Combining Imaging + RV's

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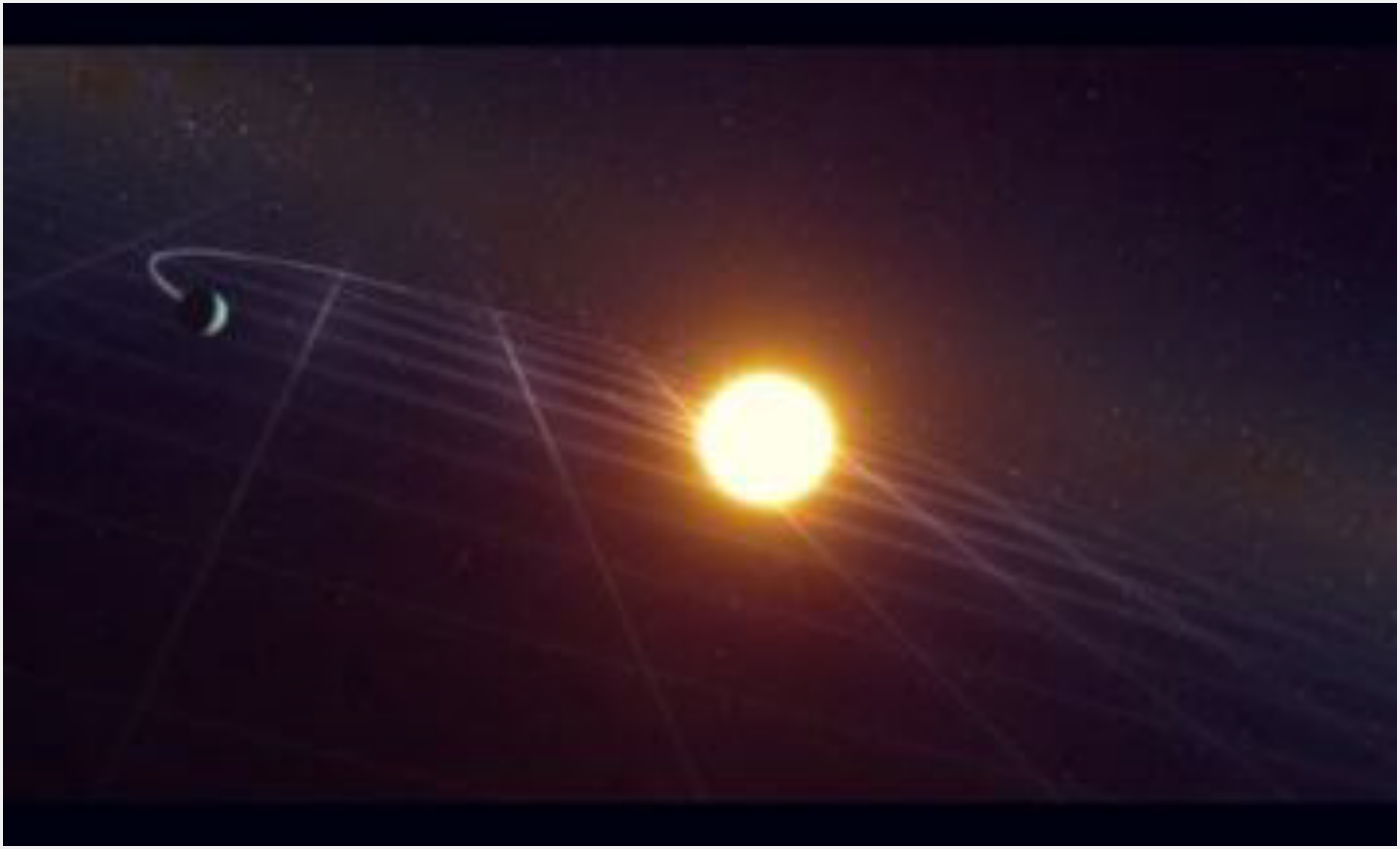
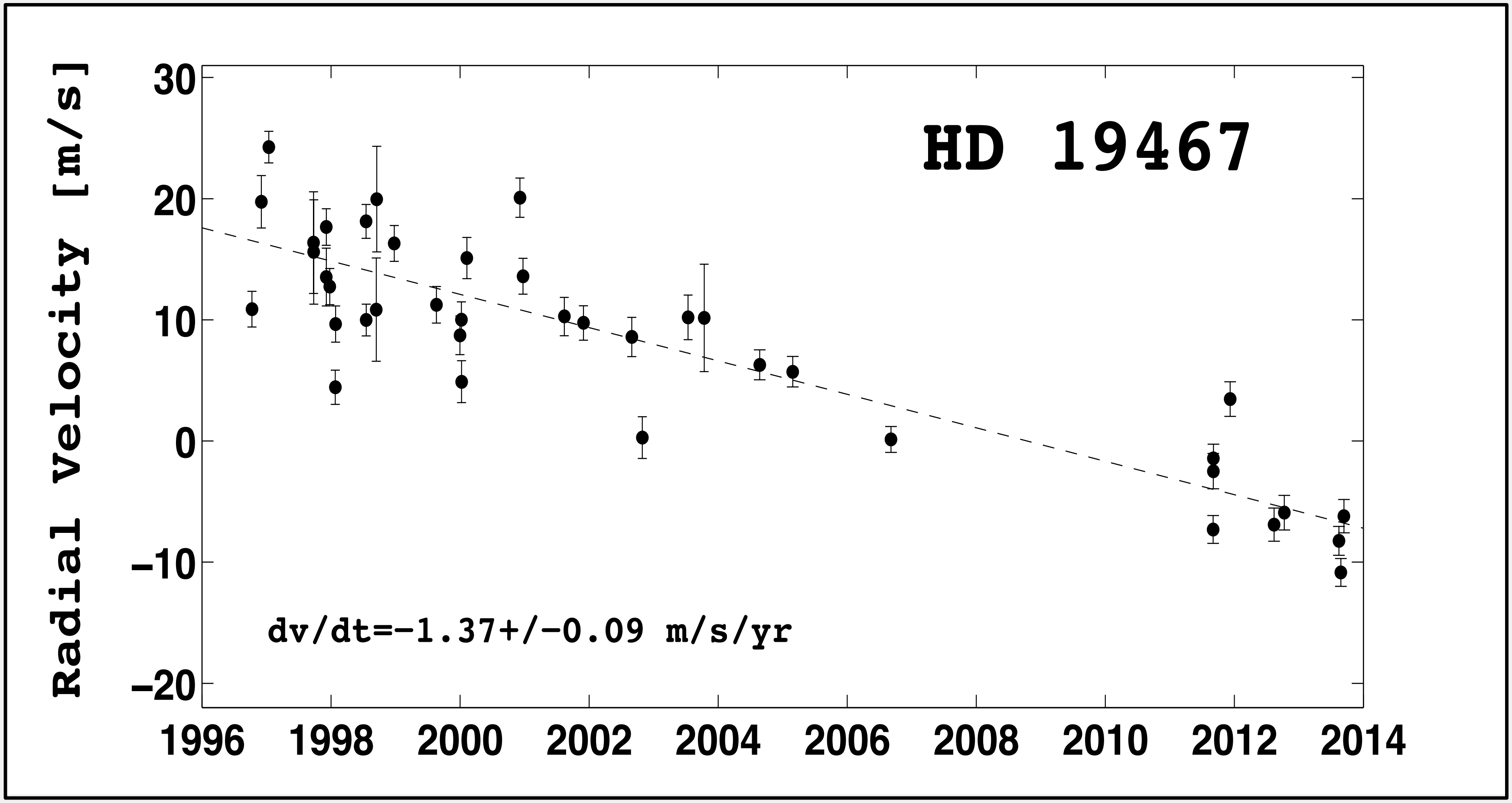
Connecting Two Distinct Techniques

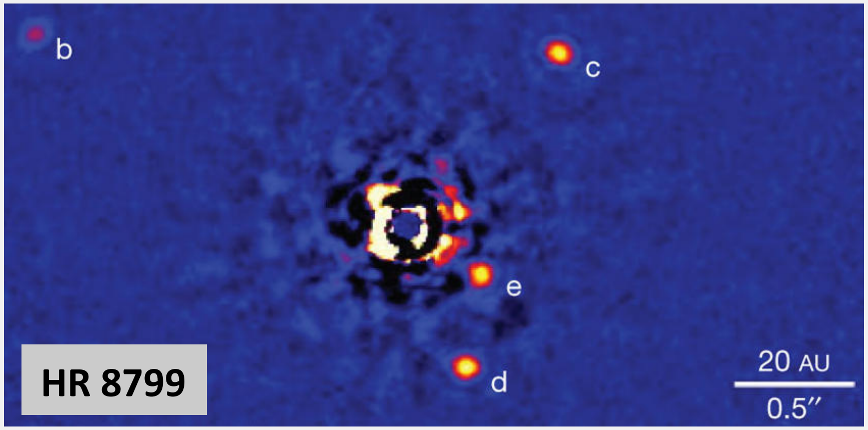


Doppler Trends

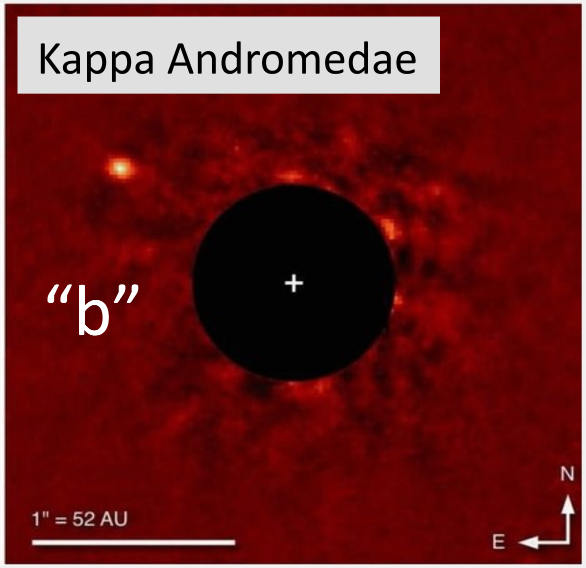


Motivation

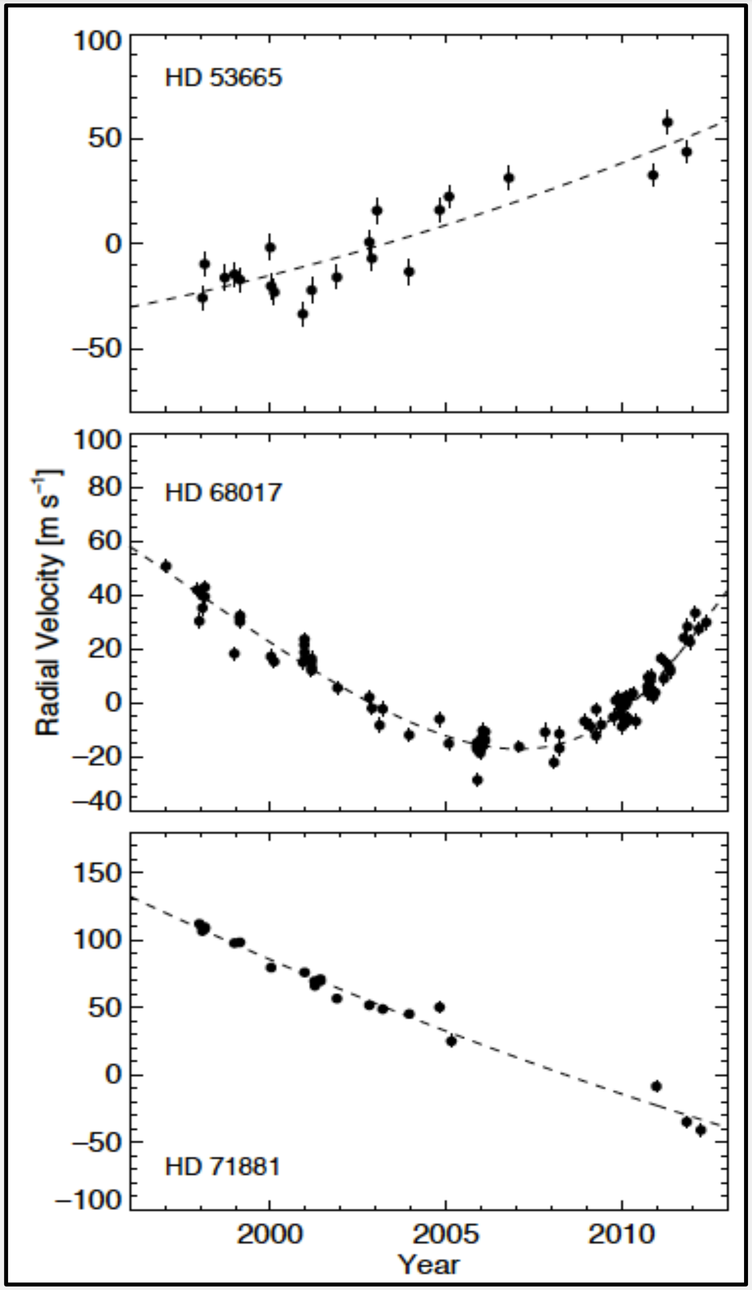
- High detection efficiency.
- Break sin(i) degeneracy, construct 3d-orbits.
- Dynamical masses of companions.
- Calibrate evolutionary models.
- Determine f_{pl} for wide orbits.



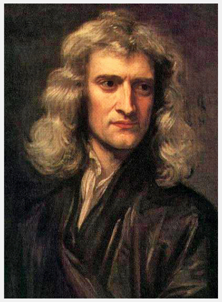
Marois et al. 2010



Carson et al. 2012



Partial Orbits



Isaac
Newton

What information can be gleaned?

(1) Minimum dynamical mass (Torres 1999).

(2) Physical separation (Howard et al. 2010).

Minimum Mass

$$\min\left(\frac{M_B}{M_{Sun}}\right) = 1.39\text{E}-5\left(\frac{d}{\text{pc}}\frac{\rho}{\text{arcsec}}\right)^2\left|\frac{d(RV)}{dt}\right|$$

where RV acceleration is measured in m s^{-1} yr^{-1}.

Physical Separation

$$\left|\frac{d(RV)}{dt}\right| = \frac{GM_B}{r_{AB}{}^2}\cos\theta, \qquad \left(\frac{r_{AB}}{\text{AU}}\right)\sin\theta = \frac{\rho}{\pi}$$

where r_{AB} is the instantaneous true physical separation.

