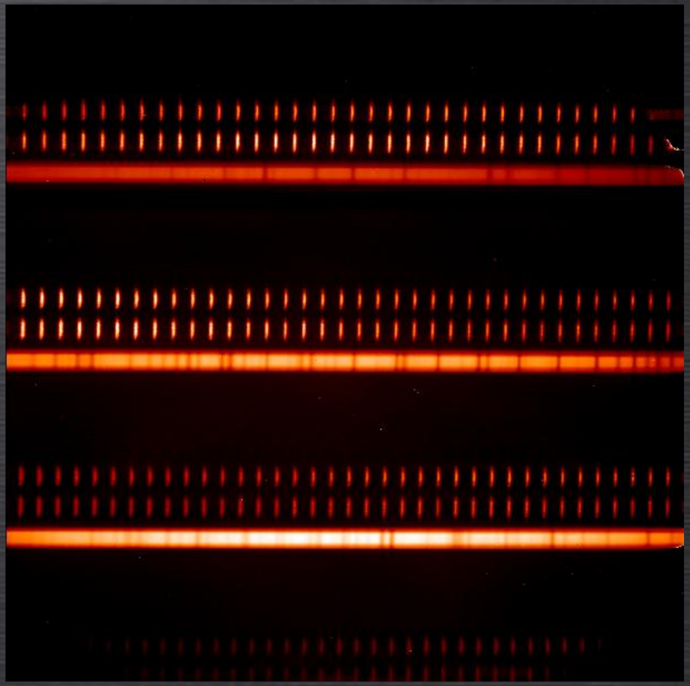
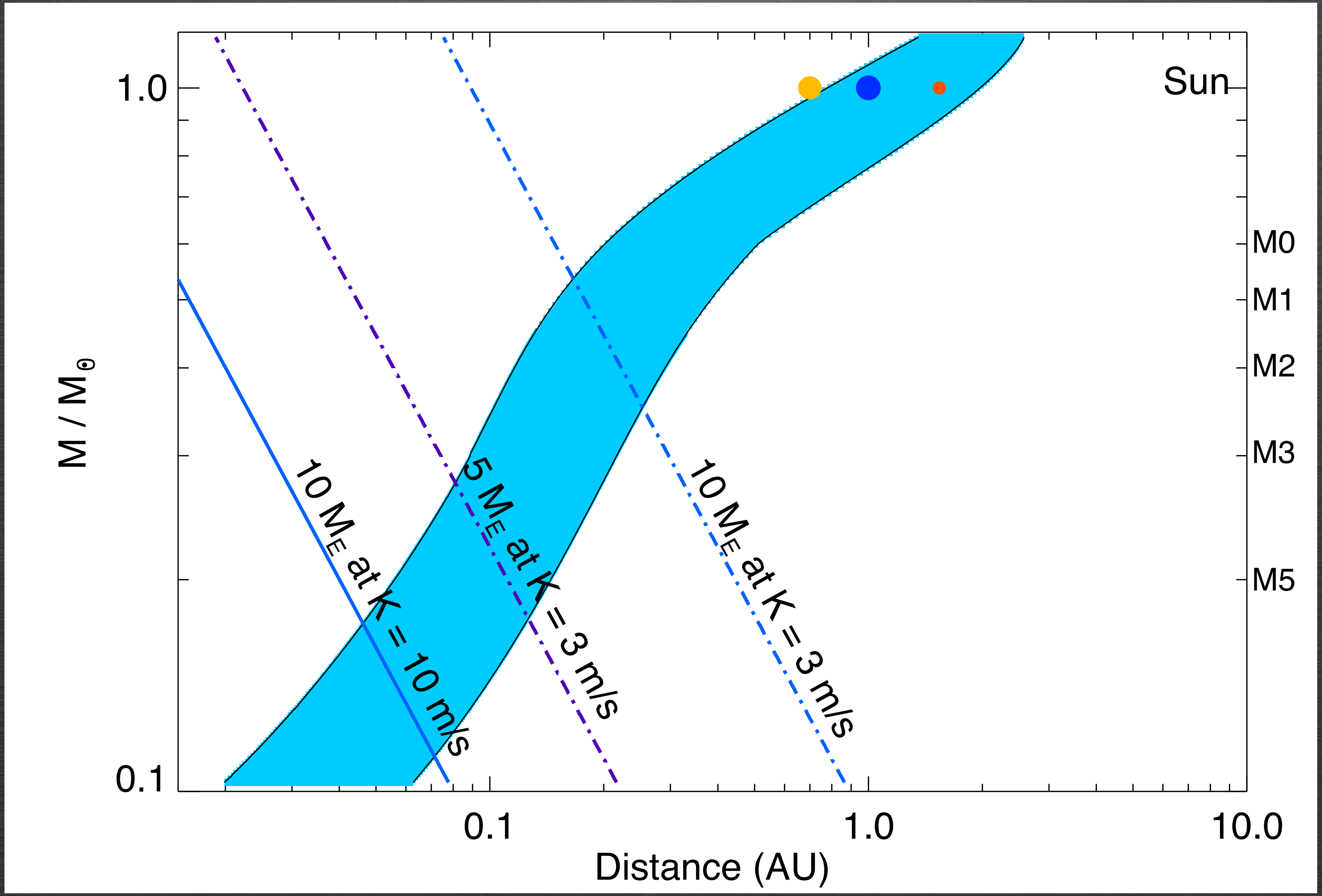
Precision RVs in the Near Infrared

Suvrath Mahadevan
(Penn State)



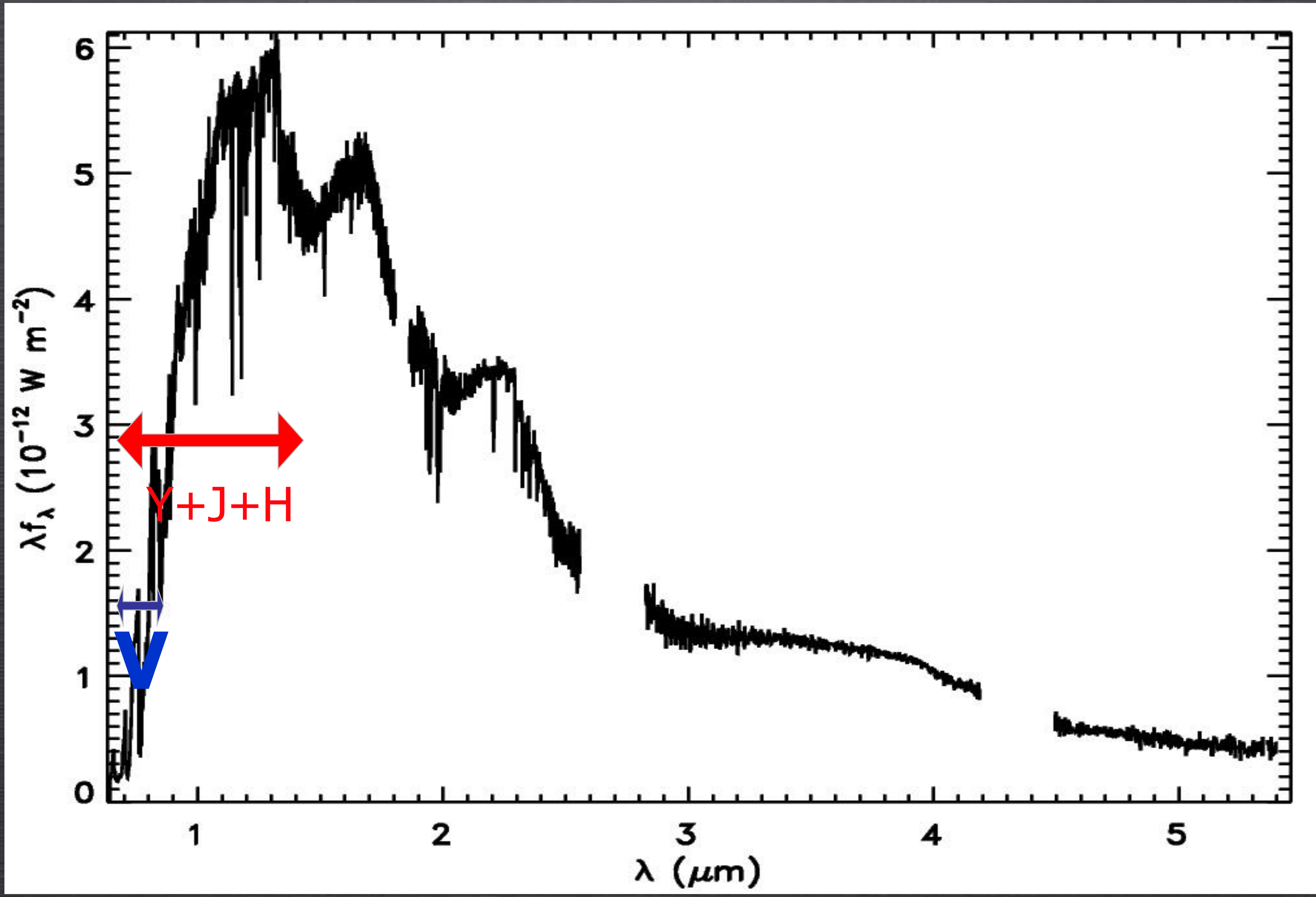
Collaborators: Larry Ramsey, Chad Bender, Ryan Terrien, Fred Hearty, Jason Wright, Sam Halverson, Arpita Roy, Jim Kasting (Penn State), Fred Hearty, Matt Nelson, Adam Burton (UVa), Steve Osterman (CU), Scott Diddams (NIST), Michael Endl (UT), Christian Schwab (Yale)

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.

Earths & Super Earths Around M Dwarfs



M dwarfs emit most of their photons in the red and NIR. (*Pavlenko et al. 2007*)

A NIR spectrograph can probe mid-to-late M dwarfs.

Habitable Zone Planet Finder (HPF) on the HET

Development of HPF Funded by NSF MRI in Sept 2011

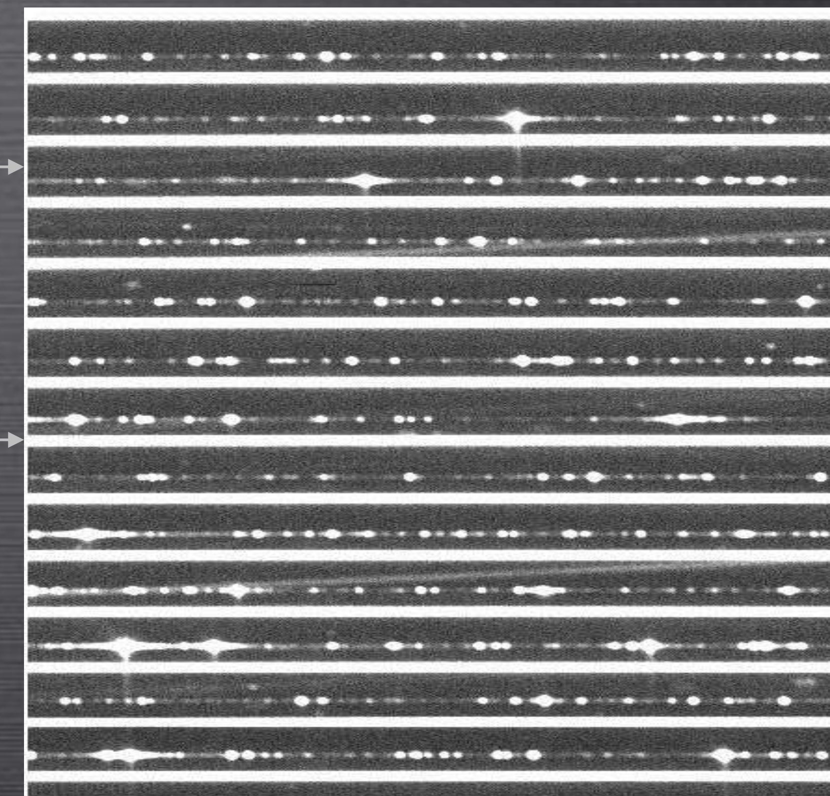
HPF on HET

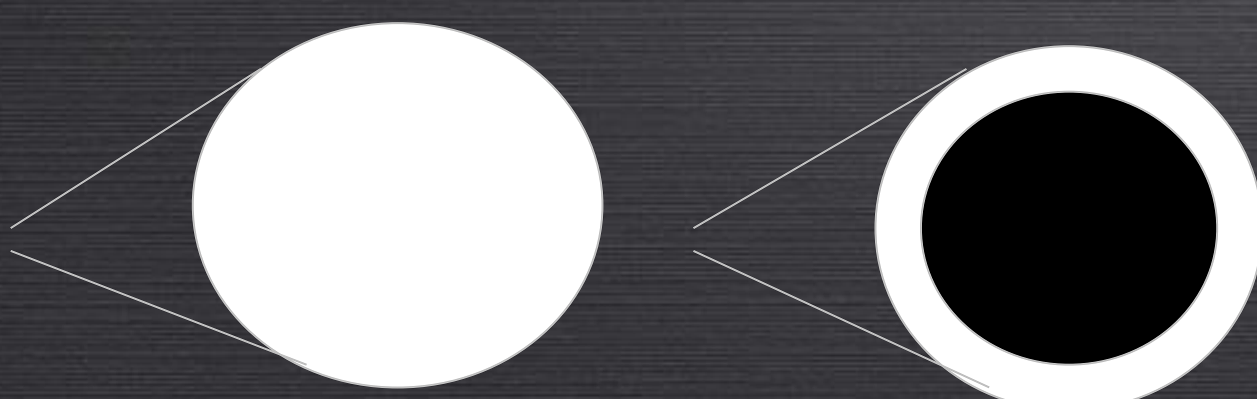
Emission Line Calibration

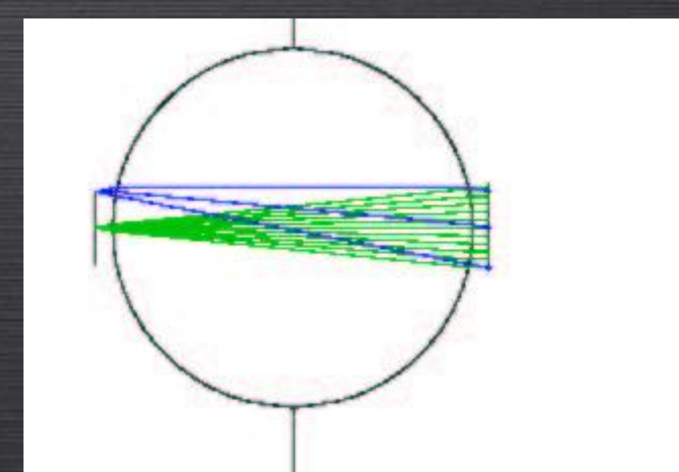
- Fiber-Fed Spectrograph
- Built to be very stable
- Spectrograph slit illumination must be very stable.

Th-Ar/ U-Ne

Star

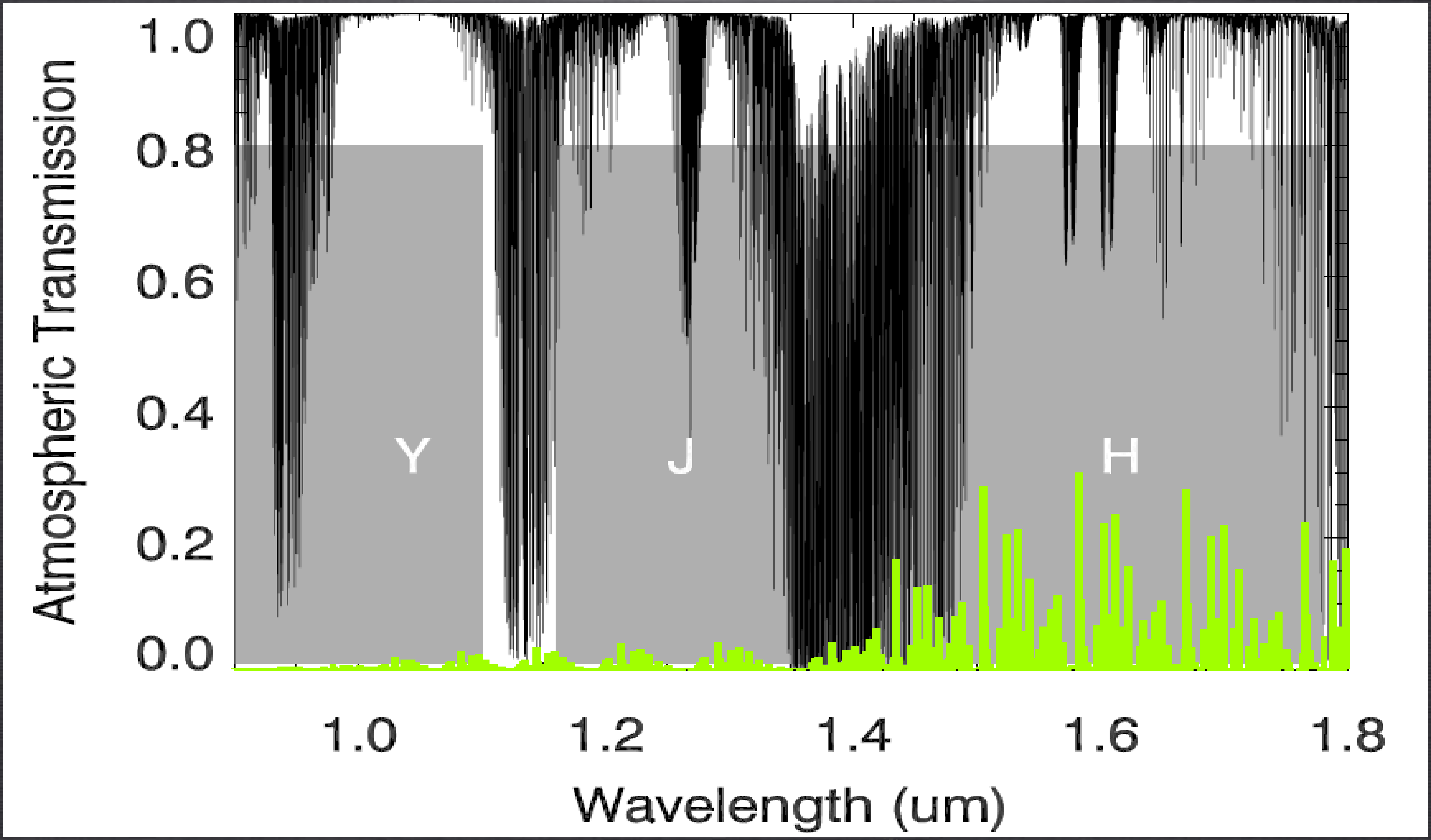






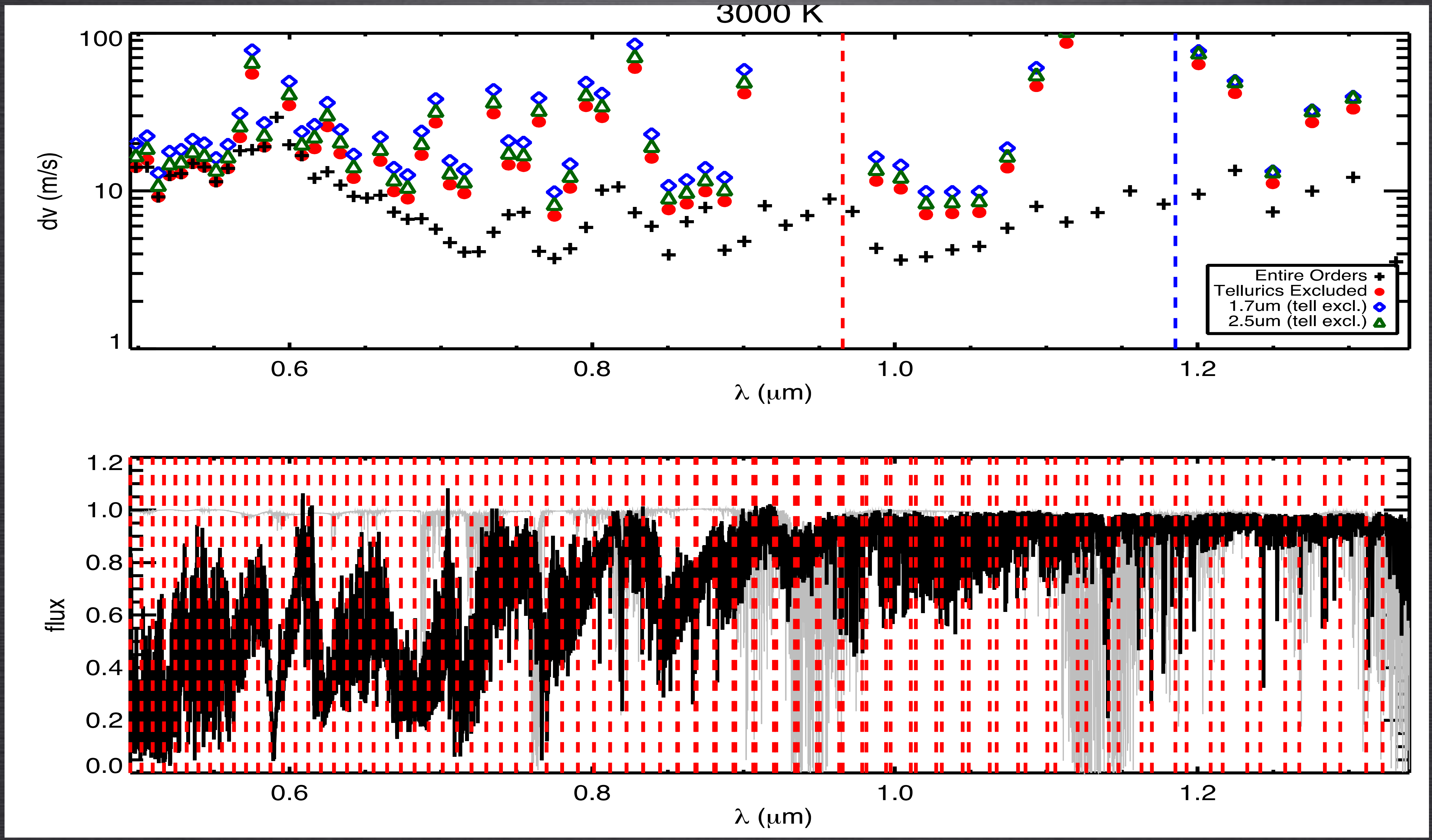
Optical Fibers Scramble Input light very well. Perfect scrambling in azimuthal direction, imperfect in radial. Double scramblers, octagonal fibers help

