Exoplanet Science with the Keck Planet Finder (KPF*)

* - formerly SHREK

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Institutional Support

SPACE SCIENCES LABORATORY UNIVERSITY OF CALIFORNIA Berkeley

Caltech

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Foundation Support

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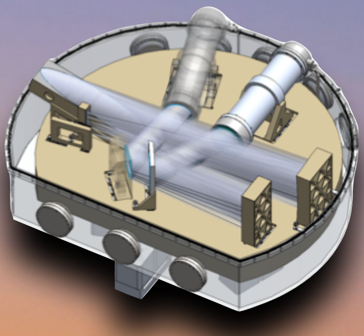
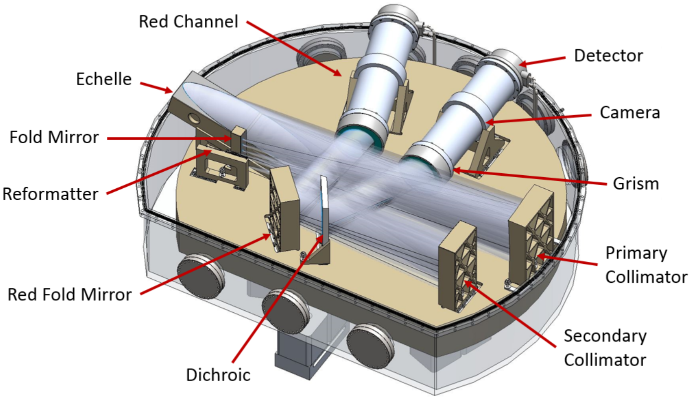


Photo: Laurie Hatch

Keck Planet Finder (KPF)

Design:

- High-precision RV spectrometer
- Cross-dispersed échelle — $R \geq 85{,}000$
- 2 channels: 440-590nm, 590-860nm
- Fiber-fed, highly stable Zerodur platform

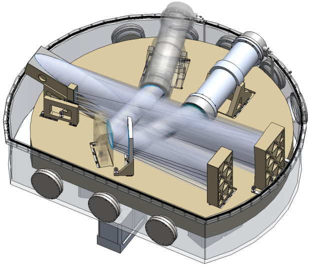


Capabilities:

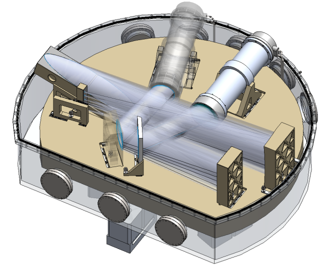
- High efficiency
- RVs delivered as facility data product
- Doppler precision: 0.3 m/s (goal) - 0.5 m/s (req)

Status:

- Top instrument priority in WMKO strategic plan
- In preliminary design phase
- Expected first light: 2020



The Science Case for KPF



Core Exoplanet Science

1. Broad *Doppler exoplanet science*, as with HIRES and HARPS; nearby star searches
2. *TESS* — planet masses
3. *Kepler* — planet masses

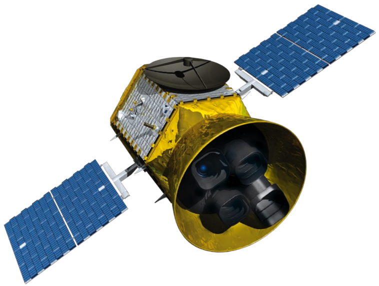
Additional Exoplanet Science

1. *WFIRST* target selection
2. Exoplanet *atmosphere spectroscopy* at high spectral resolution
3. *Stellar characterization* — properties and detailed elemental abundances
4. …

Ancillary Astronomy

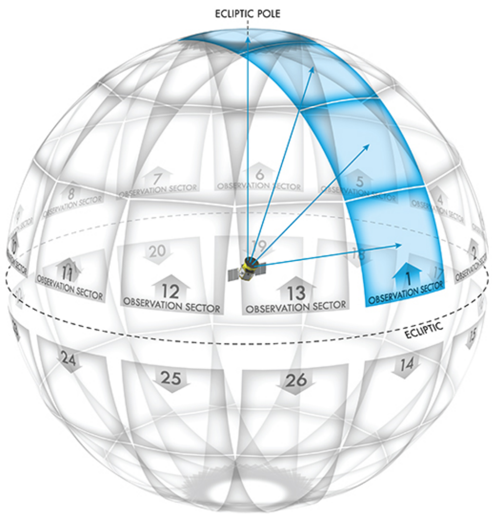
1. Detection of *expansion of universe* with Lyman-α forest
2. Galactic *chemical abundance* archaeology
3. *Solar System* spectroscopy — planets, moons, comets, asteroids, KBOs
4. *Isotopic abundance* from precise line shapes
5. *Zeeman splitting* due to B-field
6. …

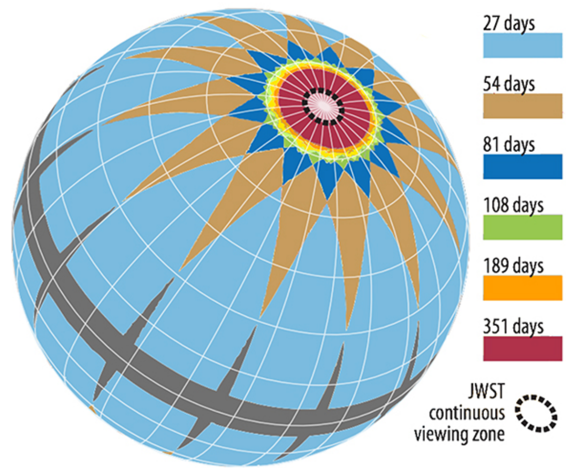
Transiting Exoplanet Survey Satellite (TESS)



TESS Mission (2018-)

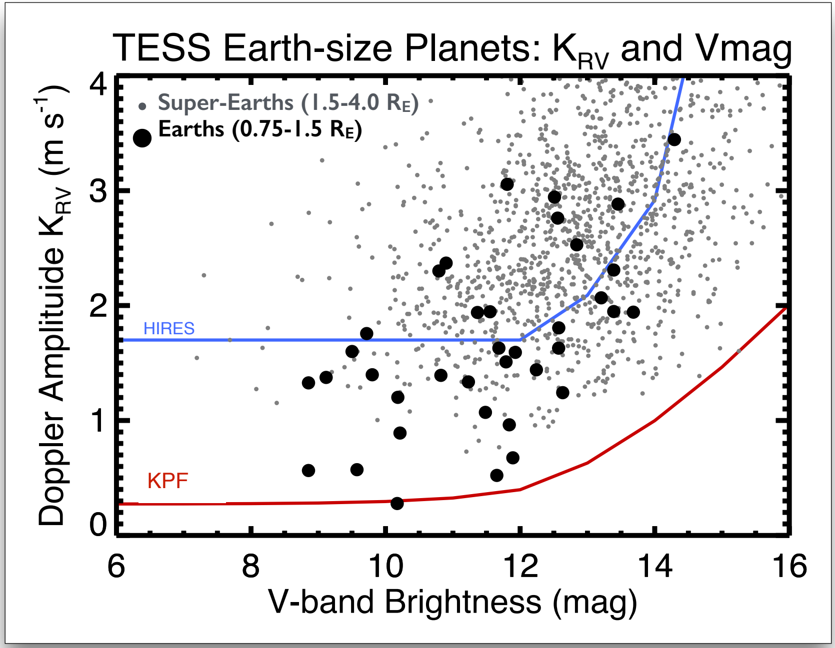
Field:	4 x (24° x 24°)
Survey :	full sky (27 days); ecliptic poles (1 yr)
Scientific Goals:	Discover planets transiting *bright* stars
	Enable detailed follow-up (masses, spectroscopy)





Simulated TESS Performance

GK Dwarf Stars



Simulation Details

Detailed model - Sullivan et al. (2015)
2-yr mission with realistic photometry
Planet population based on Kepler
Mass-radius relationship (Weiss & Marcy 2014)
200,000 pre-selected stars → 1700 planets
TTV measurements limited

Stars: GK dwarfs (T_{eff} = 4200-5900 K)
Planet temperatures: all

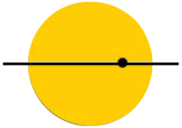
Planet Population

Mostly super-Earths (not Earth-size)
Mostly detectable with K > 1 m/s

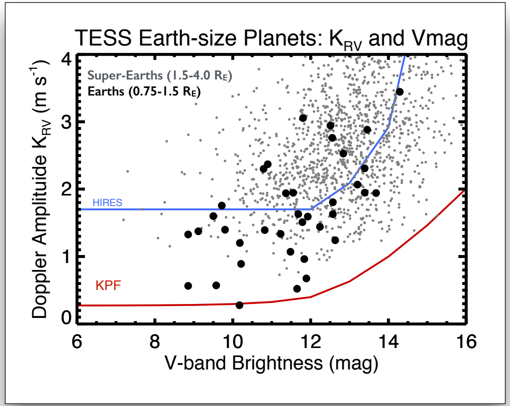
Simulated TESS Performance

GK Dwarfs — V < 14 (SHREK on 10 m Keck)

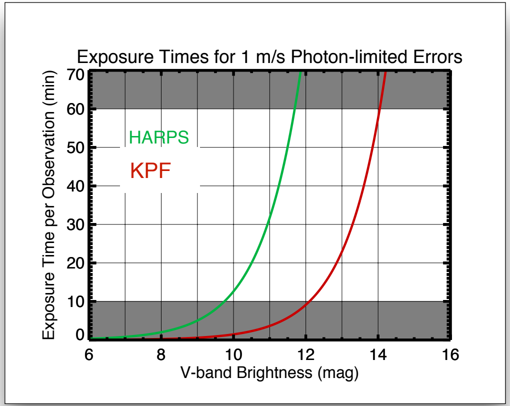
GK Dwarfs



Planet Population



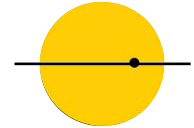
Spectrometer Performance



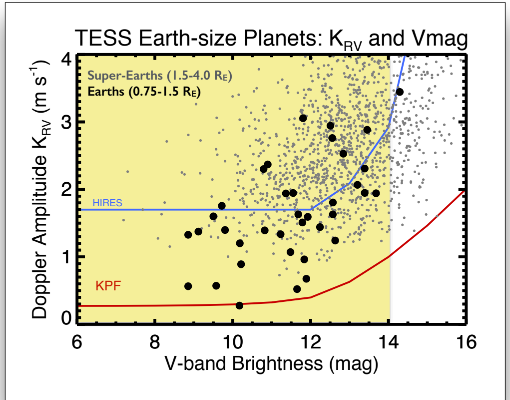
Simulated TESS Performance

GK Dwarfs — V < 14 (SHREK on 10 m Keck)

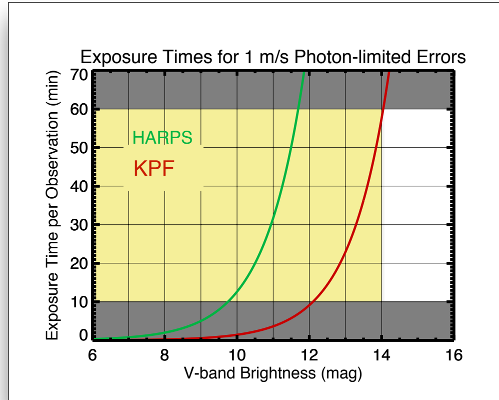
GK Dwarfs



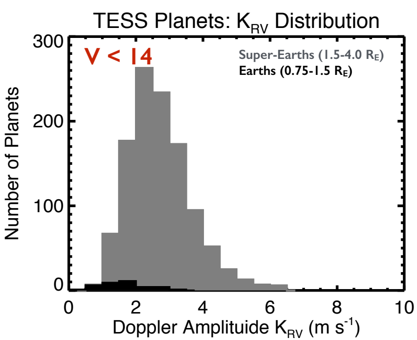
Planet Population

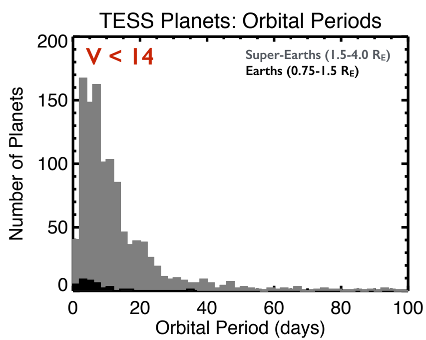


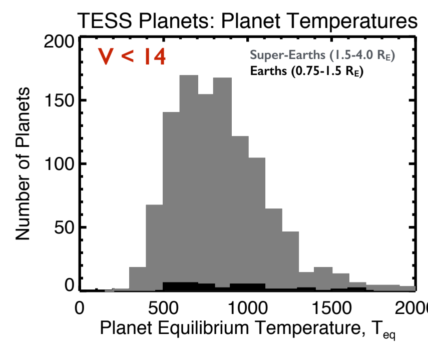
Spectrometer Performance



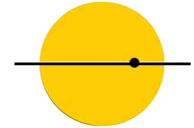
Surveys of *100s of planets* with KPF on 10 m Keck Telescope







