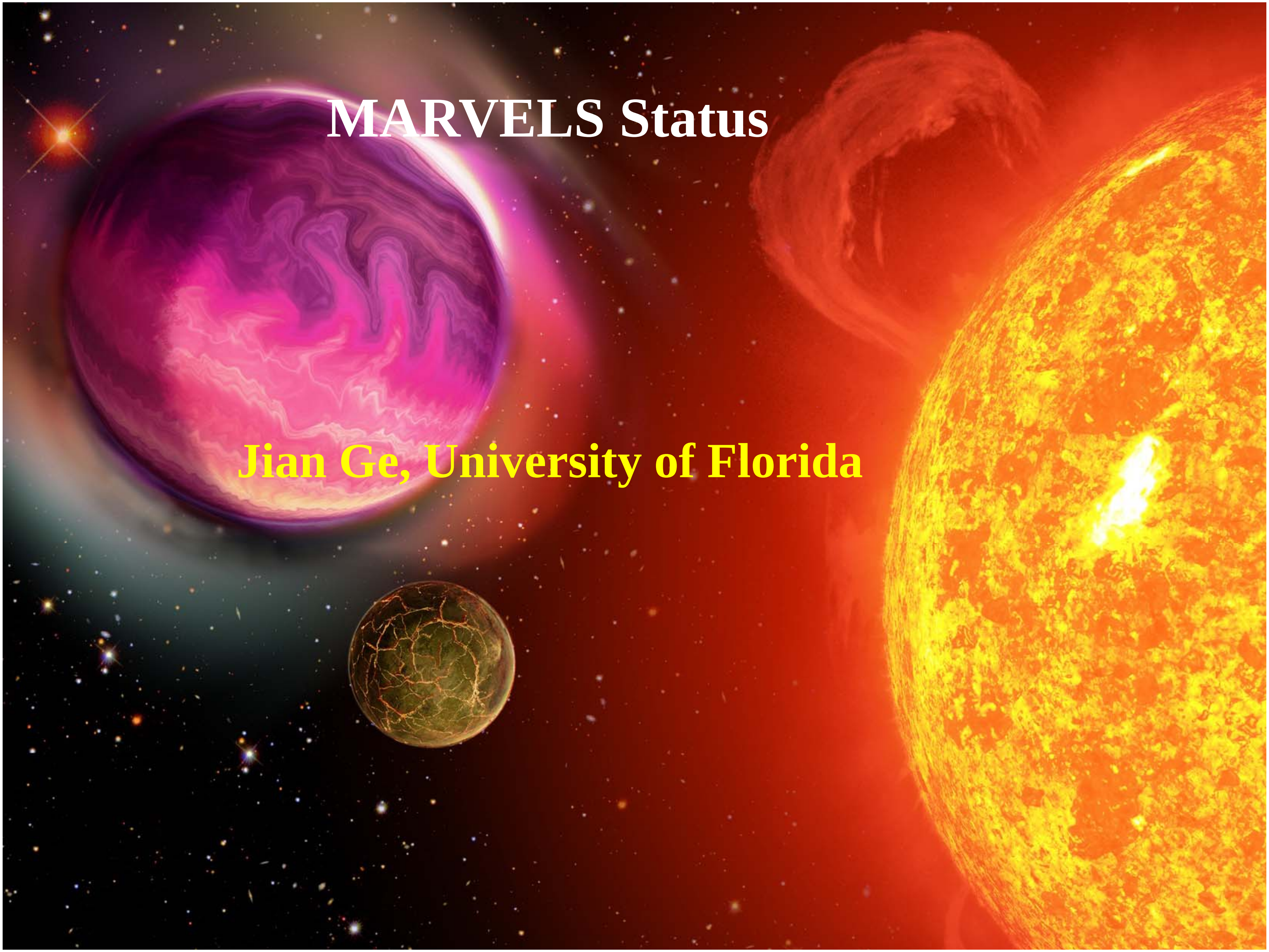


MARVELS Status

Jian Ge, University of Florida

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, first one in 2008 and the second one in 2011

•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:

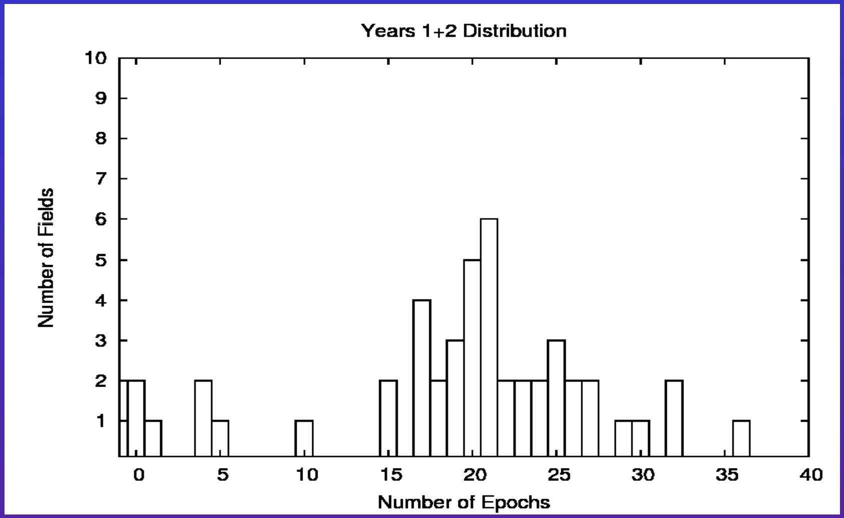
- **find a homogeneous sample of hundreds of giant planets that can be used for statistical study of planet properties and comparison to theory**
- **constrain formation, migration & dynamical evolution of planetary systems**

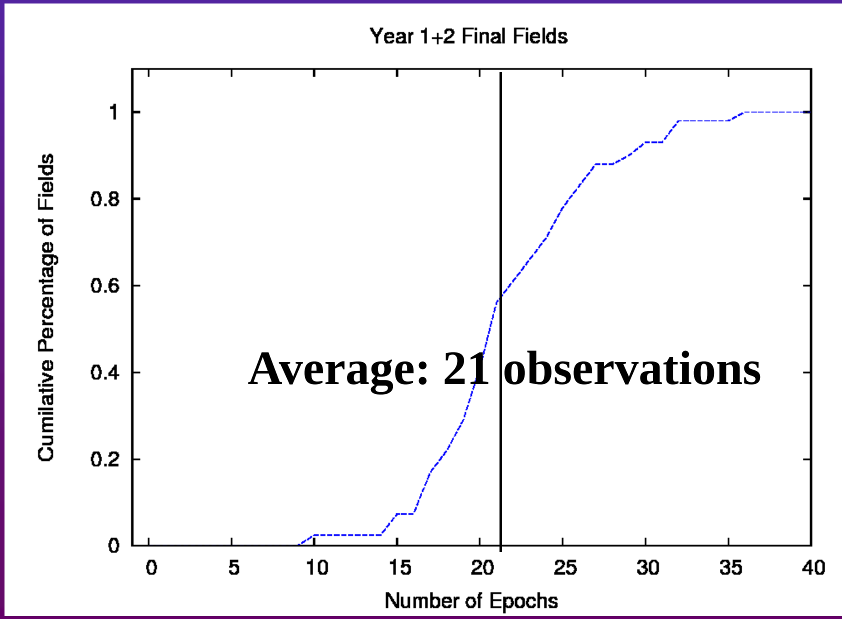
- **discovery of rare systems (e.g.** "Very Hot Jupiters", short-period super-massive planets, short-period eccentric planets, transiting planets, highly eccentric planets, rapidly interacting multiple planet systems, planets orbiting low-metallicitiy host stars, planets around active and young stars, and other rare types of planets**)**