The NIR Bands



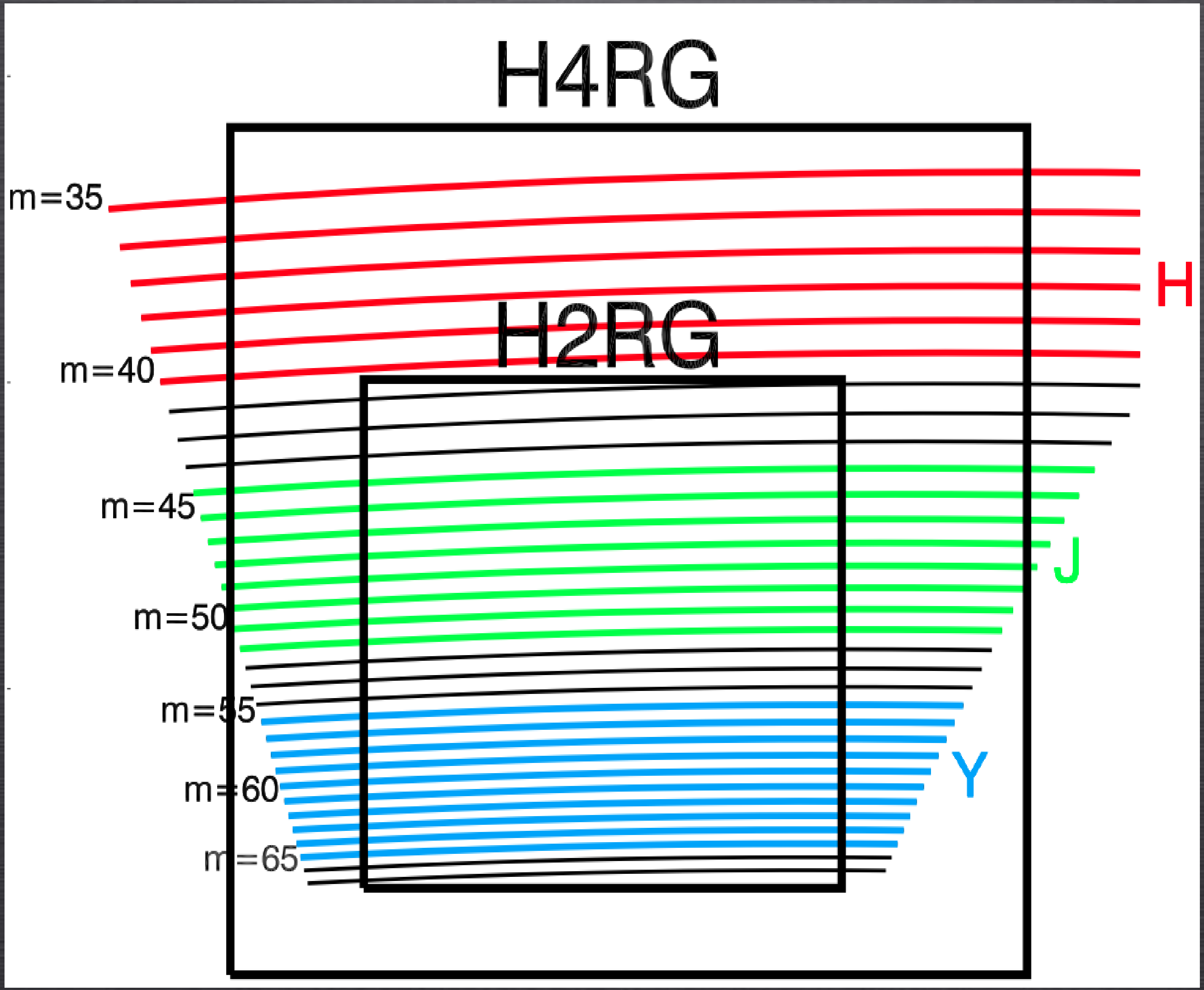
The Y band is quite clean compared to J and H, and has the most amount of RV information for mid-late M dwarfs……

The NIR Bands



The Y and z bands contribute most of the NIR RV information

HPF on HET

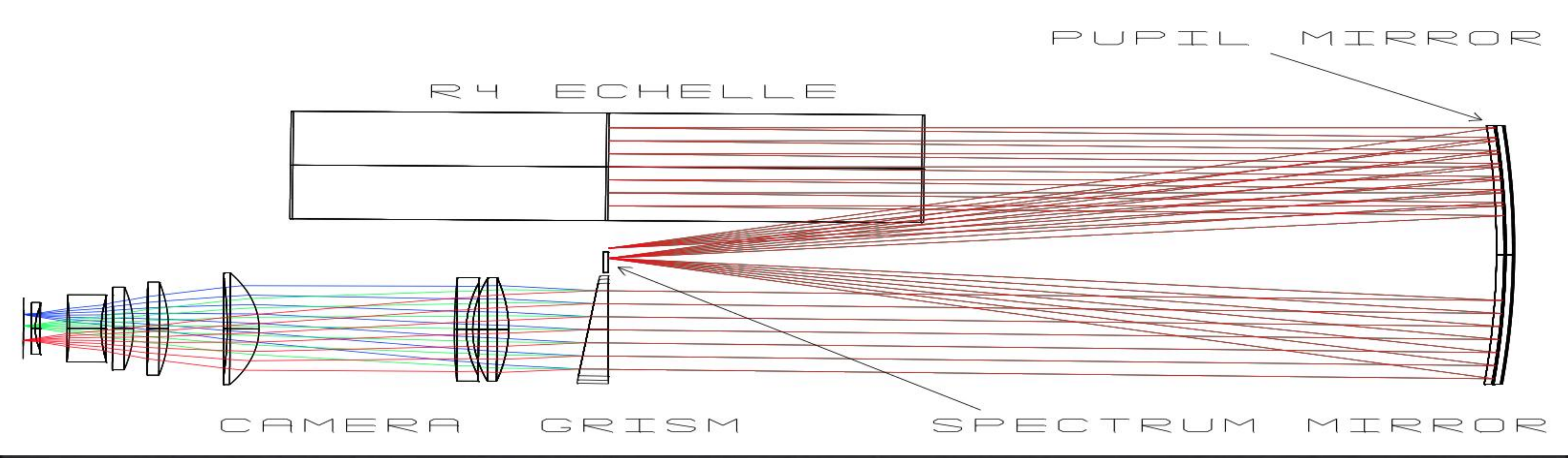


Covers Y & J bands with one H2RG, with optics built to enable a future upgrade to an H4RG

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**

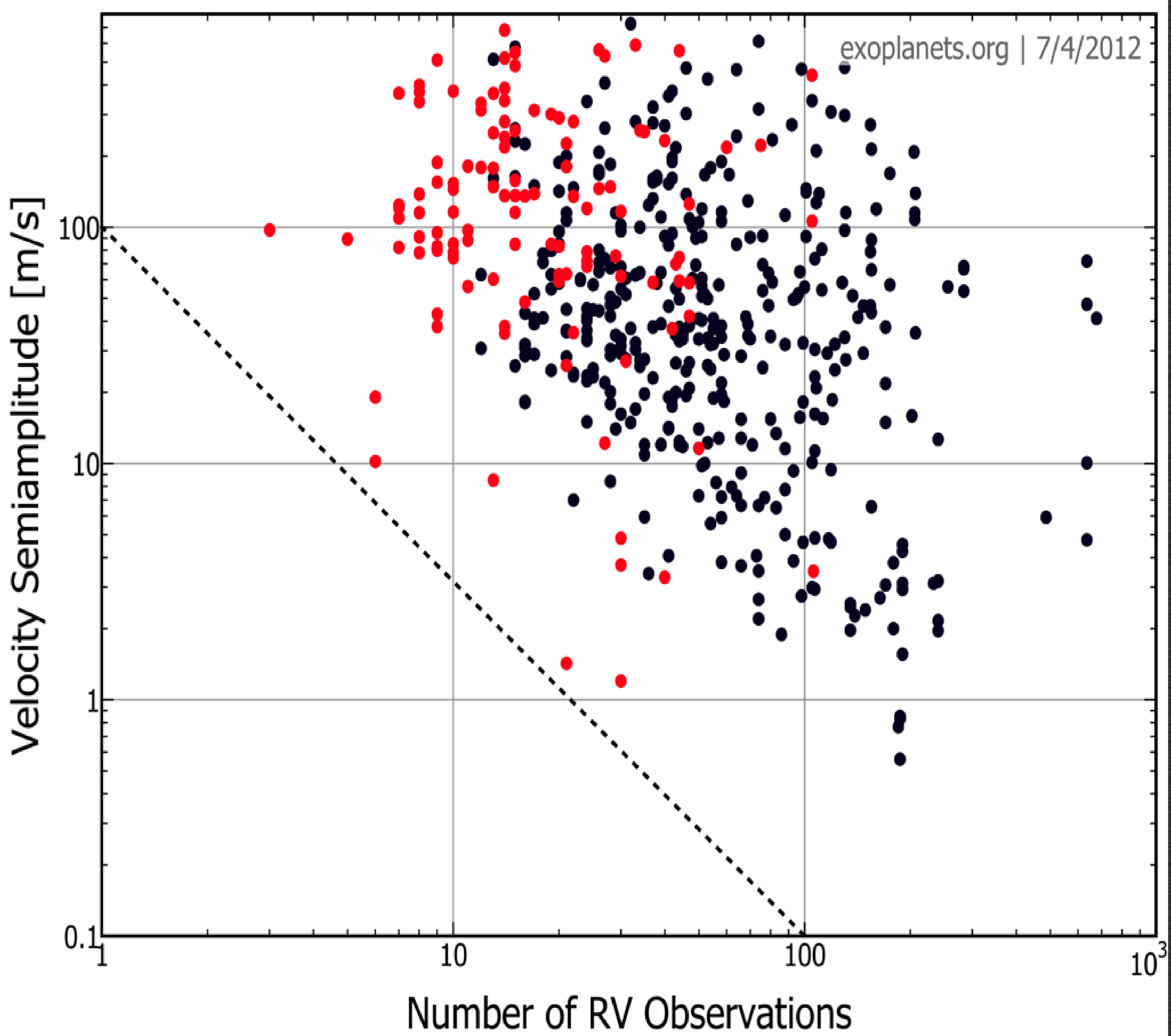
VPH based design also being considered



HPF on HET: Survey

Table 1: HZPF M dwarf RV Survey Design

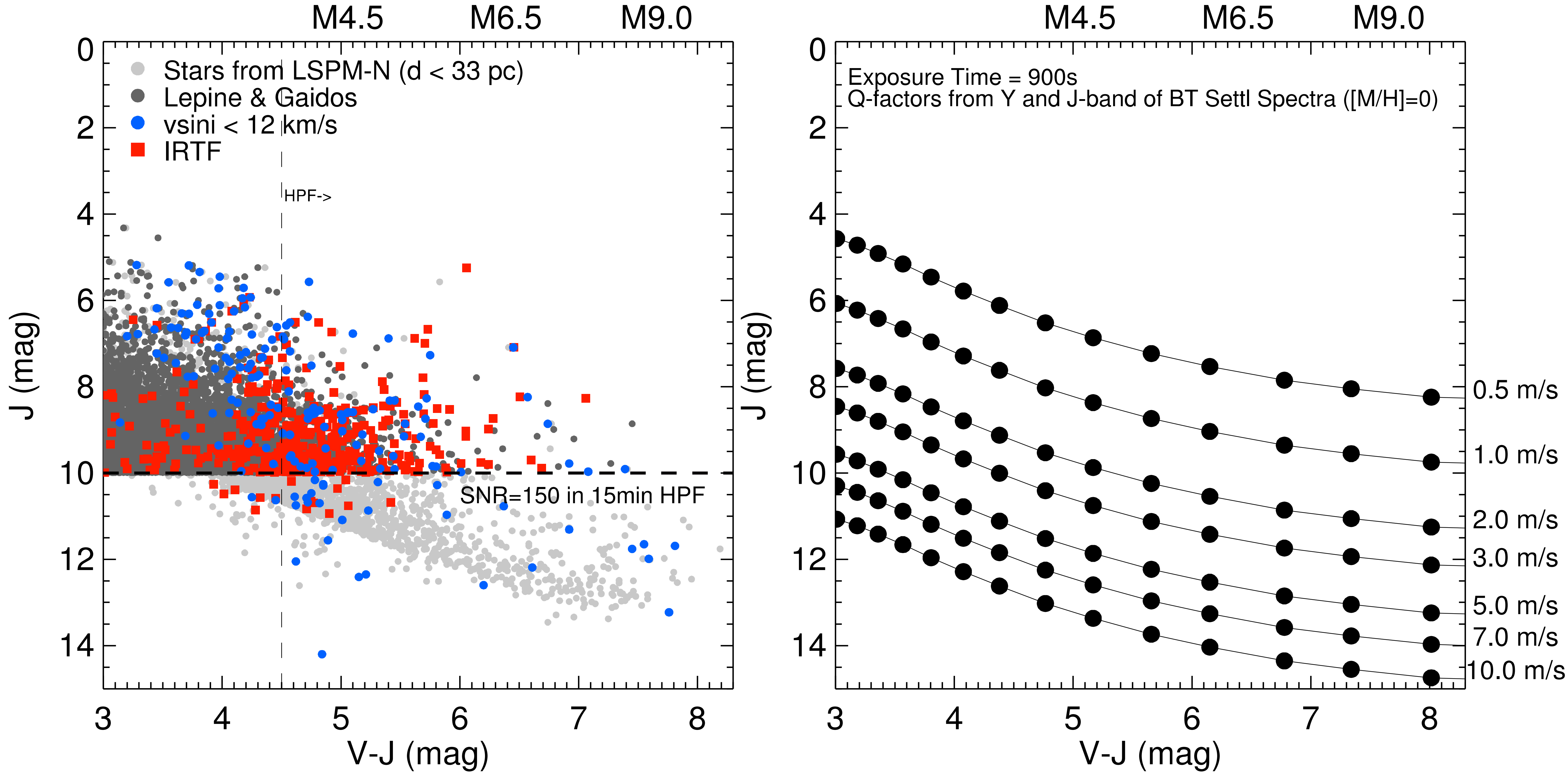
# of M stars	*Cumulative # of RV observations*
300	5
200	15
100	30
50	100



Need a large number of RV observations. Sample is ~300 M dwarfs, with ~50 most promising getting 100 observations.

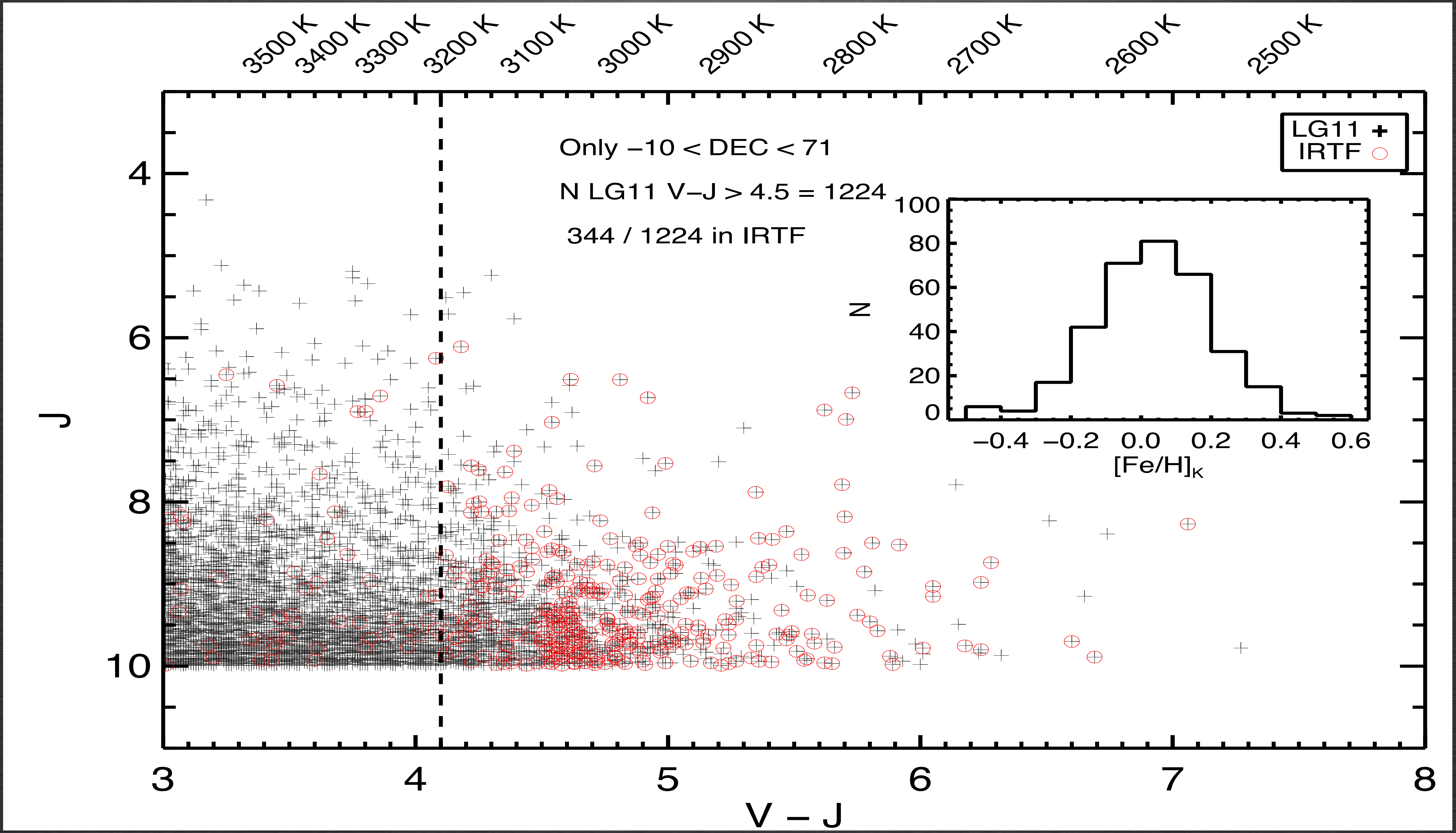
Whole HPF Survey is HET queue based

HPF on HET



Target Lists being populated, Fe/H, visni's being determined for a large number of M dwarfs with IRTF & APOGEE.

HPF on HET



Target Lists being populated, Fe/H, visni's being determined for a large number of M dwarfs with IRTF & APOGEE.

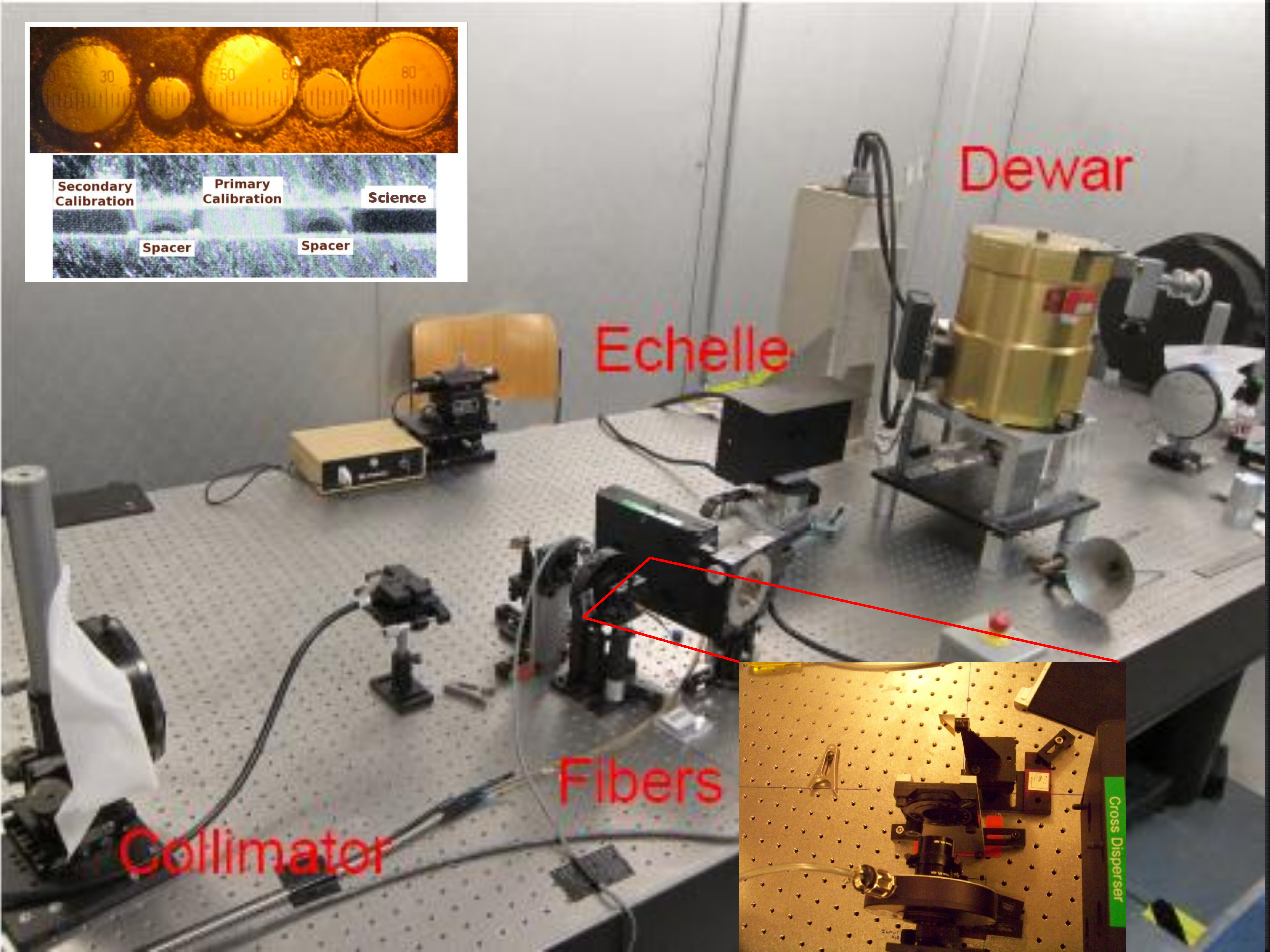
Pathfinder Instrument @ PSU

Pathfinder : One that discovers a new course or way, especially through or into unexplored regions.

