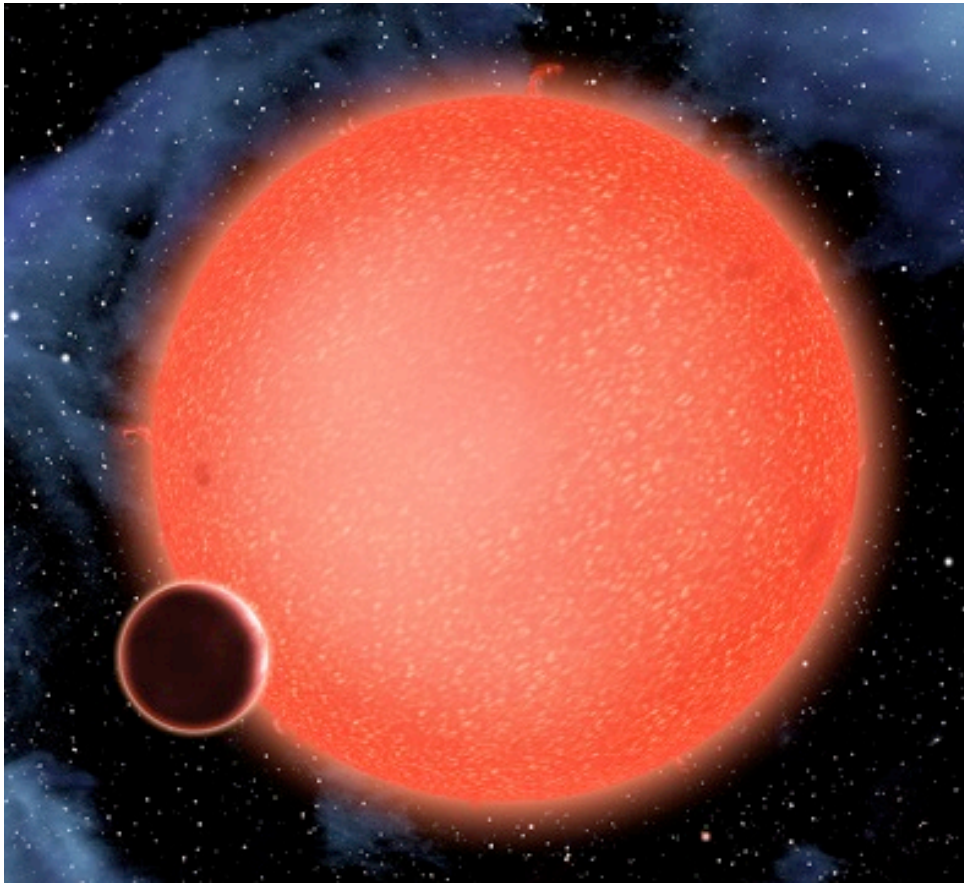
Small Planets Orbiting Small Stars



Credit: D. Aguilar - CfA

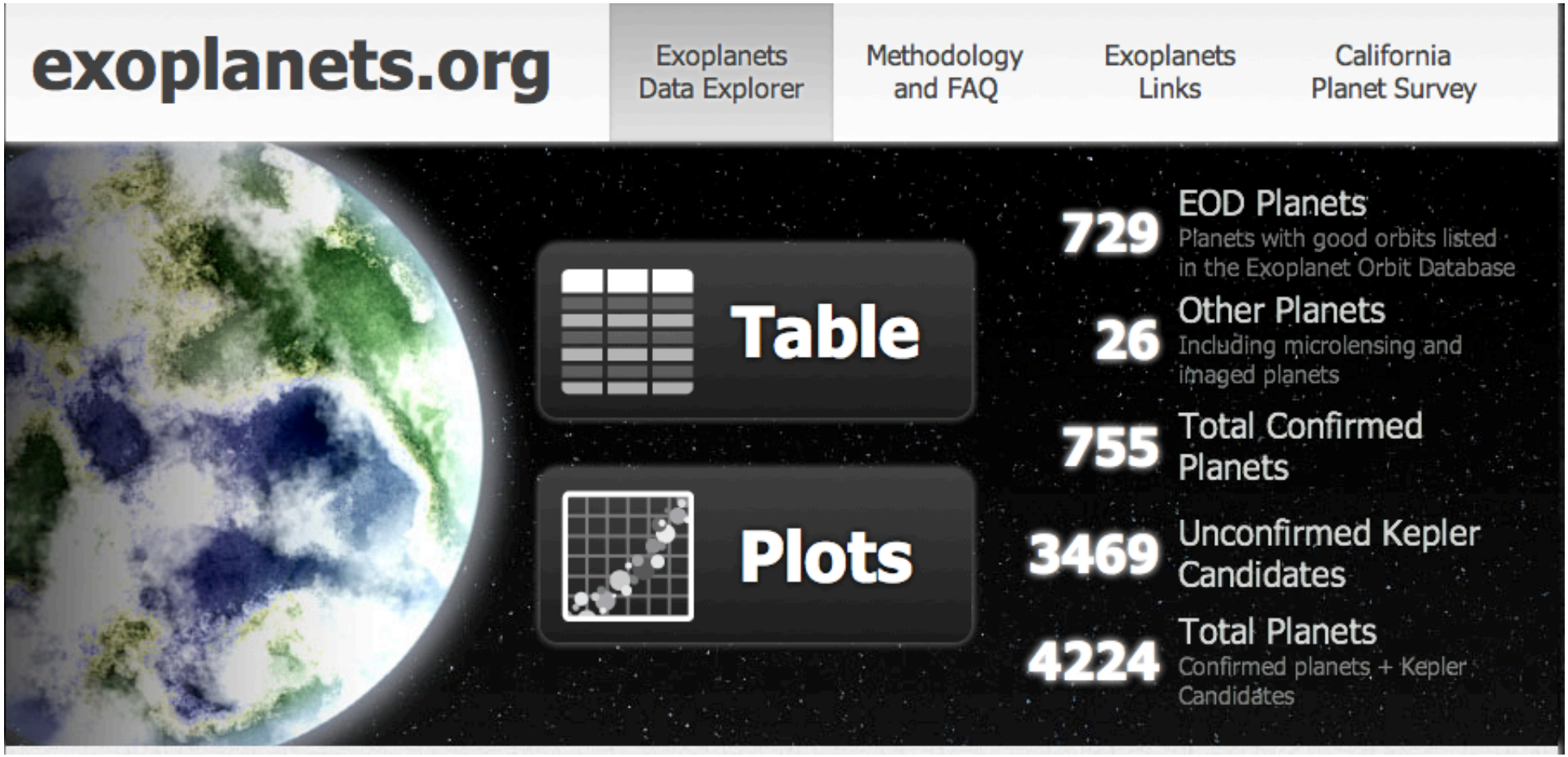
Outline

What we know about small planets orbiting small stars

What we can learn about these planets using a compact Doppler spectrometer and a small telescope

A prototype Small Red Spectrometer

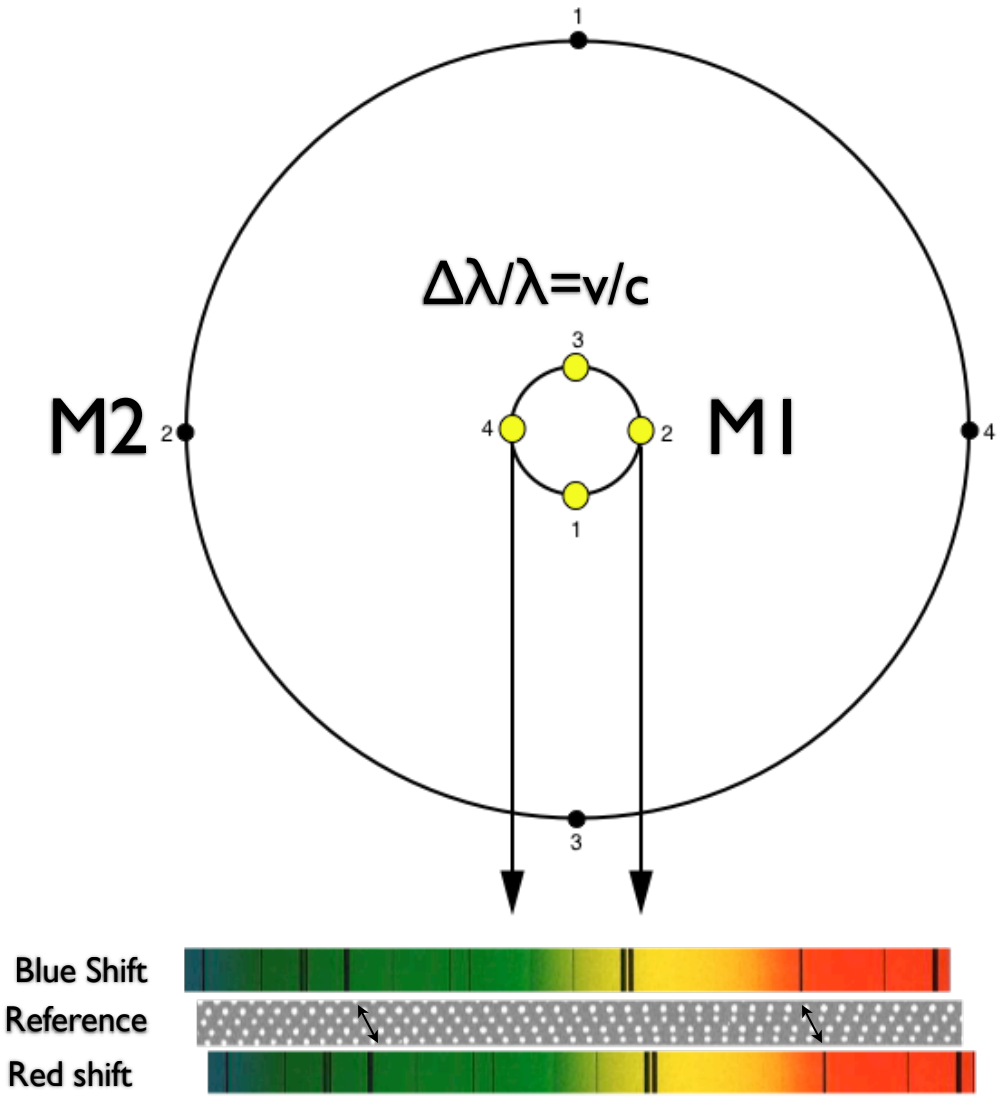
Two Decades of Discovery



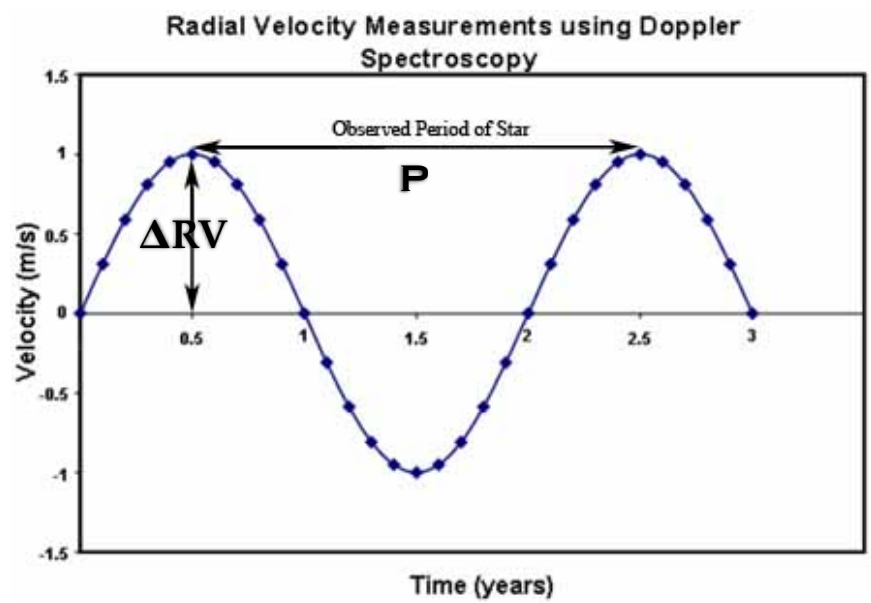
Robust statistics (for giant planets), atmospheric absorption and emission spectra, multi-planet dynamics

Doppler (RV) Method

System	ΔRV (m/s)
Sun-Jupiter	12.5
Sun-Earth	0.09

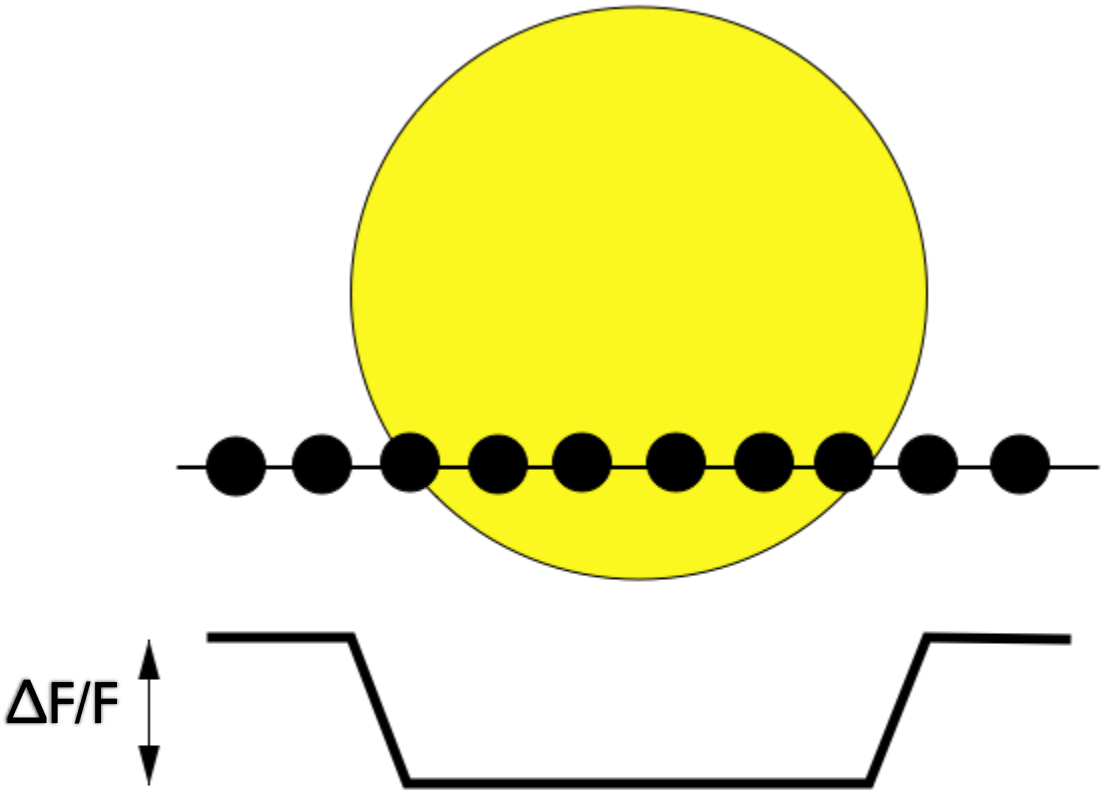


Doppler Shift



$$\Delta RV + P + M1 \rightarrow M2 \sin(i)$$

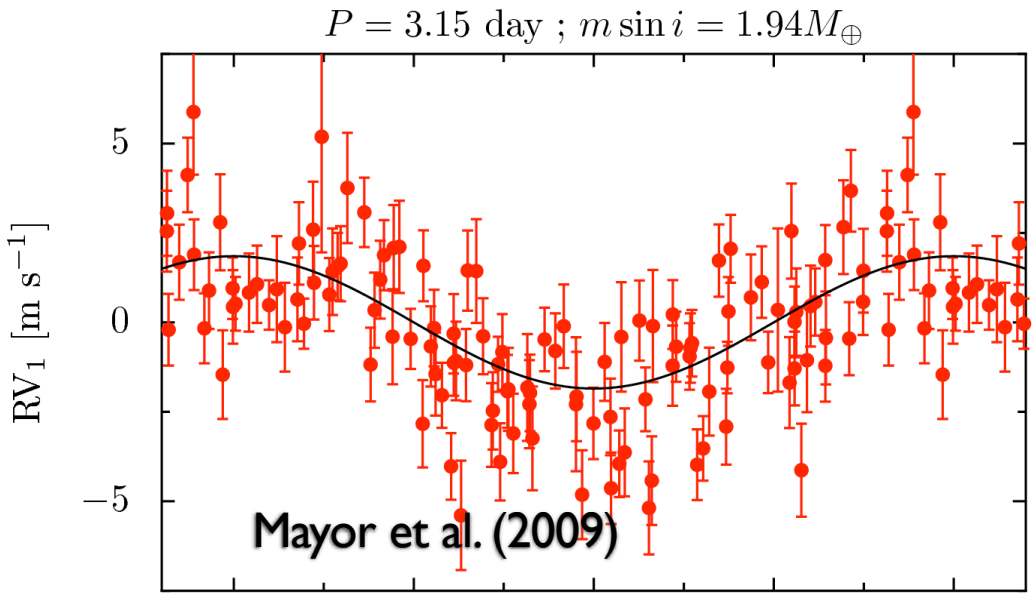
Transit Method



System	$\Delta F/F=(R_p/R_\odot)^2$
Sun-Jupiter	0.01
Sun-Earth	0.00008
Proxima-Earth	0.004

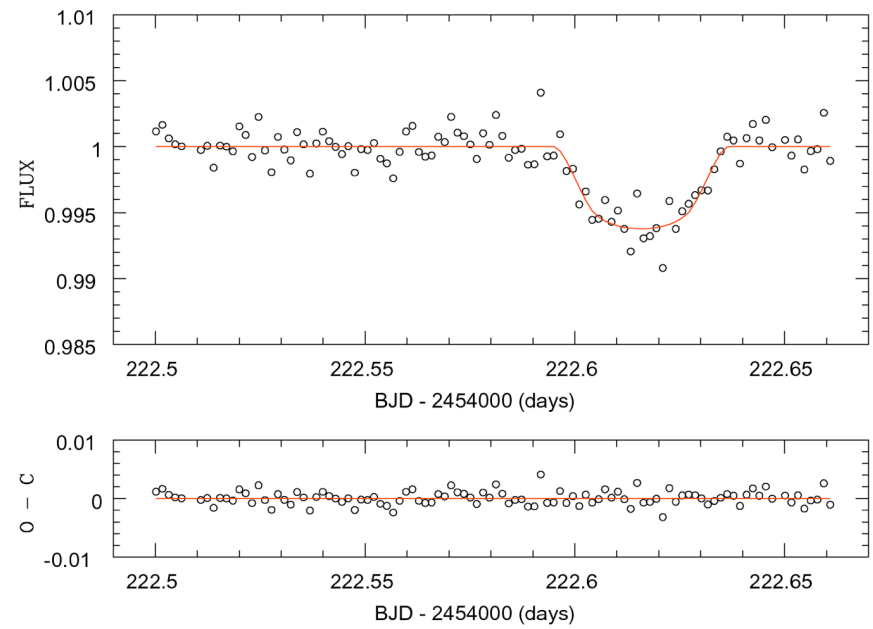
HAT, WASP, COROT, OGLE, TrES, XO, *Kepler*

Low-mass Star Advantages



Super-Earth orbiting Gl581 (M3)

$$\frac{\Delta RV = M_*^{(-2/3)}}{\text{Fixed P}}$$

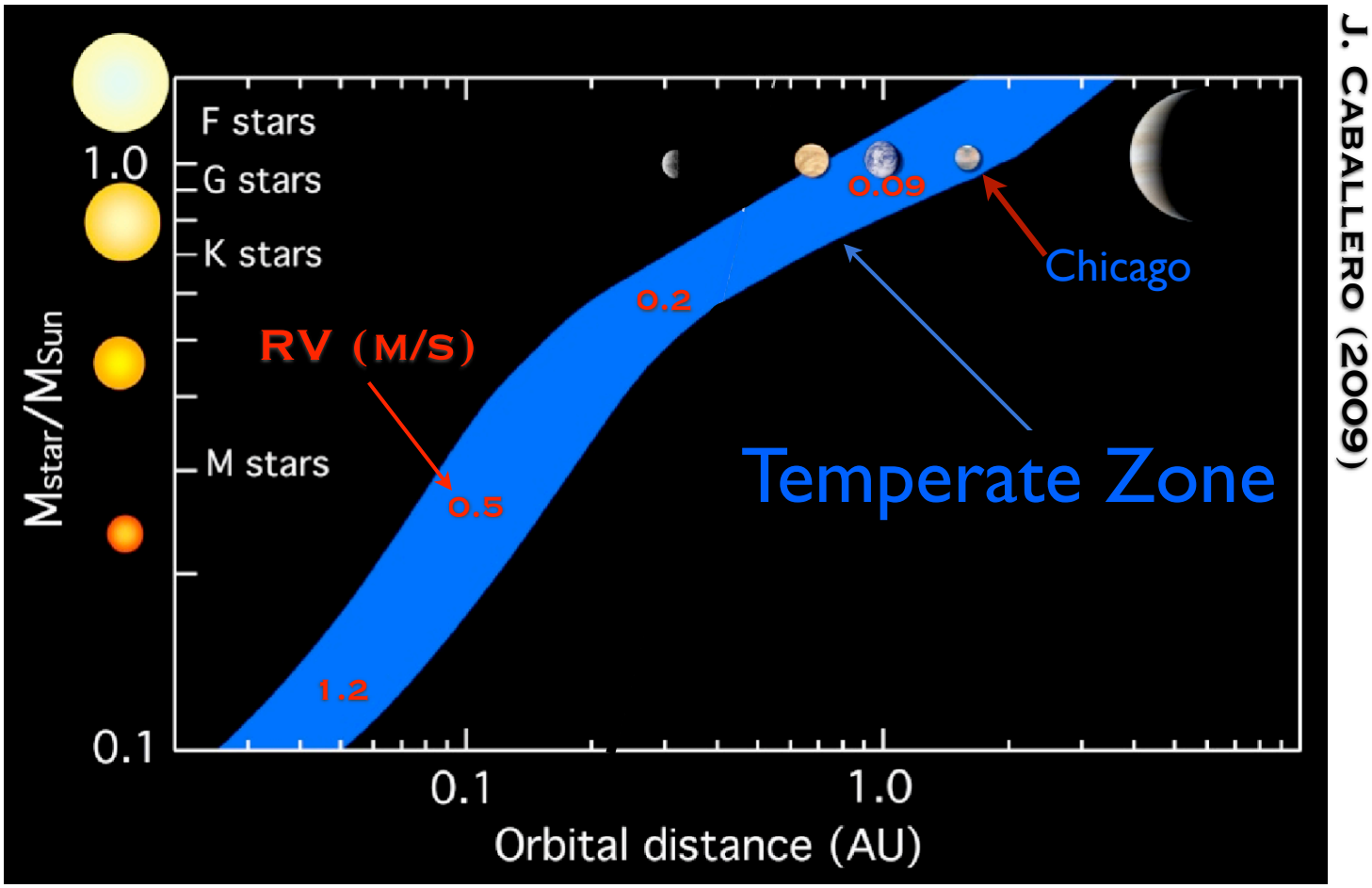


Gillon et al. (2007)

