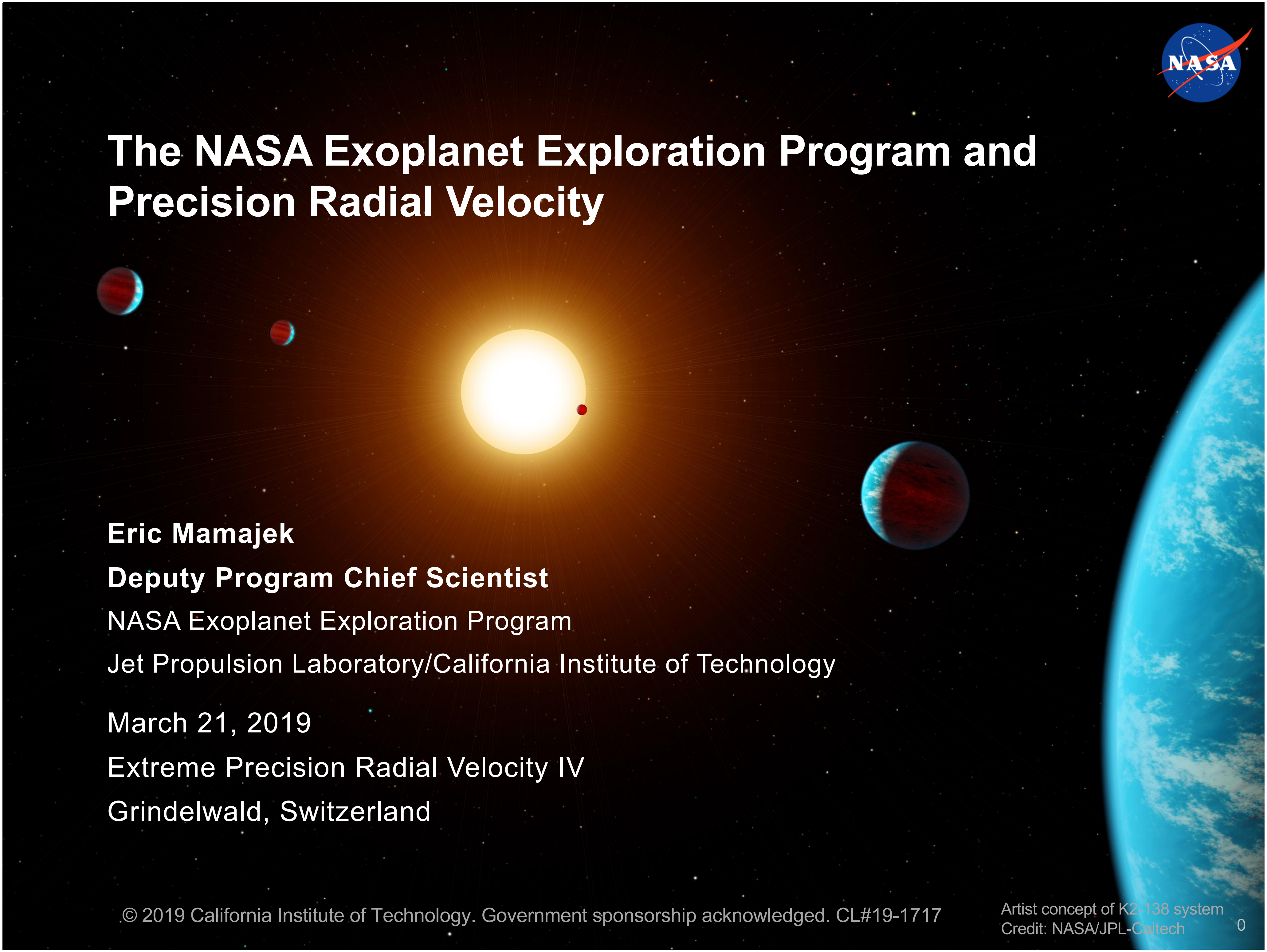
The NASA Exoplanet Exploration Program and Precision Radial Velocity