3d-Orbits and Dynamical Mass

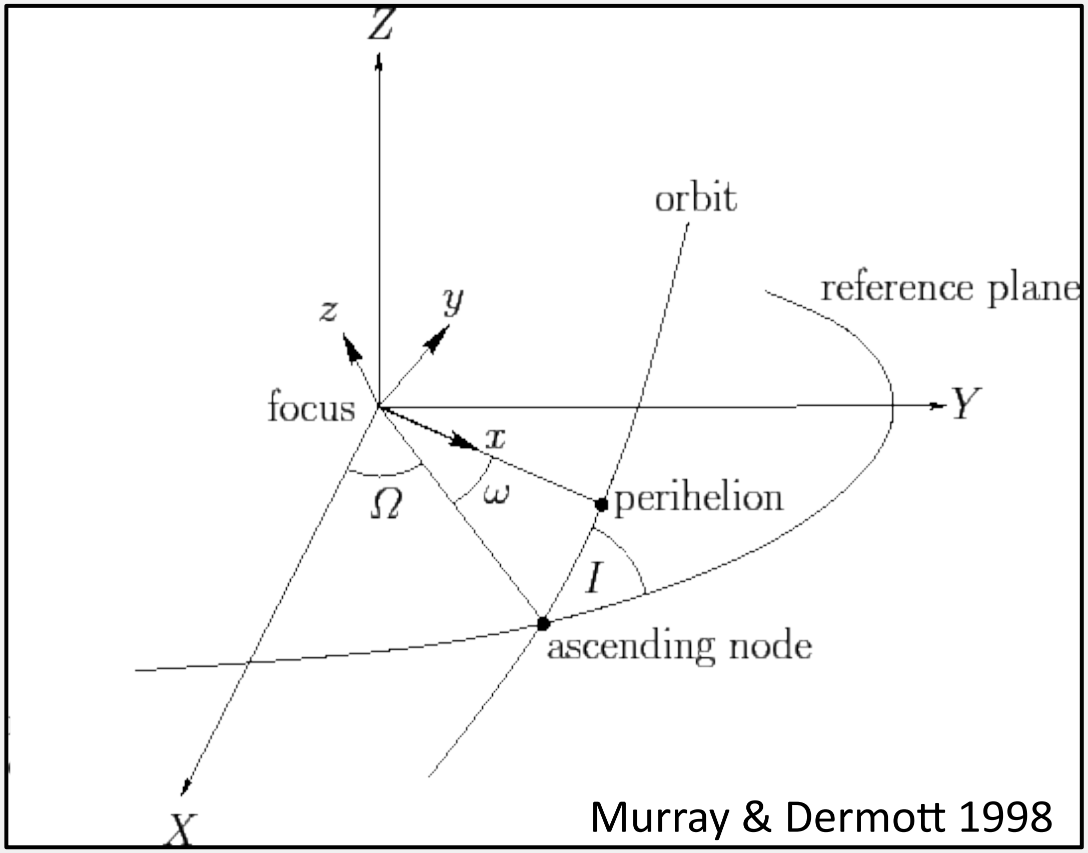
Radial Velocities:

K, P, e, ω, t_p

Astrometry:

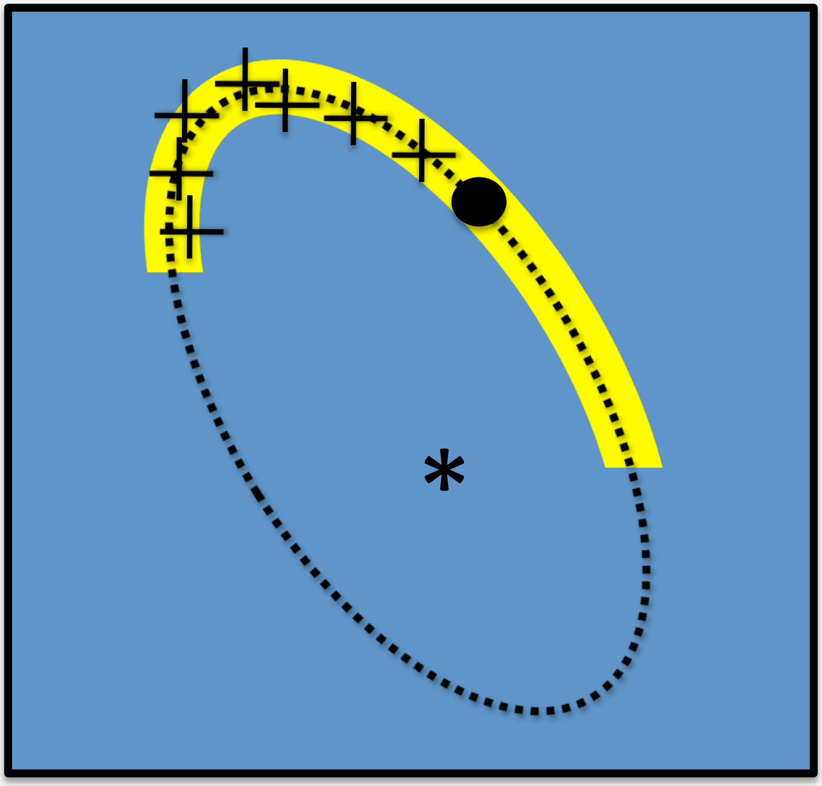
$a, i, P, e, \omega, t_p, \Omega^*$

How much information do we need to calculate the orbit and mass?



Murray & Dermott 1998

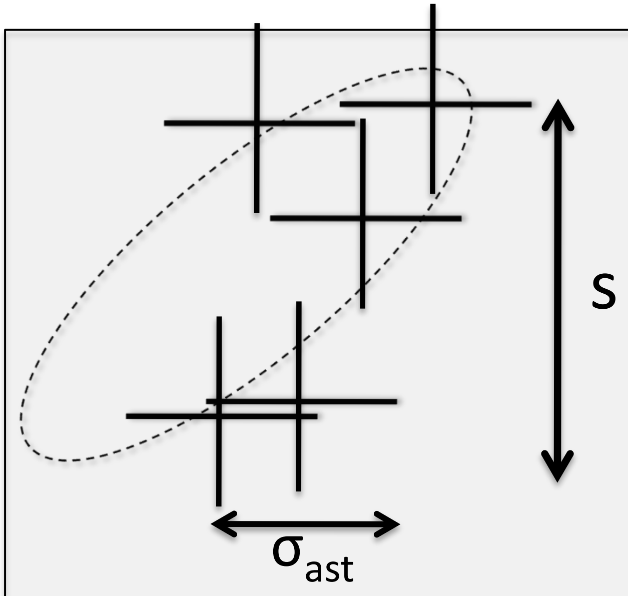
At What Point Can We Calculate the Orbit?

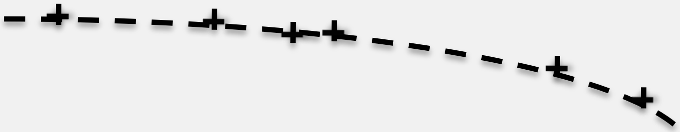


$$p^2 = \frac{4\pi^2 a^3}{G\left(M+m\right)}$$

Notice that precise parallax is essential (Dupuy & Kraus 2013)

When do constraints become interesting?

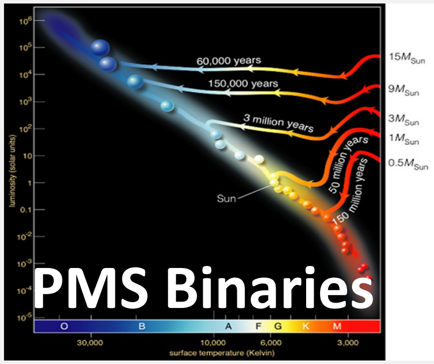


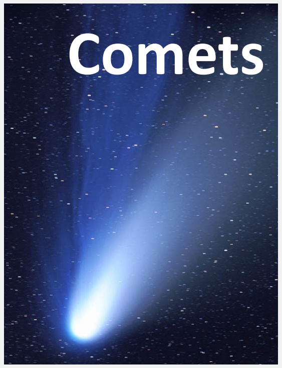


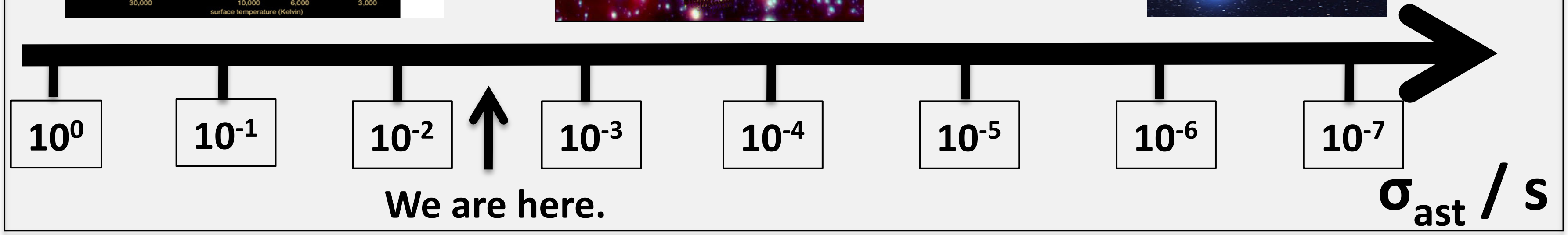
“I don’t trust anyone’s results until I see 2 phase wraps.”
- Andy Boden (Caltech)

“Yes, of course the inclination falls out immediately.”
- Jessica Lu (IfA)

“with accuracies of a few mas, it is possible to place strong constraints on KBO orbits even from very short (e.g., 24 hour) arcs … reflex motion is easily detected giving a measure of distance to the target in less than an hour.”
- Bernstein & Khushalani 2000

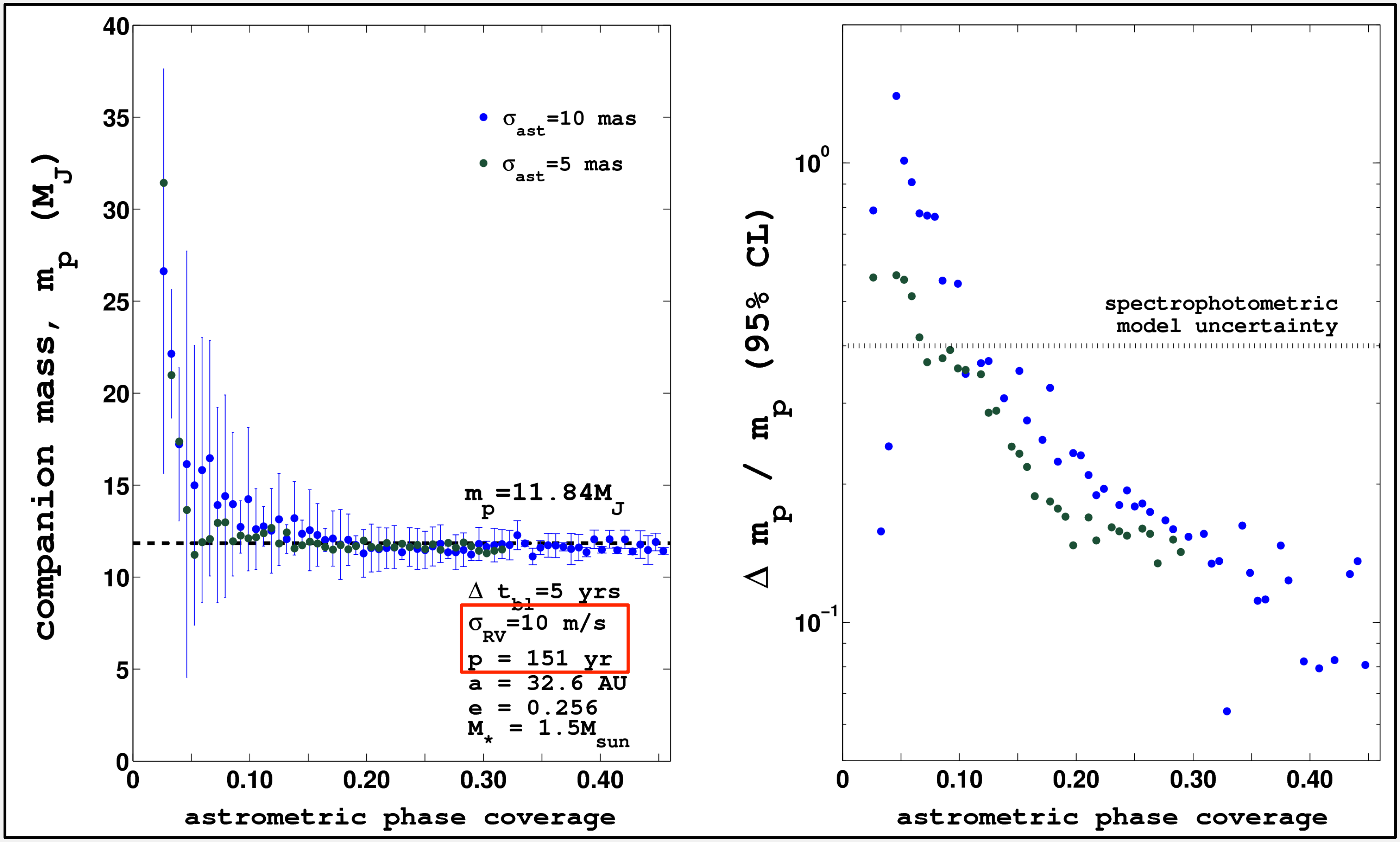






We are here.

RV + Astrometry Simulations

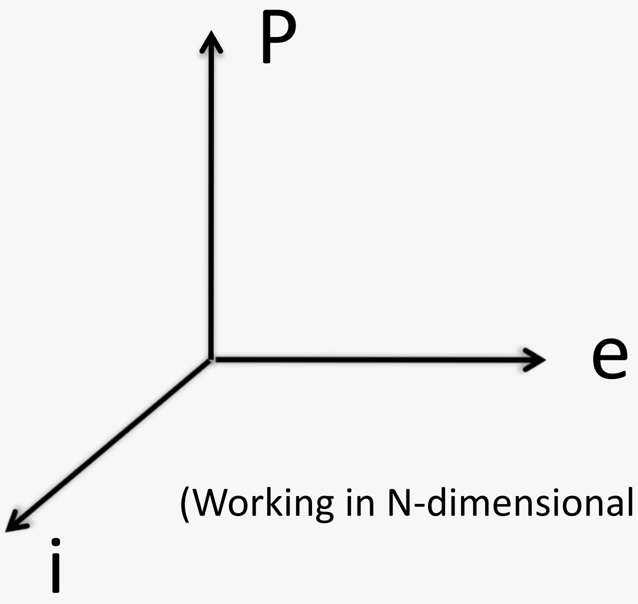


How Do We Fit Observations?

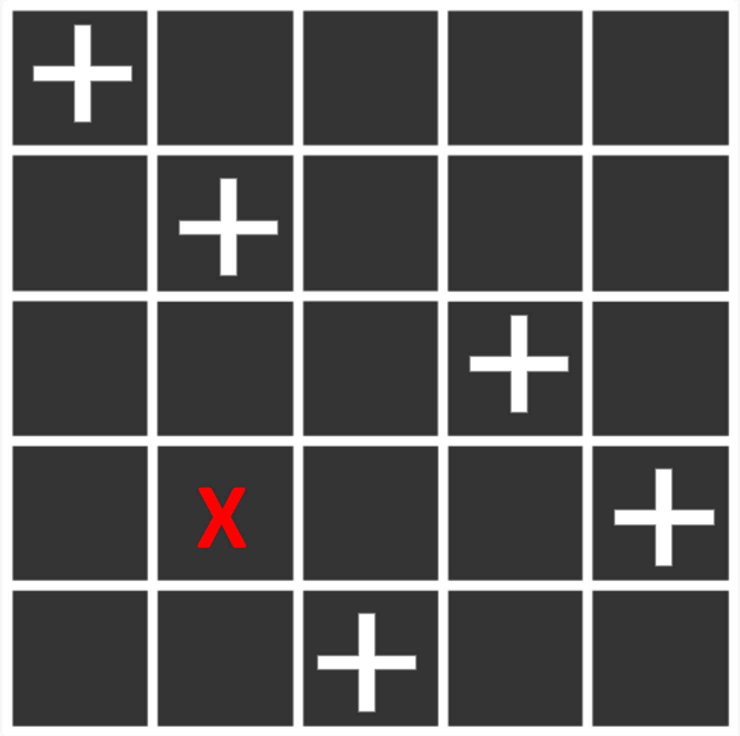
- Bayesian statistical framework.
  (“Data Analysis: A Bayesian Tutorial” by Sivia)
- Assume we understand uncertainties.
- Keplerian orbit model. Single companion.
- Markov-Chain Monte Carlo (MCMC) analysis.
  (“Quantifying the Uncertainty in the Orbits of Extrasolar Planets”, Ford 2005, AJ, 129, 1706)

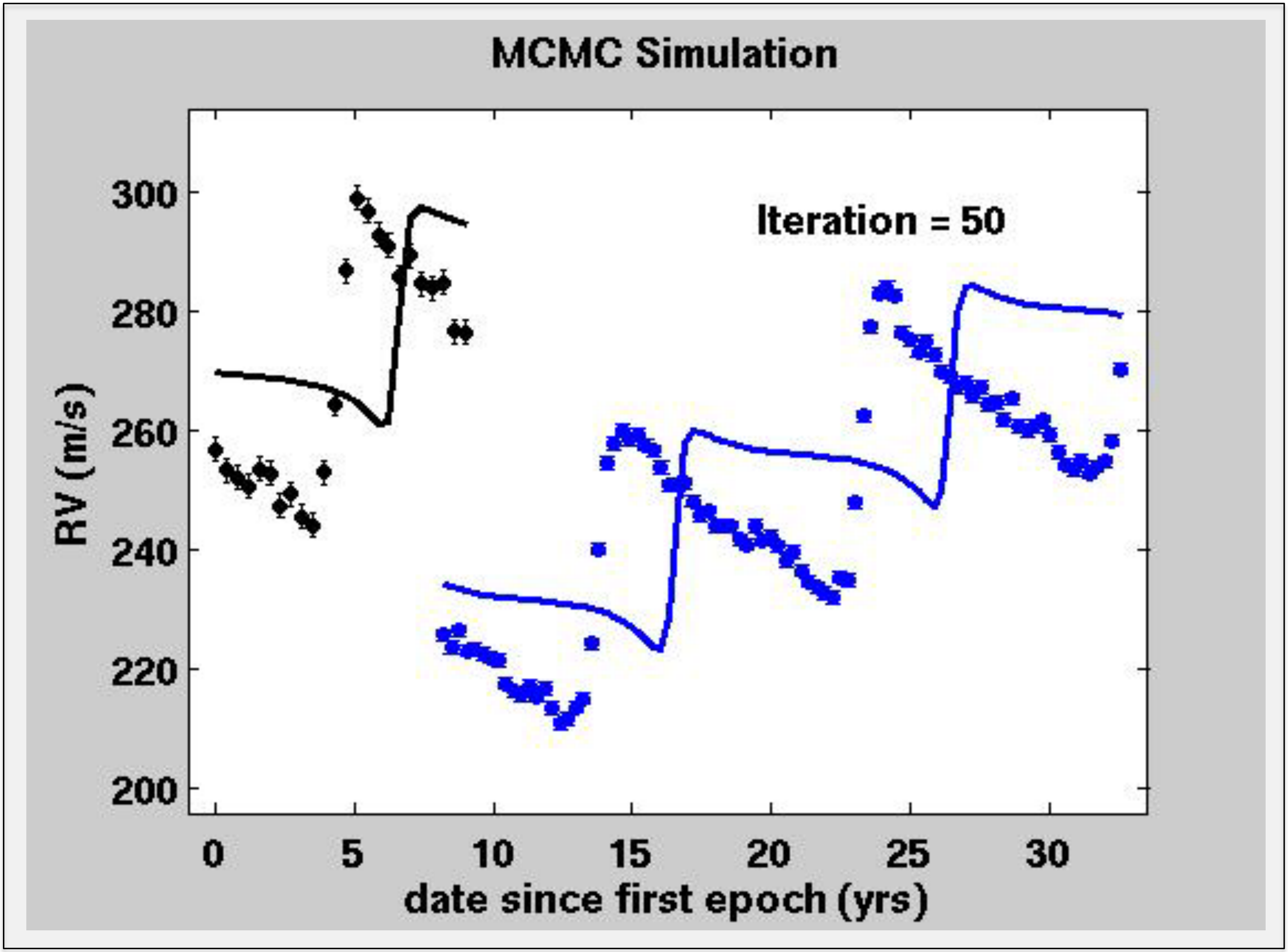
Markov Chain Monte Carlo

- Many degrees of freedom $\{P, e, i, \omega, t_p, \Omega, \ldots\}$.
- Metropolis-Hastings algorithm.



