Planet Hunting In New Stellar Domains

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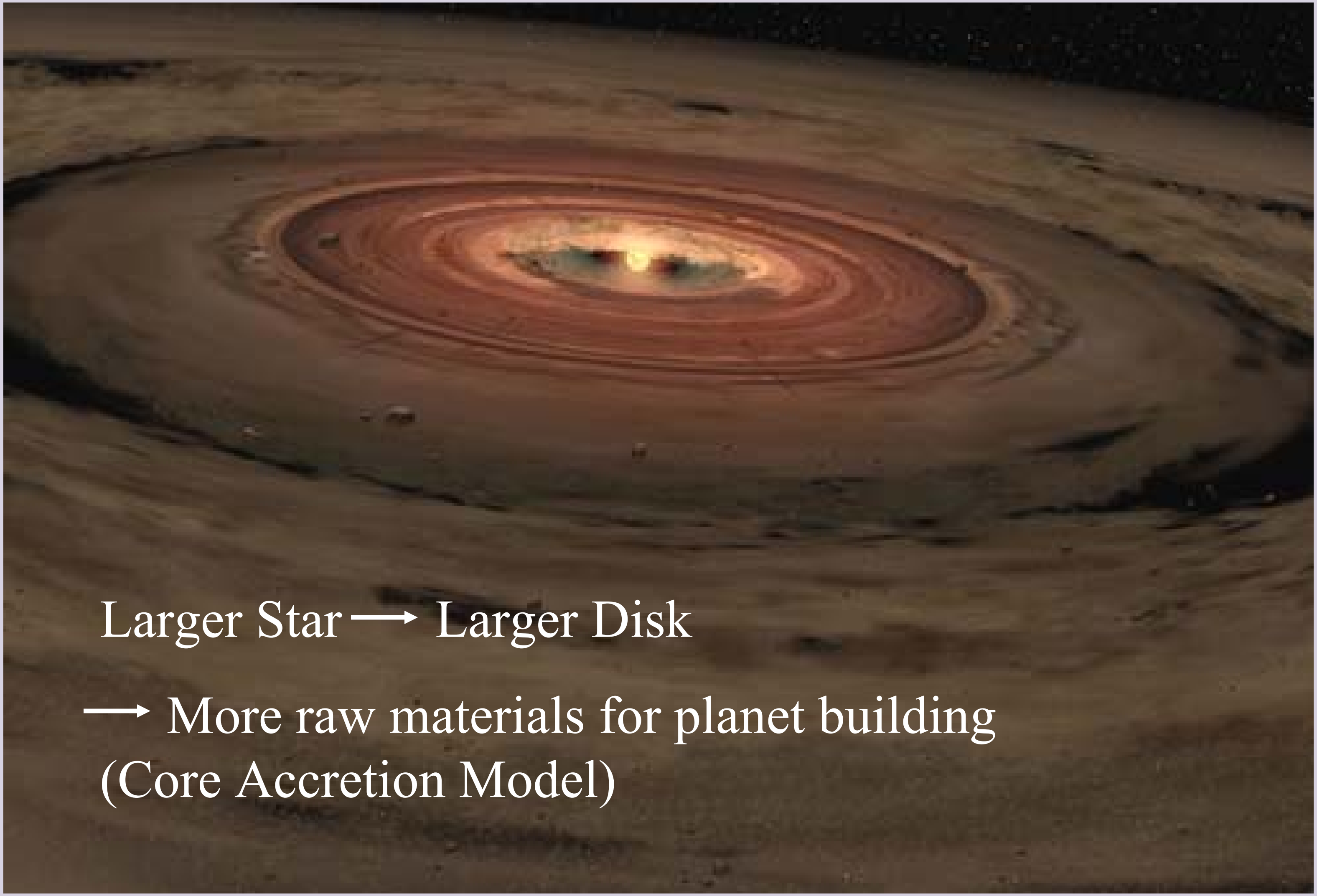
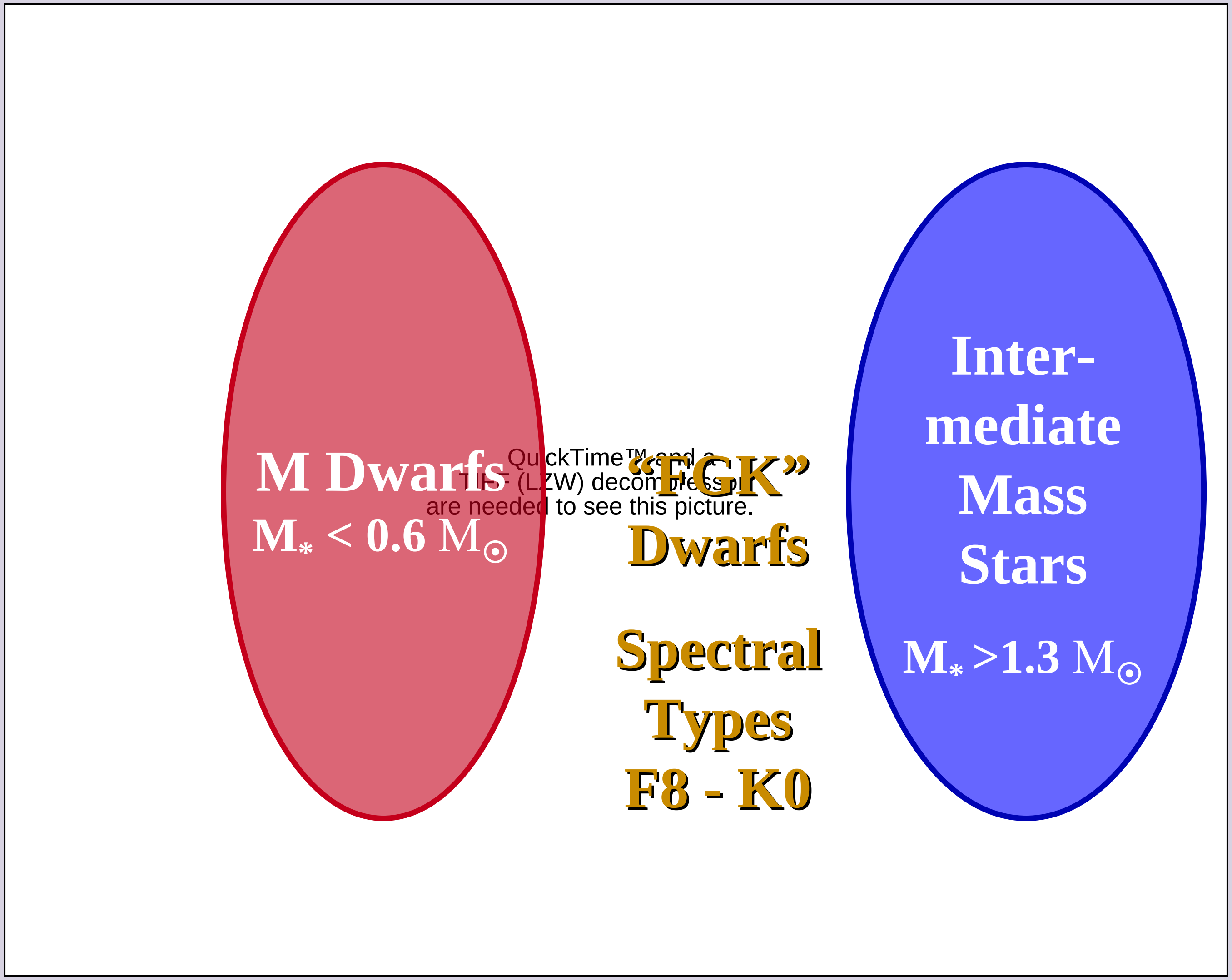
National Science Foundation
WHERE DISCOVERIES BEGIN

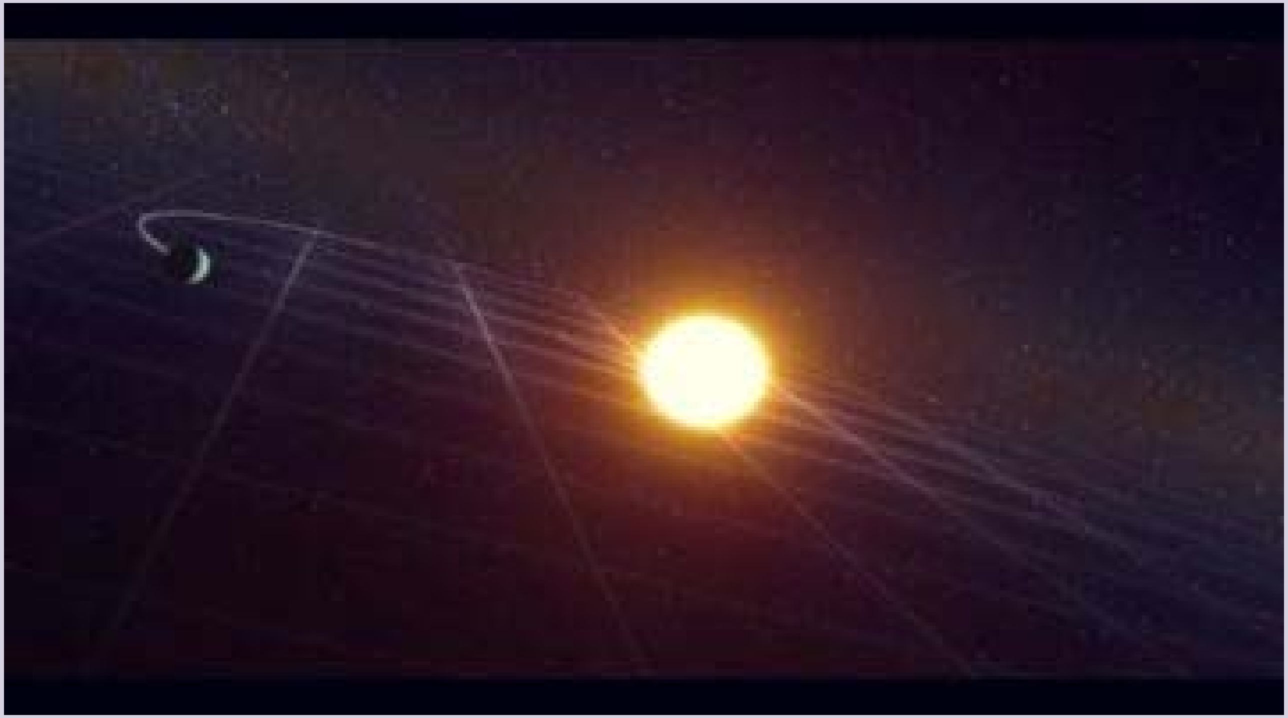
Why should *stellar* mass matter?



