Sagan Summer Workshop

Planets from Future Direct Imaging Missions: Determining Masses and Orbits

Eric Mamajek

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Jet Propulsion Laboratory, California Institute of Technology

July 29, 2022

Sagan Summer Workshop

NExScI

Friday July 29: Next Steps in Astrometry

Time (PDT)	Title	Speaker
8:30 am	Detecting Earths	Aki Roberge (NASA Goddard Space Flight Center)
9:15 am	Advancing Astrometric Reference Frames in the Gaia Era	François Mignard (Observatoire de la Côte d'Azur)
10:00 am	*Break*	
10:30 am	The JASMINE Mission	Daisuke Kawata (University College London)
11:00 am	The Gaia NIR Mission	David Hobbs (Lund Observatory)
11:30 am	The TOLIMAN Mission	Eduardo Bendek (NASA JPL)
12:00 pm	*Lunch*	
1:30 pm	Astrometry with the Roman Space Telescope	Scott Gaudi (Ohio State University)
2:00 pm	Differential Astrometry (micro-arcsecond precision) for Earths	Alberto Krone-Martins (University of California, Irvine)
2:30 pm	Planets from Future Direct Imaging Missions: Determining Masses and Orbits	Eric Mamajek (JPL)
3:00 pm	*Break*	
3:30 pm	Group Project Presentations	
5:00 pm	Closing Comments	Dawn Gelino (Caltech/IPAC-NExScI)
5:15 pm	*Adjourn*	

NASA Exoplanet Exploration Program

Astrophysics Division, NASA Science Mission Directorate

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

Program purpose per Charter
From the Astrophysics Division

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

ExEP serves the Science Community and NASA:

- As a Focal point for exoplanet science and technology
- By Integration of cohesive strategies for future discoveries

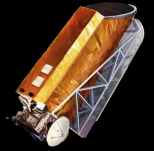
https://exoplanets.nasa.gov/exep

NASA Exoplanet Exploration Program

ExEP NASA EXOPLANET EXPLORATION PROGRAM

Mission Concepts

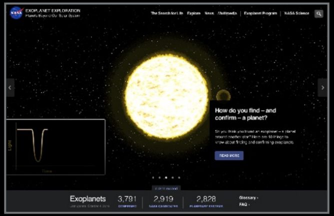
IR / O / UV Mission Concepts

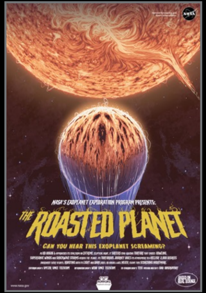


Coronagraph

Starshade

Exoplanet Communications

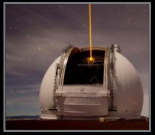




Supporting Research & Technology

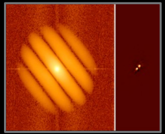
Key Sustaining Research

NN-EXPLORE



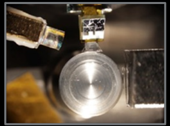
Keck Observatory

Large Binocular Telescope Interferometer

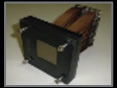


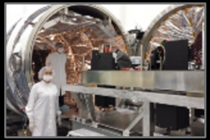
High Resolution Imaging

Technology Development



Extreme Precision Radial Velocity Technology Development

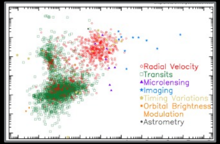




Coronagraph Technology Development

Starshade Technology Development (S5)

NASA Exoplanet Science Institute (NExScI)



Archives, Tools, Sagan Program, Professional Engagement

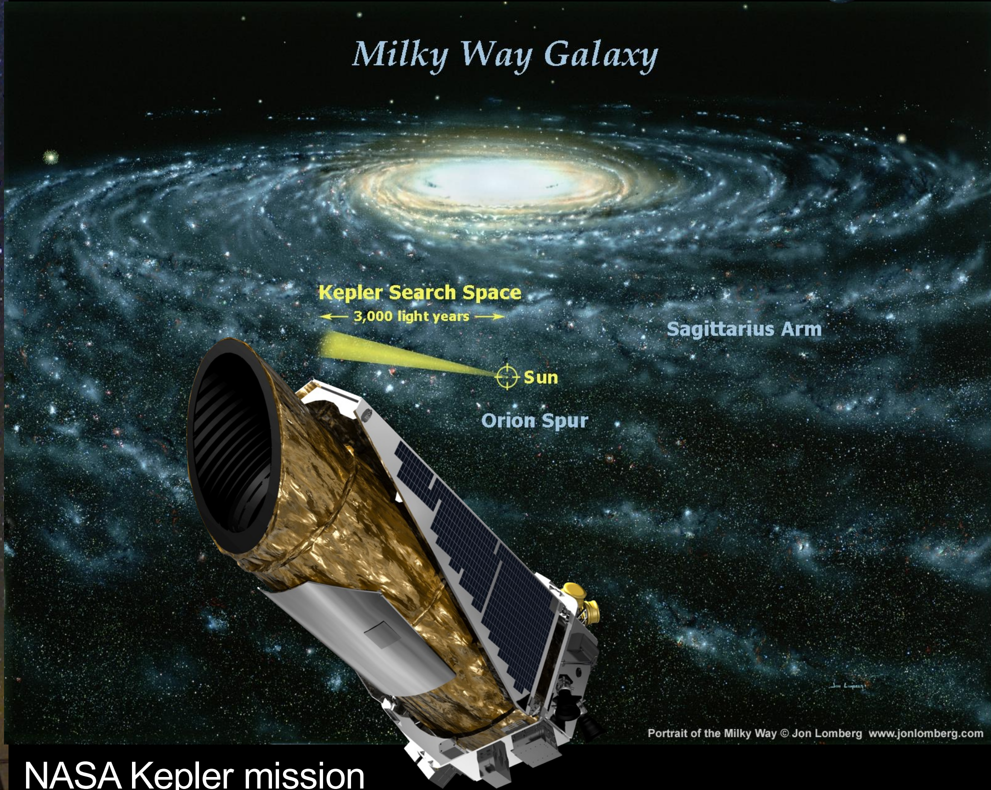
Credit: Andreas Papadopoulos

Mass of Milky Way's stars:
50 billion solar masses (±10%)
(Cautun+2020 using ESA/Gaia results)

Mean star mass:
0.40 solar mass (±10%)

Total number of stars in Milky Way:
125 billion (±15%)

Credit: *Andreas Papadopoulos*



NASA Kepler mission
(2009-2018)

Credit: *NASA*

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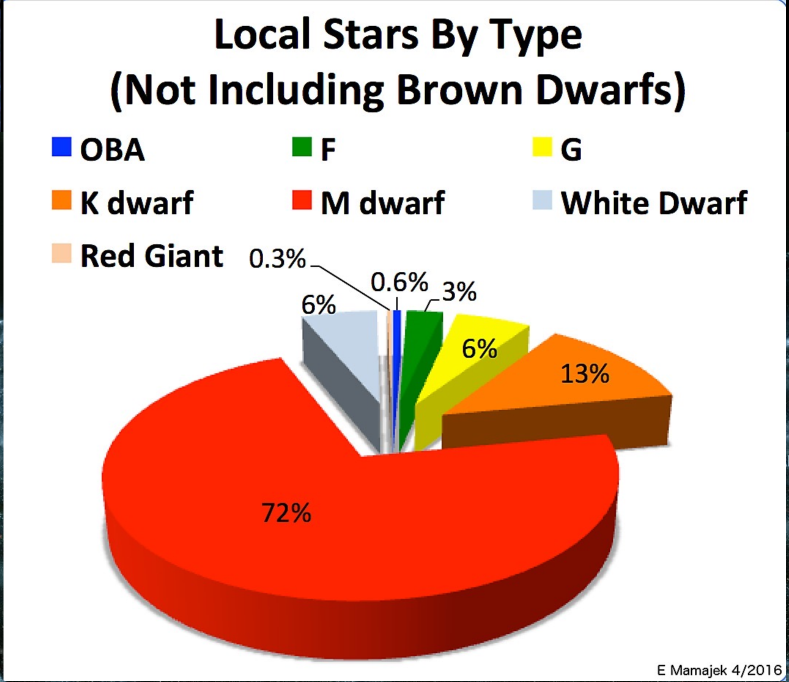

close-in exoplanets per star (NASA Kepler):
M dwarfs: $\gtrsim 4$ (Hsu, Ford & Terrien 2020)
K dwarfs: $\gtrsim 2.6$ (Kunimoto & Matthews 2020)
G dwarfs: $\gtrsim 1.7$ "
F dwarfs: $\gtrsim 0.9$ "

