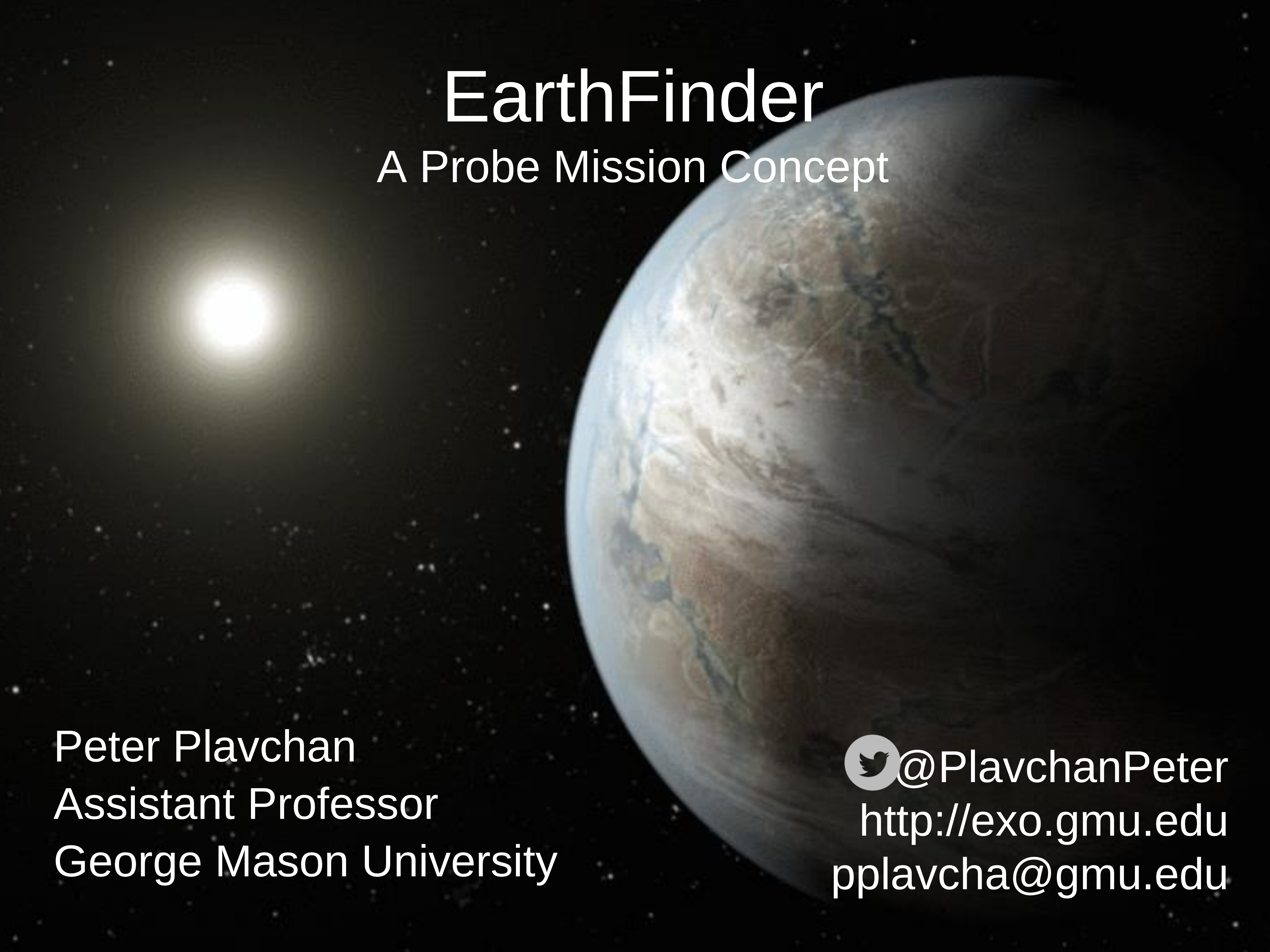

EarthFinder

A Probe Mission Concept

Peter Plavchan
Assistant Professor
George Mason University

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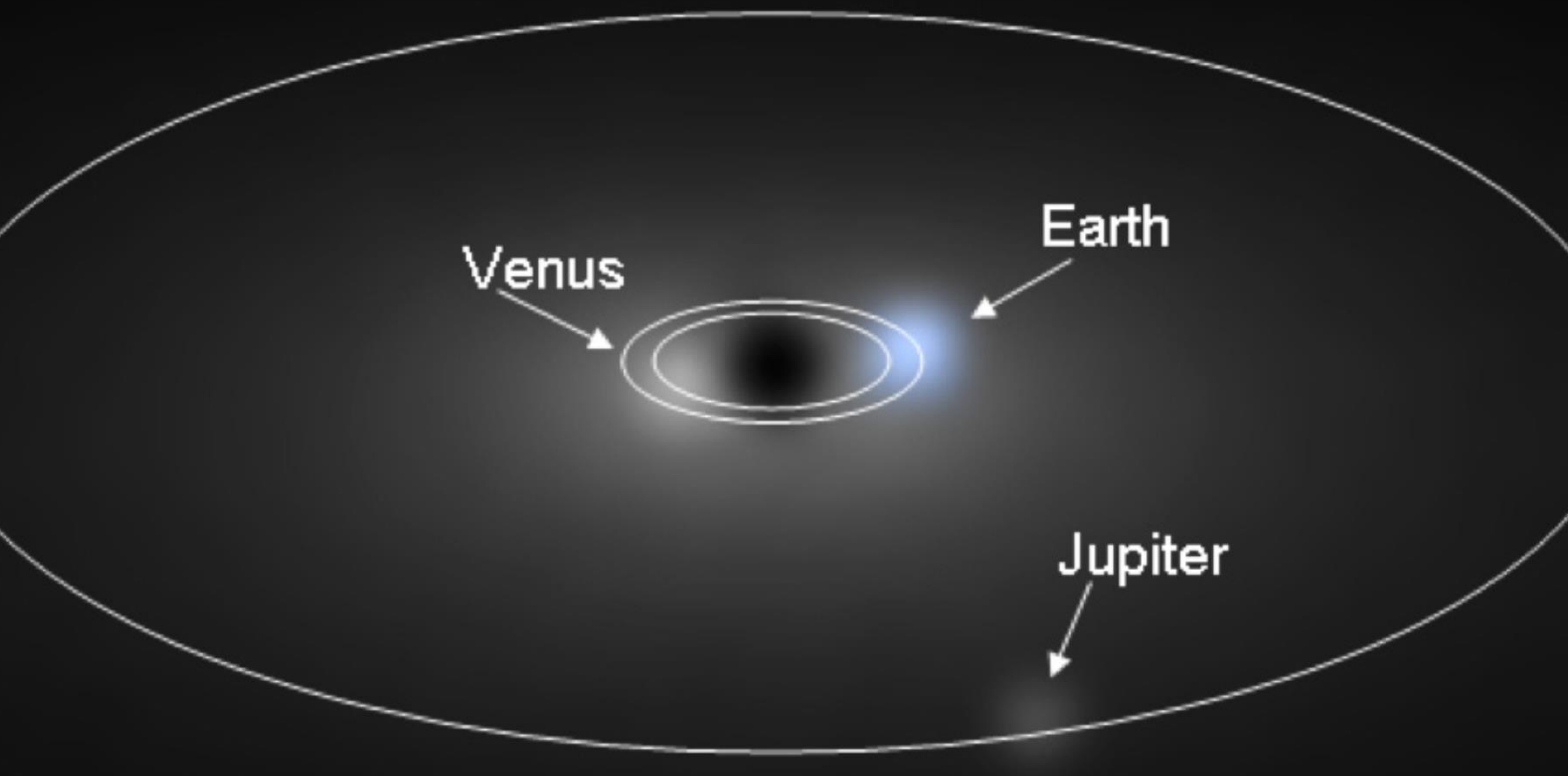
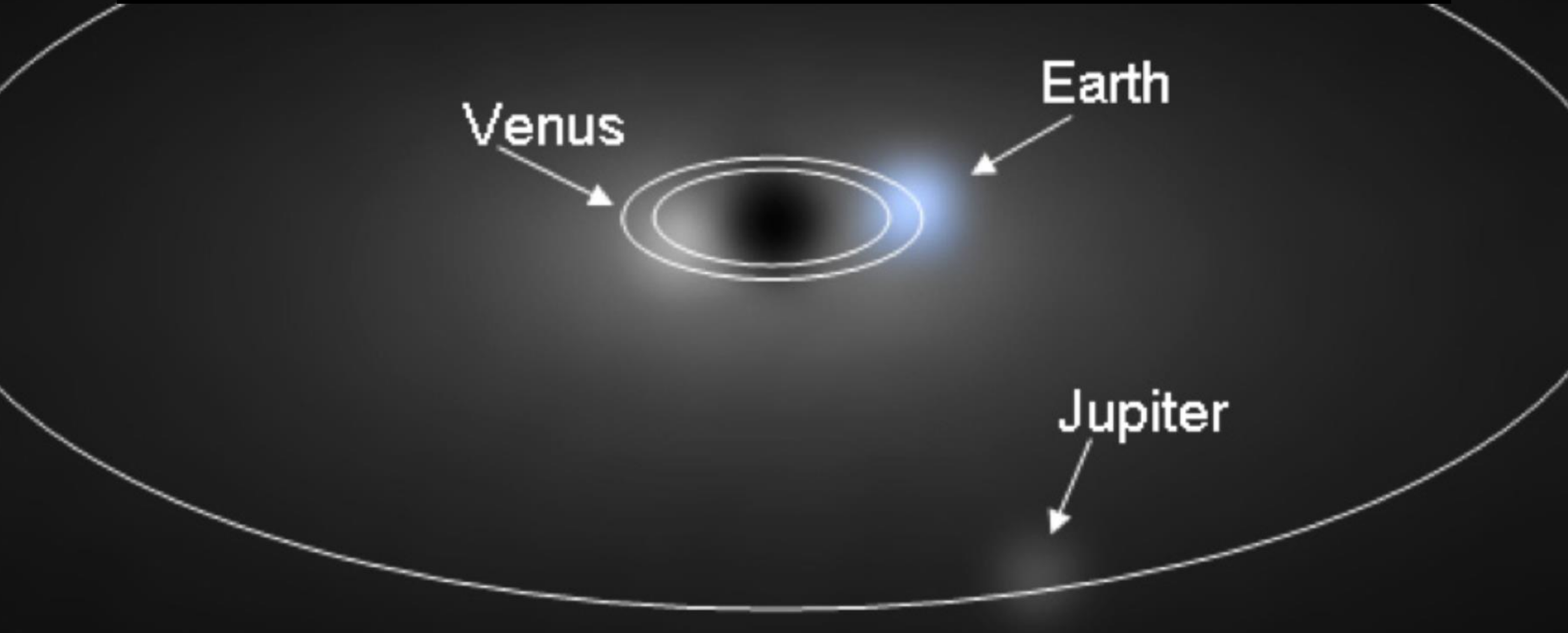
pplavcha@gmu.edu

Mission Landscape



How many stars do we need to look at?
How big (expensive) does the telescope need to be?
Will we know where and when to look?



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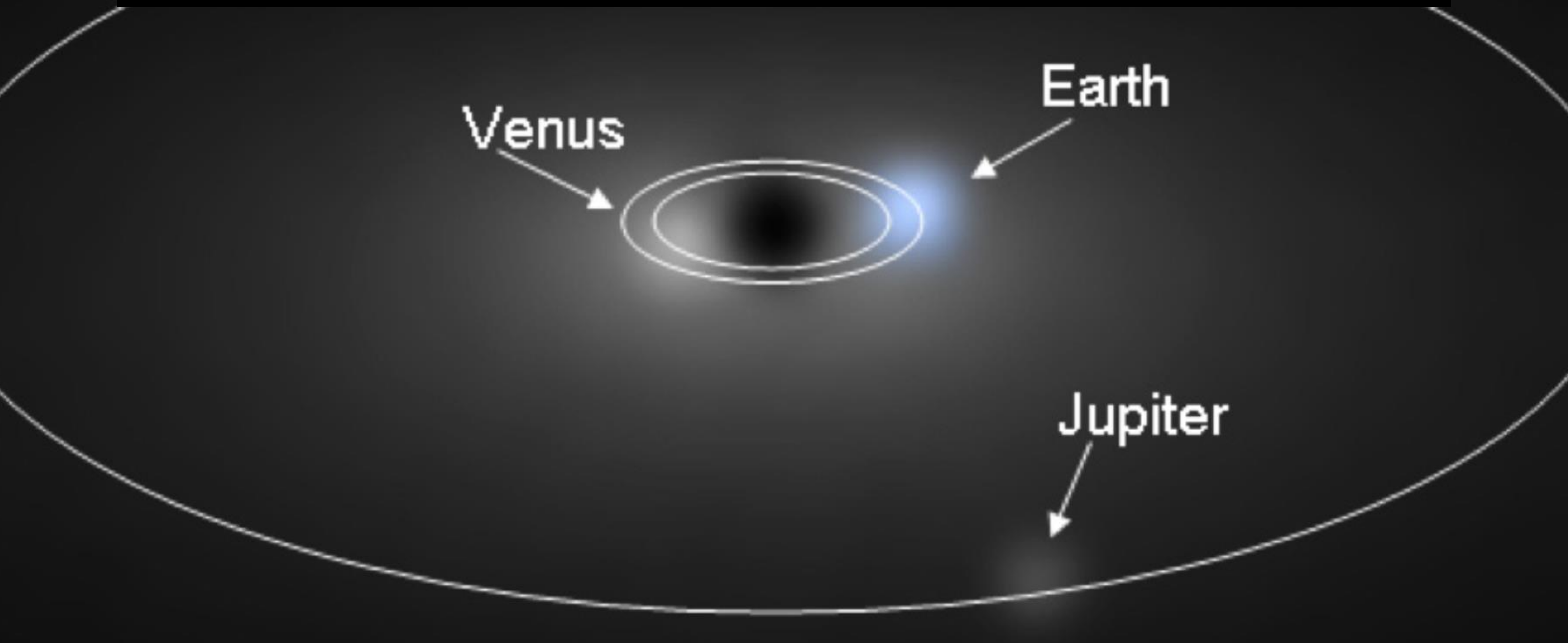
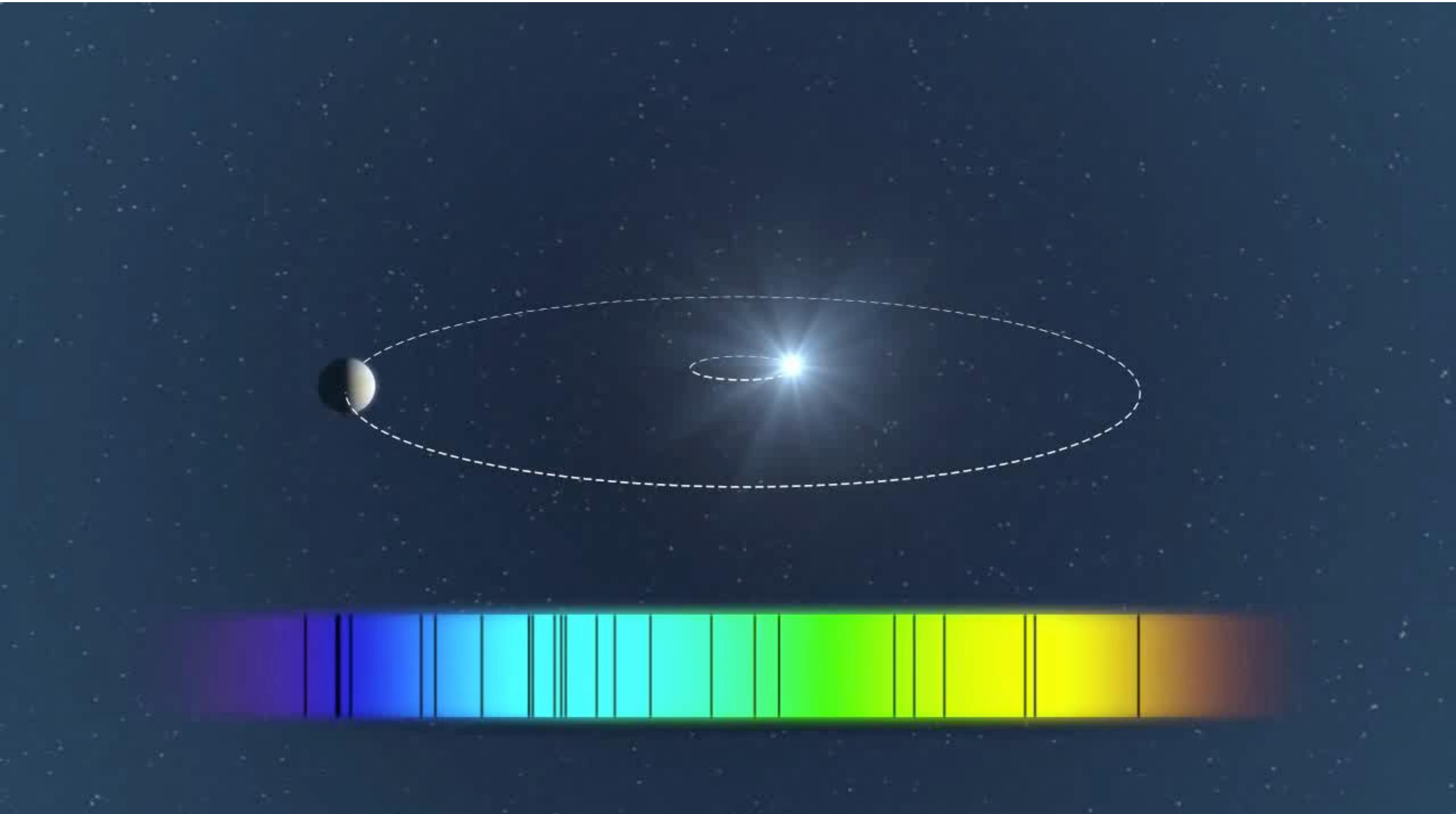
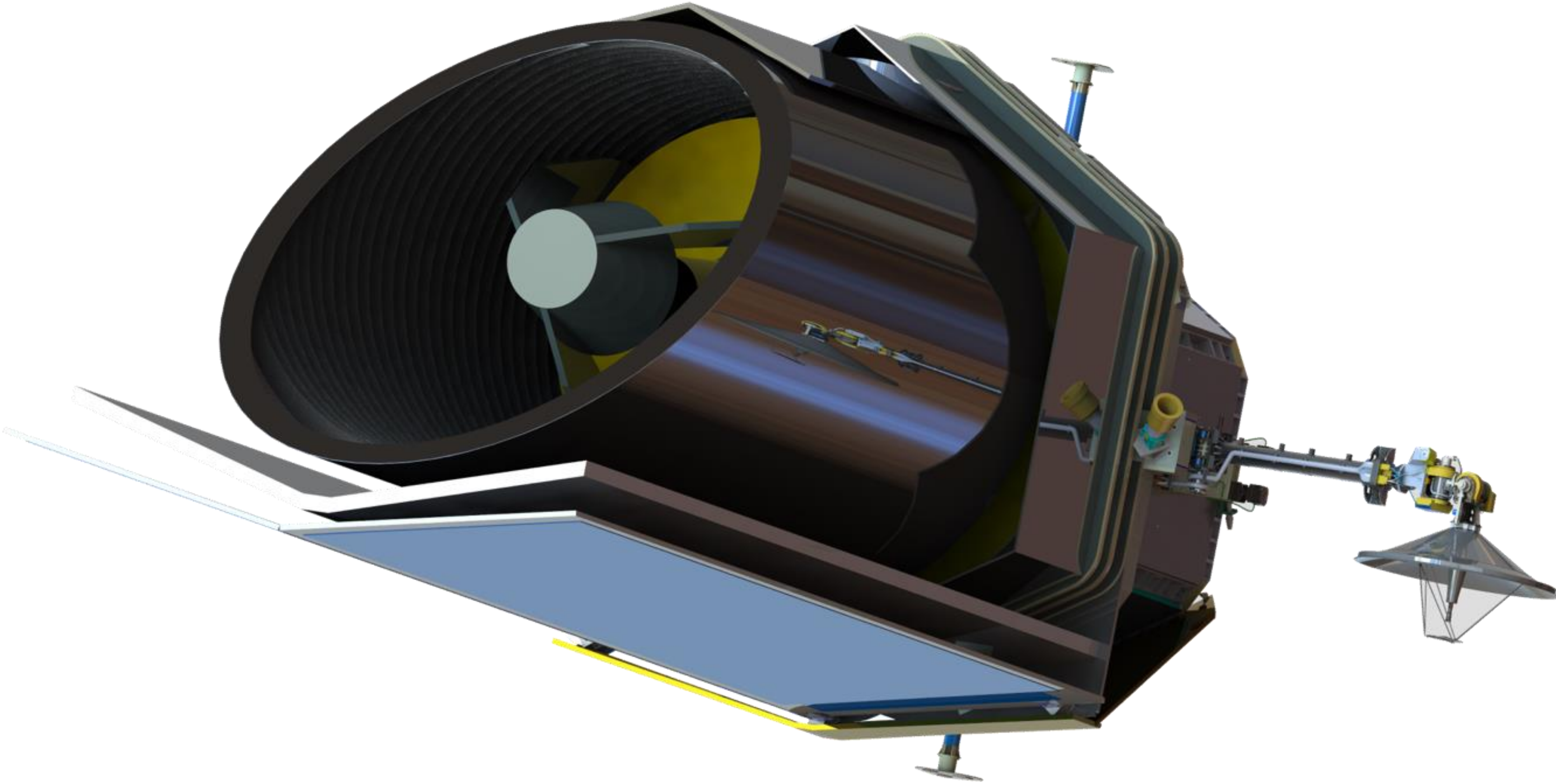


