NEID

NN-explore Exoplanet Investigations with Doppler Spectroscopy

A next generation EPDS for the US community

Chad Bender
The Pennsylvania State University

pronunciation: knew-id (like ‘fluid’)

definition: `***to see***’ in the language of the Tohono O’odham

The NEID Team

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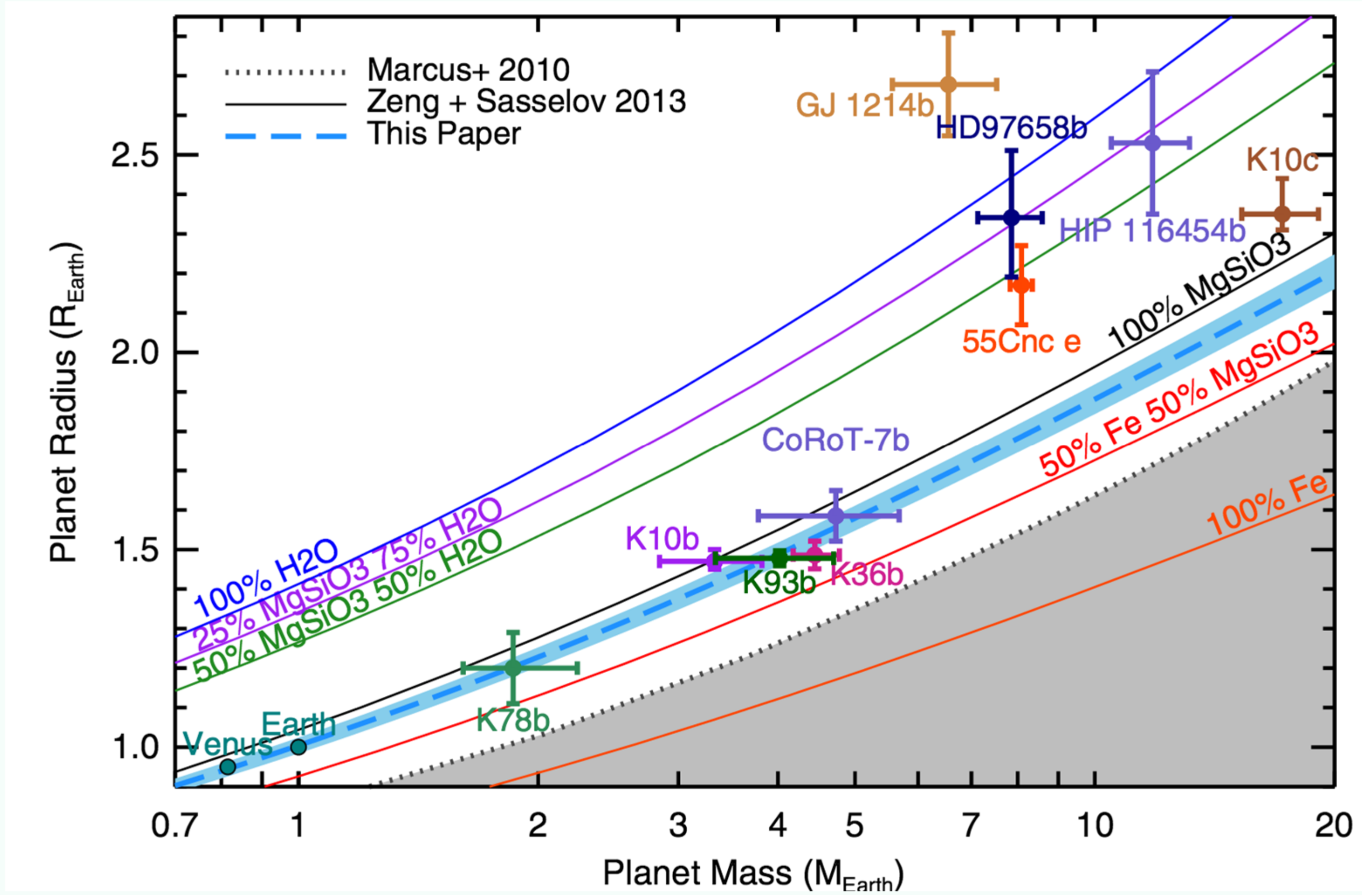
NEID

Science: The Need for sub-m/s RV

- Very precise planet masses needed to constrain composition/ formation models.
- TESS will provide transiting planets around bright stars, but EPRV resources are lacking.
- Other questions: multiplicity, obliquity, dynamics, etc. Answerable with RVs.



Dressing et al. 2015

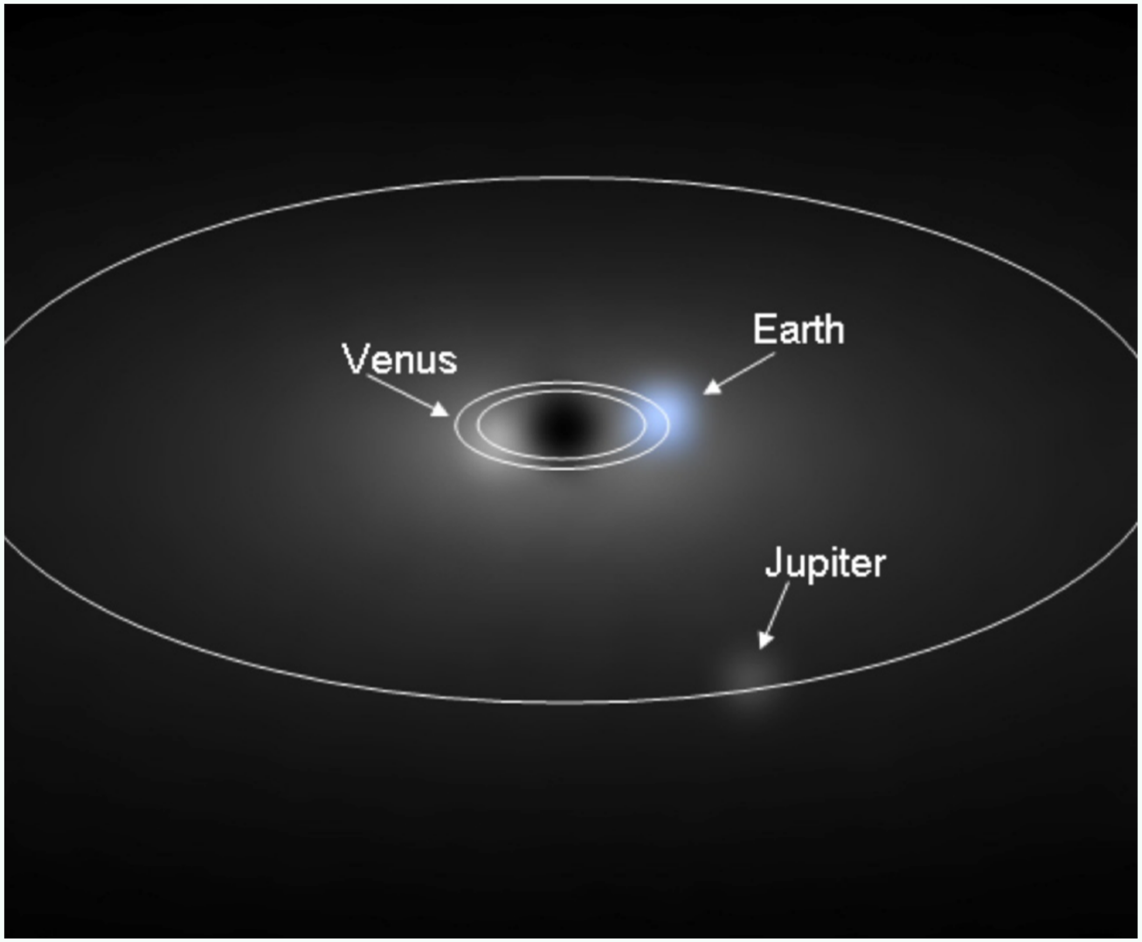
Extreme precision RV follow-up is a *requirement* for the success of TESS!

Science: The Need for sub m/s RV

Earth-mass planets in the HZ have 10-30 cm/s RV amplitudes, requiring observations on 10s to 100s of nights at <50 cm/s precision.

These planets represent the top targets for future imaging missions!

Knowing whether we have the ability to discover such planets could drive the choice of future flagship missions.