Exo-Neptune transiting
GJ 436 (M2.5)

It is possible to detect <u>small</u> planets that are currently undetectable (from the ground) orbiting Sun-like stars

Low-mass Star Advantages



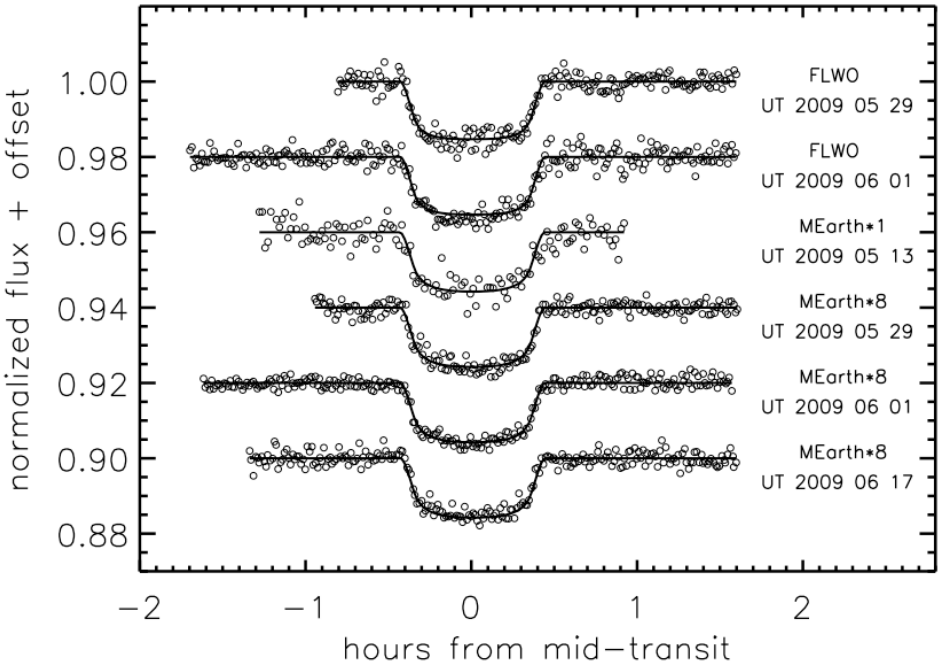
J. CABALLERO (2009)

$$\Delta RV_{TZ} = M_*^{(-11/8)}$$

Planets in the Temperate Zone are detectable with current technology (from the ground)

Temperate Zone = similar insolation to Earth today - "liquid water zone"

Many Exciting Discoveries



GJ 1214 - MEarth Project - Charbonneau, Berta et al. (2009)

CHARACTERIZING THE COOL KOIs III. KOI-961: A SMALL STAR WITH LARGE PROPER MOTION AND THREE SMALL PLANETS

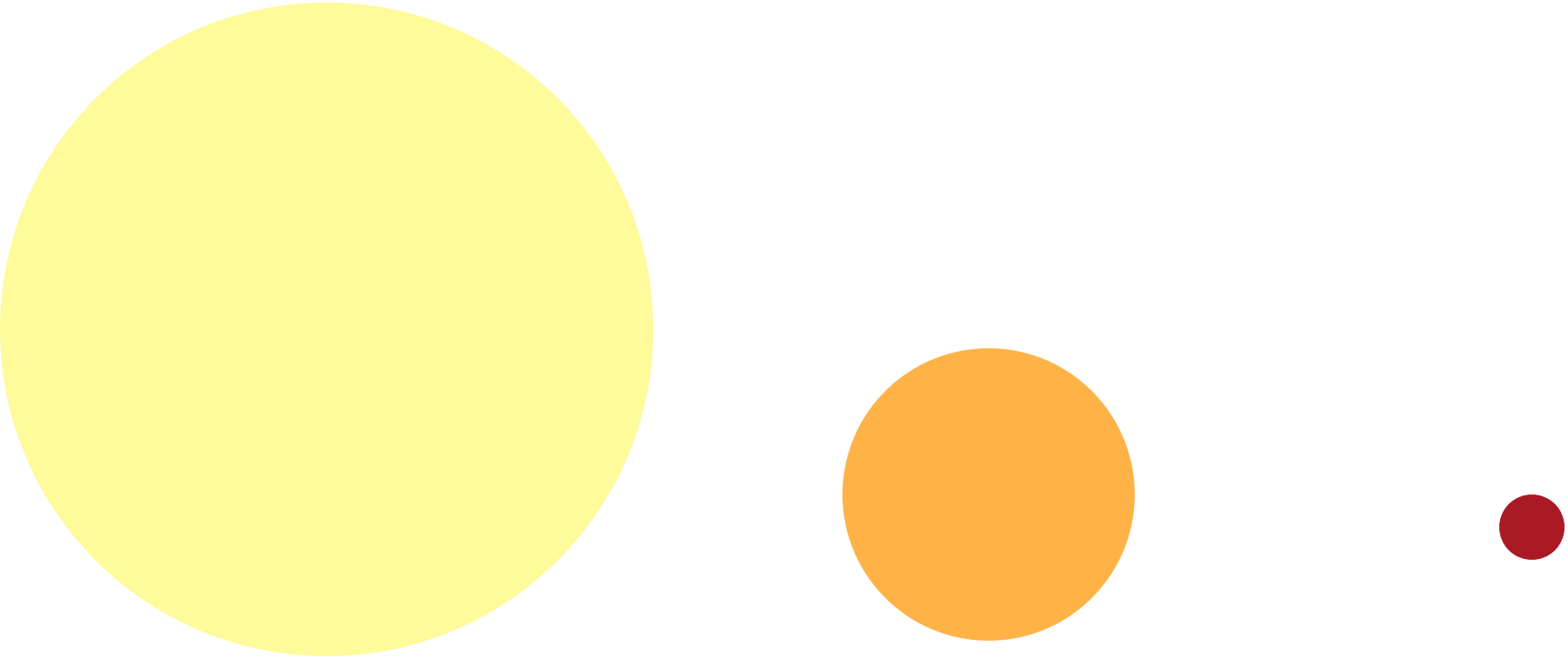
Philip S. Muirhead,[1,2] John Asher Johnson,[1,14] Kevin Apps,[3] Joshua A. Carter,[4,5] Timothy D. Morton,[1] Daniel C. Fabrycky[6,5], J. Sebastian Pineda,[1] Michael Bottom,[1] Bárbara Rojas-Ayala,[7] Everett Schlawin,[8] Katherine Hamren,[6] Kevin R. Covey,[8,5] Justin R. Crepp,[1] Keivan G. Stassun,[9, 10, 11] Joshua Pepper,[9] Leslie Hebb,[9] Evan N. Kirby,[1,5] Andrew W. Howard,[12] Howard T. Isaacson,[12] Geoffrey W. Marcy,[12] David Levitan,[1] Tanio Diaz-Santos,[13] Lee Armus,[13] James P. Lloyd[8]

(Dated:)
Draft version January 12, 2012

Transiting Mars-sized Planet From *Kepler* Data

Small Stars - “M Dwarfs”

Radii to Scale

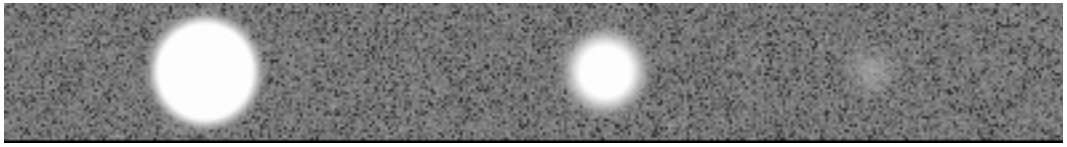


The Sun	M0 Dwarf	M5 Dwarf
M=1.0	M=0.6	M=0.12
R=1.0	R=0.5	R=0.14
T=5800K	T=3900K	T=3050K

M Dwarfs - Faint and Red

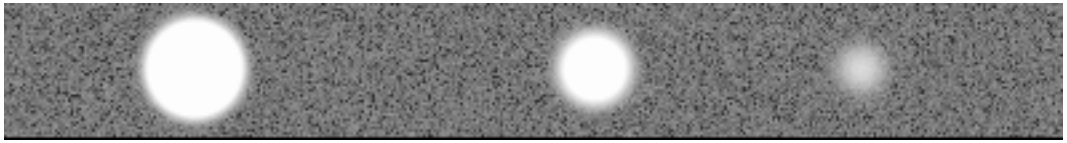
Simulated Images of Stars
Fixed Exposure Times - Same Distances

G0V M0V M5V



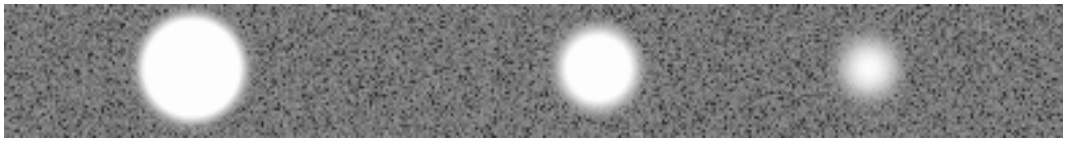
g band - 477 nm

1 : 1/160 : 1/25,000 ⟵ Relative brightnesses



i band - 763 nm

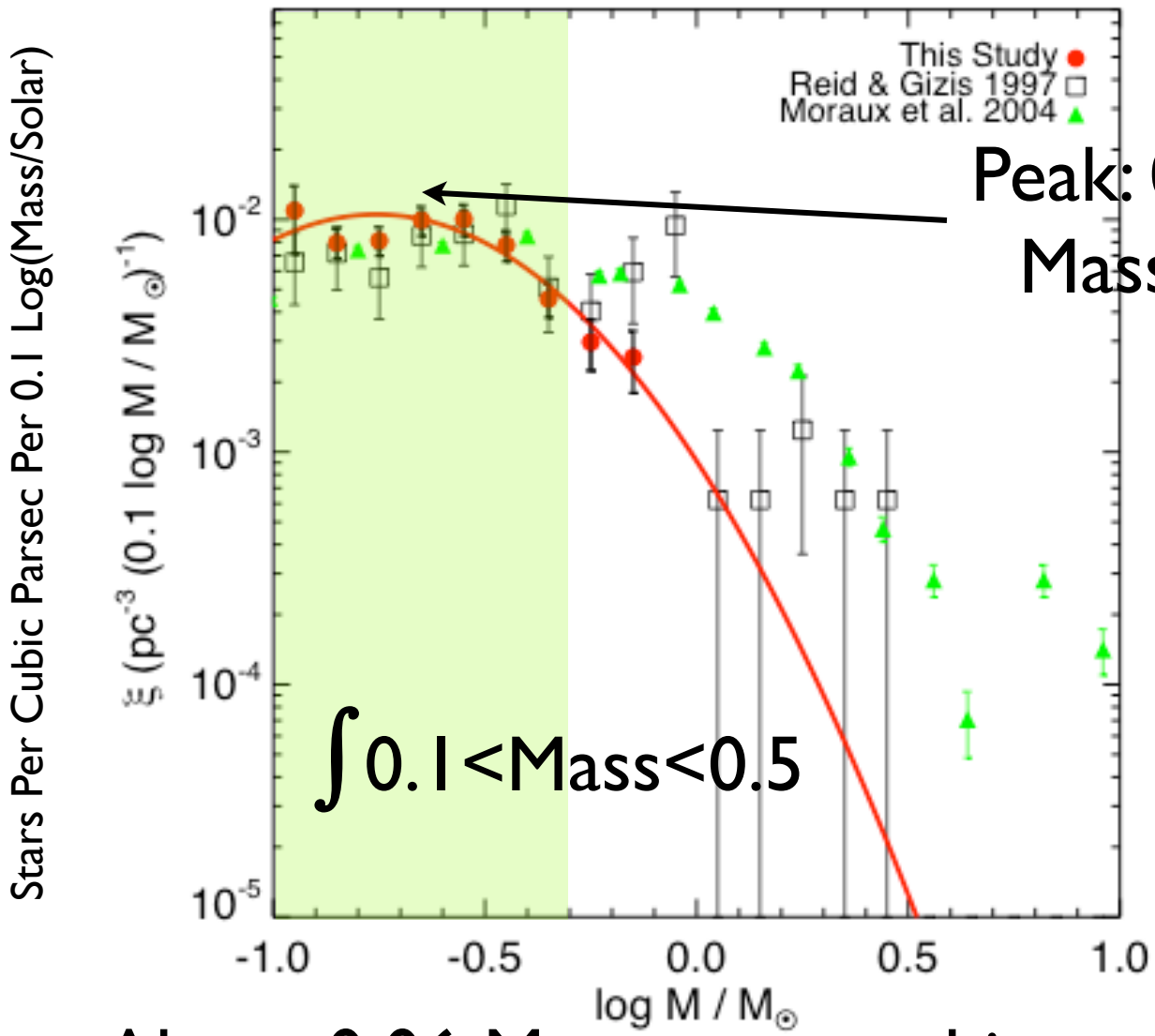
1 : 1/63 : 1/3,300



J band - 1252 nm

1 : 1/48 : 1/1,100

Strength in Numbers



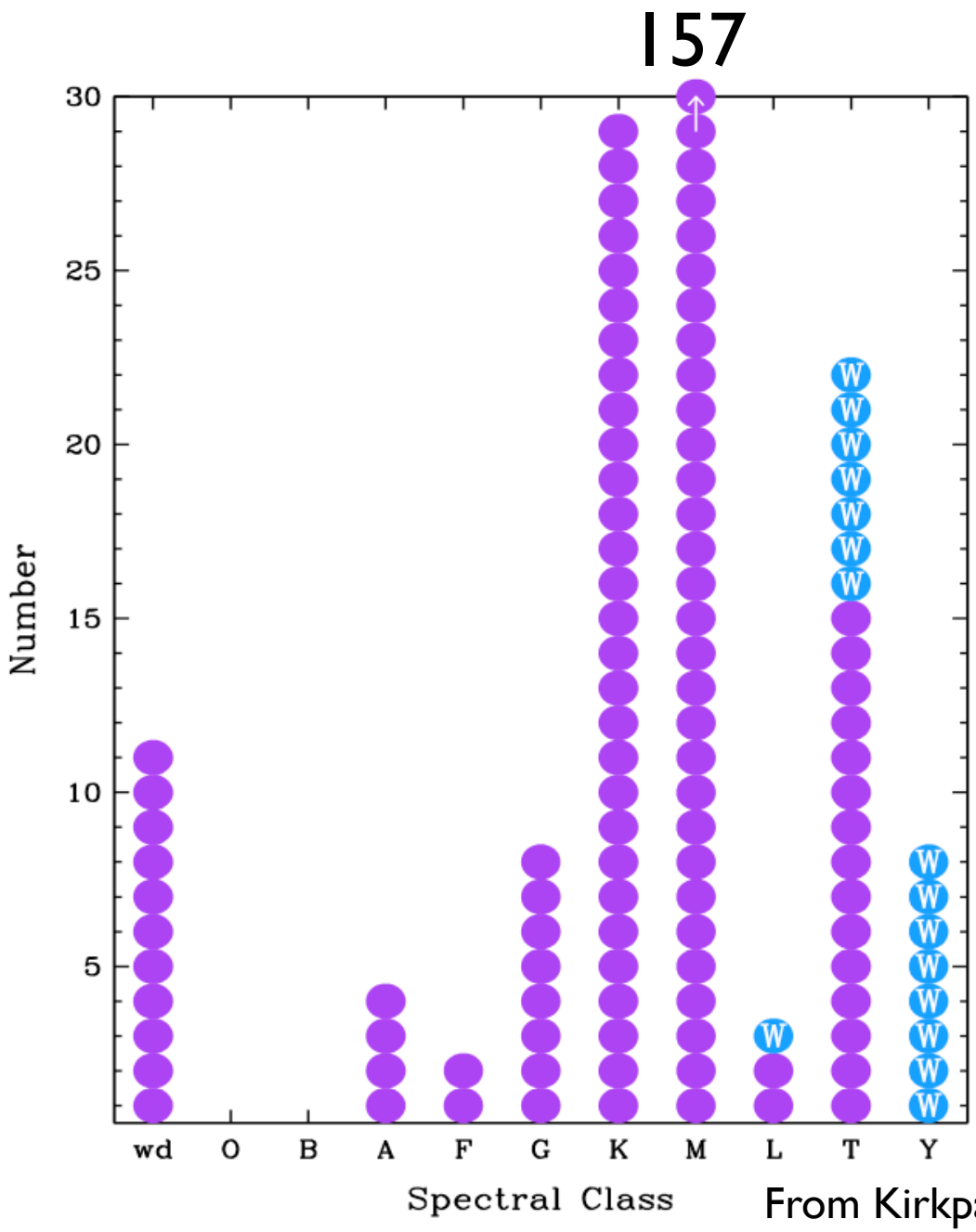
Peak: 0.25 Solar Mass; ~"M4"

About 0.06 M stars per cubic parsec

Single (Field, Disk) Star Mass Function - Bochanski et al. (2010, AJ, 139, 267)

Strength in Numbers

Tally of stars within 8 pc of the Sun



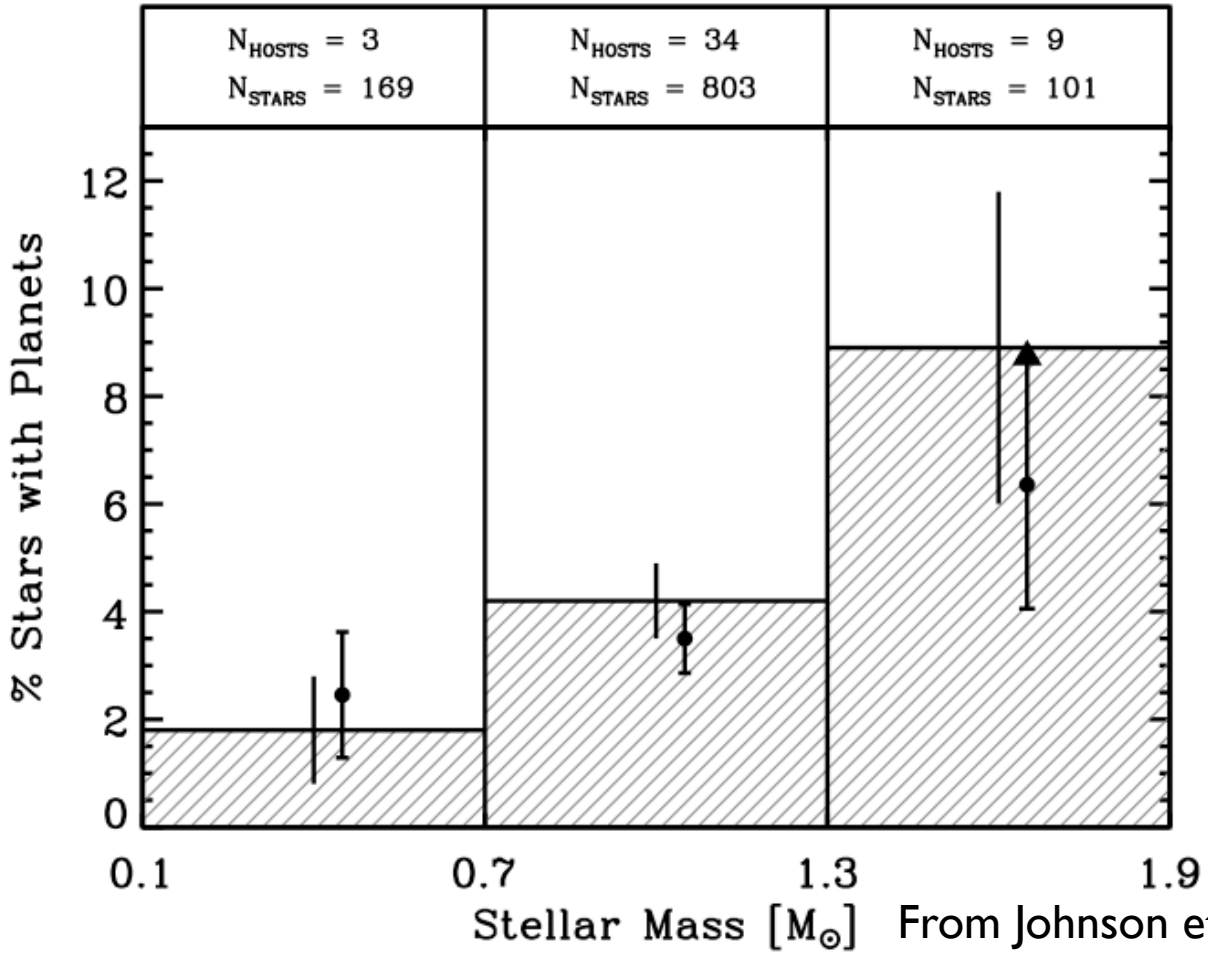
From Kirkpatrick 2013 (AN, 334, 36)

~200 Hydrogen Burning Stars

79% M stars
15% K stars
4% G stars

A few even added in the last couple of years!

