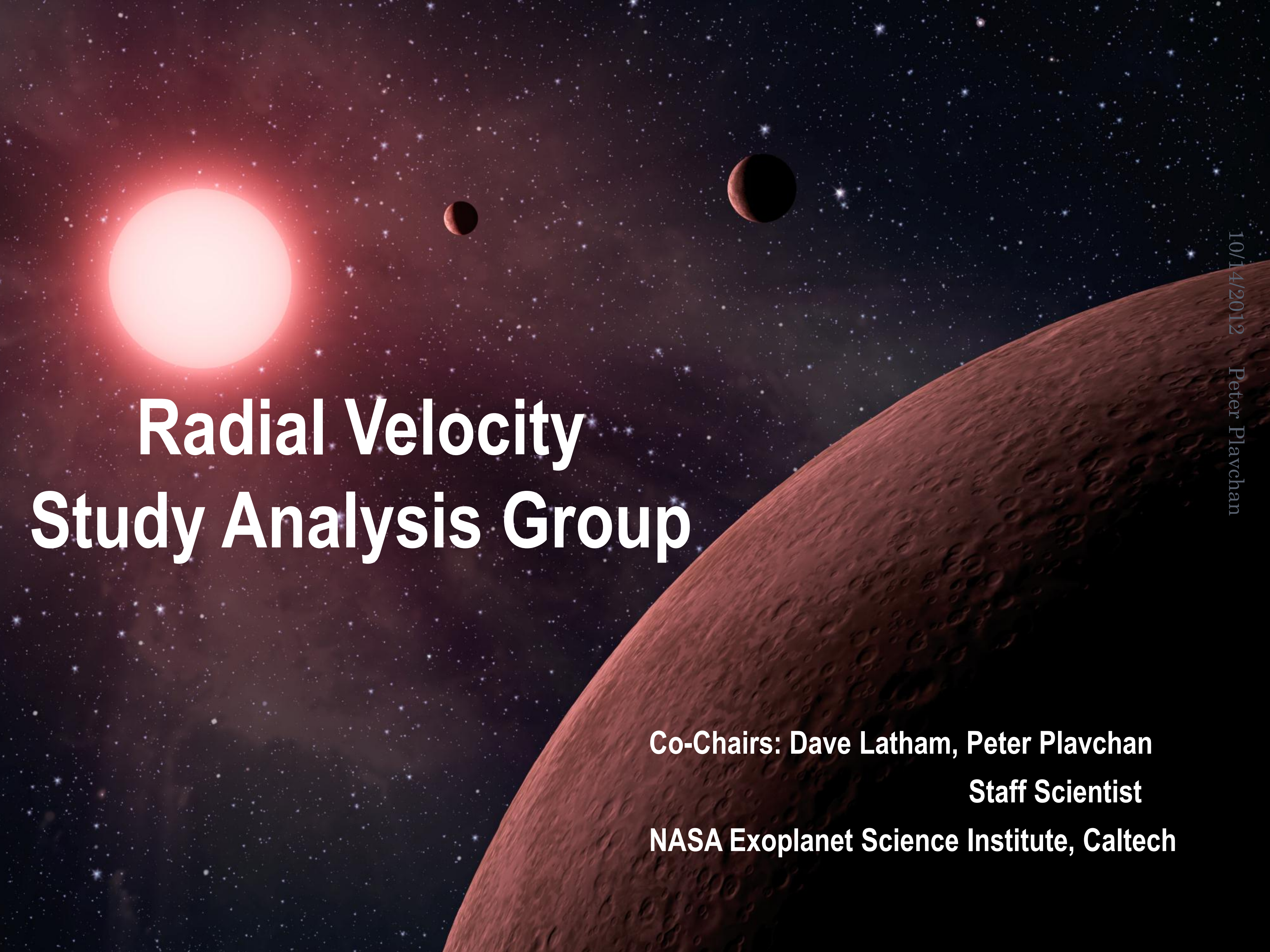
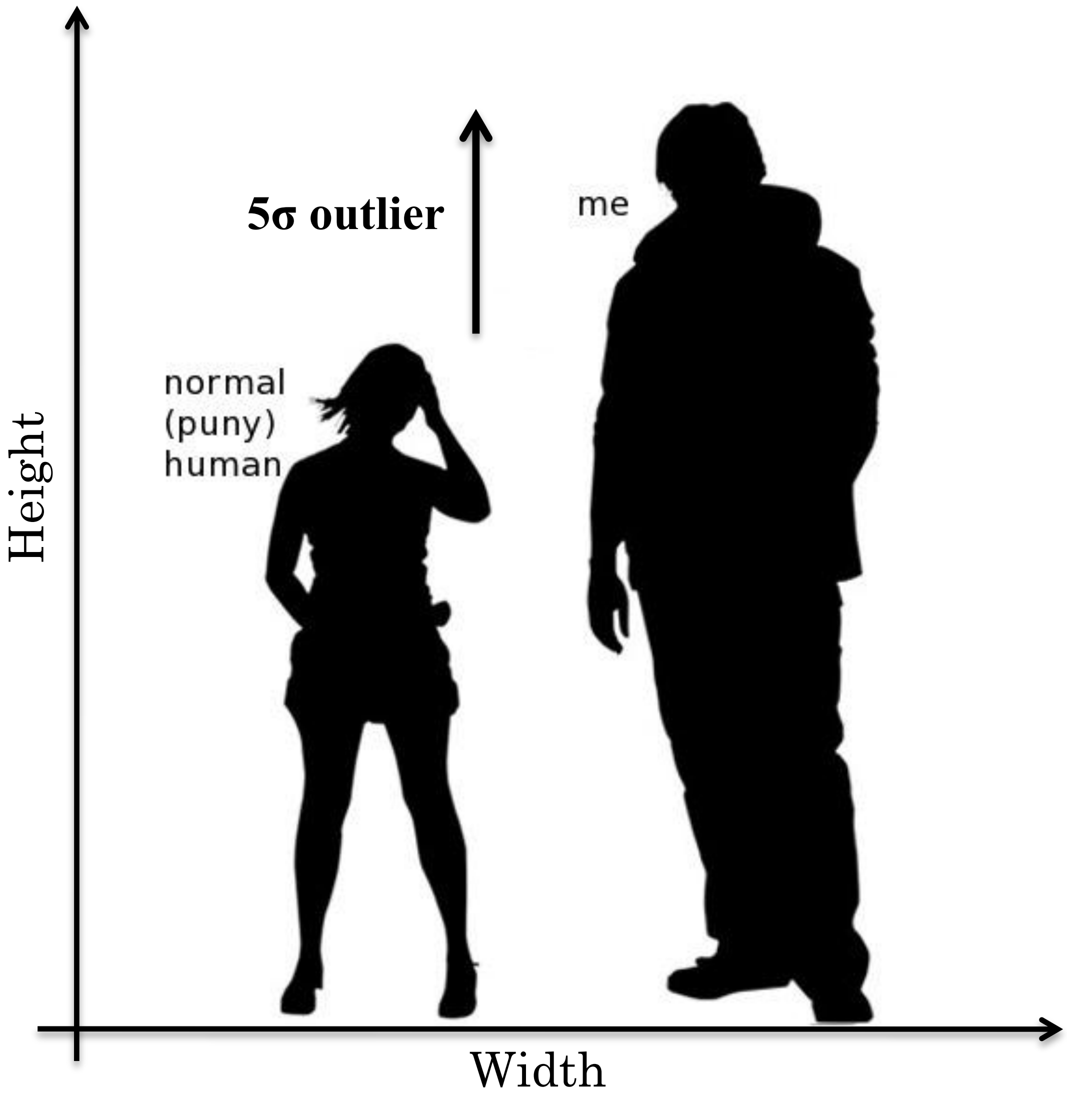


Radial Velocity Study Analysis Group

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

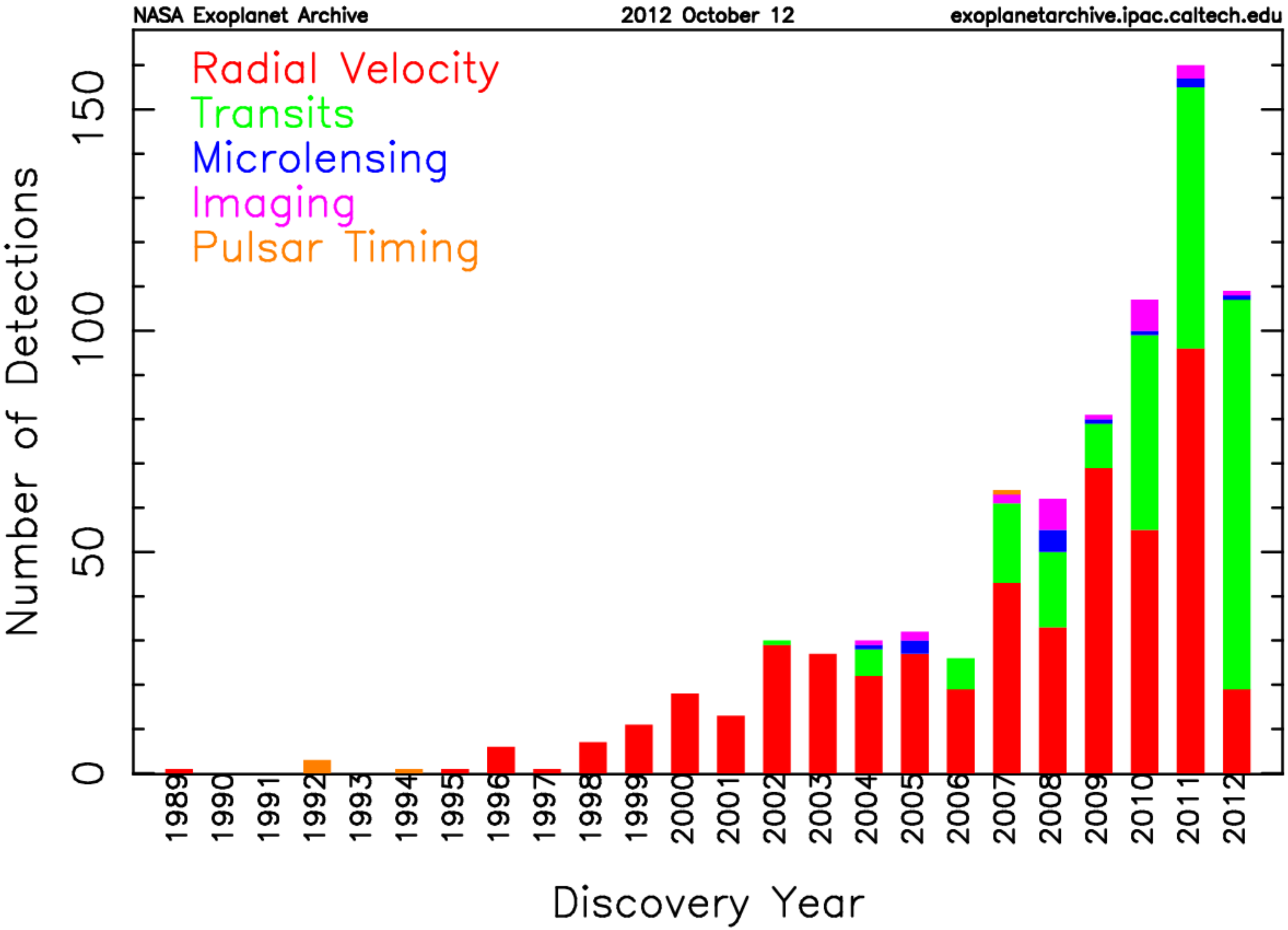
Who am I?



Outline

- RV Method Review
- Astro 2010 Report & NSF Portfolio Review
- RV SAG goals
  - Survey Science Drivers and Wavelength
  - Ongoing and Upcoming Surveys / Facilities
  - Instrumentation Approaches

RV Method Review



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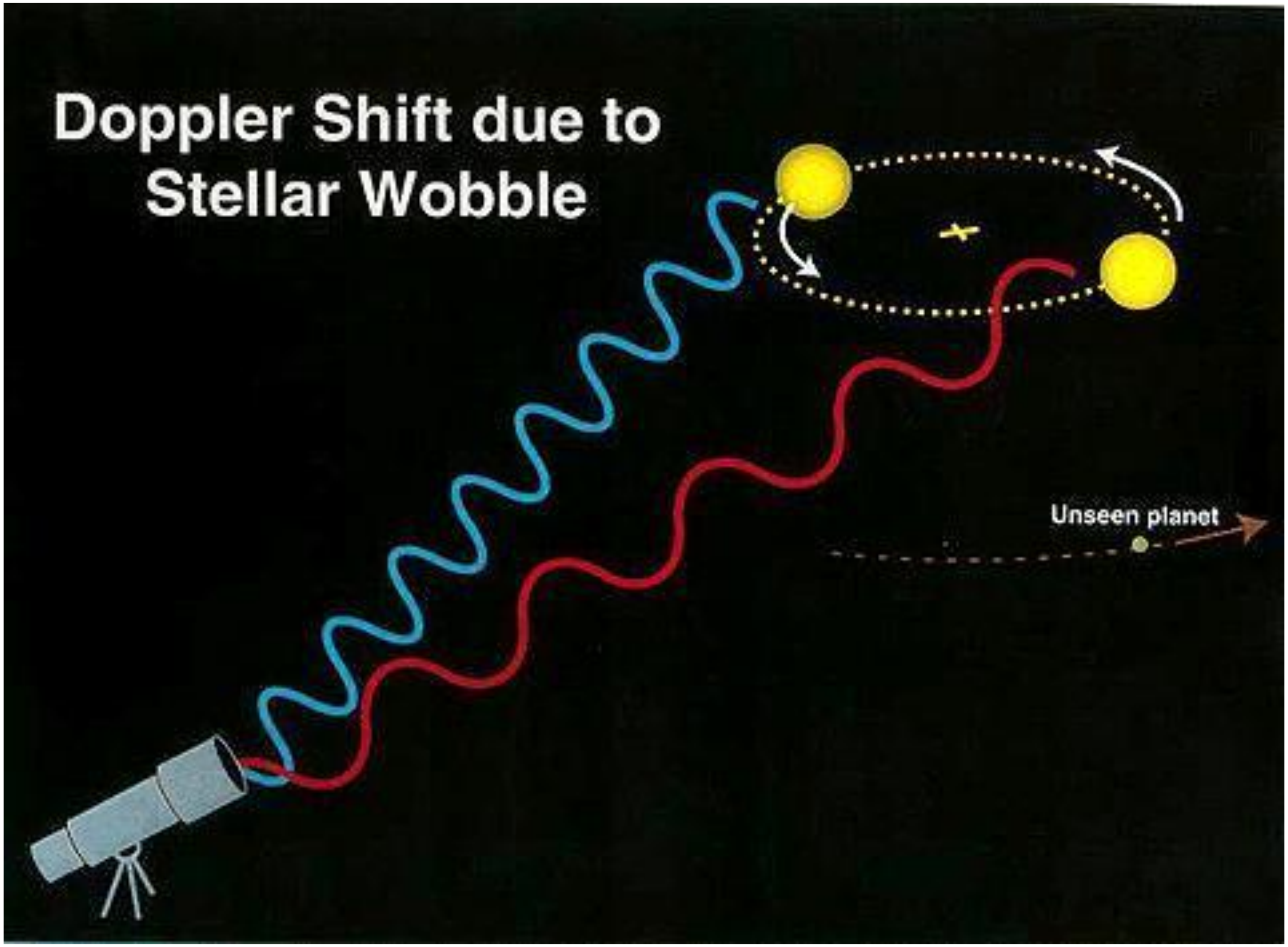

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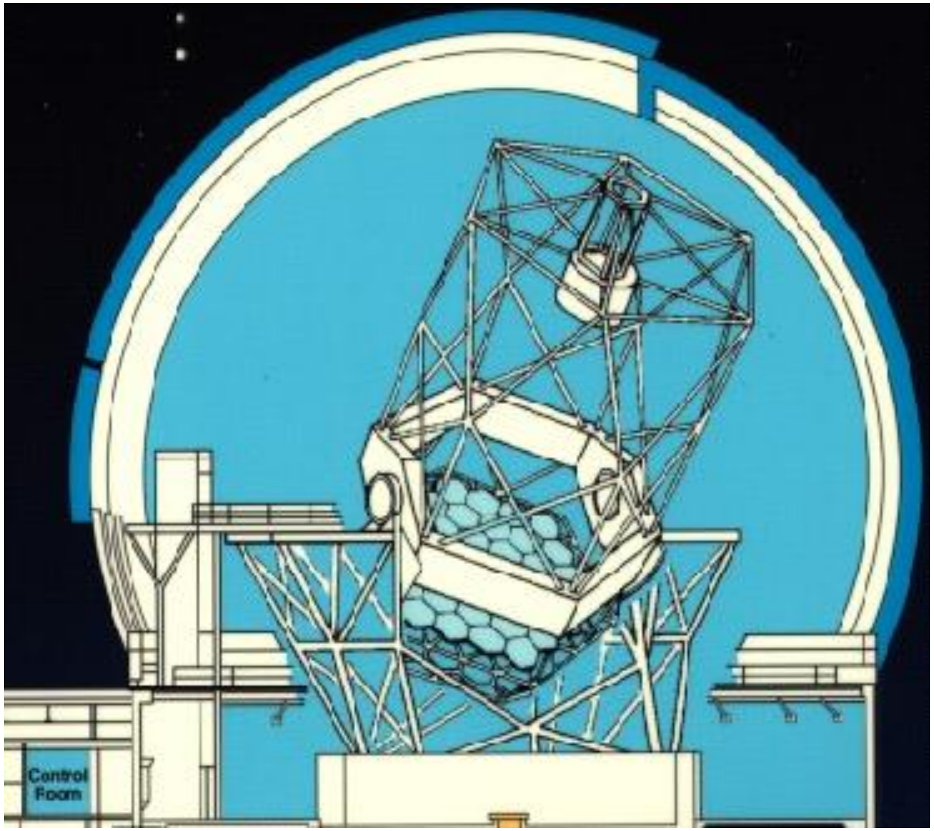

