Discoveries of Young Planets Constrain Theories of Formation and Migration

Russel White - Georgia State University

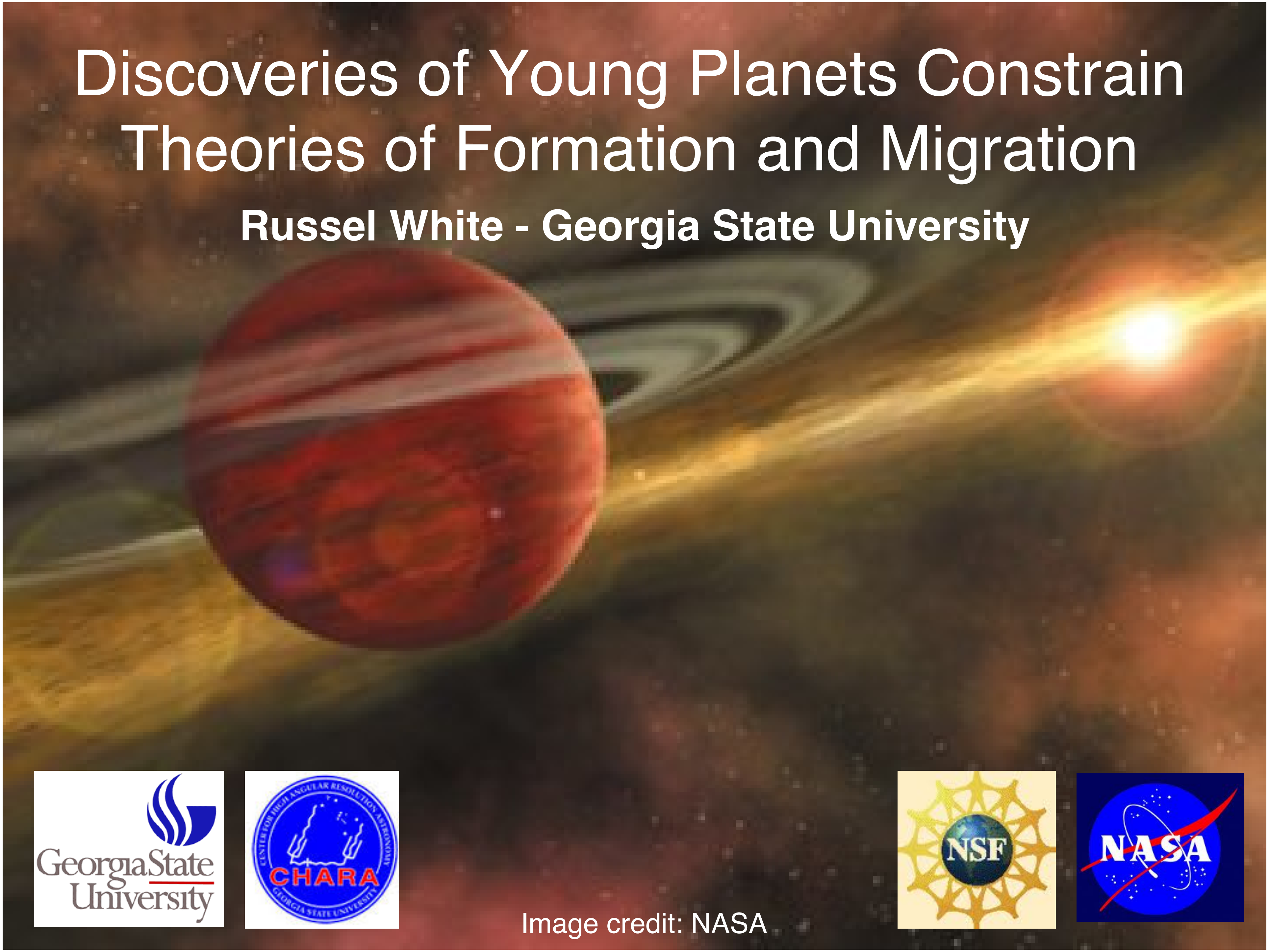
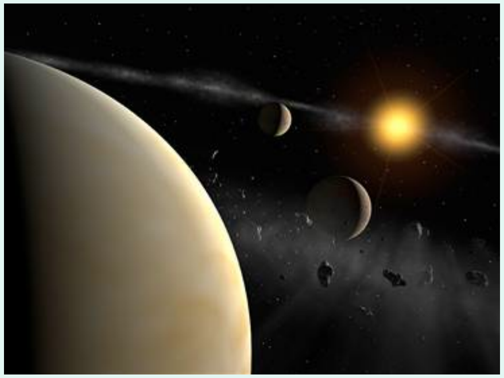


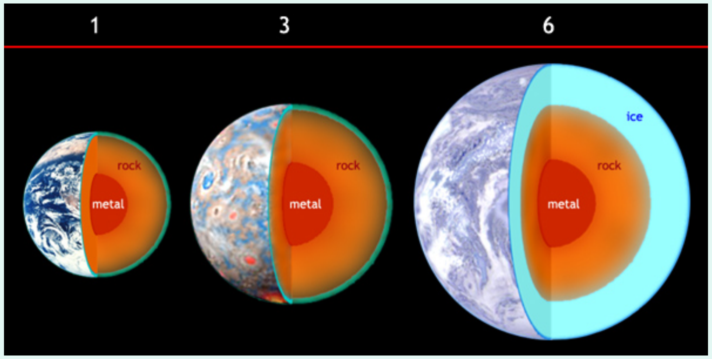
Image credit: NASA

20+ Years of Exoplanet Science…



1892 confirmed exoplanets
4696 candidates (*Kepler*)
~1/3 in multi-planets systems
NASA exoplanet archive

One in five stars has Earth-sized planet in the Habitable zone (*Kepler*)



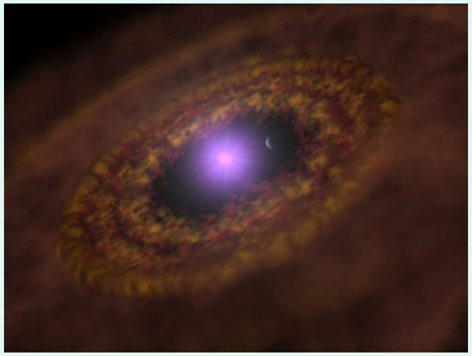
Many short-period gas giant planets
... the hot Jupiters
(1.2 ± 0.4% with $P < 10$ d; $M > 0.5\ M_{Jupiter}$)
(Wright et al. 2012)

How Do Gas Giant Planets Form?

HST image of a young star in Orion

(1) Initiated by core accretion?

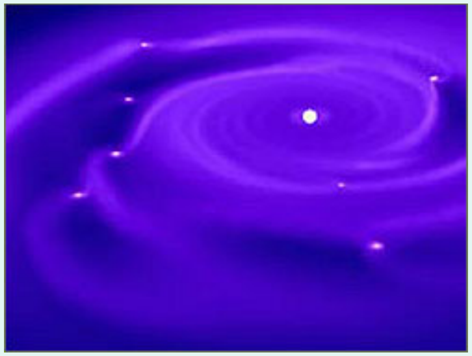
slow (few Myr) assembly



e.g. Mizuno 1980; Pollack et al. 1996

(2) Gravitational Instabilities?

quick (< 1 Myr) collapse; hotter, larger planets



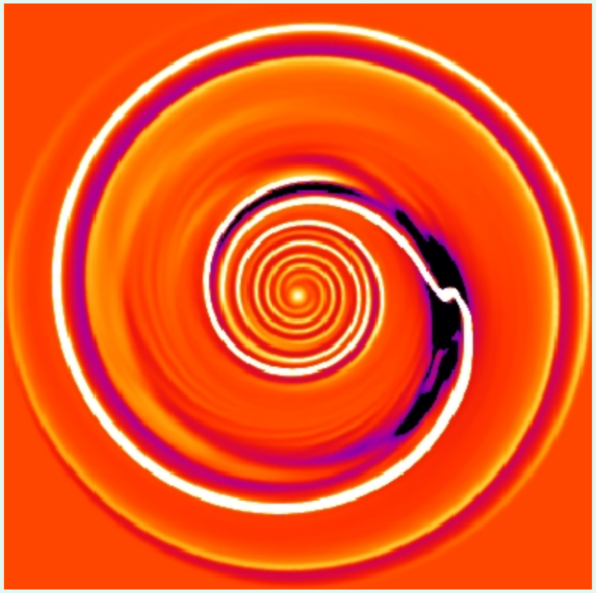
e.g. Mayer et al. 2002; Boss 2003

Marley et al. 2007; Fortney et al. 2008

Some Must Migrate Inward. How?

(1) planet - disk?

likely damp eccentricities;
occurs within 10 Myr
(e.g. Goldreich & Tremaine 1980)

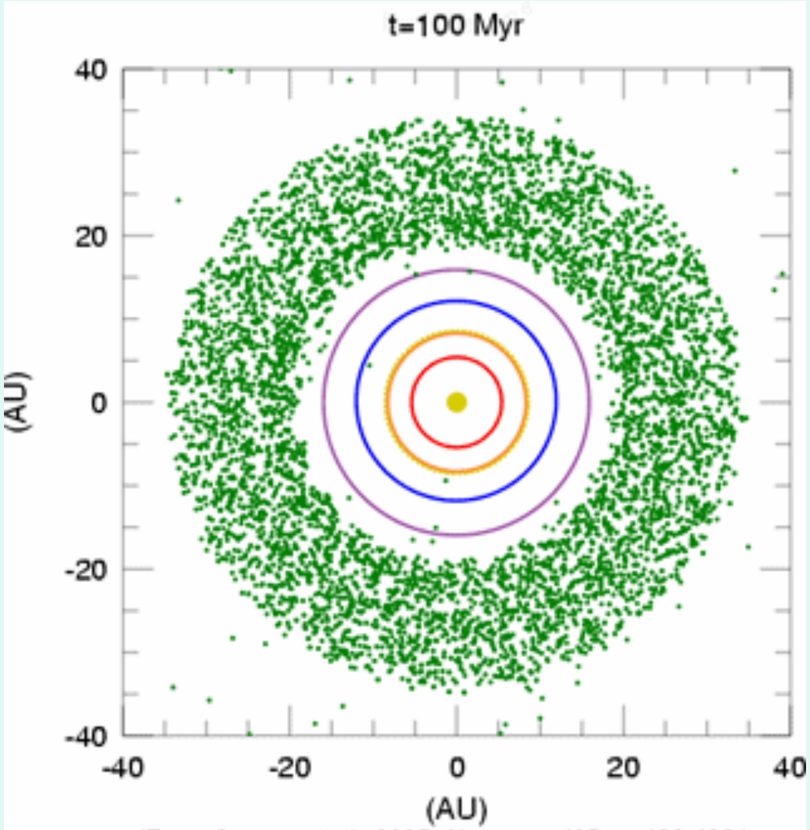


P. Artymowicz

Dynamical may be erased by tidal circularization (> 1 Gyr).

(2) planet – planet, Kozai

likely excite eccentricities;
may take 100s Myr years
(see Winn & Fabrycky 2015)



(From Gomes, *et al.*, 2005, *Nature*, v. 435, p. 466-469.)

Need to Find Young Planets

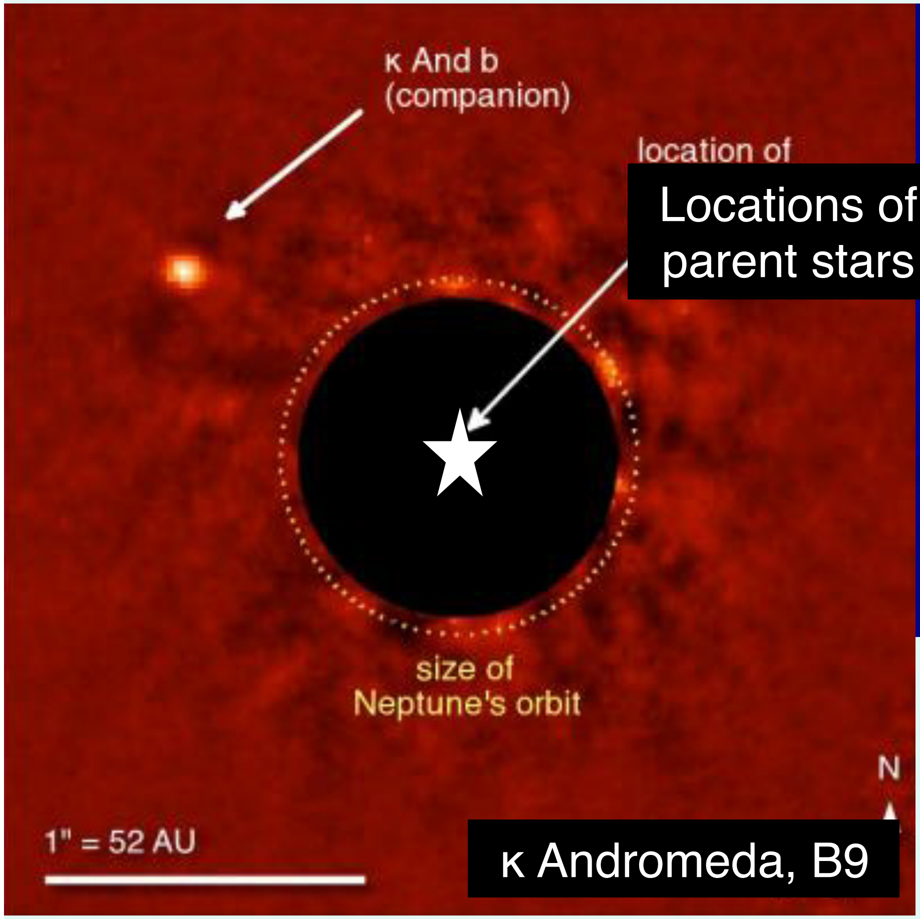
Requires looking around
young stars

Age would constrain
formation, migration timescale
(resolve mass/age ambiguity)

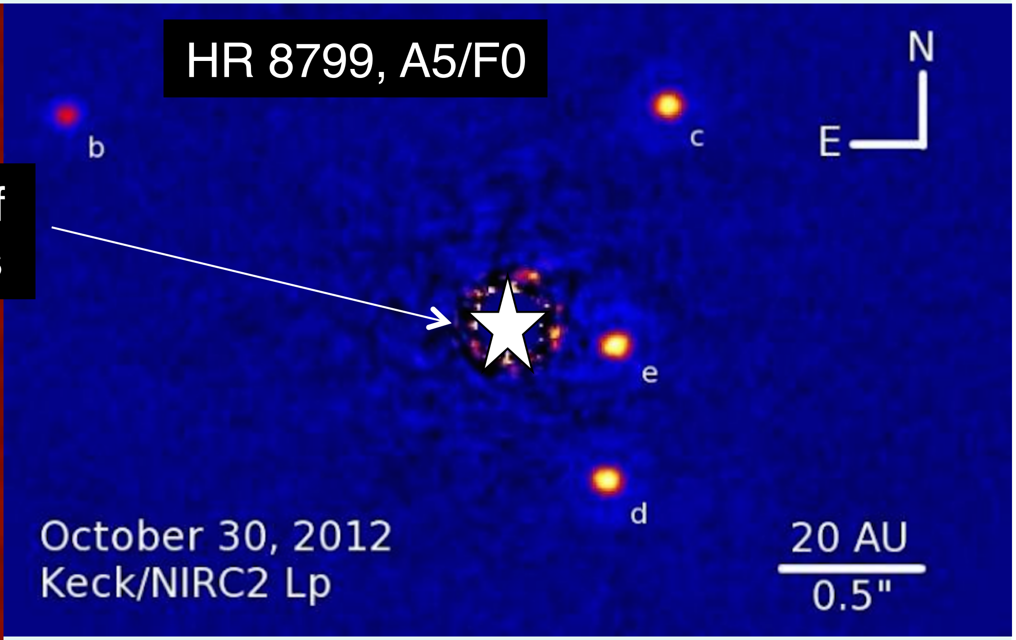
Eccentricities would
constrain migration process

Image credit: NASA

Nearby directly imaged *young planets* … maybe



e.g. Carson et al. (2012)



Marois et al. (2008, 2012)

What's a planet?

IAU Definition

1. Orbits the Sun
2. Round
3. Cleared its orbital path

Pluto is a dwarf planet

Astronomer's Convention

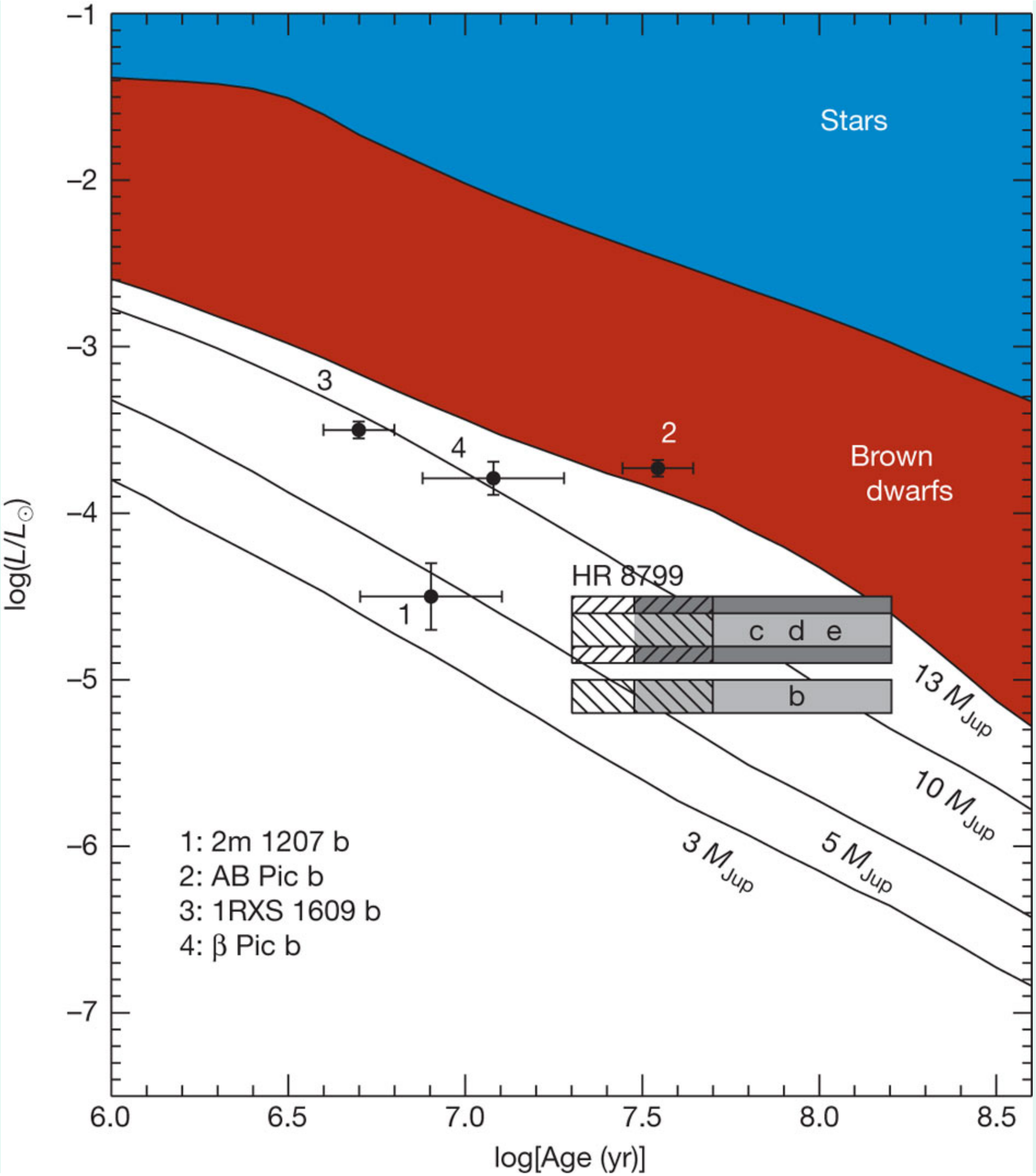
1. A low mass object that orbits a star (or brown dwarf) and …

