Radial Velocities for Exoplanet Discovery and Characterization

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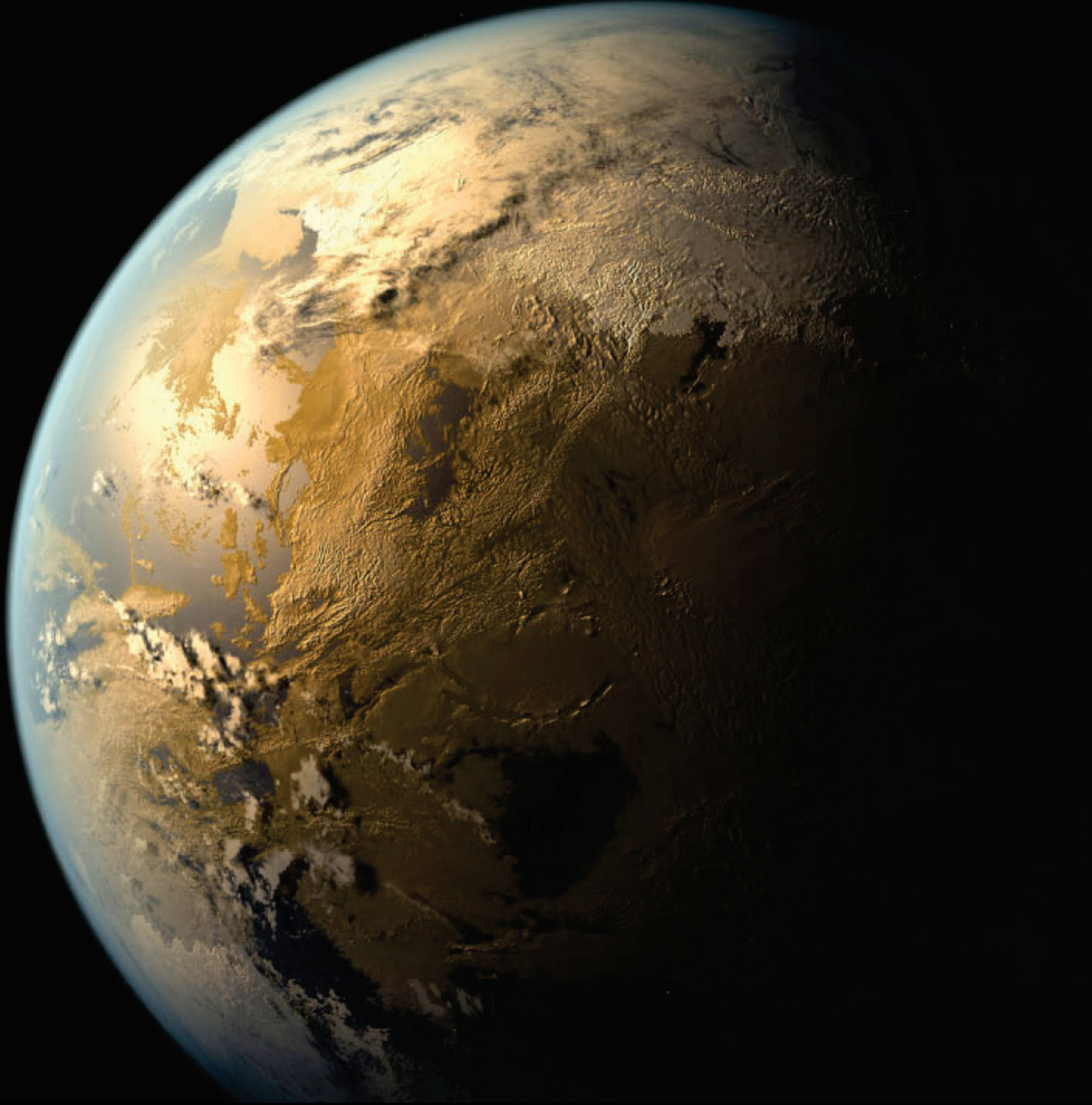
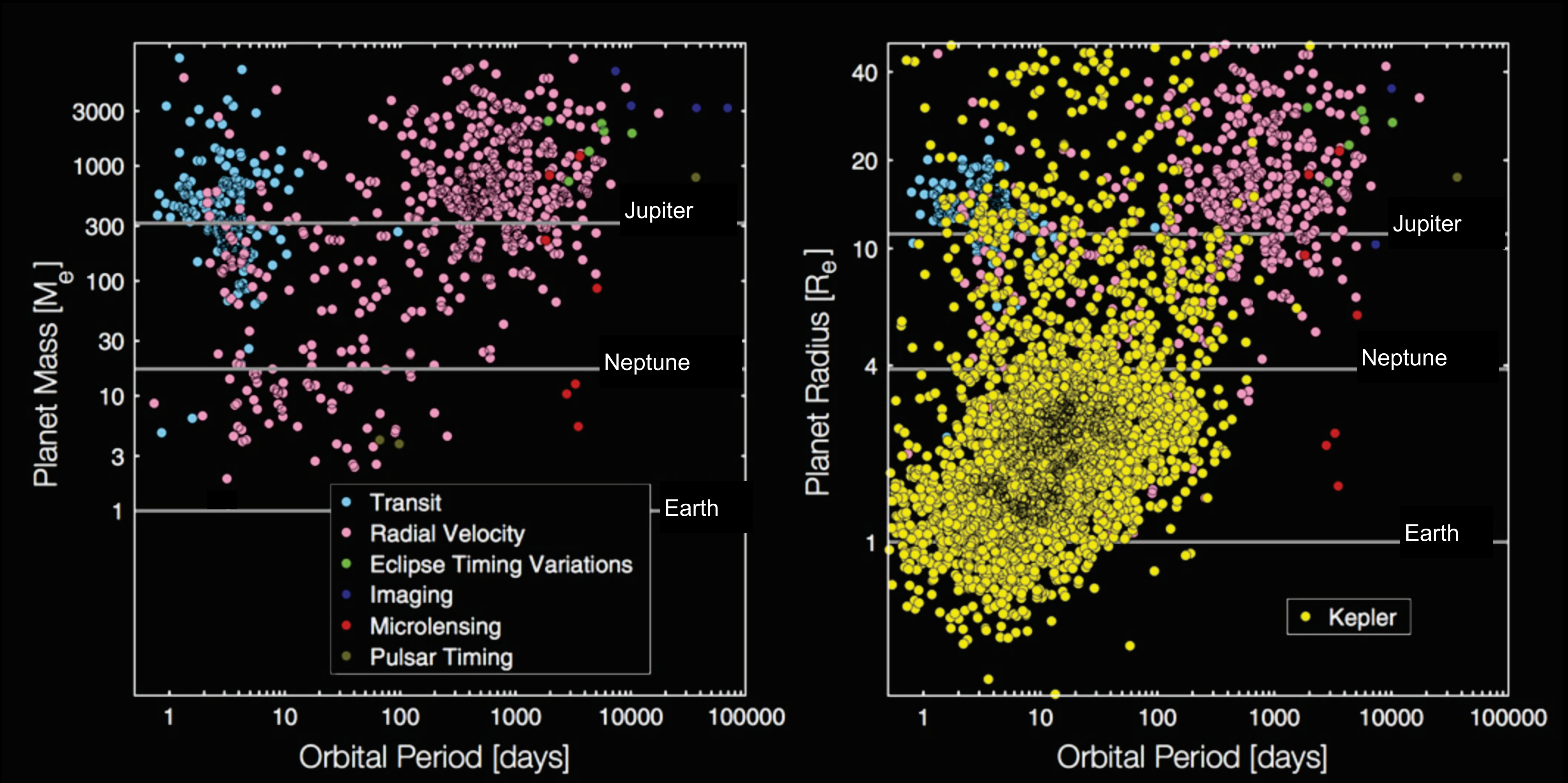




We should think about the difference b/t the left and right plots.

Kepler tells us: Most stars have planetary systems and the small planets are the most common.

The transit probability is low – 1/1000 – need EPRVs or precision astrometry to find them.

