Long-term operation of a laser frequency comb with the Habitable Zone Planet Finder

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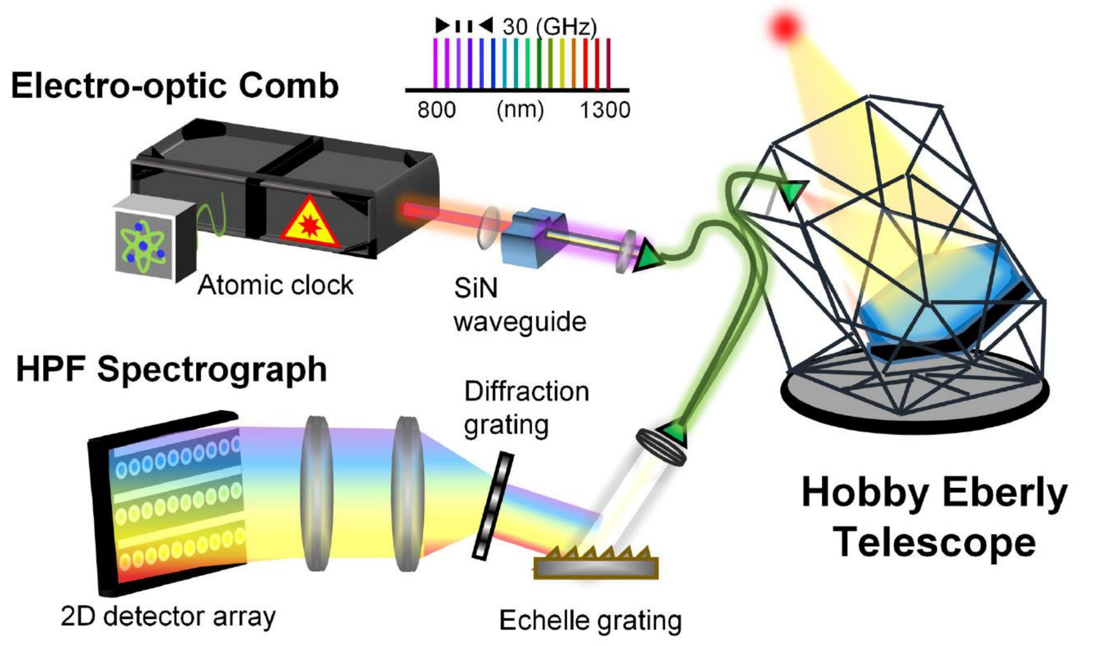
Near Infrared Radial Velocity Calibration

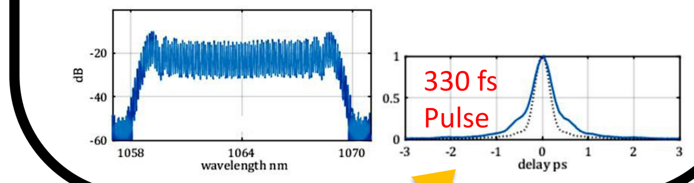
- We have constructed and installed a laser frequency comb (LFC) calibrator for the Penn State Habitable Zone Planet Finger (HPF) at the Hobby-Eberly telescope
- The LFC has now been running continuously for over two years. Here we provide details of its long-term operation



Frequency comb bandwidth: **700-1600 nm**
On-sky RV precision with HPF: **~1.5 m/s**
Intrinsic calibration uncertainty with HPF: **<10 cm/s**