- OR -

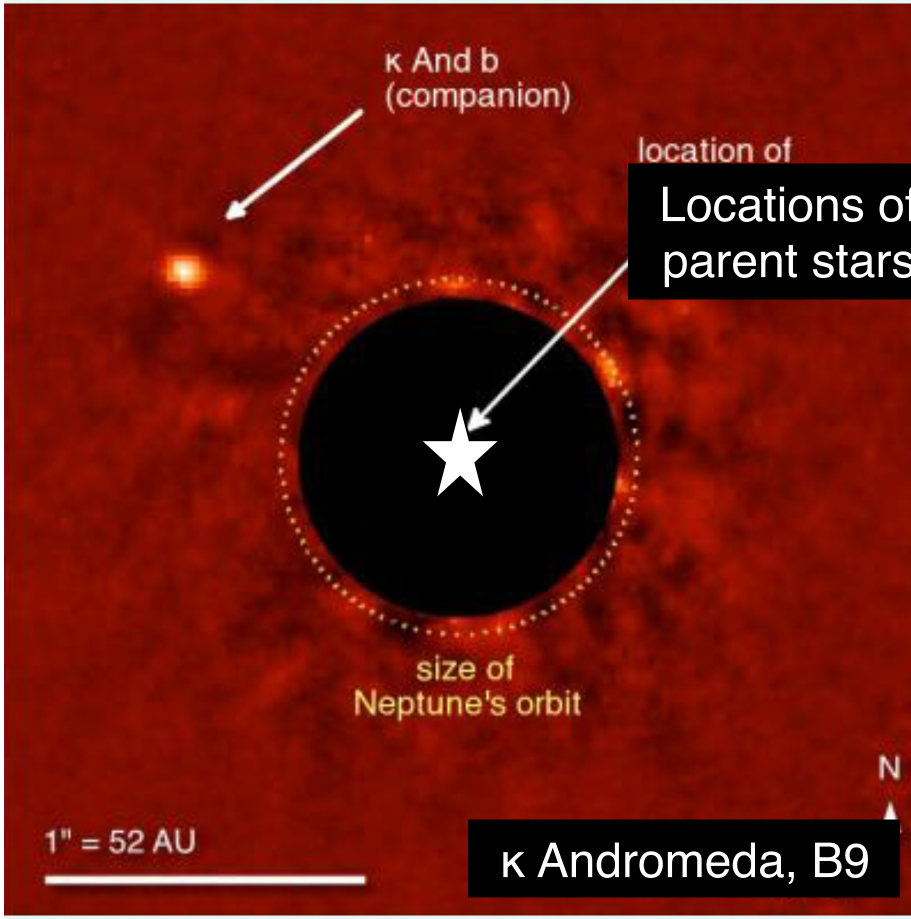
Formed out of a disk around that star

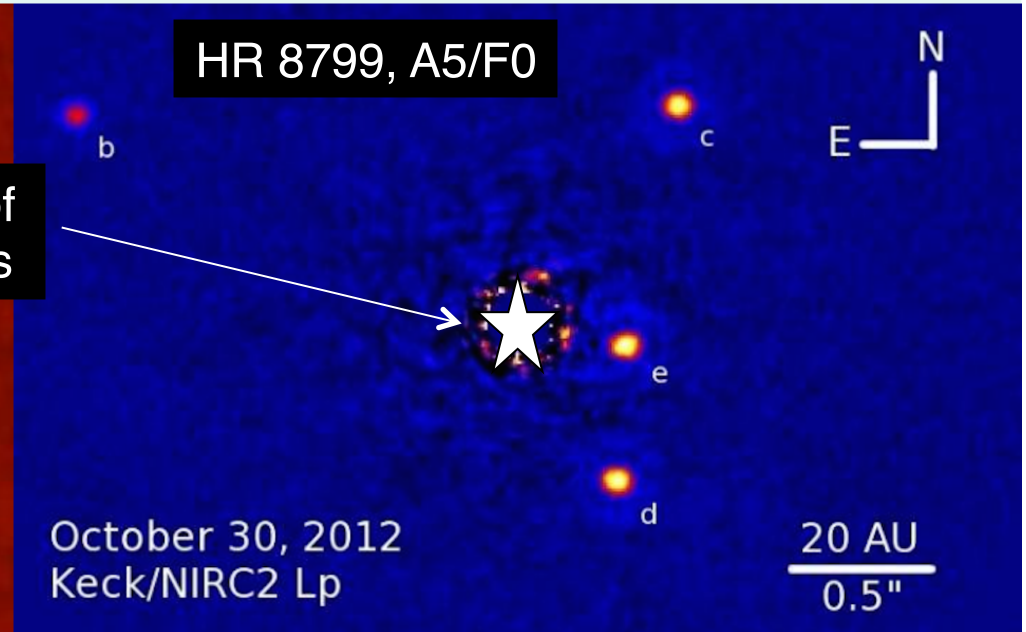
Has a mass less than ~13 M_{Jup} (doesn't fuse ^2H)

Masses for directly imaged planets come from model comparisons *at an assumed age*



Nearby directly imaged *young planets* … maybe





(e.g. Carson et al. 2012)

κ Andromeda: companions are planets if system is younger than ~35 Myr

Marois et al. 2008, 2010)

HR 8799: companions are planets if younger than 100 Myr

Other *intermediate mass star* planet hosts include β Pic, Fomalhaut, HD 95086

List of directly imaged "Planets"

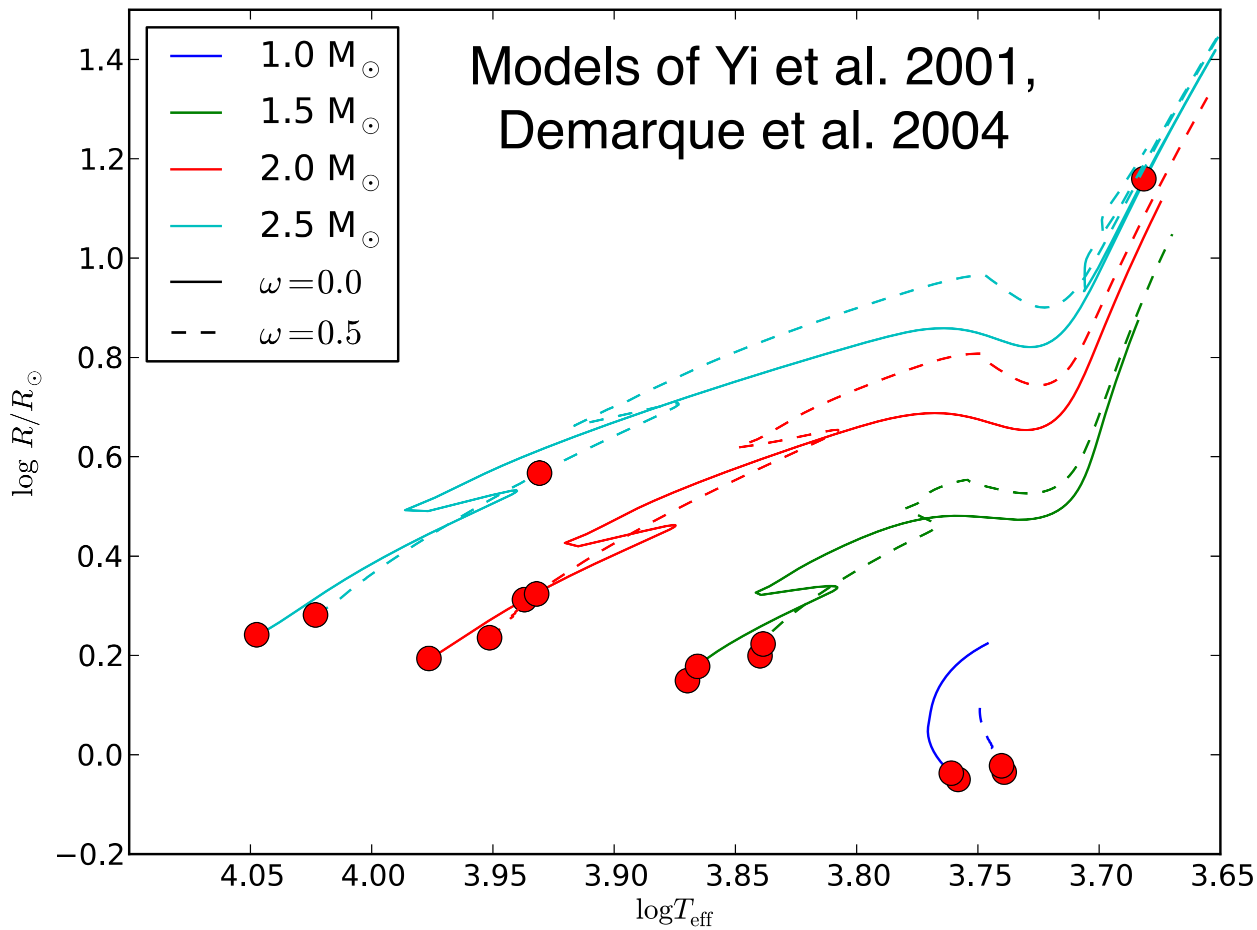
Planets masses are based on the predictions of evolutionary models, ***assuming an age***

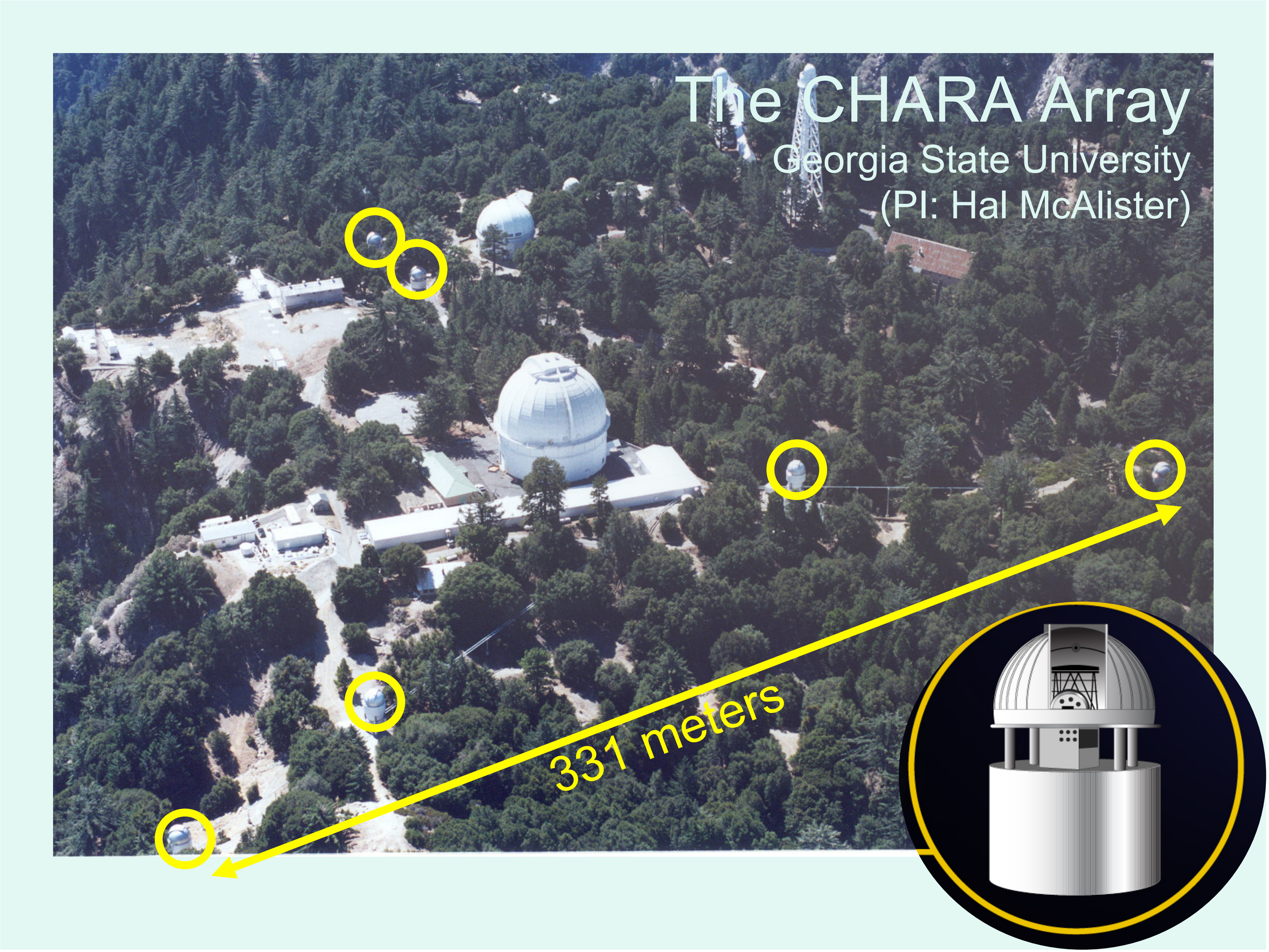
Star	SpT	Planet	D (pc)	Year
Kappa And	B9	b	52	2012
Fomalhaut	A3	b	7.6	2008
Beta Pic	A6	b	19.4	2008
HD95086	A8	b	90	2013
HR 8799	A5/F0	bcde	39	2008
GJ 504	G0	b	18	2013
LkCa 15	K5	b	145	2011
1RXS 1609	K7	b	145	2008
ROXs 42B	M0	b	135	2014
Ross 458 AB	M0.5/M7	b	11.4	2011
FW Tau AB	M5	b	145	2014
2M1207	M8	b	53	2004

Nearby
"A type" stars
10s – 100s Myr

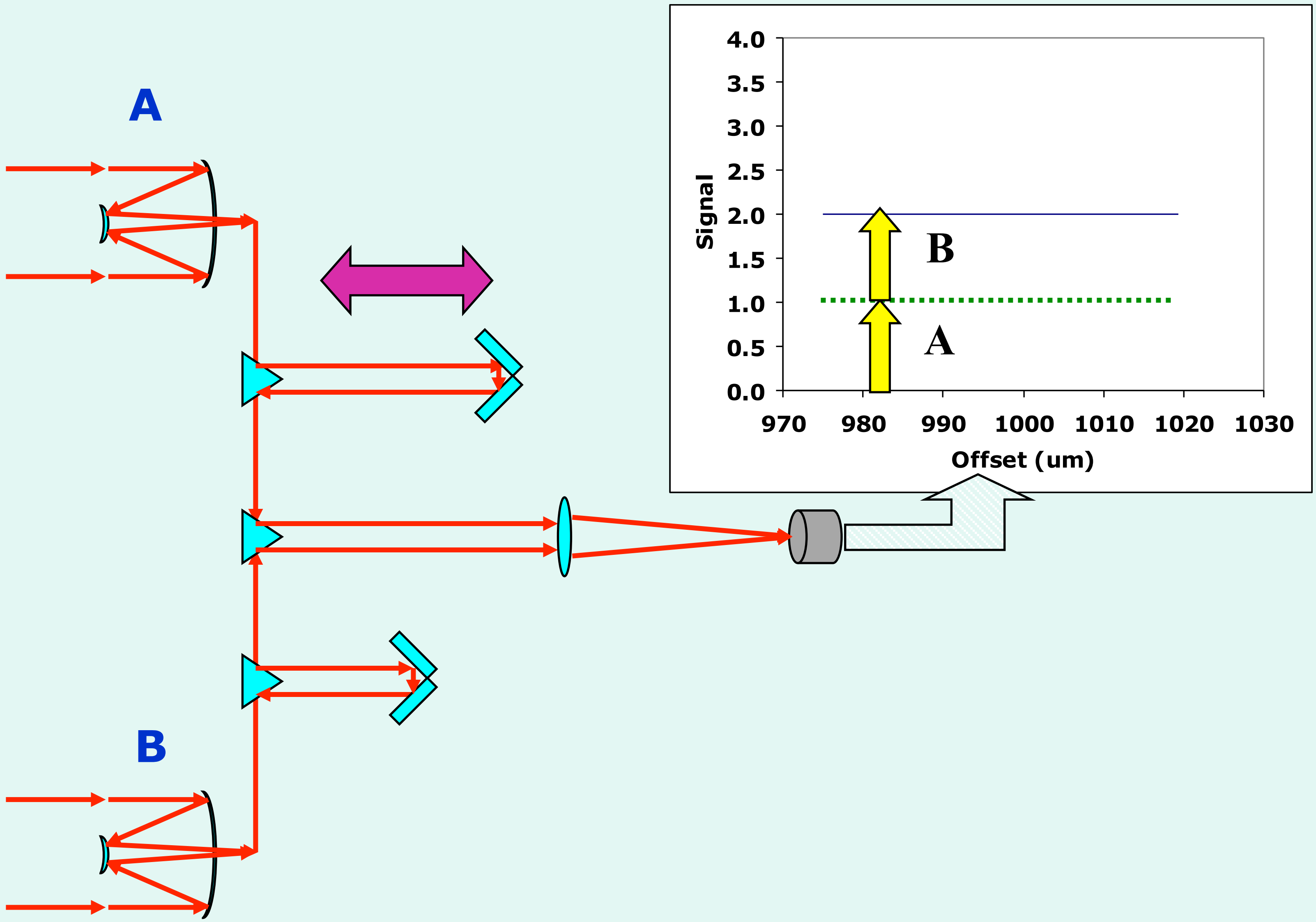
More Distant
T Tauri stars

<u>*Intermediate mass stars*</u> swell as they age. Size measurements could allow more accurate model comparisons.

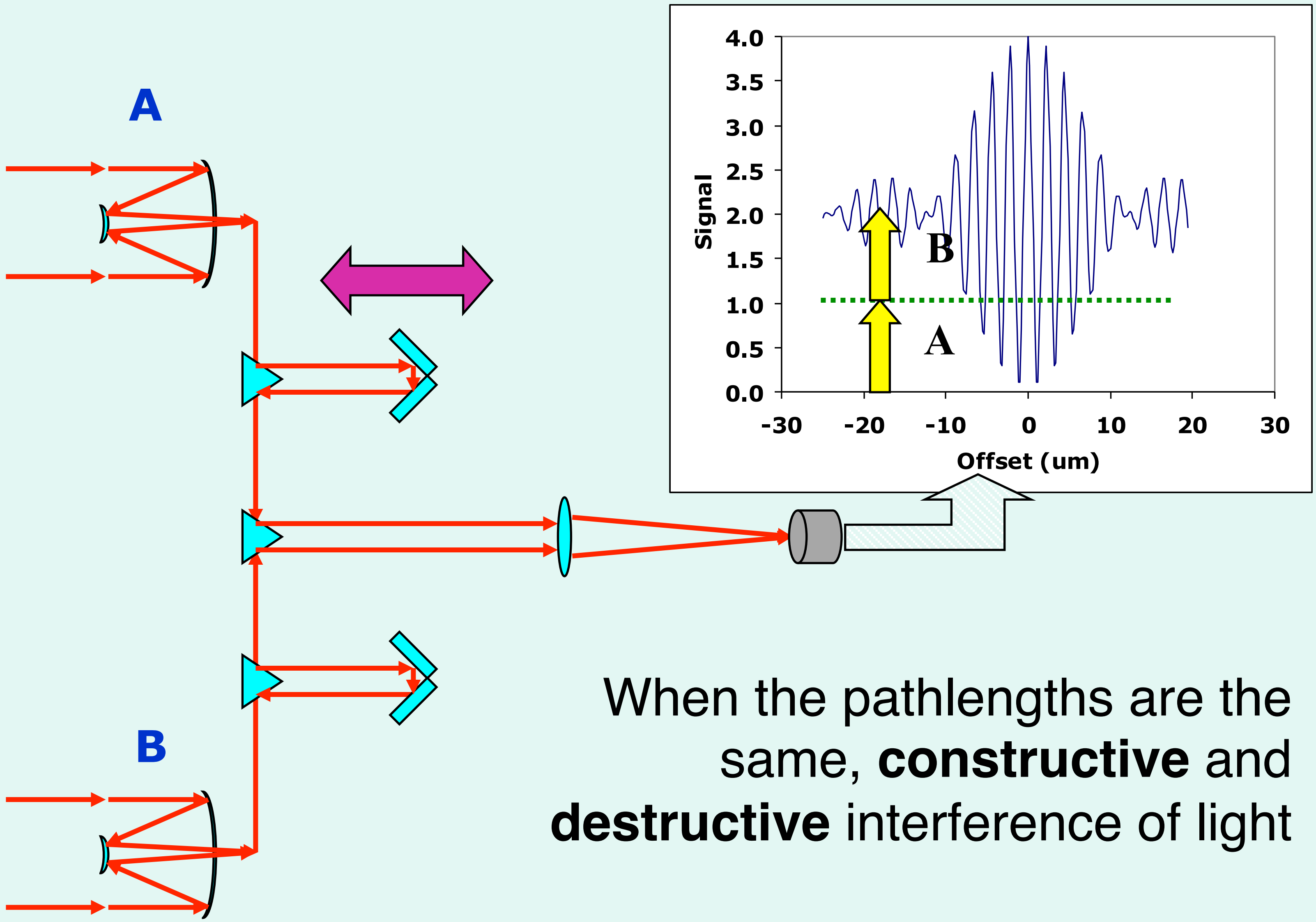



The CHARA Array
Georgia State University
(PI: Hal McAlister)
331 meters

What does an interferometer ‘see’ ?

