ASTR 421

Stellar Observations and Theory

Lecture 10
Line Profiles: III

Prof. James Davenport (UW)

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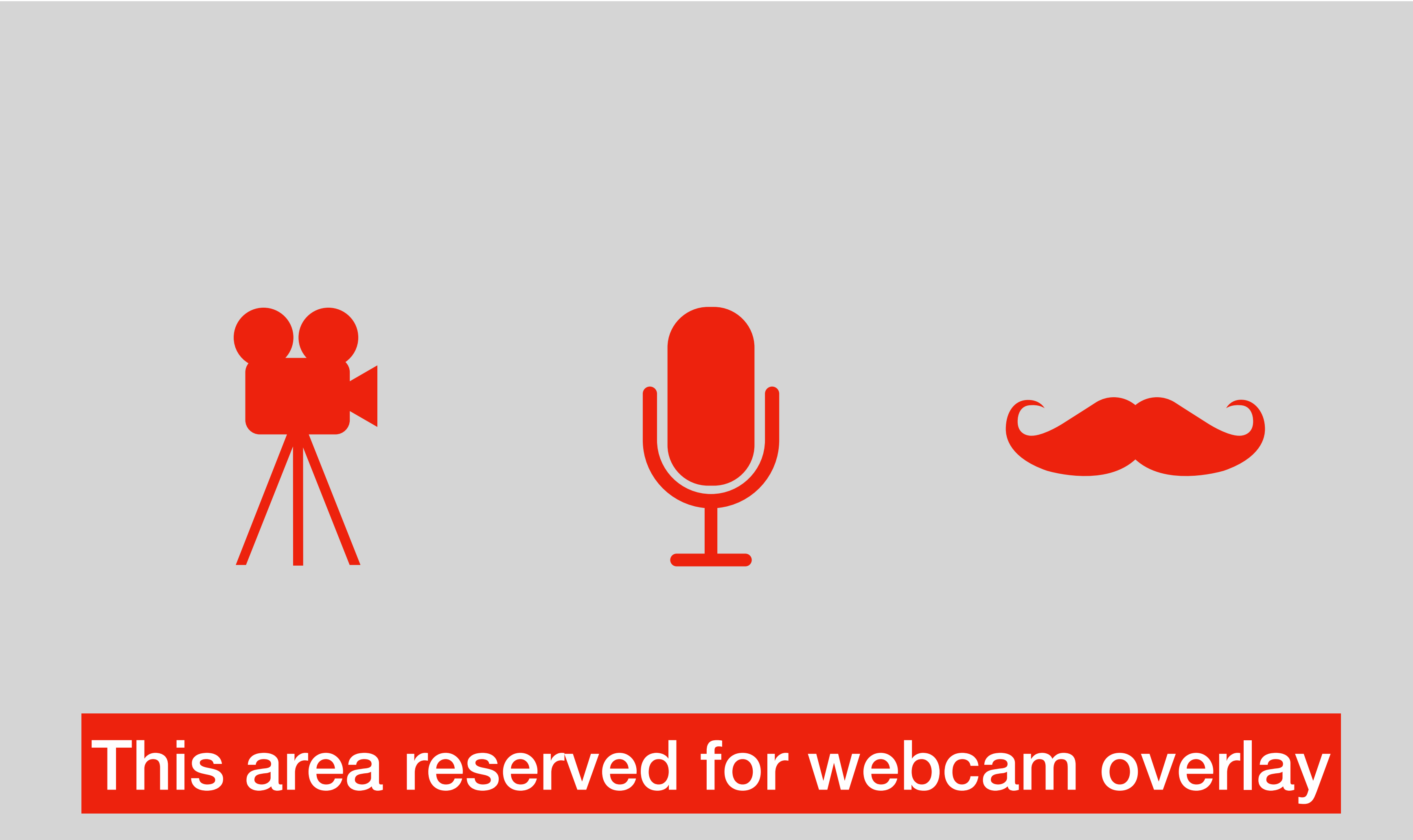
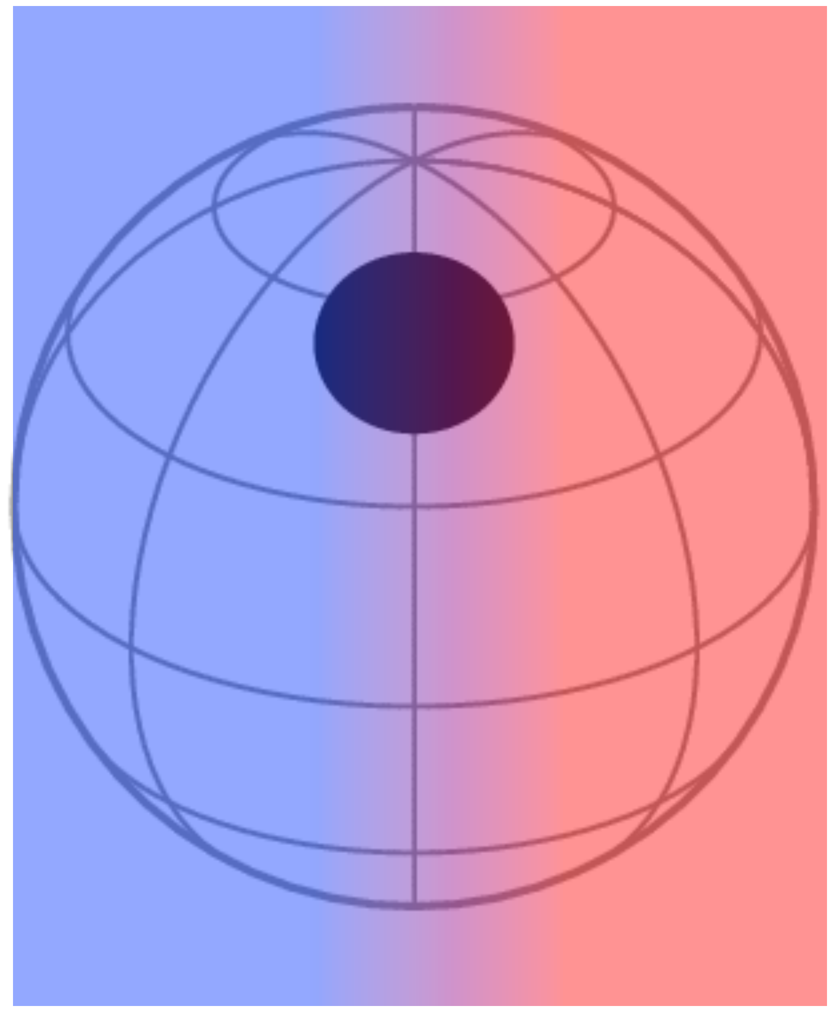
Today

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

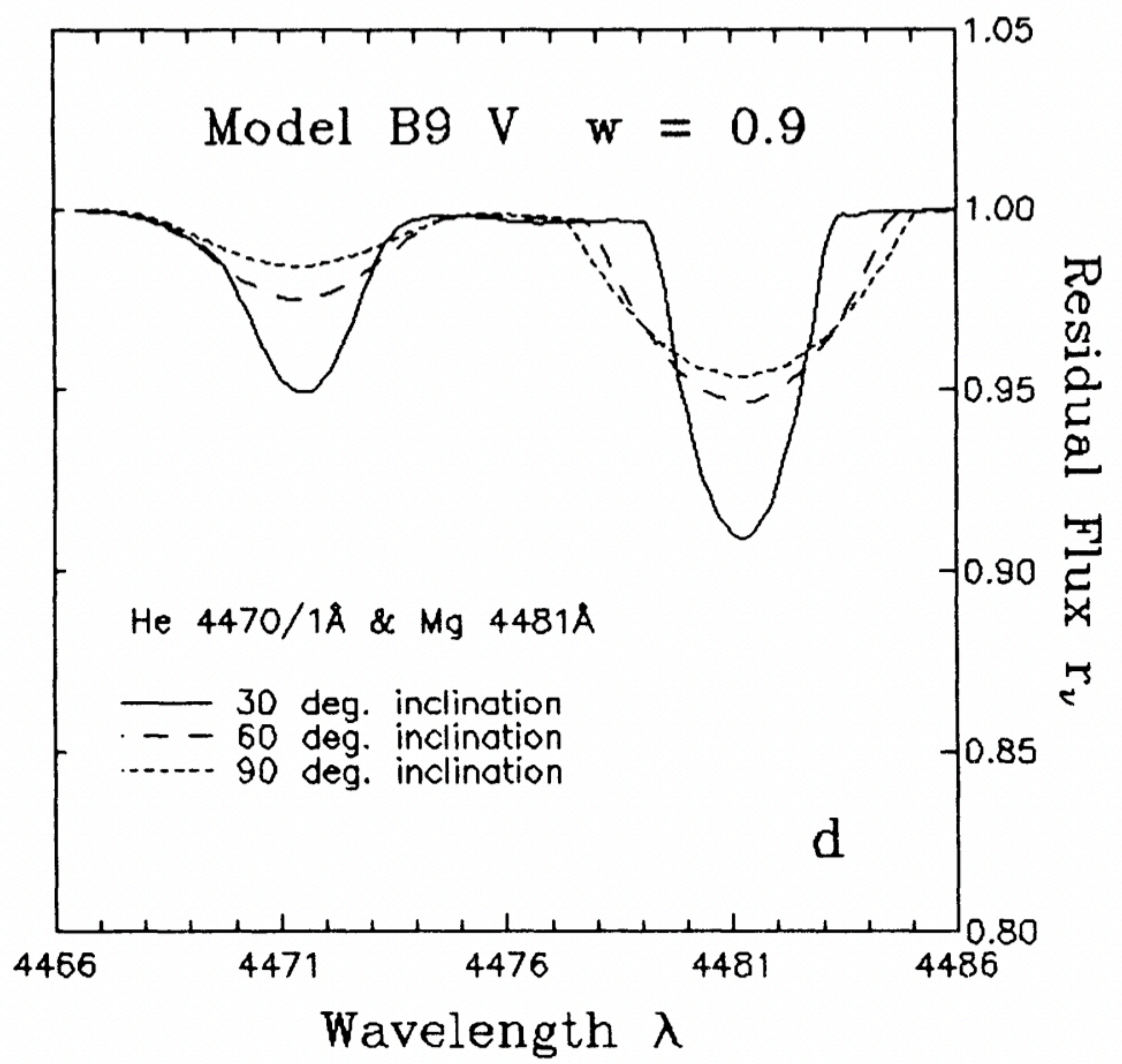


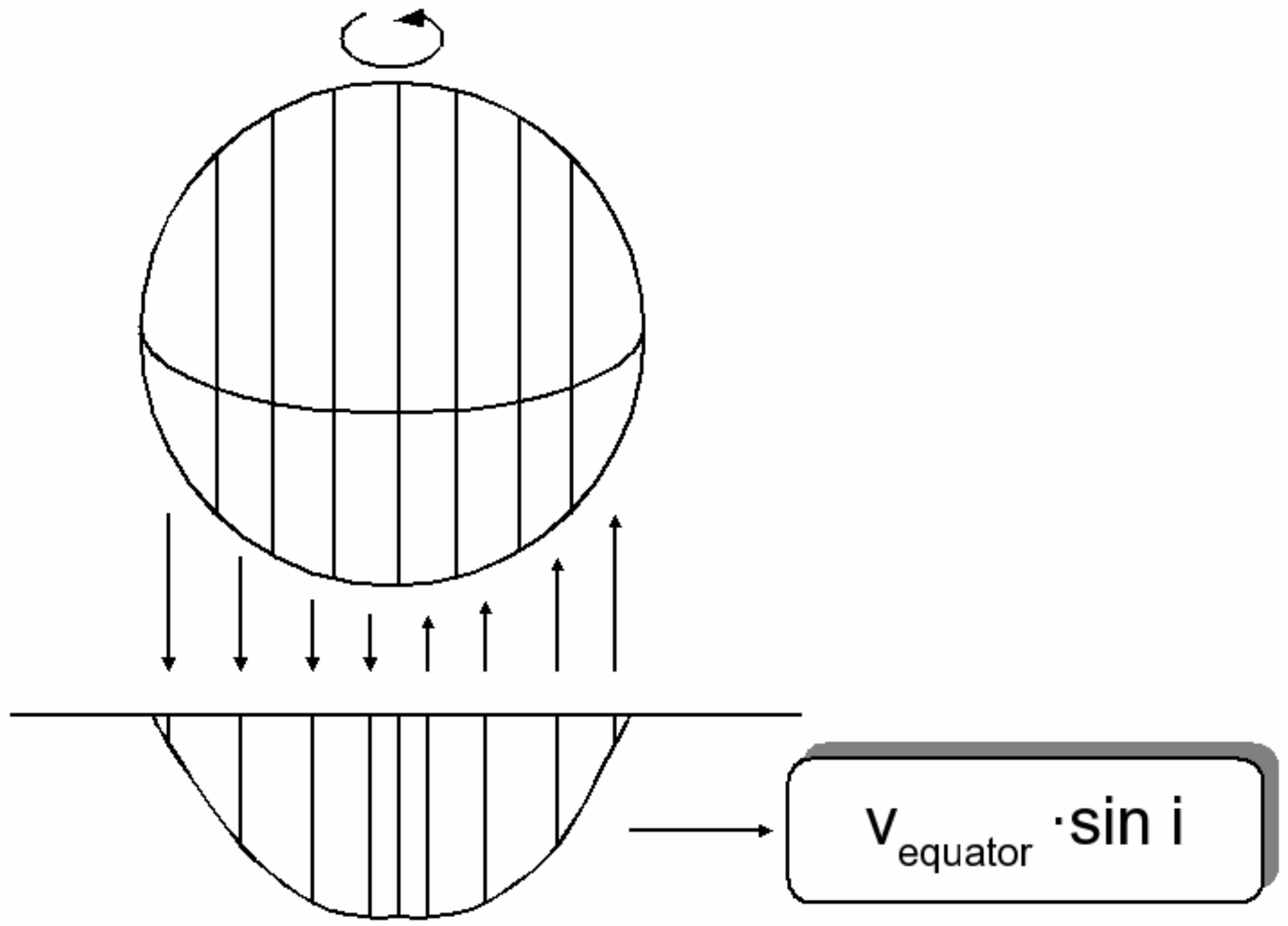
Additional sources of line broadening

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



Collins & Truax (1995)