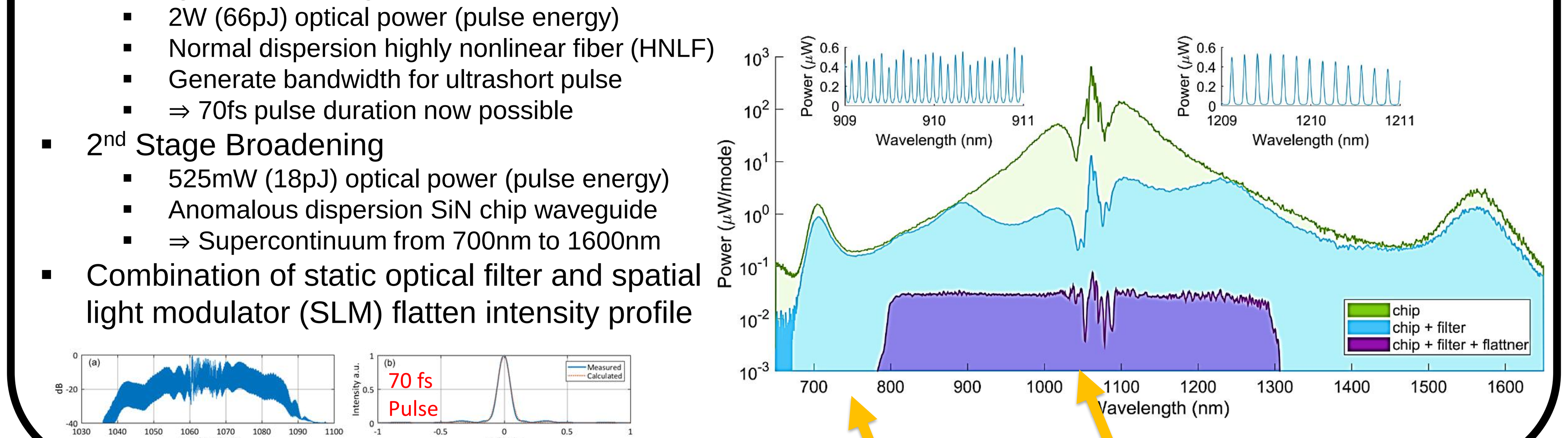
30GHz EOM Comb

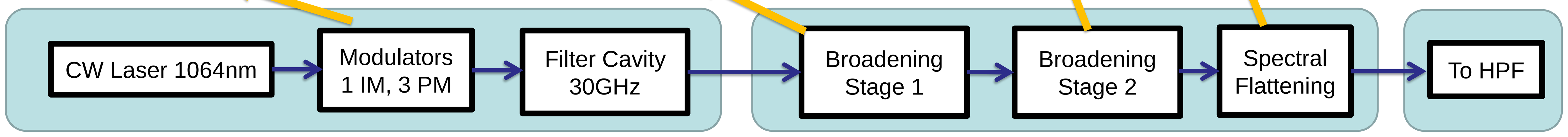
- Electro-optic modulators (EOM) convert the continuous wave (CW) laser into a 30GHz comb
  - 10nm of bandwidth
  - Centered at 1064nm
  - 330fs pulse duration
- 1 intensity modulator (IM) and 3 phase modulators (PM)
- Optical filter cavity removes broadband RF noise



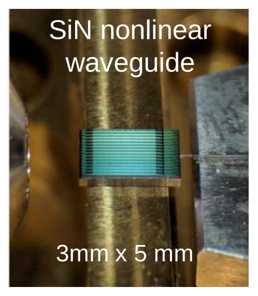
Supercontinuum Generation and Spectral Flattening

- 1st Stage Broadening
  - 2W (66pJ) optical power (pulse energy)
  - Normal dispersion highly nonlinear fiber (HNLF)
  - Generate bandwidth for ultrashort pulse
  - ⇒ 70fs pulse duration now possible
- 2nd Stage Broadening
  - 525mW (18pJ) optical power (pulse energy)
  - Anomalous dispersion SiN chip waveguide
  - ⇒ Supercontinuum from 700nm to 1600nm
- Combination of static optical filter and spatial light modulator (SLM) flatten intensity profile

