Current Decade	2020-2030	2030-2040	After 2040

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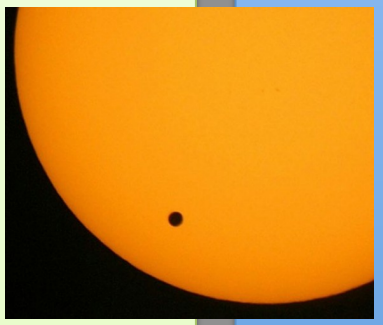
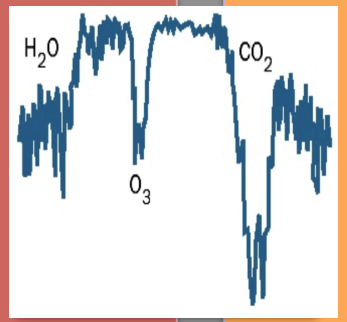
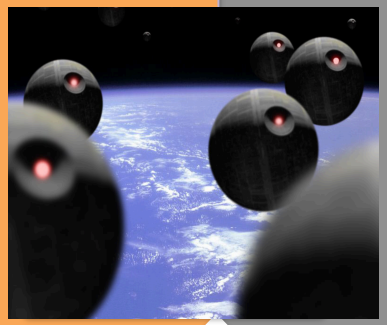
Science Roadmap

- What are the planetary architectures of nearby stars?
- Are they alive?
- How do we get there?



