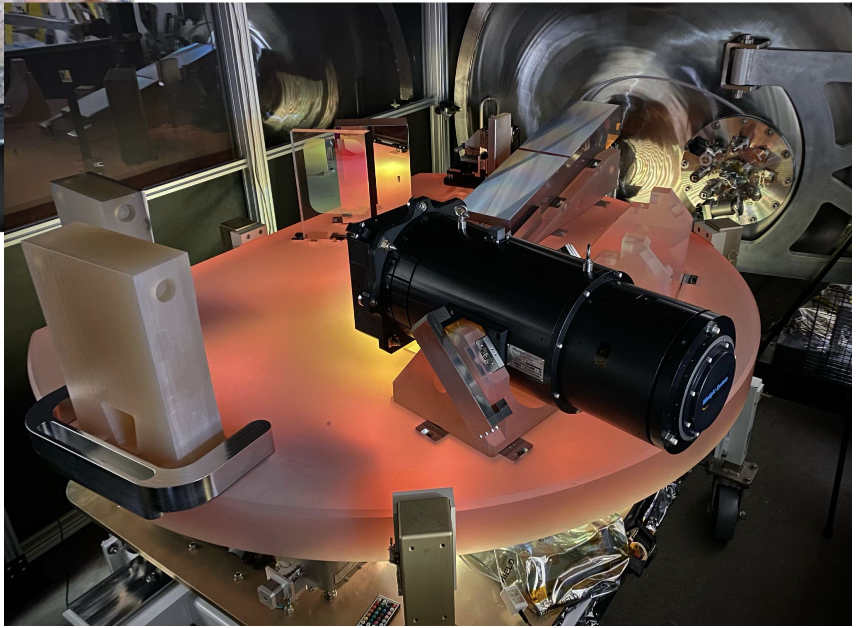
# Performance and Use of the Keck Planet Finder

Andrew Howard, Sam Halverson, Howard Isaacson, and Josh Walawender
on behalf of the KPF Team

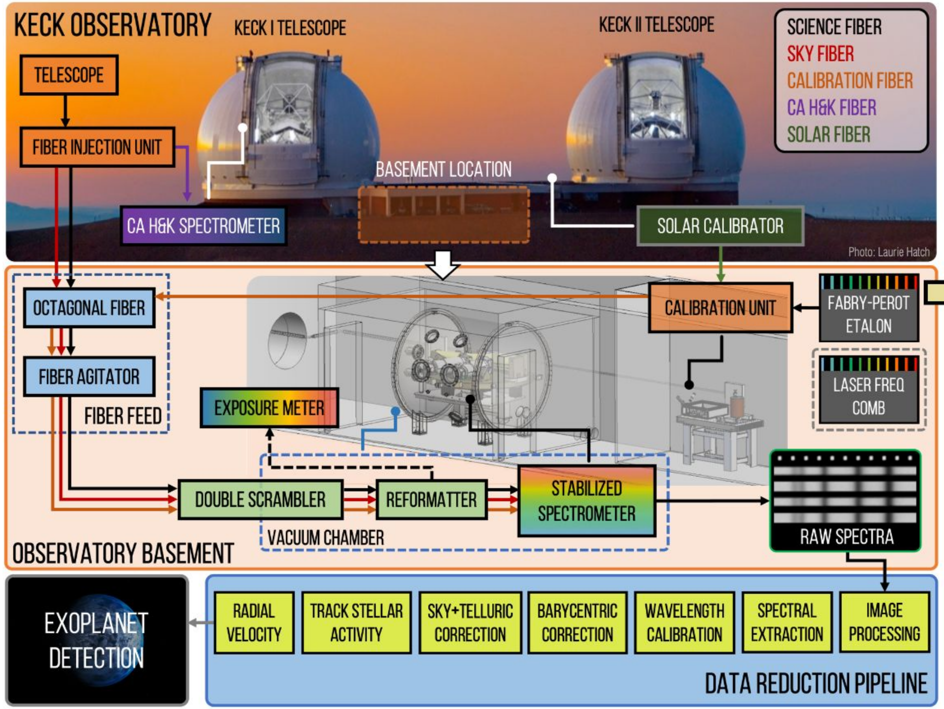
# Keck Planet Finder

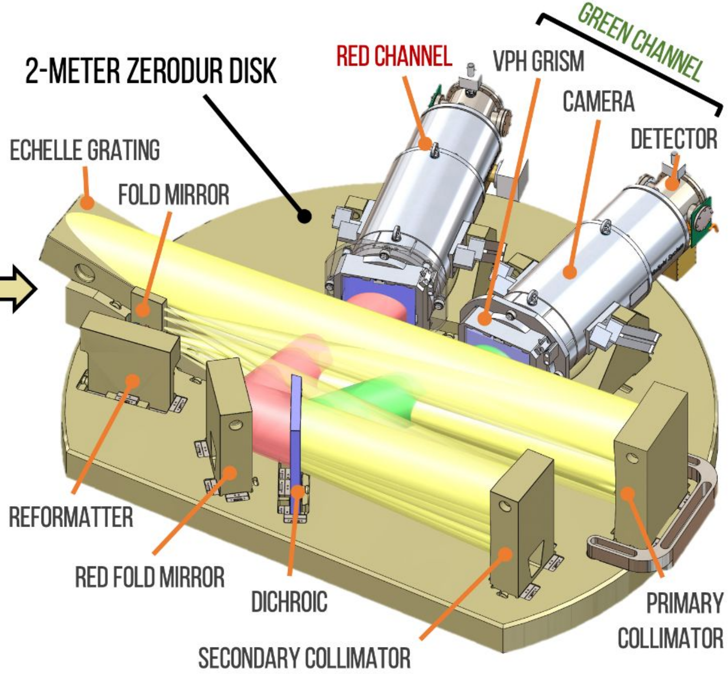

KPF team (partial) at First Light on Nov. 9, 2022

Keck Planet Finder spectrometer



# KPF Instrument




## Important subsystems:

- High-resolution Spectrometer
- Ca H&K Spectrometer
- Fiber Injection Unit
- Chromatic Exposure Meter
- Calibration System

# KPF High-resolution Spectrometer

**Optical inputs**: Science fiber: 1.14 arcsec (225 µm, octagonal cross-section)*
Sky fiber: 1.14 arcsec (225 µm, octagonal cross-section), 10 arcsec separated
Cal fiber: 64 µm

**Wavelength coverage**: 445-870 nm (primary spectrometer) + 382-402 nm (Ca H&K spectrometer)

**Resolving power**: R = 98k (primary spectrometer), 17k (Ca H&K spectrometer)

**Sampling**: 3-4 pixels/res.elem. (primary spectrometer), 3-4 pixels/res.elem. (Ca H&K spectrometer)

**RV precision**: systematic noise floor: 50 cm/s (requirement) and 30 cm/s (goal)
photon noise: set by signal SNR; e.g., 30 cm/s in 30 min for V=10.9 G2 or V=13.2 M4
stellar variability: property of the star; can be partially mitigated, especially w/cadence

**Wavelength calibration**: laser frequency comb, etalon, thorium-argon, uranium-neon

**Special Characteristics**: Solar Calibrator, Fast-read mode (15 sec), UV spectrometer for Ca II HK, sky fiber

* - the science fiber is optically sliced into three 64 µm-wide slices that are offset from each other in cross-dispersion

# Science Goals → Design Drivers

Science Goals:

- Discover and characterize exoplanets
- Measure precise planet masses and orbits

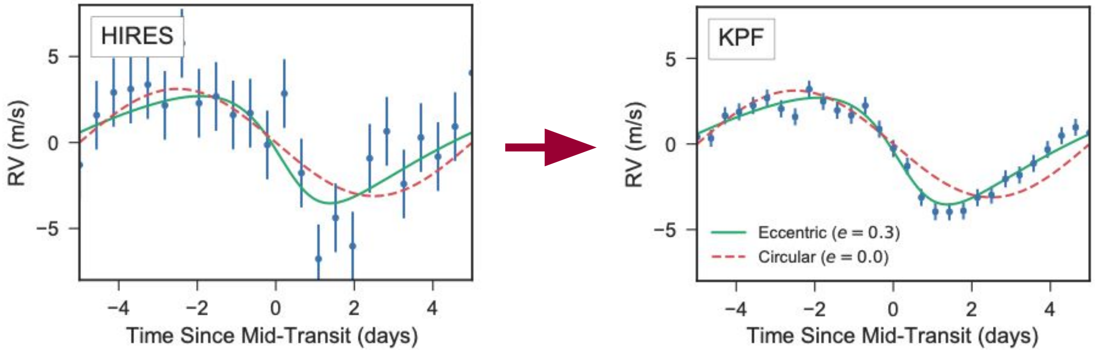
Measurement Needs

→ **High optical throughput**

→ **Doppler measurement precision**

Design Drivers

- **Optical efficiency**: optical design, coatings, fiber length, etc.
- **Stability**: material choice, optical fiber system, mechanical design, thermal design, vibration isolation, vacuum, detector choices

