A Uniform Analysis of 118 Stars with High-Contrast Imaging: Long Period Extrasolar Giant Planets are Rare around Sun-like Stars

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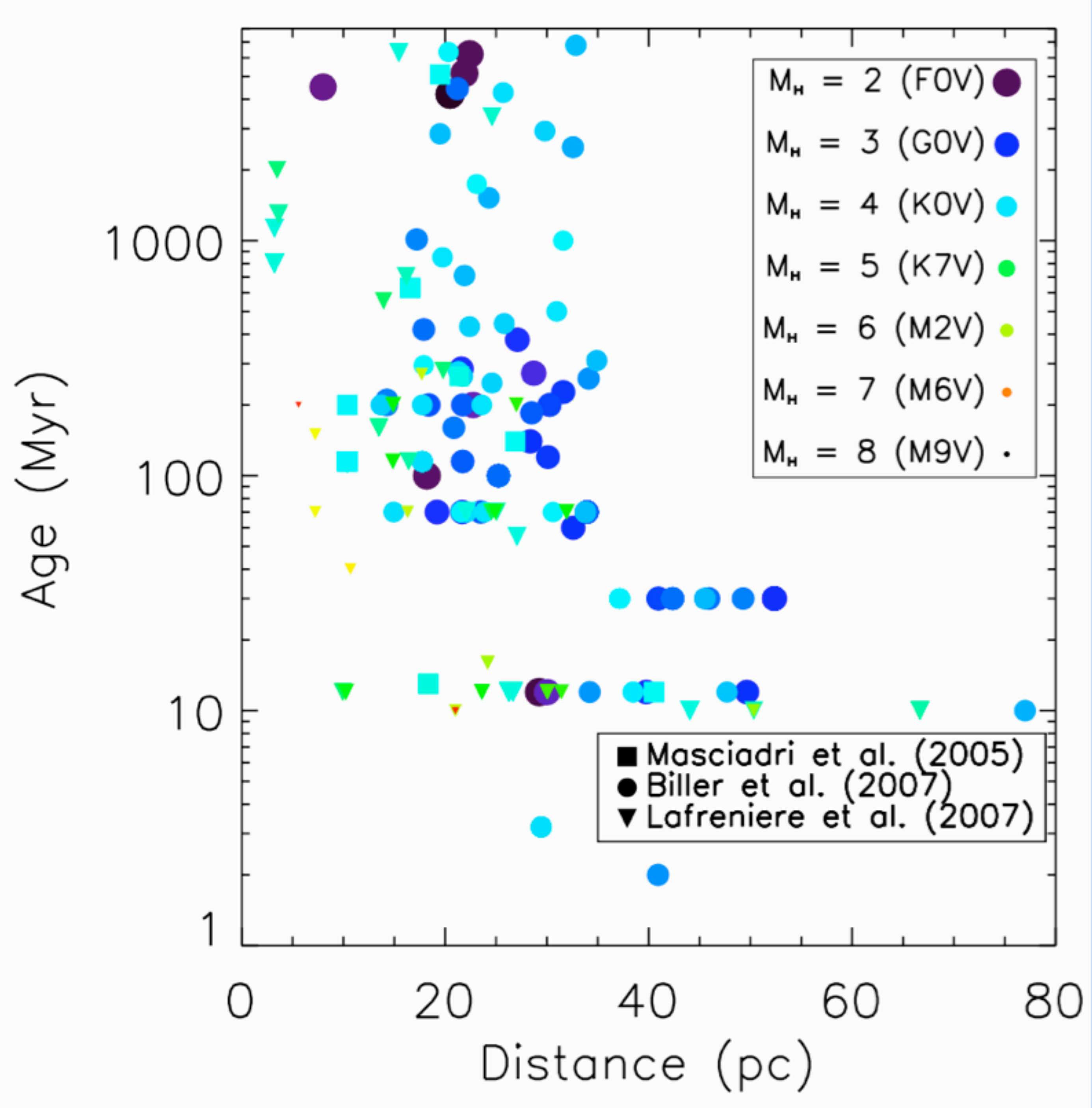
Introduction

- Adaptive optics on large telescopes and improvements in instrumentation are making looking for planets by direct imaging more powerful and efficient.
  - Finding a planet requires high contrast ($\sim 10^5$) at small separations to the parent star (<1")
- A large number of these surveys are currently underway, utilizing a variety of techniques at different wavelengths
- While there have been some successes in detecting planetary mass objects, including the exciting discoveries of planets around A stars, many of these surveys return null results
- Not finding a planet at the end of a survey is still an important result: if you consider the statistics and your sensitivity carefully, you can set upper limits on planet populations.
- Direct imaging is ideally suited to determining planet populations at large separations, and these statistics can set powerful constraints on models of planet formation and evolution.

The surveys



- 118 young, nearby stars observed with
  - 1) VLT (8m) AO broadband imaging (Masciadri et al. 2005)
  - 2) VLT and MMT (6.5m) Simultaneous Differential Imaging (Biller et al. 2007)
  - 3) Gemini North (8m), Angular Differential Imaging (GDPS, Lafreniere et al. 2007)
- Spoiler Alert: No planets found

