Frontiers in M Dwarf Radial Velocity Surveys

ExoPAG 18 - Boston

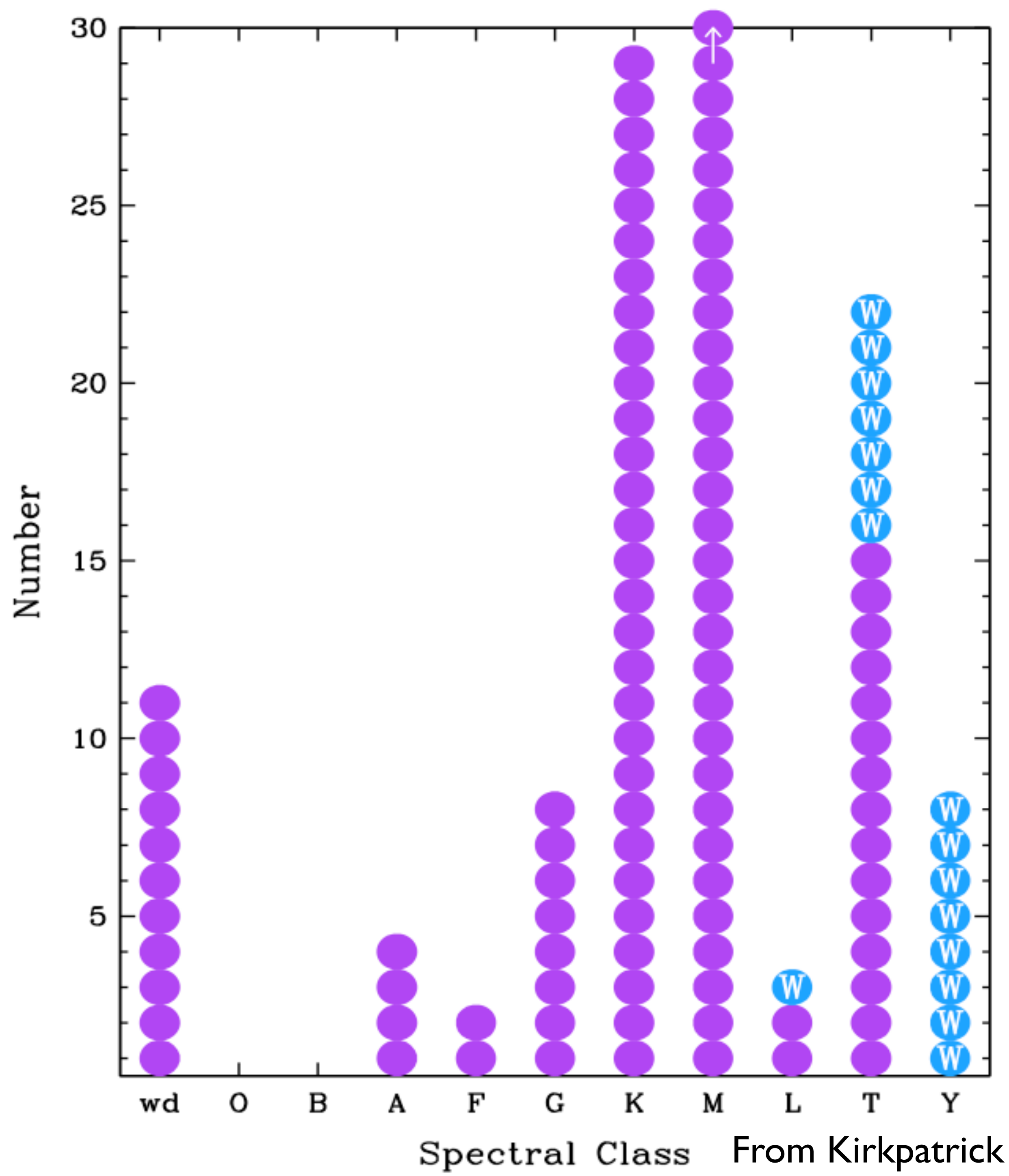
Cullen Blake - Univ. of Pennsylvania

Why Target M Dwarfs?

➜M dwarfs are numerous

➜Closest planets to Earth likely orbit M dwarfs

157 M Dwarfs!



From Kirkpatrick 2013 (AN, 334, 36)

~200 H burning stars, d<8 pc

79% are M dwarfs, T<4000K

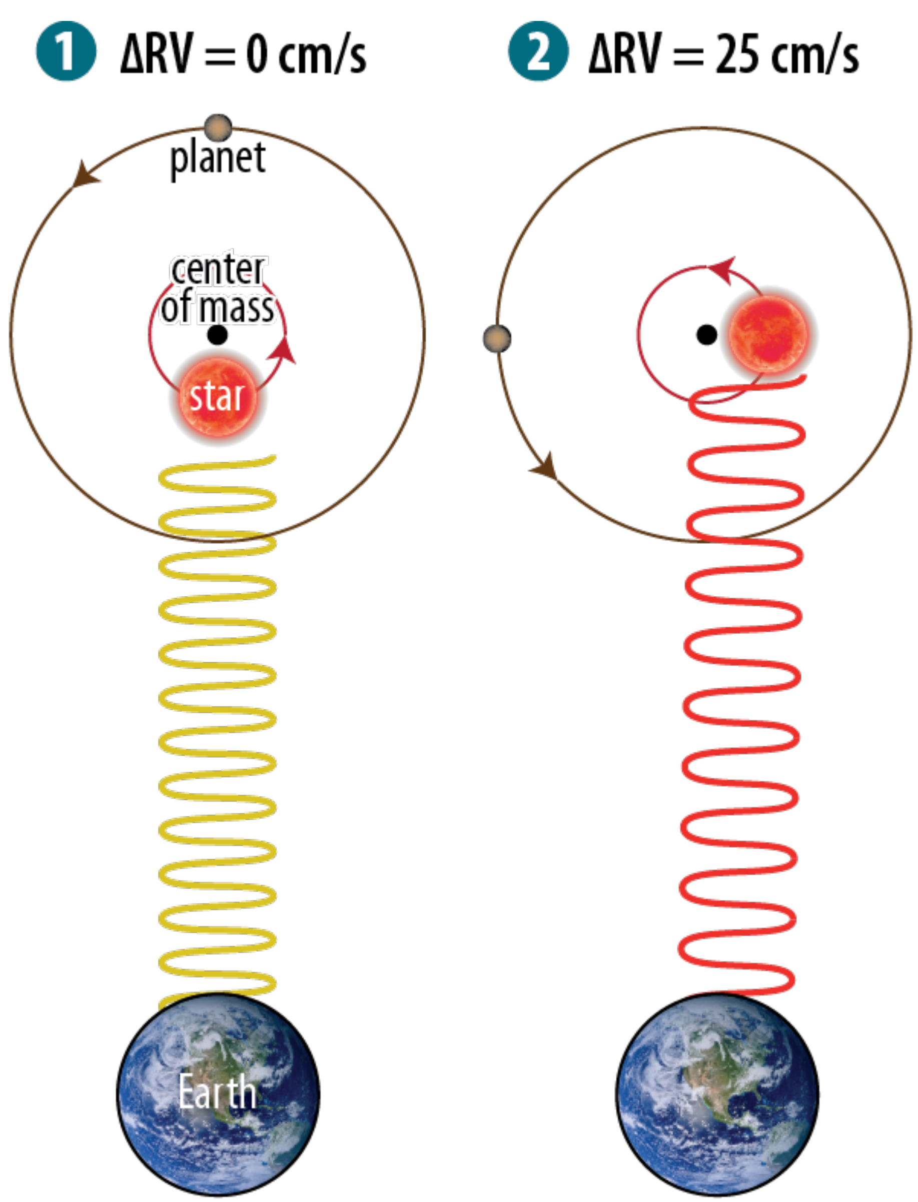
~28 M dwarfs, d<4 pc

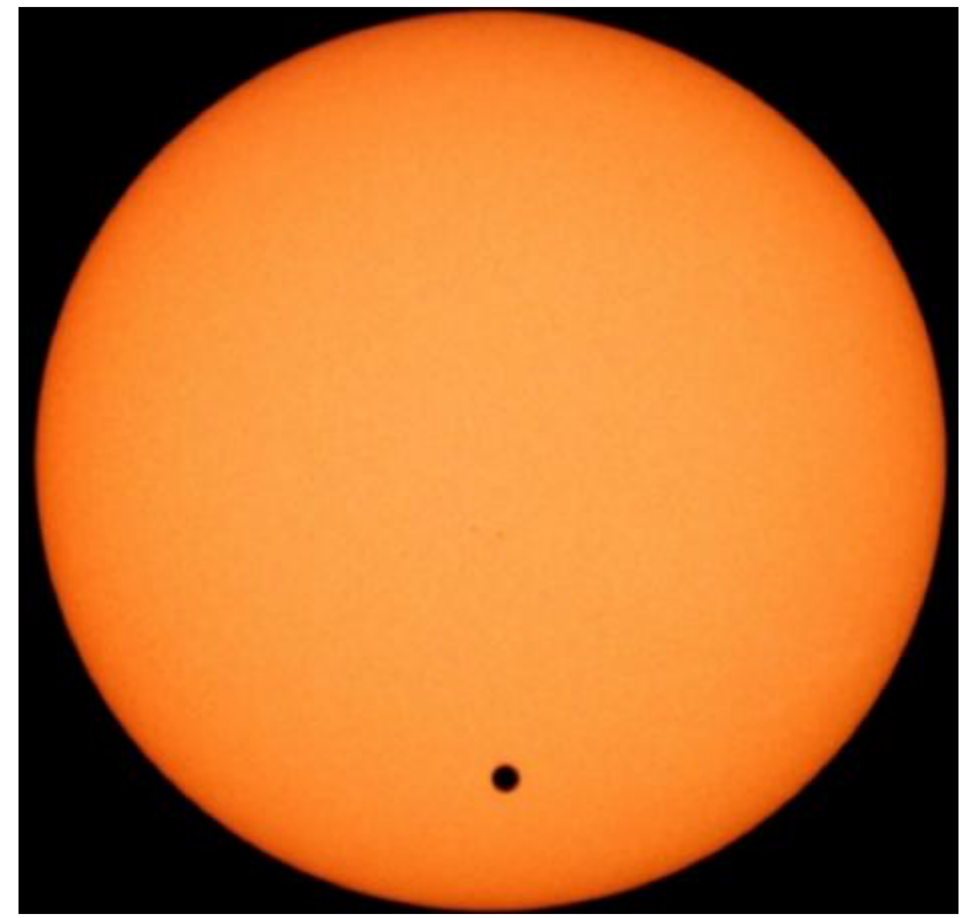
Seem to have many planets

Courtney will tell us more!

Why Target M Dwarfs?

All else being equal…





And transit spectroscopy!

<u>Doppler wobbles</u>: $\Delta RV \propto M_*^{-2/3}$

Factor of 5 in stellar mass:

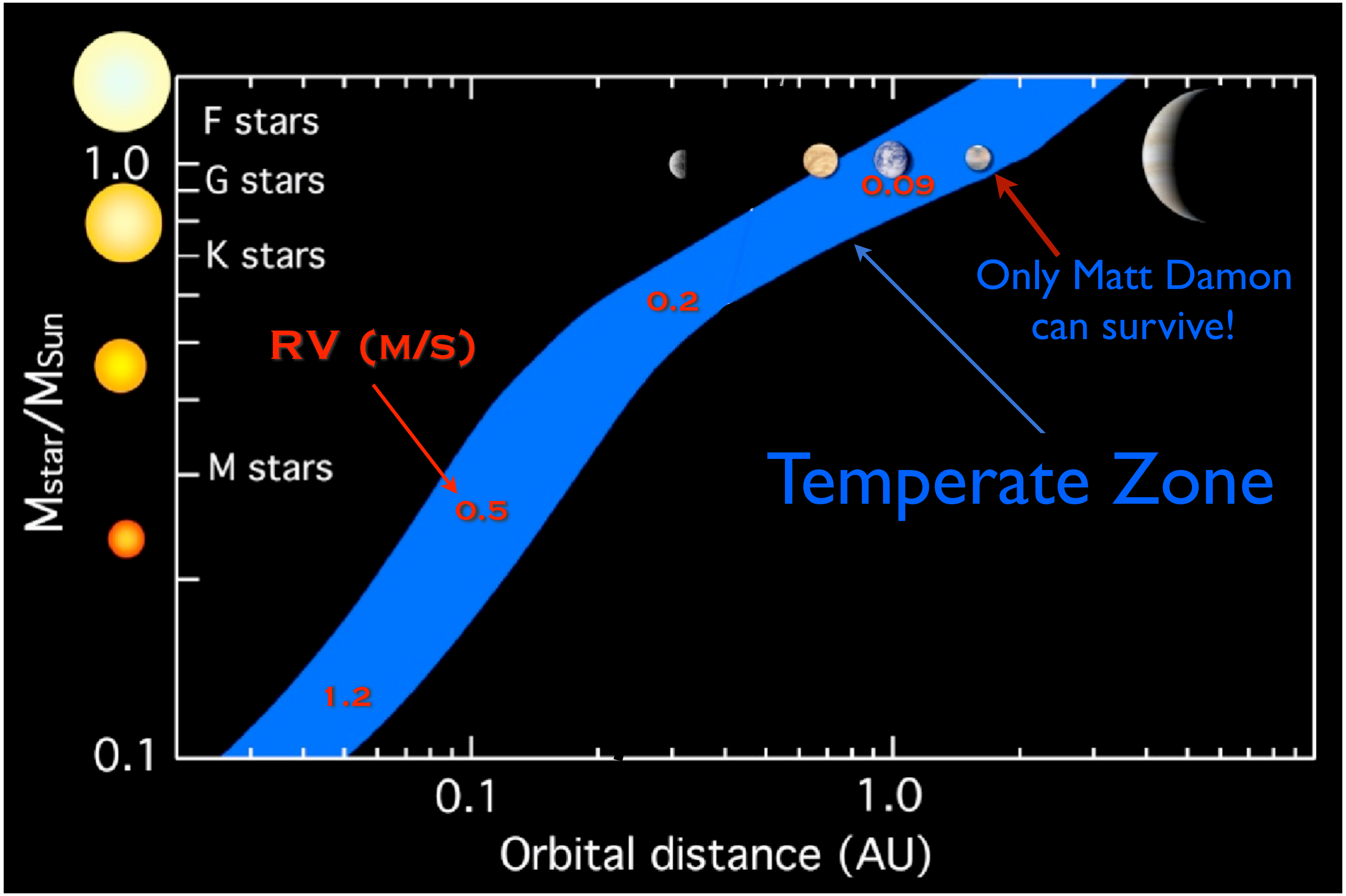
➜Factor of 3 in ΔRV

<u>Transits</u>: $\Delta F/F \propto R_*^{-2}$

Factor of 5 in stellar radius:

➜ Factor of 25 in transit depth

Why Target M Dwarfs?