•Penn State NIR Pathfinder spectrograph is a test bed to explore challenges in precision NIR radial velocities.

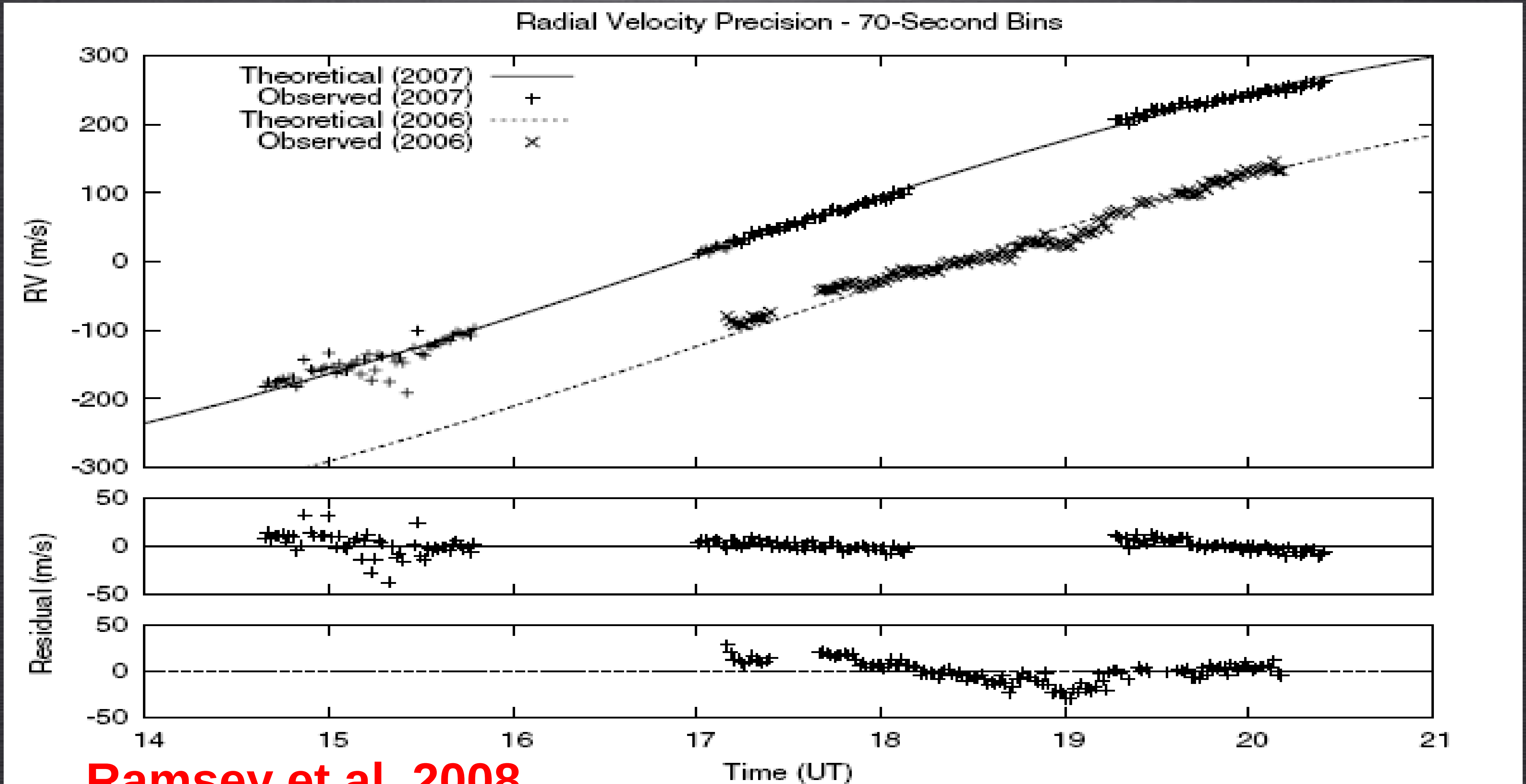
•Pathfinder is a testbed built from existing off the shelf available parts. Uncooled, uses a H1 array that is sensitive to 2.5μm

•Pathfinder is currently the only high resolution fiber fed NIR astronomical spectrograph testbed built for RV precision



30
50
60
80
Secondary Calibration
Primary Calibration
Science
Spacer
Spacer
Dewar
Echelle
Fibers
Collimator
Cross Disperser

Pathfinder : On ‘Sky’ Performance in Lab



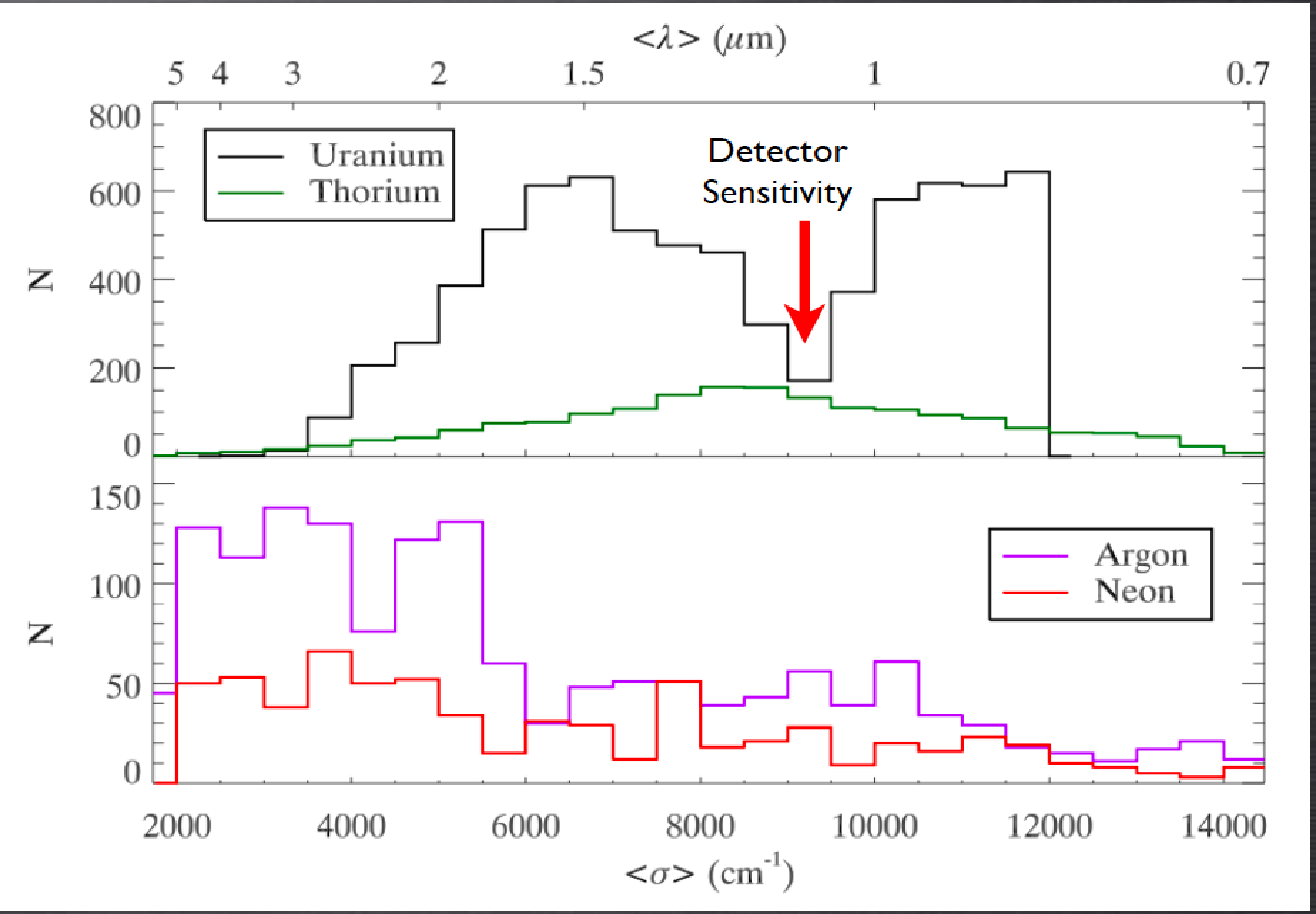
Ramsey et al. 2008

Achieve 7-10m/s rms scatter on Sunlight with two different configurations and simultaneous Th-Ar calibration. Suggests detector issues like persistence and parasitic ghosting are not a killer at ~< 10m/s. This is short term stability.

Challenges: Calibration

•Exploring Other Hollow Cathode lamps.

	Thorium ^{232}Th	Uranium ^{238}U
Heavy Element	Yes	Yes
0 nuclear spin	Yes	Yes
Long ½ life	Yes	Yes
Many Lines	Yes	Yes
Mononucleide	Yes	NO (0.7% ^{235}U)

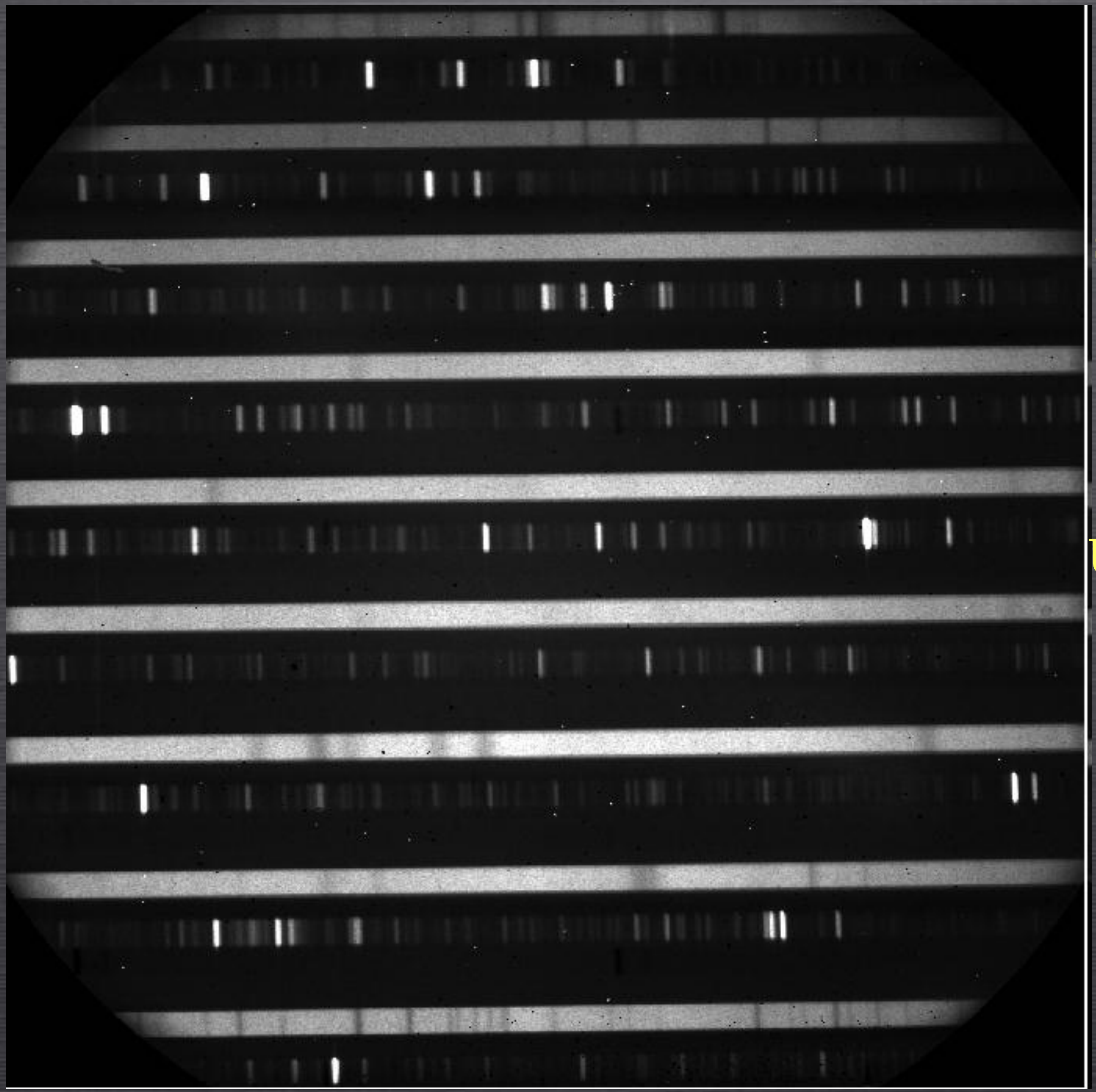


U has a lot more bright lines in the NIR than Thorium. Argon lines are extremely bright and not usable at precisions of few m/s

U-Ne lamps now in routine use in Pathfinder

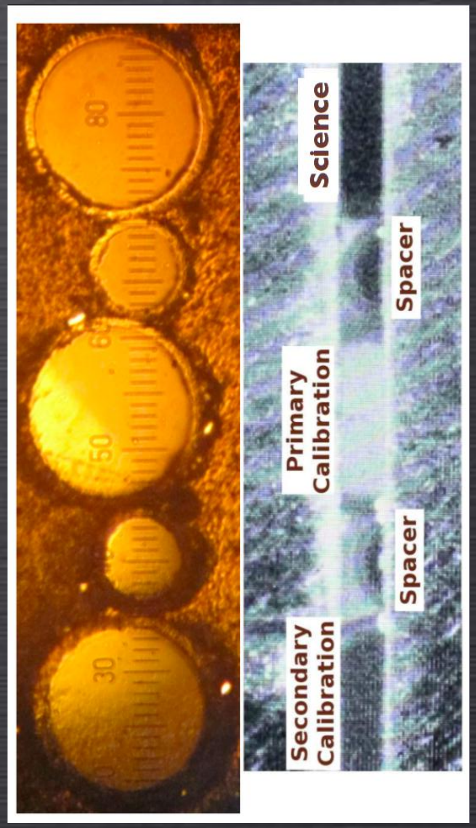
An FTS NIR Linelist OF Uranium lamps now published and available: Redman et al. 2011, 2012

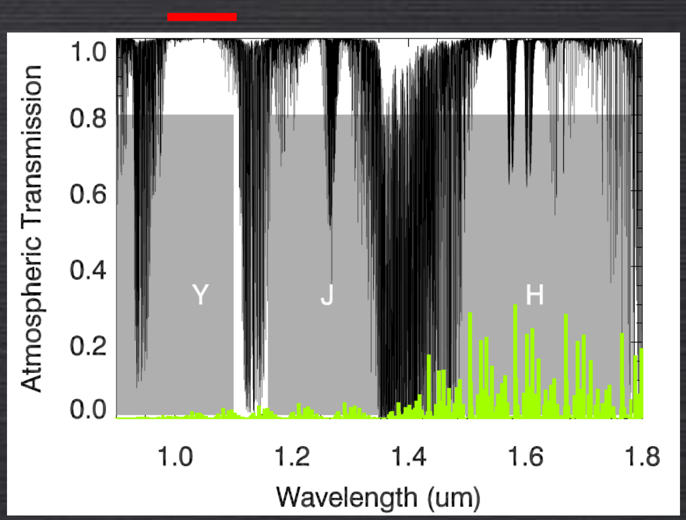
Pathfinder @ HET



star

U/Ne

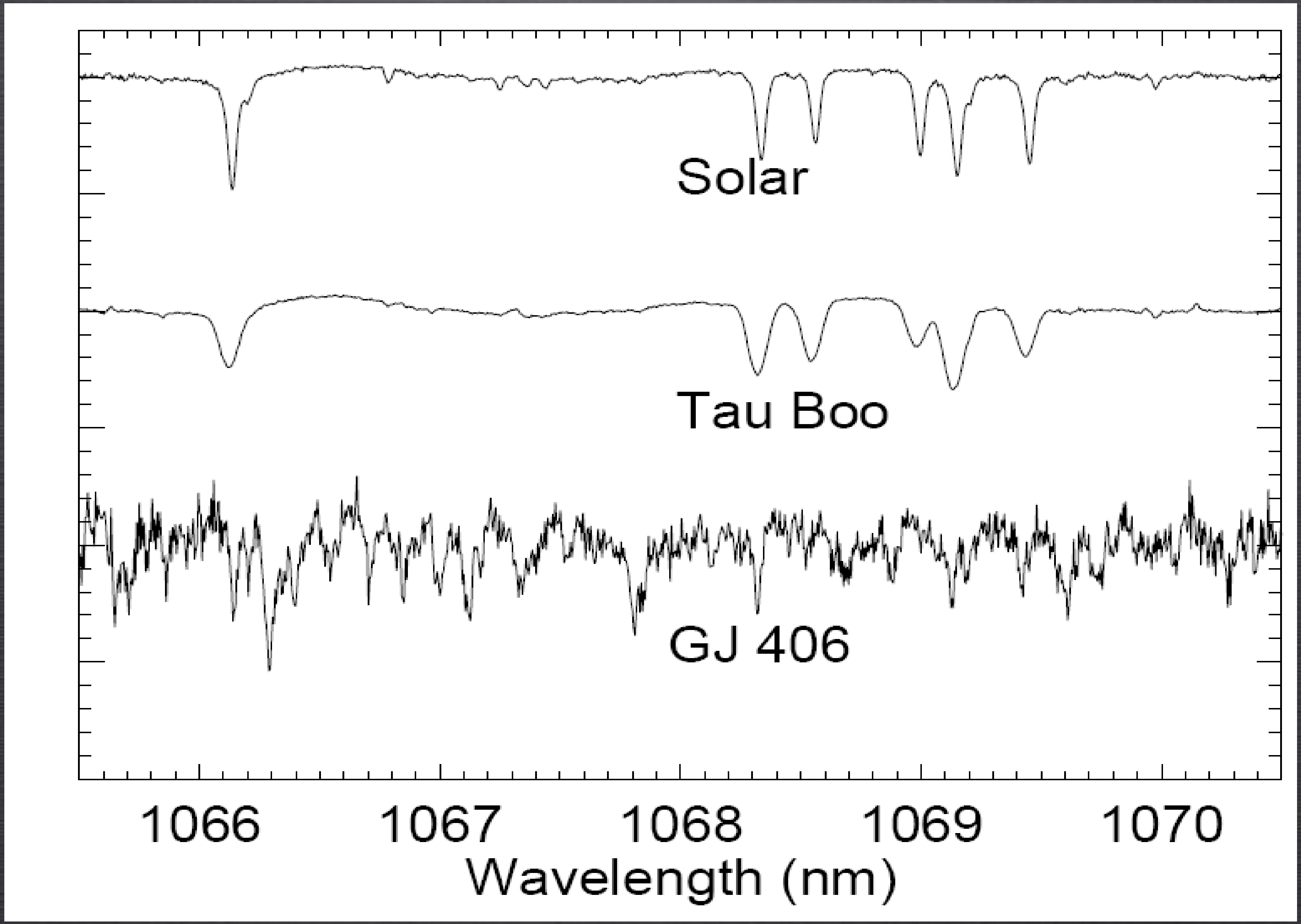




Observations of Tau Boo with Pathfinder@ HET

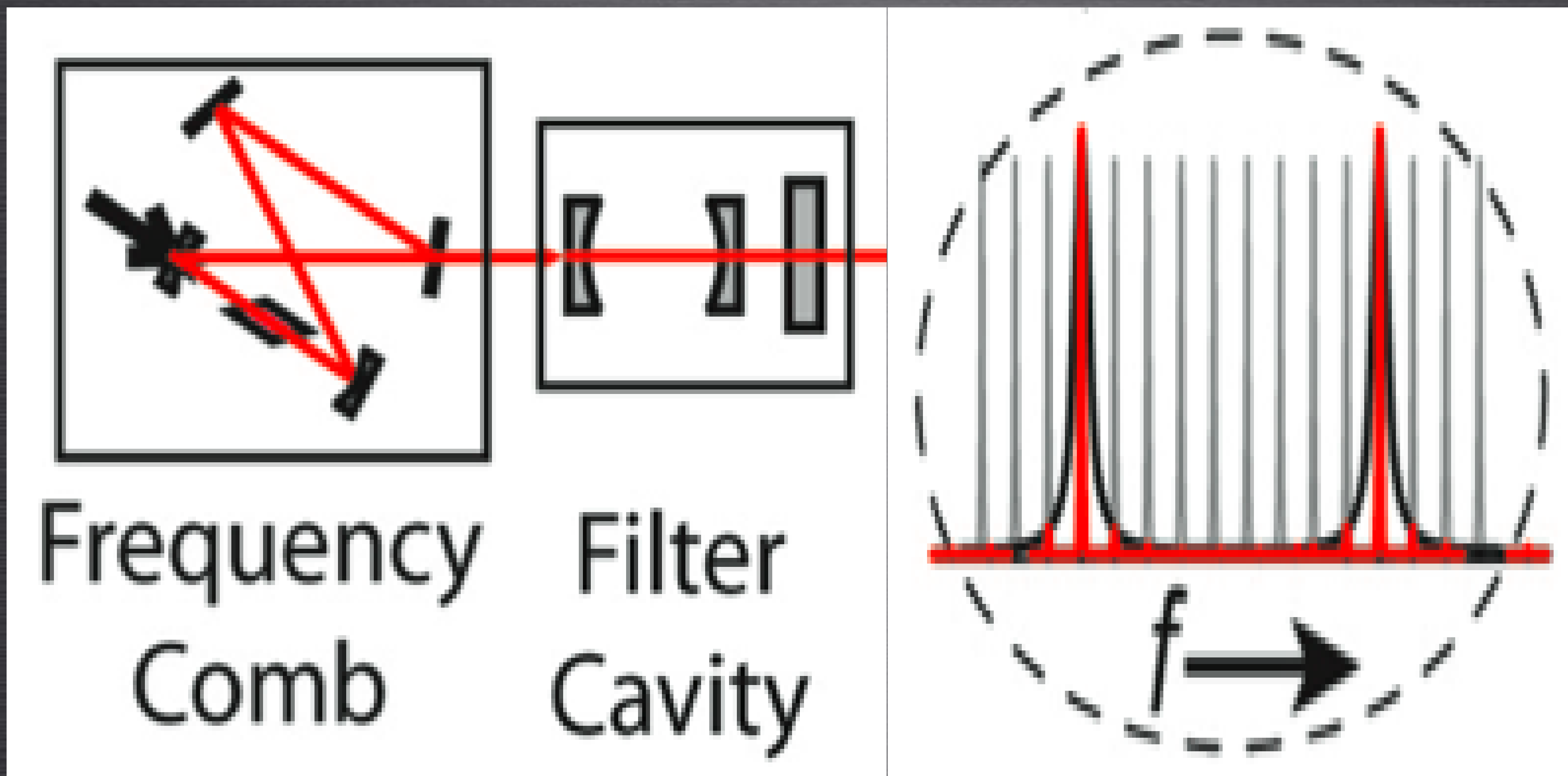
Orbit Recovered

The Penn State PATHFINDER @ the HET



Y band Spectra!

