Dispersed Fixed-delay Interferometry for High precision Doppler Measurements

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UF Led Extrasolar Planet Surveys

- **Multiple object exoplanet surveys to largely increase survey sample (including intermediate mass stars)**

  Multi-object APO Radial Velocity Exoplanet Large-area Survey (MARVELS)

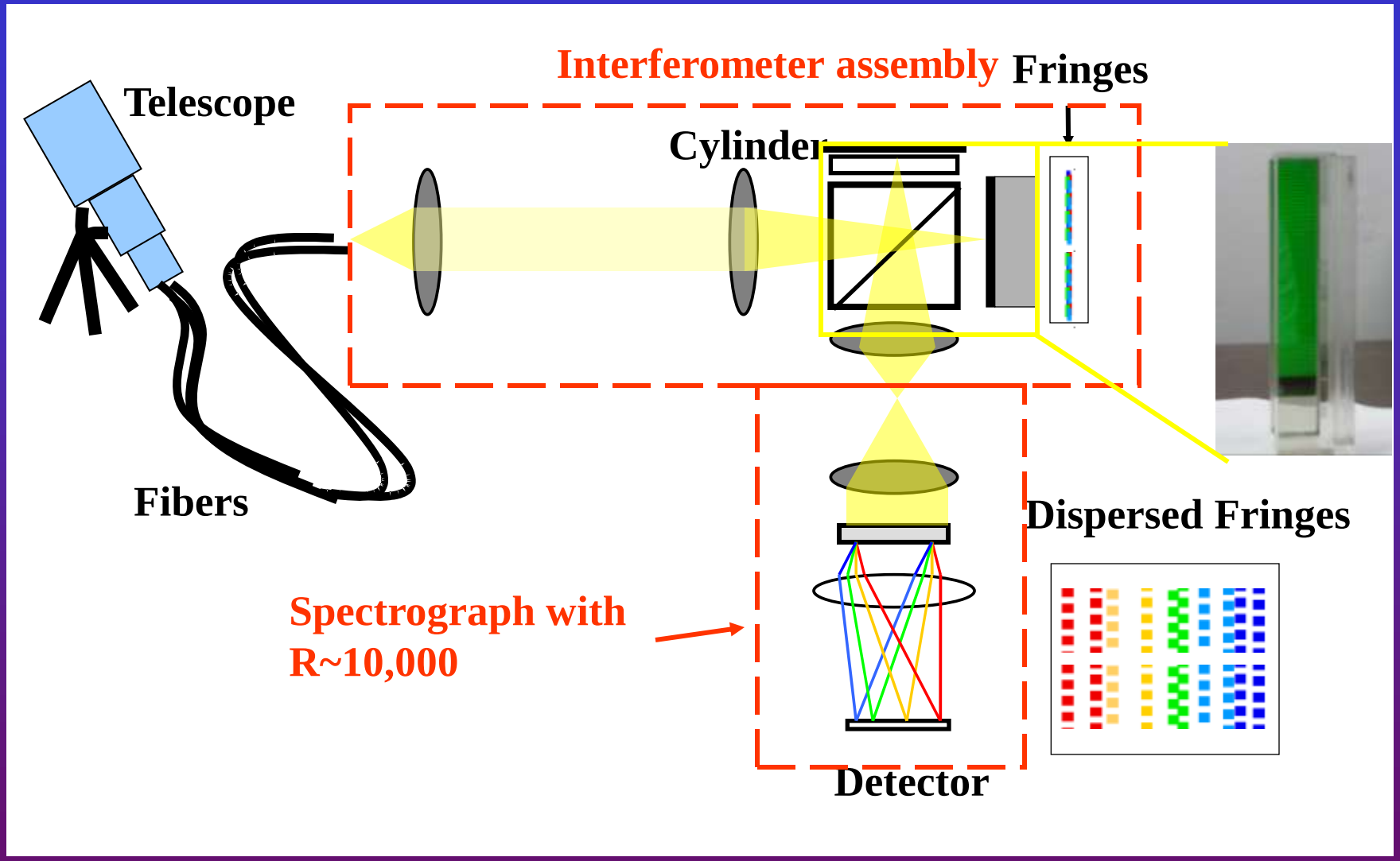
- **Global high precision Doppler instrument network to increase RV sample and better handle stellar noises**

  EXtremely high Precision Extrasolar planet Tracker (EXPERT) network

- **Infrared Doppler planet surveys to include low mass stars and young stars**

  Infrared Exoplanet Tracker (IRET) and Florida IR Silicon immersion grating spectromeTer (FIRST)

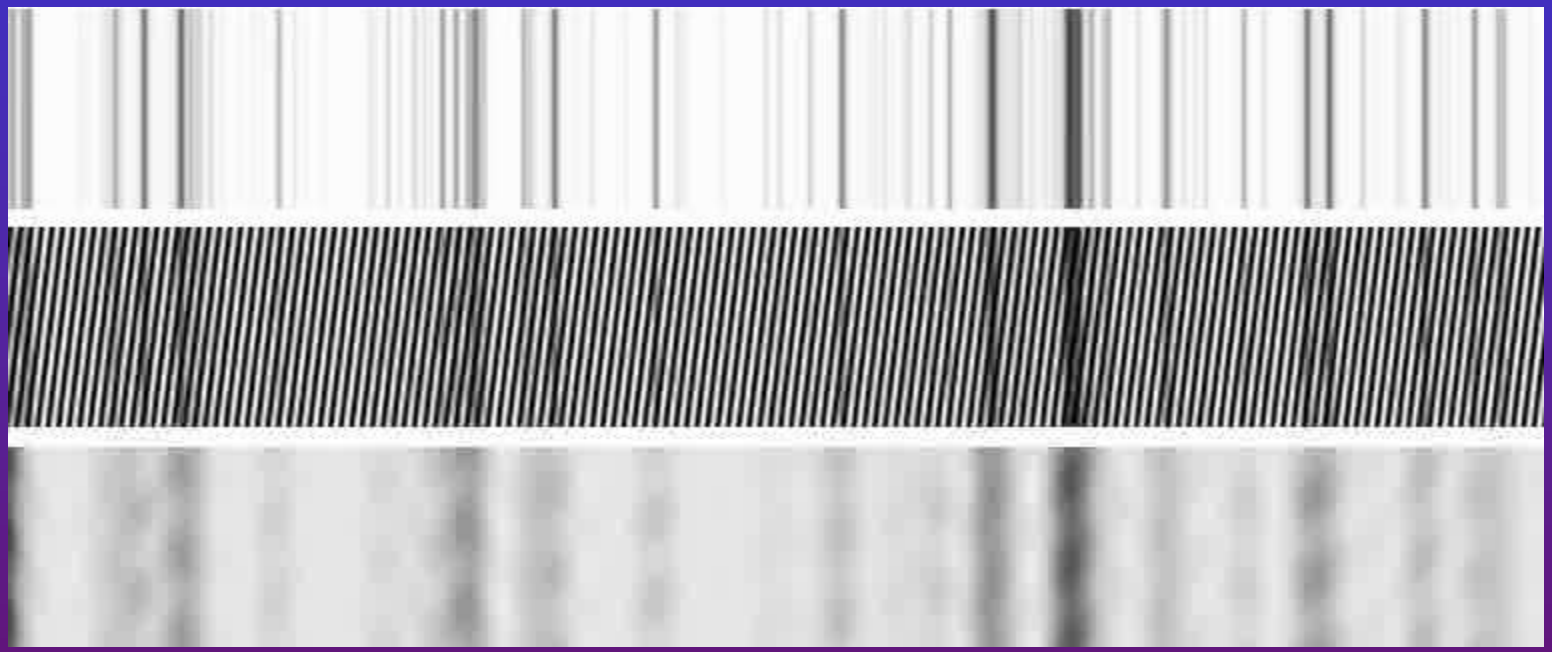
Schematic Layout of a Dispersed Fixed-delay Interferometer (DFDI)



Erskine & Ge (2000), Ge et al. (2002), Ge (2002)

Doppler shift: $\Delta V \propto \Delta \Phi$ (phase shift)

DFDI principle



Credits: Julian van Eyken

Sloan Digital Sky Survey III

MARVELS Survey

- To monitor a total of 10,000 V=7.6-12 FGK dwarfs and subgiants, & 1,000 V=7.6-10 G and K giants with minimal metallicity and age biases for detecting and characterizing ~100 giant planets using SDSS telescope in 2008-2014

- Use all of the bright time in 2008-2011 and share the bright time with APOGEE in 2011-2014

- Each of ~120 fields will be monitored about 24 times over ~18 months

- Two multi-object Doppler instruments with a total of 120 object capability

- The wavelength coverage ~ 500-570 nm

- Spectral resolution ~10,000

- Doppler precision (photon noise limit) in 1 hour exposures: 3.4m/s (V=8), 8.5 m/s (V=10) and 21.3 m/s (V=12)

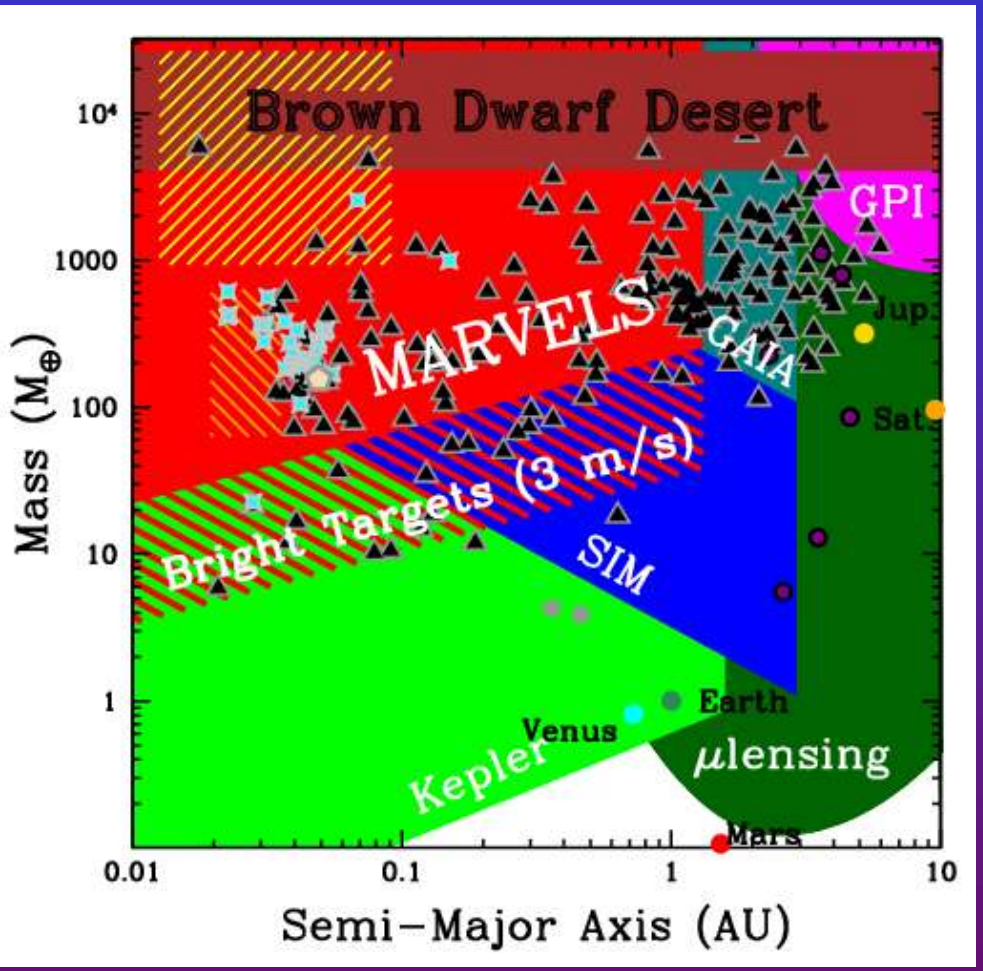
The MARVELS Survey Science Goals

Principal science goals:

- **find a homogeneous sample of hundreds of giant planets that can be used for statistical study of planet properties and comparison to theory**
- **constrain formation, migration & dynamical evolution of planetary systems**

- **discovery of rare systems (e.g.** "Very Hot Jupiters", short-period super-massive planets, short-period eccentric planets, transiting planets, highly eccentric planets, rapidly interacting multiple planet systems, planets orbiting low-metallicitiy host stars, planets around active and young stars, and other rare types of planets**)**
- **signposts for lower-mass or more distant planets**
- **quantify the emptiness of the brown dwarf desert**

MARVELS & Other Planned Large Surveys in the Next Decade



- Kepler is sensitive to the edge-on and short period planets, main targets V=12-14
- Microlensing (on-going) is sensitive to planets beyond 1AU
- GAIA (2011-) and SIM-lite (2015?-) probe lower mass but longer period systems but will not yield a comparably large sample of dynamically evolved giant planets.
- Gemini Planet Imager (2011-) is sensitive to young giant planets (<1Gyr) beyond 5AU for stars within 50 pc, and is complementary to the MARVELS giant planets

MARVELS Survey Field Selection

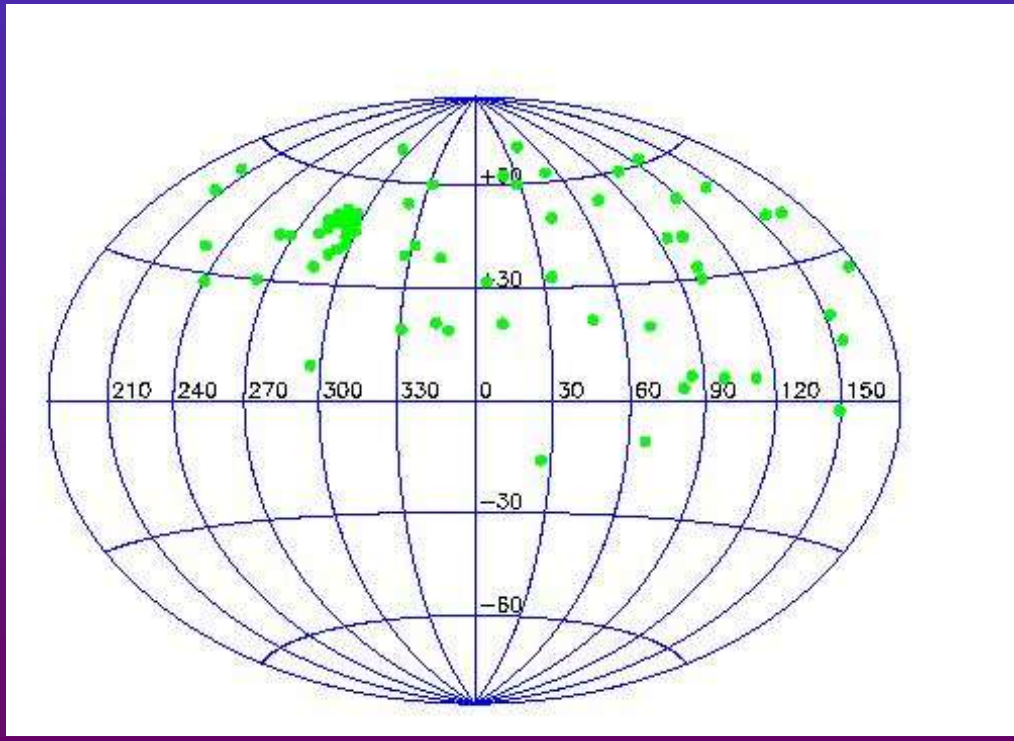
• Survey area is ~800 sq deg, a total of ~120 fields, mainly along the Galactic plane

• About 60 fields will be shared with APOGEE in 2011-2014

•Field selection is based on sufficient number of bright observable stars in each field, and some fields need to have known calibrators for initial instrument calibration

