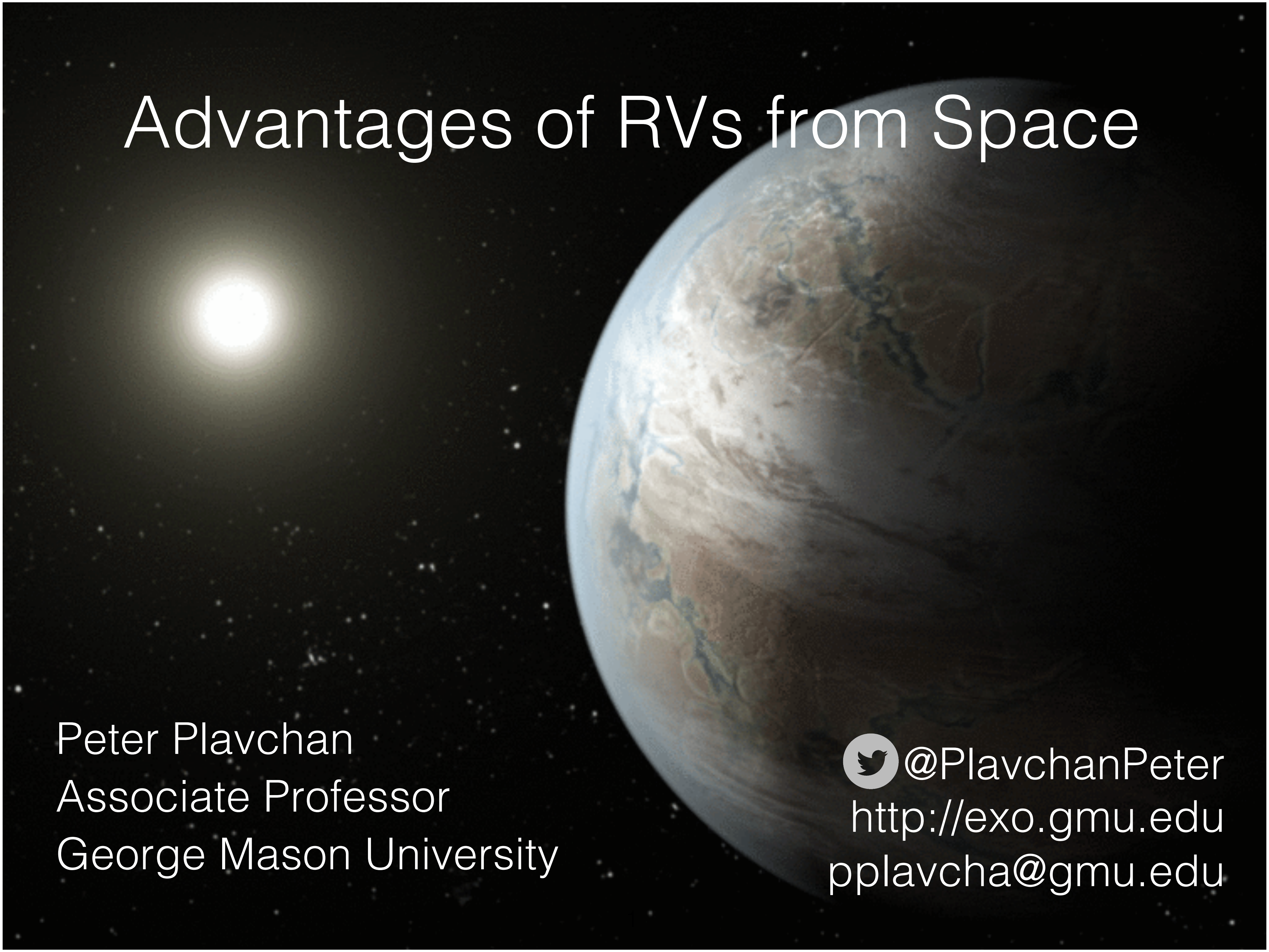
Advantages of RVs from Space



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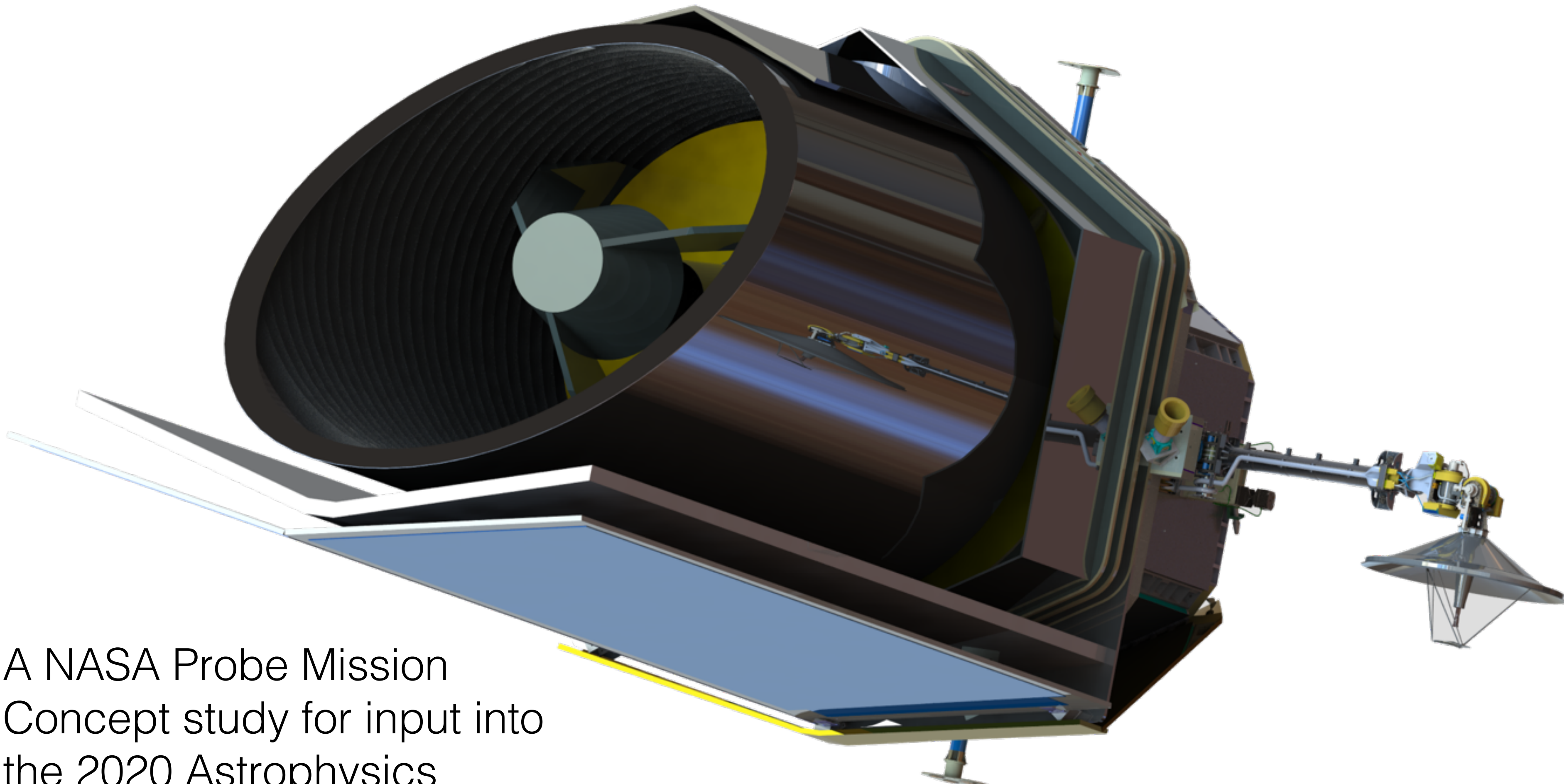
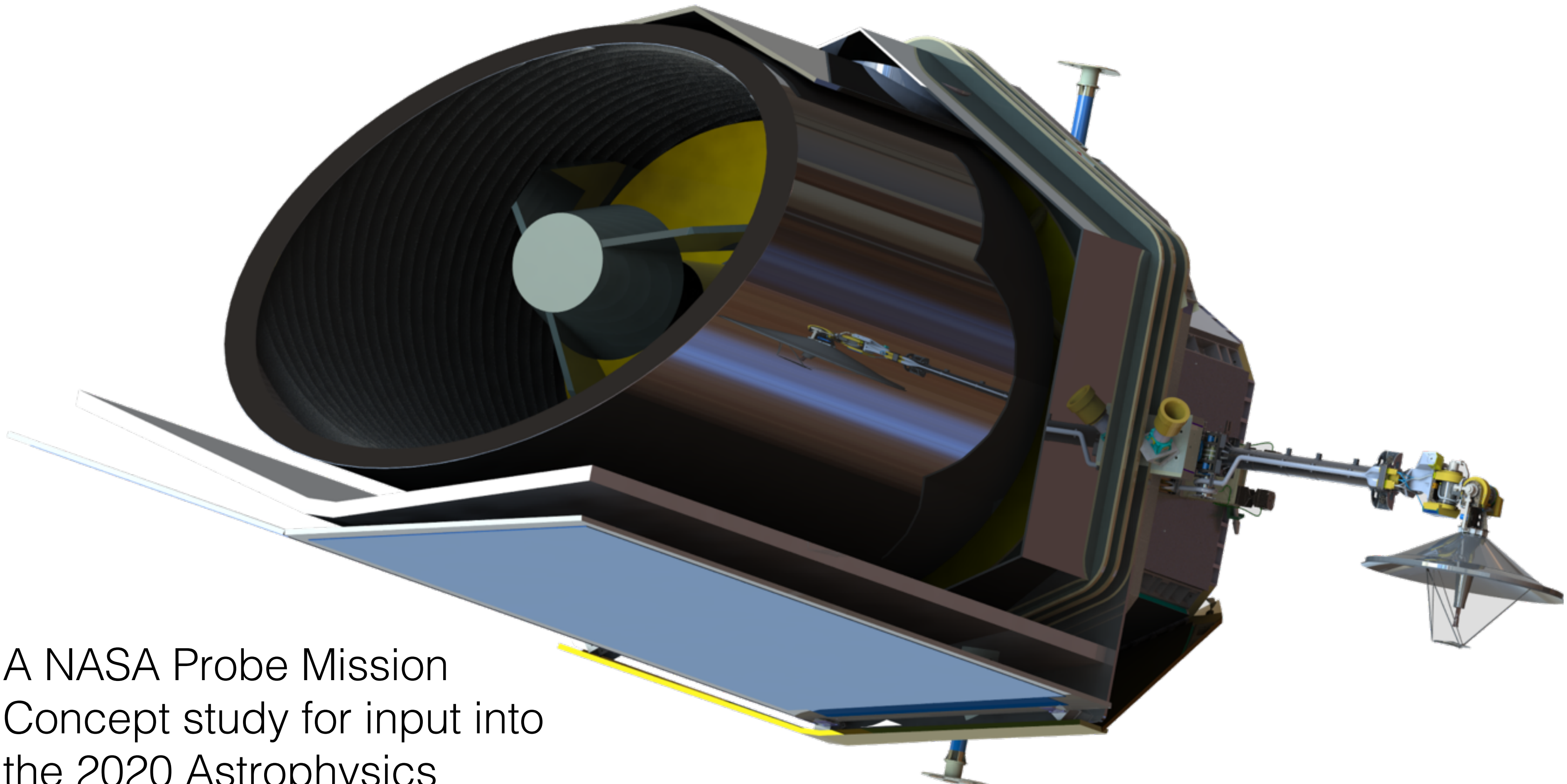
EarthFinder



A NASA Probe Mission Concept study for input into the 2020 Astrophysics Decadal

Credit: Ball Aerospace

EarthFinder

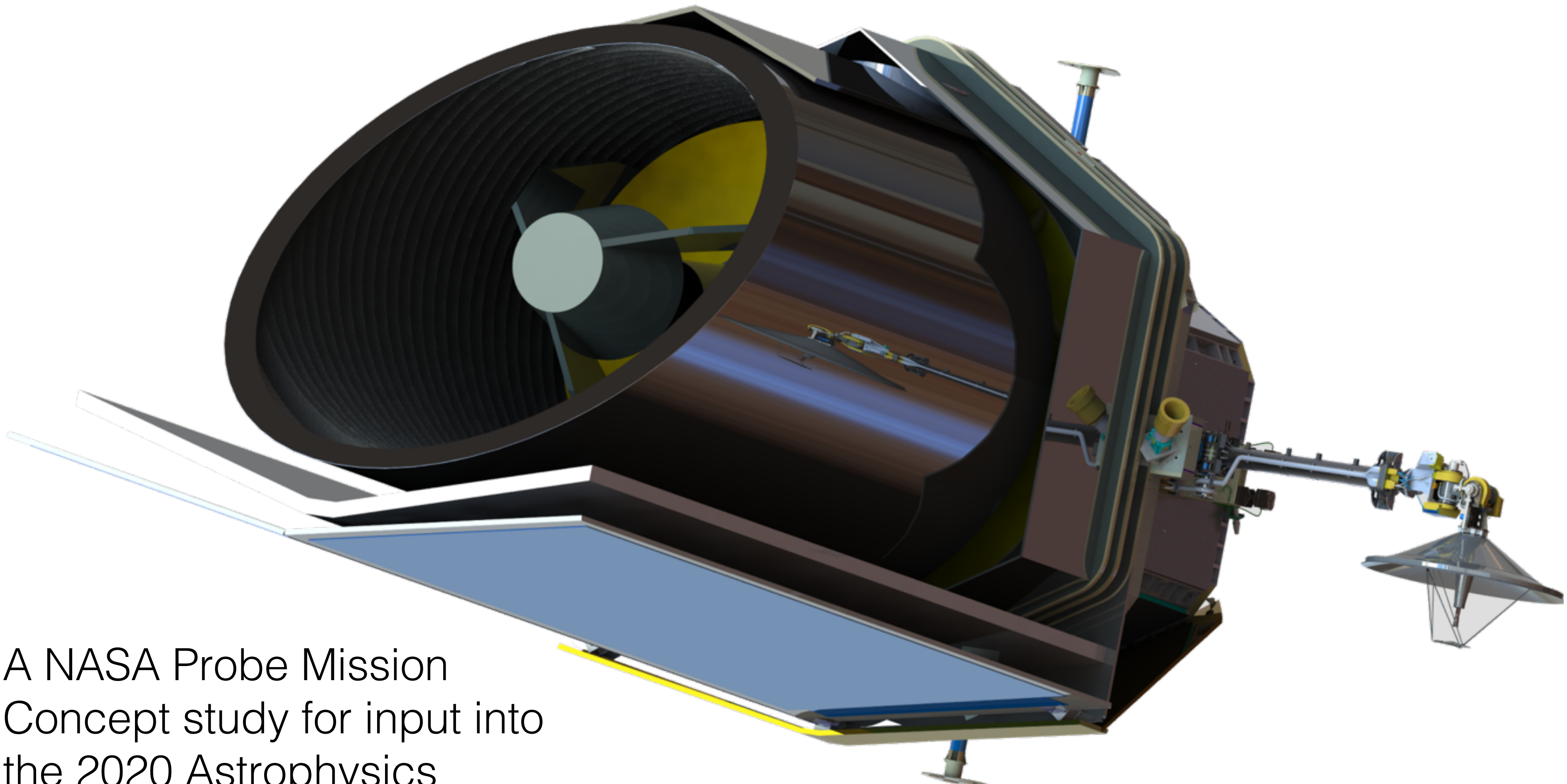


A NASA Probe Mission Concept study for input into the 2020 Astrophysics Decadal

Radial Velocities …

Credit: Ball Aerospace

EarthFinder



A NASA Probe Mission Concept study for input into the 2020 Astrophysics Decadal

Radial Velocities ... *in space!*

Credit: Ball Aerospace

EarthFinder Team

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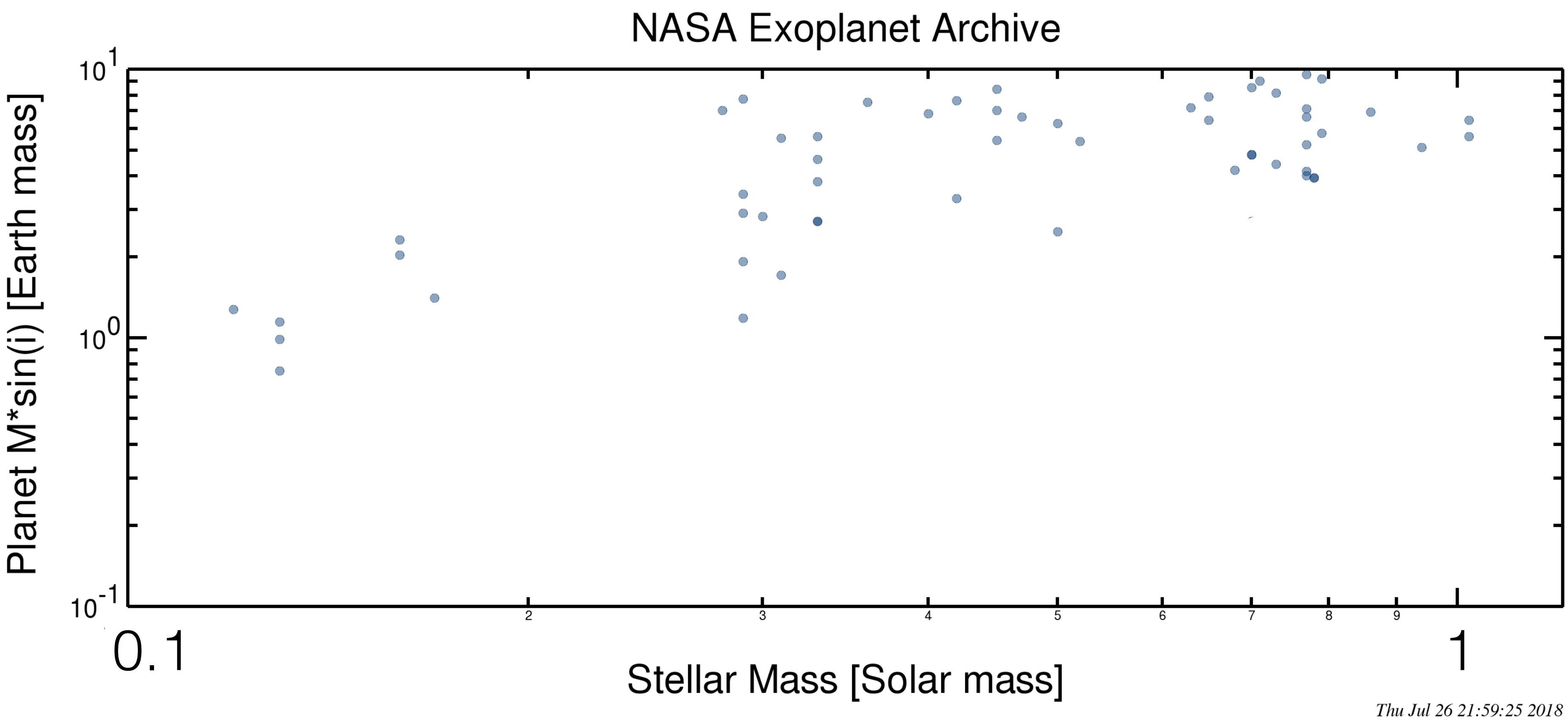
Jason Wright (Penn State)

Science

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



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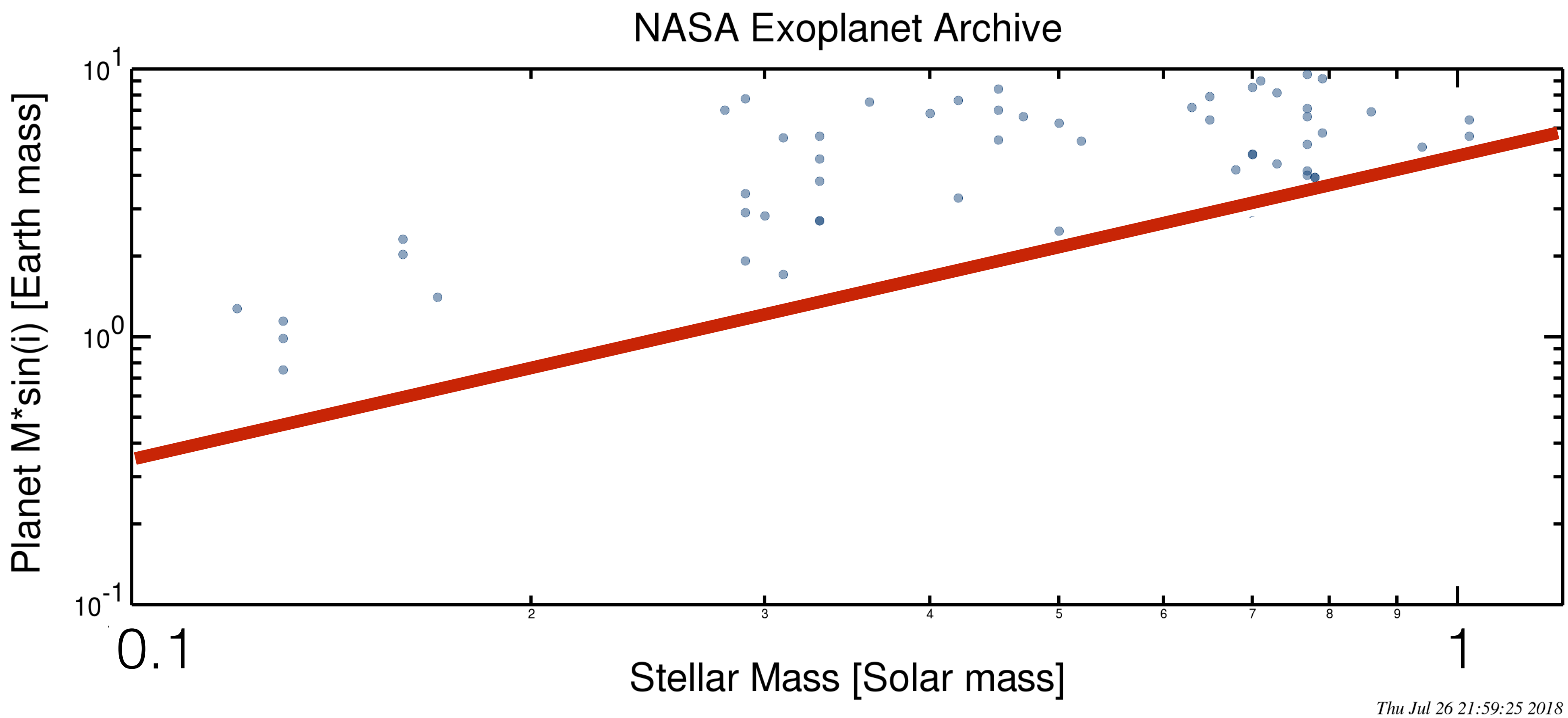

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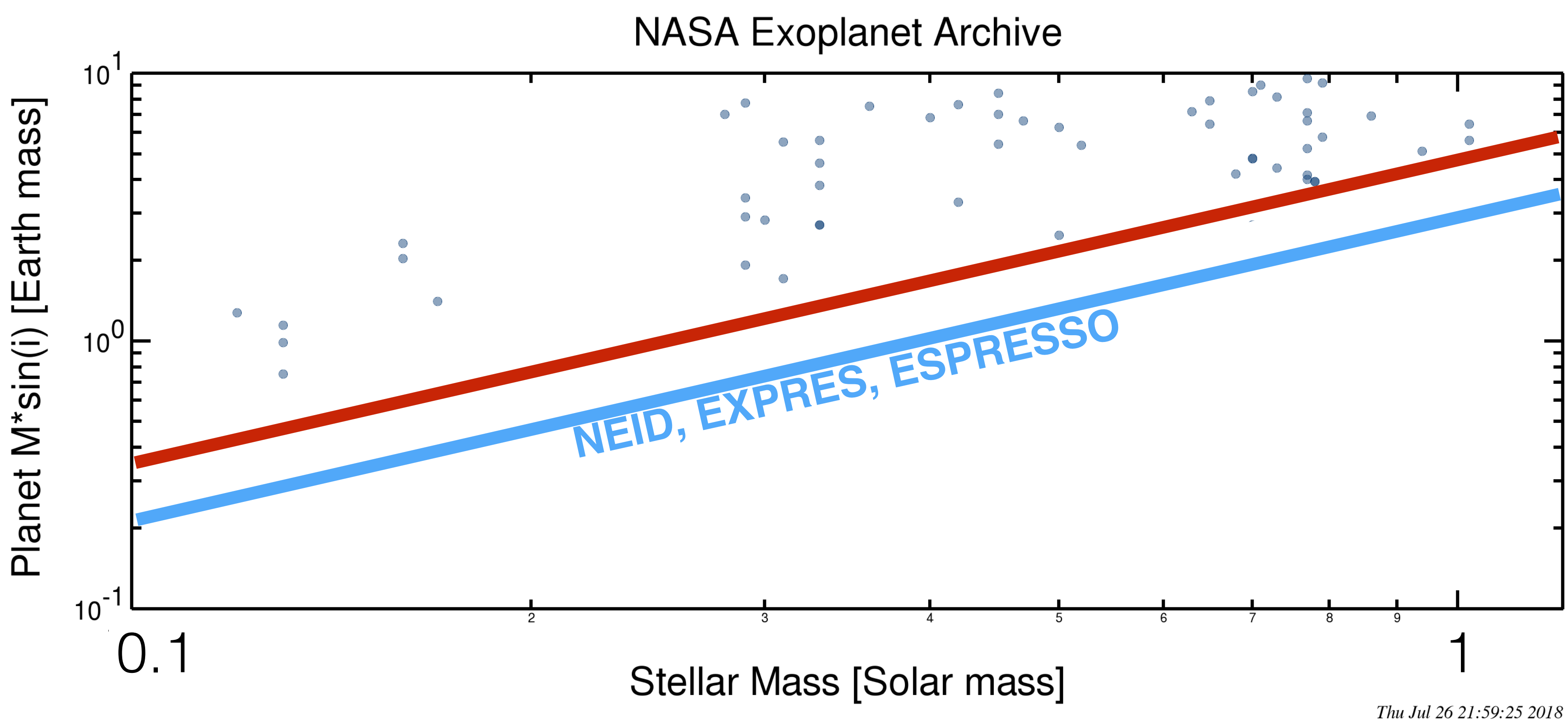

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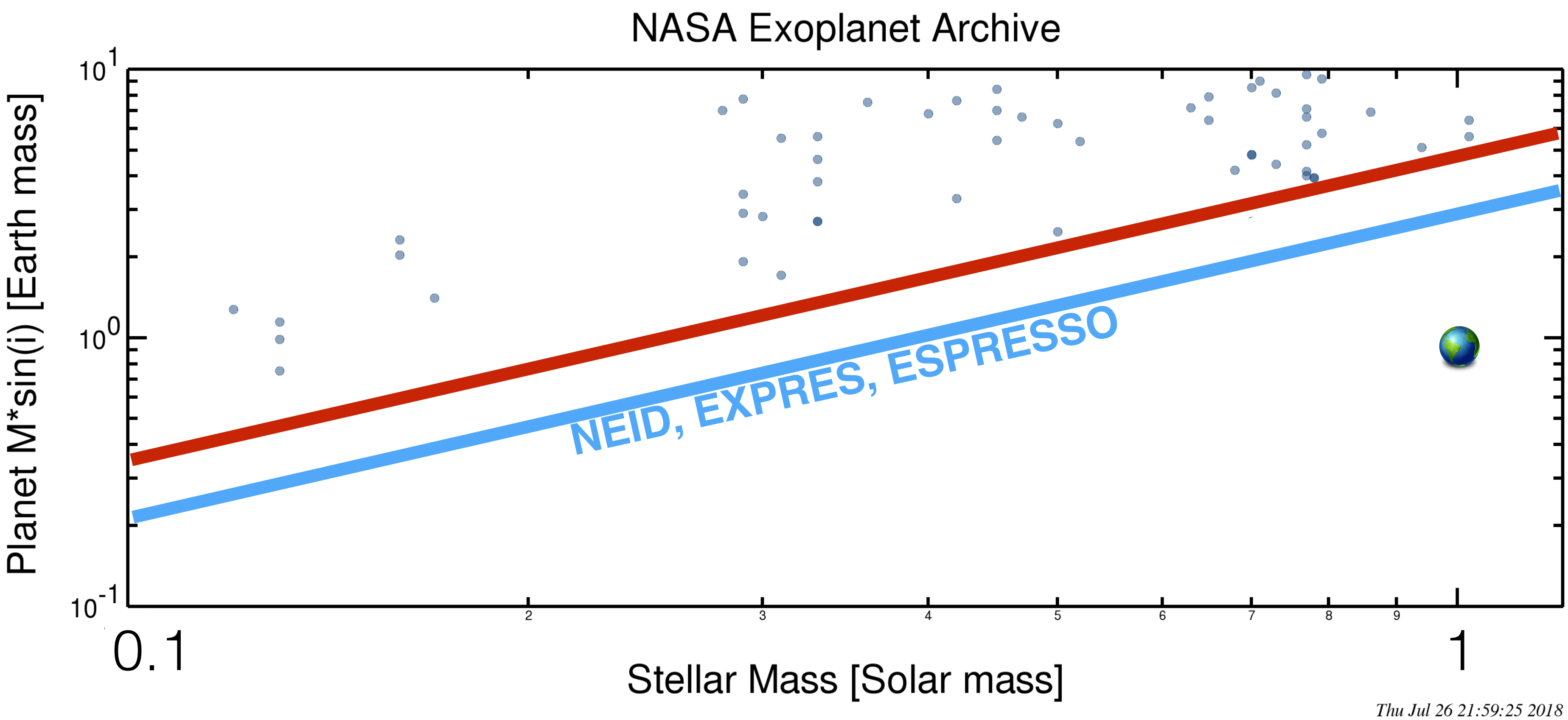

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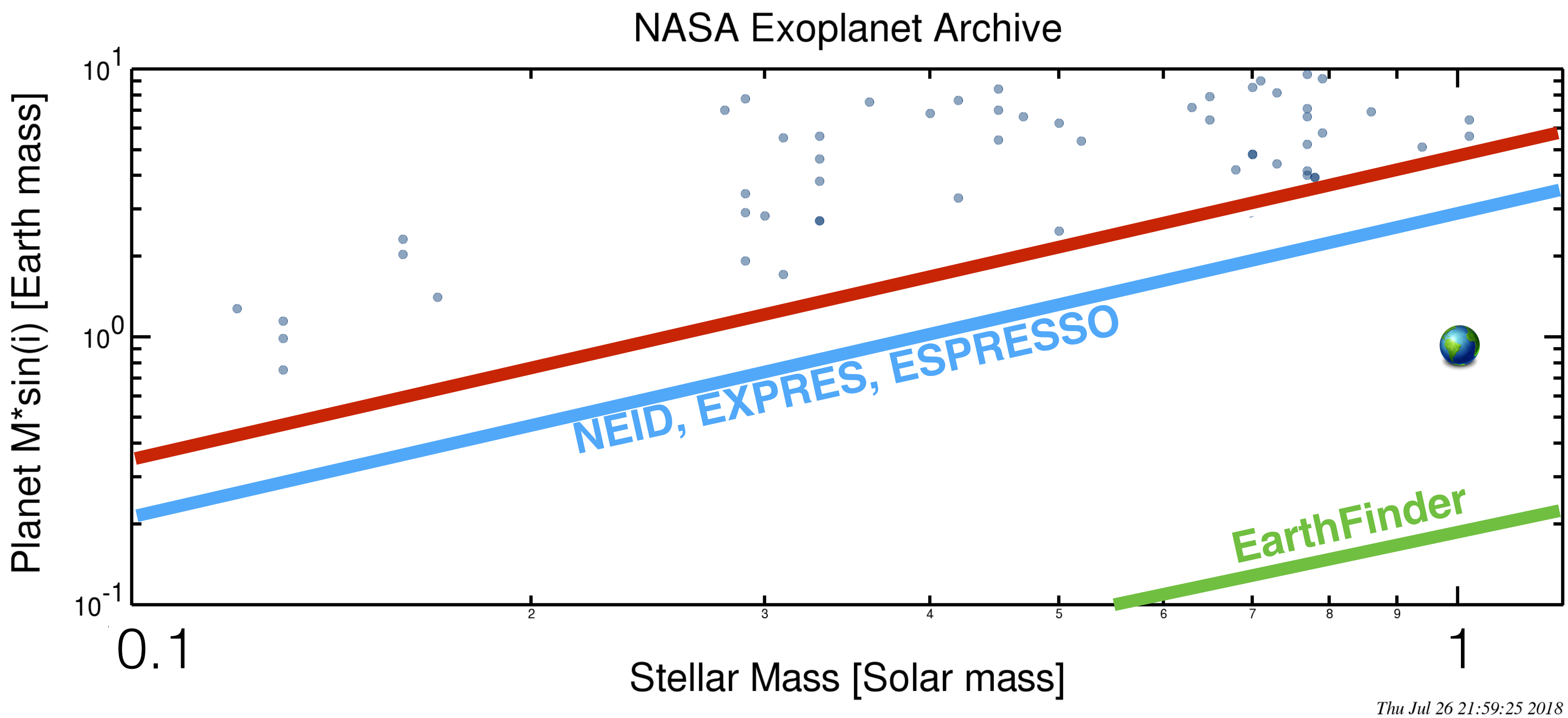

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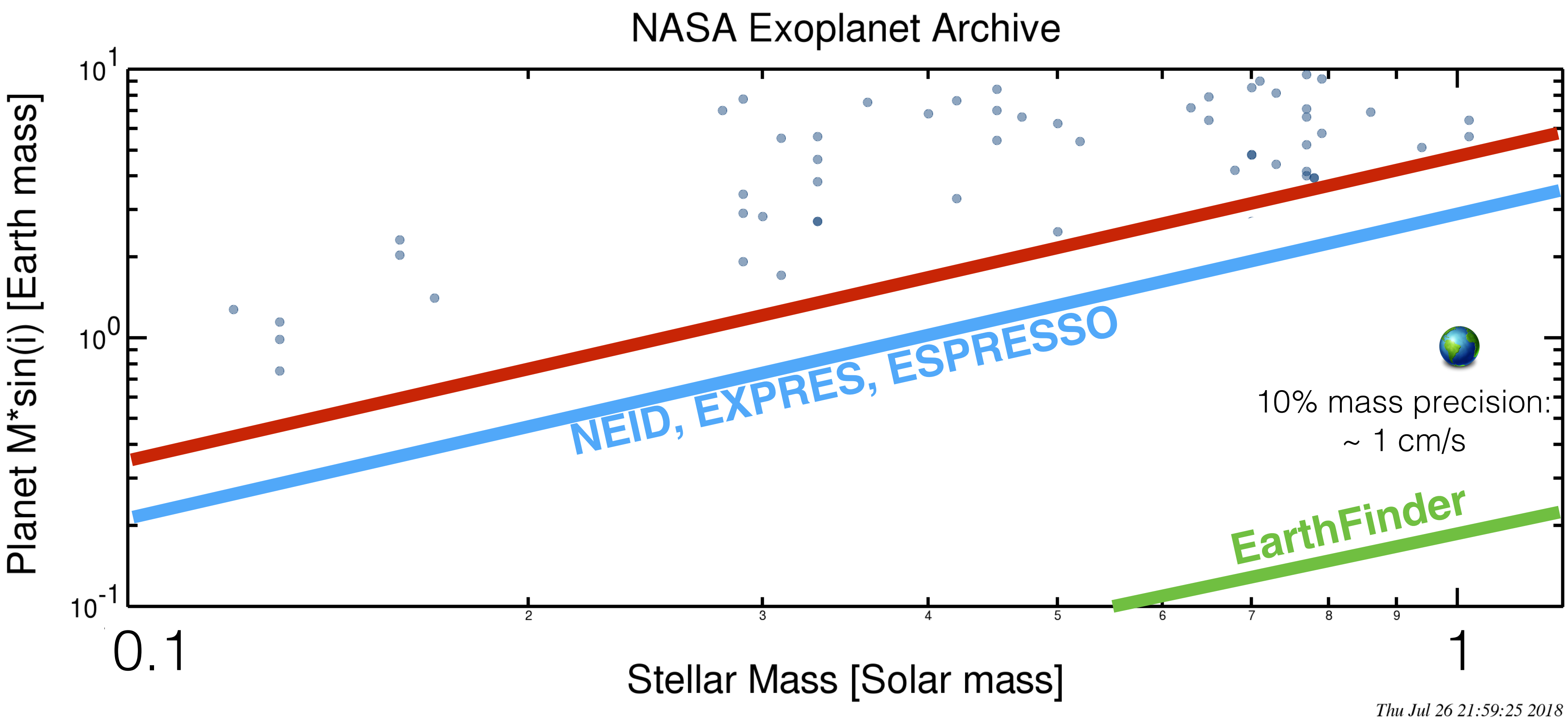
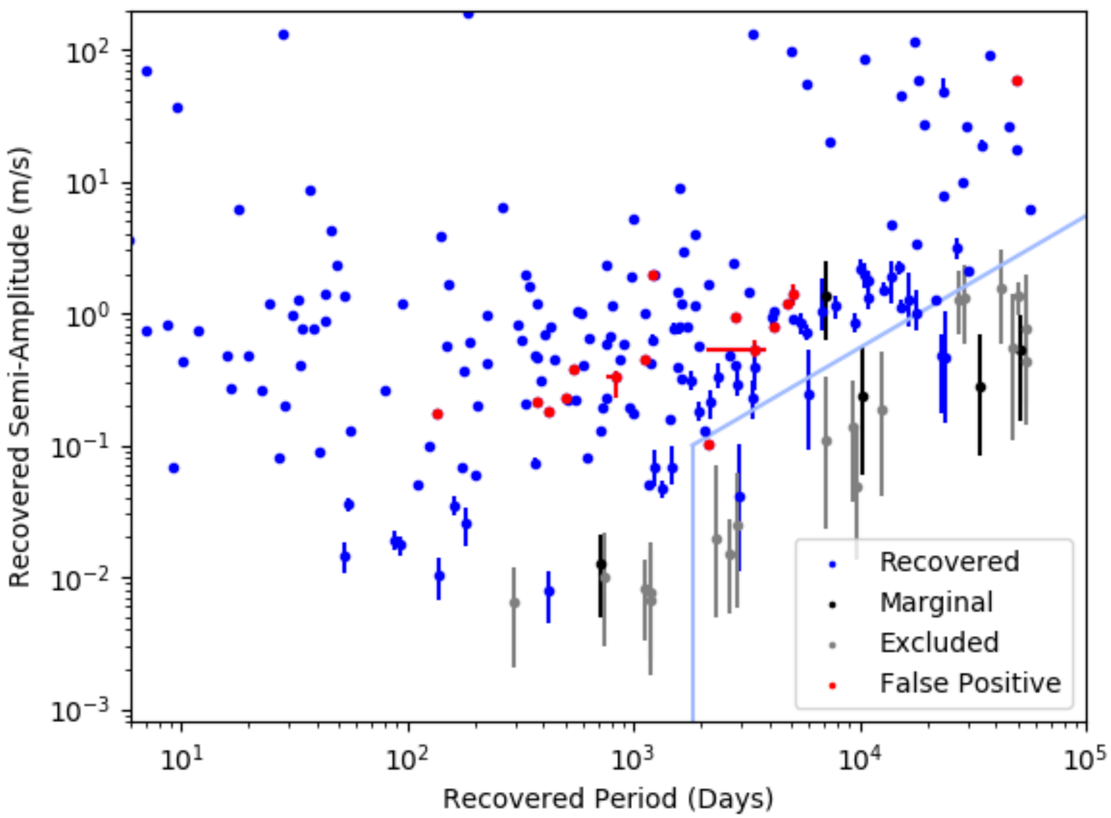


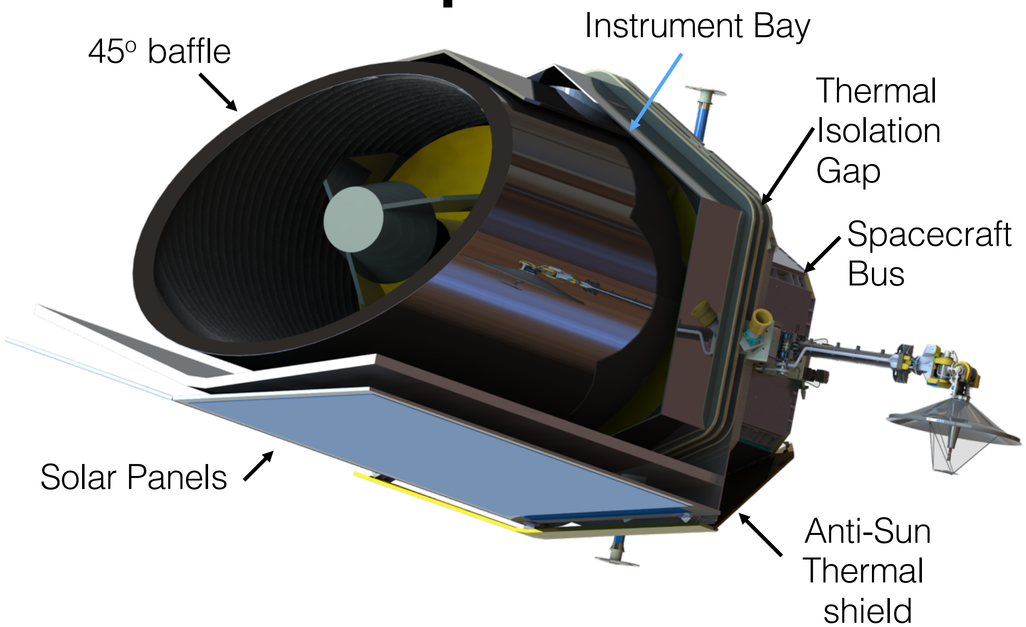
Survey Yield

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)

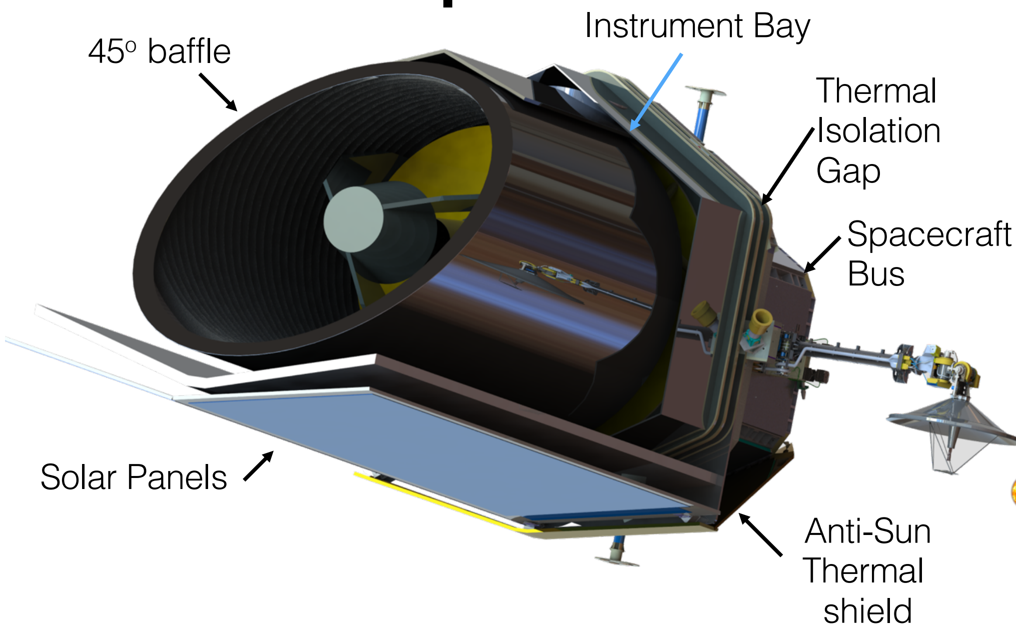


Spacecraft & Orbit



- Ball Aerospace
- Kepler, Spitzer heritage
  - Extended baffle
  - Thermal shield
- 1.45 meter primary
- 5 year primary mission
- ~50 nearest FGKM main sequence stars (V~5)

Spacecraft & Orbit



- Ball Aerospace
- Kepler, Spitzer heritage
  - Extended baffle
  - Thermal shield
- 1.45 meter primary
- 5 year primary mission
- ~50 nearest FGKM main sequence stars (V~5)
- Earth-trailing or L2 orbit
- 70.7% of sky visible at any time
  - Minimum two three-month visibility windows every year
  - 29% of sky in continuous viewing zone

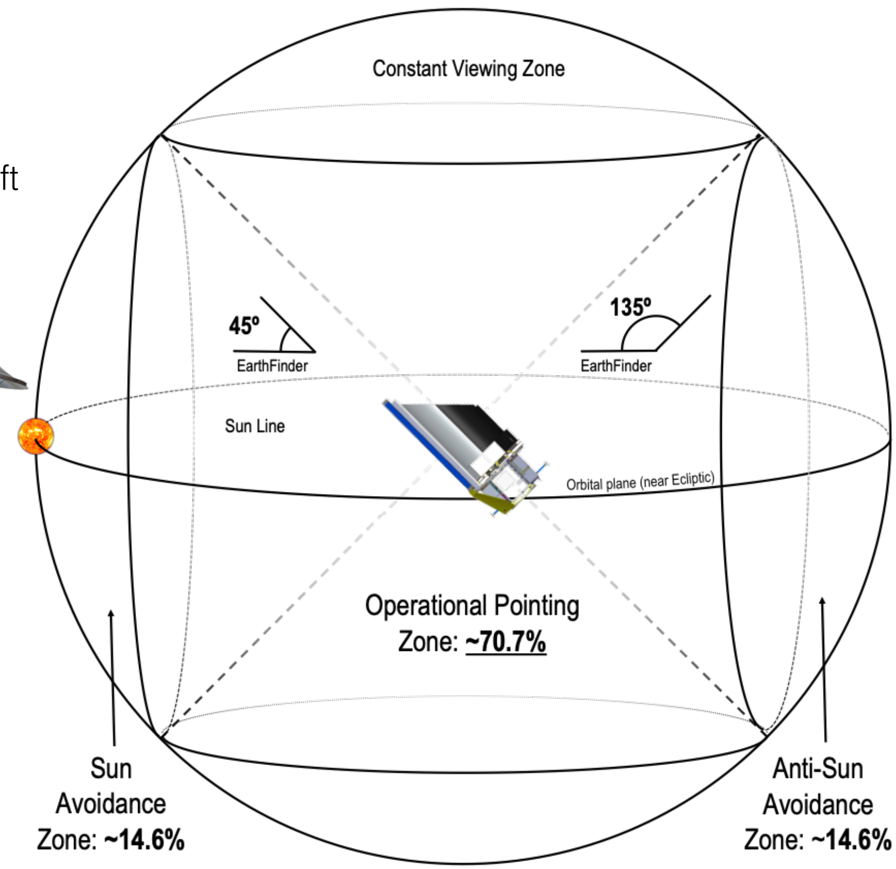
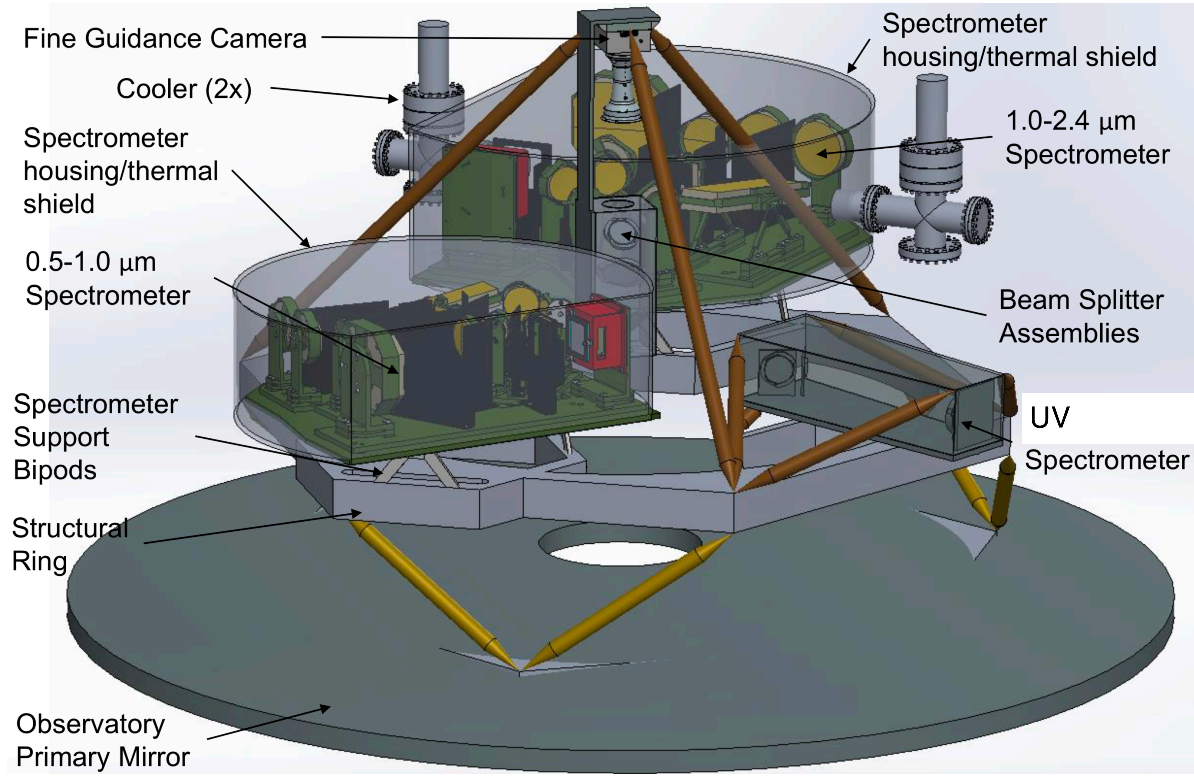


Figure from Bahaa Hamze

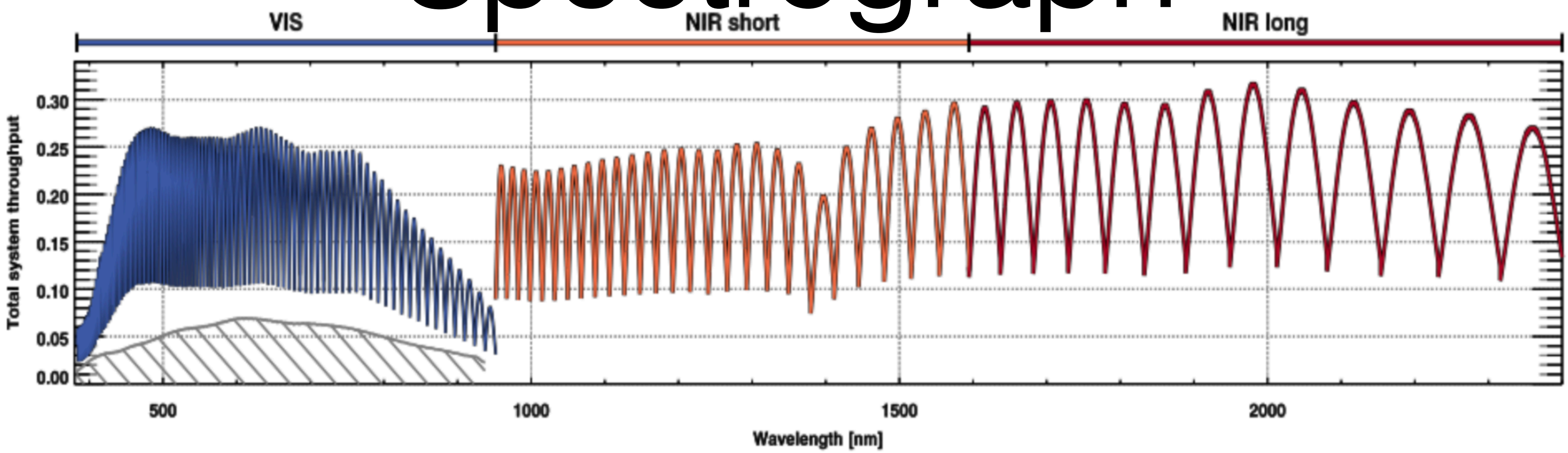
Instrument



Spectrograph:

- High-resolution (R~150-200k)
- Diffraction-limited (Single mode fiber spatial illumination stability)
- 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

Spectrograph



Significant efficiency gains when diffraction limited

Spectrograph:

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Why space?

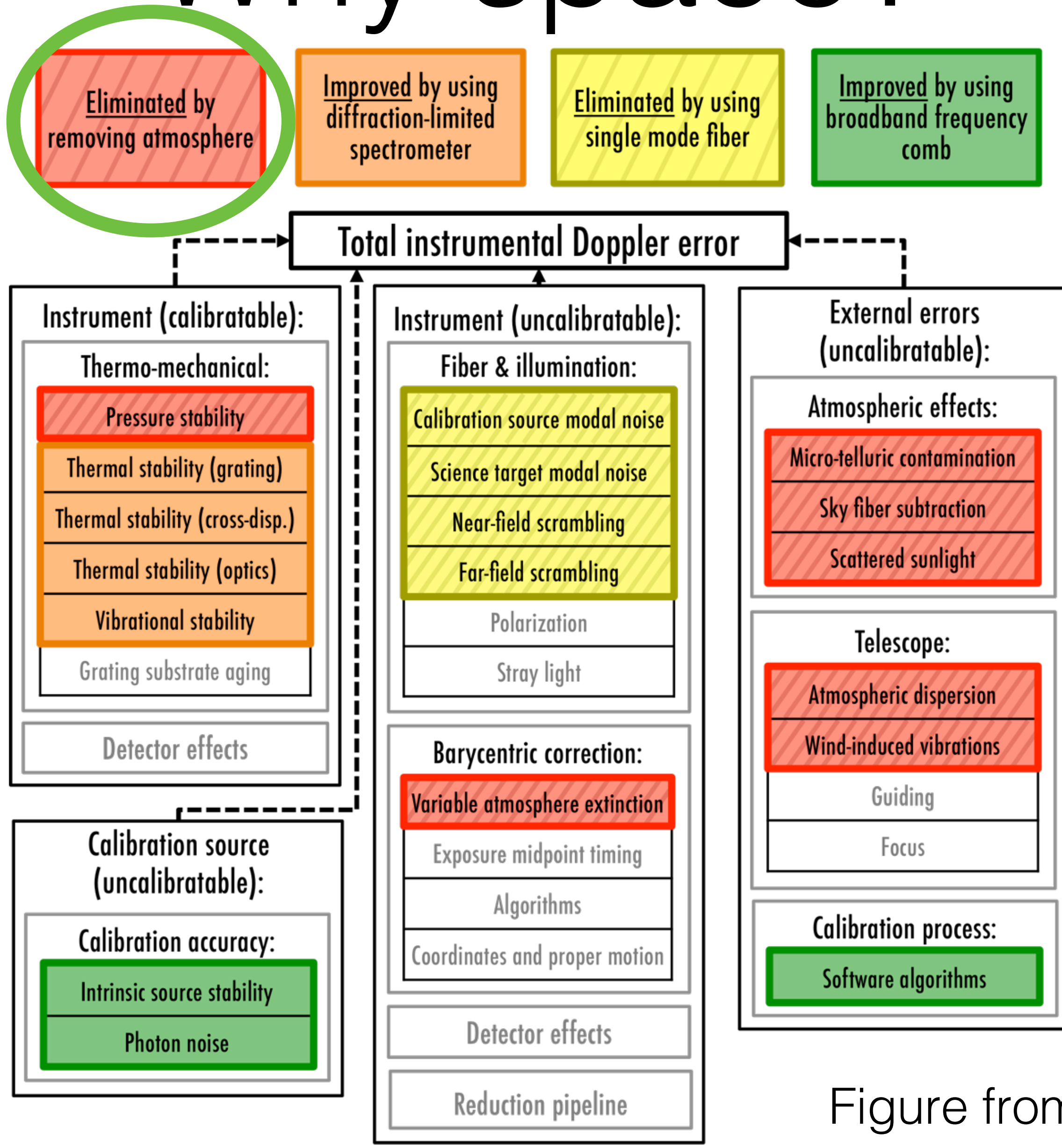
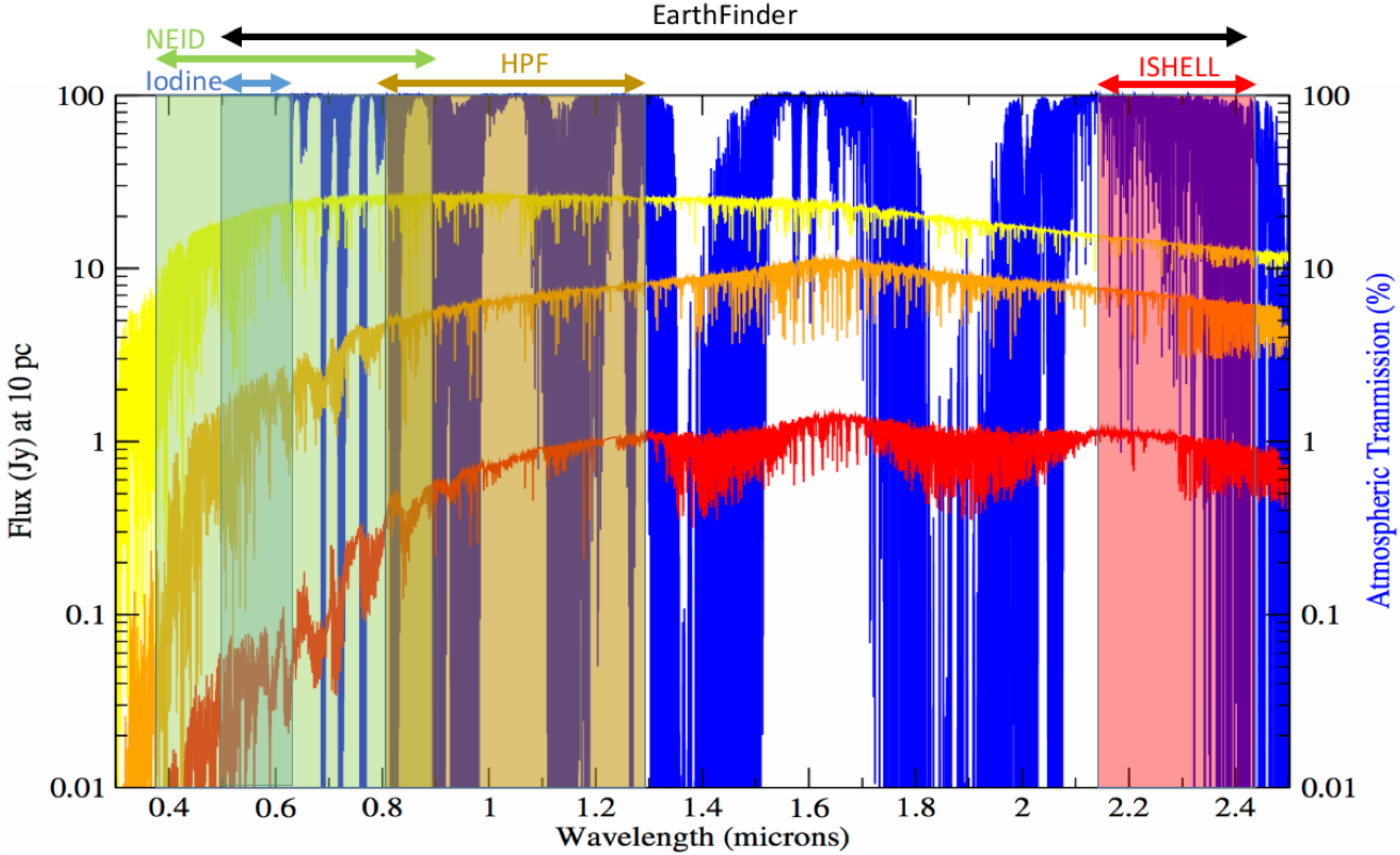
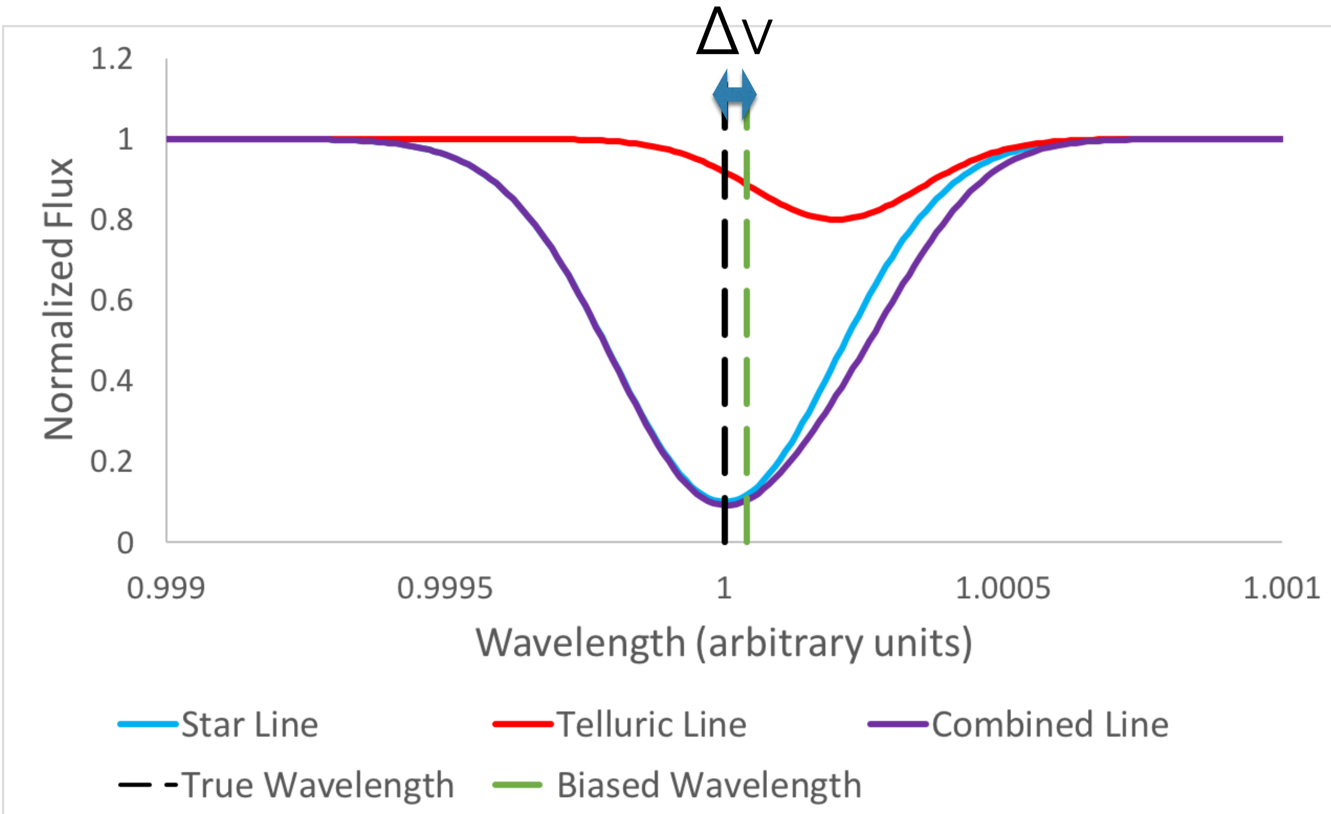


Figure from Sam Halverson

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



The telluric challenge



We simulated the impact of synthetic telluric lines in synthetic observed stellar spectra, and tested different methods of correcting them, and did an empirical comparison to iSHELL spectra

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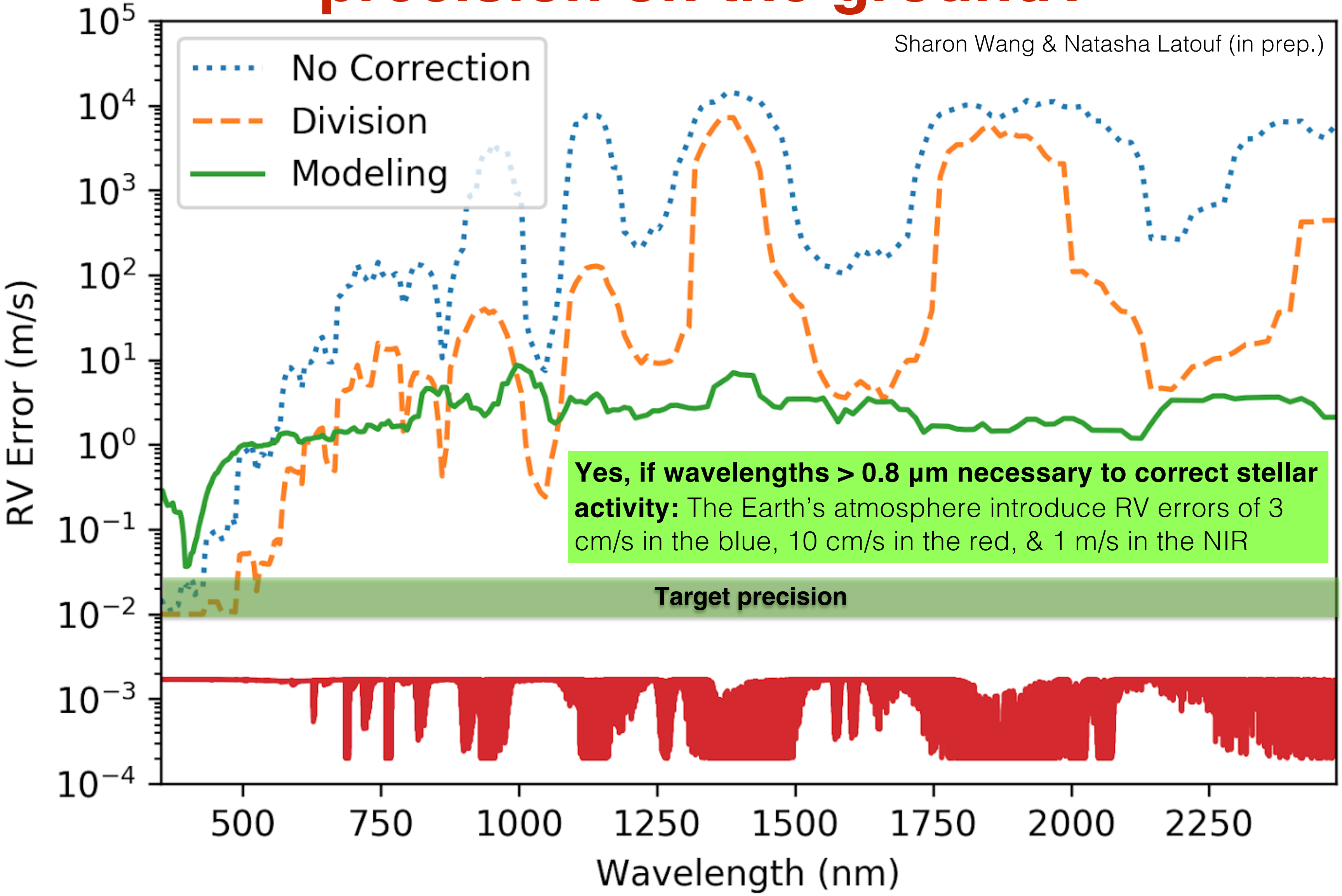


Can we “solve” stellar activity?

Approaches under exploration for activity mitigation:

Wavelength Coverage (e.g. CARMENES)

Cadence (e.g. MINERVA)

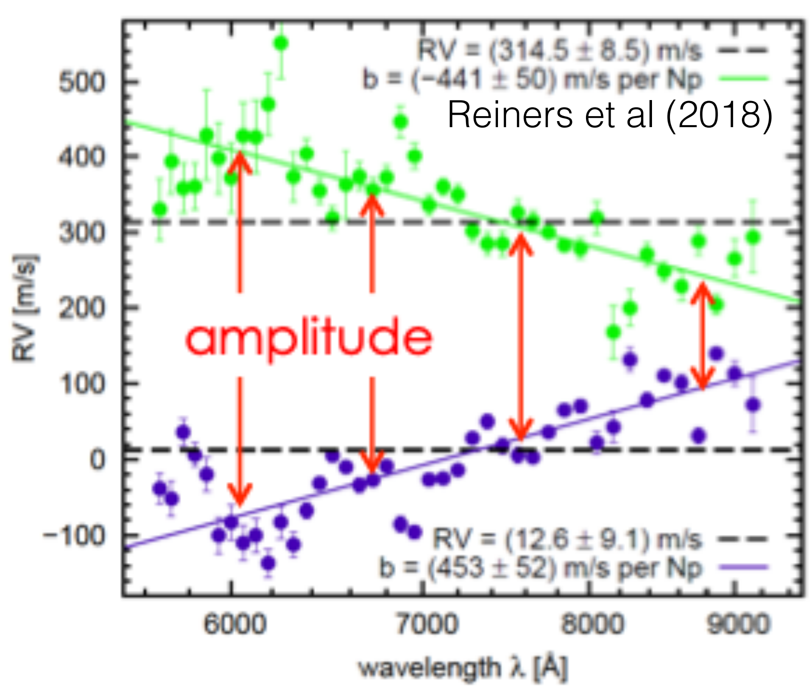
R~200k resolution (e.g. ESPRESSO)

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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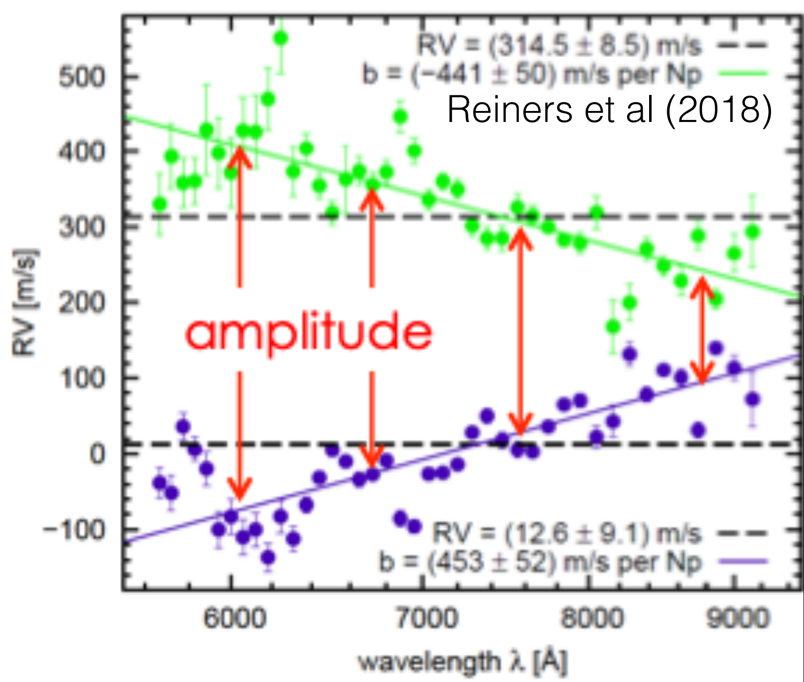
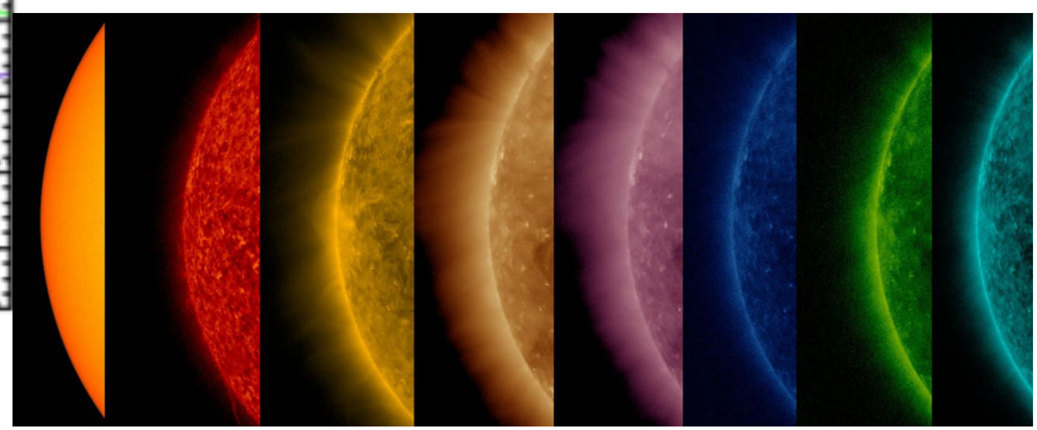


Stellar activity is not a simple function of λ, and also time-dependent



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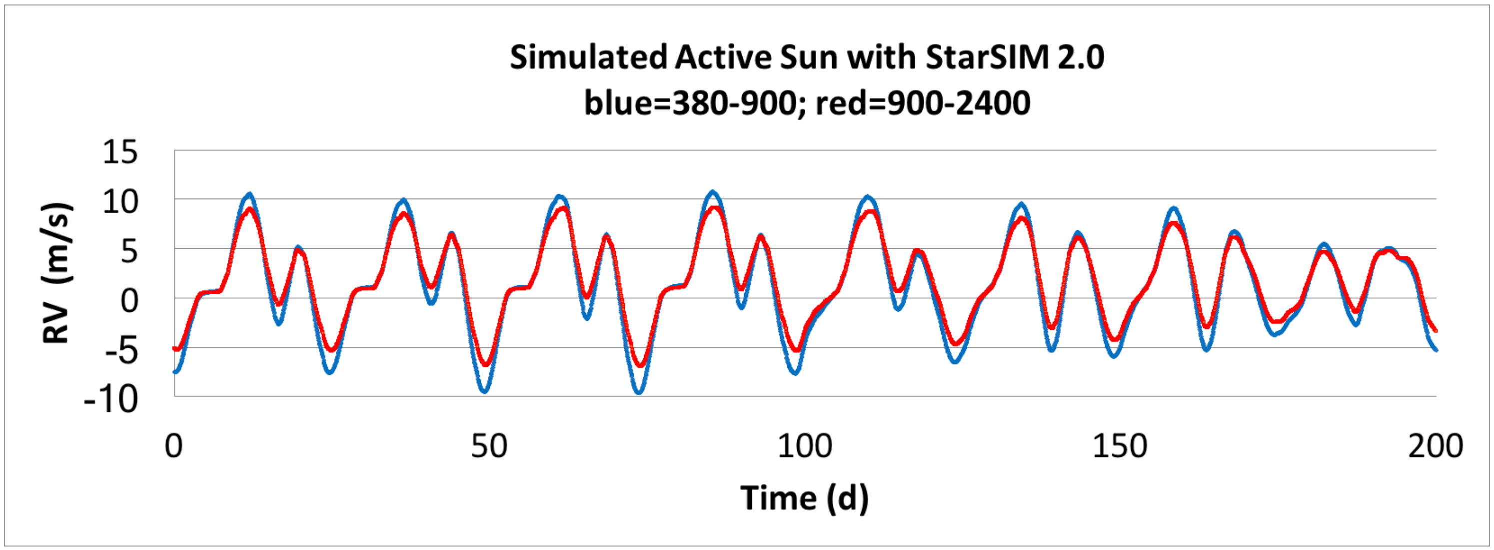
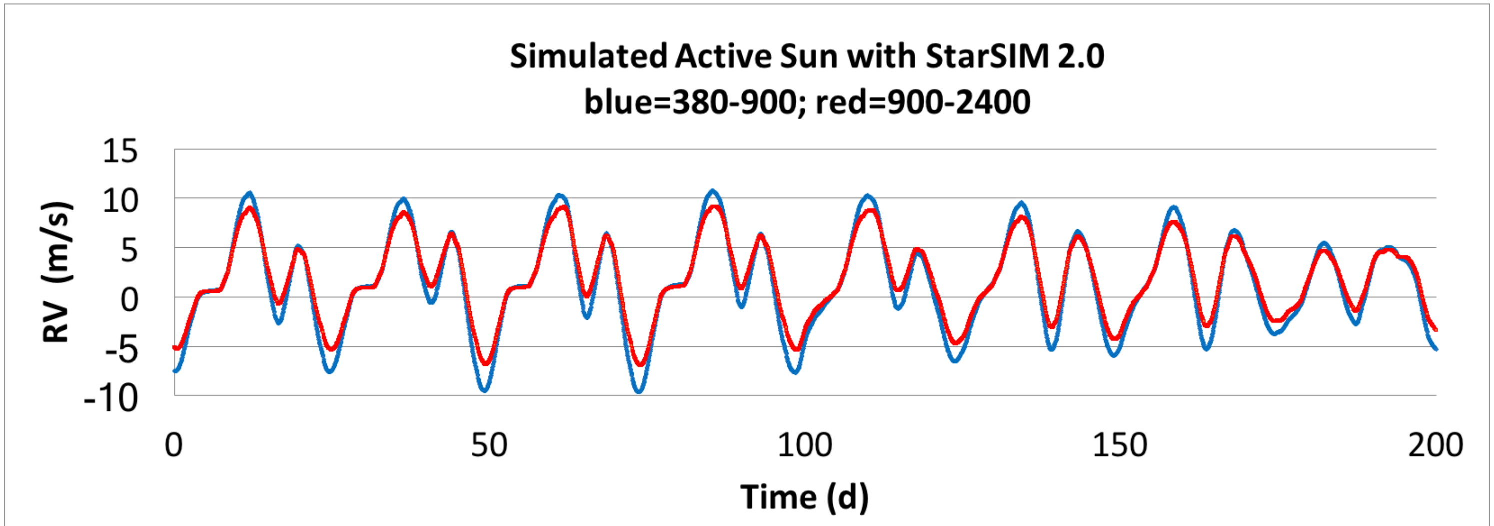
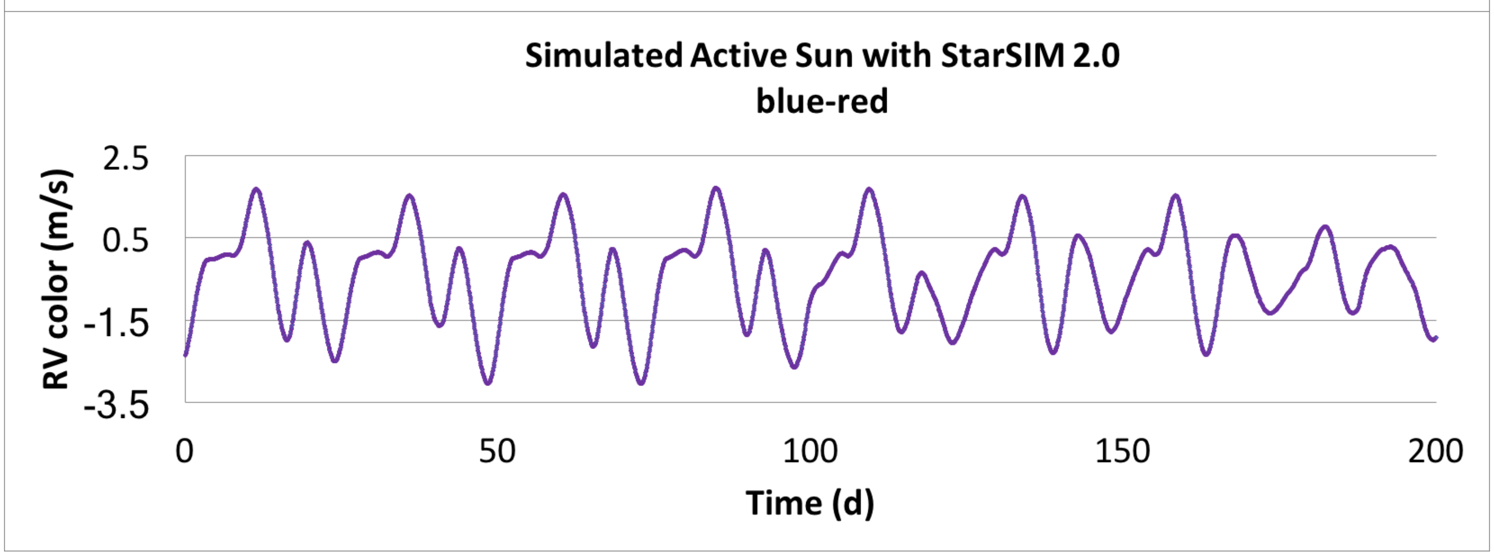


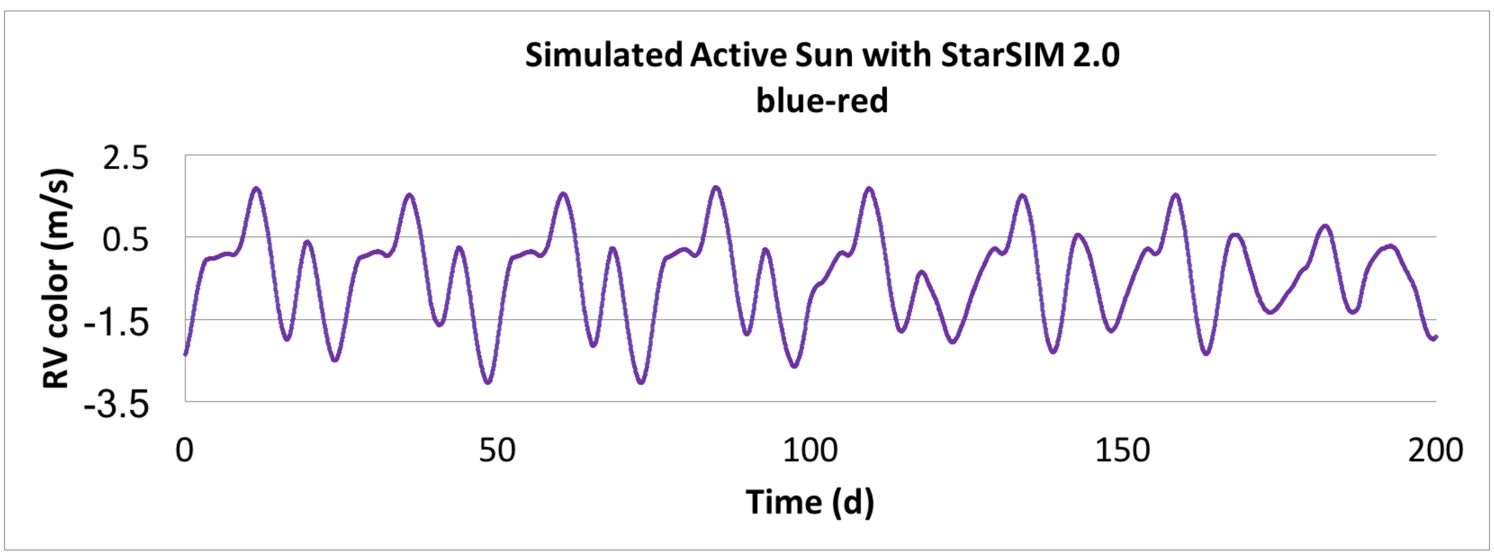
Wavelength Coverage





Wavelength Coverage

- 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 α RV color, so:
  - Isolated planet signal is still~RV - Cx(RV color)



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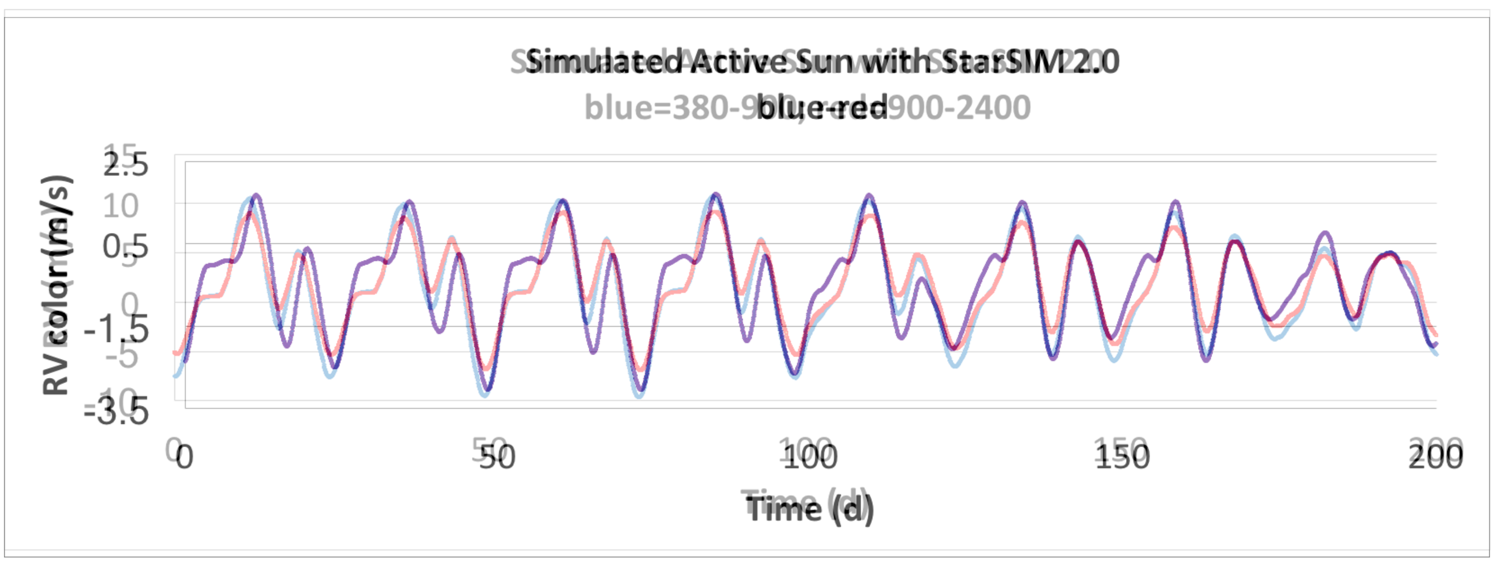

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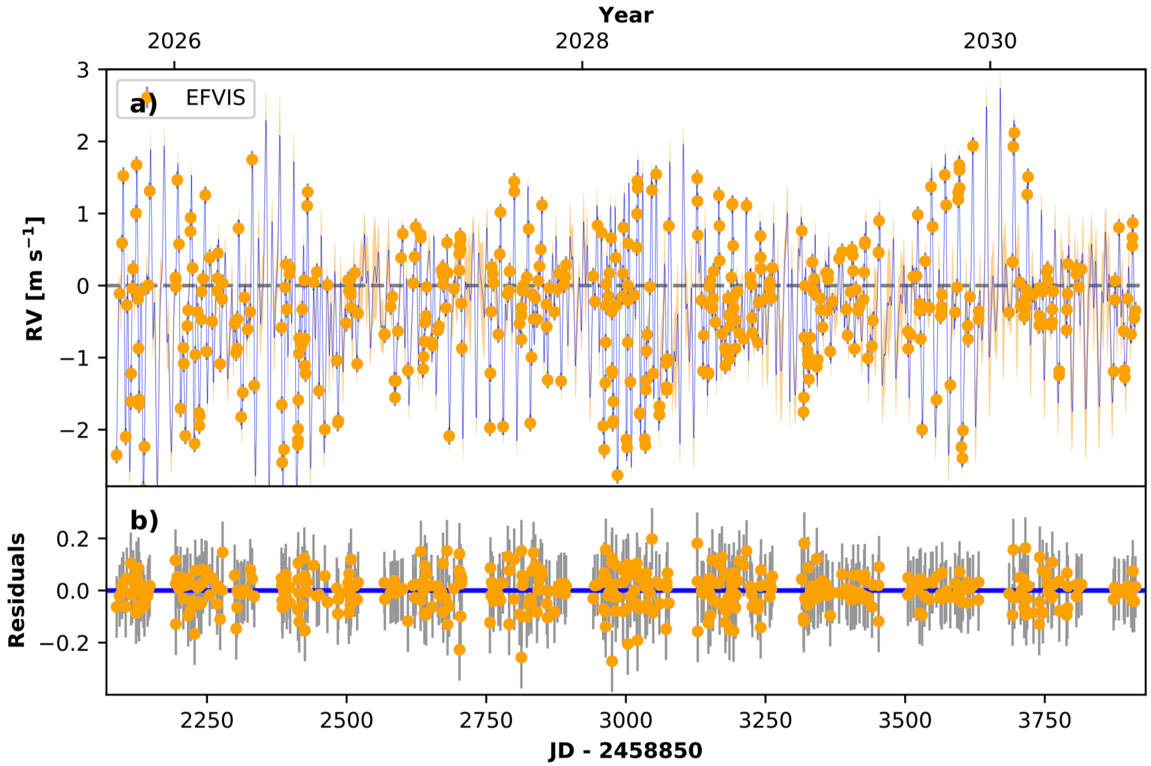

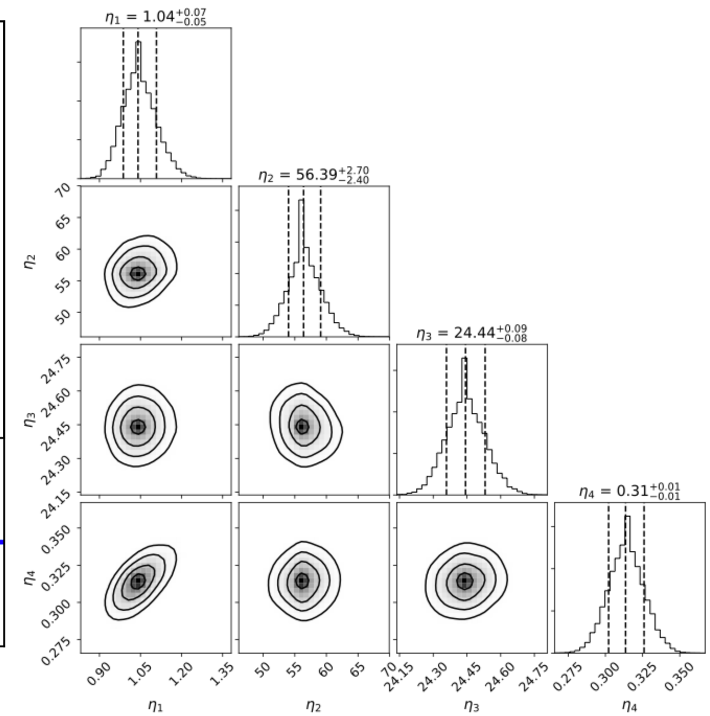

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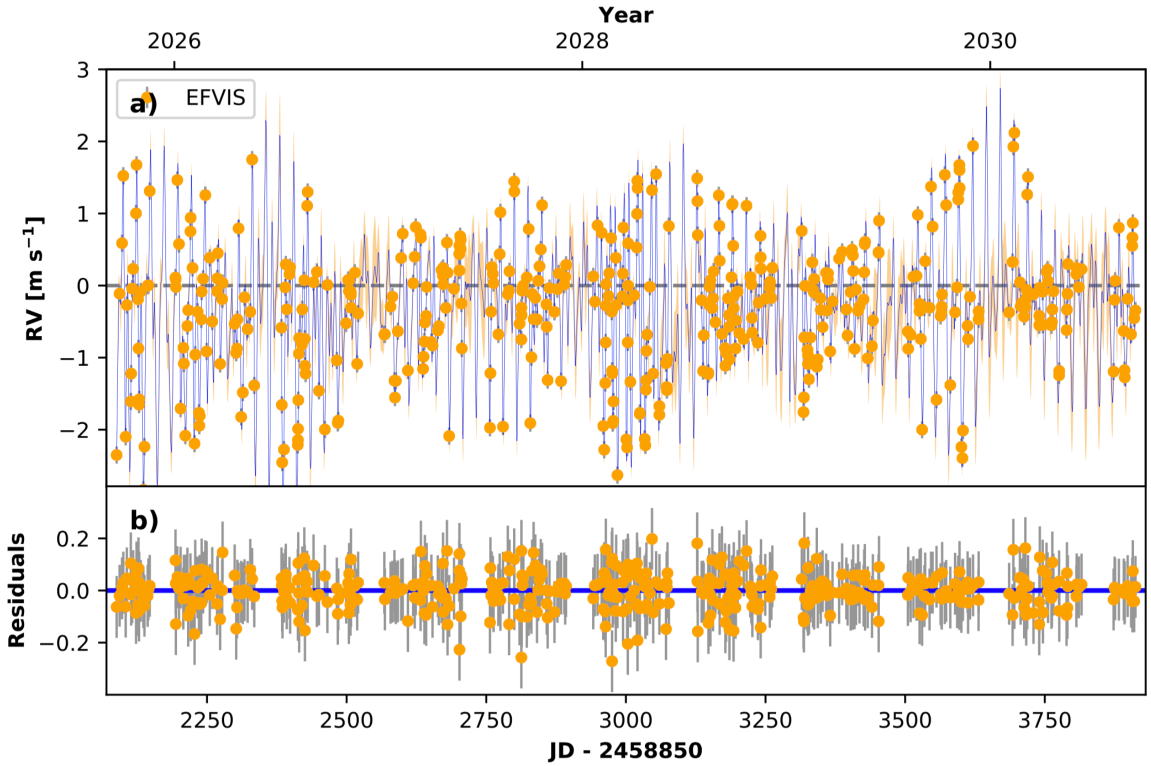
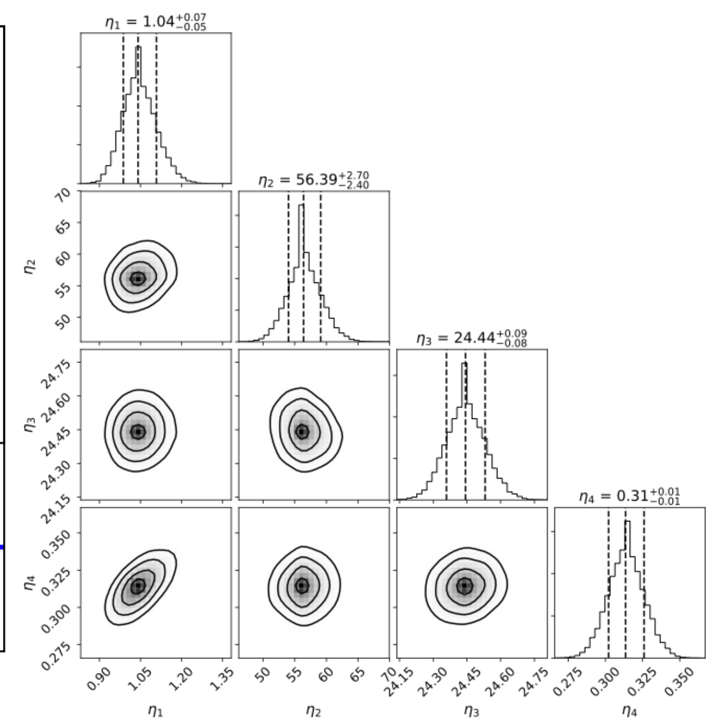
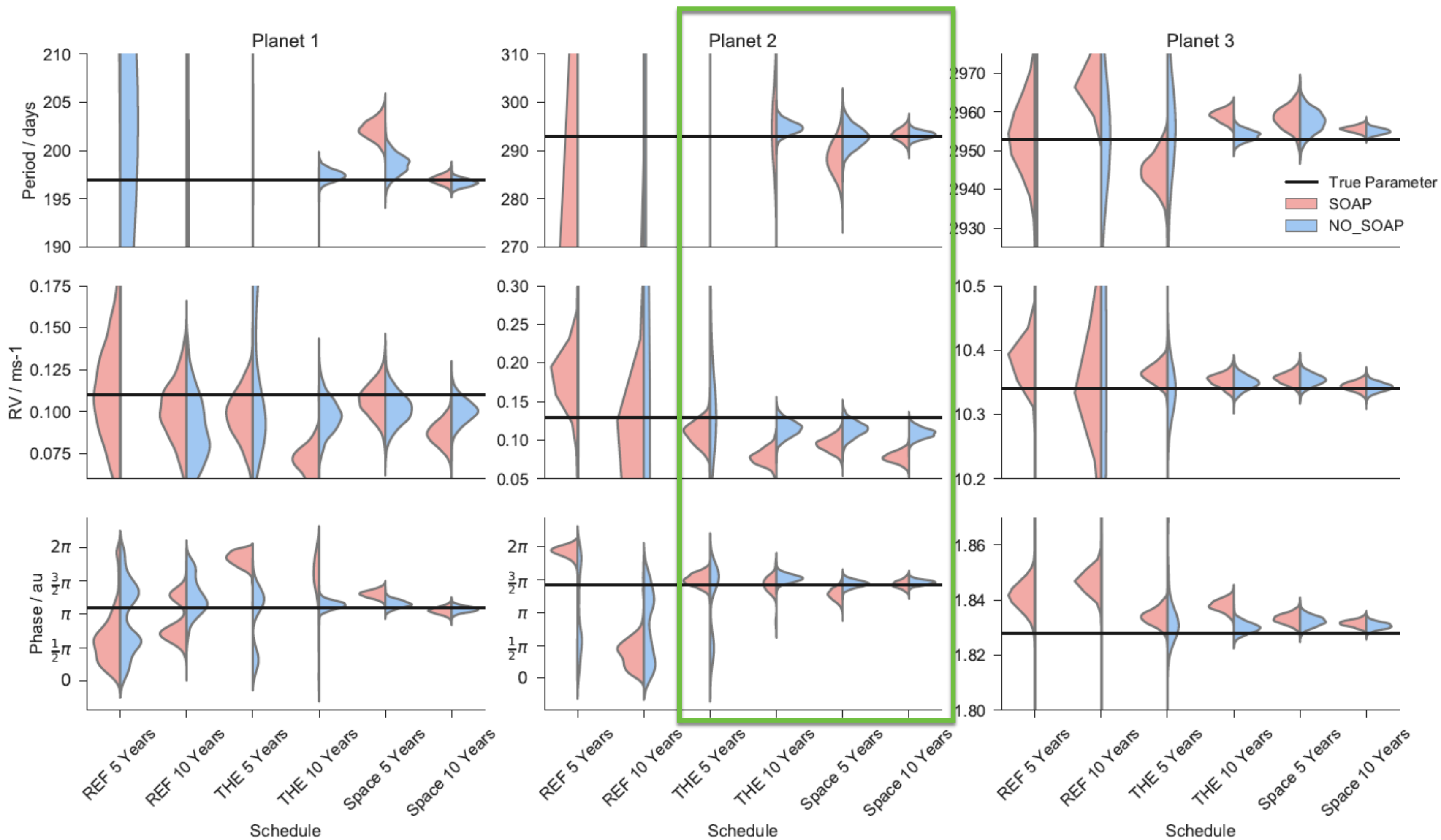




EarthFinder RV color achieves a 61% reduction in RV rms from stellar activity using only a simple linear-scaling model (e.g. no physics, limb-darkening and convective blue-shift wavelength dependence), better than the best results achieved from the ground to date, and it is not possible to get this precision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

Cadence - Hall et al. 2018



Cadence

Space

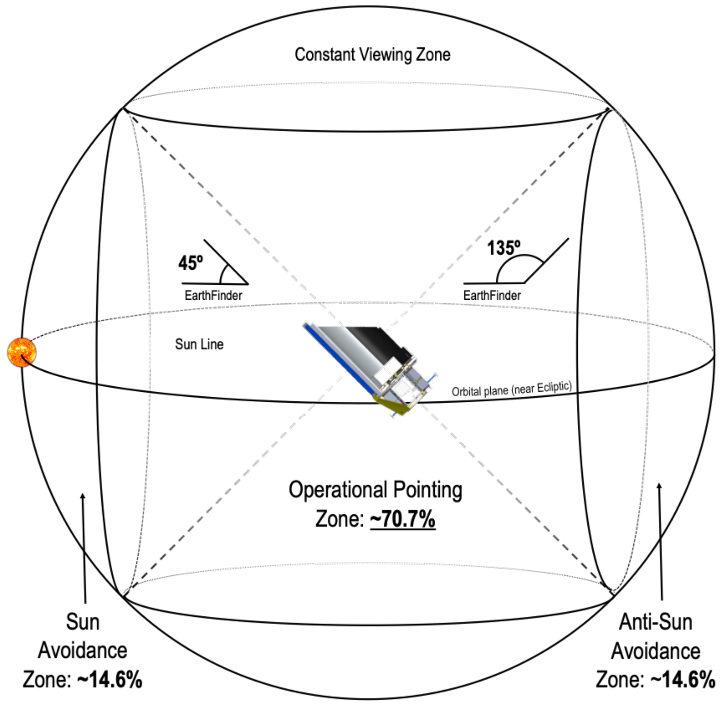
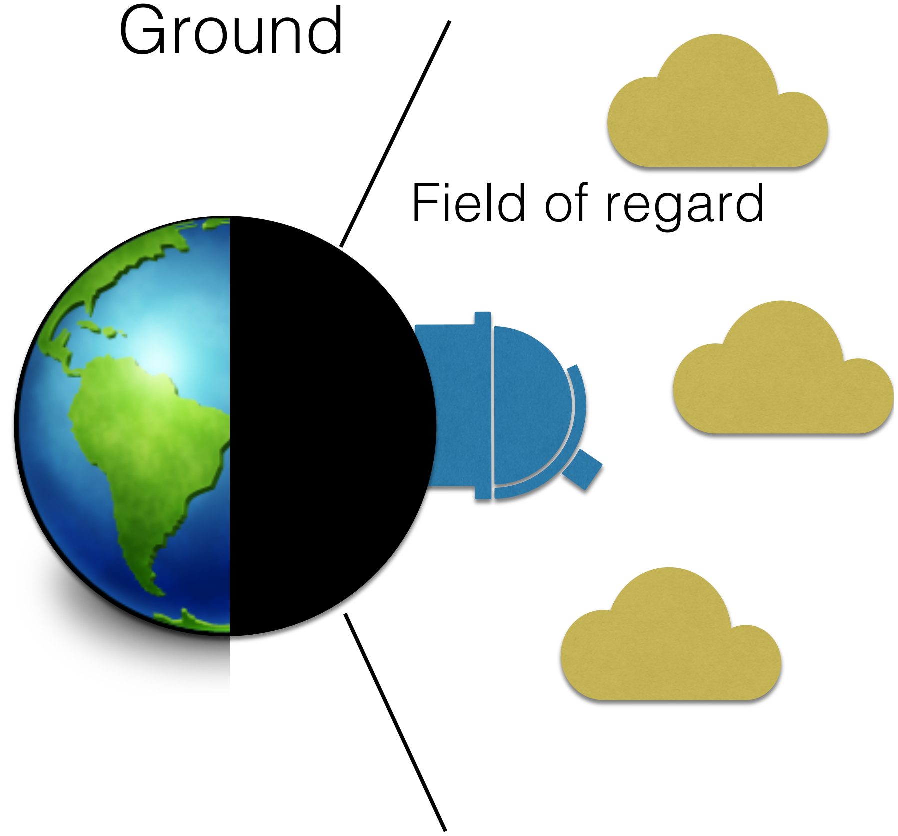


Figure from Bahaa Hamze

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

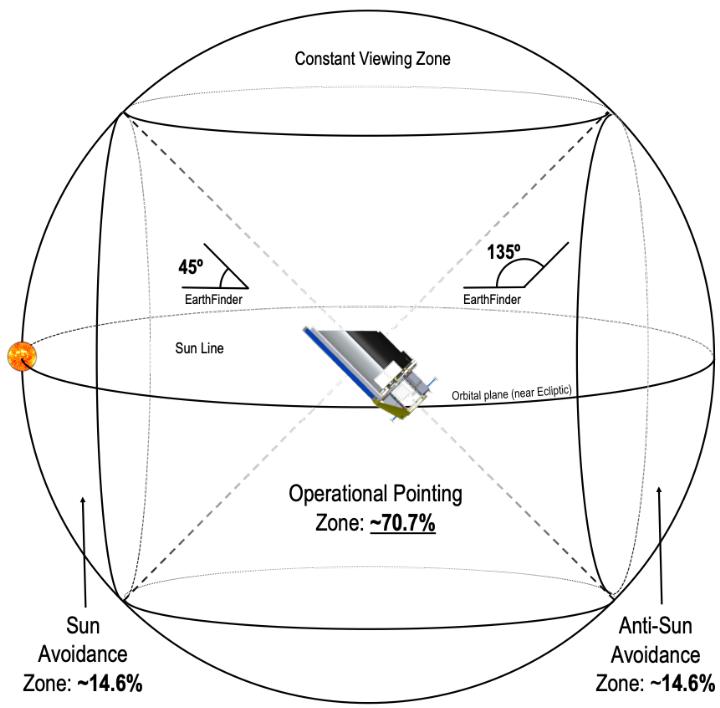
Ground



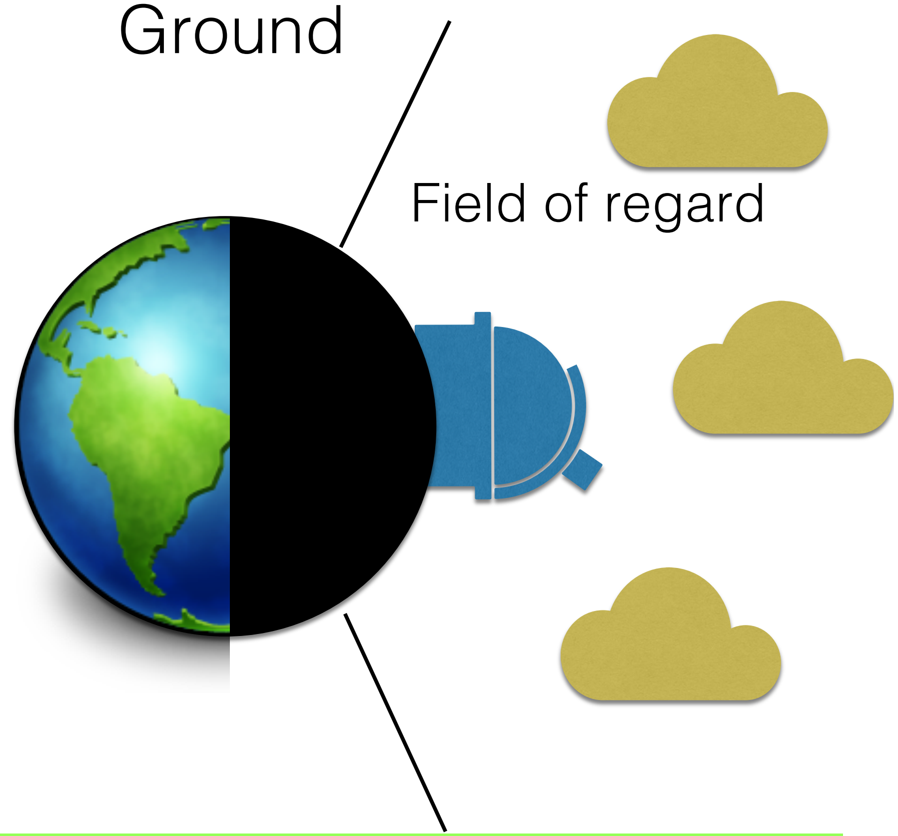
One ~3-6 month visibility window per year, minus daytime and minus weather

Cadence

Space

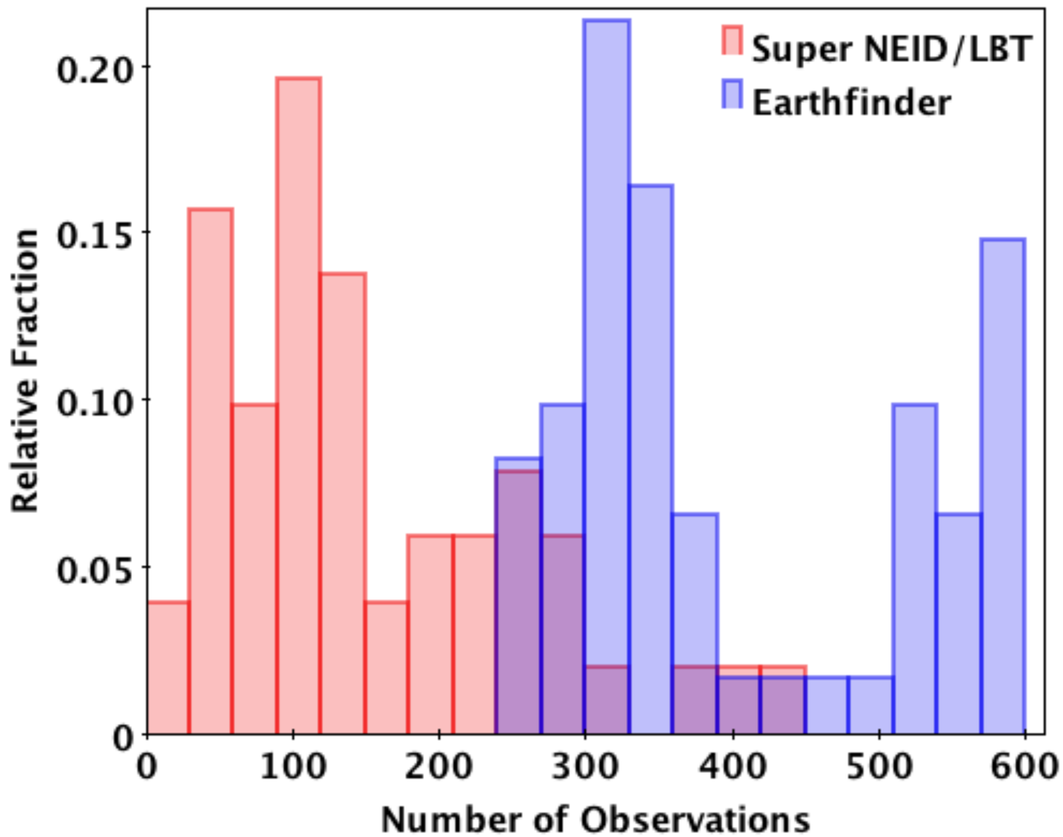


Ground



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.

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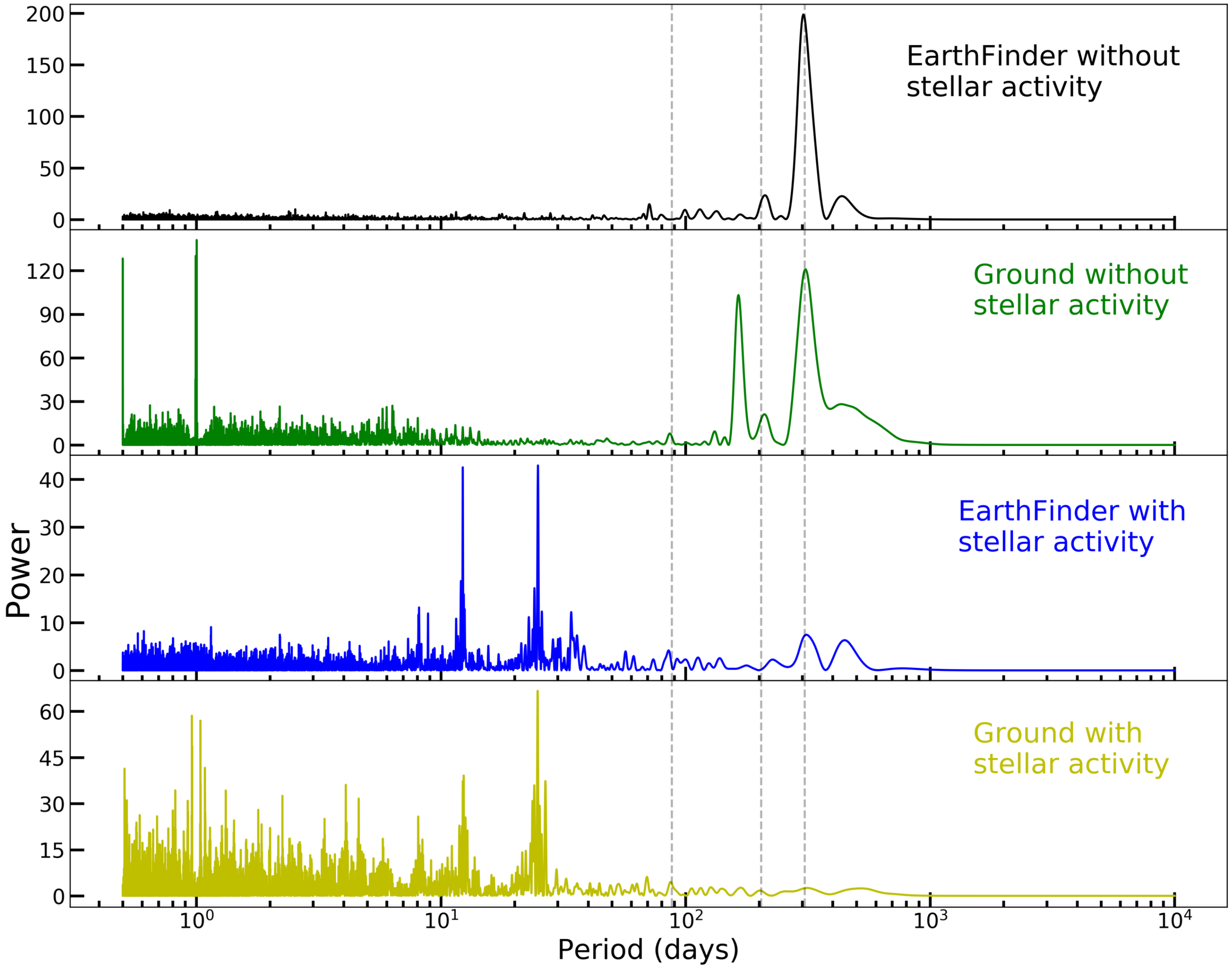

EarthFinder without
stellar activity
Ground without
stellar activity
EarthFinder with
stellar activity
Ground with
stellar activity
Power
Period (days)
200
150
100
50
0
120
90
60
30
0
40
30
20
10
0
60
45
30
15
0
10^0
10^1
10^2
10^3
10^4

R>150k & Line-by-Line Analysis

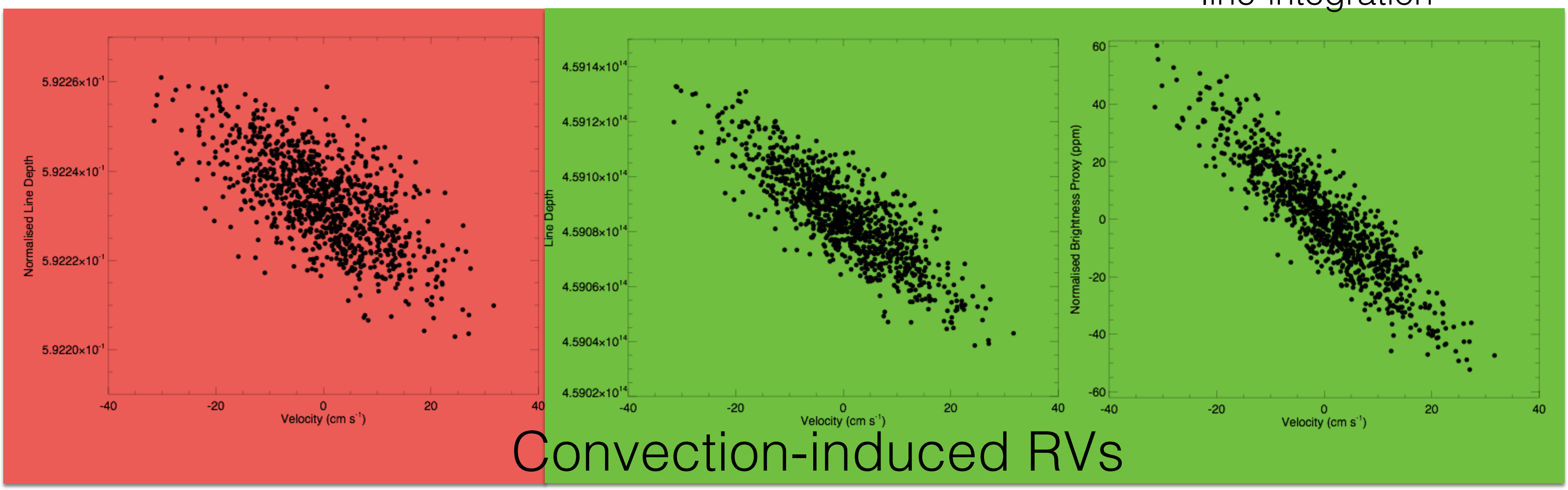
- Line-by-line analysis has recently shown promise for mitigating activity w/ HARPS data:
  - Dumusque et al. (2018) - 30% reduction in RV rms for Sun and Alpha Cen B
  - Lanza et al. (2018) - 50% reduction in RV rms for one dozen solar-like stars
  - Wise et al. (2018) - Line depth correlated with activity for optimal subsets of lines

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



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.

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

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) diffraction-limited 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

Aligned with NAS Exoplanet Science Strategy recommendations

- These efforts will benefit ground-based RV efforts at the same time as prepping for EarthFinder