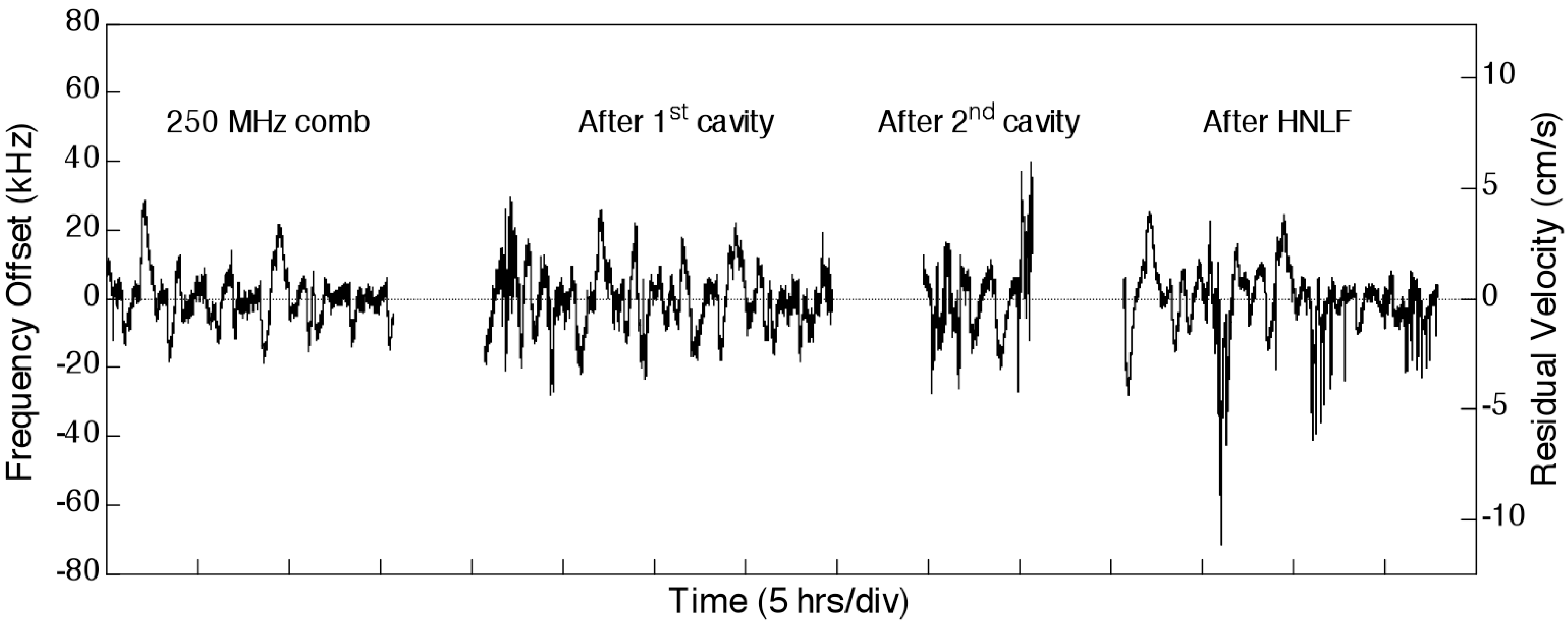
Laser Frequency Combs Tested with Pathfinder



Spacing too tight for an astronomical spectrograph, need to pick every 100th line.

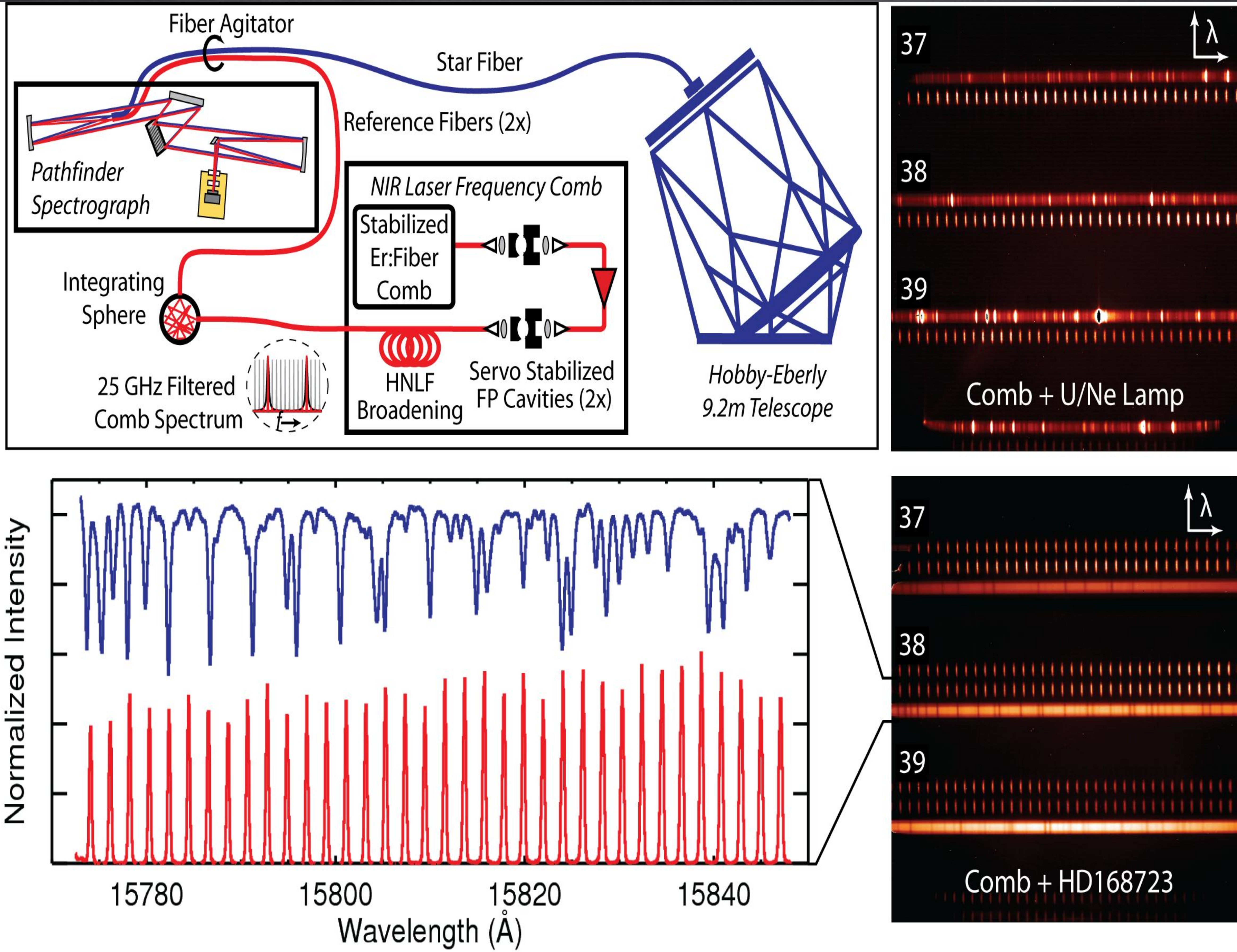
Exquisite precision. Tied to the GPS, tied to the SI definition of a second.

Laser Frequency Combs



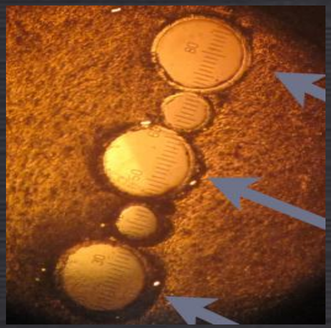
Our NIST/CU collaborators (Diddams, Osterman, Ycas) had, in mid 2010, begun to demonstrate H band combs with spacings of 12.5 and 25 GHz

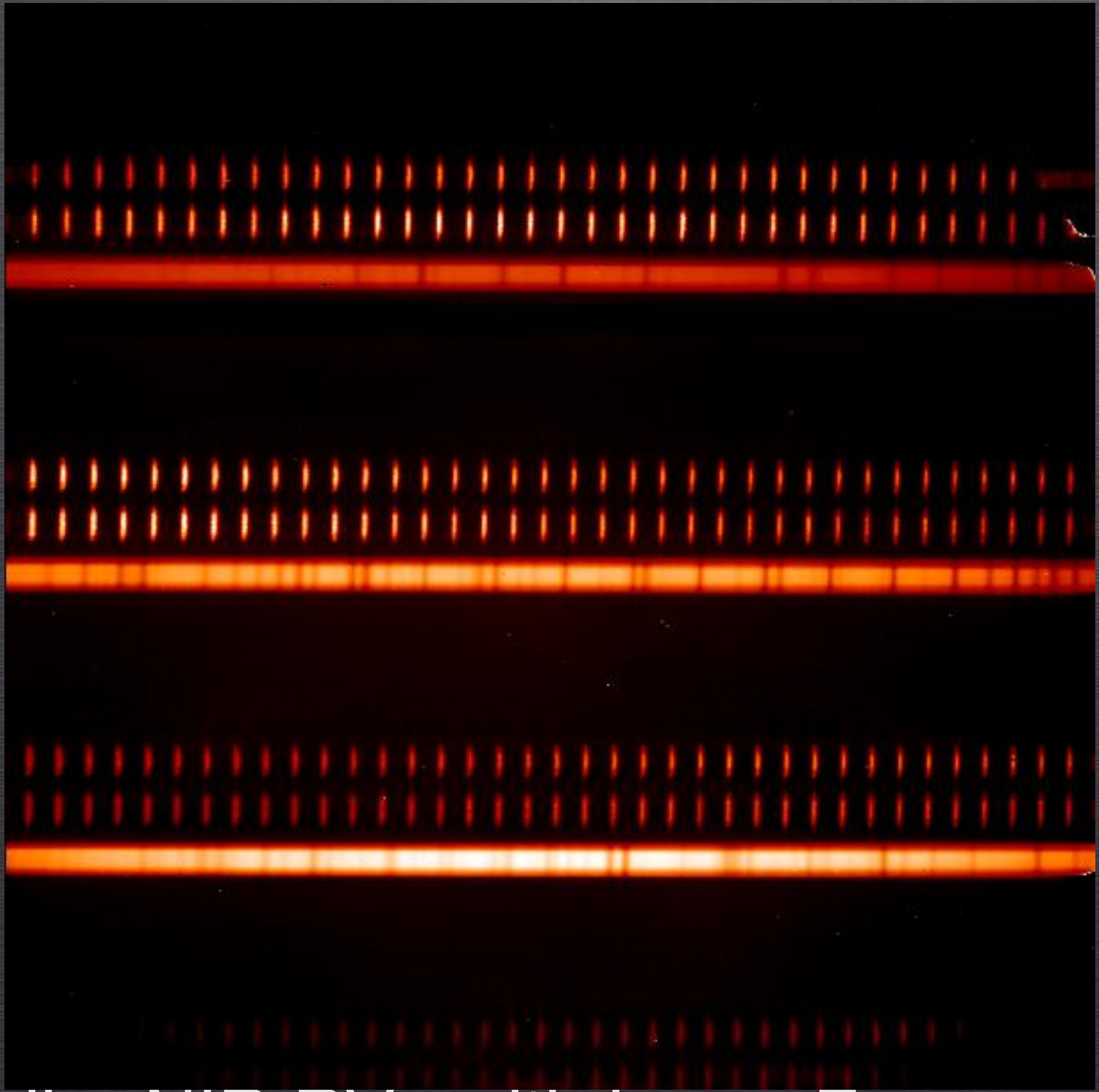
Exquisite precision. Tied to the GPS, tied to the SI definition of a second



Fiber Agitator
Star Fiber
Reference Fibers (2x)
Pathfinder Spectrograph
NIR Laser Frequency Comb
Stabilized Er:Fiber Comb
Integrating Sphere
25 GHz Filtered Comb Spectrum
HNLF Broadening
Servo Stabilized FP Cavities (2x)
Hobby-Eberly 9.2m Telescope
37
38
39
Comb + U/Ne Lamp
Normalized Intensity
15780
15800
15820
15840
Wavelength (Å)
Comb + HD168723

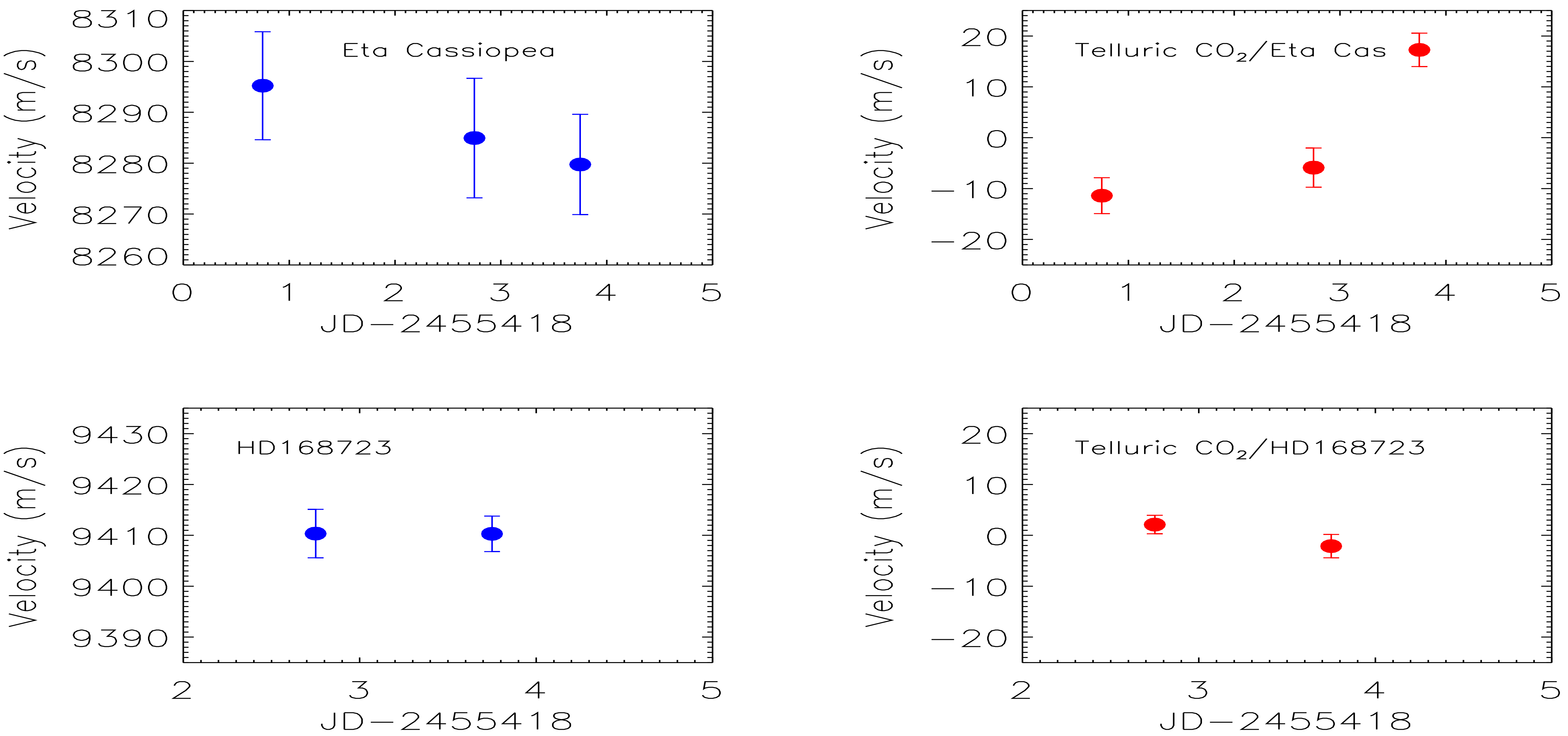
RVs with Simultaneous Ref.





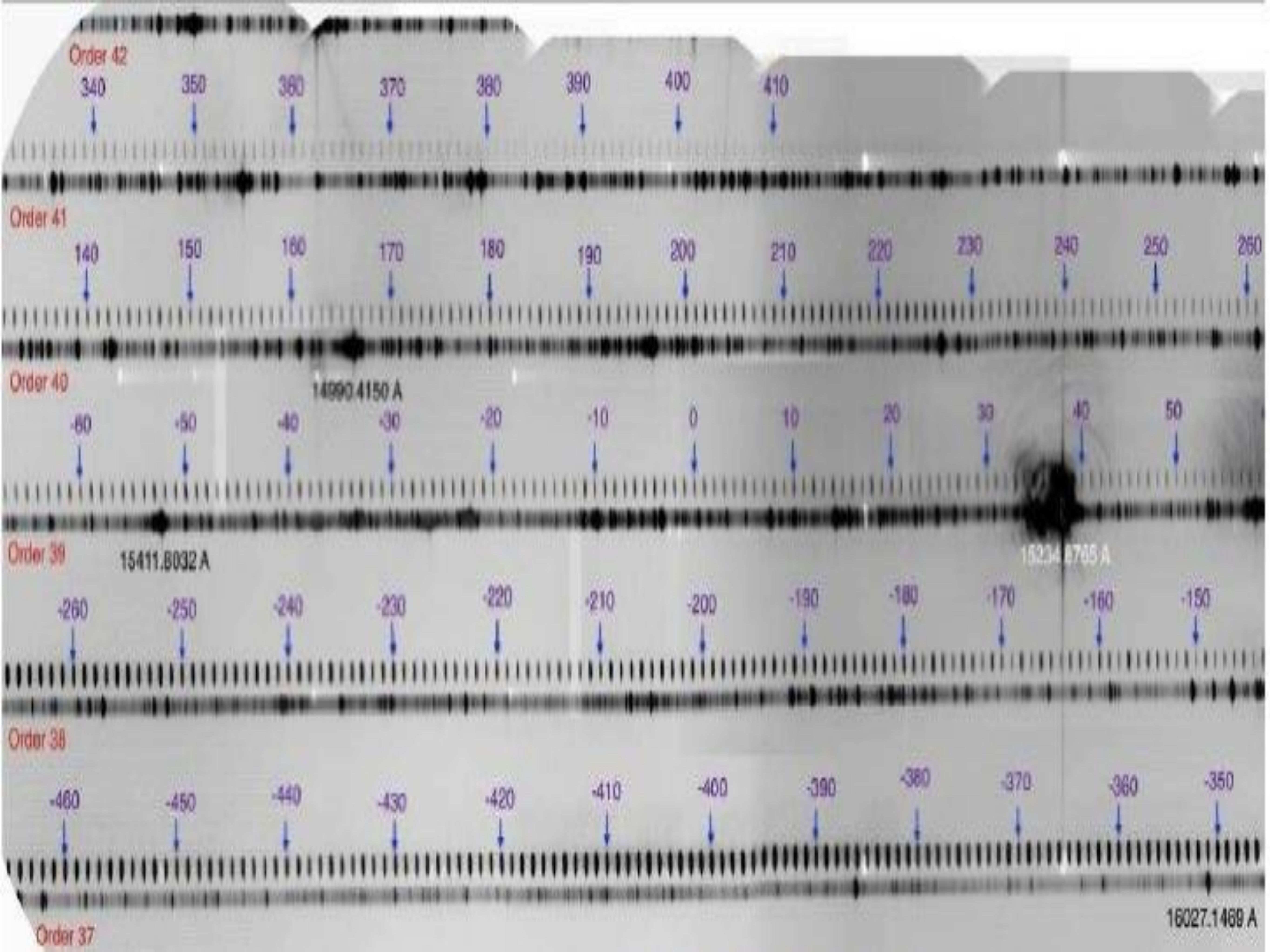
Stellar NIR RVs with Laser Frequency Comb
Ycas et al. 2012, Optics Express