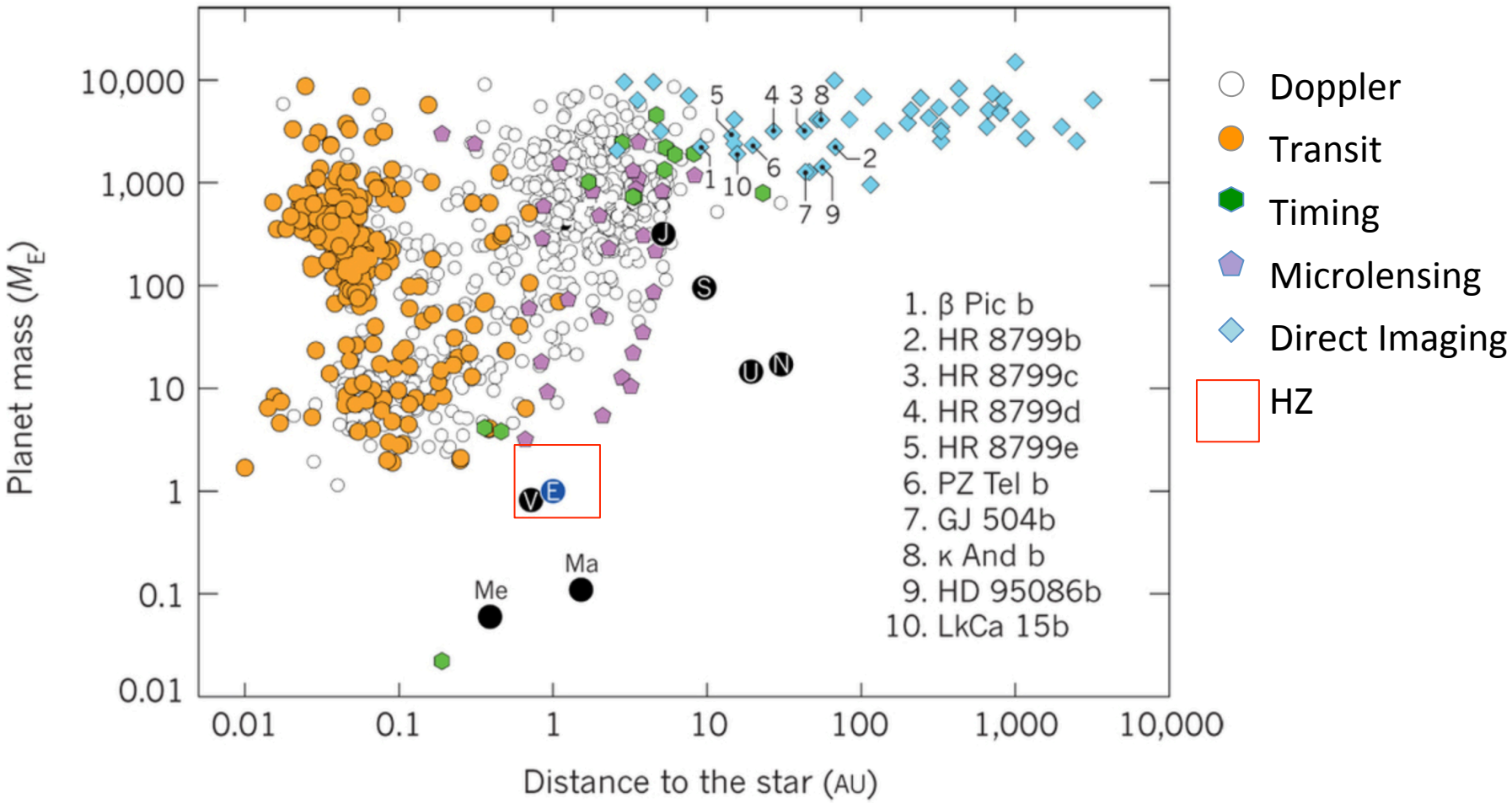




Mission Roadmap

- TESS
- JWST
- HST
- Spitzer
- Kepler
- WFIRST+C (?)
- SIM-Planet
- TPF-C
- NanoFleet

What are the planetary architectures of nearby stars?



Pepe, Ehrenreich & Meyer 2014, Nature 513, 358-366

What is Doppler precision?

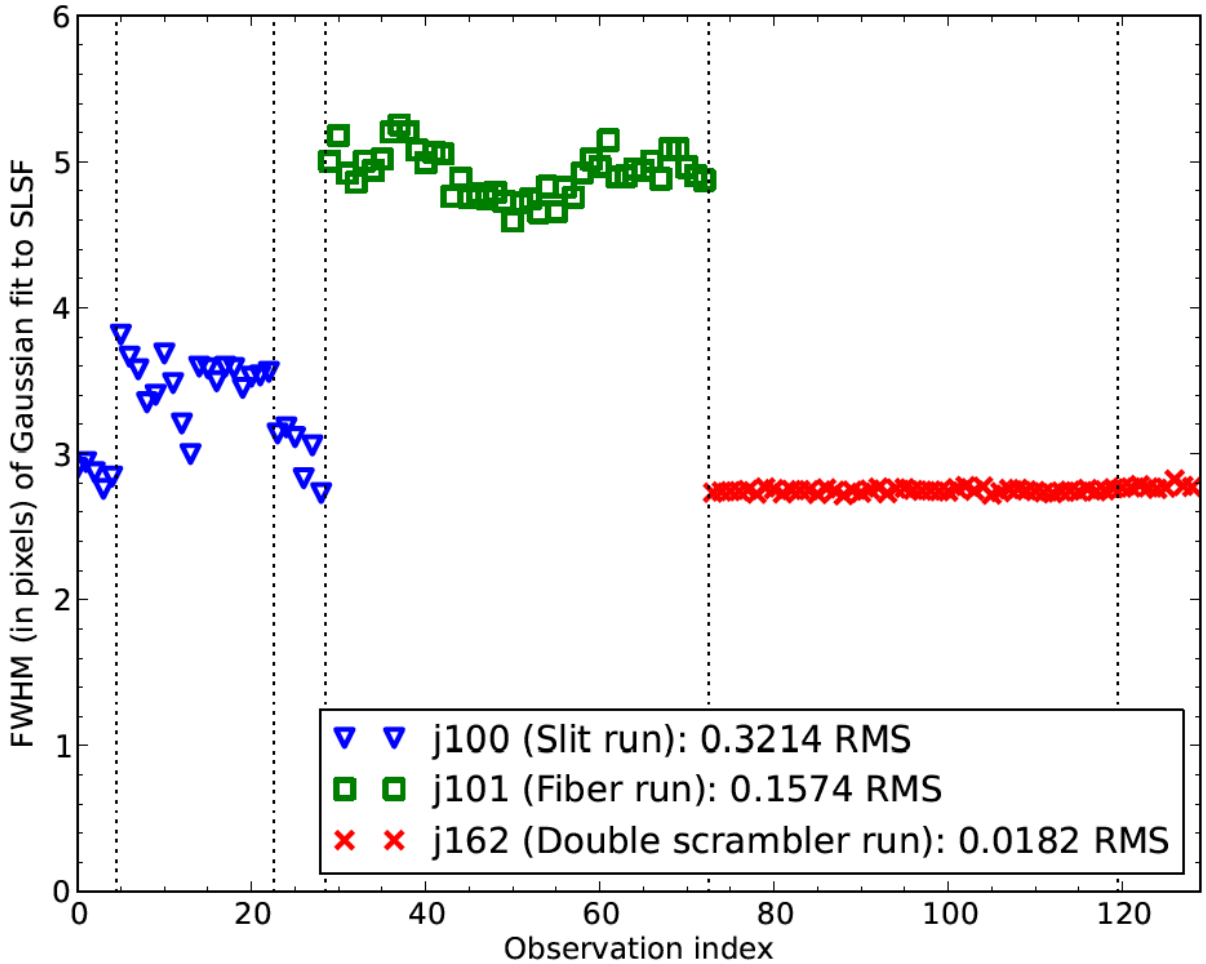
1. Single measurement precision (SMP[1]) that is f(SNR, technique, resolution…)
2. Short term RMS[2]: time baseline short compared to changes in magnetic fields, spot rotation etc. captures errors in the analysis technique and instrumental errors.
3. Long term velocity RMS (over one or more observing seasons) captures everything, including photospheric velocities / signals.