Ulrke Heiter

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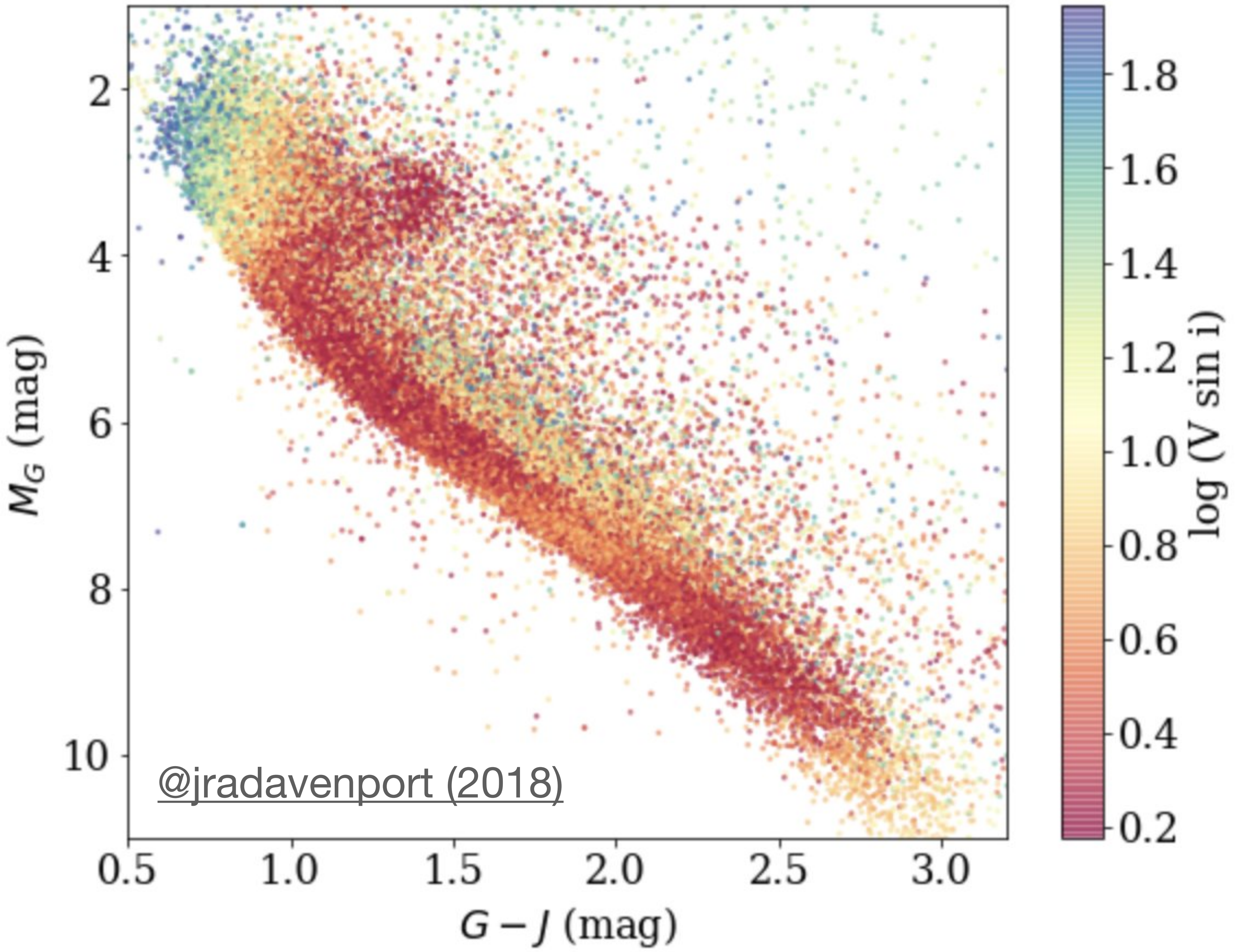
Additional sources of line broadening

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

Rotation signature from APOGEE



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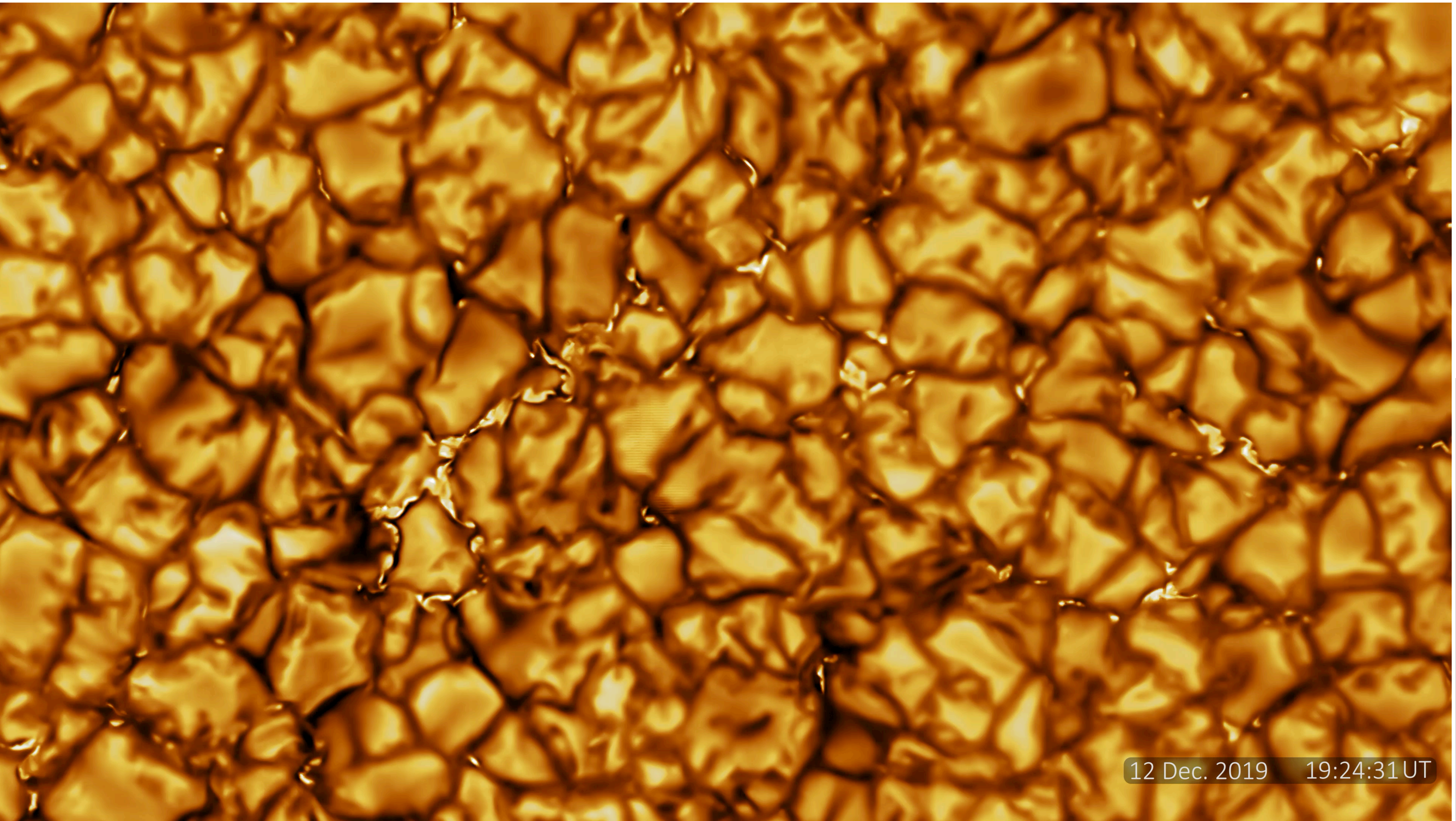
Additional sources of line broadening

- **Granulation**



DKIST

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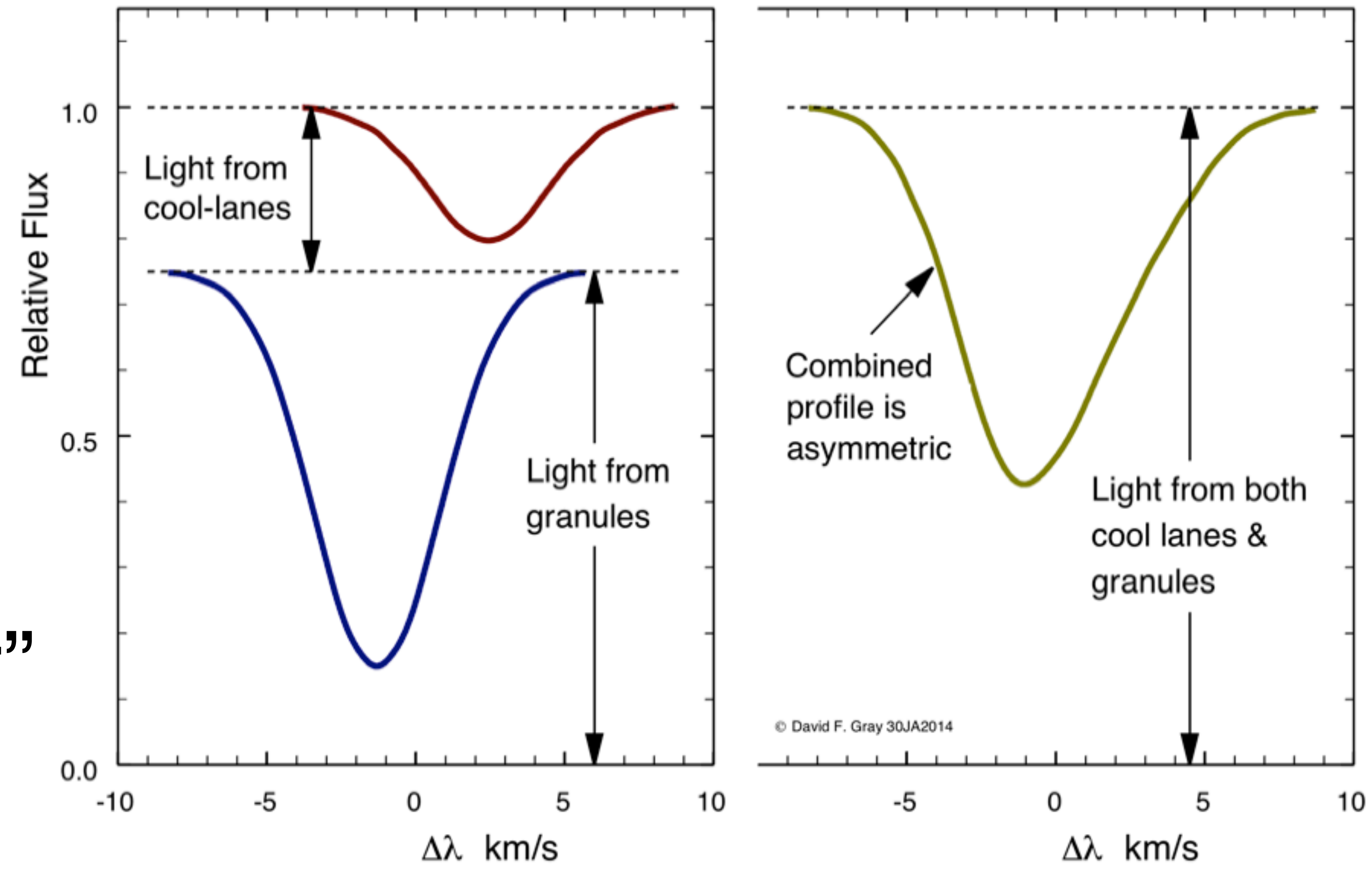
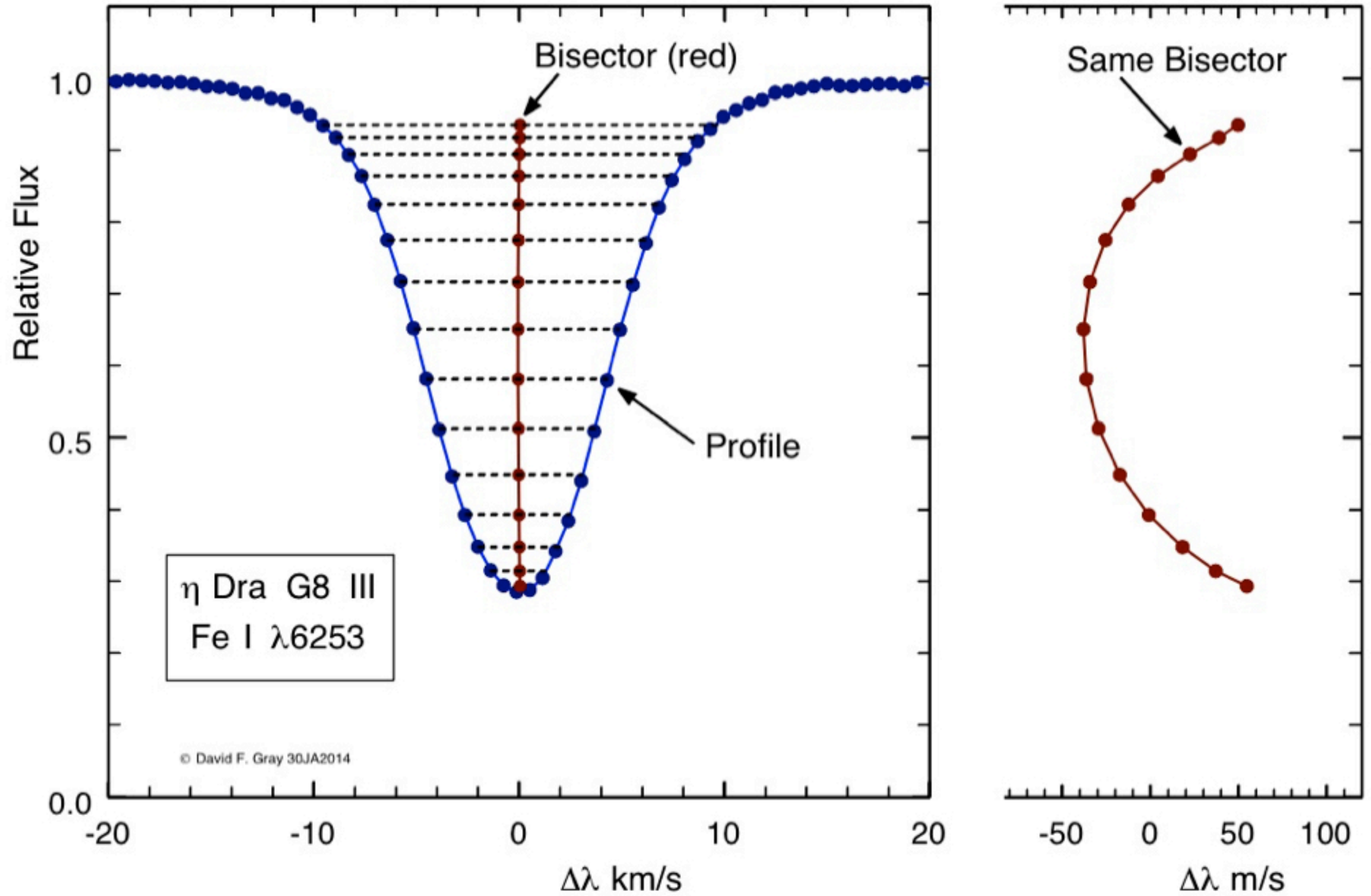
Additional sources of line broadening

