Stellar Mass Matters

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WHERE DISCOVERIES BEGIN

A few terms

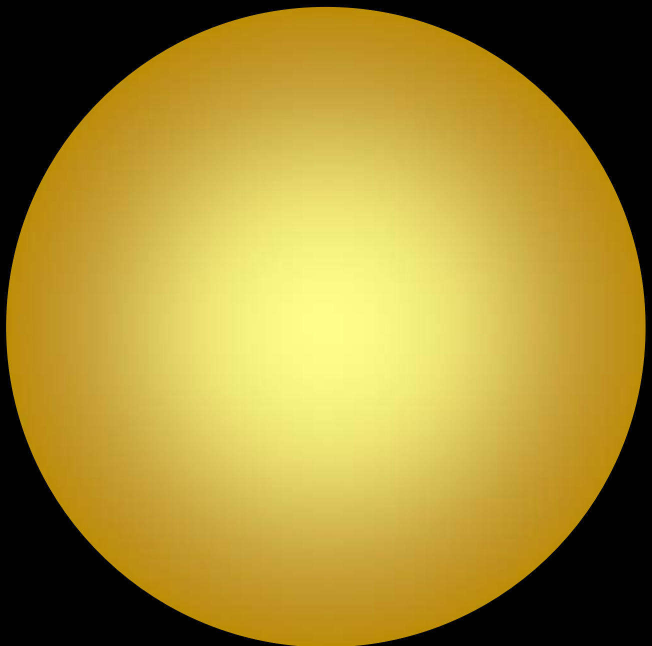
- Planet = detectable planet = gas giant
- Planet detections are those from RV surveys
- Occurrence rate = planet fraction
  = probability that a star has a planet

Stars Are Relatively Simple Objects

Mass

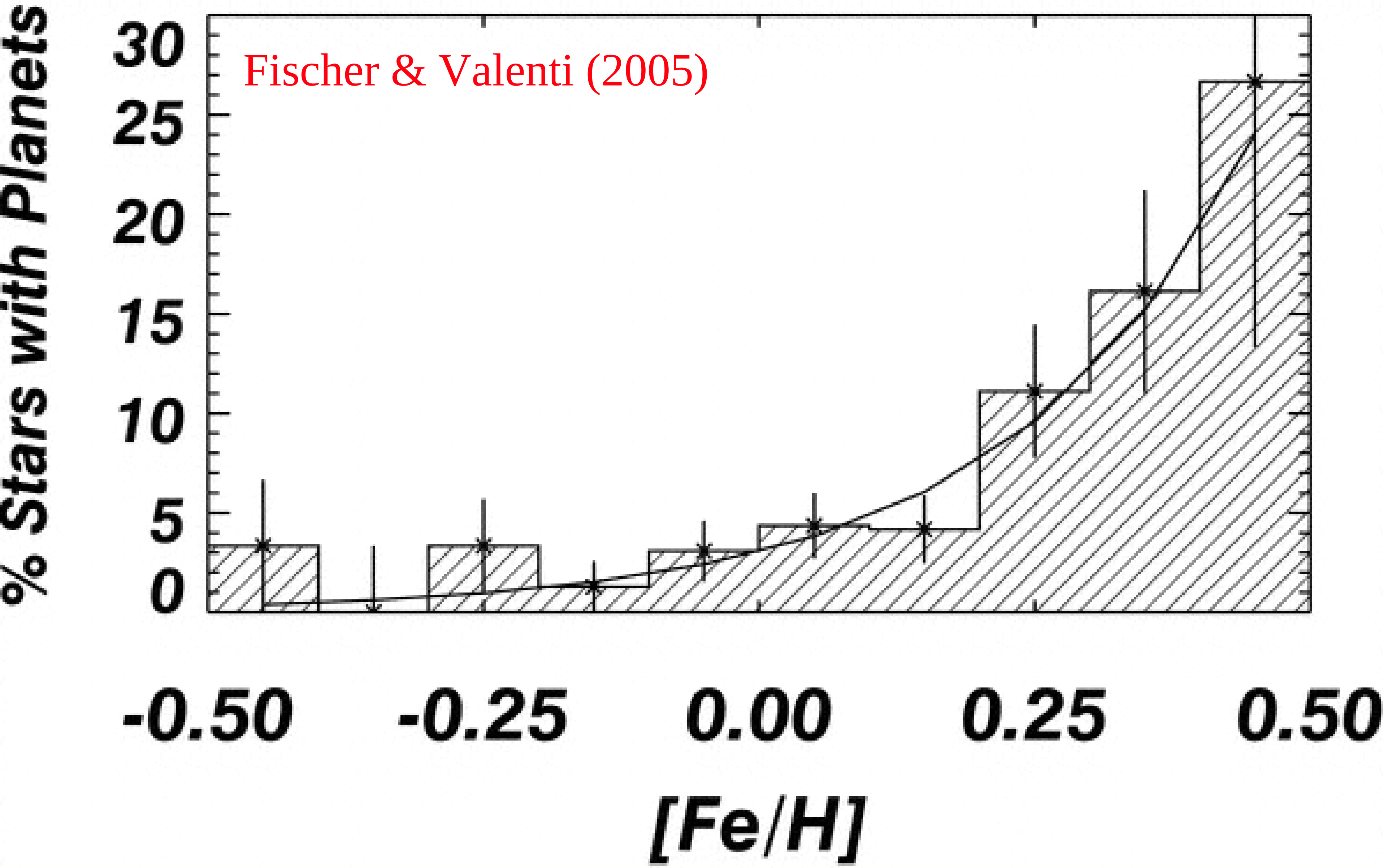
Composition

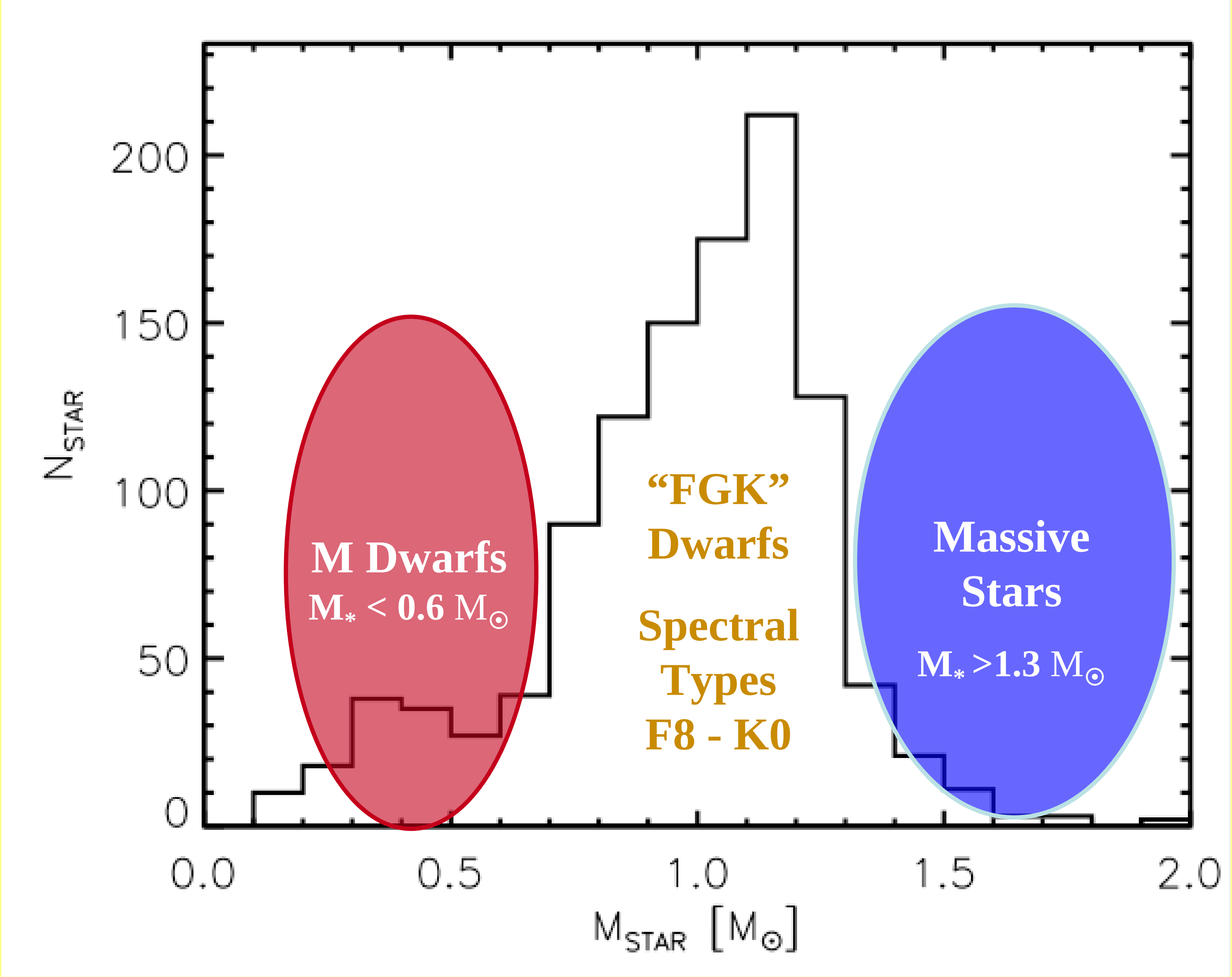
Age



The Star-Disk Connection

The Planet-Metallicity Correlation





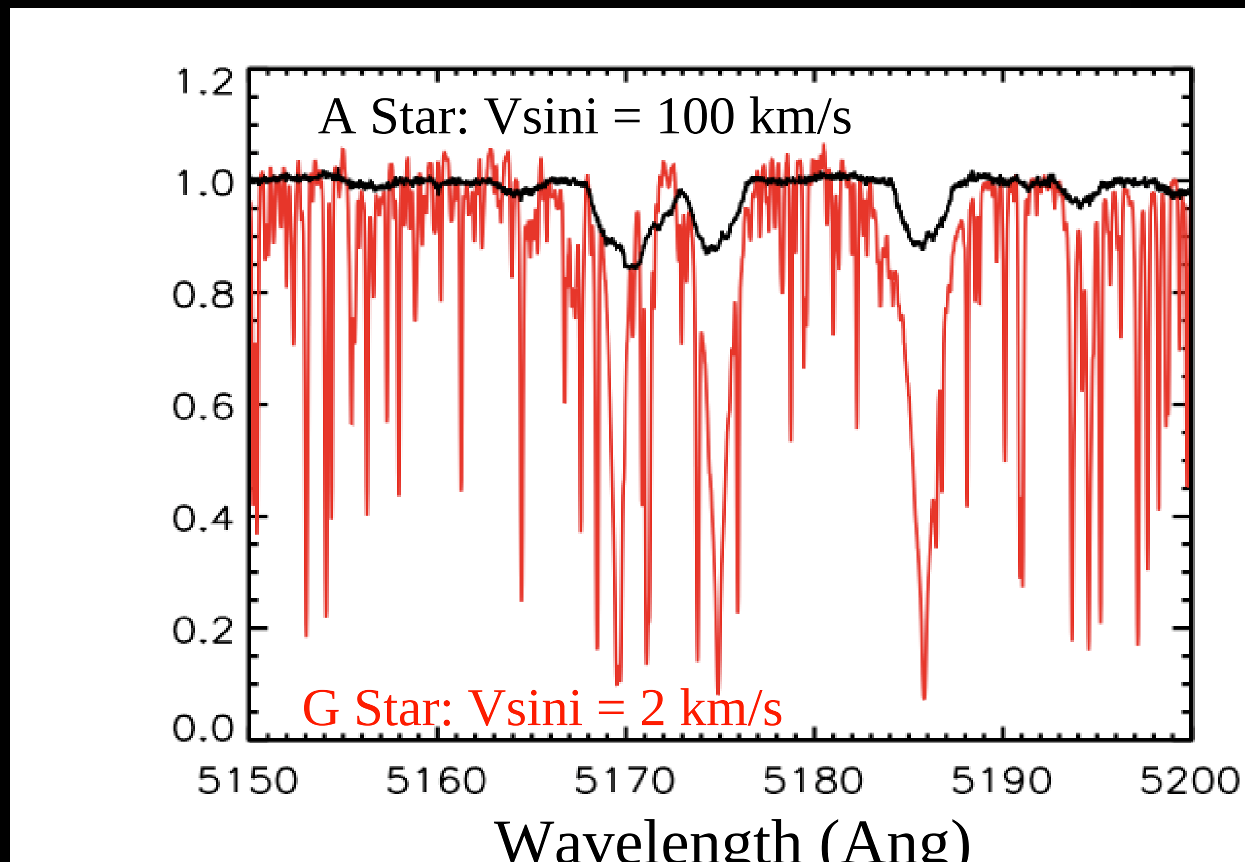
200
150
100
50
0
N_STAR
0.0
0.5
1.0
1.5
2.0
M_STAR [M☉]
M Dwarfs
M* < 0.6 M☉
"FGK"
Dwarfs
Spectral
Types
F8 - K0
Massive
Stars
M* >1.3 M☉

Main Sequence:

The Sun
1.0 Msun
1.0 Rsun
5770 K
Vsin*i* = 2 km/s
Velocity Precision: 1 m/s

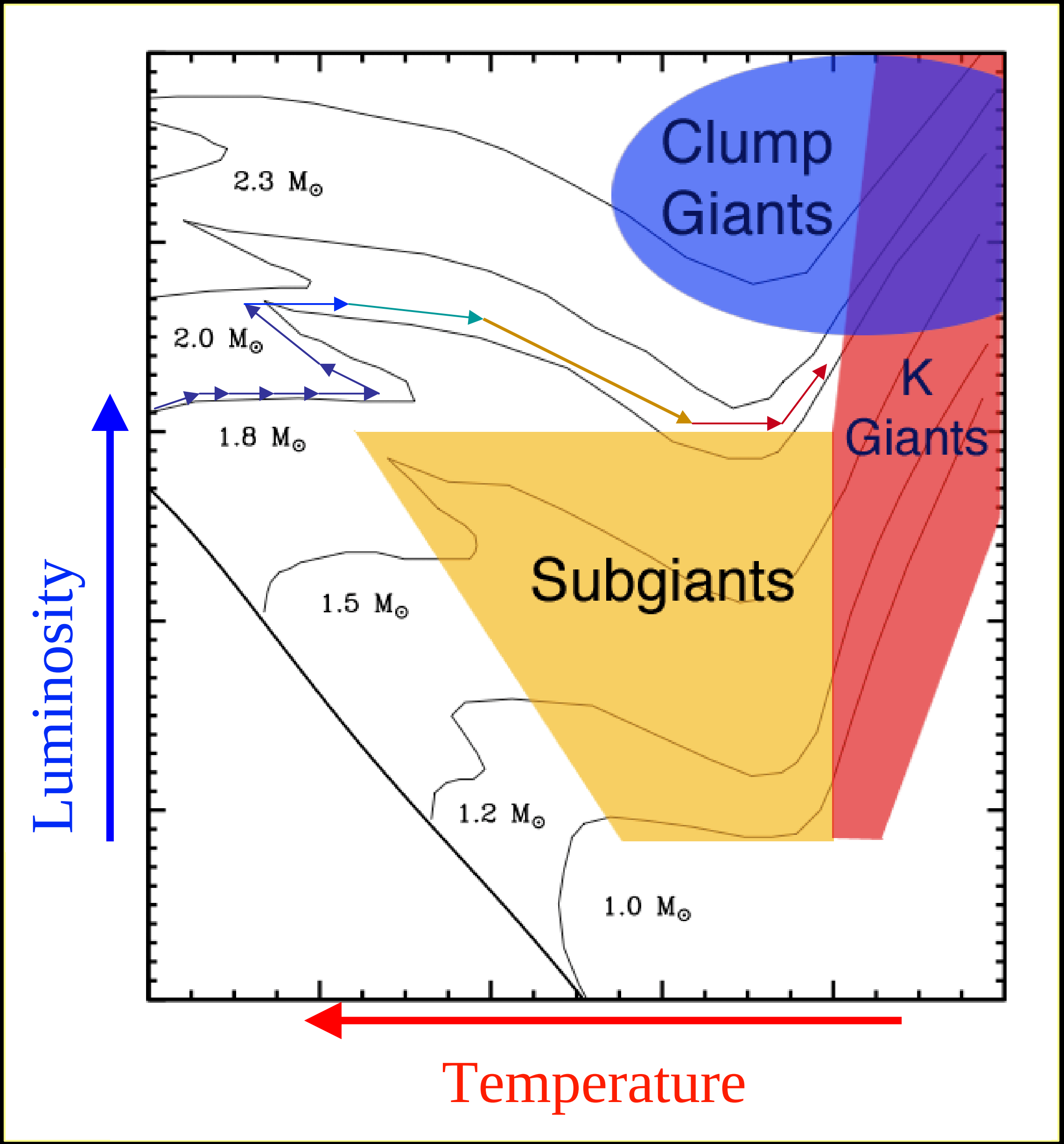
A-type Star
2.0 Msun
1.9 Rsun
8200 K
Vsin*i* = 100 km/s
Velocity Precision: ~100 m/s