- **signposts for lower-mass or more distant planets**

- **quantify the emptiness of the brown dwarf desert**

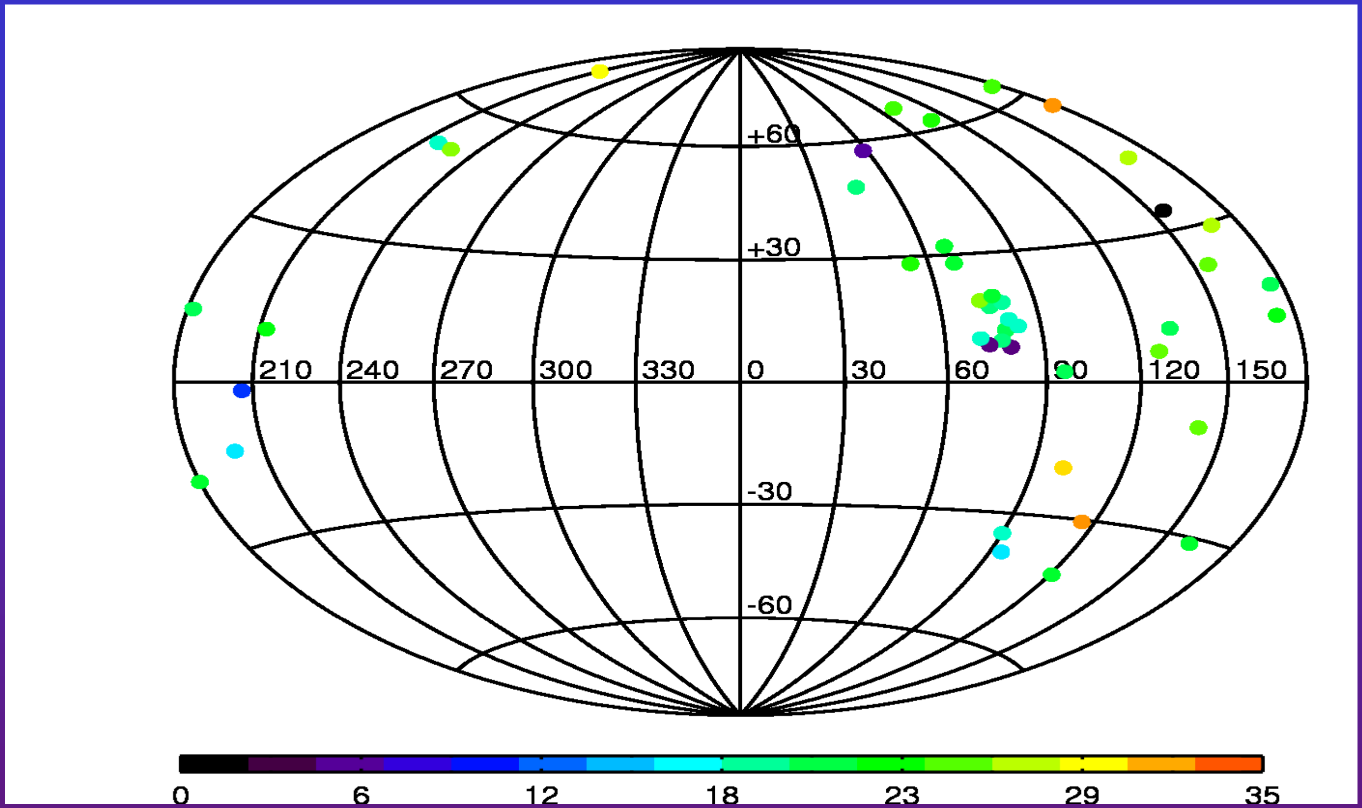
Current Survey Status





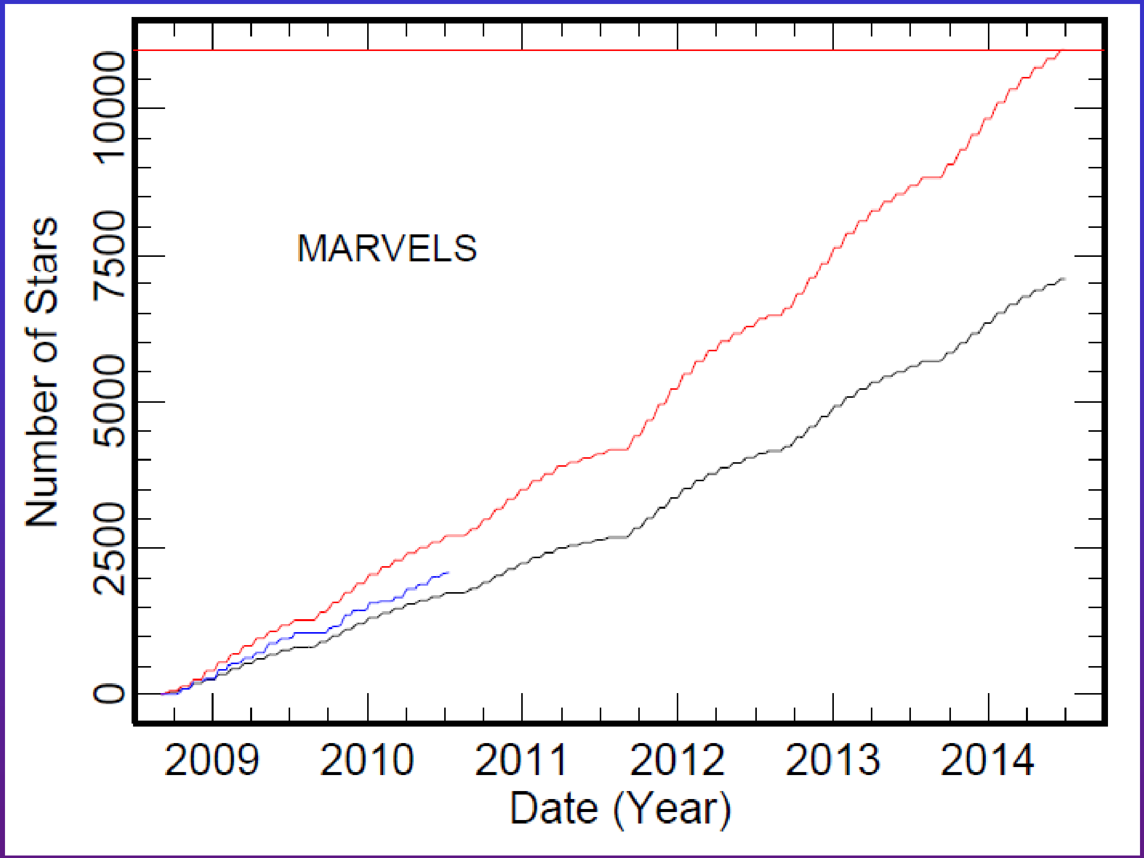
- MARVELS first instrument commissioned in Sept. 2008 and the survey observations started in Oct. 2008
- To date, 44 Fields, 308 square degree FOV observed
- 2640 stars
- 917 Epochs
- 110,040 spectra obtained

MARVELS Year 1-2 Field Distribution



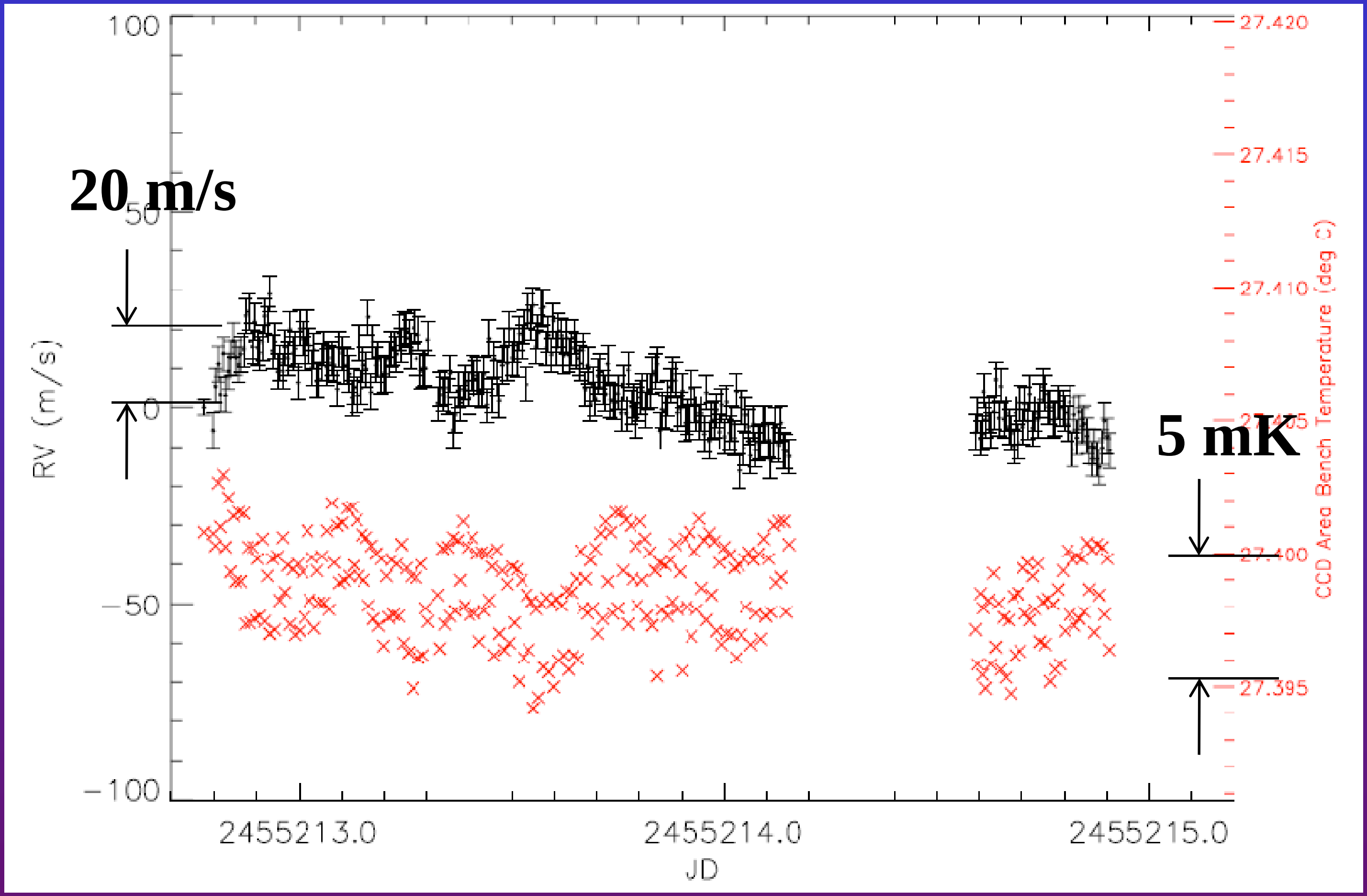
- Galatic latitude and longitude distribution for the 44 MARVELS year 1+2 fields.
- Average number of Epochs: 21

Survey Progress against Forecast



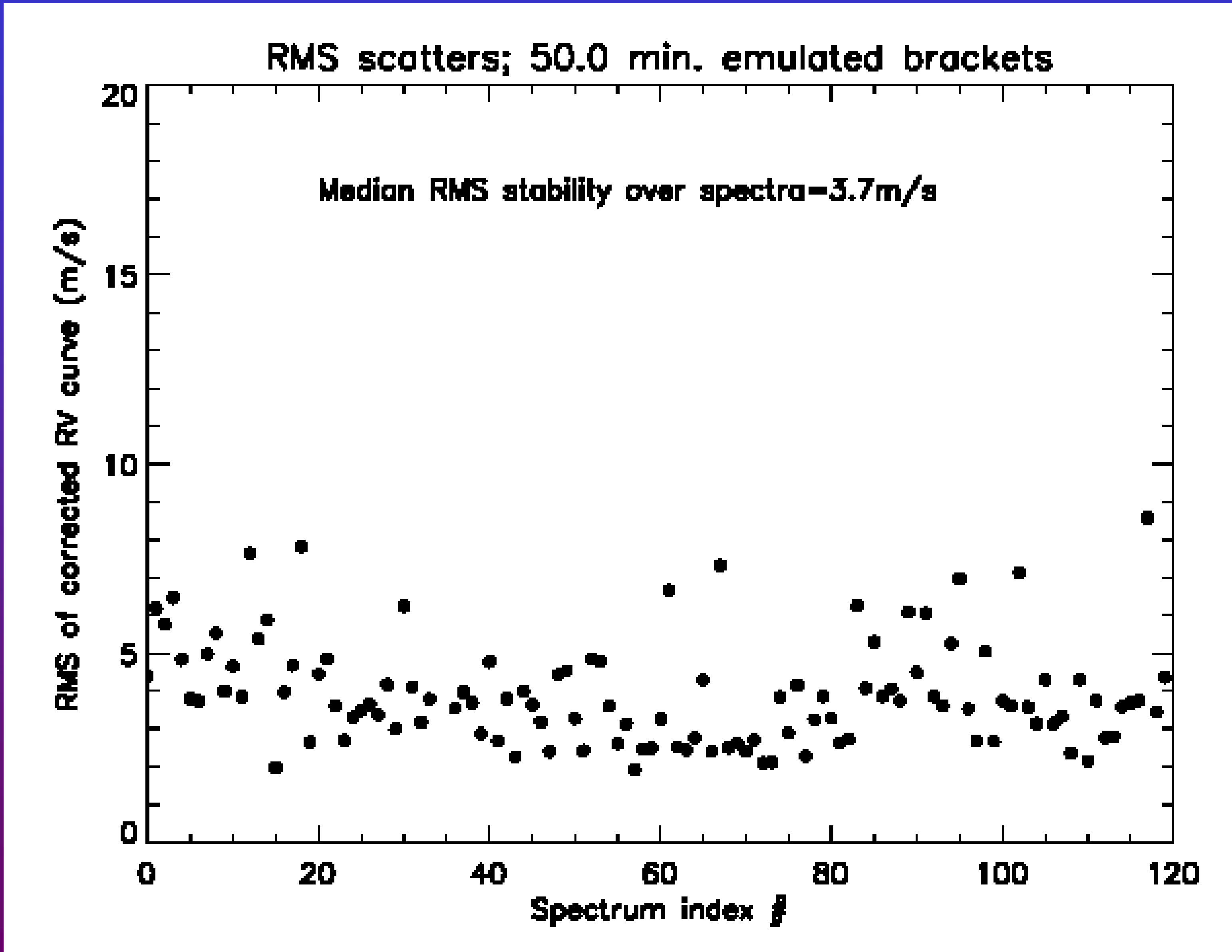
- Black line: baseline prediction assuming the second instrument available Fall 2011; Red line: requirement to reach the survey goal; Blue line: real observations
- ~75% of the original plan
- Forecast was based on 60% observable nights, first two years have 45% observable time