The Stellar Mass Distribution of Planet Searches



Doppler Wobble



97% of exoplanets detected by Doppler techniques

$1\ \mathrm{m\ s^{-1}} \approx 10^{-3}$ pixel

Iodine Cell Method

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

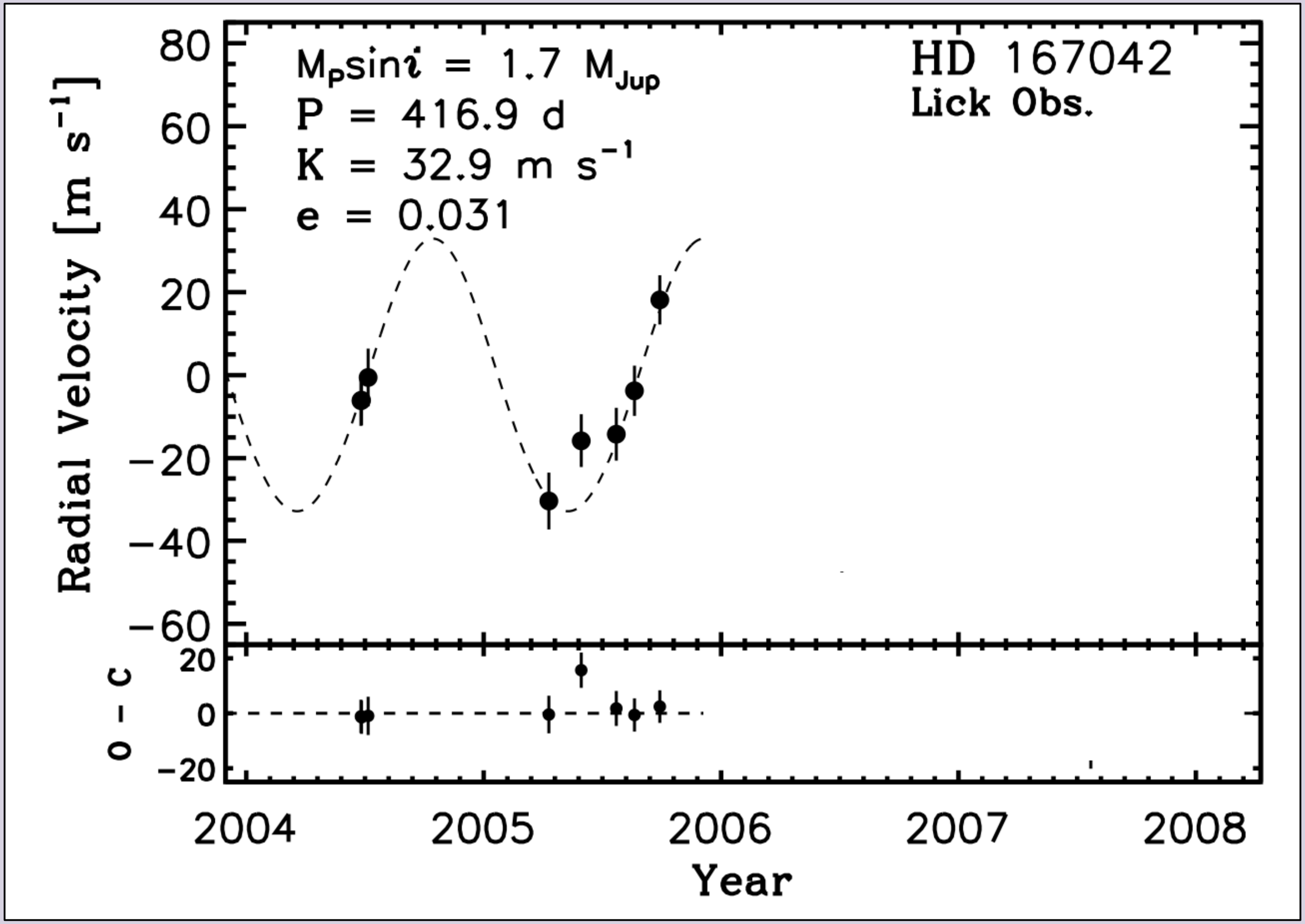
Photo courtesy of
Laurie Hatch

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Butler et al. 1996

Precision Radial Velocities

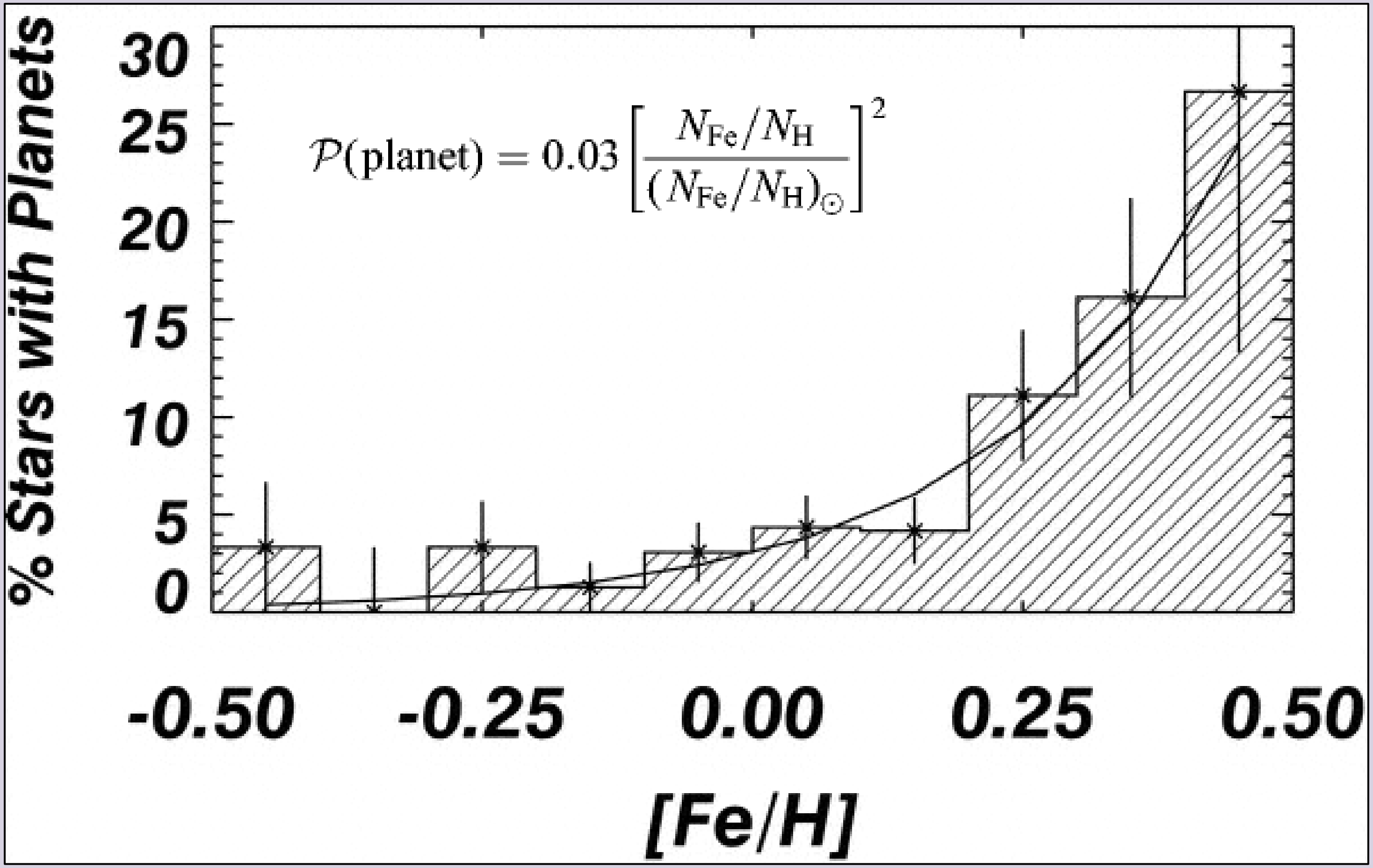
Johnson, Marcy et al. (2007)



From Anomalies to Statistics

- Catalog of Nearby Exoplanets (Butler et al. 2006)
  225 total known exoplanets (exoplanets.org)
  187 host stars within 200 parsecs of the Sun
- Planets are common, found around >7% stars.
- Occurrence rate vs. stellar properties
  - Stellar Mass
  - Chemical Composition

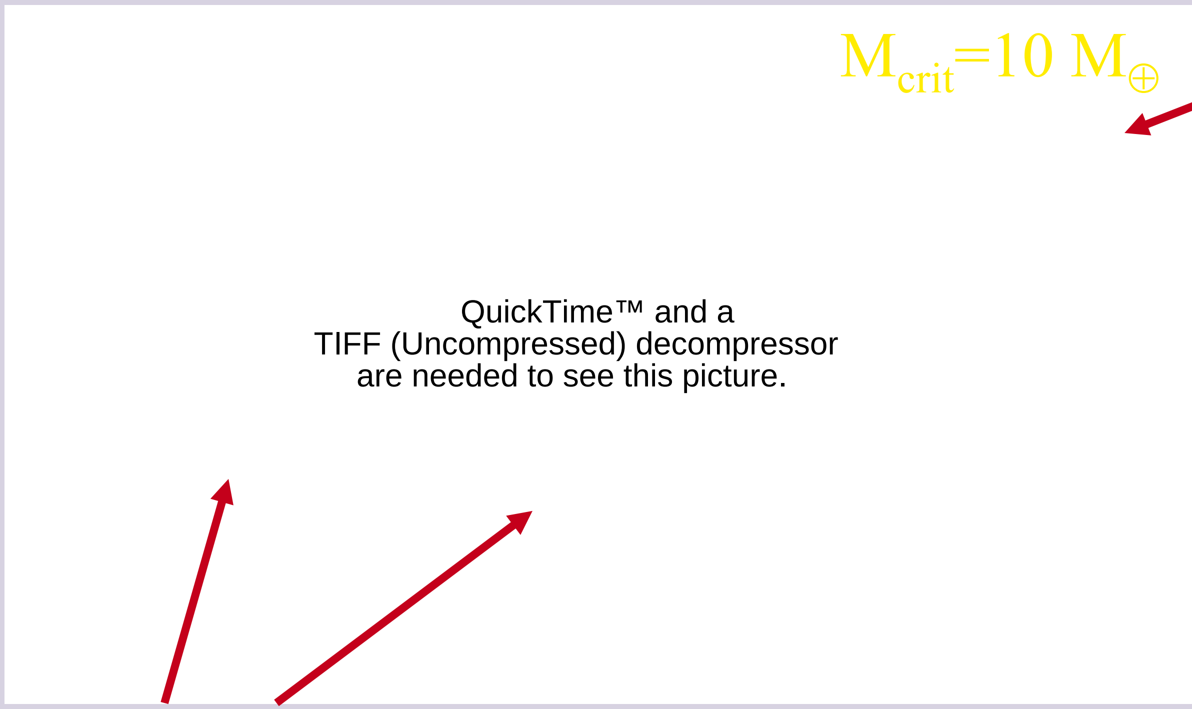
Stellar Metallicity and Planet Occurrence



Fischer & Valenti (2005)

Core Accretion Model

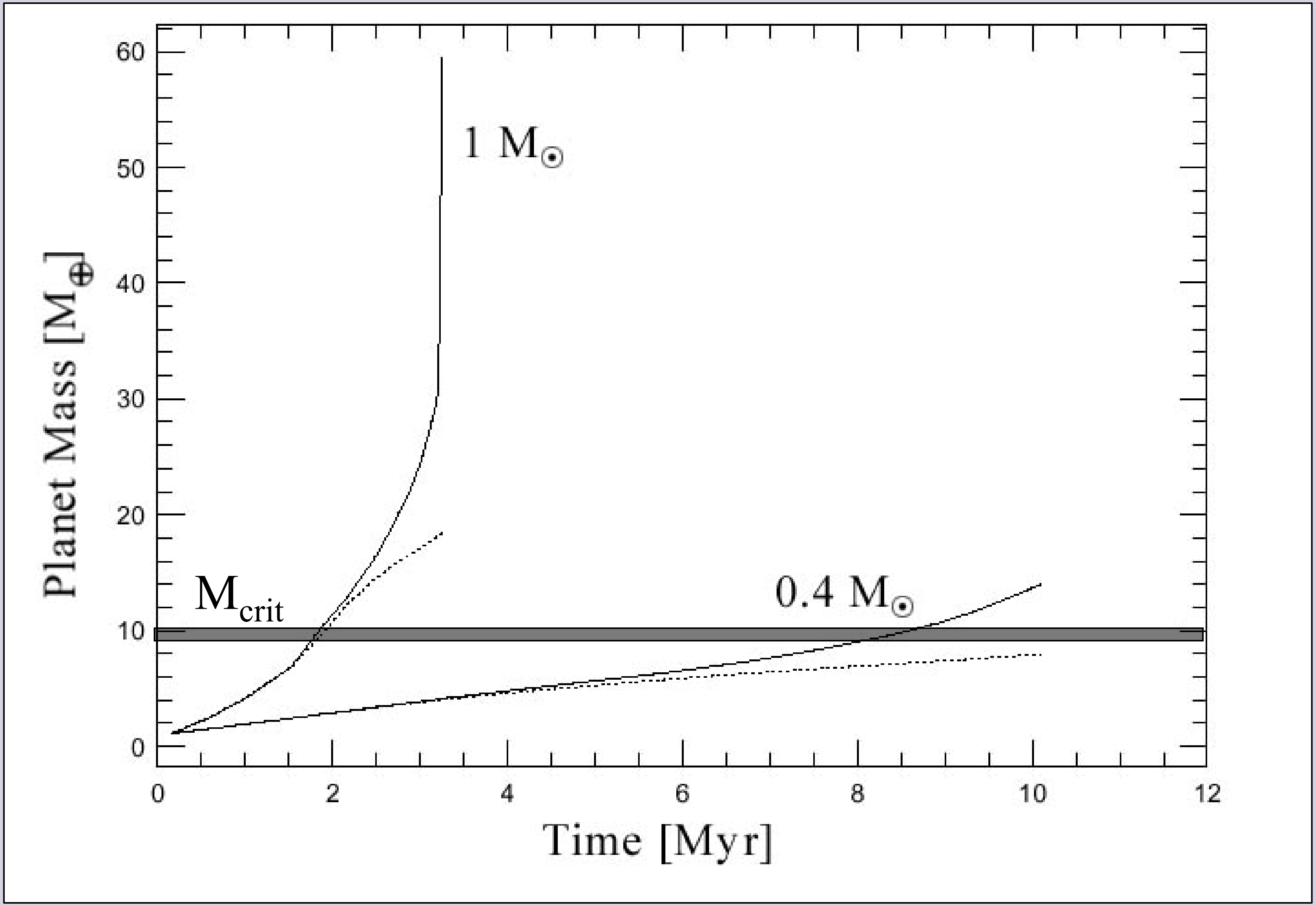
Provided there is gas left by this time!