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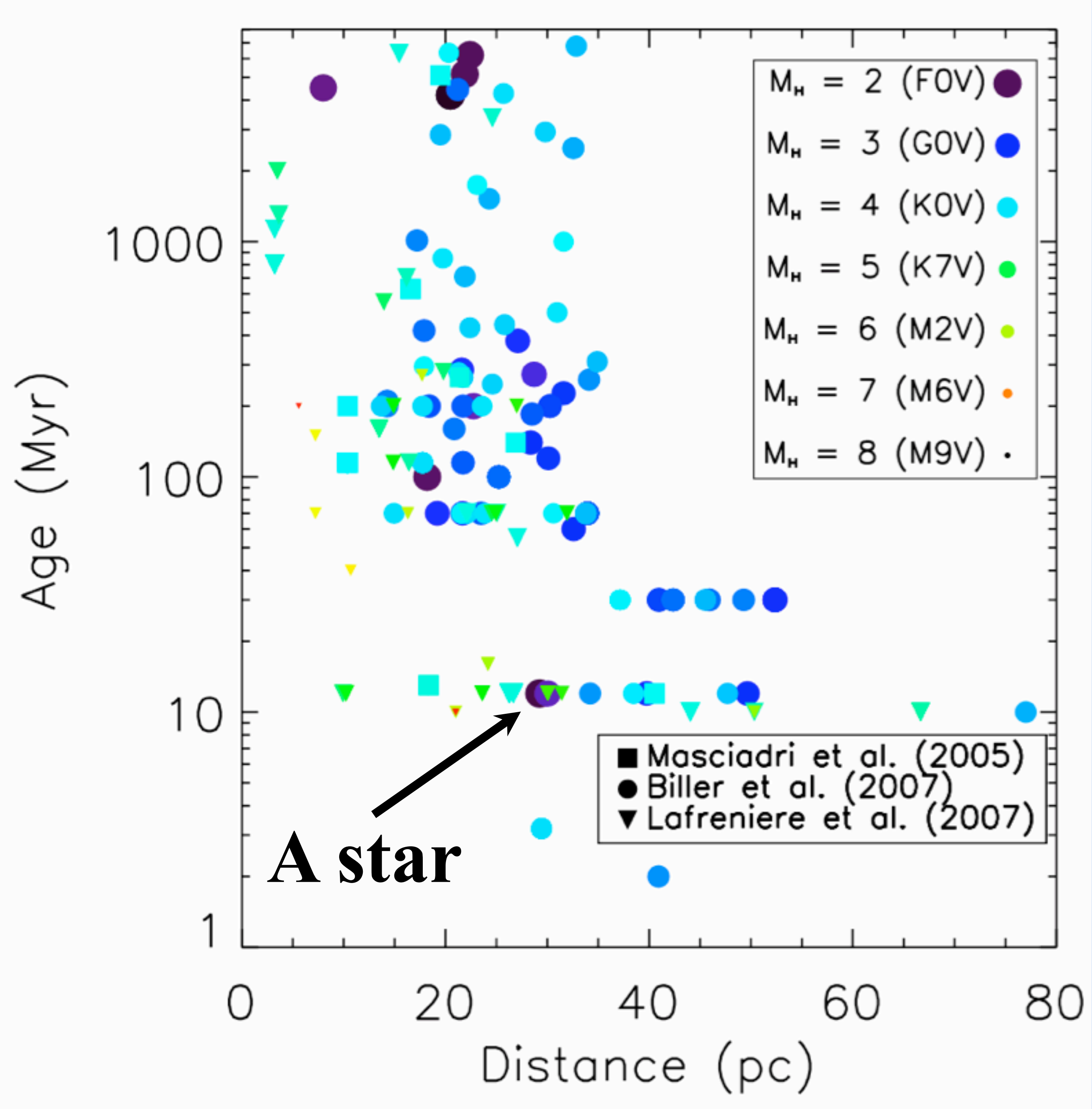
The surveys



- ~~118~~ 117 young, nearby, **solar-type** stars observed with
  - 1) VLT (8m) AO broadband imaging (Masciadri et al. 2005)
  - 2) VLT and MMT (6.5m) Simultaneous Differential Imaging (Biller et al. 2007)
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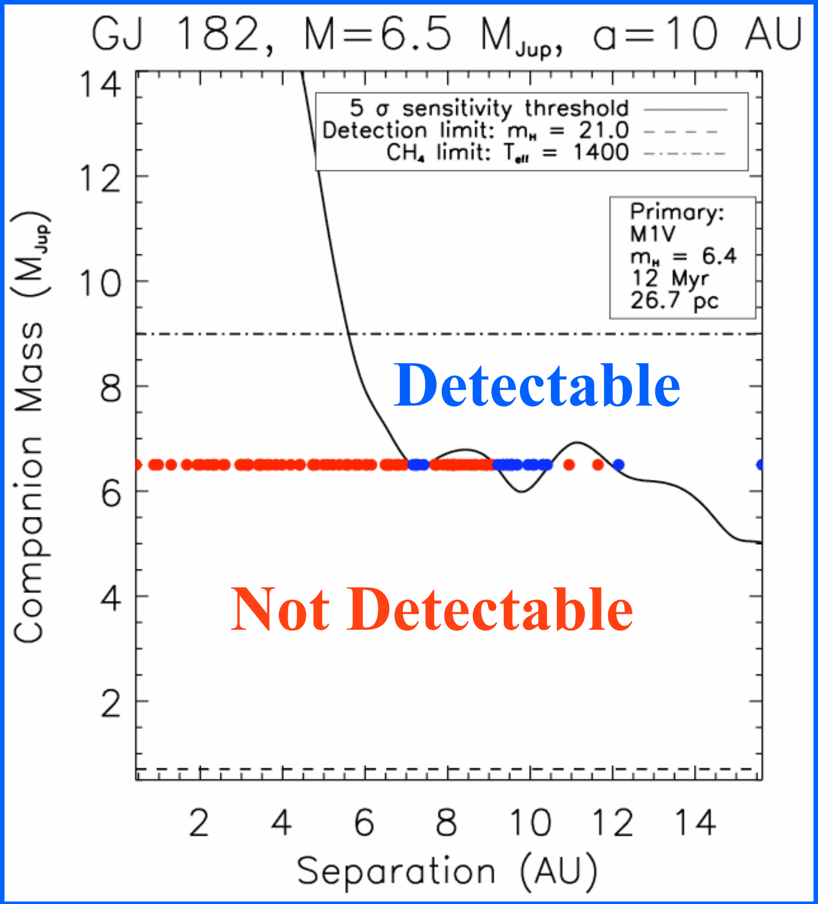
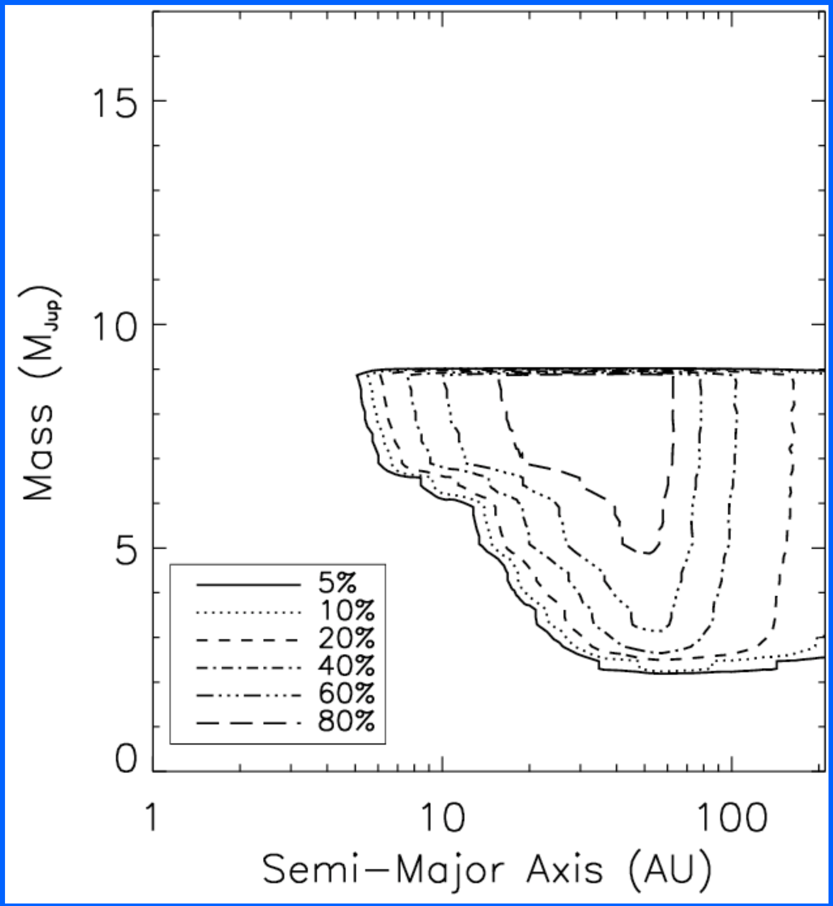
Determining the Completeness for Imaging Exoplanets Around Each Star

