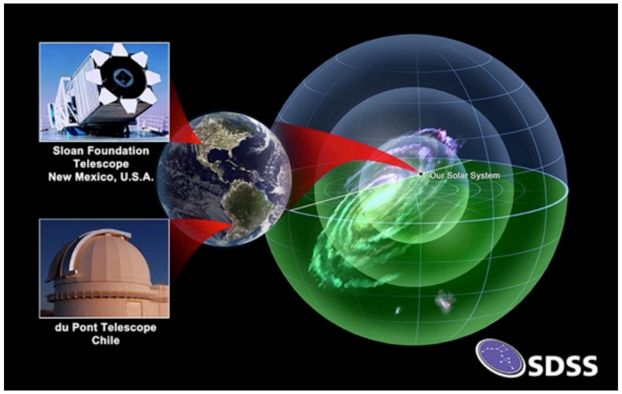
Stellar Characterization and Detailed Chemistry in Exoplanet-hosting M-dwarfs with APOGEE Spectra

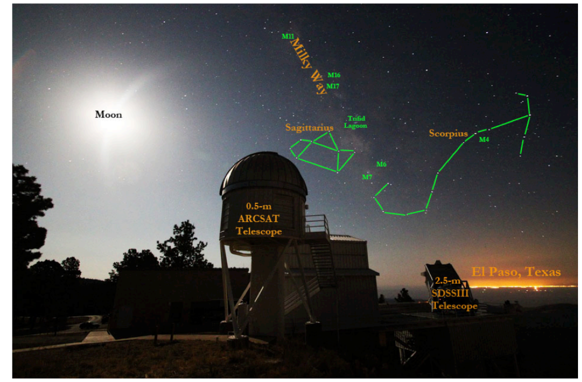
(Apache Point Observatory Galactic Evolution Experiment)



Verne V. Smith NOAO

Katia Cunha (UA)

Diogo Souto (ON)



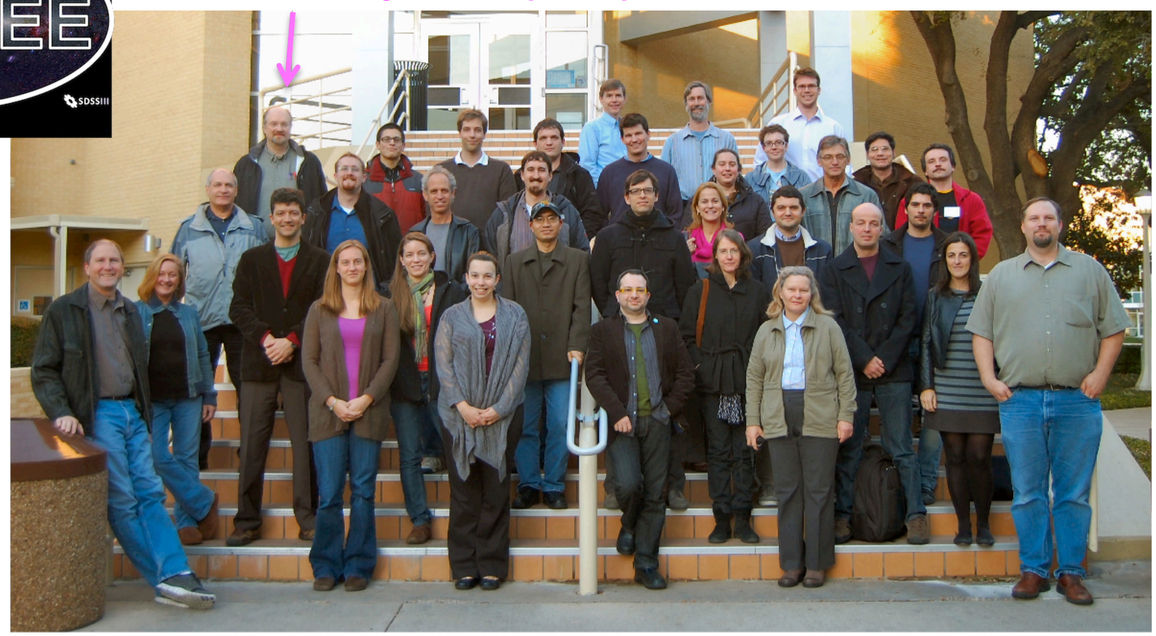
- What is APOGEE?

- Exoplanet Host Stars and APOGEE

- Stellar Characterization for Exoplanet-hosting stars → especially M-dwarfs

- Pioneering quantitative spectroscopic analysis of M-dwarfs

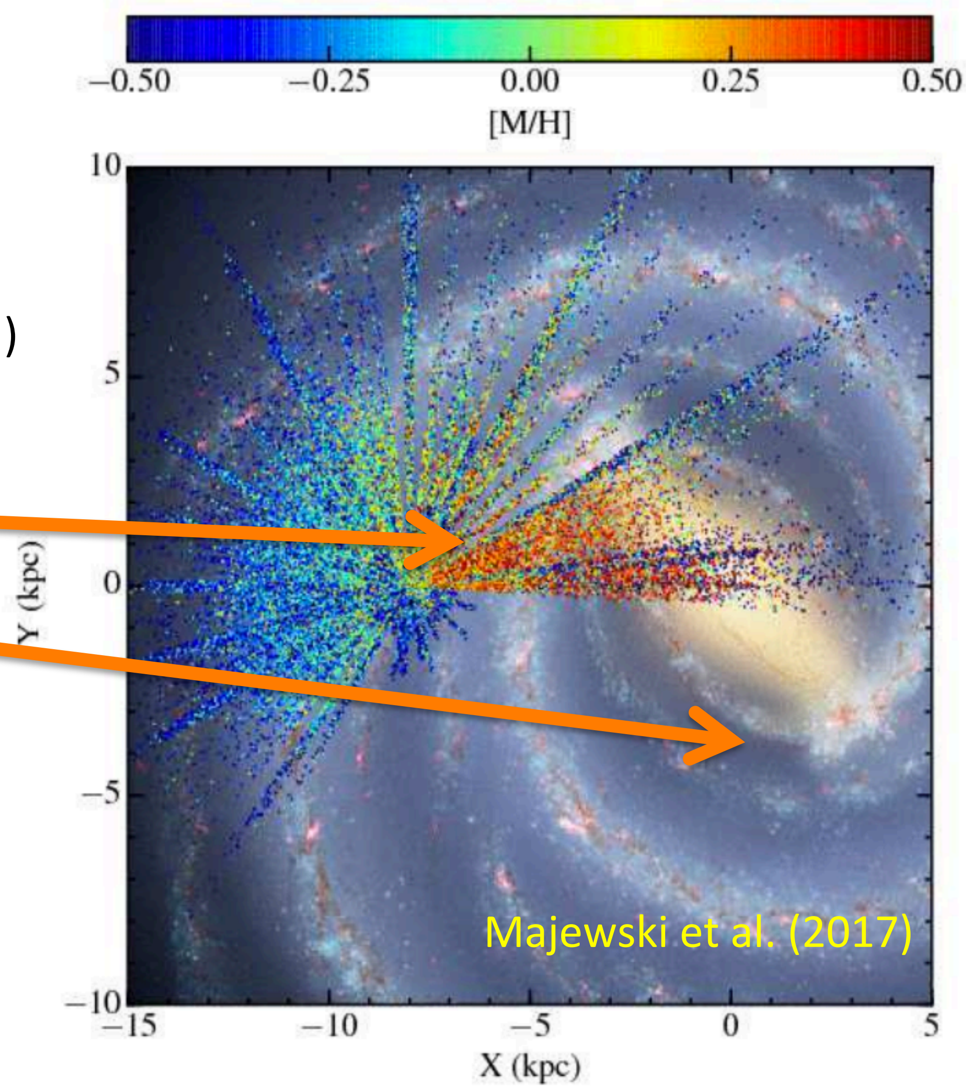
PI=Steve Majewski (UVa)



What is APOGEE?

