

Deep imaging survey of nearby young A stars

Part of the International Deep Planet Search survey

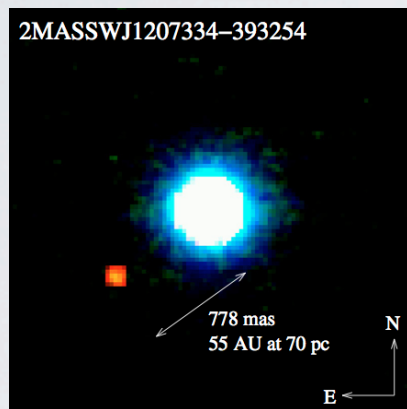
Arthur Vigan



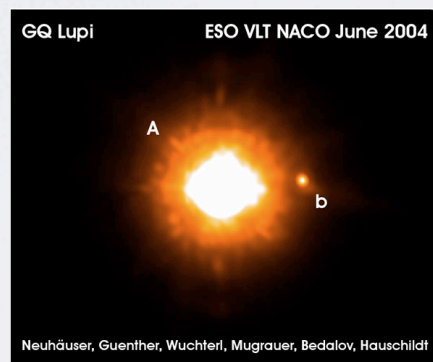
In collaboration with J. Patience, C. Marois, M. Bonavita, R. J. De Rosa, B. Macintosh, I. Song, R. Doyon,
B. Zuckerman, D. Lafrenière and T. Barman

Motivations

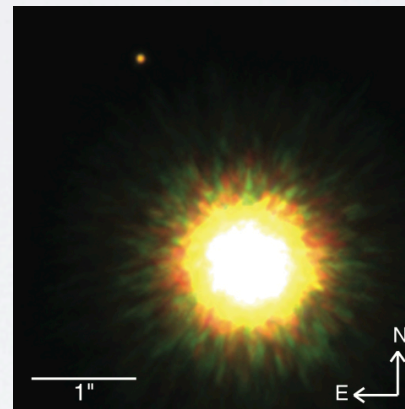
- Previous surveys focused on **Solar-type stars**
(Masciadri et al. 2005; Lafrenière et al. 2007; Kasper et al. 2007; Leconte et al. 2010; Chauvin et al. 2007)
- Very **few detections** of sub-stellar companions
→ 2M 1207, AB Pic, IRXS 1609, CT Cha, GQ Lup, ...



Chauvin et al. (2004)



Neuhauser et al. (2005)

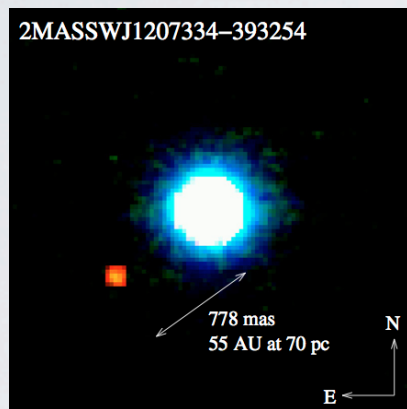


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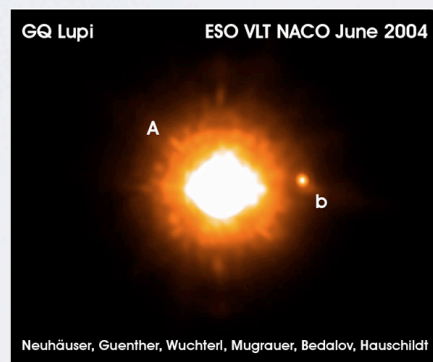
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(Janson et al. 2011) or **low-mass stars** (Delorme et al. 2012)

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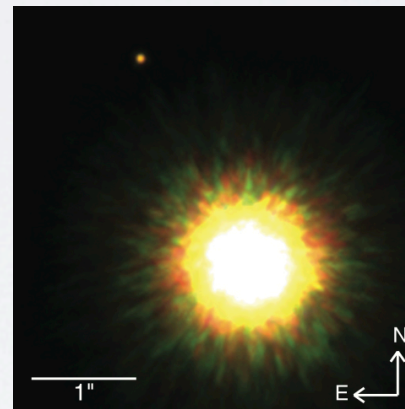
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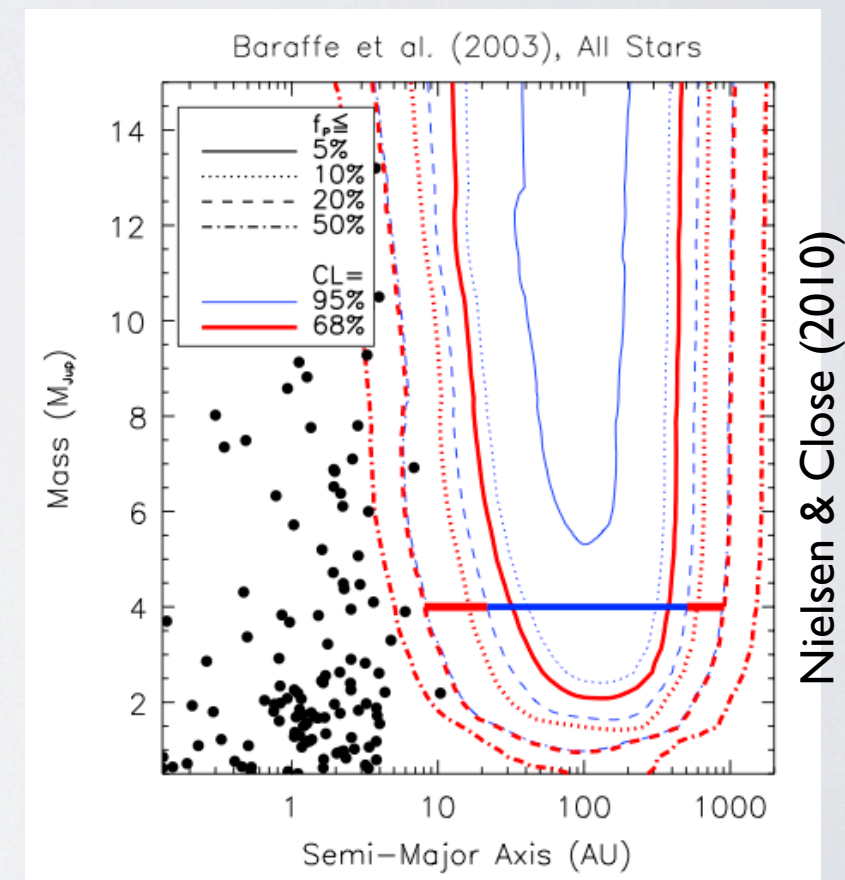


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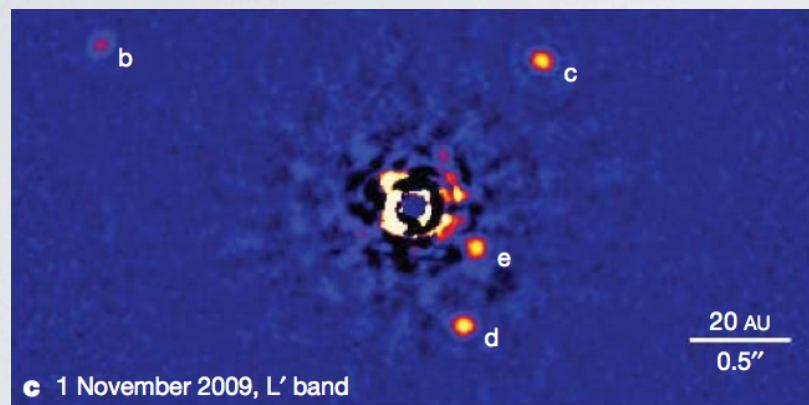


Main conclusion: **planets are rare** around FGKM stars

Motivations

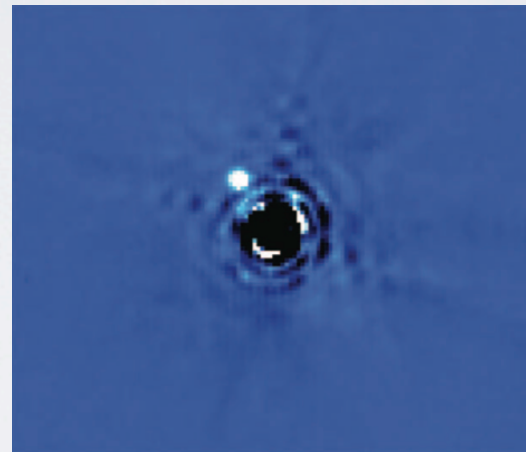
- Recent **breakthrough discoveries** around young A stars

HR 8799 - 30 Myr



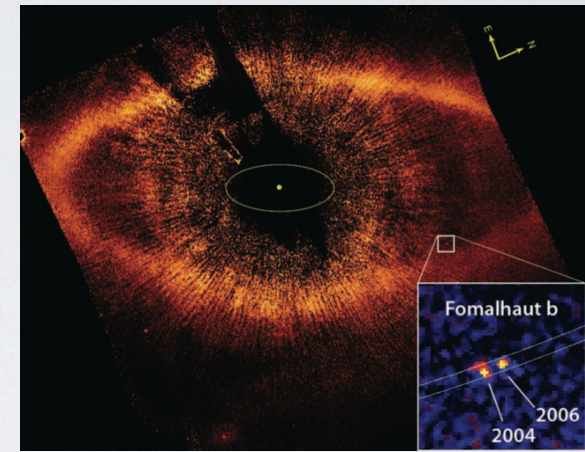
Marois et al. (2008, 2010)

β Pictoris - 12 Myr



Lagrange et al. (2010)

Fomalhaut - 100-300 Myr

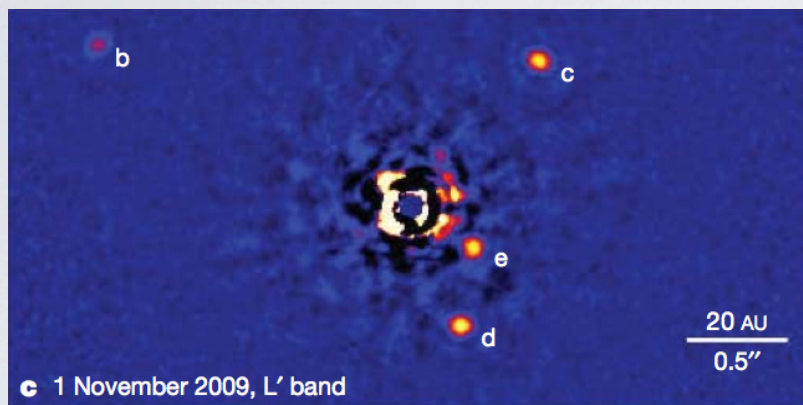


Kalas et al. (2008)

