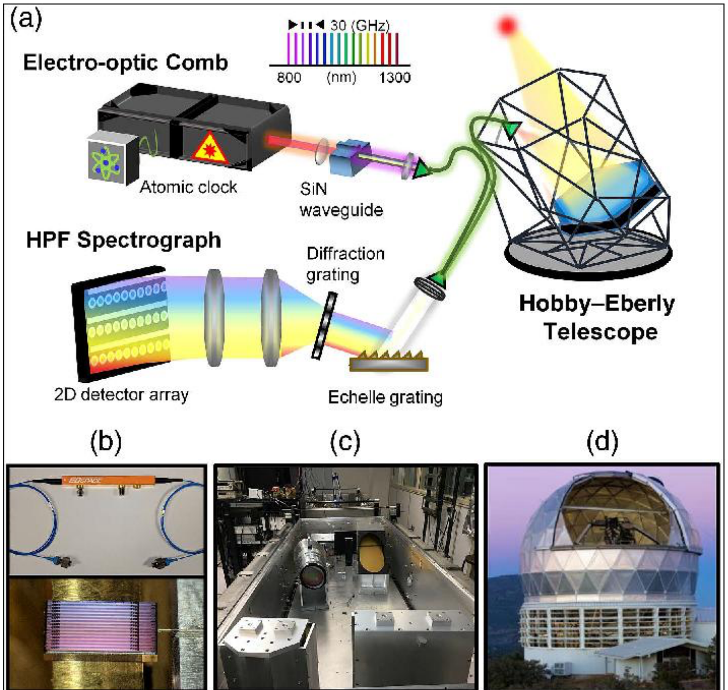
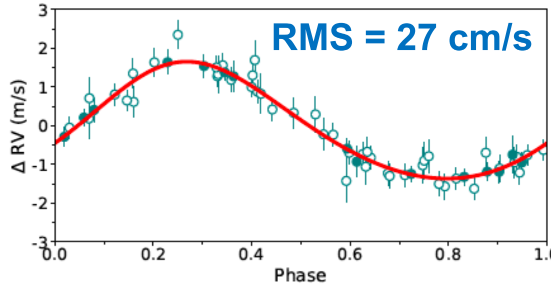
2020 Sagan Exoplanet Summer Virtual Workshop
Extreme Precision Radial Velocity

Overview of EPRV instruments



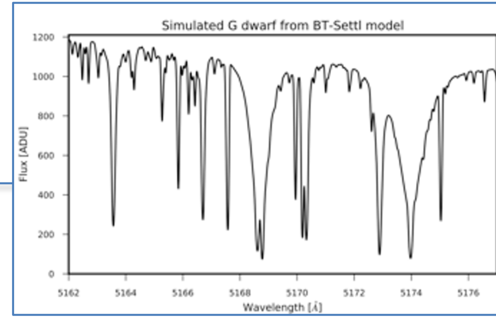


Michael Endl

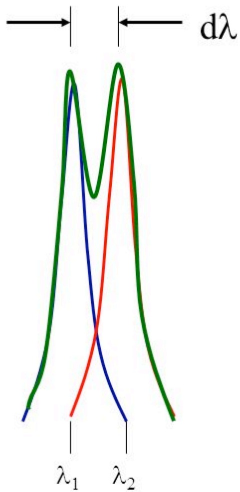
McDonald Observatory
THE UNIVERSITY OF TEXAS AT AUSTIN

Overview of EPRV instruments

The Basics:



- Bandwidth & Wavelength (optical,NIR,..)
- Resolving Power (R)



Consider two monochromatic beams

They will just be resolved when they have a wavelength separation of dλ

Resolving power:

$$R = \frac{\lambda}{d\lambda}$$

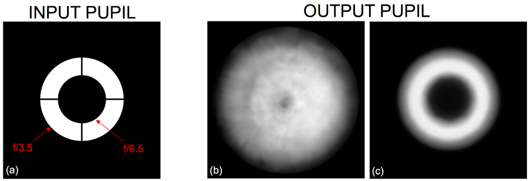
dλ = full width of half maximum of calibration lamp emission lines

- Signal/Noise

Overview of EPRV instruments

The Basics:

- Spectrograph stability:
  - opto-mechanical (no moving parts)
  - controlled environment
  - detector
  - 10 cm/s ~ 1 nm detector



(Sutherland et al. 2016)

- Stability of illumination (PSF stability):
  - fiber/image scrambling
  - fiber modal noise mitigation

- Calibration:
  - reference lamp (e.g. Th-Ar)
  - laser comb
  - Fabry-Perot Etalons

List of current EPRV instruments:

Optical:

- **HARPS (ESO 3.6m)**
- HARPS-N (TNG 3.6m)
- **ESPRESSO (ESO VLT)**
- **CARMENES (CA 3.5m)**
- EXPRESS (DCT)
- CHIRON (CTIO)
- Levy (APF)
- PSF (Magellan)
- **NEID (WIYN)**
- ….

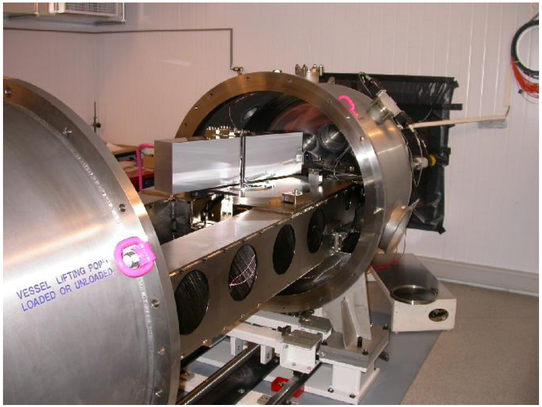
NIR:

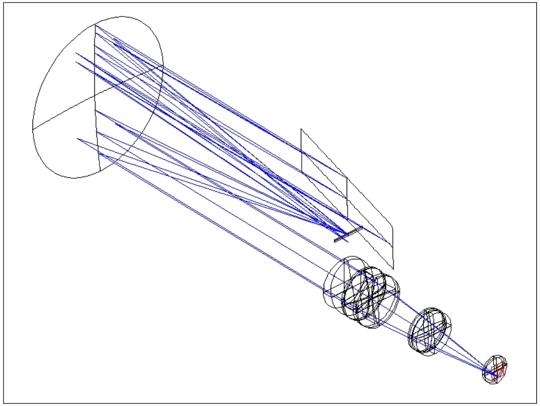
- **CARMENES (CA 3.5m)**
- **HPF (HET)**
- SPIRou (CFHT)
- …

Future:

- Maroon-X (Gemini-N)
- KPF (Keck)
- HARPS3 (INT)
- GCLEF (GMT)
- MODHIS (TMT)
- …

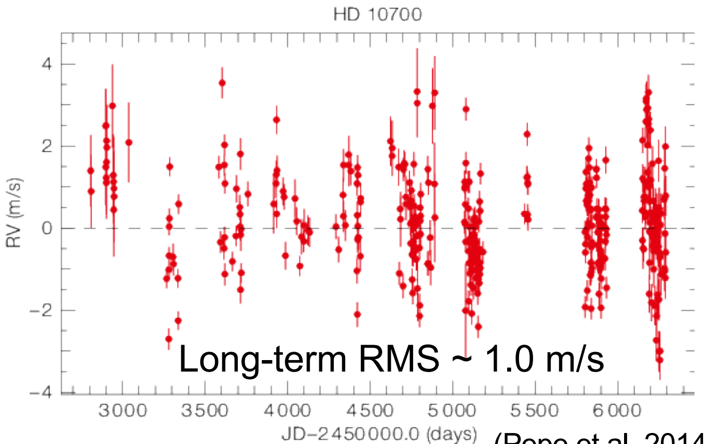
HARPS the first EPRV instrument:





Vacuum tank, R~115,000
378 – 691 nm (2 CCDs)
No moving parts
Simultaneous Th-Ar calibration
in operation since 2003

