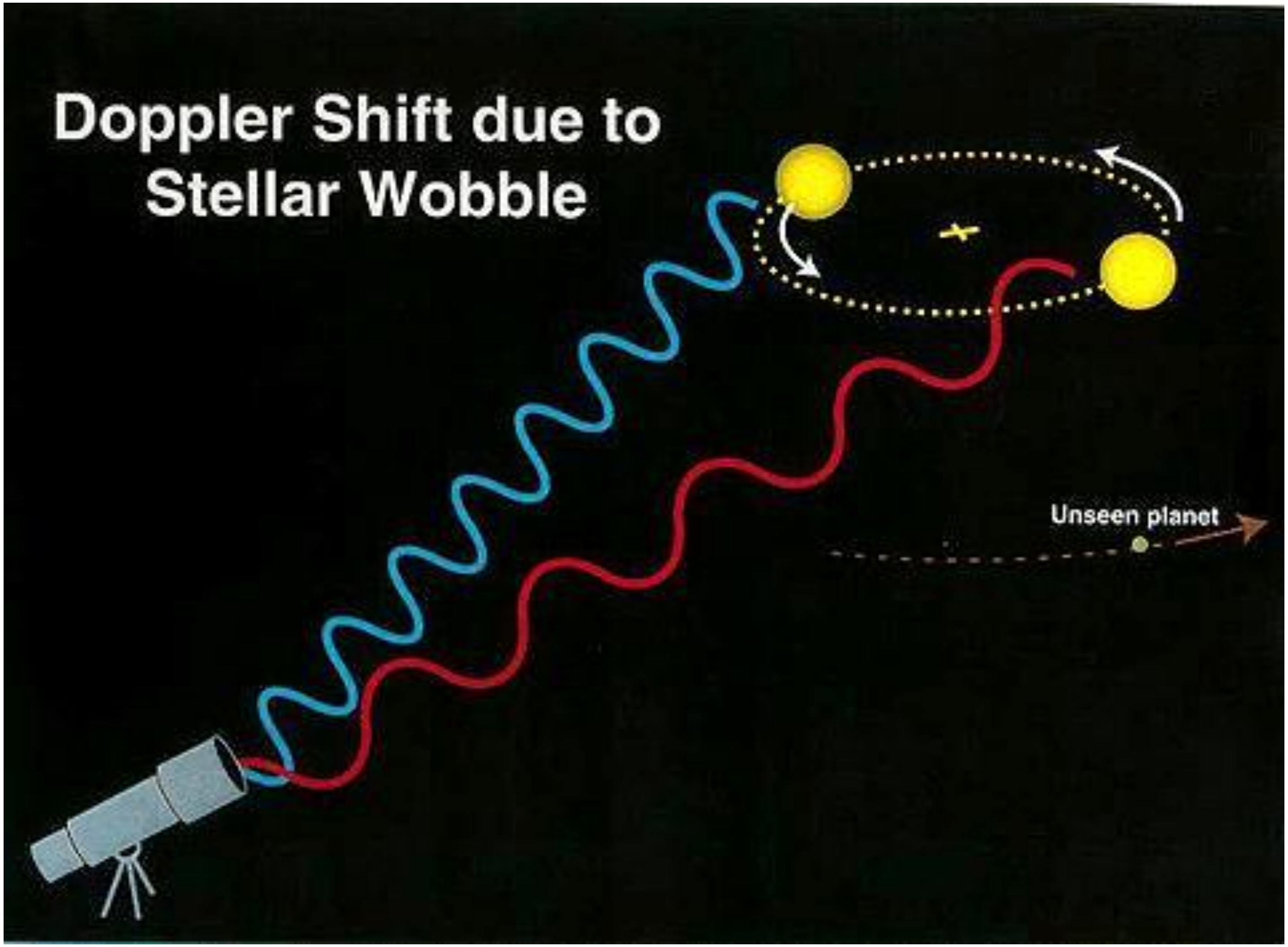
Radial Velocity Study Analysis Group 8

Co-Chairs: Dave Latham, Peter Plavchan
NASA Exoplanet Science Institute, Caltech

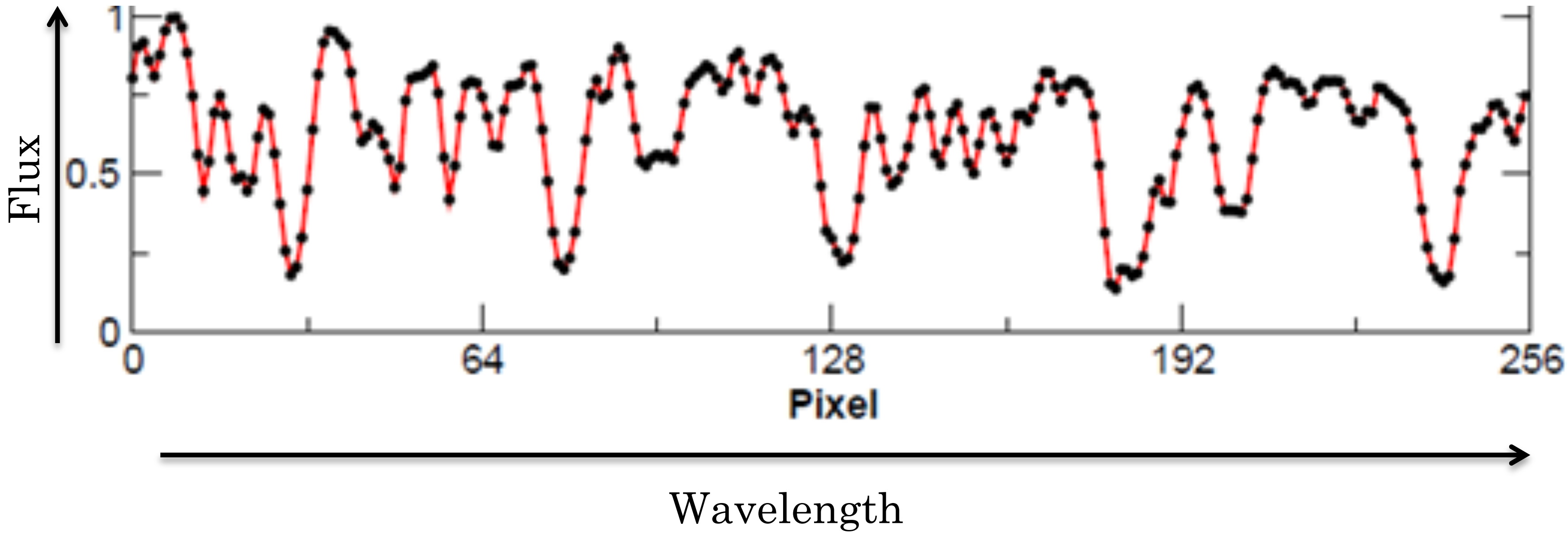
Outline

- **RV Method Review & Recent Highlights**
- ExoPAG 6 Mini-Workshop Recap
- Astro 2010 Report & NSF Portfolio Review
- RV SAG Goals & Current Status
  - Survey Science Drivers and Wavelength
  - Ongoing and Upcoming Surveys / Facilities
  - Instrumentation Approaches

RV Method Review



RV Method Review – a single order of a spectrum



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wavelength shift ~ 1 nm on a detector pixel

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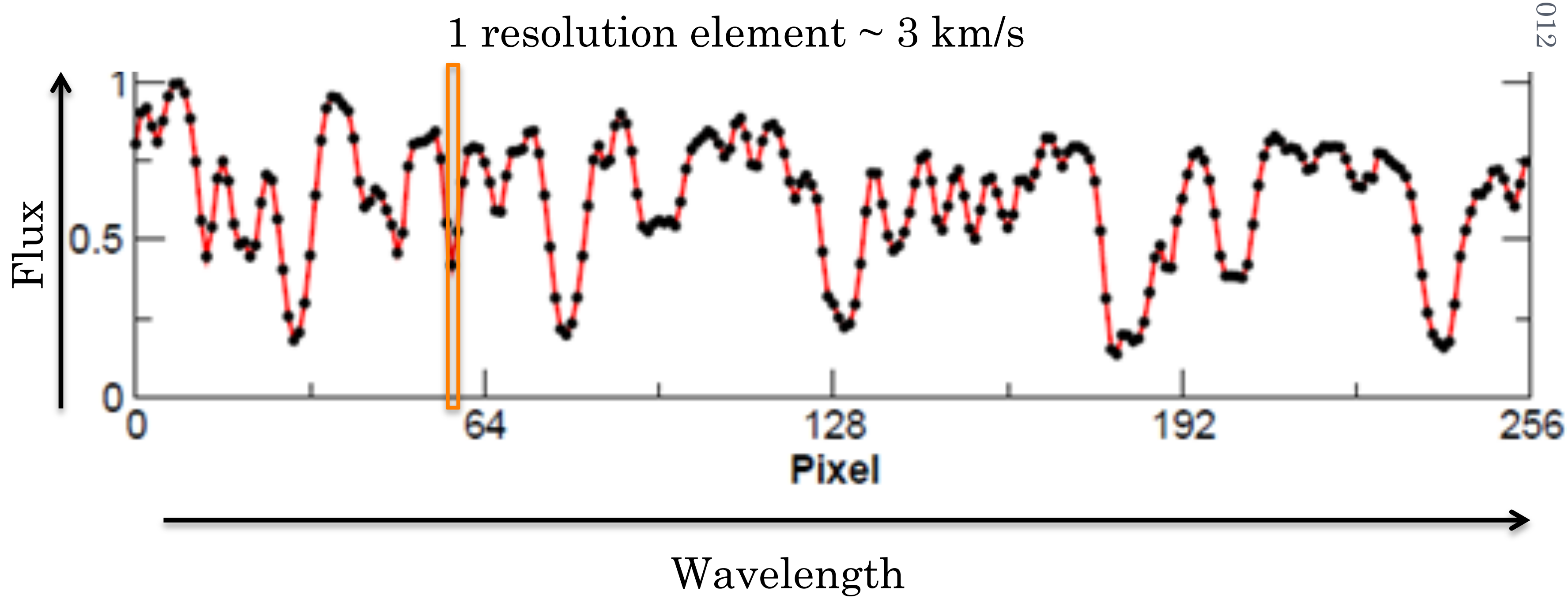

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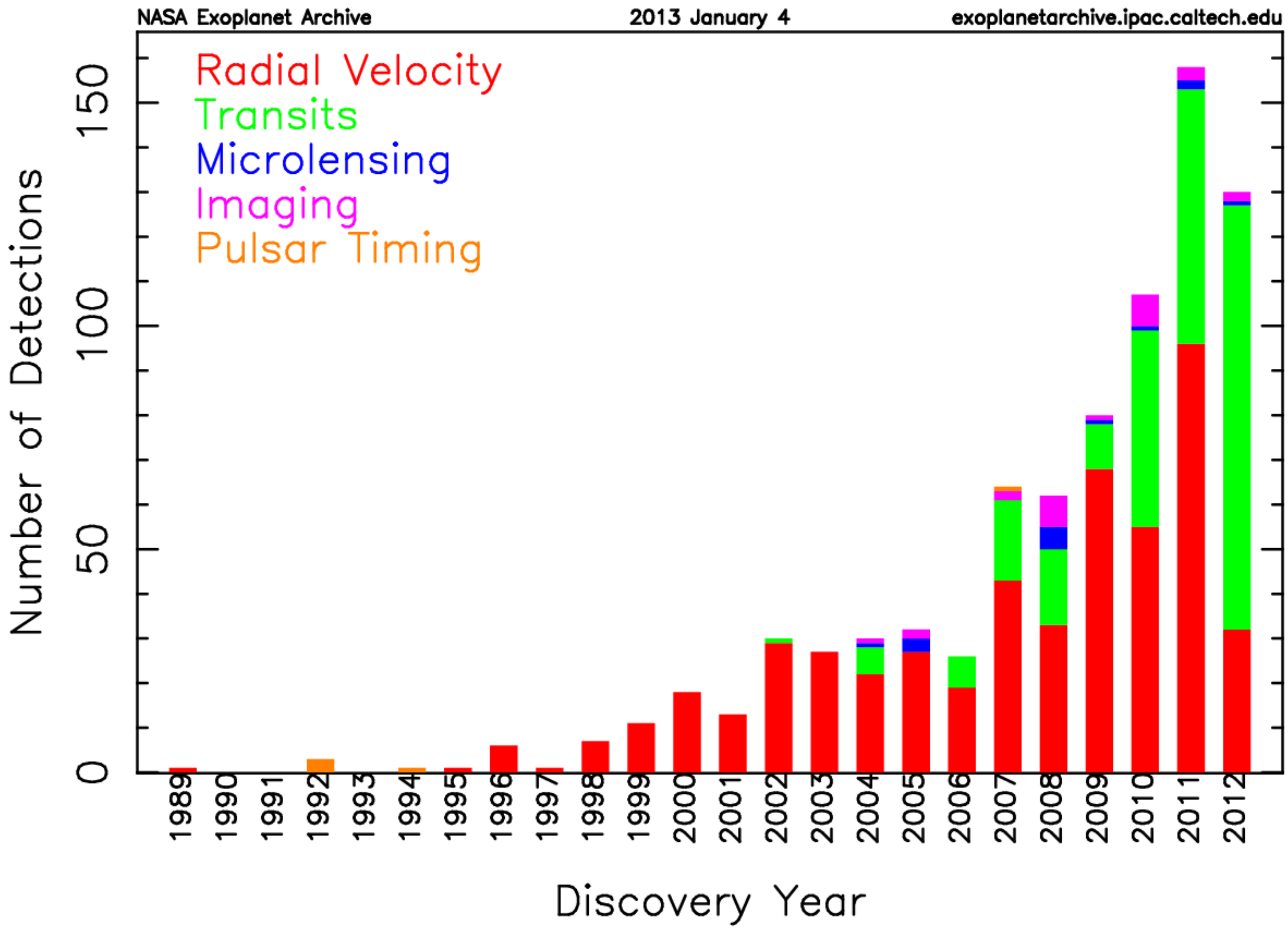
wavelength shift ~ 1 nm on a detector pixel

Takeaway: Precision RVs are firmly in the systematic noise regime

1989-2013 – Turning Science Fiction into Fact and a Census of Extrasolar Planetary Systems



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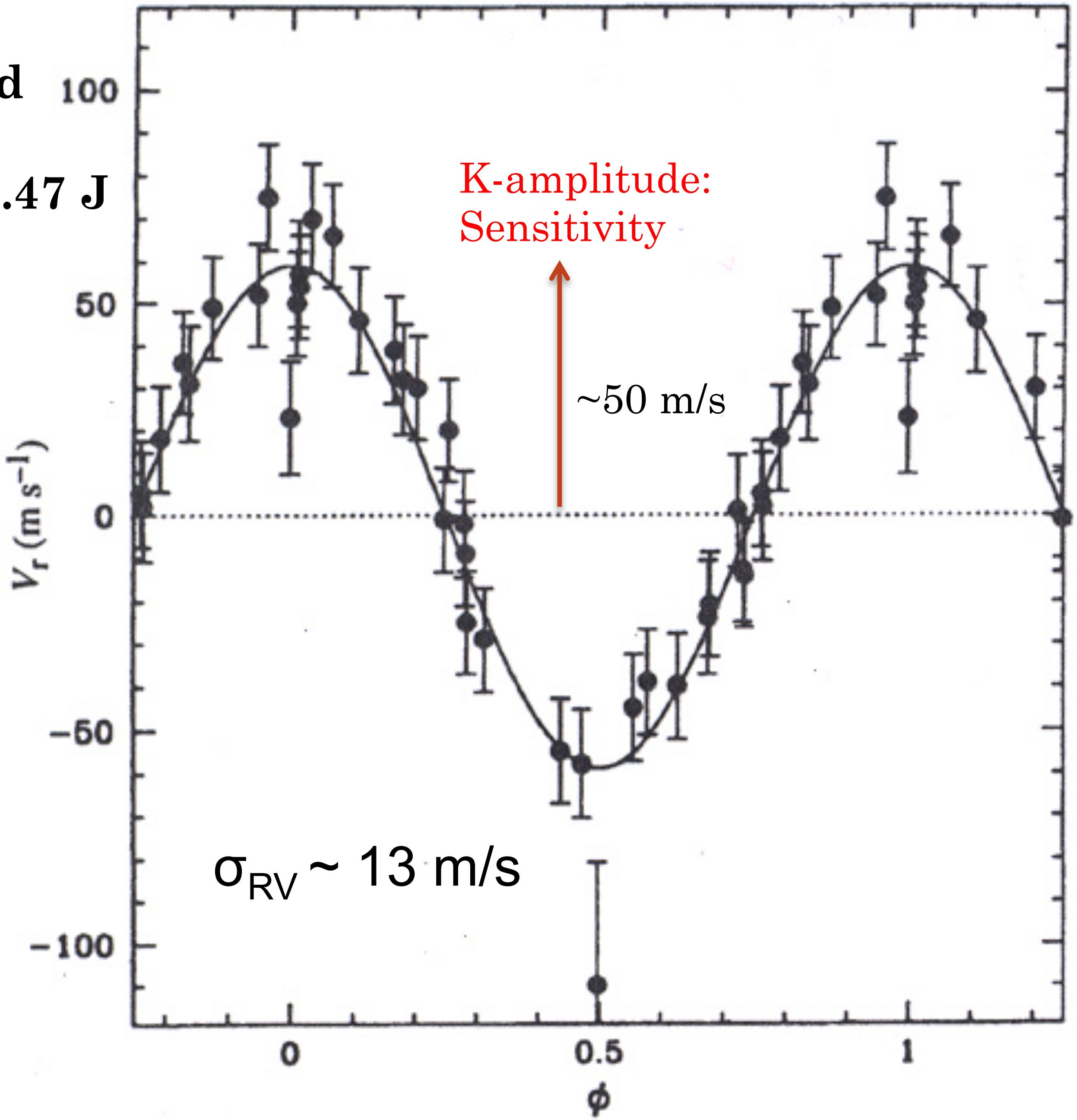
- Water-worlds & Super-Earths
- Direct RV detection (Tau Boo b; Rodler et al 2012; NIR)