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

www.oklo.org

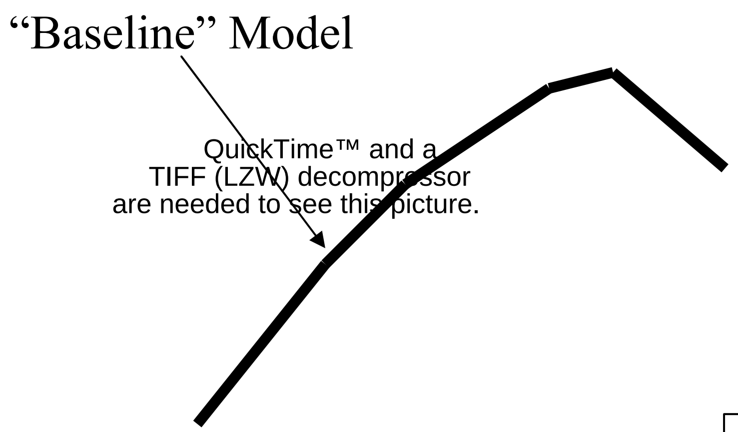
Stellar Mass and Planet Formation

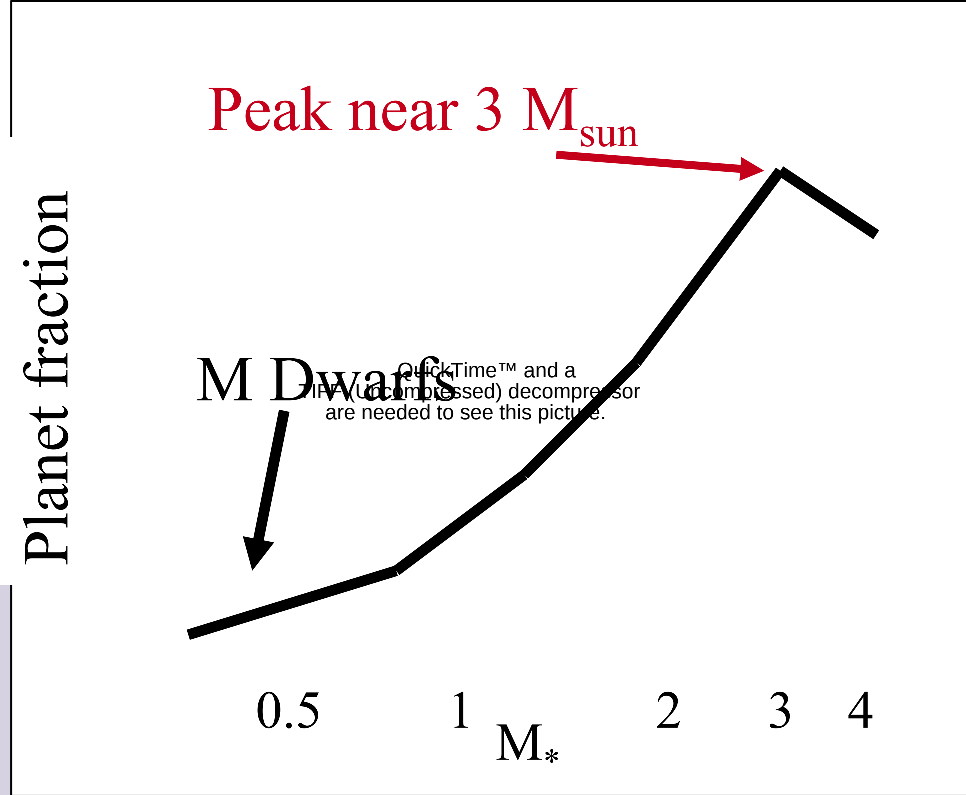


Laughlin, Bodenheimer & Adams (2004)

Kennedy & Kenyon (2007)
ApJ in press

Effect of disk temperature profile on the radial extent of core-forming region



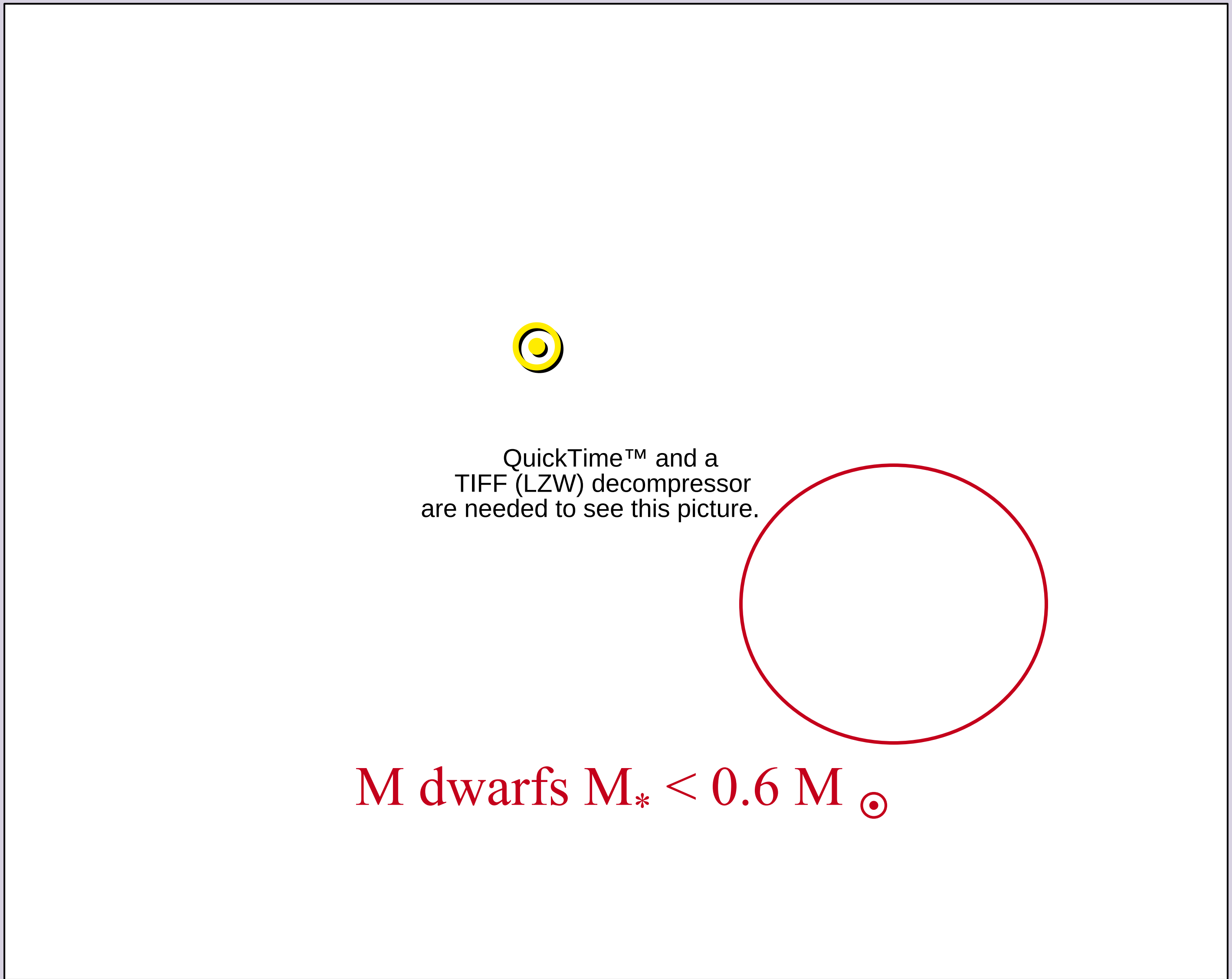


Searching for planets around stars of various masses

Uniformly Detectable Planets:

$M_P \geq 0.5\ M_{Jup}$

Extending the Search to Lower Stellar Masses



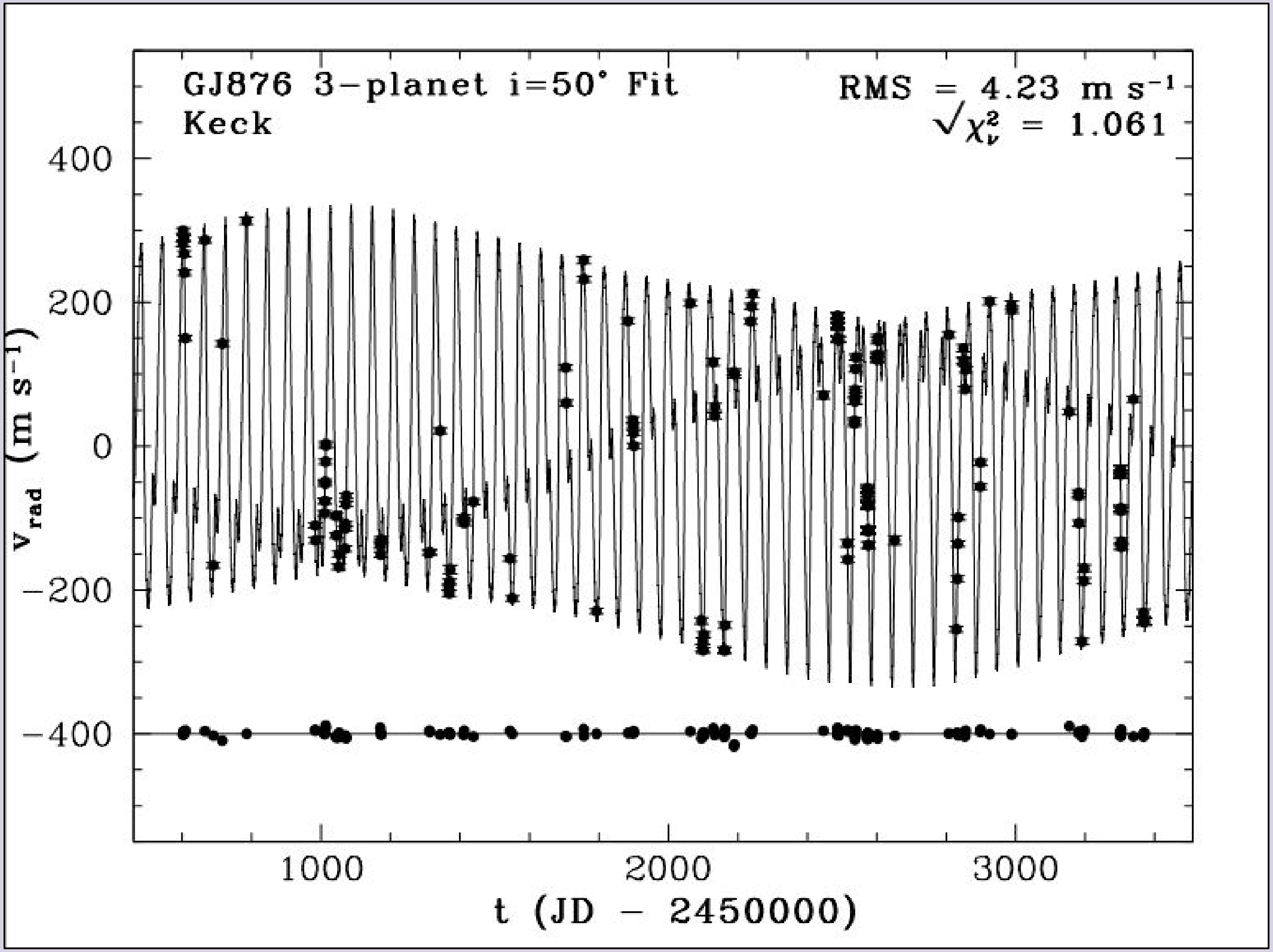
M dwarfs $M_* < 0.6\ M_\odot$

The NASA Keck M Dwarf Planet Search

- 150 K- and M-dwarfs

  $M_* < 0.7\ M_\odot$
- 8 year baseline
- 2 Neptunes (GL 436b, confirmed GL 581b)
- 4 Jupiters around **3** host stars

The GL 876 System



Rivera et al. 2006

GL 849

$0.86\ M_{jup}$

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

$P = 5.16$ yr

$e = 0.04$

Butler, Johnson et al. 2006

GL 317

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Johnson, Butler et al. (2007)

Jupiters Are Less Common Around M Stars

1.8 ± 1.2% of M dwarfs have Jupiters within 2.5 AU, compared to…

5.6 ± 1.6% of FGK dwarfs (Keck only)

Is this due to lower stellar mass, or some other variable such as metallicity?