Few (Large) Planets



From Johnson et al. 2007, AJ, 670,833

Parameter Space:

M*sini*>0.8 Jupiter

a<2.5AU

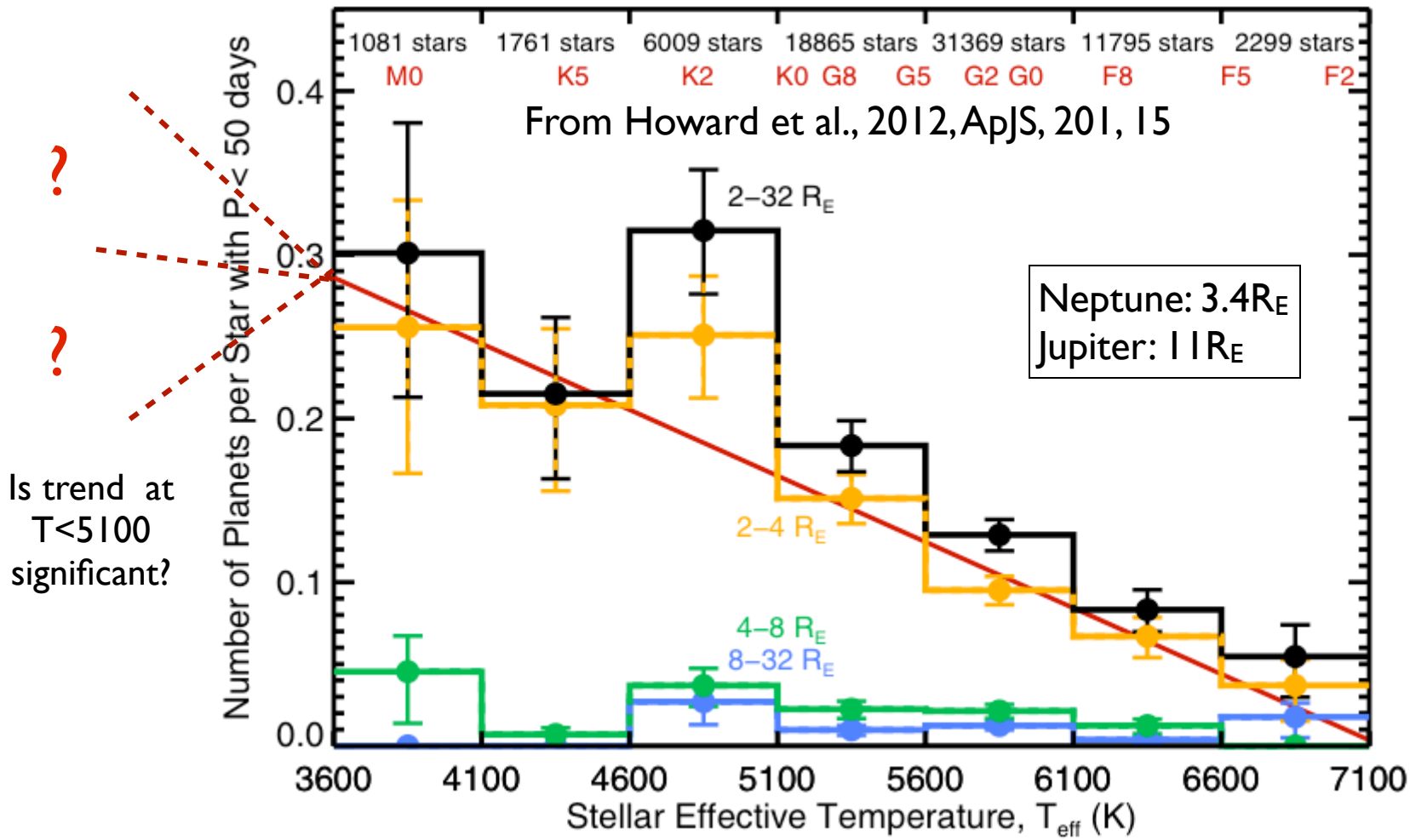
Lone Example of M star "Hot Jupiter"?

Johnson et al. (2012, AJ, 143, 111)

CHARACTERIZING THE COOL KOIs. II. THE M DWARF KOI-254 AND ITS HOT JUPITER*

John Asher Johnson[1,2], J. Zachary Gazak[3], Kevin Apps[4], Philip S. Muirhead[1], Justin R. Crepp[1], Ian J. M. Crossfield[5], Tabetha Boyajian[6,11], Kaspar von Braun[2], Barbara Rojas-Ayala[7], Andrew W. Howard[8], Kevin R. Covey[9,11], Everett Schlawin[9], Katherine Hamren[10], Timothy D. Morton[1], Geoffrey W. Marcy[8], and James P. Lloyd[9]

Plentiful (Small) Planets



Based on early *Kepler* data

Plentiful (Small) Planets

Super-Earths and Mini-Neptunes Orbiting M Stars Are Common:
greater than 60% for P<100d

$m \sin i$ $[M_\oplus]$	*f*: fraction of stars with planets — Period [day] 1–10	10–10^2	10^2–10^3	10^3–10^4
10^3–10^4	$N_d = 0$	$N_d = 0$	$N_d = 0$	$N_d = 0$
–	$N_{eff} = 96.83$	$N_{eff} = 95.83$	$N_{eff} = 94.29$	$N_{eff} = 87.99$
–	$f < 0.01(1\sigma)$	$f < 0.01(1\sigma)$	$f < 0.01(1\sigma)$	$f < 0.01(1\sigma)$
10^2–10^3	$N_d = 0$	$N_d = 2$	$N_d = 0$	$N_d = 2$
–	$N_{eff} = 92.18$	$N_{eff} = 88.54$	$N_{eff} = 81.51$	$N_{eff} = 53.77$
–	$f < 0.01(1\sigma)$	$f = 0.02^{+0.03}_{-0.01}$	$f < 0.01(1\sigma)$	$f = 0.04^{+0.05}_{-0.01}$
10–10^2	$N_d = 2$	$N_d = 0$	$N_d = 0$	$N_d = 0$
–	$N_{eff} = 69.76$	$N_{eff} = 51.96$	$N_{eff} = 30.75$	$N_{eff} = 9.47$
–	$f = 0.03^{+0.04}_{-0.01}$	$f < 0.02(1\sigma)$	$f < 0.04(1\sigma)$	$f < 0.12(1\sigma)$
1–10	$N_d = 5$	$N_d = 3$	$N_d = 0$	$N_d = 0$
–	$N_{eff} = 13.97$	$N_{eff} = 5.79$	$N_{eff} = 1.53$	$N_{eff} = 0.03$
–	$f = 0.36^{+0.24}_{-0.10}$	$f = 0.52^{+0.50}_{-0.16}$	–	–

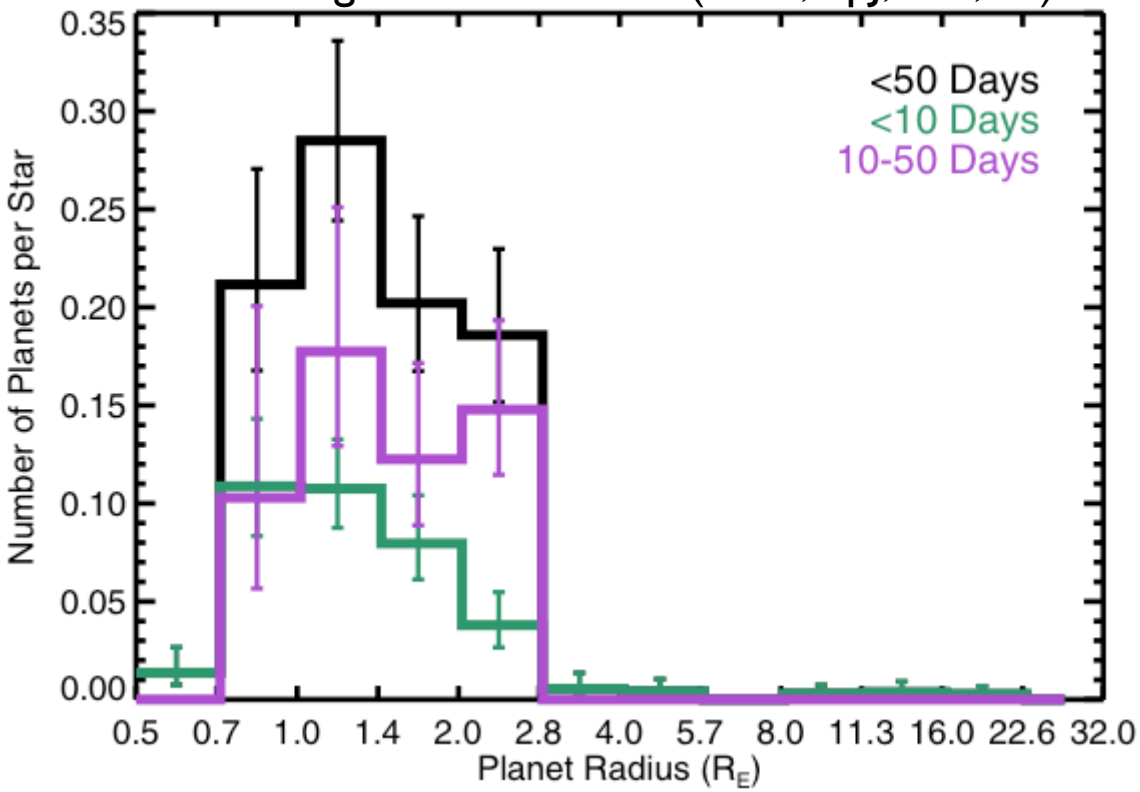
Neptune = 17 M_E - Jupiter=317 M_E

From HARPS M Dwarf RV Data

Planets Found Orbiting M Dwarfs (500 hours of observations!)
Bonfils et al. (2013, 549, 109)

Plentiful (Small) Planets

Dressing & Charbonneau (2013, ApJ, 767, 95)



From *Kepler* data

Similar results for stars ~3500K (M1) or ~3700 (~M0)

For P<50 days, R_P<3R_E (Sub-Neptune)

<u>90% of *Early* M stars have a small planet!!!</u>

(One of the most exciting results from *Kepler* data?)

<u>See Also: Morton & Swift 2013</u>

Simulating Small Star Planets

<u>Assumptions:</u>

1) Stars within 20 parsecs, observed Mass Function

2) Rough Mass --> Radius --> Teff --> Sp. Typ. Conversions

3) Uniform planet occurrence rate for 0.08 to 0.5 Solar Mass stars: f=0.6

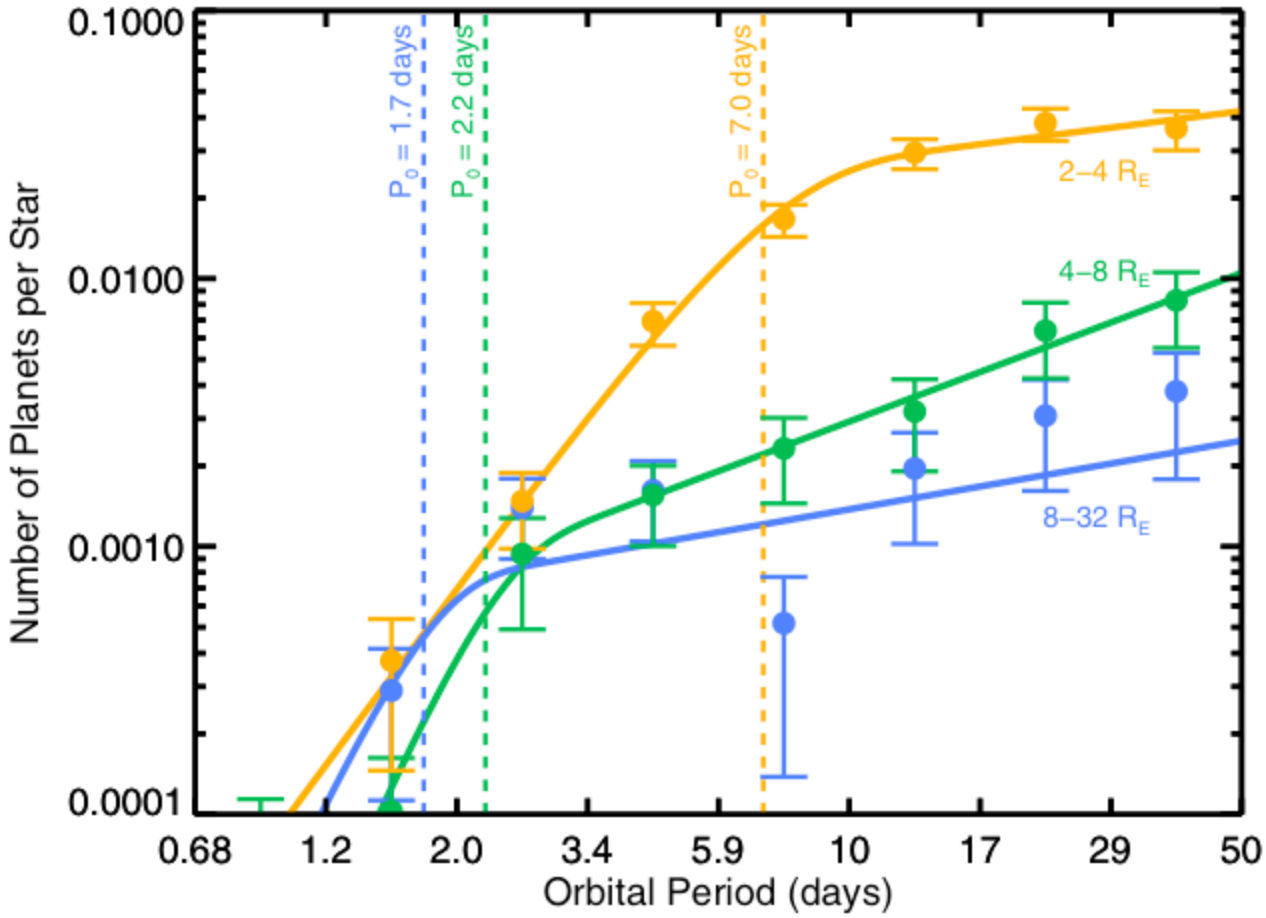
4) Uniform (in log) planet size distribution: $0.7<R_p<2.0\ R_E$

5) Power-law period Distribution: $1 < P < 50$ days

6) Planets mass-radius relation: $R \propto M^{0.27}$

Planet Period Distribution

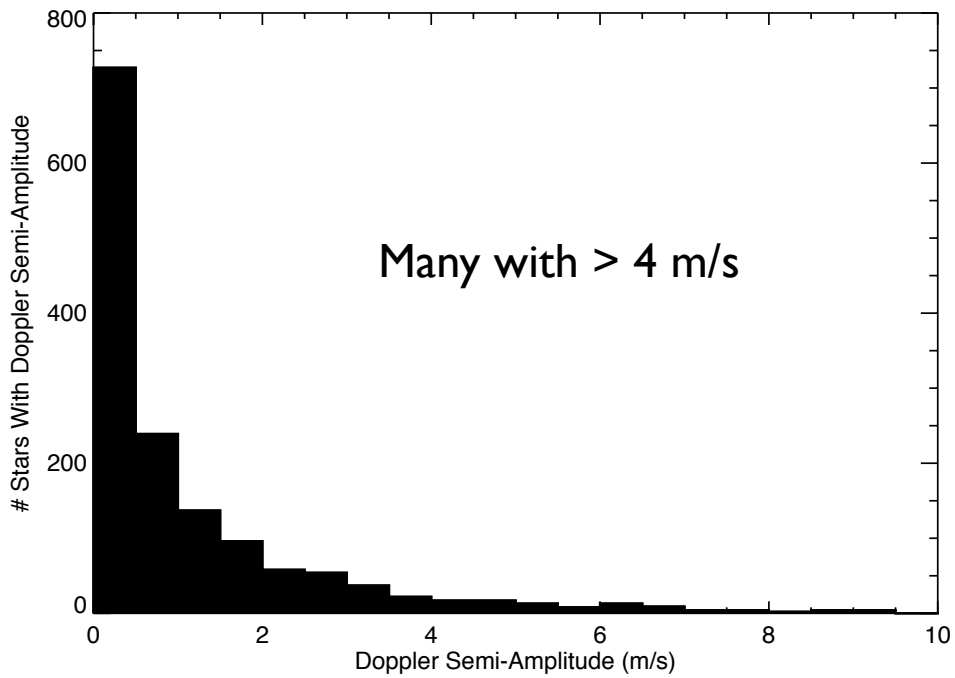
From Howard et al., 2012, ApJS, 201, 15



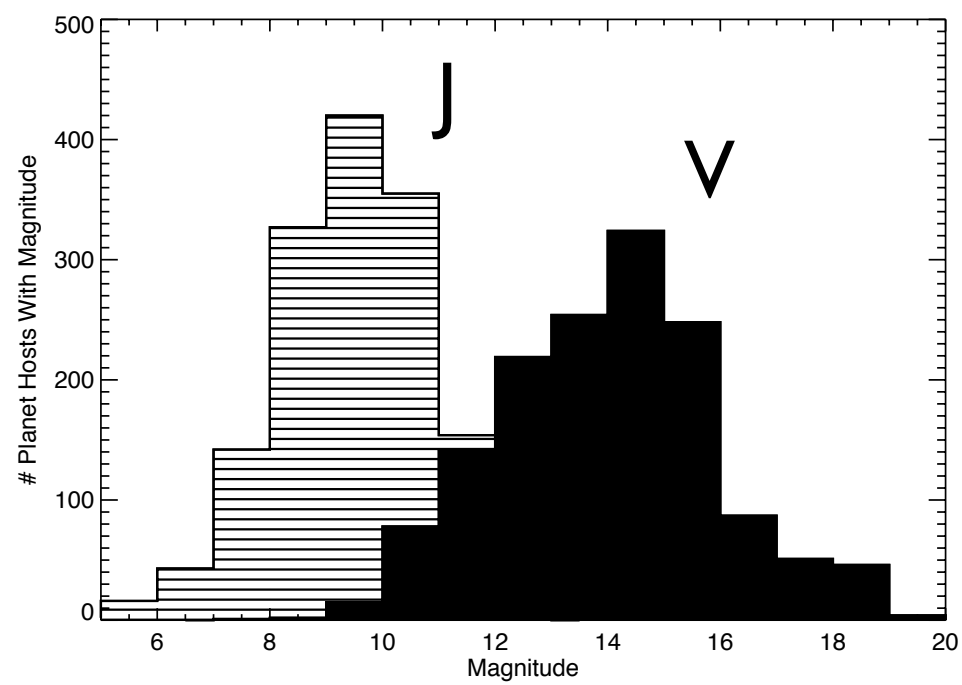
$$\frac{df(P)}{d\log P} = k_P P^{\beta}(1 - e^{-(P/P_0)^{\gamma}}).$$

I'm assuming this is valid for low-mass stars

Simulated Small Star Planet Population



Distribution of Doppler wobbles

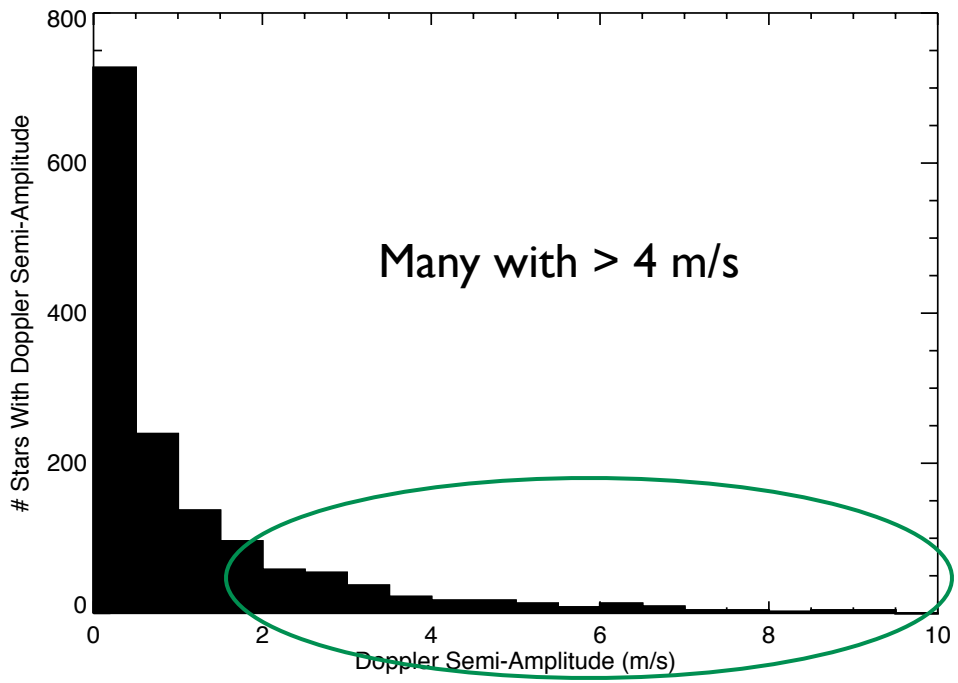


Host Magnitudes

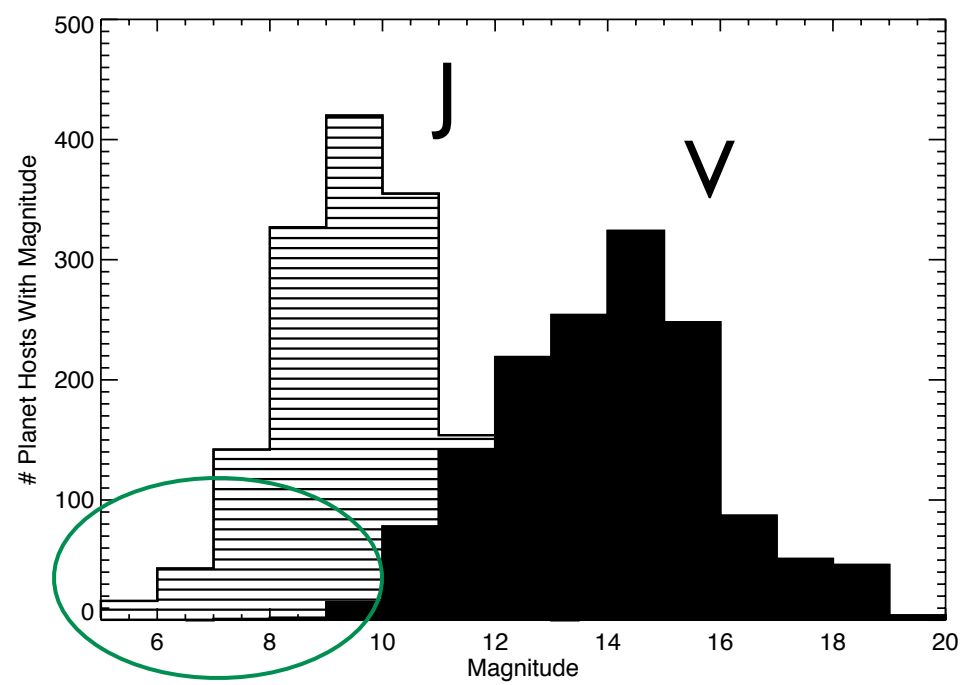
Simulate stellar population, planet population, predict Doppler (transit) signals