$$\text{ERROR} = \text{sqrt}[\ \text{SMP}^2 + \text{analysis}^2 + \text{IE}^2 + \text{photosphere}^2\ ]$$

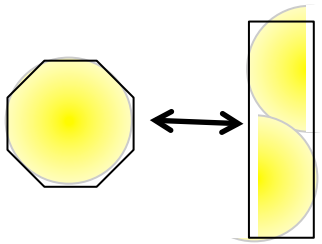
[1]Only precision that can be simulated in advance.
[2]Only precision that is useful for finding planets.

How low can we go? We are learning what doesn't work.

Keck HIRE test: slit, circular fiber, double fiber scrambler



Double Fiber Scrambler



Analyzed the DS data in 2 ways:

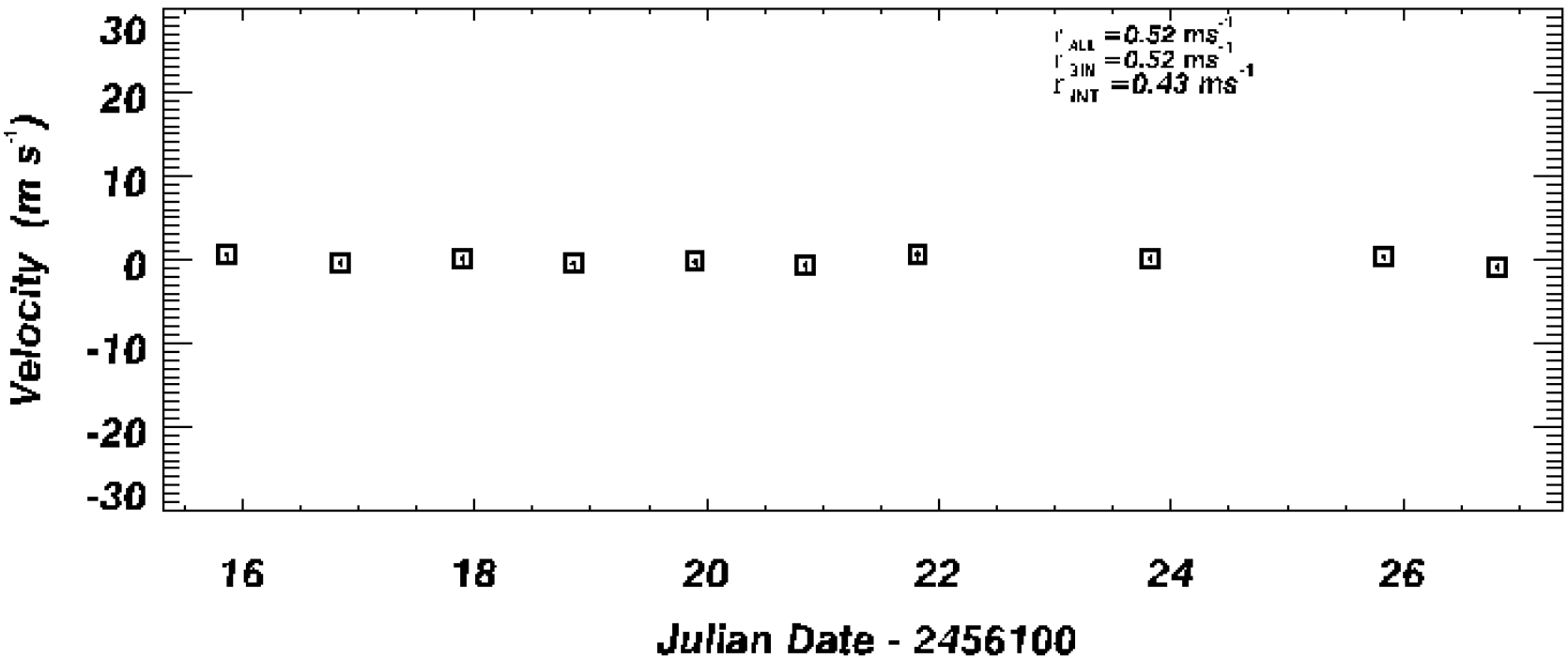
1. Same Doppler code as slit observations
(w0, disp, cont, Dopp shft, 17 PSF parameters)
Factor of 20 improvement in PSF stability.
No improvement in RV precision.

