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

Eric Mamajek

Deputy Program Chief Scientist

NASA Exoplanet Exploration Program

Jet Propulsion Laboratory/California Institute of Technology

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Artist concept of K2-138 system
Credit: NASA/JPL-Caltech

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. $\eta_{\oplus}$)
- 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/

Precision Radial Velocities

Radial velocity amplitude *K*

planet mass · orbital inclination · orbital period · star's mass

$$K = \frac{28.4\ \mathrm{m/s}}{\sqrt{1-e^2}} \left(\frac{M_P \sin i}{M_J}\right) \left(\frac{P}{1\ \mathrm{yr}}\right)^{-1/3} \left(\frac{M_\star}{M_\odot}\right)^{-2/3}$$

orbital eccentricity · Jupiter mass · solar mass

Example	Velocity Amplitude *K*
Jupiter @ 5 AU around Sun	12 m/s
Earth @ 1 AU around Sun	0.09 m/s = *9 cm/s !*
TRAPPIST-1 b (~1 M_{Earth}, 0.08 M_{Sun})	3 m/s (detected by transit, not RV)
Proxima b (~1.3 M_{Earth}, 0.12 M_{Sun})	1.4 m/s

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
  - Apply through NOAO proposal calls

NEID

NN-Explore Exoplanet Investigations with Doppler Spectroscopy

PennState

PI: S. Mahadevan

3.5m WIYN Telescope
Kitt Peak National Observatory
Arizona

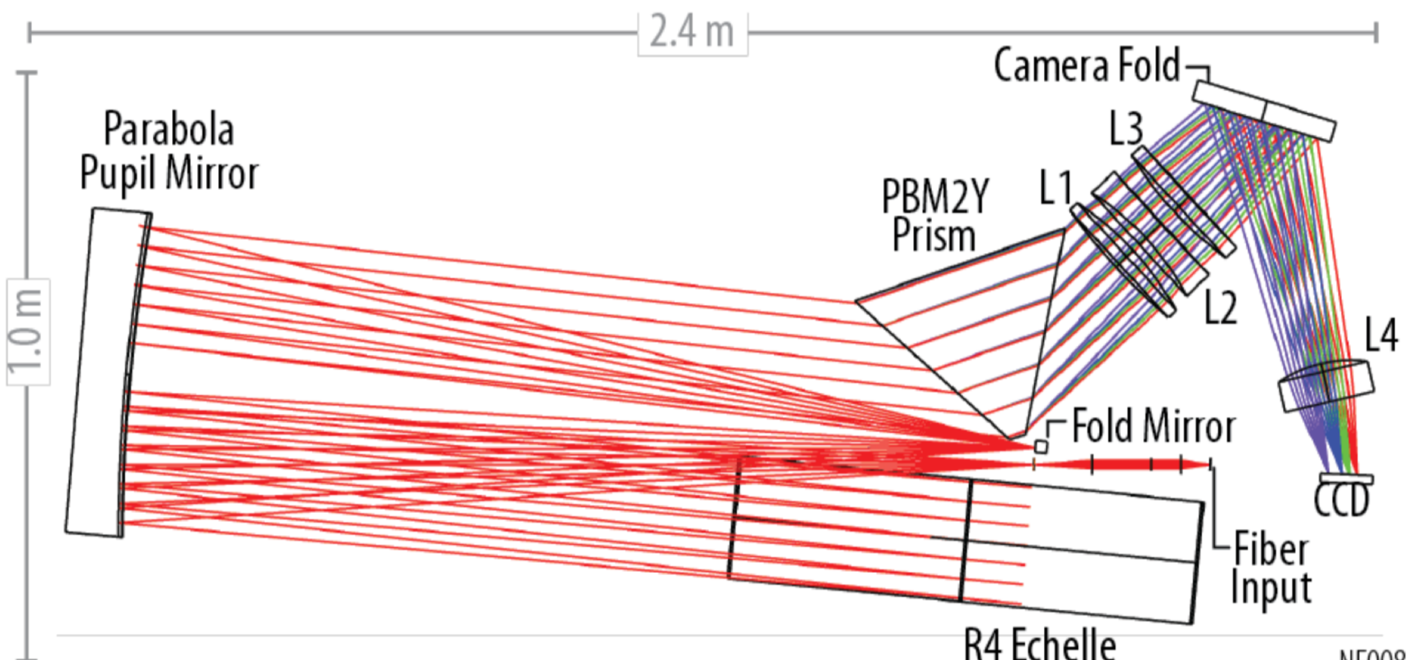
https://exoplanets.nasa.gov/exep/NNExplore/

NEID Spectrograph

NEID - NN-EXPLORE Exoplanet Investigations with Doppler Spectroscopy

(O'odham for "to discover/visualize")

