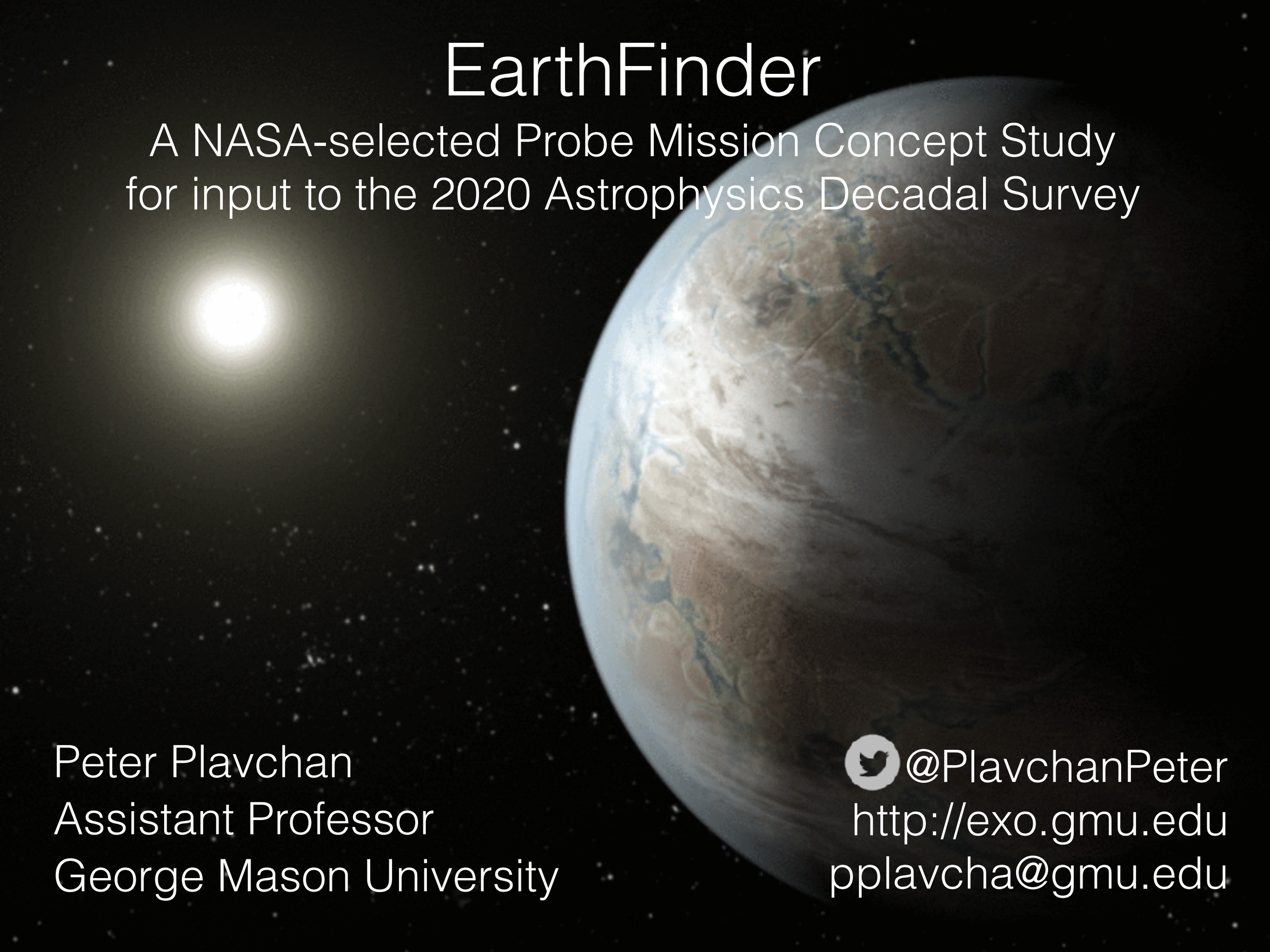
EarthFinder

A NASA-selected Probe Mission Concept Study for input to the 2020 Astrophysics Decadal Survey



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EarthFinder Team

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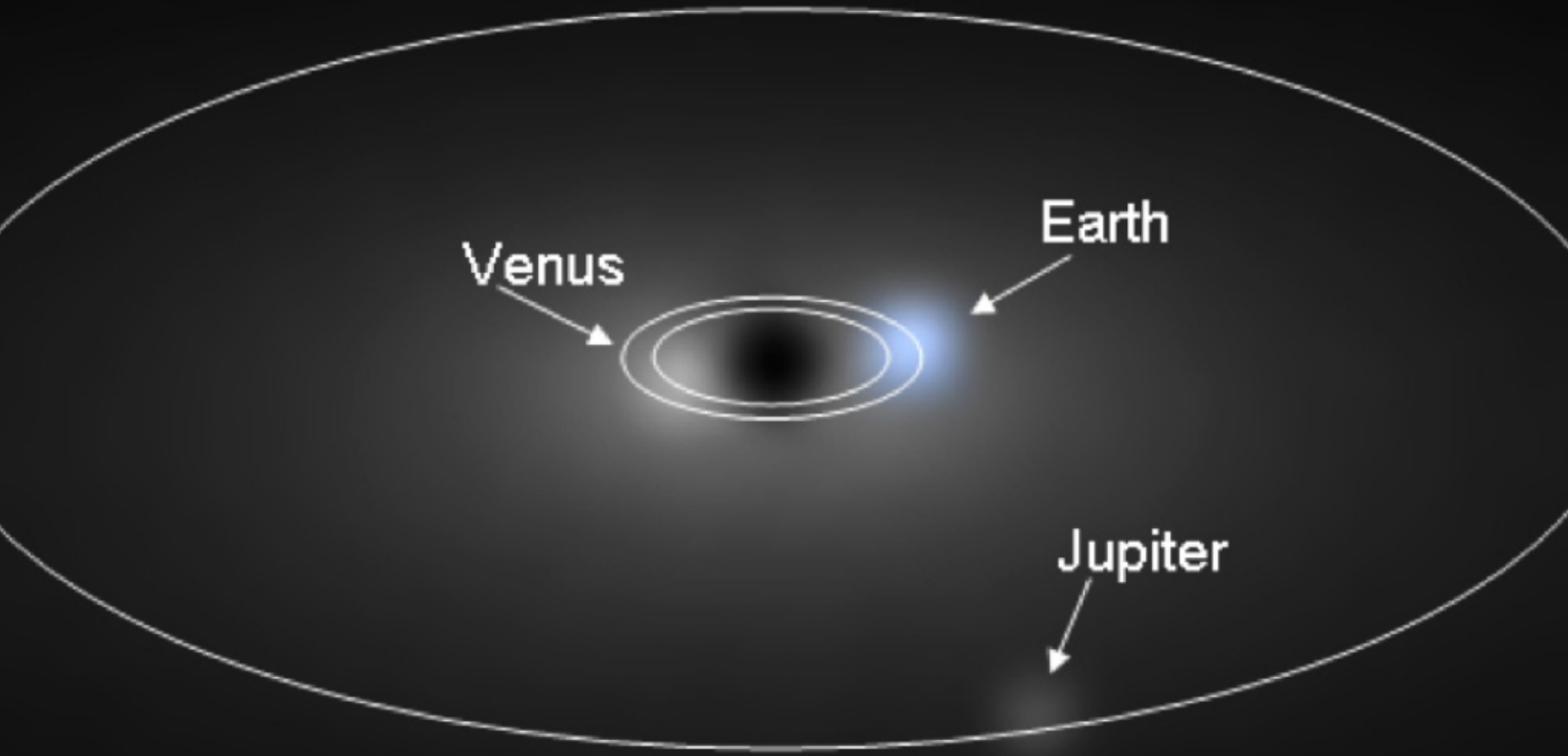
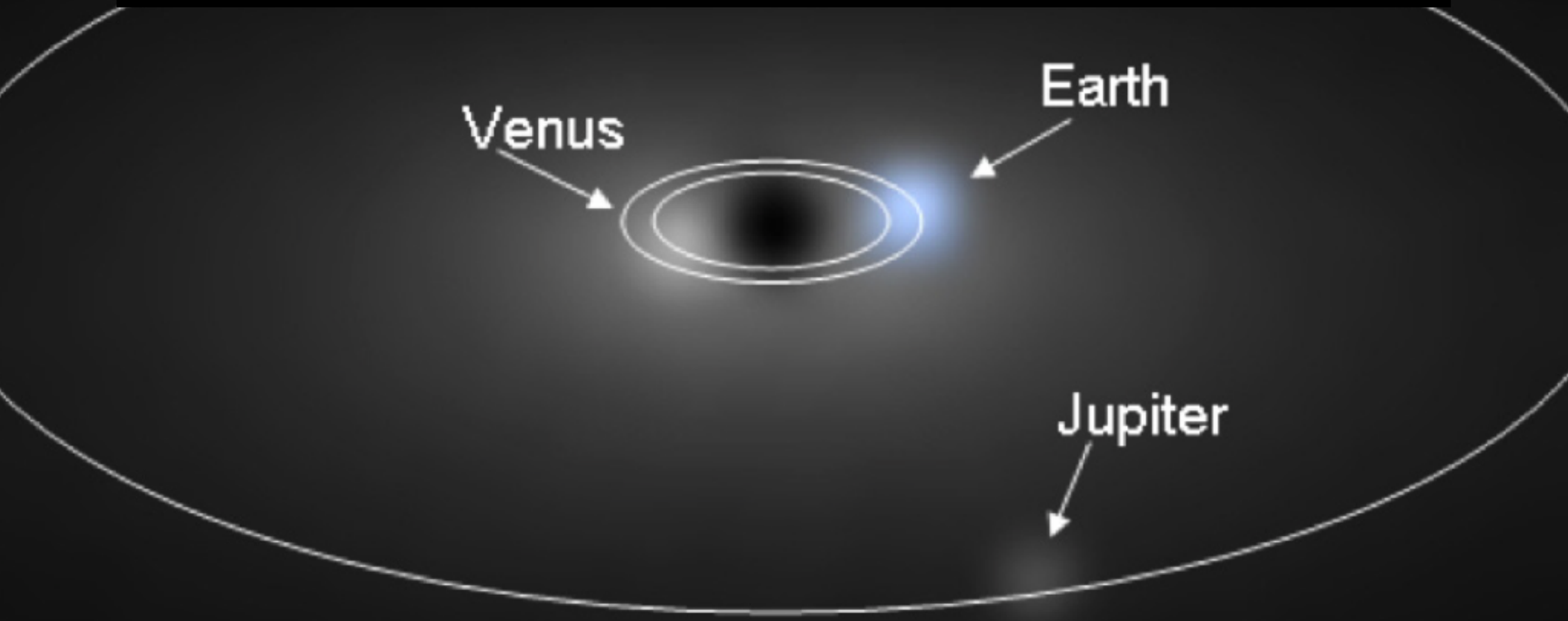

Earth
Venus
Jupiter

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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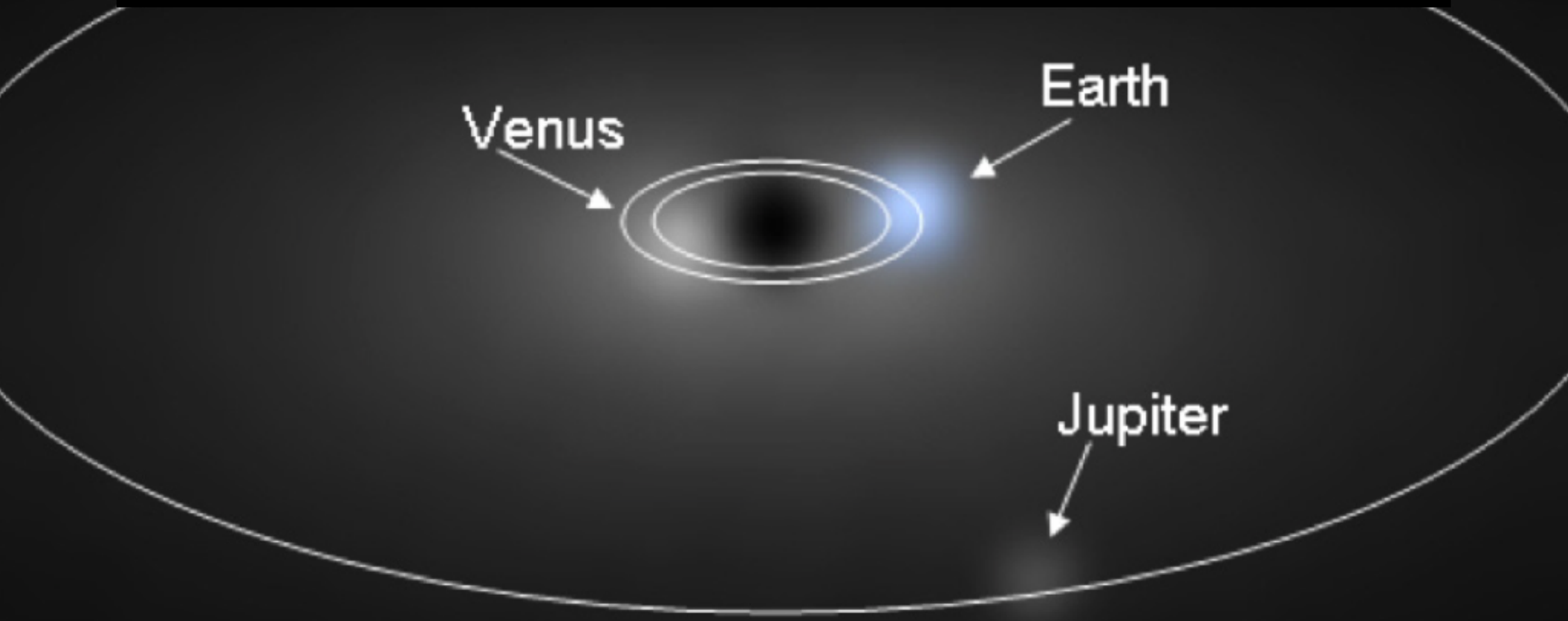
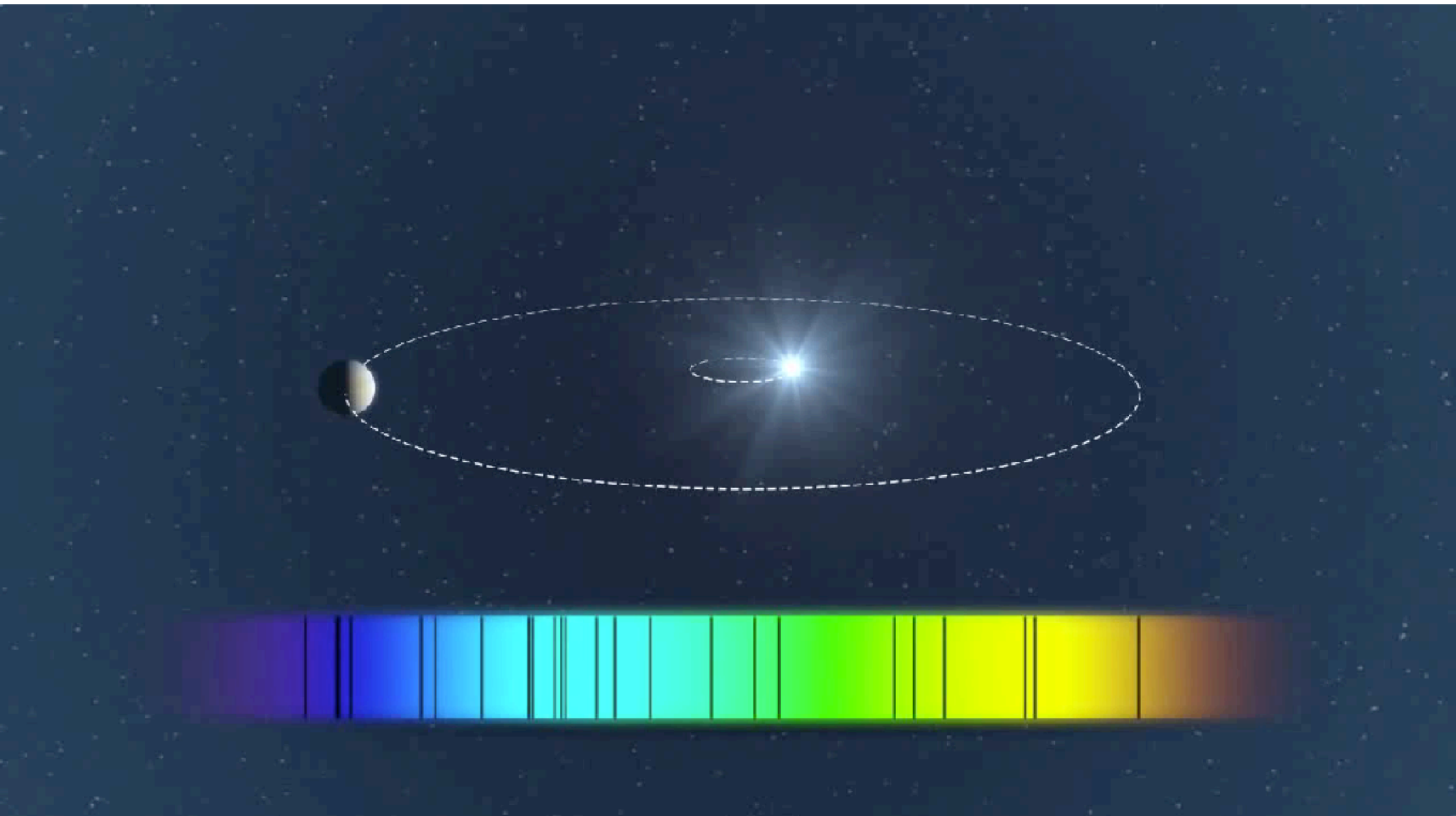
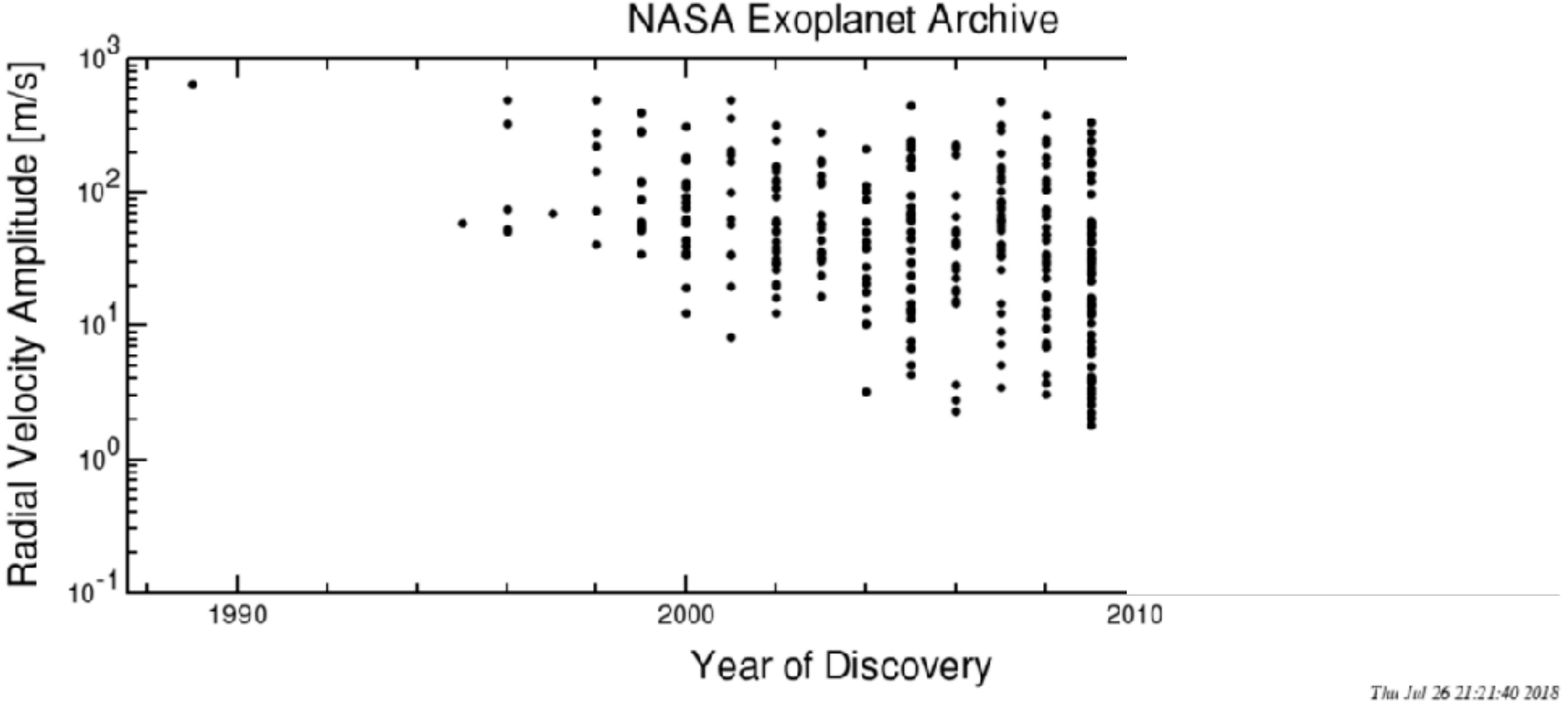


Either way, we will still need the planet masses for characterization!

The Doppler Method



The Future Promise of RVs



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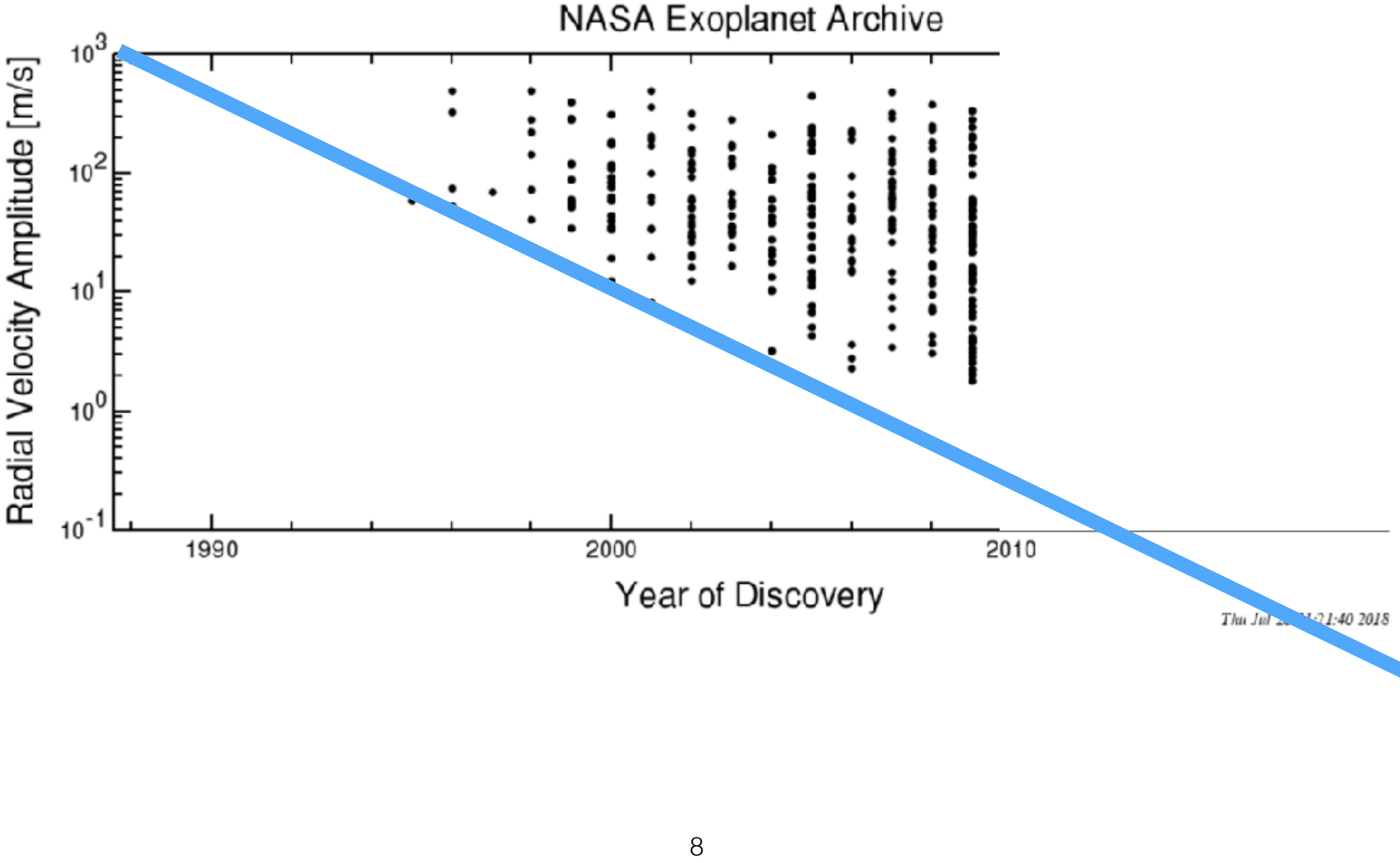

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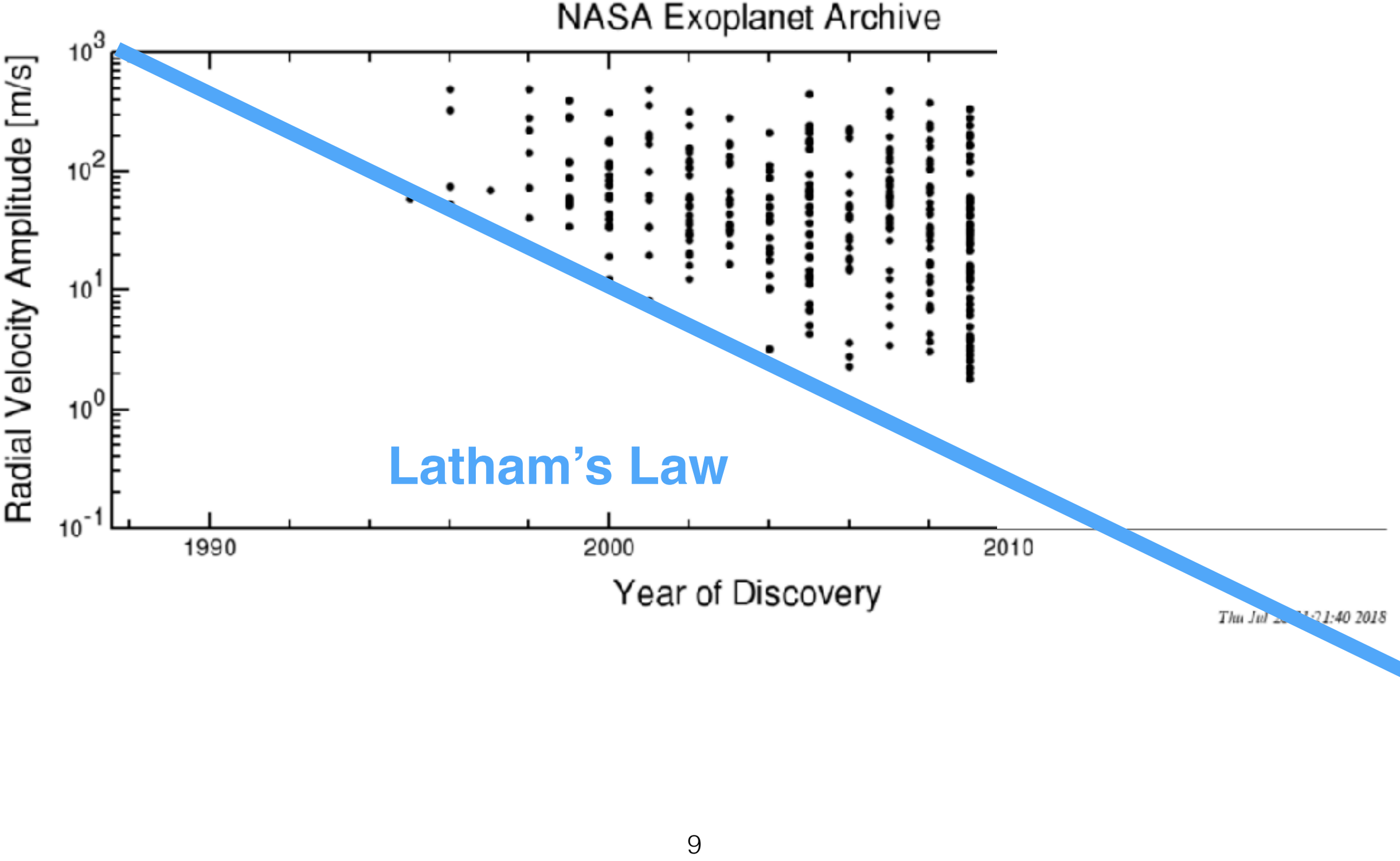

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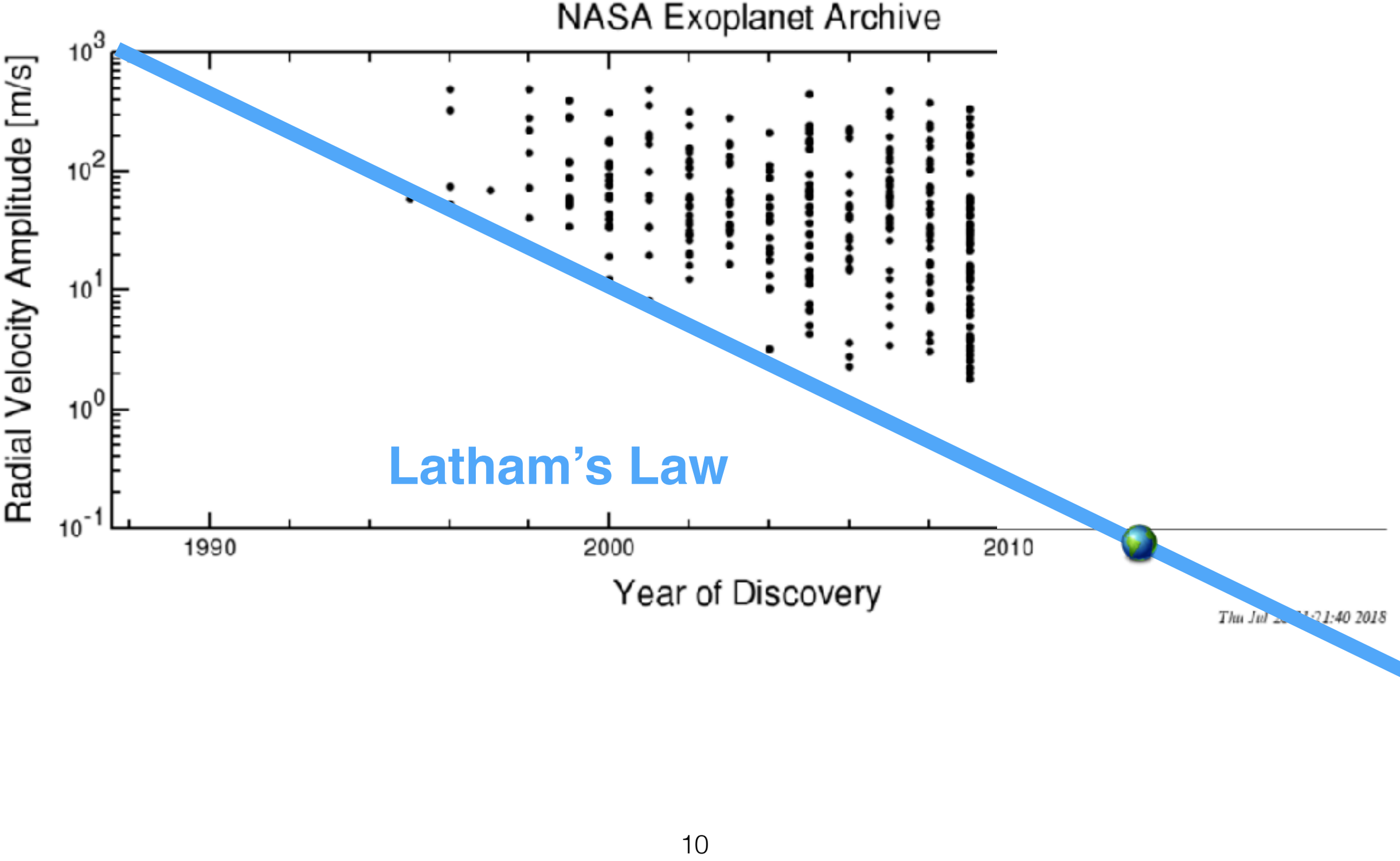