2. Calculated a median PSF from 56 Bstar observations; fixed this in the Doppler analysis (same spectra).
RV SMP dropped from 1 m/s to 0.9 m/s
RV RMS dropped from 2.1 m/s to 1.5 m/s: 40%
However, even with stable and fixed PSF, the Doppler errors with HIRES are still 1.5 m/s; not < 1.0.

1. We isolated one term in the Keck HIRES error budget: degeneracies or inaccuracies in modeling the PSF set a precision floor of 1.47 m/s. Won't find planets with HIRES with K < 1.5 m/s.

CHIRON has the advantage of high cadence, R=100,000 and more stability. In this plot showing 2 weeks of CHIRON RV measurements of Tau Ceti:

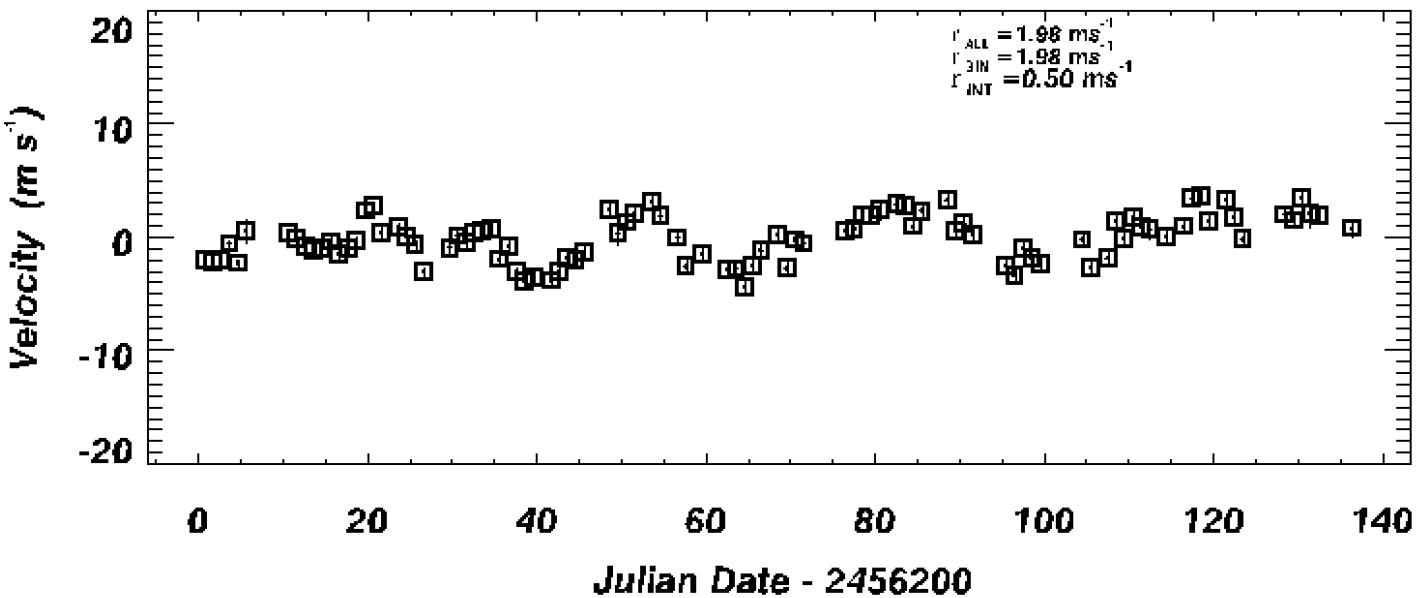
SMP=0.43 m/s and the short term RMS = 0.52 m/s.