Motivations

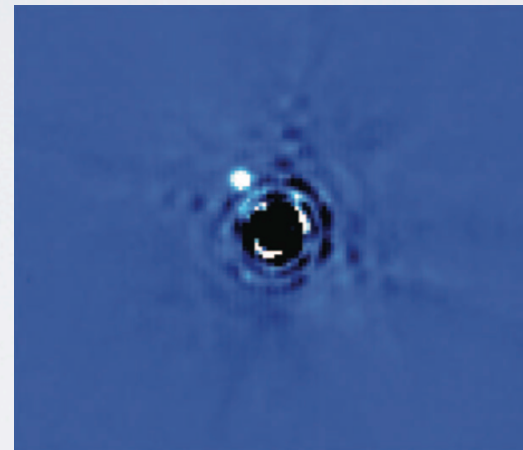
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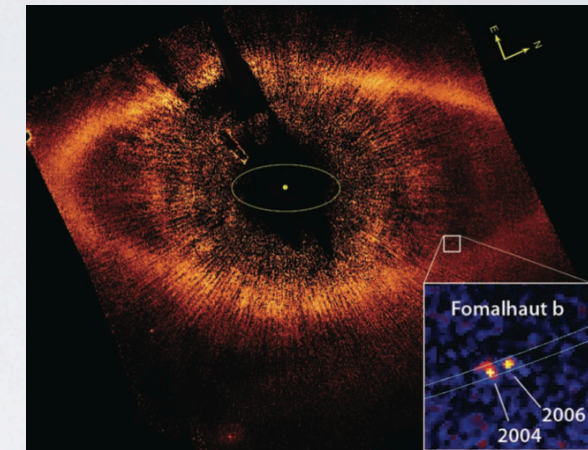
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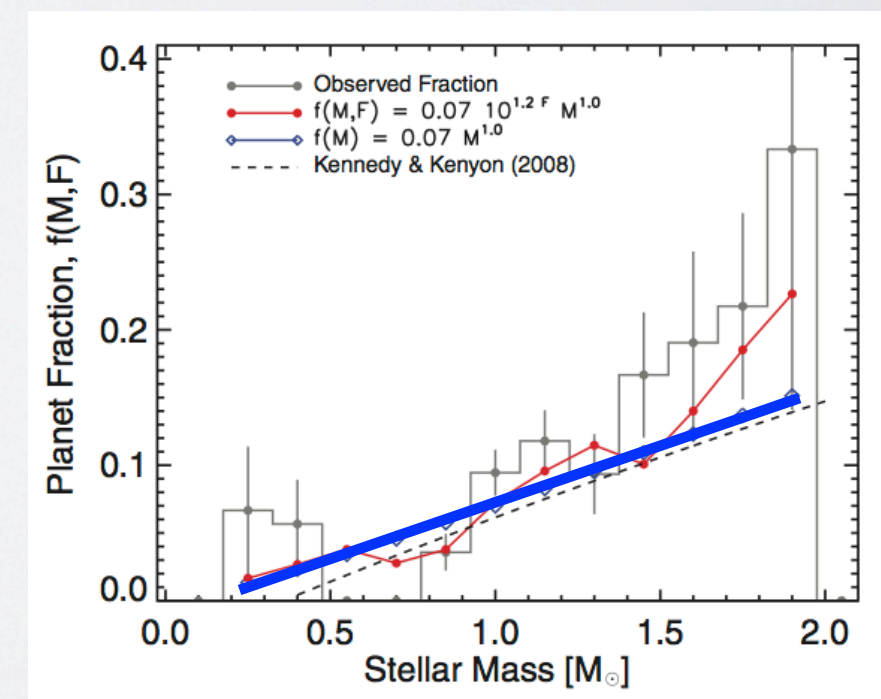
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- Recent discoveries of **RV planets around old A stars**

Lick and Keck subgiant surveys

(Johnson et al. 2010, 2011; Bowler et al. 2010)

→ strong **correlation** between stellar mass and planet mass



Johnson et al. (2010b)

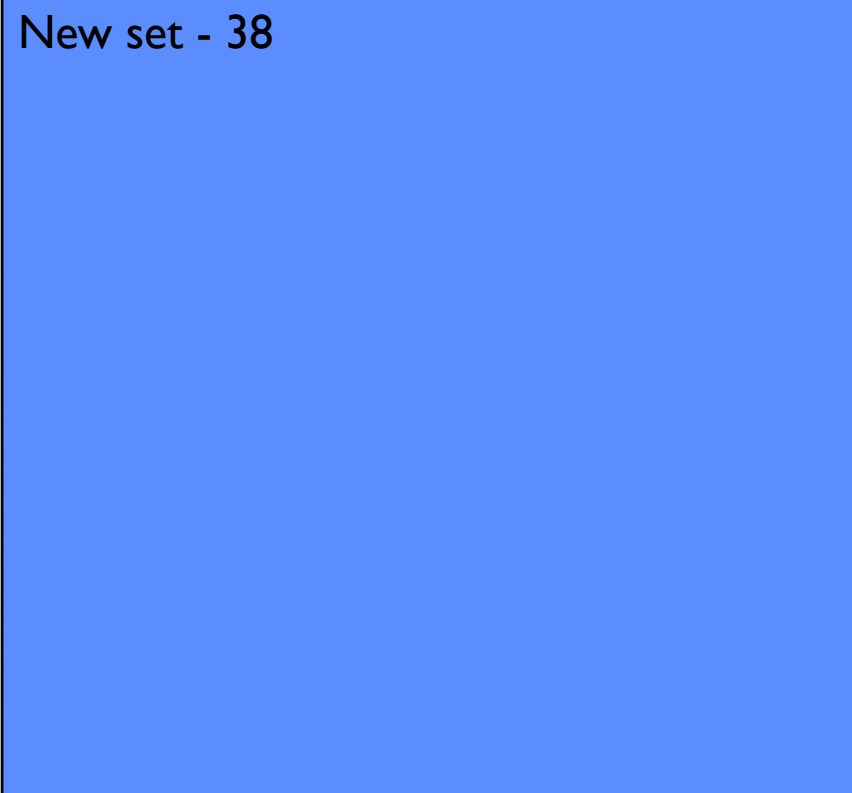
Exeter

Sample selection

- Our sample includes a total of 42 stars:
 - a **new set** of young (median age 100 Myr), nearby ($d \leq 85$ pc) A-stars (+4 early F)
 - A-stars previously observed in **planet-search surveys**

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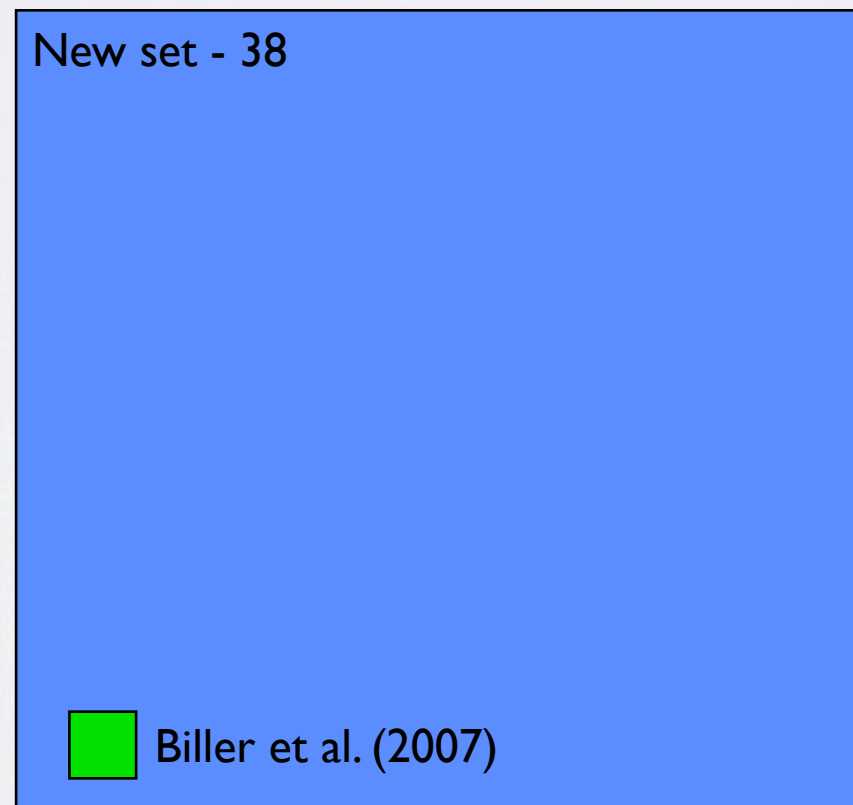
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New set - 38