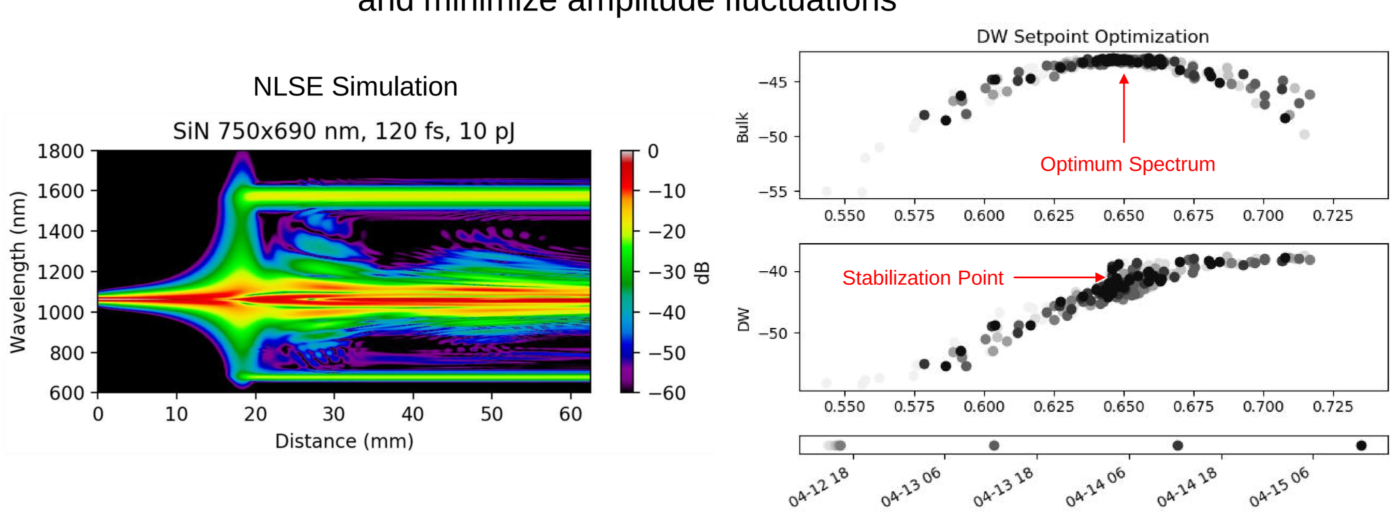




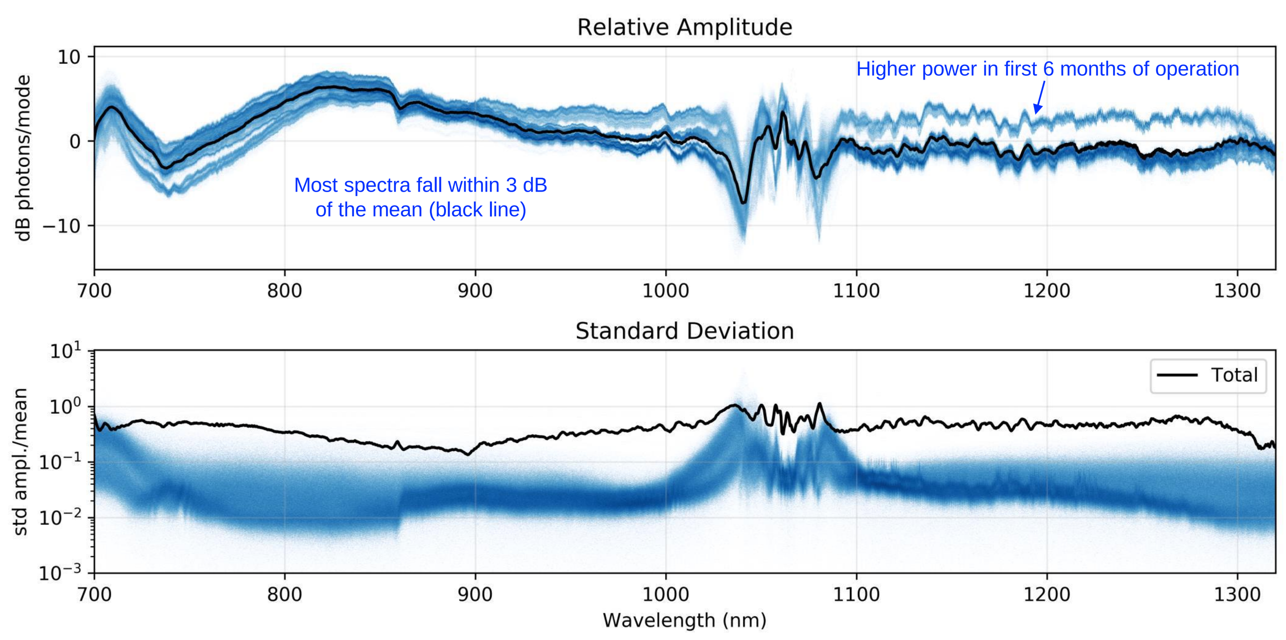
Stable and Reliable Supercontinuum



- A SiN nonlinear nanophotonic waveguide broadens the spectrum by 20x with only ~18 pJ of input pulse energy
- Over 2x10^{18} spectra have been reliably generated at the 30 GHz rate
- The supercontinuum spectrum has a stationary point where the overall (bulk) spectral amplitude is maximized at a given input power
- The dispersive wave (DW) power at 700 nm shows a linear dependence in this