Early-type Stars Are Rapid Rotators

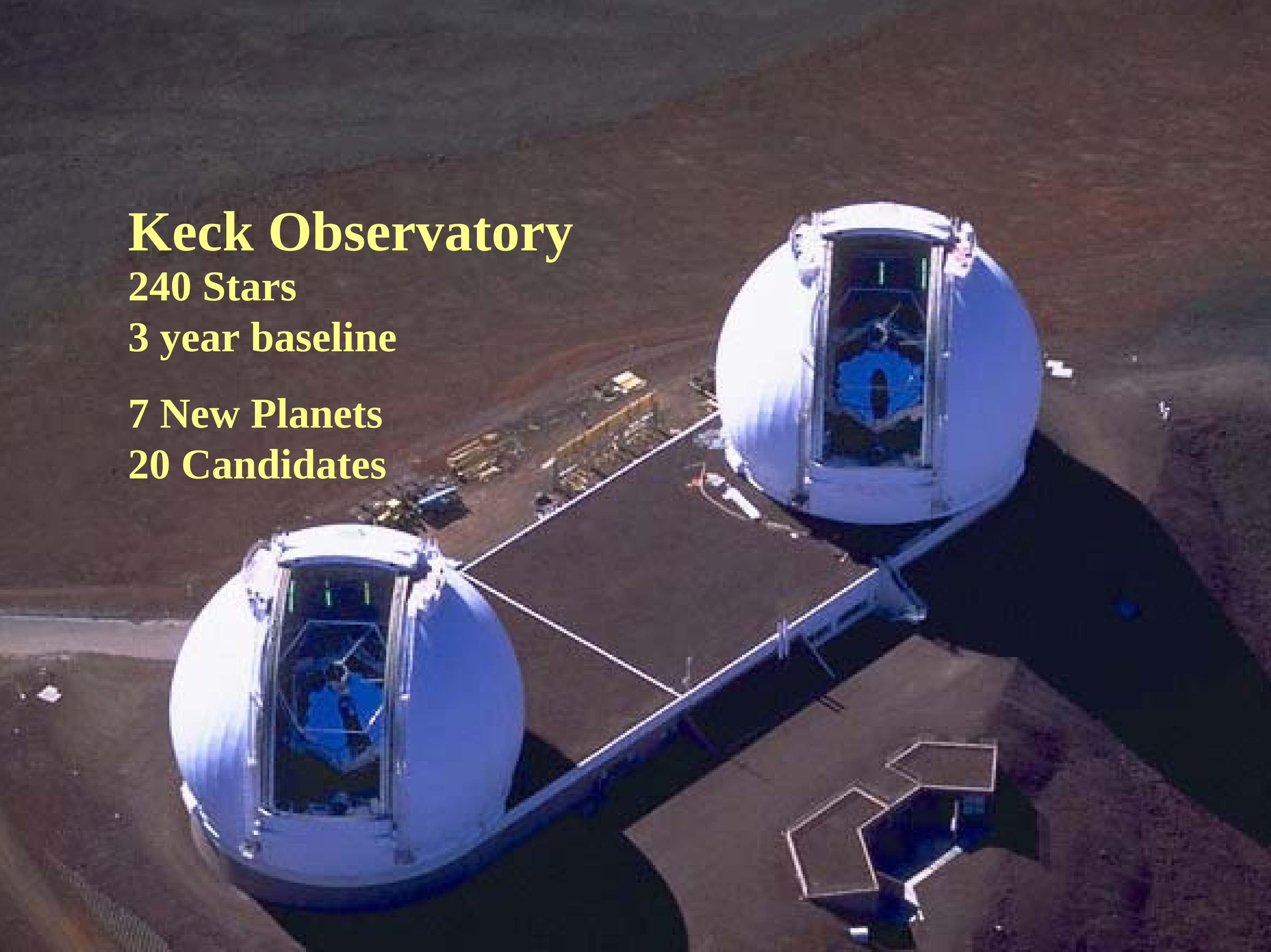


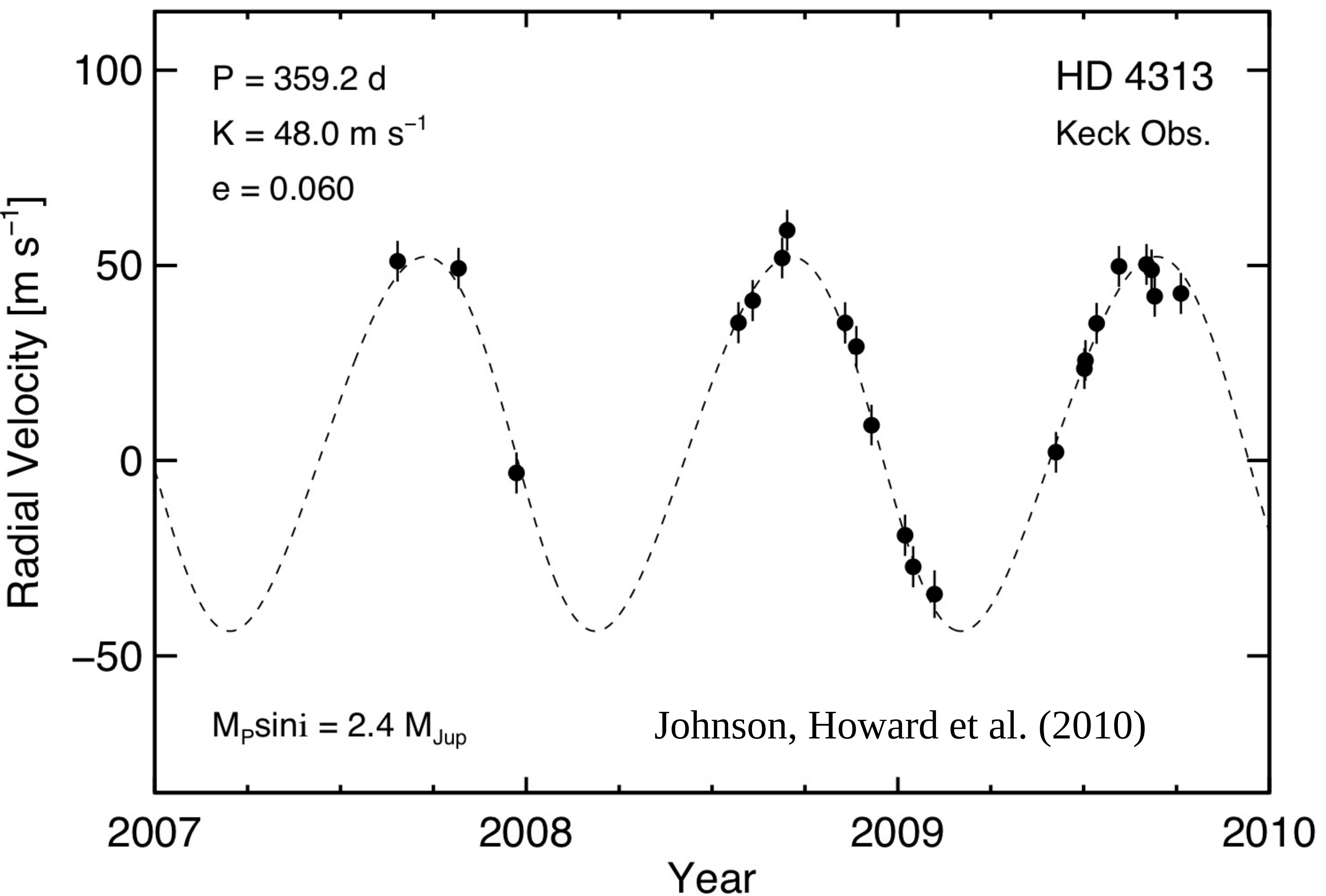
Main Sequence:

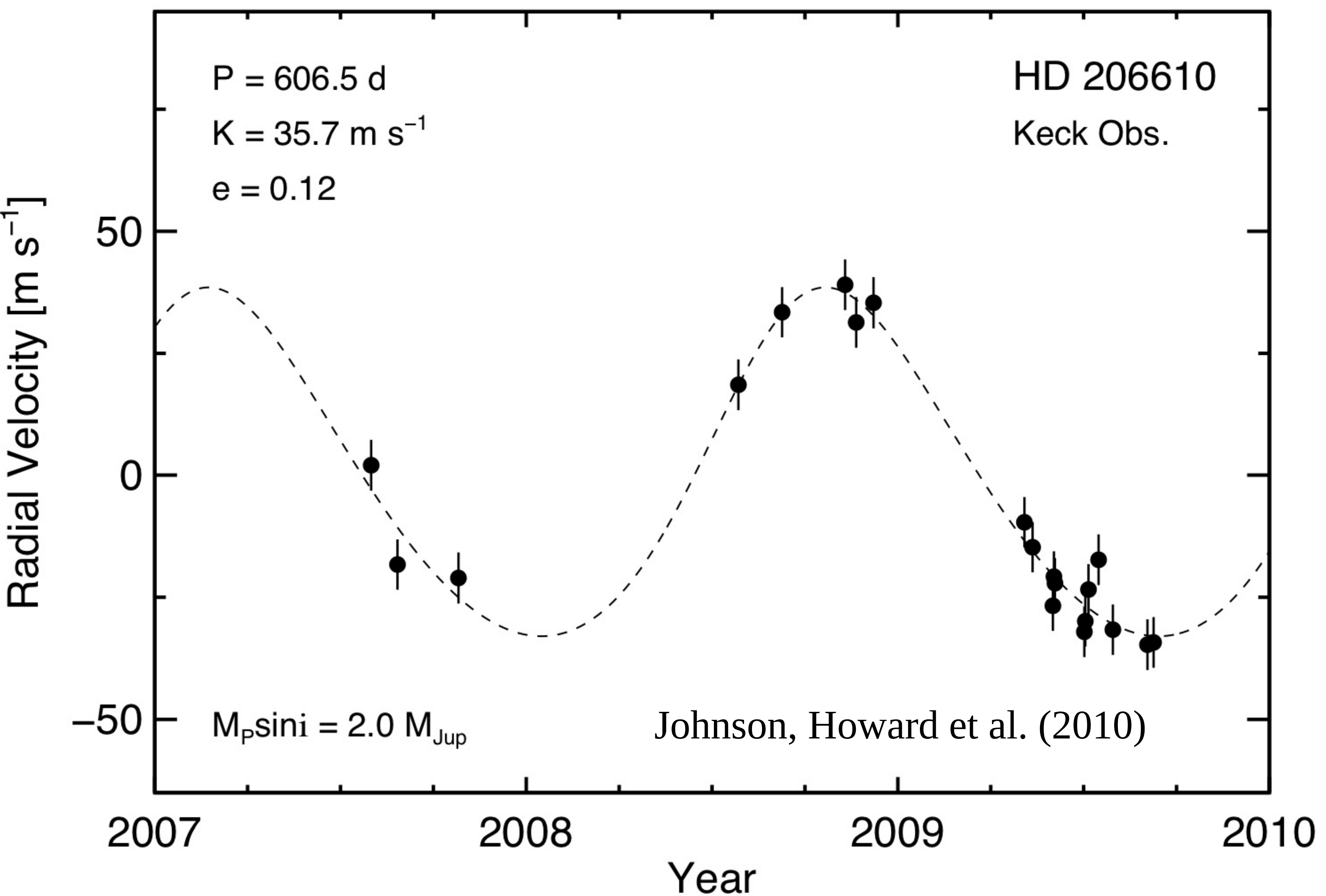
Classes of Evolved Stars




Lick
Observatory
120 Stars
6 year baseline
9 New Planets
0.6 meter
Coude
Auxiliary
Telescope


Keck Observatory
240 Stars
3 year baseline
7 New Planets
20 Candidates


P = 359.2 d
K = 48.0 m s^{-1}
e = 0.060
HD 4313
Keck Obs.
$M_P$sini = 2.4 M_{Jup}
Johnson, Howard et al. (2010)
100
50
0
−50
Radial Velocity [m s^{-1}]
2007
2008
2009
2010
Year