Later in 2012:

SMP=0.5 m/s but the velocity RMS = 1.98 m/s

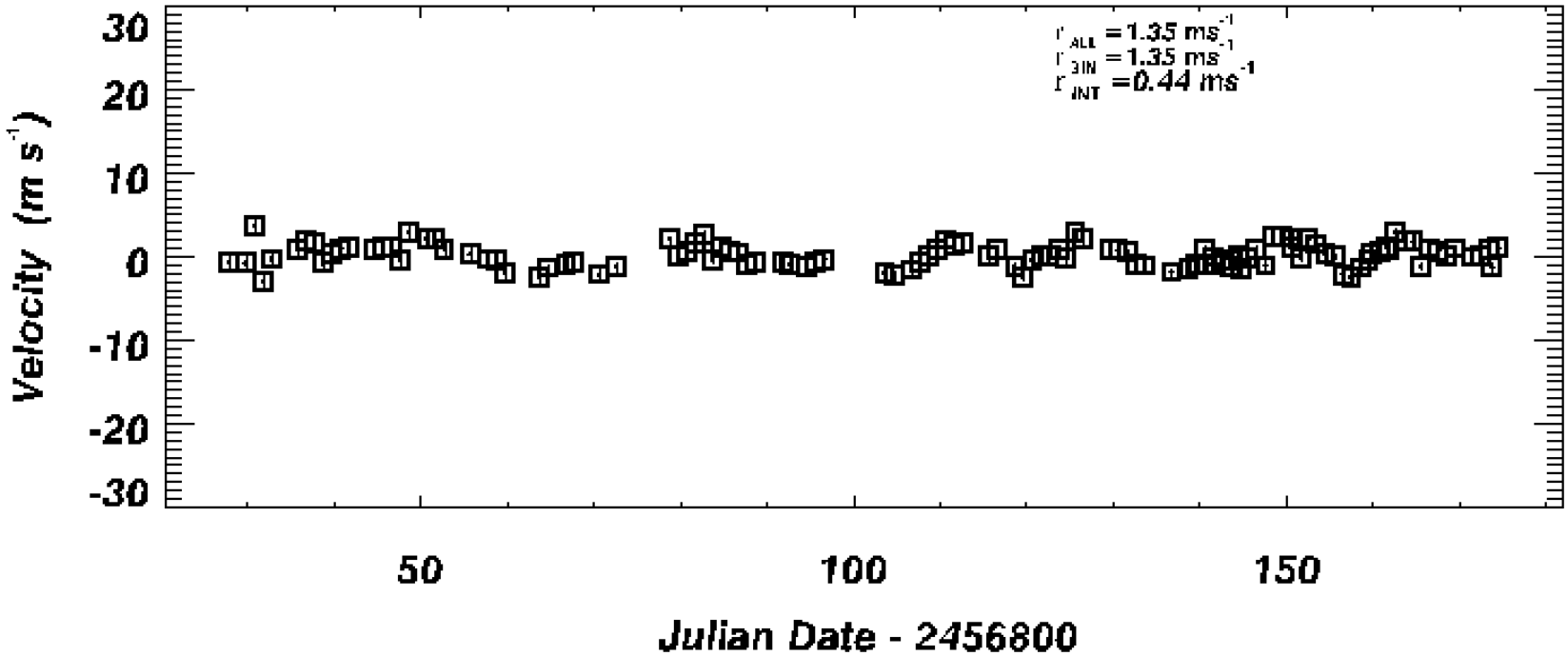
And there is clear structure – looks like spot noise (?).



