Stellar Characterization and Detailed Chemistry of M-dwarfs from APOGEE Spectra

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Know Thy Star

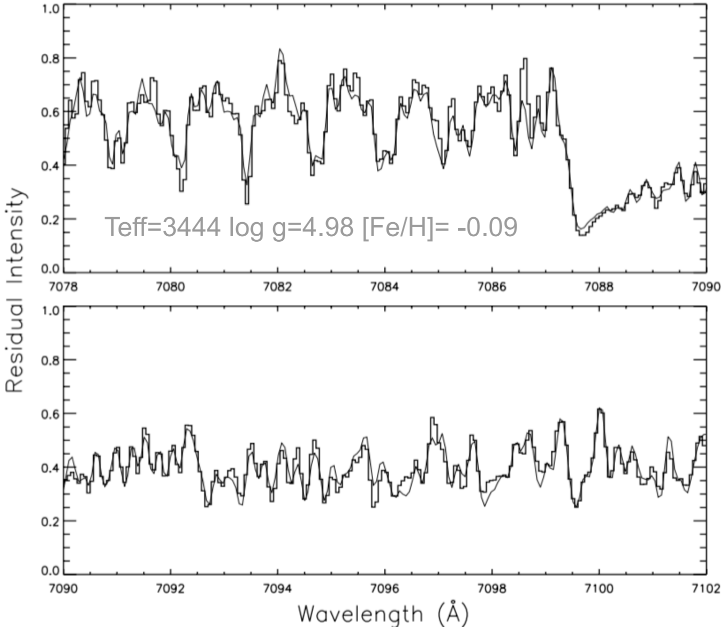
- Accurate stellar parameters for exoplanet host stars are crucial; Need to know the stellar radius to know the planet radius
- Stellar metallicity influences planet formation. The detailed chemistry of the stars plays a role in planet formation

Why M-dwarfs?

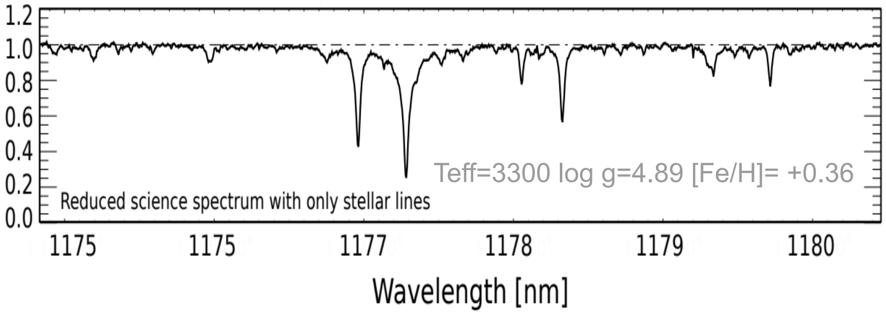
- Most numerous type of star in the Galaxy – Important for Galactic Archeology (*Know Thy Galaxy*!)
- Low-mass; Low luminosity; Long-lived (almost live for ever); not evolved
- M-dwarfs are important in the search for Earth-like exoplanets: M dwarfs have more small planets
- Kepler2 targets skewed towards the cooler dwarfs: ~40% of K2 targets are K + M dwarfs
- Look towards future exoplanet searches— Future missions like TESS will discover lots of Earth-like exoplanets around M-dwarfs.
- M-dwarfs are the least studied class of stars; detailed chemistry not known

M-dwarfs: The usefulness of IR

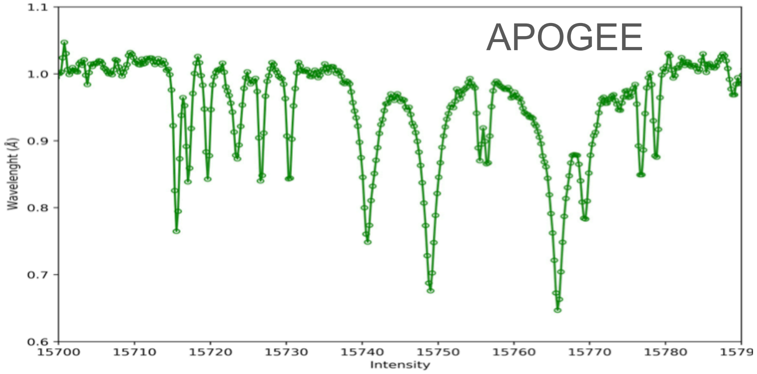
- Most of the chemical abundance work to date has been done for FGK stars in the optical
- M dwarfs:
  Fainter at optical wavelengths than in the IR
- Detailed chemical compositions via optical spectroscopy is difficult—at best
- Optical spectra are covered with molecular lines / bands; atomic lines are compromised by TiO +
- Near-infrared spectra are much cleaner e.g., APOGEE spectra



Bean et al. (2006)



Lindgren & Heiter (2017)