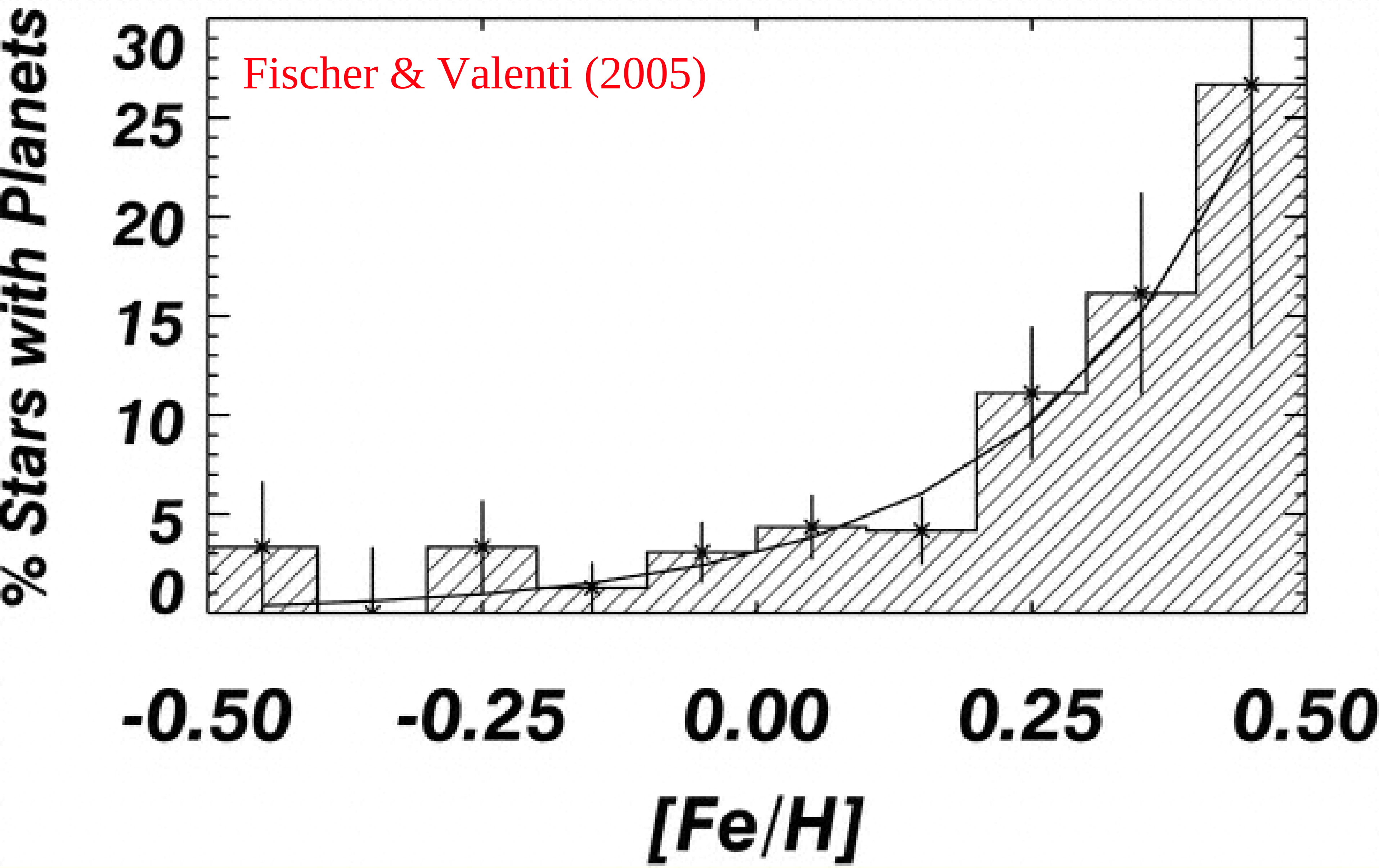
P = 606.5 d
K = 35.7 m s⁻¹
e = 0.12
HD 206610
Keck Obs.
M_P sini = 2.0 M_Jup
Johnson, Howard et al. (2010)
Radial Velocity [m s⁻¹]
50
0
−50
2007
2008
2009
2010
Year

Planet Occurrence vs Stellar Mass

- Limit the analysis to planets with
  a < 2.5 AU
  K > 20 m/s
  $N_{obs} > 7$

- Compare subgiants with CCPS sample of M dwarfs and Sun-like stars

Fitting to a histogram



A Bayesian Framework

For a set of data *d* fitted by a model with parameters A

$$\Pr(A|d) \propto \Pr(d\,|A)\,\Pr(A)$$

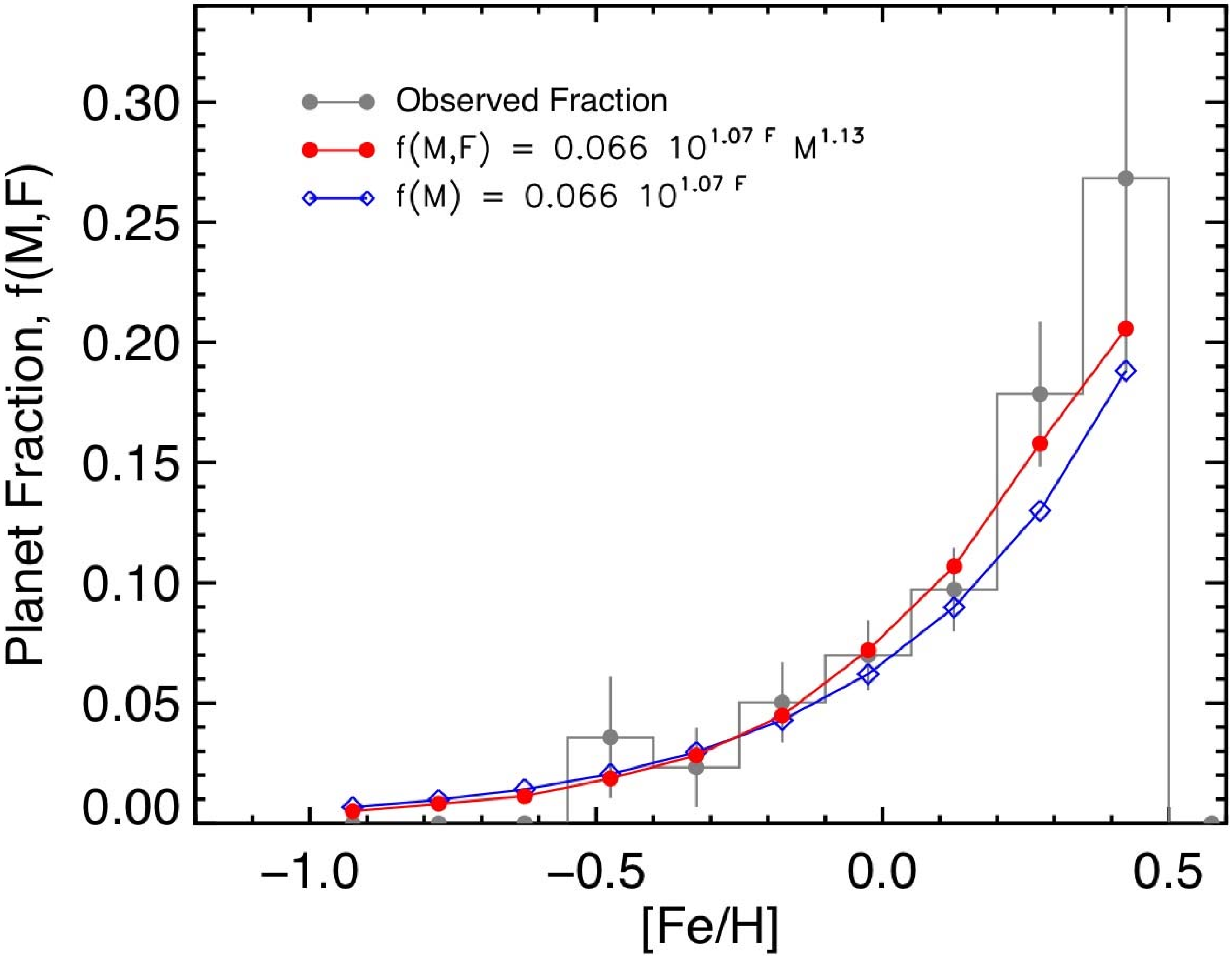
$$\prod_{i}^{\text{all stars}} \begin{cases} f(Fe_i, M_i; A) & \text{If it has a planet} \\ 1 - f(Fe_i, M_i; A) & \text{If not} \end{cases}$$

$$f(Fe, M; A) = A_0\, 10^{A_1 Fe}\, M^{A_2}$$

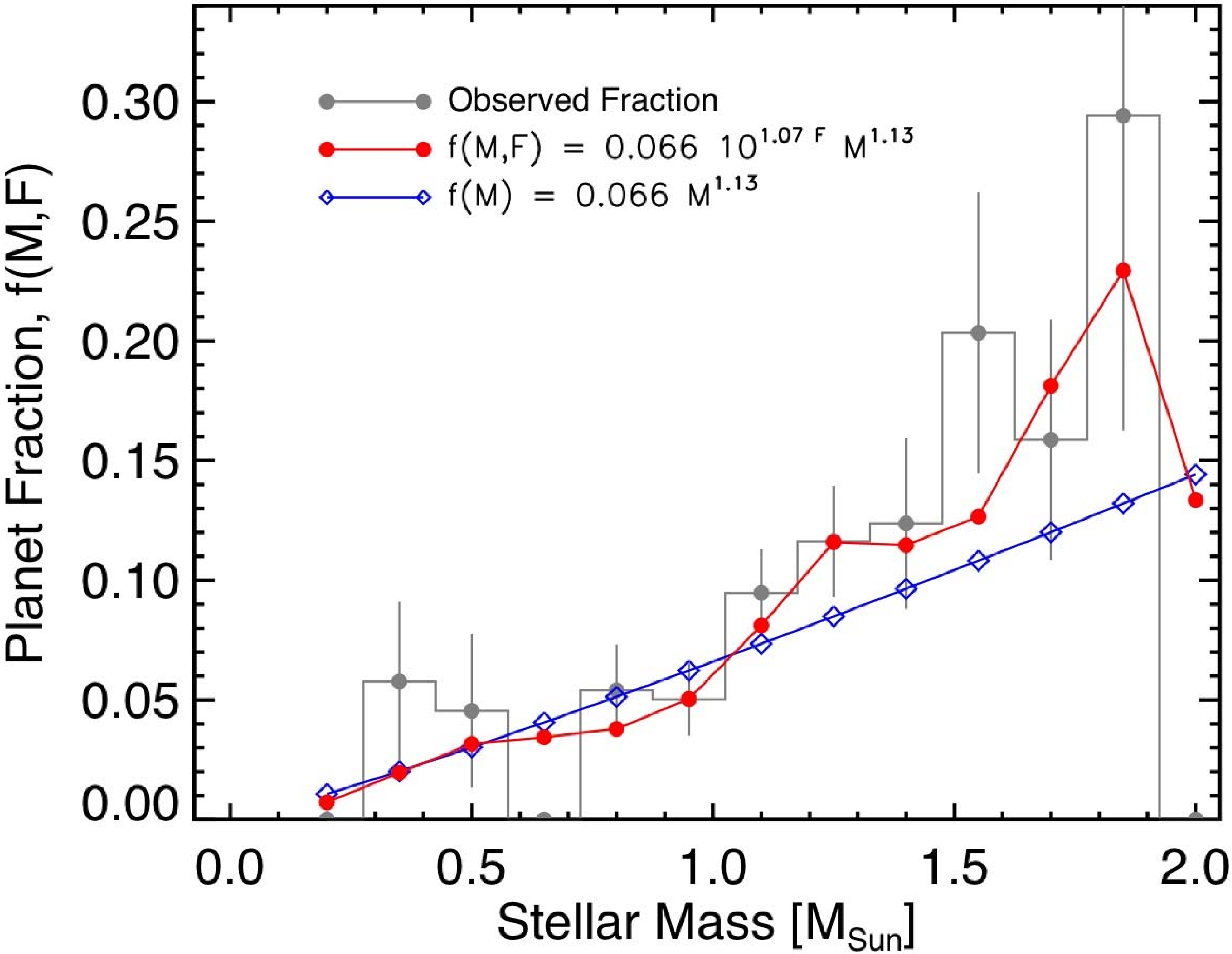
Maximize Pr(A|d) to find best-fitting parameters A

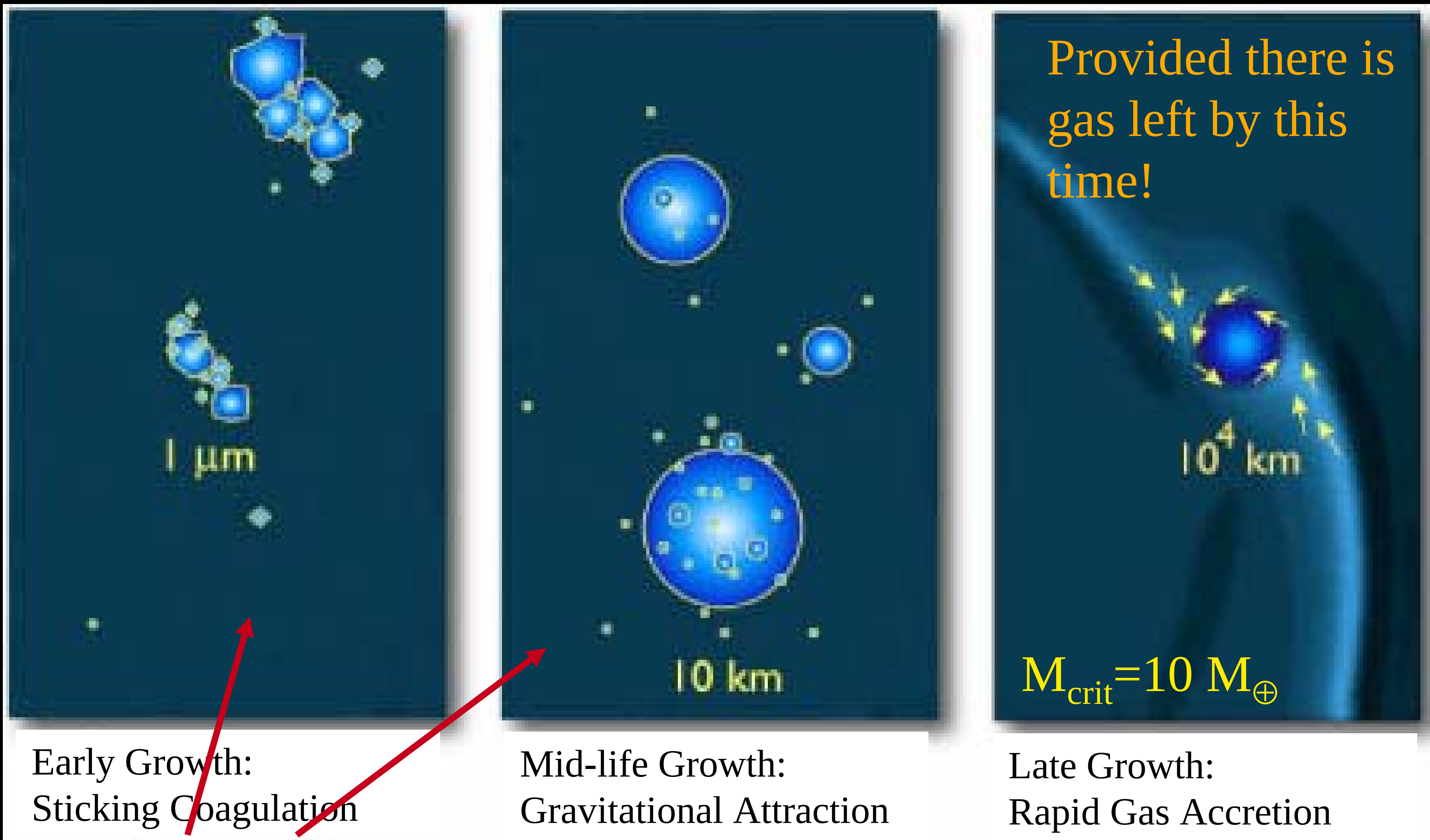
Johnson, Aller et al. 2010 in prep

Johnson, Aller et al. 2010 in prep



Johnson, Aller et al. 2010 in prep





Higher Mass or [Fe/H] means more raw materials and faster growth

oklo.org

Stellar Mass and Planet Formation

Laughlin, Bodenheimer & Adams (2004)

