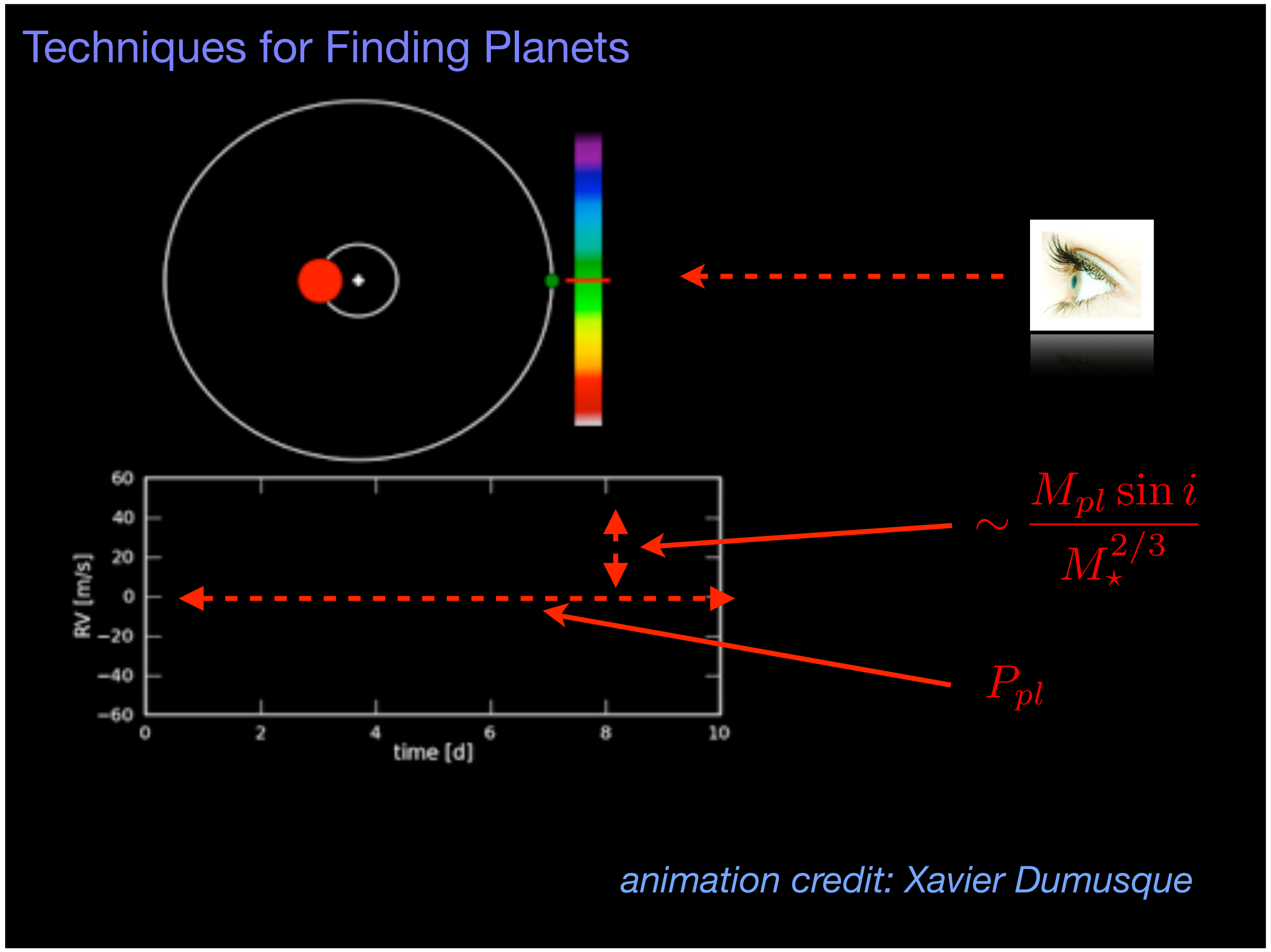
The Second Workshop

Extreme Precision Radial Velocities

Yale University, New Haven Connecticut | 5 - 8 July 2015

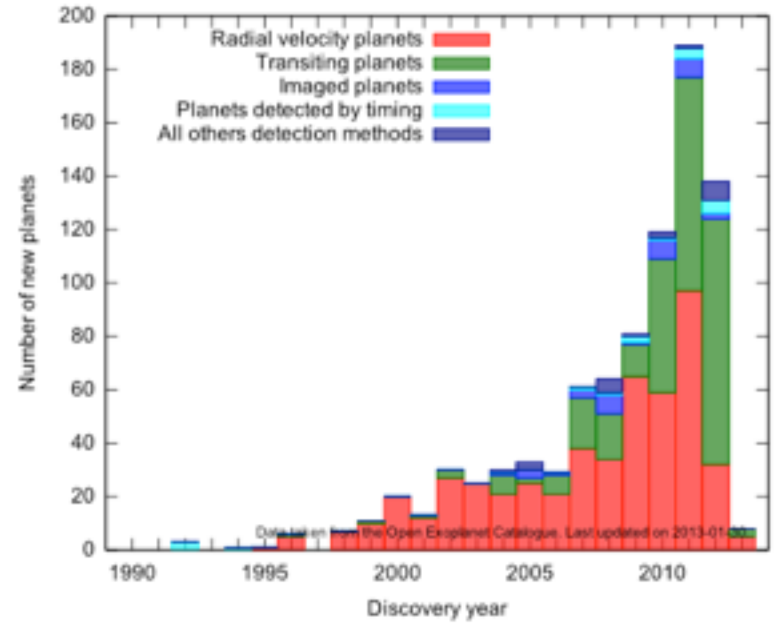
http://exoplanets.astro.yale.edu/workshop/EPRV/Program.html
recorded plenary talks