Portrait of the Milky Way © Jon Lomberg www.jonlomberg.com

Minimum number of planets in Milky Way galaxy:
$\gtrsim$ 400,000,000,000

Credit: Andreas Papadopoulos

Credit: NASA

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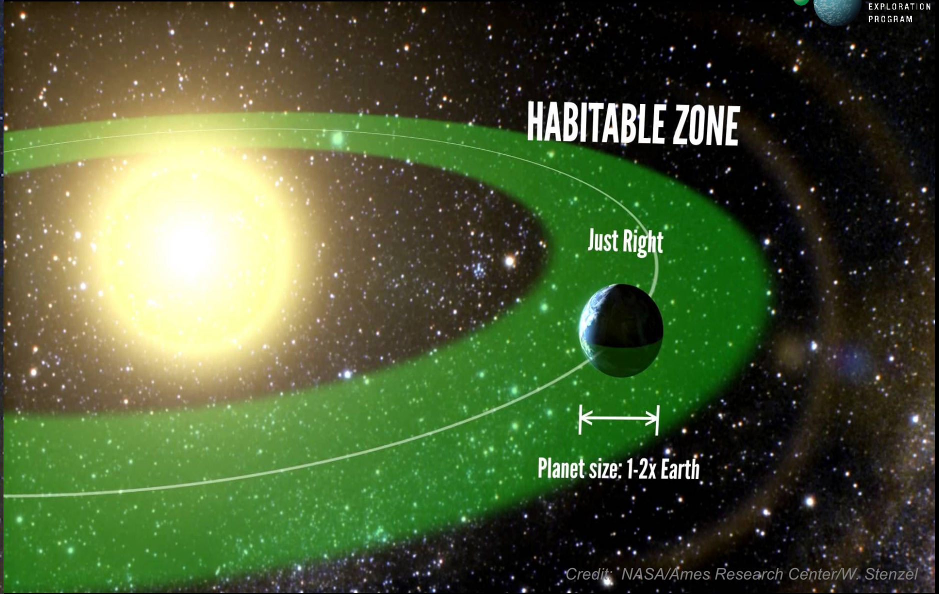


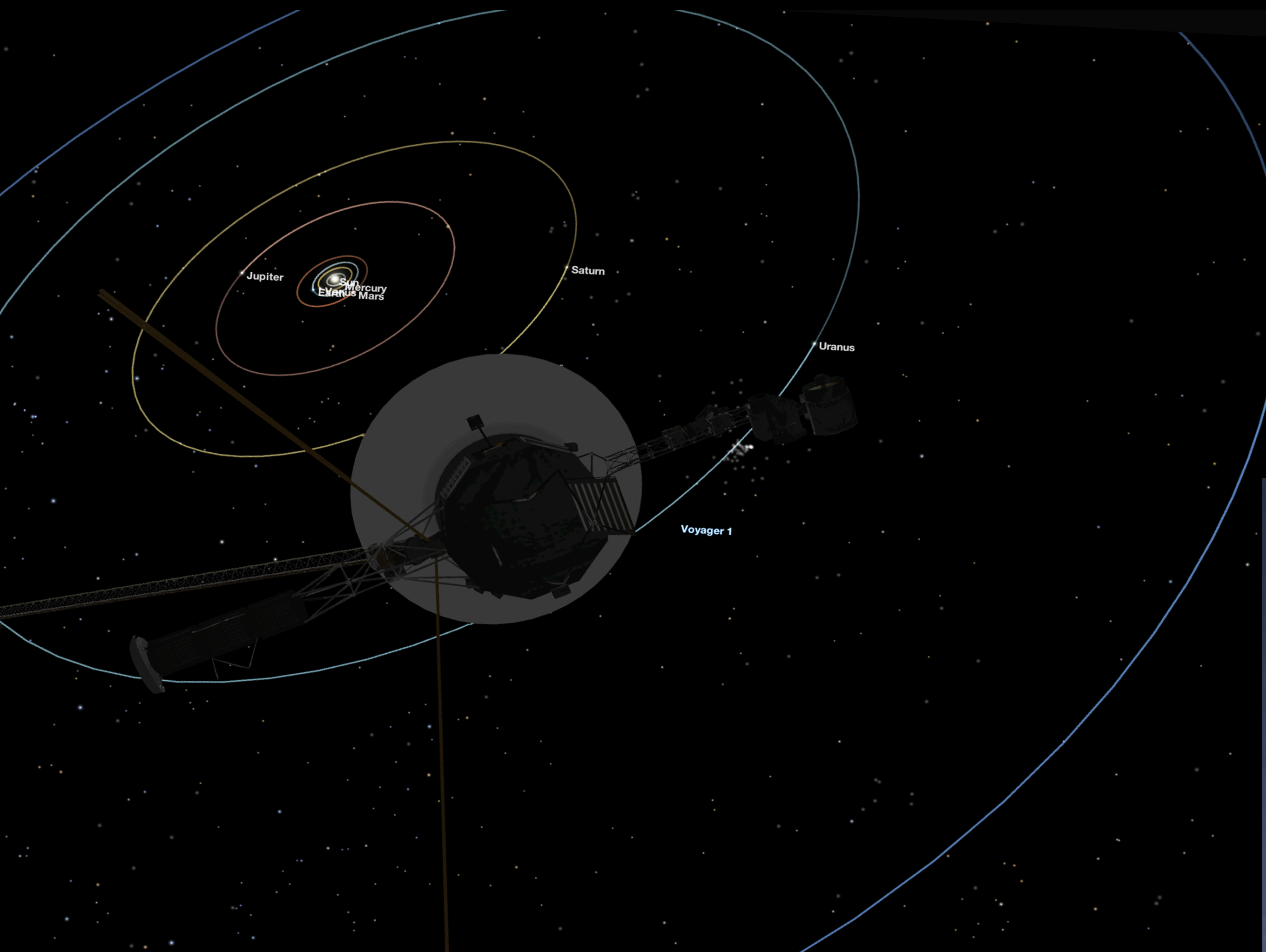
Number of small rocky planets in "habitable zone" per star (NASA Kepler):
Sun-like stars: ~0.24* (Bryson+2021)
M dwarf stars: ~0.33 (Hsu, Ford & Terrien 2020)

Number of rocky temperate exoplanets in Milky Way:
~30 billion (very rough estimate)!

