# The Search for 100 Earths

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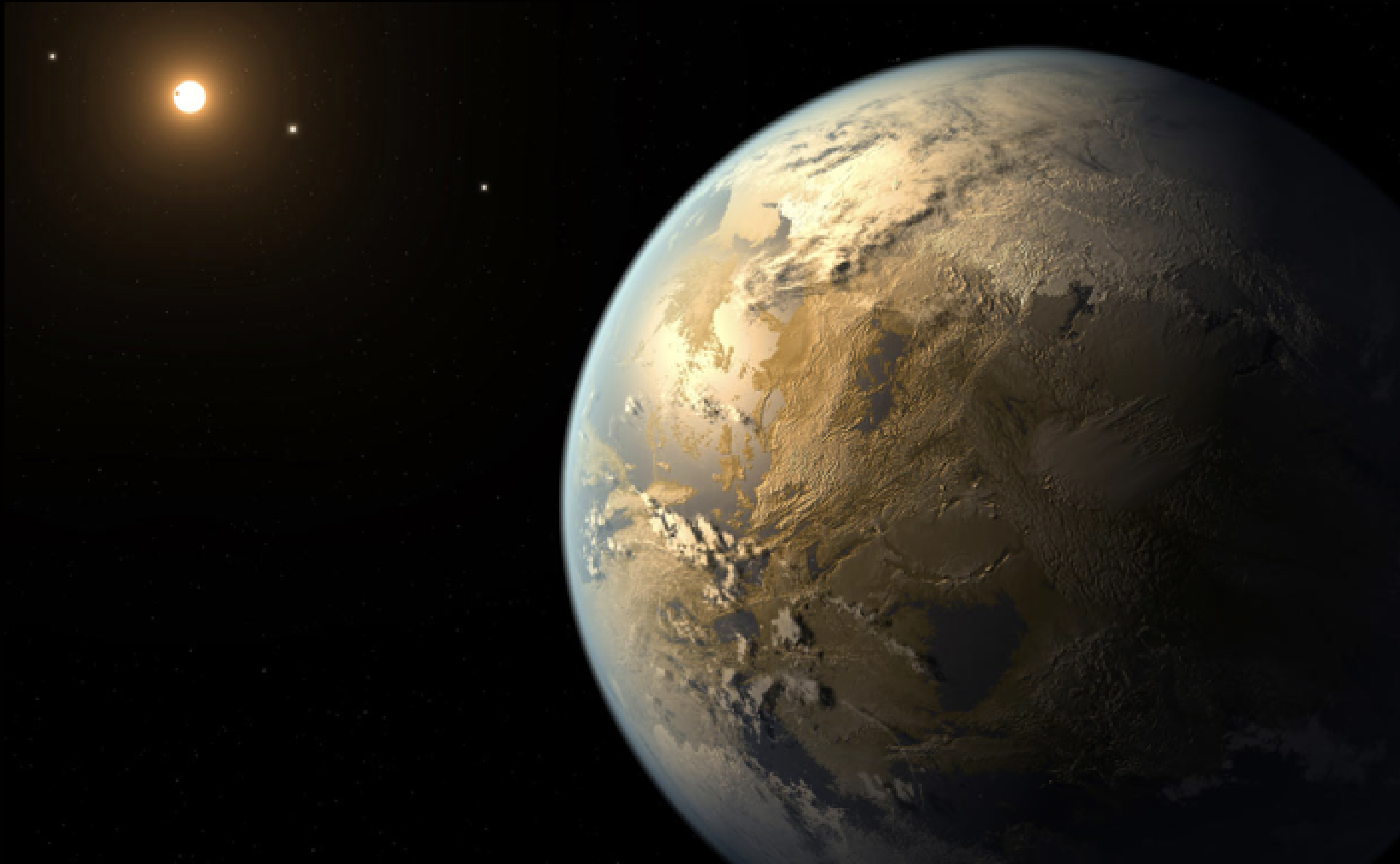
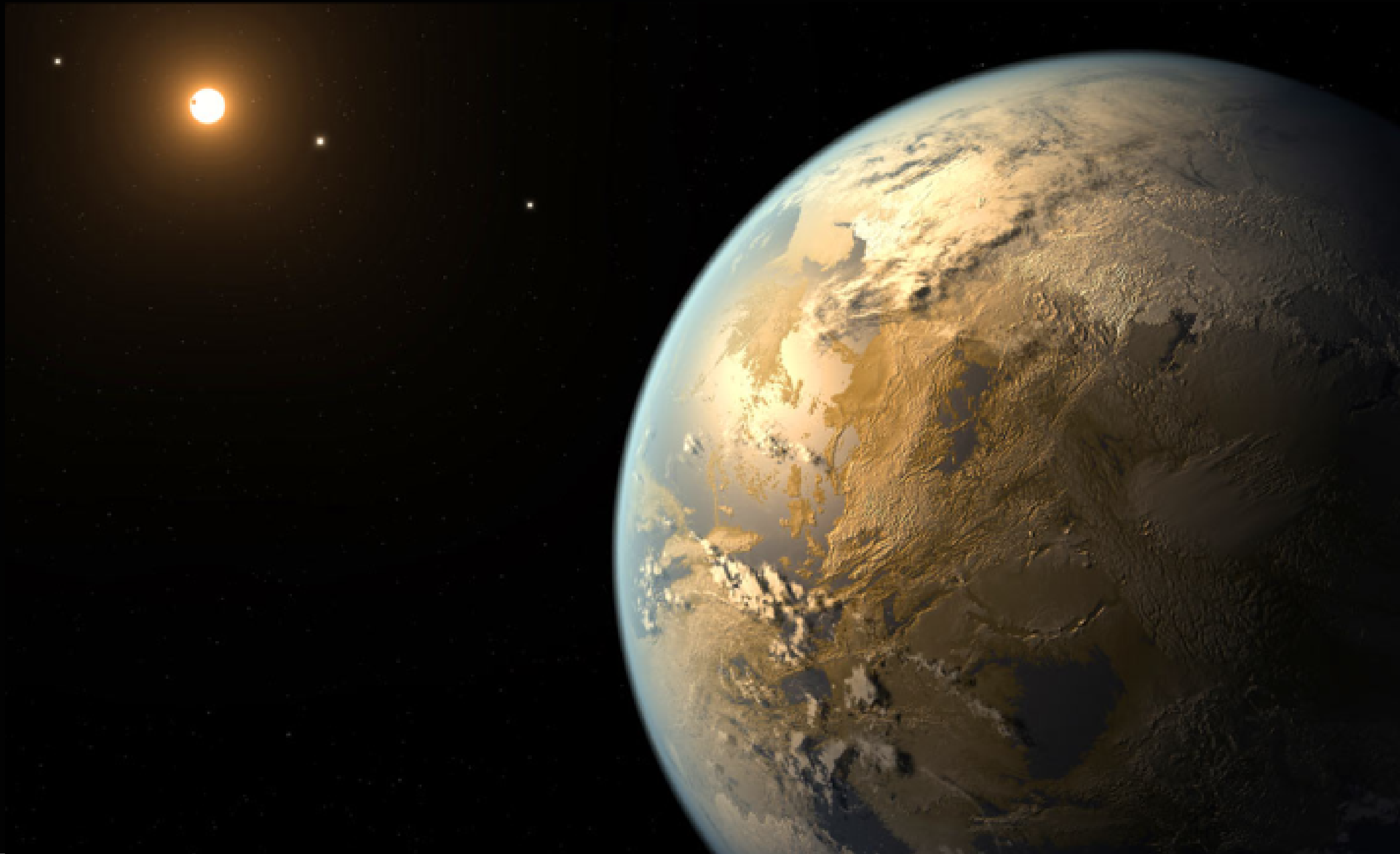


# Outline of this talk

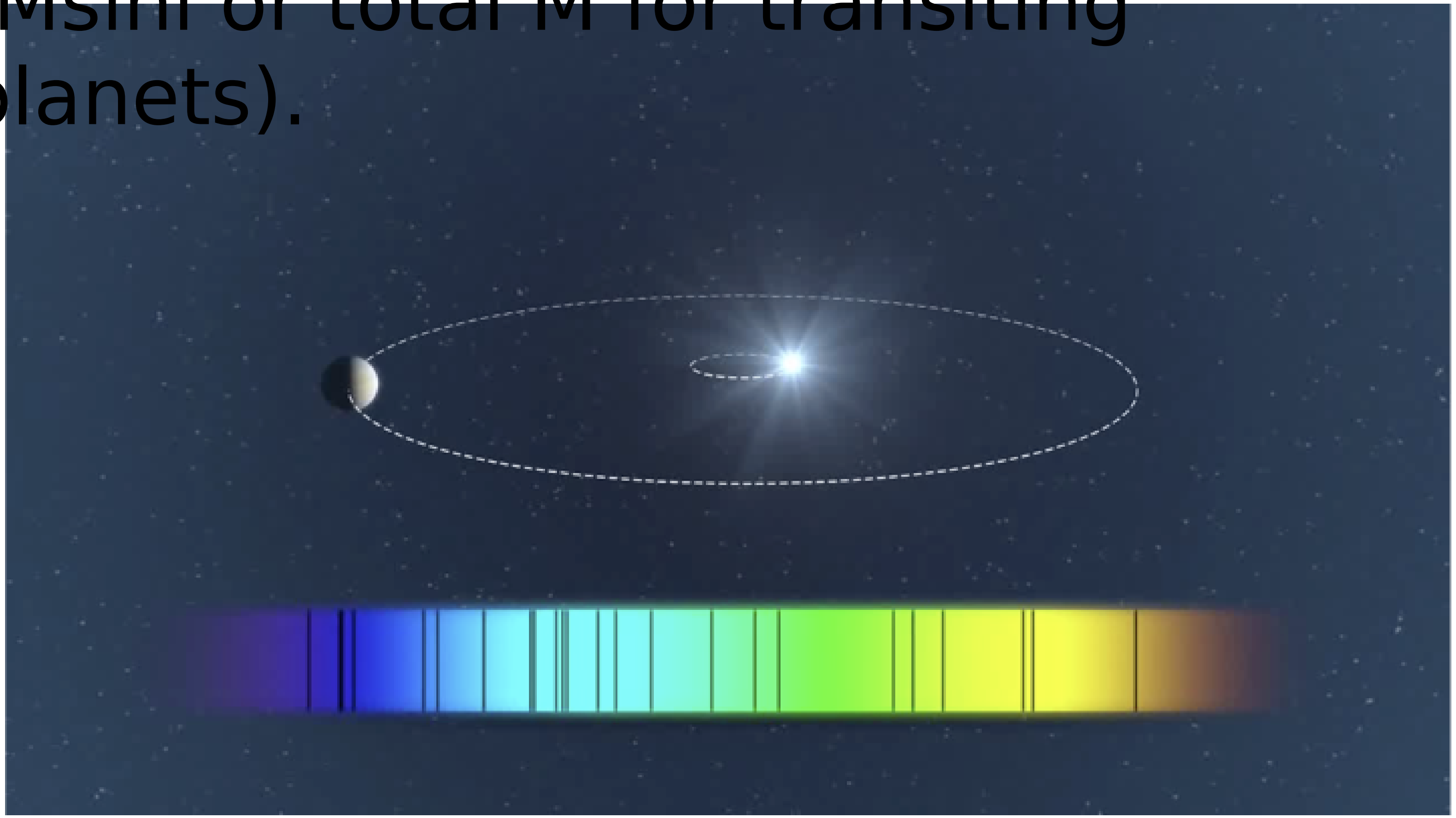
1. History and future.
2. RV and Transit observations – we need both!
3. EXPRES: RV error budget < 20 cm/s, commissioning in November 2017 at the 4.3-m Discovery Channel Telescope
4. Replicate EXPRES for SOAR. Roll forward all of our software and pipelines, build to print.
5. Southern sky independent of ESO time pressure. Follow-up capability for TESS, K2, JWST, WFIRST strengthens collaborations.