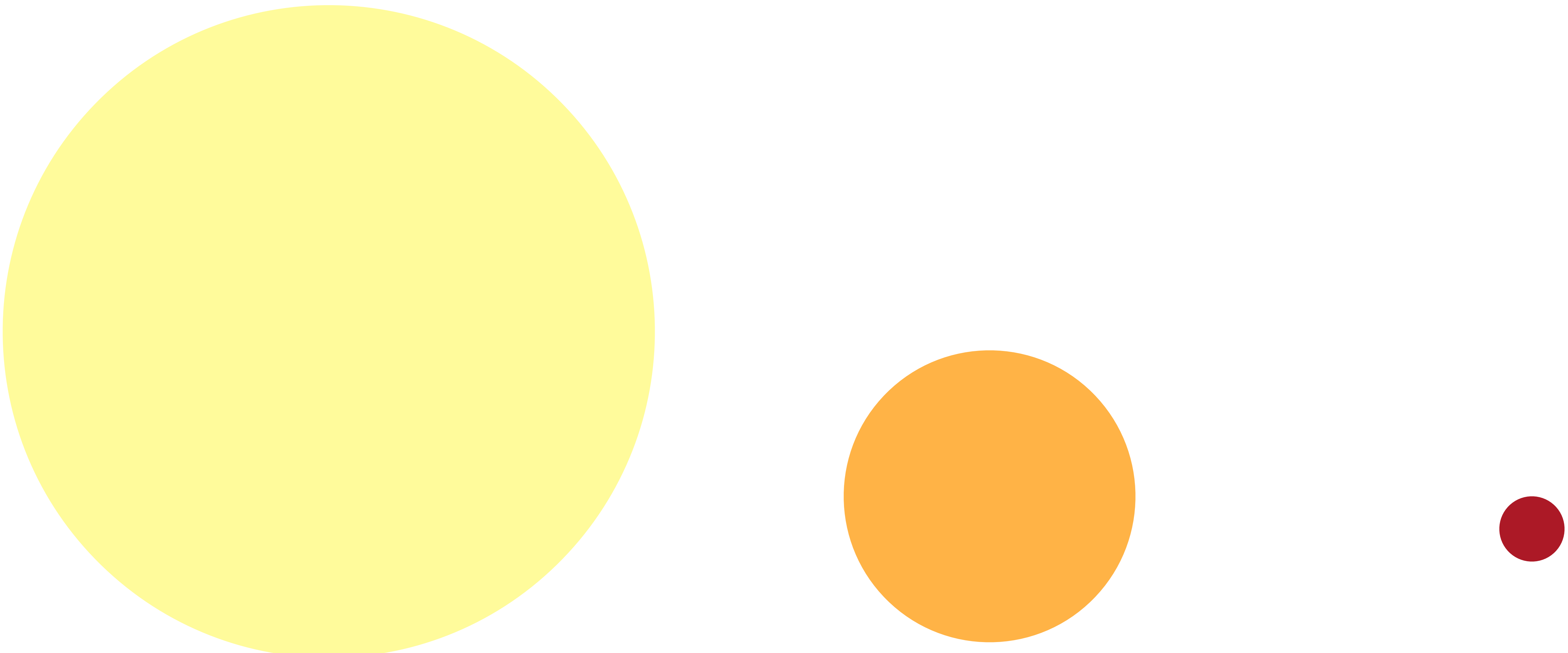


Doppler wobbles are substantially larger for planets in the *Temperate Zones* of M dwarfs

$\Delta RV_{TZ} \propto M_*^{-1.4}$

M Dwarfs

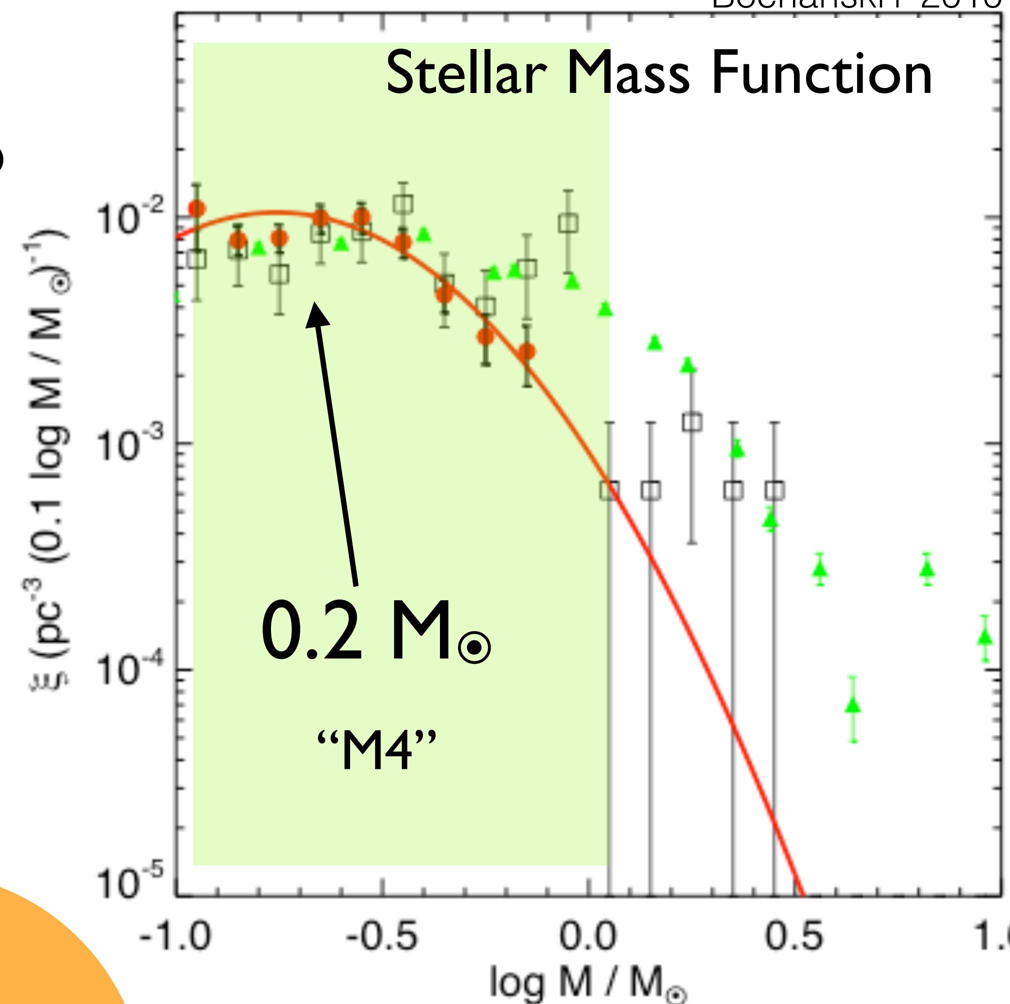
Radii to Scale



The Sun	M0 dwarf	M5 dwarf
M=1.0	M=0.6	M=0.12
R=1.0	R=0.5	R=0.14
T=5800K	T=3900K	T=3050K

M Dwarfs

Radii to Scale



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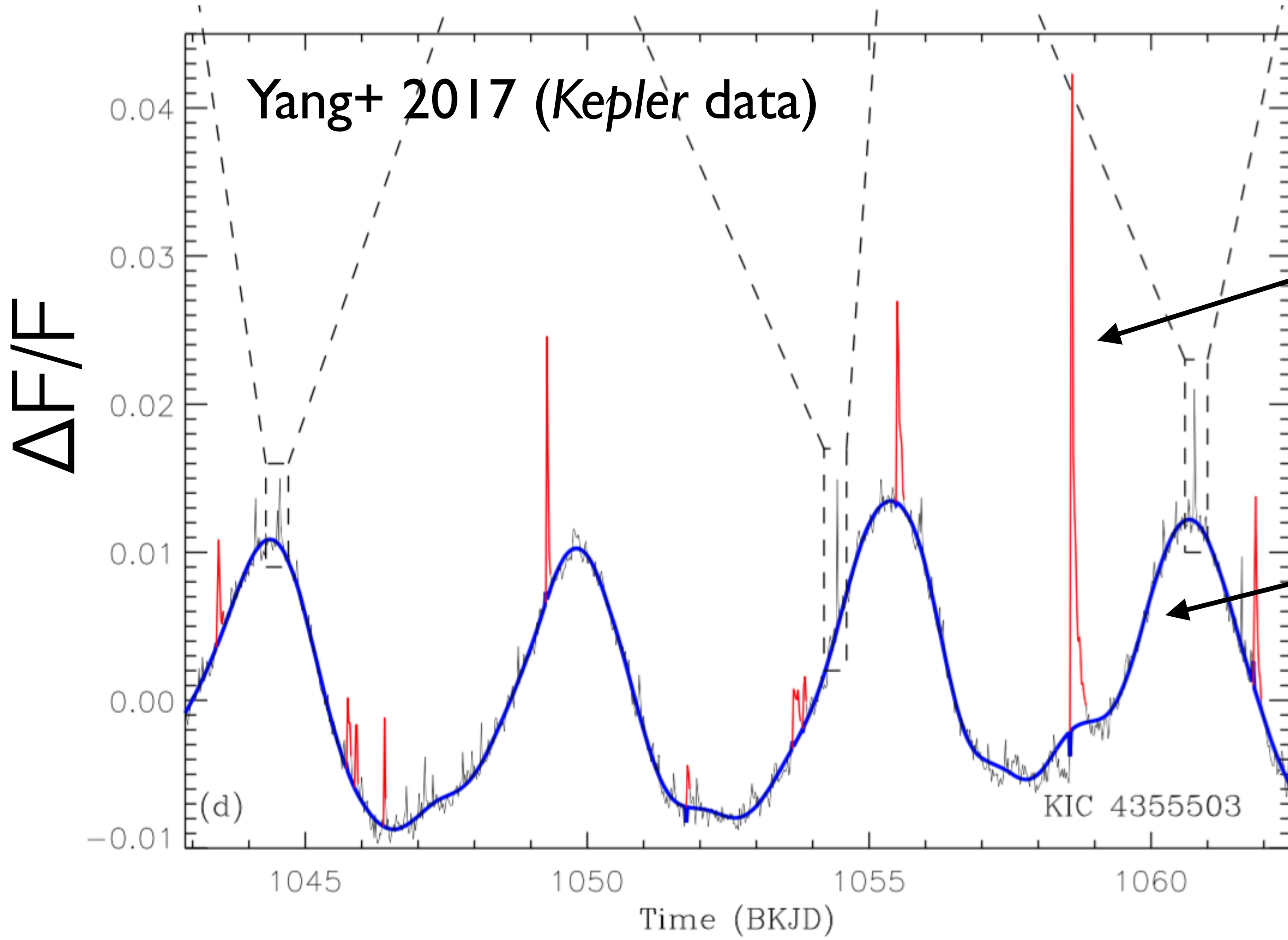
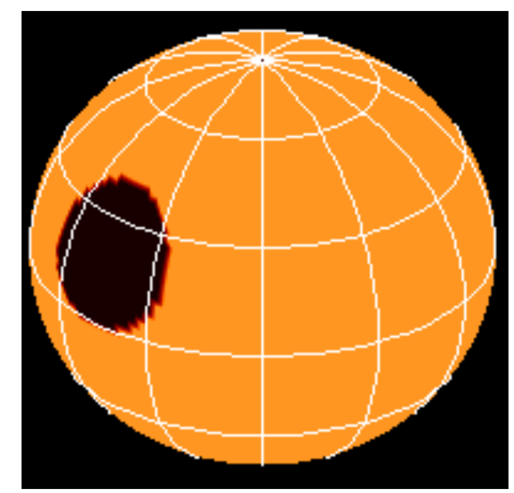
M Dwarf Challenges

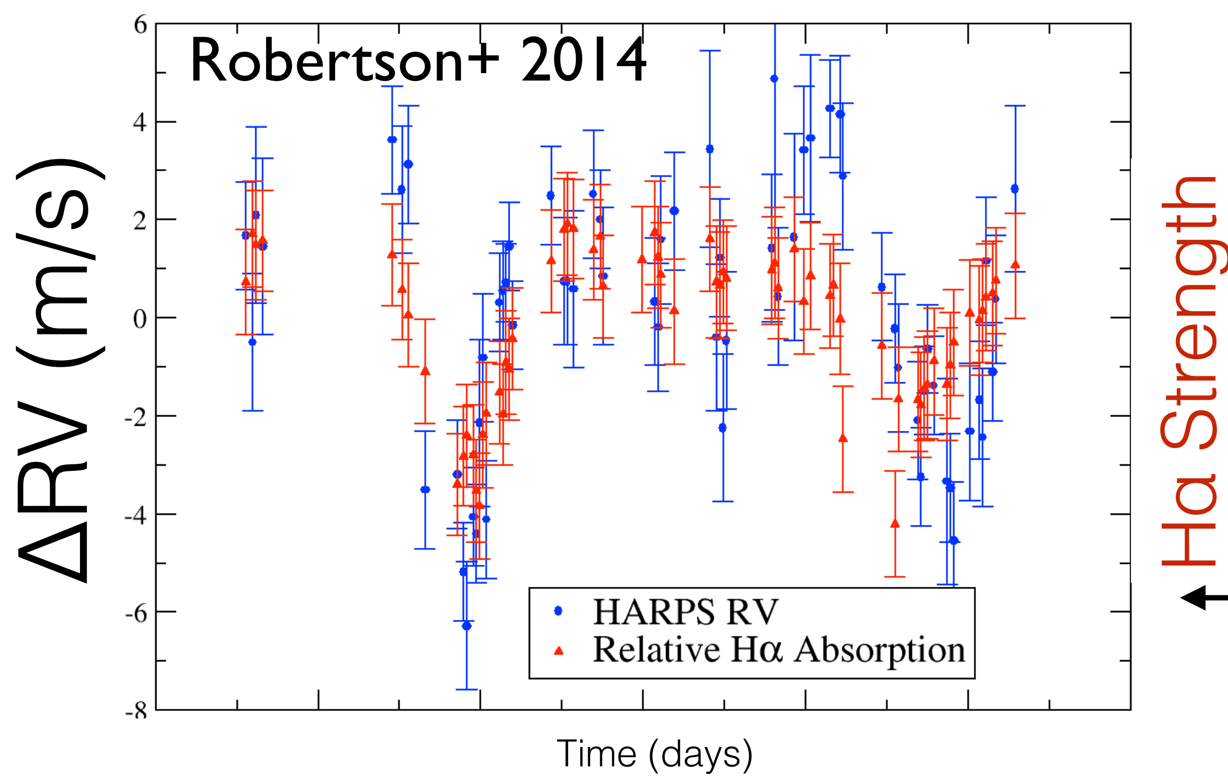


Flares
(chromospheric activity)