51 Peg **Mayor & Queloz 1995**

P = 4.23 d

m sin$i$ = 0.47 J



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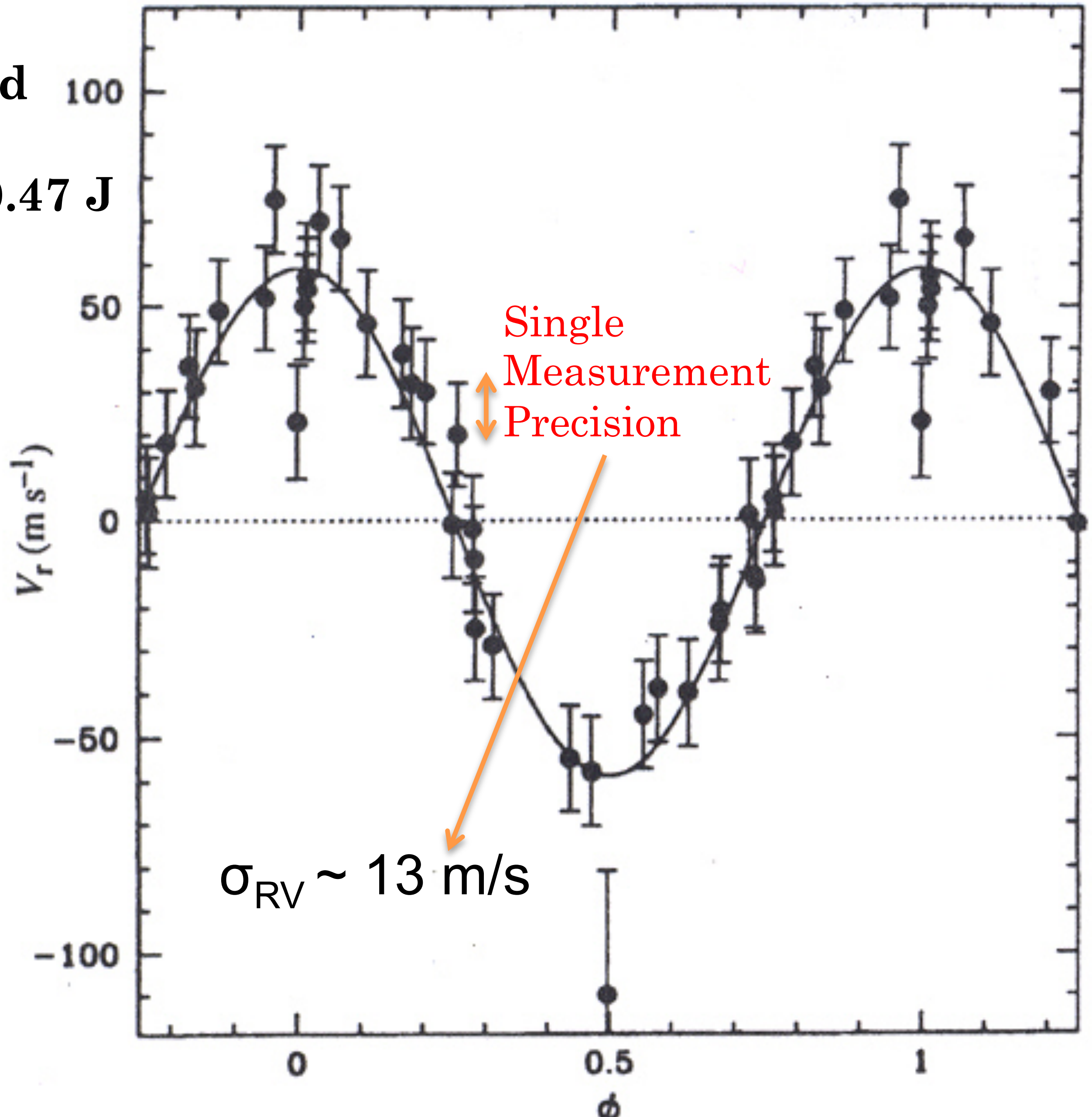

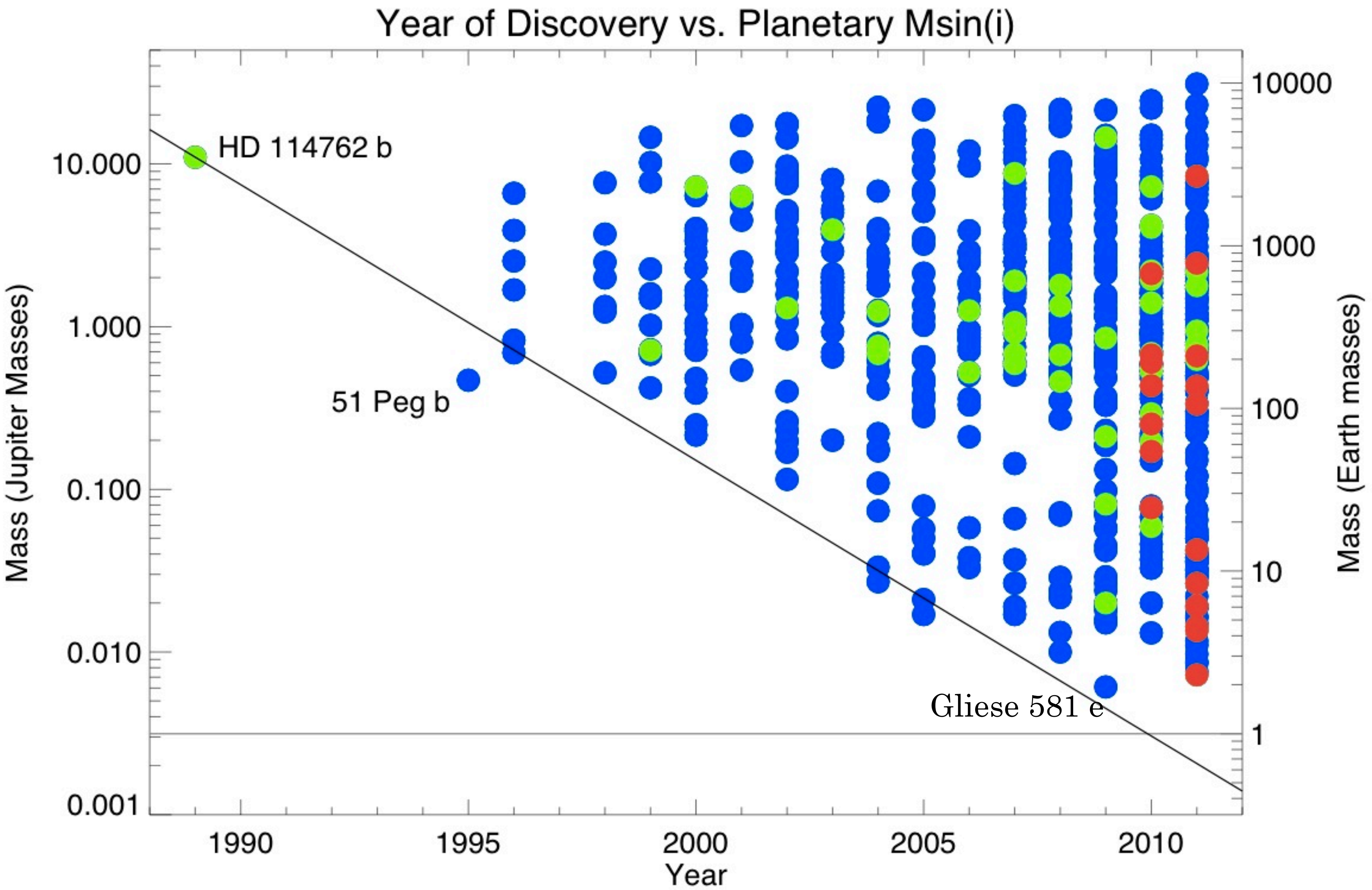

Year of Discovery vs. Planetary Msin(i)
HD 114762 b
51 Peg b
Gliese 581 e
Mass (Jupiter Masses)
10.000
1.000
0.100
0.010
0.001
Mass (Earth masses)
10000
1000
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10
1
1990
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2010
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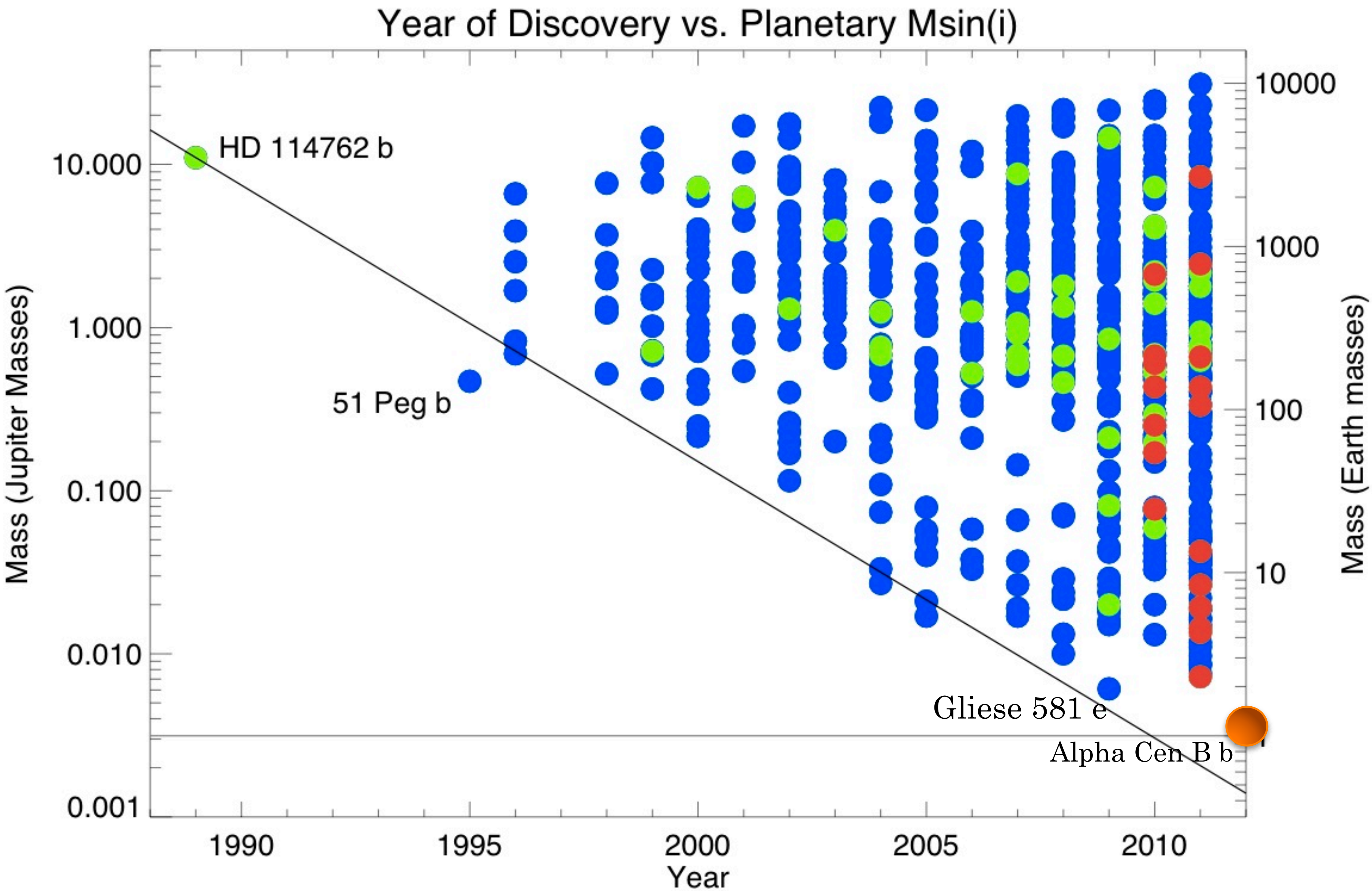
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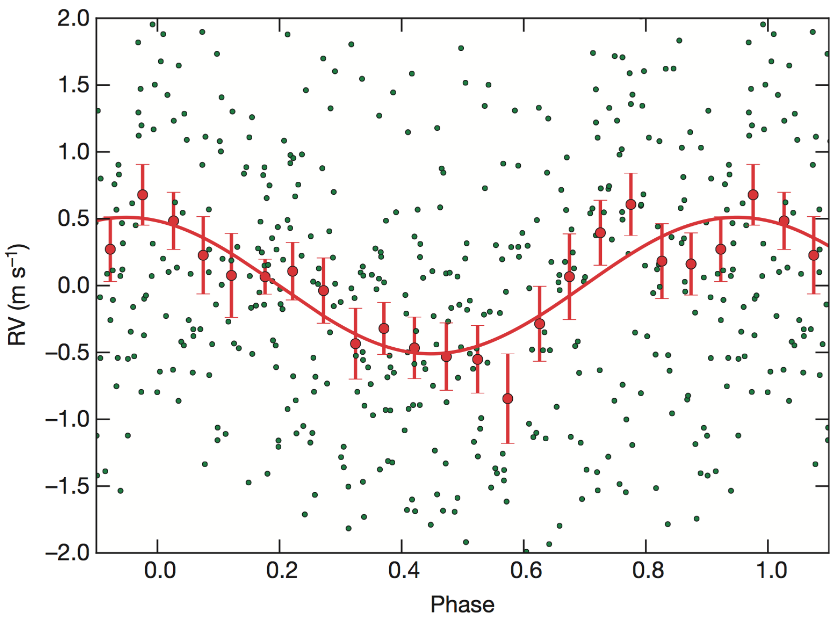
Alpha Cen B b - Dumusque et al. 2012, Nature, 491, 207

- 3.2357 day period (~11 stellar radii)
- 1.13 Earth masses
- 0.934 Solar Mass host star in 80 year binary
- K = 51 cm/s RV semi-amplitude
- 4 cm/s RV semi-amplitude uncertainty
- 459 observations over four observing seasons
- 1.2 m/s RV residuals → lots of binning and understanding “noise” from both star and instrument really well.



→ Dave Latham’s talk tomorrow

Takeaway: Alpha Cen B b is the nearest known exoplanet to our Sun, and represents a non-incremental advance with the RV technique.

A New "Statistical Planet" Regime for RVs: Tau Ceti Tuomi et al. 2013, A&A

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- Planet periods seen in multiple independent data sets

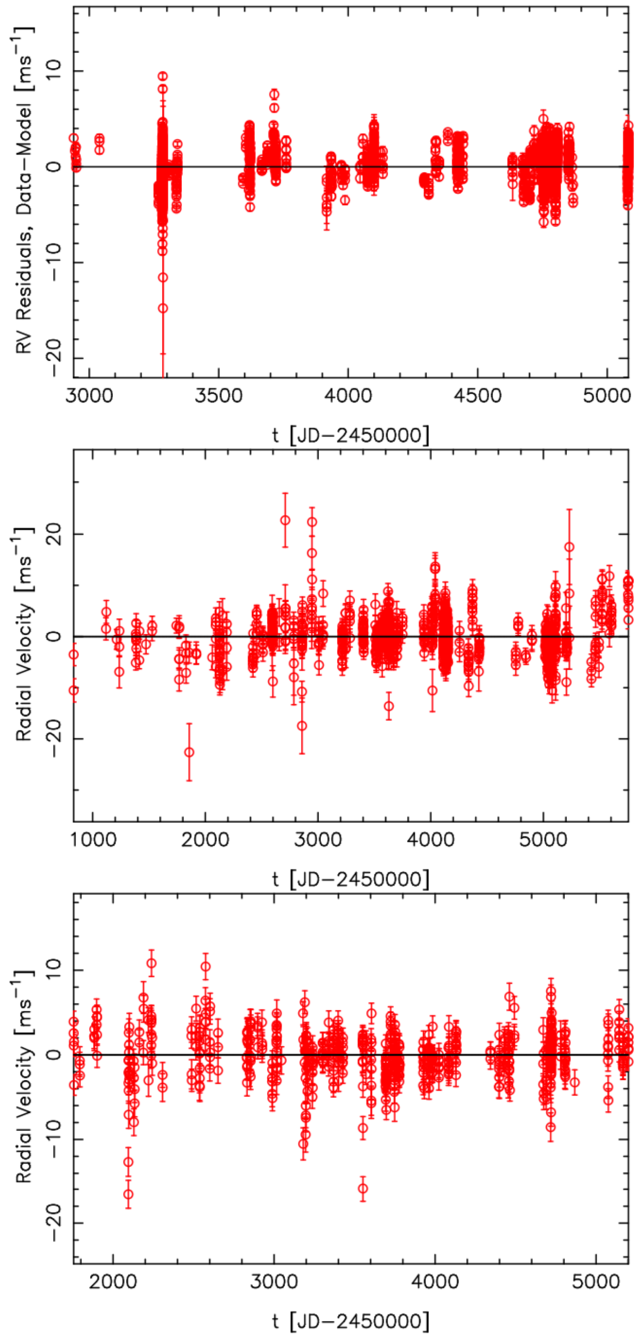

Fig. 1. HARPS (top), AAPS (middle), and HIRES (bottom) RVs with their respective mean estimates subtracted.