Either way, we will still need the planet masses for characterization!

The Doppler Method

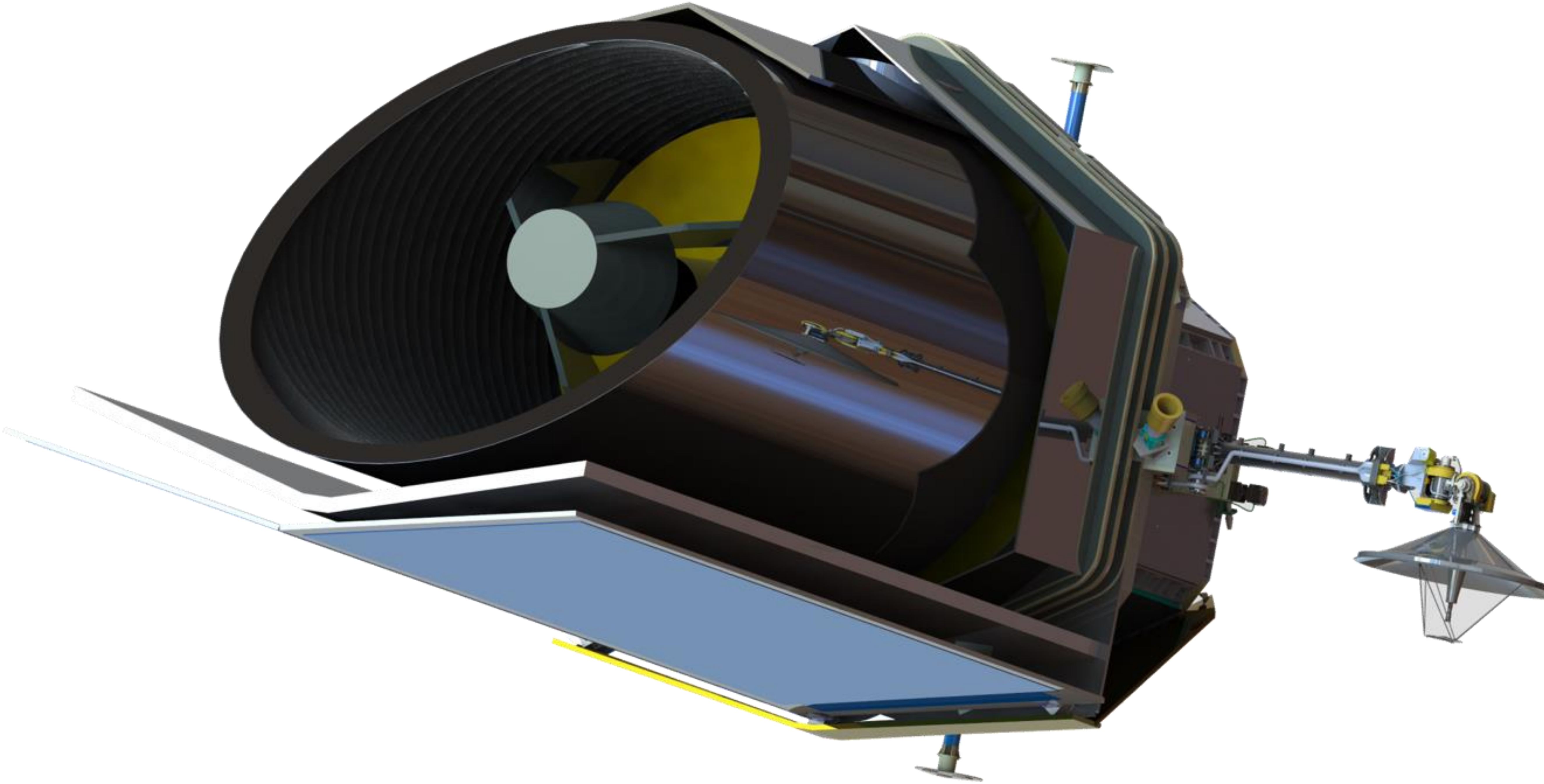


EarthFinder



Credit: Ball Aerospace

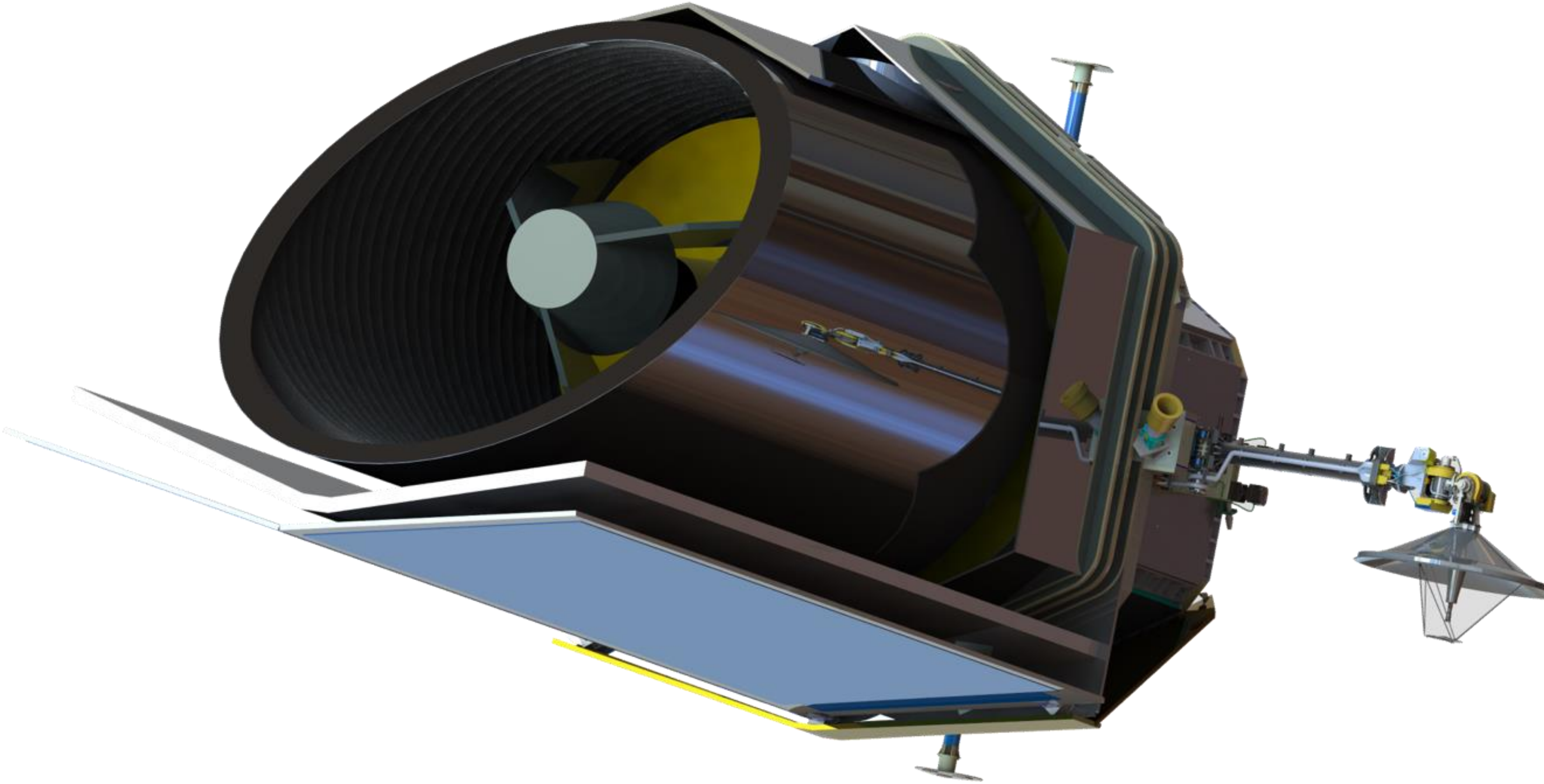
EarthFinder



Radial Velocities …

Credit: Ball Aerospace

EarthFinder

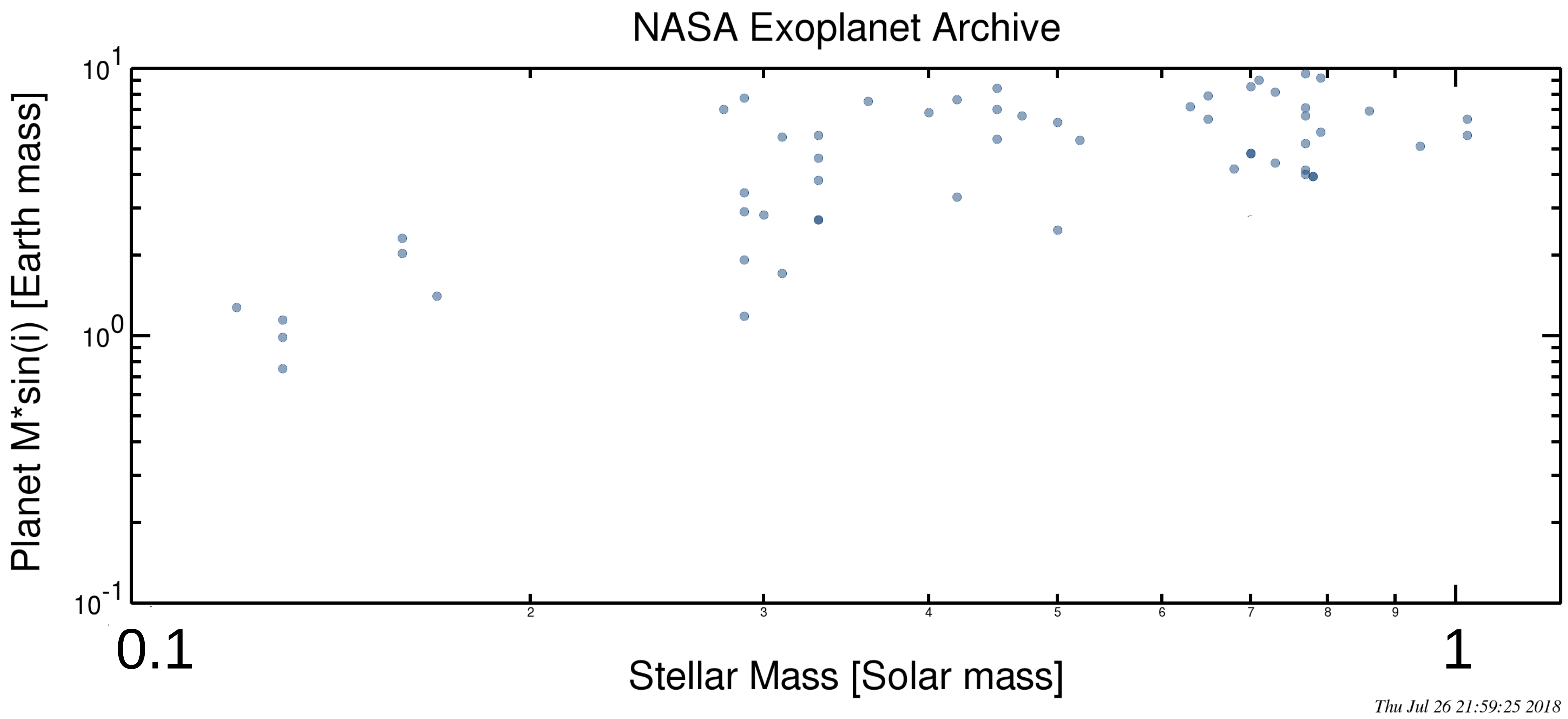


Radial Velocities … ***in space!***

Credit: Ball Aerospace

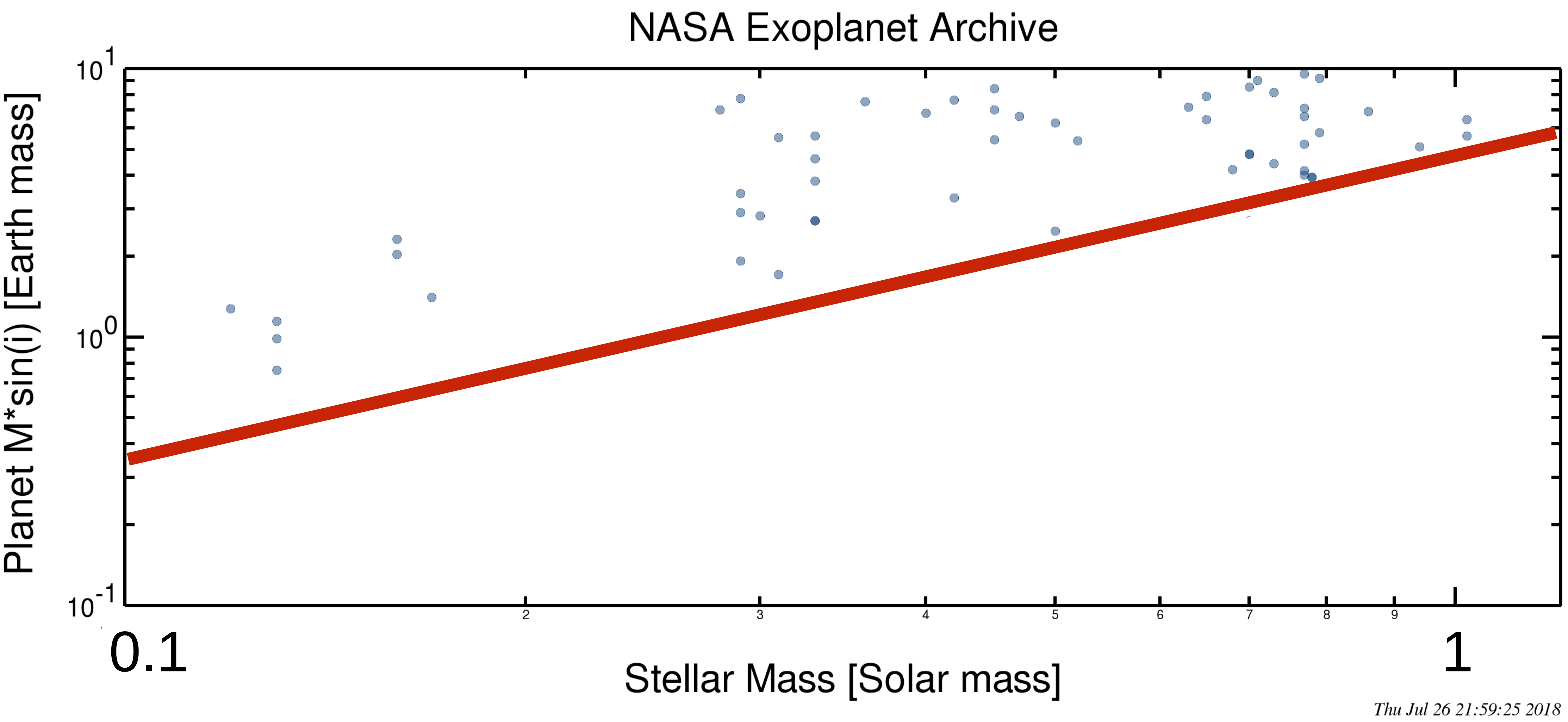
Science

Discovery, mass and orbit characterization of Earth-mass exoplanets orbiting nearest Sun-like stars



Science