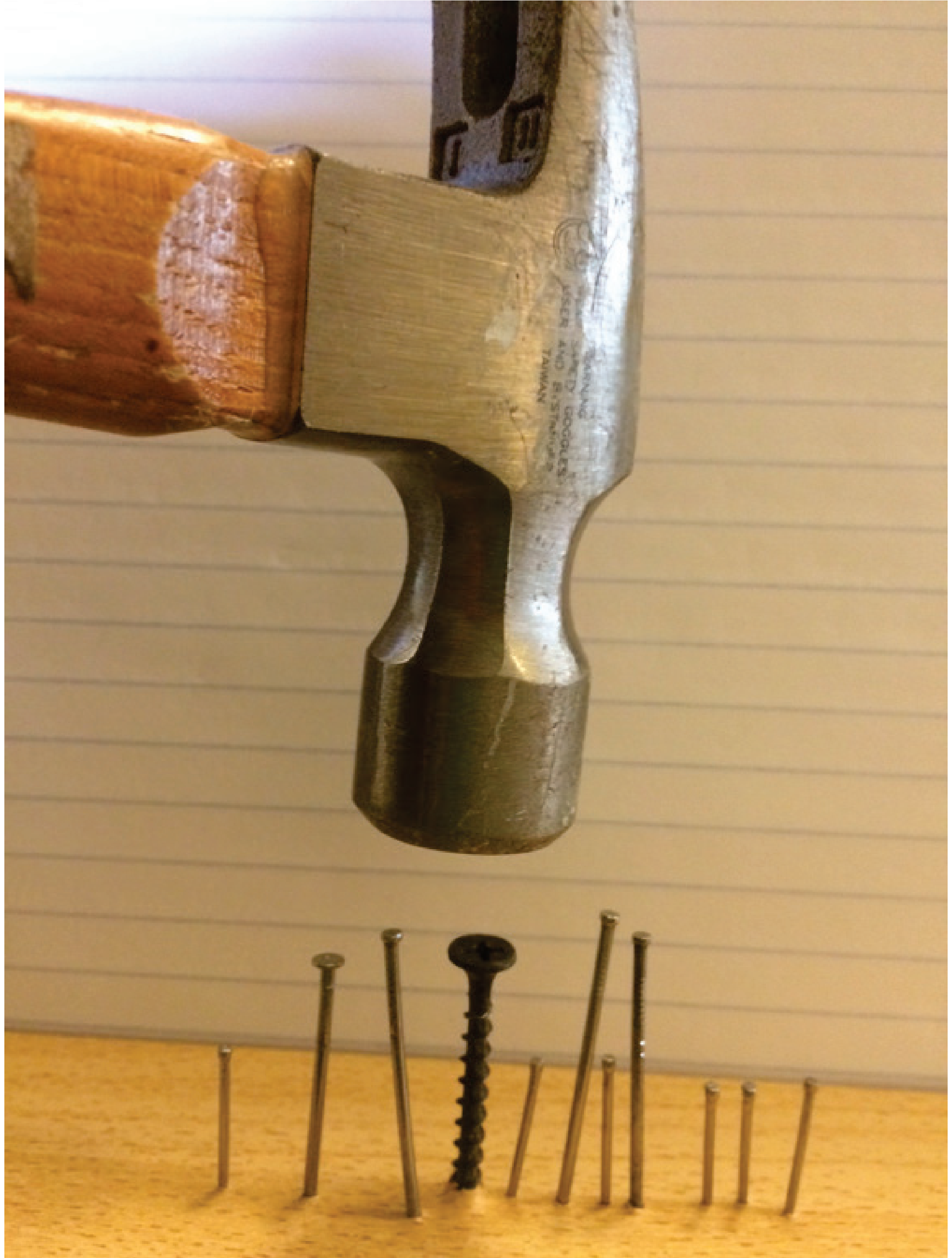
Even with transiting planets, we need mass measurements to know if they are like Earth!

There must be swarms of low mass planets orbiting all of the nearby stars – we've missed them!

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

1. Stellar photospheres
2. Instrumental errors (detectors)
3. cadence, cadence, cadence.
4. telluric contamination

Most profound mistake that people keep making with exoplanet detection: there are 100 things that can go wrong and if we only get 99 of them right, it may not be good enough.