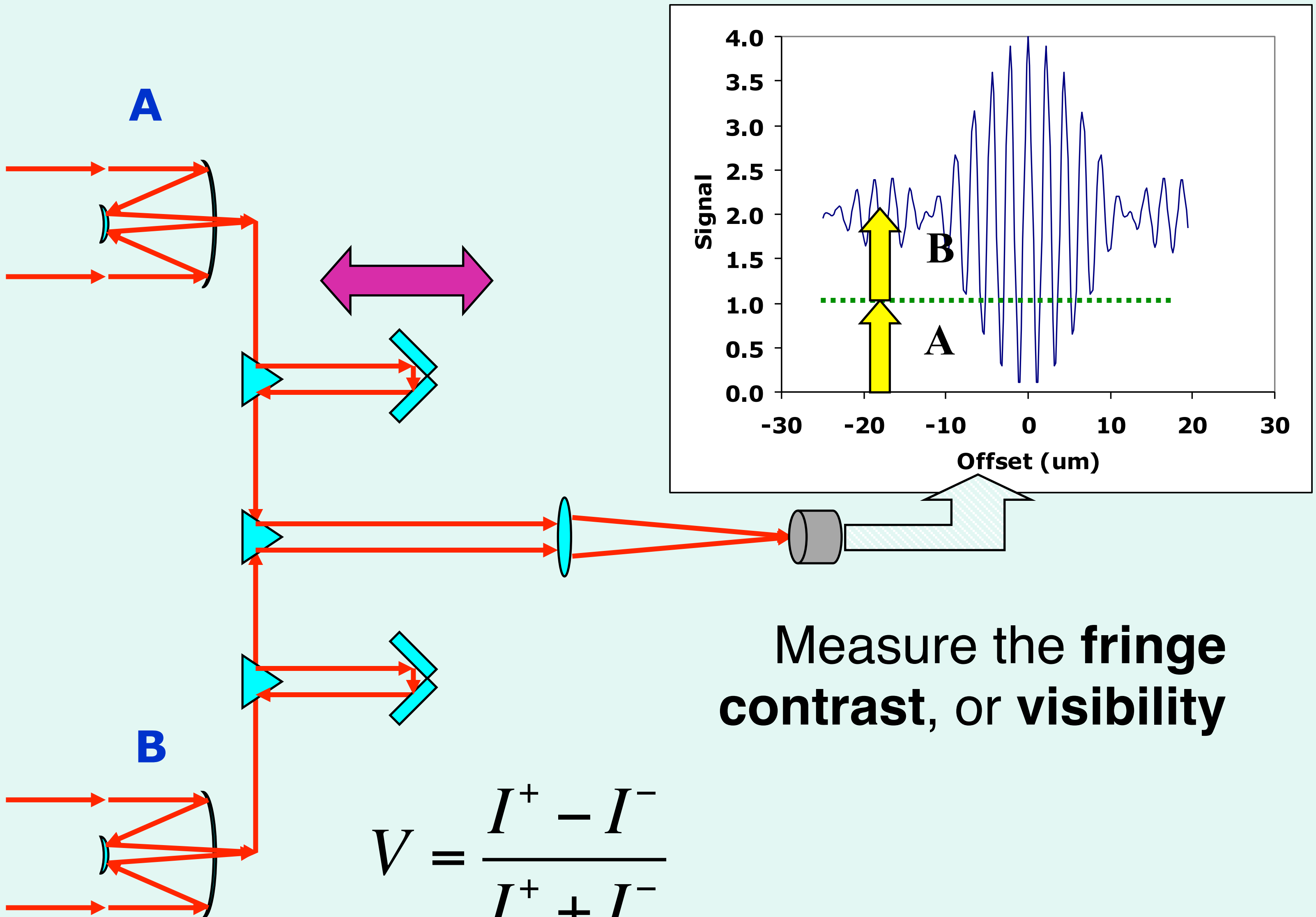


What does an interferometer 'see' ?



When the pathlengths are the same, **constructive** and **destructive** interference of light

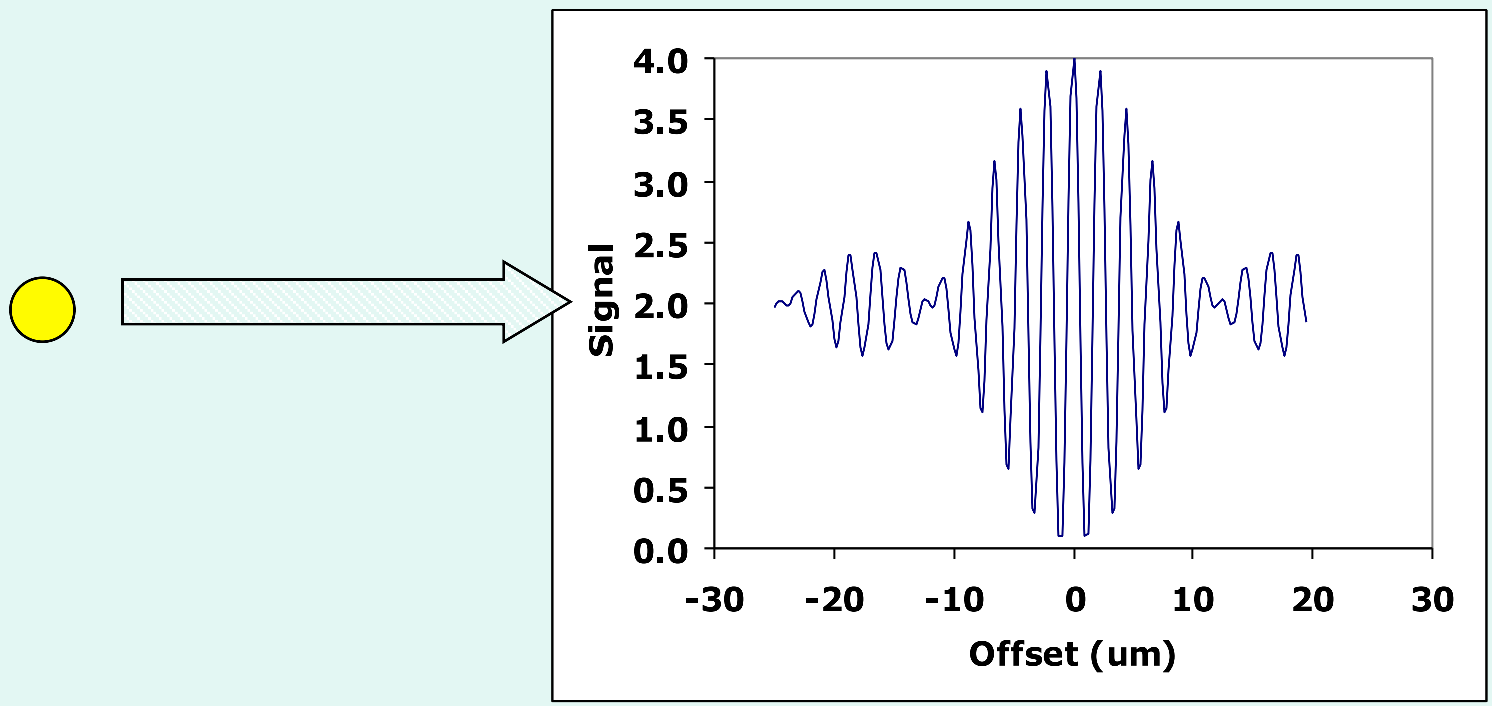
What does an interferometer ‘see’ ?



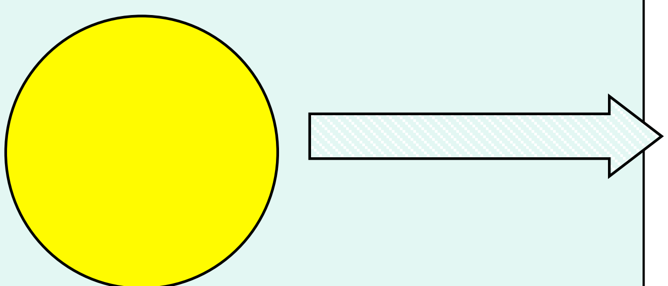
Measure the **fringe contrast**, or **visibility**

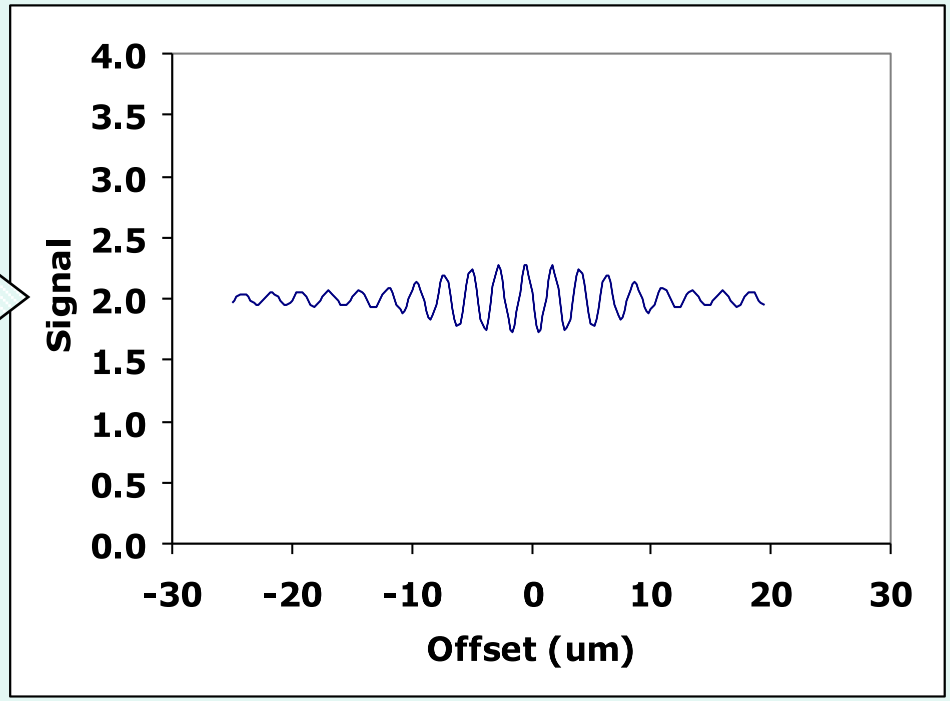
$$V = \frac{I^{+} - I^{-}}{I^{+} + I^{-}}$$

For small stars (θ < 0.25 mas), fringe contrast will be high

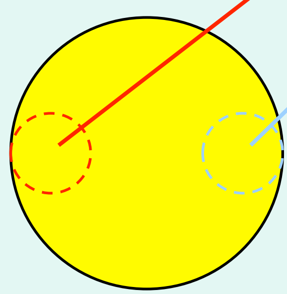


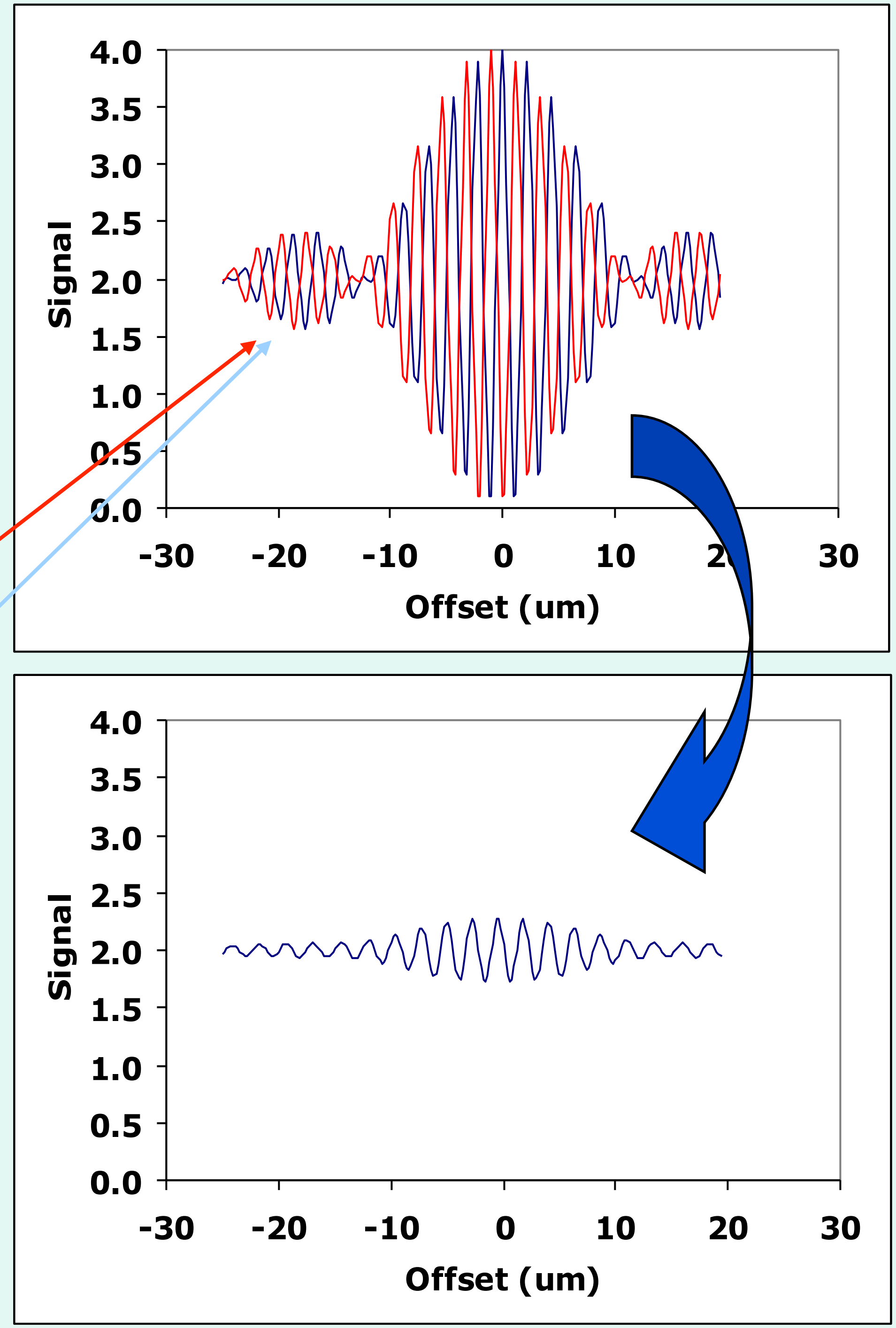
For large stars (θ ~ 0.5-3.0 mas), fringe contrast will be small





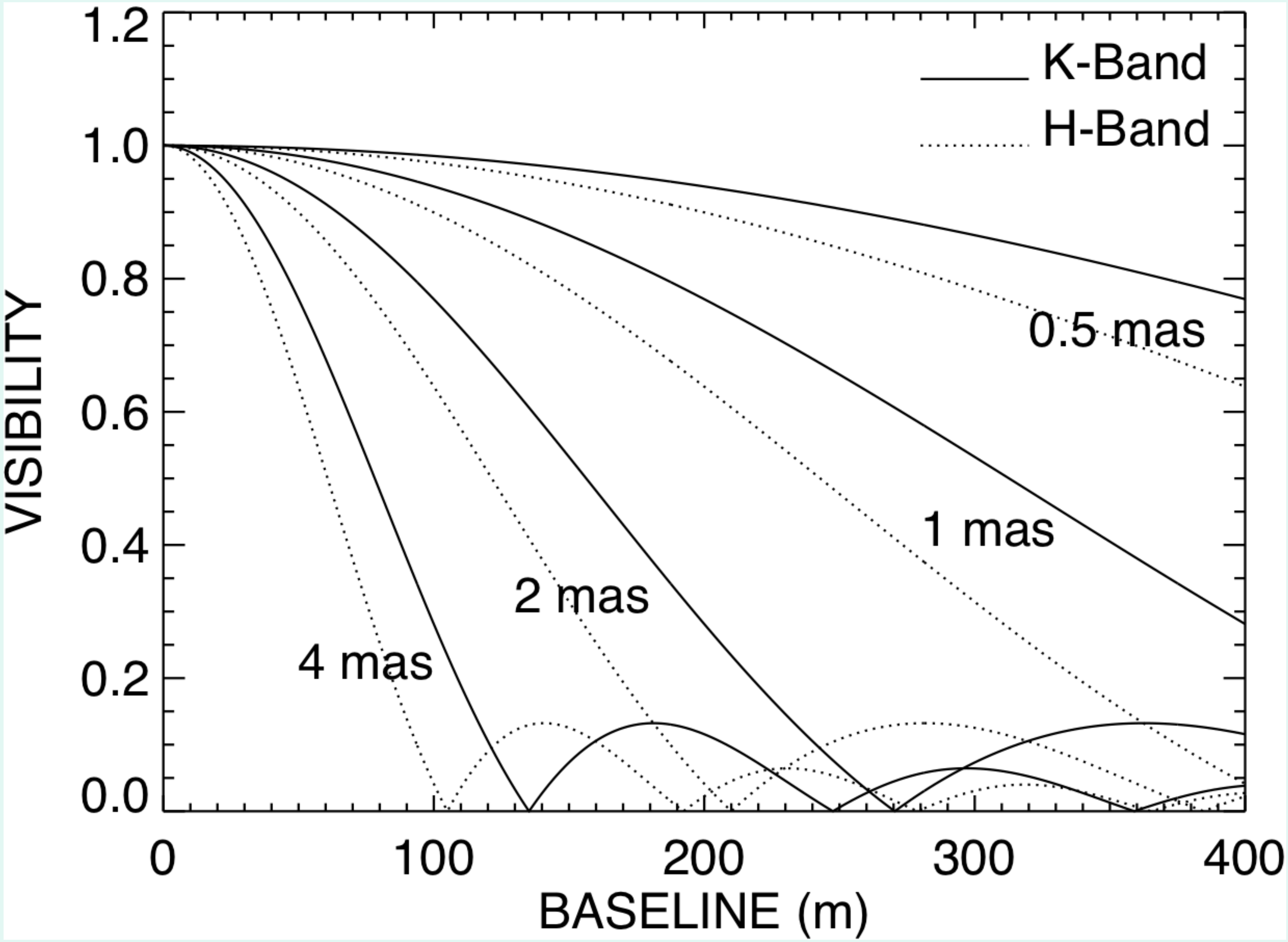
Why is This?