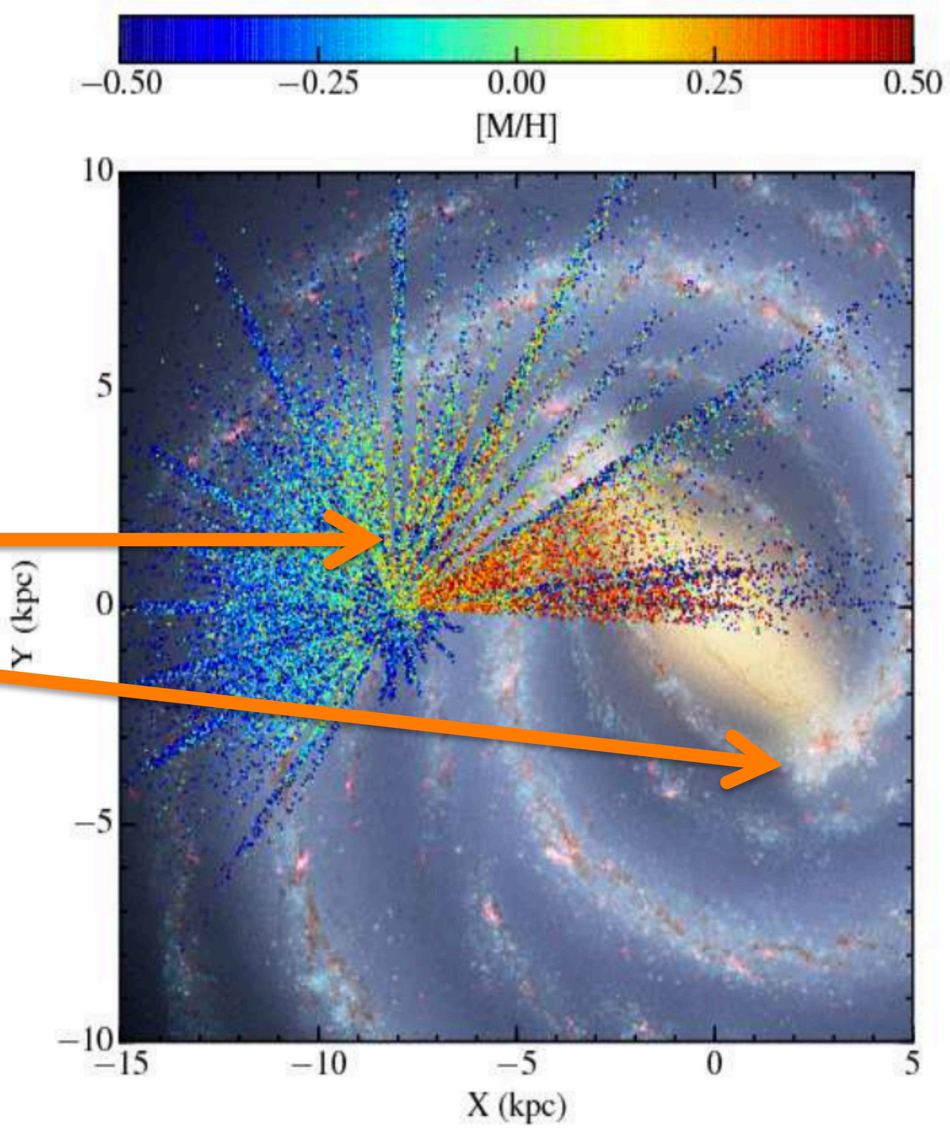


Souto et al. (2017)

APOGEE: The “Big Picture”

- Chemical Abundance survey > Galactic Chemical Cartography; the primary mission is focused on red giants
- APOGEE spectrograph: R = 22,500 NIR H-band (λ1.52-1.69μm); 300-fibers
- Part of SDSS III & IV
- ~280,000 stars in most recent release: DR14
- APOGEE-1 (2011 – 2014)
- APOGEE-2 adds complete sky coverage from Las Campanas 2.5m
- 500,000 stars by 2020
- All data and data products are public

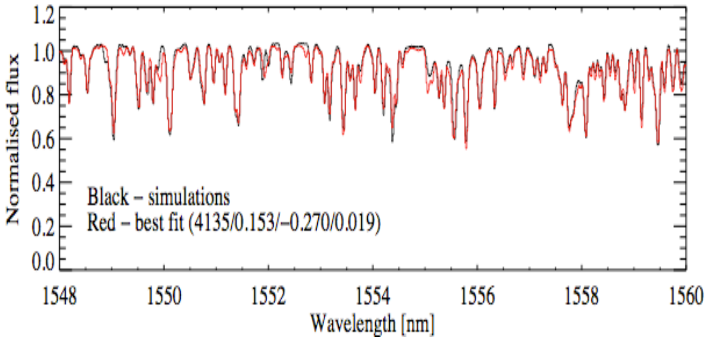
Probe the Milky Way through the extinction



APOGEE Abundance Pipeline: ASPCAP

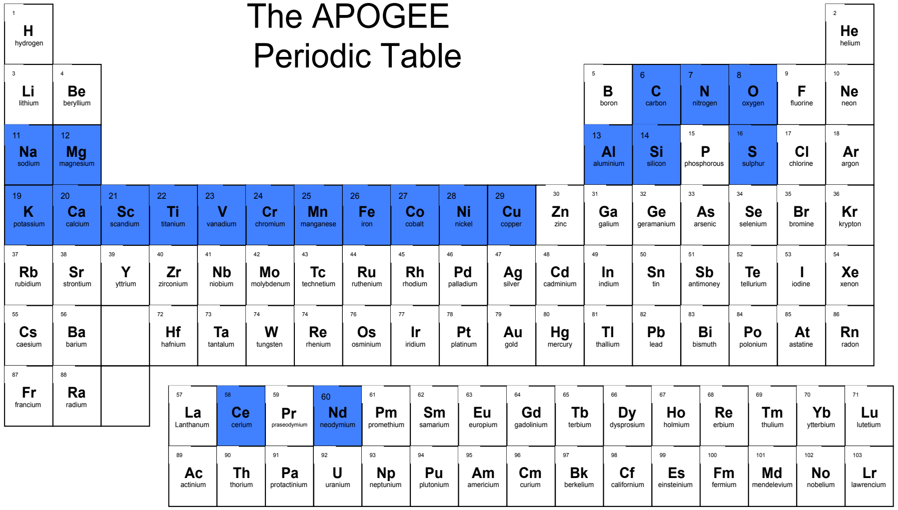
Best fit synthetic spectra from matches to synthetic library

Via simultaneous 7-D optimization of $T_{\rm eff}$, log g, [Fe/H], [C-N-alpha/Fe],(ξ)
(no C and N but vsin i in dwarfs)



APOGEE Data Products:

- Radial Velocities (~150 m/s precision); multiple epochs
- Stellar atmospheric parameters
- Chemical Abundances of **21 elements in red giants** (≤ 0.1 dex internal precision); elements from most of the different types of nucleosynthesis