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

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March 21, 2019

Extreme Precision Radial Velocity IV

Grindelwald, Switzerland

NASA Exoplanet Exploration Program

Astrophysics Division, NASA Science Mission Directorate

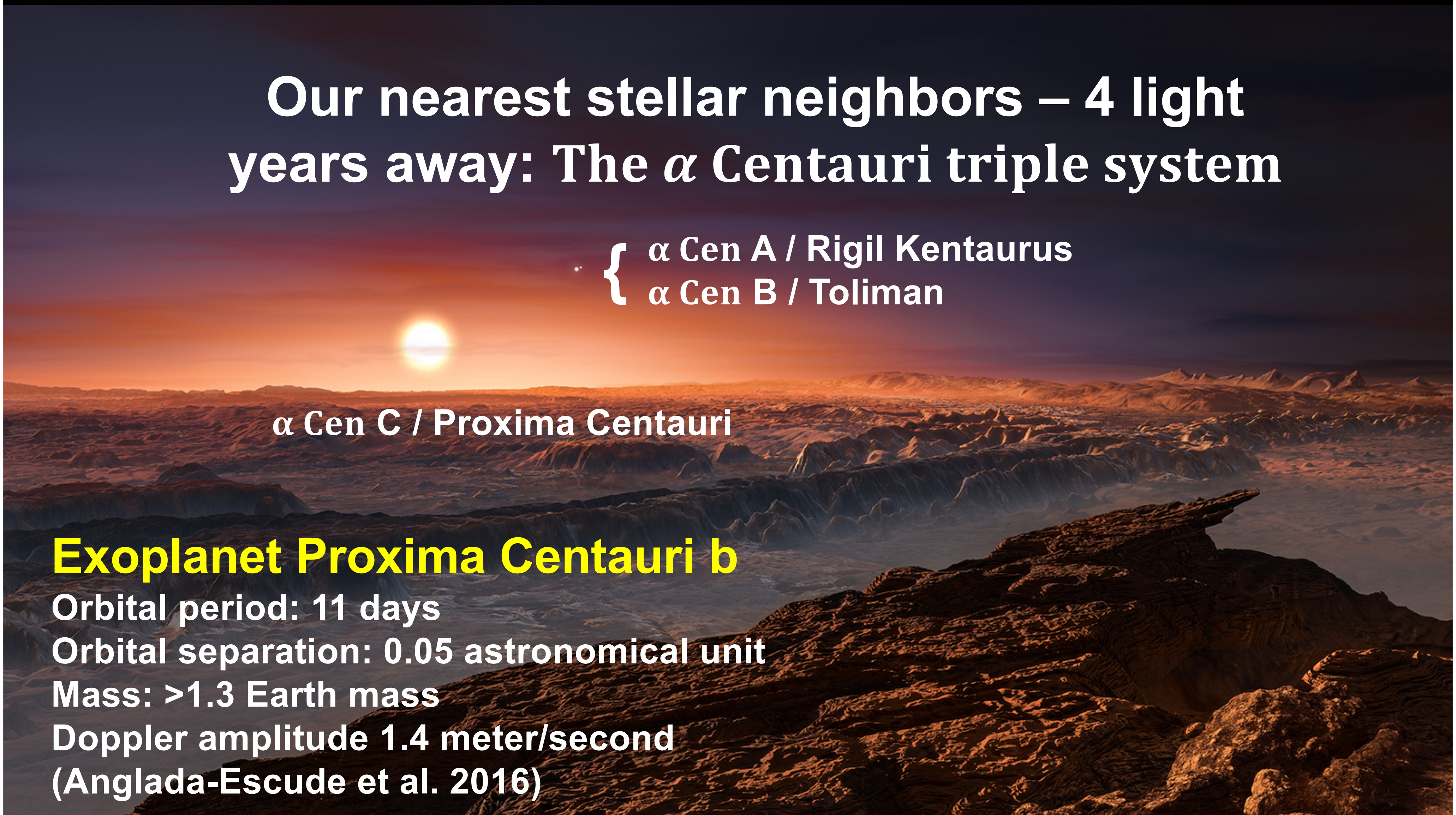
NASA's search for habitable planets and life beyond our solar system

Program purpose described in
2014 NASA Science Plan

1. **Discover planets around other stars**
2. **Characterize their properties**
3. **Identify candidates that could harbor life**