(Working in N-dimensional space)

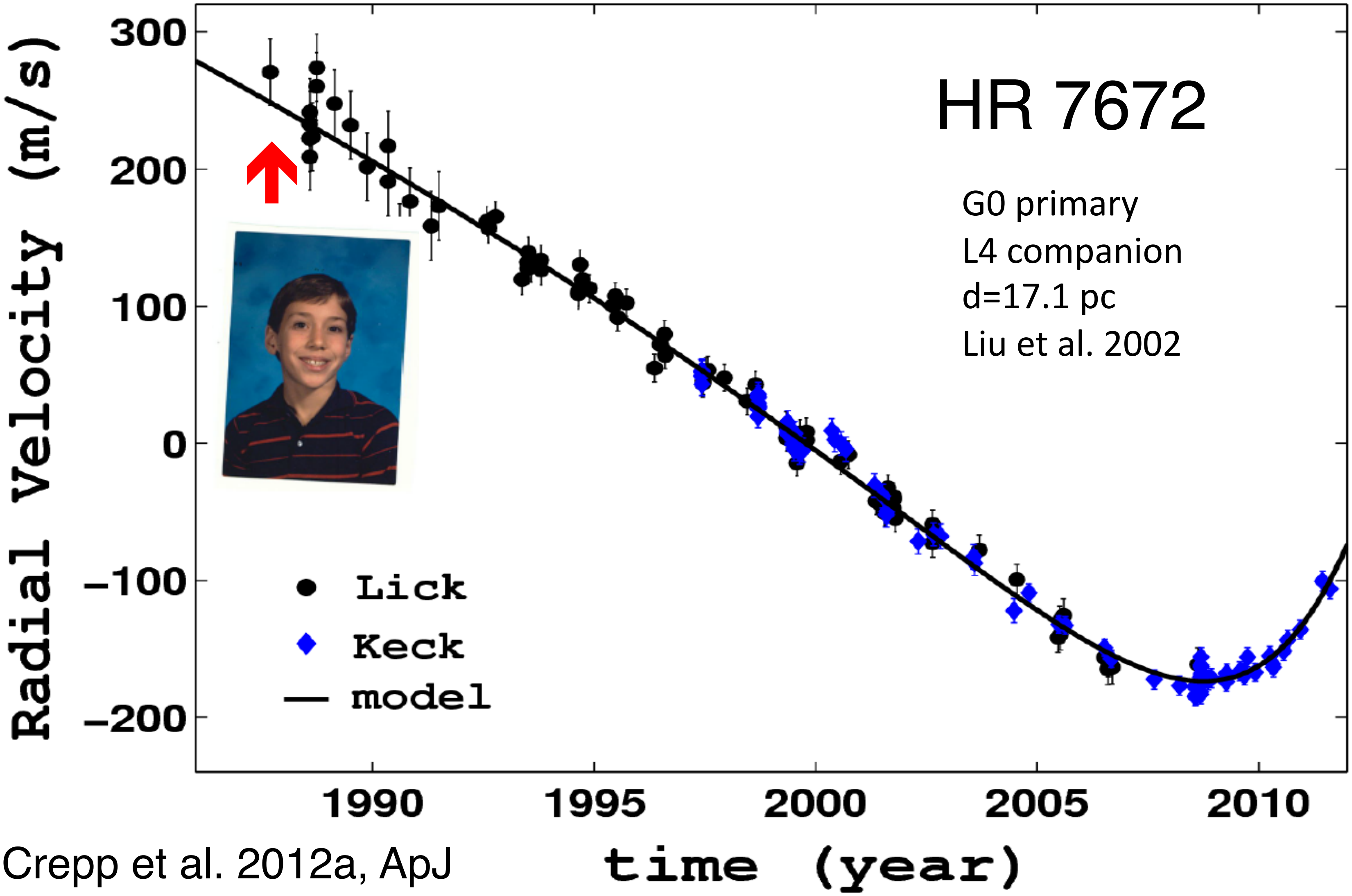



MCMC Simulation
Iteration = 50
RV (m/s)
300
280
260
240
220
200
0
5
10
15
20
25
30
date since first epoch (yrs)

Metropolis-Hastings Pseudo-Code:

```
(1) Cull P, a, e, i, $\omega$, $t_p$, $\Omega$, + nuissance parameters.
(2) Calculate Likelihood, L, for parameters.
     Use both RV, Imaging data simultaneously.
(3) if ($L > L_0$)
          record new chain entries.
     else
          if (rand[0,1] < $L / L_0$)
               record new chain entries.
          else
               record old chain entries.
          end
     end
(4) Wash, Rinse, Repeat to determine posterior.
```