Discovery, mass and orbit characterization of Earth-mass exoplanets orbiting nearest Sun-like stars



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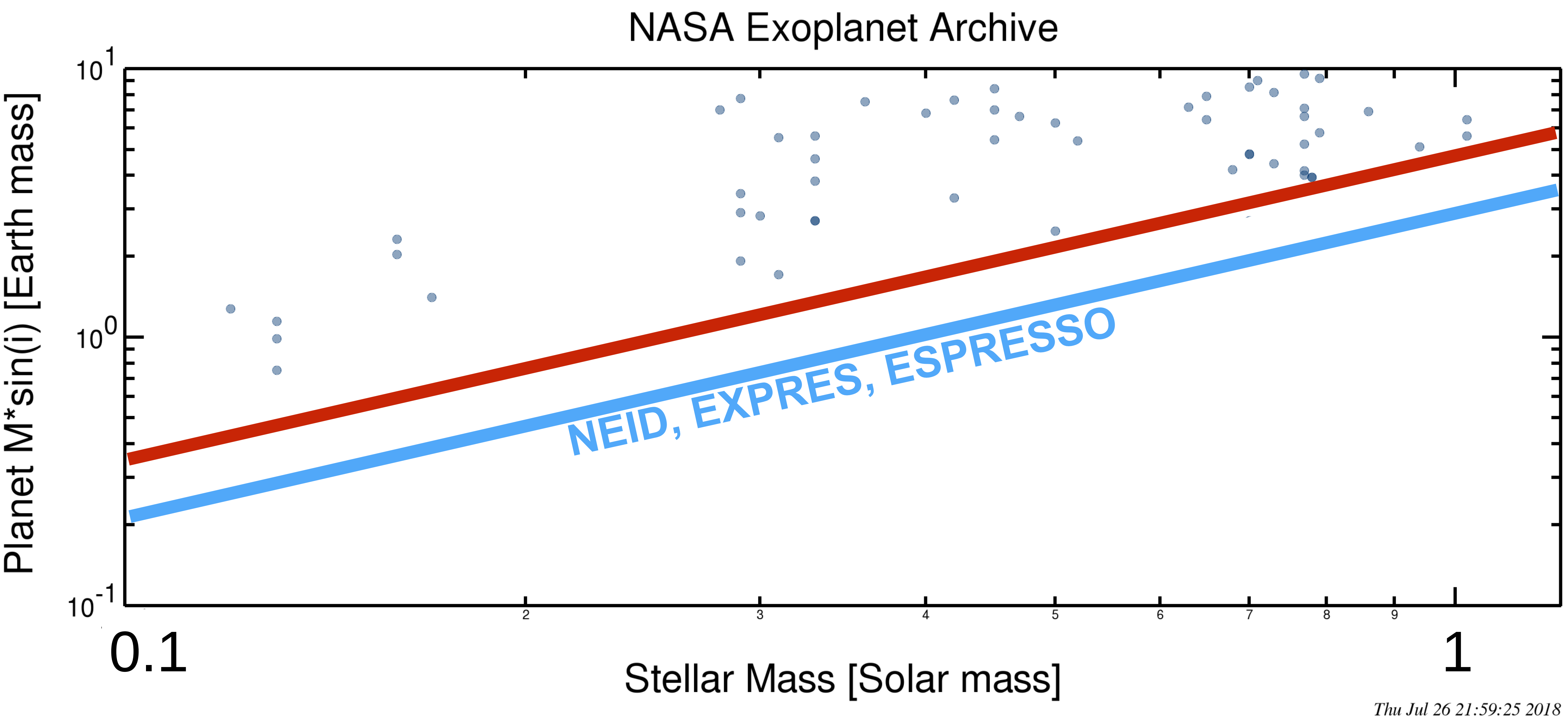

Science

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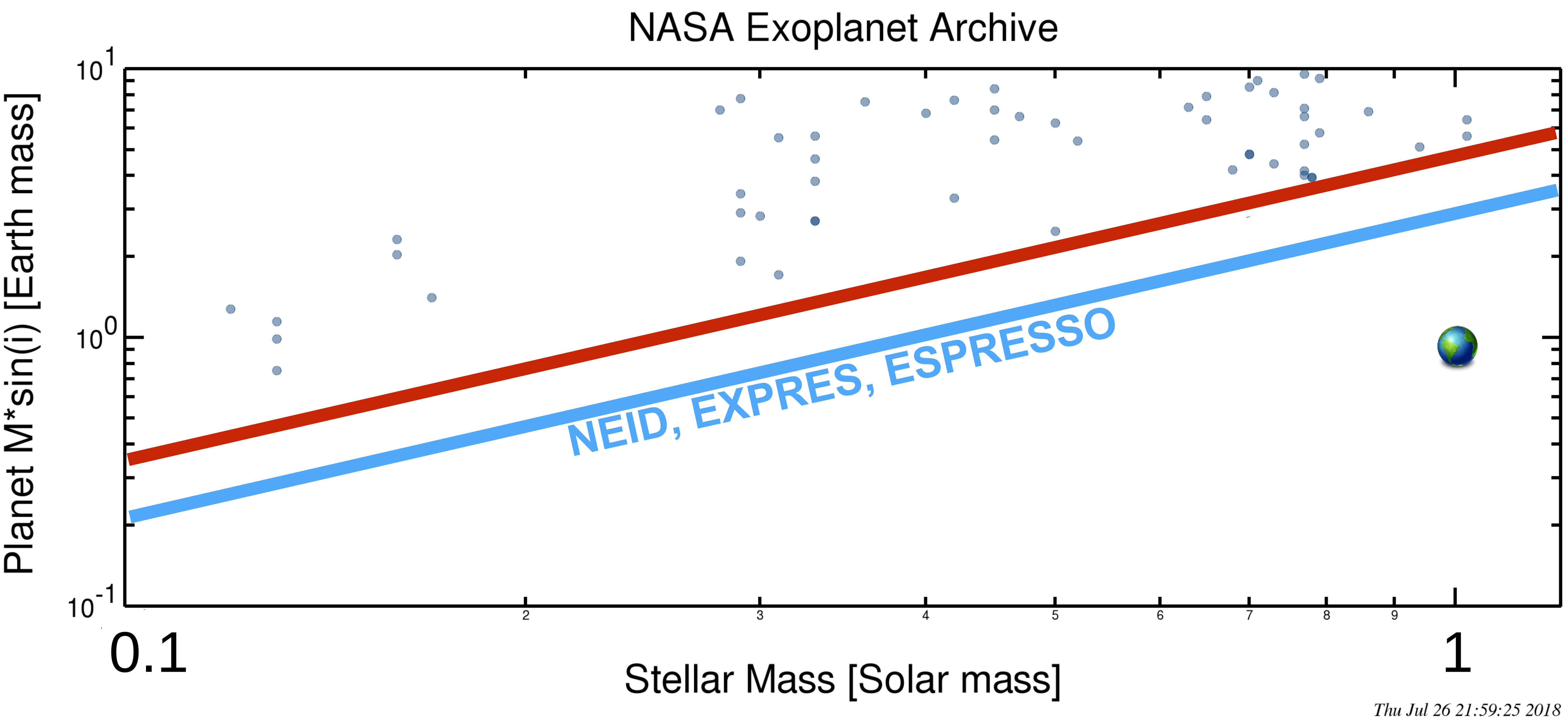

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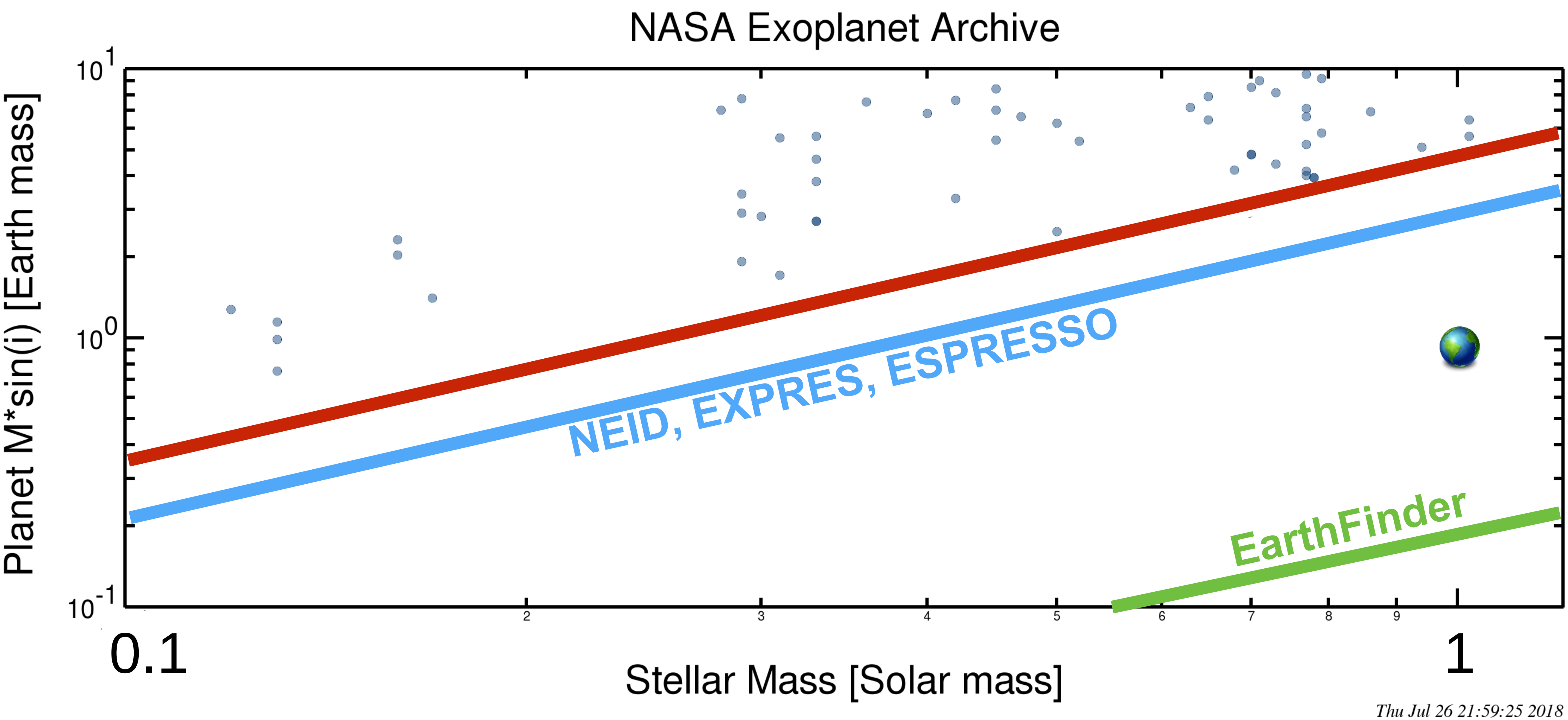

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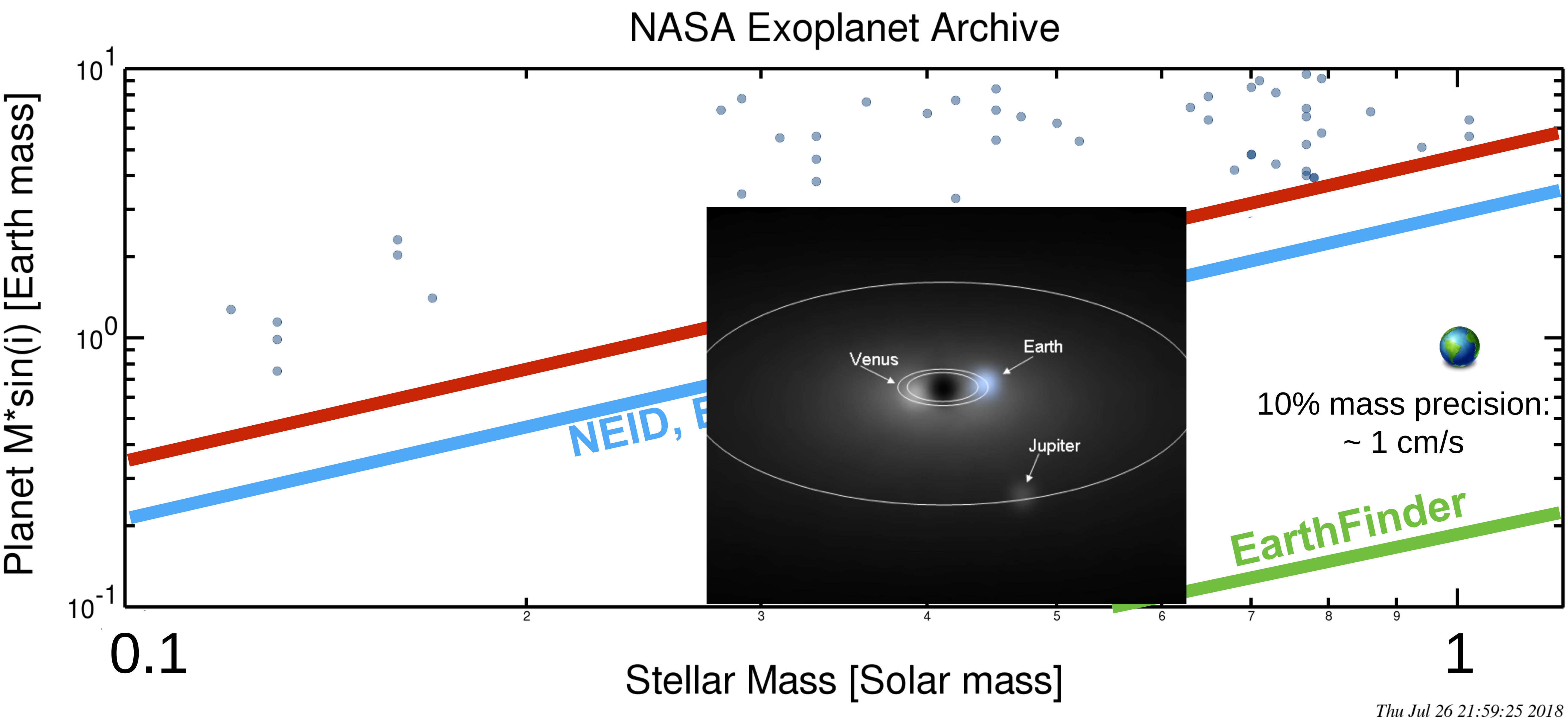
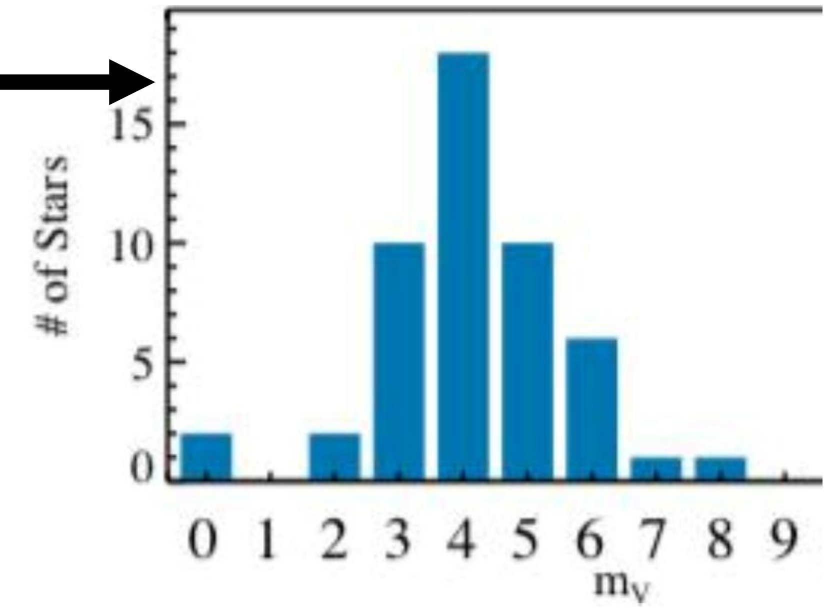
Discovery, mass and orbit characterization of Earth-mass exoplanets orbiting nearest Sun-like stars

