



ExEP Report on Future of Extreme Precision Radial Velocity (EPRV)

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ExEP Report on Future of Extreme Precision Radial Velocity (EPRV)

- Brief update on NN-EXPLORE program & NEID spectrograph
- EPRV Working Group – providing a blueprint on an EPRV initiative for the 2020s for NASA & NSF in response to Exoplanet Science Strategy (2018) NAS report



Important reminder:

NASA doesn't invest in ground-based astronomy for the sake of doing good science; NASA invests in ground-based astronomy because there is a compelling mission need to do so.



NASA ExEP Science Gap List (2018)

(grouped by topic, no implied priority in ordering)

- Spectral characterization of small exoplanets
 - Modeling exoplanet atmospheres
 - Spectral signature retrieval
 - Understand the abundance and substructure of exozodiacal dust
 - Measurement of accurate radii for transiting exoplanets
- Planetary system architectures
 - Occurrence rates for HZ exoplanets (e.g. η_{\oplus})
 - Yield estimates for exoplanet direct imaging missions
 - Improve target lists and stellar parameters for exoplanet missions
 - Mitigate stellar jitter as a limitation to exoplanet dynamical measurements
 - Dynamical confirmation of exoplanet candidates, determination of their masses & orbits
 - Precursor surveys of direct imaging targets

EPRV-related

ExEP Science Plan Gap List & Appendix:

<https://exoplanets.nasa.gov/exep/science-overview/>



NN-EXPLORE

Partnership for Exoplanet Discovery and Characterization



- Motivation

- 2010 Decadal Survey called for precise ground-based spectrometer for exoplanet discovery and characterization
- Follow-up & precursor science for current missions (K2, TESS, JWST, WFIRST)
- Inform design/operation of future missions

- Scope:

- Extreme precision radial velocity spectrometer (<0.5 m/s) with 40% of time on WIYN telescope
 - Penn State NEID proposal selected in March 2016
 - Instrument to be commissioned late 2019
 - $R = 100,000$; 380-930 nm wavelength coverage
- Guest Observer program using NOAO share (40%) of telescope time for exoplanet research



NN-Explore Exoplanet Investigations with Doppler Spectroscopy



PennState

PI: S. Mahadevan

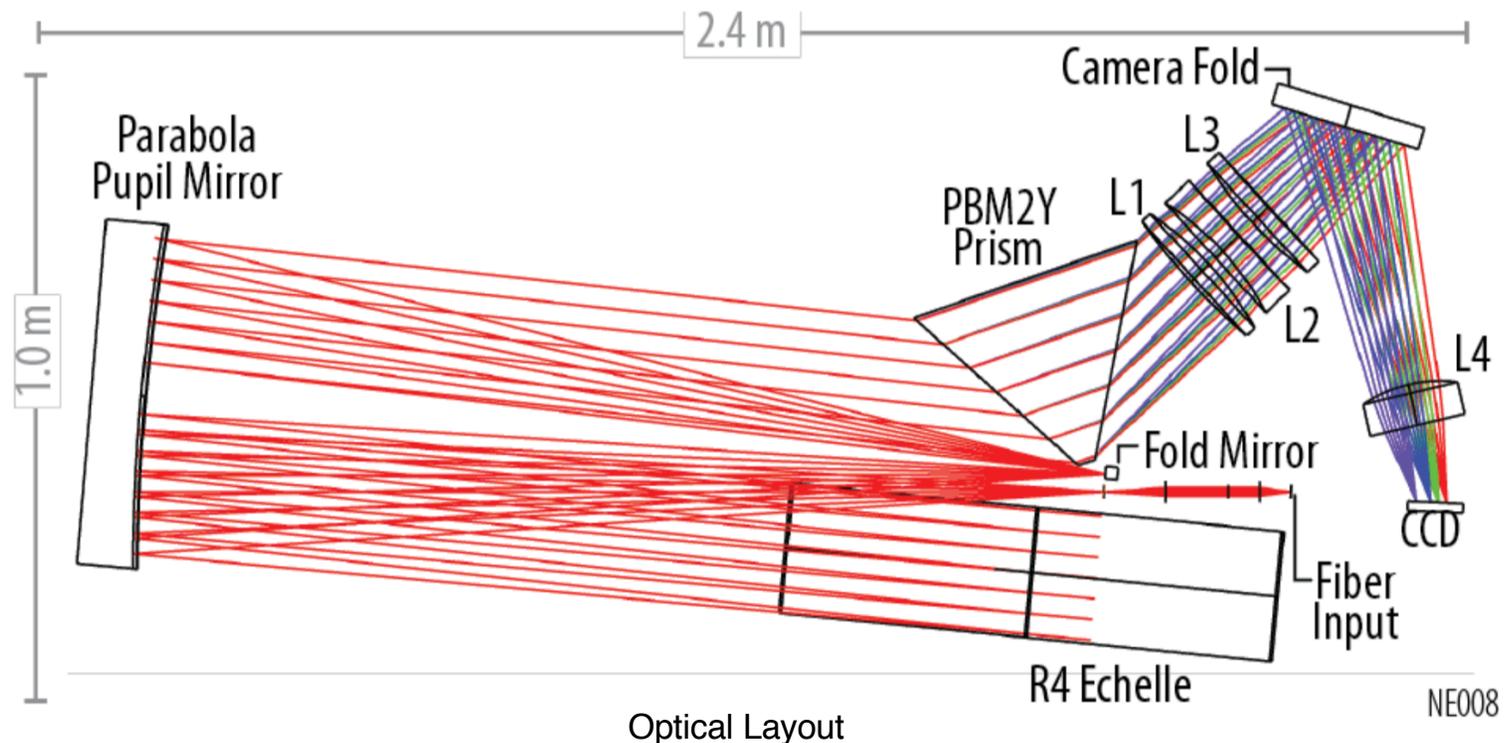


3.5m WIYN Telescope
Kitt Peak National Observatory
Arizona

NEID Spectrograph

NEID - NN-EXPLORE Exoplanet Ivestigations with Doppler Spectroscopy (O'bdham for "to discover/visualize")

- Precision radial velocity of **~27 cm/s**
- **380 nm - 930 nm** bandwidth (RV coverage for F-M stars and stellar activity indicators)
- $R = 100,000$ spectral resolution of bright ($V < 12$) stars
- e2v 9k x 9k CCD with $10 \mu\text{m}$ pixels
- **Environmental chamber with $P < 10^{-7}$ torr and $\Delta T < \pm 1$ mKelvin**
- **Laser Frequency Comb calibration**