Dynamical Masses

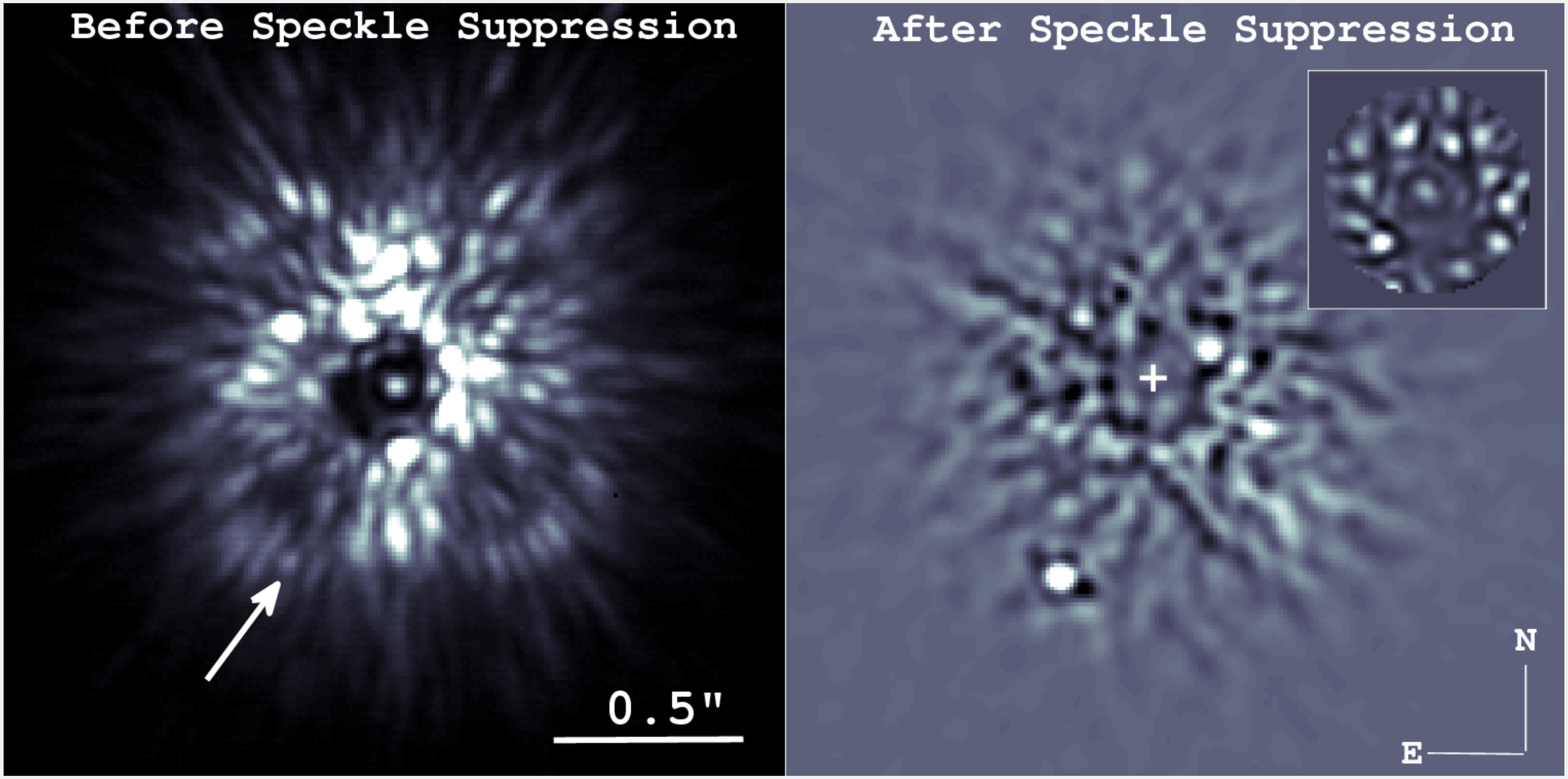


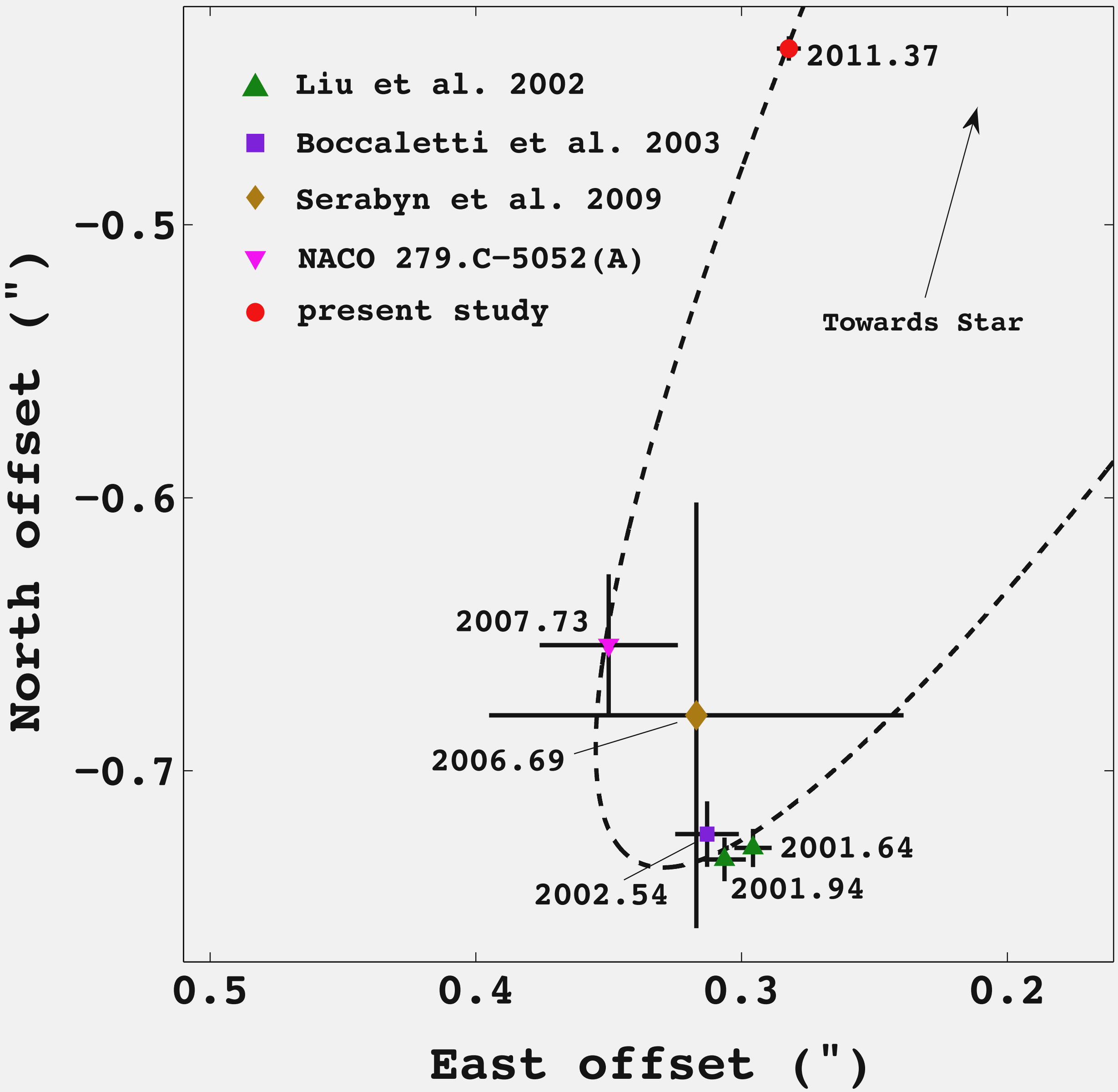
HR 7672

G0 primary
L4 companion
d=17.1 pc
Liu et al. 2002

Crepp et al. 2012a, ApJ

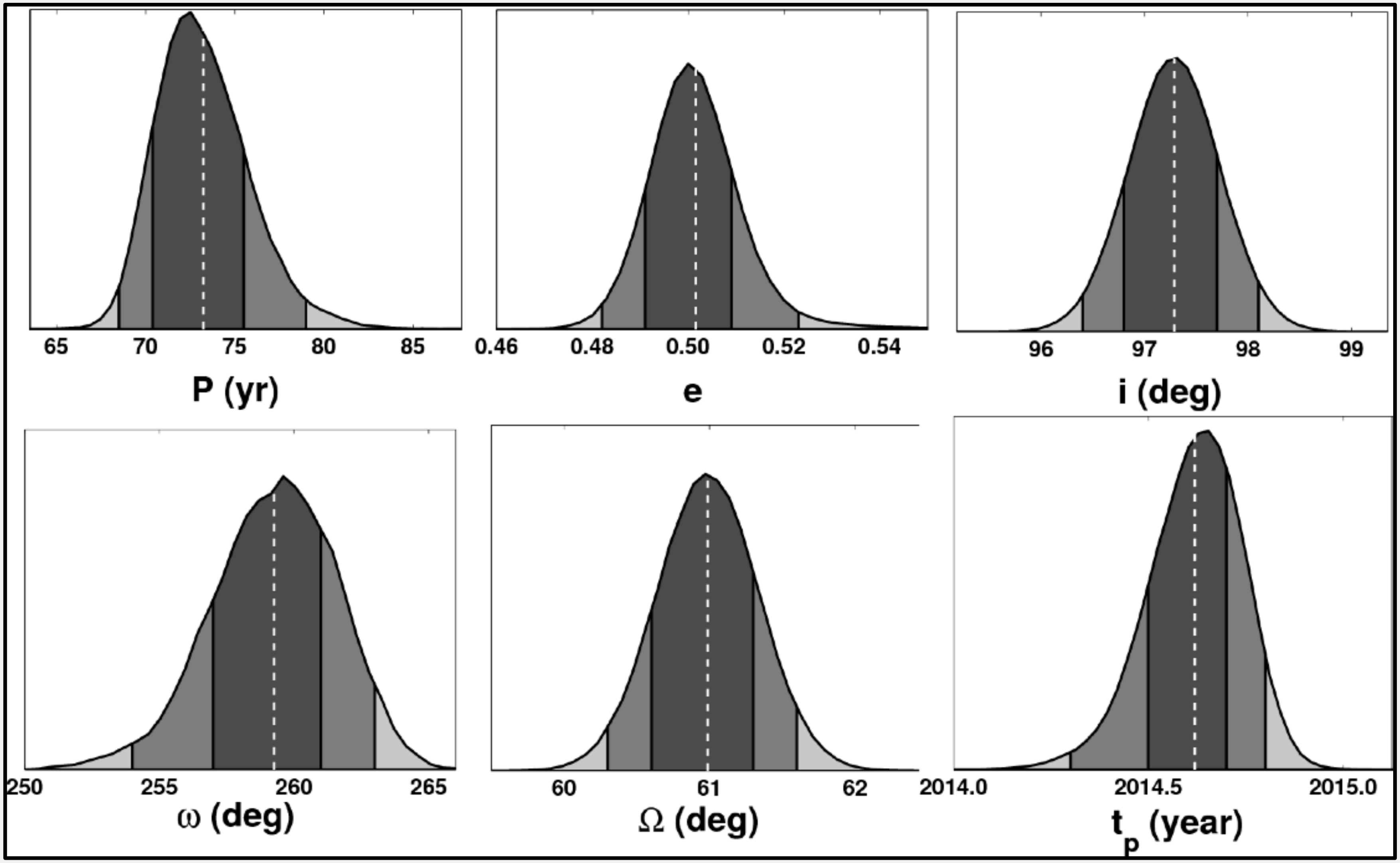
Direct Image, Keck/NIRC2 2011



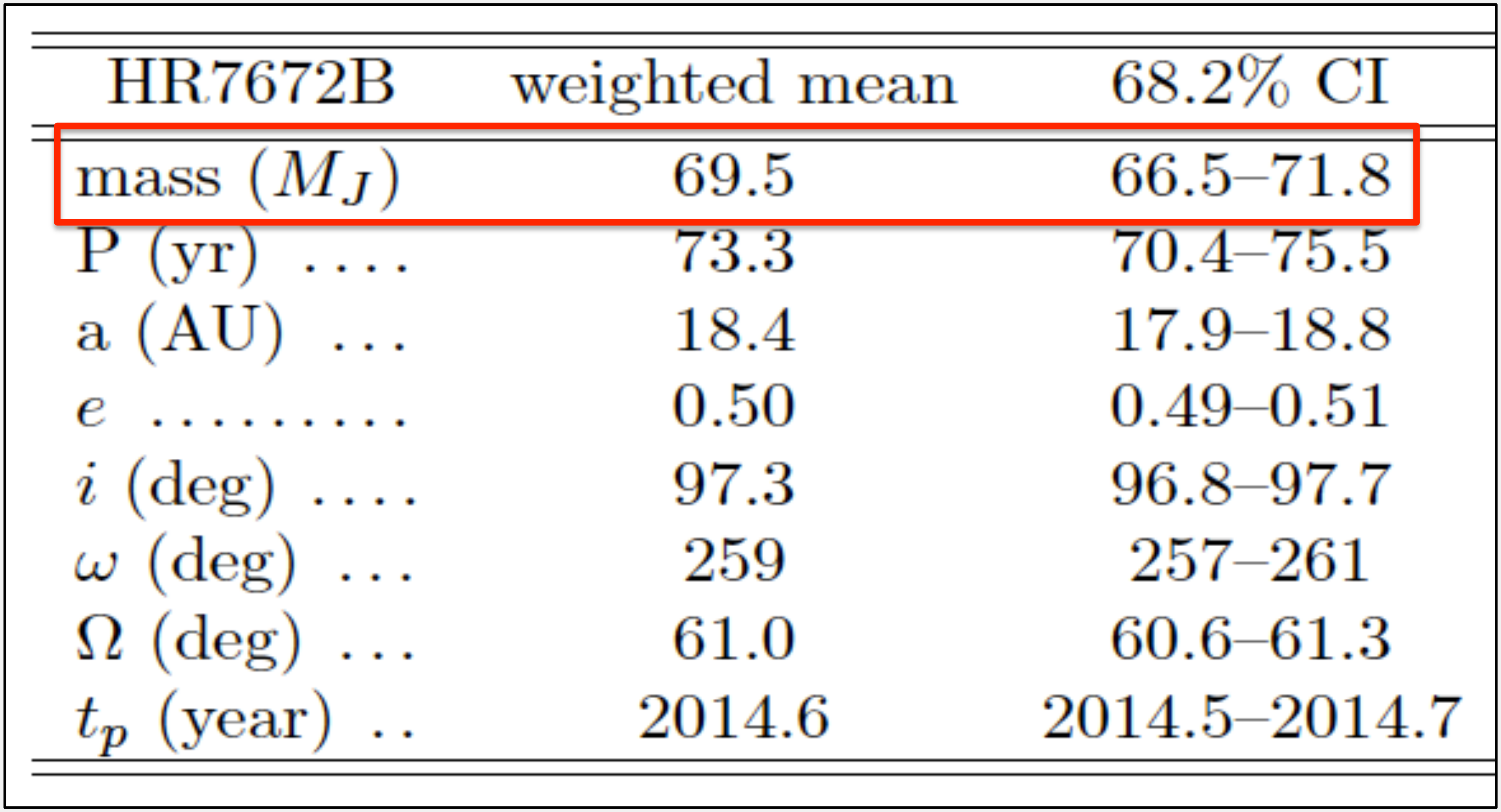


Crepp et al. 2012a, ApJ

All Six Orbit Parameters



3d-Orbit and Dynamical Mass

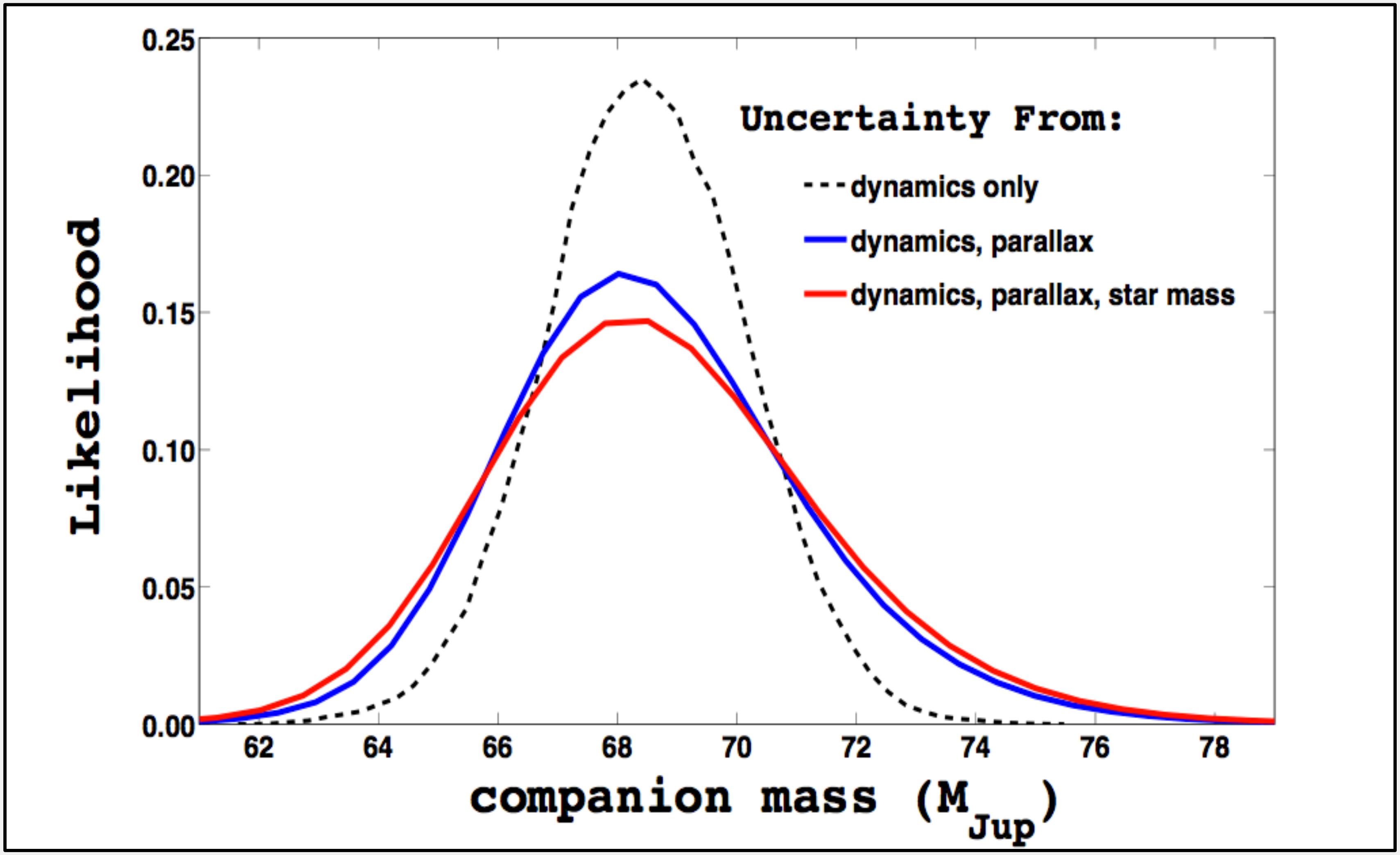


HR7672B	weighted mean	68.2% CI
mass (M_J)	69.5	66.5–71.8
P (yr)	73.3	70.4–75.5
a (AU)	18.4	17.9–18.8
e	0.50	0.49–0.51
i (deg)	97.3	96.8–97.7
ω (deg)	259	257–261
Ω (deg)	61.0	60.6–61.3
t_p (year)	2014.6	2014.5–2014.7

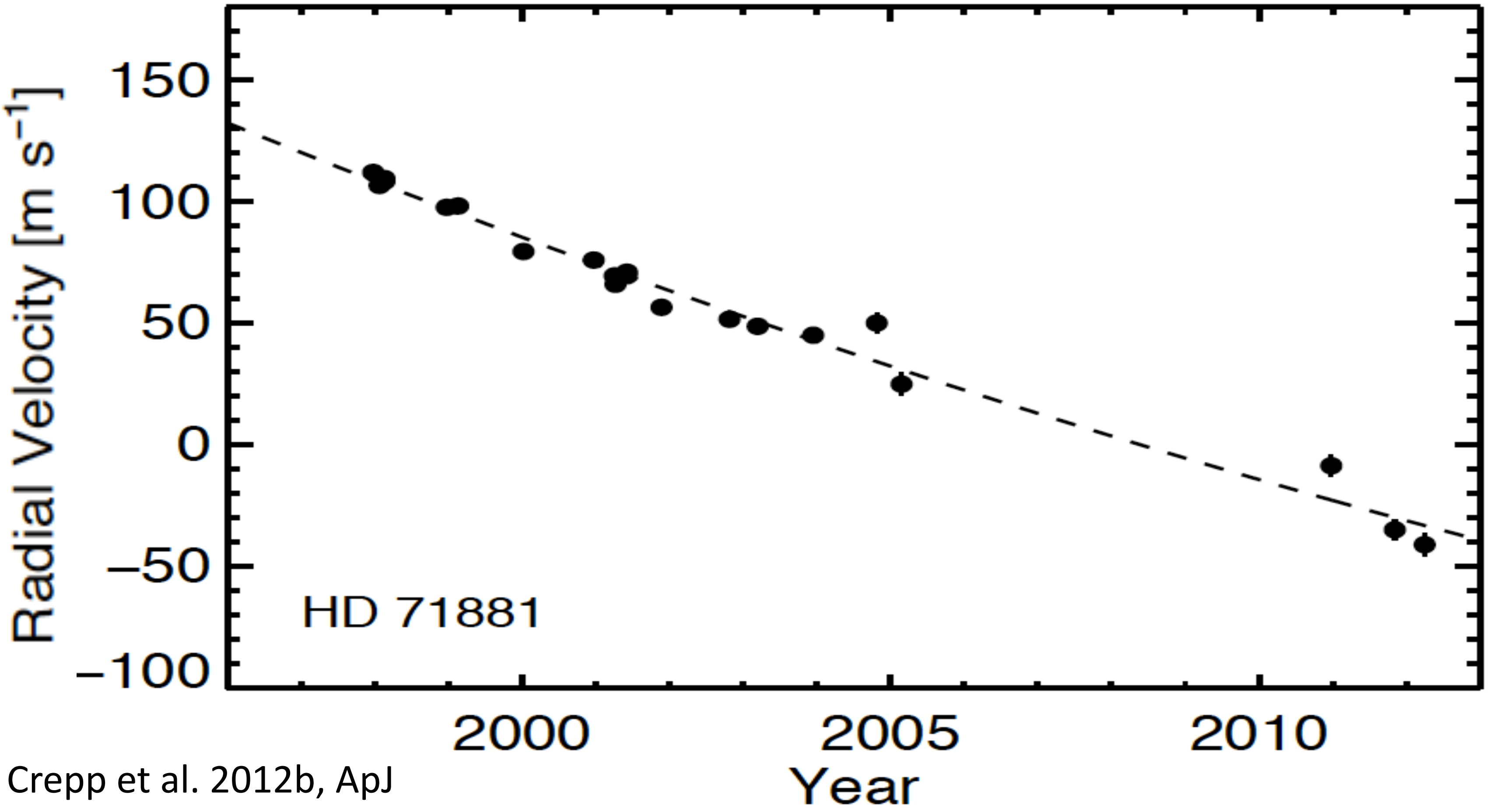
Crepp et al. 2012a, ApJ

More accurate and precise than theoretical evolutionary models(!)

Mass of a Directly Imaged Brown Dwarf



The “TrenDS” High-Contrast Imaging Program



Crepp et al. 2012b, ApJ

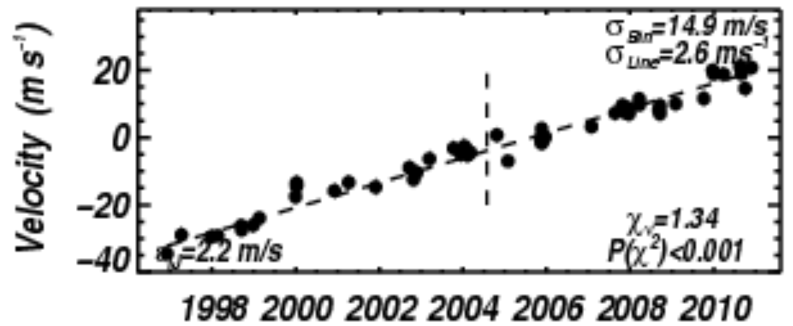
RV+Imaging: The Best of Both Worlds

[K1, HIRES]