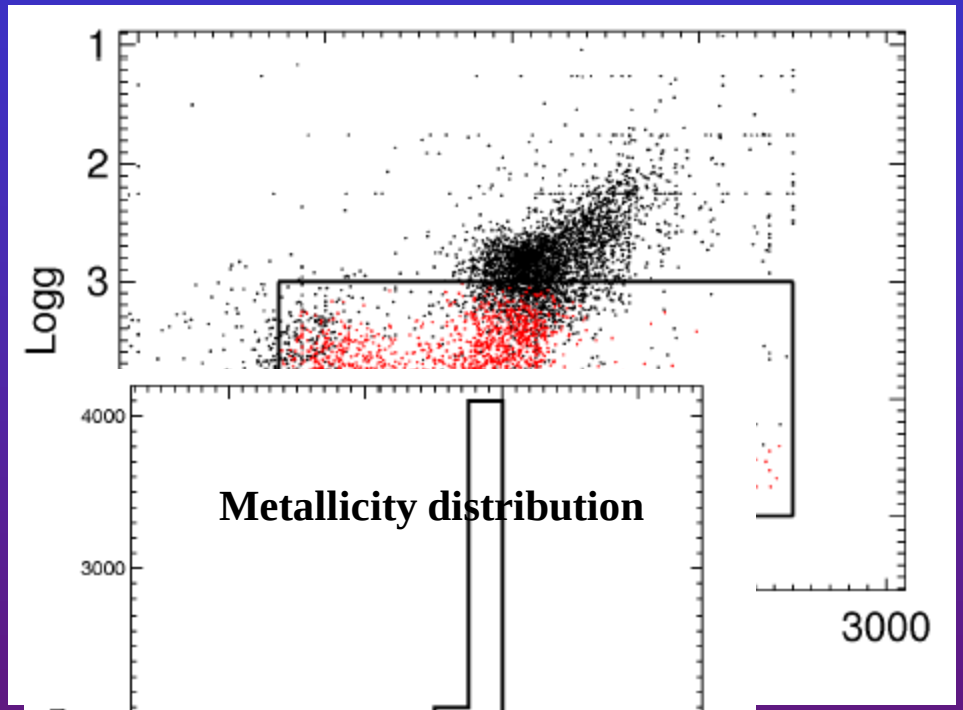
•64 fields, including some calibration fields, have been selected for the first two years of operation

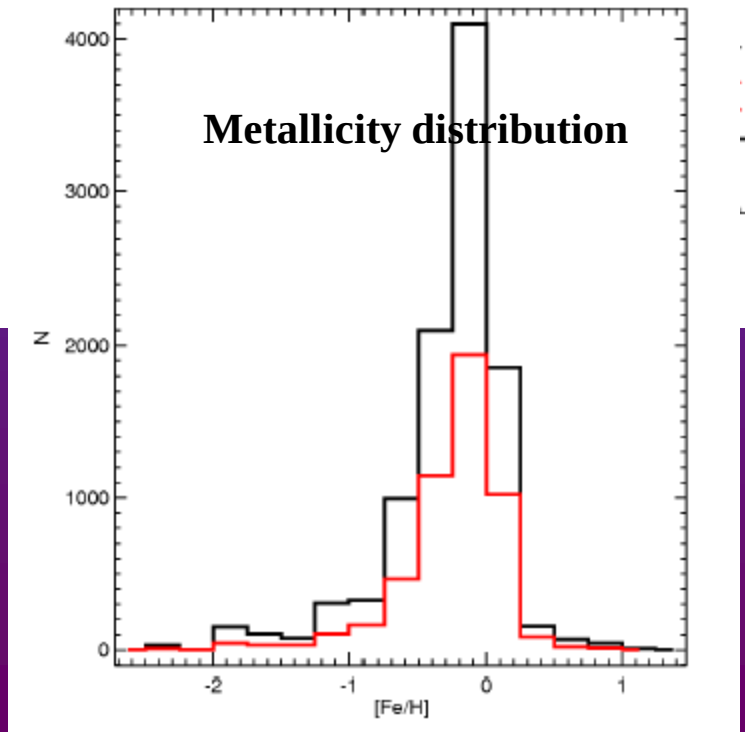
•A number of fields have also been selected to coincide with the one of the 21 CCD modules of the planned KEPLER space mission



MARVELS Survey Target Selection

Effective temperature and gravity plot of target candidates of 7 fields

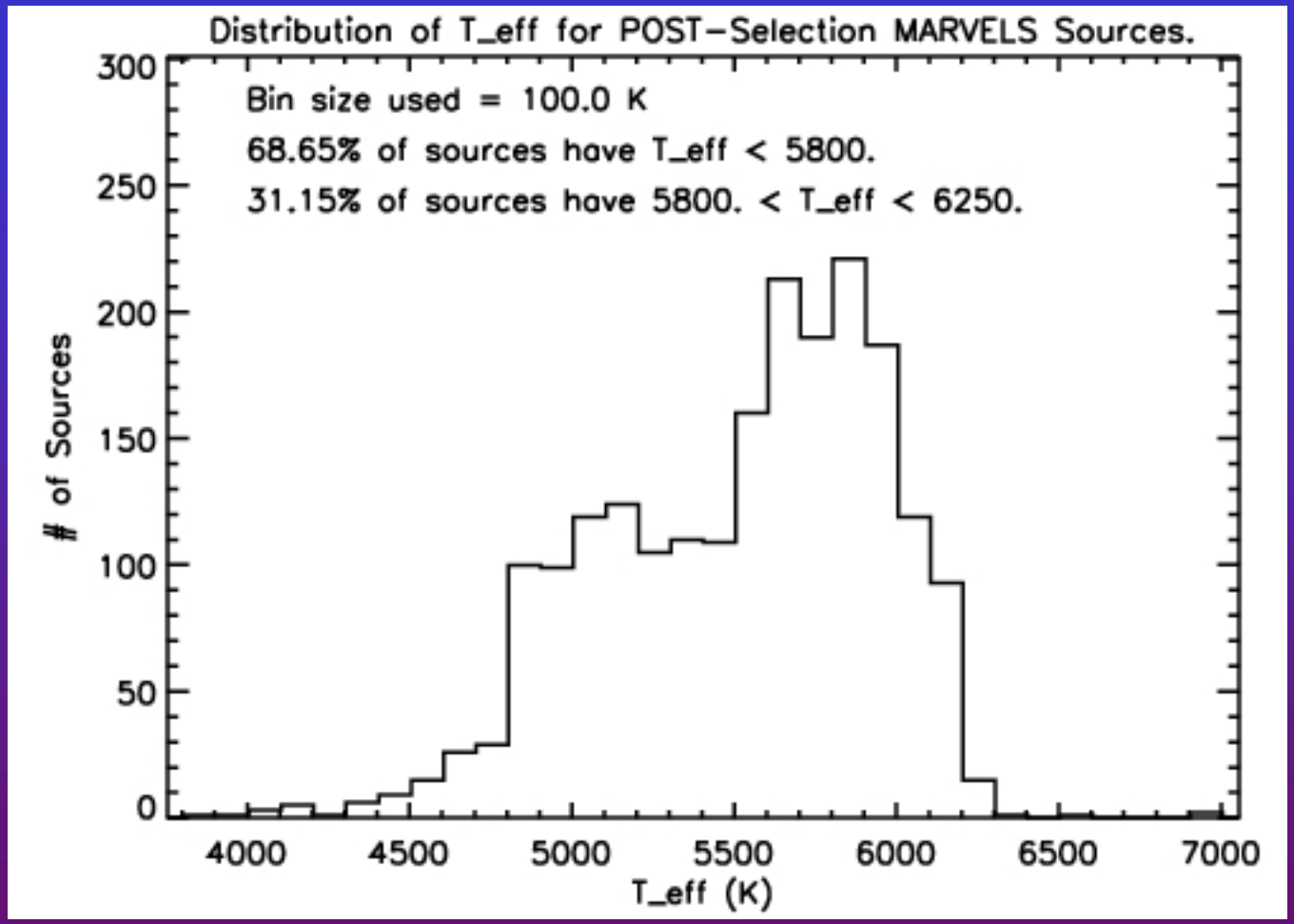




- Targets initially selected from GSC2.3 catalog matched up with 2MASS for J, H, K colors

- SDSS spectroscopy pre-selection efficiently remove giants (e.g., *log g < 3.0*) and stars that are too hot (e.g., T_{eff} > *6250* K) from the initially color selected targets
- 25-35% of the ~500 candidates per field are acceptable targets
- Recently, we found that the SDSS SSPP code tends to fail for log g < 4, particularly for cool temperatures of Teff < 5000 K
- We are using reduced proper motion cut to separate dwarfs and subdwarfs from giants for year 3+4 targets

Distribution of POST-Selection T_{eff} of MARVELS Targets



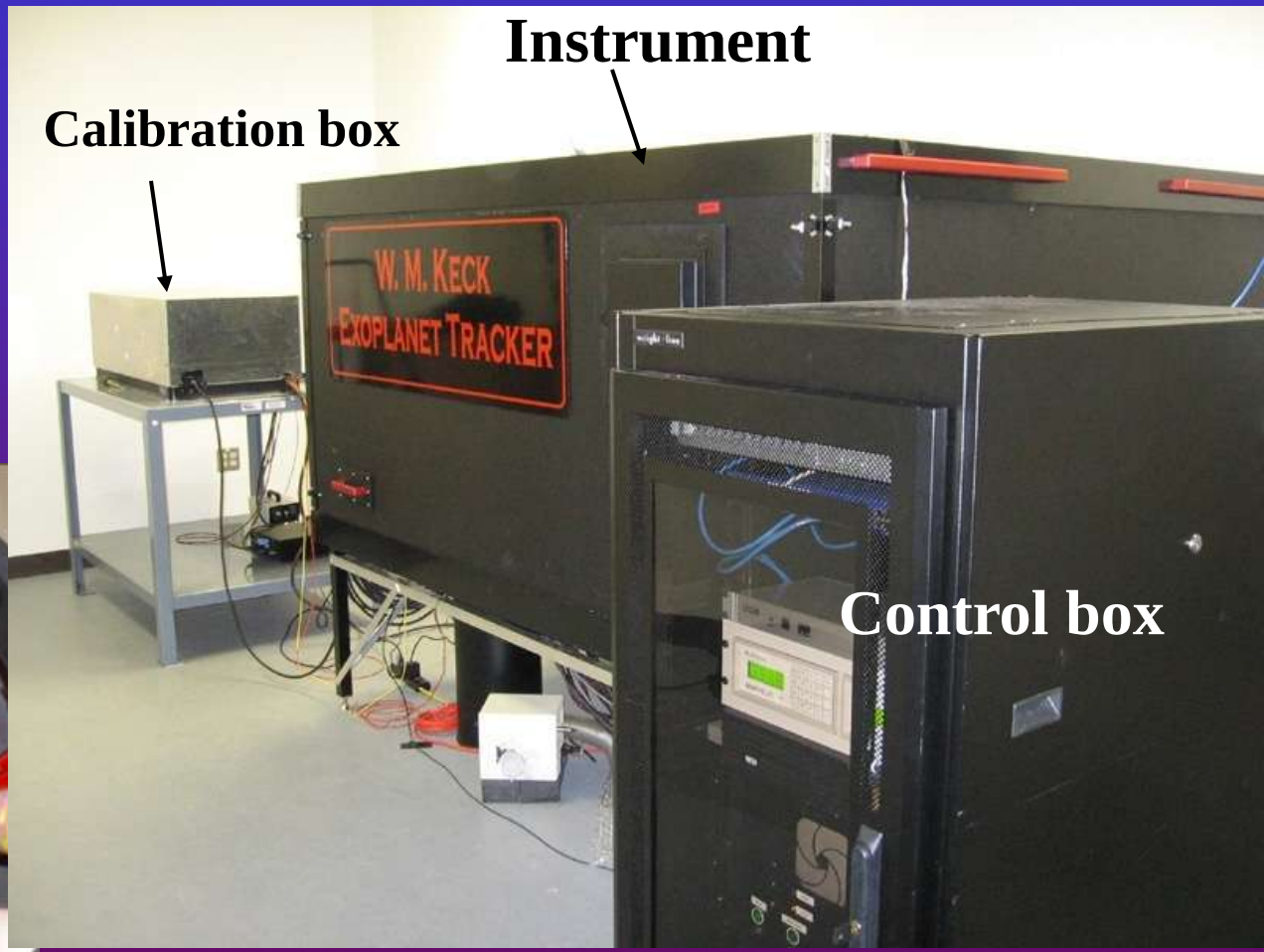
- ~30% of our sample between F8-G2, ~70% are later than G2