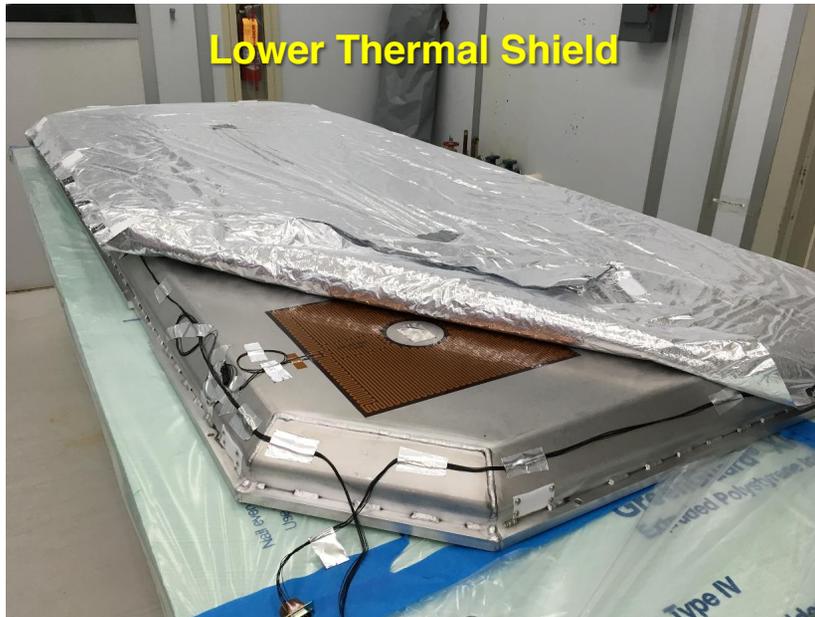
NEID Chamber/ECS



MLI Blanket Fit-Up



Lower Hood and LN2 Tank Assembly



Lower Thermal Shield



NEID Chamber

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Off-Axis Paraboloid Mirror



*NEID M1 Parabolic mirror
Rayleigh Optical Corporation*



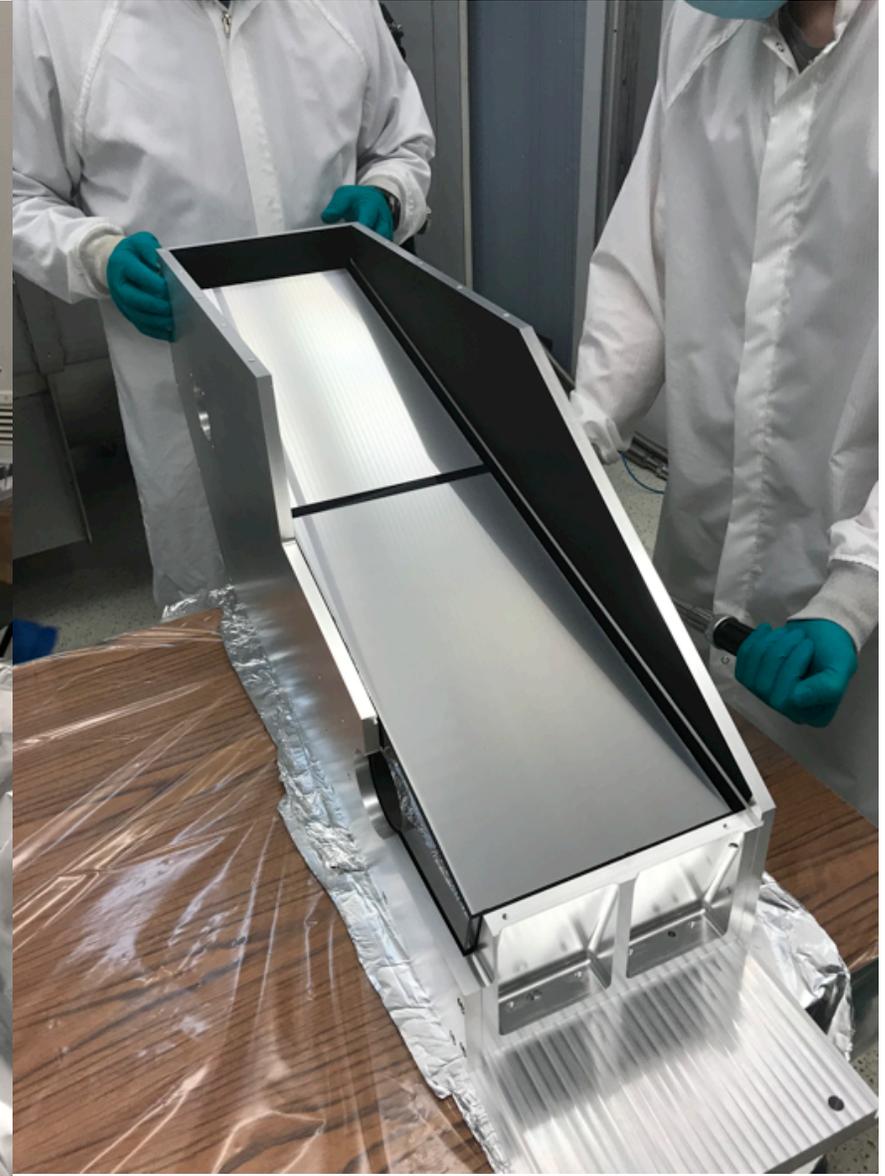
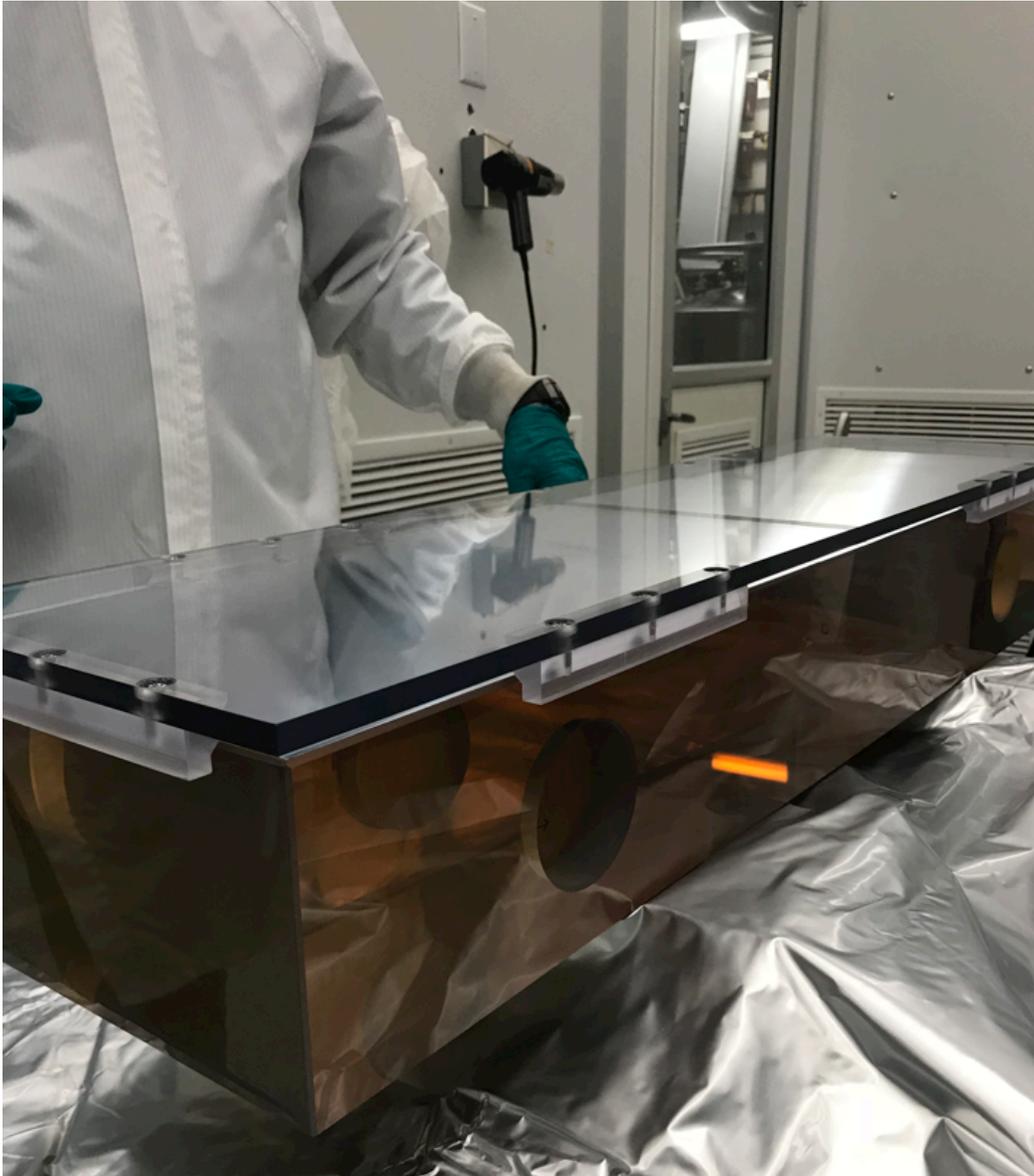
Off-Axis Paraboloid Mirror



