A Uniform Analysis of 118 Stars with High-Contrast Imaging: Long Period Extrasolar Giant Planets are Rare around Sun-like Stars (re-submitted to ApJ, Nielsen and Close 2009)

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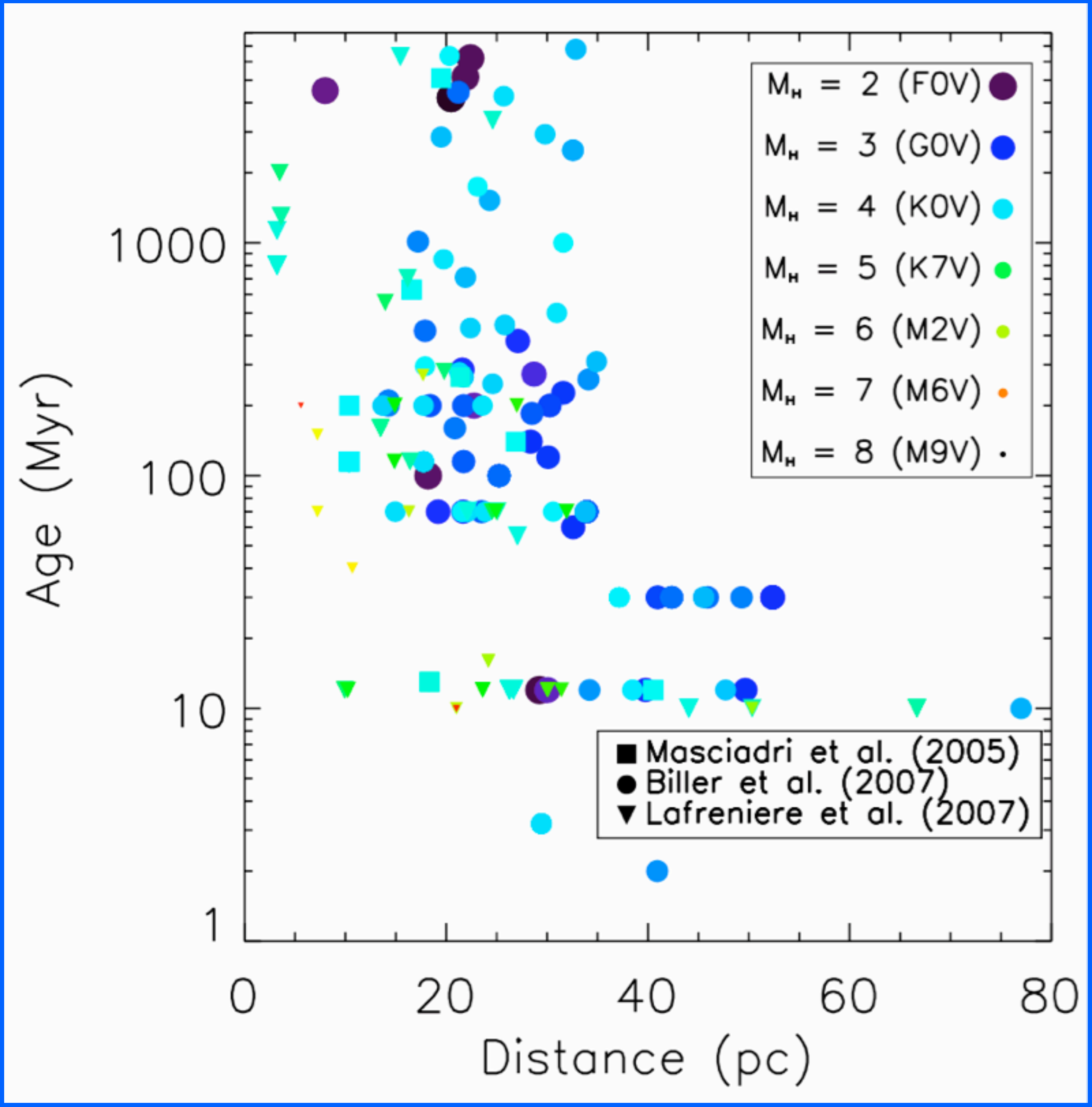
Laird Close (Steward). Also based on work done with Michael Liu, Beth Biller, and Zahed Wahhaj (IfA)

AAS Pasadena 2009

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.