ExEP serves the science community and NASA by implementing NASA's space science vision for exoplanets

https://exoplanets.nasa.gov



Our nearest stellar neighbors – 4 light years away: The α Centauri triple system

α Cen A / Rigil Kentaurus
α Cen B / Toliman

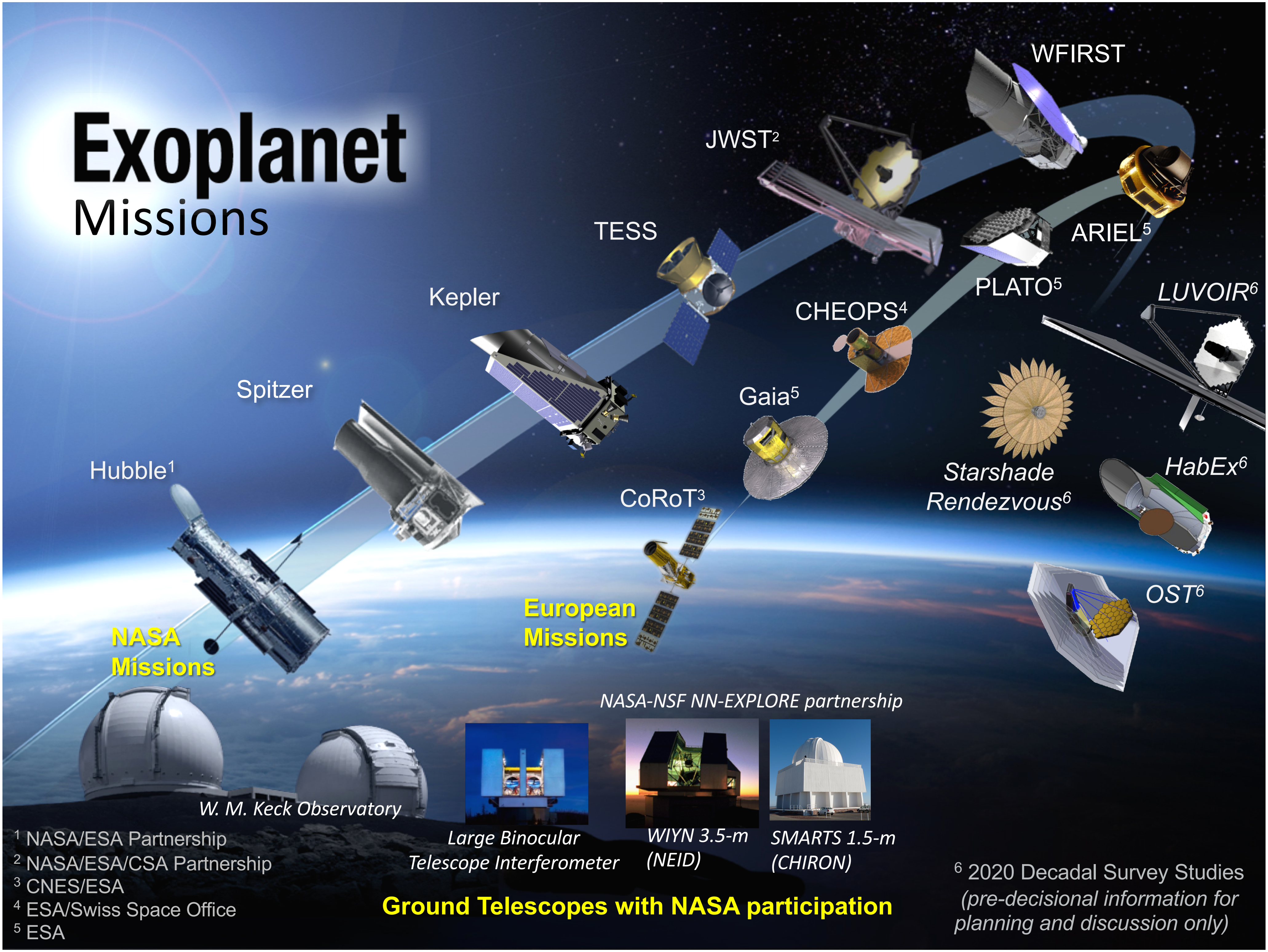
α Cen C / Proxima Centauri