The Multi-object Optical Doppler instrument at SDSS in Sept 08

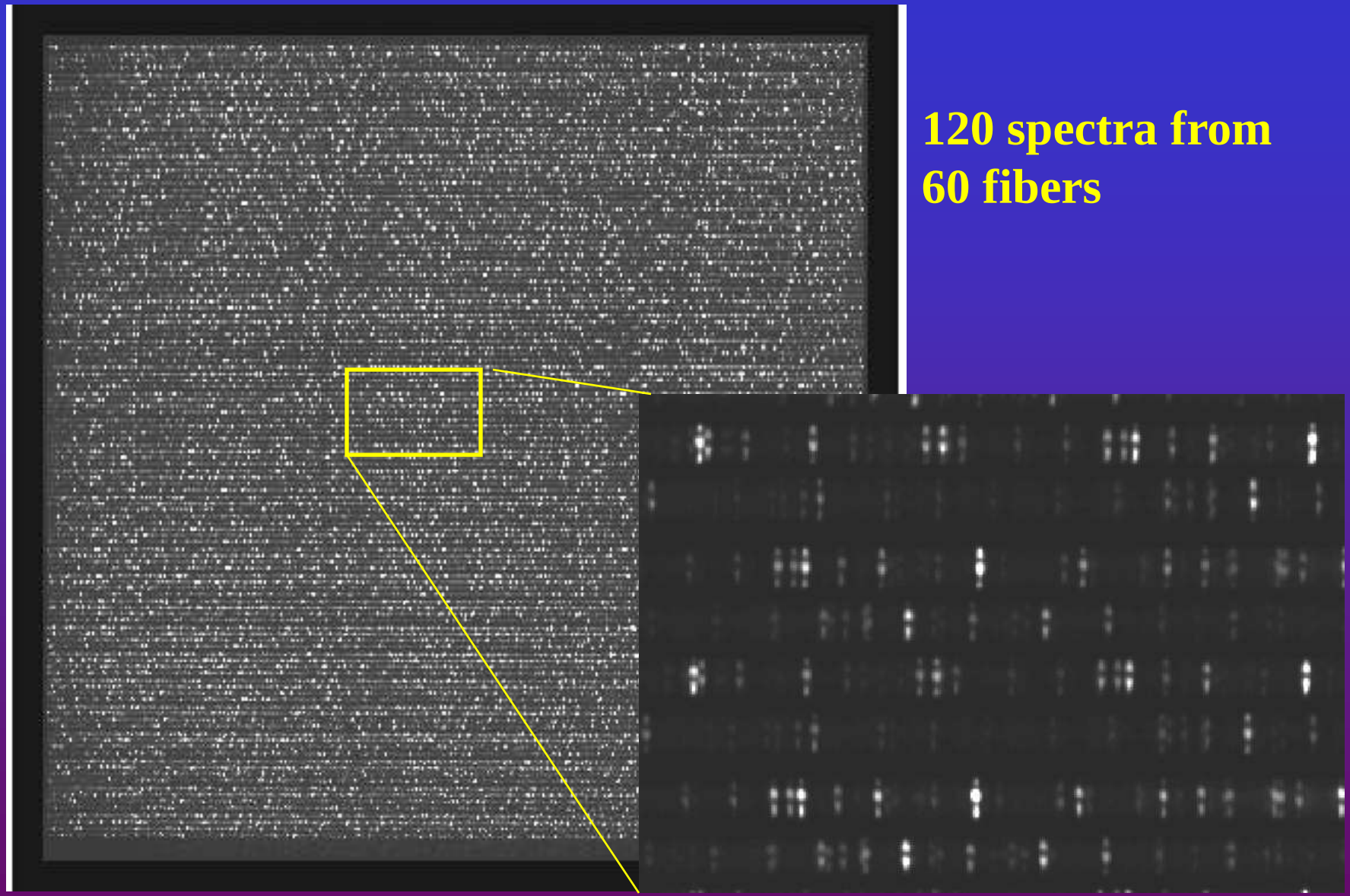
MARVELS Plugging Plate

MARVELS Fibers

MARVELS-I inside an air condition room



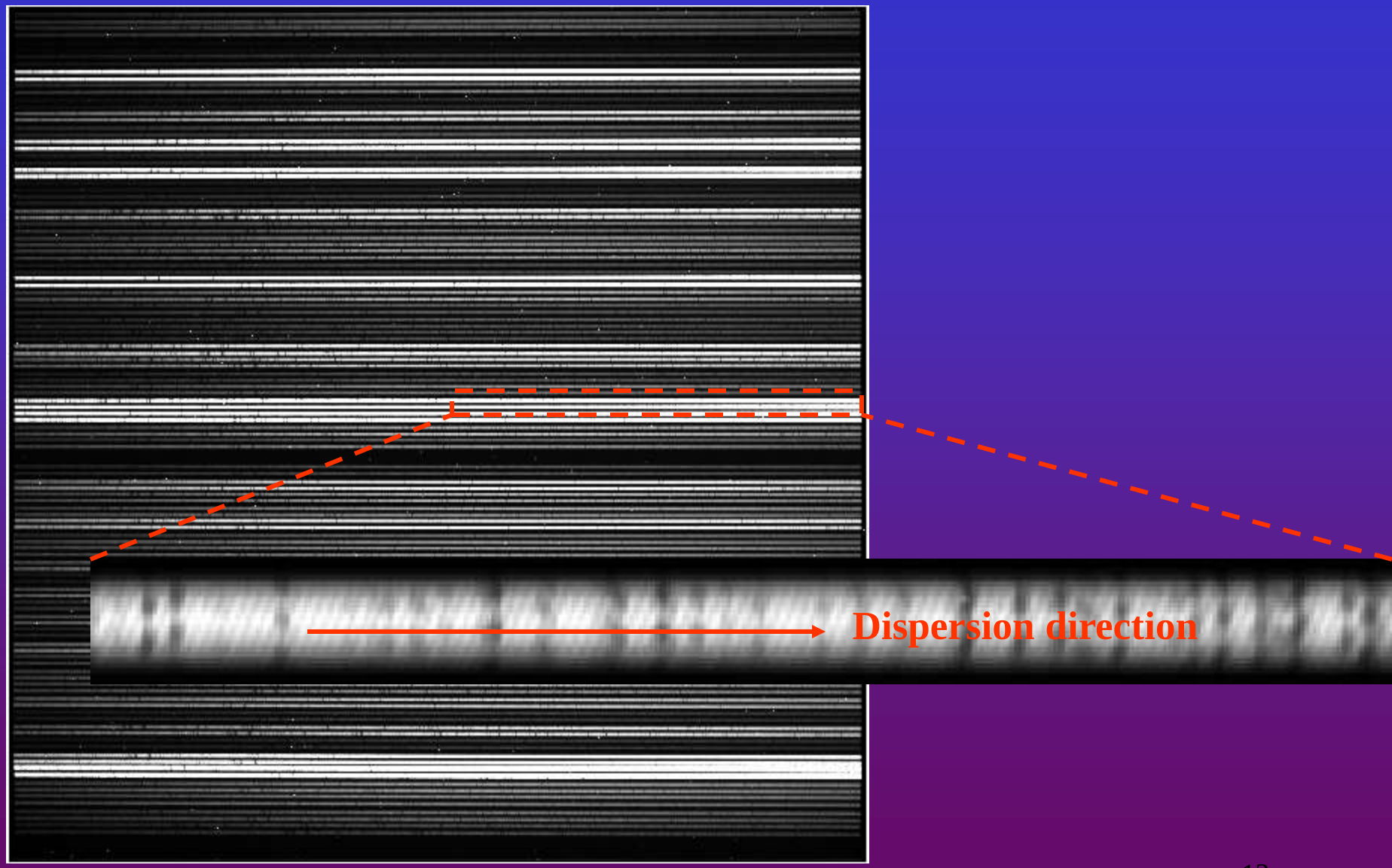
A full frame of a ThAr spectrum with MARVELS instrument



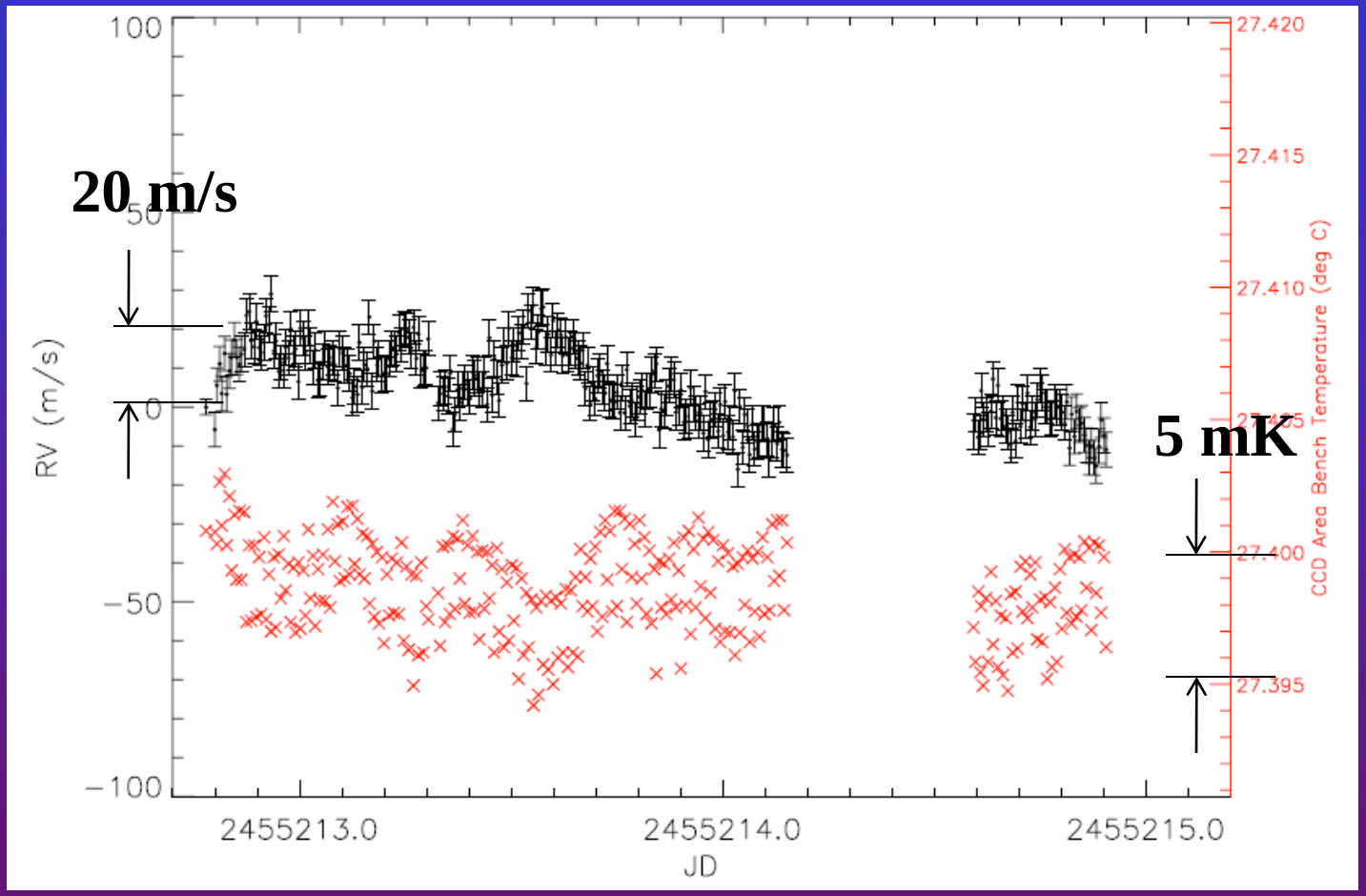
120 spectra from 60 fibers

A total of 120 ThAr spectra occupy middle 4000x4096 pixels of the 4kx4k CCD

A full frame of 120 stellar fringing spectra from the HAT-P-1 field in 40 min with MARVELS instrument

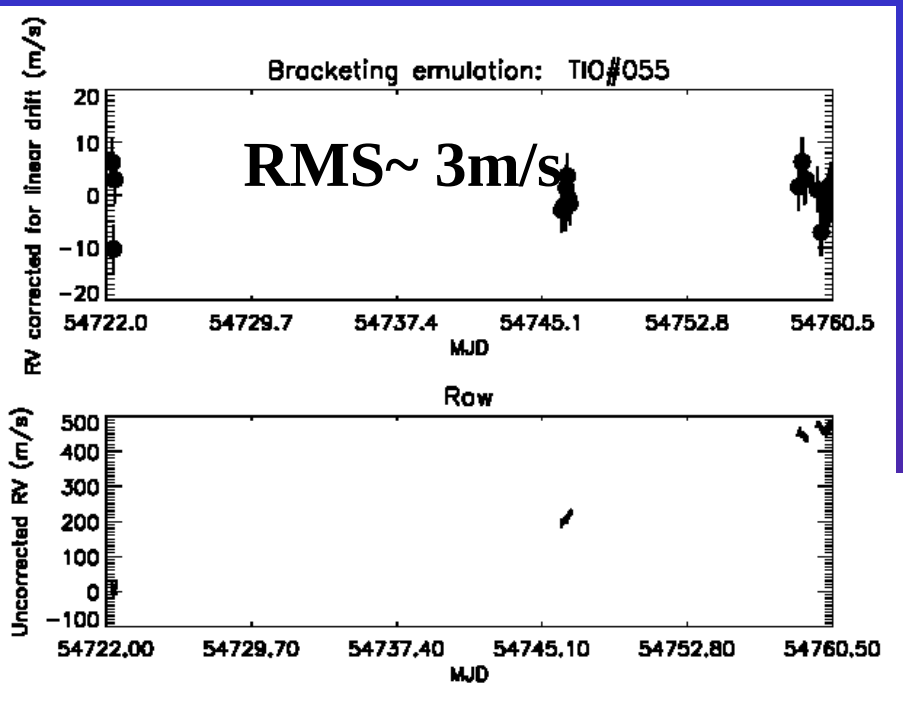


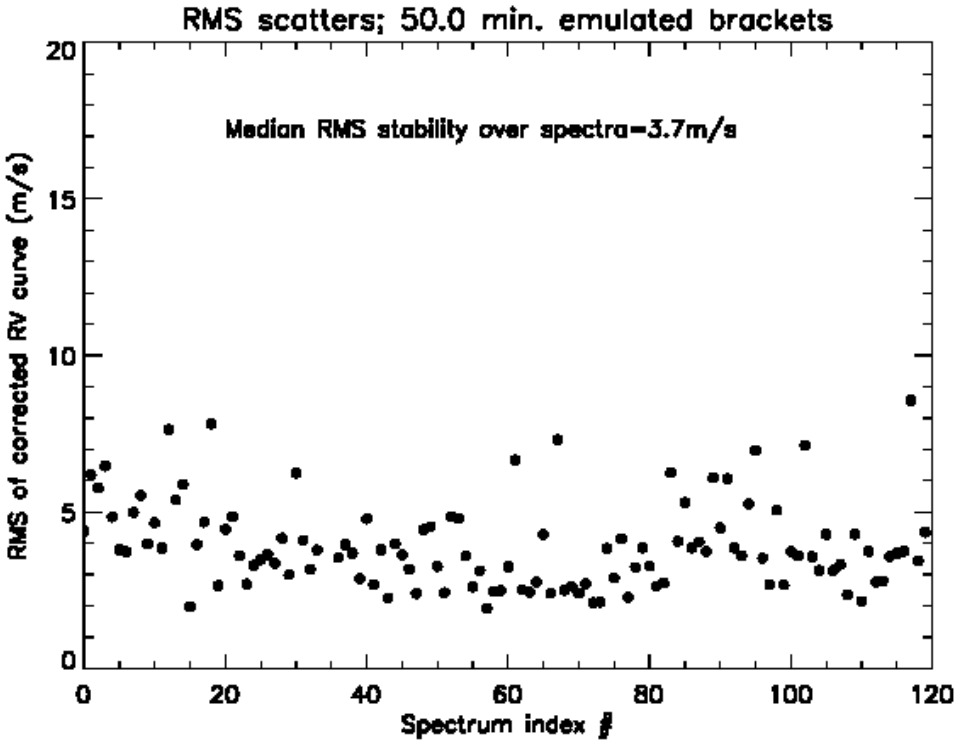
MARVELS RV drift



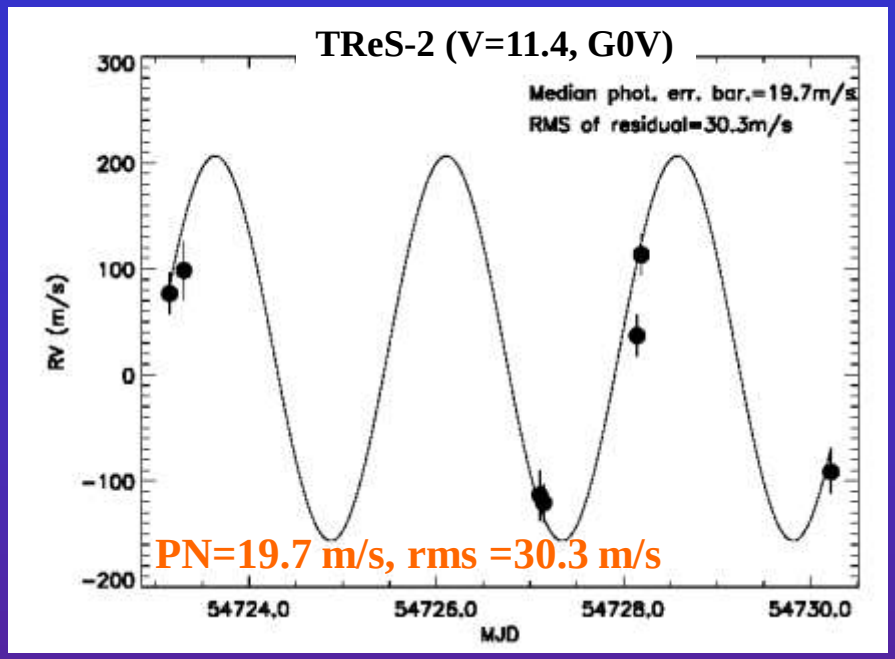
- **RV drift is about 20 m/s over ~3 days**
- **Temperature change is about 5 mK over ~3days.**

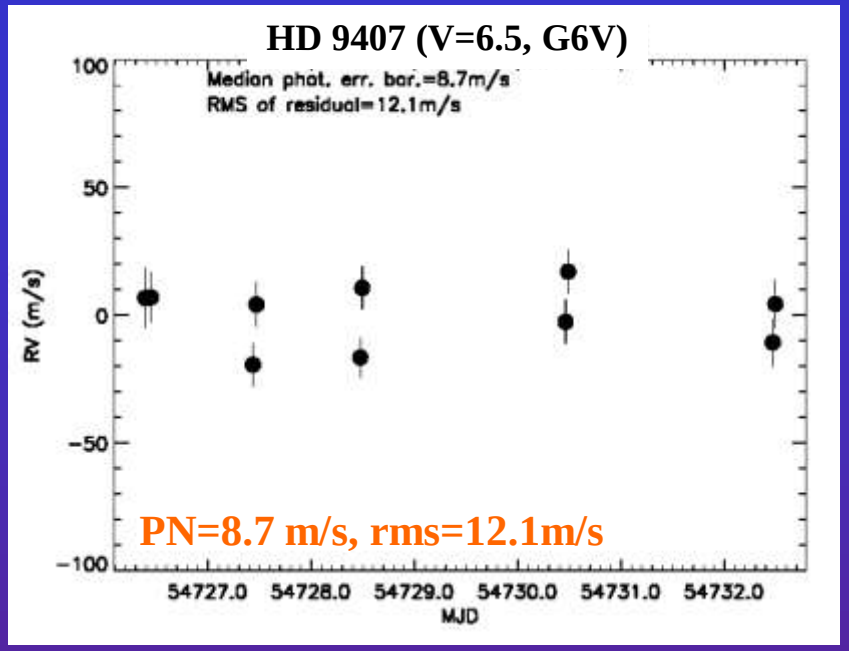
Doppler Measurement Precision over 40 days