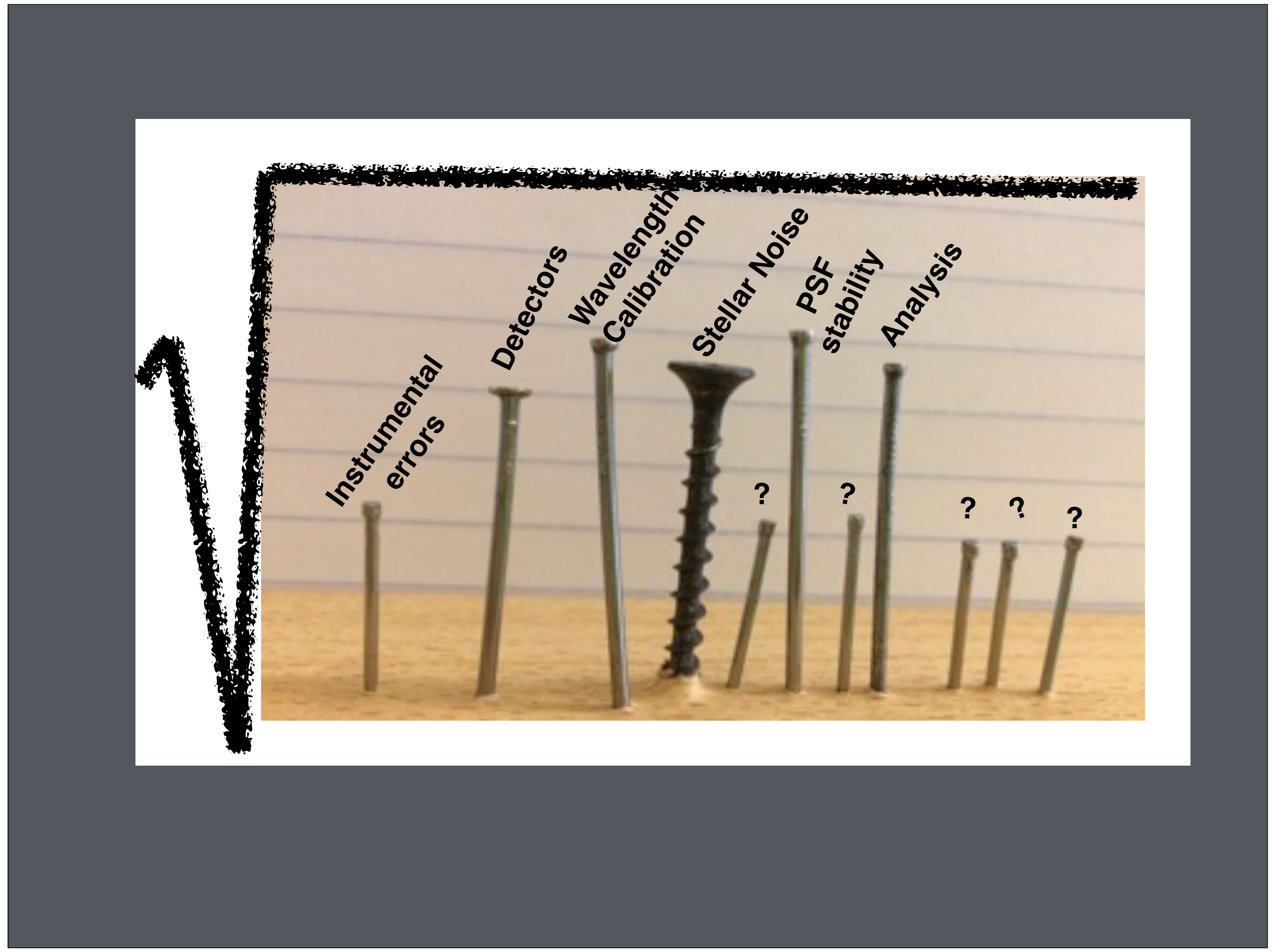
Msini, so there is a limit on inclination, but not as severe as for transits.
For nearby stars, this gives us access to more planets around closer stars, and with time, access to wider orbital radii.

Turn over in RV detections:

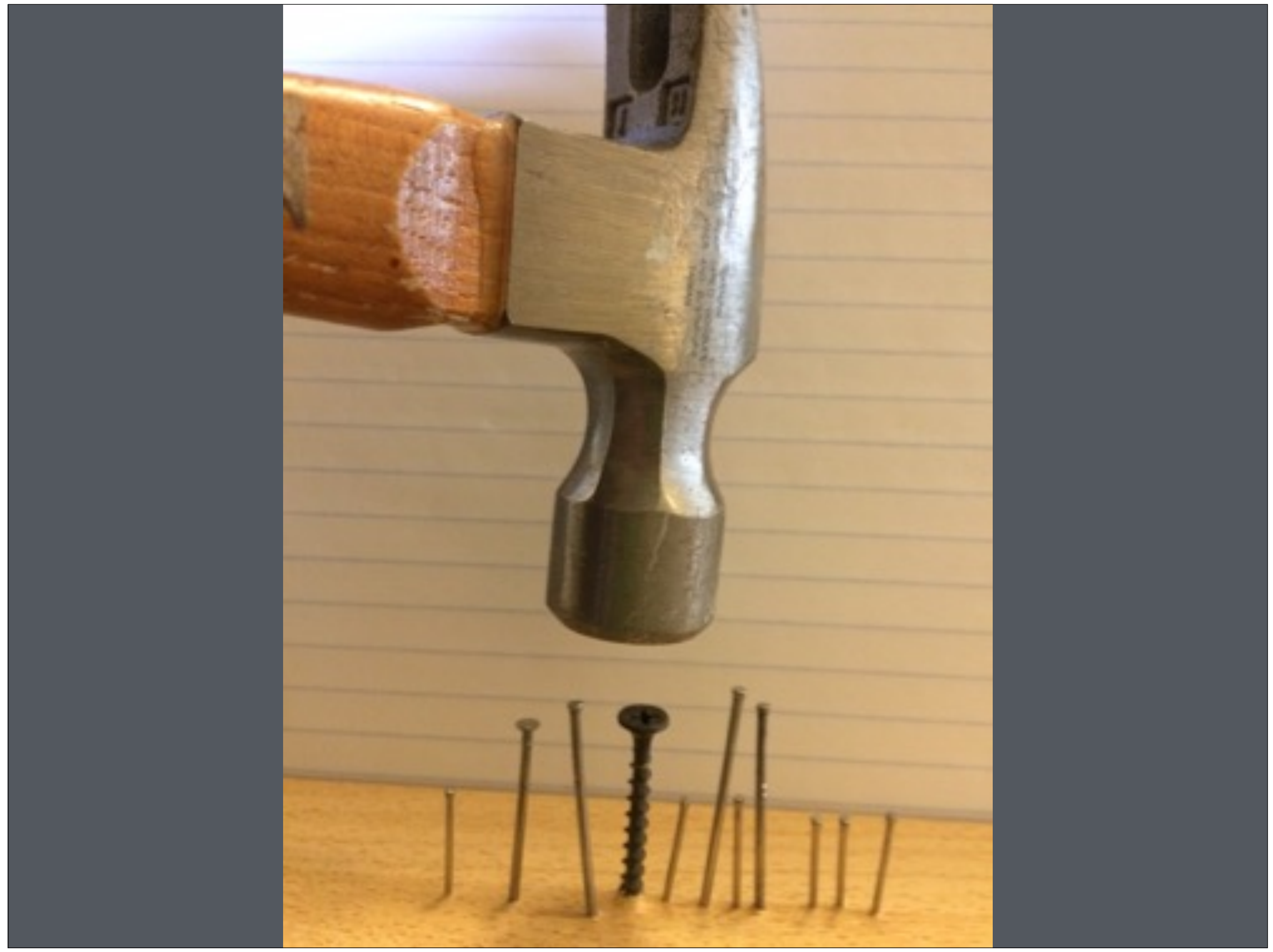
At a time when we know that planets with radii (masses) between 1 - 3 REarth (1 - 10 MEarth) are common is the Doppler technique reaping this harvest?   ***No!***