Spot-induced
photometric modulation

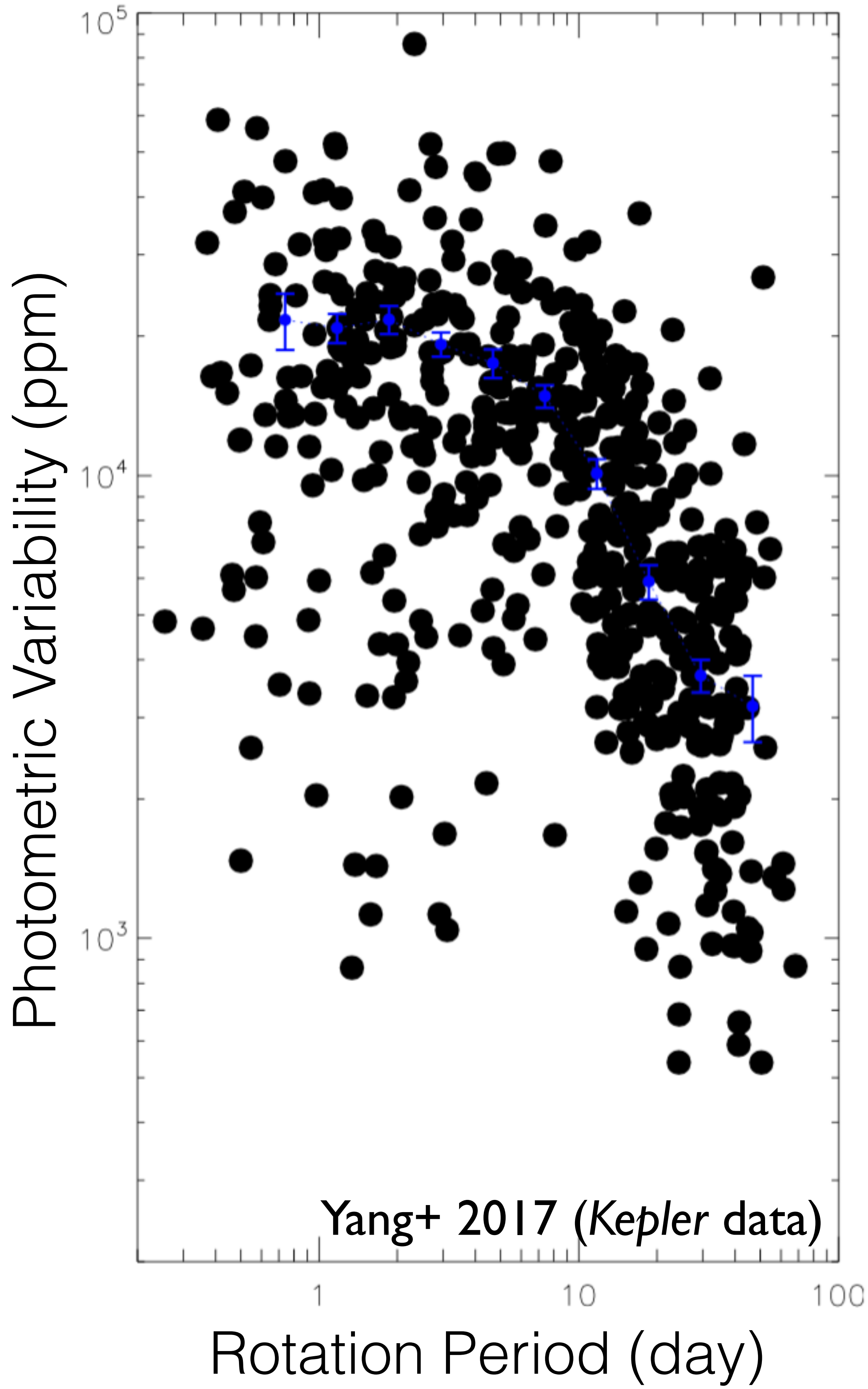


Spots on rotating stars
Periods can be days



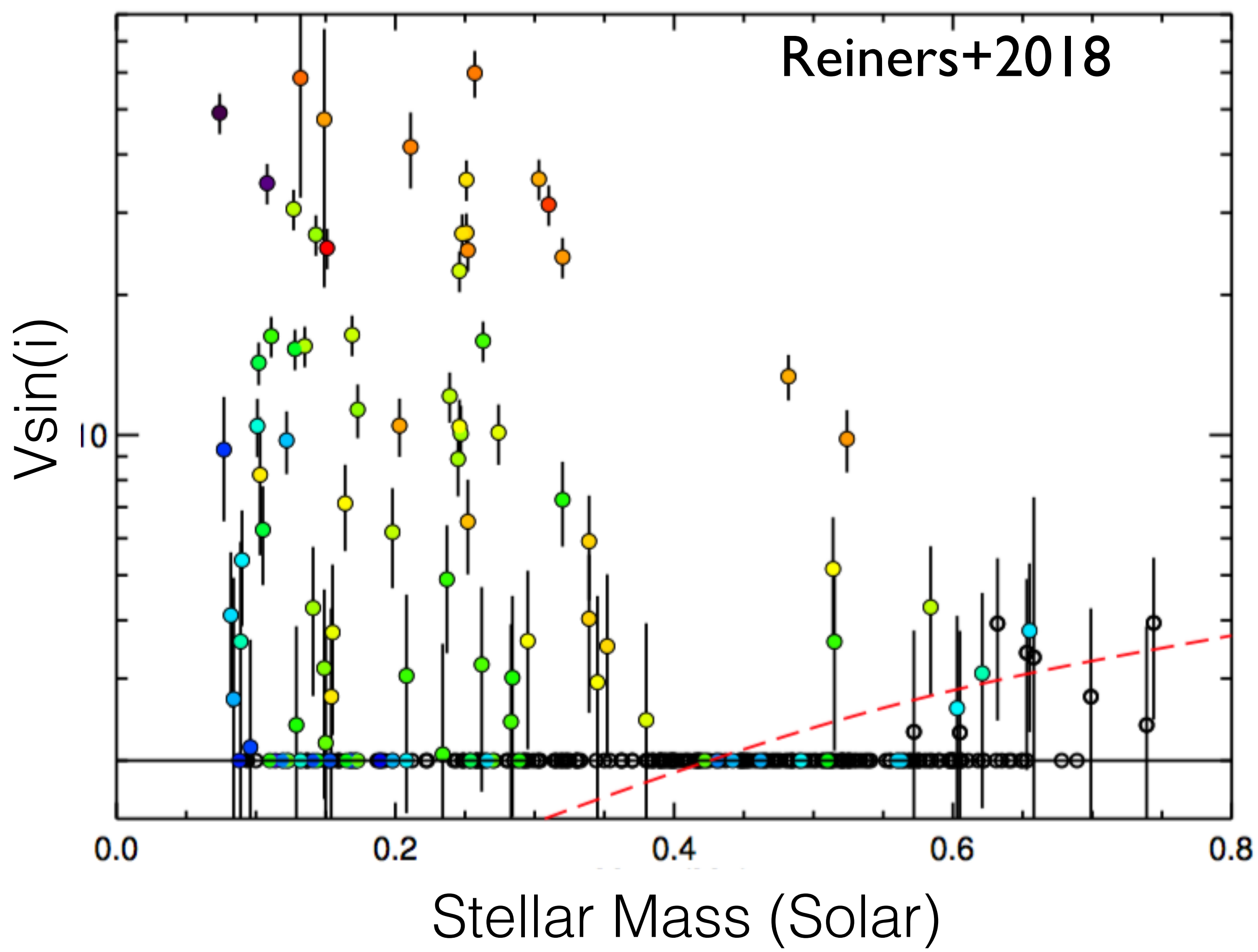
Observed correlation between
optical RV and Hα strength

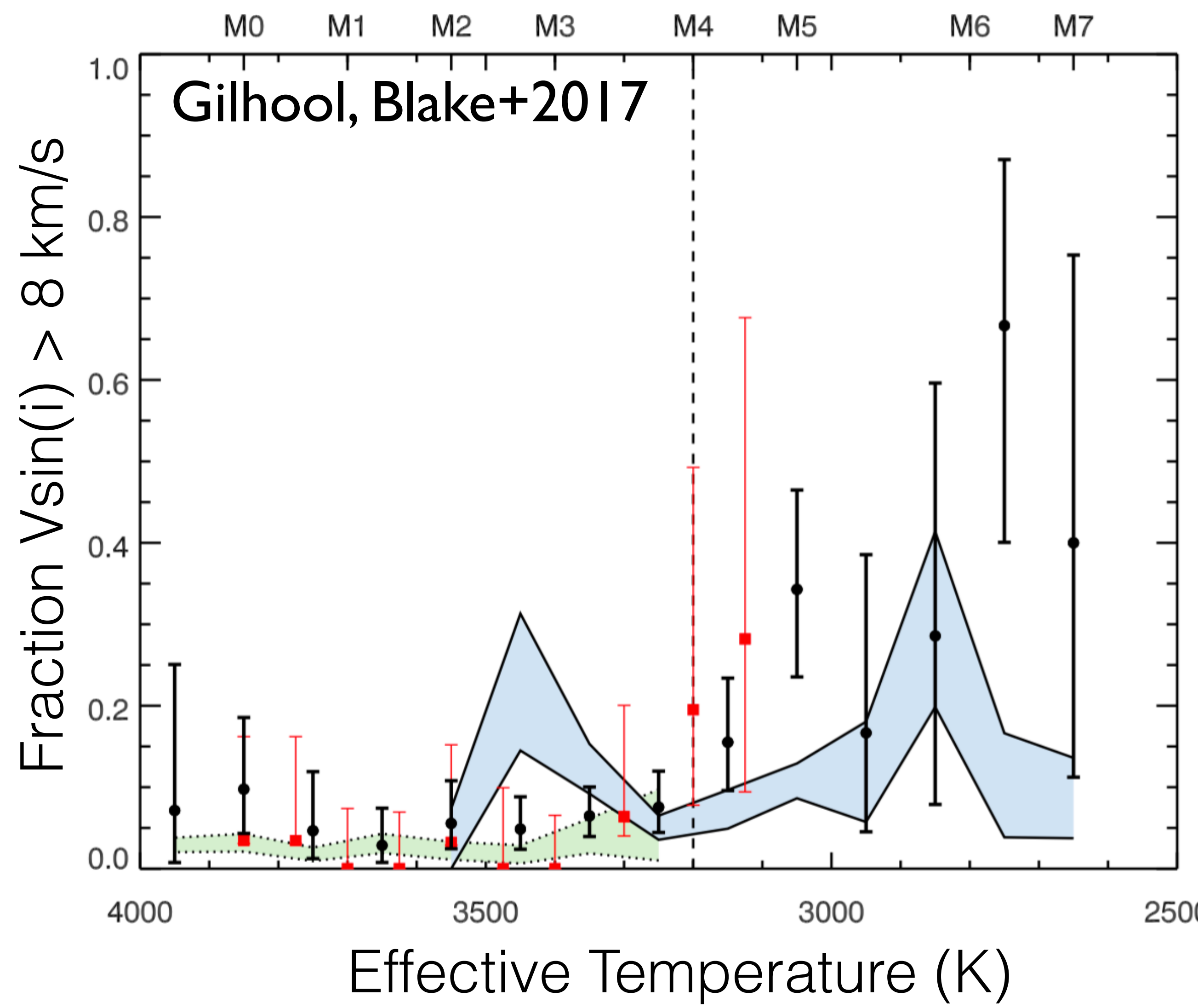
M Dwarf Challenges



<u>*Kepler:* M Dwarfs with Flares</u>	
M0	<10%
M2/M3	20%
M3/M4	22%
M4/M5	27%
M5/M6	45%

M Dwarf Challenges



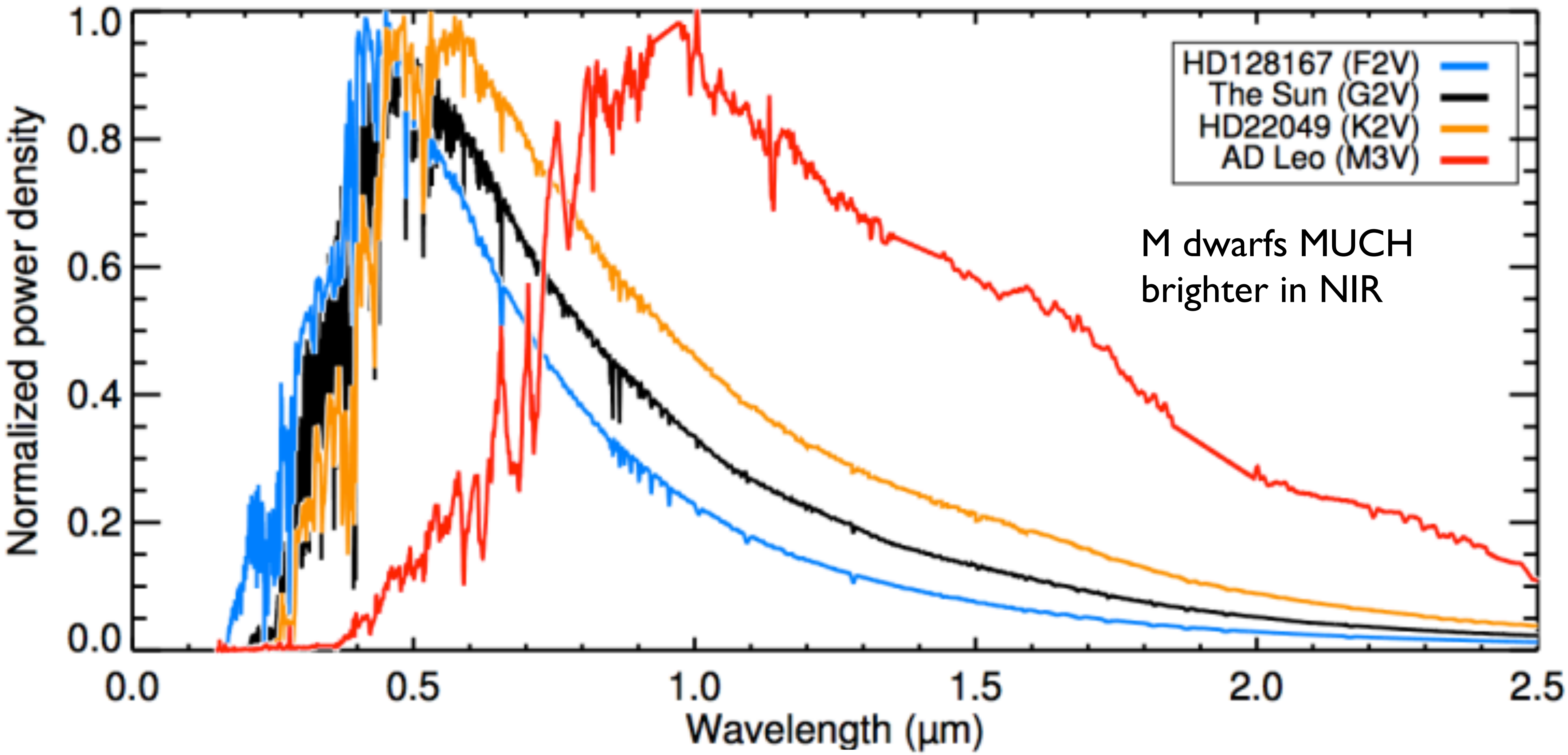


A significant fraction of M4 and later dwarfs rotate faster than 10 km/s

(spot coverage fraction) x (rotation velocity) = RV jitter?