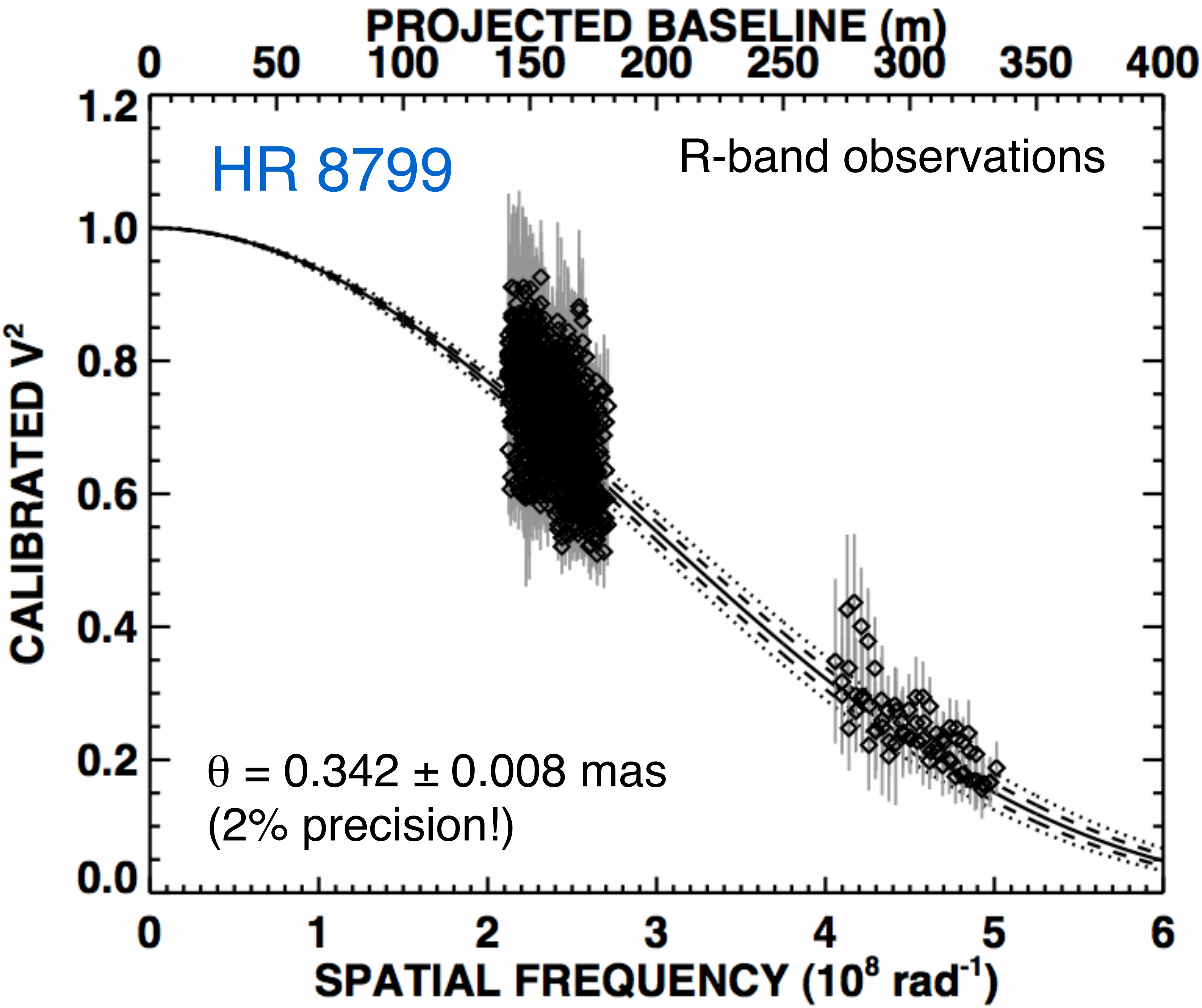


Parts of star interfere at different path lengths

Fringe contrast, or visibility = $2[J_1(\pi\theta b / \lambda)]/(\pi\theta b / \lambda)$

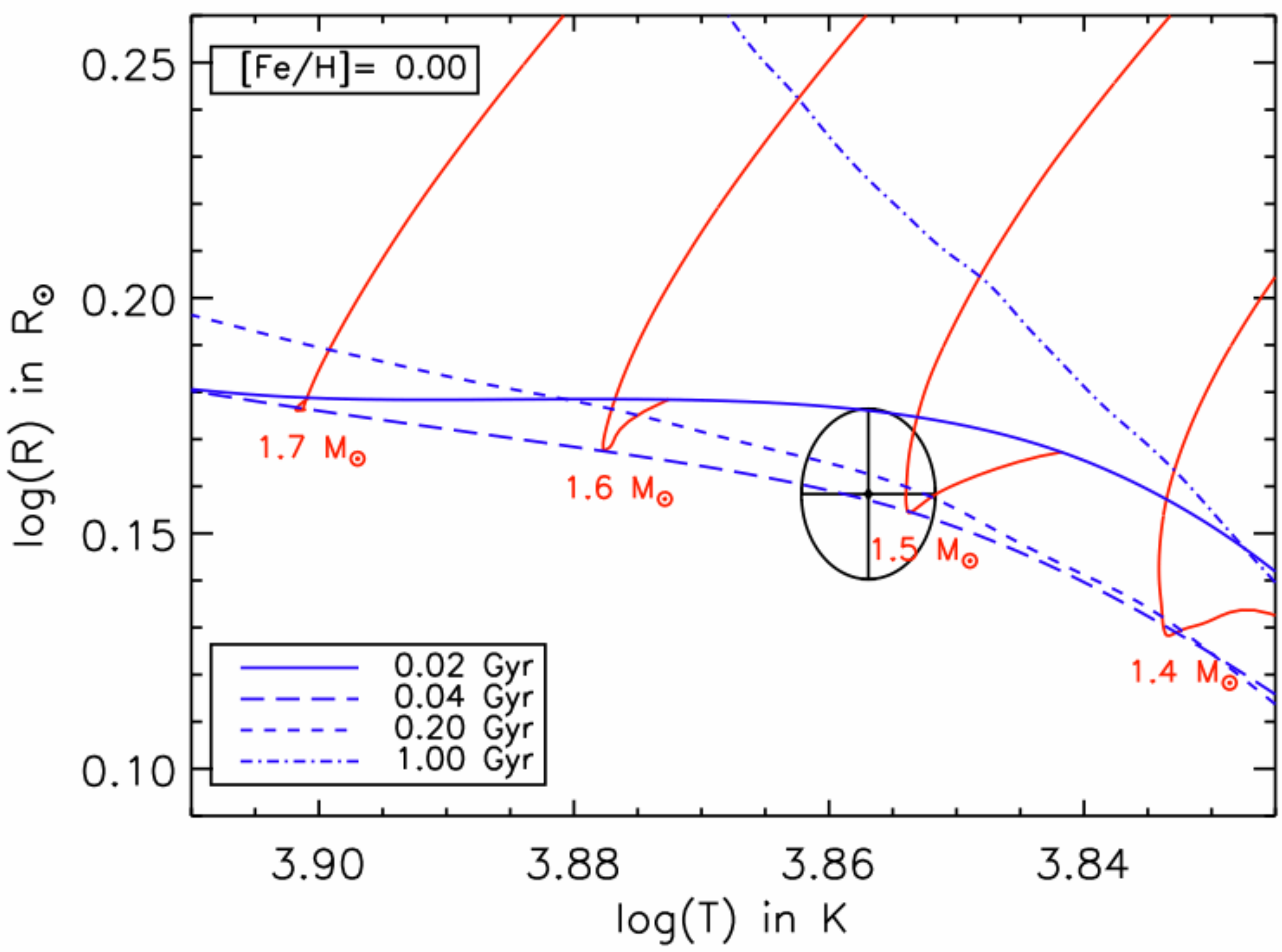


longer baselines, shorter λ = better resolution


PROJECTED BASELINE (m)
0
50
100
150
200
250
300
350
400
1.2
1.0
0.8
0.6
0.4
0.2
0.0
CALIBRATED V²
HR 8799
R-band observations
θ = 0.342 ± 0.008 mas
(2% precision!)
0
1
2
3
4
5
6
SPATIAL FREQUENCY (10⁸ rad⁻¹)

With an accurate luminosity, can get an accurate temperature too ($L = 4\pi R^2 \sigma T^4$)

($R=1.44 \pm 0.06\ R_{Sun}$, $T=7193 \pm 87$ K)



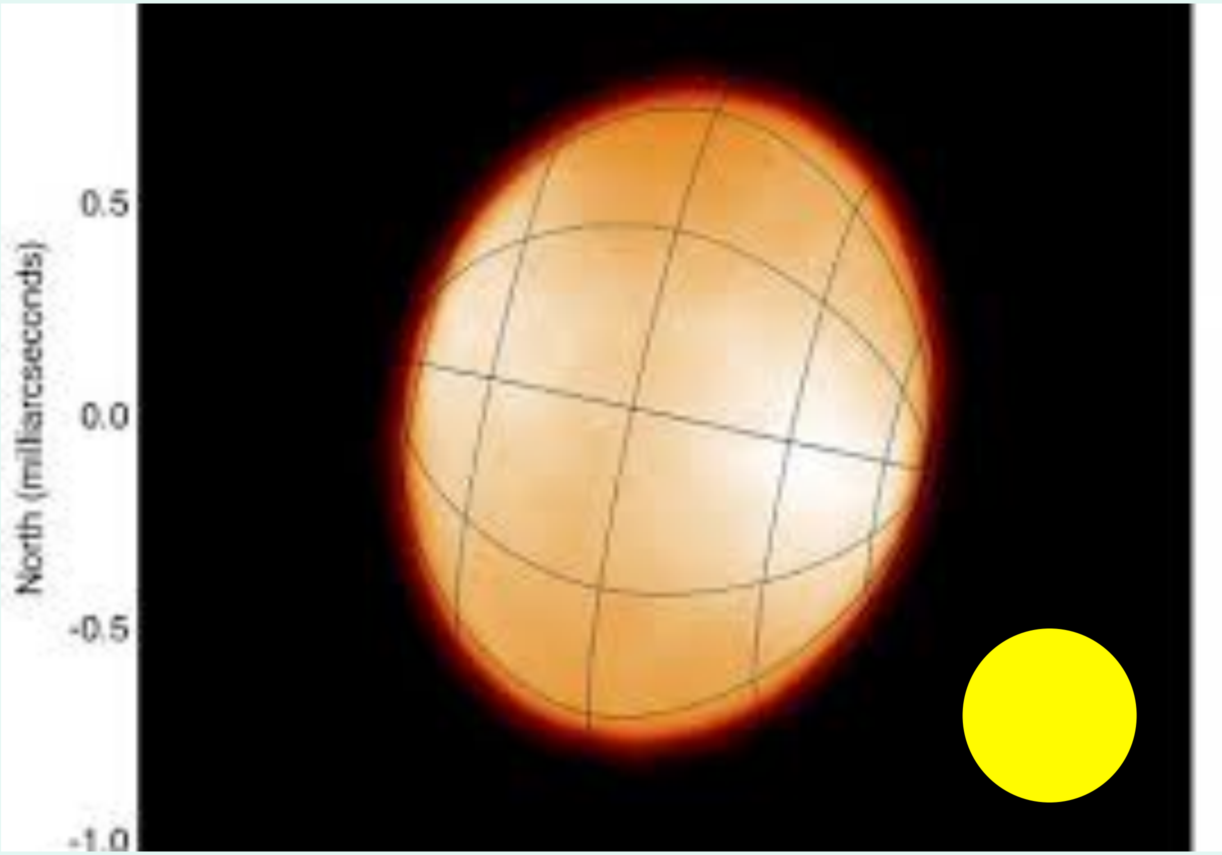
Age:
33 Myr if contracting,
90 Myr if expanding

Companions are planets!

Baines, White, Jones et al. 2012

But not as easy for many A stars because of their rapid rotation

(For example, Kappa And has a vsini = 176 km/s)

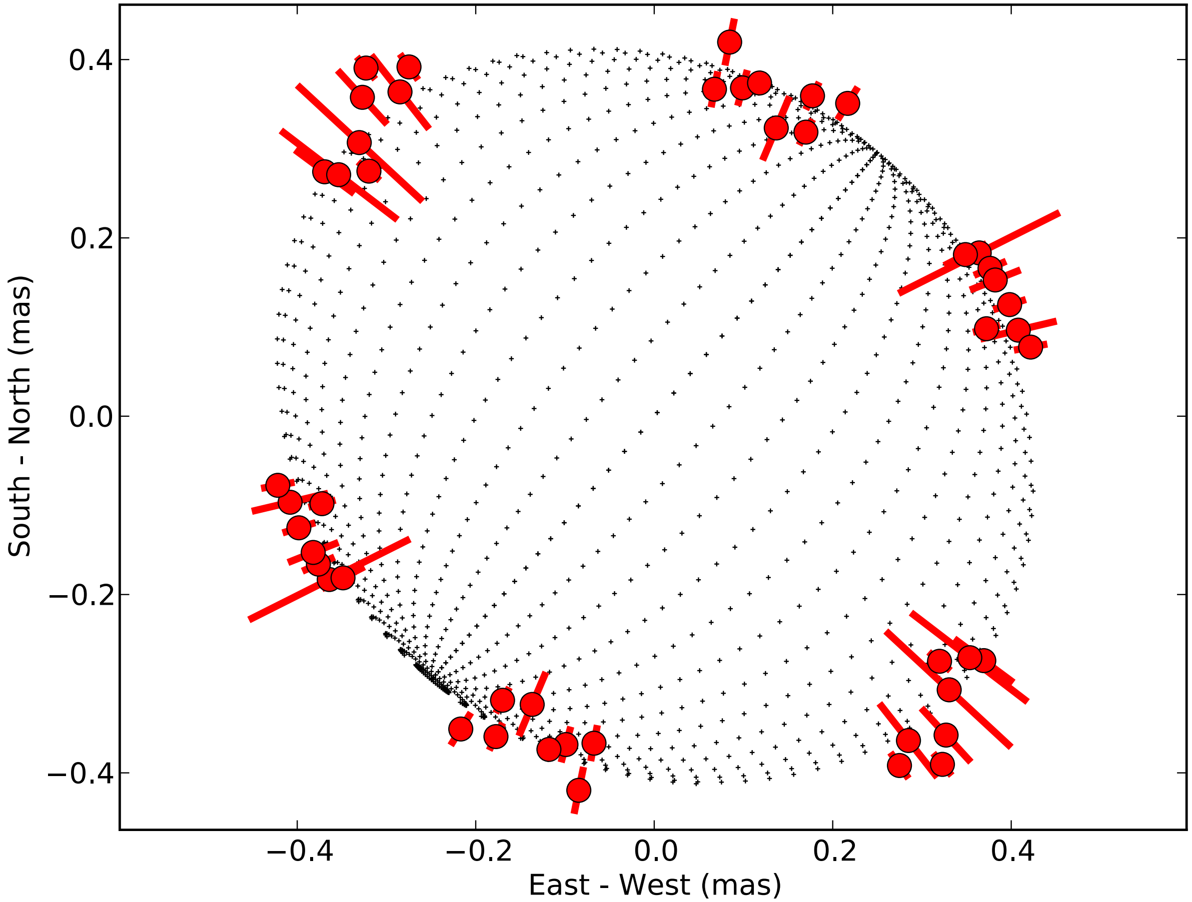


The rapidly rotating star Regulus, imaged with the CHARA Array (Monnier et al. 2007) shows “gravity darkening”.

Radius, temperature, and luminosity are all orientation dependent!

Ph.D. work of Mr. Jeremy Jones (GSU):
Ages of all nearby northern, single A stars.

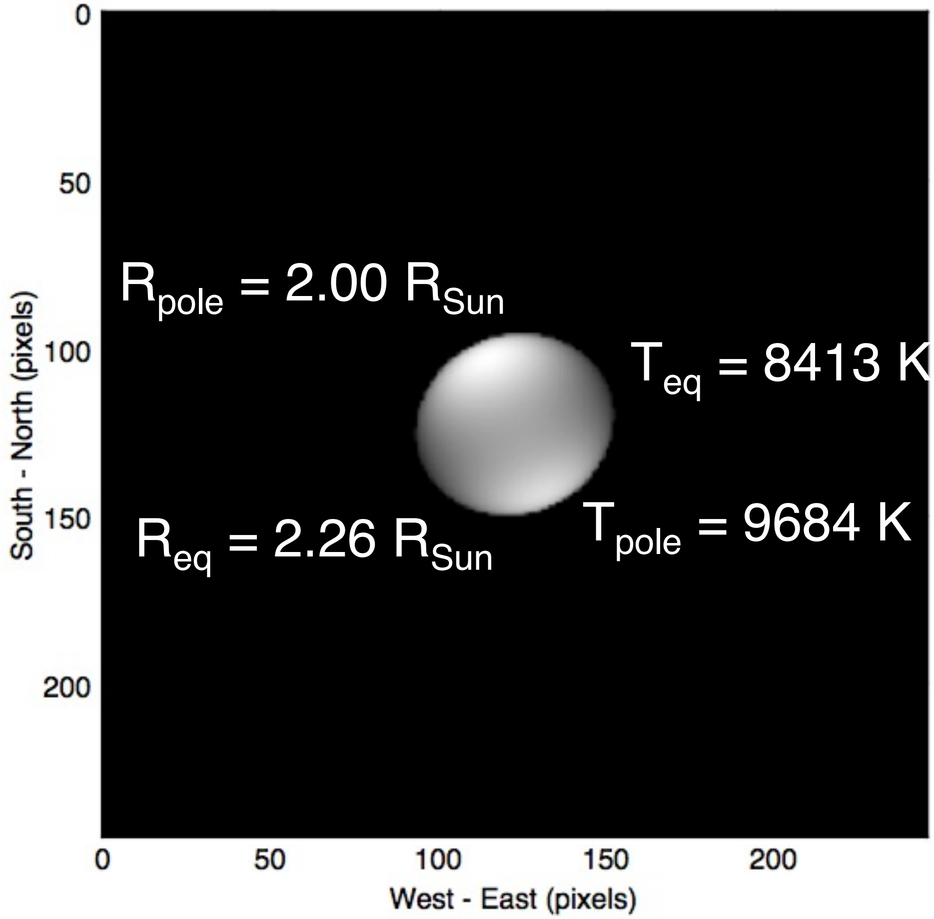
Measure oblateness, adopt a gravity law, and model visibilities (results for Megrez = δ UMa)



(Positional)
Ages
~ 10%
Masses
~ 5%

Ph.D. work of Mr. Jeremy Jones (GSU):
Ages of all nearby northern, single A stars.

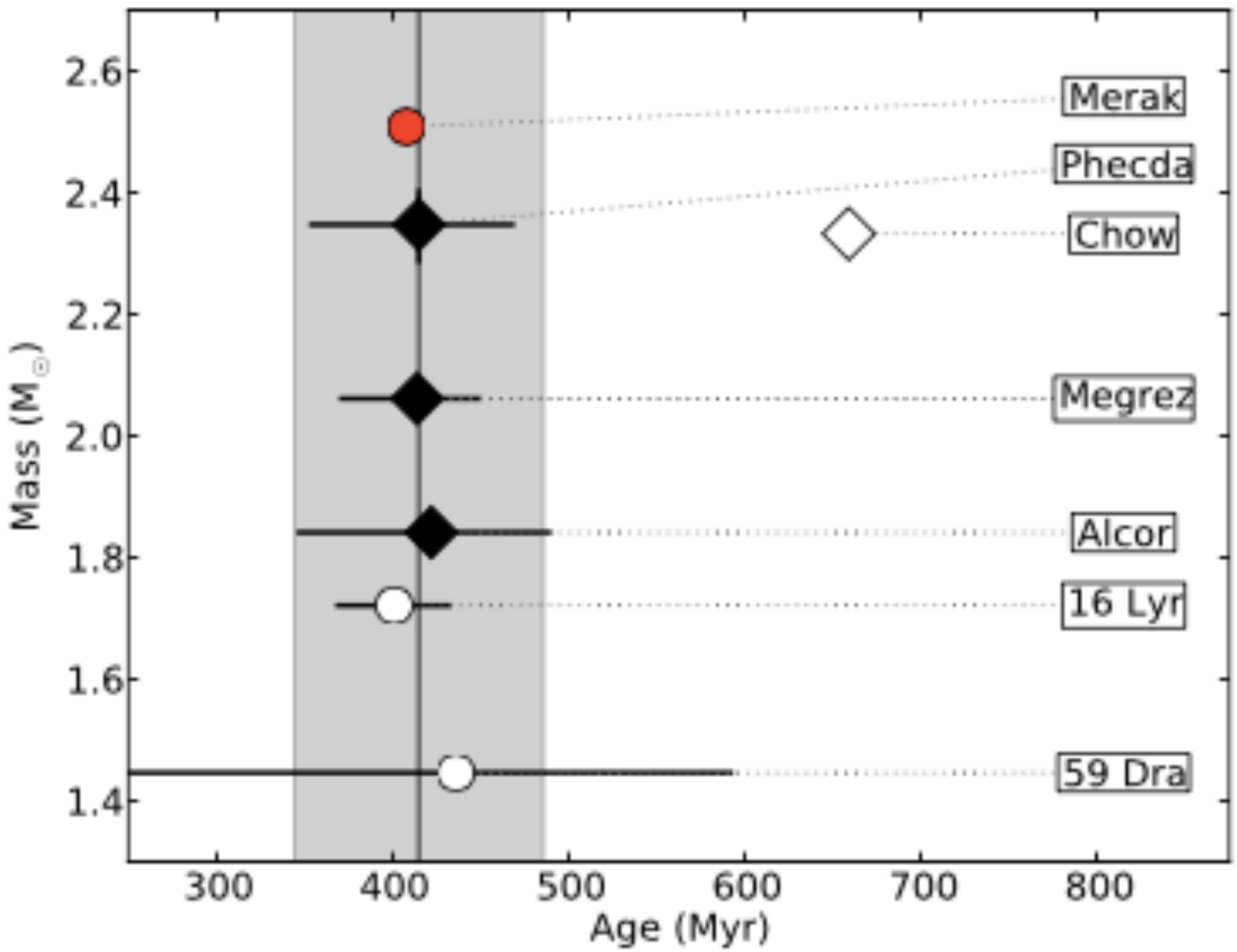
Measure oblateness, adopt a gravity law, and model visibilities (results for Megrez = δ UMa)



(Positional)
Ages
~ 10%
Masses
~ 5%

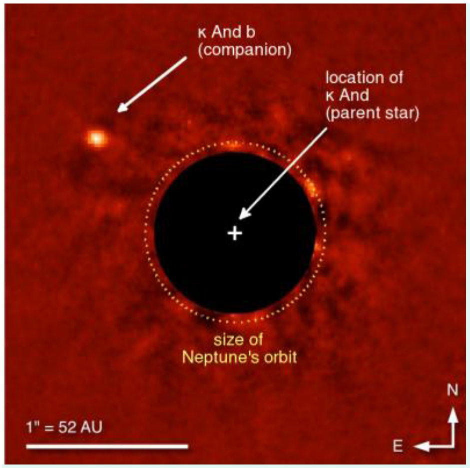
Ph.D. work of Mr. Jeremy Jones (GSU): Ages of all nearby northern, single A stars.