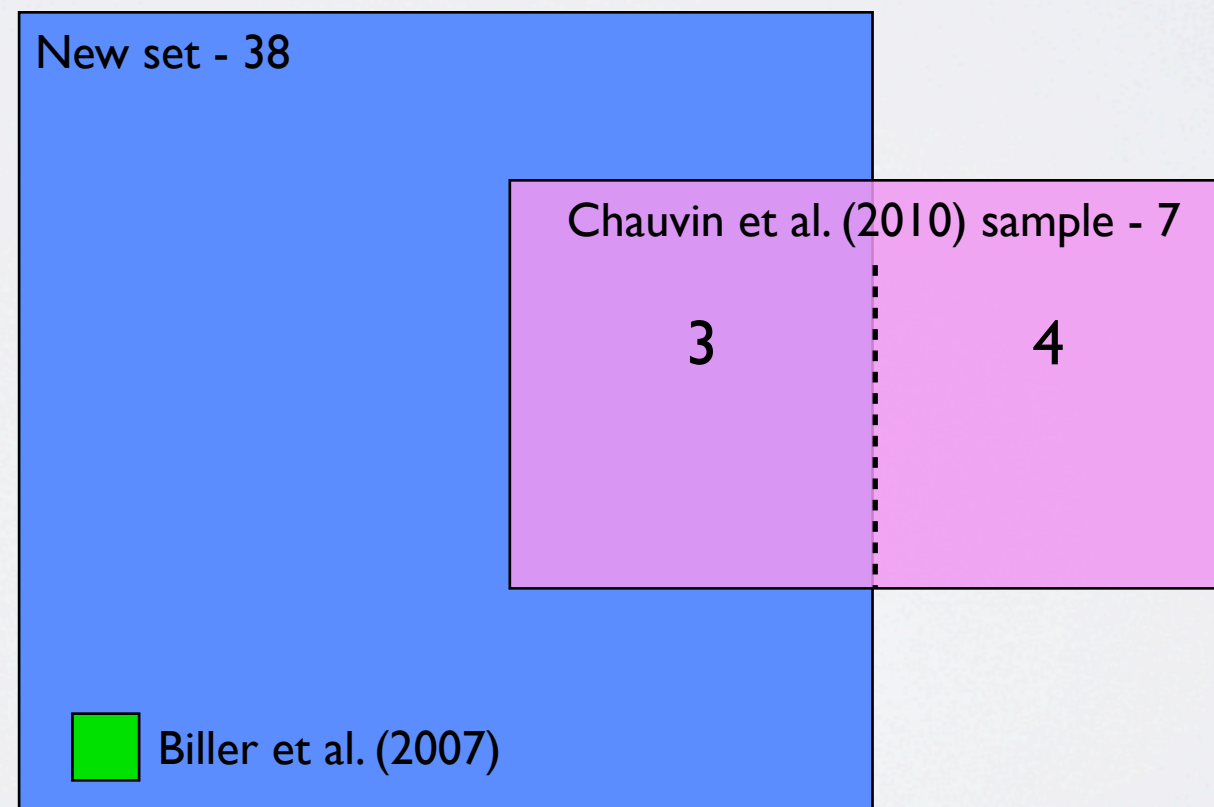
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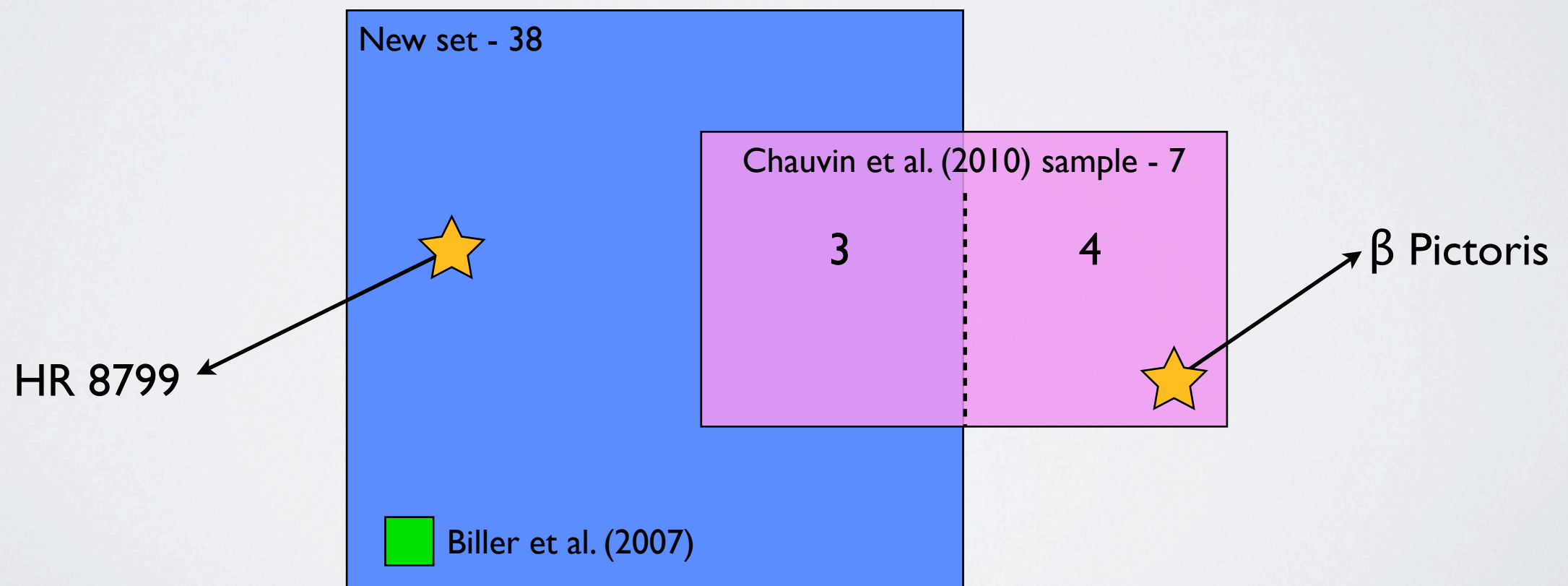
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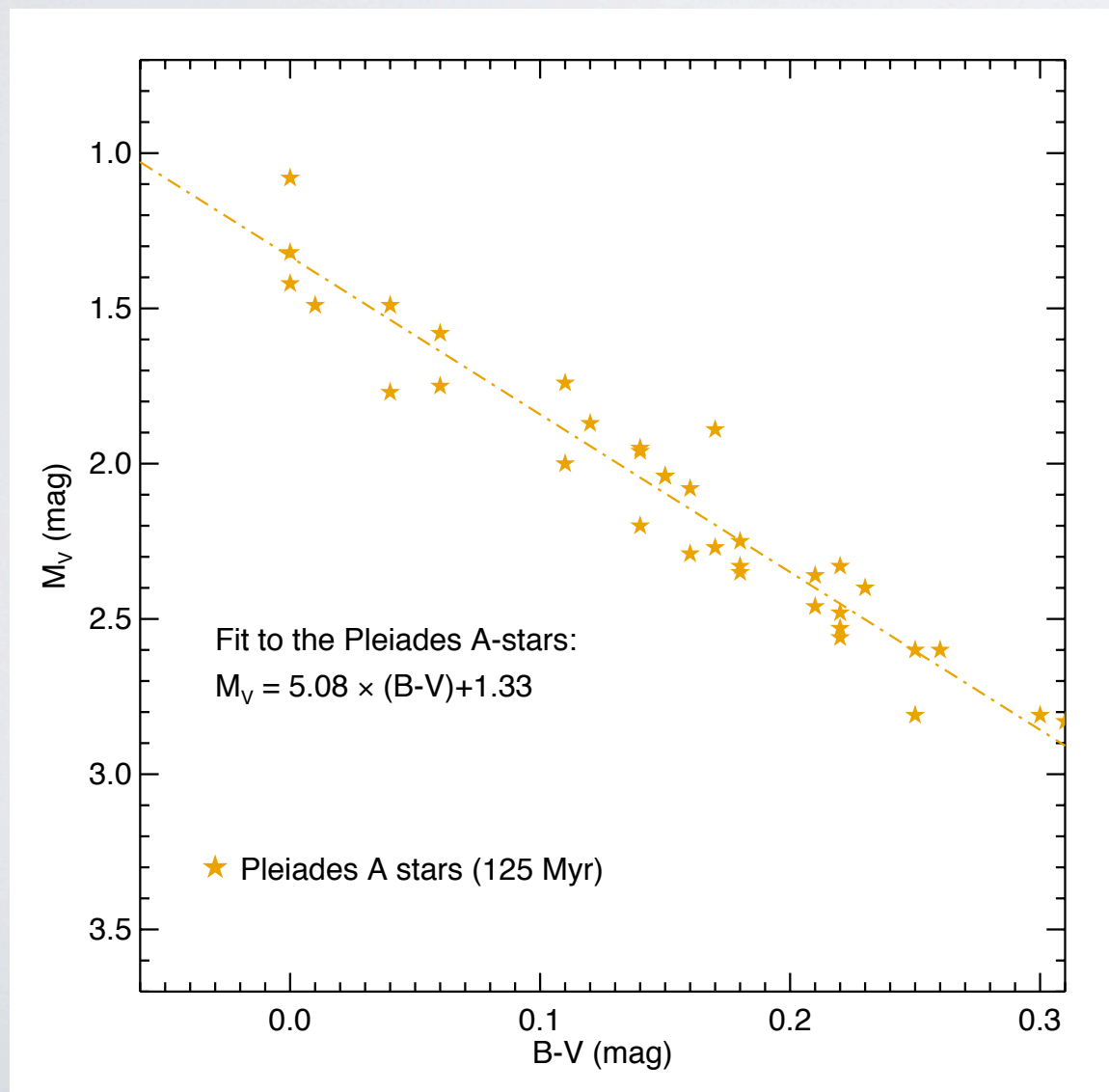
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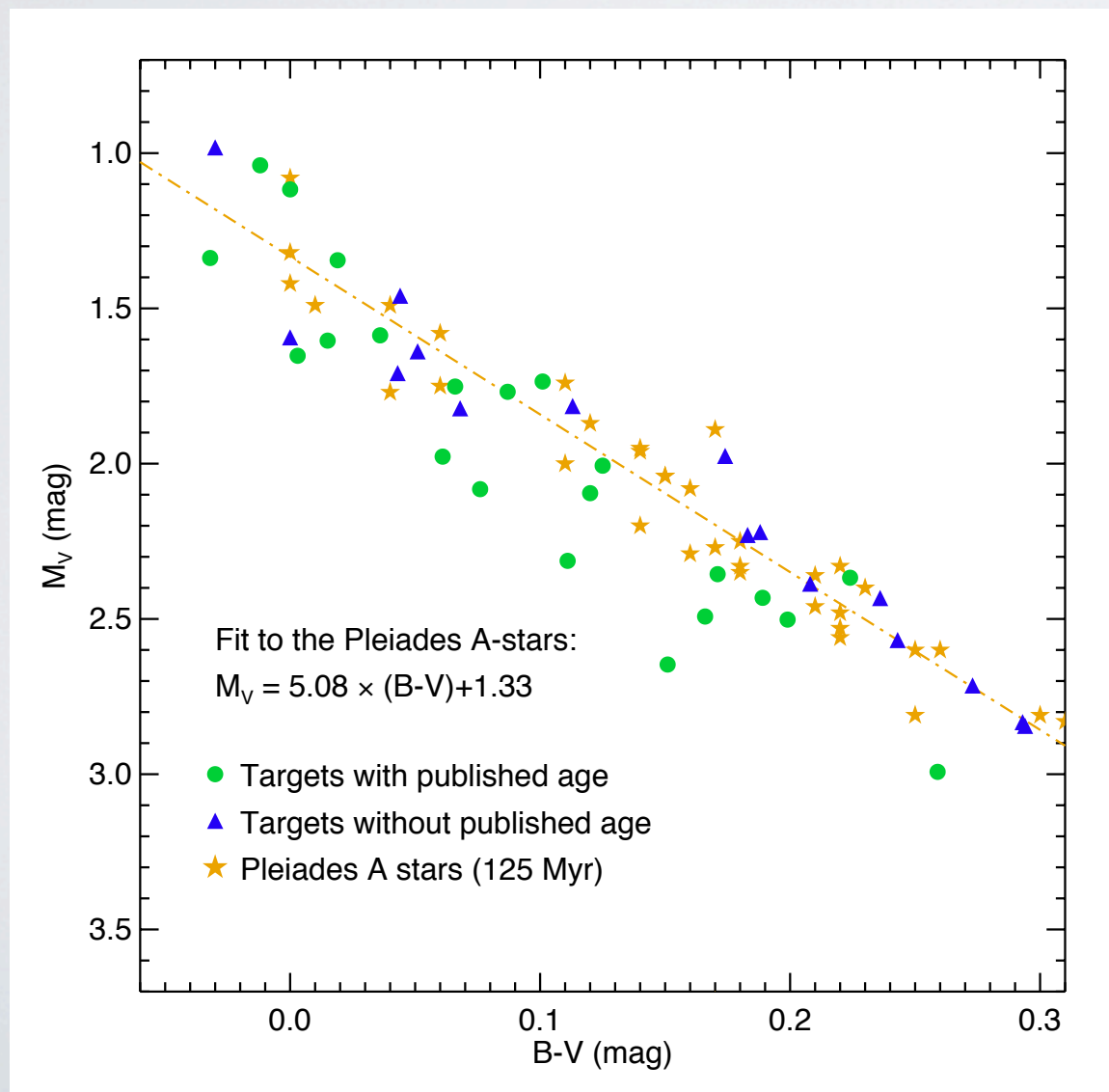
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 - initial **fit to the Pleiades** A-stars (125 Myr)
 - search for published ages in initial selection