Butler, Johnson et al. 2006

Metallicity Bias Among M Dwarfs?

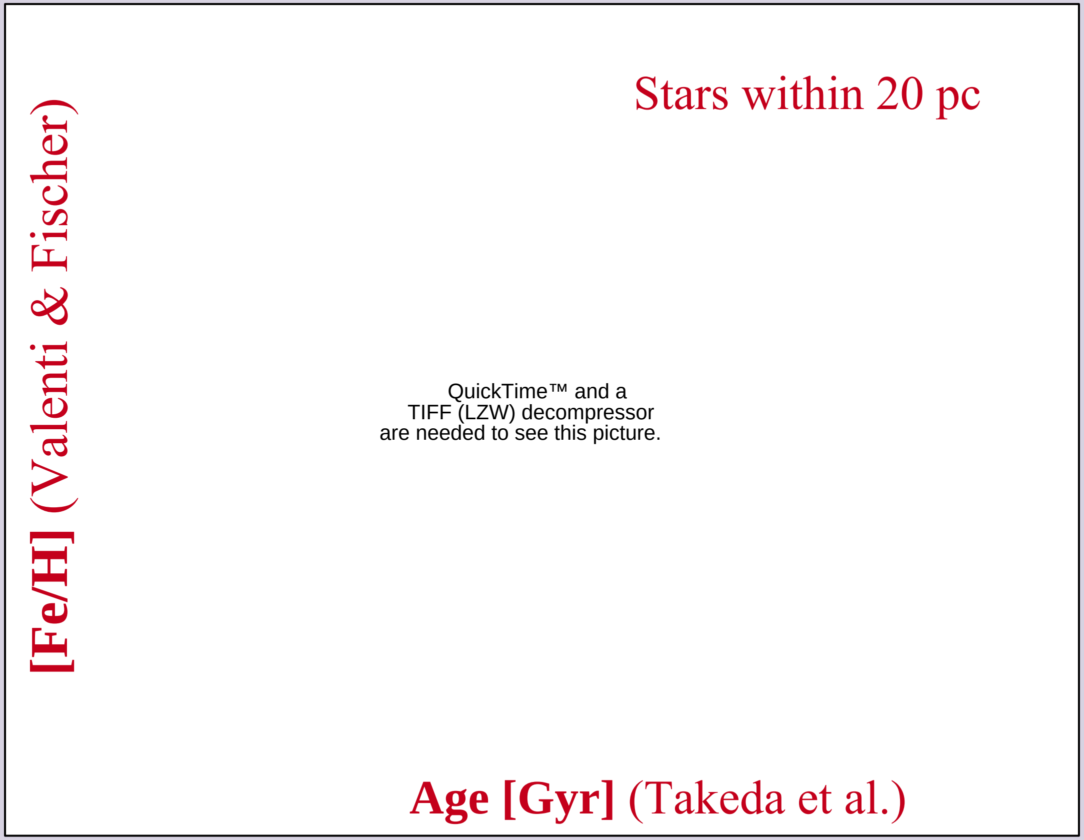
Standard Argument:

- Spectroscopic [Fe/H] unknown for M dwarfs
- M Dwarfs have lifetimes longer than the age of the Galaxy
- Old stars are metal-poor
- Our M Dwarfs must be systematically metal-poor, which explains the lack of planets

Metallicity Bias
Among M Dwarfs?

- There is no well defined age-metallicity relationship in the Galactic Disk

Nordstrom et al. 2004
Nordstrom et al. 2007
Takeda et al. 2007



Metallicity Bias Among M Dwarfs?

- No metallicity trend with spectral type

F G K M

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

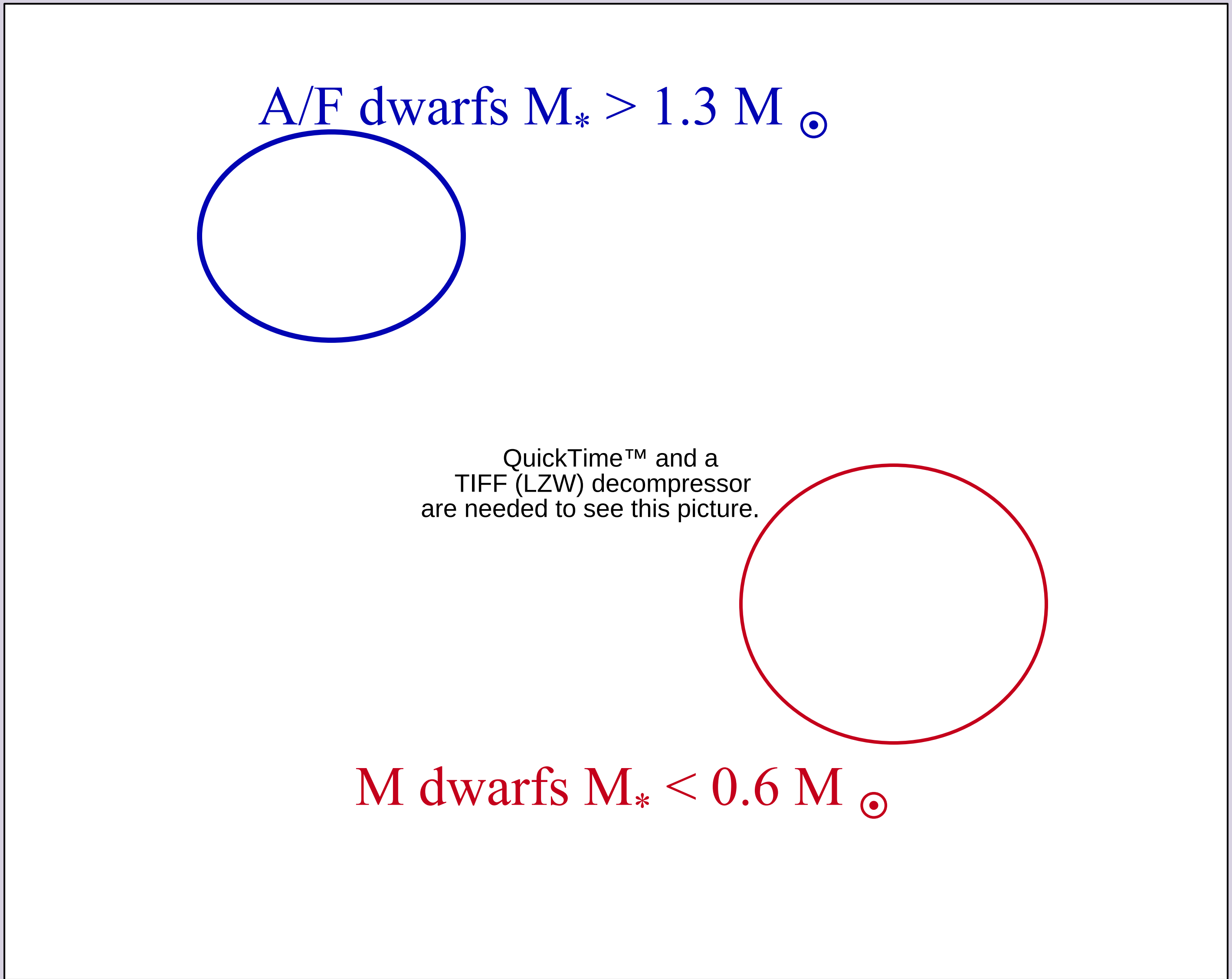
Stars within 20 pc

Mean [Fe/H] for Solar Neighborhood is -0.06

Why so few planets around M Dwarfs?

- It’s not due to a metallicity bias
- It’s likely due to stellar mass
- We can test the mass hypothesis by going to higher stellar masses.

Extending the Search to Higher Stellar Masses



Problem: Massive dwarfs are poor Doppler targets

- Fewer spectral lines
- Rotational broadening
  - A and F-type stars are rapid rotators (vsini >> 50 km/s)
- Large velocity jitter
  - Jitter = excess radial velocity noise
  - Likely due to pulsation, rotational modulation of surface features

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

A Star: Vsini = 70 km/s

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

G Star: Vsini = 2 km/s

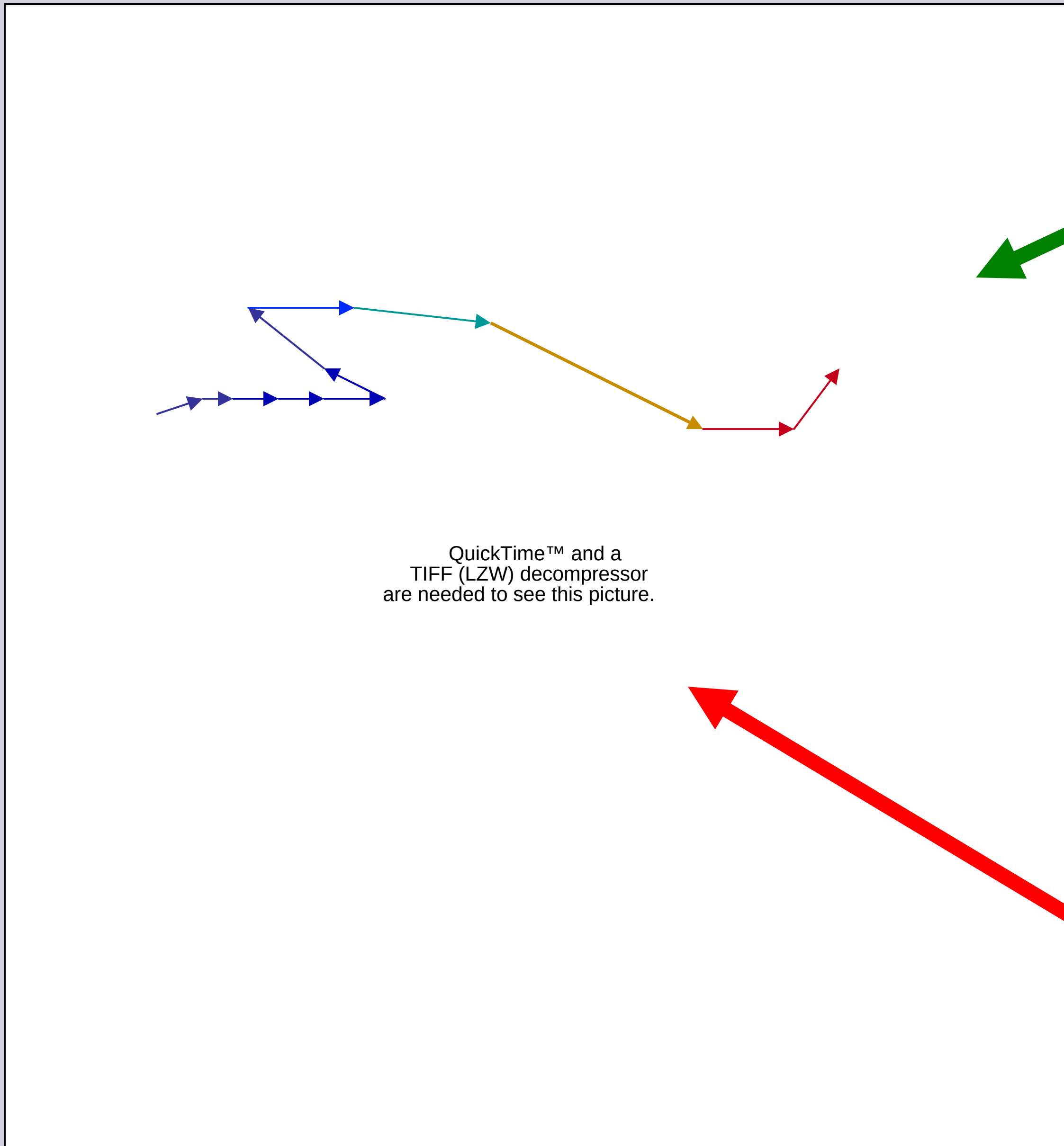
Wavelength (Ang)