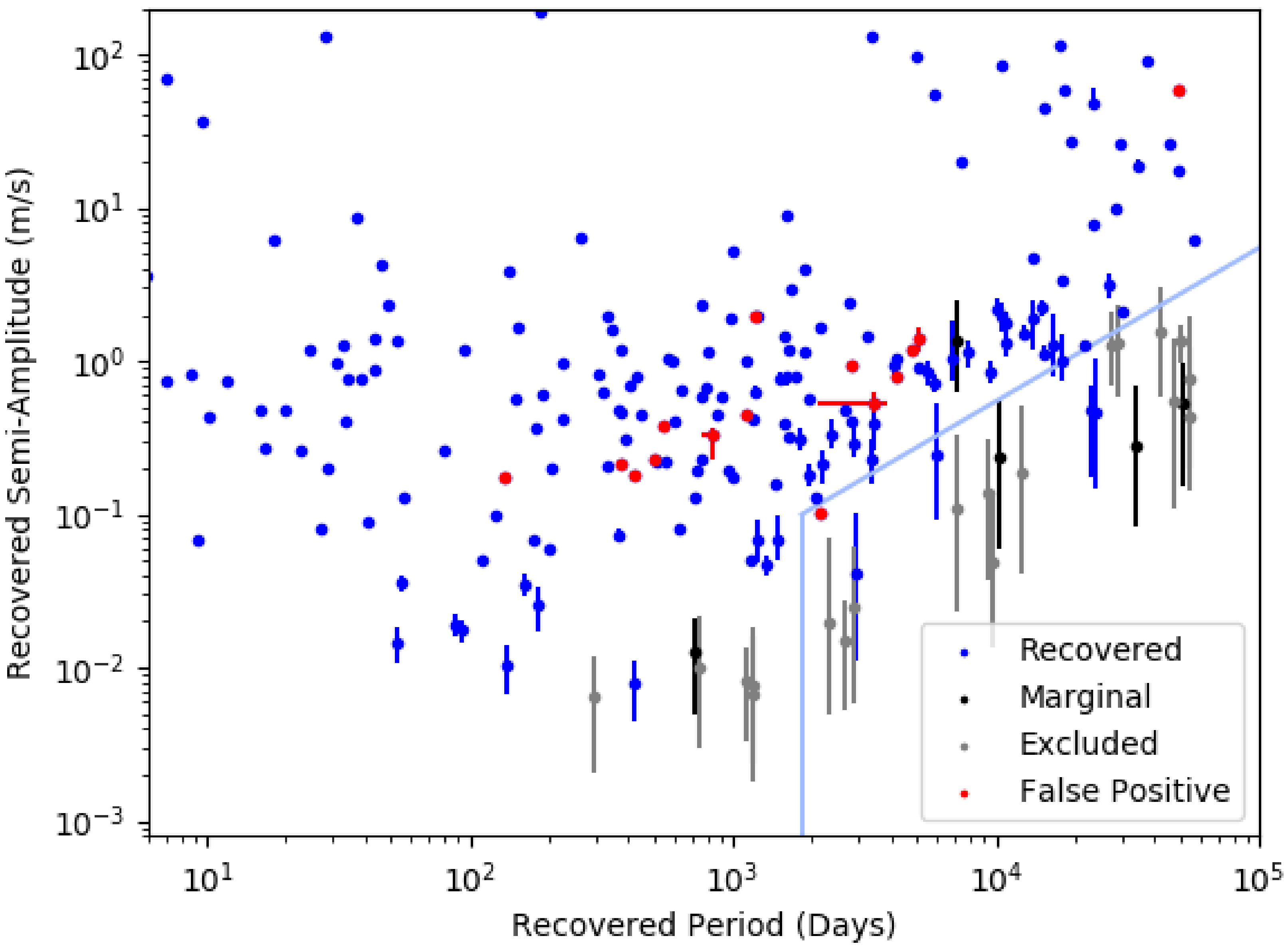


Survey Yield

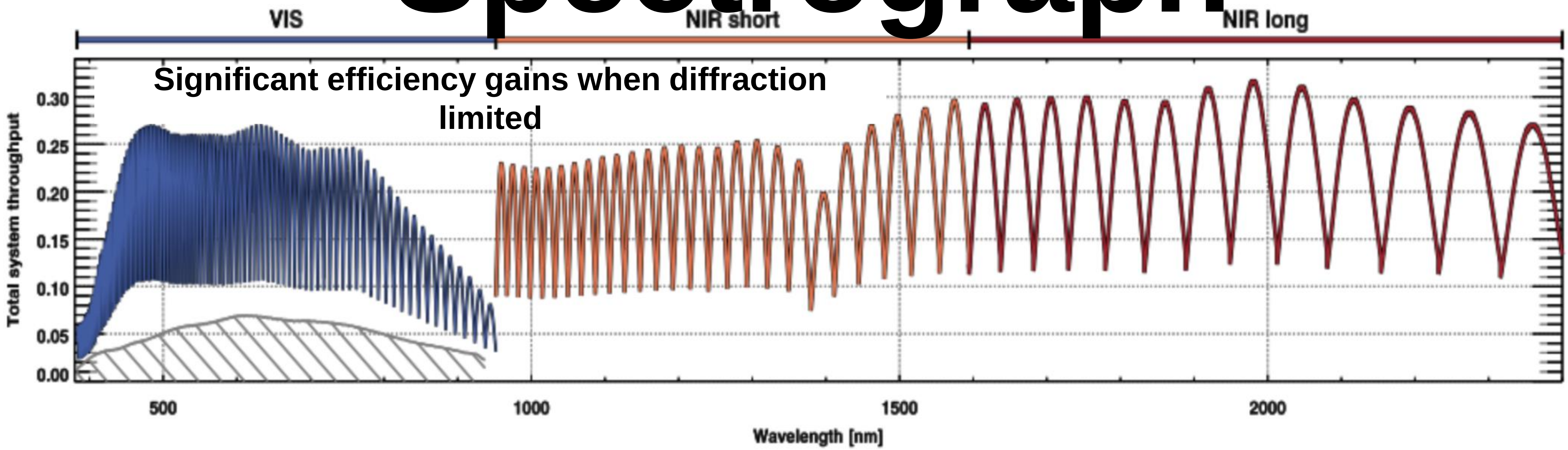
Simulated yield from 5 year survey
- 63 HabEx **direct imaging** targets
- Simulated planetary systems for each
- Simulated space-cadence with EarthFinder field of regard
- With perfect stellar activity correction



Yes, EarthFinder can recover Earth-mass planets orbiting the target stars (e.g. it has the photons)

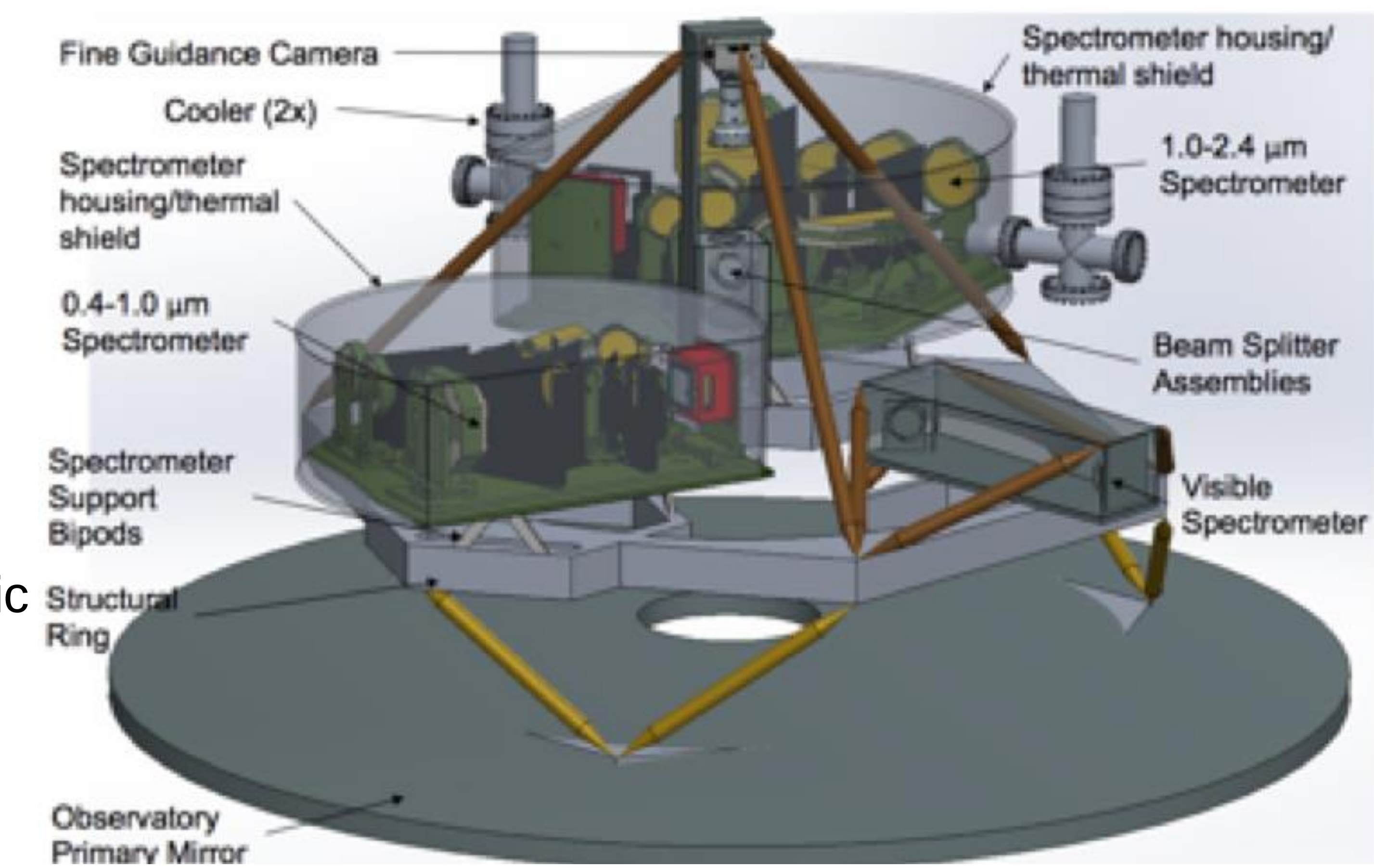


Spectrograph



Spectrograph:

- High-resolution (R~150-200k)
- Diffraction-limited (Single mode fiber spatial illumination stability)
- Compact: 50x100 cm
- Laser frequency micro-comb wavelength calibration & 1 cm/s thermal stability
- Visible arm: 380-900 nm
- NIR arm: 900-2400 nm
- Small UV arm for 280 nm MgI chromospheric activity indicator
- No moving parts except fast steering mirror
- High TRL except LFC/etalon tech which is rapidly advancing



Why space?

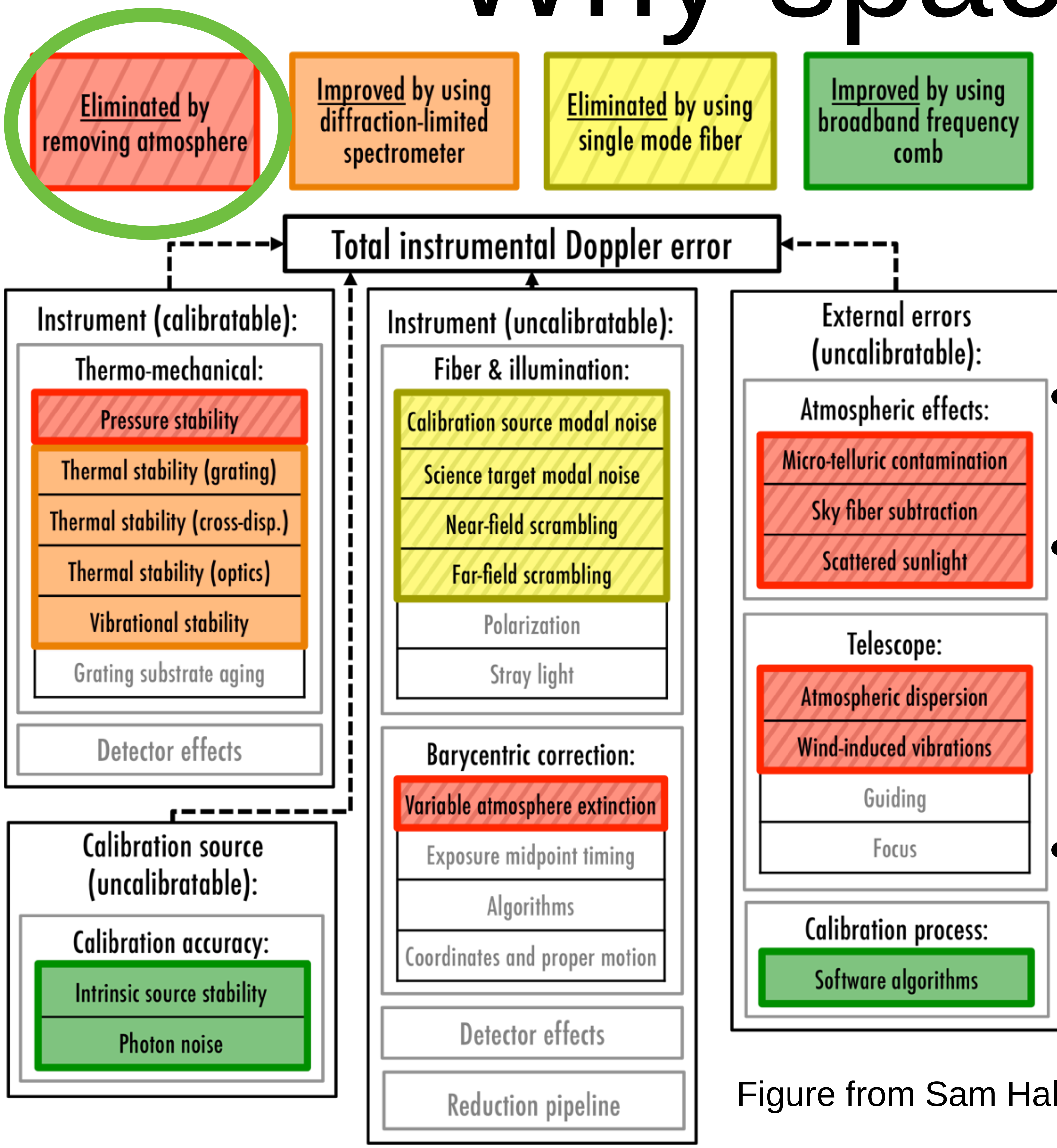
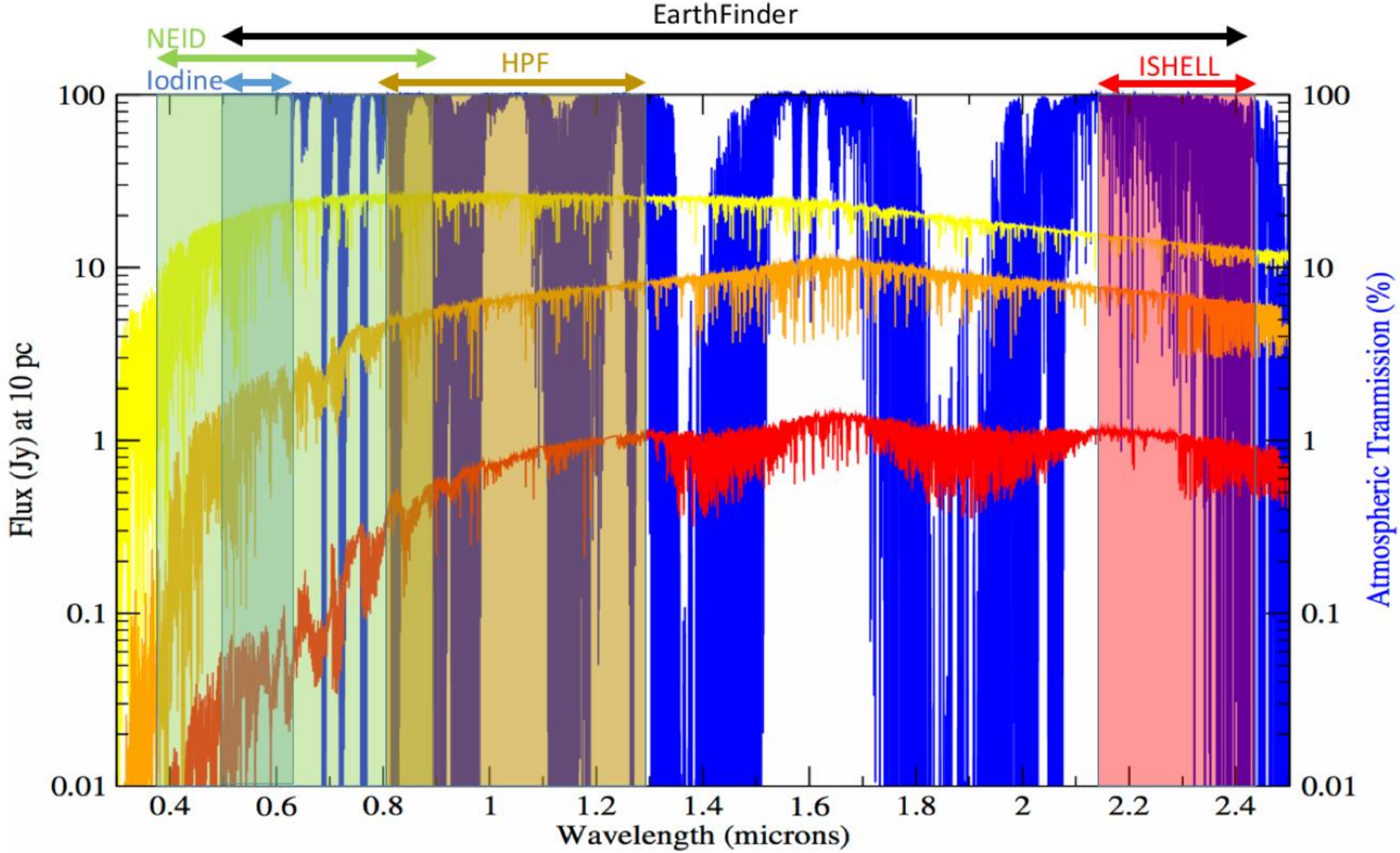


Figure from Sam Halverson

Three top reasons:

- Remove tellurics completely
- Very wide spectral grasp with precise absolute continuum normalization
- Ideal uniform random cadence

Will the Earth's atmosphere limit RV precision on the ground?



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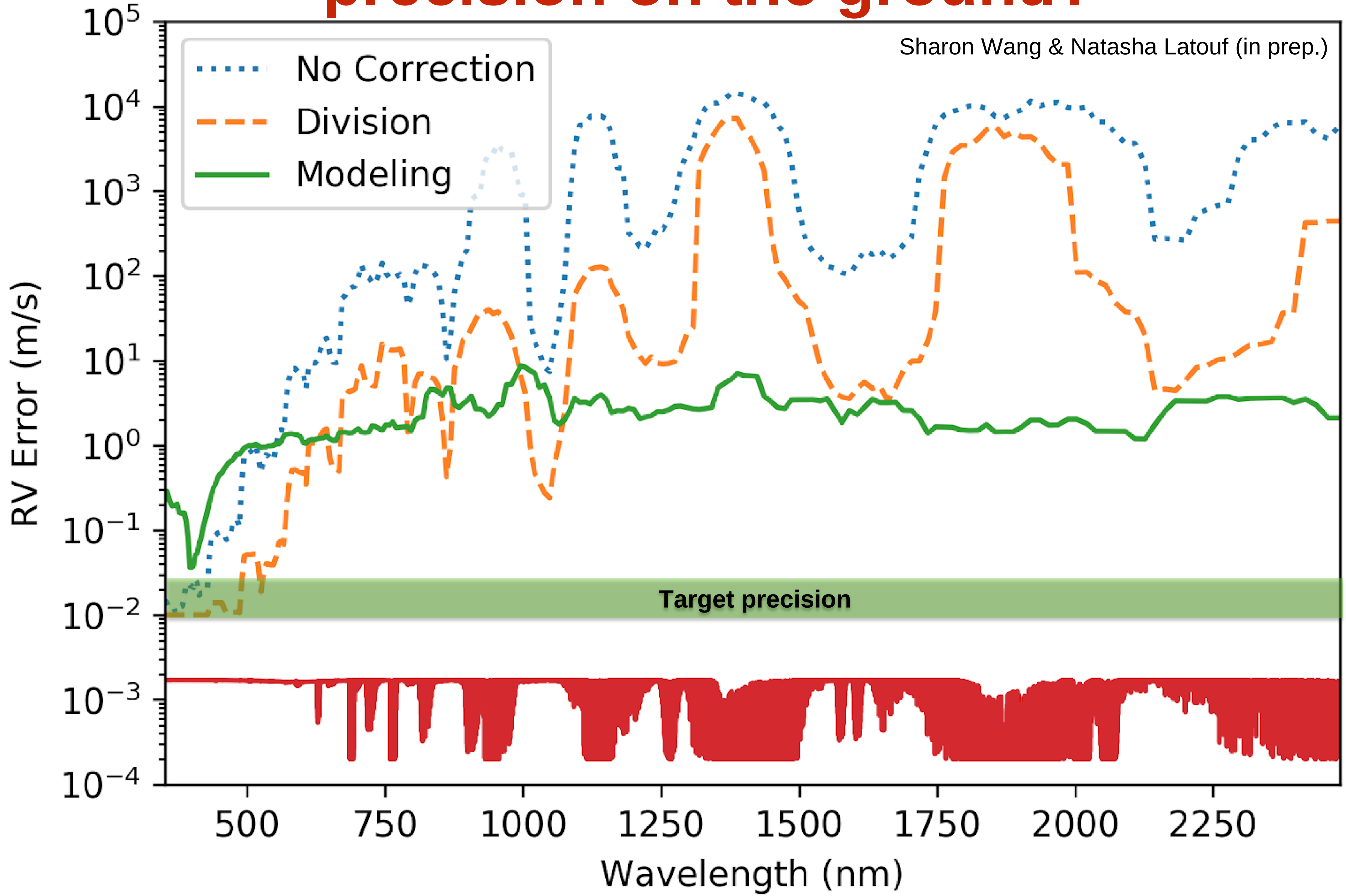

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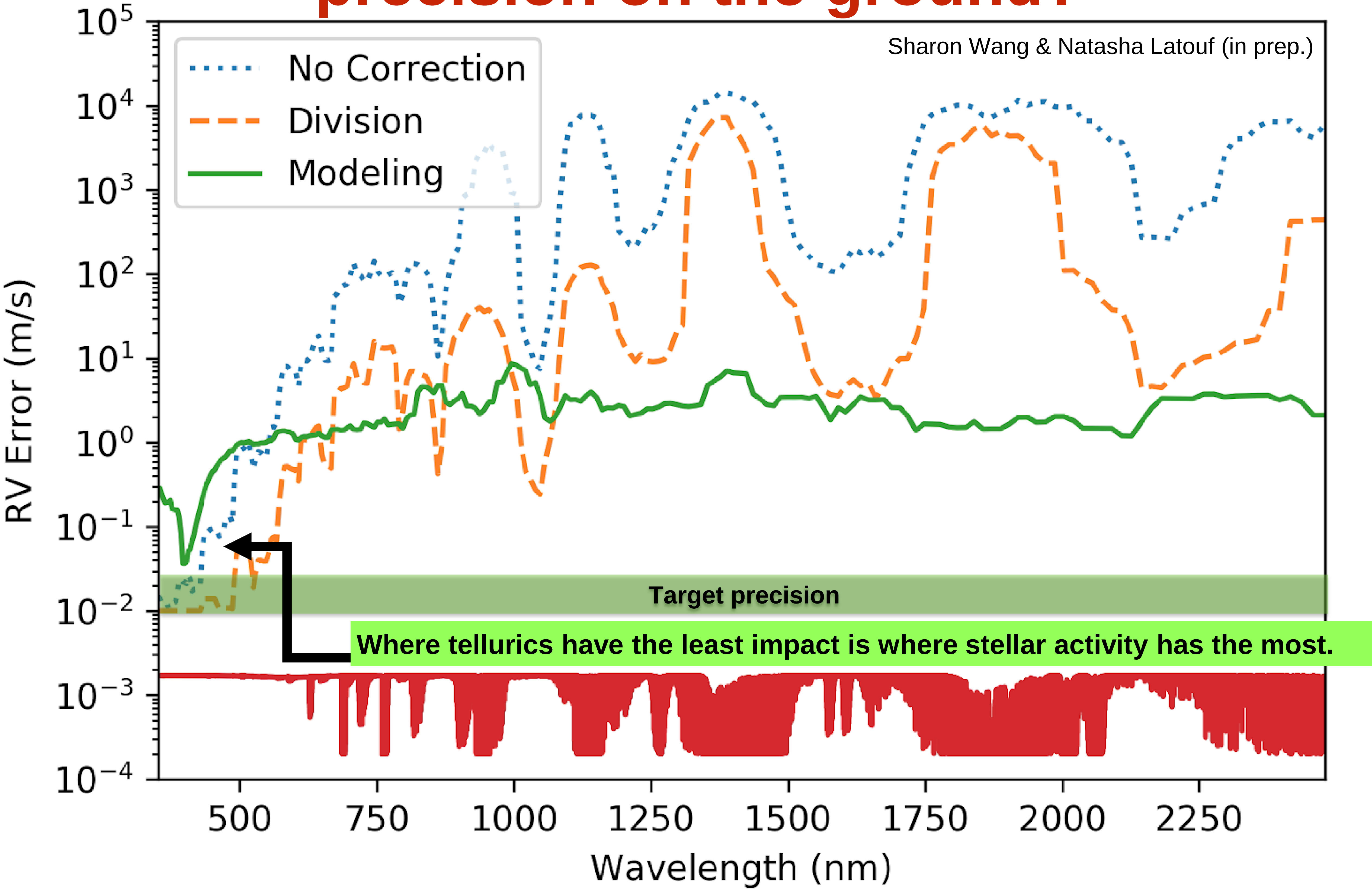

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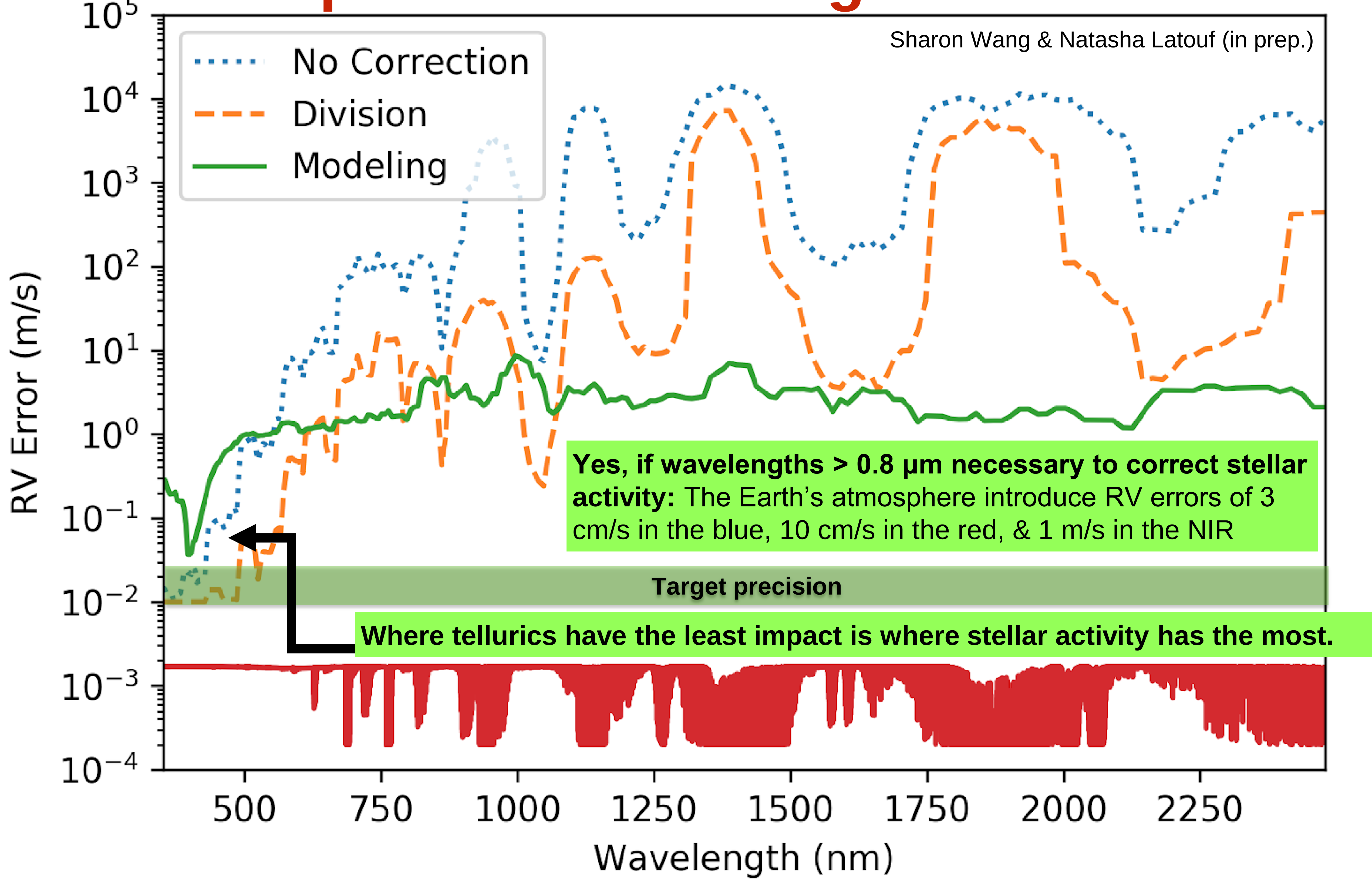


Can we "solve" stellar activity?

<u>Approaches under exploration for activity mitigation:</u>

Wavelength Coverage (e.g. CARMENES)

Cadence (e.g. MINERVA)

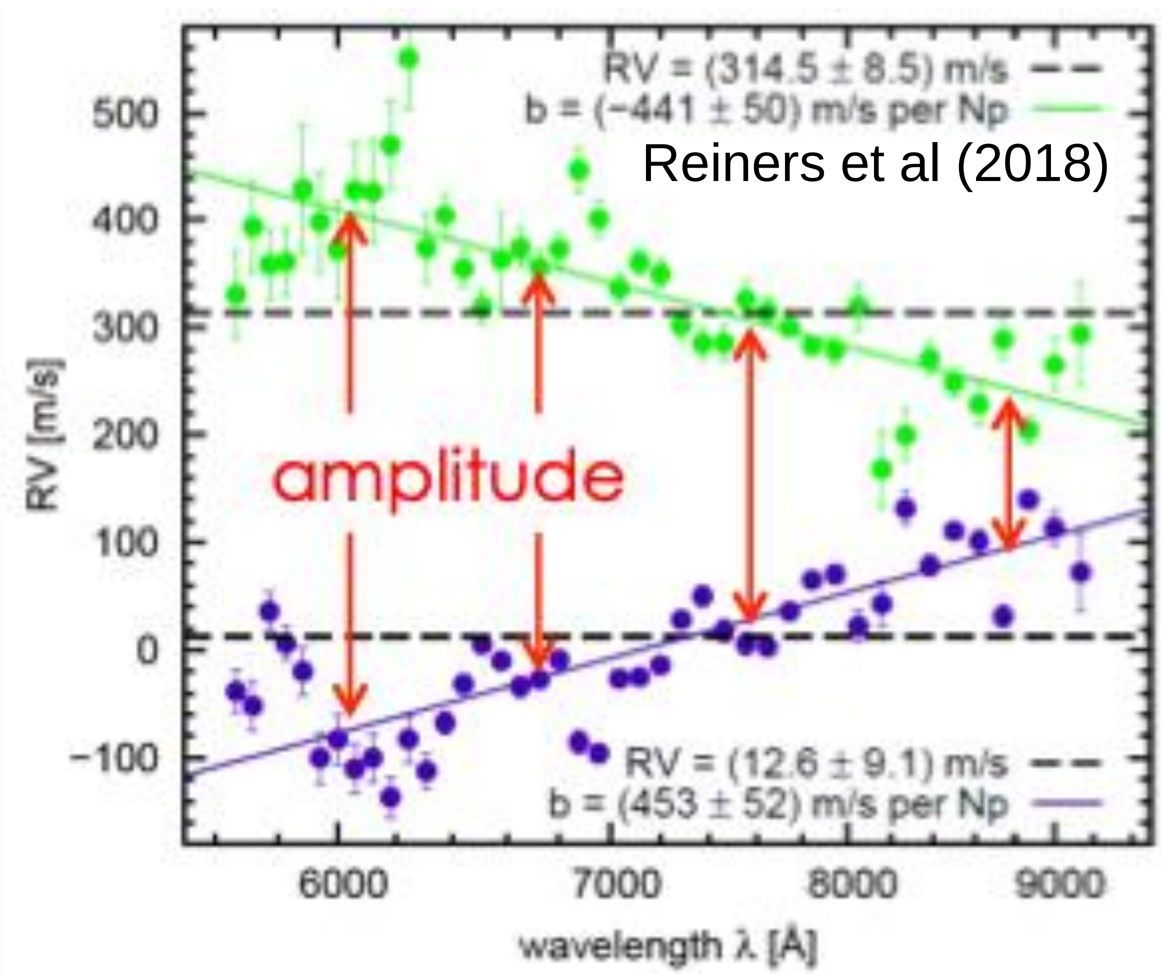
R~200k resolution (e.g. ESPRESSO)

Line-by-line analysis (Lanza et al. 2018)

Simultaneous photometry (e.g. Oshagh et al. 2017, RVxK2)

Wavelength Coverage

To first order, RV~1/λ was expected for cool starspots (eg Reiners et al. 2010),and observed for T Tauri stars, Barnard's star with HARPS, and now CARMENES:



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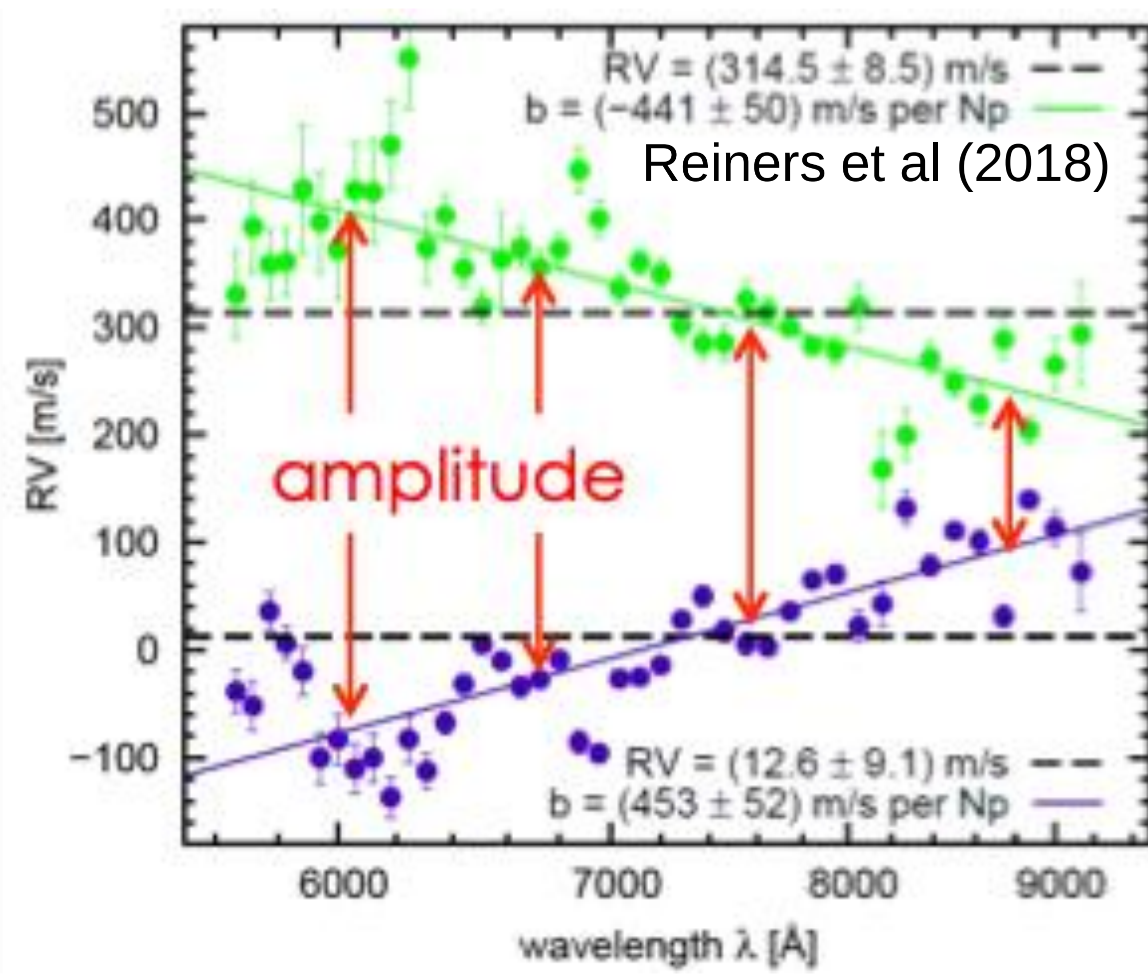
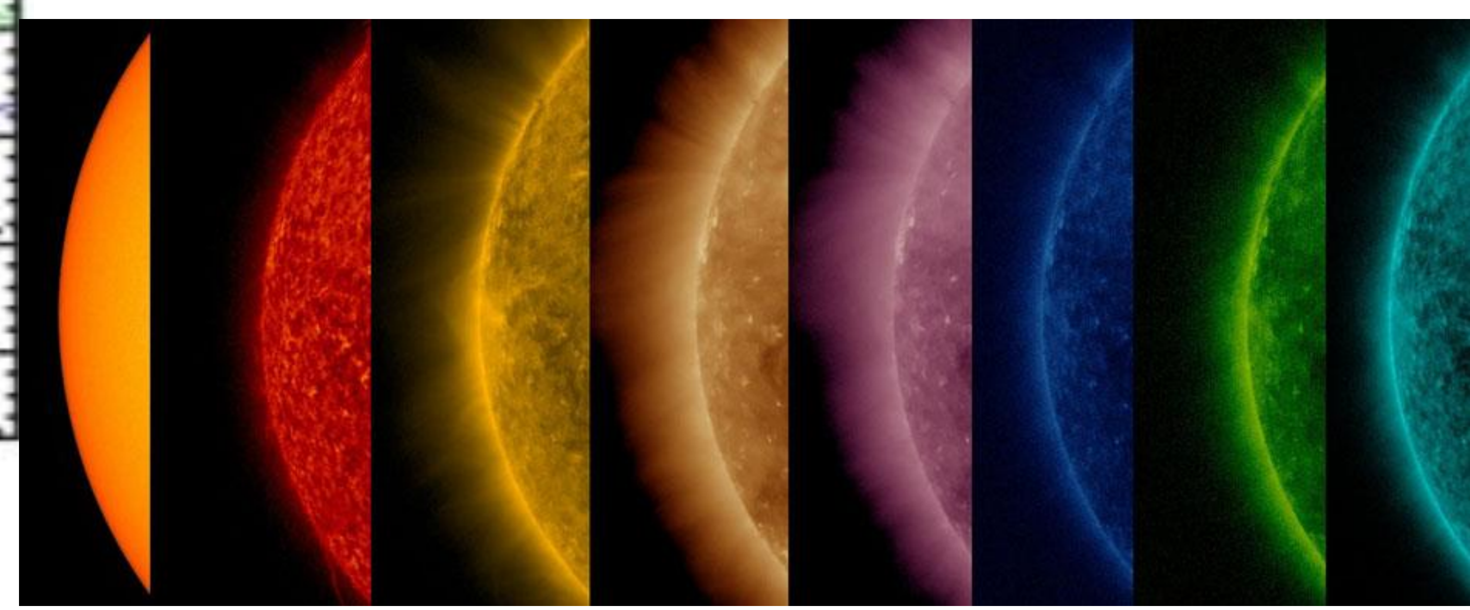
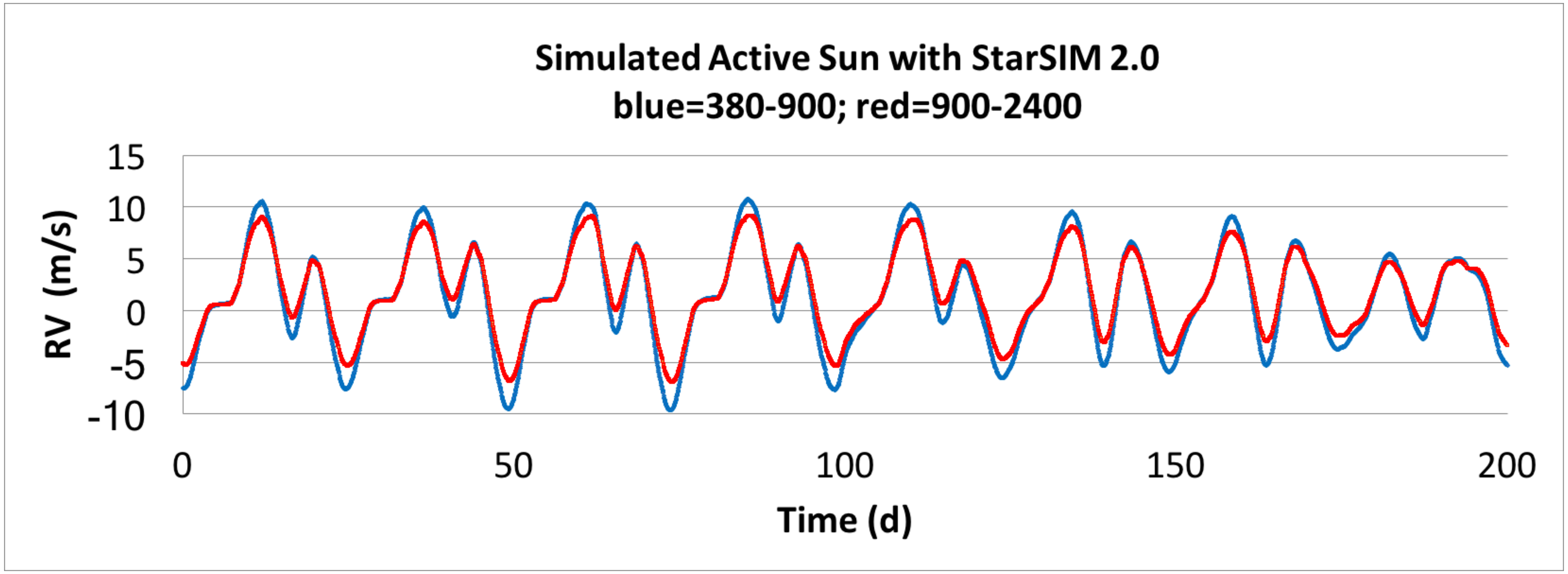


Stellar activity is not a simple function of λ, and also time-dependent



Wavelength Coverage

EarthFinder RV color achieves a 61% reduction in RV rms from stellar activity using only a simple linear-scaling model (e.g. no physics, limb-darkening and convective blue-shift wavelength dependence), better than the best results achieved from the ground to date. It is **not** possible to get this precision on the RV color from the visible alone.



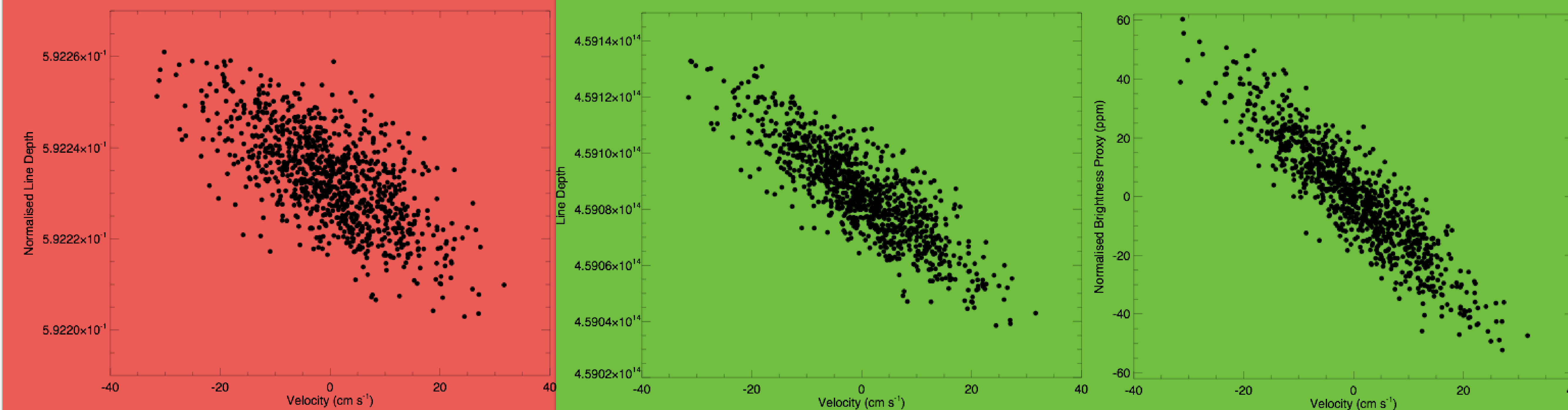
- Simultaneous RV color subtracts planet signal(s) completely!
- “Clean” measure of RVs due to chromatic activity!
- Needs modeling to go from RV color —> RV from activity
- To zeroth order, activity RV $\propto$ RV color, so:
  - Isolated planet signal is still~RV - Cx(RV color)

R>150k & Line-by-Line Analysis

Ground continuum normalized line-profile depth

Space absolute line-profile depth

Space absolute line-profile depth proxy from line-integration



Convection-induced RVs

Sun-as-a-star simulations of a magnetically quiet star with surface magnetoconvection (Cegla et al. 2019). Line-by-line analysis of activity is easier in space! From the ground, correlations of RVs with activity sensitive line parameters degrade due to the uncertainty in continuum normalizing spectra from variable atmospheric transmission and variable blaze functions.

R>150k & Line-by-Line Analysis

Ground continuum normalized line-profile depth

Space absolute line-profile depth

Space absolute line-profile depth proxy from line integration

EarthFinder improves absolute flux continuum precision by over an order of magnitude compared to the ground.

EarthFinder : Spectroscopy :: Kepler : Photometry

Sun-as-a-star simulations of a magnetically quiet star with surface magnetoconvection (Cegla et al. 2019). Line-by-line analysis of activity is easier in space! From the ground, correlations of RVs with activity sensitive line parameters degrade due to the uncertainty in continuum normalizing spectra from variable atmospheric transmission and variable blaze functions.

Cadence

Space

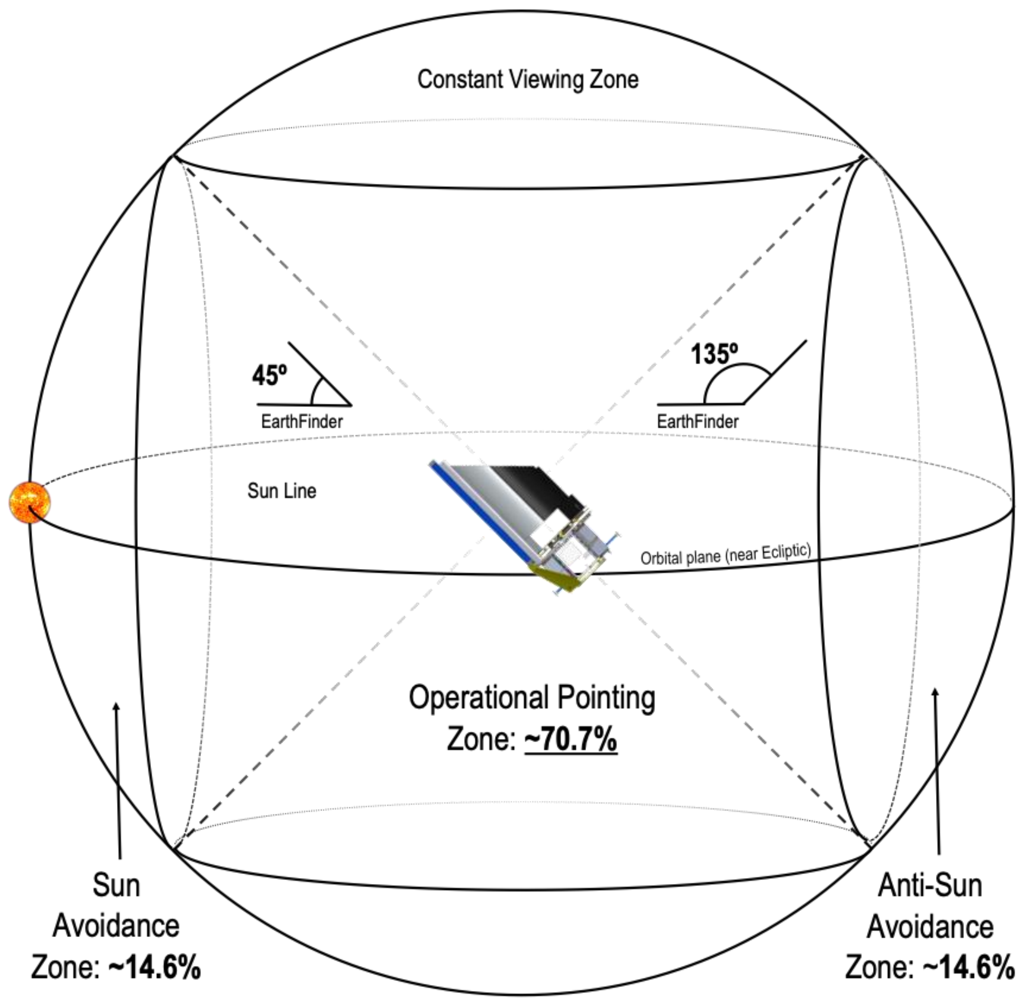
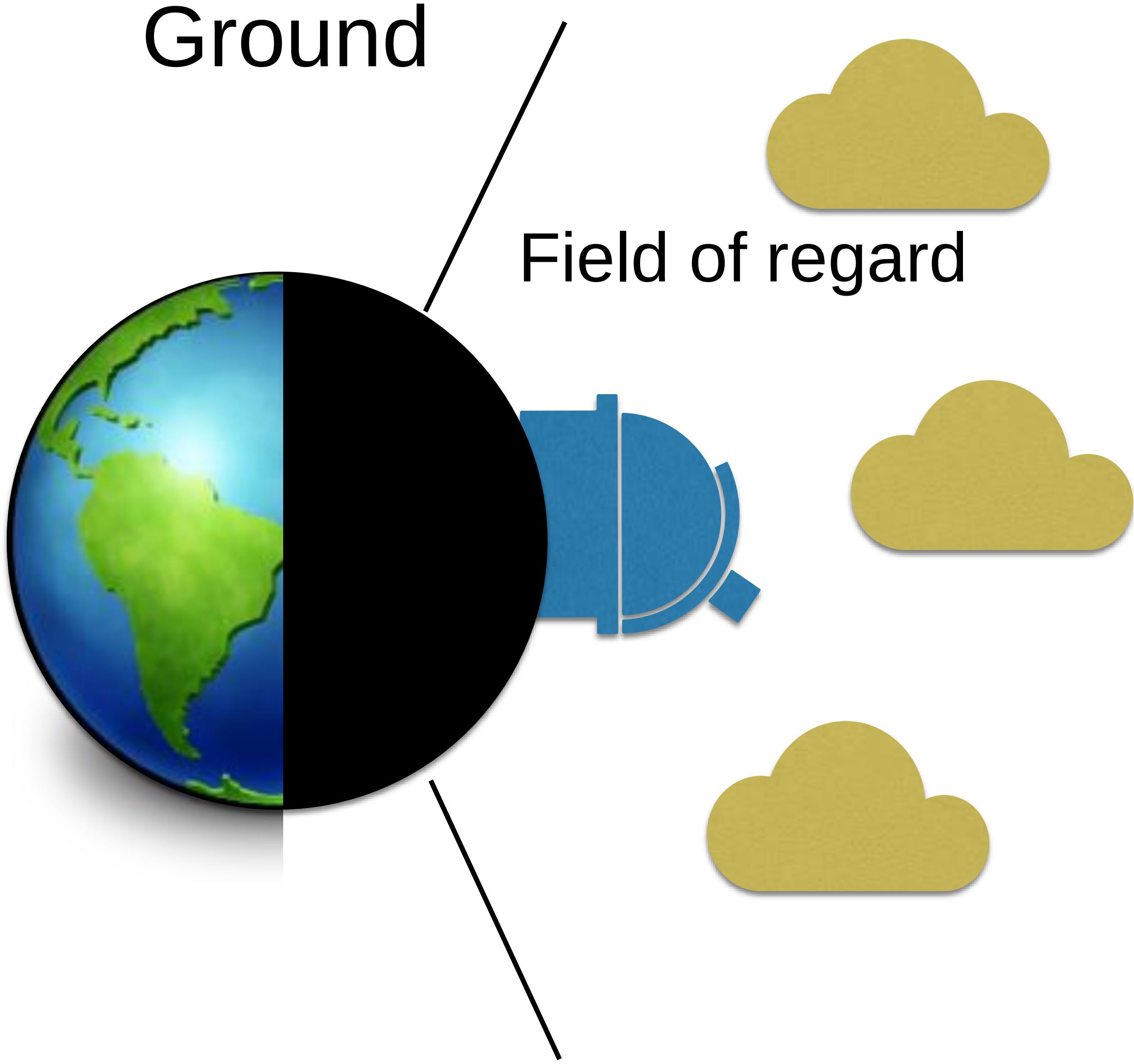


Figure from Bahaa Hamze

Two 3-6 month visibility windows per year (critical for 0.5-2 yr HZ orbital periods), no daytime (no 1 day aliases!)

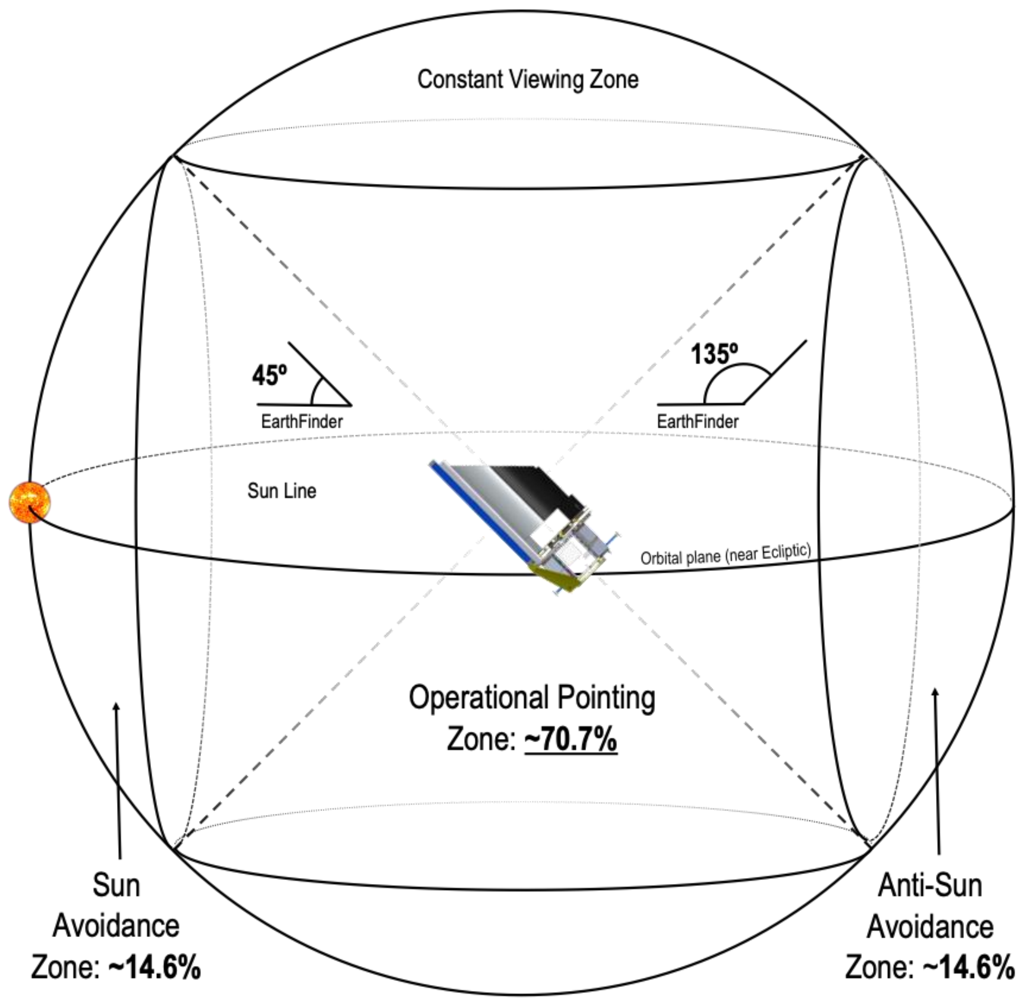
Ground



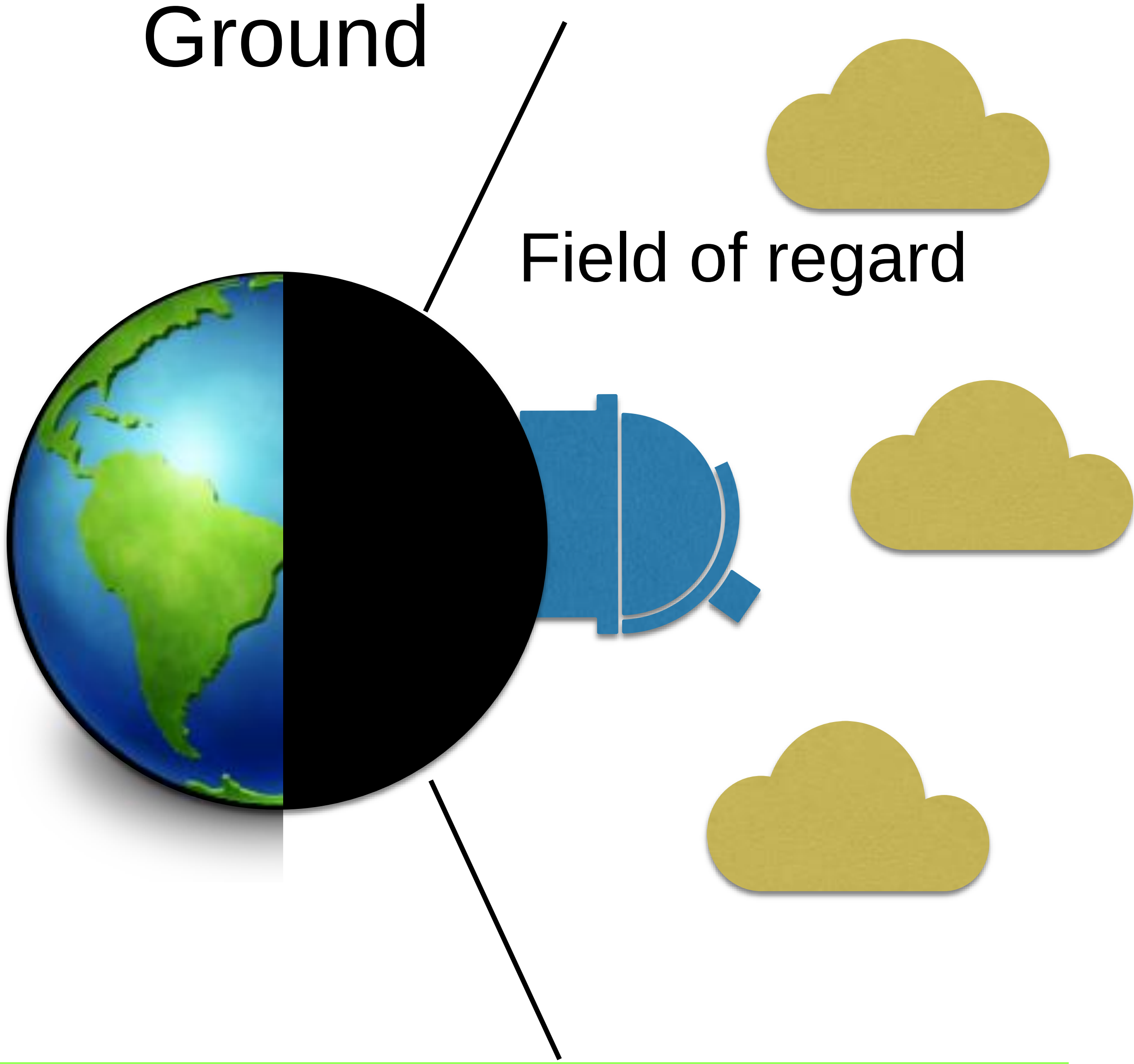
One ~3-6 month visibility window per year, minus daytime and minus weather

Cadence

Space

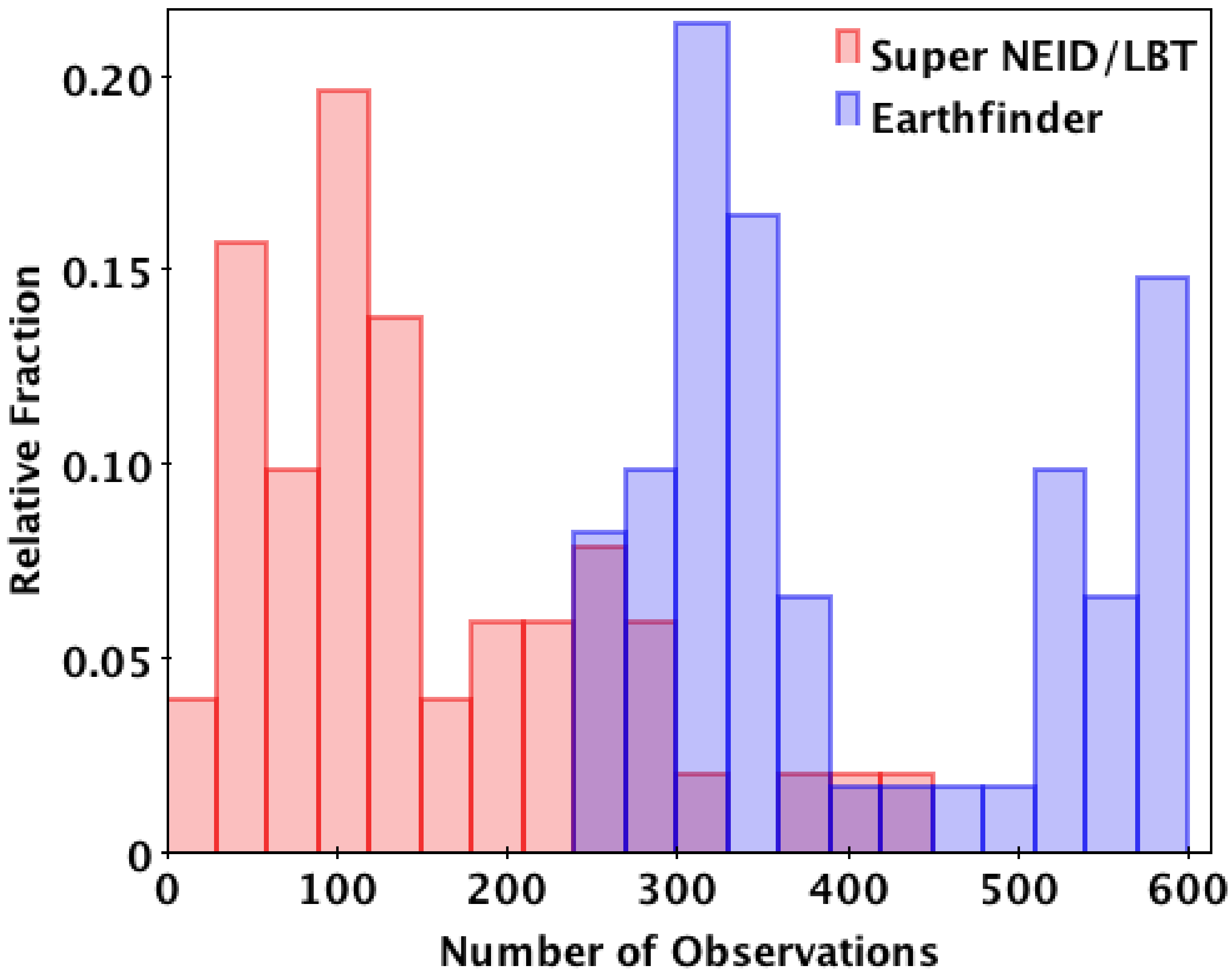


Ground



The little telescope that could: Due to loss of observing time on the ground due to daytime and weather, a 1.5-m telescope in space has the photon gathering power of a 3.5-m telescope on the ground. Add in efficiency gains from the diffraction-limited optics in space, and one achieves the equivalent of a 5-m telescope on the ground.

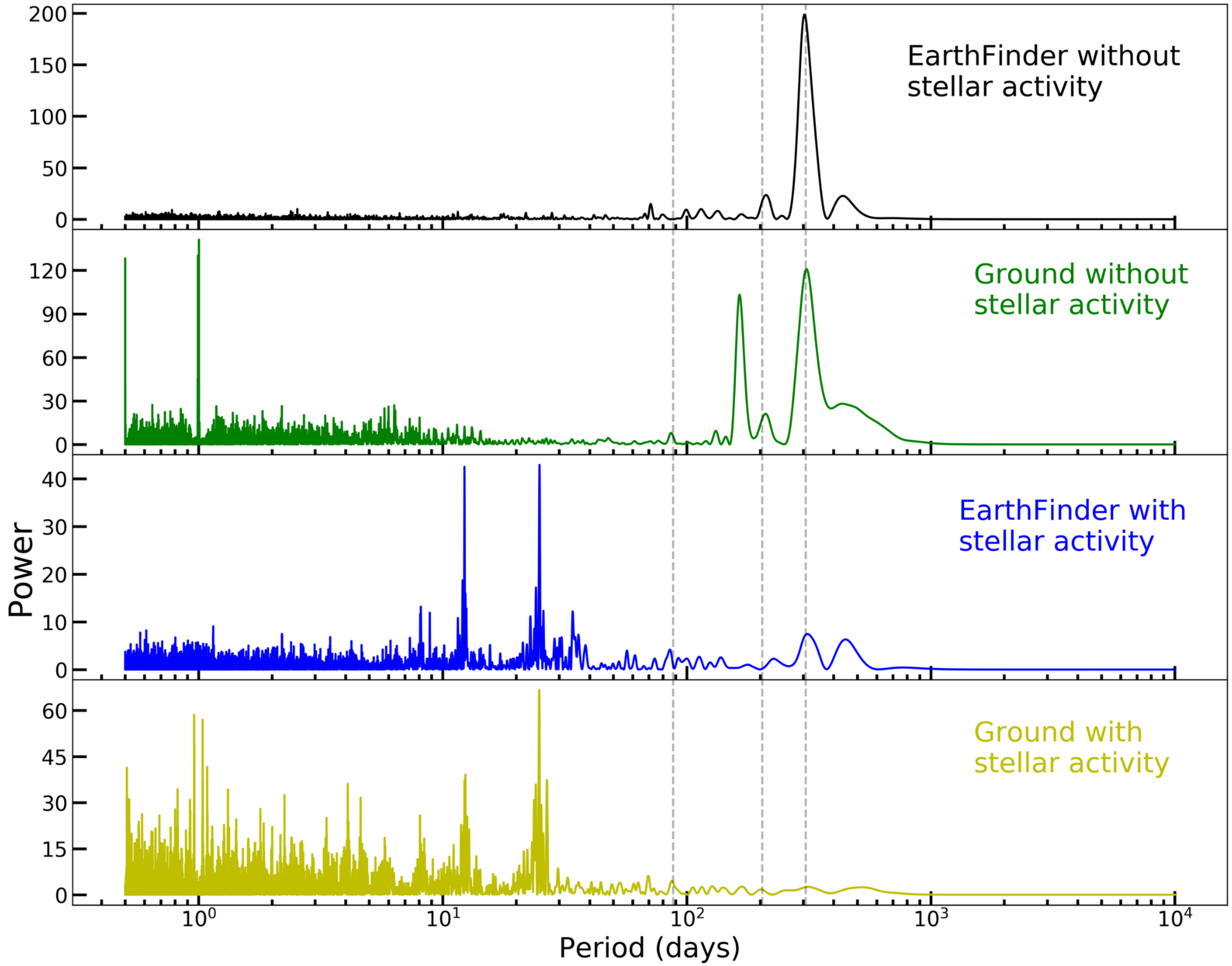
Cadence



Distribution of number of observations per star for a ground based survey of 61 future flagship mission direct imaging targets (25% time for 5 years on the LBT with a 3 cm/s “Super NEID”) and EarthFinder.

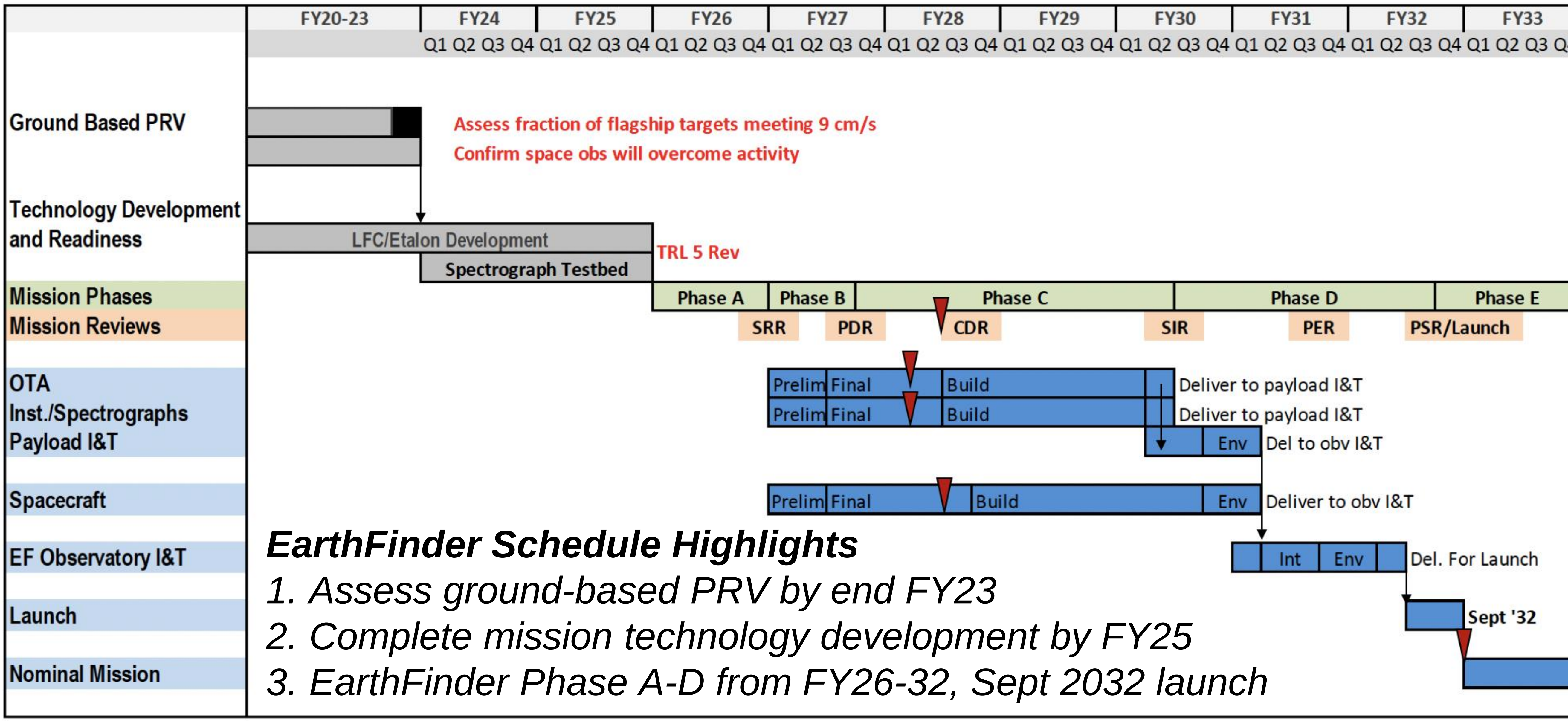
The little telescope that could: Due to loss of observing time on the ground due to daytime and weather, a 1.5-m telescope in space has the photon gathering power of a 3.5-m telescope on the ground. Add in efficiency gains from the diffraction-limited optics in space, and one achieves the equivalent of a 5-m telescope on the ground.

Cadence



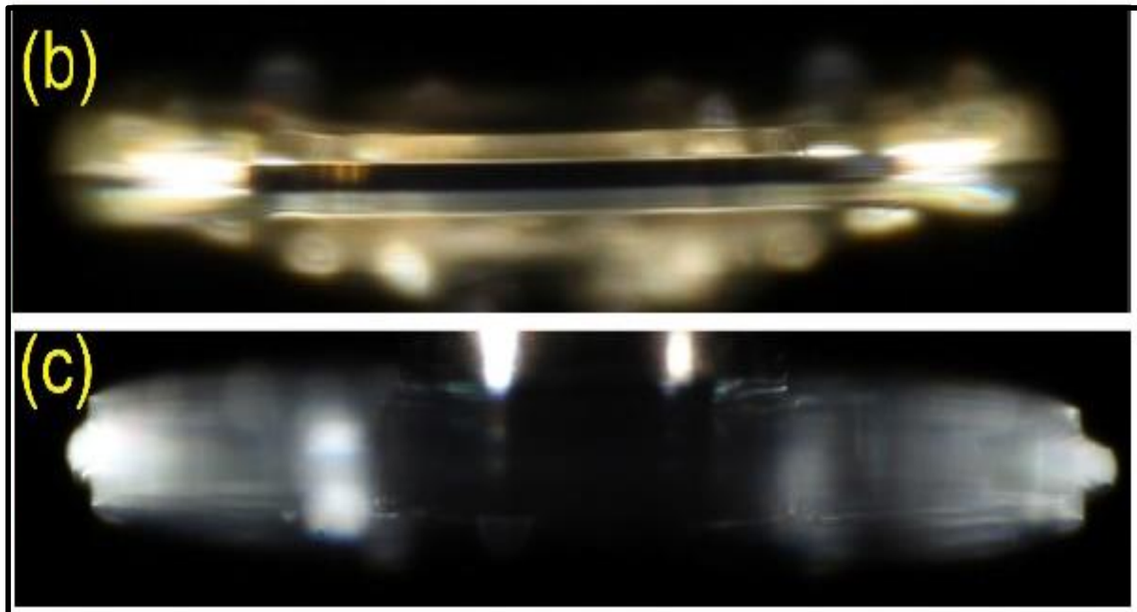
EarthFinder without stellar activity
Ground without stellar activity
EarthFinder with stellar activity
Ground with stellar activity
Power
Period (days)
200
150
100
50
0
120
90
60
30
0
40
30
20
10
0
60
45
30
15
0
10^0
10^1
10^2
10^3
10^4

Project Schedule

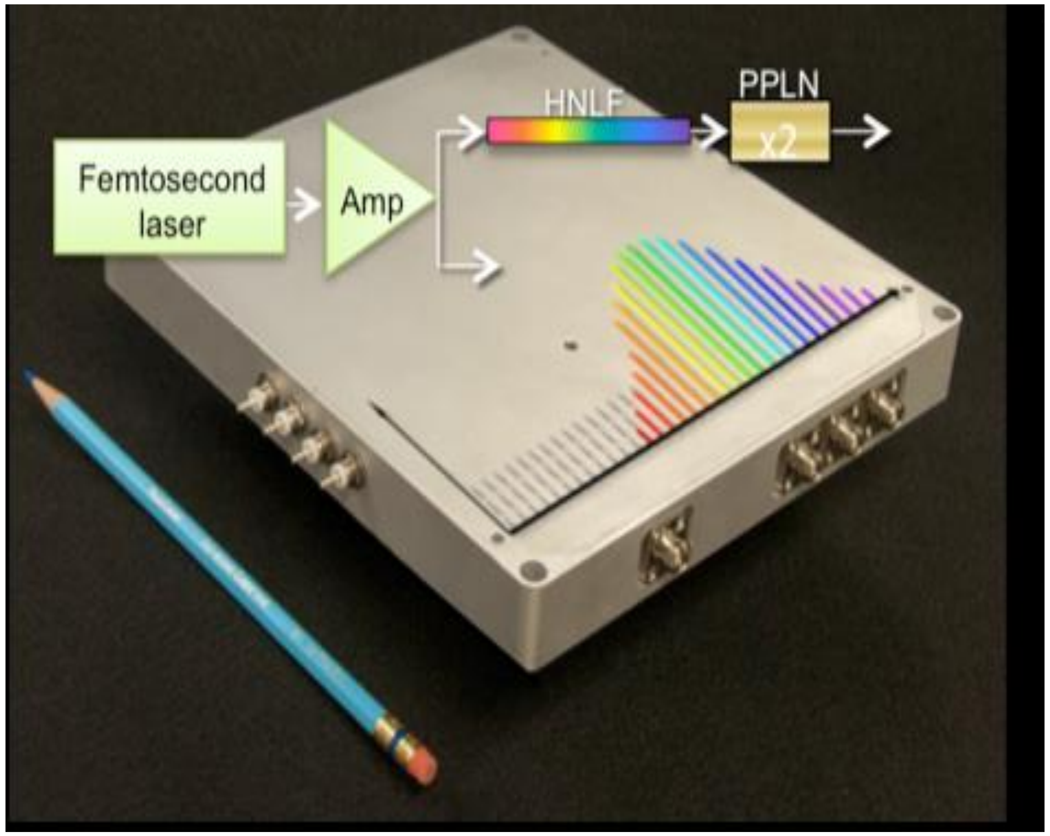


Risks - Stable Frequency Standards for Space

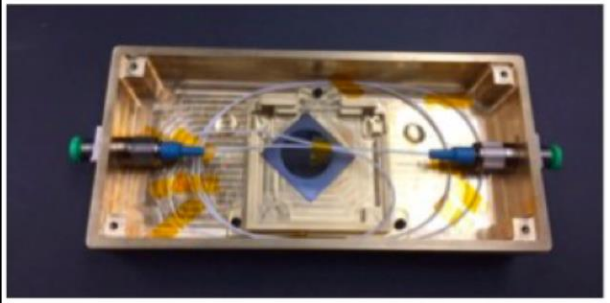
- Long term PRV stability of <1 cm/s is essential for detection of Earth Analogs (9 cm/s signal)
- Compact, low power, visible light etalons and Laser Frequency Combs (LFC) are being developed as frequency standards suitable for spaceflight
- Etalons may prove most effective from 400-800 nm while LFCs can cover from 700-2400 nm
- A number of technology efforts are underway with TRL 5 possible by 2025 with suitable investments

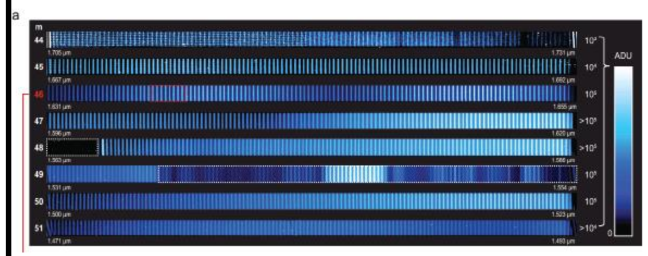


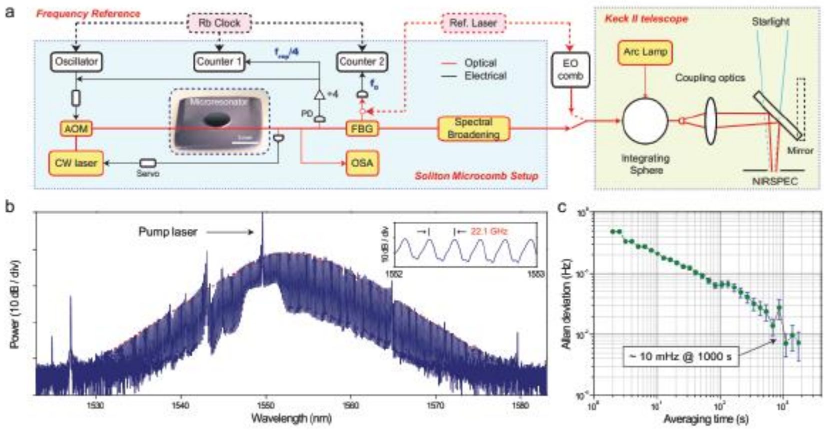
Top) An approved NASA SAT program (Leifer et al 2019) is developing a CaF_2 Whispering Gallery Mode (WGM) resonator. The unit is 0.1 cm in diameter and 50 μm thick and be used for a compact, low weight, visible light etalon-based frequency standard stable to 1 cm/s.
Bottom) A low power, self referenced frequency comb from NIST can serve as an absolute reference for the etalon (Manurkar et al 2018 OSA Contin,1, 274).



A chip-based soliton microresonator has been demonstrated with NIRSPEC at the Keck Observatory (Suh et al 2017) and is currently under development through an NSF grant.







EarthFinder Summary

- We will learn a lot from the new RV spectrometers at the sub-m/s level from ESPRESSO, EXPRES and NEID over the coming 5 years
- EarthFinder is a space-based 1.45-m observatory Probe mission concept
- Extremely precise and stabilized high-resolution UV-VIS-NIR spectrograph

Findings – Why space?

- **EarthFinder offers a unique combination of space advantages that aid in mitigating stellar activity:**
    - Uninterrupted wavelength coverage to isolate stellar activity
    - Uninterrupted cadence to improve statistical planet recovery eliminating diurnal and seasonal aliases
    - Diffraction limited provides extreme spectral resolution for line-by-line analysis and absolute continuum flux normalization
    - Activity from multiple scale-heights with UV coverage of Mg II lines
- Telluric lines will limit RV precision from ground at 3 cm/s in the blue, 10 cm/s in the red, and 1 m/s in the NIR. If red or NIR velocities are needed to mitigate activity, it will not be possible to do from the ground.
- Ancillary science cases:
    - Asteroseismology
    - Water in the local Universe
    - UV space capability
    - He I 1 μm direct detection spectroscopy
    - And more!

EarthFinder Summary

Recommendations:

- Develop a national testbed (e.g. upgrade-able) spectrograph facility with a target single measurement precision and long-term RV stability path towards 1 cm/s
  - Empirical >> simulation
  - EarthFinder will not fly without a ground-based pathfinder demonstration first for our Sun and/or a small subset of nearby stars
- Investment in frequency comb technology development for wavelength calibration (such as micro resonator & EOM combs)
- Investment in detector characterization
  - Many detector error terms in the RV error budget crop up at the ~5 cm/s level
- Foster new collaboration with NASA Heliophysics
- Possible balloon and SmallSAT demonstrations opportunities

<u>Aligned with NAS Exoplanet Science Strategy recommendations</u>

- These efforts will benefit ground-based RV efforts at the same time as prepping for EarthFinder
- We fully support the NAS ESS recommendation to invest in a big science coordinated effort for ground-based PRVs to better understand the challenges of mitigating stellar activity, as currently being explored for implementation by a NASA-NSF EPRV Working Group co-chaired by Scott Gaudi and Gary Blackwood (report due to NASA 3/23/2020)

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