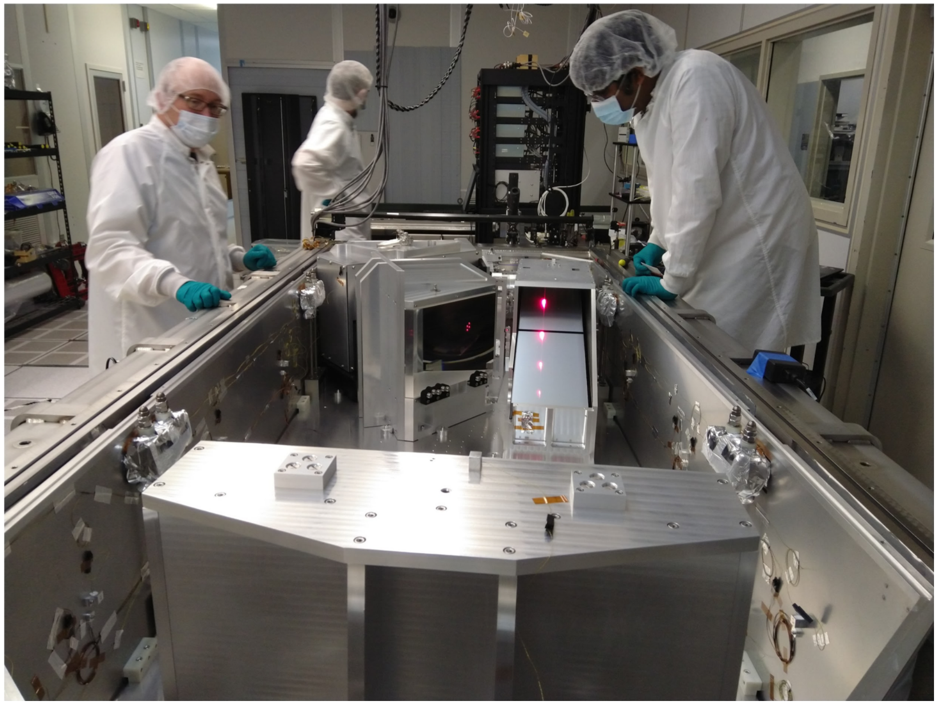
- Precision radial velocity of **~27 cm/s**
- **380 nm - 930 nm** bandwidth (RV coverage for F-M stars and stellar activity indicators)
- R = 100,000 spectral resolution of bright (V<12) stars
- e2v 9k x 9k CCD with 10 μm pixels
- **Environmental chamber with P < 10^{-7} torr and ΔT < ±1 mKelvin**
- **Laser Frequency Comb calibration**
- More details at NEID site: https://neid.psu.edu/