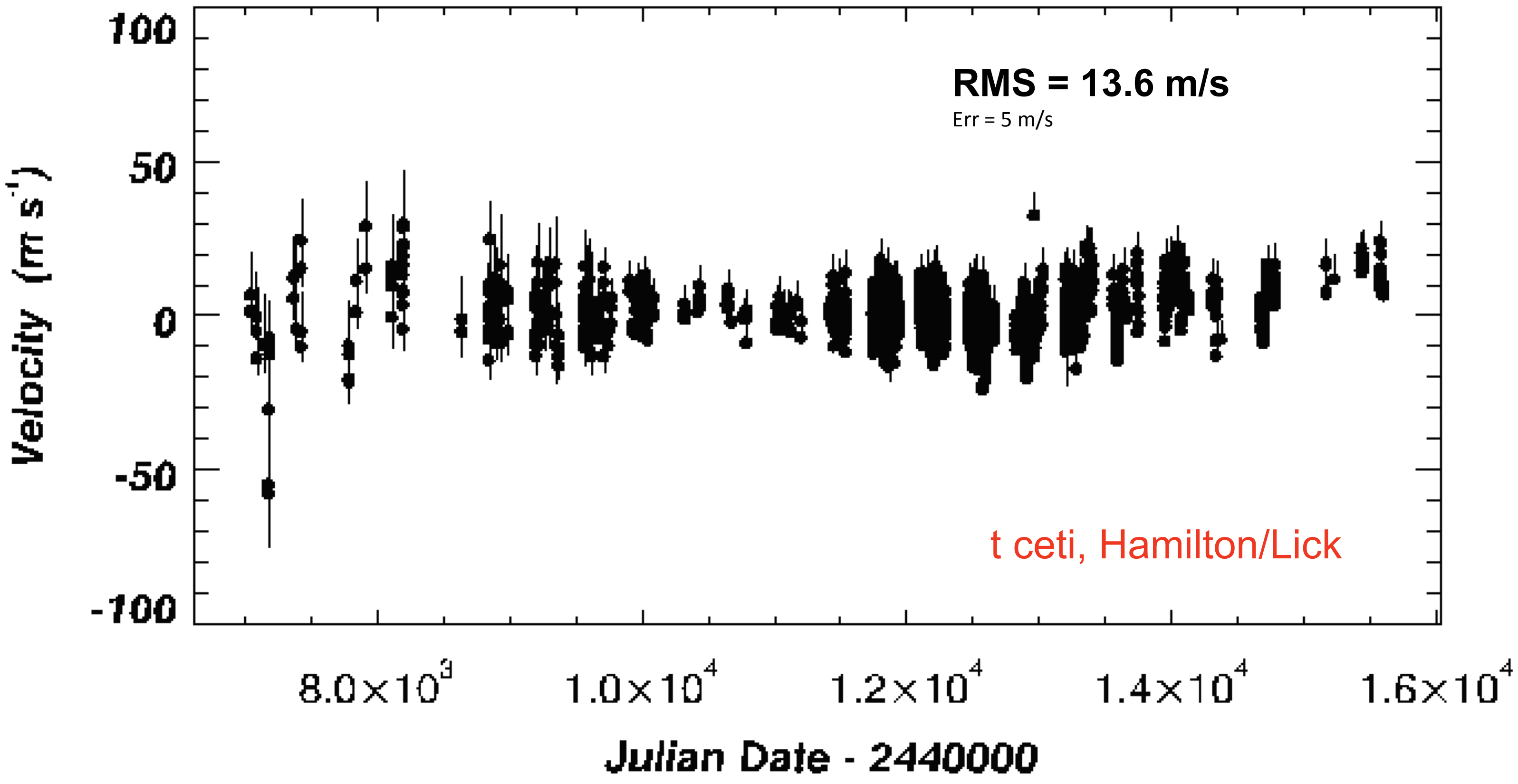


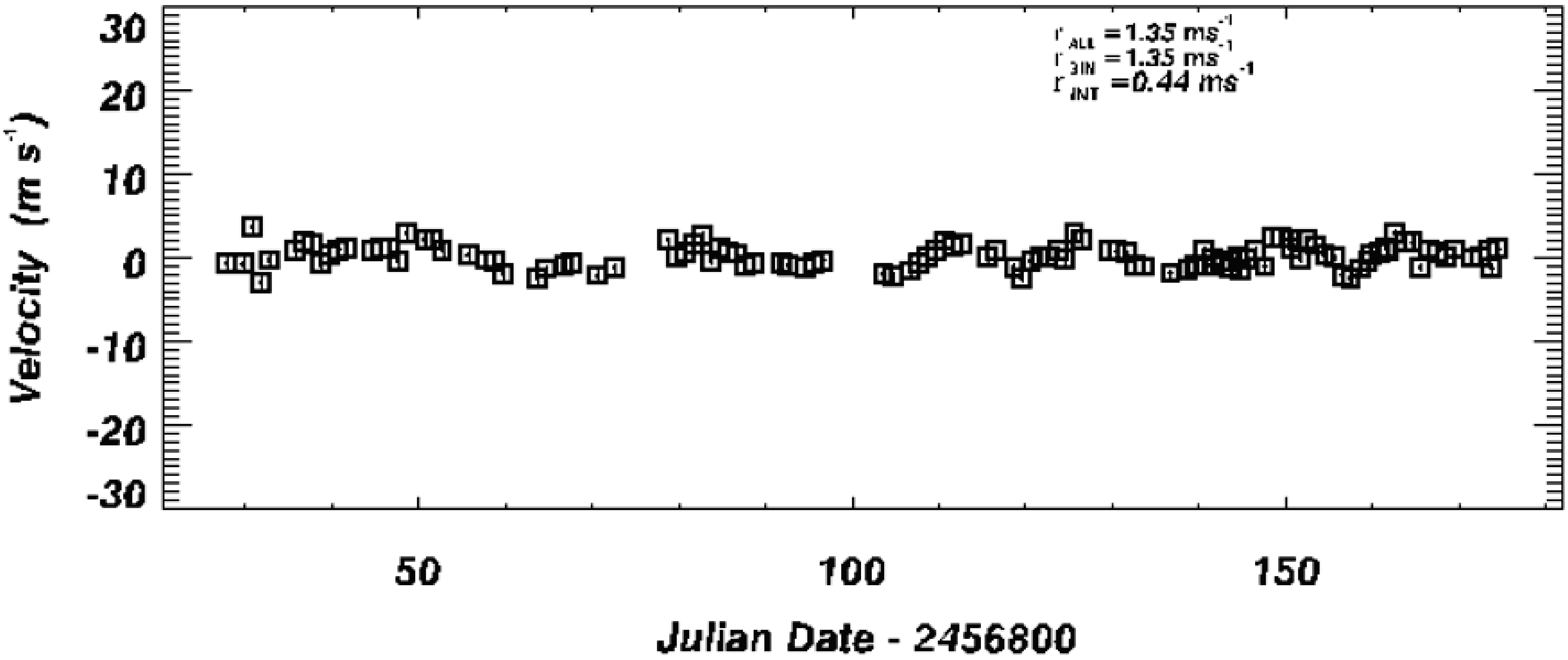
The problem going from 10 m/s to 1 m/s were the number of unanticipated, unidentified errors.

The problem going from 1 m/s to 10 cm/s is the number of unanticipated and uncharacterized errors.

It is probably true that the challenge in going below 10 cm/s (which we have not yet reached) will be the number of unanticipated terms in the error budget and we will need new tools to address them.

20 years with an (un)stabilized spectrometer 1989 - 2011

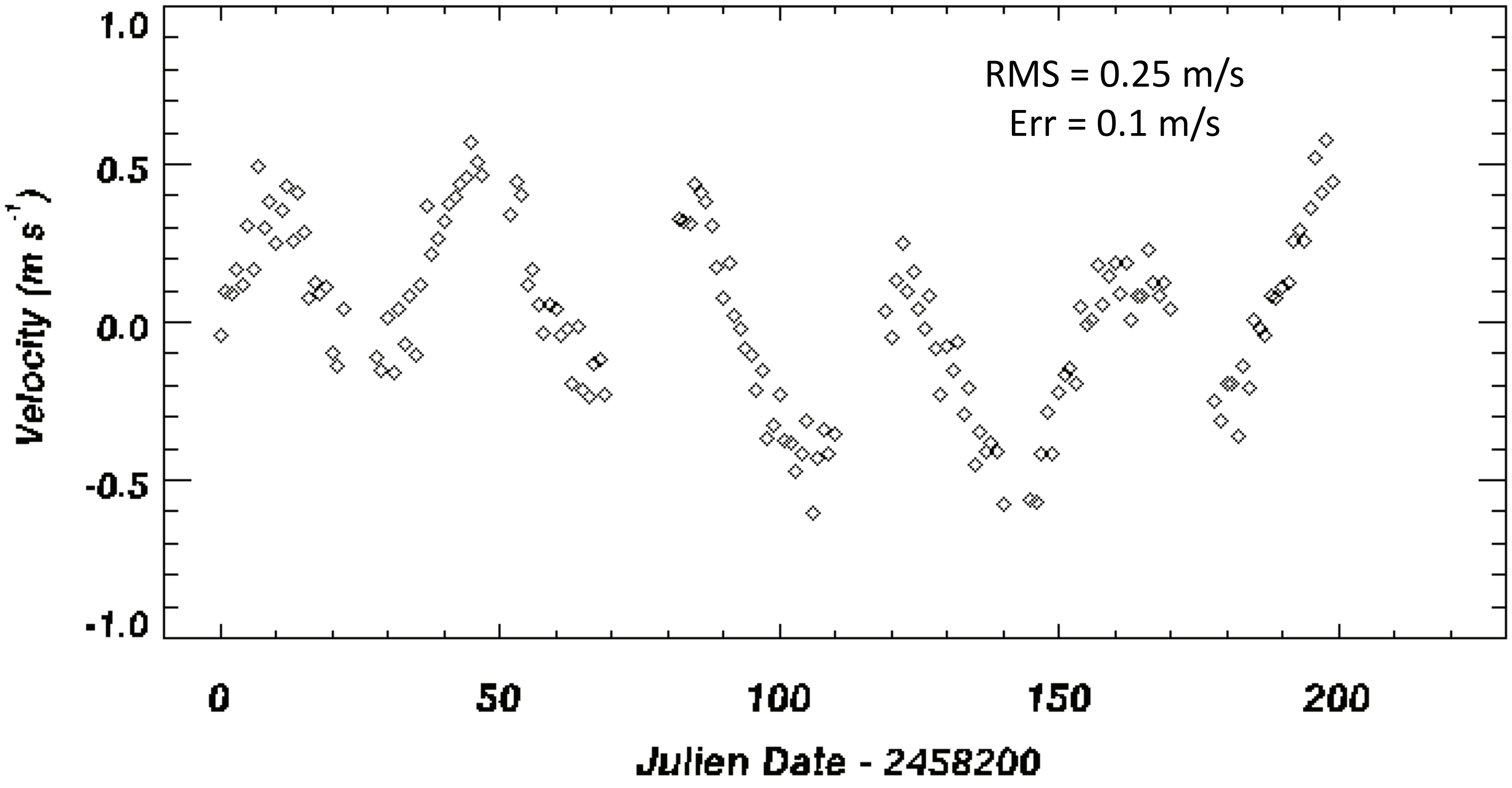




2014: Tau Ceti with CHIRON Pretty clear power in the periodogram of CHIRON data, but that signal is NOT in the HARPS data.

The future for ground-based RVs.

2019: Tau Ceti with EXPRES (simulated data with 2 small planets)



1. Photospheric noise

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

Butler et al. 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)

(Generally matched to our measurement error bars.)