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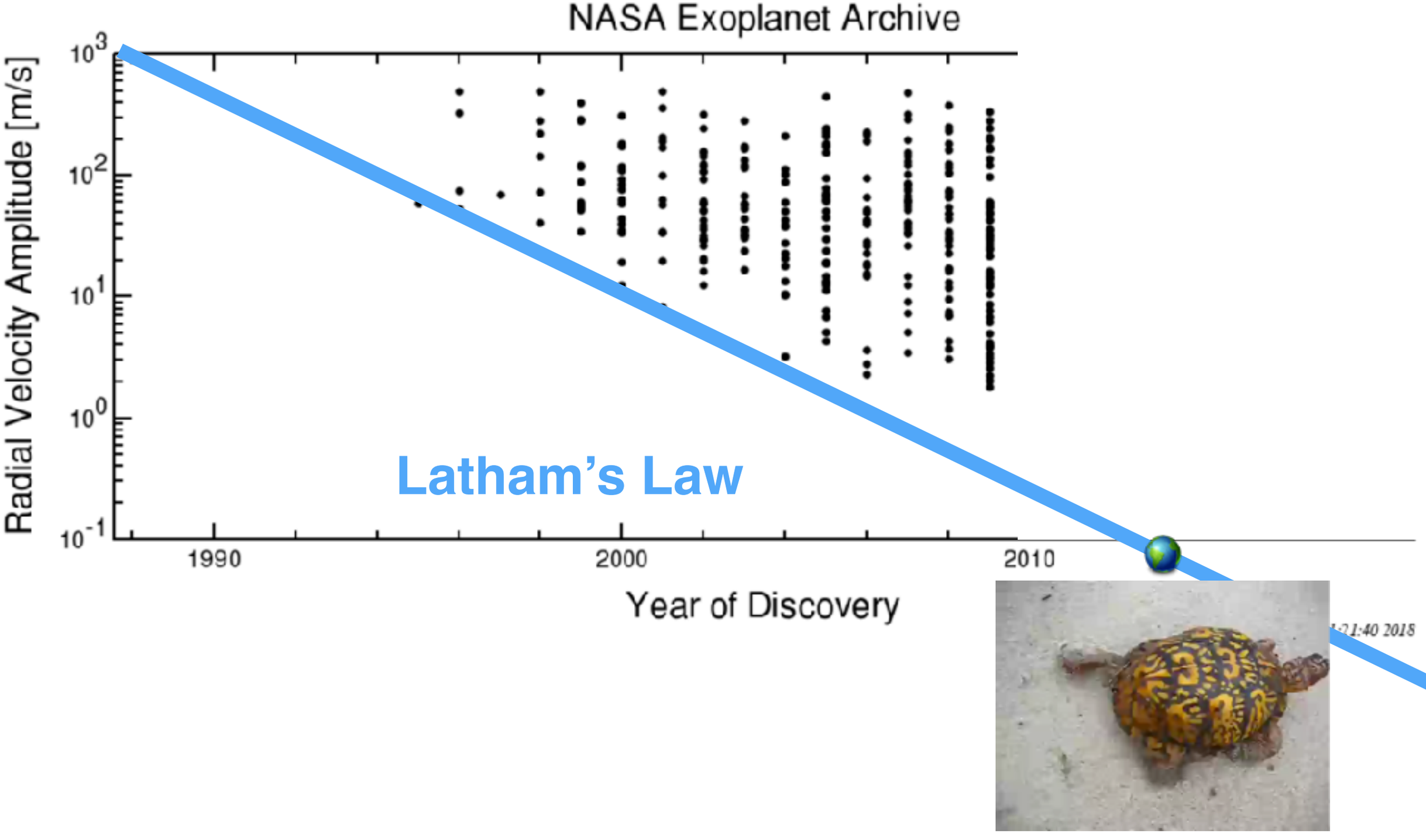

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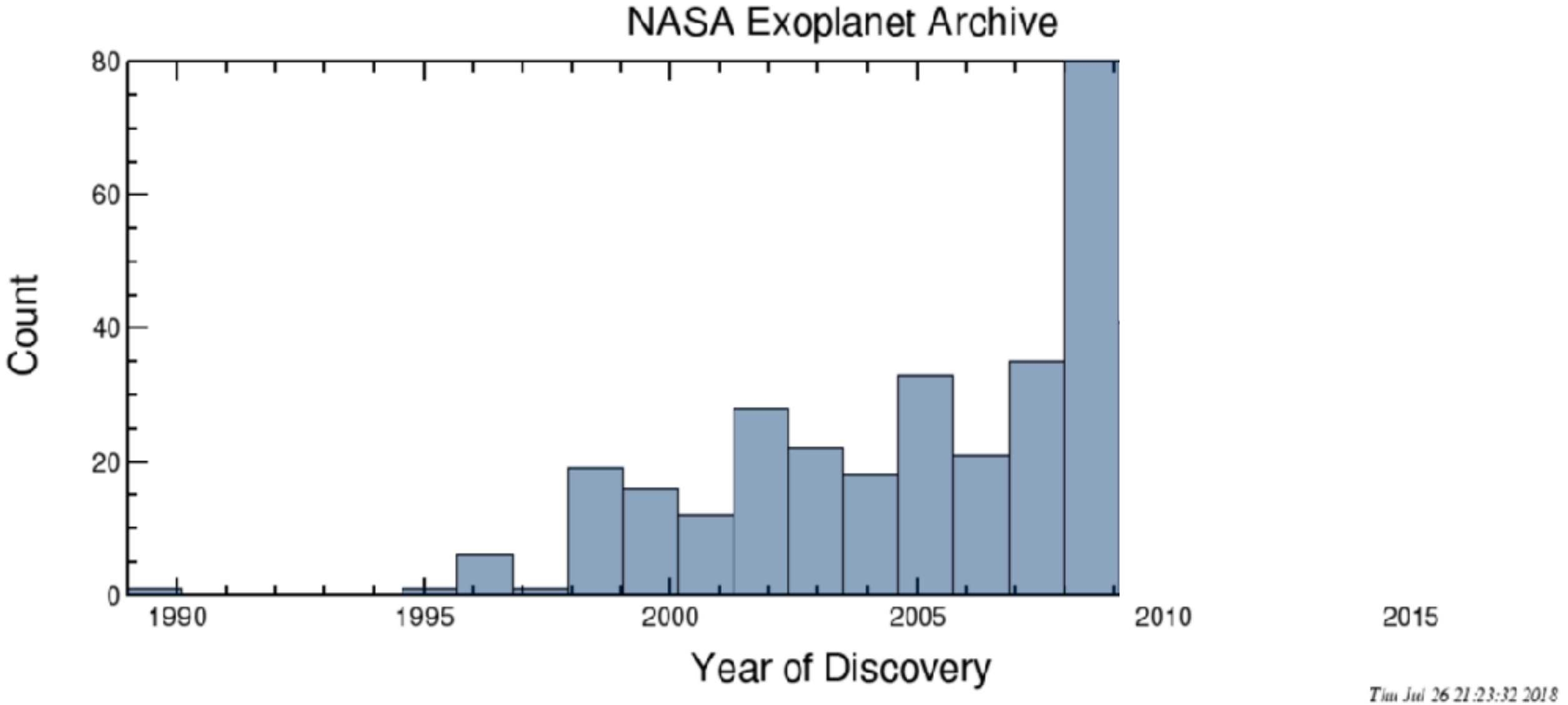

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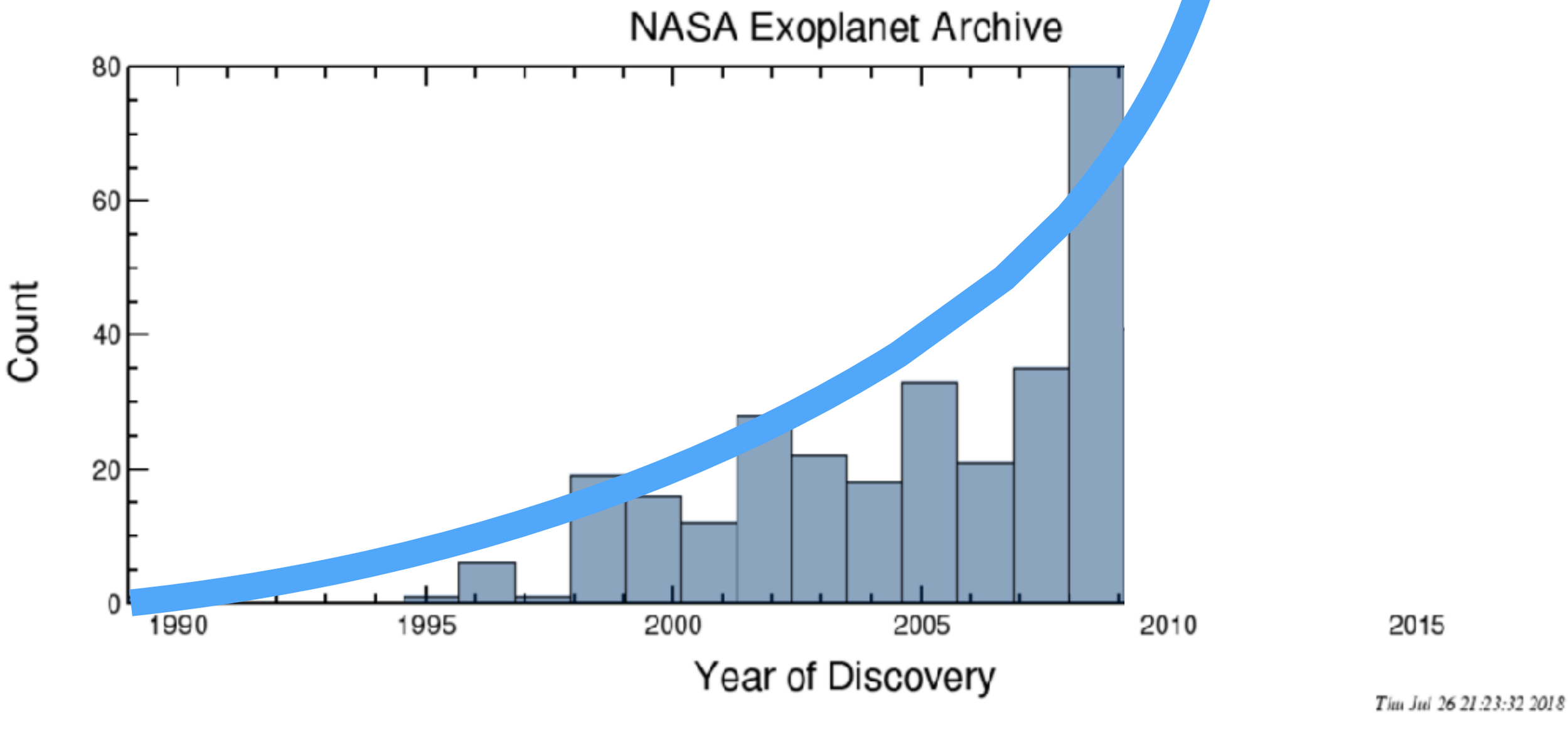

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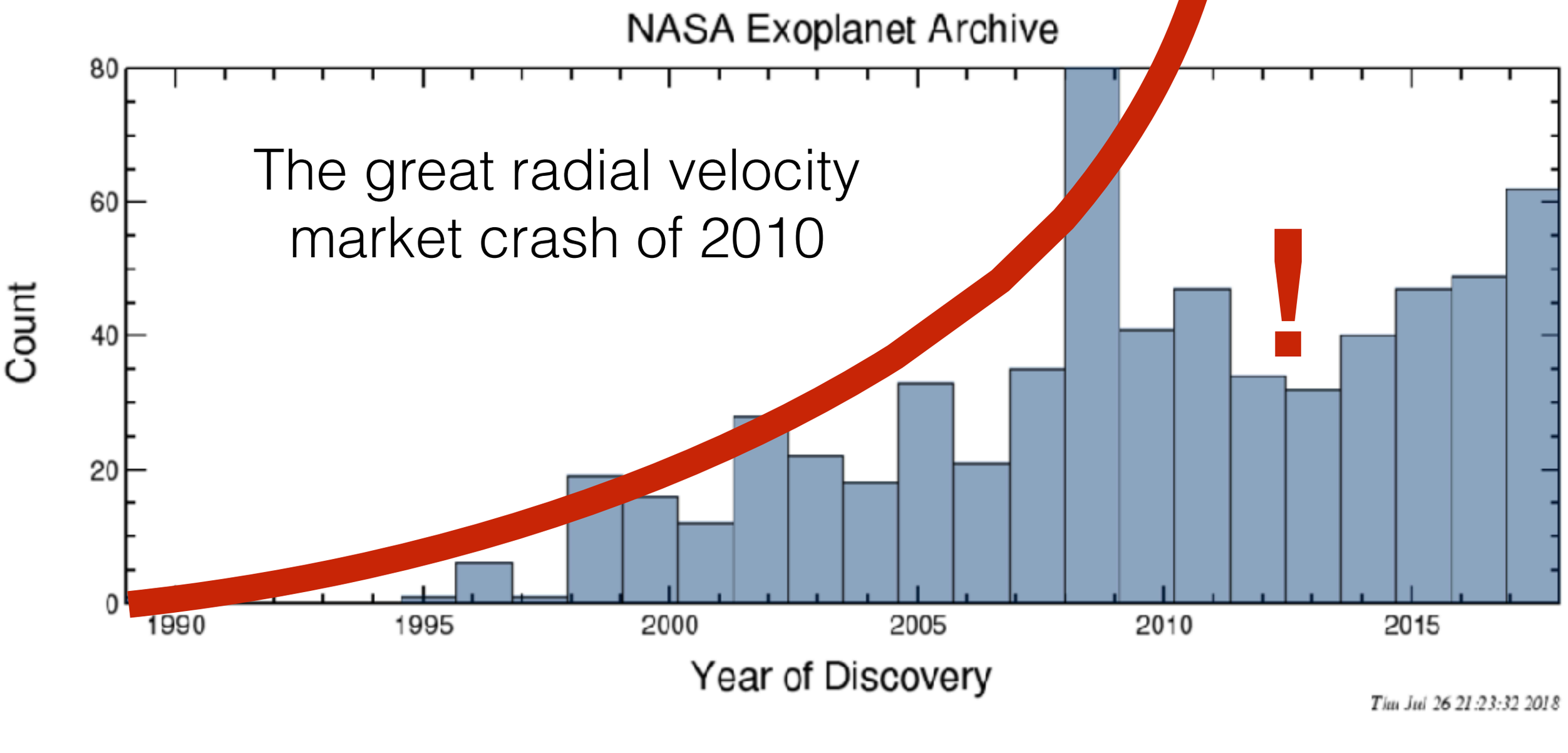

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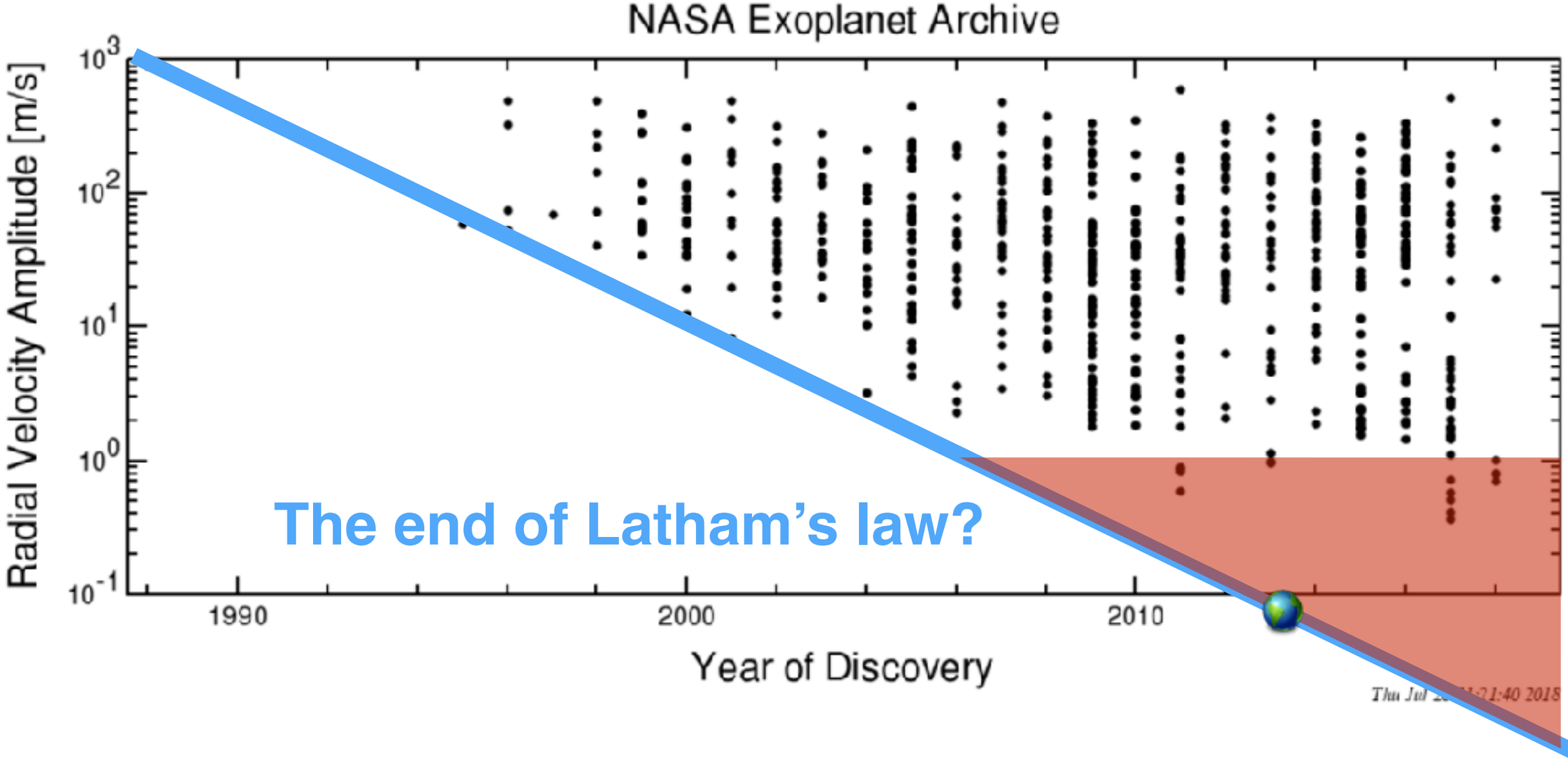
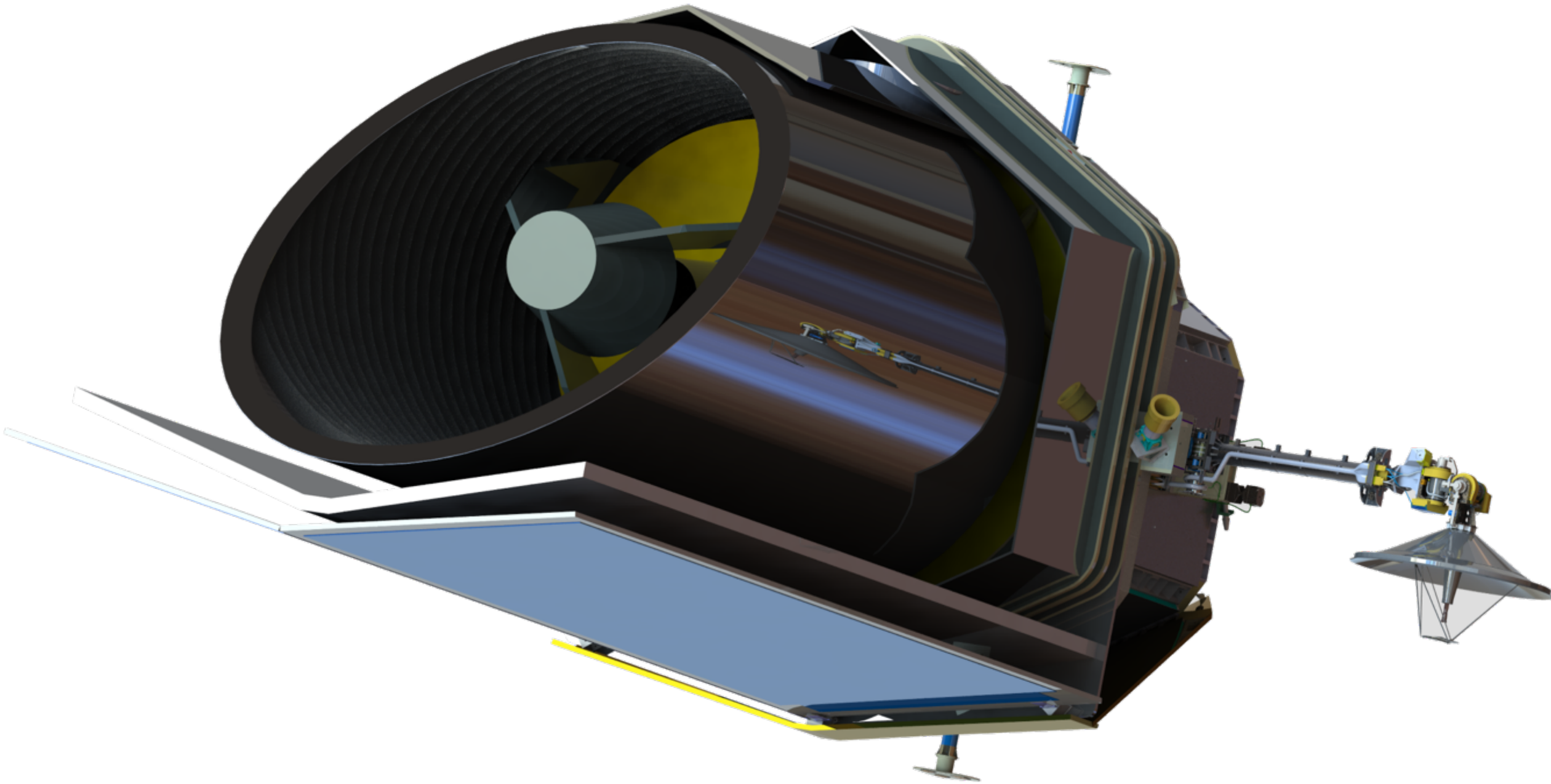


Causes of the RV recession

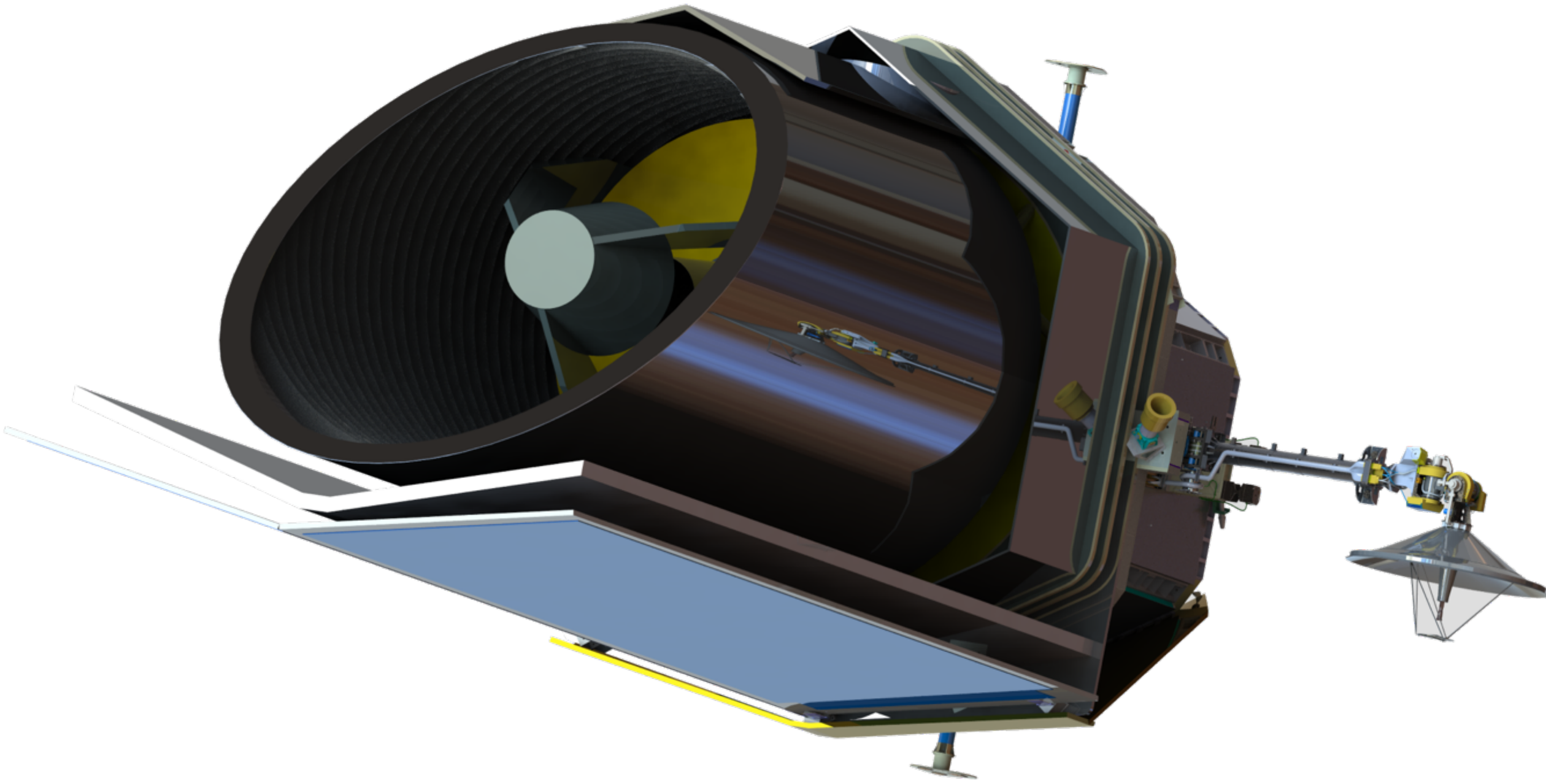
- **Kepler** - Redirection of resources and personnel
- **Instrumentation** - 1 m/s single measurement precision from HARPS, 2-3 m/s from iodine technique
- **Telescope time** - 10x improvement in precision requires 100x increase in telescope time (or reduction in target lists); multi-planet system number of discovery epochs increases non-linearly (30: 1 planet;100+: 2 planets; 500+: 3+ planets)
- **Pipeline analysis** - CPS code is 20 years old, designed for computation-limited environment. HARPS code is basic CCF with line-masking
- **Stellar Activity** - Targeting quietest stars running its course