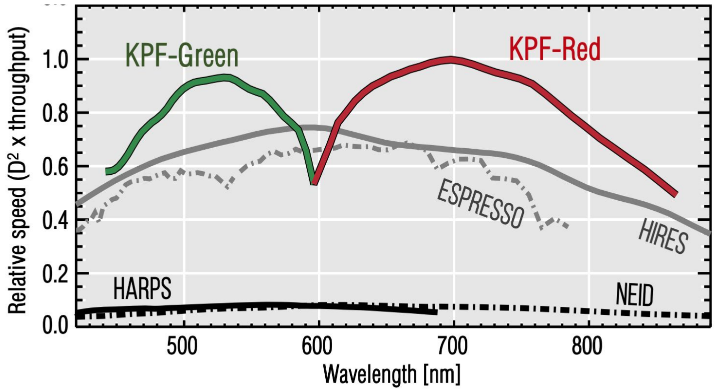



## Doppler Error Budget

TOTAL ERROR: 30 CM S$^{-1}$

| FIBER & ILLUMINATION: 14 CM S$^{-1}$ | INSTRUMENTAL: 20 CM S$^{-1}$ | % INSTRUMENTAL ERROR CORRECTED BY CALIBRATION: 90 / COMPUTATION: 18 CM S$^{-1}$ | DETECTOR EFFECTS: 7 CM S$^{-1}$ | EXTERNAL SOURCES: 18 CM S$^{-1}$ |
|---|---|---|---|---|
| Modal noise (star + cal.) | Therm. stability (bench) | | Pixel center offsets | Telescope & FIU guiding |
| Near + far-field scrambling | Therm. stability (gratings) | | Pixel inhomogeneities | ADC variation |
| Stray light + ghosts | Therm. stability (camera) | | Charge transfer efficiency | Focus variation |
| Fiber-fiber contamination | Vibrational stability | Barycentric corrections | CCD thermal expansion | Fiber injection angle |
| Polarization variation | Pressure stability | Calibration process | Readout thermal change | Micro-tellurics |
| FRD (star + calibration) | Zerodur phase change | Reduction and software | Brighter-fatter effect | Scattered sunlight |

## Measurement Speed of KPF



# KPF Timeline

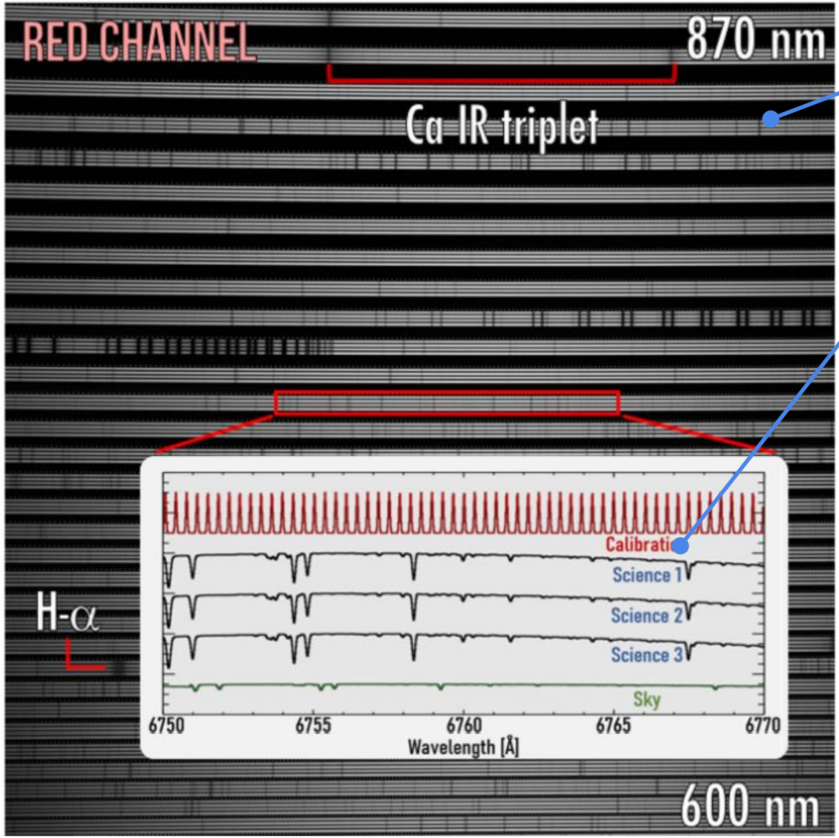
## Past:

- ❑ **Design, Fundraise, Test, Build – 2014-2022**
- ❑ **Ship to Hawaii, reassemble, test, and First Light (summer 2022 → November 9, 2022)**
- ❑ **Commissioning – November 2022 – ~April 2023**

## Current and Future:

- ❑ **Science Observations – ~April 2023+**
- ❑ **Ongoing improvements to operations, DRP, specific subsystems – May 2023 +**
  - DRP – Improvements to wavelength solution determination, cosmic ray rejection, other issues
  - Fiber Injection Unit – lab/on-sky
  - Numerous refinements to operations
- ❑ **"Service Mission" – ~3 weeks in December 2023 to February 2024 (to be scheduled)**
  - Install thermal enclosure
  - Fix focus issue on edge of green CCD
  - Adjust "Reformatter" for more even slice shapes/intensities
  - Install baffling on ion pumps
  - Install precision wedge filters in calibration system for ultraprecise calibrations
  - There will be an RV offset between pre/post Service Mission data!  Plan accordingly!