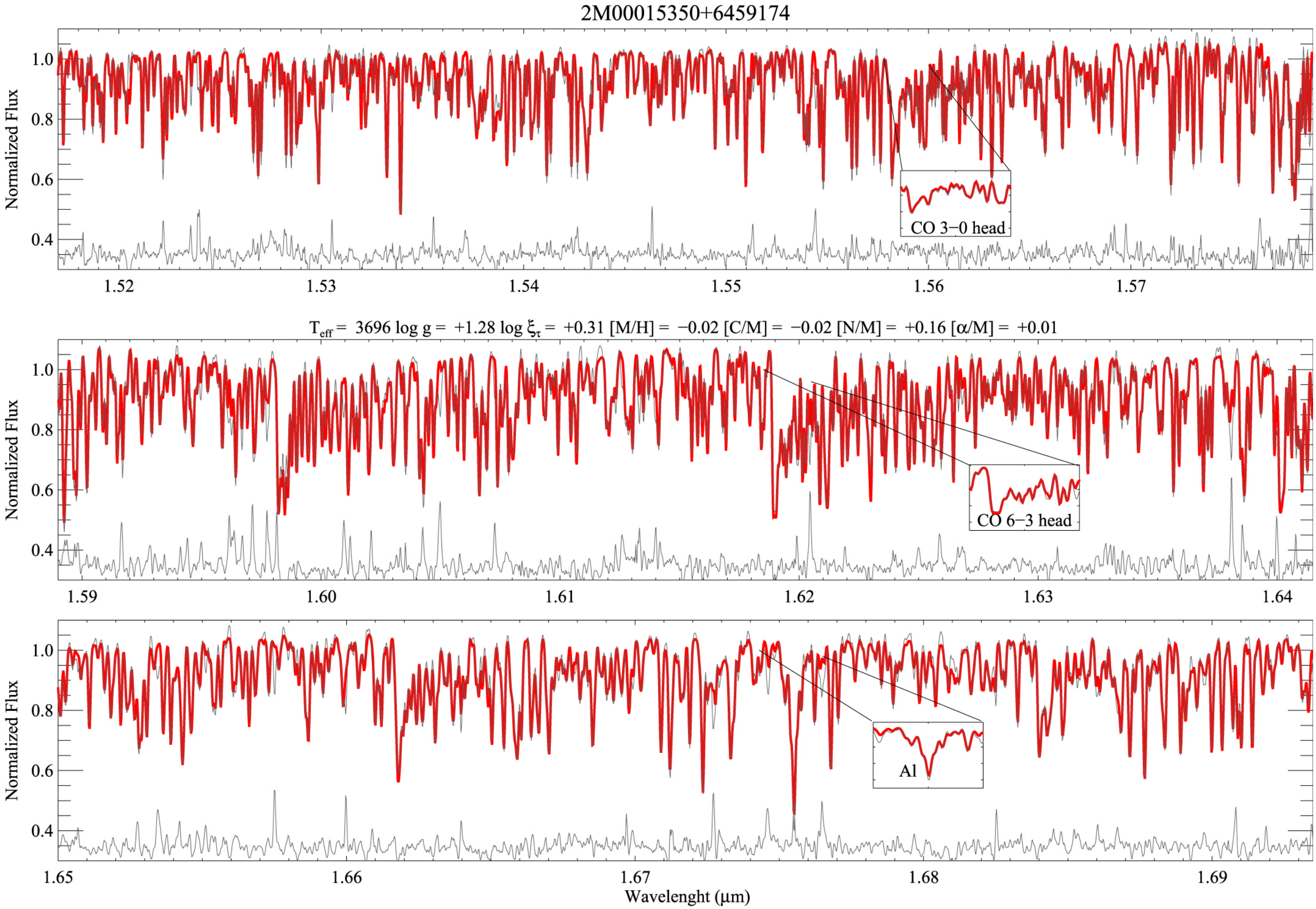
- Galactic Chemical Cartography : focus on red giants
- Part of SDSS III & IV
- R=22,500 NIR H-band (λ1.52-1.69μm) 300-fibers
- Kinematic (~100 m/s): can get 30m/s with effort
- Chemical (~0.1 dex)
- ~20 elements per star → f(T_{eff}, log g, [m/H])
- 277,000 stars in DR14
- 500,000 stars by 2020
- APOGEE-1 (2011 – 2014)
- APOGEE-2 adds complete sky coverage from Las Campanas 2.5m
- Last Data Release 14 (DR14) − public

- ***H-band region excellent for quantitative spectroscopy of M-dwarfs (+ hotter FGK dwarfs)!***
  - *host star characterization*
  - *detailed chemistry*
  - *TESS targets*