Credit: Andreas Papadopoulos

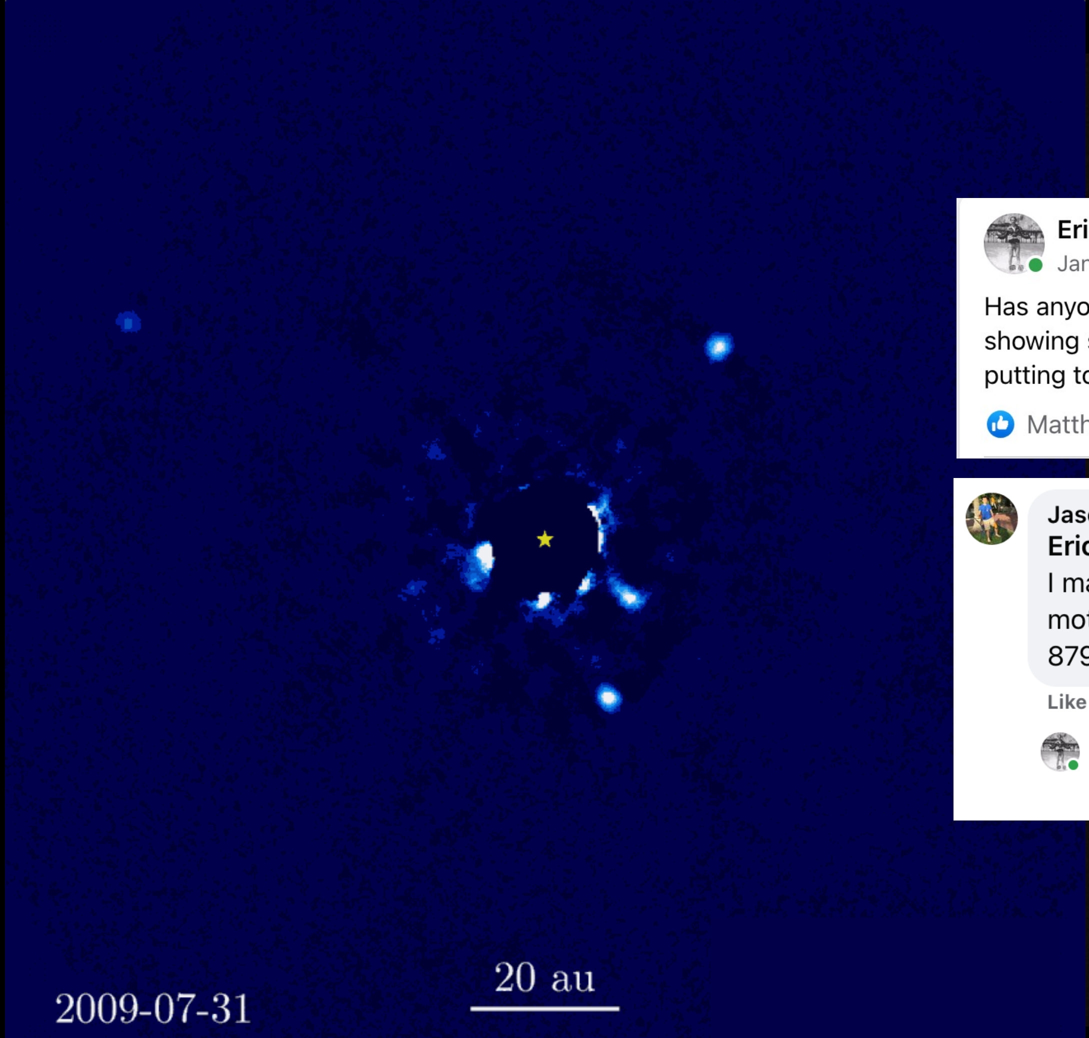
Credit: NASA

ExEP
NASA EXOPLANET EXPLORATION PROGRAM

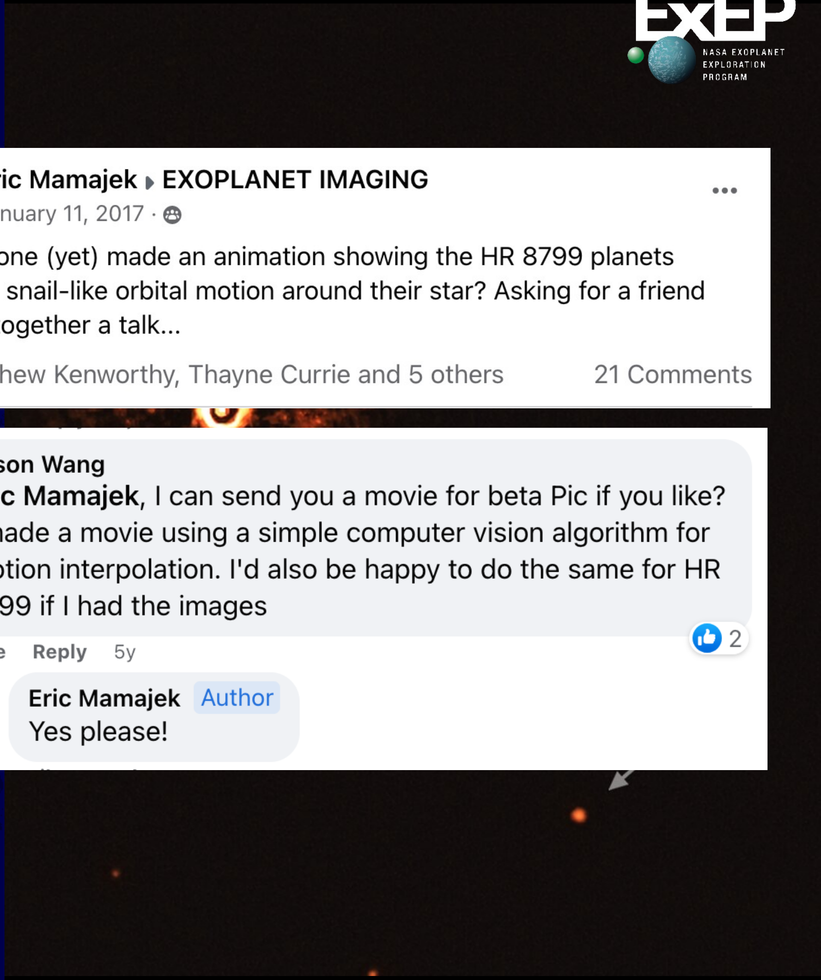


Voyager 1 (1990) “The Family Portrait” Credits: NASA/JPL-Caltech

Voyager 1 (1990) “Pale Blue Dot”
Credits: NASA/JPL-Caltech



HR 8799 system / Keck – Credit: Jason Wang et al.



Eric Mamajek ▸ EXOPLANET IMAGING
January 11, 2017 ·

Has anyone (yet) made an animation showing the HR 8799 planets showing snail-like orbital motion around their star? Asking for a friend putting together a talk...

Matthew Kenworthy, Thayne Currie and 5 others — 21 Comments

Jason Wang
Eric Mamajek, I can send you a movie for beta Pic if you like? I made a movie using a simple computer vision algorithm for motion interpolation. I'd also be happy to do the same for HR 8799 if I had the images

2

Like Reply 5y

Eric Mamajek Author
Yes please!

TYC 8998-760-1 (YSES 1) system / VLT – Credit: Alex Bohn et al.