The APOGEE Periodic Table

1 **H** hydrogen																	2 **He** helium
3 **Li** lithium	4 **Be** beryllium											5 **B** boron	🟦 6 **C** carbon	🟦 7 **N** nitrogen	🟦 8 **O** oxygen	9 **F** fluorine	10 **Ne** neon
🟦 11 **Na** sodium	🟦 12 **Mg** magnesium											🟦 13 **Al** aluminium	🟦 14 **Si** silicon	15 **P** phosphorous	🟦 16 **S** sulphur	17 **Cl** chlorine	18 **Ar** argon
🟦 19 **K** potassium	🟦 20 **Ca** calcium	🟦 21 **Sc** scandium	🟦 22 **Ti** titanium	🟦 23 **V** vanadium	🟦 24 **Cr** chromium	🟦 25 **Mn** manganese	🟦 26 **Fe** iron	🟦 27 **Co** cobalt	🟦 28 **Ni** nickel	🟦 29 **Cu** copper	30 **Zn** zinc	31 **Ga** galium	32 **Ge** geramanium	33 **As** arsenic	34 **Se** selenium	35 **Br** bromine	36 **Kr** krypton
37 **Rb** rubidium	38 **Sr** strontium	39 **Y** yttrium	40 **Zr** zirconium	41 **Nb** niobium	42 **Mo** molybdenum	43 **Tc** technetium	44 **Ru** ruthenium	45 **Rh** rhodium	46 **Pd** palladium	47 **Ag** silver	48 **Cd** cadminium	49 **In** indium	50 **Sn** tin	51 **Sb** antimoney	52 **Te** tellurium	53 **I** iodine	54 **Xe** xenon
55 **Cs** caesium	56 **Ba** barium		72 **Hf** hafnium	73 **Ta** tantalum	74 **W** tungsten	74 **Re** rhenium	76 **Os** osminium	77 **Ir** iridium	78 **Pt** platinum	79 **Au** gold	80 **Hg** mercury	81 **Tl** thallium	82 **Pb** lead	83 **Bi** bismuth	84 **Po** polonium	85 **At** astatine	86 **Rn** radon
87 **Fr** francium	88 **Ra** radium																

57 **La** Lanthanum	🟦 58 **Ce** cerium	59 **Pr** praseodymium	🟦 60 **Nd** neodymium	61 **Pm** promethium	62 **Sm** samarium	63 **Eu** europium	64 **Gd** gadolinium	65 **Tb** terbium	66 **Dy** dysprosium	67 **Ho** holmium	68 **Re** erbium	69 **Tm** thulium	70 **Yb** ytterbium	71 **Lu** lutetium
89 **Ac** actinium	90 **Th** thorium	91 **Pa** protactinium	92 **U** uranium	93 **Np** neptunium	94 **Pu** plutonium	95 **Am** americium	96 **Cm** curium	97 **Bk** berkelium	98 **Cf** californium	99 **Es** einsteinium	100 **Fm** fermium	101 **Md** mendelevium	102 **No** nobelium	103 **Lr** lawrencium

APOGEE can study elements from most of the different types of nucleosynthesis

APOGEE elements in blue
SN II: α-elements— O, Mg, Si, S, Ca,Ti
SN II: Z-dependence—Na, Al, K, Sc, V, Mn, Co, Cu
SN II (?): r-Process→ Eu, Yb?
SN II: Neutrino Process→ ^{19}F
SN Ia: Fe, Ni, Si (mostly SN II)
Red Supergiants/Giants: ^{13}C, ^{14}N
AGB: s-Process→Y, Zr, Ba, ^{12}C(?), Ce, Nd
AGB: Hot Bottom Burning→ ^{7}Li, ^{14}N

- APOGEE is primarily a survey of red giants; the abundance pipeline cannot properly handle M-dwarfs
- BUT M-dwarfs have been observed with APOGEE

Enter APOGEE @ M-dwarf Territory

- The APOGEE Survey is opening a new window to characterize M-dwarfs in detail — plays to APOGEE's strengths

- Transforming the APOGEE survey of red-giants into a survey that also targets M-dwarfs

Initially not targeting M-dwarfs:

- M-dwarfs observed serendipitously + one RV project

- Proposed by ancillary projects:
  PI V. Smith: "M-dwarfs with planets in the Kepler and K-2 fields"

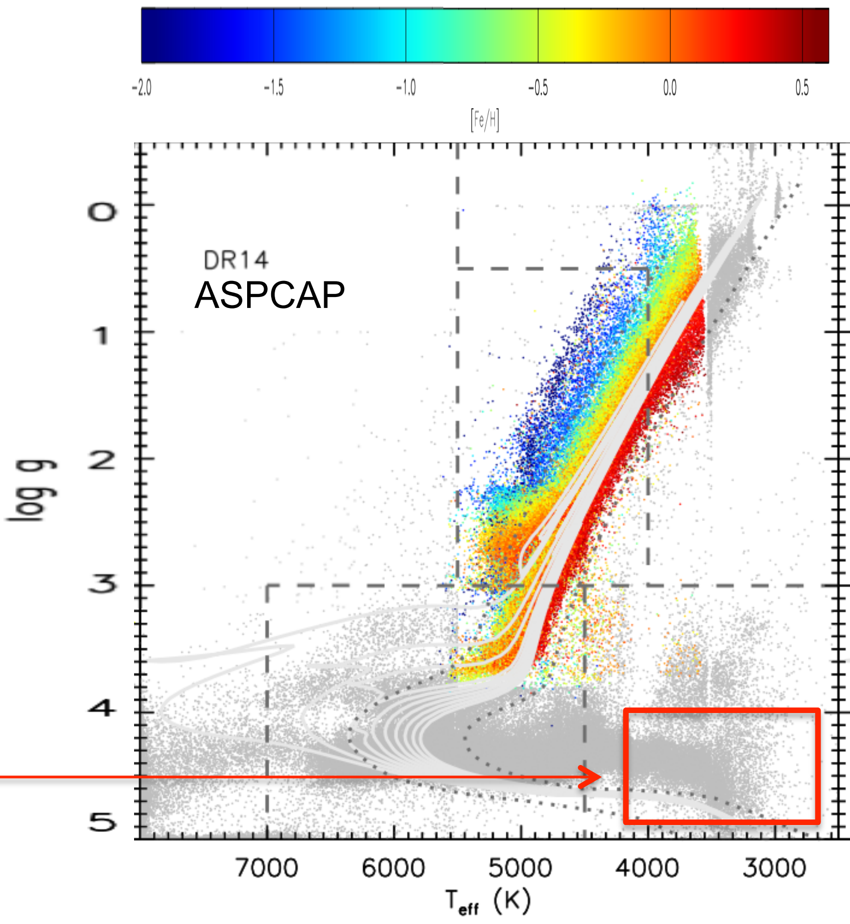
- Currently adding M-dwarfs to plates whenever possible

APOGEE-1 + on going APOGEE-2

- ~12,000 M-dwarfs already observed with APOGEE (Sloan telescope + NMSU 1-m telescope)

- Survey mode: Potential to observe large number of M-dwarfs at high-resolution in the H-band