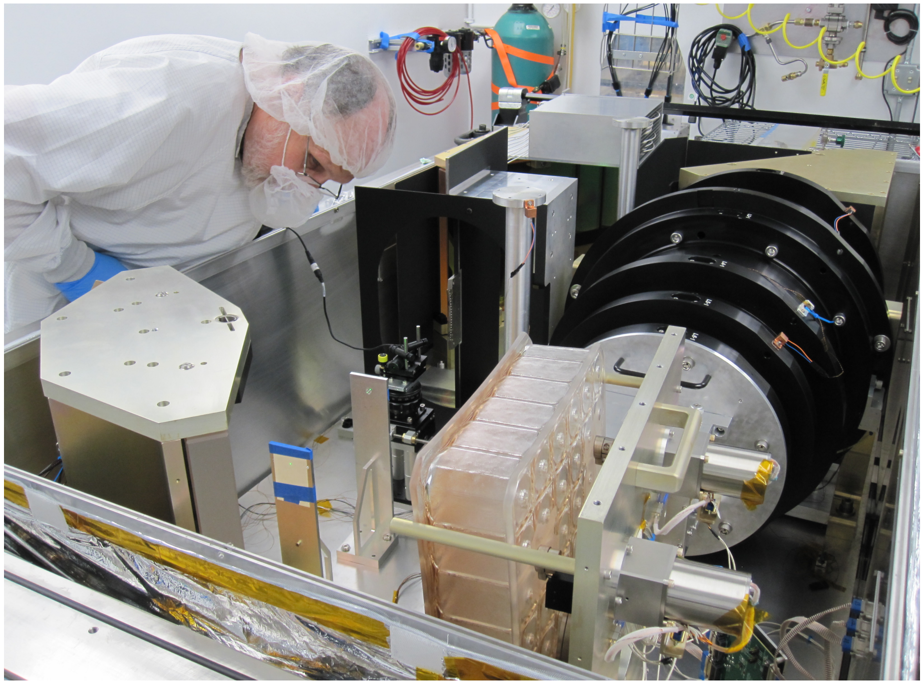
APOGEE Data: typical red giant

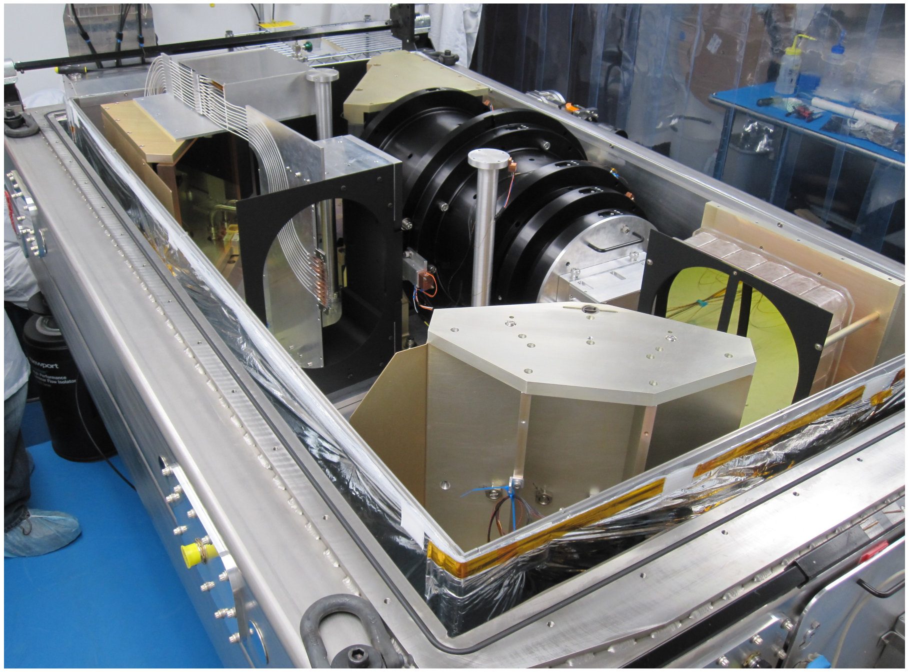
- Observed normalized spectrum + fit

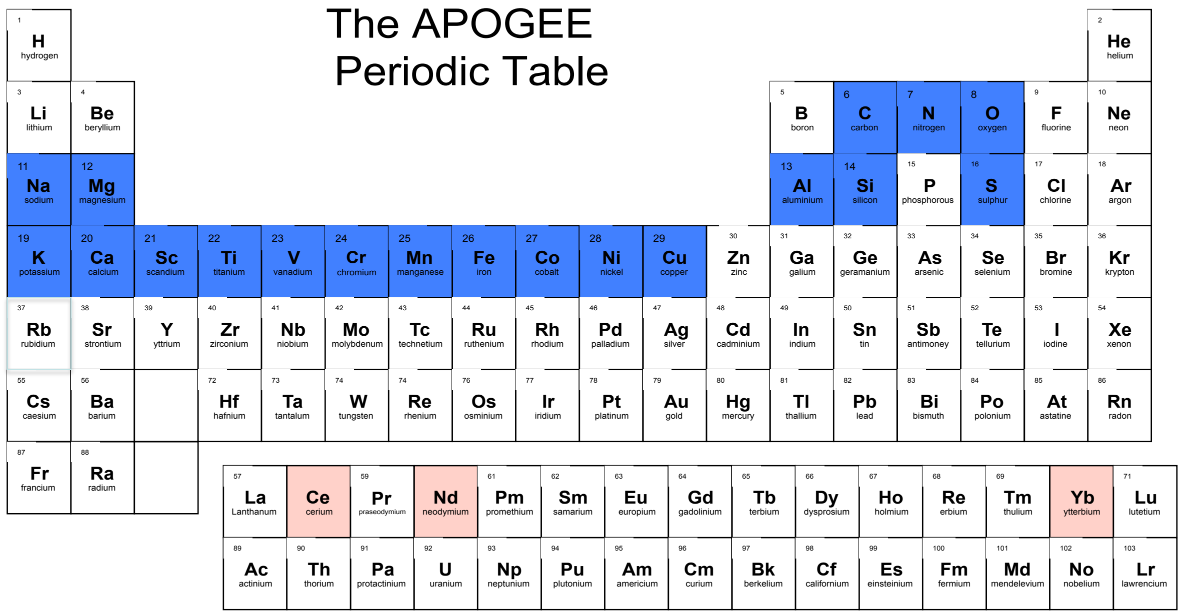


The APOGEE Instrument

- **Built at the University of Virginia** with private industry and other SDSS-III collaborators.
    - John Wilson: Instrument Scientist
    - Fred Hearty: Project Manager
    - Mike Skrutskie: Instrument Group Leader
- The APOGEE instrument employs 300-fiber multiplexing / high resolution / infrared.







- Targets dominated by red giants: quantitative spectroscopy of cool giants
  - Now includes cool dwarfs
- T_{eff}= 3000 – 6000K
- λ1.52 – 1.69μm
- C, N, O determined from molecular transitions: CO, OH, CN
- Everything else→ atomic lines, almost all neutral. Ti II, Nd II, Ce II, Yb II
- Stellar parameters and chemical abundances all hang on the APOGEE spectral line list
- Line list in a state of ~constant evolution/upgrades: new version in 2018
  - each analysis version is an improvement

THE ASTRONOMICAL JOURNAL, 151:144 (20pp), 2016 June
doi:10.3847/000
© 2016. The American Astronomical Society. All rights reserved.

The Automated Analysis Pipeline

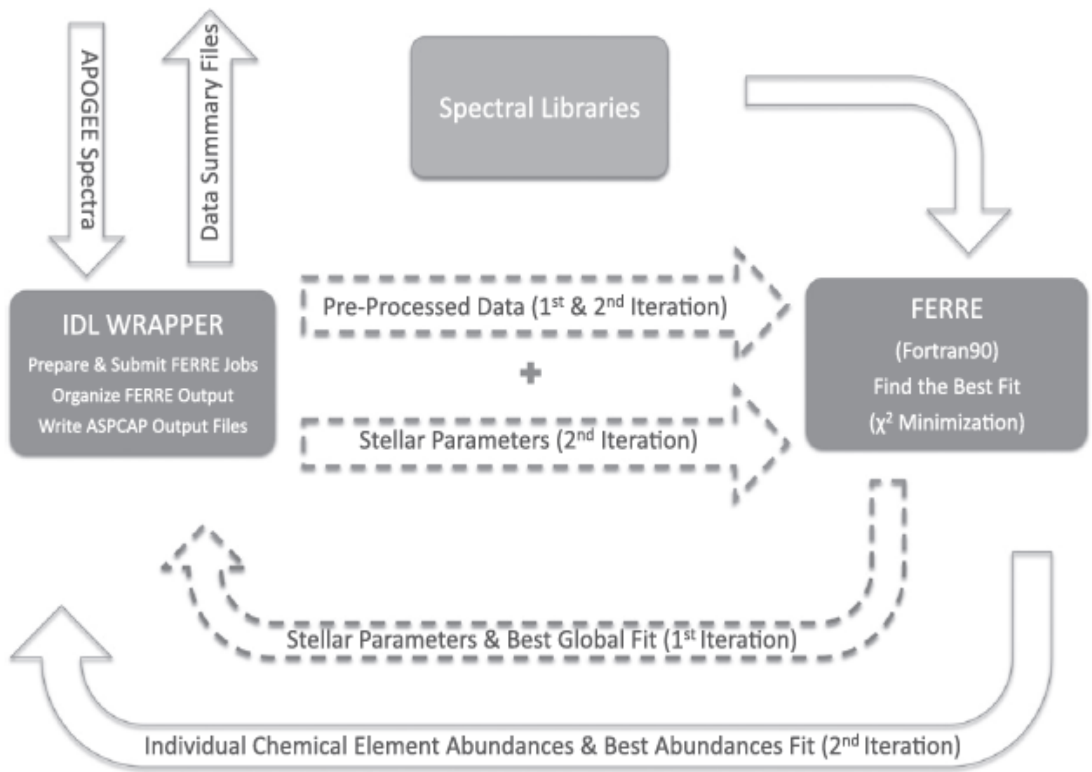
CrossMark

ASPCAP: THE APOGEE STELLAR PARAMETER AND CHEMICAL ABUNDANCES PIPELINE

ANA E. GARCÍA PÉREZ[1,2,3], CARLOS ALLENDE PRIETO[2,3], JON A. HOLTZMAN[4], MATTHEW SHETRONE[5], SZABOLCS MÉSZÁROS[6], DMITRY BIZYAEV[7,8], RICARDO CARRERA[2,3], KATIA CUNHA[9,10], D. A. GARCÍA-HERNÁNDEZ[2,3], JENNIFER A. JOHNSON[11], STEVEN R. MAJEWSKI[1], DAVID L. NIDEVER[12], RICARDO P. SCHIAVON[13], NEVILLE SHANE[1], VERNE V. SMITH[14], JENNIFER SOBECK[1], NICHOLAS TROUP[1], OLGA ZAMORA[2,3], DAVID H. WEINBERG[11], JO BOVY[15], DANIEL J. EISENSTEIN[16], DIANE FEUILLET[4], PETER M. FRINCHABOY[17], MICHAEL R. HAYDEN[4], FRED R. HEARTY[18], DUY C. NGUYEN[19], ROBERT W. O'CONNELL[1],