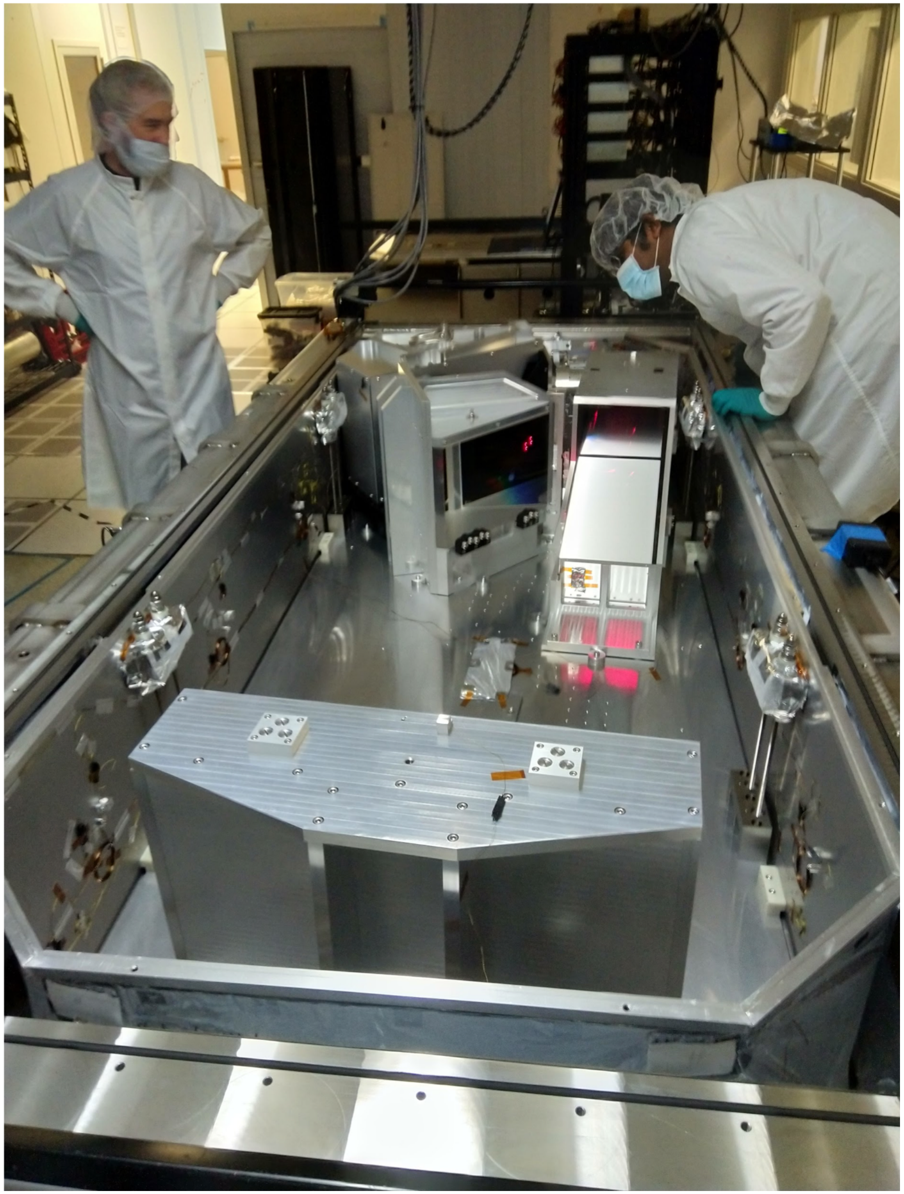


Optical Layout

Schwab et al. 2016, Proc. SPIE 9908, 99087H

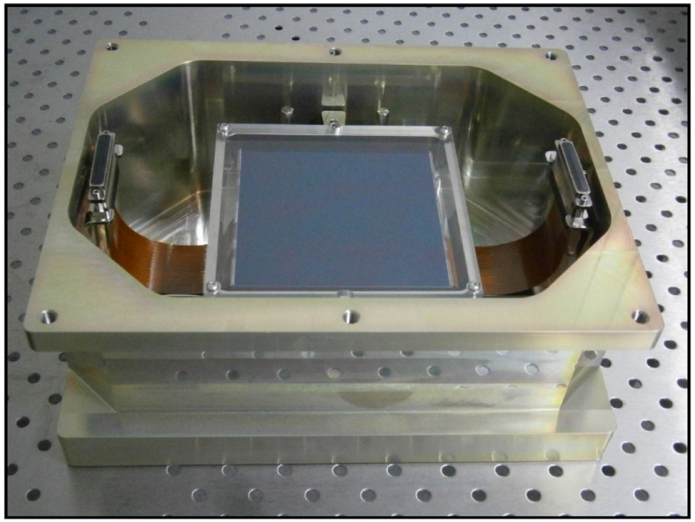
Spectrograph Alignment



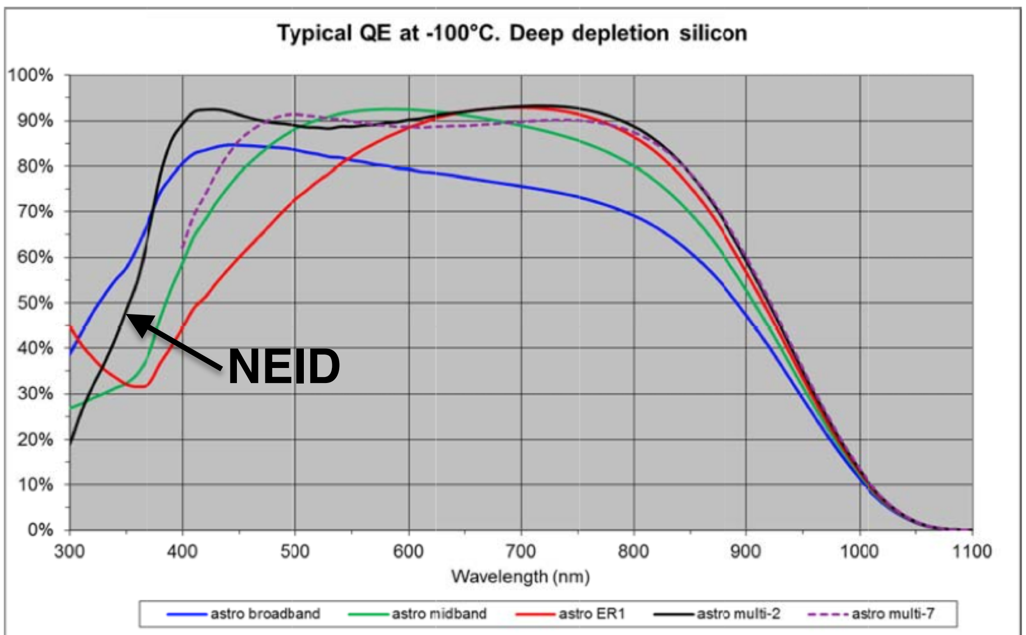


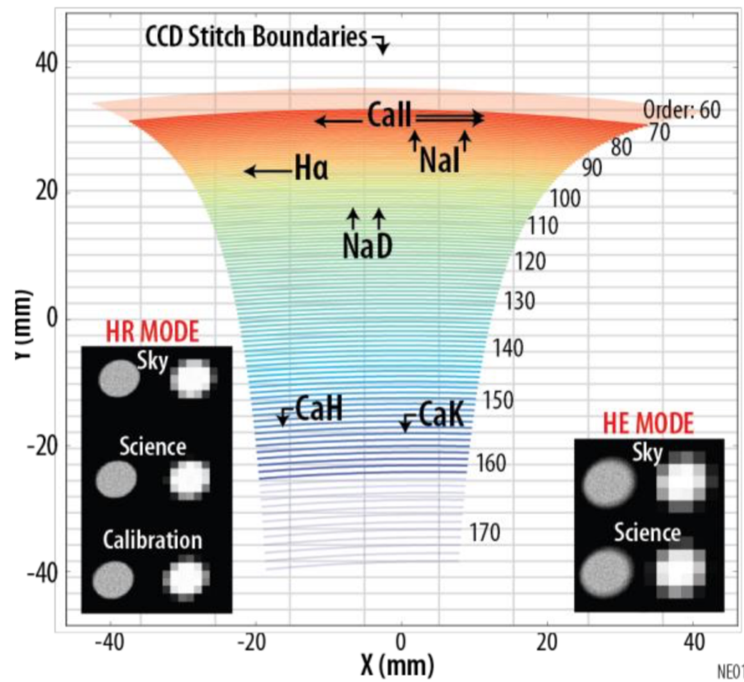
neid.psu.edu

e2v CCD



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





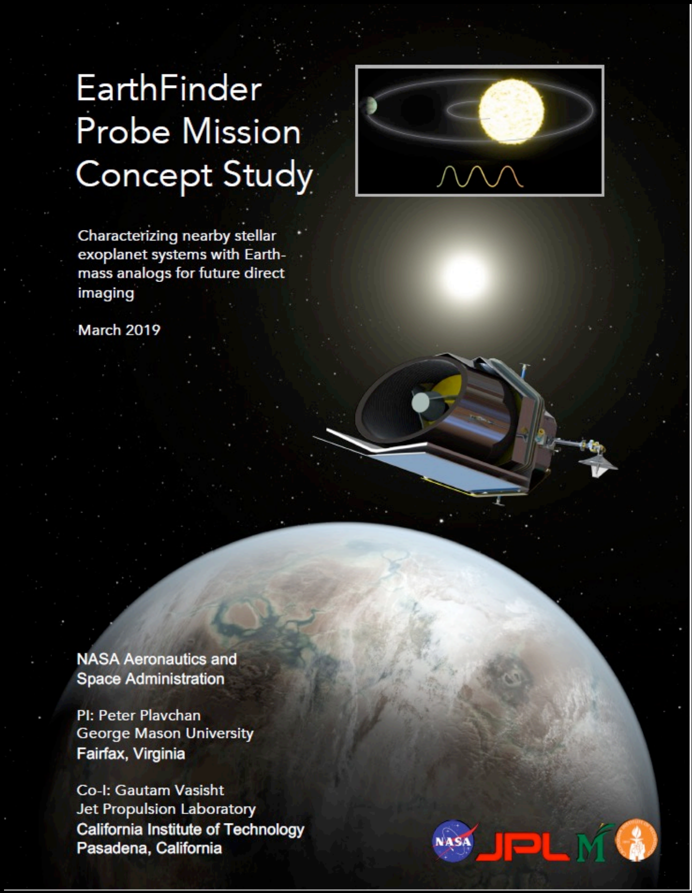
neid.psu.edu

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
- Recently additional time purchased on SMARTS 1.5-m (CHIRON) and AAT (VELOCE) to help w/TESS followup (through NOAO proposal calls)
- Community access to Keck HIRES (managed through Keck Cooperative Agreement for NASA time)
- KPF on Keck will be available for science mid-2021. 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=170k (0.6/λ)
  - Near-IR Spectrometers: 0.96-2.4 μm at R=170k (1.6/λ)
  - 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 >180d; 30% CV) reduces aliasing
- Merits of dedicated space mission vs. greater ground investment needs a lot more discussion



PI: Peter Plavchan
& team of 55 coauthors

2020 Decadal Survey Concept Study reports (including EarthFinder): https://science.nasa.gov/astrophysics/2020-decadal-survey-planning

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.	Lab: Electro-optic-modulation frequency combs demonstrated on ground-based observatories with needed mode spacing, need miniaturization and power reduction. Non-NASA work is advancing miniaturization. Flight: 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.	Space-based Laser Frequency Combs to calibrate high resolution, fiber-fed spectrographs for radial velocity precision better than 10 cm/s. Desired parameters are: • 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.

NAS Exoplanet Science Strategy (2018)