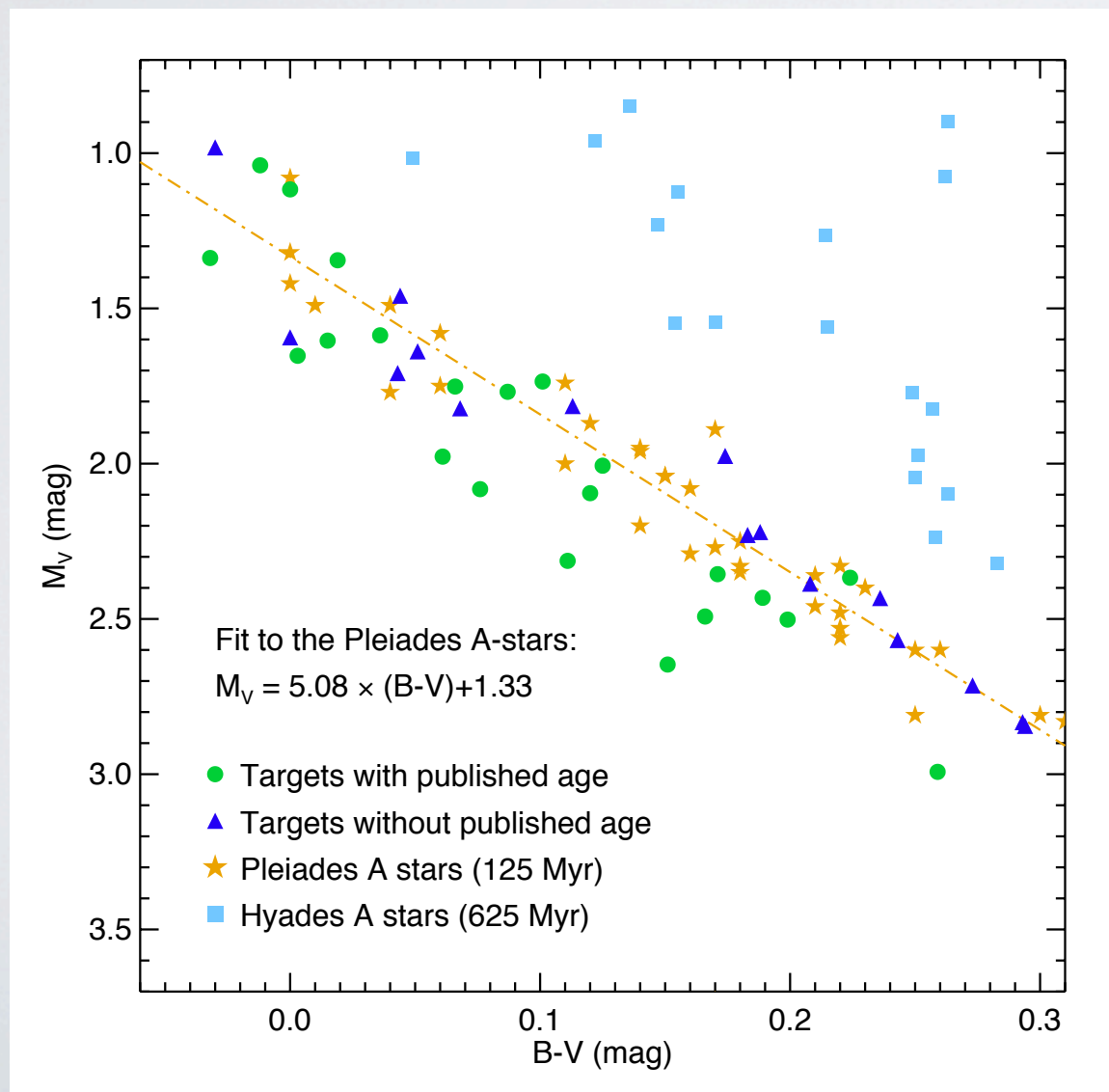
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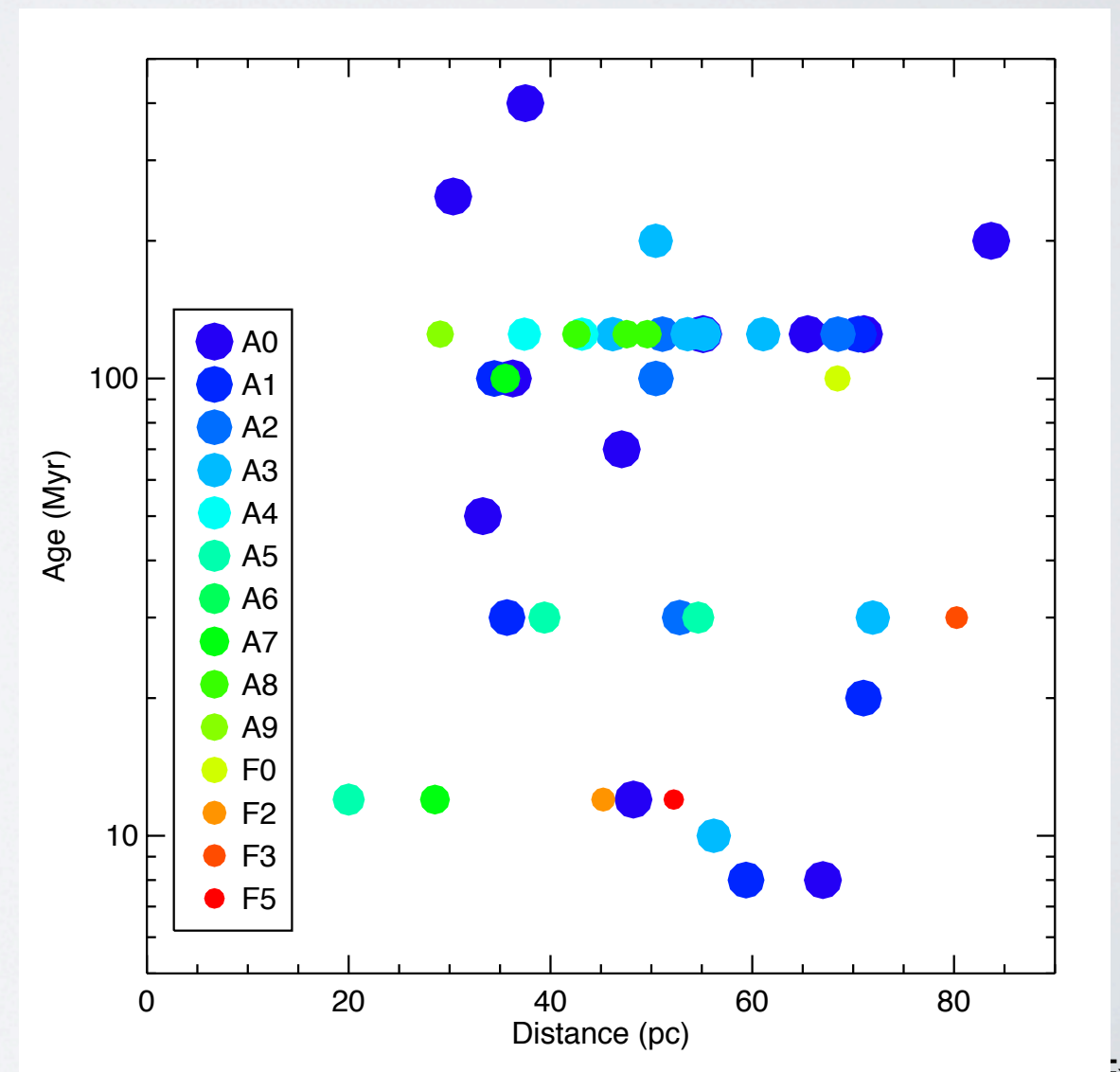
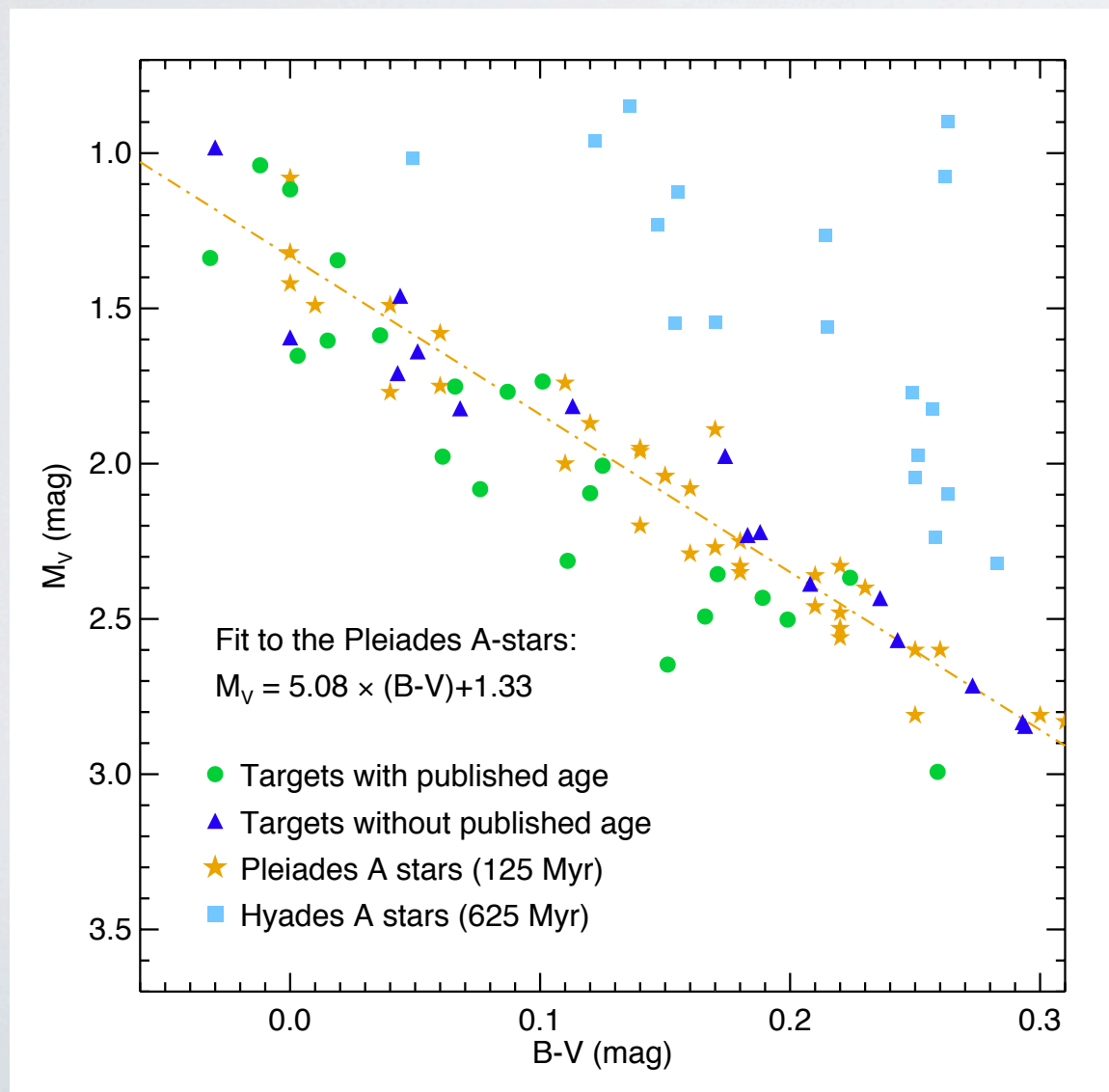
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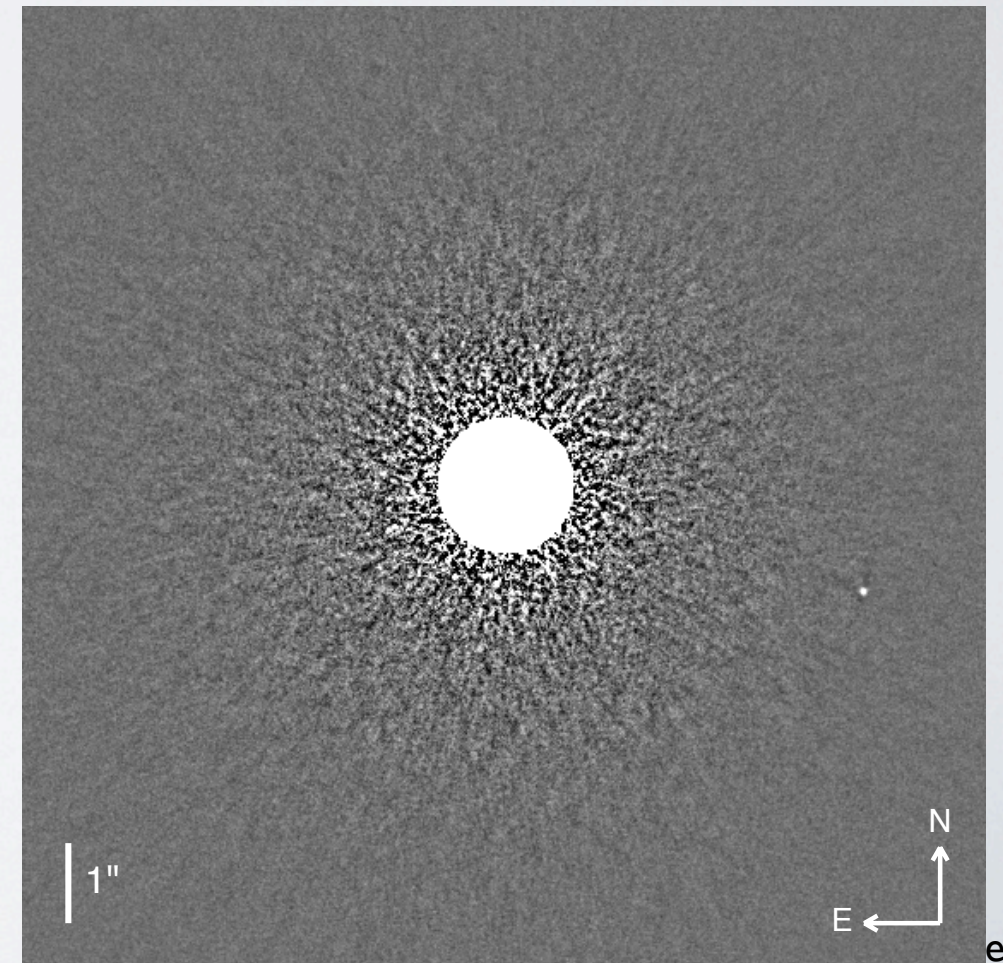
Observations

	<i>VLT/NaCo</i>	<i>Gemini/NIRI</i>
<i># of targets</i>	18	20
<i>Filters</i>	Ks	K' + CH4short
<i>Periods</i>	2009-2012	2007-2010
<i>Pixel size</i>	~13.20 mas	~21.4 mas
<i>Field of view</i>	~13.5''	~22''
<i>Config.</i>	pupil-tracking	field lens
<i>Mode</i>	saturated imaging	saturated imaging

- typical field of view rotation = 30°
- conditions from poor to excellent

Data reduction and analysis

- standard data reduction
- frame registration using Moffat profile fitting
- frame selection based on encircled energy and maximal flux
- unsaturated PSF used for normalization
- analysis of the data sets with LOCI:
 - $N_{\delta} = 0.75$ FWHM
 - $N_A = 300-500$ PSF footprints