region and its power is used to lock the spectrum and minimize amplitude fluctuations



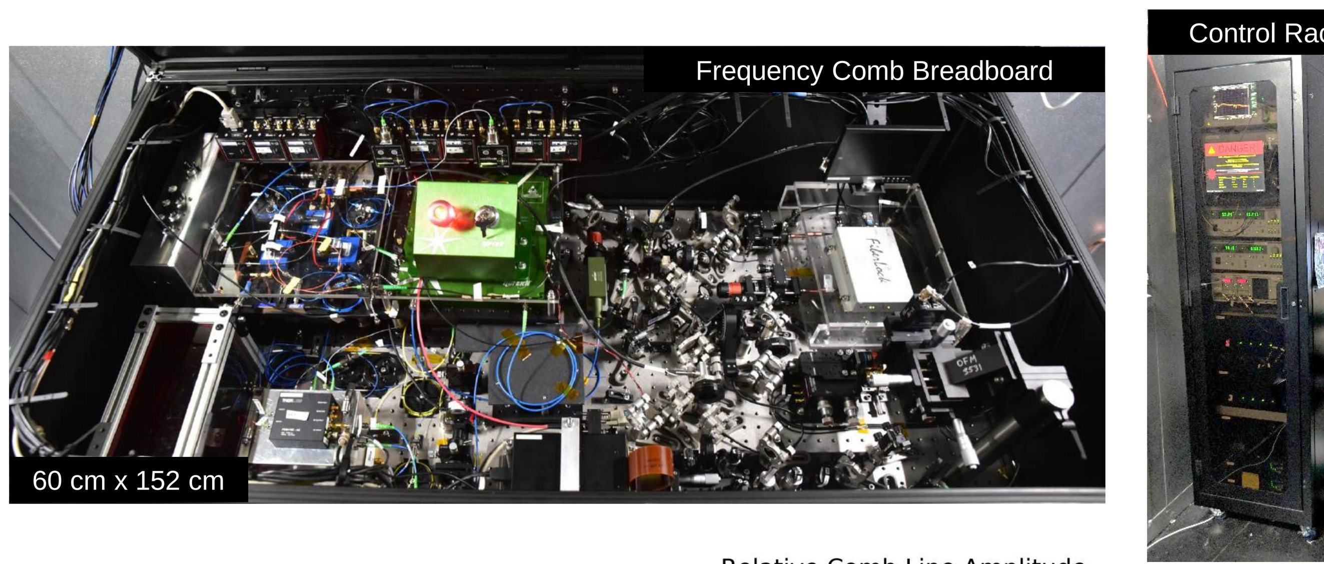
- We continuously monitor the LFC spectrum with an independent optical spectrum analyzer (OSA), measuring a spectrum every 100 s.
- 10 individual spectra are binned (averaged) and stored. Approximately 75,000 binned spectra collected over two years of continuous operation are shown below
- The black line is the average and the density of the blue lines shows variations about the mean