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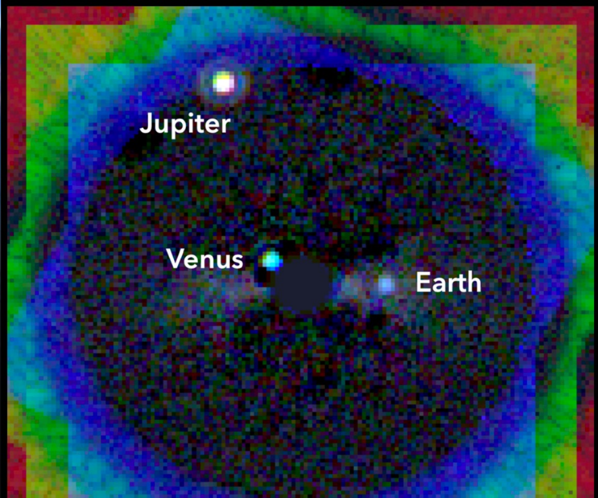
Astrophysics

Decadal Survey Missions

- **1972** Decadal Survey *Hubble*
- **1982** Decadal Survey *Chandra*
- **1991** Decadal Survey *Spitzer*
- **2001** Decadal Survey *Webb*
- **2010** Decadal Survey *Roman*
- **2021** Decadal Survey



Simulated image w/coronagraph – star @ 12pc
LUVOIR Report (2019)

Credit: Paul Hertz (NASA HQ)

Decadal Survey on Astronomy & Astrophysics 2020 (Astro2020)

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The Frontiers: Major New Projects (Space)

IR/O/UV Large Strategic Mission

- IR/O/UV telescope for exoplanet characterization and general astronomy. Mission-specific funding to begin mid-late decade after mission and technology maturation program
- Total implementation and operations cost (5 years) estimated at $11 billion[a]

Enabling Programs (Space)

Great Observatories Mission and Technology Maturation Program

Program to co-mature large strategic missions and technologies. First entrant: IR/O/UV observatory, Far-IR and high resolution X-ray observatories recommended to enter in second half of the decade

Recommendation: After a successful mission and technology maturation program, NASA should embark on a program to realize a mission to search for biosignatures from a robust number of about ~25 habitable zone planets and to be a transformative facility for general astrophysics. If mission and technology maturation are successful, as determined by an independent review, implementation should start in the latter part of the decade, with a target launch in the first half of the 2040s.

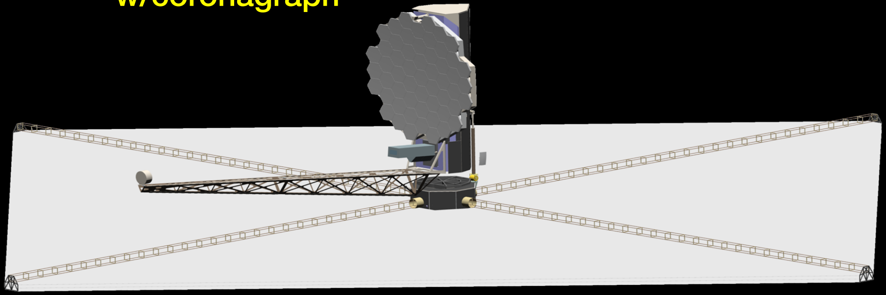
Image cre

NASA’s 2020 Astrophysics Decadal Mission Concept Studies:

https://science.nasa.gov/astrophysics/2020-decadal-survey-planning

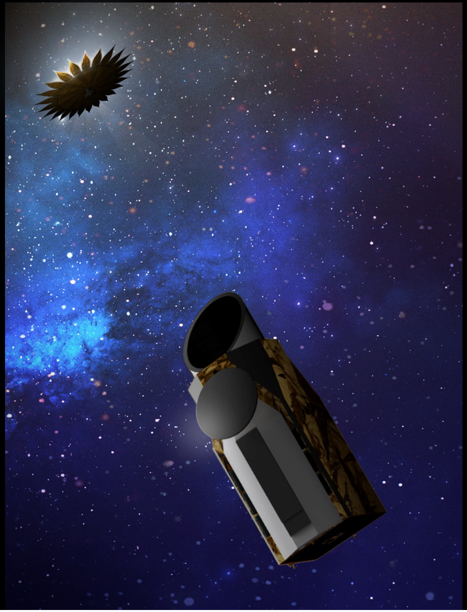
LUVOIR-B

8-m, off-axis
w/coronagraph



HabEx

4-m monolith telescope with coronagraph and formation-flying starshade



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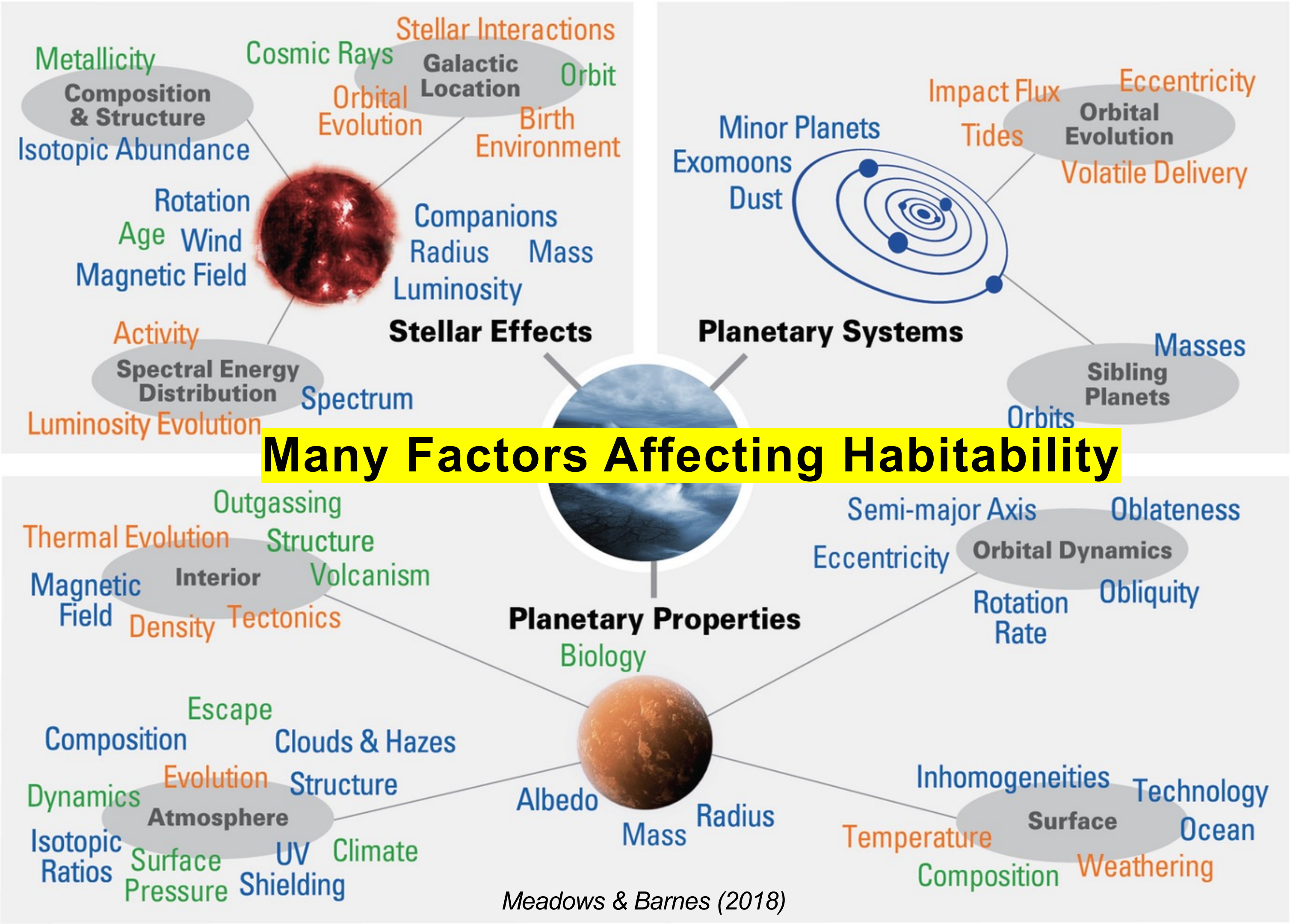
The Need to Measure Exoplanet Masses

"*Mass is the most fundamental property of a planet, and knowledge of a planet's mass (along with a knowledge of its radius) is essential to understand its bulk composition and to interpret spectroscopic features in its atmosphere. If scientists seek to study Earth-like planets orbiting Sun-like stars, they need to push mass measurements to the sensitivity required for such worlds.*"