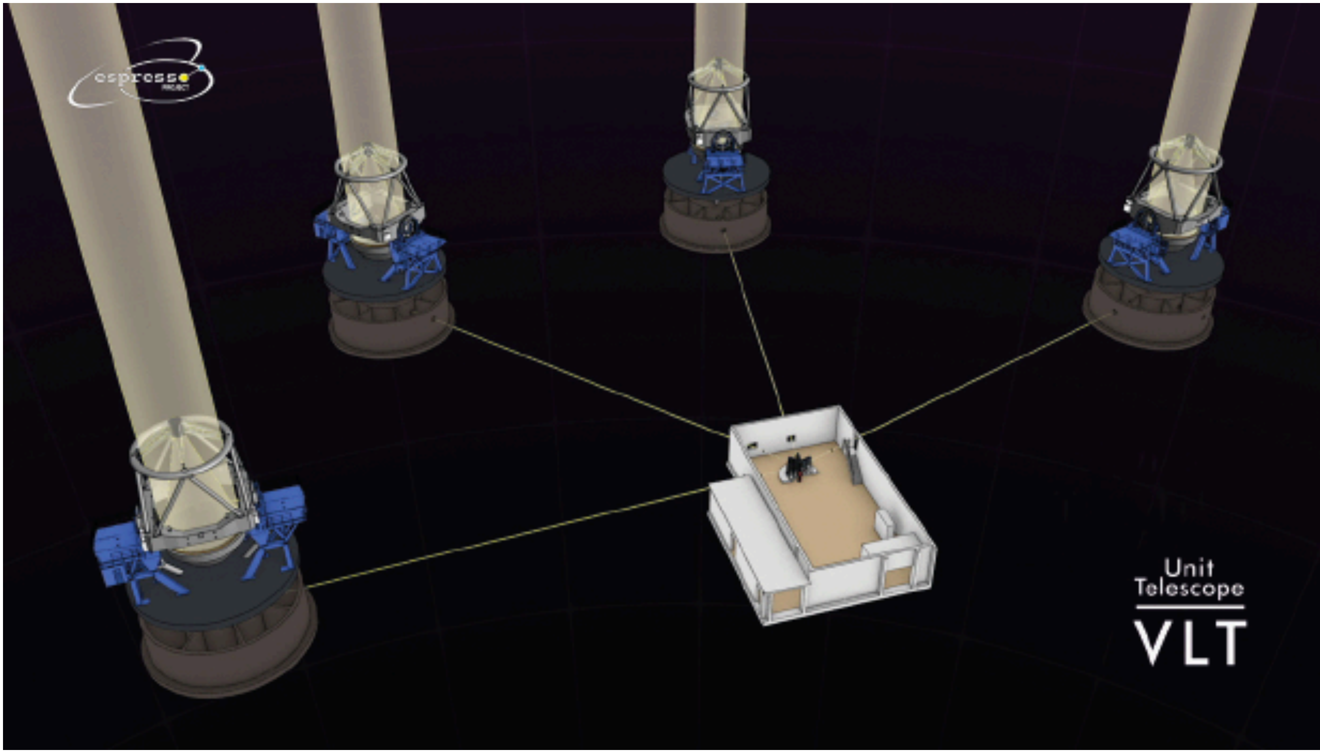
Clones:
HARPS-N at TNG
Future: HARPS3 (INT)



(Pepe et al. 2014)

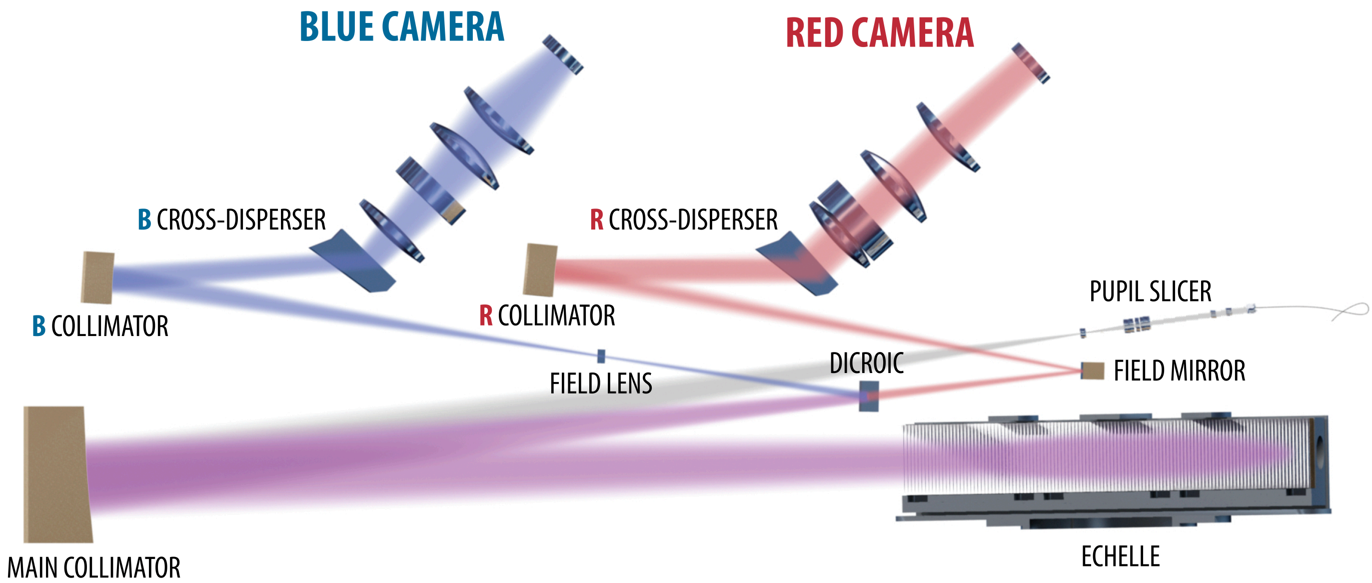
ESPRESSO (ESO VLT):

Combined Coudé Lab:



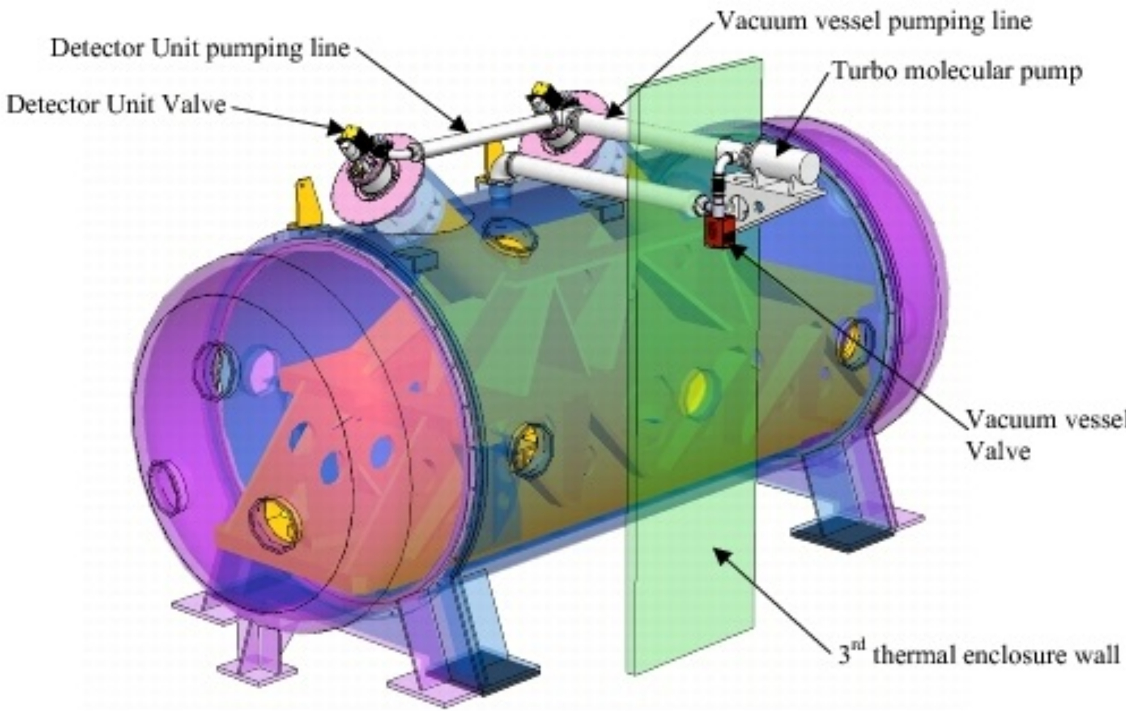
ESPRESSO (ESO VLT):

Optical Layout:



ESPRESSO (ESO VLT):

Instrument enclosure:

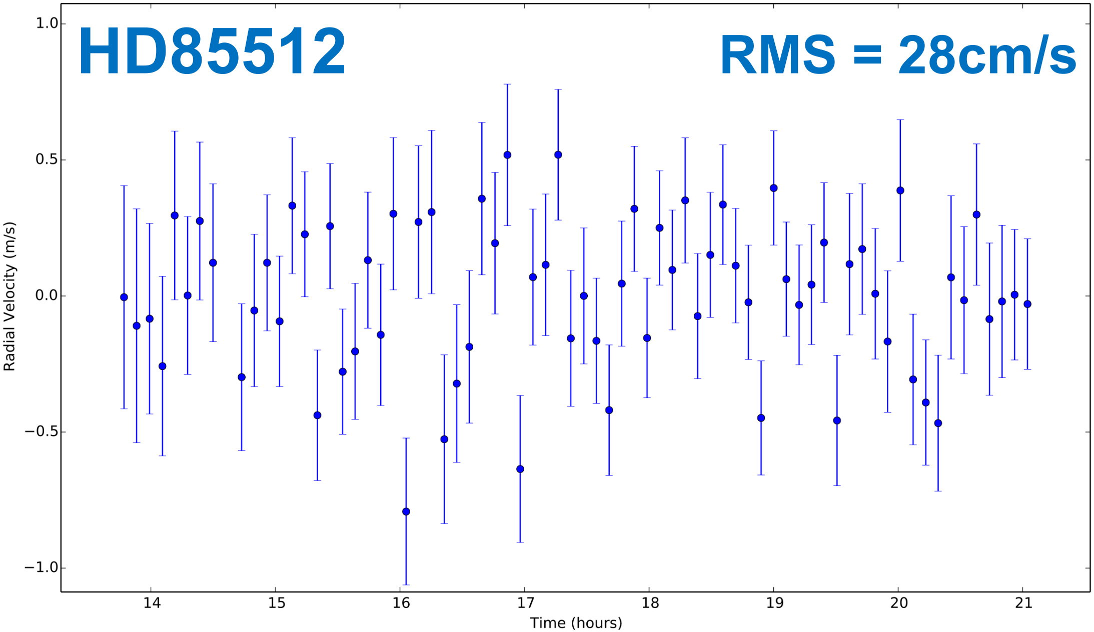


ESPRESSO (ESO VLT):

Parameter	*singleUHR*	*singleHR*	*multiMR*
Wavelengths	Blue arm: 380 – 520 nm Red arm: 520 – 780 nm		
Spectral coverage	Full		
Spectra format	Echelle, up to 4 spectra per order (2 fibers, 2 spectra / fiber)		
Resolving power	225’000	134’000	59’000
Aperture on sky	0.5 arcsec	1.0 arcsec	4x1.0 arcsec
Spectral sampling	2.5 pixels	4.5 pixels	10 pixels
Spatial sampling	9 pixels	18 pixels	44 pixels
Available binning	1x1	1x1 or 2x1	4x2 or 8x4
Sky/Simultaneous reference	Yes (mutually exclusive)		
Instrumental RV precision	<10 cm/s	<10 cm/s	~1 m/s

ESPRESSO (ESO VLT):

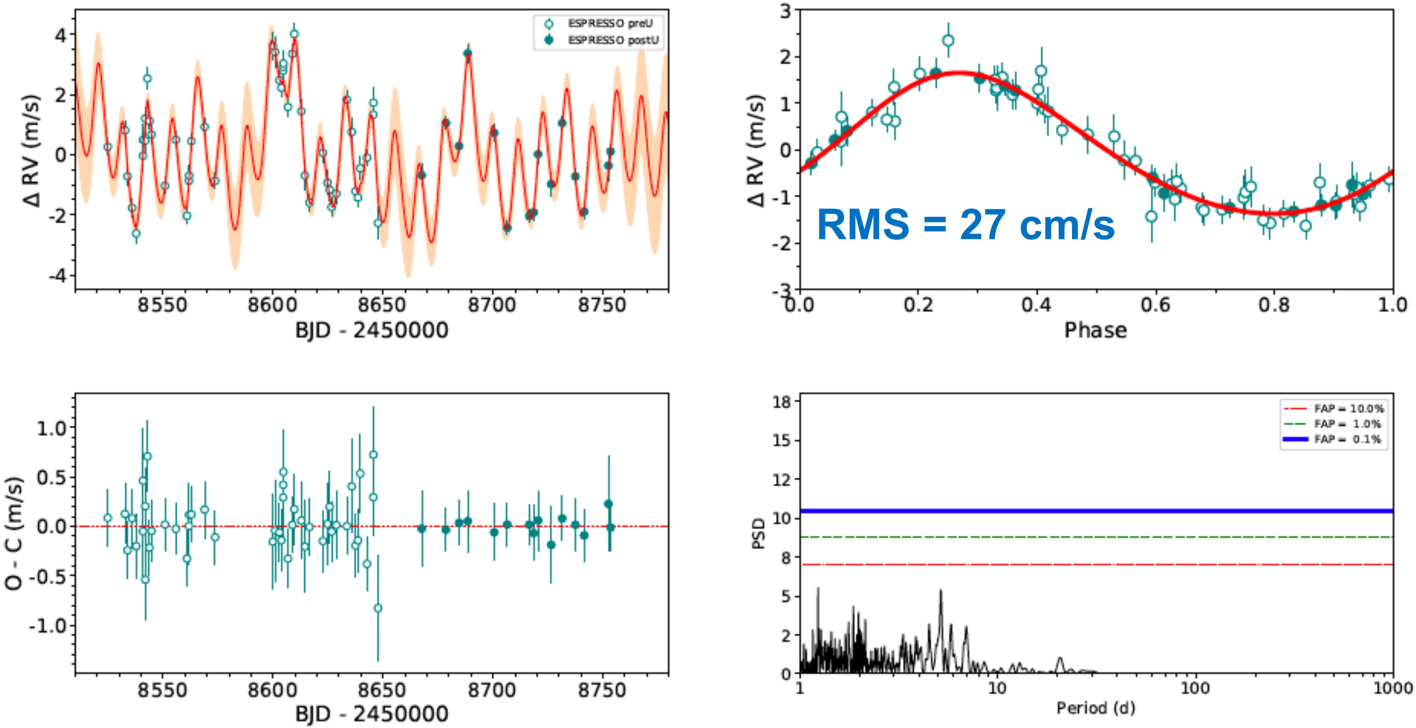
Short-term RV precision:



Benchmarks: Mv=7.65, Texp = 5 min. -> 25 cm/s
Mv=10, Texp = 2.5 min. -> 1 m/s
Mv= 4, Texp = 1 min. -> 10 cm/s

ESPRESSO (ESO VLT):