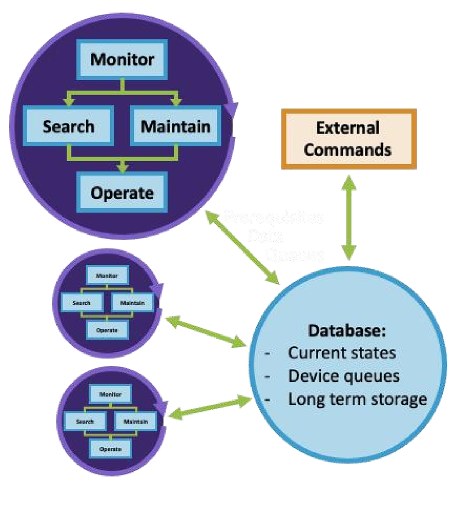


- In the lower plot, the black line is the normalized standard deviation of all data
- The blue traces are the normalized standard deviation of 10 binned spectra, showing that the spectral amplitude fluctuations are in the 1-10% range on a 1000 s timescale

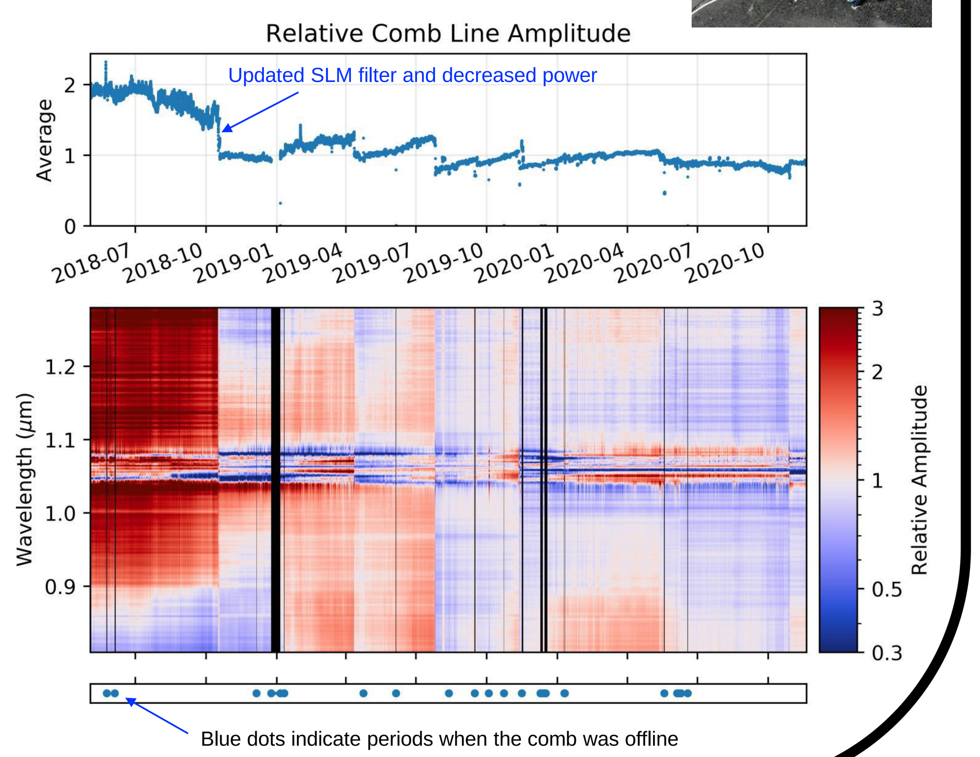
Autonomous Frequency Comb

- The comb has been running autonomously at McDonald Observatory since May 2018
- Built on robust fiber-integrated electro-optic modulator technology
- The entire comb fits on a 2' x 5' optical breadboard
- Power supplies and control electronics fit in a standard electronics rack
- Control software automates the upkeep of the comb and interfaces with the HPF