Exoplanet Proxima Centauri b

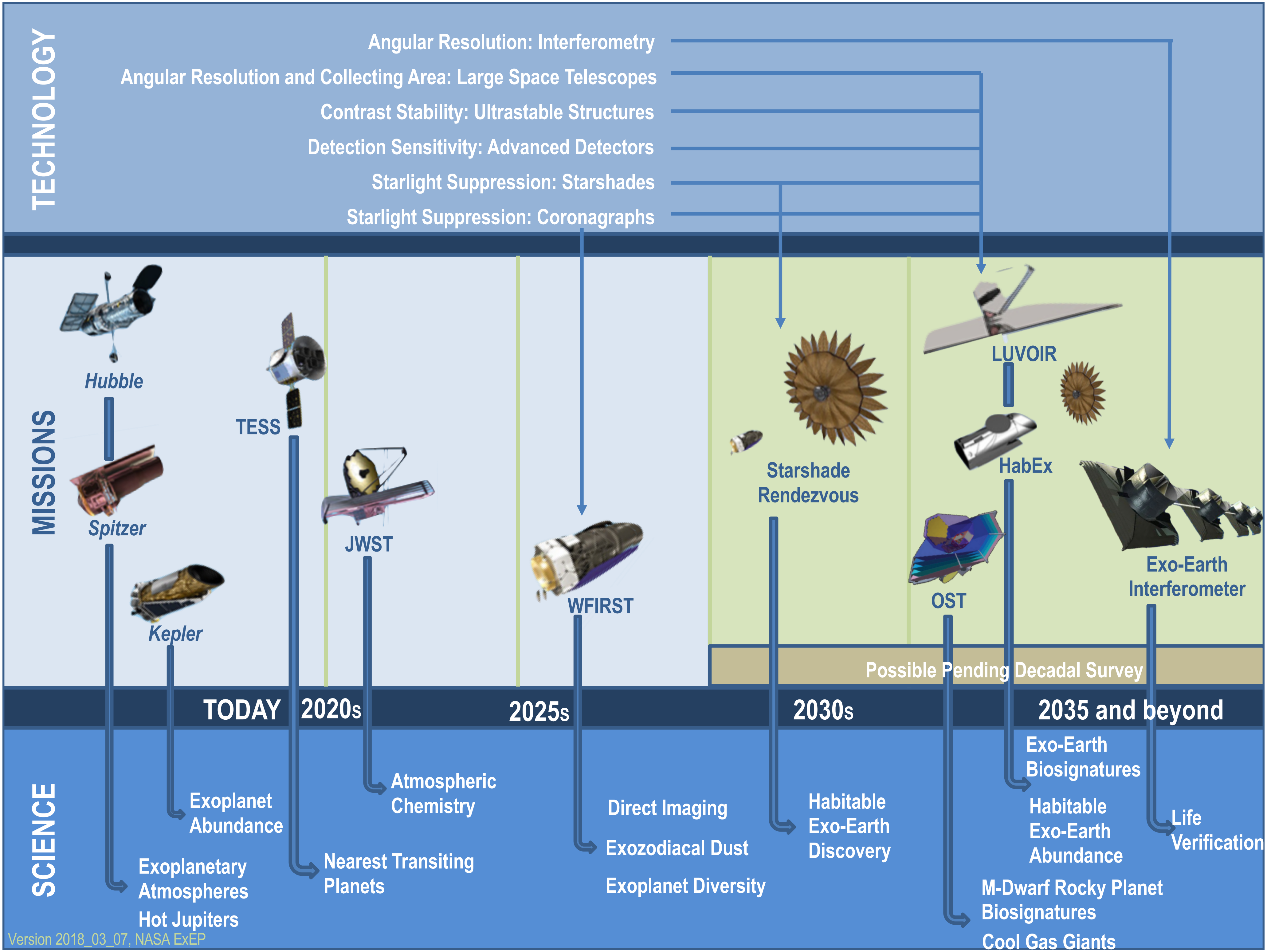
Orbital period: 11 days
Orbital separation: 0.05 astronomical unit
Mass: >1.3 Earth mass
Doppler amplitude 1.4 meter/second
(Anglada-Escude et al. 2016)

Credit: ESO/M.Kornmesser

EPRV is discovering and characterizing important exoplanet targets in search for life!