0.02 x 10 (km/s) = not good (m/s)

M Dwarfs - Faint and Red

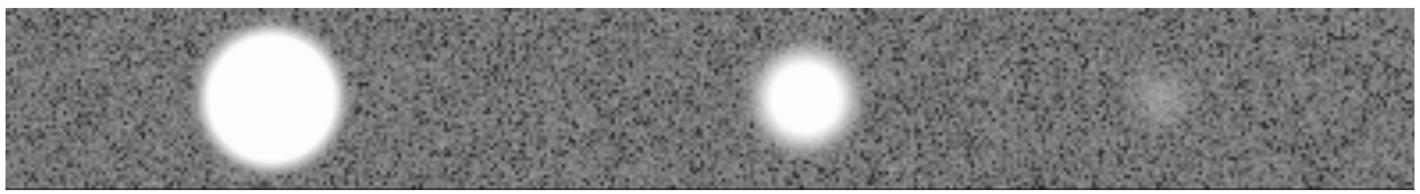


M dwarfs MUCH brighter in NIR

M Dwarfs - Faint and Red

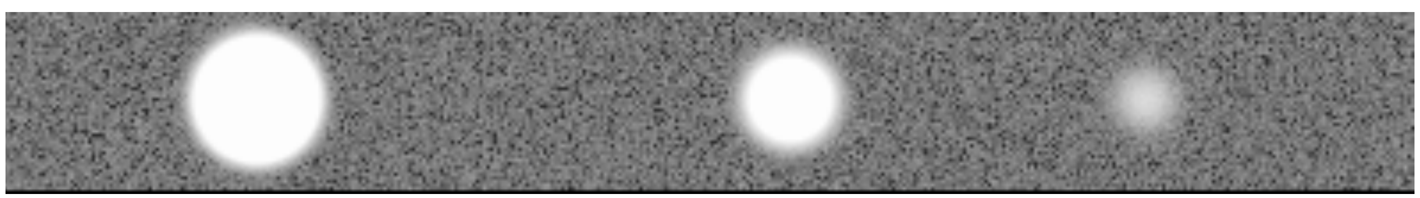
Simulated Images of Stars
Fixed Exposure Times - Stars at Same Distance

G0V M0V M5V



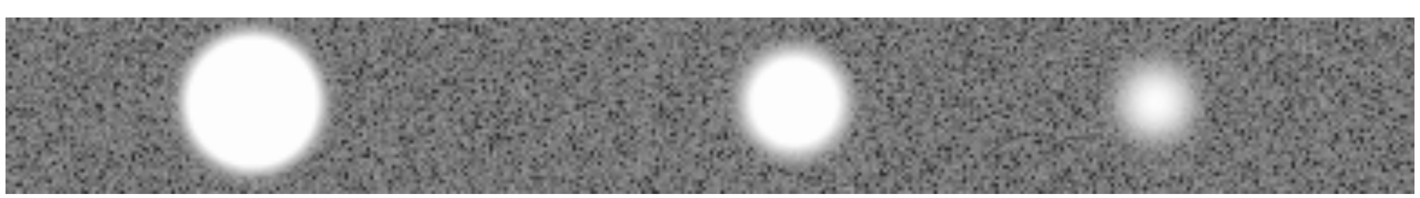
g band - 477 nm

1 : 1/160 : 1/25,000 ← Relative brightness



i band - 763 nm

1 : 1/63 : 1/3,300

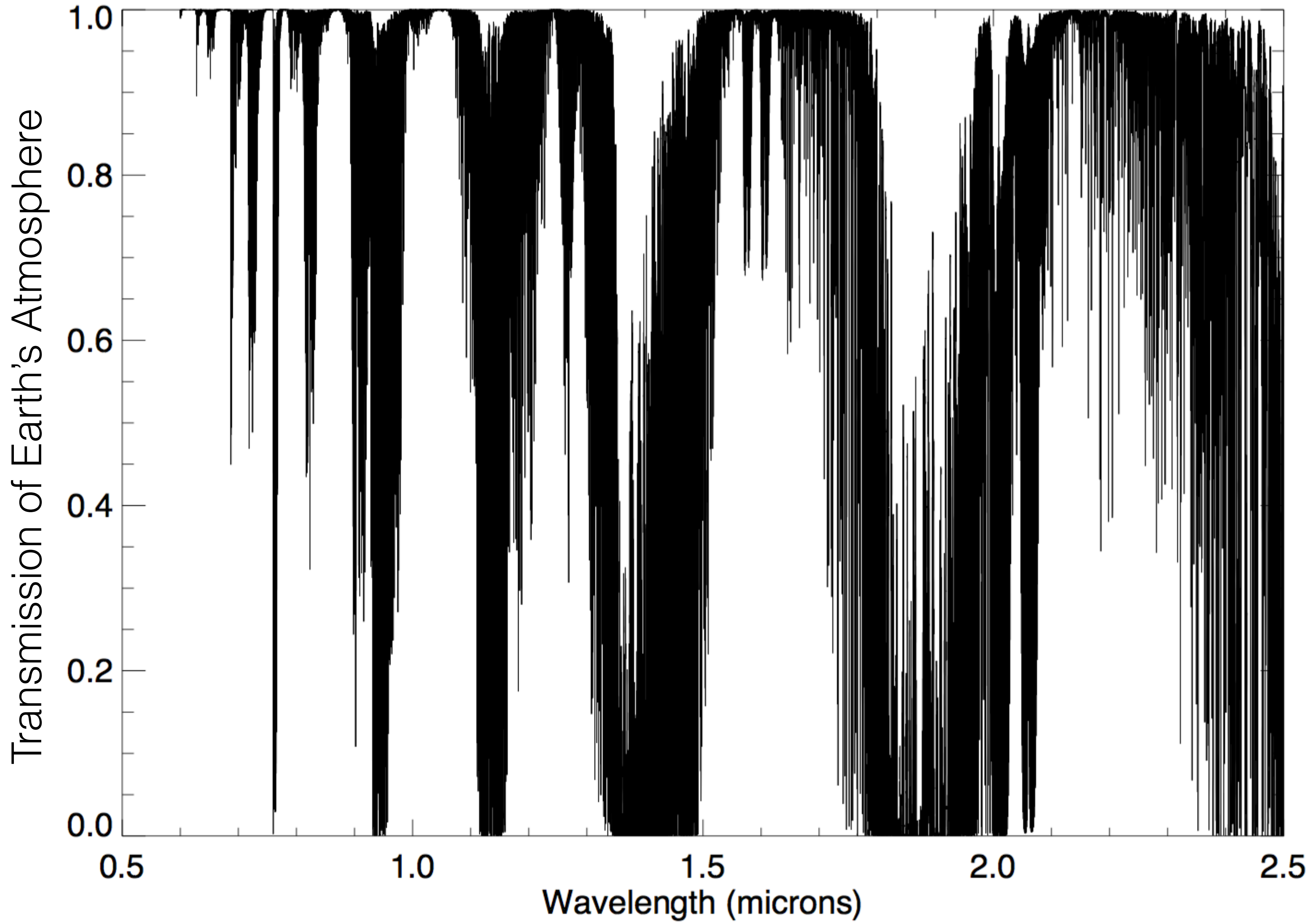


J band - 1252 nm

1 : 1/48 : 1/1,100

M Dwarf Challenges - Telluric Lines

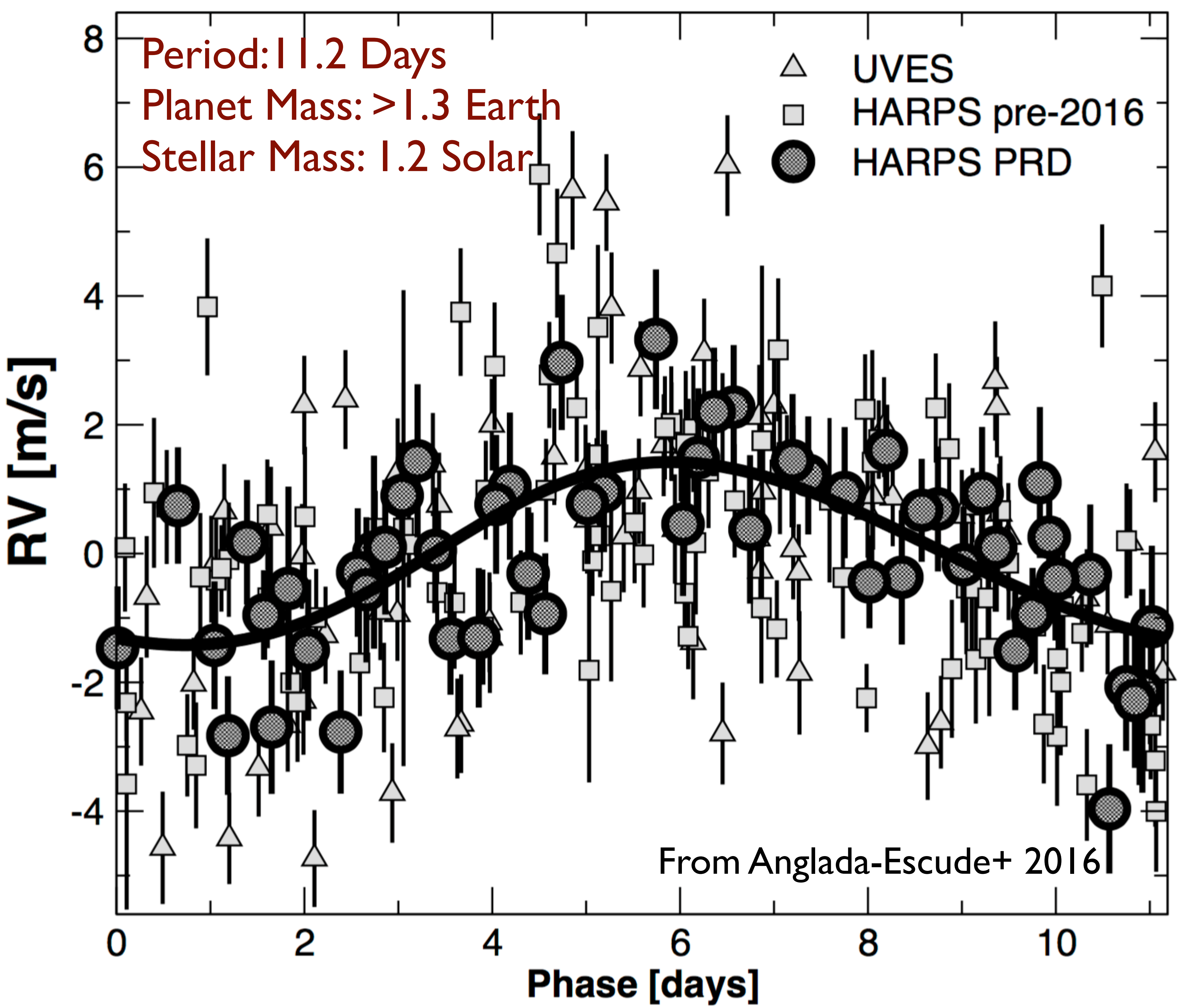
Predominantly H_2O, also O_2 (optical), CH_4, CO_2 (NIR)



Can small lines at λ>700 nm be mitigated to <<1m/s level?

Possibly…but *TBD* - warrants additional investigation!

Proxima Cen b



Exciting Times for M Dwarf RVs

Dozen+ new facilities in 2018-20 designed (at least in part) for PRVs of M dwarfs:

Currently Operational:

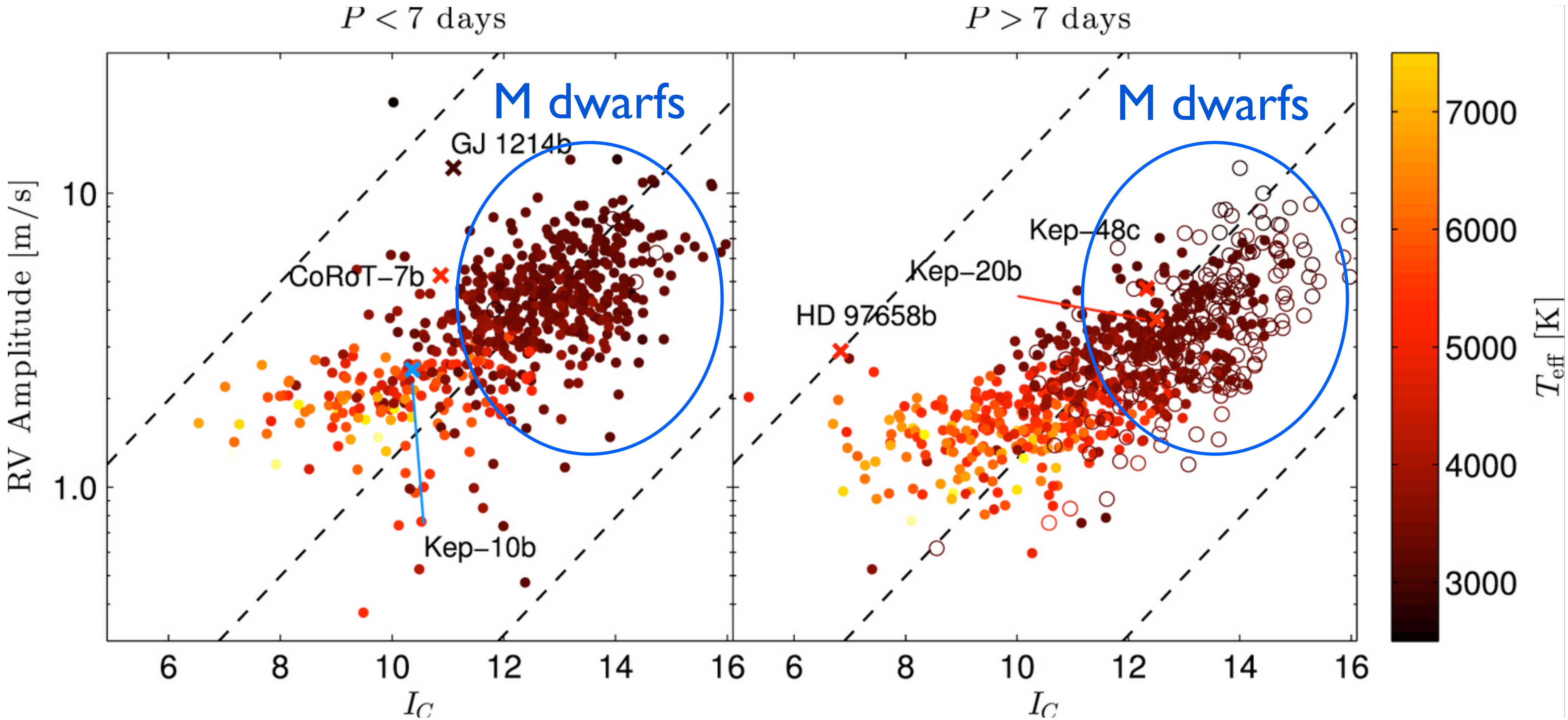
- Habitable Zone Planet Finder - HET
- Carmenes - Calar Alto
- IRD - Subaru
- Spirou - CFHT
- iShell - IRTF

Commissioning in 2019 or 2020:

- NIRPS - ESO 3.6
- NEID - WIYN
- iLocator - LBT
- MINERVA-Red - FLWO
- Marooon-X - Gemini-N
- KPF - Keck
- Veloce Rosso - AAT
- Espresso - VLT
- PARVI - Palomar

Simulated Doppler Signals

TESS Planet Candidates



A very nice plot from Sullivan et al. (2015)

Many planets expected orbiting M dwarfs!