Simulated image of the solar system as viewed by a future space-based LUVOIR imager. (Webster Cash, Univ. Colorado)

Radial Velocity Error Budget

CBE = Current Best Estimate
MEV = Max Expected Value (Baseline)
MPV = Max Possible Value = MEV (1+ 50% margin)

Contingency = sqrt(MEV²-CBE²)
Reserve = 1 - MPV² / Threshold² = 37%

	CBE	Cont.	MEV	MPV
INSTRUMENT TOTAL [cm/s]	**14.0**	**22.6**	**26.6**	**39.8**

% Contribution to Final MEV		CBE	Cont.	MEV	MPV
1.1%	**Instrument [cm/s] (calibratable)**	**5.6**	**9.7**	**11.2**	**16.8**
0.5%	**Thermo-mechanical**	**3.7**	**6.9**	**7.8**	**11.7**
0.3%	Room Thermal Stability [K]	0.2	0.57	0.6	0.9
	Vacuum Thermal Stability [mK]	1.0	2.83	3.0	4.5
0.1%	Thermal Stability (XD)[cm/s]	1.0	2.8	3.0	4.5
0.1%	Thermal Stability (Echelle)[cm/s]	1.2	3.3	3.5	5.3
0.1%	Thermal Stability (Bench)	1.0	2.8	3.0	4.5
0.0%	Vibrational Stability	1.0	1.7	2.0	3.0
0.0%	Pressure stability	0.0	0.1	0.1	0.2
0.0%	LN2 fill transient	0.0	1.0	1.0	1.5
0.2%	Zerodur phase change	3.0	4.0	5.0	7.5
0.6%	**Detector**	**4.2**	**6.9**	**8.1**	**12.1**
0.0%	Pixel inhomogeneities [cm/s]	0.1	1.0	1.0	1.5
0.0%	Electronics Noise [cm/s]	0.1	1.0	1.0	1.5
0.1%	Stitching error [cm/s]	2.0	2.2	3.0	4.5
0.0%	CCD thermal Expansion [cm/s]	1.0	1.7	2.0	3.0
0.2%	Readout Thermal Changes [cm/s]	2.5	4.3	5.0	7.5
0.2%	Charge Transfer Efficiency [cm/s]	2.5	4.3	5.0	7.5
21.2%	**Telescope**	**5.7**	**10.8**	**12.2**	**18.3**
1.7%	Guiding* [RMS arcsec]	0.05	0.09	0.10	0.15
1.7%	Guiding* [cm/s]	0.9	3.39	3.5	5.3
6.9%	ADC* [Peak to Valley arcsec]	0.10	0.17	0.20	0.30
6.9%	ADC* [cm/s]	3.1	6.21	6.9	10.4
3.5%	Focus [cm/s]	2.5	4.33	5.0	7.5
9.1%	Windshake* [cm/s]	4.0	6.93	8.0	12.0
28.4%	**Atmospheric**	**8.5**	**11.3**	**14.1**	**21.2**
14.2%	Micro-Telluric Correction [cm/s]	8.0	6.0	10.0	15.0
14.2%	Sky Fiber Subtraction [cm/s]	3.0	9.5	10.0	15.0

fraction of instrument error that propogates through: 25%

% Contribution to Final MEV		CBE	Cont.	MEV	MPV
	From Instrument [cm/s] (calibratable)	**1.4**	**2.4**	**2.8**	**4.2**
18.7%	**Calibration Source**	**6.6**	**9.4**	**11.5**	**17.2**
4.5%	**Calibration Accuracy**	**4.3**	**3.7**	**5.7**	**8.5**
2.3%	stability [cm/s]	2.8	2.9	4.0	6.0
2.3%	photon noise [cm/s]	3.2	2.4	4.0	6.0
14.2%	**Calibration Process**	**5.0**	**8.7**	**10.0**	**15.0**
14.2%	Algorithm and Software [cm/s]	5.0	8.7	10.0	15.0
30.6%	**Instrument (Un-calibratable)**	**6.7**	**13.1**	**14.7**	**22.0**
8.9%	**Fiber and Illumination**	**2.6**	**7.4**	**7.9**	**11.9**
0.9%	calibrator modal noise [cm/s]	1.0	2.3	2.5	3.8
0.9%	science modal noise [cm/s]	1.0	2.3	2.5	3.8
	near-field scrambling* [GAIN]	20000	2x	10000	5000
3.5%	far-field scrambling*[cm/s]	2.0	4.6	5.0	7.5
3.5%	stray light [cm/s]	1.0	4.9	5.0	7.5
0.4%	**Barycentric Correction**	**0.7**	**1.6**	**1.7**	**2.6**
0.1%	Algorithms [cm/s]	0.1	1.0	1.0	1.5
0.1%	Exposure midpoint time [cm/s]	0.7	0.7	1.0	1.5
0.1%	Coords and proper motion [cm/s]	0.1	1.0	1.0	1.5
7.1%	**Detector cal vs. sci fiber**	**3.5**	**6.1**	**7.1**	**10.6**
3.5%	Readout Thermal Changes [cm/s]	2.5	4.3	5.0	7.5
3.5%	Charge Transfer Efficiency [cm/s]	2.5	4.3	5.0	7.5
14.2%	**Reduction Pipeline**	**5.0**	**8.7**	**10.0**	**15.0**
14.2%	Software Algorithms [cm/s]	5.0	8.7	10.0	15.0
49.6%	**External Errors**	**10.3**	**15.6**	**18.7**	**28.0**

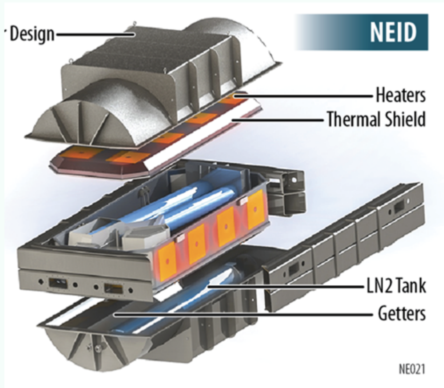
Our **Error Budget** is a compilation of sources of error, which add quadratically to inform the final performance baseline.

Total Instrument Error:
27 cm/s

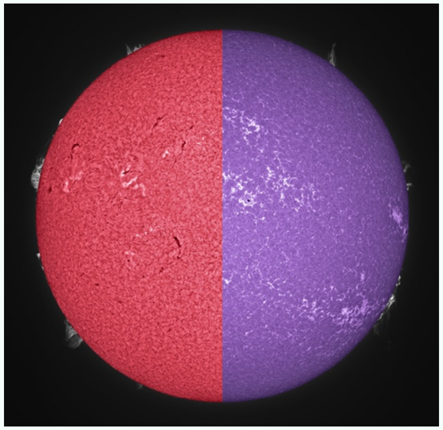
Instrument:	30.6%
Atmosphere:	28.4%
Telescope:	21.2%
Calibration:	18.7%
Calibratable Inst:	1.1%

So What Do We Need?

High Instrumental RV precision



Understand Stellar Activity

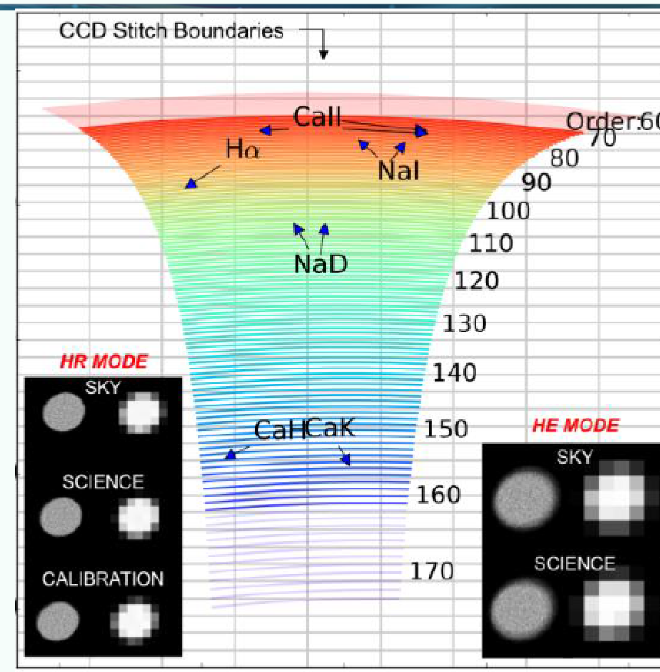


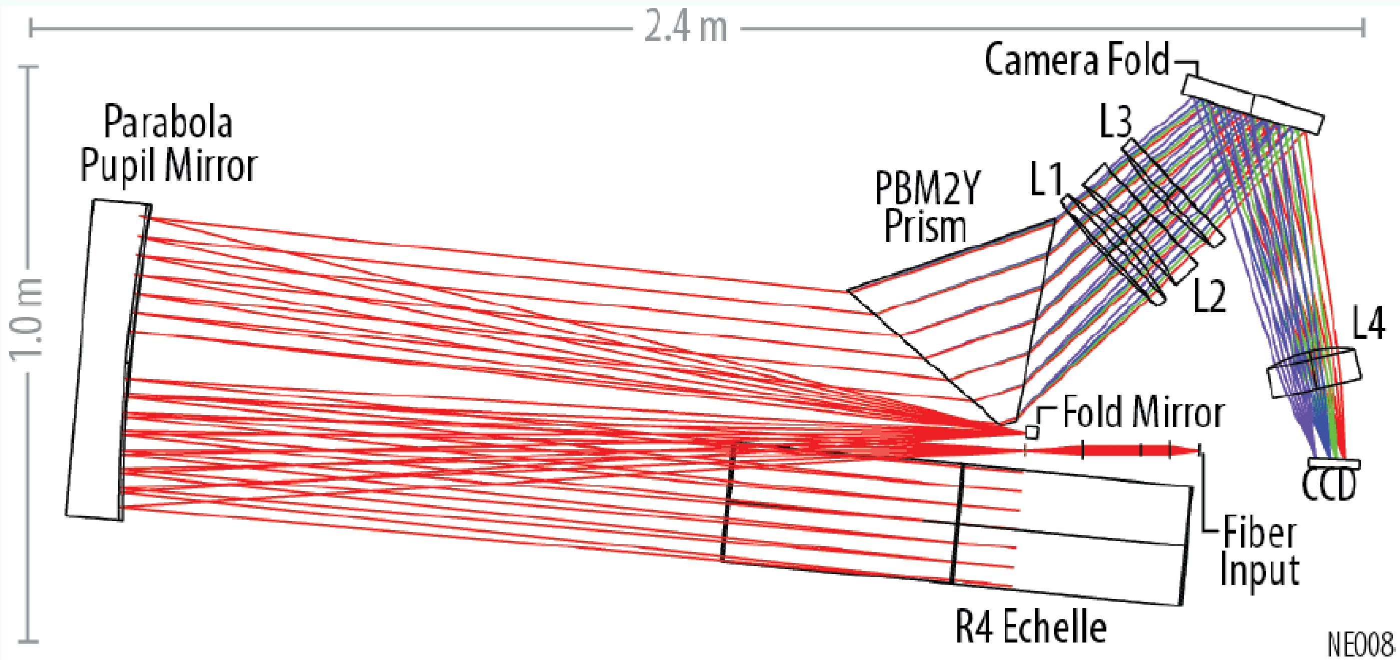
Substantial Observing Time via a Queue

Optical Design

Implementation: Single arm white pupil Echelle

- Single mirror white pupil relay, 200mm beam
- 2x1 mosaic R4 Richardson Echelle
- Single prism cross disperser: Ohara PBM2Y
- Refractive camera, 4 elements, folded
- Single e2v CCD: 9k x 9k, 10 µm pixels
- 380 – 930 nm, complete coverage