- After SLOAN 4 > will continue to fulfill this potential



Jonsson et al. (2017)
(PARSEC isochrones used)

- ASPCAP stellar parameters in public DR 14 show significant offsets for M-dwarfs

Using APOGEE to Pioneer Precision Chemical Abundances in M-dwarfs

- The effort of the APOGEE team is focused on modeling red giants

❖ Need a chemical abundance analysis tailored for the M-dwarfs

Sample

“Proof of concept” Sample: high S/N, warm (Teff~3850K; log g~4.75) … demonstrate that this is feasible

- ➢ Kepler-138**:** 3 exoplanets; Kepler-138b > Mars-like size planet
- ➢ Kepler-186**:** 5 exoplanets; Kepler-186f > earth-size planet @ HZ

“Benchmark” Sample: Calibration sample for establishing the baseline scales for Teff, metallicity + abundances, investigate offsets in the results

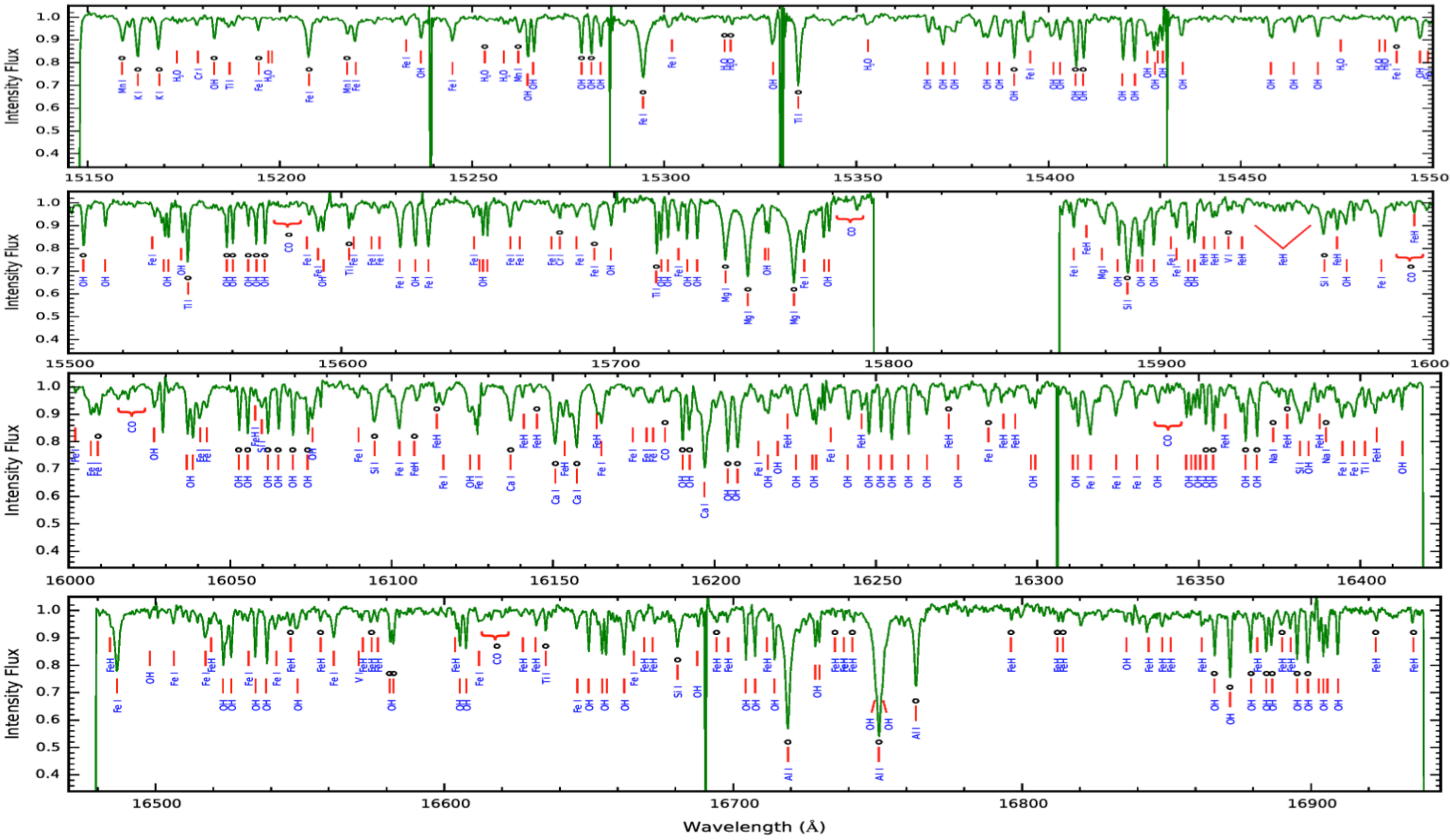
- 11 are in binary systems with hotter companions (these can be analyzed from optical spectra) +

- 2 stars with interferometric radii (Teff can be obtained directly) (Boyajian et al. 2012)

- M-dwarfs in open clusters > M67; Pleiades (PhD thesis of Cintia Martinez)

How many elements can be analyzed in the APOGEE spectra of M-dwarfs?

- 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 (recently added for metal-rich stars)
- 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



- Dominated by OH lines
- H2O is weak at Teff~3850 K

APOGEE spectrum of Kepler 138

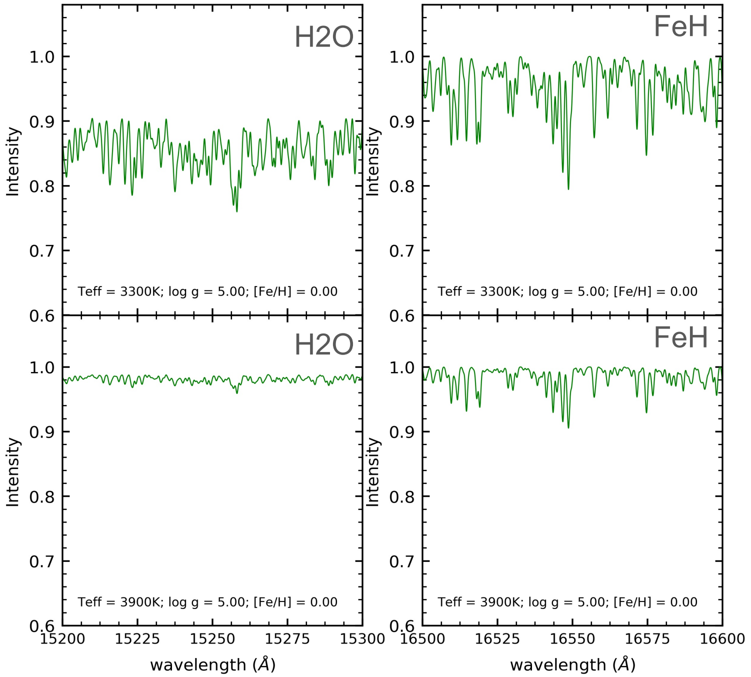
Souto et al. (2017)