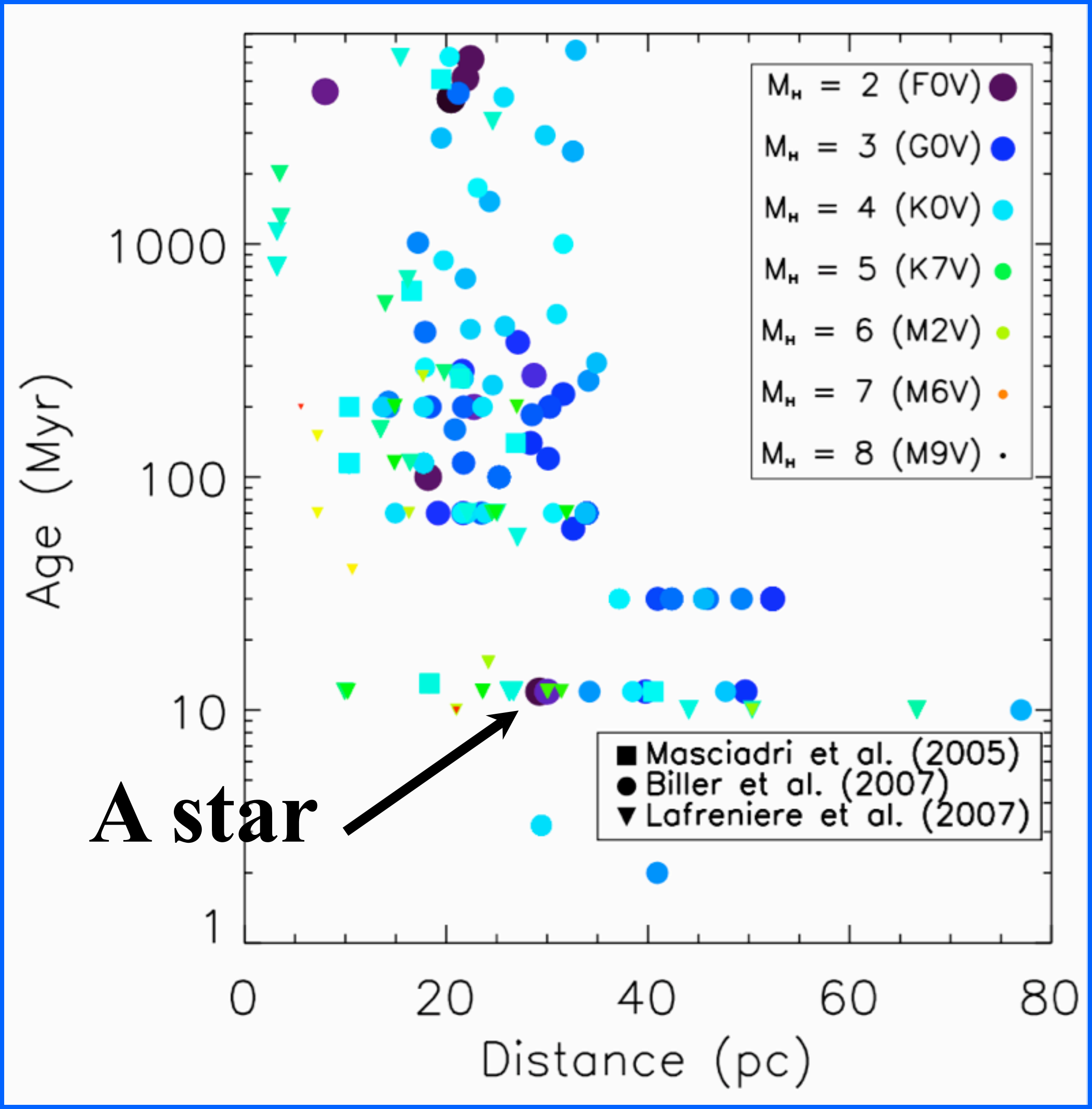
The surveys



Nielsen and Close 2009

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

The surveys



Nielsen and Close 2009

- ~~118~~ 117 young, nearby, **solar-type** stars observed with
  - VLT (8m) AO broadband imaging (Masciadri et al. 2005)
  - VLT and MMT (6.5m) Simultaneous Differential Imaging (Biller et al. 2007)
  - Gemini North (8m), Angular Differential Imaging (GDPS, Lafreniere et al. 2007)
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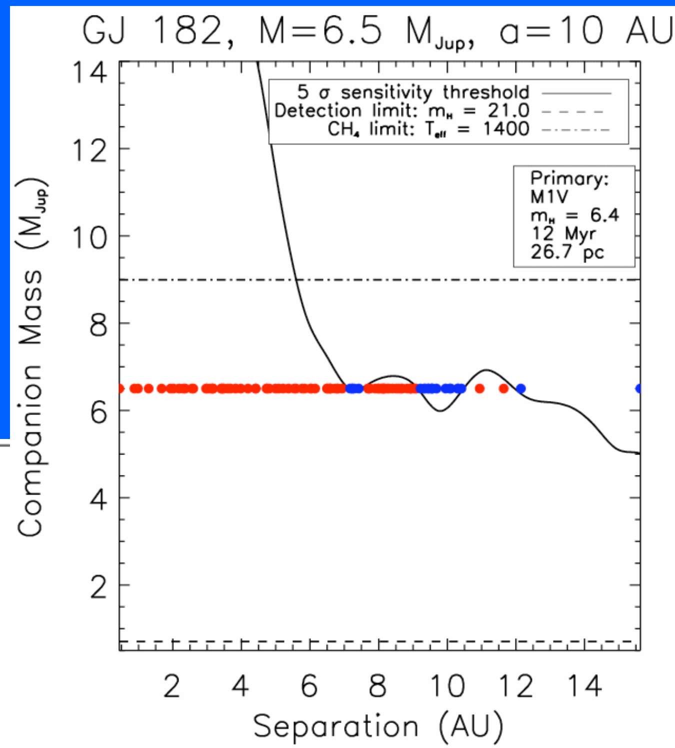
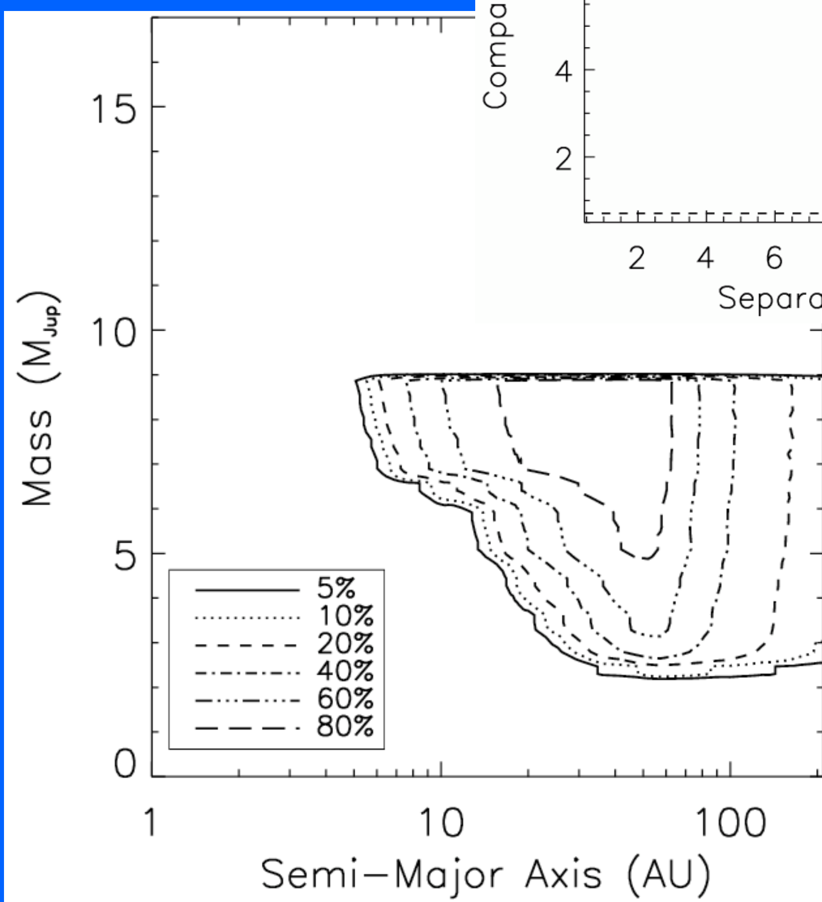
Making Completeness Plots from Non-Detection of Planets Around a Given Target Star

Nielsen et al. 2008

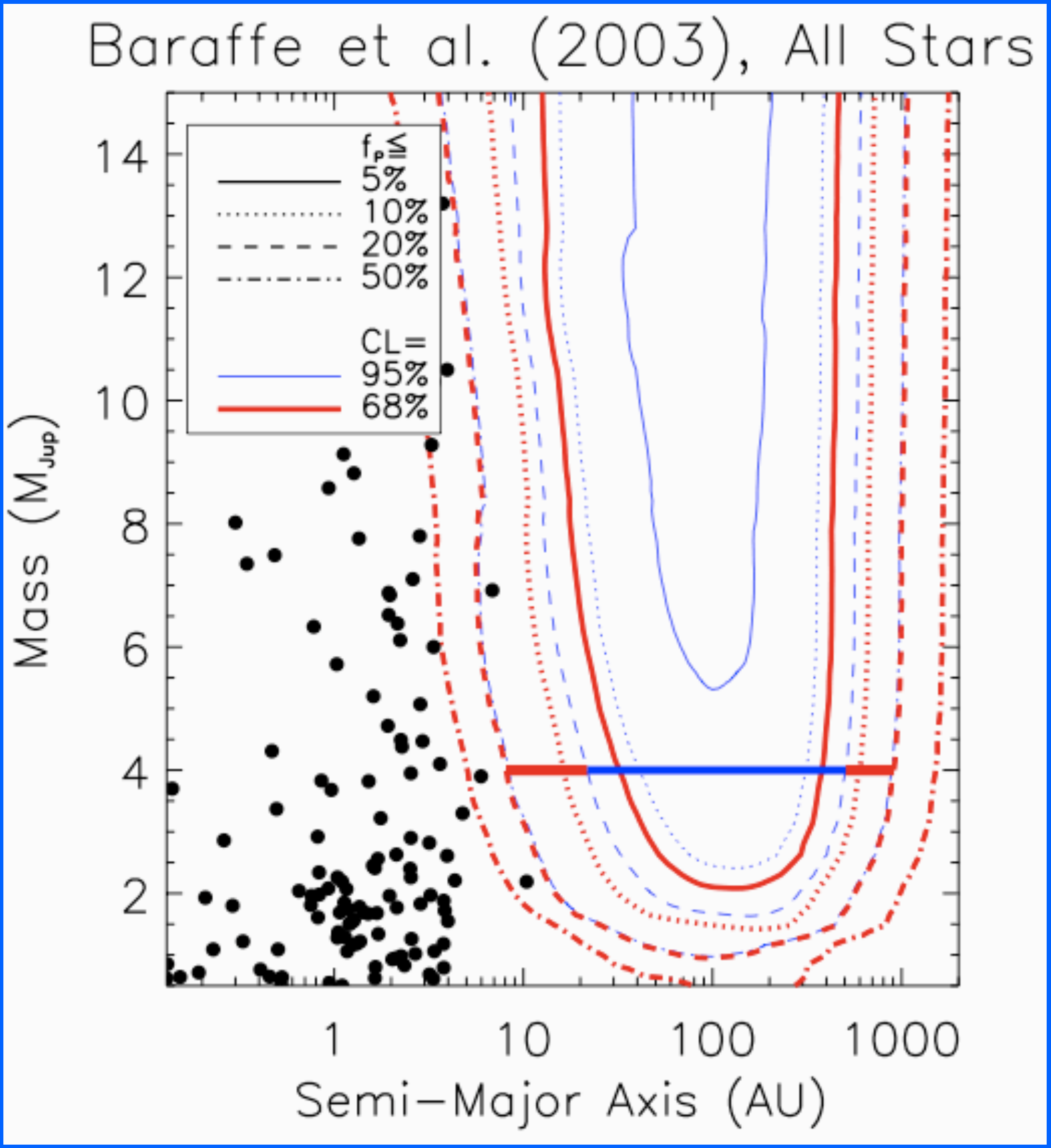




- Start with measured contrast curve for a given target star: how faint an object we could detect as a function of radius
- Run Monte Carlo simulations for multiple mass/semi-major axis grid points, combine results.
- Within inner contour, if GJ 182 had a planet of mass ~7 M_{Jup}, and a~20 AU, we'd have had an 80% chance of detecting it.
- Nominal SDI field of view is ~60 AU, but it's possible to see longer period planets for fortuitous combinations of orbital parameters