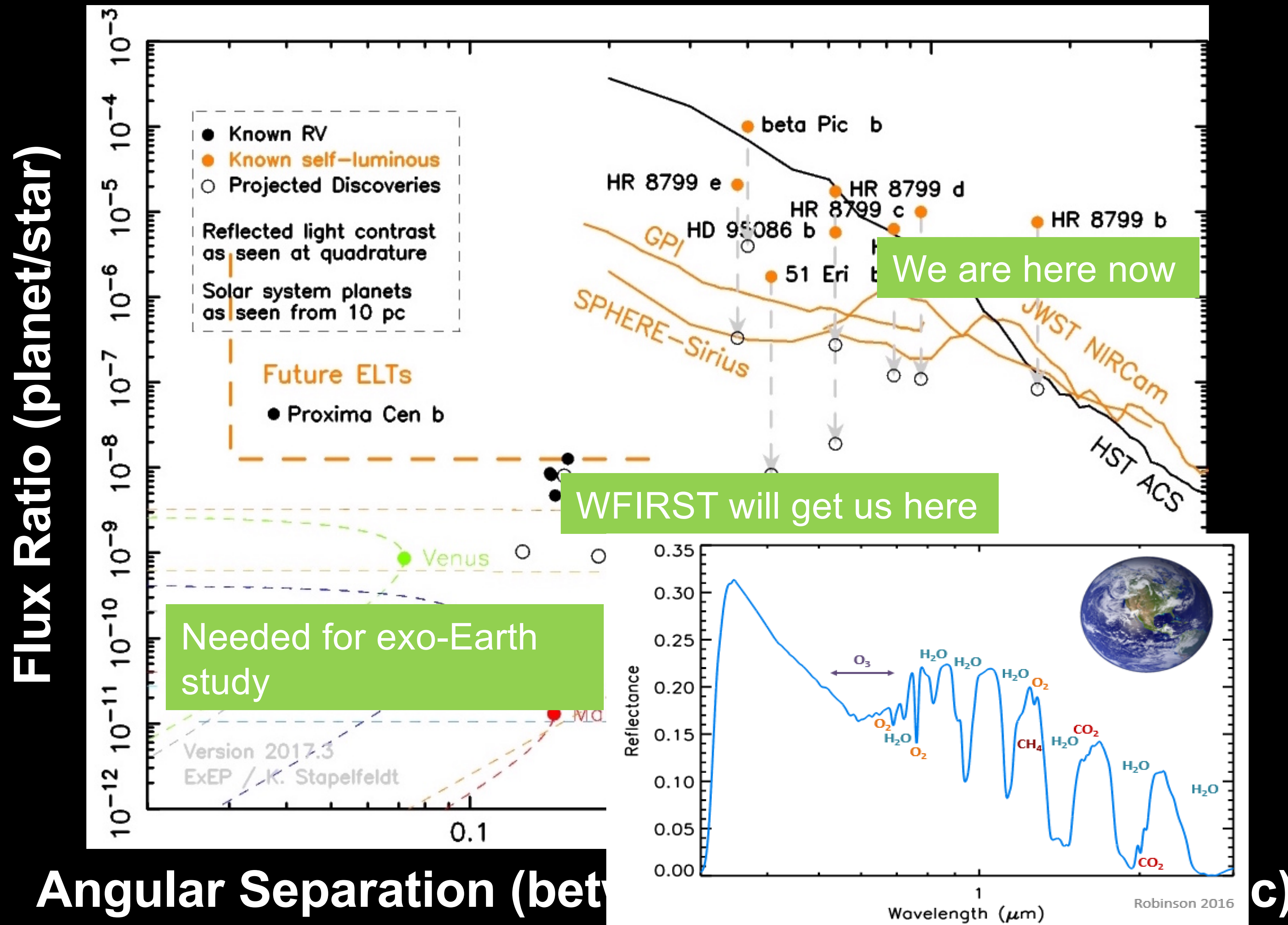


Exoplanet
Missions
Hubble[1]
Spitzer
Kepler
TESS
JWST[2]
WFIRST
ARIEL[5]
PLATO[5]
CHEOPS[4]
Gaia[5]
CoRoT[3]
LUVOIR[6]
Starshade Rendezvous[6]
HabEx[6]
OST[6]
NASA Missions
European Missions
NASA-NSF NN-EXPLORE partnership
W. M. Keck Observatory
Large Binocular Telescope Interferometer
WIYN 3.5-m (NEID)
SMARTS 1.5-m (CHIRON)
Ground Telescopes with NASA participation
[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA
[4] ESA/Swiss Space Office
[5] ESA
[6] 2020 Decadal Survey Studies (pre-decisional information for planning and discussion only)



