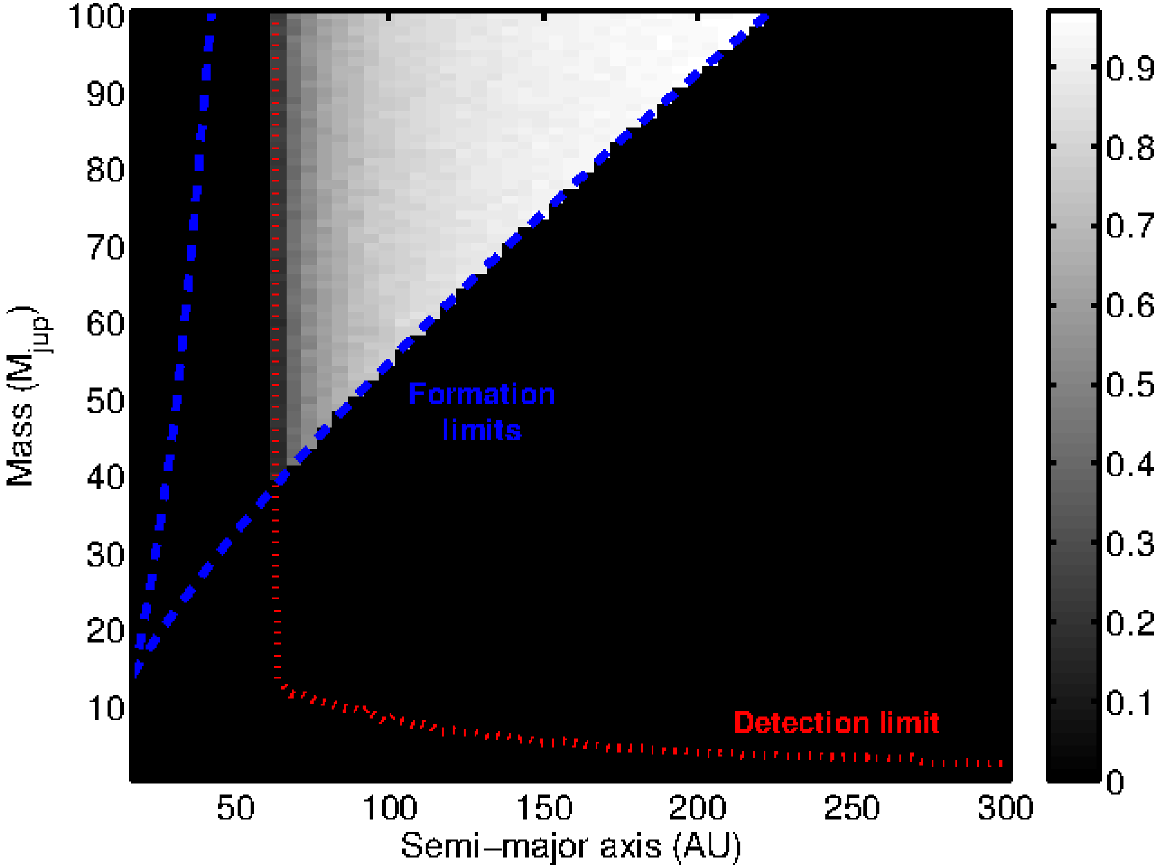
For any outer disk radius below 500 AU,
f_{max} is always lower than 9.9% at 99% confidence!

Conclusions

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

- Less than 9.99 % of FGKM stars form and retain in-situ companions within 500 AU trough disk instability at 99% confidence

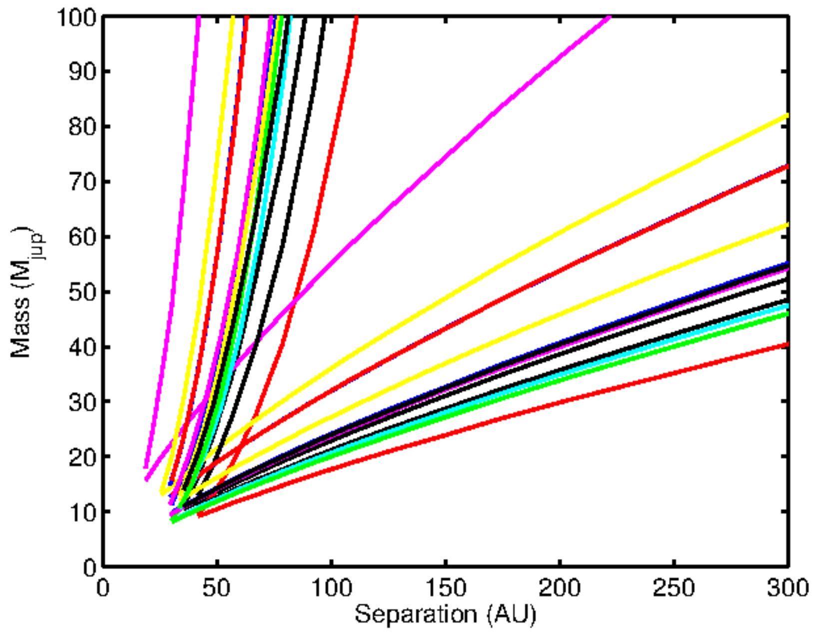
The value of the mass of the generated planet is compared to the detection limit at the corresponding projected separation, And a detection probability map is finally obtained.