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





https://physics.uwo.ca/~dfgray/granulation.html

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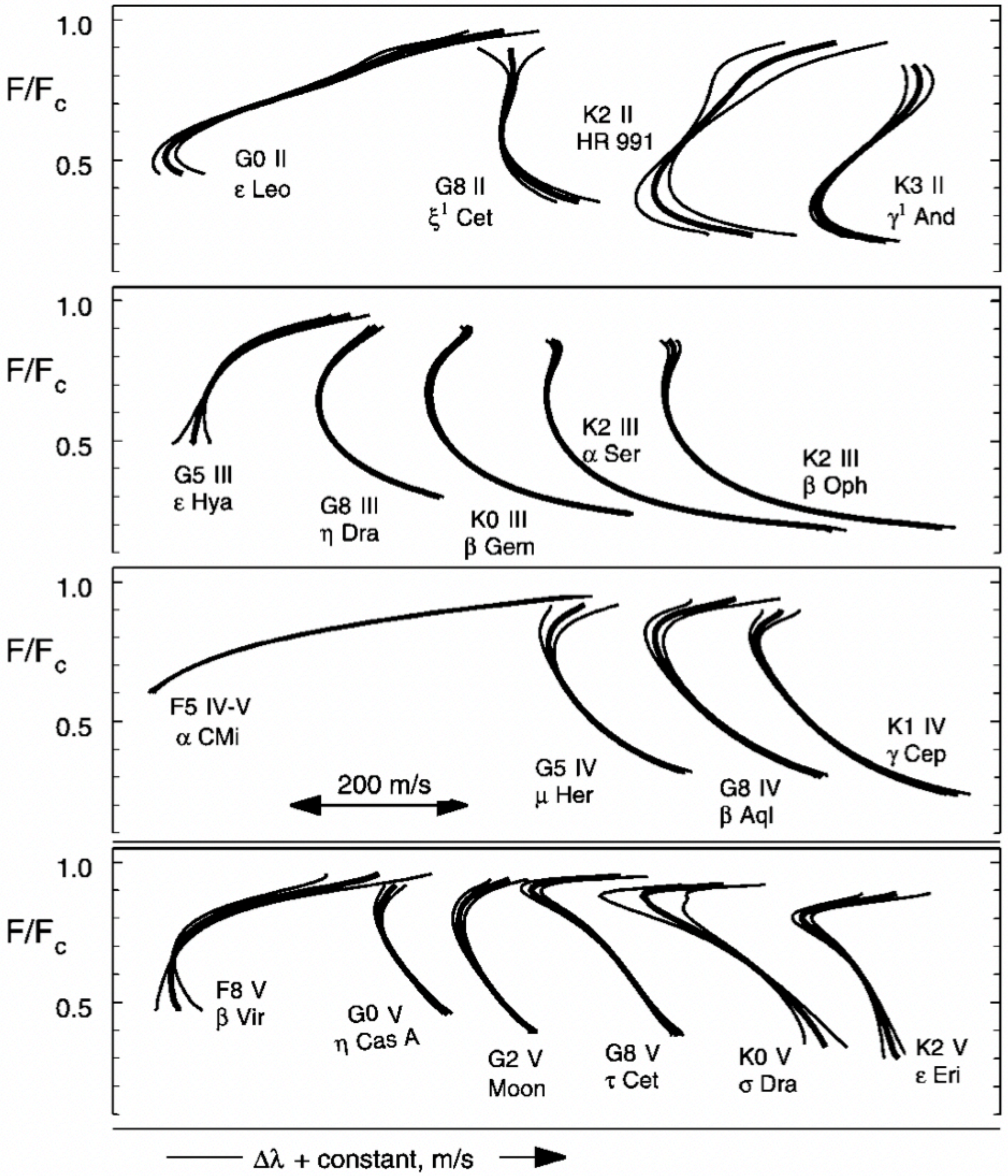
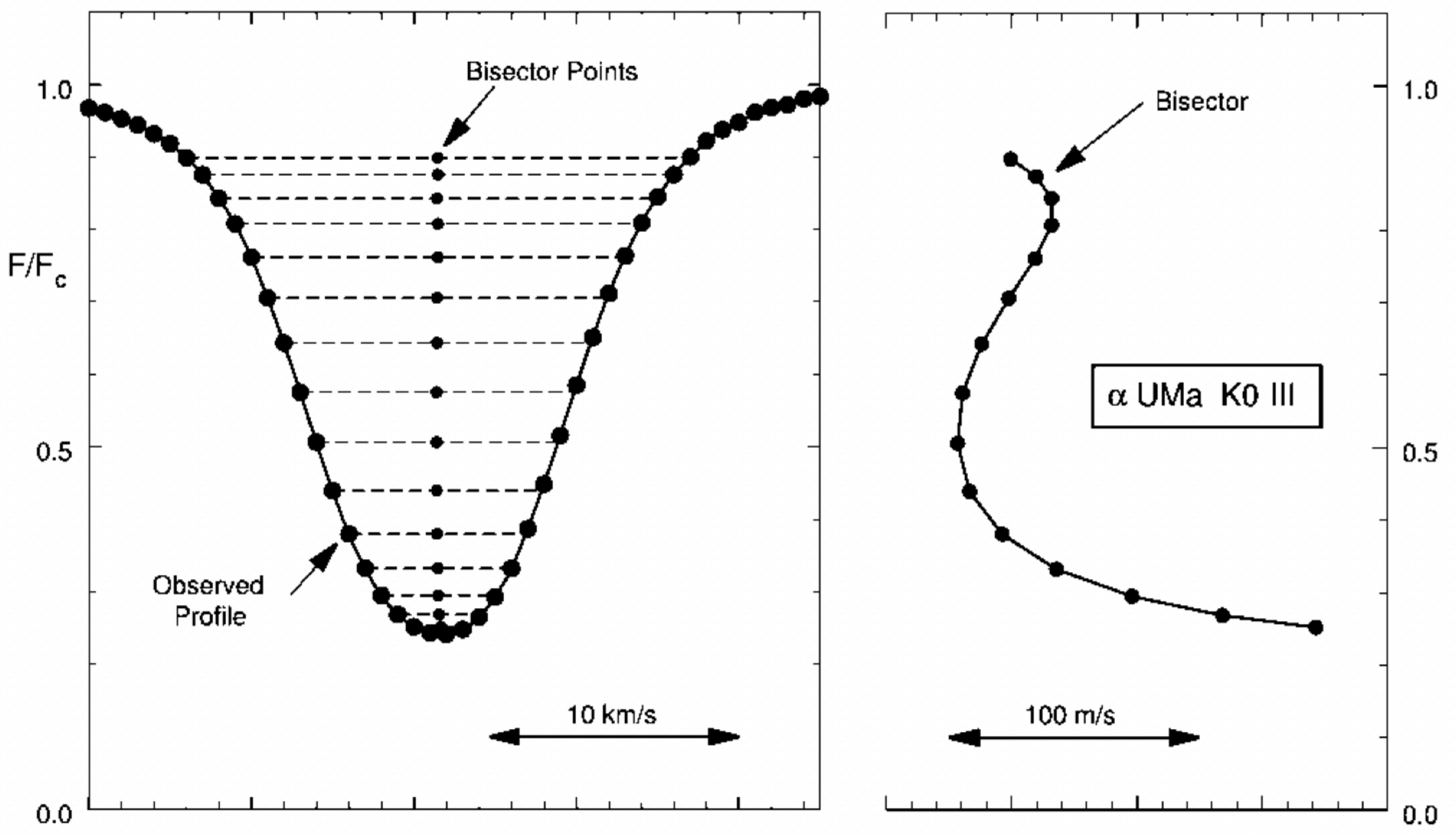
Additional sources of line broadening

- **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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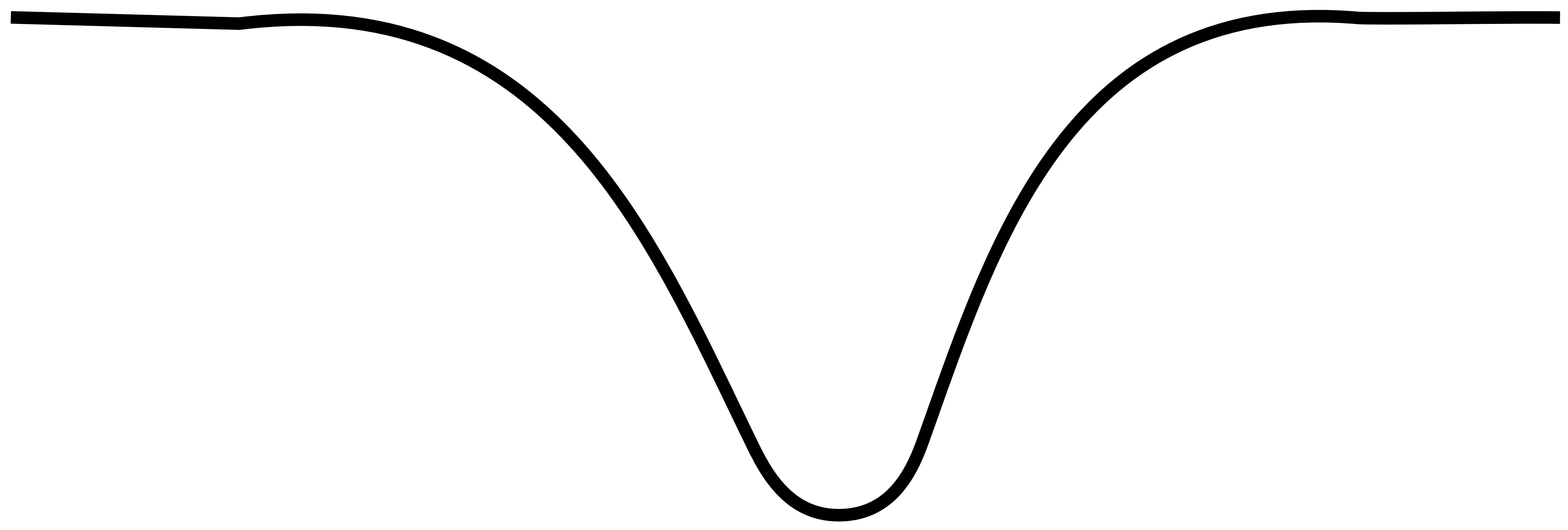
Review: Sources of Line Broadening



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

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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

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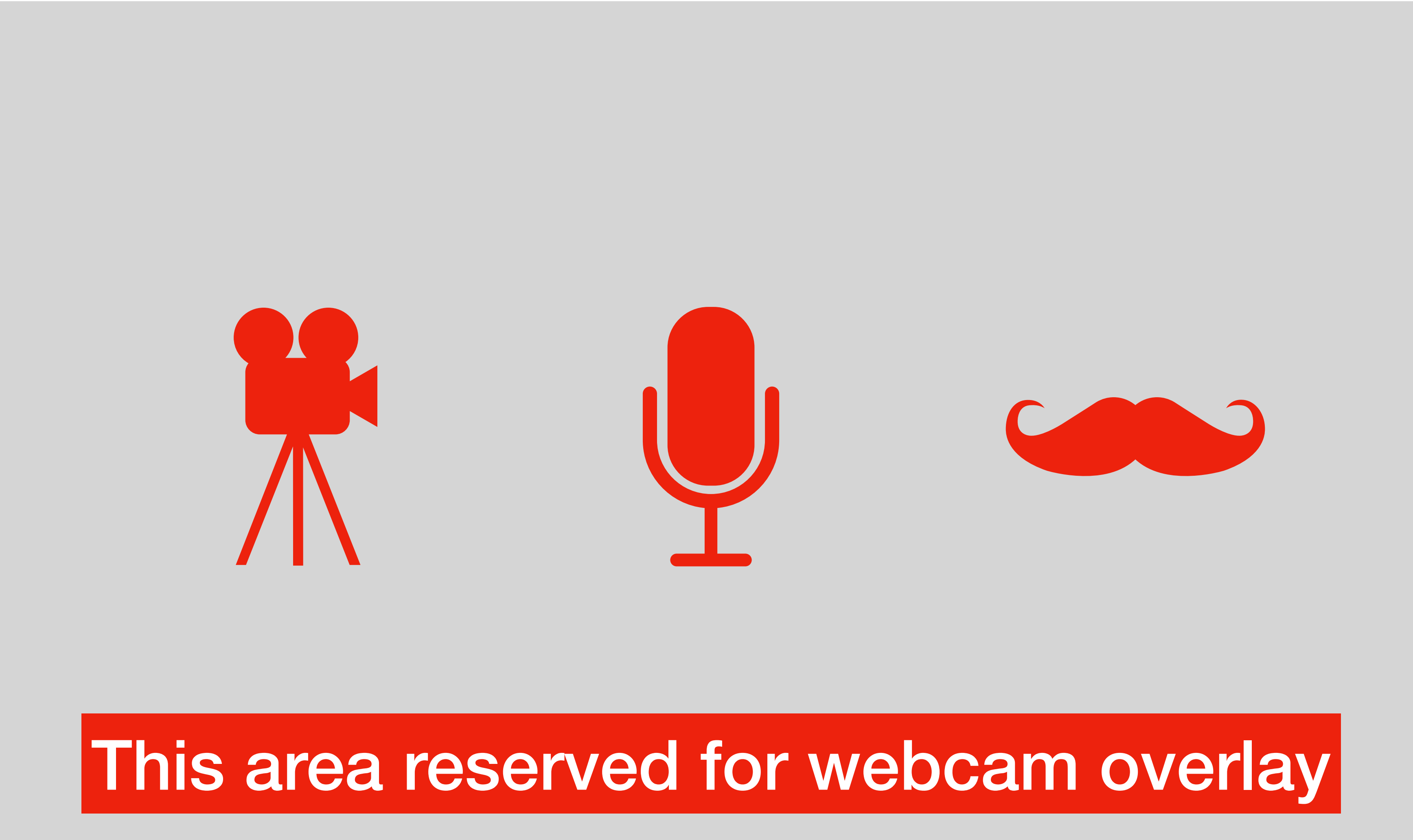
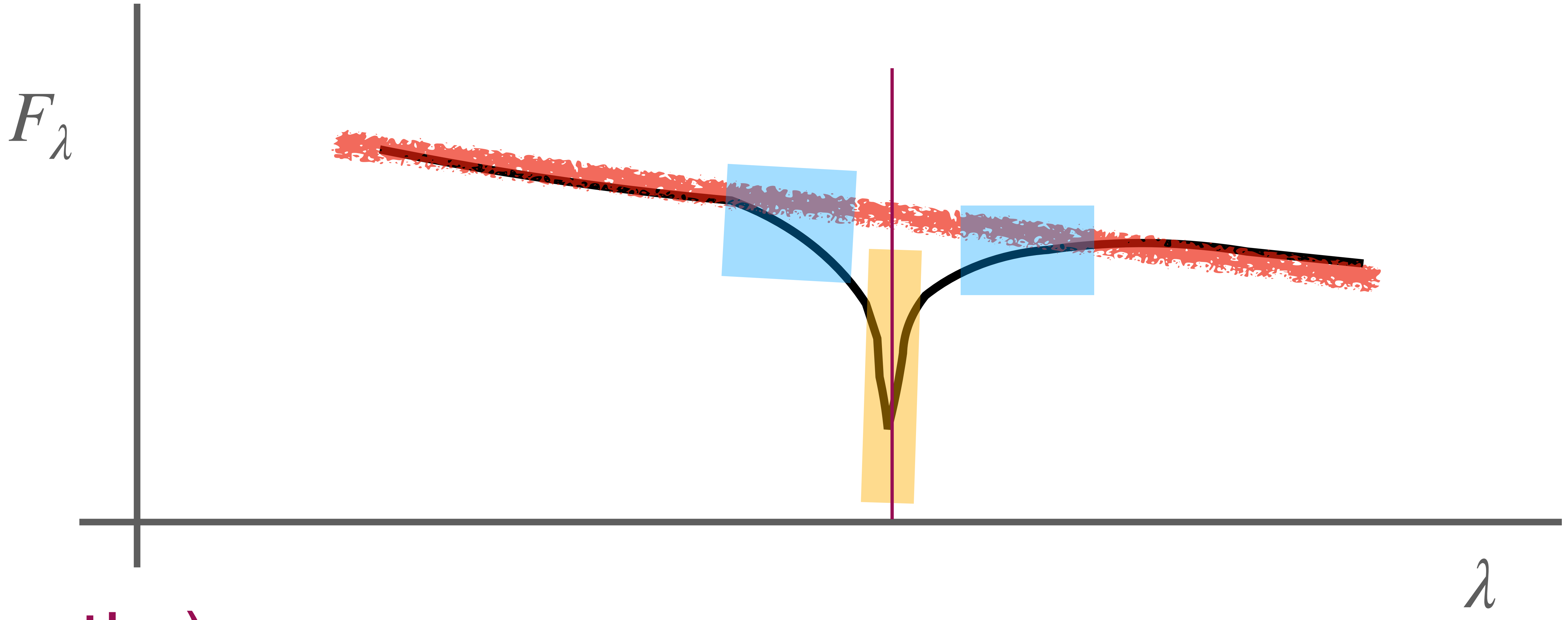
It’s complicated…