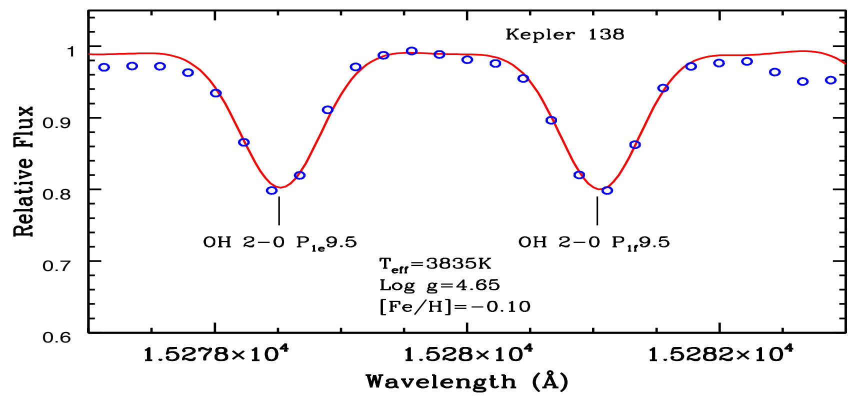
- T_{eff}
- Log g
- ξ - microturbulence
- [M/H]
- [α/M]
- [C/M]
- [N/M]
- Spectral Libraries are 1D models in LTE
- DR14: ATLAS9 + MARCS
- Future releases will use MARCS

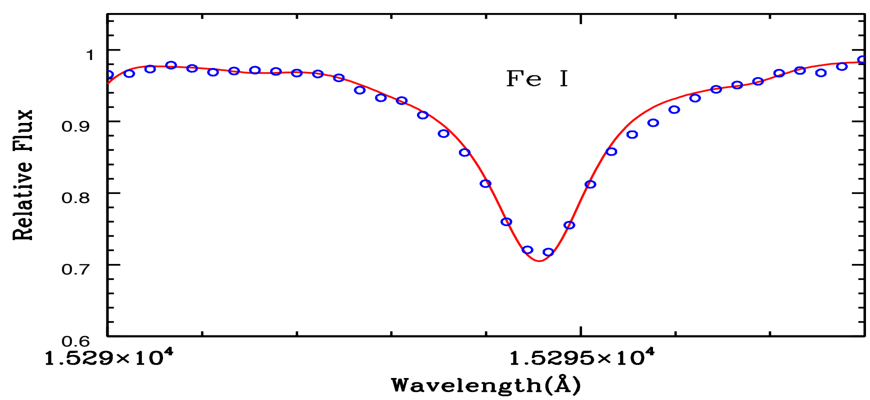
THE ASTRONOMICAL JOURNAL, 151:144 (20pp), 2016 June

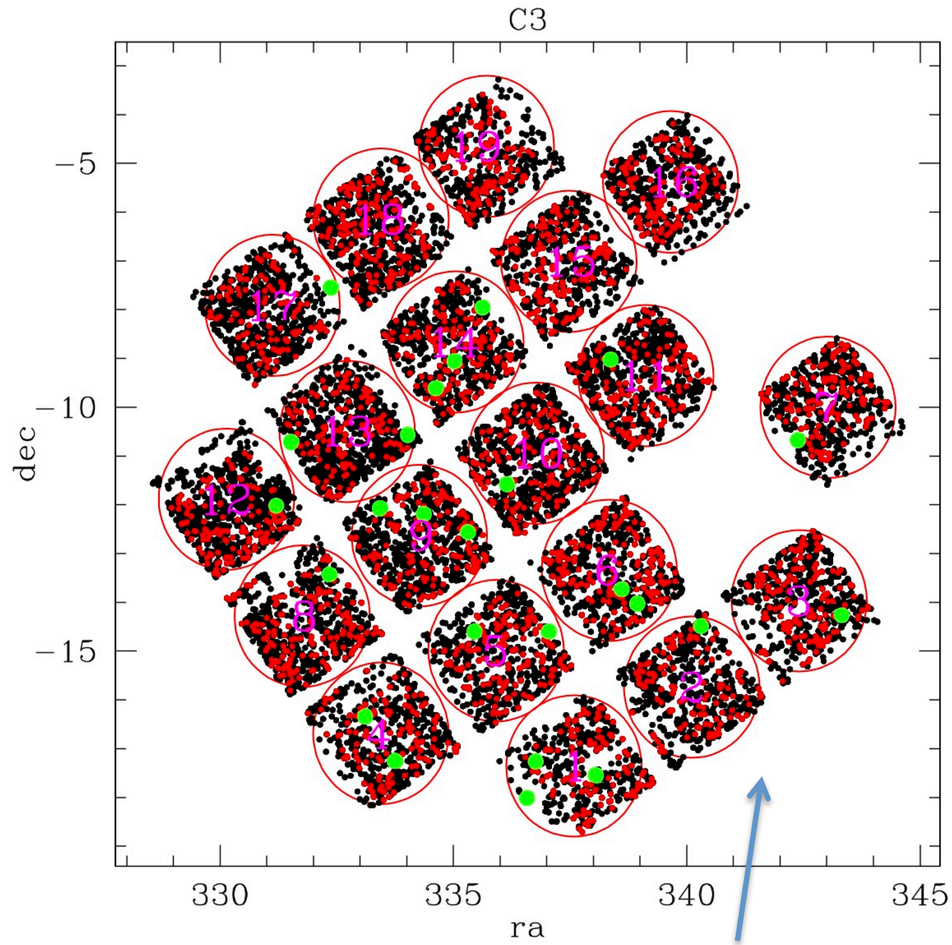


Exoplanet Host Stars in APOGEE

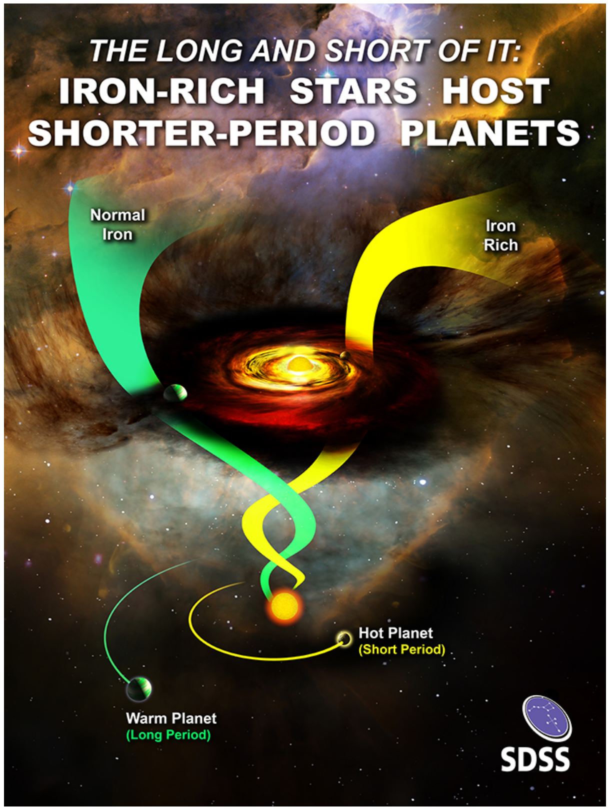
- Dwarfs were not targets of the initial science goals
- NIR spectral region found to be particularly suitable for M-dwarfs → ExoPlanet hosts
- M-dwarfs (+ FGK) now targeted





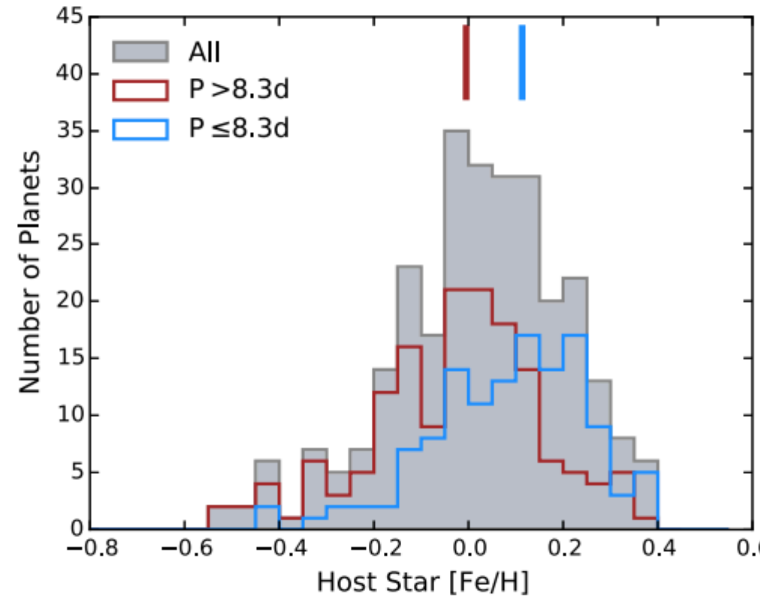


An example of APOGEE targeting in the K2 C3 field. The red dots represent M-dwarfs observed by K2 and now targeted as part of APOGEE-2. There is also a program to observe TESS M-dwarfs.