Based on MESA evolutionary models



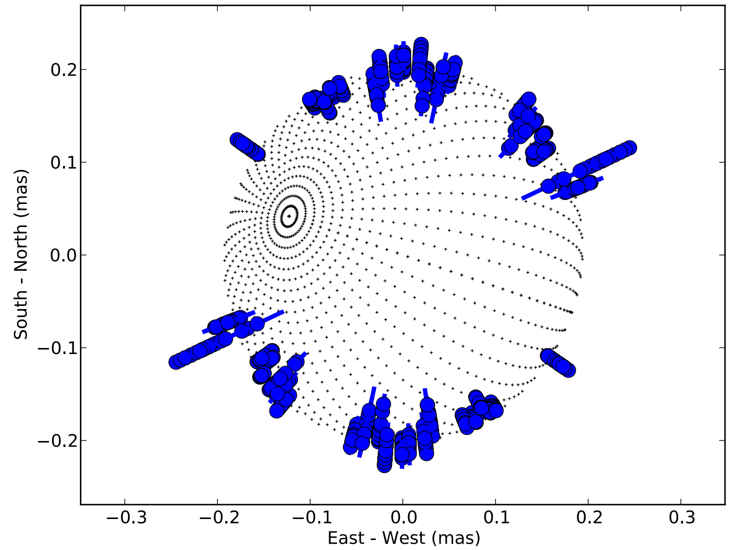
A test of the technique: Members of the Ursa Majoris Moving Group should be coeval

Jones, White et al. 2015

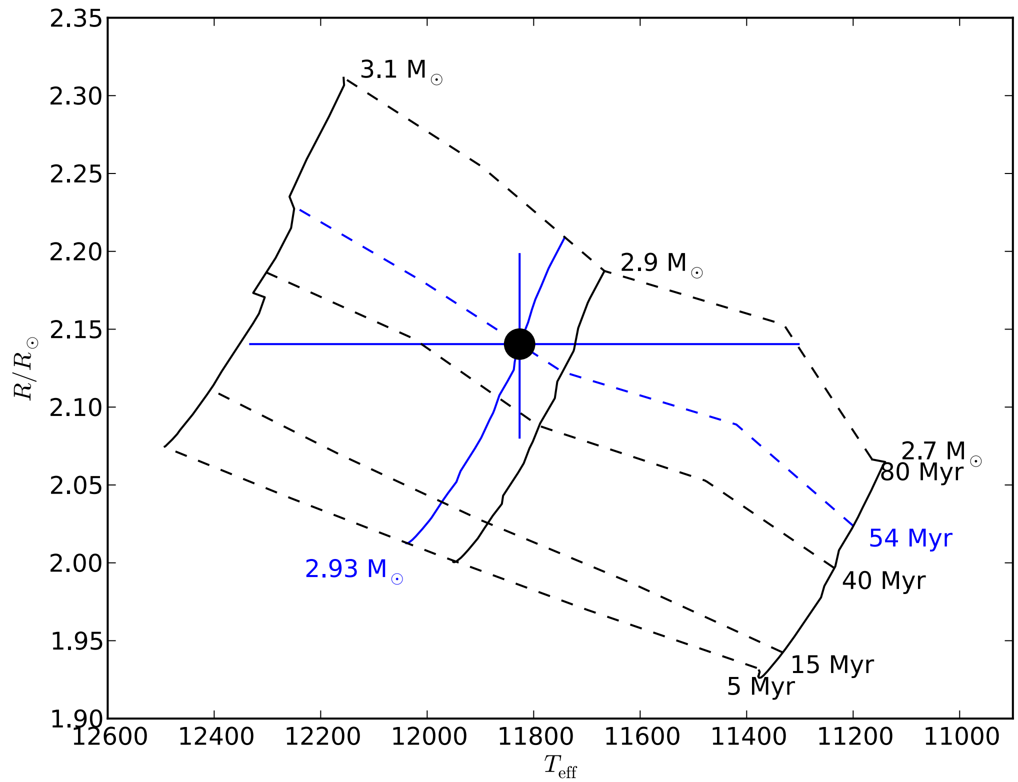


κ Andromeda

Is companion a planet (Carson et al. 2012) or a brown dwarf (Hinkley et al. 2014)?



At ~54 Myr, companion is a very low mass brown dwarf (15 M_{Jup})

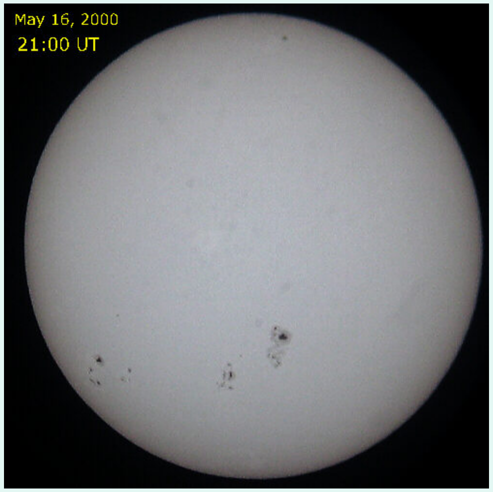


Jones, White et al. in prep.


Need to Identify Young Planets
^
Short Period
Age would constrain
formation, migration timescale
(resolve mass/age ambiguity)
Eccentricities would
constrain migration process
Image credit: NASA

Young Stars Are Typically Avoided in Radial Velocity (RV) Surveys

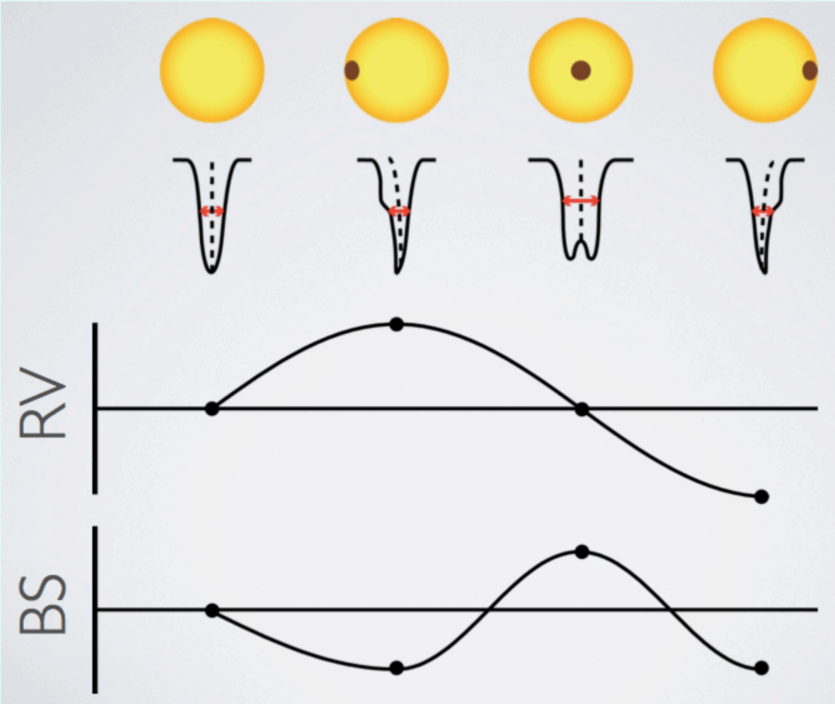
- Young star are visibly fainter
  (the Sun was only 4400 K at 2 Myr, vs 5800 K today)
- More rapidly rotating
- Spots cause optical RV "noise" (many 100 m/s)
  (Paulson & Yelda 2006; Heurta et al. 2007; Huelamo et al. 2008)



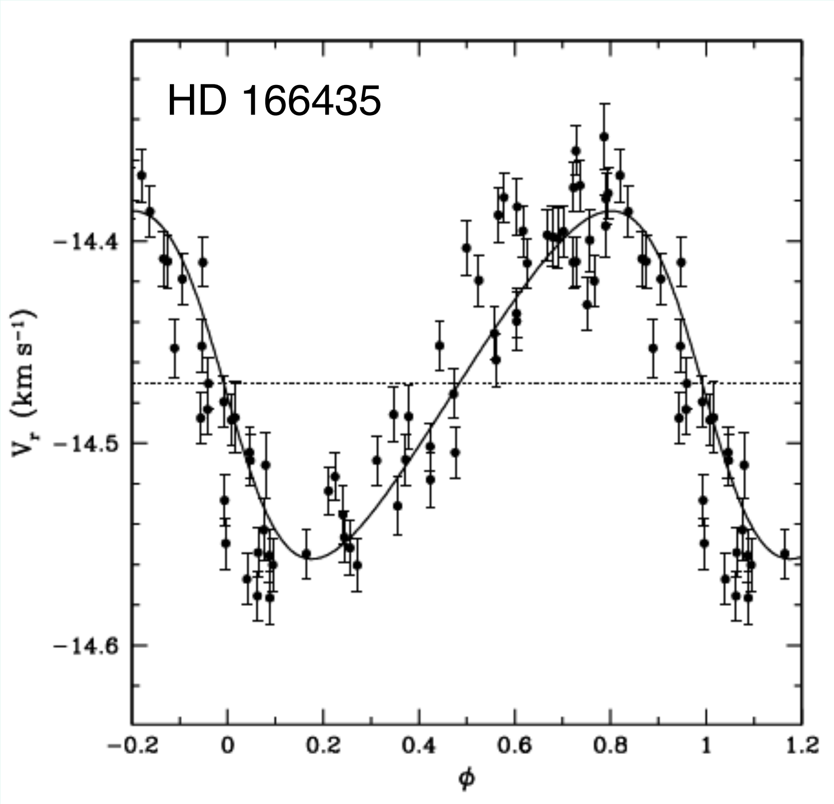
The Sun

A young spotted star

Spots can cause apparent RV shifts

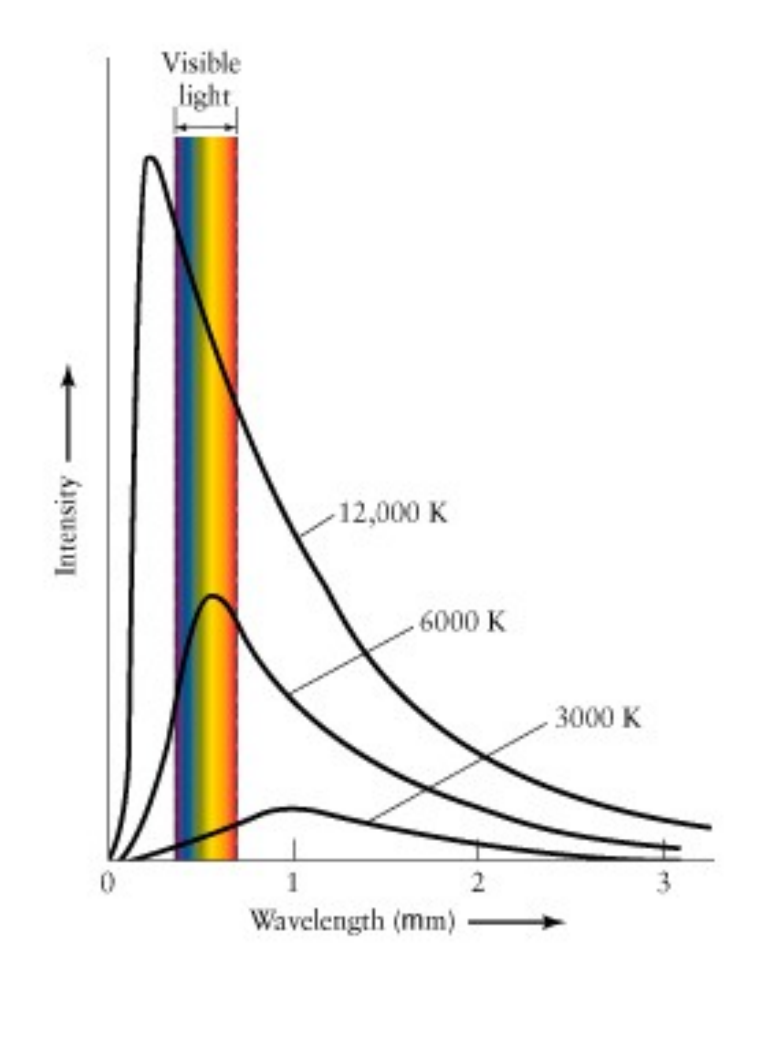


The line bisector can reveal this artificial signal



from Queloz et al. (2001), using *optical* spectra

Advantage of Infrared Spectra



- Cool stars are relatively brighter

- Reduced spot contrast should reduce RV noise

Optical

Infrared


RV Programs to Find Young Planets

- John Bailey (former UAH undergrad, now at Mich.)
- Justin Cantrell (GSU staff/grad.)
  - T Tauri age stars (1-20 Myr) *infrared*

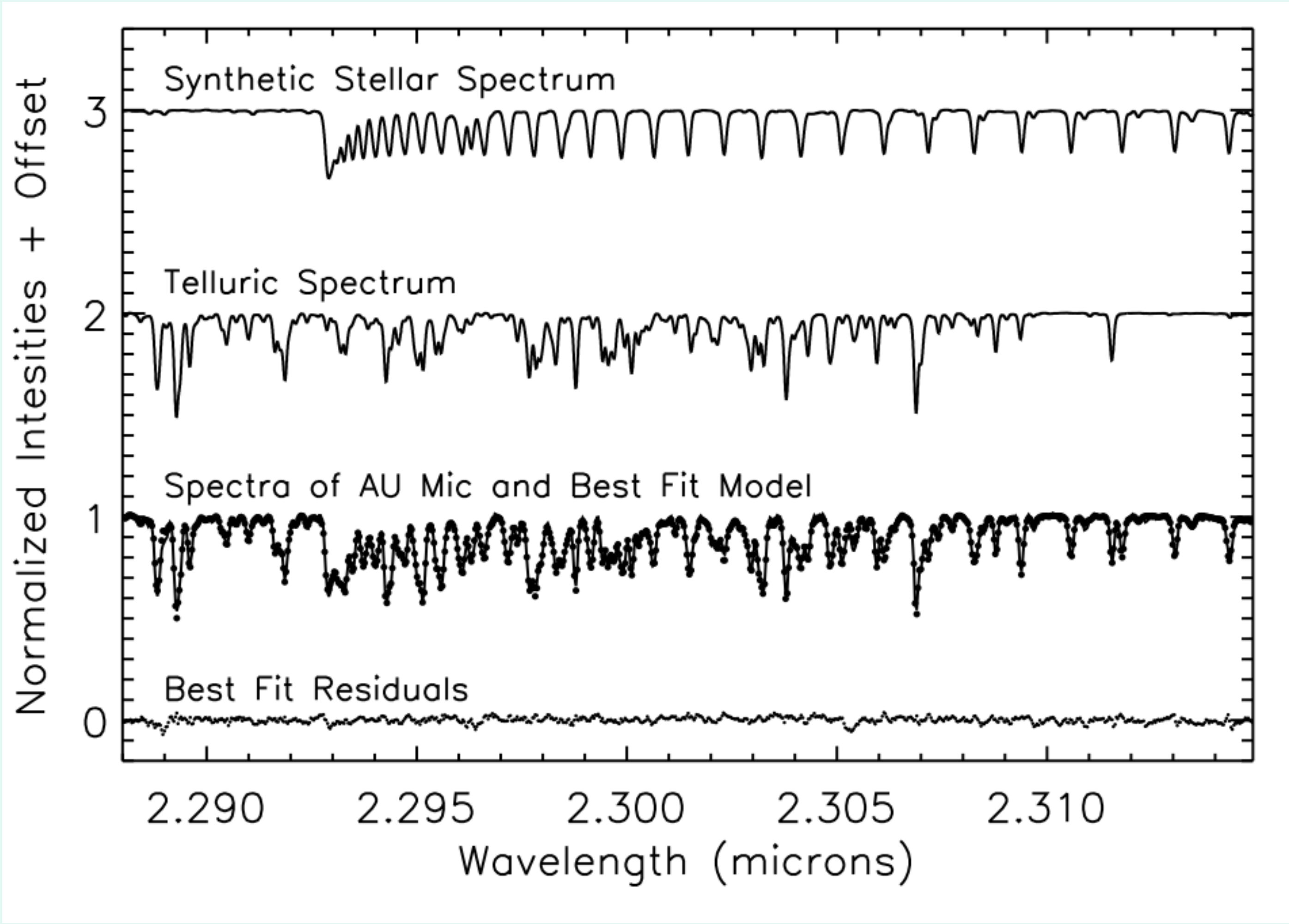
- Nicole Cabrera (GSU; NSF Grad Fellow)

- Cassy Davison (GSU; former NSF Grad Fellow)
  - Adolescent age stars (10 – 150 Myr) *Infrared & optical*

- Sam Quinn (GSU; NSF Grad Fellow)
  - Open cluster stars (60 – 600 Myr) *optical*

First results in Bailey et al. 2012
20 stars in TWA, β Pic (8-20 Myr)