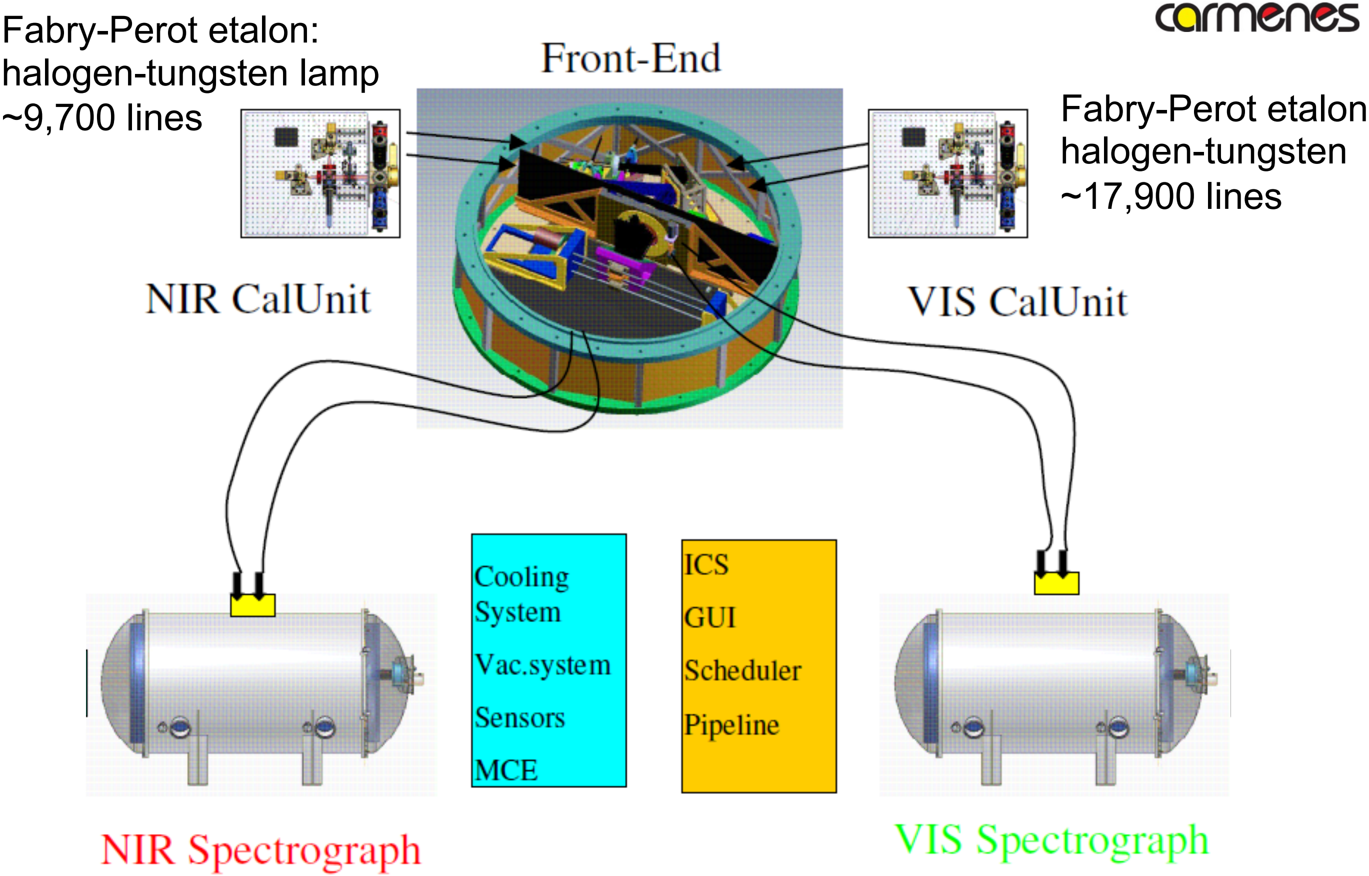
Proxima b: long-term RV precision:



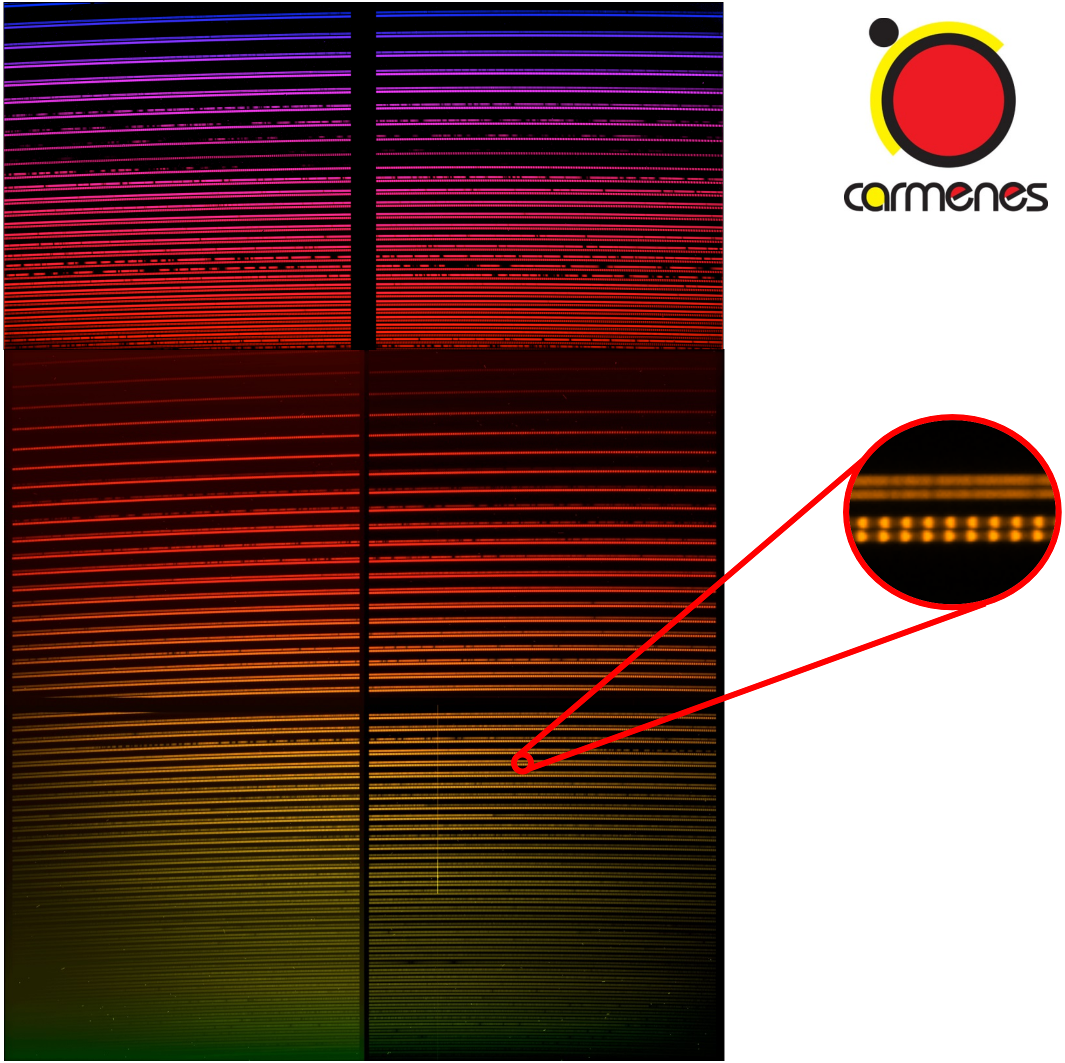
Properties of the CARMENES Spectrographs

- Optical spectrograph
  - 0.53 … 1.05 μm, R = 94,600
  - Precision ~1 m/s
  - Vacuum tank, temperature stabilized
  - 4k x 4k deep depletion CCD detector
- Near-Infrared spectrograph
  - 0.95 … 1.7 μm, R = 80,400
  - Vacuum tank, cooled to 140K, stabilized
  - Precision goal 1 m/s
  - Two 2k x 2k HAWAII-2RG 2.5 μm detectors