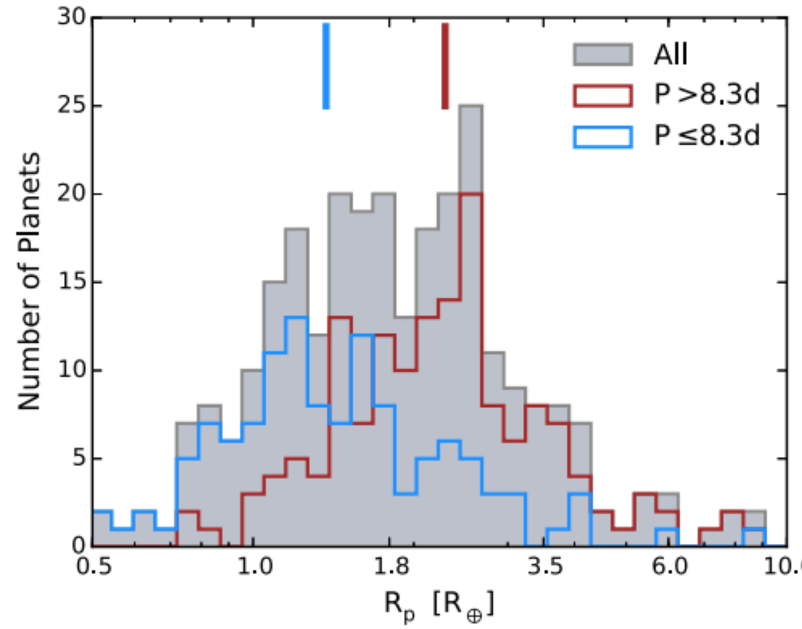


An Example: APOGEE and Kepler Exoplanet Systems

Wilson, Teske, Majewski, Cunha, Smith, Souto et al. (2018)



- Analyzed FGK 624 KOIs
  - using ASPCAP results
- Focus on 282 KOIs with P<100d
- Find a critical period P=8.3 days below which small exoplanets orbit more metal-rich stars
- possible metallicity trend of inner radius of protoplanetary disk at time of planet formation?



Focus →The Importance of APOGEE Analyses of M-dwarfs

Why M-dwarfs?

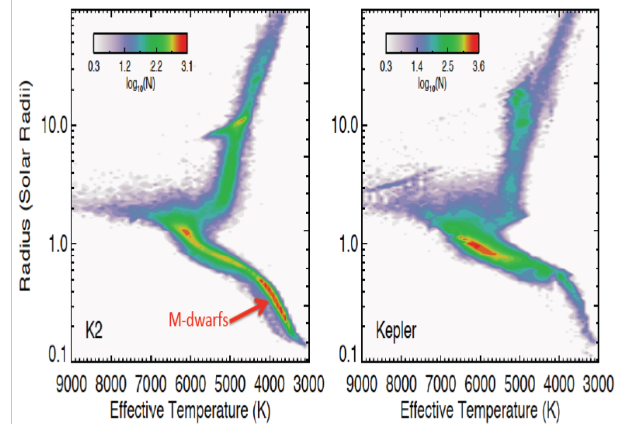
- Most numerous type of star in the Galaxy
- Low-mass; Low luminosity; Long-lived (almost live for ever); not evolved
- M-dwarfs are the least studied class of stars; detailed chemistry not known

The Opportunity of M-dwarfs for APOGEE — plays to APOGEE's strengths

- Detailed chemical compositions of M-dwarfs via optical spectroscopy is difficult—at best due to line blanketing
- Near-infrared spectra are cleaner; APOGEE region has lines of many elements
- M-dwarfs are bright in IR

Connection with Exoplanet field

- M-dwarfs are important in the search for Earth-like exoplanets: M dwarfs have more small planets (Dressing et al.)
- Accurate stellar parameters for exoplanet host stars are crucial
- Need to know the stellar radius to know the planet radius (transits: measure Rp/R*)
- Stellar metallicity influences planet formation. To what level the detailed chemistry of stars also influence planet formation? similar C/O ratios control ice chemistry in protoplanetary disk
- K2 targets skewed towards the cooler K + M dwarfs
- Important fraction of TESS targets are M-dwarfs



Stellar radius versus T_{eff} for ~119,000 K2 targets (left panel) from Huber et al. (2015) and ~190,000 Kepler targets from Huber et al. (2014), color-coded by the log of number of targets. Note the shift towards a much larger fraction of M-dwarfs in the K2 mission, pointing to the importance of M-dwarf studies in current exoplanet transit missions, such as TESS.

Progress Report on M-dwarf work with APOGEE

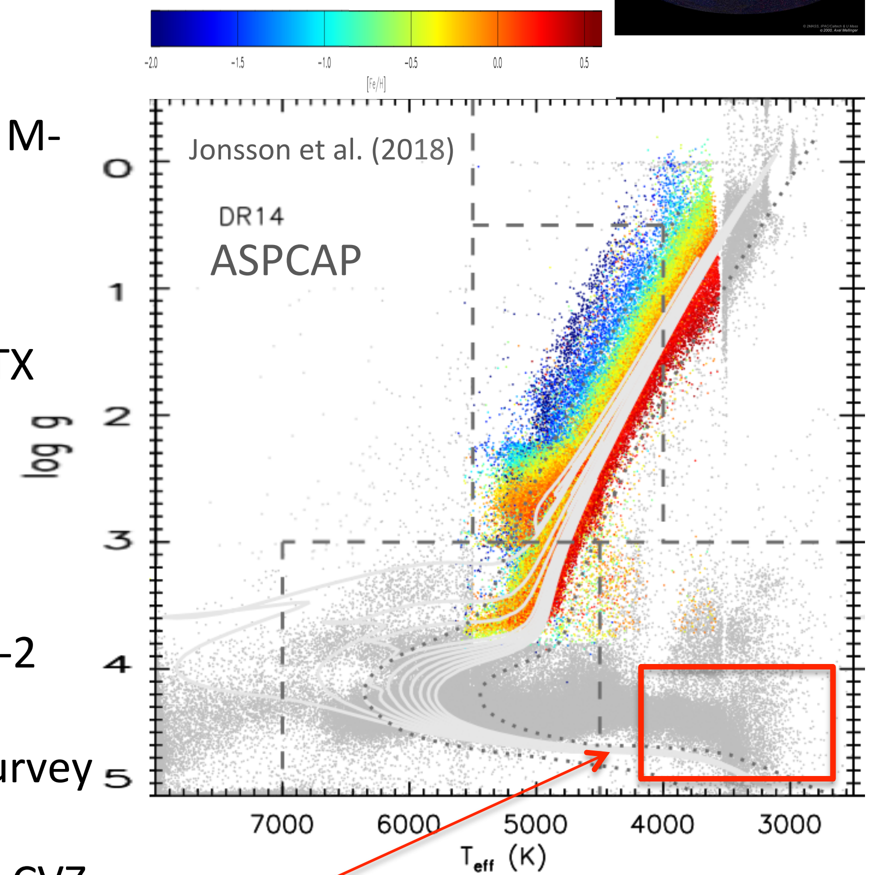
- APOGEE is opening a new window to characterize M-dwarfs; change the landscape