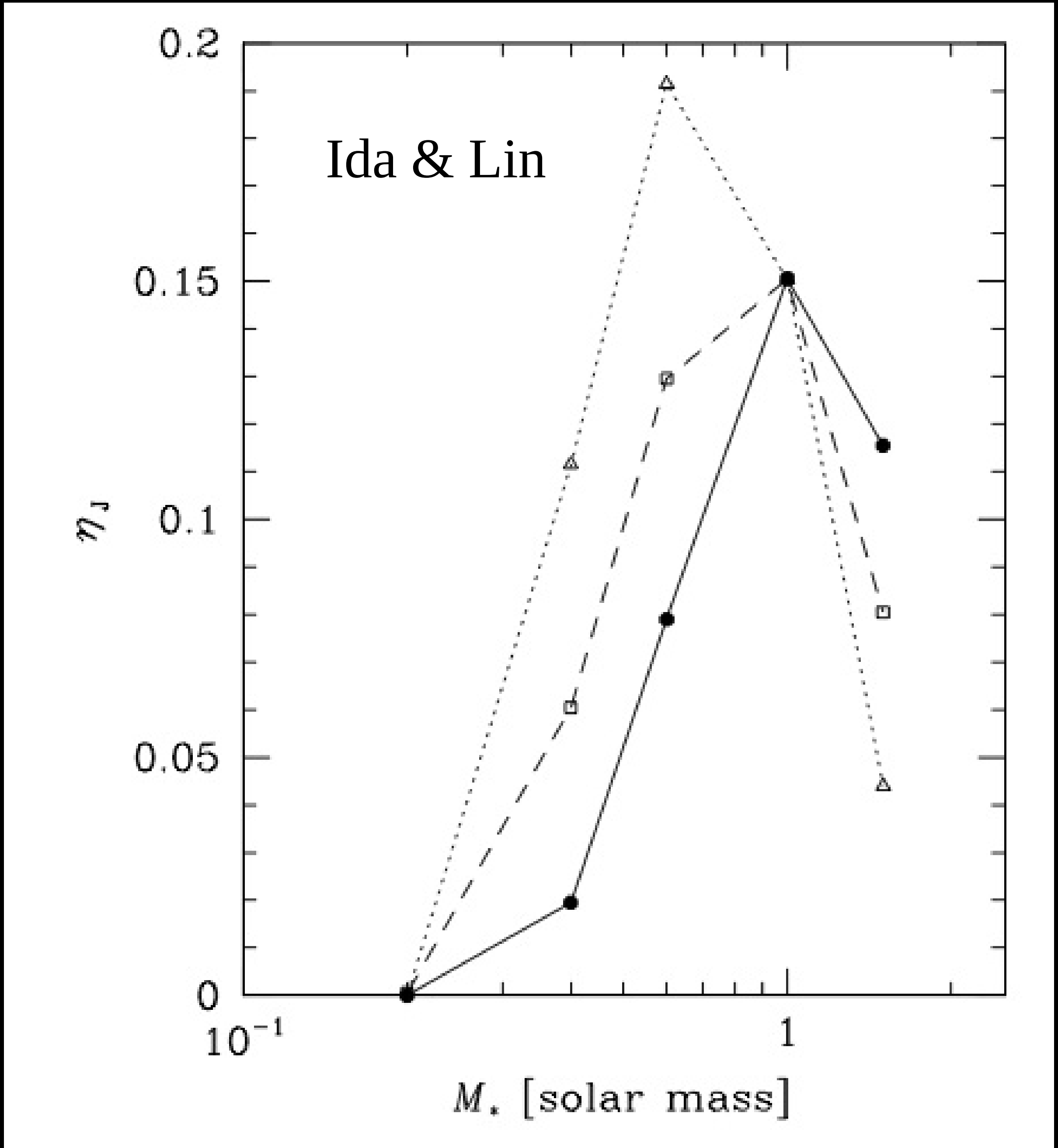
Kep Freq ~P^{-1}

$$\frac{dM_C}{dt} \sim \Sigma \Omega R_H^2 \sim M_*^{0.8}$$

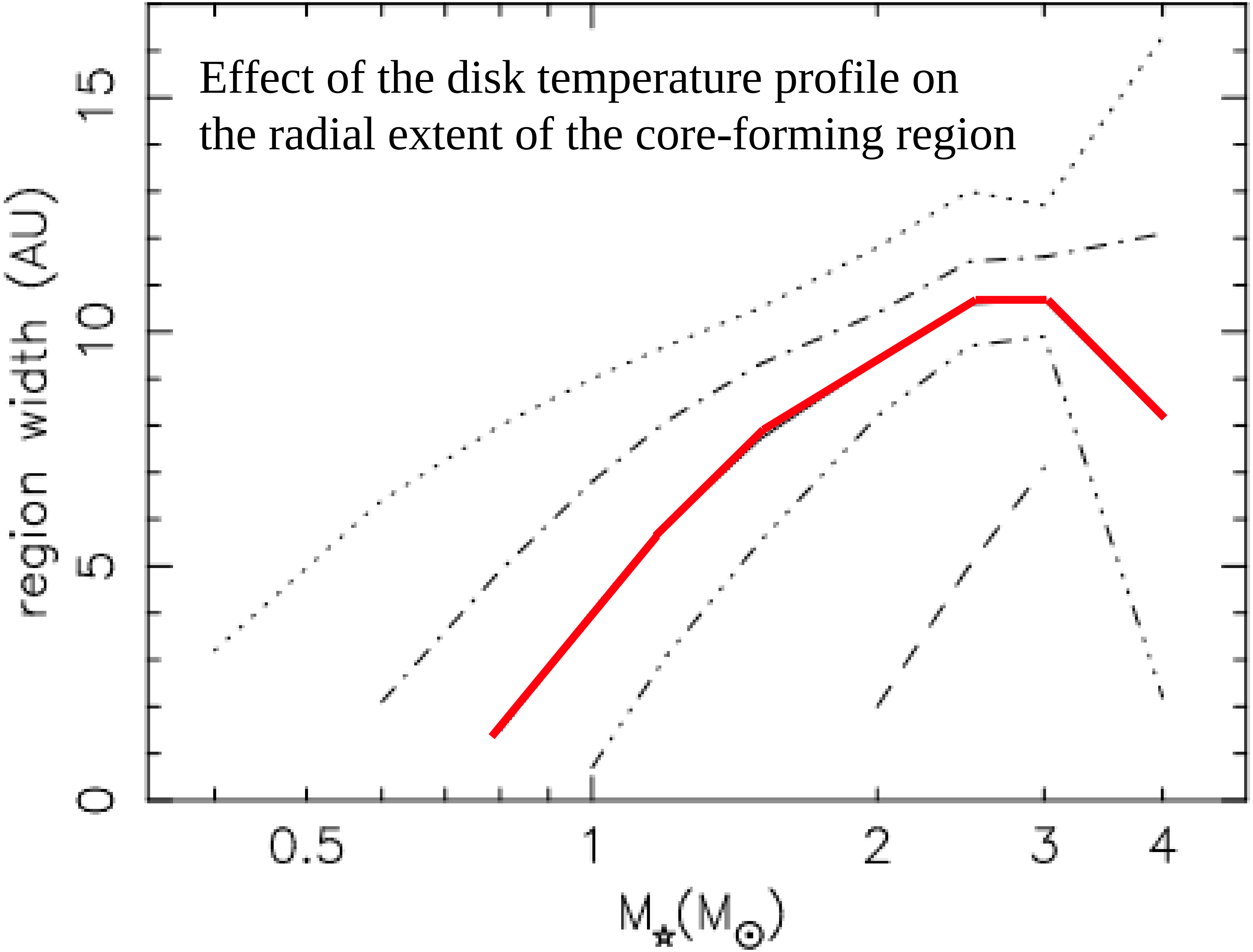
Surface Density

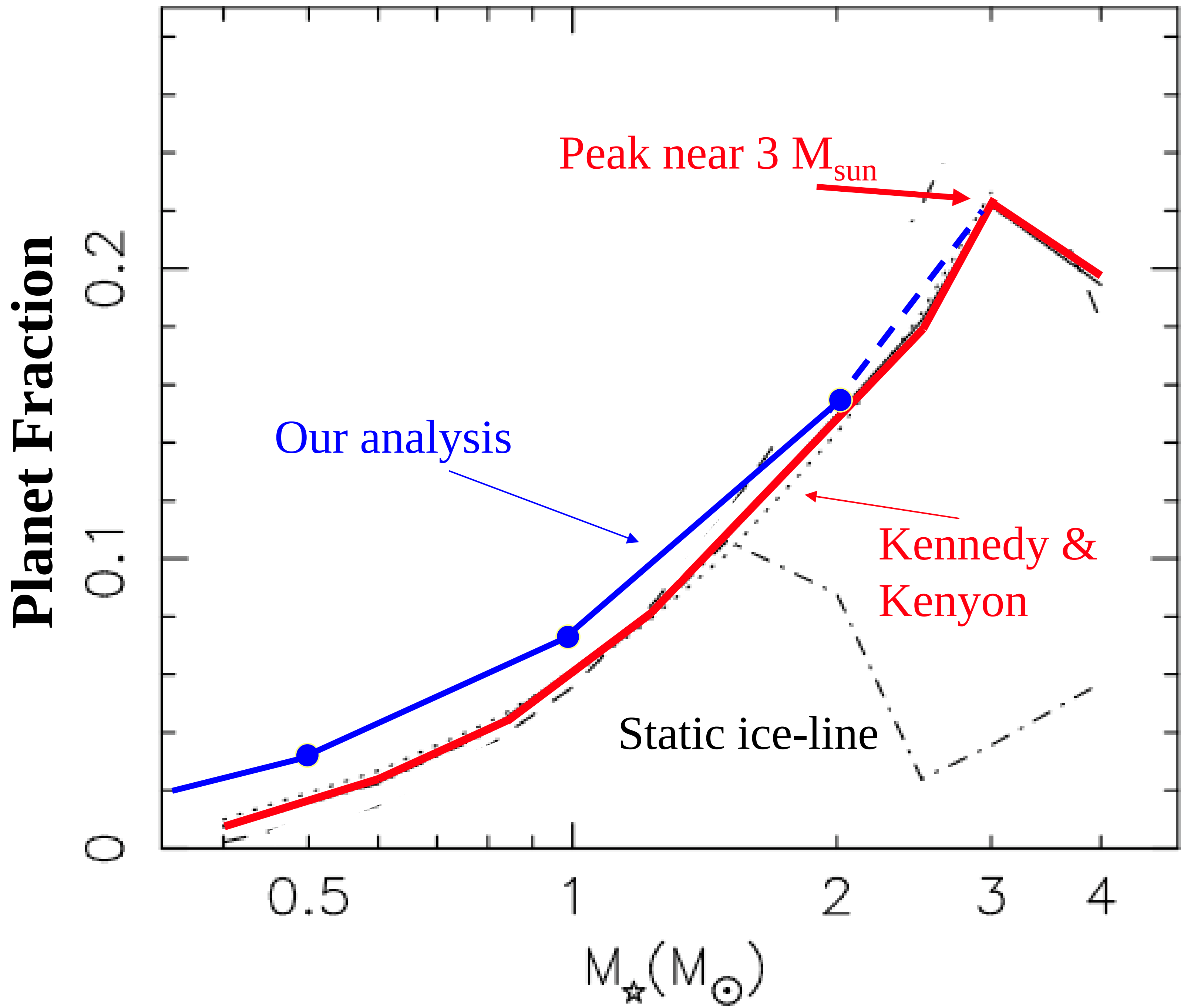
Hill Sphere Radius

Static Ice-Line



Kennedy & Kenyon (2007)



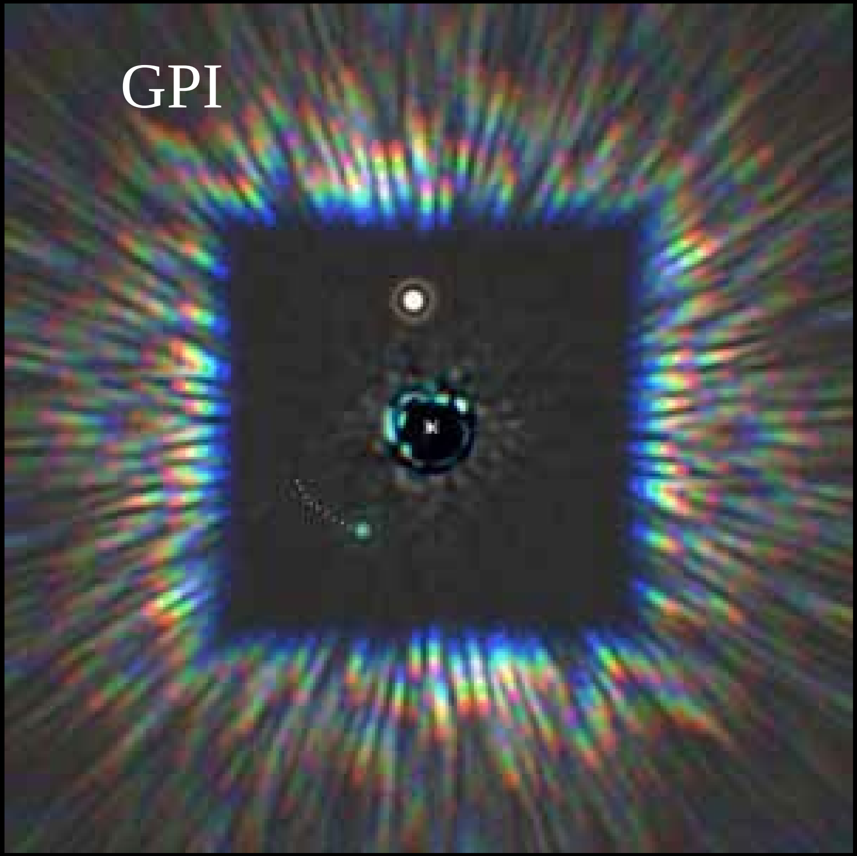


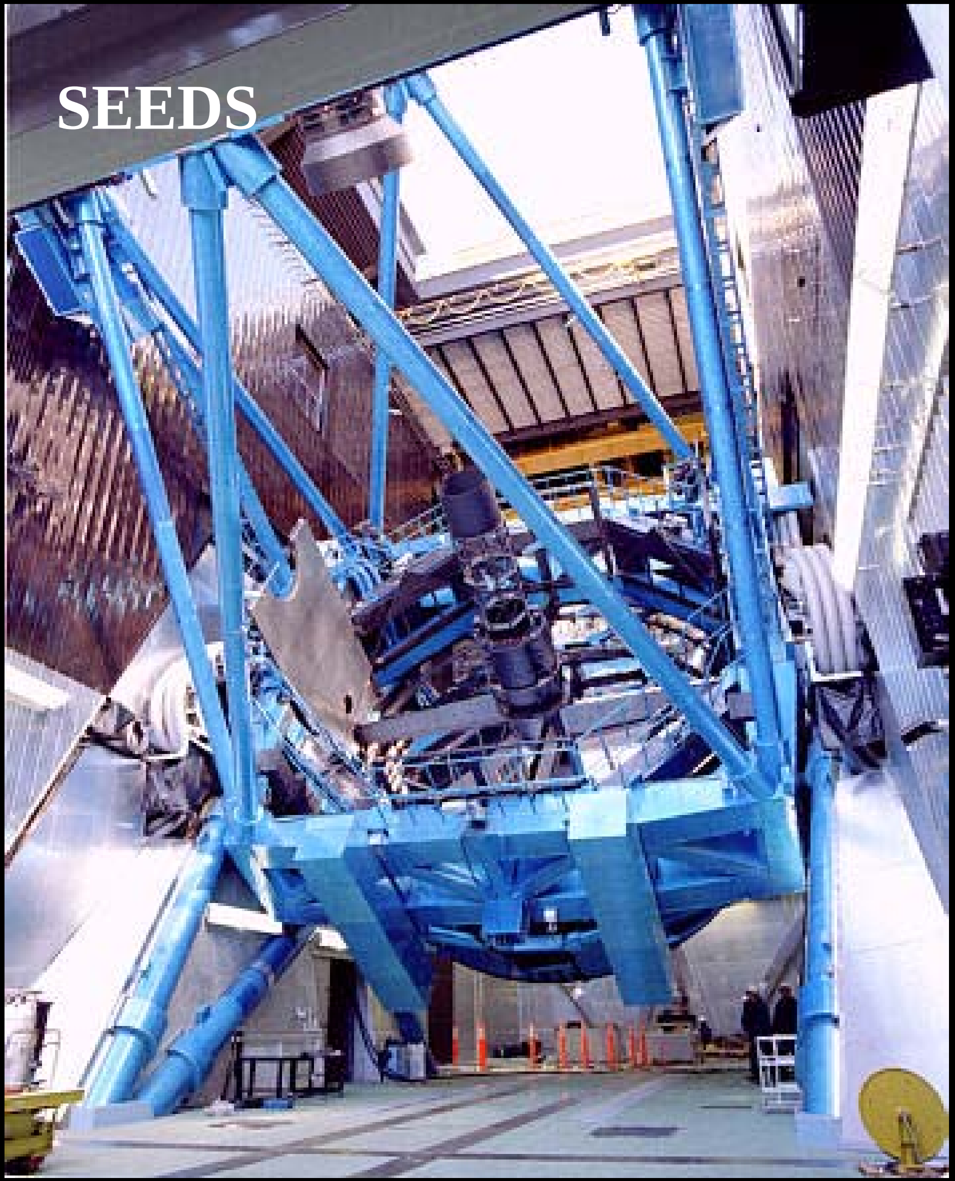
Planet Fraction
0.2
0.1
0
0.5
1
2
3
4
$M_\star(M_\odot)$
Peak near 3 M_{sun}
Our analysis
Kennedy &
Kenyon
Static ice-line