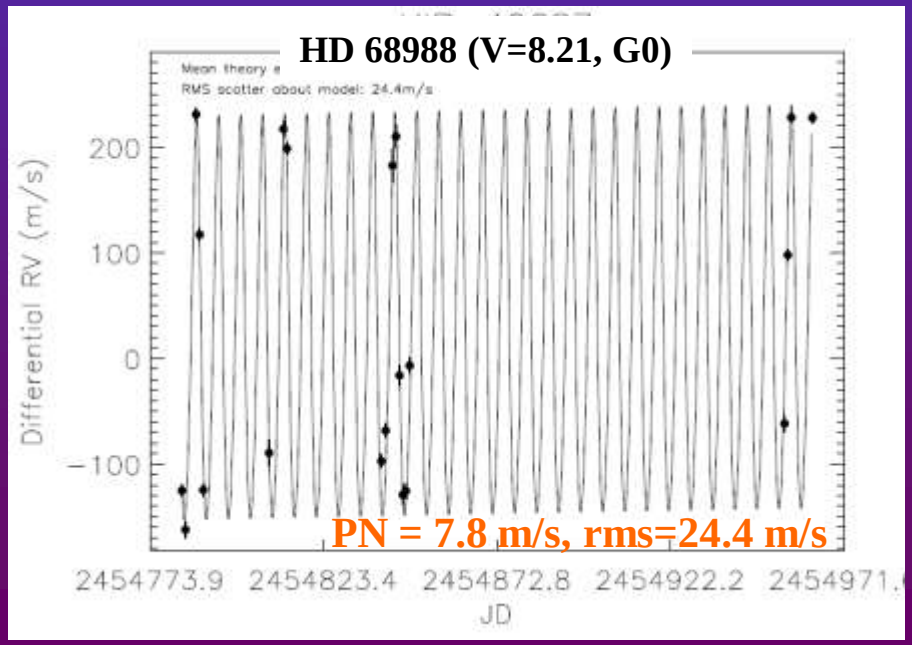


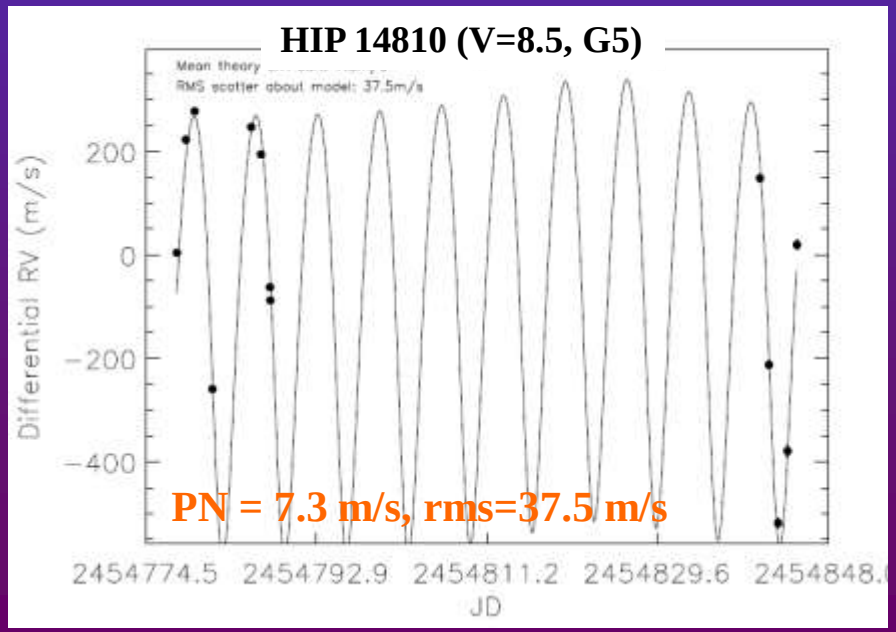


Results for Some Reference Stars



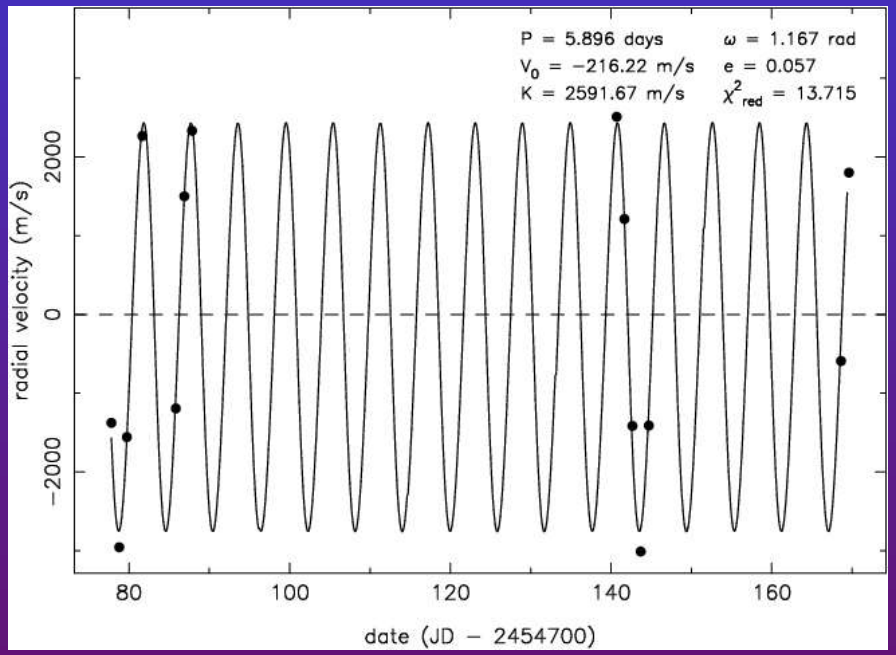






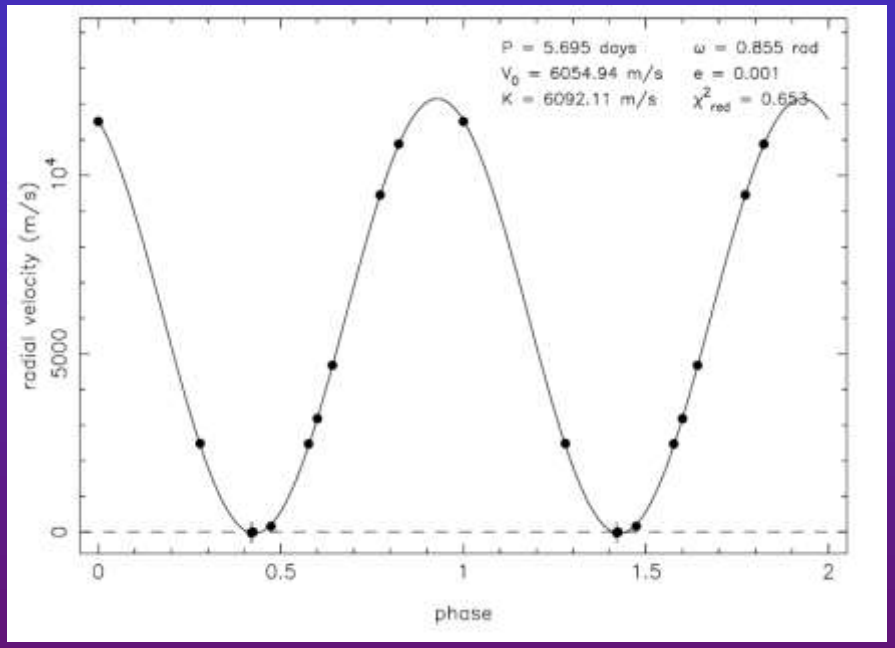
Discoveries of Two Brown Dwarfs by MARVELS

A new brown dwarf with 28 Jupiter masses and 5.9 day period, TYC 1240



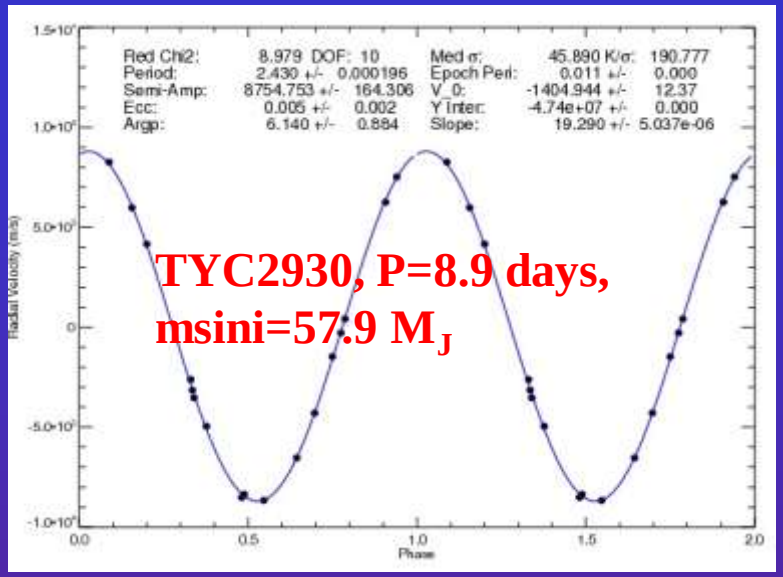
Lee et al. 2010, ApJ submitted

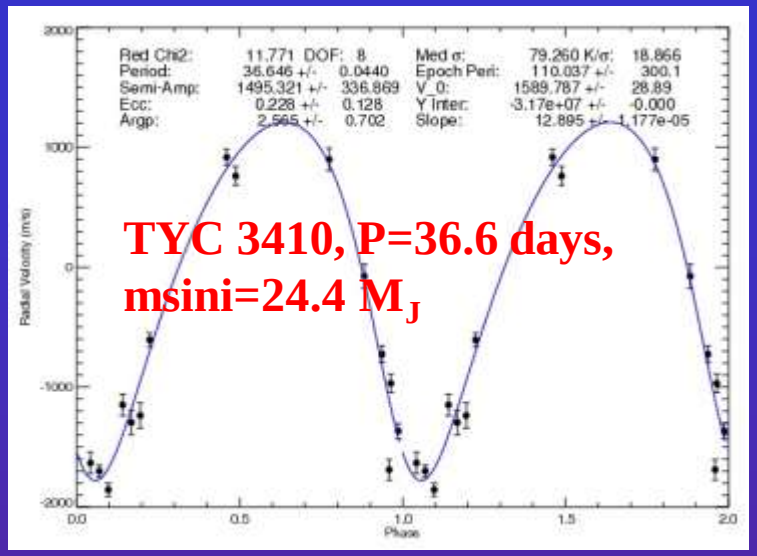
A new brown dwarf with 58 Jupiter masses and 5.8day period, TYC

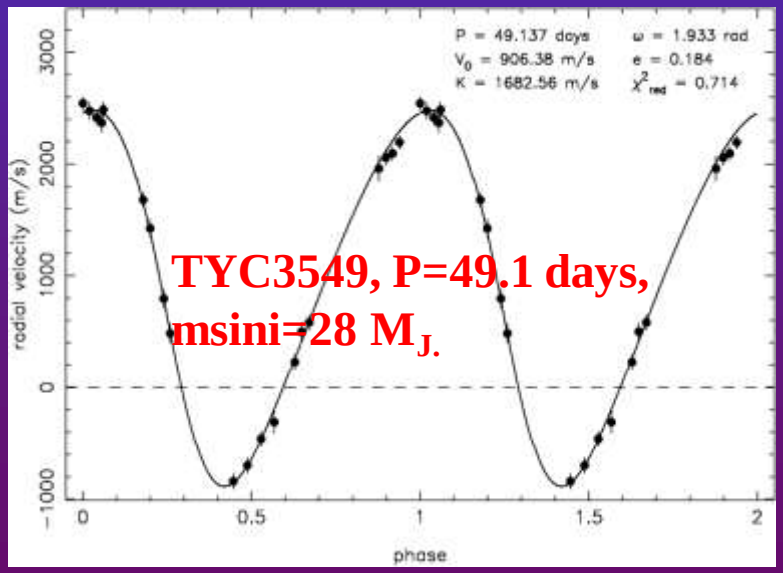


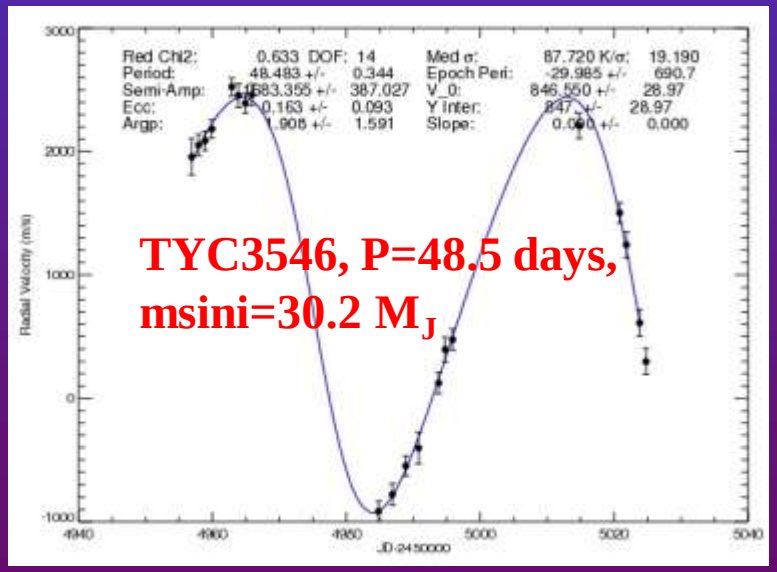
Fleming et al. 2010, ApJ in press

New Brown Dwarfs by MARVELS



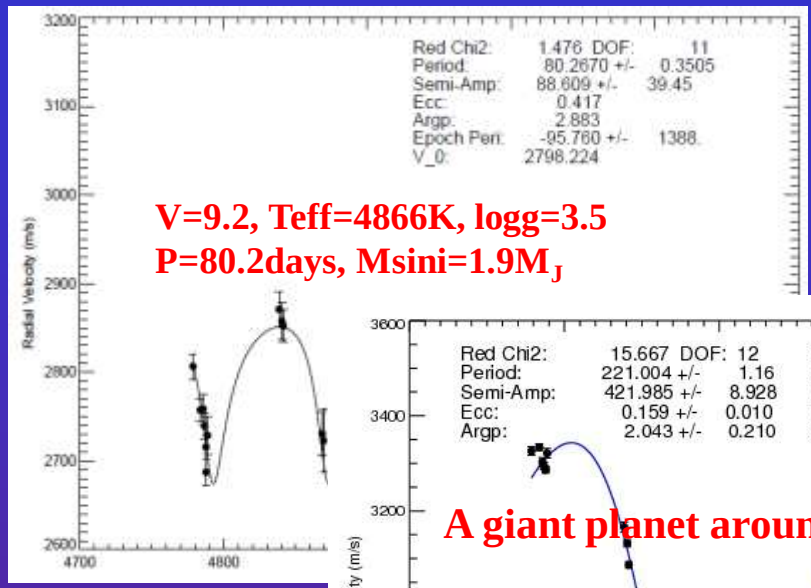




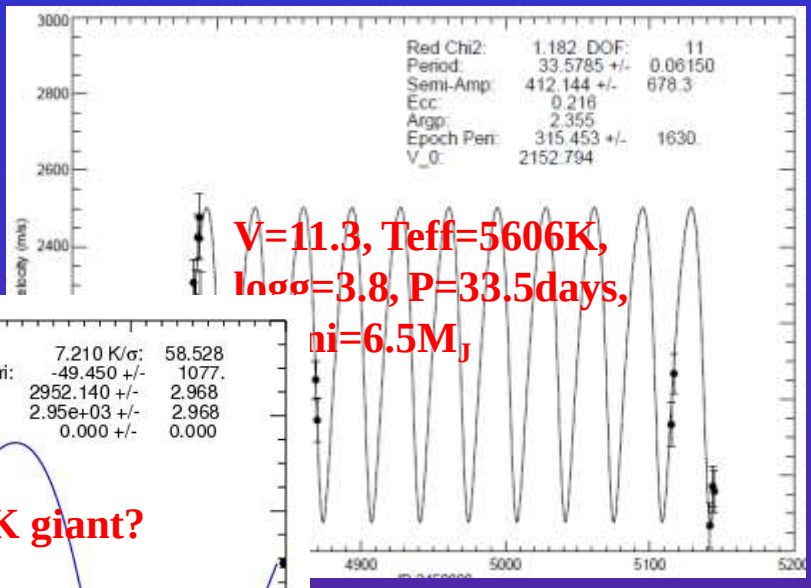


- **A total of 8 new brown dwarfs detected by MARVELS, addressing dryness of brown dwarf desert**