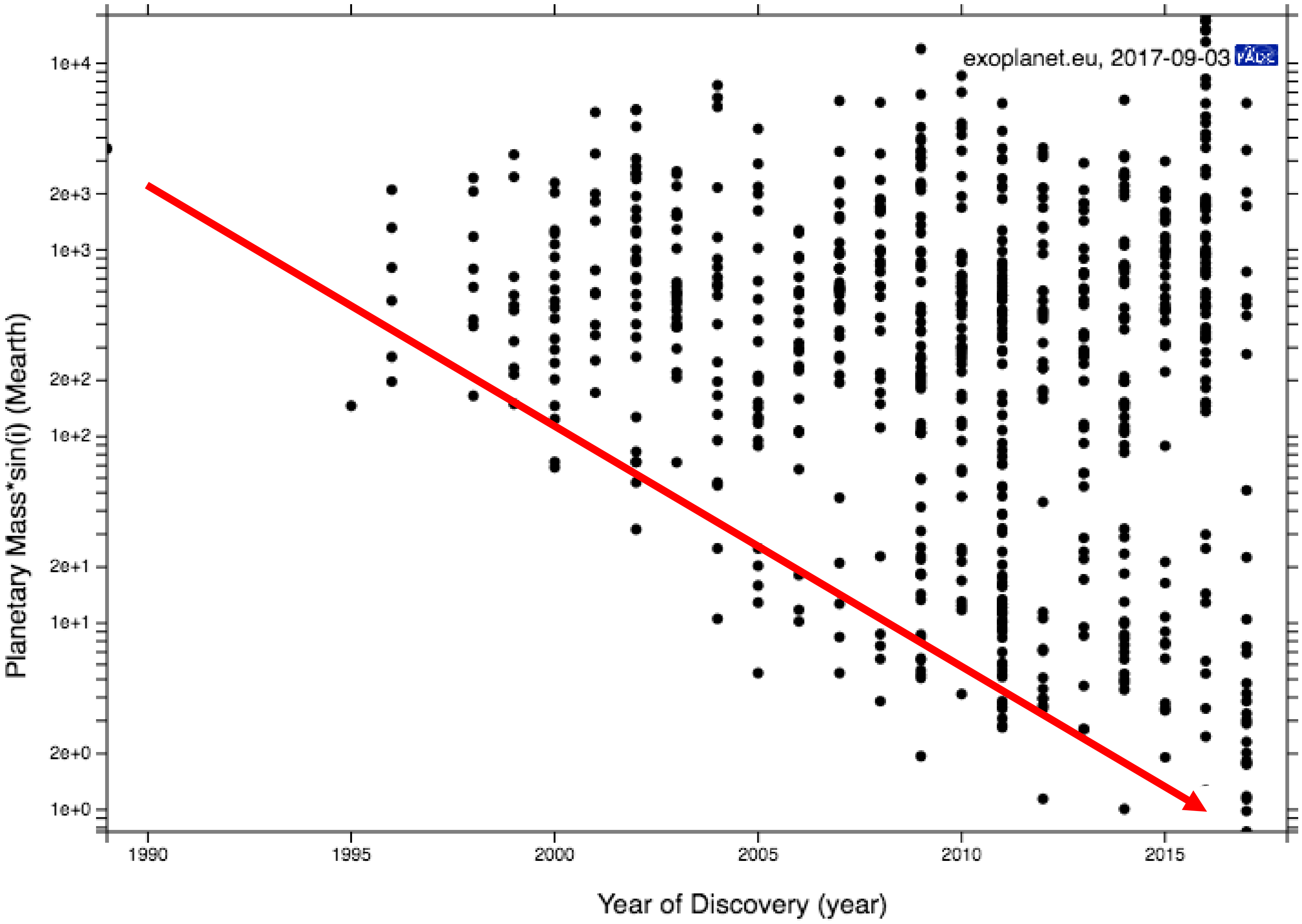
1990: Most stars do not have planets.

Life is rare.



Doppler Technique: Measure the velocity of the star in its orbit. Uniquely measures planet mass (Msini or total M for transiting planets).

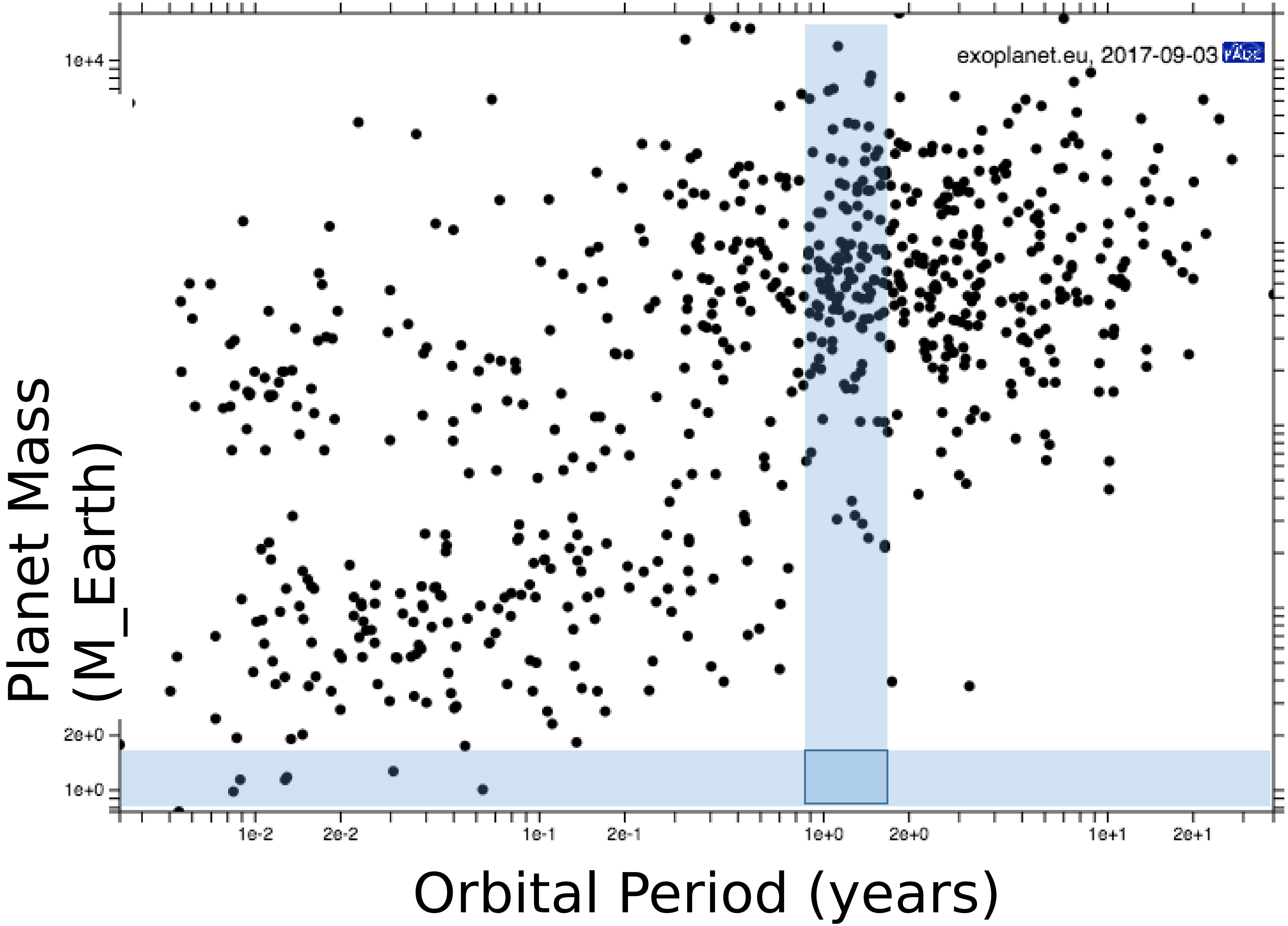




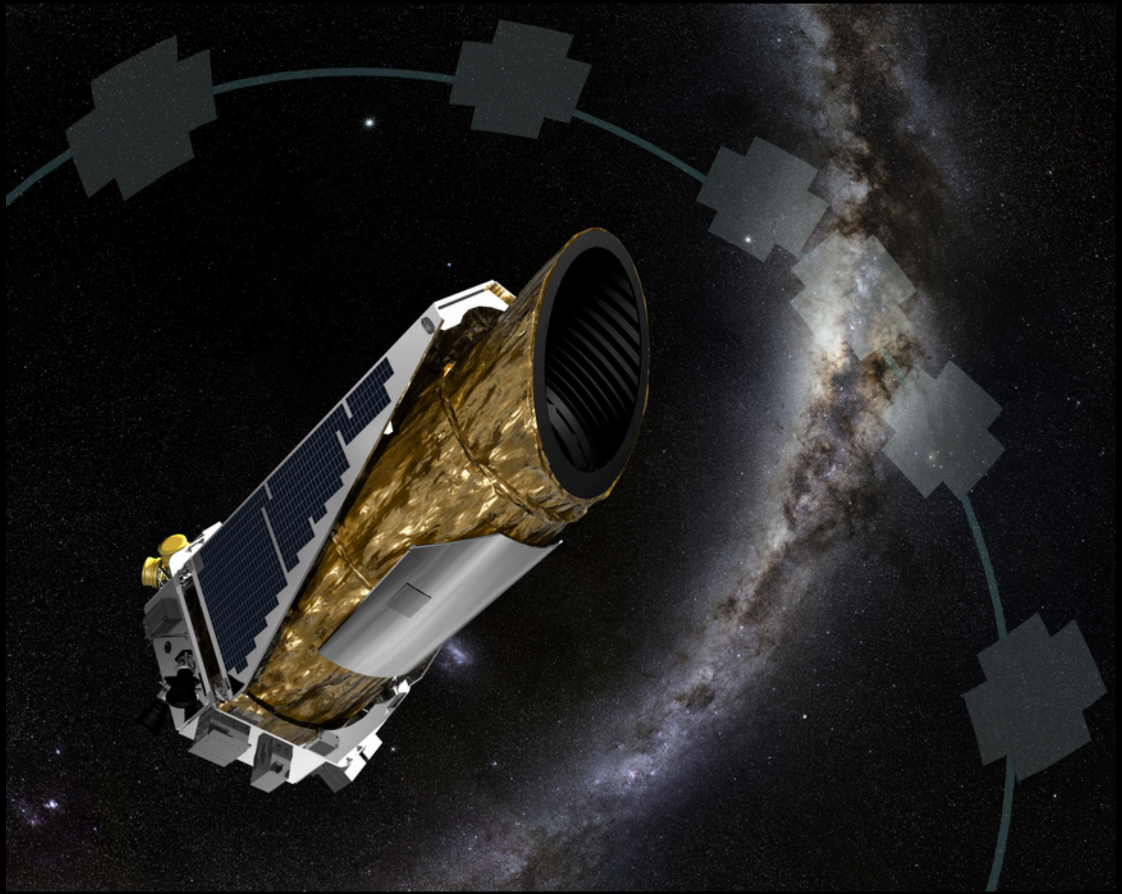

RV precision has improved over time!