MARVELS RV Stability on Short Term

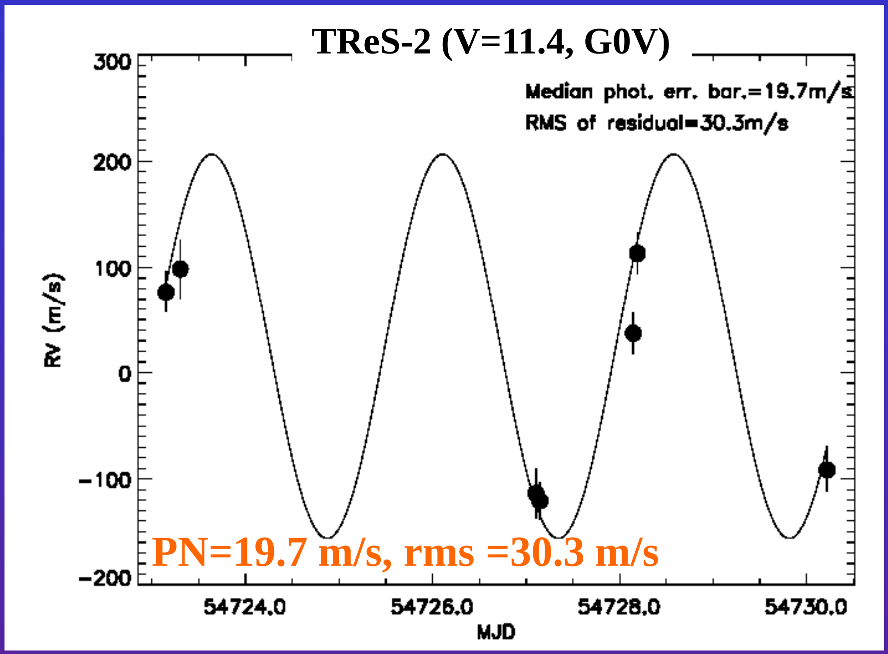


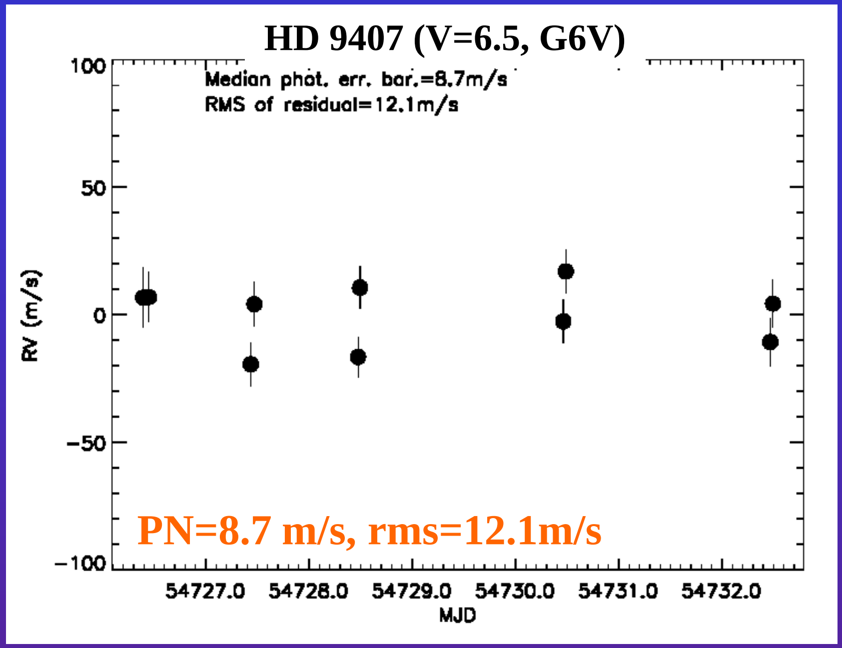
- MARVELS instrument is very stable, RV drift is about 20 m/s over ~3 days
- Temperature change is about 5 mK over ~3days.

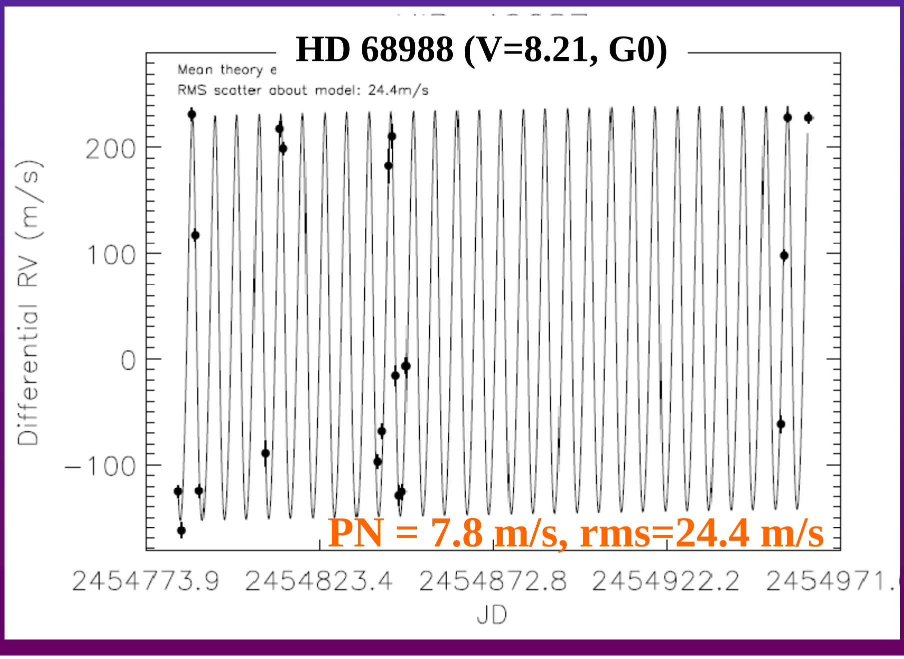
Doppler Measurement Calibration Precision