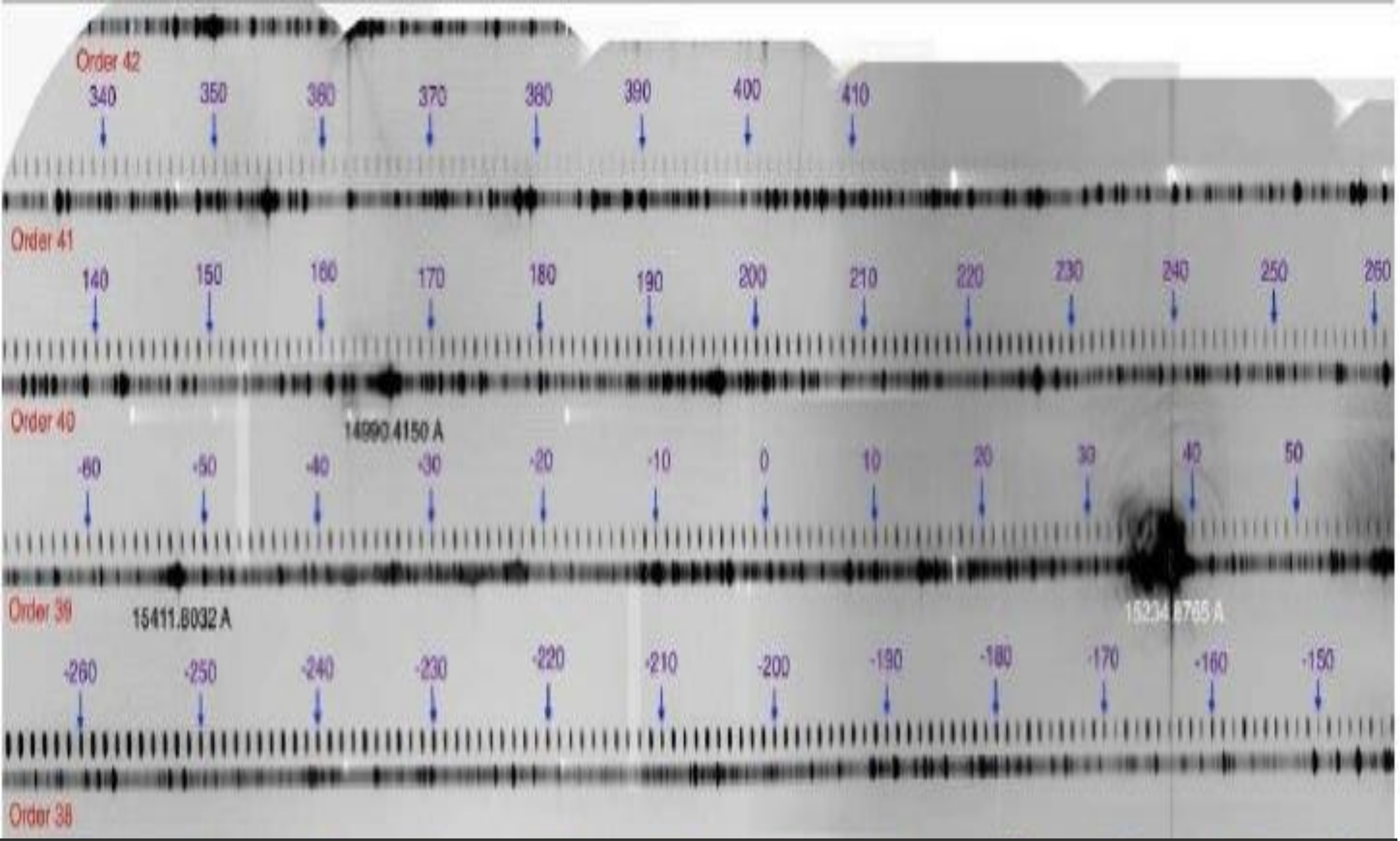
On-Star RV Results with a NIR Frequency Comb!



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

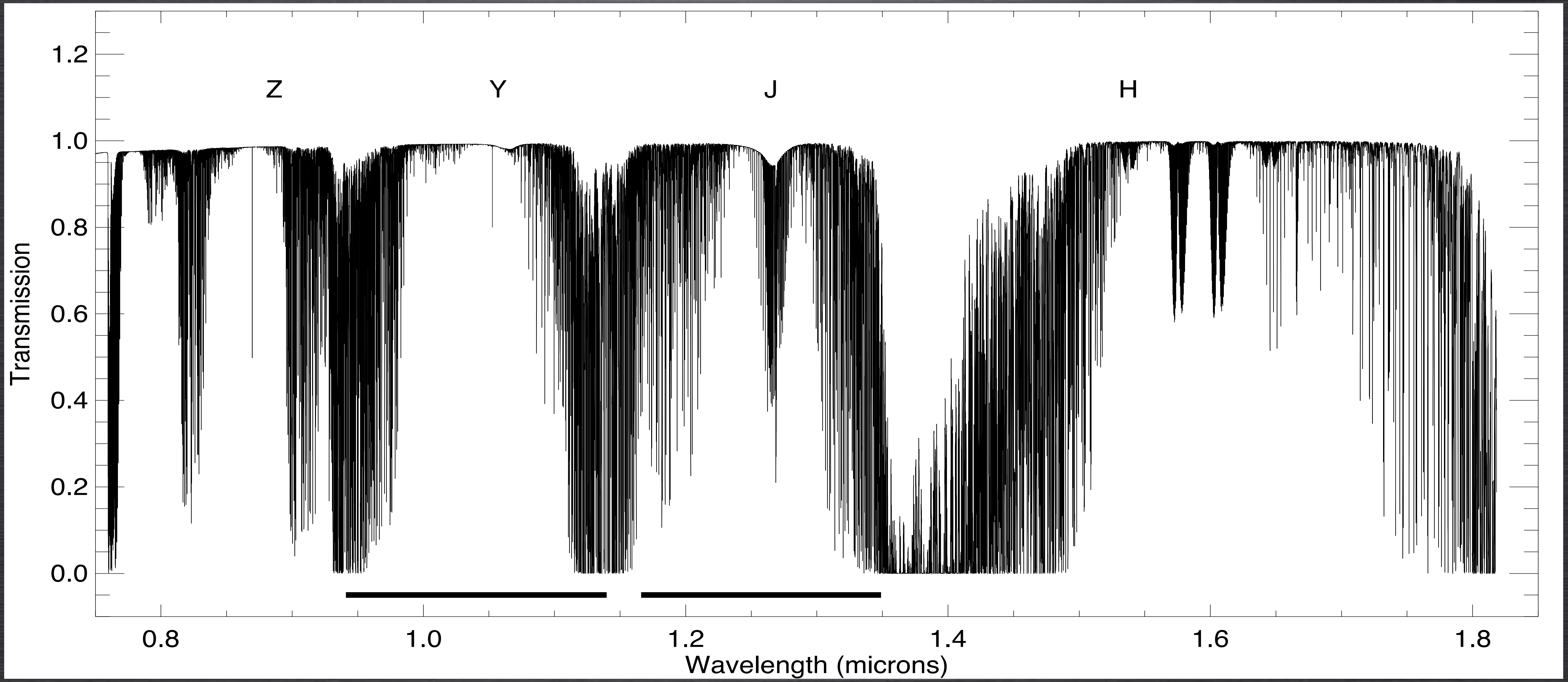
“Absolute” RV for Eta Cas consistent with Nidever et al. 2002 to ~25m/s


Order 42
340
350
360
370
380
390
400
410
Order 41
140
150
160
170
180
190
200
210
220
230
240
250
260
14990.4150 A
Order 40
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
Order 39
15411.8032 A
15234.8765 A
-260
-250
-240
-230
-220
-210
-200
-190
-180
-170
-160
-150
Order 38
-460
-450
-440
-430
-420
-410
-400
-390
-380
-370
-360
-350
16027.1469 A
Order 37



An FTS NIR Comb-Calibrated H band of Uranium lamps now published and available: Redman et al. 2012, APJS

LFC For HPF



- Not funded by MRI. Need to pursue funding from NSF/NASA
- Will be necessary achieve 1m/s
- Design Fabry Perots for each band separately

Challenges:Fiber Modal Noise

1550 nm

Static

Machine Agitated

Hand Agitated

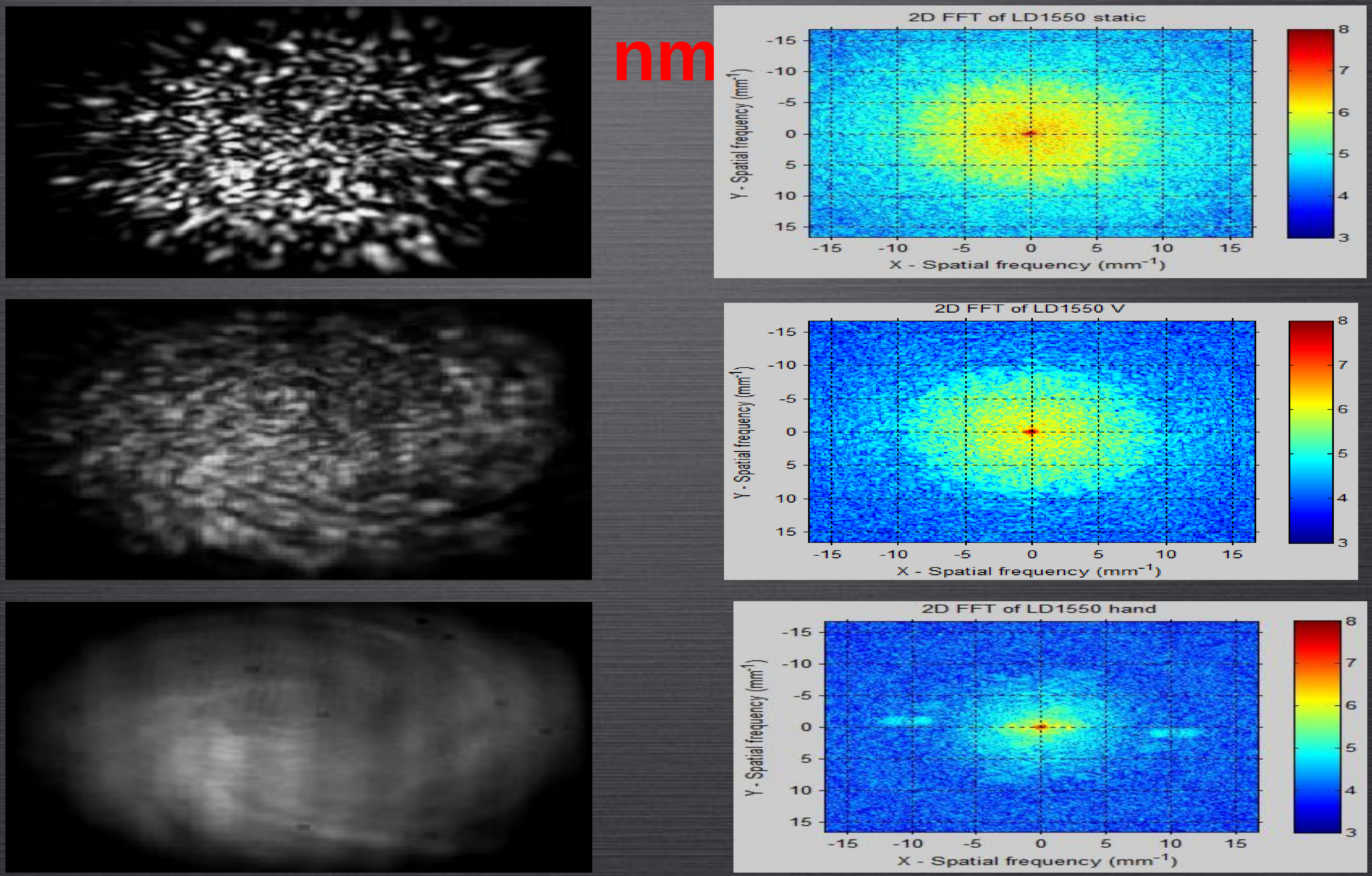
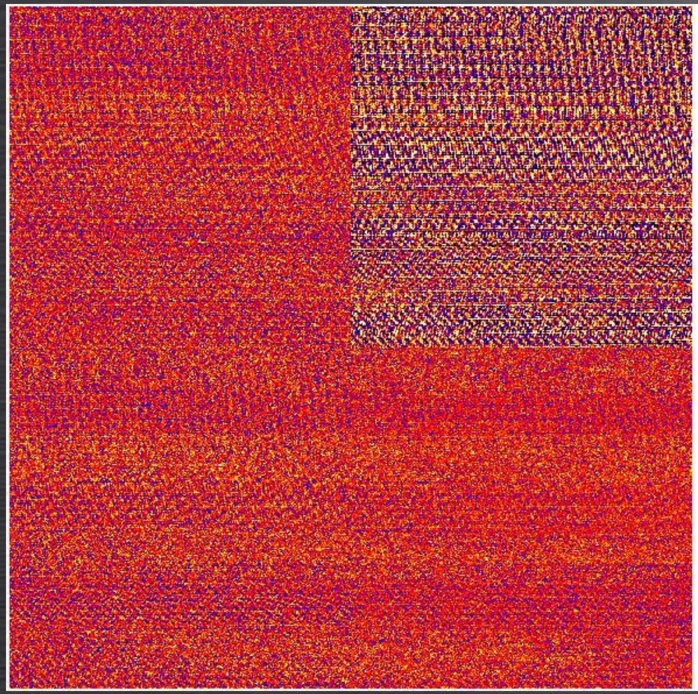


Figure 4-12: 1550 nm laser diode tests (Xenics camera) – (top left) static image, (top right) static image 2D FFT, (middle left) mechanical vibration image, (middle left) mechanical vibration image 2D FFT, (bottom left) hand agitation image, (bottom right) hand agitation image 2D FFT.

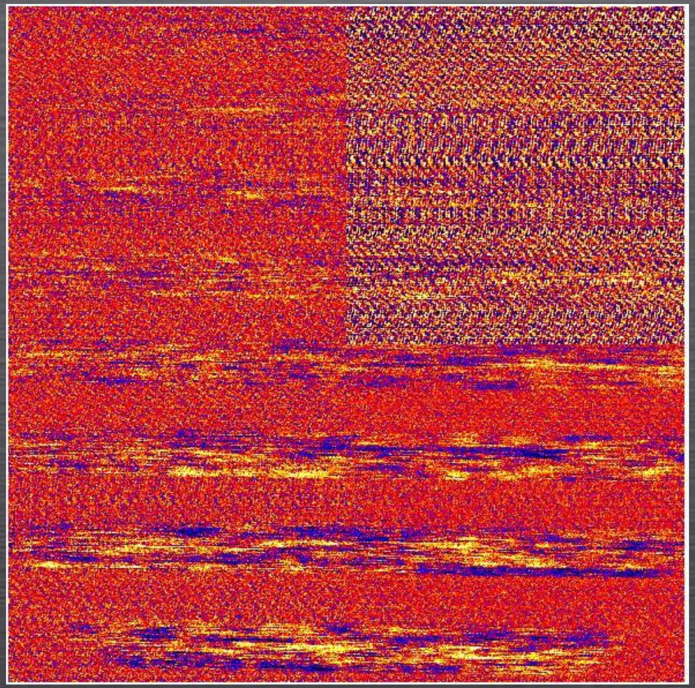
Noise due to Finite
# of TE TM modes
in FIber

Challenges:Fiber Modal Noise

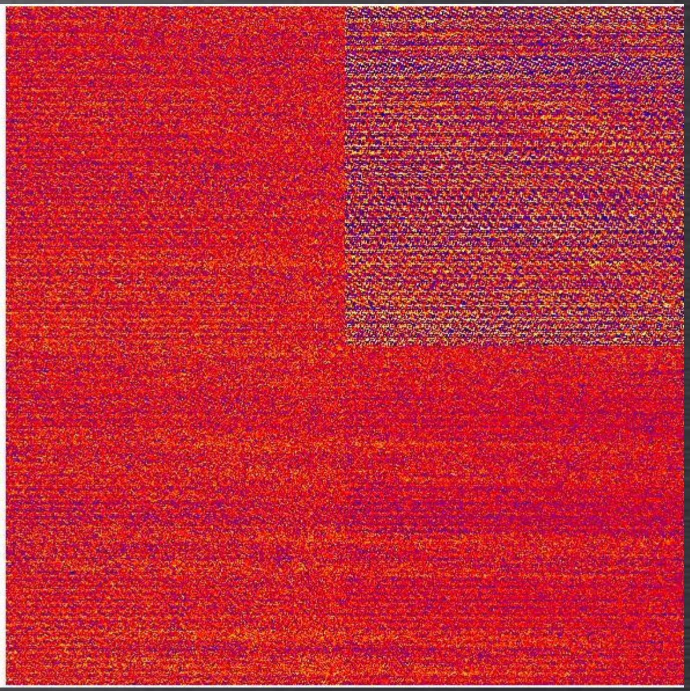
Modal Noise Experiment: J band



Ratio of consecutive Flats with no fiber disturbance

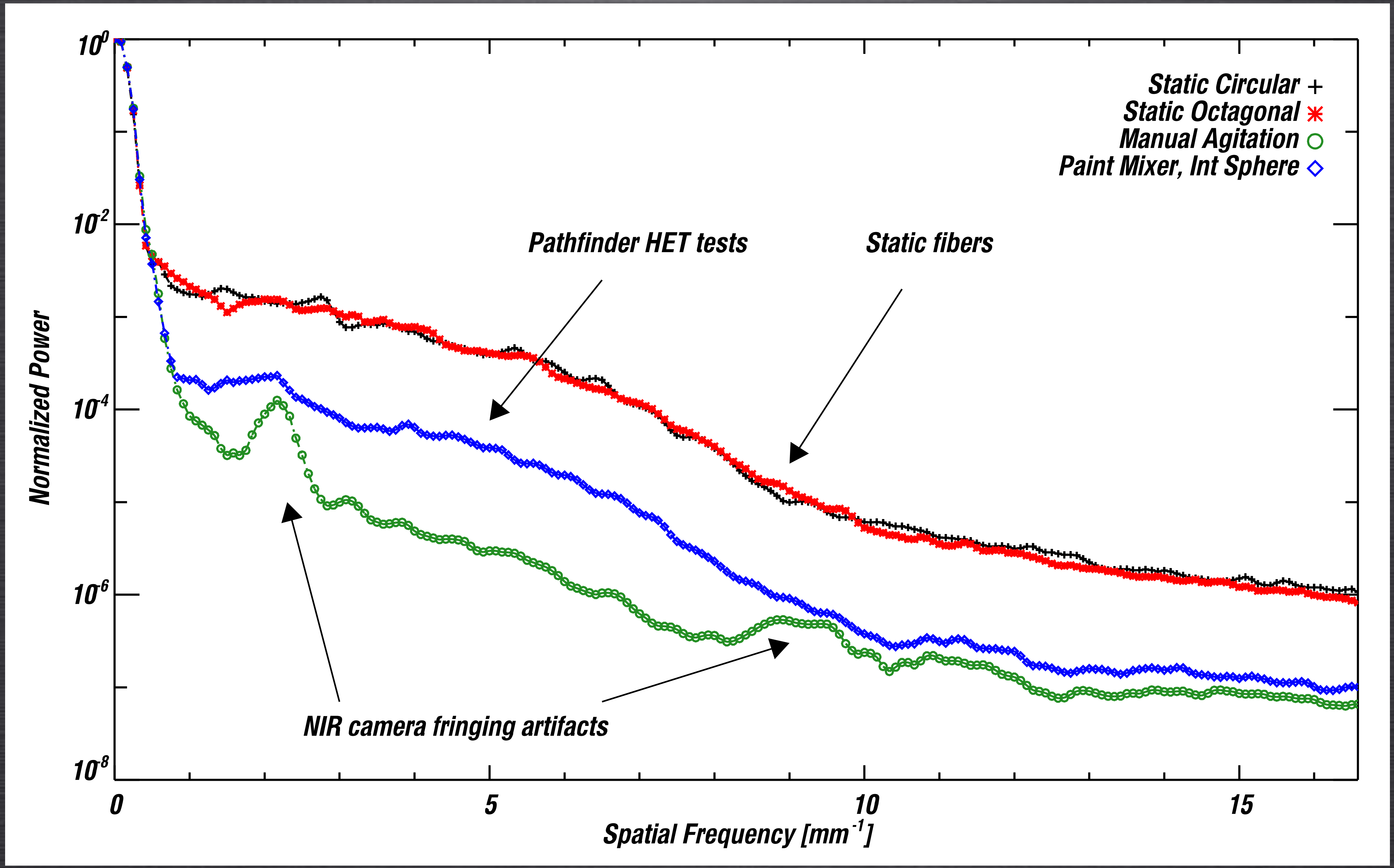


Ratio of consecutive Flats with fiber disturbance



Ratio of consecutive Flats with fiber disturbance and vibration

Challenges:Fiber Modal Noise

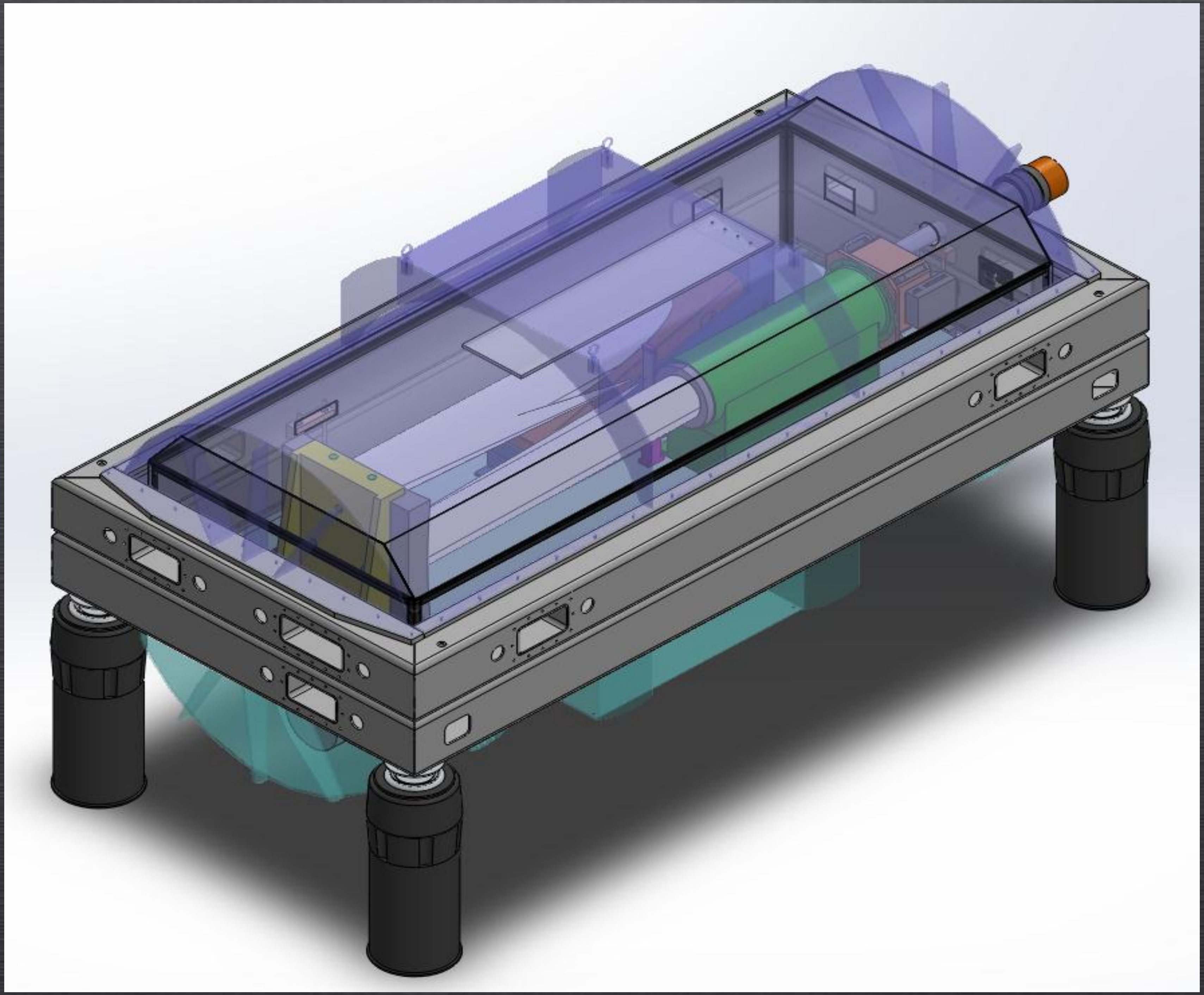


NIR modal noise , even coupling SMF to MMFs, is substantially mitigated by bulk agitation of fiber