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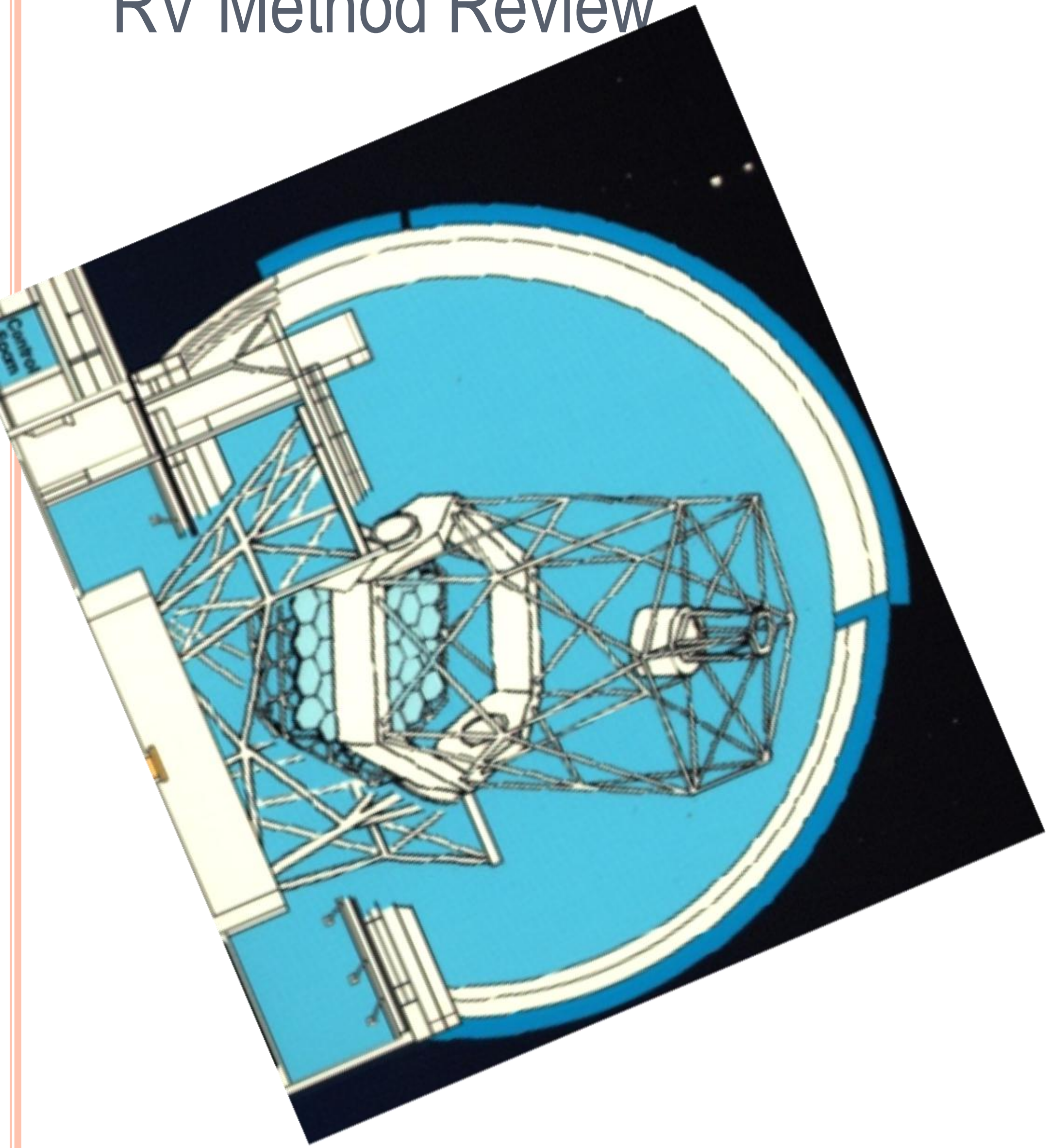

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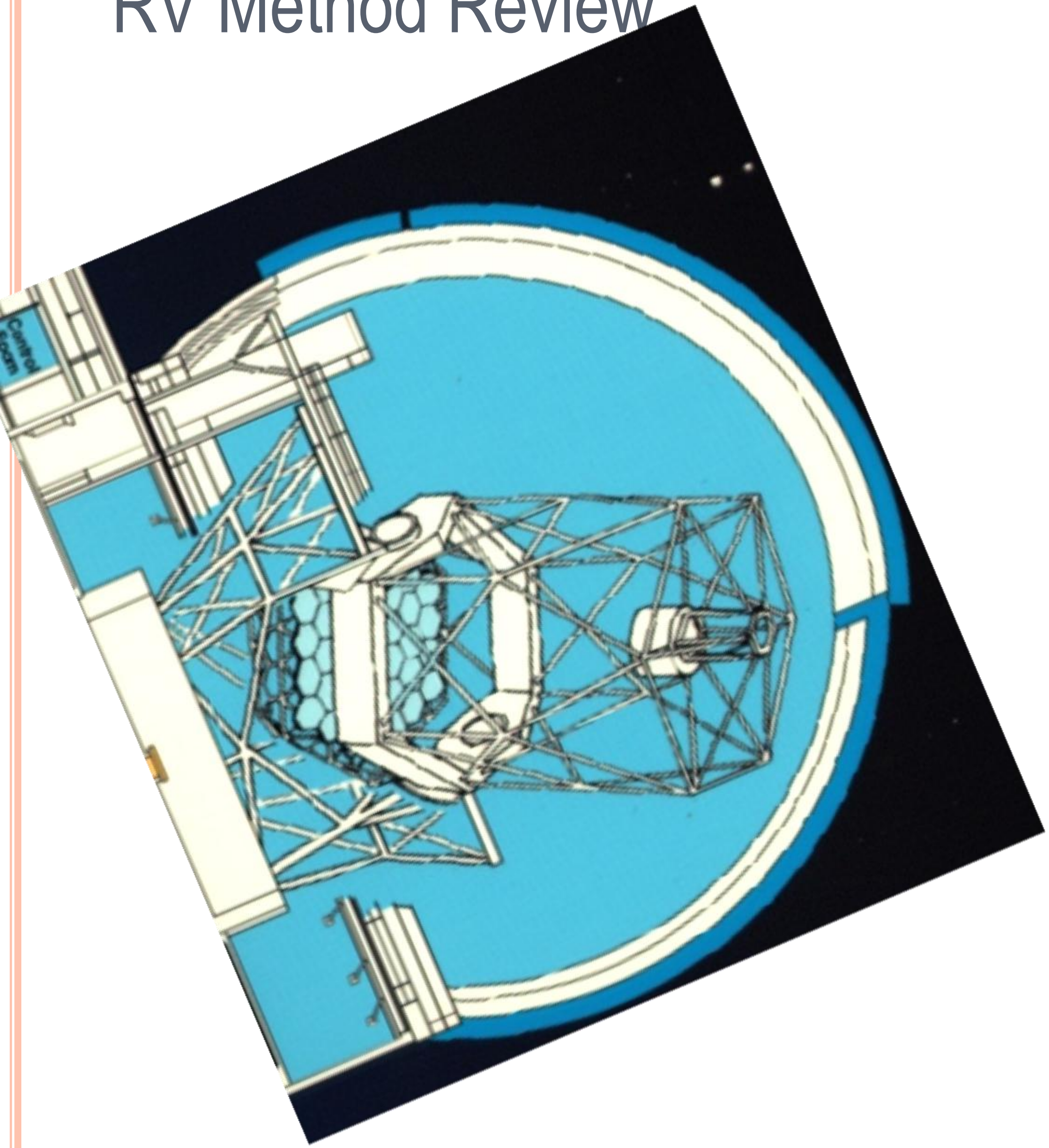

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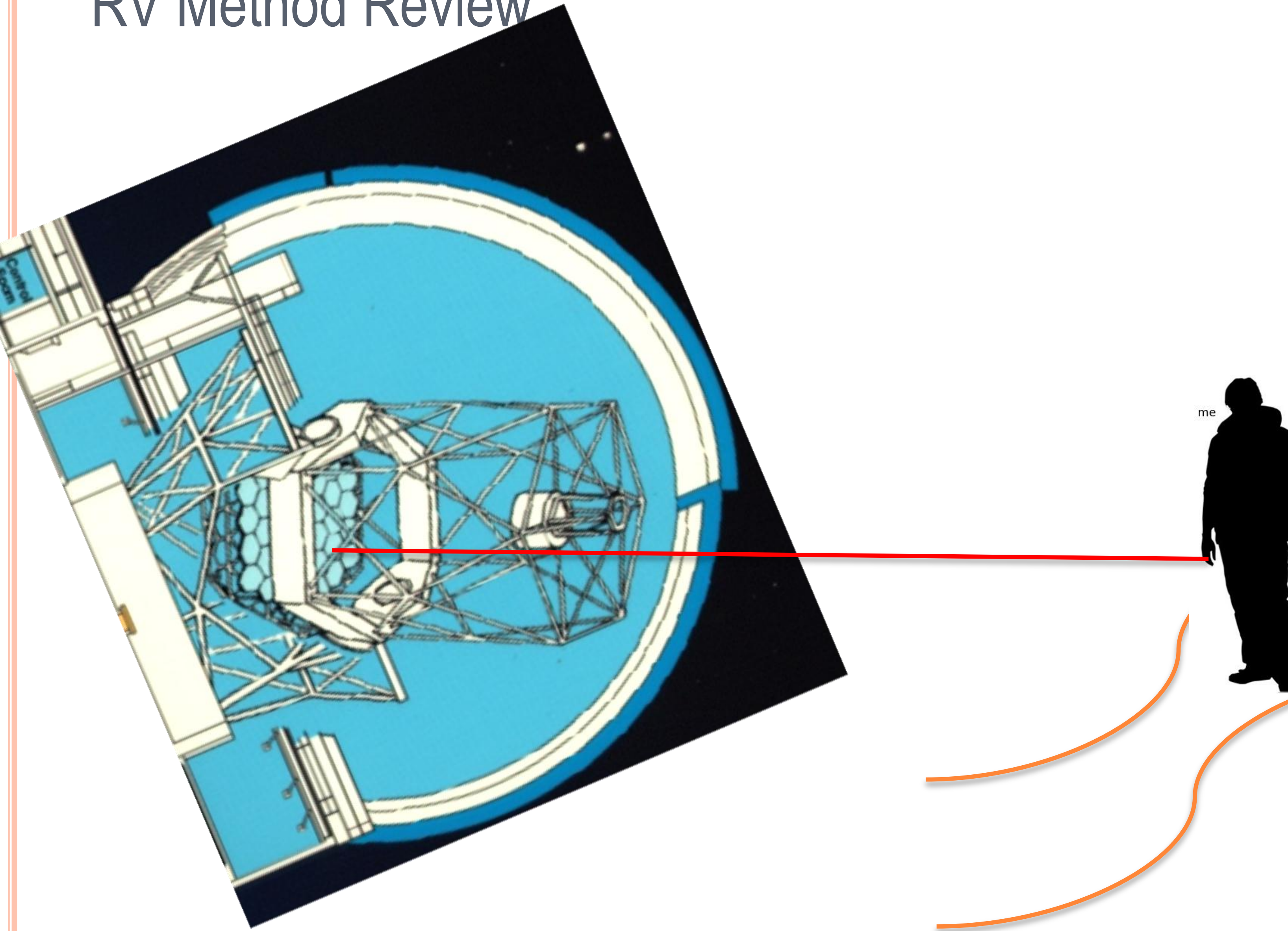