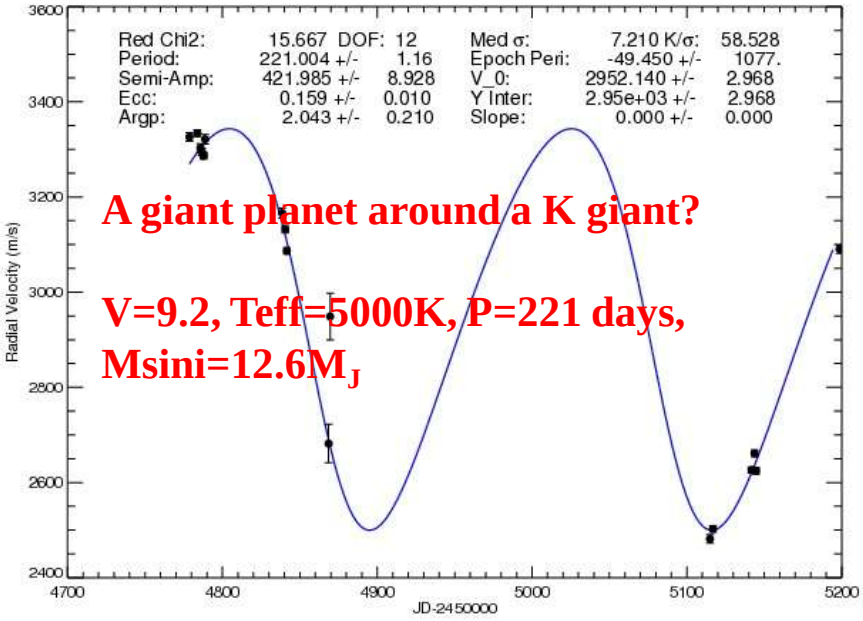
Planet Candidates by MARVELS



V=9.2, Teff=4866K, logg=3.5
P=80.2days, Msini=1.9M_J

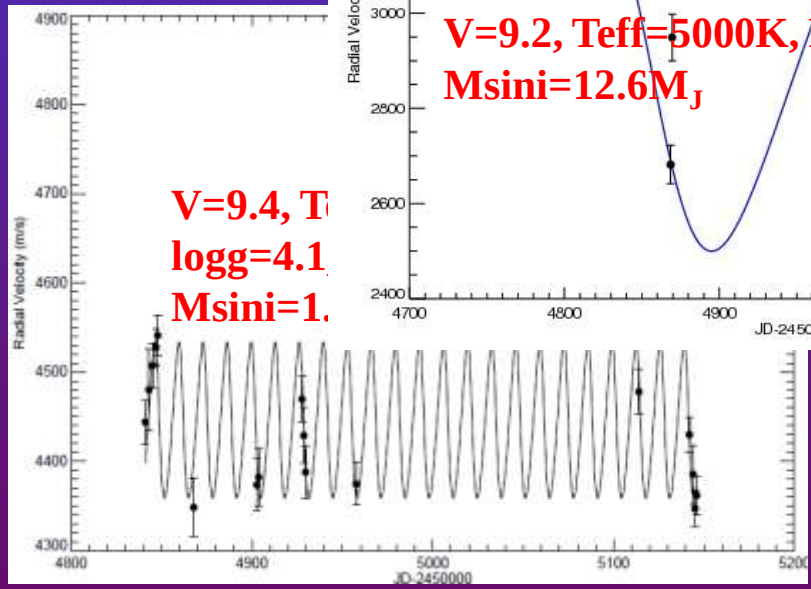


V=11.3, Teff=5606K,
logg=3.8, P=33.5days,
Msini=6.5M_J

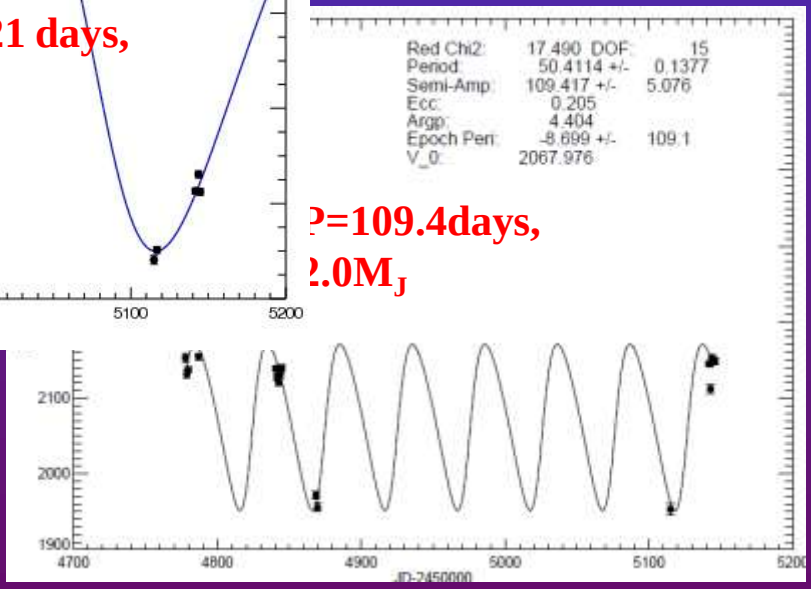


A giant planet around a K giant?

V=9.2, Teff=5000K, P=221 days,
Msini=12.6M_J



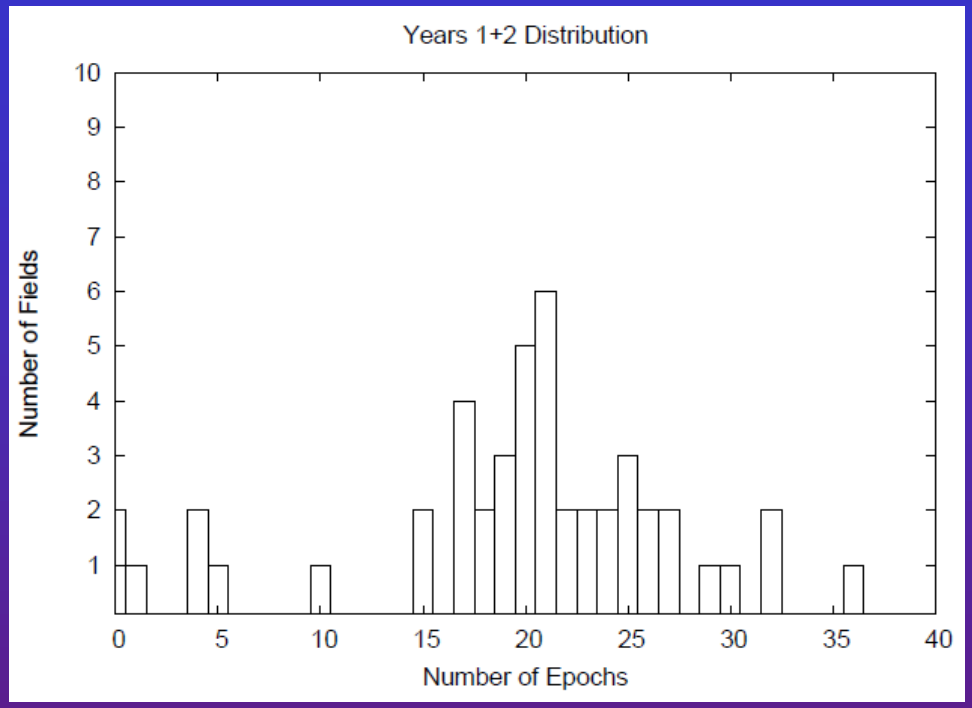
V=9.4, T
logg=4.1
Msini=1.



P=109.4days,
2.0M_J

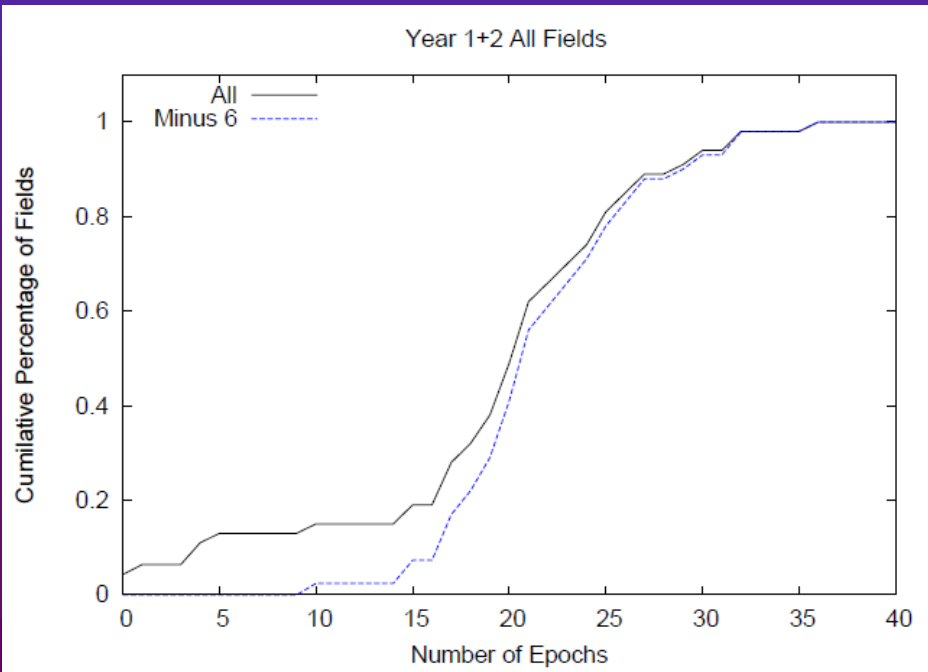
- Over 10 planet candidates being followed up for confirmation and characterization
- Pipeline requires fine tuning, long term RMS ~ 2-8 times photon errors

First Two Year Survey Summary

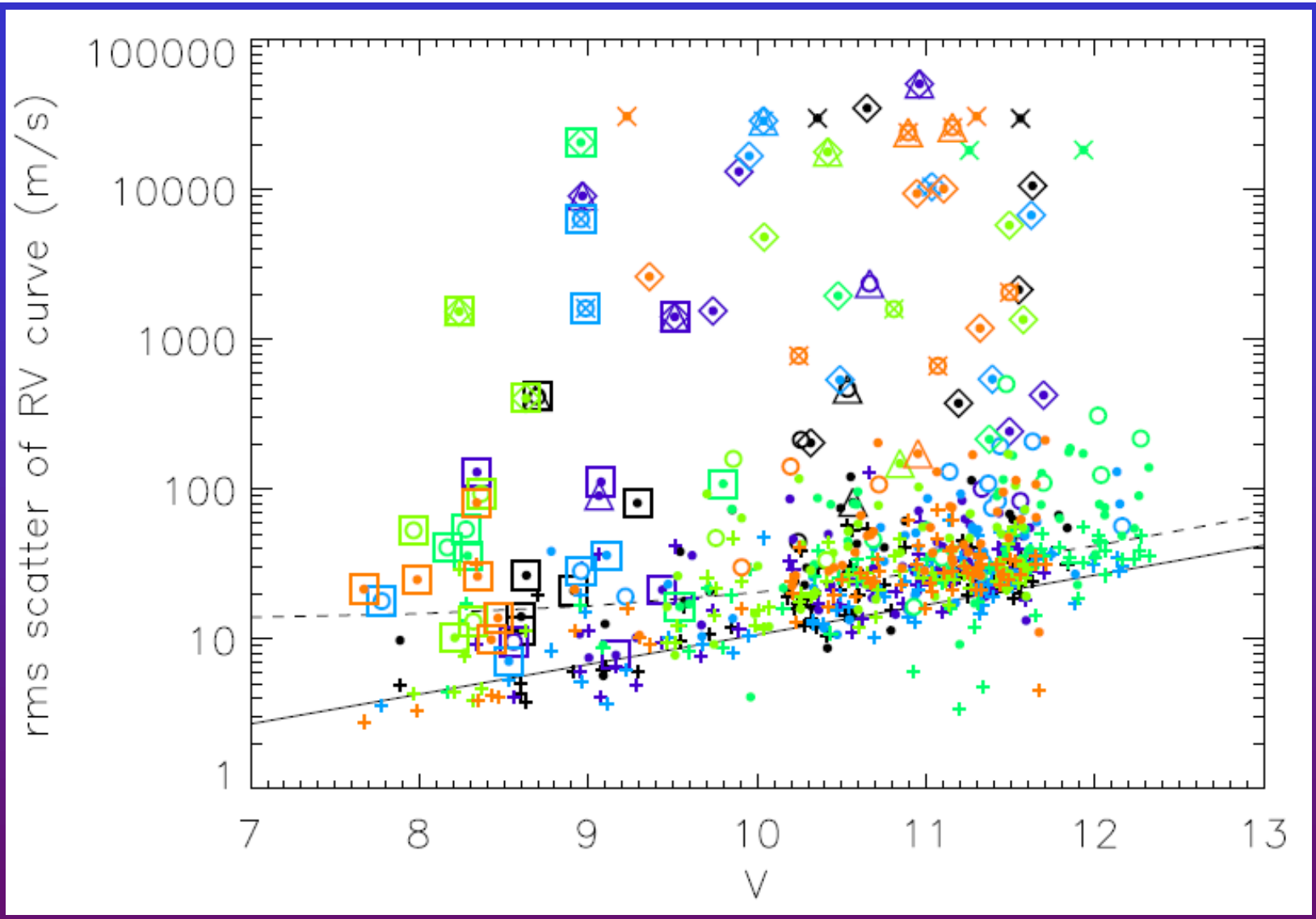


- **Number of Survey Observations: 917**
- **Number of fields Observed: 47**

Total Number of stars: 2820



RV uncertainty as a function of V magnitude



• ~75% stars with rms errors within 1-2 photon limiting errors, ~25% with much large RMS due to short period binaries, giant stars, low visibility, outliers etc.

•Further refining of data pipeline to approach photon noise limiting performance.

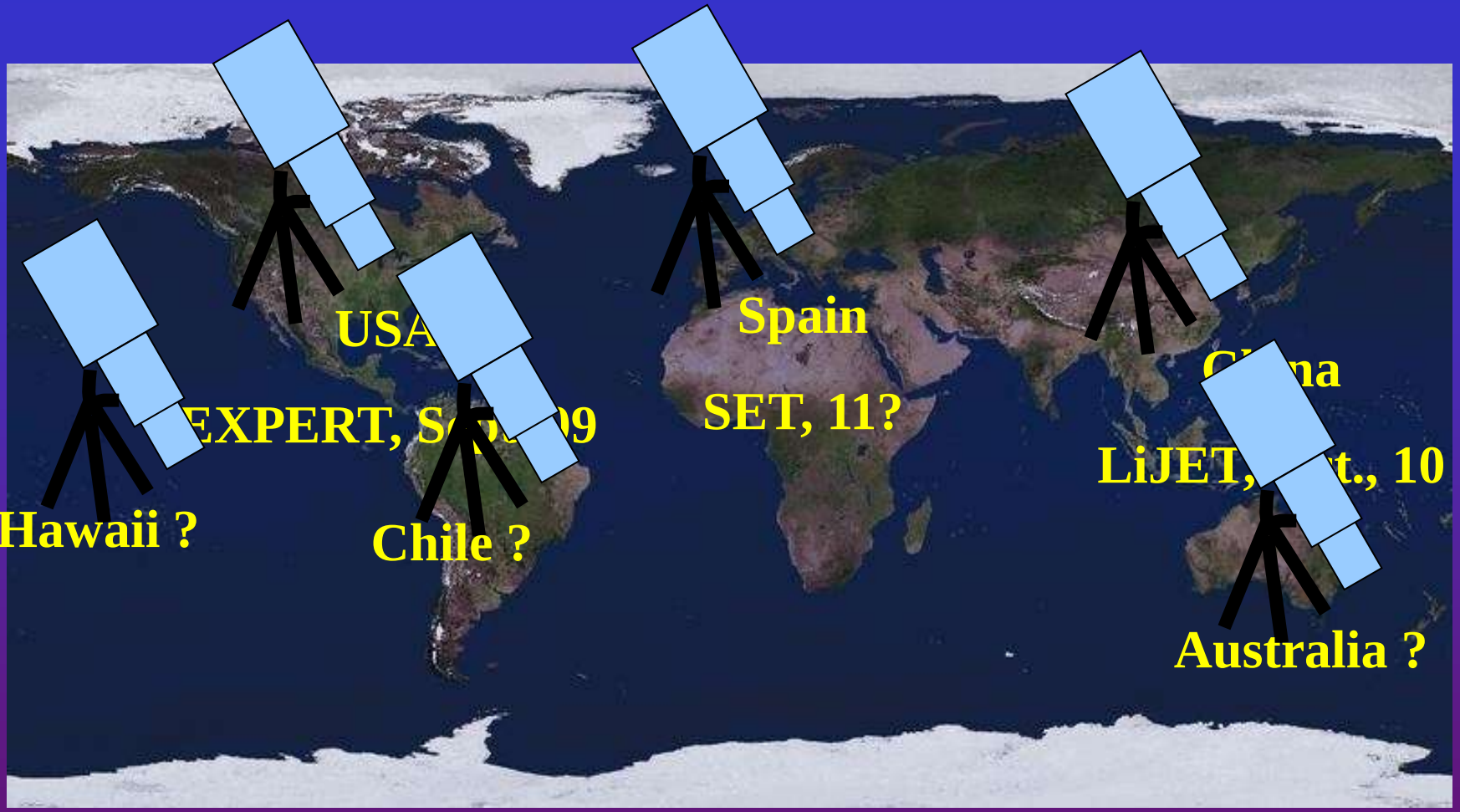
MARVELS Follow-up opportunities

- **High precision Doppler follow-ups to confirm planet detection and detect additional planets**

- **High precision Photometry for rejecting false positives and detecting transit planets**

- **High resolution optical spectroscopy for measuring the line bisectors to reject false positives caused by stellar activities and also determining stellar parameters**