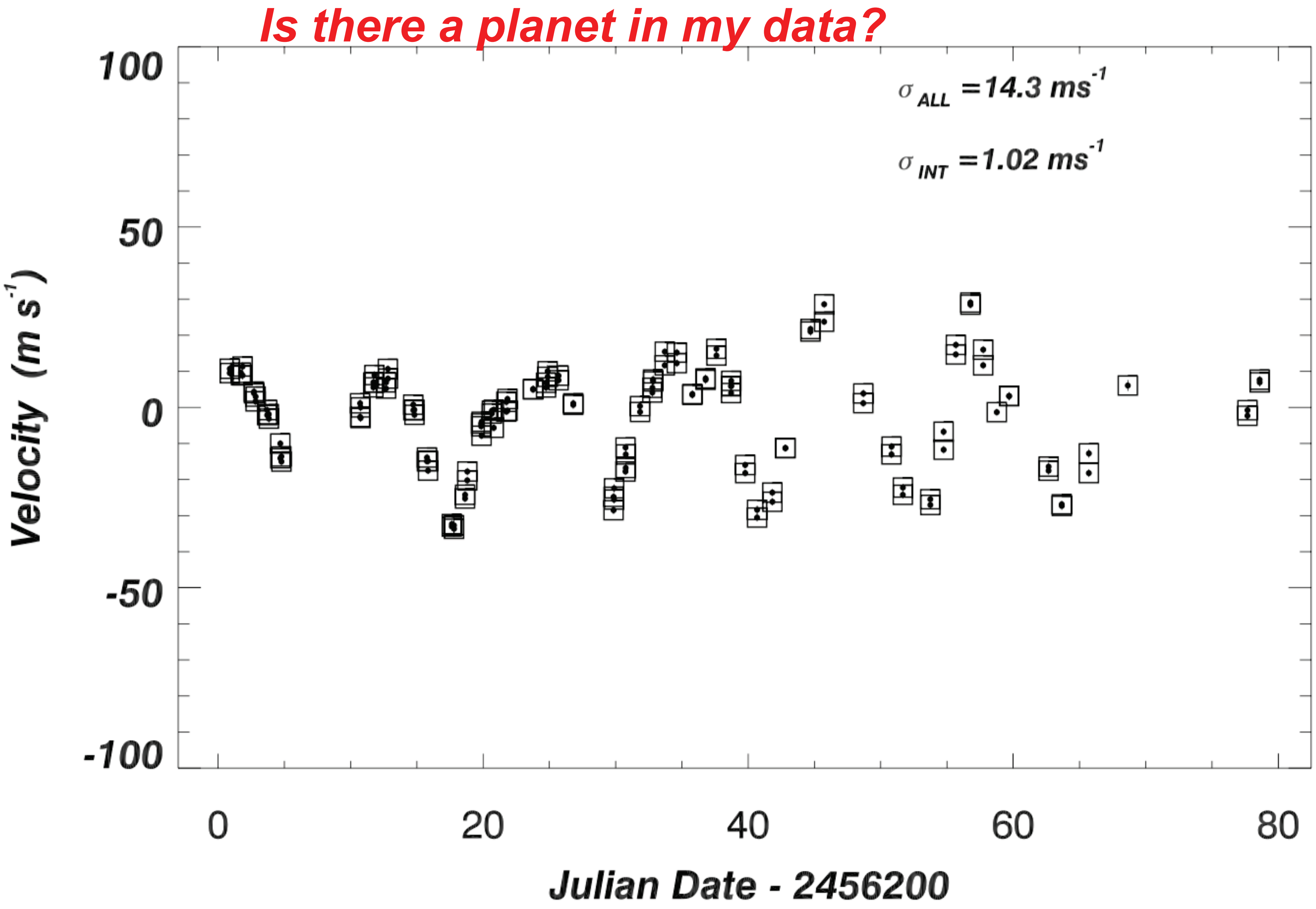
1. Photospheric noise

Stellar “jitter” includes Doppler velocities from:

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

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

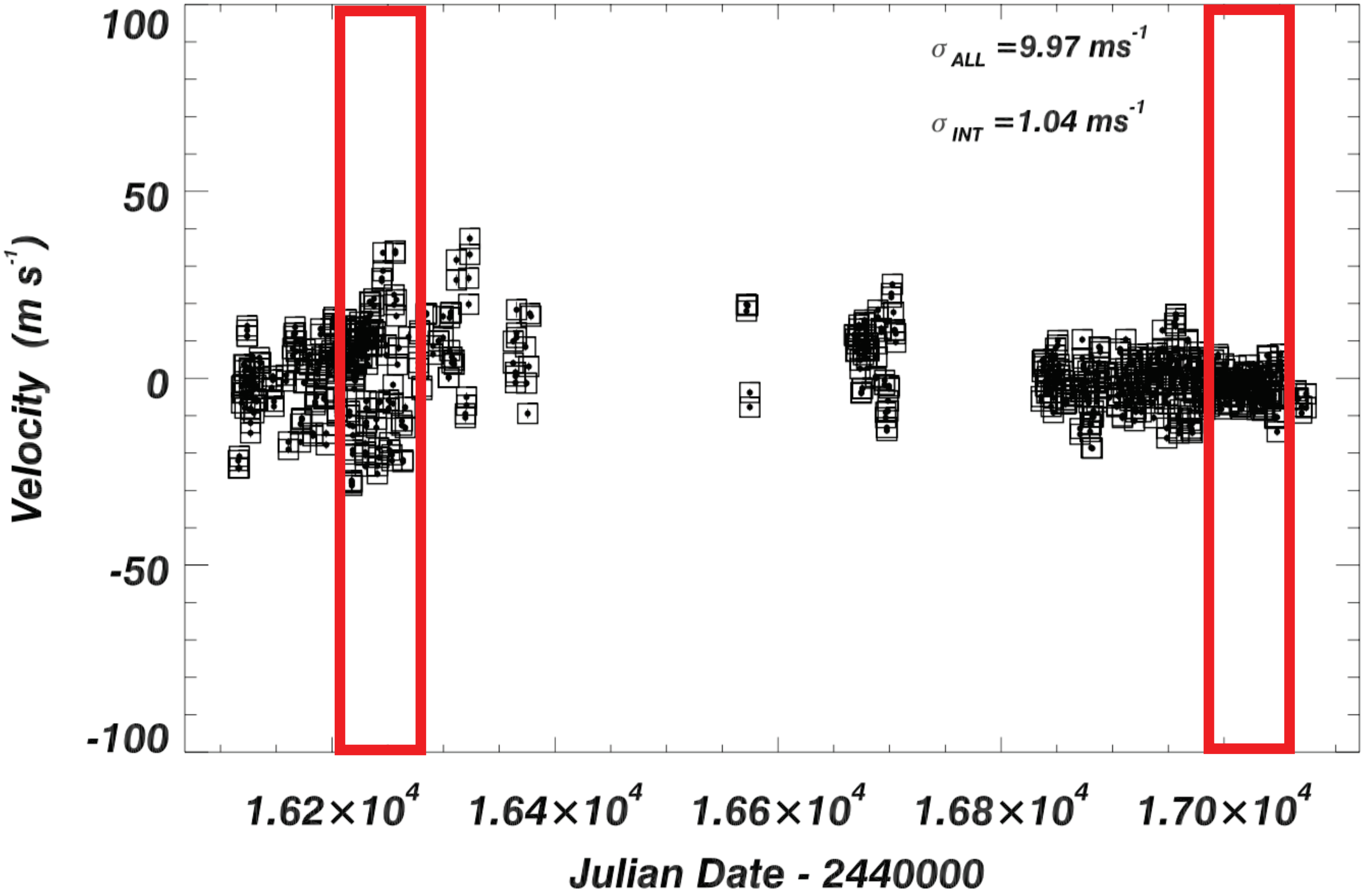
1. Photospheric noise



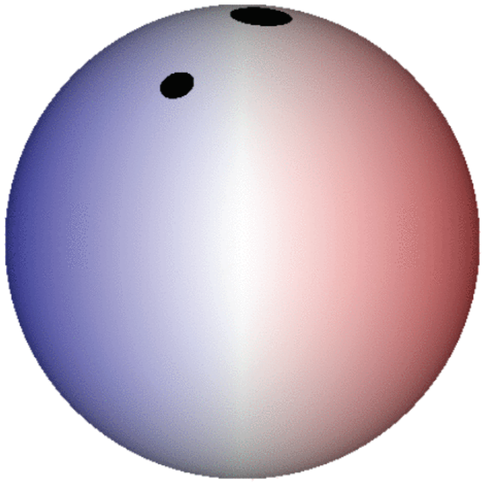
Epsilon Eridani RV Data from CHIRON at CTIO - Fischer