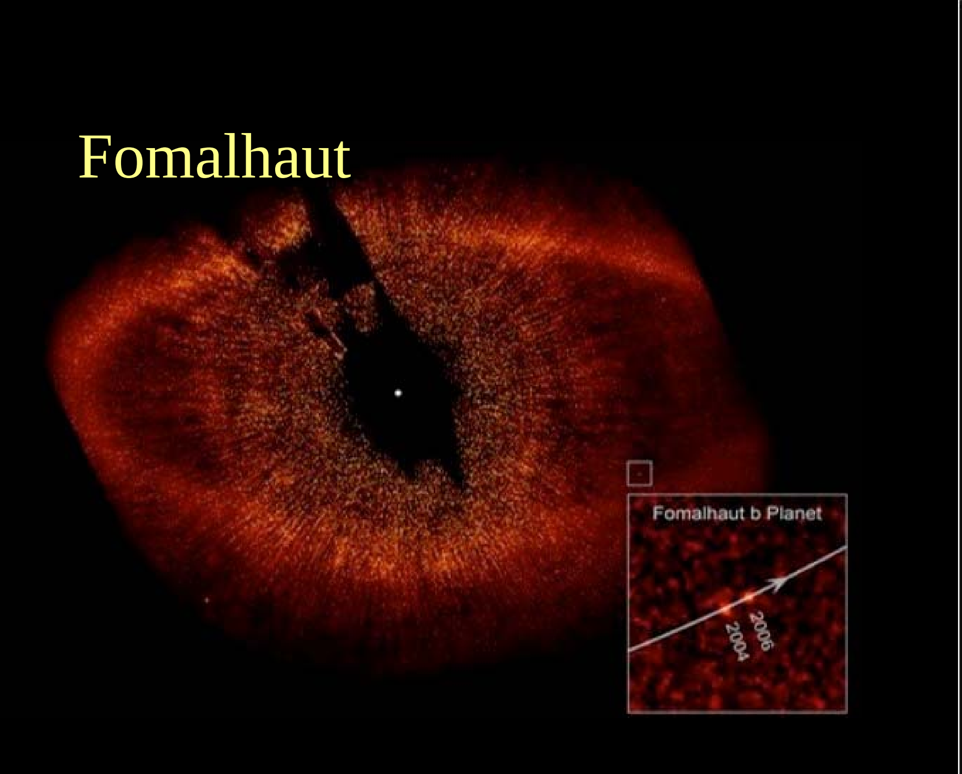
Knowing Where to Look

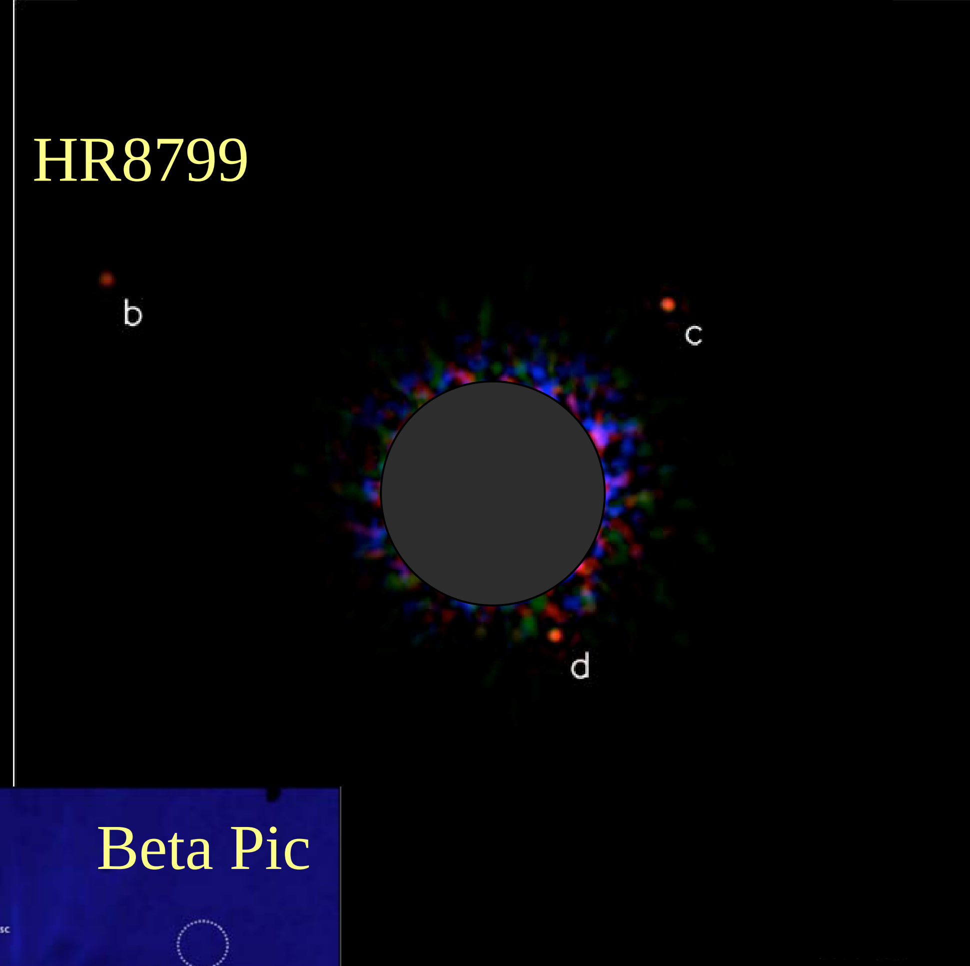
Stellar mass is a predictor of "planeticity."

A stars are "naturally young"



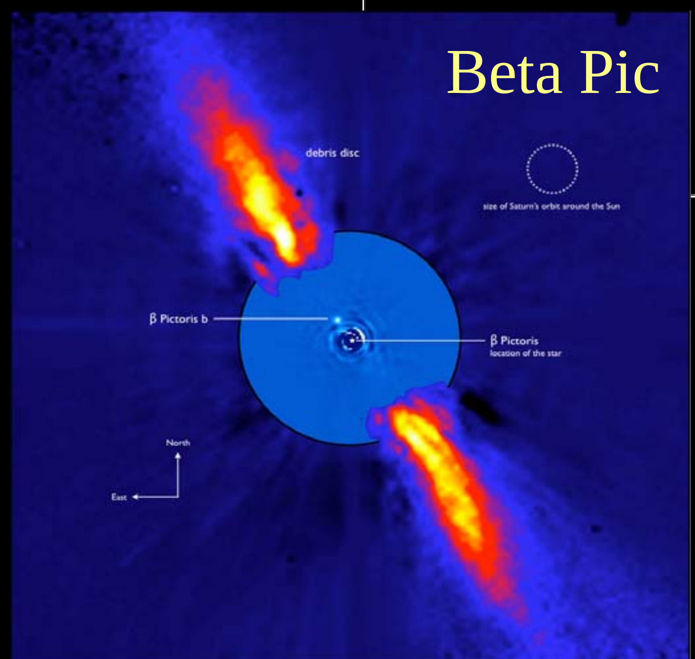






A Stars

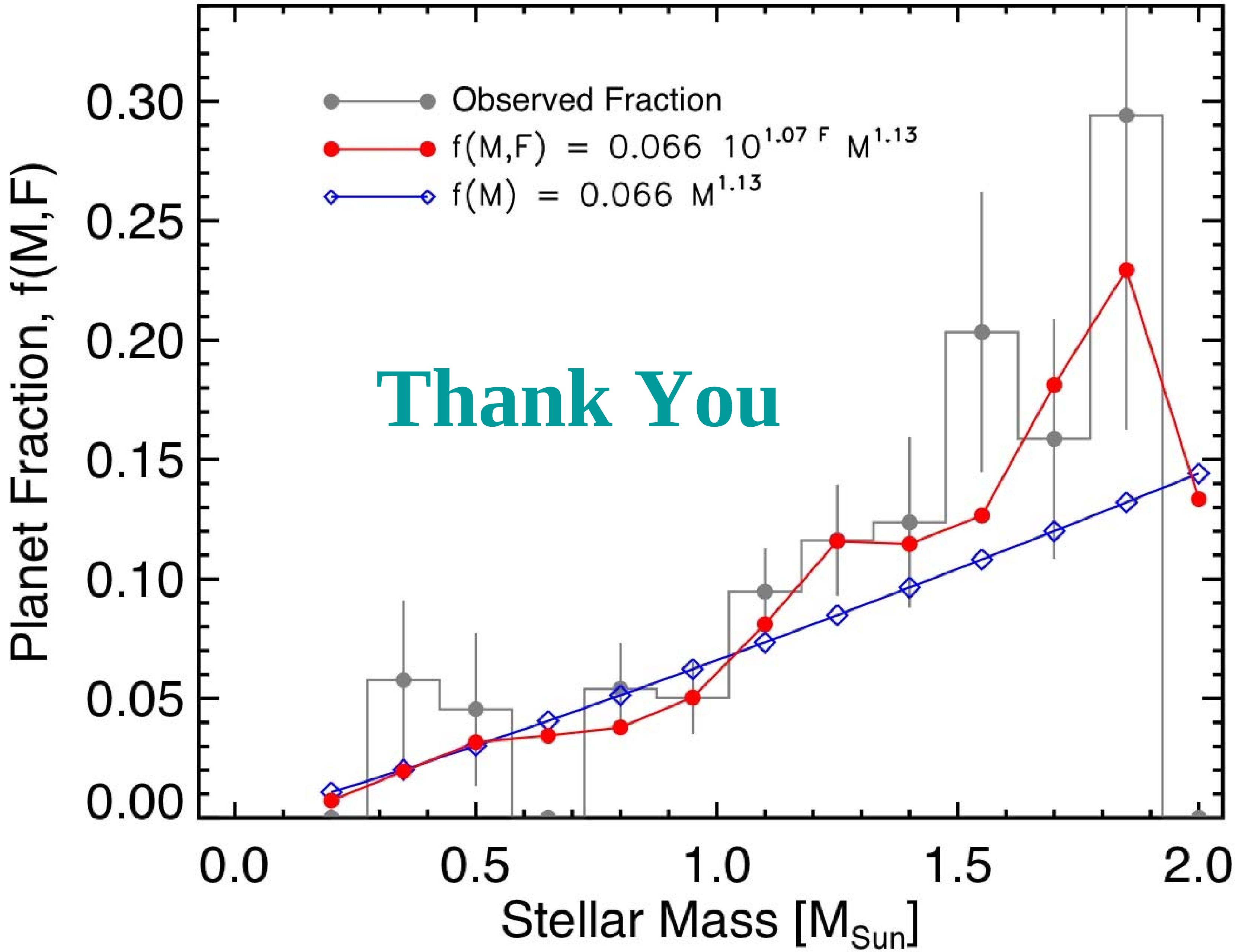
$M_* > 2\ M_{Sun}$



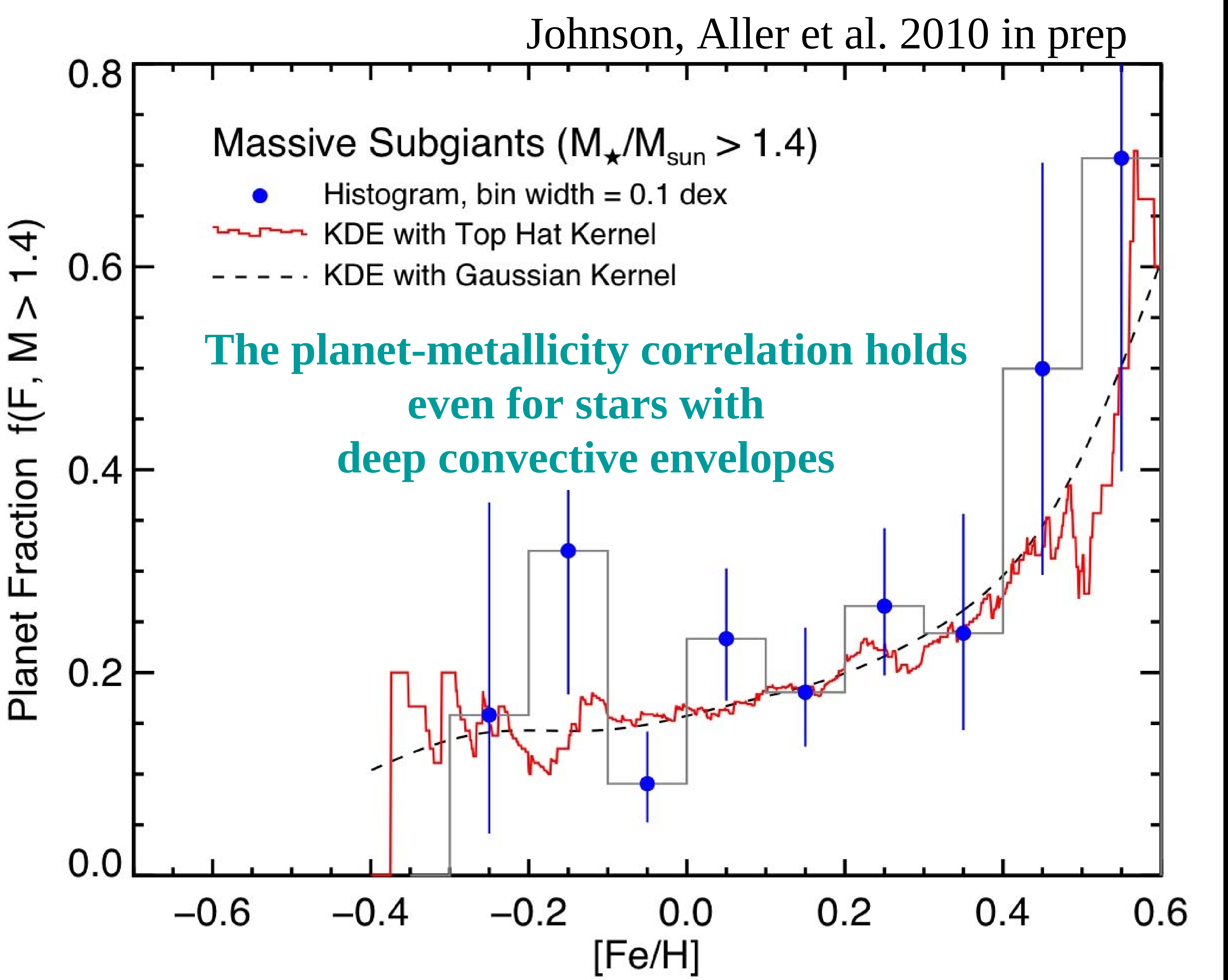
Conclusions

- Planet frequency correlates strongly with both metallicity *and stellar mass*.
- Informs the target selection of future planet search efforts
- Successful models of planet formation must account for mass and composition of star/disk system