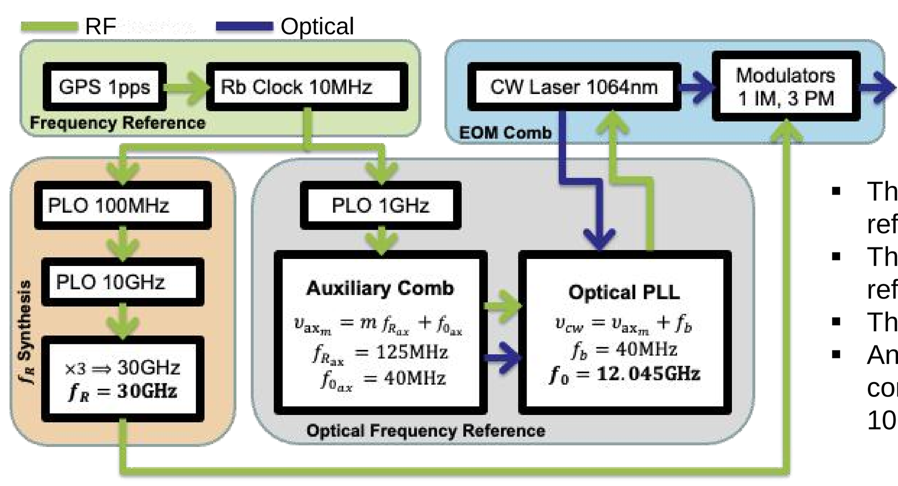




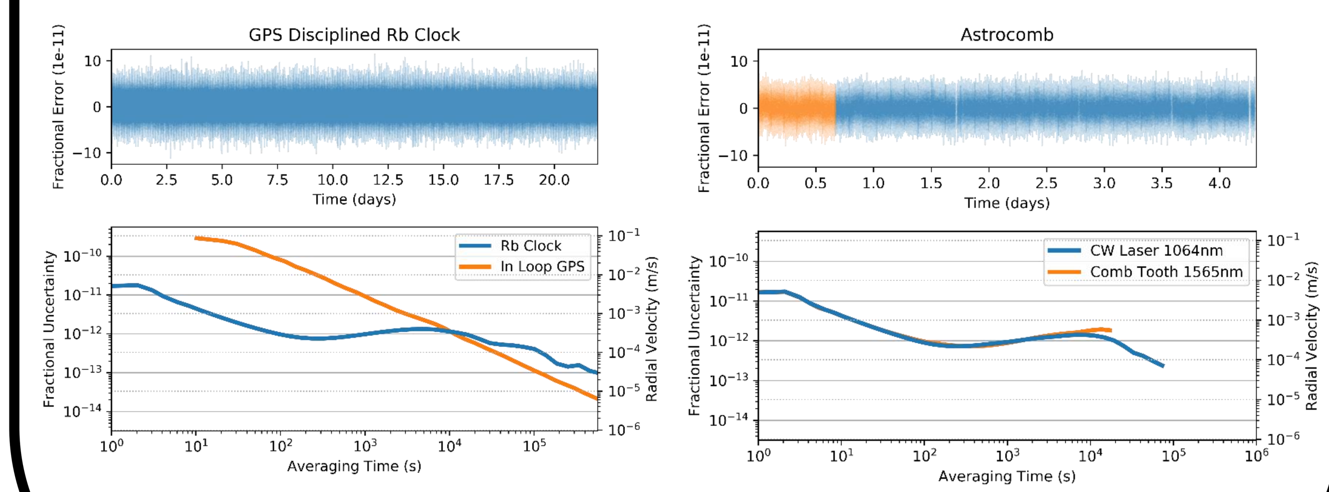
Overall uptime: **97%**



Absolute Frequency Stabilization



- The frequency comb is referenced to the SI second
- The short-term frequency reference is a Rb clock
- This is guided long-term by GPS
- An auxiliary 125 MHz Er:fiber comb fixes the frequency of the 1064 nm CW laser



Laboratory characterization of the GPS-guided Rb clock via comparison to a NIST H-maser

Independent measurements of comb line frequencies. The equivalent RV uncertainty is <1mm/s for averaging times >20 s