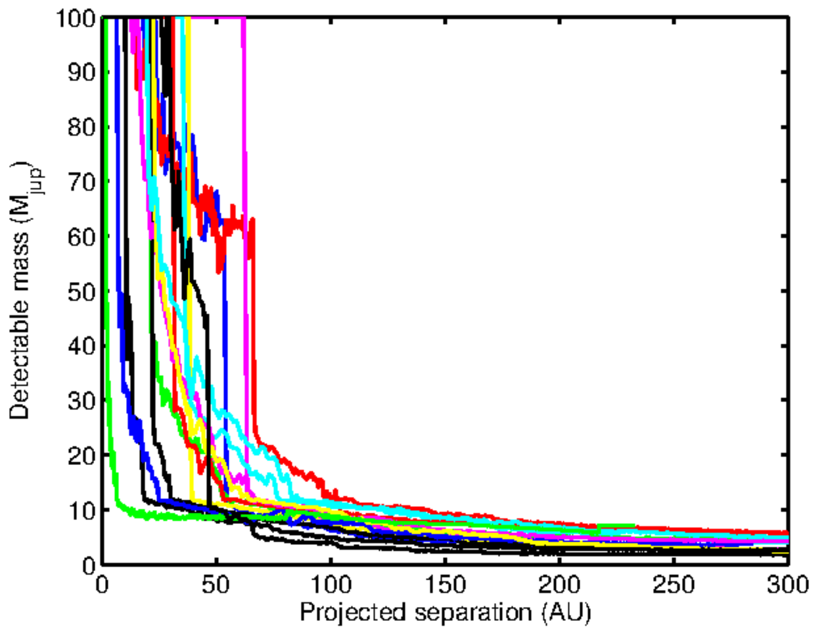


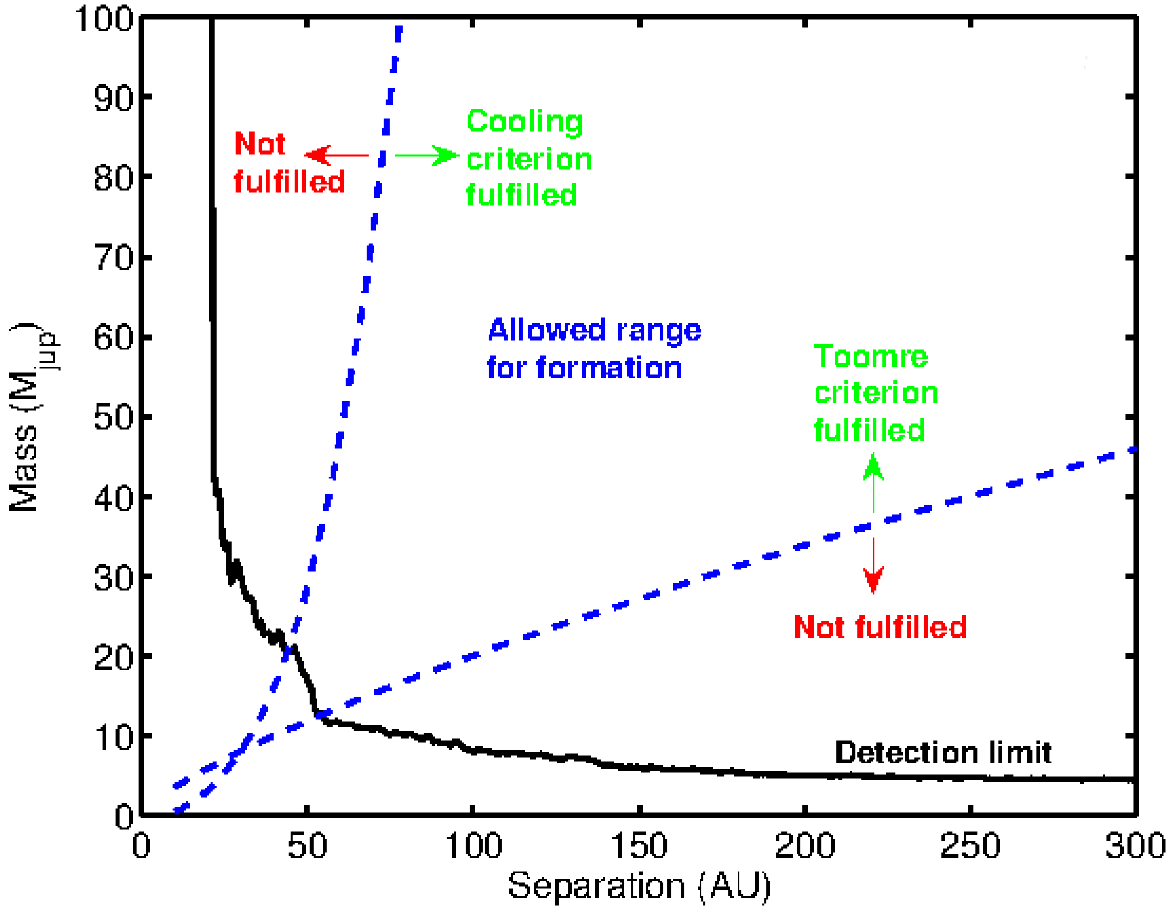
If the result of the survey is a null detection, the probability of detecting no companions, assuming f as a value of the expected frequency is given by