Adjusting the APOGEE line list to analyze M-dwarfs

Goal: To construct a line list between 1.5 -- 1.7 microns that is adequate for M-dwarfs

Construction of the original APOGEE line list:

- Compilation of initial list from the Kurucz semi-empirical line list + laboratory-based atomic and molecular data from a variety of literature sources ✦(Shetrone et al. 2015)
- Astrophysical gfs: Modify the line list by fitting the Sun & Arcturus with adjustments to gf-values (+ lambdas + damping constants); NOT changing the gf –values of molecular lines + additional elements from unidentified lines, e.g., Nd & Ce (Hasselquist et al. 2016 & Cunha et al. 2017)



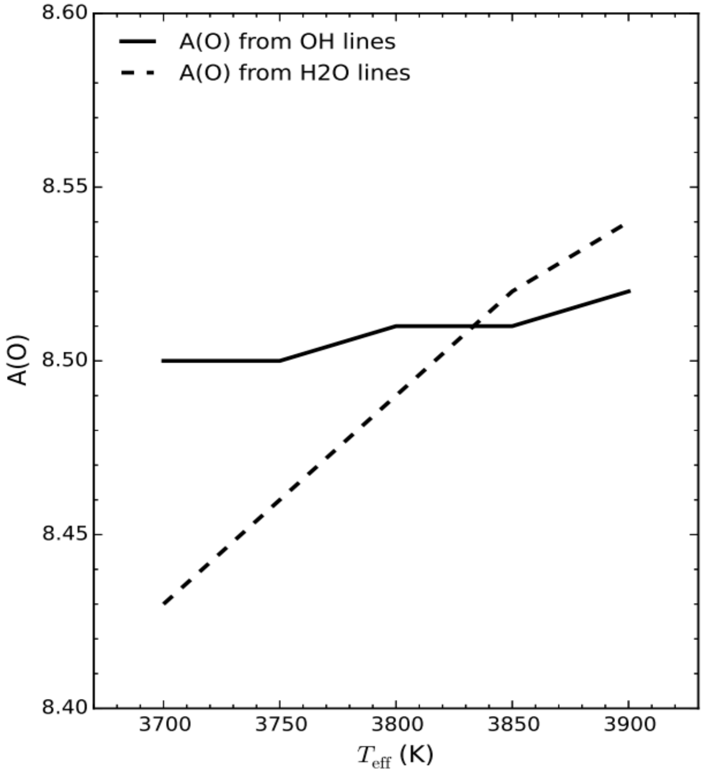
- Need to add crucial molecular transitions not in the original APOGEE line list that are visible in the cool dwarfs but weak or non-existent in the low gravity red giants
- Presence of H2O that becomes very important for low Teffs and FeH that does not appear in the red giants

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)
- *Work in progress*: Continue to improve and identify missing lines (other hydrides?)

✦ Molecular lines: CN Kurucz (CD-ROM 18) + Brooke et al. 2014; CO Kurucz (CD-ROM 18) + Goorvitch (1994); OH Goldman et al. (1998); C_2 Kurucz (CD-ROM 18) + Brault et al. (1982) and Kokkin et al. (2007); H_2 Kurucz (CD-ROM 18) + Atomic lines

Examples of the sensitivity of the OH, H2O



- OH is not very sensitive to Teff but more sensitive to log g

Log g

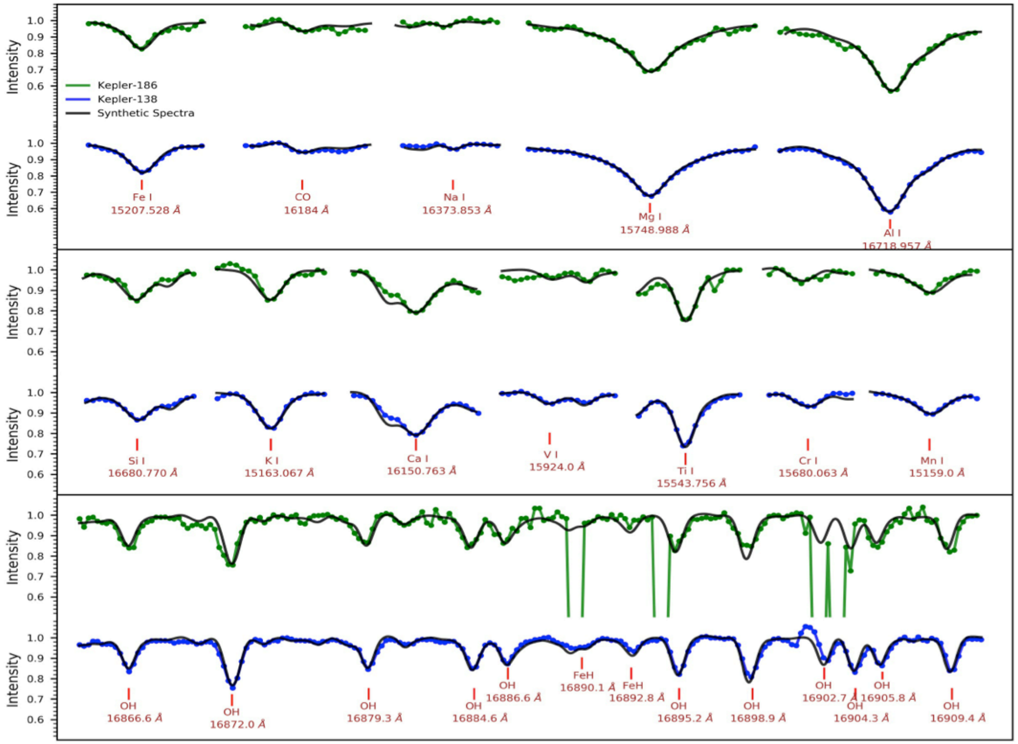
Log g

Use windows to isolate pixels with most information…minimize residuals

Select lines/windows and derive abundances for 14 elements from atomic lines…

- **Step 2** > Computation of detailed abundances
- Select spectral lines/windows to derive the abundances of 14 elements

Examples of Best fit syntheses

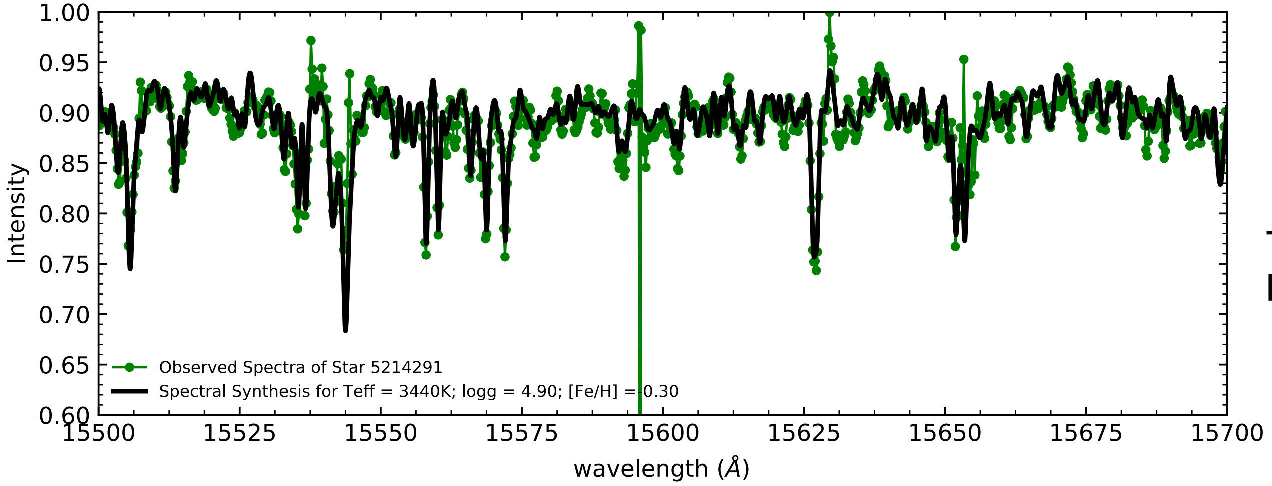


Souto et al. (2017)

Computation of Synthetic Spectra

- ➢ 1-D LTE plane parallel
- ➢ MARCS model atmospheres (Gustafsson et al. 2008)

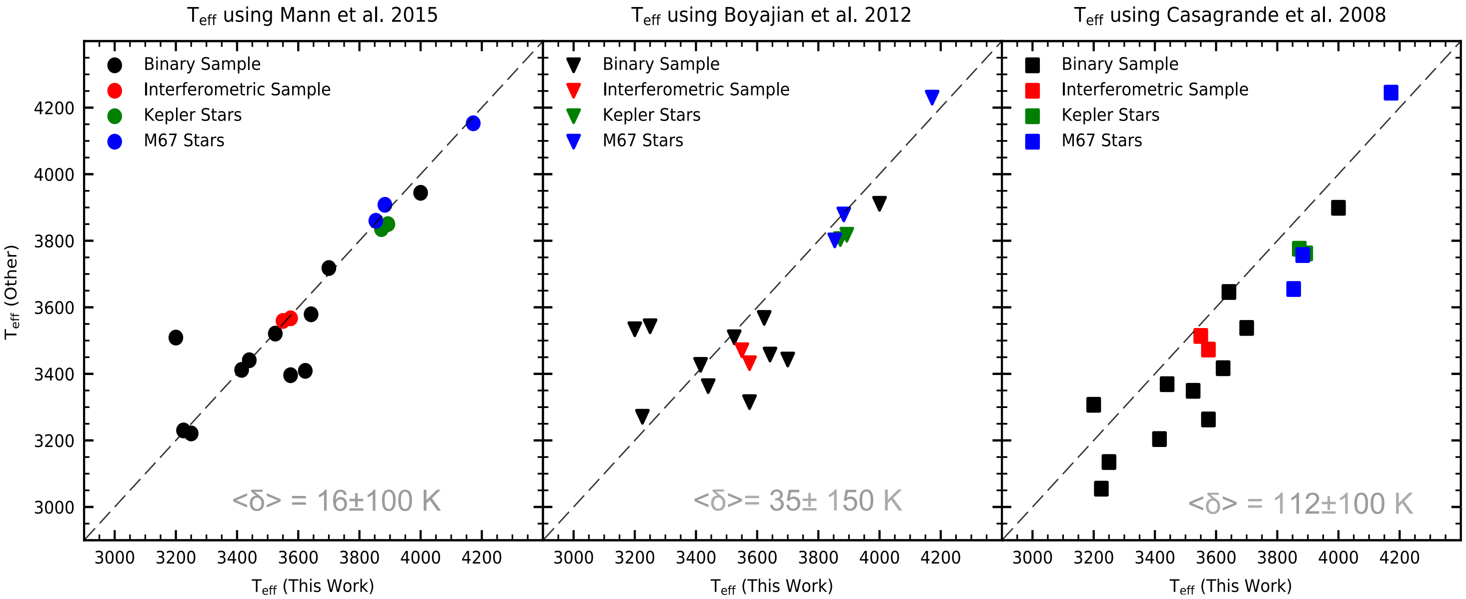
- ➢ Turbospectrum synthesis code (Plez 2012)