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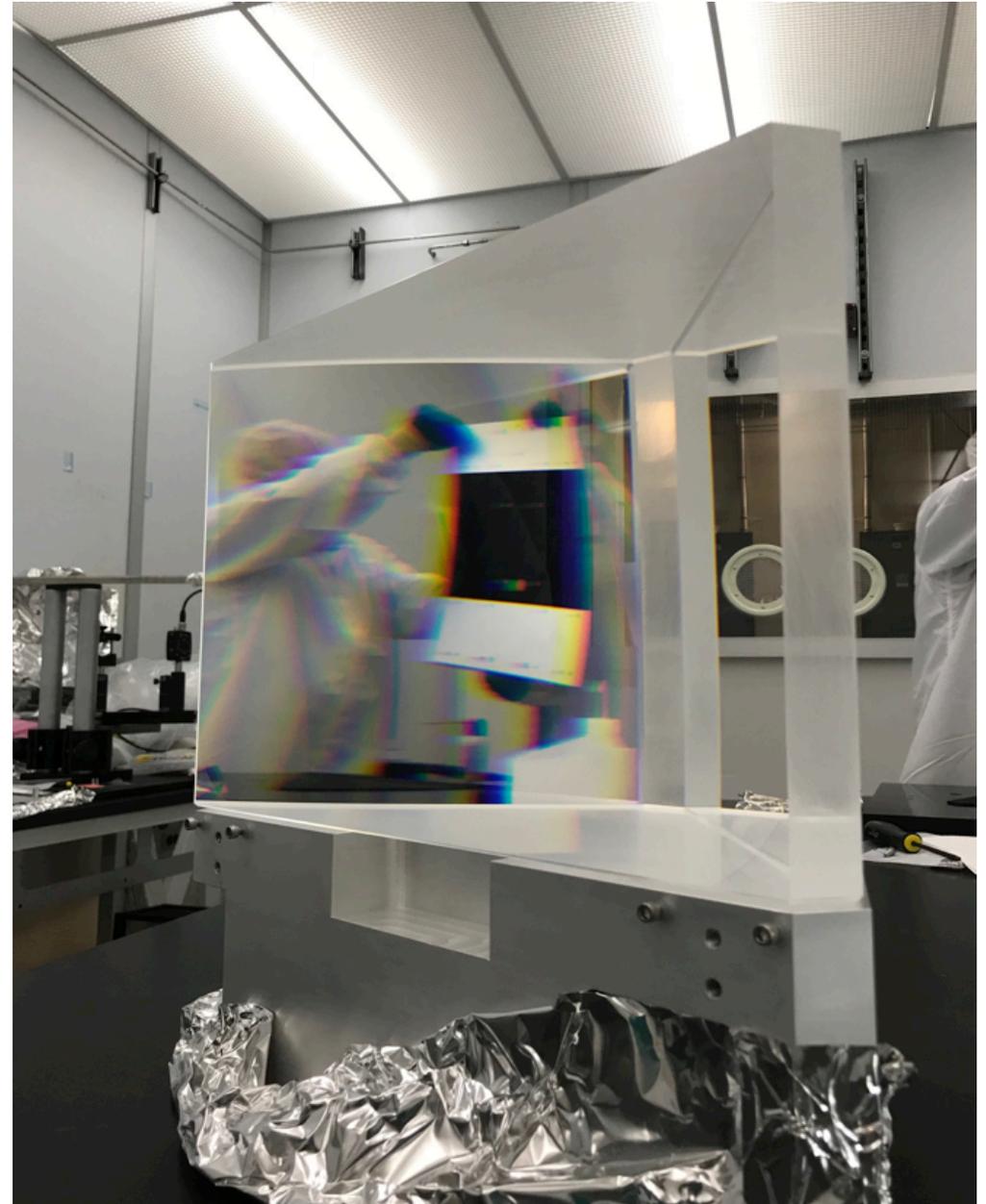
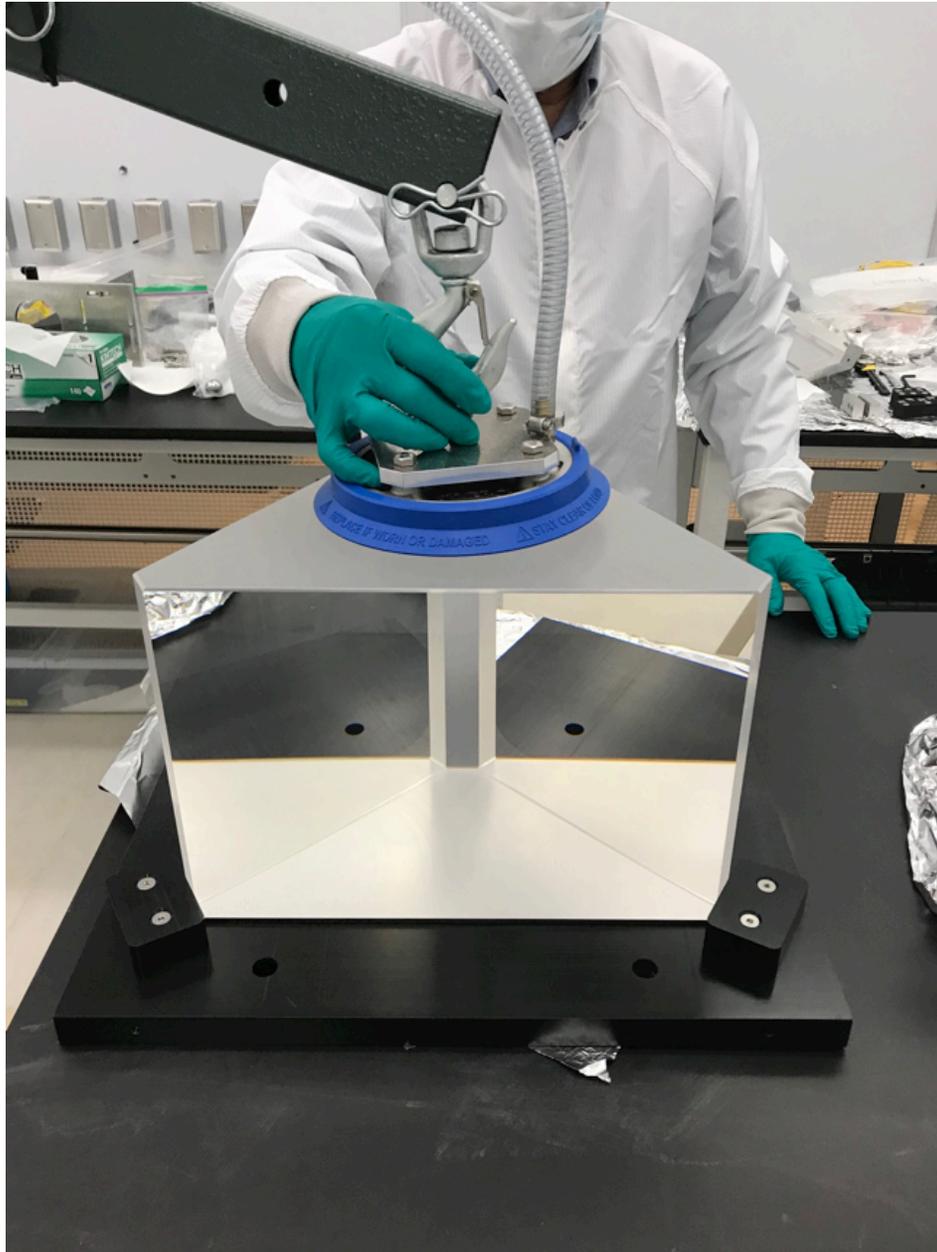