EarthFinder



Credit: Ball Aerospace

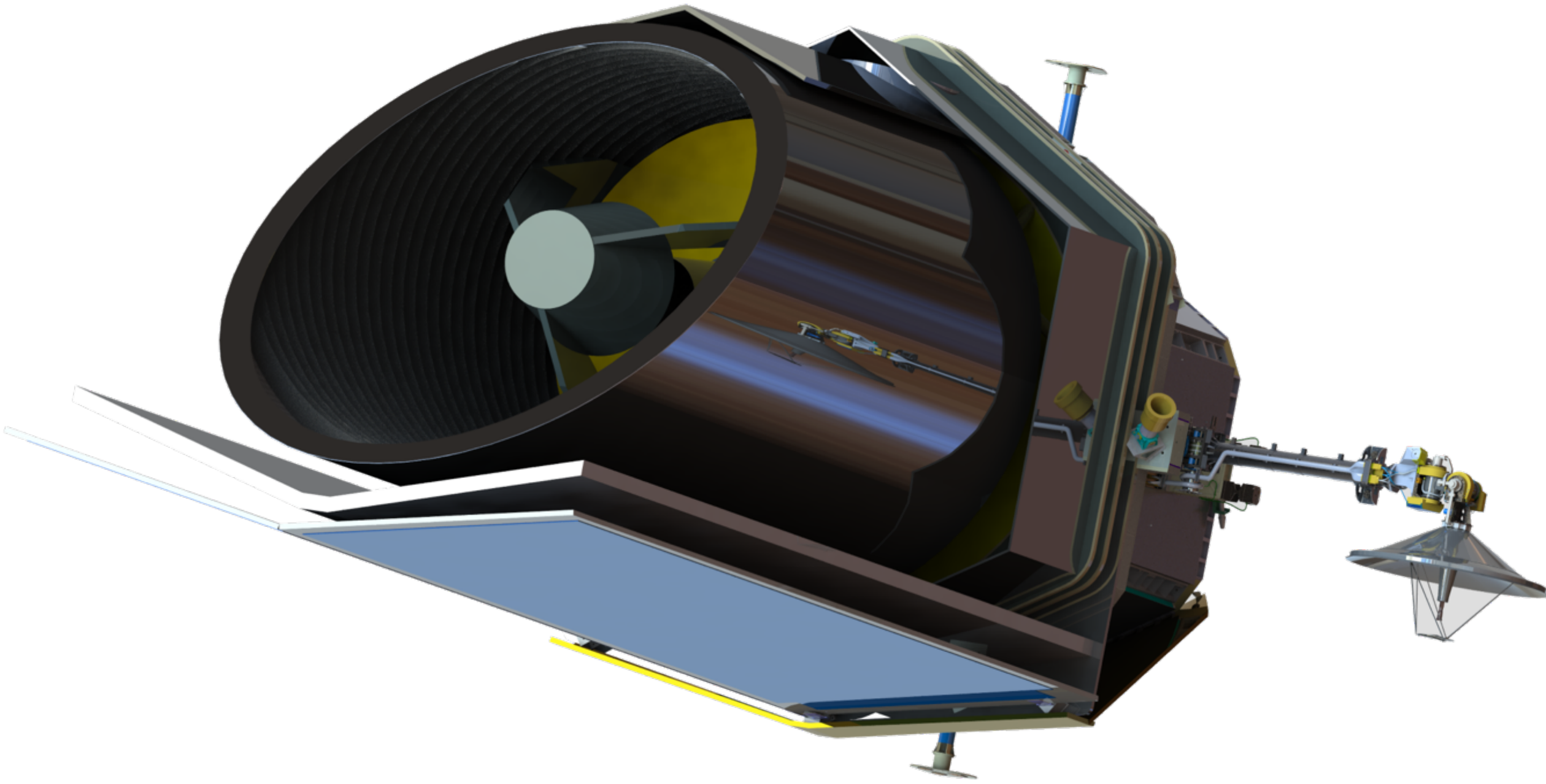
EarthFinder



Radial Velocities …

Credit: Ball Aerospace

EarthFinder

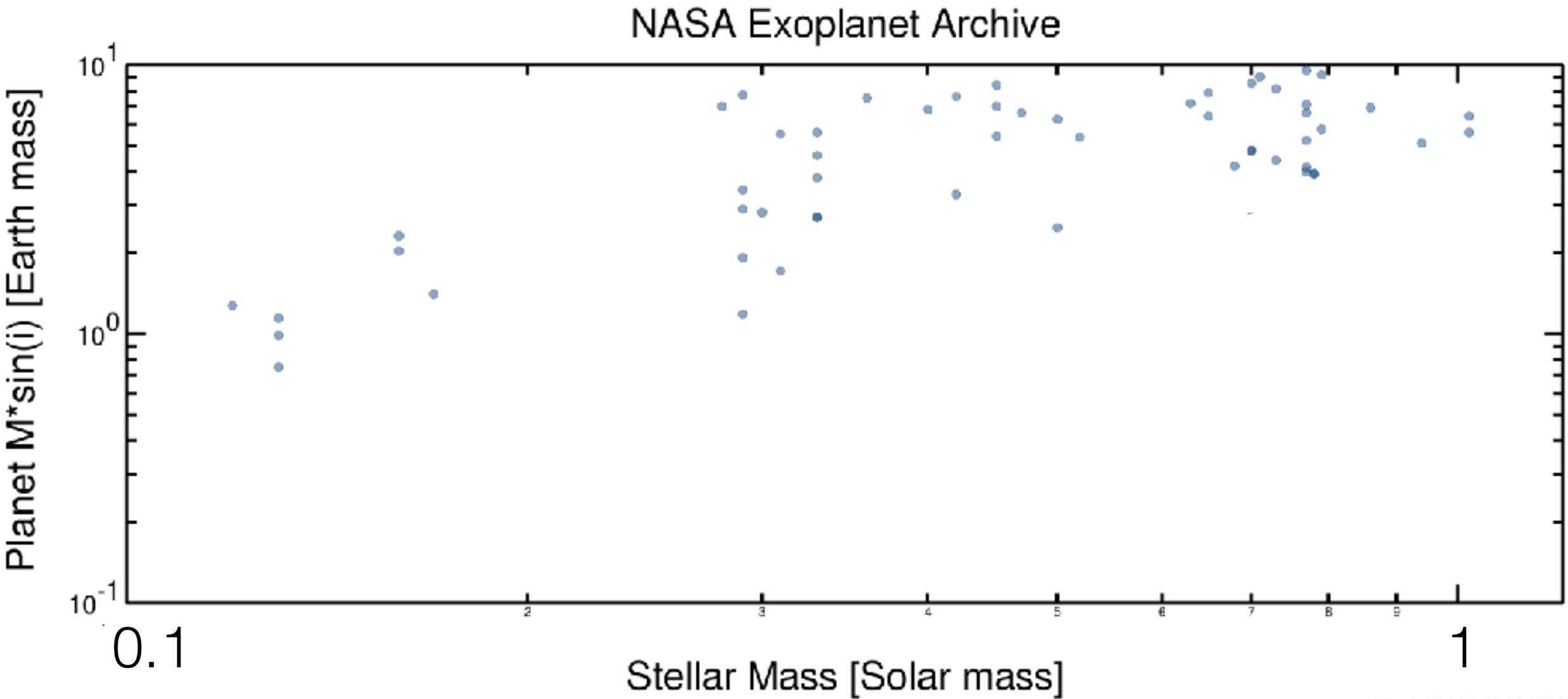


Radial Velocities … *in space!*

Credit: Ball Aerospace

Science

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



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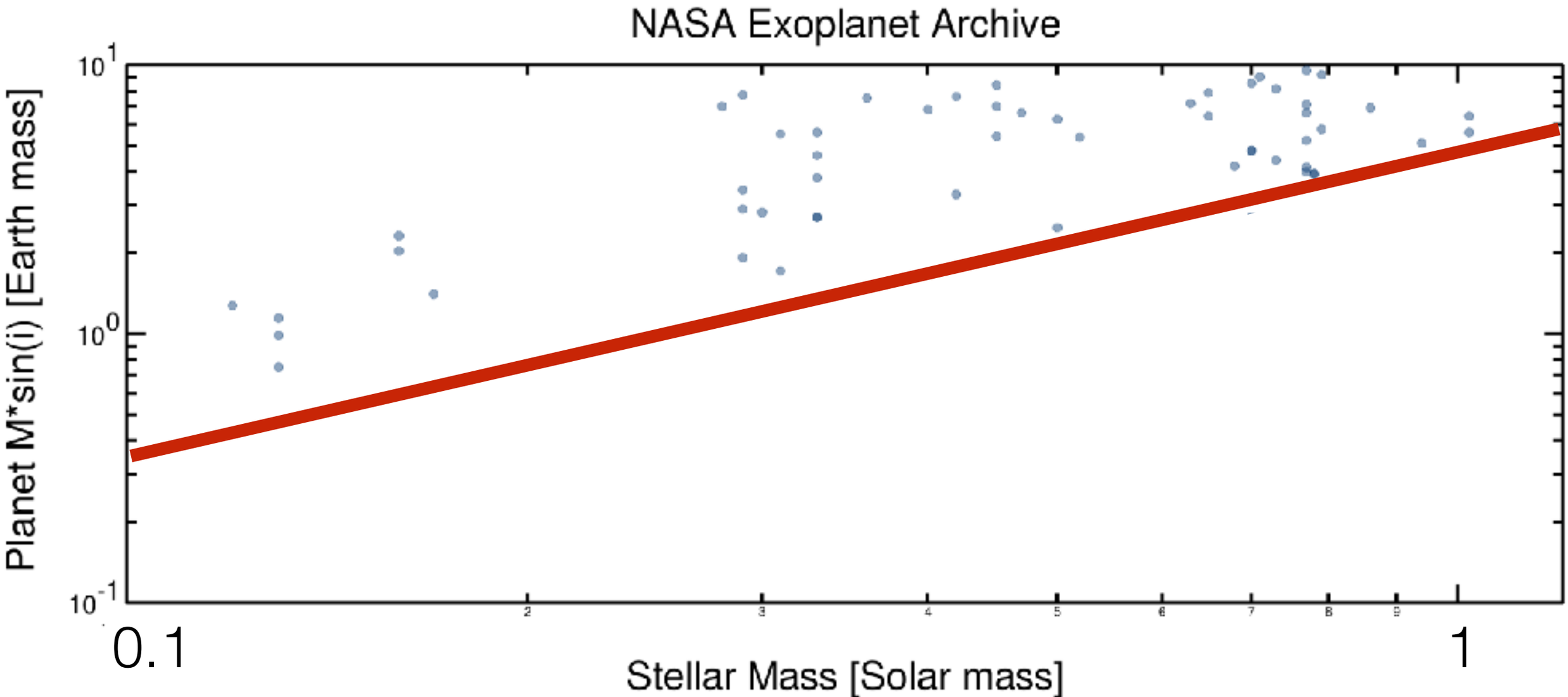

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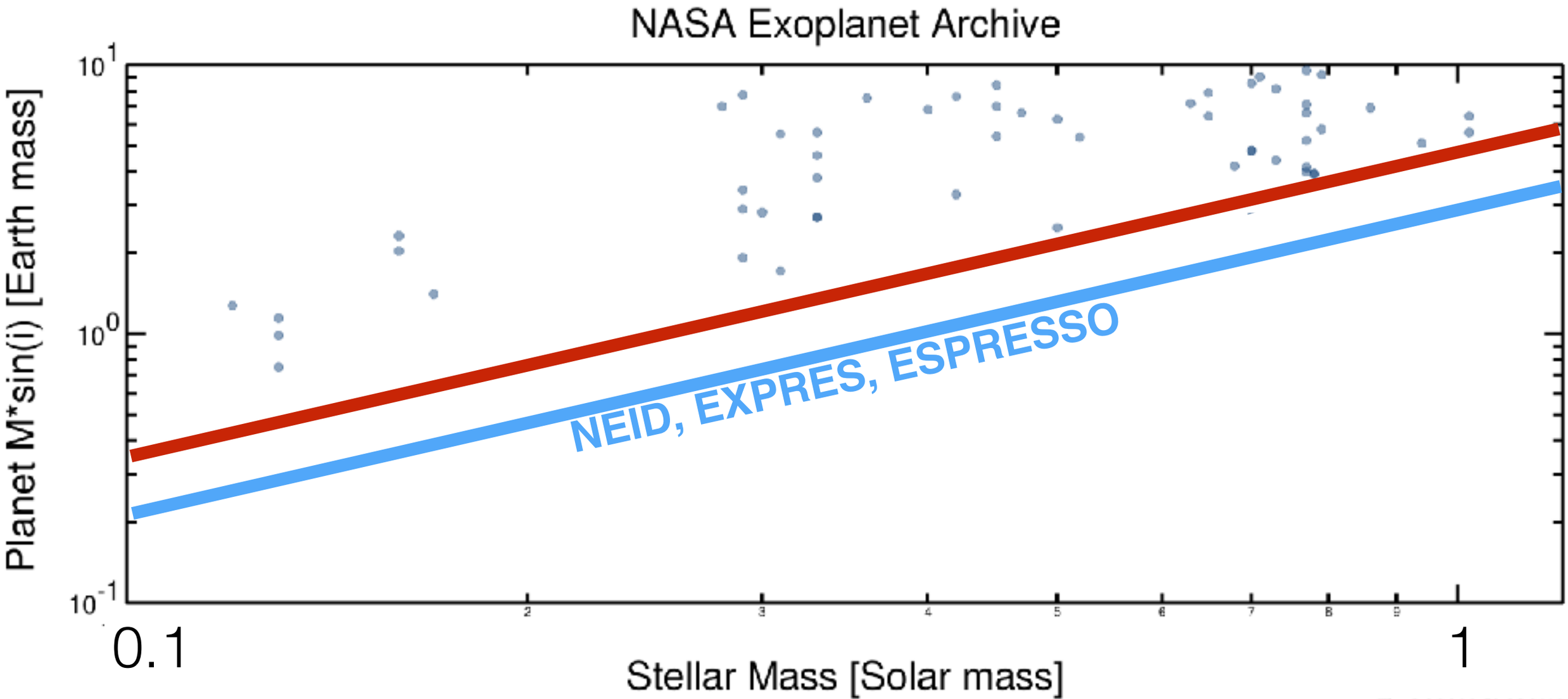

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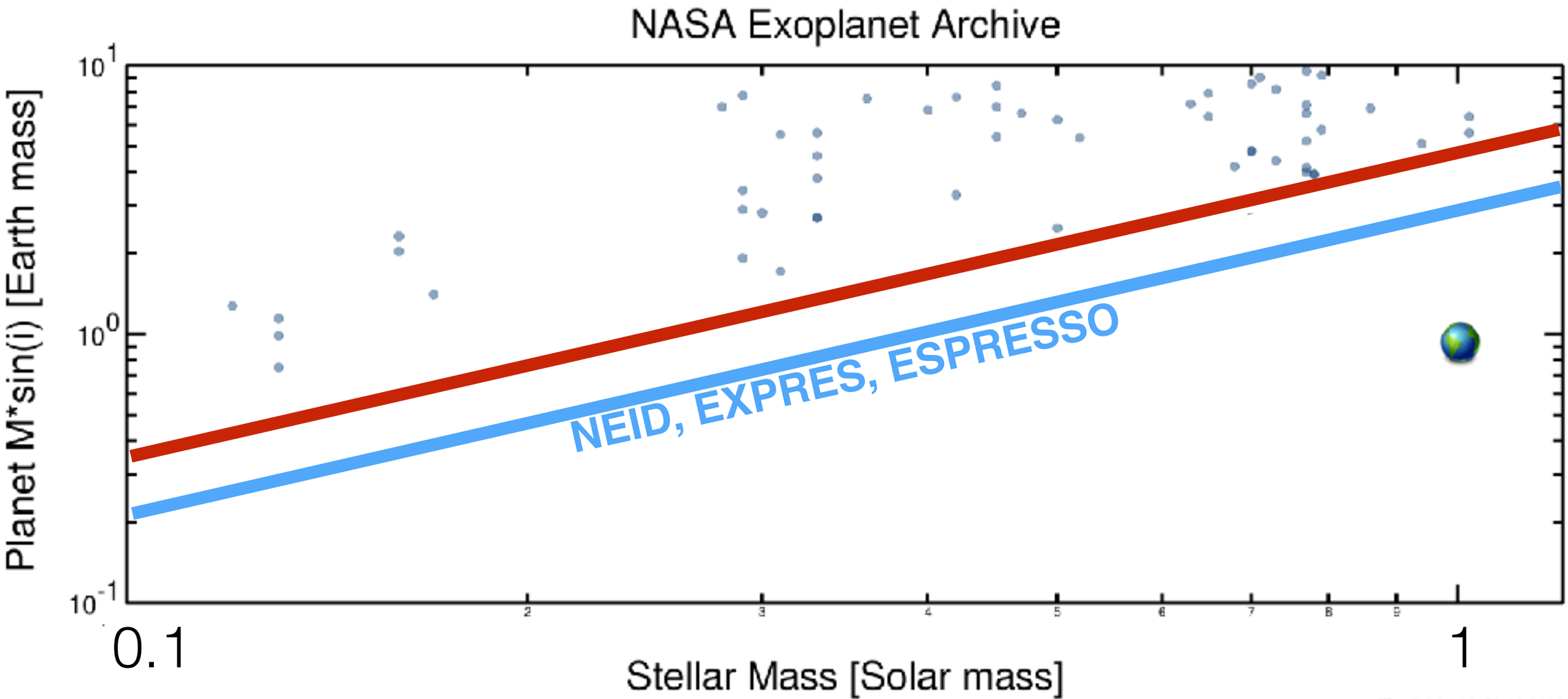

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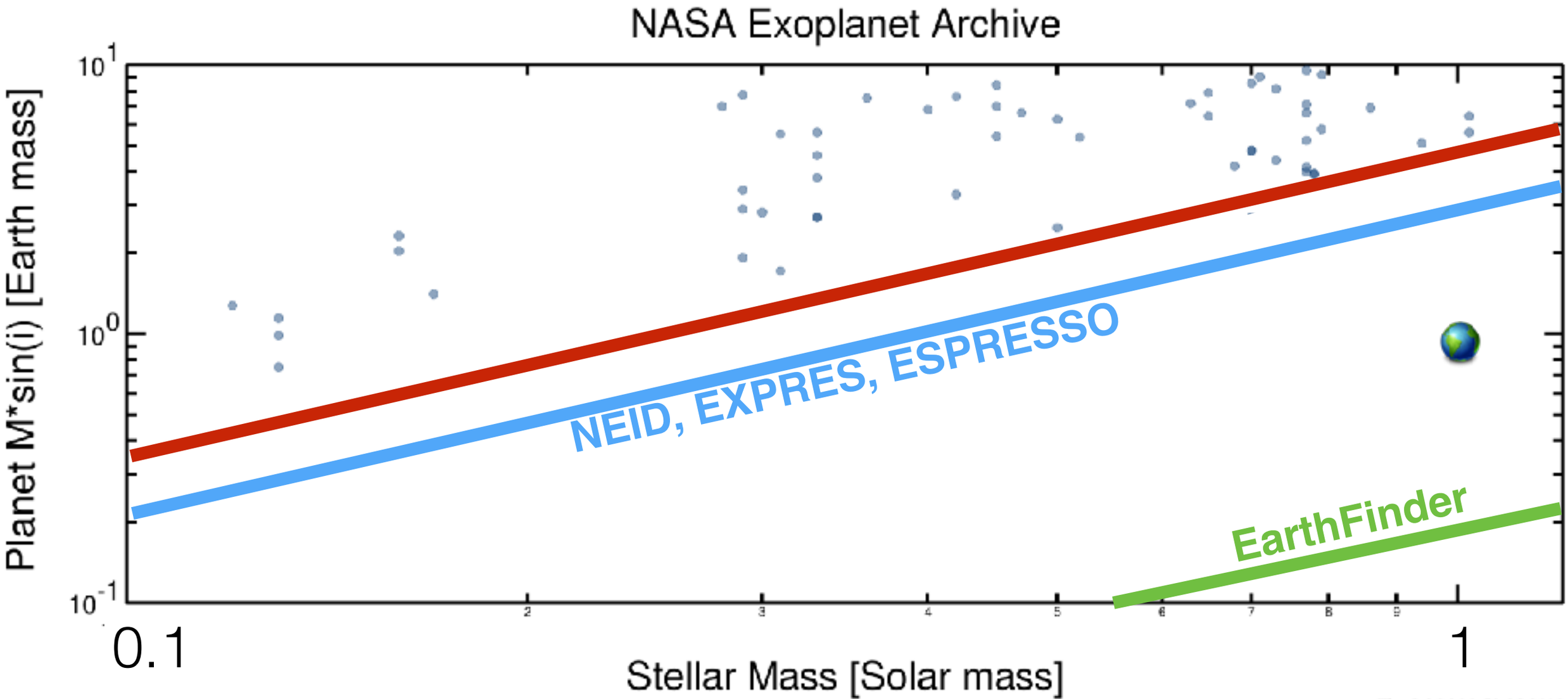

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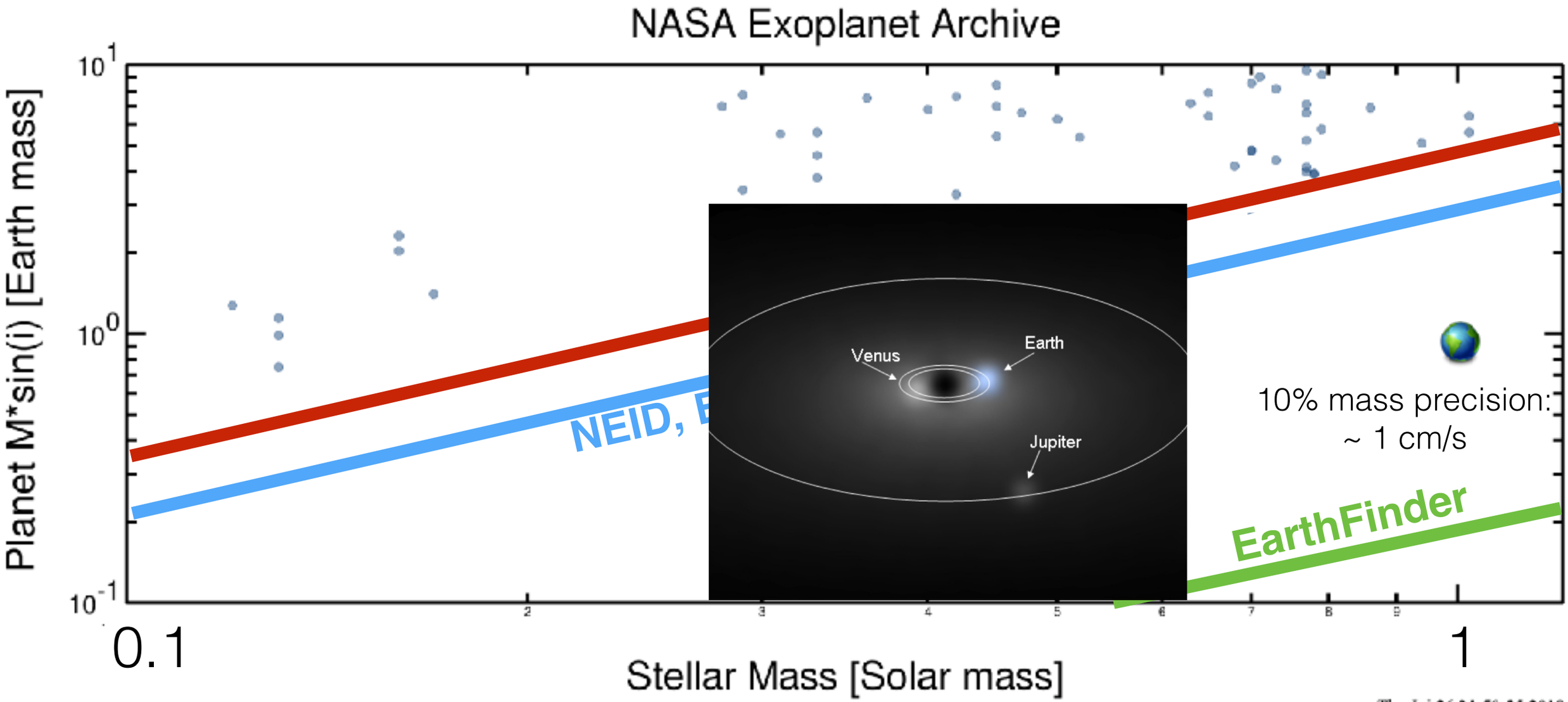

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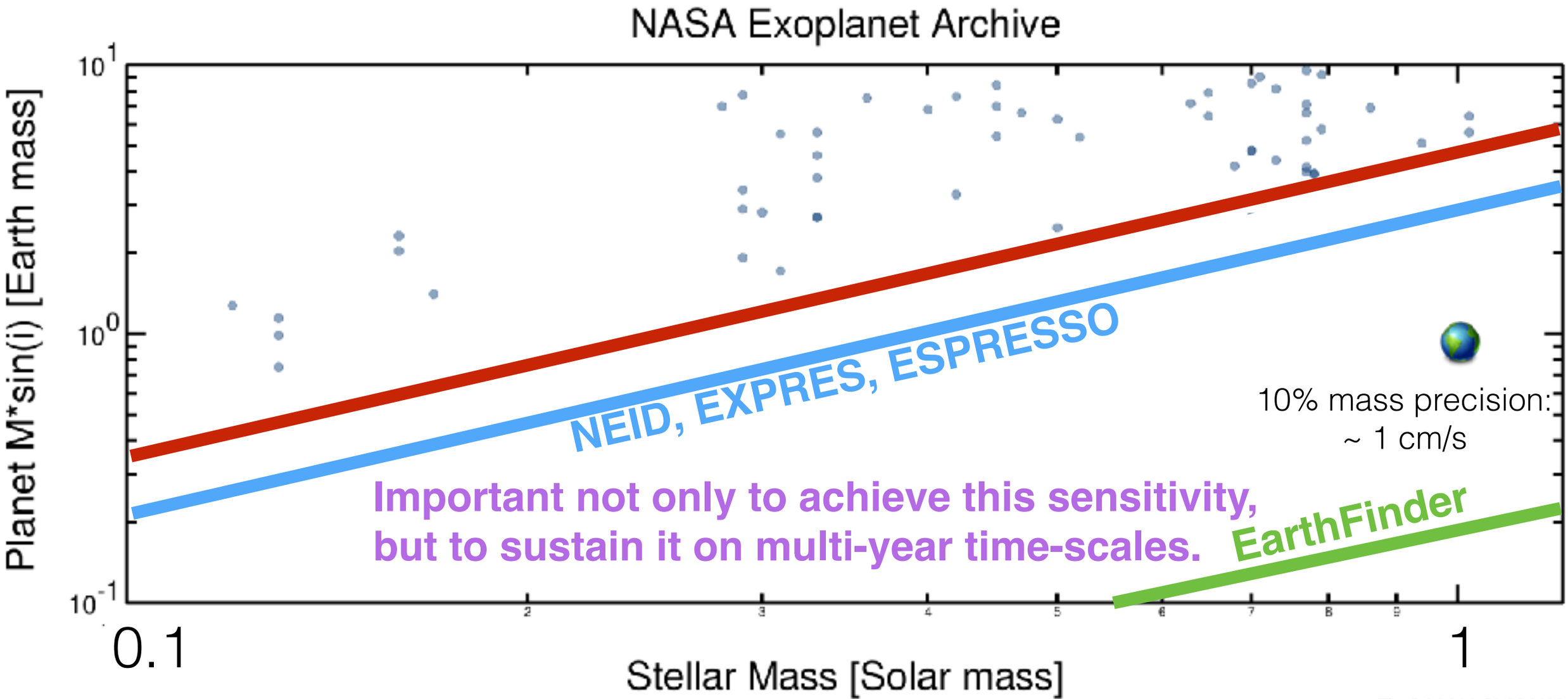

Study Focus

We are not building the mission;

We are not proposing to build the mission;

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We are tasked to:

Evaluate the *scientific rationale* for going to space vs. staying on the ground:

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  Can we "solve" stellar activity?
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- What can't you do from the ground?

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

Study Teams

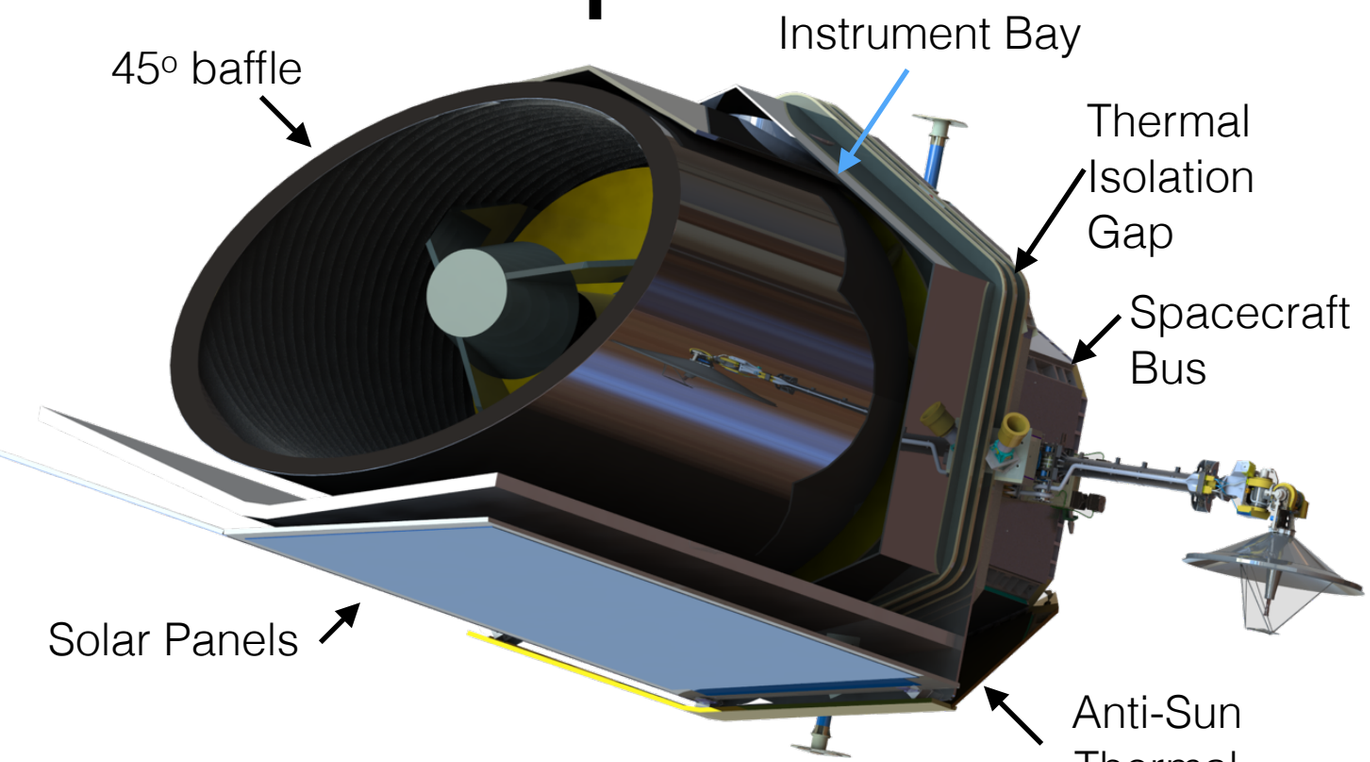
Instrument & Mission Gautam Vasisht

Tellurics Sharon Wang

Stellar Activity Heather Cegla, Xavier Dumusque

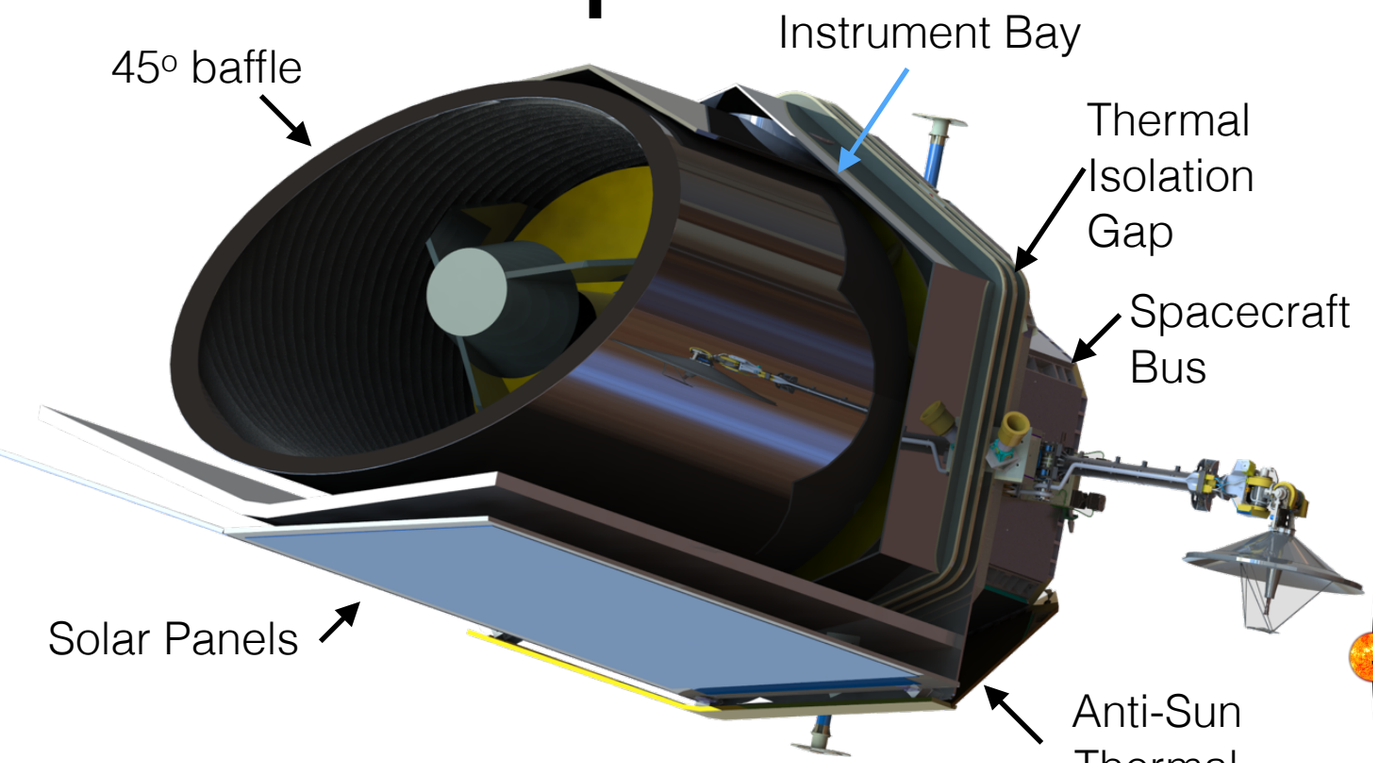
Ancillary Science Courtney Dressing, Peter Gao