Companion candidates

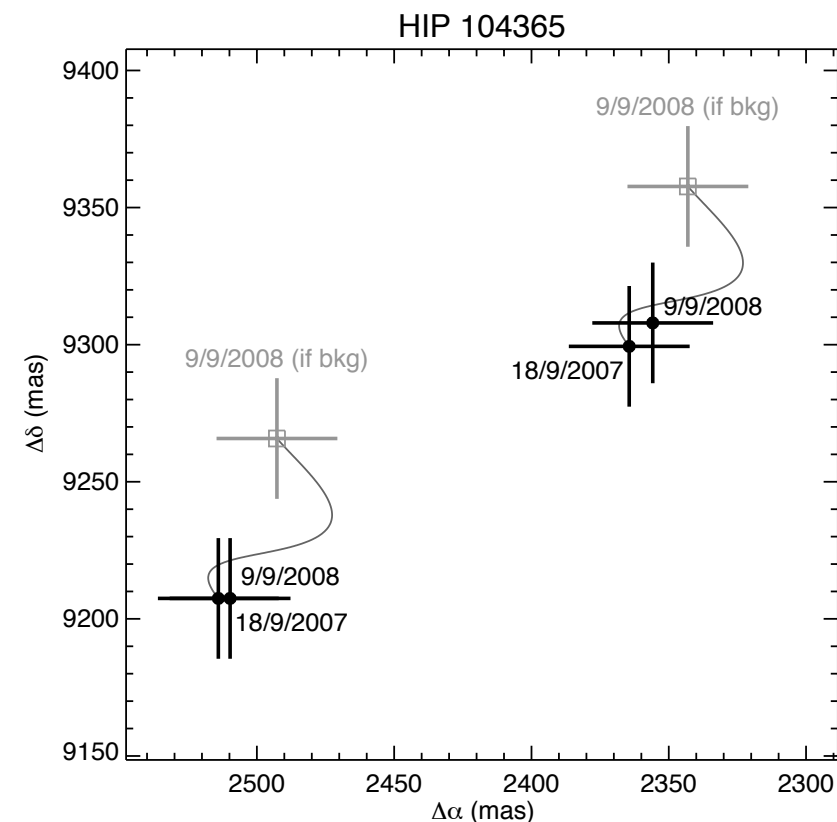
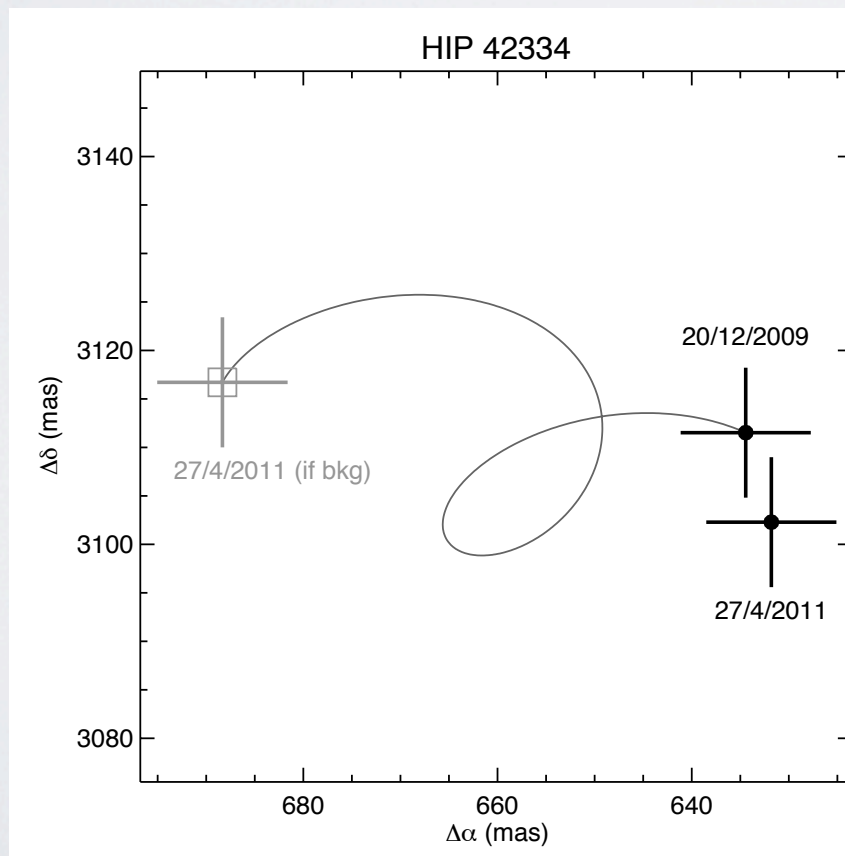
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- ~ 50 candidates $\geq 5\sigma$ around 22 of the targets
- second epoch for candidates with separation ≤ 320 AU
- no new substellar companions

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HIP 42334
- A0V
- 125 Myr
- 71 pc

M7/M8
companion

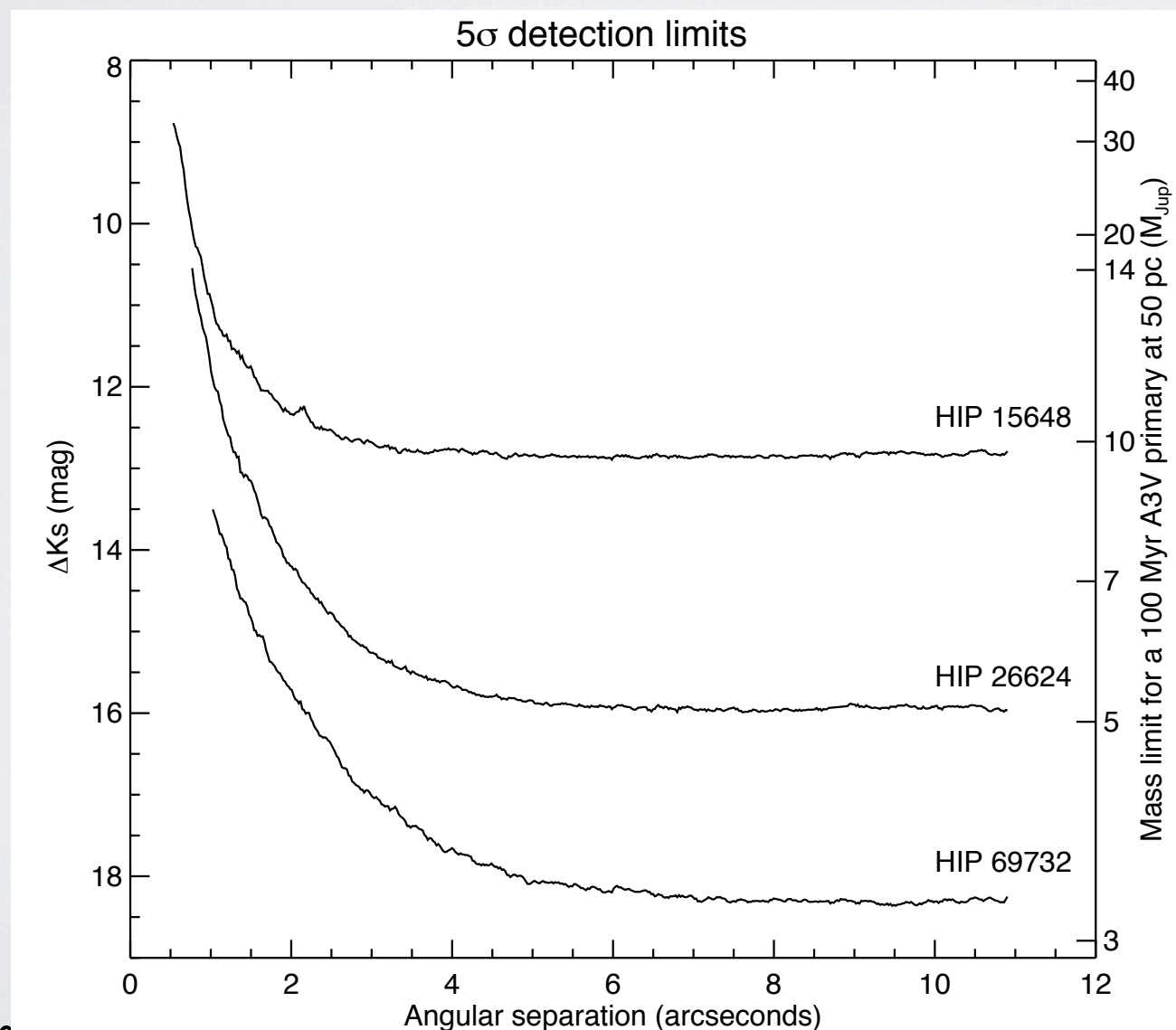


HIP 104365
- A0V
- 125 Myr
- 55 pc

M6/M7
companions

Detection limits

- **noise in annuli** of increasing radius $\rightarrow$ 5σ detection limits
- normalisation by **unsaturated PSF** obtained with neutral density (NaCo) or narrow-band filters (NIRI)



Median target of the sample

- A3V

- 100 Myr

- 50 pc

$\rightarrow$ reach 3-10 M_{Jup}

Statistical analysis

- What statistical properties can be inferred from the data?
- Previous surveys have used **non-detections** to:
 - set **upper limits** on the fraction of stars with planets
 - set constraints on the population of planets at wide separation
- Now that there are detections... what can we say?

Statistical formalism

- Formalism of Carson et al. (2006) and Lafrenière et al. (2007)
- Likelihood of the data given f :

$$L(\{d_j\}|f) = \prod_{j=1}^N (1 - fp_j)^{1-d_j} \cdot (fp_j)^{d_j}$$

- Probability of f given our data (Bayes' theorem):

$$p(f|\{d_j\}) = \frac{L(\{d_j\}|f) \cdot p(f)}{\int_0^1 L(\{d_j\}|f) \cdot p(f) df},$$

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posterior
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prior

Choice of the prior:

- linear-flat, “maximum ignorance”
- but **log-flat** is more natural

Statistical formalism

- **posterior distribution** used to determine $f_{\min}$ / $f_{\max}$ with a confidence level α :

$$\alpha = \int_{f_{\min}}^{f_{\max}} p(f|\{d_j\})df,$$

- Since we have detections, an **equal-tail confidence interval** is calculated:

$$\frac{1 - \alpha}{2} = \int_{f_{\max}}^1 p(f|\{d_j\})df$$
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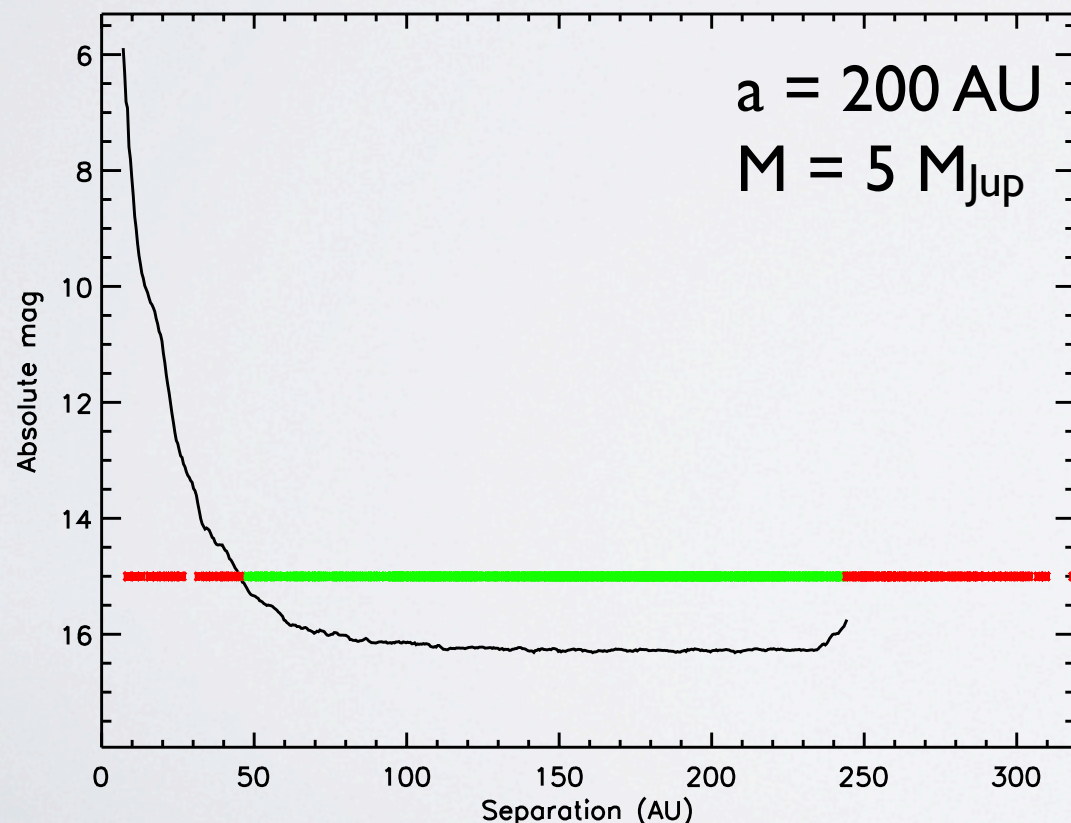
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**Numerical
integration to
obtain $f_{\min}$ and $f_{\max}$**