Challenges:Fiber Modal Noise

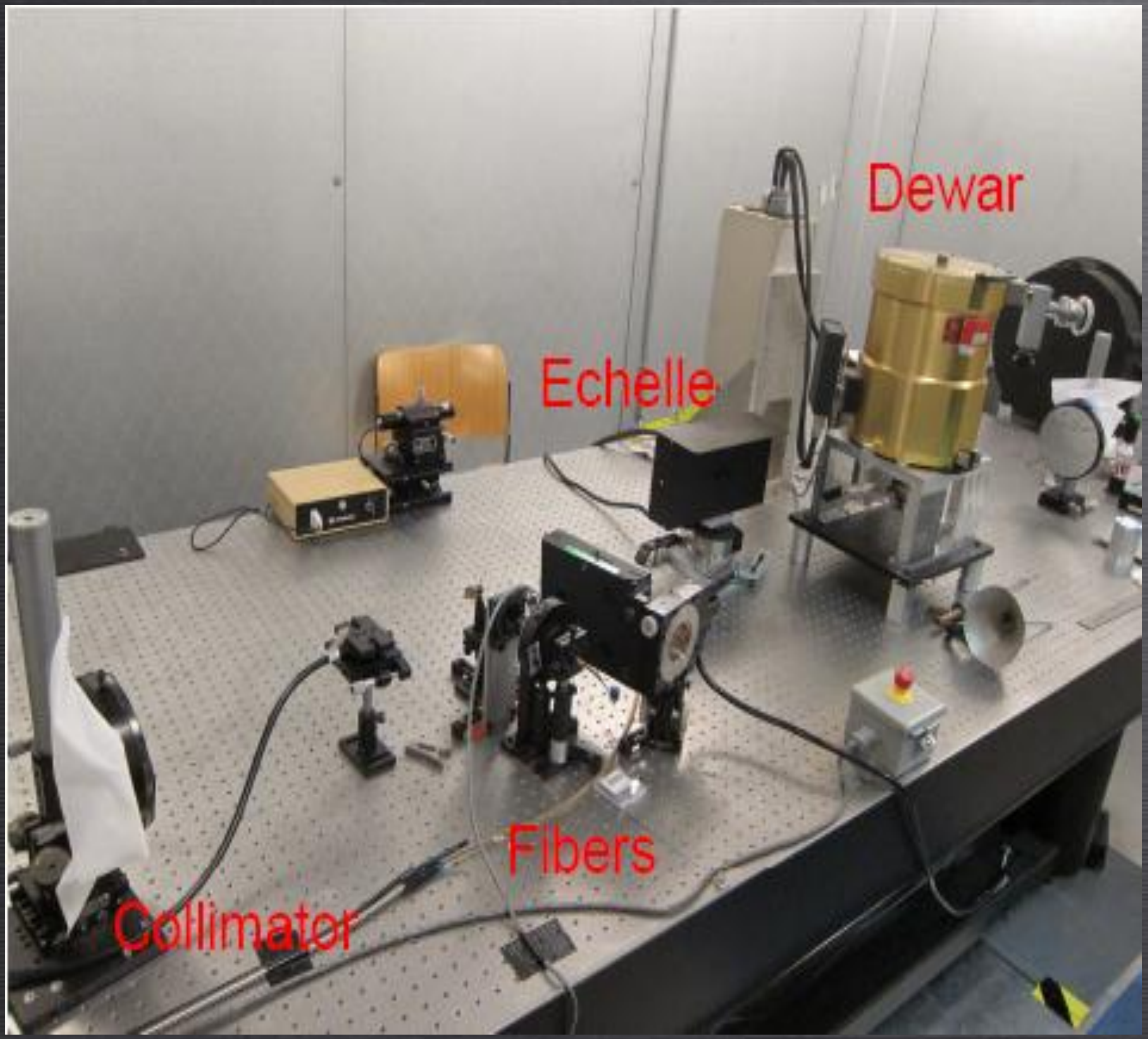
NIR modal noise , even coupling SMF to MMFs, is substantially mitigated by bulk agitation of fiber

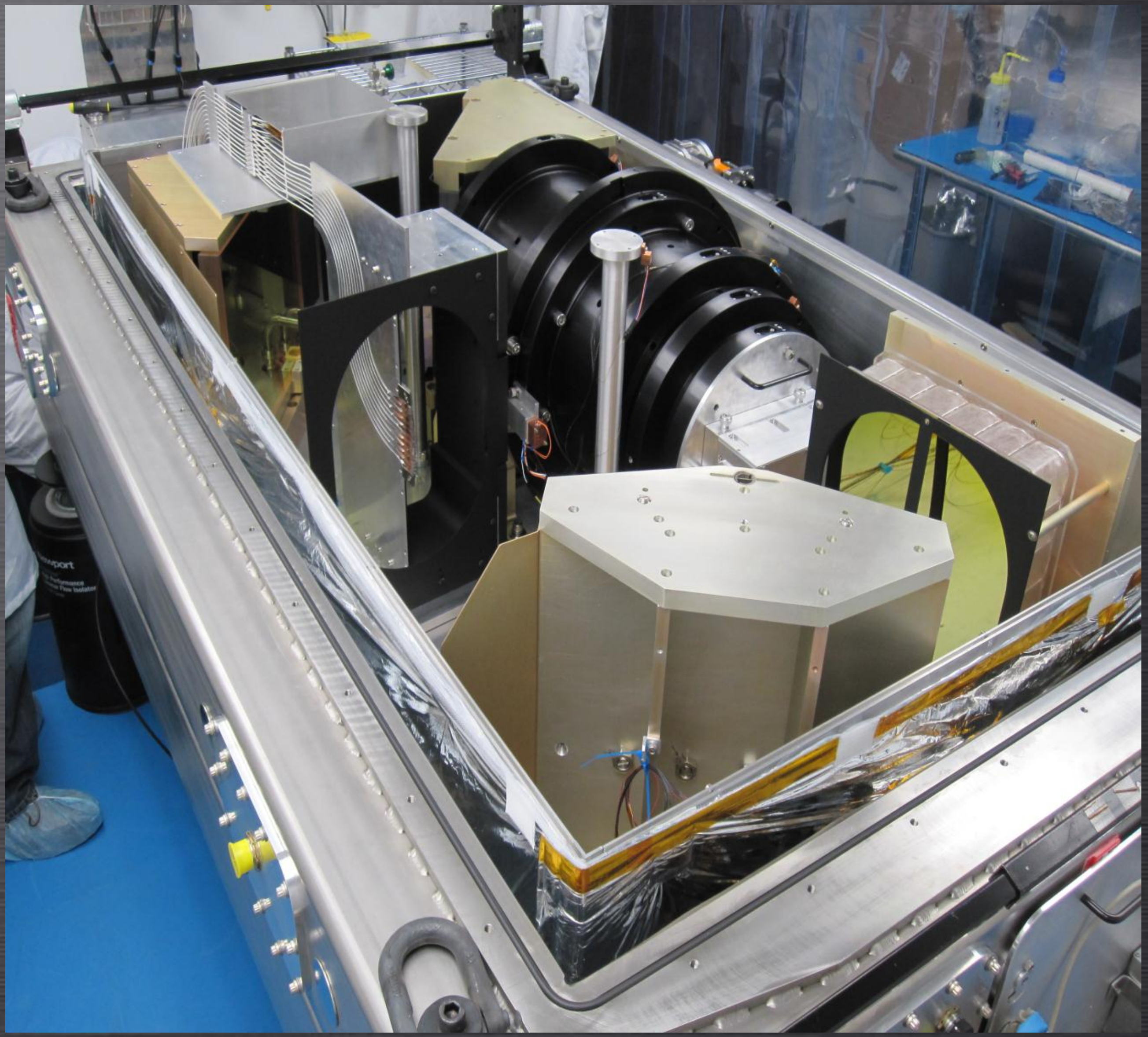
HPF Cryostat



HPF Cryostat is based on the very successful design of the recently commissioned SDSS-APOGEE NIR Spectrograph

Calibration Is KEY





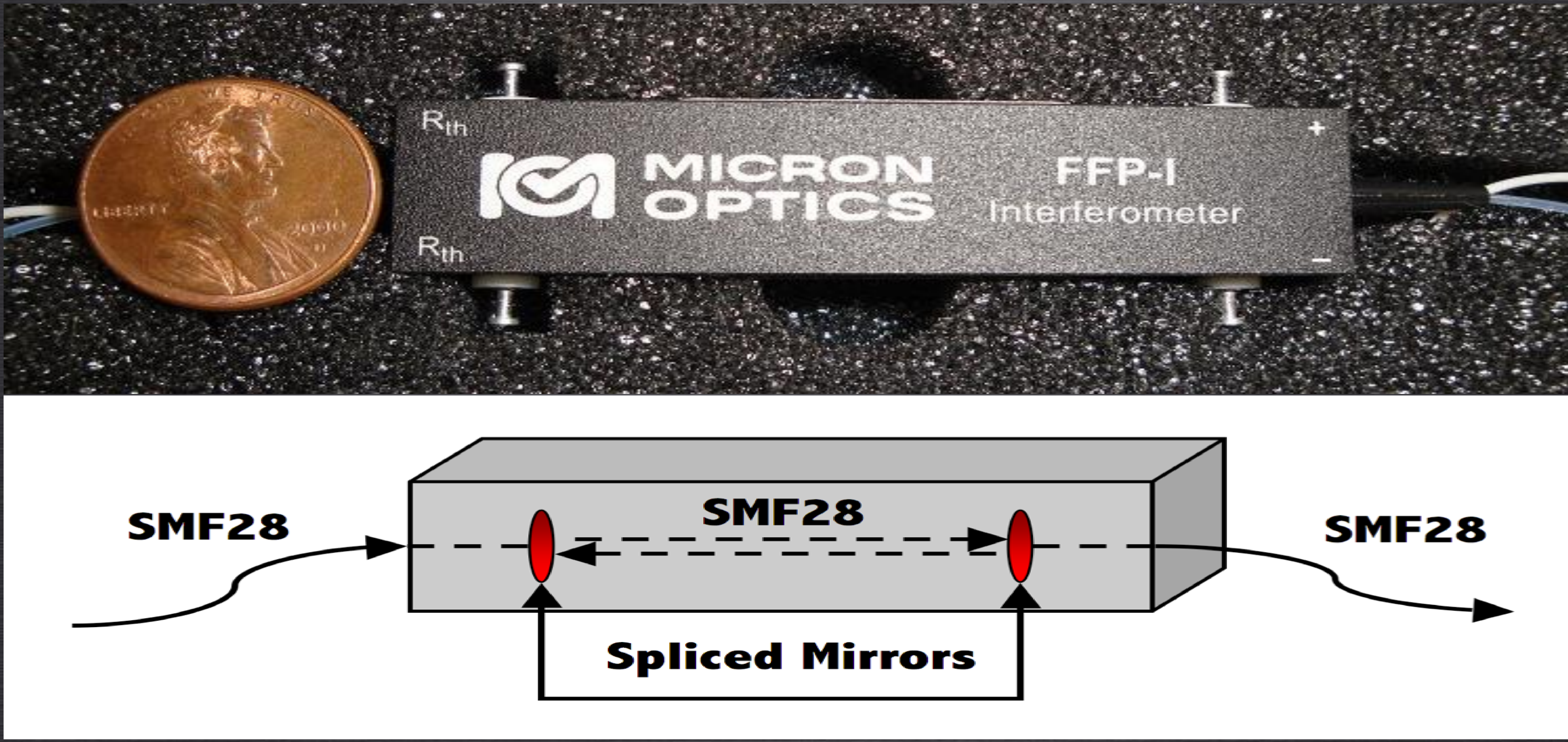
PATHFINDER
~10m/s

SDSS APOGEE
~100m/s

U/Ne, Freq. Comb.

Th-Ar, U-Ne, Sky OH

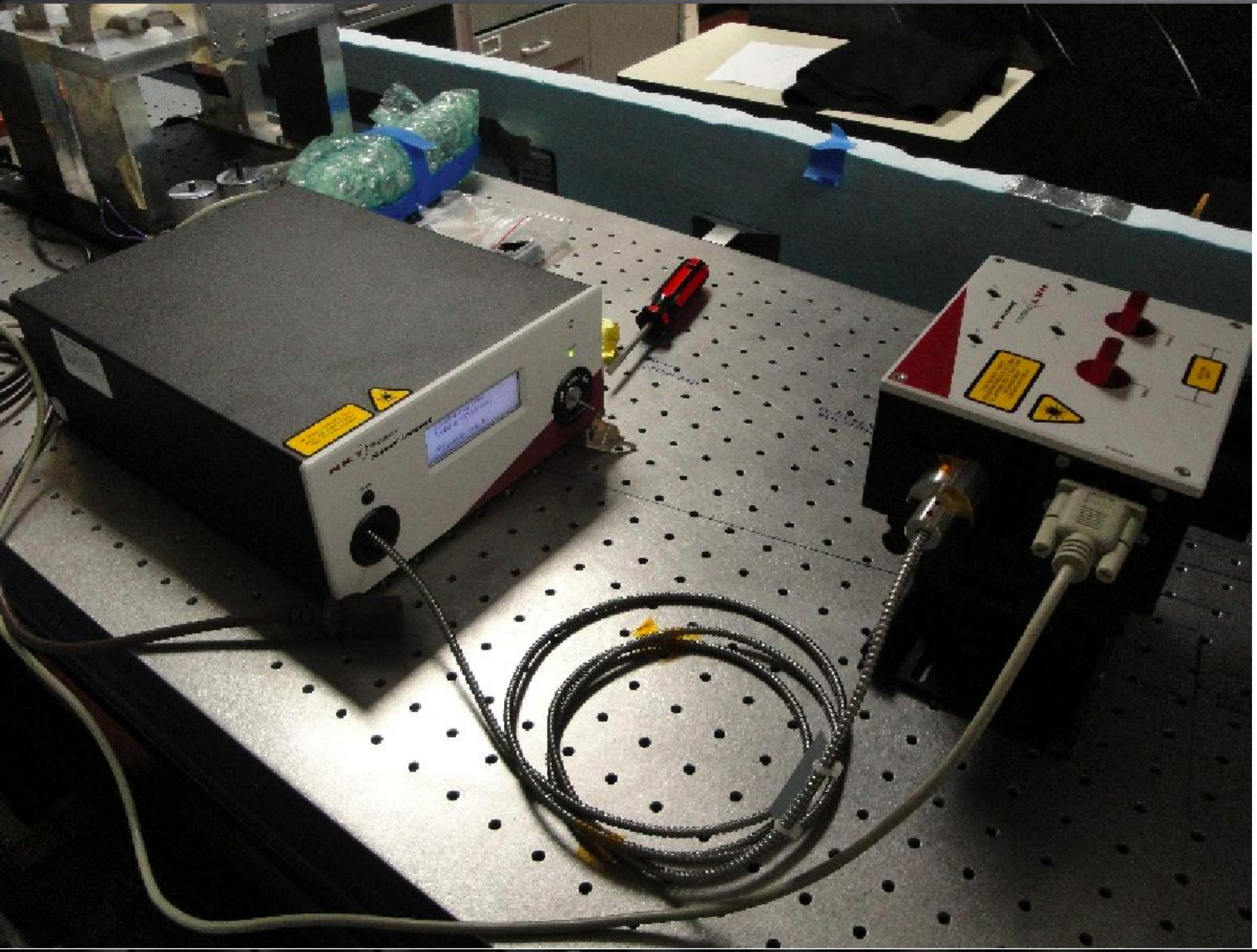
Fiber Fabry Perot: FFP

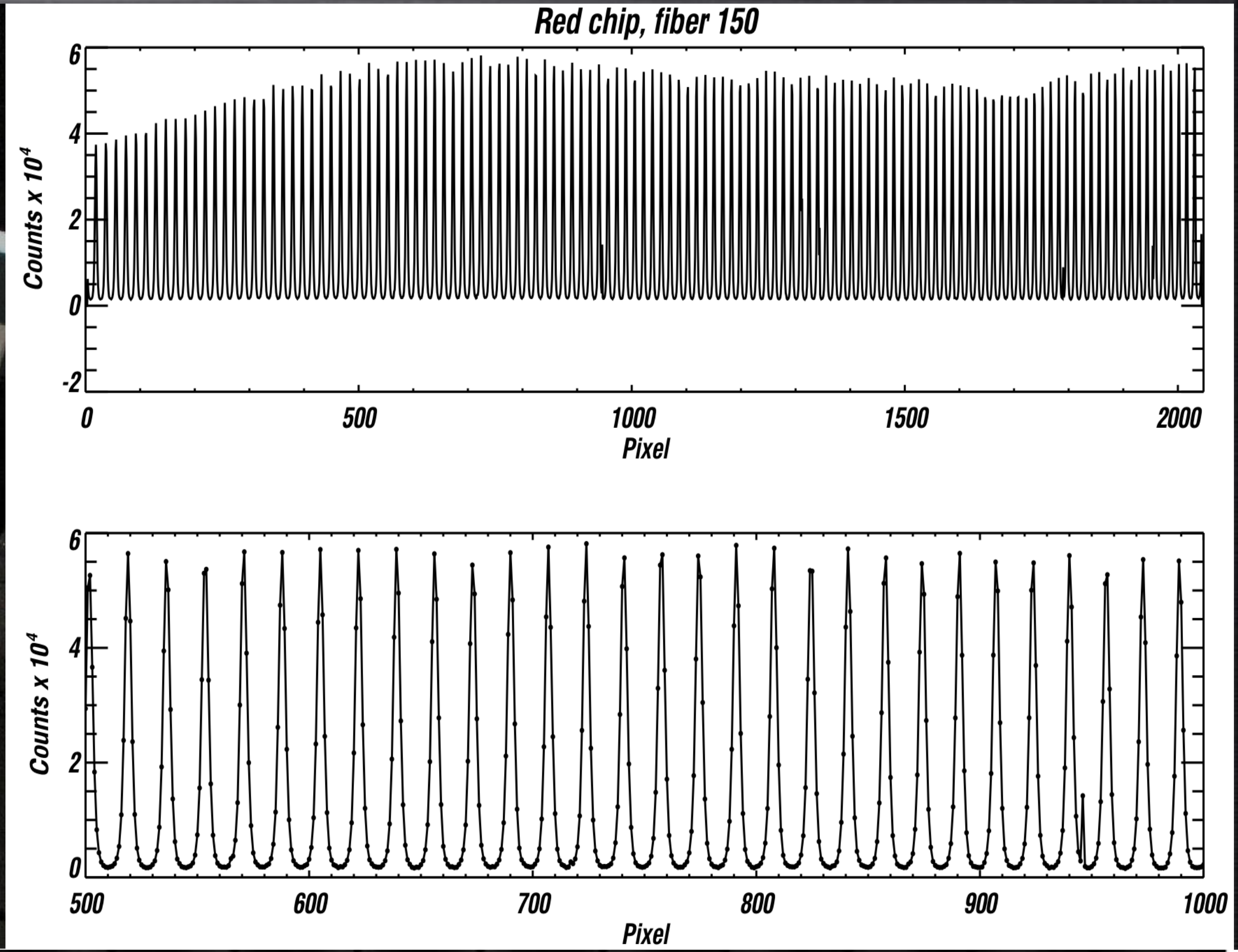


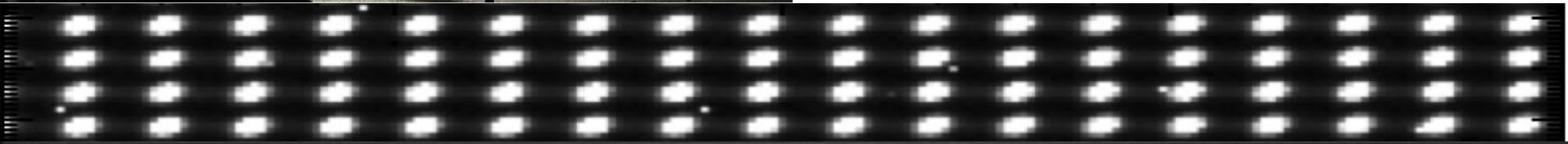
Fiber Fabry Perot: Compact, Insensitive to Vibrations.Collimation is not a Problem.

