

ASTR 421

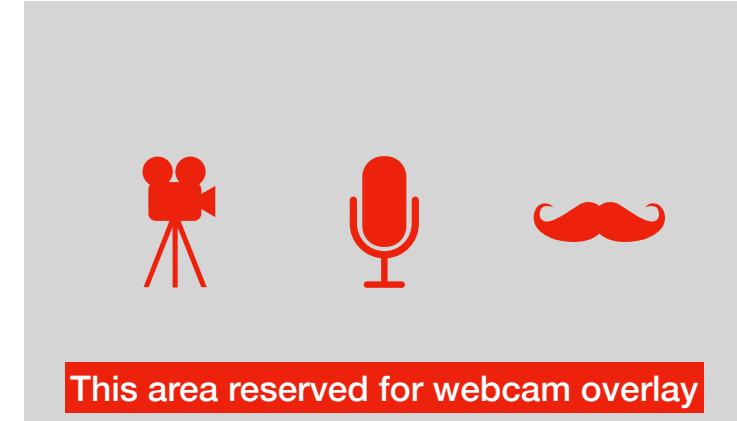
Stellar Observations and Theory

Lecture 10

Line Profiles: III

Prof. James Davenport (UW)

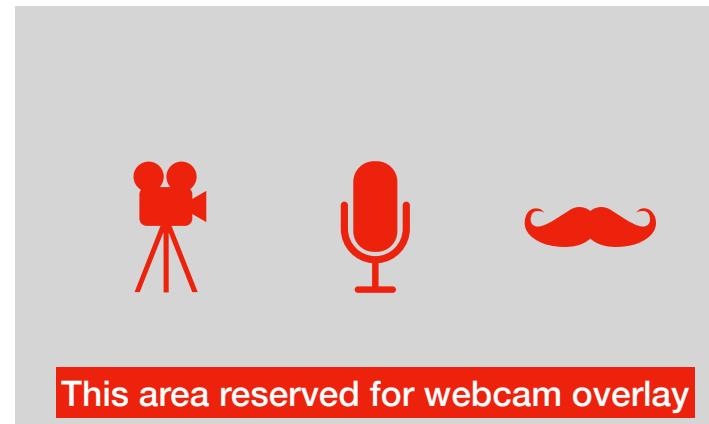
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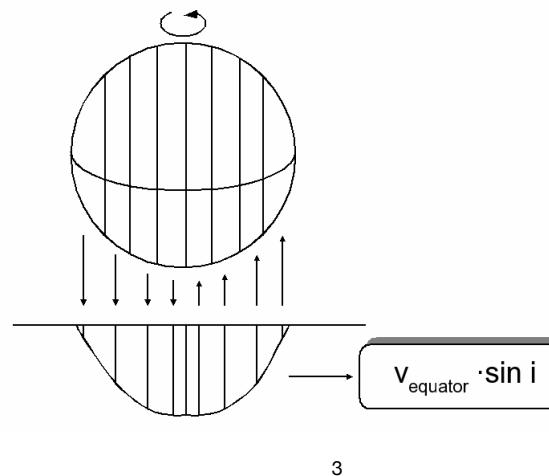
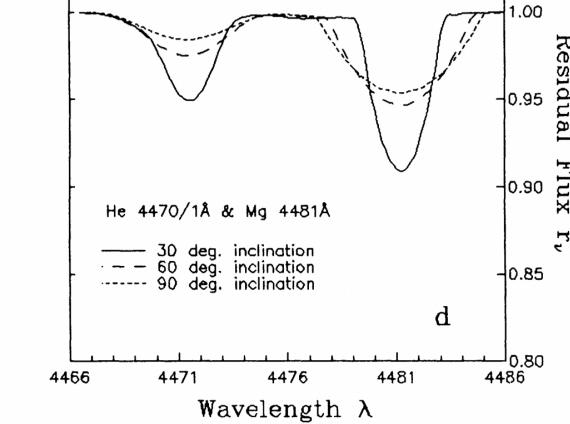
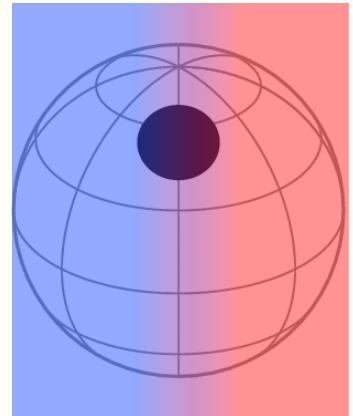
Today

- A few other sources of broadening...
- Actual measurements of lines (esp. FWHM & EW)
- How we get “stellar parameters” out of spectra

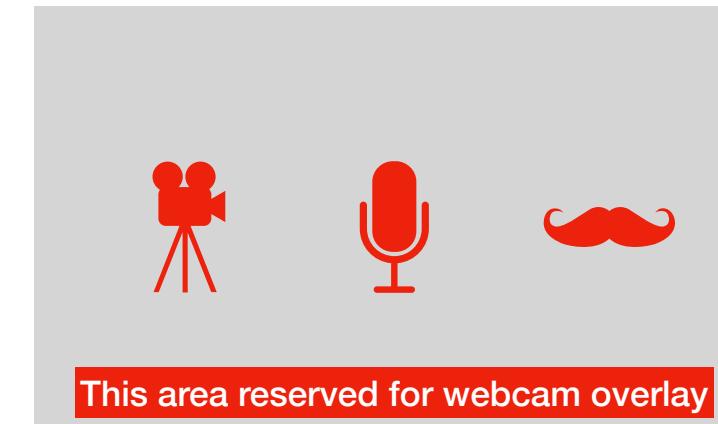


Additional sources of line broadening

- **Rotation**
 - Conceptually an extra form of Doppler broadening
 - FWHM measures $V \sin i$ ($i = 90^\circ$ is equator facing us)
 - Profile is *non-Gaussian* b/c convolution of doppler shift & limb darkening... becomes ~parabolic