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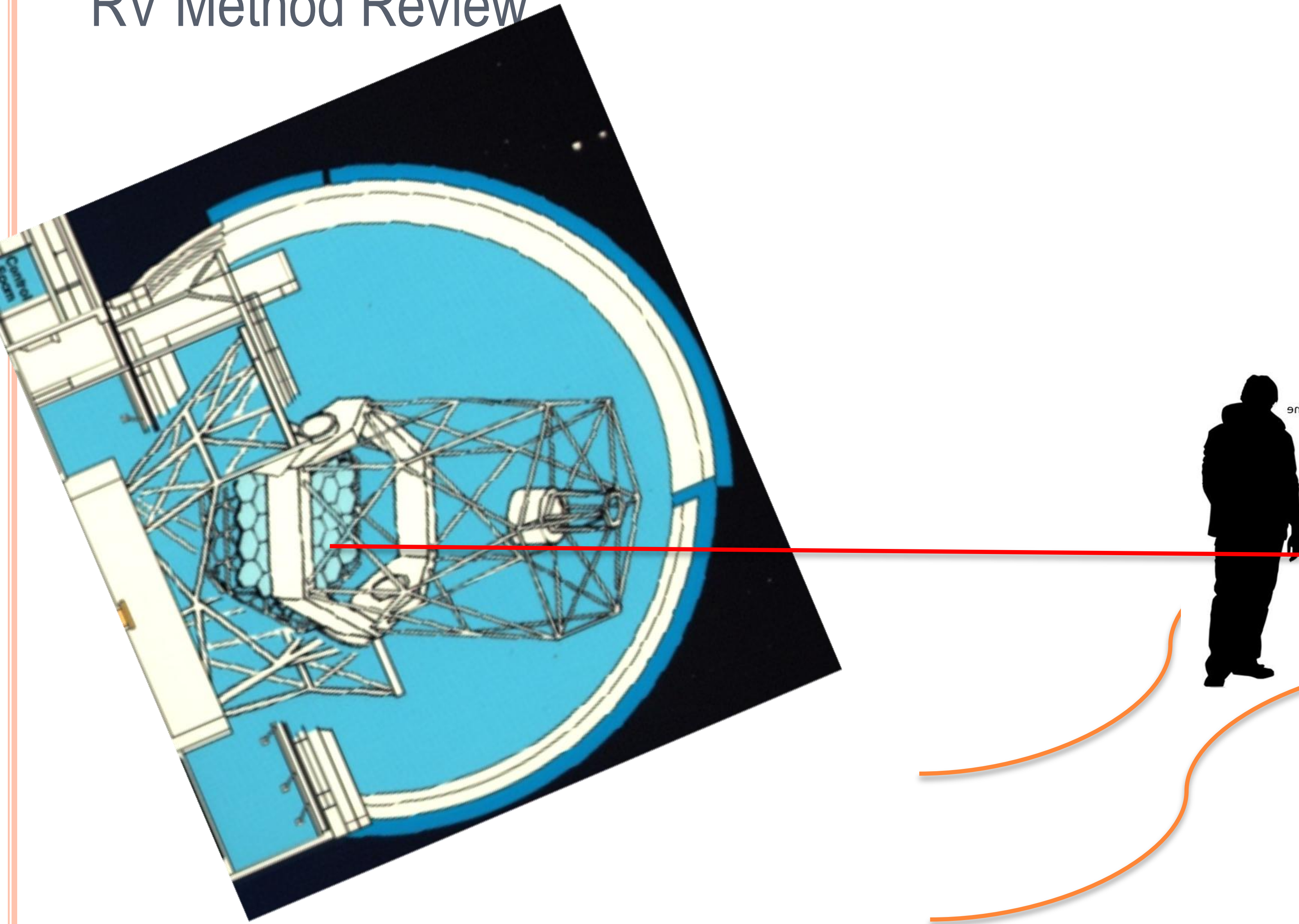
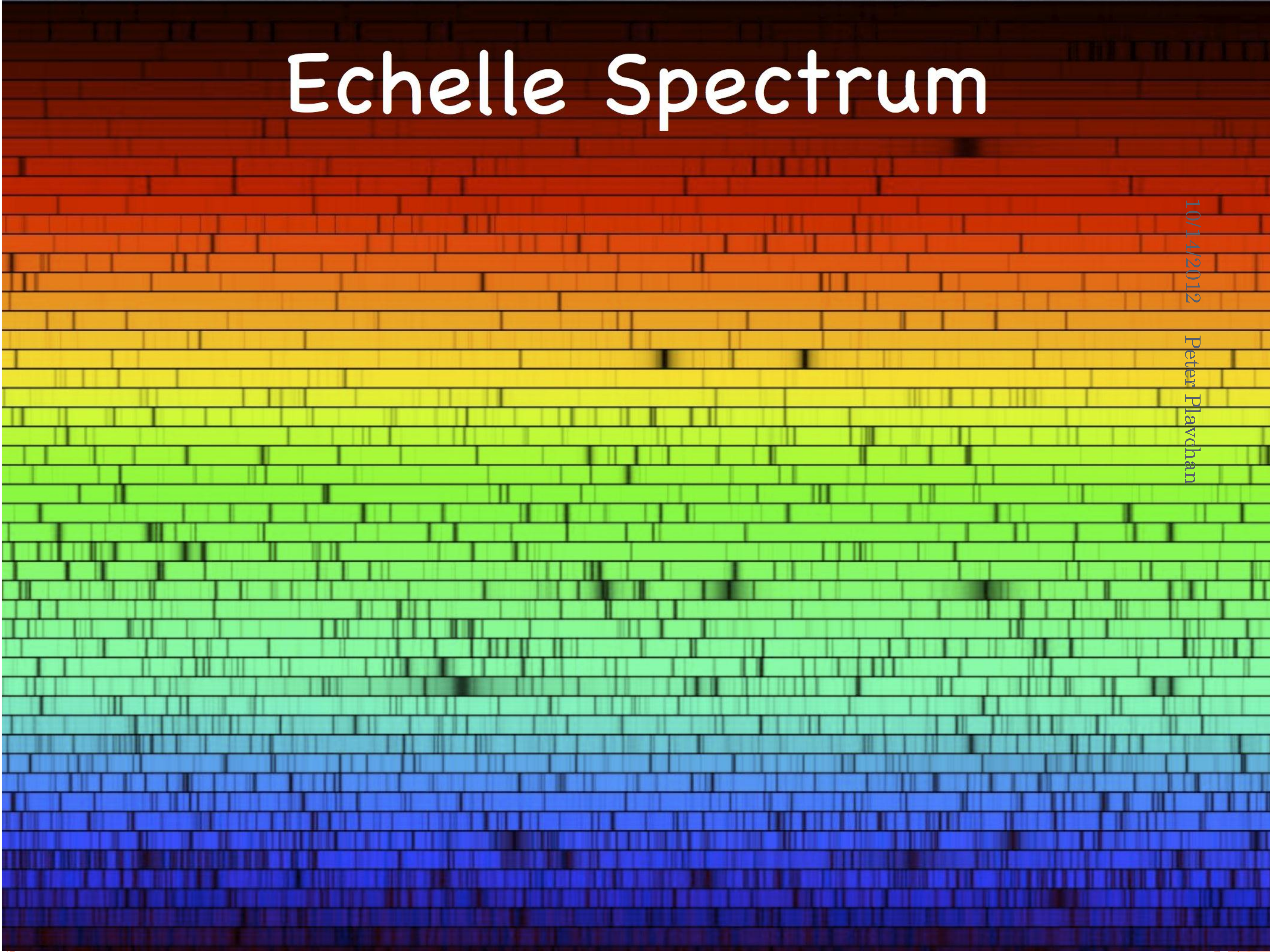
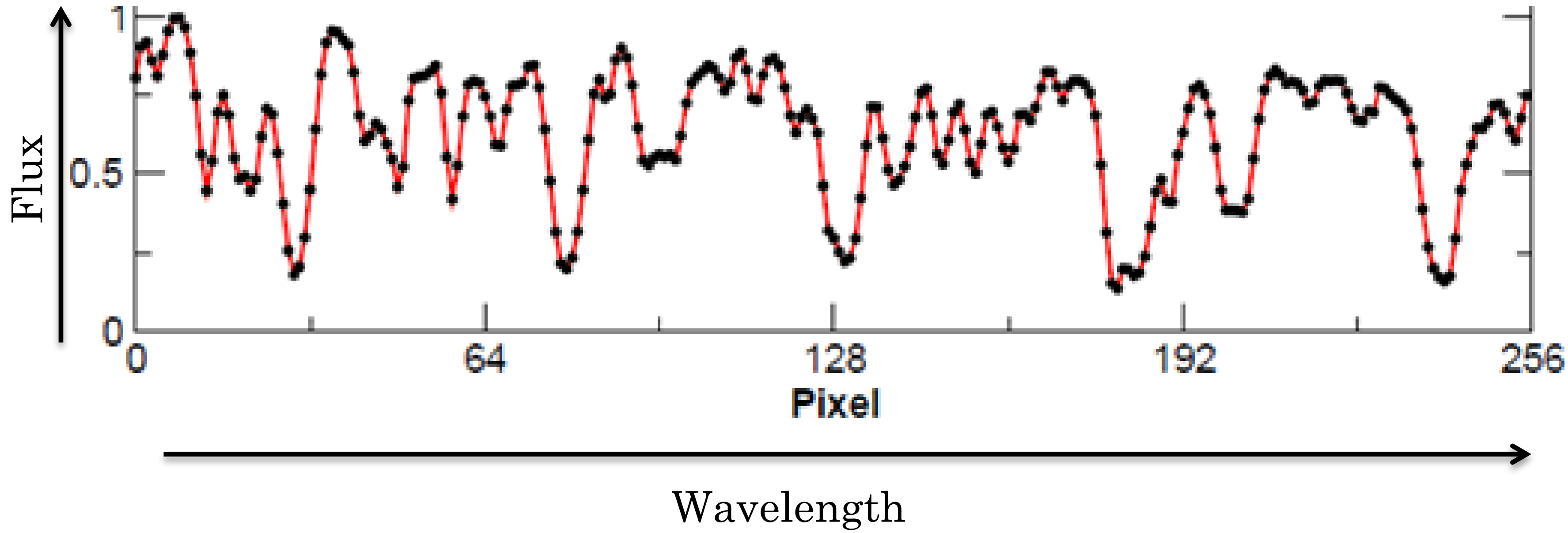


Echelle Spectrum



RV Method Review – a single order of a spectrum



1 m/s ~1/3,000th of a resolution element

wavelength shift ~ 1 nm

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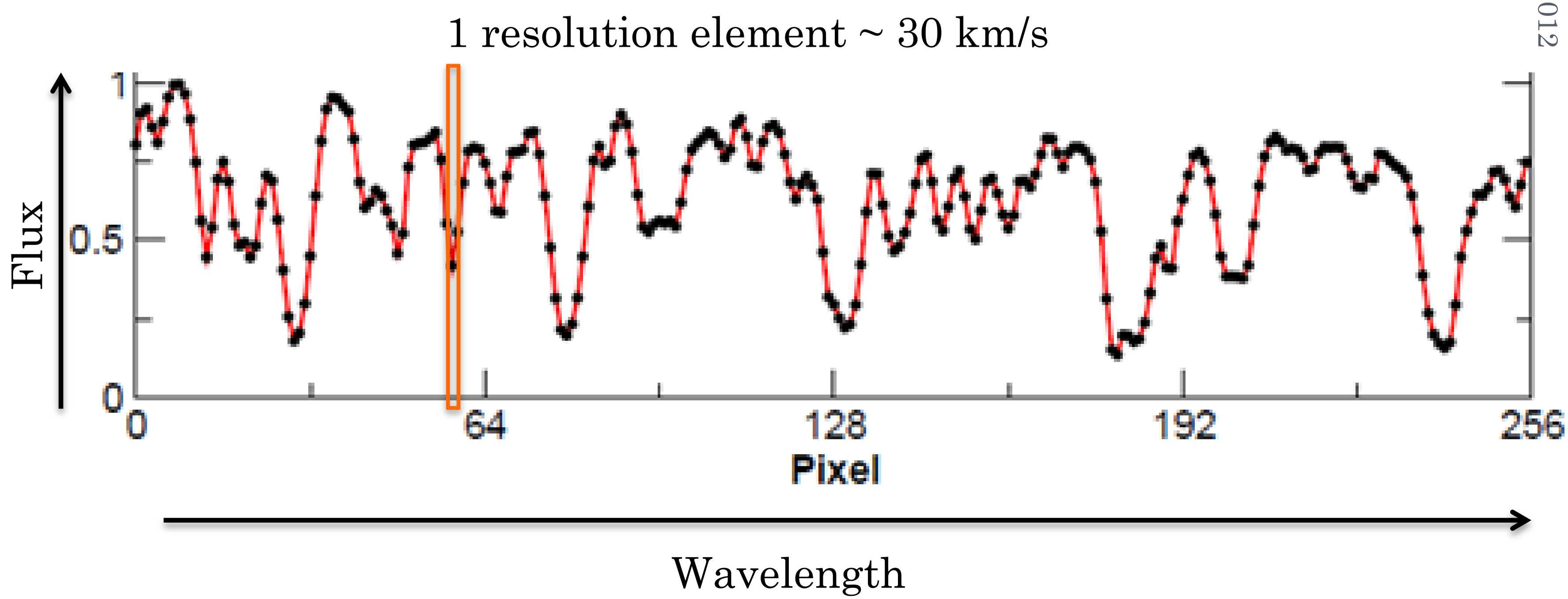

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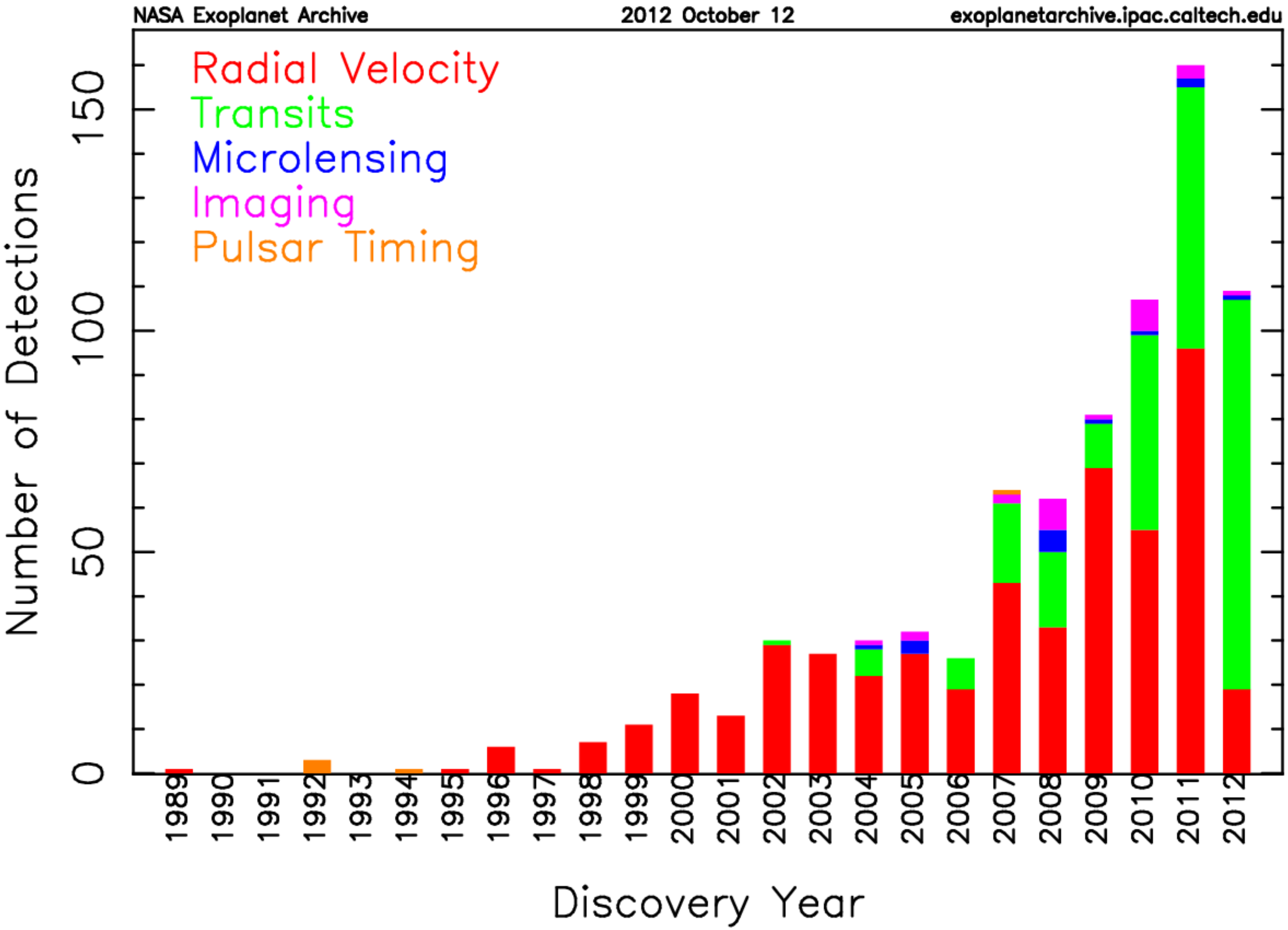
→ Precision RVs are firmly in the systematic noise regime

RV Method Review



1989 – HD 114762 b & Gamma Cephei Ab

10/14/2012

letters to nature

Nature **339**, 38 - 40 (04 May 1989); doi:10.1038/339038a0

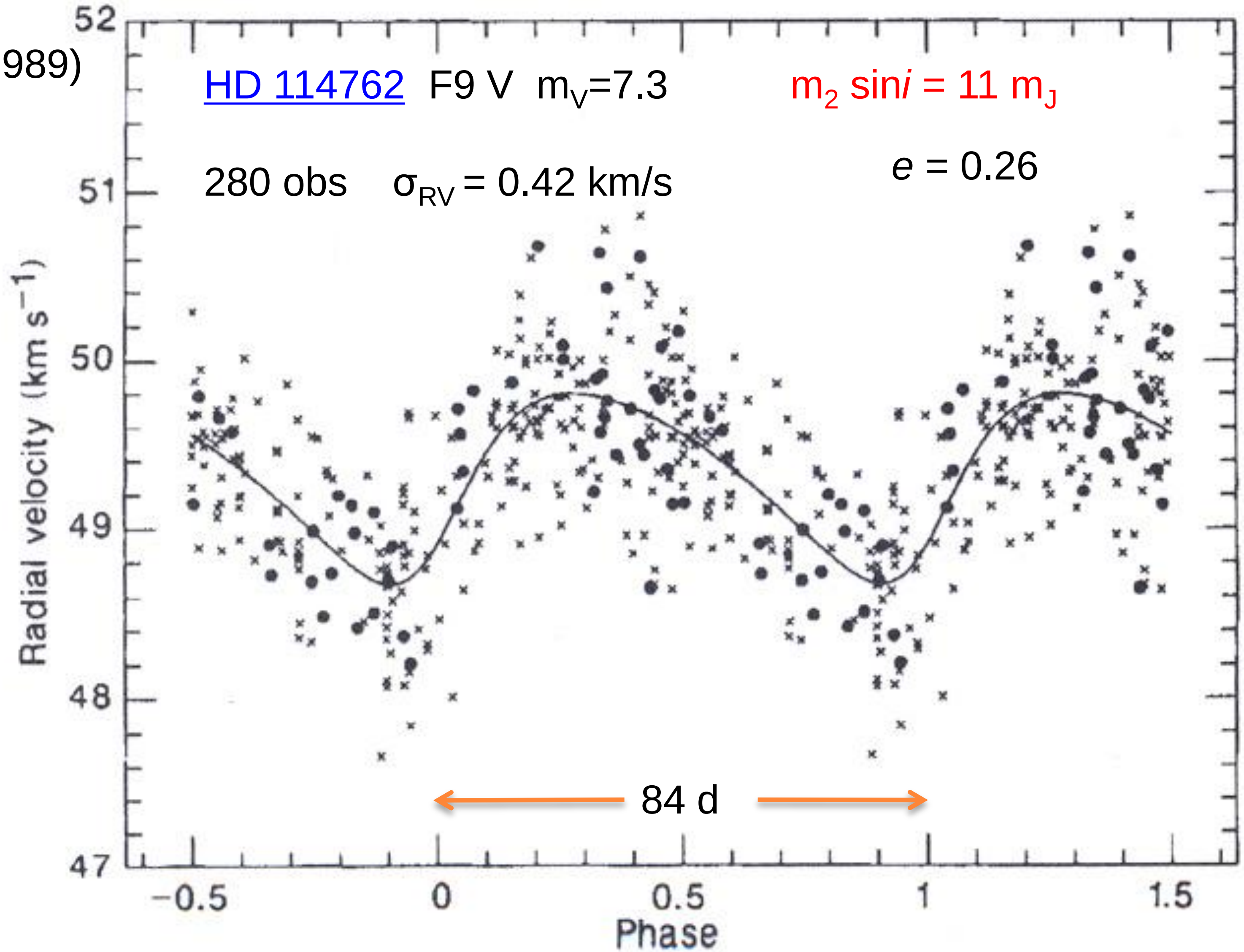
The unseen companion of HD114762: a probable brown dwarf

DAVID W. LATHAM[*], TSEVI MAZEH[†], ROBERT P. STEFANIK[*], MICHEL MAYOR[‡] & GILBERT BURKI

[*]Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138, USA
[†]School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Science, Tel Aviv University, Tel Aviv 69978, Israel
[‡]Observatoire de Geneve, Chemin des Maillettes 51, Ch-1290 Sauverny, Switzerland

BROWN dwarfs are substellar objects with too little mass to ignite hydrogen in their cores. Despite considerable effort to detect brown dwarfs astrometrically[1–4], photometrically[4–9], and spectroscopi-cally[10–12], only a few good candidates have been discovered. Here we present spectroscopic evidence for a probable brown-dwarf companion to the solar-type star HD114762. This star undergoes periodic variations in radial velocity which we attribute to orbital motion resulting from the presence of an unseen companion. The rather short period of 84 days places the companion in an orbit similar to that of Mercury around the Sun, whereas the rather low velocity amplitude of about 0.6 km s^{-1} implies that the mass of the companion may be as low as 0.011 solar masses, or 11 Jupiter masses. This leads to the suggestion that the companion is probably a brown dwarf, and may even be a giant planet. However, because the inclination of the orbit to the line of sight is unknown, the mass of the companion may be considerably larger than this lower limit.