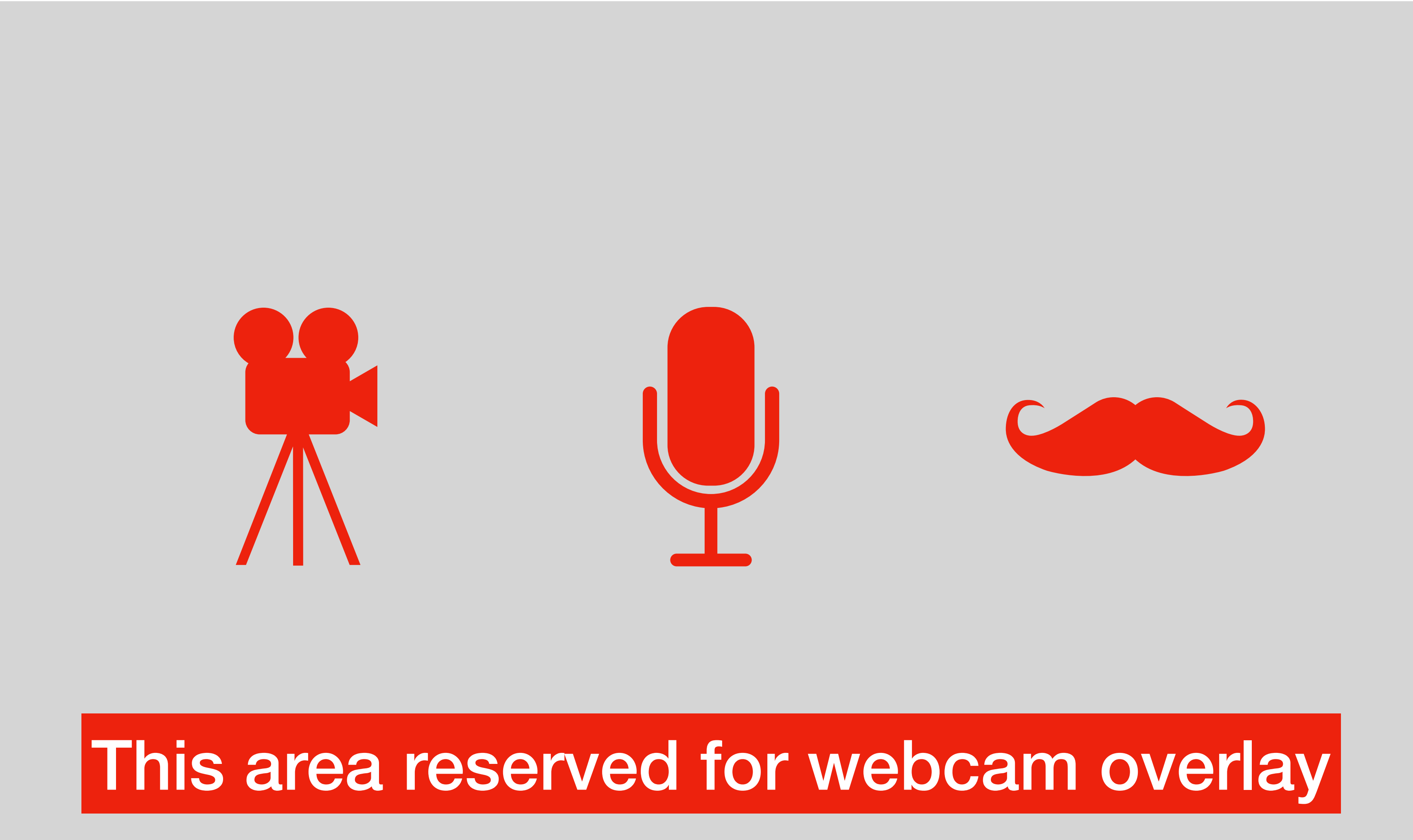
- We can “cheat”
  - Use 1-D models & “**model grids**”
  - Make simplifying assumptions (e.g. LTE)
  - Separate pieces of the problem
    (e.g. radiative transfer w/o worrying about MHD)
  - Fit individual absorption lines separately
- Even the “easy” way is quite difficult for any given stellar spectrum



Line terminology

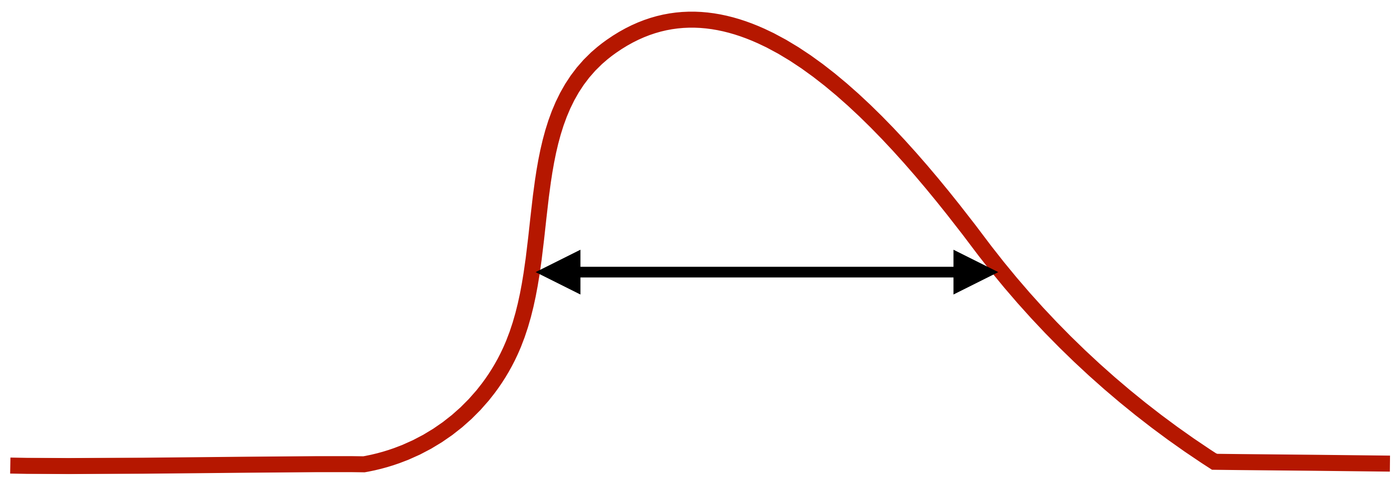
- Spectrum $\equiv (\tau = 2/3)$
- Continuum (blackbody)
- Wings (both sides)
- Core (center)
- λ_{lab} (note: vac or air wavelengths)
- **FWHM**

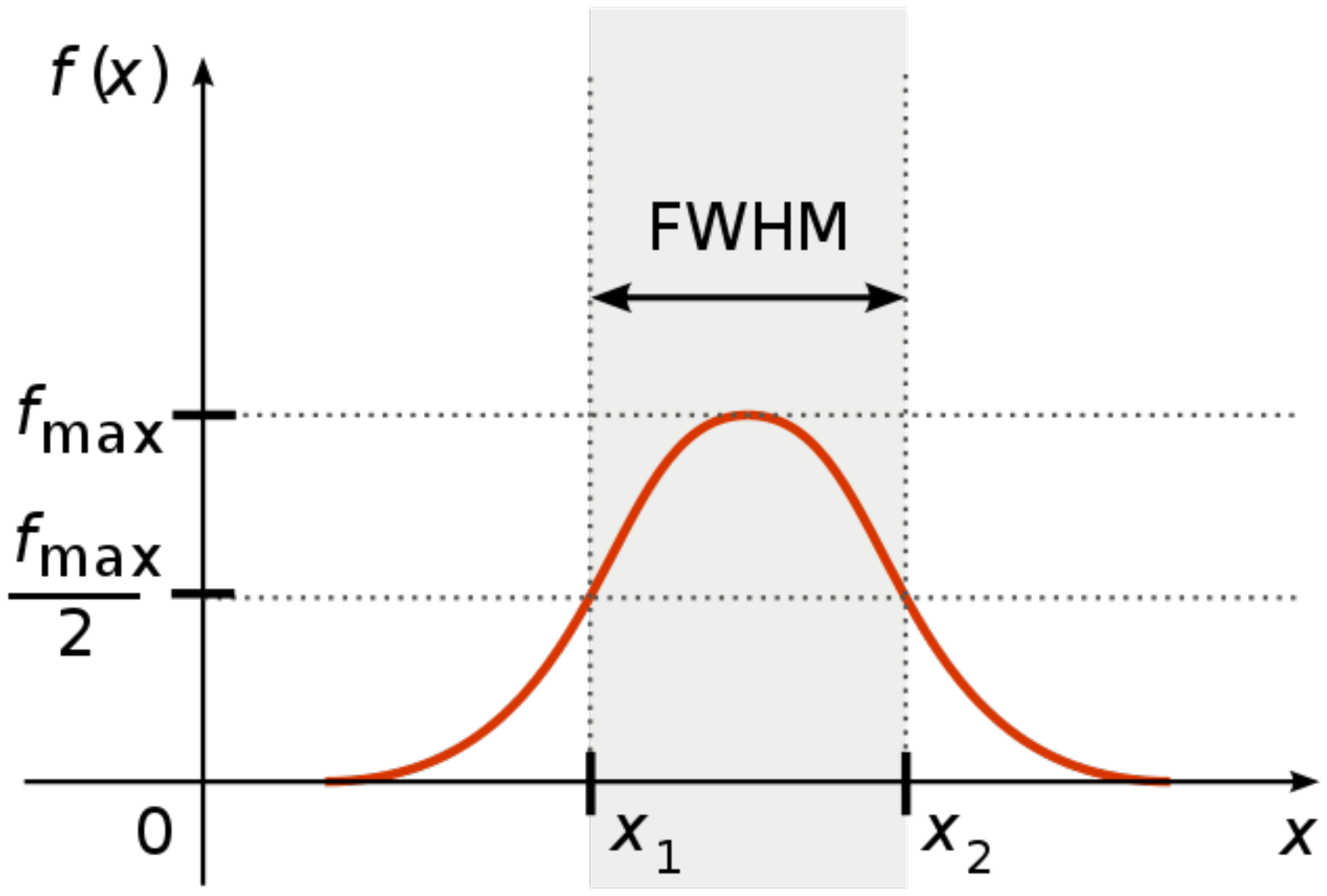




FWHM

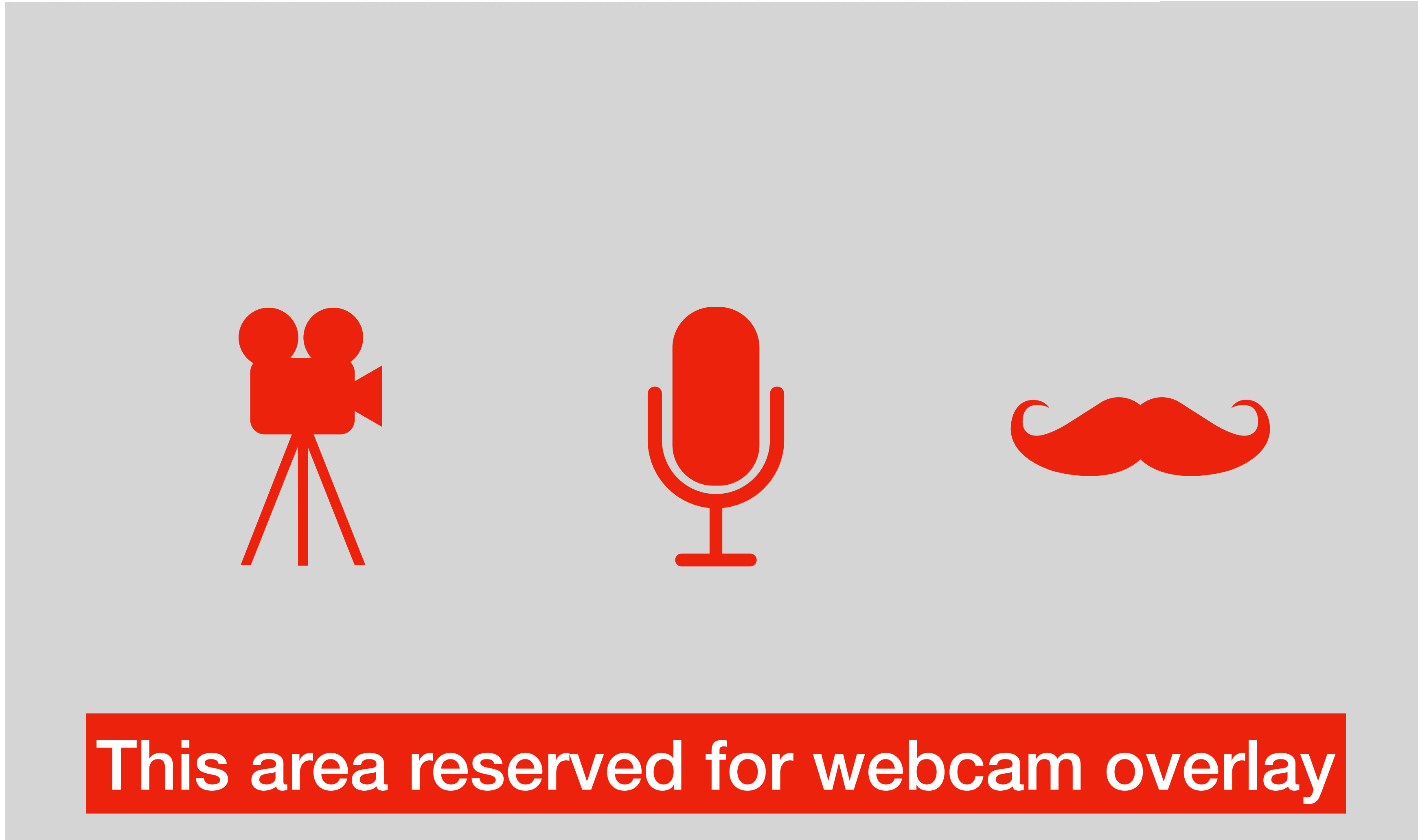
- A simple measure of the line width
- Used lots across astronomy (not just in spectroscopy)
- Easier to estimate in presence of noise
- Can be measured for asymmetric or unusual profiles