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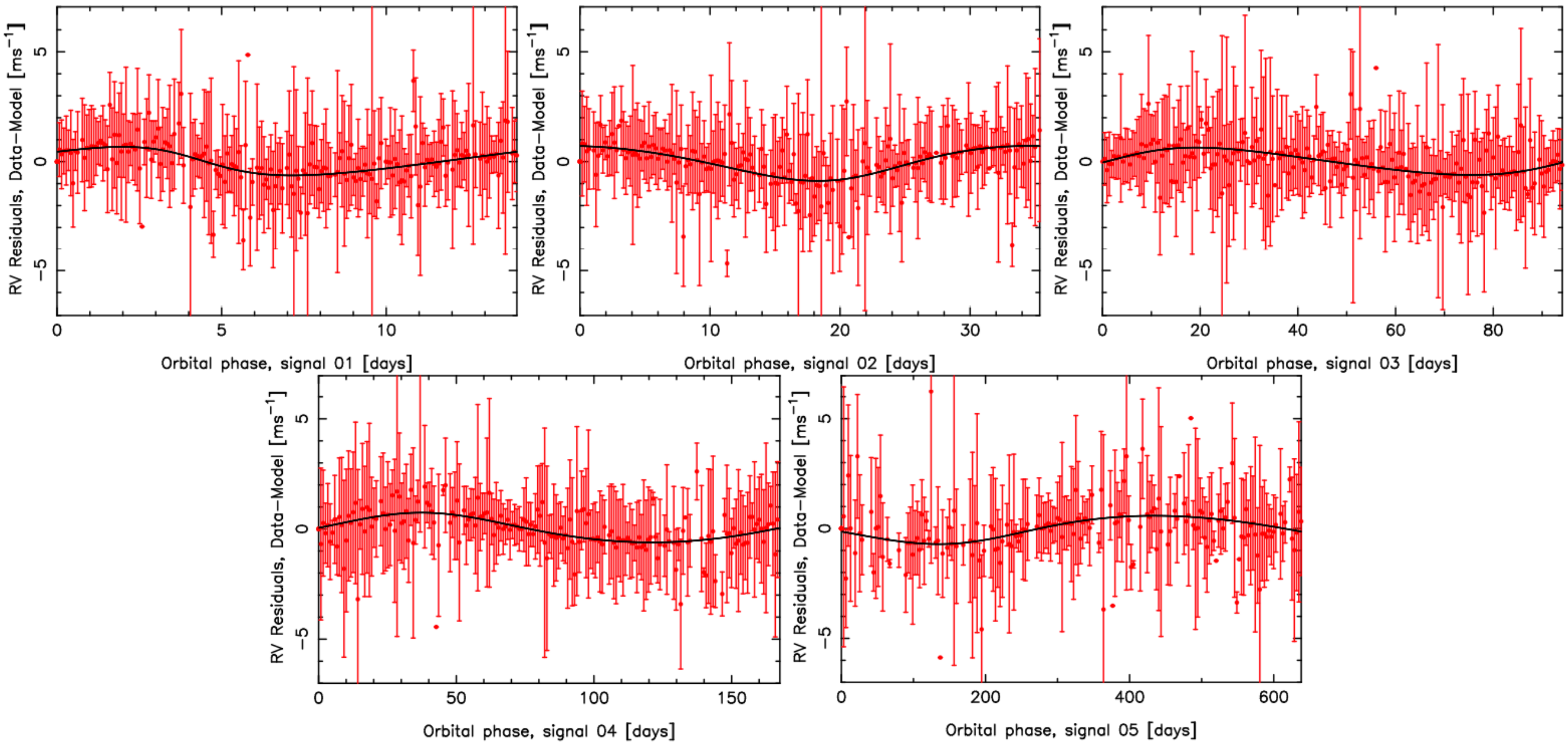

Fig. A.1. Phase-folded Keplerian signals for the combined HARPS, HIRES, and AAPS data. Orbital phase of each signal is divided into 200 bins and the means and the corresponding standard deviations of the data in each bin are plotted together with the Keplerian signal.

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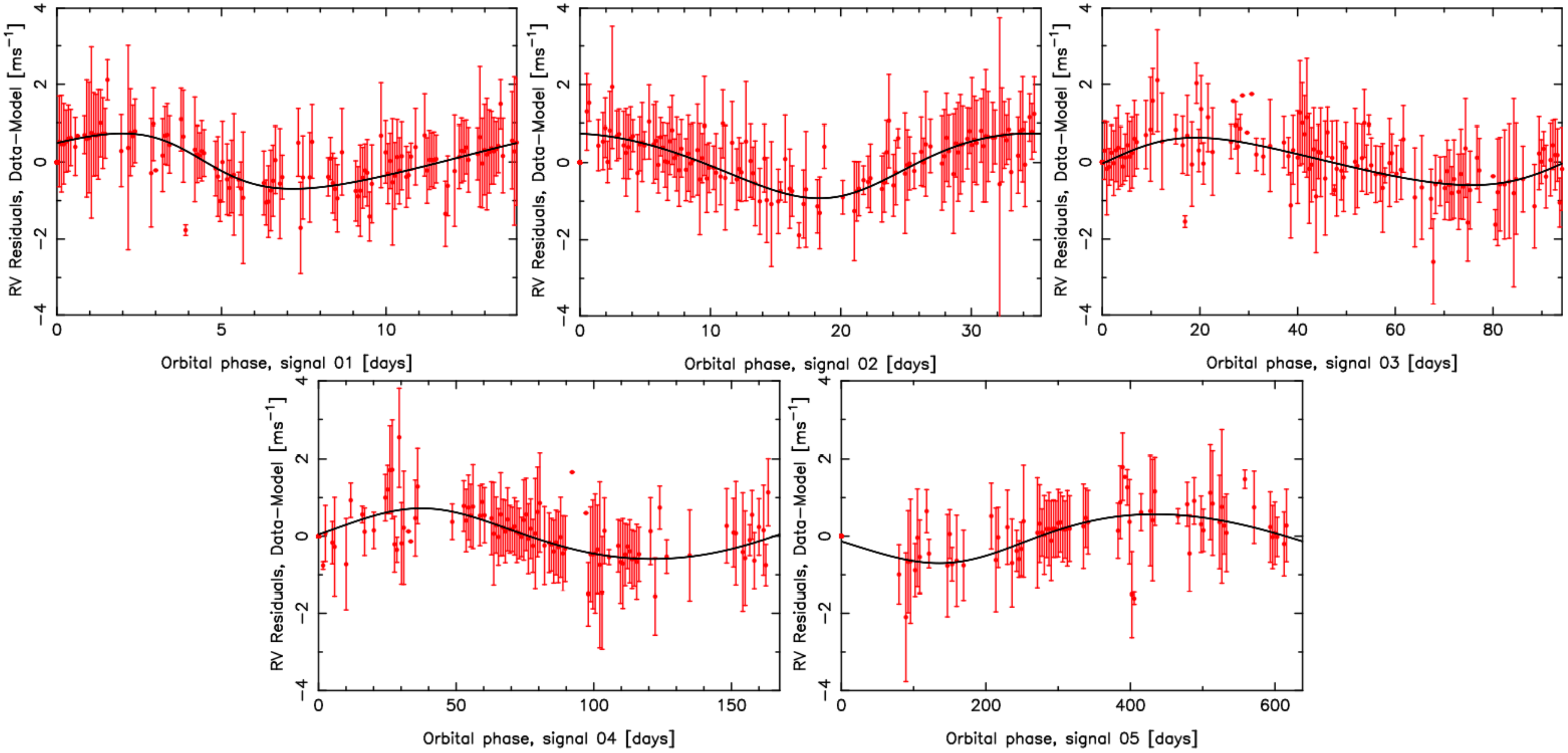

Fig. A.2. As in Fig. A.1 but for the high-precision HARPS data alone.

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- Analysis relies heavily on a large number of observations and binning
- Simple Gaussian noise model replaced with:
  - Moving average correlated noise component with a variable width
  - An exponential decay auto-regressive noise component with a variable decay time
  - Two Gaussian white noise component for measurement noise and “excess noise”
- Bayesian evidences are compared for 0..N planets with the assumption that the noise model is correct
  - In principle, this set of hypotheses could be incomplete if the noise model is inaccurate – ie, if some of the RV variations are not due to planets but stellar components
- Periods strongly converge with MCMC analysis

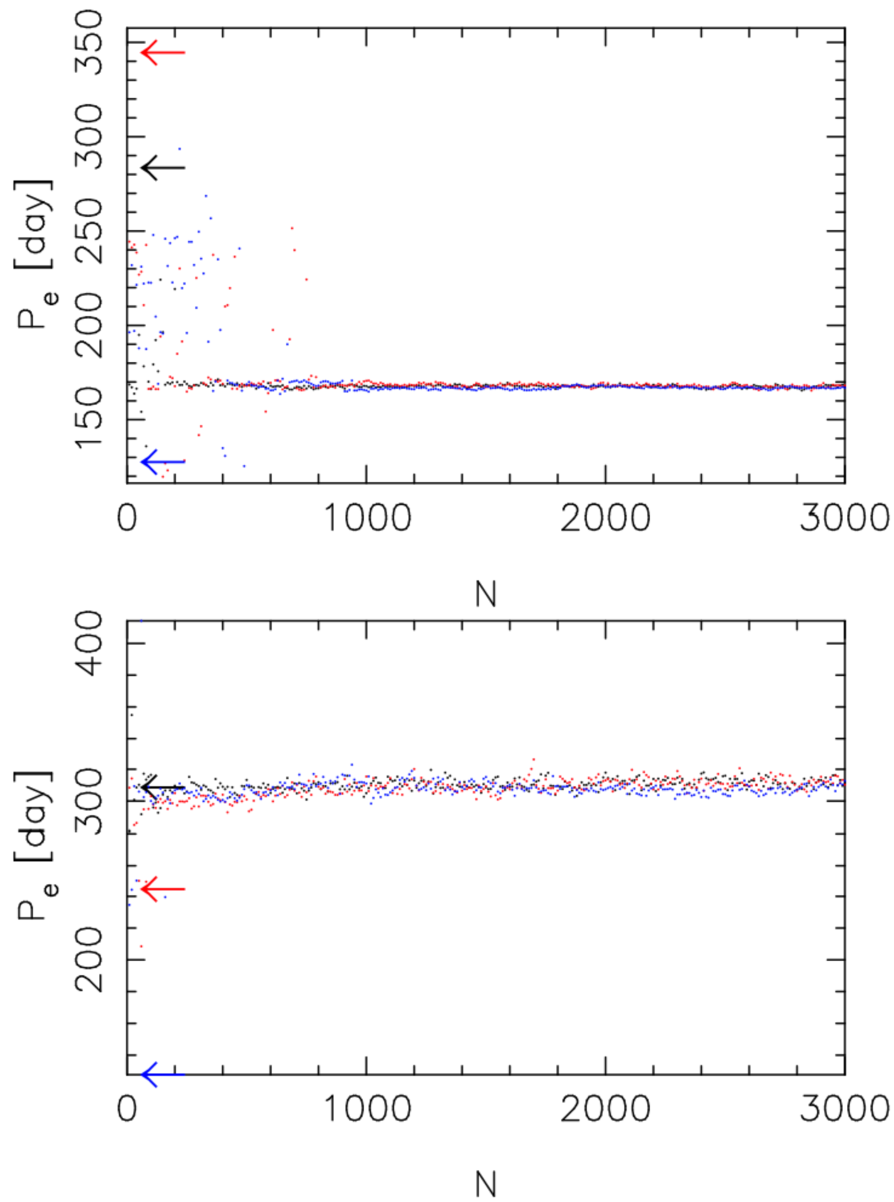

Fig. 12. Convergence of the period of the fifth Keplerian as a function of Markov chain length to periods of 168 (top) and 315 days (bottom). The details of the panels are as in Fig. 11 but the chains have been thinned by a factor of ten.

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- Periods strongly converge with MCMC analysis
- Authors are able to recover injected signals at similar periods and semi-amplitudes
- Semi-amplitudes are less reliable and biased towards larger values than injected

A New "Statistical Planet" Regime for RVs: Tau Ceti Tuomi et al. 2013, A&A

- This type of Bayesian analysis applied to radial velocity is not new:
  - Gregory, P. & Loredo 1992, ApJ, 398,146 – Bayesian Periodograms
  - Feroz, Balan & Hobson, 2010, MNRAS, 415, 3462
  - Feroz, Balan & Hobson, 2011, MNRAS, 416, L104
  - Gregory, P. & Fischer, D., 2011, MNRAS, 403, 71 – 47 Ursa Majoris
  - Gregory, P., 2011, MNRAS, 410, 94 – methodology
  - Gregory, P., 2011, MNRAS, 415, 2523 – GJ 581
  - Gregory, P., 2012, MNRAS, submitted – GJ 667C
    - A number of periods identified appear to be dynamically unstable, and could be associated with differential stellar rotation. → False-positives?
  - Etc.
- Takeaway points:
  - Important question for the community: how will we "confirm" these statistical exoplanets and/or validate this statistical approach?
  - These recent announcements and analysis are intriguing but deserve further validation and scrutiny.

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ExoPAG 6 Mini-Workshop Recap

Talks by:

- Peter Plavchan, Overview & SAG Goals
- Dave Latham, Kepler Followup + HARPS-N
- Andy Szentgyorgyi, G-CLEF
- Phil Muirhead, General PRV / High-Res Requirements
- Suvrath Mahadevan, NIR RVs + HPF
- Valeri Makarov, Limits of RV Precision

More PRV talks today and tomorrow!

- Andreas Quirrenbach – CARMENES
- John Johnson - The Ingredients for Precision Radial Velocimetry
- Dave Latham - The Case of Alpha Cen B

An incomplete list of current and upcoming visible RV facilities:

HIRES/eta Earth Future: SHREK?	1.5 – 2.0 m/s precision ~ 20 nights per year
HARPS-N&S (N first light 2012)	Sub-1 m/s precision ~ 80-100 nights per year
APF Currently inactive	1.5 – 2.0 m/s precision ~ year-round
CHIRON	Sub-1 m/s precision
LCOGT, MINERVA	Distributed telescope arrays Sub-1 m/s precision

EXPRESSO/VLT, G-CLEF/GMT, CODEX/E-ELT
Etc…

The future of NIR PRVs:

Takeaway: There is a rich ensemble of planned instrumentation in both the visible and NIR

CARMENES	Calar Alto	0.5-1.8 microns R~80k	Andreas Quirrenbach
CRIRES	VLT	5 m/s @ K R~100k	Bean et al. 2010
CSHELL	IRTF	~7 m/s @ K R~46k	Anglada-Escude, Plavchan et al. 2012
ESPaDOnS	CFHT	0.3-1 micron R~70k	Jean-Francois Donati
HPF	HET	~3 m/s @ YJH (~10 m/s w/ PATHFINDER) R~50k	Suvrath Mahadevan
iSHELL	IRTF	~2-3 m/s @ K R~75k	John Rayner
iGRINS	Harlan Smith @ McDonald	HK R~40k	Dan Jaffe
NIRSPEC2	Keck	JHKLM R~50-100k?	Ian McLean

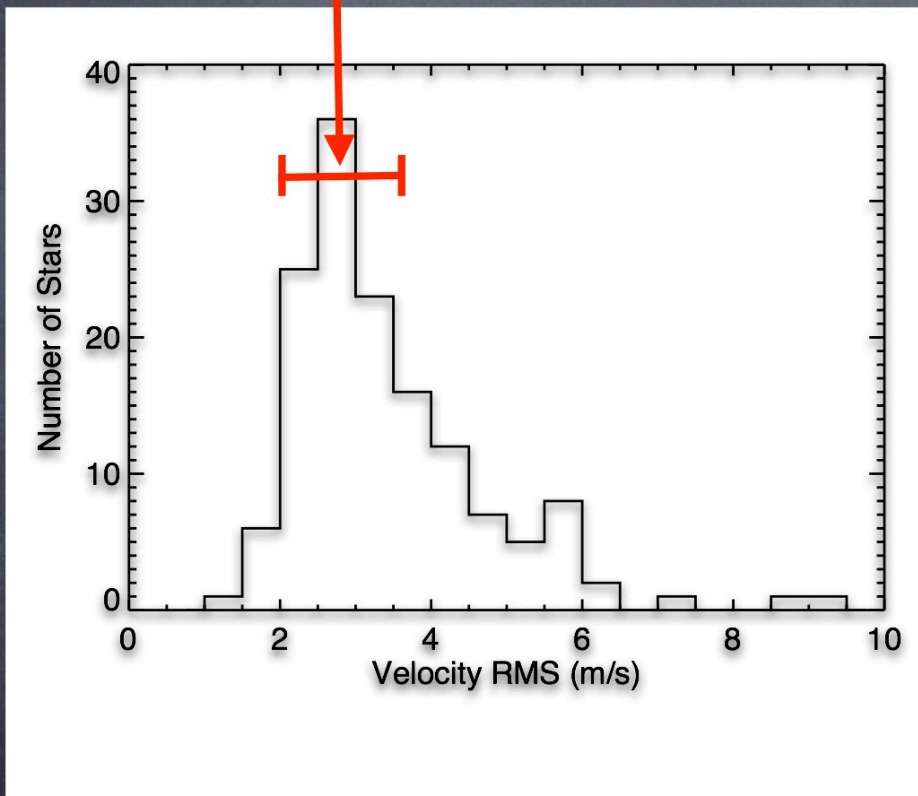
Techniques for Precision RVs

- Essentially there are two instrumentation philosophies
  - Gas cells + fiber scrambler (HIRES)
    - Correct for systematics from imperfect spectrographs in data processing with common optical path wavelength calibration
  - End-to-end extreme stabilization of telescope and spectrograph + lamps (HARPS)
    - Allows for non-common optical path wavelength calibration
  - → Philosophies not mutually exclusive

Velocity RMS

2-3.5 m/s

1-3 m/s



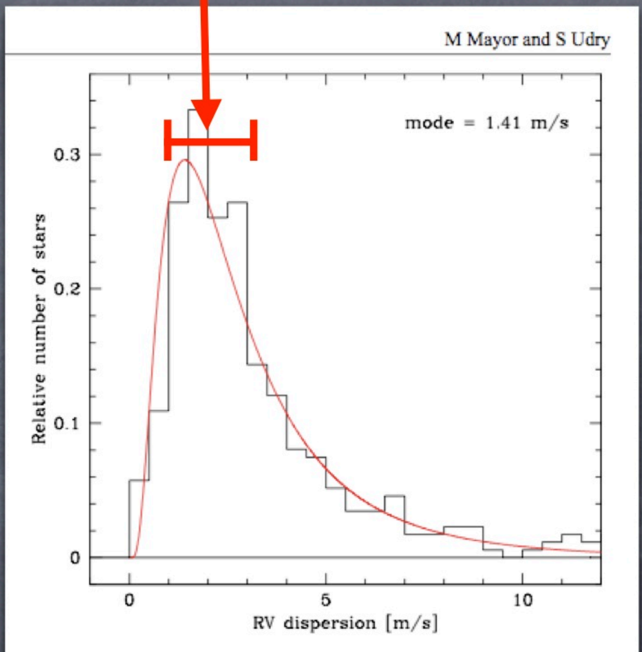


Figure 2. Histogram of radial-velocity rms for the stars in the high-precision HARPS subprogramme aiming at detecting very low-mass planets. Part of the 'large' rms observed in the tail of the distribution results from stellar activity or from still undetected planetary systems.