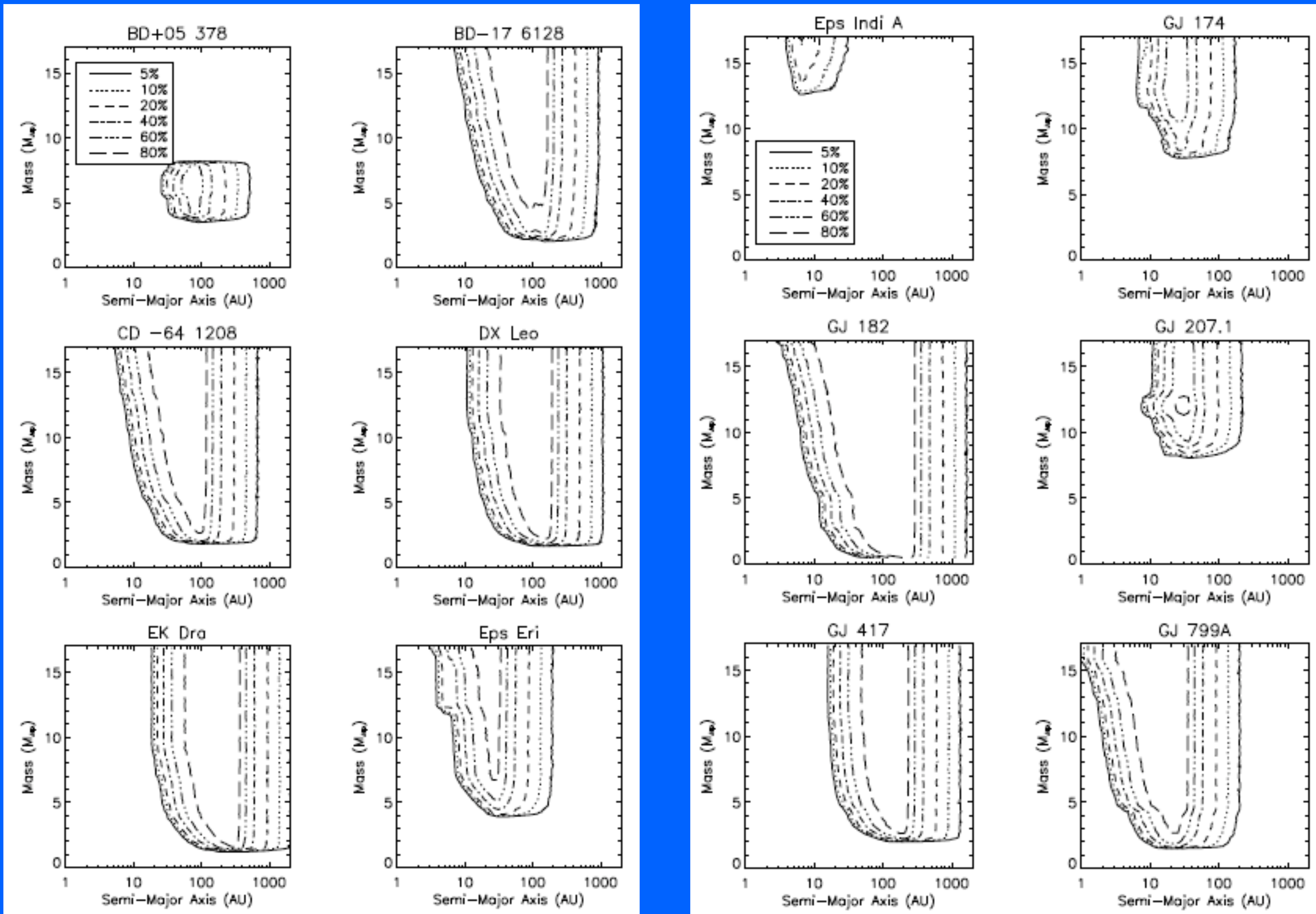




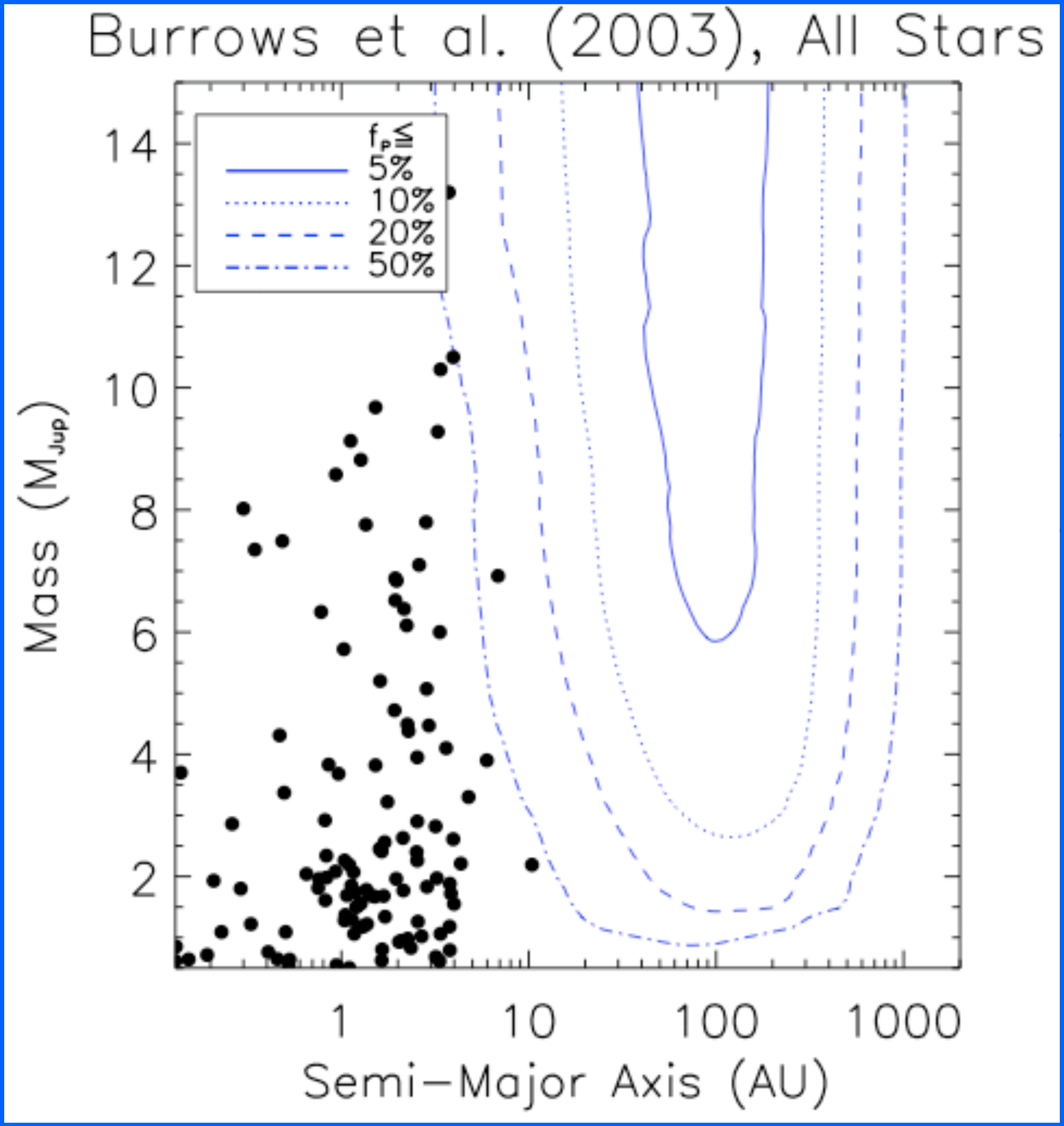
Nielsen et al. 2008

- Take measured contrast curve for each star, run Monte Carlo simulations for multiple mass/semi-major axis grid points, combine results.
- Within inner contour, if GJ 182 had a planet of mass ~7 M_{Jup}, and a~20 AU, we'd have had an 80% chance of detecting it.

Completeness plots for all 118 target stars are available online, for your viewing pleasure (12 are shown here)