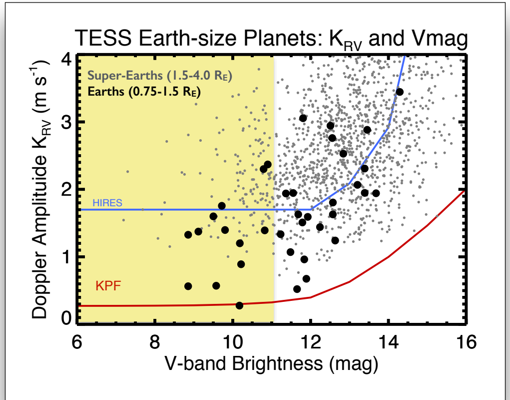
GK Dwarfs



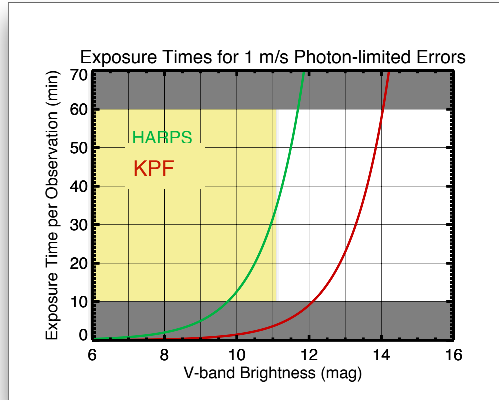
Simulated TESS Performance

GK Dwarfs — V < 11 (3-4 m telescopes)

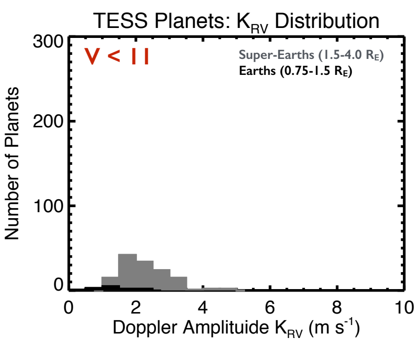
Planet Population

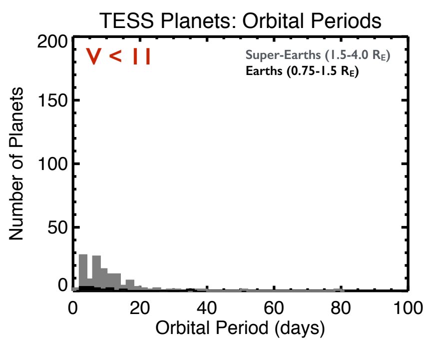


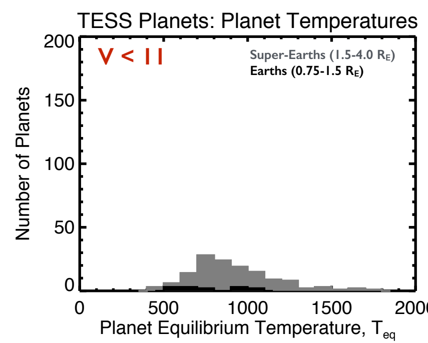
Spectrometer Performance

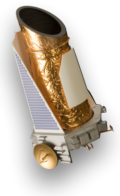


Surveys of *10s of planets* with 3-4 m telescopes (HARPS, HARPS-N, WIYN, etc.)



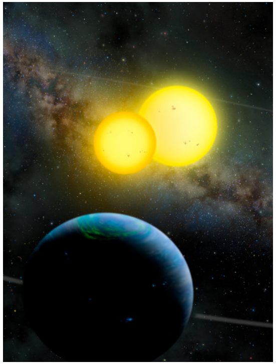




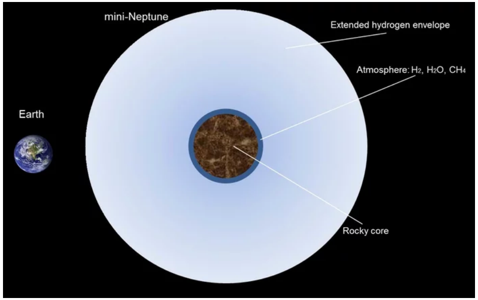


Kepler — New Opportunities

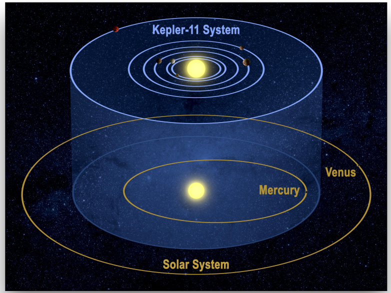
Circumbinary Planets



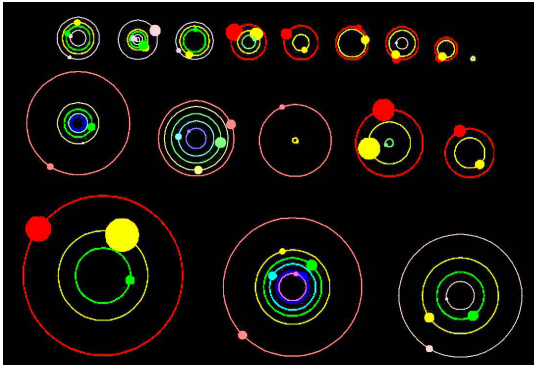
'Super-puffs' (Ultra low density)



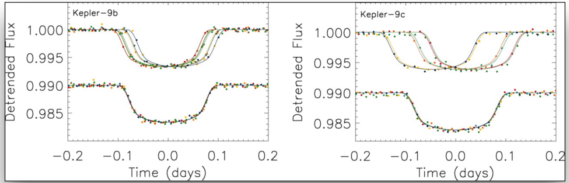
High-multiplicity systems (e.g. Kepler-11)



Planetary System Architectures



Transit Timing Variations (TTV) Systems



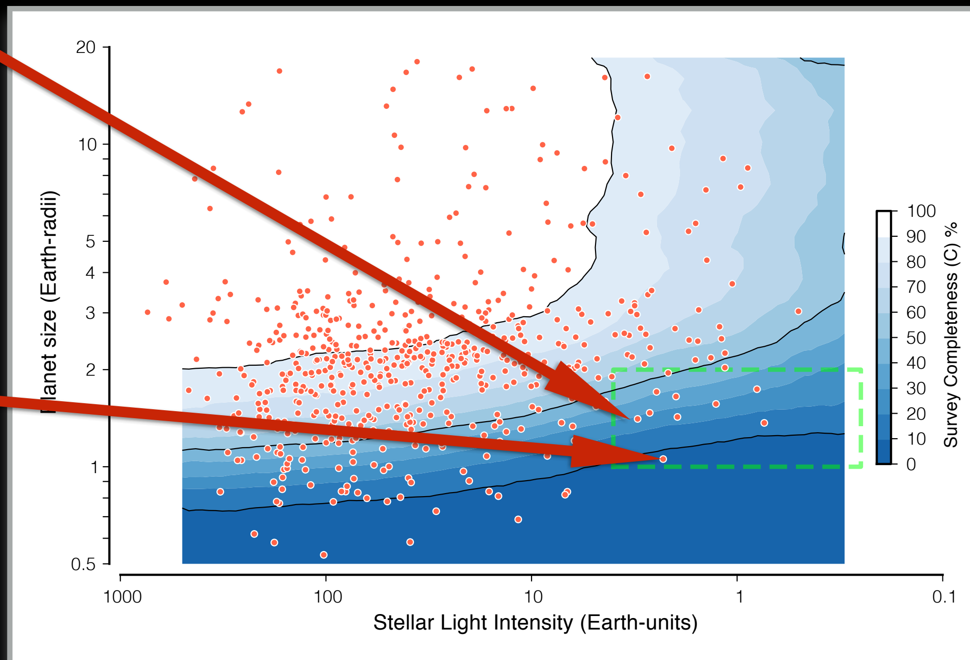
Rocky

or

Puffy?

Determine if cool Earth-size planets are rocky.

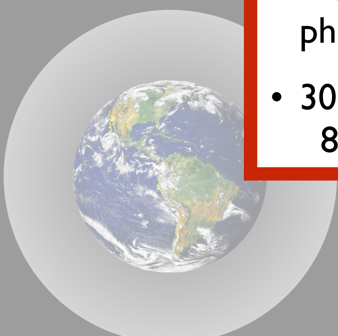
Earth-size planets known from Kepler



Petigura, Howard, & Marcy (2013)

Rocky

or



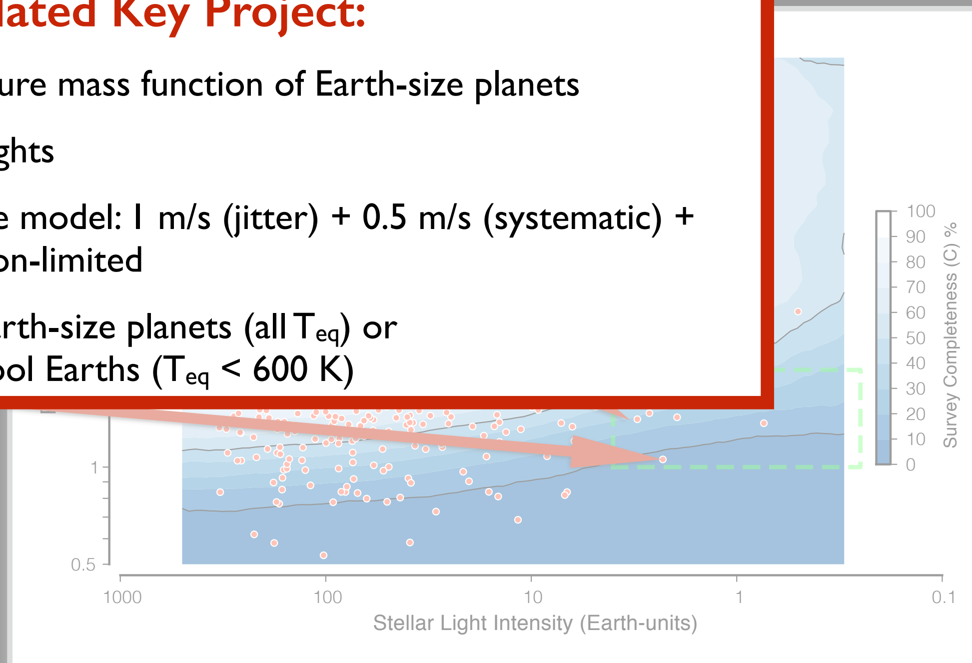
Puffy?

Determine if cool Earth-size planets are rocky.