HIRES

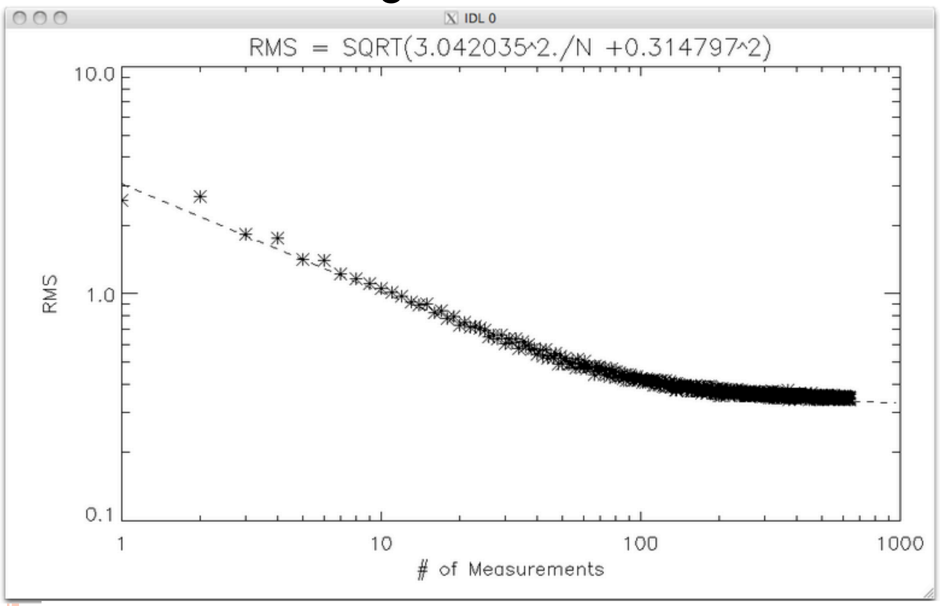
GK stars in Eta-Earth Survey
Known planets removed

HARPS

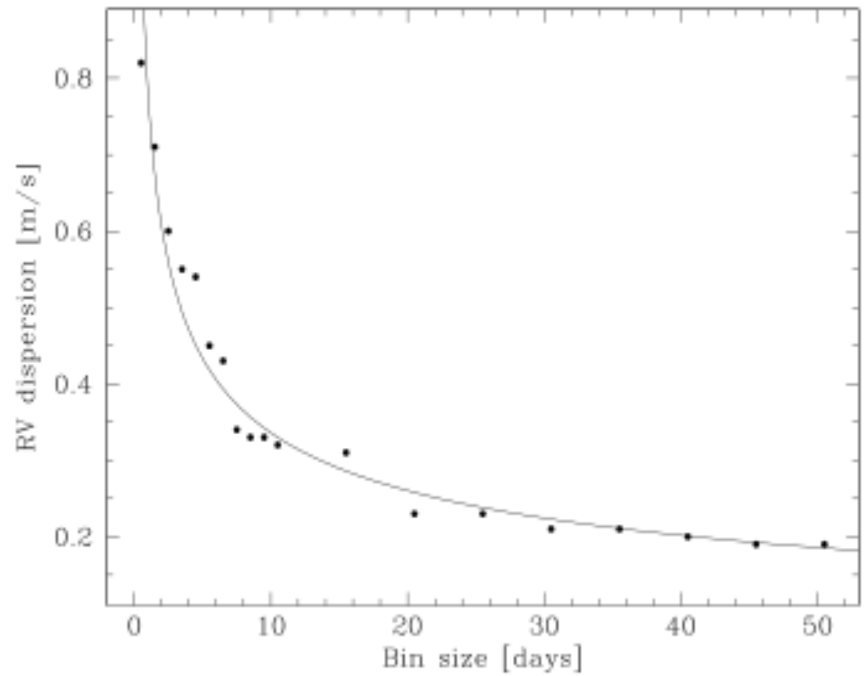
Mayor and Udry, 2008,
Phys. Scr. T130, 014010

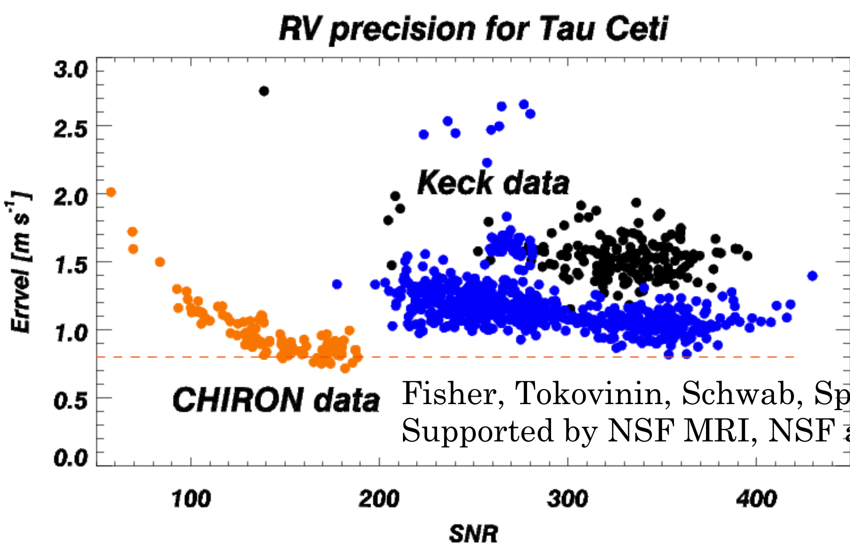
Velocity RMS – Binning helps… to a point

HIRES – Sig Dra



HARPS





Fisher, Tokovinin, Schwab, Spronck
Supported by NSF MRI, NSF and NASA

Takeaway: The number of observations (for binning) and illumination stability matter, but both approaches are successful

PRVs in the NIR and Visible

- Current and future efforts span ~4 orders of magnitude in precision:
  - Telluric lines: ~25 – 100 m/s in NIR (Bailey et al. 2010, Crockett et al. 2011); ~10 m/s in the visible (Figuera et al.)

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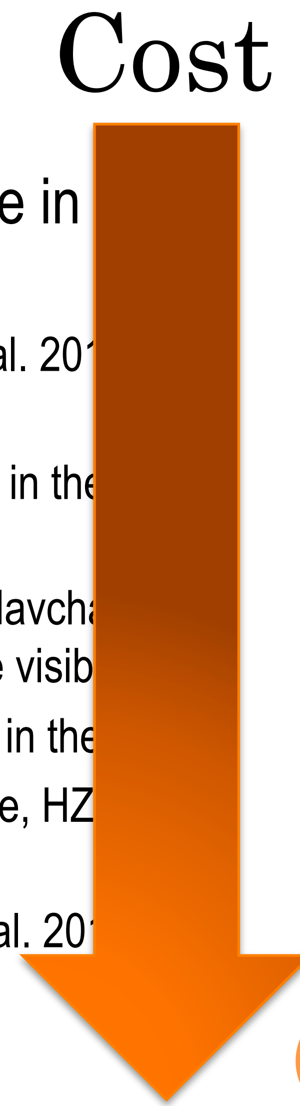

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Takeaway: RV technology development is a hotbed of activity, but running into cost-constraints.

HARPS: Instrumental stability

ΔRV = 0.1 m/s

⇕

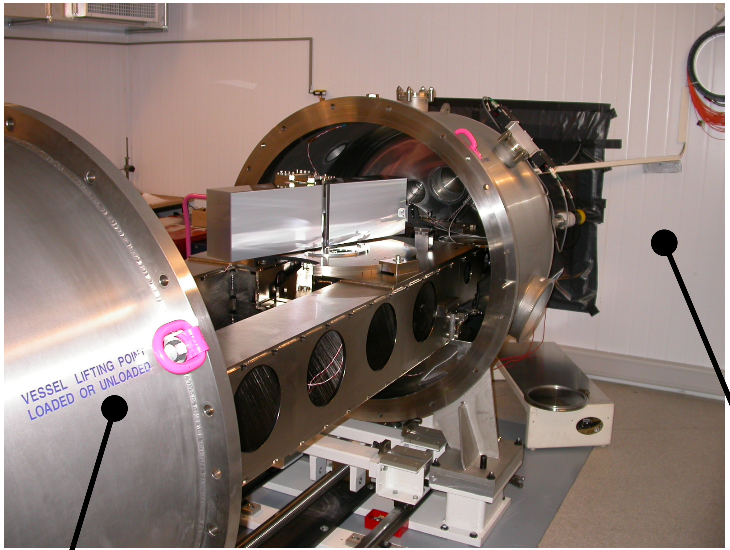
Δλ = 0.000001 A

⇕

1.5 nm

⇕

1/10000 pixel



ΔRV = 0.1 m/s

⇕

ΔT = 0.001 K

⇕

Δp = 0.001 mBar

Vacuum operation

Temperature control

HARPS-N Guaranteed Time Program

80 nights/year for five years, two projects

- Follow up of small KEPLER candidates
- Rocky Planet Search: 10 nearby, bright, quiet FGK dwarfs, 3x 15 min visits per night

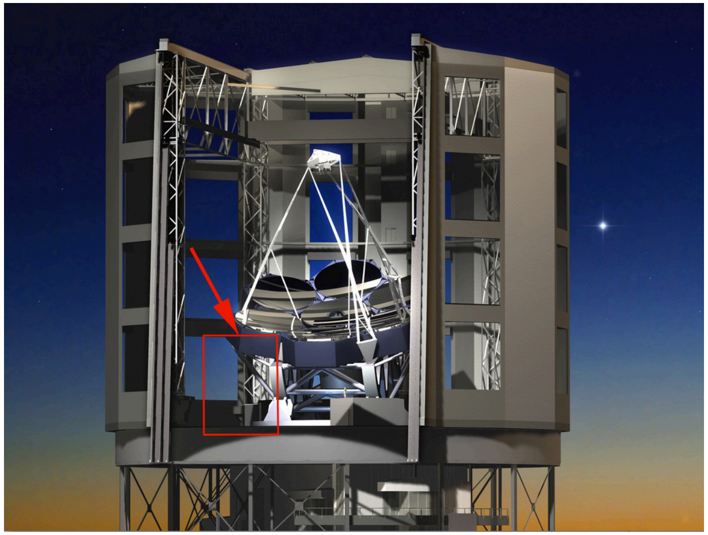
Science Team: 16 Co-Is plus collaborators

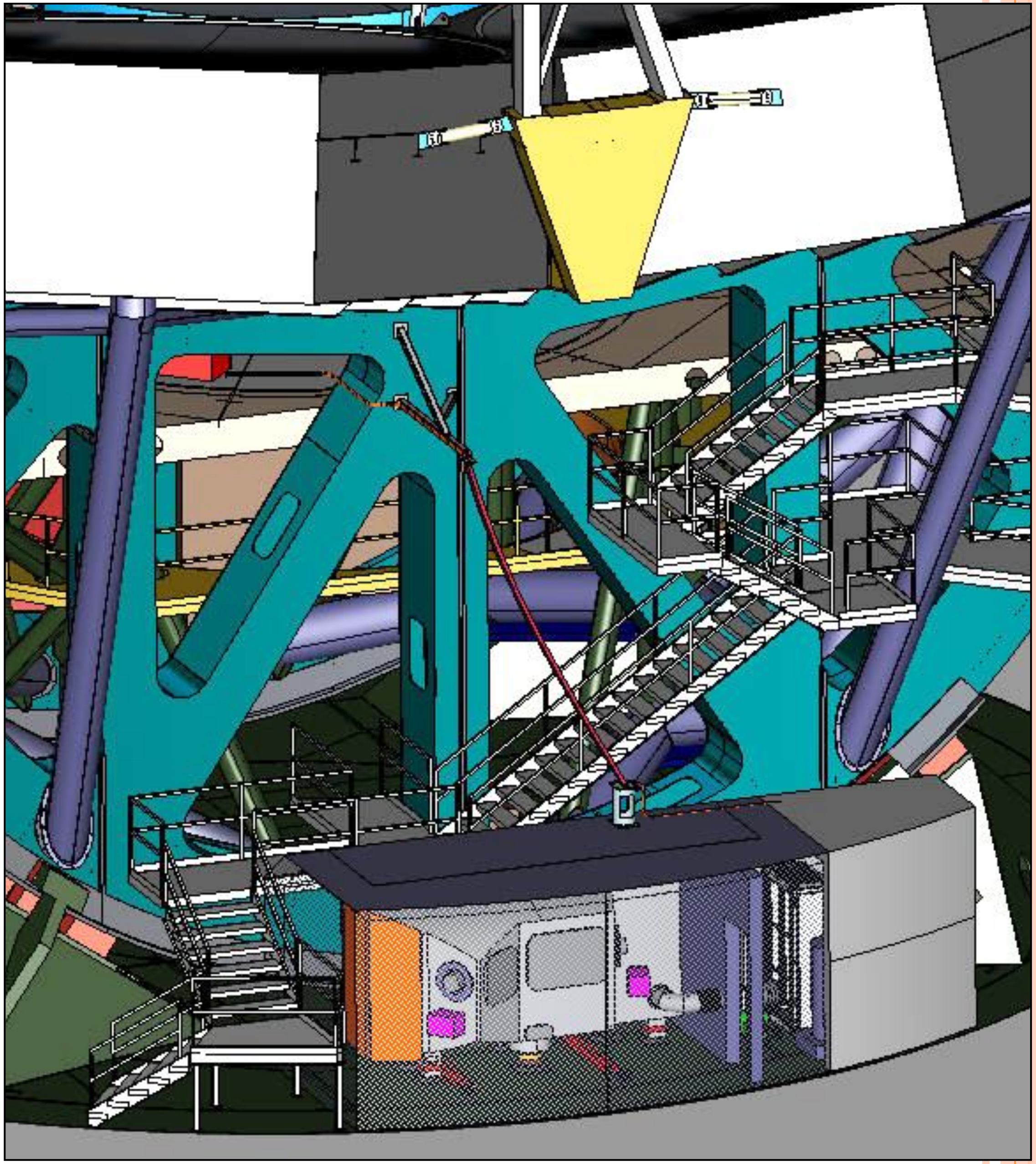
- Manage program, target selection, observing, publications

- HARPS-N time open for proposals from the community via the INAF TAC

Takeaway: Dedicated facilities with stable instrumentation focused on a small number of targets with a high cadence is critical.

G-CLEF Mounting on the GMT Azimuth Platform and Fiber Run





G-CLEF Science Working Group

Anna Frebel (CfA ➢ MIT), Chair
Jacob Bean (CfA ➢ Chicago),
Edo Berger (Harvard U),
Jamie Bolton (UMelbourne),
David Charbonneau (Harvard U),
Bill Cochran (UTexas),
Ryan Cooke (Cambridge IoA)
Andrea Dupree (SAO),
Stefan Keller (ANU),
David Latham (SAO),
Heewon Lee (Sejong U)
Andrew McWilliam (Carnegie),
Michael Murphy (Swinburne),
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Michael Rauch (Carnegie),
Ian Roederer (Carnegie),
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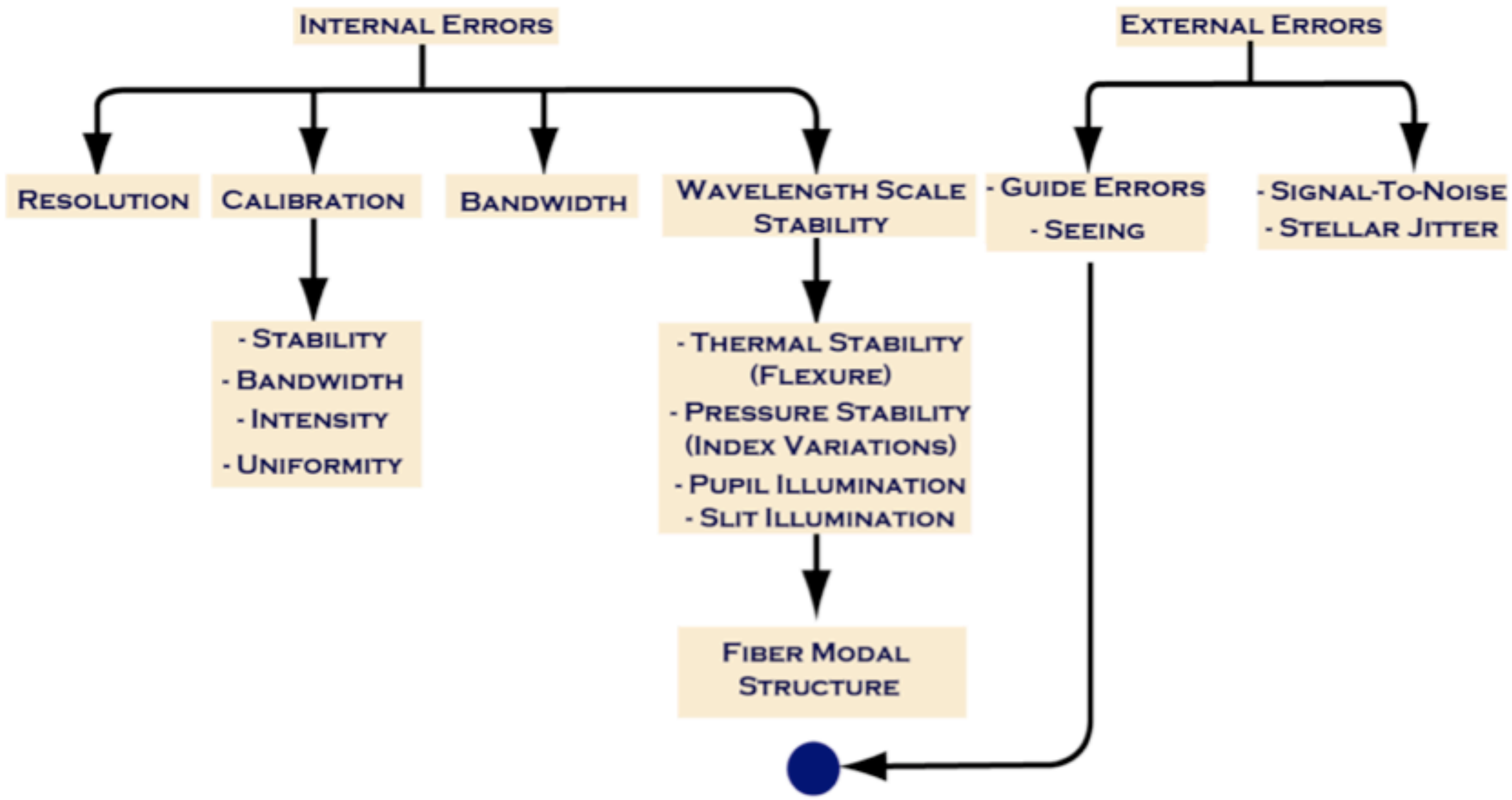
Guillermo Torres (SAO),
Ronald Walsworth (Harvard),
Matthew G. Walker (CfA)
David Yong (ANU)
Manuela Zoccali (Catolica)