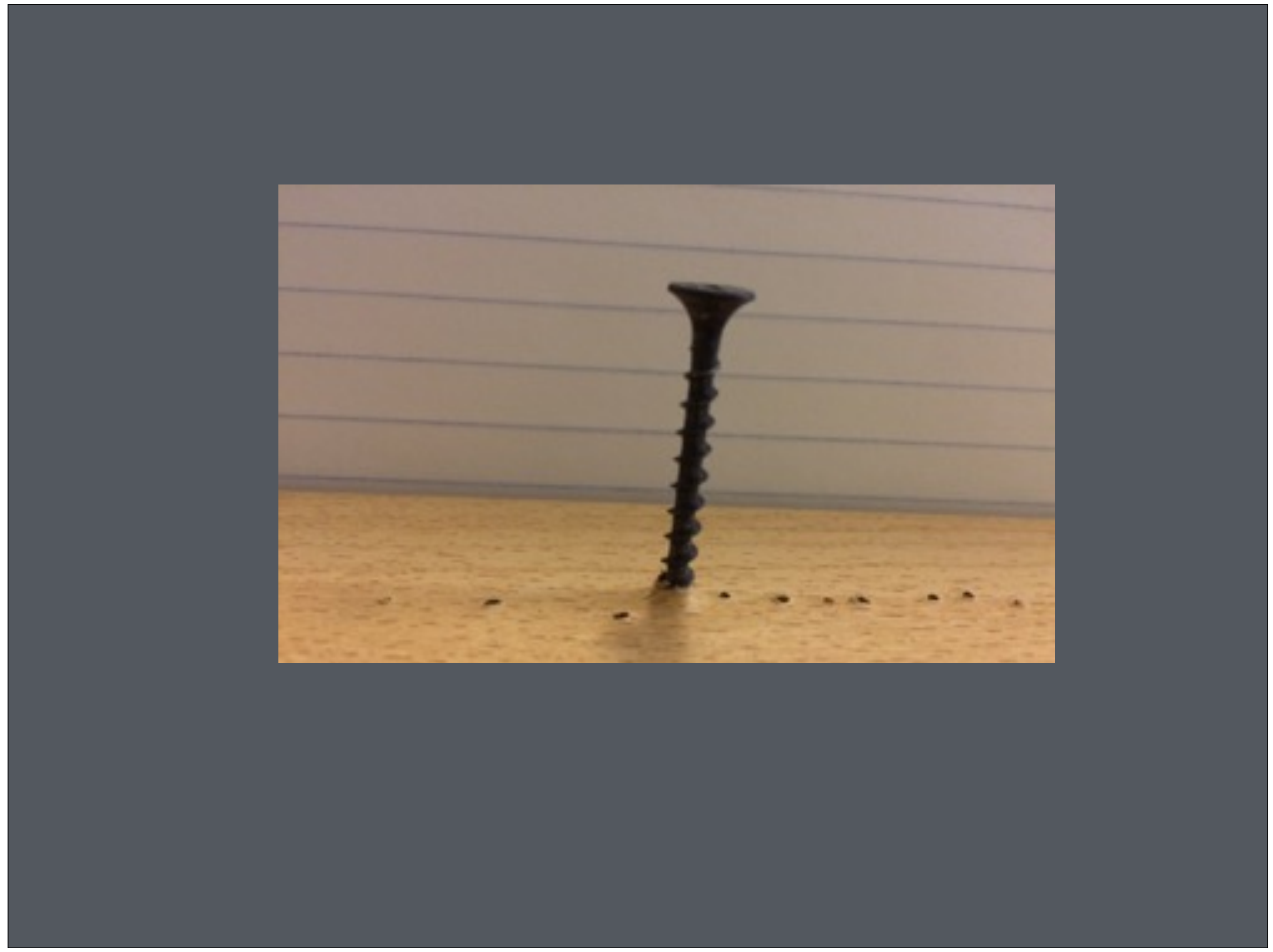
courtesy Hanno Rein



We have worked hard over the past 2 decades to improve RV precision. Now seem to be at a point where the largest terms in the error budget are similar magnitude. As we push down, we may encounter new surprises.



We need to use the right tools - we are together here for the next few days to identify the significant errors and to brainstorm about ways to solve these challenges.



If we eliminate all other error sources except stellar noise, we won't see significant precision gains. We'll be… well… screwed.

During the workshop we hope to model a new spirit of collaboration to tackle these challenges - we hope that this spirit will continue in the coming years - we will need perseverance.
Hopefully, by Wednesday, we will identify some of the important tools that we need to drill down to cm/s precision!

State of the art

Observatory	Wavelength range [nm]	Spectral resolution	Wavelength calibrator	Number of stars	Duration of program
Lick / Hamilton	390 – 800	50,000	Iodine	350	1987 – 2011
Keck / HIRES	364 – 800	55,000	Iodine	4000	1996 – present
McDonald / Tull Coudé	345 – 1000	60,000	Iodine	200	1998 - present
McDonald / HRS	408 – 784	60,000	Iodine	> 100	2001 - 2013
La Silla / HARPS	380 – 690	115,000	ThAr lamp + simultaneous	~400	2003 - present
Magellan 6.5m PFS	390 – 670	76,000	Iodine	530	2010 - present
OHP 1.93-m Sophie	387 – 694	75,000	Th-Ar	190	2011 - 2018
CTIO / CHIRON	440 – 650	90,000	Iodine	25	2012 – present
Lick / Levy (Vogt)	376 – 970	150,000	Iodine	96	2013 - present
Lick / Levy (Howard)	374 – 940	100,000	Iodine	Few hundred	2013 – present
Hertzprung SONG	440 – 690	90,000	Iodine	12	2014 - present

In the next decade, we are trying to achieve another ***factor of ten*** improvement in precision.

What is currently limiting RV precision?

1. instrumentation
2. data analysis techniques
3. separating stellar photospheric velocities from dynamical velocities.

The meeting brought together people from adjacent fields and industry (NIST, data science, e2V, fibertech optica, menlo systems)

Excellent review paper on PRV for EXOPag (Plavchan et al 2015 on astro-ph).

instrumentation

Andy Szentgyorgyi
Two basic spectrometer designs

- Standard (e.g. white pupil) with many lenses. The beam size scales with the size of the telescope.
- Anamorphic design - smaller, more efficient, but harder to manufacture, align and debug (ESPRESSO)

Suvrath Mahadevan
Environmental stability

- Pressure: 10^{-2} removes refractive index variations but 10^{-7} Torr removes molecular transfer to get a system that is radiatively coupled and extremely stable
- Temperature: 1 milli-Kelvin stability

All instruments drift on long timescales -
extremely stable frequency combs will calibrate:

- thermo-elastic distortions that shift the spectra and affect focus
- mechanical stability and pressure
- CCD stitching errors

Can't calibrate out:

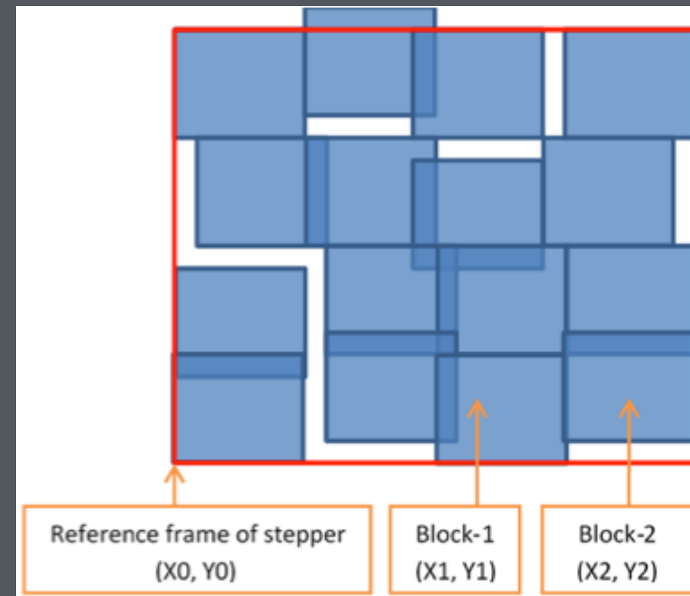
- barycentric errors
- telluric contamination
- software fitting errors
- micro-vibrations
- detector errors (intra-pixel QE variations, detector heating on readout, flux-dependent CTE errors)
- stray light
- focus and guiding (including ADC) errors

Wavelength calibration

Scott Diddams

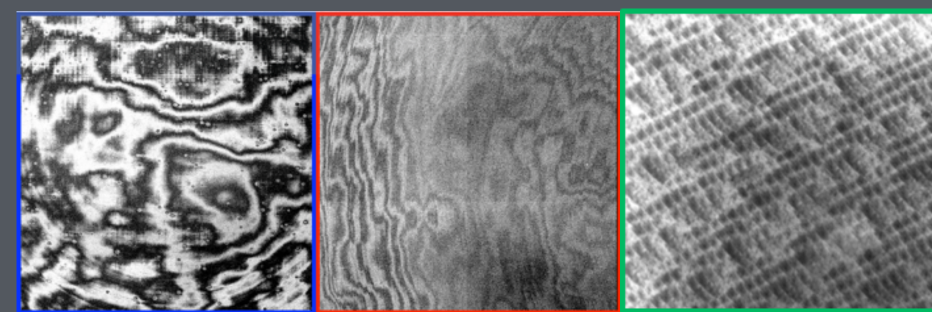
Laser frequency combs, LR-EOFC, Etalons, Fabry-Pérots…

Detectors



Example of the pixel image blocks required to create a 2k x 2k pixel CCD with exaggerated random position errors relative to the reference frame.

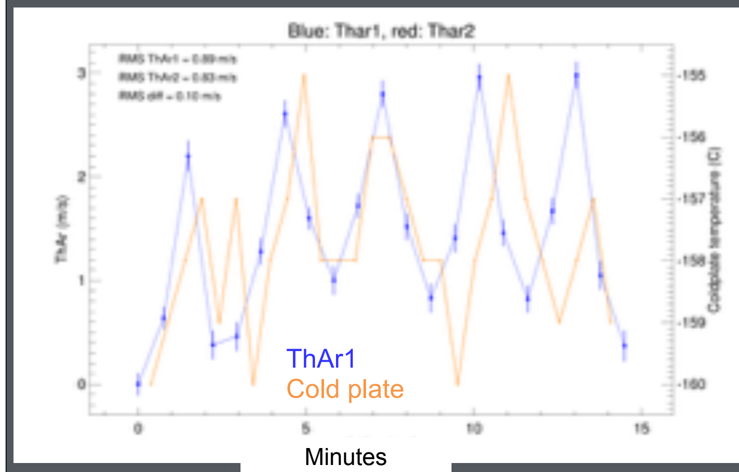
Detectors



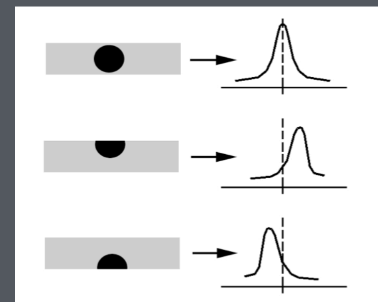
(left) z-band fringing at 2% of background level on a standard 15 micron thick e2V CCD; (middle) same z-band image with a 70 micron deep depletion e2V CCD showing fringing reduced to 0.4%; (right) narrow band image of the laser anneal pattern on a 2k x 2k CCD at 334 nm

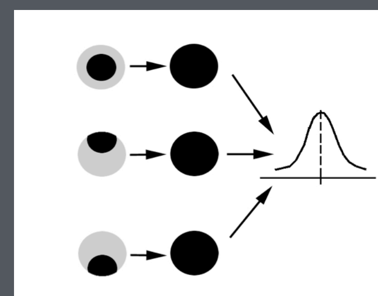
HARPS-N CALIBRATION STABILITY

instrumentation



Lars Buchhave



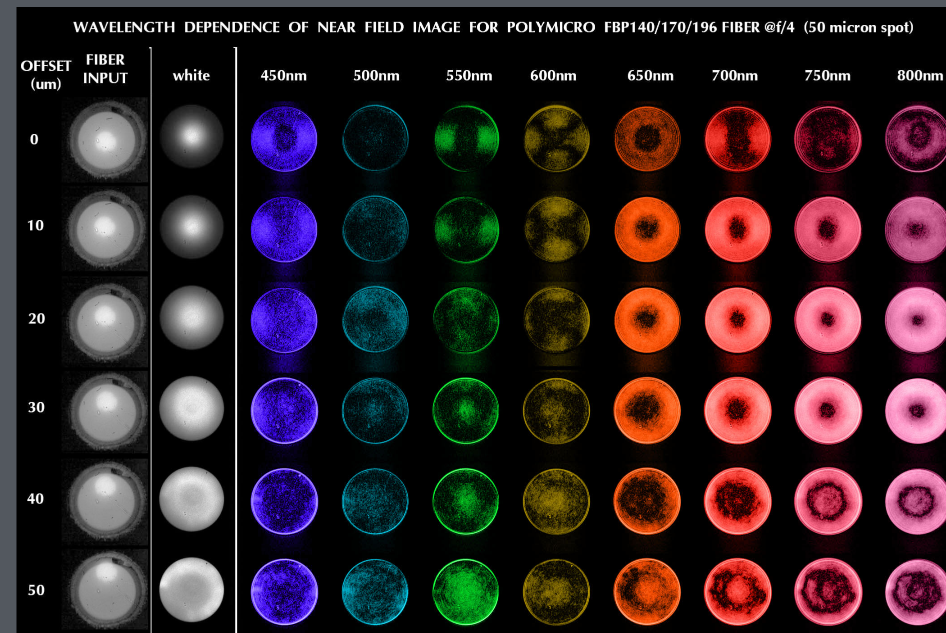


Every spectral line is the monochromatic image of the slit.