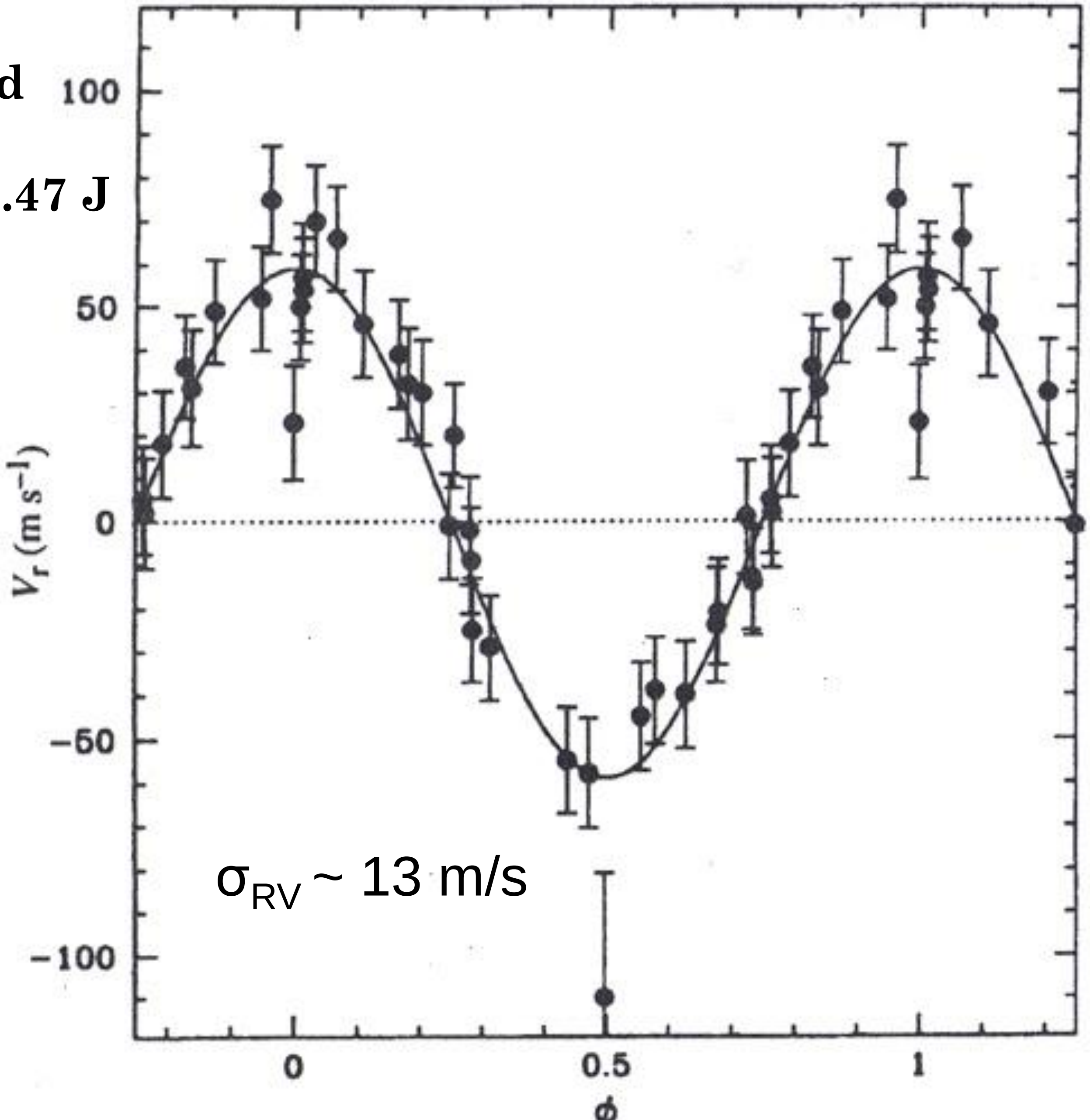
Latham, Stefanik, Mazeh, Mayor, Burki -- CfA speedometer & CORAVEL (1989)



51 Peg **Mayor & Queloz** **1995**

***P* = 4.23 d**

***m* sin*i* = 0.47 J**



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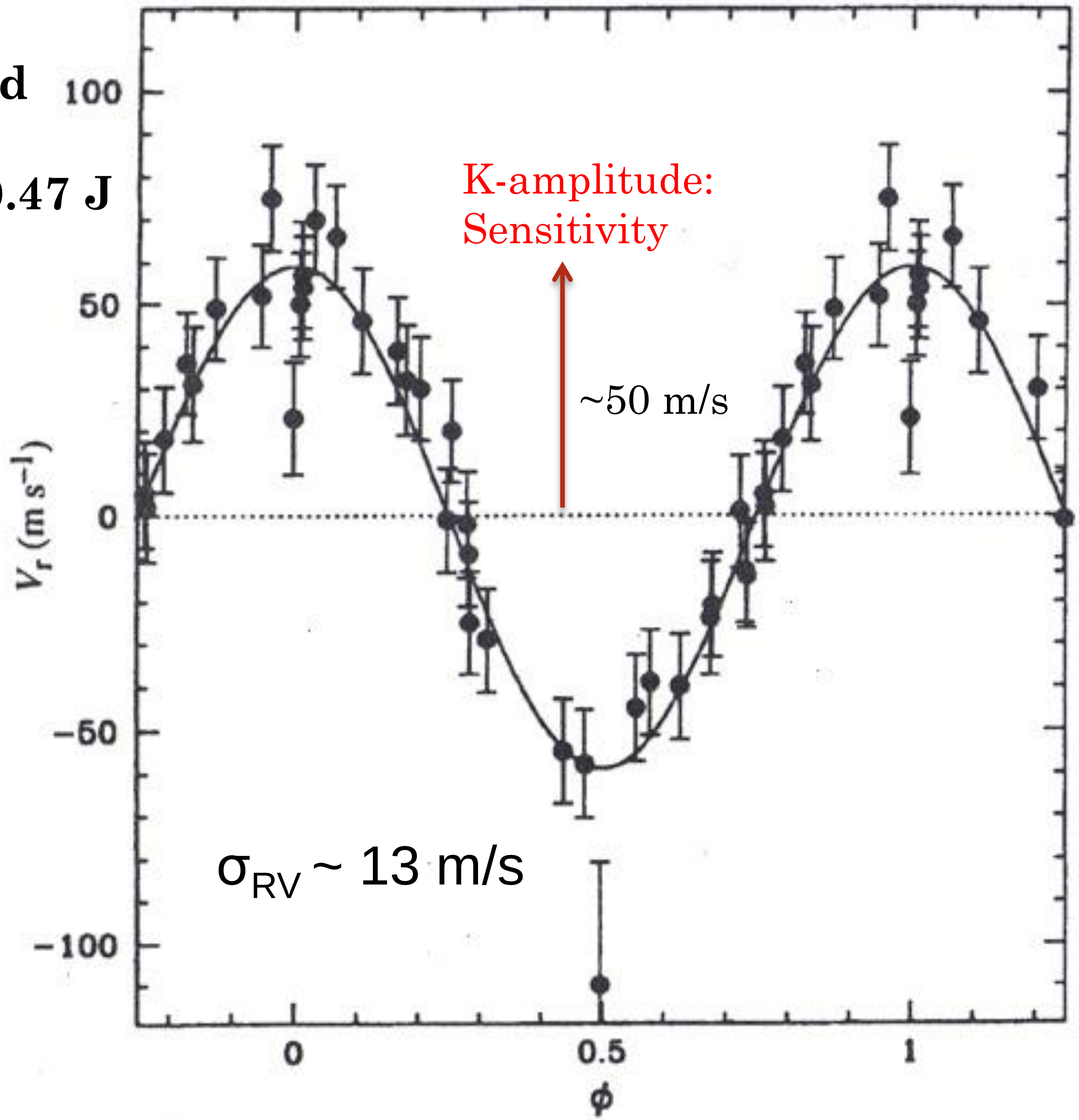

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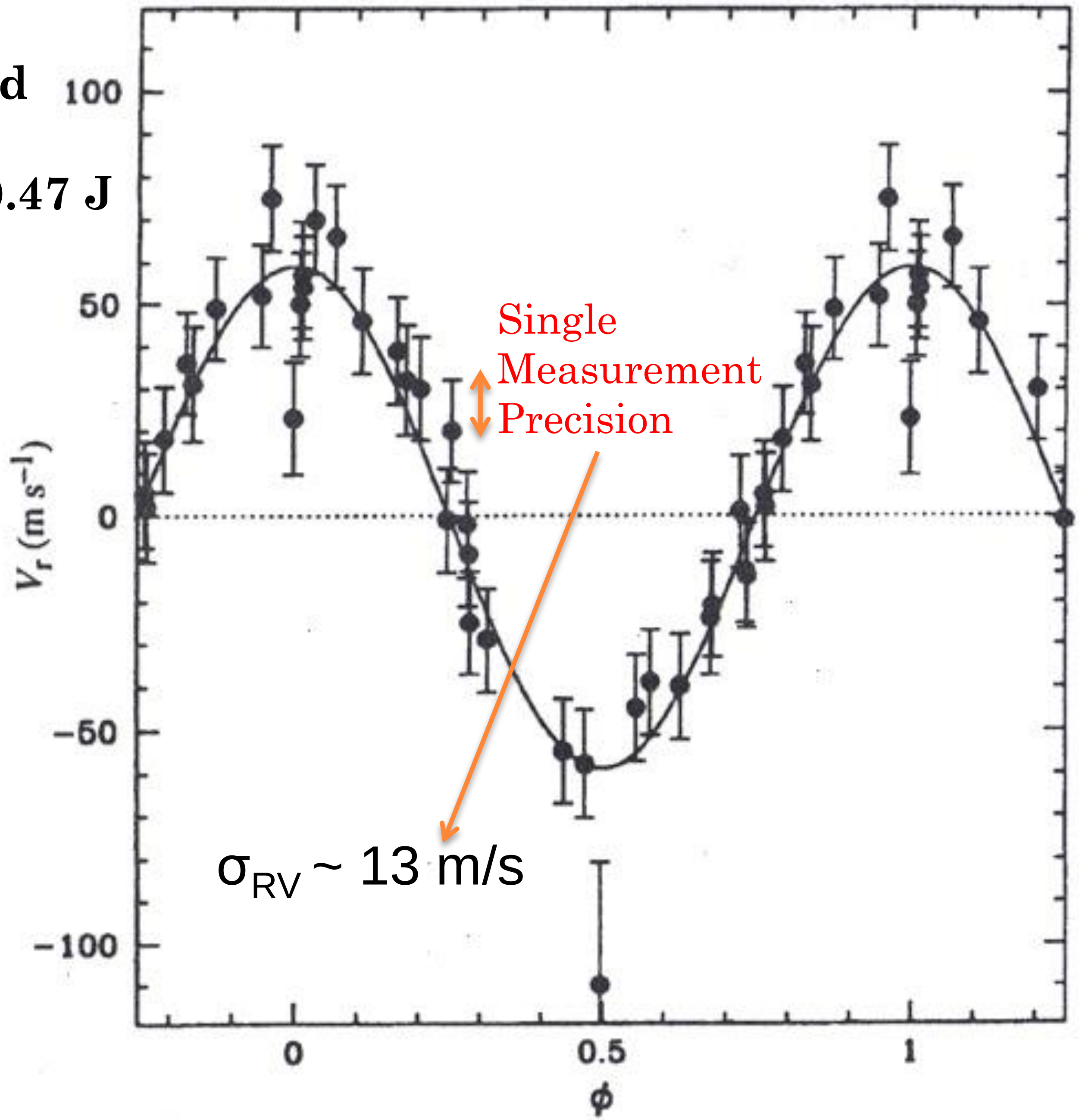

1995-2010 – Turning Science Fiction into Fact and a Census of Extrasolar Planetary Systems

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Peter Plavchan

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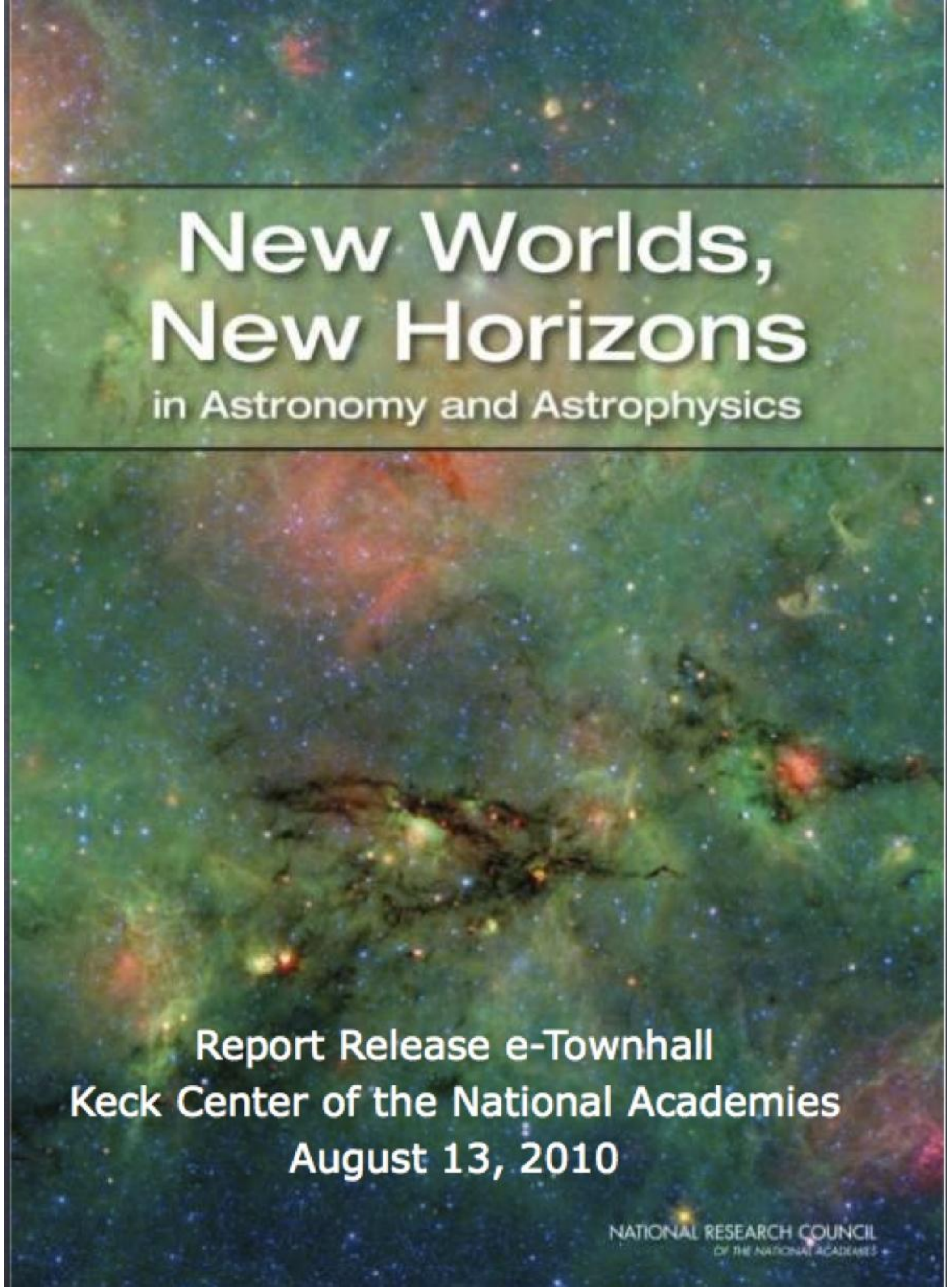
New Worlds,
New Horizons
in Astronomy and Astrophysics
Report Release e-Townhall
Keck Center of the National Academies
August 13, 2010
NATIONAL RESEARCH COUNCIL

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).

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

Key science questions include:

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- What are the near-term, medium-term, and long-term needs for Doppler measurements to support NASA science objectives - how many stars of what magnitudes and spectral types?

Primary Science Driver

Find the nearby Earth-like planets in habitable zone orbits around a Sun-like star, corresponding to a 10 cm/s edge-on orbit RV K semi-amplitude for a one solar mass-star.

