

Yunnan/Beijing 2019

Stellar Atmospheres

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5. Spectral Analysis

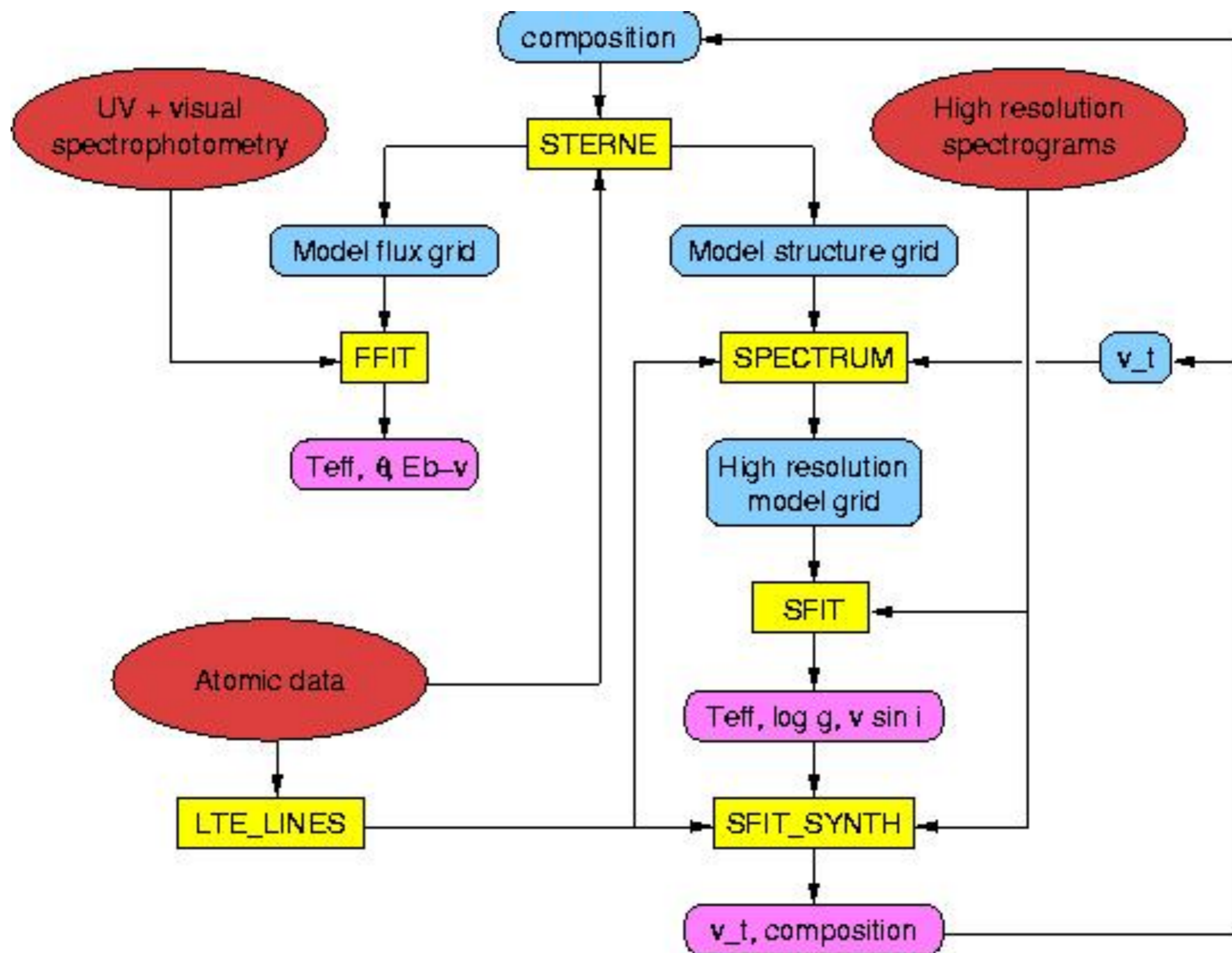
Programme

- 1.[Historical and Observational Introduction]
- 2.Theoretical Framework
- 3.Computational Tools
- 4.Practical
- 5.Stellar Spectral Analysis
- 6.Practical

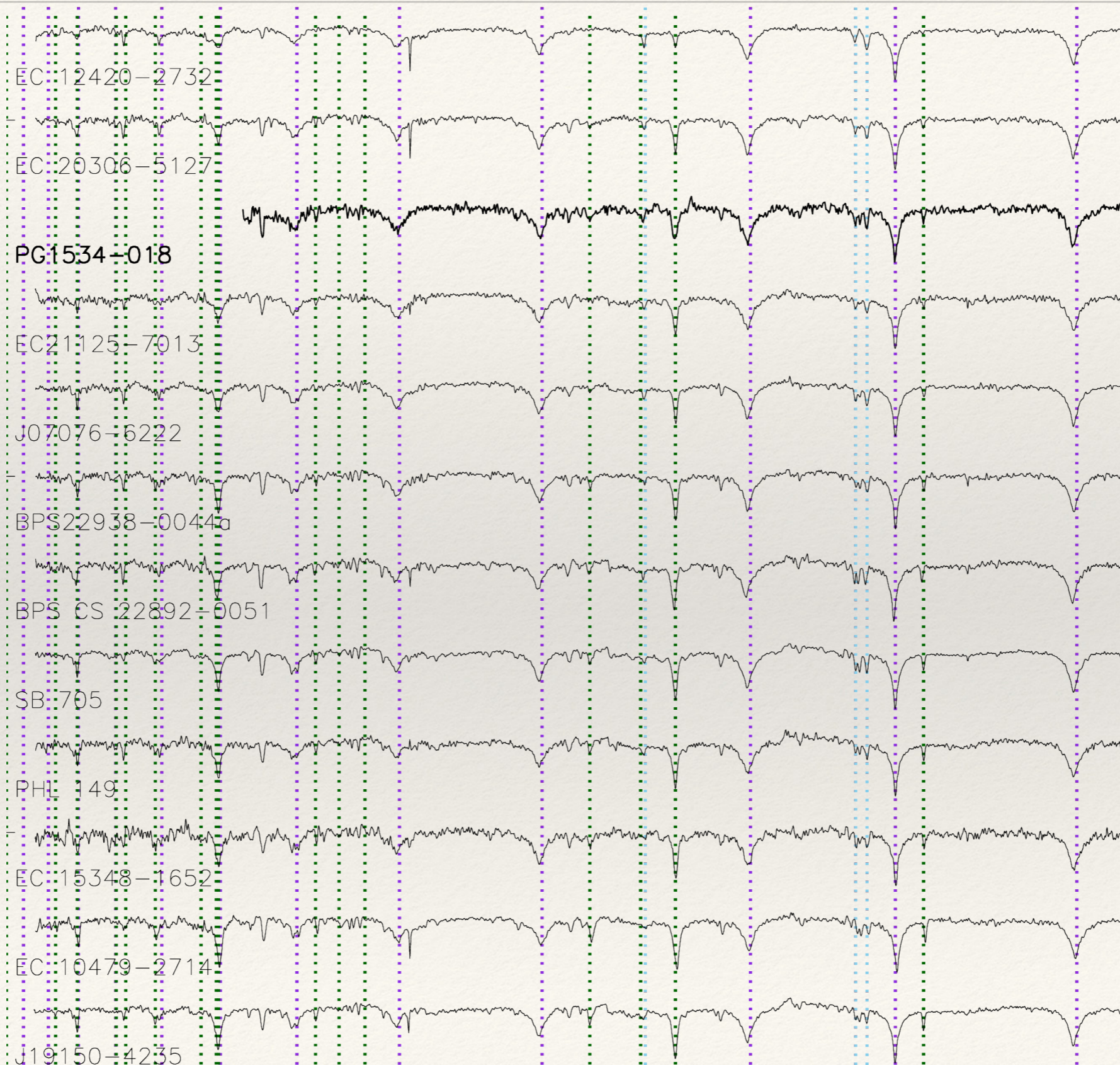
5. Stellar Spectral Analysis

1. Spectral classification
2. Spectral energy distribution (SED) fitting
3. Coarse analysis (for T_{eff} , $\log g$)
4. Fine analysis (for abundances)
5. Optimisation (χ^2 , ANN, PCA, GA, ...)
6. Errors

Stellar Atmospheres Software



5.1 Spectral classification



A plea for classification

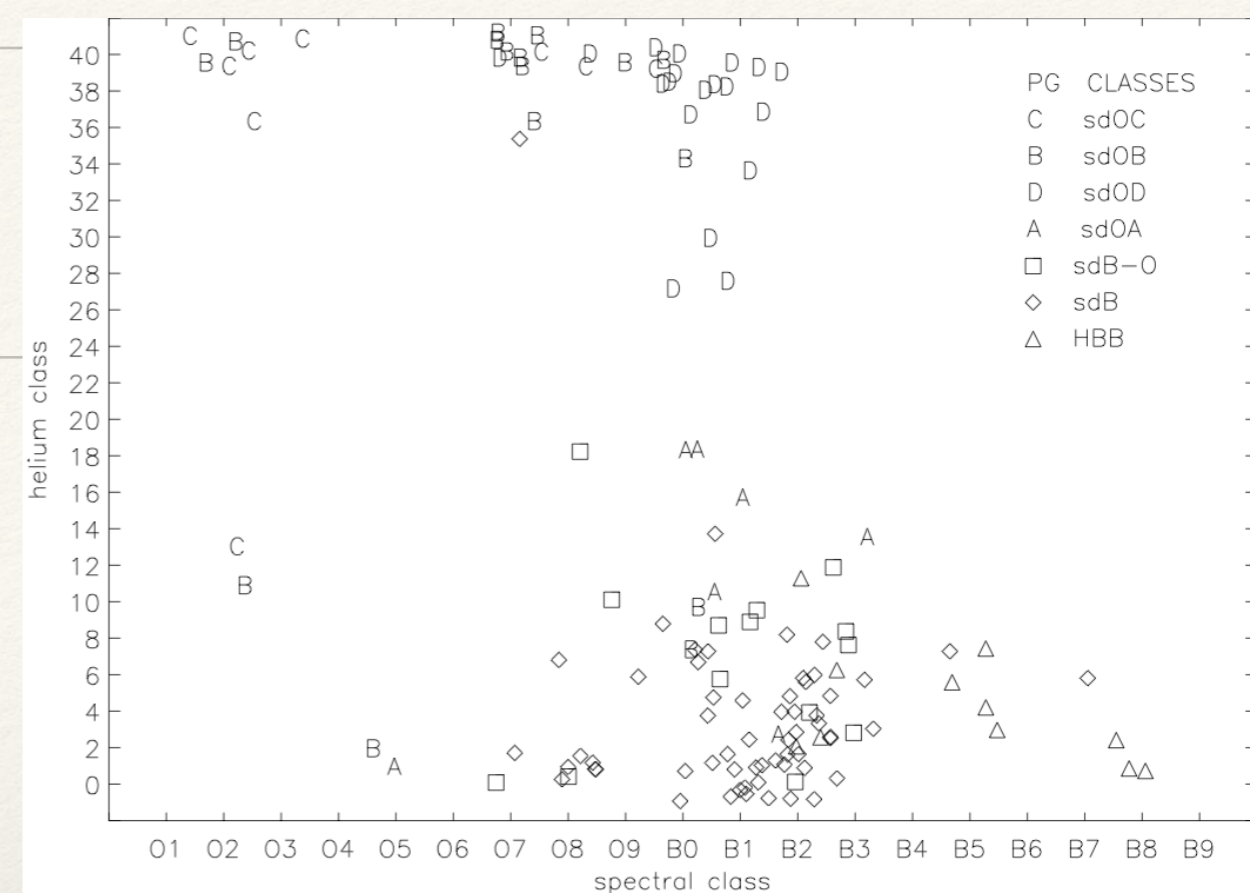
- ❖ Adopt Drilling et al. 2013 subdwarf classifications

- ❖ Degrade spectra to classification resolution $\sim 1 \text{ \AA}$

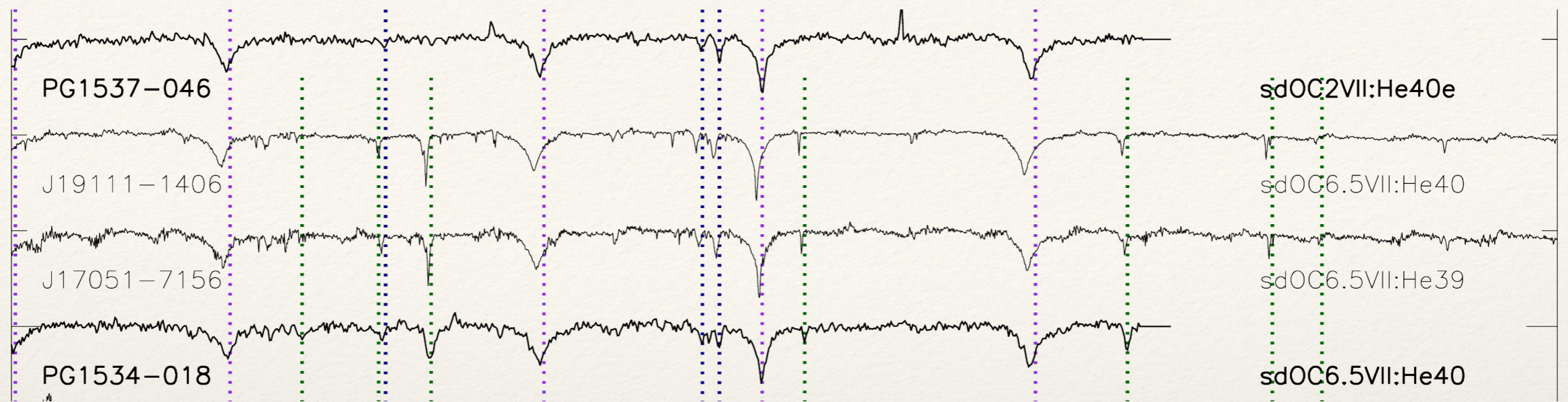
- ❖ Automate spectral type and helium class

- ❖ Eyeball luminosity class and carbon/nitrogen subtypes

- ❖ Cross-check with Drilling standards



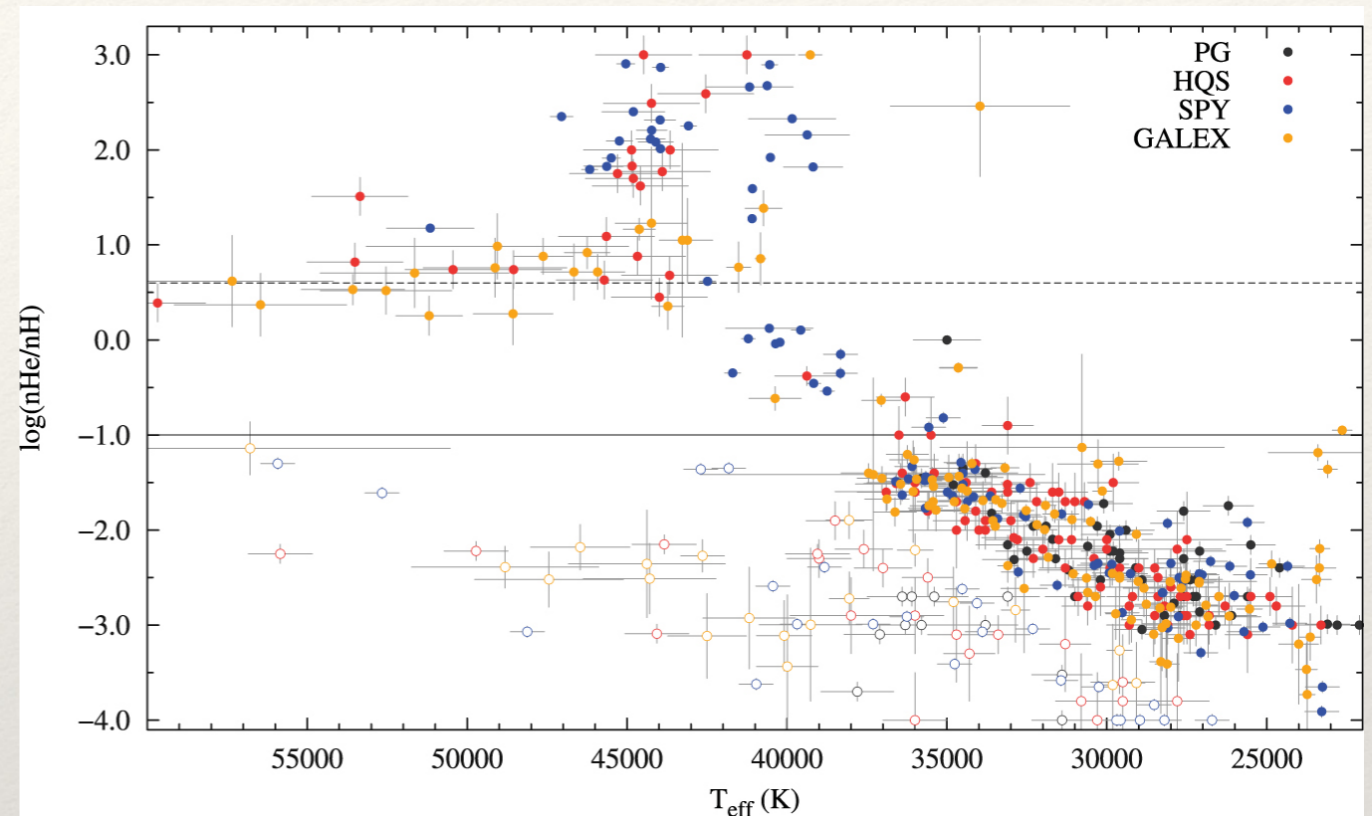
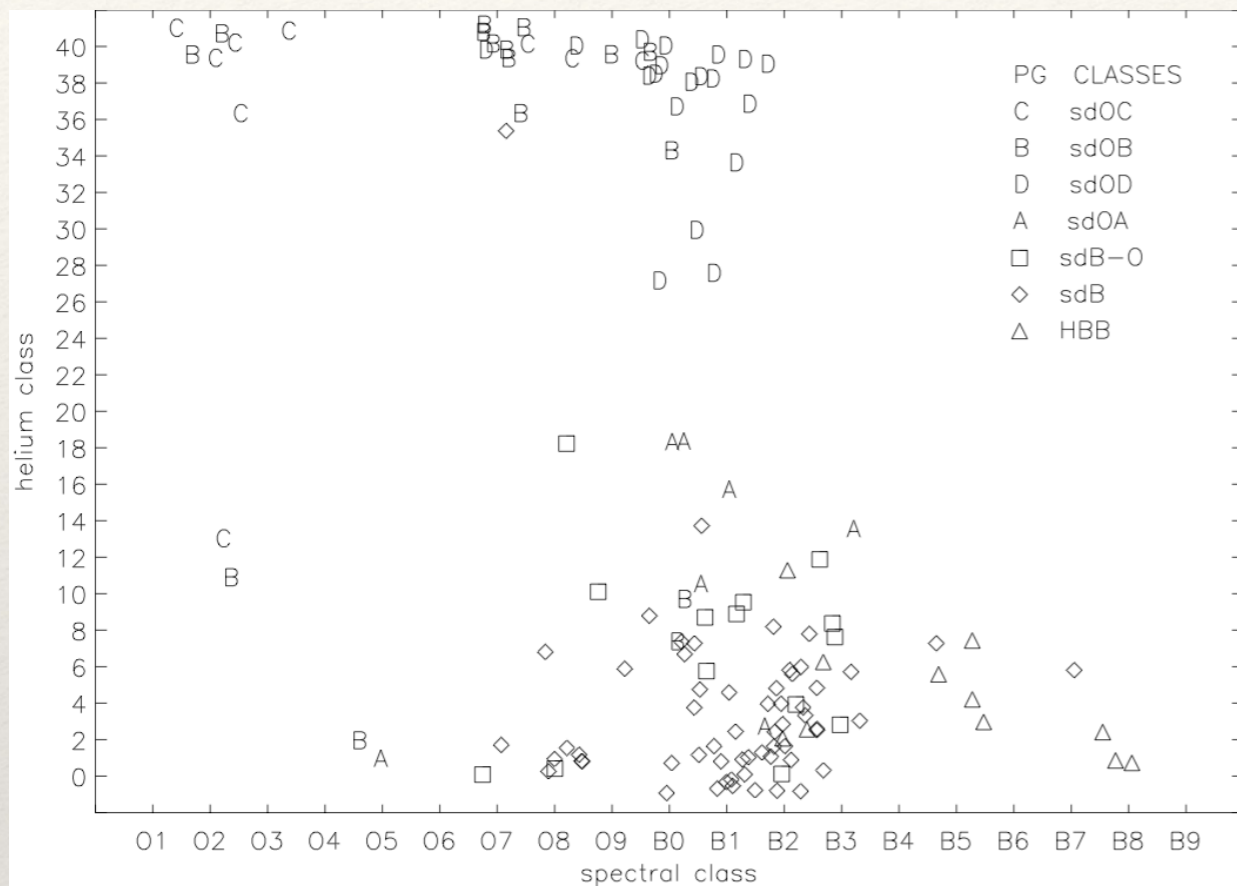
HRS



RSS



A plea for classification



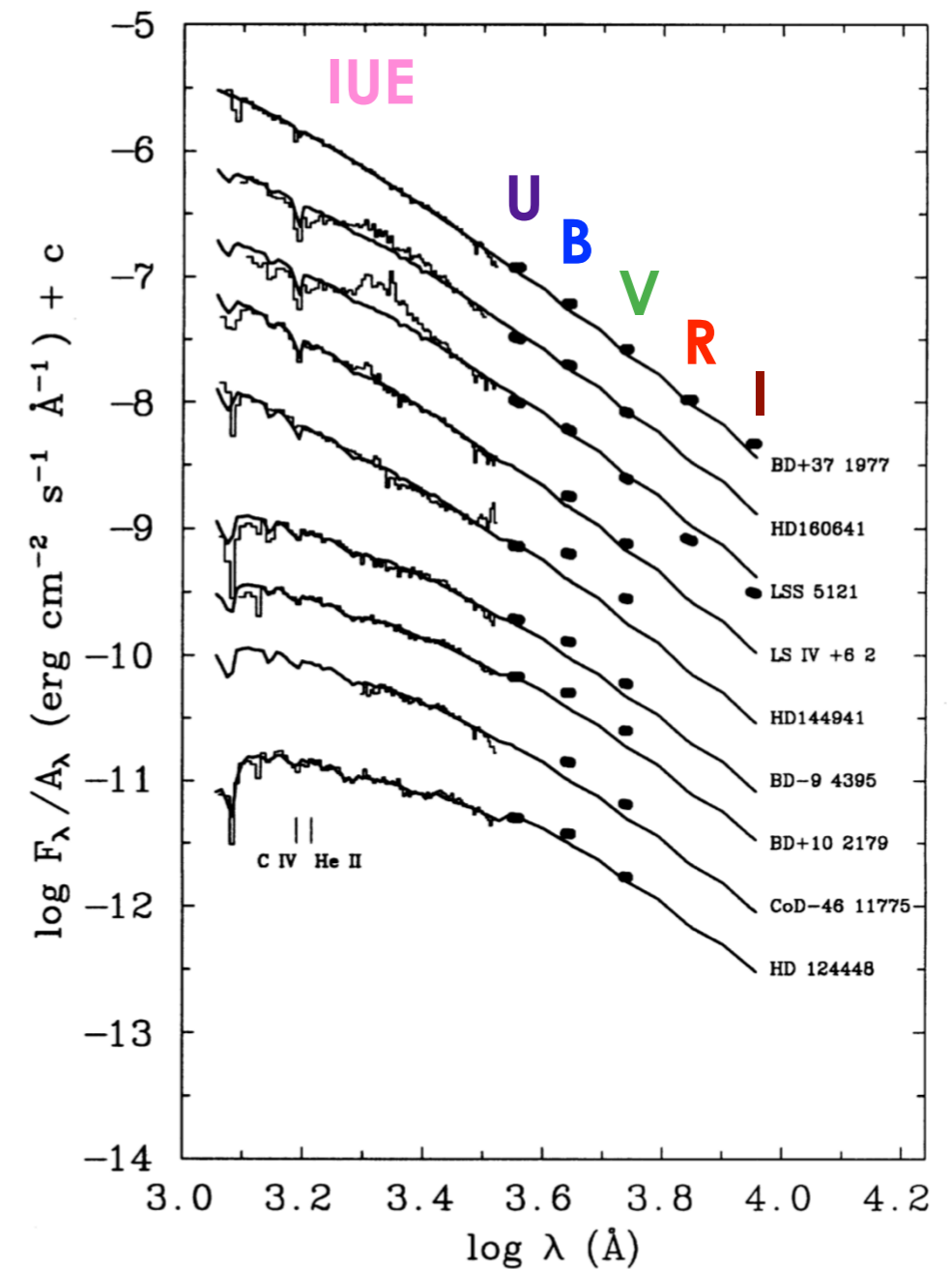
1. If you know the spectral type with sufficient precision, you may not need to analyse the spectrum!
2. The spectral type is defined entirely by standards, not models. If models change, T_{eff} , g , change, **Sp** does not.

5.2 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 ($F_{\lambda i}$). *Propagate errors* ($\delta F_{\lambda i}$).
- ❖ Collect theoretical SEDs for fit ($f_{\lambda i}$). Resample to same wavelength bins as $F_{\lambda i}$. 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
$$\chi^2 = \sum_i \left(\frac{F_{\lambda i} - f_{\lambda i}}{\delta F_{\lambda i}} \right)^2 / \sum_i \left(\frac{1}{\delta F_{\lambda i}} \right)^2$$
- ❖ 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

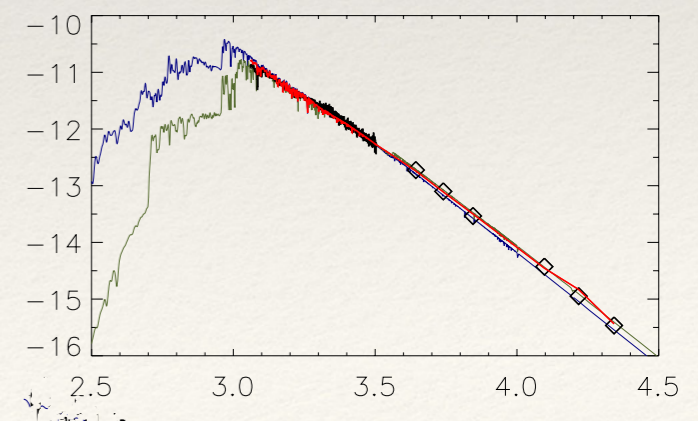
Defines wavelengths and filter bands for fit

Initialises parameters

Reads IUE data and visual/IR magnitudes

Optimizes solution

IDL script plots best fit



Coarse analysis recipe

- ❖ Assess spectra (e.g. right star? classification, S/N, normalisation, resolution, bad pixels / gaps).
- ❖ Remove instrumental response and normalise to “continuum” $S_\lambda = F_\lambda / F_c$
- ❖ Measure radial velocity v_{rad} relative to lab frame and LSR. Record both!!!
- ❖ Collect a grid of theoretical spectra $s_\lambda(T_{\text{eff}}, \log g, \text{He/H}^*)$ appropriate for your stars.
- ❖ For each spectrum S_λ , estimate $T_{\text{eff}}, \log g, \text{He/H}$.
 - ❖ 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_{rad}
 - ❖ Compute
- ❖ Adjust $T_{\text{eff}}, \log g, \text{He/H}, v \sin i$ until χ^2 optimised.
- ❖ Check continuum good enough, otherwise renormalise and repeat.
- ❖ Works for binary stars as well.

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

* 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
```

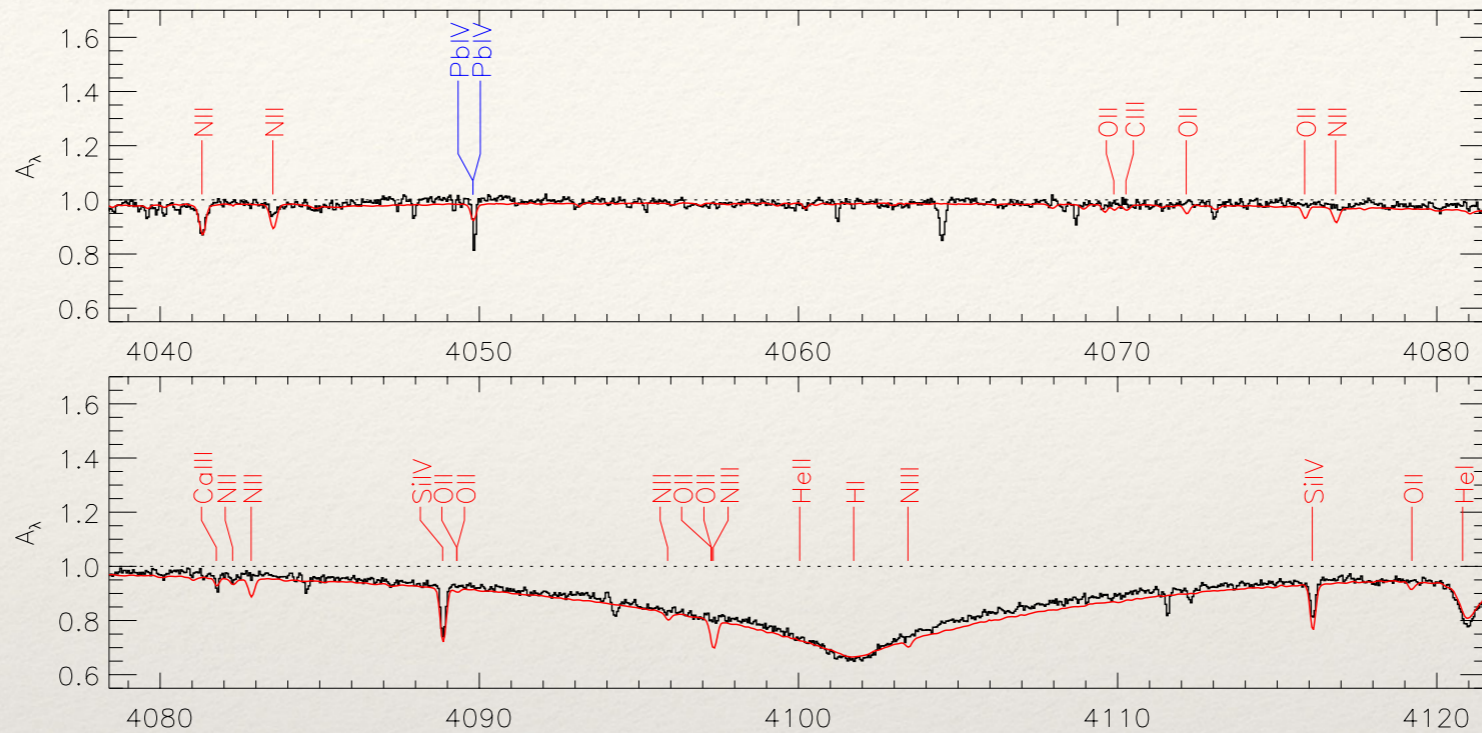
```
solve
```