The CoDR Science Case for G-CLEF

1. Planetary science
    a. Detection and characterization of exoplanets
    b. Ultra-high precision abundances in solar analogs›› and twins
2. Stellar science
    a. Asteroseismology
    b. Hot subdwarfs and substellar companions
    c. Chemical abundances in stars
    d. Isotopic ratios in metal-poor stars
    e. Age dating the oldest stars
3. Galactic and Local Group science
    a. Globular clusters
    b. Chemical Abundances in the Inner Galaxy
    c. Galactic structure
    d. Metallicities and chemical abundances of stars in dwarf galaxies
    e. Velocity dispersions and dark matter profiles
    f. Massive stars in the Magellanic Clouds
4. Extragalactic science, cosmology & fundamental physics
    a. Dissecting galaxies with supergiants
    b. Probing the cosmic dawn
    c. Probing the nature of the first stars with high redshift protogalaxies
    d. Gamma-ray bursts
    e. Fundamental constants

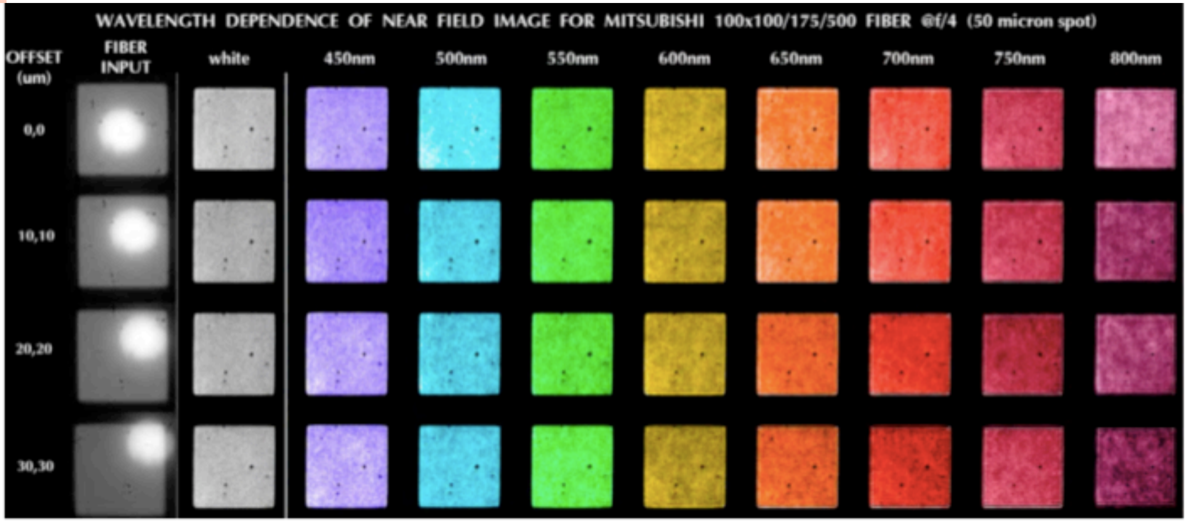
A stand-alone document
65 pages long

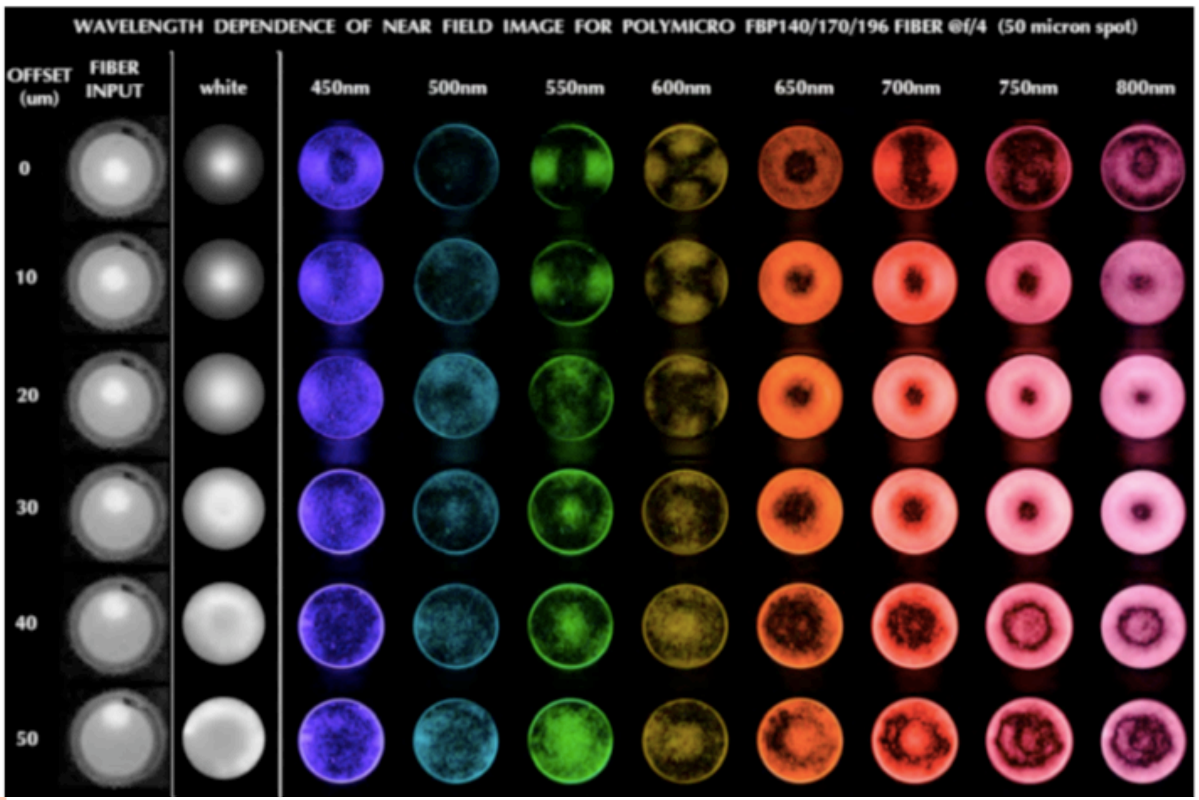
RV Error Contributors



Note: HARPS achieves month-long 9 cm/s stability against ThAr calibrator

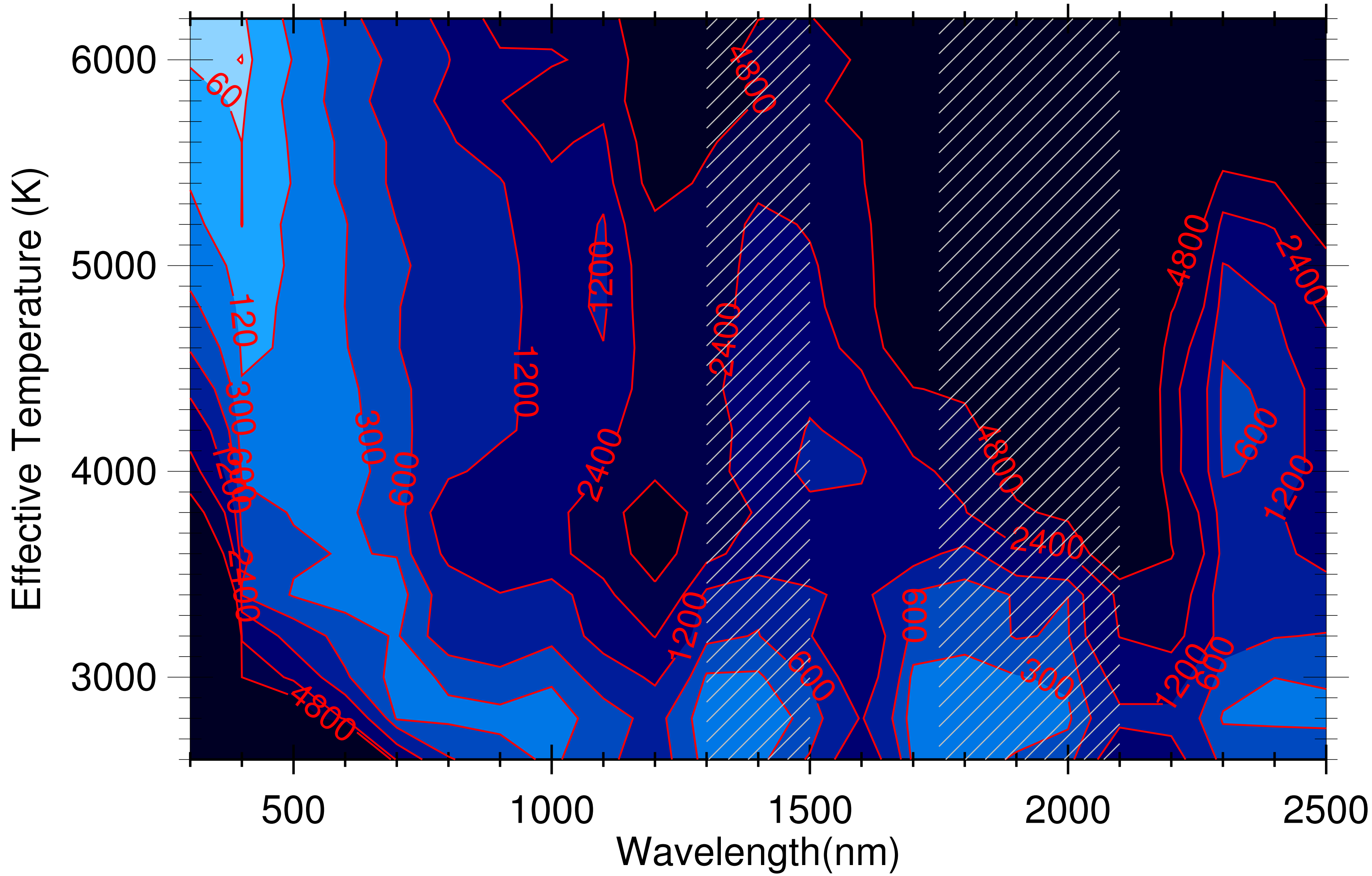
Takeaway: Future efforts have grown considerably in sophistication.



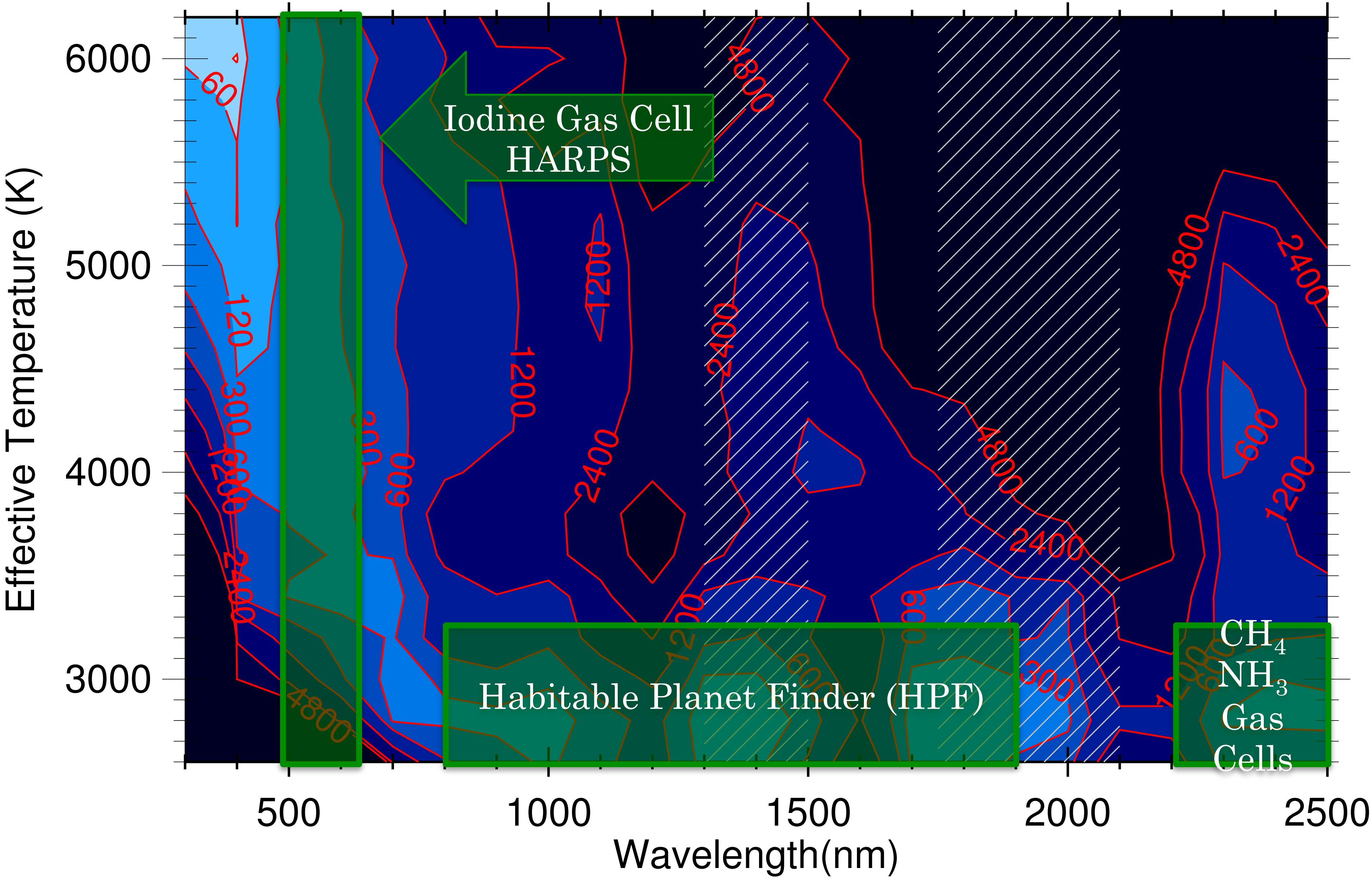


Credit:
Andy Szentgyorgyi's group at CfA.

Takeaway: Non-circular (octagonal) core fibers are nearly universally desired by the community for scrambling the illumination



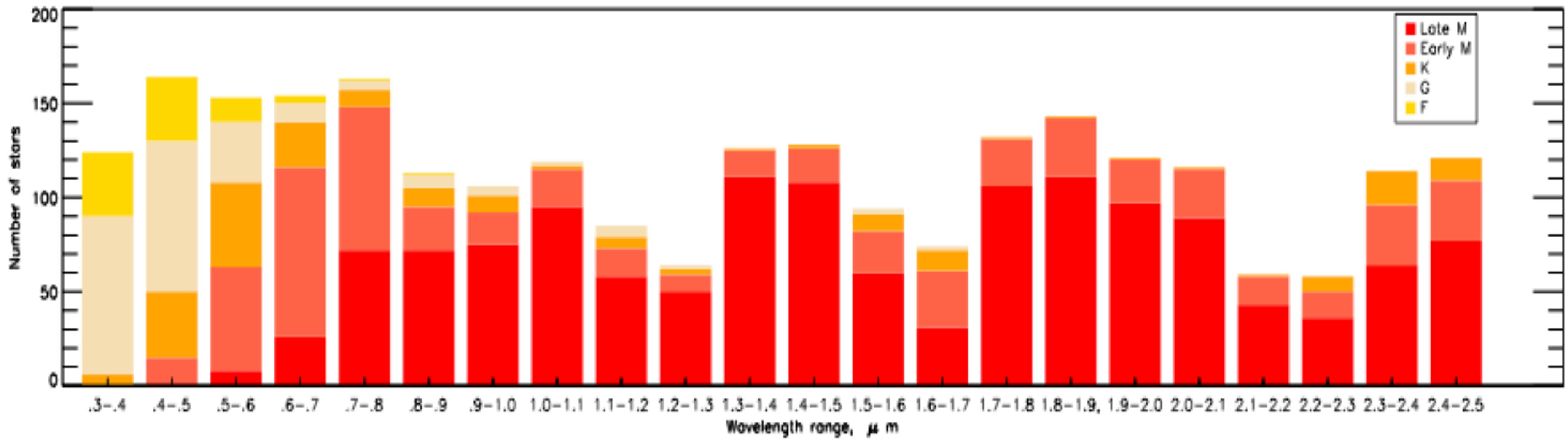
Bottom et al. submitted.
Relative integration time to detect a planet in the HZ, star at 10 pc



Bottom et al. submitted.