R4 Echelle Grating



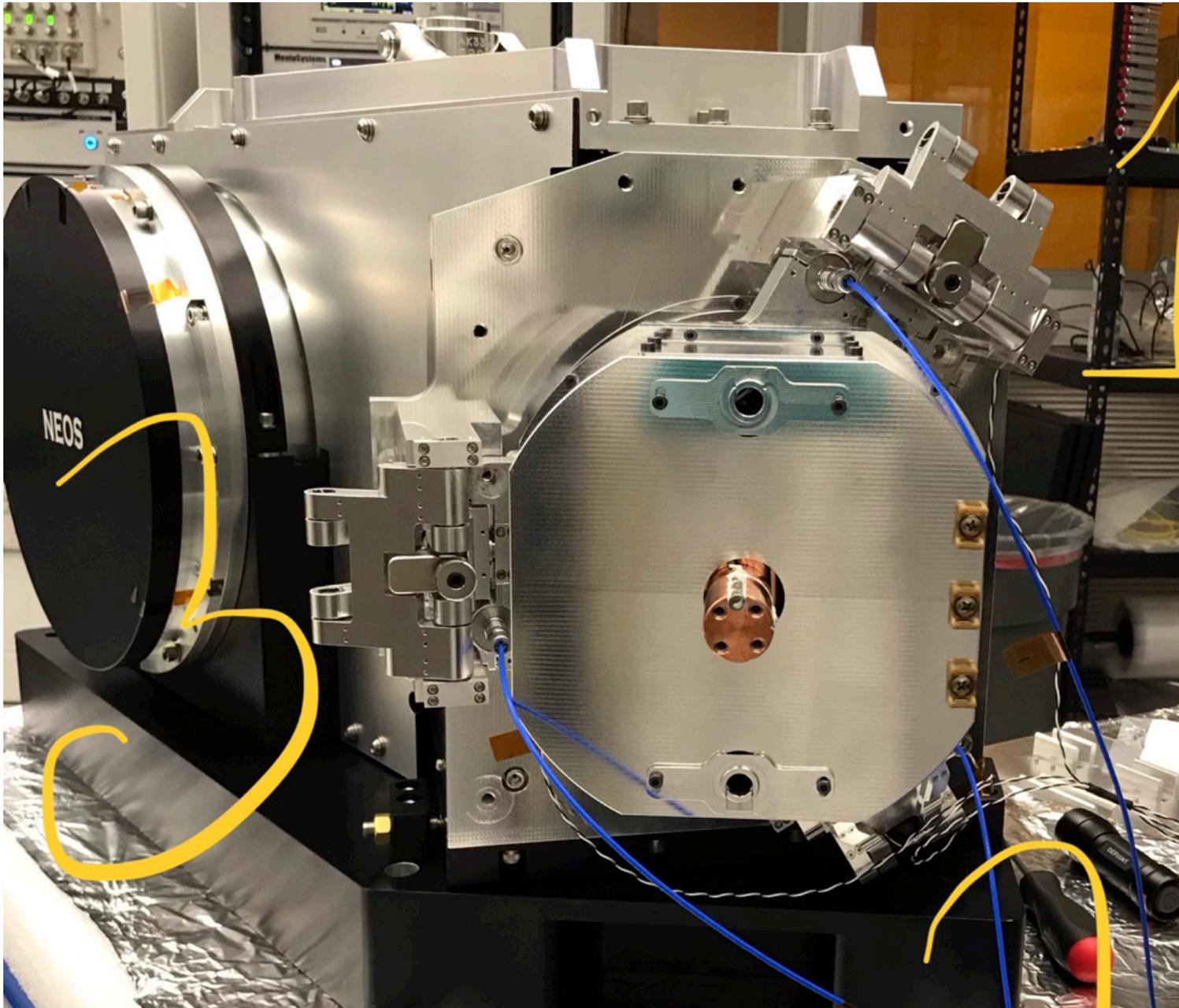


Cross-Dispersion Prism





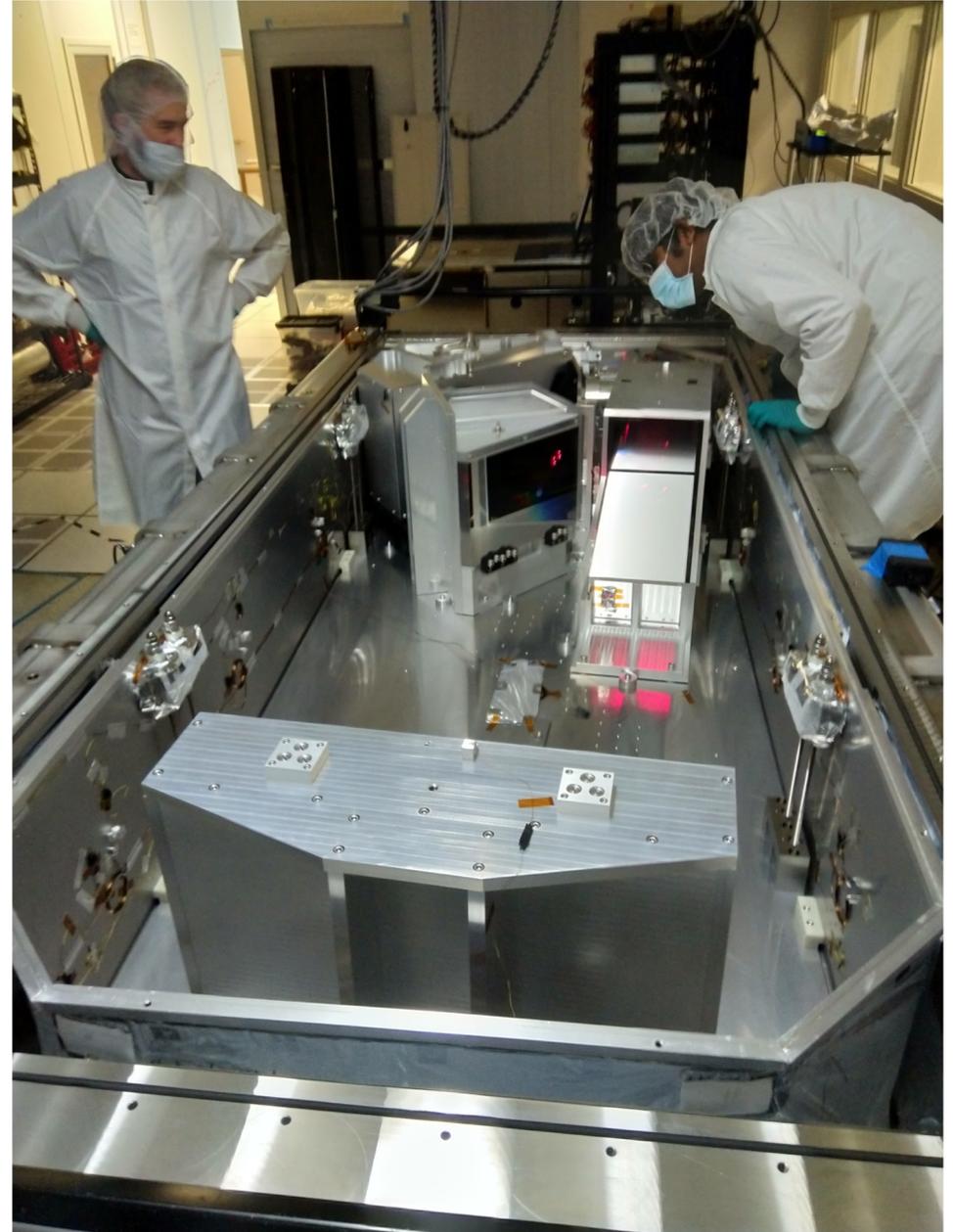
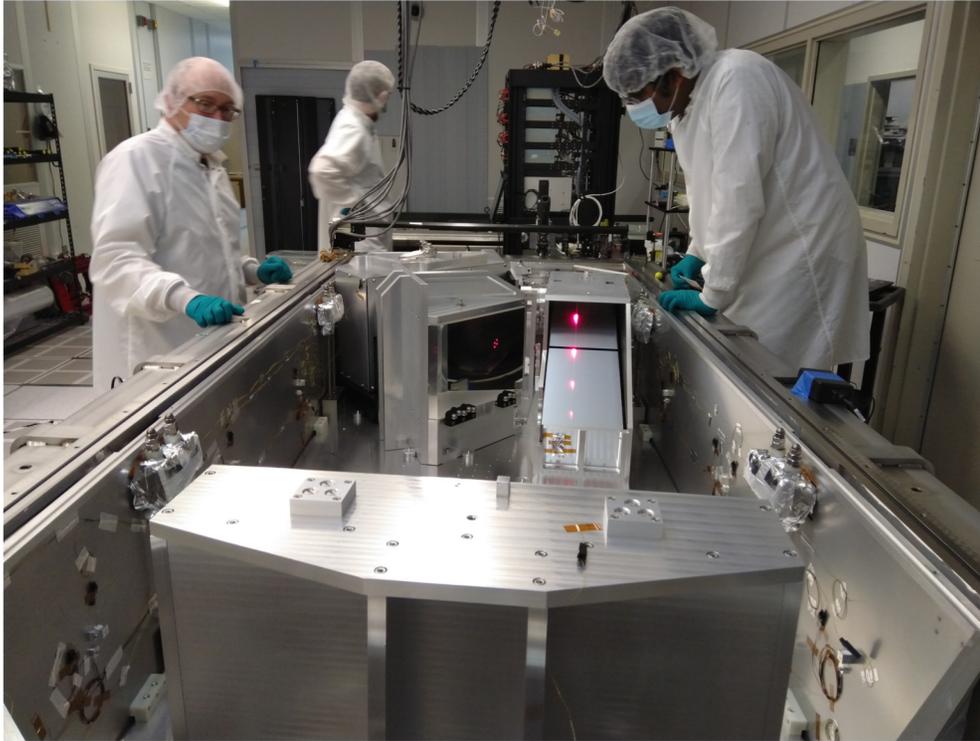