Global Extremely High Precision Exoplanet Tracker Network

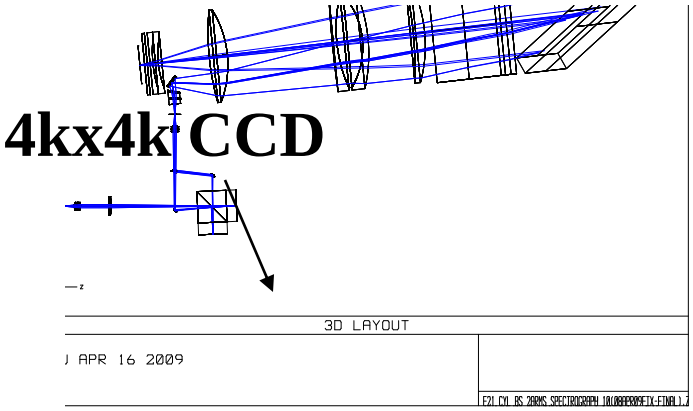


- Follow up planet candidates from SDSS-III MARVELS planet survey
- Offer continuous high precision radial velocity measurements for V<8 FGK stars with 0.5-1 m/s Doppler precision in 15-30 min
- Compact and low cost design (~$750K per instrument including hardware and labor)

Drives for the Global Doppler Network

- **Take advantage of many available 2 meter telescopes for long term surveys**
- **Target bright F,G,K dwarfs (V<8) with slow rotation for detection of super Earth mass planets, including habitable ones**
- **Integrate at least 15 min to minimize RV noises from stellar oscillations for low mass planet detection**
- **A nearly perfect match of ~15 min exposure time requirements and photon noise limit offered by a 2 meter telescope for 0.5-1 m/s**
- **For asteroseismology, only target V<5 stars and ~1 min exposures**

High Precision RV Mode



Prism

Echelle

Slit

Output 1

Collimator-camera

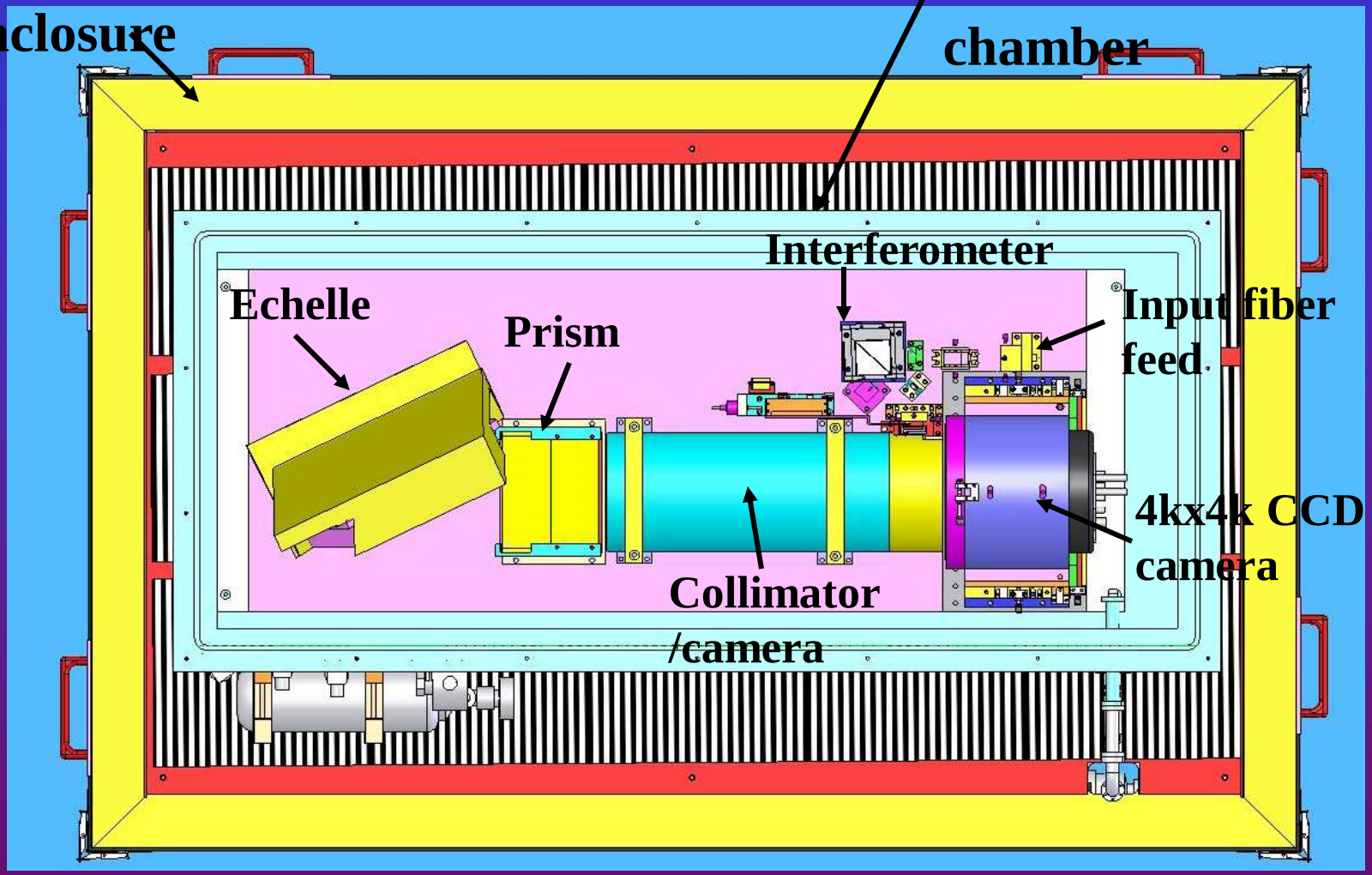
Output 2

Fiber input

Michelson Interferometer

- A combination of a fixed-delay interferometer with a high throughput cross-dispersed echelle spectrograph with R=18,000
- A simultaneous wavelength coverage of 0.39-0.70 μm
- 0.5-1 m/s in 15-30 min for V< 8 solar type stars with 2 m telescopes

Opt-mechanical Design of EXPERT



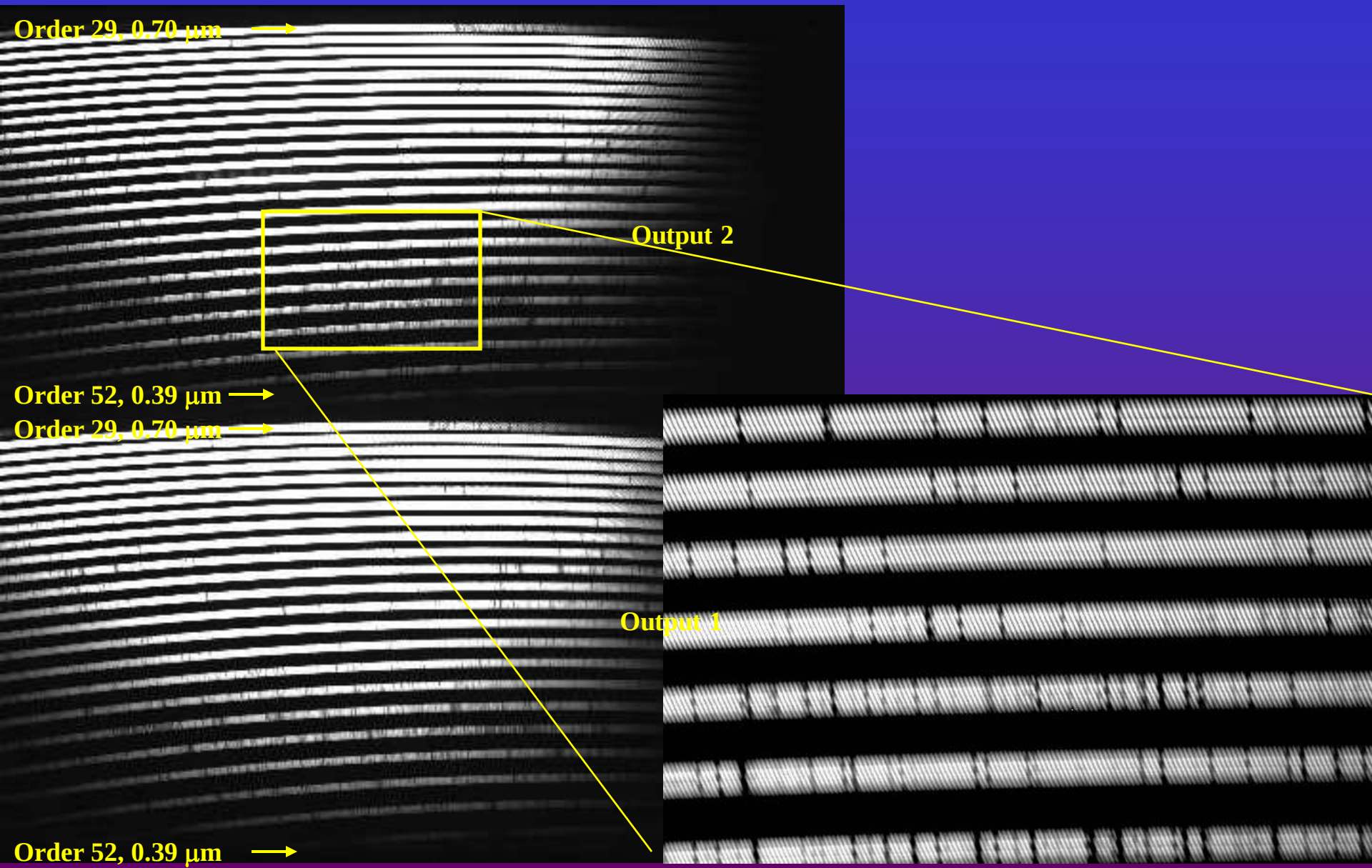
- The thermal enclosure dimension: 69" x 45" x 39.9".

EXPERT hardware setup at Kitt Peak 2.1m in October 2009

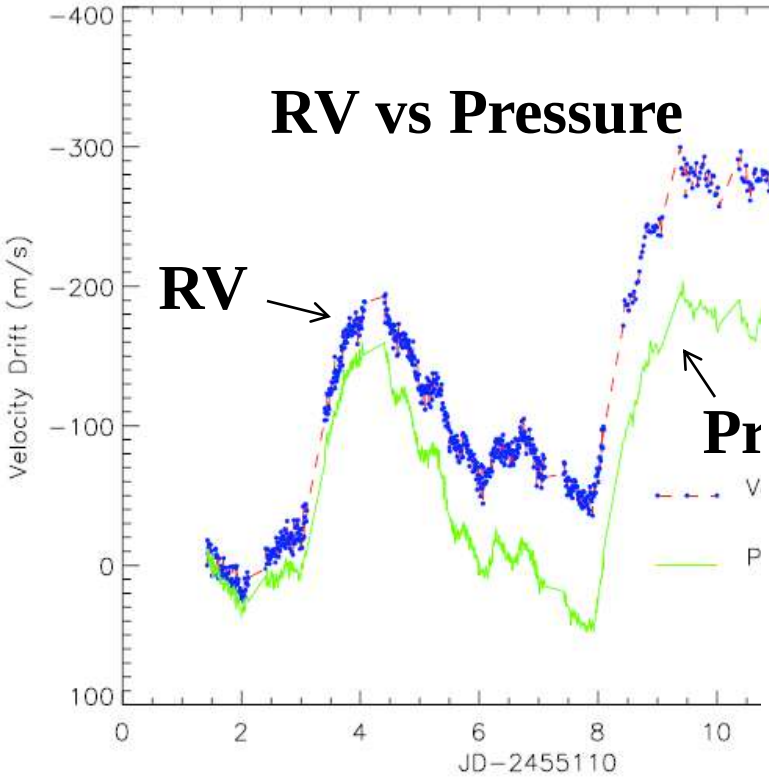
EXPERT inside a 2.1m Coude room

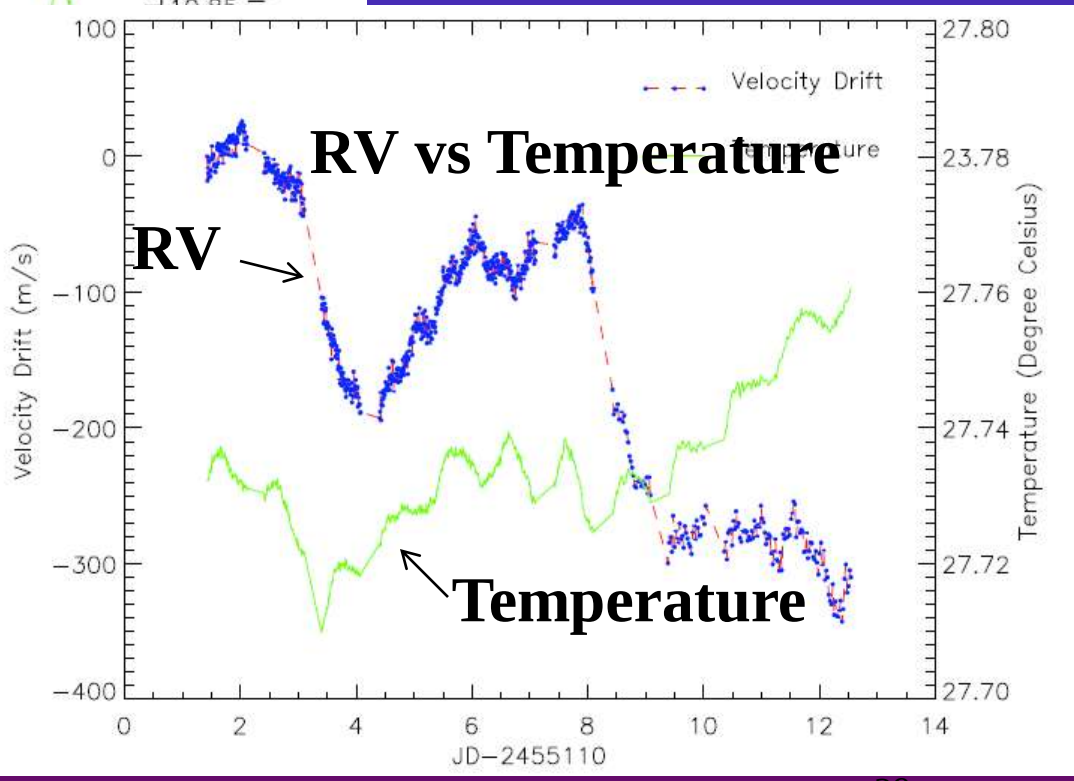
EXPERT control chassis

Solar Spectra on the Detector with EXPERT



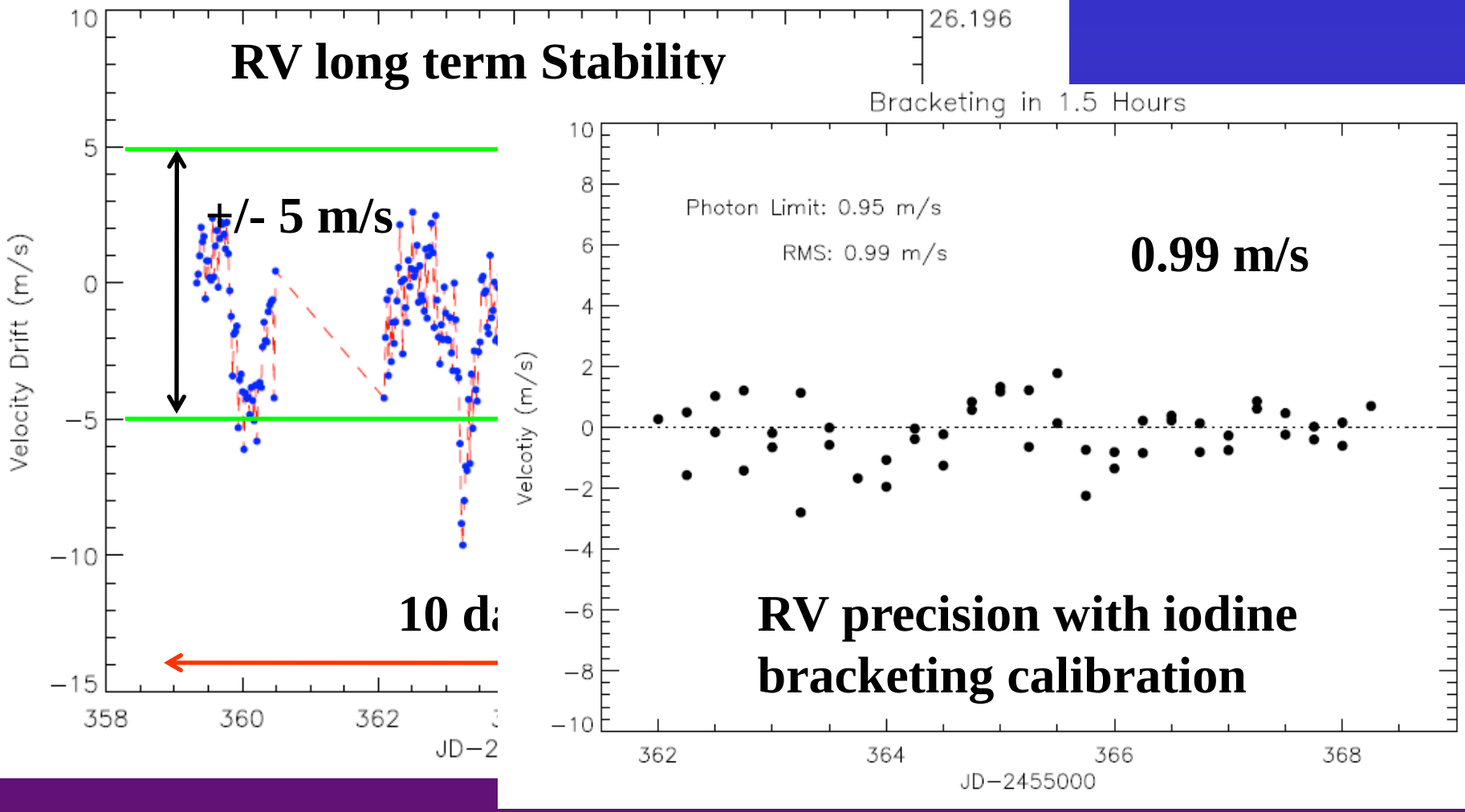
RV Drifts vs. Pressure and Temperature variation with EXPERT in Oct. 2009