Main Sequence:

The Sun
1.0 M_{sun}
1.0 R_{sun}
5770 K
$V\sin i$ = 2 km/s
Velocity Precision: 1 m/s

A-type Star
2.0 M_{sun}
1.9 R_{sun}
8200 K
$V\sin i$ = 100 km/s
Velocity Precision: ~100 m/s

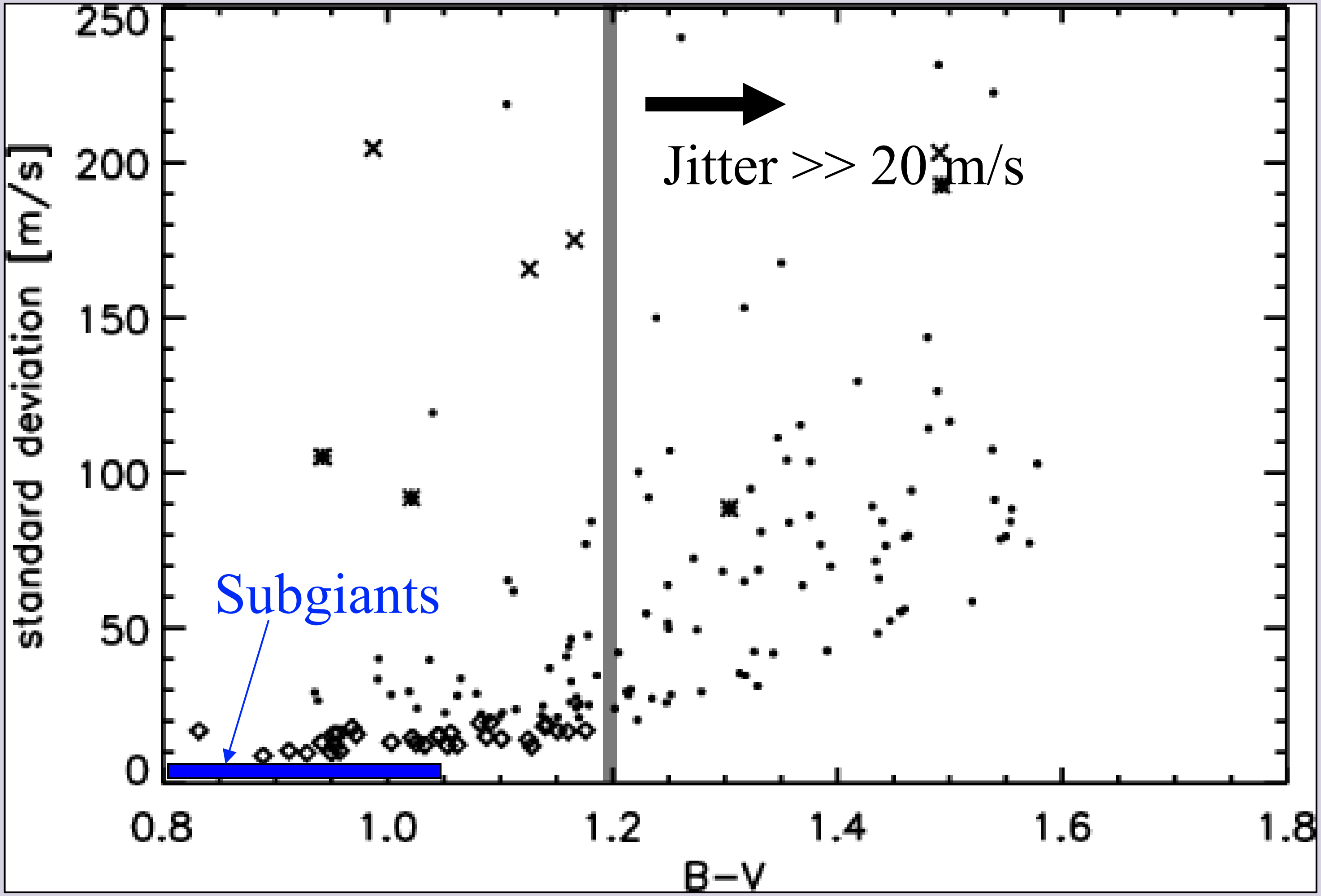
Classes of Evolved Stars



Bright,
Numerous

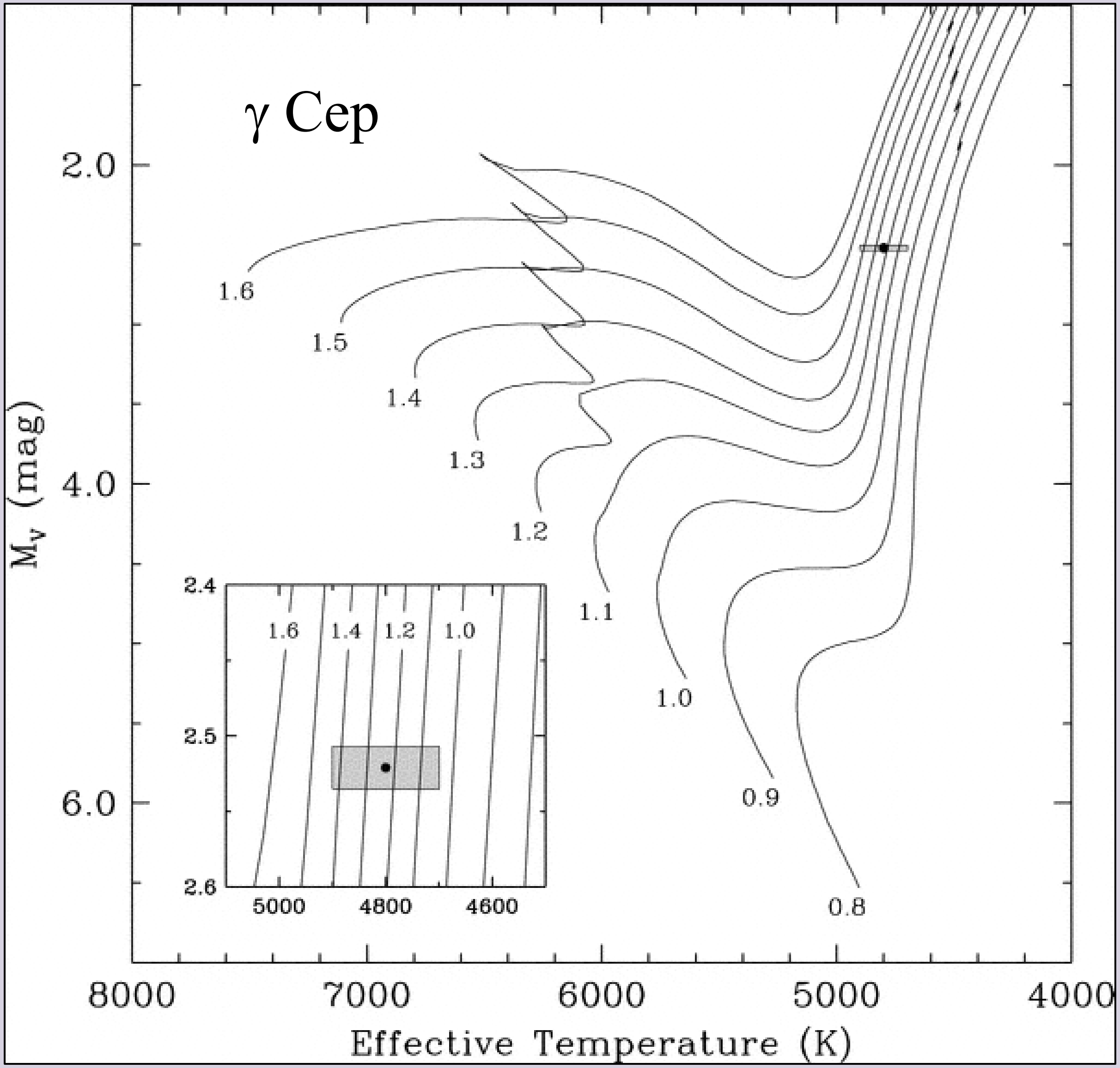
Rare

Disadvantages of K Giants



Hekker et al. (2006)

Disadvantages of K Giants



Torres et al. (2007)

Stellar Radii and Short-Period Planets

20% of known exoplanets have P<10 day

TIFF (LZW) decompressor
are needed to see this picture.

Johnson, Fischer et al. (2007a)

Subgiants: Ideal Intermediate-Mass Targets

- A and F-type main sequence stars rotate too fast, too few lines
- K giants are slow rotators but jittery
  - Large, fluffy atmospheres
  - Difficult to determine stellar masses
- Subgiants:
  - Widely spaced mass tracks
  - Low jitter (~5 m/s)
  - Small radii, probe hot Jupiters

Subgiants: My Sample

159 stars at Lick and Keck Observatories

119 Subgiants $M_V > 2.0$

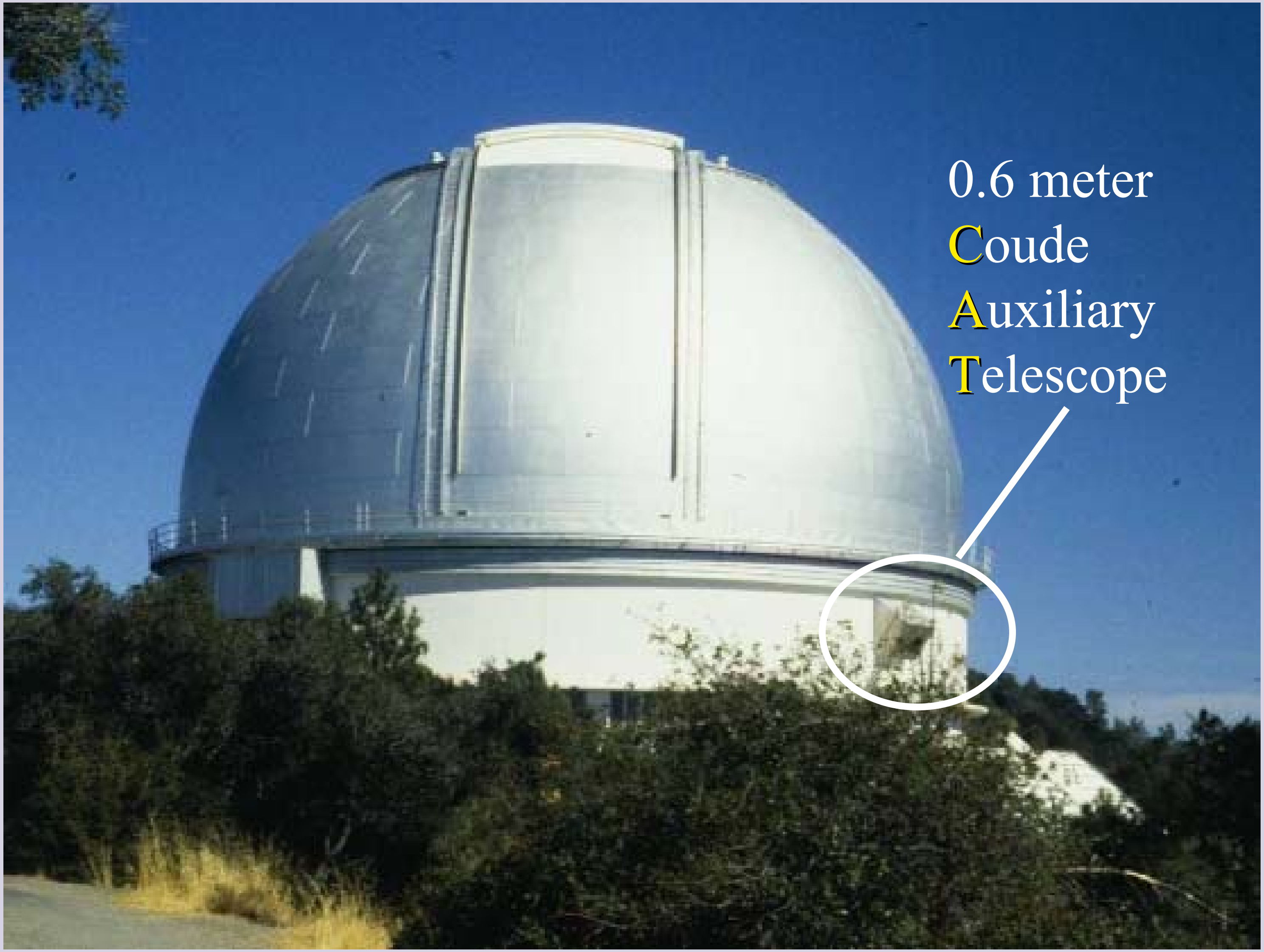
40 Giants $M_V < 2.0$

$1.1 < M_* < 2.0\ M_\odot$

Mass Distributions

“Normalized” Histograms

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.