TECHNOLOGY
Angular Resolution: Interferometry
Angular Resolution and Collecting Area: Large Space Telescopes
Contrast Stability: Ultrastable Structures
Detection Sensitivity: Advanced Detectors
Starlight Suppression: Starshades
Starlight Suppression: Coronagraphs
MISSIONS
Hubble
Spitzer
Kepler
TESS
JWST
WFIRST
Starshade Rendezvous
LUVOIR
HabEx
OST
Exo-Earth Interferometer
Possible Pending Decadal Survey
TODAY
2020s
2025s
2030s
2035 and beyond
SCIENCE
Exoplanet Abundance
Exoplanetary Atmospheres
Hot Jupiters
Nearest Transiting Planets
Atmospheric Chemistry
Direct Imaging
Exozodiacal Dust
Exoplanet Diversity
Habitable Exo-Earth Discovery
Exo-Earth Biosignatures
Habitable Exo-Earth Abundance
M-Dwarf Rocky Planet Biosignatures
Cool Gas Giants
Life Verification
Version 2018_03_07, NASA ExEP

Challenge to Directly Image Exo-Earths



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.

PRVs will provide essential NASA mission support for:

Mission	Target identification for mission science yield optimization	Follow-up validation & characterization of low mass transiting exoplanets	Exoplanet mass & orbit determination
Kepler		✓	✓
K2	✓	✓	✓
TESS	✓	✓	✓
JWST	✓	✓	✓
AFTA/probe Coronagraph or Starshade direct imaging *(WFIRST)*	✓		✓
Future Flagship direct imaging	✓		✓

Table 1. Summary of PRV support for NASA mission science objectives.

Plavchan, Latham et al. (2015) ExoPAG SAG 8 report

NASA ExEP Science Gap List (2018)

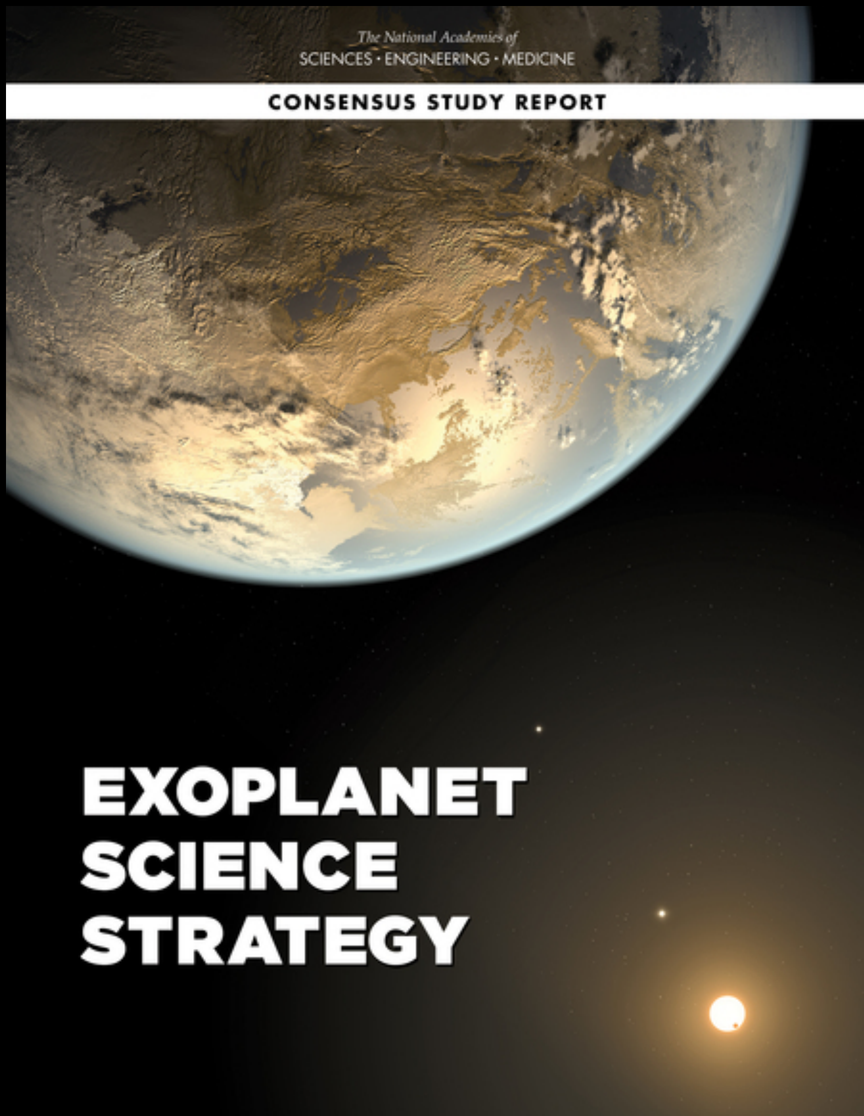
(grouped by topic, no implied priority in ordering)

- **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/

Exoplanet Science Strategy (2018)



SEC. 508. EXTRASOLAR PLANET EXPLORATION STRATEGY.