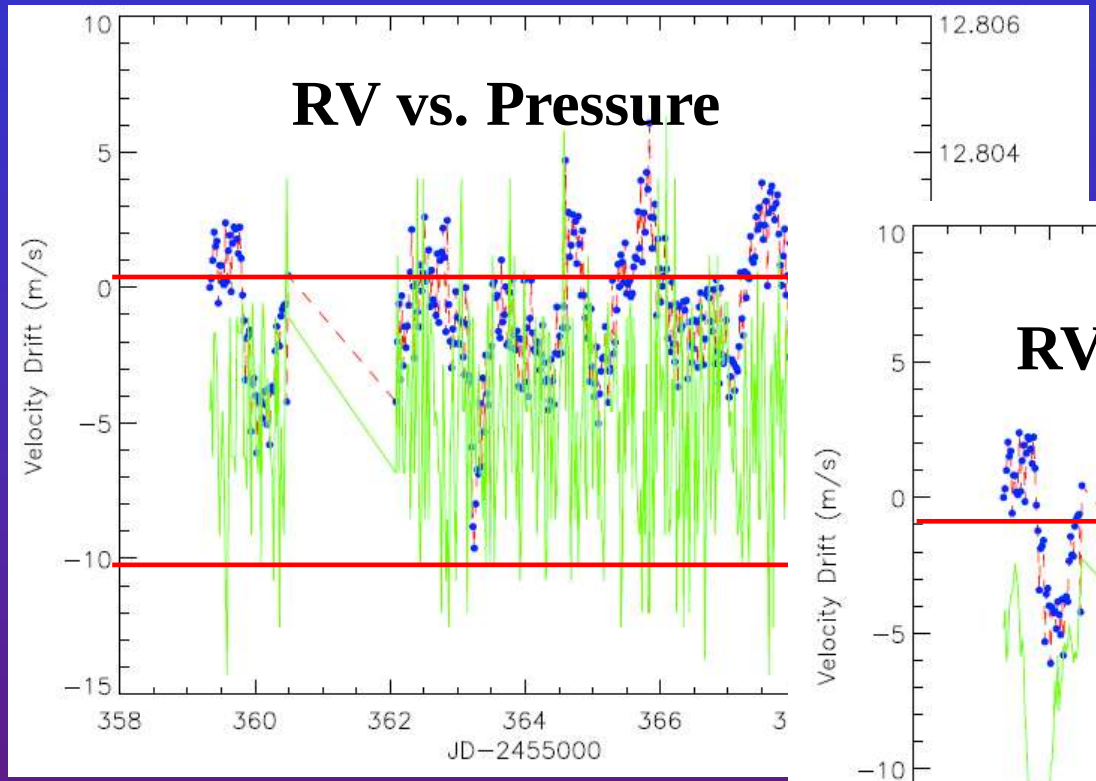
•Need to control pressure and temperature to reach higher RV stability

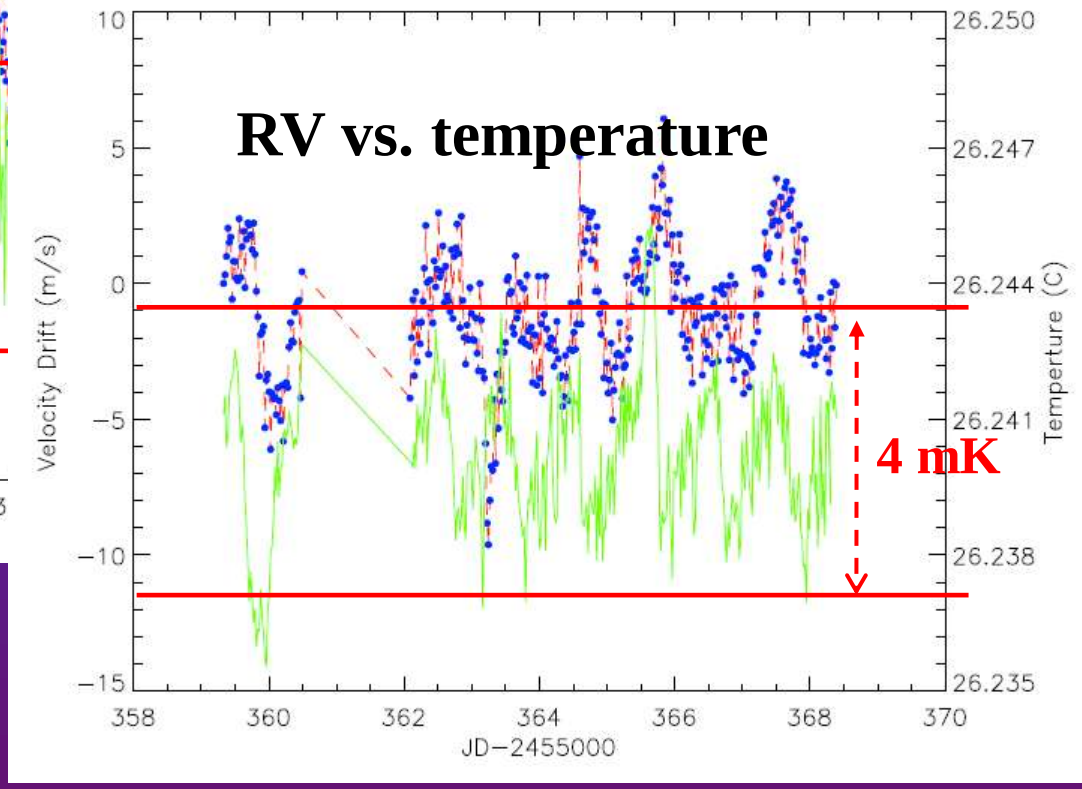
EXPERT Instrument RV Monitoring in Jun. 2010



- RV long term stability within +/- 5 m/s over 10 days
- RV shows diurnal variation
- RV precision after iodine calibration = 0.99 m/s, limited by narrow band (~100nm) and early version of the data pipeline

EXPERT Instrument RV Monitoring in Jun. 2010

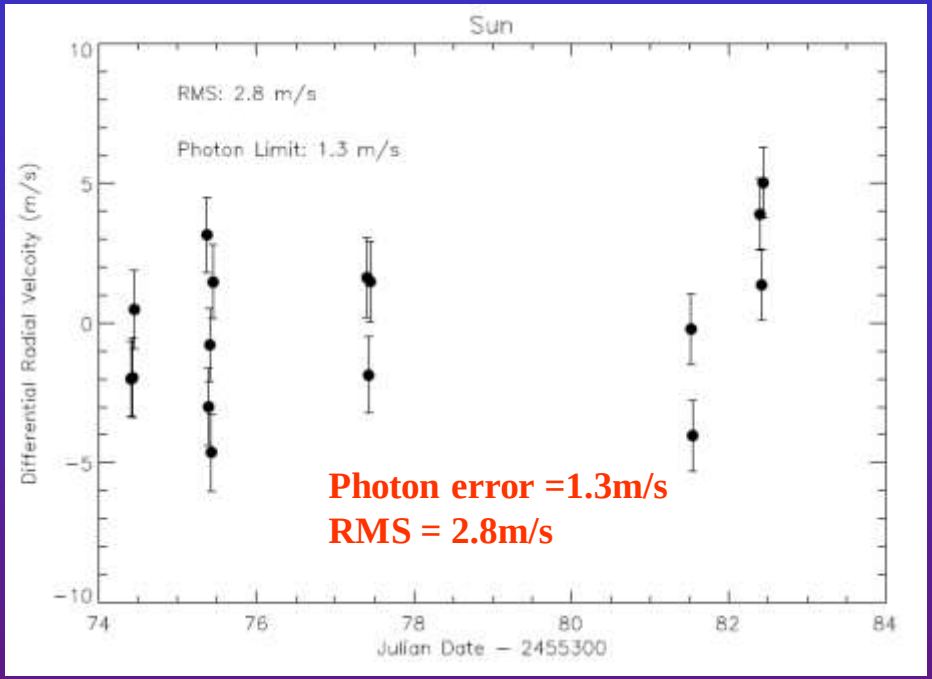




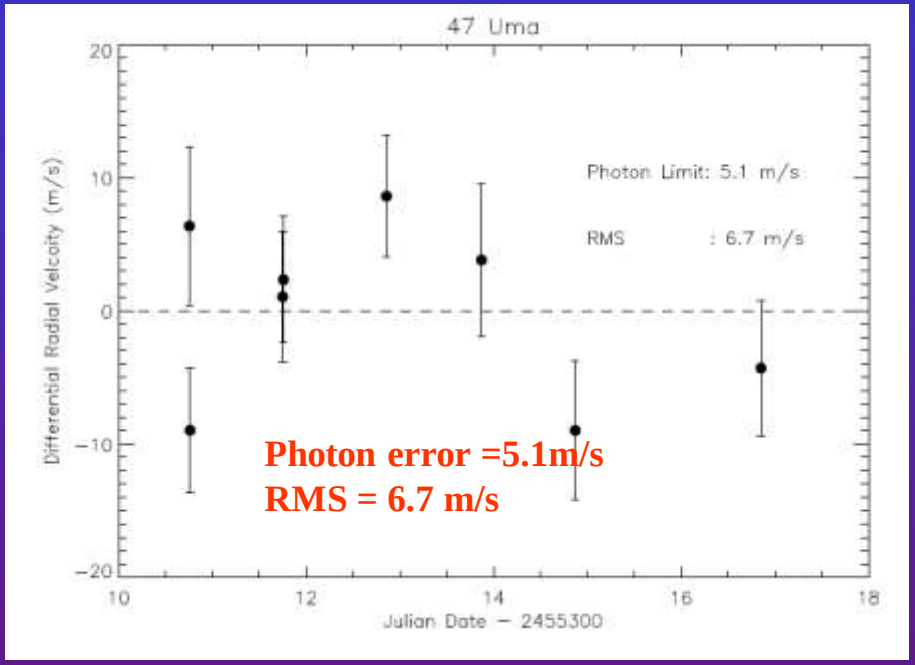
- RV diurnal variation is not correlated with pressure
- RV diurnal variation is strongly correlated with temperature variations → further improvement of the long term stability is possible by controlling the instrument diurnal temperature variation

Early RV Measurement Results with EXPERT

RV Measurements of Sky over 10 days



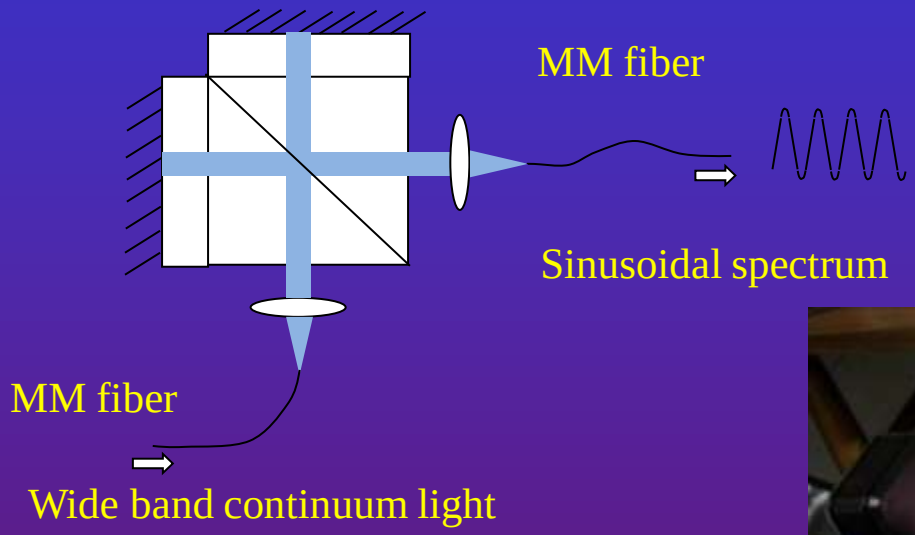
Observations with RV stable star, 47 UMa



- **Main challenge is to develop a data pipeline to process RV measurements over a broad wavelength**
- **RV calibration requires new data pipeline with ThAr emission spectra**

A Very Stable Fixed-delay Interferometer for RV Calibration

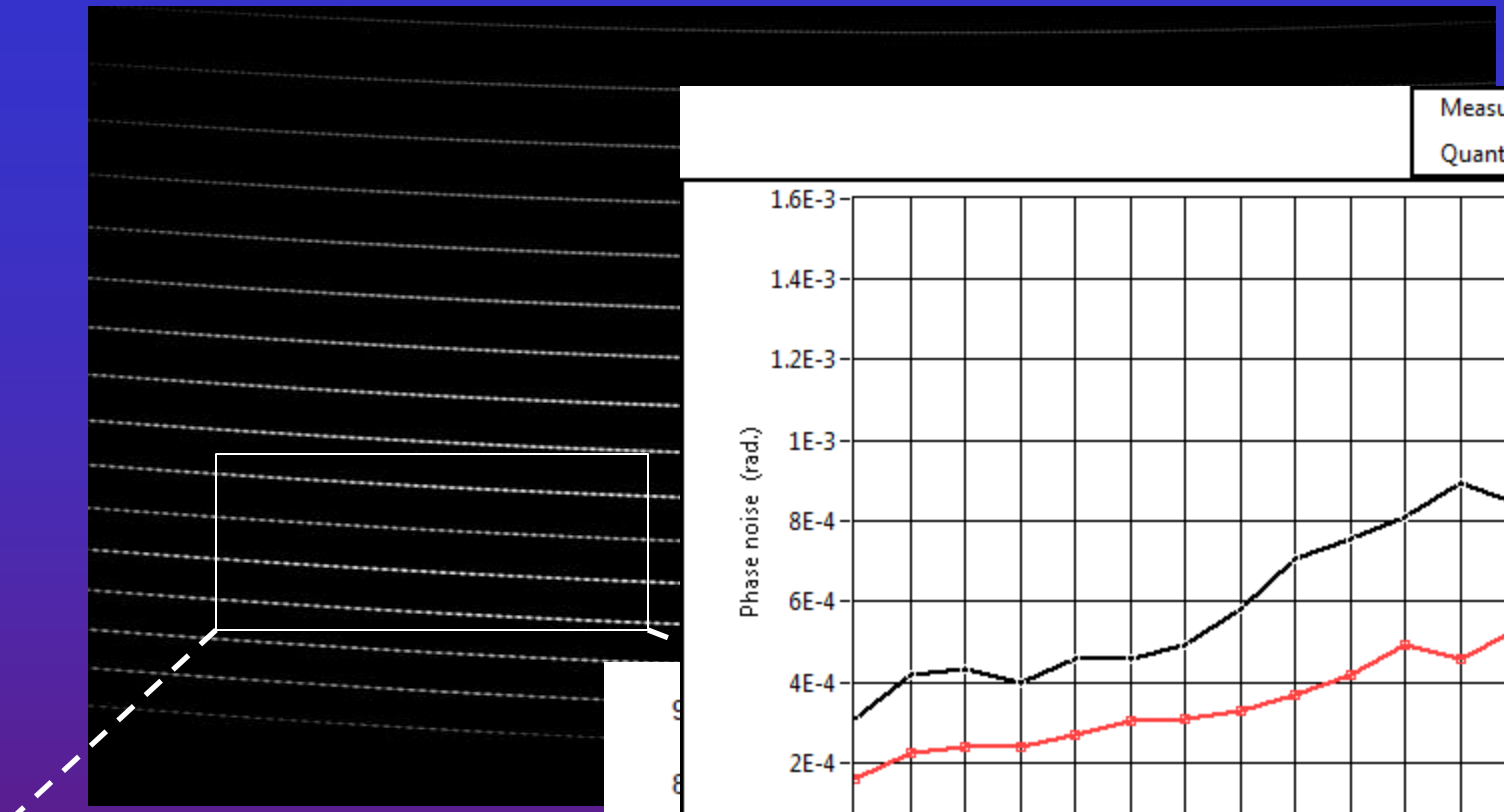
The integration of interferometer and multimode fiber coupling