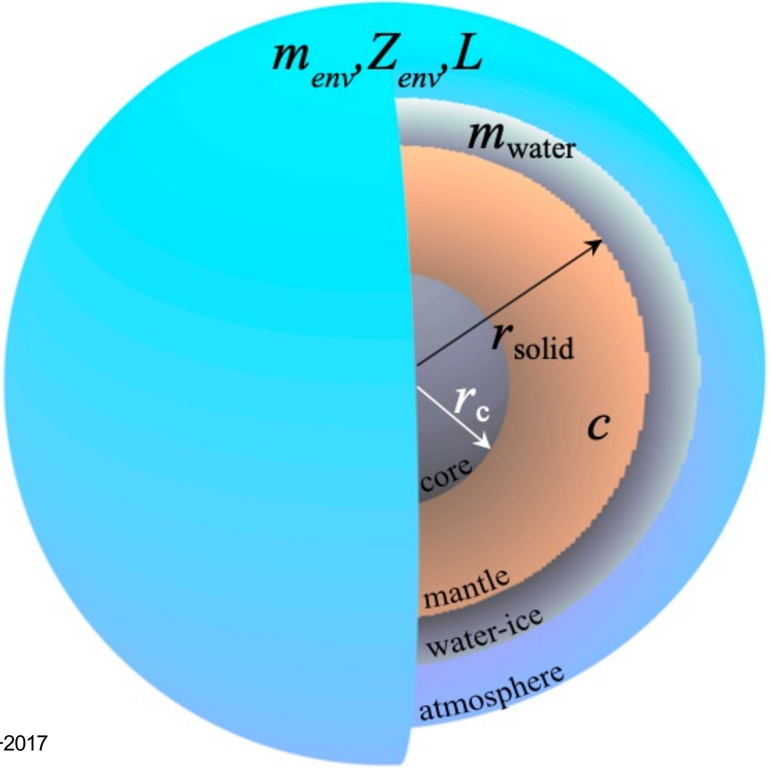
-National Academy of Sciences
Exoplanet Science Strategy (2018)

EPRV Working Group Presentation to NASA & NSF (2020)
https://exoplanets.nasa.gov/exep/NNExplore/EPRV/

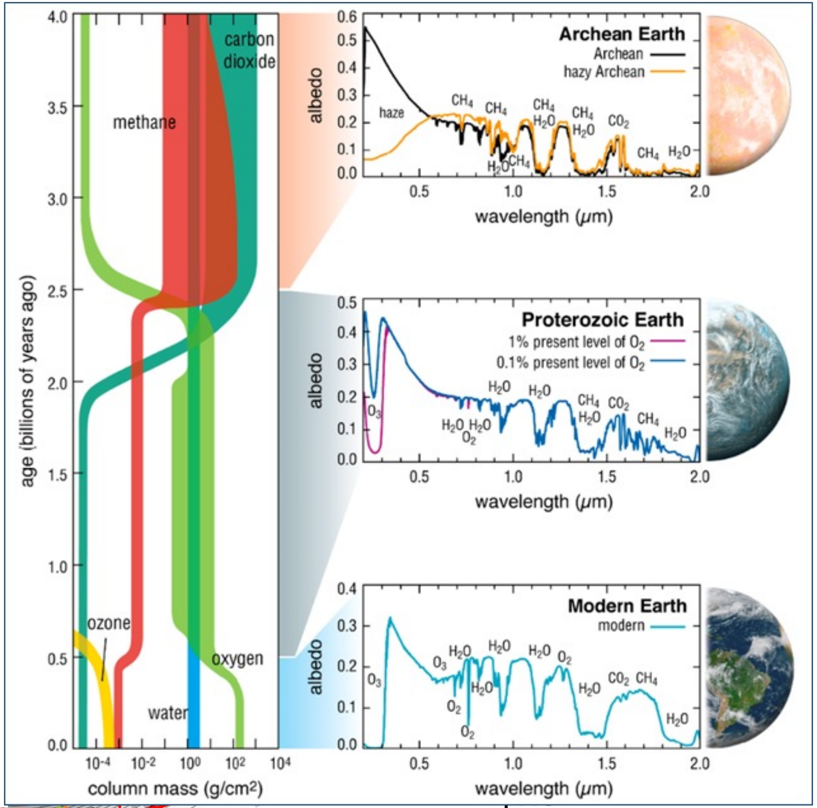


Many Factors Affecting Habitability

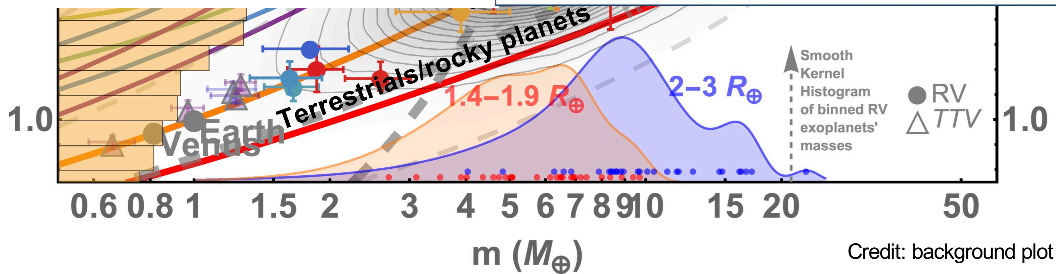
Meadows & Barnes (2018)



Credit: Dorn+2017

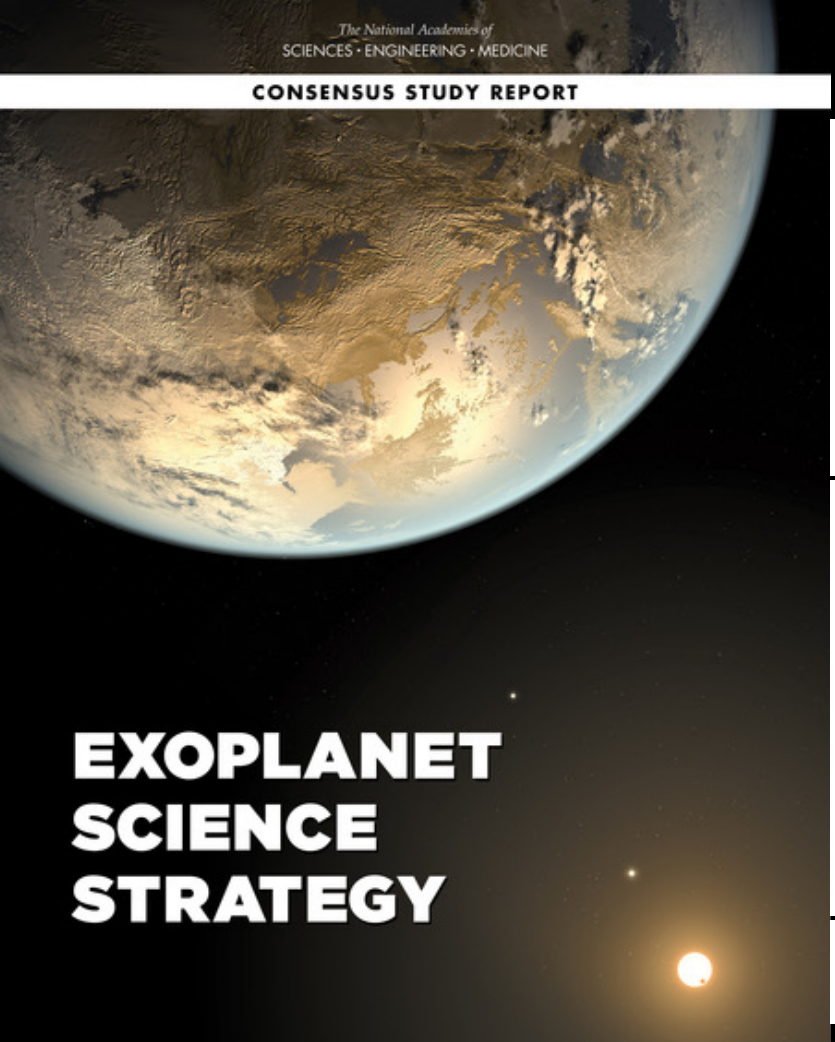


Credit: G. Arney (NASA GSFC) / S. Domagal-Goldman (NASA GSFC) / T. B. Griswold (NASA GSFC)



Credit: background plot from Li Zeng (CfA)

ExEP NASA EXOPLANET EXPLORATION PROGRAM



http://sites.nationalacademies.org/SSB/CurrentProjects/SSB_180659

Finding: A coronagraphic or starshade-based direct imaging mission is the only path currently identified to characterize Earth-size planets in the habitable zones of a large sample of nearby Sun-like stars in reflected light.

