Yunnan/Beijing 2019

Stellar Atmospheres

Simon Jeffery
Armagh Observatory and Planetarium

3. Spectral Analysis

Programme

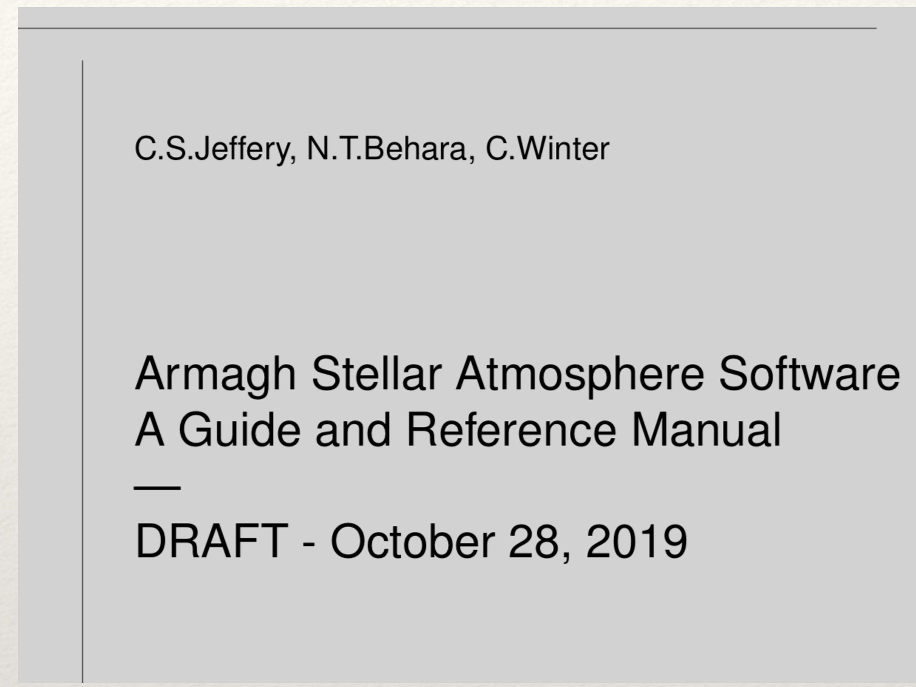
1. The Model Atmosphere
2. The Line Profile
3. Spectral Analysis

3. Spectral Analysis

1. Spectral classification
2. Spectral energy distribution (SED) fitting
3. Coarse analysis (for Teff, log g)
4. Fine analysis (for abundances)
5. Optimisation (χ^2, ANN, PCA, GA, …)
6. Errors

lte-codes
Armagh Stellar Atmospheres Software Collection

http://193.63.77.2:2805/~SJeffery/software_store/index.html

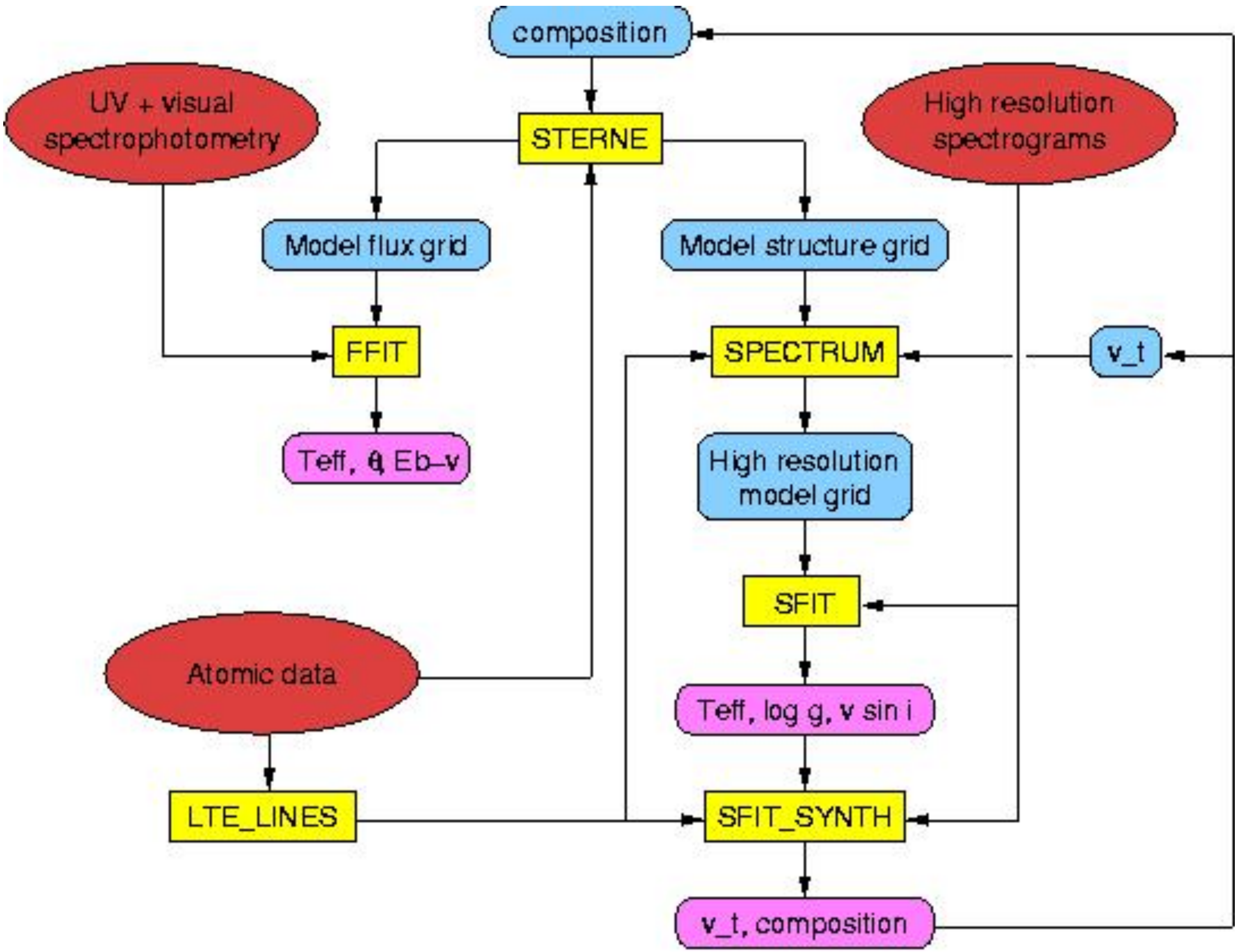

C.S.Jeffery, N.T.Behara, C.Winter

Armagh Stellar Atmosphere Software
A Guide and Reference Manual
—
DRAFT - October 28, 2019

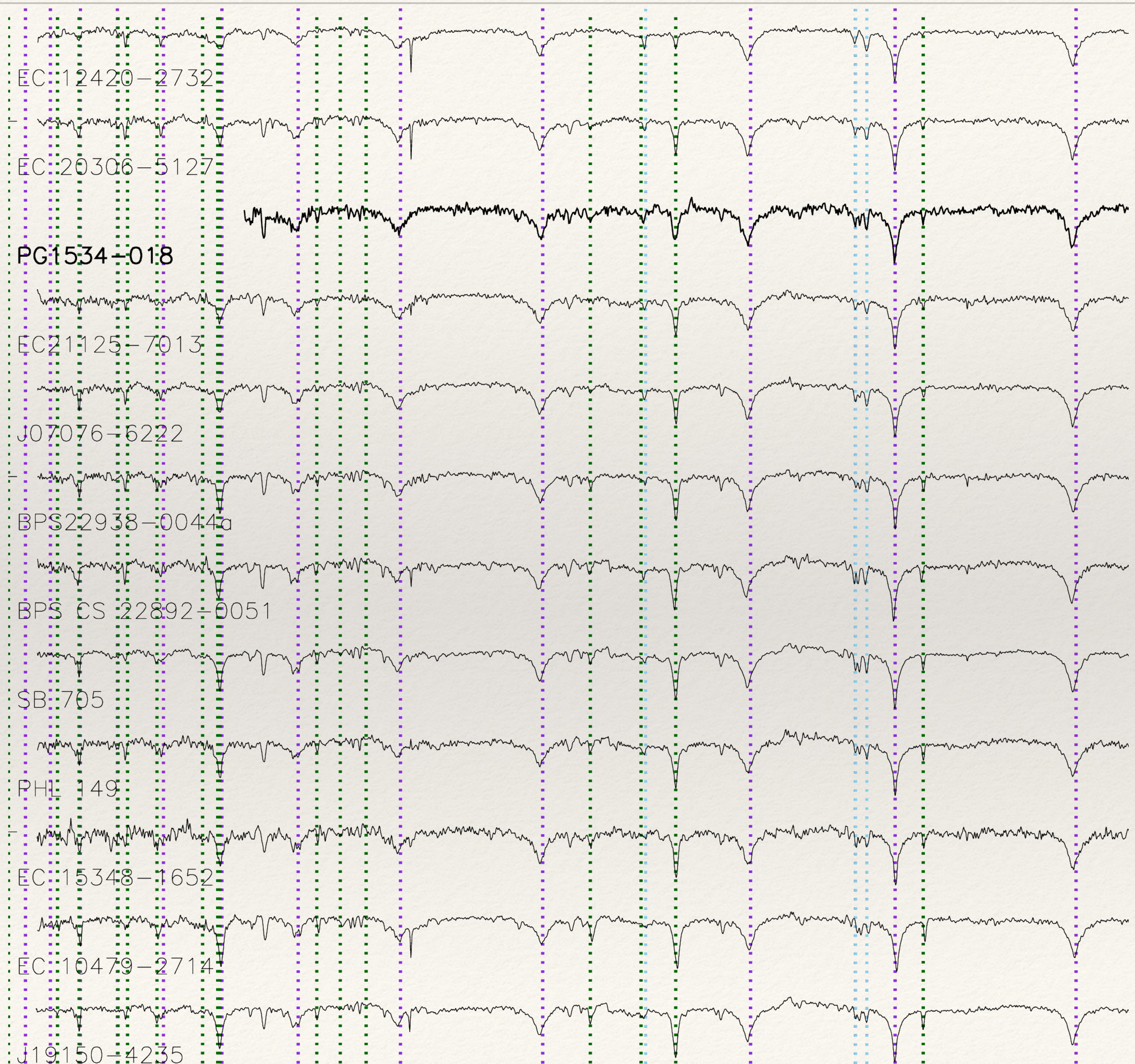
- sterne - model atmospheres
- spectrum - formal solutions
- ffit - optimization to fluxes
- sfit - optimization to spectra
- lte_lines - atomic data
- idlines - line identification and fit verification
- [isfit - interactive spectral fitting]

https://armaghop.sharepoint.com/sites/SJeffery/lte_codes/

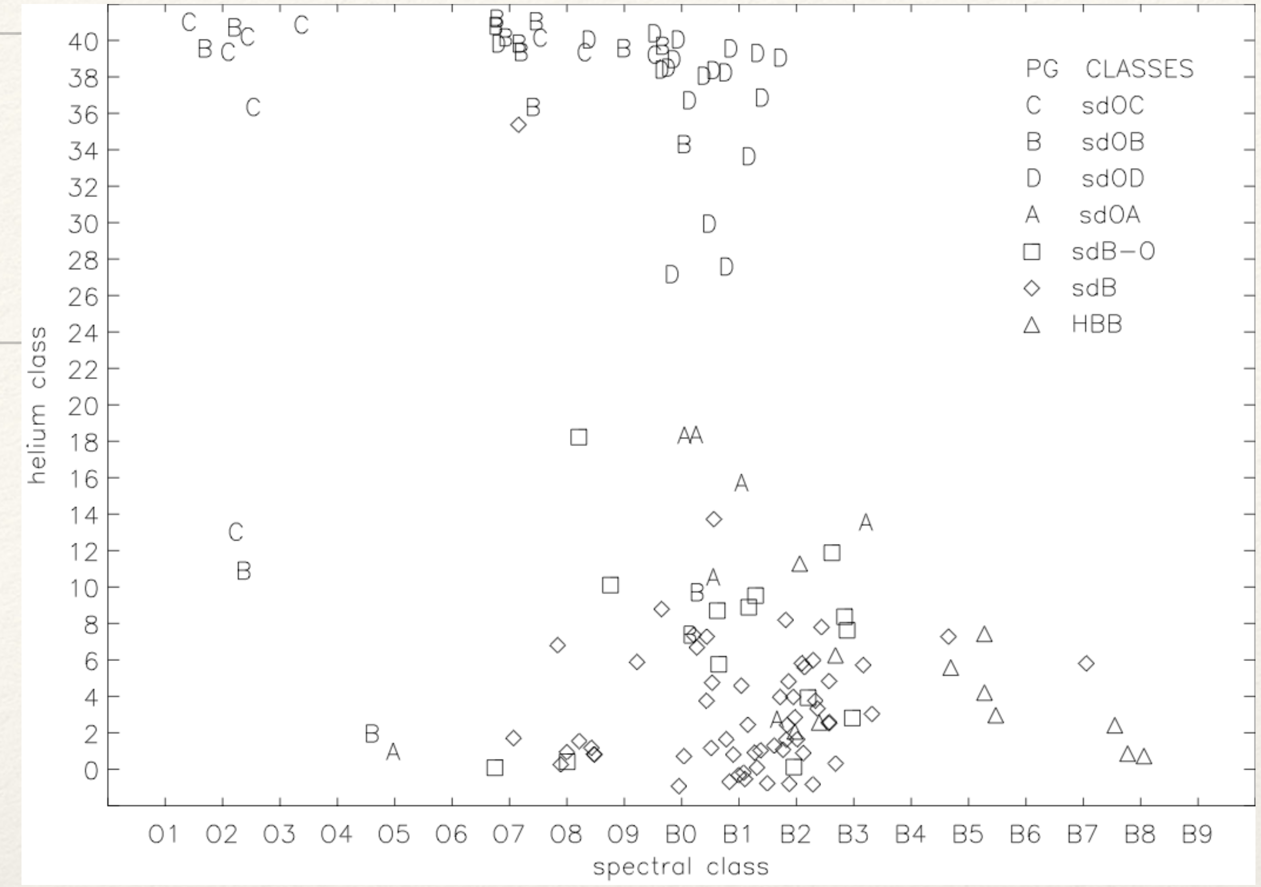
Stellar Atmospheres Software



3.1 Spectral classification

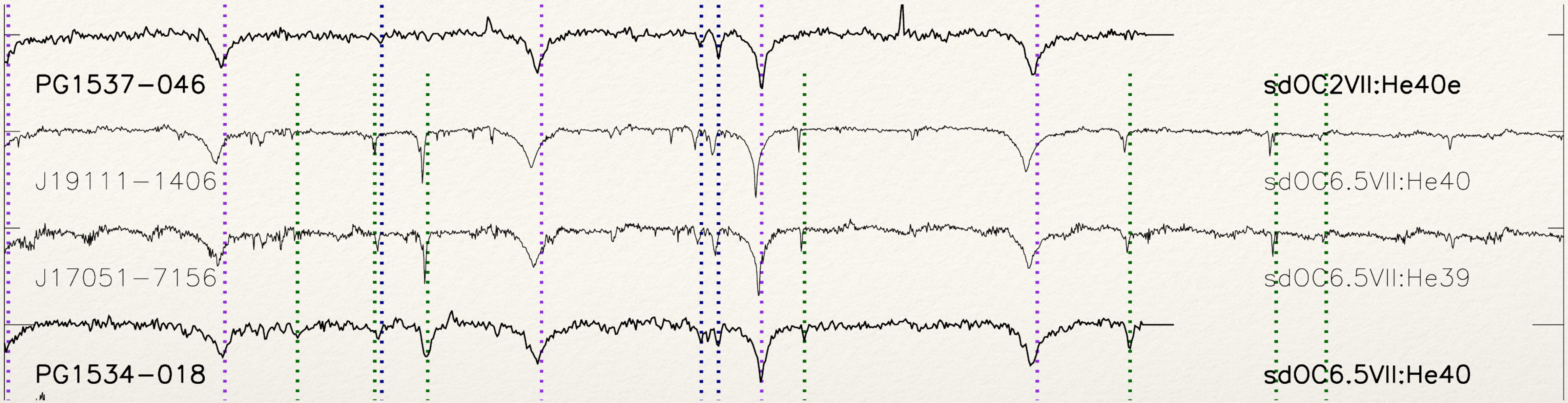


A plea for classification



- Adopt Drilling et al. 2013 subdwarf classifications
- Degrade spectra to classification resolution ~ 1 A
- Automate spectral type and helium class
- Eyeball luminosity class and carbon/nitrogen subtypes
- Cross-check with Drilling standards

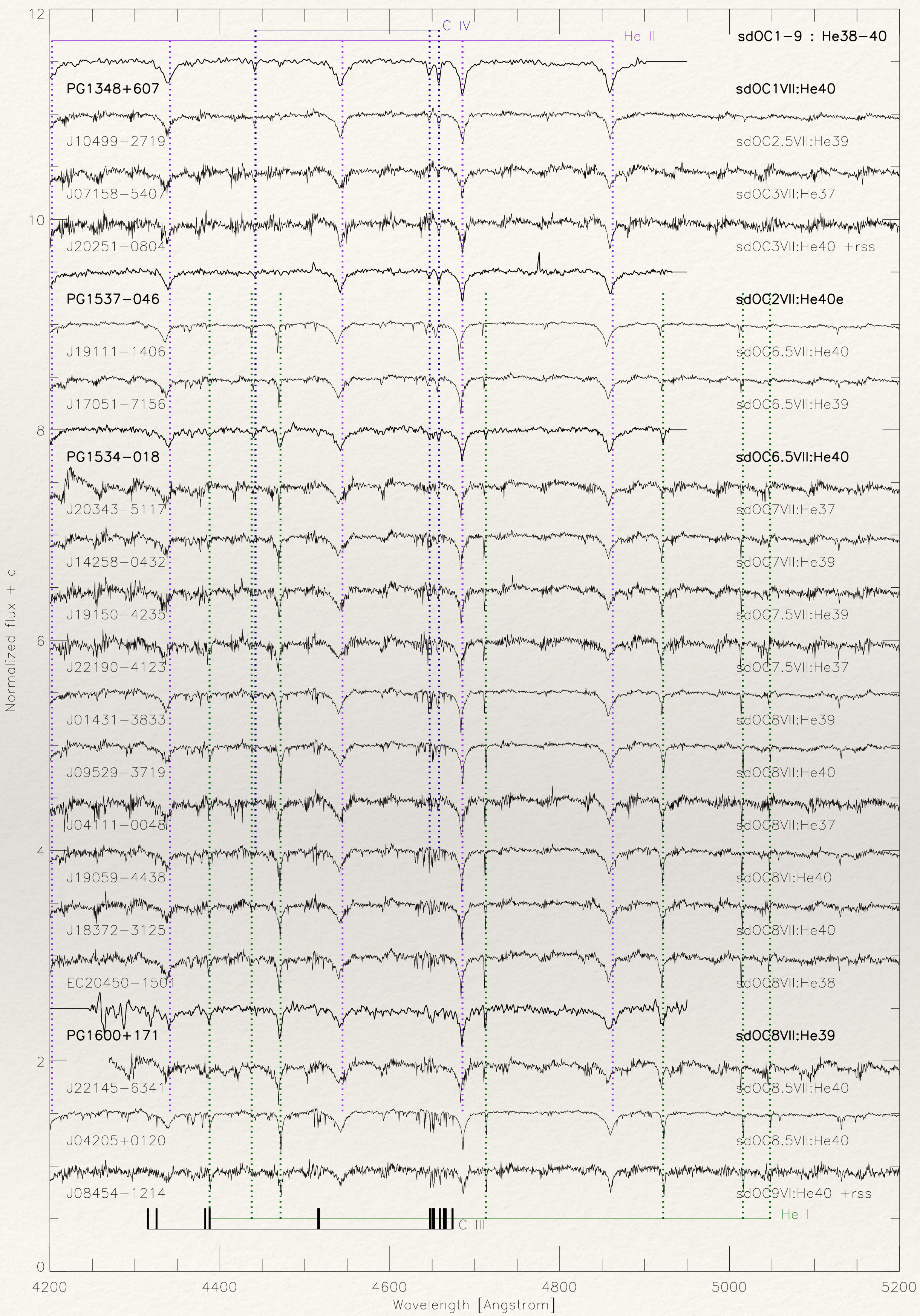
HRS


PG1537−046
sdOC2VII:He40e
J19111−1406
sdOC6.5VII:He40
J17051−7156
sdOC6.5VII:He39
PG1534−018
sdOC6.5VII:He40

RSS

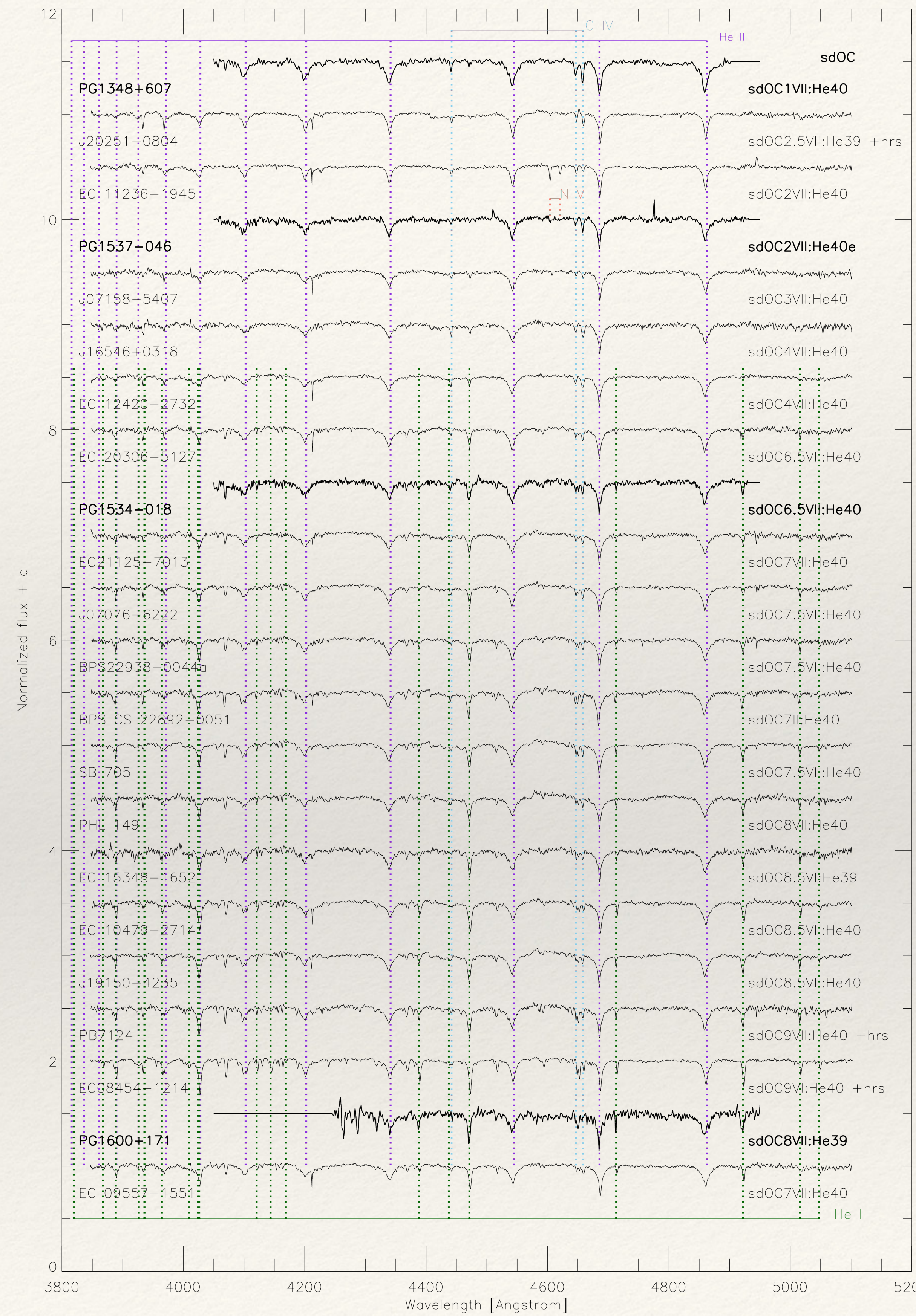

EC 12420−2732
sdOC4VII:He40
EC 20306−5127
sdOC6.5VII:He40
PG1534−018
sdOC6.5VII:He40
EC21125−7013
sdOC7VII:He40
J07076−6222
sdOC7.5VII:He40
BPS22938−0044a
sdOC7.5VII:He40

HRS



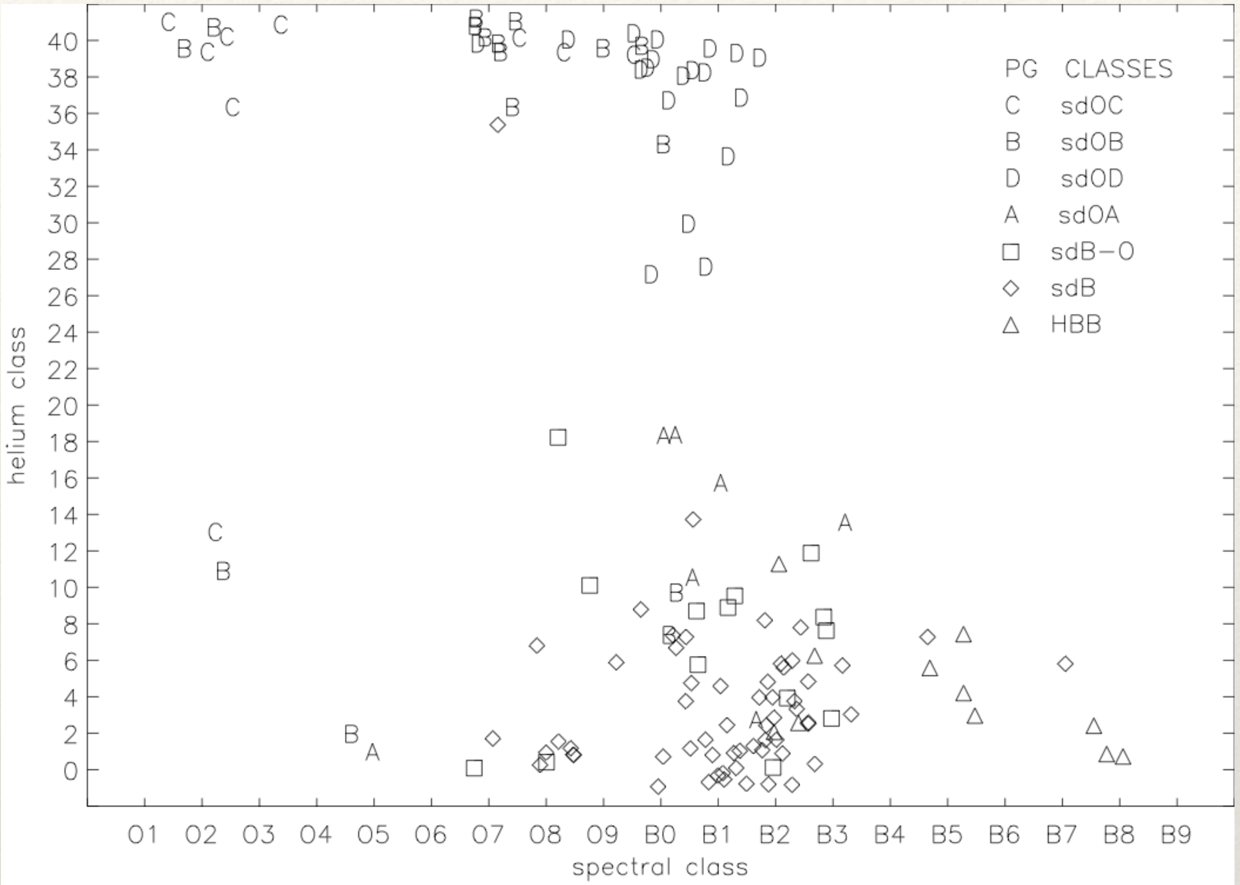
sdOC1−9 : He38−40
C IV
He II
PG1348+607
sdOC1VII:He40
J10499−2719
sdOC2.5VII:He39
J07158−5407
sdOC3VII:He37
J20251−0804
sdOC3VII:He40 +rss
PG1537−046
sdOC2VII:He40e
J19111−1406
sdOC6.5VII:He40
J17051−7156
sdOC6.5VII:He39
PG1534−018
sdOC6.5VII:He40
J20343−5117
sdOC7VII:He37
J14258−0432
sdOC7VII:He39
J19150−4235
sdOC7.5VII:He39
J22190−4123
sdOC7.5VII:He37
J01431−3833
sdOC8VII:He39
J09529−3719
sdOC8VII:He40
J04111−0048
sdOC8VII:He37
J19059−4438
sdOC8VI:He40
J18372−3125
sdOC8VII:He40
EC20450−1501
sdOC8VII:He38
PG1600+171
sdOC8VII:He39
J22145−6341
sdOC8.5VII:He40
J04205+0120
sdOC8.5VII:He40
J08454−1214
sdOC9VI:He40 +rss
He I
C III
Normalized flux + c
Wavelength [Angstrom]

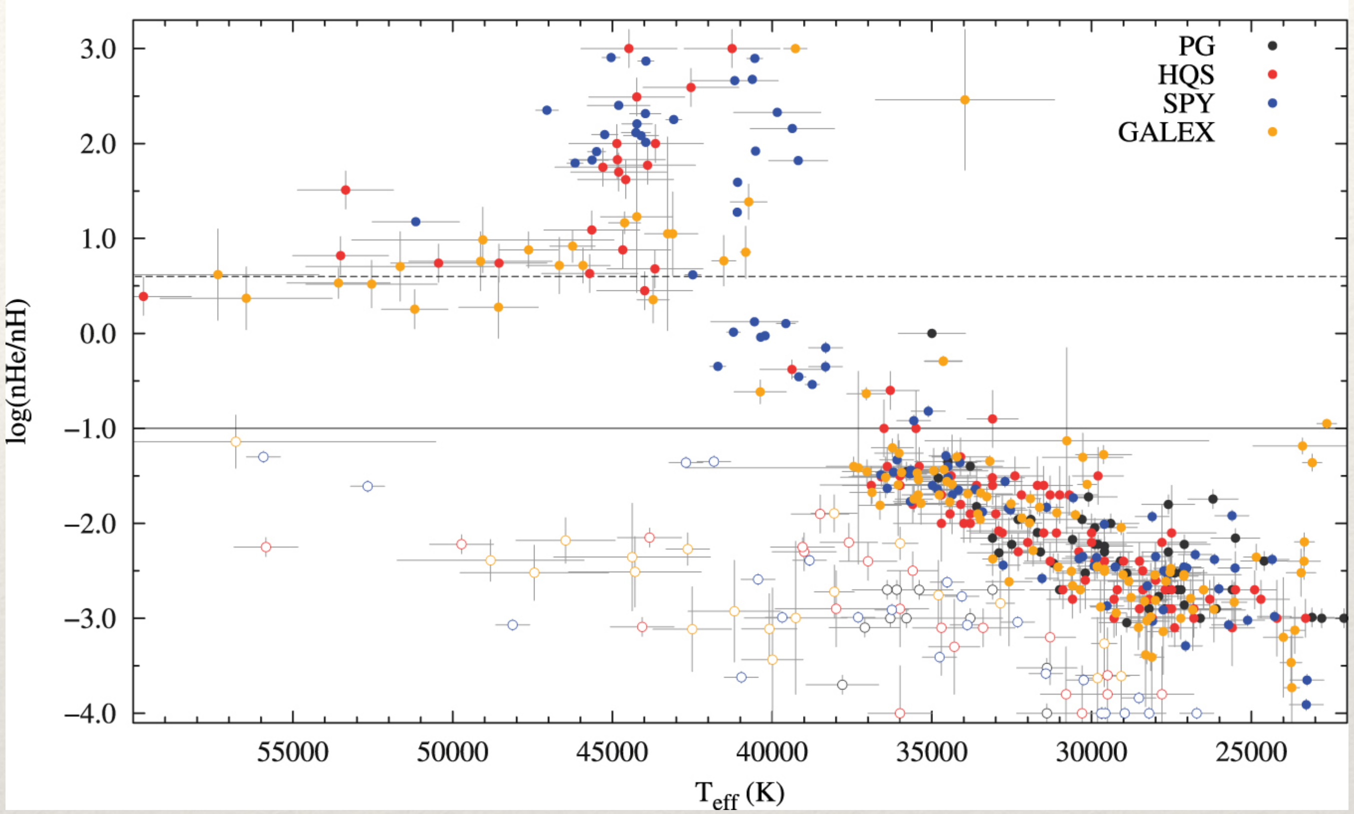
RSS



C IV
He II
sdOC
PG1348+607
sdOC1VII:He40
J20251−0804
sdOC2.5VII:He39 +hrs
EC 11236−1945
sdOC2VII:He40
N V
PG1537−046
sdOC2VII:He40e
J07158−5407
sdOC3VII:He40
J16546+0318
sdOC4VII:He40
EC 12420−2732
sdOC4VII:He40
EC 20306−5127
sdOC6.5VII:He40
PG1534−018
sdOC6.5VII:He40
EC 21125−7013
sdOC7VII:He40
J07076−6222
sdOC7.5VII:He40
BPS22938−0044a
sdOC7.5VII:He40
BPS CS 22892−0051
sdOC7II:He40
SB 705
sdOC7.5VII:He40
PHL 149
sdOC8VII:He40
EC 15348−1652
sdOC8.5VII:He39
EC 10479−2714
sdOC8.5VII:He40
J19150−4235
sdOC8.5VII:He40
PB7124
sdOC9VII:He40 +hrs
EC08454−1214
sdOC9VI:He40 +hrs
PG1600+171
sdOC8VII:He39
EC 09557−1551
sdOC7VII:He40
He I
Normalized flux + c
Wavelength [Angstrom]

A plea for classification





1. If you know the spectral type with sufficient precision, you may not need to analyse the spectrum!

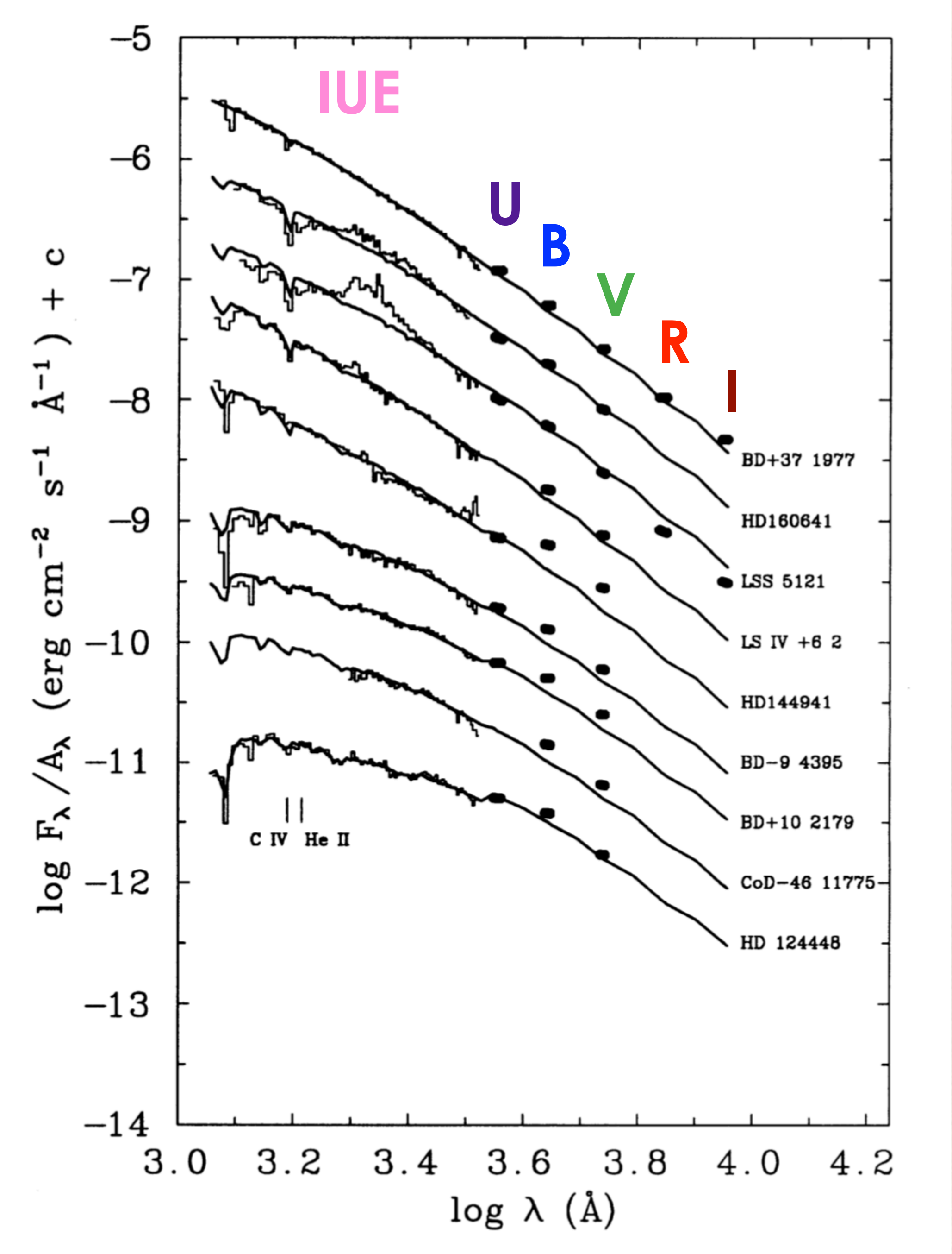
2. The spectral type is defined entirely by standards, not models. If models change, $T_{\rm eff}$, g, change, **Sp** does not.

3.2 SED fitting

Good for T_{eff}, θ.

Essential for measuring luminosities from Gaia distances.

Requires precise photometry with large wavelength coverage (and knowledge of whether variable!).



SED fitting recipe

- Gather photometric data (fluxes, magnitudes, …) *with errors*.
- Where necessary convert magnitudes to flux units ($\boldsymbol{F_{\lambda i}}$). *Propagate errors* ($\boldsymbol{\delta F_{\lambda i}}$).
- Collect theoretical SEDs for fit ($f_{\lambda i}$). Resample to same wavelength bins as $\boldsymbol{F_{\lambda i}}$. Where necessary, convolve SEDs with photometric filter functions.
- Estimate E_{B-V}, deredden observed fluxes using appropriate reddening law (**OR** redden theoretical fluxes … equivalent). *Propagate errors.*
- Estimate T_{eff}, normalise theoretical SED to observed SED (either globally or at a fixed wavelength). The normalisation factor is θ^2.
- Compute $\chi^2 = \Sigma_i \left(\frac{F_{\lambda i} - f_{\lambda i}}{\delta F_{\lambda i}} \right)^2 / \Sigma_i \left(\frac{1}{\delta F_{\lambda i}} \right)^2$
- Adjust T_{eff} until χ^2 minimized. Several algorithms for optimising χ^2.
- Works for binary stars as well.

lte_codes: ffit

- 2019.China.DEMO/FLUXES/IUE_fit

  IDL script combines 2 IUE spectra to form j0825_merged.dat

  ffit < j0825_fine.ffit

    Reads small grid of SEDs

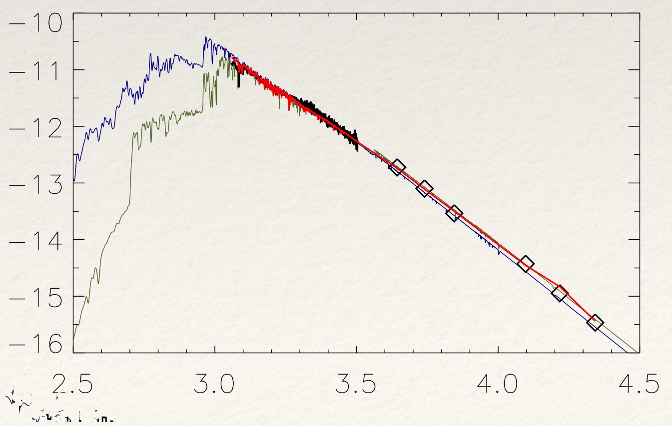
    Defines wavelengths and filter bands for fit

    Initialises parameters

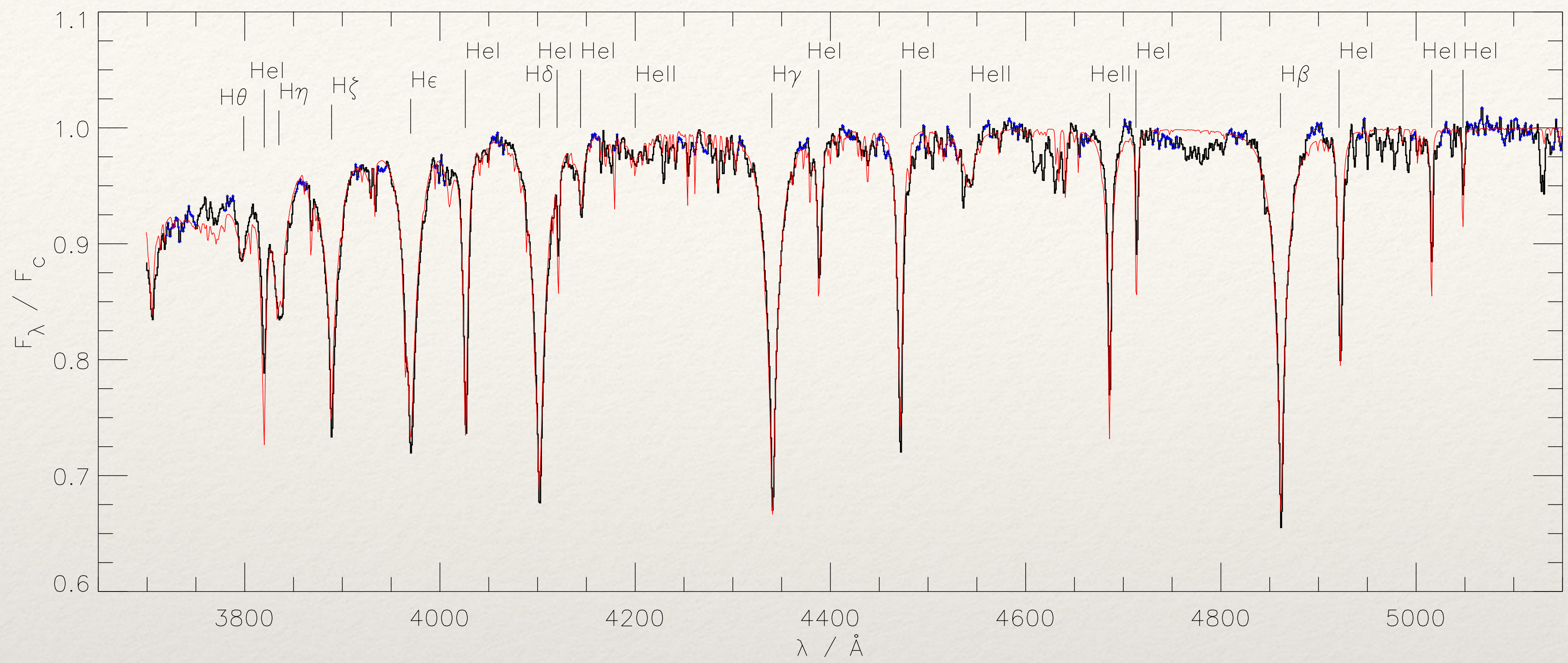
    Reads IUE data and visual/IR magnitudes

    Optimizes solution

  IDL script plots best fit



3.3 Coarse Analysis



Good for: T_{eff}, g, **[He/H], [Fe/H]**, $v_{\mathbf{rad}}$

Requires well-calibrated spectrum covering sufficient well-resolved lines sensitive to the parameters of interest.

Potentially good for analysing large numbers of similar spectra from a single instrument.

Coarse analysis recipe

- Assess spectra (e.g. right star? classification, S/N, normalisation, resolution, bad pixels / gaps).
- Remove instrumental response and normalise to "continuum" $S_\lambda = F_\lambda / F_\mathrm{c}$
- Measure radial velocity $v_\mathbf{rad}$ relative to lab frame and LSR. Record both!!!
- Collect a grid of theoretical spectra s_λ(T_eff, **log** g, **He/H***) appropriate for your stars.
- For each spectrum S_λ, estimate T_eff, **log** g, **He/H.**
  - Extract s_λ from model grid (interpolate or use nearest model).
  - Resample to same wavelength bins as $S_{\lambda i}$.
  - Convolve with instrumental profile
  - Apply $v_\mathbf{rad}$
  - Compute

$$\chi^2 = \Sigma_i \left(\frac{S_{\lambda i} - s_{\lambda i}}{\delta S_{\lambda i}} \right)^2 / \Sigma_i \left(\frac{1}{\delta S_{\lambda i}} \right)^2$$

- Adjust T_eff, **log** g, **He/H,** v **sin** i until χ^2 optimised.
- Check continuum good enough, otherwise renormalise and repeat.
- Works for binary stars as well.

* Fe/H may be a more appropriate grid dimension

Coarse analysis: warnings

- Normalisation
- Automatic normalisation ?
- Parameter correlation

lte_codes: sfit

- 2019.China.DEMO / LORES / ALFOSC_fit

  # — define basic grid
  sfit.csh sdb_alfosc_grid.sfit

  # — solve with basic grid
  sfit.csh sdb_alfosc_solve.sfit

  # — plot result
  …
  # — copy output of first fit with renormalisation
  cp j0825_alfosc.sp2 j0825_alfosc_fine.sp2

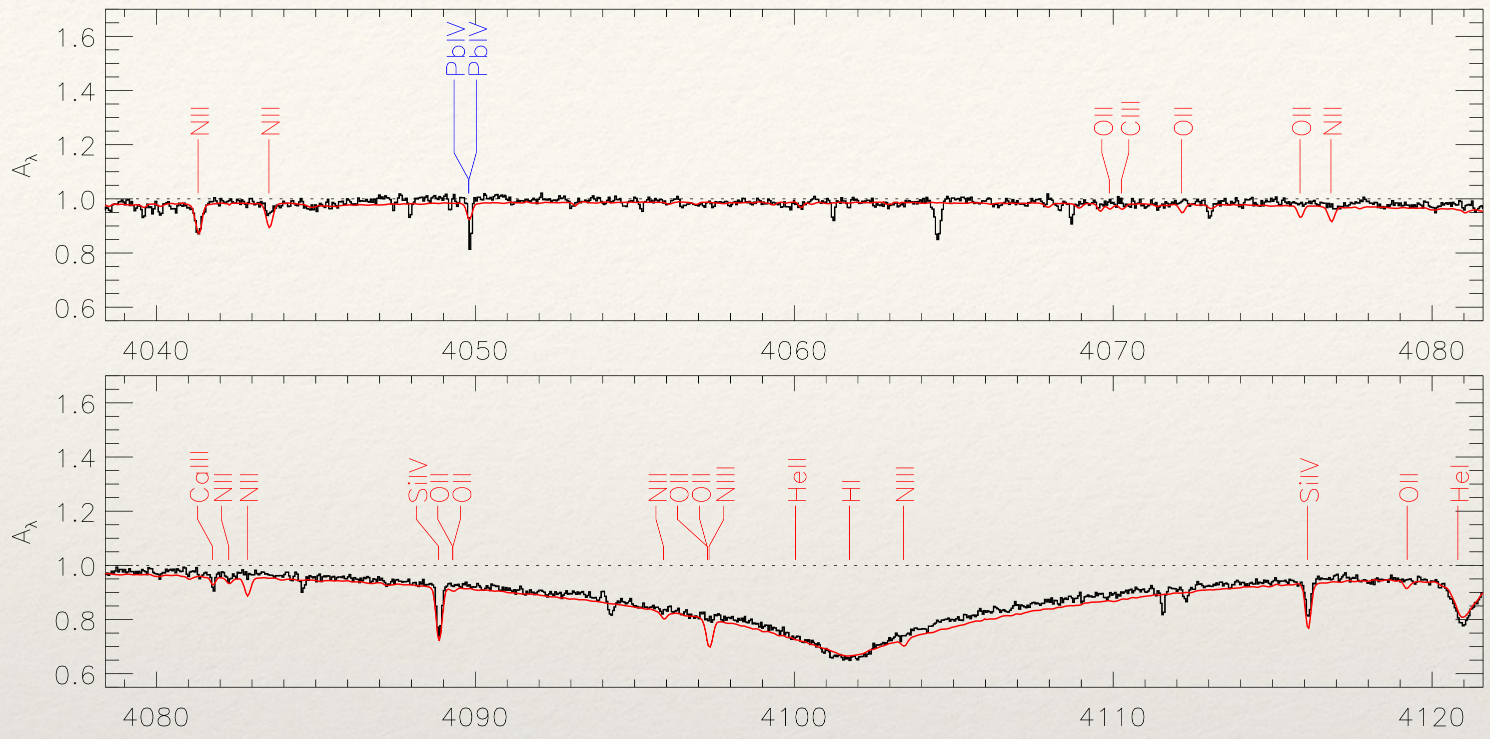
  # — define fine grid
  sfit.csh sdb_alfosc_fine.sfit

  # — run sfit to get best effective temperature
  Sfit.csh cw83_alfosc_solve.sfit

  # — plot result
  …

```
! Version 1 - 2016 April - coarse grid
read_grid sdb_alfosc.grd

method_levenburg            ! Levenburg-Marquardt optimisation
method_range  3700 5150
method_tolerance 0.001.   ! convergence criterion

data_spectrum j0825_alfosc.sp2      ! file name
data_sigma 0.01                     ! average error on each datum
data_instrument 1.0                 ! instrumental profile FWHM (Angstroms)
data_cosmic 1.1                     ! threshold for cosmic ray rejection

! Define continuum windows
crs 3680 3682
crs 3720 3750
crs 3780 3789
…
crs 5140 5150

fix_vsini1 0.0
fix_vrad1  12.0
fix_ahe1  0.3
fix_teff1 30.0
fix_logg1 6.0

cont_filter 200   !  Don't 'overnormalise'
normalise

fix_vsini1 0.0  10.
slv_vrad1  08.0  10.
fix_ahe1  0.15        !! version 1 - coarse grid
slv_teff1 42.0  2.
slv_logg1 6.2 0.3
solve

slv_ahe1  0.15 0.1        !! version 1 - coarse grid
slv_teff1
slv_logg1
solve

normalise
solve

normalise
solve

end
```

3.4 Fine Analysis



Good for: T_{eff}, g, [He/H], [Fe/H], n_i, v_{rad}, $v \sin i$, v_{turb}, …

Requires well-calibrated spectrum covering sufficient well-resolved lines sensitive to the parameters of interest.

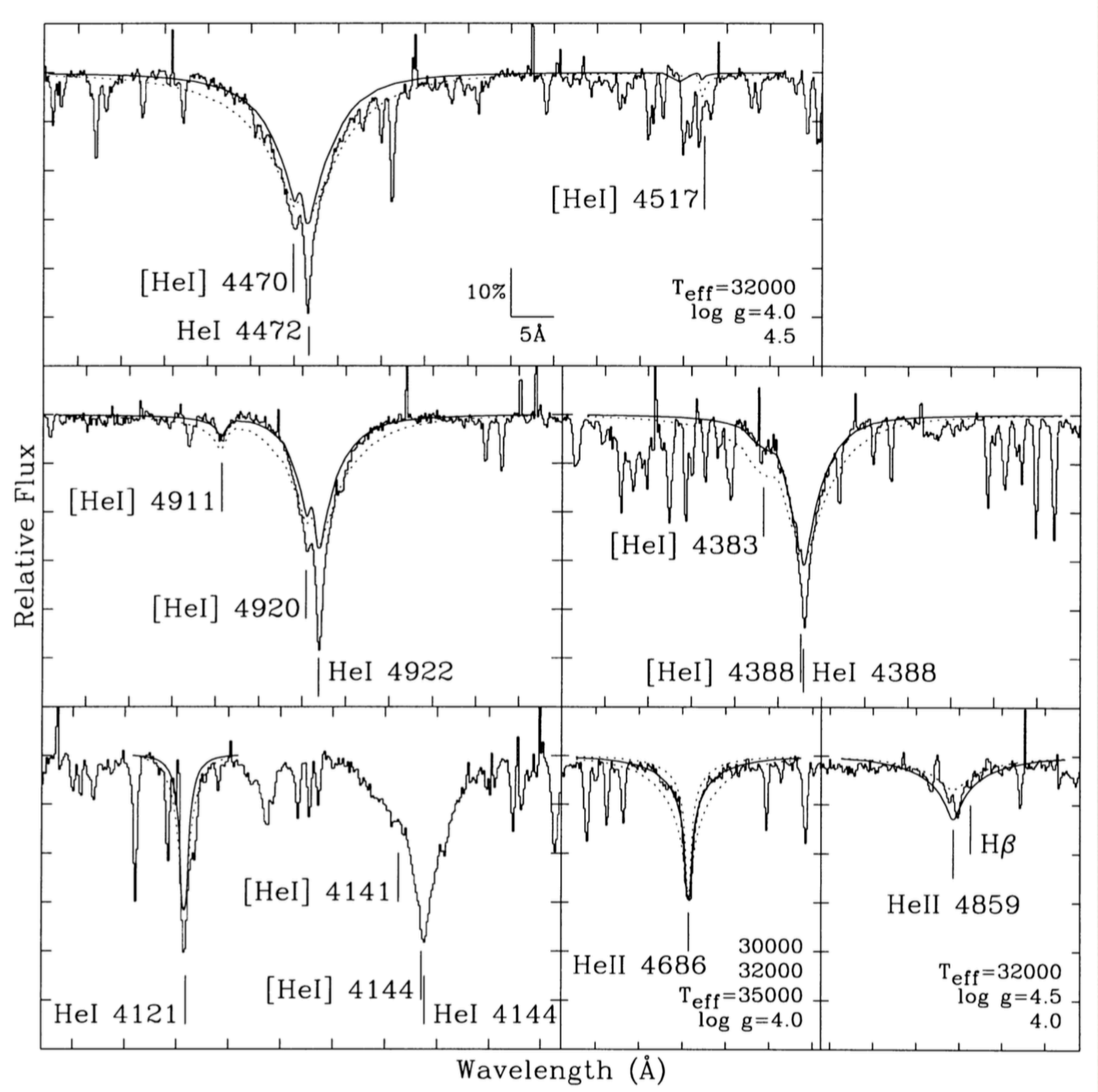
Generally time consuming, unless analysing a restricted set of lines in a sample of very similar spectra.

Fine analysis recipe

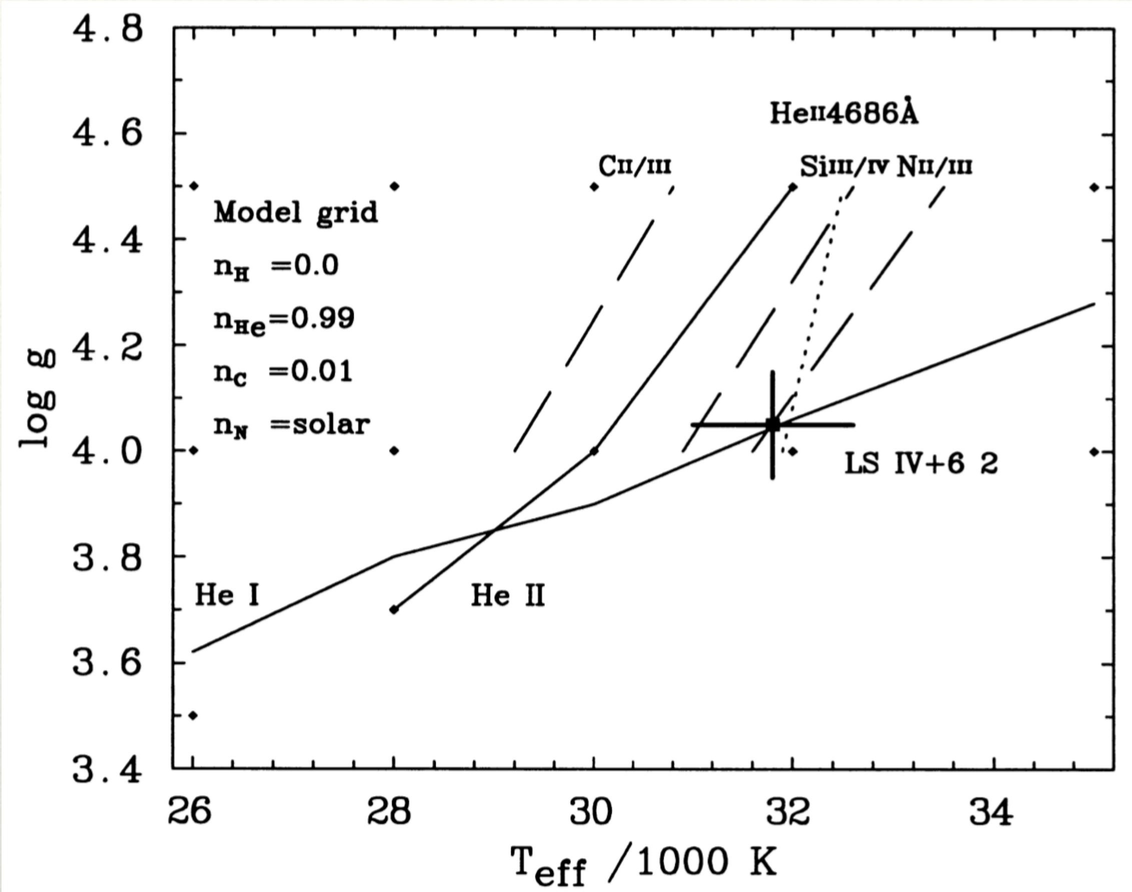
- *Assuming* an initial surface composition, n_{i0} (e.g. solar:), one *may* commence exactly as for Coarse Analysis to determine an initial $T_{\rm eff}$, **log** g, **He/H,** v **sin i.**
- Having an initial result for principal parameters, or otherwise, identify as many lines as possible (idlines).
- Two approaches are then possible:
  - I. Line-by-line analysis
  - II. Spectrum synthesis
- Both give abundances for each element n_i, *in addition to* $T_{\rm eff}$, **log** g, v **sin i.**
- IF $n_i \neq n_{i0}$: recompute model atmosphere grid for new composition and repeat analysis.

Fine analysis I: line-by-line

- Assuming 'Coarse Analysis' not done
- For elements with gravity-sensitive lines, compute line profiles for fixed T_{eff} and several g, compare with observed profiles, and find $g(T_{eff})$ for each line.



Fine analysis I: line-by-line

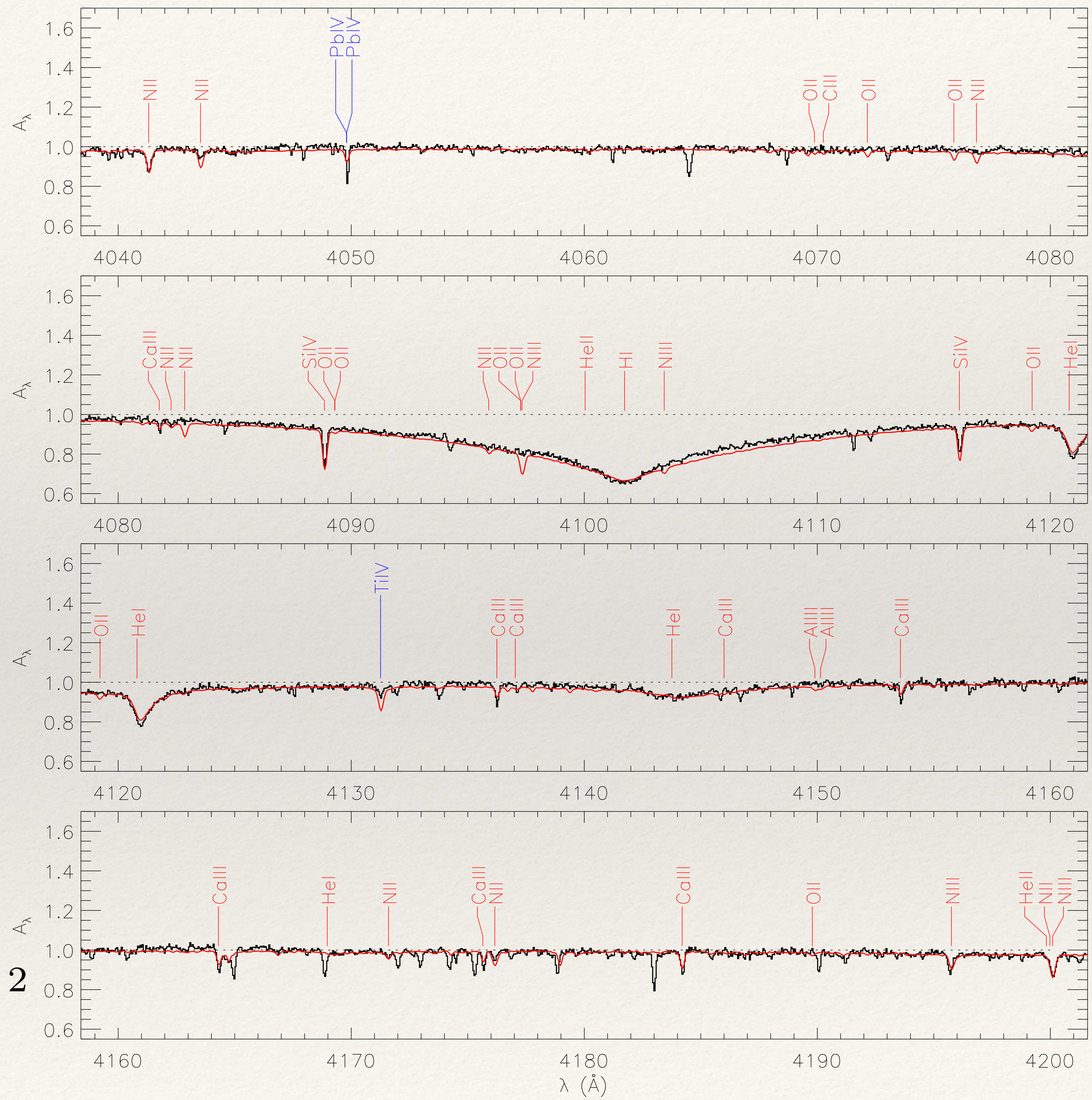


- Measure equivalent widths W_λ for key lines.
- For species with > 1 ionisation stage, or for species with wide range of lower-level excitation potentials:
- For multiple $T_{\rm eff}$, g, compute abundance n_{ijk} from W_λ
- For element i (eg carbon) construct $<n_{ij}>$ and $<n_{ij+1}>$ and compare for fixed g and several $T_{\rm eff}$, to find ionisation equilibrium $T_{\rm eff}(g)$. Repeat for other elements.
- Determine best values for $T_{\rm eff}$ and g satisfying above criteria.
- Compute 'final' model atmosphere with $T_{\rm eff}$, g and n_{i0}
- Compute all n_i from W_λ

Fine analysis II: synthesis

- Compute model atmosphere with $T_{\rm eff}$, g, **He/H**, from coarse analysis and n_{i0}
- Compute synthetic spectrum s_λ with n_{i0}
- Adjust n_i, $v \sin i$, v_{turb}, to minimise

$$\chi^2 = \Sigma_i \left(\frac{S_{\lambda i} - s_{\lambda i}}{\delta S_{\lambda i}} \right)^2 / \Sigma_i \left(\frac{1}{\delta S_{\lambda i}} \right)^2$$



Fine analysis recipe

- *Assuming* an initial surface composition, $\boldsymbol{n_{i0}}$ (e.g. solar:), one *may* commence exactly as for Coarse Analysis to determine an initial $T_{\rm eff}$, **log** $\boldsymbol{g}$**, He/H,** $\boldsymbol{v}$ **sin i.**
- Having an initial result for principal parameters, or otherwise, identify as many lines as possible (idlines).
- Two approaches are then possible:
  - I. Line-by-line analysis
  - II. Spectrum synthesis
- Both give abundances for each element $\boldsymbol{n_i}$, *in addition to* $T_{\rm eff}$, **log** $\boldsymbol{g}$**,** $\boldsymbol{v}$ **sin i.**
- IF $n_i \neq n_{i0}$: recompute model atmosphere grid for new composition and repeat analysis.

Fine analysis: warnings

- Its hard !

lte_codes: sfit

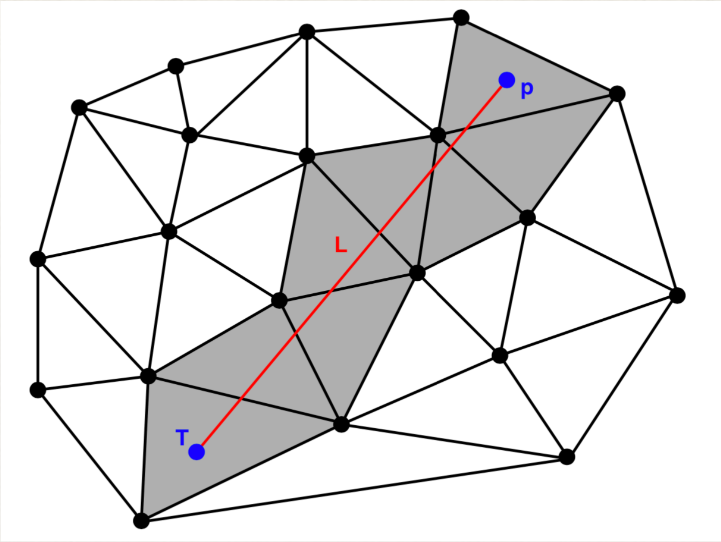
- 2019.China.DEMO/HIRES/SUBARU_fit

```
# Set up the fine high-resoluton grid
# Sfit.csh sdb_subaru_fine.sfit

# Run Sfit in solve mode
Sfit.csh j0825_subaru_solve_fine.sfit

# Second iteration ... NHe fixed -- but better models for the normalisation
Sfit.csh j0825_subaru_solve_fine.sfit

# Print with idlines
# not optimal ... eps file not good for multipages
idl <<%%%
atoms=[1,2,6,7,8,10,12,13,14,16,18,22,38,39,40,82]
idlines,'J0828.cr.merge.bin.sp2.fit','j0825_eqwids.000',3600,5150,50,
[0.45,1.60],atoms,.002,50,/fit,/ew,/quad,/print
%%%
mv idlines.eps j0825_solve_idlines.eps
open j0825_solve_idlines.eps

# Copy renormalised output to an sp2 file  -- use dipso
# ... opportunity to remove the bad regions.
rm  J0828.cr.merge.bin.renorm.sp2
dipso <<%%%
…
%%%

# Run Sfit in synth mode# This is where abundances would be solved for, 2 or
3 at a time.
Sfit.csh j0825_subaru_synth.sfit  gf_subaru.lte

# Run Spectrum in line-mode to get list of equivalent widths
# Edit the ".spc" file to give better abundances
Spectrum.sh  ../h80he20xxx/t390g600xxx.q gf_subaru.lte j0825_ewcalc_vt02.spc
j0825_eqwids
rm j0825_eqwids.fcon. j0825_eqwids.flux

# Calculates a HIRES formal solution
Spectrum.sh  ../h80he20xxx/t390g600xxx.q gf_subaru.lte j0825_formal.spc
j0825_formal
```

3.5 Optimisation

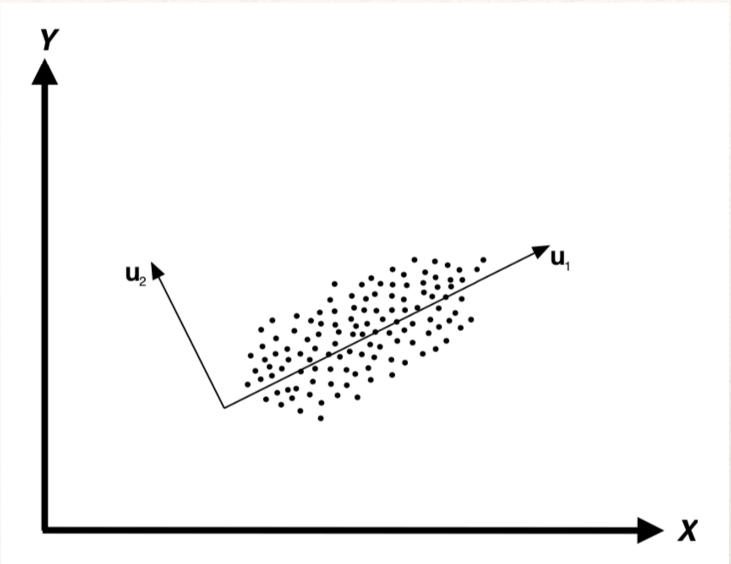
$$\chi^2 = \Sigma_i \left(\frac{S_{\lambda i} - s_{\lambda i}}{\delta S_{\lambda i}}\right)^2 / \Sigma_i \left(\frac{1}{\delta S_{\lambda i}}\right)^2$$

- Minimise χ^2 (p_i, $i=1,\ldots,n$)
- Model grids s_λ ($T_{\rm eff}$, **log g, He/H**)
  - Regular
  - Irregular - Delauney tetrahedralization
- Spectrum 'synth' on the fly s_λ (n_i, $v_{\rm turb}$, **v sin i**)
- Optimisation options
  - Downhill simplex (amoeba)
  - Levenburg-Marquardt (χ^2 differentiable)
  - Genetic algorithm



Automation

- Artificial Neural Networks
- Principal Components Analysis



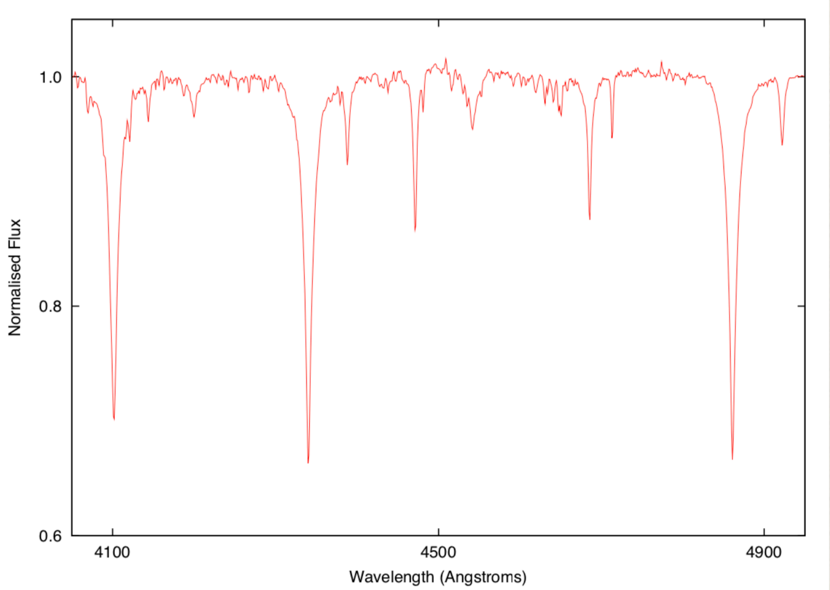


Figure 4.2: Mean spectrum of the Drilling et al. (2006) sample.

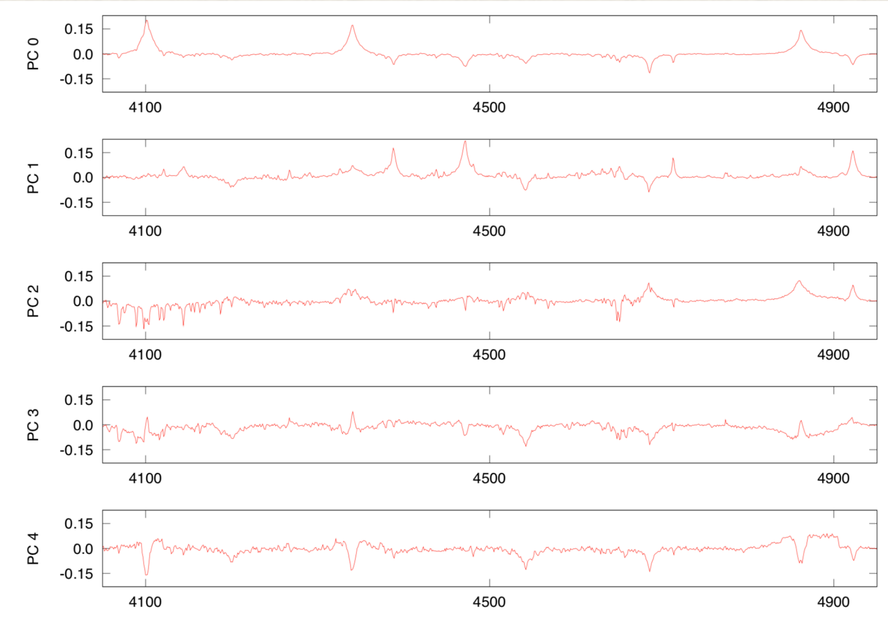


Figure 4.3: First five PCs of the Drilling et al. (2006) sample.

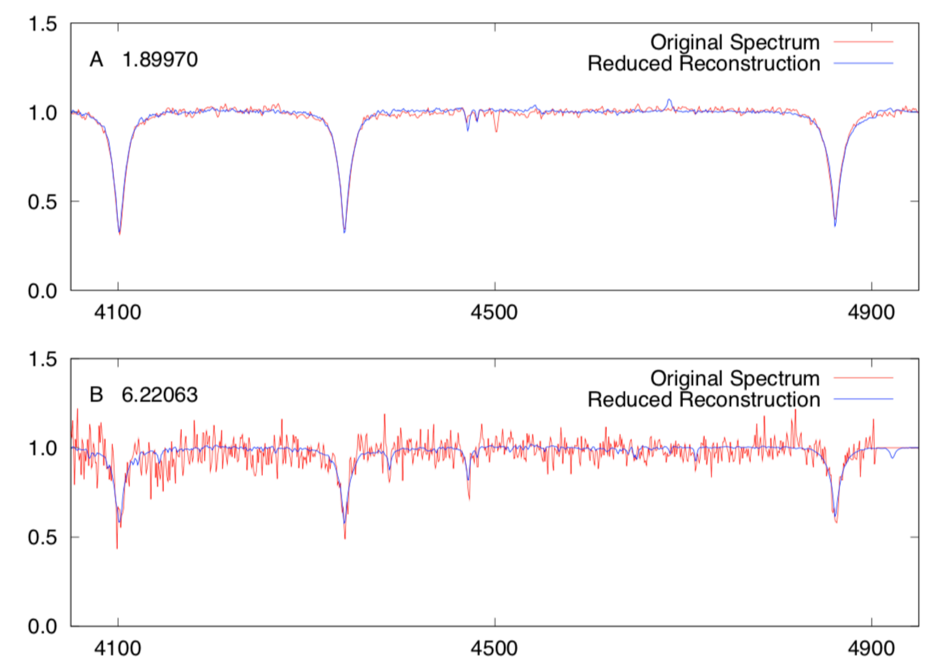


Figure 4.6: Illustration of projecting hot subdwarf spectra onto the first four PCs of the Drilling et al. (2006) standards.

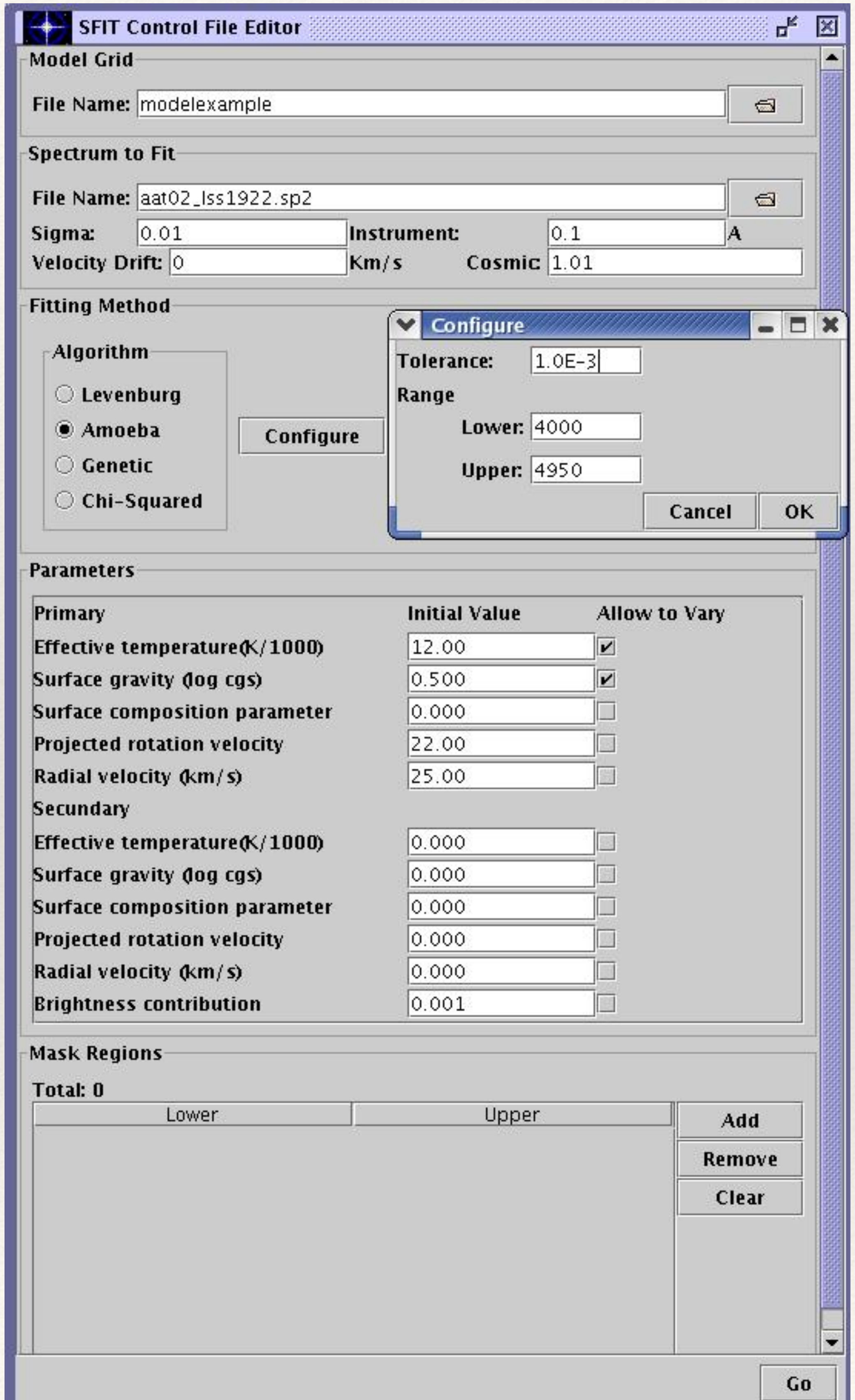
Obtain mean spectrum, and variances around the mean

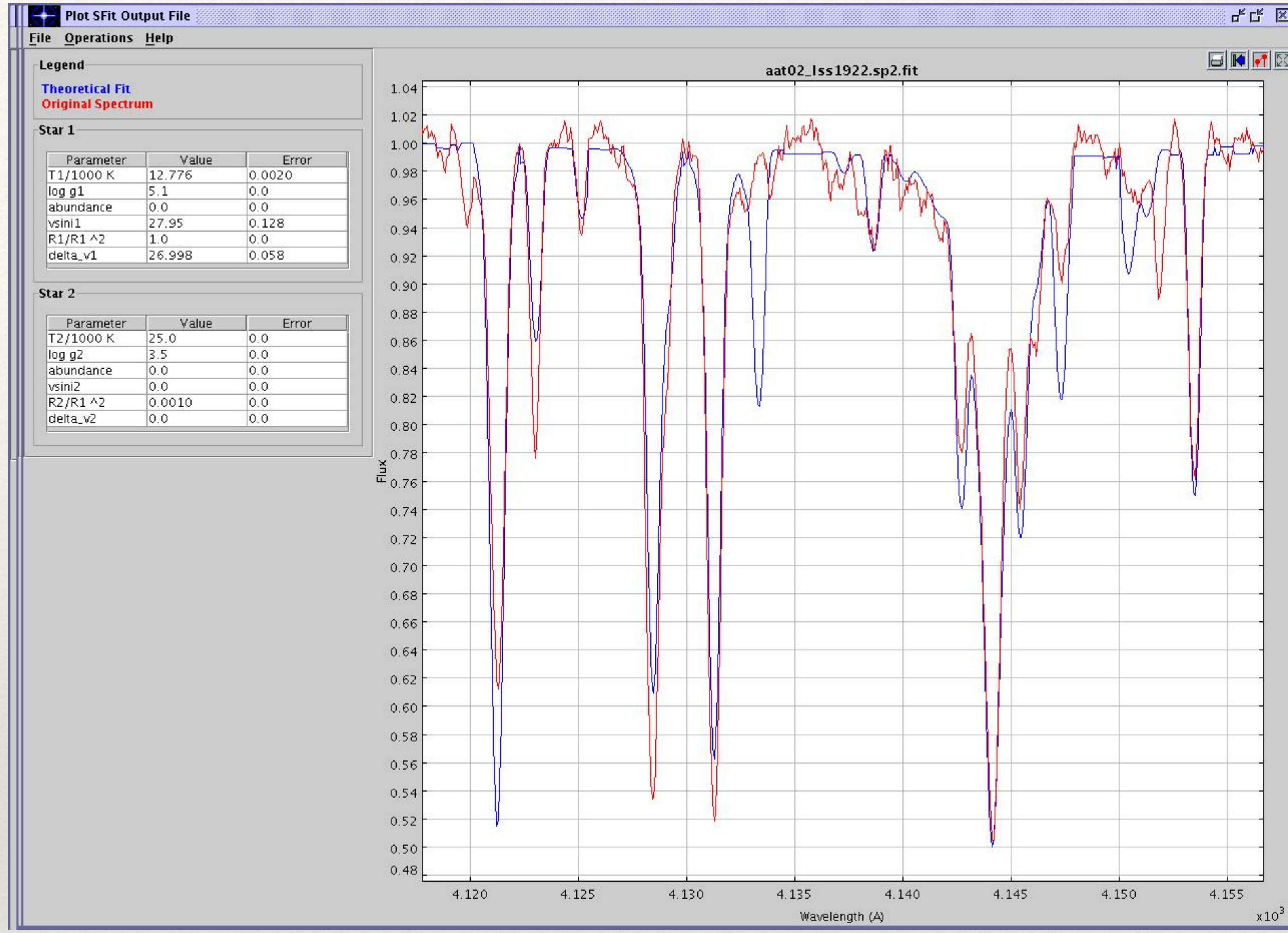
First five PCs of the Drilling sample

Reconstruction of spectra from PCs

Potential of PCA derived from models for analysis

ISFIT: interactive spectrum fitting





Prototype interactive JAVA interface to SFIT.

Offer spectrum, estimated parameters, choice of method, … . Yield best-fit solutions within model grid including free-form visualisation.

Issues include solution stability and uniqueness ….

ISPEC: interactive spectrum fitting

https://www.blancocuaresma.com/s/iSpec

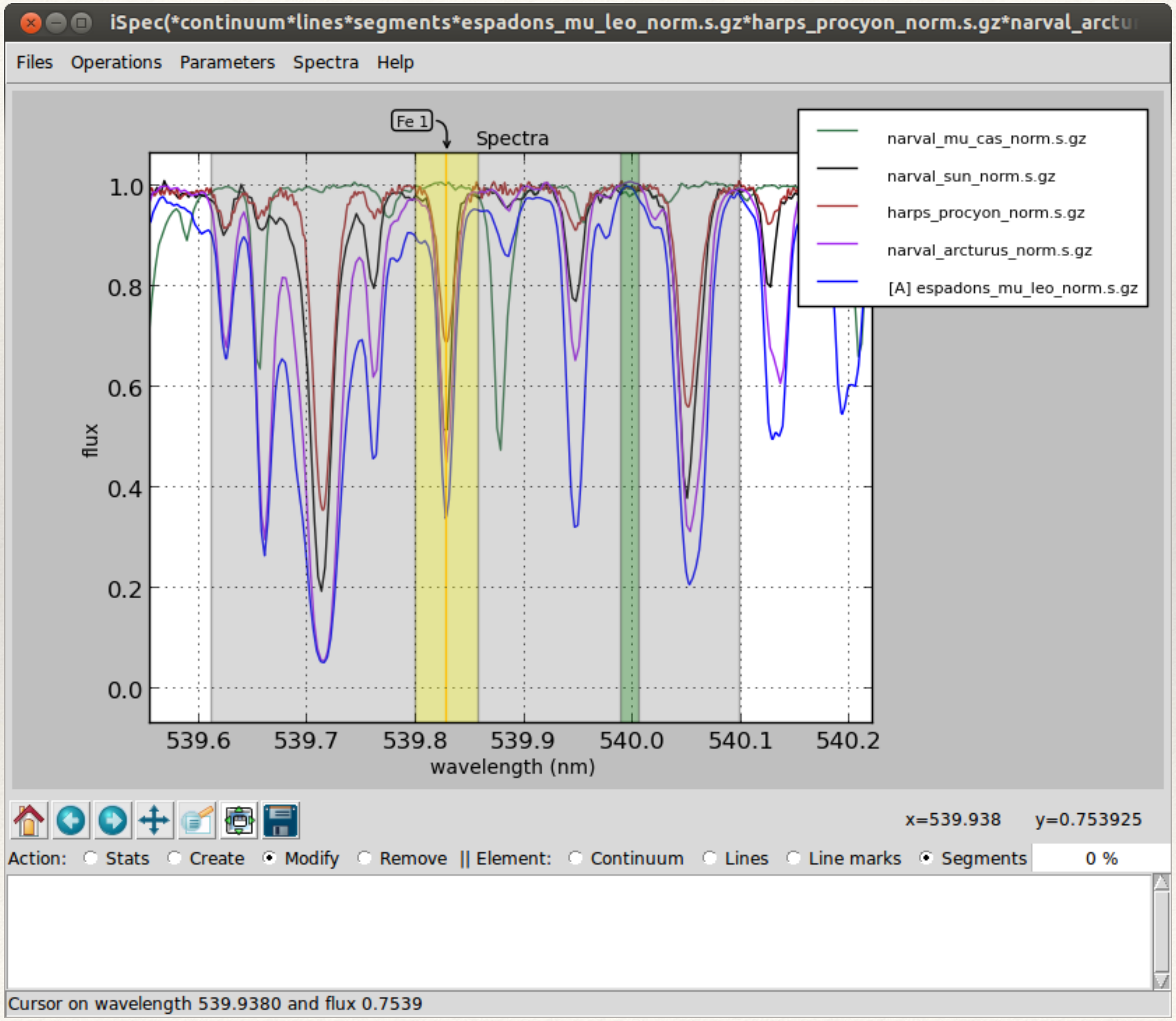
iSpec is an open source framework for spectral analysis (Blanco-Cuaresma et al. 2014a).

Includes RT codes:

- SPECTRUM R. O. Gray
- Turbospectrum Bertrand Plez
- SME Valenti & Piskunov
- MOOG Chris Sneden
- Synthe/WIDTH9 Kurucz/Atmos

Better functionality than lte_codes, and more robust.

Does not treat B stars or hotter.

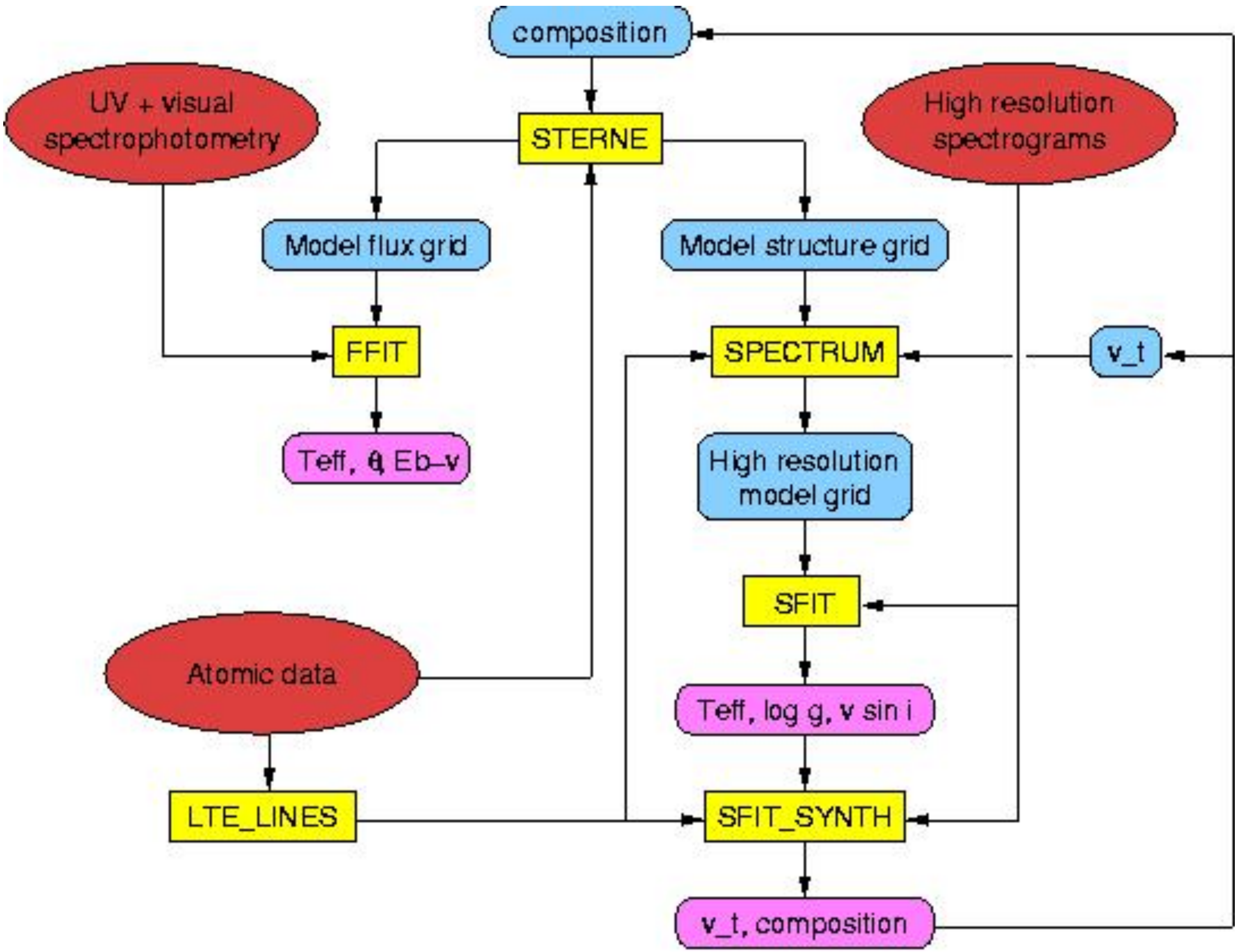


3.6 Errors

$$\chi^2 = \Sigma_i \left(\frac{S_{\lambda i} - s_{\lambda i}}{\delta S_{\lambda i}} \right)^2 / \Sigma_i \left(\frac{1}{\delta S_{\lambda i}} \right)^2$$

- Random — S/N
  - Propagated through the covariance matrix …
- Systematic — observational : e.g. continuum, spectral range, calibration
- Systematic — models : e.g. LTE vs non-LTE, gf values
  - Estimate by numerical tests …

Stellar Atmospheres Software



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3. Spectral Analysis
    3.1. Practical