Instrument Overview



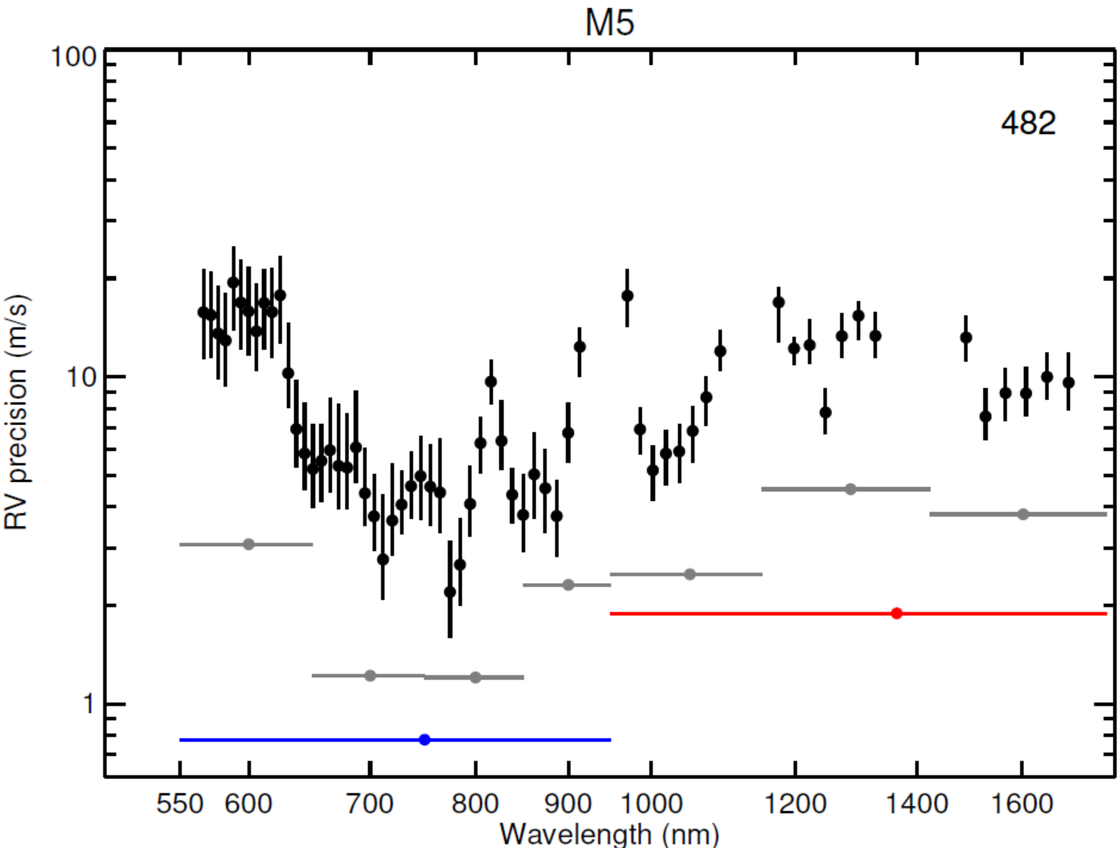
NIR 28 orders
0.96-1.71 µm



carmenes

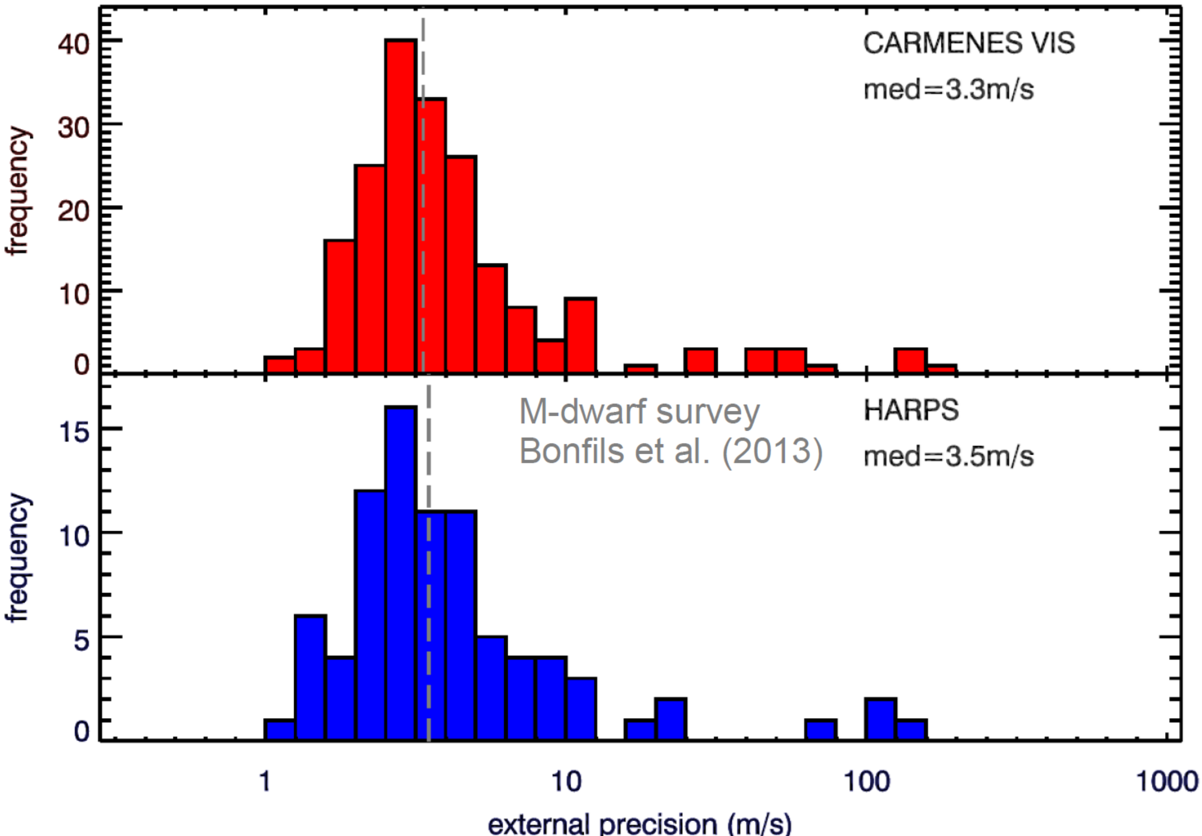
VIS 61 orders
0.52-0.96 µm

RV Precision for Different Wavelength Bands

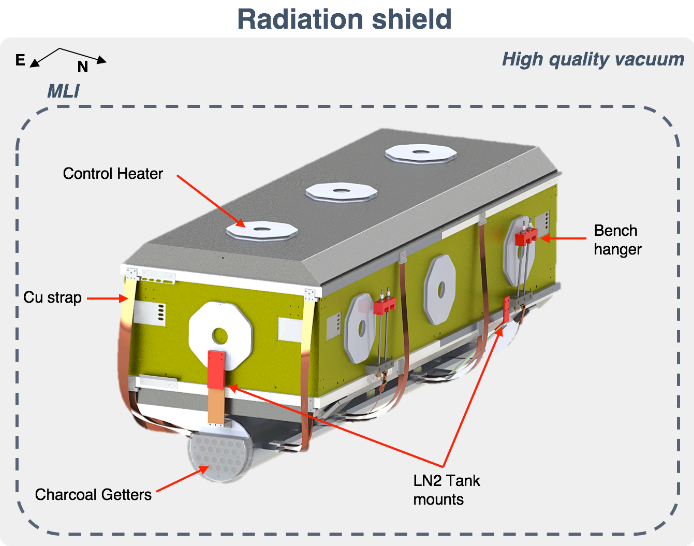


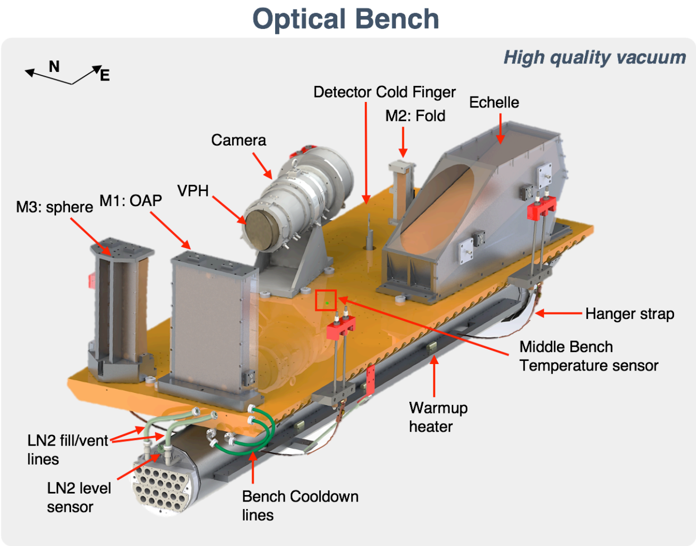
Reiners et al.
(A&A 2018)

Comparison with HARPS



HPF @ HET:

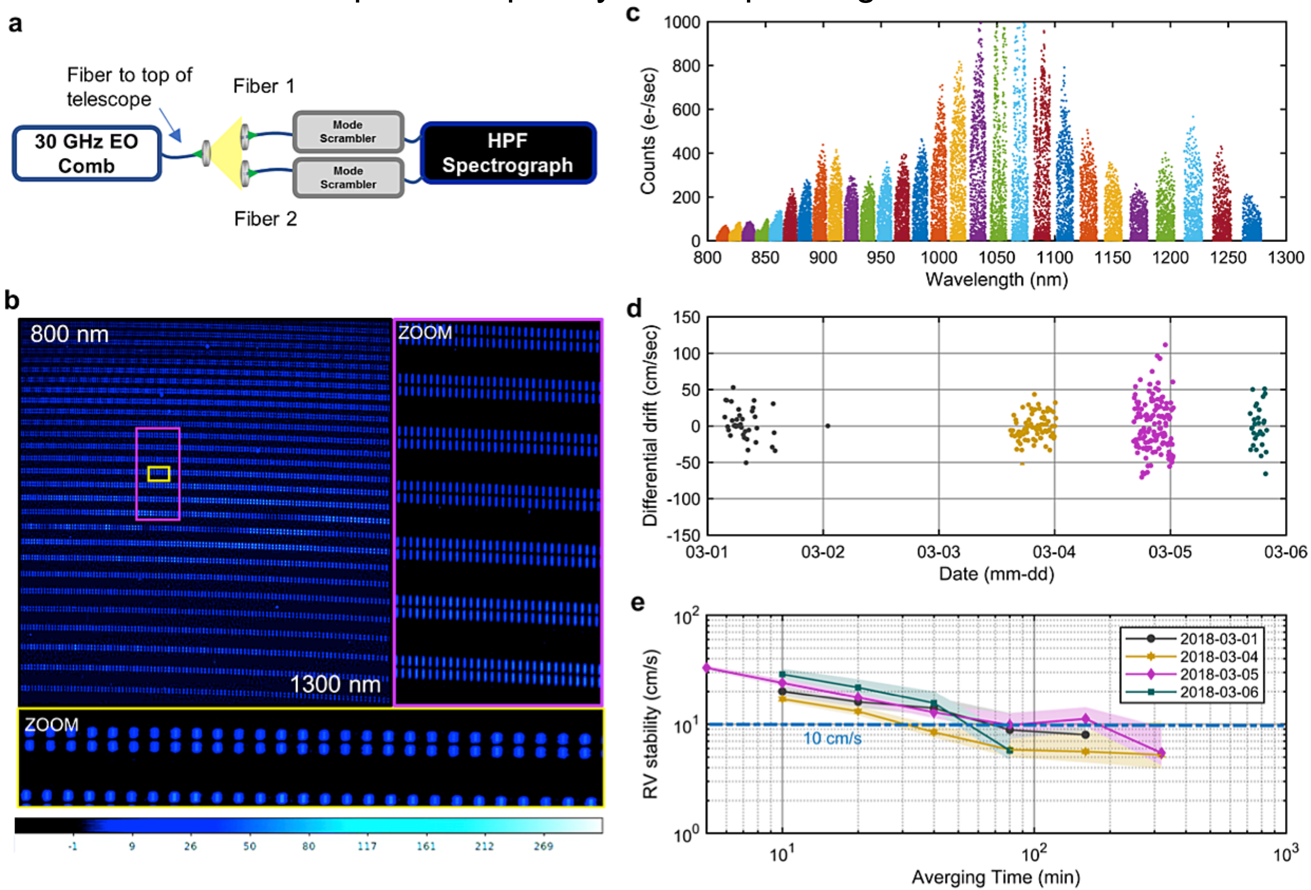




- white pupil spectrograph, vacuum cryostat cooled to 180 K (at milli-kelvin level)
- gold-coated mirrors & mosaic echelle grating
- single Teledyne Hawaii-2RG (H2RG) NIR detector with 1.7-micron cutoff
- covering parts of the information rich z, Y and J NIR bands (800-1300 nm)
- spectral resolution of R~50,000
- near and far-field fiber scrambling, double scramblers and octagonal fibers.
- Optimized for PRVs of mid M dwarfs (M4/5)

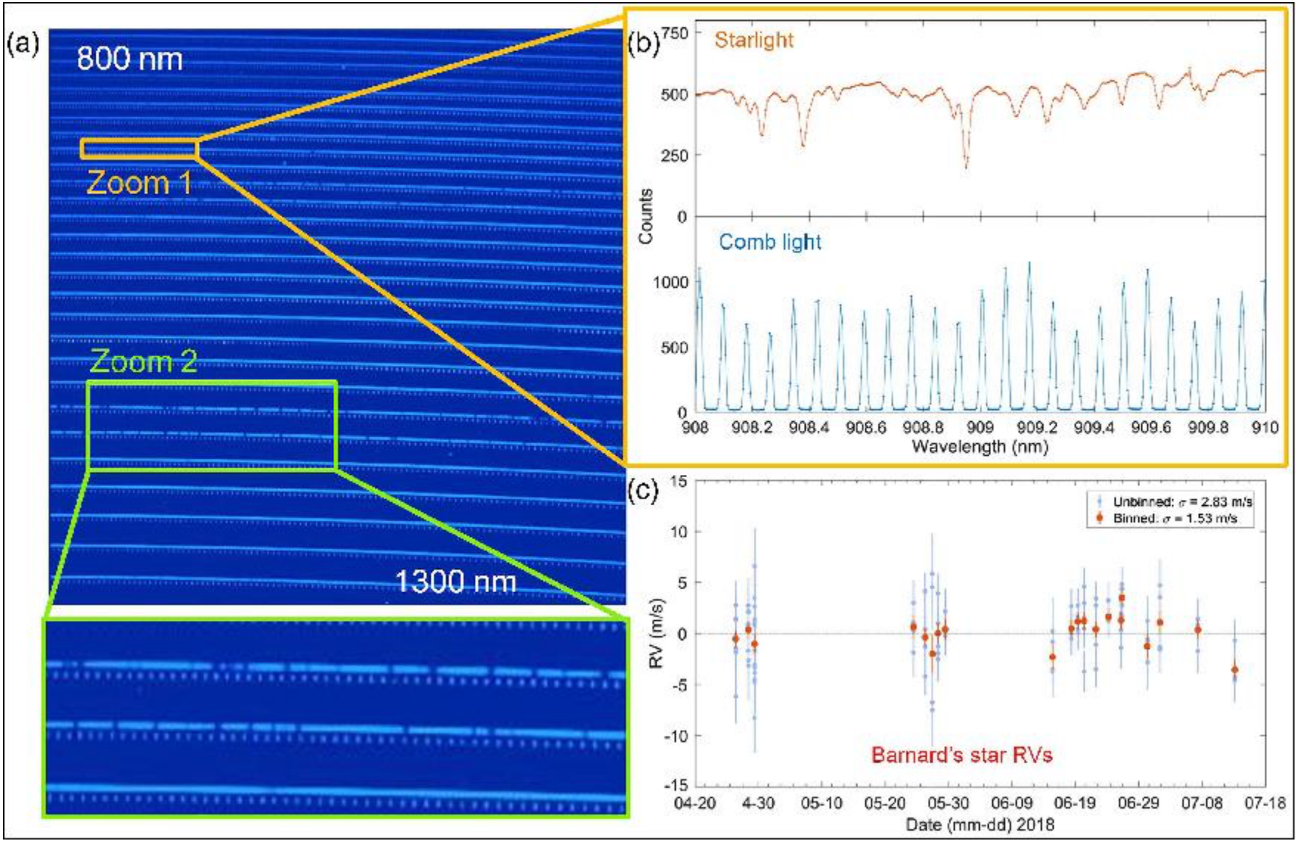
HPF @ HET:

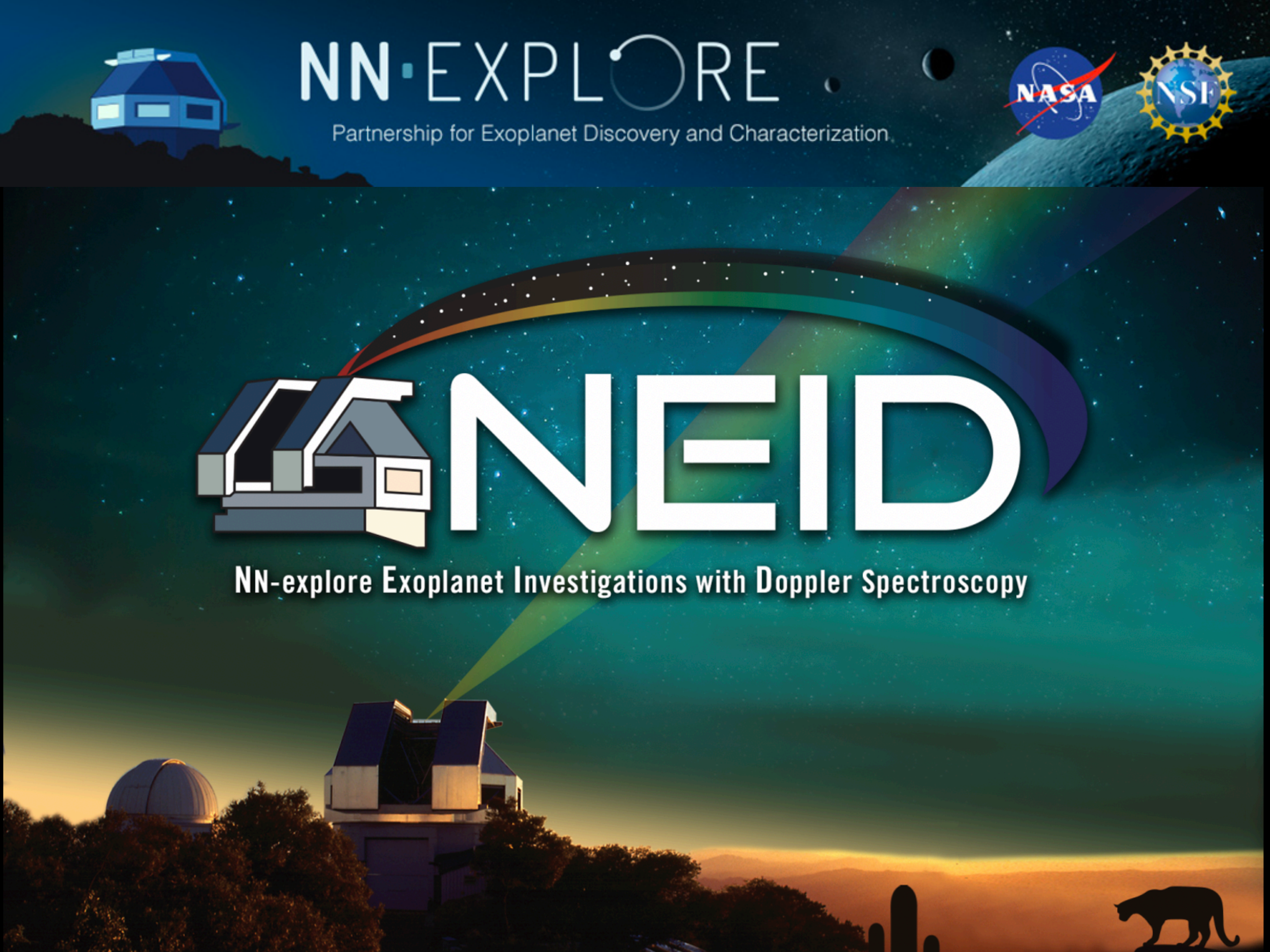
30 GHz optical frequency comb spanning 700–1600 nm



HPF @ HET:

30 GHz optical frequency comb spanning 700–1600 nm




NN·EXPLORE
Partnership for Exoplanet Discovery and Characterization
NASA
NSF
NEID
NN-explore Exoplanet Investigations with Doppler Spectroscopy

Telescope: 3.5m WIYN Telescope @ KPNO

Waveband & Resolution: 380 – 930 nm, complete coverage, R ~ 120K

Expected Precision: ~30 cm/s baseline goal (single measurement precision)

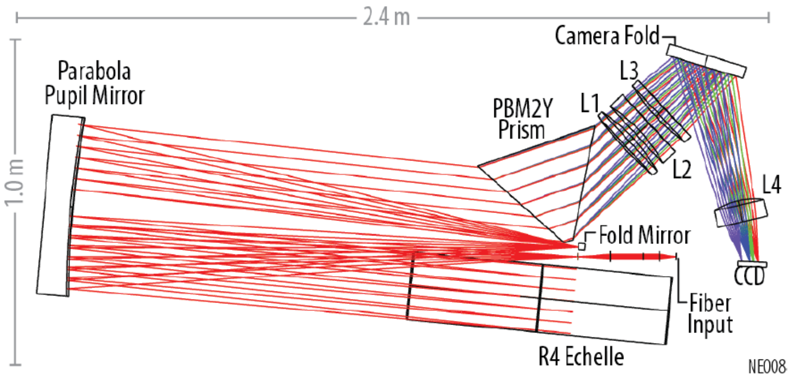
Commissioning Started but interrupted by Covid-19 shutdown