Finding: Recently acquired knowledge of the frequency of occurrence of small planets, and advances in the technologies needed to directly image them, have significantly reduced uncertainties associated with a large direct imaging mission.

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. (Chapter 4)

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. (Chapter 4)

Finding: High-precision, narrow-angle astrometry could play a role in the identification and mass measurement of Earth-like planets around Sun-like stars, particularly if the radial velocity technique is ultimately limited by stellar variability.

Radial velocity & astrometric amplitudes: measuring the gravitational tug of exoplanets on their stars

$$K_1 = \frac{8.95\,\mathrm{cm\,s^{-1}}}{\sqrt{1-e^2}} \frac{m_2 \sin i}{M_\oplus} \left(\frac{m_1 + m_2}{M_\odot}\right)^{-1/2} \left(\frac{a}{1\,\mathrm{au}}\right)^{-1/2}$$

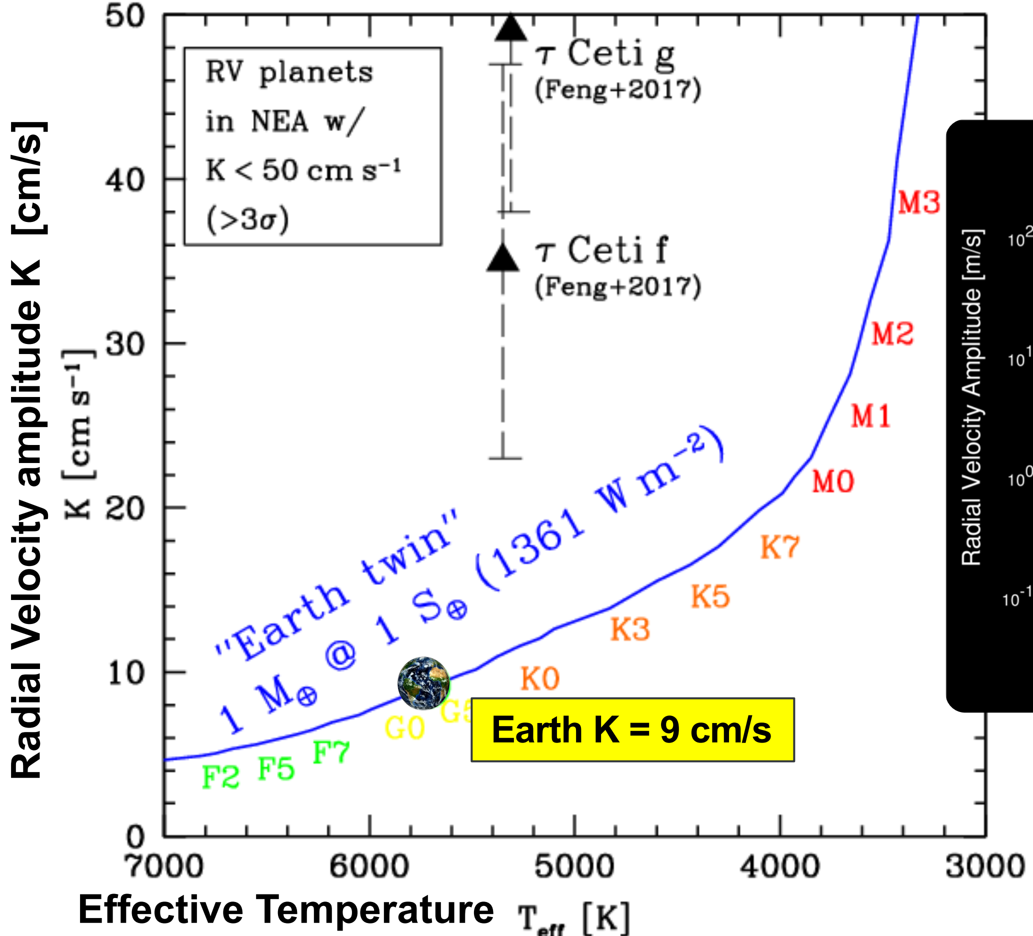
Doppler/RV amplitude

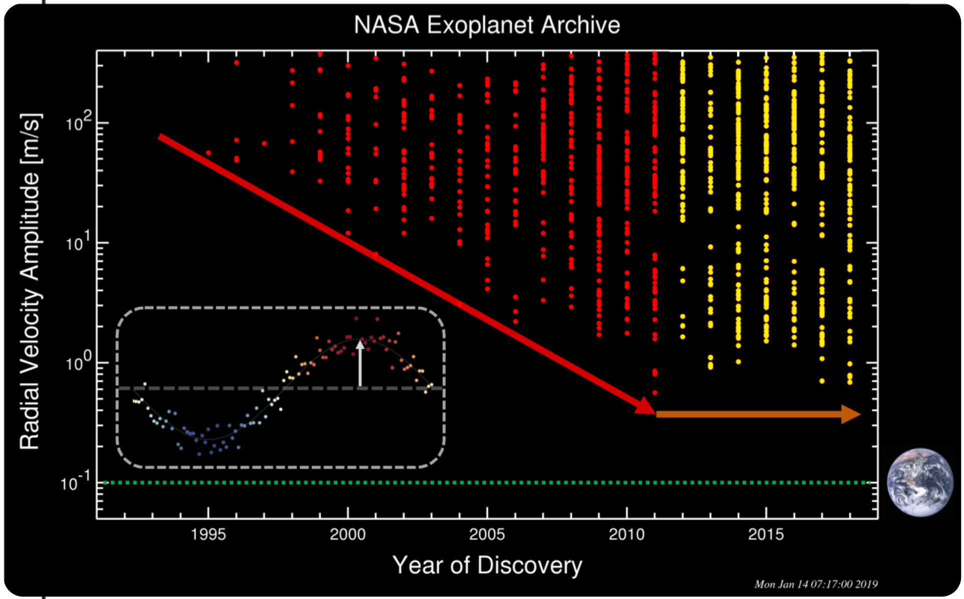
$$\alpha = 3.00 \frac{M_\odot}{M_*} \frac{M_\mathrm{p}}{M_\oplus} \frac{a}{1\ \mathrm{AU}} \frac{1\ \mathrm{pc}}{D}\ \mu\mathrm{as},$$

Astrometric amplitude

refs: Lovis & Fischer 2010, Unwin+2009

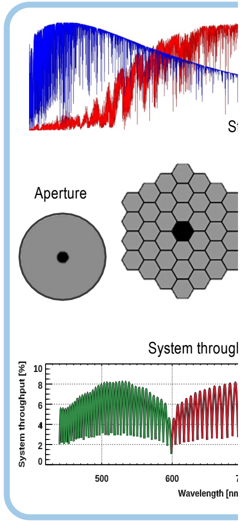
Predicted Radial Velocity Amplitude for 1 M_{Earth} Planet Orbiting in Habitable Zone of Main Sequence Stars