Monte-Carlo simulations

- MC simulations are used to estimate p_j
- **MESS tool** (Bonavita et al. 2012) was used
- generation of 10^4 planets at each point of a grid in mass/SMA
- other orbital parameters are randomly chosen

$$L(\{d_j\}|f) = \prod_{j=1}^N (1 - f p_j)^{1-d_j} \cdot (f p_j)^{d_j}$$



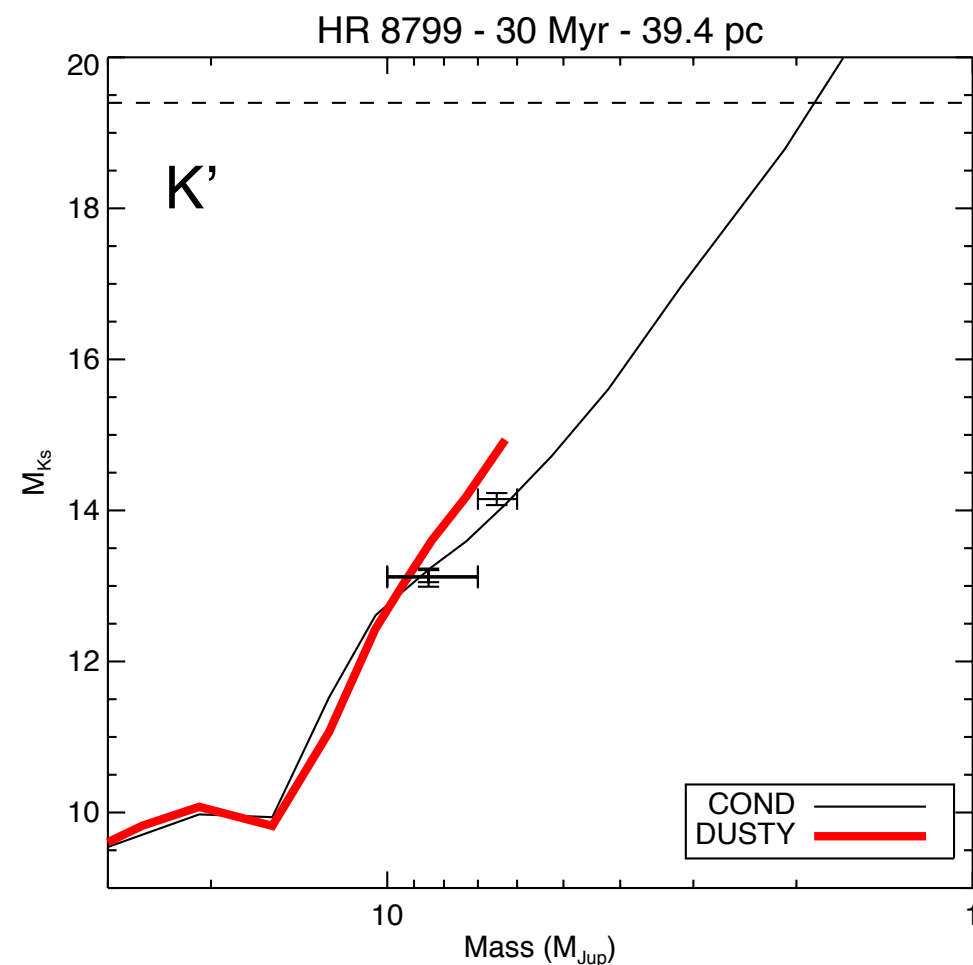
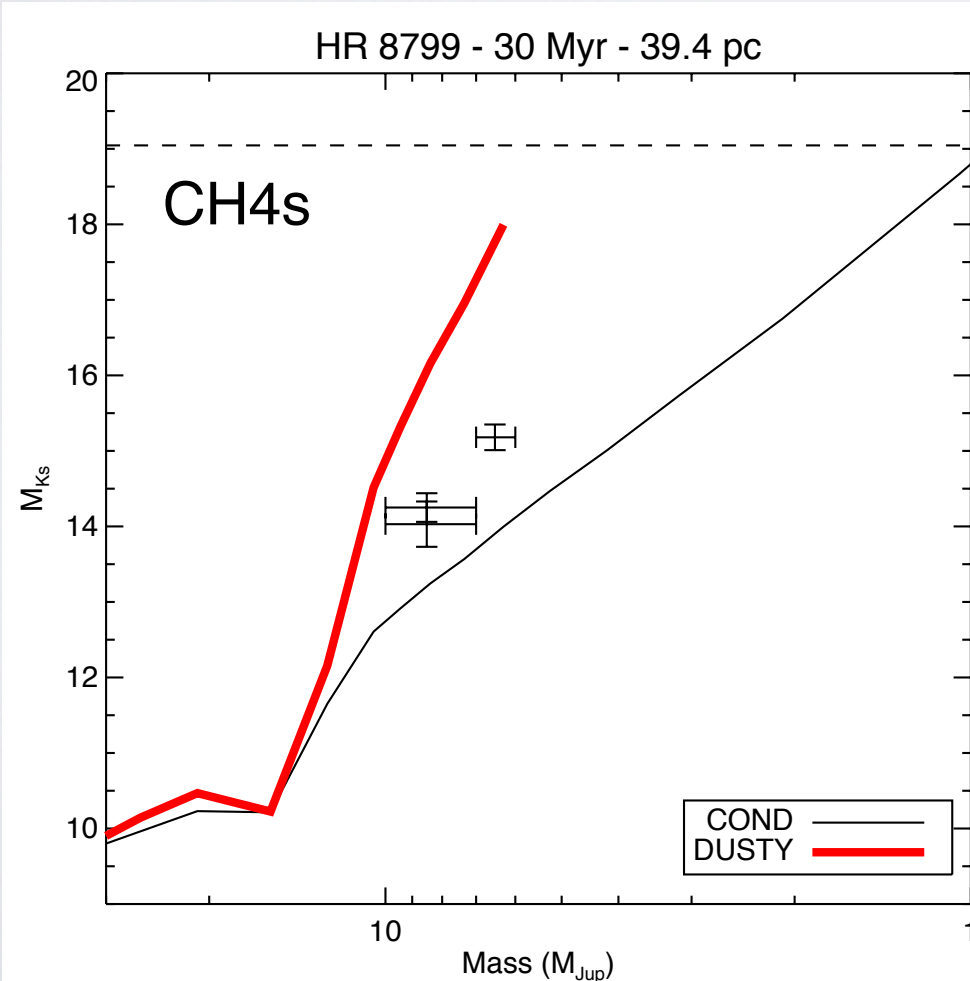
mass to mag

→ **COND models** (Baraffe et al. 2003)