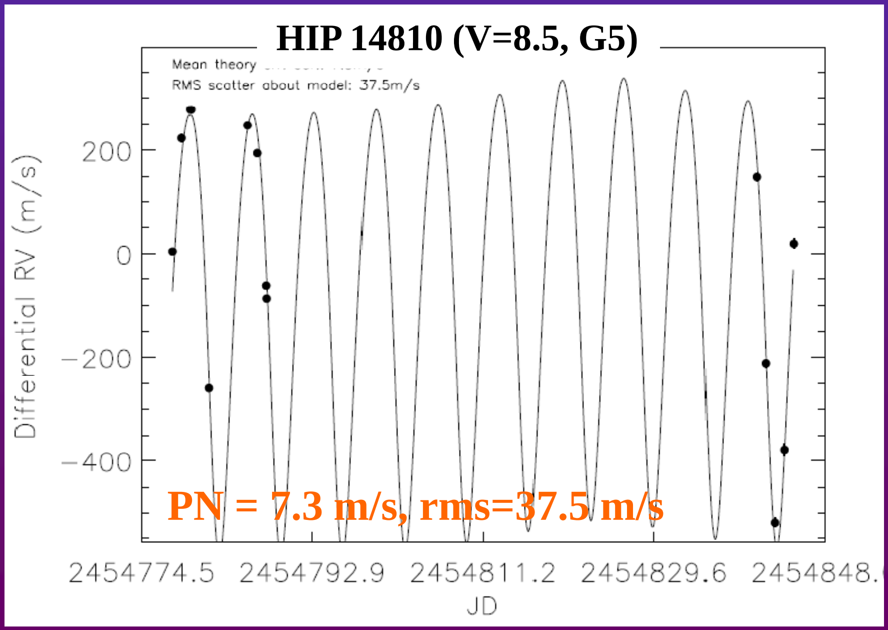


Results for Some Reference Stars



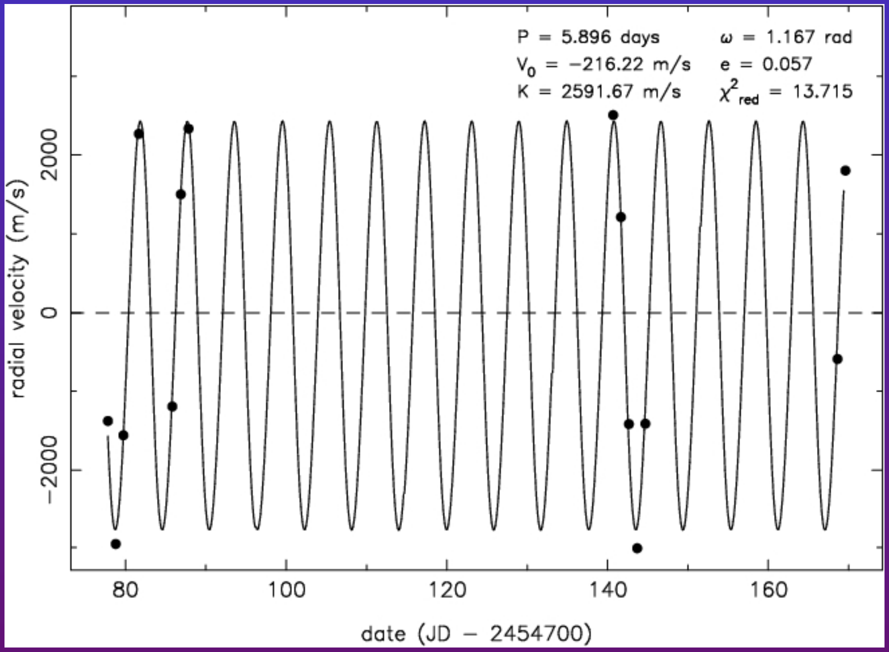






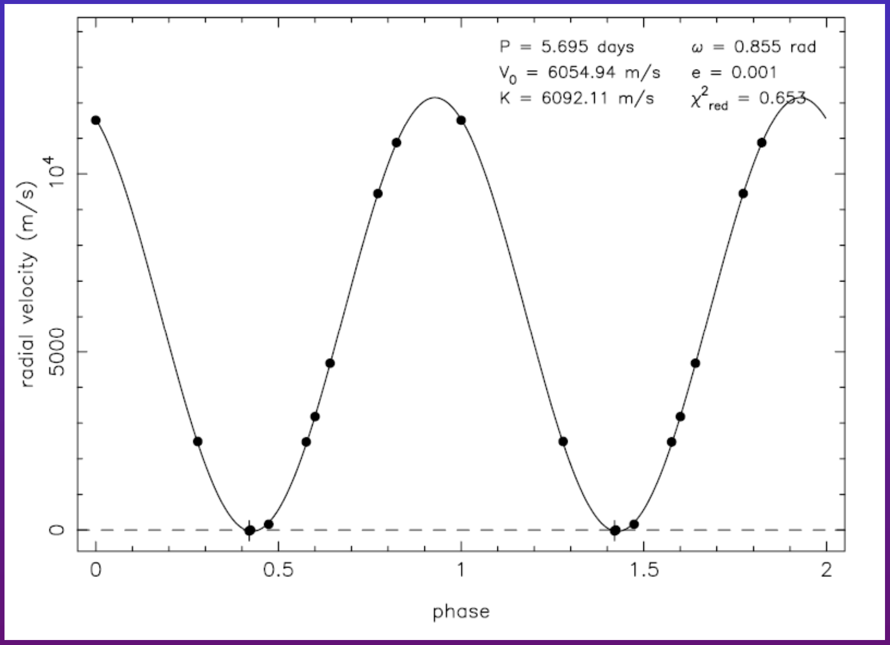
Discoveries of Two Brown Dwarfs by MARVELS

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



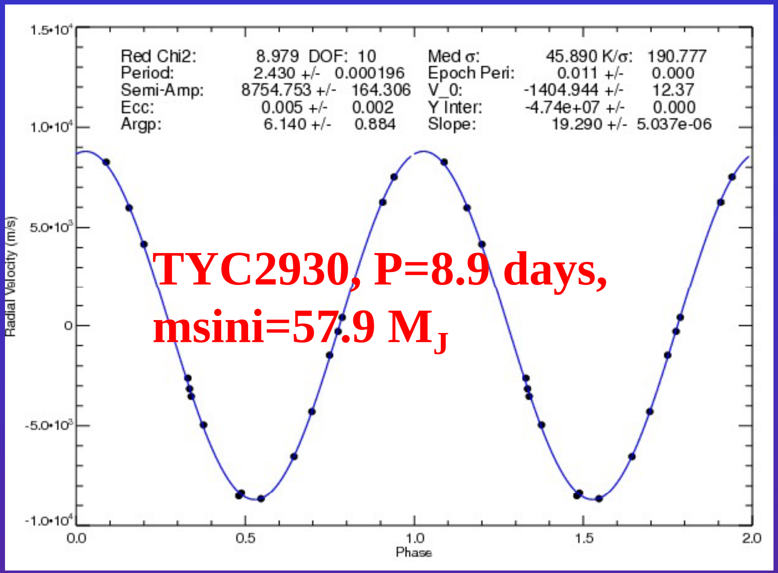
Lee et al. 2010, ApJ submitted

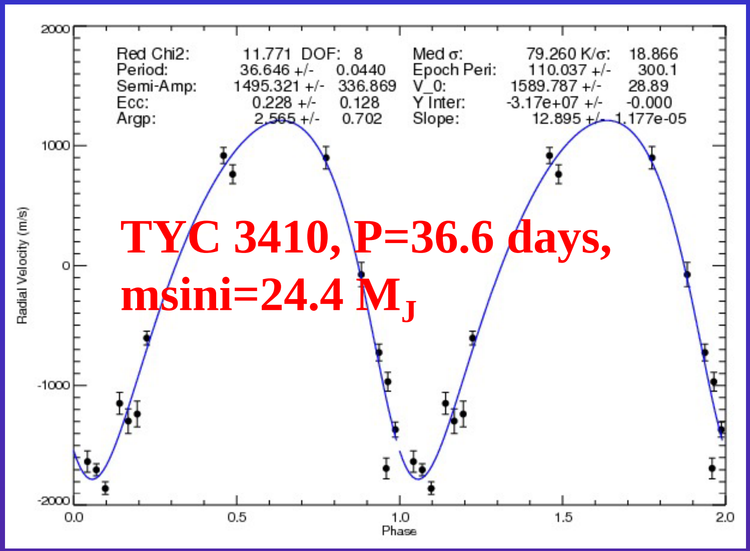
A new brown dwarf with 58 Jupiter masses and 5.8day period, TYC 2949