Bottom et al. submitted – Habitable Zone complete (Phil Muirhead's talk)

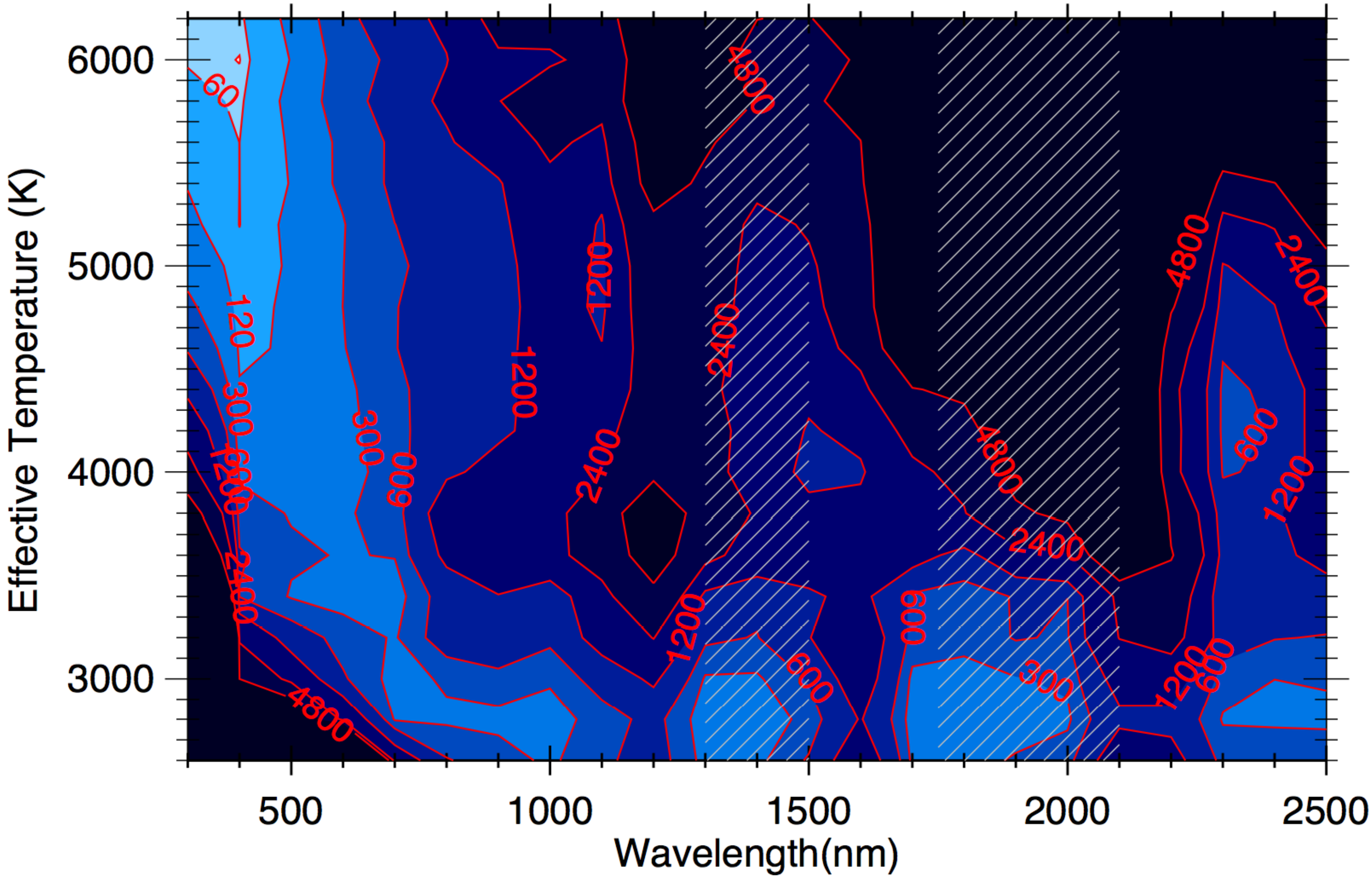
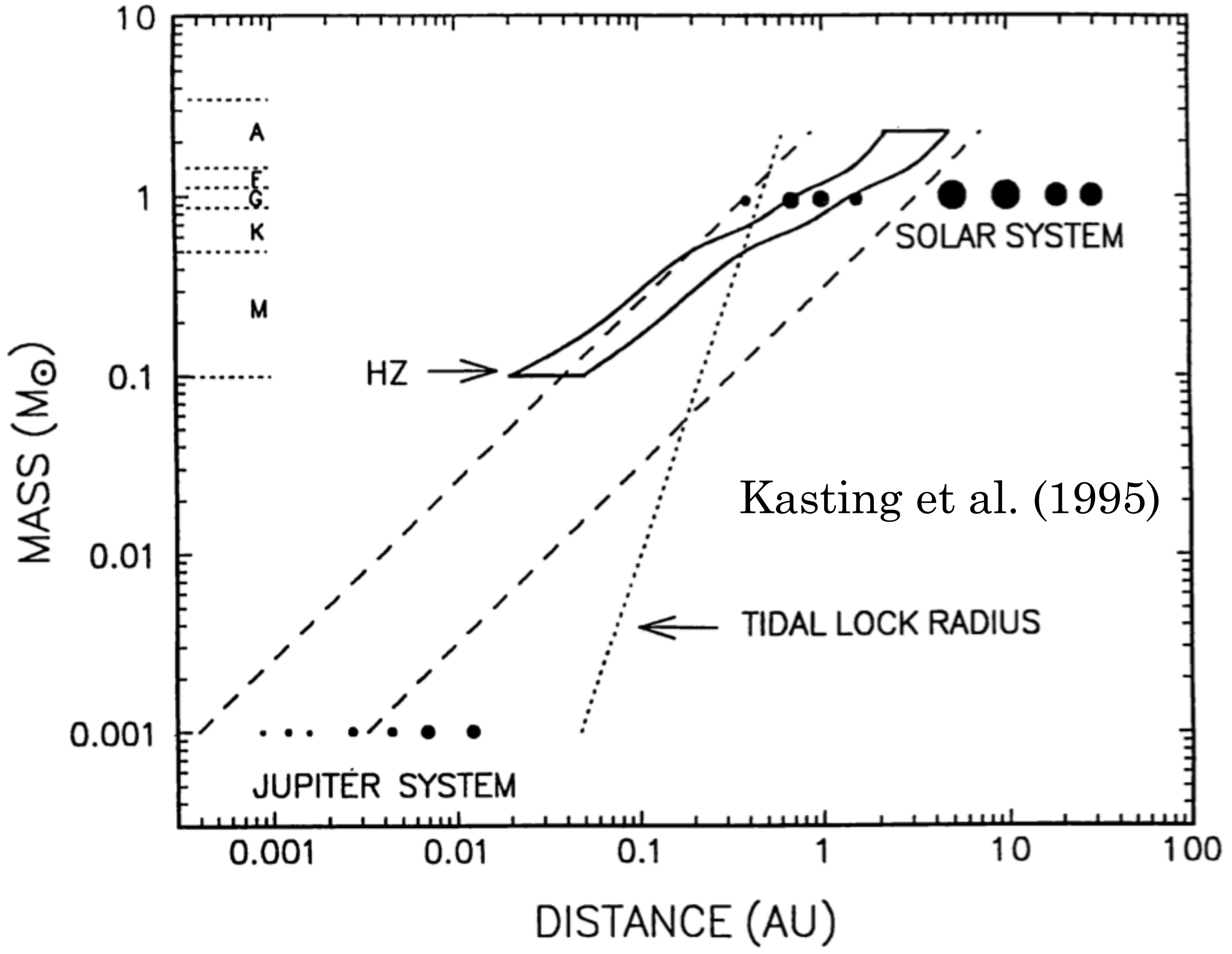
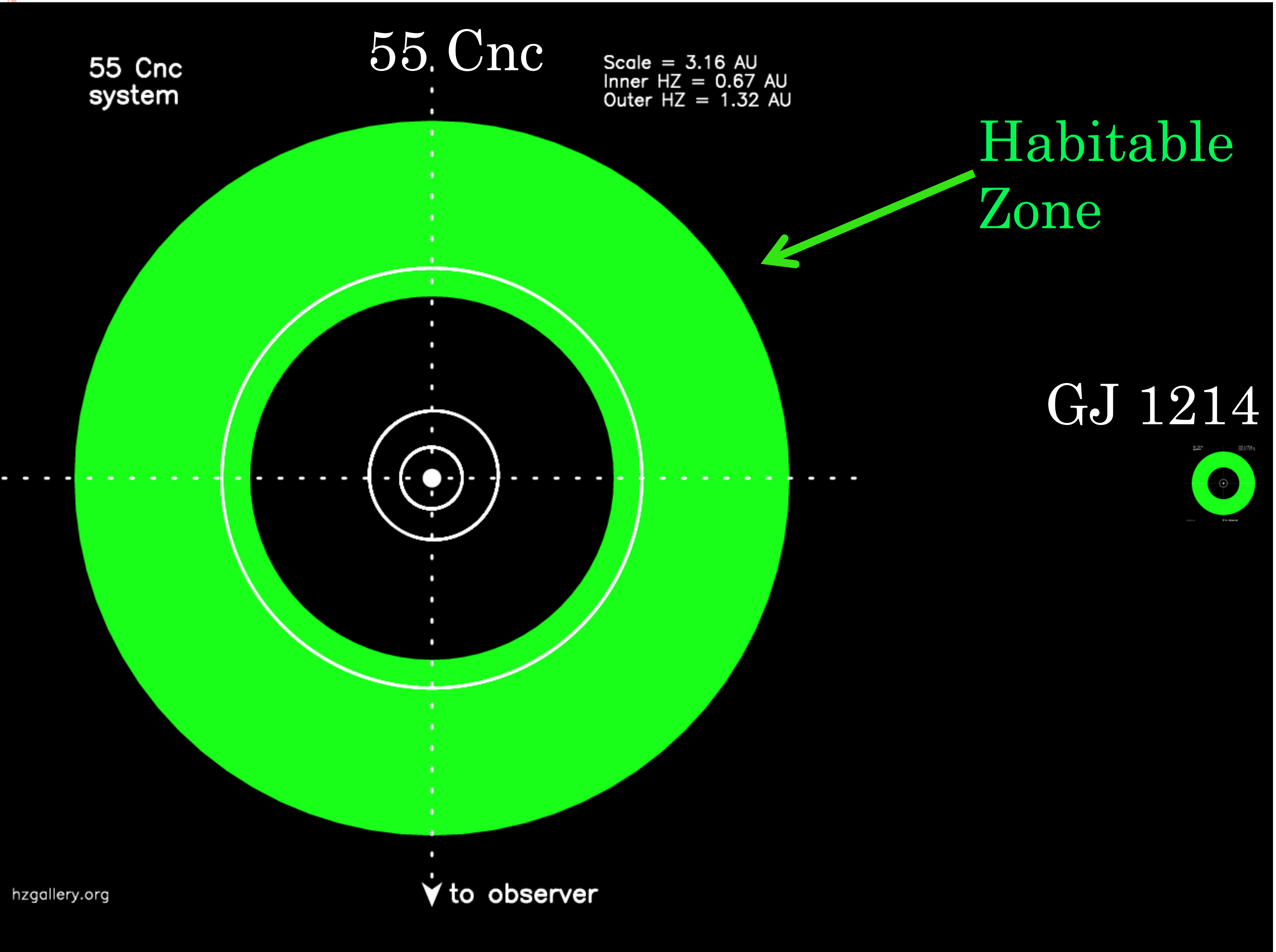


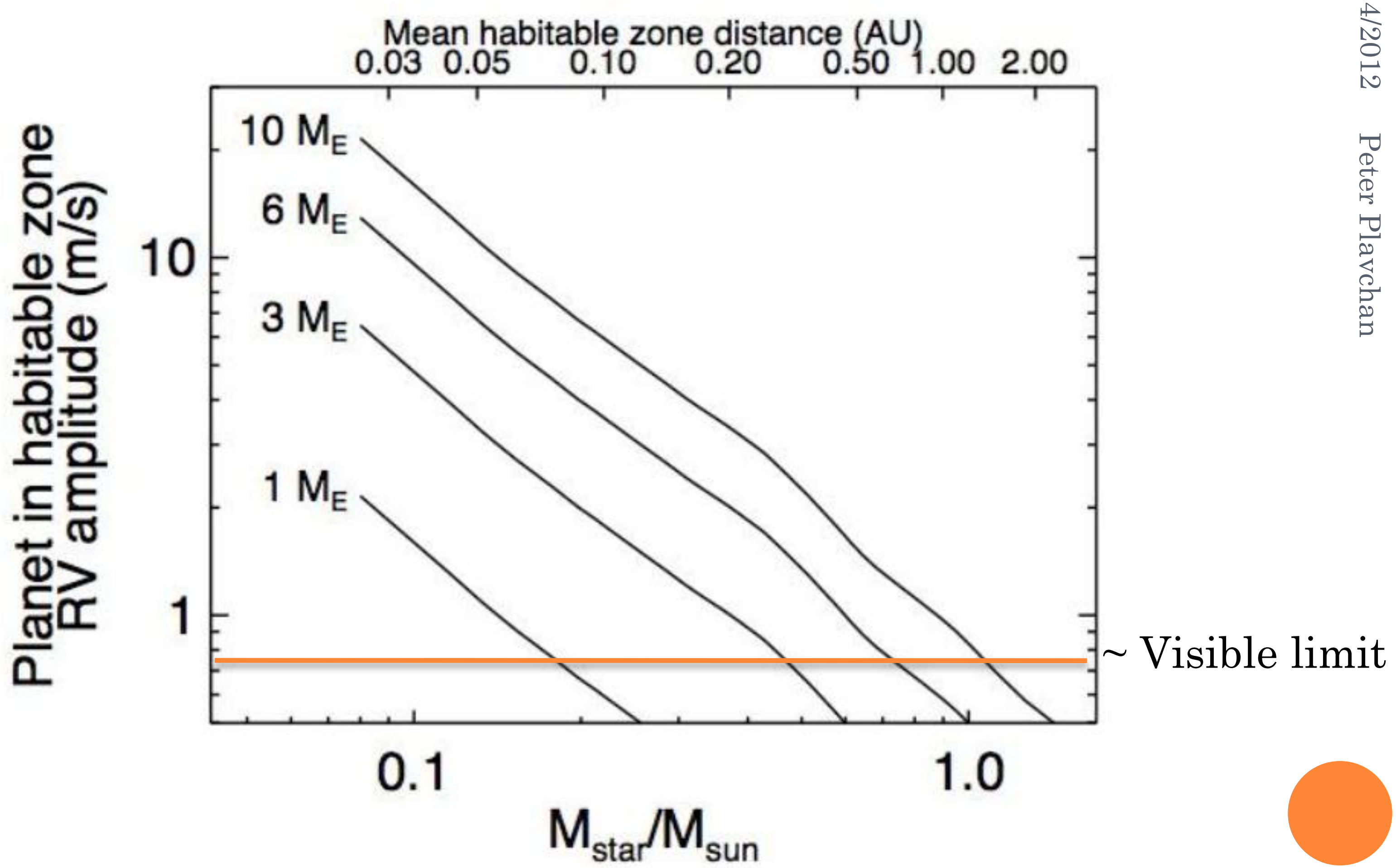
FIG. 4.— The time (seconds) to detect ($\sigma_v = K$) a 5 $M_\oplus$ planet in the habitable zone of its parent star, 10 parsecs away, for a range of observing wavelengths and stellar effective temperatures. The hashed regions correspond to wavelengths where the infrared absorption is too high for ground-based observations to be effective.

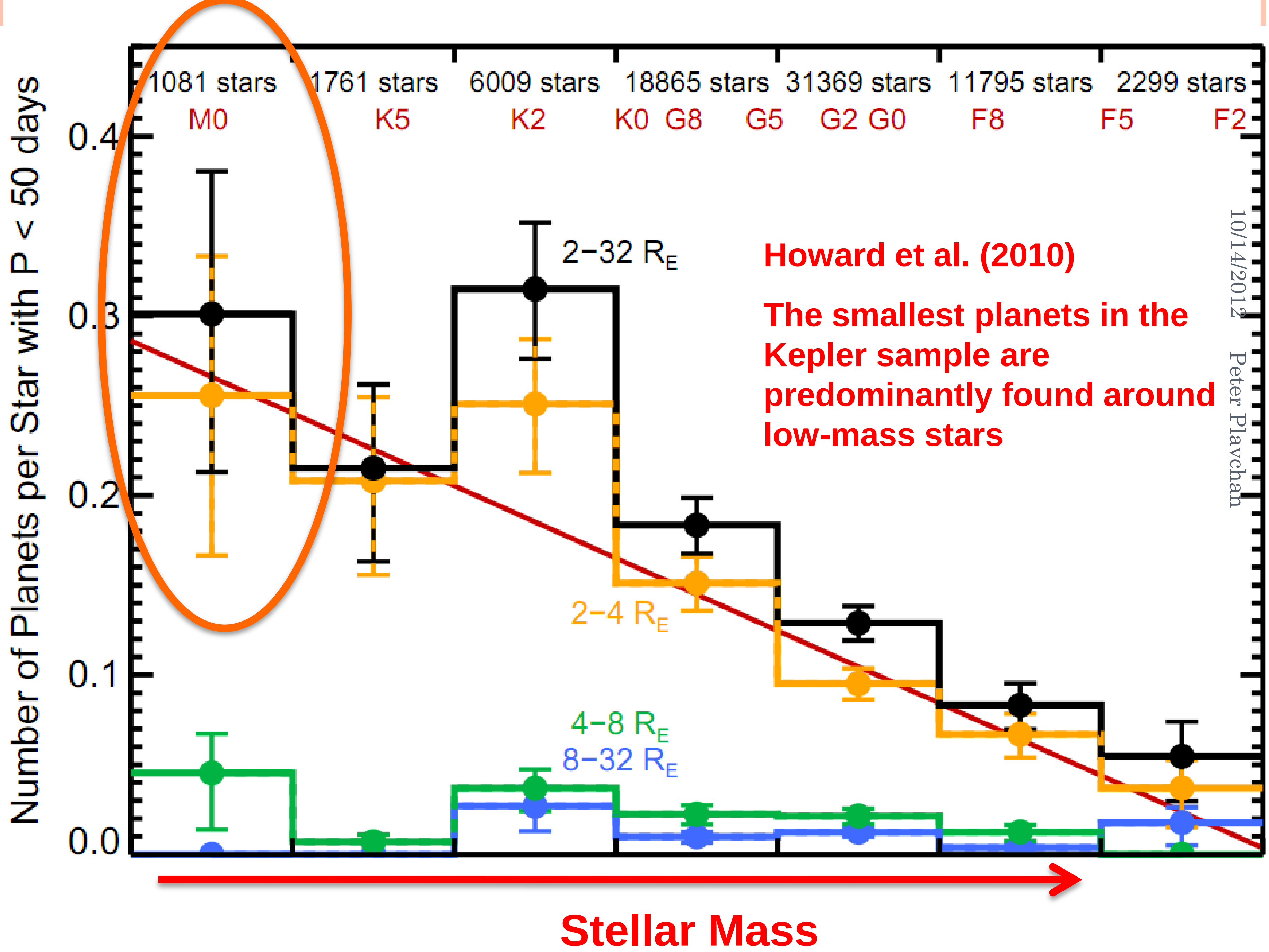
Habitable Zone as a Function of Spectral Type