(Thanks to Remi Soummer for the idea of making completeness plots like this)

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



Nielsen and Close 2009

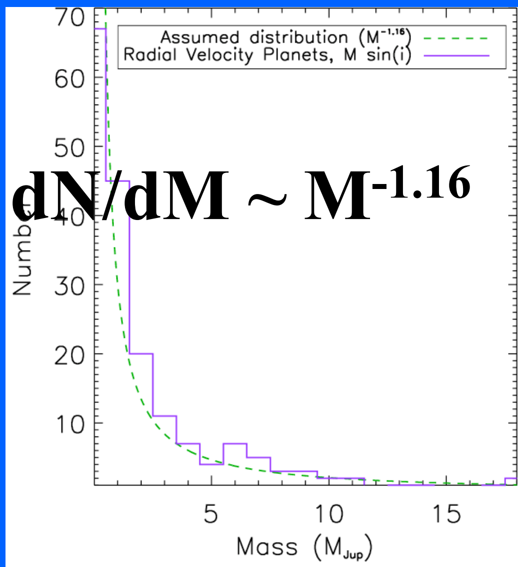
- Planet fraction (f_p): fraction of stars with a planet of a given mass and semi-major axis

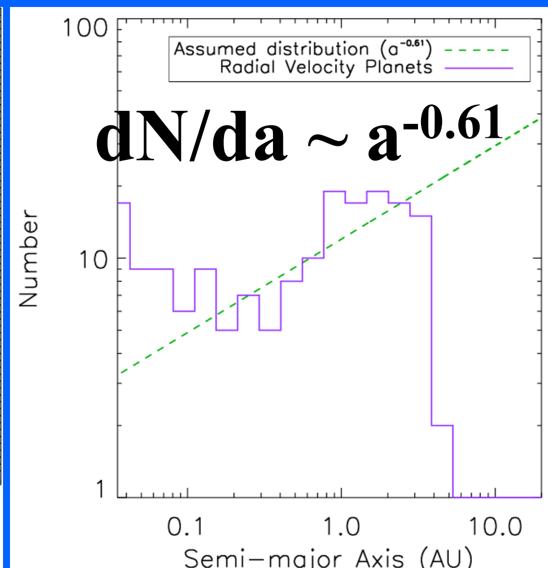
$$N(a, M) = \sum_{i=1}^{N_{obs}=60} f_p(a, M) P_i(a, M)$$

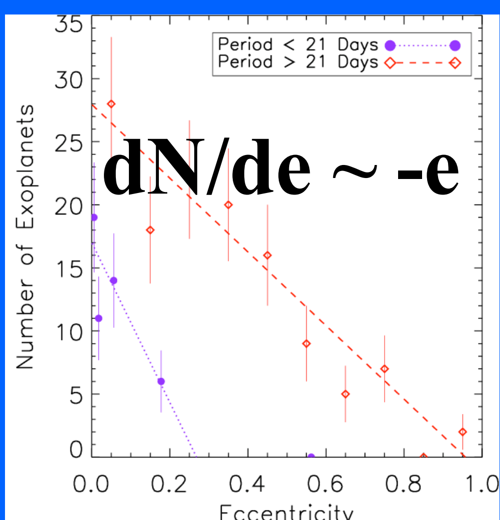
$$f_p(a, M) \leq \frac{3}{\sum_{i=0}^{N_{obs}} P_i(a, M)}$$

- Contours show upper limits on planet fraction as a function of planet mass and semi-major axis, at 68% (red) and 95% (blue) confidence levels
- Black dots are known radial velocity 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.

Taking the Next Step: Extrapolating from what we know from Radial Velocity Surveys



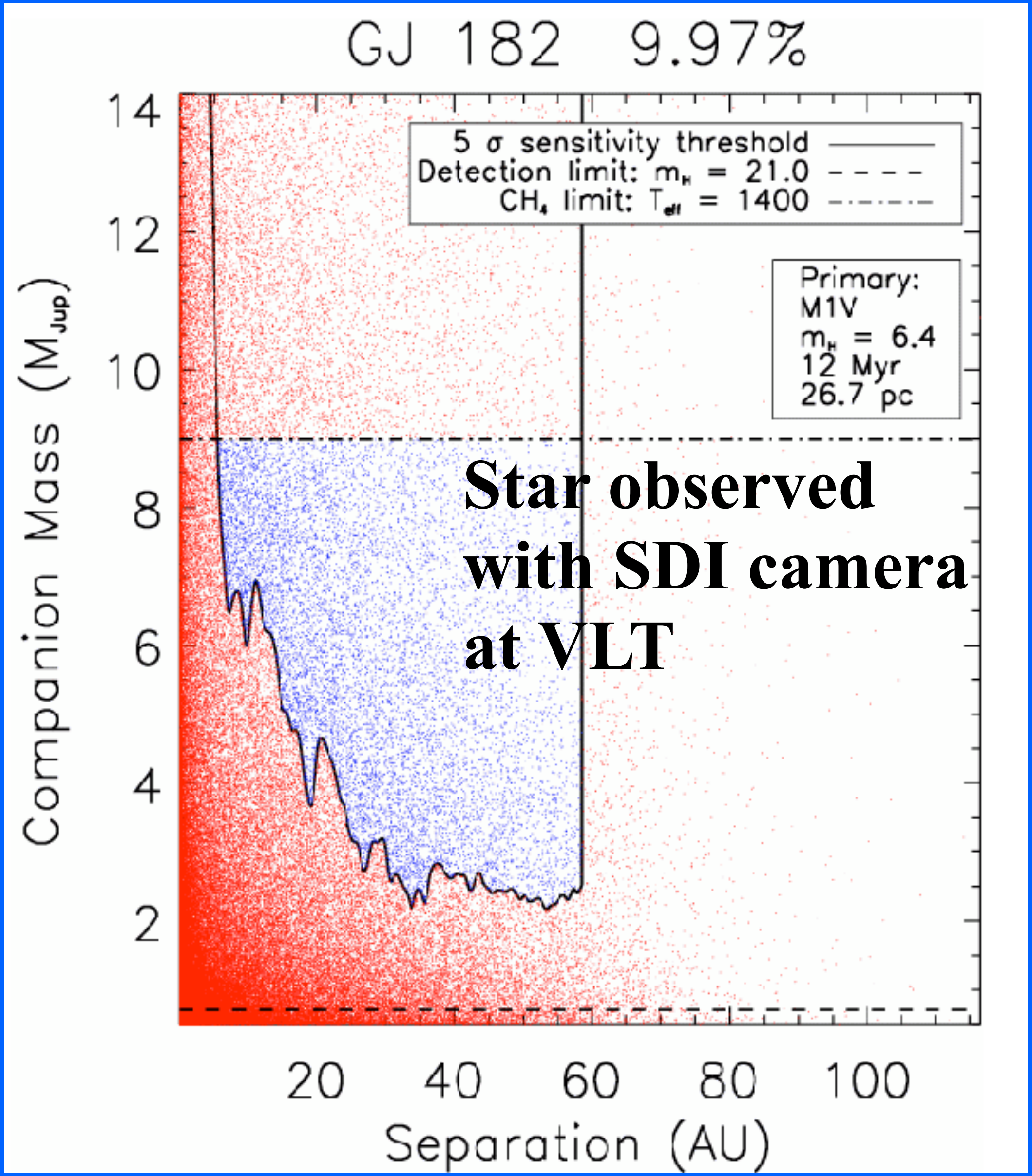




Planet distributions from exoplanets.org Mass fit from Butler et al. 2006, semi-major axis power law from Cumming et al. 2008. Figures from Nielsen et al. 2008.