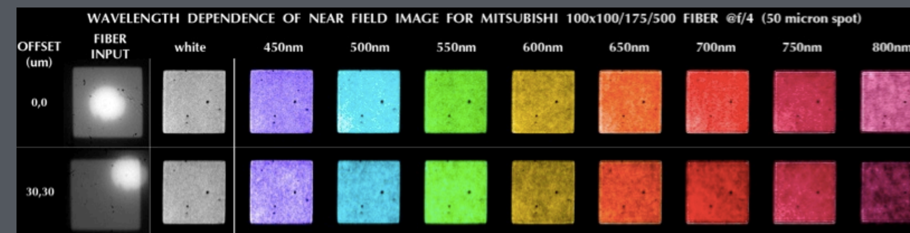
Variations in the light intensity distribution at the slit results in variations in the spectral line profile.

Variations in illumination of the spectrometer optics (far field) imprints on the spectral line.

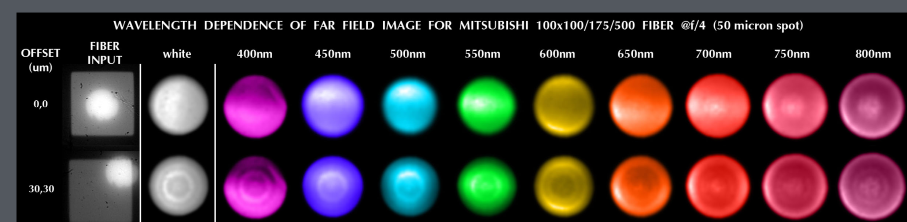
 Gabor Furesz and Paul Fornier



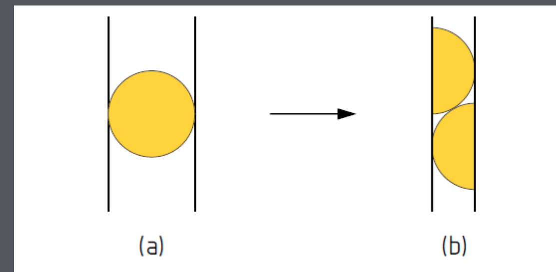
square, rectangular, octagonal, d-shape fibers provide even illumination function and more stable LSF



However, scrambling of the far field is insufficient - need a double fiber scrambler and agitation.

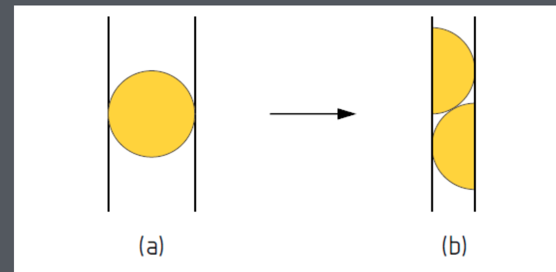


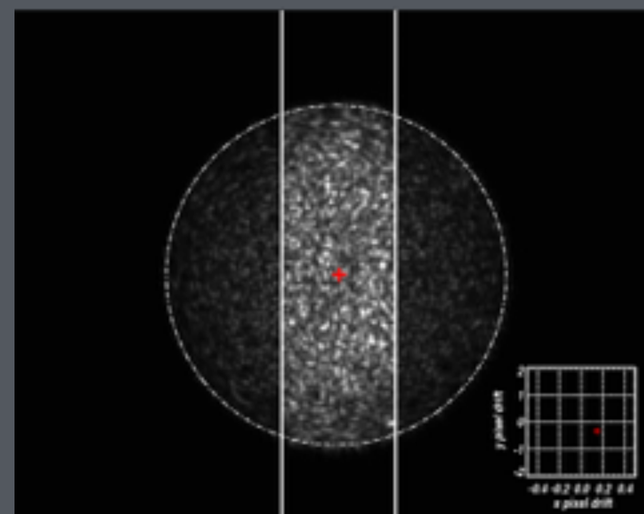
instrumentation - modal noise



Fibers are great for scrambling. Often you would also like to rearrange the illumination distribution to get higher resolution.

instrumentation - modal noise





When you do this, you lose energy conservation (depending on how the light is recombined).

This could have a destabilizing effect.

Solution: agitation and recombine into a single (rectangular) fiber.

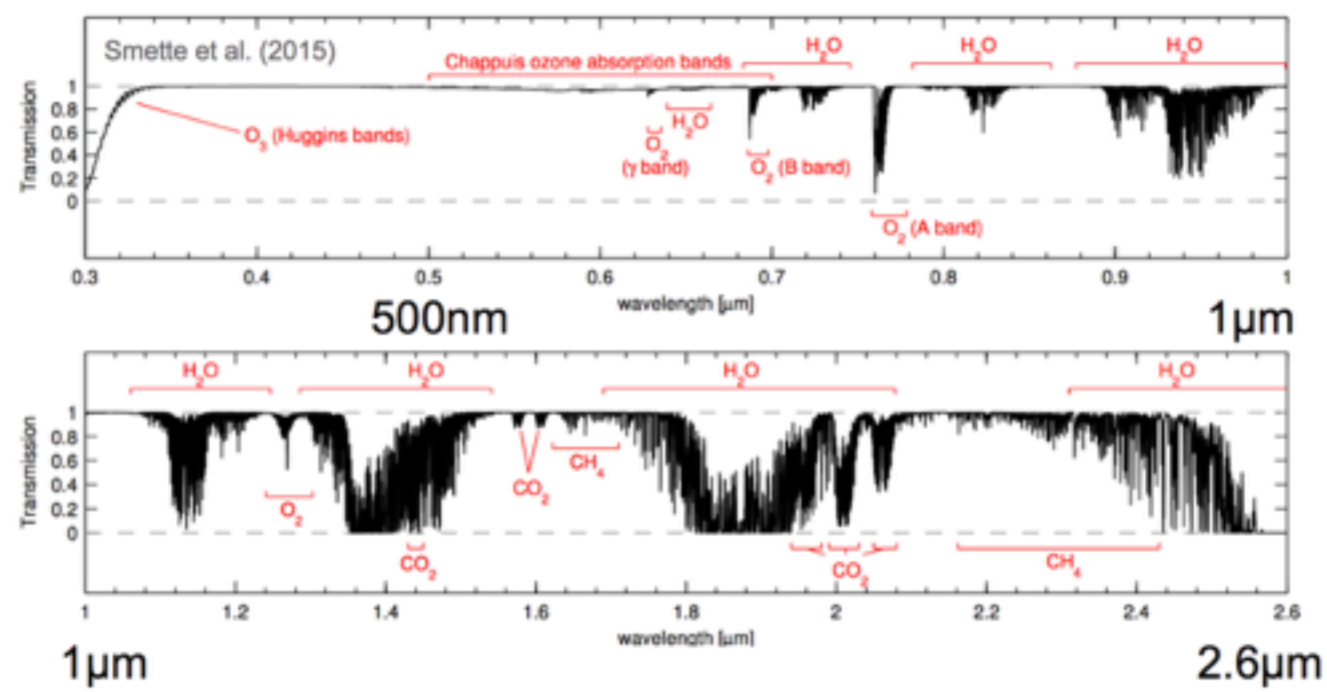
barycentric corrections
Jason Eastman and Lars Buchhave