Relative integration time to detect a planet in the HZ, star at 10 pc

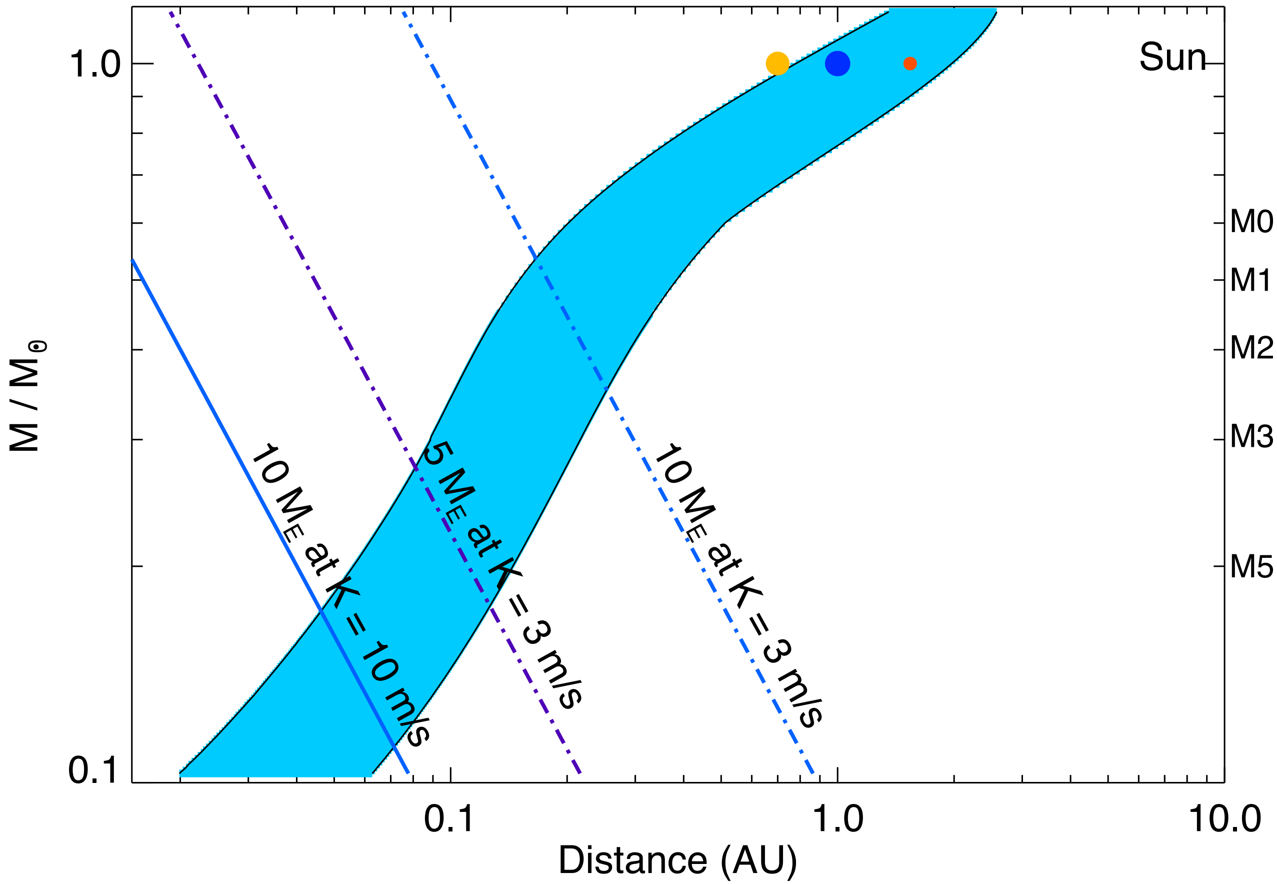
RECONS 7 pc Sample



- Bottom et al. submitted calculated number of stars you can survey for 5 M_{Earth} planets in the HZ for fixed observing time and tele size

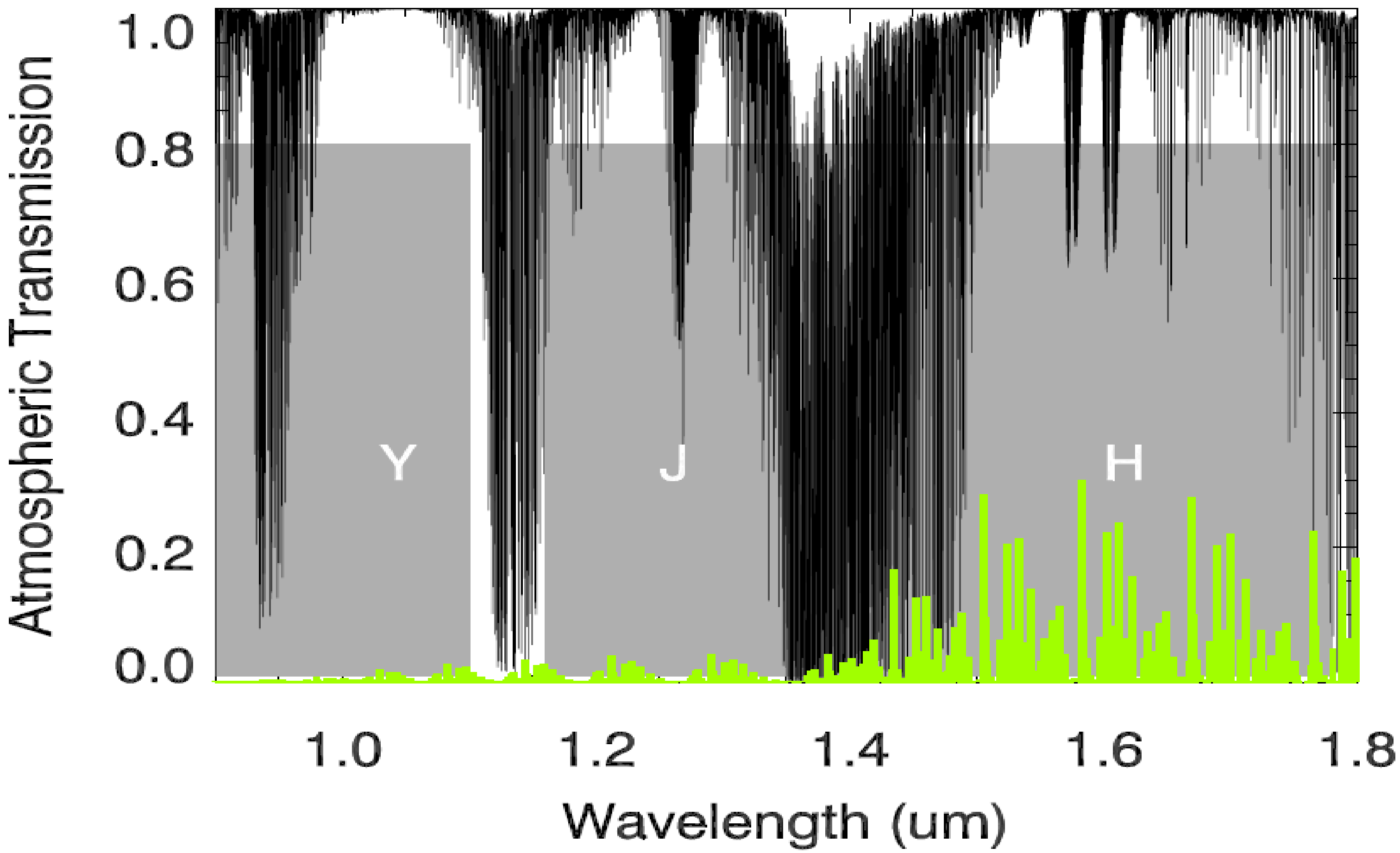
Takeaway: Visible/NIR efforts are optimally designed for HZ surveys and complementary in targets.

Earths & Super Earths Around M Dwarfs



Mid/Late M stars are attractive targets since RV amplitude of terrestrial planets in HZ is so much higher than around F, G, K.

The NIR Bands

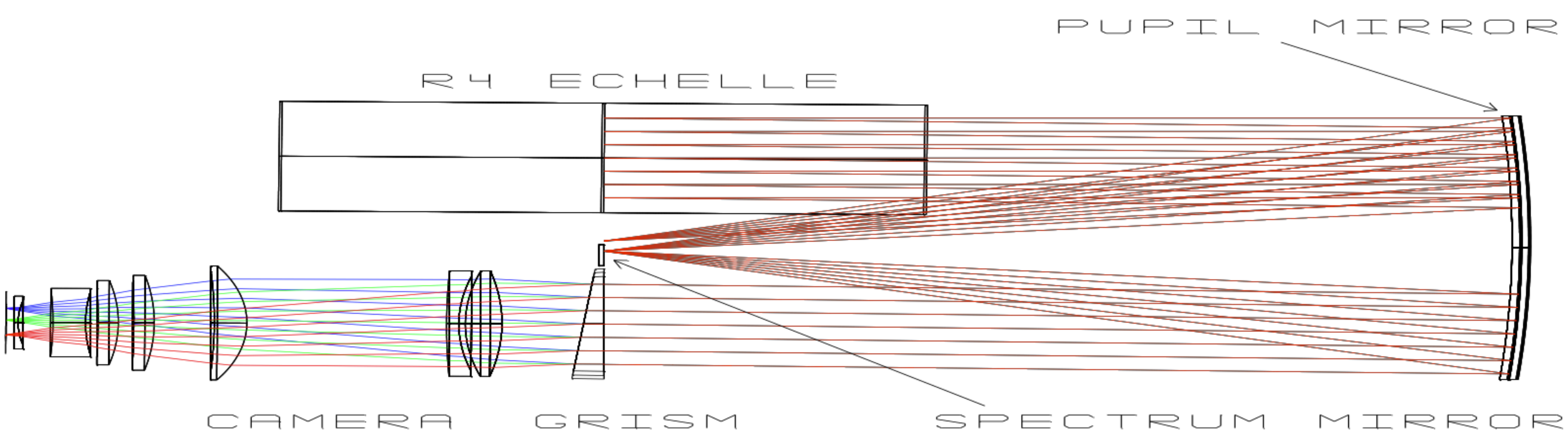


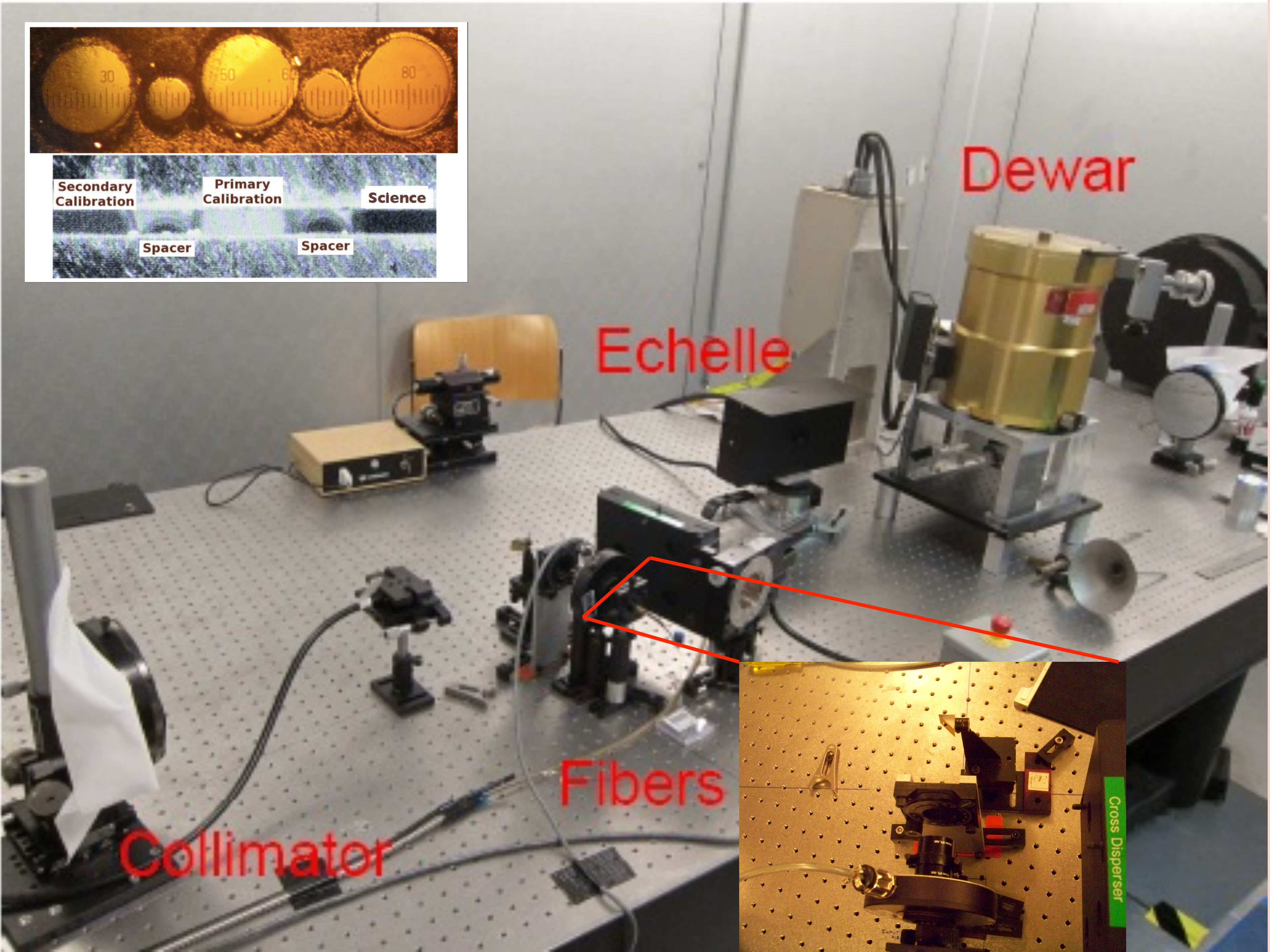
The Y band is quite clean compared to J and H, and has the most amount of RV information for mid-late M dwarfs…

HPF on HET: Baseline Design

- R~ 50,000
- f/3.65 fiber input at telescope focal plane
- 3pixel sampling of Resolution element
- 4% efficiency assuming 7m unobstructed HET aperture
- RV precision < 3m/s (requirement), goal of 1m/s
- H2RG cooled to 80K
- Rest of instrument cooled to 170-200K

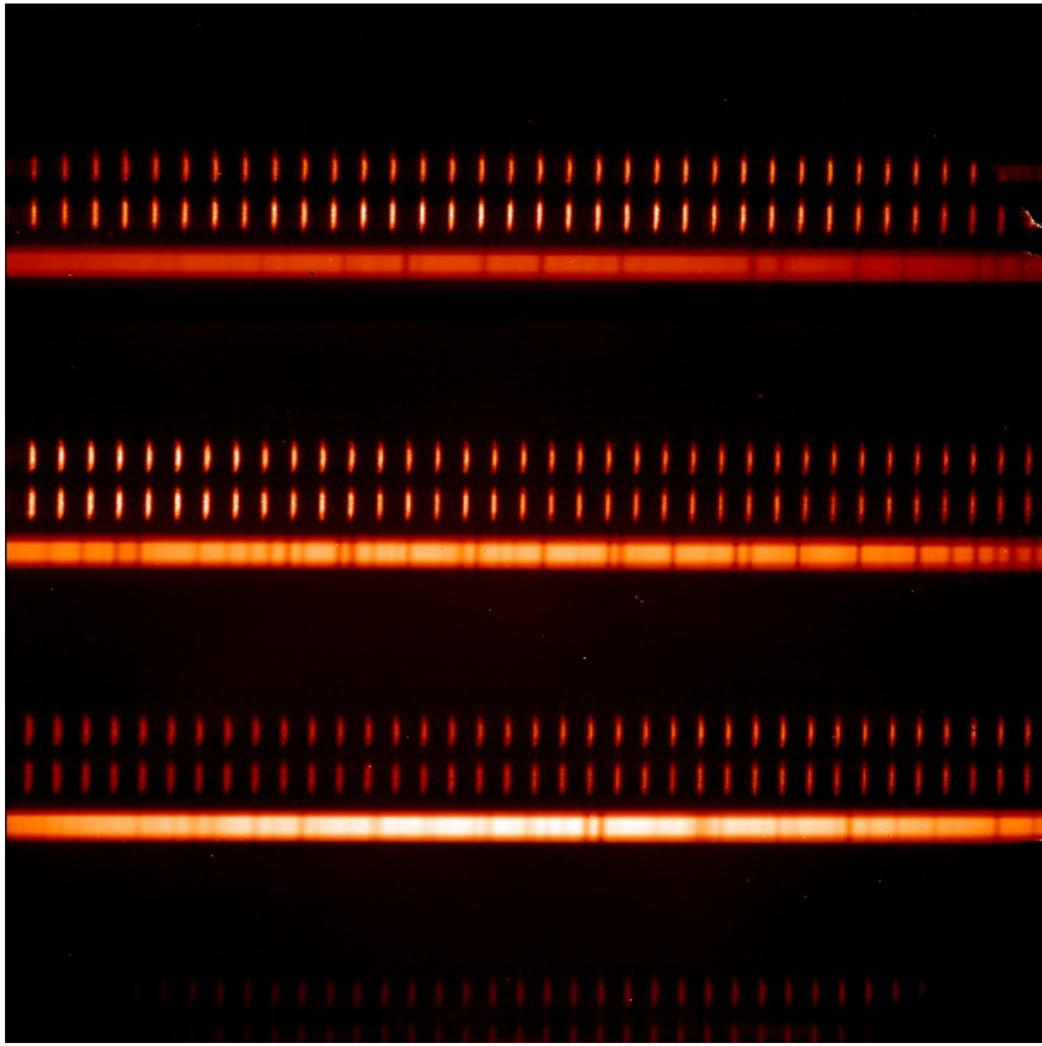
VPH based design also being considered

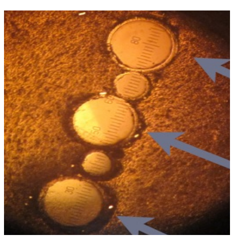




Secondary Calibration
Primary Calibration
Science
Spacer
Spacer
Dewar
Echelle
Fibers
Collimator
Cross Disperser

RVs with Simultaneous Ref.