Deconstructing Radial Velocity Measurement Precision

σ photo



Telescope /
and Cad

Pro

Extreme Precision Radial Velocity Working Group

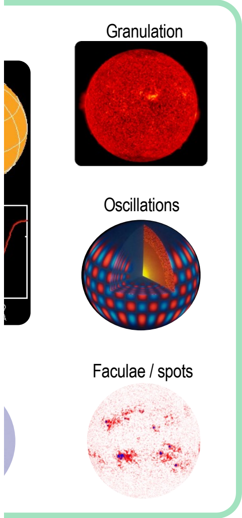
Final Report

July 2021

Edited by:
Jonathan Crass, Department of Physics, University of Notre Dame
Scott Gaudi, Department of Astronomy, The Ohio State University
Stephanie Leifer, Jet Propulsion Laboratory, California Institute of Technology

https://arxiv.org/abs/2107.14291
https://exoplanets.nasa.gov/exep/NNExplore/EPRV/

σ star



Variability and
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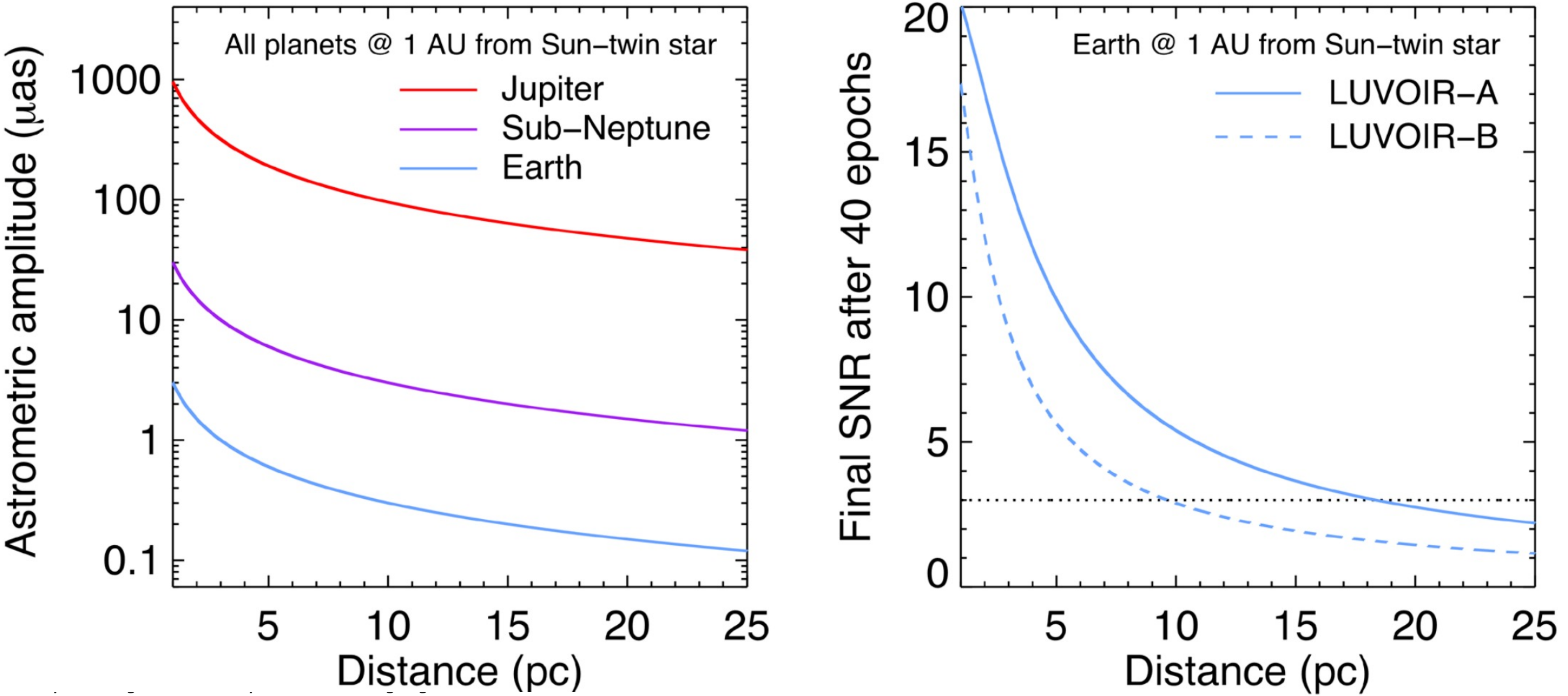
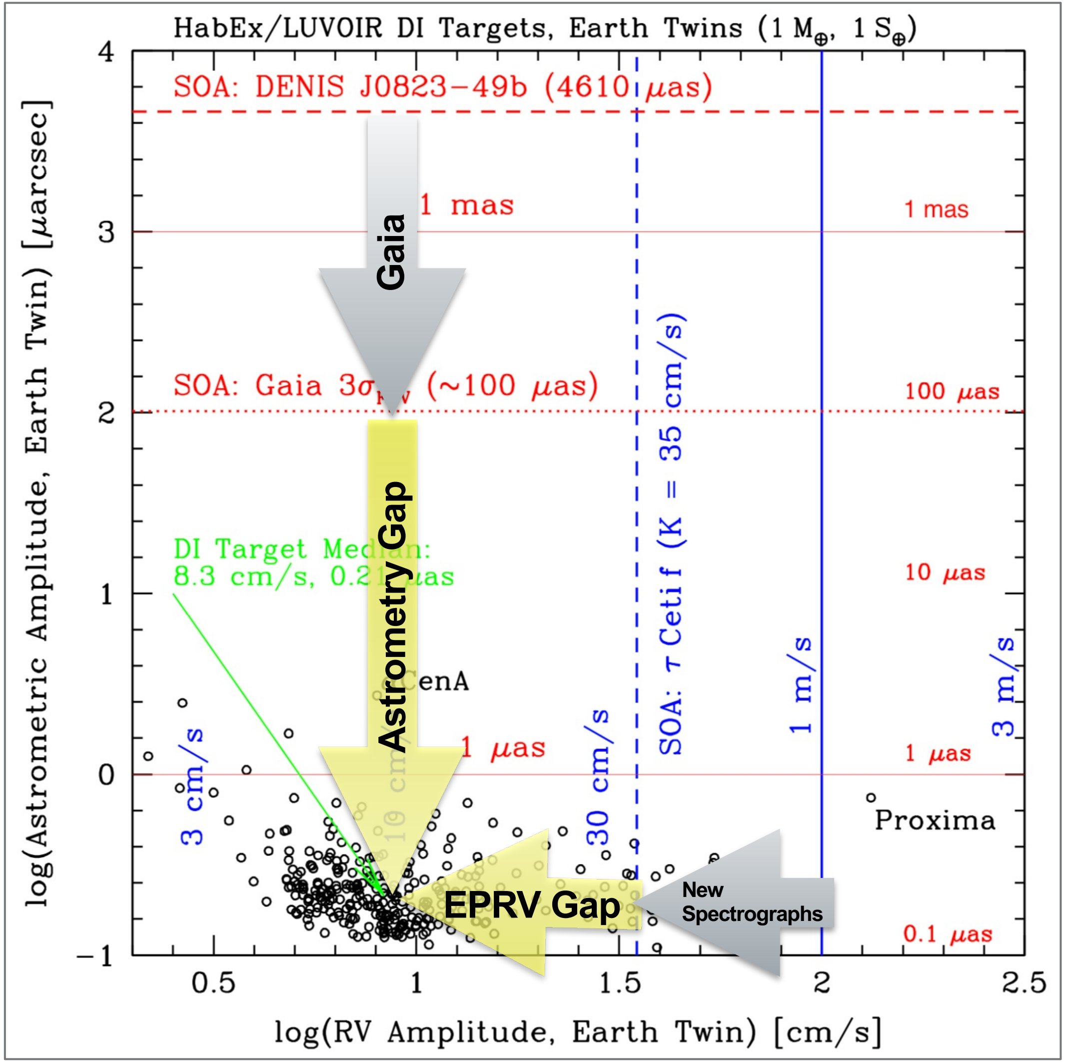
Initial prospects for astrometry – LUVOIR study