1471 small ($P<50$ - $1<R<2$ R_E) planets orbiting small stars within 20 pc of the Sun

Simulated Small Star Planet Population



Distribution of Doppler wobbles

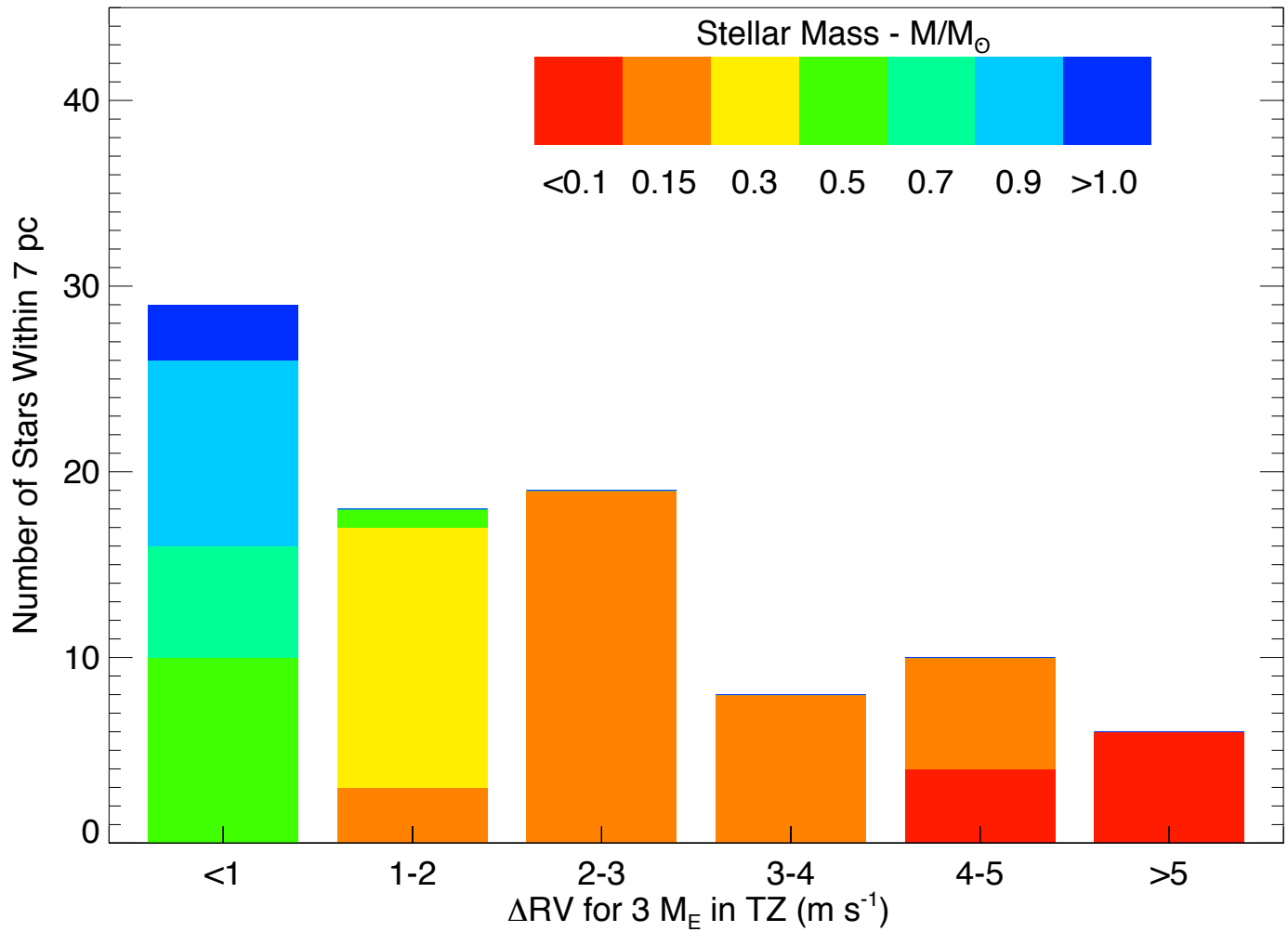


Host Magnitudes

Simulate stellar population, planet population, predict Doppler (transit) signals

1471 small ($P<50$ - $1<R<2$ R_E) planets orbiting small stars within 20 pc of the Sun

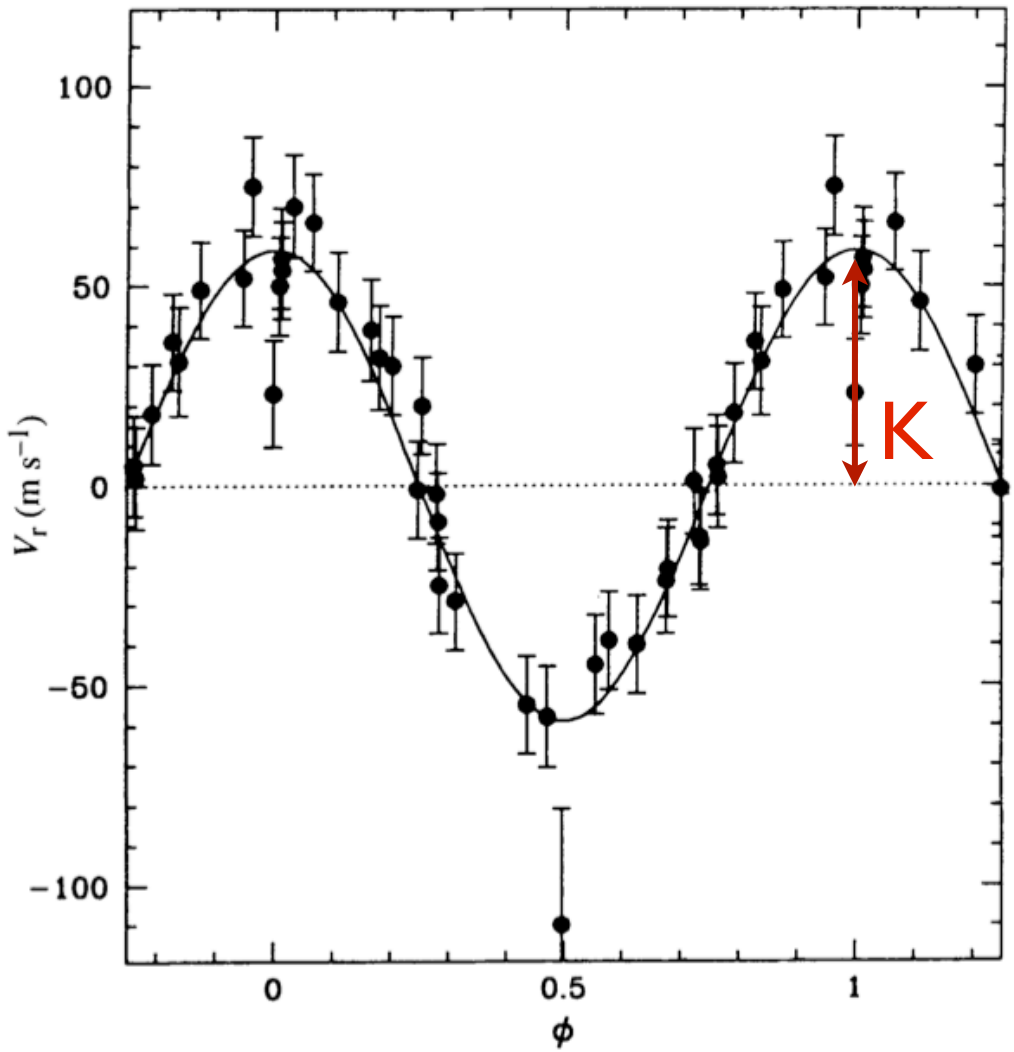
Our Nearest Neighbors



All the (main sequence) stars within 7 pc of the Sun

The Doppler wobble for a 3 Earth mass companion in TZ

What Constitutes "Detection"?



From Mayor & Queloz (1995, Nature, 378, 355)

Semi-Amplitude: K=59 m/s

Number Obs: 35

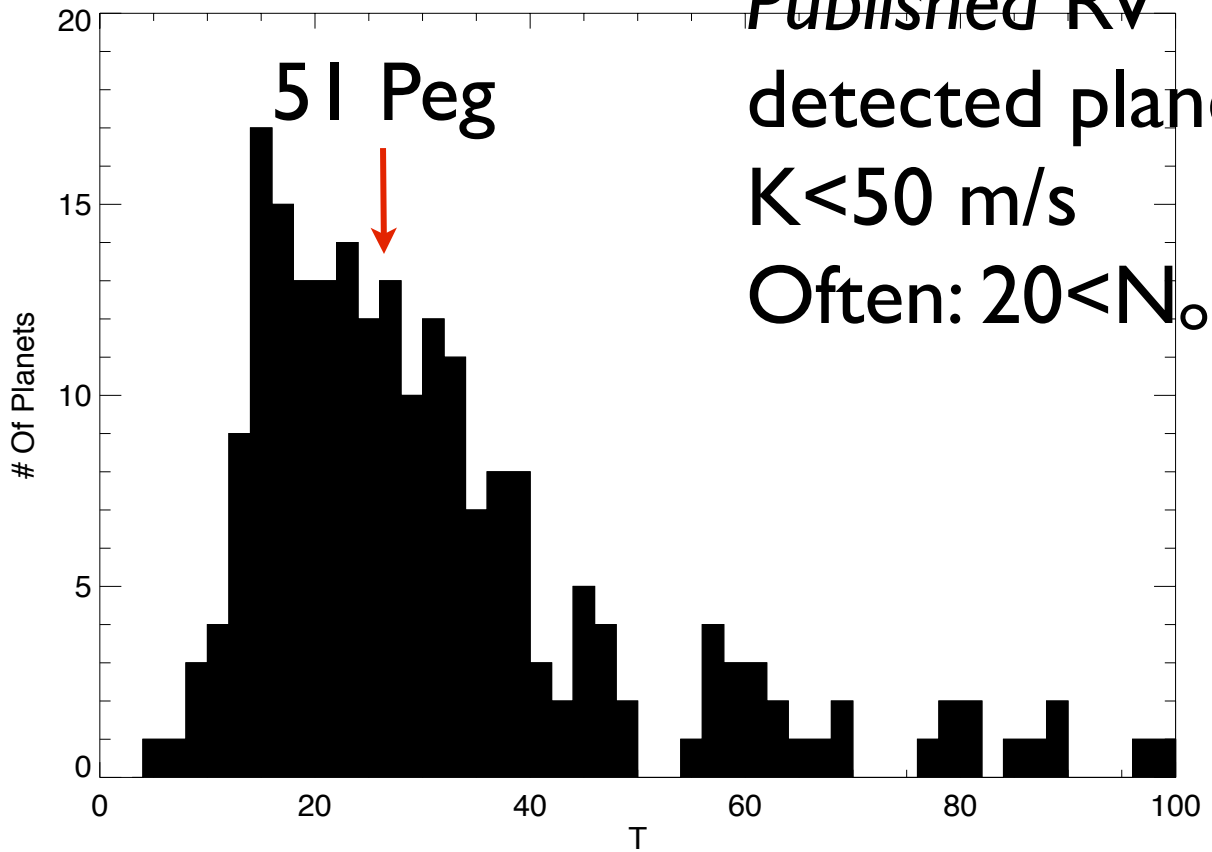
RMS Residuals: σ=13 m/s

Figure of Merit:

$$T = \frac{K}{\sigma / \sqrt{N}}$$

T=27 for 51 Peg discovery

What Constitutes "Detection"?



Published RV detected planets

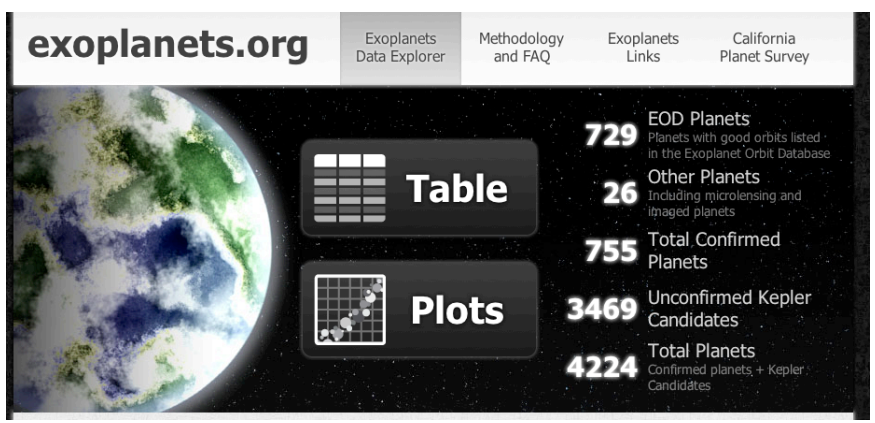
K<50 m/s

Often: $20<N_{obs}<60$

Caveats:

T presumably smaller for 2nd planet in a system

Not just discovery RVs



Doppler Precision?

Limited by star, instrument, and telescope time

$$\sigma_{RV} \propto \frac{1}{SNR}\frac{1}{R}\frac{1}{Q}\frac{1}{\sqrt{B}}\left(v\sin i\right)^2$$

SNR - Signal to Noise per resolution element ($N\gamma^{1/2}$)
Q - "Quality Factor"
R - Resolution - $\lambda/\Delta\lambda$ (might be more like $R^{-1.3}$)
B - Bandwidth of spectrum
vsini - Projected Rotation (fast rotation is bad)

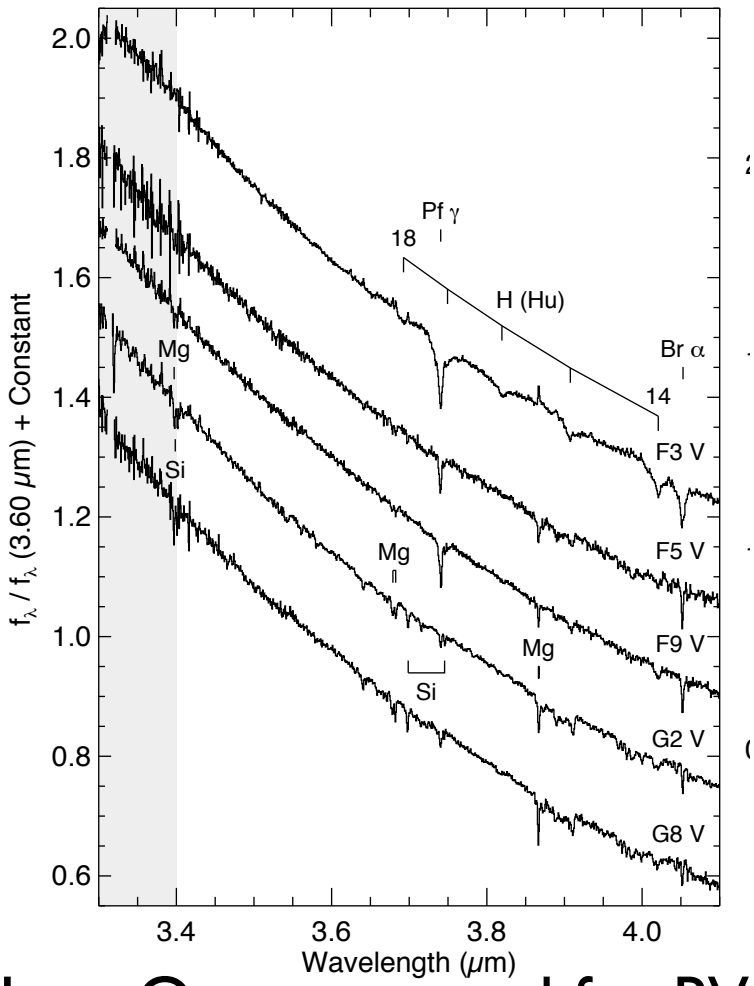
Photon-limited Regime

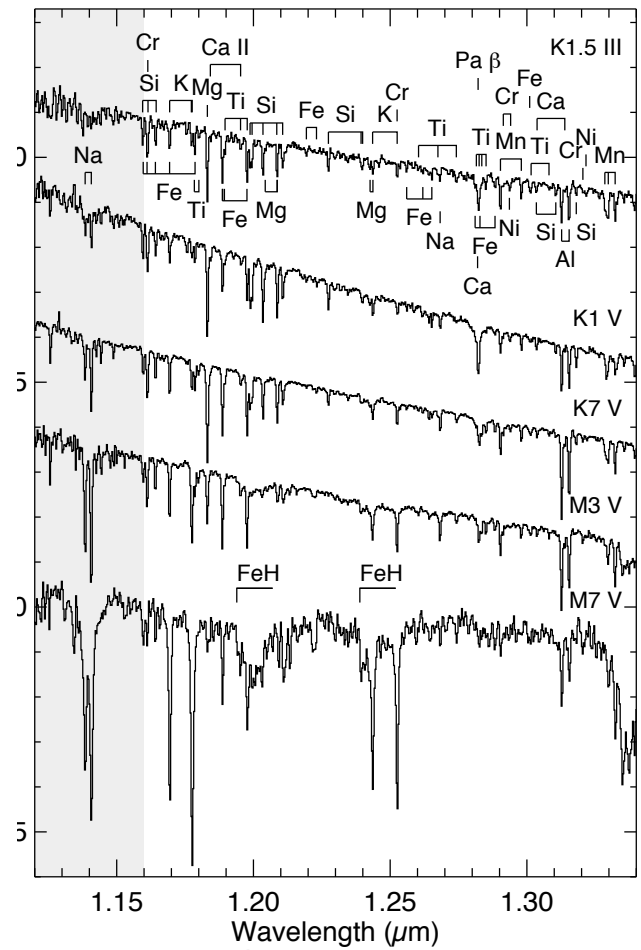
Following Bouchy et al. (2001, 374, 733)

Quality Factor

Precise RVs require numerous, deep, sharp stellar lines

From Rayner et al. (2009, ApJS, 185, 289)



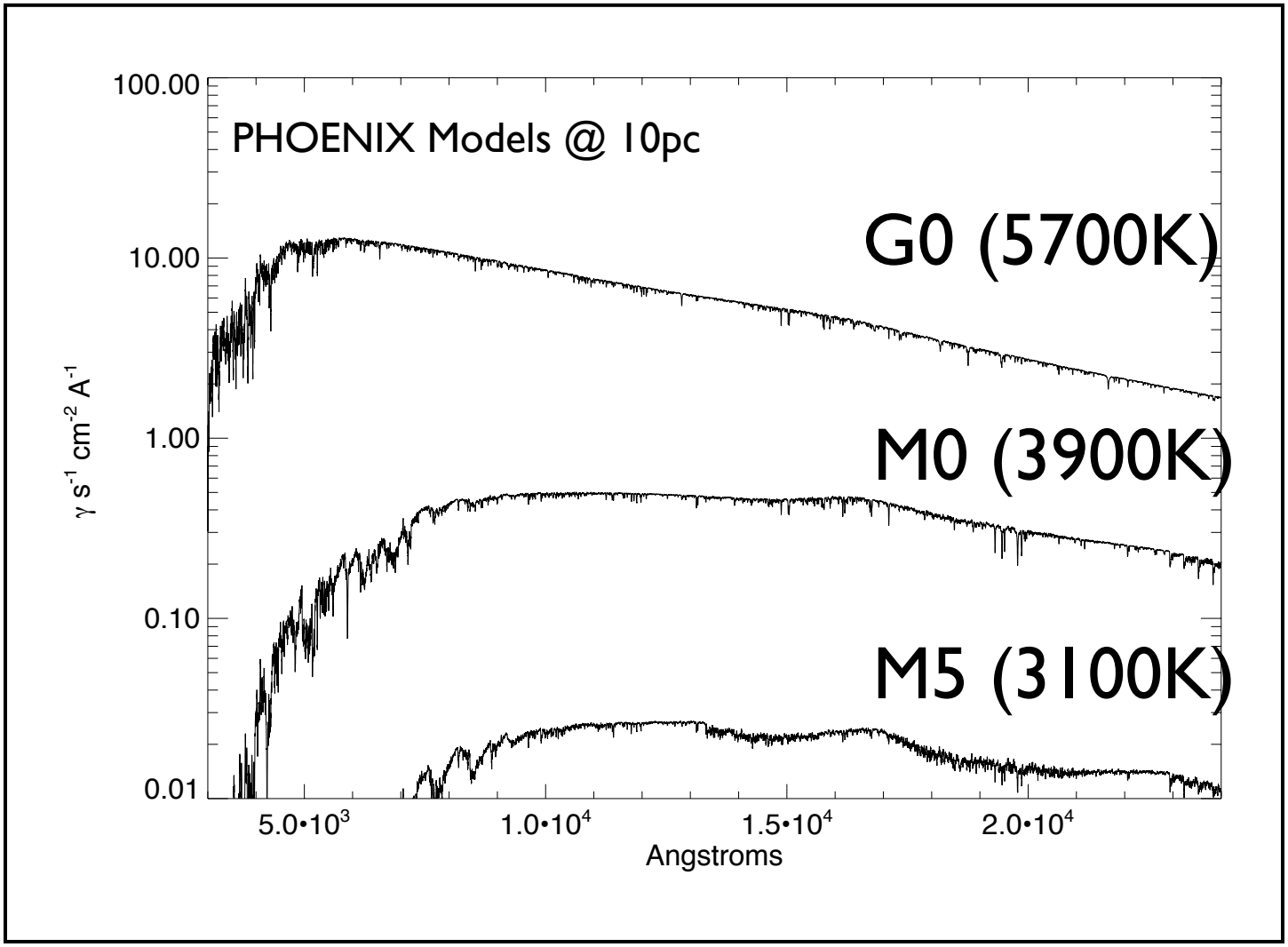


Low Q: not so good for RVs

Higher Q: better for RVs

Qs for M Stars: Reiners et al. (2010, ApJ, 710, 432), Rodler et al. (2011, A&A, 532, 31)
Wang et al. (2011, arxiv:1107.4720)

Only A Big Telescope Game?