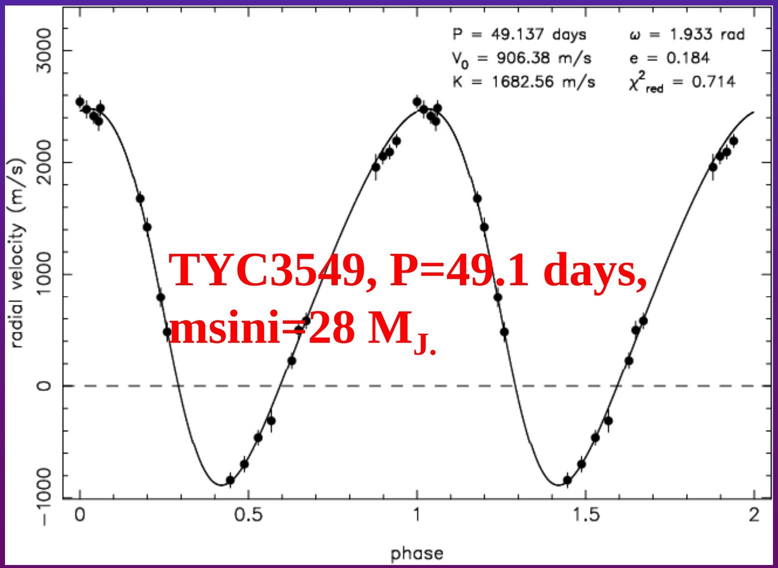


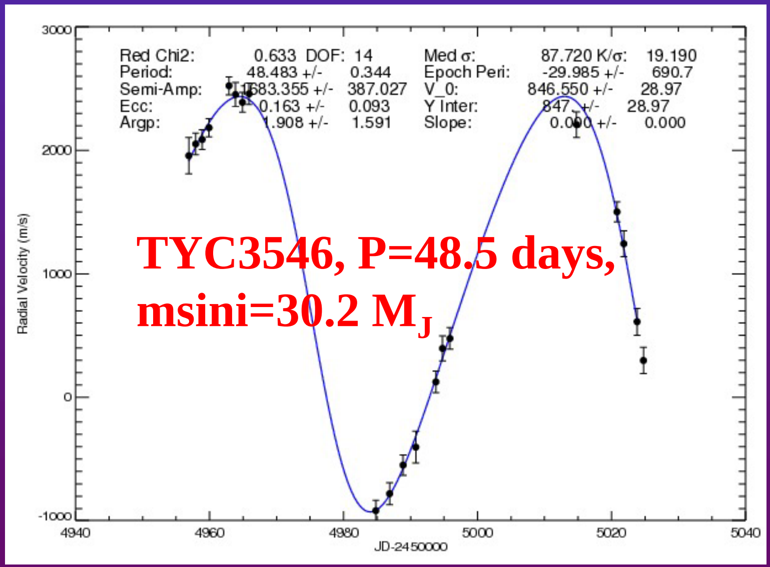
Fleming et al. 2010, ApJ,718

New Brown Dwarfs by MARVELS



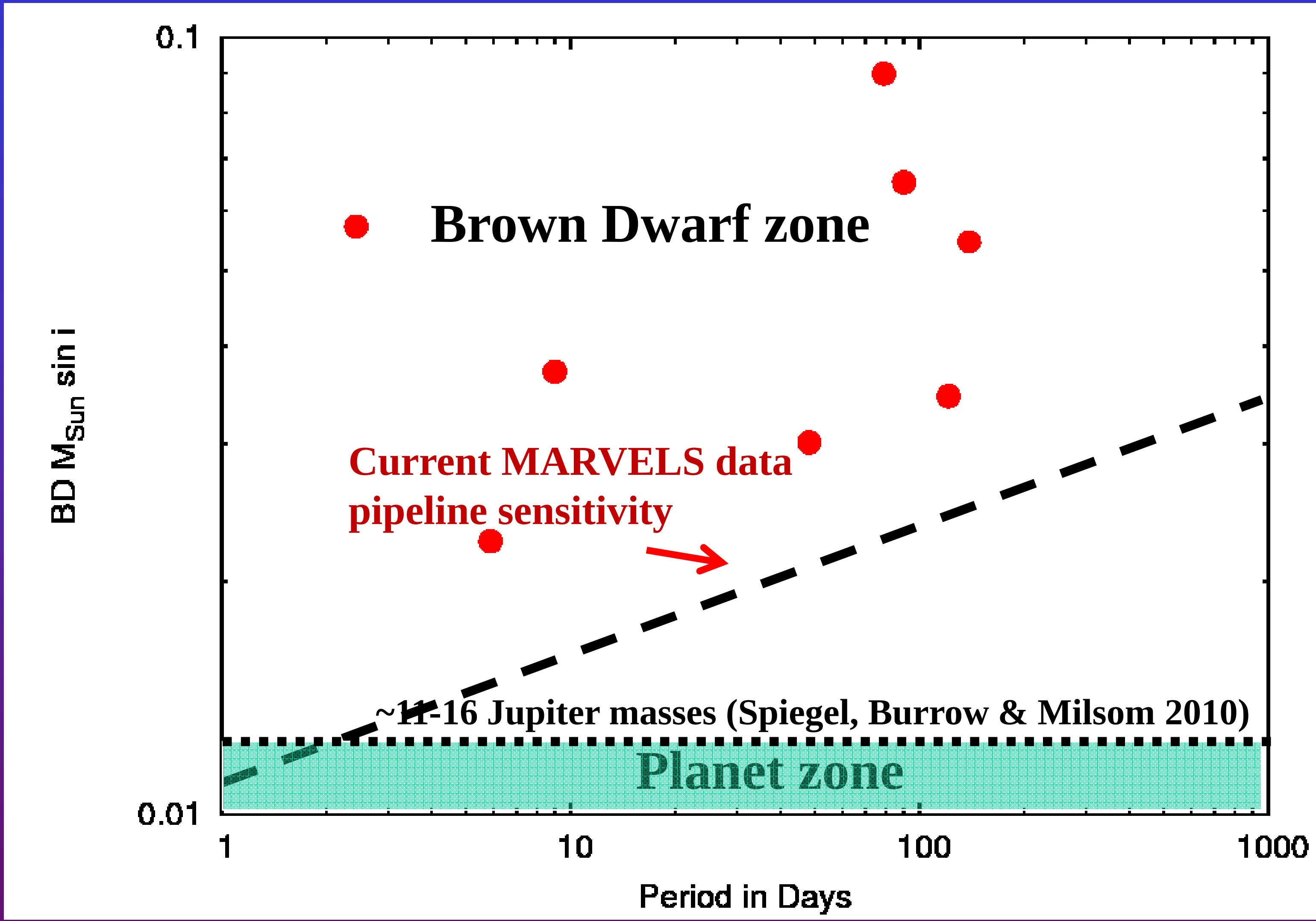






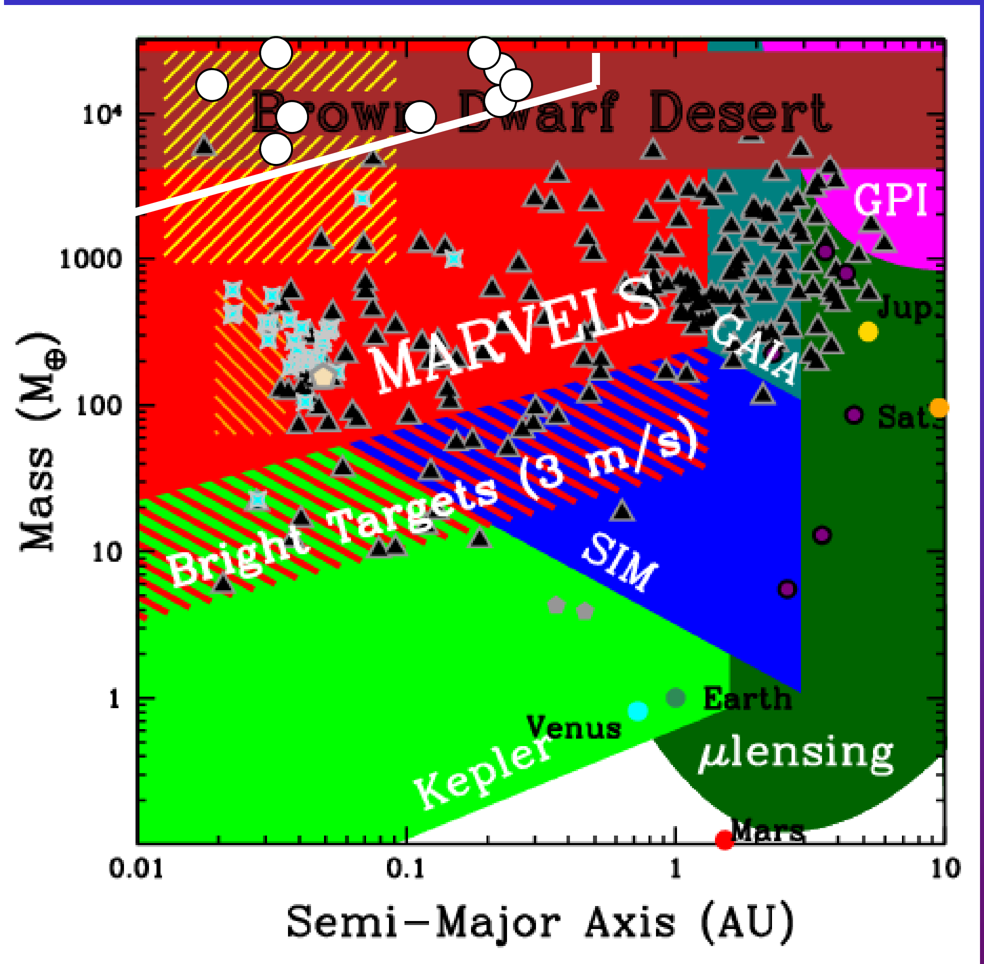
- **A total of 8 new brown dwarfs detected by MARVELS, addressing dryness of brown dwarf desert (see Gaudi's talk for details)**

Brown Dwarfs in Brown Dwarf Desert



• **Roughly 0.5% of MARVELS stars have BDs with periods less than 180 days, the first accurate measurement**

MARVELS & Other Planned Large Surveys in the Next Decade



- MARVELS starts to fill the planet-brown dwarf mass-radius map
- 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-) probe longer period giant planets systems
- Gemini Planet Imager (2011-) is sensitive to young giant planets (<1Gyr) beyond 5AU for stars within 50 pc

Active MARVELS Follow-up Observation Resources

Photometry Follow-up

Institution	Telescope	Location	PI
OSU	DEMONEX 0.5m	Southern AZ	Scott Gaudi
OSU	MDM 1.3m	Southern AZ	Scott Gaudi
UW	ARC 3.5m	Sunspot, NM,	Eric Agol
NMSU	NMSU1.0m	Sunspot, NM	Jon Holtzman
PITT	PITT 0.4m	Pittsburgh, PA	Michael Wood-Vasey
Vanderbilt	SMARTS 0.9m	CTIO, Chile	Keivan Stassun
Vanderbilt	SMARTS 1.0m	CTIO, Chile	Keivan Stassun
Vanderbilt	SMARTS 1.3m	CTIO, Chile	Keivan Stassun
Vanderbilt	HAO 11-inch	Hereford, AZ	Joshua Pepper

Doppler Follow-up

Institution	Telescope	Location	PI
Florida	KPNO 2.1m/EXPERT	Arizona, USA	Jian Ge
Florida	LiJET 2.4m	Yunnan, China	Jian Ge
Penn St.	HET/HRS 9 m	Texas, USA	Don Schneider
IAC	TNG 3.5m	La Palma, Spain	Rafael Robelo
Vanderbilt	SMARTS 1.3m	CTIO, Chile	Keivan Stassun

High Resolution Spectroscopy Follow-up

Institution	Telescope	Location	PI
UFRJ/Obs. do Valongo	OPD 1.6m	Brazopolis, Brazil	Gustavo Mello
Observatorio Nacional	ESO/FEROS 2.2m	La Silla, Chile	Ricardo Ogando
IAC	TNG 3.5m	La Palma, Spain	Rafael Robolo

High Contrast Imaging Follow-up

Institution	Telescope	Location	PI
Caltech	Palomar 5m	Palomar, CA	Justin Crepp
Caltech	Keck 10m	Manna Kea, Hawaii	Justin Crepp
IAC	FASTCAM/1.5m	Teide Obs., Spain	Rafael Robolo

List of Paper Assignments with MARVELS Science Team

List has been removed since it contains sensitive info.

- **Over 20 refereed papers have been assigned to individual investigators, with two papers completed (one published in ApJ and the other close to be accepted)**

Remaining Major Tasks and Schedule

- Replace Current 112 μm fibers with 154 μm to increase MARVELS I spectrograph throughput

  November-December 2010

- Major improvement of Data pipeline to reduce long term systematics

  September 2010- March 2011

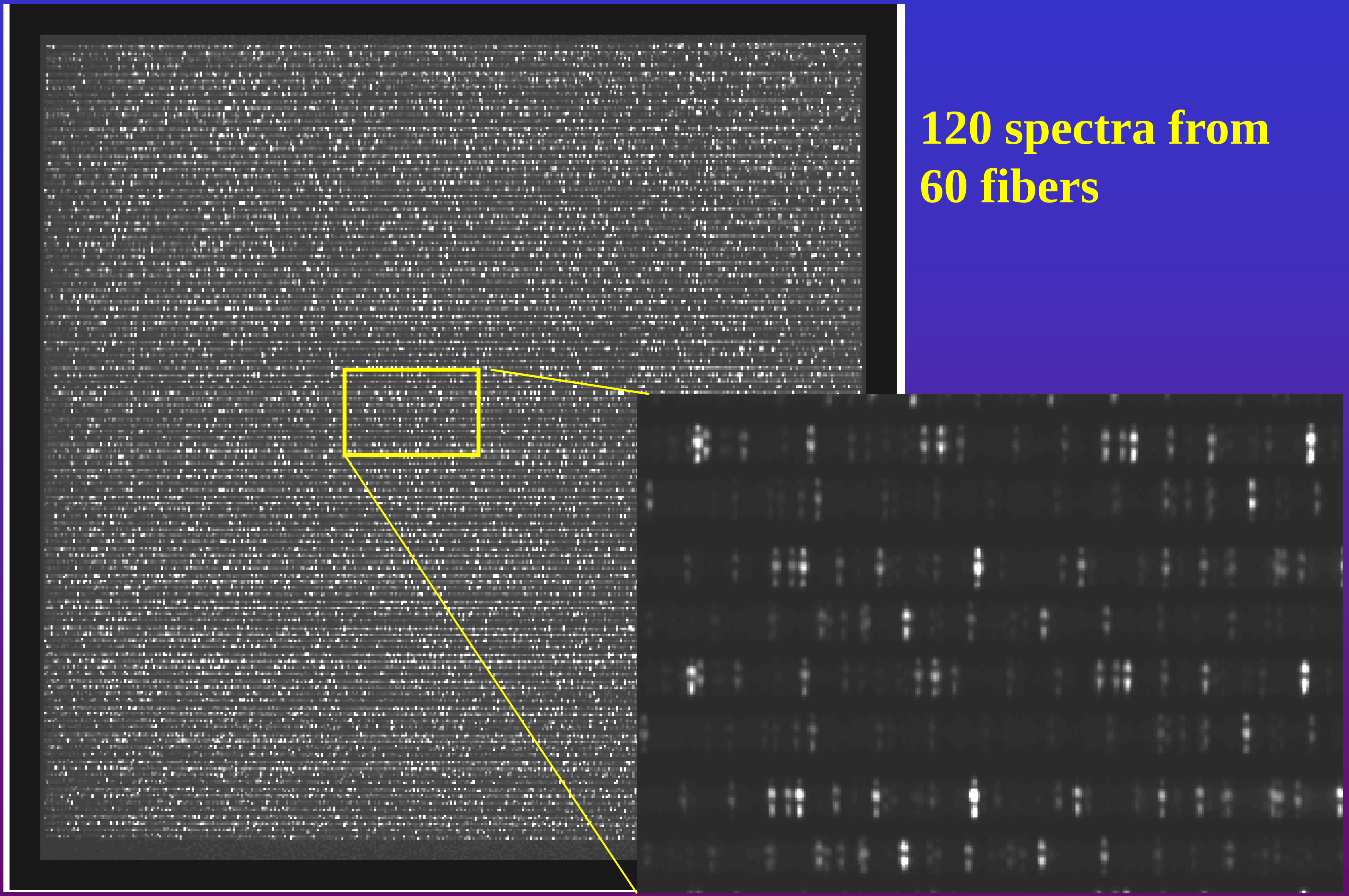
- Coordination with APOGEE for Year 3-6 operations