- Over 200 planets give us pretty good statistics, so we can fit simple functions to the behavior of mass, semi-major axis, and eccentricity of giant planets
- All that's left to figure out is what planets do beyond a few AU, where radial velocity can't find them so easily

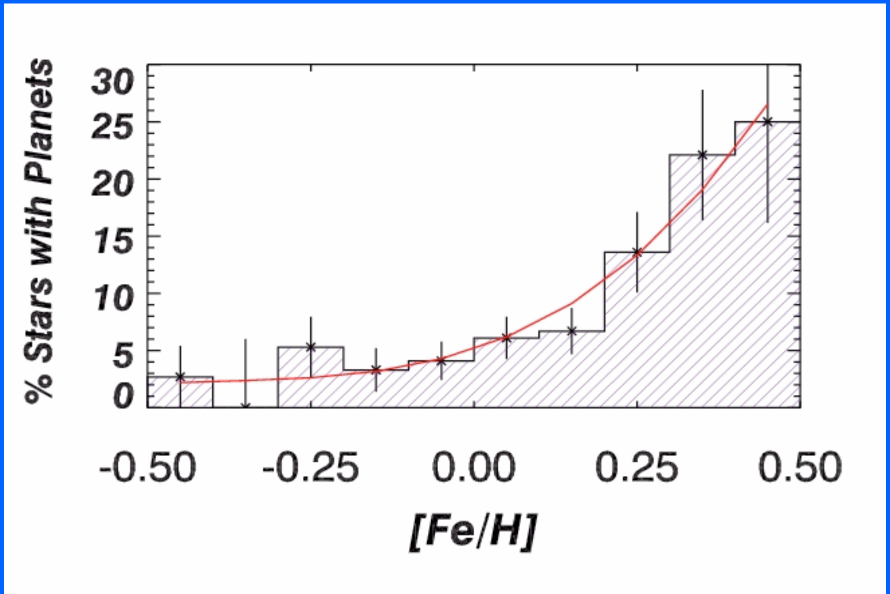
Monte Carlo Simulations using a Specific Model of Planet Populations



Nielsen et al. 2008

- If we assume power law distributions for mass and semi-major axis, we can find the fraction of planets we could detect for any target star (if the star has one planet, this is the chance of detecting that planet)
- For this star, with this semi-major axis distribution (power law index −0.61, upper cut-off 70 AU), we can detect 10% of the simulated planets (the blue points)

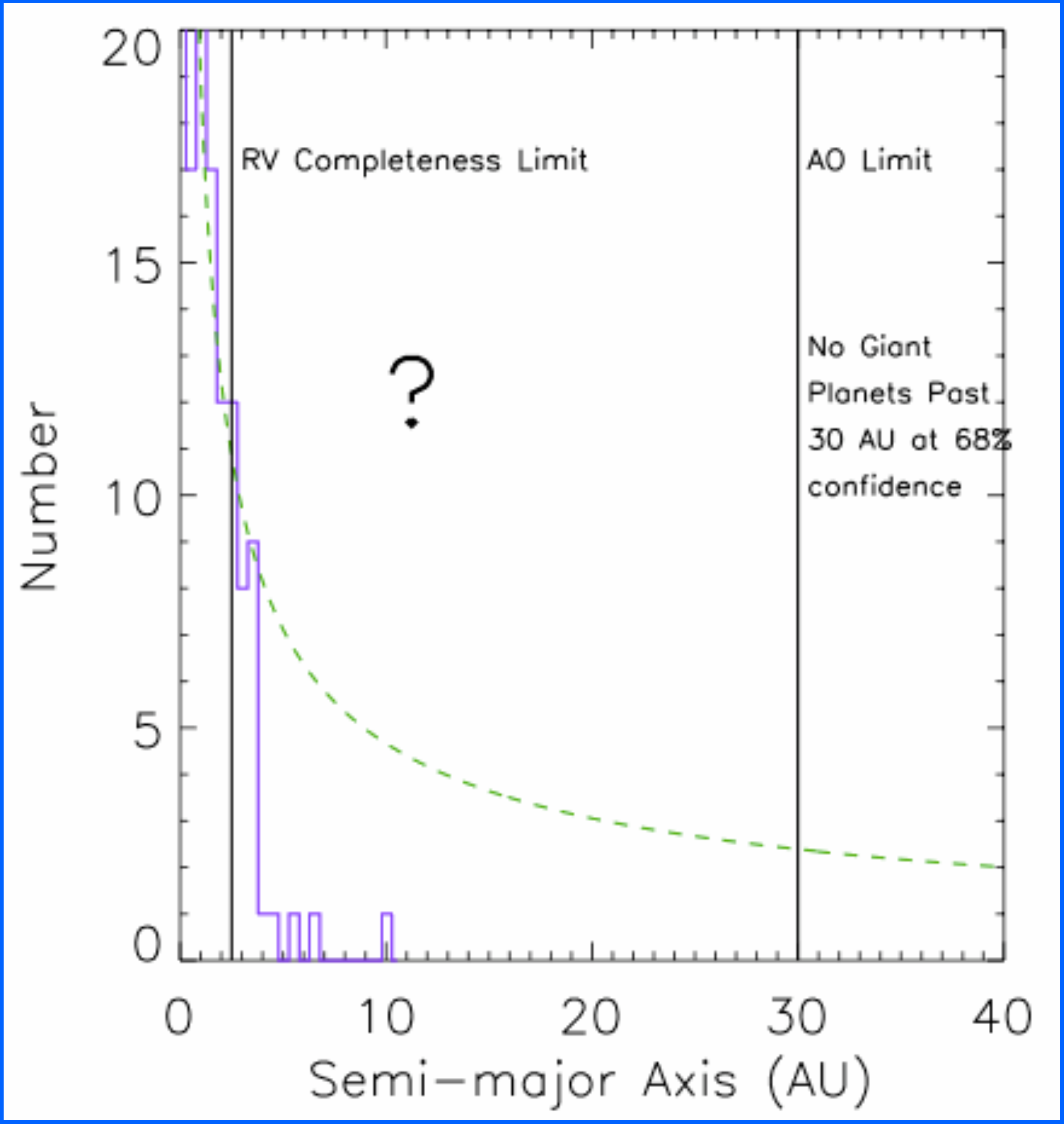
Getting the Overall Fraction of Stars with Planets from Radial Velocity Surveys



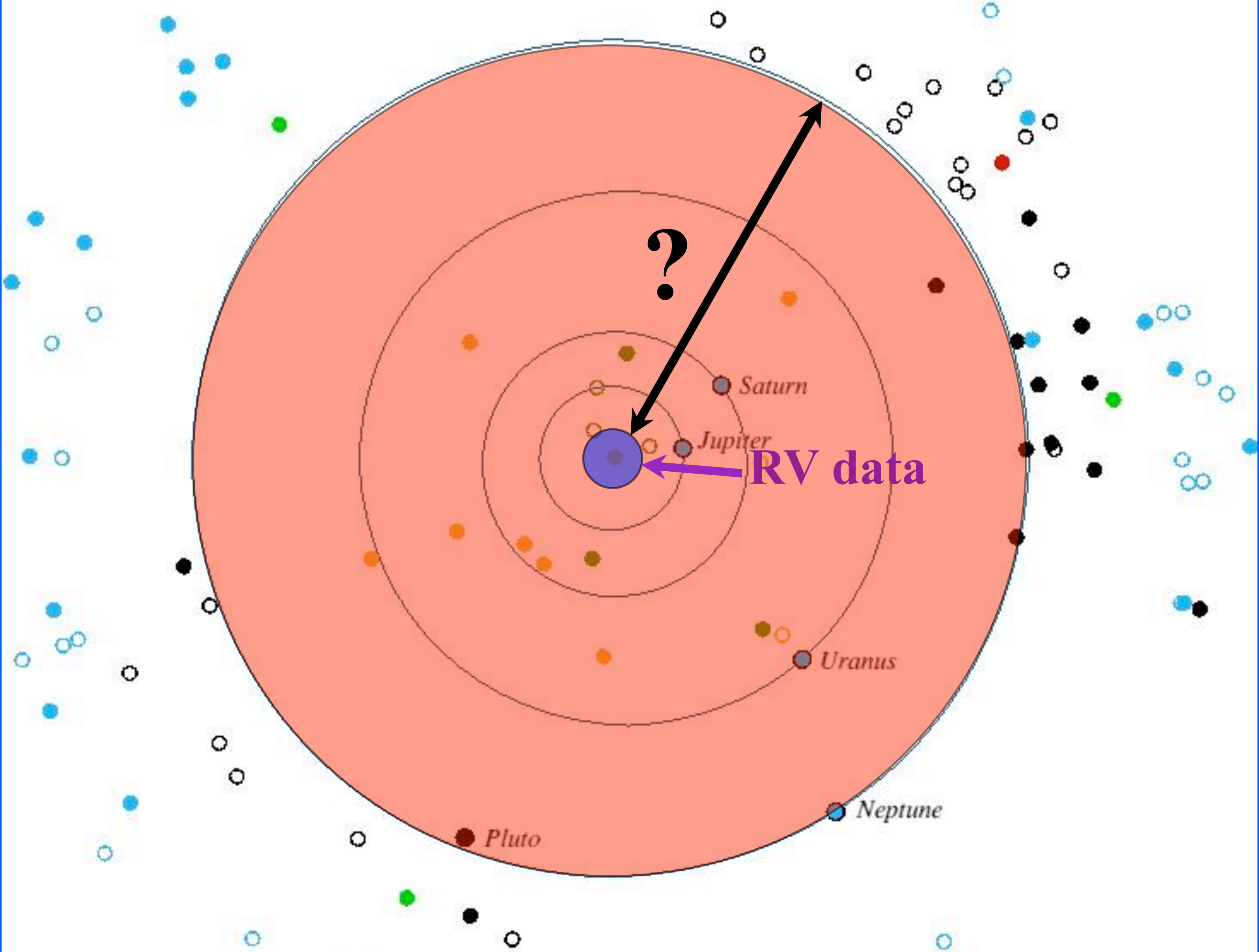
- Considering target stars with and without detected planets shows that the more metals a star has, the more likely it is to host a planet (within 4 years, 2.5 AU, and above 1.6 Jupiter masses)
- Overall, about 5% of all stars have such a planet