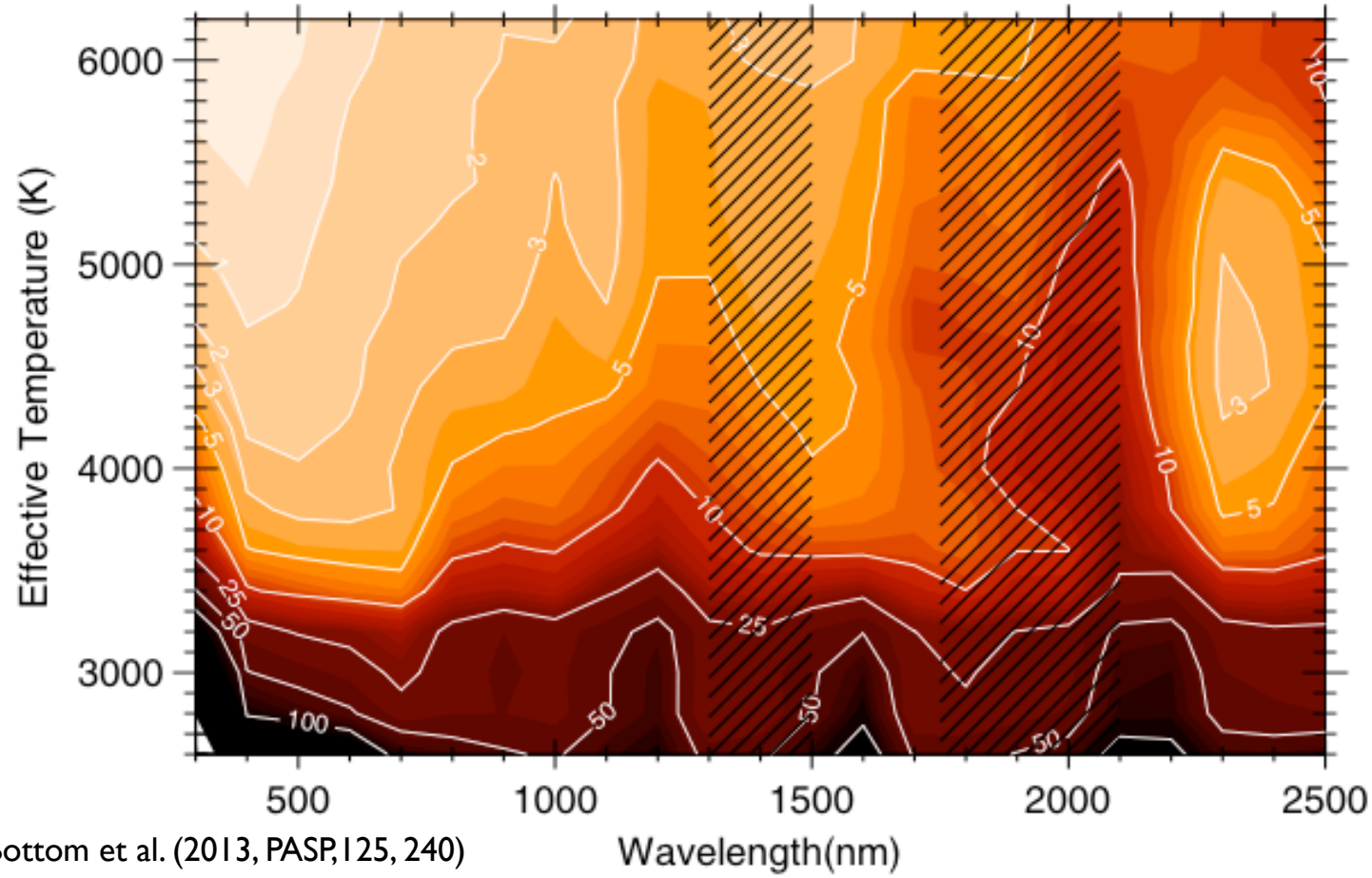


How about a 0.5 m telescope, 20% QE, $\lambda/\Delta\lambda$=50,000?

S/N = 100 in two hours @ λ=800nm

Planets Per Square Meter Per Hour

Expected RV Precision in 60s, 1m telescope, QE=10%, 100nm bandwidth, d=10pc



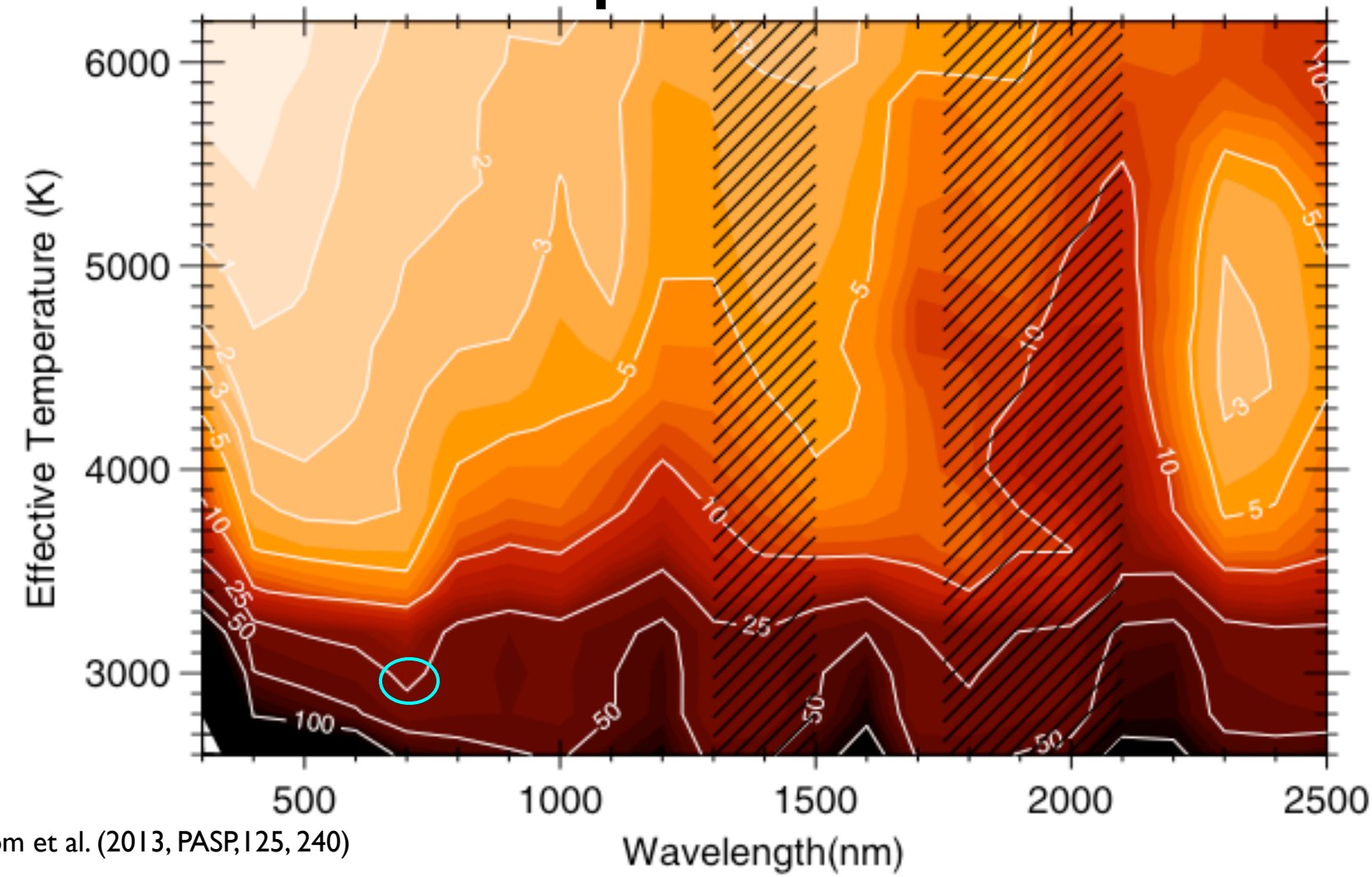
Bottom et al. (2013, PASP,125, 240)

Mike Bottom
(Cal Tech)

$$\sigma_{RV} \propto \left(\frac{60s}{t}\right)^{1/2} \left(\frac{100nm}{B}\right)^{1/2} \left(\frac{1m}{D}\right)\left(\frac{d}{10pc}\right)$$

R>45,000

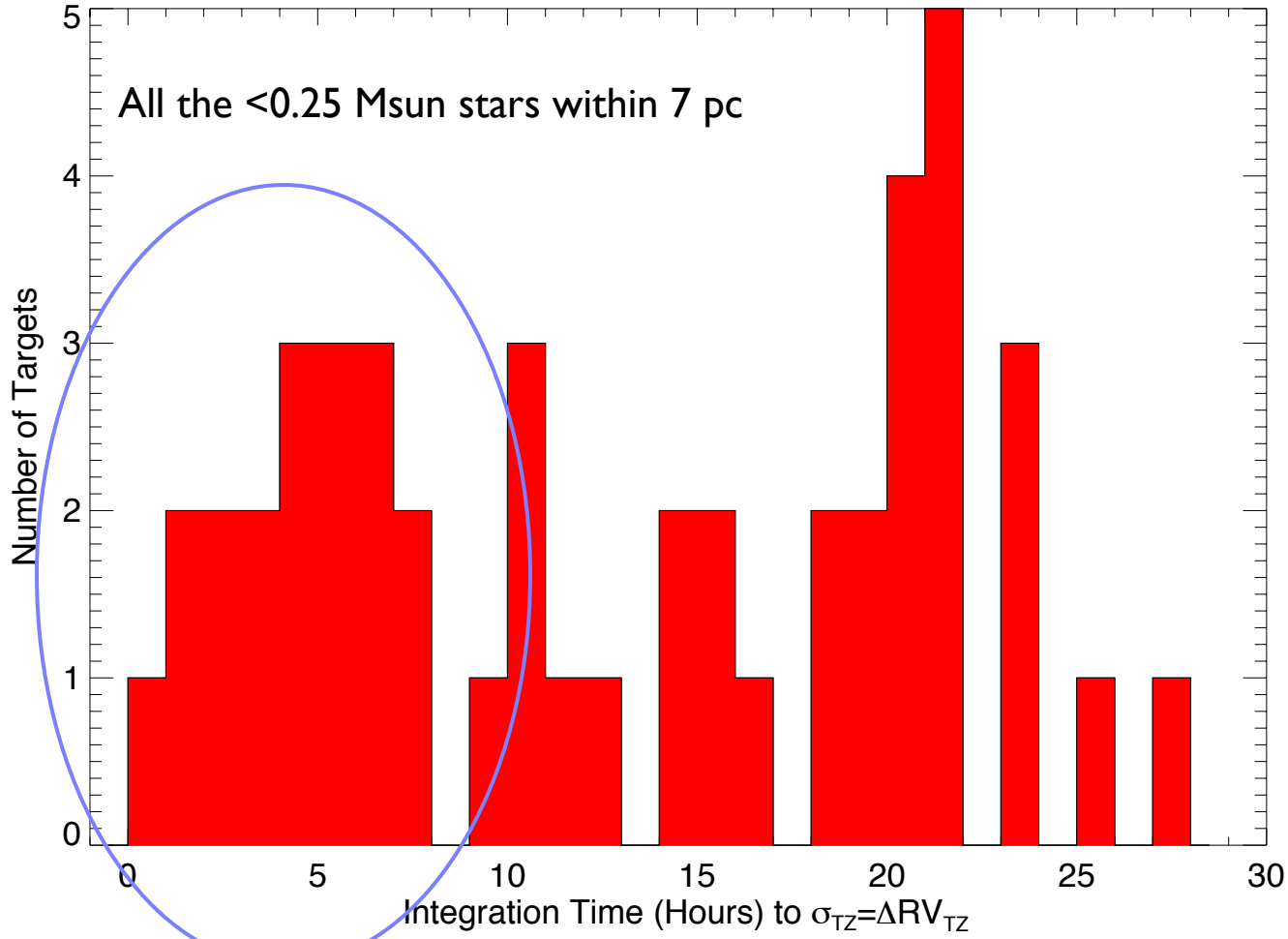
Planets Per Square Meter Per Hour



Bottom et al. (2013, PASP,125, 240)

If I observe a 2900K star 10pc away for 60 seconds with a 1 meter telescope, 100 nm bandwidth at 700 nm, and 10% efficiency: <u>σ=25 m/s</u>

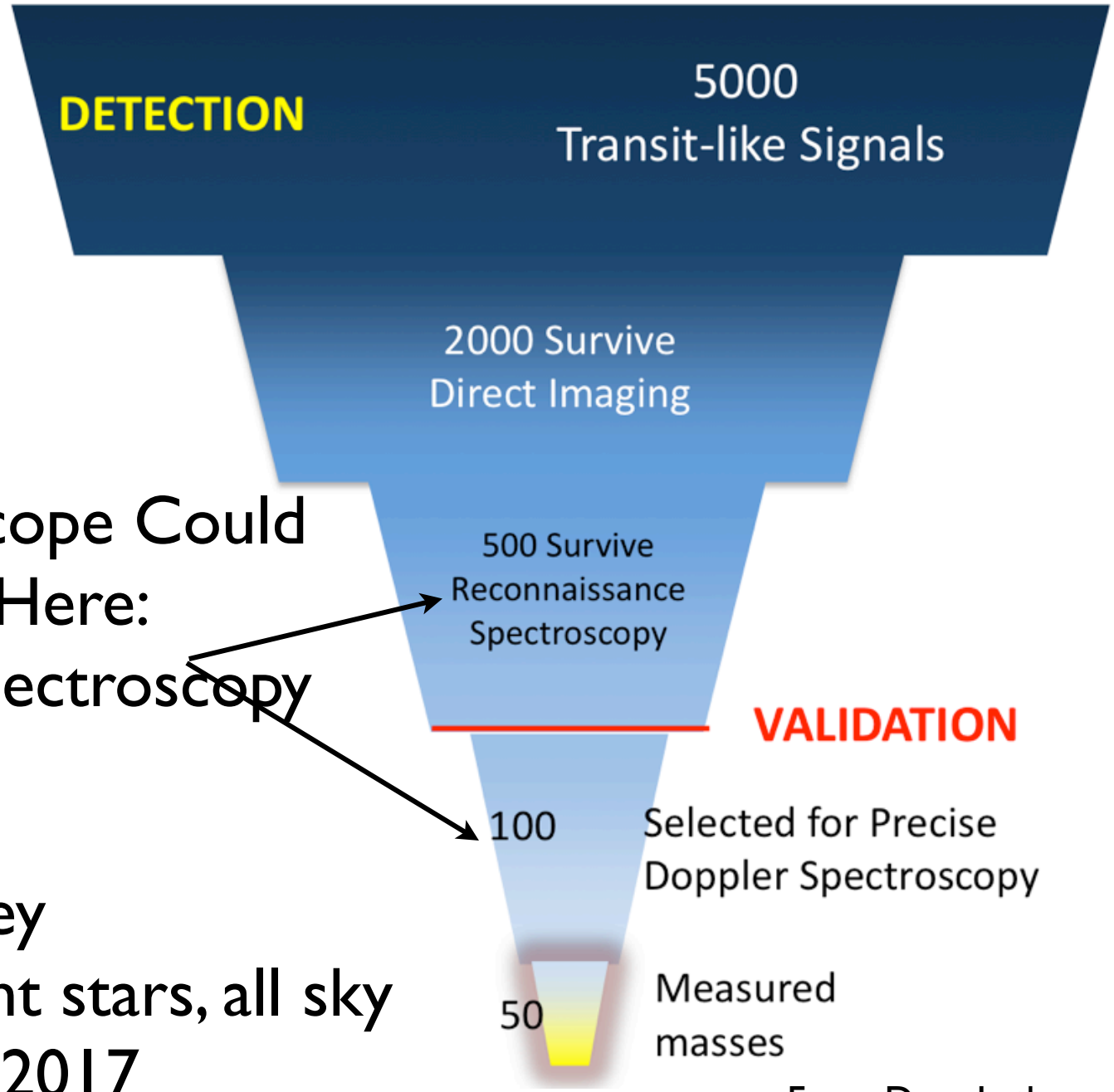
A (Small Telescope) Survey of The Nearest M Stars



Integration times to get (statistical) RV precision equal to Doppler wobble for 3 Earth-mass companions in TZ

0.7 m telescope, realistic noise model, instrument efficiency, etc.

Spectroscopic Followup Pyramid

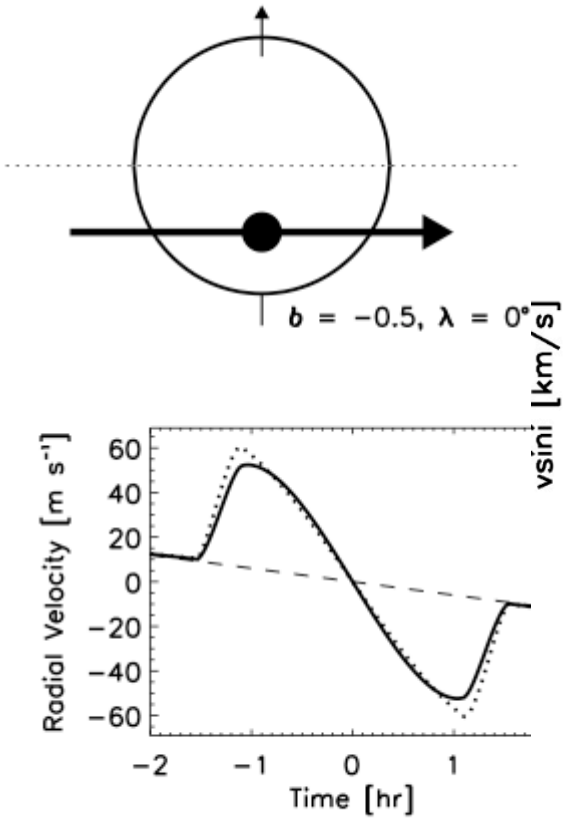


Little Telescope Could
Help Here:
"Recon" Spectroscopy

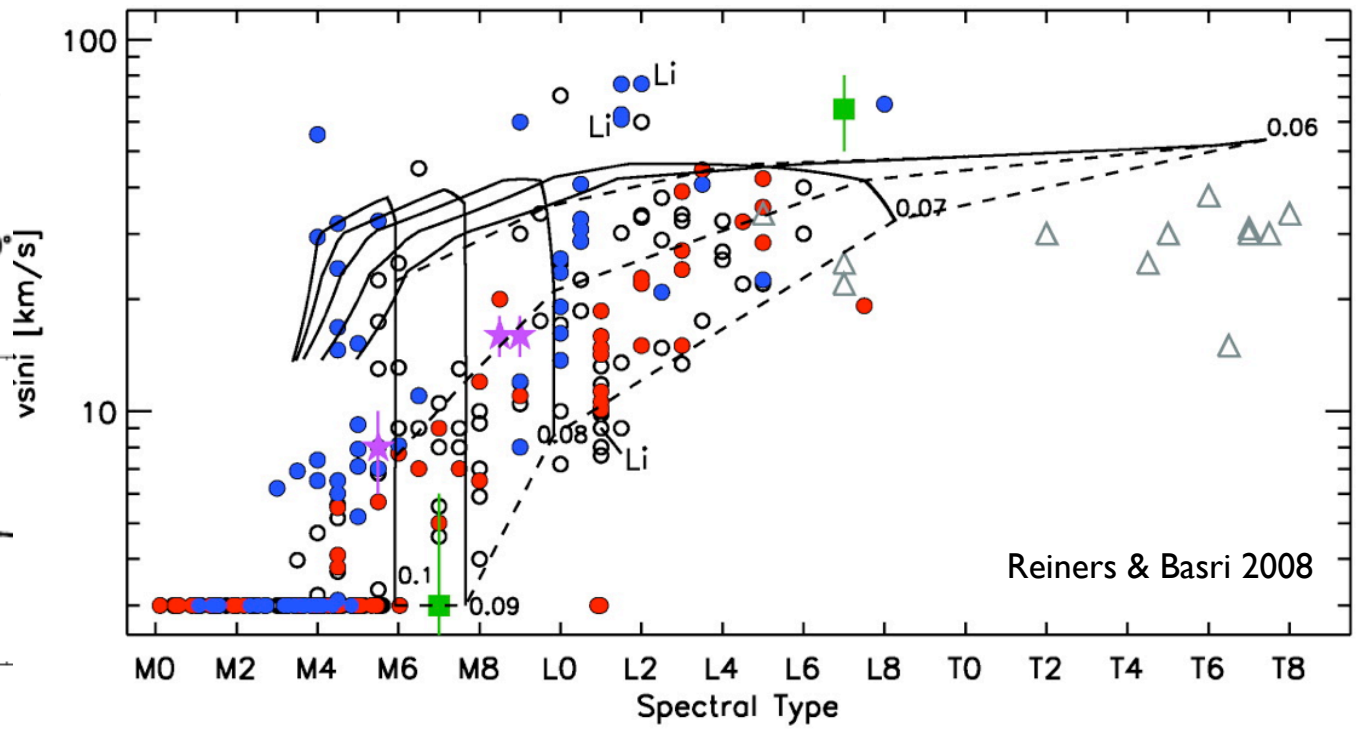
<u>TESS</u>
Transit survey
Targets bright stars, all sky
Launches in 2017

From Dave Latham

What About The R-M Effect?