Spacecraft & Orbit



- Ball Aerospace
- Kepler, Spitzer heritage
  - Extended baffle
  - Thermal shield
- 1.45 meter primary
- 5 year primary mission
- 25-50 nearest FGKM main sequence stars

Spacecraft & Orbit



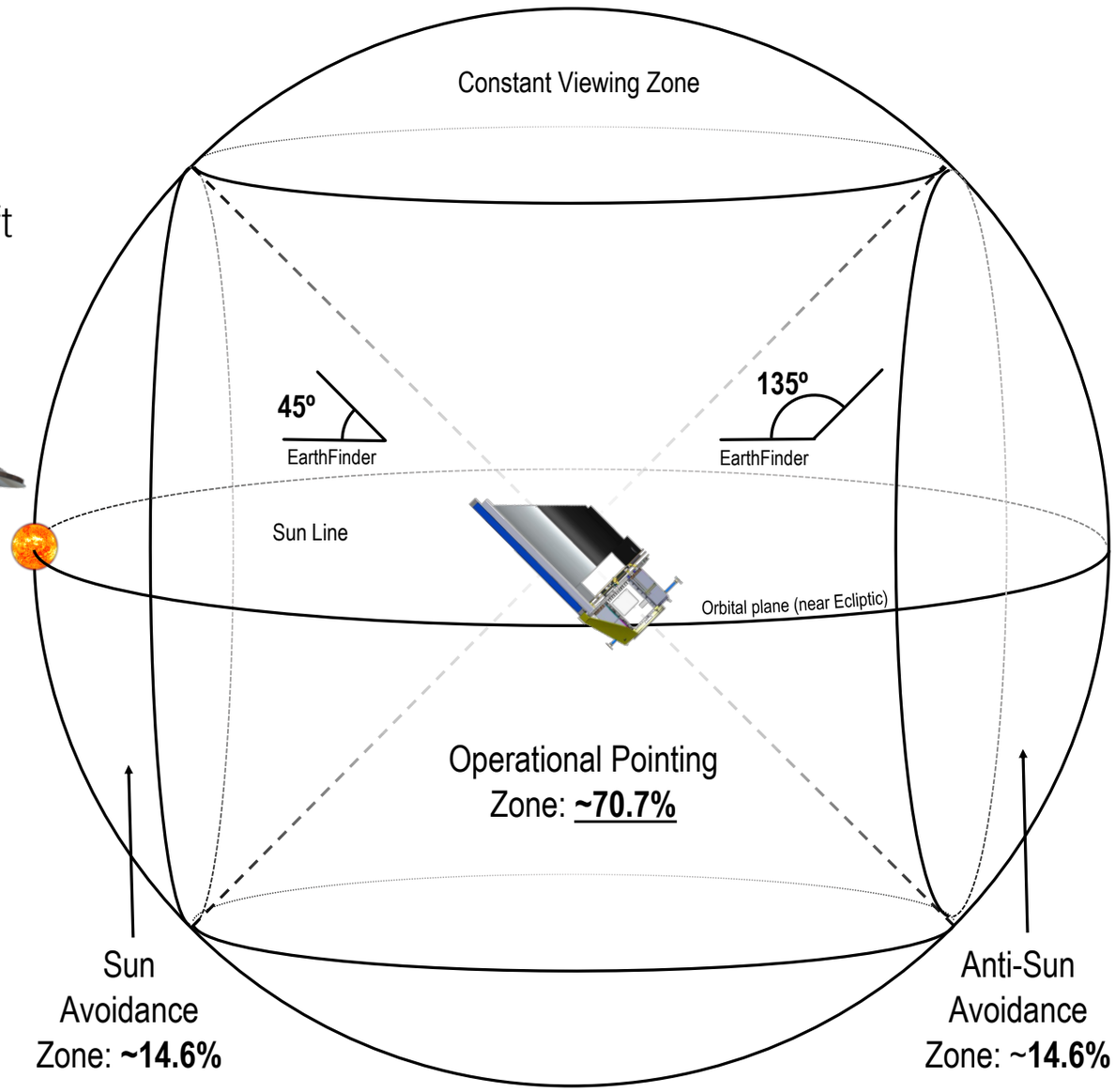
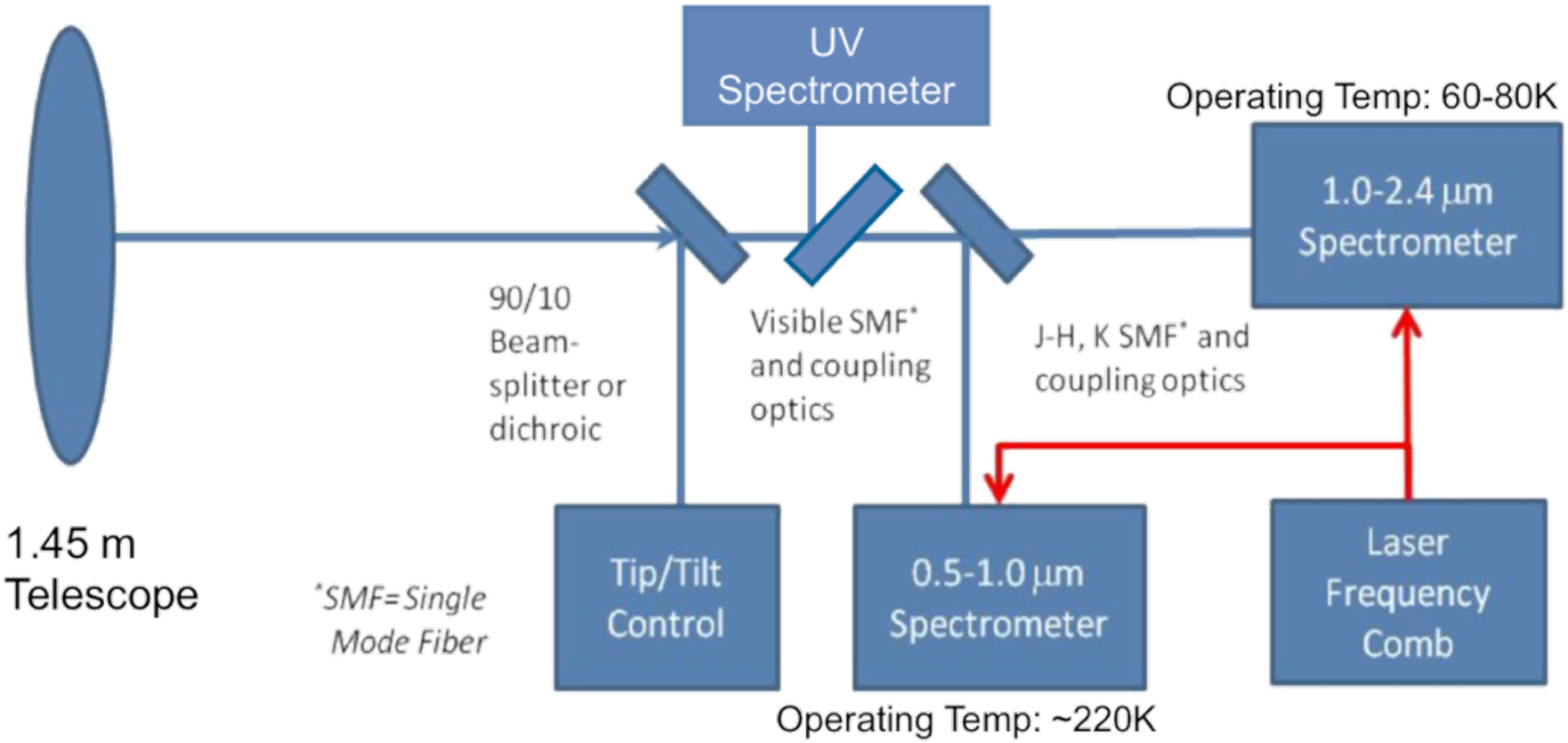


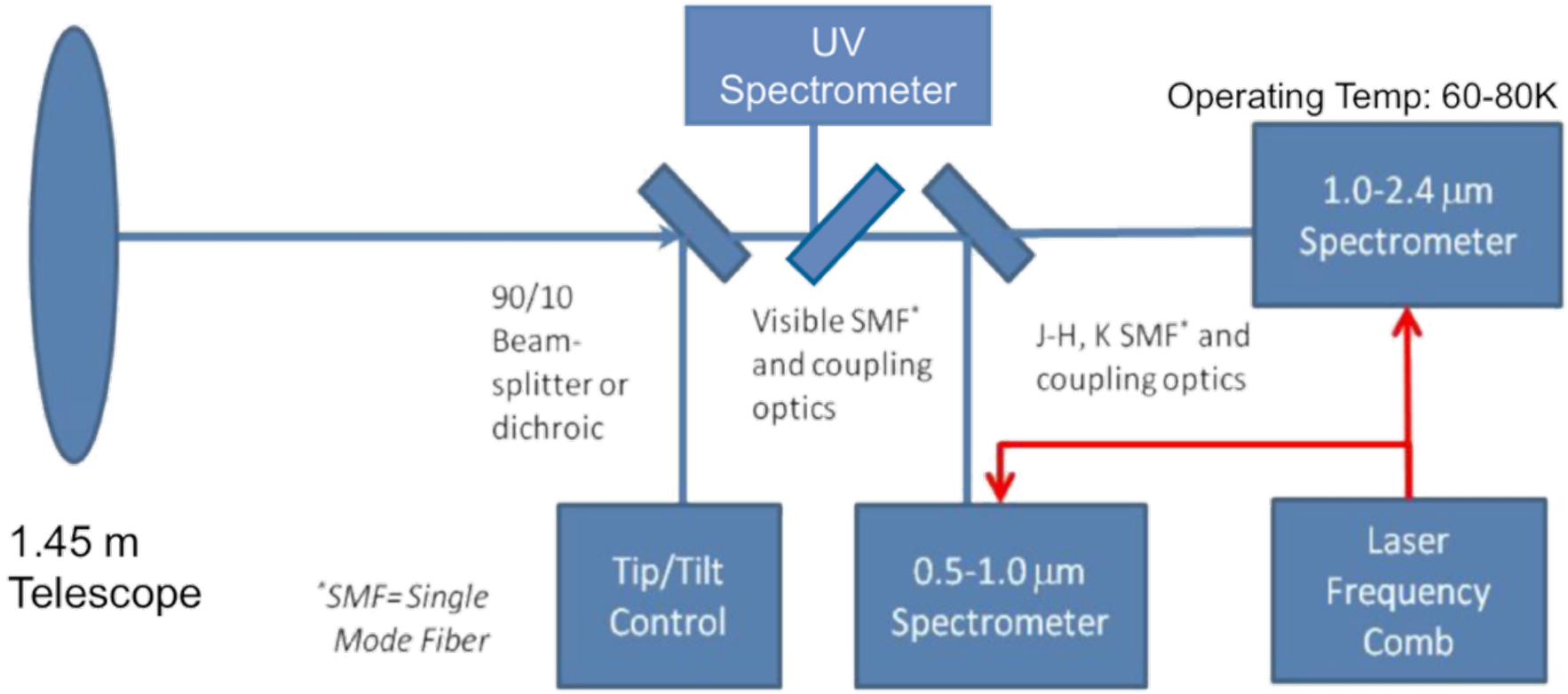
Figure from Bahaa Hamze

- Ball Aerospace
- Kepler, Spitzer heritage
  - Extended baffle
  - Thermal shield
- 1.45 meter primary
- 5 year primary mission
- 25-50 nearest FGKM main sequence stars
- 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

Instrument


UV Spectrometer
Operating Temp: 60-80K
1.0-2.4 μm Spectrometer
90/10 Beam-splitter or dichroic
Visible SMF* and coupling optics
J-H, K SMF* and coupling optics
1.45 m Telescope
*SMF=Single Mode Fiber
Tip/Tilt Control
0.5-1.0 μm Spectrometer
Laser Frequency Comb
Operating Temp: ~220K

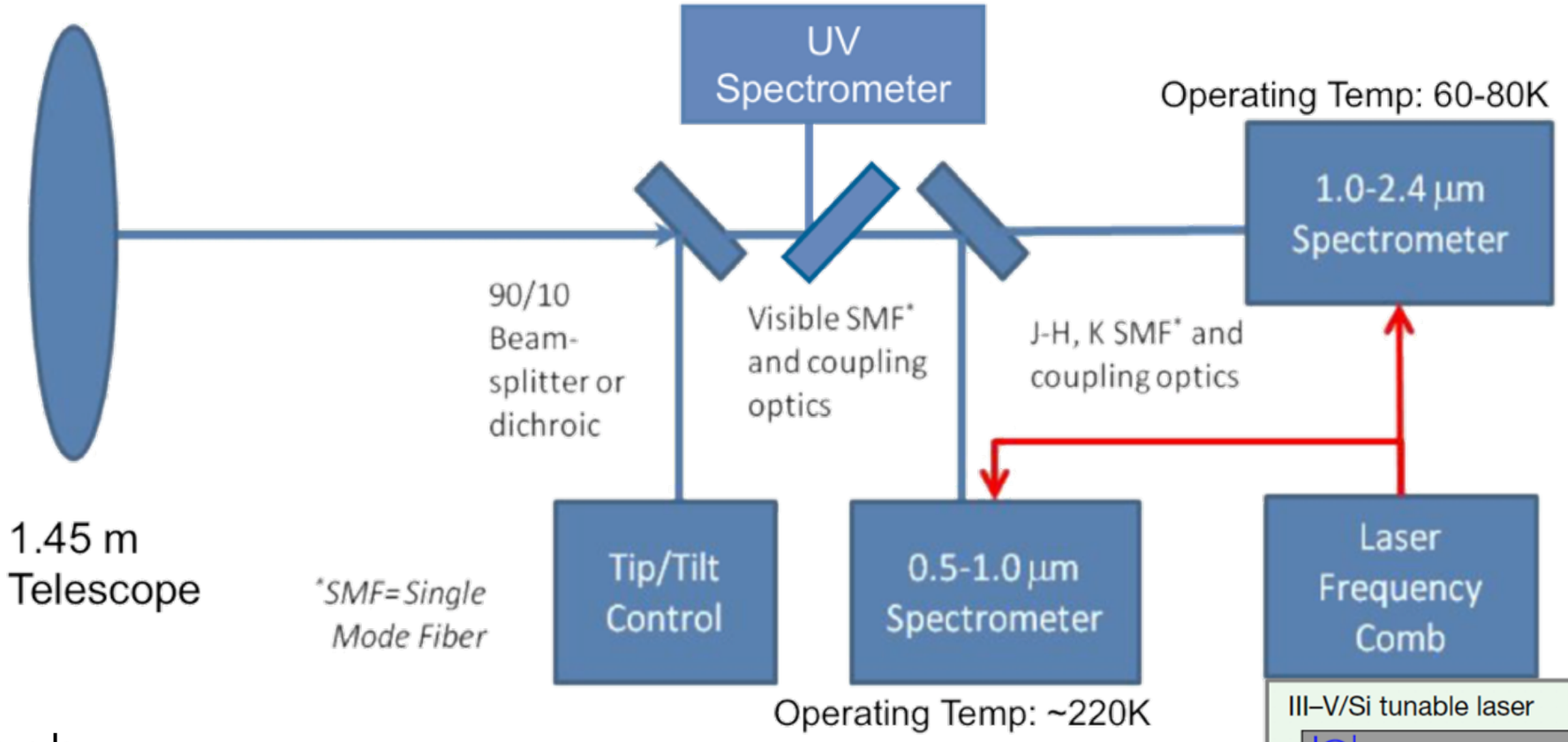
Instrument



Spectrograph:

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

Instrument



Spectrograph:

- High-resolution (R~150-200k)
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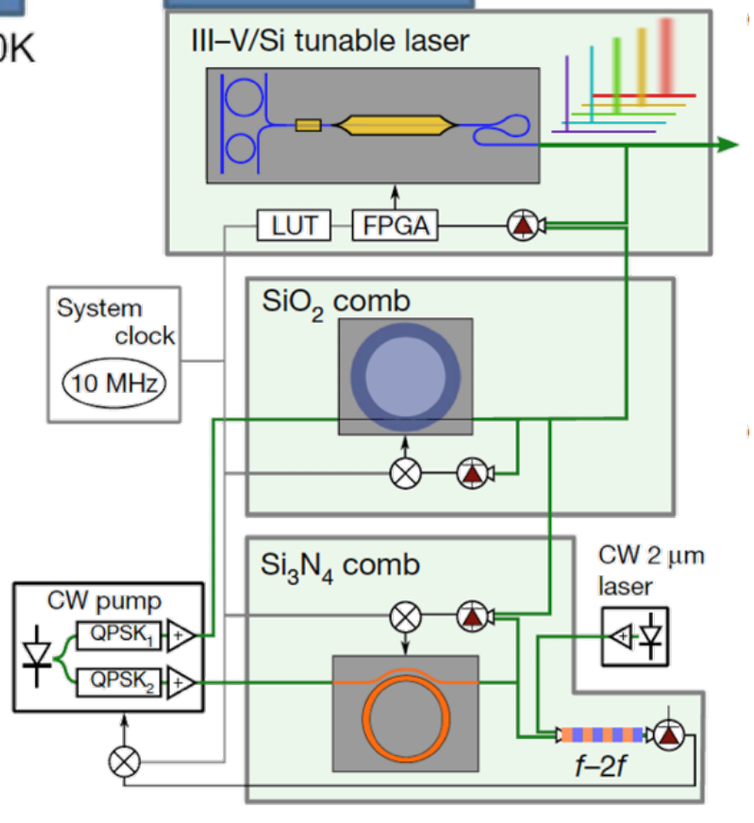
- Laser frequency micro-comb wavelength calibration & 1 cm/s thermal stability



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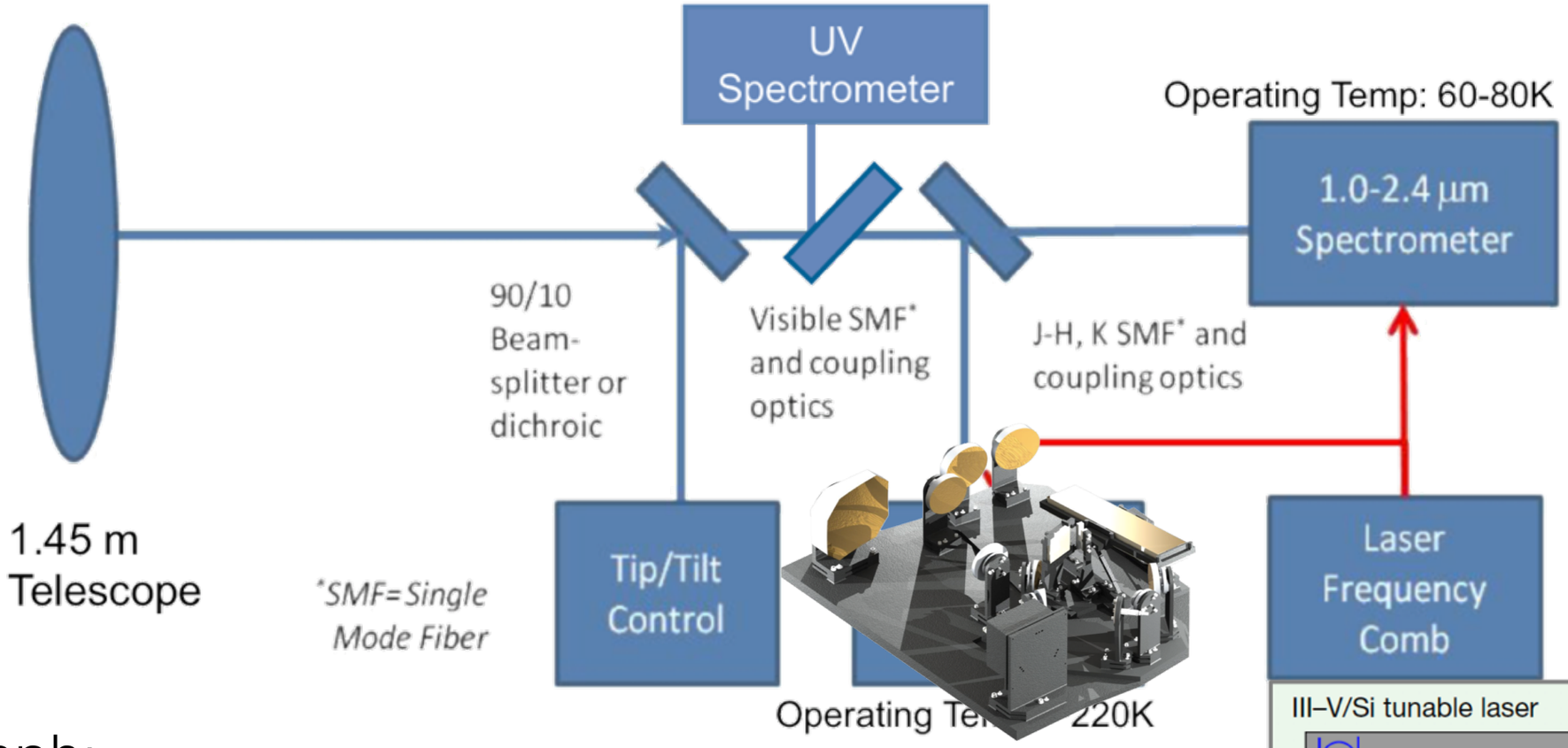

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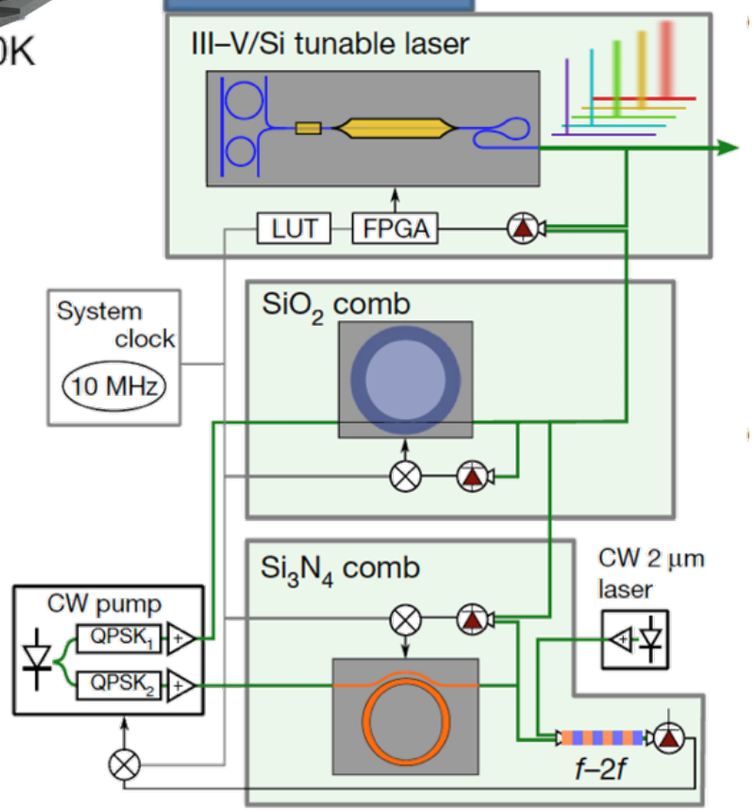
- Visible arm: 380-900 nm



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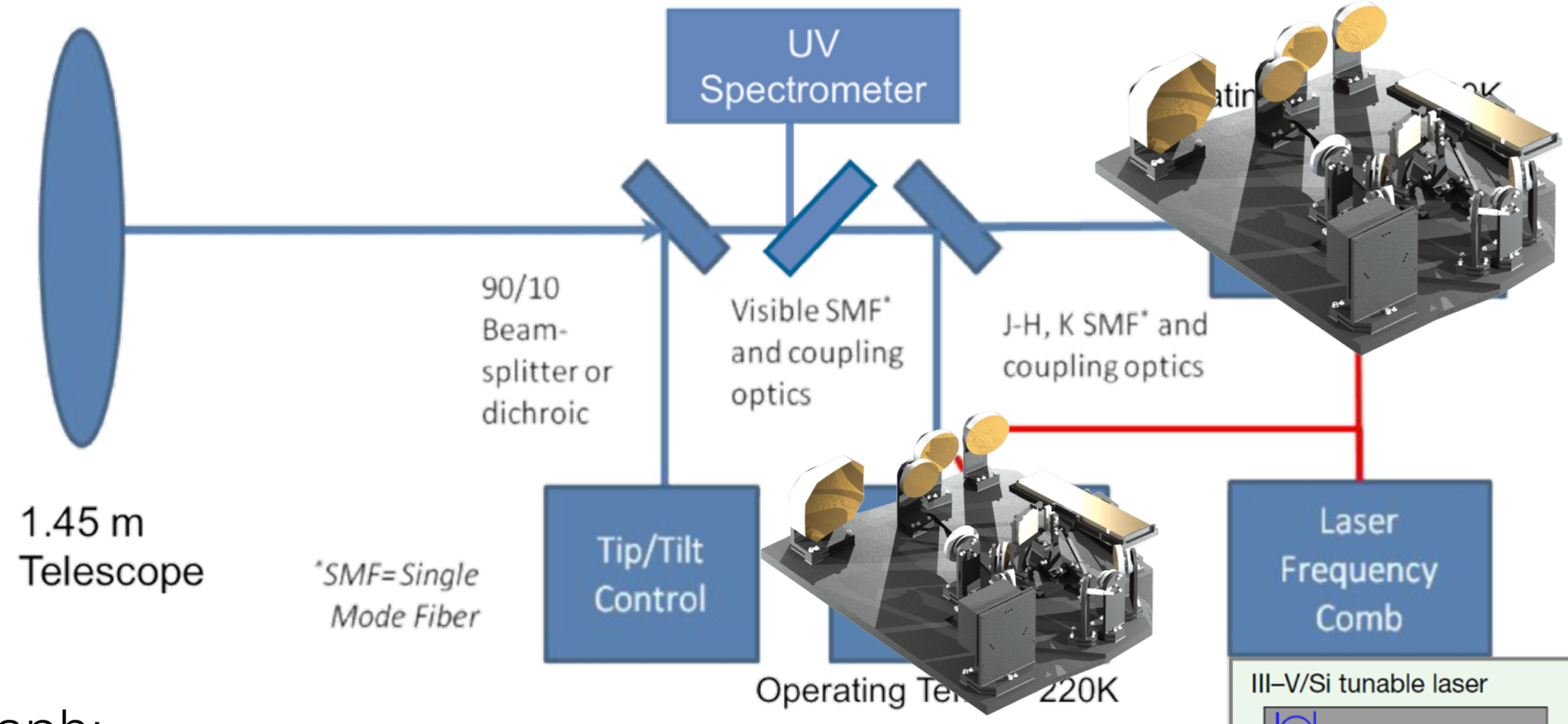

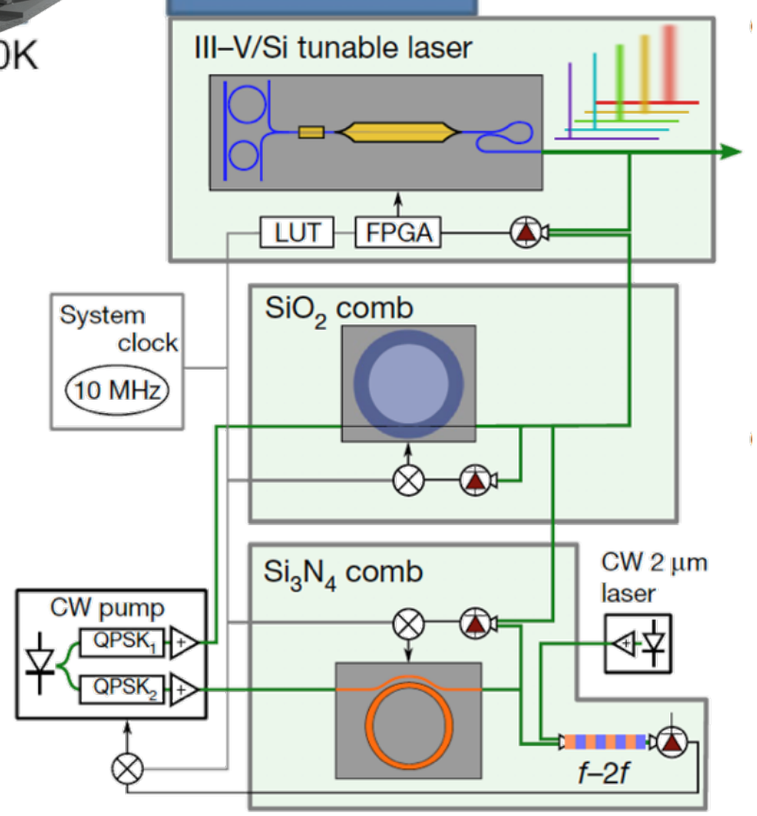

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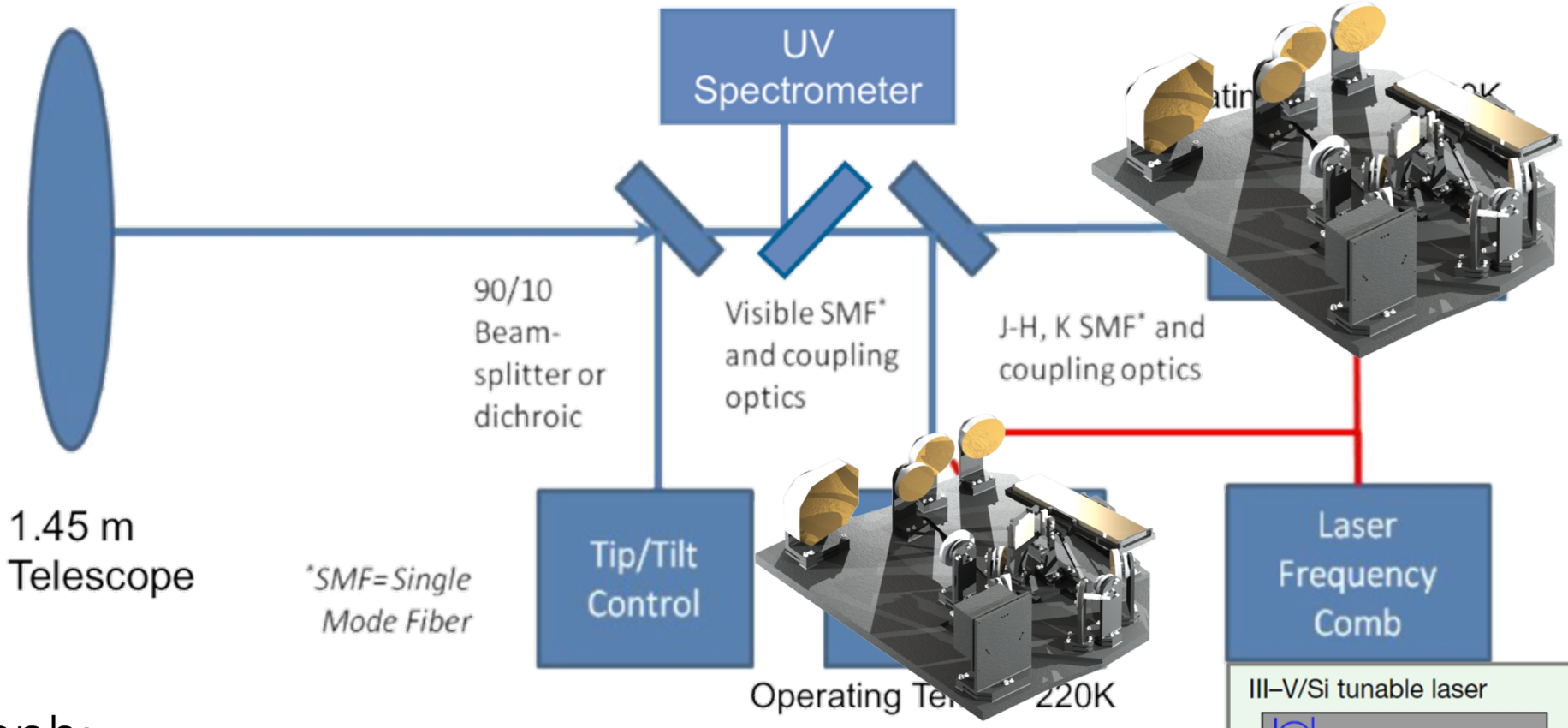