Fischer and Valenti 2005

The Distribution of Outer Planets for Stars of a Solar Mass and Below

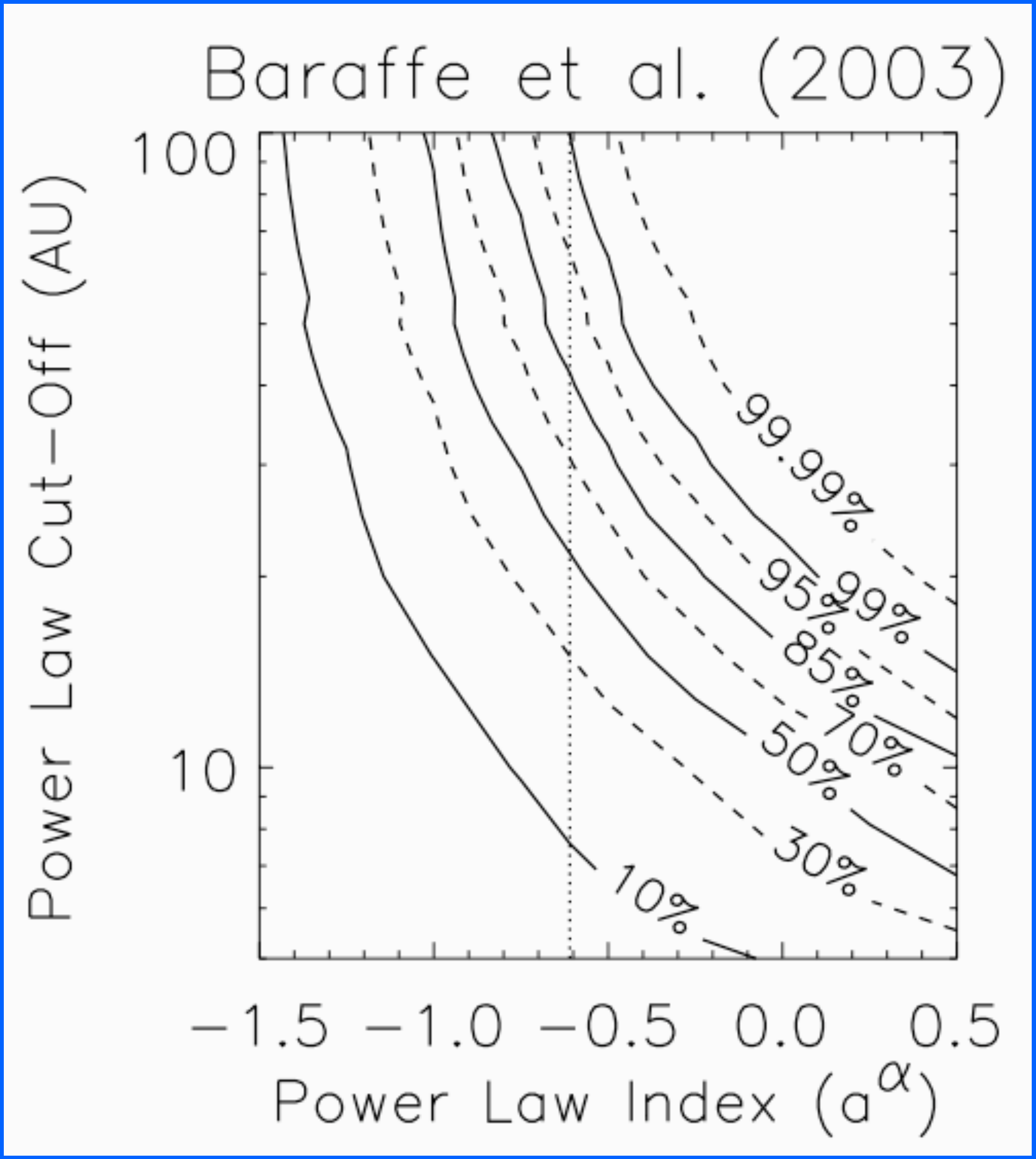


No Giant Planets Here (for one solar mass or less)
Nielsen and Close (2009)



Original Figure from Zeljko Lipanovic

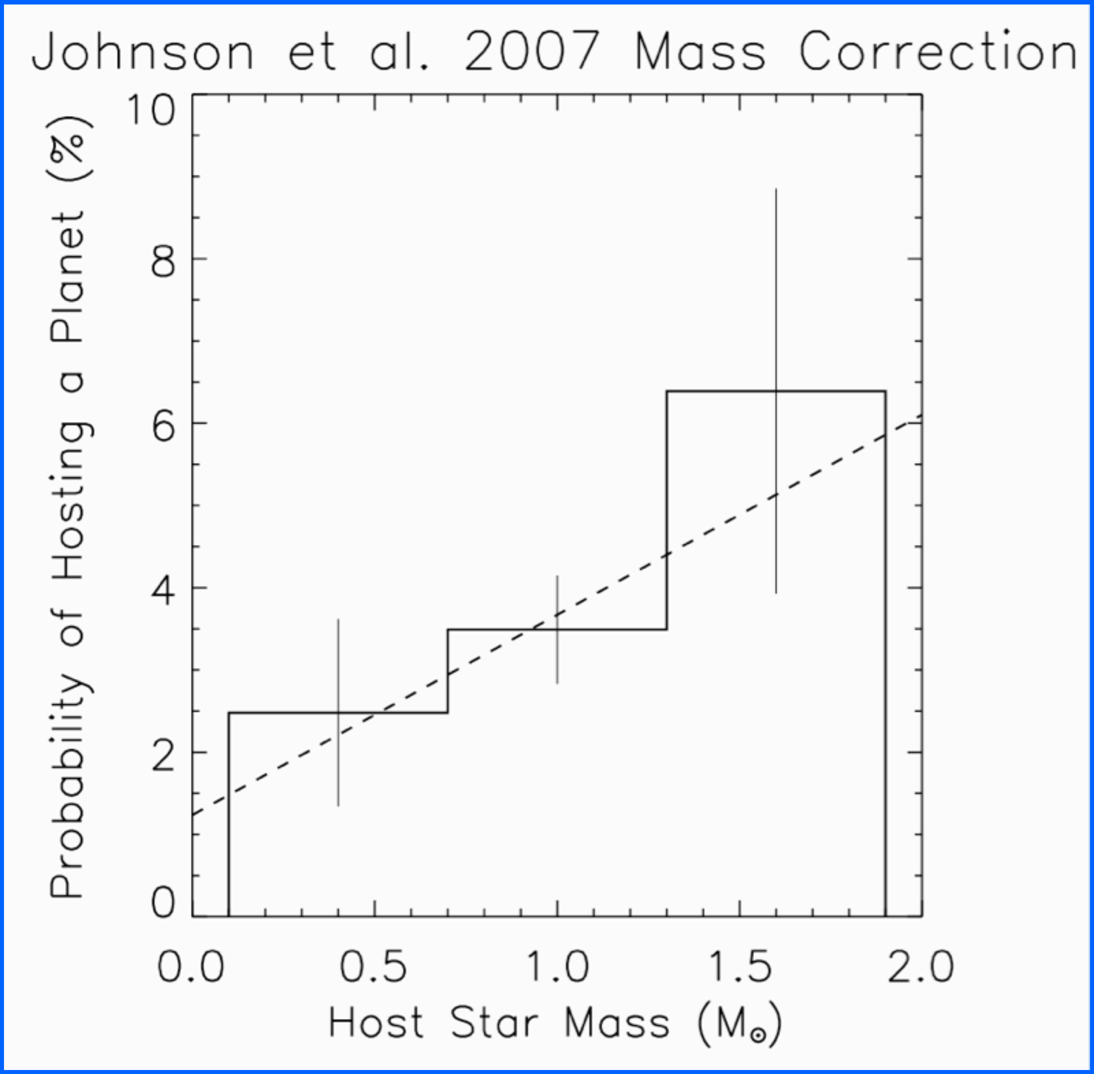
Constraining the Power Law Index and Upper Cut-off of the Semi-major Axis Distribution of Giant Planets