  Spring 2009- July 2014

- Complete MARVELS II hardware development

  May 2010-July 2012

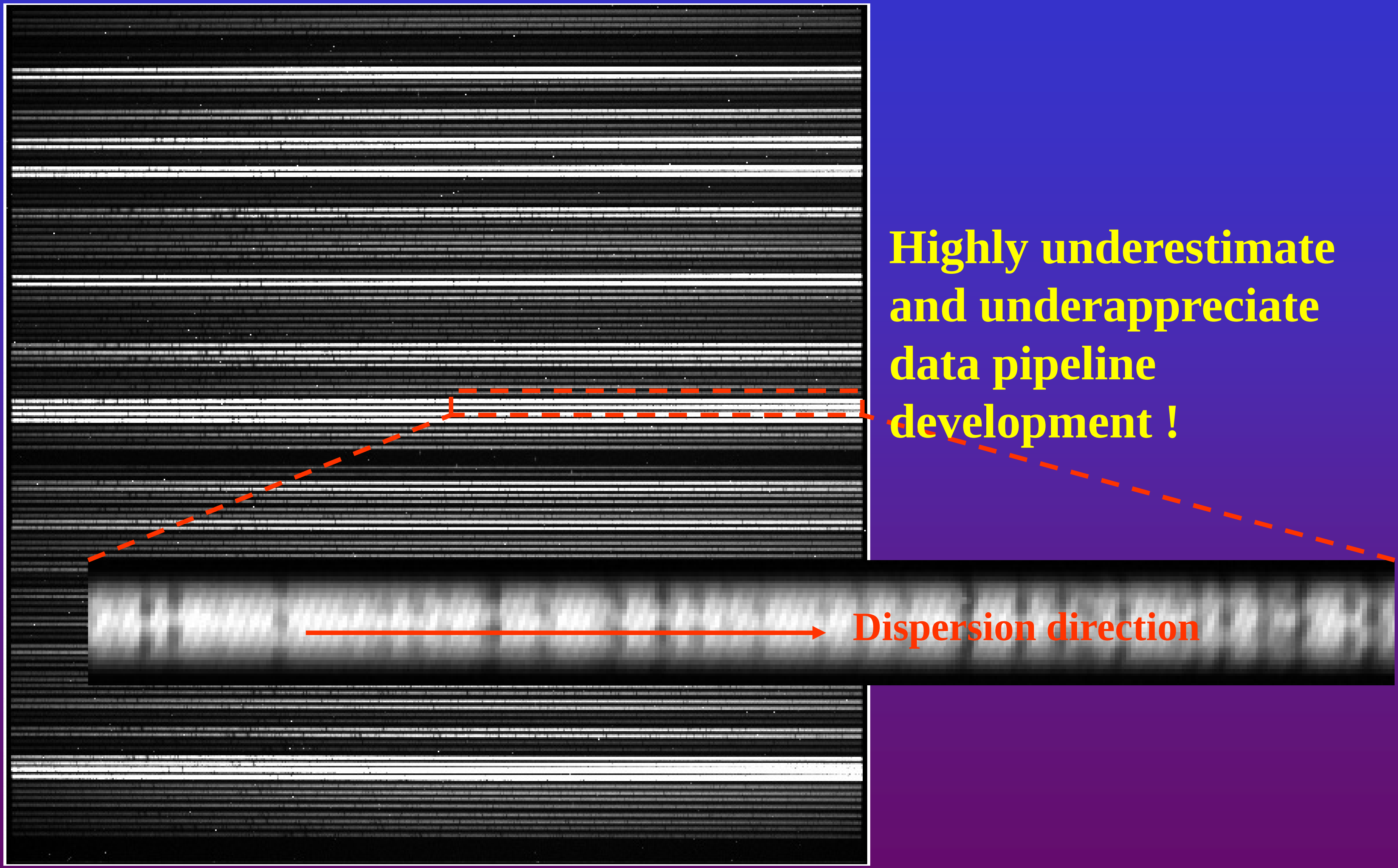
A full frame of a ThAr spectrum with MARVELS instrument



120 spectra from 60 fibers

•Fringing spectral images have their own characteristics at the different part of the detector

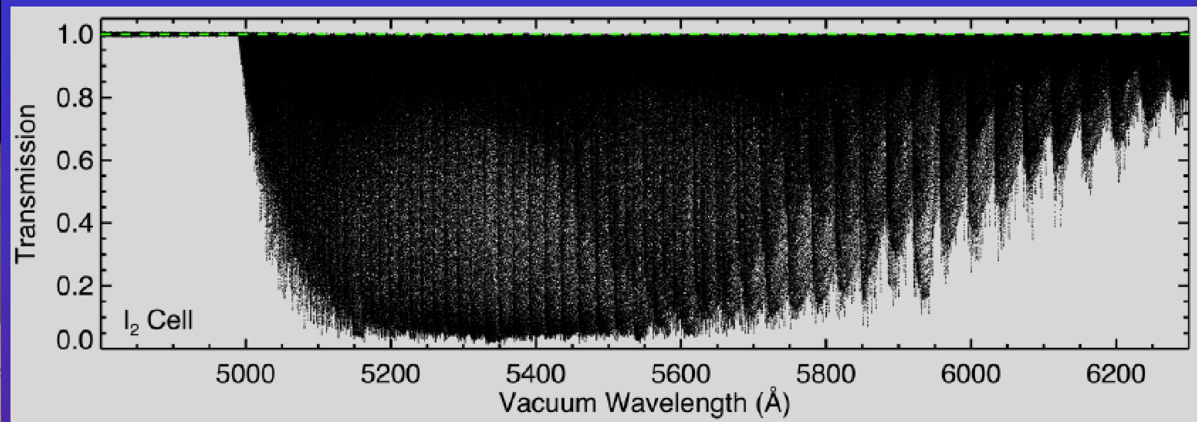
120 stellar fringing spectra from the HAT-P-1 field



Highly underestimate and underappreciate data pipeline development !

Additional complication dealing stellar observations: Different brightness, large barycentric velocity, long term instrument drift and image characteristics change, line illumination profile changes, PSF changes and cosmic rays ……

Data Pipeline Development Has Been Major Efforts for Other Single Object Doppler Planet Survey Groups