# KPF Data Products: Spectra and Radial Velocities

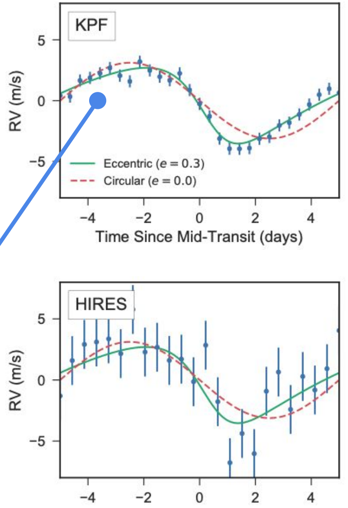



**Raw echelle spectra**
**[Level 0]**

**1D spectra**
**(intensity vs. wavelength)**
**[Level 1]**

**Radial Velocities (RVs)**
**[Level 2]**

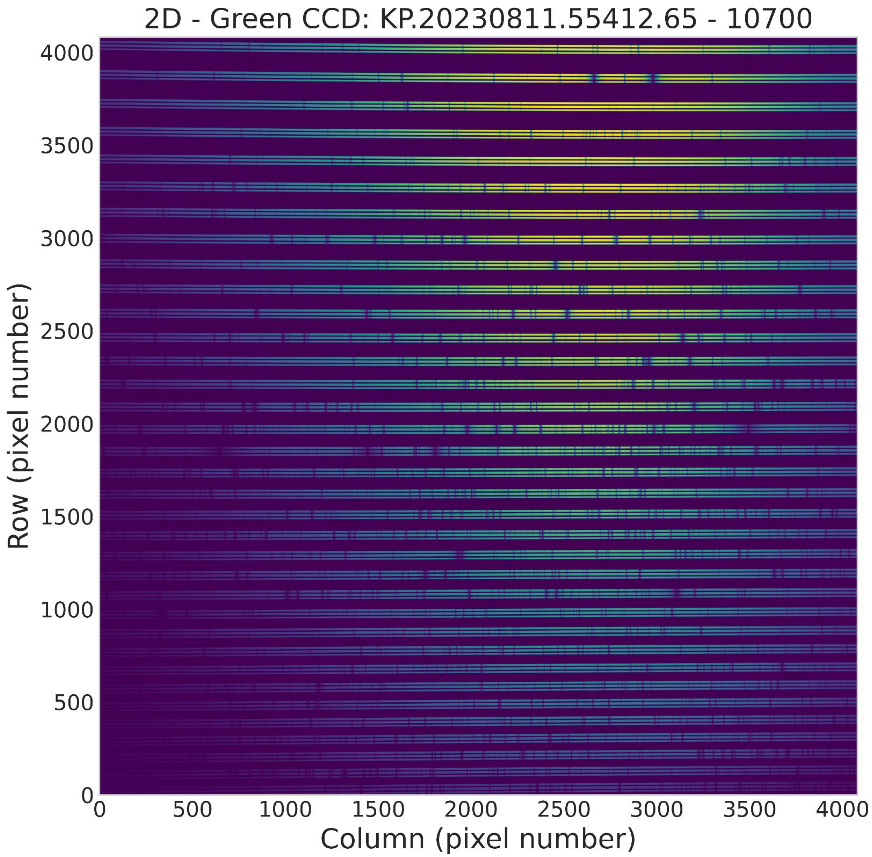
**Radial Velocities - KPF vs. HIRES**

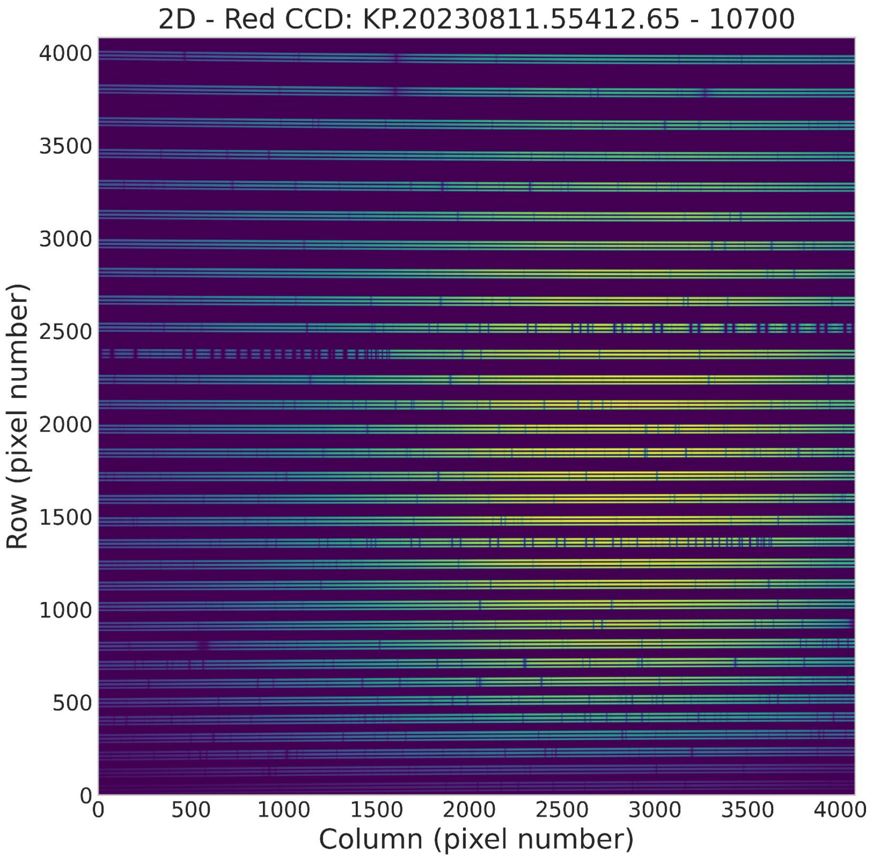



All data products are produced automatically by **KPF Data Reduction Pipeline** and uploaded to Keck Observatory Archive.

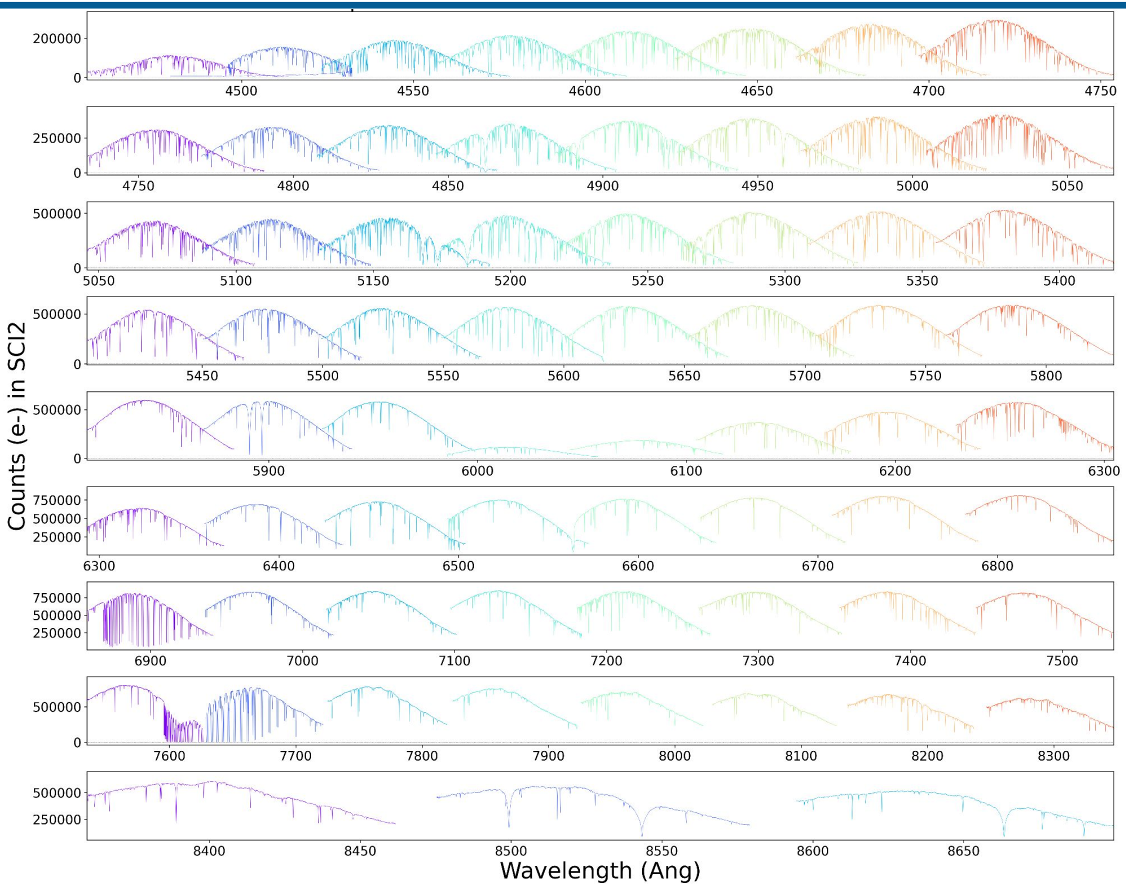
https://github.com/Keck-DataReductionPipelines/KPF-Pipeline/