1. Photospheric noise

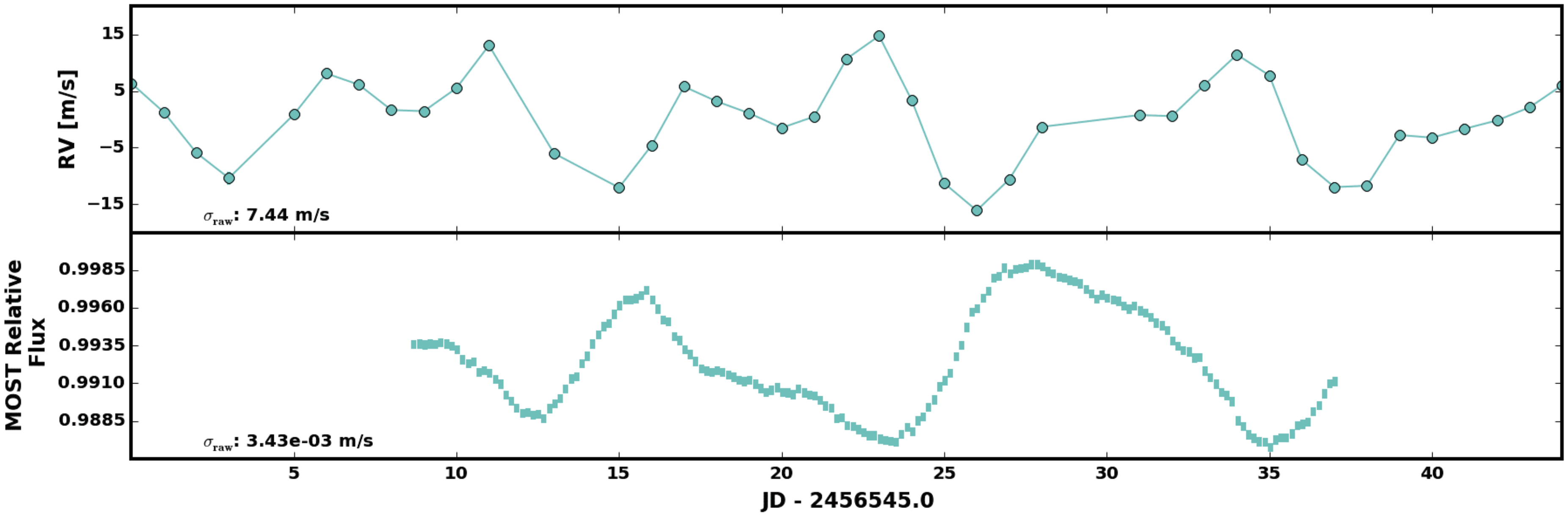
Nope, it's just a star spot!



Epsilon Eridani RV Data from CHIRON at CTIO - Fischer



Epsilon Eridani modeling simultaneous CHIRON + MOST data



Simulation credit: Matt Giguere

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.
- Some features (spots / faculae) have a wavelength dependence (higher contrast in blue than red)

2. Instrumental errors

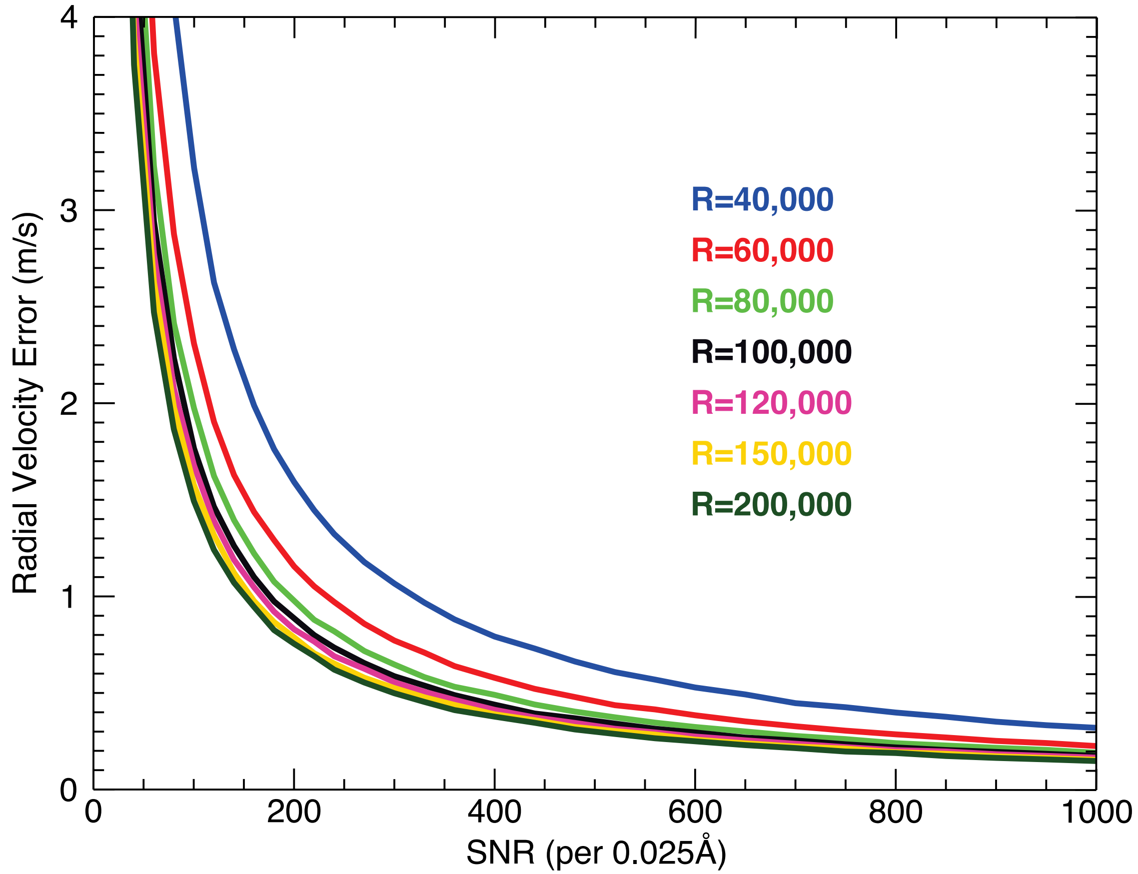
Challenge:

Extremely high fidelity spectra.

We need:

- Higher resolution
- Higher S/N
- Higher cadence observations

These simulations (by my team) were misleading b/c we treated this as a resolution vs S/N issue, only.



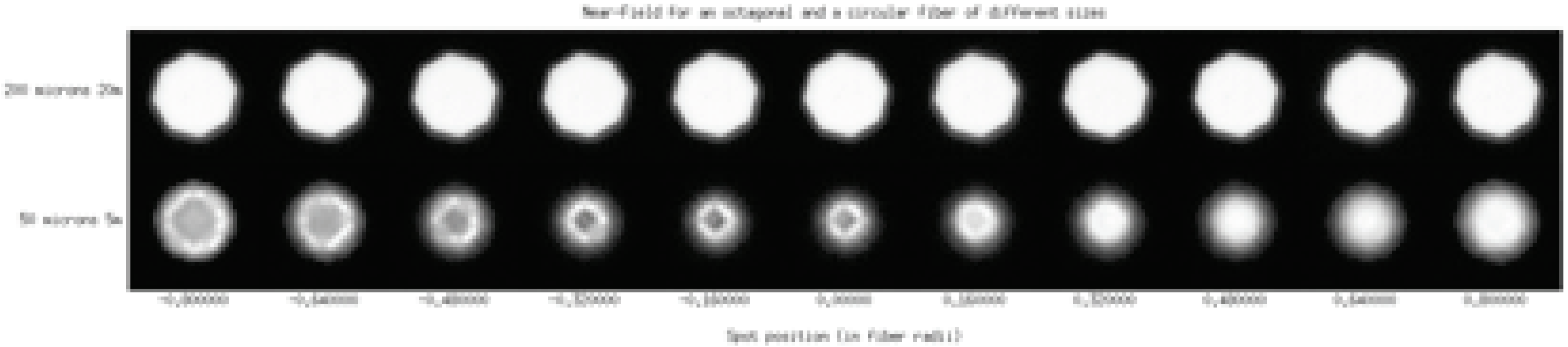
.....100 things that can go wrong and if we only get 99 of them right, it's not good enough.

Challenge:

Extremely high fidelity spectra.

Solution: stable instrument, uniform illumination of the optics.

- vacuum enclosure with precise temperature control
- special fibers with agitation for mode scrambling



Fiber scrambling – Halverson et al. 2015, Petersburg et al. 2018

2. Instrumental errors

Challenge:

Extremely high fidelity spectra.

Solution: unique optimization in camera design.