NEOS Camera



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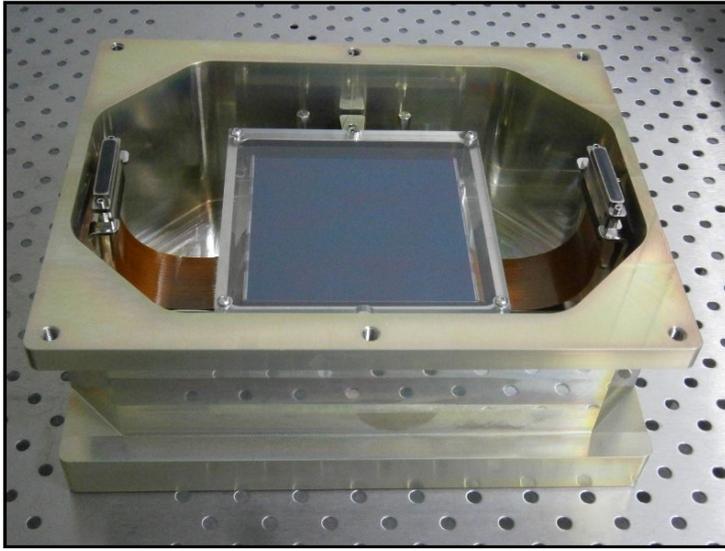
Spectrograph Alignment