# KPF Data Products: Beautiful Spectra

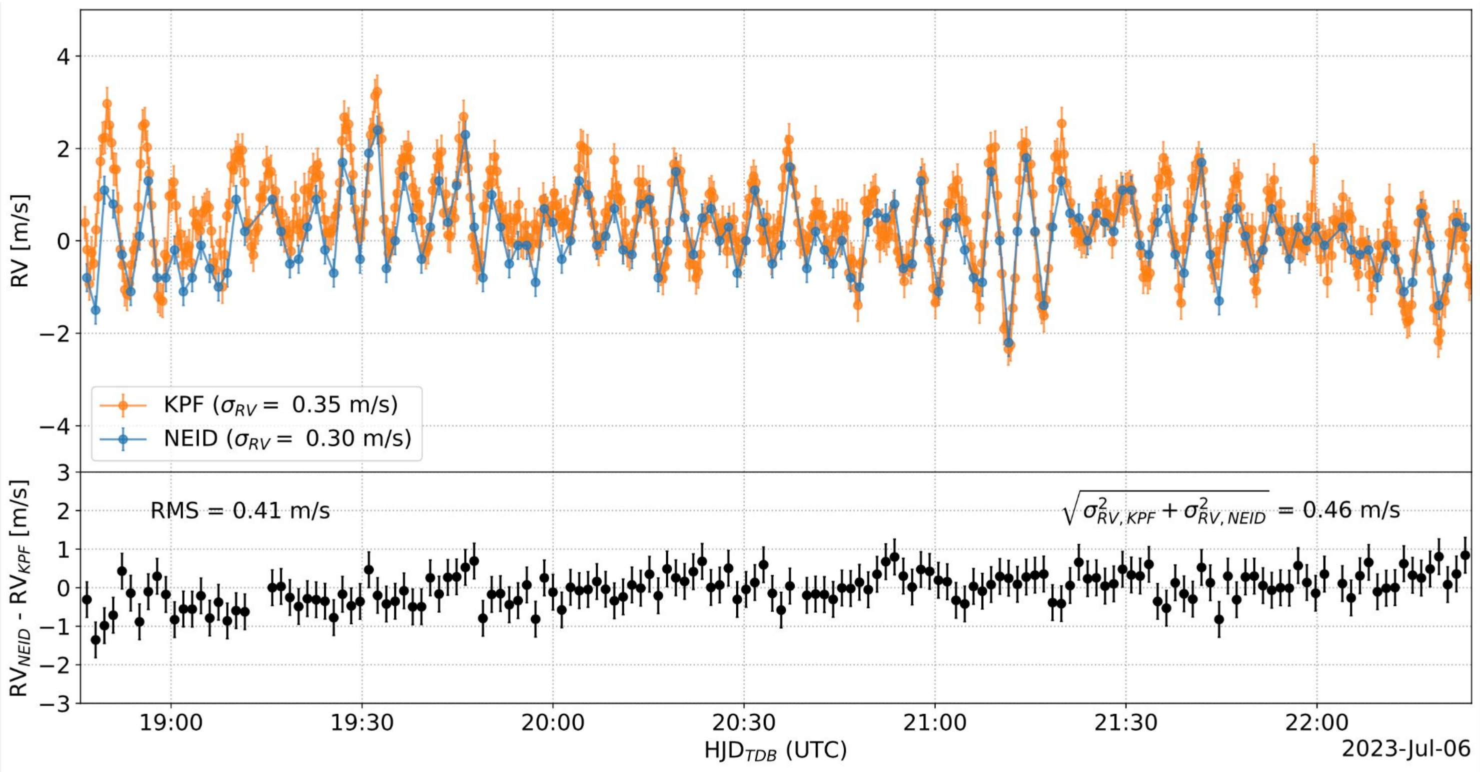


# KPF Data Products: Beautiful Spectra



# KPF Science Examples – KPF Solar Calibrator

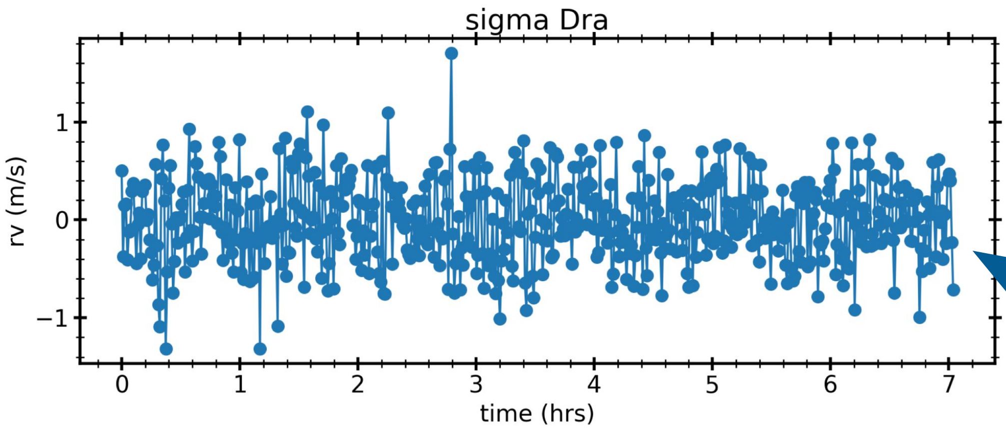



**KPF + SoCal:** 21 sec cadence: 5s exposures + 16 sec (!) readout

**NEID:** 85 sec cadence: 55s exposures + 30 sec readout

Rubenzahl et al. (in prep)

# KPF Science Examples – Asteroseismology




**Sigma Draconis:**

**K0V, V=4.7**

560 exposures:

30s exposures + 15s readout

**40 cm/s over 7 hours (including signal!)**

**14 cm/s peak amplitude**

**2 cm/s noise (per mode)**

Huber et al. (in prep)

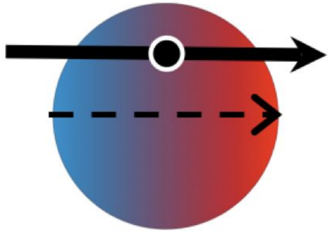
# KPF Science Examples – Stellar Obliquity

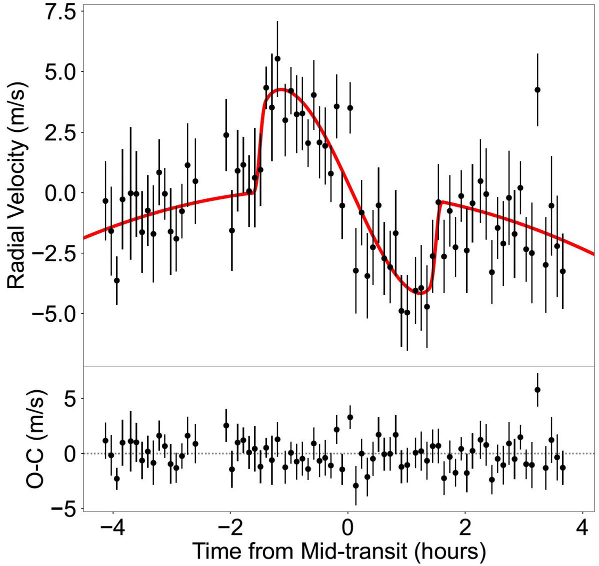


**TOI-4495:**

Young Planetary System with two planets

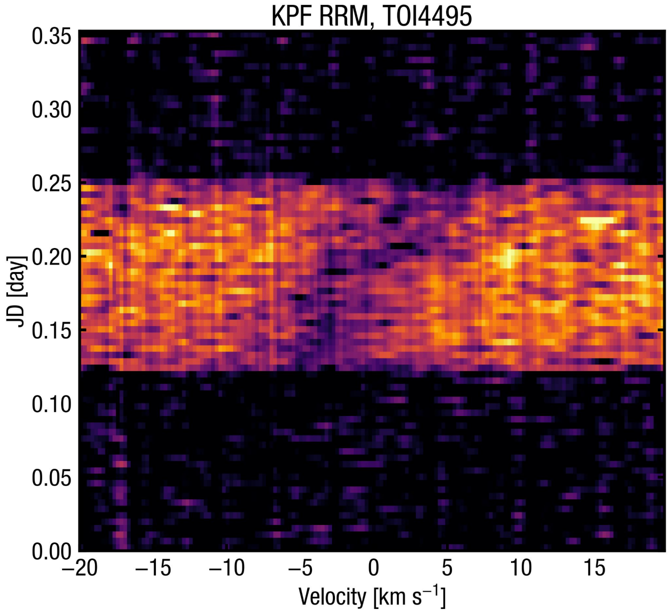
Obliquity Measurement with KPF






**Rossiter-McLaughlin analysis**

RM amplitude ~ 3 m/s, easily detected




**Reloaded R-M**

Signal is ~400 ppm, one of the lowest ever recorded

Dai et al. (in prep); plot from S. Halverson

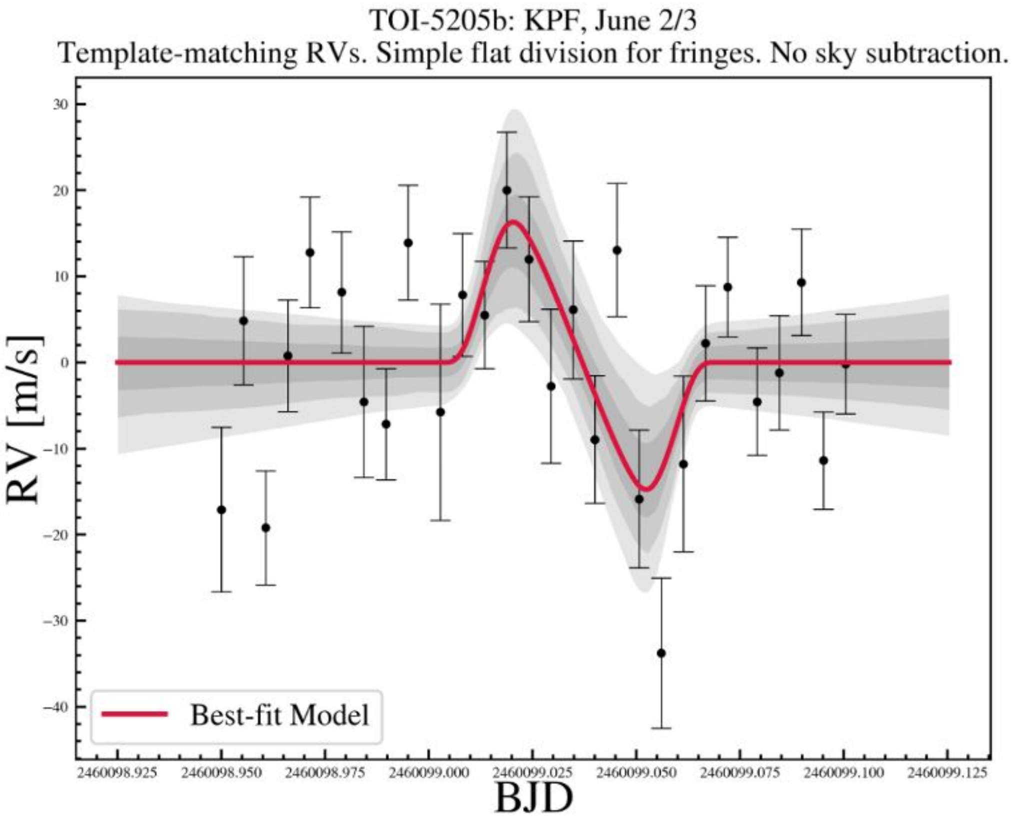
# KPF Science Examples – Stellar Obliquity

**TOI-5205b:**

First Hot Jupiter around M dwarf

Obliquity Measurement with KPF
Upcoming JWST atmos. observ.