$$P = \prod_i 1 - f p_i$$

Results – I: Massive Stars






Not fulfilled
Cooling criterion fulfilled
Allowed range for formation
Toomre criterion fulfilled
Not fulfilled
Detection limit
Mass (M_{jup})
Separation (AU)
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300

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

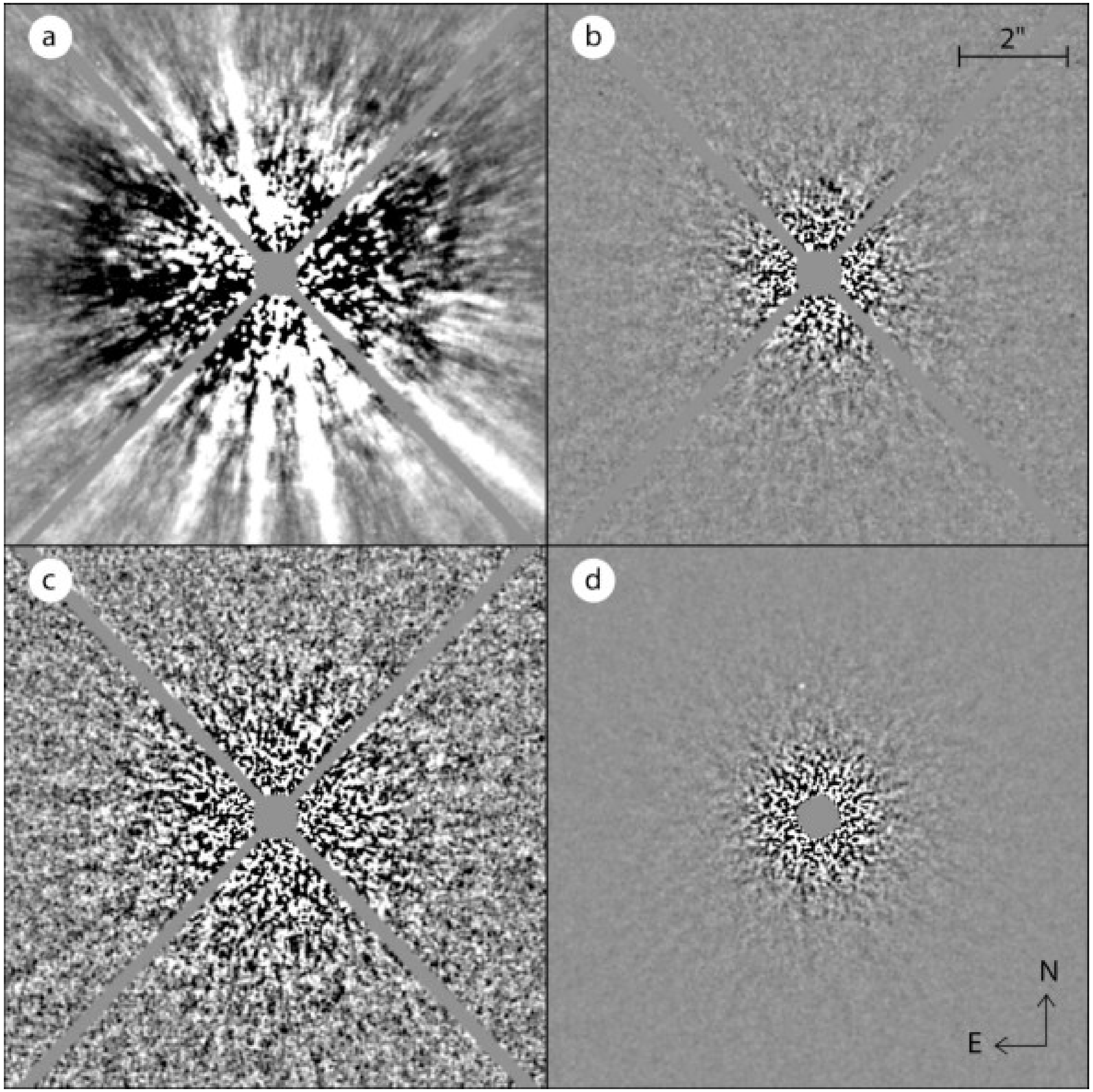


Figure from Lafreniere et al. 2007 ApJ 670.1367

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