0.6 meter
Coude
Auxiliary
Telescope

Results From The Subgiants Planet Search

Planets Orbiting Massive Stars

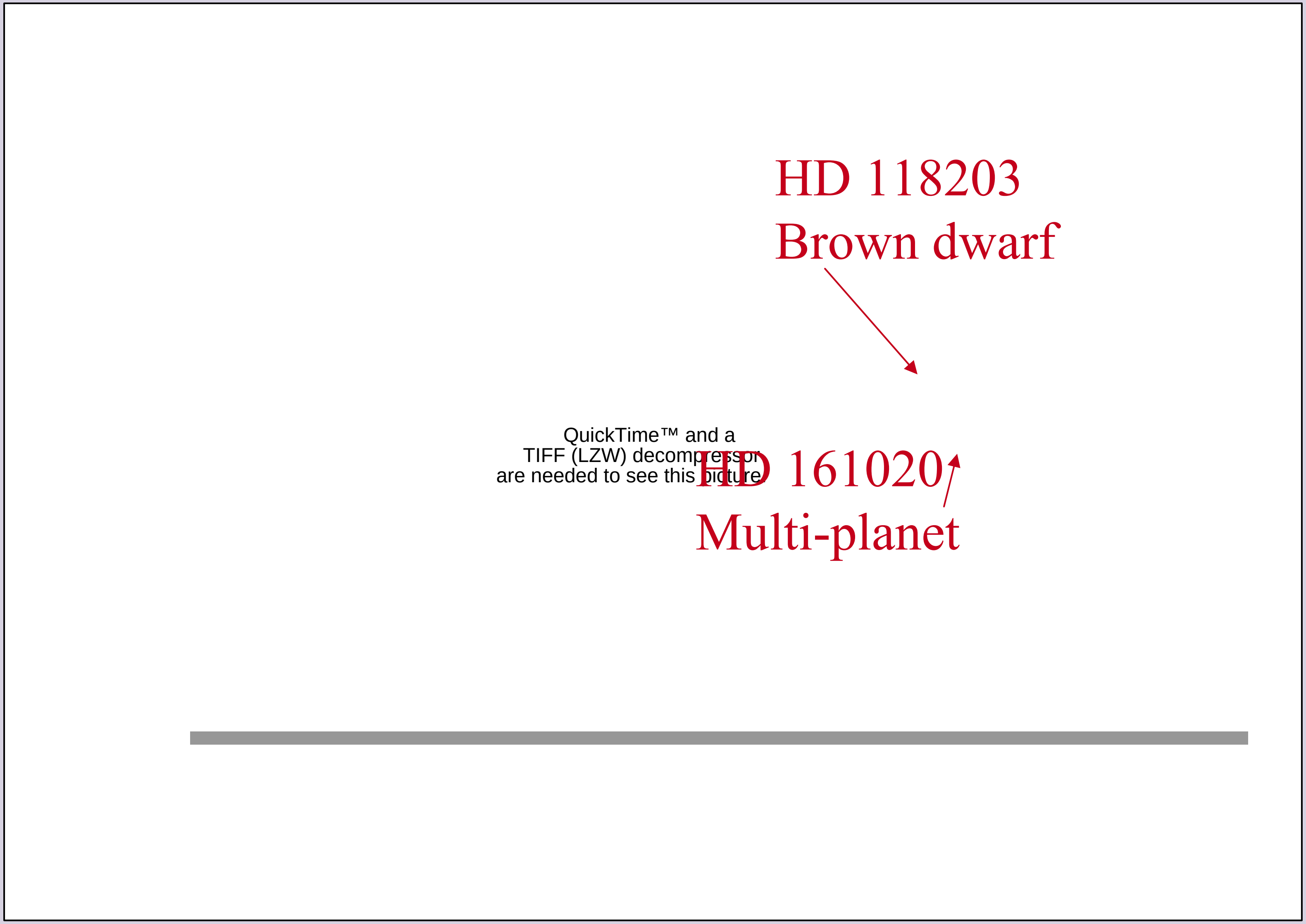
An Eccentric Hot Jupiter

$M_{*}=1.3\ M_{\odot}$

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Johnson, Marcy et al. (2006b)

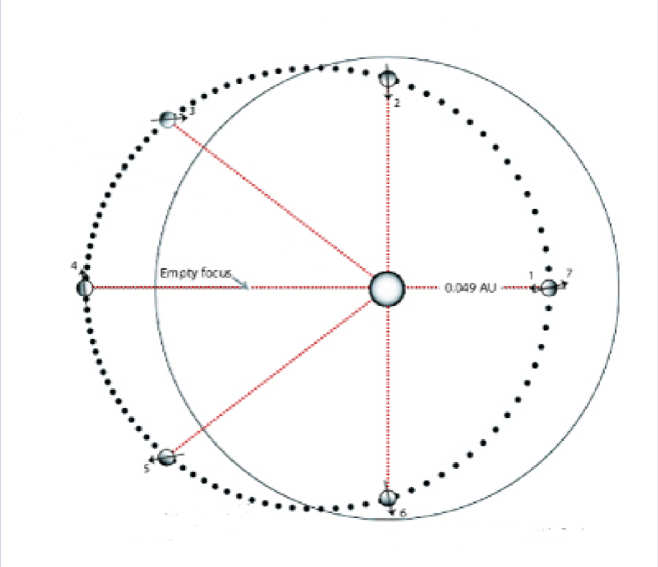
An Eccentric Hot Jupiter



Johnson, Marcy et al. (2006b)

The Wild Seasonal Variations of HD 185269

QuickTime™ and a
decompressor
are needed to see this picture.



The 345% variation in stellar irradiation during the 6.8 day "year" cause dramatic seasonal variability

Courtesy of Jonathan Langton, Greg Laughlin and www.oklo.org

HD 192699: $M_* = 1.68\ M_\odot$

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Johnson, Fischer et al. (2007)

HD 175541: $M_* = 1.65\ M_\odot$

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Johnson, Fischer et al. (2007)

HD 210702: $M_* = 1.85\ M_\odot$

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

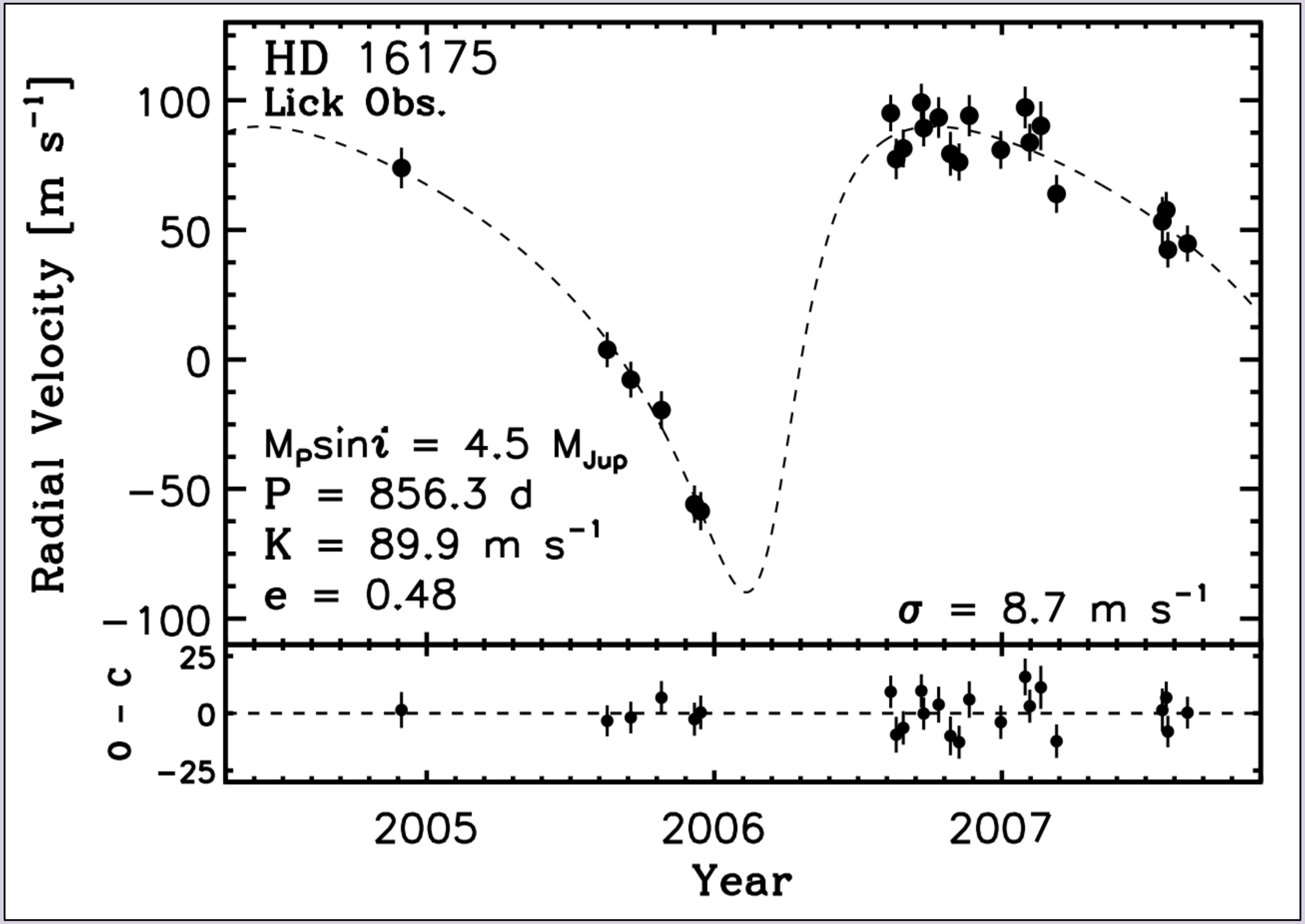
Johnson, Fischer et al. (2007)

Retired A-Stars and Their Planets

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

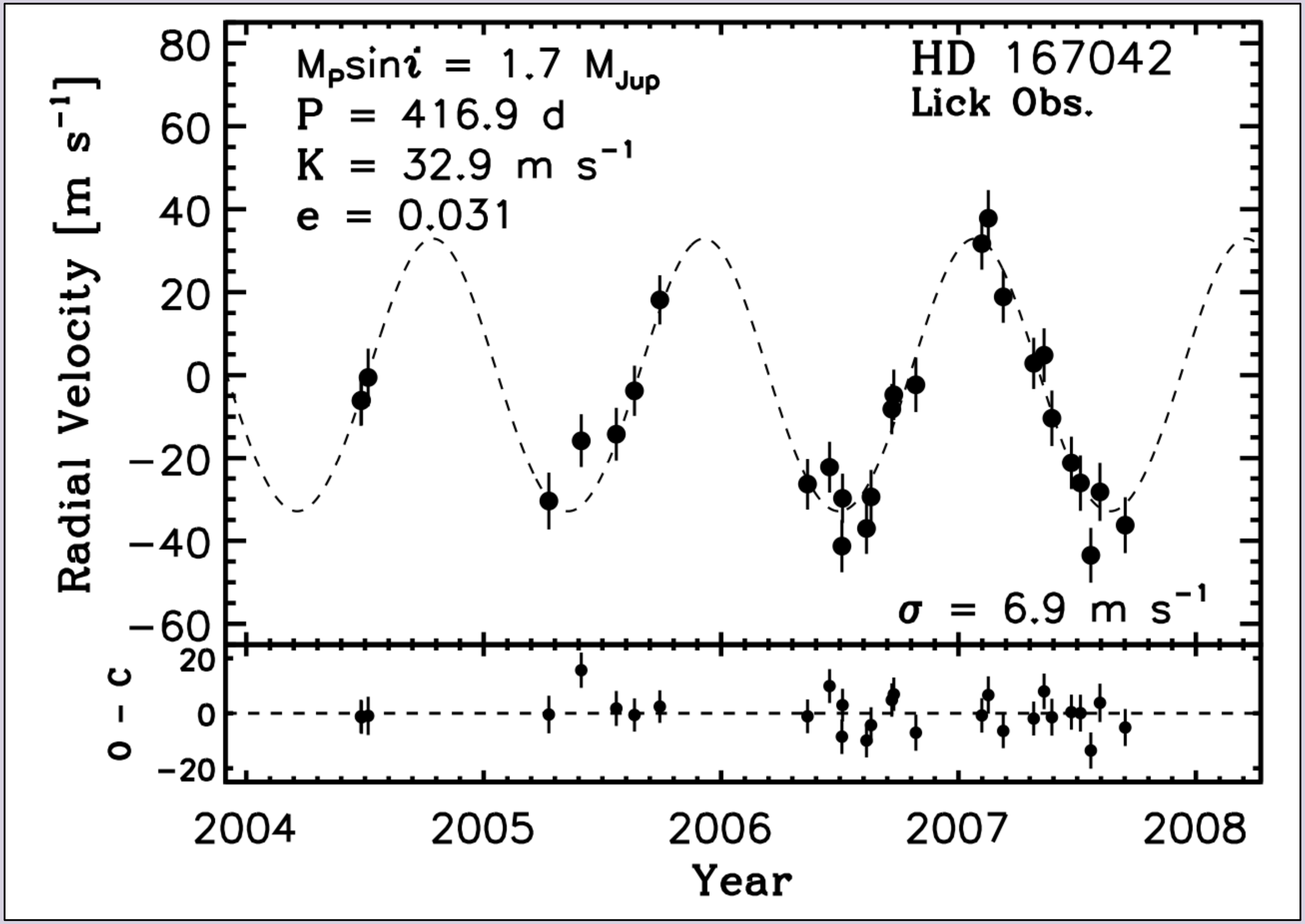
Johnson, Fischer et al. (2007)