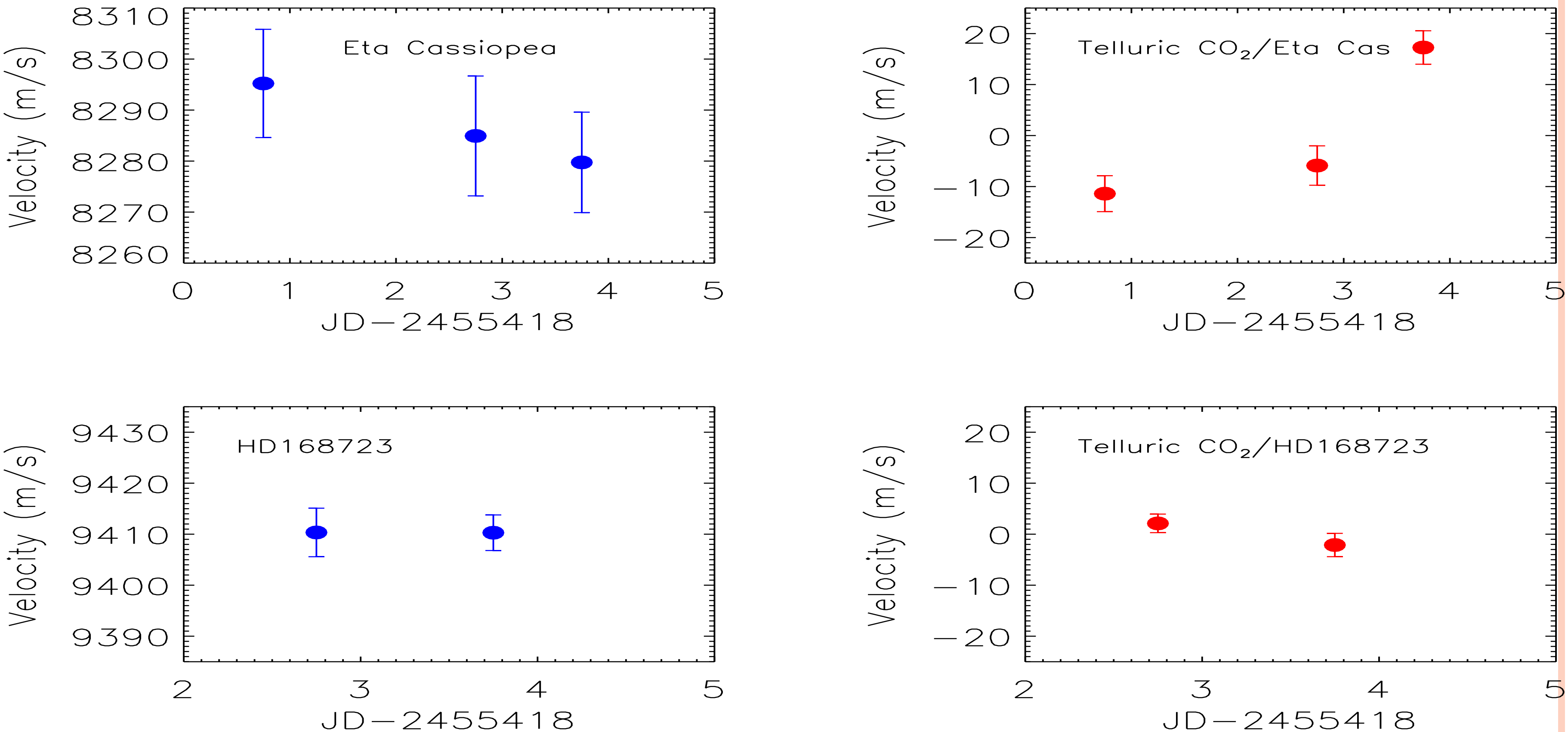


Stellar NIR RVs with Laser Frequency Comb

Ycas et al. 2012, Optics Express

On-Star RV Results with a NIR Frequency Comb!

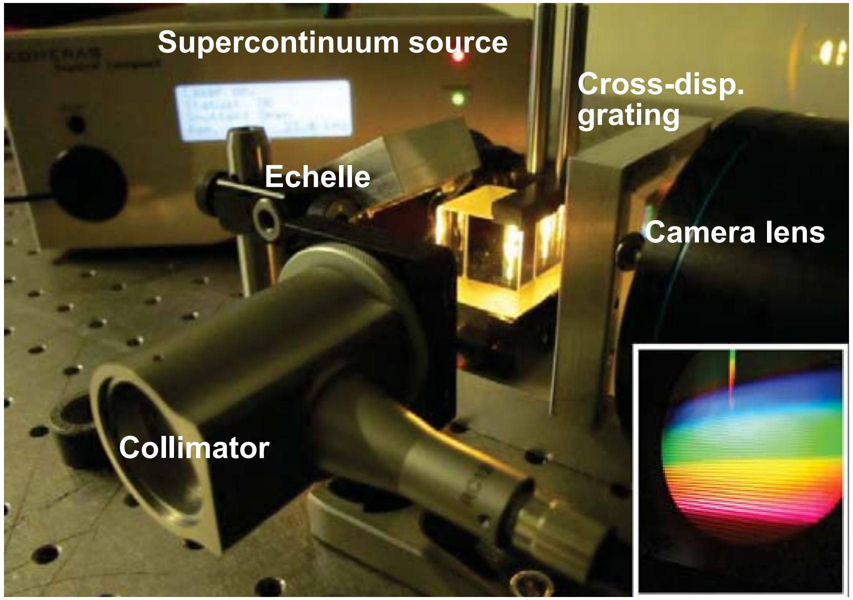
Takeaway: The next generation of NIR PRV instrumentation will be competitive with the current generation of optical PRV instrumentation.

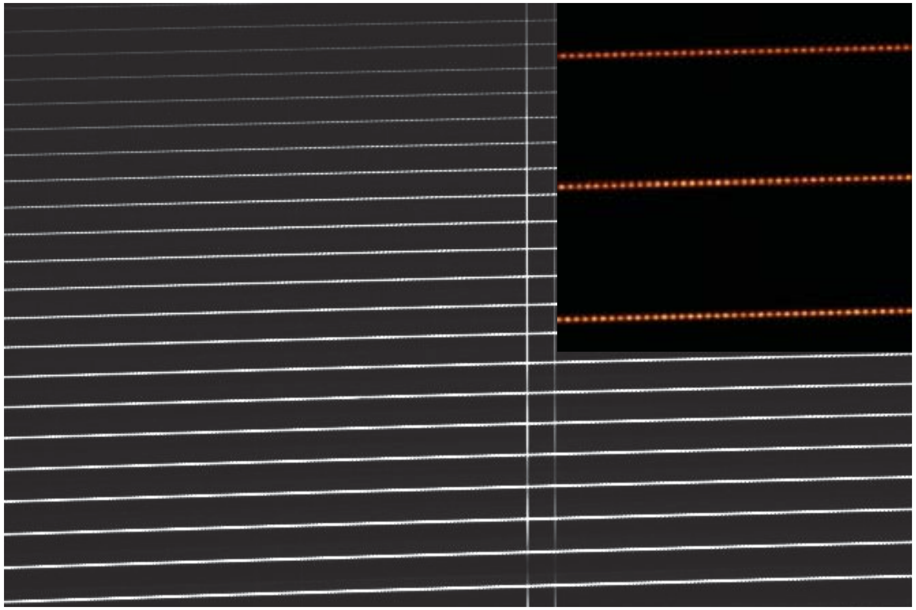


May-August 2010: 7-15m/s Rv precision

"Absolute" RV for Eta Cas consistent with Nidever et al. 2002 to ~25m/s

SMF Spectrographs





Significant Potential to enhance the state of The field, and achieve new levels of RV precision.

Some Cautionary notes: SMFs have two polarization modes. Modal noise has not gone away completely due to polarization dependence of gratings etc. (Mahadevan Et al. in prep)

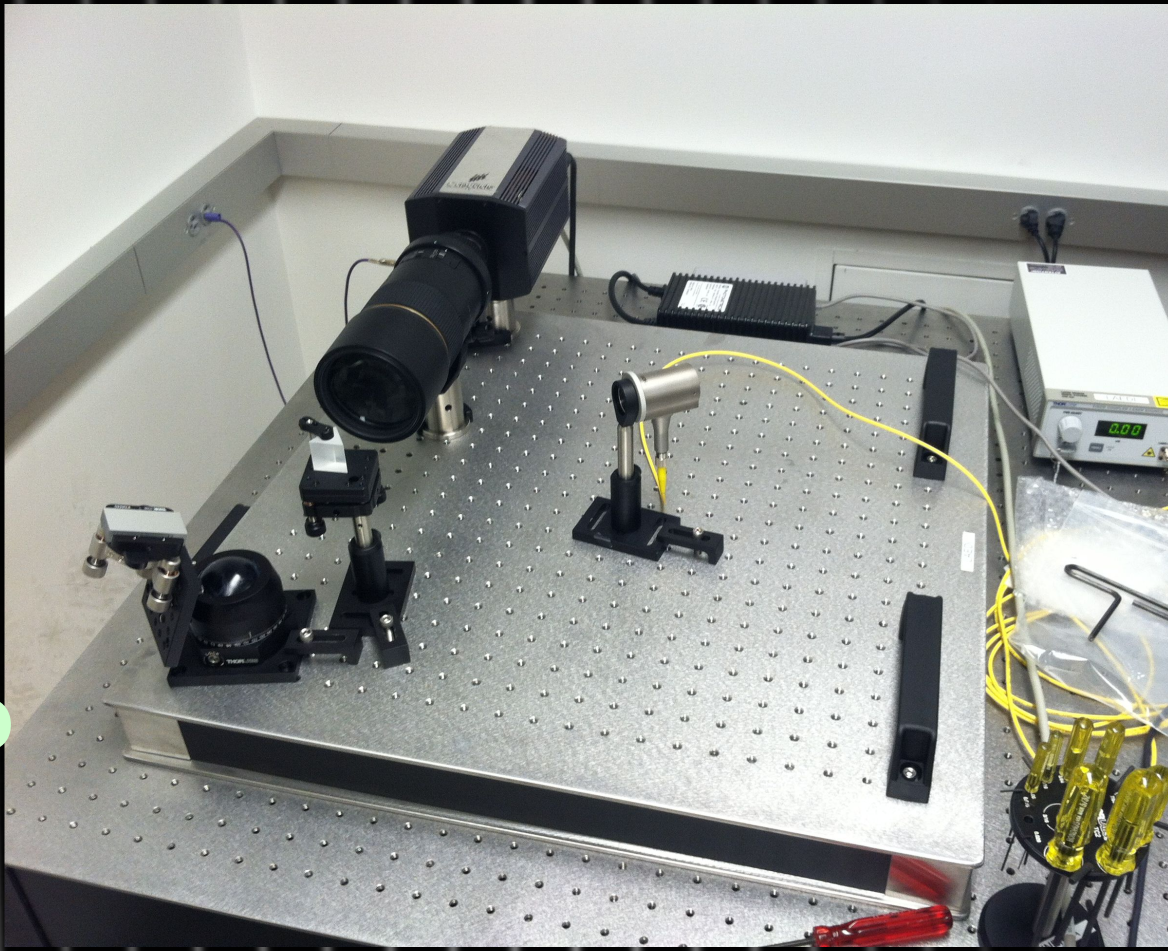
Image Credit: Christian Schwab, 2012 IAU

New Project: LAEDI

Uses a zero-readnoise detector

Single-mode fiber feed for high coherence

Frequency locked-laser for mm/s OPD calibration.



Takeaway: SMF spectrographs are a novel new instrumentation technique.

Astrophysical Sources of RV Noise (Dumusque et al. 2011)

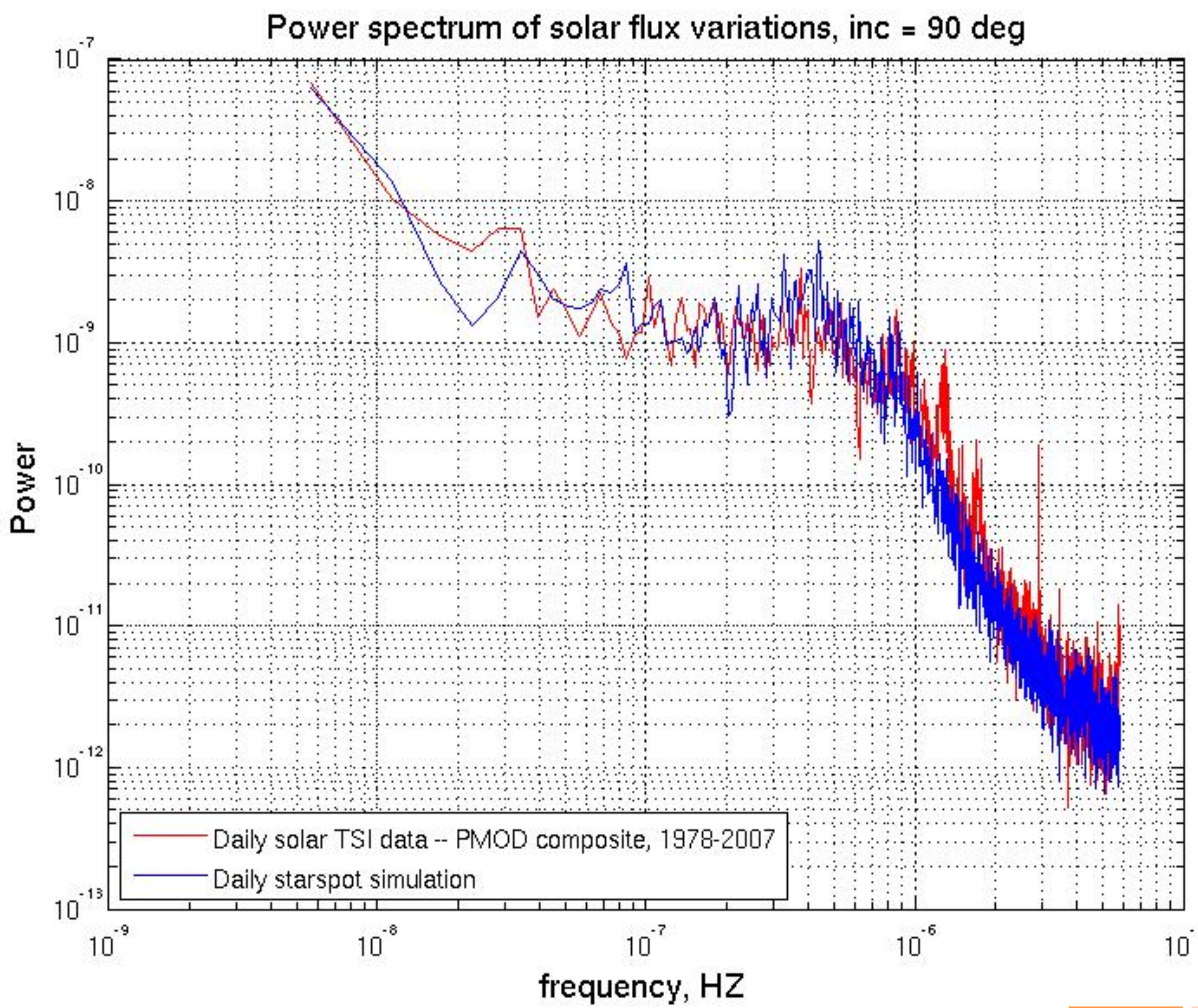
- P-mode oscillations ~ Minutes → Integrate over oscillations
- Granulation, Plages ~ Hours → multiple visits / night
- Spots ~ 30 Days → wavelength dependent
- Activity Cycle ~ Decade → Activity indicators, baseline
- Rotational broadening

in younger stars → less RV content /line

Takeaway: Stellar "noise" is a signal, and methods exist to mitigate the limitations of stellar jitter

Valeri Makarov: Starspot RV Jitter Simulations

- Adjust sunspot parameters (rate, area, lifetime) until the simulated power spectrum looks like the TSI data
- No Maunder butterfly – all spots on the equator
- No spot decay
- Predicted RMS jitter: photocenter 0.9 μAU; RV 0.4 m/s



Quiet Sun

- Most of the long-term photometric variability of the Sun (442 ppm) comes from the solar cycle
- Divide PMOD data into 962-day segments and re-determine TSI variance
- The largest sigma is about 260 ppm, the smallest ~70 ppm
- At quietest times, the expected spot jitter is

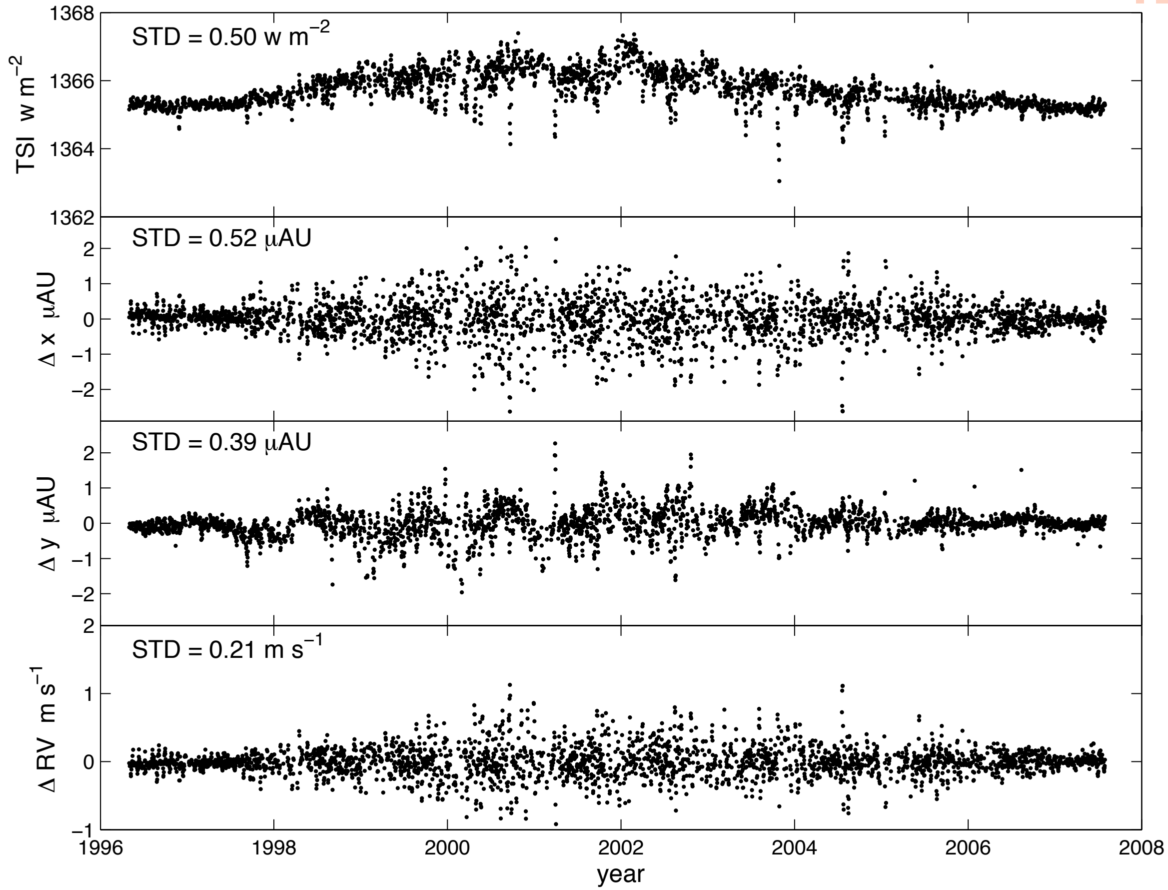
$$0.448 \times 7\text{E-}5 \times 2 \text{ km/s} = 0.062 \text{ m s}^{-1}$$

Catch the low-activity spans!