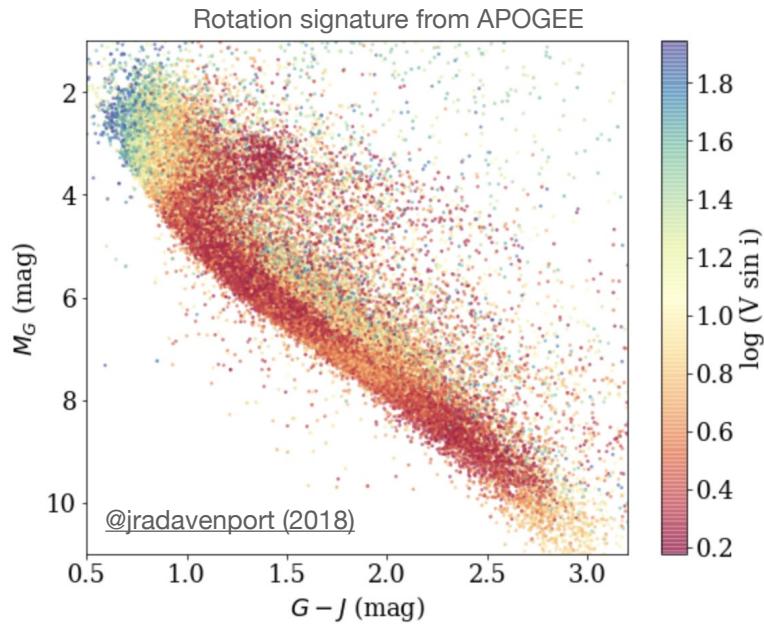


Ulrike Heiter

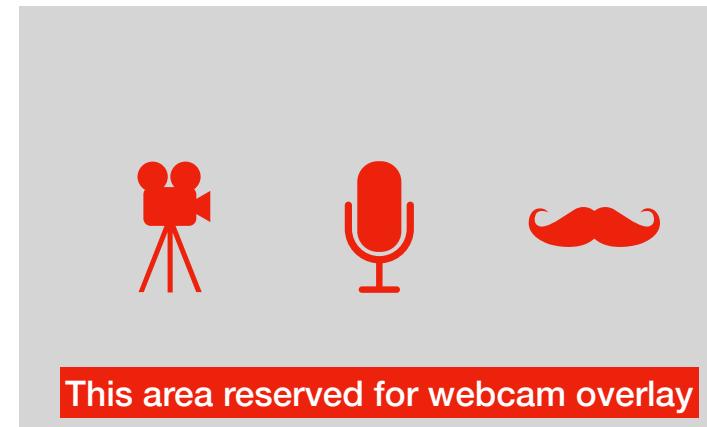


Additional sources of line broadening

- Rotation
 - Was THE way to measure rotation for a long time
 - Starspot modulations now dominant method, but $V \sin i$ still important!

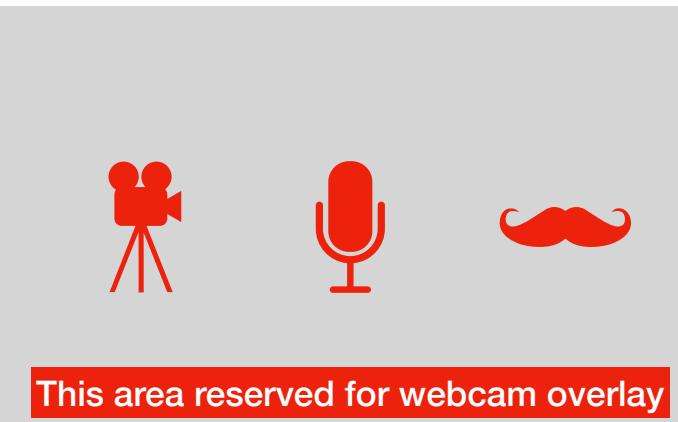
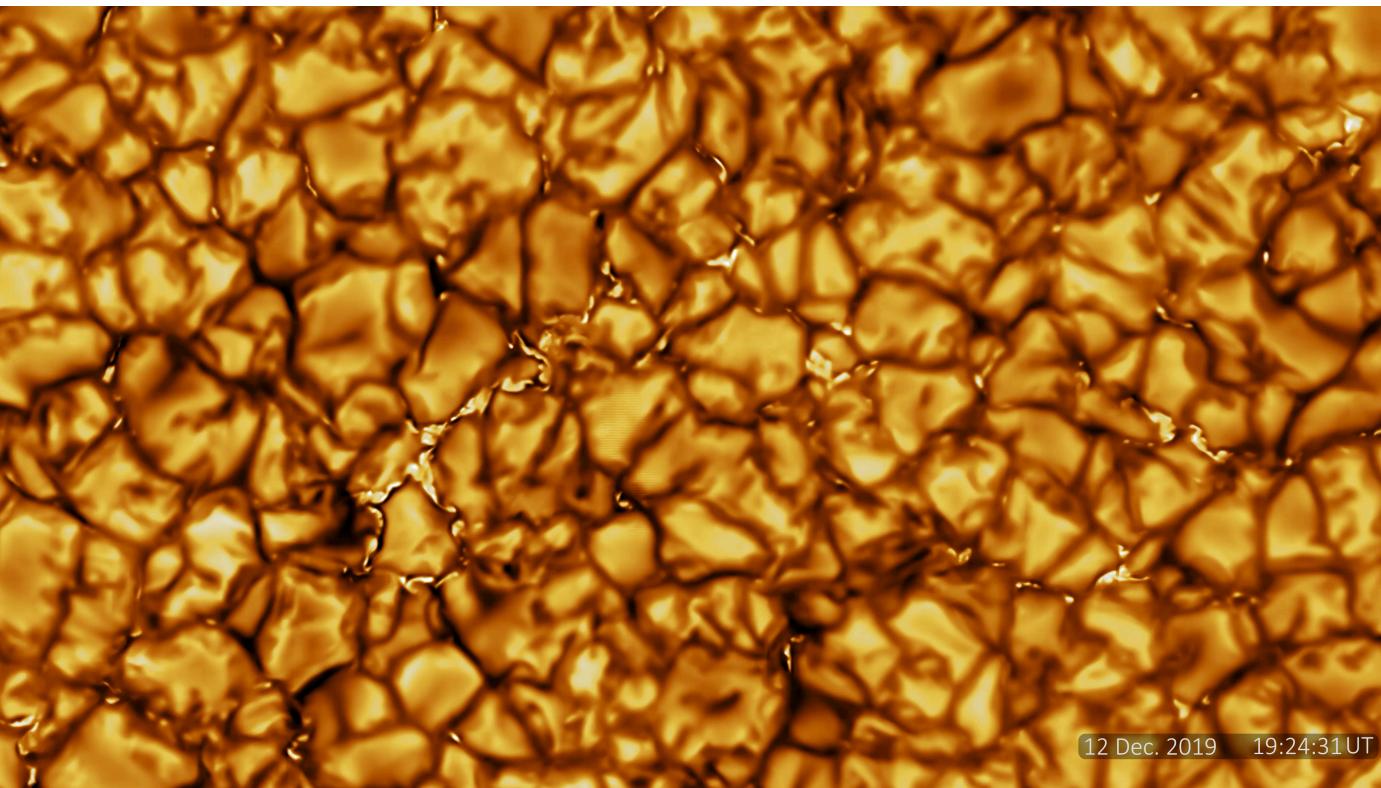