Lab prototype testing in 2010

- Produce combs over very broad wavelengths in optical and IR
- Offer ~0.1 m/s calibration accuracy with contemporary temperature control (<10mK) (Wan & Ge 2010)
- Very compact, moderate cost and easy to implement and maintain

Comb Spectra Obtained with EXPERT Direct Echelle Mode

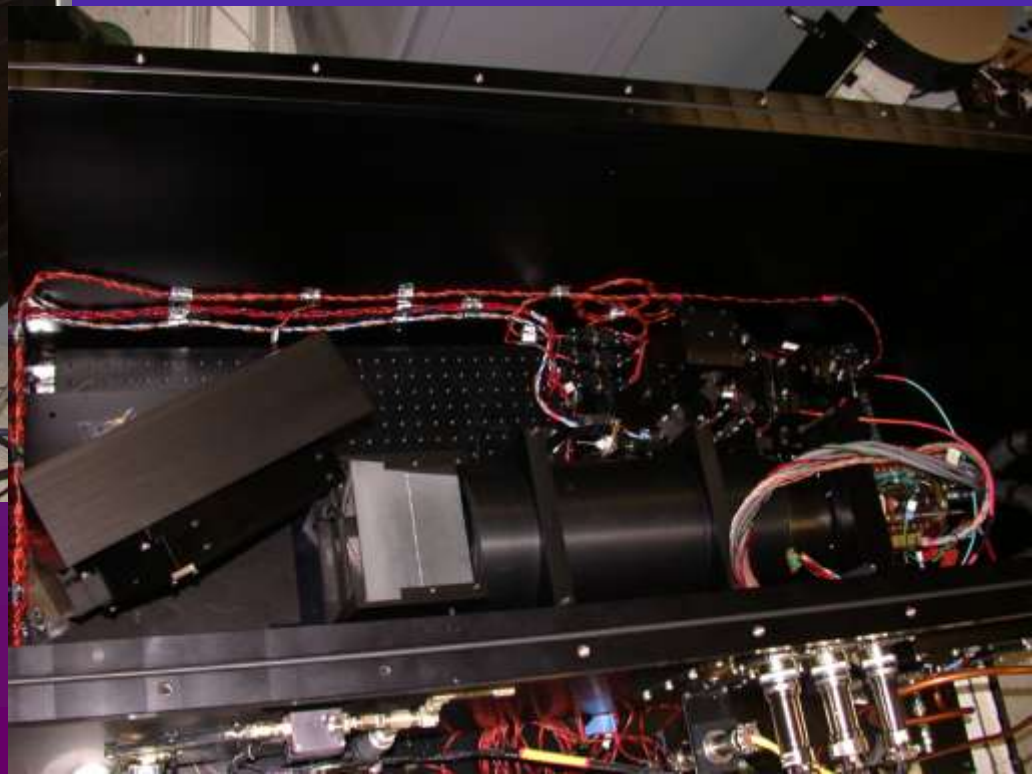


- **Early demonstration shows ~0.5 m/s with 17 cross-dispersed order spectra**

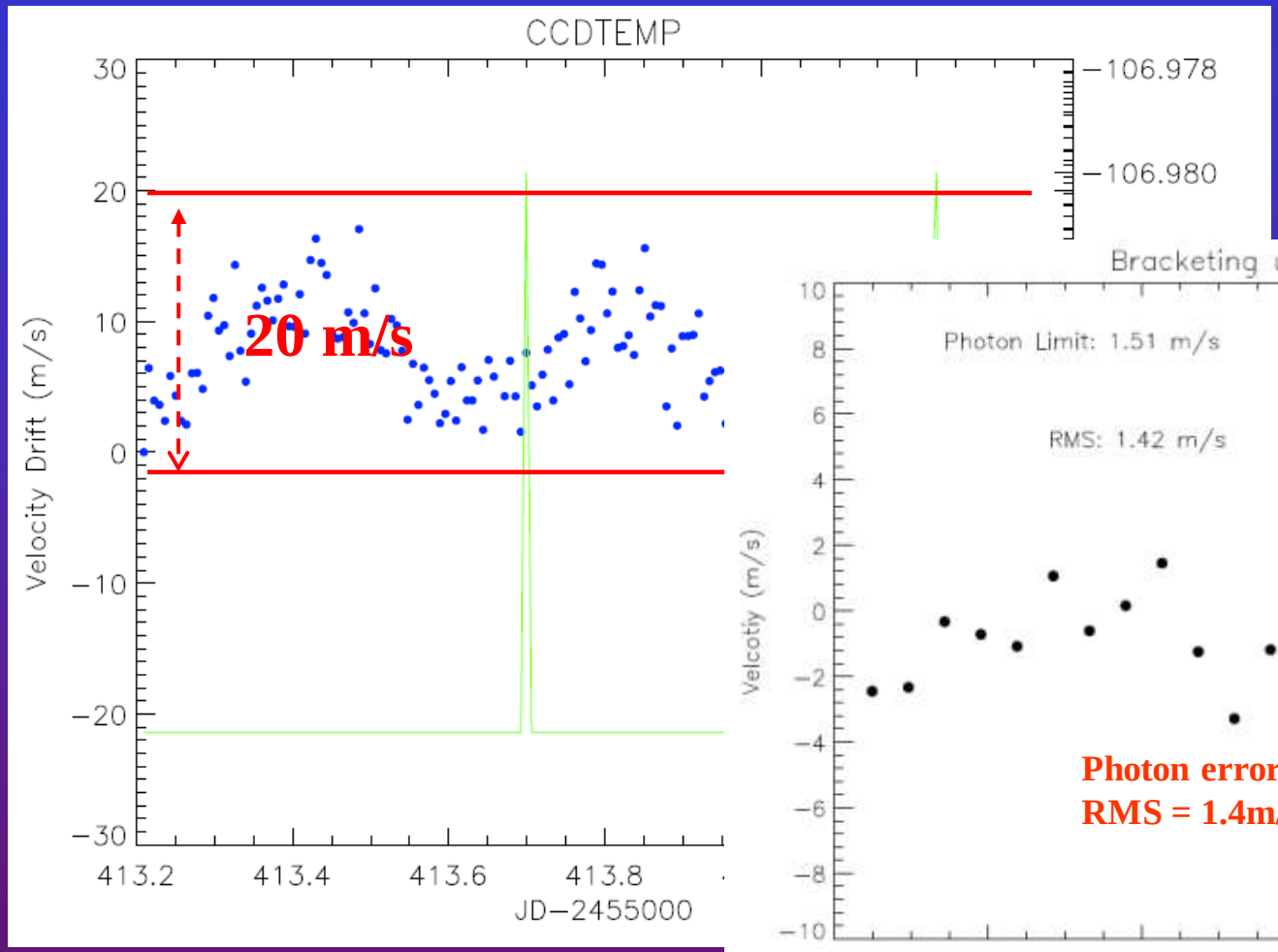
LiJET hardware setup at the UF lab in Jan. 2010

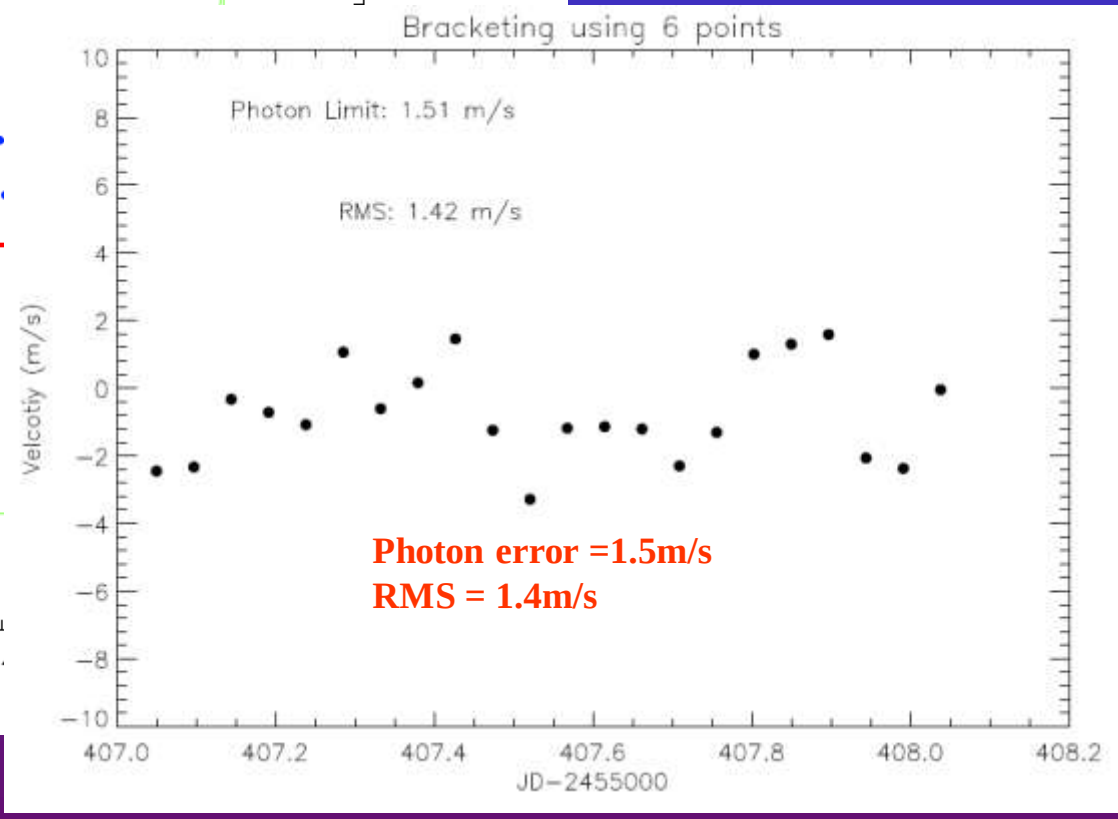
LiJET setup in the UF lab

LiJET in the UF Lab



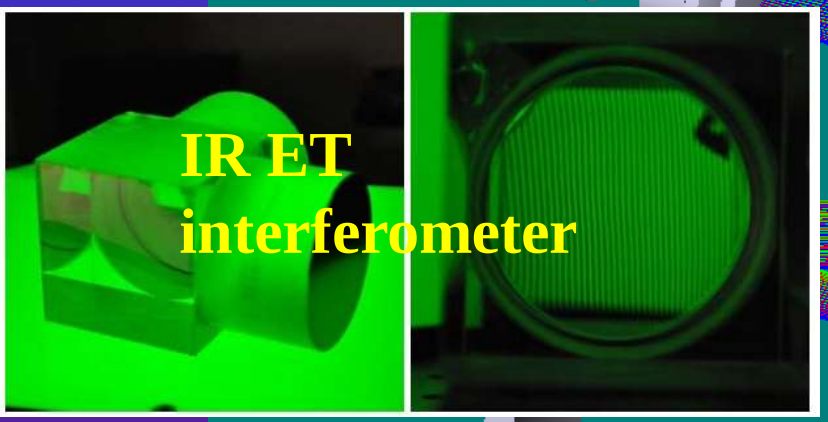
LiJET Instrument Acceptance Test in Aug. 2010





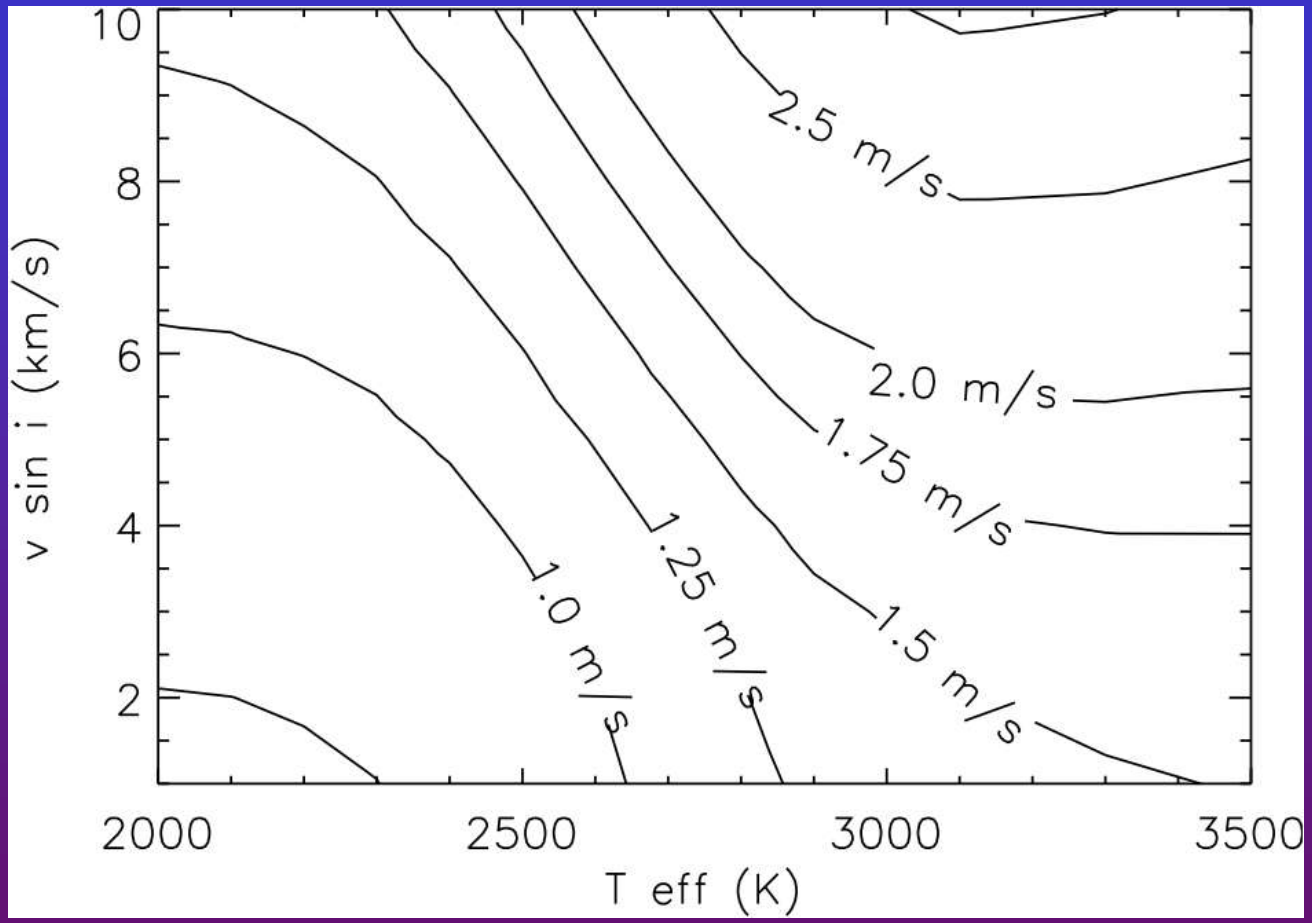
- RV quite stable, but the RMS still relatively large ~1.5 m/s
- Further improvement in RV stability and precision before commissioning in Oct. 2010

Infrared Exoplanet Tracker (IRET) and Florida IR Silicon immersion grating spectromeTer (FIRST)



- IRET with R=22,000, 0.8-1.35 μm in a single exposure; FIRST with R=55,000, 1.4-1.8 μm

Predicted Photon Noise Limited RV precision with FIRST in 15 min for H=7.5 M Dwarfs with APO 3.5m



- **Doppler precision ~1-3 m/s**

Summary

• SDSS-III MARVELS has already produced steady survey data, ~2500 FGK stars have been observed

•The MARVELS survey have identified ~8 brown dwarfs, several planet candidates and ~200 new short period binaries
•EXPERT delivers ~29% throughput without telescope and fiber in the inerferometer mode
•Pressure control to within 2 mpsi over ~10 days
•Temperature control to within 4 mK over ~10 days
•RV drift within +/-5 m/s over 10 days
•Reach ~1 m/s with iodine bracketing calibration for 1 hour integration, goal to reach 0.5 m/s with the ThAr or white light interferometer comb calibration over 0.39-0.7 um
•Science operation with EXPERT in April 2010, with LiJET in October 2010, and more later
•EXPERT direct echelle, covering 0.39-1.0 um with R=27,000, can reach ~3 m/s for mid-late M dwarfs for a J=7 M dwarf in 10 min ➔ planet survey with M dwarfs
•FIRST/IRET design is done, commissioning in Spring 2011 at APO 3.5m

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