Setting Upper Limits on Planet Fraction as a Function of Mass and Semi-major Axis



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Planet fraction (f_p): fraction of stars with a planet of a given mass and semi-major axis

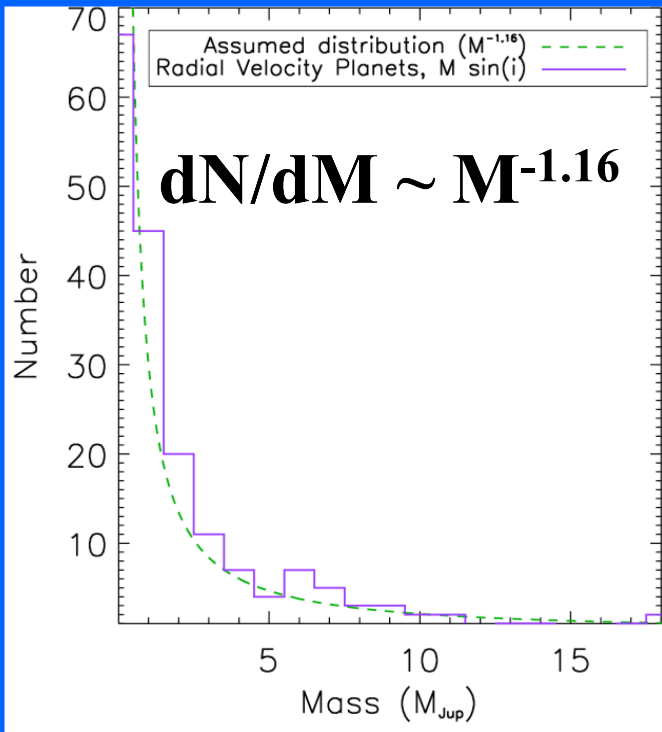
$$N(a, M) = \sum_{i=1}^{N_{obs}=60} f_p(a, M) P_i(a, M)$$

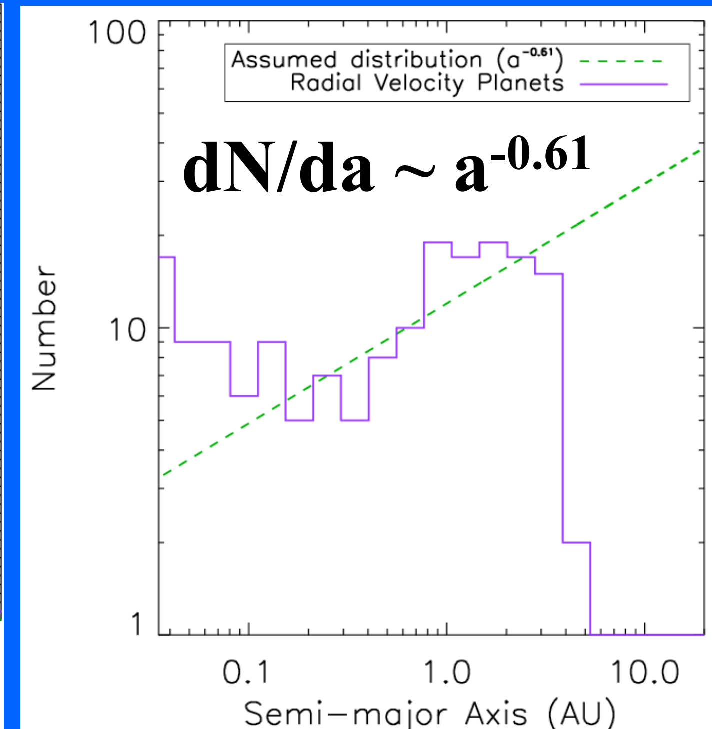
$$f_p(a, M) \leq \frac{3}{\sum_{i=0}^{N_{obs}} P_i(a, M)}$$