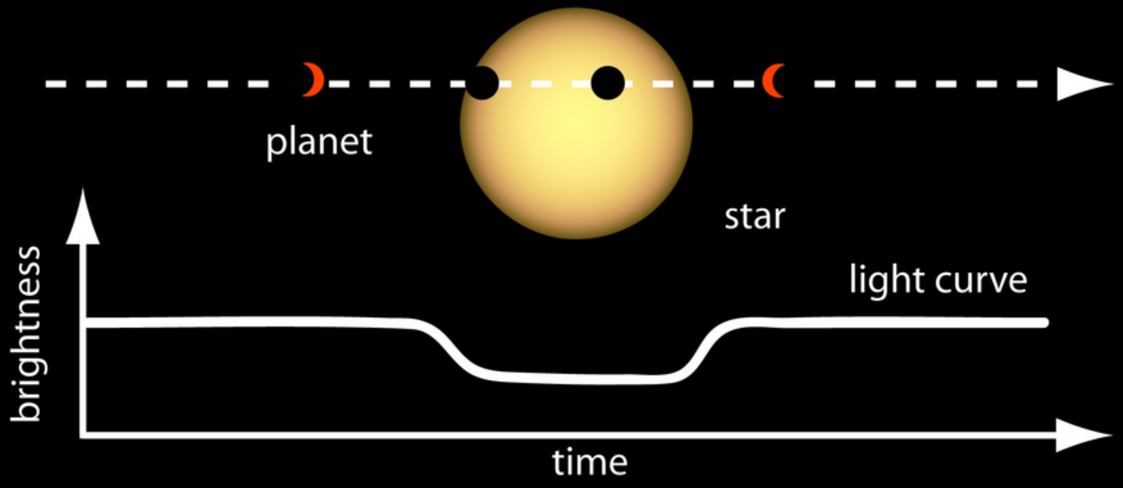
Proxima Cen b

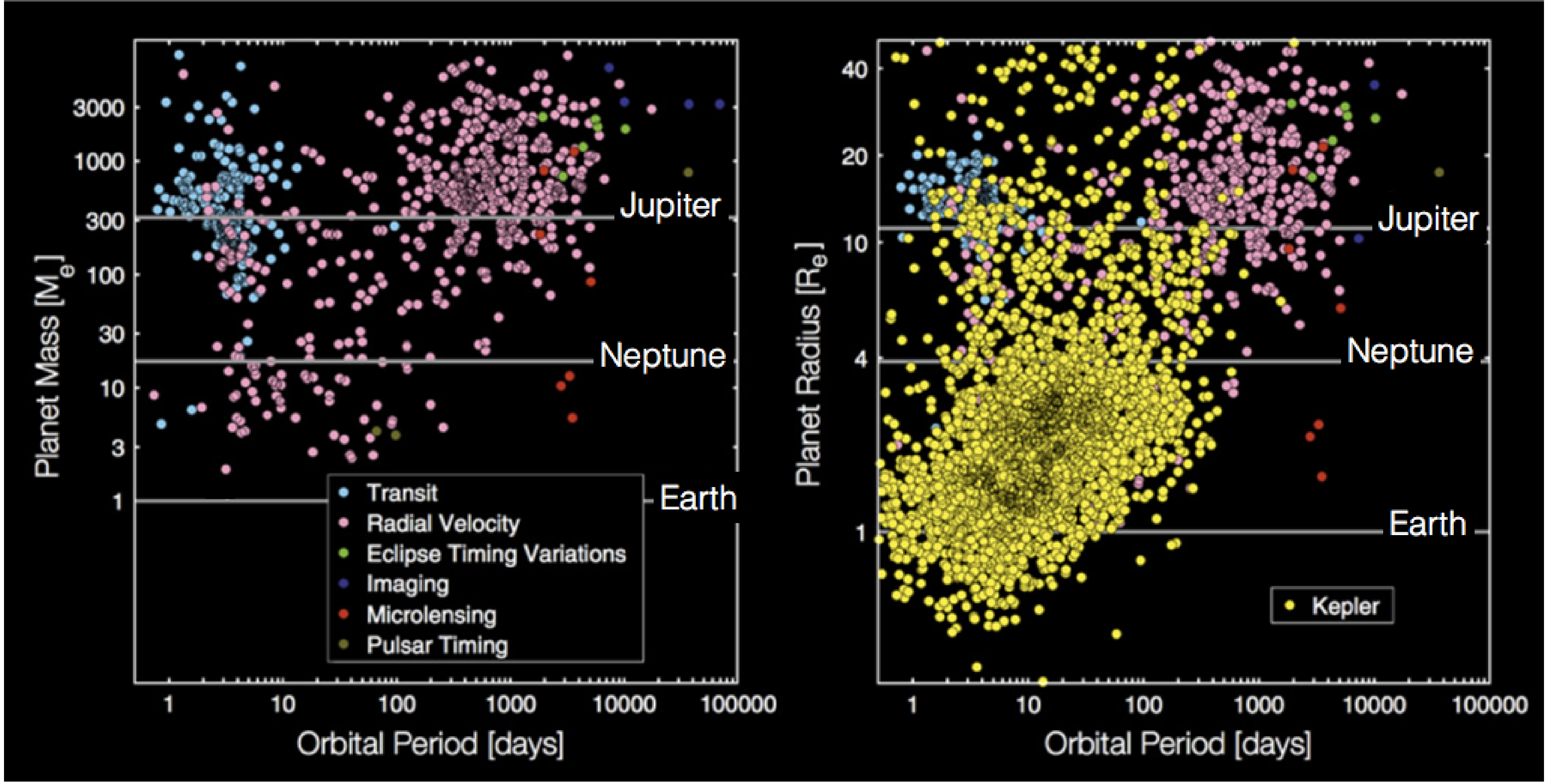
TRAPPIST-1 b, c, d, e, f,


exoplanet.eu, 2017-09-03
Planet Mass (M_Earth)
1e+4
2e+0
1e+0
1e-2
2e-2
1e-1
2e-1
1e+0
2e+0
1e+1
2e+1
Orbital Period (years)

# Kepler and K2 transit detections

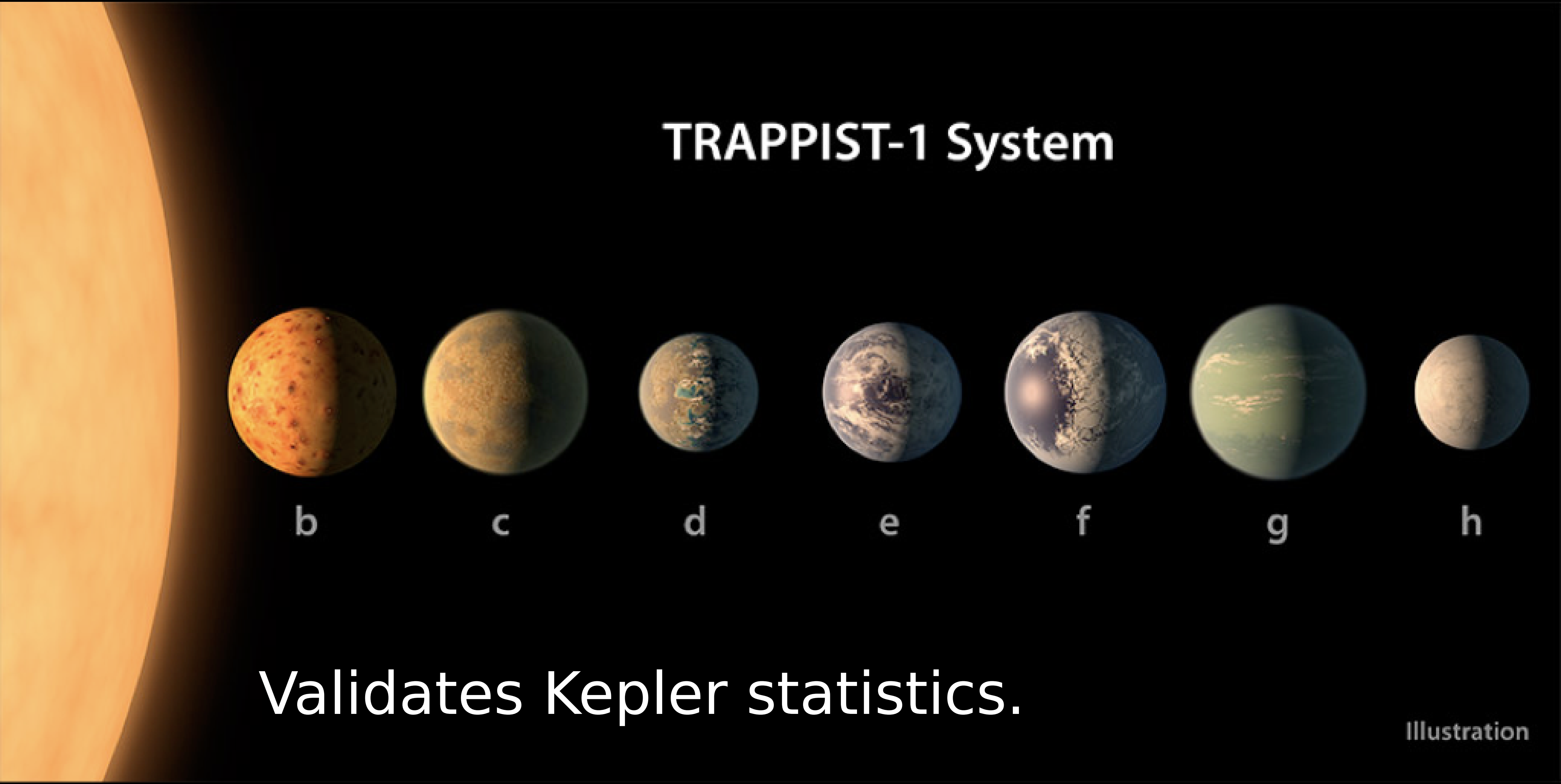




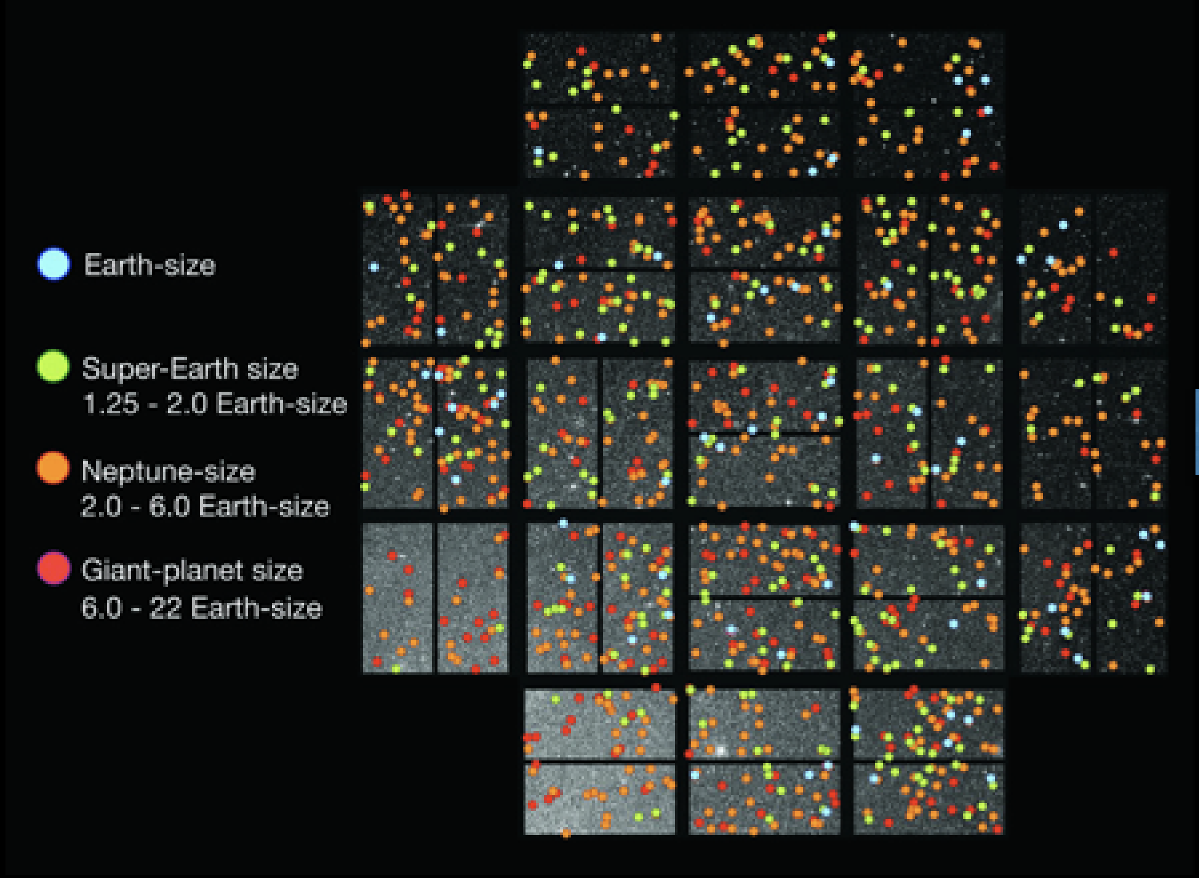


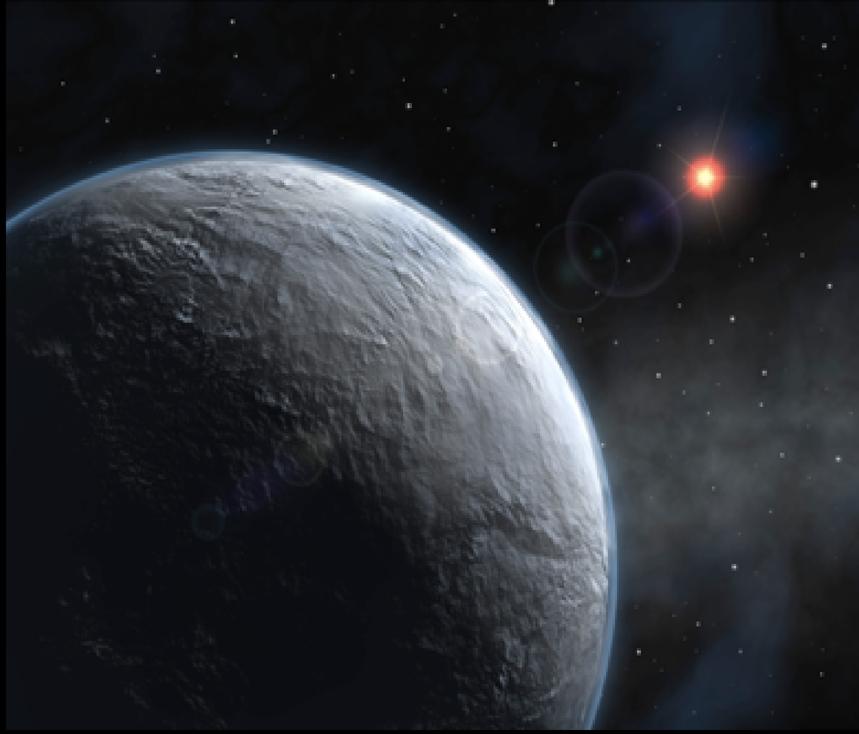

With higher RV precision, we are guaranteed of success.