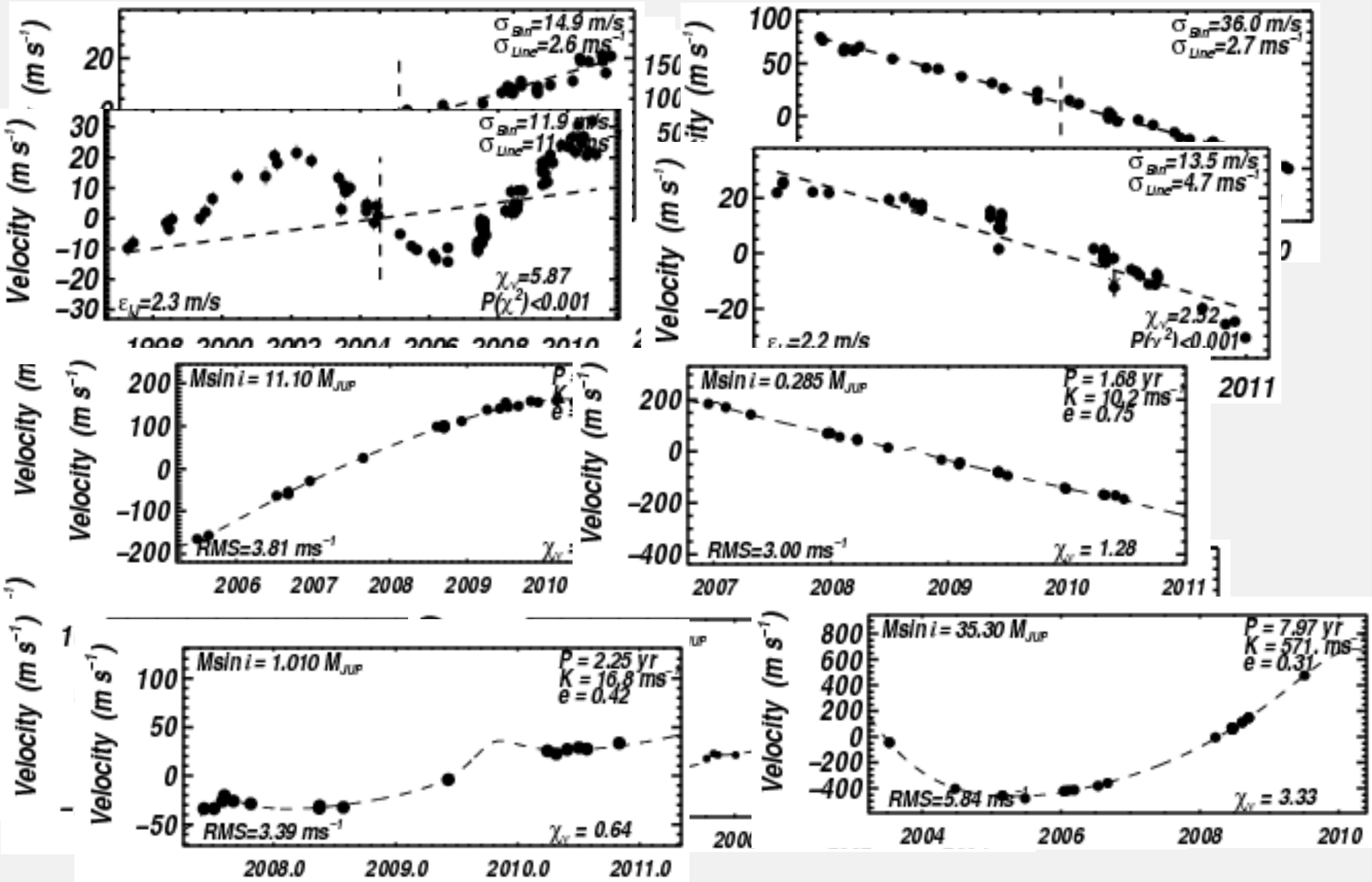
precision RVs
long time baselines

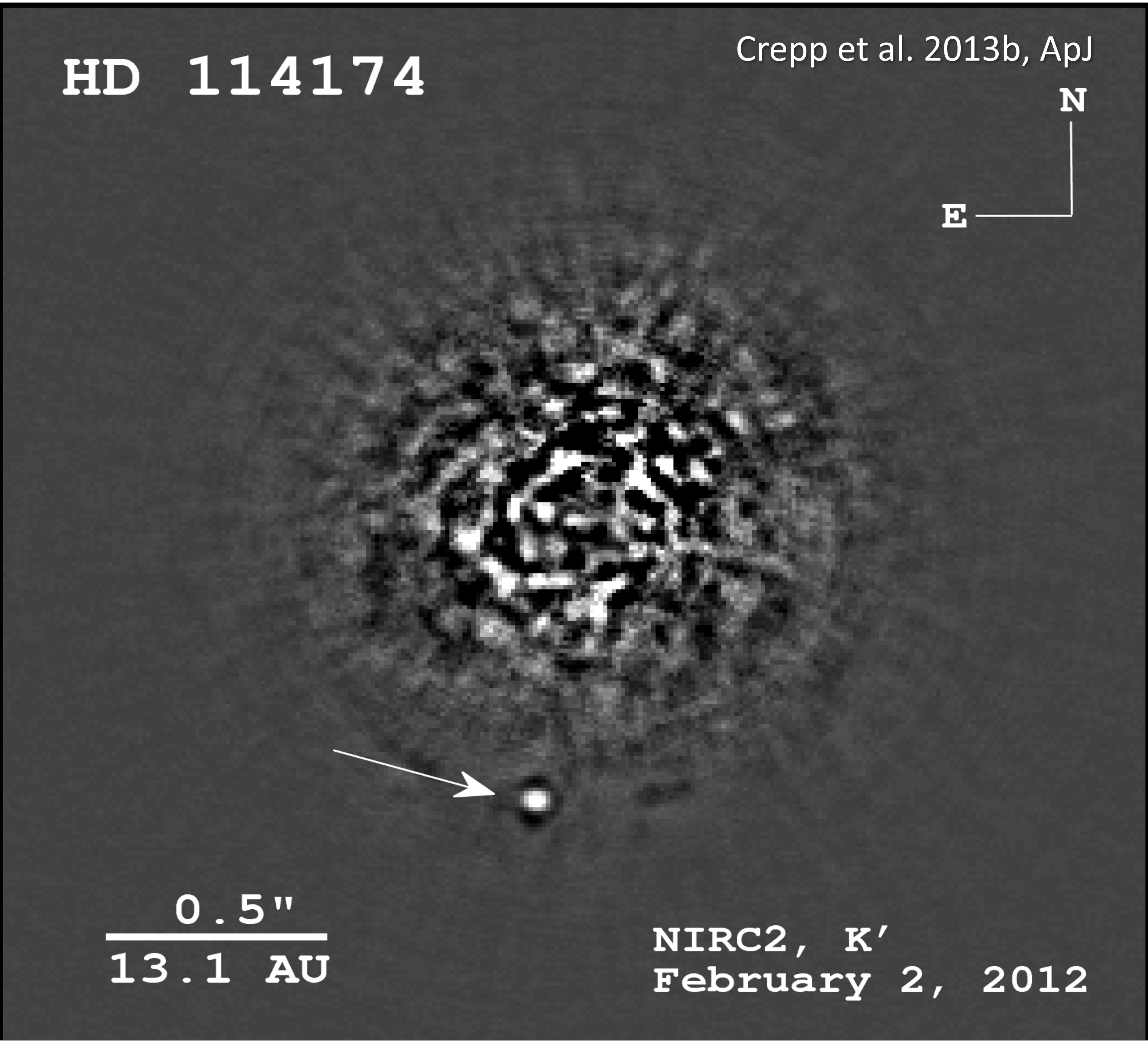
[K2, NIRC2]

adaptive optics
coronagraphy
speckle suppression



California Planet Search (CPS)

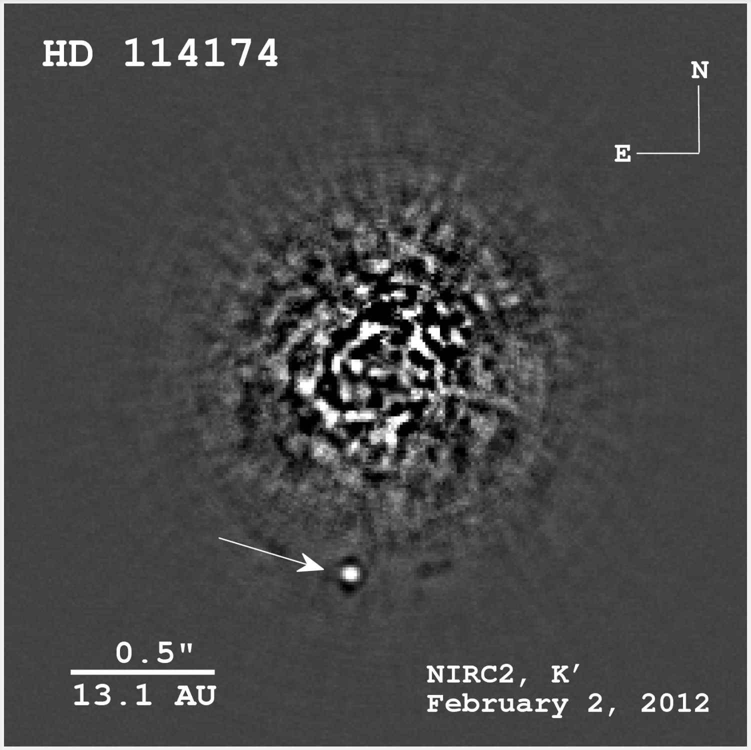




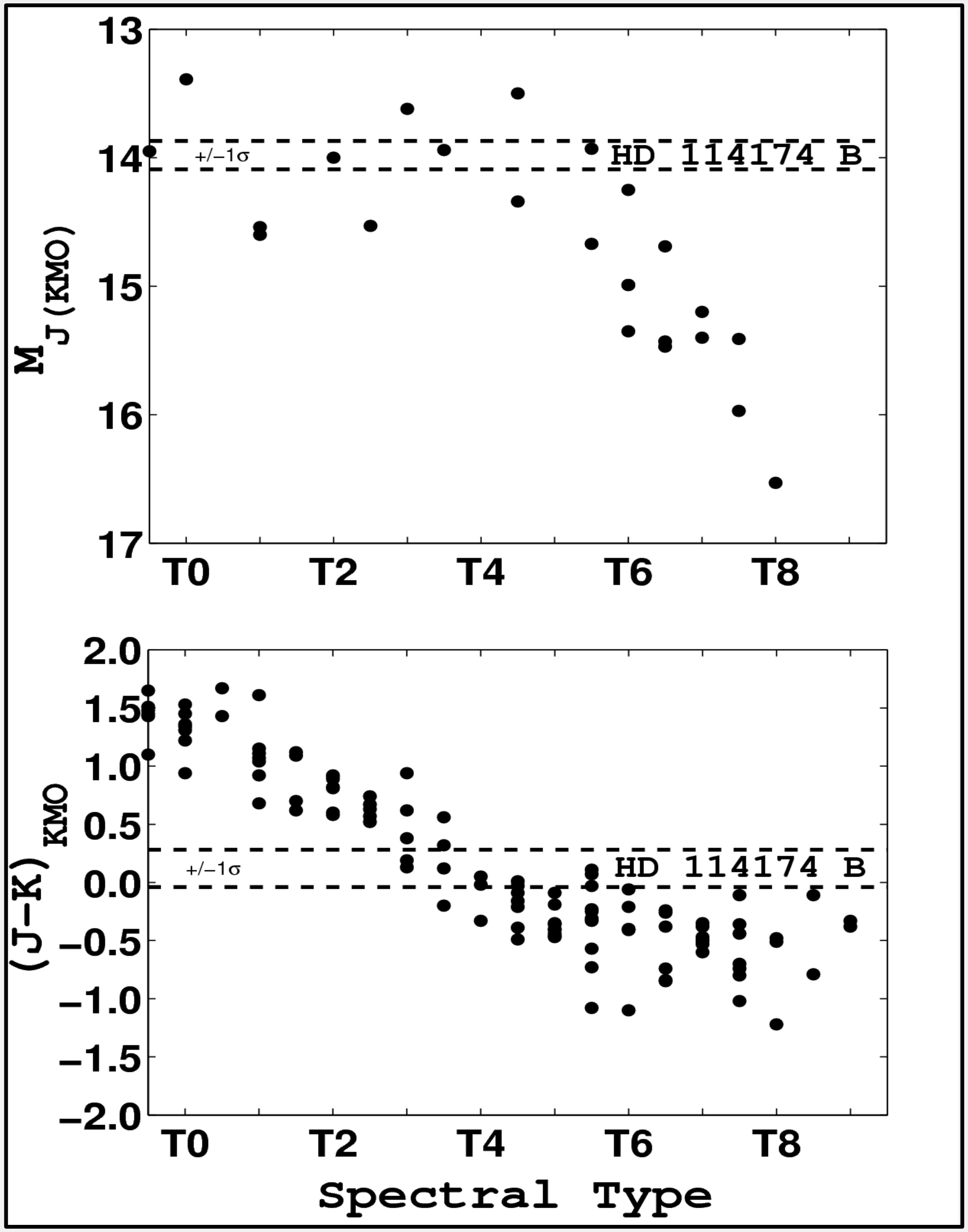
HD 114174

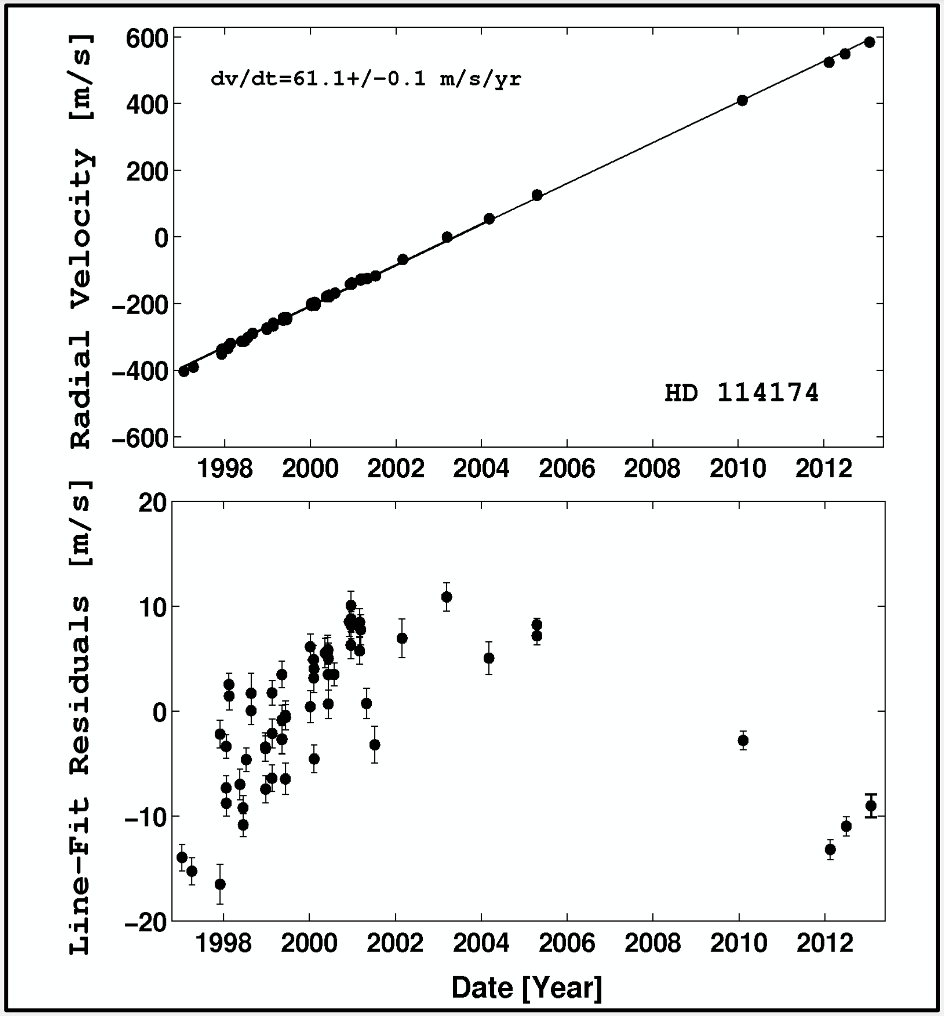
Crepp et al. 2013b, ApJ

NIRC2, K′
February 2, 2012

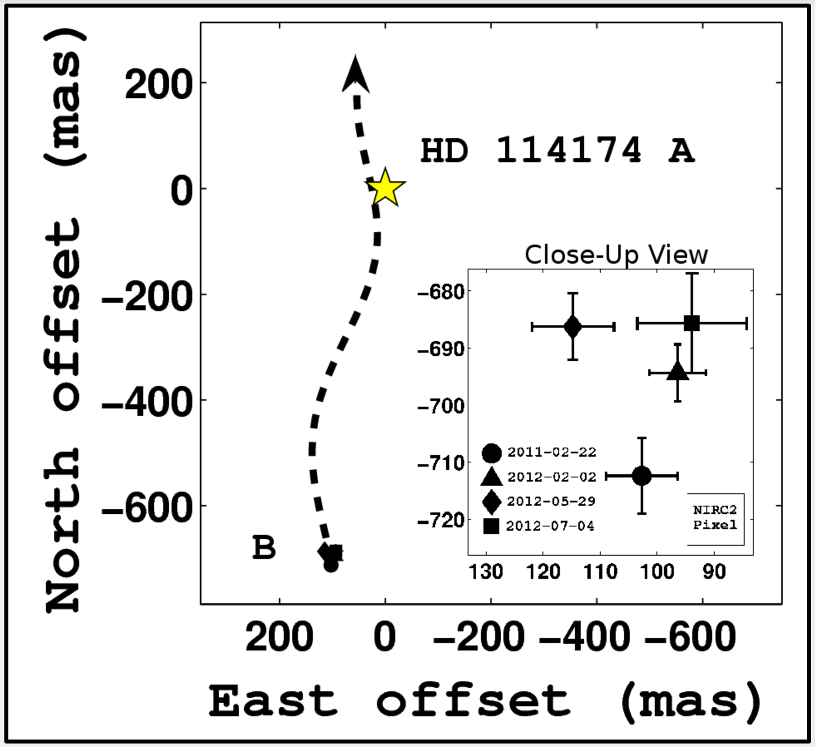


Host Star	
Mass [$M_\odot$]	1.05 ± 0.05
Radius [$R_\odot$]	1.06
Luminosity [$L_\odot$]	1.13
Age [Gyr]	$4.7^{+2.3}_{-2.6}$
[Fe/H]	0.07 ± 0.03
log g [cm s^{-2}]	4.51 ± 0.06
$T_{\rm eff}$ [K]	5781 ± 44
Spectral Type	G5 IV
v sini [km/s]	1.8 ± 0.5
Companion[a]	
ΔJ	10.48 ± 0.11
ΔK	10.75 ± 0.12