55 Cnc
55 Cnc system
Scale = 3.16 AU
Inner HZ = 0.67 AU
Outer HZ = 1.32 AU
Habitable Zone
GJ 1214
to observer
hzgallery.org

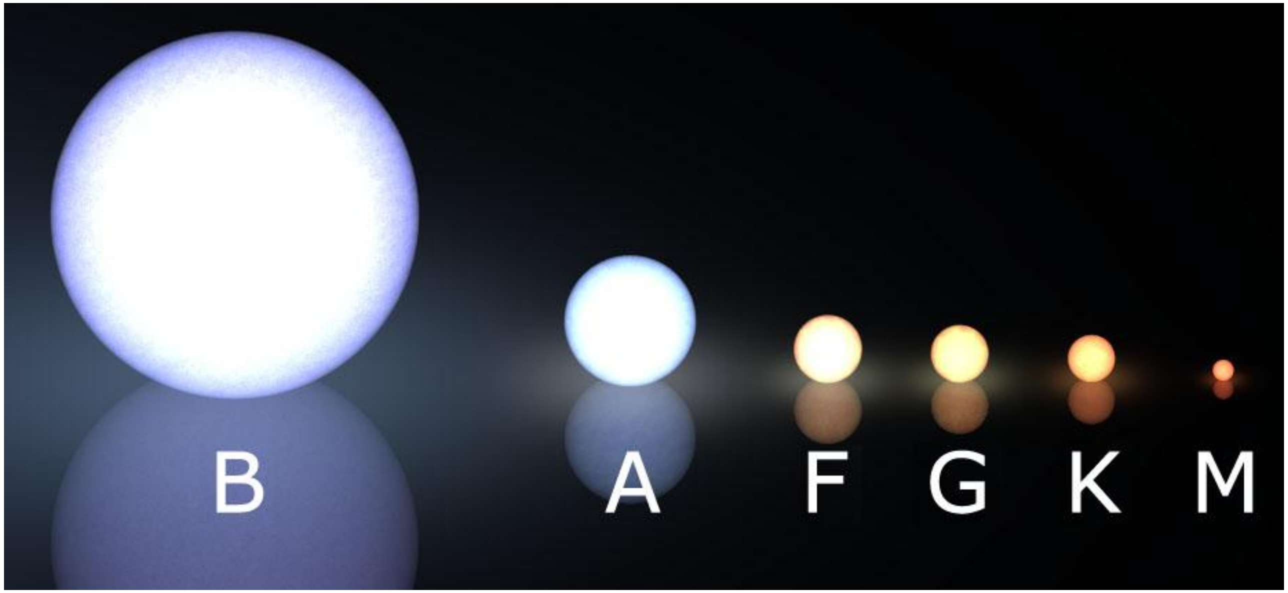
Habitable Zone RV amplitude




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
0.4
0.3
0.2
0.1
0.0
Number of Planets per Star with P < 50 days
2−32 R_E
2−4 R_E
4−8 R_E
8−32 R_E
Howard et al. (2010)
The smallest planets in the Kepler sample are predominantly found around low-mass stars
10/14/2012
Peter Plavchan
Stellar Mass

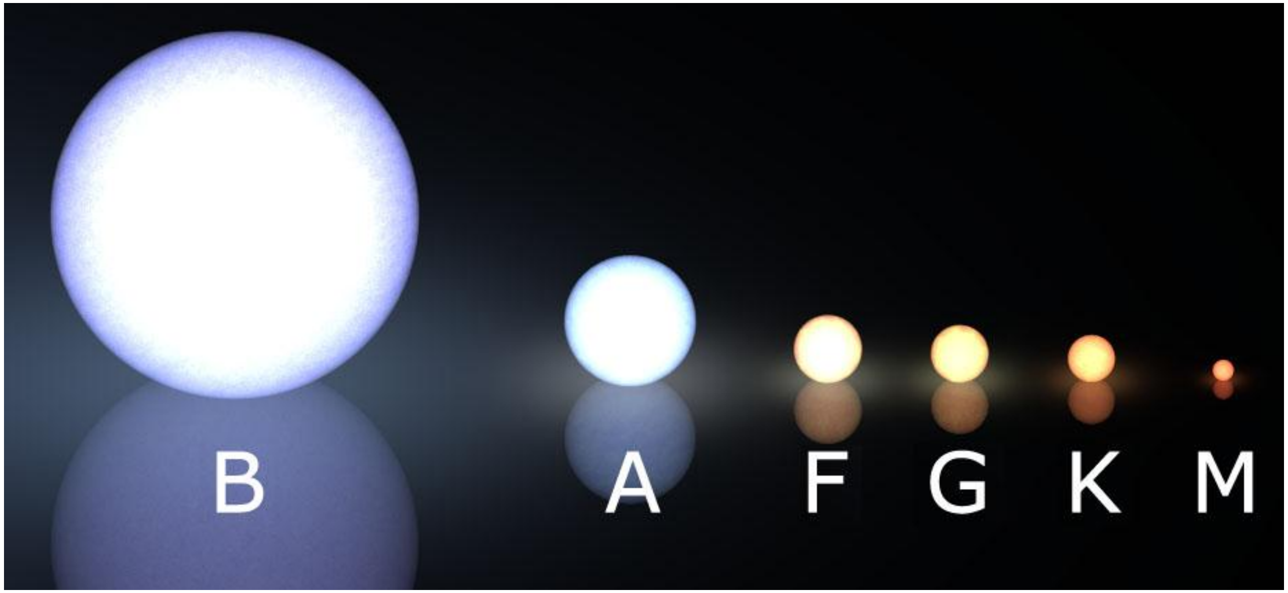
The M Dwarf Opportunity

- 70% of main sequence stars are M dwarfs
  - Abundant within 10 pc
  - Until recently, neglected compared to FGK stars



The M Dwarf Opportunity

- Span a factor of ~5 in Mass/Radius, ~10^3 in Luminosity
  - For comparison, all of AFGK stars span a factor of ~2.5 in Radius, ~5 in mass, ~300 in Luminosity
- M dwarfs are red, V-K > ~3.5
  - Only 4 >M4 with V<12



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- 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?

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

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

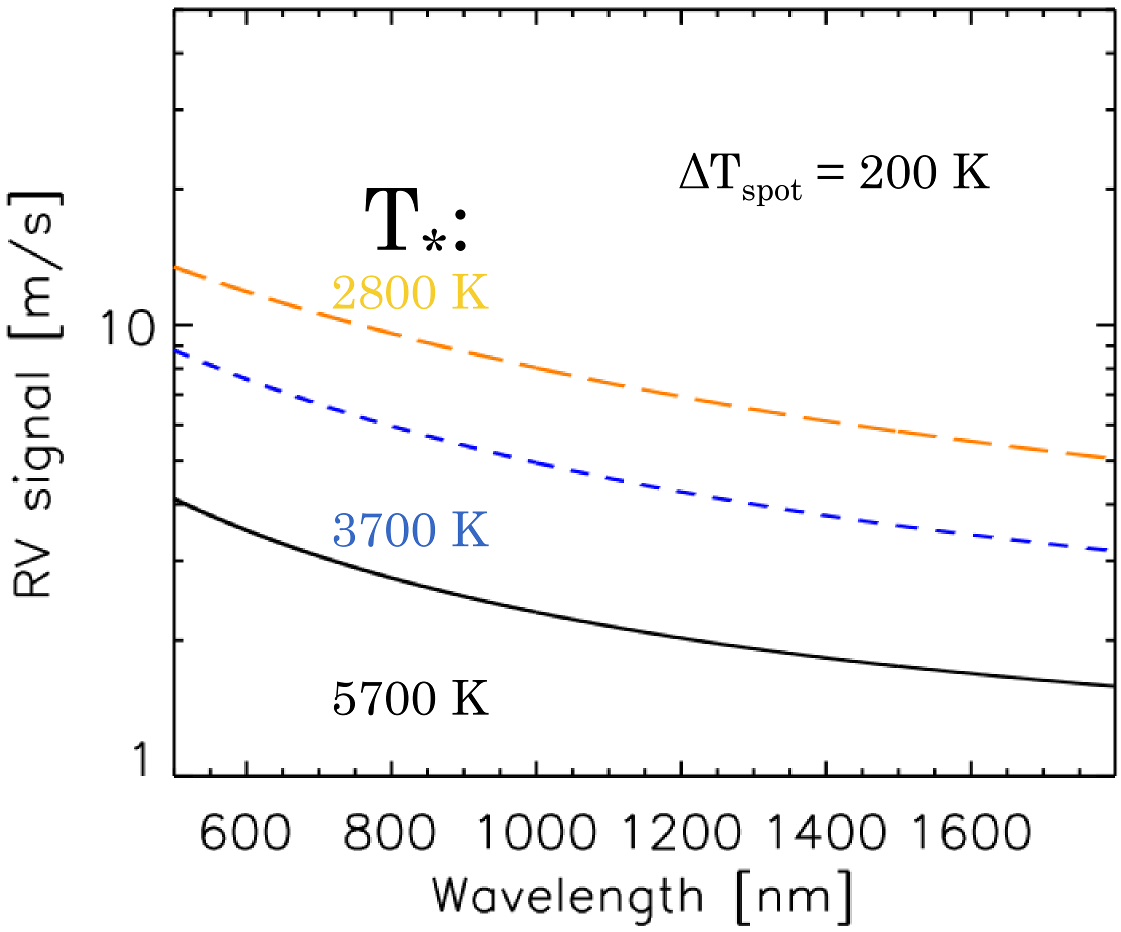
Dominant RV variability may not be a planet.

But is this a problem?

Example & Counter-Example: Kepler light curves show most solar type stars are on average more active than the Sun.

→ Valeri Makarov's talk later today, plus Andrew Howard's talk from previous EXOPAG meeting

Single Star Spot RV Noise Toy Model



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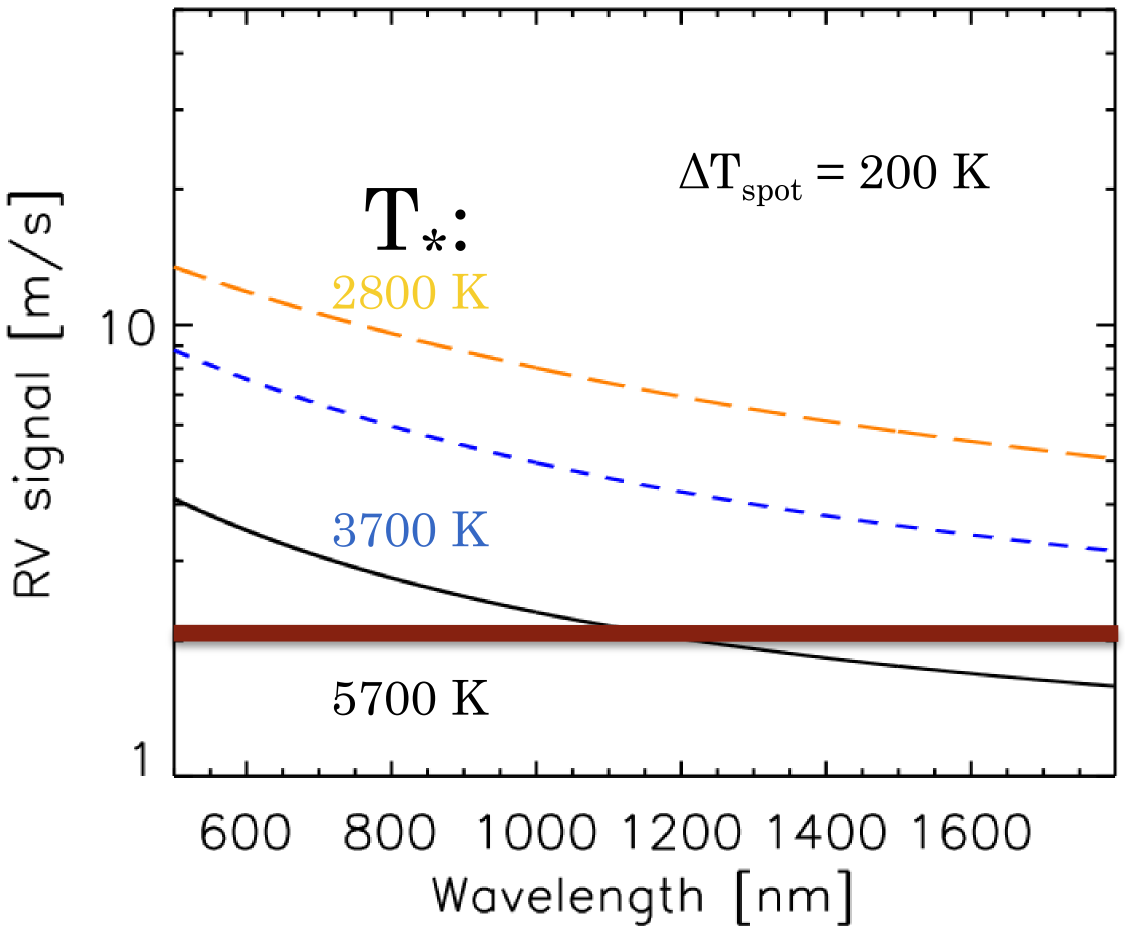

Anglada-Escude & Butler 2012

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- 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.