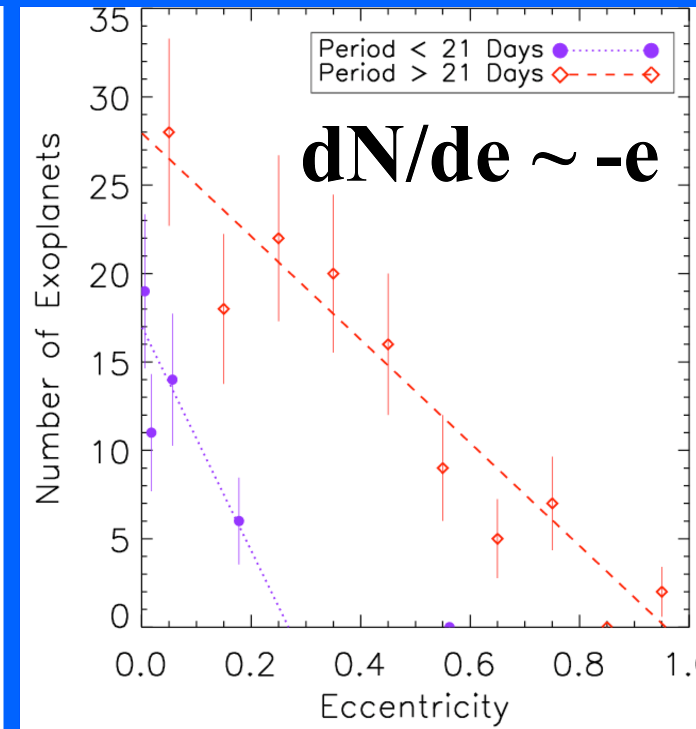
Contours show upper limits on planet fraction at 95% confidence level, black dots are RV planets for comparison

Less than 20% of stars can have planets more massive than 4 M_{Jup} between 22 and 507 AU, at 95% confidence.

Extrapolating from what we know from Radial Velocity Surveys

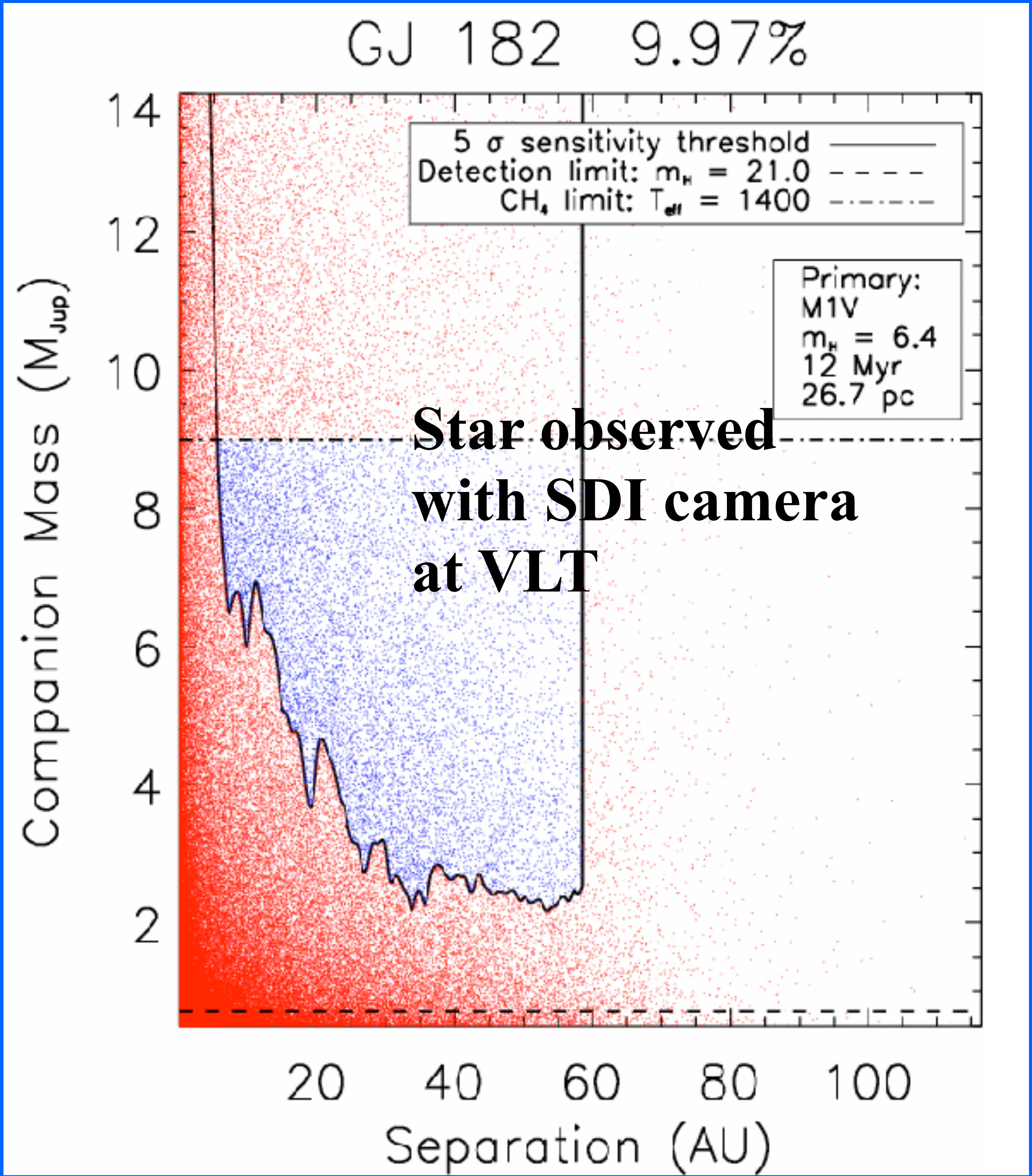






Planet distributions from exoplanets.org
Mass fit from Butler et al. 2006
Semi-major axis power law from Cumming et al. 2008
Figures from Nielsen et al. 2008