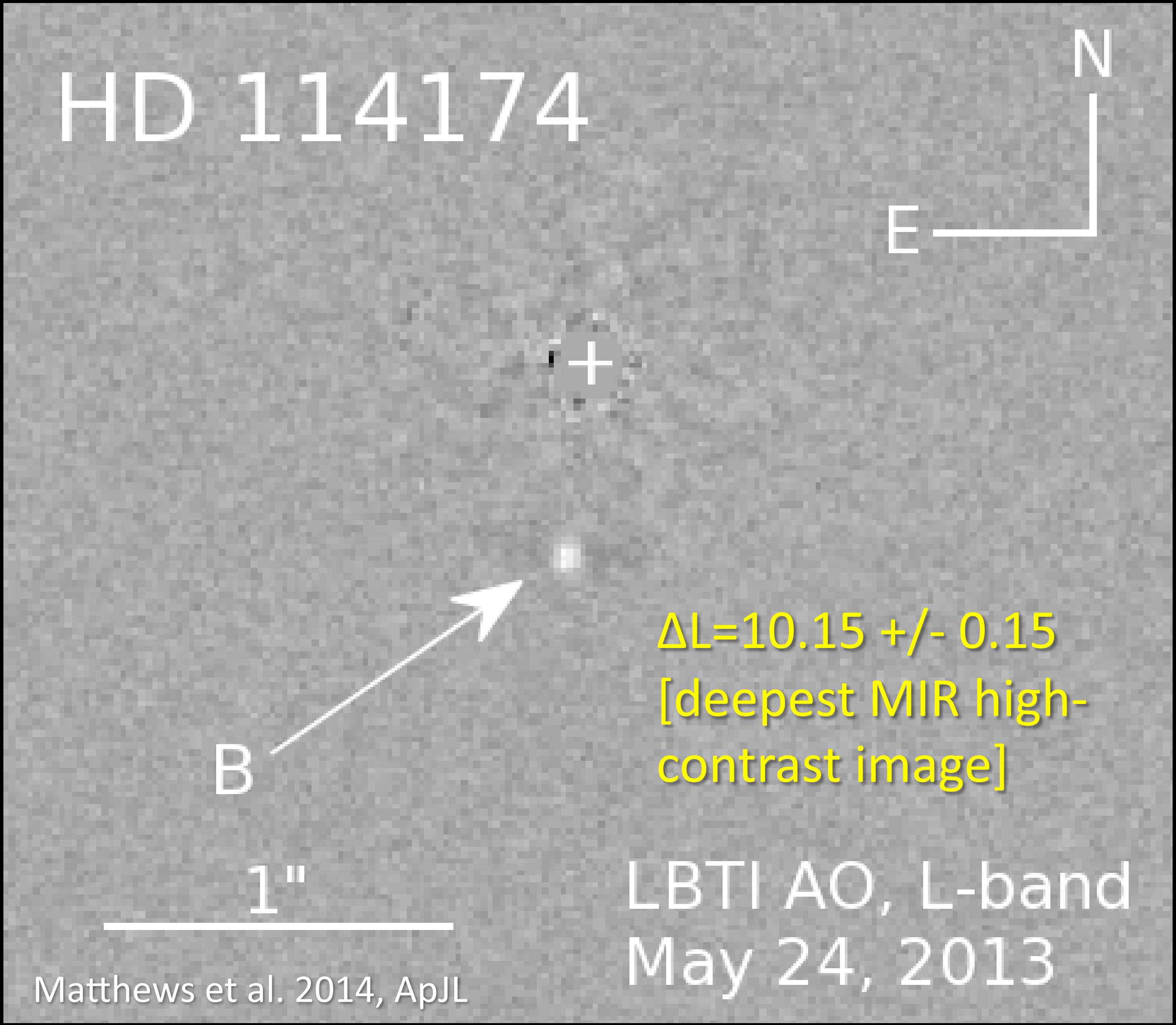
Doppler Measurements



Astrometry Measurements

White Dwarf(!)

m > 0.260+/-0.010Msun



HD 114174

ΔL=10.15 +/- 0.15 [deepest MIR high-contrast image]

LBTI AO, L-band
May 24, 2013

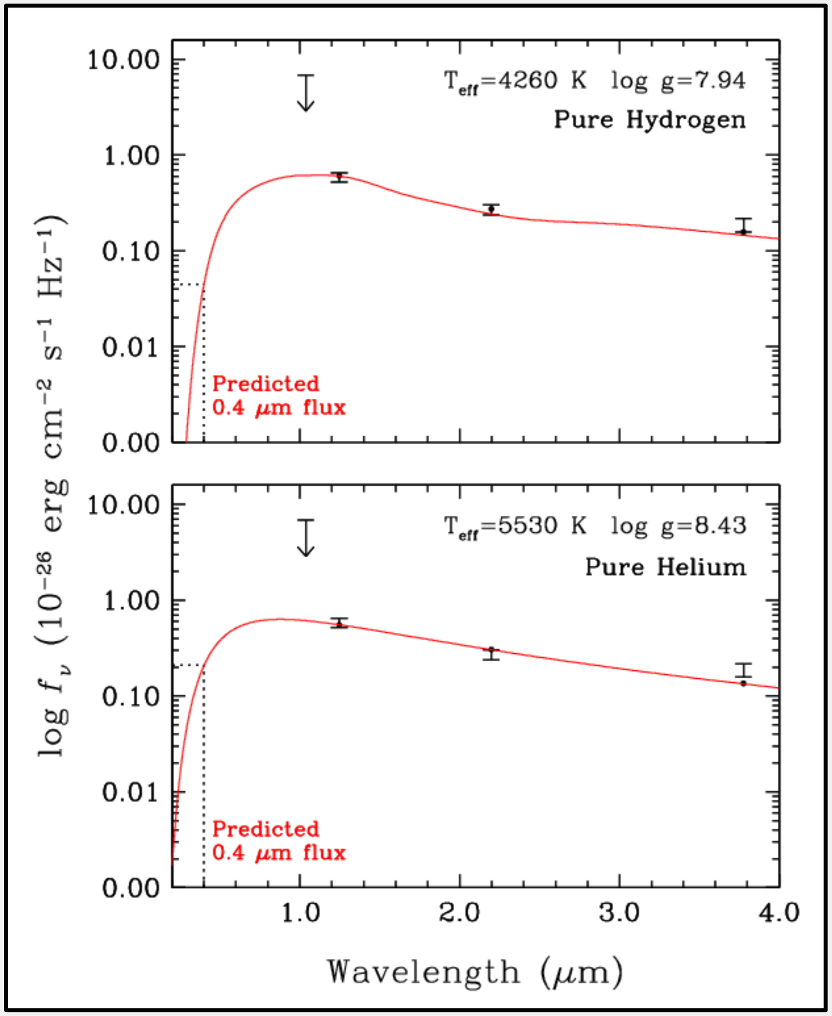
Matthews et al. 2014, ApJL

HD 114174 B:
An Apparent Age Discrepancy?

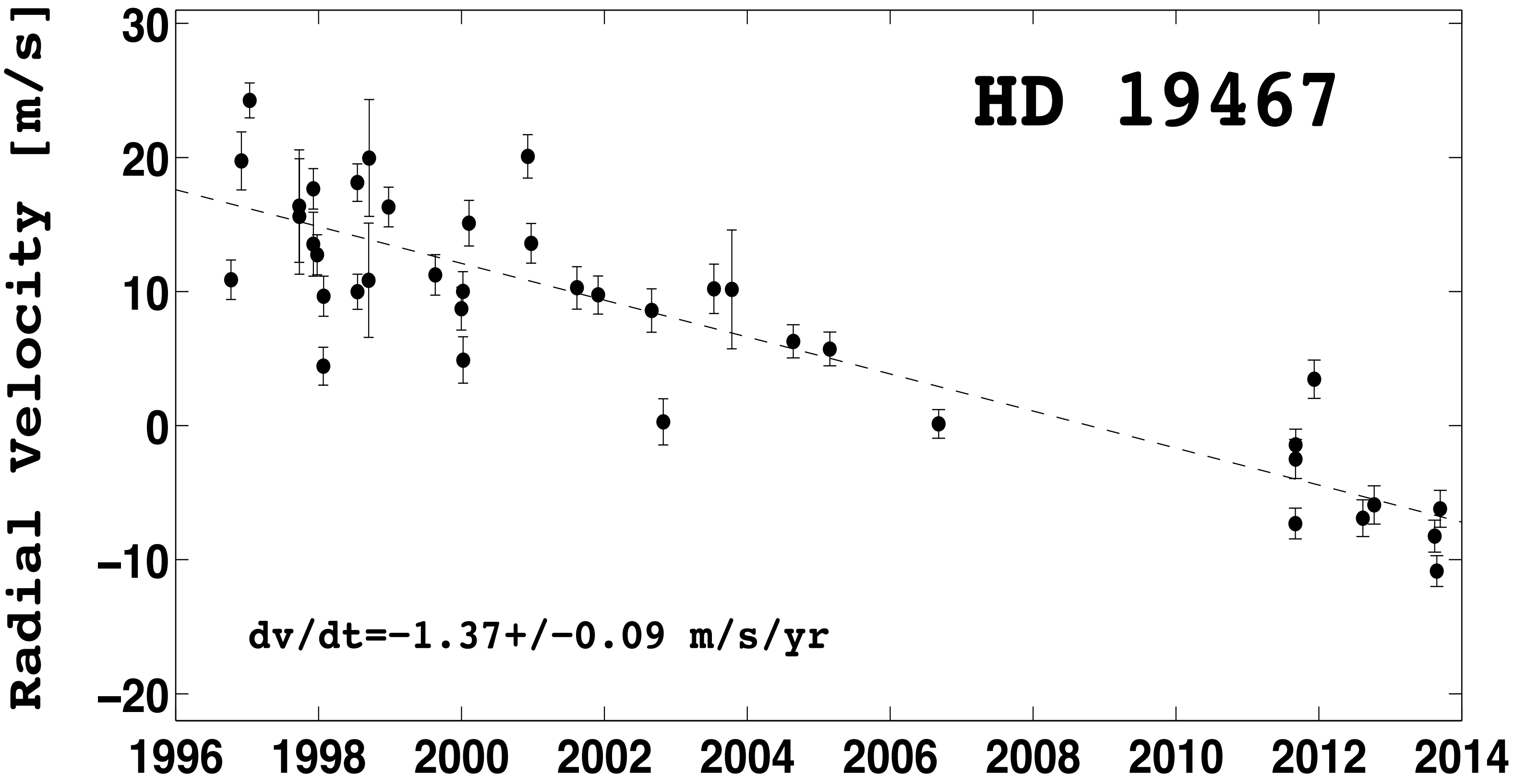
Gyrochronology:
 4.0 +/- 1.0 Gyr
Isochronal:
 4.7 +/- 2.3 Gyr

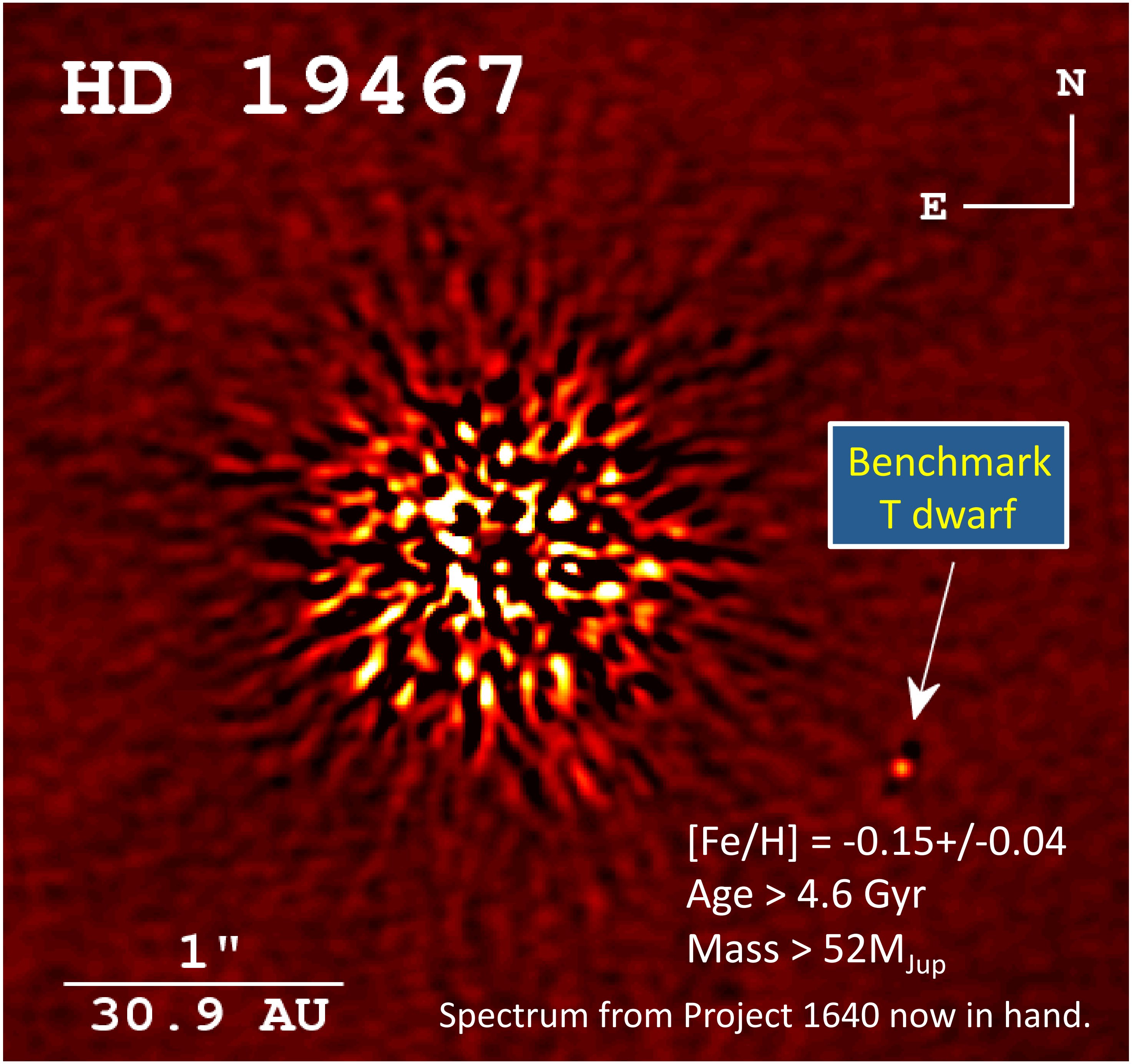
WD Cooling Age:
 7.8 +/- 0.2 Gyr

Matthews et al. 2014, ApJL
Zurlo et al. 2013, AA [HD 8049]