- Use radial velocity results (Fischer & Valenti 2005) to normalize the distributions, given how many planets are within 2.5 AU (although we include M stars, and they didn't)
- A distribution with a positive power-law index is pretty much ruled out, with some constraints on an index of -0.61

Thanks to Daniel Apai for the idea for plotting the results this way. Nielsen and Close 2009.

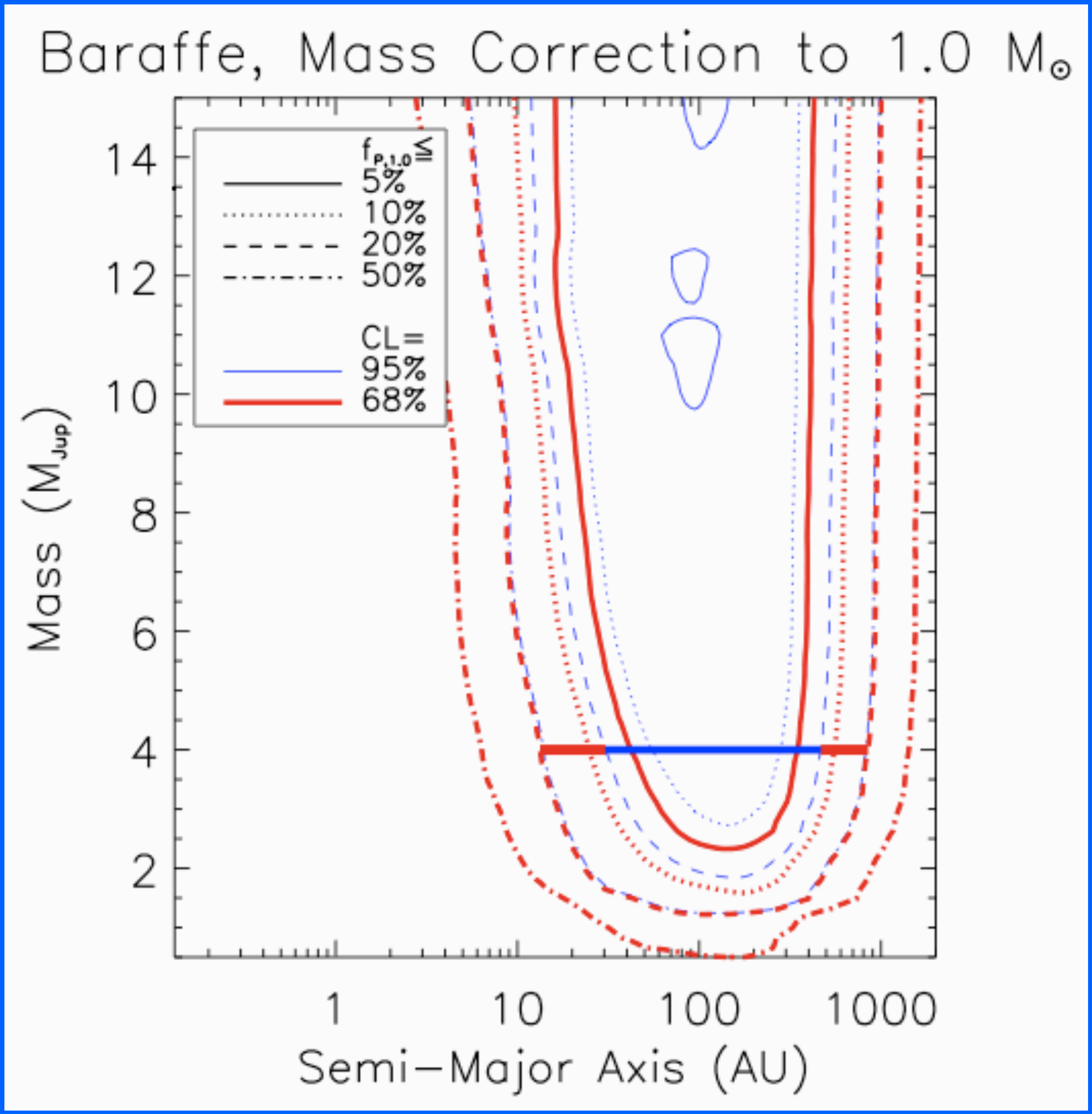
What about Stellar Mass?



- 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.

Histograms from Johnson et al. 2007, Figure from Nielsen and Close 2009.

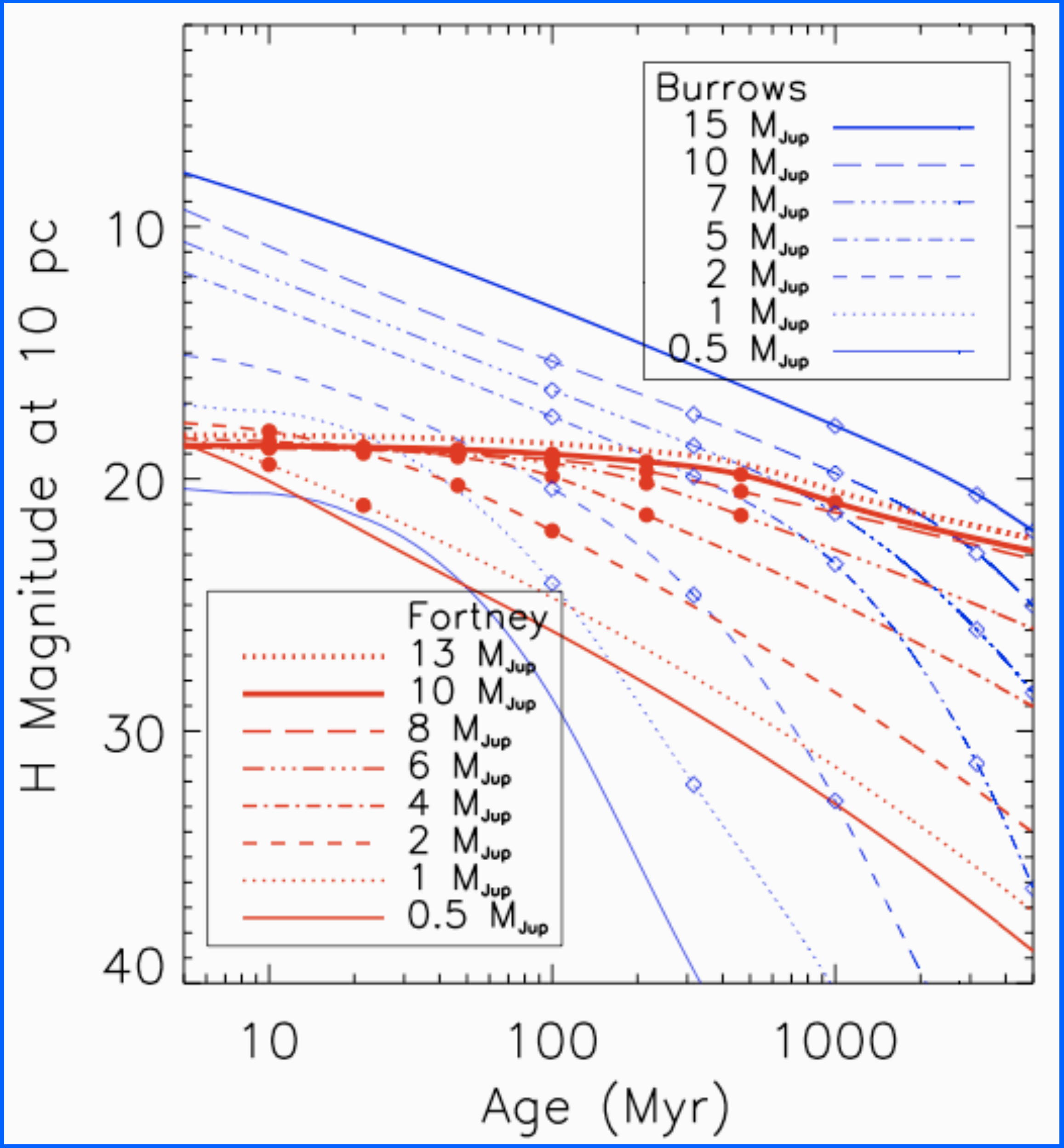
What about Stellar Mass?