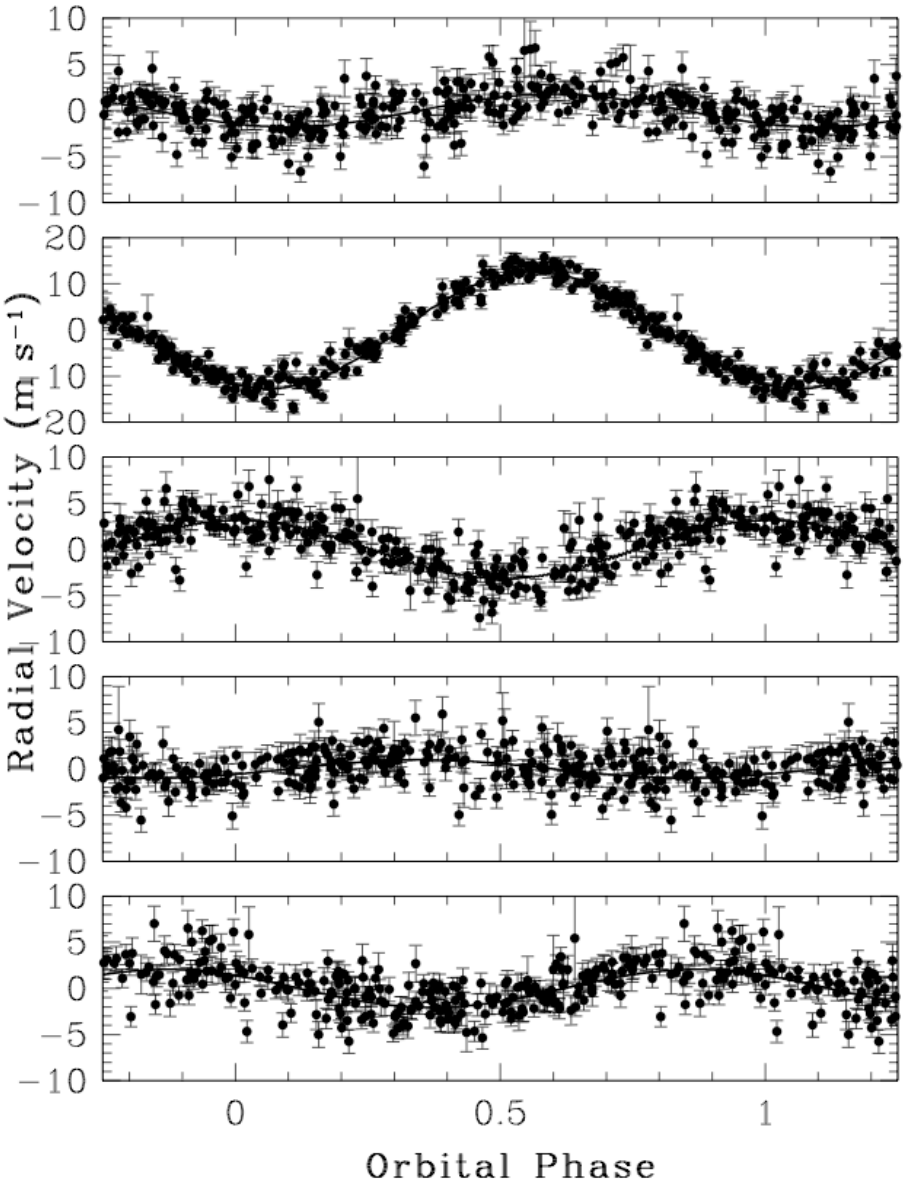
From Winn (2006)



$$A_{RV} = 52.8 \text{ m s}^{-1} \left(\frac{V_s}{5 \text{ km s}^{-1}} \right) \left(\frac{r}{R_{Jup}} \right)^2 \left(\frac{R}{R_o} \right)^{-2}$$

Can be 10s of m/s for Super-Earth and rapidly rotating late-M

Long-term Monitoring



GJ 581 Update- Voigt et al. (2013, AN, 333, 1)

<u>Intensive Observations of Systems Found By Other Surveys</u>

Confirmation

Multi-Planet Systems

Long-term Trends

Why A Doppler Instrument For Small Telescopes?

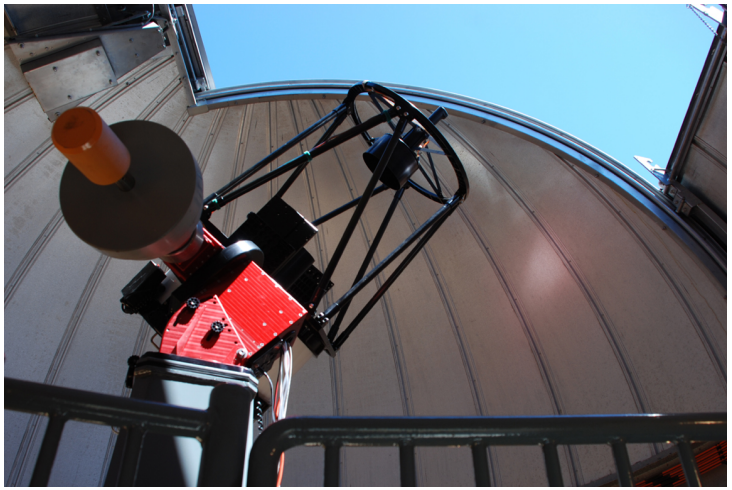
1) Powerful tool in parts of exoplanet discovery space
   e.g. the nearest low-mass stars

2) Recon spectroscopy and transiting planet confirmation
   Will be crucial for TESS

3) Flexible scheduling (and all the observing time)
   Time-sensitive RV measurements

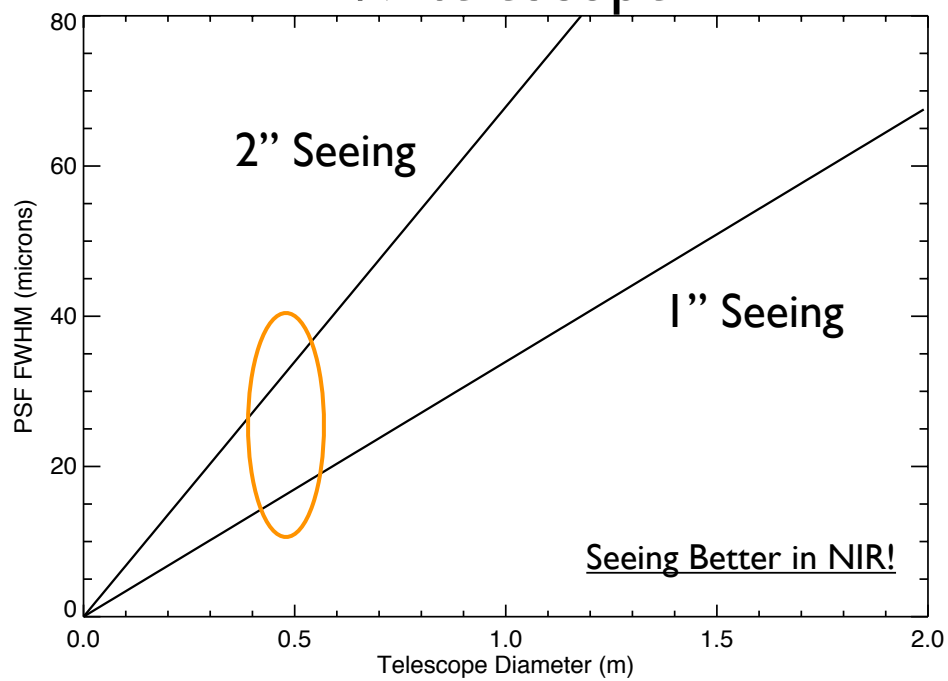
4) Intensive observations of known systems
   Study planet multiplicity and long-term trends

What Would An Instrument Look Like?



How Big Is The Focused Star?

f/7 telescope



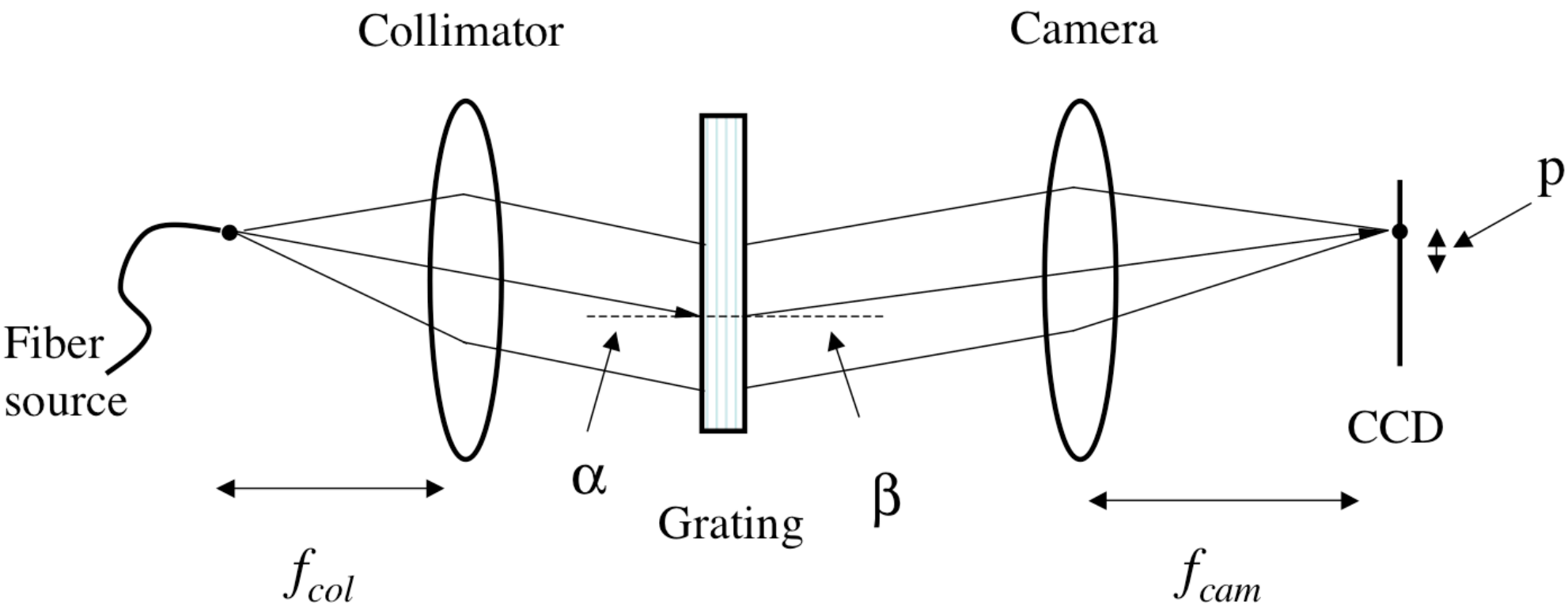
0.5 meter Telescope

Commercial mount
Community-developed software
<$75K

$$R \propto \frac{D}{B}$$

For fixed resolution, R=λ/Δλ, an instrument designed for a smaller telescope has a smaller beam size B

Schematic Spectrometer

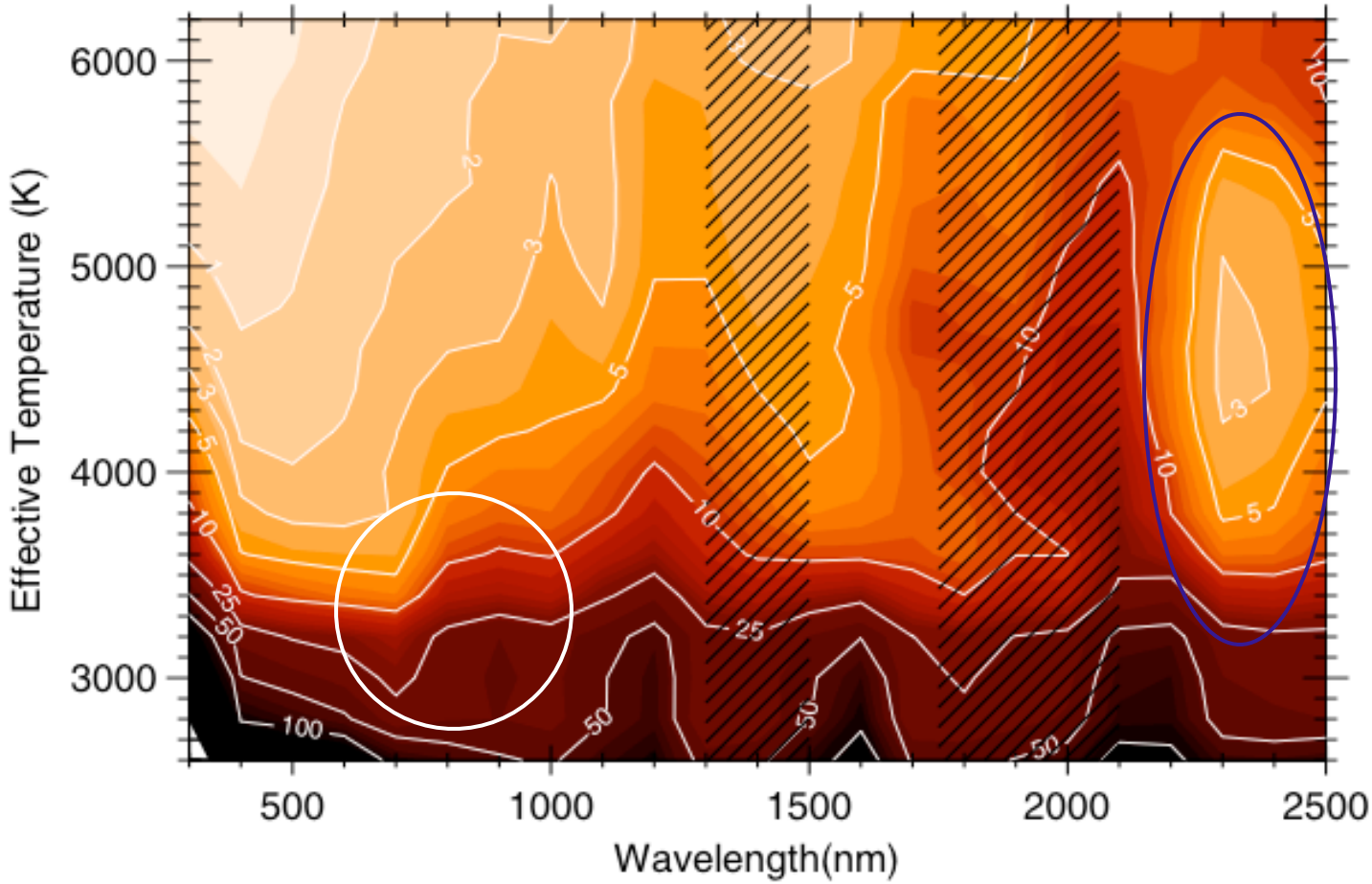


From James Graham

Instrument is small when slit/fiber is small!

What Wavelengths To Use?

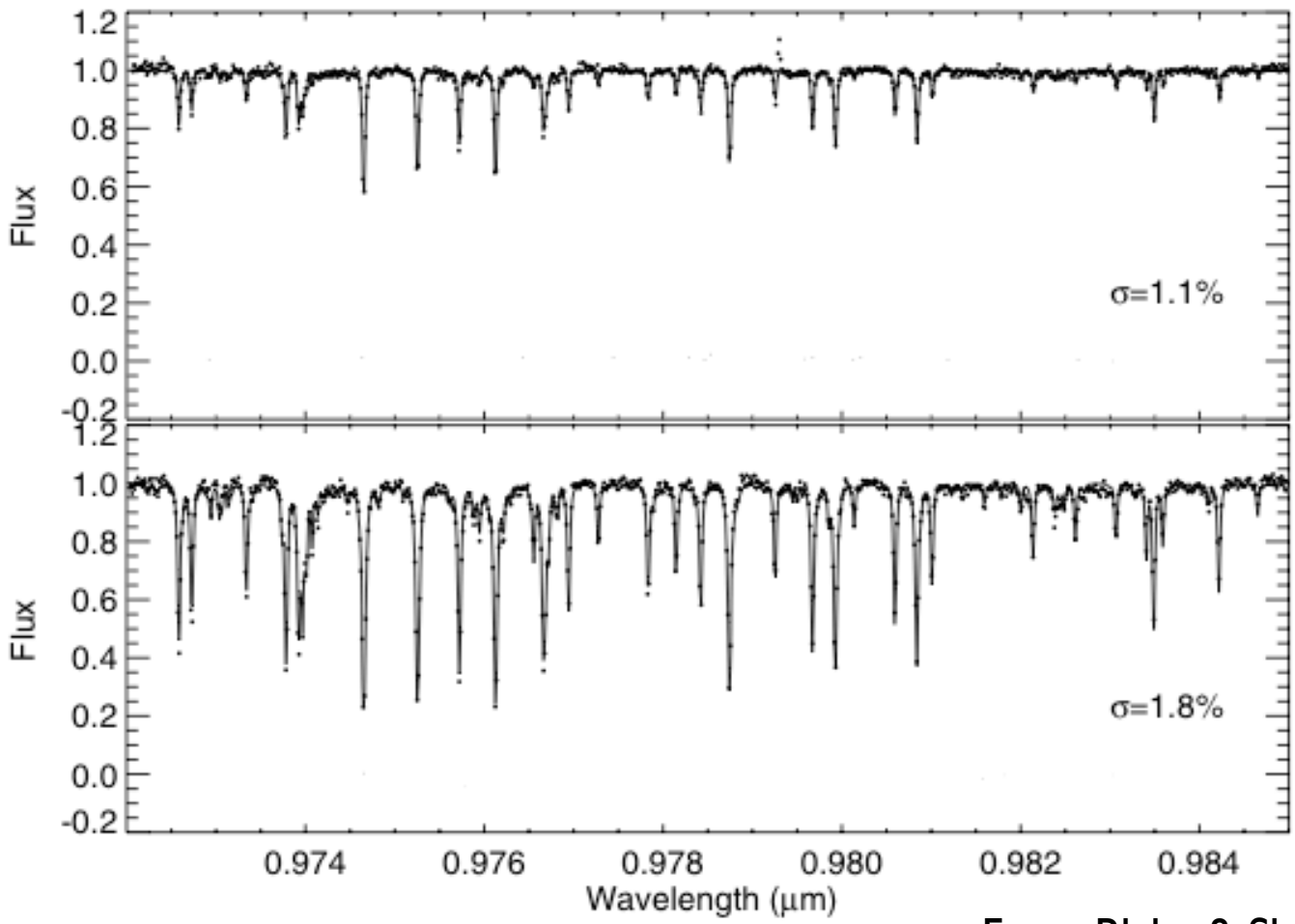
Expected RV Precision in 60s, 1m telescope, QE=10%, bandwidth of 100nm, d=10pc



-The "Deep Red" looks promising - 700-1000 nm

-You don't gain *that* much by going to the NIR, but instrument is much more complex/expensive at ~2.3 micron -- and the sky+telescope glow

Water Lines Are Highly Variable



R=35,000

Hot star spectra

All telluric water lines

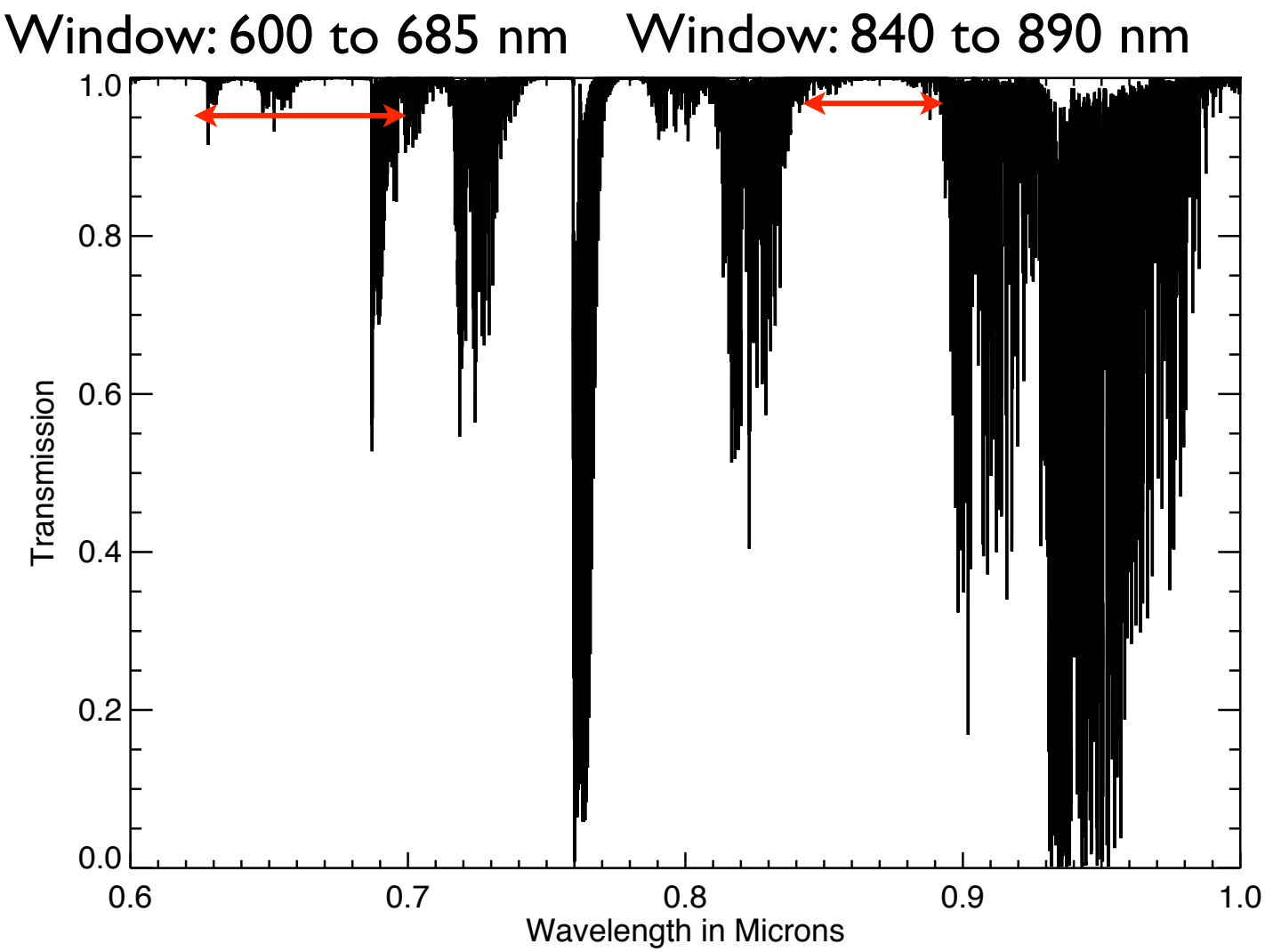
Points: data

Lines: model

From Blake & Shaw (2011, PASP, 123, 1302)

-Water column can change a lot, and rapidly
-These lines can be modeled very well...but that is whole other can of worms

Water And Oxygen Are Overrated



Strong O2 and H2O bands throughout red optical

What We Need: A Small Red Spectrometer

-R = $\lambda/\Delta\lambda$ ~40-50K (sufficient for rotating stars M stars)

-Inexpensive (<$200K?)