Wright & Eastman, 2014, PASP
http://astroutils.astronomy.ohio-state.edu/exofast/

- BC not additive (cross term)
- Earth Precession
- Time standard
- relativistic terms
- gravitational redshift
- nutation
- UT1-UTC corrections
- light travel time
- Shapiro delay
- polar motion

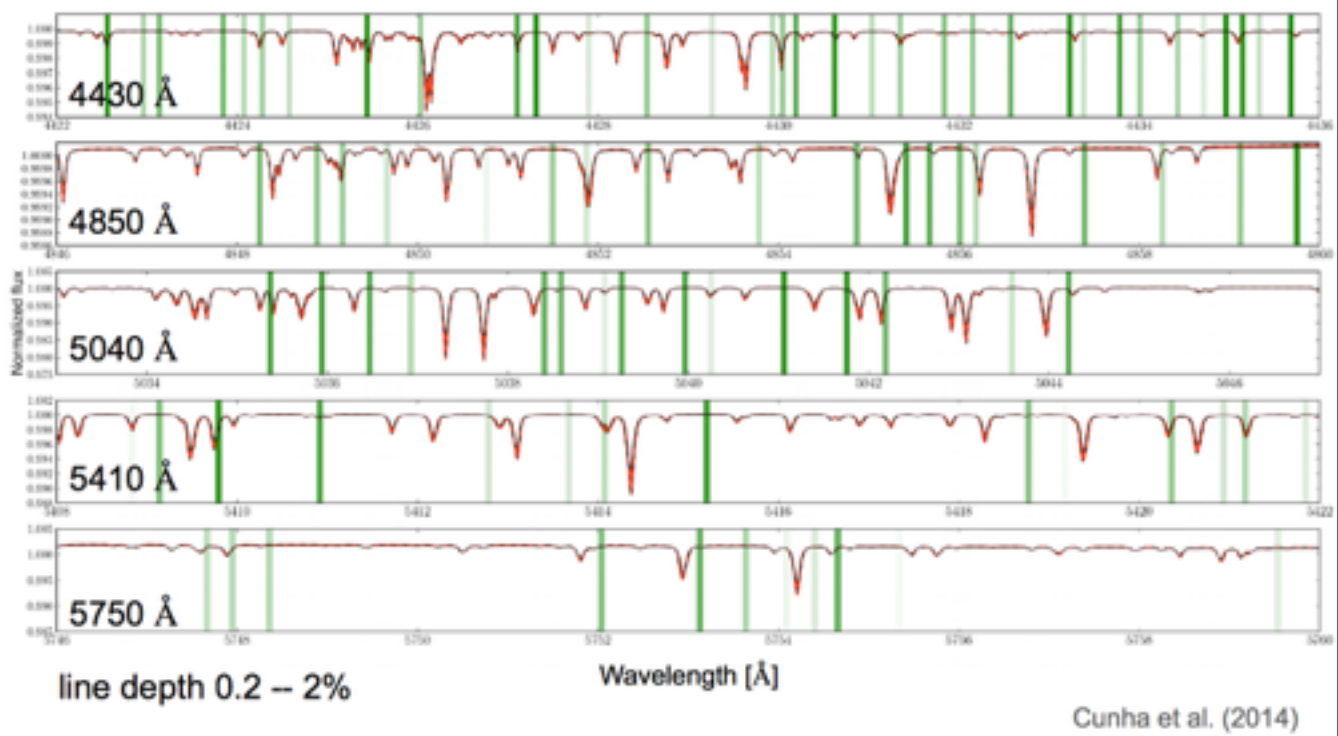
New result: not correct to use the flux-weighted exp time. Integrate correction over exposure time - each point weighted by exposure meter. (30 cm/s error)

telluric contamination
Sharon Wang, Jason Wright



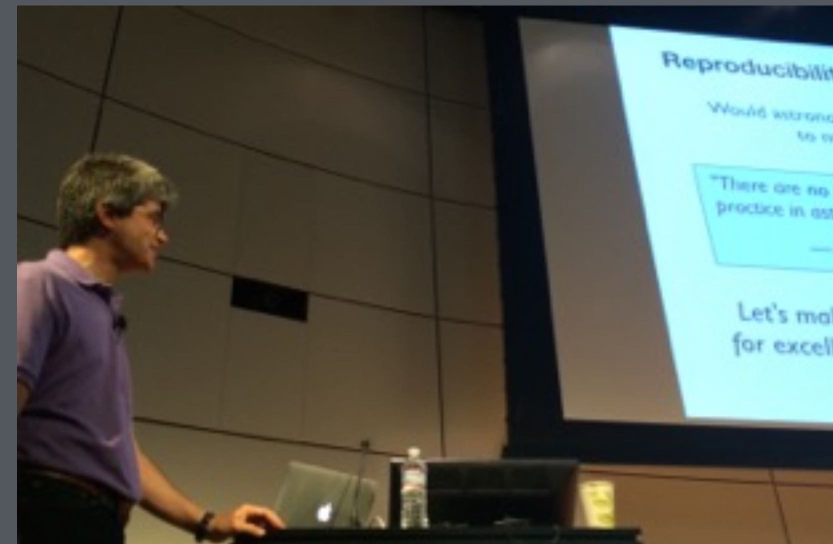
Limits precision for NIR to few m/s….

telluric contamination
Sharon Wang, Jason Wright



Likely limits 10 cm/s precision in optical bandwidth….

data analysis techniques



Loredo: There is a reproducibility crisis in science. Exoplanets would likely not survive the scrutiny given to medial research. As a field that attracts public attention, we should aim to be a model for reproducibility. Statistics is not merely a tool, but rather a language for performing quantitative science. Quantitative results (particularly for planets with amplitudes comparable to stellar activity or measurement noise) requires careful attention to proper choice and application statistical methods.

data analysis techniques

Loredo:

"This detection has a signal-to-noise ratio of 4.1 with an estimated upper limit on false alarm probability of 1.0%

"…the fall alarm probability for this signal is rather high at a few percent."

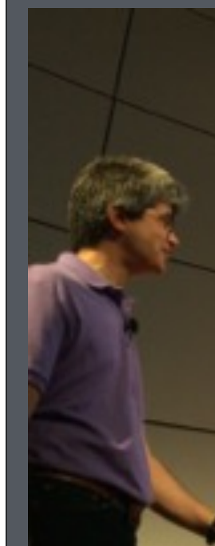
"This signal has a false alarm probability of < 4% and is consistent with a planet of minimum mass …"

"We find a false-alarm probability < 10-4 that the RV oscillations attributed to CoRoT-7b and CoRoT-7c are spurious effects of noise and activity."

What a p-value really means…
"In a world with absolutely no exoplanets, with a threshold set so we wrongly claim to detect planets 100 * p% of the time, this data would be judged to be a detection.

p-values are not statements about detected signals, but statements about the ensemble of possible null-generated signals.