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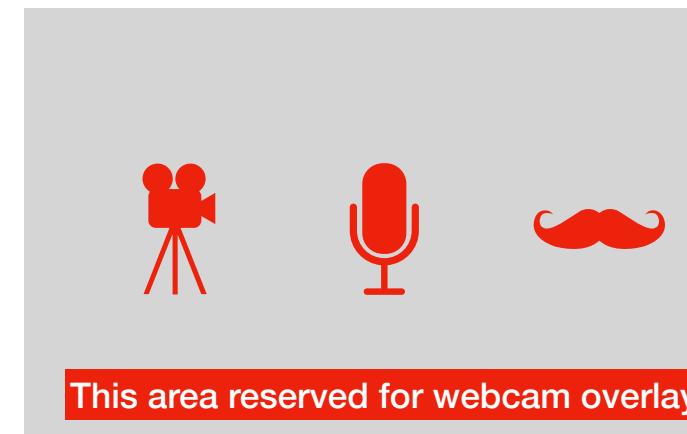
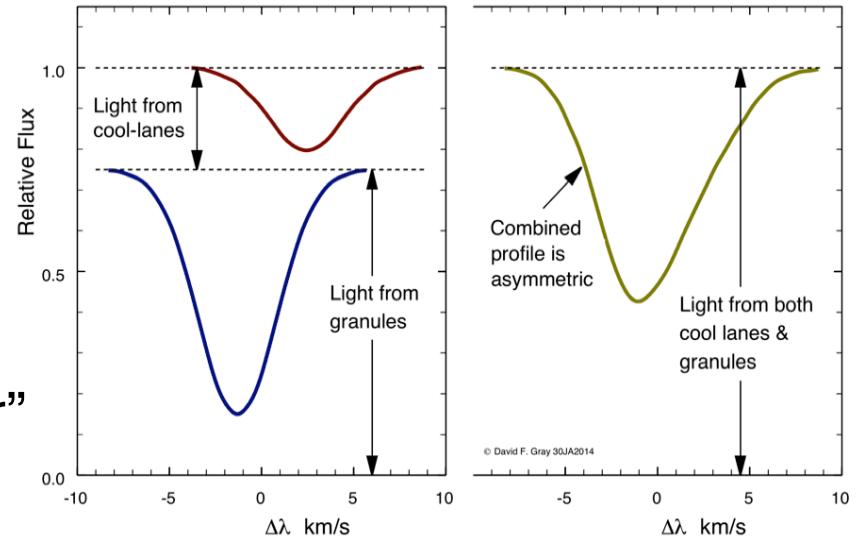
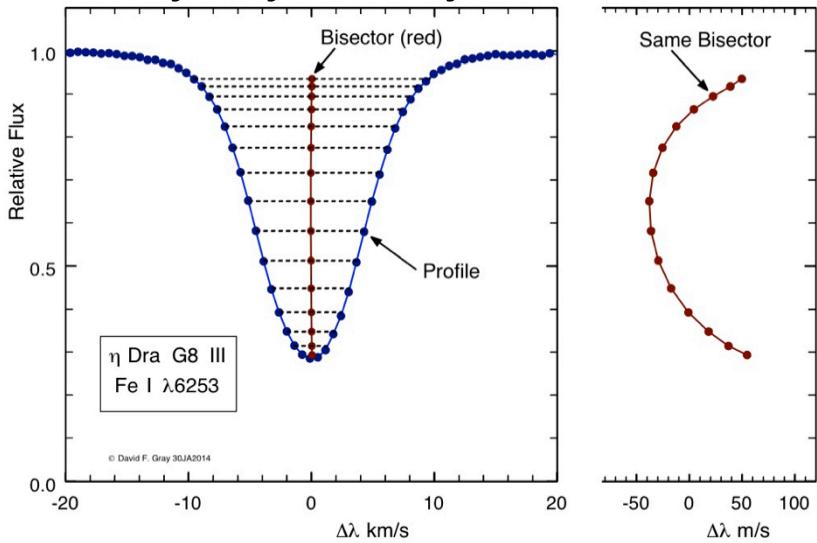
Additional sources of line broadening

- Granulation



Additional sources of line broadening

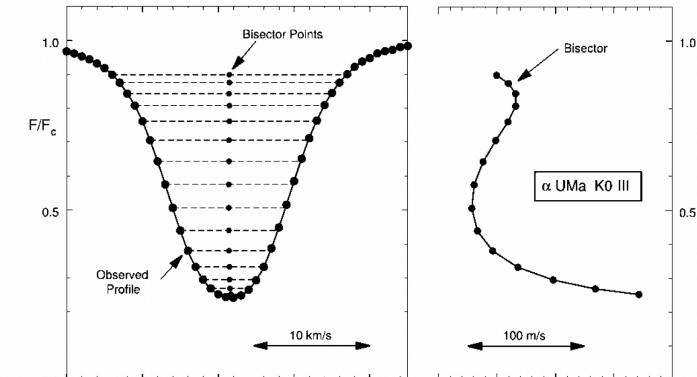
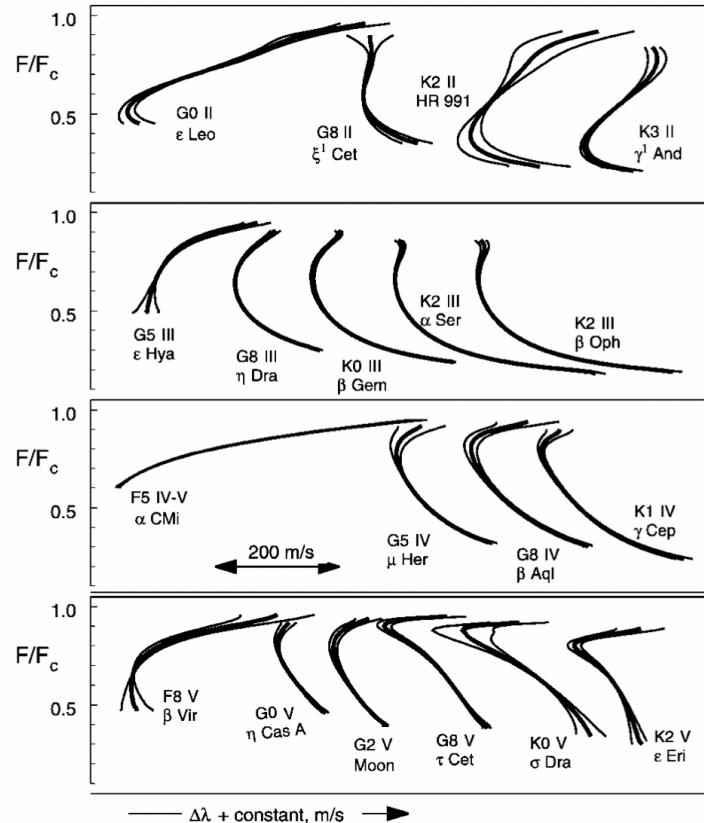
- **Granulation**
 - Velocity motions: doppler broadening
 - Line *asymmetry* due to bright granules
 - Tiny asymmetry measured using “bisector”



Additional sources of line broadening

- **Granulation Line Bisectors**

- Need high-res spectroscopy
- Telling us a complex story about gas velocities as a function of optical depth
- Hard to reproduce with models!



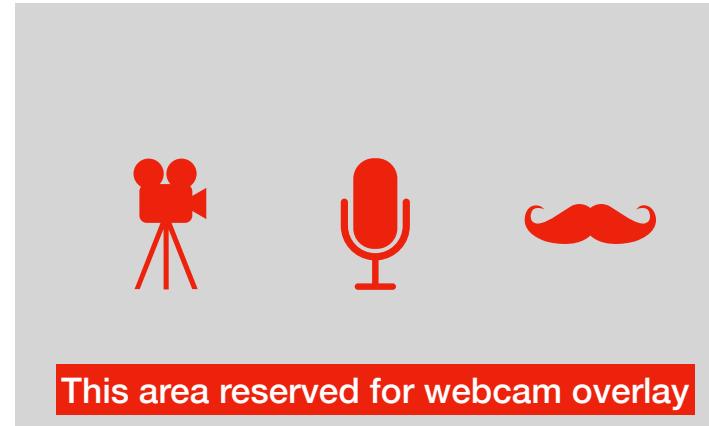
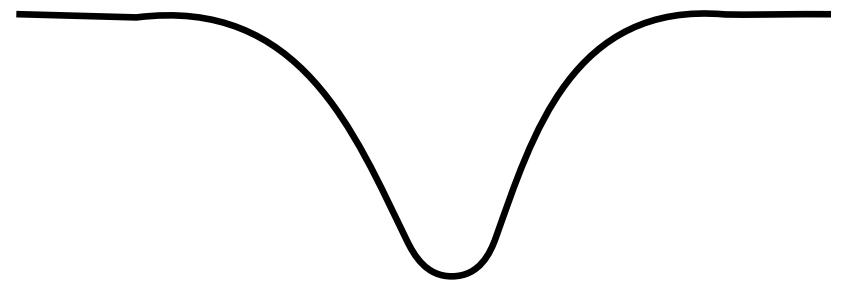
Gray (2005)