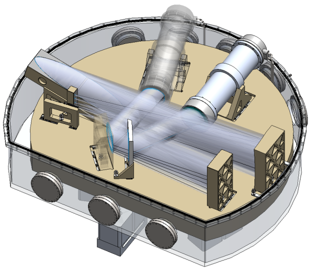
Earth-size planets known from Kepler

Simulated Key Project:

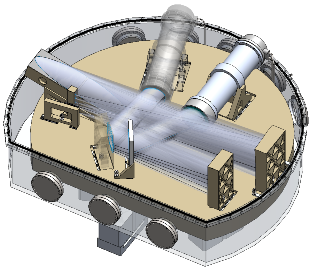
- Measure mass function of Earth-size planets
- 50 nights
- Noise model: 1 m/s (jitter) + 0.5 m/s (systematic) + photon-limited
- 30 Earth-size planets (all T_{eq}) or
  8 cool Earths (T_{eq} < 600 K)



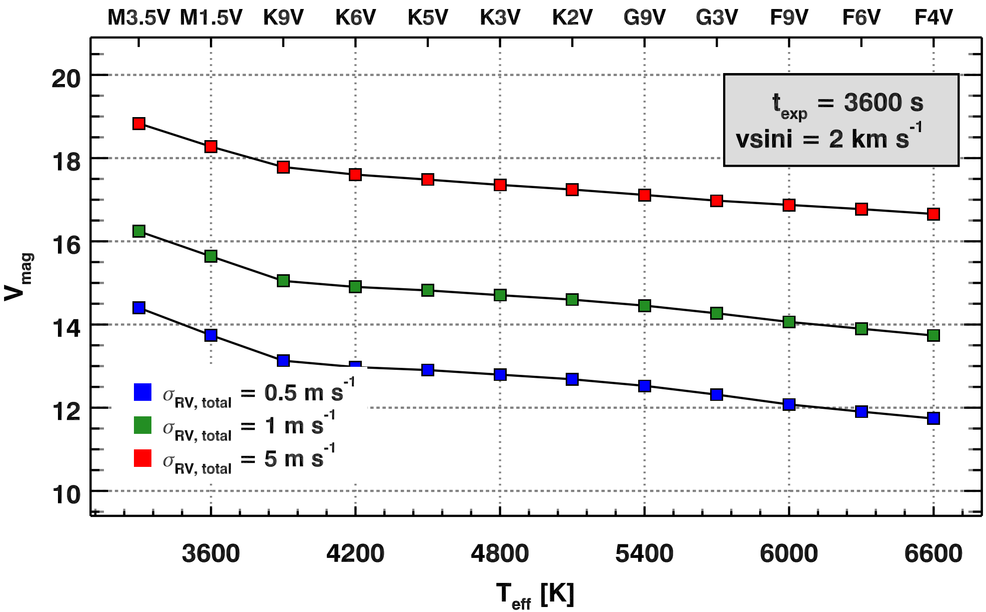
Petigura, Howard, & Marcy (2013)



Science with KPF



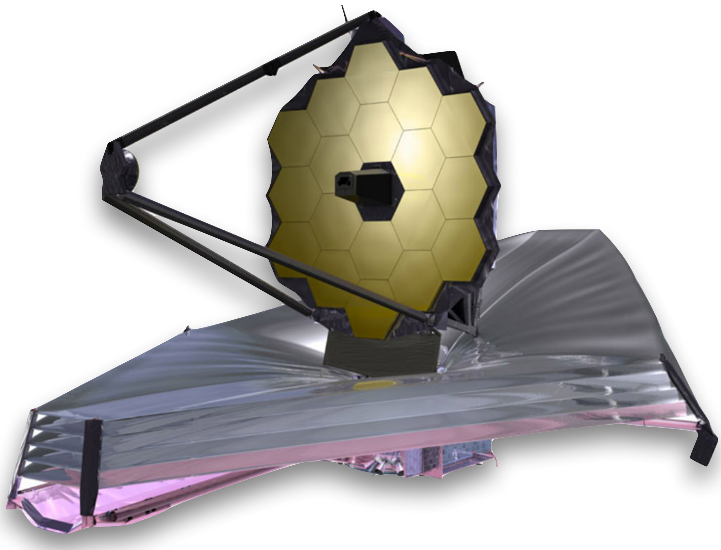
Doppler Precision



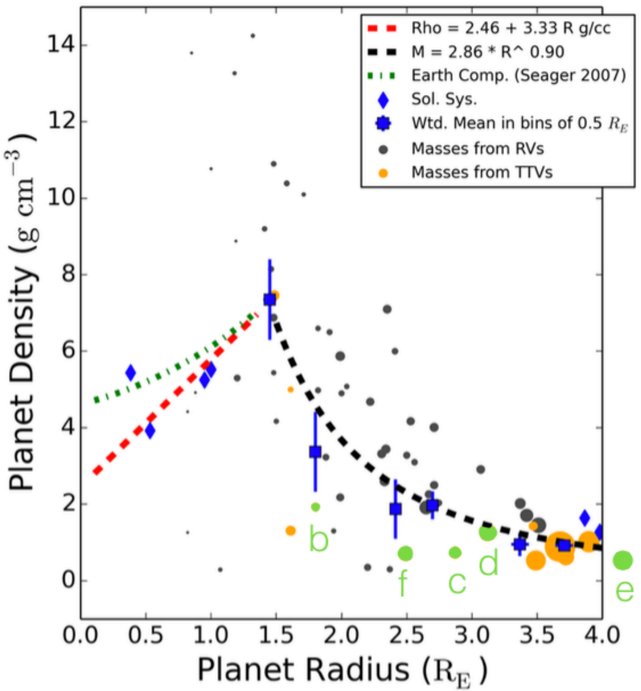
Exposure calculator available — Doppler precision, SNR per order

End

JWST

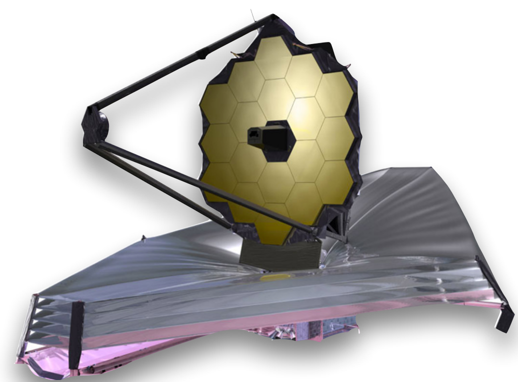


Masses Needed to Interpret JWST Transit Spectra



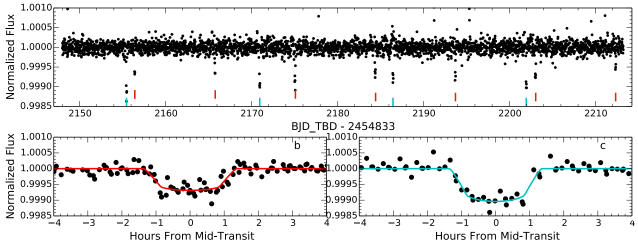
Planet Masses Needed before JWST Observations

- Bulk mass and radius provide basic understanding of planet.
- Planet mass determines surface gravity and atmospheric properties.
- Mass needed to plan observations (SNR per transit, etc.)

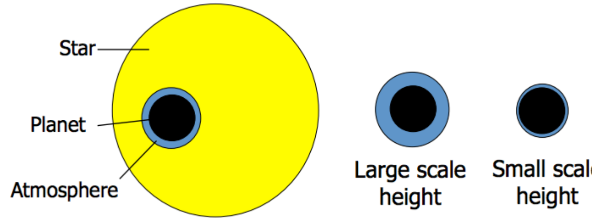


Precise Masses Needed for JWST Transmission Spectroscopy

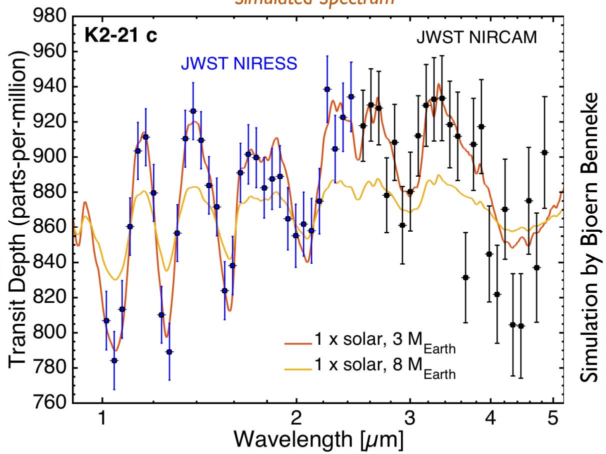
K2-21 — system of two Earth-size planets from K2 Mission
Petigura et al. (2015)

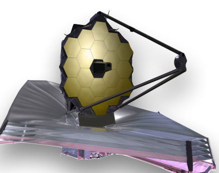


P = 9 day, R_p = 1.6 R_E P = 15 day, R_p = 1.9 R_E



Simulated Spectrum





Measure Atmospheric Scale Height

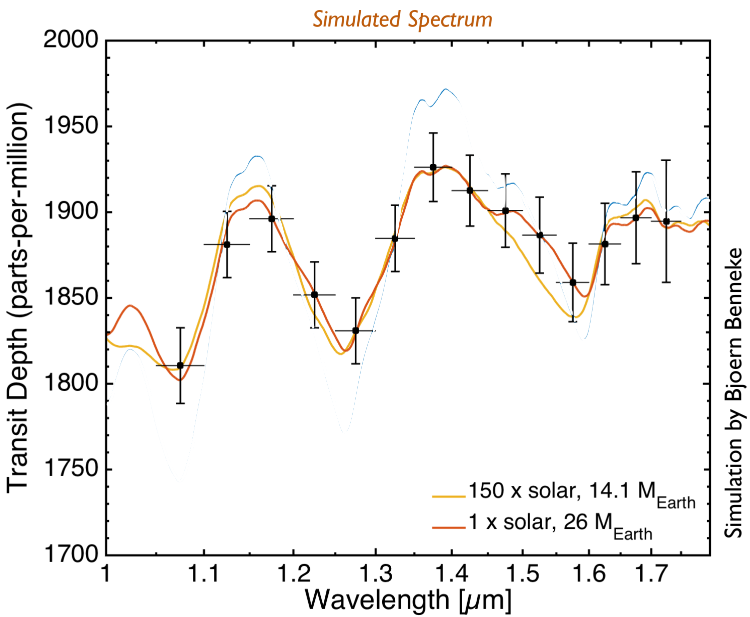
$$H = \frac{kT}{\mu g} \propto \frac{1}{\mu M_{\rm pl}}$$

Mean molecular weight
(atmosphere composition)
μ = 2 for H_2, μ = 18 for H_2O

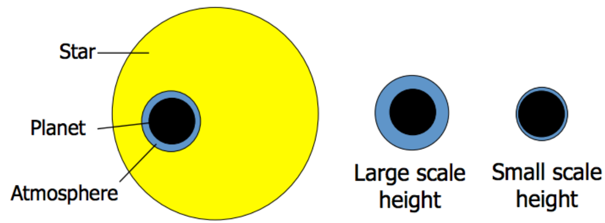
Planet Mass

fundamentally degenerate

Precise Masses Needed for JWST Transmission Spectroscopy



K2-3b
P = 10 day
R_p = 2.1 R_E
V = 12.1 mag



Measure Atmospheric Scale Height

$$H = \frac{kT}{\mu g} \propto \frac{1}{\mu M_{\rm pl}}$$

Mean molecular weight
(atmosphere composition)
μ = 2.3 for H, μ = 18 for H_2O

Planet Mass

fundamentally degenerate

Planet Mass and Atmosphere Composition Fundamentally Degenerate

WFIRST

Nearby Stars

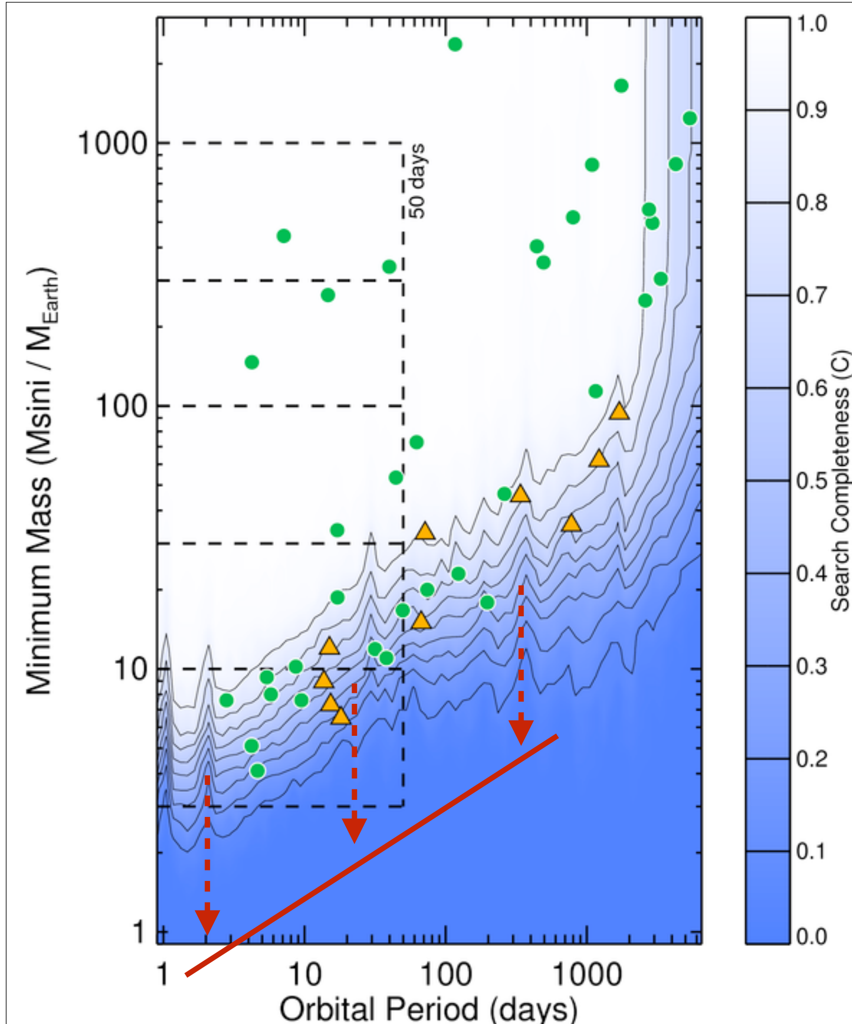
Continue the Keck + Lick legacy

Search for smaller planets orbiting nearby stars

Intrinsically interesting planet population.