We need a way to give colleagues a way to have confidence in a result. There are connections between p-values and Bayesian factors, but need to be clear about what they are telling us.

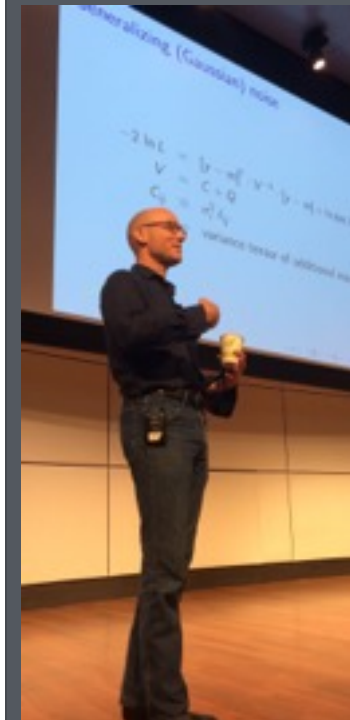


Loredo:
On the K-S test: the K-S test is incorrectly used in over 500 refereed papers each year in the astronomical literature.

Assumes continuous underlying distributions. Even if true, not very sensitive to finding the distance between populations.

https://asaip.psu.edu/Articles/beware-the-kolmogorov-smirnov-test

data analysis techniques



Hogg: If you are using chisq fitting, you could be doing something a lot better. Don't subtract out systematics or stellar activity. Include them in your model and marginalize over them. If you're willing to assume things are Gaussian, then you can marginalize over thousands of model parameters efficiently using linear algebra. Anything that can be constructed in Fourier domain can be turned into a kernel function for Gaussian processes.

Suck it up: you cannot do precision spectroscopy without fancy math - partner with statistically savvy colleagues.

For RV data, you simultaneously learn kernel parameters and exoplanets at the same time (harder than transit data). Only understand your noise in the context of the model for the planets (if a 6-planet system becomes a 7-planet system then it reduces your beliefs about the noise).

Instrument builders can help by providing (e.g. likelihood function for temperature). Do not regress out the temperature - include it in your model.

data analysis techniques

Ford: In the 90's we used a frequentist approach - disproving the null hypothesis (seems silly today). Most important thing: don't make a mistake - waited years before publishing data.

Goals shifting to find lower mass planets. We don't know if it's possible to separate activity and RVs (maybe, but not certain).

Bayesian approach: answers questions you want, forces you to write down priors and quantify uncertainties. Make sure you understand the algorithm - don't just apply a blackbox code. Know convergence criteria. Problem with large models that include everything is that you lose intuition.

Collaborate with people to build on the strengths of our community. Implementing robust and efficient algorithms is non-trivial, but essential.

data analysis techniques

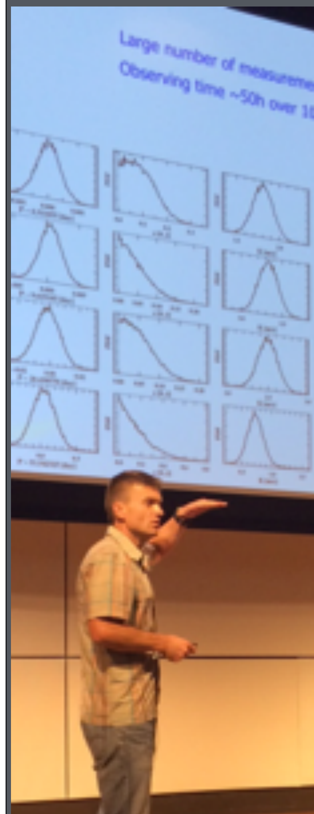
Ford:
1. Good starting point is to use simulations to validate techniques and to tweak your algorithm.
2. Need larger data sets to characterize noise properties.
3. Don't make ad-hoc revisions to models once you're fitting real data.

Need to report more than time, RV, error; also report non-Gaussian characteristics, PDFs, activity diagnostics.

Surveys need to have realistic goals - enough time for stars you observe.

- Long term activity
- Multiple planets

separating stellar photospheric velocities



Ségransan:

Low amplitude signals - life is hard below 1 m/s

- Used adaptive error bars scaled to the log R’HK activity.
- Identified the impact of CCD stitching; produced annual signal in the RVs as the barycentric velocities roll the spectrum across the stitching blocks: **50 - 70 cm/s**
- residual tellurics **50 - 100 cm/s**
- calibration errors -?
- gaps in observing -?

Any of these errors can produce outliers that are hard to treat with Bayesian priors

separating stellar photospheric velocities

Lovis: Stellar activity apparent even on inactive stars using a stable spectrograph.

The fact that stellar activity is pulling the RVs means that the signals are imprinted in the spectrum. The signal is fundamentally different from a Doppler shift. The remaining question is whether we can distinguish the photospheric signals from center of mass motion.

separating stellar photospheric velocities

Carroll: There is information that can help disentangle planet-induced Doppler shifts from stellar activity encoded in the depth and shape of spectra lines and different subsets of spectral lines.

Carried out principal component analysis of the CCF and found that the eigenvalues of the PCA could be correlated with noise. This is a BIG breakthrough - these were quiet slowly rotating stars.

separating stellar photospheric velocities

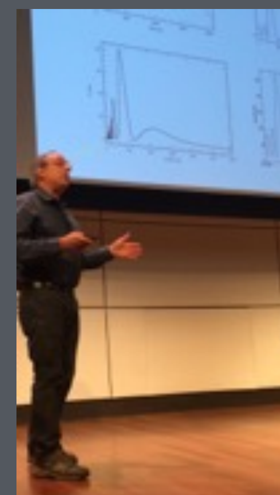
Dawson: Signals due to aliasing can often be recognized by patterns in the periodogram (or the likelihood marginalized over all parameters except period).

Outlined approaches for identifying aliases.