(a) STRATEGY.—

(1) IN GENERAL.—The Administrator shall enter into an arrangement with the National Academies to develop a science strategy for the study and exploration of extrasolar planets, including the use of the Transiting Exoplanet Survey Satellite, the James Webb Space Telescope, a potential Wide-Field Infrared Survey Telescope mission, or any other telescope, spacecraft, or instrument, as appropriate.

(2) REQUIREMENTS.—The strategy shall—

(A) outline key scientific questions;

(B) identify the most promising research in the field;

(C) indicate the extent to which the mission priorities in existing decadal surveys address the key extrasolar planet research and exploration goals;

(D) identify opportunities for coordination with international partners, commercial partners, and not-for-profit partners; and

(E) make recommendations regarding the activities under subparagraphs (A) through (D), as appropriate.

(b) USE OF STRATEGY.—The Administrator shall use the strategy—

(1) to inform roadmaps, strategic plans, and other activities of the Administration as they relate to extrasolar planet research and exploration; and

(2) to provide a foundation for future activities and initiatives related to extrasolar planet research and exploration.

(c) REPORT TO CONGRESS.—Not later than 18 months after the date of enactment of this Act, the National Academies shall submit to the Administrator and to the appropriate committees of Congress a report containing the strategy developed under subsection (a).

NASA Auth. Bill S.442 (2017)

ESS (2018) National Academies report can be downloaded at:
https://www.nap.edu/catalog/25187/exoplanet-science-strategy

Exoplanet Science Strategy (2018)

Goal 1 is to understand the formation and evolution of planetary systems as products of the process of star formation, and characterize and explain the diversity of planetary system architectures, planetary compositions, and planetary environments produced by these processes. This leads to three scientific findings that will guide an implementation strategy:

> **Finding:** Current knowledge of the demographics and characteristics of planets and their systems is substantially incomplete. Advancing an understanding of the formation and evolution of planets requires two surveys: First, it requires a survey for planets where the census is most incomplete, which includes the parameter space occupied by most planets of the Solar System. Second, it requires the characterization of the atmospheres and bulk compositions of planets spanning a broad range of masses and orbits.
>
> **Finding:** An understanding of planet formation requires a census of protoplanetary disks, young planets, and mature planetary systems across a wide range of planet-star separations.

Goal 2: Learn enough about the properties of exoplanets to identify potentially habitable environments and their frequency, and connect these environments to the planetary systems in which they reside. Furthermore, researchers need to distinguish between the signatures of life and those of nonbiological processes, and search for signatures of life on worlds orbiting other stars.

Exoplanet Science Strategy (2018) key recommendations:

Recommendation: ***NASA should lead a large strategic direct imaging mission capable of measuring the reflected-light spectra of temperate terrestrial planets orbiting Sun-like stars.***

Recommendation: ***The National Science Foundation should invest in both the GMT and TMT and their exoplanet instrumentation to provide all-sky access to the U.S. community.***

Recommendation: ***NASA should launch WFIRST to conduct its microlensing survey of distant planets and to demonstrate the technique of coronagraphic spectroscopy on exoplanet targets.***

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.

Recommendation: ***NASA should create a mechanism for community-driven legacy surveys of exoplanet atmospheres early in the JWST mission.***

Recommendation: ***Building on the NExSS model, NASA should support a cross-divisional exoplanet research coordination network that includes additional membership opportunities via dedicated proposal calls for interdisciplinary research.***

Recommendation: ***NASA should support a robust individual investigator program that includes grants for theoretical, laboratory, and ground-based telescopic investigations; otherwise, the full scientific yield of exoplanet missions will not be realized.***

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)

ESS Recommendation: EPRV Initiative

(p.6-2)