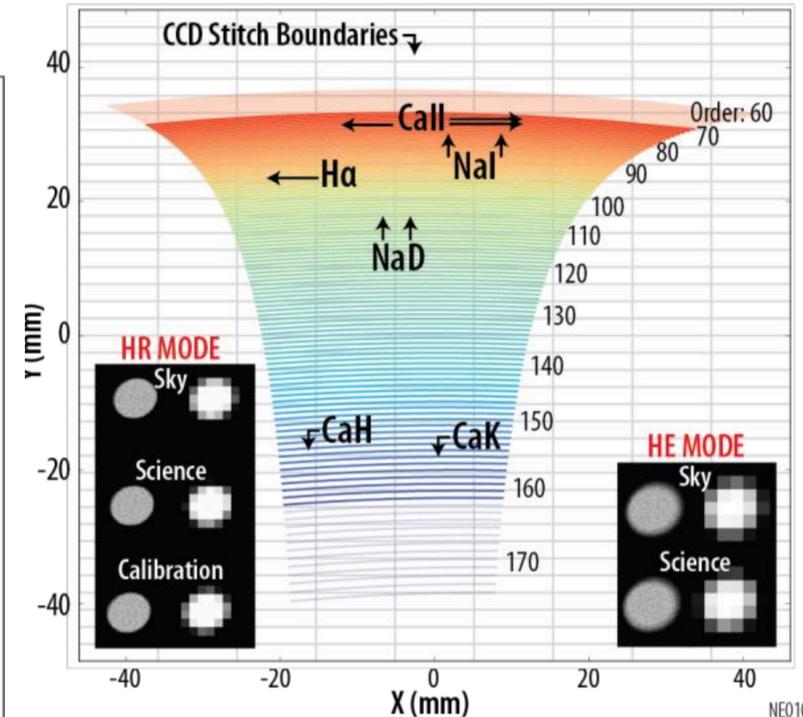
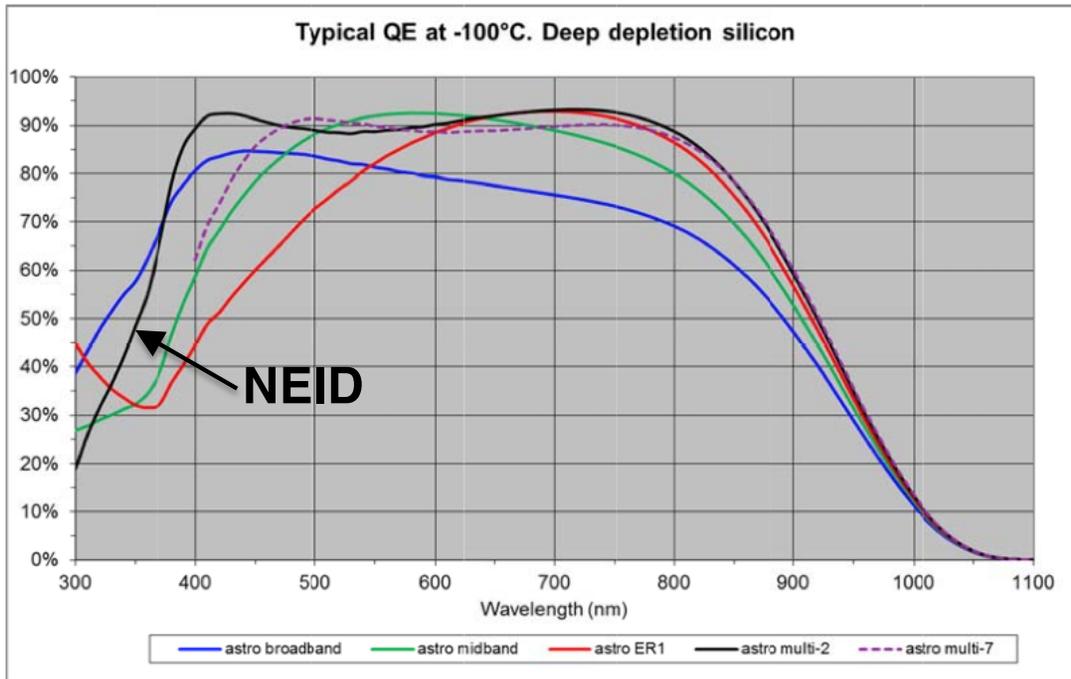
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e2v CCD



- 9k x 9k pixels with 10 μm pitch
- 40 μm thick substrate:
Excellent red response
Very low fringing at $> 800 \text{ nm}$
- 16 readout channels
- Very fast readout possible (< 5 seconds)
- Excellent CTE: 99.9995 or better

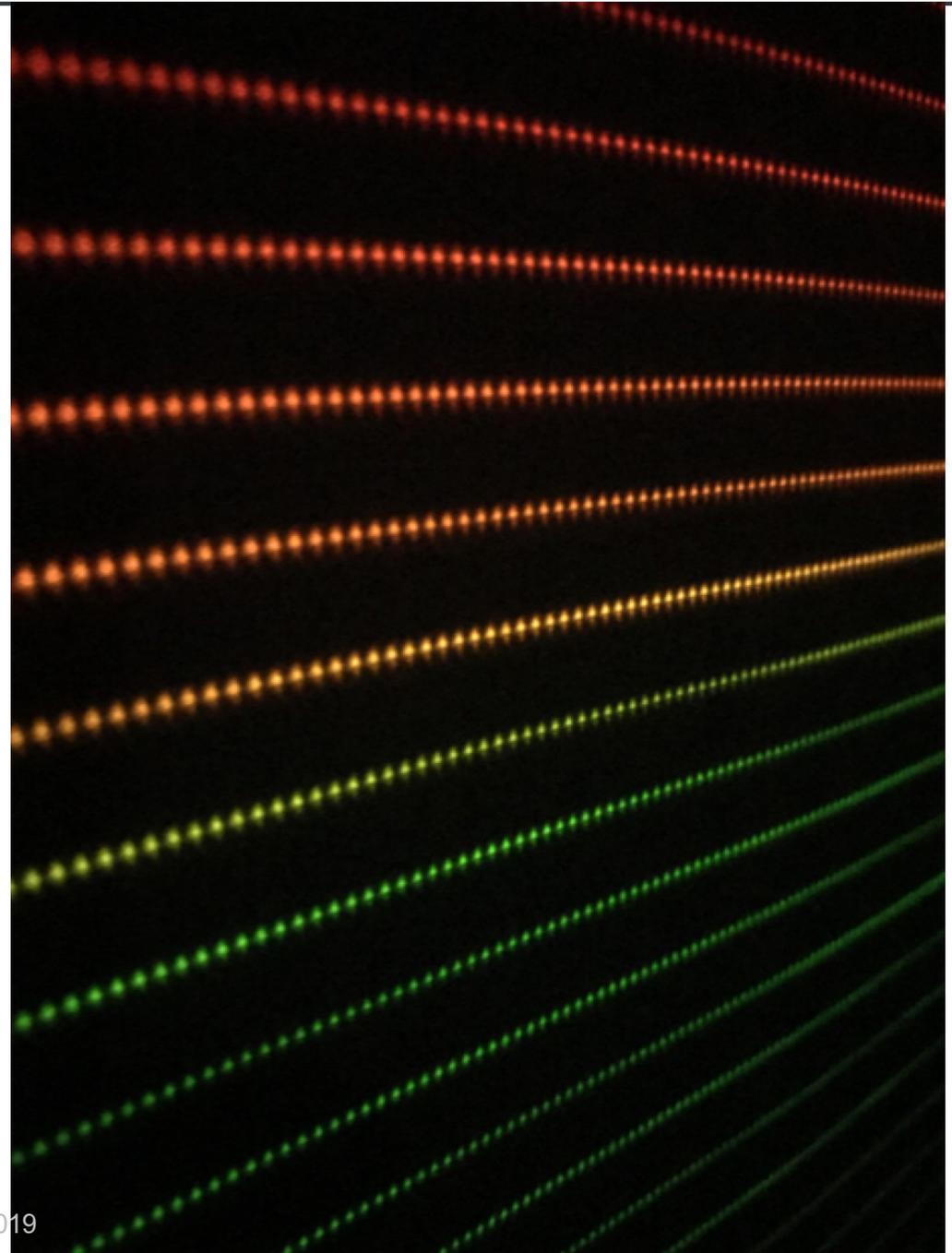




Menlo Systems Astro Laser Frequency Comb (LFC)