separating stellar photospheric velocities

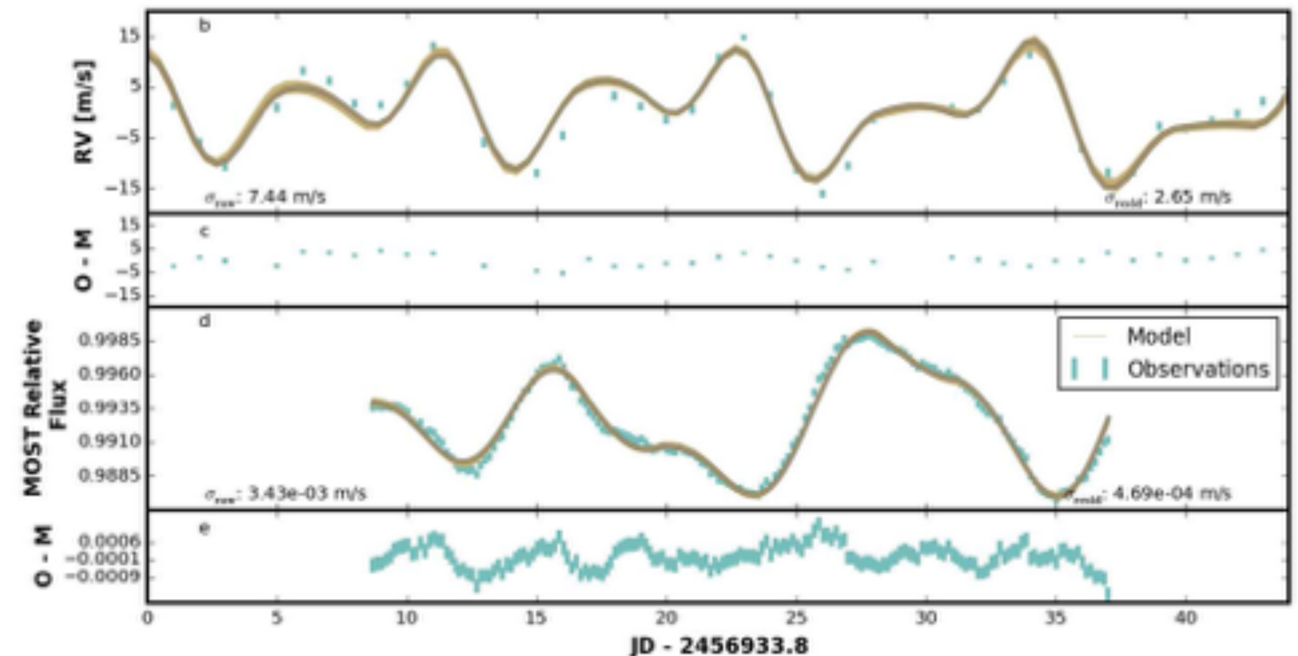
Herrero: There is information that can help disentangle planet-induced Doppler shifts from stellar activity encoded in the depth and shape of spectra lines and different subsets of spectral lines.

separating stellar photospheric velocities

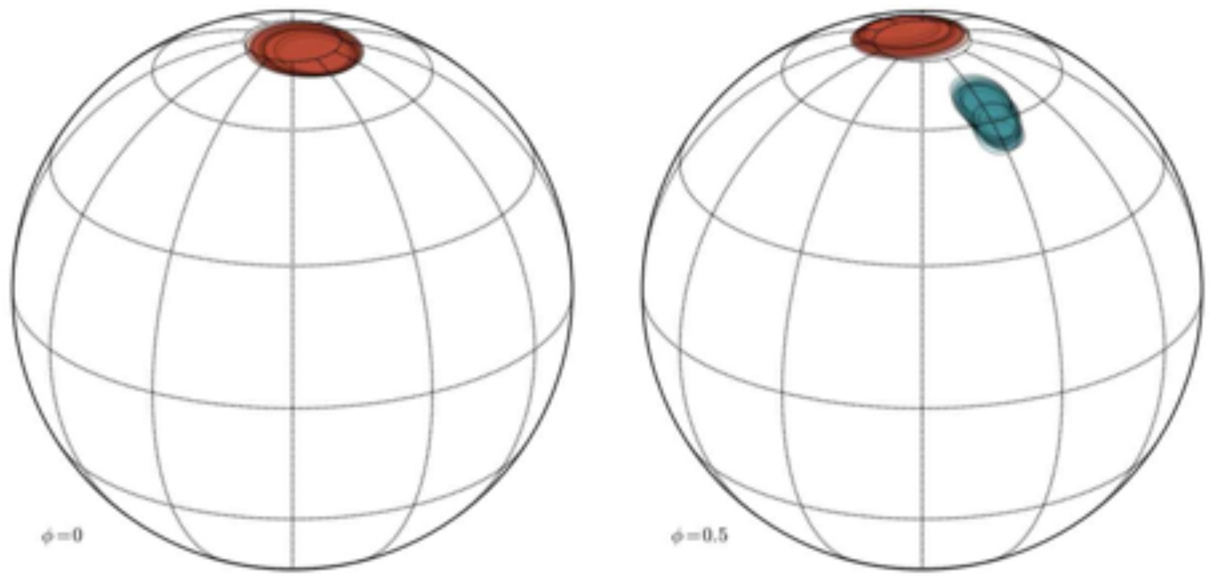


Hatzes: Frequentist methods can be useful for identifying cases when there's something funny going on in the data.

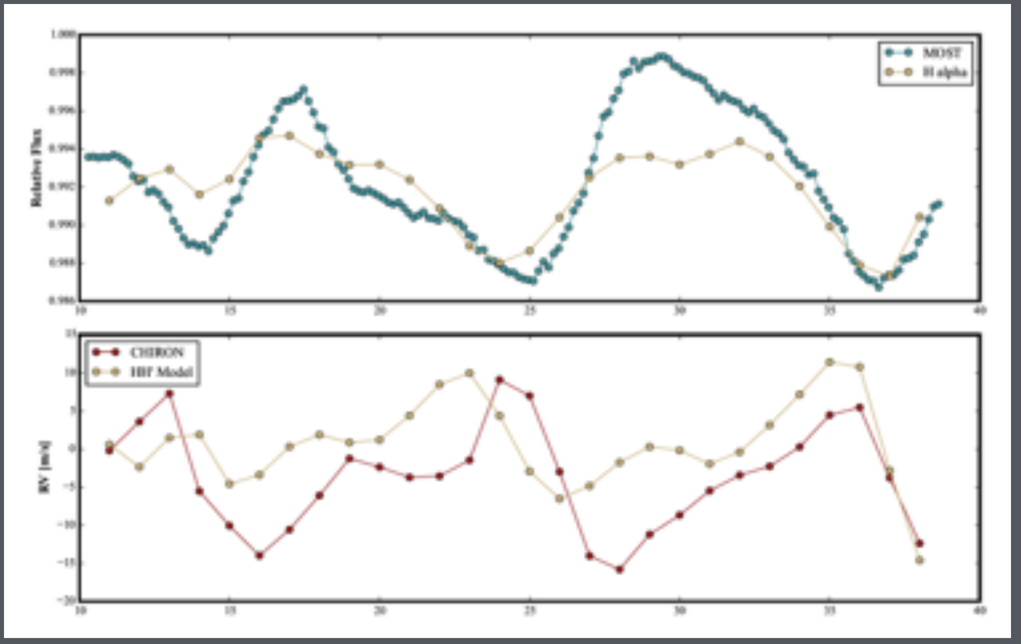
Matt Giguere (thesis work) modeling MOST + CHIRON



Matt Giguere (thesis work) modeling MOST + CHIRON



Matt Giguere (thesis work): HH'



A first step with one line; the information about stellar activity is embedded in our observations.

Take away message:

We don’t know if we will reach Earth v2.0 - detecting precision in RV measurements.

We still have some ideas to address the many challenges. As scientists we need to focus on the impossible as well as the possible.

The correct statement is this:

We don’t know that we cannot reach Earth v2.0 detecting RV precision!