For a Gaussian curve only:

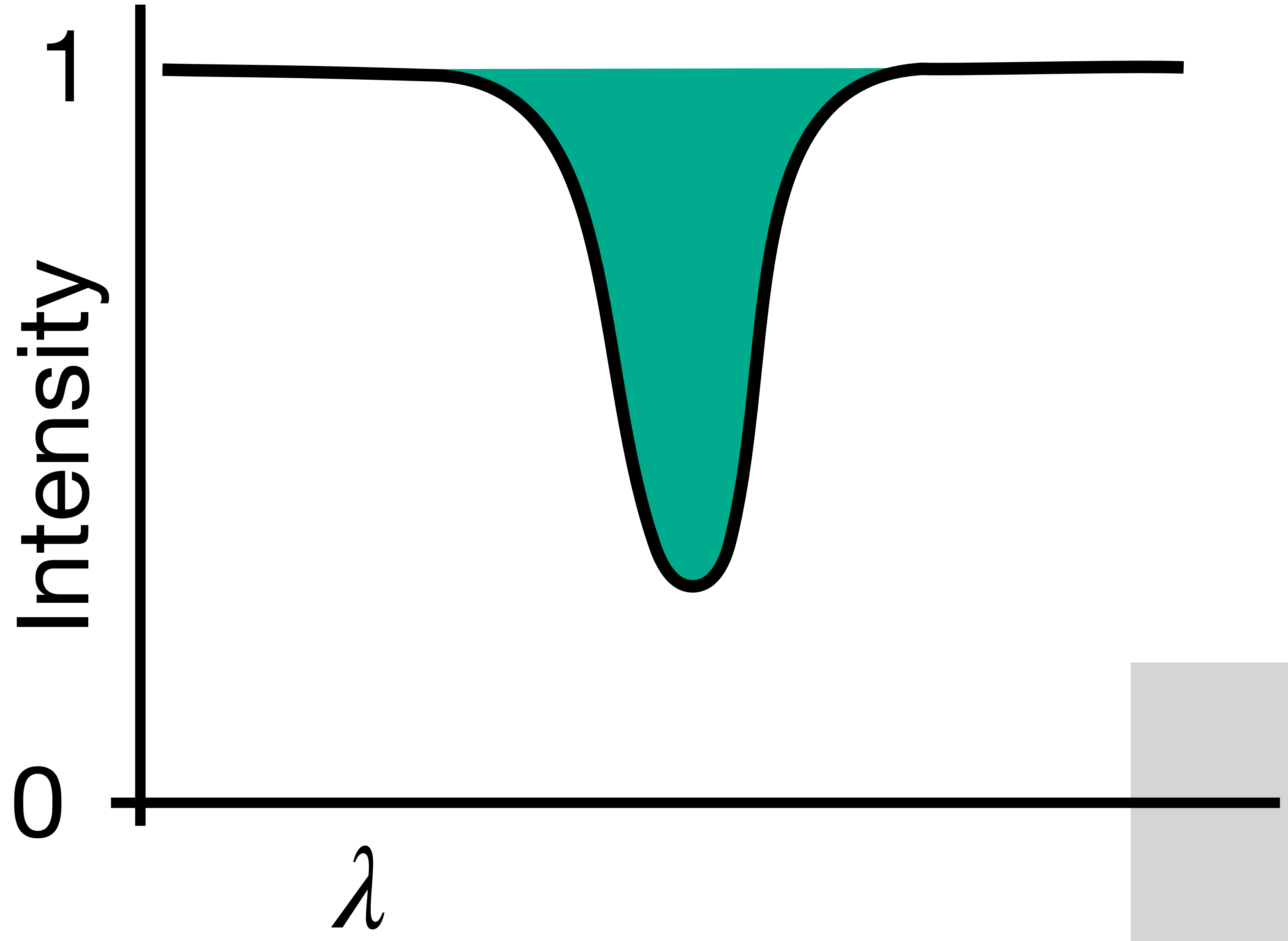
$$\mathrm{FWHM} = 2\sqrt{2\ln 2}\,\sigma \approx 2.355\,\sigma$$



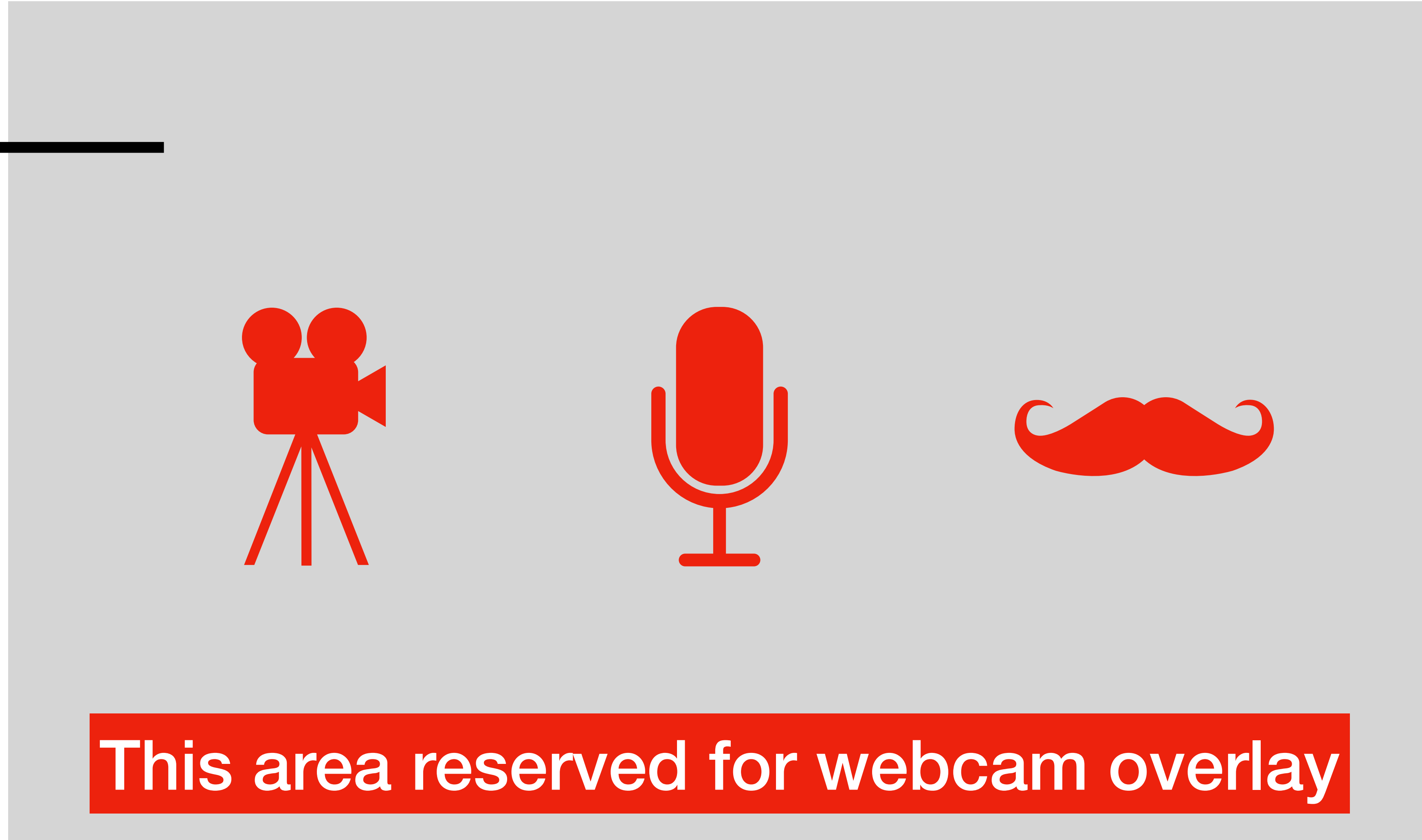
Equivalent Width

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 "$1\mathring{A}$ equiv. widths"…



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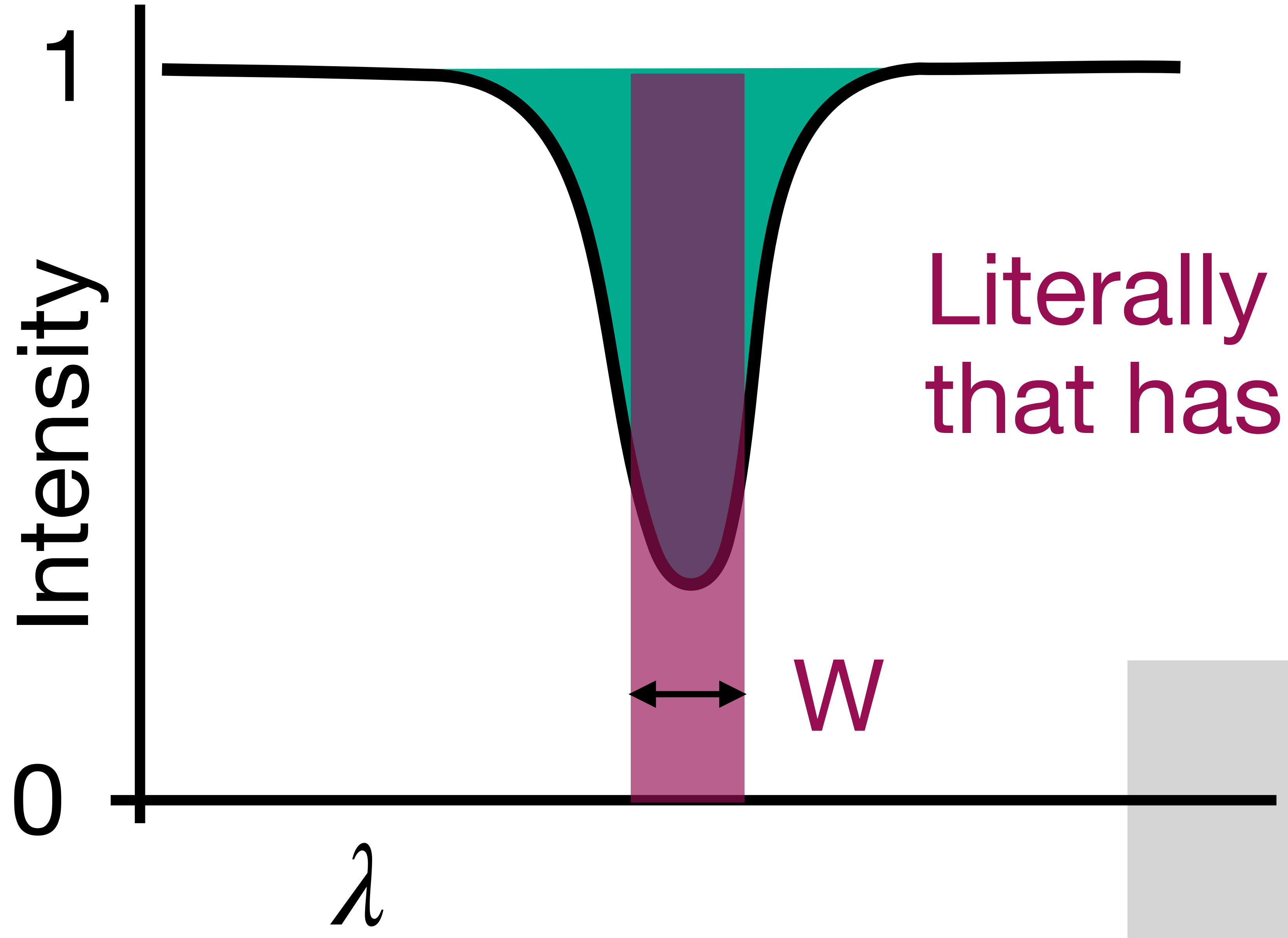
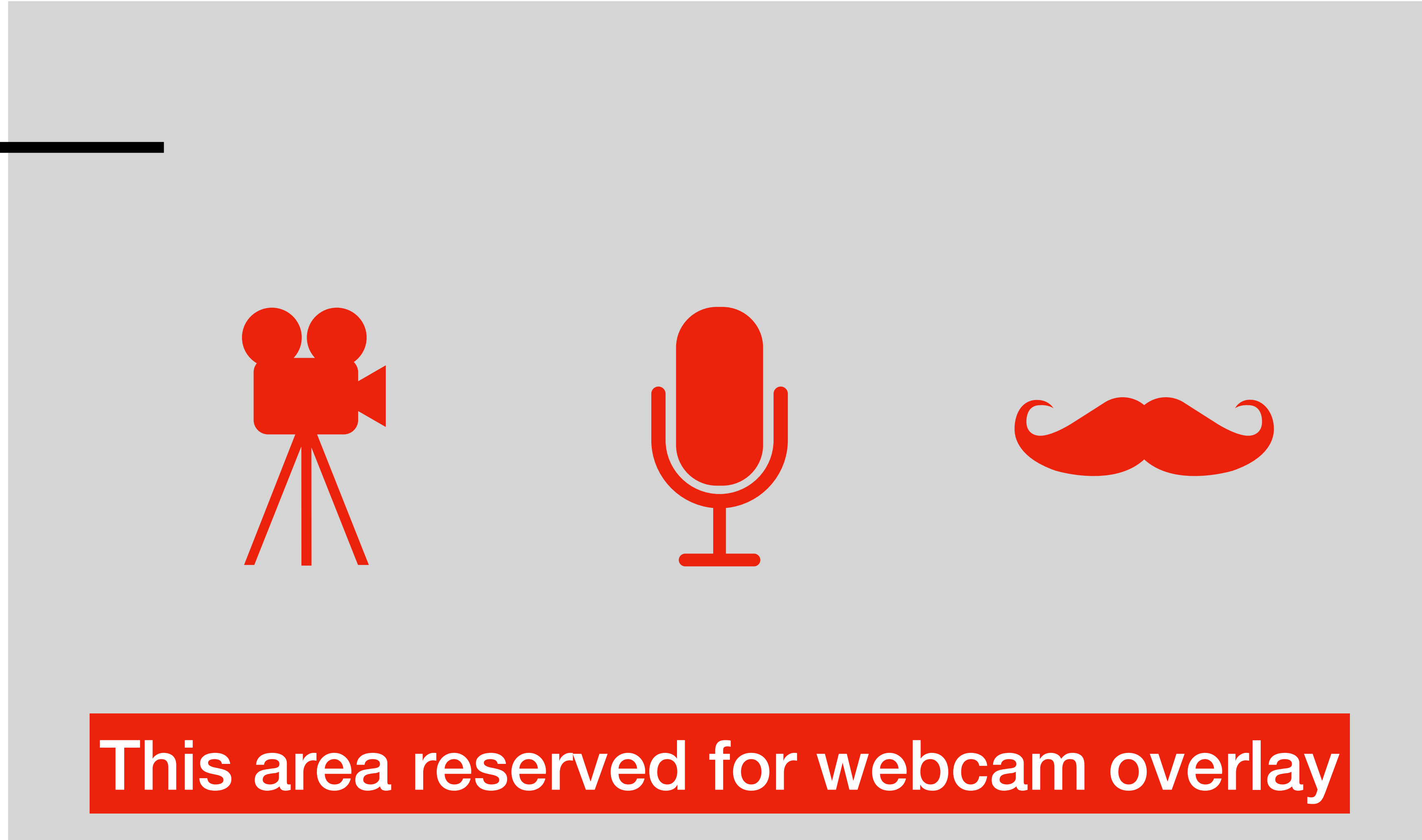