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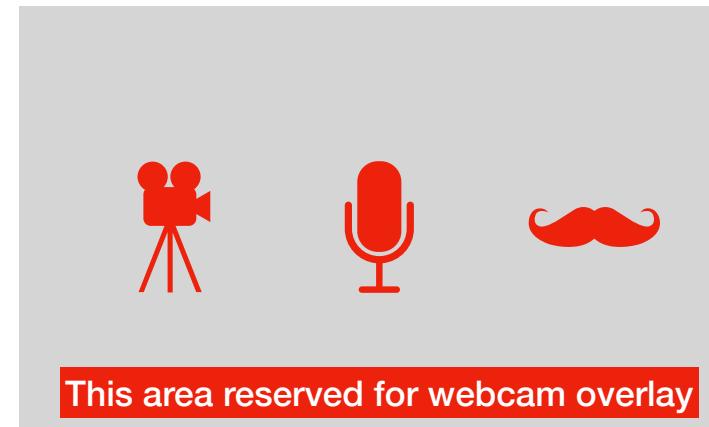
Review: Sources of Line Broadening

- Doppler/thermal broadening
- Natural broadening
- Pressure broadening
- Granulation/microturbulence
- P Cygni profiles
- Rotation



Things that lines can teach us

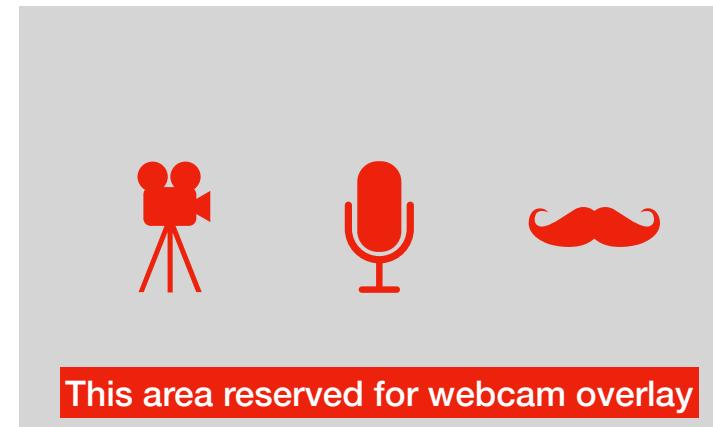
- The depth & shape of lines tells us A LOT about the stellar atmosphere
 - Line intensity ratios from the same species: temp & density
 - Line intensity between species: metallicity
 - Line profile shapes: density, temperature, turbulence, rotation...
- So, how do we go from spectra -> stellar parameters?



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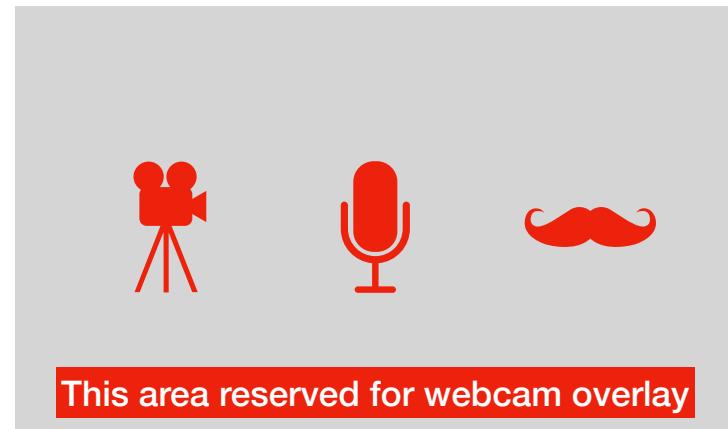
It's complicated...

- Can't just integrate a bunch of Balmer lines to count number of H atoms...
- We need 3D Magneto-hydrodynamic simulations + realistic stellar atmosphere (and interior) + Radiative Transfer
- Very tough to model all lines/species
- Many free parameters
- VERY computationally expensive
- (Currently) impossible to model all size & time scales at work simultaneously



It's complicated...

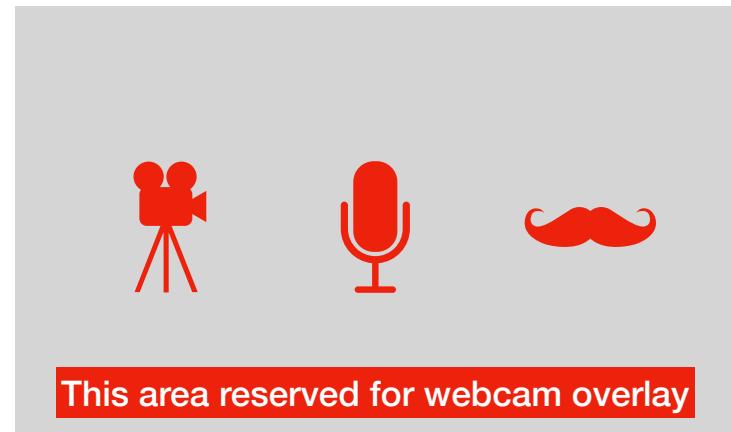
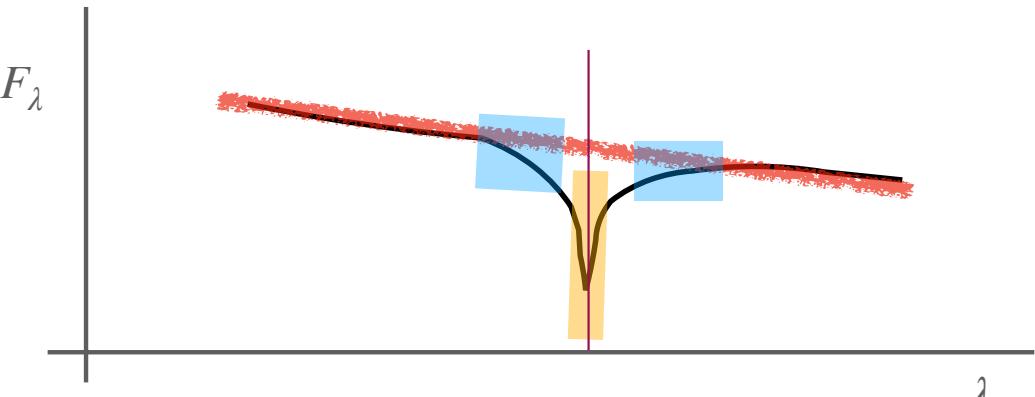
- We can “cheat”
 - Use 1-D models & “**model grids**”
 - Make simplifying assumptions (e.g. LTE)
 - Separate pieces of the problem
(e.g. radiative transfer w/o worrying about MHD)
 - Fit individual absorption lines separately
- Even the “easy” way is quite difficult for any given stellar spectrum



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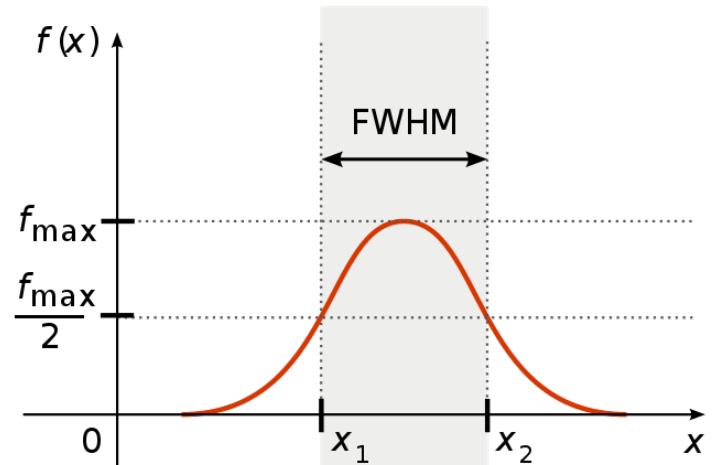
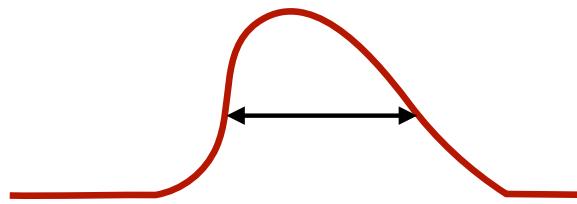
Line terminology

- Spectrum $\equiv (\tau = 2/3)$
- Continuum (blackbody)
- Wings (both sides)
- Core (center)
- λ_{lab} (note: vac or air wavelengths)
- FWHM



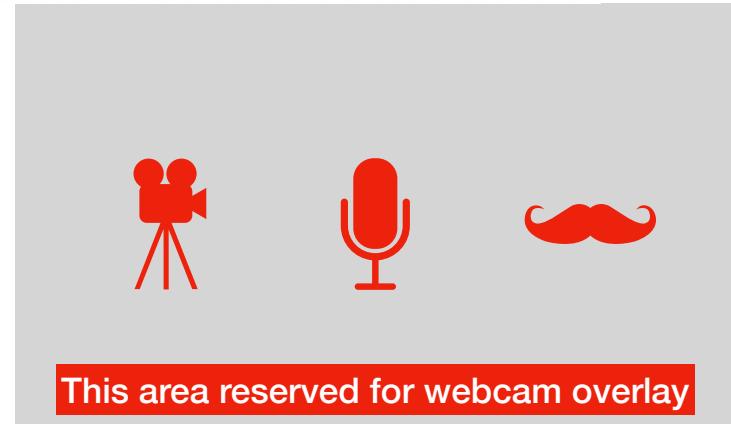
FWHM

- A simple measure of the line width
- Used lots across astronomy (not just in spectroscopy)
- Easier to estimate in presence of noise
- Can be measured for asymmetric or unusual profiles



For a Gaussian curve only:

$$\text{FWHM} = 2\sqrt{2 \ln 2} \sigma \approx 2.355 \sigma$$

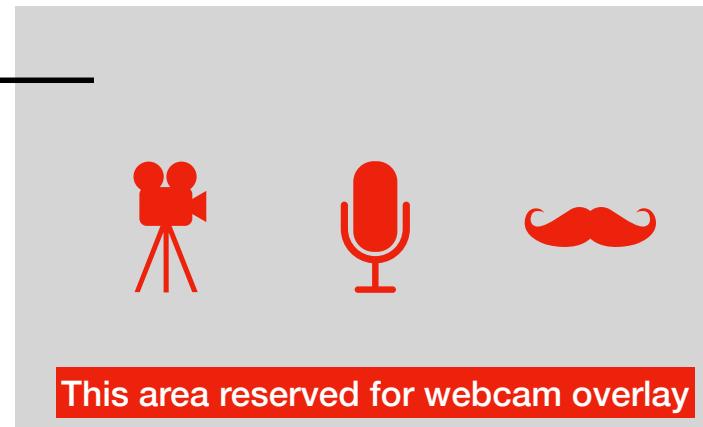
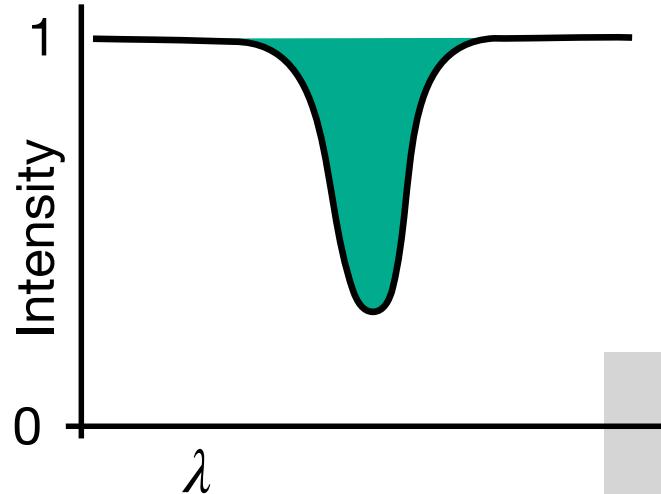


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Equivalent Width

A strangely useful unit of measurement...

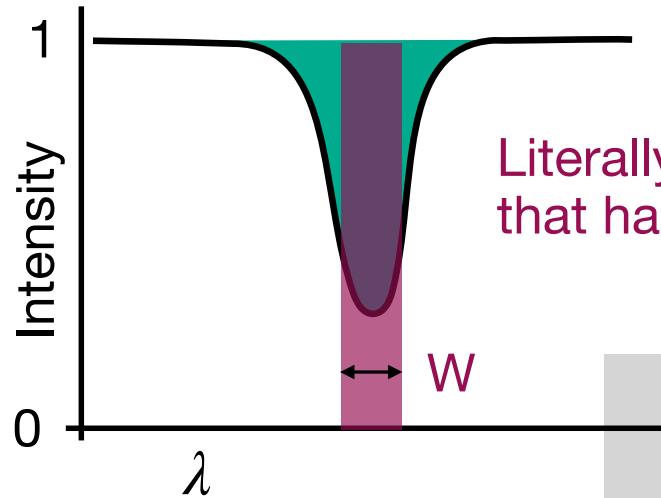
- When we talk about “line widths” we sometimes mean broadening (e.g. FWHM) and sometimes Equivalent Widths (i.e. **line intensity**)
- How to compute:
 - Normalize line to the **continuum**
 - **Integrate area**
 - Since Intensity here is unit-less, area under the curve has units of λ
 - Hence we talk about “ 1\AA equiv. widths”...



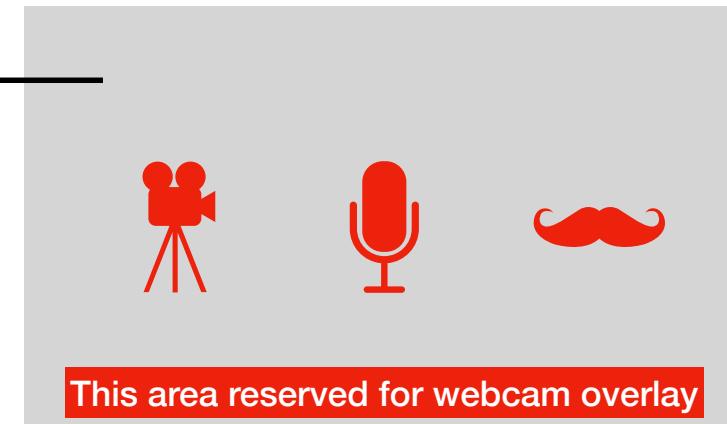
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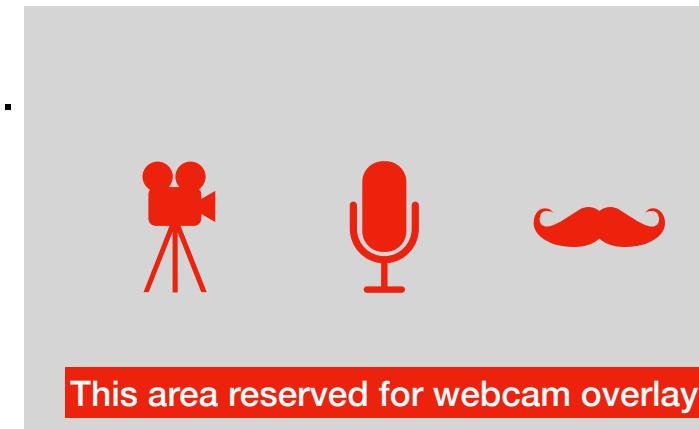
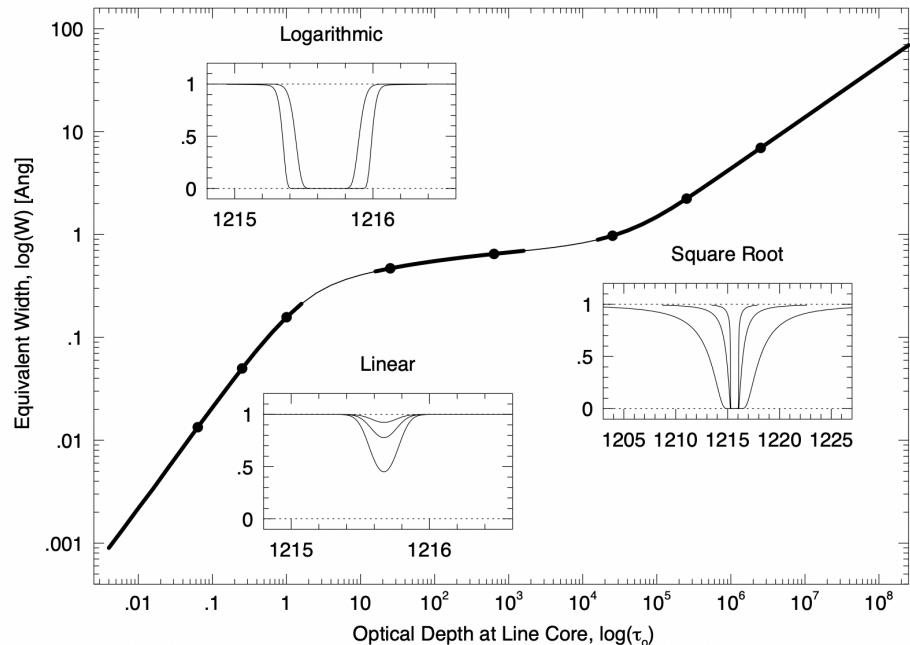


Literally the **width** of the rectangle that has the **equivalent** area



Curve of Growth

- How Equiv. Width changes with τ_λ
- $W_\lambda = \int (1 - \frac{F_\lambda}{F_0}) d\lambda = \int (1 - e^{-\tau_\lambda}) d\lambda$
- For optically thin ($\tau < 1$), $(1 - e^{-\tau_\lambda}) \approx \tau_\lambda$
The “linear regime”
- When line core (doppler component) becomes optically thick, pressure damping not significant yet.
 $W_\lambda \propto b\sqrt{\ln \tau_\lambda}$ (b the Gaussian core width)
The “flat” or “logarithmic regime”



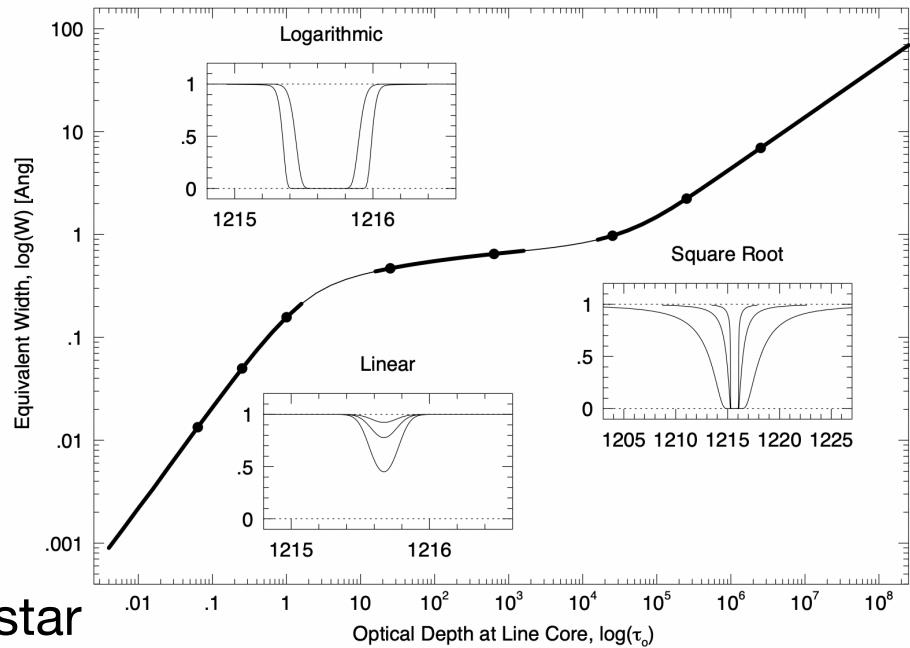
Curve of Growth

- At high optical depths, damping becomes strong (Lorentizan wings), Equiv. Width starts to grow faster again

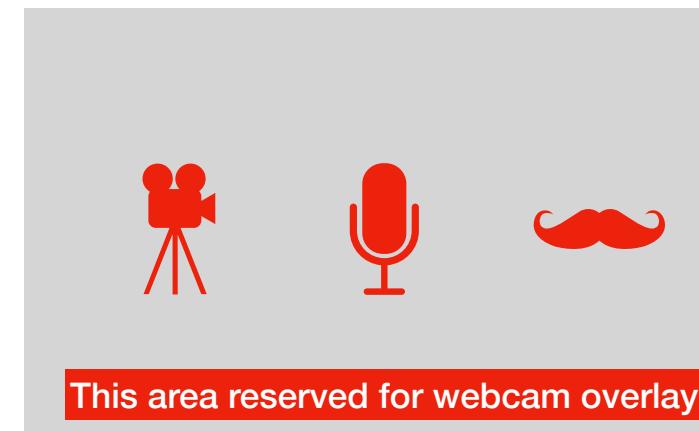
$$W_\lambda \propto \sqrt{\tau_\lambda}$$

The “Square Root” regime

- All 3 regimes can be observed on a given star for various species & lines, giving information about abundances of elements

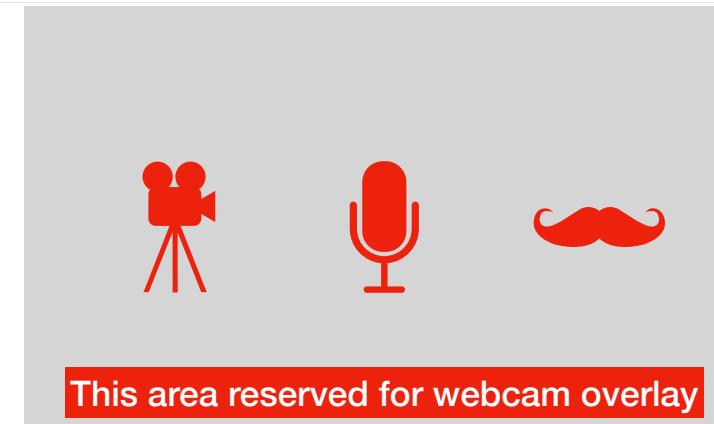
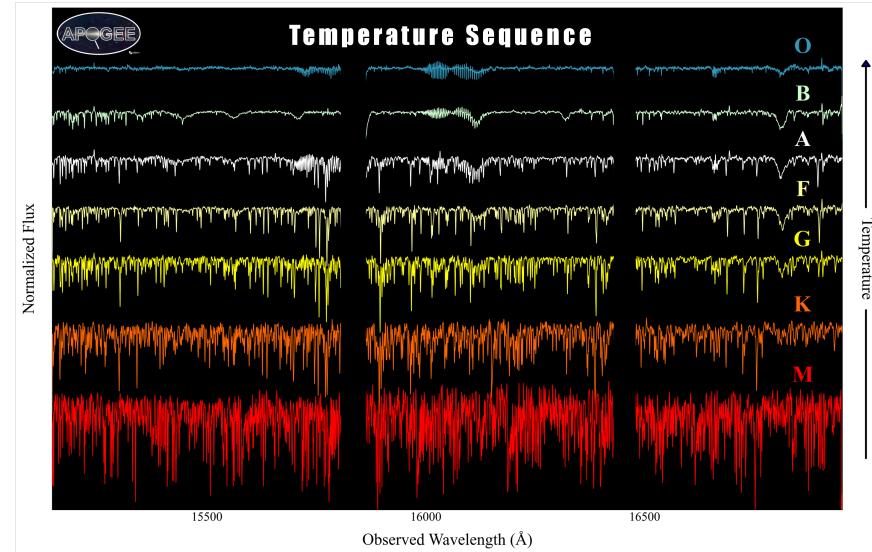


A good overview by Michael Richmond
<http://spiff.rit.edu/classes/phys440/lectures/curve/curve.html>



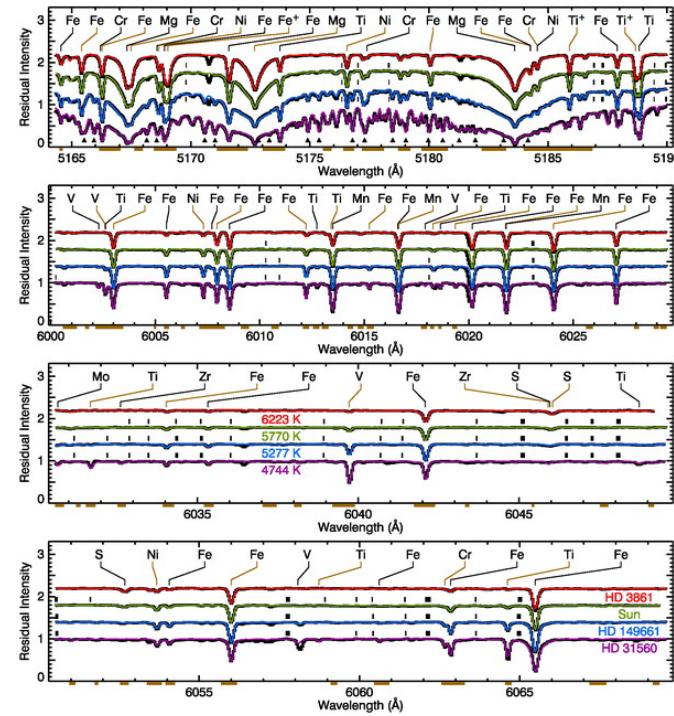
Stellar Properties from Spectra

- So how do we *actually* get stellar properties from spectra?
- We fit **model atmospheres** to the data (high resolution spectra)!
- These are complex pieces of code, lots of physics, hard to run... a bit of an art
- People can get very... particular about *which* models they use/believe for various stars.



Spectroscopy Made Easy (SME)

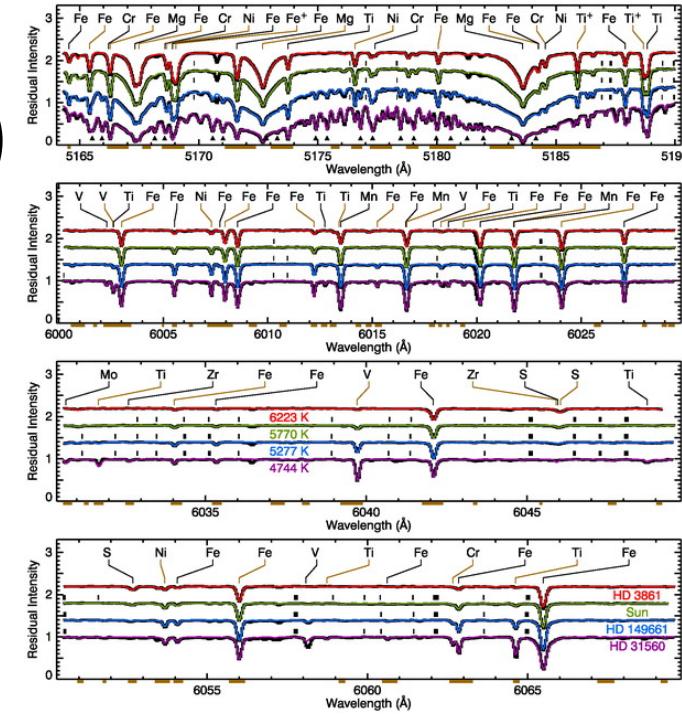
- <https://www.stsci.edu/~valenti/sme.html>
- Fits high-res spectra w/ spectral synthesis code, incl. molecular & ionization equilibrium (EOS), continuous opacities, line opacities, rad. trans...
- Computes 6 ionization stages for first 99 atoms
- Partition functions for ~300 molecules
- Computes voigt profiles, natural, stark, van Der Waals broadening
- Automated & GUI modes...



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Spectroscopy Made Easy (SME)

- Solves for stellar params (T_{eff} , log g, [m/H])
- Solves for individual abundances
- Not trivial to learn, but very powerful
- Not *usually* automated...
- Competitors include MOOG, TURBOSPECTRUM, others... None are perfect

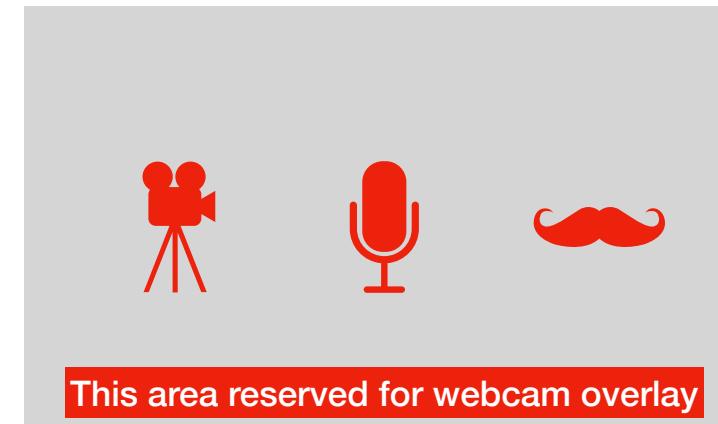


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ASPCAP

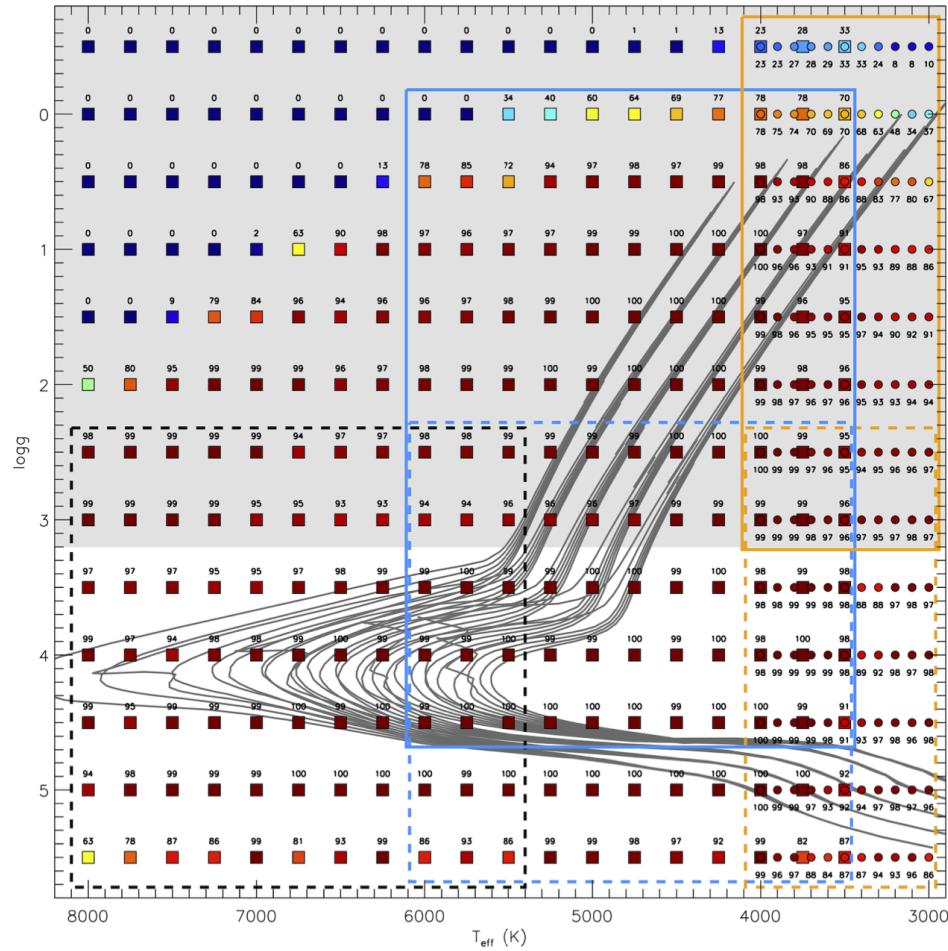
Garcia Perez+(2016)

- **APOGEE Stellar Parameters & Chemical Abundances Pipeline**
- Need to get parameters from high-res (IR) spectra for +400k stars... can't do things by hand!
- Instead rely on a big, pre-computed “grid” of models, with range of RV, T_{eff} , log g, [m/H] (for many elements)
- For each spectrum you find the closest example from the model grid (or library)
 - Can do slightly better by interpolating between the best few models



ASPCAP & APOGEE

Jönsson+2020

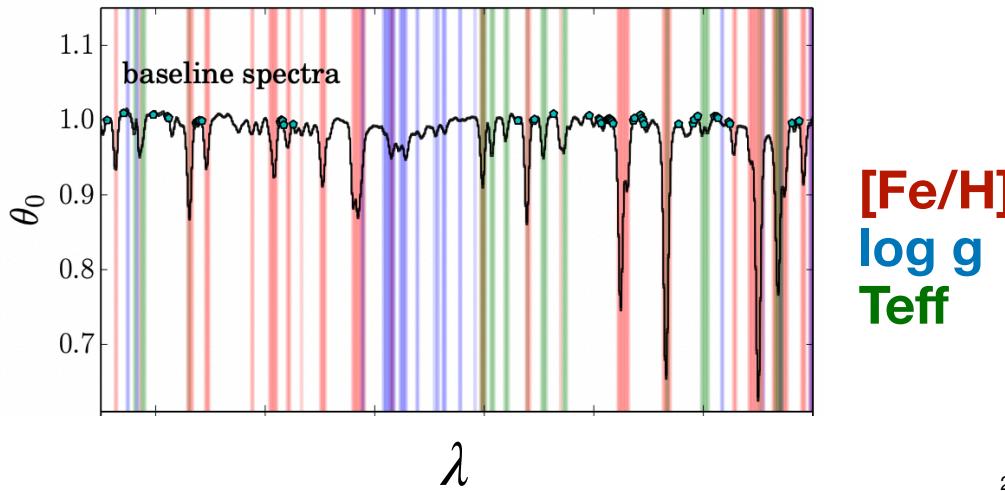


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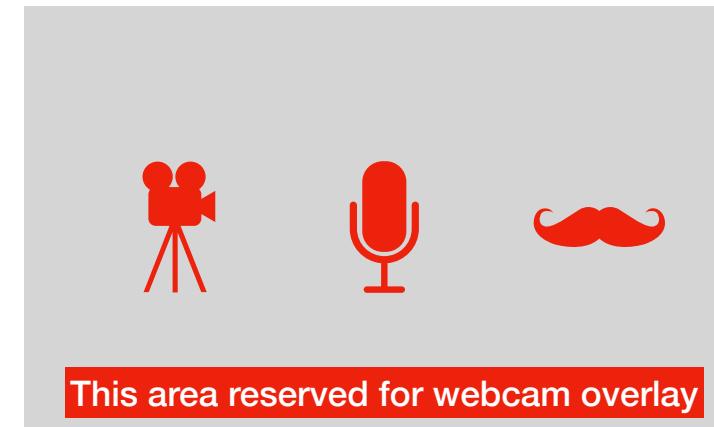
The Cannon

Ness+2015

- Named after Annie Jump Cannon
- Fancy, very accurate tool for inferring stellar parameters, works well for noisy data even!
- Trained on reference spectra (critical to have good training data!)
- “Generative probabilistic model” (similar to machine learning)

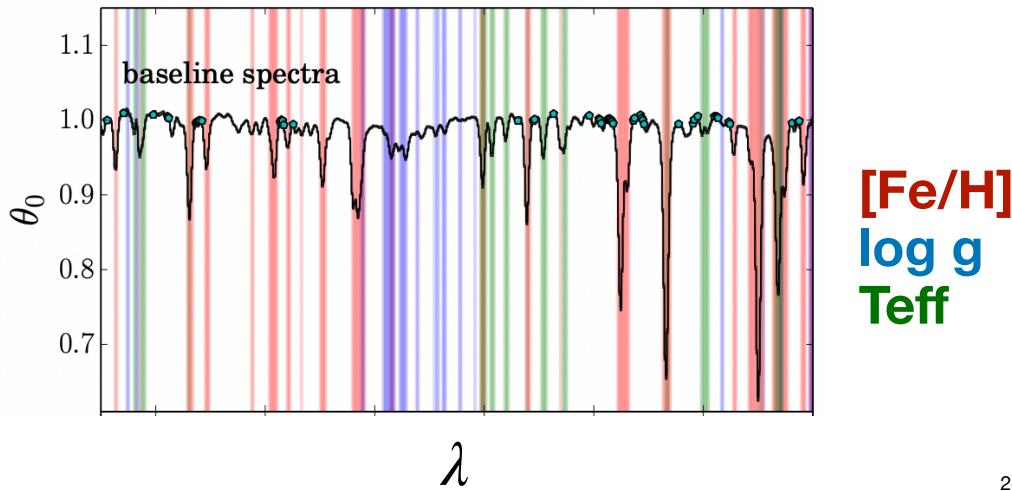


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The Cannon

- Designed with APOGEE in mind, but should be usable for other surveys
- This approach is representative of new classics of statistical or “data-driven” models designed for useful inference of physical parameters
- Totally dependent on training data... it can’t label what it doesn’t learn



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