- 20-GHz line spacing
- 420-900 nm bandwidth requirement, 400-930 nm best effort
- Individual line centers known to < 3 cm/s
- Absolute accuracy better than 1 part in 10^{10}

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NASA support of precision radial velocity work

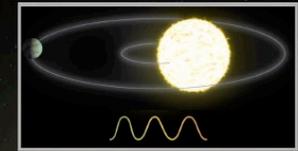
- Development of NN-Explore instrument **NEID** (collaboration w/NSF). This will lead to community access to state-of-the-art PRV spectrograph on northern 4-m class telescope, and pipeline/data archiving at NExScI
- Community access to Keck **HIRES** (managed through Keck Cooperative Agreement for NASA time), and recently additional time purchased on SMARTS 1.5-m (**CHIRON**) and AAT (**VELOCE**) to help w/TESS followup
- **KPF** on Keck will be available 2020. Support by NExScI.
- IRTF/**iSHELL** observations (NASA telescope, managed by Planetary Sciences Division; astrophysics limited to 50%)
- EarthFinder probe study – develop case for precision RV from space
- R&A Programs (e.g. XRP)
- Other examples:
 - Seed funding for CHIRON (CTIO 1.5-m, PI Fischer), iLocator (LBT, PI Crepp), MINERVA-Red (PI: Blake)
 - Technology grant to develop laser frequency comb (MIT, testing HARPS-N)



EarthFinder Probe Mission Concept Study

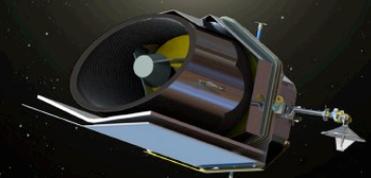
- Study brightest 50 targets for imaging missions
- 1.45 m telescope in Earth-trailing/L2 orbit
 - Visible Spectrometer: 0.4-0.96 μm at $R=170,000$ ($0.6/\lambda$)
 - Near-IR Spectrometers: 0.96-2.4 μm at $R=170,000$ ($1.6/\lambda$)
 - Small UV Spectrometer for Mg II chromospheric activity: 0.28-0.38 μm
- No Telluric atmospheric effects
- Extreme Resolution and λ coverage to reduce jitter
 - $R > 150,000$ & continuum normalization for line analysis
 - Vis-NIR color to isolate jitter from Doppler signals
- L2 Orbit for Instrument Stability
 - Line Spread Function from single mode fibers
 - mK thermal control for < 10 cm/s measurement accur.
 - Micro-resonator LFC for 1 cm/s long term stability
- High cadence (70% of sky $> 180\text{d}$; 30% CV) reduces aliasing

EarthFinder Probe Mission Concept Study



Characterizing nearby stellar exoplanet systems with Earth-mass analogs for future direct imaging

March 2019



NASA Aeronautics and Space Administration

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Pasadena, California



PI: Peter Plavchan
& team of 55 coauthors

credit: Peter Plavchan

from NASA ExEP Technology Plan (2019)



Exoplanet Exploration Program

2019 Technology Plan Appendix

ID	Technology	Technology Gap	Technology Description	Current Performance	Needed Performance
M-2	Laser Frequency Combs	Radial Stellar Motion	Laser Frequency Combs (LFCs) are precise calibration sources for extreme-precision radial velocity measurement.	<p><u>Lab:</u> Electro-optic-modulation frequency combs demonstrated on ground-based observatories with needed mode spacing, need miniaturization and power reduction.</p> <p>Non-NASA work is advancing miniaturization.</p> <p><u>Flight:</u> Fiber laser-based optical frequency combs demonstrated on sounding rocket (TEXUS 51 4/15 and TEXUS 53 1/16) w/ ~ few hundred MHz mode spacing. System mass is > 10 kg.</p>	<p>Space-based Laser Frequency Combs to calibrate high resolution, fiber-fed spectrographs for radial velocity precision better than 10 cm/s. Desired parameters are:</p> <ul style="list-style-type: none"> • mode spacing of 5-10 GHz • bandwidth span 380 nm to 2400 nm • Allen deviation < 10⁻¹⁰ • Low SWaP
M-1	Extreme Precision Ground-based Radial Velocity	Radial Stellar Motion	Ground-based radial velocity instrumentation capable of measuring the mass of candidate exo-Earths in the habitable zone and to maximize efficiency of space telescope surveys.	Stability of 28 cm/s over 7 hours (VLT/ESPRESSO).	Signal from exo-Earths is 10 cm/s; Need to reduce systematic errors to 1 cm/s on multi-year timescales; statistical uncertainties of 1 cm/s on monthly timescales for late F, G, and early K stars

ExEP Technology Plan: <https://exoplanets.nasa.gov/exep/technology/technology-overview/>
 NASA Research Opportunities in Space & Earth Sciences (ROSES)
 Strategic Astrophysics Technology (SAT) Program – see languages in proposal calls

Exoplanet Science Strategy



Improving the Precision of Radial Velocity Measurements Will Support Exoplanet Missions

FINDING: The radial velocity method will continue to provide essential mass, orbit, and census information to support both transiting and directly imaged exoplanet science for the foreseeable future.

FINDING: Radial velocity measurements are currently limited by variations in the stellar photosphere, instrumental stability and calibration, and spectral contamination from telluric lines. Progress will require new instruments installed on large telescopes, substantial allocations of observing time, advanced statistical methods for data analysis informed by theoretical modeling, and collaboration between observers, instrument builders, stellar astrophysicists, heliophysicists, and statisticians.

RECOMMENDATION: NASA and NSF should establish a strategic initiative in extremely precise radial velocities (EPRVs) to develop methods and facilities for measuring the masses of temperate terrestrial planets orbiting Sun-like stars.



Credit: <http://www.swisswintersports.co.uk>



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From P. Hertz' CAA Presentation, March 2019

Exoplanet Science Strategy Extreme Precision Radial Velocity Initiative

Exoplanet Science Strategy Recommendation:

“NASA and NSF should establish a strategic initiative in extremely precise radial velocities (EPRVs) to develop methods and facilities for measuring the masses of temperate terrestrial planets orbiting Sun-like stars”

- Combine efforts in instrumentation, survey execution, and data analysis techniques involving stellar astrophysics and heliophysics
- Undertake the coordinated, sustained effort to tackle the myriad of error terms that currently limit RV precision.
- Assess ultimate goal to control systematics at ~ 1 cm/s, accounting for stellar variability and tellurics

Response: NASA and NSF are jointly commissioning a community-based “Extreme Precision Radial Velocity (EPRV) Working Group” (EPRV-WG) to develop a blueprint for a strategic EPRV initiative.