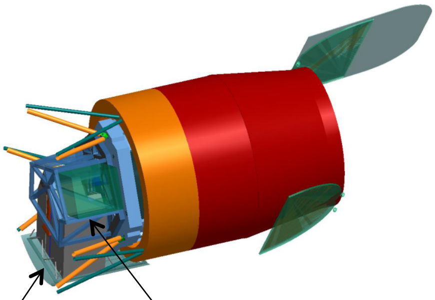
Provide targets for imaging missions with masses, eccentricities, system architectures.

Imaging missions/instruments include WFIRST, TMT, future NASA Flagship mission in 2030s (?)



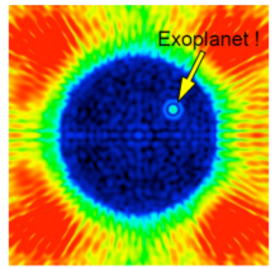
Howard et al. (2010)

WFIRST

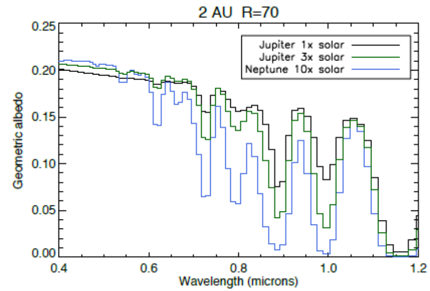


Wide field instrument

Coronagraph Instrument



Exoplanet Direct imaging



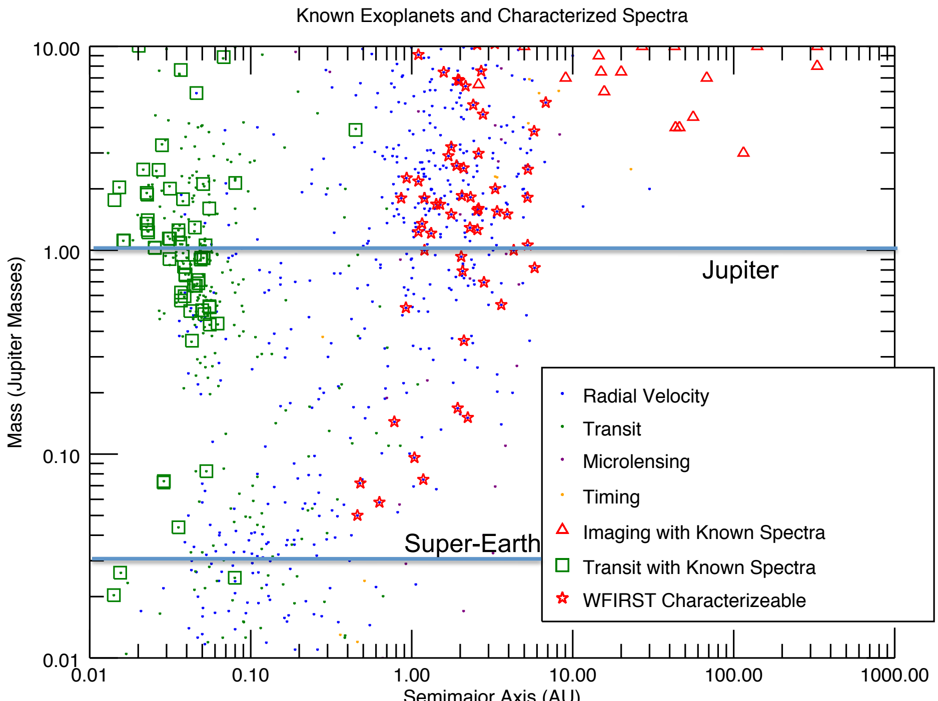
Exoplanet Spectroscopy

Graphics from J. Kasdin

<u>Nearby planet searches are valuable to WFIRST</u>

- Identify targets for WFIRST observations, including small planets
- Save time on WFIRST search phase
- Measure planet masses and eccentricities — important to interpret spectra

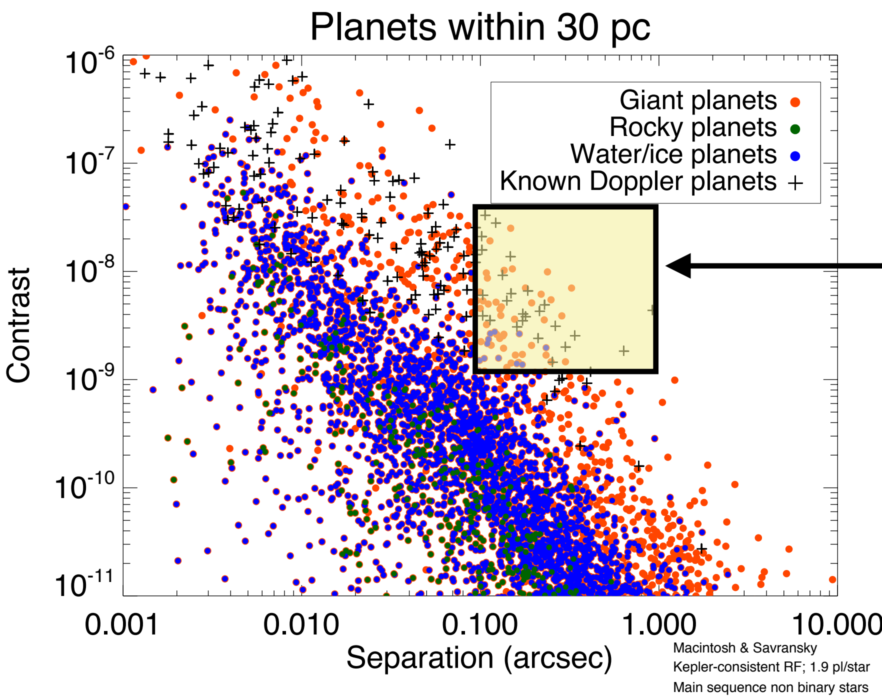
WFIRST



WFIRST Characterizable Doppler planets (PIAACMC case)

Figure from J. Kasdin

WFIRST — Spectroscopy of Small Planets



WFIRST Sensitivity

Discover super-Earths/Neptunes with SHREK before WFIRST launch
→ efficient WFIRST operations; less searching, more spectra

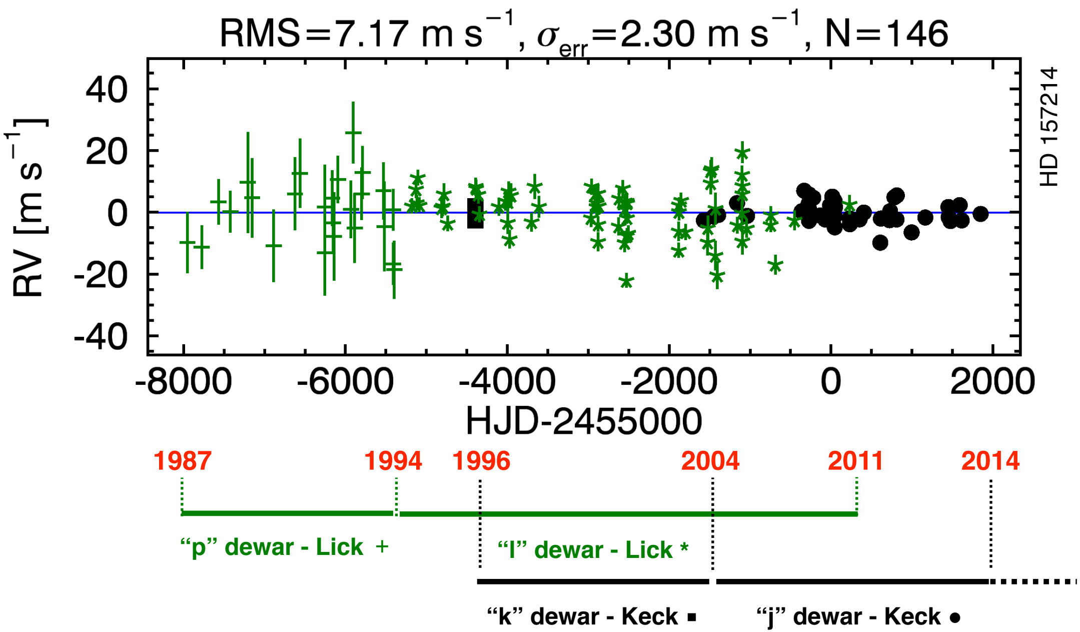
Enable spectroscopy of small planets
→ albedo spectra (new view)
→ connect dominant planet type from Kepler with imaging

Step toward Earth-imaging mission

Figure from B. Macintosh

Historic Keck + Lick RVs Powerfully Constrain Exoplanet Population

Results from major study of Lick + Keck RV data sets in preparation for an imaging mission:

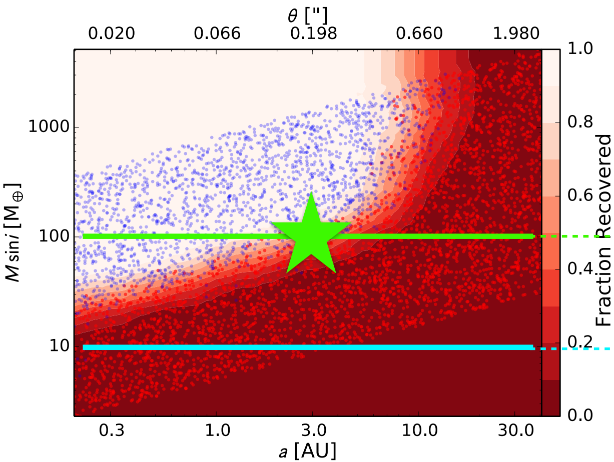


Howard & Fulton (2015, submitted)

SHREK RV Campaign

Sensitivity to Super-Earths for WFIRST Imaging in 2020s

HD 182572 (G8 dwarf, 15 pc)