Old and Cold T-Dwarf





Benchmark T dwarf

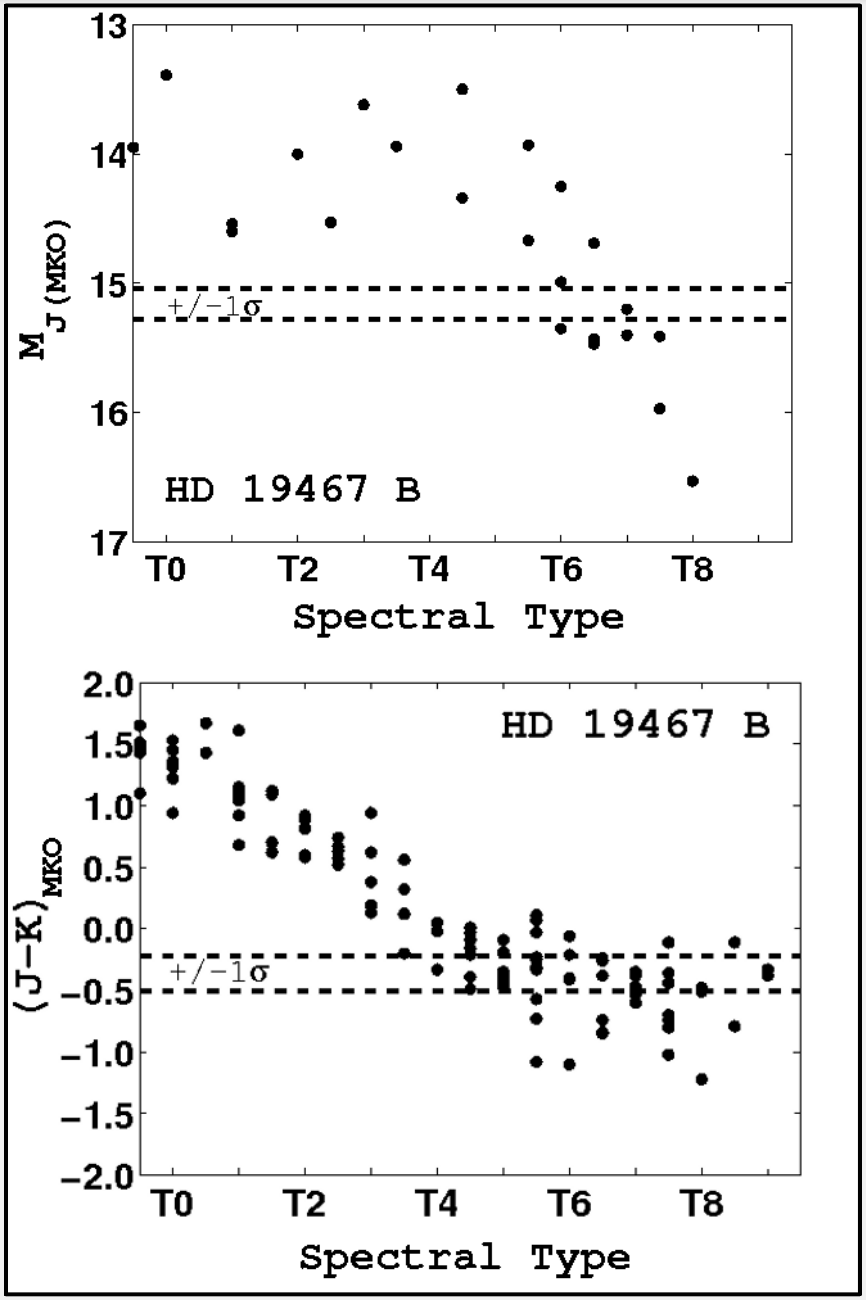
[Fe/H] = -0.15+/-0.04

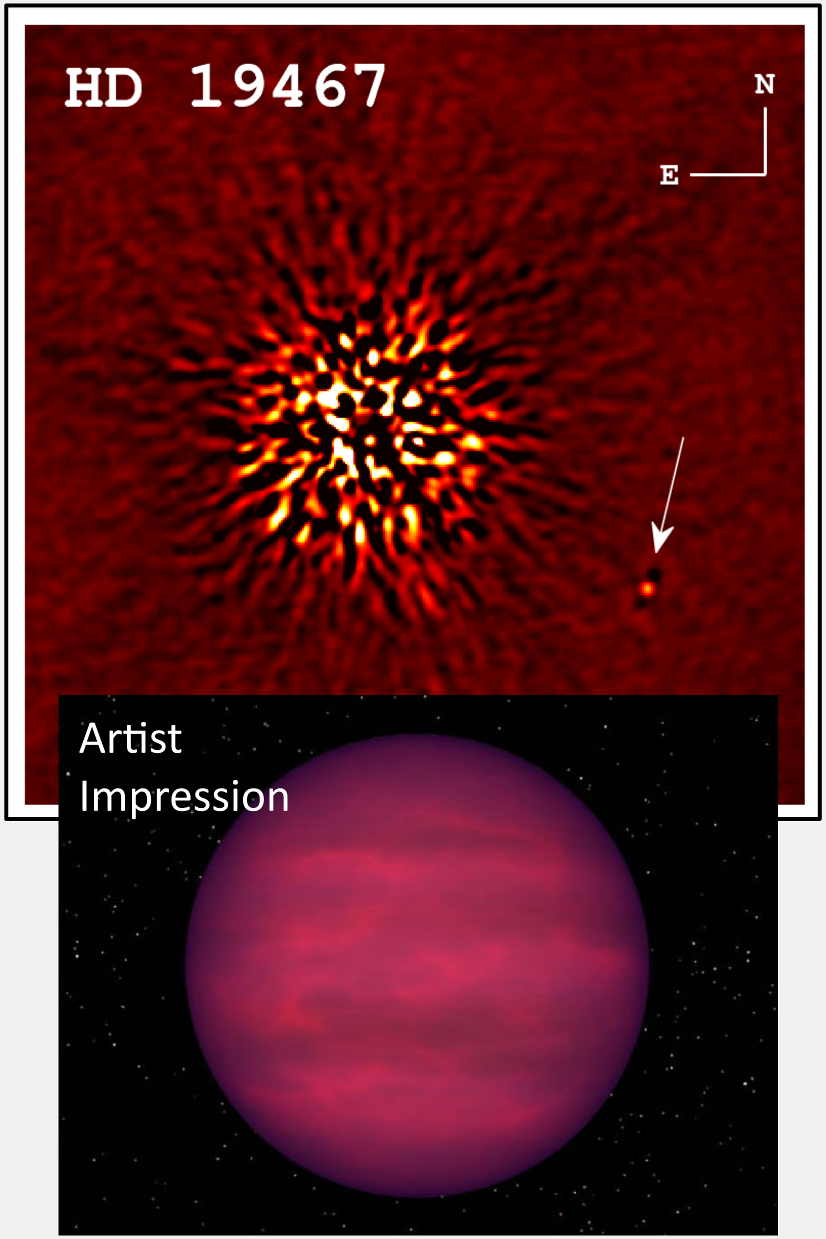
Age > 4.6 Gyr

Mass > $52M_{Jup}$

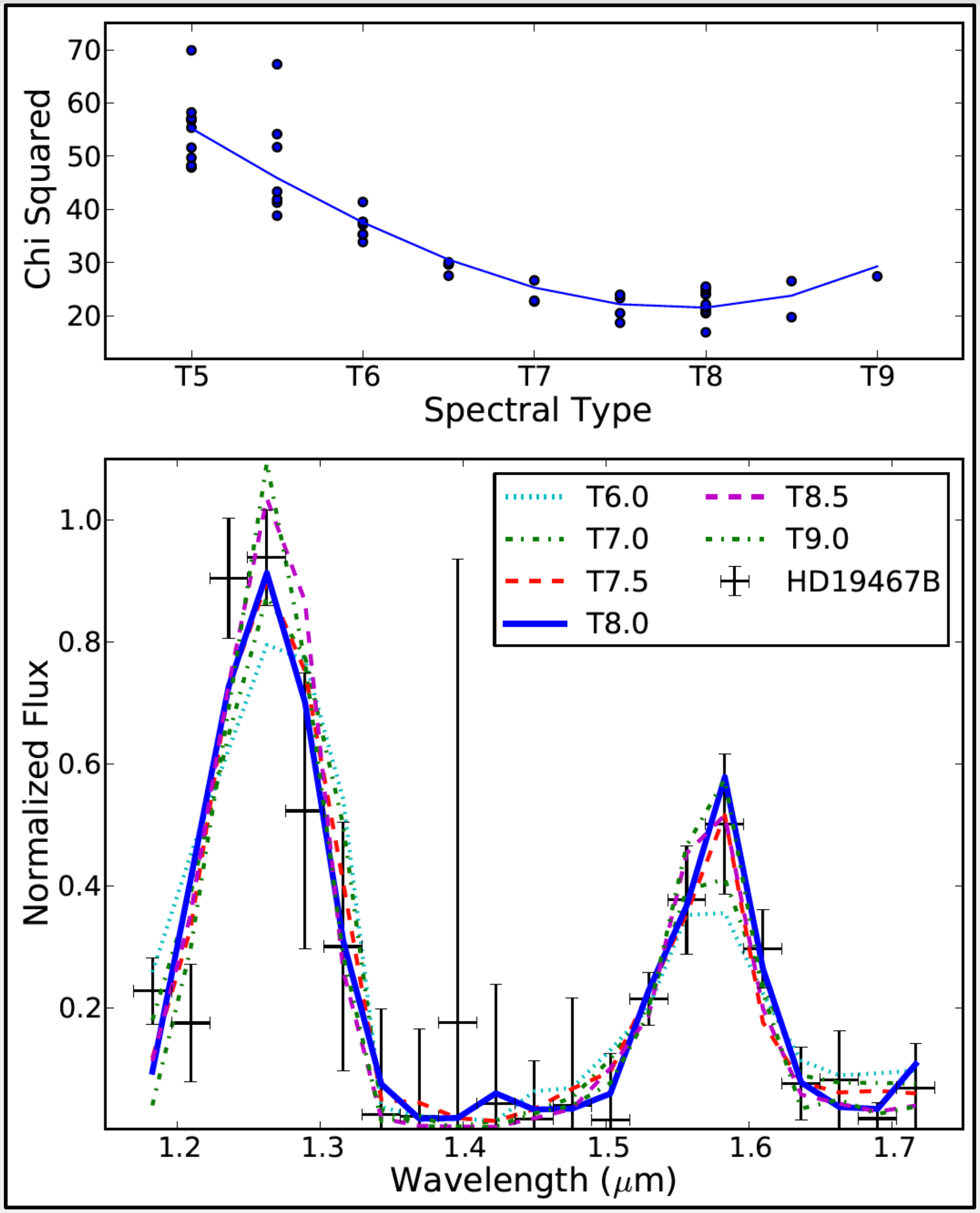
Spectrum from Project 1640 now in hand.

Crepp et al. 2014, ApJ, 781, 29

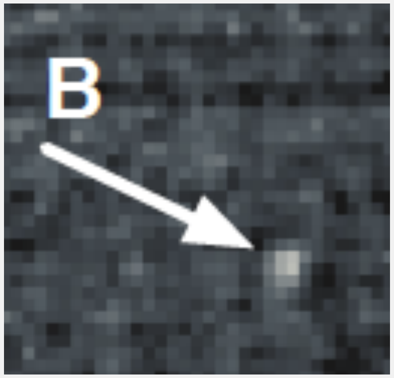

13
14
15
16
17
$M_{J\,(MKO)}$
+/−1σ
HD 19467 B
T0
T2
T4
T6
T8
Spectral Type
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
$(J-K)_{MKO}$
HD 19467 B
+/−1σ
T0
T2
T4
T6
T8
Spectral Type


HD 19467
N
E
Artist
Impression

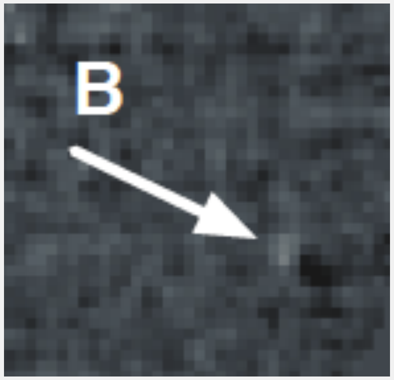
Methane Absorption



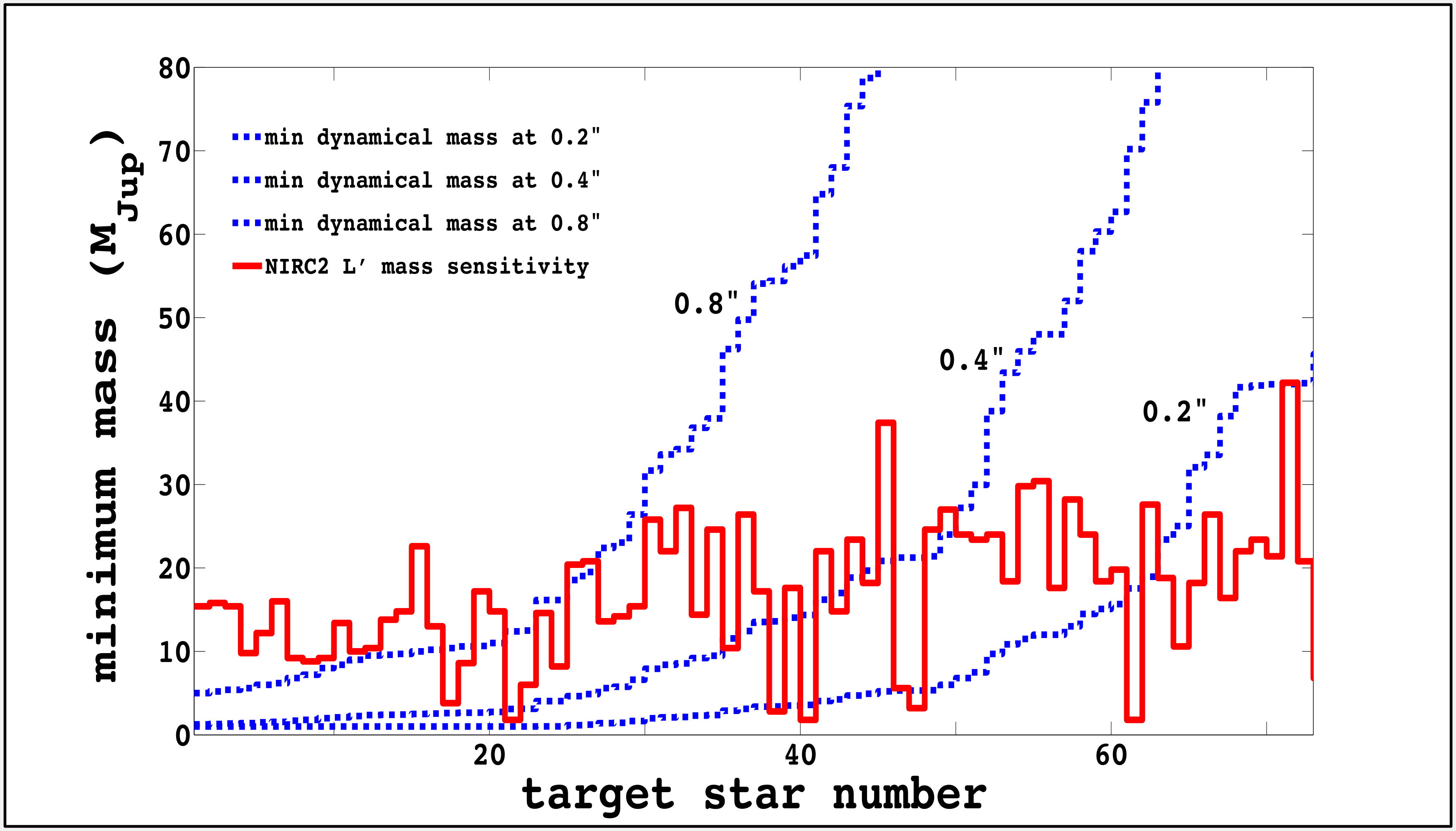
CH_4 Short



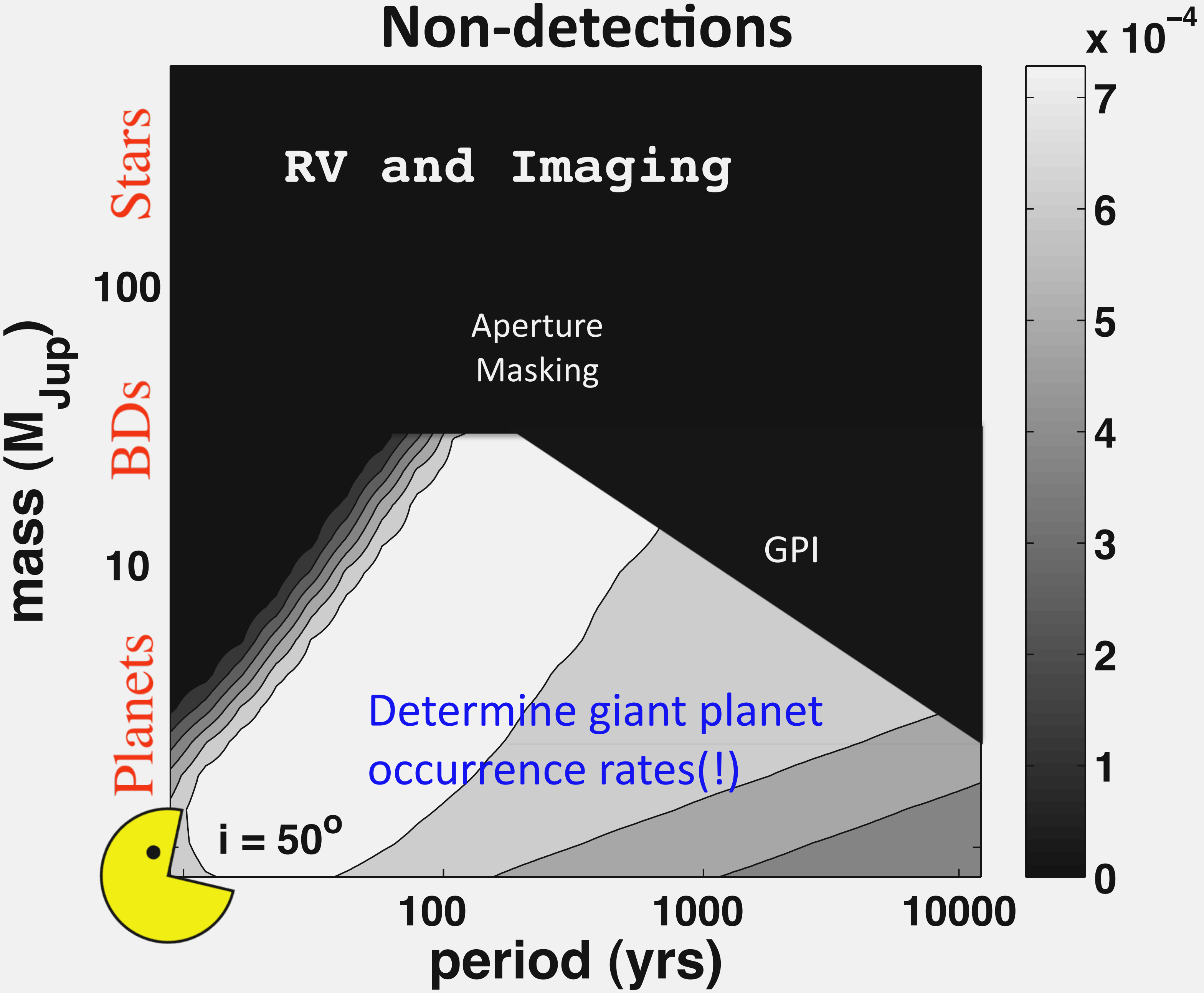
CH_4 Long



Can we detect planets? Yes!