While many small-scale efforts are best supported by openly advertised, competitive individual investigator opportunities, the committee finds one particular area in need of strategic investment from now through the mid-term time scale. Mass is a fundamental planetary property, necessary to understand bulk compositions and system architectures as well as to interpret atmospheric spectra. The committee finds that radial velocity measurement is the technique most likely to provide masses for a substantial number of Neptune, super-Earth, and terrestrial-mass planets. However, the success of efforts to improve radial velocity precision to the required level is not assured. In addition to improvements in instrument capabilities, the varied velocity signals produced by surface processes on stars will need to be understood at a substantially better level. The committee considers this problem too large to be addressed by principal investigators (PIs) in possession of individual investigator grants and thus recommends that NASA and the NSF establish an extreme precision radial velocity initiative to support and organize these efforts in order to maximize the science yield of future missions and the GSMTs. The committee emphasizes that a single co-located center is not recommended for this endeavor. Rather, the varied expertise of investigators at a range of institutions will be needed. The committee suggests that progress in precision measurement of masses through the radial velocity (RV) technique would benefit from NASA's established ability to organize large groups of investigators in pursuit of demanding, unprecedented, and clearly defined goals.

NAS Exoplanet Science Strategy (2018)

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)

- 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

NEID

NN-Explore Exoplanet Investigations with Doppler Spectroscopy

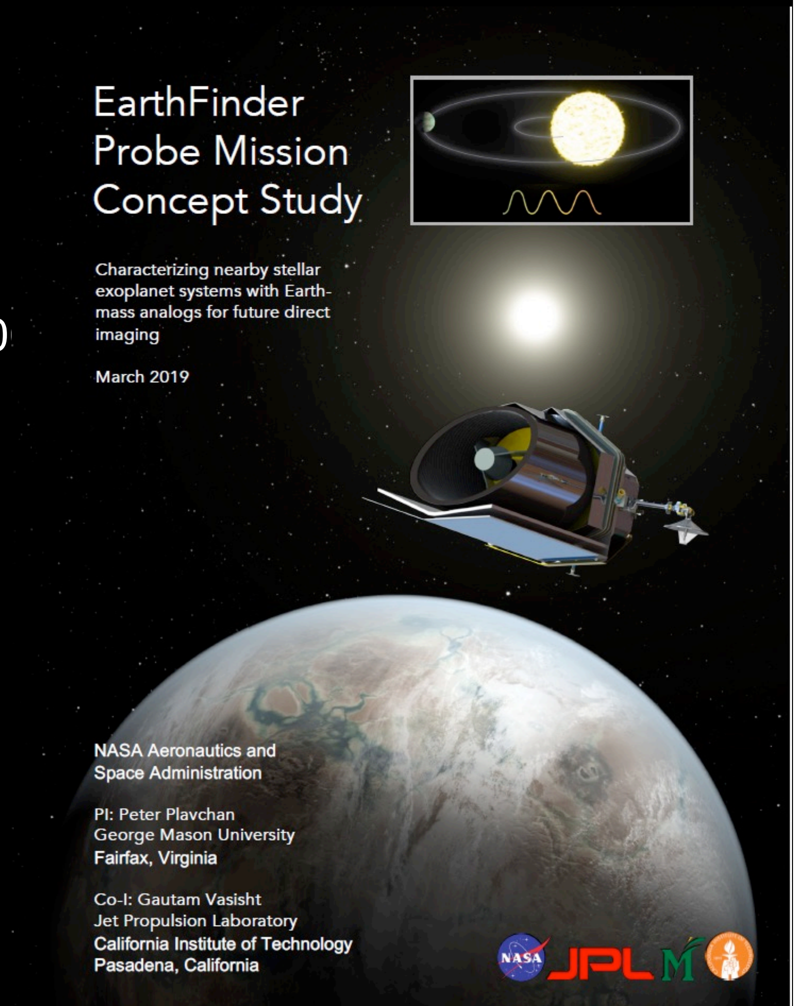
PennState

PI: S. Mahadevan

3.5m WIYN Telescope
Kitt Peak National Observatory
Arizona

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/λ)
  - Near-IR Spectrometers: 0.96-2.4 μm at R=170,00 (1.6/λ)
  - Small UV Spectrometer for MgII 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



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.	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

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

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

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

Closing Comments

- EPRV provides essential NASA mission support for follow-up validation and characterization of transiting exoplanets, determination of masses and orbits, and target identification for future direct imaging missions (more generally: EPRV is essential tool for *both* the ground- and space-based paths in the quest to detect biosignatures, hopefully within next decade or two)
- NASA and NSF are partnering on response to recommendations from National Academies Exoplanet Science Strategy (ESS) report regarding EPRV (Stay tuned)
- See you at EPRV5 !

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

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