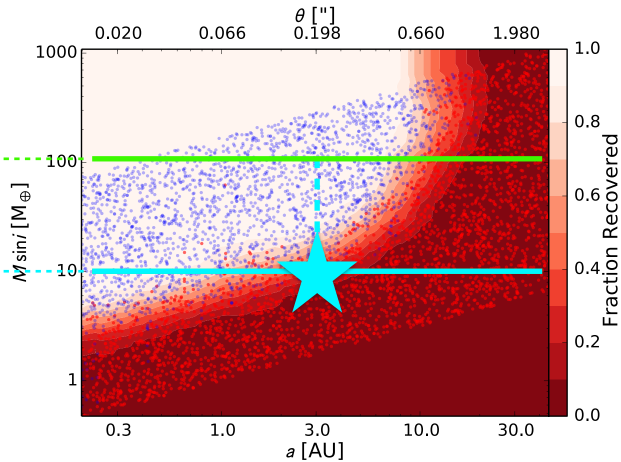


<u>Current RVs:</u>

N_{obs} = 82 RVs

T_{span} = 17.8 yr

σ_{RV} = 4.0 m/s



<u>Ideal Survey:</u>

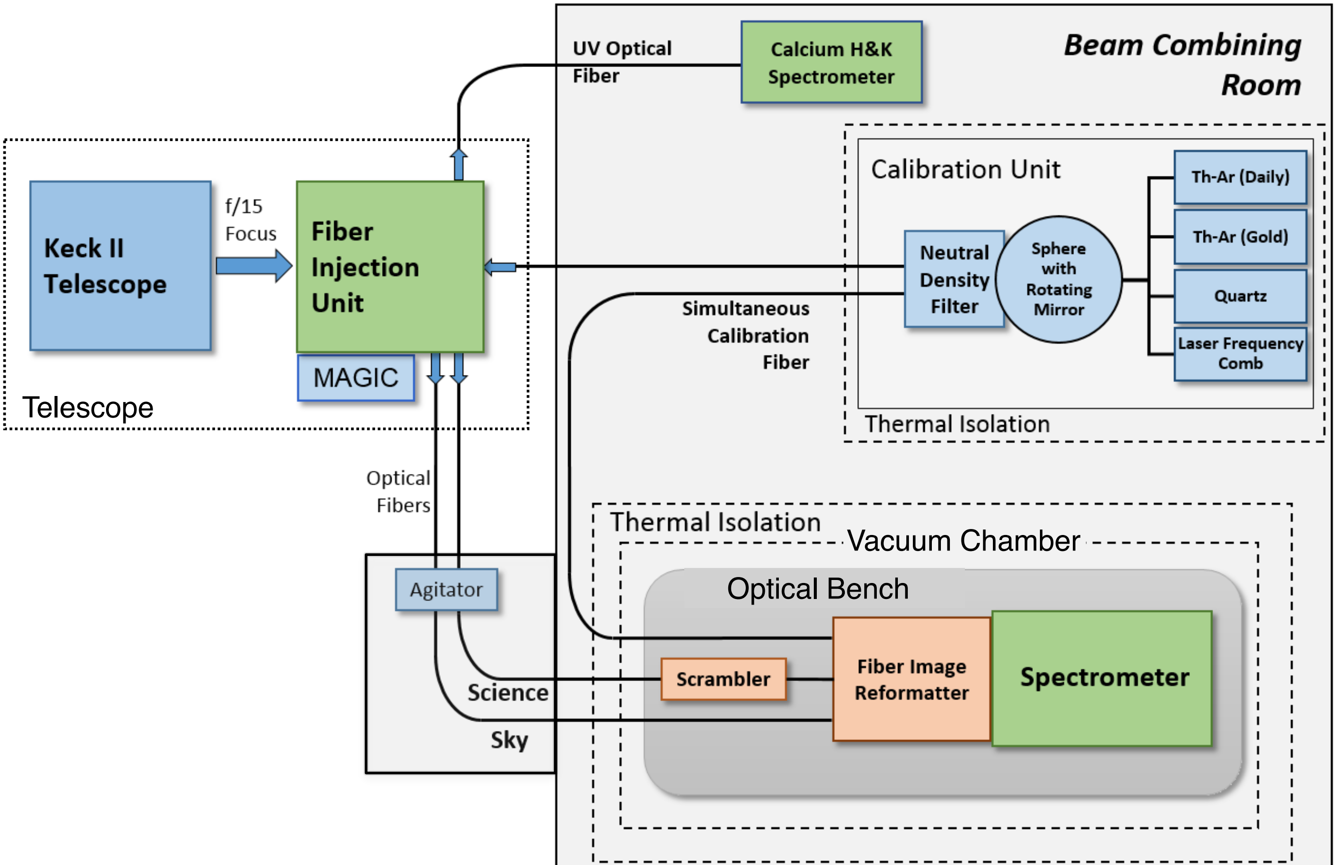
N_{obs} = 82 + 100 RVs

T_{span} = 17.8 yr + 10 yr

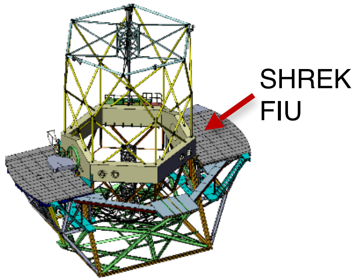
σ_{RV} = 0.5 m/s (new RVs)

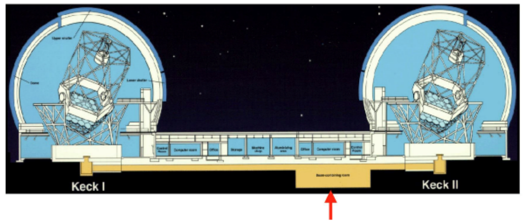
Howard & Fulton (2015, submitted)

SHREK System Overview

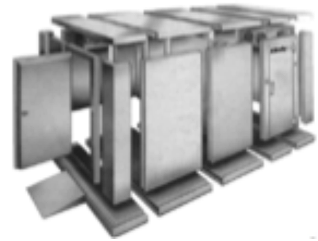


SHREK System Overview

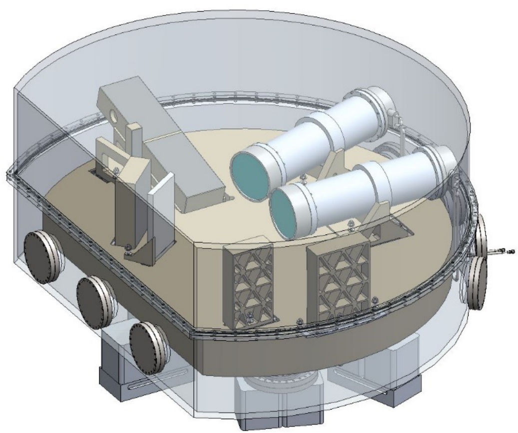




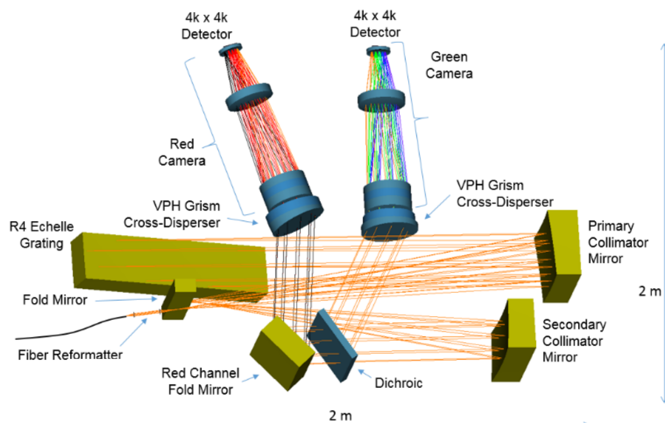
Beam combining room



Thermal Enclosure
in Beam Combining room



Spectrometer in Vacuum Chamber



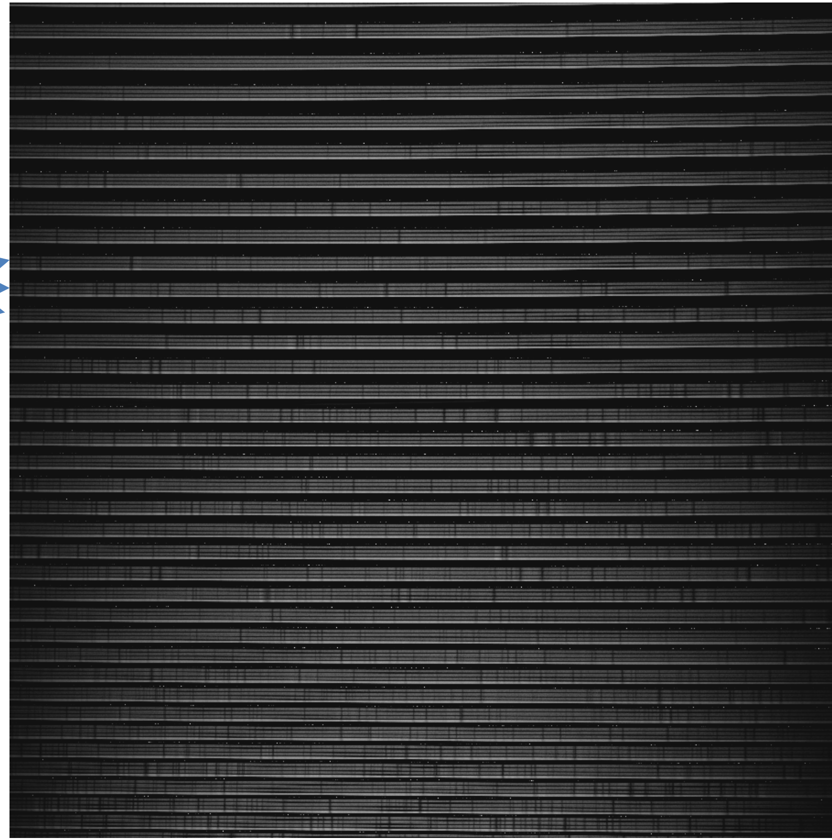
Spectrometer Optical Layout

SHREK System Overview

Data Format

Full Zemax Raytrace Simulation of the Green Channel Spectrum

Echelle Orders

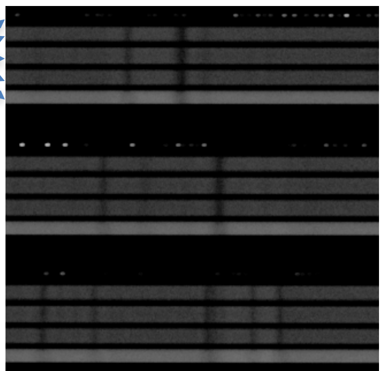


Orderlets

Cal: Th-Ar

cience (3x): Solar

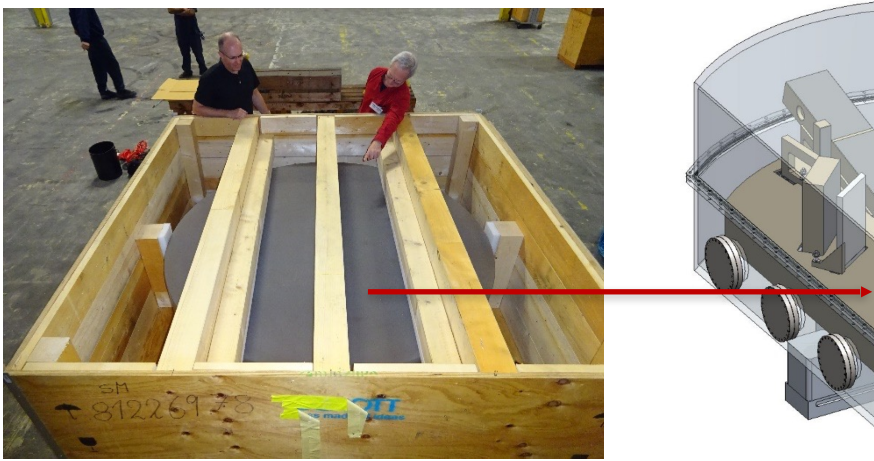
Sky: Solar

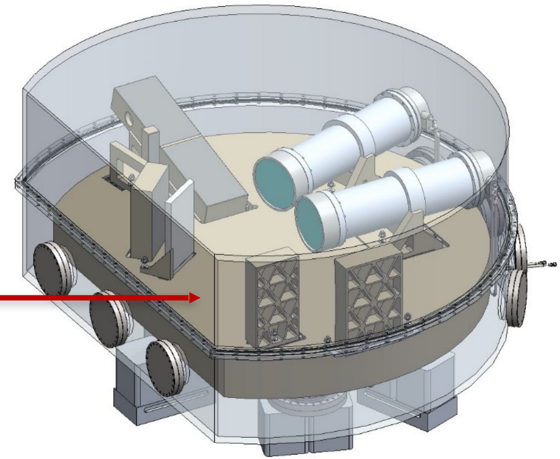


CCD: 4k x 4k 15µm pixels
61 mm x 61 mm

Design Highlight: Optical Bench

Unique opportunity: availability of 2 m x 0.4 m Zerodur disk



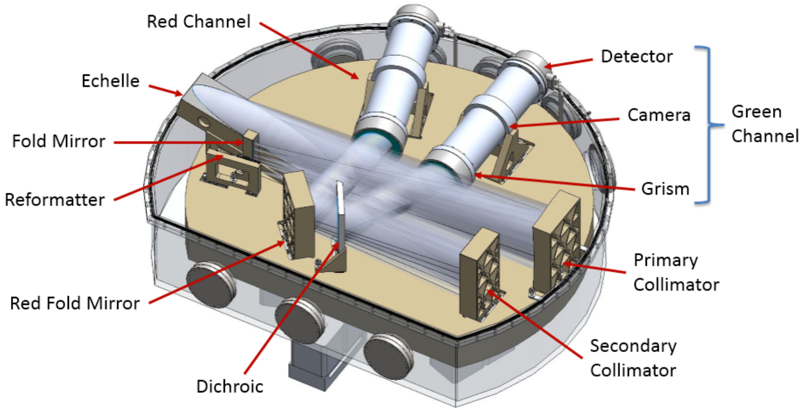


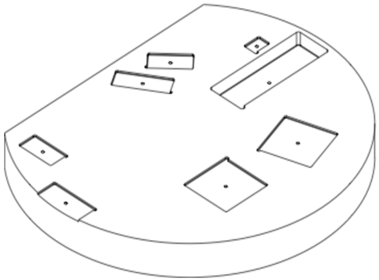
Primary advantage is very low CTE:
(provides stability against thermal expansion)