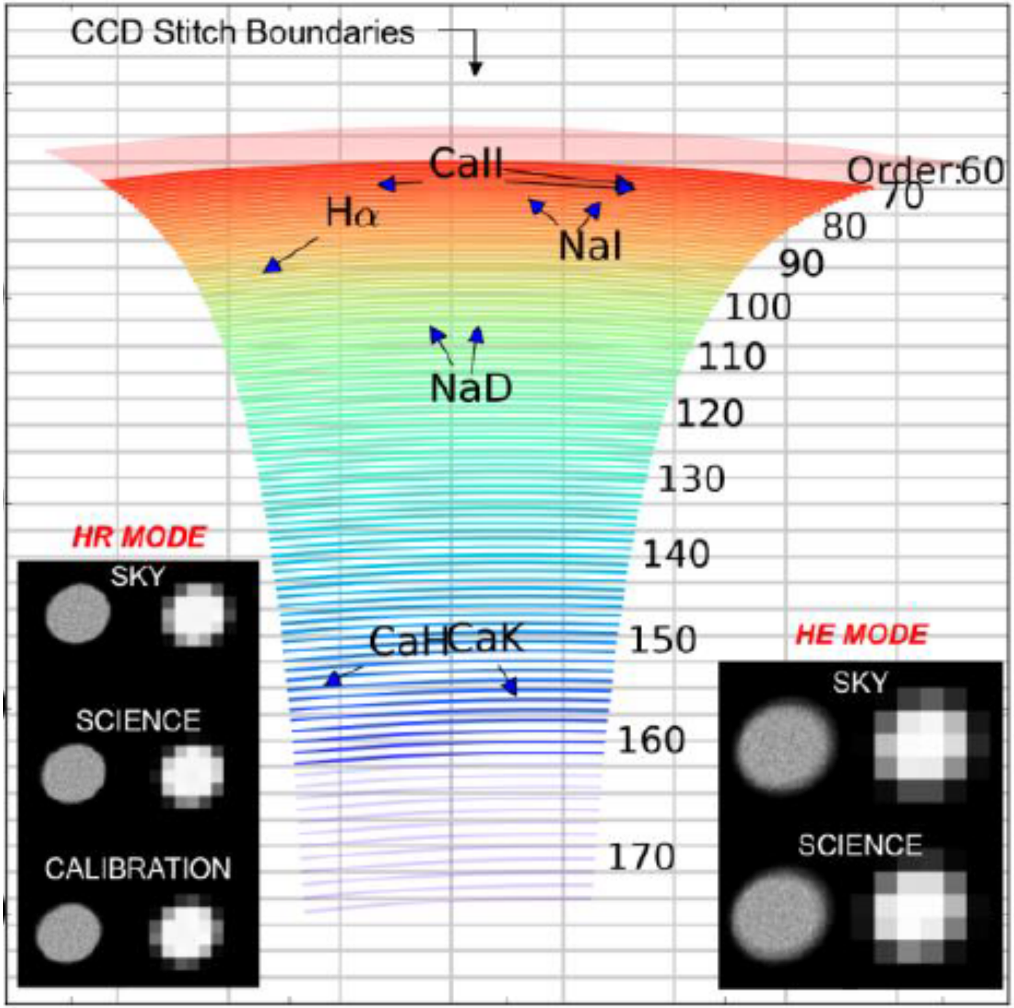
Available to the Public via NN-EXPLORE

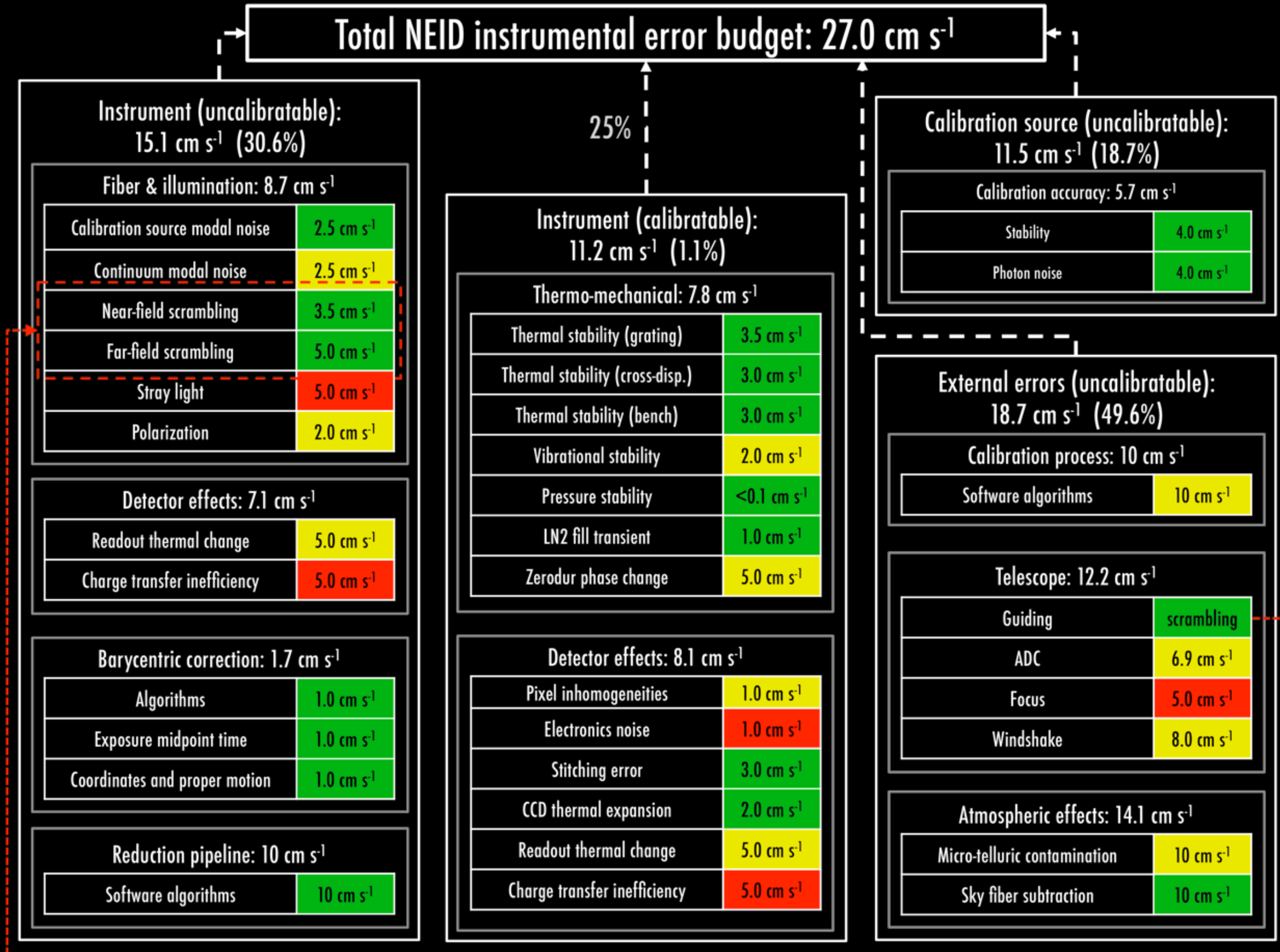
Two Observing Modes:

- HR (R~120,000)
  - Highest precision RVs on bright targets (V<12, e.g. TESS)
  - Simultaneous Cal
- HE (R~60,000)
  - Faint targets (V<16)
  - Poor weather
  - e.g. K2

NEID Optical Design:

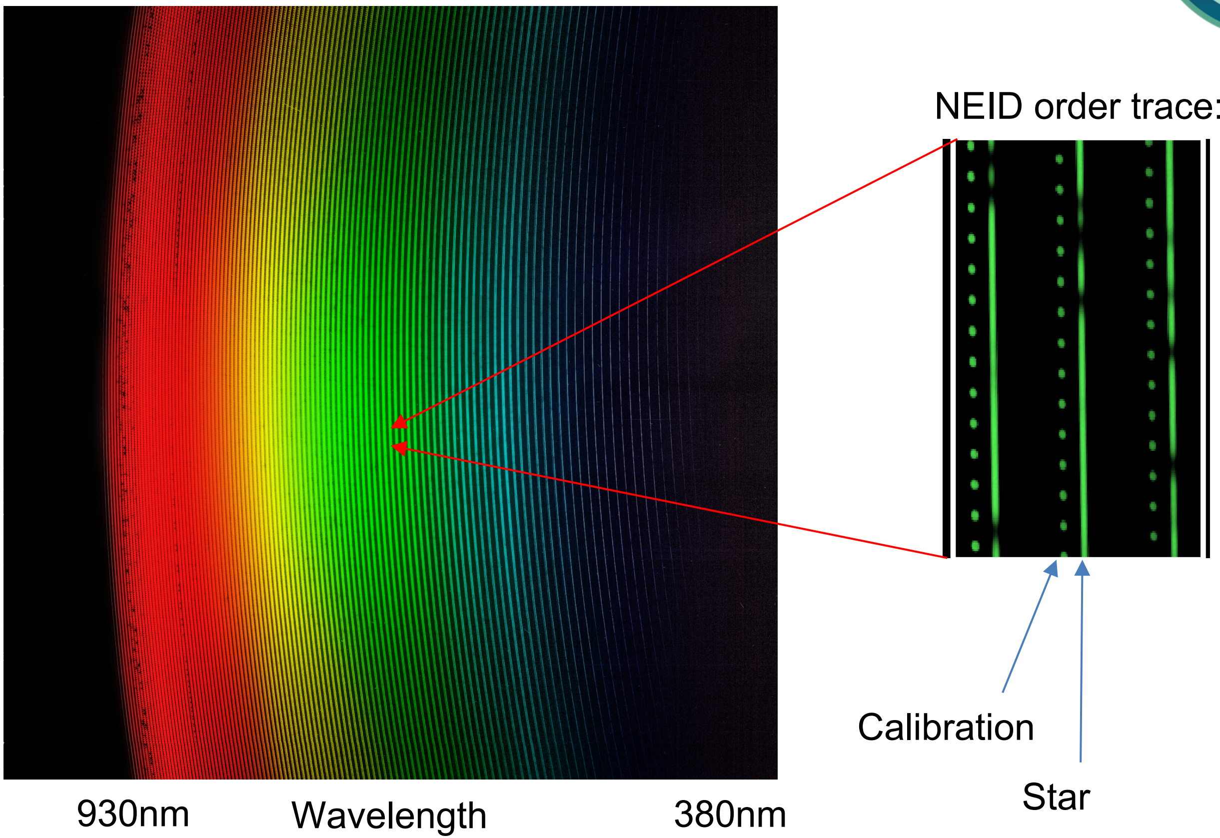



CCD Stitch Boundaries
CaII
Hα
NaI
Order:60
70
80
90
100
110
NaD
120
130
140
HR MODE
SKY
SCIENCE
CALIBRATION
CaH
CaK
150
HE MODE
SKY
SCIENCE
160
170



Halverson et al. (2016)

Dec. 13, 2019. NEID First Light: 51 Pegasi

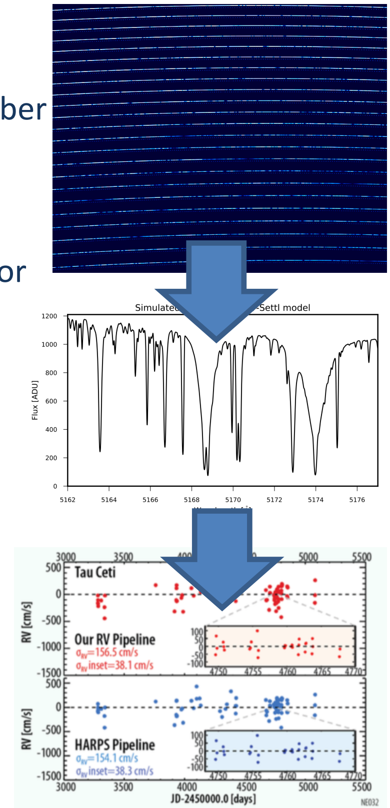


- Data will be fully reduced by the data reduction pipeline provided by the instrument team
- Every PI will have access to high-quality RVs produced by a common pipeline
- The archive will host three levels of reduced data for each observation:

- Level 0 - Raw data
  - One FITS file for each exposure
  - Each instrument readout (16 total) in an HDU
  - HDUs for exposure meter, guider image and coherent fiber bundle

- Level 1 – Extracted Spectra
  - 2D FITS images (order x pixel column) with extensions for sky, calibration, science fibers, and wavelength solution

- Level 2 – Radial Velocities
  - Cross correlation function data
  - Sky and telluric models
  - Activity indicators
  - Additional keywords include
  - Barycentric correction
  - RV per order
  - Drift terms



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Thank you!

Acknowledgements:
- Paul Robertson (UCI)
- Andreas Quirrenbach (Heidelberg)
- Francesco Pepe (Geneva)
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