Surface brightness maps

Makarov, Parker & Ulrich 2010, ApJ 717 integrated high-resolution solar surface brightness maps derived from Mount Wilson observations

The RV std varies between 0.02 m s^{-1} on the quietest months and 0.5 m s^{-1} at the maximum of activity in 2000



χ^2 periodogram

A generic planet detection algorithm detects two bogus planets at >99% confidence with

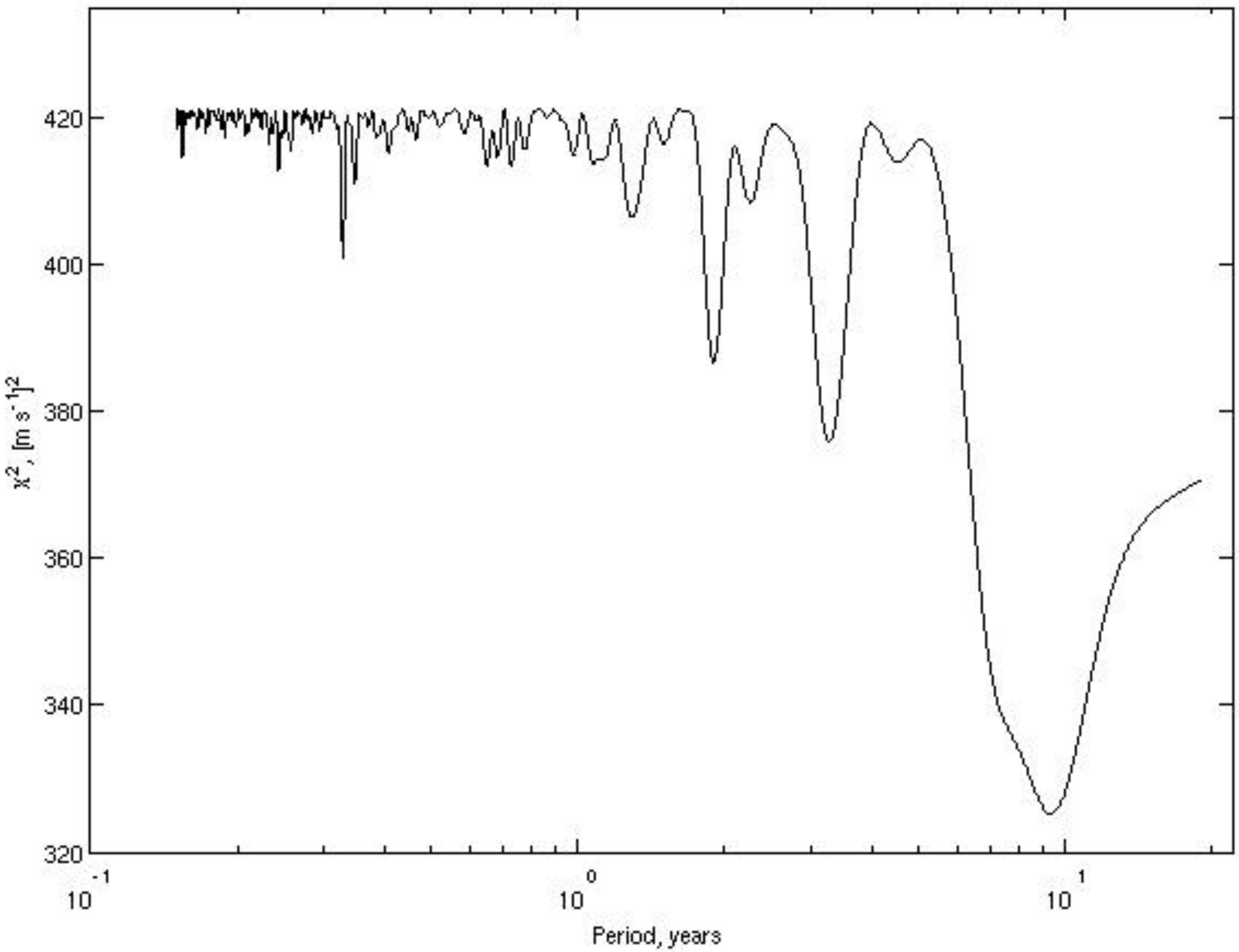
P_1=9.35 yr,

M_1=26 M_E

and

P_1=6.35 yr,

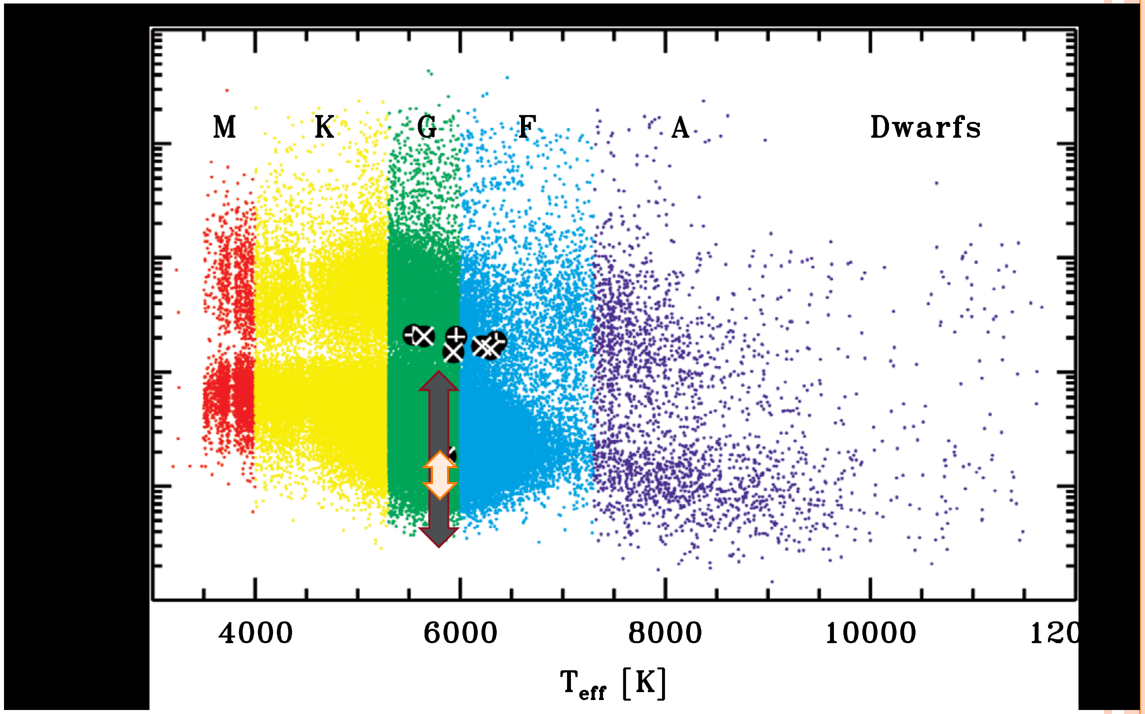
M_2=15 M_E



Takeaway: Activity indicators are critical

Variability of dwarfs

- On the timescale of 1 month, the lowest σ (TSI) is 23 ppm, the largest ~1300 ppm
- The range of solar cycle variation is overplotted on the graph showing the Kepler data for dwarfs
- The Sun is exceptionally inactive – but only when it's quiet



From Ciardi et al. 2011

Anglada-Escude & Butler 2012

- Recently demonstrated that Barnard's Star (M4V) is stable down to 80 cm/s over 4 years when using the red-most part of the HARPS wavelength range (between 650-680 nm).
- Including the bluer part of the spectrum (380-650 nm) increased the long term noise (RMS about 1.4 m/s), and using the Iodine wavelength range only (450-620 nm) the RMS was as high as 1.6 m/s.
- Moreover, the same study claimed that the increased noise at bluer wavelengths is not related to the lower SNR only, but due to wavelength dependent sources of stellar noise acting stronger in the blue.
- This gives further motivation to move to redder wavelengths in order to achieve sub m/s long term precision especially on the later stellar types.
- ***Does this result extend to earlier spectral types and/or longer wavelengths?***

Takeaway: Wavelength dependence of stellar jitter matters

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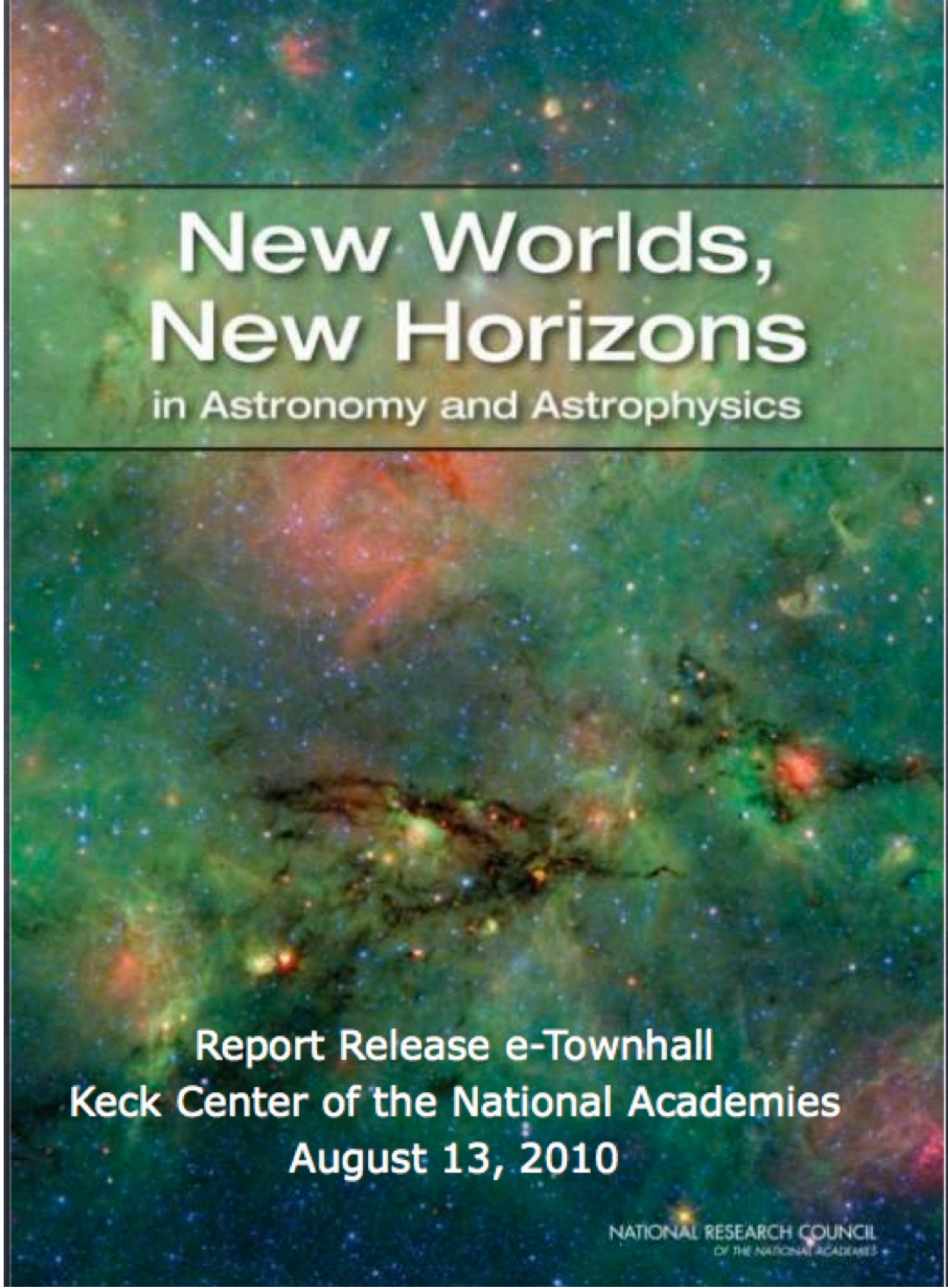
- RV Method Review & Recent Highlights
- ExoPAG 6 Mini-Workshop Recap
- **Astro 2010 Report & NSF Portfolio Review**
- RV SAG Goals & Current Status
  - Survey Science Drivers and Wavelength
  - Ongoing and Upcoming Surveys / Facilities
  - Instrumentation Approaches


New Worlds,
New Horizons
in Astronomy and Astrophysics
Report Release e-Townhall
Keck Center of the National Academies
August 13, 2010
NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

Astro 2010 Report

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- The charge from the decadal survey is to “discover planets within a few times the mass of Earth as potential targets for future space-based direct-detection missions.” (e.g. JWST) This is listed as a “Mid-Scale Innovations Project” top three priority for ground-based work in the $12 million to $40 million range.

NSF Portfolio Review

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- Critically needed technical capabilities to address this research question are high precision (≤1 m/s) radial velocity programs for Doppler planet detection and Kepler follow-up (of larger, higher mass planets), high resolution spectroscopy to characterize the properties of host stars, small-to-moderate telescopes for photometric follow-up of microlensing events/ground-based transit surveys, and instrument development for extreme-precision optical spectrometers (to reach 10 cm/s) and high-resolution near-IR spectrographs to detect planets orbiting cool stars (later than M4V).

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RV SAG Goals

Assess the State of Precision RV measurements for Planetary census –

Planet detection an characterization via precision radial velocity measurement has been the workhorse technique in the exoplanet field. This group will consider the important continuing role of RV measurements, both scientific and programmatic.

RV SAG Goals

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- What are the astrophysical limitations on radial velocity precision for measurements of nearby stars?
- How does this precision vary as a function of stellar type and wavelength?
- What are the implications of these limitations for new ensemble survey science goals and for finding the nearest low-mass exoplanets for future characterization?

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- What are the benefits or disadvantages of increased investment in telescope time (and for which class of telescope)?
- What competitive opportunities exist in the short and long term in the context of existing and planned US and European facilities?
- How should we prioritize increased investment in existing telescope resources versus investment in new, dedicated facilities and/or technology development for precision calibration/stabilization?

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- What can be done to increase the efficiency and sensitivity of radial-velocity facilities?
- What potential exists for red/near-infrared radial velocity precision?

Take-Away Points (so far)

- Precision RVs are firmly in the systematic noise regime
- Alpha Cen B b is the nearest known exoplanet to our Sun, and represents a non-incremental advance with the RV technique
- Important question for the community: how will we "confirm" these statistical exoplanets and/or validate this statistical approach? These recent announcements and analysis are intriguing but deserve further validation and scrutiny
- There is a rich ensemble of planned instrumentation in both the visible and NIR
- The number of observations (for binning) and illumination stability matter, but both the gas cell and instrument stabilization approaches are successful and complementary
- RV technology development is a hotbed of activity, but running into cost-constraints
- Dedicated facilities with stable instrumentation focused on a small number of targets with high cadence is critical
- Visible/NIR efforts are optimally designed for HZ surveys and complementary in targets
- The next generation of NIR PRV instrumentation will be competitive with the current generation of optical PRV instrumentation
- SMF spectrographs are a novel new instrumentation technique
- Stellar "noise" is a signal, and methods exist to mitigate the limitations of stellar jitter
- Activity indicators are critical
- Wavelength dependence of stellar jitter matters
- RVs are soundly supported by Astro 2010 and the NSF Portfolio Review

RV SAG Current Status

Several groups are actively pushing the frontiers in RVs in terms of wavelength, precision and data analysis, as we will hear in the rest of this meeting, to potentially fulfill the bold predictions of the decadal survey.

Some draft text has been written, revisions in progress before we'll move to a wider circulation for comments and additions.

Want to join the RV SAG8 and help contribute to the report we will prepare? Membership is open and being put together this spring.

Talk to Peter Plavchan (plavchan@ipac.caltech.edu) & Dave Latham (latham@cfa.harvard.edu)