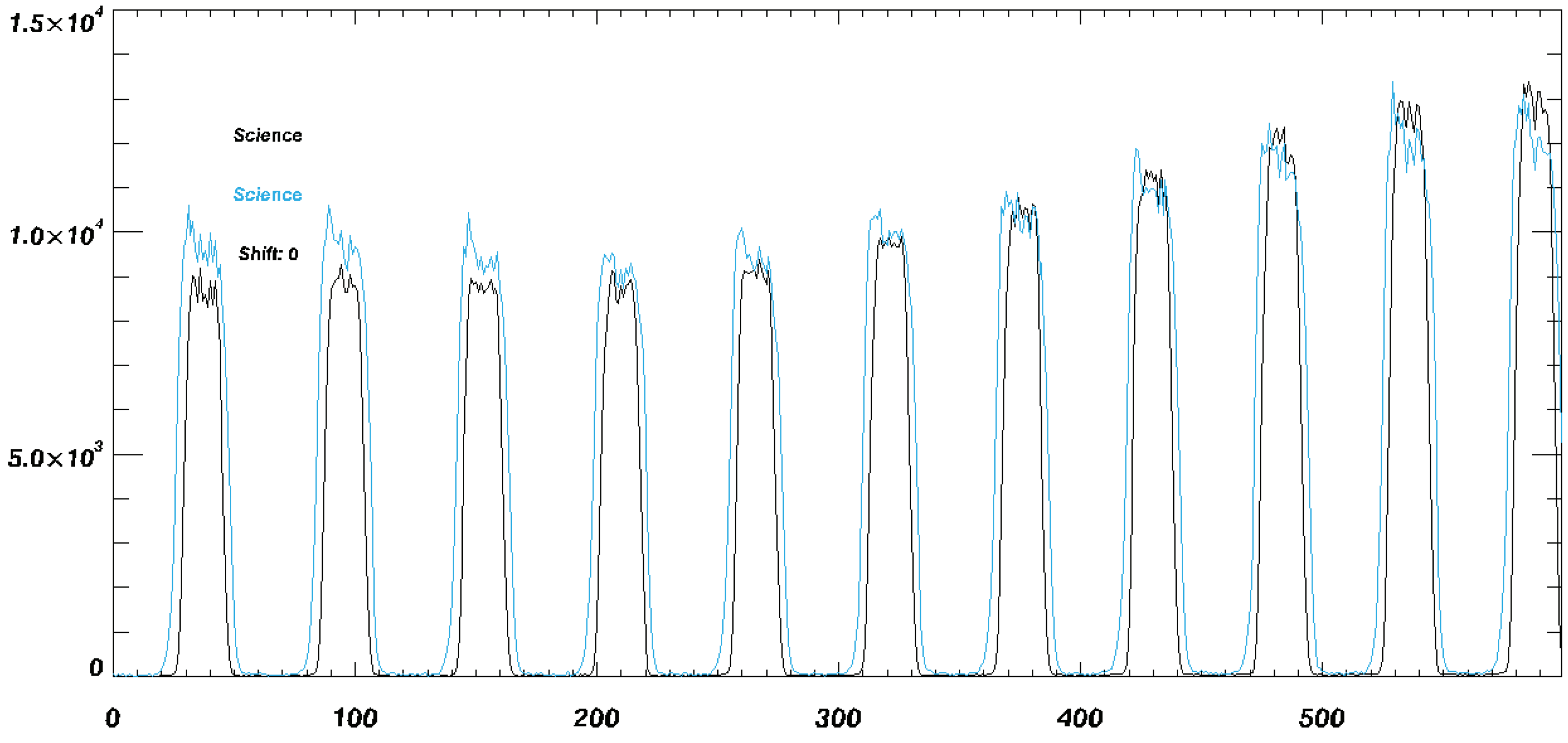
- camera design optimized to be insensitive to changes in pupil illumination
- camera design for a uniform and symmetric spectral line spread function
- focus control (?)

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



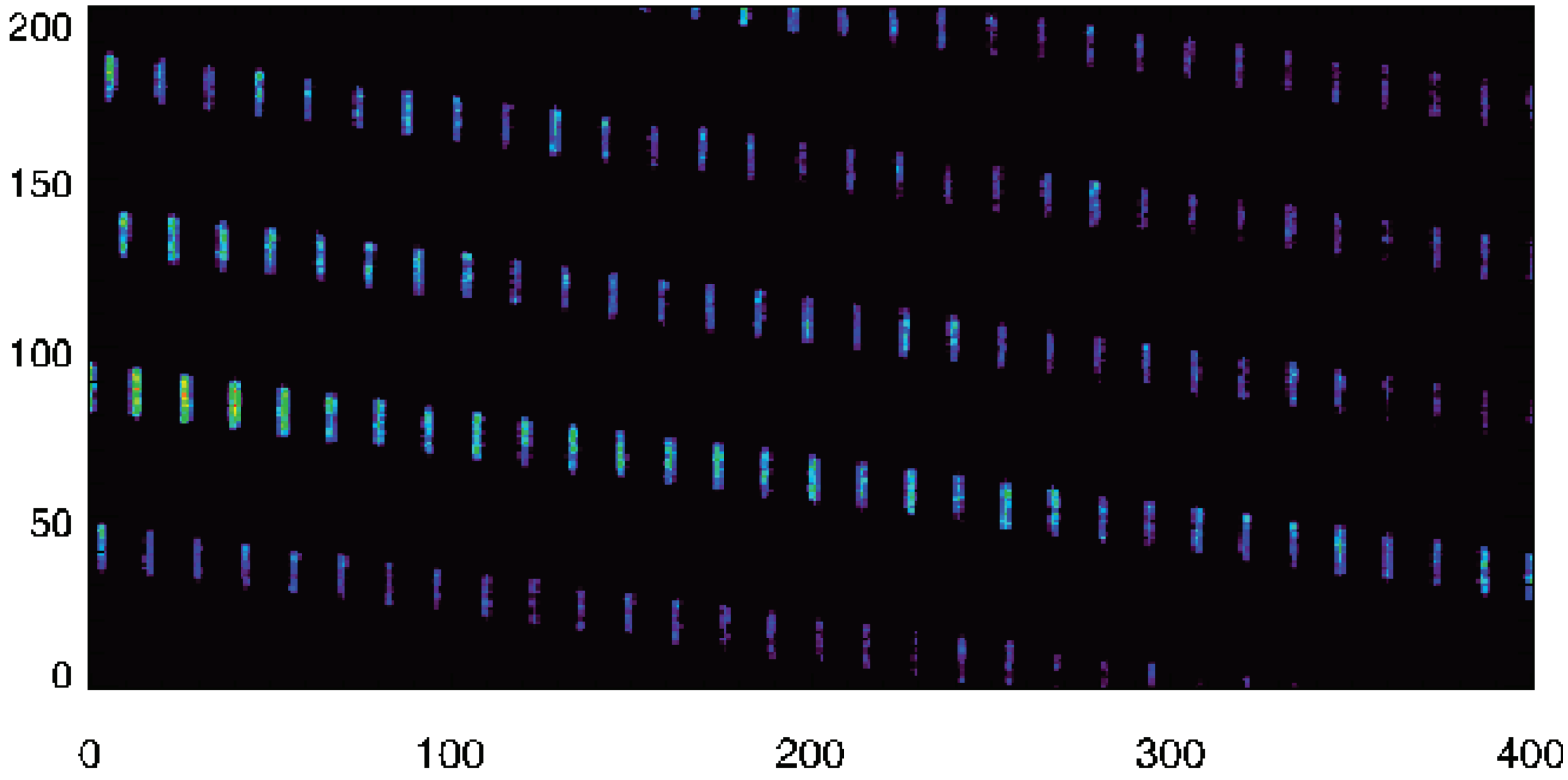
EXPRES data - Fischer

2. Instrumental errors

Challenge:

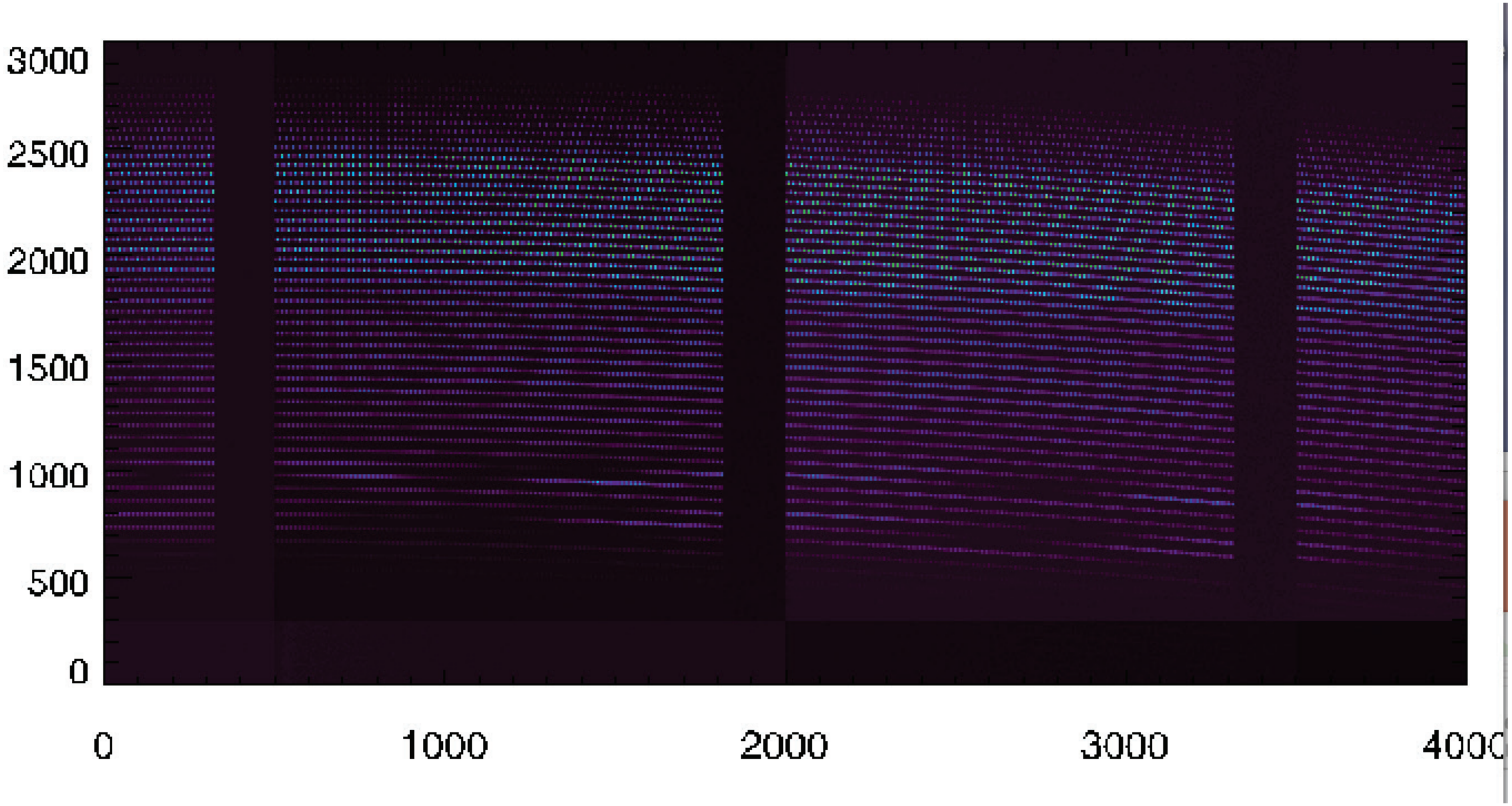
Extremely high fidelity spectra.

Solution: laser frequency comb for wavelength calibration



2. Instrumental errors

(stable at cm/s level, but limited wavelength range)



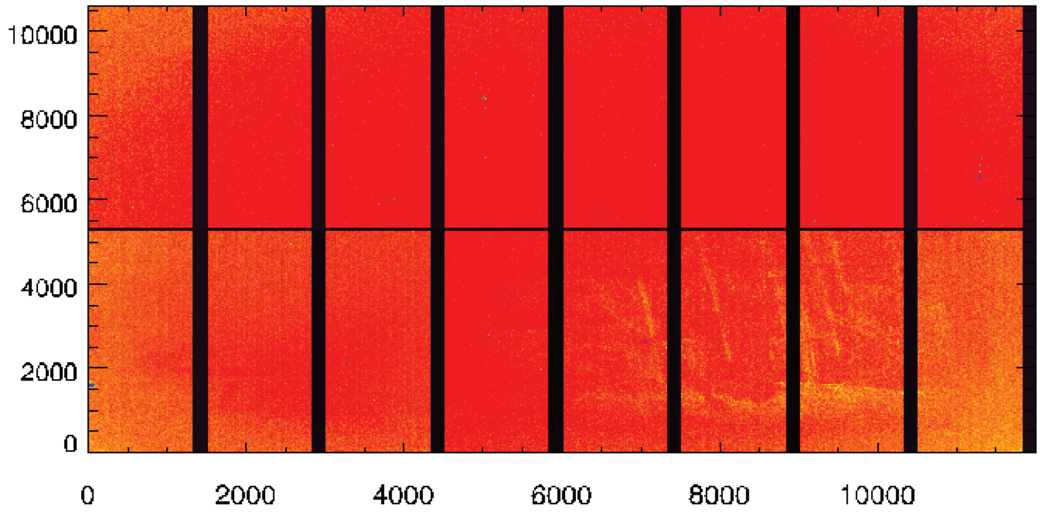
2. Instrumental errors

Challenge:

Extremely high fidelity spectra.

Solution: well-calibrated detector.

- Stitching errors, transfer efficiency, PRNU effects, intra-pixel QE variations
- Interferometric scanning of the detector to reduce pixel position errors to 0.001 pixel width, decrease wavelength errors from ~15 cm/s to ~2 cm/s.



There is no spectrograph in the world where detector noise completely flat-fields out.

2. Instrumental errors

Challenge:

Extremely high fidelity spectra.

Solution: improved barycentric corrections.

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

Barycentric Velocties, Wright & Eastman 2016, Blackman et al. 2017

3. Cadence, Cadence, Cadence

Challenge:

High cadence data.

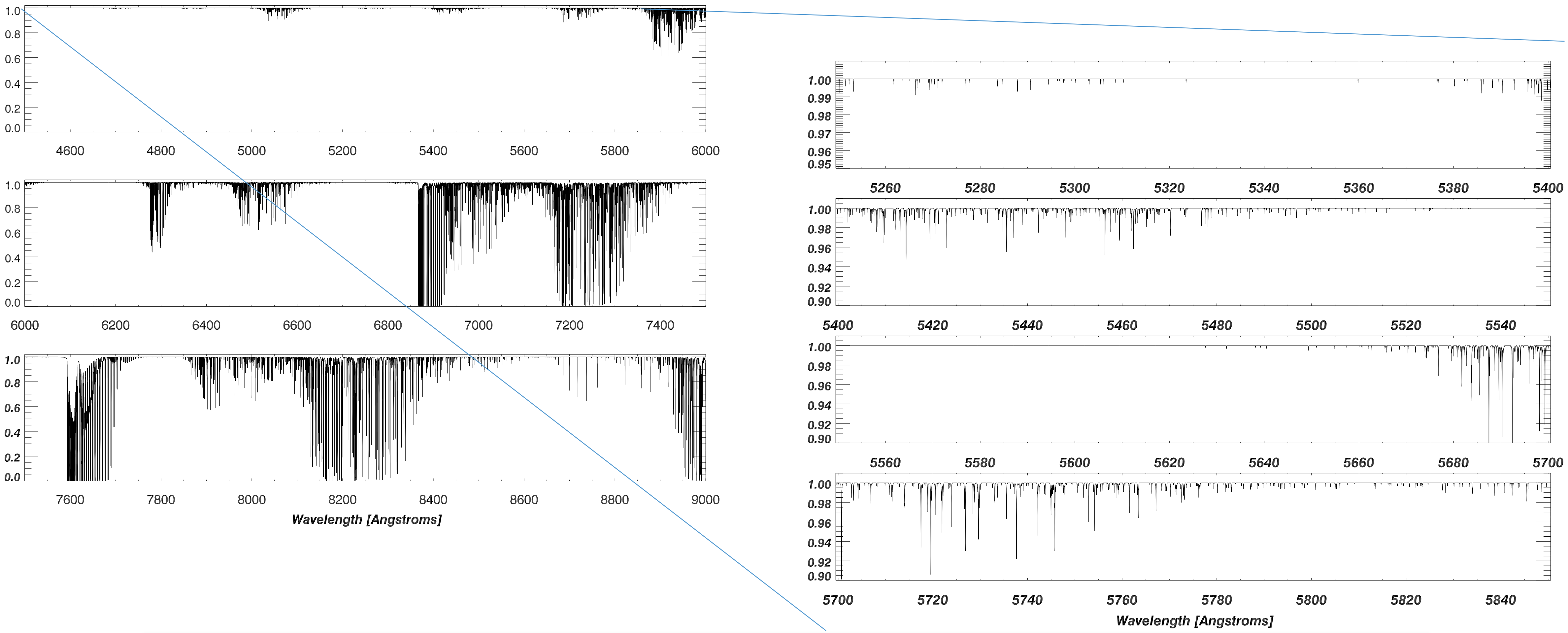
Solution: flexible scheduling of the DCT.