Masses are critical for increasing value of transits




Validates Kepler statistics.



# Exoplanet masses.

- yield bulk densities of transiting planets
- interpret spectral features of exoplanet atmospheres
- Follow-up for JWST, TESS, WFIRST

# Transits yield radii – need masses to confirm and characterize planets

arXiv.org > astro-ph > arXiv:1708.08455

Search or Article

(Help | Advanced sea

Astrophysics > Solar and Stellar Astrophysics

## Three statistically validated K2 transiting warm Jupiter exoplanets confirmed as low-mass stars

Avi Shporer, George Zhou, Andrew Vanderburg, Benjamin J. Fulton, Howard Isaacson, Allyson Bieryla, Guillermo Torres, Timothy D. Morton, Joao Bento, Perry Berlind, Michael L. Calkins, Gilbert A. Esquerdo, Andrew W. Howard, David W. Latham

*(Submitted on 28 Aug 2017)*

We have identified three K2 transiting star-planet systems, K2-51 (EPIC 202900527), K2-67 (EPIC 206155547), and K2-76 (EPIC 206432863), as stellar binaries with low-mass stellar secondaries. The three systems were statistically validated as transiting planets, and through measuring their orbits by radial velocity monitoring we have derived the companion masses to be $0.1459^{+0.0029}_{-0.0032}$ $M_{Sun}$ (EPIC 202900527 B), $0.1612^{+0.0072}_{-0.0067}$ $M_{Sun}$ (EPIC 206155547 B), and $0.0942 \pm 0.0019$ $M_{Sun}$ (EPIC 206432863 B). Therefore they are not planets but small stars, part of the small sample of low-mass stars with measured radius and mass. The three systems are at an orbital period

# 2017: Most stars have planets

Have not found Earth analogs (rocky w/water)

Life may not be rare.

## Guaranteed of success if we reach high enough RV precision. What is stopping us?

1. Instrumental errors
2. radial velocities intrinsic to the stellar photospheres.

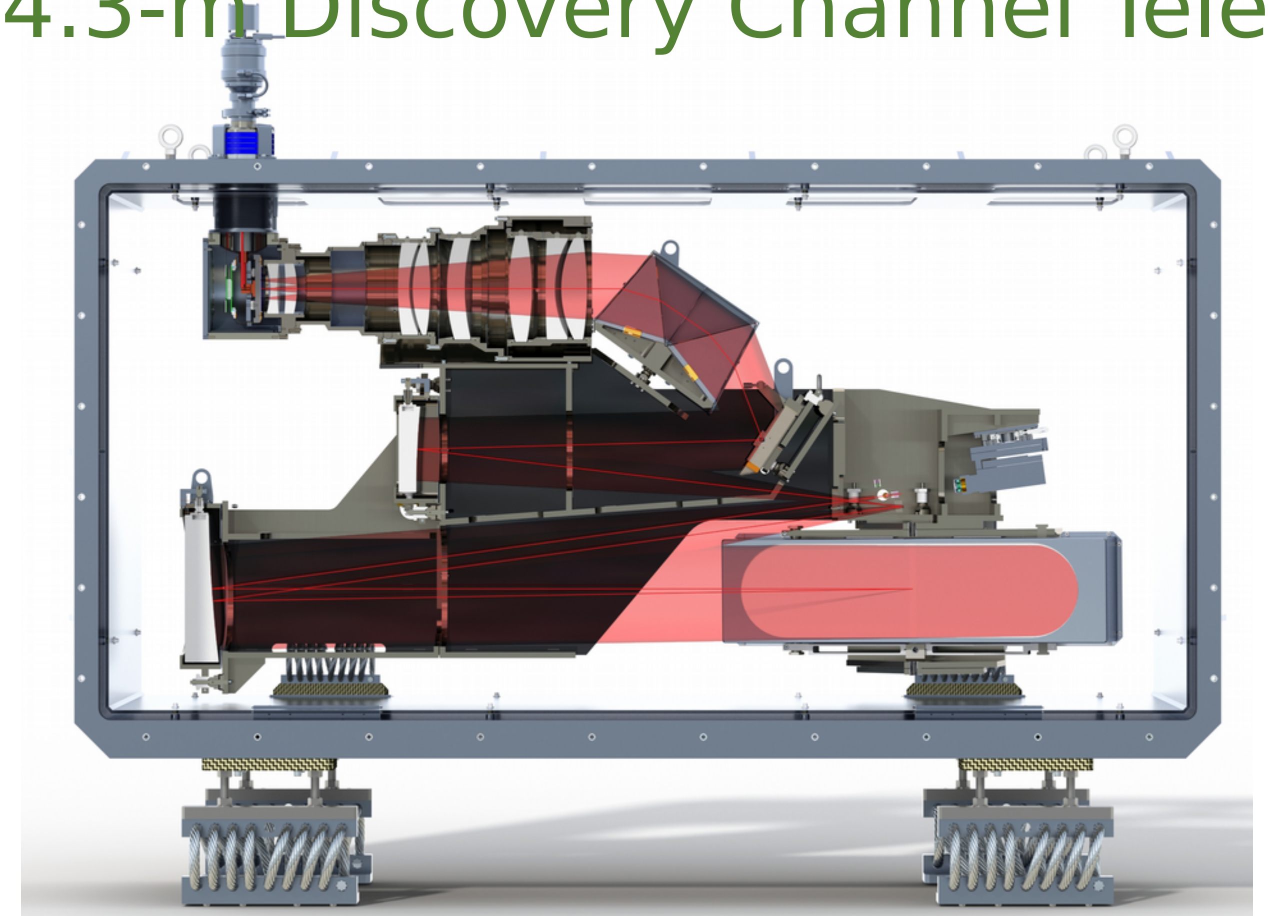
We have plans to push forward on both of these challenges.

# 1. Instrumental errors

*EXPRES*:

Extreme Precision Spectrograph: precision goal of < 20 cm/s

4.3-m Discovery Channel Telescope (Nov 2017)



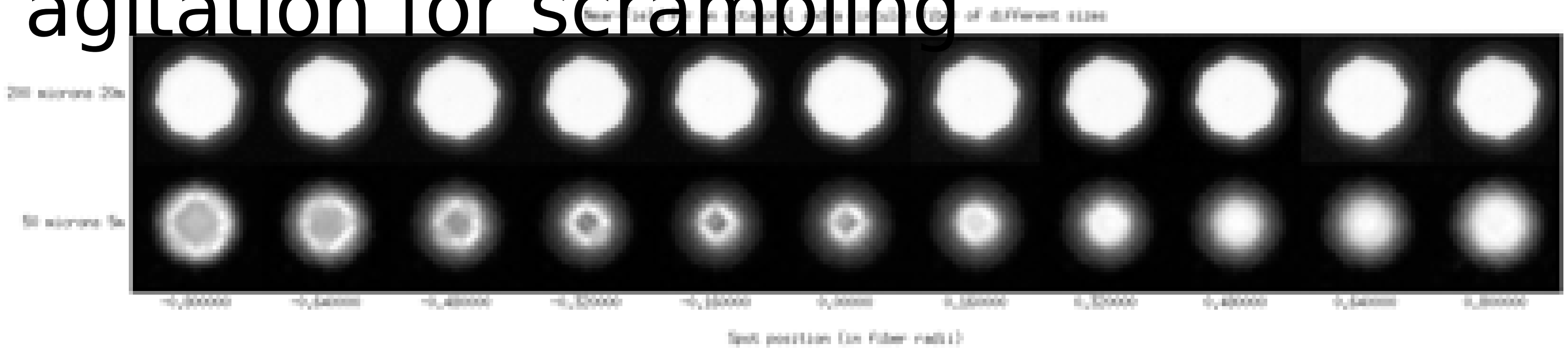
## 1. Instrumental errors

*Challenge*:

Extremely high fidelity spectra.

Solution: stable instrument, uniform illumination of the optics.

- vacuum enclosure with precise temperature control
- invar optical bench
- octagonal + rectangular fibers with pupil slicing and agitation for scrambling



## 1. Instrumental errors

*Challenge*:

Extremely high fidelity spectra.

Solution: unique optimization in camera design.

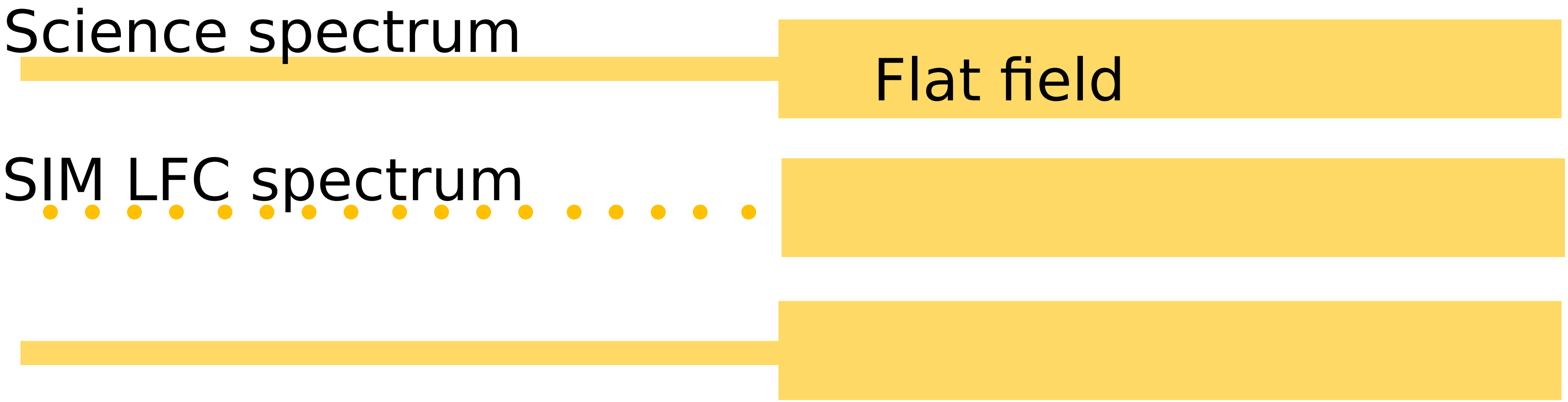
- camera design optimized to be insensitive to changes in pupil illumination
- camera design for a uniform and symmetric spectral line spread function
- focus control

*Challenge*:

Extremely high fidelity spectra.

Solution: excellent flat-fielding.

- 2-d flat fielding with a “wide flat”
- LED “flat” lamp with inverse spectral response calibration – uniform flat field



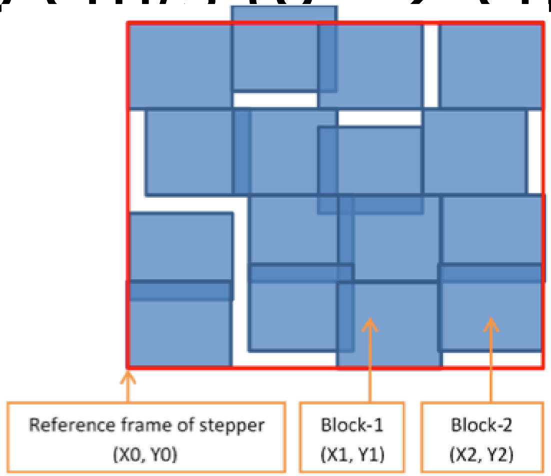
## 1. Instrumental errors

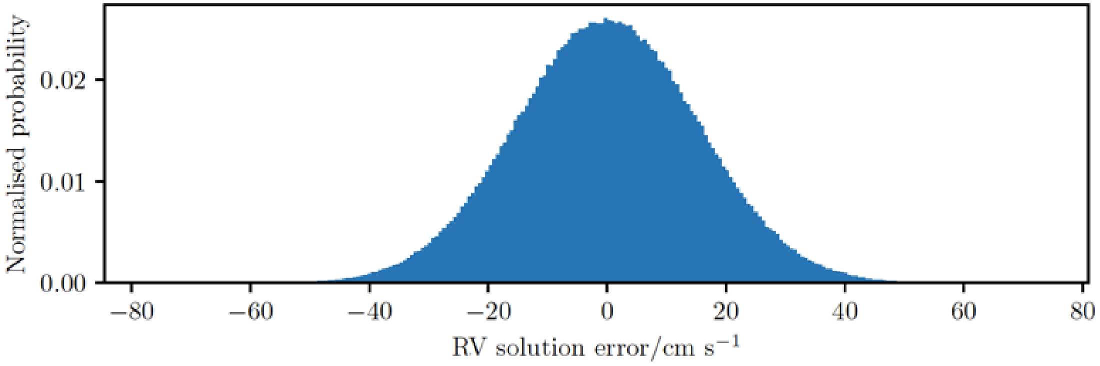
*Challenge*:

Extremely high fidelity spectra.