- 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 2009.

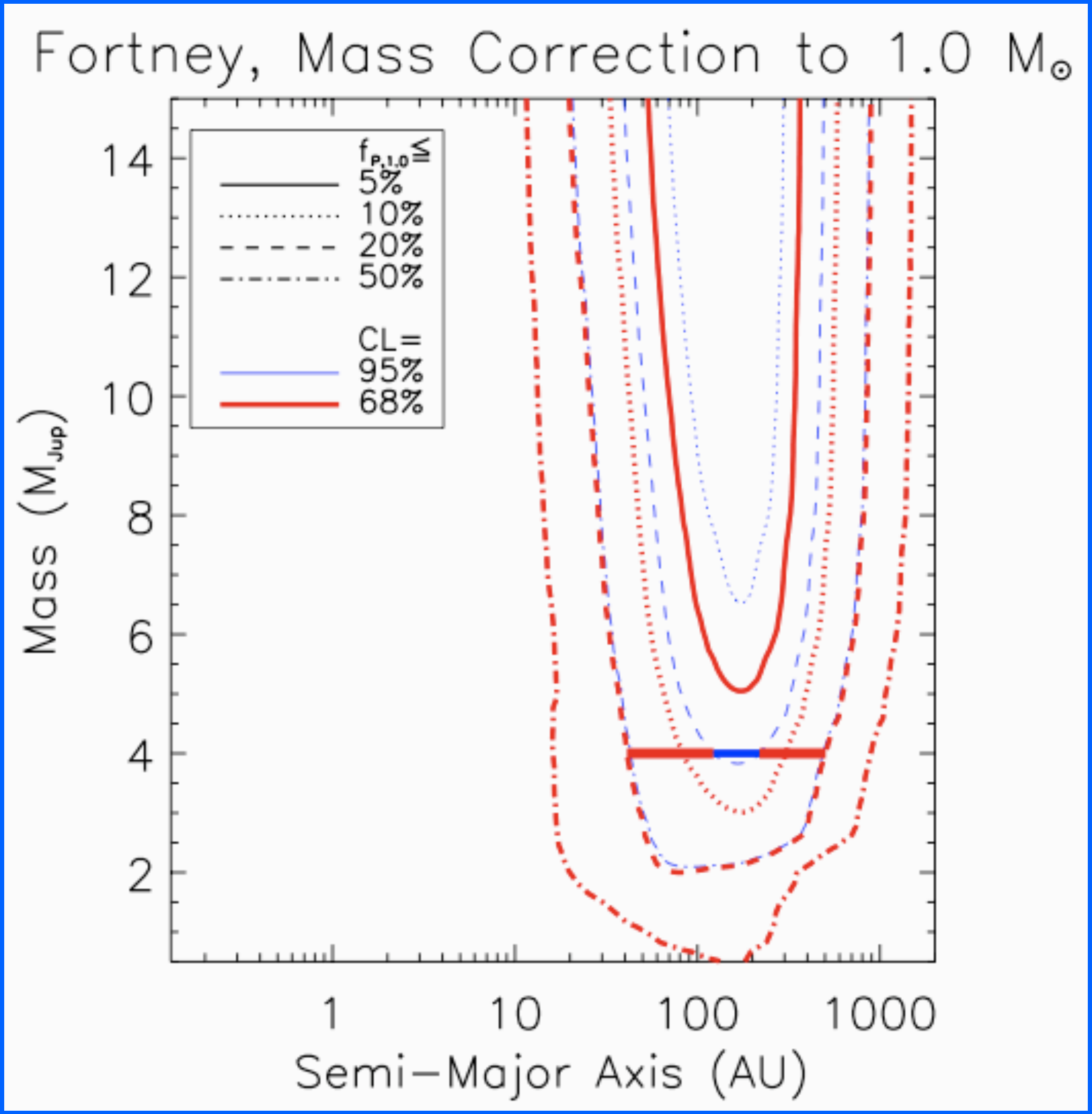
What if Planets are Even Fainter?



Nielsen and Close 2009.

- 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.

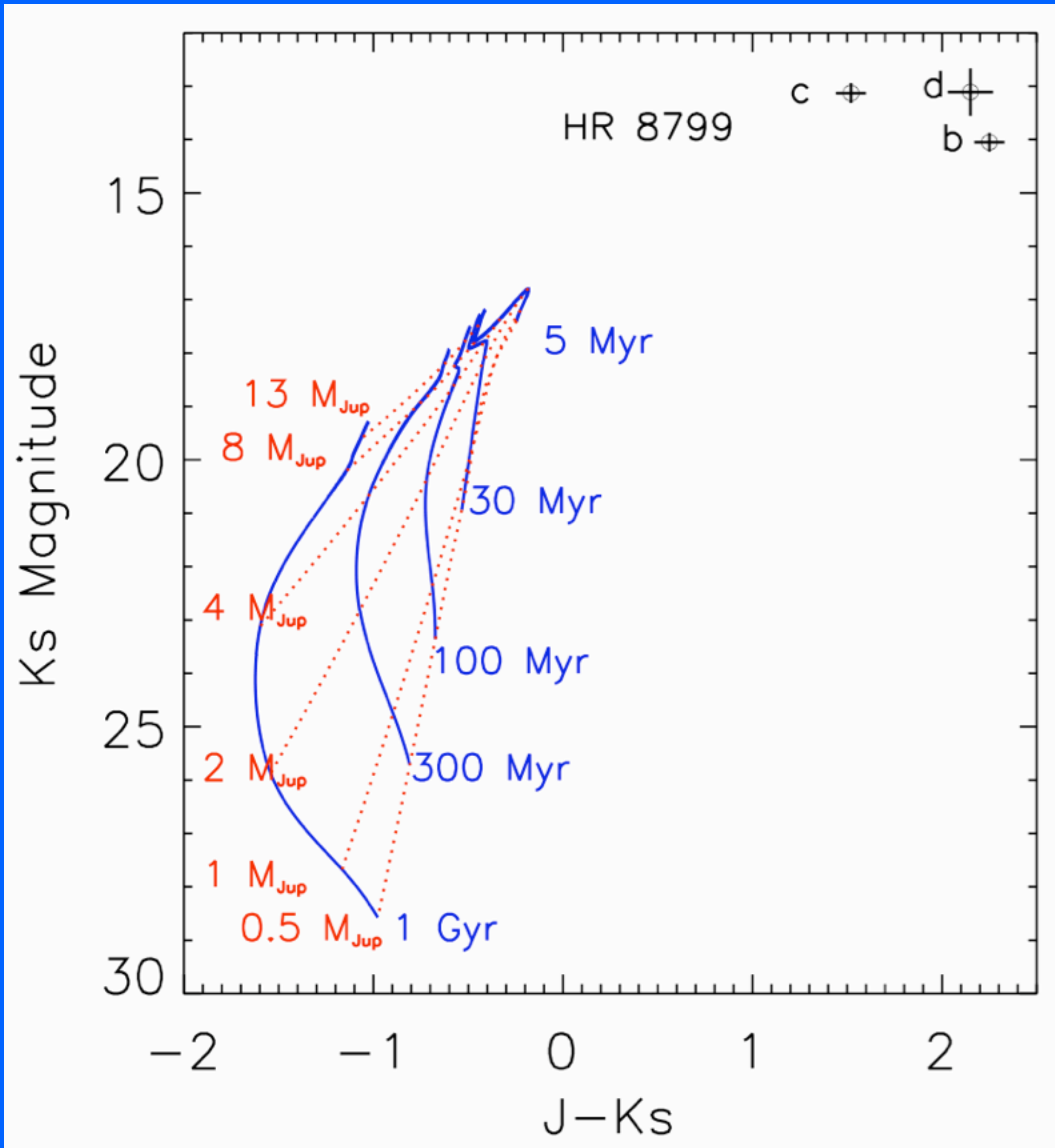
What if Planets are Even Fainter?