Initially, M-dwarfs were not APOGEE survey targets
- Observed serendipitously + Ancillary projects + BTX

APOGEE-1:
PI S. Mahadaven: 1400 M-dwarfs for RVs, vsin i
PI V. Smith: M-dwarfs exoplanet hosts (~70 stars)
APOGEE-2:
PI V. Smith: “M-dwarfs with planets in the Kepler + K-2 fields” (e.g. ~2,500 M-dwarfs in K2 C3 field)
+ adding M dwarfs to plates (when observing main survey targets and Manga fields)
BTX; w/ SDSS V: M-dwarfs part of the targets in TESS CVZ

- More than ~20,000 M-dwarfs observed with APOGEE (includes observations from the NMSU 1m telescope)

- Survey mode: Potential to observe large number of M-dwarfs change the landscape in terms of M dwarf stellar characterization



Calibrated ASPCAP results for DR14 ~ 280,000 stars

Solid grey isochrones (PARSEC):
[Fe/H]=0.0; ages 1 - 10 Gyr
Dotted dark gray isochrones (PARSEC):
[Fe/H]= -1.0; age 10 Gyr and [Fe/H]=+0.5; age 10 Gyr

Using APOGEE to Pioneer Precision Chemical Abundances Analysis of M-dwarfs

- Need an analysis method tailored for the M-dwarfs: Modified the APOGEE line list; selected spectral windows (*initial APOGEE science goals not focussed on dwarfs*)

"Proof of concept" Sample (Diogo Souto et al. 2017)
warm M dwarfs (Teff~3850K; log g~4.75)

➢ Kepler-138**:** 3 exoplanets; Kepler-138b > Mars-like size planet

➢ Kepler-186**:** 5 exoplanets; Kepler-186f > earth-size planet @ HZ

Detailed Chemistry: C, O, Na, Mg, Al, Si, K, Ca, Ti, V, Cr, Mn, Fe, Ni

"Benchmark" Sample: Calibration sample for establishing the baseline scales for T_{eff}, metallicity + chemical abundances

- M dwarfs @ binary systems with hotter companions (analyzed from optical)

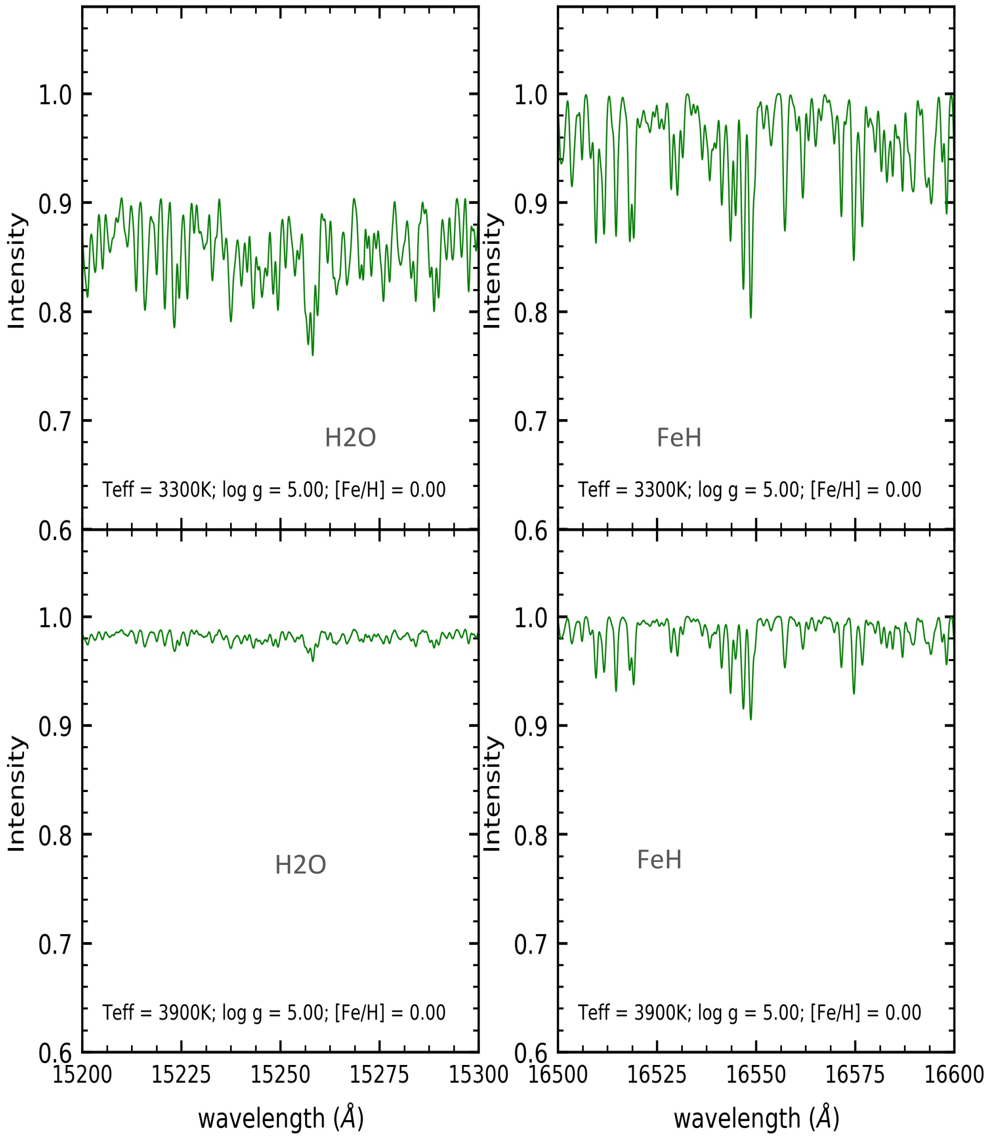
- M-dwarfs in open clusters > Pleiades (Ph.D. thesis Cintia Martinez at ON)
  Rotation; activity; magnetic fields → effects on radii

Extending to cooler M dwarfs: M4.0 exoplanet-hosting star at ~3pc (Teff=3230K; log g=4.96) Souto et al. (2018)