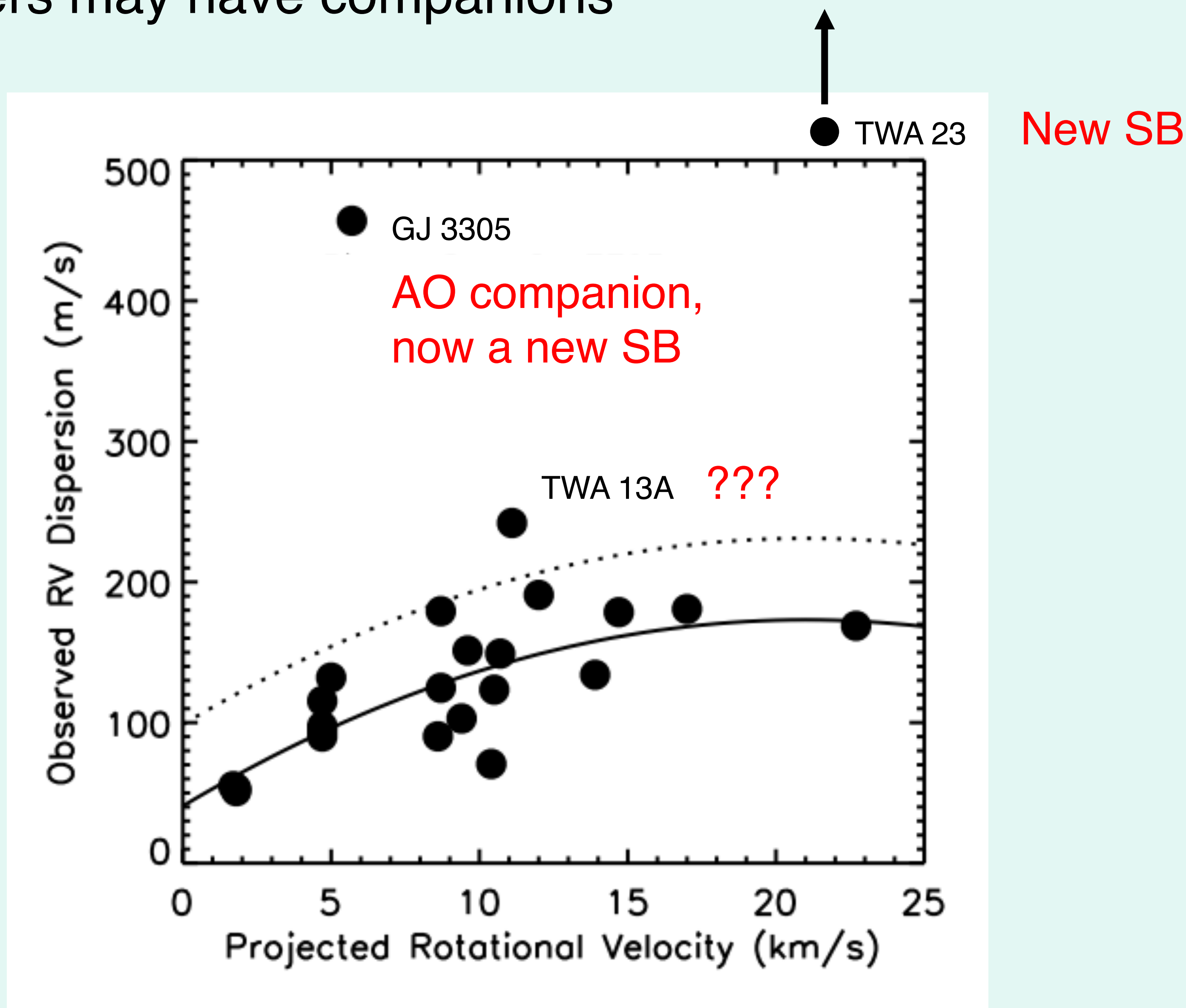
using NIRSPEC at the Keck Observatory



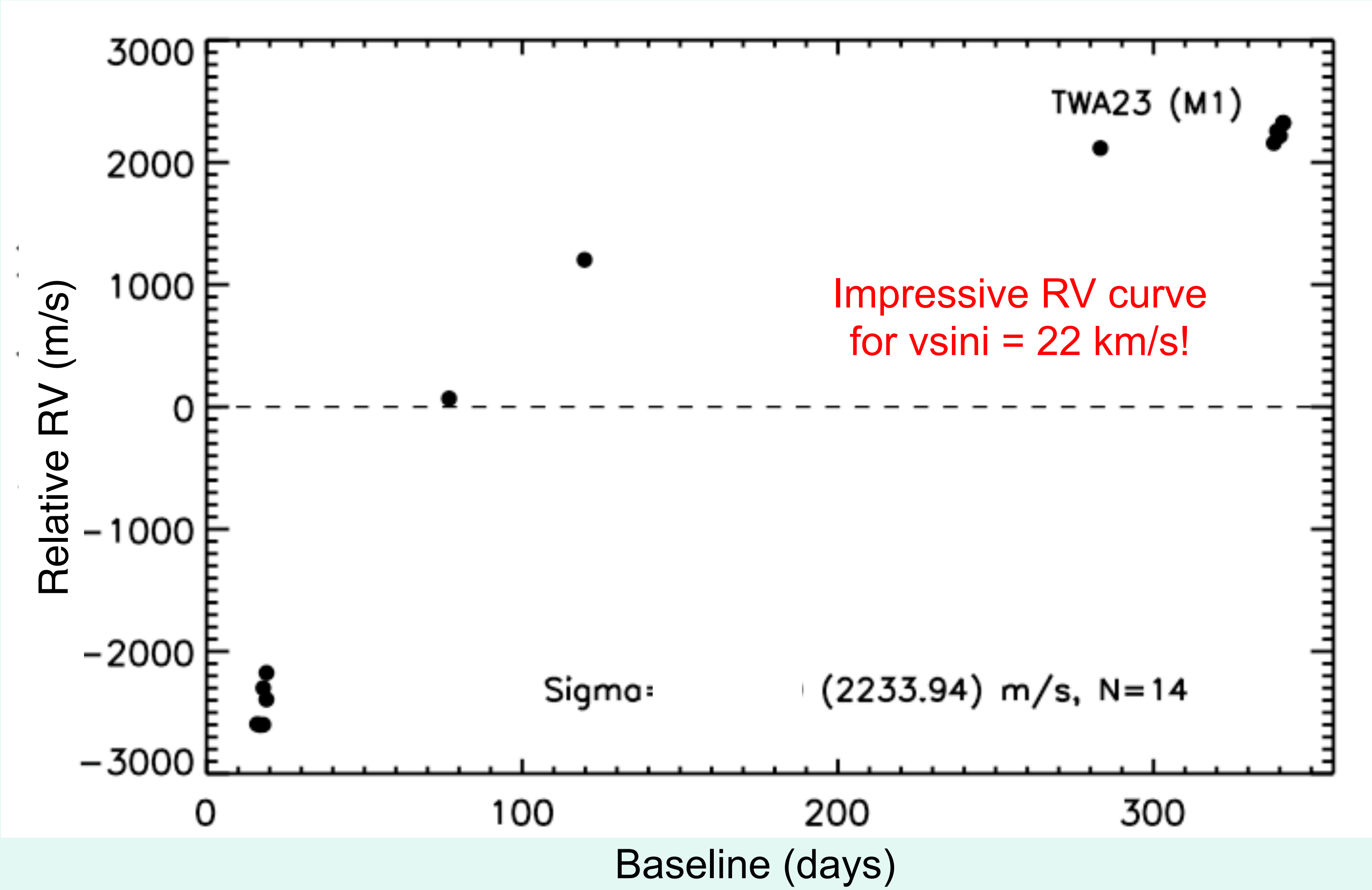
Yields ~50 m/s precision

Observed Dispersions: increase with vsini

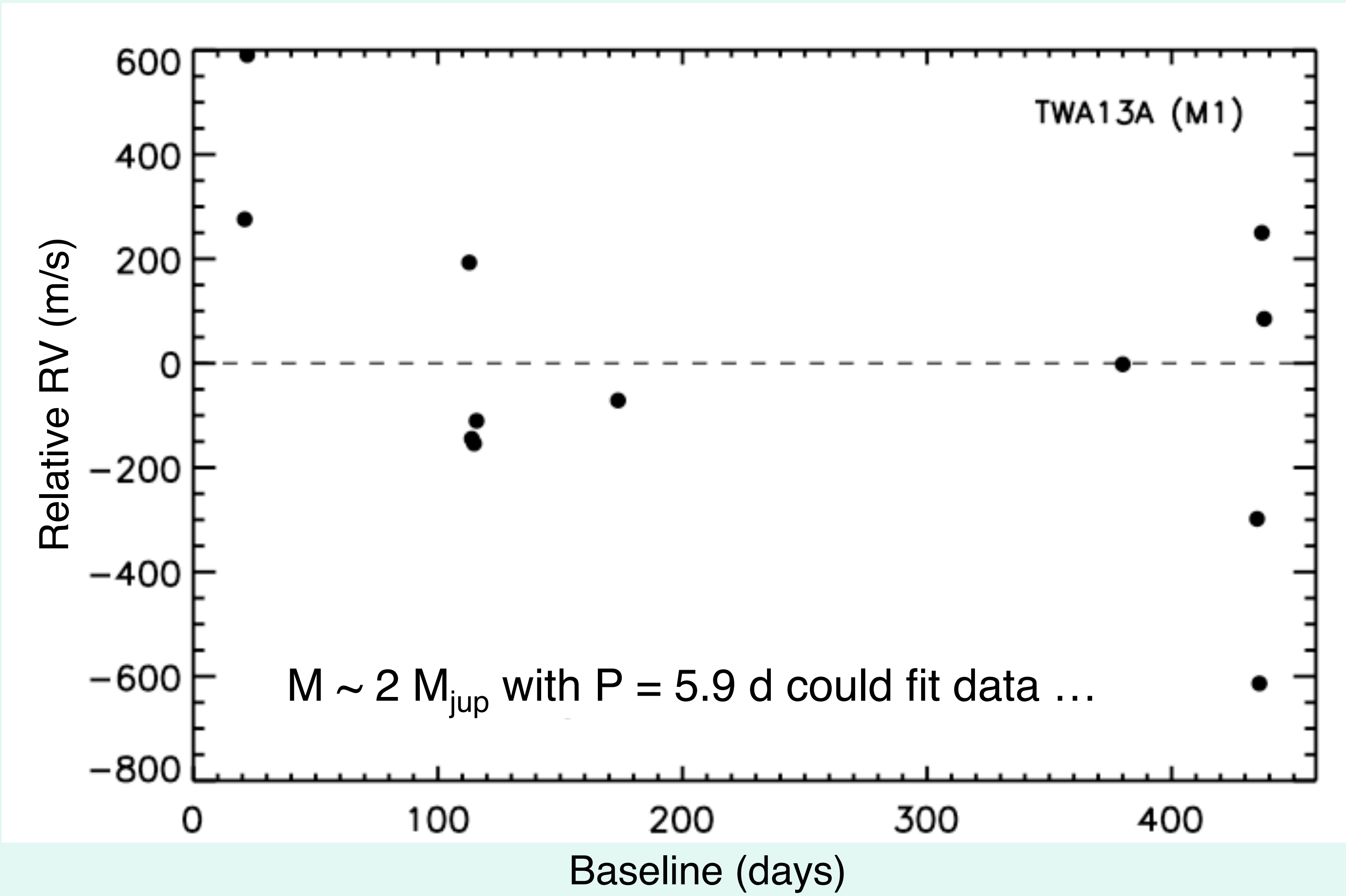
outliers may have companions



TWA 23 has a companion, but companion is a star



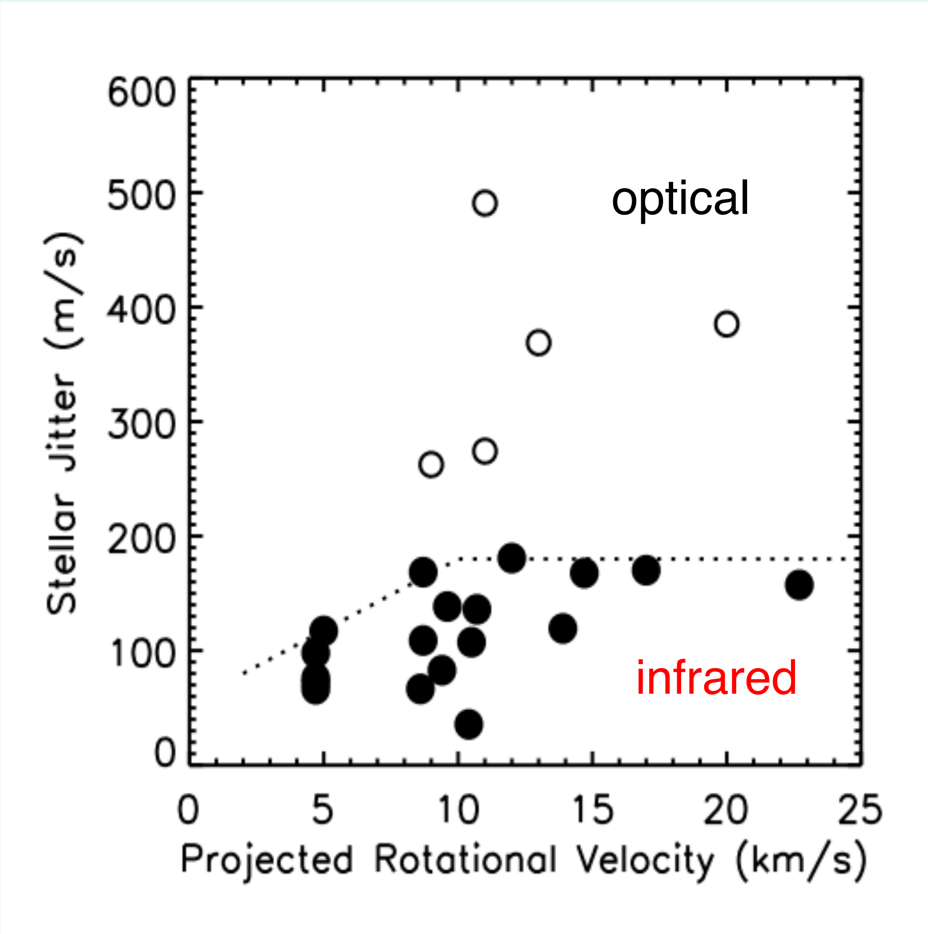
Does TWA 13A Harbor a Young Hot Jupiter?



How much stellar "jitter" is there?

$$\sigma^2_{jitter} = \sigma^2_{obs} - \sigma^2_{instrumental} - \sigma^2_{photon}$$

(e.g. Butler et al. 1996)



- ~100 m/s (for vsini < 10 km/s)
- saturates at 180 m/s?
- Improvement over optical by 2-5 x!

(comparing to Paulson & Yelda 2006)

Companion Detection Limits

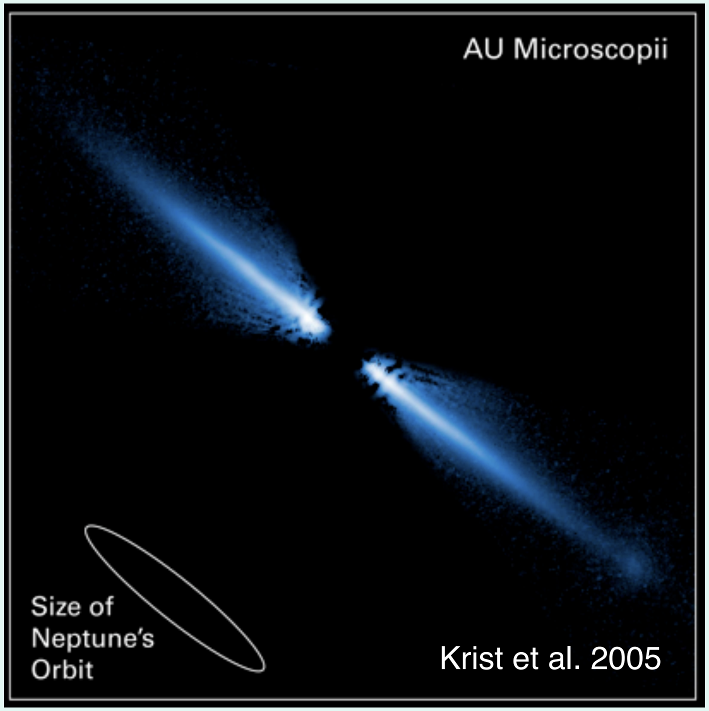
Monte Carlo Simulations

- circular 3 and 30 day orbits
- random inclinations

$< M_{limit}$ (3d) $> = 8\ M_{jupiter}$

$< M_{limit}$ (30d) $> = 17\ M_{jupiter}$

No hot or warm massive planets!



For AU Mic (assuming edge-on orbit):

$< M_{limit}$ (3d) $> = 1.8\ M_{jupiter}$

$< M_{limit}$ (30d) $> = 3.9\ M_{jupiter}$

No hot or or warm Jupiters!

Finding *Very* Young (short-period) Planets Will be Hard

See also Plavchan et al. 2013; Crockett et al. 2012; van Eyken et al. 2012

Why not search in open clusters?

Ages of 10s – 100s Myr; properties well established

A brief history of cluster planet searches

Cluster	Year	Authors	Method	Short period planets*
Hyades	2004	Paulson+	RV	0
NGC 7789	2005	Bramich+	Transit	0
NGC 2158	2006	Mochejska+	Transit	0
NGC 7086	2006	Rosvick+	Transit	0
NGC 6791	2007	Montalto+	Transit	0
NGC 188	2008	Mochejska+	Transit	0
Praesepe	2008	Pepper+	Transit	0
NGC 2362	2008	Miller+	Transit	0
M37	2009	Hartman+	Transit	0
M67	2012	Pasquini+	RV	0

*2 long period super-Jupiters are known to orbit massive evolved stars in the Hyades (Sato+ 2007) and NGC 2423 (Lovis & Mayor 2007).

Unlucky, or do clusters inhibit formation/migration?

A Search for Planets in Praesepe

Ph.D. thesis work of Mr. Sam Quinn

With Dr. David Latham, Guillermo Torres (SAO)

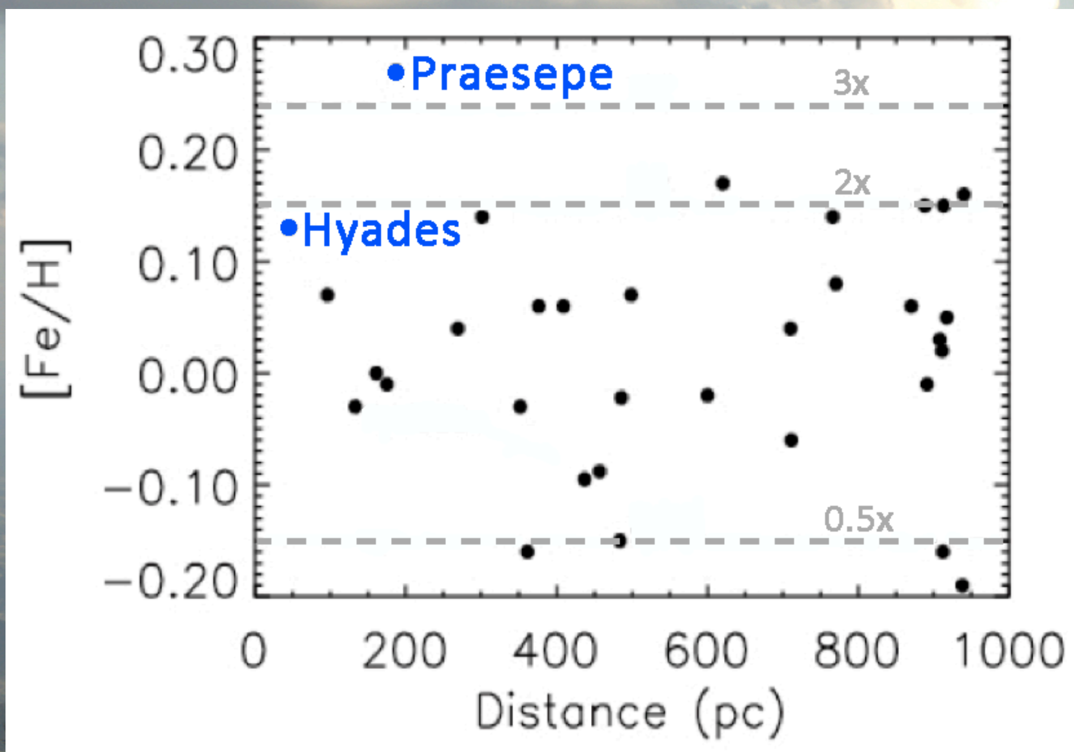
Observed 53 FGK Praesepe members with TRES (optical; ~10 m/s precision)

60” Tillinghast Reflector, Fred L. Whipple Observatory, Mt Hopkins, AZ

A Search for Planets in Praesepe

Ph.D. thesis work of Mr. Sam Quinn

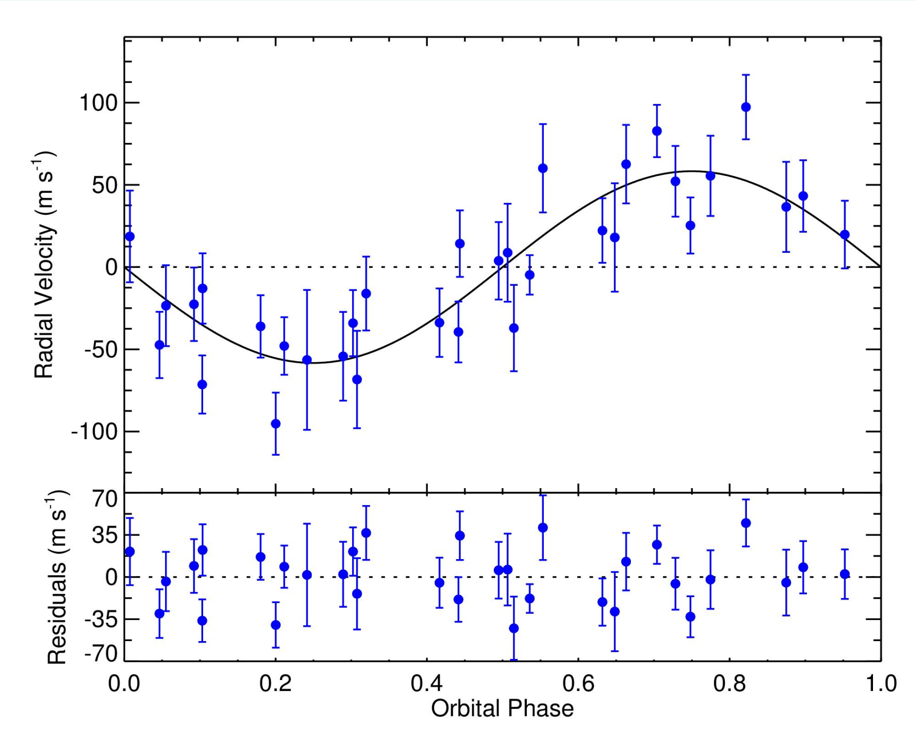
With Dr. David Latham, Guillermo Torres (SAO)

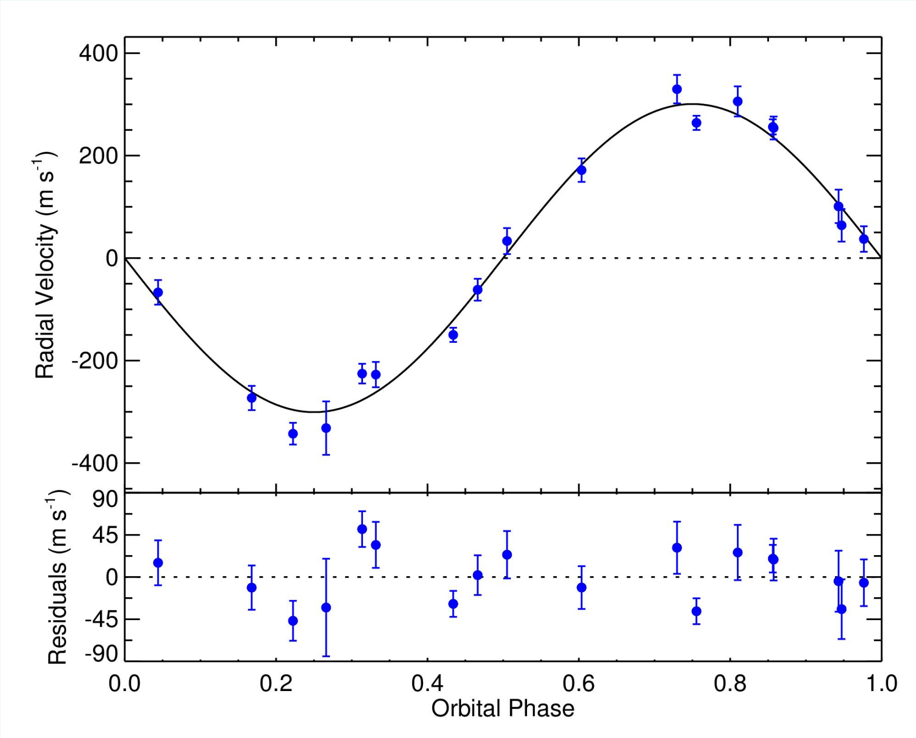


Observed 53 FGK Praesepe members with TRES (optical; ~10 m/s precision)