In 2014: again see clear structure, but attenuated.

SMP=0.44 m/s but the velocity RMS = 1.35 m/s

We just completed a MOST campaign to check for photometric correlations with Eps Eri and Tau Ceti RVs.



A number of people are working on clever solutions to de-correlate embedded photospheric noise from center of mass Doppler shifts.

Aigrain et al. 2012: FF' method
Dumusque et al. 2014: SOAP 2.0
Robertson & Mahadevan 2014: FWHM variations in CCF
Bastien et al 2014: Photometric Flicker

All of the published work describes techniques for getting to residual RMS of 1.0 m/s. Hundreds (!) of observations are required to do better and it will be very challenging (maybe impossible) to get below residual RMS of 0.5 m/s.

WE ARE STUCK. WE HAVE BEEN STUCK FOR A LONG TIME.
It is time to get out of this box…. We won't be happy if all we can do is de-correlate photospheric signals.

WHY ARE WE STUCK?

Spectrometers with R < 100K cannot distinguish line profile variations from Doppler shifts. We will always get 1 m/s precision with these instruments.

Photospheric signals perturb the spectral line profile.
Photospheric signals have a dependence on line depth
(formation height in the star).
Photospheric signals have a color dependence (spot
contrast is lower at redder wavelengths.

Doppler shifts don't have these dependencies:
delta lambda = lambda * v/c

Should be able to distinguish these signals with very high resolution spectrometers (R~200K or more) – but then need big telescopes!

HOW DO WE GET UNSTUCK?

High resolution (R~100,000 can give 0.5 m/s errors, but not useable unless we understand “jitter” photospheric contributions).

Not enough to measure jitter – we need to solve for it. Probably need R > 200,000 to detect stellar noise – we are running simulations now to look for a break point in R.

High cadence. High cadence. High cadence.

New wavelength calibrators – I2 won’t work (and you want it out of the spectrum to see the photospheric effects and need broader wavelength coverage to use all the signal).

Are they alive?