**Very faint: V = 15.9 !**
(most signal comes from red optical spectrum)




Stefansson et al. (in prep)

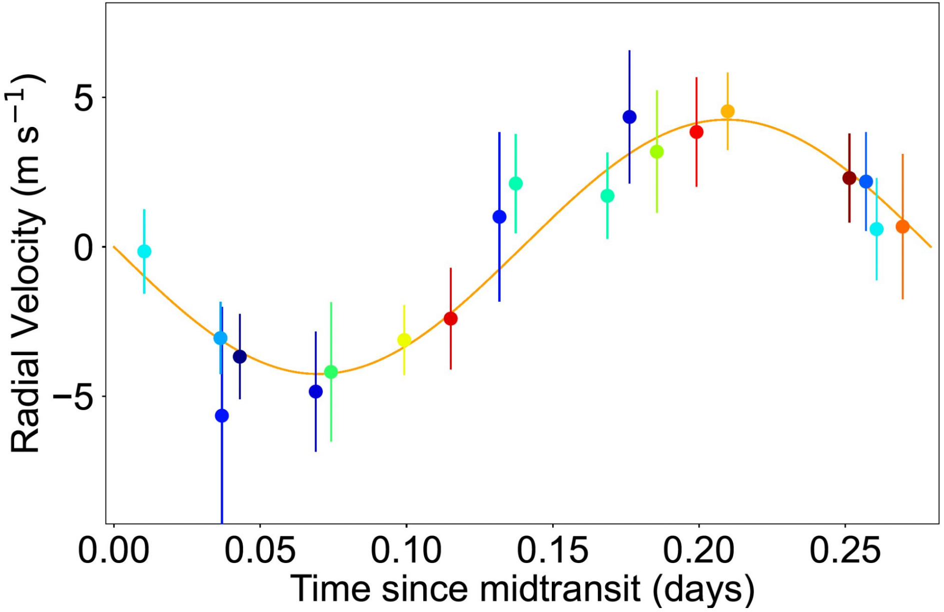
# KPF Science Examples – Measuring Planet Masses

**TOI-6324b:**

Earth-size planet (1.0 Earth-radii)
ultrashort-period orbit (0.28 days)
RVs are phasing up! →

Excellent JWST target to determine surface mineralogy

part of ongoing NASA KSMS program; PI: Fei Dai




Dai et al. (in prep)

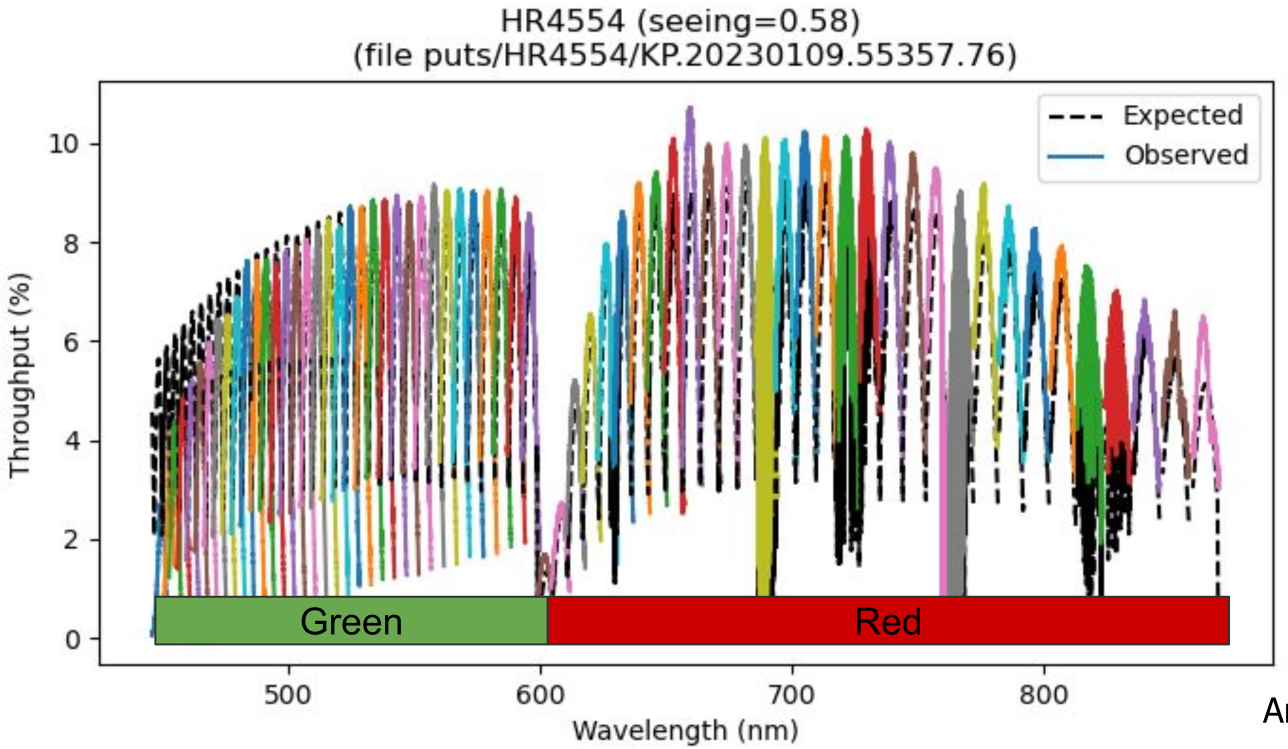
# Mid-breakout Q&A

## Part II Topics:

**Performance**
**Proposal Planning**
**Observing with KPF**
**Current Challenges and Plans**

# KPF Performance – Throughput

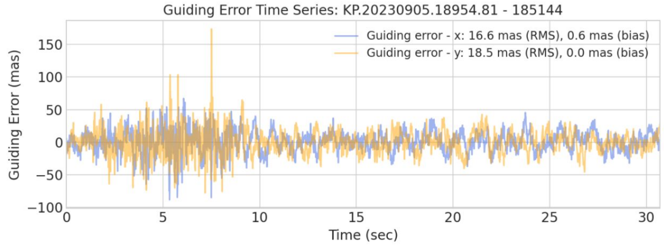
- Overall throughput is meeting (or exceeding!) expectations across the bulk of the spectrum.
- Blue throughput is lower than expected. ADC is possibility, as we have yet to verify the prism angles.

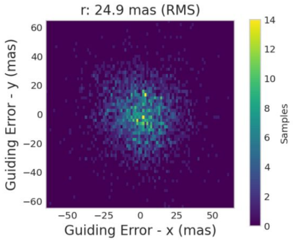


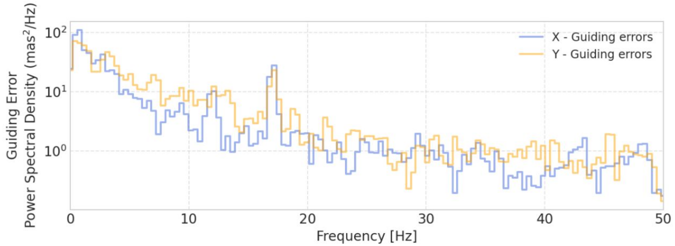

Analysis by Ashley Baker

# KPF Performance – Fiber Injection Unit

- FIU guider performance is beating requirements on most targets.
  - Guiding *precision* of **<20 mas RMS** routinely achieved
  - Guiding *accuracy* still to be quantified in 2023B
  - Tested guiding to J ~ 14 mag.
  - Guiding on close binaries is currently challenging – work in progress
- Overheads are 4 min (average) and **readout is 48 seconds**, fast readout is ~15 seconds.
- Outstanding issues related to ADC performance are being assessed in 2023B



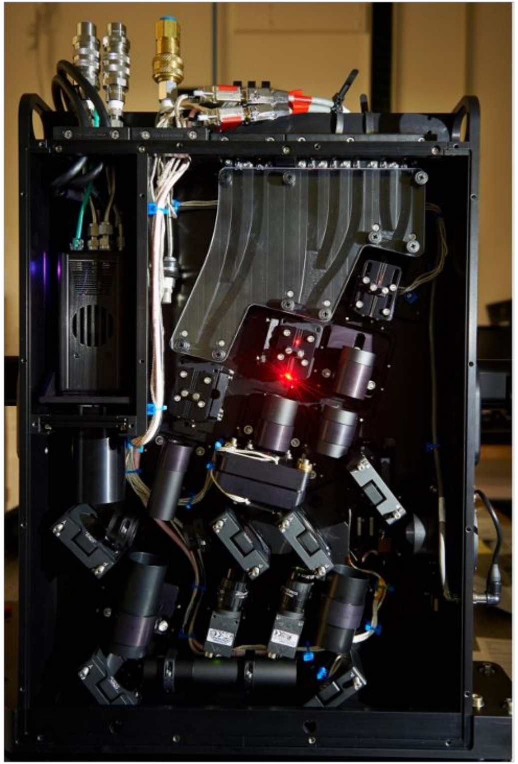




J = 3.42, G = 4.45
100 fps, Medium gain

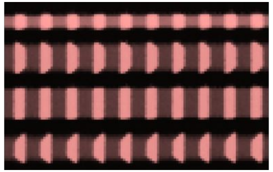
3071 guider frames. Fraction with:
saturated pixels: 1.17%
pixels at >90% saturation: 2.70%