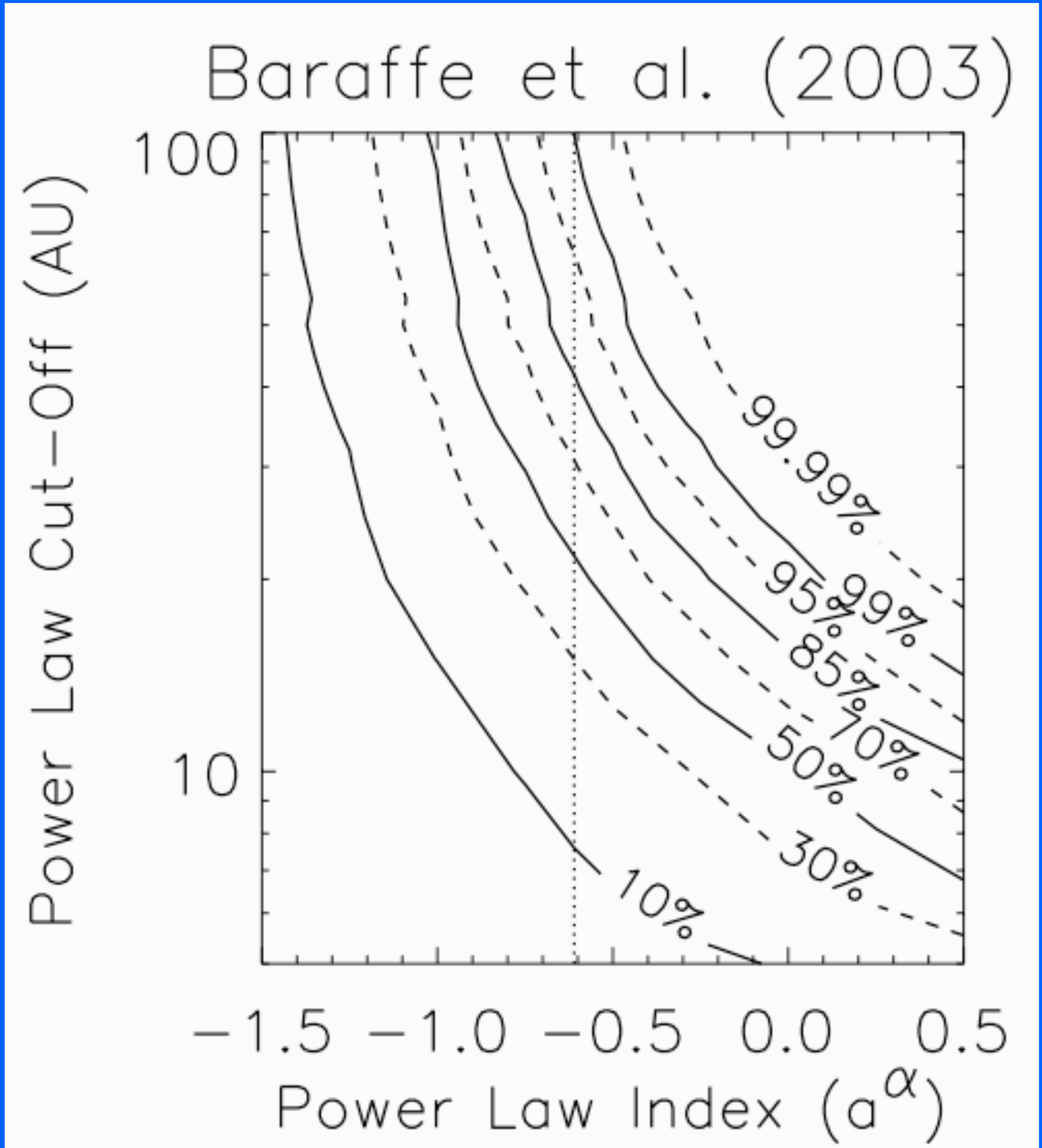
Monte Carlo Simulations using a Specific Model of Planet Populations



- Monte Carlo simulation assuming planet properties follow RV plants out to 70 AU
- For this star, with this semi-major axis distribution, we can detect 10% of the simulated planets (the blue points)

Nielsen et al. 2008

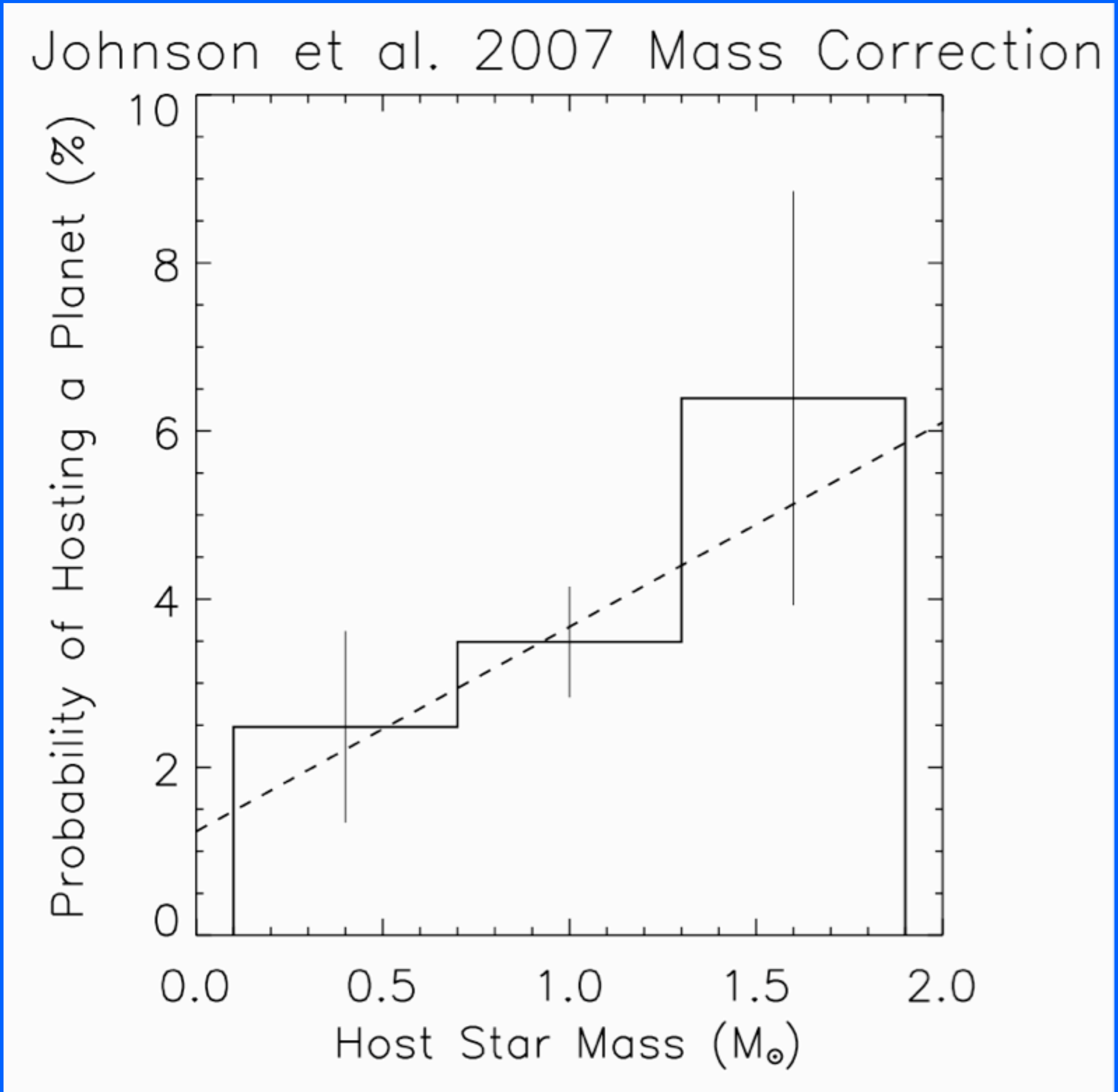
Constraining the Power Law Index and Upper Cut-off of the Semi-major Axis Distribution of Giant Planets



- Use radial velocity results (Fischer & Valenti 2005) to normalize the distributions
- A distribution with a positive power-law index is pretty much ruled out, with some constraints on an index of −0.61

Nielsen and Close 2010.