➢ Ross 128: Msin(i)= 1.35 Mearth; 9.9 day period exoplanet

Detailed chemistry: C, O, Mg, Al, K, Ca, Ti, and Fe

Adjusting the APOGEE line list to analyze M-dwarfs



Synthetic Spectra

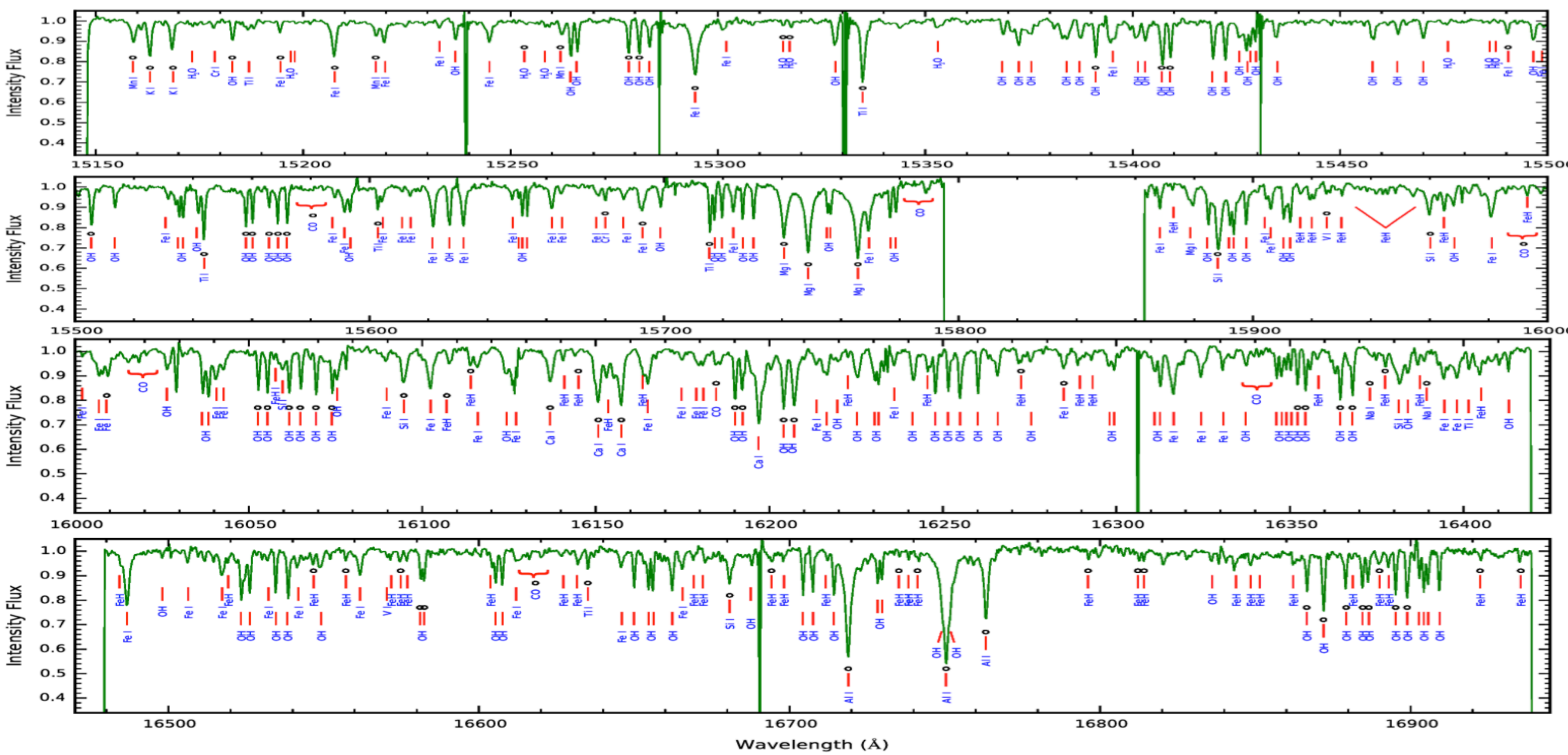
Molecular lines important for M-dwarfs

- H_2O (Barber et al. 2006) → 26M lines in APOGEE window; cut to ~1M lines for inclusion in line list
- FeH (Hargreaves et al. 2010) + SiH Kurucz (CD-ROM 18) + other hydrides (not in DR14)
- Presence of H_2O that becomes important for low Teffs (top panel)
- FeH: not important for red giants
- *Work in progress*: Continue to improve and identify missing lines (other hydrides?)

Kepler 138 & Kepler 186

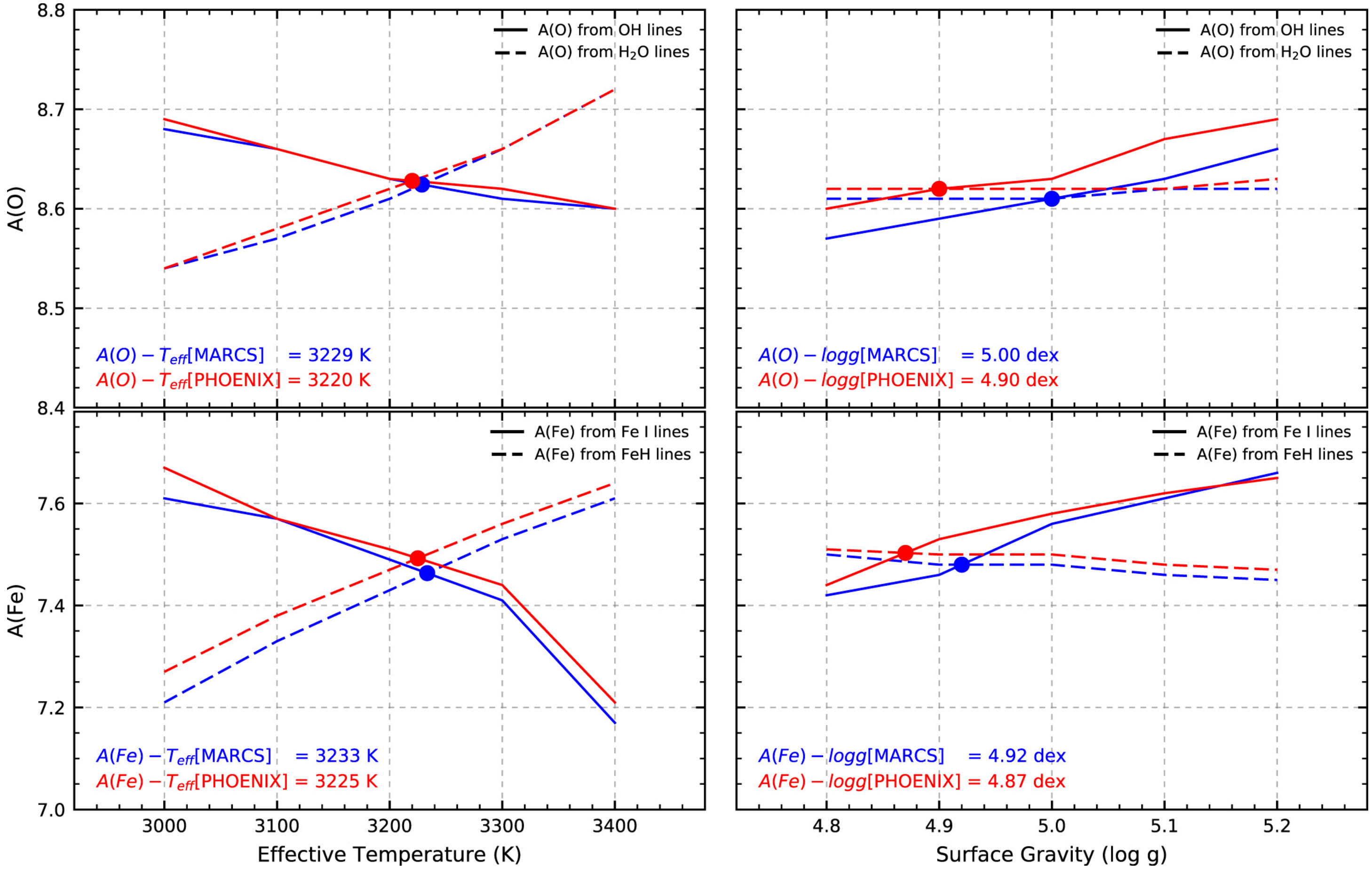
- Apogee pixels carry information on the detailed chemistry of M-dwarfs: 14 elements — C, O, Na, Mg, Al, Si, K, Ca, Ti, V, Cr, Mn, Fe + Ni
- Not as many elements as in the red giants as some of the spectral lines become too weak: e.g. CN
- Atomic lines of 12 species; only A(C) and A(O) come from molecular lines only

Souto et al. (2017)



APOGEE spectrum of Kepler 138

Spectroscopic diagnostics and pushing to cooler M-dwarfs: Ross 128 (Souto et al. 2018)