HD 16175: $M_* = 1.38\ M_\odot$



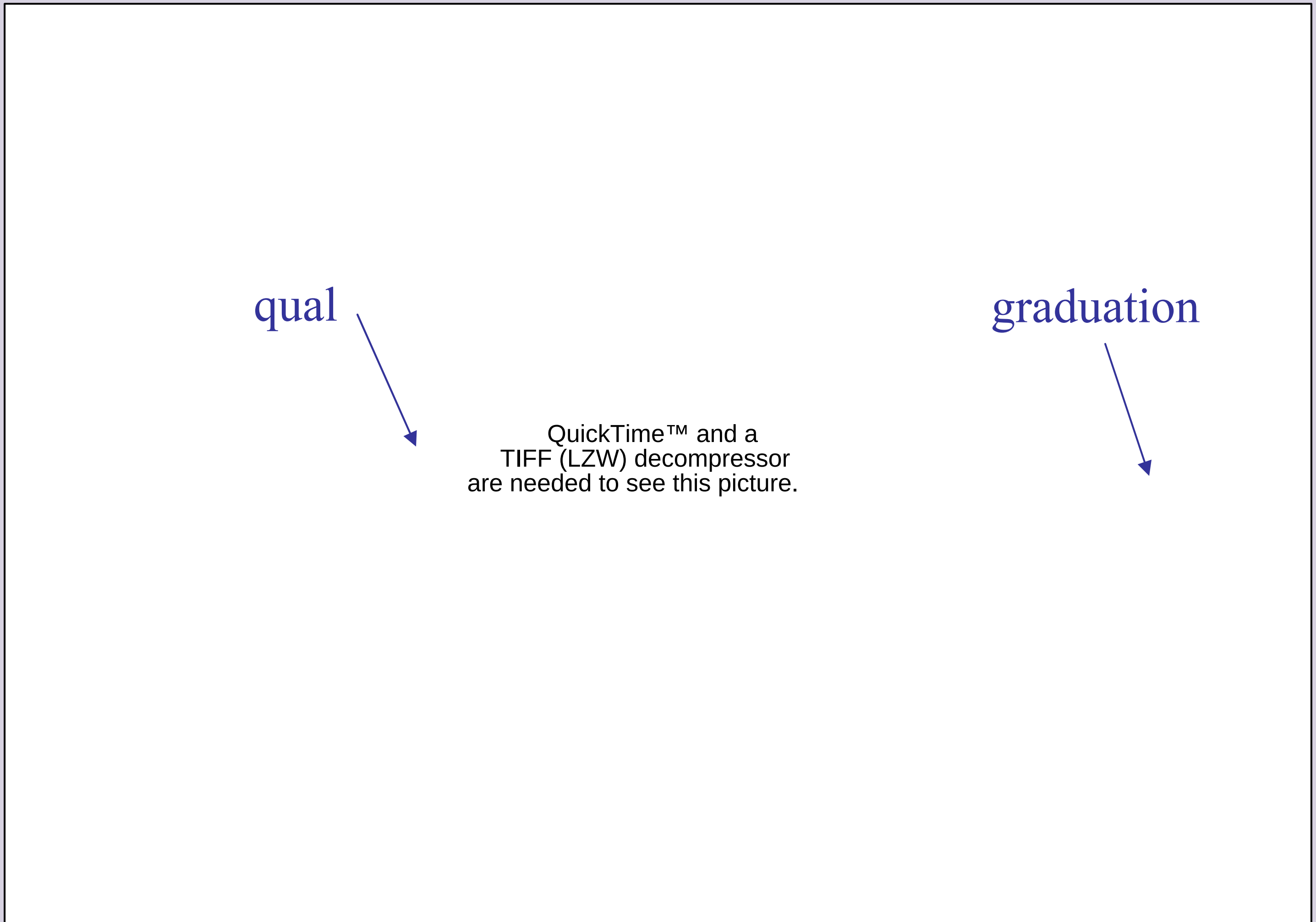
Johnson, Marcy et al. (2007)

HD 167042: $M_* = 1.65\ M_\odot$



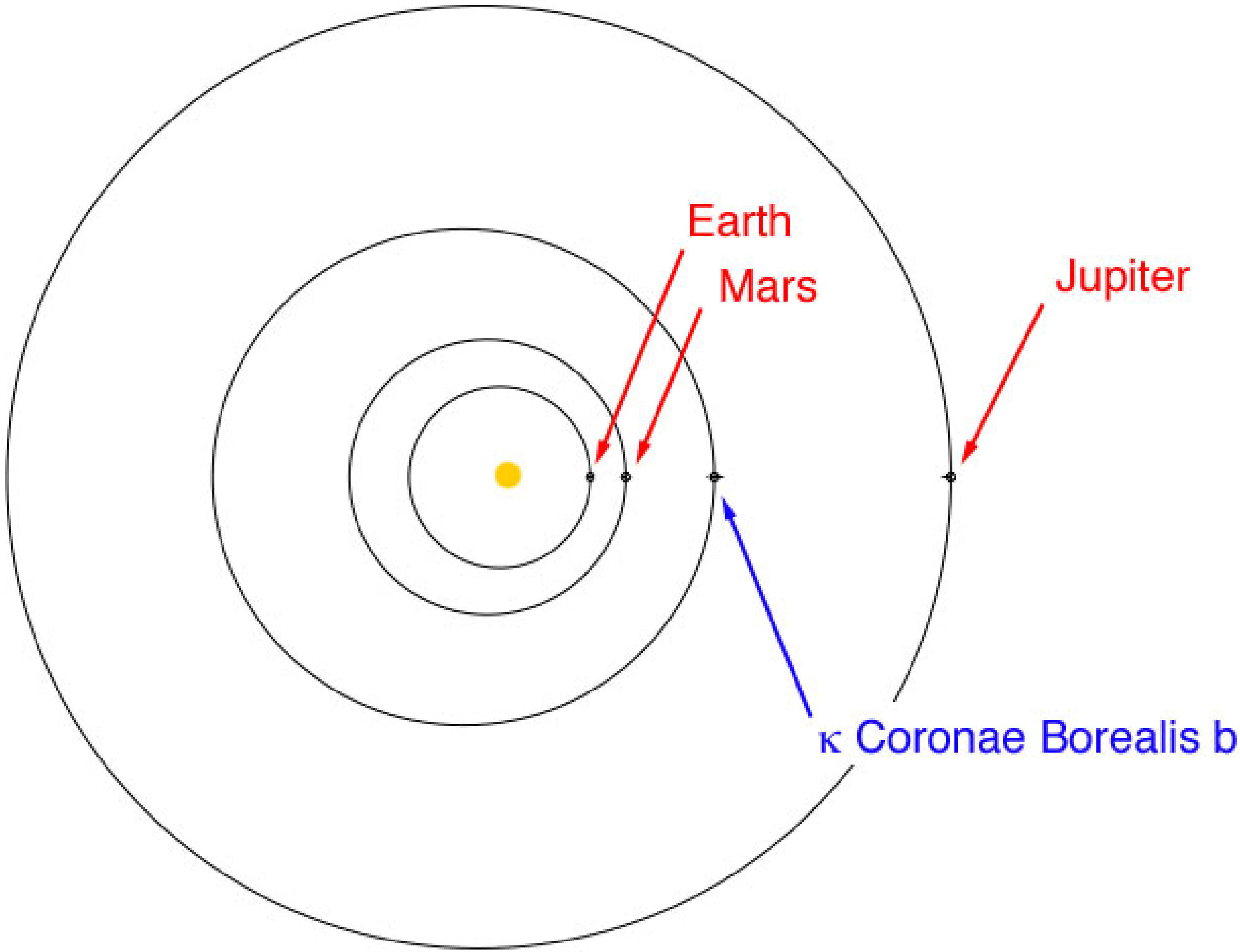
Johnson, Marcy et al. (2007)

κ Corona Borealis: $M_* = 1.80\ M_\odot$



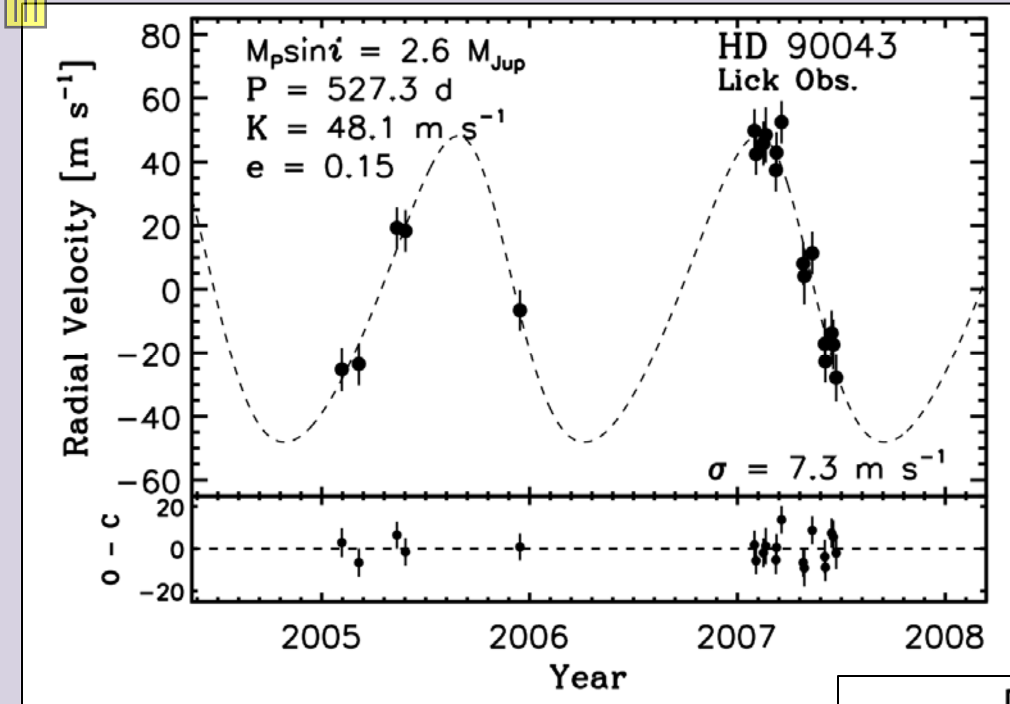
Johnson, Marcy et al. (2007)