-Works around 800 to 900 nm (CCD based - *not* cryogenic)

-Fiber-fed (easier for robotic operation)

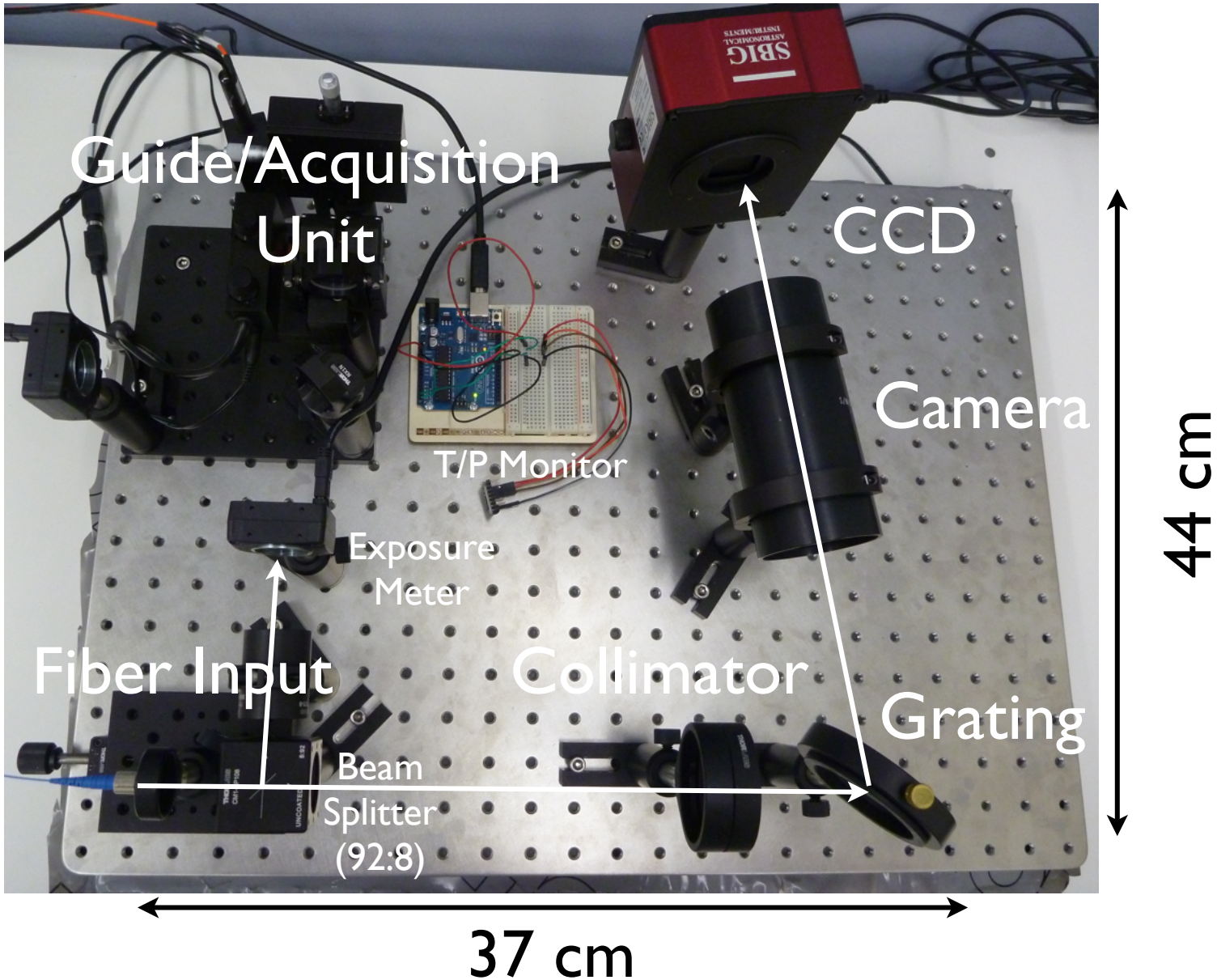
-Made from as many "off the shelf" parts as possible

-Very efficient (high total throughput)

-Capable of 1 m/s precision floor

-Single mode fiber would be nice

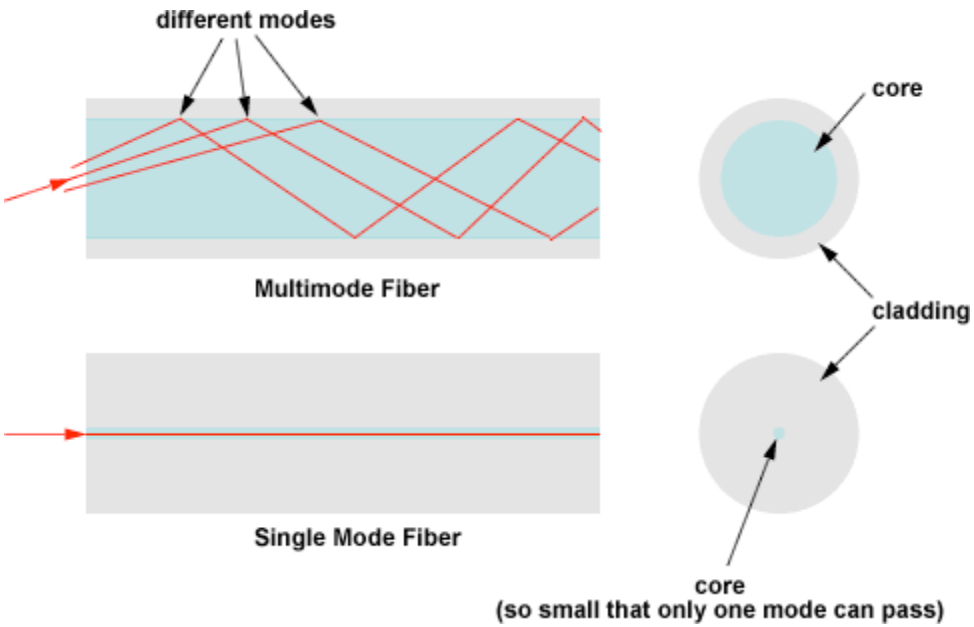
A Small Red Spectrometer



Development supported my the NASA Nancy Grace Roman Fellowship Program

Fancy Fiber

Large Mode Area, Endlessly Single Mode, Photonic Crystal Fiber
(That's a mouthful - PCF will do)



Total Internal Reflection Guides Light In Normal Fiber

Special Pattern Of Air Holes Guides Light In Core

Fancy Fiber

<u>Pros:</u>

-Single mode over wide wavelength range - no “modal noise”

-large Mode Field Diameter - 16.5 microns for LMA-20 fiber

-Standard SM fiber more like 5 microns
-Easier guiding tolerances
-Better match to native PSF size on small telescope

-Reasonably low losses in the red optical:
~1% per 10 meters for λ>800nm

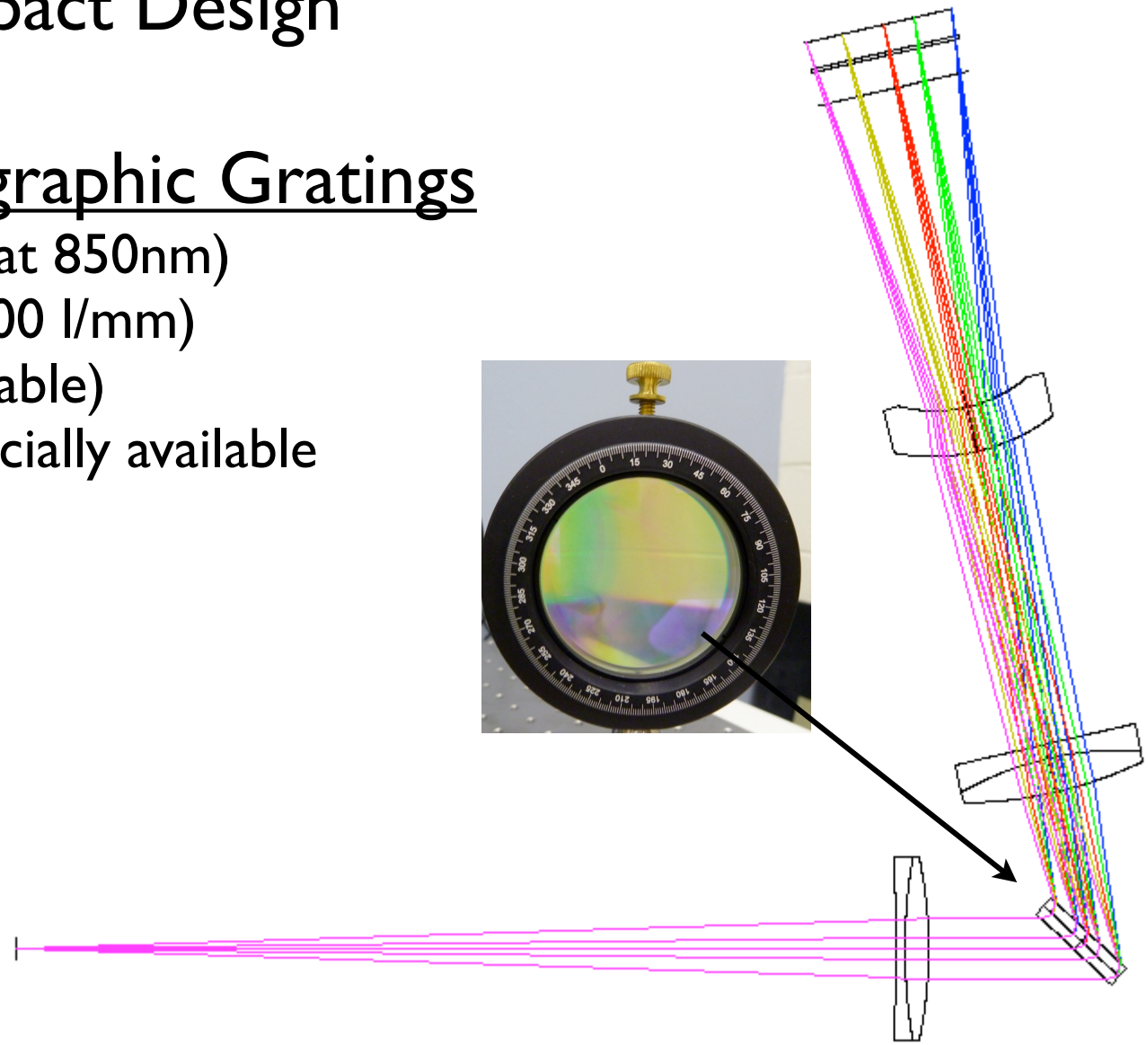
-Extremely low Numerical Aperture (f-ratio):
-About 0.04 or F/12 -- well-matched to telescope
-Slower (simpler) instrument optics overall

Grating

A Transmission Grating Enables
A Simple, Very Compact Design

<u>Volume Phase Holographic Gratings</u>

-Very high efficiency (90% at 850nm)
-High Groove Density (1800 l/mm)
-Large (50 mm, larger available)
-Cheap (<$1000), commercially available
-Excellent optical quality



Optics

Camera:

-Custom 3 lens system designed by Dr. Stuart Barnes

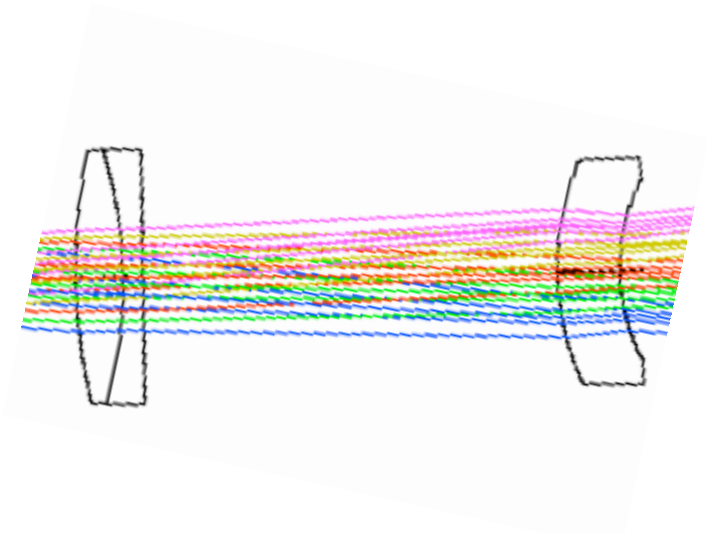
-Glasses and coatings optimized for 840-890 nm range

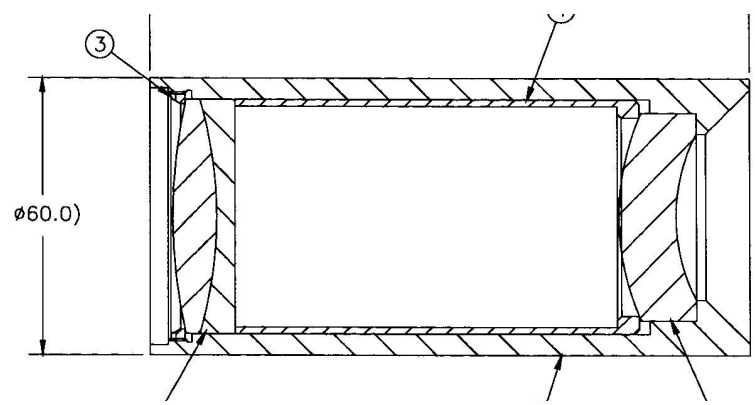
-Focal length 258 mm

-Accommodates beam up to 40 mm wide

-Diffraction limited over wavelength range (840-890 nm)

-Also diffraction limited for +/-3 mm off axis input (i.e. can accommodate several fibers)

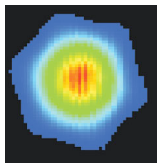




CCD Detector

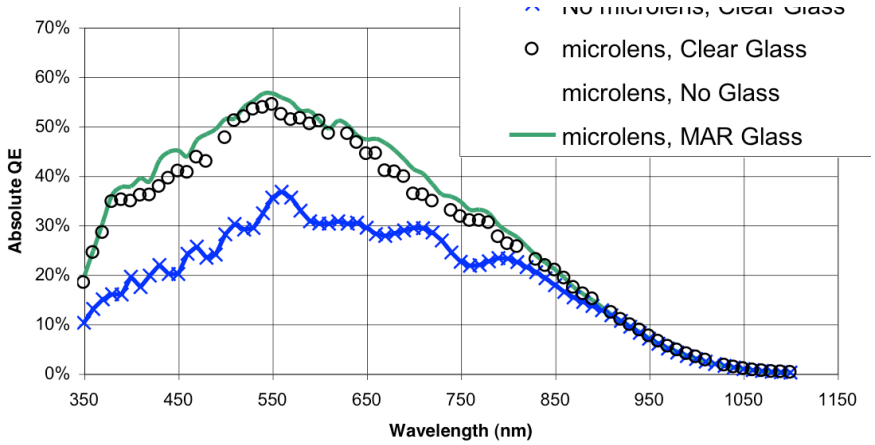
No magnification: $f_{col} \sim f_{cam}$

Fiber Mode Field Diameter: 16.5 microns



CCD must have ~6 micron pixels to sample Line Spread Function with more than 2.5 pixels

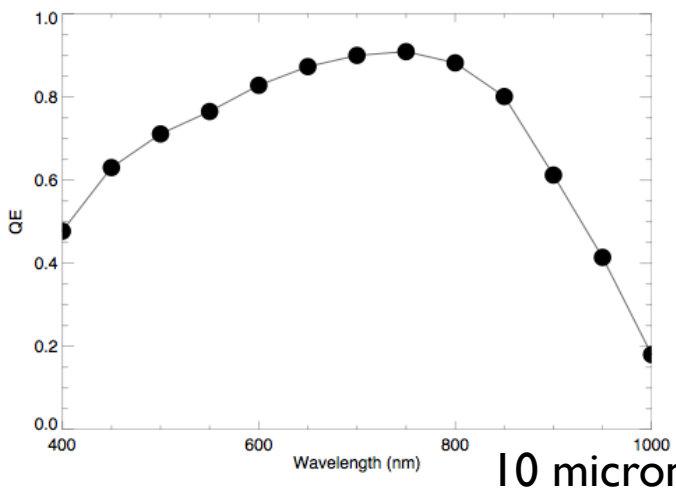
Kodak 8300

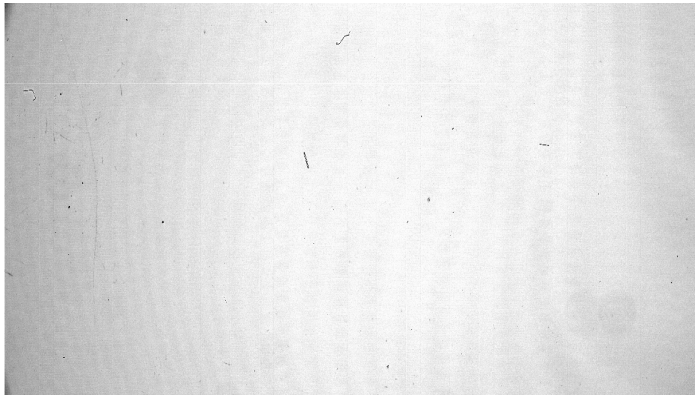


Current Detector:

- -Kodak 8300
- -5.4 micron pixels, 3300 x 2500
- -Microlenses (yikes)
- -Anti-blooming gates (double yikes)
- -<u>Low QE: 20% at 850nm</u>

<u>Upgrade To Larger Format Red Sensitive CCD ($$)</u>

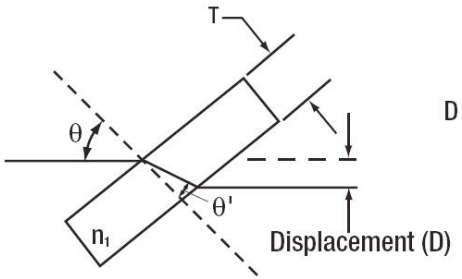




10 micron pixel MIT/LL 6Kx3K device

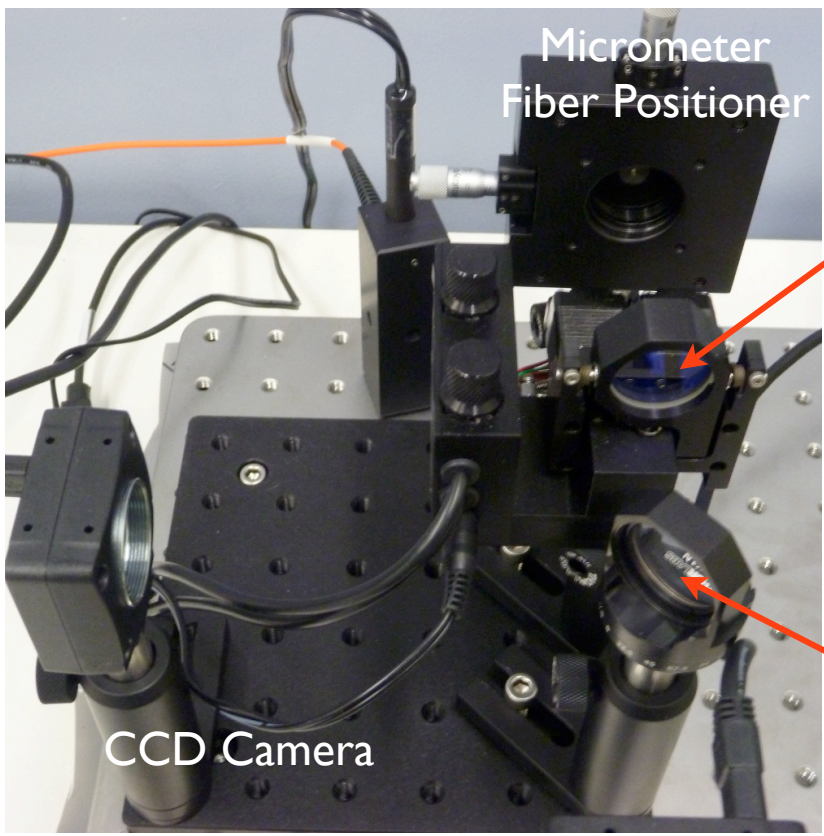
Guiding and Acquisition

Getting light onto 16 micron fiber and keeping it there is hard



$$D = T \cdot \sin\theta \left(1 - \frac{\cos\theta}{n_1 \cdot \cos\theta'}\right)$$