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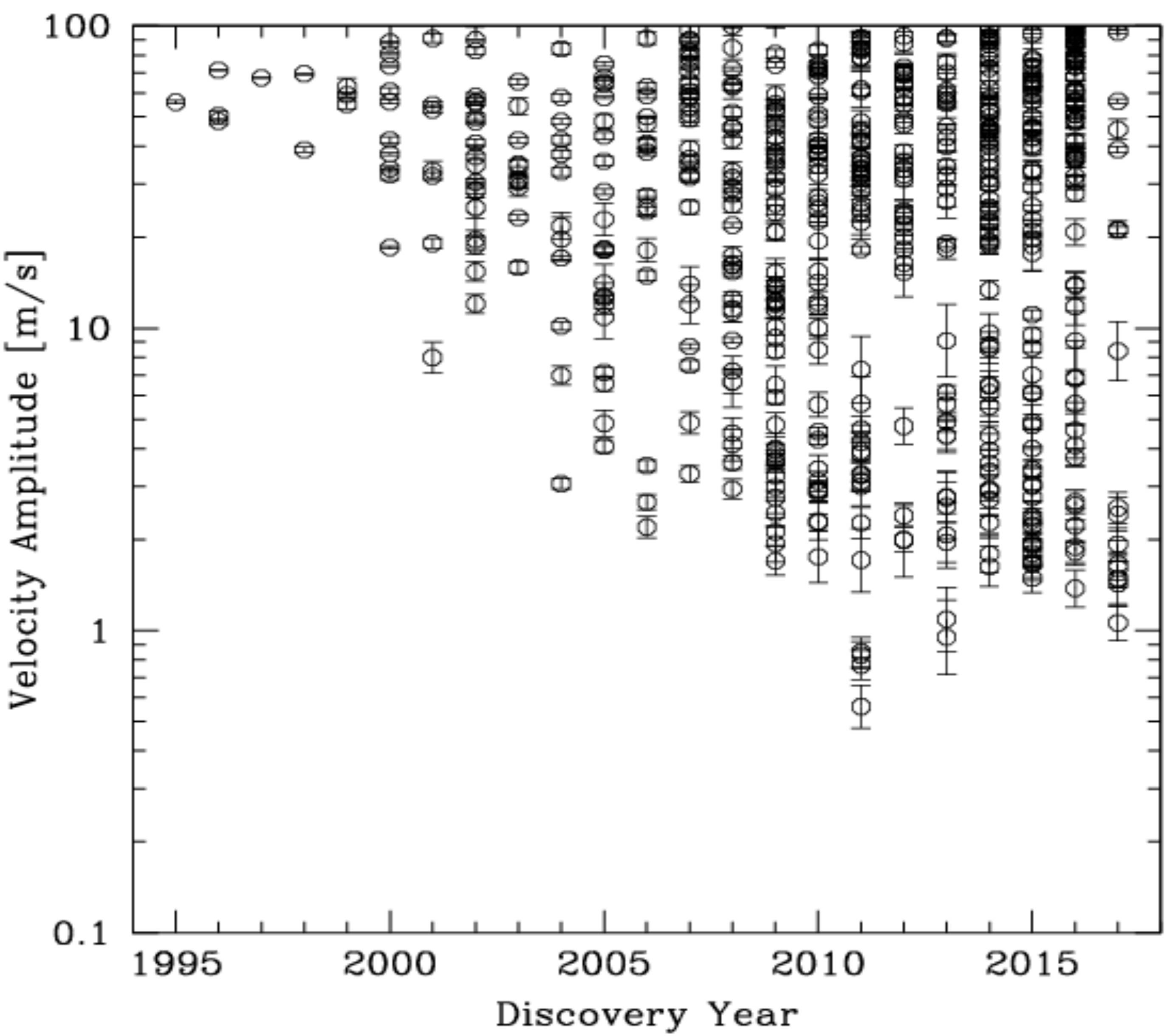
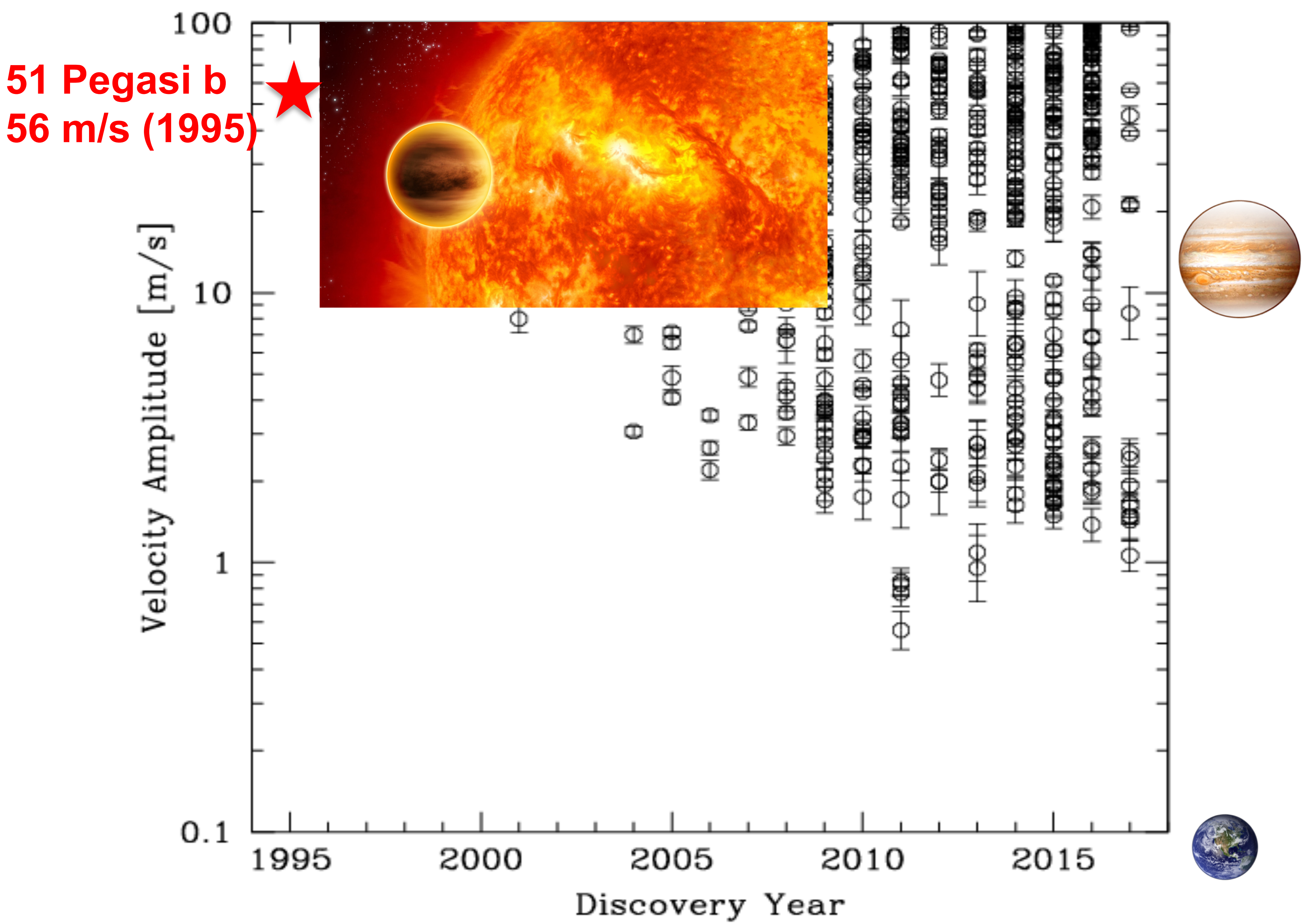
California Institute of Technology