About 650 planets with $\Delta RV > 3$ m/s for $T_{eff} < 3600$ K

MAROON-X

New Radial Velocity Instrument for M Dwarfs at Gemini-N

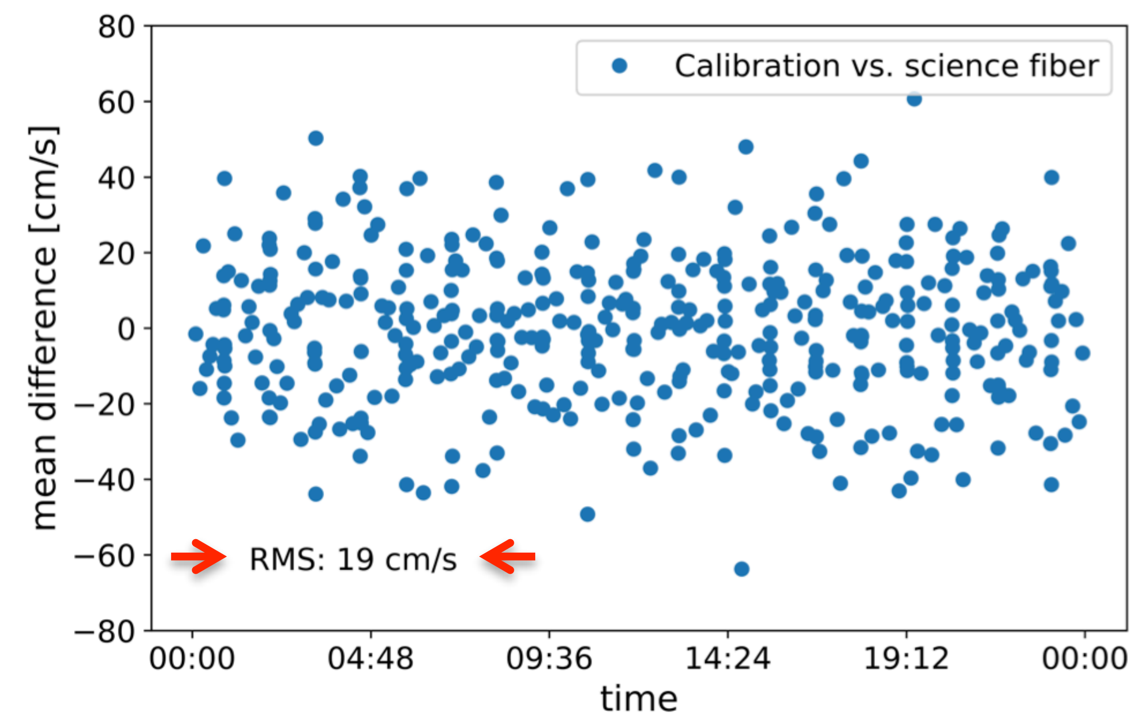
Jacob Bean & Andreas Seifahrt, U. Chicago
arXiv:1805.09276

Primary science driver: RV follow-up of transiting, temperate, and terrestrial planets that are feasible targets for atmospheric spectroscopy (i.e., *TESS* discoveries that are potential high-value *JWST* targets)

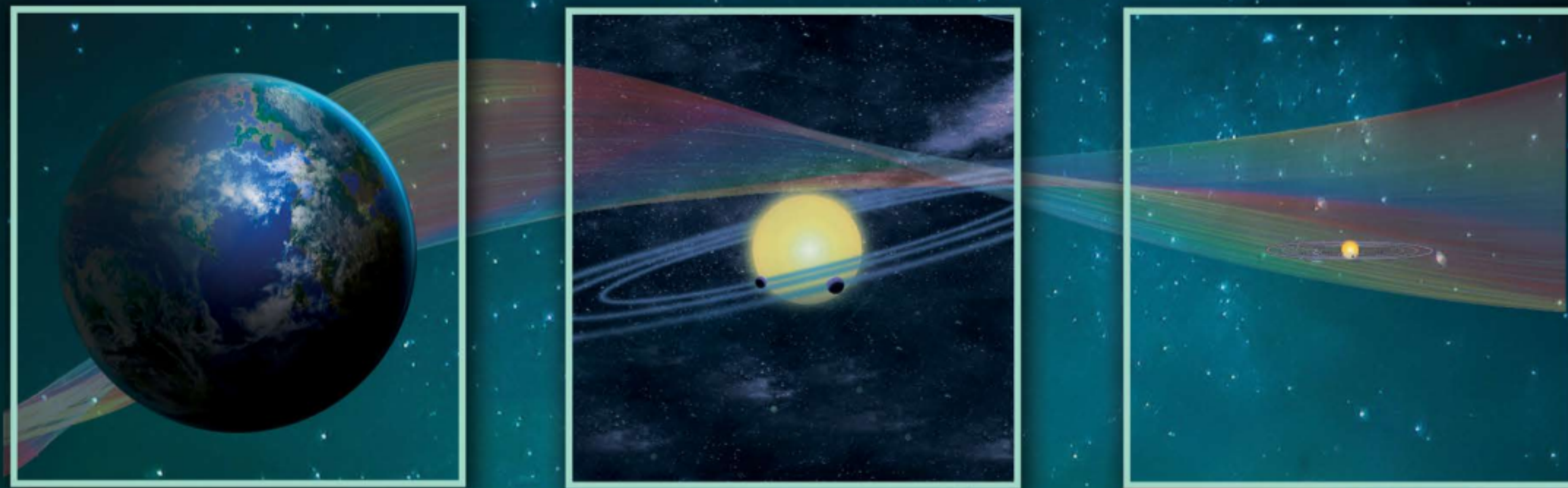
Goal: σ = 1 m s^{-1} in <30 min for late M dwarfs out to 20 pc (V=17.0).

Approach: A highly-stabilized, fiber-fed spectrograph covering 500 – 900 nm at R=80k with simultaneous calibration feed and pupil slicing.

Currently: Final integration and lab testing ongoing, commissioning to begin in Q1 2019



Instrument stability tests suggest <<1m s^{-1} performance will be achieved



NEID:

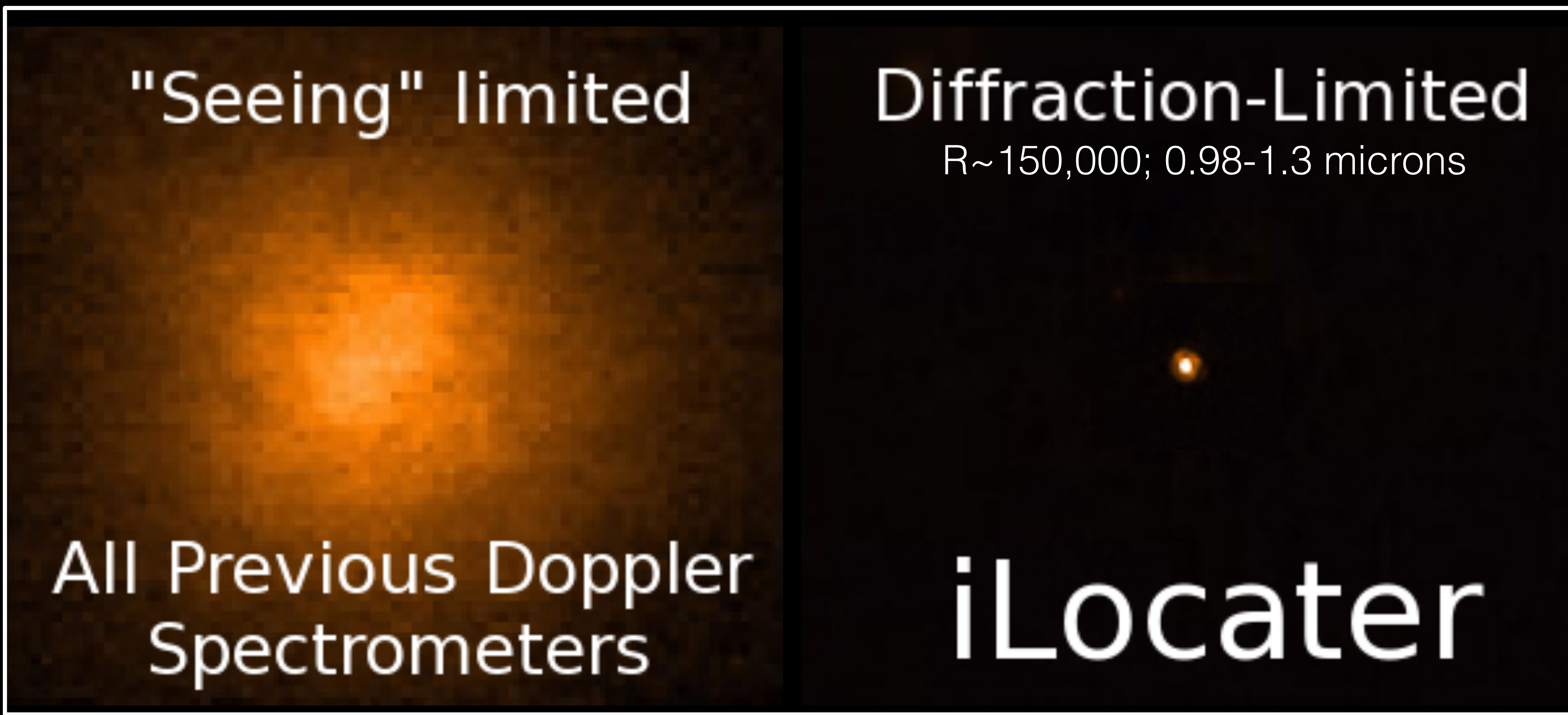
A next-generation Doppler spectrometer for the WIYN telescope

Wavelength Coverage: 380 to 930 nm at R=100,000
Optimized for red optical performance: deep depletion CCD
Extreme thermal stability: sub-milli Kelvin temperature variations
Instrumental precision: Better than 50 cm/s
Commissioning in Q1 2019

Funded by NASA and the NSF – PI Suvrath Mahadevan at PSU

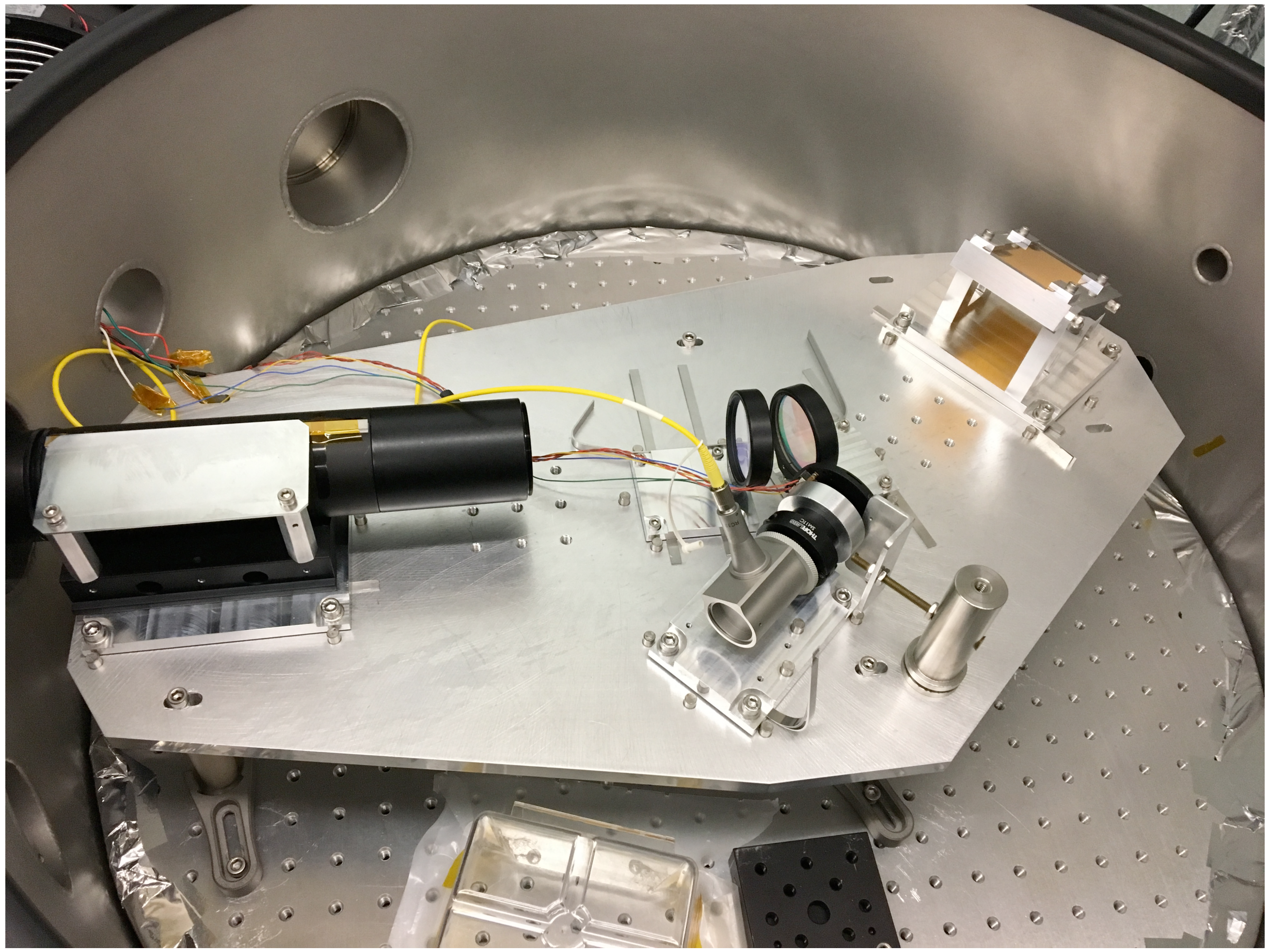
A Diffraction-Limited Doppler Spectrometer for the LBT