T: Thickness of Optical Plate



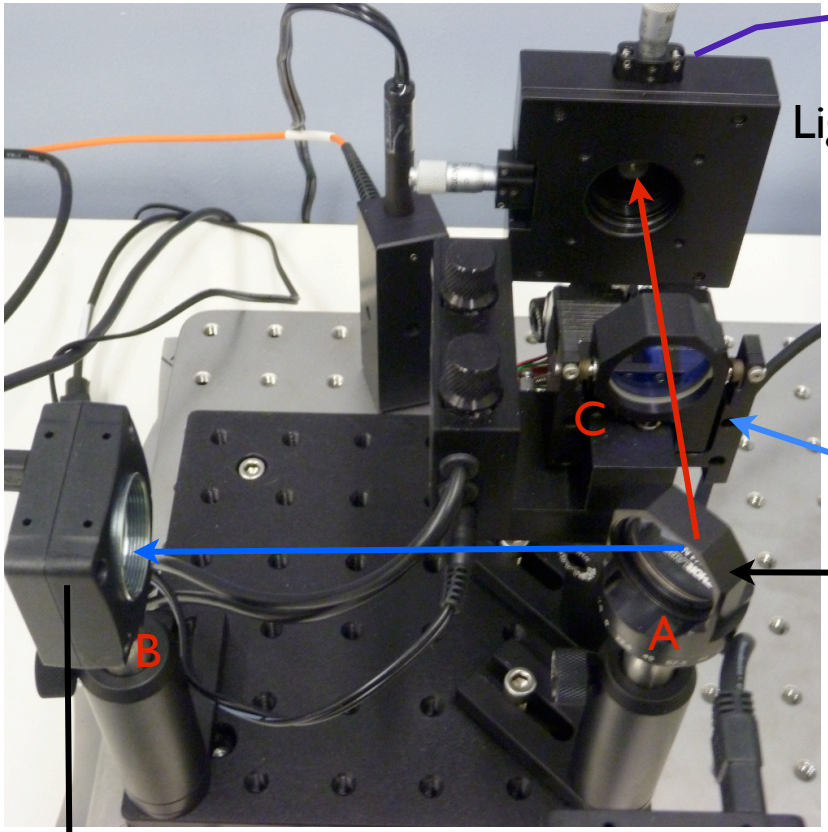
Gimbal mount with BK7 Optical Window

Tip-tilt Optical Window +/-6° at Few Hz To Move Star +/-150 microns In Two Axes

Dichroic

Guiding and Acquisition

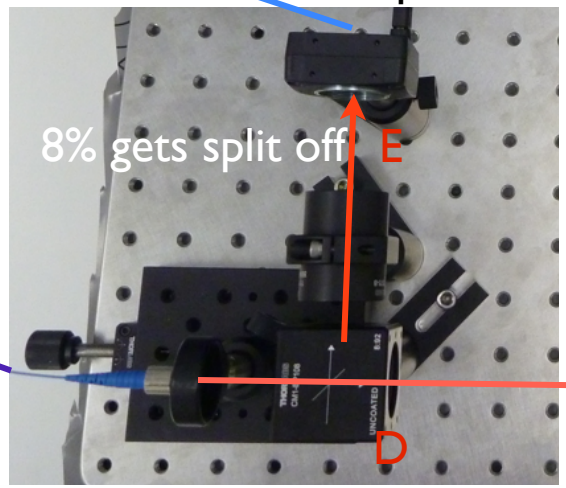
This contraption mounts on back of telescope



Light Couples To PC Fiber
Over Here

Light From Telescope

Exposure Meter



Blue image of star
used for
autoguiding directly
through telescope
mount ~0.2 Hz

This other CCD provides
feedback to initially place star
on the fiber
Also acts as "Exposure
Meter"

Some Numbers

Slit-limited resolution equation

$$R = 2\tan(\alpha)\frac{f_{col}}{\Delta S}$$

b is grating groove spacing - 1/1800 (l/mm) = 0.55 micron

α=51.1° @ 865nm $2b\sin(\alpha) = \lambda$ Grating equation in Littrow (α=β), m=1

fcoll = 300 mm (collimator length)

Beam size in spectrograph: NA of PCF is 0.035, so B=21 mm

ΔS=16.5 microns

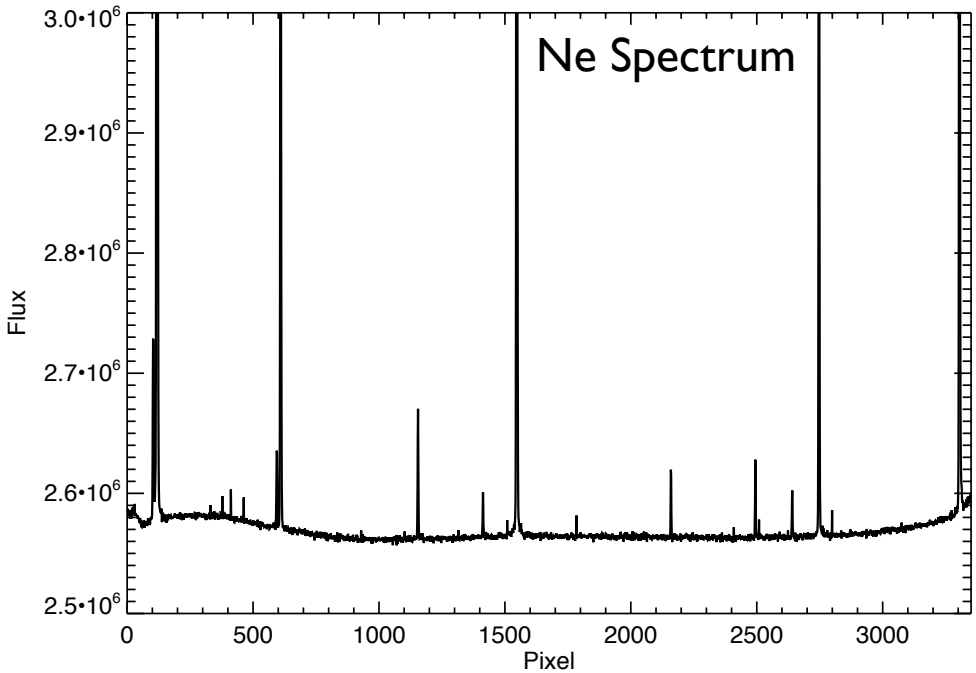
<u>R= 47,000</u>

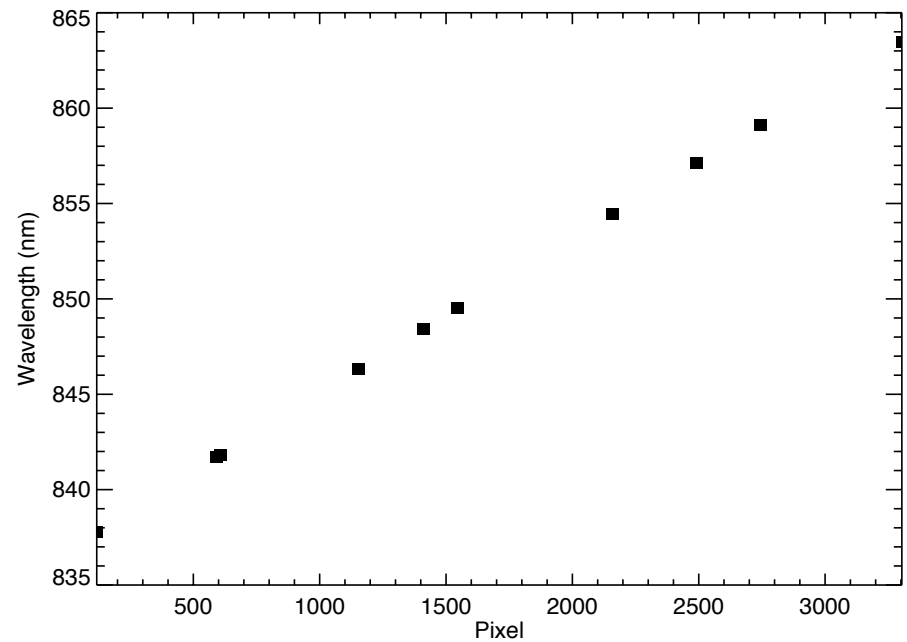
<u>Spectral Bandwidth On Detector : 26 nm</u>

Spectra!

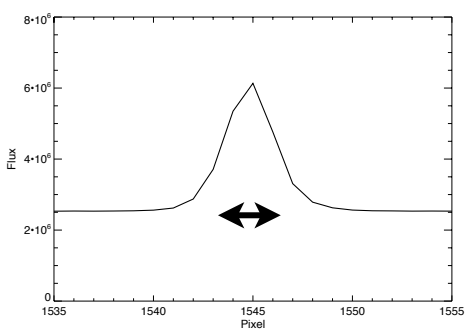
(Of Calibration Lamps)

Zoomed way in, big Ne lines are bright!
Alternating long and short integrations

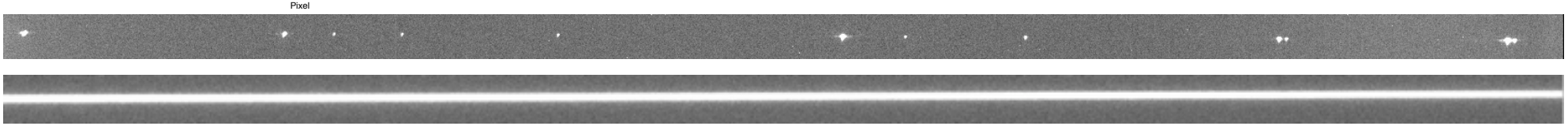




Dispersion is 0.0079 nm/pixel
26 nm on Kodak Chip



Line FWHM =0.019 nm --> R=45,000!

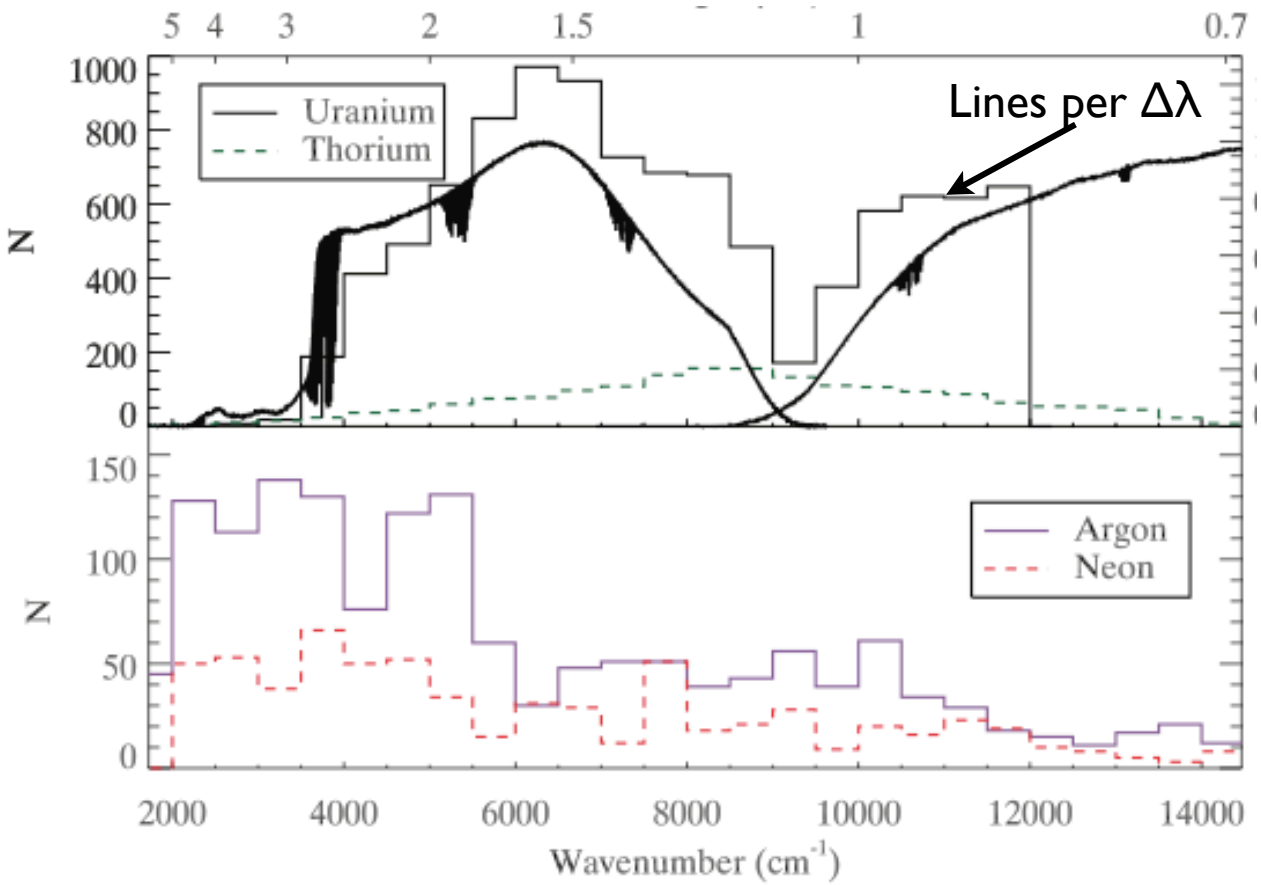


Calibration: Future

Ultimate Goal: 1 m/s

Emission Lamps Could Do the Trick

From Redman et al. (2011, ApJS, 194, 24)

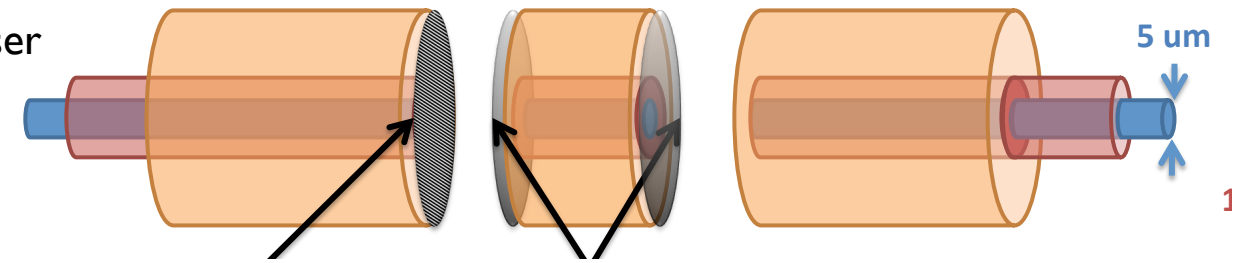


U-Ne Lines Plentiful for λ>850 nm

An Even Better Calibration Source: A Fiber Fabry-Perot (FFP) Etalon

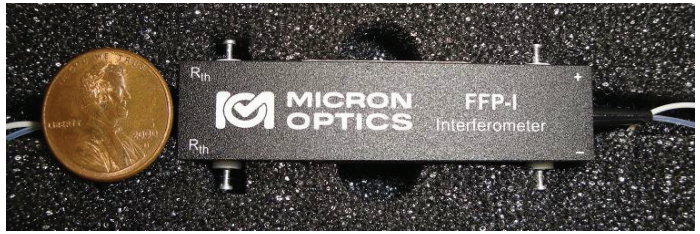
Temperature Of Cavity Inside Ceramic Ferrule and Copper Heat Sink
Controlled to +/- 20 micro-Kelvin

Backlit with
Supercontinuum laser



All Single Mode Fiber

Cavity Spacing Corresponds to Free Spectral Range of 30 GHz (or about 0.075 nm)

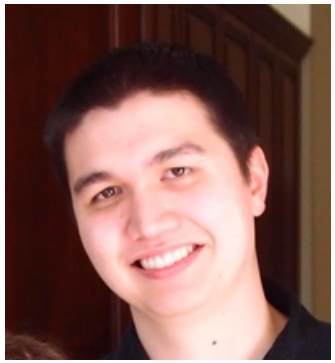


Halverson et al. 2012

Development of a New, Precise Near-infrared Doppler Wavelength Reference: A Fiber Fabry-Perot Interferometer

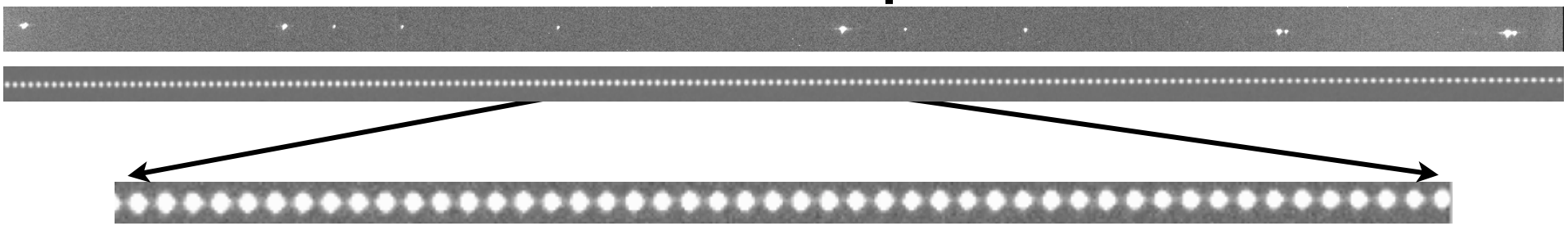
Samuel Halverson[a], Suvrath Mahadevan[a,b], Lawrence Ramsey[a,b], Stephen Redman[c], Gillian Nave[c], John C. Wilson[d], Fred Hearty[d], Jon Holtzman[e]

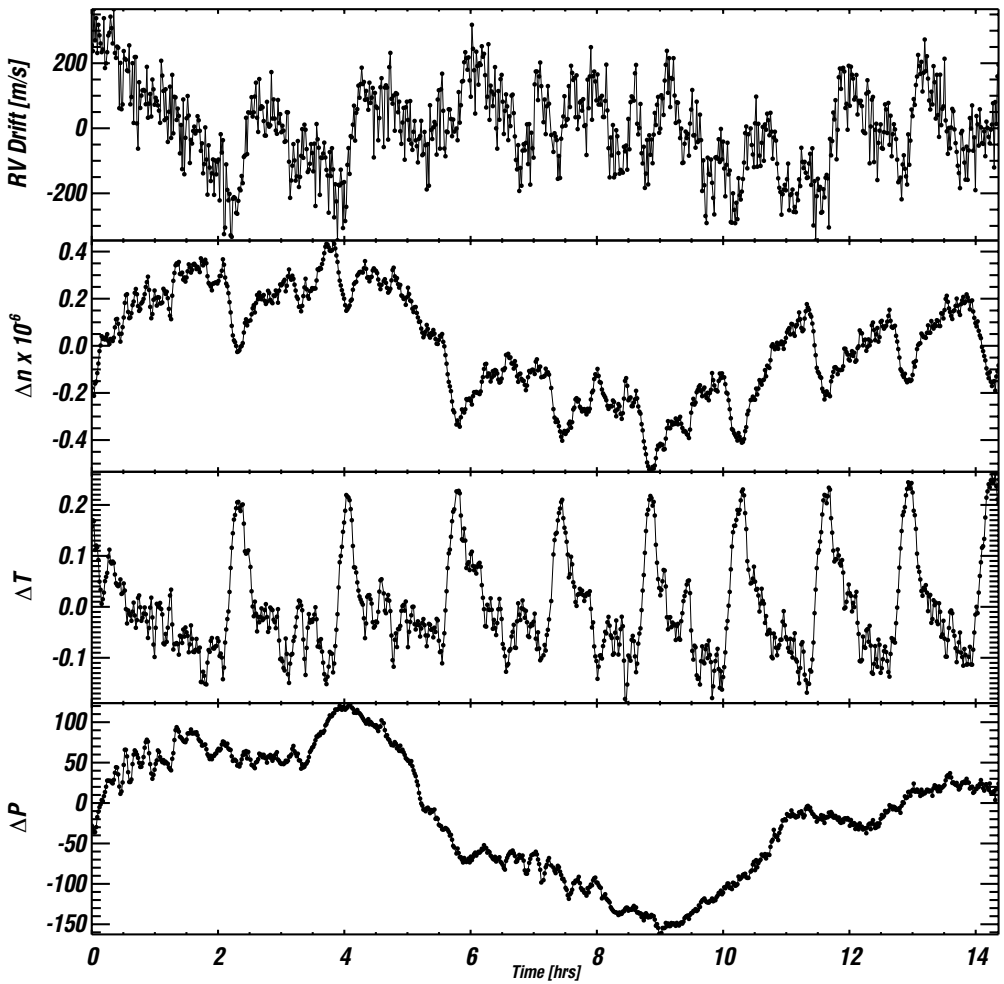
This is a new technology application pioneered by Sam
You can buy these things (telecoms applications), Sam also makes them



Sam Halverson
Penn State

Testing an FFP
With Small Red Spectrometer





Given S/N, line density:

Definitely sufficient for 1 m/s calibration

Next Steps - Spring, 2014

Temperature- and pressure-stabilized enclosure

New CCD camera, detector with higher QE, larger format

U-Ne calibration source and FFP

Spectra of stars more than 1 AU away

<u>The Small Red Spectrometer is looking for a home!</u>
(and maybe some siblings)

Conclusions

Small planets orbiting small stars are numerous:

-Hundreds of Super-Earths are orbiting M stars within 20 pc of the Sun

Little telescopes, have an important role - discovery and follow up:

-"Recon" spectroscopy
-Confirmation of transiting candidates
-Long-term monitoring
-R-M observations
-Surveys targeting the brightest, nearest M dwarfs

A Small Red Spectrometer:

-Simple, works with a small telescope, inexpensive
-Specifically designed for M star exoplanet science

Thanks!