Solution: well-calibrated detector.

- Menlo laser frequency comb
- CCD with no stitching errors, higher transfer efficiency
- Interferometric scanning of the detector at JPL yields pixel position errors to 0.001 pixel width, decrease errors from ~50 cm/s to ~2 cm/s.



## 1. Instrumental errors

*Challenge*:
Extremely high fidelity spectra.
Solution: improved barycentric corrections.

- wavelength-weighted flux corrections for subtracting the velocity of the Earth

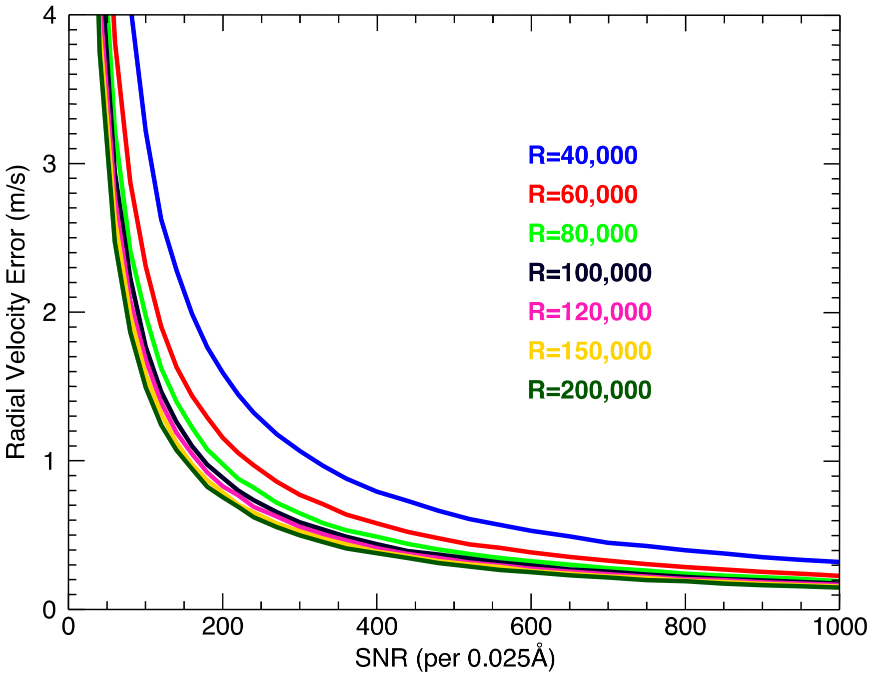
## 1. Instrumental errors

# *Challenge*:

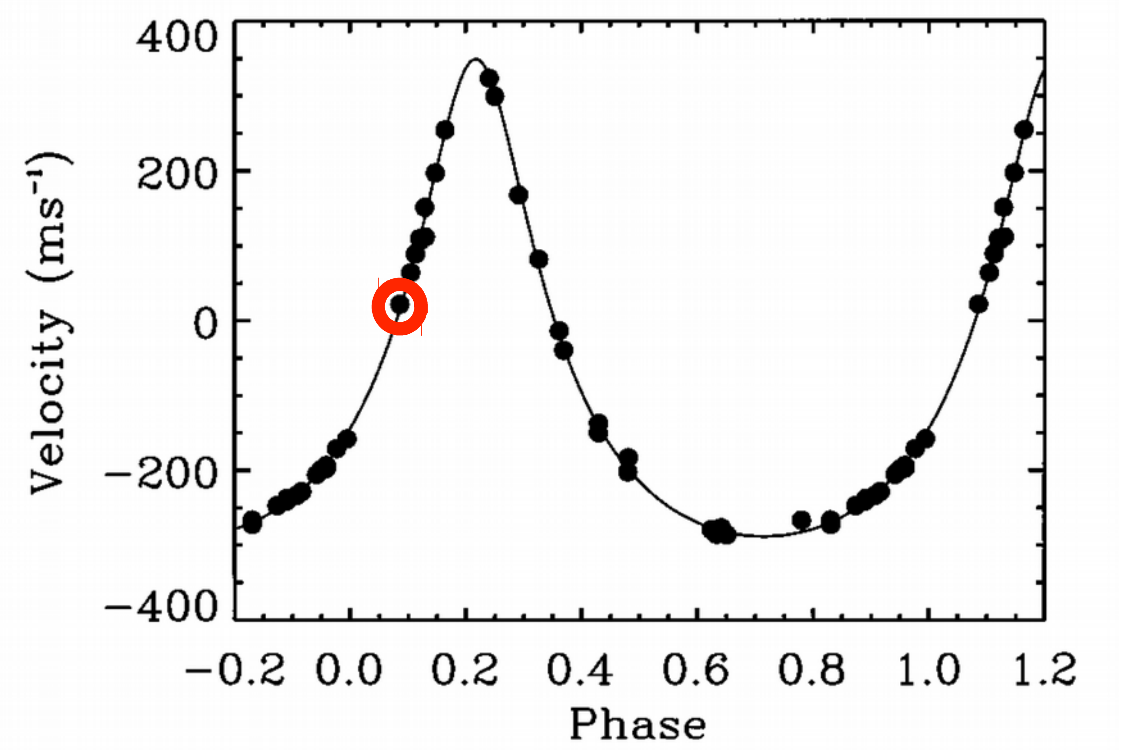
Extremely high fidelity spectra.

Solution: higher resolution, flexible scheduling.

- R=150,000
- deployable tertiary permits nightly cadence on the 4.3-m DCT and strategic scheduling of observations



2. Photospheric noise

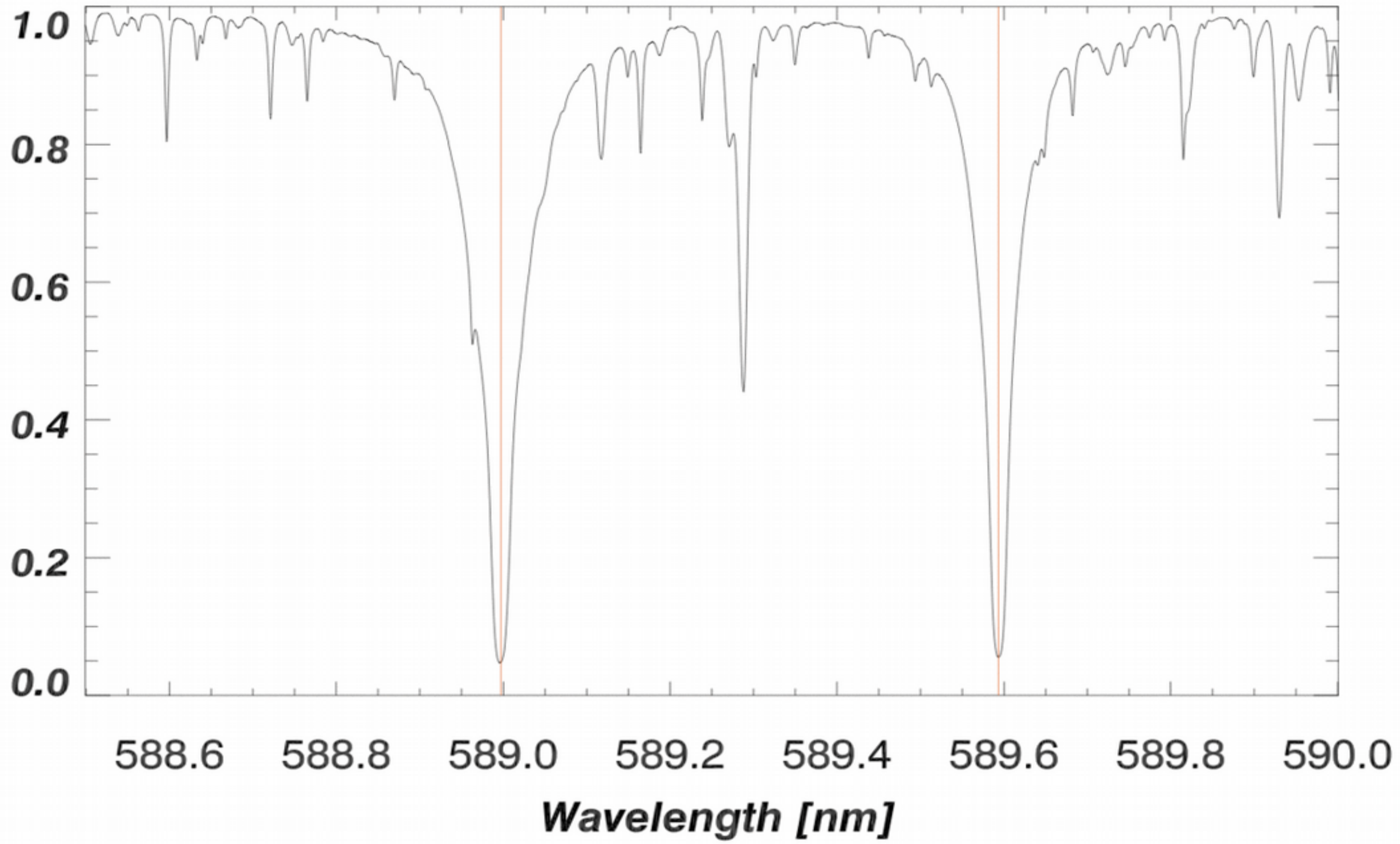



This is a set of radial velocities over time, phase-folded at the orbital period of a planet.

What goes into the analysis of each of these data points?

## 2. Photospheric noise

With each spectrum, we measure $\frac{\delta\lambda}{\lambda} = \frac{v}{c}$
(i.e. we get one velocity point)