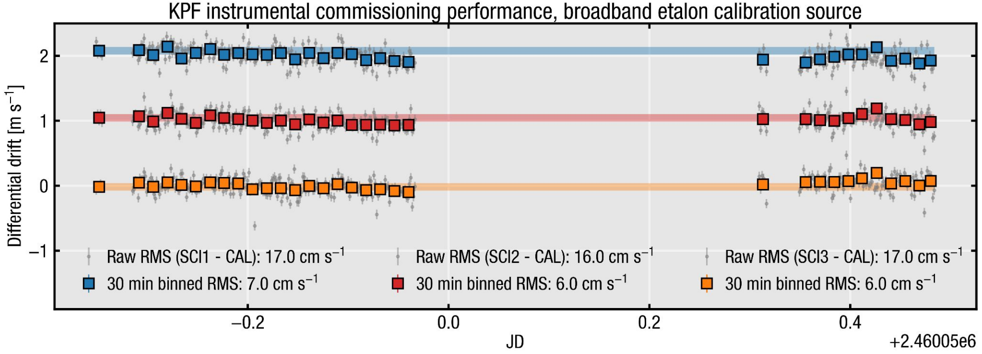
Sun's altitude below horizon = 10 deg
Lunar separation = 83 deg

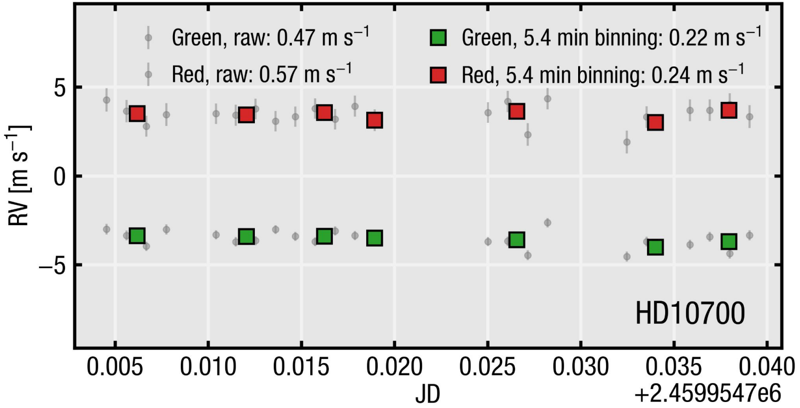


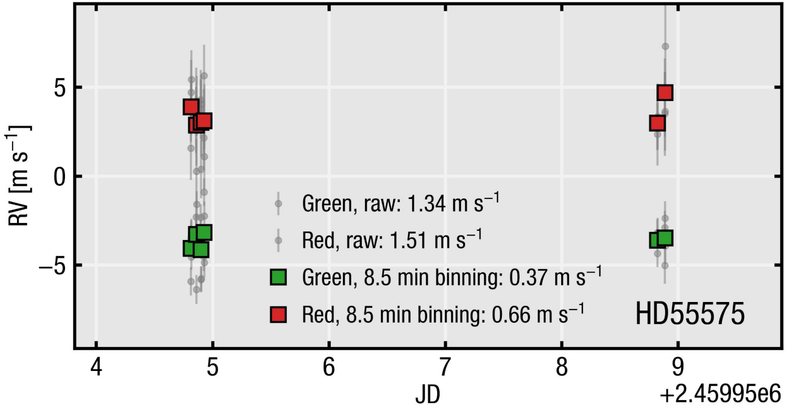
# KPF Performance – Doppler Performance

- ❑ Differential stability (SCI - CAL) is <10 cm/s over short time scales.
- ❑ On-sky RVs over ~hour-to-day timescales are generally stable at the <1 m/s level *prior to calibration*



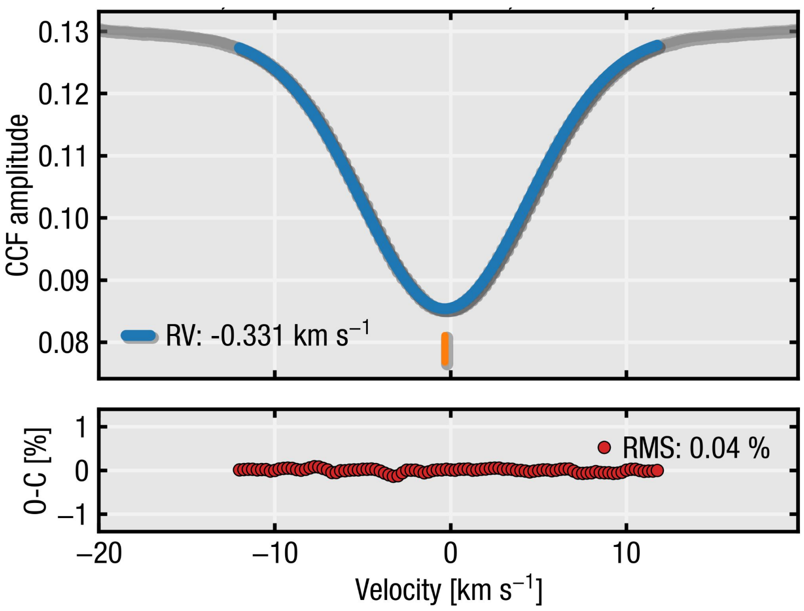


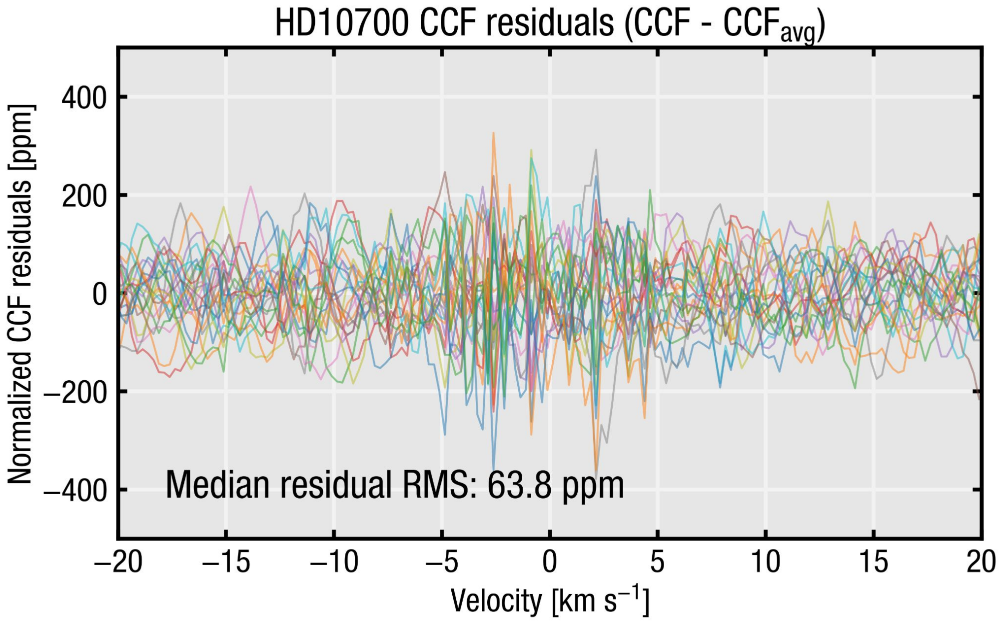



# KPF Performance – Doppler Performance

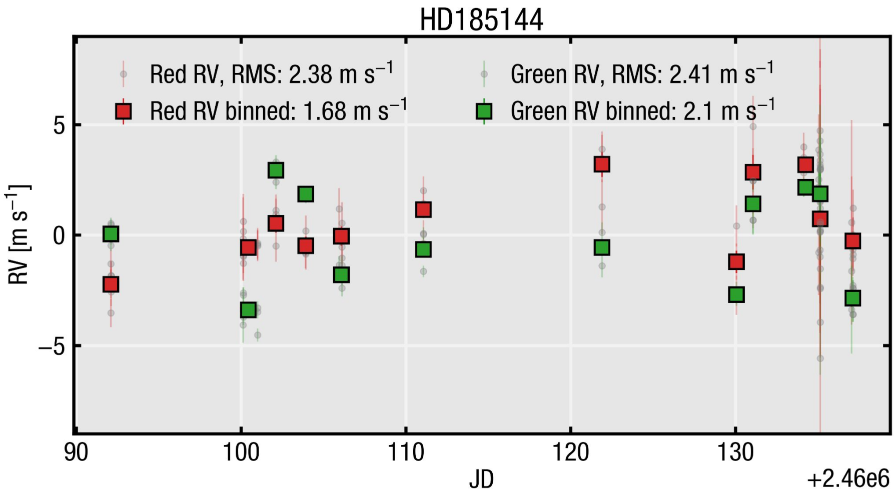
- Demonstrated PSF stability is at the 10's of ppm level over short time periods.
  - Key for obliquity measurements, transit spectroscopy, stellar activity mitigation