- Hence we talk about "1Å equiv. widths"…



Curve of Growth

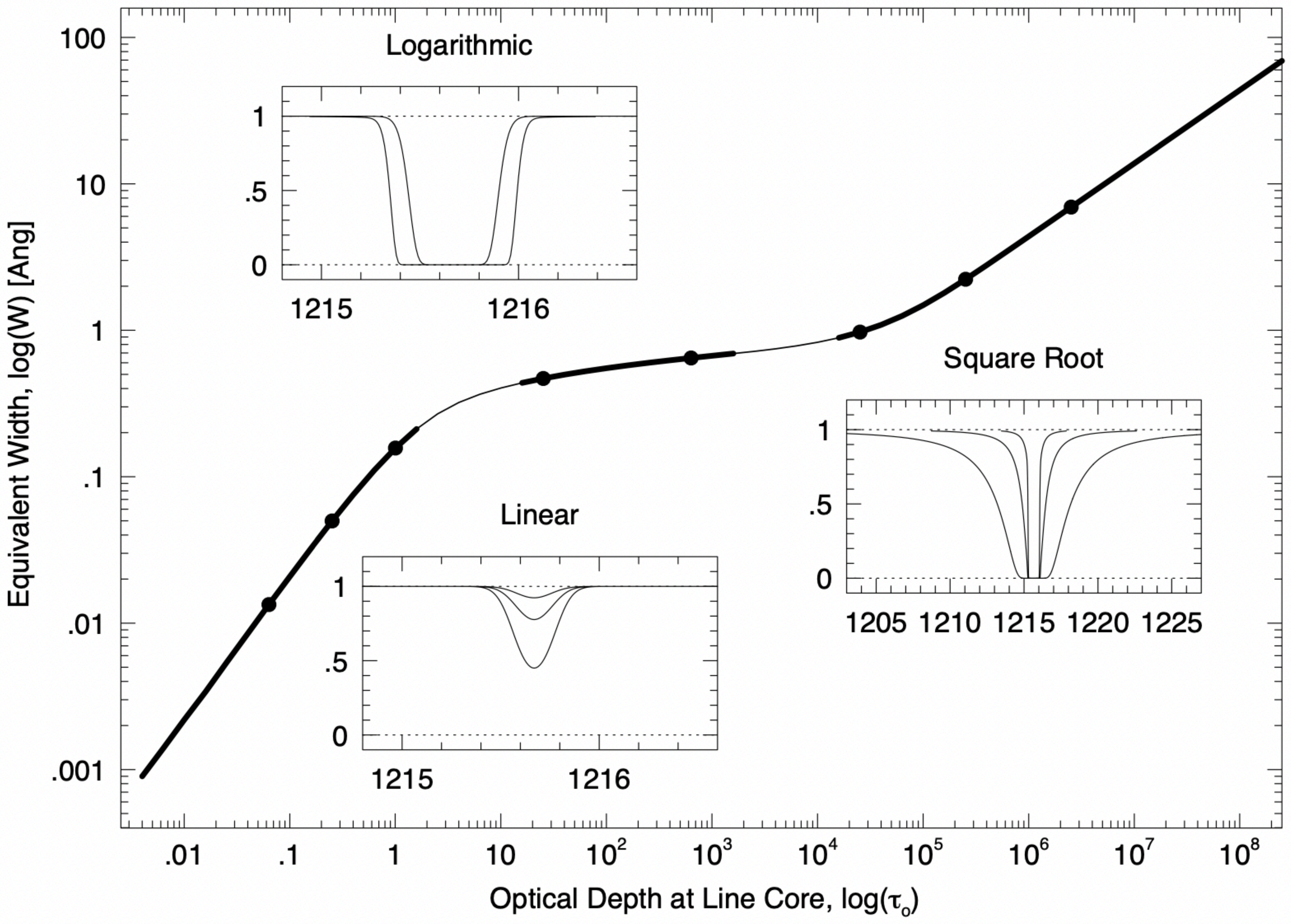
- How Equiv. Width changes with τ_λ
- $W_\lambda = \int (1 - \frac{F_\lambda}{F_0})\, d\lambda = \int (1 - e^{-\tau_\lambda})\, d\lambda$

  recall: $I_\lambda = I_{\lambda,0}\, e^{-\tau_\lambda} + S_\lambda\, (1 - e^{-\tau_\lambda})$
- 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"



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

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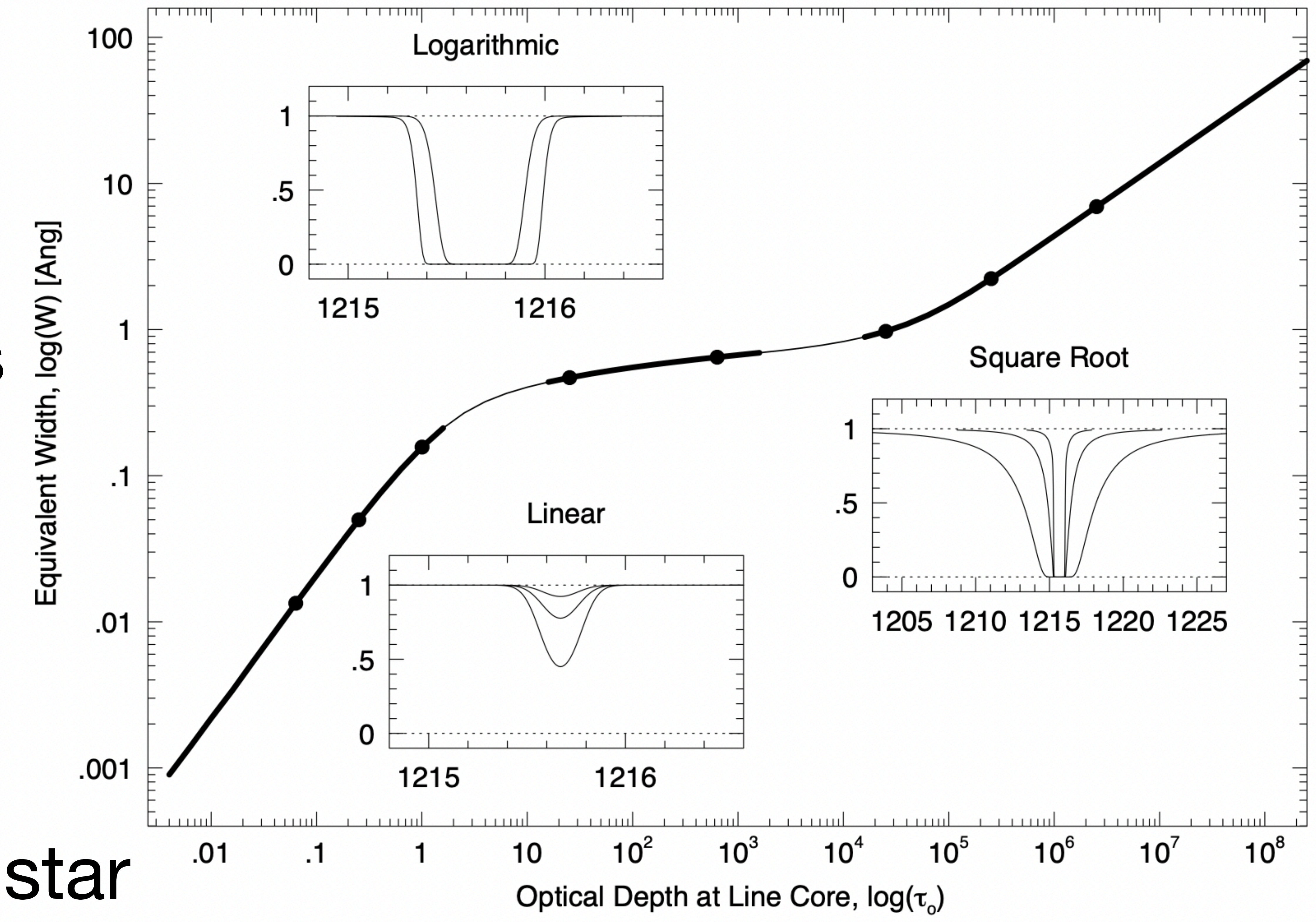
Curve of Growth

- 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



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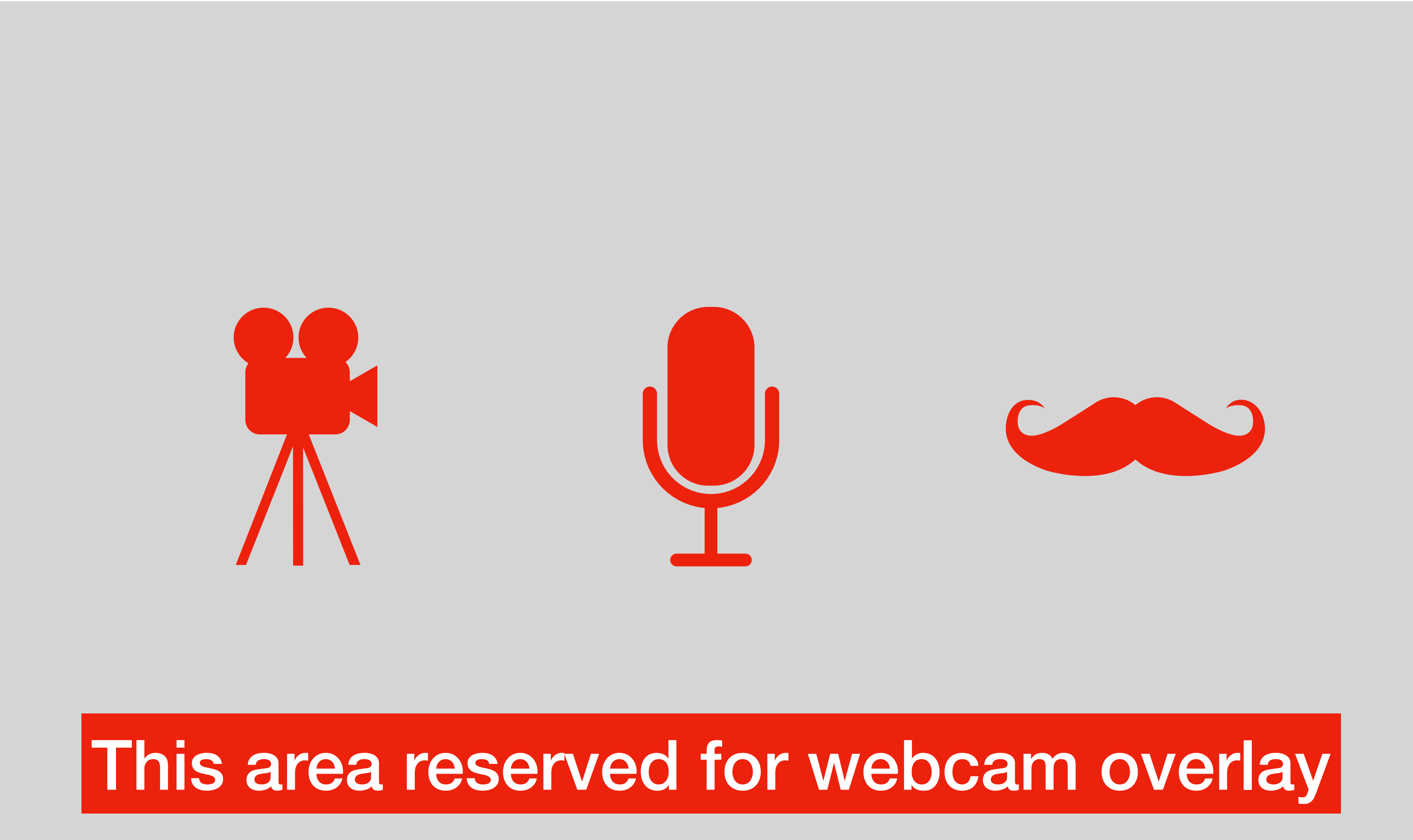
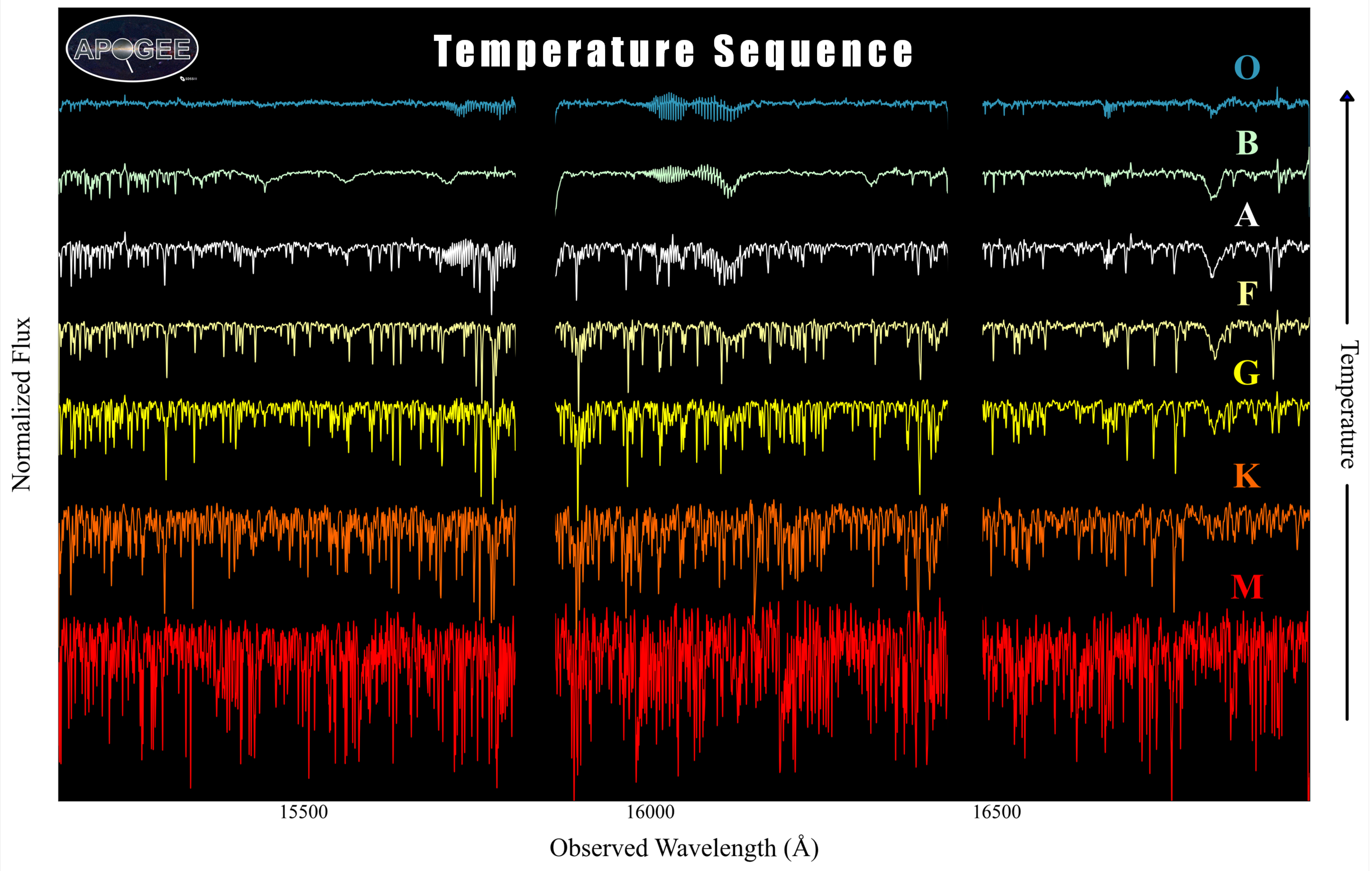


Stellar Properties from Spectra

- 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.



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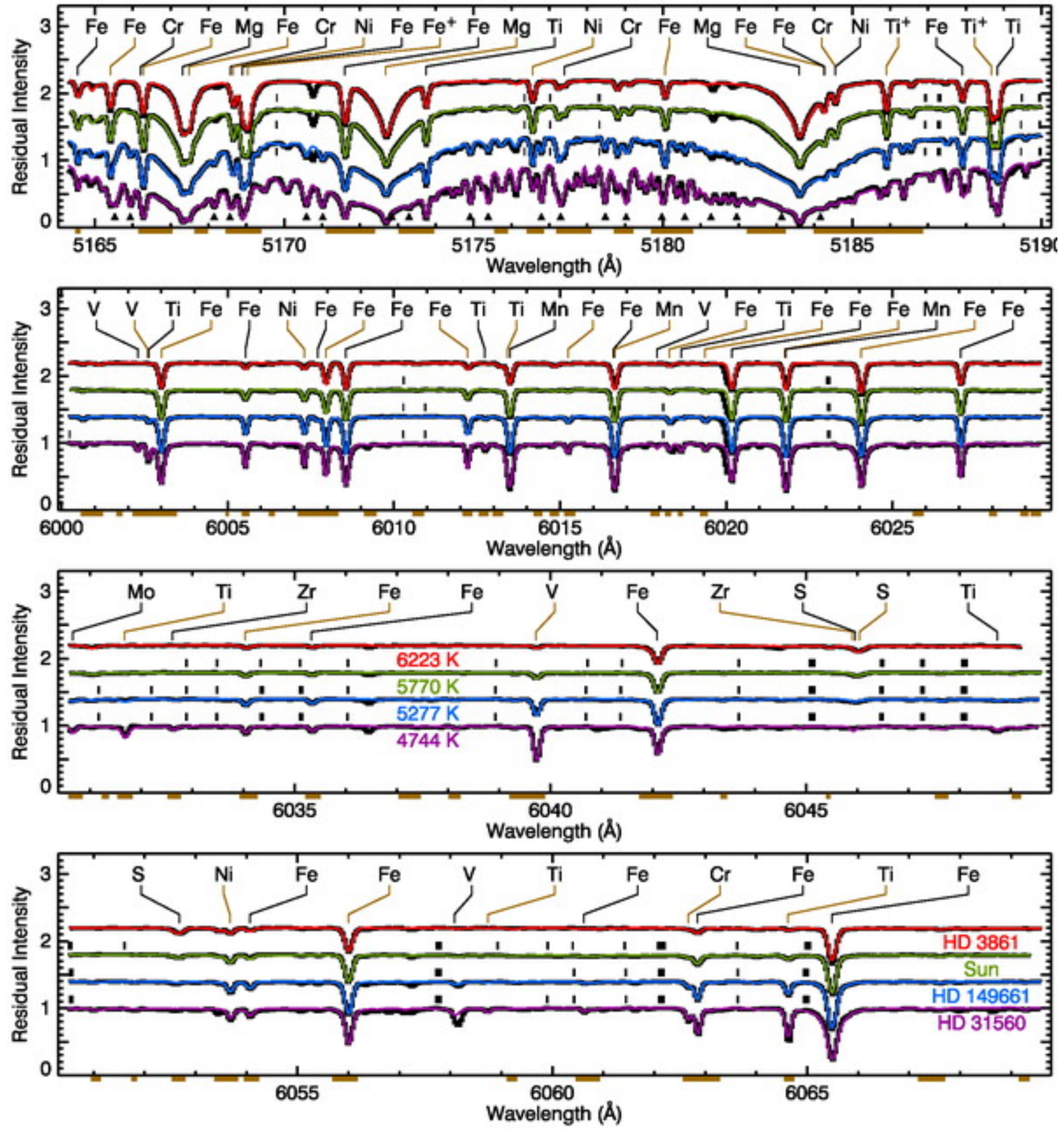
Spectroscopy Made Easy (SME)

- 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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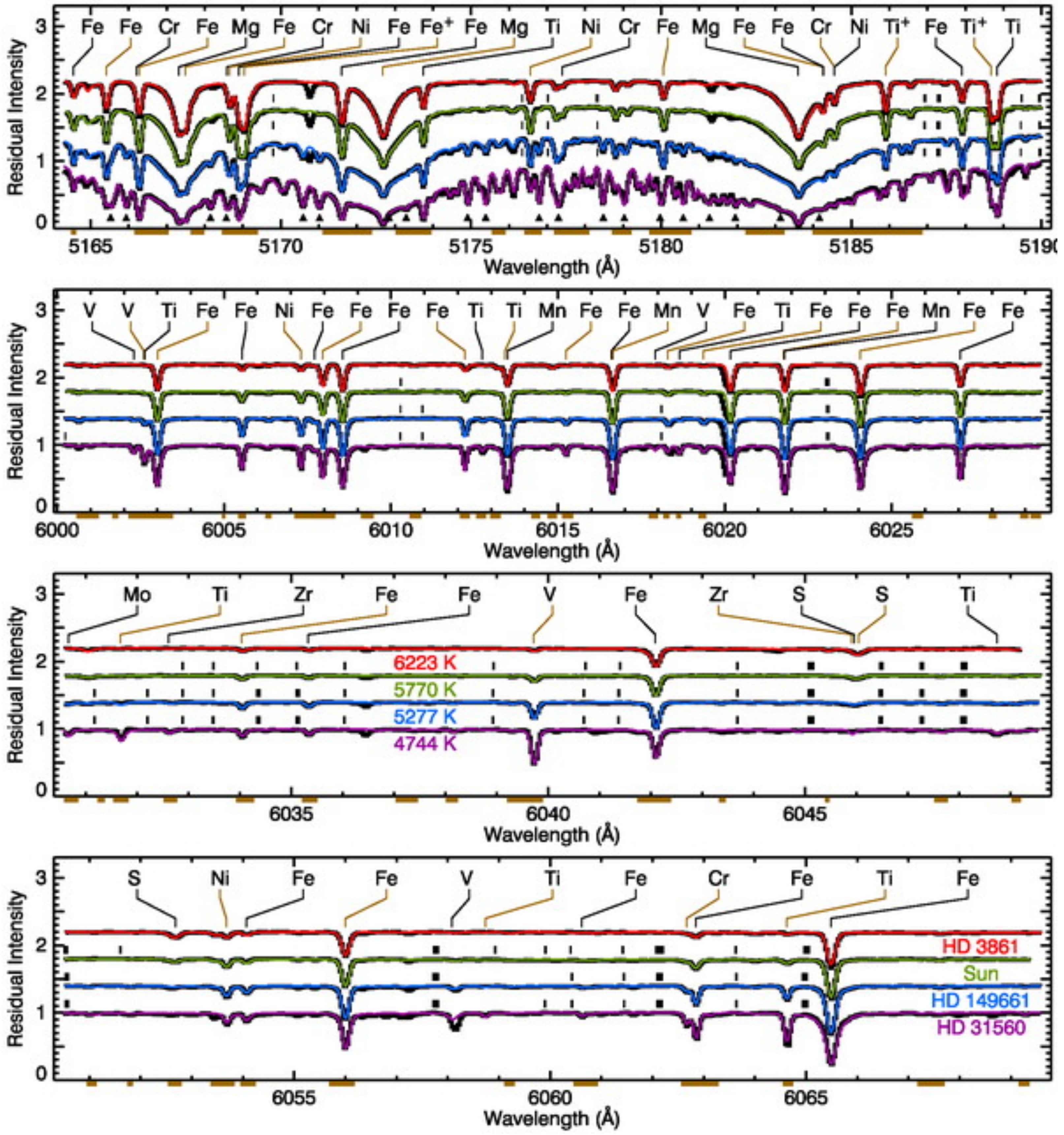
Spectroscopy Made Easy (SME)



- 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

Blanco-Cuarsema (2019)
https://academic.oup.com/mnras/article/486/2/2075/5475413

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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

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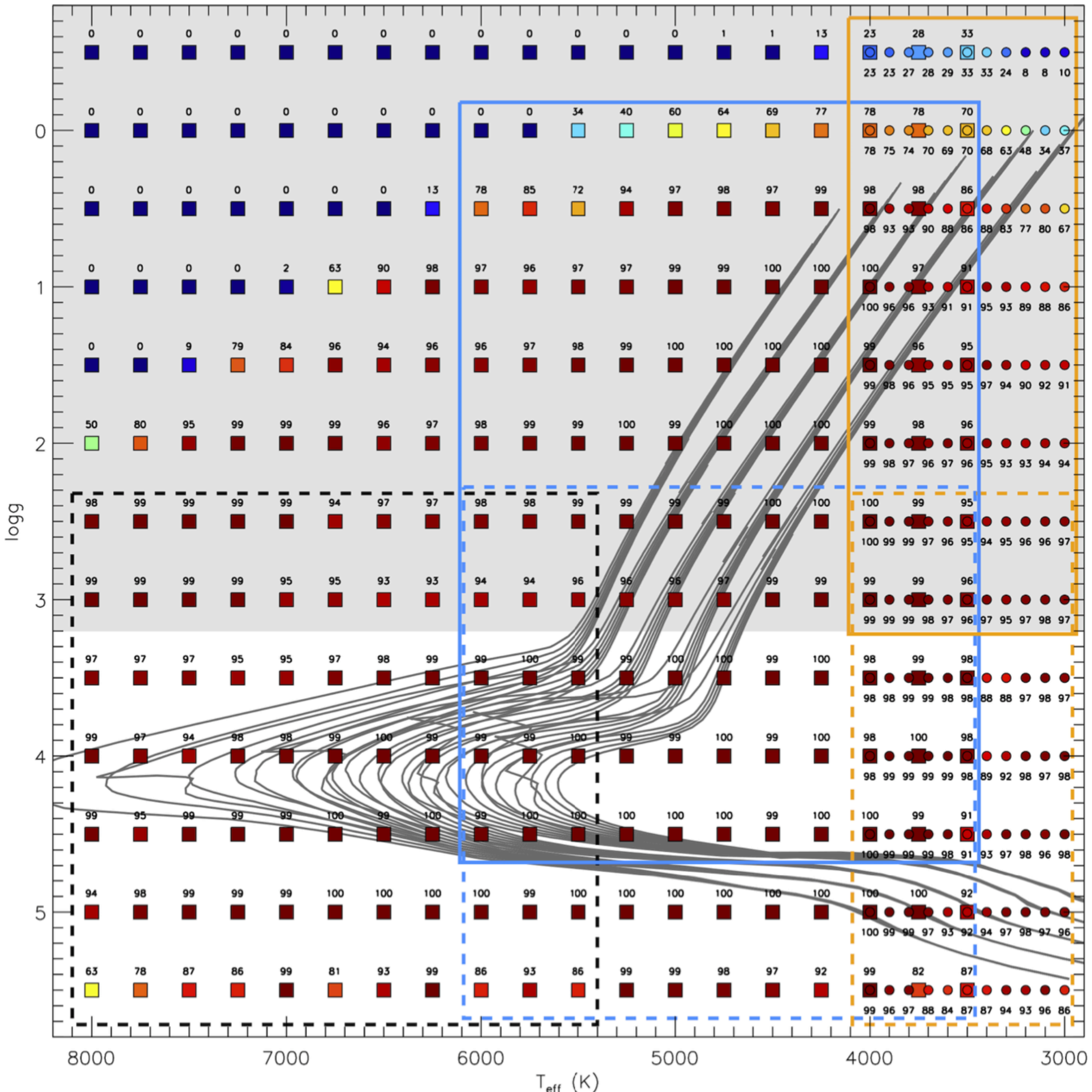
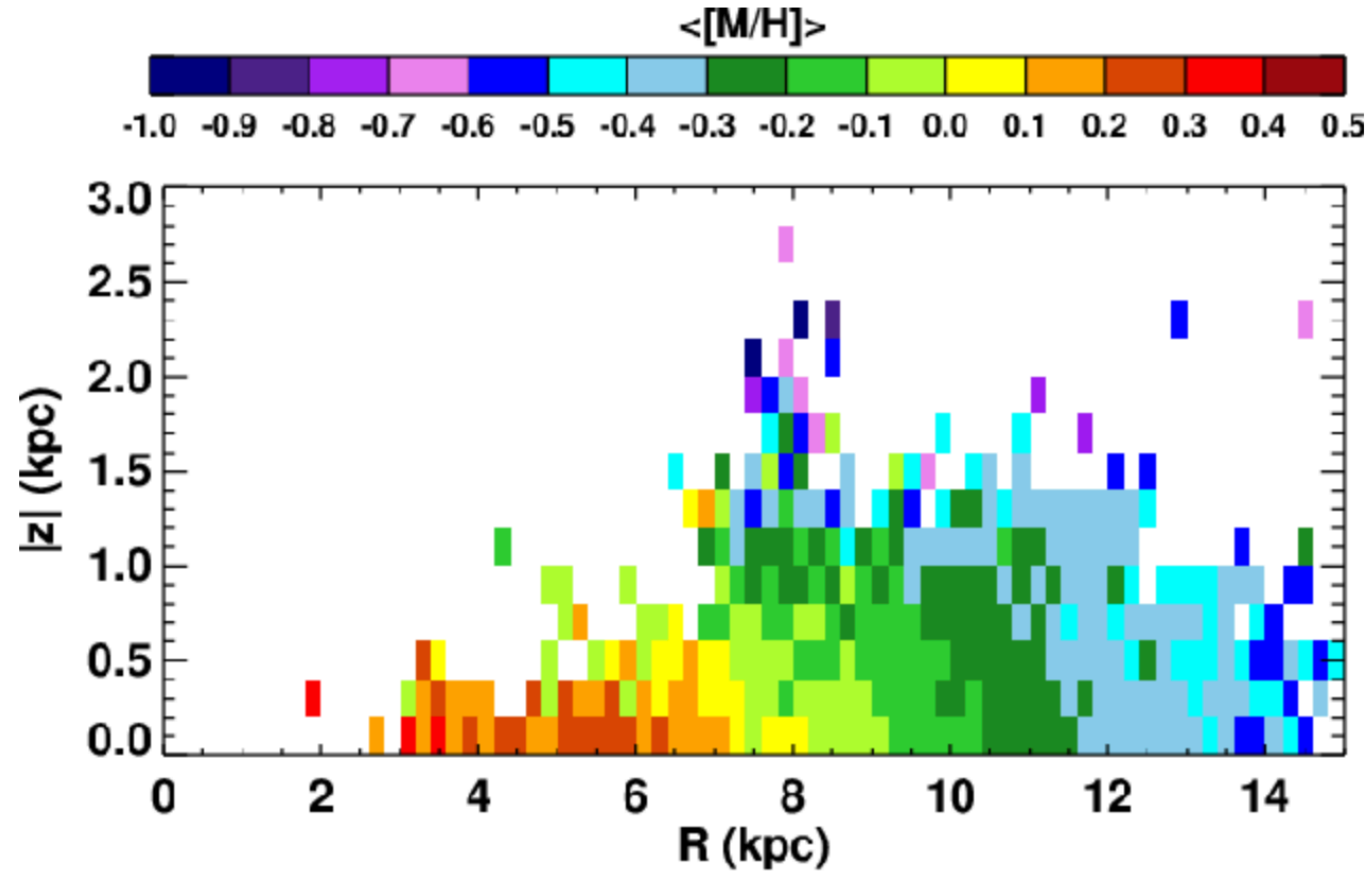
ASPCAP & APOGEE