Halverson et al. 2012

FFP+APOGEE



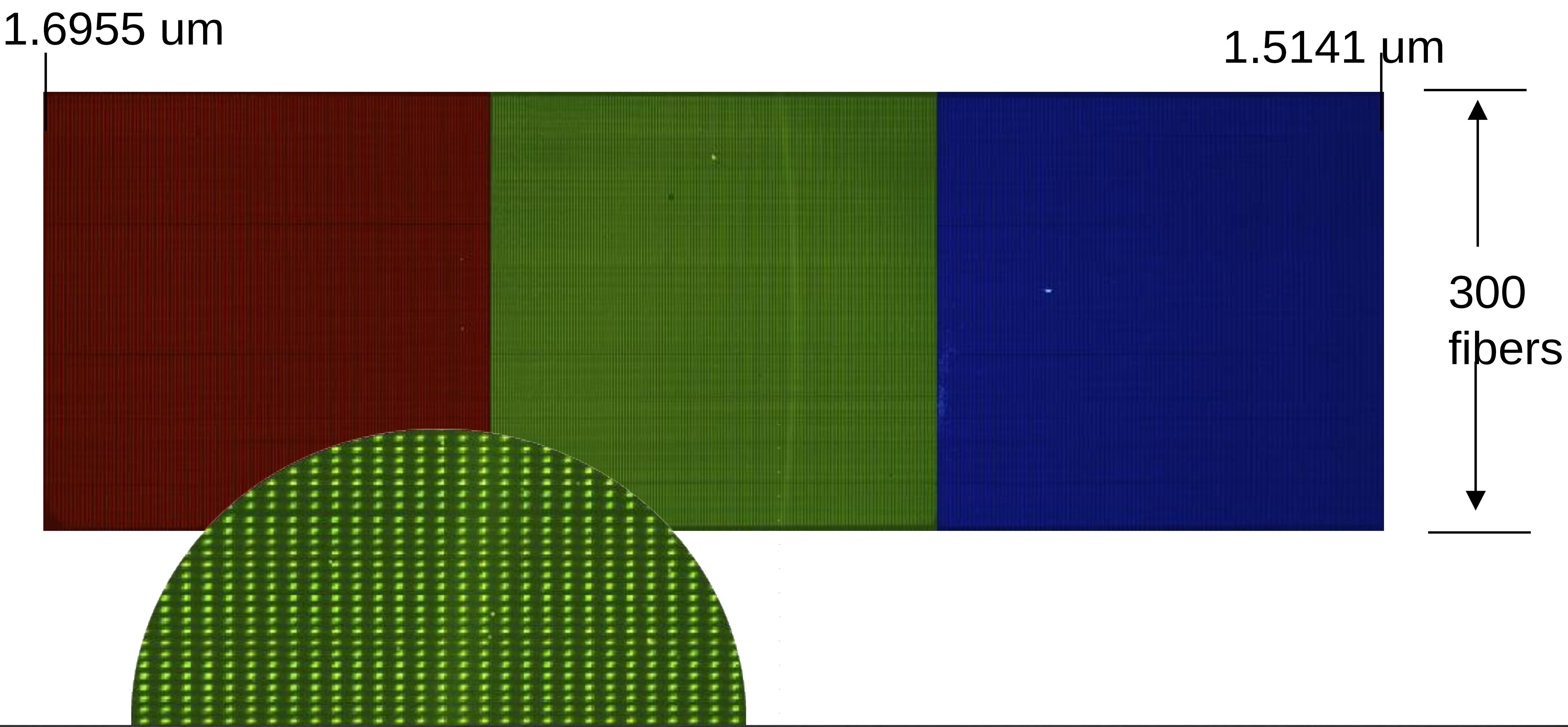




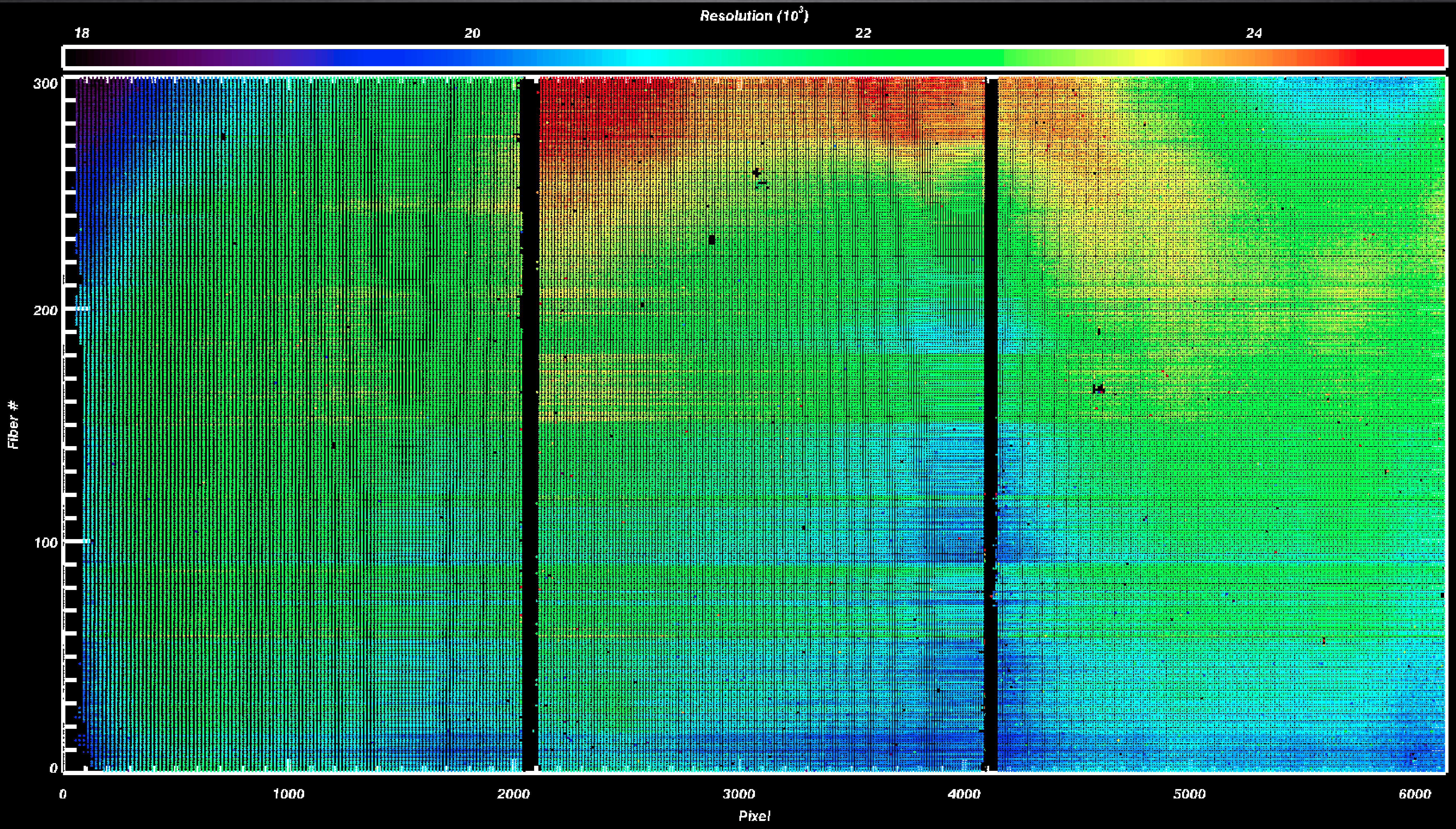
Needs a supercontinuum source to feed enough light through the 8micron core.

Expected Stability ~1m/s

FFP+APOGEE

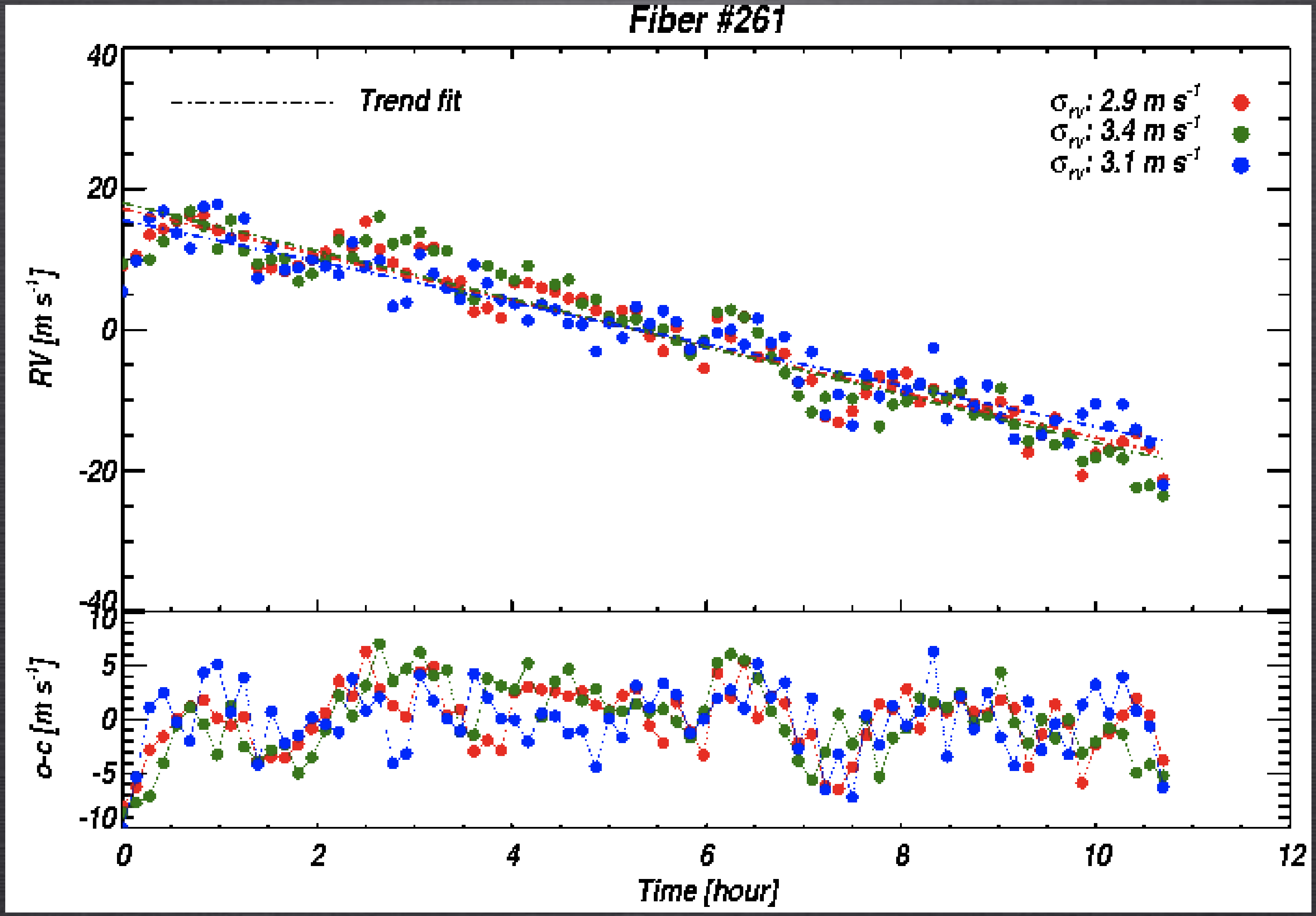


FFP+APOGEE



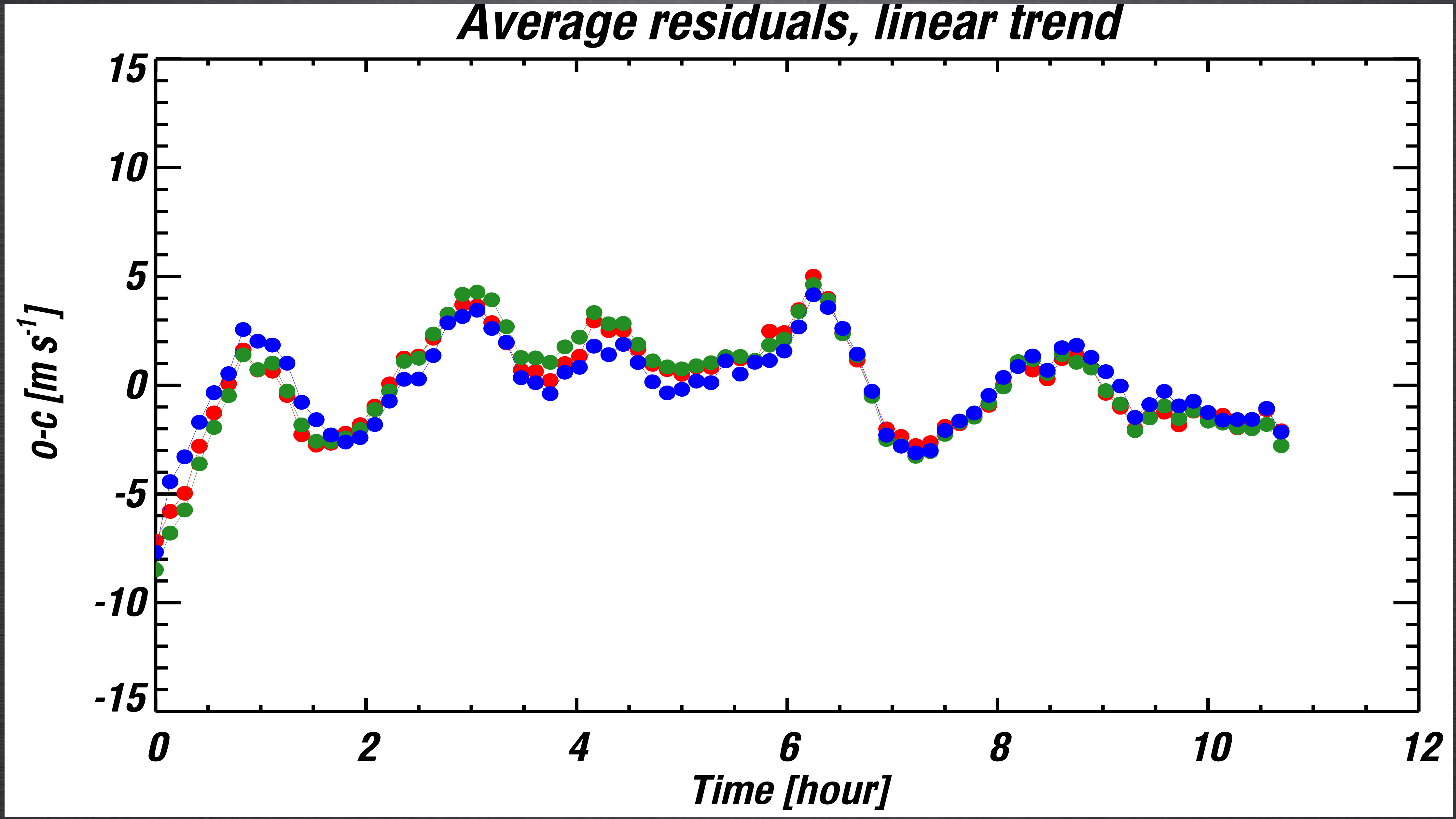
FFP Provides: Resolution, PSF, Persistence, Instrument Drift calibration……

FFP+APOGEE



~3-5m/s structure seen after removing ~50m/s Linear trend. Calibration is KEY!

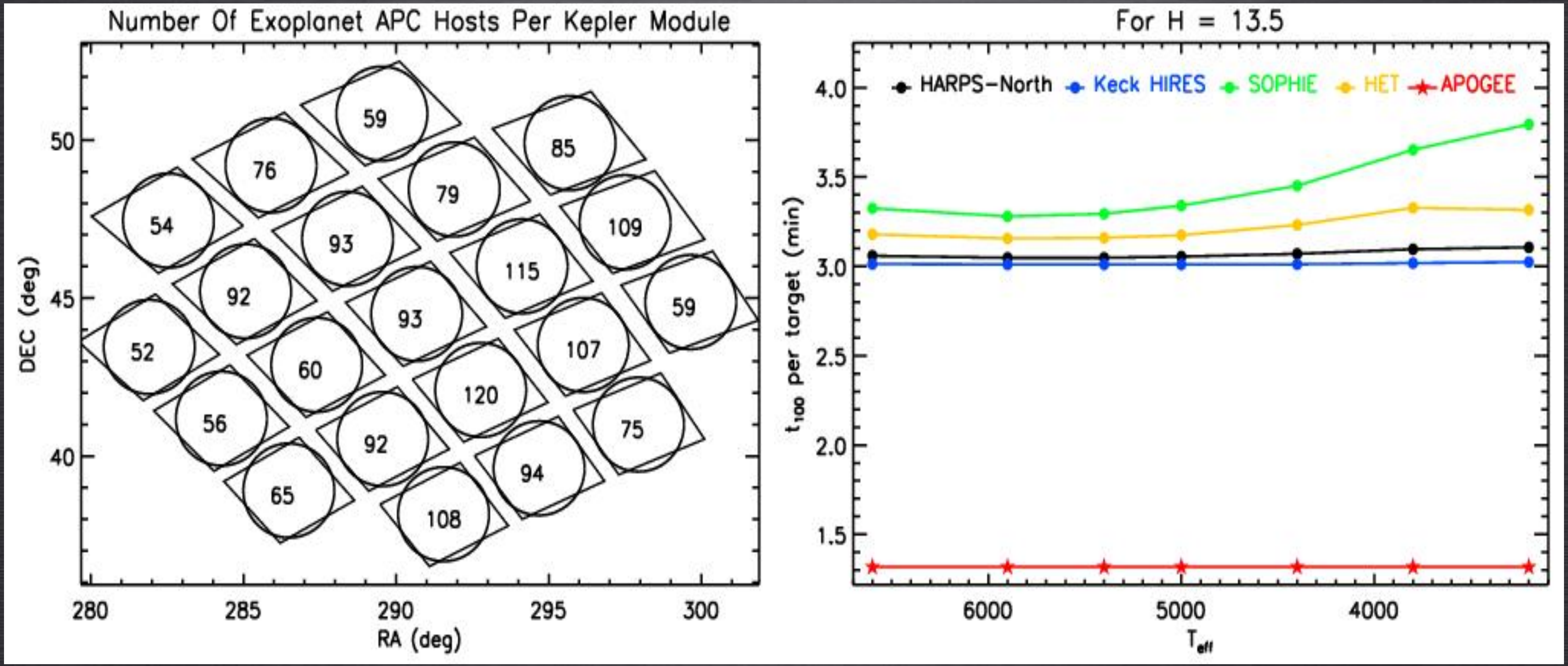
FFP+APOGEE



~3-5m/s structure seen after removing ~50m/s Linear trend.