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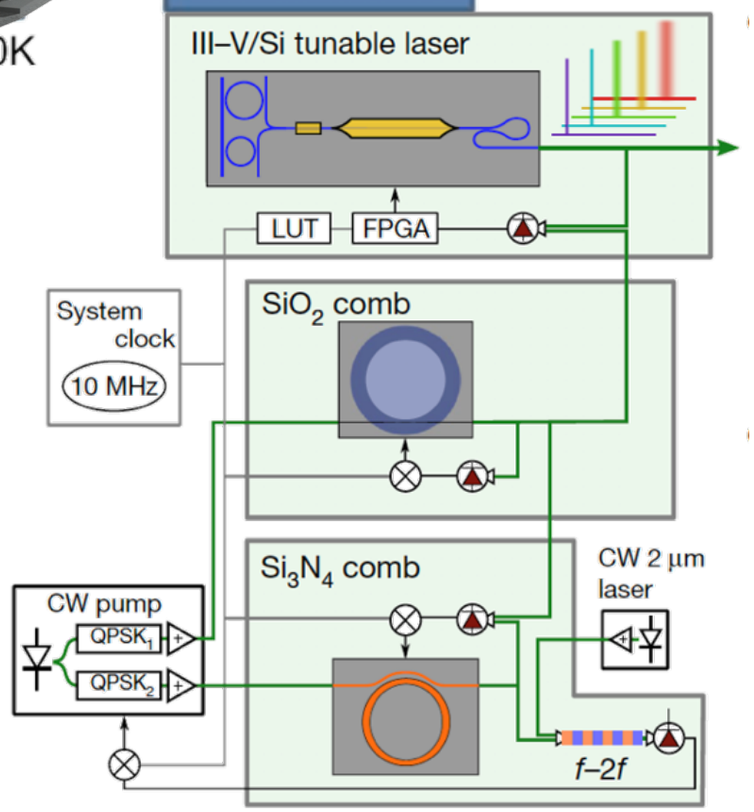

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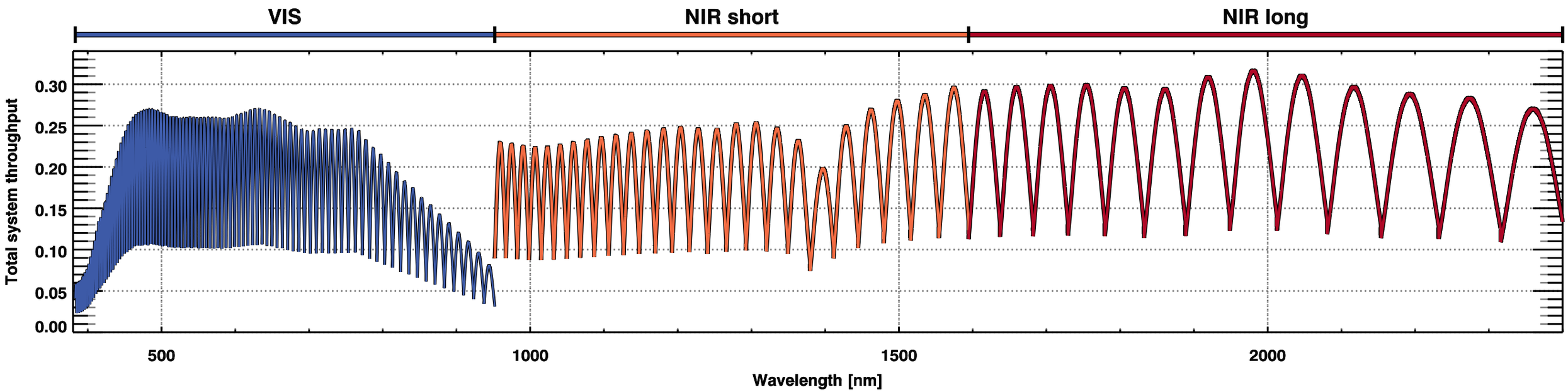

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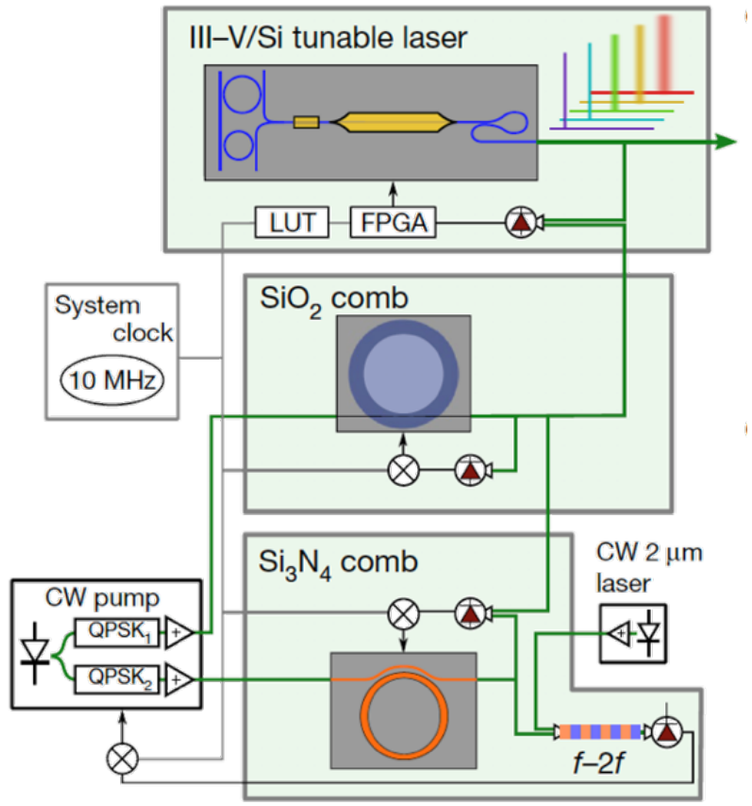

Why space?

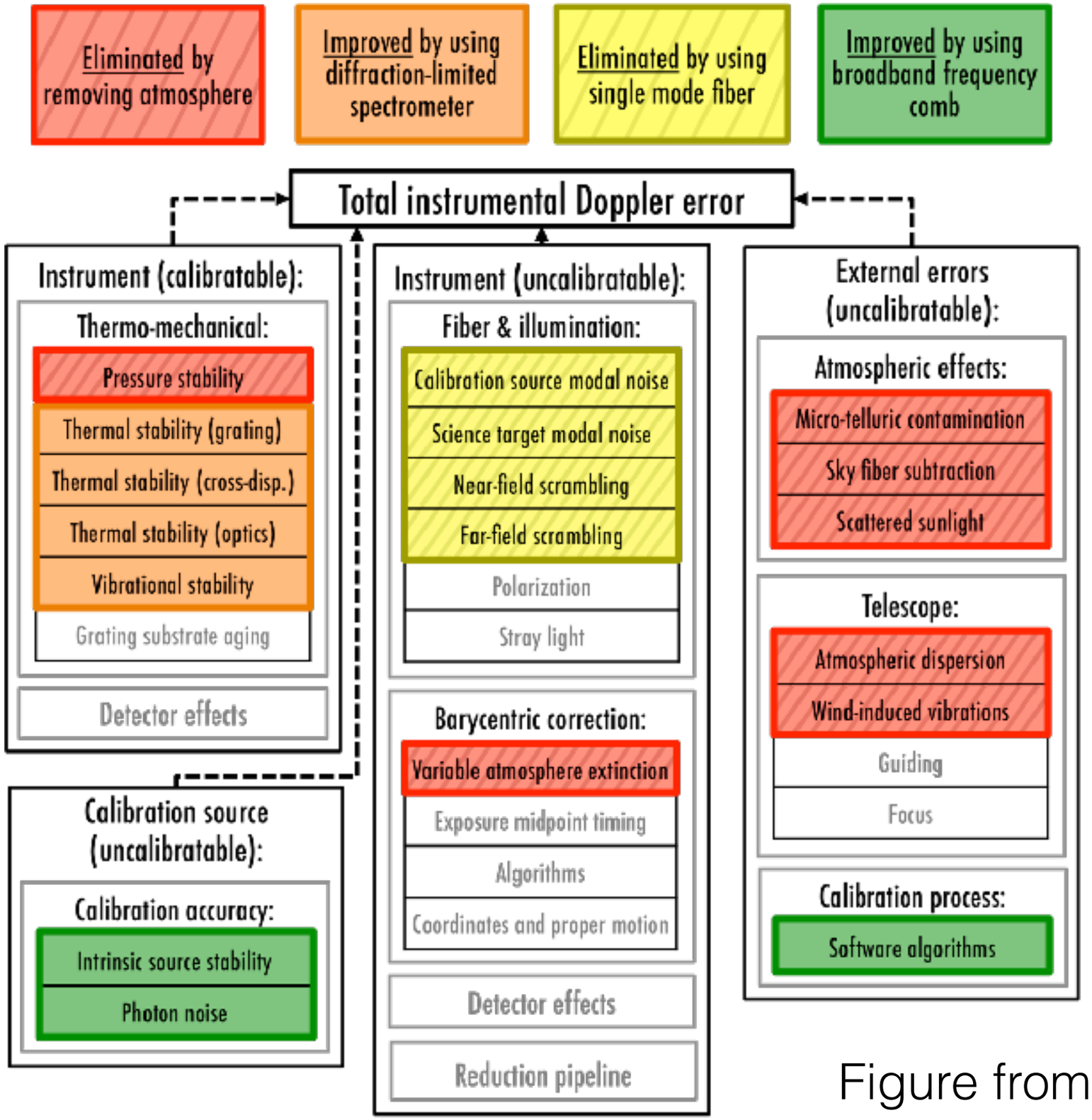

Figure from Sam Halverson

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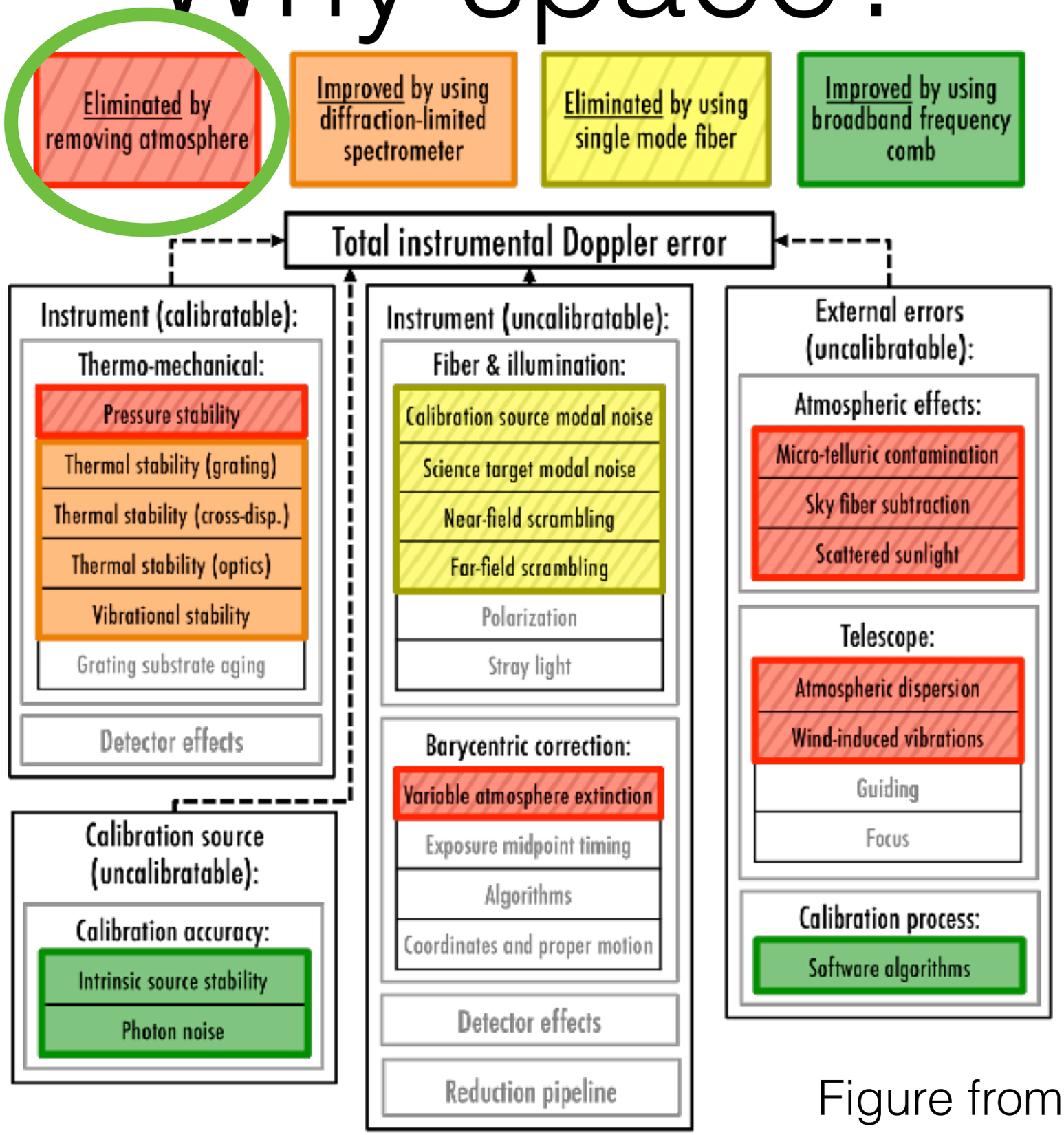
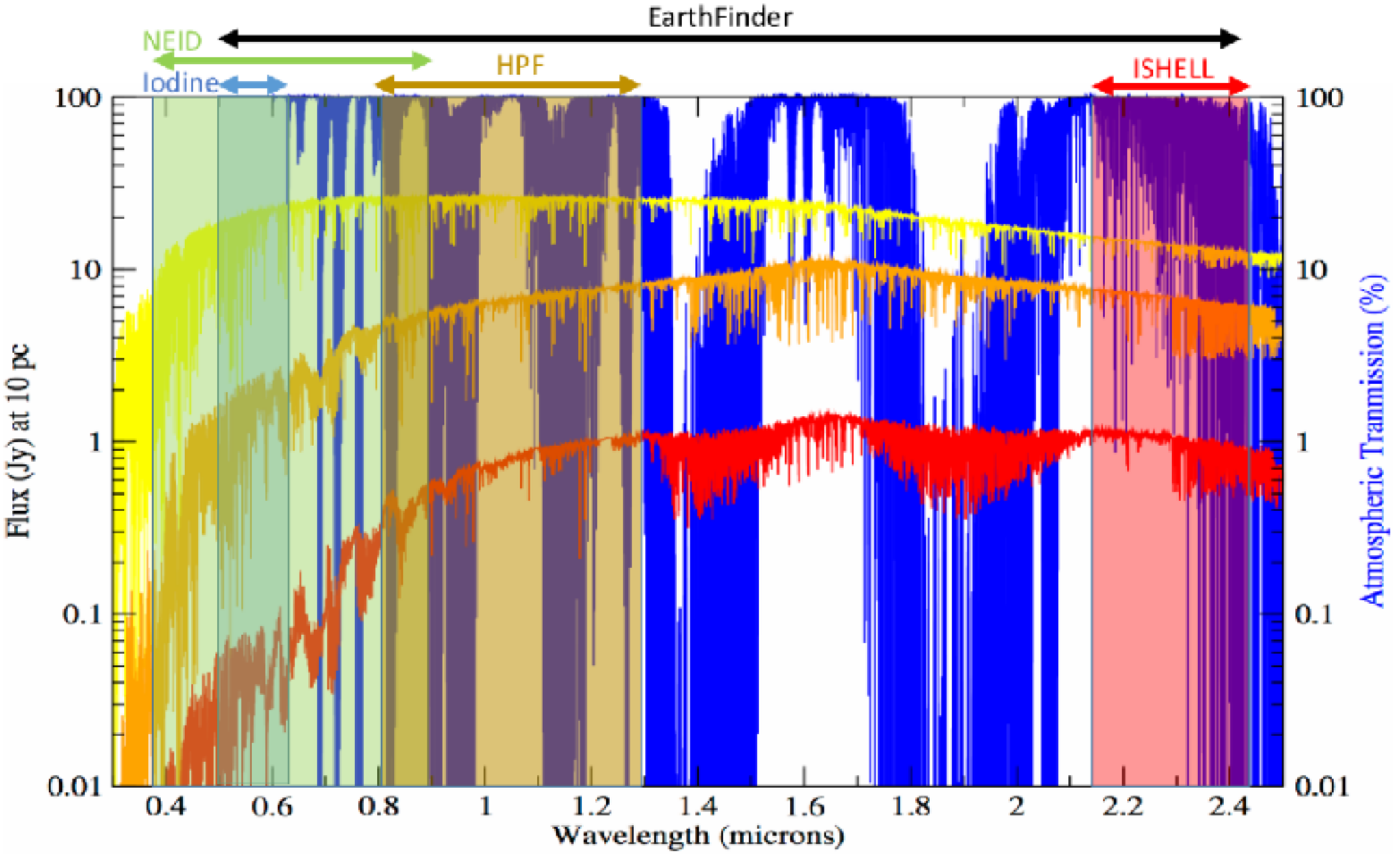


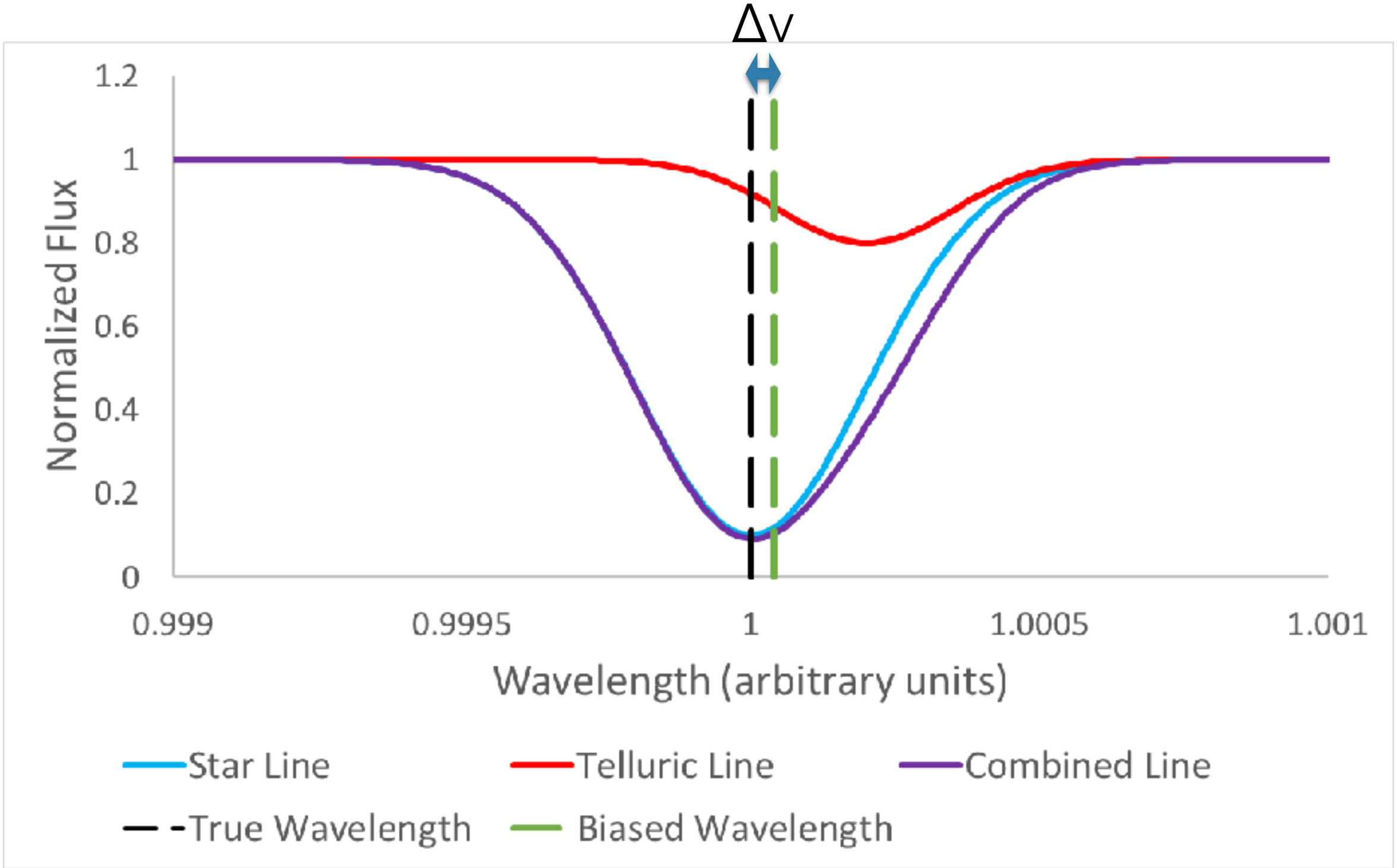
Figure from Sam Halverson

What can't be done from the ground?

The Earth's atmosphere may introduce RV errors of ~10 cm/s in the visible, & ~1 m/s in the NIR

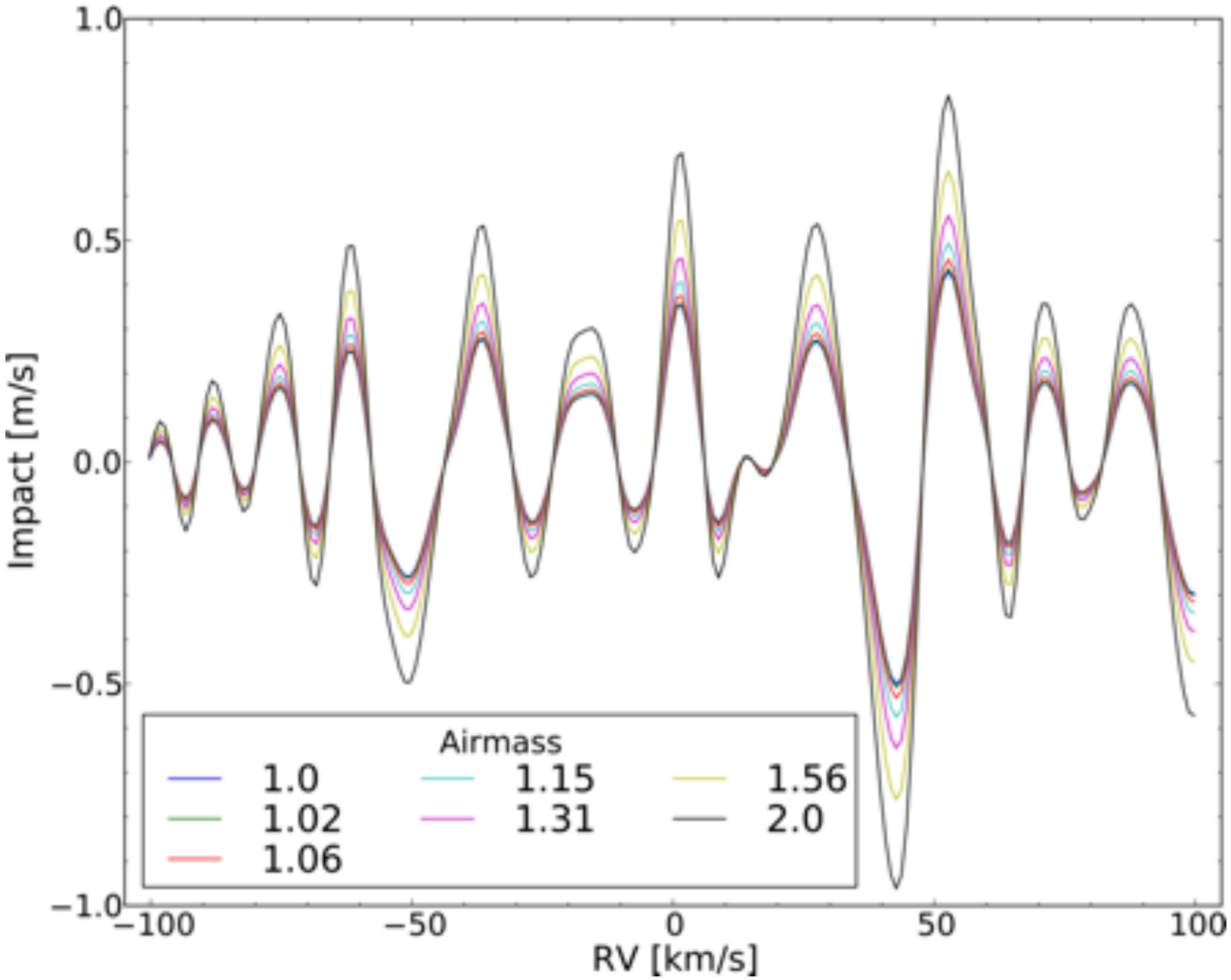


The telluric challenge



Cunha et al. 2014

Impact for HARPS data from ignoring micro-telluric



Divide by telluric model or standard?

Sameshima et al. 2018:

”We also develop a new diagnostic method for evaluating the accuracy of telluric correction and use it to demonstrate that our method achieves an accuracy better than 2% for spectral parts for which the atmospheric transmittance is as low as ~20% if telluric standard stars are observed under the following conditions: **(1) the difference in airmass between the target and the standard is <0.05; and (2) that in time is less than 1 h.** In particular, the time variability of water vapor has a large impact on the accuracy of telluric correction and minimizing the difference in time from that of the telluric standard star is important especially in near-infrared high-resolution spectroscopic observation.”

Divide by telluric model or standard?

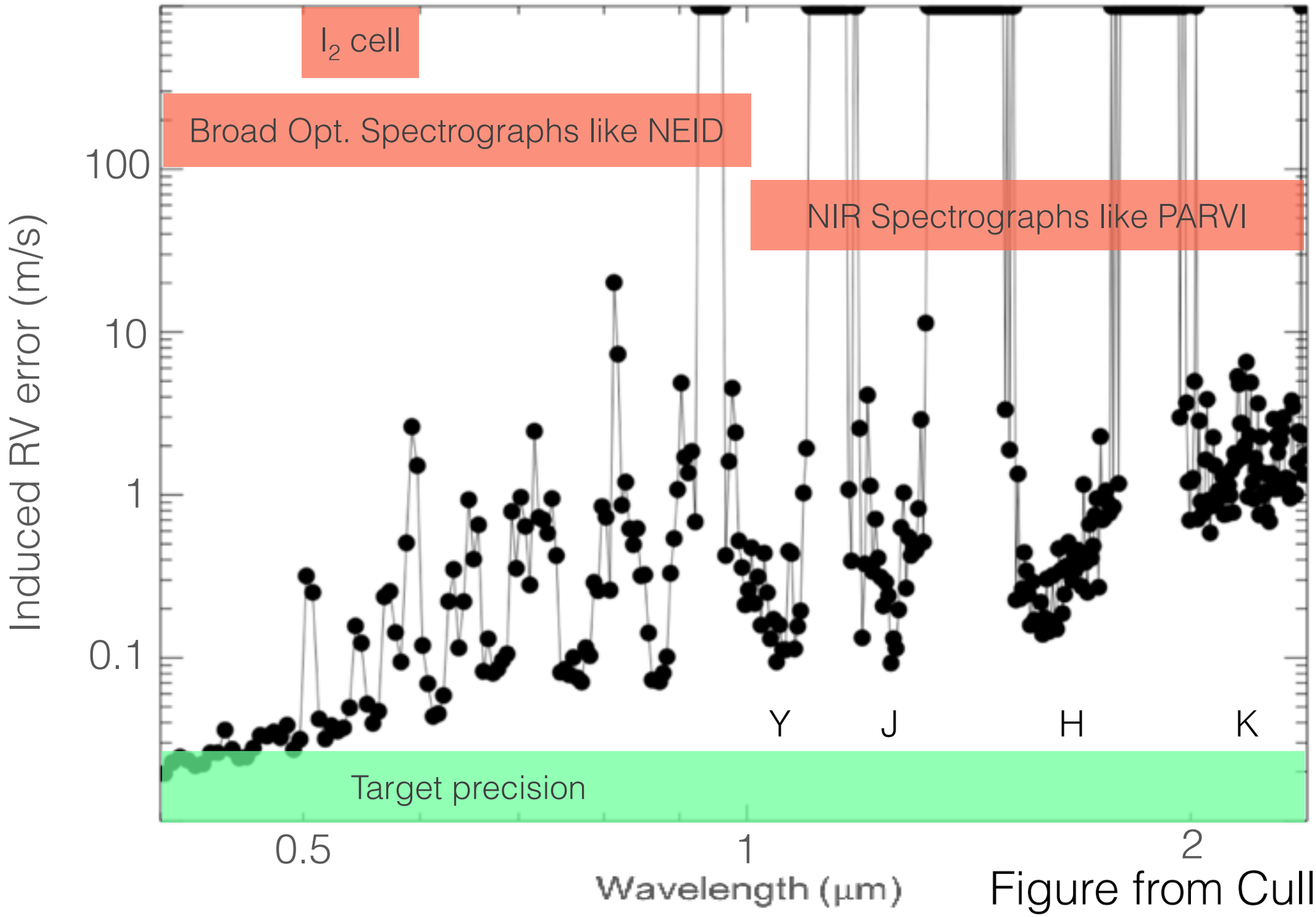


Figure from Cullen Blake

Stellar Activity

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

Wavelength Coverage (e.g. CARMENES)

Cadence (e.g. MINERVA)

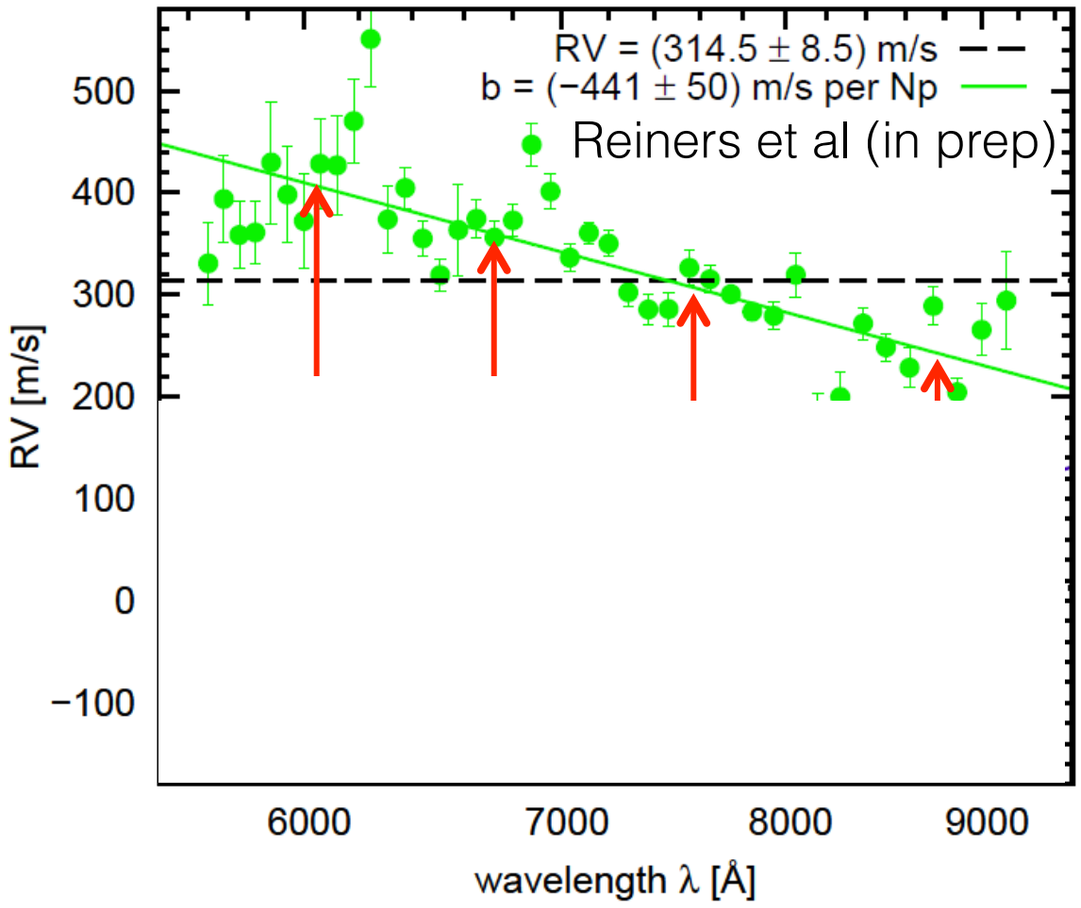
R~200k resolution (e.g. ESPRESSO)

Line-by-line analysis

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

Wavelength Dependence

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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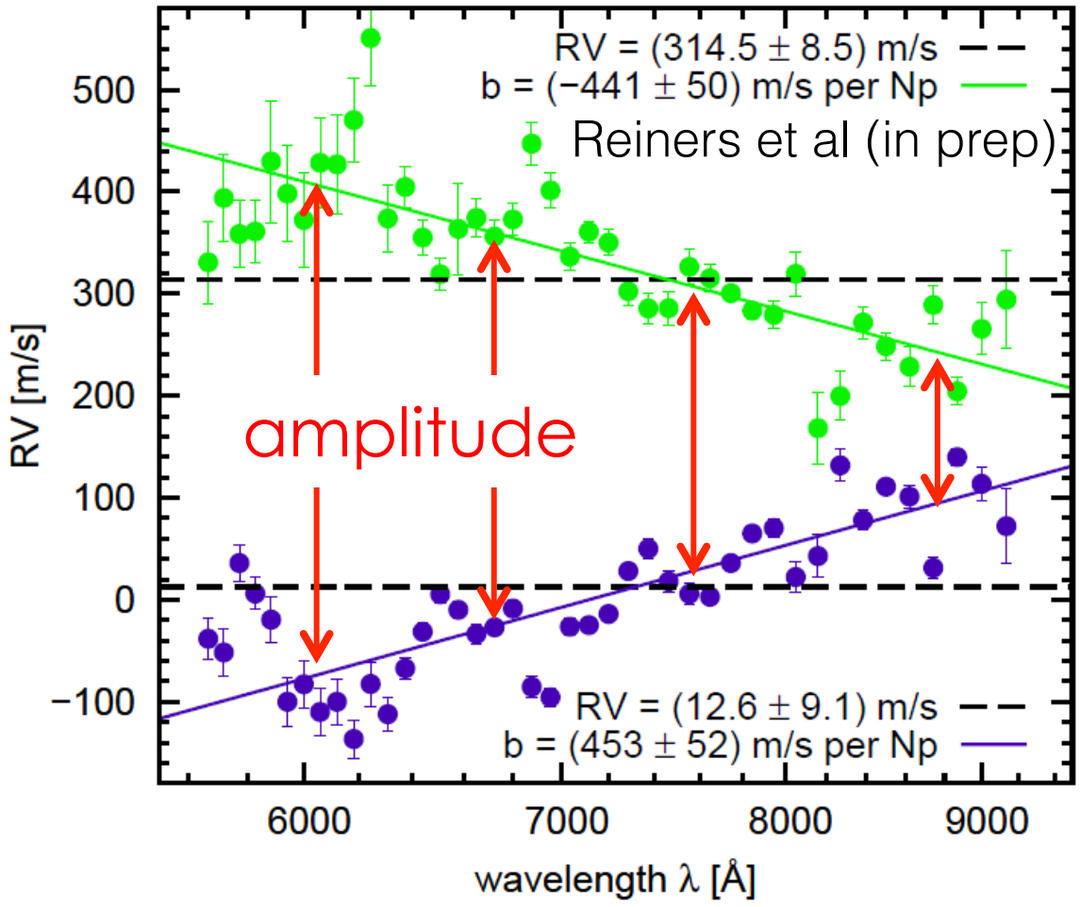

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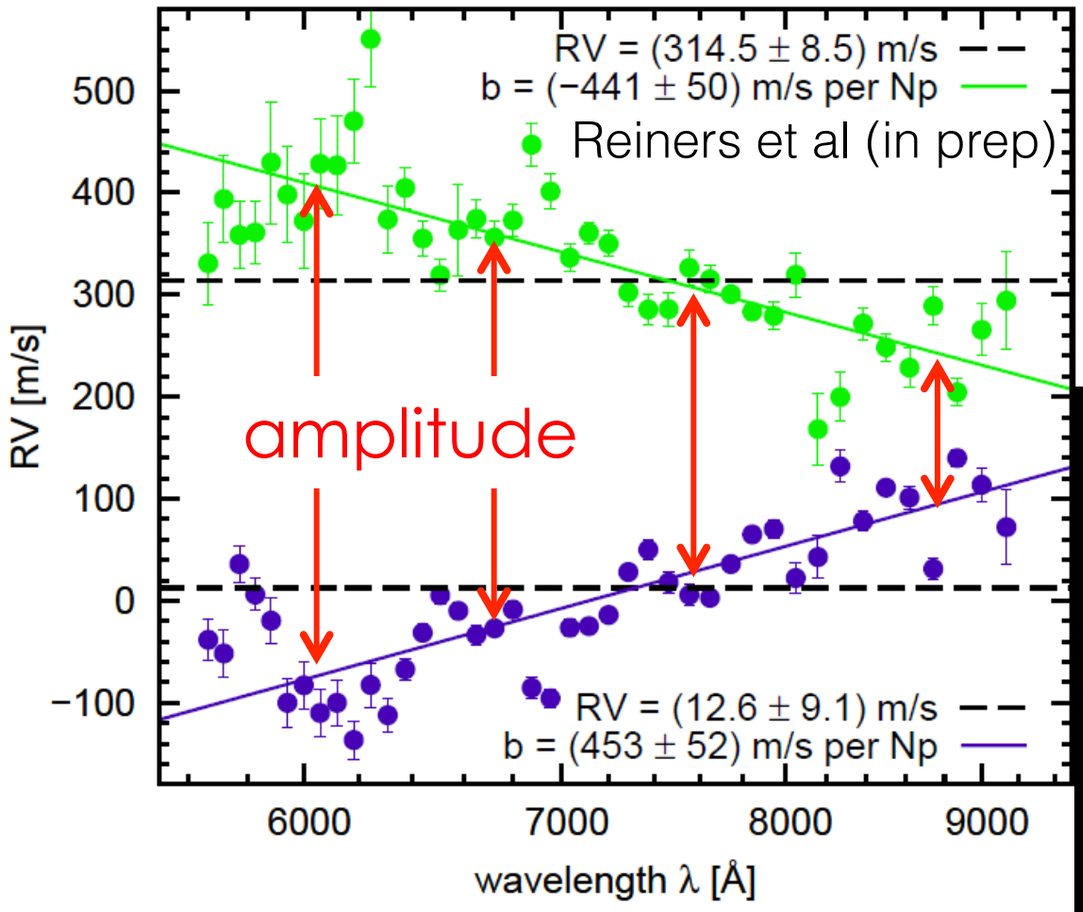
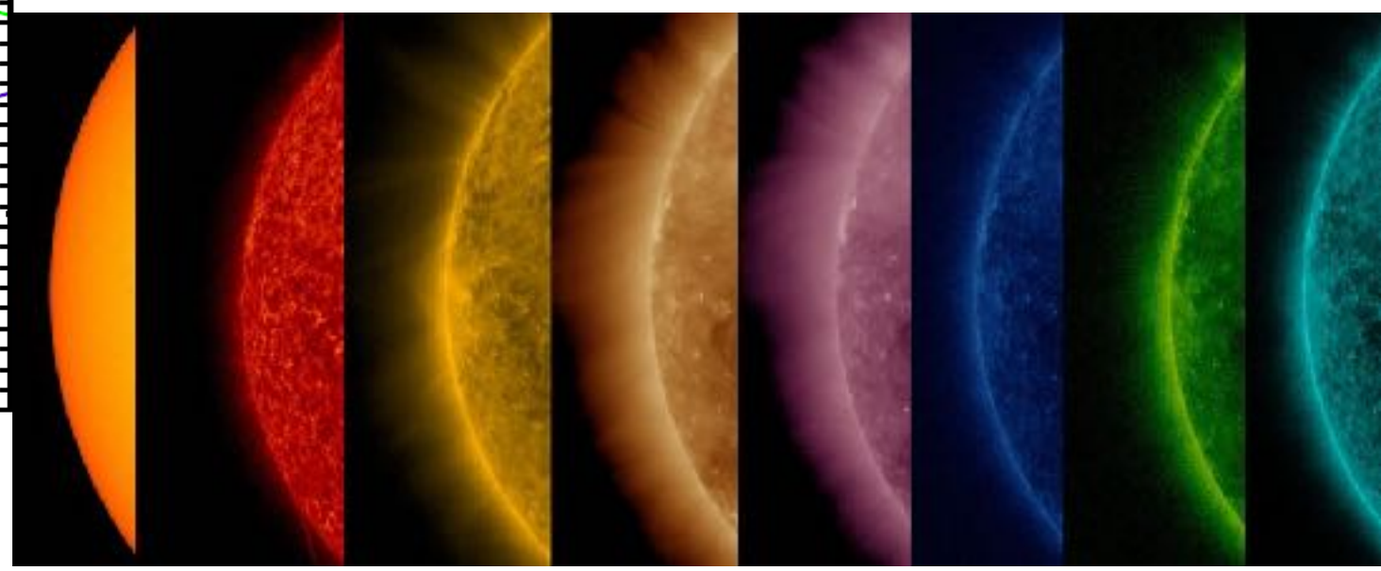


Stellar activity is not a simple function of λ, and also time-dependent

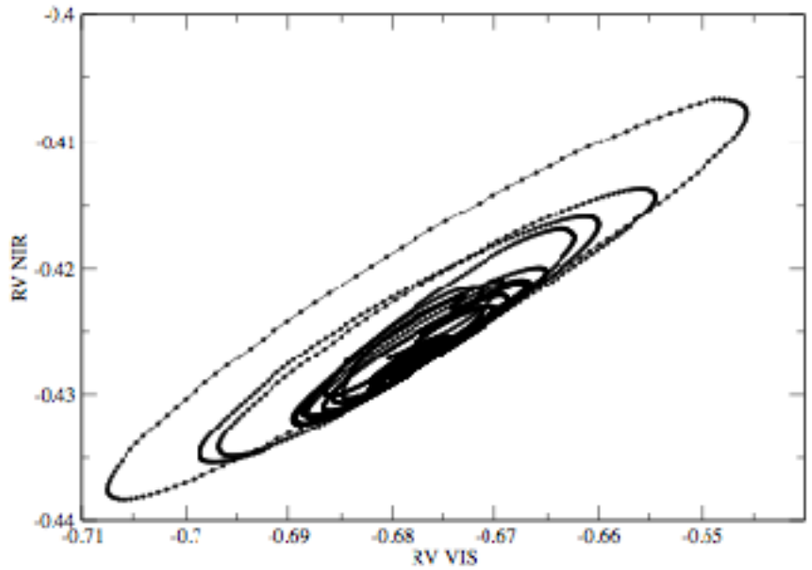


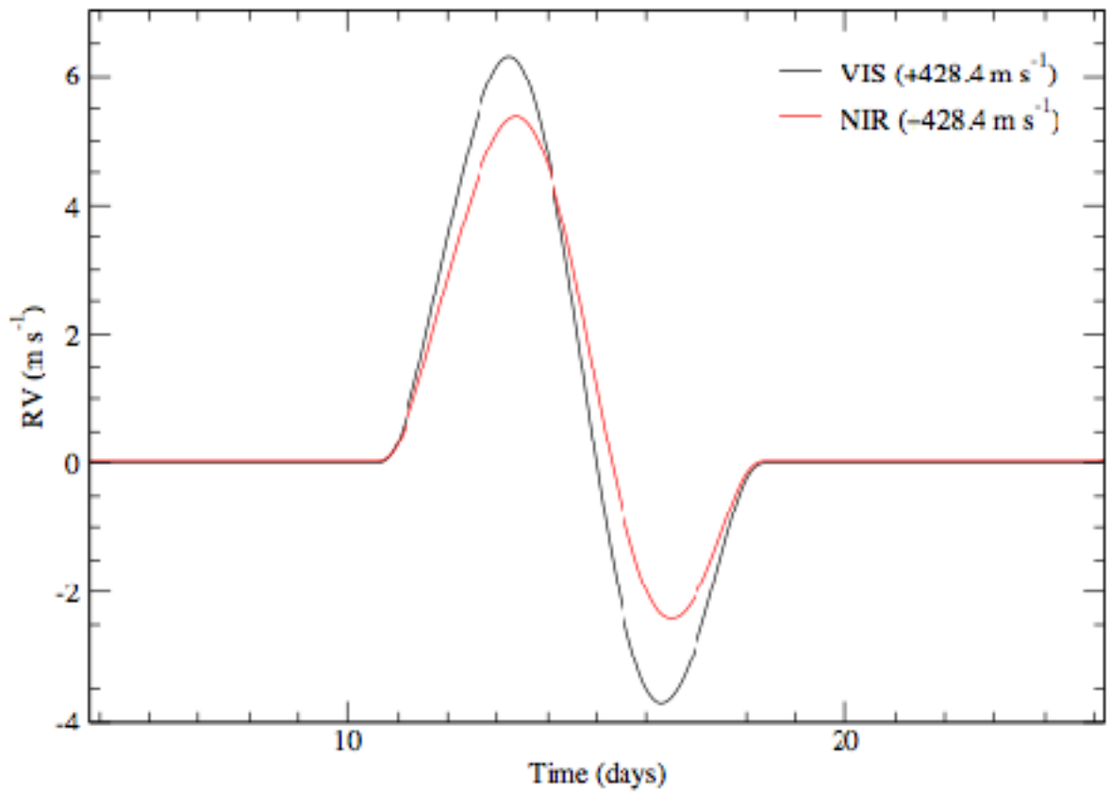
Wavelength Dependence

StarSim 2.0

VIS & NIR RV data to correct out stellar activity

- Is NIR scaled version of VIS? ⇨ NO!

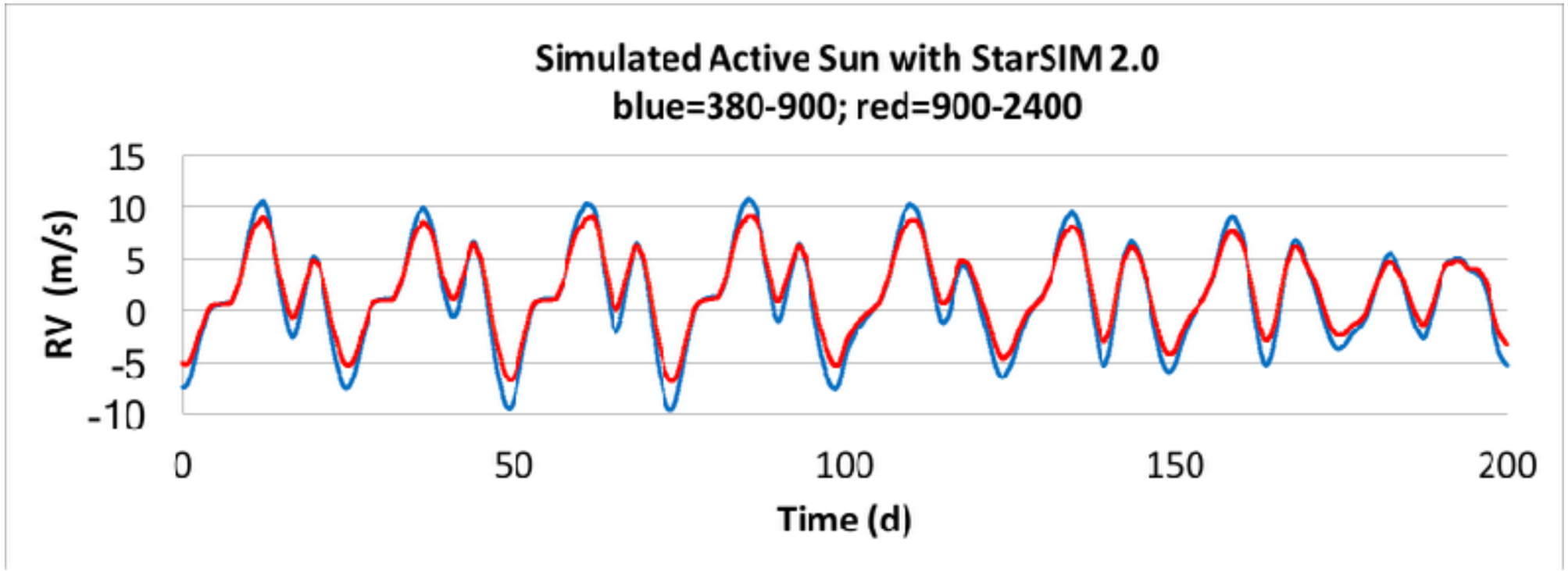




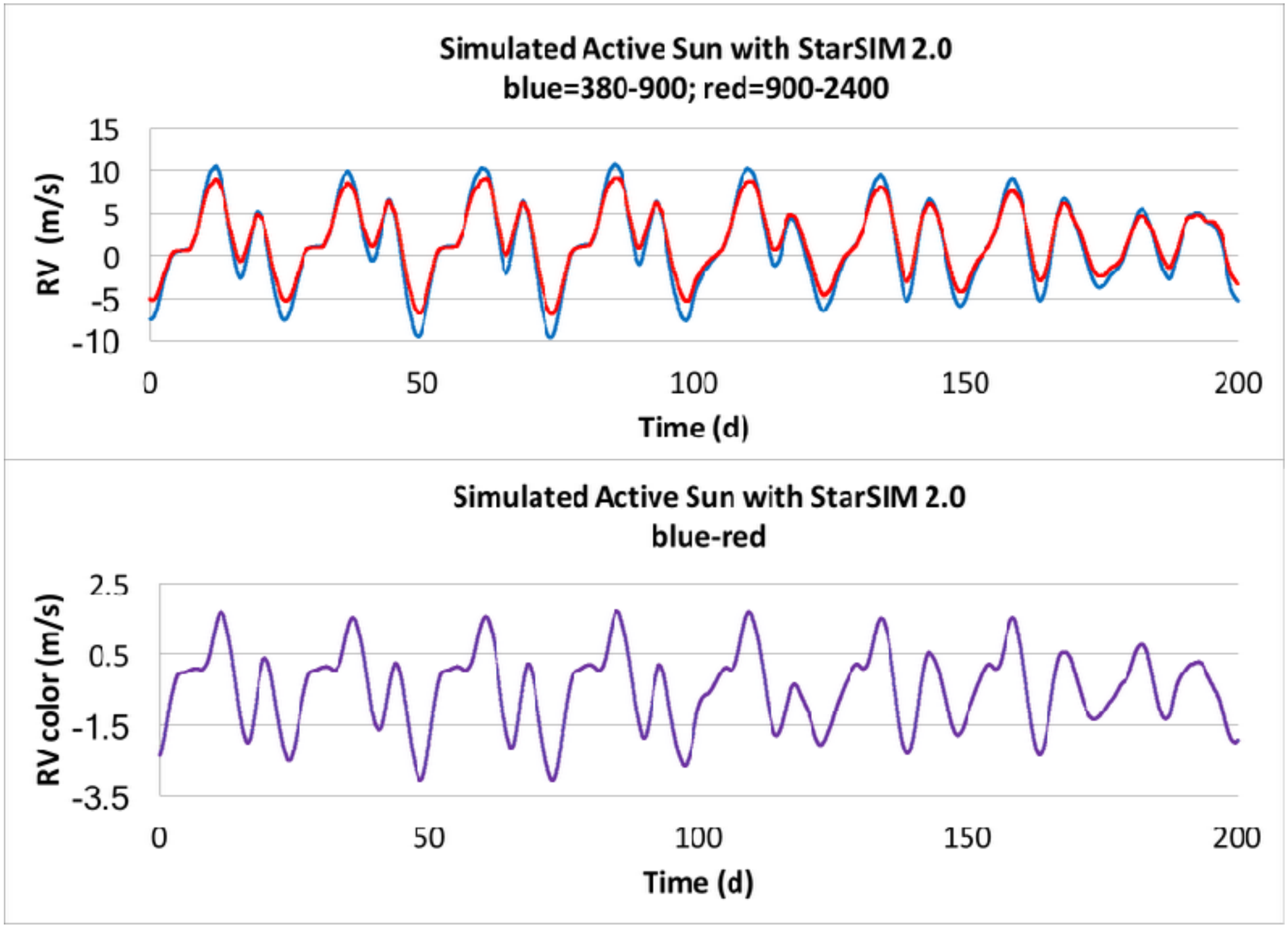
- There is a phase shift
- Not so easy… work in progress

Slide from Ignas Ribas group

Wavelength Dependence

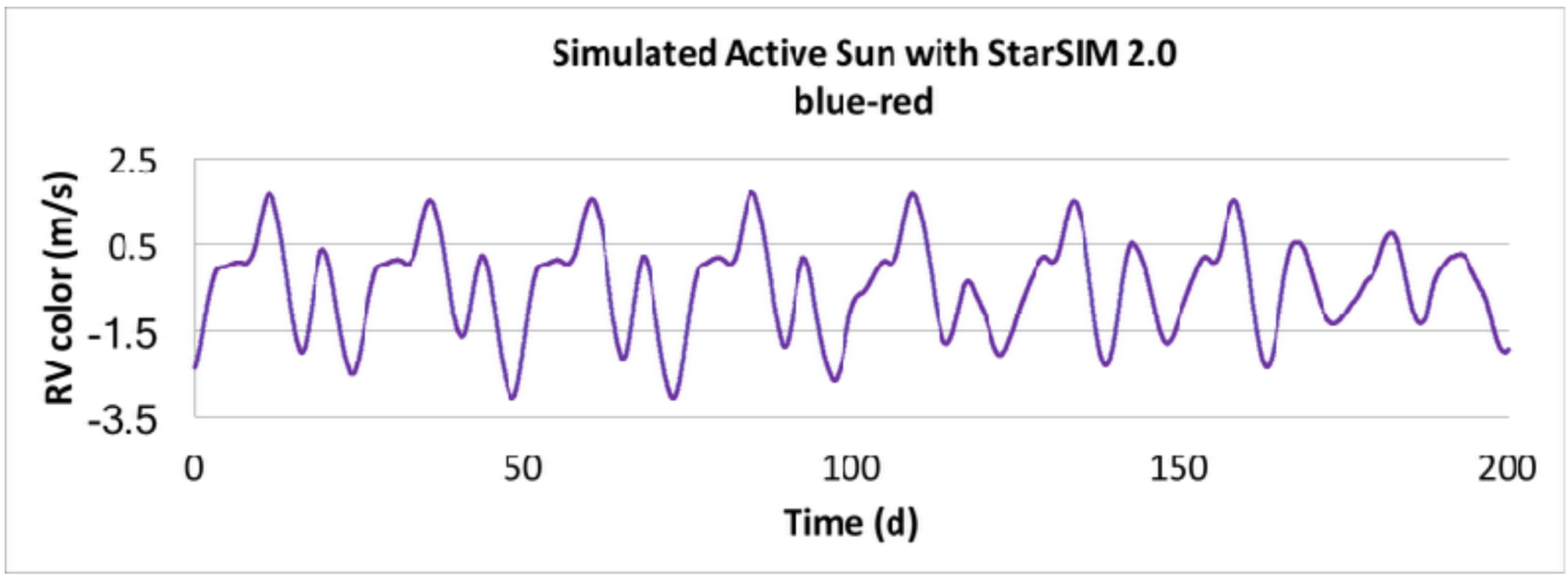


Wavelength Dependence

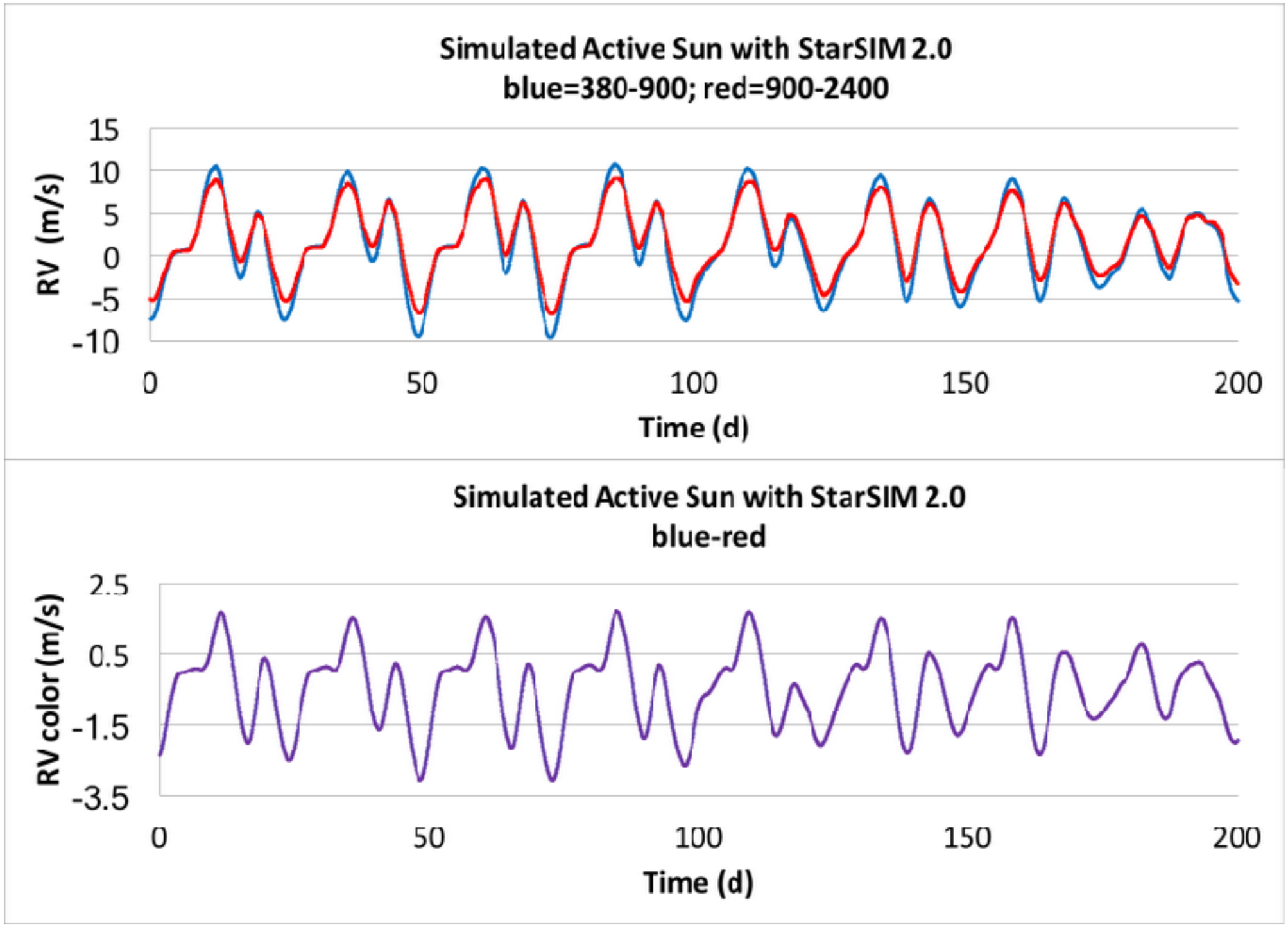


Wavelength Dependence

- 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 ~RV - Cx(RV color)



Wavelength Dependence



The cadence advantage of space

Pinning down the mass of Kepler-10c: the importance of sampling and model comparison

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[2] Centre for Star and Planet Formation, Natural History Museum of Denmark, University of Copenhagen, DK-1350 Copenhagen, Denmark

Recovering planet radial velocity signals in the presence of starspot activity in fully convective stars

J.R. Barnes[1], S.V. Jeffers[2], G. Anglada-Escudé[3], C.A. Haswell[1], H.R.A. Jones[4], M. Tuomi[4], F. Feng[4], J.S. Jenkins[5], P. Petit[6,7]
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[3] School of Physics and Astronomy, Queen Mary, University of London, 327 Mile End Rd. London, UK
[4] Centre for Astrophysics Research, University of Hertfordshire, College Lane, Hatfield AL10 9AB, UK
[5] Departamento de Astronomía, Universidad de Chile, Camino del Observatorio 1515, Las Condes, Santiago, Chile.
[6] Université de Toulouse, UPS-OMP, Institut de Recherche en Astrophysique et Planétologie, 31000 Toulouse, France.
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Accepted for publication in MNRAS (2016 December 2)

day 2

on of the enigmatic planet Kepler-10c suggested a mass of $\sim 17\ M_\oplus$, igh for a planet with radius $2.32\ R_\oplus$; further observations and subse- (possibly much) lower mass, but masses derived using RVs from two HARPS-N and HIRES) were incompatible at a 3σ level. We demon- ss discrepancies may readily arise from sub-optimal sampling and/or a single coherent signal (stellar, planetary, or otherwise) that may be present a plausible resolution of the mass discrepancy, and ultimately as having mass $7.37^{+1.32}_{-1.19}\ M_\oplus$, and mean density $3.14^{+0.63}_{-0.55}$ g cm^{-3}.

ividual: Kepler-10 – planetary systems – methods: data analysis – ties – stars: activity

"We have clearly demonstrated that high cadence observations on the timescale of the stellar rotation period are essential for reliable RV detection of planets orbiting active stars."

The cadence advantage of space

Space

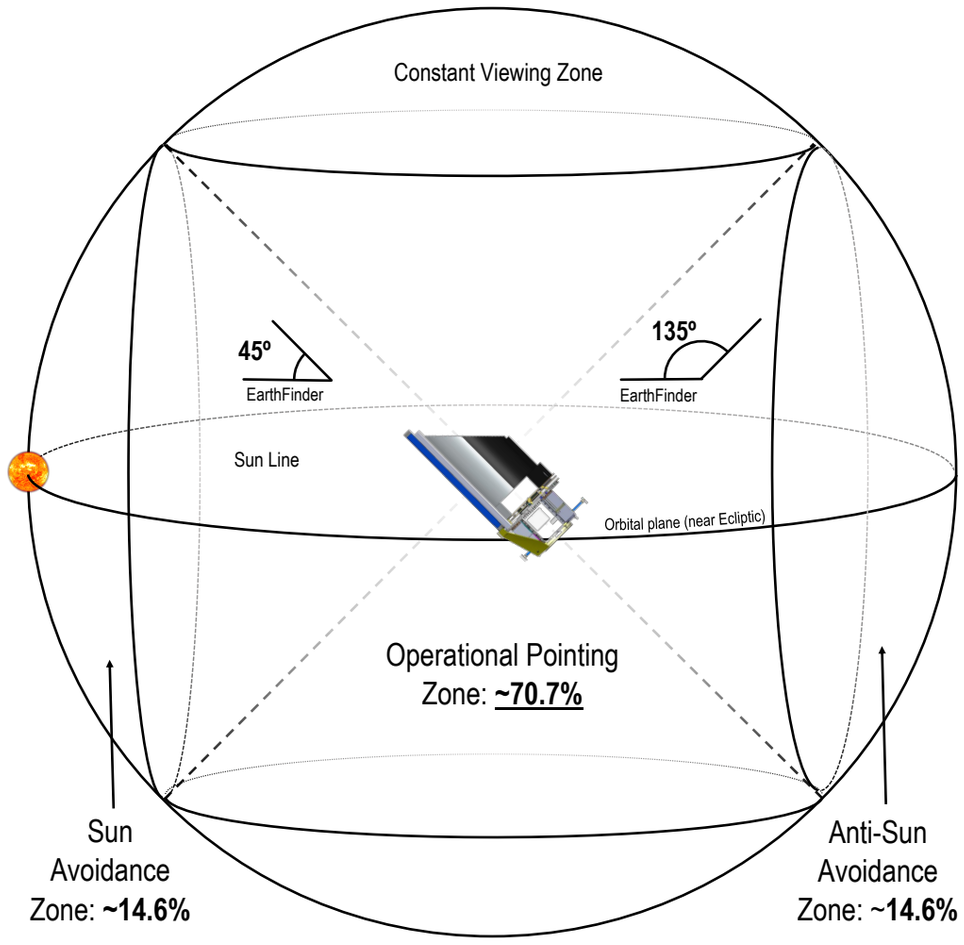
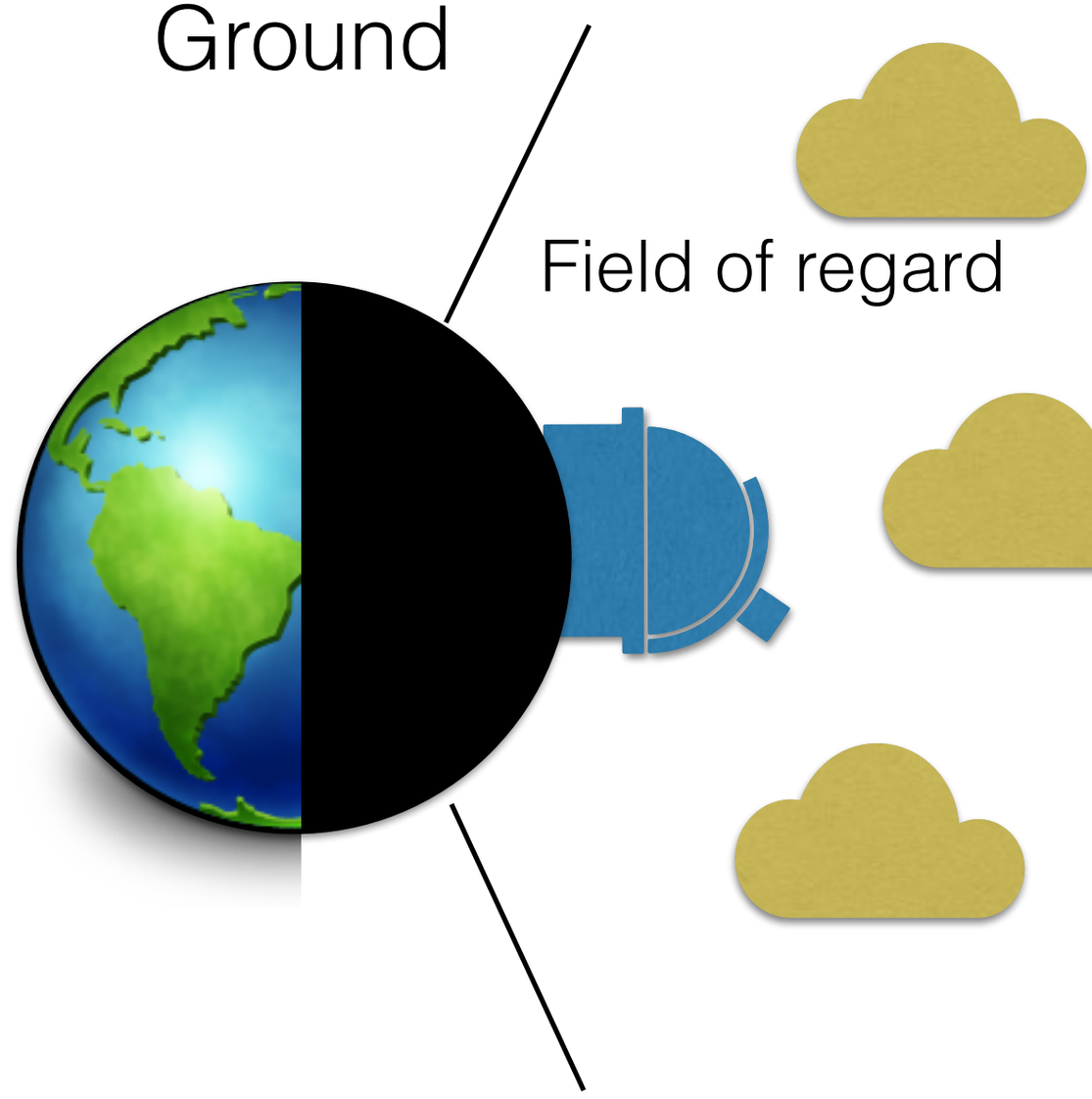


Figure from Bahaa Hamze

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

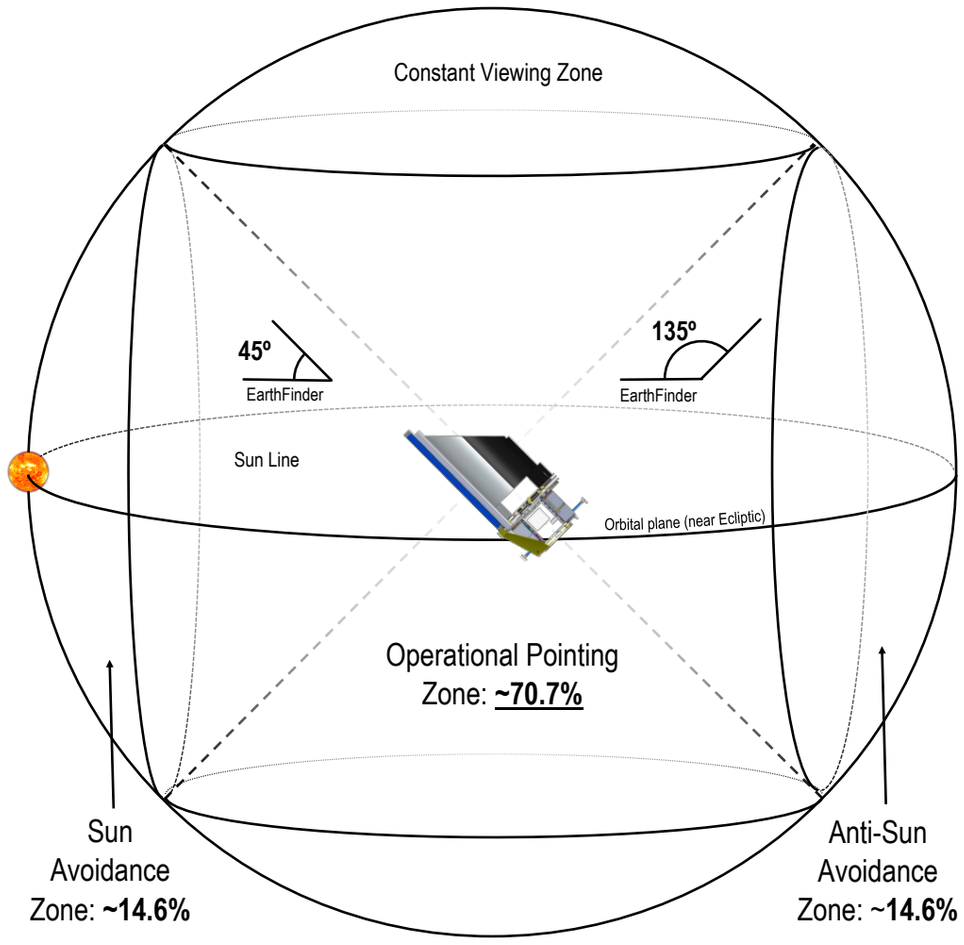
Ground



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

The cadence advantage of space

Space



Ground

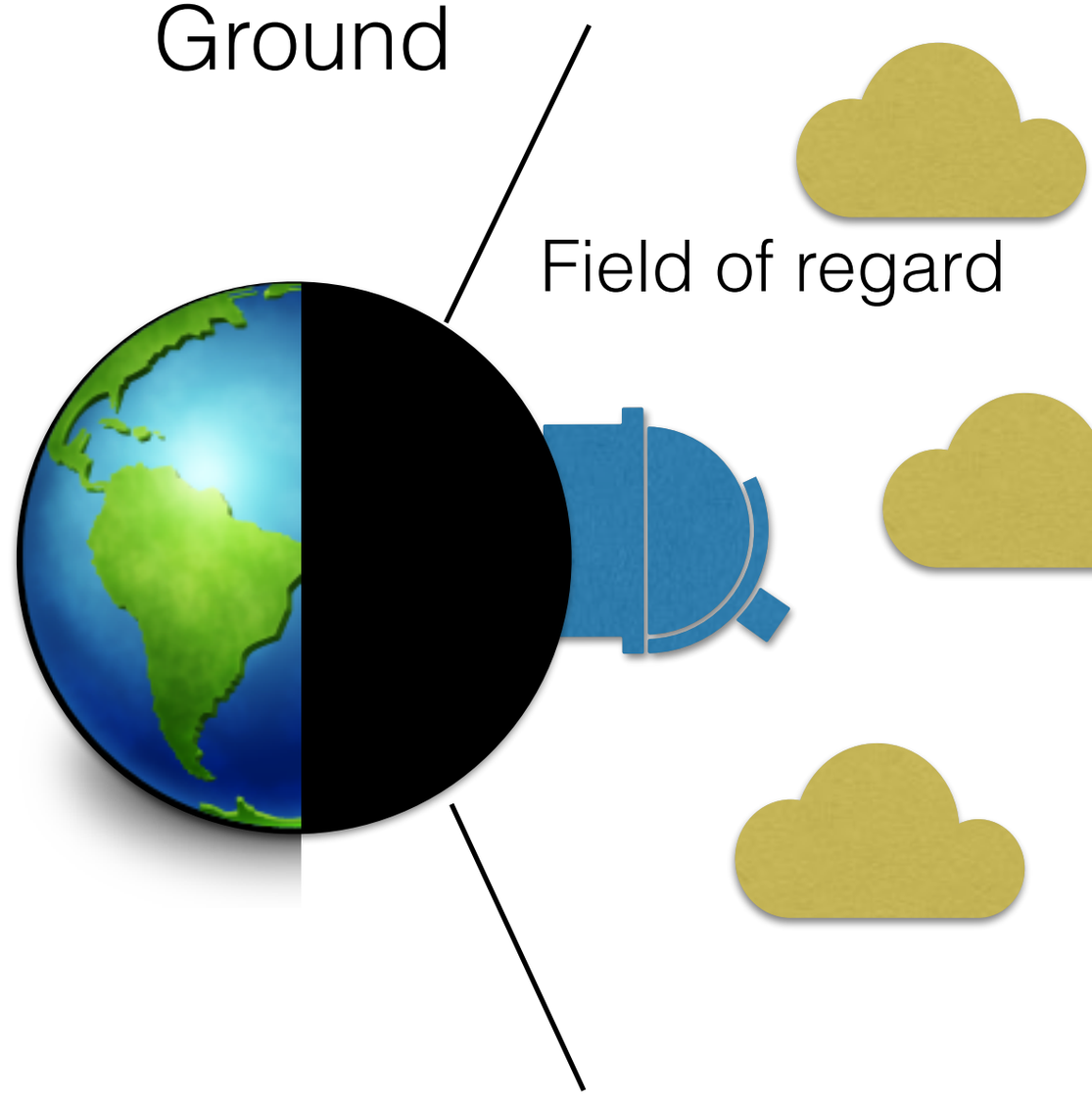
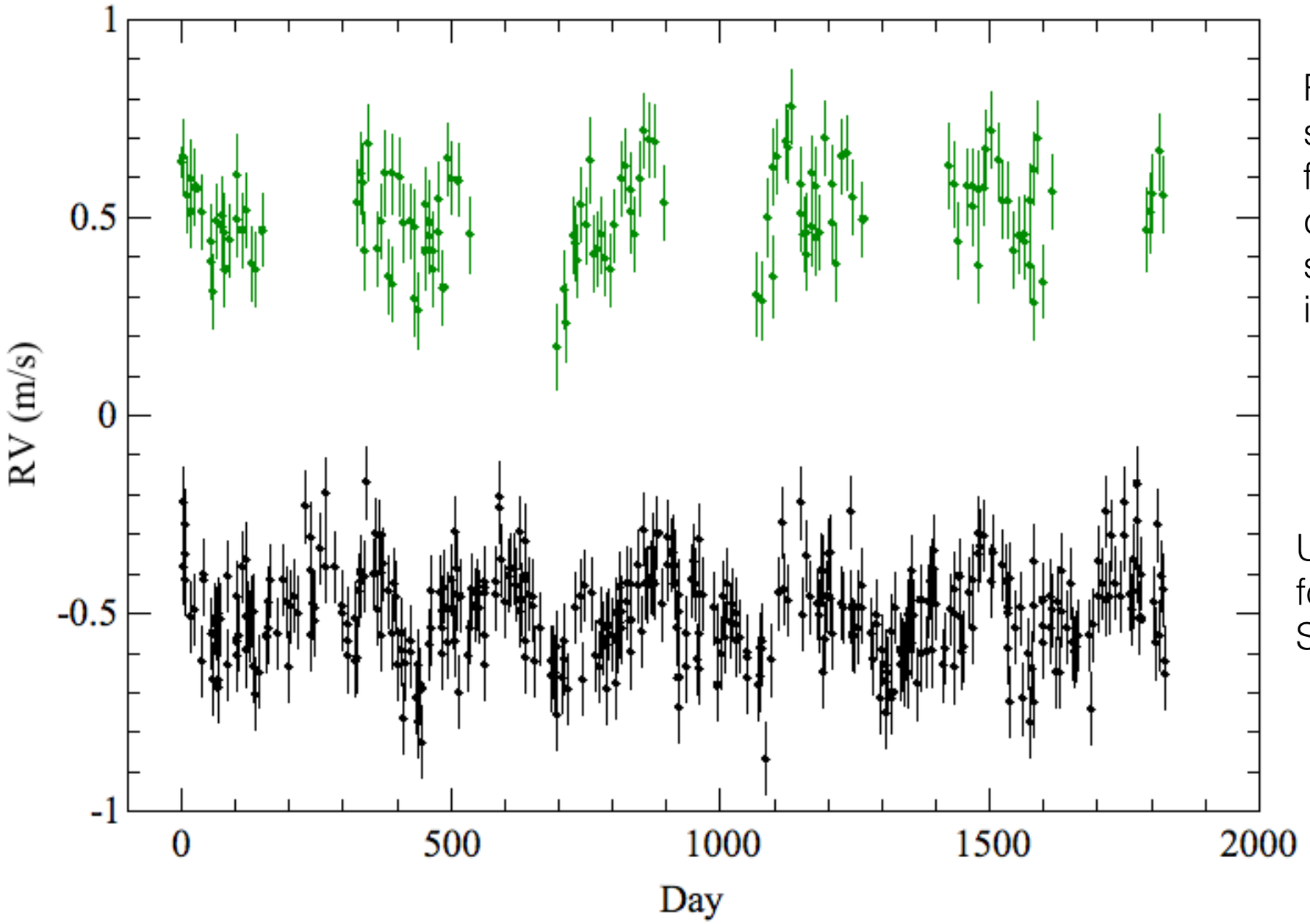


Figure from Bahaa Hamze

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.

The cadence advantage of space

– Median target with 2 terrestrial planets from a 5 yr, 42 target "super-NEID" vs. EarthFinder survey of direct imaging targets.

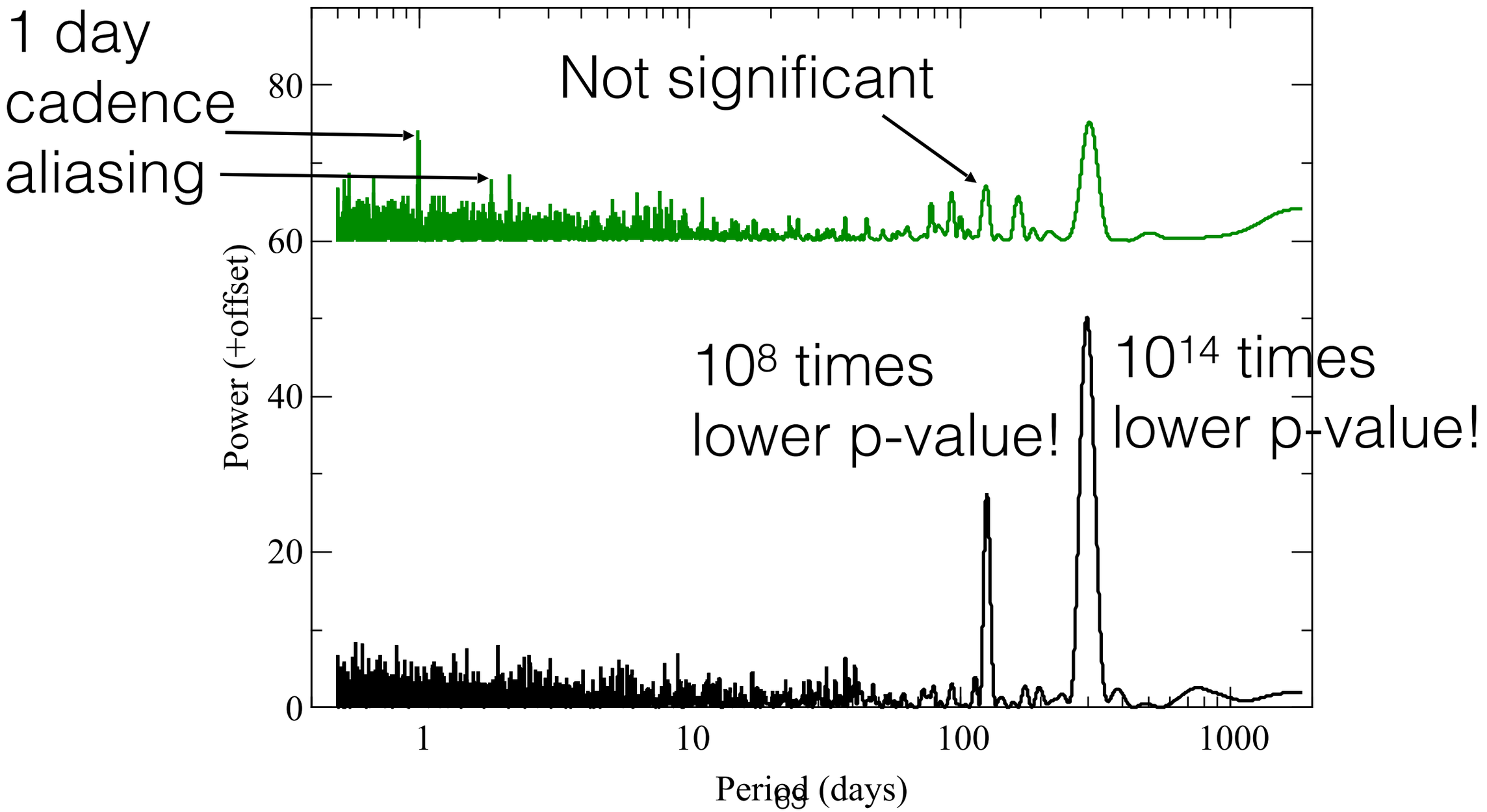


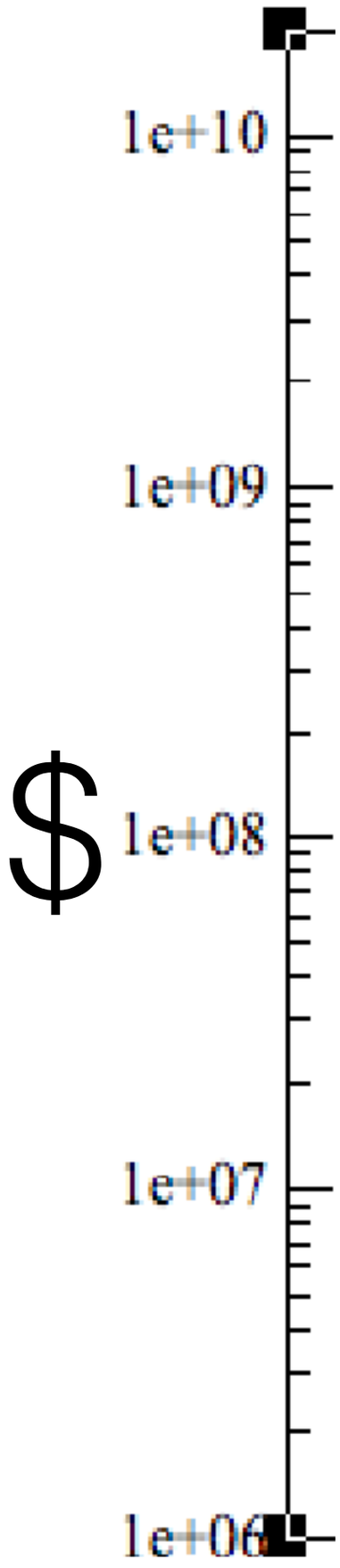
Realistic survey simulation accounting for weather and daytime, target list, stellar host RV information content

Uniform random cadence for target in CVZ;
See also Hall et al. (2018)

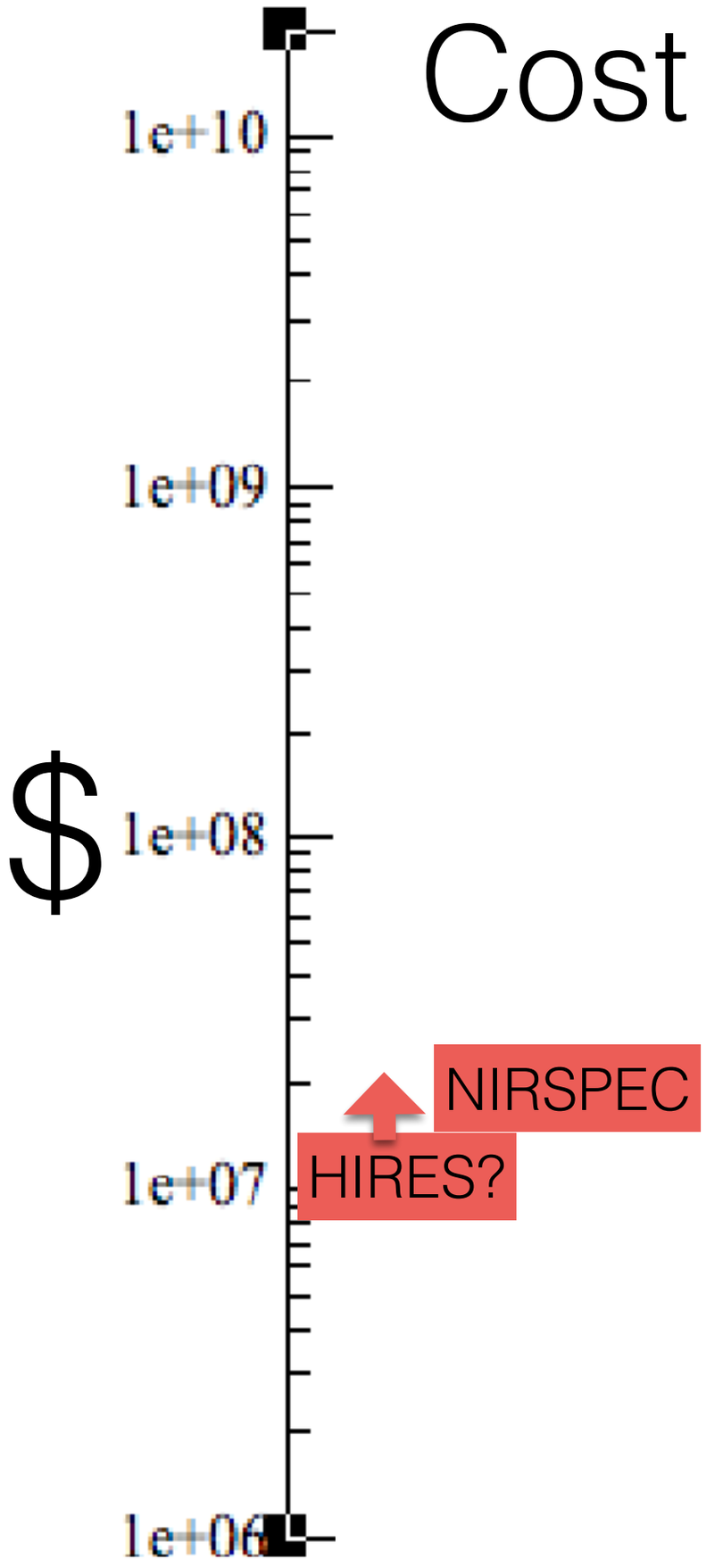
The cadence advantage of space

– Median target with 2 terrestrial planets from a 5 yr, 42 target "super-NEID" vs. EarthFinder survey of direct imaging targets.

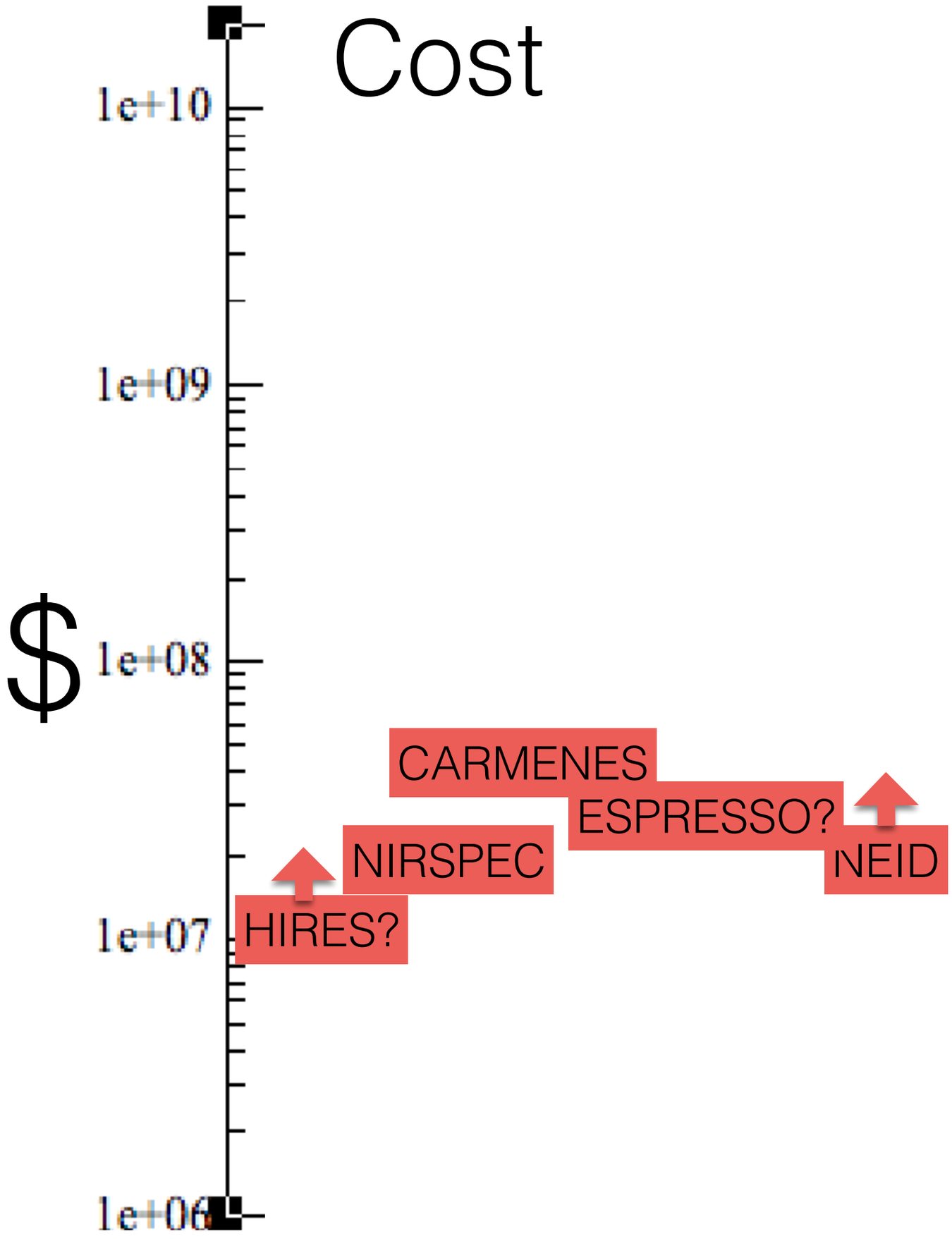



Cost
$
1e+10
1e+09
1e+08
1e+07
1e+06

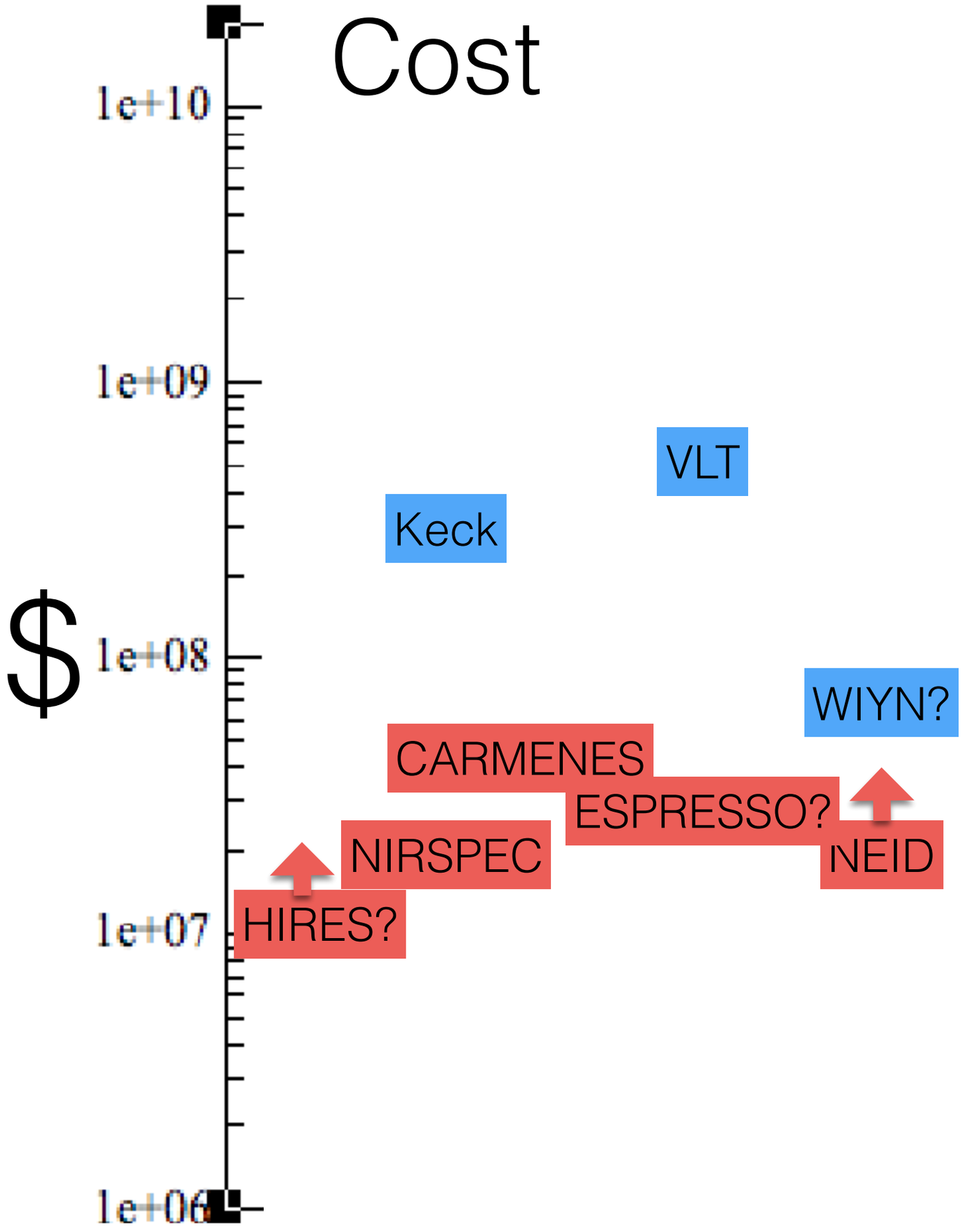
Cost



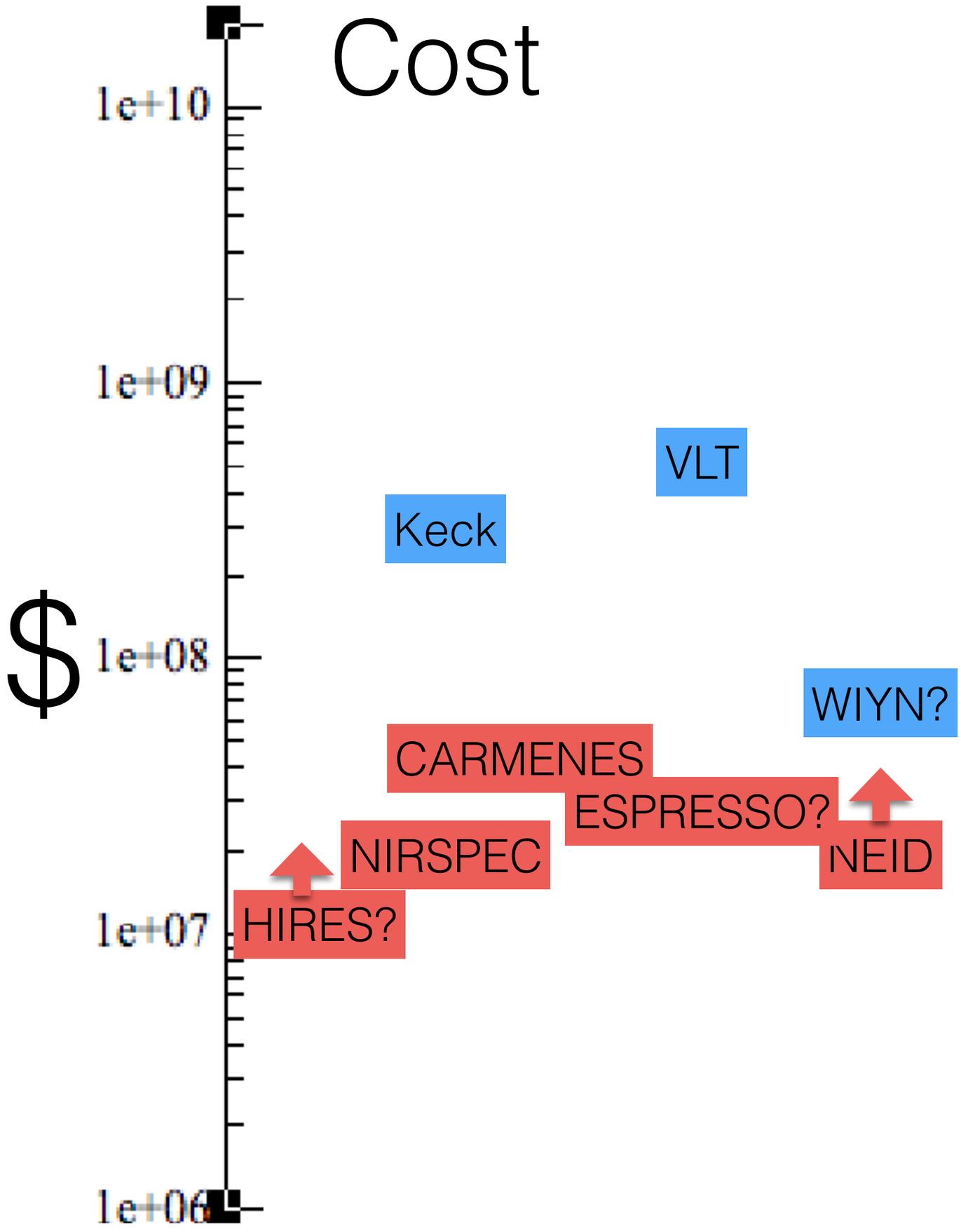
Cost


$
1e+10
1e+09
1e+08
1e+07
1e+06
HIRES?
NIRSPEC
CARMENES
ESPRESSO?
NEID

Cost


$
1e+10
1e+09
1e+08
1e+07
1e+06
Keck
VLT
WIYN?
CARMENES
ESPRESSO?
NIRSPEC
NEID
HIRES?

Cost


$
1e+10
1e+09
1e+08
1e+07
1e+06
GMT/TMT/ELT
VLT
Keck
WIYN?
CARMENES
ESPRESSO?
NIRSPEC
NEID
HIRES?

Cost

$

1e+10
1e+09
1e+08
1e+07
1e+06

GMT/TMT/ELT

VLT

Keck

WIYN?

1 ground RV 1 cm/s

CARMENES

ESPRESSO?

NIRSPEC

NEID

HIRES?

Cost

$

1e+10

1e+09

1e+08

1e+07

1e+06

GMT/TMT/ELT

VLT

Keck

6 global network RV 1 cm/s

WIYN?

1 ground RV 1 cm/s

CARMENES

ESPRESSO?

NIRSPEC

NEID

HIRES?

Cost

$

1e+10

1e+09

1e+08

1e+07

1e+06

Keck

VLT

WIYN?

CARMENES

ESPRESSO?

NIRSPEC

NEID

HIRES?

GMT/TMT/ELT

RV 1 cm/s + telescopes

6 global network RV 1 cm/s

1 ground RV 1 cm/s

Cost

$

1e+10

1e+09

1e+08

1e+07

1e+06

HST (cumulative)

HST (launch)

GMT/TMT/ELT

RV 1 cm/s + telescopes

VLT

Keck

6 global network RV 1 cm/s

WIYN?

1 ground RV 1 cm/s

CARMENES

ESPRESSO?

NIRSPEC

NEID

HIRES?

Cost

$

1e+10

1e+09

1e+08

1e+07

1e+06

HST (cumulative)

JWST

HST (launch)

GMT/TMT/ELT

Kepler

RV 1 cm/s + telescopes

VLT

Keck

6 global network RV 1 cm/s

WIYN?

1 ground RV 1 cm/s

CARMENES

ESPRESSO?

NIRSPEC

NEID

HIRES?

Cost

$

1e+10

1e+09

1e+08

1e+07

1e+06

LUVOIR/ATLAST

HST (cumulative)

JWST

HabEx

HST (launch)

GMT/TMT/ELT

Kepler

VLT

RV 1 cm/s + telescopes

Keck

6 global network RV 1 cm/s

WIYN?

1 ground RV 1 cm/s

CARMENES

ESPRESSO?

NIRSPEC

NEID

HIRES?

Cost

$

1e+10

1e+09

1e+08

1e+07

1e+06

LUVOIR/ATLAST

HST (cumulative)

JWST

HabEx

HST (launch)

GMT/TMT/ELT

EarthFinder

Kepler

VLT

RV 1 cm/s + telescopes

Keck

6 global network RV 1 cm/s

WIYN?

1 ground RV 1 cm/s

CARMENES

ESPRESSO?

NIRSPEC

NEID

HIRES?

EarthFinder Summary

- EarthFinder is a space-based 1.45-m observatory Probe mission concept
- Extremely precise and stabilized high-resolution UV-VIS-NIR spectrograph
- Developing scientific rationale for measuring stellar velocities of the nearest FGKM dwarf stars from space
- Absence of the Earth's atmosphere improves the obtainable radial velocity precision
- Unique combination of space advantages aid in mitigating stellar activity:
    - Uninterrupted wavelength coverage
    - Uninterrupted cadence
    - Diffraction-limited
    - Extreme spectral resolution
- Ancillary science cases:
    - Asteroseismology
    - Water in the local Universe
    - Acceleration of the Universe
    - UV space capability spanning Hubble - HabEx/LUVOIR. temporal gap
    - And more!

Thank you

Stellar Activity Masquerading as Planets in the Habitable Zone of the M dwarf Gliese 581

Paul Robertson[1,2], Suvrath Mahadevan[1,2,3], Michael Endl[4], Arpita Roy[1,2,3]

[1]Department of Astronomy and Astrophysics, The Pennsylvania State University

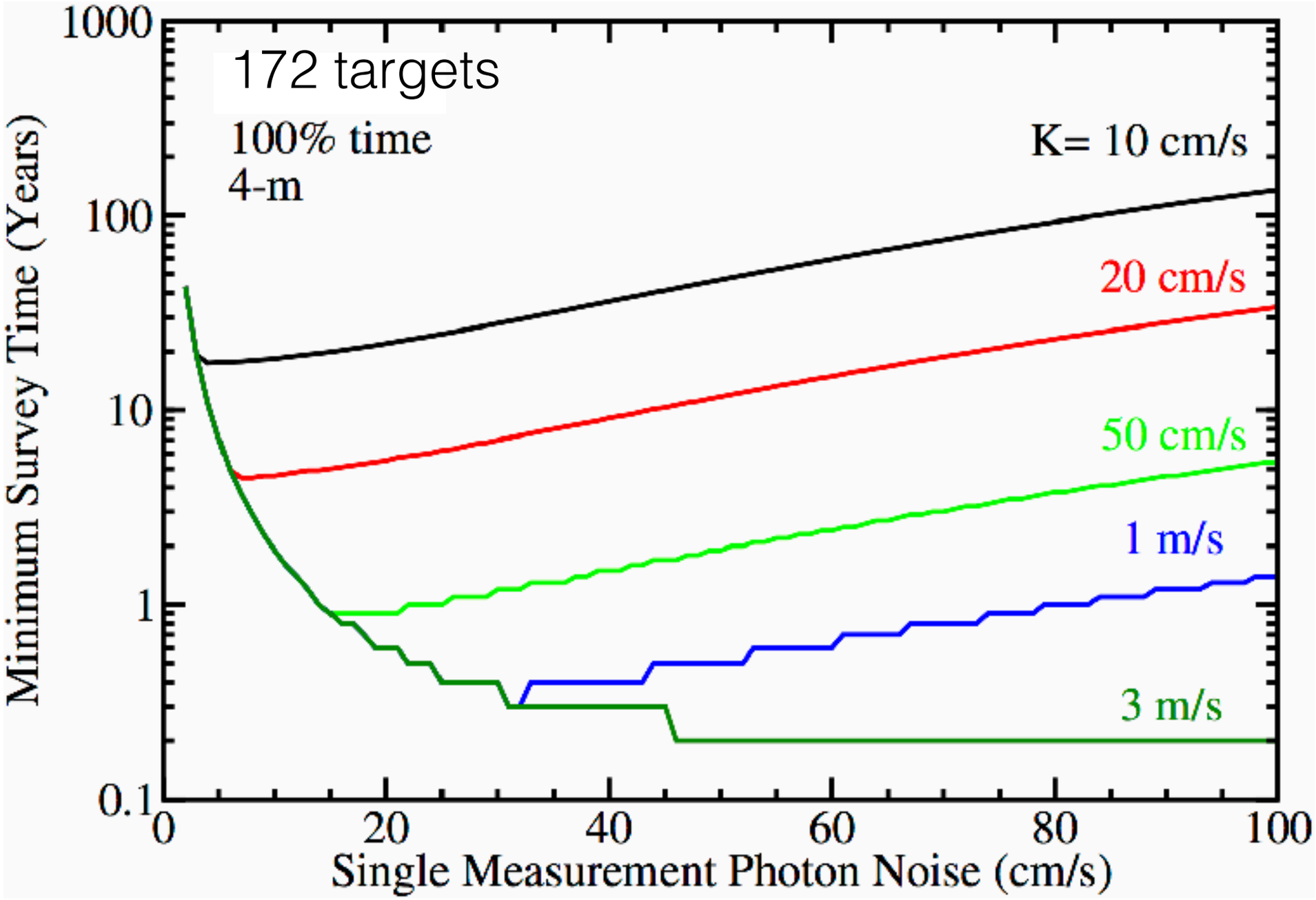
[2]Center for Exoplanets & Habitable Worlds, The Pennsylvania State University

[3]The Penn State Astrobiology Research Center, The Pennsylvania State University

[4]McDonald Observatory, The University of Texas at Austin

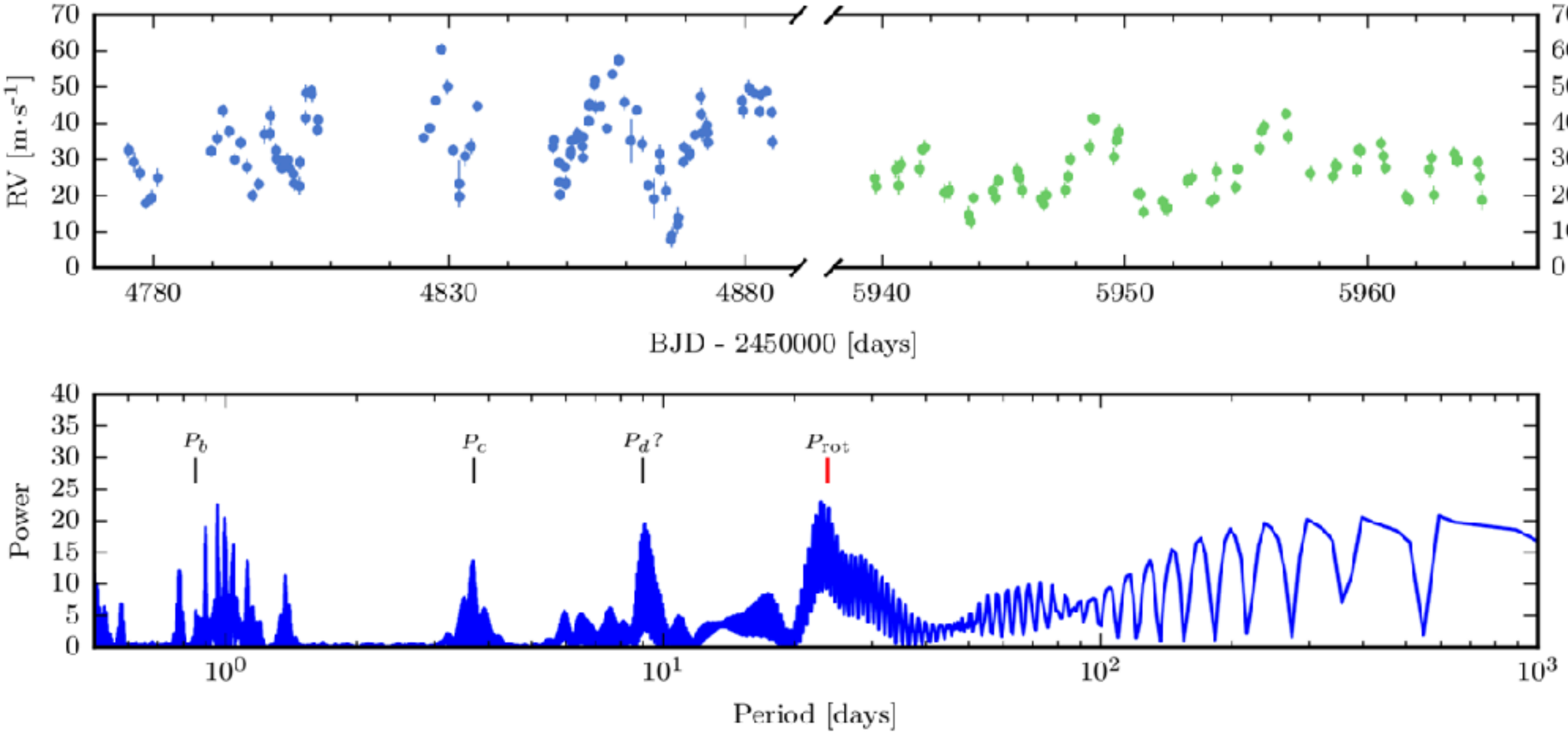
2014

MINERVA - Photons



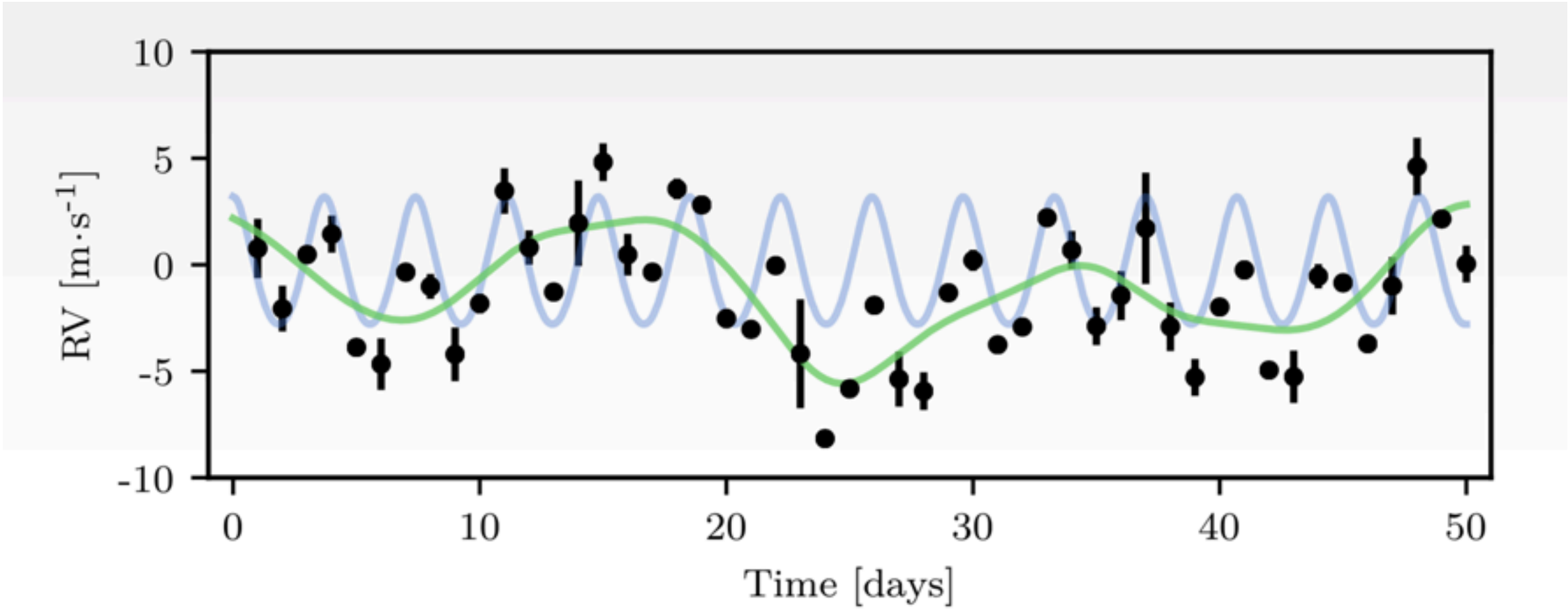
MINERVA - Time

HARPS RVs of CoRoT 7



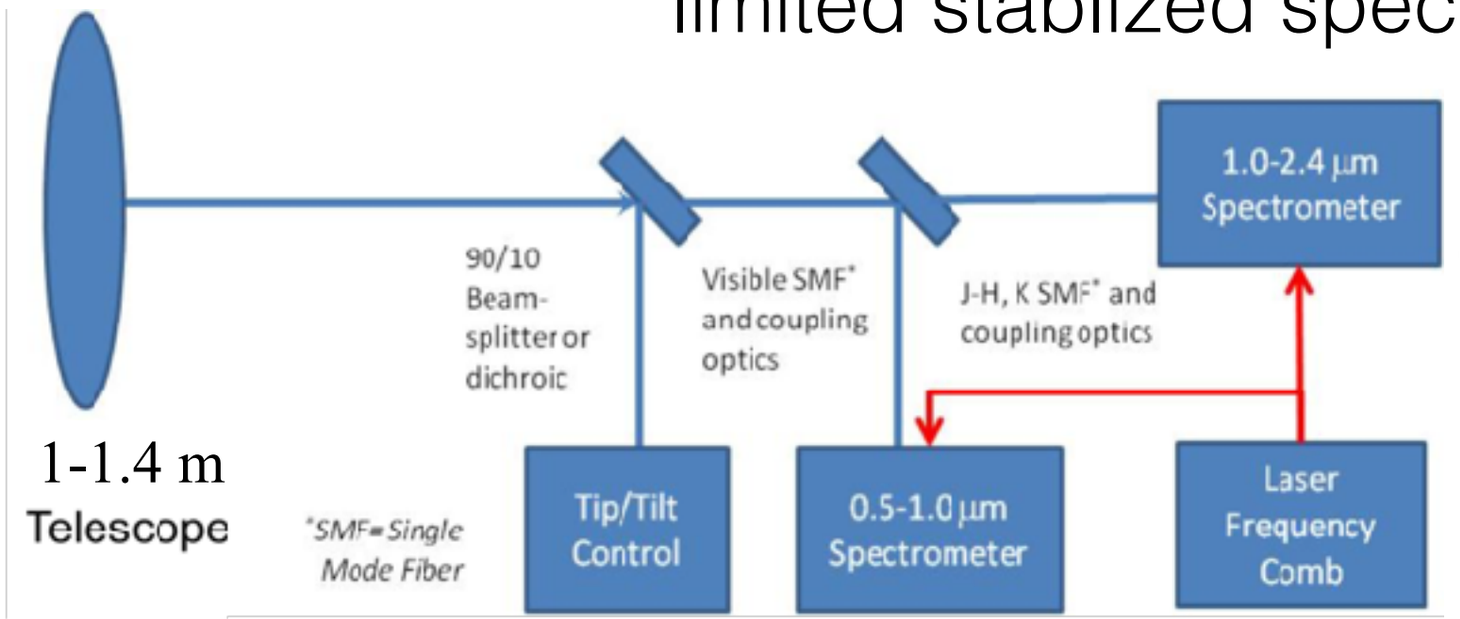
MINERVA - Time

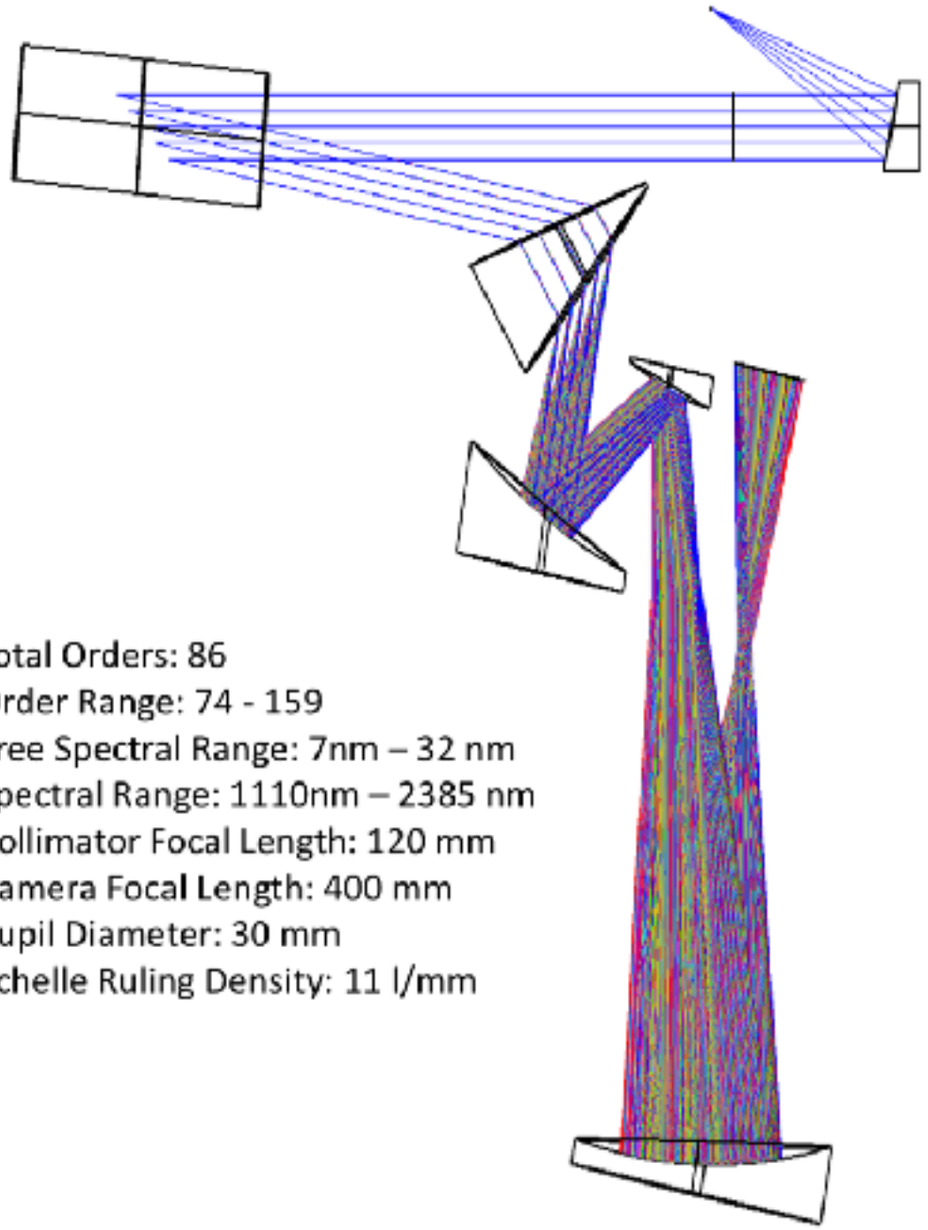
Gaussian Processes - Figure from João P. Faria

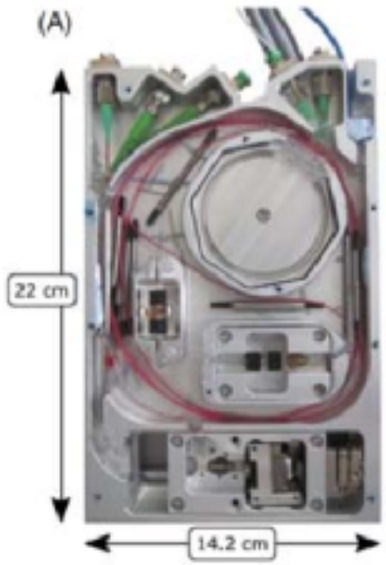


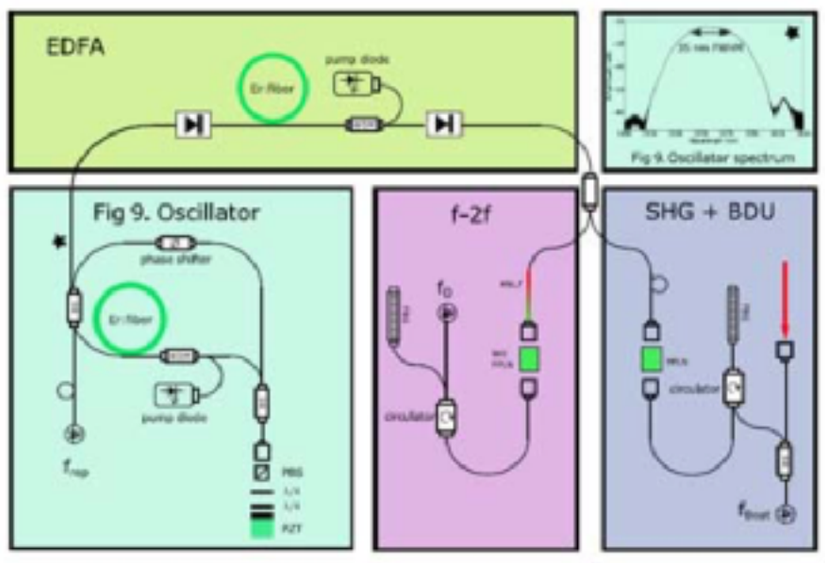
Instrument

High-resolution (R~200k) UV-Optical-NIR diffraction-limited stablized spectrograph









Total Orders: 86
Order Range: 74 - 159
Free Spectral Range: 7nm – 32 nm
Spectral Range: 1110nm – 2385 nm
Collimator Focal Length: 120 mm
Camera Focal Length: 400 mm
Pupil Diameter: 30 mm
Echelle Ruling Density: 11 l/mm

200 mm

Figure 4. A NIR laser frequency comb was recently flown on a TEXUS sounding rocket in a compact package weighing less than 22 kg. See Lezius et al (2016) for details.

Figure from Gautam Vasisht