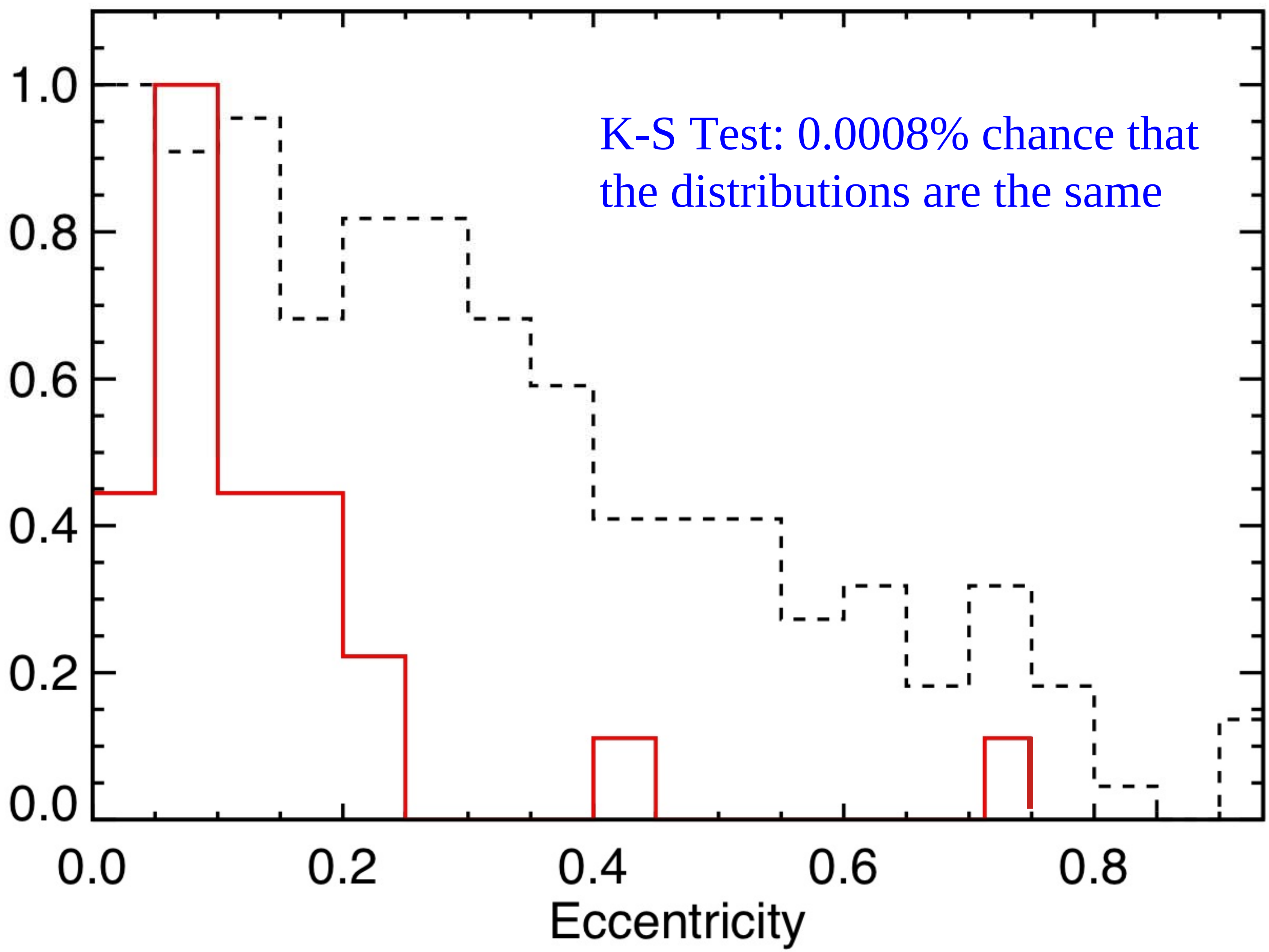
Johnson, Aller et al. 2010 in prep



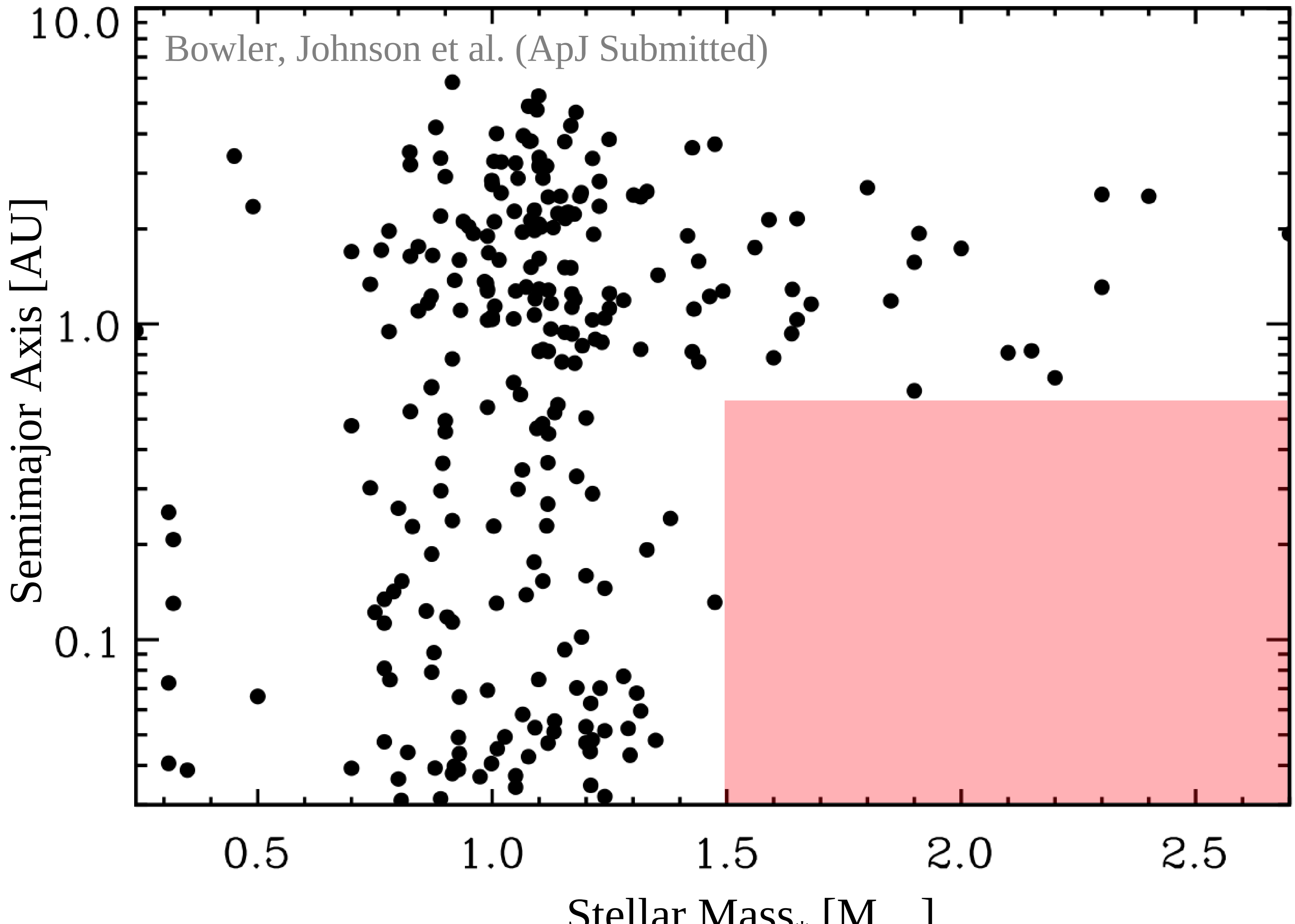
Thank You


Johnson, Aller et al. 2010 in prep
Massive Subgiants ($M_\star/M_{sun} > 1.4$)
Histogram, bin width = 0.1 dex
KDE with Top Hat Kernel
KDE with Gaussian Kernel
The planet-metallicity correlation holds even for stars with deep convective envelopes
Planet Fraction f(F, M > 1.4)
[Fe/H]
0.0
0.2
0.4
0.6
0.8
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6

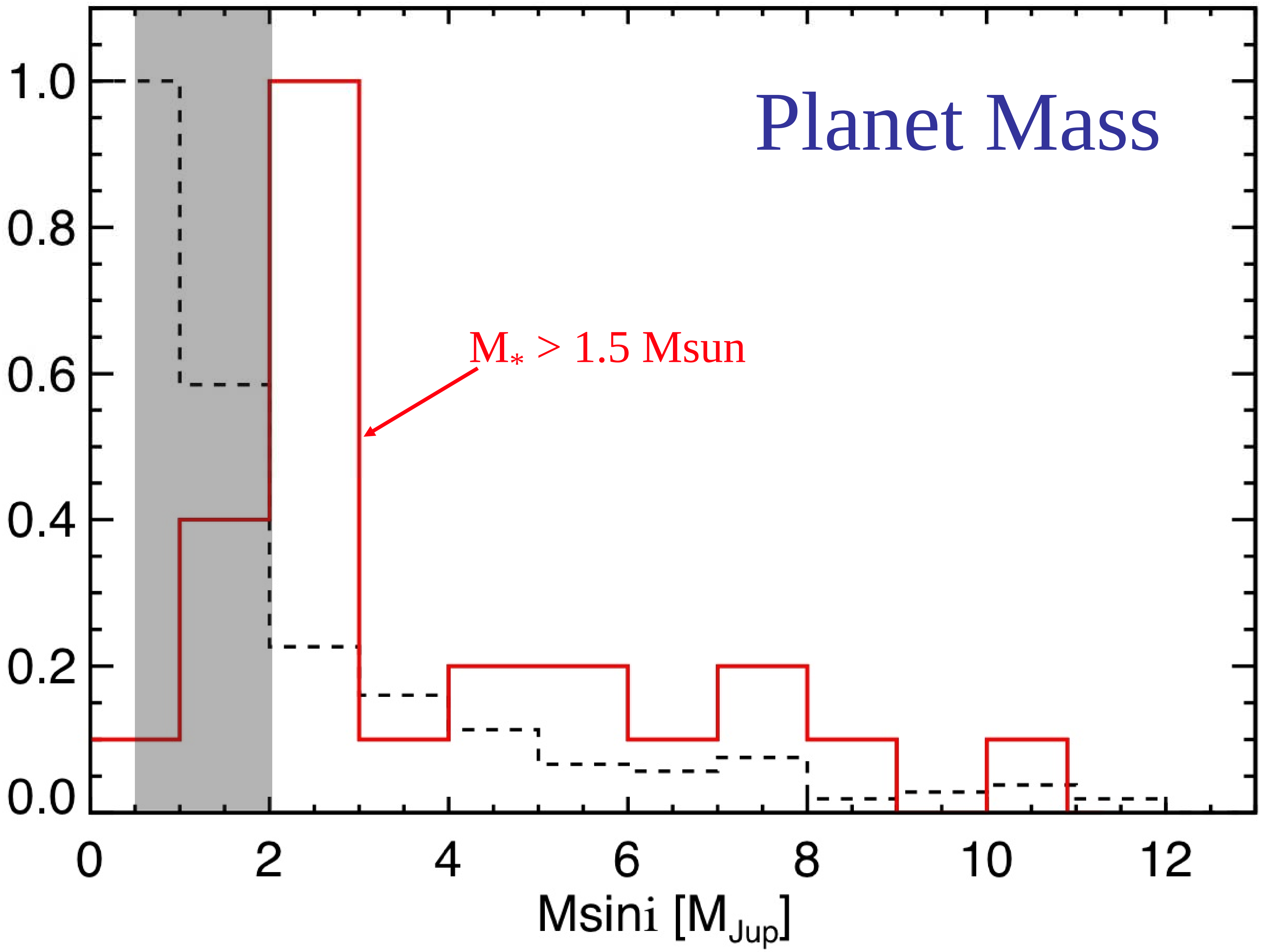
The Properties of Planets Around Massive Stars



K-S Test: 0.0008% chance that
the distributions are the same
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
Eccentricity



Bowler, Johnson et al. (ApJ Submitted)
10.0
1.0
0.1
Semimajor Axis [AU]
0.5
1.0
1.5
2.0
2.5
Stellar Mass* [Msun]



Planet Mass
M* > 1.5 Msun
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
12
Msini [MJup]

Comparing planet mass-semimajor axis distributions

For planets around Sun-like stars:

$$dN \propto M^{\alpha} P^{\beta} d\ln M d\ln P$$

$\alpha = -0.3 \pm 0.2$ Increase toward lower planet masses

$\beta = 0.3 \pm 0.1$ Gentle rise toward larger periods

Cumming et al. 2008

Question

Are planets found around A stars and Sun-like stars drawn from the same population?