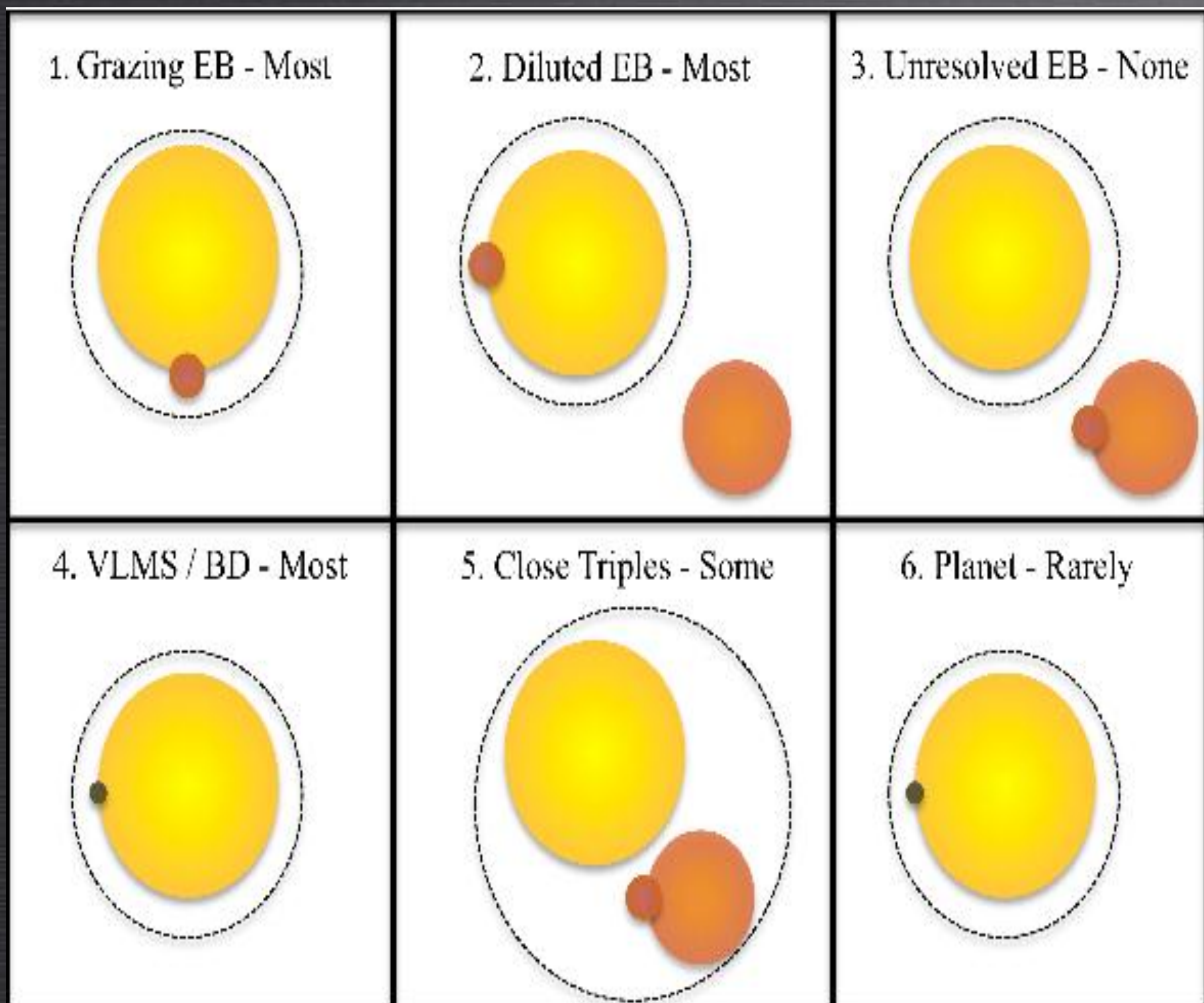
Now Developing a Y&J band FFP for HPF.

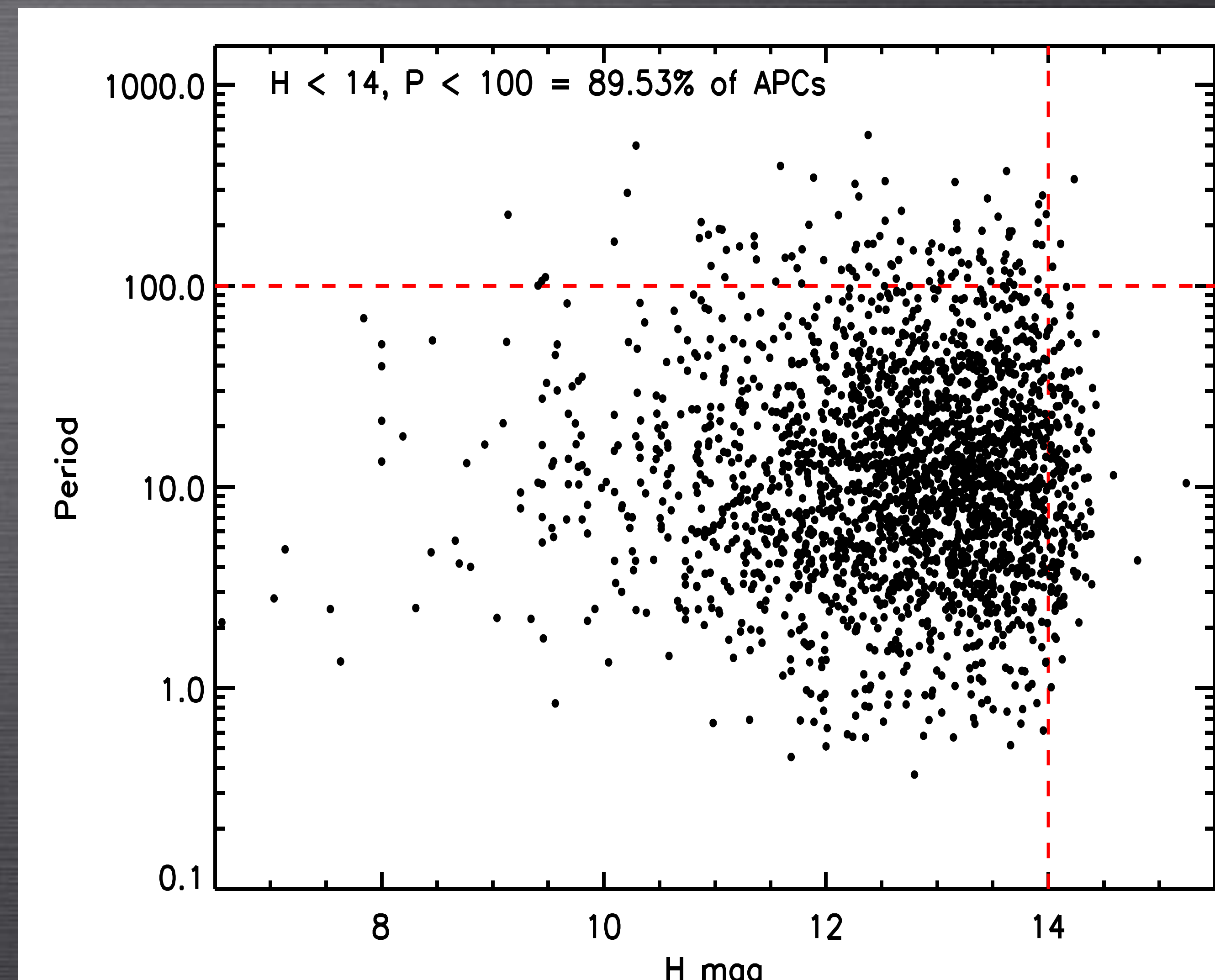
APOGEE+KEPLER



Can efficiently observe all KOIs with APOGEE on SDSS in the NIR H band. R~22.5k, 10 epochs of RVs at ~100m/s Excellent way to identify false positives, additional companions, elemental abundances etc..

APOGEE+KEPLER

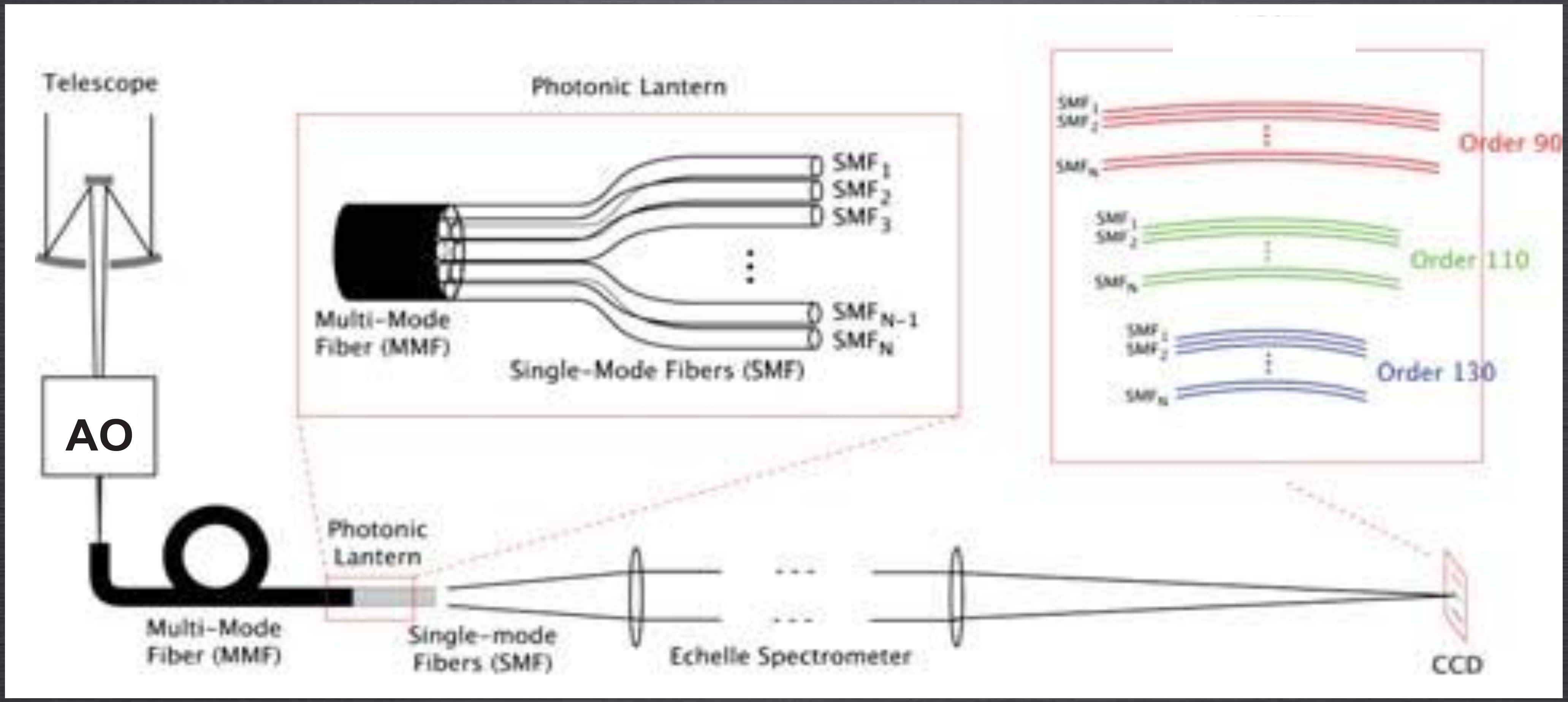




Proposed as a Key Project for APOGEE as part of the Next phase of SDSS starting in Fall 2014.

Paper (Fleming et al.) being submitted this week.

SMF Spectrographs

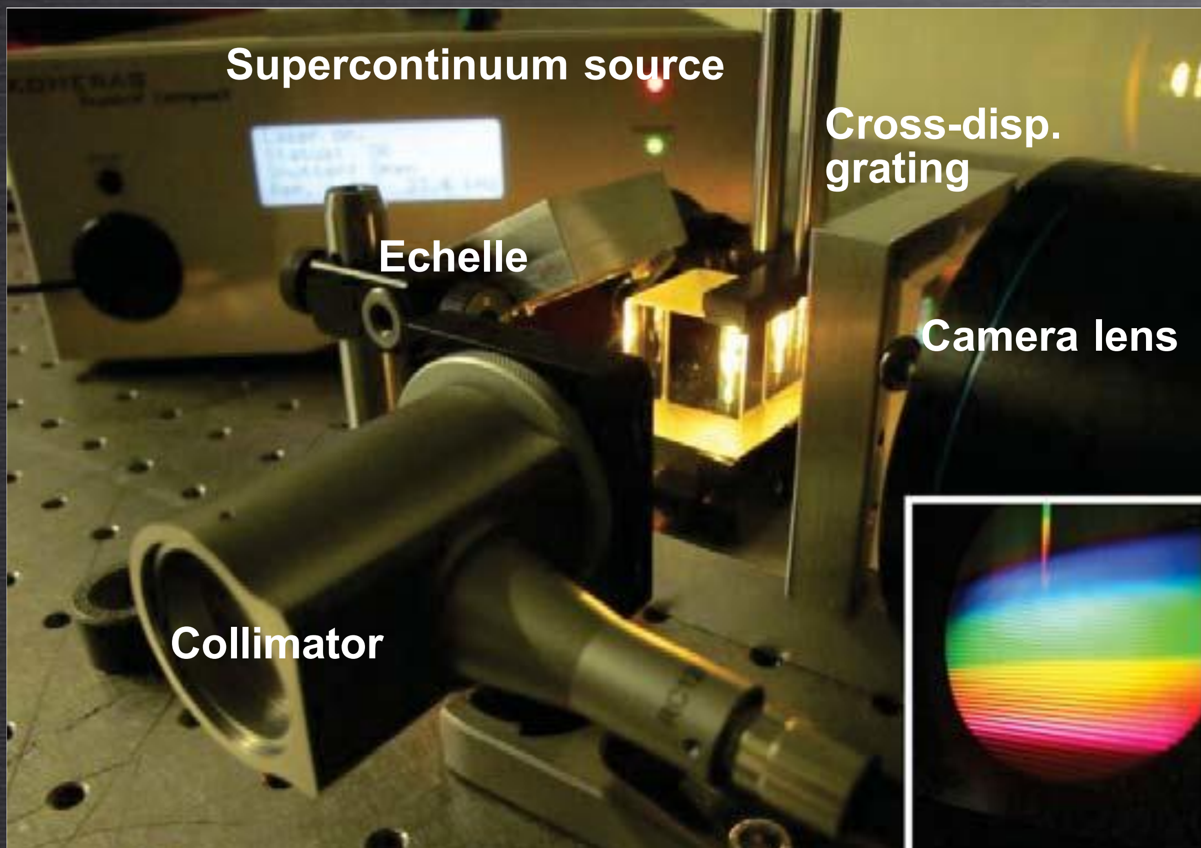


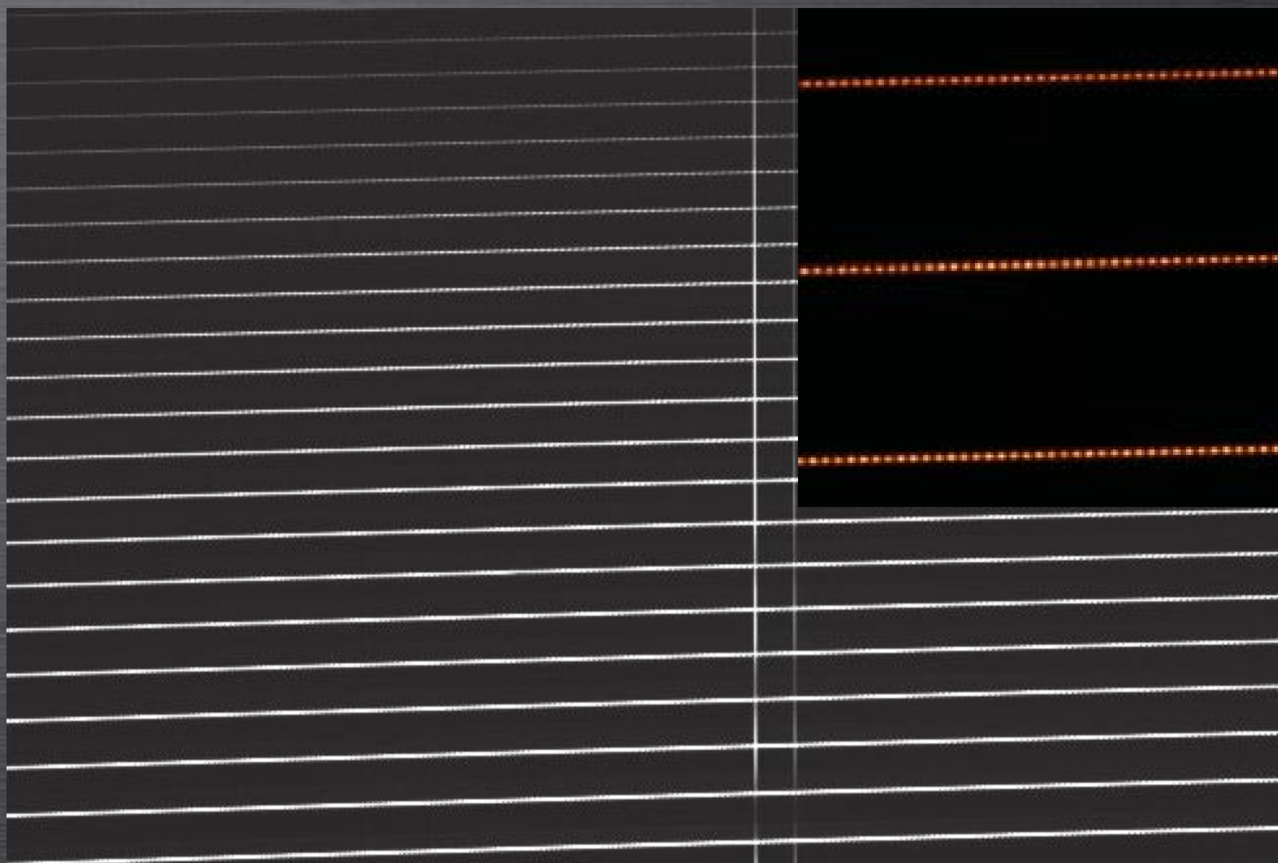
Single mode fibers coupled with high Strehl AO systems enable compact NIR instruments, with ‘perfect scrambling’.

Number of groups considering, testing simple variants (Mutterspaugh et al. 2012, Schwab et al. 2012, Crepp private communication)

Image Credit: Christian Schwab, 2012 IAU

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

Can We (eventually) Detect Earth Mass Planets in the HZs of Solar Type stars with RV?

Technically: Probably Yes

The best spectrographs May well deliver ~10cm/s innate precision in the coming decade. Aspects of stellar activity will be wavelength dependant, allowing optical and NIR spectrographs together to discriminate against these…

Sociological Issues in Deploying Significant time on Large expensive facilities on small subsets of bright stars.

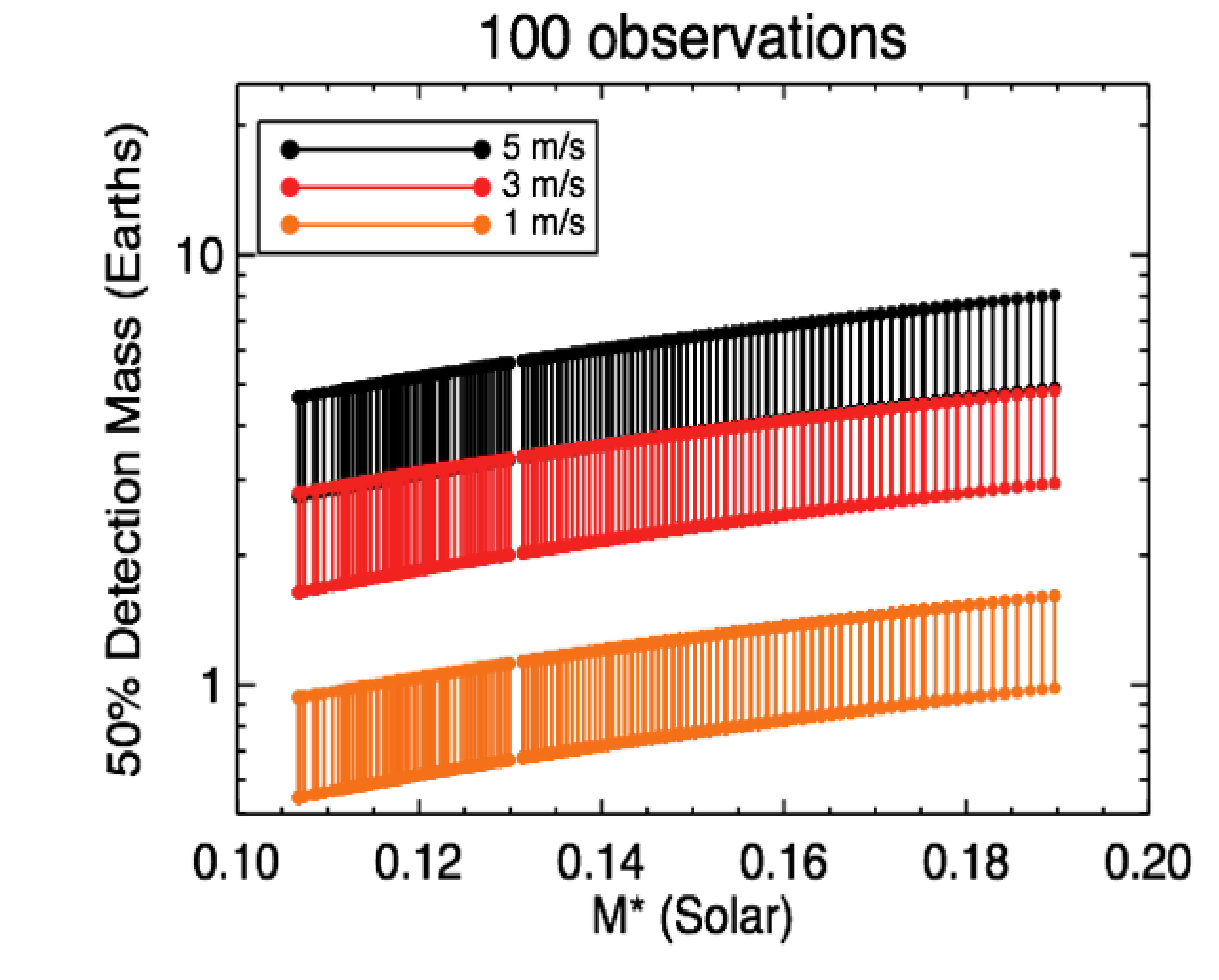
In Summary

•Significant challenges in NIR RVs are being overcome with AMO/Laser Physics, astrophotonics, filter design, astronomical spectrograph design etc.

•Testbeds are REALLY useful………

•HPF is being built, incorporating lessons learnt from Pathfinder & APOGEE

•By their nature, NIR instruments cost more money. Sustained investment in technology, as well as innovative use of existing instruments, will likely lead to significant progress in RV precision.


100 observations
5 m/s
3 m/s
1 m/s
10
1
50% Detection Mass (Earths)
0.10
0.12
0.14
0.16
0.18
0.20
M* (Solar)