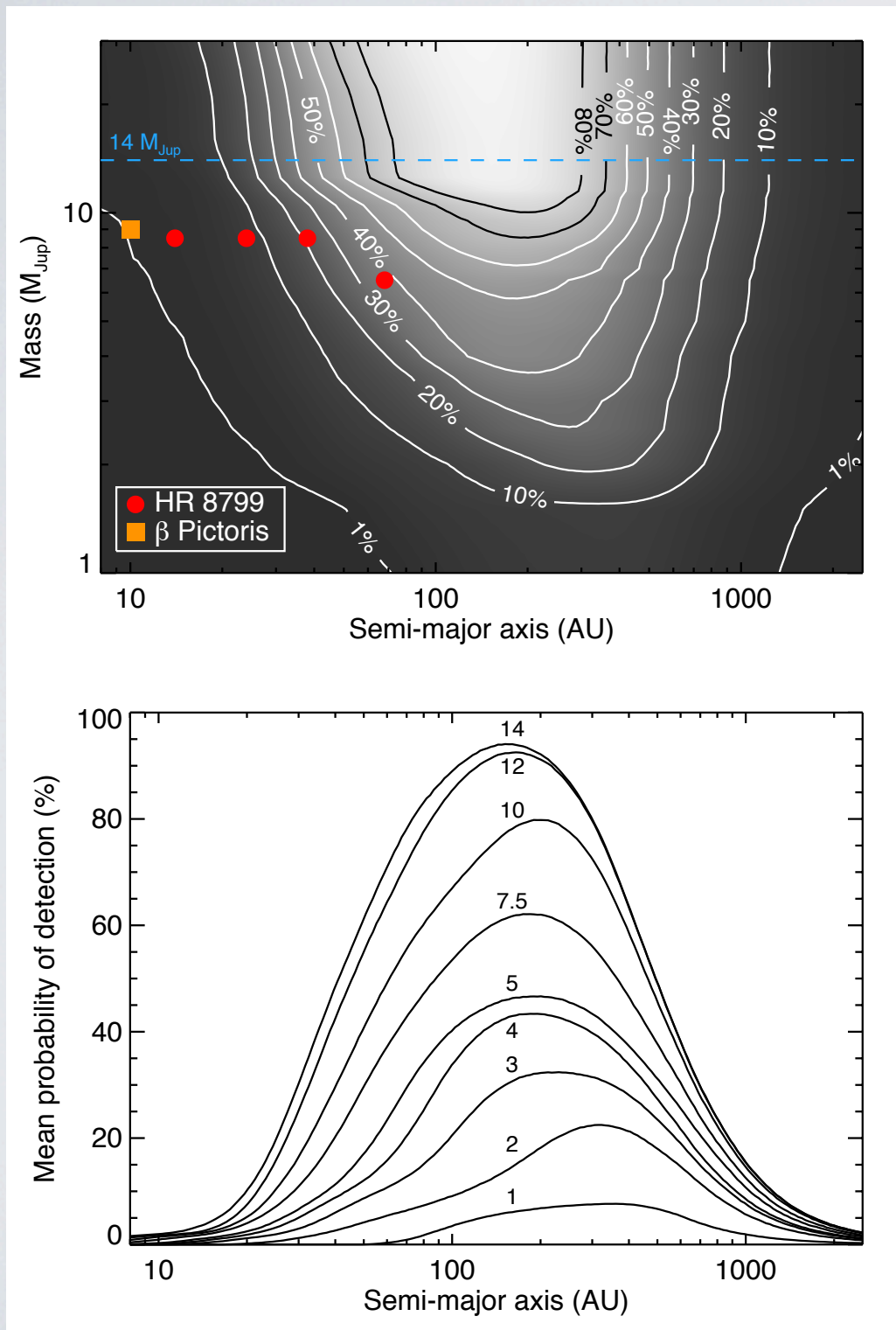
p_j = fraction of detected planets

Choice of evolutionary models

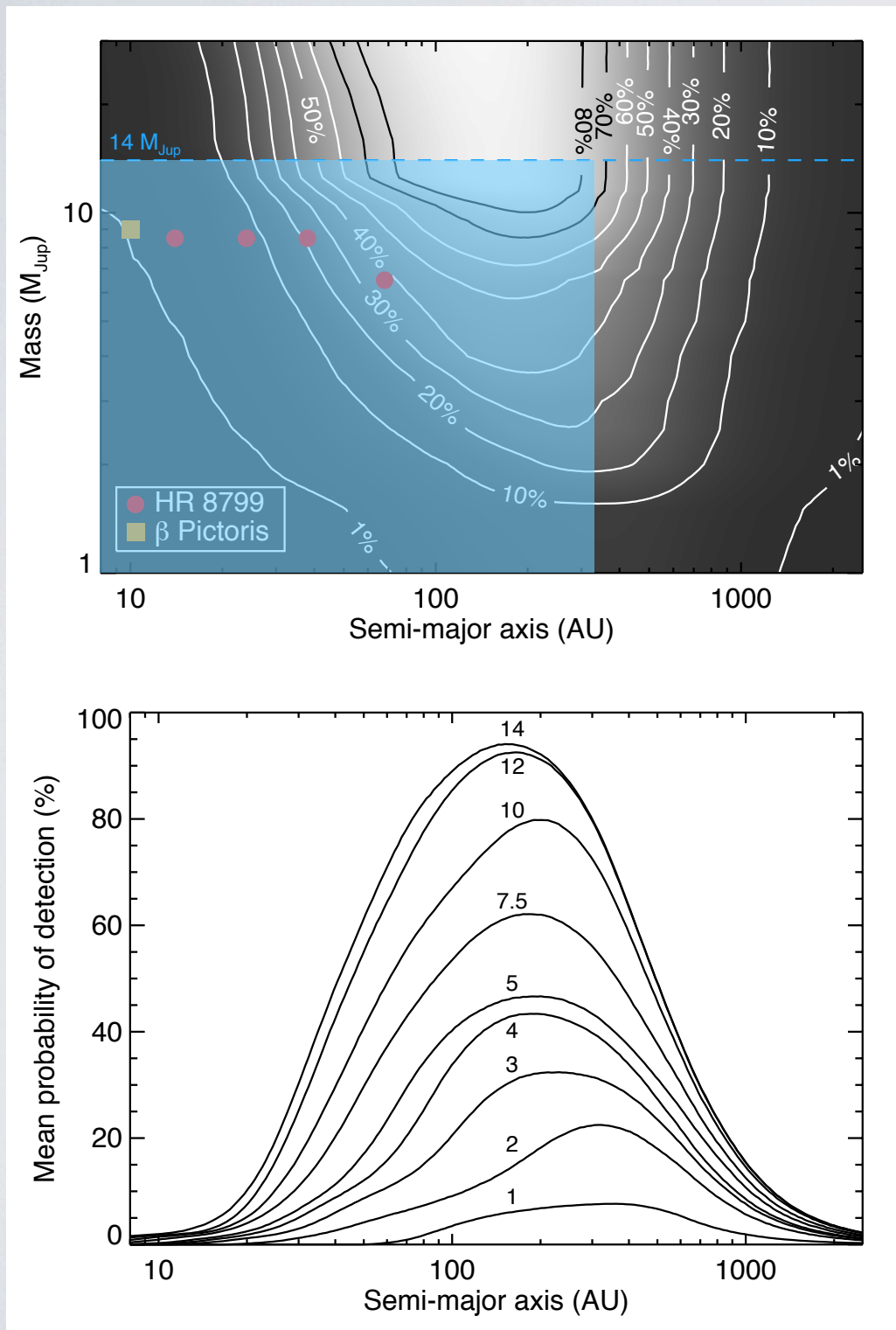
- only COND are going deep enough
- COND are in agreement with data in Ks, but less in CH4s
- main effect: **underestimation of detectable masses**, increasing with obs. depth (i.e. with angular separation)



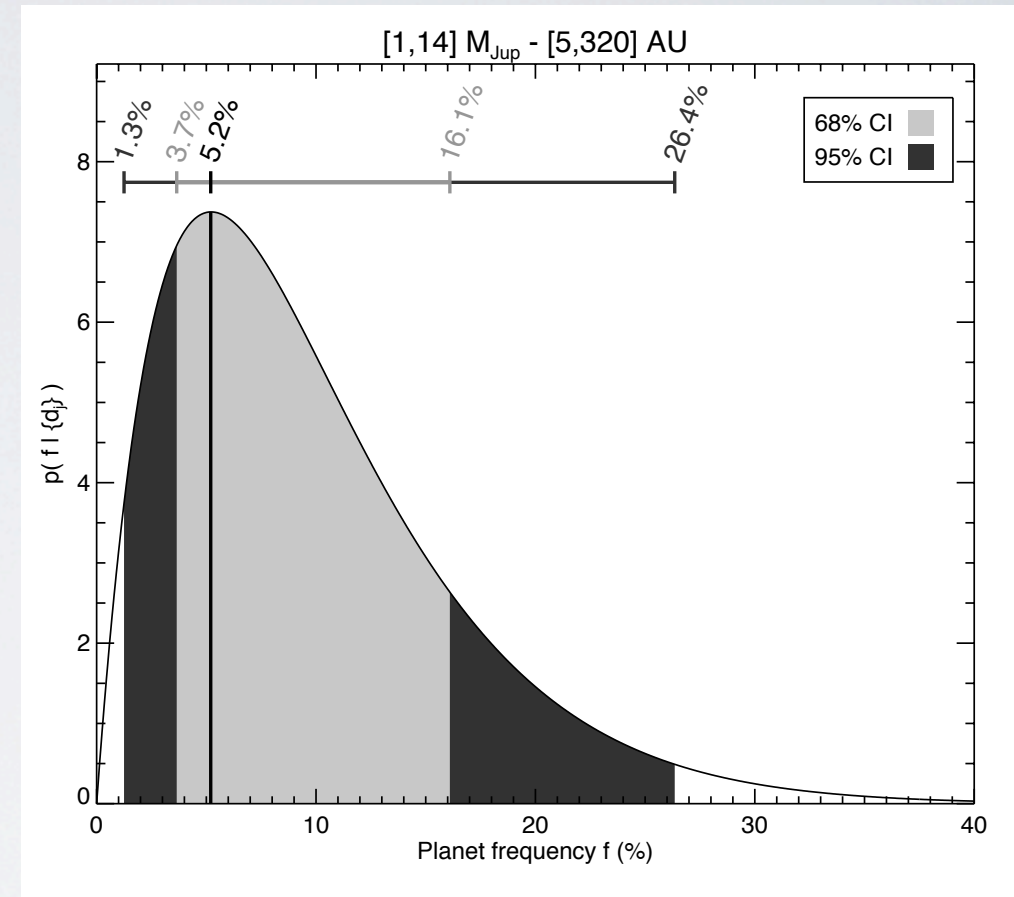
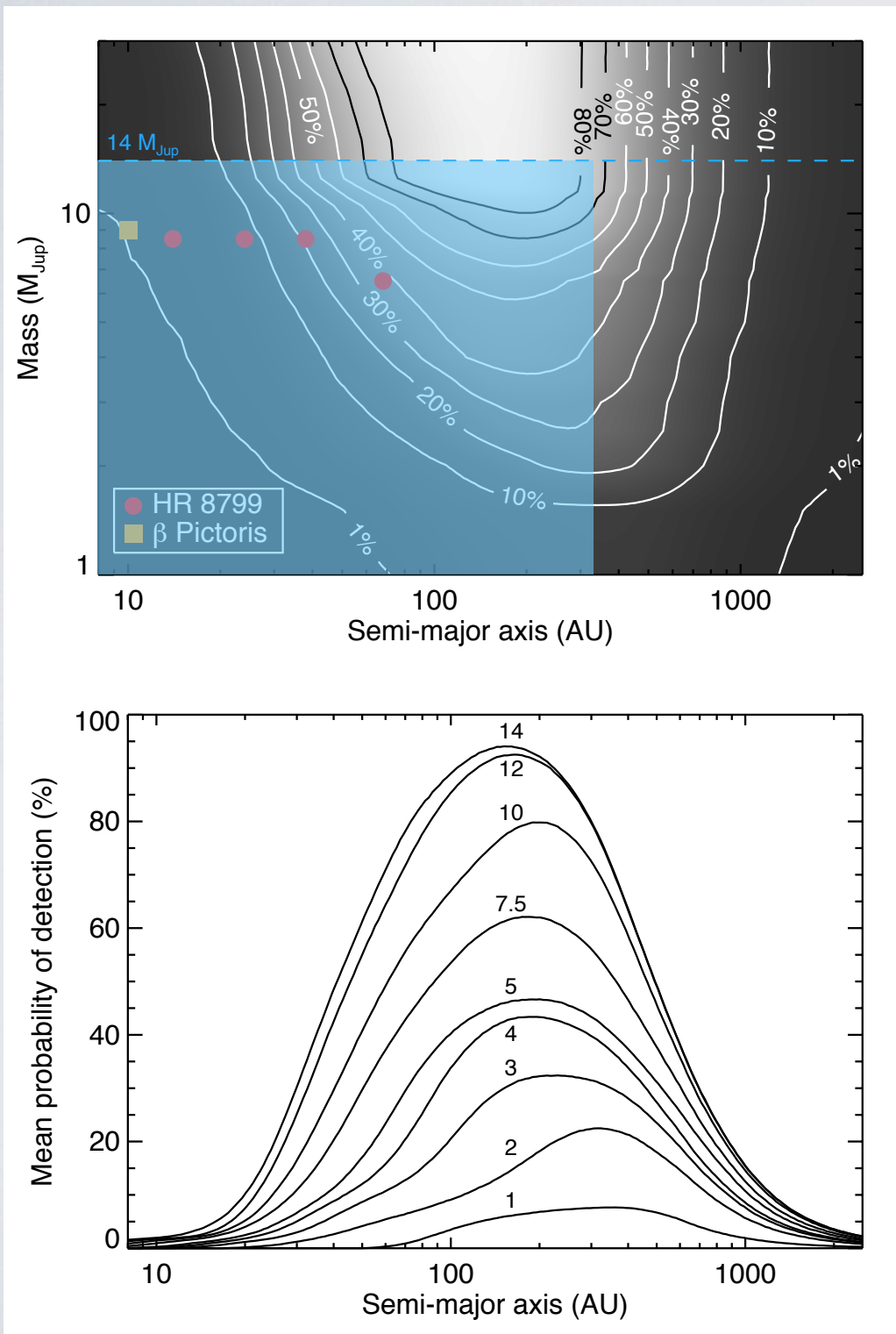
Wide-orbit planets frequency



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$f \in [3.7\%, 16.1\%]$ at 68% confidence

$f \in [1.3\%, 26.4\%]$ at 95% confidence

- $1 M_{\text{Jup}} \leq \text{mass} \leq 14 M_{\text{Jup}}$

- $5 \text{ AU} \leq a \leq 320 \text{ AU}$

β Pic: to include or not to include?

That is a good question!

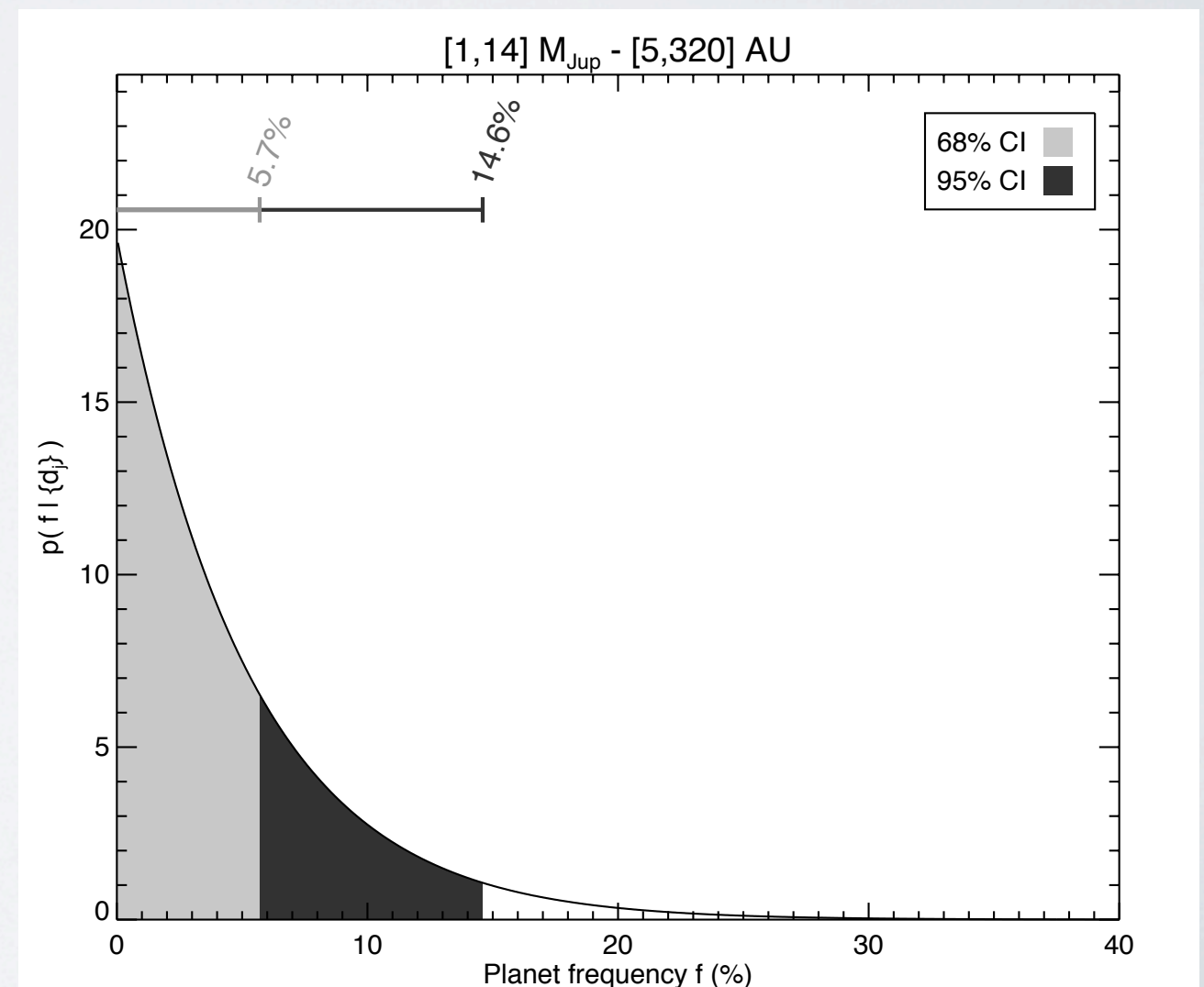
- borderline case
- β Pictoris was part of Chauvin et al. (2010) survey...
... but planet **detected by chance** in earlier data
... and **confirmed later on!**
- what happens if it's not included in the statistics?