PI: Justin R. Crepp, Notre Dame



Crepp 2014, Science; Crepp et al. 2016, SPIE

MINERVA-Red



Single-mode fiber input
R~50,000; 840-920 nm
High throughput
milli-Kelvin temperature stability
Mostly "off the shelf" parts

Robotic 0.7 m telescope

Supported by NASA through RTF program

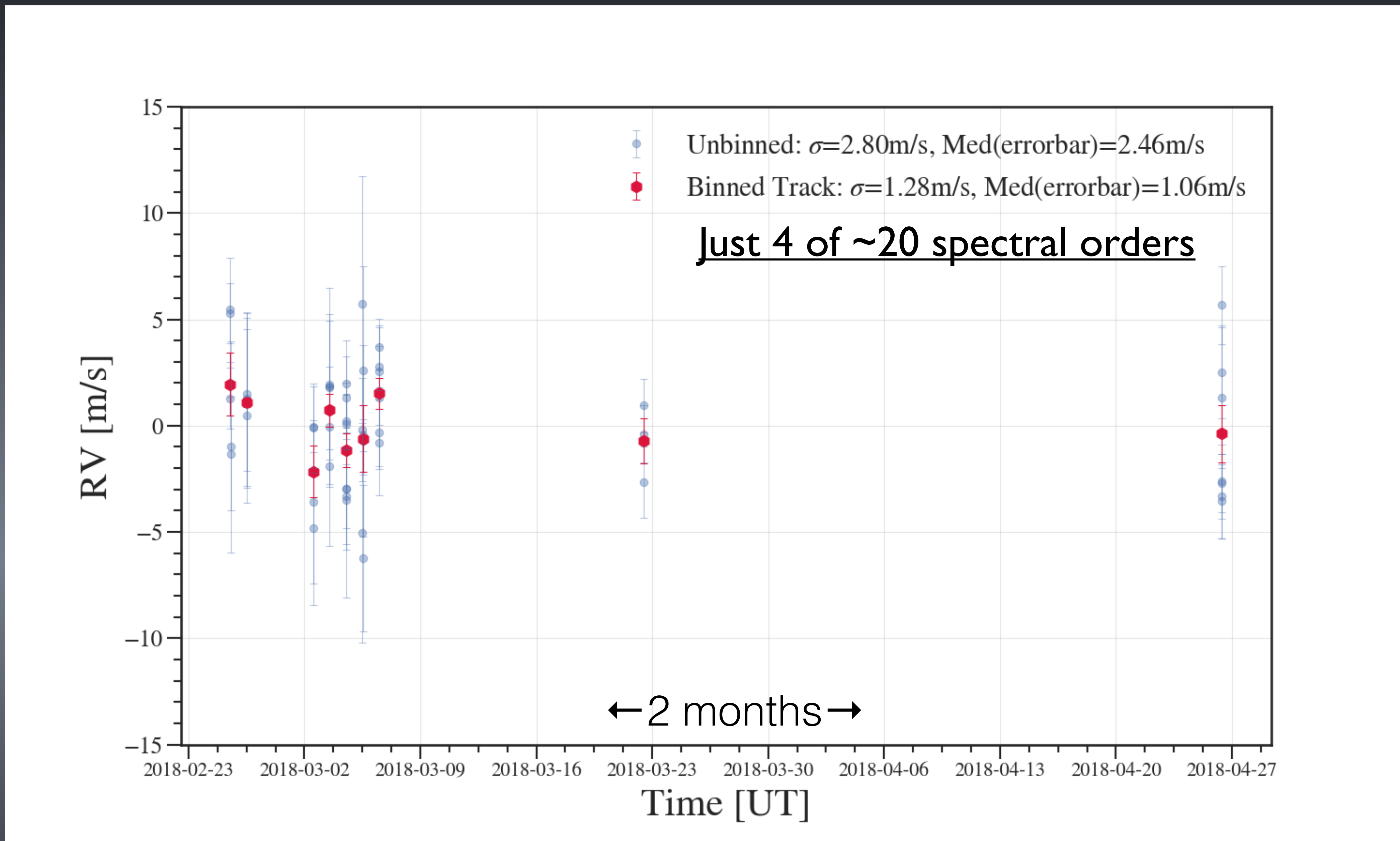
The Habitable Zone Planet Finder

- R ~ 55,000, fiber-fed NIR spectrograph (0.8-1.3um)
- Simultaneous calibration fiber
  - Highly temperature and pressure stabilized
- Deploy at 10m Hobby-Eberly Telescope in 2017
- Survey 100 M dwarfs (1-3 m/s RV precision)

PI - Suvrath Mahadevan

sites.utexas.edu/het/

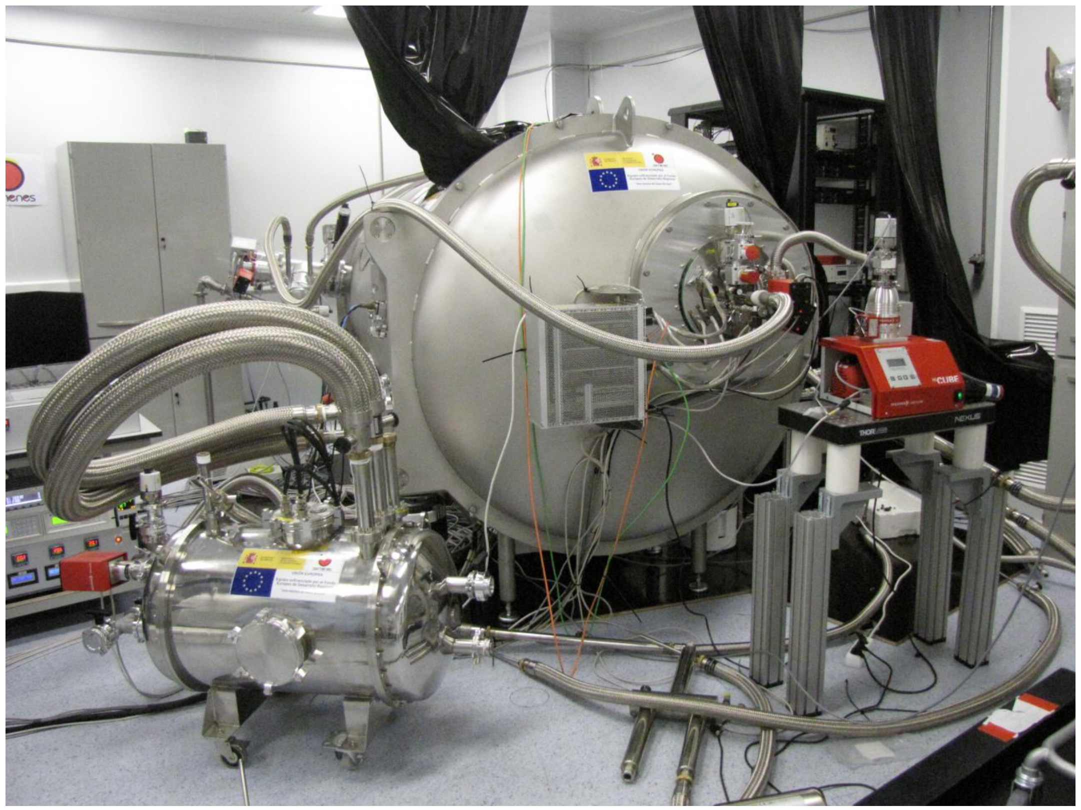
HPF's current on-sky RV Precision



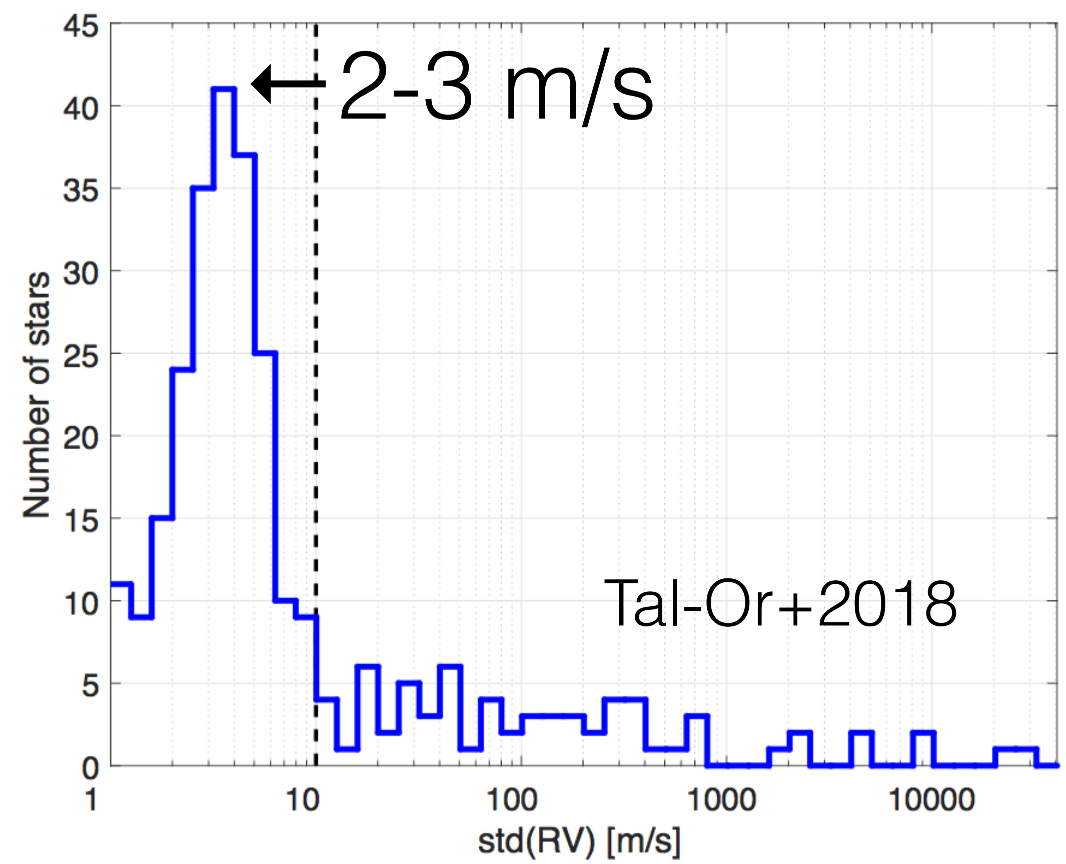
Barnards Star (GJ 699) , rms <1.3 m/s

Credit: S. Mahadevan

carmenes



R~80,000 Optical (500 to 960 nm) *and* NIR (960 to 1700 nm)



Located at Calar Alto

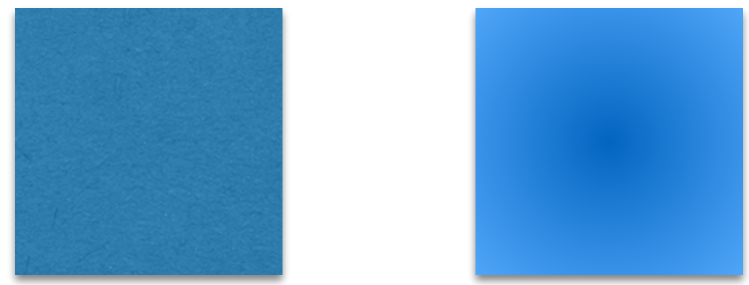
PI - Andreas Quirrenbach

<u>Optical</u> measurements of ~300 M dwarfs

In optical: 30% of mid-M Dwarfs exhibit intrinsic RV scatter >10 m/s

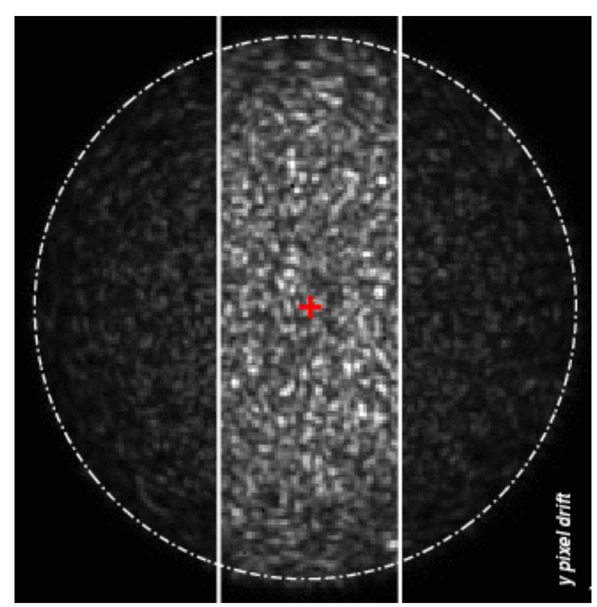
Hardware Challenges

NIR detectors (or thick CCDs): Noise properties, pixel properties



Pixels uniformly sensitive? Adjacent pixels correlated? Diffusion?