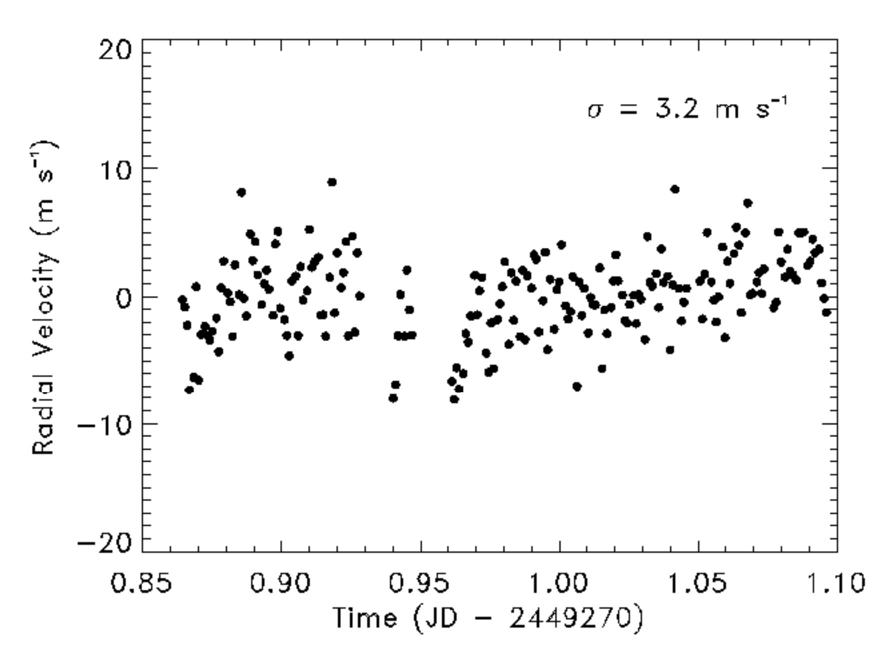


Superimposing of iodine absorption lines on stellar lines at 0.5-0.62 μm

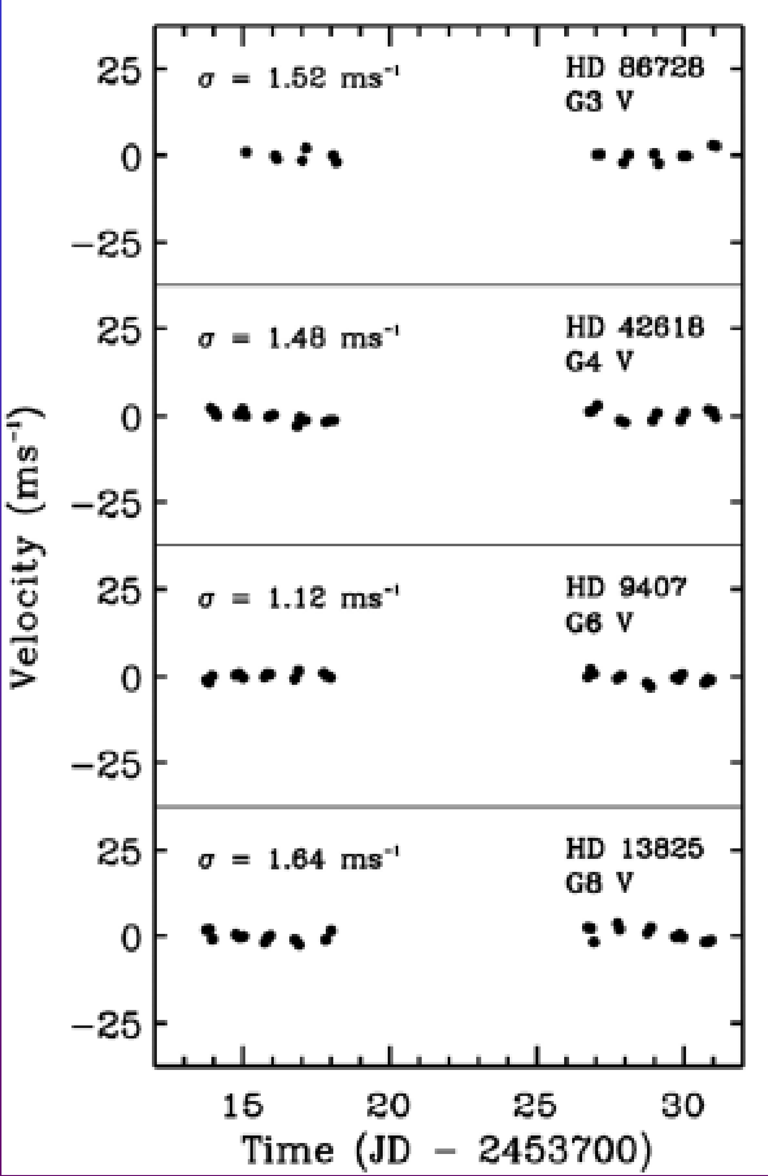
•Model observations as the product of the intrinsic stellar spectrum, I_S, and the iodine absorption spectrum, T_{12} and convolved with the spectrograph PSF and binned to the wavelength extent of the CCD pixels.

$$I_{obs}(\lambda) = k\left[T_{12}(\lambda) I_s(\lambda + \Delta\lambda)\right] * PSF$$

Over 10 years to Improve RV Precision from ~3 m/s to ~1 m/s

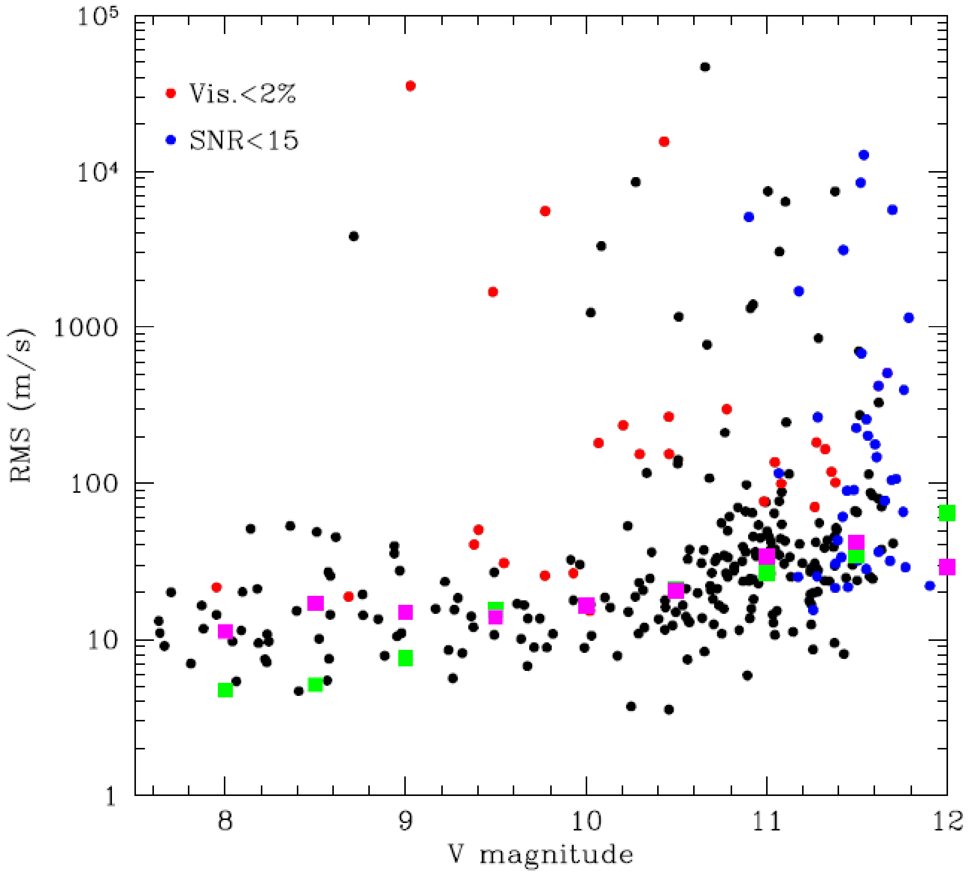


107 Psc (V = 5.2 mag) over 6 hours with Keck HIRES (Butler et al. 1996)



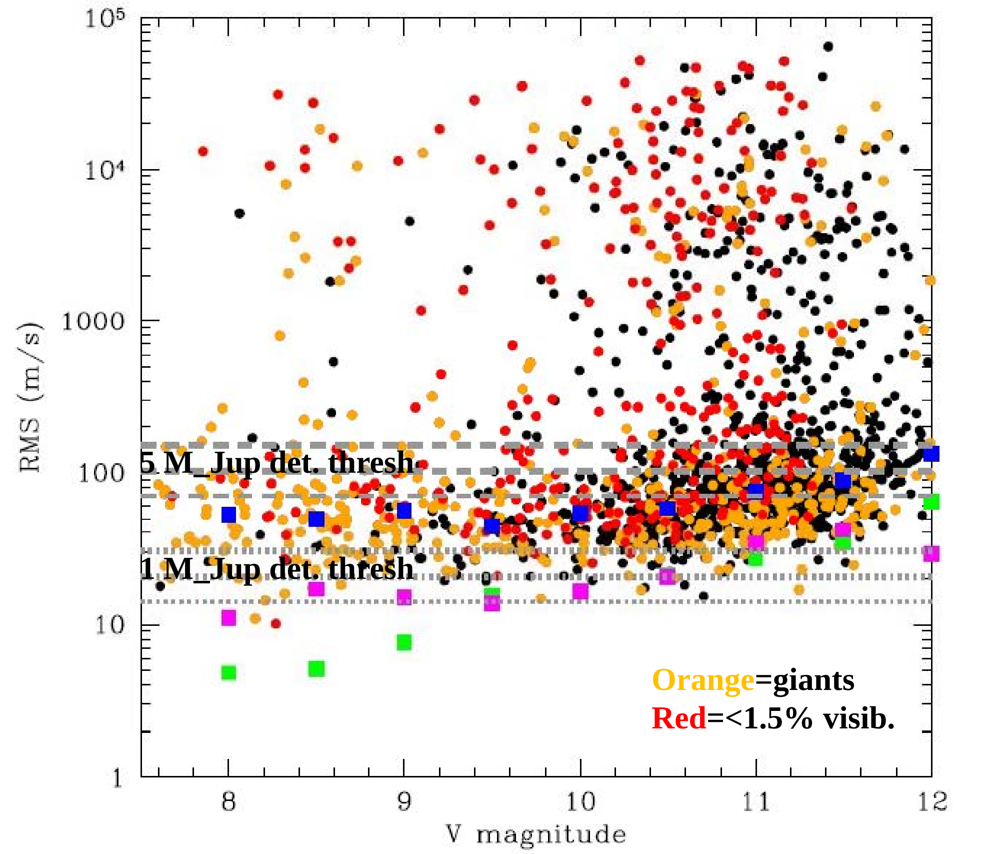
RV stable stars with Keck HIRES (Vogt et al. 2008)