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?***

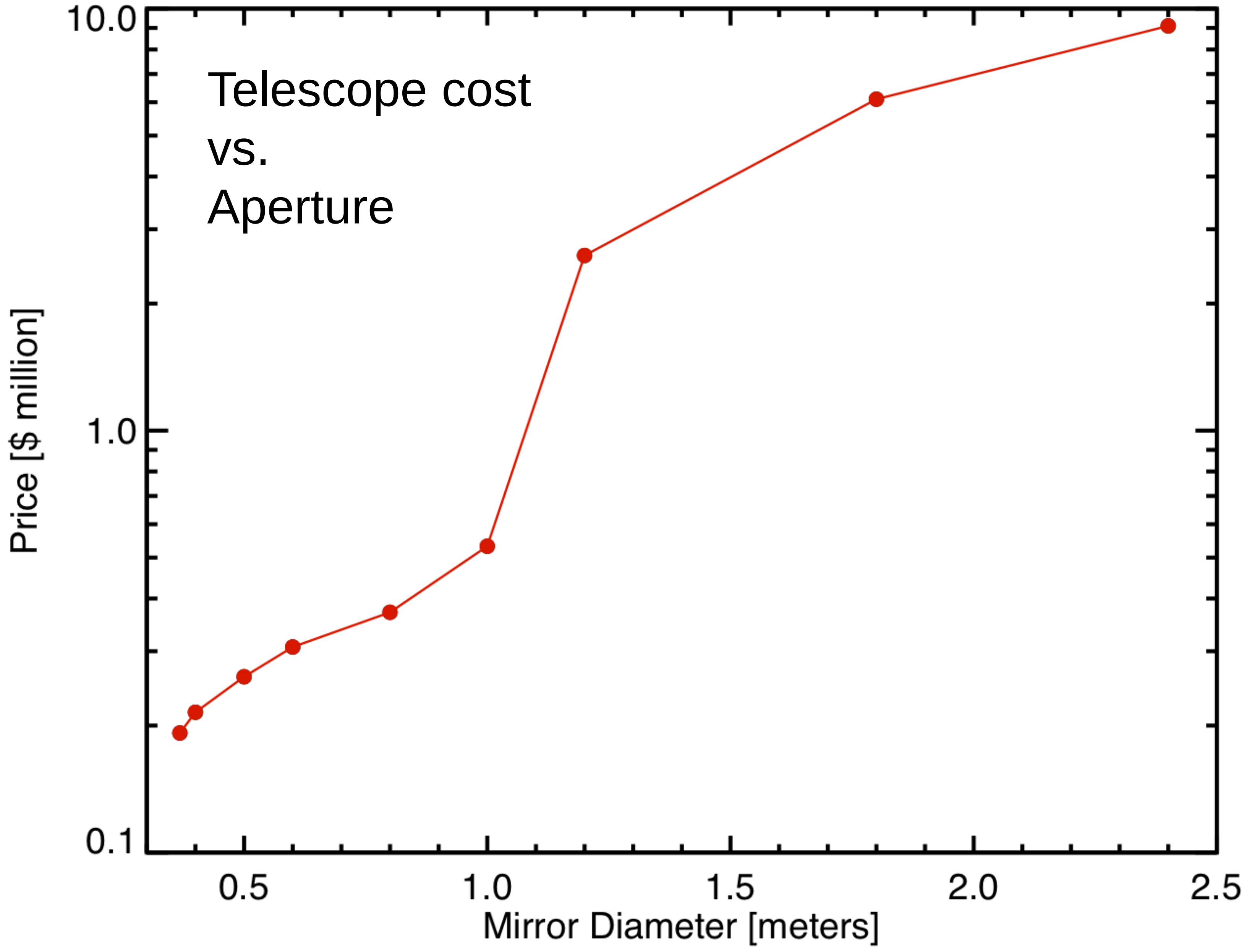
RV SAG Goals

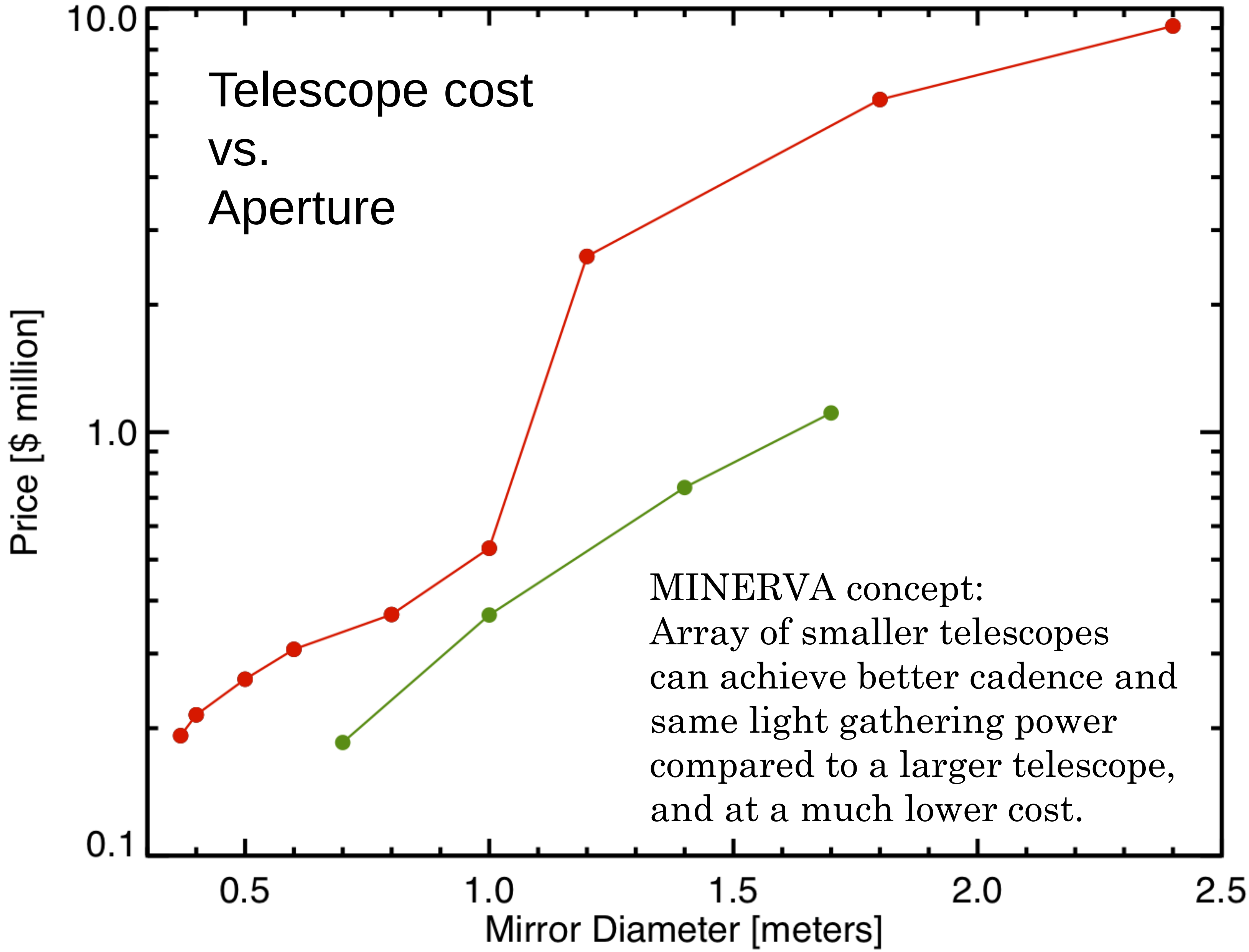
Programmatic questions to be considered include:

RV SAG Goals

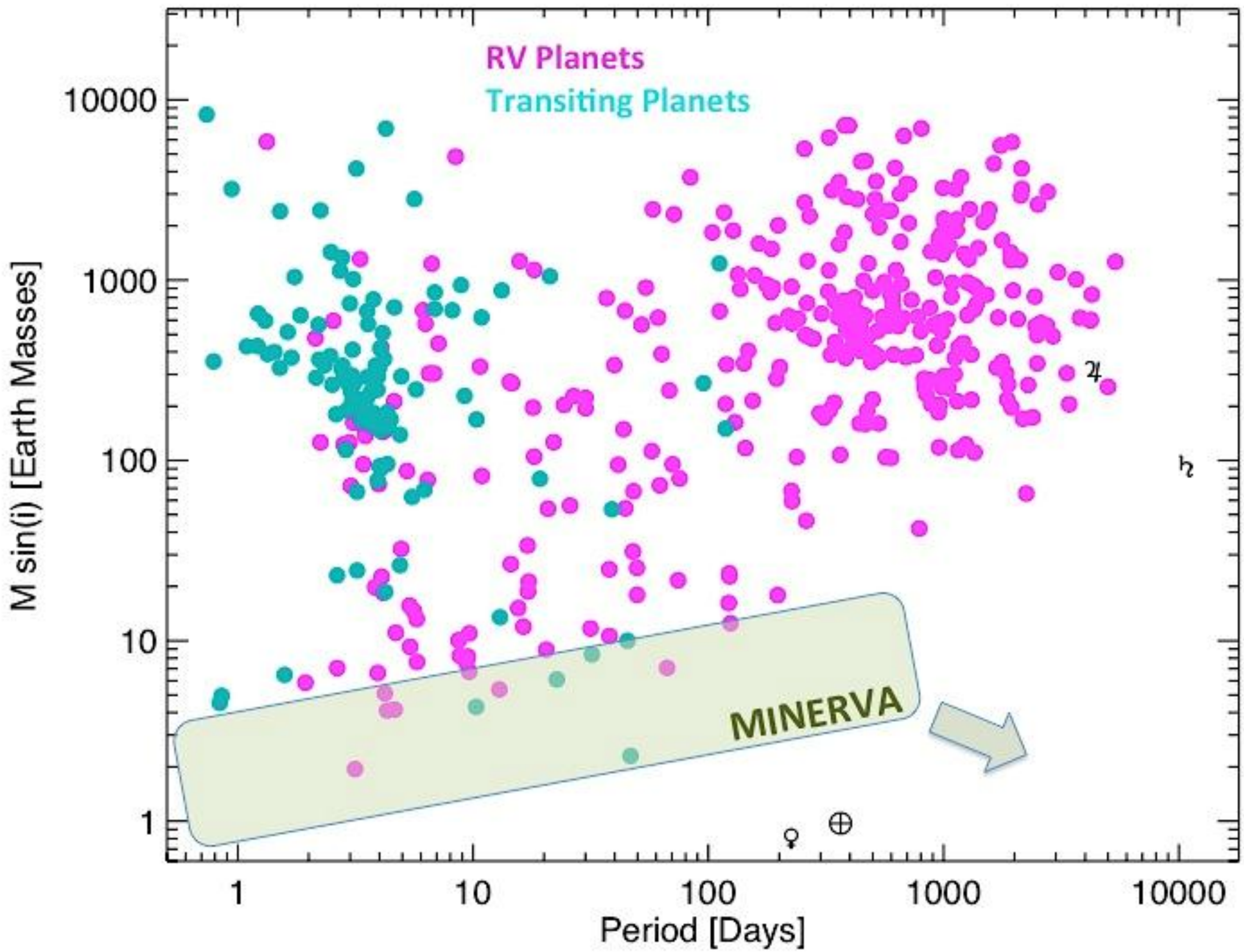
Programmatic questions to be considered include:

- What are the benefits or disadvantages of increased investment in telescope time (and for which class of telescope)?


Telescope cost
vs.
Aperture
10.0
1.0
0.1
Price [$ million]
0.5
1.0
1.5
2.0
2.5
Mirror Diameter [meters]


Telescope cost
vs.
Aperture
10.0
1.0
0.1
Price [$ million]
0.5
1.0
1.5
2.0
2.5
Mirror Diameter [meters]
MINERVA concept:
Array of smaller telescopes
can achieve better cadence and
same light gathering power
compared to a larger telescope,
and at a much lower cost.

MINERVA



RV Planets
Transiting Planets
MINERVA
M sin(i) [Earth Masses]
Period [Days]
10000
1000
100
10
1
1
10
100
1000
10000

RV SAG Goals

Programmatic questions to be considered include:

- 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?

An incomplete list of current and upcoming visible RV facilities:

HIRES/eta Earth Future: SHREK?	1.5 – 2.0 m/s precision RV ~ 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 RV ~ year-round
CHIRON	Sub-1 m/s precision

LCOGT – similar to MINERVA, also funded

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

etc… See also Dave Latham's talk

The future of NIR PRVs:

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
HZPF	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

RV SAG Goals

Programmatic questions to be considered include:

- 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?

NASA Programmatic Investment

- Historically NASA has not invested in ground-based RV research at the program level, with the exception of PI-based grant programs such as Origins, and Kepler team RV followup
- As part of the RV SAG in line with the Decadal Survey, should this possibility be on the table?
- NASA investment in ground-based astronomy (e.g. Keck Interferometer, LBTI, IRTF) must have clear and explicit ties to current or planned space-based missions.
  - JWST precursor science surveys (target identification)
  - Kepler follow-up
  - RVs in space?

Gordon Walker, PRV meeting @Penn State in 2010:

the future ?

space

4-m at L2 – Strehl ~ 0.5

spectrograph

R>250,000

λ 0.3 to 2 μm

→ ***No telluric absorption, relatively more stable PSF!***

RV SAG Goals

Instrument/technical questions include:

RV SAG Goals

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- What approaches can improve radial-velocity instrumental precision to the astrophysical limits?

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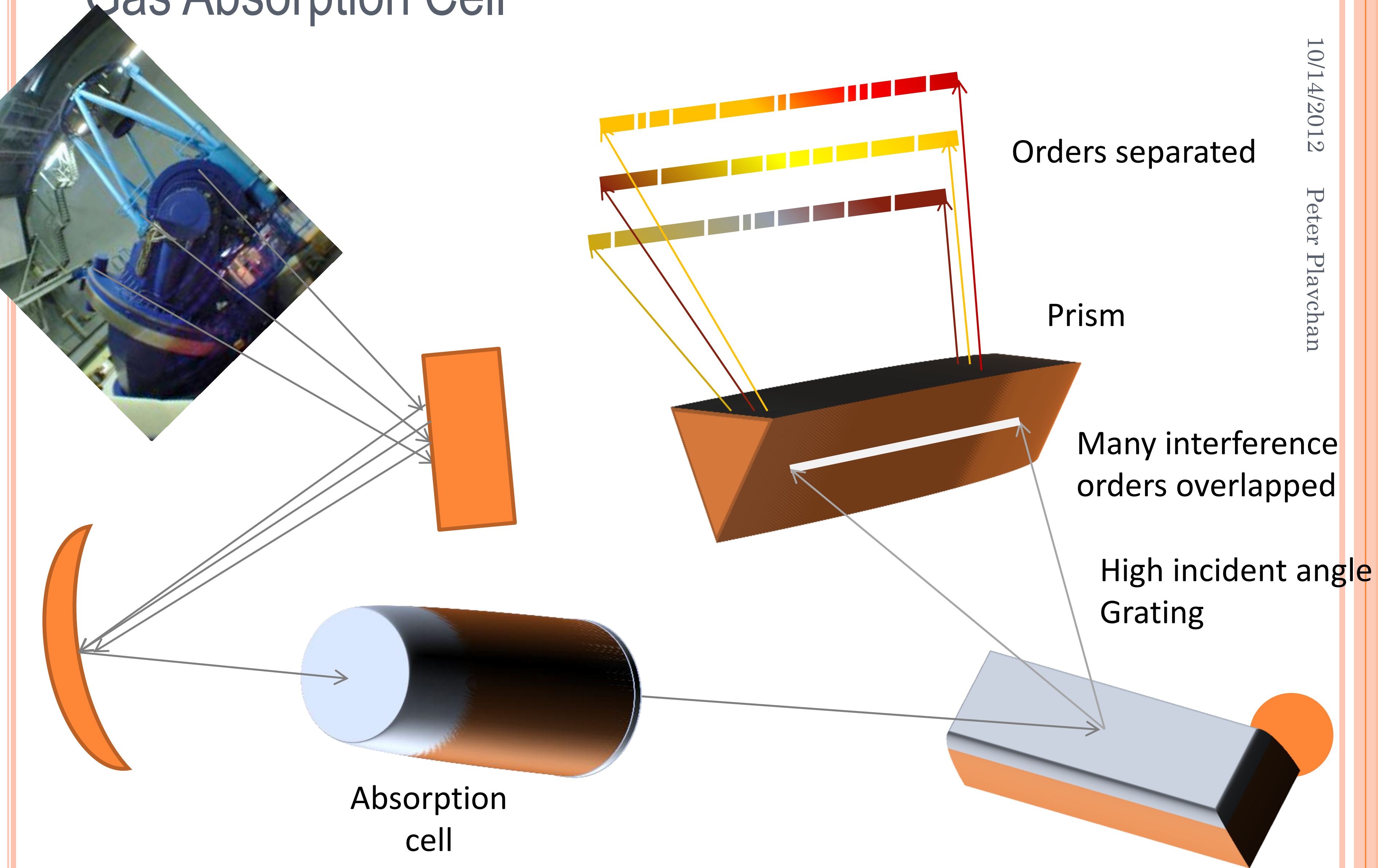
Instrument/technical questions include:

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

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

Gas Absorption Cell



Iodine Cell

Techniques for Precision RVs

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  - End-to-end extreme stabilization of telescope and spectrograph + lamps (HARPS)
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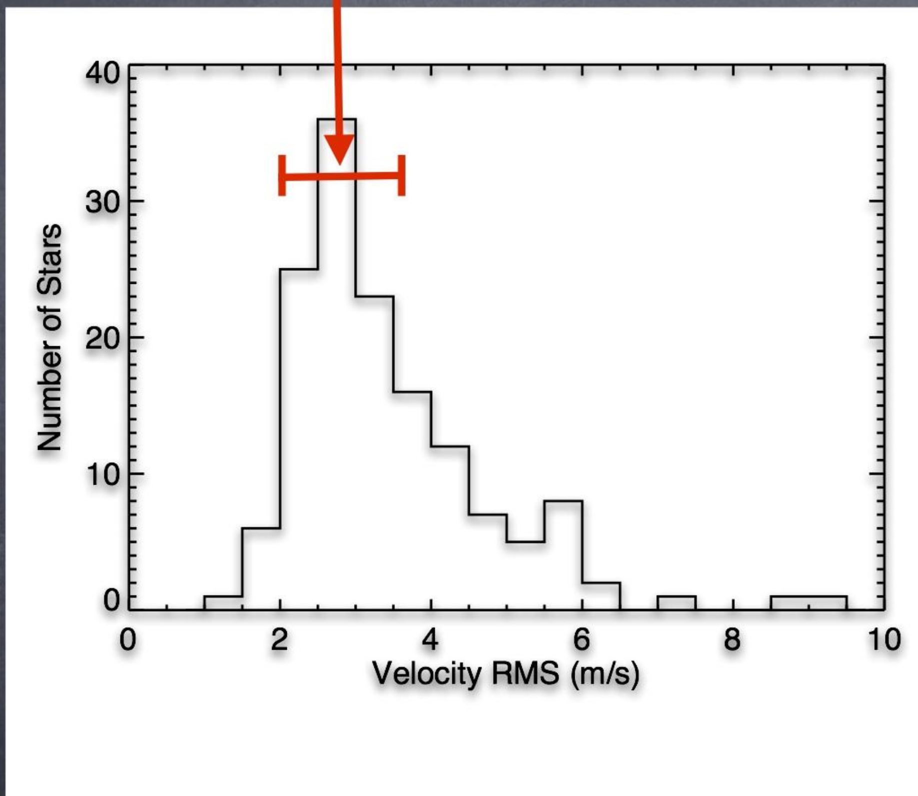
  - → Philosophies not mutually exclusive

Velocity RMS

2–3.5 m/s

1–3 m/s



M Mayor and S Udry

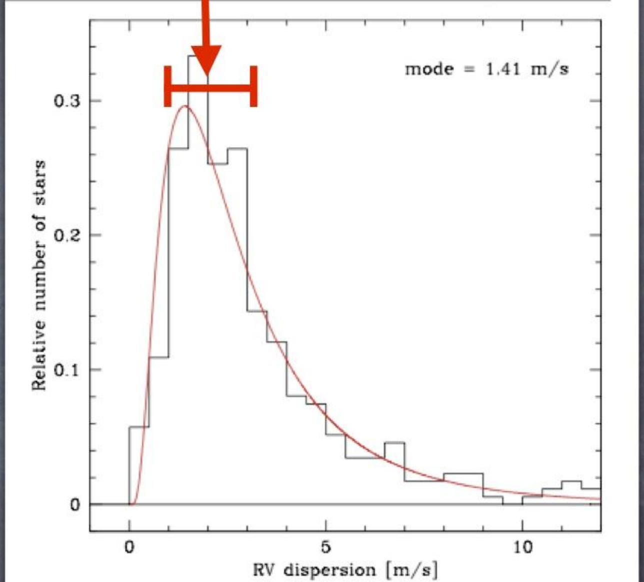


Figure 2. Histogram of radial-velocity rms for the stars in the high-precision HARPS subprogramme aiming at detecting very low-mass planets. Part of the 'large' rms observed in the tail of the distribution results from stellar activity or from still undetected planetary systems.