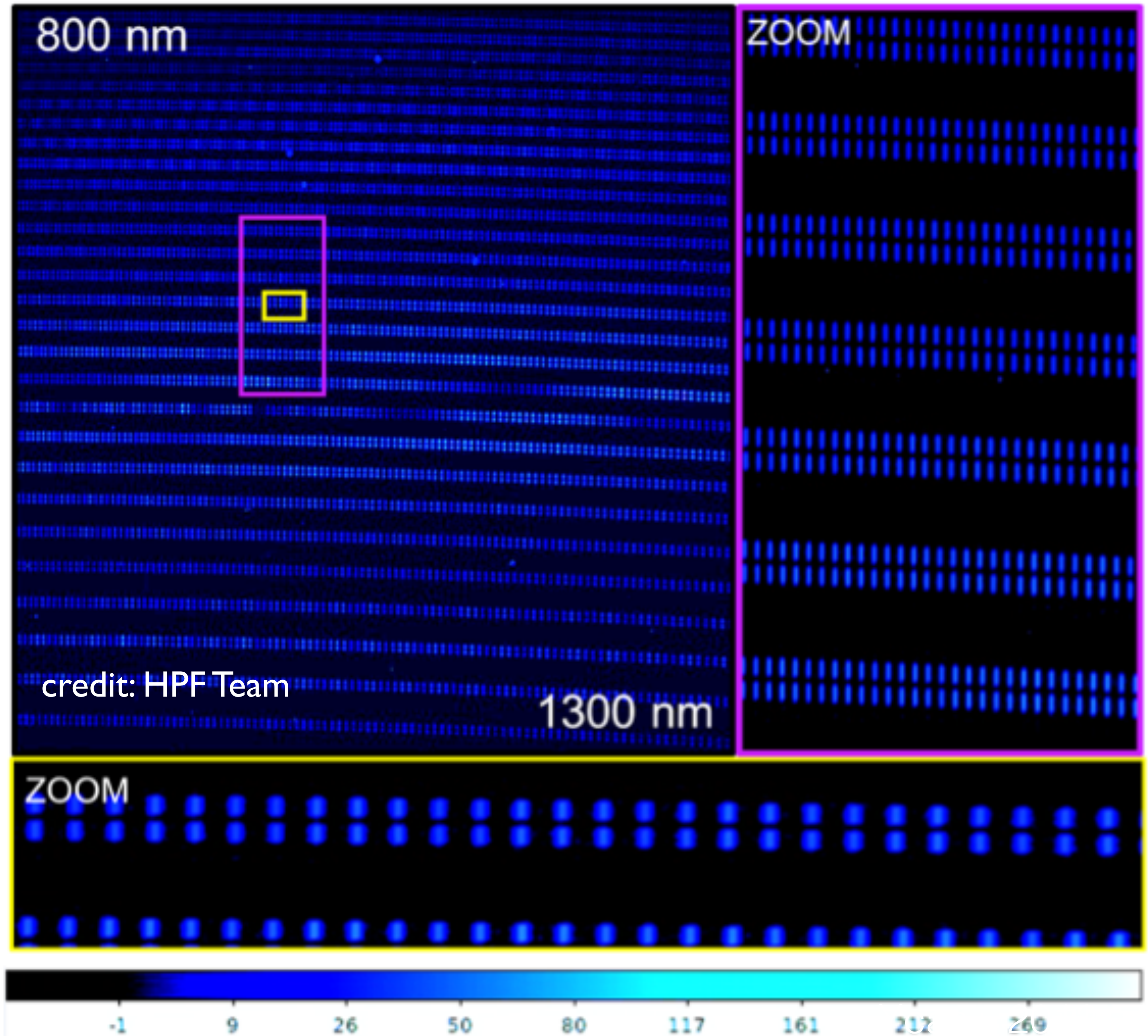
Modal noise in optical fibers: usually worse at longer wavelengths



Credit: Sam Halverson

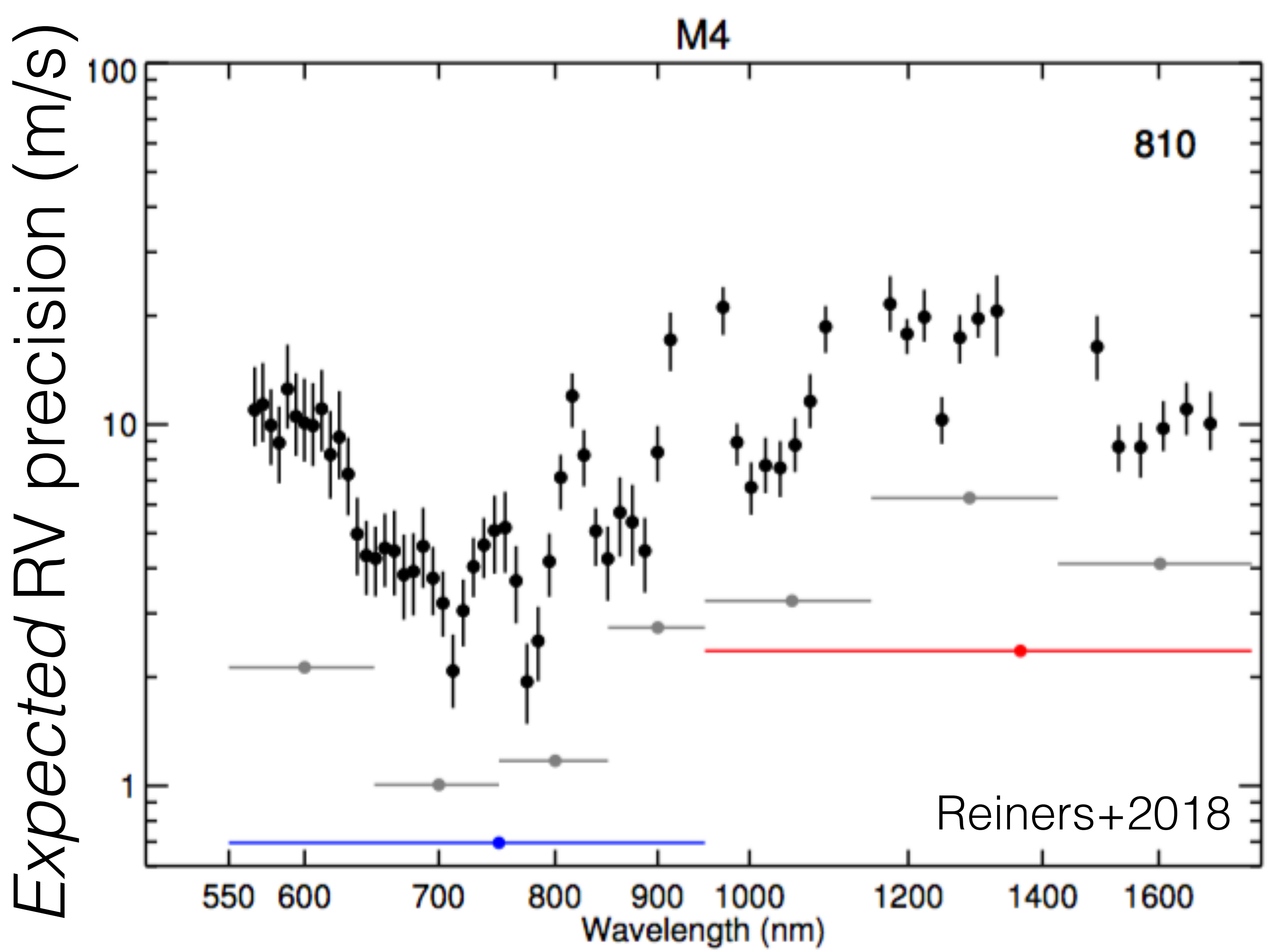
What are the best methods for suppressing modal noise?

Hardware Challenges



How to use frequency combs and etalons to understand our detectors/instruments and achieve optimal RV performance?

What is the Optimal Spectral Region?



For almost all M dwarfs, 700 nm to 900 nm *appears* optimal

Caveats: Intrinsic stellar RV noise could be *much* better in NIR

Dealing with telluric lines in RV analyses

Astrophysical Noise Sources

Spots modulated by rotation: could be 100+ m/s

Depends on star/spot contrast, rotation, spot coverage

Spots also impact convective shifts (Kürster+ 2013)

Reiners+(2010), Barnes+(2011)

Zeeman Splitting: could be 10s of m/s

M dwarfs can have large magnetic fields

Reiners+(2013)

Chromospheric Emission: could be 10s of m/s

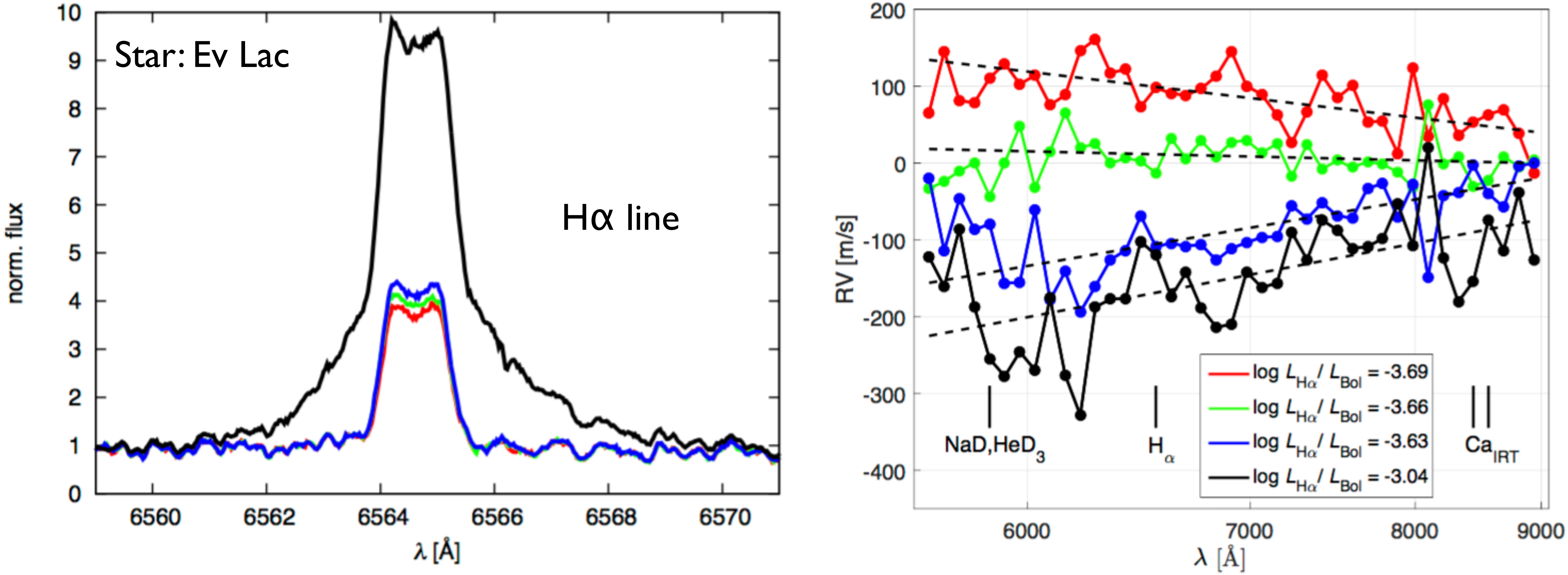
Observed correlations between RV, Hα, photometry

Tal-Or+(2018)

<u>Signals could be different in optical and NIR</u>

Astrophysical Noise Sources

From Tal-Or+(2018)



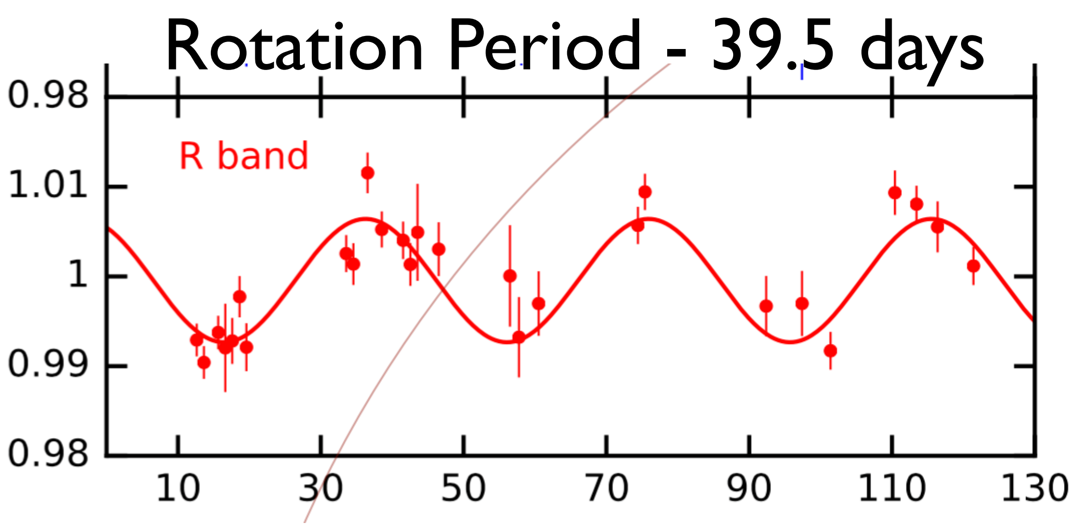
Four different carmenes epochs, four different Hα emission levels

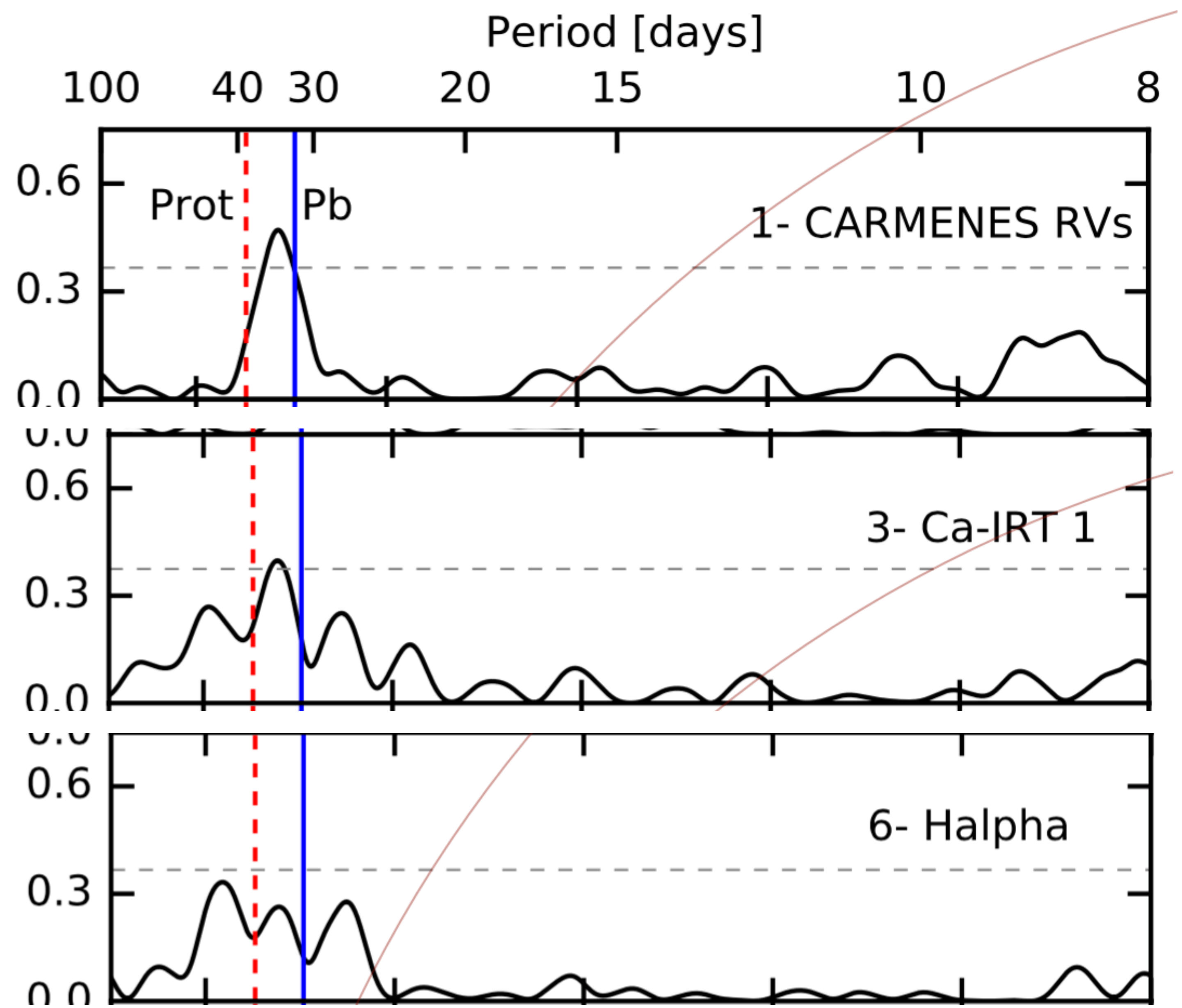
Measured RV is a function of wavelength, Hα strength