Comparison of the orbits of the Solar System Planets to the orbit of κ CrB b



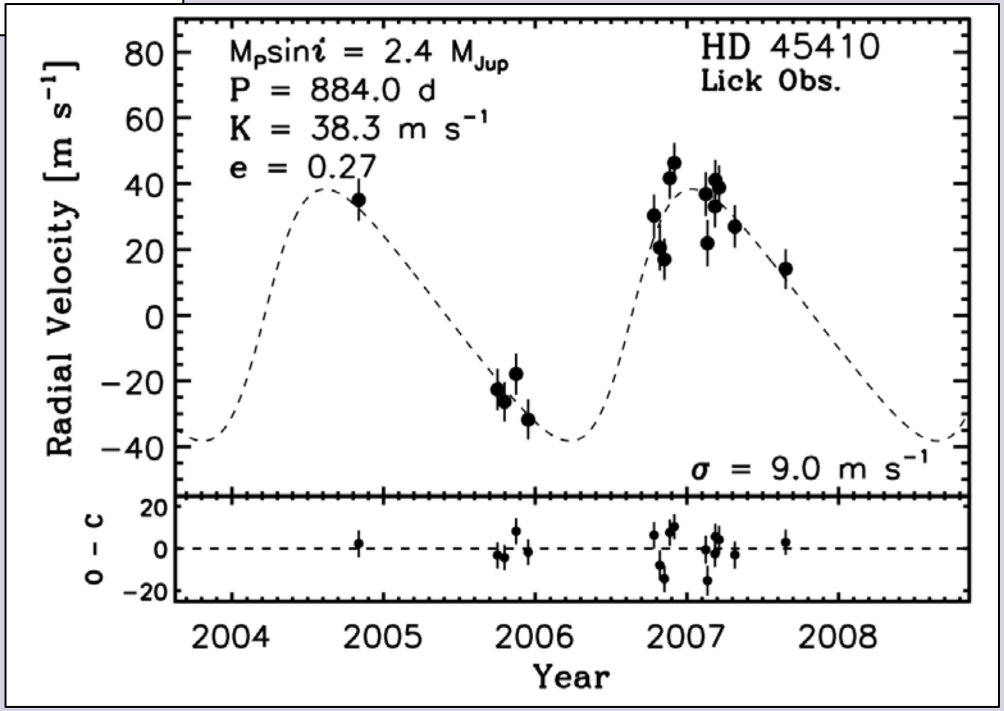
Additional Planet Candidates

Follow-Up Observations Needed



24 Sextans:

$M_* = 1.8\ M_\odot$

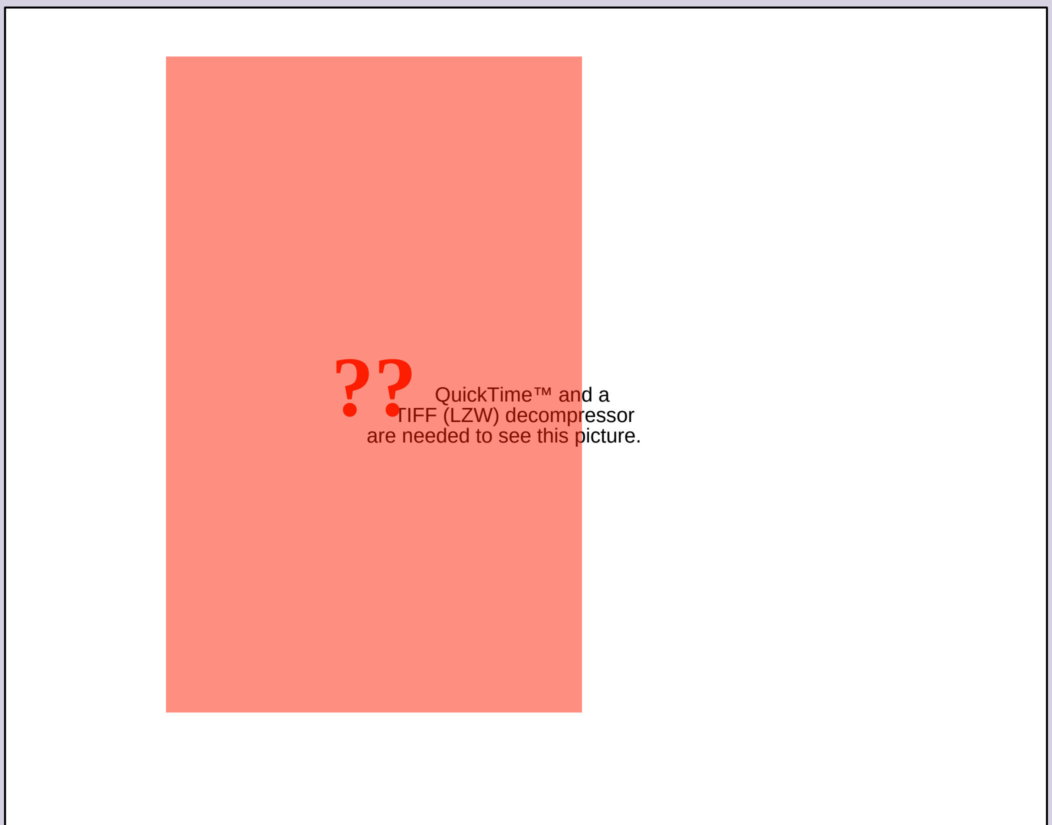


6 Lynx:

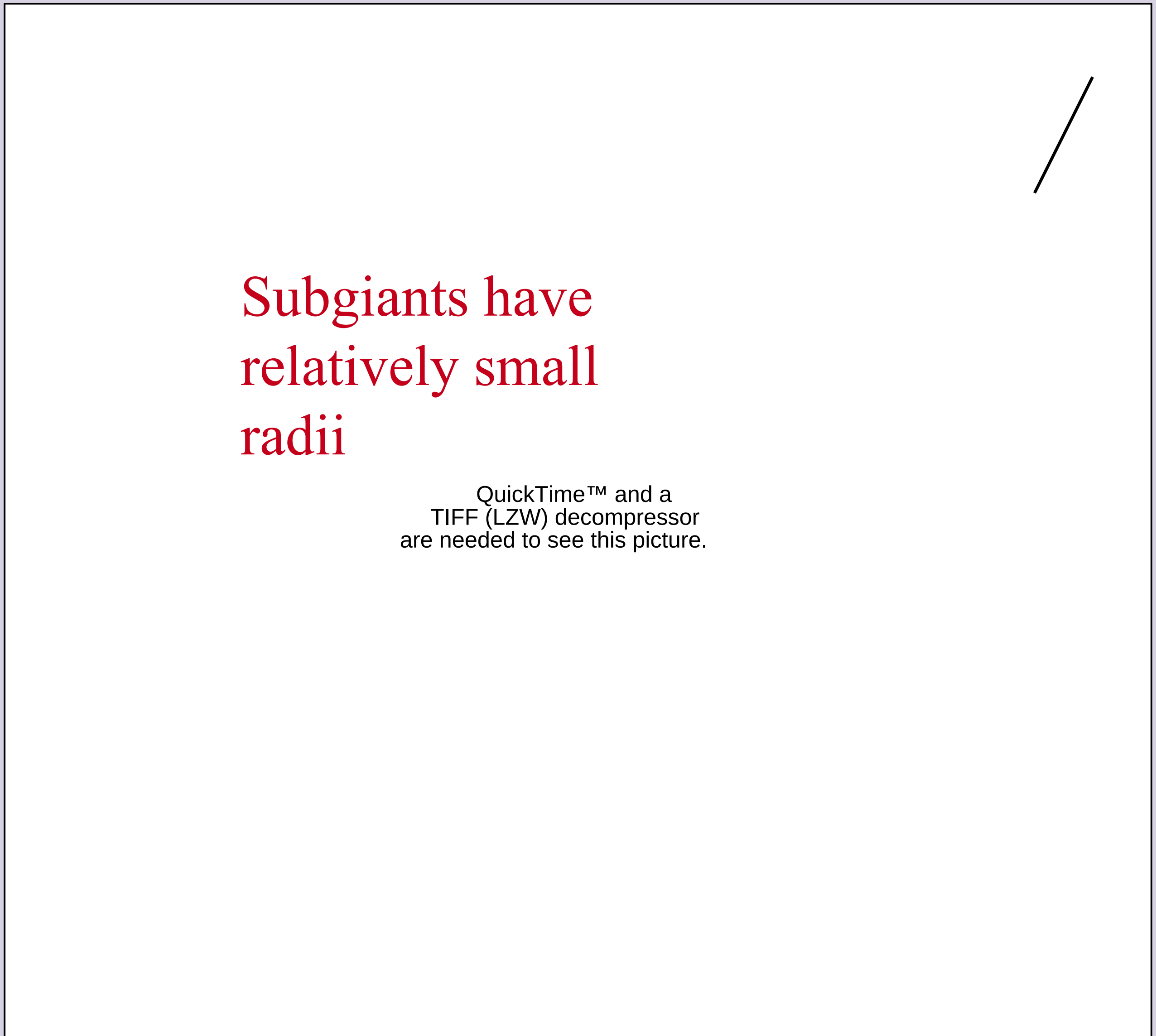
$M_* = 1.9\ M_\odot$

Distribution of Semimajor Axes

- Combine with K giants and clump giants
- 13 out of 13 planets around stars with $M_* > 1.5\ M_{sun}$ orbit beyond 0.8 AU!



Stellar Radii and Short-Period Planets



Subgiants have relatively small radii

Johnson, Fischer et al. (2007a)

Evaluating Planet Occurrence as a Function of Stellar Mass

- 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 Rate

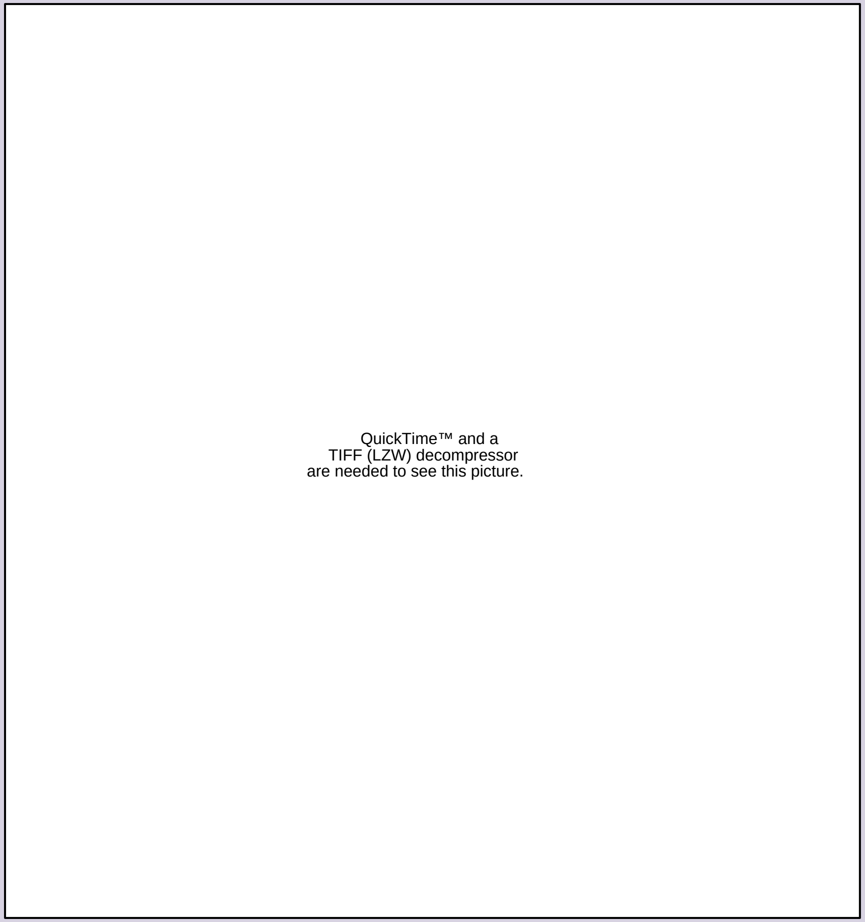
For a < 2.5 AU, $m_p \sin i > 0.8\ M_{Jup}$, $N_{obs} > 8$

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Johnson, Butler et al. (2007)

An Expanded Subgiants Planet Search

- 320 additional stars at Keck and Lick Observatory
  - Decrease error bars by ~2
- Higher precision of Keck/HIRES
- Targets in "sweet spot" of H-R diagram
  - High Mass
  - Low $V_{rot}\sin i$
  - Low jitter
- Catalog of Spectroscopic Properties for 450 Subgiants



Metallicities of Subgiants

All stars:

$\langle[\mathrm{Fe/H}]\rangle = 0.0$

Stars w/ Planets:

$\langle[\mathrm{Fe/H}]\rangle = 0.0$

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Conclusions

- Subgiants are ideal proxies of A and F stars
  - Mass of an A dwarf, precision of a G dwarf
- Semimajor Axis Distribution at higher masses not consistent with Sun-like stars
  - Relic of Formation/Migration?
  - Higher occurrence rate for $M_* > 1.3 M_\odot$
  - Treasure trove of planets around A stars.