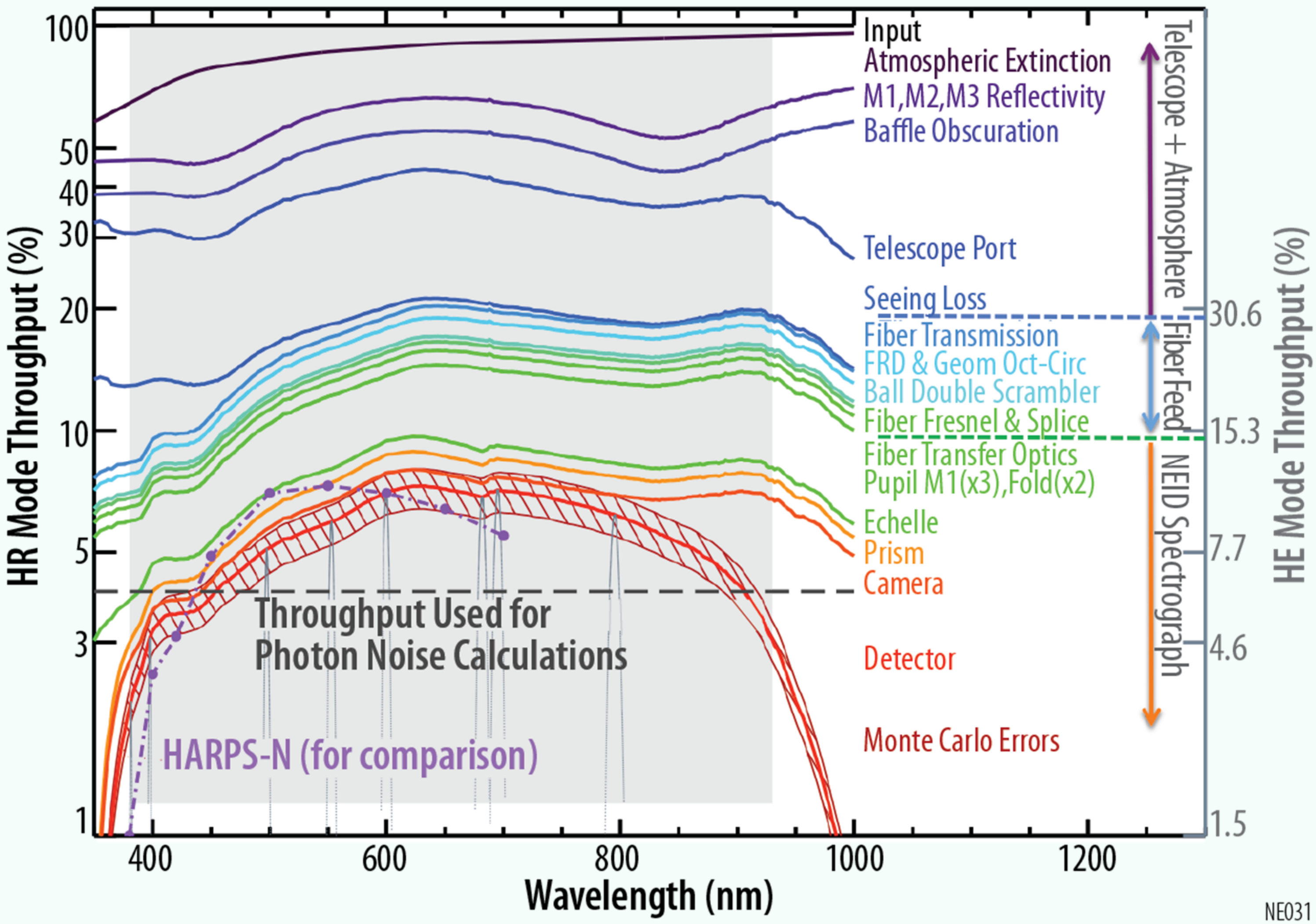


Two Observing Modes:

- HR (R~100,000)
  - 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

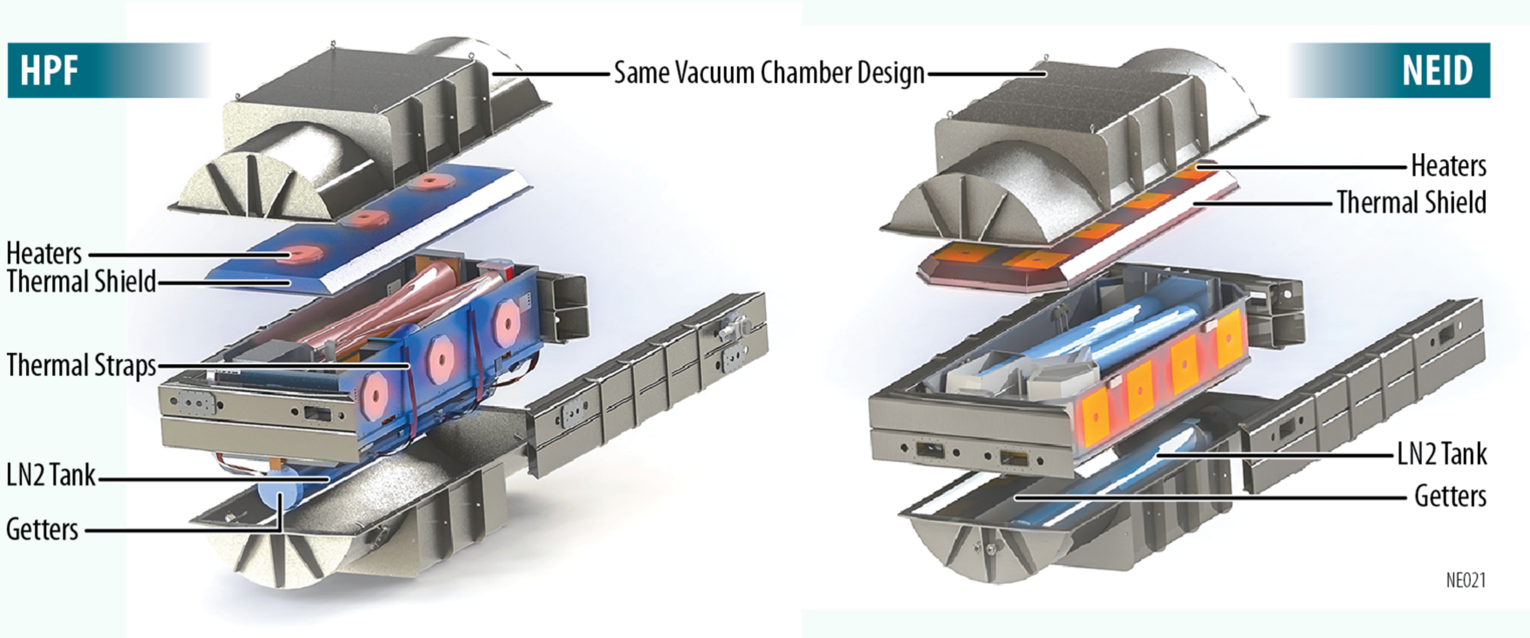
System Throughput

- Spectrometer throughput **>40%** at 500 nm
- Mean system throughput of **5.6%** (blaze peak) over the full bandpass.
- **Matches HARPS over a wider bandpass**



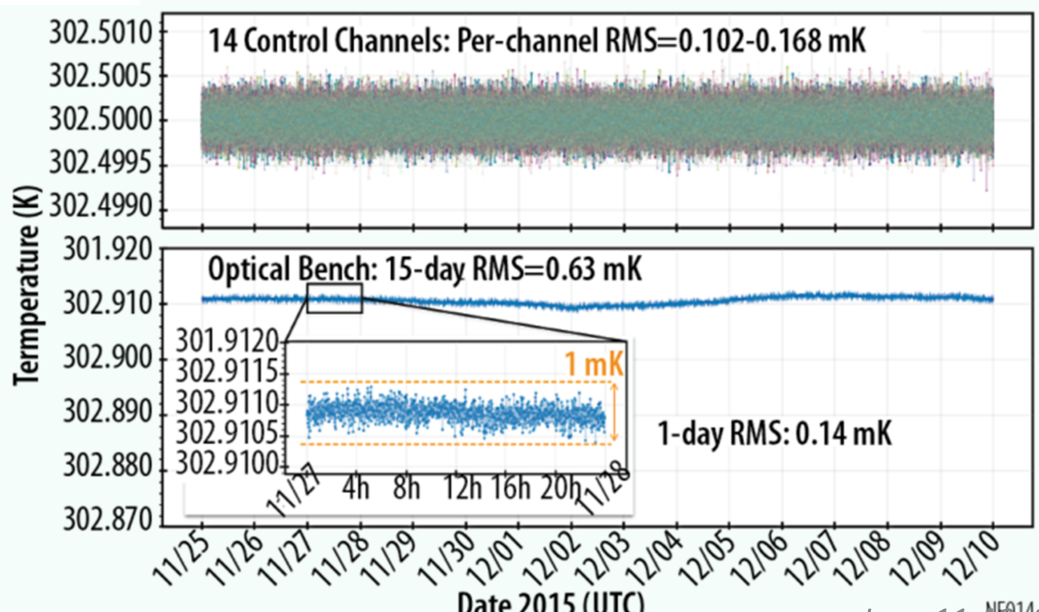
Environmental Control

Vacuum chamber inherits HPF design, modified for 300 K operation



Full scale tests with HPF cryostat at 300 K demonstrate:

- **$\Delta T < 1$ mK**
- **$P < 10^{-7}$ Torr**



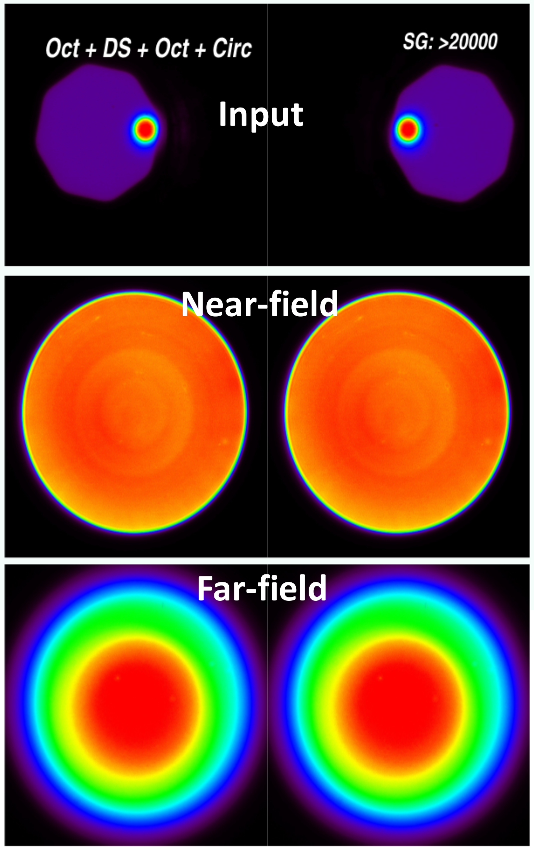
Fiber Feed

Feed identical **Science** & **Sky** fibers at the Upper Bent Cass port

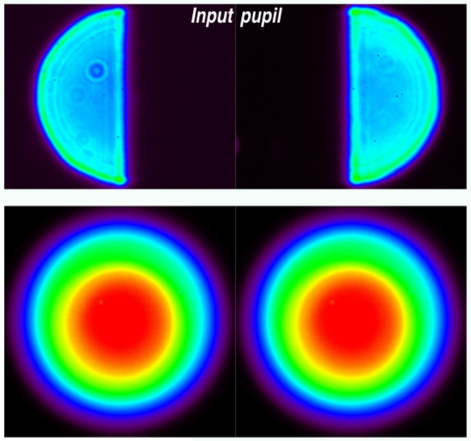
- Polymicro FBP octagonal
- HR: 62.5 µm (0.92”)
- HE: 100 µm (1.47”)

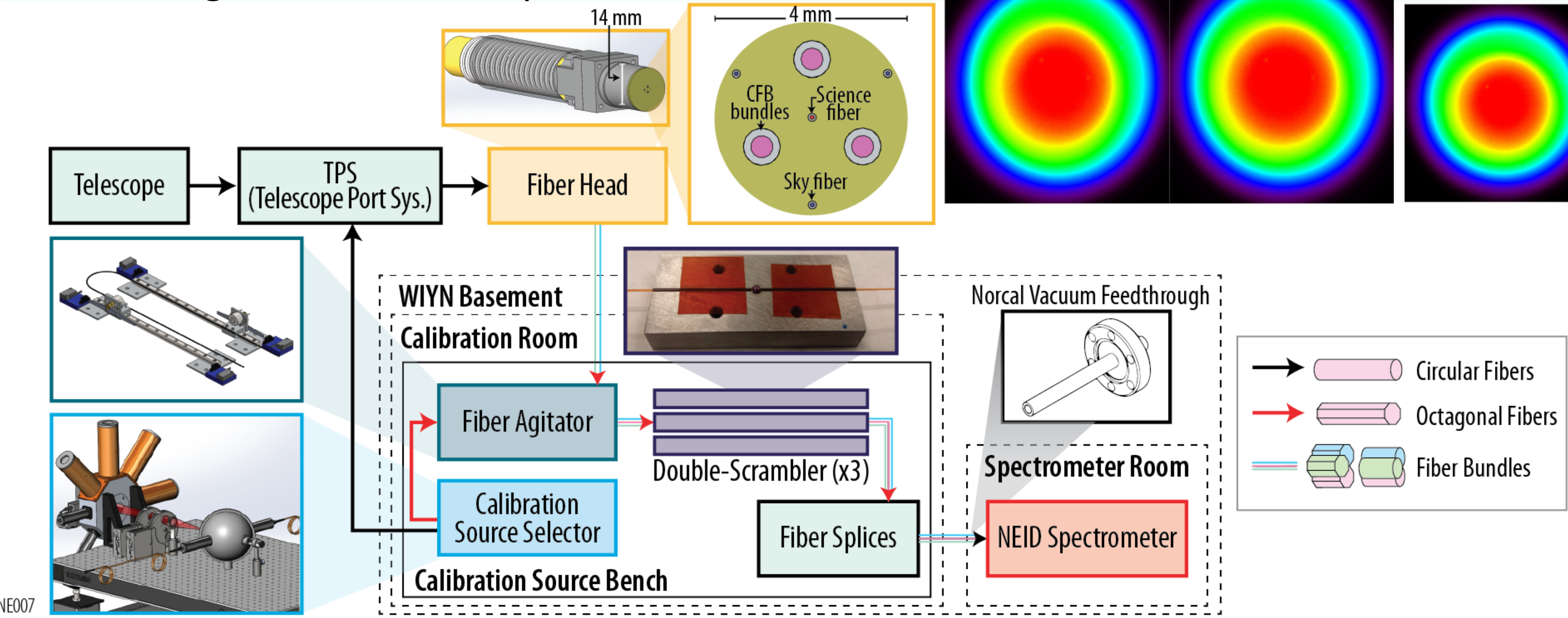
Provide a stable PSF, insensitive to guiding or illumination changes

- Ball lens double scrambler
- Octagonal -> circular splices

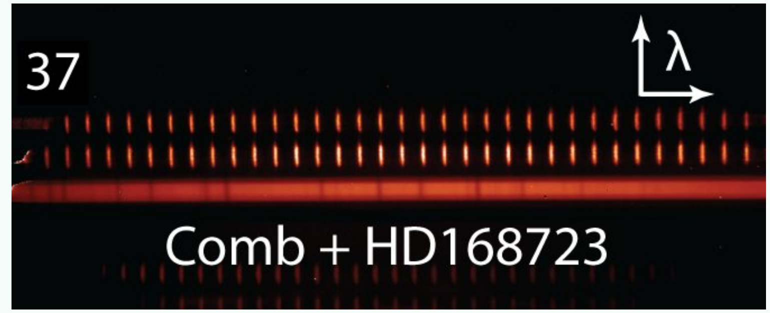


Lab measurements of the fiber feed





Wavelength Calibration

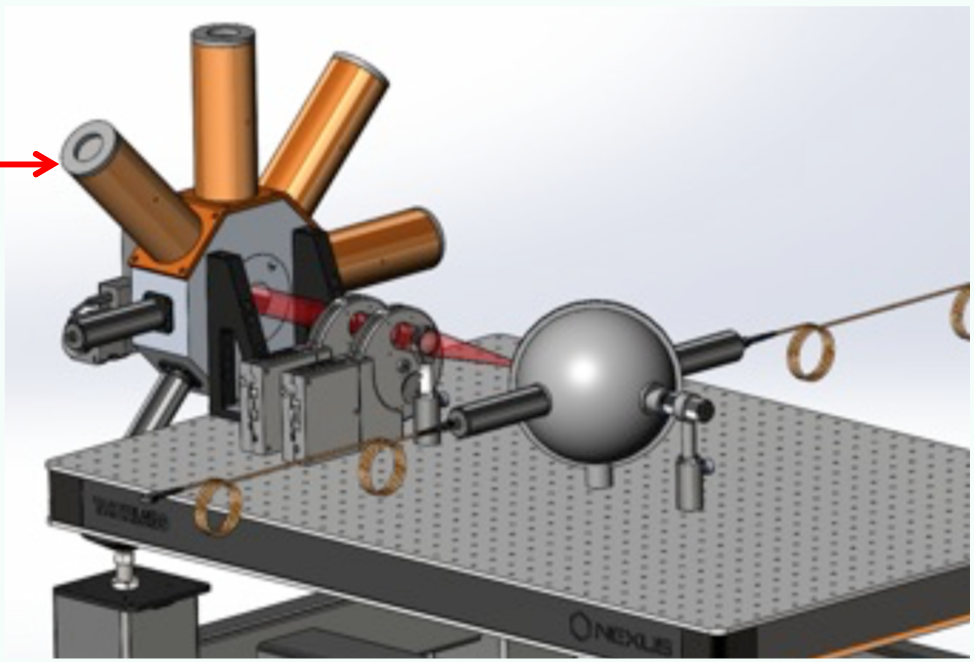


Menlo Systems Astro Laser Freq. Comb

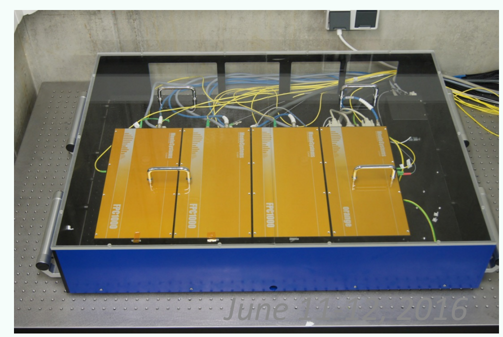
- 20 GHz line spacing
- 420-900 nm requirement, 400-930 nm best effort
- Individual line centers known to < 3 cm/s
- Absolute accuracy better than 1 part in 10^{10}
- Being used by HARPS, ESPRESSO
- Comb-comb test at HARPS achieve ~4 cm/s

Input Sources:

- LFC
- FFP
- ThAr
- Une
- Flat

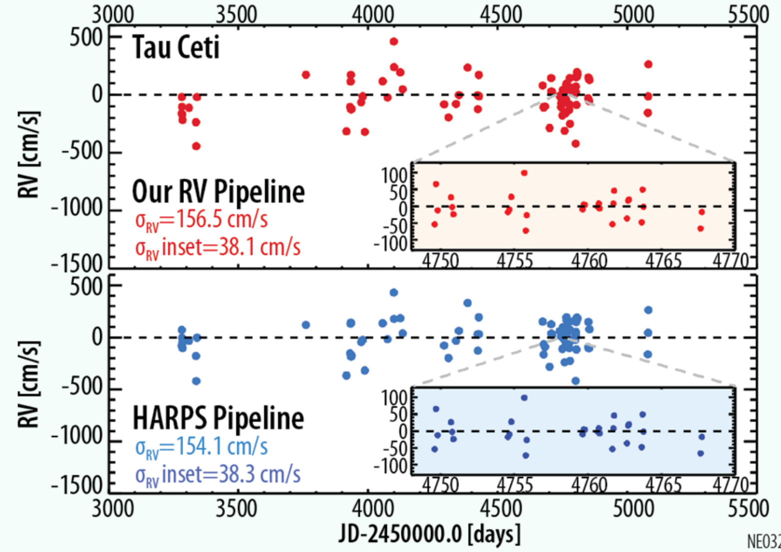


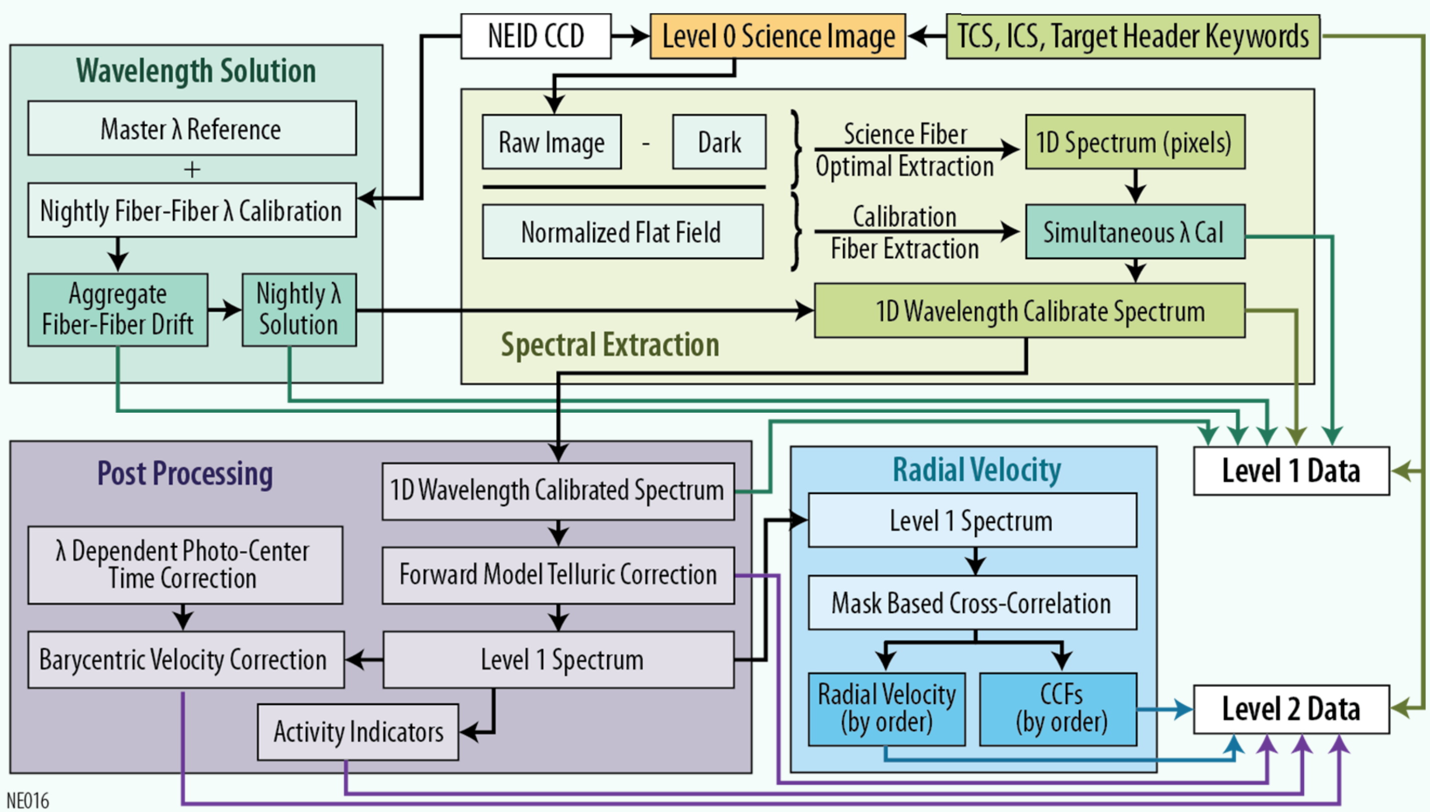
NEID Calibration Bench



Data Pipeline

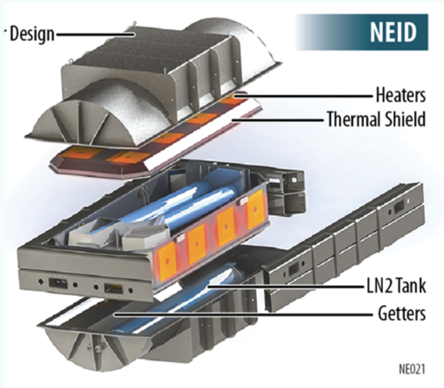
- Automated pipeline runs daily at NExScI
- Data served to GO PIs and the community via a NExScI portal
  - Raw images, reduced spectra, RVs, ancillary products (activity metrics, telluric metrics, barycentric correction, etc.)



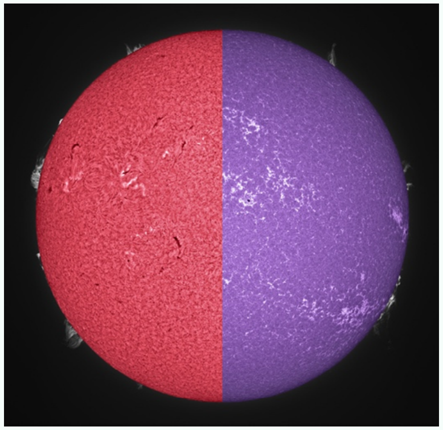


So What Do We Need?

High Instrumental RV precision



Understand for Stellar Activity



Substantial Observing Time via a Queue

Stellar Activity Will Contaminate RVs

At RV=1m/s and below, all stars are plagued by stellar activity signals

Typical RV Amplitudes:

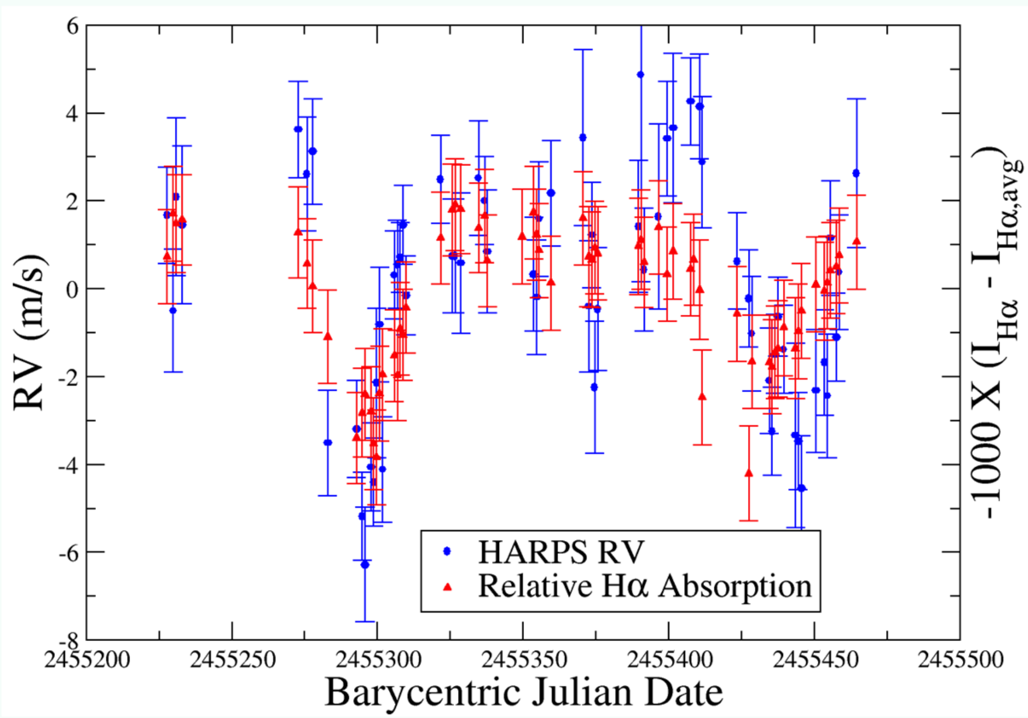
- short-term magnetic activity: few m/s
- long-term magnetic activity cycles: few to 10+ m/s
- granulation: ~10+ cm/s

For NEID (and other new PRV spectrometers) astrophysical noise is at least as important as instrument induced measurement noise!

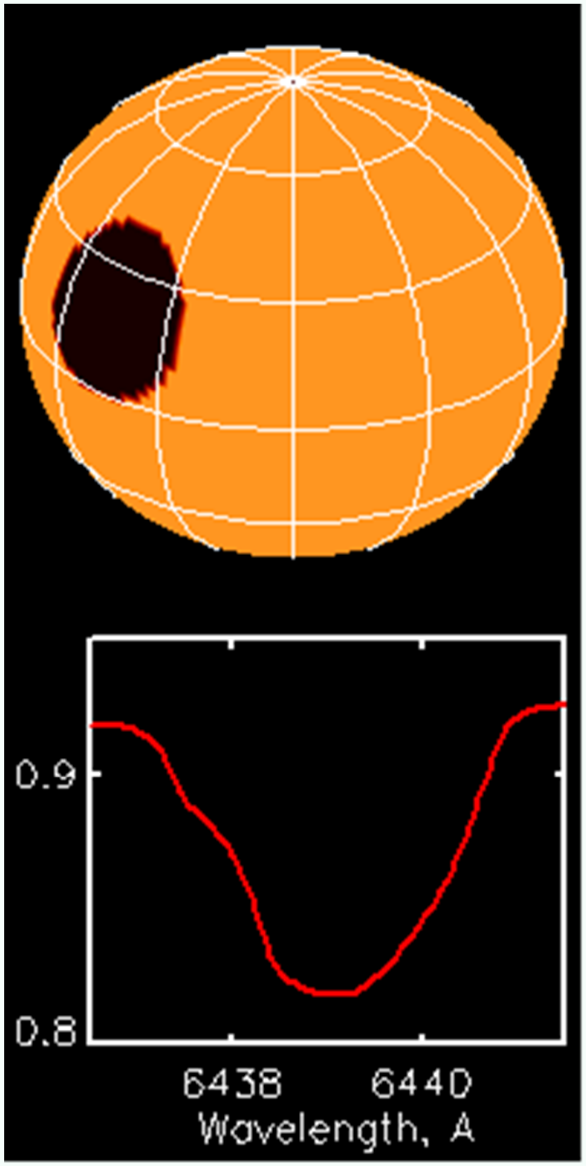
Magnetic Activity Masquerading as Planets

Rotating spots and active regions create periodic RV signals at the rotation period ***and*** harmonics

Gliese 581d RV 'signal' corresponds to stellar rotation period (Robertson, Mahadevan, Endl & Roy *Science, 2014)*



This is a problem for detecting true Earth analogs!

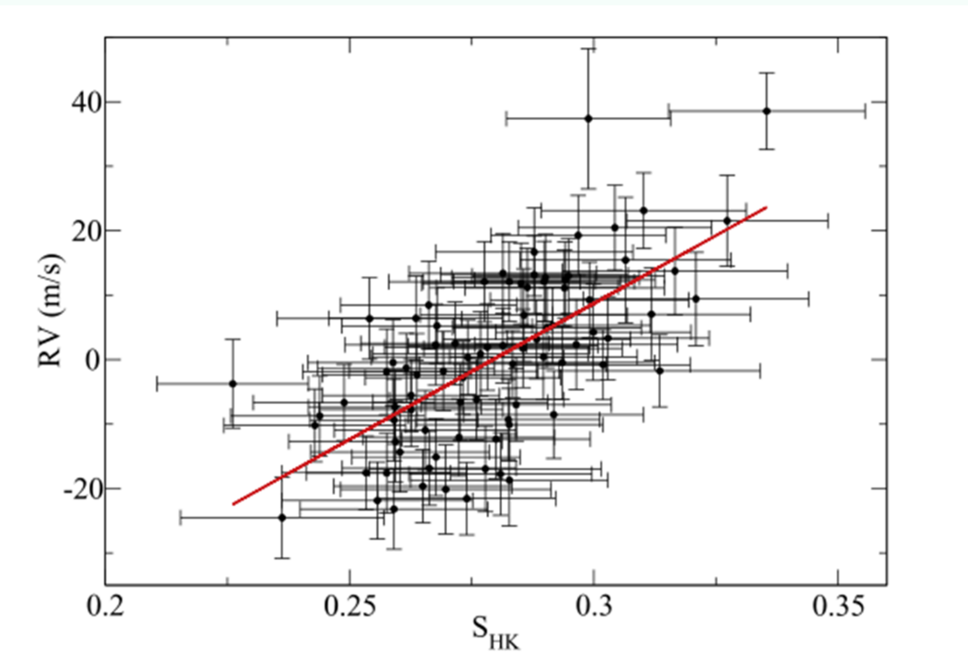


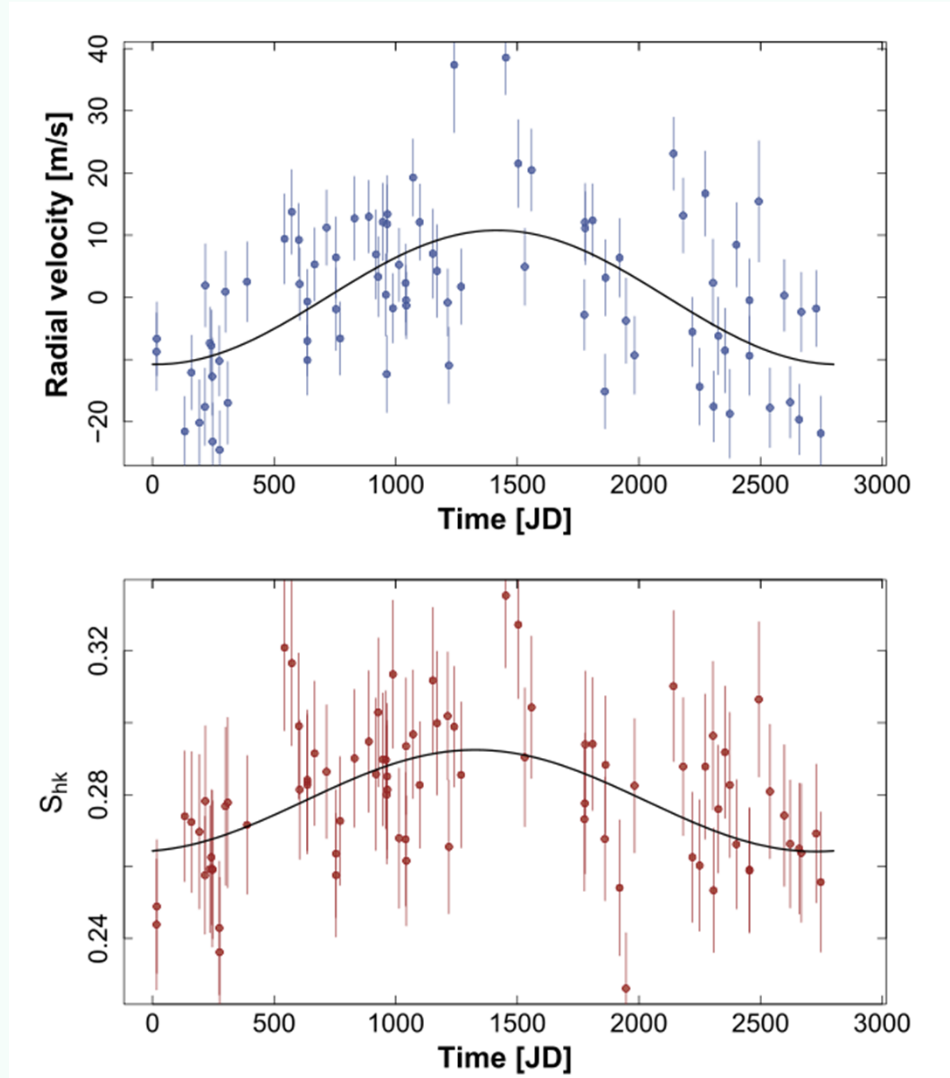
Animation via Svetlana Berdyugina

Activity Cycles Mimic Jupiter Analogs

HD 10086 (Endl et al. 2016):

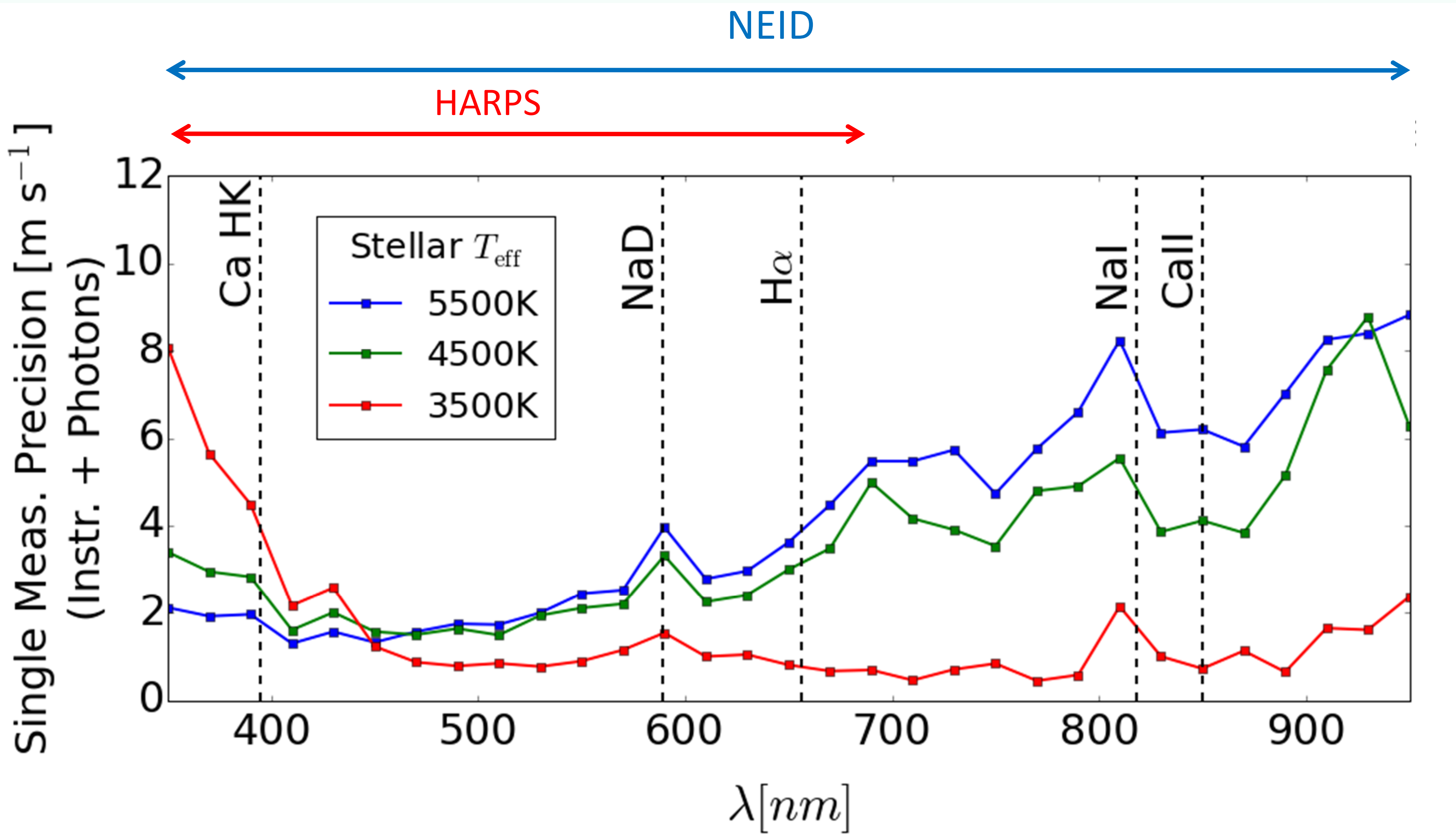
- 7.7 year periodic signal
- K = 11 m/s
  - Msini = 0.74 Mjup @ 3.9 AU
- Highly correlated with periodic signal in Ca H & K index
  - **Not a planet!**





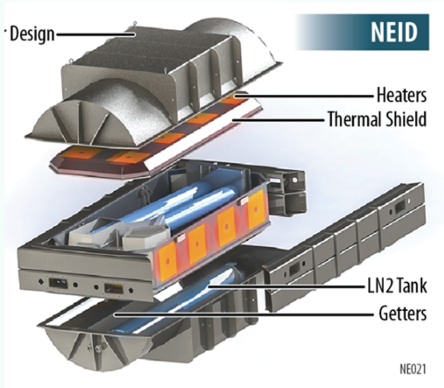
NEID captures the important activity indicators

and most of the Doppler information for F-K dwarfs

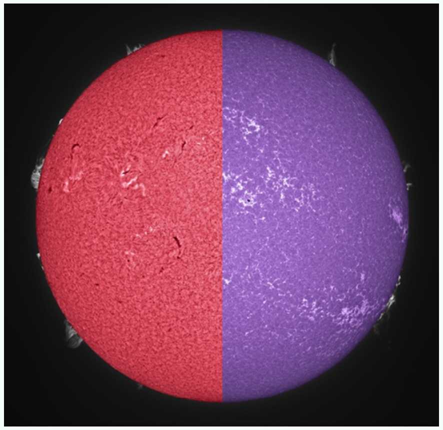


So What Do We Need?

High Instrumental RV precision



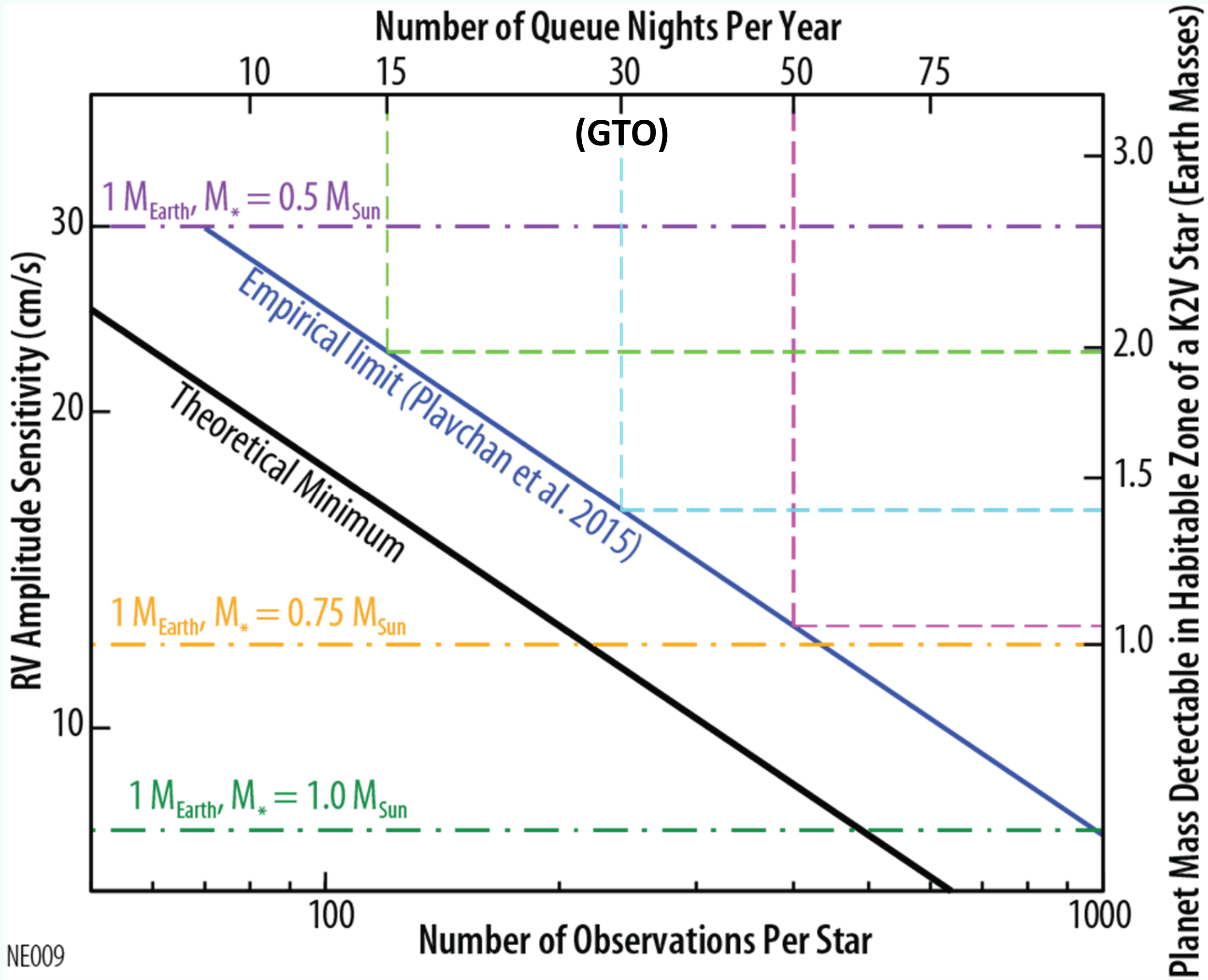
Understand Stellar Activity



Substantial Observing Time via a Queue

The need for time

Instrumental precision only translates into rocky planet discoveries with significant time investment



WIYN NEID time will operate in a queue mode to optimize efficiency across programs

Science: GO campaigns

Typical GO campaign (5 nights/yr for 5 years)

Yellow line = 1 Earth-mass planet @ given RV amplitude sensitivity

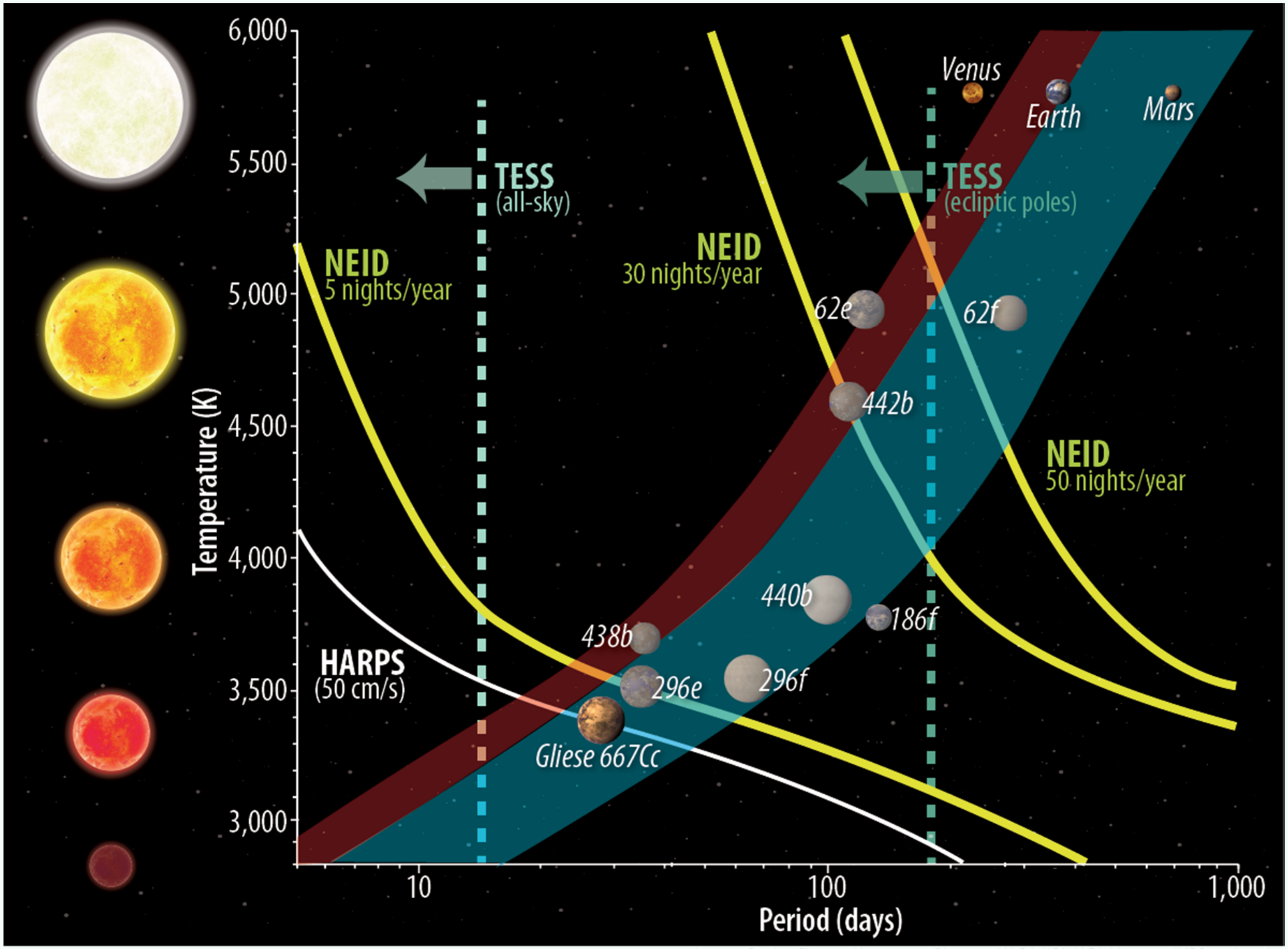


Image Credit: Chester Harman Planets: NASA/JPL/APL/Arizona/UPR at Arecibo

"Hot Earths" orbiting G-K stars for *JWST* spectroscopy

***TESS*, *K2* confirmation** and masses of rocky planets

Nearby giant exoplanet **imaging candidates**

Science: GTO / Large GO Campaigns

GTO / large GO campaign (30 nights/yr, 5yr): 2 Earth-mass planet in HZ of K dwarfs

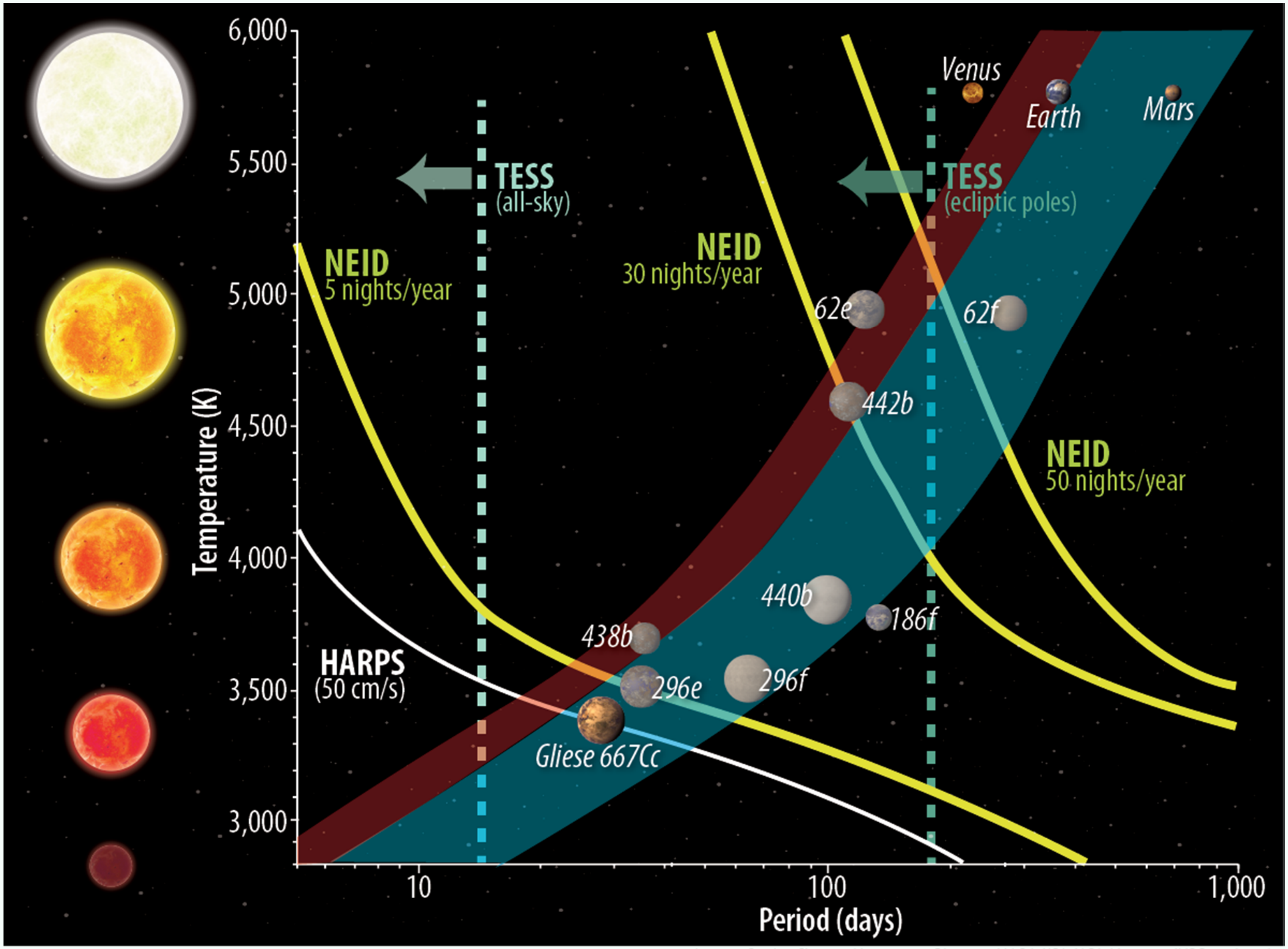


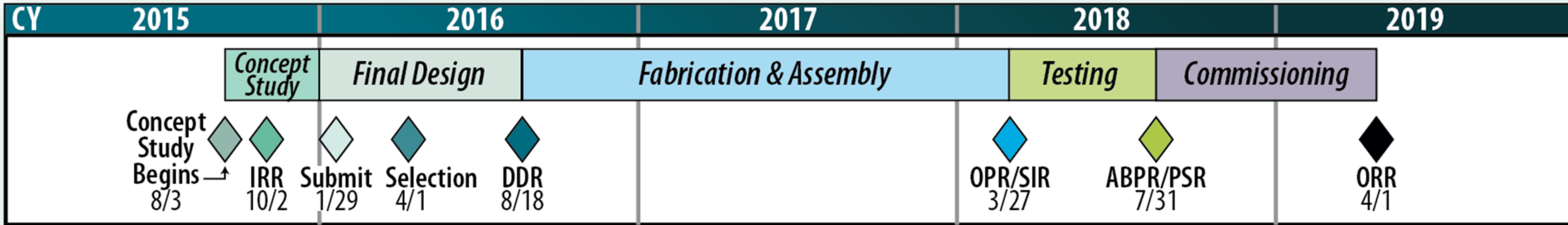
Image Credit: Chester Harman Planets: NASA/JPL/APL/Arizona/UPR at Arecibo

HZ Earth-mass planets orbiting M-K stars

Nearby less massive exoplanet **imaging candidates**

Masses for non-transiting planets in ***TESS/Kepler*** **TTV systems**

Schedule & Status



- JPL & PSU contract finalized 4/21/2016
- UPenn & UC subcontracts underway
- Long-lead procurements:
  - Vacuum chamber fab (Pulseray)
    - Materials ordered this week. Fab schedule to start June 22.
    - Delivery to PSU October 2016
    - TCS fab at PSU underway
  - Prism
    - Glass melt underway @ Ohara (~9-12 month anneal)
    - Fab vendor visits underway
  - Echelle Grating (Newport/RGL)
    - PO is out (~12-14 month fab)
- Focusing now on:
  - OAP
    - SoW being finalized
  - Detector (e2v)
    - UPenn sole source this month
  - Camera (NEOS)
    - NRE underway
    - 54 week delivery
  - Menlo Comb – FY17
- DDR moved to winter 2016 to accommodate available funding profile
- **On schedule for April 2019 delivery**

Stay Tuned for Frequent Updates!

NEID will be here by October 2016

Habitable Zone Planet Finder

Our integration clean-lab at Penn State

We're hiring:

Software Postdoc (data pipeline) – ad is out now
UPenn Detector Postdoc – ad is out now
PSU Research Associate (instrumentation generalist) – ad will appear soon