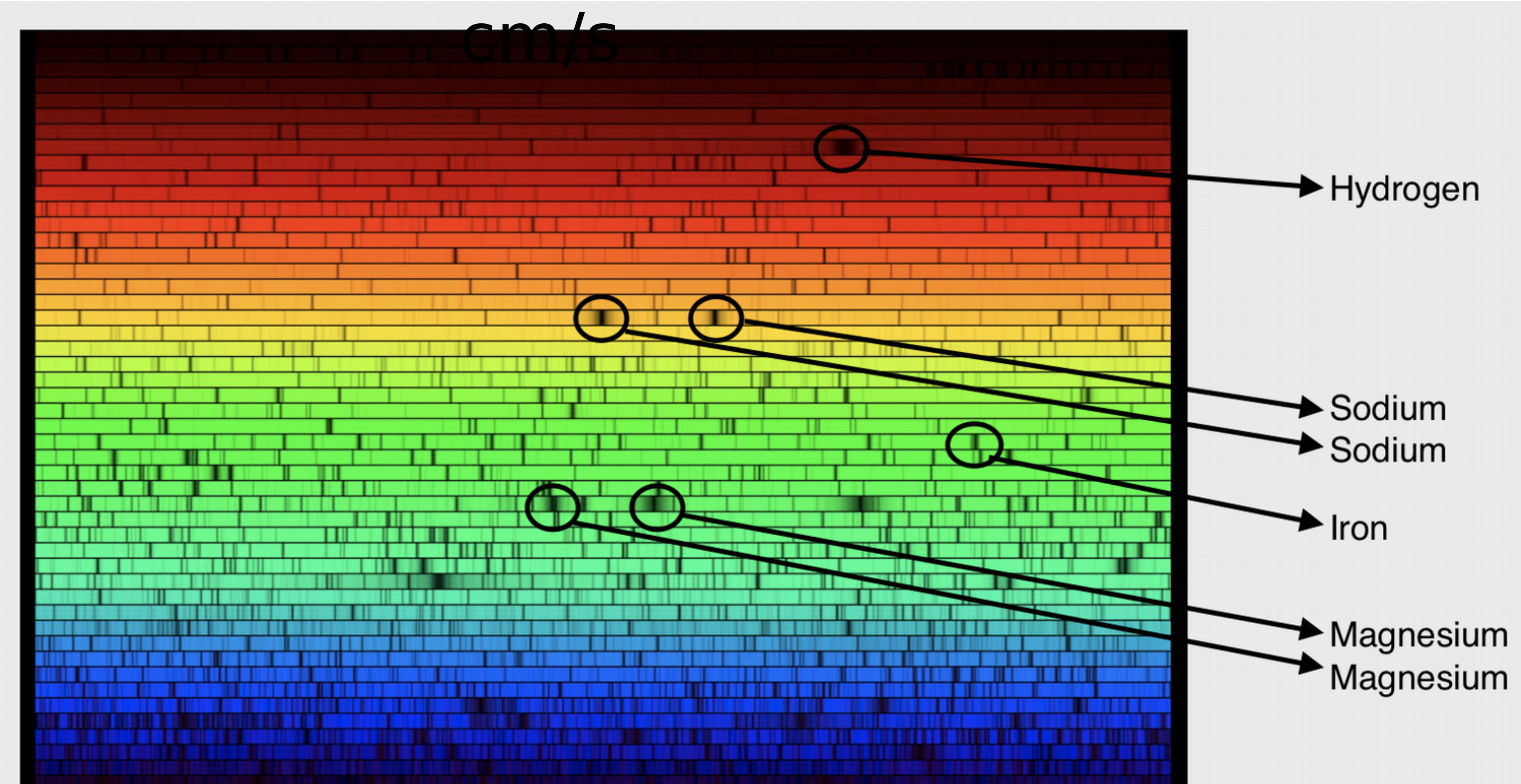


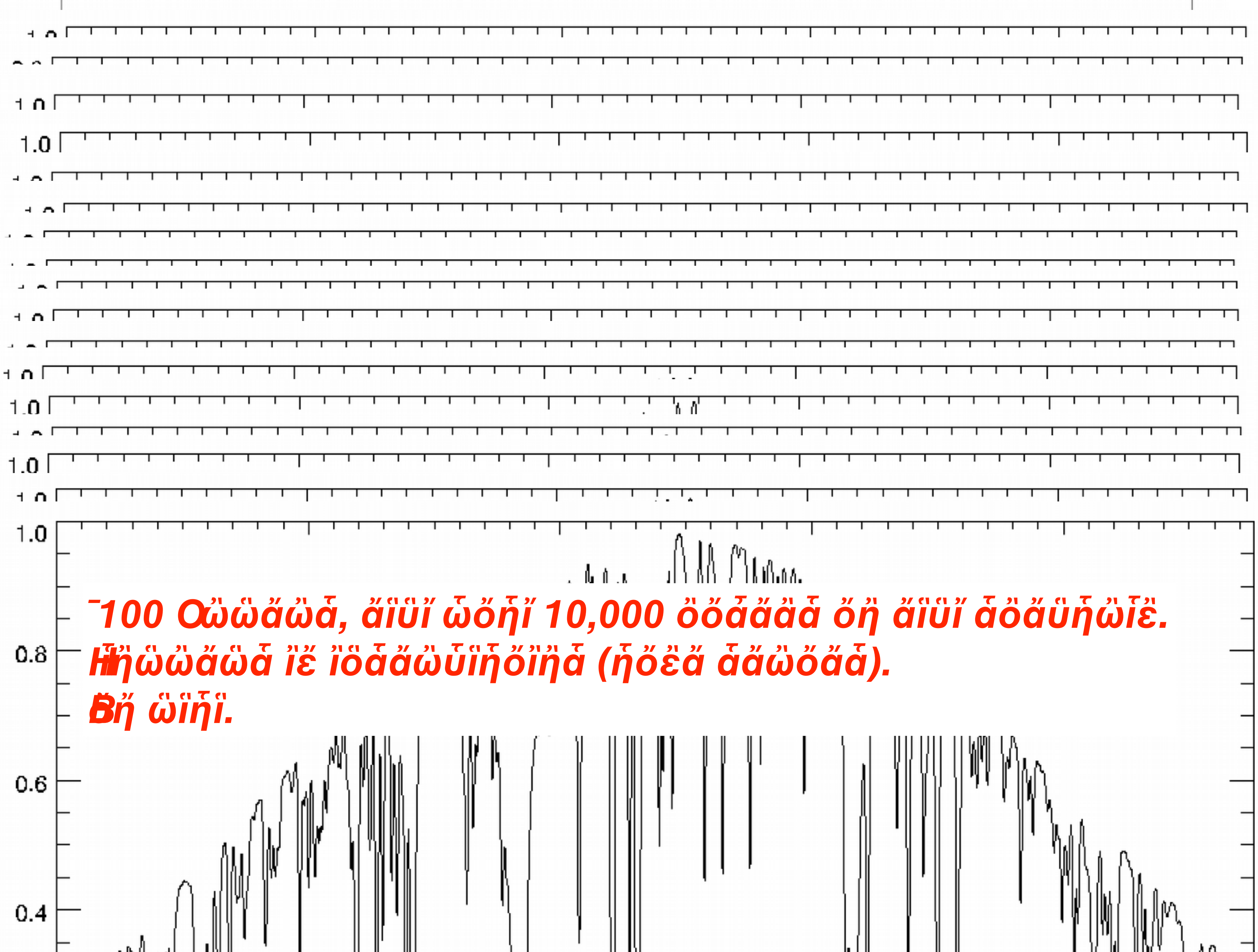
2. Photospheric noise

Use thousands of lines to measure 1/1000th pixel shifts, corresponding to 1 m/s.

Jupiter: 12 years and 12 m/s

Earth / Venus: ~1 year and 10 cm/s




1.0
0.8
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~100 Oὤὤἄὤἀ, ἄΐΰΐ ὤὄἢΐ 10,000 ὀὄἄἄἄἀ ὄἢ ἄΐΰΐ ἀὀἄΰἢὢΐἒ.
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## 2. Photospheric noise

### "Floor of the Doppler precision set by stellar noise."

*Bḯȁǎὢ ǎή ΐȁ. 1996*

"Ultimately the limit to velocity precision is set by the stars themselves. On long time scales stellar magnetic cycles, analogous to the solar cycle, could insidiously cause an apparent periodic change in radial velocity (Jimenez et al. 1986; Deming et al. 1987)."

The floor of the RV precision was:

3 m/s in 1996 (Lick / Keck)

1 m/s in 2005 (HARPS)

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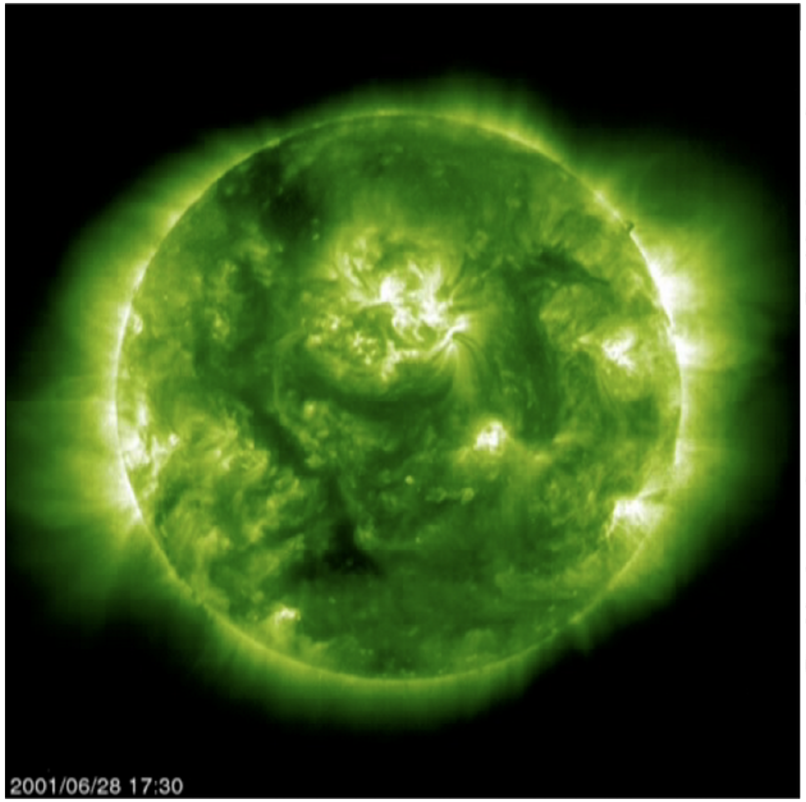
## 2. Photospheric noise

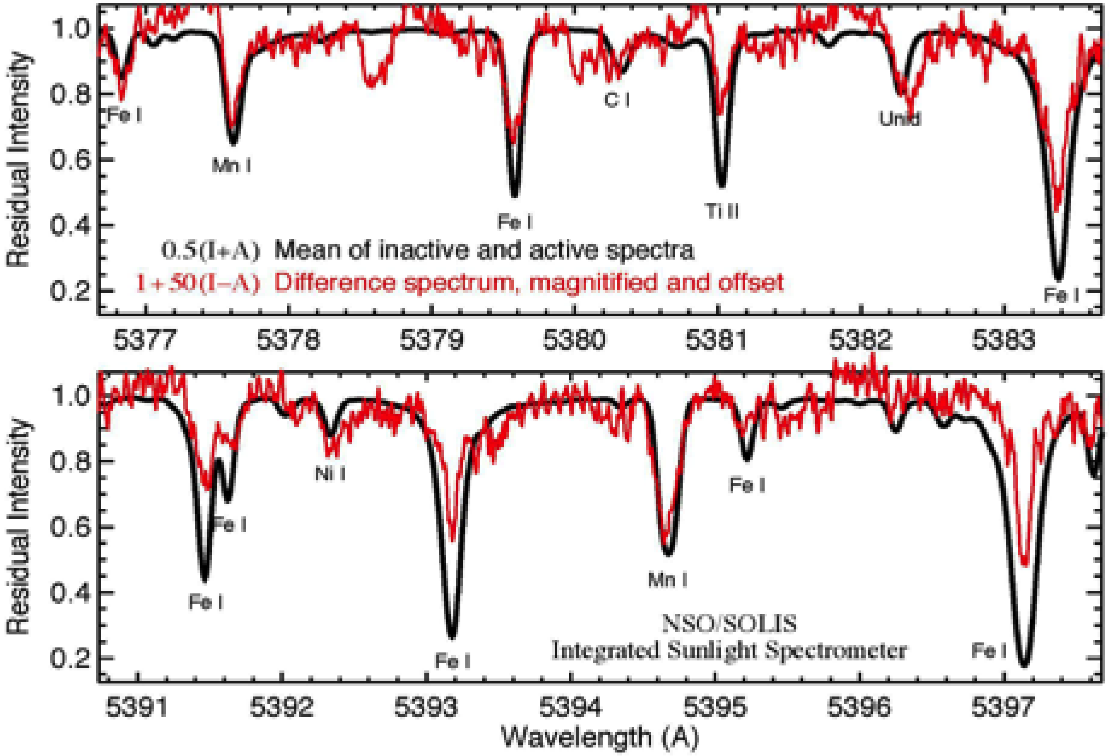
Stellar "jitter" includes Doppler velocities from:

- pulsation
- spots
- faculae
- meridional flows
- time-varying granulation

Spots are complicated - a family of spots, not single spots.
Not clear that we will ever be able to these model spectral features from first physical principles.

## 2. Photospheric noise




Any instrument that does not disentangle the photospheric velocities is doomed to 1-2 m/s rms precision at best

2. Photospheric noise

## HOWEVER, stellar jitter has two important properties:

- it is not a persistent Keplerian signal – it waxes and wanes and it varies on timescales that are different from orbital velocities

- the underlying physical phenomena that spawn jitter have line-by-line spectroscopic signatures that should be distinguishable from orbital Doppler shifts.