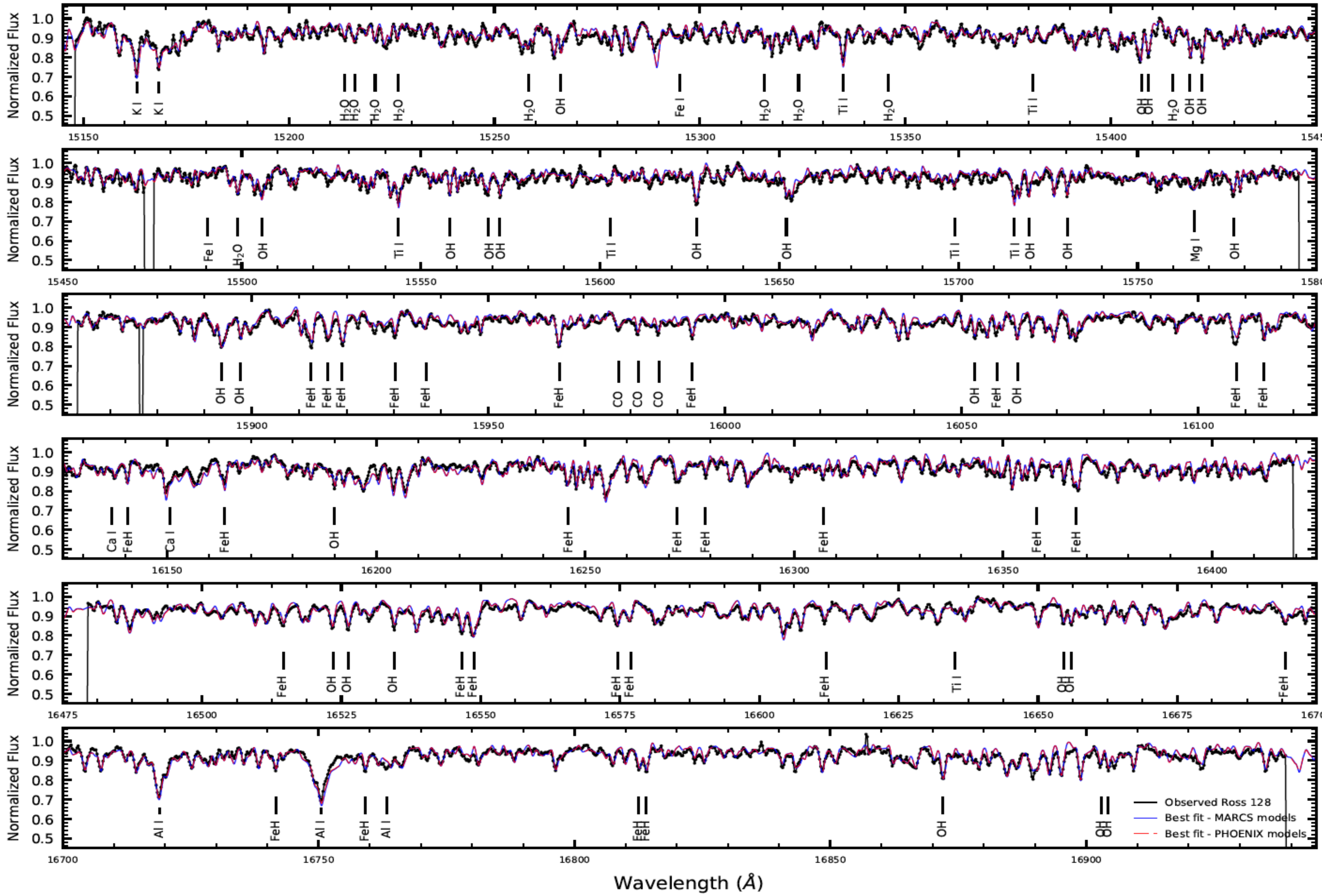
Examples of the sensitivity of the OH, H_2O, FeH, FeI

4 indicators to set T_{eff}, log g, A(Fe) and A(O) for the computation of model atmospheres

Stellar and Planetary Characterization of the Ross 128 Exoplanetary System from APOGEE Spectra

T_{eff}=3230K

Souto, Unterborn, Smith, Cunha, Teske et al. (2018)



Detailed Chemistry for M dwarfs in the Galaxy

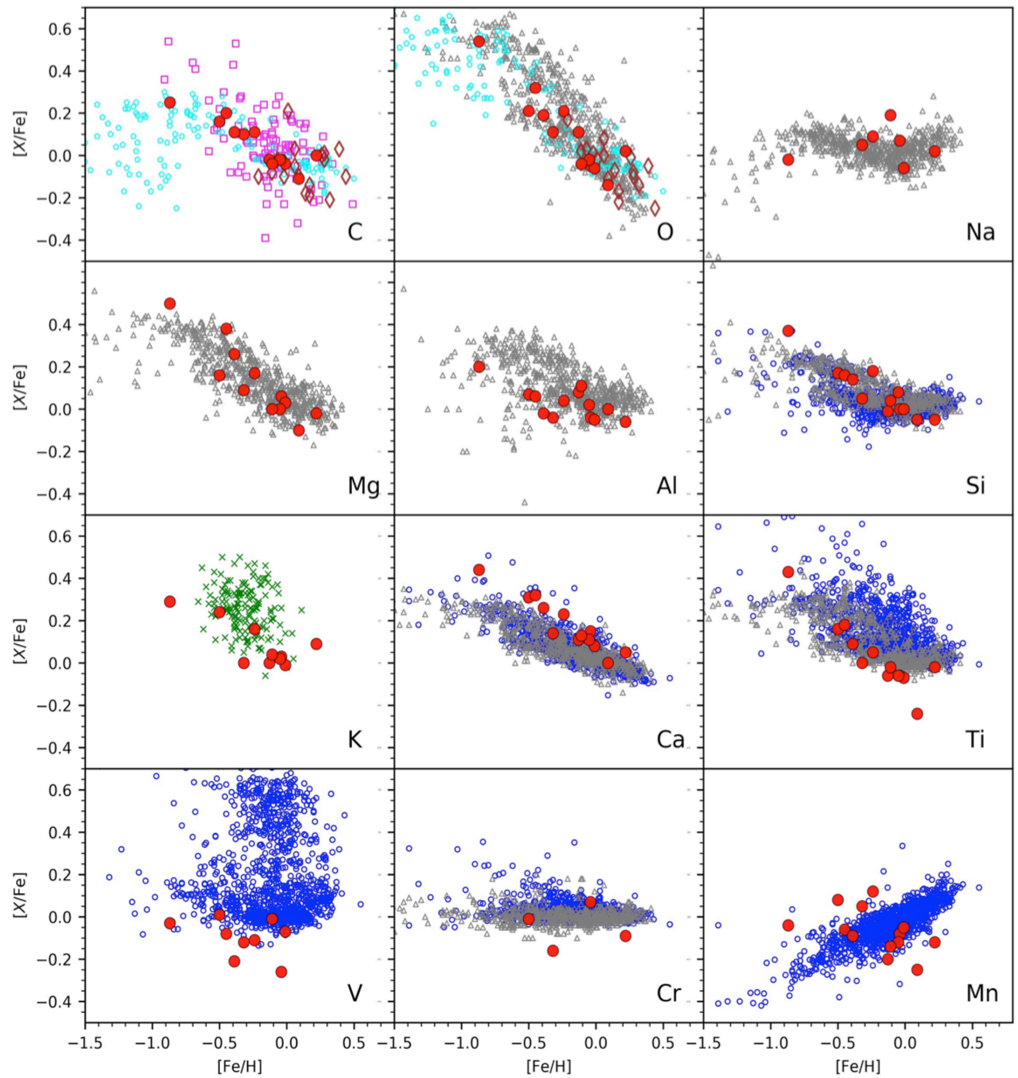
- [El/Fe] vs [Fe/H] for the local Disk pop.
- Abundances for FGK dwarfs used to define the behavior of el/Fe vs Fe/H in the local Disk are from optical high-res
- No M dwarfs results for comparison…

These would be the first results for several chemical elements for M-dwarfs

- Some differences for some elements, such as, V, Mn (need some work); but some optical also for V? K? perhaps Ti?
- Still need to investigate systematic differences; promising results for most elements
- Just starting to probe the detailed chemistry of the Galactic population with the largest number of stars

Souto Ph.D. Thesis

- M-dwarfs Binary star sample



Brown (Teske et al. 2015); Blue (Adibekyan et al. 2012); Gray (Bensby et al. 2014) Pink (Allende Prieto et al 2004); Cyan (Nissen et al 2014); Green (Reddy et al. 2003)

Conclusions: APOGEE and M-dwarfs

- 20,000 M-dwarfs observed and counting...
- Southern APOGEE spectrograph began observing in 2017 from Las Campanas 2.5-m → full-sky coverage
- Line list will continue to be improved (2018 is latest update): more complete lists, better atomic data, in particular f-values, more molecules as needed
- Working to establish ASPCAP for M-dwarf analysis → pathfinder manual analyses completed/underway
- Include M-dwarfs and push down to L- and T-dwarfs
- Currently Kepler/K2 follow-up → future follow-up of TESS