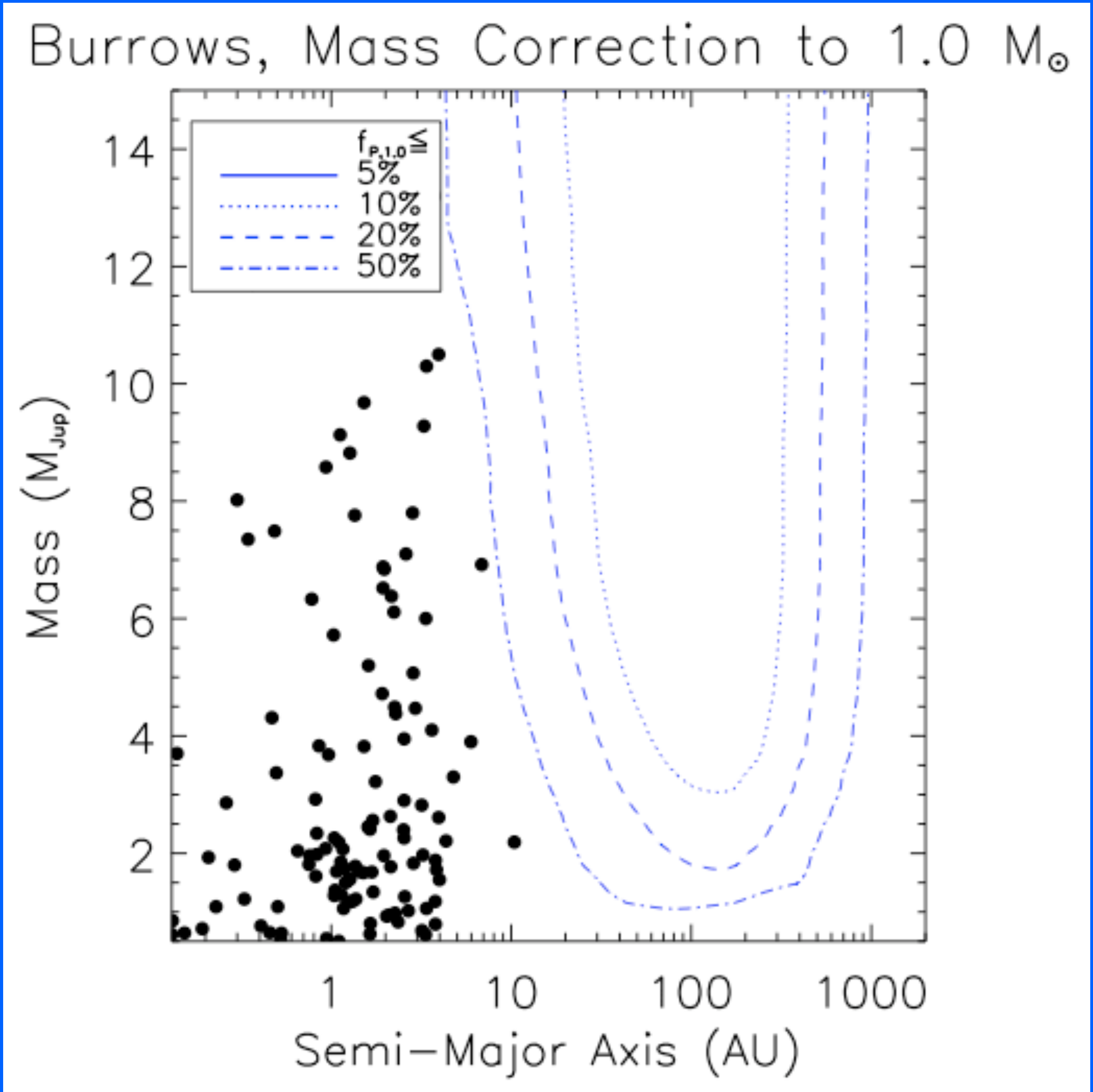
What about Stellar Mass?



Histograms from Johnson et al. 2007, Figure from Nielsen and Close 2010

- Using the radial velocity method, higher-mass stars are found to be more likely to host giant, close-in planets.
- If this trend holds at larger separations, the low-mass stars in our survey are getting too much weight.

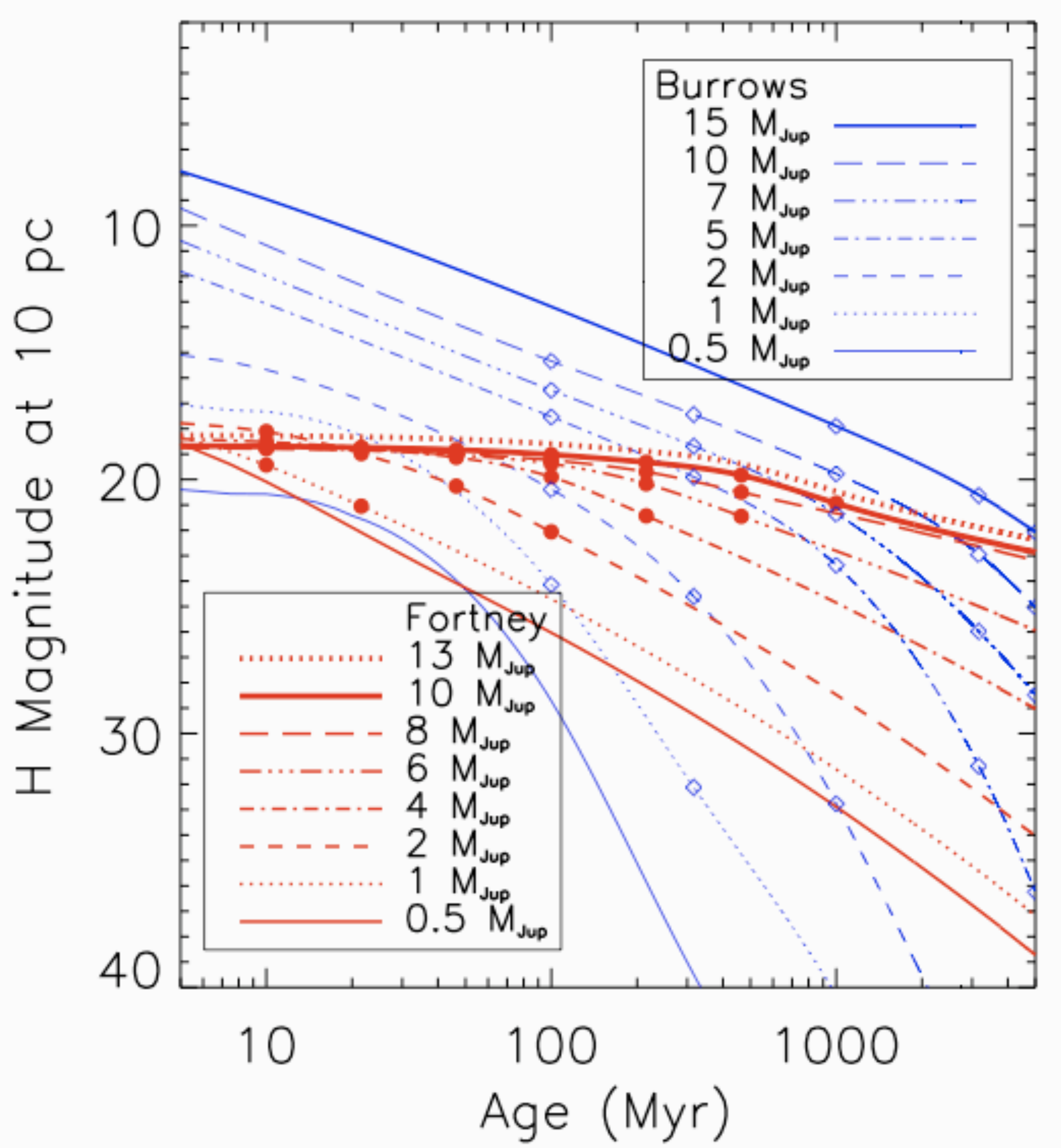
What about Stellar Mass?