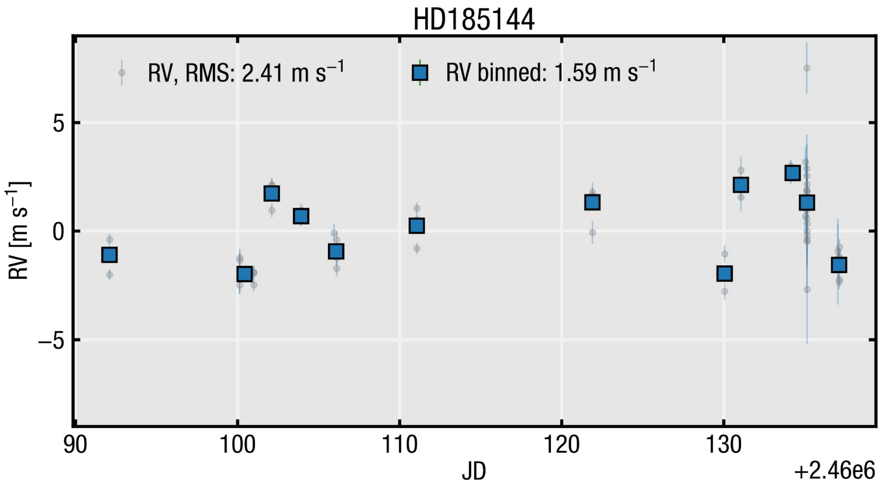


# KPF Performance – Doppler Performance

- Multi-week performance is limited by wavelength solution derivation, drift correction capability
- Current DRP does not reliably derive daily wavelength solutions
- Instantaneous instrumental drifts are being computed, but not being applied due to uncertainty in calibration source stability. (coupled with wavelength solution algorithmic issues)
- ***Data to make this measurably better already exist.***

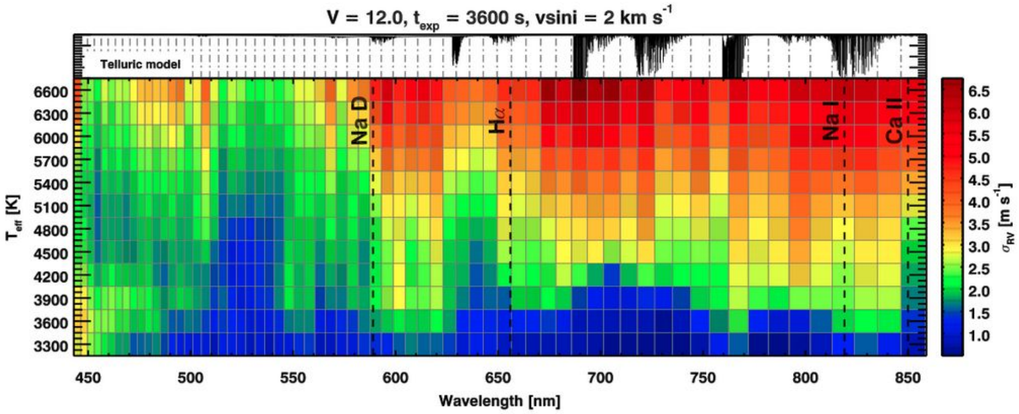


# Proposal Planning - Doppler Precision

- The **Exposure-Time-Calculator** offers a simple way to calculate KPF exposure time as function of radial velocity precision based on the KPF noise model, and information content of stars by spectral type.
- Radial velocity uncertainties for single-night projects (Rossiter-McLaughlin or other in-transit observations) have minimum uncertainties of 50 cm/s per observation.
- Radial velocity drift over months-long timescales is ~1.6 m/s. *We expect this to improve significantly in 2023B.*
- Note difference between single-night and multi-night performance.

$$\sigma^2_{\text{total}} \approx \sigma^2_{\text{photon}} + \sigma^2_{\text{instrument}} + \sigma^2_{\text{stellar activity}}$$

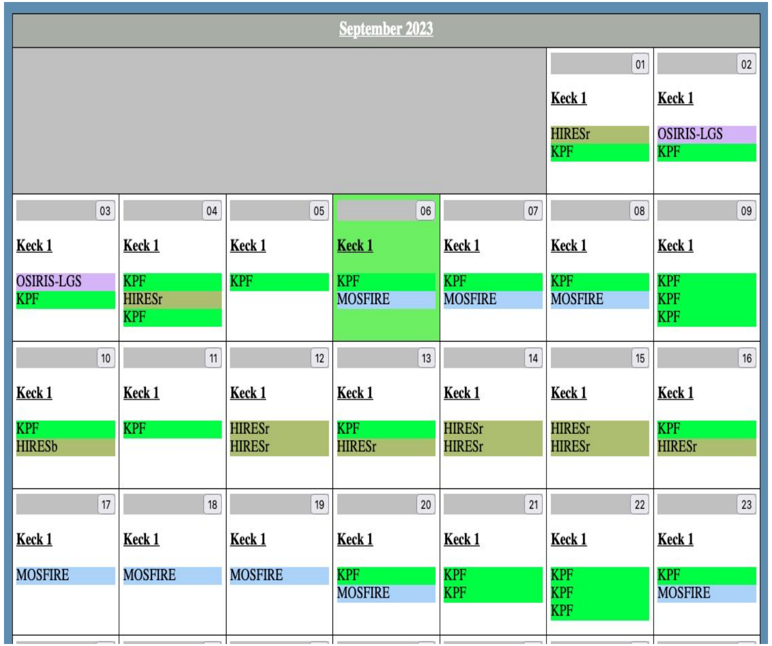



| | 30 cm/s in 30 min *or* 1 m/s in 3 min | 1 m/s in 30 min |
|---|---|---|
| M4 (3200K) | V=13.2 | V=15.7 |
| K6 (4200K) | V=11.8 | V=14.3 |
| K2 (5200 K) | V=11.3 | V=13.8 |
| G2 (5700 K) | V=10.9 | V=12.4 |
| F5 (6600 K) | V=10.3 | V=12.8 |

**https://github.com/California-Planet-Search/KPF-etc**

# Proposal Planning - Cadence Observing

- KPF observing is open to all Keck users. The California Planet Search (CPS) currently organizes most KPF observing, using algorithm-based starlist generation to maximize efficiency and observing cadence. Observing with CPS is not required.
- KPF allows for an easier observing setup compared to HIRES by moving more preparation to the daytime.
- **Real-time data processing** allows for immediate identification of sub-system functionality.
- We encourage collaborators to request *fractional nights (¼,½,¾)* spread across more nights to improve our ability to make cadence observations.
- Sometime in the future, we intend to hand-off the capability to perform **Community Cadence** observing to Keck Observatory.

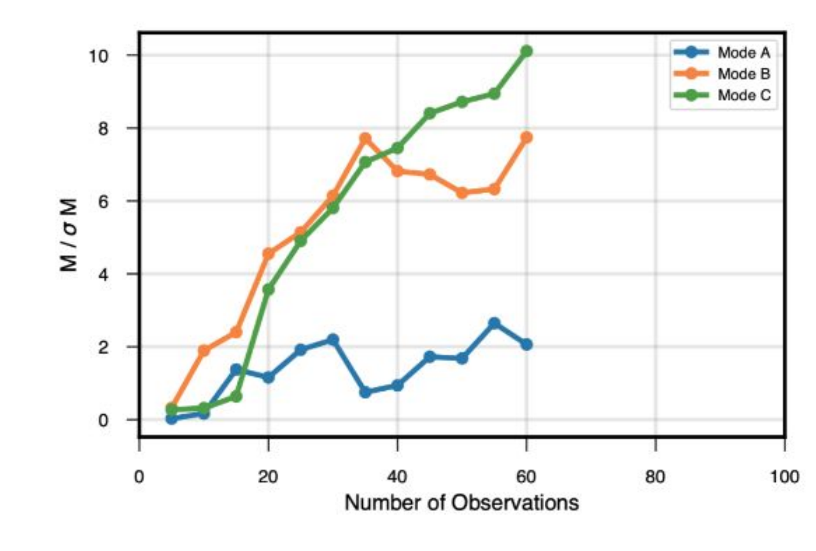


# KPF Observing - Community Cadence

- Future observations will maximize the number of fractional nights available to KPF, more observations can be taken over shorter timescales allowing for improved planet mass measurements.

- Variations on the stellar surface that cause increased RV noise will be minimized and planet mass precision will be maximized.

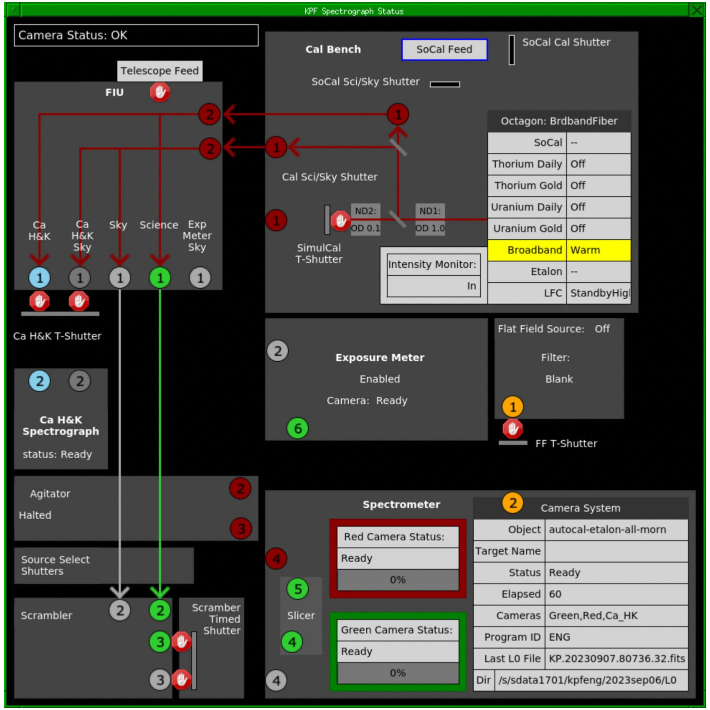
- Complex orbital architectures such as planets with high eccentricity and multi-planet systems will be more and more capable of detection as the cadence increases.