Problem: The only uniform sample of high-mass stars contains just 28 stars and 7 planets

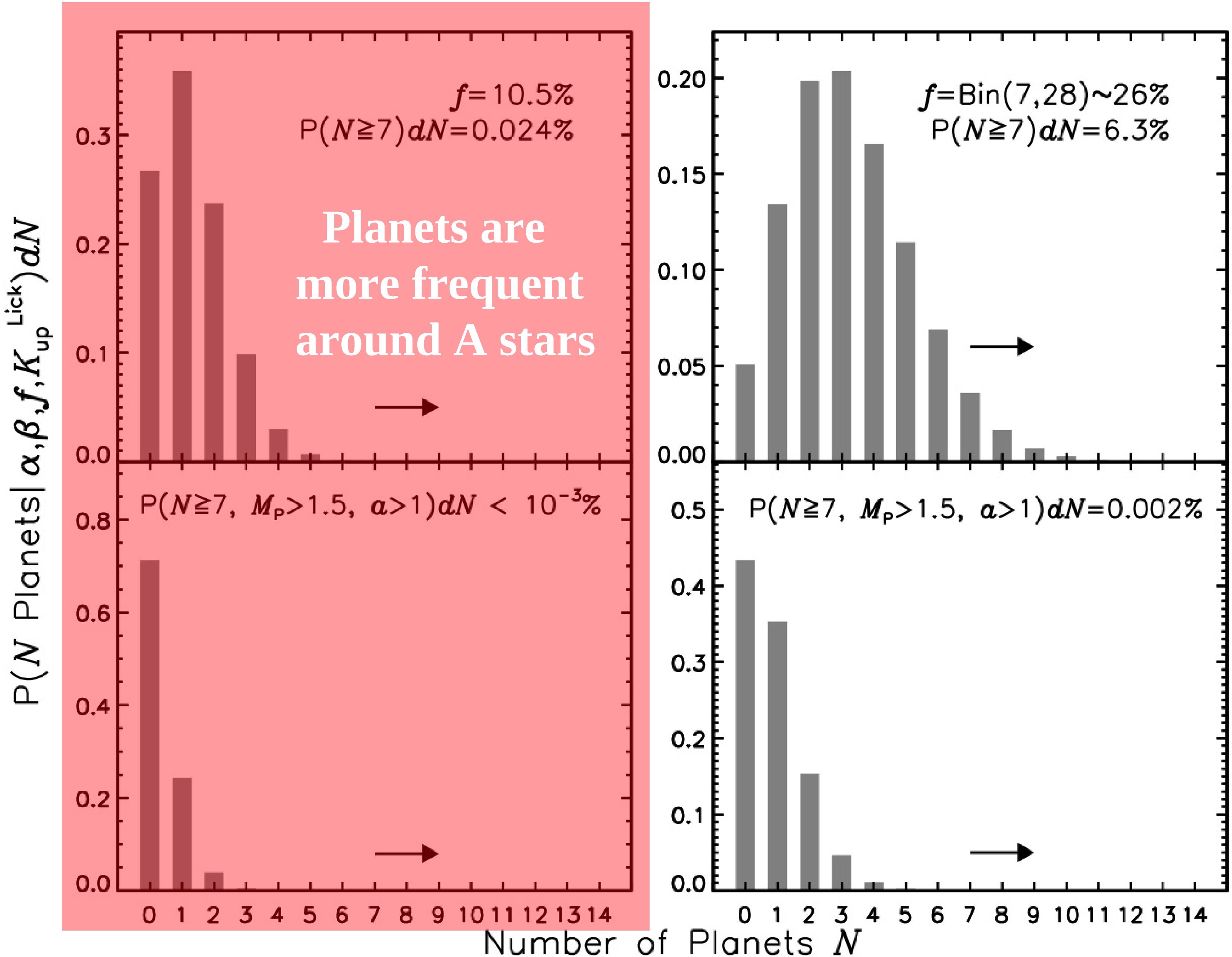
Planets from the uniform sample of high-mass stars have P > 300 days and M sin*i* > 1.5 M_{Jup}

The Test

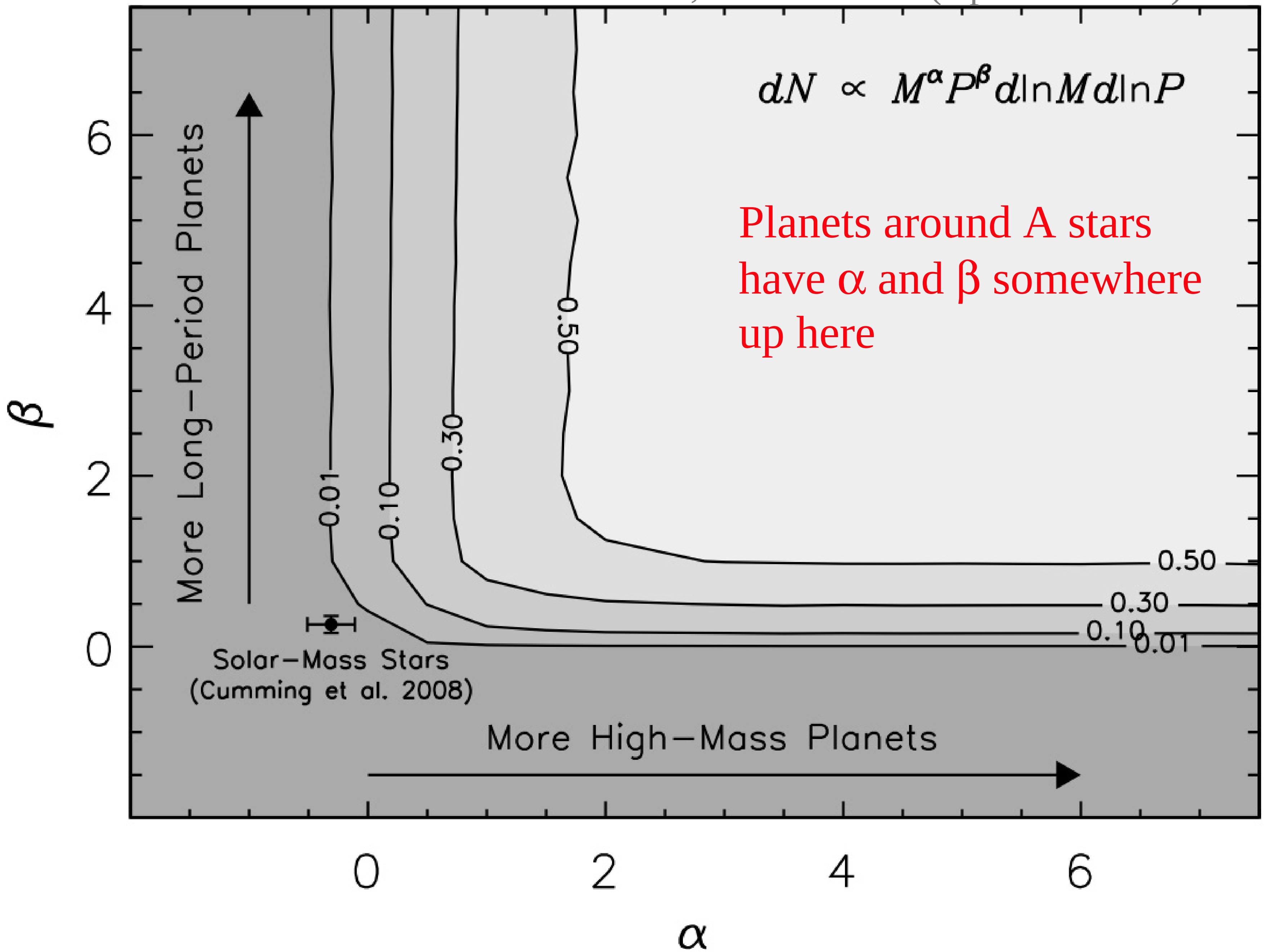
1. Assume an occurrence rate of f = 7/28 = 25%
2. Randomly populate a sample of 28 stars with planets drawn from Cumming et al. M-P dist.
3. Assess detectablity using actual velocity measurements
4. Repeat 1-3 for 10,000 trials
5. Record fraction of trials with 7 detections having P > 300 days and M > 1.5 M_{Jup}

Bowler, Johnson et al. (ApJ submitted)

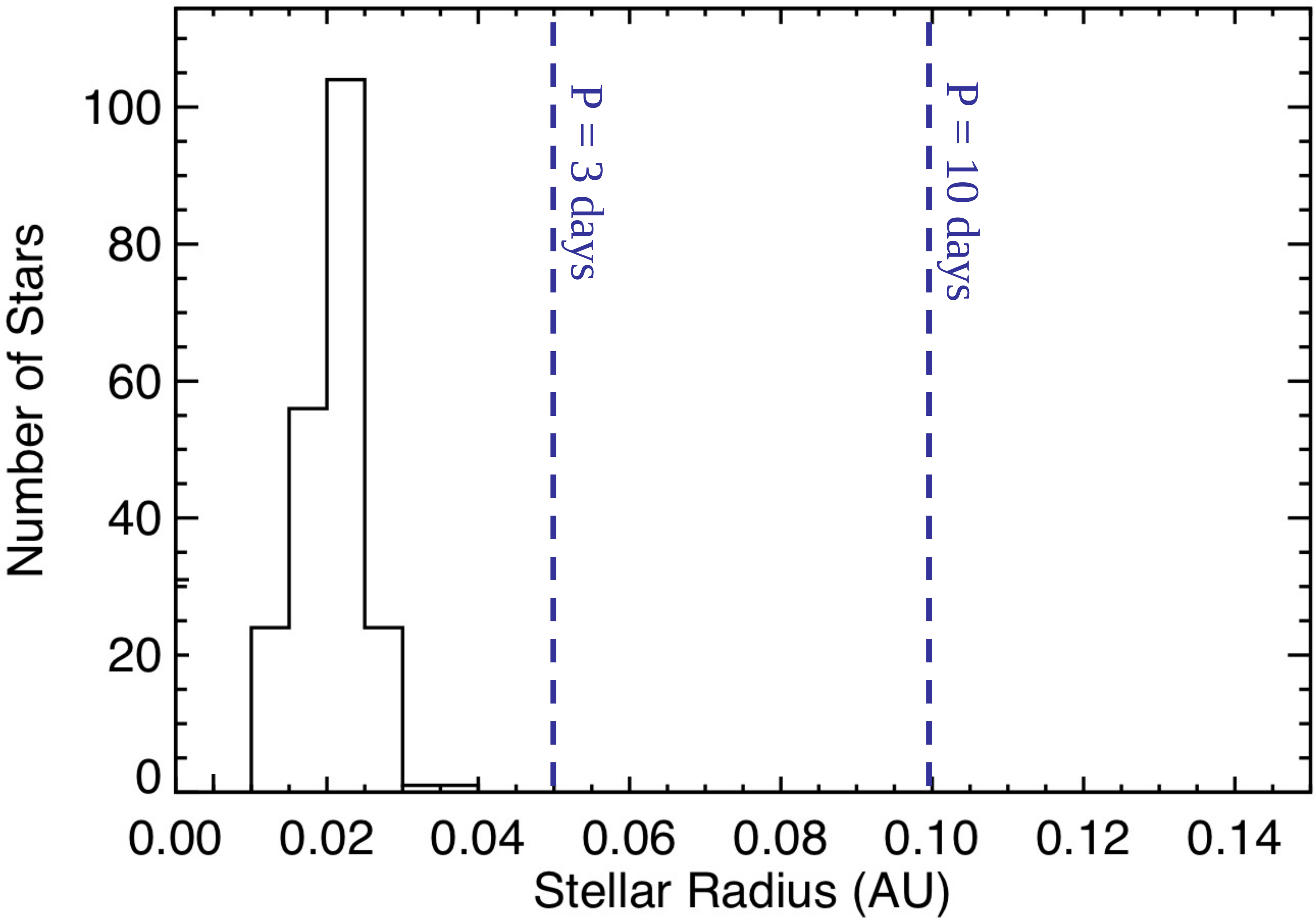
Bowler, Johnson et al. (ApJ Submitted)



Bowler, Johnson et al. (ApJ Submitted)

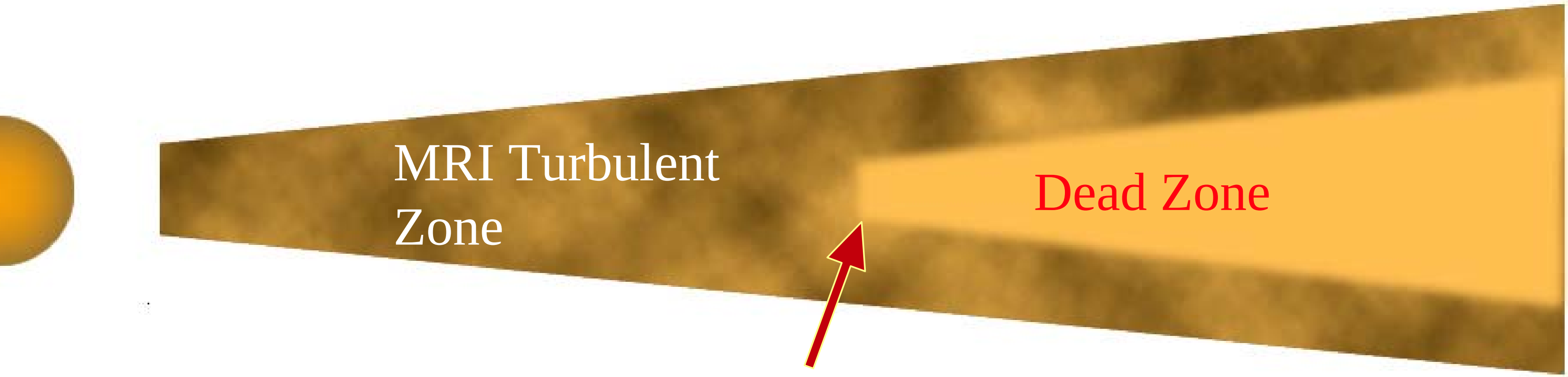


Where are all the close-in planets?



P = 3 days
P = 10 days
Number of Stars
Stellar Radius (AU)
0
20
40
60
80
100
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14

Kretke et al. (2008)



$$\{\rho, P\}_{MRI} < \{\rho, P\}_{DZ}$$

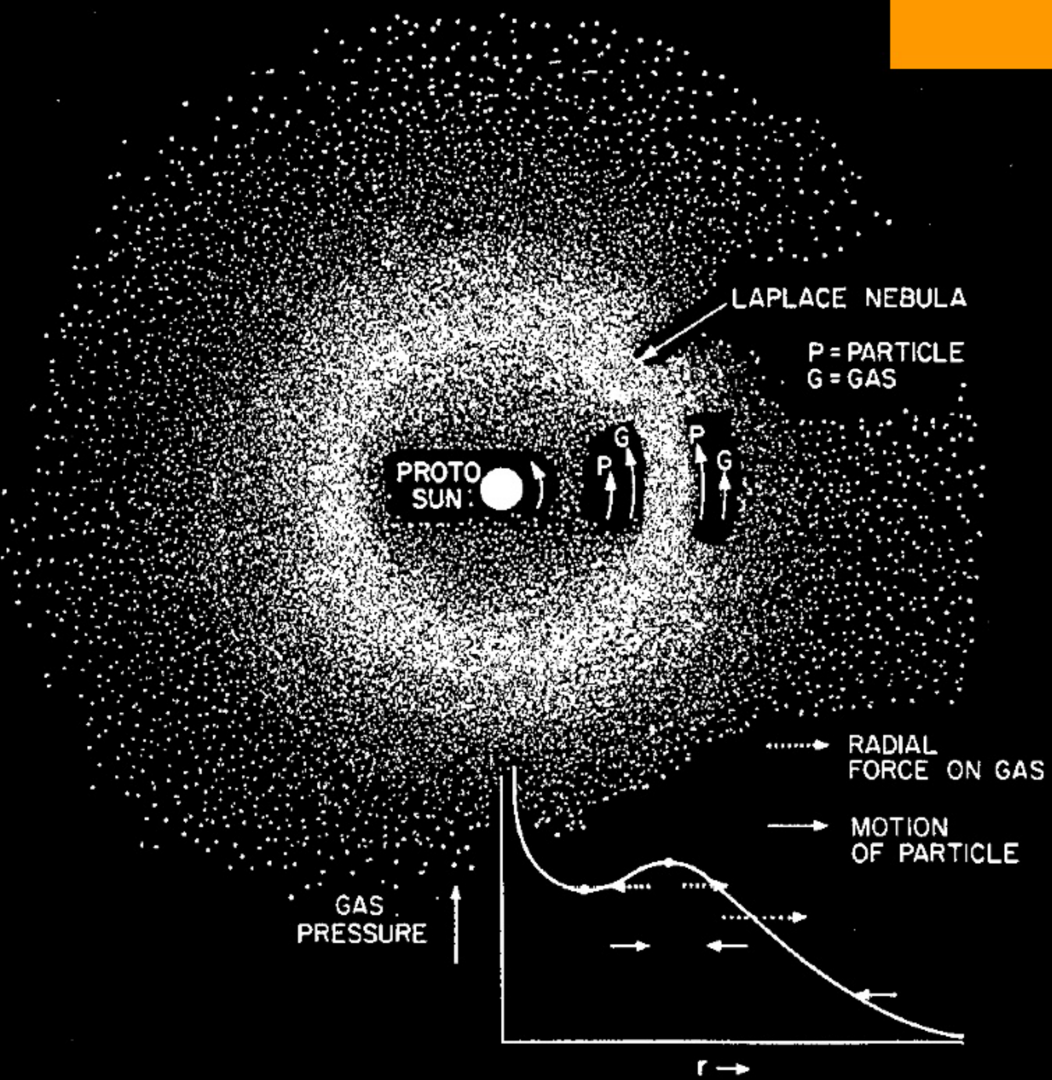
Kretke et al. 2007
Haghighipour 2003

For Solids

$$r\omega^2 = r\omega_K^2$$

Keplerian Frequency

Pressure Gradient



Objects outside the maximum pressure feel a headwind and spiral toward the star, whereas objects inside feel a tailwind and spiral out.