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log-flat prior:
! detection is not enough to
constrain the lower limit!



Constraints on wide-orbit planets population

- Extrapolation of RV survey results
- **Solar-type stars** → Cumming et al. (2008) measure

$$f = 10.5\%$$

for $0.3-10 M_{\text{Jup}}$ planets with $P < 1826$ days

$$dN \propto M^{-1.31} dM$$

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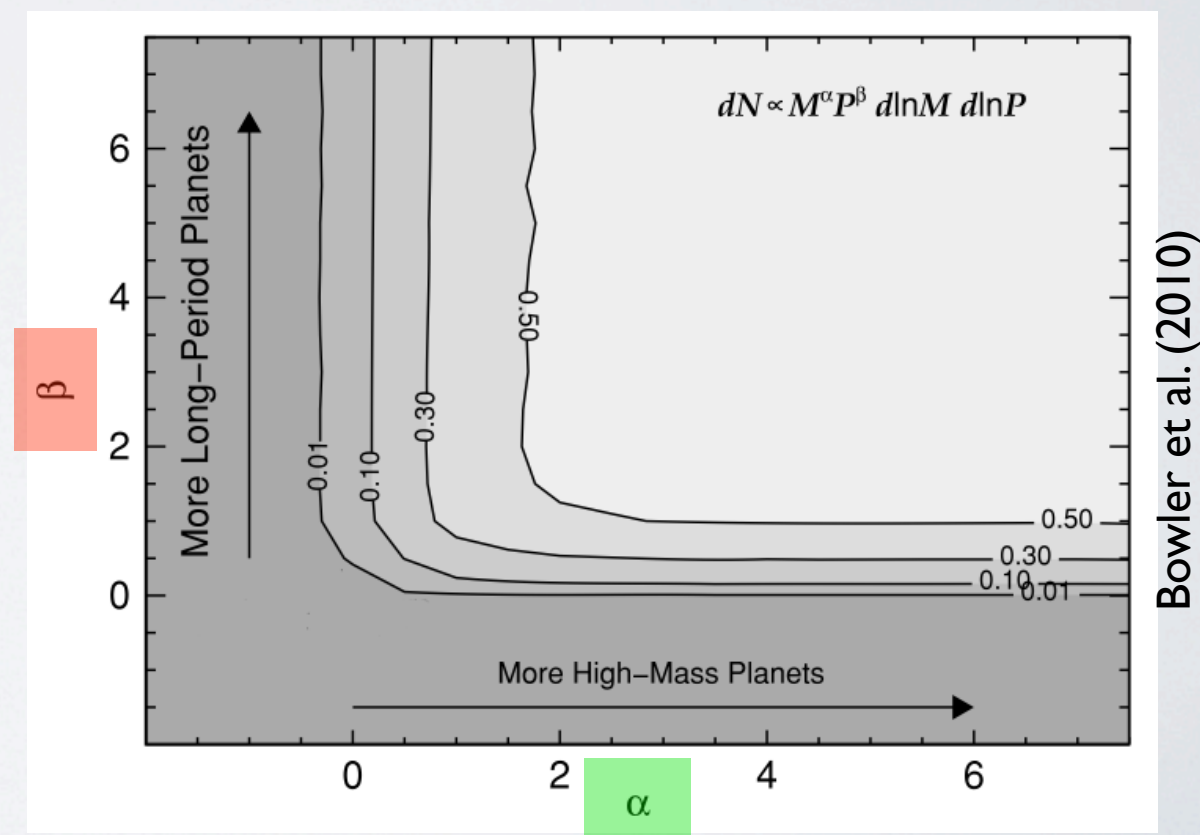
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- **Early-type stars** (old stars)

→ Johnson et al. (2010)
measure $f = 11 \pm 2\%$
for $0.5\text{--}14 M_{\text{Jup}}$ in $0.1\text{--}3.0$ AU

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some constraints on α and β



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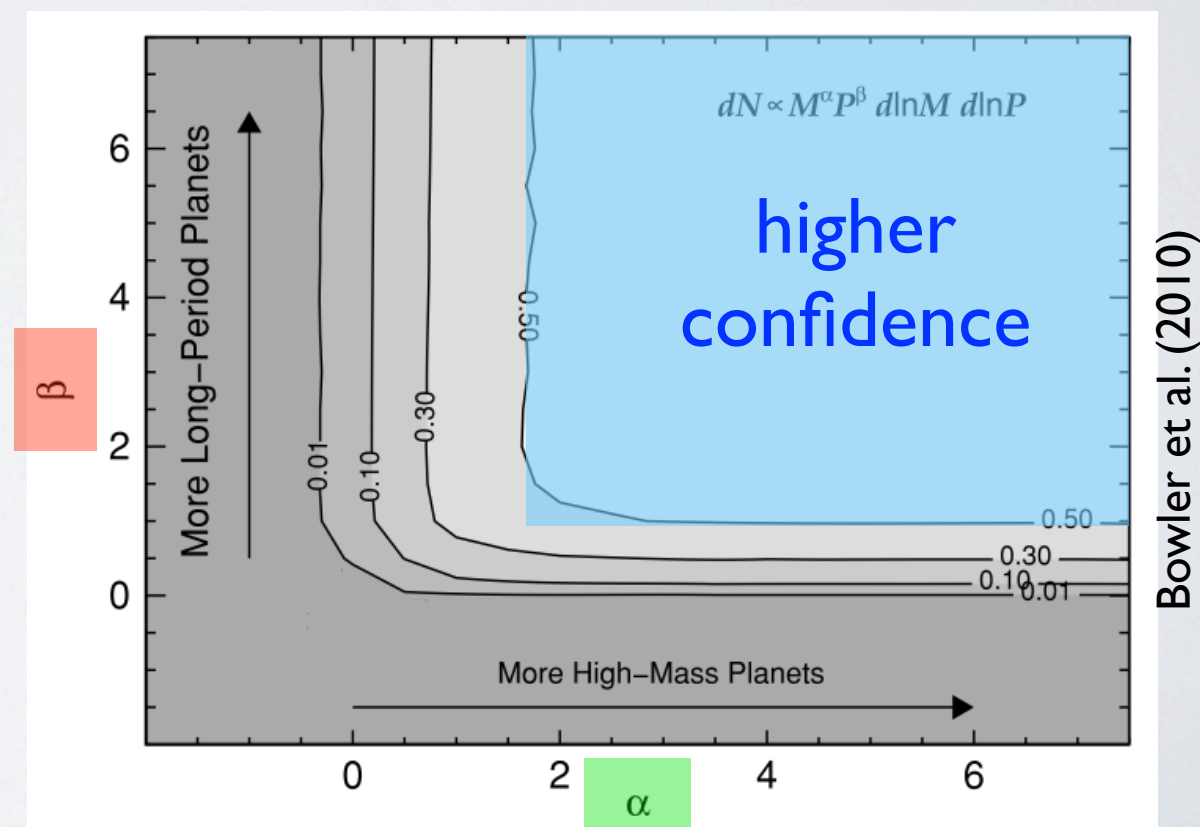
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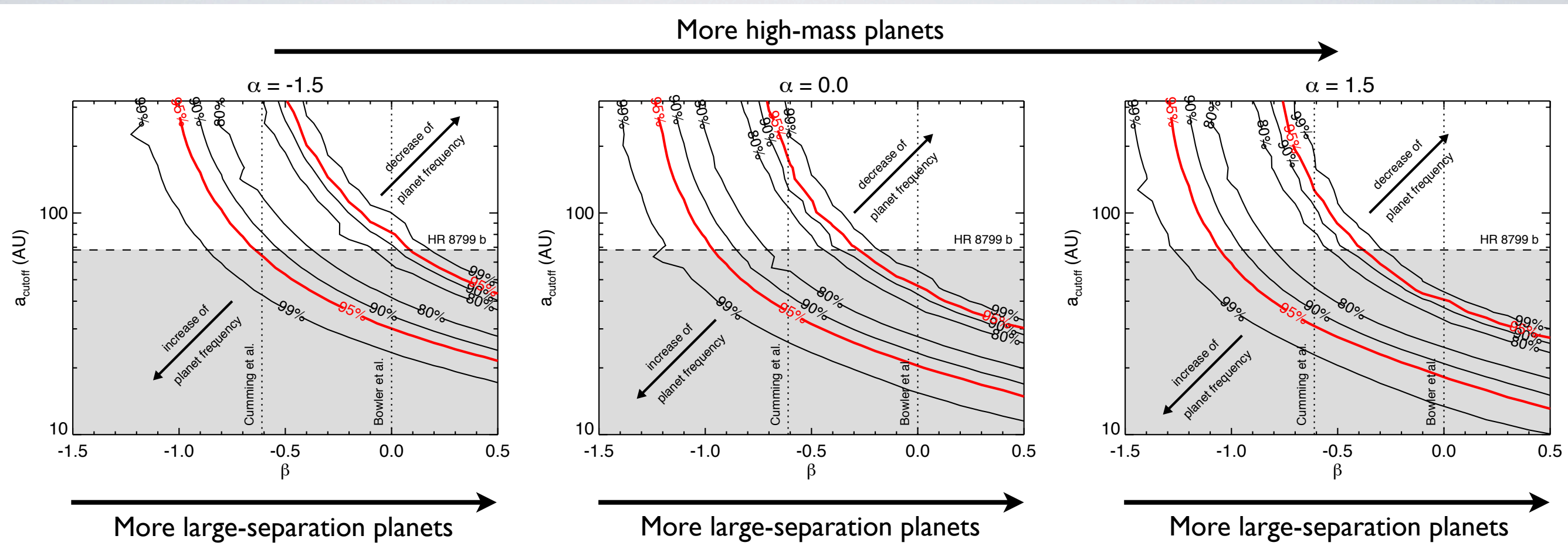
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Constraints on wide-orbit planets population

- simulations with **populations drawn from powerlaws**
- **cutoff** on semimajor axis distribution (a_{cutoff})
 - α from -1.5 to 1.5 by steps of 0.1
 - β from -1.5 to 0.5 by steps of 0.1
 - a_{cutoff} from 10 to 320 AU by steps of 10 AU
- assumed frequency $f = 11 \pm 2\%$ (Johnson et al. 2010)
for 0.5-14 M_{Jup} planets in 0.1-3.0 AU
- $\sum$ fraction of detected planet $\times$ normalised frequency
= number of **expected detections**

Constraints on wide-orbit planets population



- values **not in agreement** with RV constraints from Bowler et al.
 - different planet population at wide orbit?
 - population cannot be described by a single powerlaw?

Conclusions

- survey of 42 A and early-F stars
- data from NaCo and NIRC analysed with LOCI
- Monte Carlo simulations for the statistical analysis
- wide-orbit planet frequency $f \in [1.3\%, 26.4\%]$ @ 95% confidence
 - for $1 M_{\text{Jup}} \leq \text{mass} \leq 14 M_{\text{Jup}}$
 - for $10 \text{ AU} \leq a \leq 320 \text{ AU}$
- constraints on the population show differences with RV studies

Thanks for your attention!