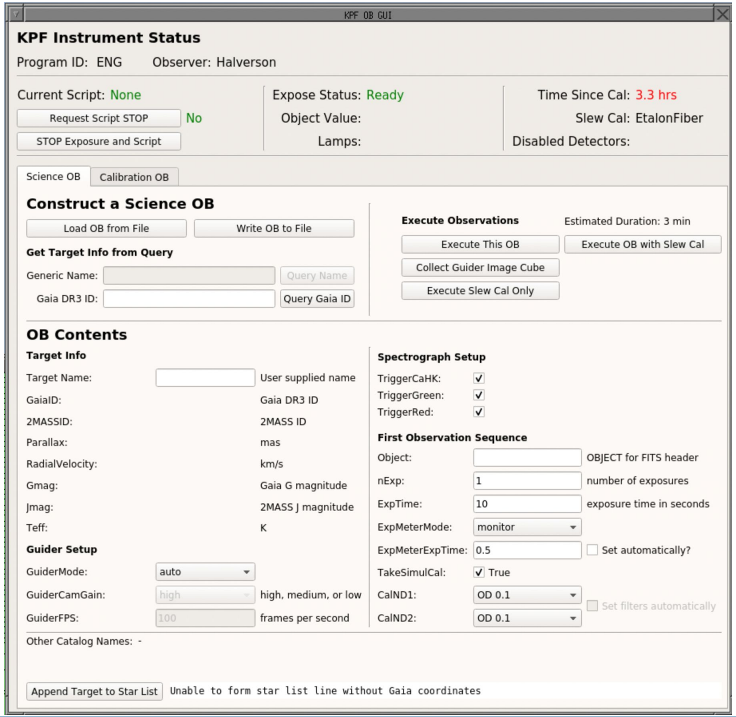



Improved Mass determination with CC (green) compared to current practice (orange)

# Current Nighttime Observing

- Currently nighttime observations are done by classical observers to achieve cadence by collaborating.
- The mechanics of KPF observing is highly scripted (OBs, etc.) and are part of the future of WMKO.
- At the base through, this is similar in execution to other Keck instruments (VNC/observing sites; GUIs; etc.)



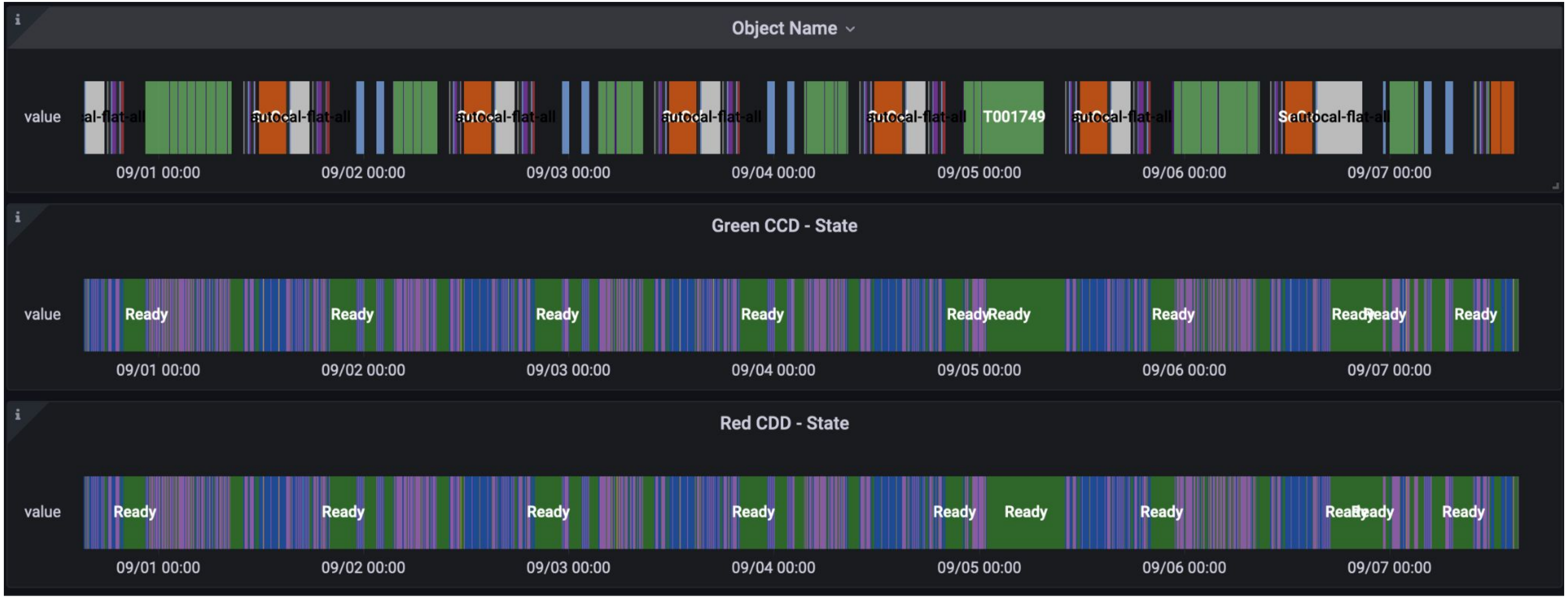



# KPF / HIRES Performance Comparison

| | **KPF** | **HIRES** |
|---|---|---|
| **Optical Input** | 1.14 arcsec octagonal *fibers* for science and sky (fixed format) | Selectable *deckers and slits* for different sky projections, e.g., B5 = 0.87 x 3.5 arcsec; C2 = 0.87 x 14 arcsec |
| **Wavelength Coverage** | Fixed format: 445-870 nm (high-res)<br>382-402 nm (med-res) | ~300-1000 nm in an adjustable format<br>(moving a 3 CCD array over the spectral format) |
| **Resolving Power** | R=98k (445-870 nm) | depends on slit<br>E.g., R=49k for 0.86 arcsec-wide slit<br>R=80k for 0.40 arcsec-wide slit |
| **Throughput (sky to CCD)** | ~8-10% peak-of-blaze (measured) | 5-6% peak-of-blaze for B5-B1 deckers (measured) |
| **Doppler Precision** | 0.5 m/s noise floor (req.) & 0.3 m/s (goal) | ~2 m/s systematic noise floor |
| **Doppler Speed** | ~8-10x faster than HIRES | Limited by need for high SNR to model iodine spectrum |

# Observing - Operations

- **KPF is never 'off'.** Reliable calibrations are essential for maintaining RV performance
  - Daily calibrations are automated, 2x per day. This includes flats, darks, biases, wavelength cals that are triggered at fixed times each day.
  - SoCal fills in gap between morning and evening calibrations.
- Telemetry is automatically collected and stored in FITS records



# Challenges and Plans - Calibration and DRP

- **Calibration sources** (laser frequency comb, etalon, thorium-argon lamp) have imperfect reliability.
  - Plan for better software to model slow evolution of the wavelength solution vs. time
  - Expected improvements in the LFC operation (full calibration at the bluest wavelengths)
  - Planned testing of the etalon stability
- **Data Reduction Pipeline** currently produces all data products.
  Doppler performance within a night is superb, but the long-term Doppler scatter is not yet at full precision. Extensive work on the DRP is ongoing.
  - Wavelength solution code – significant ongoing work to better model slow evolution using the multiple calibration sources
  - Cosmic-ray rejection – in development
  - Forward-model approach to RV determination is under development – needed for M dwarfs. RVs are currently computed with the cross-correlation method.
  - A Quality Control infrastructure was just built and is being deployed.
  - The optimal extraction algorithm is being refined.
  - **We can use your help with DRP projects small and large!**

# Challenges and Plans - Future Developments

- **Small Refinements to Operations**

- **Testing of Atmospheric Dispersion Compensator** in Fiber Injection Unit – determine absolute guiding accuracy

- **"Service Mission" – ~3 weeks in December 2023 to February 2024 (to be scheduled)**
  - Install thermal enclosure
  - Fix focus issue on edge of green CCD
  - Adjust "Reformatter" for more even slice shapes/intensities
  - Install baffling on ion pumps
  - Install precision wedge filters in calibration system for ultraprecise calibrations
  - Reminder: there will be an RV offset between pre/post Service Mission data! Plan accordingly!

- A **second fiber feed for KPF at Keck II** will improve cadence observations and make WMKO as a whole more efficient.