Disk Dissipation Time Scale

Burkert & Ida (2007), Currie (2009)

- Gas giants form at larger orbital radii and take longer to migrate inward
  - The ice Line is 4-5 times further out around A stars (20-25 AU)
- Gas disks have shorter lifetimes around massive stars
  - The accretion rates observed in open clusters scale as M_*^2
- Results in planets getting stranded further away from their host stars when the inner gas-disk clears

Combination?

- Gas giants form at ~1 AU, inside the ice line
- Dissipation of inner gas disk strands planets near birthplaces.

Occurrence Rate

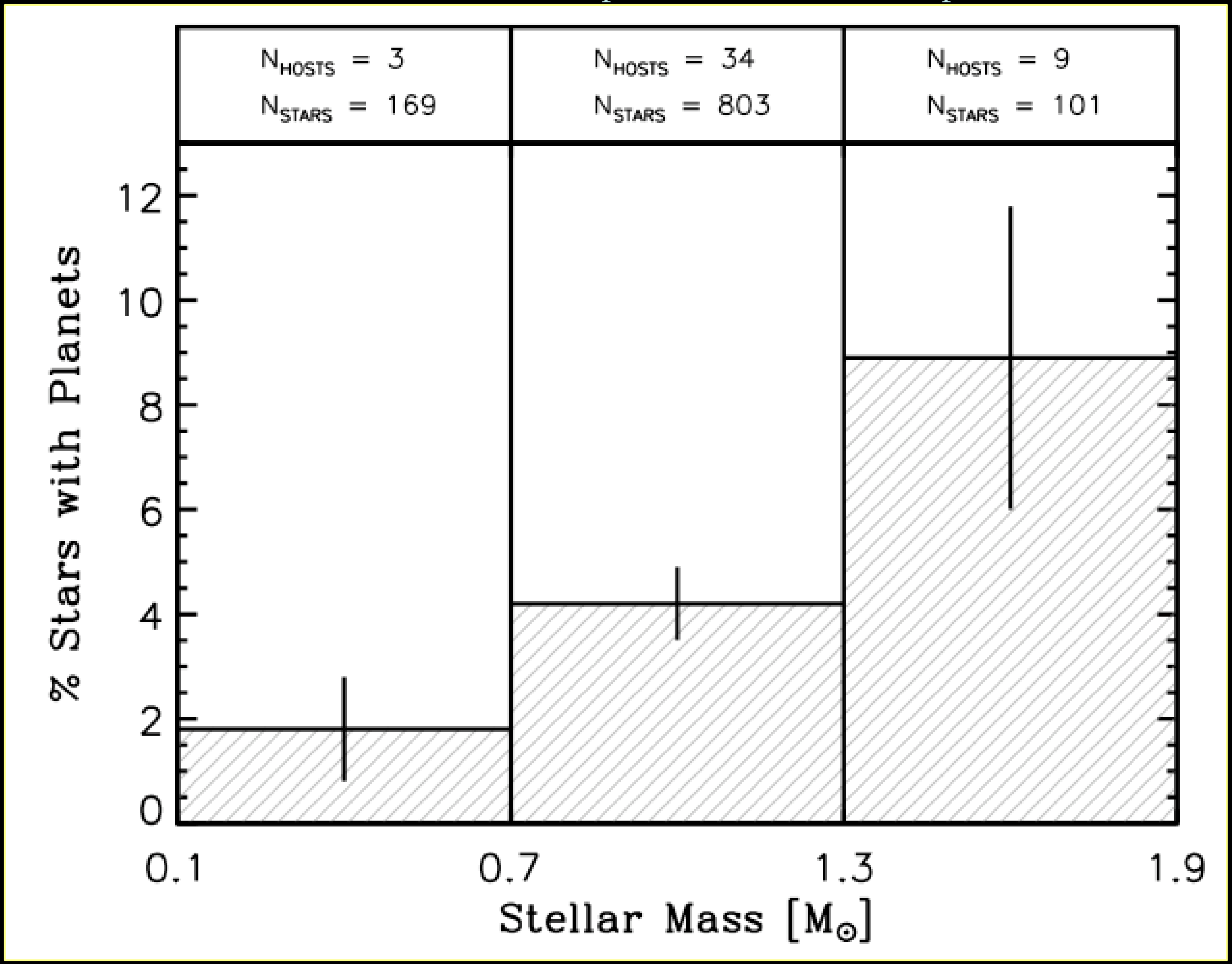
Planet Occurrence vs Stellar Mass

- Limit the analysis to planets with
  $a < 2.5$ AU
  $m_p \sin i > 0.8\ M_{jup}$
  $N_{obs} > 8$

- Compare w/ CCPS sample of M dwarfs and Sun-like stars

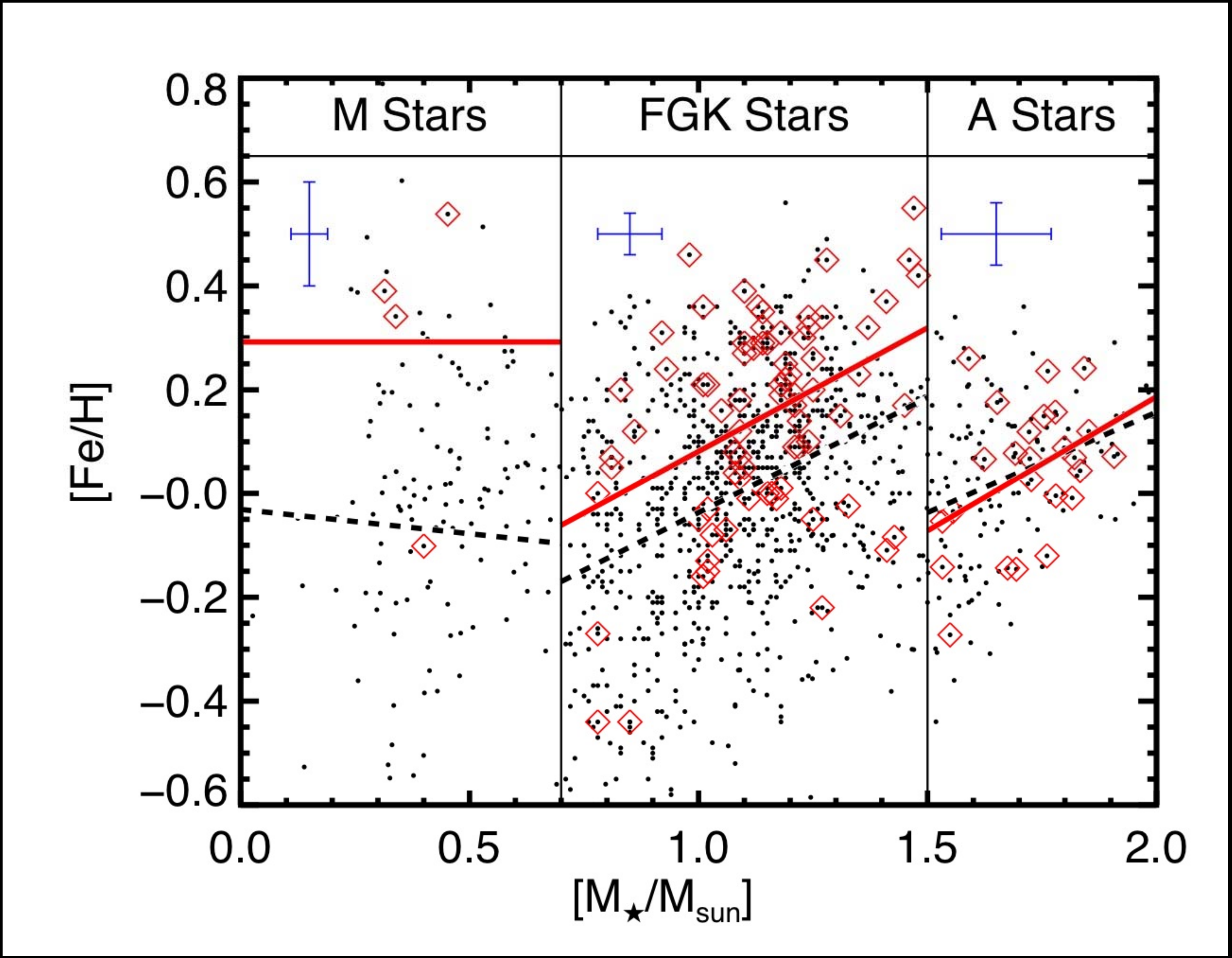
Planet Occurrence vs Stellar Mass

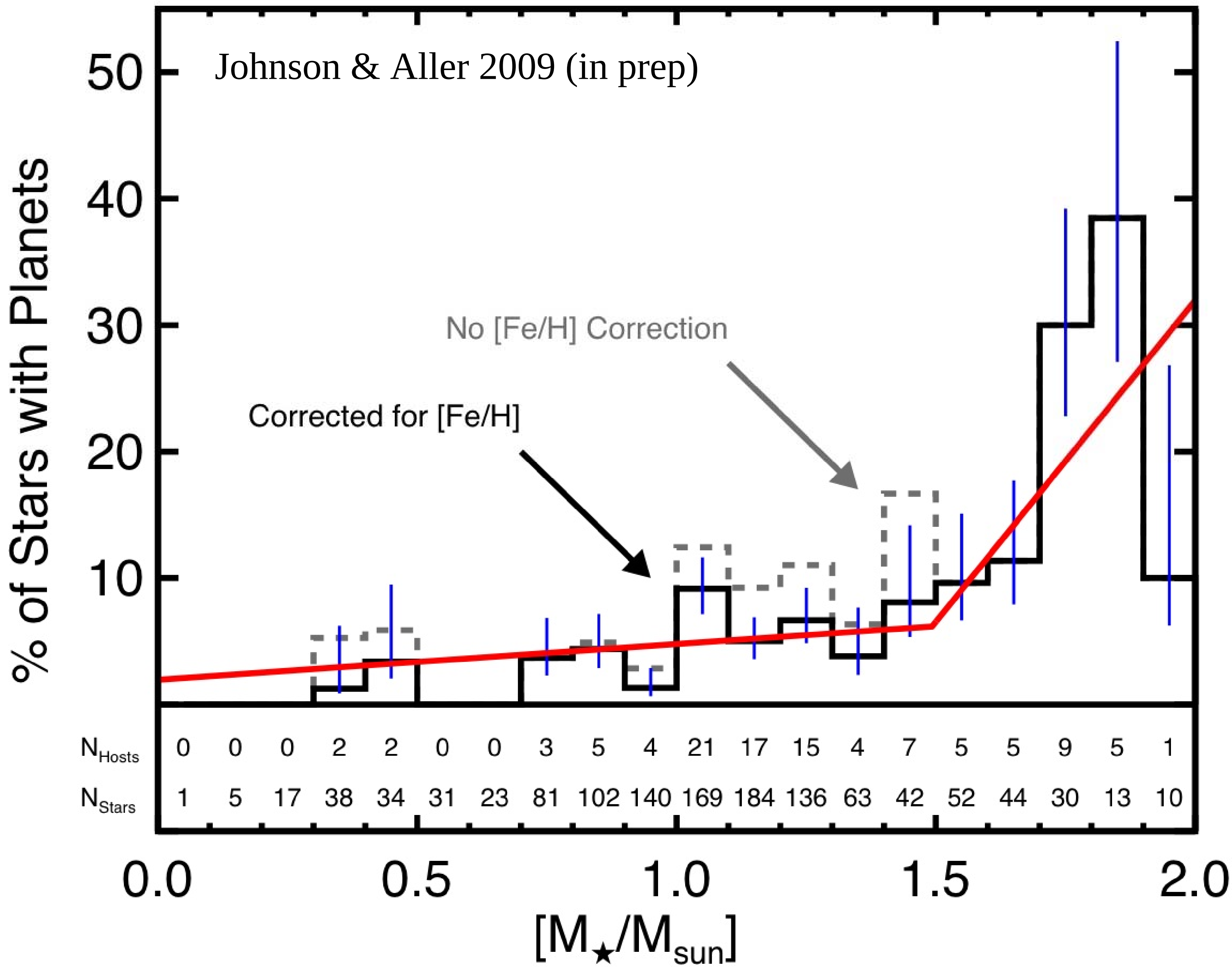
For a < 2.5 AU, $m_p \sin i$ > 0.8 M_{Jup}, N_{obs} > 8



Johnson, Butler et al. (2007)

Johnson & Aller 2009 (in prep)





Johnson & Aller 2009 (in prep)
No [Fe/H] Correction
Corrected for [Fe/H]
% of Stars with Planets
50
40
30
20
10
N_Hosts 0 0 0 2 2 0 0 3 5 4 21 17 15 4 7 5 5 9 5 1
N_Stars 1 5 17 38 34 31 23 81 102 140 169 184 136 63 42 52 44 30 13 10
0.0
0.5
1.0
1.5
2.0
[M★/M_sun]

Conclusions

- Subgiants are ideal proxies of A and F stars
  - Masses of A dwarfs, precision of G dwarfs
- All measurable properties of exoplanets detected around retired A stars are very different than those of planets around Sun-like stars:
  - Eccentricities are lower
  - Planet masses are higher
  - Semimajor axes larger (no planets within 0.8 AU)
- Planet occurrence correlates with stellar mass
  - Treasure trove of planets around A stars
  - Tells us where to look
  - Informs planet formation models

Thank You.

And Thanks to
My Collaborators:

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