The Comb as Seen by HPF

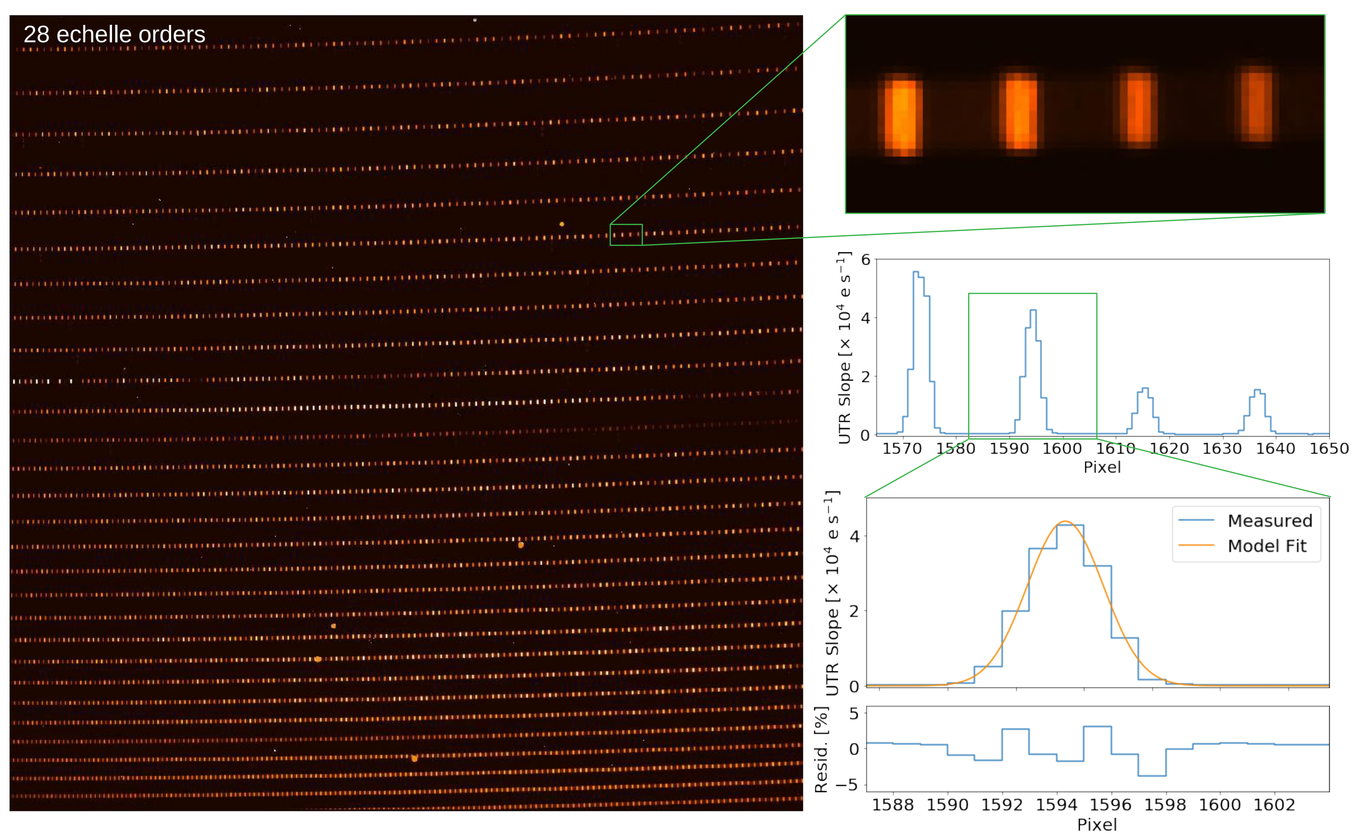
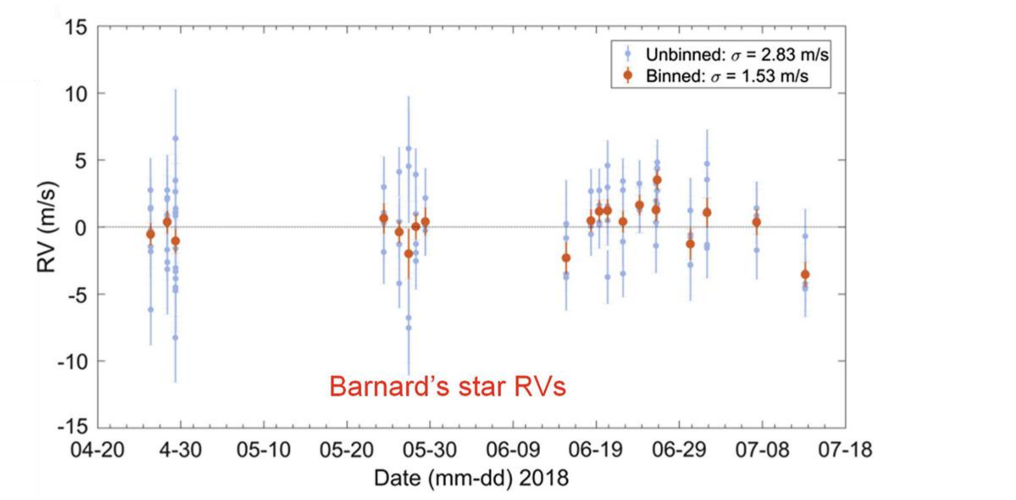