Current 1 Month Stellar RV rms Scatter with MARVELS Data Pipeline

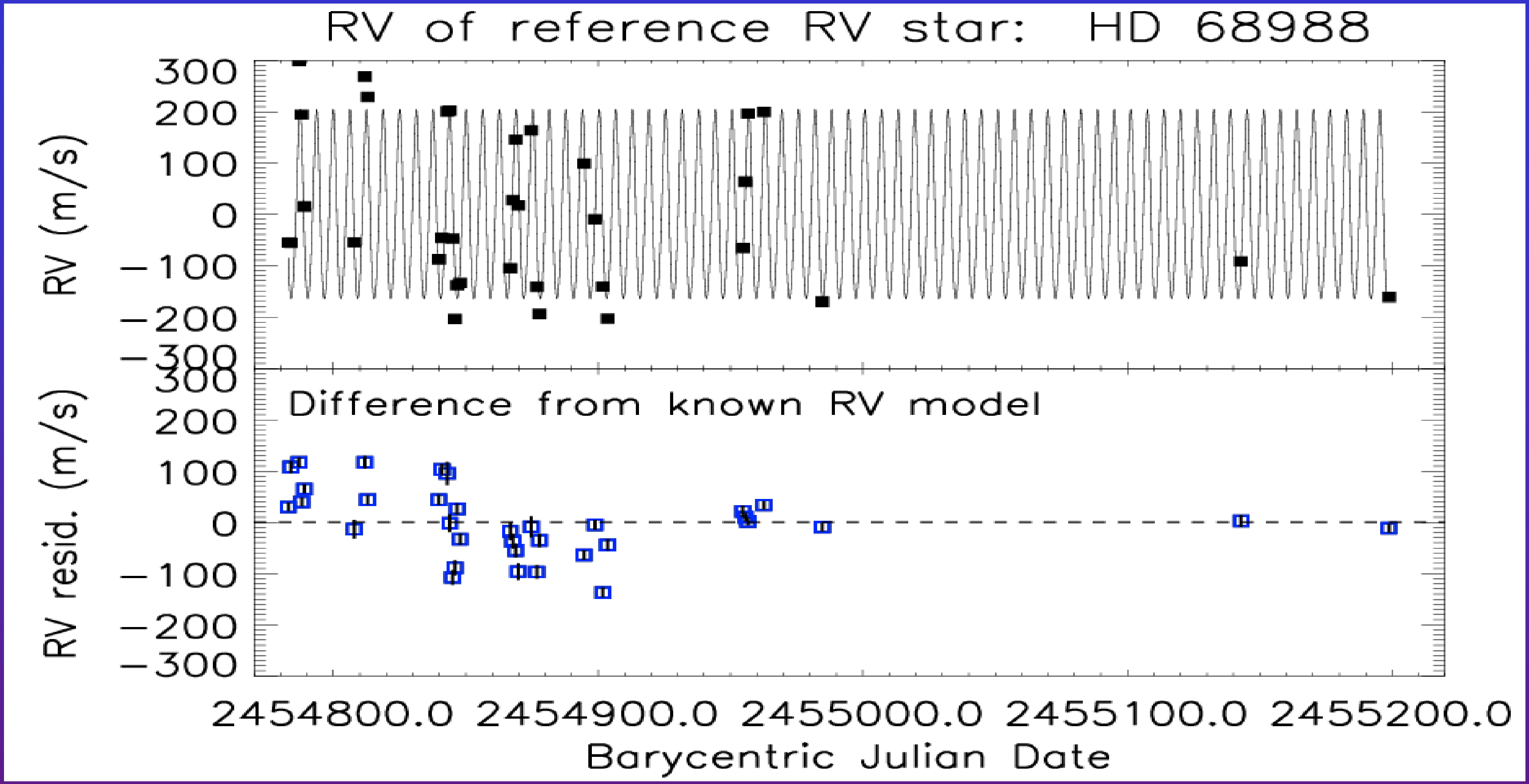


- -300 stars (5 plates) from Oct. 2009
- -Noise floor @ 10 m/s
- -One-month timescales are basically okay, with rms approximately at the level of the instrument requirements
- -Green squares = median phot. limits of mag. bins
- -Magenta squares = median total rms of mag. bins

Current Multi-month (<17 months) Stellar RV rms Scatter



- -1680 stars (28 plates) from yrs. 1-2
- -rms scatter ~2x the phot. limit at faint magnitudes
- -Bright-end noise floor@ 50 m/s- much larger than the one-month floor
- -Noise due to slowly-varying month-to-month offsets (see next slide for specific example)
- -Green squares = median phot. limits of mag. bins
- -Magenta squares = median 1-month total rms of mag. bins
- -Blue squares = median multi-month total rms of mag. bins



Specific example of multi-month systematic noise (400 days)

-Planet-bearing RV reference star HD 68988

-RV offsets and varying background slopes between months

Possible culprits

An effect which interacts with the barycentric correction (i.e., RV measurement must track RV to better than 1/1000 over a 60 km/s range in order for barycentric correction to subtract off cleanly)

- Preprocessing details? Imperfect correction of: spectrum slant, spectrum curvature, illumination profile, optical distortion
- Calibration details? Instrument drift prescription currently only single-variable (RV)

Pipeline Refining Plan and Schedule

In Oct. 2010 to March 2011, our major efforts:

(1) Refine current pipeline

- Develop new algorithms for correcting different image effects
- Establish and use a testbed for quickly processing and checking the results
- Develop a fully functional reverse modeling to quantitatively assess improvements for every new step and improved step in the data pipeline
- Implement and upgrade data pipeline

(2) Investigate the fringing spectral images

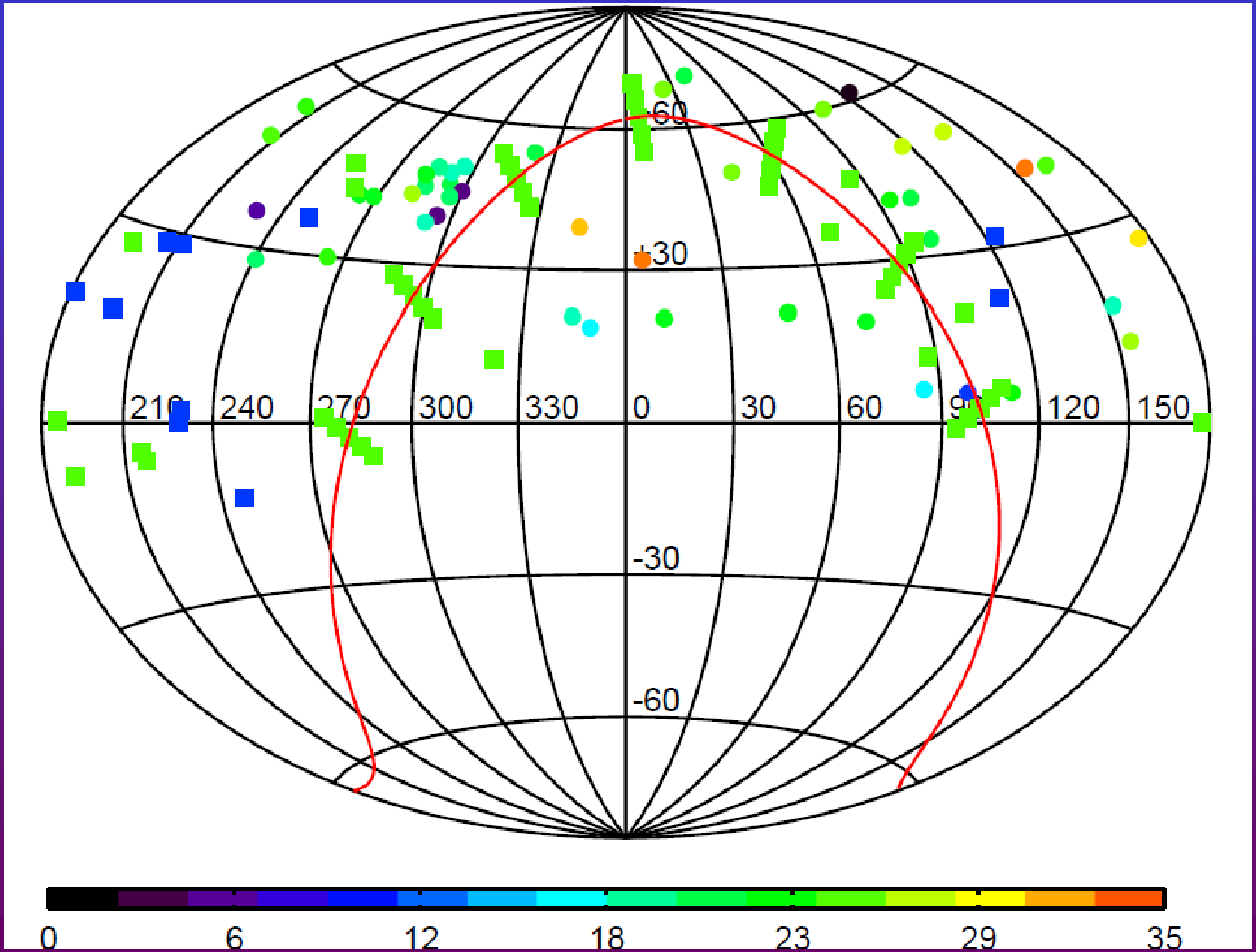
- Implement correct physics and mathematics models in the data pipeline
- Understanding image formation on the detector and its characteristics
- Construct detailed proper simulations incorporating as much of the physics and image characteristics
- Conduct path-finding researches to look for new ideas and data extraction techniques
- Forward modeling and moonlight contamination

Our goals are to reduce our RMS values at all magnitudes on many-month timescales to within 20% of the measured RMSs on one-month timescales to robustly select strong planet candidates from the survey data

Target Selection for Years 3-6

- Observing 58 fields in concert with APOGEE
  - 3500 stars with one instrument, up to 6500 with 2nd instrument
- New target selection process reduces giant fraction from 30% to desired 10%
- Primary Obstacle – finding fields in Galactic Halo rich enough to provide sufficient targets once 2nd instrument arrives
- Target selection expected to be finalized by January 2011

Sky APOGEE/MARVELS Joint Fields in Year 3-6



Summary

- MARVELS has produced ~110,000 fringing spectra for over 2600 FGK stars over 300 square degree FOV on sky with 21 observations per field
- Survey instrument has been extremely stable, reach a mean of 3.7 m/s calibration precision
- Over a month, most of the survey data rms error within 1.5 times of photon limited errors
- Over ~1.5 years, rms errors are ~2-5 times worse due to long term systematics not removed
- A total of 9 new brown dwarfs discovered, several hundreds of new binaries identified, and over 10 planet candidates identified
- Over 20 refereed science papers have been assigned to various investigators
- Science team is conducting very active follow-up observations with a long list of follow-up resources.
- Data pipeline team is concentrated on MARVELS pipeline improvement
- Replace old fibers with large diameter fibers in Nov. 10 to improve its throughput
- Developing the second survey instrument to be commissioned by summer 2011
- Coordinate with APOGEE on field/target selection for 2011-2011

The MARVELS Team

Principal investigator: Jian Ge (UF)

Survey scientist: Scott Gaudi (OSU)

Science Team Chair: Keivan Stassun (VU)

Instrument scientist: Xiaoke Wan (UF)

SWG coordinator : Eric Agol (UW)

Data coordinator: Brian Lee (UF)

MARVELS Science Team Members:

J. Ge, S. Gaudi, K. Stassun, E. Agol, B. Lee, N. De Lee, & D. Nguyen, S. Fleming, P. Jiang, B. Ma, J. Wang, J. Pepper, M. Paegart, John P. Wisniewski, S. Mahadevan, J. van Eyken, E. Ford, H. Ford, D. Schneider, J. Eastman, R. Siverd, J. Crepp, R. Barnes, B. Gary, M. Esposito, R. Robelo, J. Holtzman, S. Seager, R. Moorhead, S. Thirupathi, D. Eisenstein, D. Weinberg, J. Gunn, L. Hebb, G. Luan, G. F. Porto de Mello, R. L. C. Ogando, M.A.G. Maia, L. N. da Costa, C. Laws, M. Blanton, J. Wright, J. Bochanski, A. Wolczczan, A. Niedzielski, S. Hawley, D. Schlegel, & S. Snedden, K.K. Pan, B. Dmitry, H. Brewington, O. Malanushenko, V. Malanushenko, D. Oravetz, A. Simmons, L.M. Dou, J.W. Xie, & B. A. Weaver

Technical Team members: J. Ge, X. Wan, B. Zhao, Scott Powell, F. Varosi, J. Liu, S. Schofield, F. Hearty, J. Groot, L. Chang, A. Fletcher, T. Bosman, S. Bollampally, A. Delgado, H. Jakeman, S. McDowell, D. Long, F. Leger, & P. Harding