# 2. Photospheric noise

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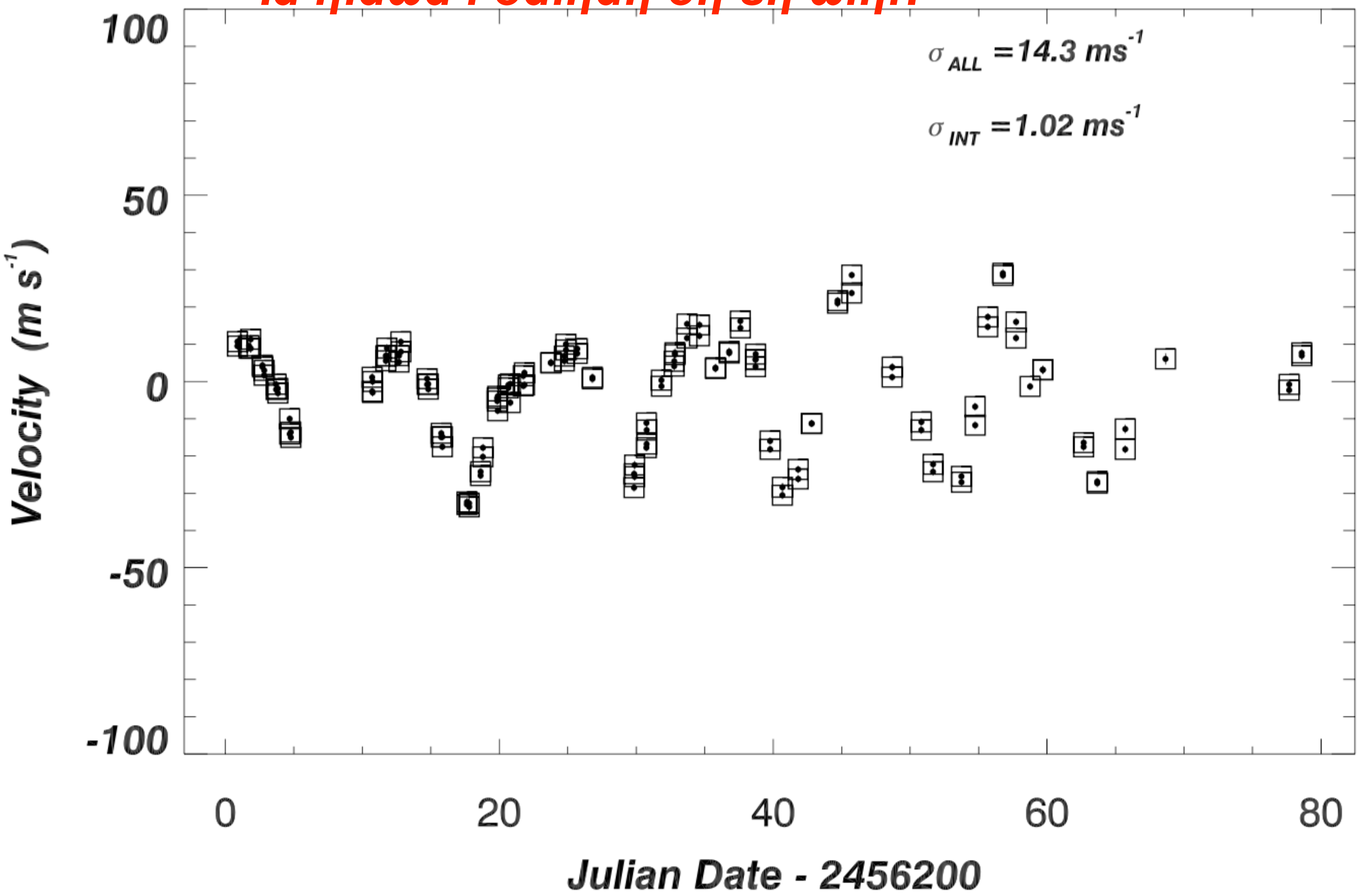


Epsilon Eridani RV Data from CHIRON at CTIO - Fischer

# 2. Photospheric noise

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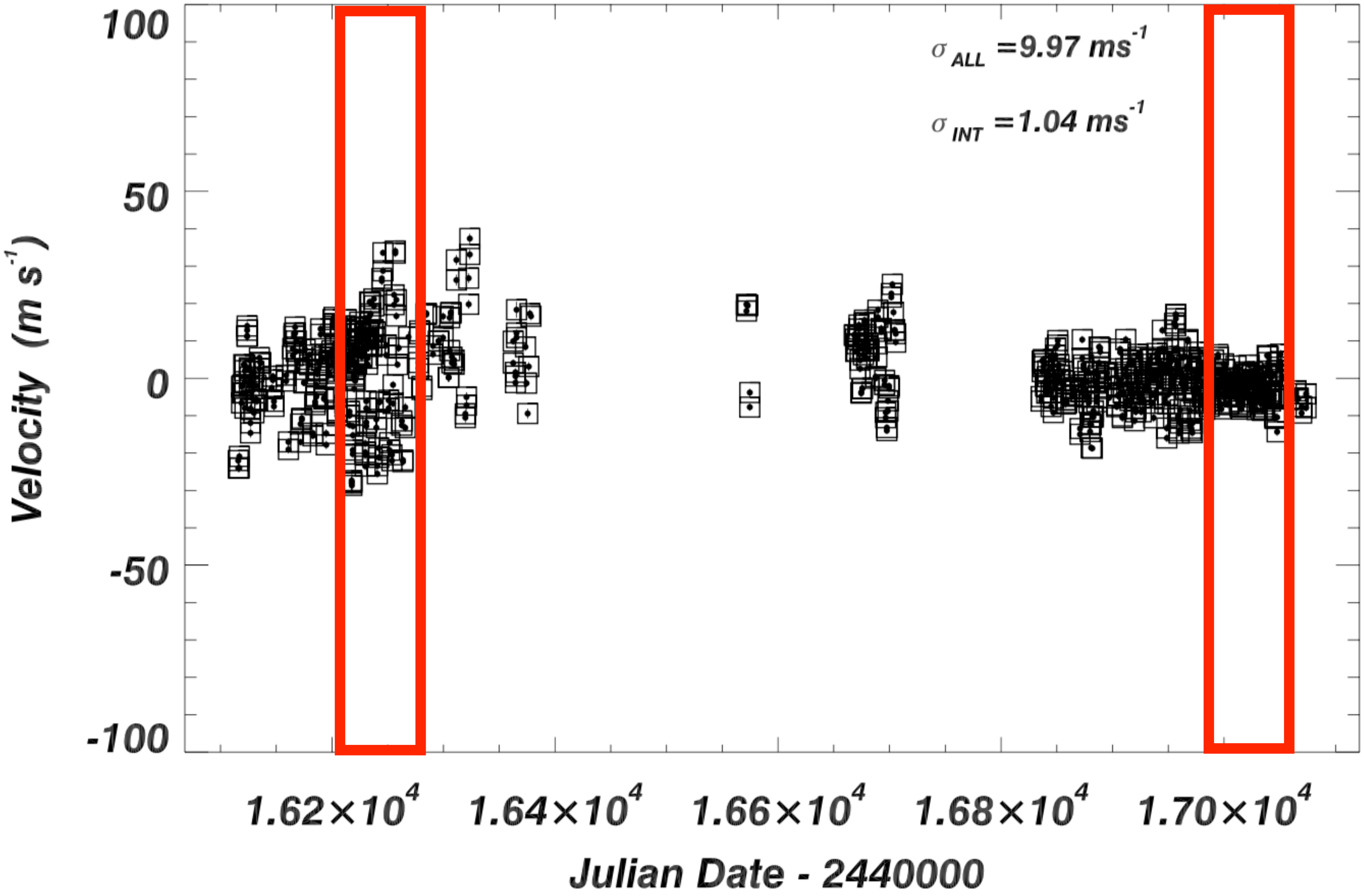


Epsilon Eridani RV Data from CHIRON at CTIO - Fischer

# 2. Photospheric noise

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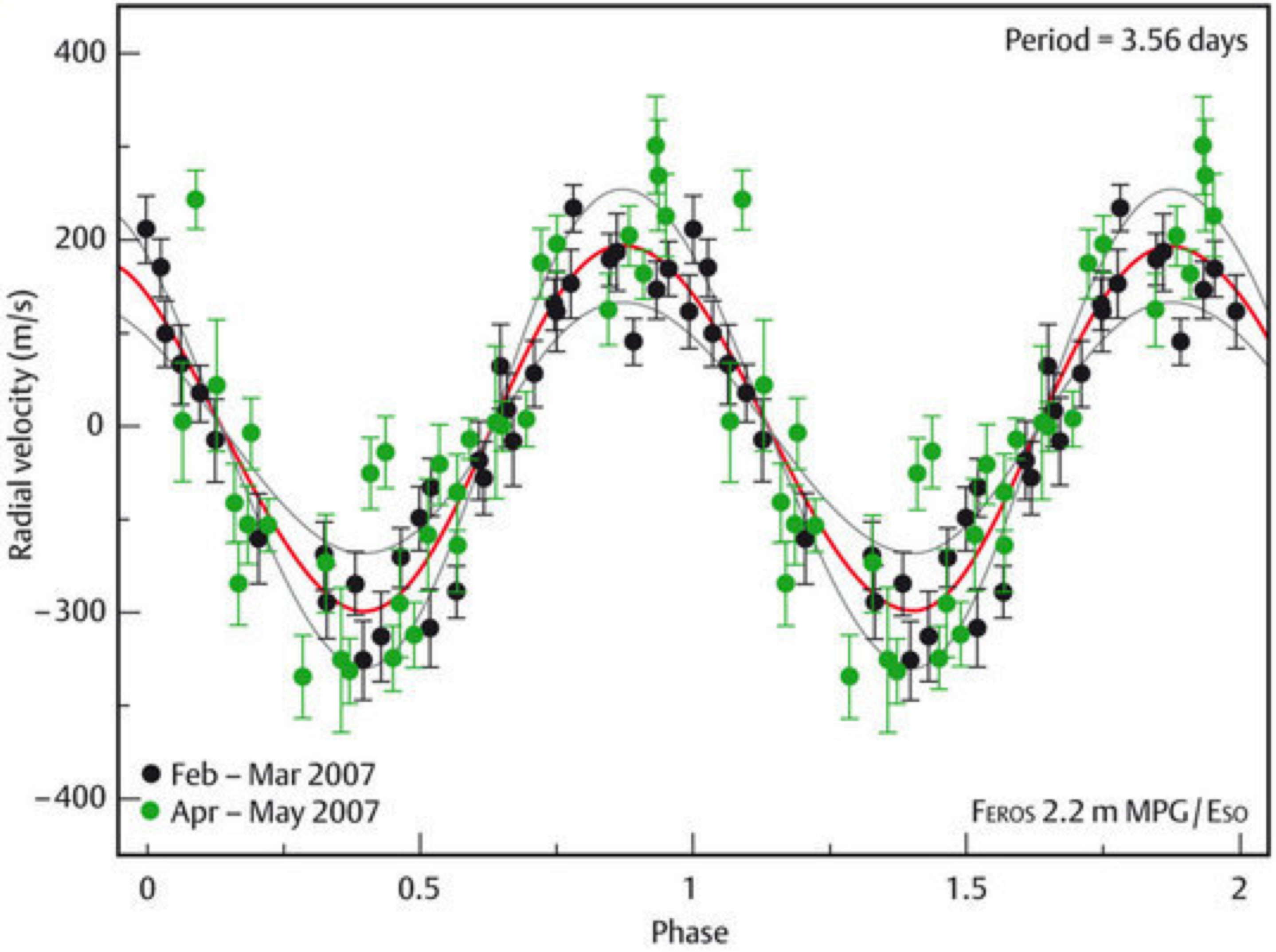


Optical high-res spectra; two epochs; no line bisector variation

Setiawan et al. 2007, Nature

# 2. Photospheric noise

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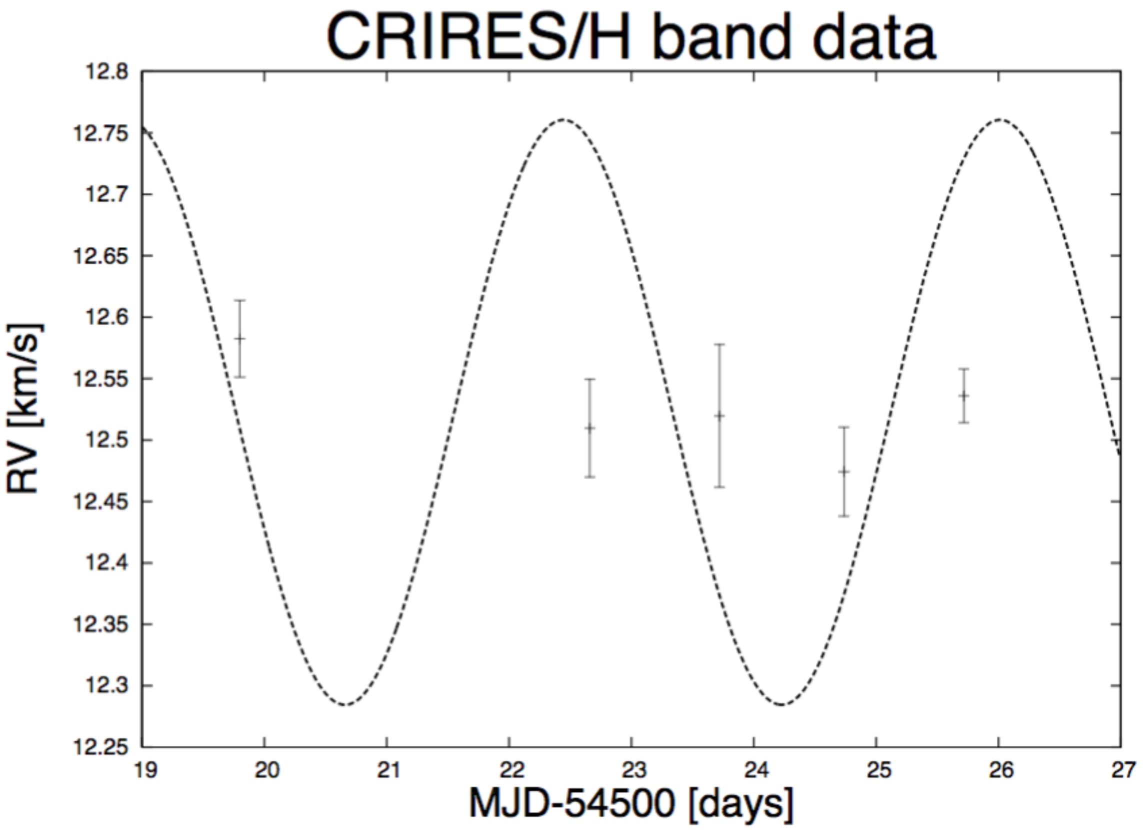