- M stars had provided our strongest constraints at small separations.
- Accounting for M stars being less likely to host planets moves inner contours to the right
- At 95% confidence, less than 20% of stars can have a planet more massive than 4 M_{Jup} between 30 and 466 AU

Nielsen and Close 2010

What if Planets are Even Fainter?



- Fortney et al. 2008 have produced a series of planet models that begin with the core accretion formation theory
- At young ages, these new models predict significantly fainter planets then the “hot start” models such as Burrows et al. 2003.

Nielsen and Close 2010

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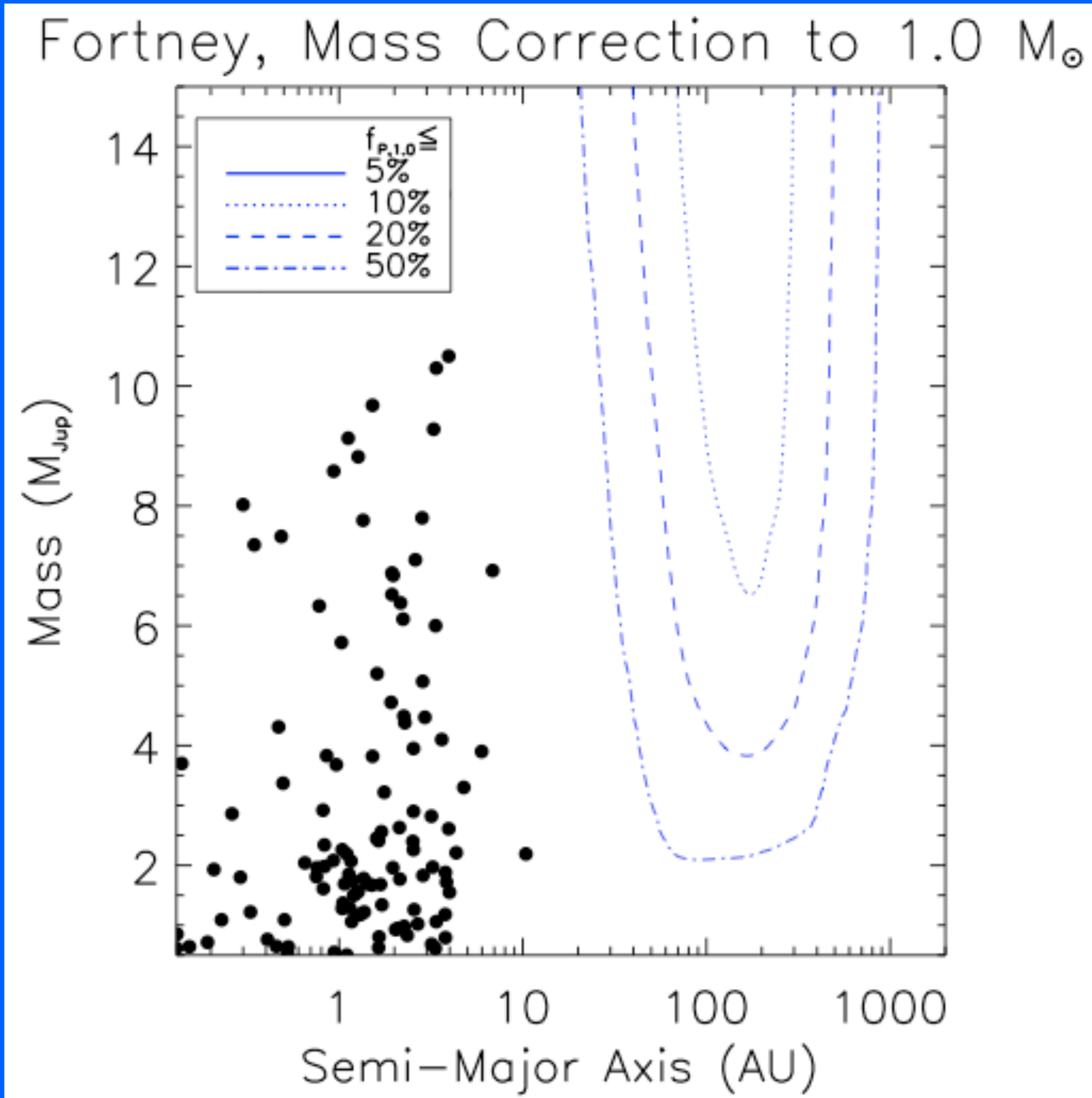

- As planets are predicted to be fainter, we're less able to constrain planet populations with our null results
- Given these assumptions, less than 20% of stars (a solar mass of less) can have a planet more massive than 4 M_{Jup} between 123 and 218 AU, at 95% confidence

Nielsen and Close 2010

Future Work

- Include other direct imaging surveys with null results for planets
- Include direct imaging surveys with detected planets
- Future and ongoing surveys (NICI, GPI, SPHERE), with more telescope time and more sensitive instruments, can strongly benefit from considering previous work:
  - Where are long-period planets most likely to be found?
  - If a target star has been observed before, is it worth re-observing at higher sensitivity, or choosing a less appealing, but unobserved, target star?

Conclusions

- There isn't an oasis of giant planets at large separations around stars of solar mass and smaller (not surprising, but good to confirm)
- If current trends from Radial Velocity surveys are uniform across parameter space, planets mostly confine themselves to the inner tens of AU around their solar-type parent star
- Future Direct Imaging surveys should focus on smaller-mass planets at smaller separations, and there is promising progress being made in this direction
- Remember that just because you didn't find planets, it doesn't mean your data aren't useful and interesting