- Working Group forming now, first in-person workshop \sim June 2019
- EPRV-WG to submit a candidate program architecture by Feb 2020 for consideration by Agencies during annual budget formulation process



Extreme Precision Radial Velocity WG: Deliverables

- Deliver to the NASA Astrophysics Division (APD) and the NSF Division of Astronomical Sciences (AST) a report, as a first step, that includes a **recommendation for the best program architecture and implementation** to achieve the goal of measuring the masses of temperate terrestrial planets orbiting Sun-like stars.
- The **recommendation will define a roadmap** that NASA/APD and NSF/AST can carry out jointly or separately.
- Deliver by March 2020.
- The report will include scope, schedule, and planning-level funding requirements.
- NASA/APD and NSF/AST will discuss the report's findings within the context of the existing NASA-NSF Exoplanet Observational Research (NN-EXPLORE) partnership agreement.
- NASA and NSF will consider the recommendations for implementation through their own processes.



Extreme Precision Radial Velocity WG: Participation

Steering Group

Scott	Gaudi	Co-chair	The Ohio State University
Gary	Blackwood	Co-chair	NASA ExEP / Jet Propulsion Laboratory
Andrew	Howard		Caltech
David	Latham		Harvard-Smithsonian Center for Astrophysics
Debra	Fischer		Yale University
Eric	Ford		Pennsylvania State University
Heather	Cegla		University of Geneva
Peter	Plavchan		George Mason University
Andreas	Quirrenbach		Landessternwarte; University of Heidelberg
Jennifer	Burt		Massachusetts Institute of Technology
Eric	Mamajek	Ex officio	NASA ExEP / Jet Propulsion Laboratory
Chas	Beichman	Ex officio	NASA Exoplanet Science Institute / Caltech

Members

Chad	Bender	U. Arizona
Jonathan	Crass	Notre Dame U.
Scott	Diddams	NIST
Xavier	Dumusque	Université de Genève
Jason	Eastman	Harvard CfA
BJ	Fulton	NASA Exoplanet Science Institute / Caltech
Sam	Halverson	MIT
Raphaelle	Haywood	Harvard CfA
Fred	Hearty	Pennsylvania State University
Stephanie	Leifer	NASA/JPL
Johannes	Loehner-Boettcher	UCAR
Annelies	Mortier	Kavli Institute for Cosmology
Ansgar	Reiners	University of Göttingen
Paul	Robertson	UC Irvine
Arpita	Roy	Caltech
Christian	Schwab	Macquarie University
Andreas	Seifahrt	University of Chicago
Andrew	Szentgyorgyi	Harvard-Smithsonian CfA
Ryan	Terrien	Carleton
Johanna	Teske	Carnegie Observatories/DTM
Samantha	Thompson	University of Cambridge
Gautam	Vasisht	NASA/JPL

Participants

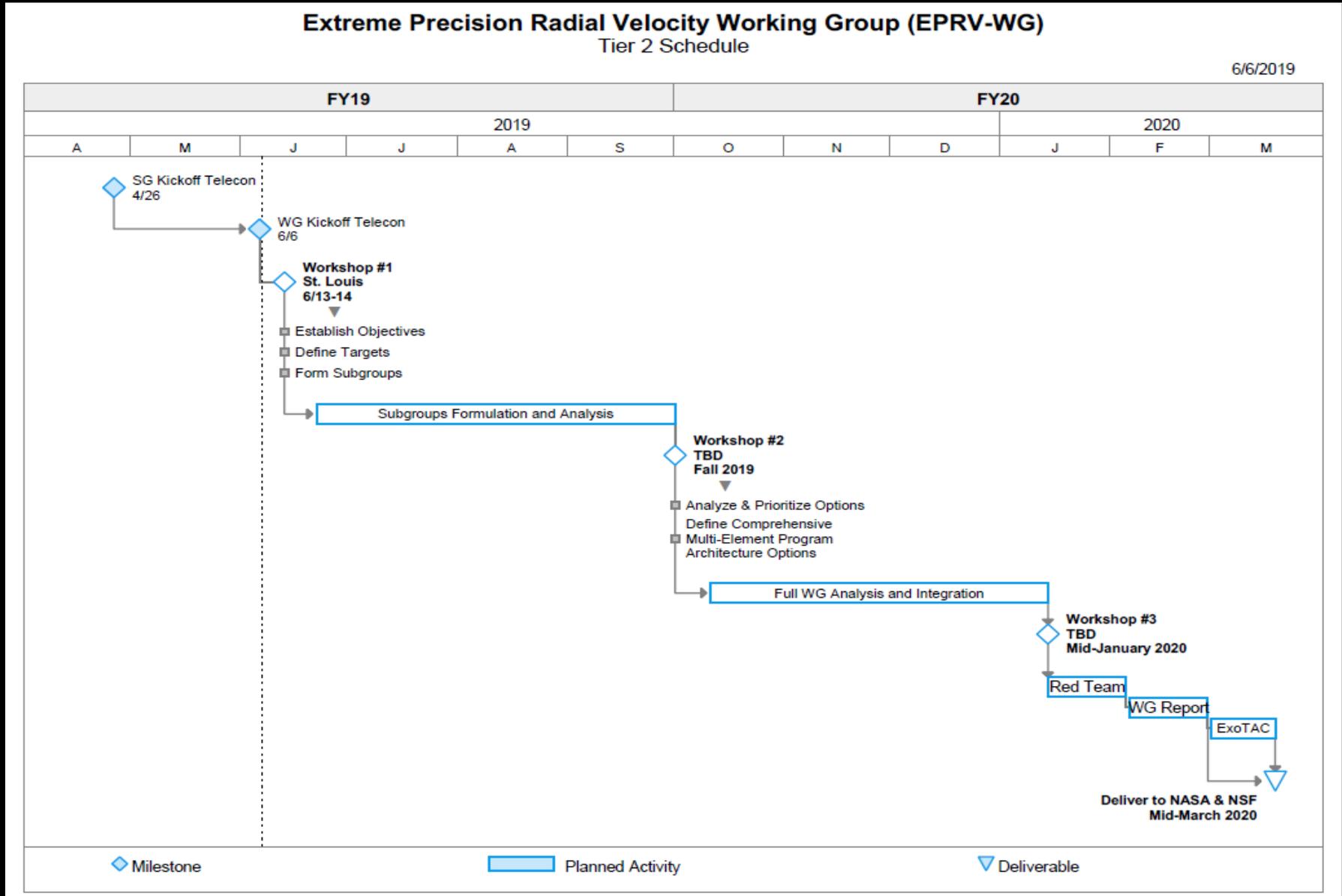
Rebecca	Bernstein		Carnegie Observatories
John	Callas	Ex officio	NASA ExEP / Jet Propulsion Laboratory
David	Ciardi	Ex officio	NASA Exoplanet Science Institute / Caltech
Andrew	Collier-Cameron		Saint Andrews
John	O'Meara		W. M. Keck Observatory
Jessi	Cisewski-Kehe		Yale University

ExoTAC (Exoplanet Technical Assessment Committee)

Alan	Boss	Chair	Carnegie Institution for Science
Rebecca	Oppenheimer		American Museum of Natural History
Joe	Pitman		Heliospace Corporation
Lisa	Poyneer		Lawrence Livermore Laboratory
Stephen	Ridgeway		National Optical Astronomy Observatory



Extreme Precision Radial Velocity WG: Schedule





Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov