DETERMINING STELLAR PARAMETERS FROM SPECTROSCOPIC OBSERVATIONS

Philip Muirhead
Department of Astronomy
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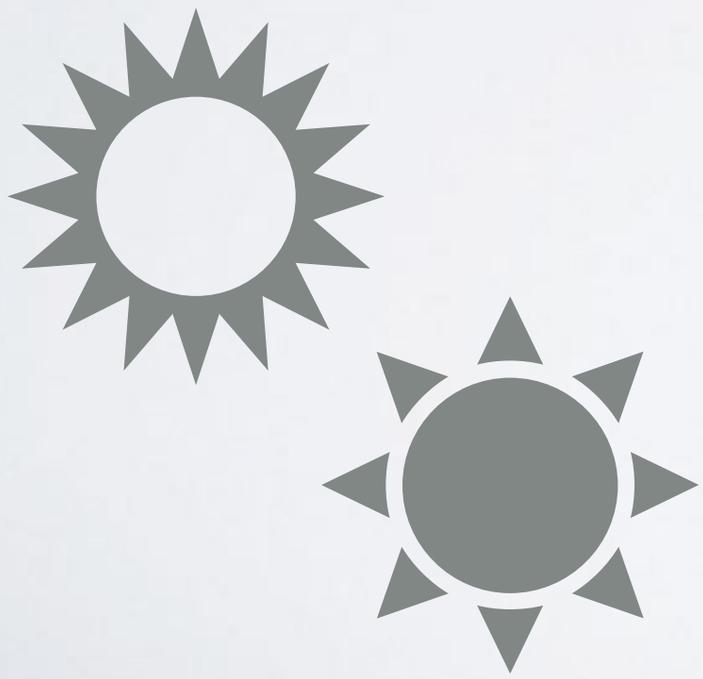
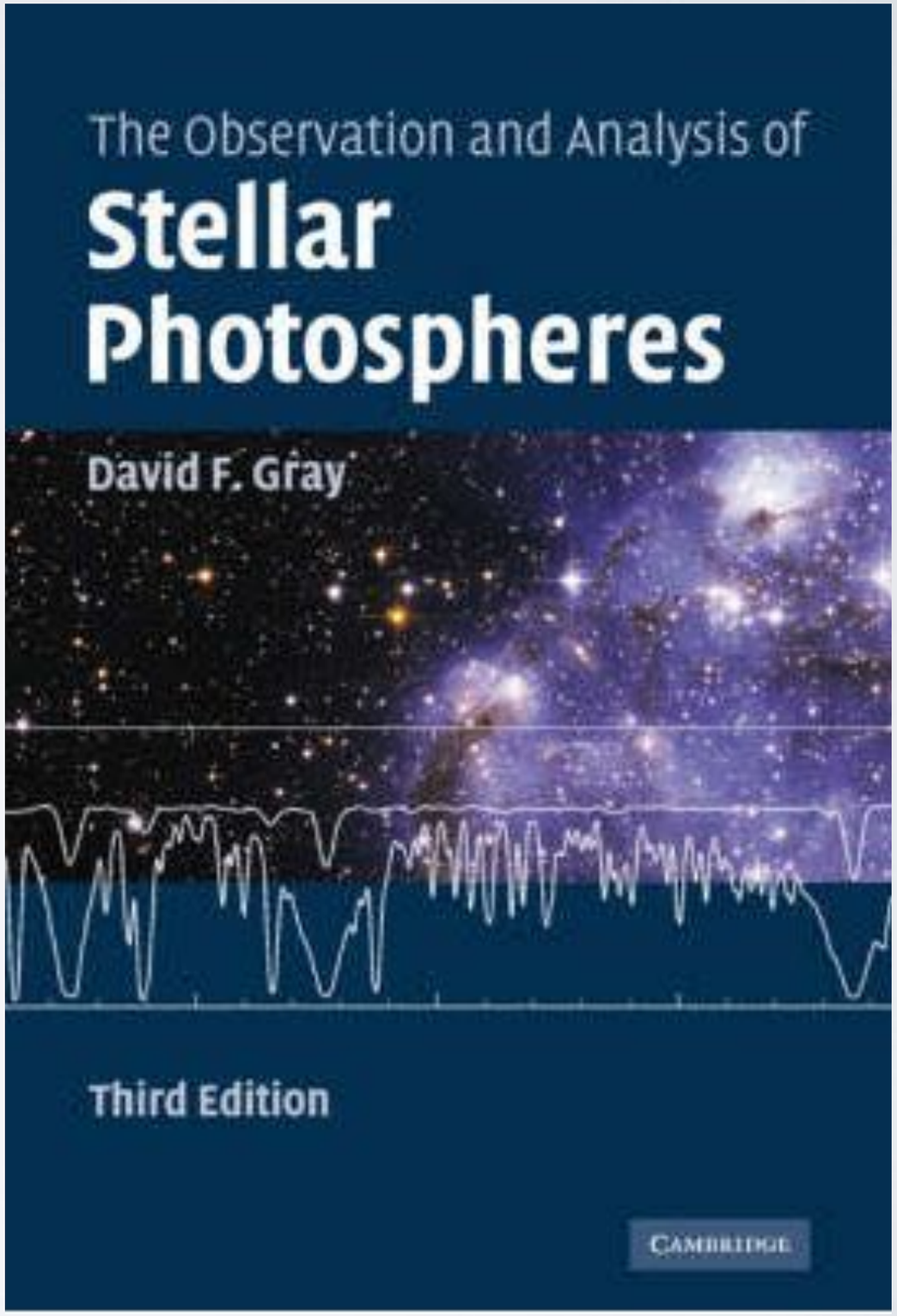


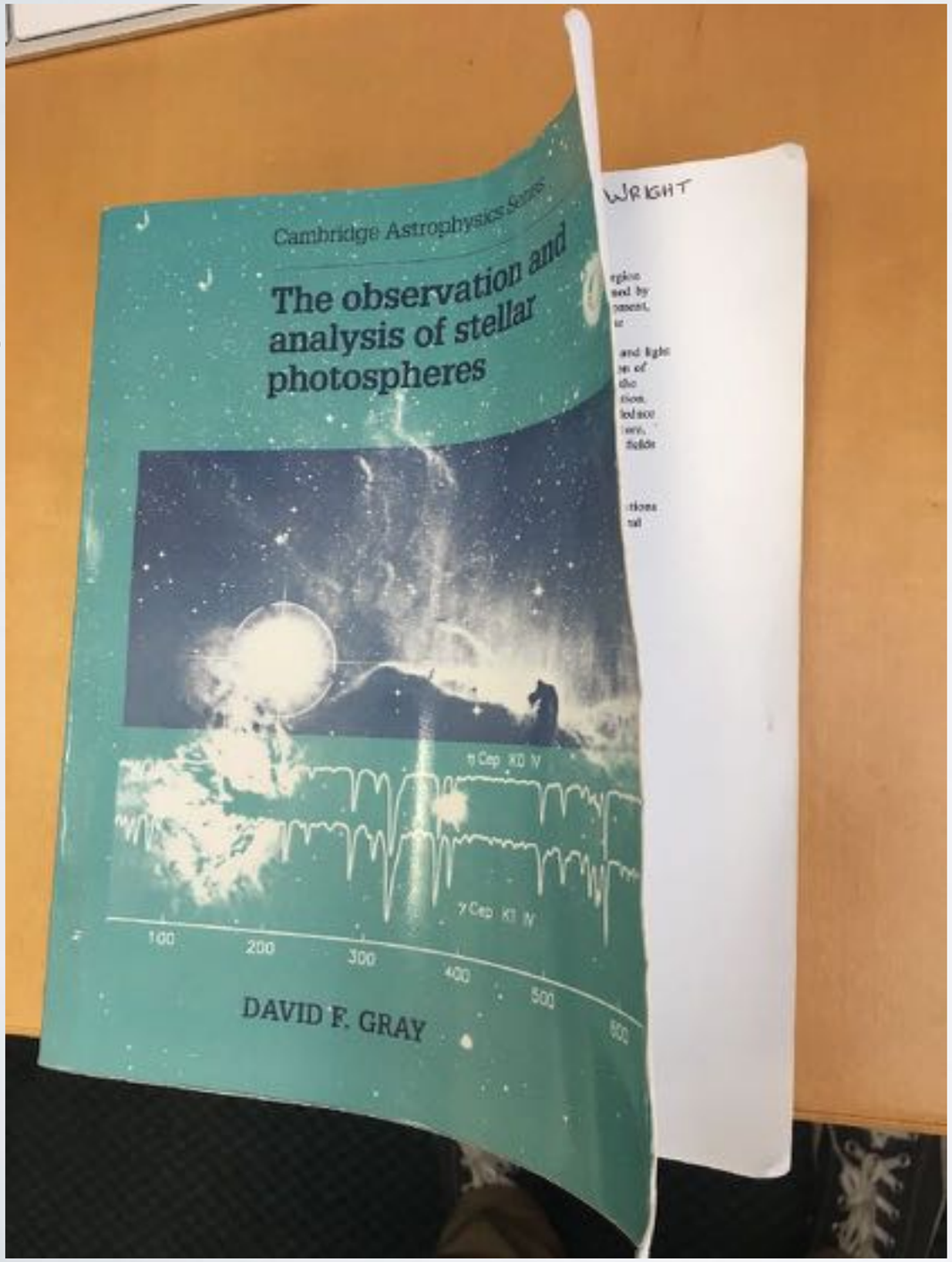
FOR THE FUNDAMENTALS

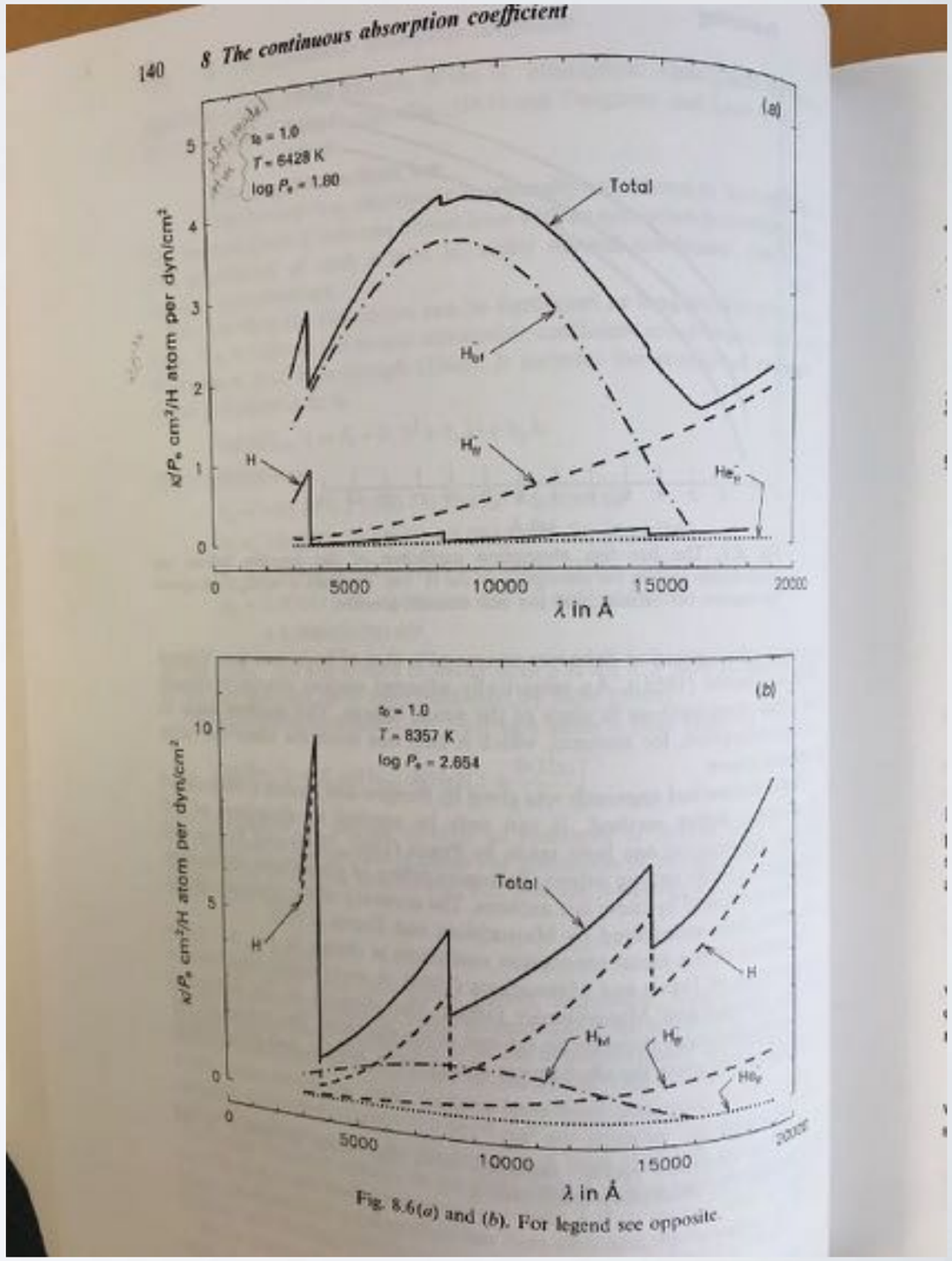
- My personal recommendation for the fundamentals of acquiring and interpreting stellar spectra.

- Includes the basics of **stellar atmosphere models**.



I OWN JASON WRIGHT'S COPY

- 



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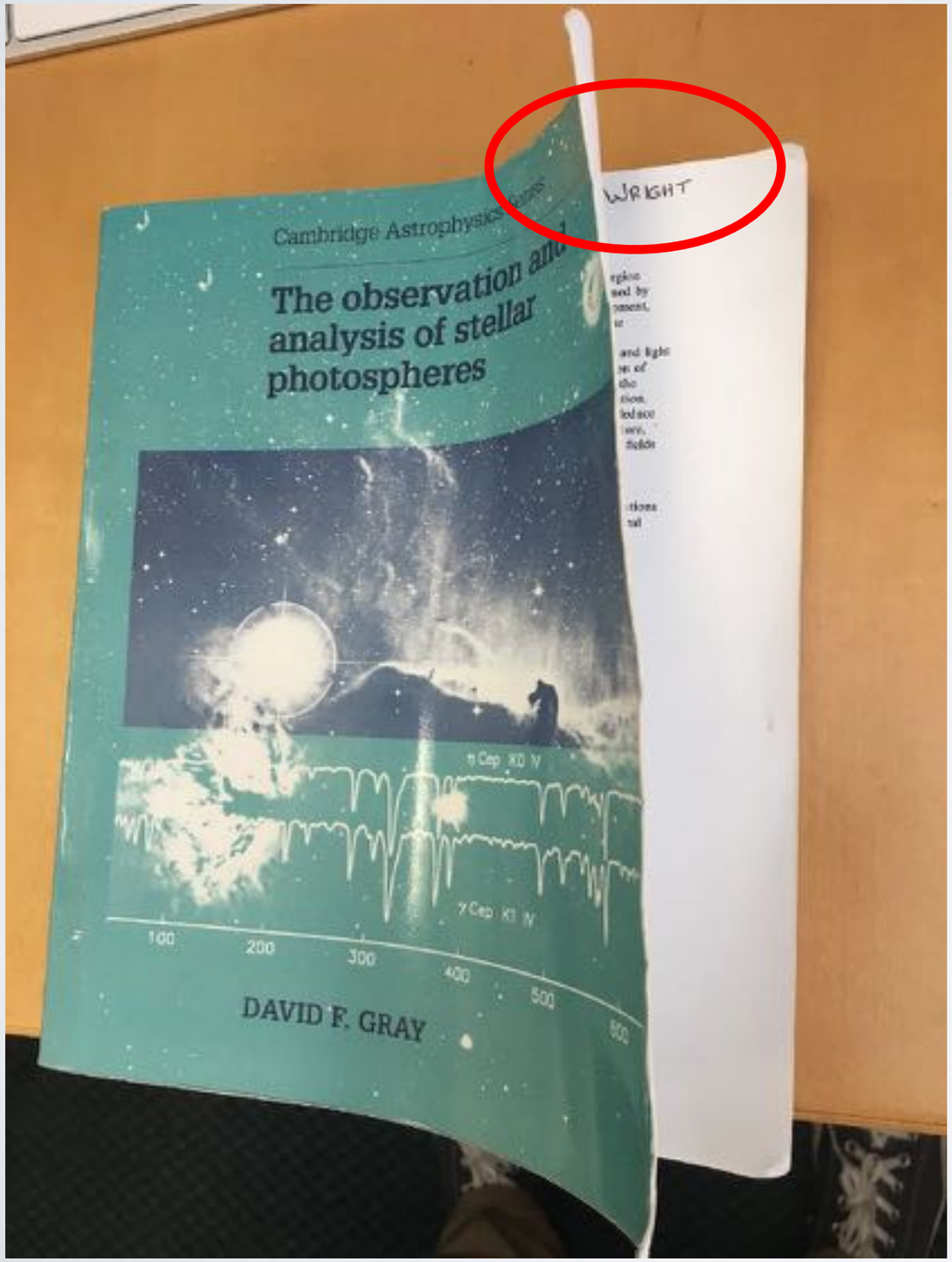
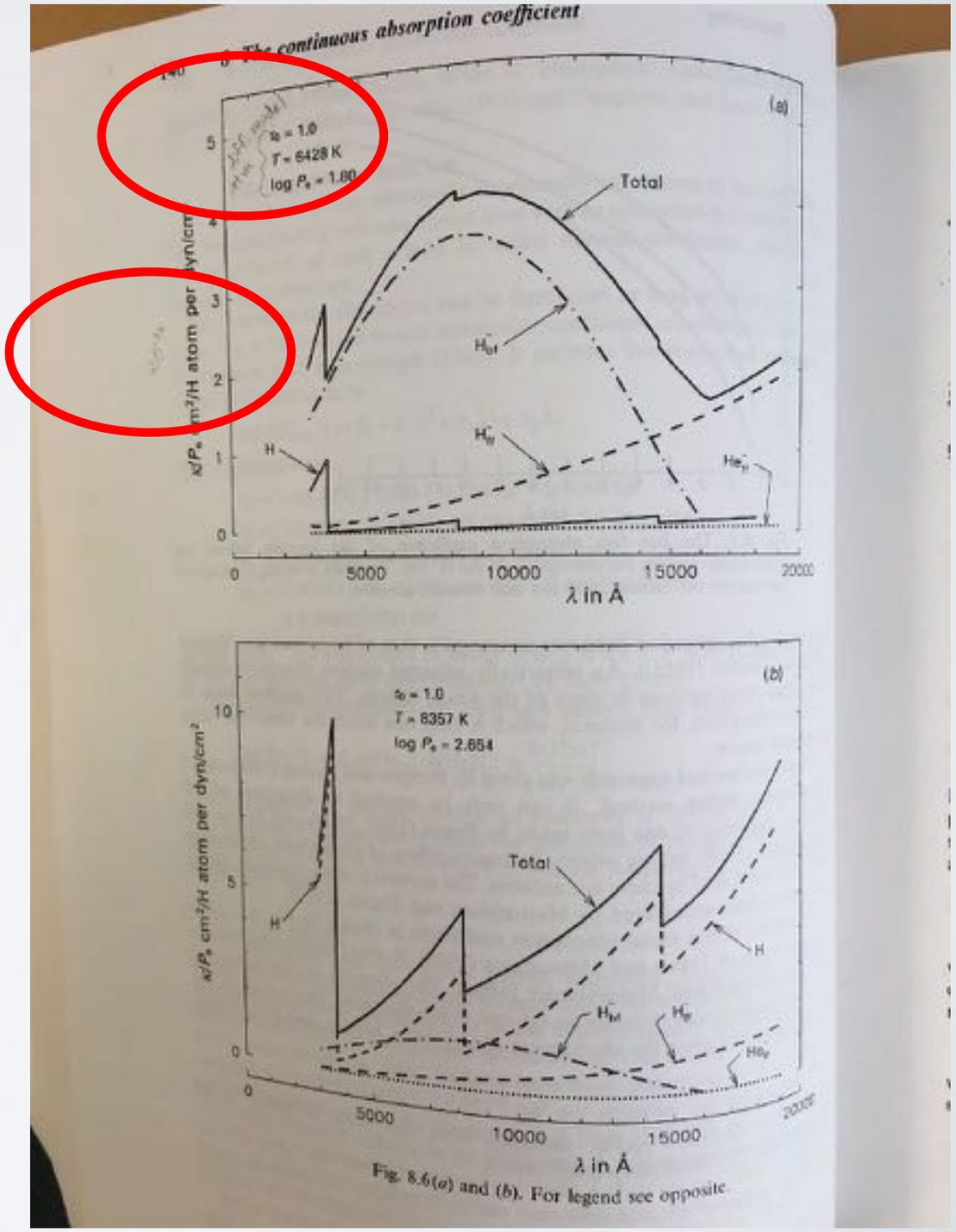
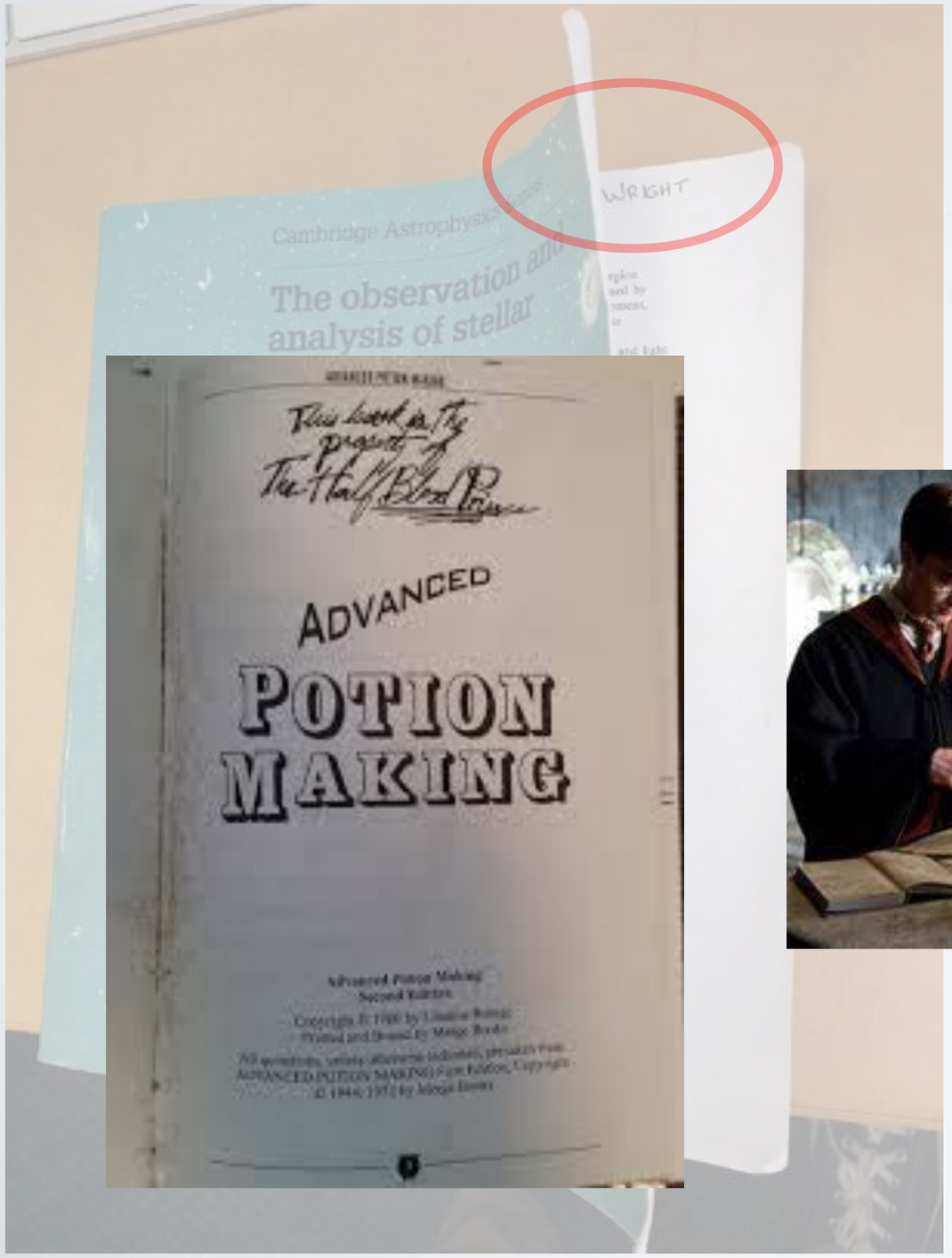
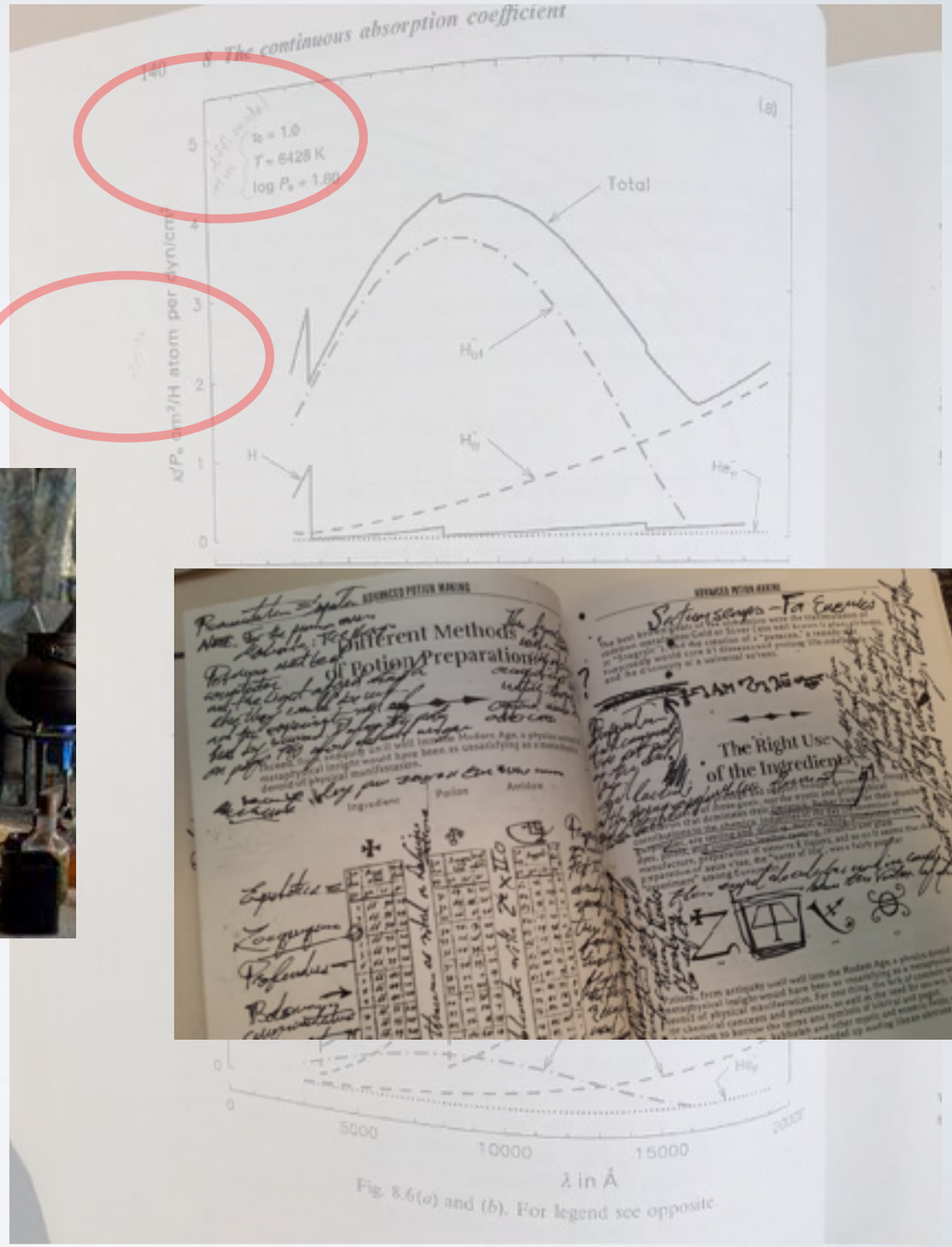




KEITH IS RIGHT,
IT IS A DARK ART





ATTEND THIS SUMMER SCHOOL

- Annual early-career workshop on Modules for Experiments in Stellar Astrophysics (MESA).

- Great for understanding the fundamentals of **stellar evolutionary models**.

2017 MESA Summer School : August 14 - 18

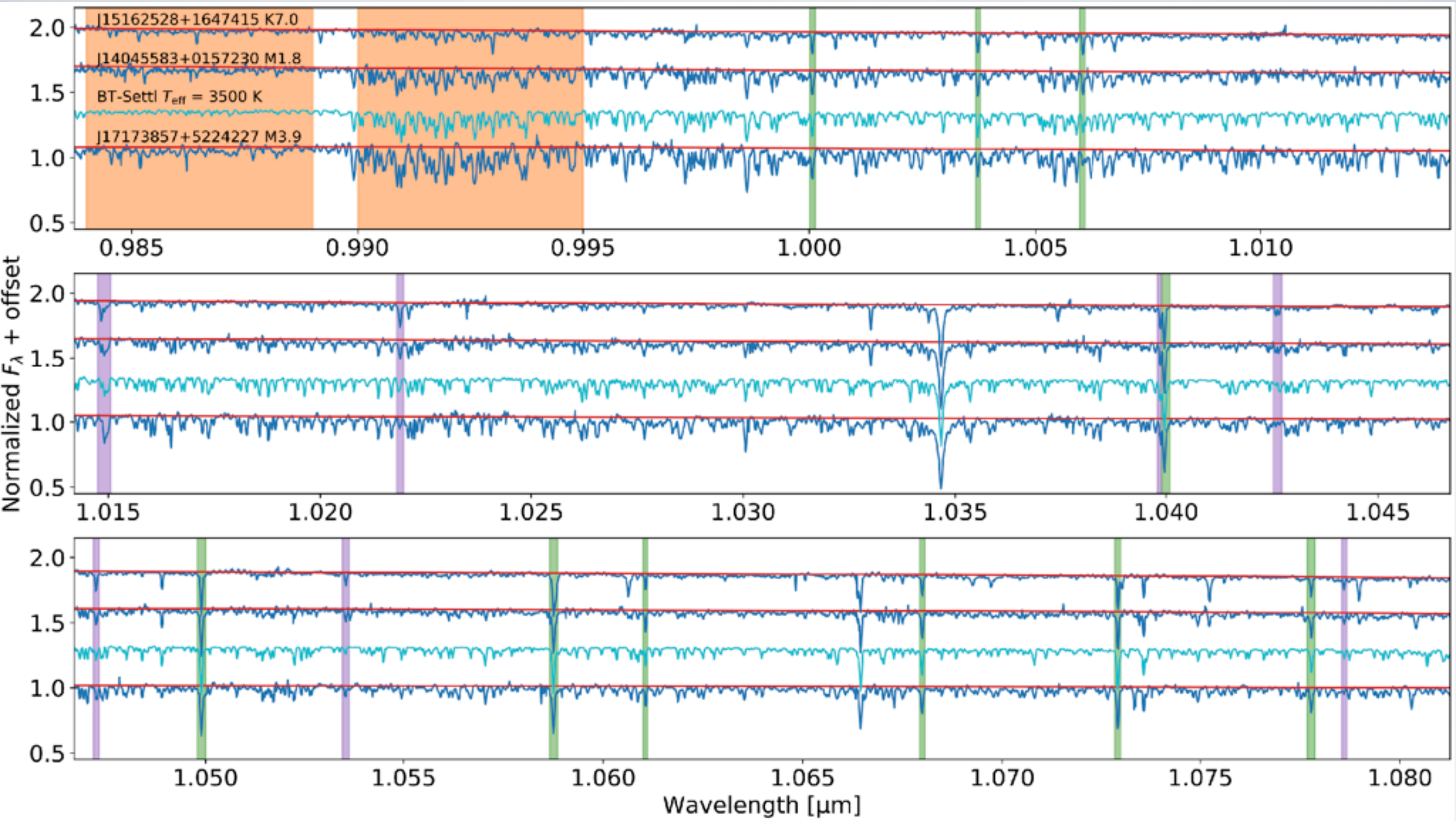
Home Application Agenda Lodging Participants Directors Feedback

The 6th Annual MESA Summer School will be held August 14-18, 2017 at UC Santa Barbara. Though extensive hands-on labs, participants will gain familiarity with MESA and learn how to make better use of MESA in their own research. Featured MESA topics include planets, binaries and much more with Leslie Rogers, Jonathan Fortney, Selma De Mink, and Pablo Marchant. See the Agenda for additional information. Enrollment is limited and the Application period closes March 1, 2017.

MESA has attracted over 900 registered users and provides a portal for the stellar community to openly share knowledge. The instrument papers MESA I, MESA II, and MESA III describe MESA. Summer Schools were previously offered in 2016, 2015, 2014, 2013, and 2012.

MESA UCSB UNIVERSITY OF CALIFORNIA SANTA BARBARA ASU NSF

M Dwarfs in Y Band (Keck-NIRSPEC)



Spectra contain an **enormous** amount of information (not just RV!)

Figure from Veyette, Muirhead, Mann et al. (submitted)

REDUCE TO A HANDFUL OF PARAMETERS

- Spectral Type
- Effective temperature
- Surface gravity
- Abundances

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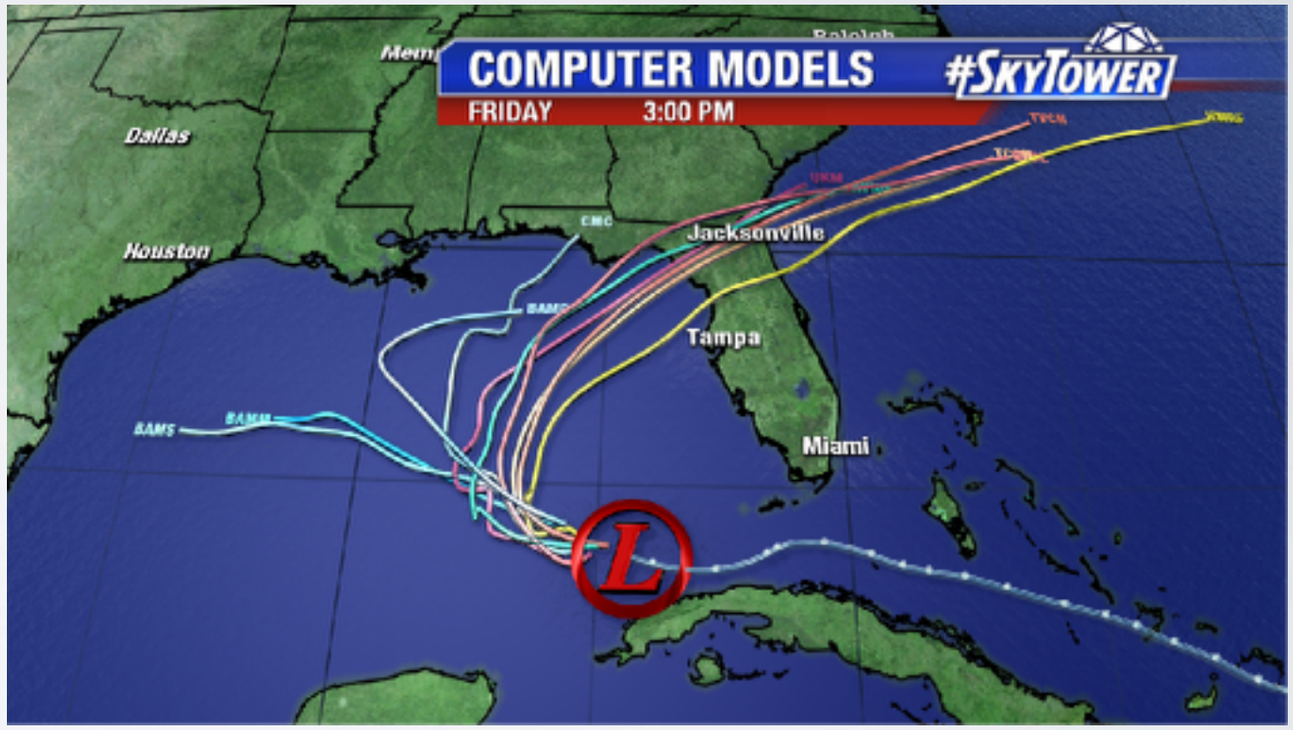
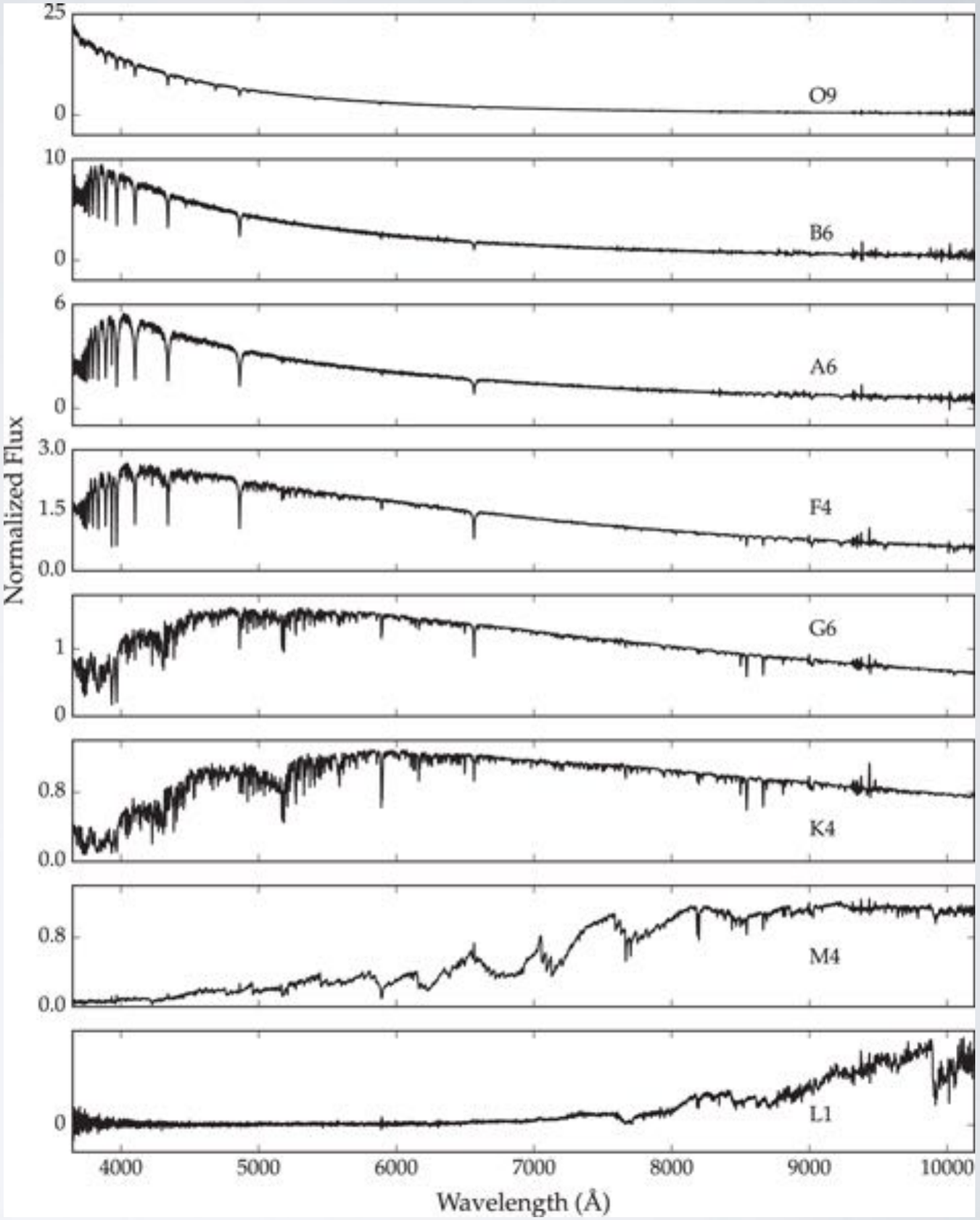


Lots of data -> few desired parameters
(e.g. hurricane landfall)
Bound to have disagreements

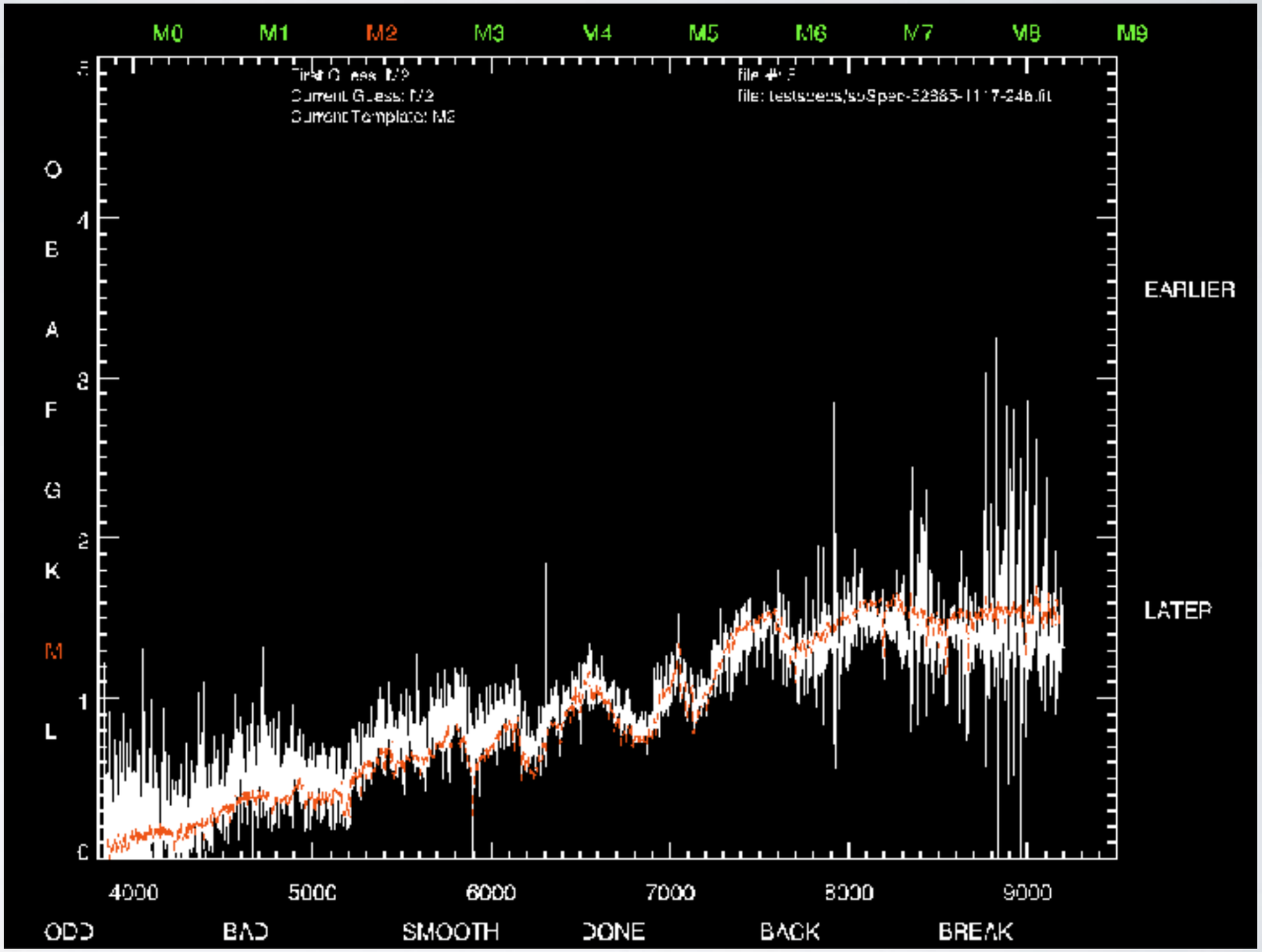
- **Spectral Type**
- Effective temperature
- Surface gravity
- Abundances



From PYHAMMER (Kesseli et al. 2017)

SPECTRAL TYPE

- A "by eye" process ever since Annie Jump Cannon.



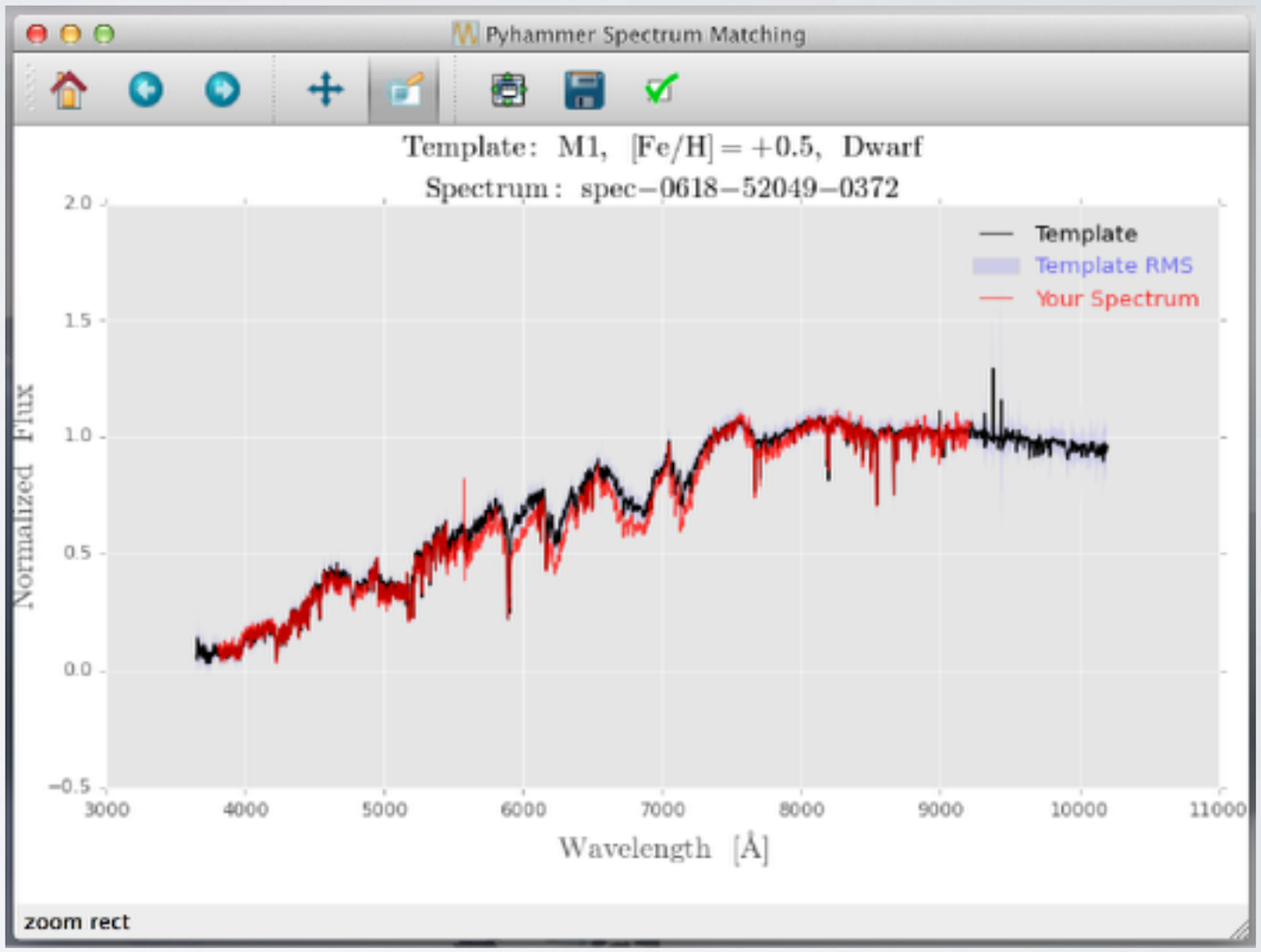
The Hammer (Covey et al. 2007)

SPECTRAL TYPE

- Recently, new software developed to auto-spectral type large data sets.

- PYHAMMER

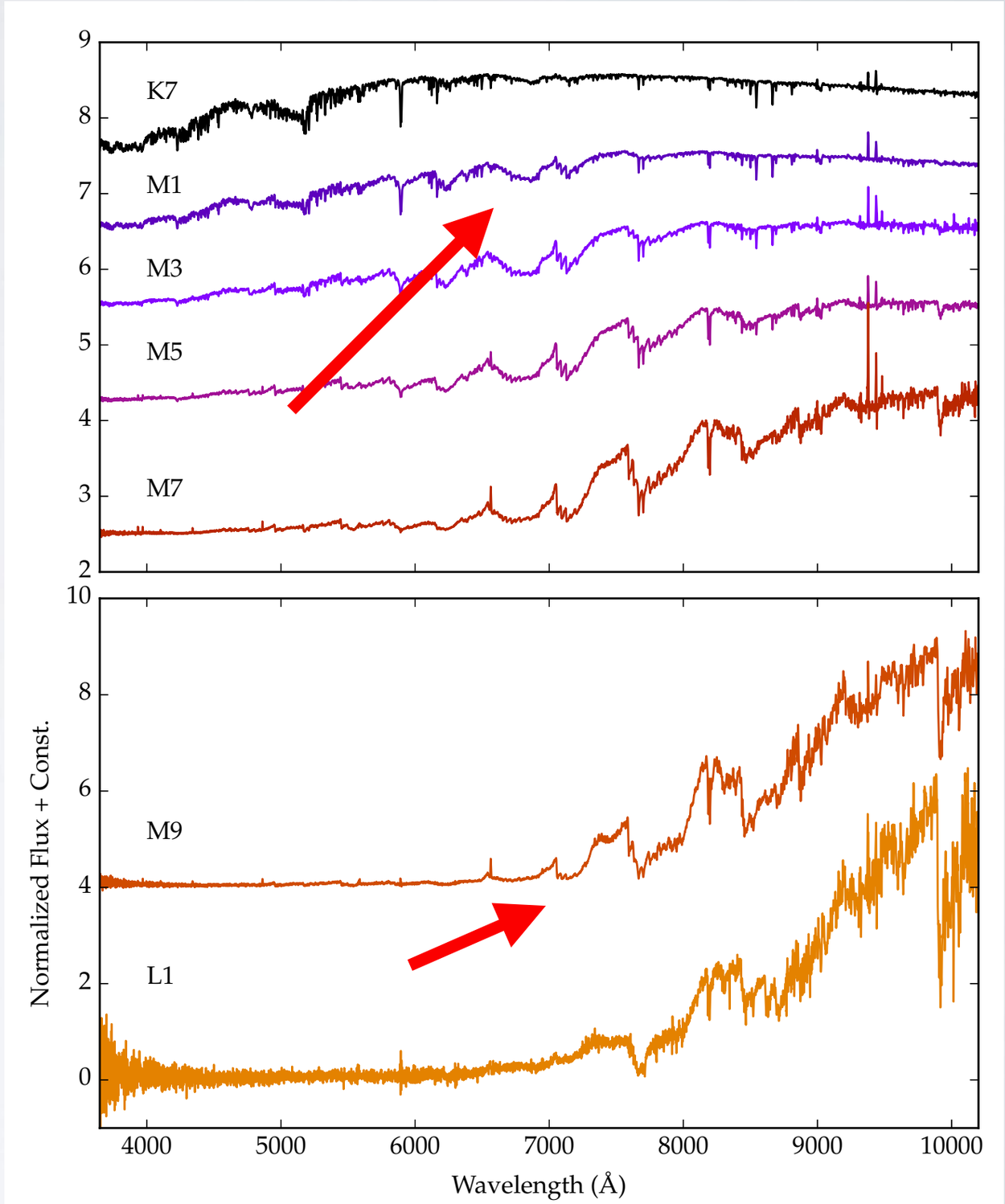
  - Kesseli et al. 2017



https://github.com/BU-hammerTeam/PyHammer

SPECTRAL TYPE: LIMITS OF USE

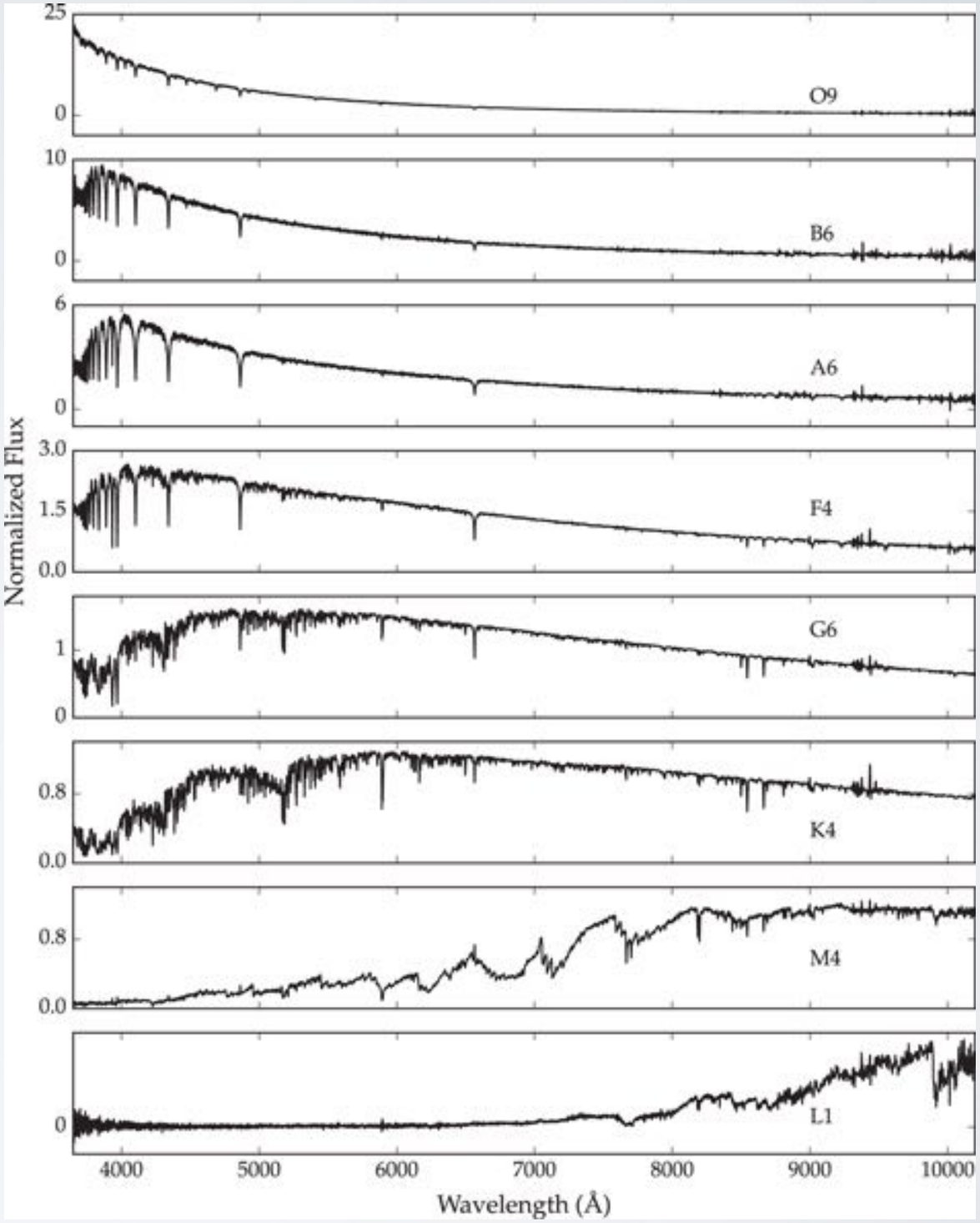
- Fundamentally qualitative.
- The boundaries between spectral types are arbitrary and **depend on spectral resolution**
  - K-M transition is the onset of oxide molecular features.
- But the Sun has oxide molecular features at high resolution…
- M-L transition is **not** a substellar transition (more on that this afternoon).



From PYHAMMER (Kesseli et al. 2017)

SPECTRAL TYPE: THE MERITS

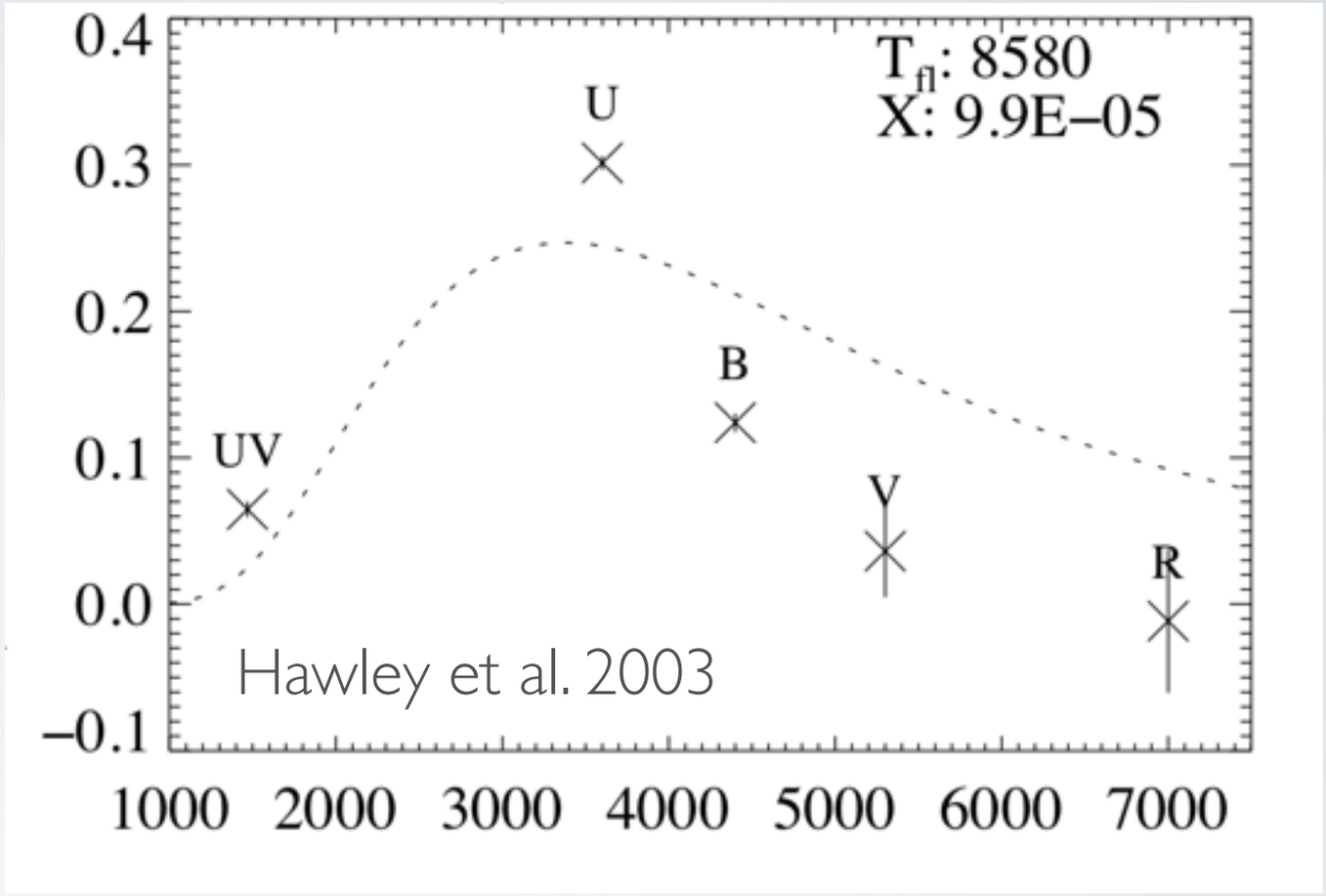
- **But it places your exoplanet hosts in context.**



From PYHAMMER (Kesseli et al. 2017)

SPECTRAL TYPE: THE MERITS

- Consider that when AD Leo flares, it goes from an **M dwarf to an A star.**



What is the spectral type of Proxima Centauri during a flare?
A young TRAPPIST?

(Ask Davenport et al.)

- Spectral Type

$$L_{\rm bol} = 4\pi R^2 \sigma T_{\rm Eff}^4$$

- **Effective temperature**
- Surface gravity
- Abundances

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$$L_{\rm bol} = 4\pi R^2 \sigma T_{\rm Eff}^4$$

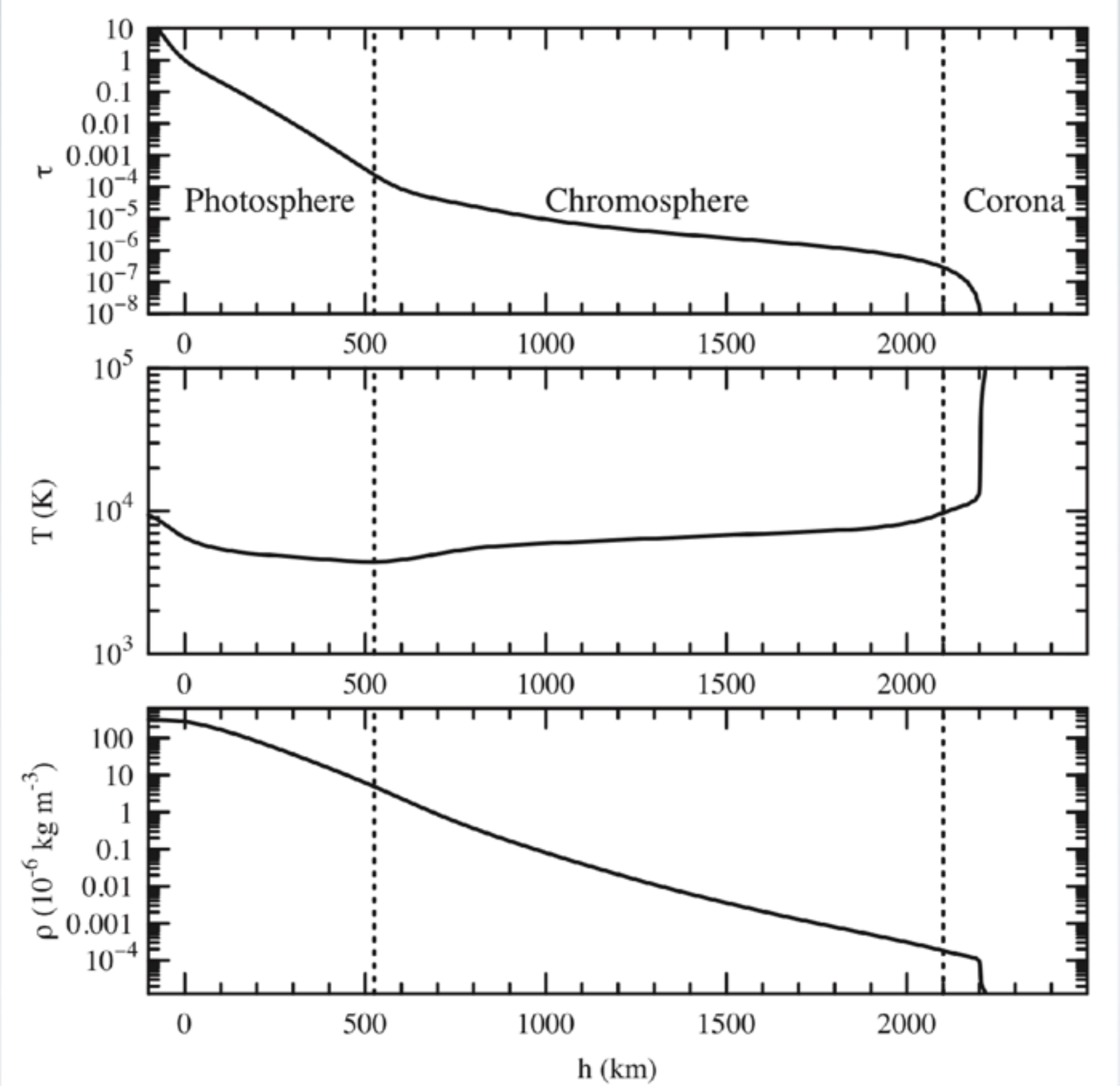
As defined, effective temperature is the **bolometric surface brightness** of a star in units of Kelvin

- Spectral Type
- **Effective temperature**
- Surface gravity
- Abundances

$$L_{\rm bol} = 4\pi R^2 \sigma T_{\rm Eff}^4$$

As defined, effective temperature is the **bolometric surface brightness** of a star in units of Kelvin

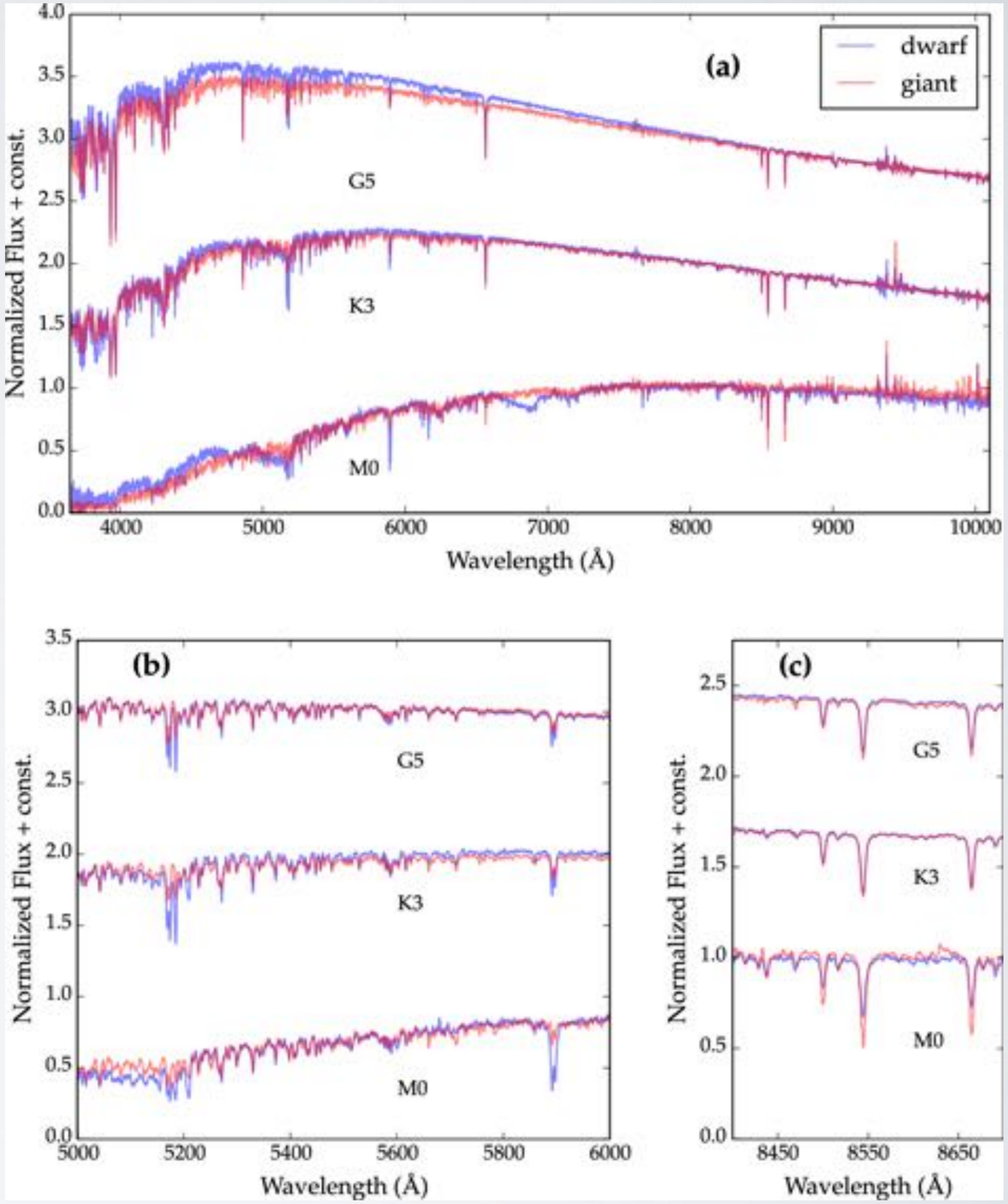
Historically inferred from from the shape of a spectrum or a color (B-V)



Solar Profiles from B. Ryden's Textbook

DWARF-GIANT DISCRIMINATION: BY EYE

- Spectral Type
- Effective temperature
- **Surface gravity**
- Abundances



Kesseli et al. 2017

- Spectral Type
- Effective temperature
- **Surface gravity**
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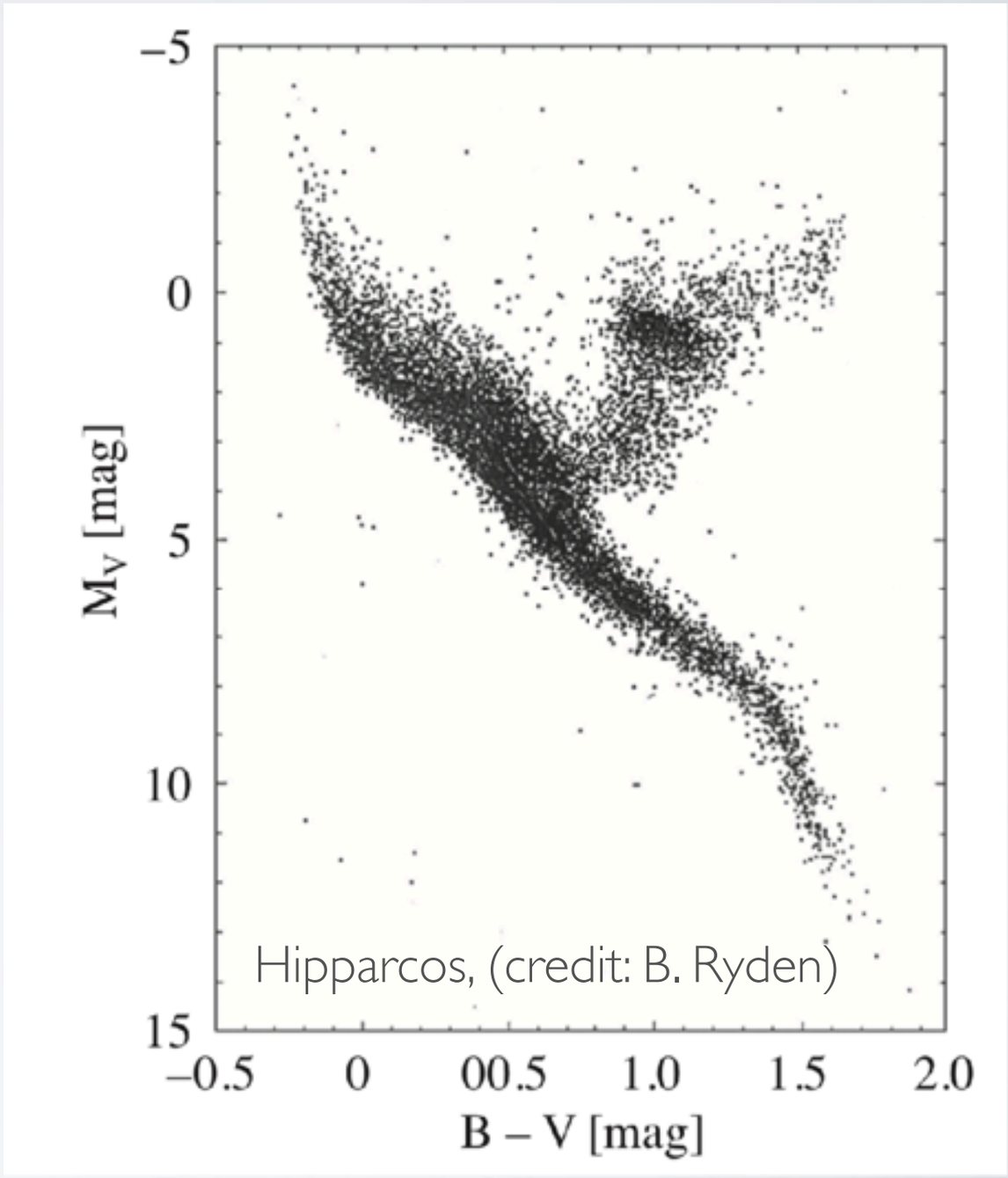
Precise log(g) historically deduced from the location on a HR diagram (requiring a **parallax**)



- Spectral Type
- Effective temperature
- Surface gravity
- **Abundances**

With **T_{Eff}** (from **color**) and **log(g)** (from **parallax**), a high-resolution spectrum can tell you the abundances from the **curve of growth**

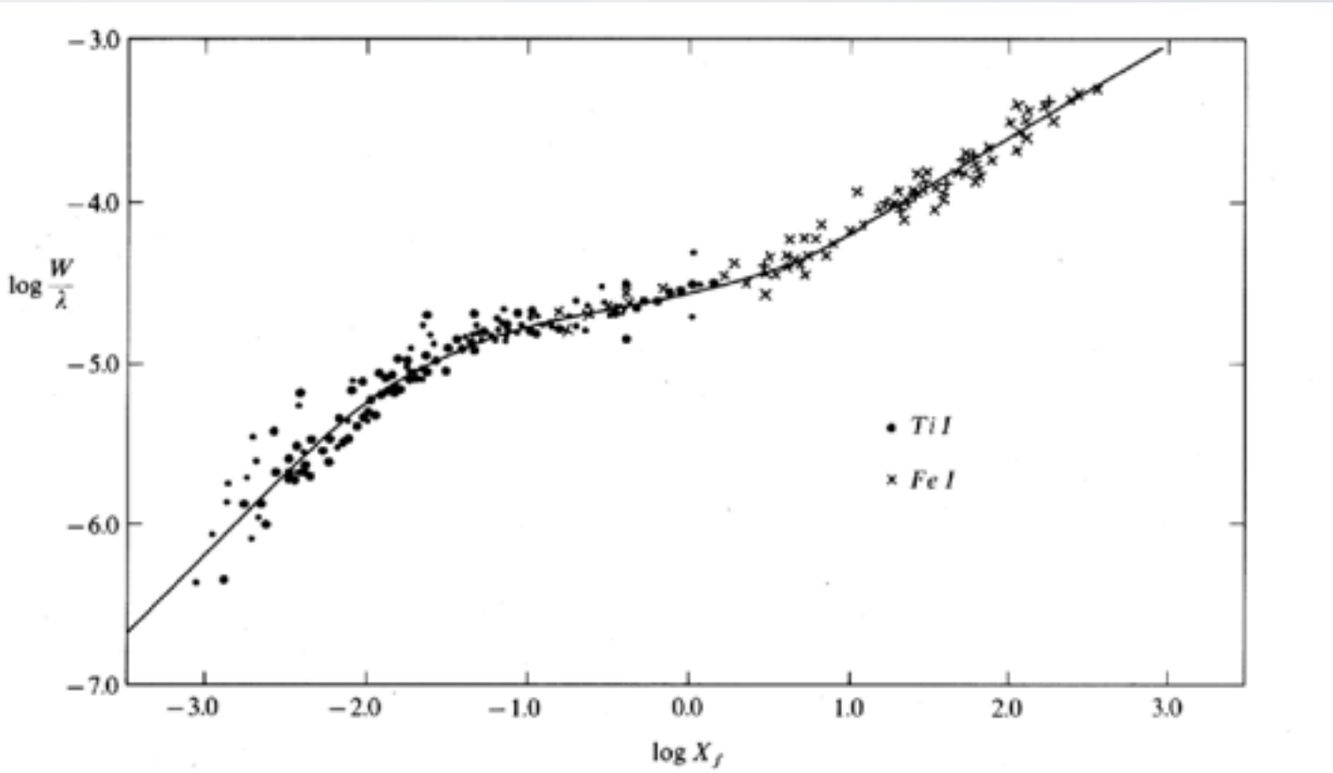


Figure 9.4: Empirical curve of growth for solar Fe I and Ti I lines. Taken from Mihalas (1970) who took it from Wright (1948). Wright measured the equivalent widths of 700 lines in the Utrecht Atlas.

The Old School
Figure from Rutten (2003)

- Spectral Type
- **Effective temperature**
- **Surface gravity**
- **Abundances**

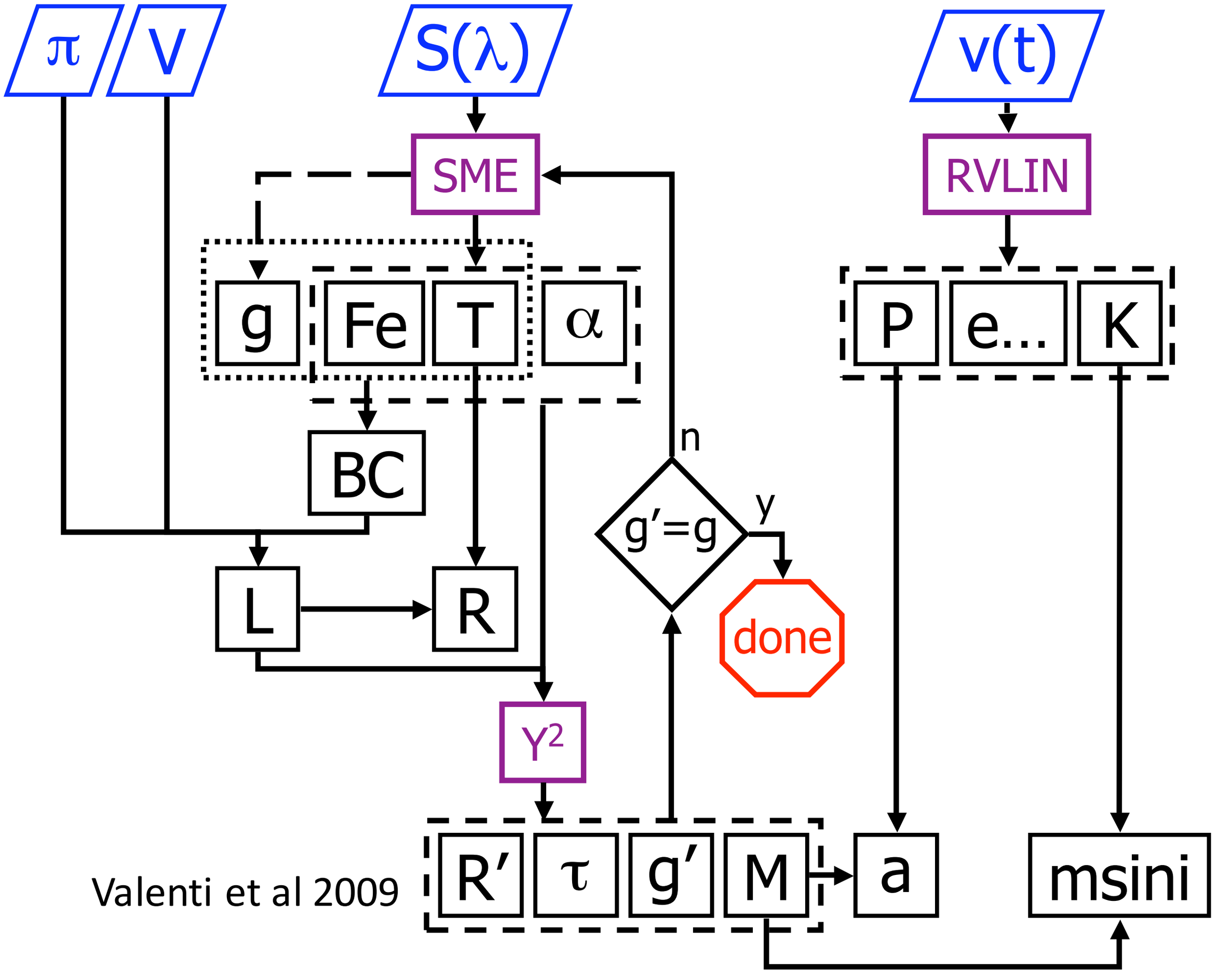
The New School (1990+)

Let's fit **all three at once**, directly from spectra.

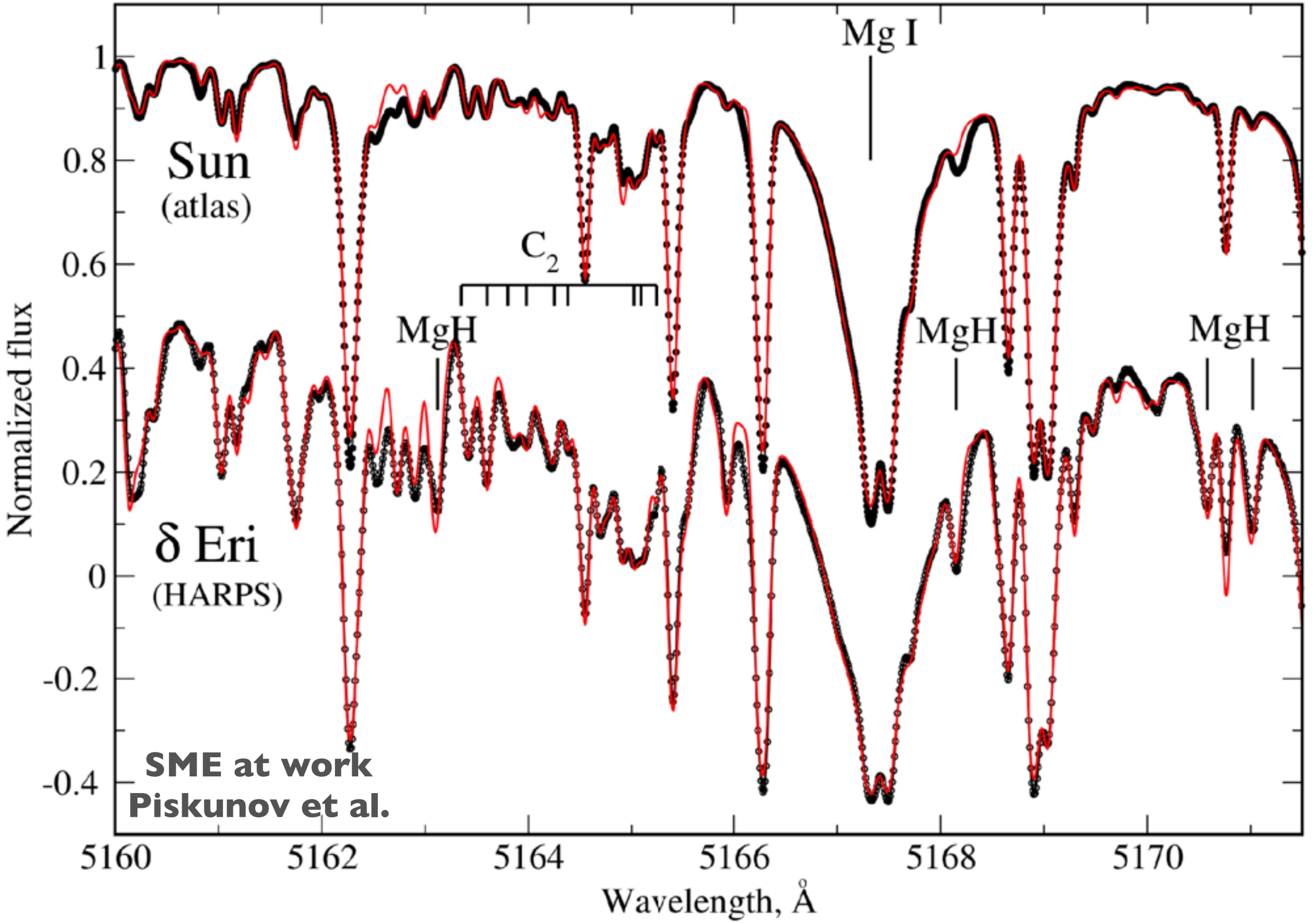
If you have a parallax, that helps, but not required.

E.G. Spectroscopy Made Easy (SME)

Similar approaches include SPC, VWA, ROTFIT



Valenti et al 2009


Mg I
Sun
(atlas)
C2
MgH
MgH
MgH
δ Eri
(HARPS)
SME at work
Piskunov et al.
Normalized flux
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
5160
5162
5164
5166
5168
5170
Wavelength, Å

ACCURATE GRAVITIES OF F, G, AND K STARS FROM HIGH RESOLUTION SPECTRA WITHOUT EXTERNAL CONSTRAINTS

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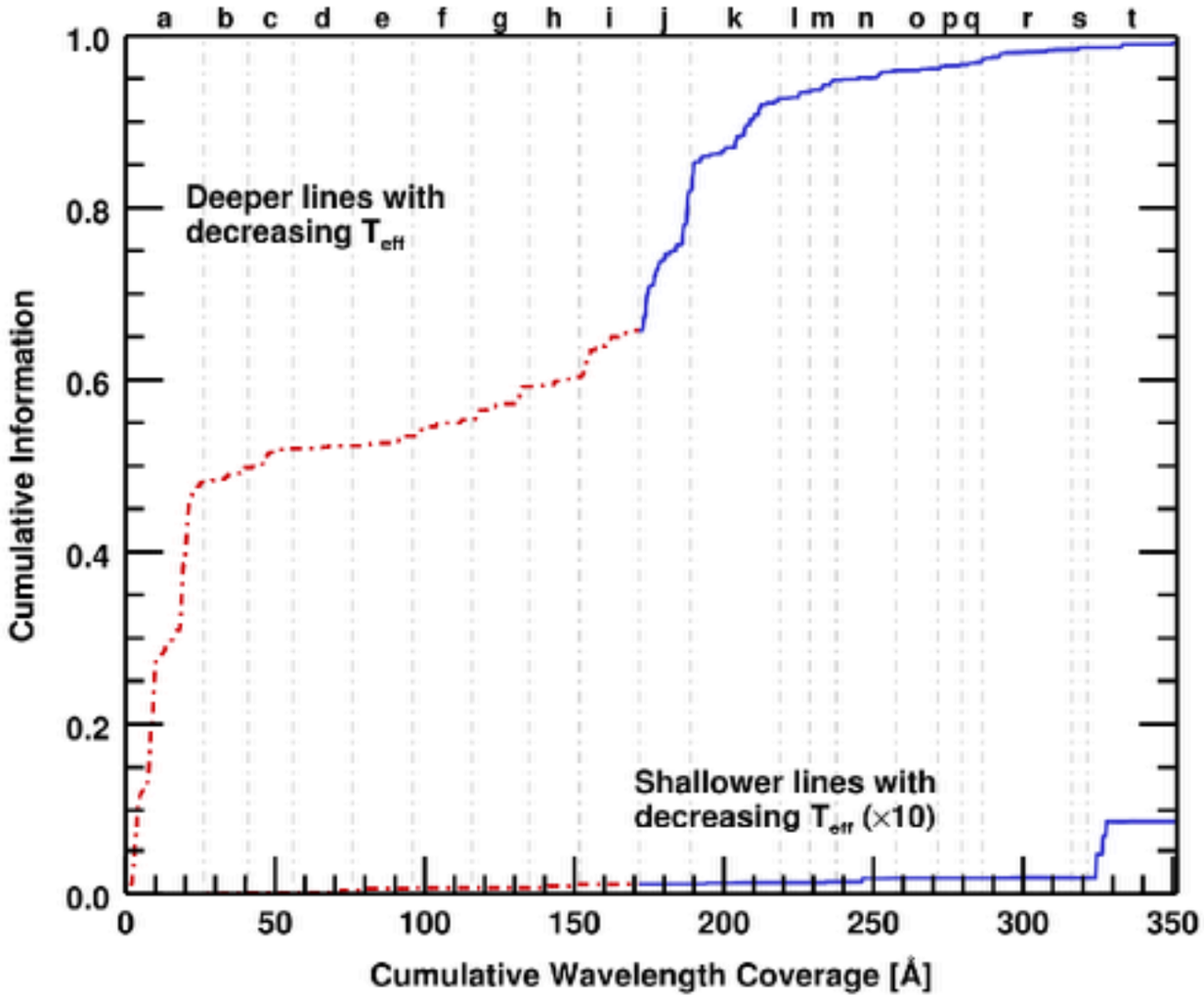
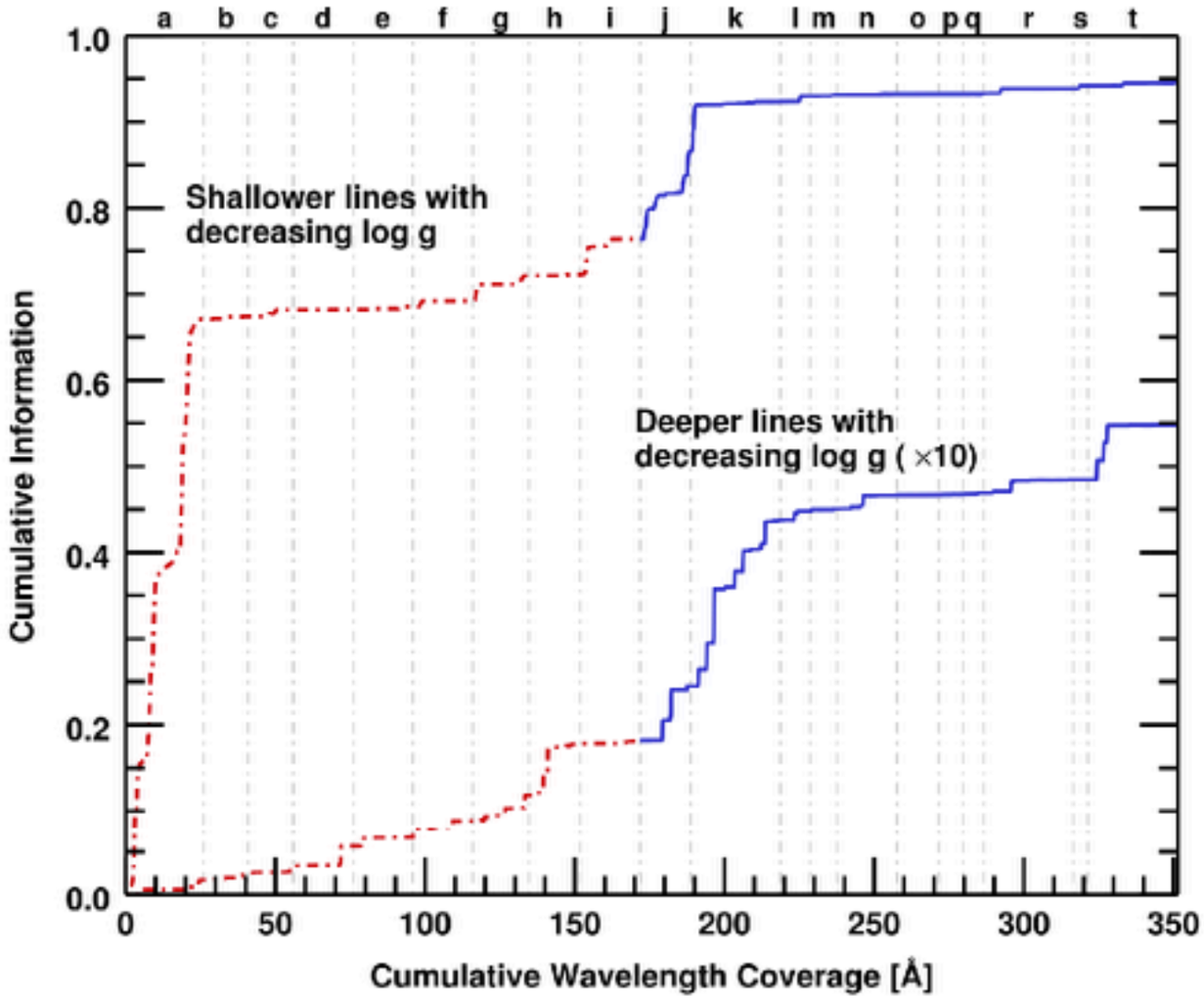
Received 2014 December 22; accepted 2015 March 30; published 2015 May 28





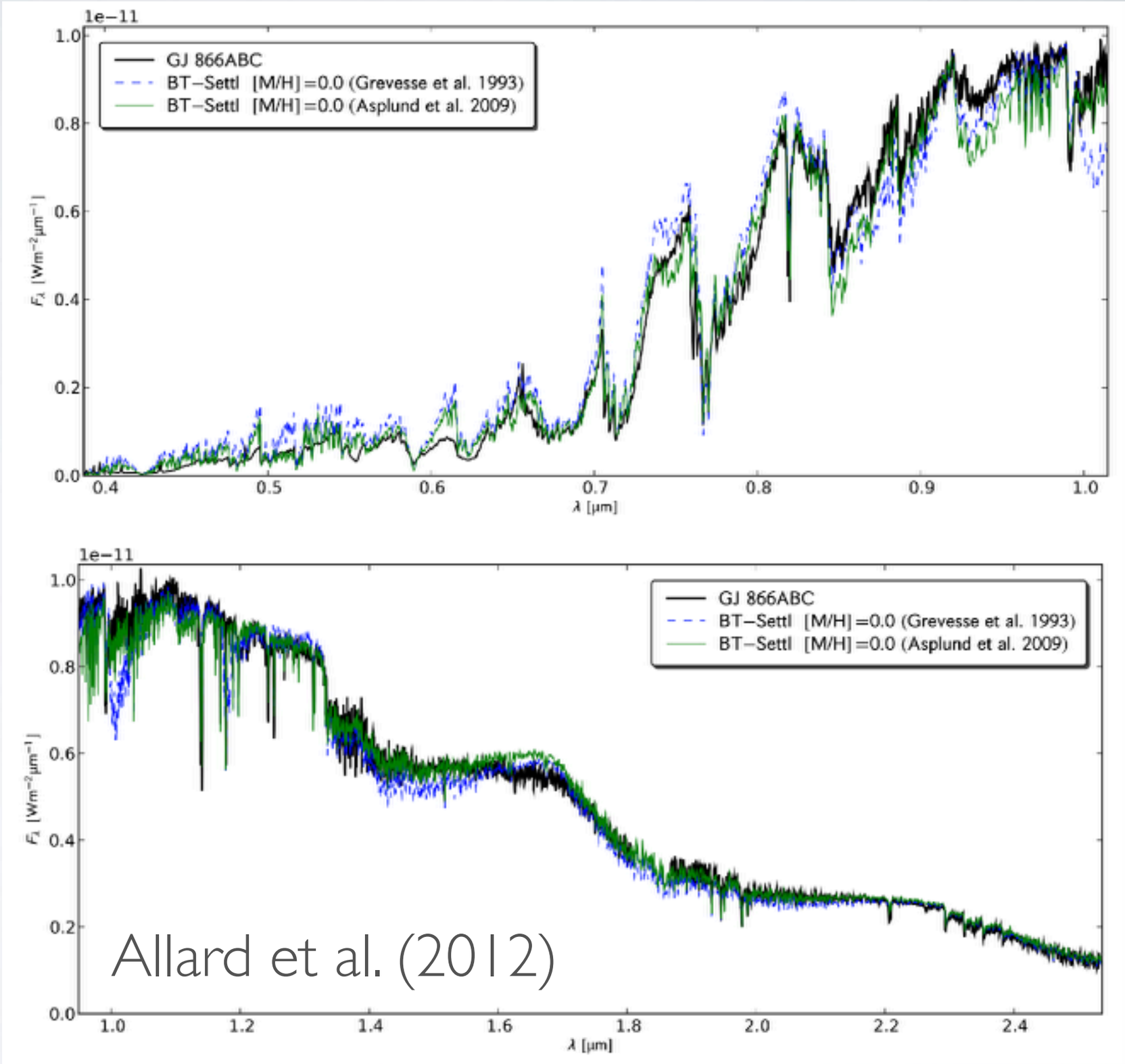
- Spectral Type
- **Effective temperature**
- **Surface gravity**
- **Abundances**

For M dwarfs, this approach is not as straightforward.

But there has been substantial progress over the last decade.

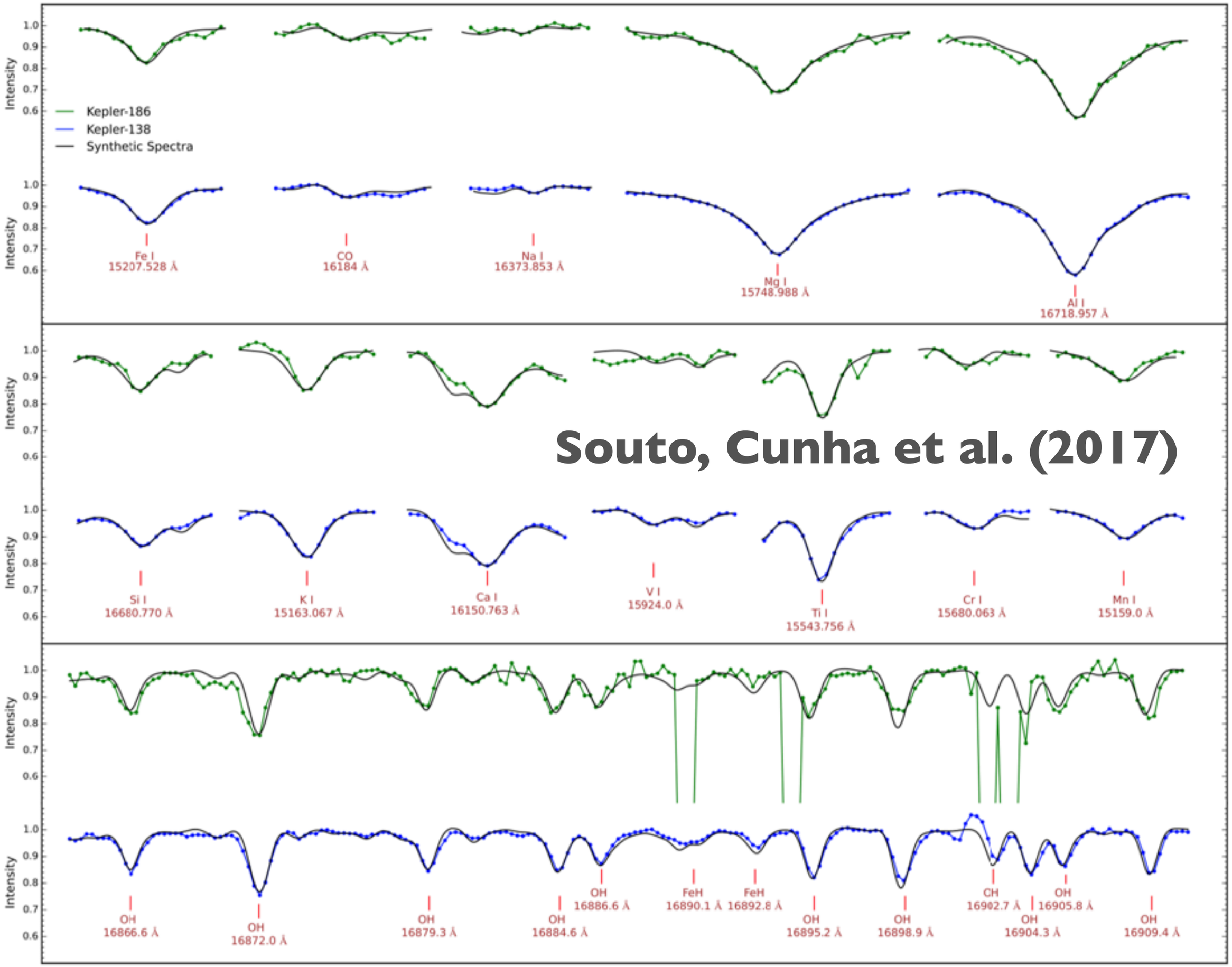
M DWARF SPECTROSCOPY

- Continuum opacity sources no longer dominate
  - Not enough electrons for H-
- Opacities are blended molecular transitions



M DWARF SPECTROSCOPY

- Two approaches:
  - **Empirically calibrate spectral indices** to Teff, log(g) and abundances sing FGK + M systems
    - Bonfils et al., Rojas-Ayala et al., Mann et al., Newton et al., Terrien et al.
    - Errors in FGK analysis are propagated!
- **Fit models directly to spectra**
  - Souto, Cunha et al., Tsuji et al., Tsuji & Nakajima



Souto, Cunha et al. (2017)

- Spectral Type
- **Effective temperature**
- **Surface gravity**
- **Abundances**

The Newer New School (2010+)

Combined measured spectra of touchstone stars to match measured spectrum of the target.

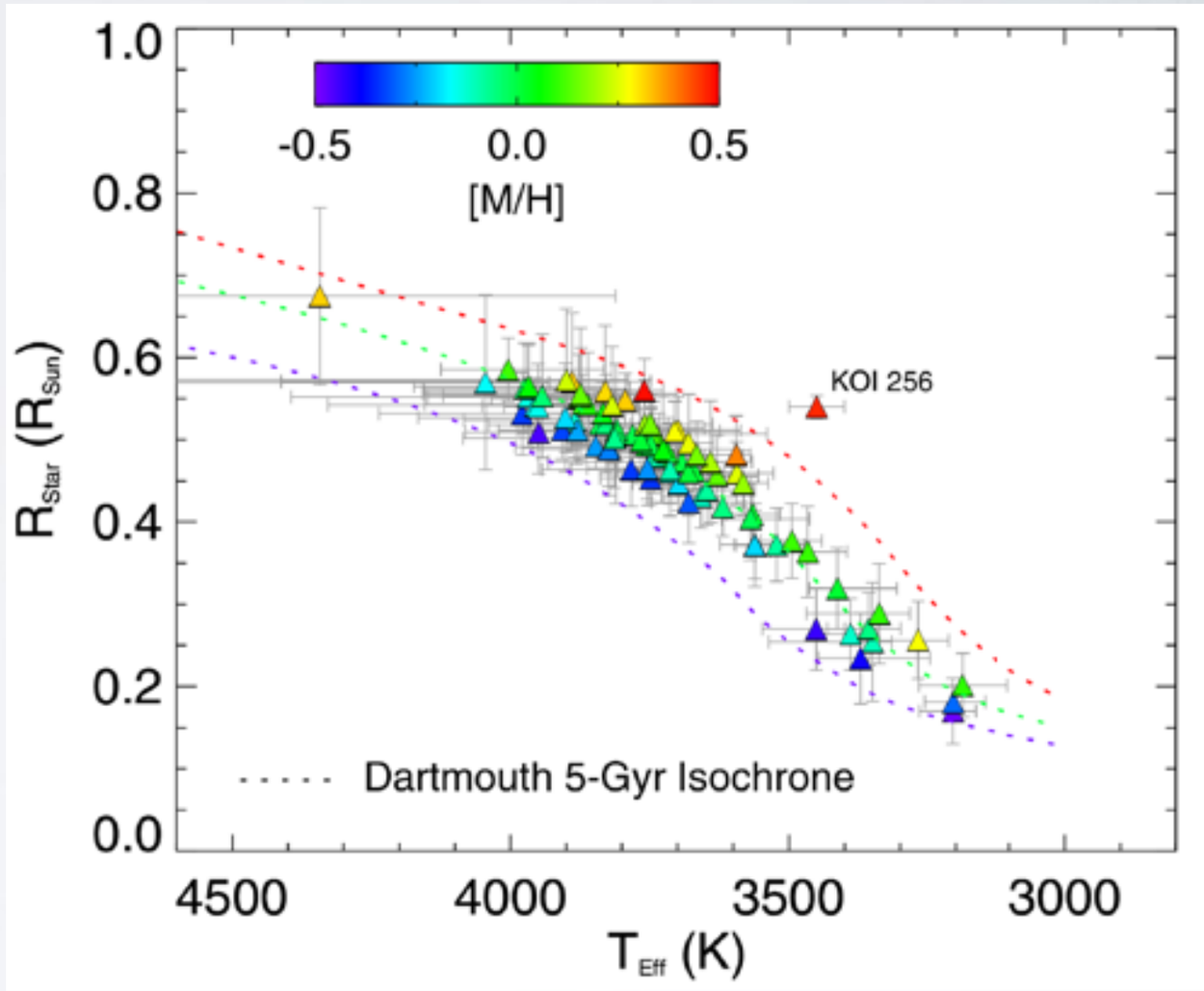
SpecMatch: Petigura et al. (2017)

Applied to Barnard's Star (M4)

ATMOSPHERE MODELS + EVOLUTIONARY MODELS

- By combining best fitted atmosphere parameters with predictions from **evolutionary** models, stellar mass, radius and age can be determined.

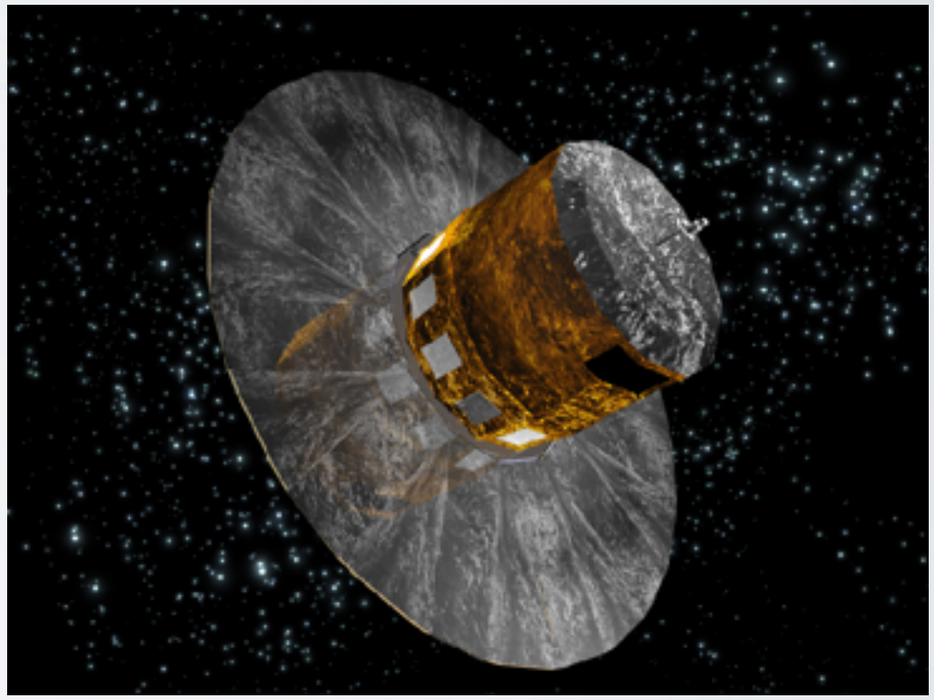
- (Just remember, evolutionary models have atmosphere models *built in)*



Muirhead et al. (2014a)

ABUNDANCES, ABUNDANCES, ABUNDANCES

- With Gaia luminosities on the horizon, abundances become the most important stellar parameter from spectroscopy.



- Trigonometric parallaxes are **empirically calibrated** to masses and radii for main-sequence stars.

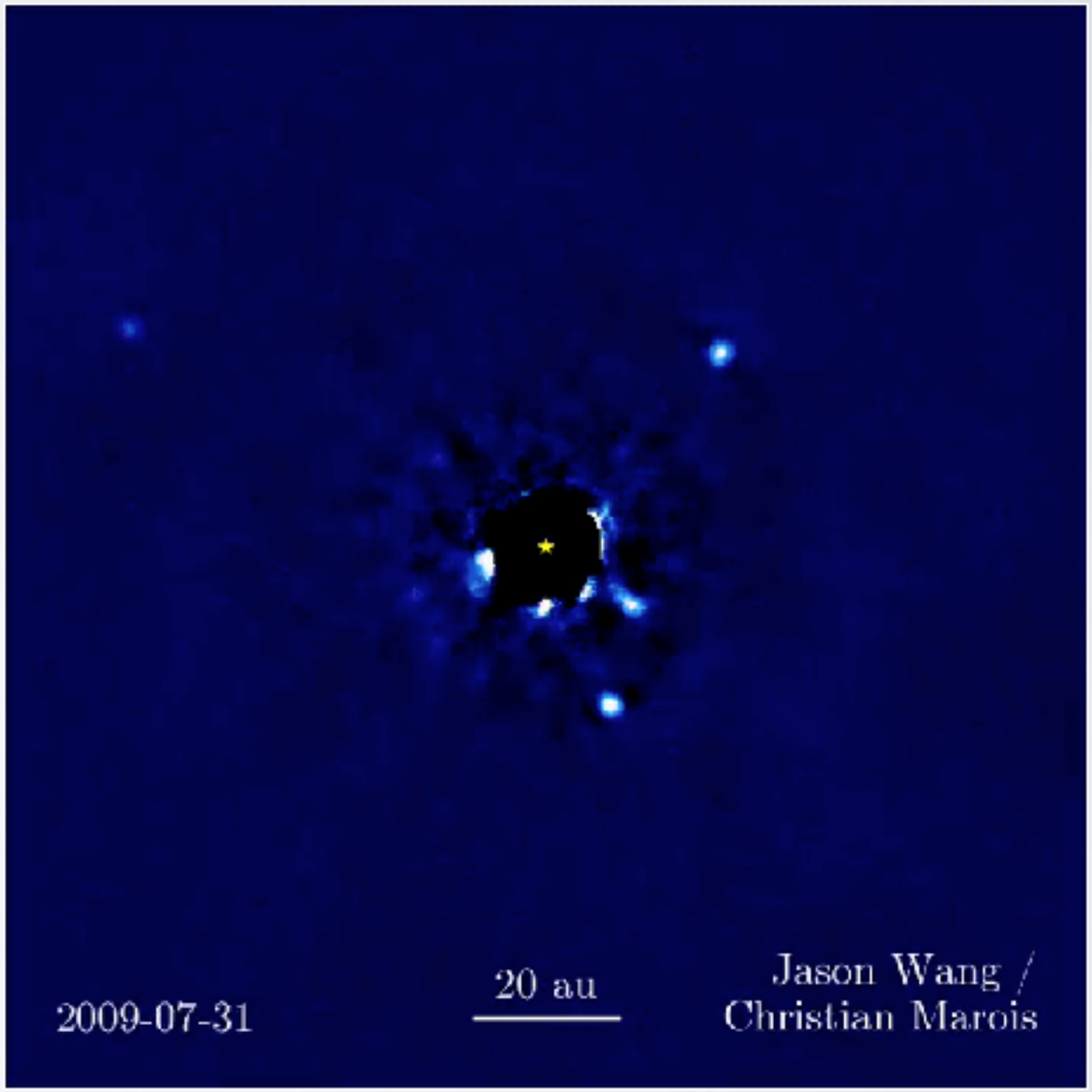
- Spectroscopy becomes less useful in this regard, but **abundances** are still critical.

ABUNDANCES: FORMATION MECHANISMS FOR DIRECTLY IMAGED PLANETS

- Do directly imaged planets have the same C-to-O ratios as their host stars (indicating gravitational collapse)?

- Or different C-to-O ratios (indicating disk-based core-accretion)?

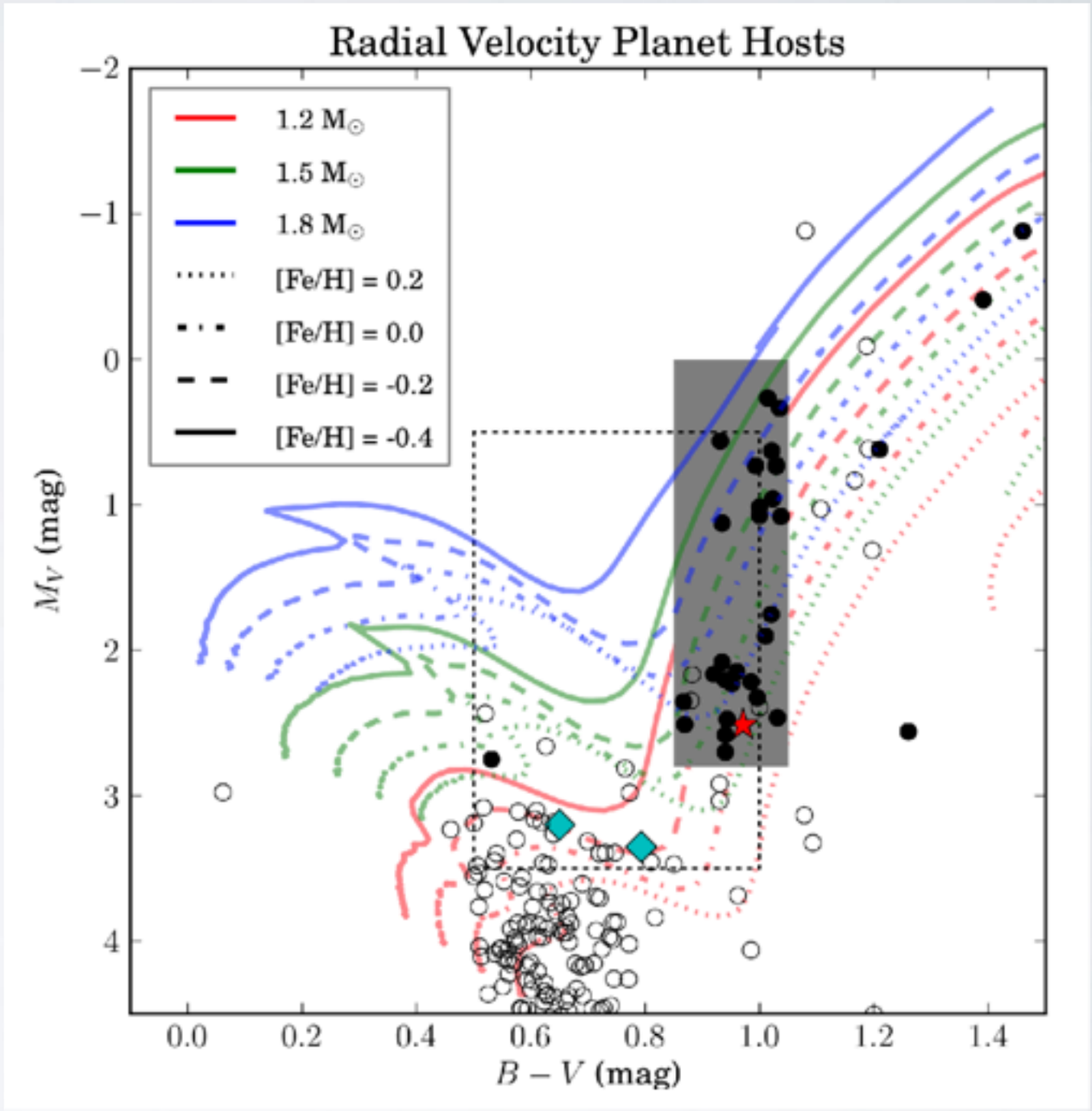
- Keck-NIRSPEC program led by M. Bryan



ABUNDANCES: SOLVING THE SUB GIANT MASS CONTROVERSY

- Lloyd 2011 argued that sub-giant exoplanet host masses from Johnson et al. are overestimated.

- Implicit to the argument is that the sub-giant abundances are systematically in error.

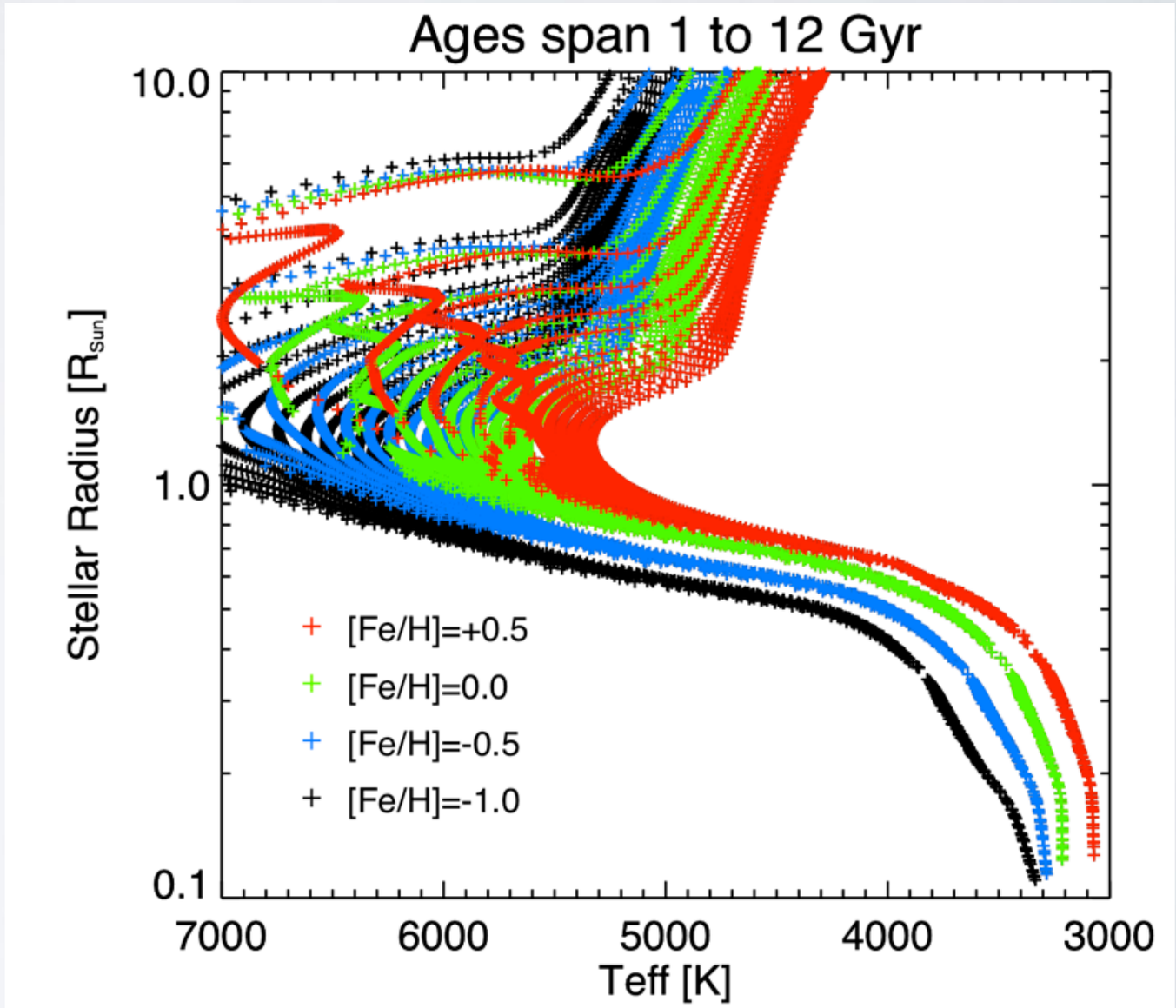


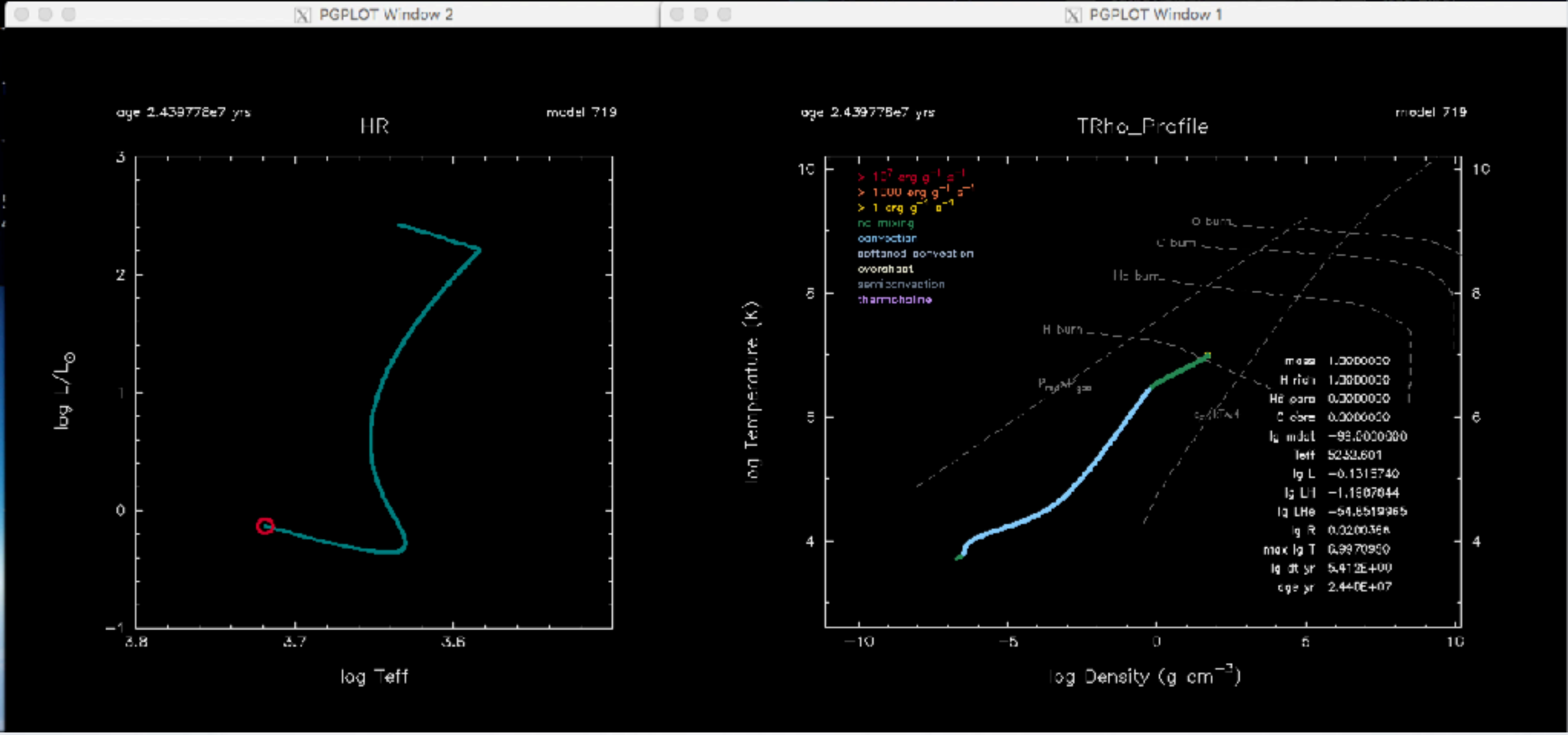
Lloyd 2011

ABUNDANCES: AGING FGK STARS

- In the absence of asteroseismic data, metallicity is required to determine stellar *ages*.

- Dartmouth Evolutionary models



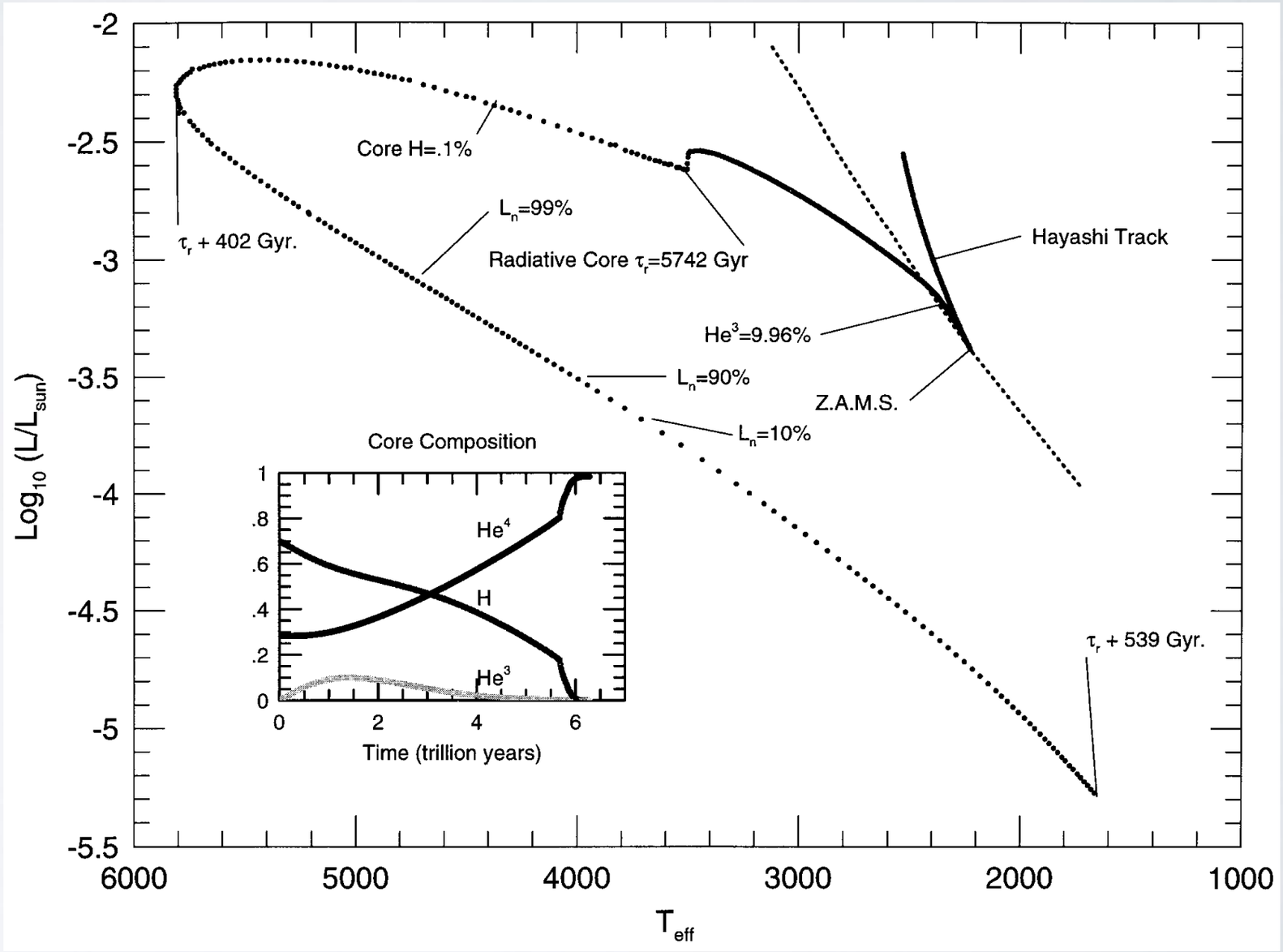


MESA Model of a Sun-like Star

(I ran it this morning. It's super easy.)

ABUNDANCES: MEASURING M DWARF AGES

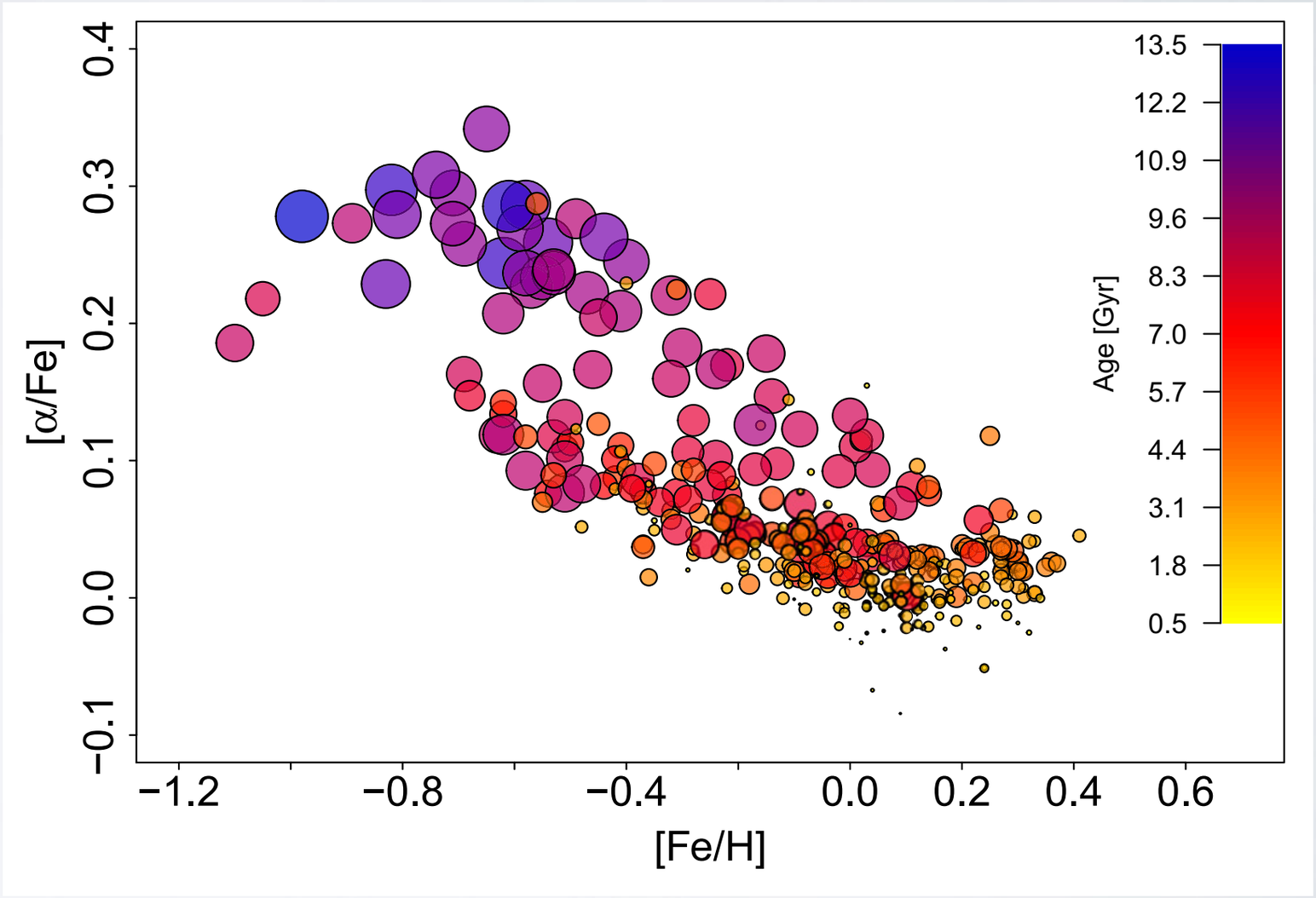
- M Dwarfs are notoriously difficult to age.
- Change by less than 0.1% in luminosity and 1 Kelvin in Teff every Gyr
- Compare to FGK stars (~5 % in luminosity every Gyr)



Laughlin et al. (1997)

ABUNDANCES: MEASURING M DWARF AGES

- If M dwarfs follow FGK trends, **alpha-enrichment** should age M dwarfs with uncertainties of 1 Gyr.



Haywood et al. 2013

ABUNDANCES: MEASURING M DWARF AGES

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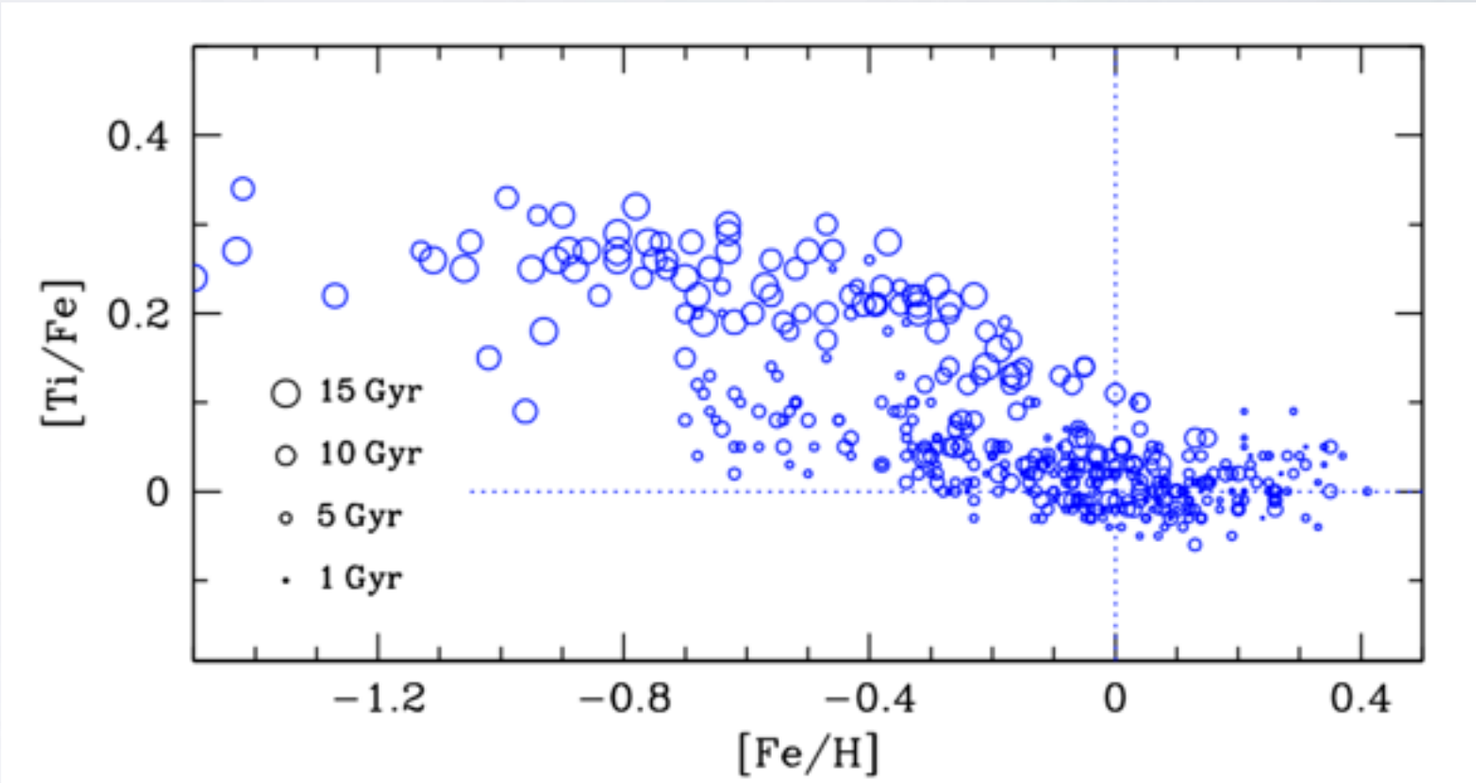
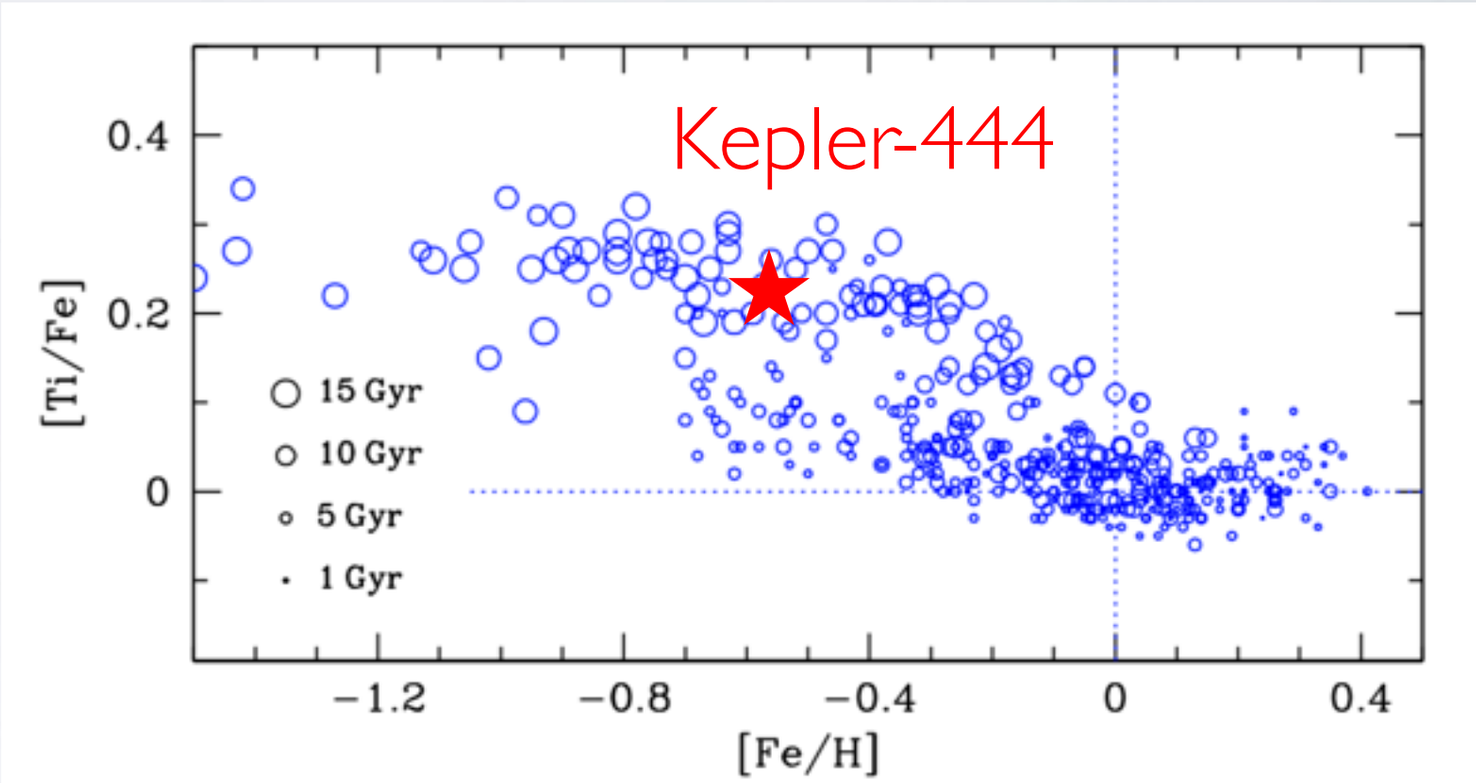


Similar correlations from Bensby et al. (2014)

ABUNDANCES: MEASURING M DWARF AGES

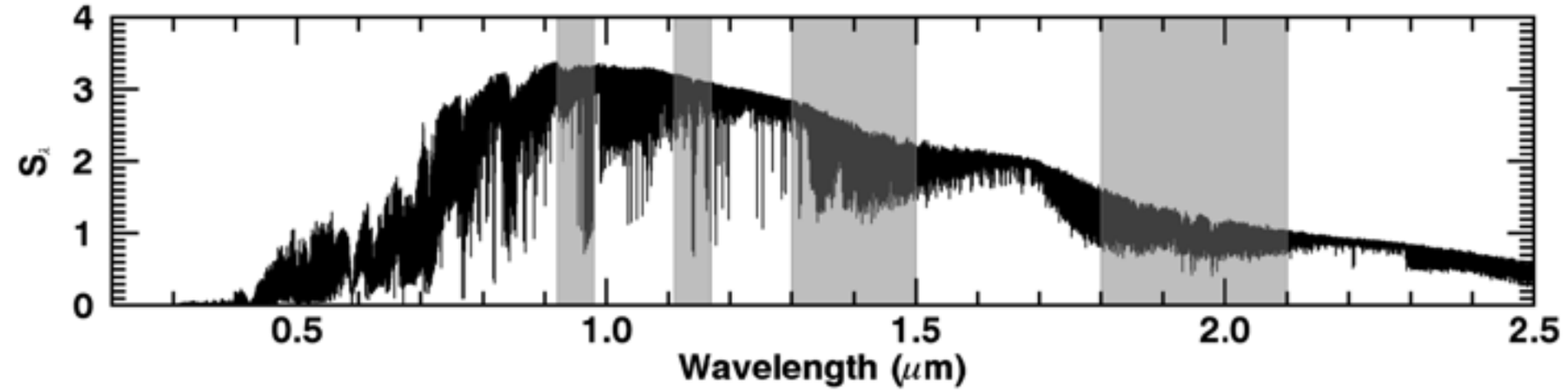
- If M dwarfs follow FGK trends, **alpha-enrichment** should age M dwarfs with uncertainties of 1 Gyr.

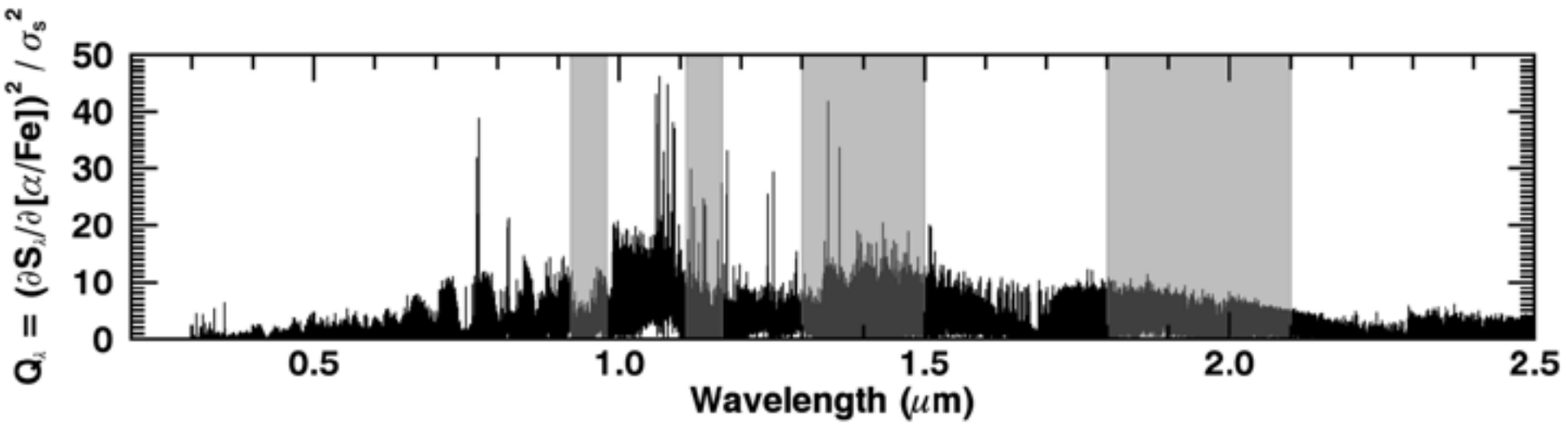


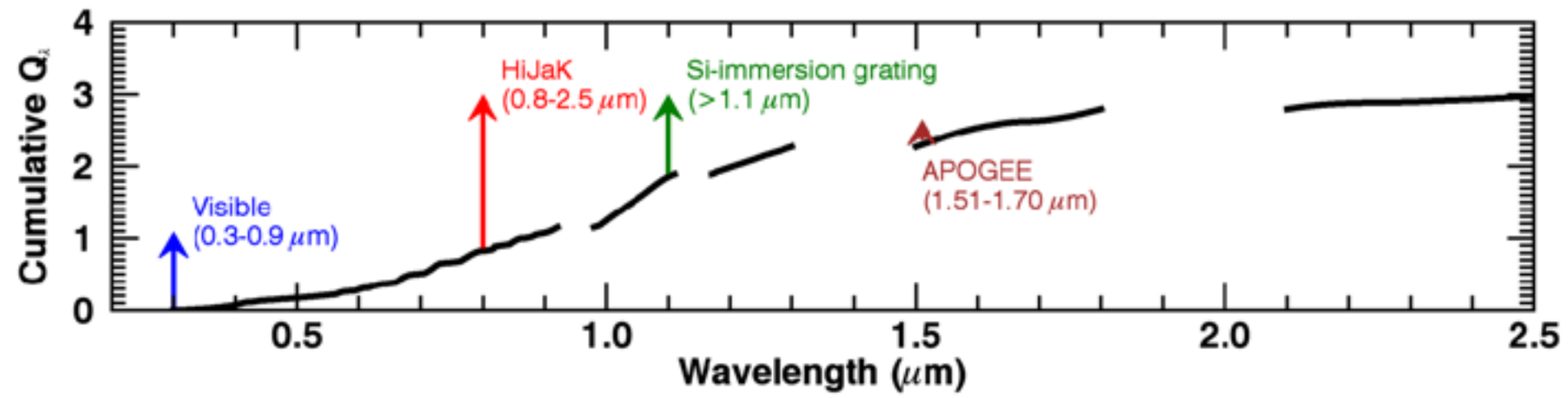
"An ancient star with 5 Sub-Earths"
Ti/Fe consistent with asteroseismic age
Campante et al. (2015)

Alpha content in M dwarfs vs. wavelength

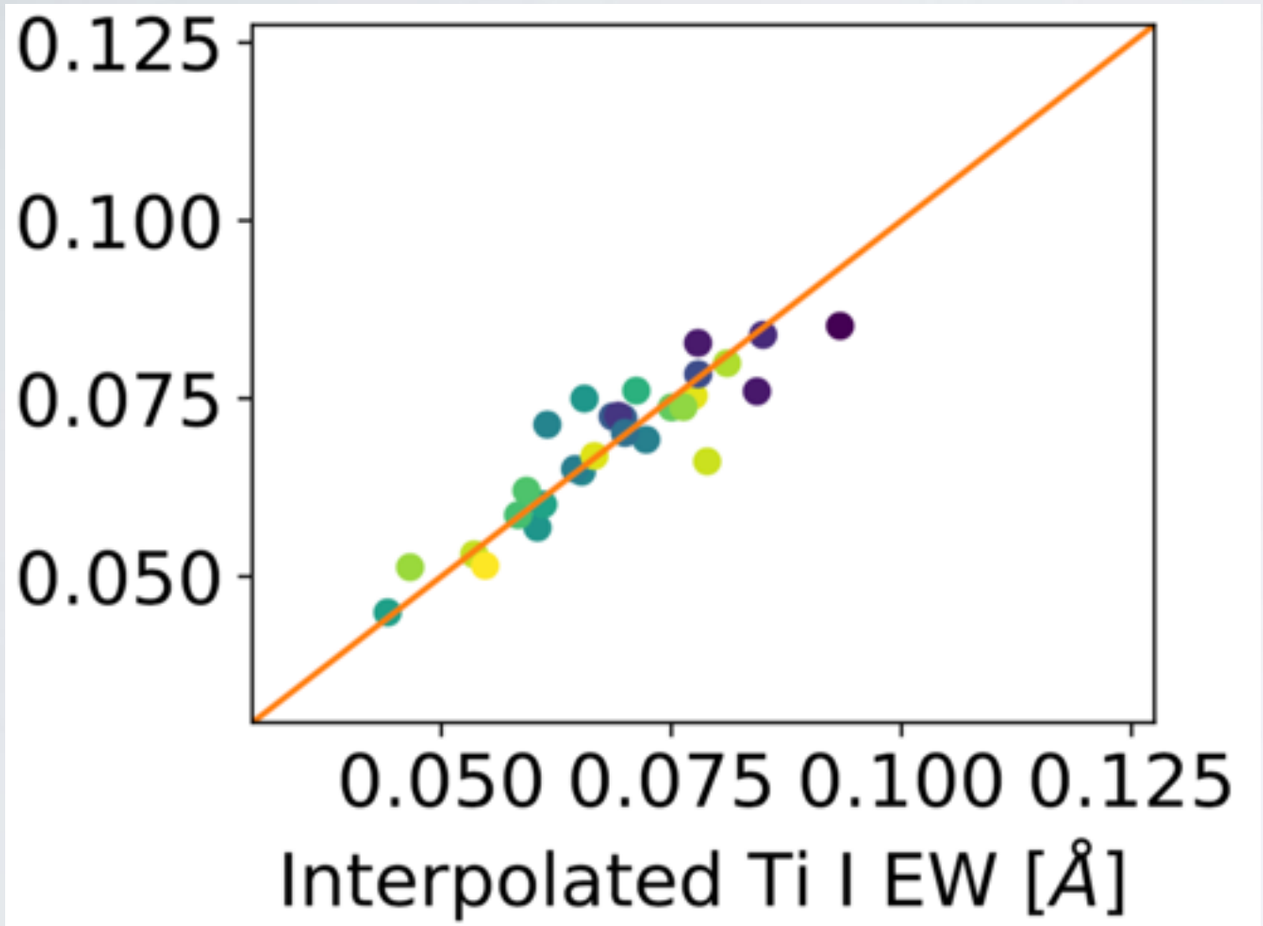
Muirhead et al. (2014a)

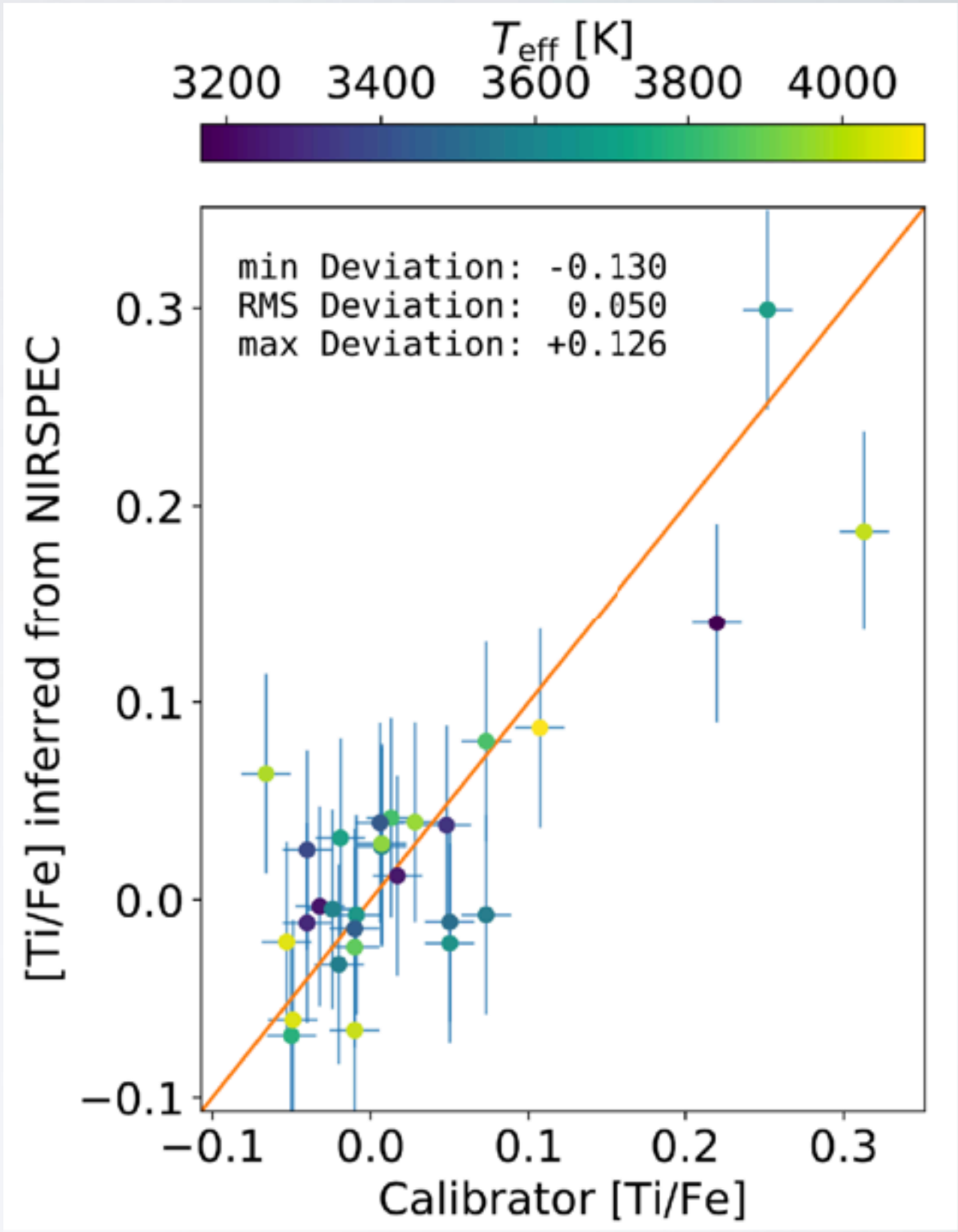






TI IN M DWARFS

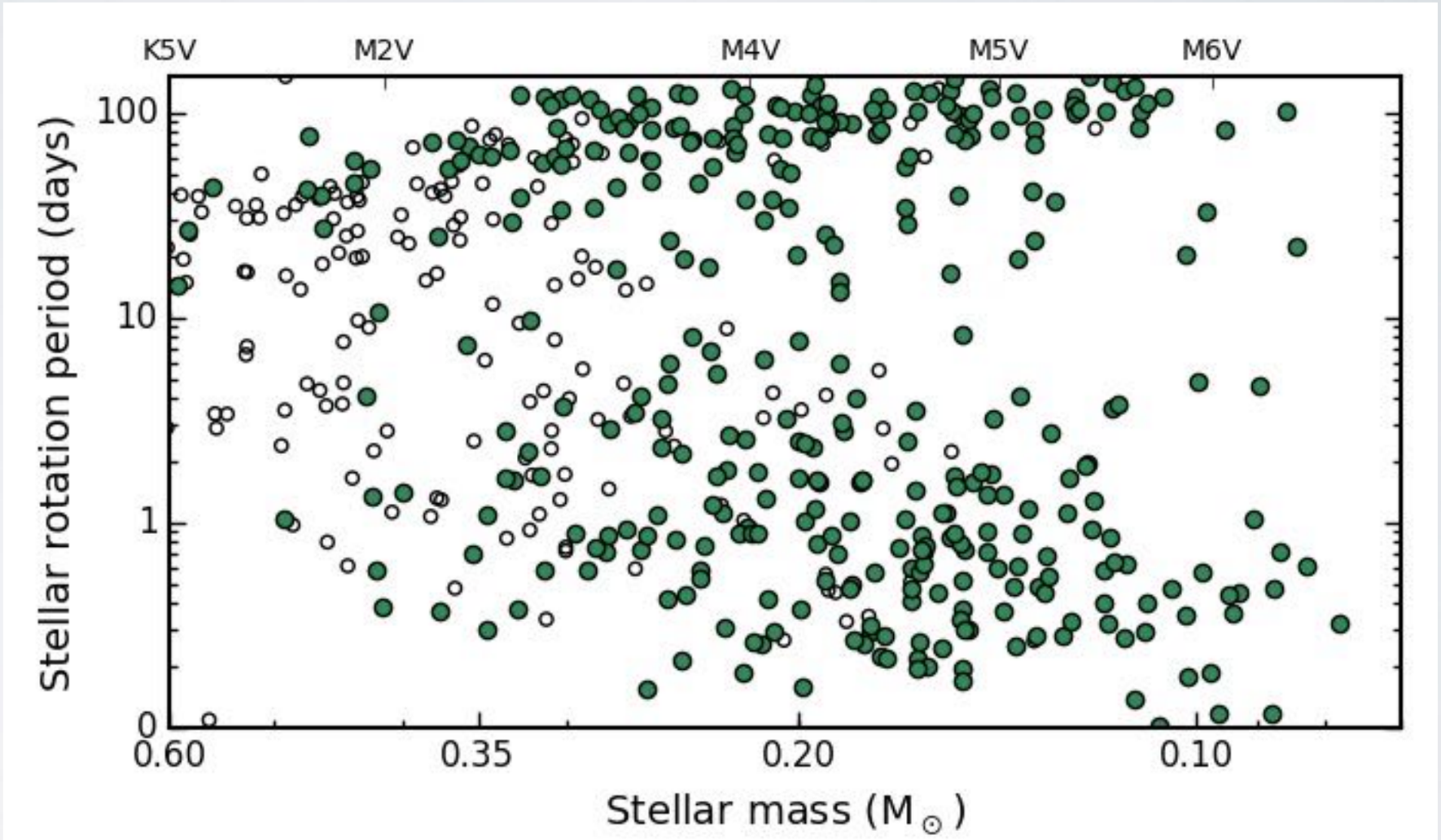




Veyette, Muirhead, Mann et al. (submitted)

ABUNDANCES: MEASURING M DWARF AGES

MEarth rotation periods from Newton et al. (2015)



- With Ti from Veyette (2017), we can determine the **timescale for M dwarf spin flip**

Dwarf Stars and Clusters with K2: a Workshop

January 16-18, 2018
Boston University

COOL STARS 20

20th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun

Boston | Cambridge July 29 - August 4, 2018

Smithsonian Astrophysical Observatory
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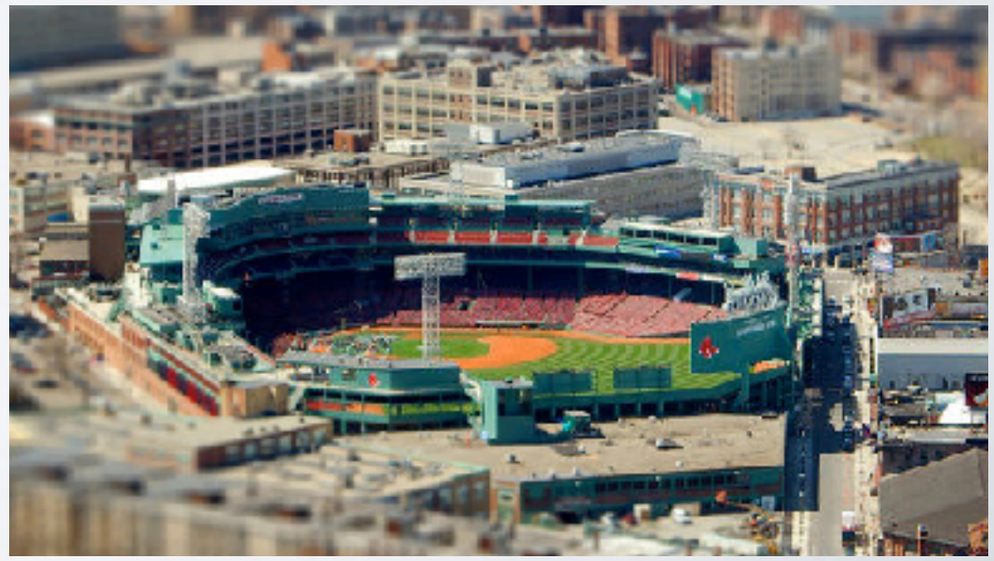
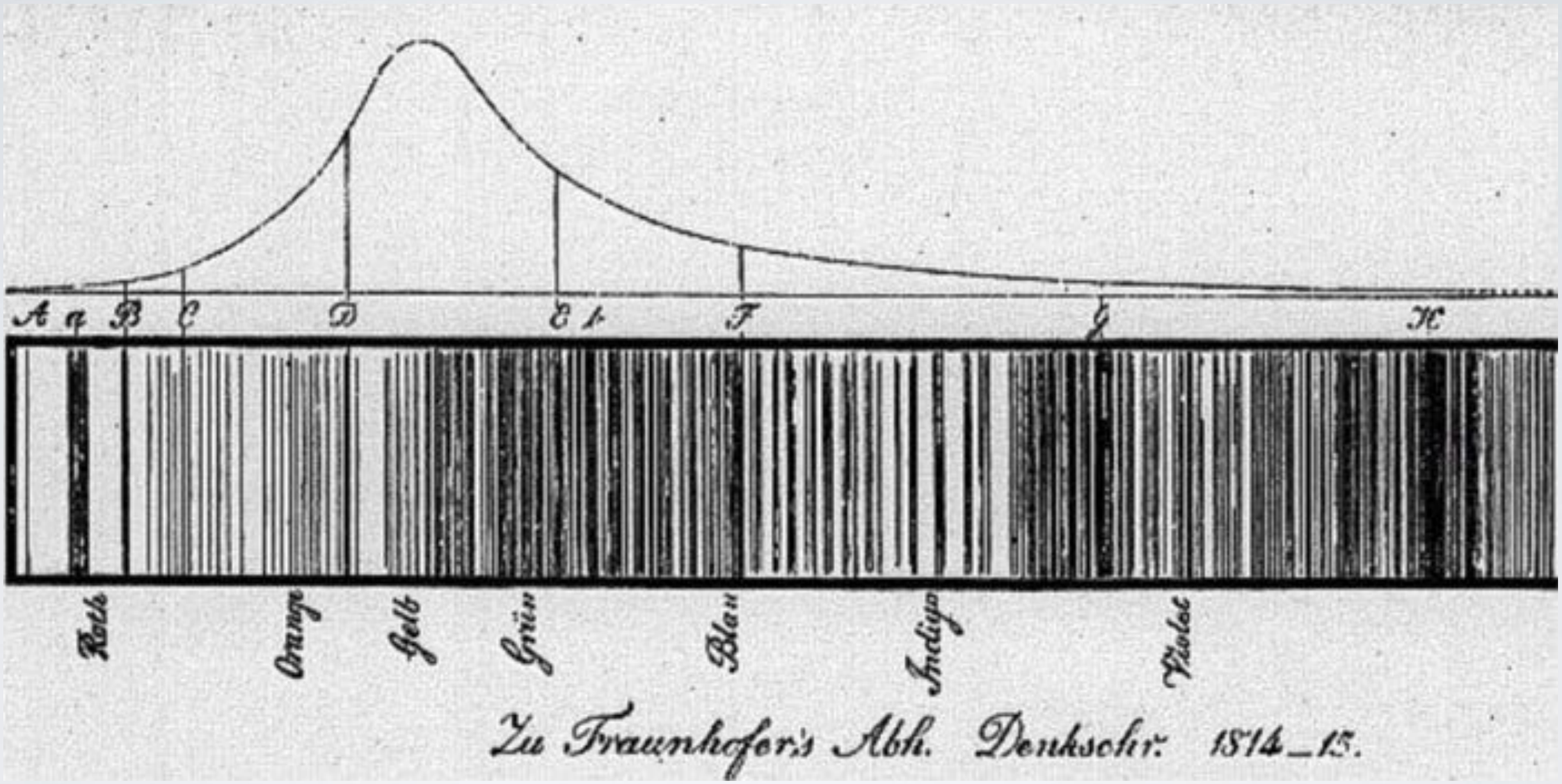


SOME POINTS TO TAKE HOME

- Spectral type is not useless
- Abundances disentangle overlapping regions on the HR diagram.
- Alpha enhancement (e.g. [Ti/Fe]) may enable measurements of M dwarf ages.

SPECTROSCOPY



- Fraunhofer lines (1814): Astronomy becomes Astrophysics