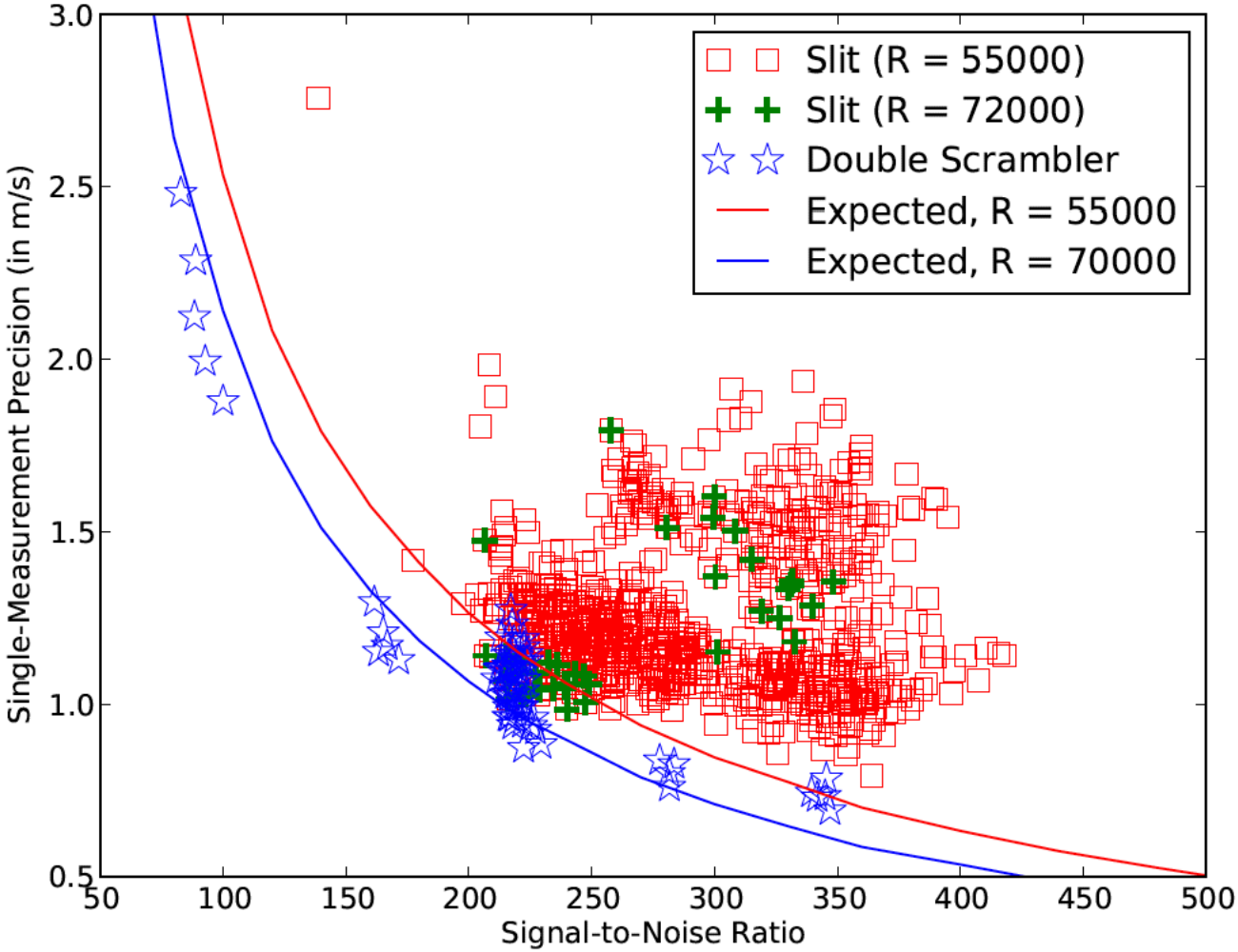
How do we get there?

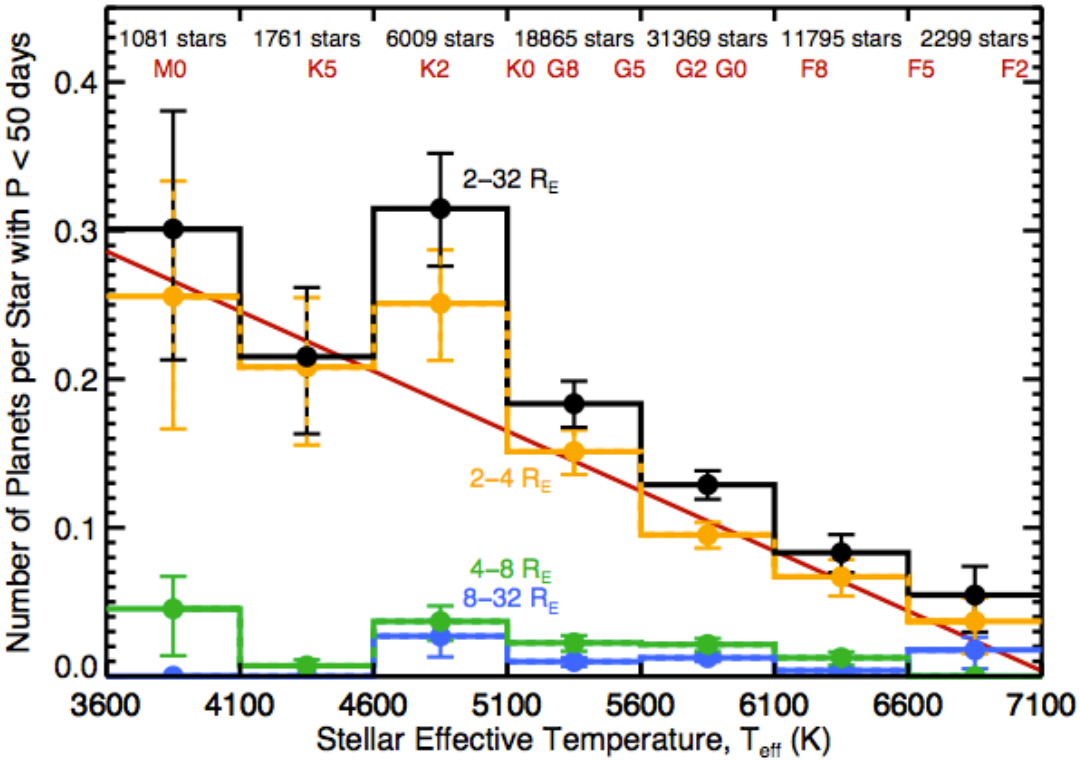
If we really do want to get to these big questions, we have to find the planets around nearby stars and understand the complex architectures.