Bench Material	CTE [10^{-6} K^{-1}]	Relative to Zerodur
Zerodur	0.05	1x
Invar 36	1.0	20x
Stainless 416	8.5	170x
Stainless 304	14.7	294x

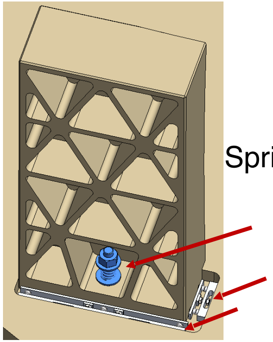
Design Highlight: Optical Mounts

- Intent is to take full advantage of the low CTE of the Zerodur disk
  - Avoid high CTE materials where possible: metals, RTV, plastics, epoxy
- Mounting scheme is to mechanically contact optics and mounts - also made of Zerodur, where possible - directly to the Zerodur bench





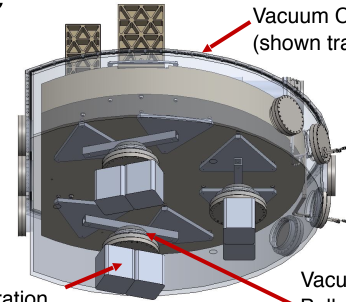
CNC-machined pockets to locate optics



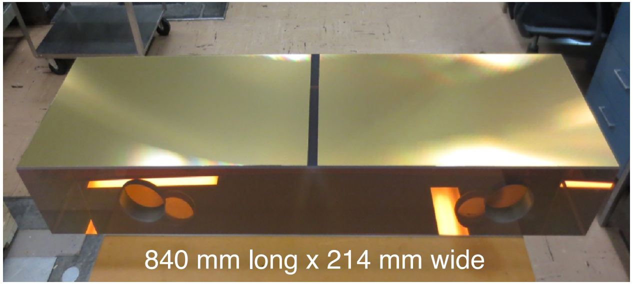
Springs hold optics in place

More Design Highlights

Whiffletree Support

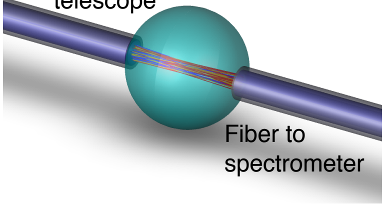


Echelle Grating

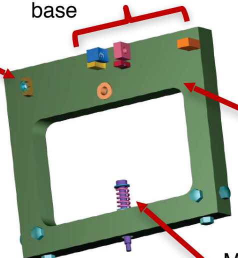


Early purchase to secure spot in production queue

Ball Lens Scrambler

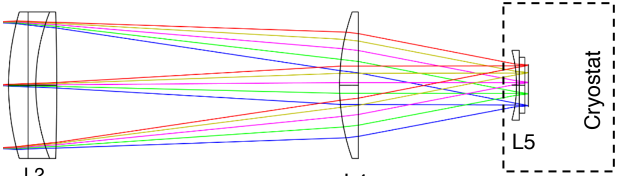


Reformatter



Early purchase to
fully test and
characterize

Camera



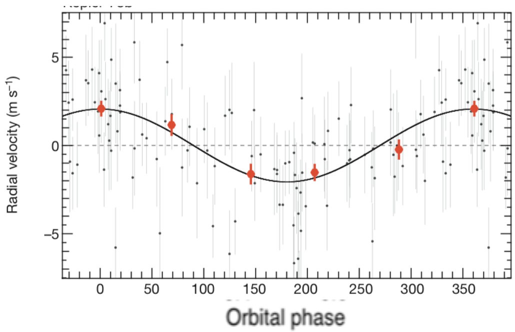
Extras Slides

TNG-HARPS is as fast as Keck-HIRES

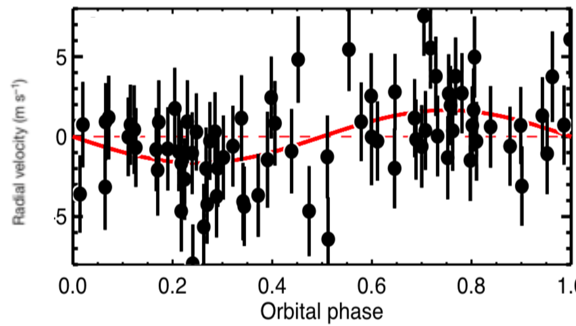
TNG/HARPS-N (3.6-m)

Keck/HIRES (10-m)

Kepler-78 with HARPS-N RMS=2.0 m/s



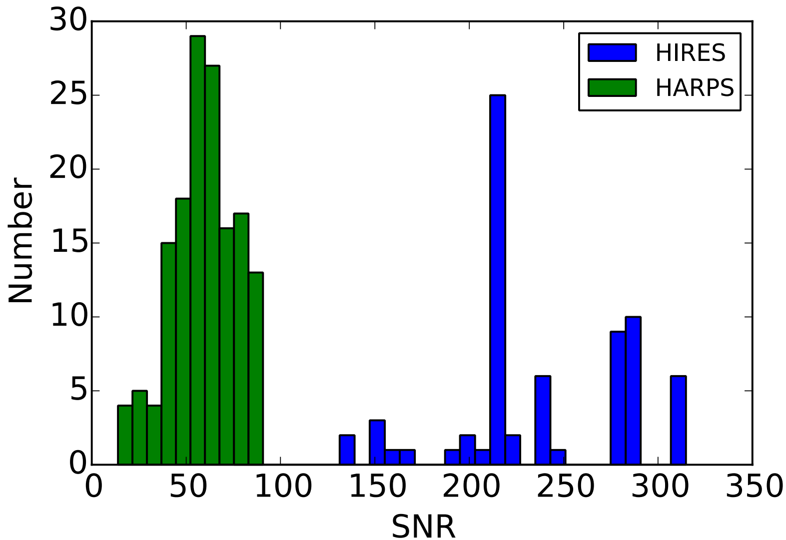
Kepler-78 with HIRES RMS=2.0 m/s



Both Telescopes used 30 minute exposures.
Both Telescopes achieved RV precision of 2 m/s.
But the TNG has 1/8 the collecting area!

TNG-HARPS is as fast as Keck-HIRES

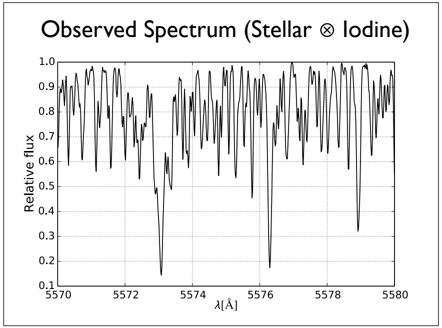
Reason:
Stable Spectrometers require only SNR = 70.
HIRES requires SNR = 200.

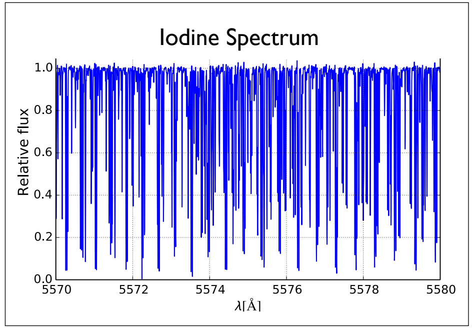


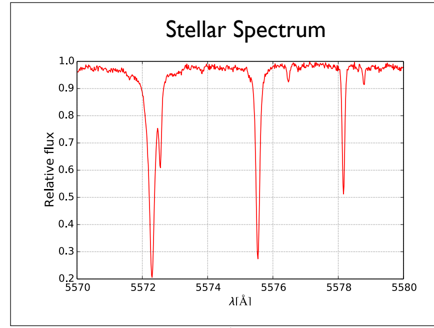
HARPS-N obtains a typical SNR ~ 70 while HIRES is forced to obtain SNR ~ 200 to compete.
HARPS-N achieves the comparable Doppler precision as HIRES with 1/8 the photons.

Stable Spectrometers are 8x Faster than HIRES for RVs.
Reason: HIRES must post-calibrate every exposure with polluting iodine.

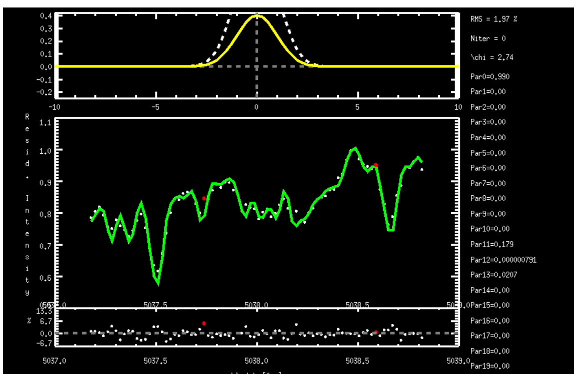
The Challenge of Forward Modeling Iodine ⊗ Stellar Spectra







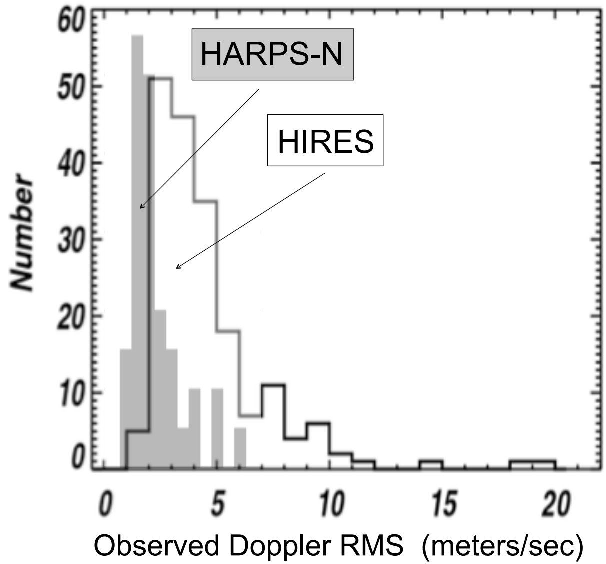
$$I_{obs}(\lambda) = k[T_{I2}(\lambda) \cdot I_S(\lambda + \Delta\lambda)] \otimes PSF$$



Iodine Doppler Method

1. Requires ~10,000 free parameters per spectrum. Only interested in one parameter — RV!
2. Requires high SNR spectra to model.
3. PSF is spatially and temporarily variable.
4. Intrinsically limited by ability to model PSF and wavelength solution.

Observed Doppler RMS of FGK Stars
HARPS-N vs HIRES



Observed Doppler RMS of FGK stars with HIRES (line, from Howard et al. 2010) and from HARPS-N (Motabeli et al. 2015).