Nielsen and Close 2009.

- 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

Those Pesky A star Planets

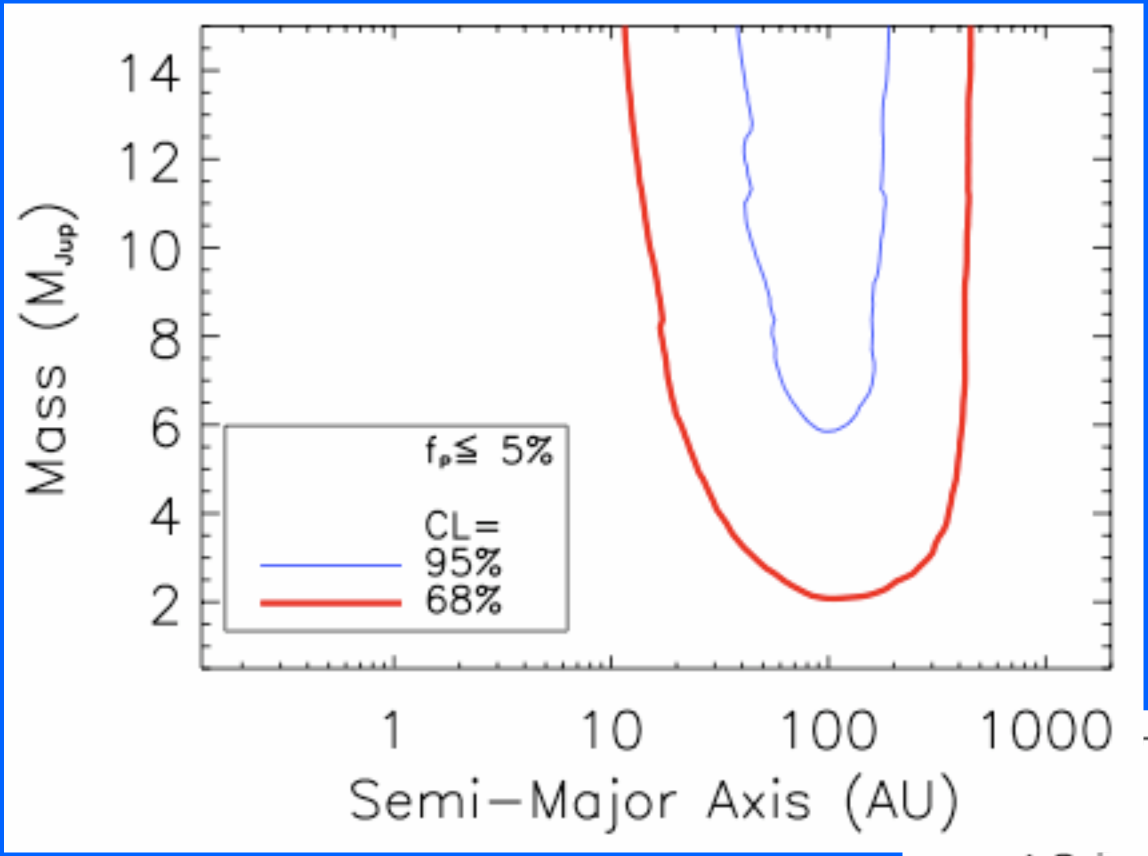


- The new planets around HR 8799 are totally inconsistent with the Fortney models
- Could suggest two modes for planet formation: gravitational collapse (Burrows and Baraffe models) and core accretion (Fortney)

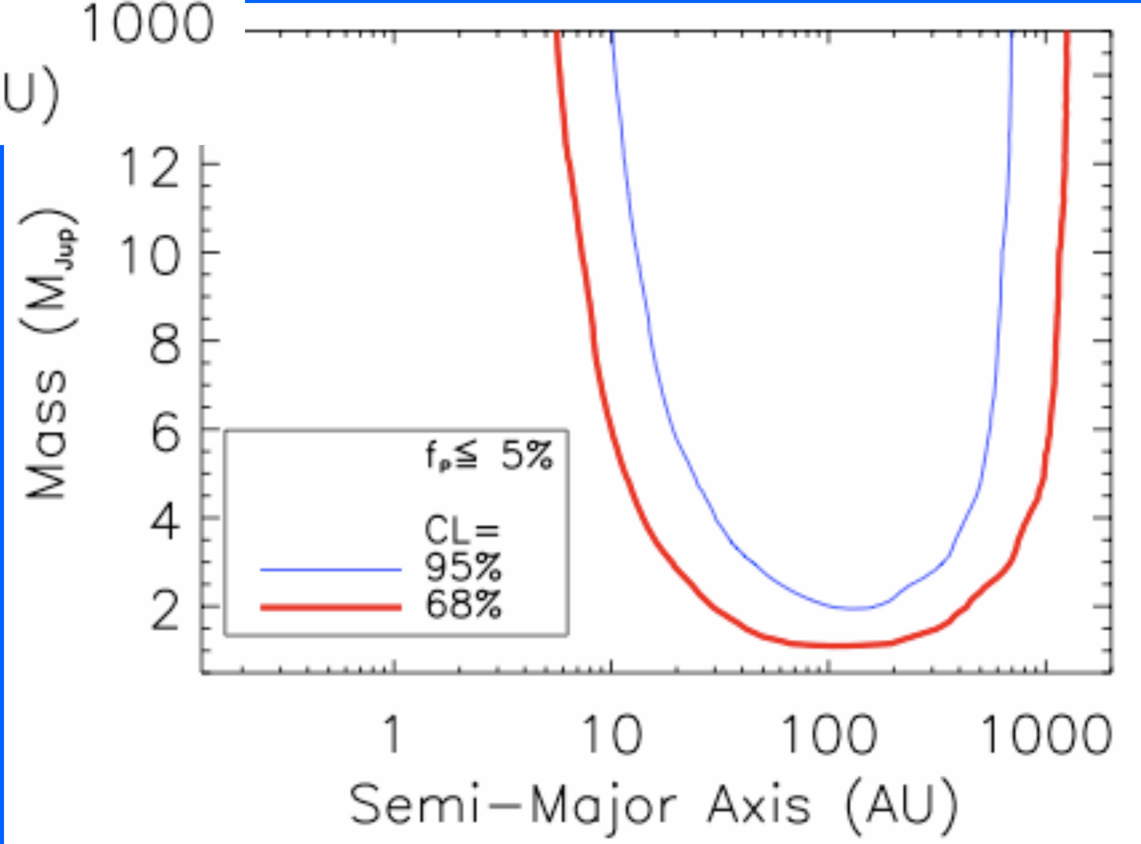
Future Work

- There are other past and present surveys for planets, also with null results, to be incorporated into the overall null results
- There are also surveys with detected planets (Christian's talk!), and including stars from those surveys (both with and without planets) will improve what we know about statistics of extrasolar giant planets
- Future 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?

VLT H and Ks, VLT and MMT SDI, and GDPS null results only



Including a null result from the 500-hour NICI survey



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