Precision Radial Velocities

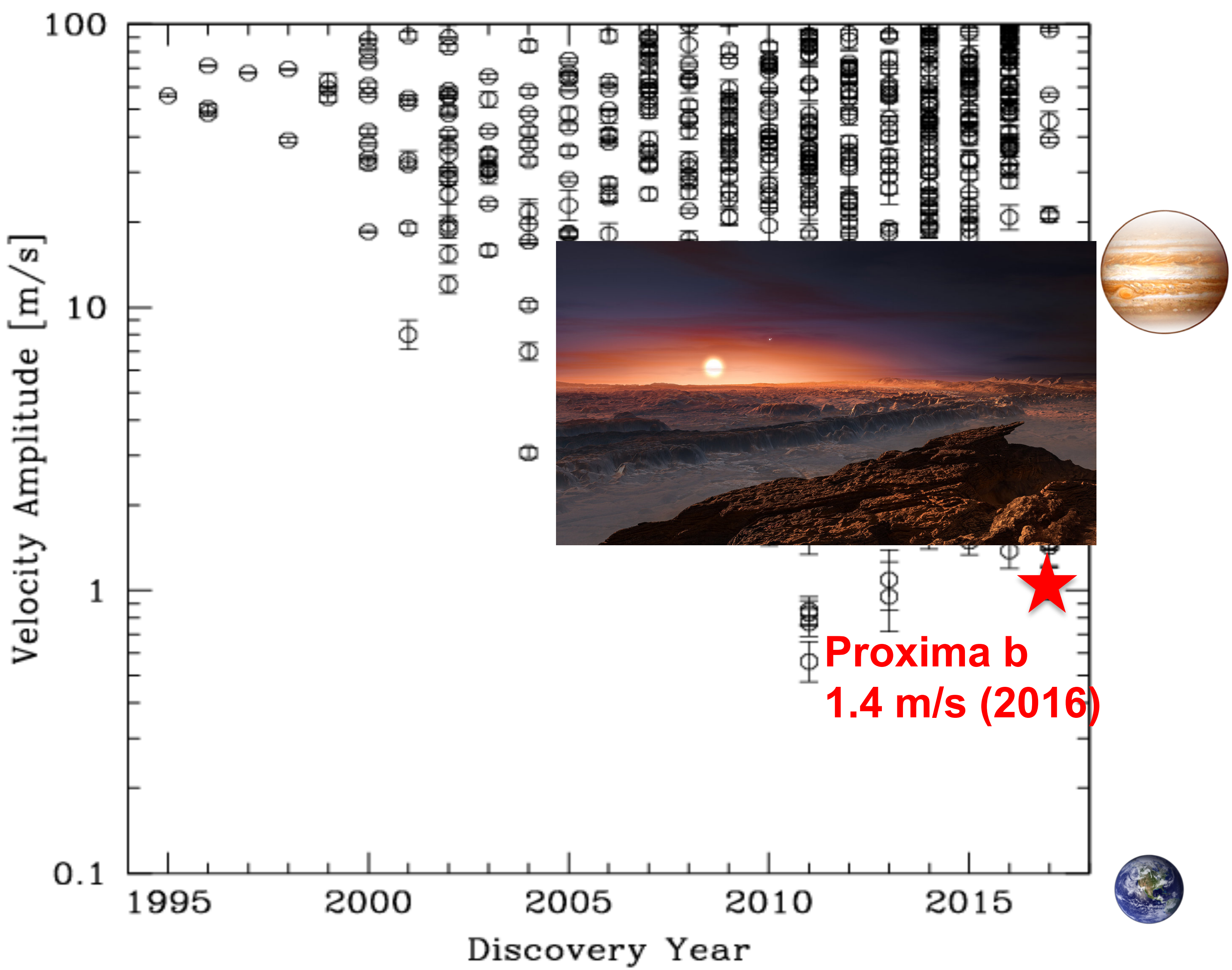


Jet Propulsion Laboratory
California Institute of Technology

Precision Radial Velocities



Precision Radial Velocities



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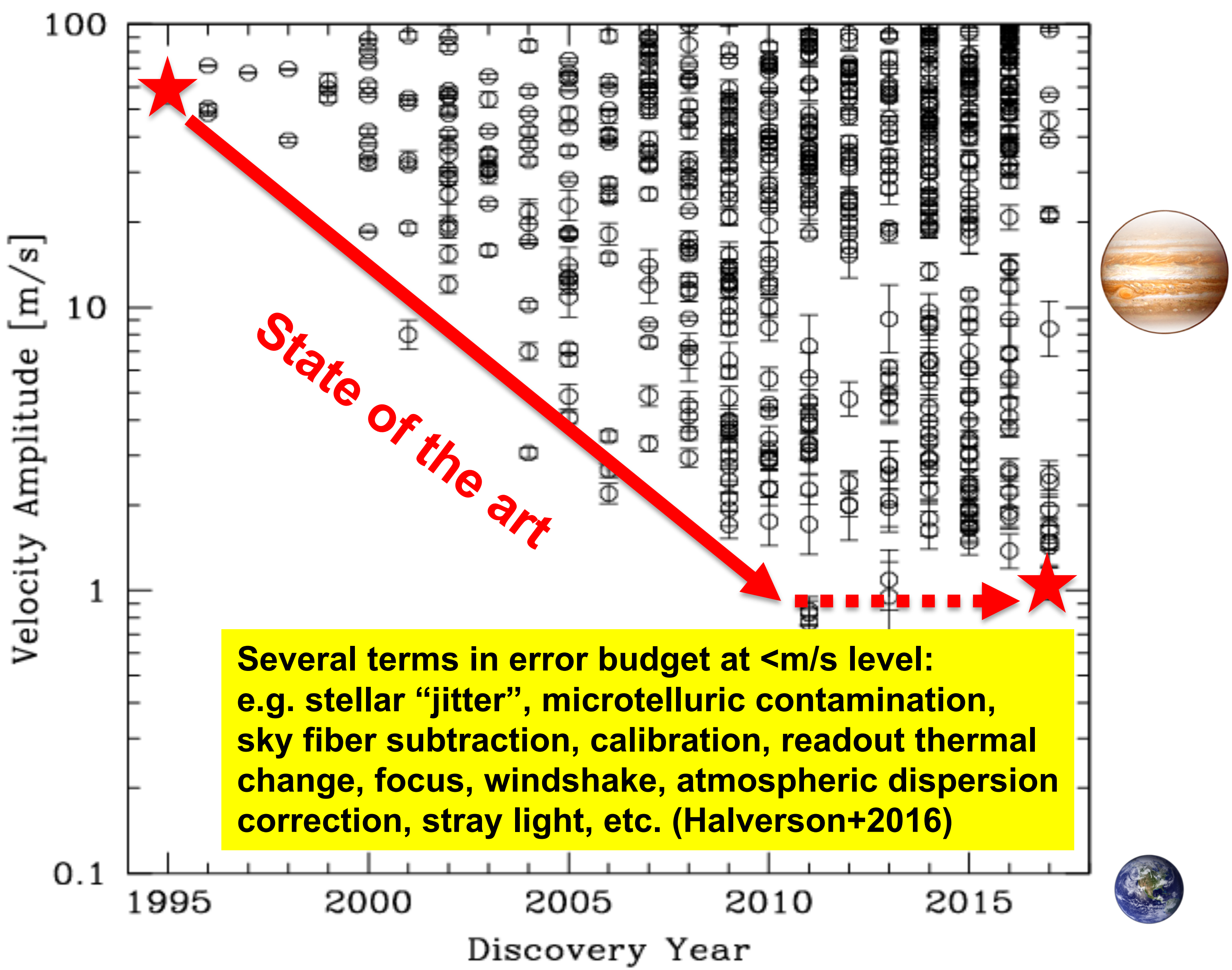
Precision Radial Velocities



Several terms in error budget at <m/s level: e.g. stellar "jitter", microtelluric contamination, sky fiber subtraction, calibration, readout thermal change, focus, windshake, atmospheric dispersion correction, stray light, etc. (Halverson+2016)

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 ~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