HIRES

GK stars in Eta-Earth Survey
Known planets removed

HARPS

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

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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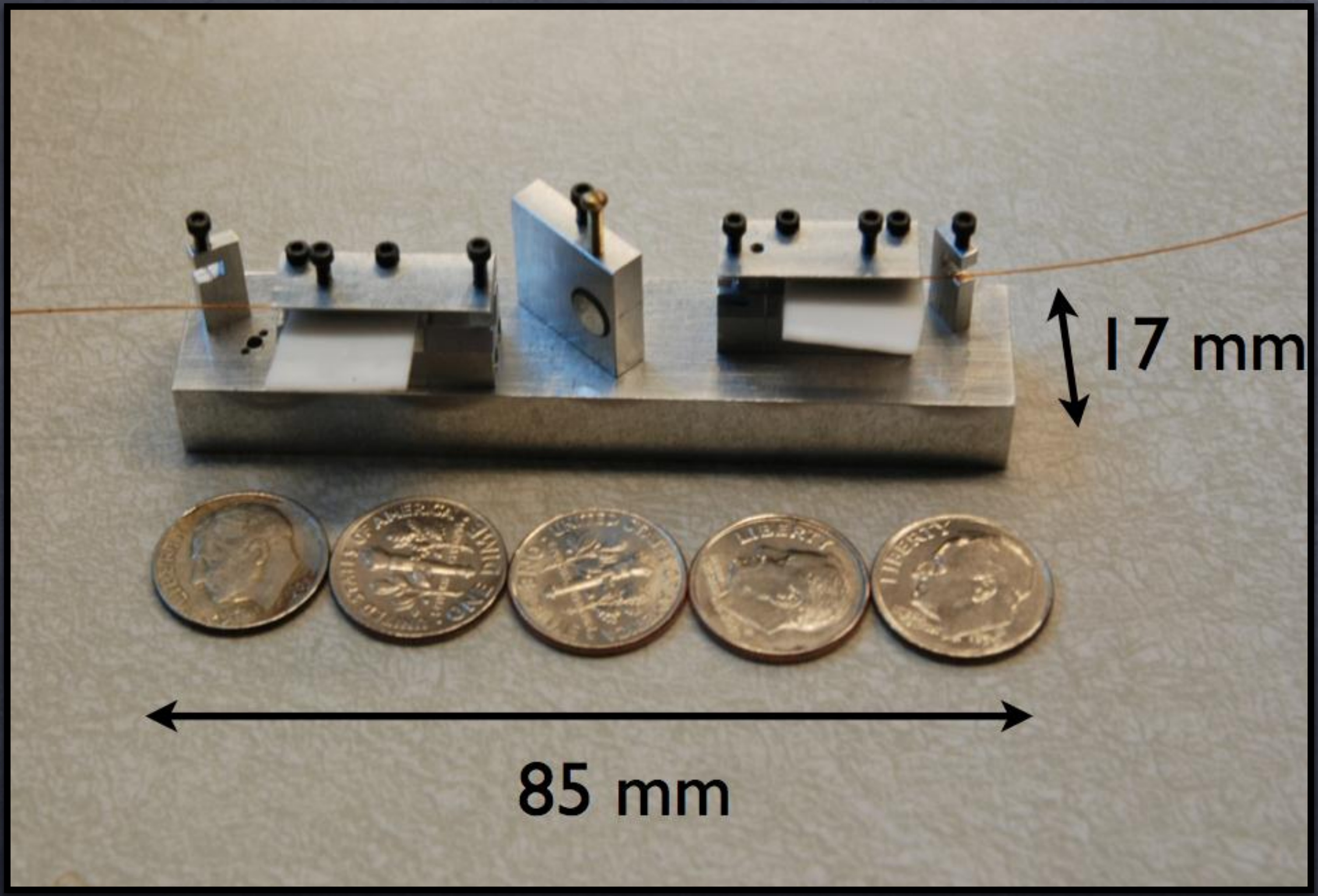
Suvrath's talk

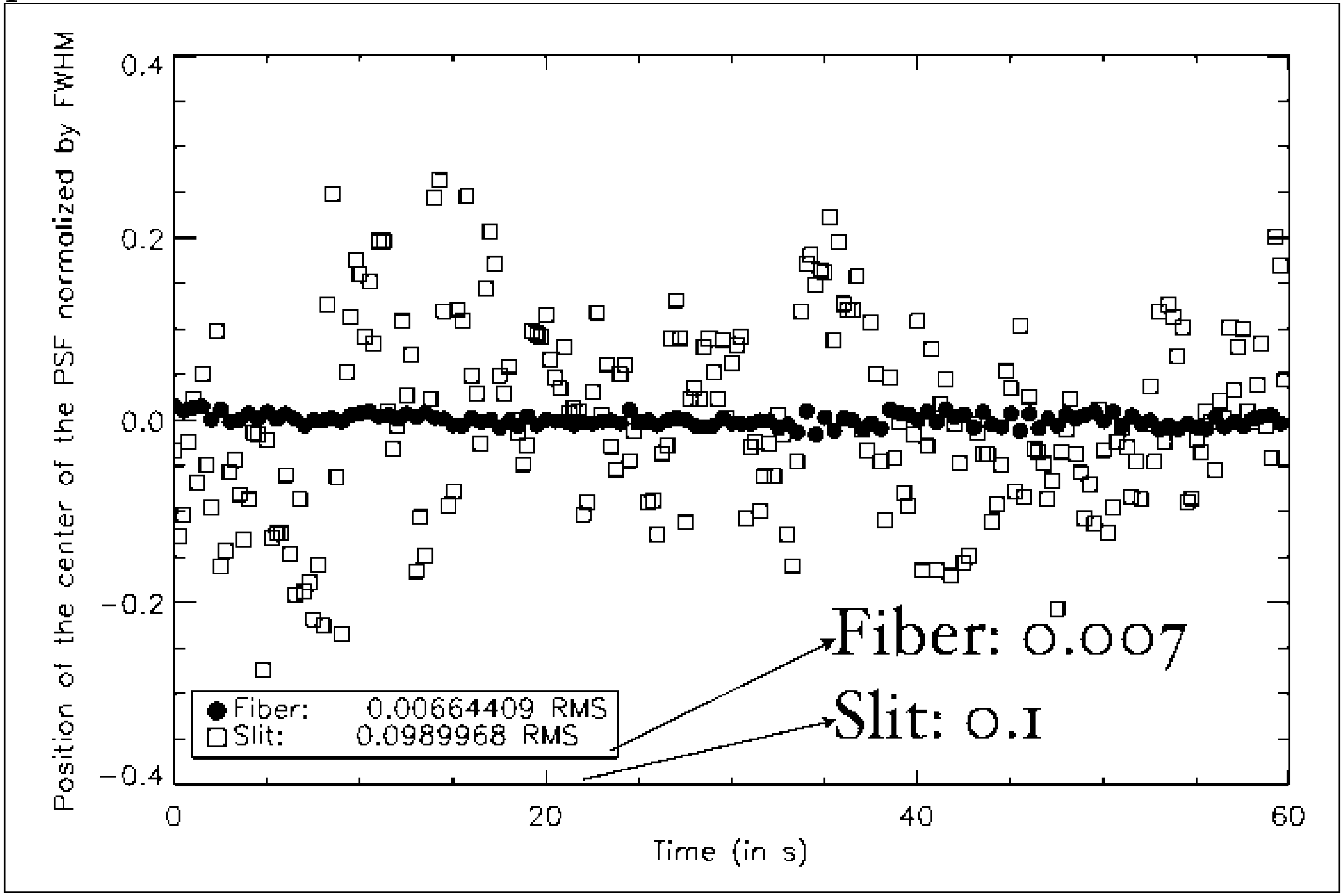
Keck Fiber Scrambler



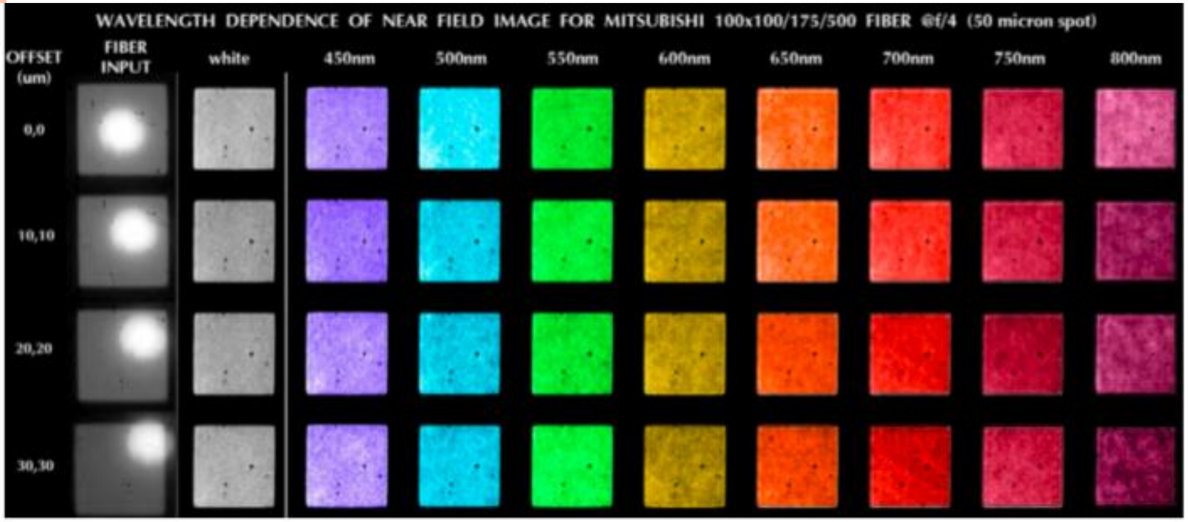
Julien Spronck - Yale

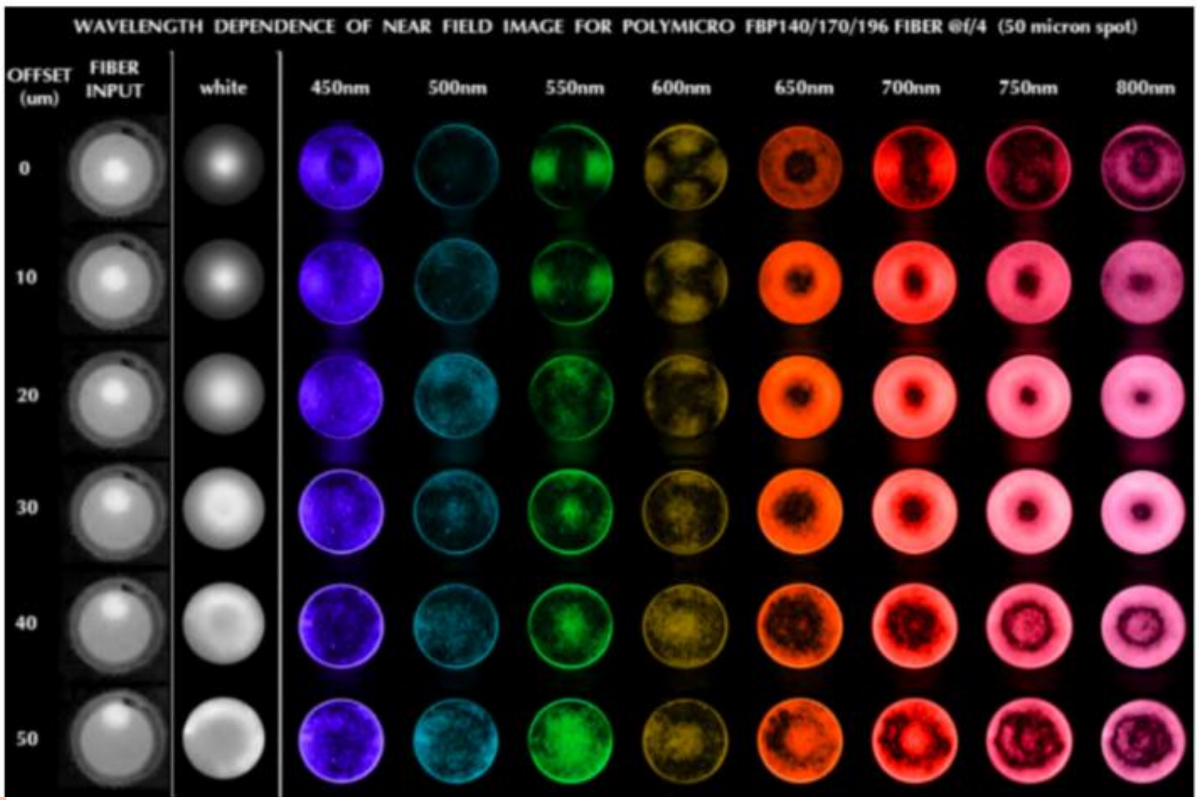
PSF Stability (Centroid)

Spronck et al. 2011 – Visible fiber scrambler with circular core fiber



=> Improvement in PSF stability by a factor 10 or more





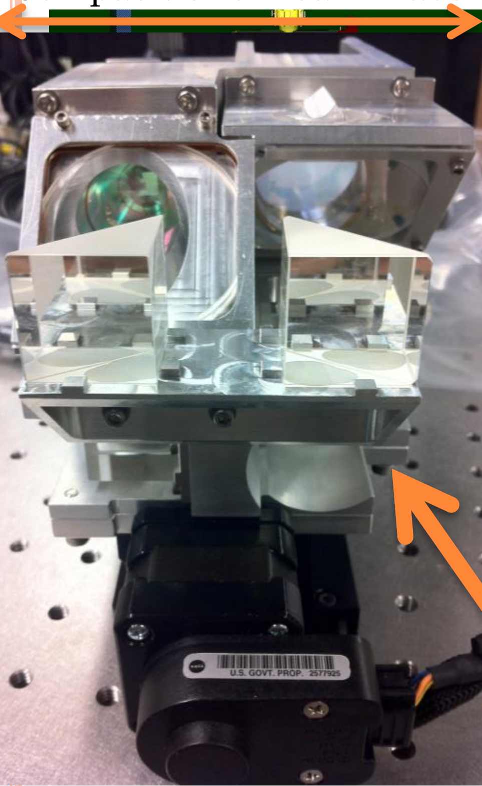
Credit:
Andy Szentgyorgyi's group at CfA.

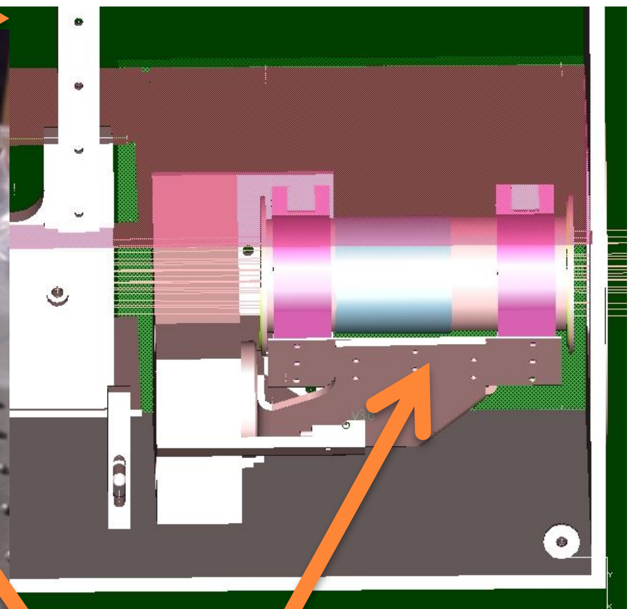
Fiber Scrambler First Light @1.6 microns, May 2012

Limiting RV Noise Source:
PSF stability, ie the illumination of echelle and detector in both the far and near field respectively
→ Replace starlight with stable output from a fiber
→ **FIBER SCRAMBLER:**

- Improves PSF centroid and FWHM stability by factors of >10
- Improves corresponding LSF stability
- Easier to model LSF and improves resulting RV precision

Compact! 3” of beam travel





SV Peg with fiber scrambler & gas cell in tandem

Raw spectra taken with a 50x100 micron rectangular non-circular core 10 m agitated fiber.

Gas cell – 13 cm length

Prototype fiber scrambler

Conclusion

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 session, to potentially fulfill the bold predictions of the decadal survey.

Want to join the RV SAG and help contribute to the report we will prepare?

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