CRIRES/H-band RVs overplotted on the Setiawan et al.
theoretical fit for TW Hyrdrae

Huélamo et al. 2008

## 2. Photospheric noise

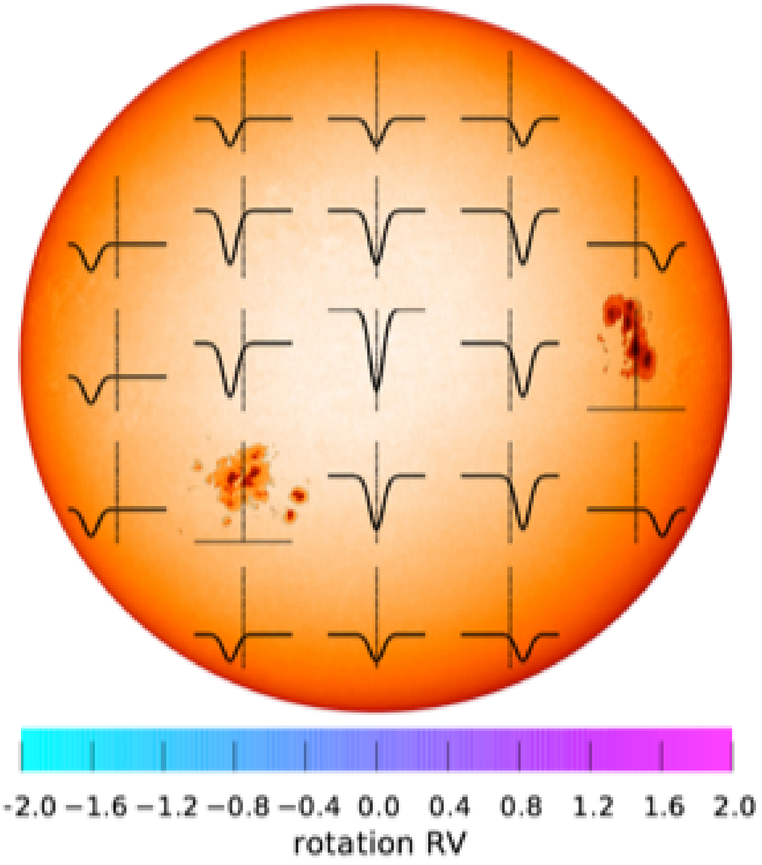
We derive a velocity measurement from a spectrum.

Line bisectors? FWHM of the CCF? Correlation with H-alpha or Ca II H&K? Photometric monitoring? Gaussian processes?

All of these approaches operate on a single number: the radial velocity measurement. They can only be approximately correct.

2. Photospheric noise

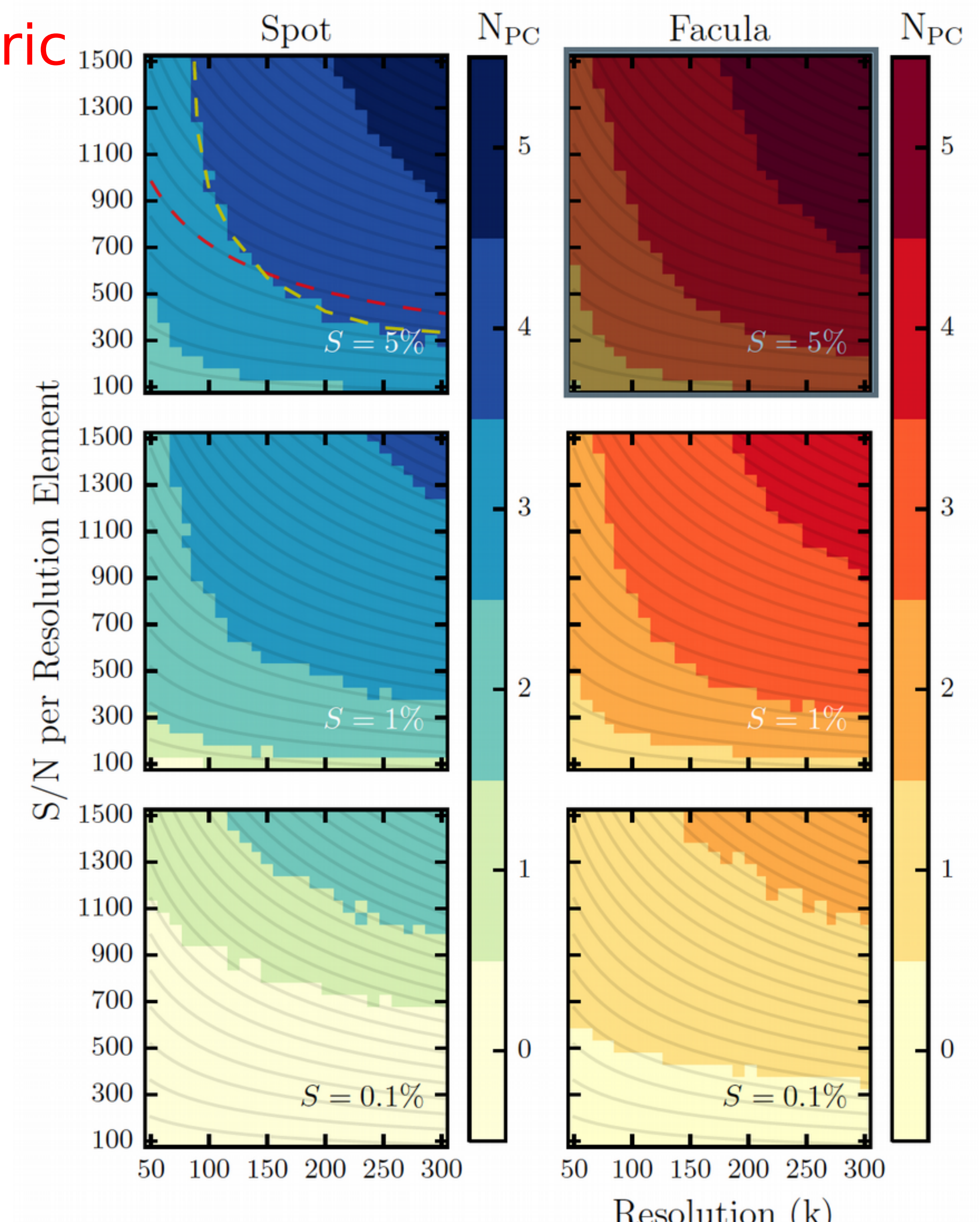
Simulations…..




Simulated spectra (SOAP 2.0) Xavier Dumusque generates time series spectra with spots, faculae, and planets.

R ~ 500,000 and SNR ~1000

2. Photospheric noise




PCA analysis demonstrates that spots, faculae are imprinted differently than Keplerian Doppler shifts and we can see this at the pixel-level in our spectra.

Resolution and S/N critical for disentangling stellar

Davis et al 2017

# 2. Photospheric noise

Work to date with PCA has explored the **information content** of simulated spectra. Now, we need techniques that will allow us to model out stellar jitter.

(a) Original image (b) Back projection (c) Proposed sparse reconstruction

SORCERESS: Replicate EXPRES
($1.6M cost savings and build it in half the time)
Roll forward all software from EXPRES: data reduction to provide users with raw data, reduced and wavelength calibrated data, and velocities (ala HARPS).

Cost:
FEM
$450,000
Spectrograph:
$3,945,000
Site development
$250,000
IR arm (optional upgrade)

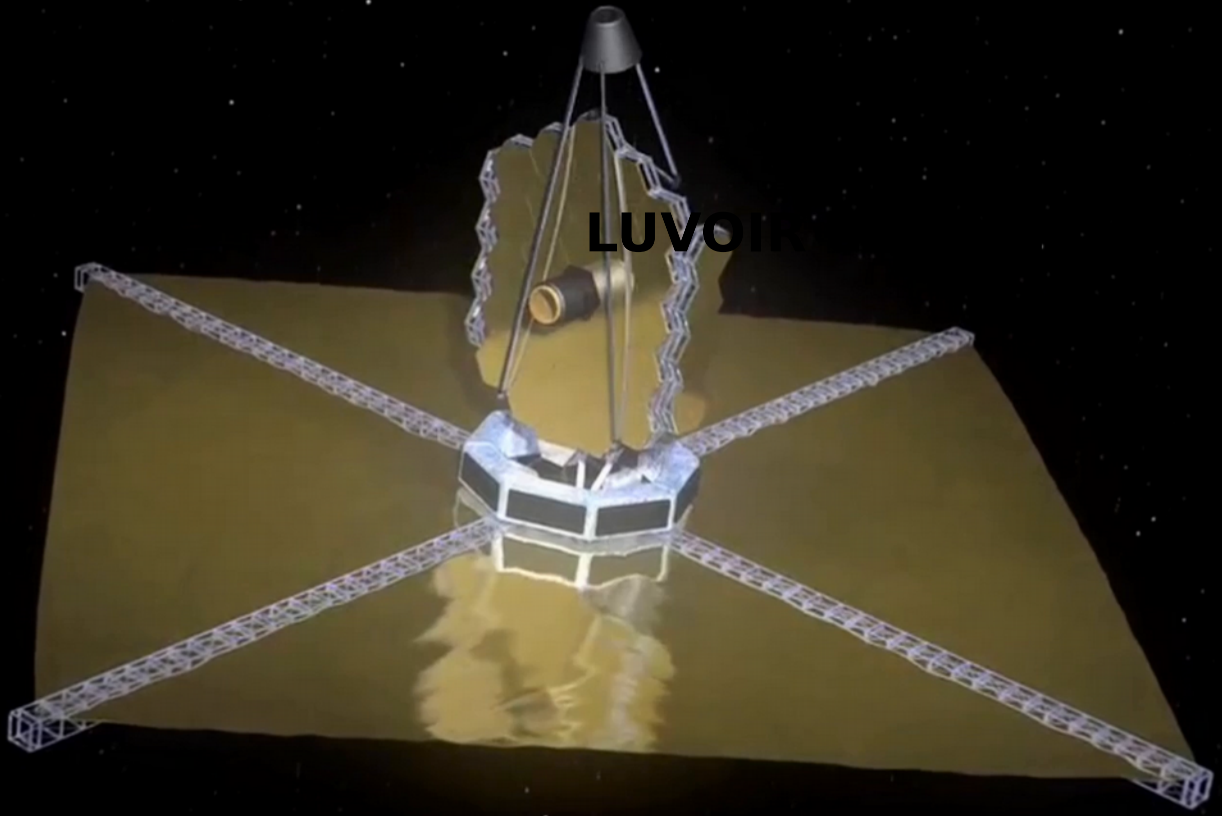
Timeline: 18 months
If funding can be secured in 2018, then the instrument commissioning occurs in 2020.

## Science drivers:

- ExoEarths at HZ distances
- Killer app: alpha Cen AB (Starshot Breakthrough), though ESPRESSO may get there too (we all need to wait until ~2019 for projected separation to increase)
- Masses for transiting planets
- Masses for Gaia planets
- Spectral analysis that requires extraordinary fidelity and resolution (isotopes? Zeeman splitting? Lithium?)

# 2030’s: LUVOIR

## Large UV and OIR survey telescope



Look again at that dot. That’s here. That’s home. That’s us.
On it everyone you love, everyone you know, everyone
you ever heard of, every human being who ever was…
every king and peasant, every young couple in love, every
mother and father, hopeful child, inventor and explorer…
every saint and every sinner  in the history of our species
lived there – on a mote of dust, suspended in a sunbeam.

CARL SAGAN