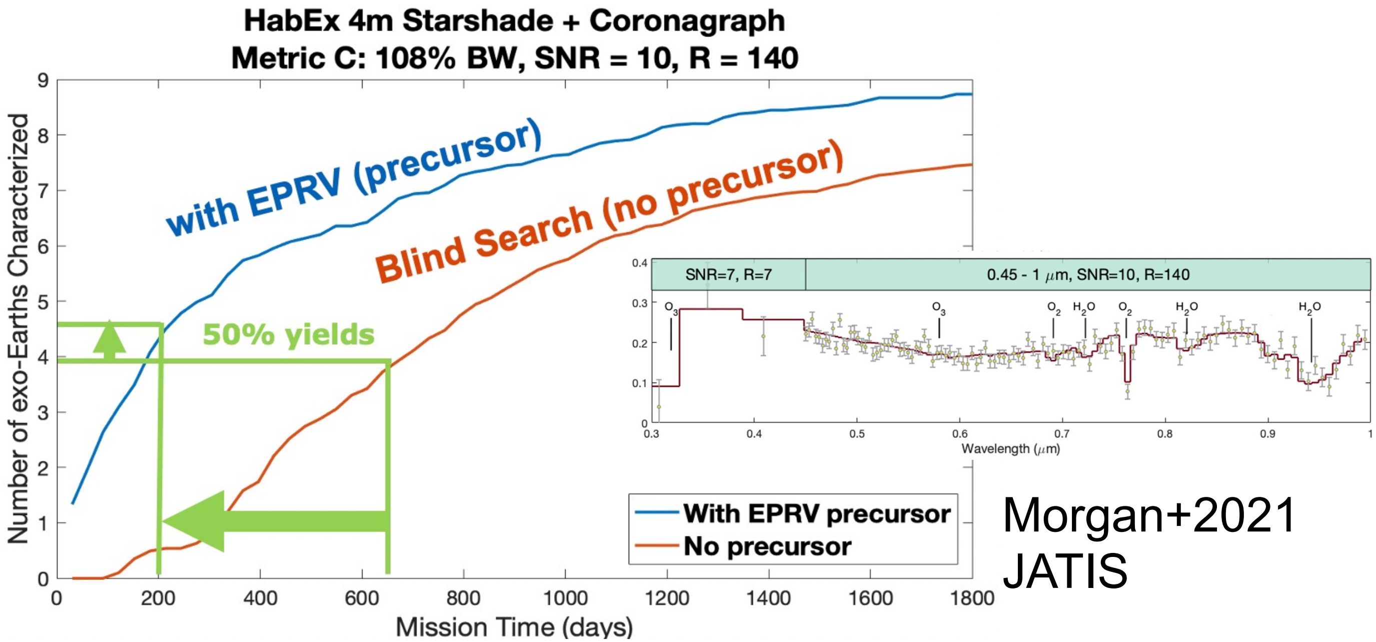


Credit: D. Windemuth (UW) / A. Roberge (NASA GSFC)



Predicted astrometric & radial velocity amplitudes for exo-Earth twins (Earth mass, insolation) orbiting LUVOIR & HabEx target stars (mostly FGK stars within 25pc)

Extremely Precise Radial Velocities Accelerates the ExoEarth Yield for Flagship



Morgan+2021 JATIS

- **EPRV precursor observations reduce mission time to achieve 50% of yield or characterized planets by a factor of 3!**
  - High impact science occurs earlier in the mission, allowing time for follow up characterization
  - More immediate science results excite the public and science community
  - Mitigates risk of early mission failure
- **EPRV makes missions more nimble and powerful**
  - Precursor spectral targets on Mission Day 1 ensure robust scheduling opportunities for starshade arrival at optimal viewing epochs

Important Open Questions for the Community to Guide the “Mass Strategy” for the IROUV Space Observatory Recommended by Astro2020

1. *What degree of precursor knowledge will we want* for the masses and orbits of exoplanets (esp. small HZ planets) imaged and spectrally characterized by IROUV?

2. *What are the astrophysical and technical limits to the accuracy of the astrometry and radial velocity techniques*, with respect to the goals of measuring accurate masses for potentially habitable worlds orbiting IROUV target stars?

3. *What are the astrometry capability options* in support of IROUV exoplanet imaging/spectroscopy science?

4. *What combination of astrometry and radial velocity capabilities will we plan to* for accurately measuring the masses and orbits of potentially habitable worlds orbiting IROUV target stars?

Thoughts on options for community to consider for ‘mass strategy’ for IROUV mission

Measure precursor mass/orbit data **before** exo-Earth imaging/spectroscopy

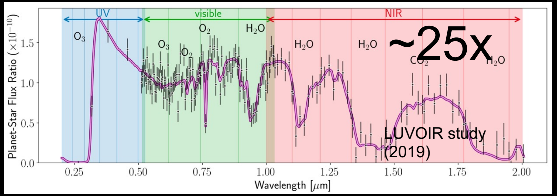
- ***EPRV Initiative*** *– follow EPRV Working Group plan - reach decision point in mid/late 20s on feasibility of ground EPRV solution (but we already know ~30% of stars not amenable to EPRV for exo-Earths, maybe higher)*
- ***Advance options for astrometry from space w/dedicated mission****? What scale(s)? When? Who?*

Measure precursor mass/orbit data **during/after** exo-Earth imaging/spectroscopy

- ***Astrometry w/Astro2020 mission*** *concept studies was just started to be explored in concept study reports, but further analysis and exploration of options needed (see A. Roberge talk)*

Live without accurate masses for some (possibly most) exo-Earths imaged/spectroscopically characterized

- *“Best effort” - Accept that EPRV can’t measure masses for all small planets for which direct imaging mission can measure spectra. Accept risk to Decadal goal (~25x...) of not having precursor orbit/mass knowledge before IROUV mission.*



Sagan Summer Workshop

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Voyager 1 (1990) “Pale Blue Dot” Credits: NASA/JPL-Caltech

Backup Slides

Jet Propulsion Laboratory
California Institute of Technology

exoplanets.nasa.gov

Extreme Precision Radial Velocity Working Group

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

Methodology

ExEP NASA EXOPLANET EXPLORATION PROGRAM

- Established Terms of Reference: membership, ground rules
  - World experts (>50)
  - Open, accessible via google drive folder
- Formed an EPRV working group (~36)
- Established eight sub-groups
  - (bi-)weekly teleconferences
  - each formulating research recommendations
- Held 3 face-to-face, multi-day workshops (St. Louis, New York, Washington)
  - Used Kepner-Trego methods to develop solution
    - formulated decision statement
    - Formulated success criteria
    - formulated candidate architectures
    - conducted weighted trade studies and accounted for risks
  - and established an "existence proof" that the EPRV objective can be achieved
  - reached full consensus on above
- Conducted Red Team review (02/06/2020)
- Held ExoTAC briefing (03/10/2020)

Decision Statement: Recommend the best ground-based program architecture and implementation (aka Roadmap) to achieve the goal of measuring the masses of temperate terrestrial planets orbiting Sun-like stars

NASA NSF

Extreme Precision Radial Velocity Working Group

Final Report

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