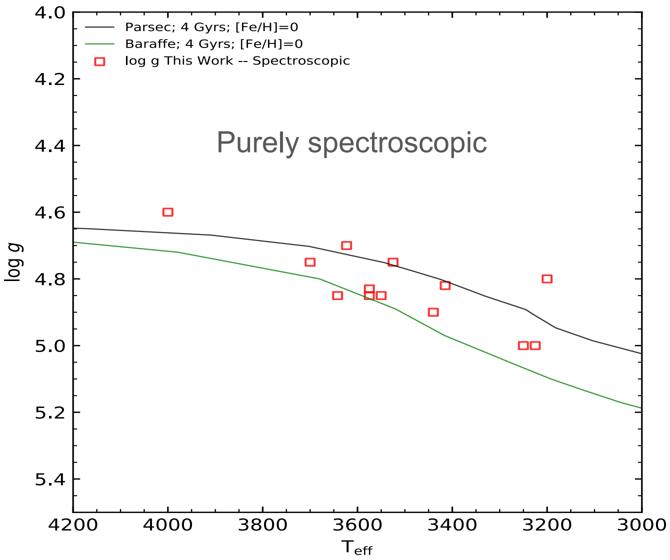


Typical spectrum
Not perfect telluric removal

APOGEE Results for M-Dwarfs

Effective Temperature & Surface Gravity scales Preliminary…





Teff

- Good agreement and reasonable scatter with the calibration from Mann et al., with almost no offset
- Small offset with the calibration of Boyajian et al. with a larger scatter
- Bigger offset with Casagrande et al. (2008) > Their scale is cooler

Log g

- Our spectroscopic log gs are preliminary; look reasonable

APOGEE Results for M-Dwarfs

Metallicity Scale [Fe/H] : Binary Star Sample

Preliminary…

- M-dwarfs in binary systems with hotter primaries of spectral types FGK

- Metallicities for M-dwarfs
- Probing regime:
  Teff: ~ 3200K -- 4000K;
  [m/H]: ~ -0.9 -- +0.2 dex

- Green points from the H2O+OH Teff scale with metallicities from Fe I (Souto et al. 2017)

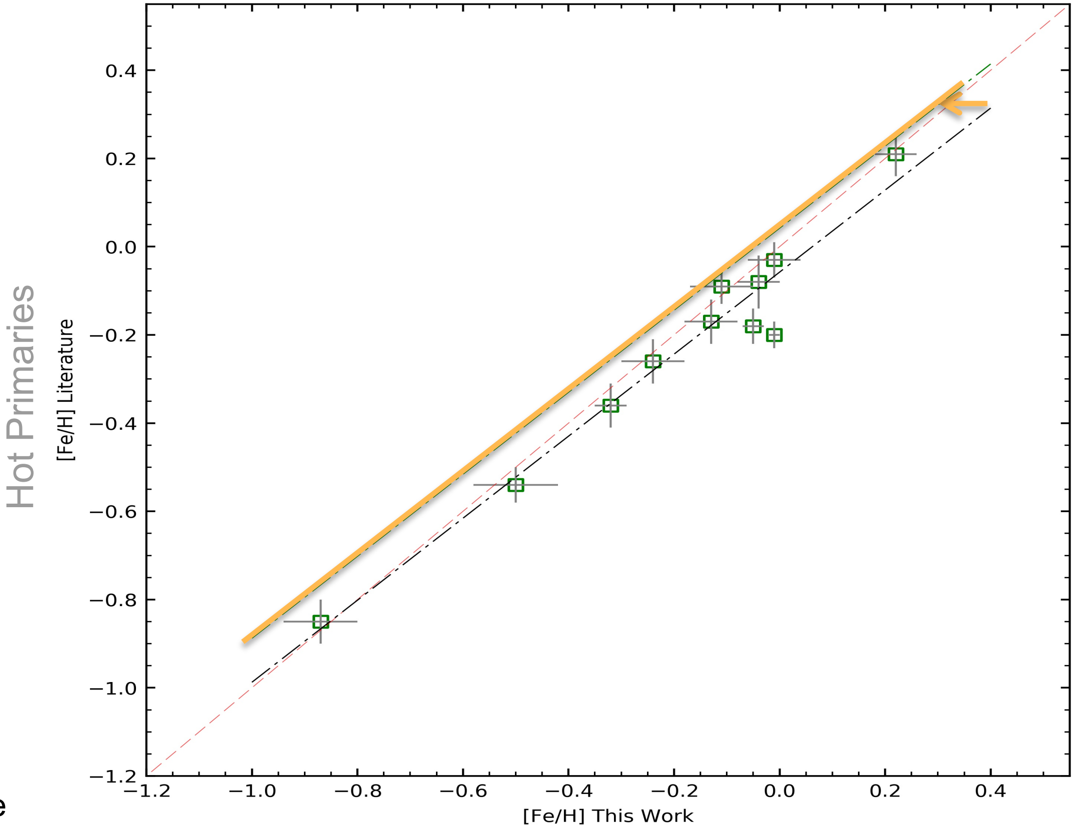
- <δ A(Fe) (M-dwarfs - Hot primaries)> = 0.035 ± 0.063

- Work in progress: move to a more metal poor scale?

Metallicities of hot Primaries:

- From high-resolution studies @ optical
- Not homogeneous
- Several determinations per star (average [Fe/H])

Binary stars



M-Dwarfs

Adibekyan et al. 2012; Bensby et al. 2014; Carretta 2013; de Silva et al. 2015; Mann et al.2013; Ghezzi et al. 2010; Lambert et al. 2004; Mishenina et al. 2008; Ramírez et al. 2007, 2012; Reddy et al. 2006; Santos et al. 2003

APOGEE Results for M-dwarfs: Kepler targets

Chemical Abundances of M-Dwarfs from the Apogee Survey. I.
The Exoplanet Hosting Stars Kepler-138 and Kepler-186
Souto, D., Cunha, K., …Smith, V. V. ,… Teske, J. et al., 2017, ApJ, 835, 239

Kepler 138 and **Kepler 186**:

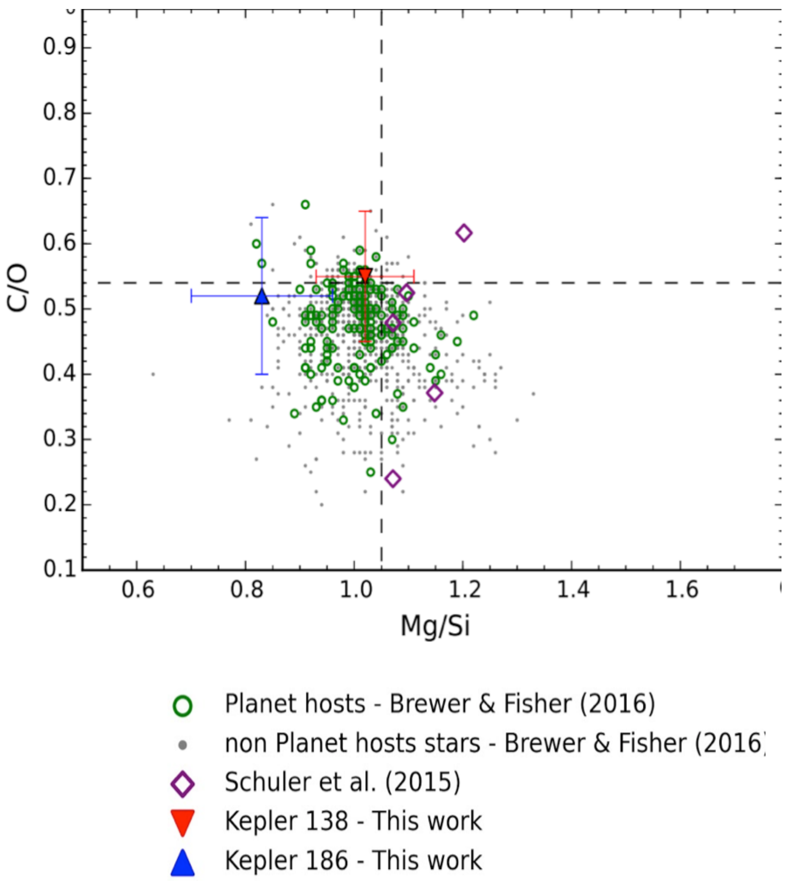
- Similar Teff and log g
- Similar sub-solar metallicities: [Fe/H] ~ -0.20 (updated using all 4 Teff indicators)

- Also have similar C/O ratios (controls ice chemistry in protoplanetary disk)
  Kepler 138 C/O = 0.55
  Kepler 186 C/O = 0.52

  However,

  Kepler-186 is silicon rich: **[Si/Fe] = +0.18**
  Kepler-138 is not: **[Si/Fe] = 0.00**

❖ Different Mg/Si can affect core-to-mantle mass ratios in rocky exoplanets (Unterborn et al. 2016)
Kepler 138 Mg/Si = 1.02
Kepler 186 Mg/Si = 0.82



Conclusions

- M-dwarfs can be analyzed from high-resolution APOGEE spectra at 1.5 – 1.7 micra !!!!!

- Stellar parameters (Teff, log g, metallicities) + Detailed abundances for 14 elements can be derived from APOGEE spectra (Ni recently included)

– investigate planet-star connections

- M-dwarfs in binary systems with hotter components, as well as M dwarfs members of the M67 open cluster, play an important role in confirming the M dwarfs APOGEE metallicity scale and establishing the benchmark metallicity that does not suffer from atomic diffusion in M 67

Work in Progress…

- This is a pioneering detailed chemical study of M-dwarfs from high-resolution APOGEE spectra in the H-band

- We have updated the line list to better handle M-dwarfs and will continue this work

- Progress has been made on a new FeH line list; new FeH line list solved most of the missing lines from the line list

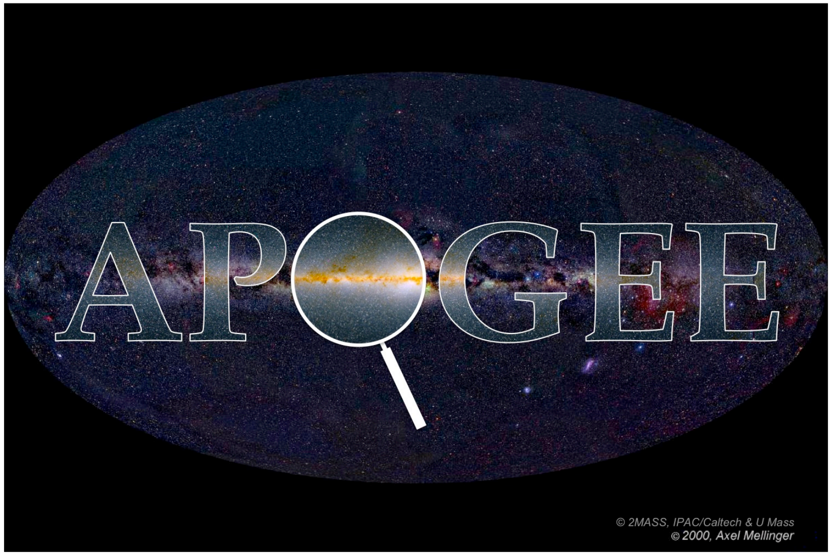
- Work continues to identify remaining unknown lines in the observed M-dwarf spectra: a small number of lines are still unidentified

- Need to study effects of activity

- 'Perfecting' M-dwarf analysis is important for future exoplanet studies
  Data Driven modeling needs good sets of abundances as training sets.

@diogo_souto

THANK YOU!



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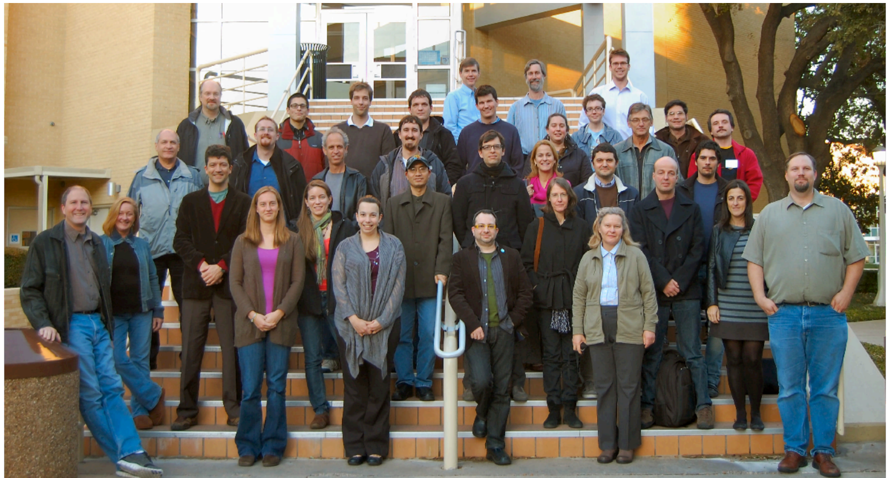

Thanks to the APOGEE team! The many people who contributed to the APOGEE targeting, observing, data reduction, model atmospheres calculations, line list construction etc…)