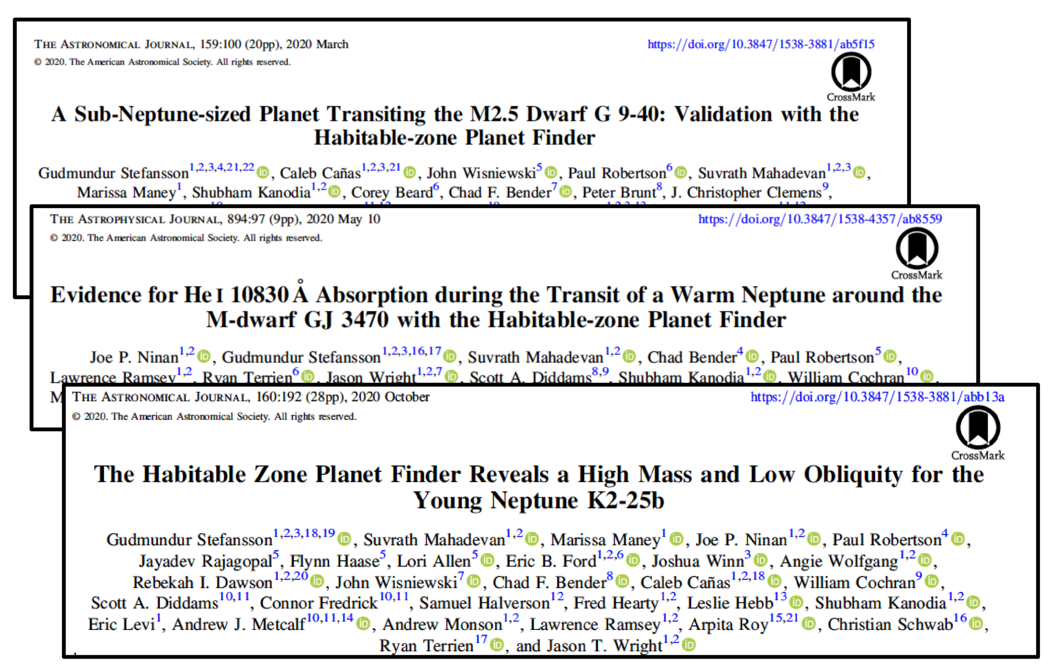
Image of the LFC spectrum with the HPF's H2RG Detector

Enabling Tool for NIR Precision RVs

HPF yields state-of-the-art long-baseline stellar RVs at NIR wavelengths



Multiple new publications, and more results coming…..



References

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