The community has grossly underestimated the cadence that is needed both to detect complex low mass planetary systems and to disentangle photospheric velocities and other systematics.

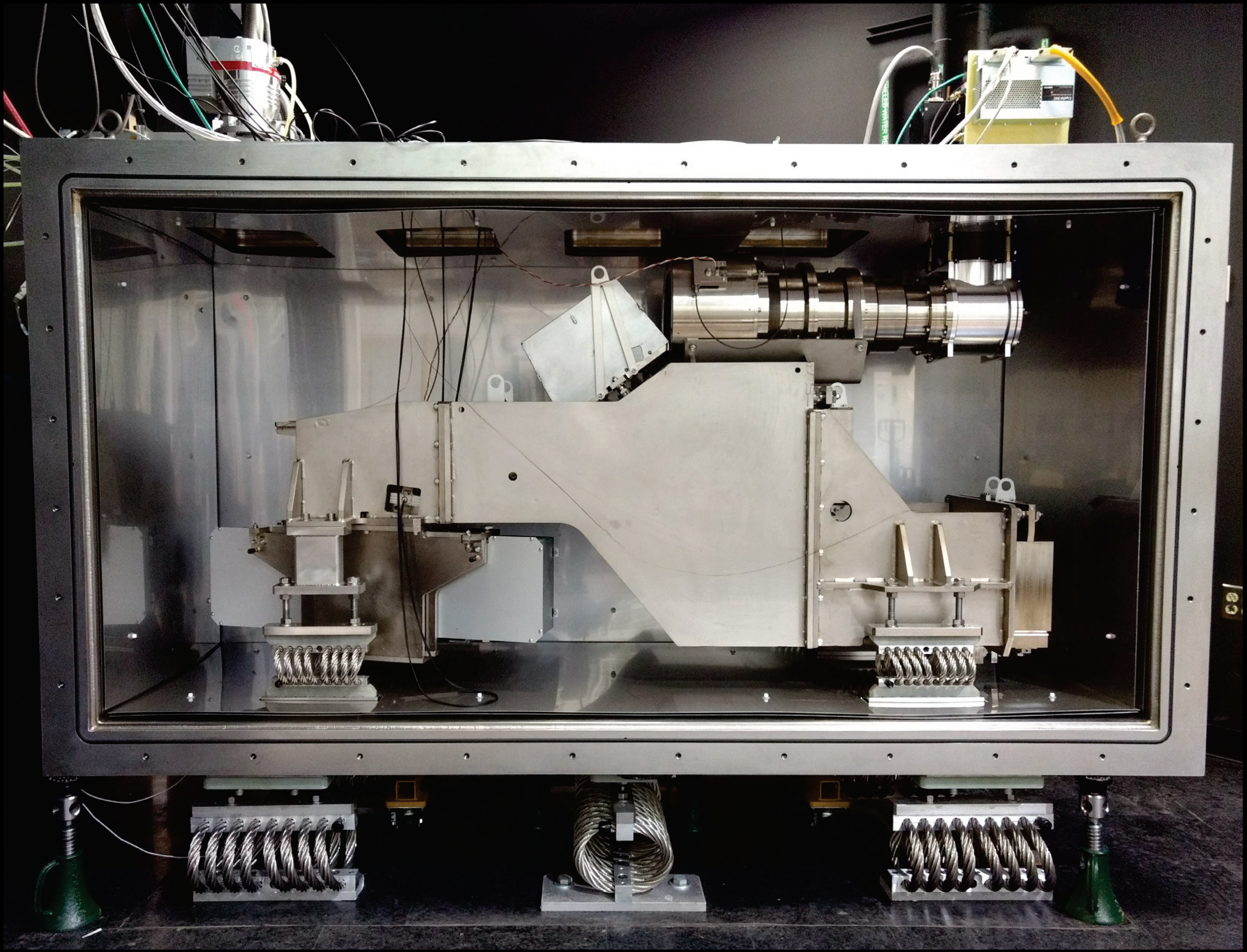
4. Telluric contamination

Challenge:
Modeling tellurics, esp water vapor

New methods are being developed to fit telluric and micro-telluric absorption features.



NOAO / NSO solar data Wallace 1997



Ground based spectrographs (ESPRESSO and EXPRES)

R=150,000
390 – 770 nm

Vacuum chamber stability
Vibration isolation
Laser frequency comb
Well-characterized CCD

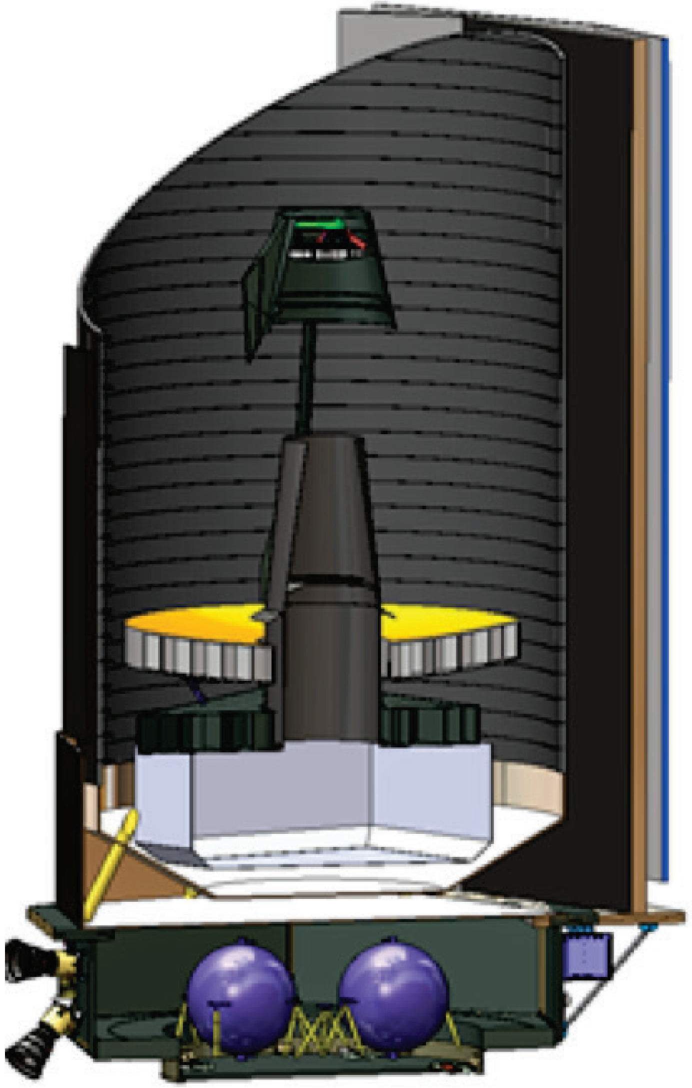
RV error budget terms circa 2018 / 2019	Status (cm/s)
Instrumental Terms (18 cm/s)	
Detectors	**15**
Wavelength calibration	**10**
Environmental stability	**3**
Fibers (modal noise)	**3**
Cadence	**?**
Analysis (18 cm/s)	
Photospheric velocities	**15**
Tellurics	**10**
Barycentric corrections	**2**
Doppler code	**2**

RV error budget has dropped from:

10 m/s (1995)
3 m/s (1997)
1 m/s (2005)

Not a function of time.

A function of innovation – outside of commercial ventures, are we investing in technical innovation in this country?



Space-based spectrographs – goal: 1 cm/s

R=200,000
500nm - JHK

All benefits of ground-based RVs AND

Zero out several terms in the RV error budget:

- SMF: no modal noise and provides R~200,000
- VIS – IR spectrum – helps with some photospheric velocity contributions.
- High cadence (no weather, only sun avoidance)
- No tellurics

Will still face challenge of photospheric noise, imperfect detectors and unknown error sources below 10 cm/s.

A few parting thoughts:

1. Full characterization: radius, mass, atmospheric spectra.
2. Scientists care about planet formation and architectures.
3. The public cares about finding life – rocky planets with liquid water are a logical place to search; currently a gaping hole in the exoplanet distribution.

- If we can separate out photospheric velocities, we have a hope of improving RV precision to 0.1 - 0.2 m/s. We have no idea whether it is possible to do correct photospheric velocities at a level that is better than this.

- Failure at improving RV precision comes at a big cost, the future characterization of exoplanets and our entire field will struggle and will have a much flatter trajectory. Synergy of techniques – stronger together.