60” Tillinghast Reflector, Fred L. Whipple Observatory, Mt Hopkins, AZ

The Praesepe Planets





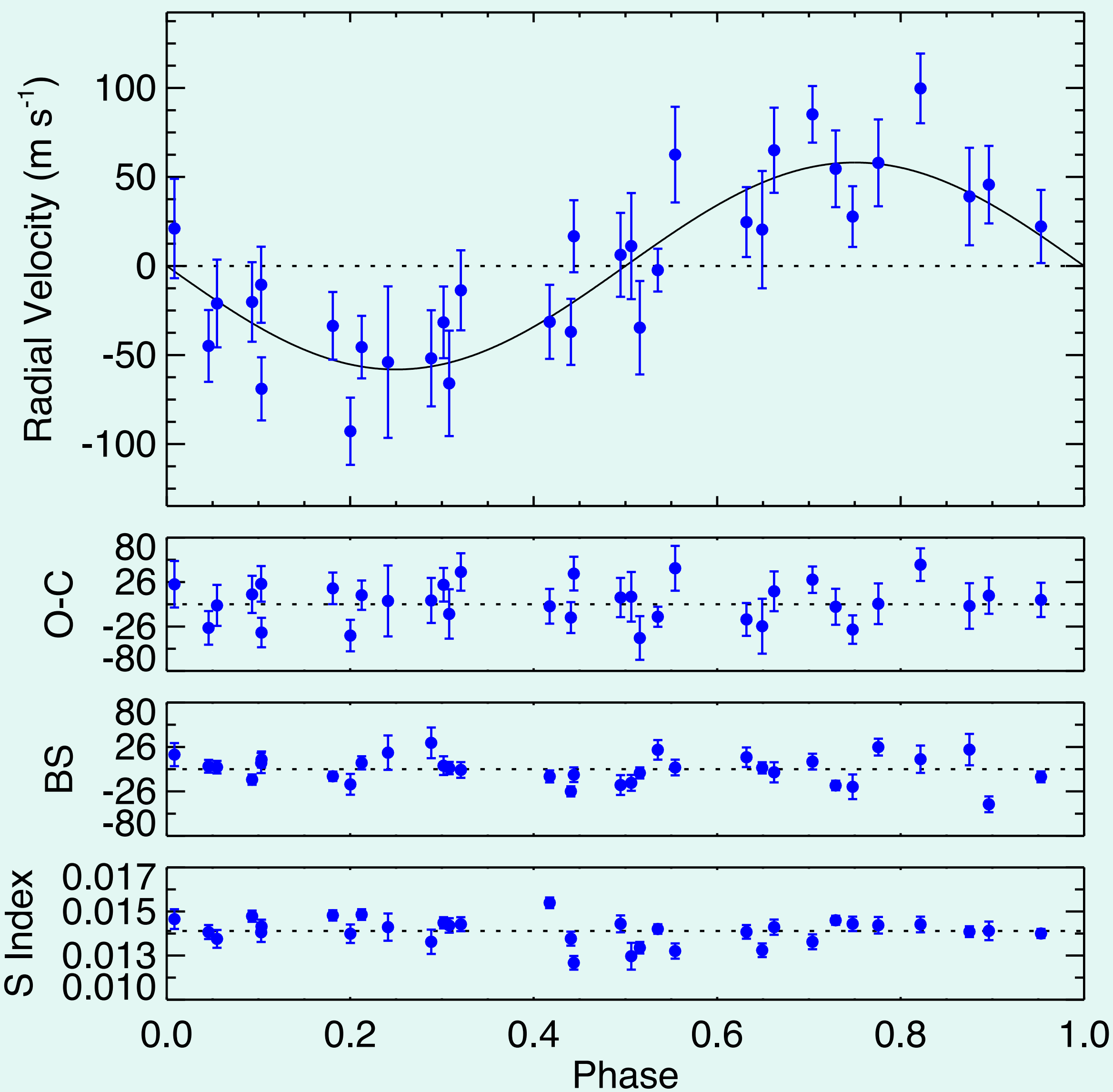
$M \sin(i) = 0.540 \pm 0.039\ M_J$
$P = 4.4264 \pm 0.0070$ days

$M_* = 1.234 \pm 0.034\ M_\odot$
$R_* = 1.167 \pm 0.121\ R_\odot$

$M \sin(i) = 1.844 \pm 0.064\ M_J$
$P = 2.1451 \pm 0.0012$ days

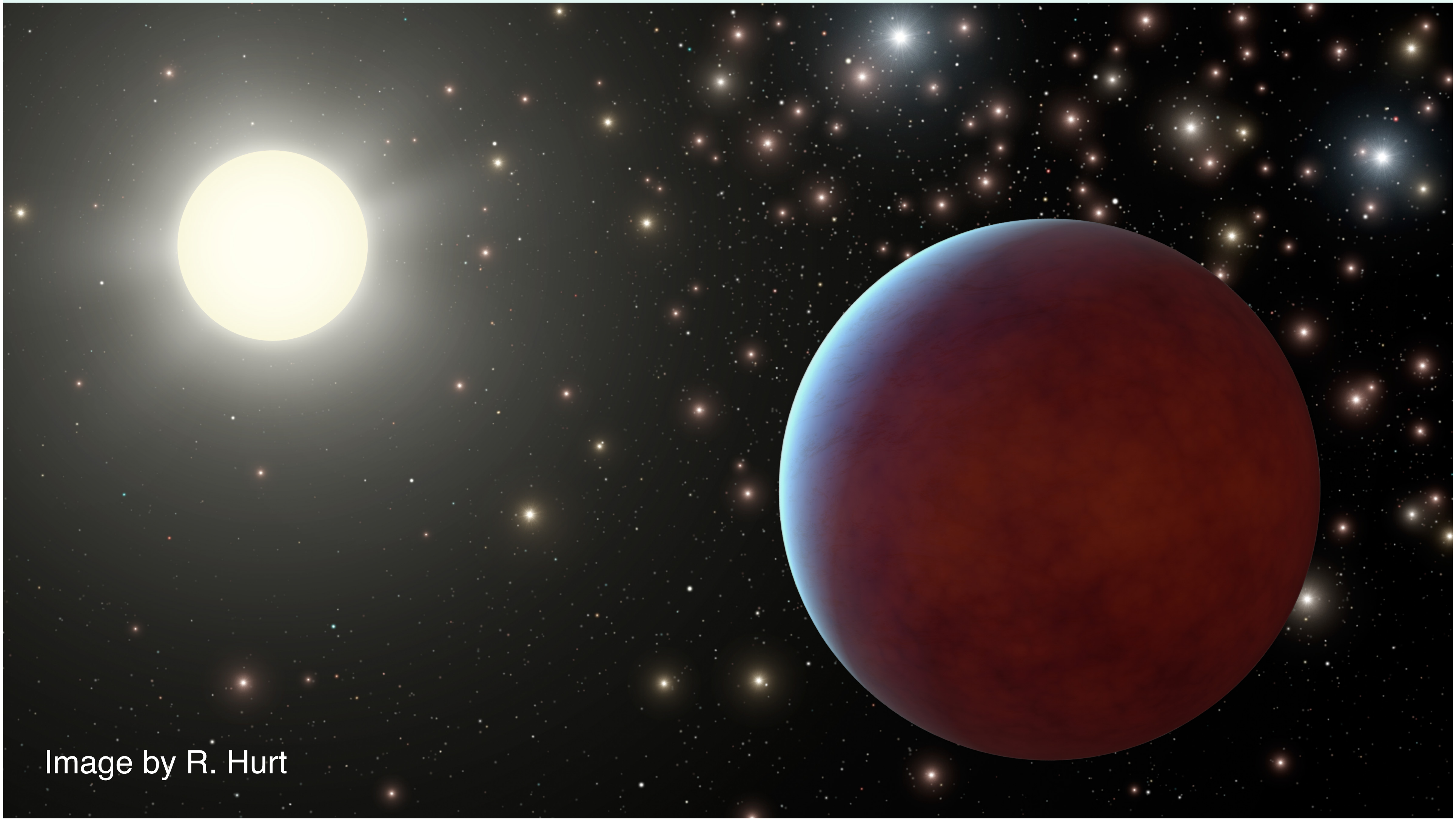
$M_* = 0.952 \pm 0.040\ M_\odot$
$R_* = 0.868 \pm 0.078\ R_\odot$

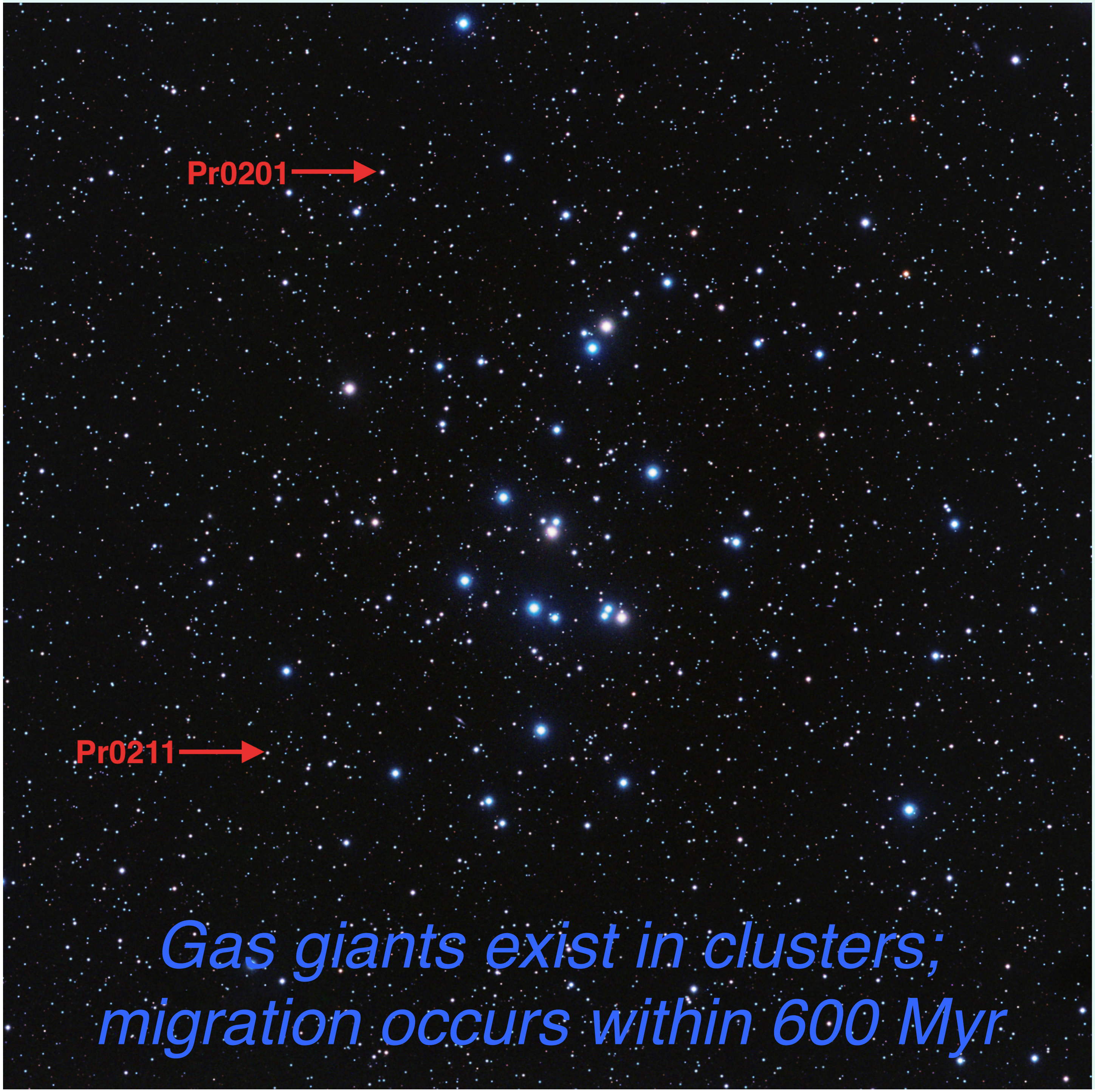
No correlation with line bisector or chromospheric activity tracer



NASA Press Release:

Two ‘b’s in the Beehive





Stars have consistent metallicities

No constraints on migration mechanism

Tidal circularization timescale < Age of Cluster

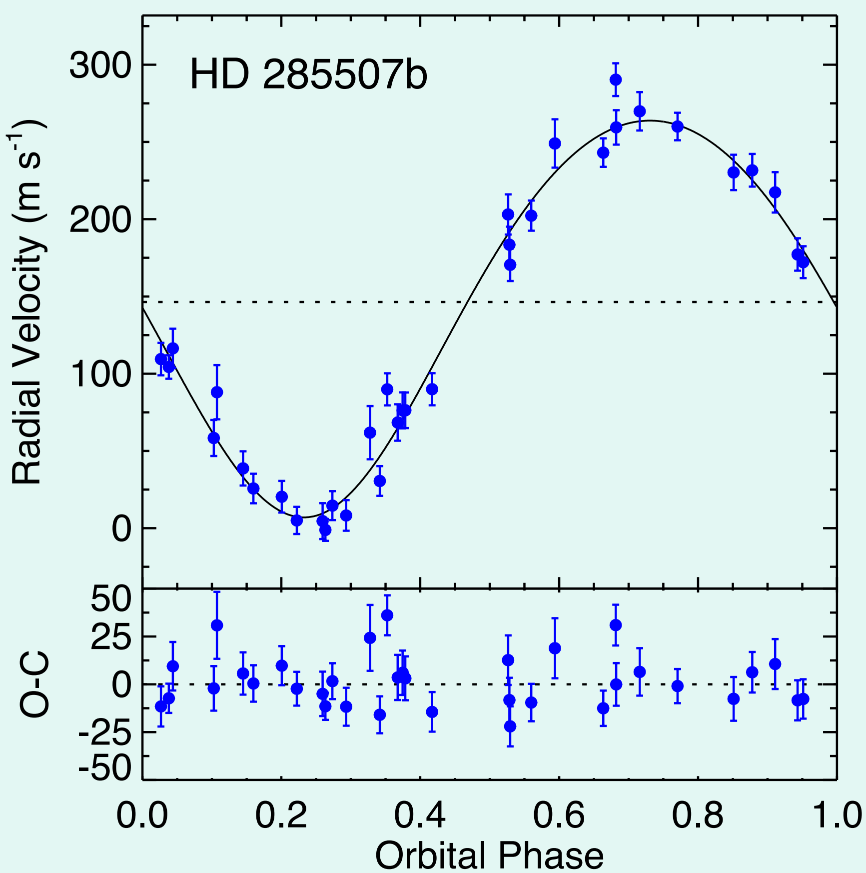
We need to find more planets!

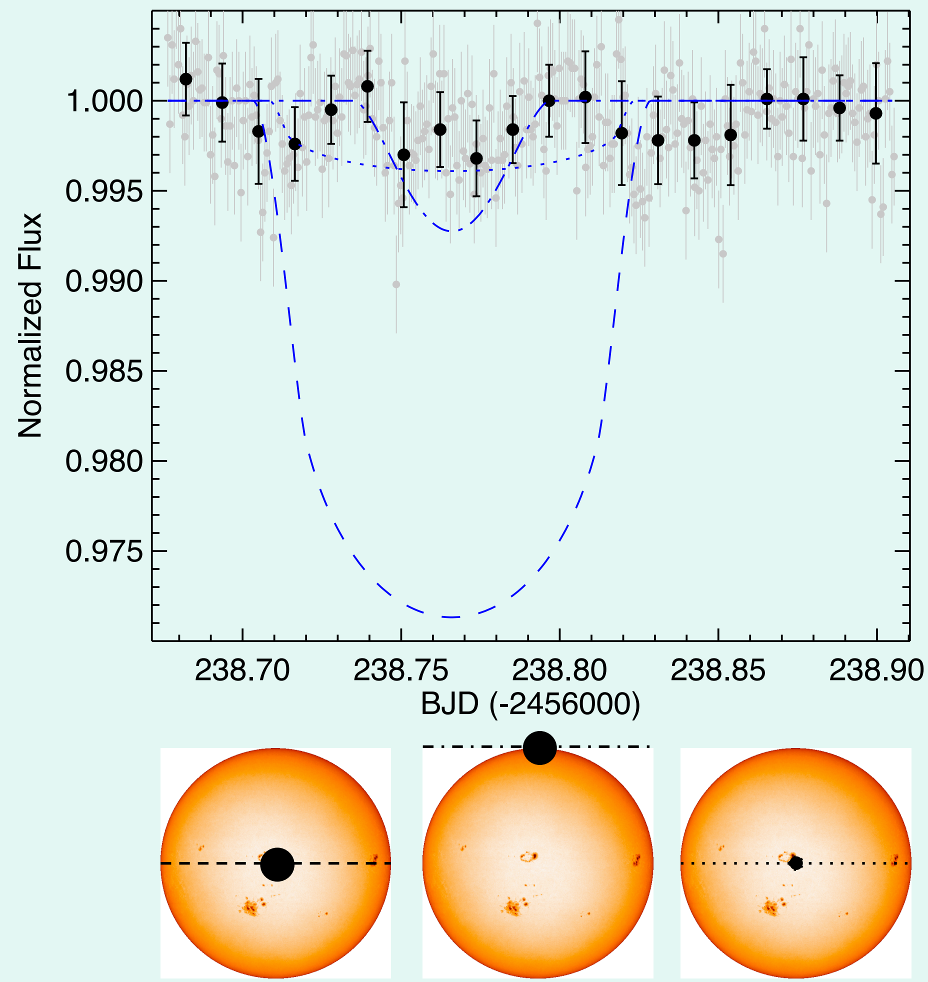
Project is now targeting 5 nearest open clusters:

Cluster	Dist. (pc)	Age (Myr)	[Fe/H] (dex)
Praesepe	182	580	+0.19
Hyades	46	625	+0.13
Coma Ber.	87	450	-0.06
Pleiades	120	110	+0.03
α Persei	172	60	+0.00

The First Hyades hot Jupiter

Quinn et al. (2014)



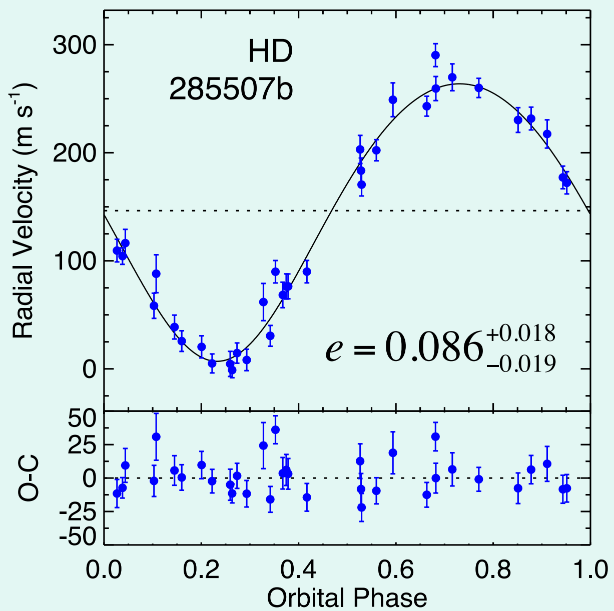


$M_p \sin(i) = 0.92\ M_J \quad P = 6.09$ d

Transits are ruled out

HD 285507b is Slightly Eccentric

Eccentricity could be a remnant of the migration process if it hasn't yet tidally circularized