Jönsson+2020





Hayden+2013

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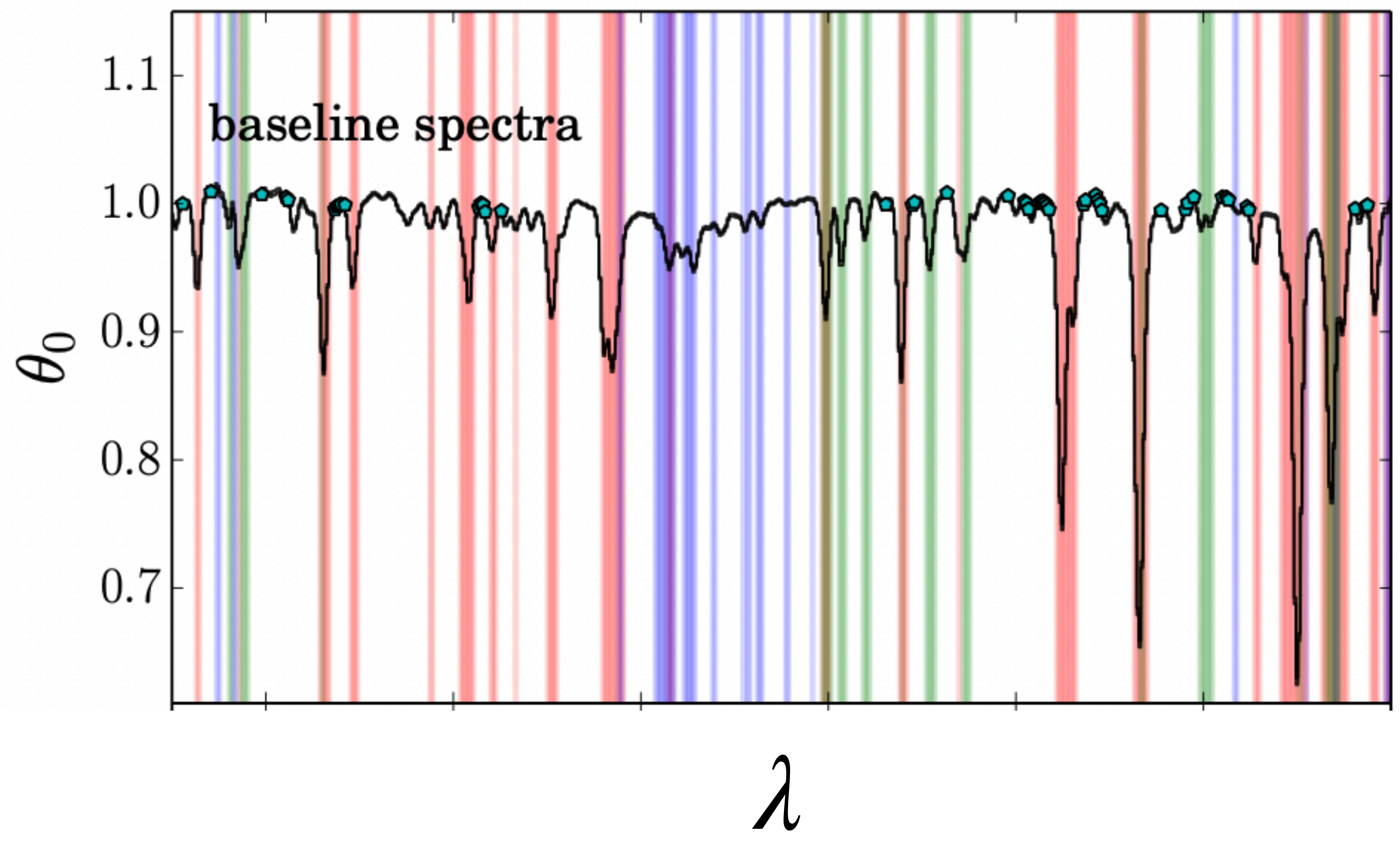
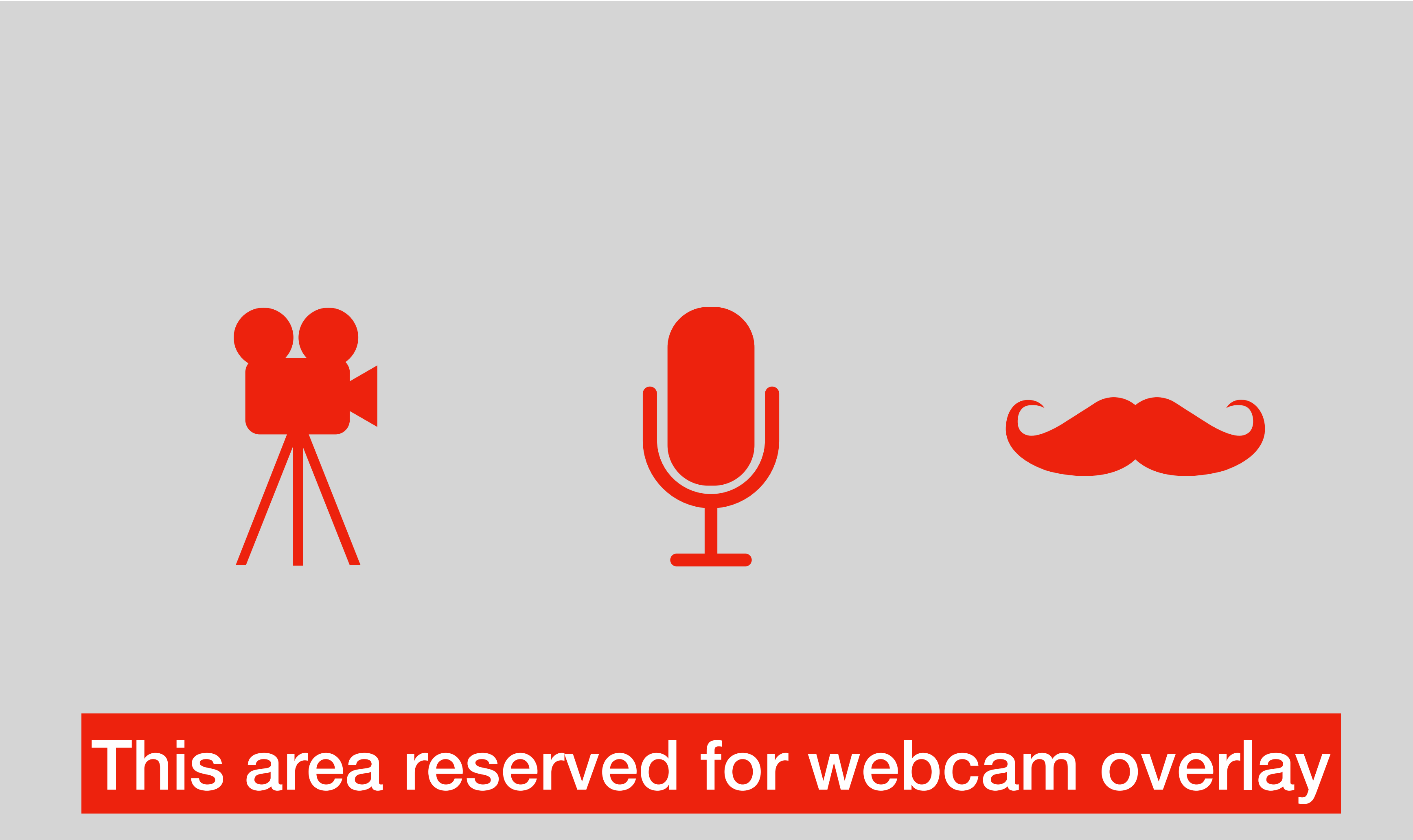
The Cannon

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)

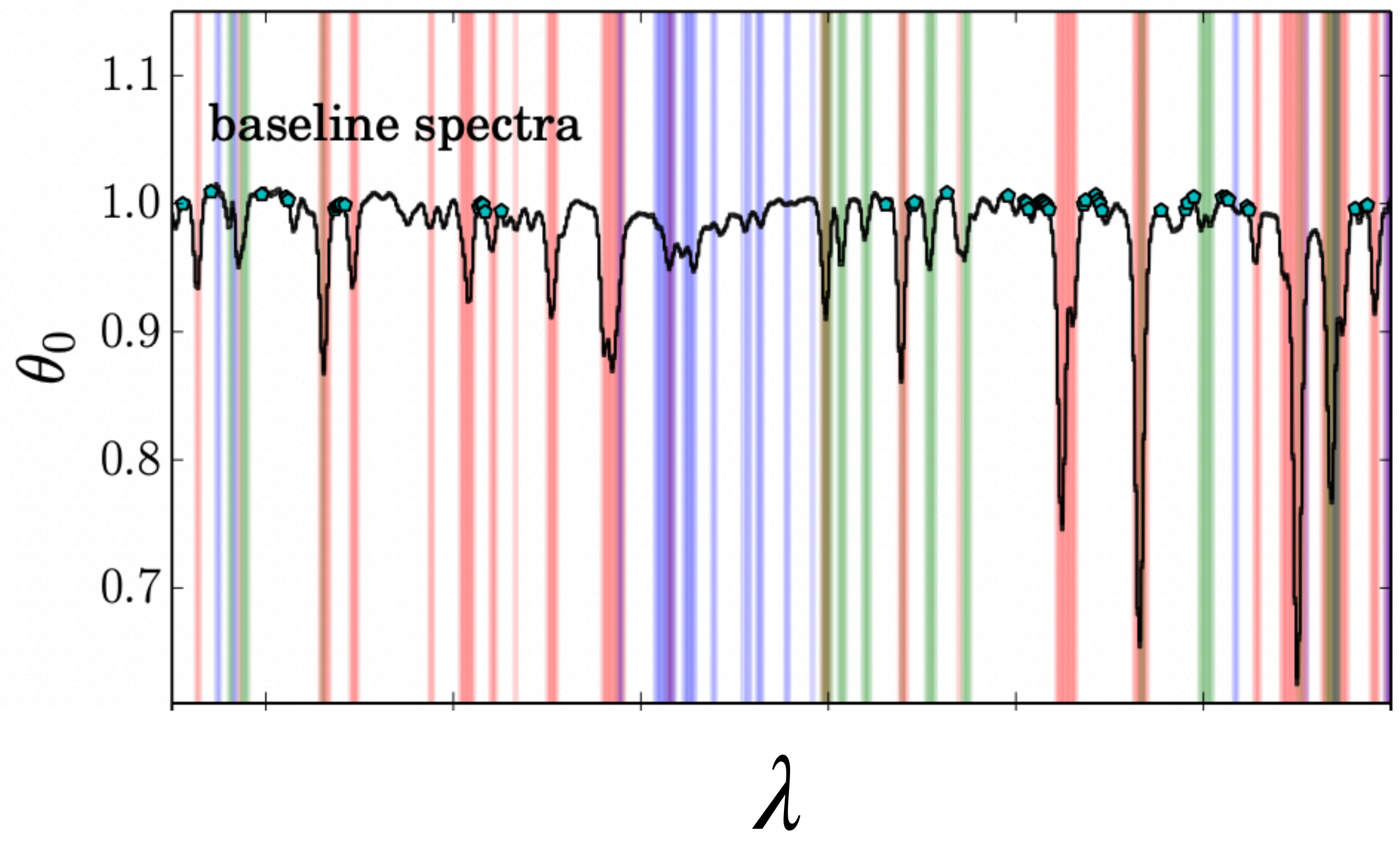


[Fe/H]
log g
Teff



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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