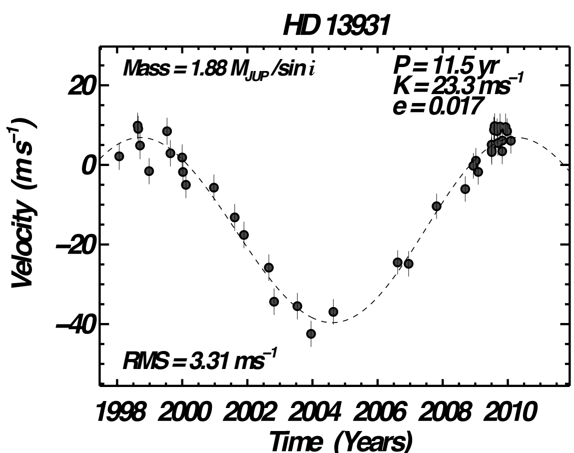
HARPS-N has an error floor of 0.5 m/s. HIRES has an error floor of 1.8 m/s.

Doppler Planet Measurements

Doppler Signals — Scale

$$K = \frac{3.7\,\mathrm{m\,s^{-1}}}{(1-e^2)^{1/2}} \cdot \left(\frac{P}{5\,\mathrm{days}}\right)^{-1/3} \cdot \left(\frac{M_\star}{M_\odot}\right)^{-2/3} \cdot \frac{M_{\rm pl}}{10 M_\oplus}$$

Doppler Planet Discovery



Howard et al. (2010)

Source of Doppler Error

Photon-limited (Poisson):

- HARPS-N: 1 m/s in 30 min for V = 11 mag star (K0 dwarf)
- SHREK: 1 m/s in 4 min for 8X aperture and 6% throughput for same V = 11 mag star

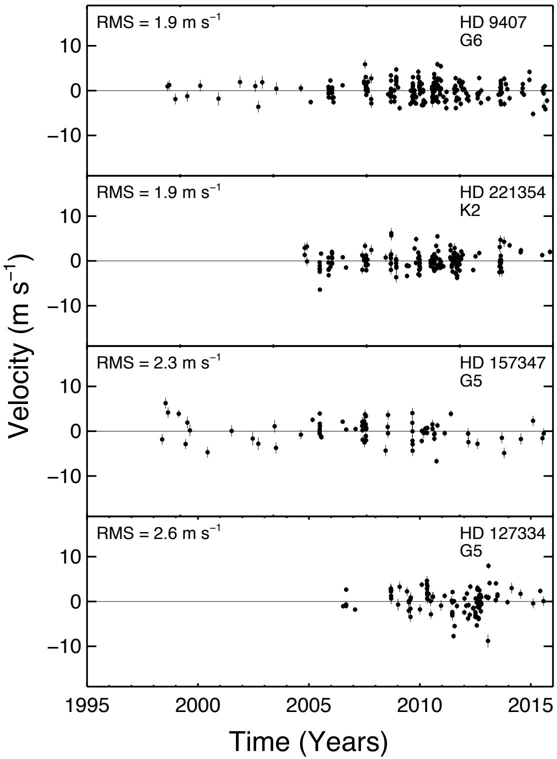
Astrophysical Jitter:

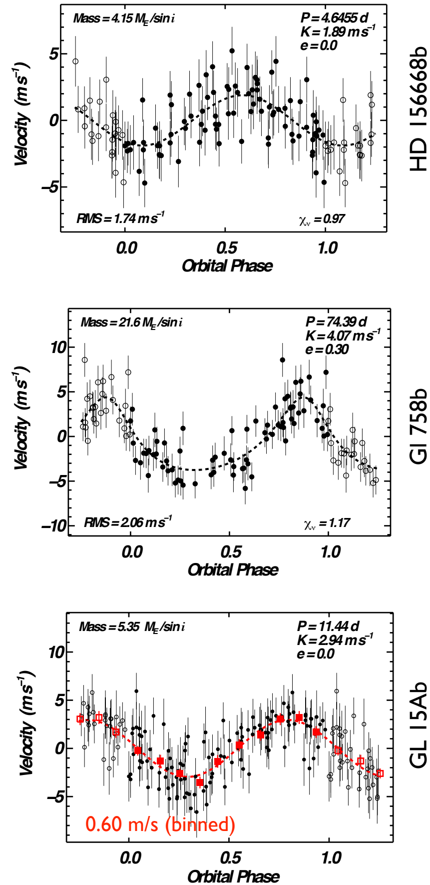
- Acoustic oscillations — ~1 m/s on ~3-5 min timescale
  - mitigation: observing strategy
- Granulation (surface convection) — ~1 m/s on ~hour timescales
  - mitigation: observing strategy
- Magnetic Activity — ~0-3 m/s on ~month timescales from spots/plage, rotation
  - mitigation: activity metrics: Ca II H&K lines, FWHM/BIS of CCF

Instrumental Precision:

- Simultaneous PSF calibration — iodine technique} (HIRES) limited to ~2 m/s.
- Stable reference — stable spectrograph (HARPS) achieves < 0.8 m/s (probably 0.3-0.5 m.s)

HIRES — Best Performance
Doppler Planet Discovery — Bright Stars

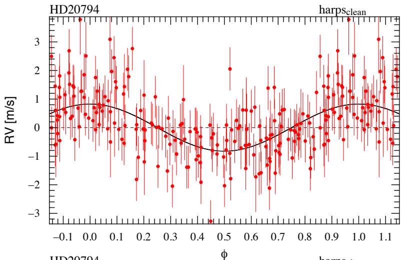




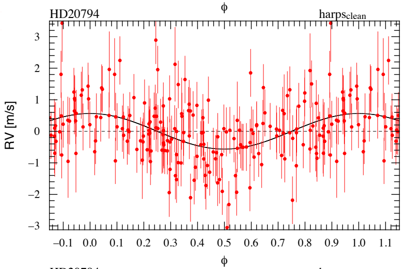
Howard et al. (2010, 2011, 2014)

HARPS — Best Performance
Doppler Planet Discovery — Bright Stars

HD 20794



HD 20794 b
P = 18 d
K = 0.83 ± 0.09 m/s
Msini = 2.7 ± 0.3 M_E
χ^2 / DOF = 1.4



HD 20794 c
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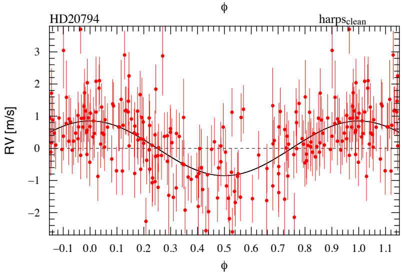

HD 20794 d
P = 90 d
K = 0.85 ± 0.10 m/s
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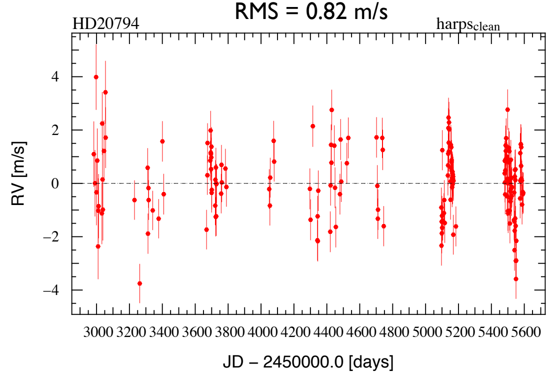
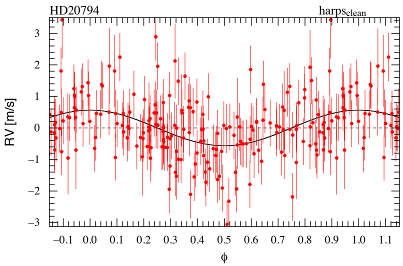
Residuals to 3-planet Fit
RMS = 0.82 m/s



Pepe et al. (2011)

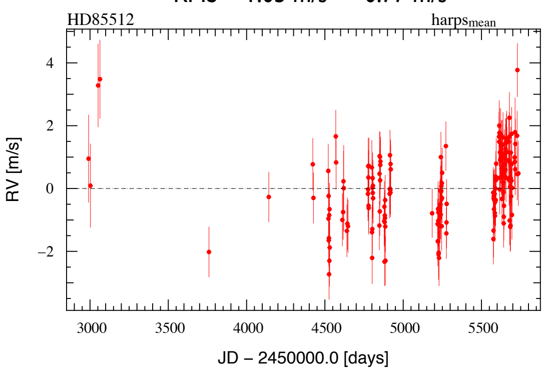
HARPS — Best Performance
Doppler Planet Discovery — Bright Stars

HD 85512



HD 85512 b
P = 58 d
K = 0.77 ± 0.10 m/s
Msini = 3.6 ± 0.5 M_E
χ^2 / DOF = 1.0

1-planet Model
RMS = 1.05 m/s → 0.77 m/s



Pepe et al. (2011)

τ Ceti (HD 10700)
RMS = 0.92 m/s

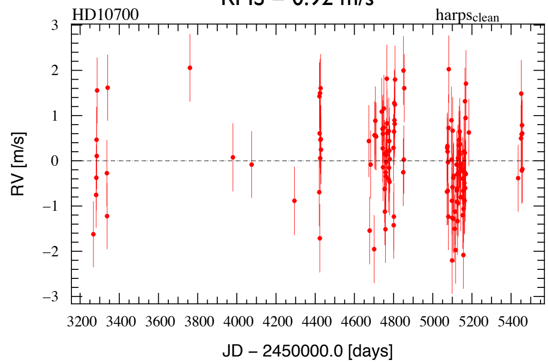


Table 2. Observations of the targets with HARPS

Target	Data points	Time span [days]	*RV* scatter [$m\,s^{-1}$]	$\log(R'_{HK})$
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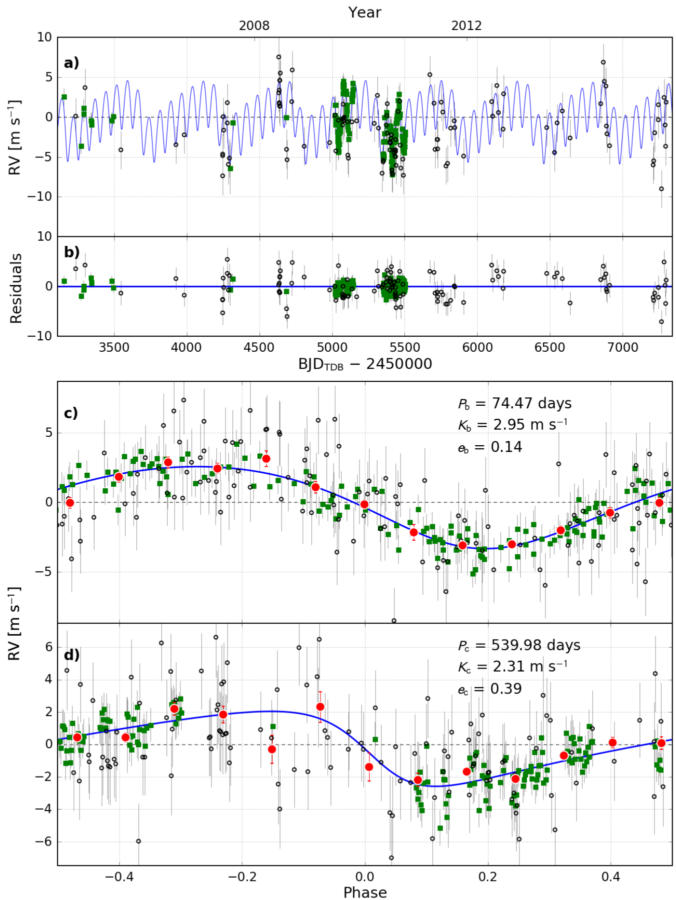
HARPS vs. HIRES — Observations of the Same Star



Gl 785 (HD 192310)

nearby, bright star
K0V
V = 5.7 mag

Good test of noise sources:

bright → *not photon-limited*
test of systematic errors + jitter

Planets discovered:

Planet b - Howard et al. (2011)
Planet c - Pepe et al. (2011)

RMS to 2-planet fit:

HIRES = 2.2 m/s
HARPS = 1.0 m/s

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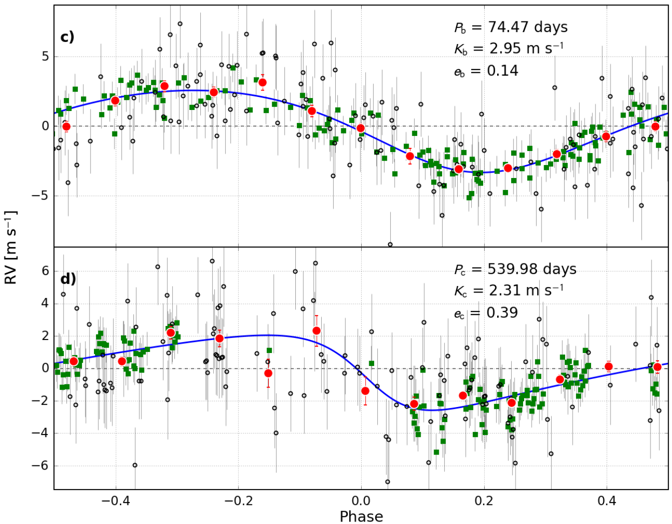

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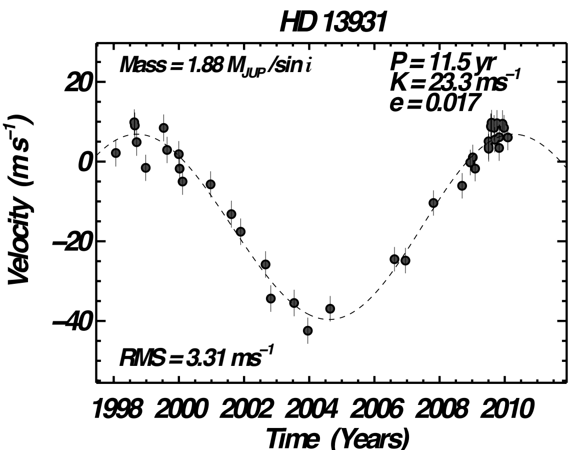
Doppler Planet Discovery



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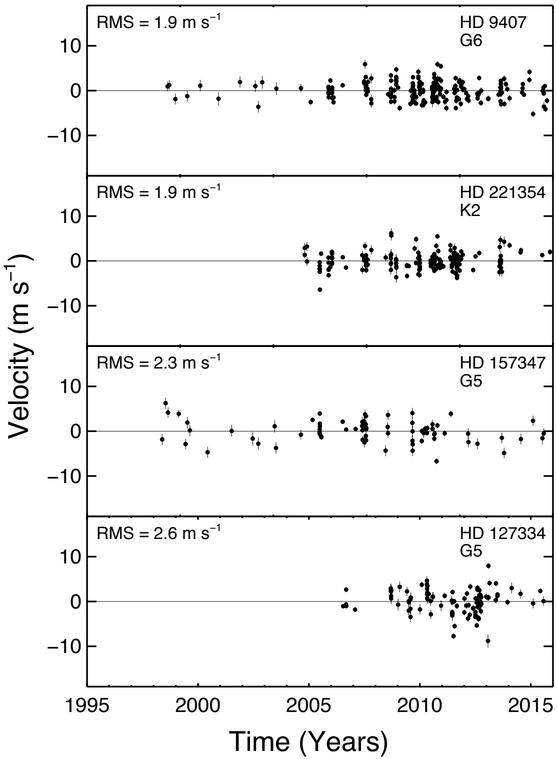
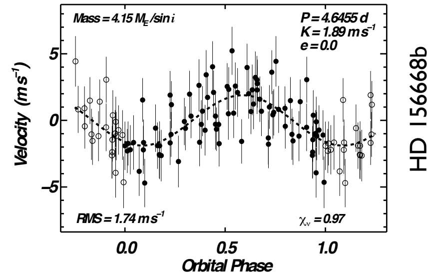
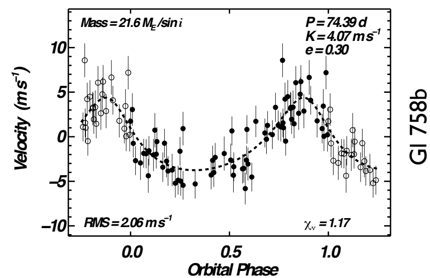
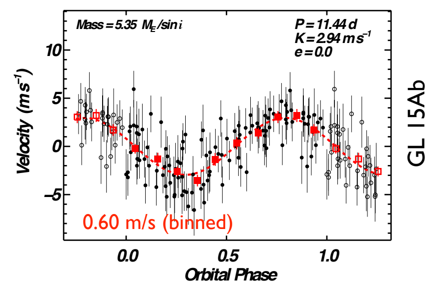
HIRES — Best Performance
Doppler Planet Discovery — Bright Stars









Howard et al. (2010, 2011, 2014)

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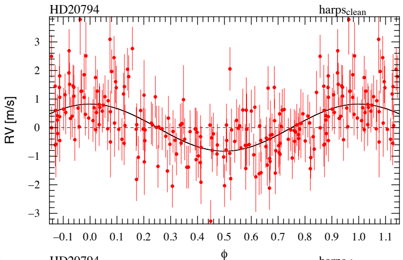

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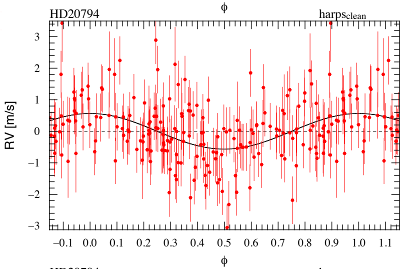

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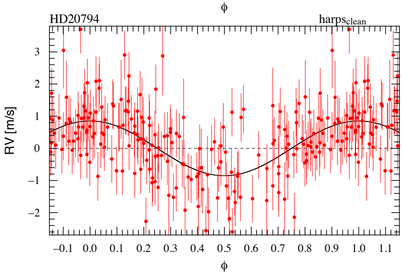

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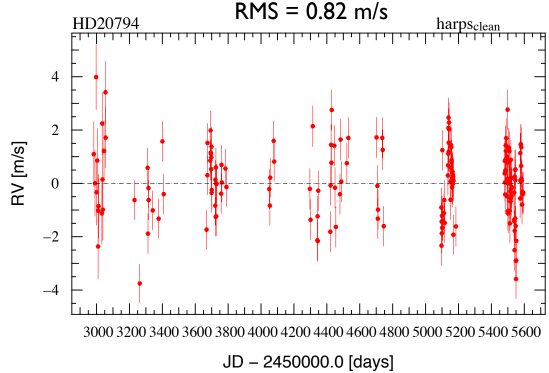

Pepe et al. (2011)

HARPS — Best Performance
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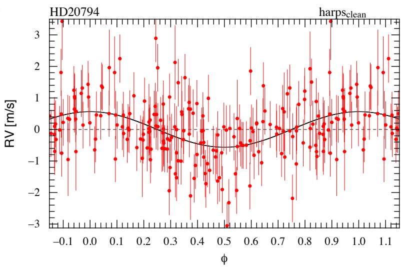
HD 85512



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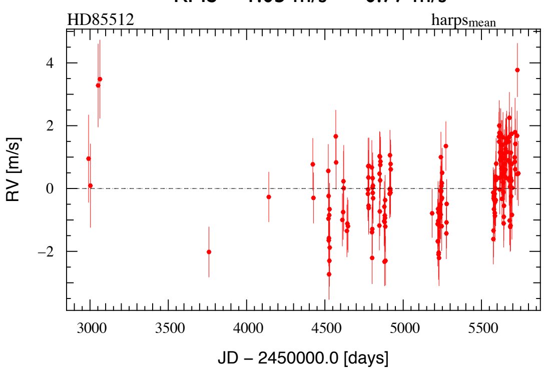

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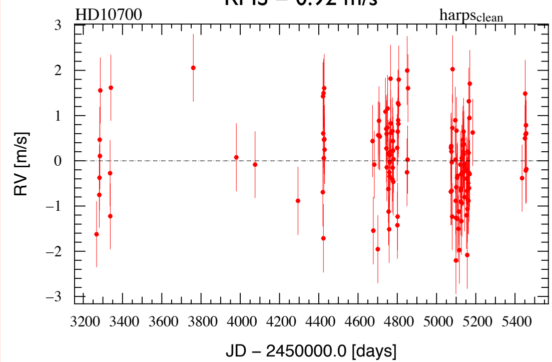

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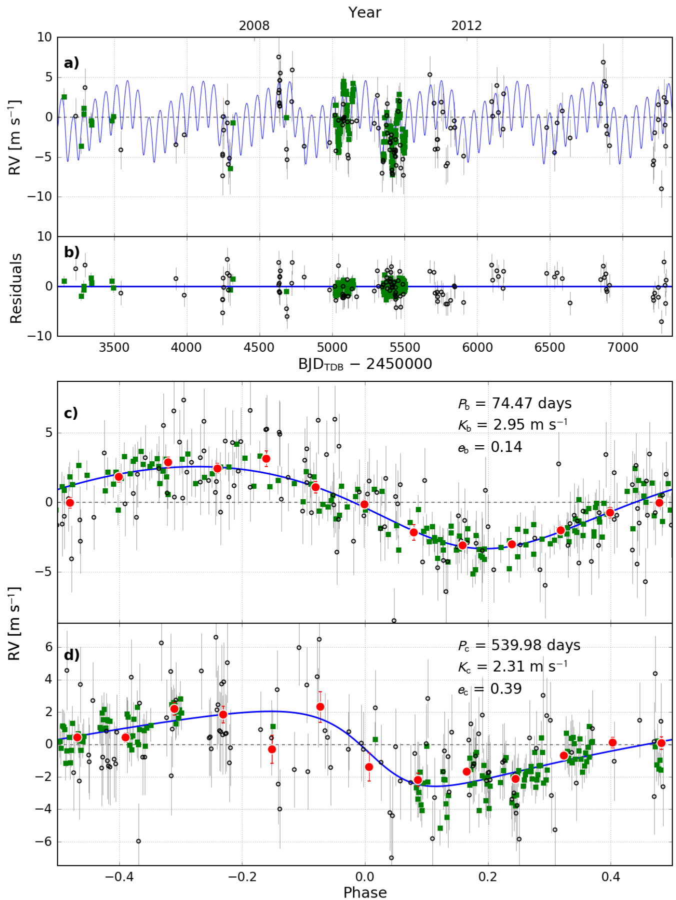

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Planet b - Howard et al. (2011)

Planet c - Pepe et al. (2011)

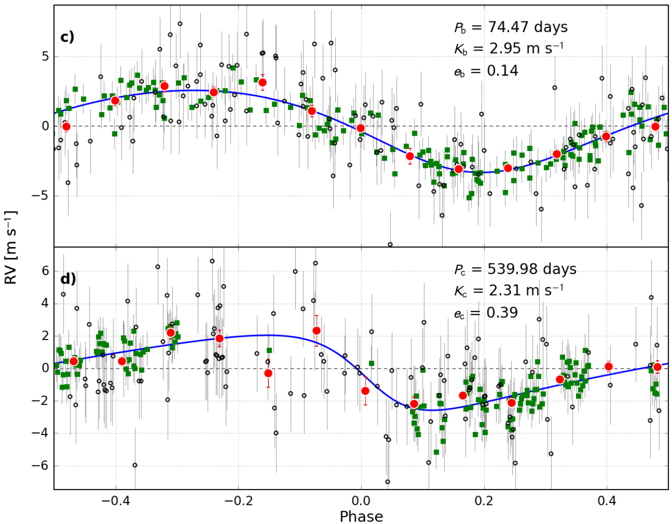
RMS to 2-planet fit:

HIRES = 2.2 m/s

HARPS = 1.0 m/s

HARPS vs. HIRES — Observations of the Same Star

RMS to 2-planet fit:
HIRES = 2.2 m/s
HARPS = 1.0 m/s



Gl 785 (HD 192310)

nearby, bright star
K0V
V = 5.7 mag

Good test of noise sources:
not photon-limited
test of systematic errors + jitter

Planets discovered:
Planet b - Howard et al. (2011)
Planet c - Pepe et al. (2011)

RMS to 2-planet fit:
HIRES = 2.2 m/s
HARPS = 1.0 m/s