Hyades: $t_{\mathrm{age}} = 625$ Myr

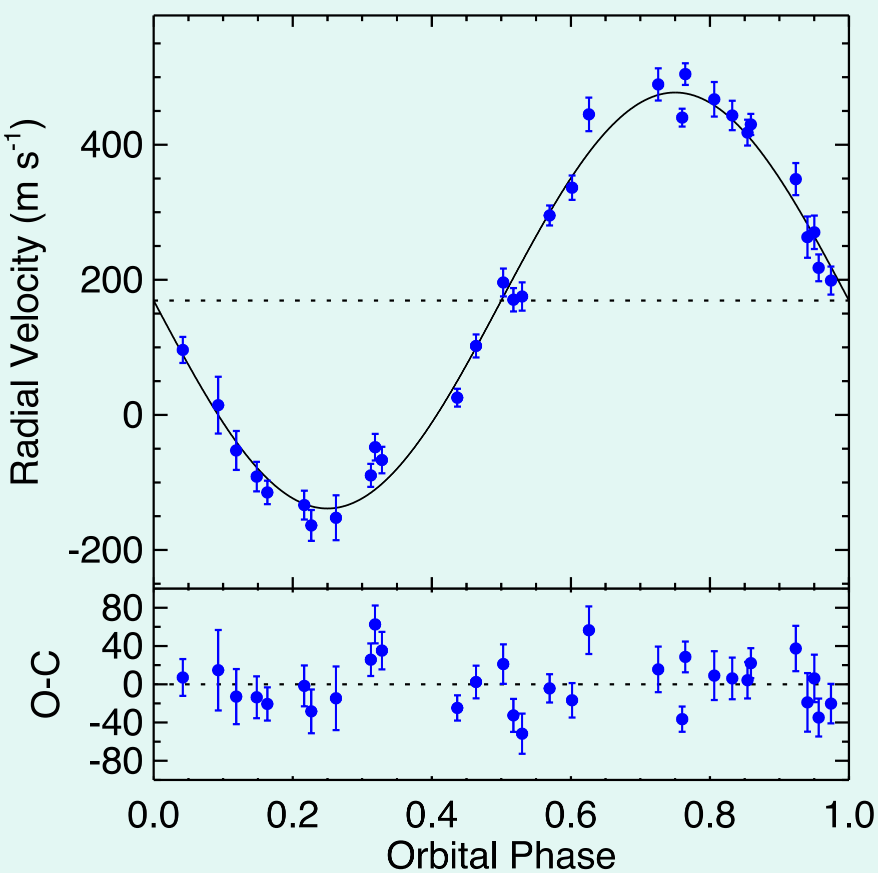
HD 285507b circularization timescale:

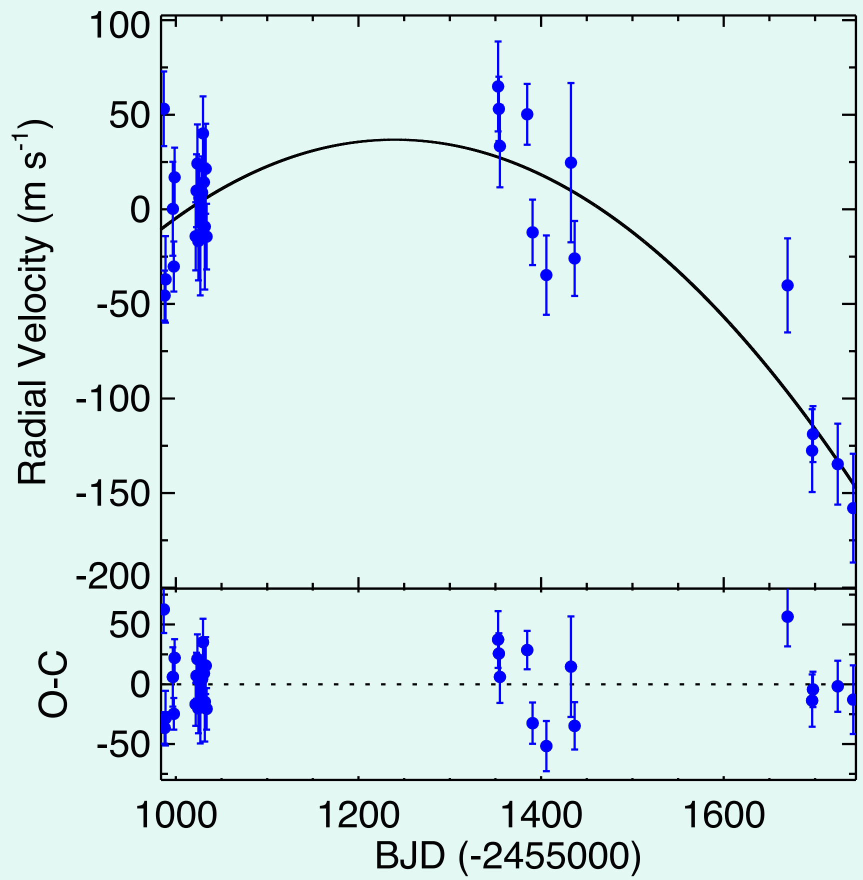
$$t_{\mathrm{cir}} = 1.6\,\mathrm{Gyr} \times \left(\frac{Q_{\mathrm{P}}}{10^6}\right) \times \left(\frac{M_{\mathrm{P}}}{M_{\mathrm{Jup}}}\right) \times \left(\frac{M_*}{M_{\mathrm{Sun}}}\right)^{-1.5} \times \left(\frac{R_{\mathrm{P}}}{R_{\mathrm{J}}}\right)^{-5} \times \left(\frac{a}{0.05\,\mathrm{AU}}\right)^{6.5} \approx 11.8\,\mathrm{Gyr}$$

(Adams & Laughlin 2006)

We call HD 285507b "dynamically young" ($t_{\mathrm{age}} < t_{\mathrm{cir}}$); it may have migrated via planet-planet scattering or Kozai cycles

A two planet system in Praesepe?
(Did c cause the migration of b?)

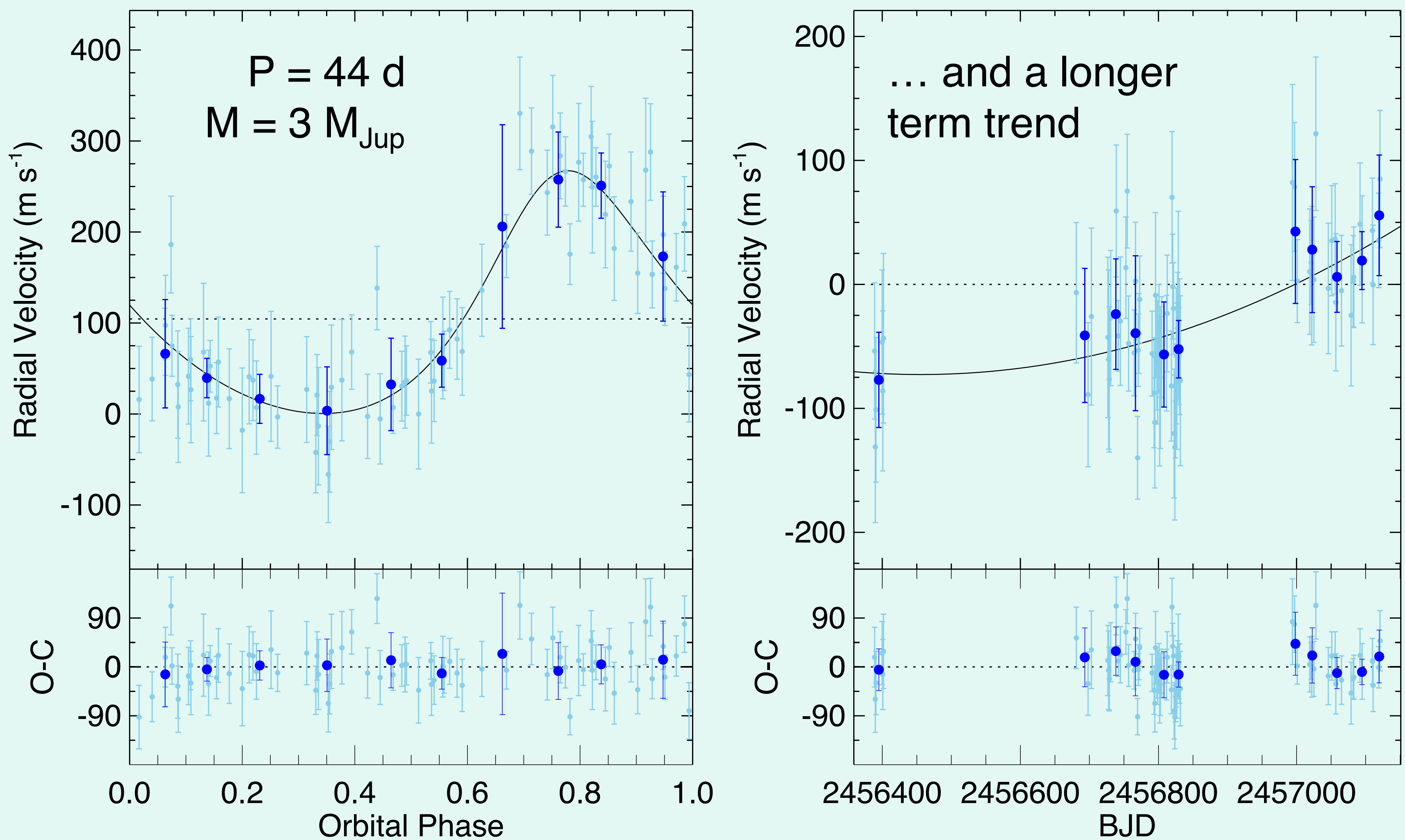




Pr0211b

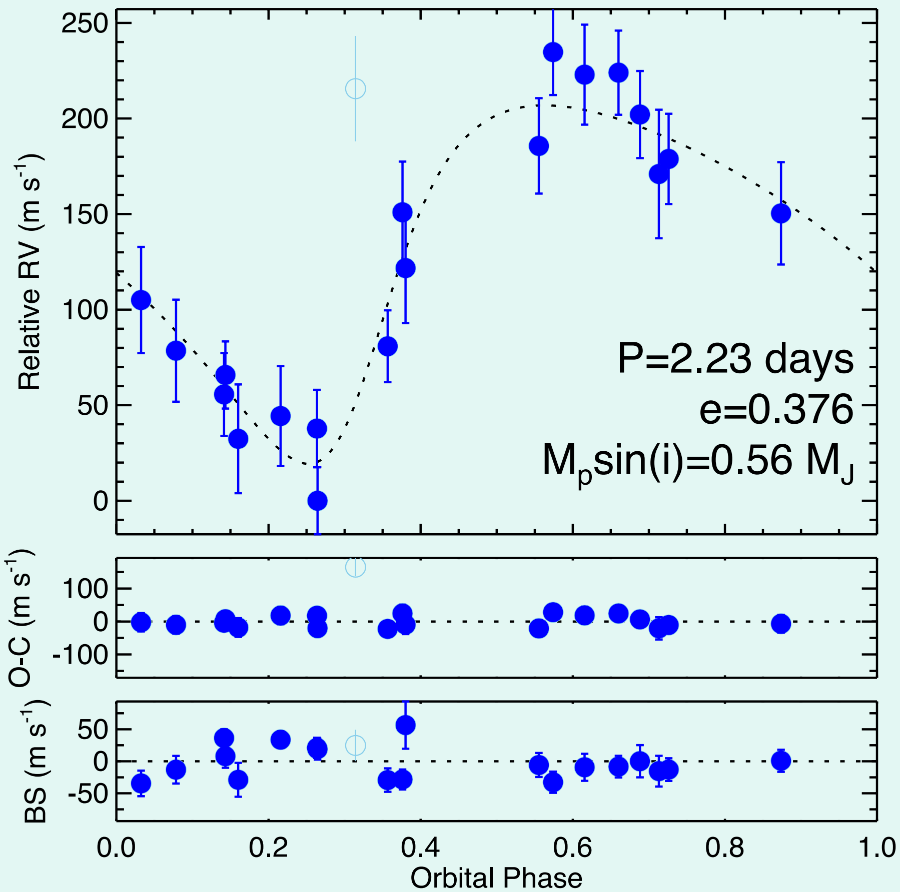
Pr0211c

A Warm Jupiter in Coma Berenices

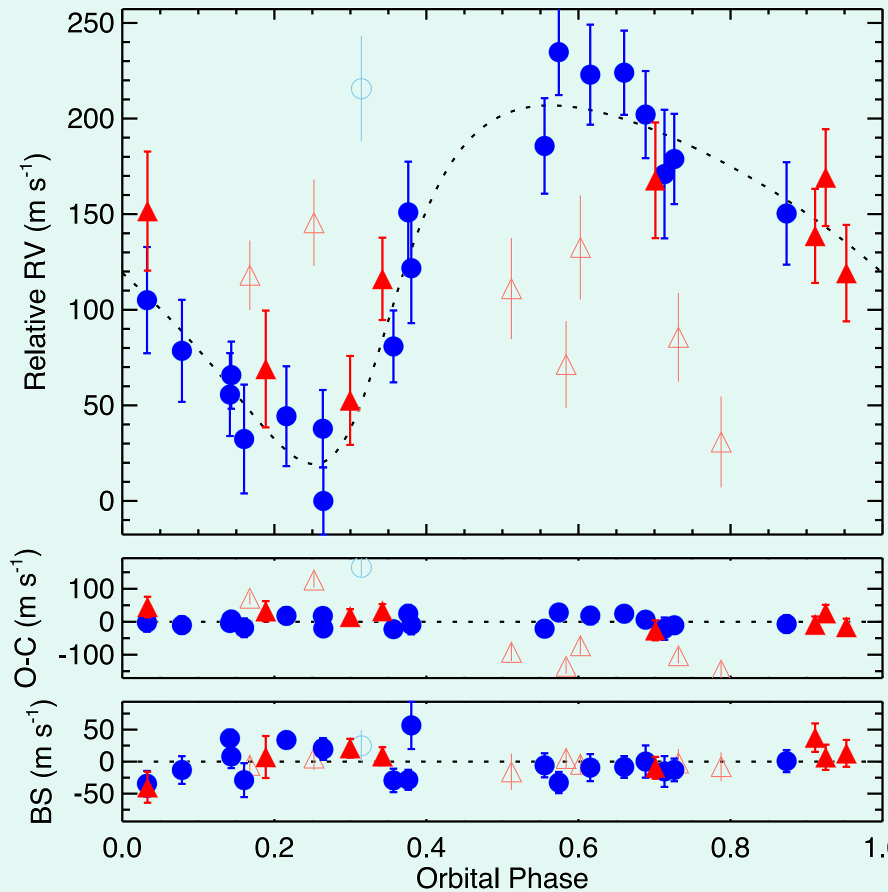


The Pleiades: stellar activity or planets?

(120 Myr)



ΔT = 93 days
N = 20



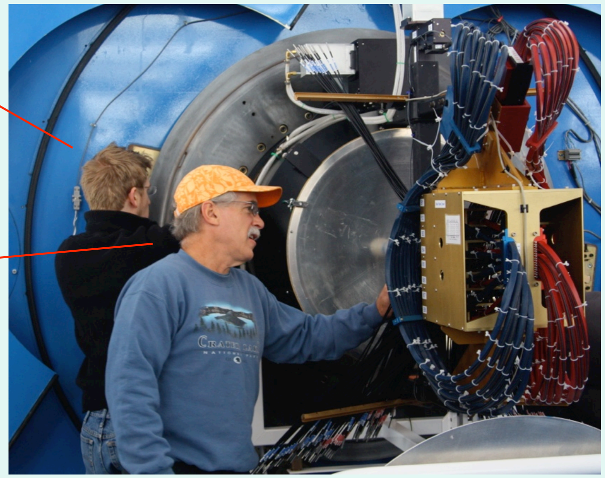
ΔT = 35 days
N = 15

John (“Jeb”) Bailey PhD Thesis

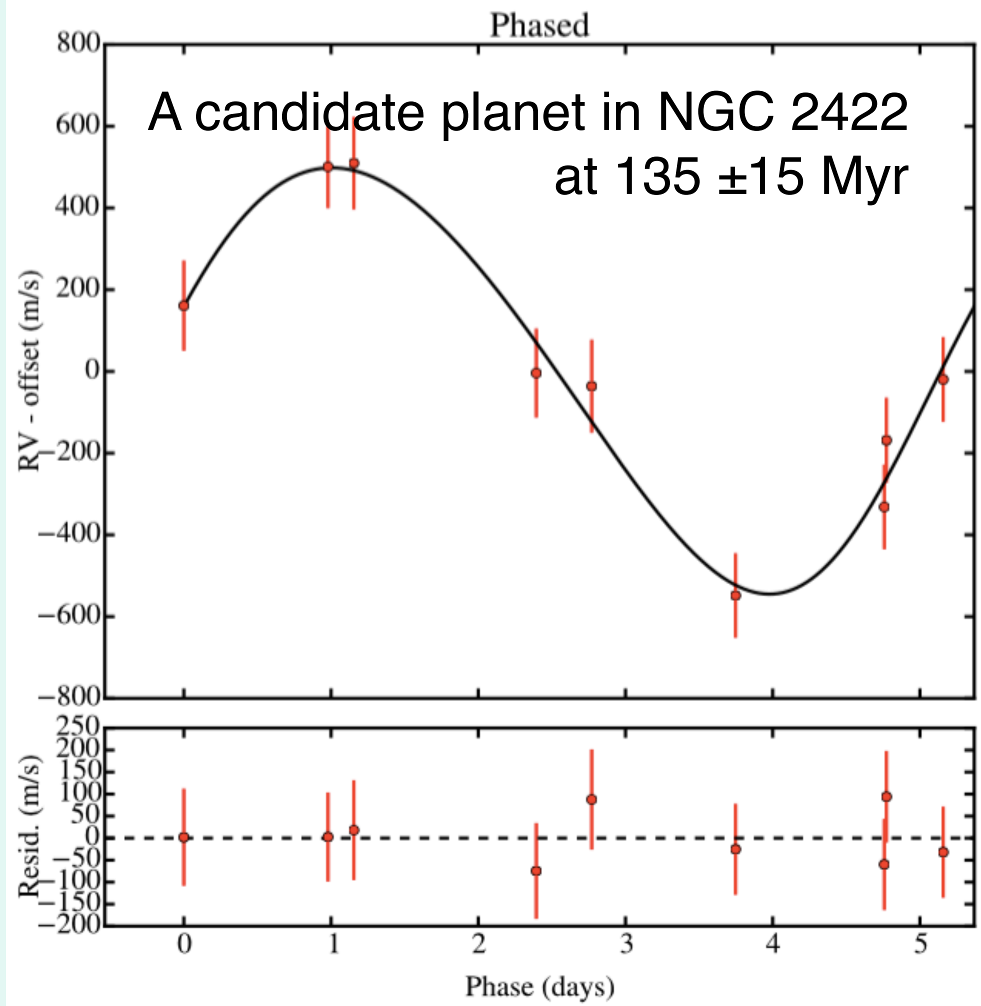
… a more efficient way to survey open clusters for planets

Jeb

Dr. Mario Mateo (adviser)



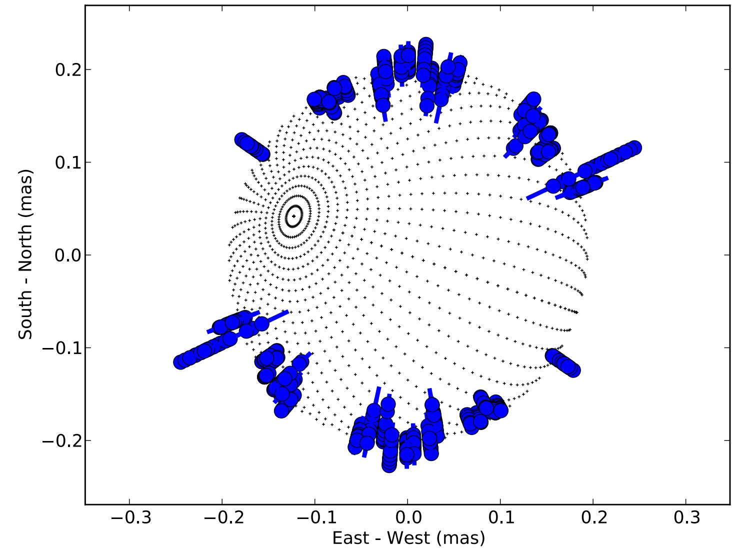
Details in Bailey, Mateo, White et al. 2015, submitted



Helped build M2FS, a multiple fiber-fed high-dispersion spectrograph for the 6.5-m Magellan Telescope (Las Campanas, Chile)

Summary

CHARA size (oblateness) measurements greatly improves age estimates of imaged planet hosts



Infrared RVs are still maturing (techniques/instruments)

- likely offer the best chance of finding the *youngest* planets

Planets exists in open clusters

- hot Jupiter frequency = $1.97^{+1.92}_{-1.07}$ %
- dynamical interaction influence migration

- on-going surveys will identify the first *transiting* hot Jupiter with precise age!