➜But not *as strong* at 900 nm as 600 nm

Astrophysical Noise Sources

Kepler K2-18 - Transiting planet with P=32.94 days





Recovering low-level RV signals when planet period is *known* is a project

GLS periodograms of carmenes optical RVs, Ca IR triplet line shape, Hα line shape

From Sarkis+2018

Conclusions

A very exciting time for M dwarf PRV studies:

➜Many instruments coming on line in next two years

Years of work by community has solved many technical challenges:

➜1-3 m/s RVs for large samples of M dwarfs within reach

Important challenges remain:

➜How best to deal with telluric lines at red/NIR wavelengths

➜How best to incorporate activity- and spot-related information into RV analyses

Contemporaneous characterization of astrophysical noise:

➜Key part of RV measurement process, not just ancillary data

➜Probably more data required to detect planet with given period, semi-amplitude if host is an M dwarf (e.g. Barnes+2011)

Approximate M Star Physical Properties

Problem: Spectral type is a blunt instrument

Sp. Type	Teff (K)	R/R_s	M/M_s	M_V +/-0.5	M_J +/-0.5
M0	3900	0.57	0.59	9.3	6.1
M1	3500	0.4	0.41	10.9	7.1
M2	3450	0.37	0.38	11.1	7.3
M3	3400	0.33	0.34	11.4	7.5
M4	3200	0.18	0.14	14.3	9.4
M5	3100	0.15	0.12	14.7	9.8
M6	2800	~0.1	0.11	15.2	10
M8	2600	~0.1	0.08	18.3	11

Using: Boyajian et al. (2012) - interferometric radii + parallaxes
Rajpurohit et al. (2013) - Sp. Typ. and Teff from spectral fitting
Delfosse et al. (2000), Bonfils et al. (2013) - Abs. Mag. from Mass

See Also: Mann et al. (2013); Lepine et al. (2013)
See paper by Harvard grad student Elisabeth Newton (Newton et al. 2013)

Challenges of M Dwarfs

$$\sigma_{RV} \propto \frac{1}{SNR}\frac{1}{R}\frac{1}{Q}\frac{1}{\sqrt{B}}\left(v\sin i\right)^{0.6}$$

SNR - Signal to Noise per resolution element

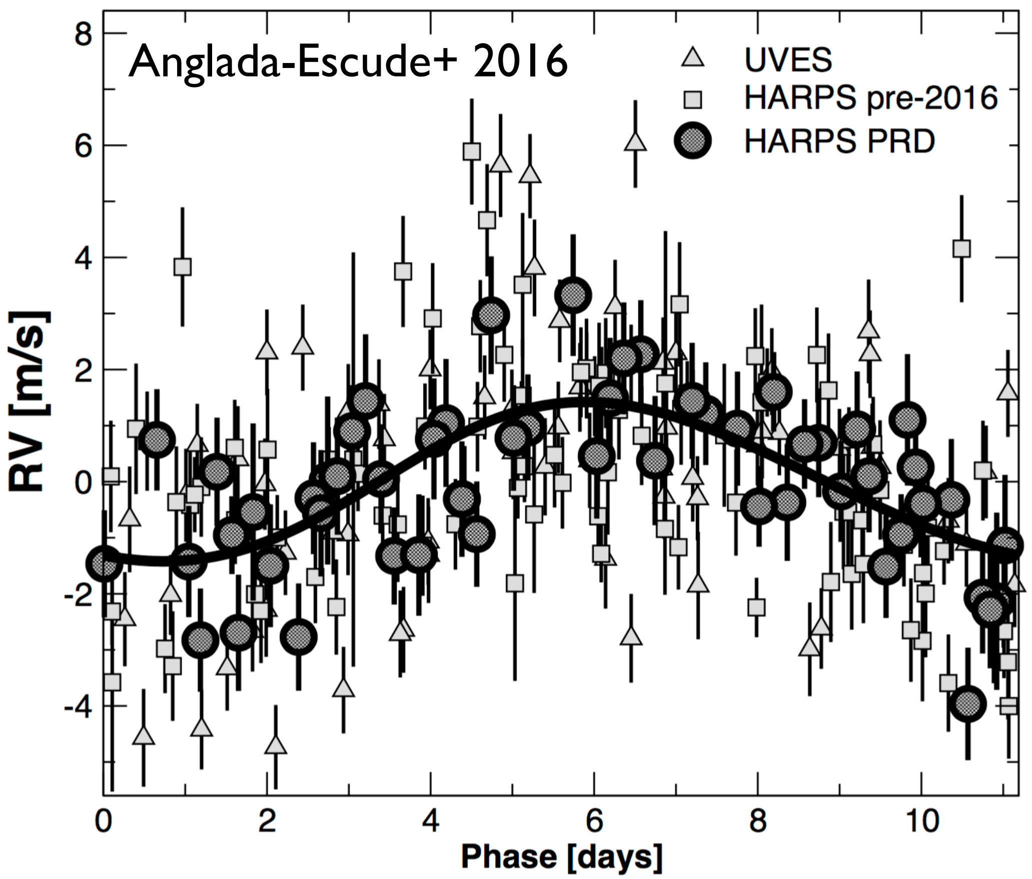
Q - "Quality Factor" (line sharpness, depth, number)

R - Resolution - λ/Δλ

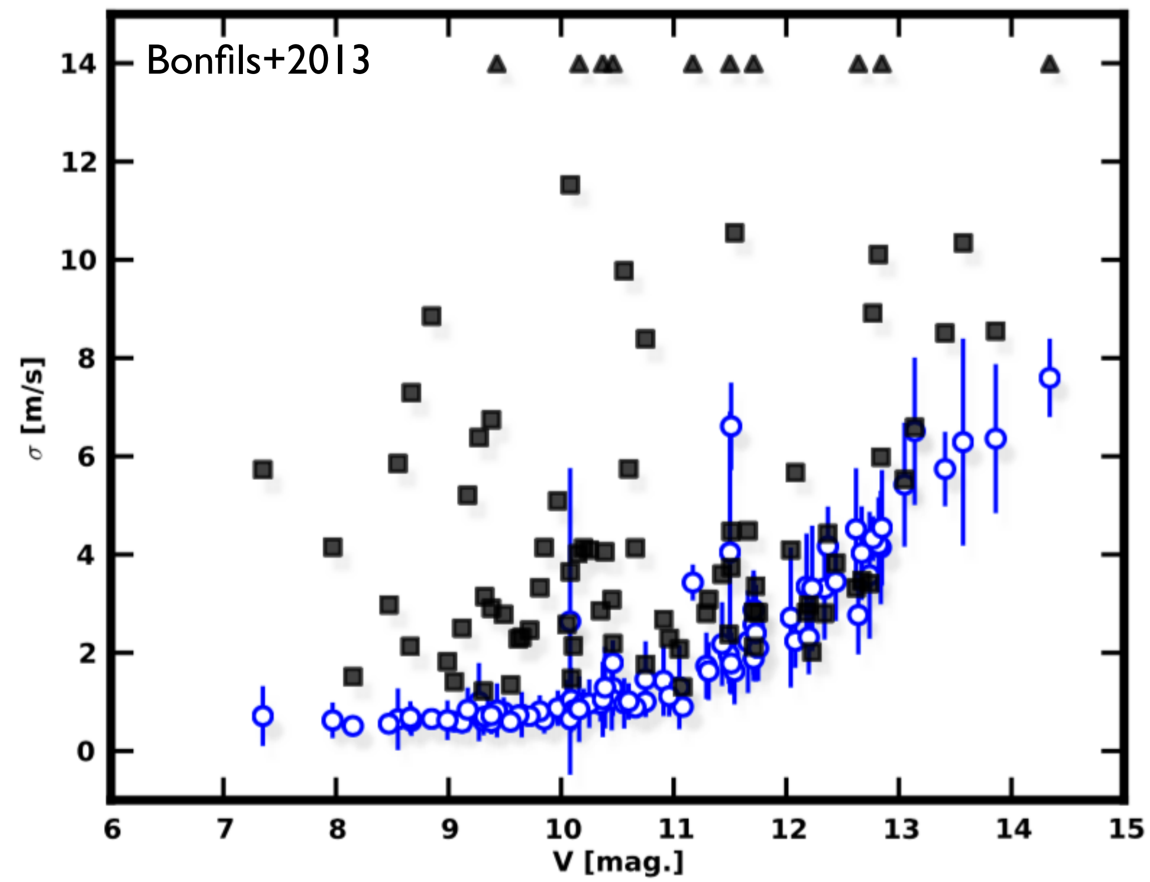
B - Bandwidth of spectrum (wavelength coverage)

Vsin(i) - Projected Rotation (fast rotation is bad)

Photon Limited Doppler Precision - Following Bouchy+ (2001), Reiners+ (2018)

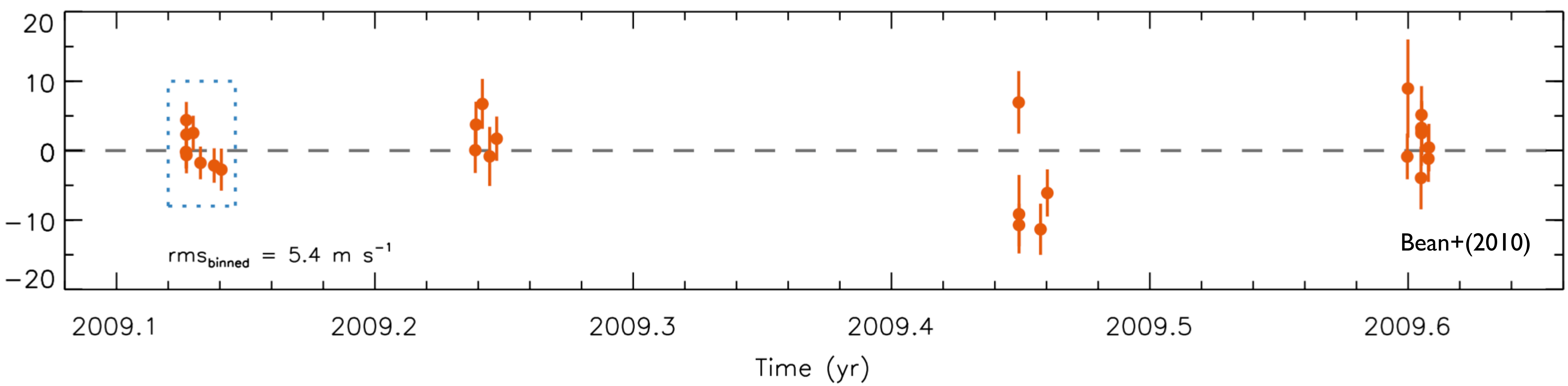


Proxima Cen +/- 1.2 m/s
with HARPS+photometry



M dwarfs observed with HARPS

Proxima Cen +/- 5m/s with CRIRES



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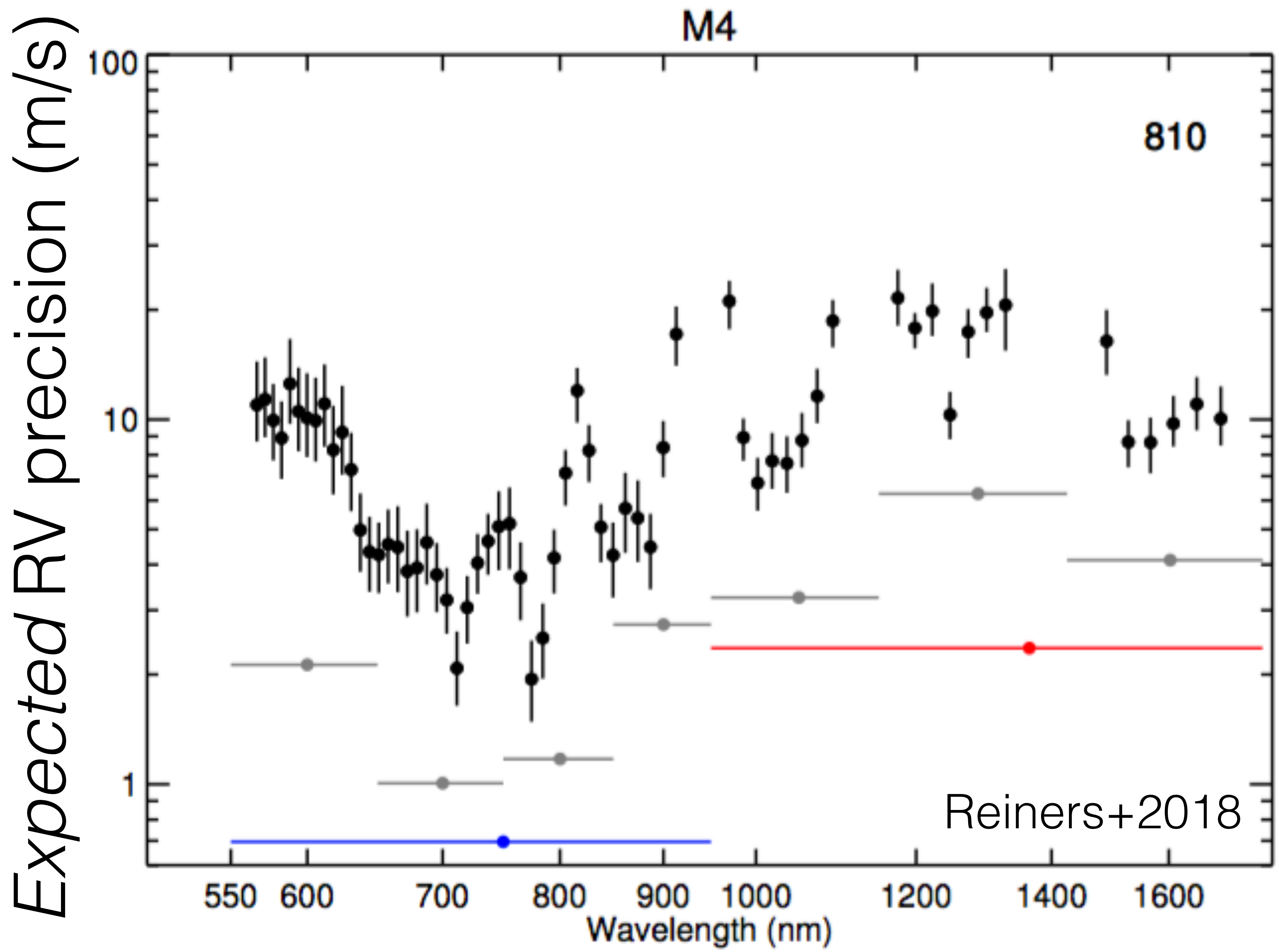

Carmenes spans optical and NIR - direct comparisons possible

Trade-off: S/N (⬆NIR) vs. spectral content (⬆optical)