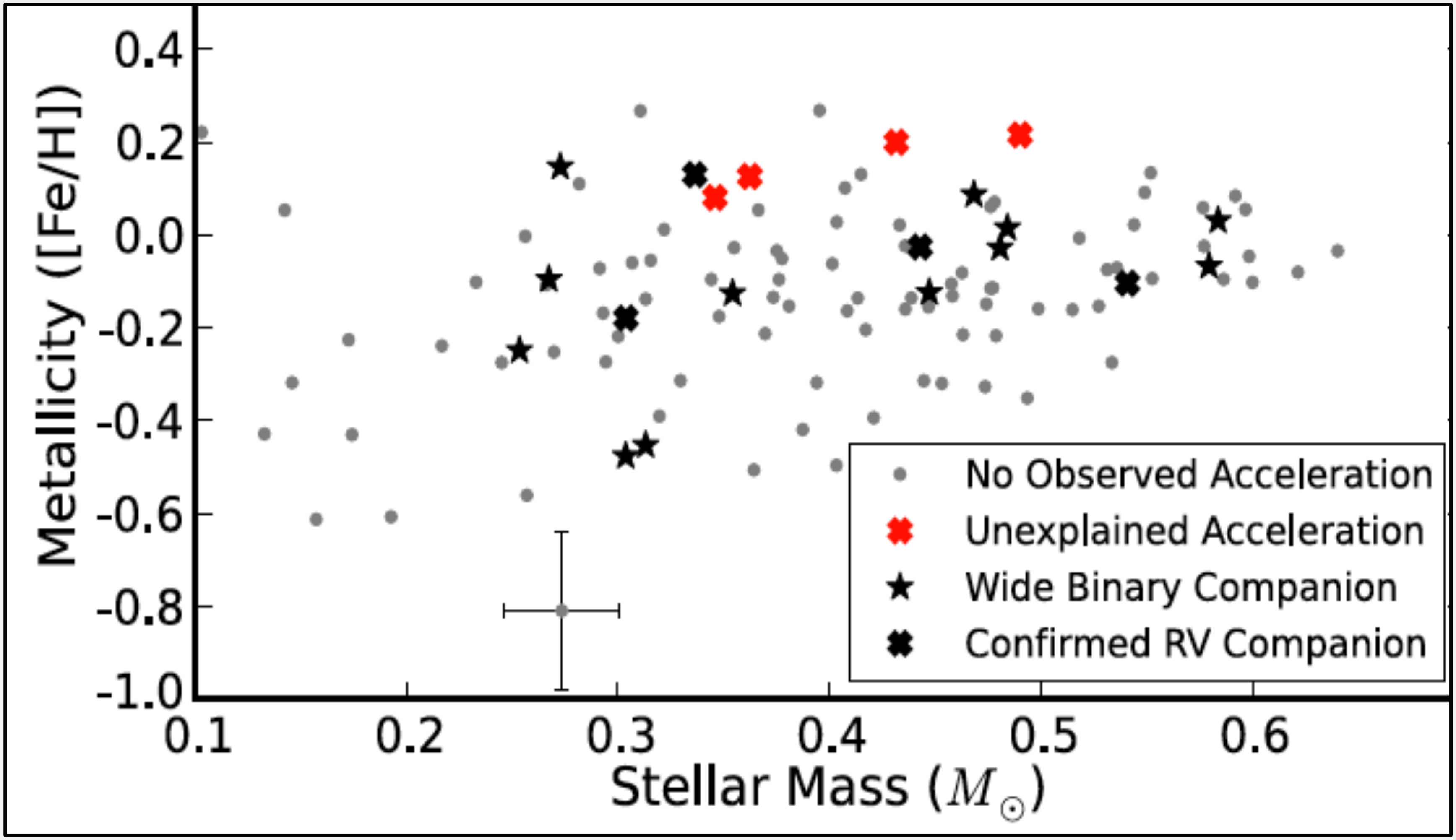


Non-detections



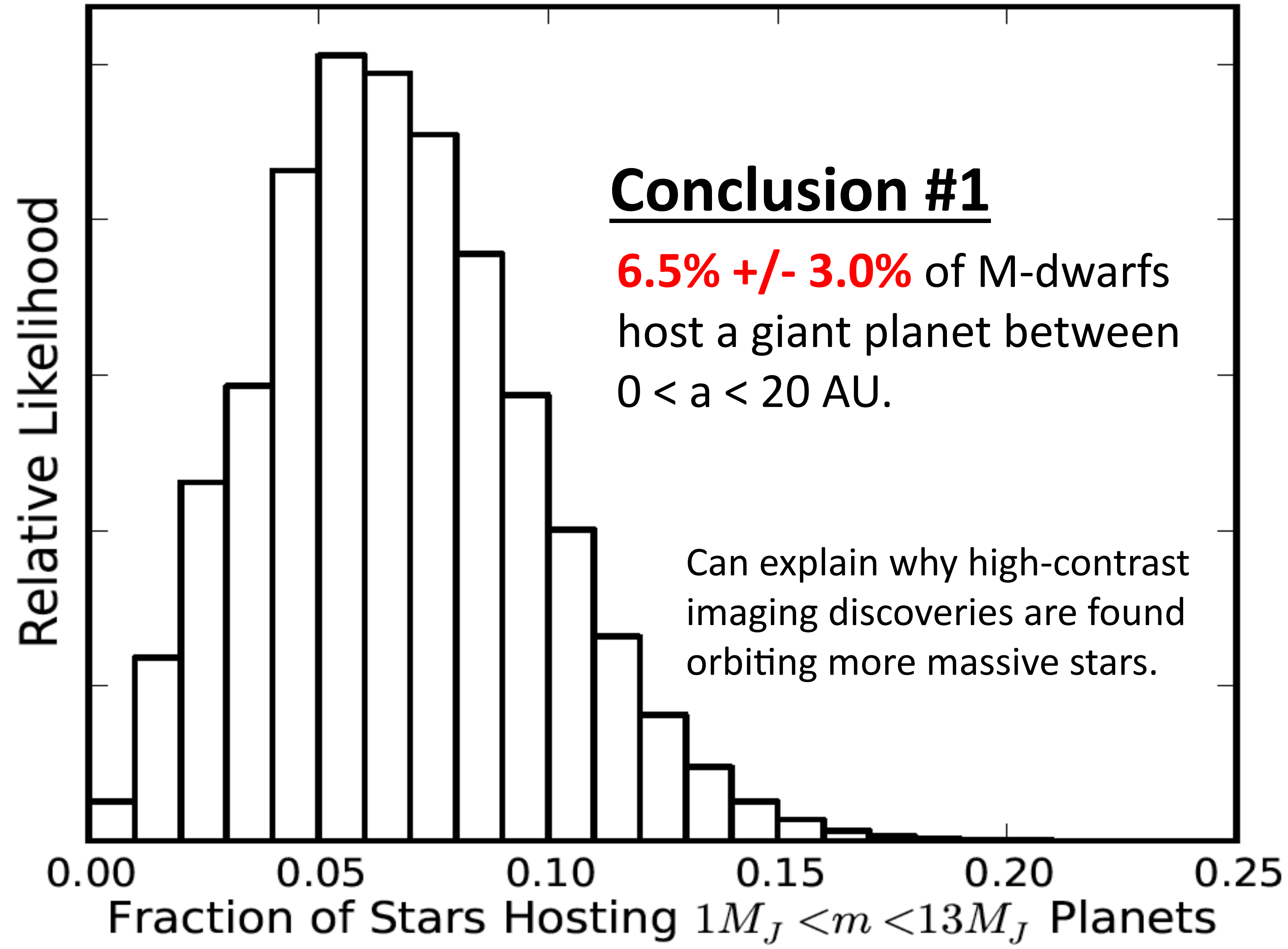
Determine giant planet occurrence rates(!)

The Frequency of Giant Planets around M-dwarfs



Montet et al. 2014, ApJ, 781, 28

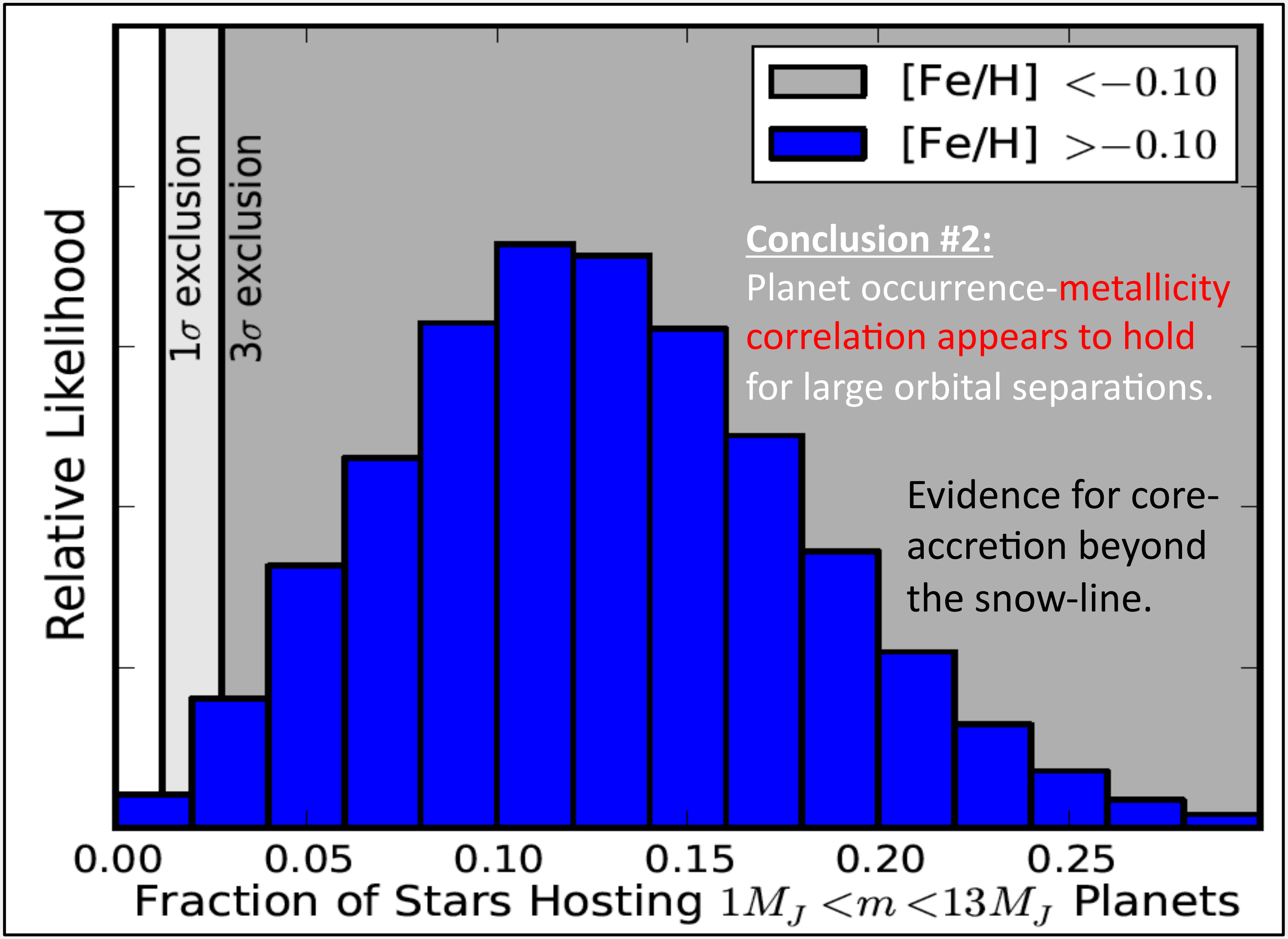
11.8 year time baseline
29 RV measurements



Conclusion #1

6.5% +/- 3.0% of M-dwarfs host a giant planet between $0 < a < 20$ AU.

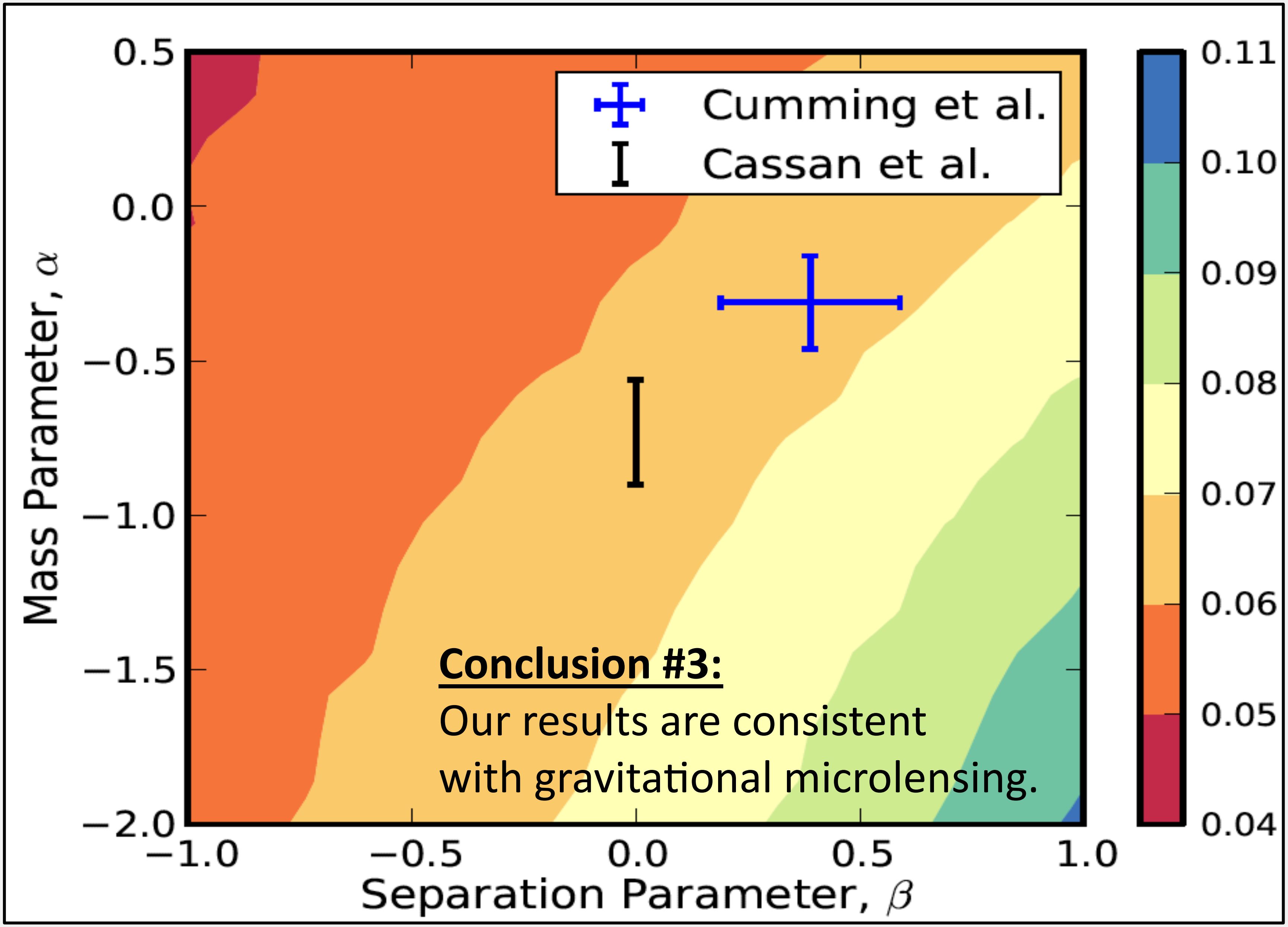
Can explain why high-contrast imaging discoveries are found orbiting more massive stars.



Conclusion #2:

Planet occurrence-metallicity correlation appears to hold for large orbital separations.

Evidence for core-accretion beyond the snow-line.



Conclusion #3:

Our results are consistent with gravitational microlensing.

Summary

- Combined RV+Imaging is more powerful than sum of individual parts.
- TRENDS high-contrast survey:
  - HD 114174 B [WD age discrepancy]
  - HD 19467 B [benchmark T-dwarf]
- *Non*-detections are Important:
  - (i) M-dwarfs have few gas giant planets (6.5%+/-3.0%) from 0-20 AU for 1-13M_{Jup}.
  - (ii) Planet-metallicity correlation holds at wide orbit separations.
  - (iii) First independent check of microlensing results for wide-separation planets.