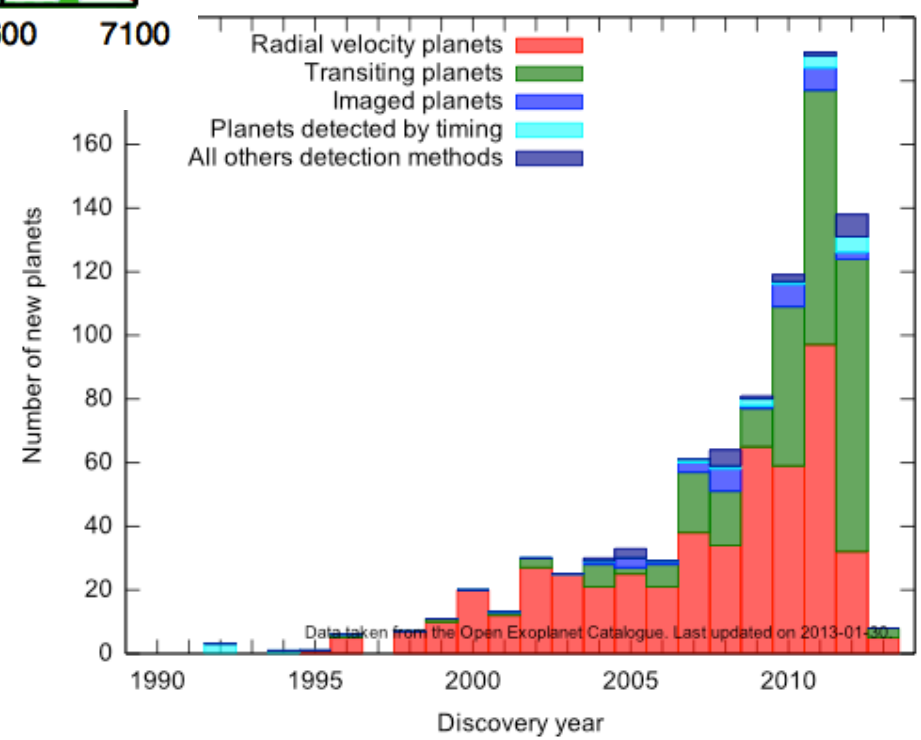
Unfortunately, we won't make significant progress with current instrument designs. We need out of the Doppler box thinking and some seed money for investing in technology development.

Likely need synergy of many techniques: circle of friends, not inward shooting!

Extra slides


Slit (R = 55000)
Slit (R = 72000)
Double Scrambler
Expected, R = 55000
Expected, R = 70000
Single-Measurement Precision (in m/s)
Signal-to-Noise Ratio
3.0
2.5
2.0
1.5
1.0
0.5
50
100
150
200
250
300
350
400
450
500


1081 stars
1761 stars
6009 stars
18865 stars
31369 stars
11795 stars
2299 stars
M0
K5
K2
K0 G8
G5
G2 G0
F8
F5
F2
2–32 R_E
2–4 R_E
4–8 R_E
8–32 R_E
Number of Planets per Star with P < 50 days
Stellar Effective Temperature, T_eff (K)
0.0
0.1
0.2
0.3
0.4
3600
4100
4600
5100
5600
6100
6600
7100


Radial velocity planets
Transiting planets
Imaged planets
Planets detected by timing
All others detection methods
Number of new planets
Discovery year
Data taken from the Open Exoplanet Catalogue. Last updated on 2013-01-30
0
20
40
60
80
100
120
140
160
1990
1995
2000
2005
2010