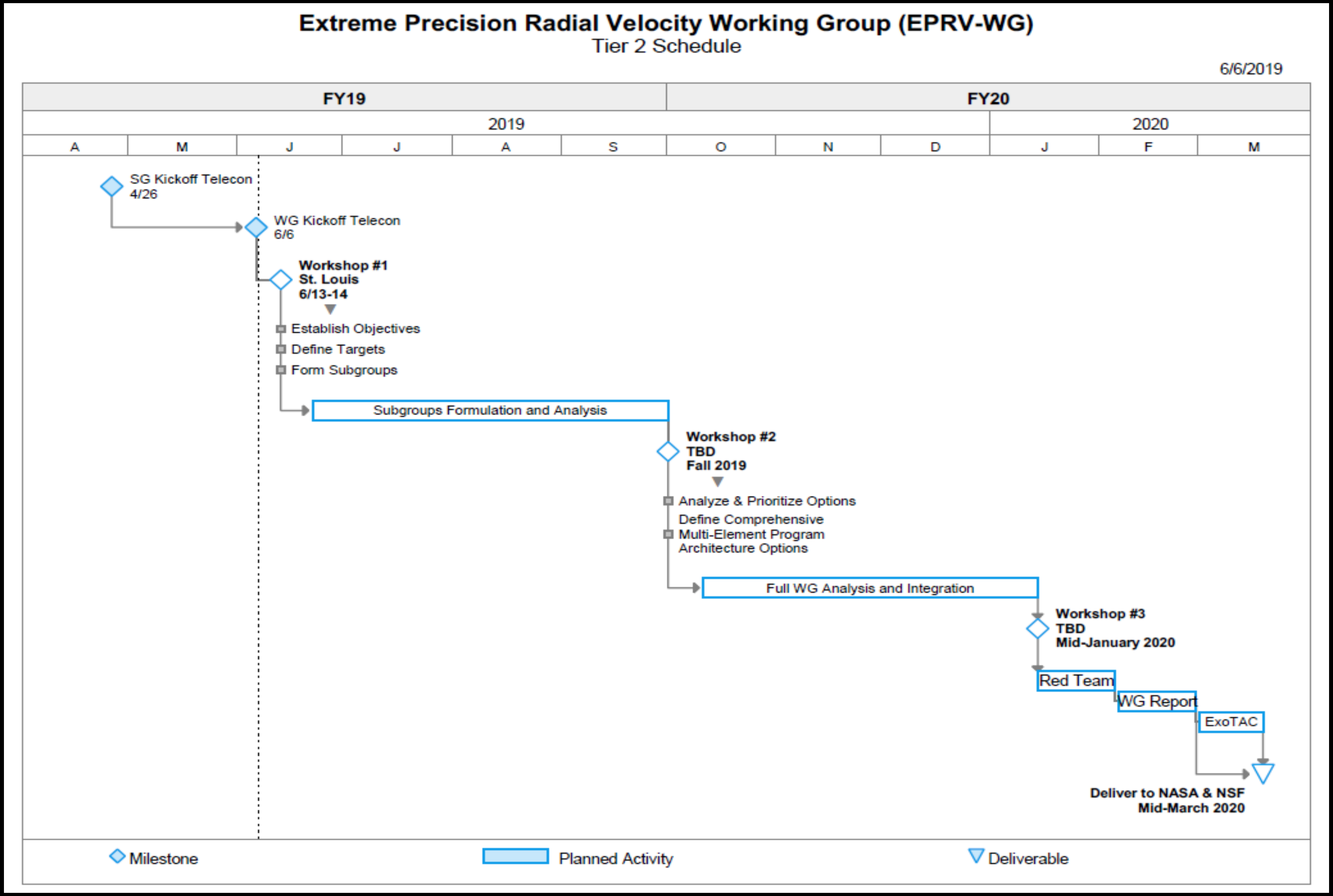
ExoTAC (Exoplanet Technical Assessment Committee)

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: Subgroups

Group A- Science	Science Mission Drivers	Andrew Howard Chad Bender
Group B- Performance Evaluation	Error budgets	Debra Fischer Sam Halverson
Group C- EPRV Instrumentation	Technology, Instruments, Wavelength Calibration	Stephanie Leifer Andy Szentgyorgyi
Group D- Intrinsic Stellar Limits to EPRV	Stellar Variability, Helio, Stellar Atmos, Solar Obsv	Heather Cegla Raphaelle Haywood
Group H- Tellurics	Tellurics and Earth's Atmosphere	Chad Bender
Group E- Survey Strategies	RV Observing Scenarios, Ground Observatories	Jenn Burt Johanna Teske
Group F- Turning Raw Data Into Planets	Pipelines, Data Analysis, Statistical Inference	Eric Ford Arpita Roy
Group G- Reality (TBR Resource Evaluation)	Cost and Schedule Evaluation, Technical and Risk Evaluation	Andres Quirrenbach Scott Diddams
Main EPRV Working Group		Scott Gaudi Gary Blackwood

Extreme Precision Radial Velocity WG: Schedule



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jpl.nasa.gov