```
normalise
```

```
solve
```

```
end
```


5.4 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.

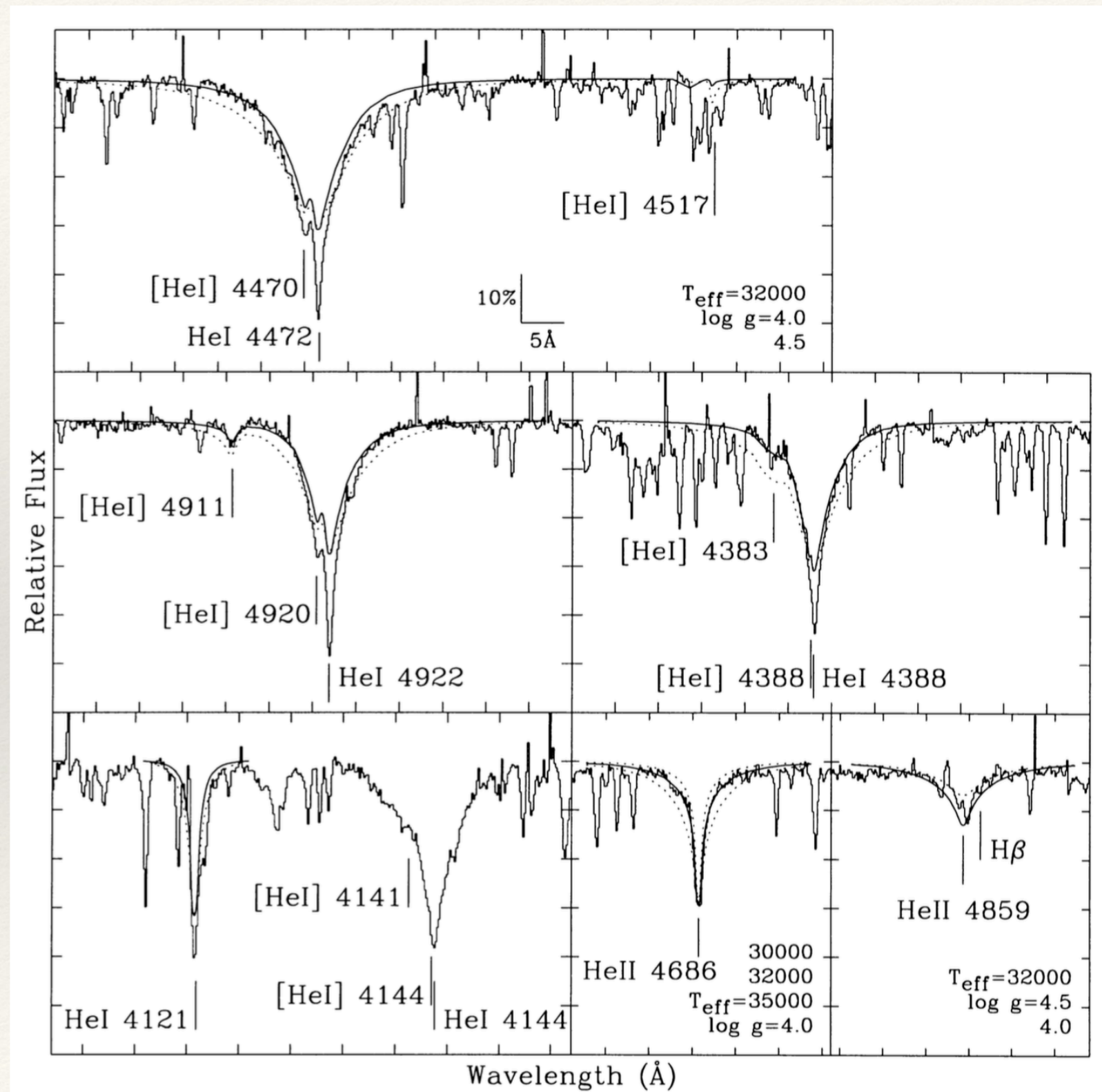
Generally time consuming, unless analysing a restricted set of lines in a sample of very similar spectra.

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_{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_{eff} , $\log g$, $v \sin i$.
- ❖ IF $n_i \neq n_{i0}$: recompute model atmosphere grid for new composition and repeat analysis.

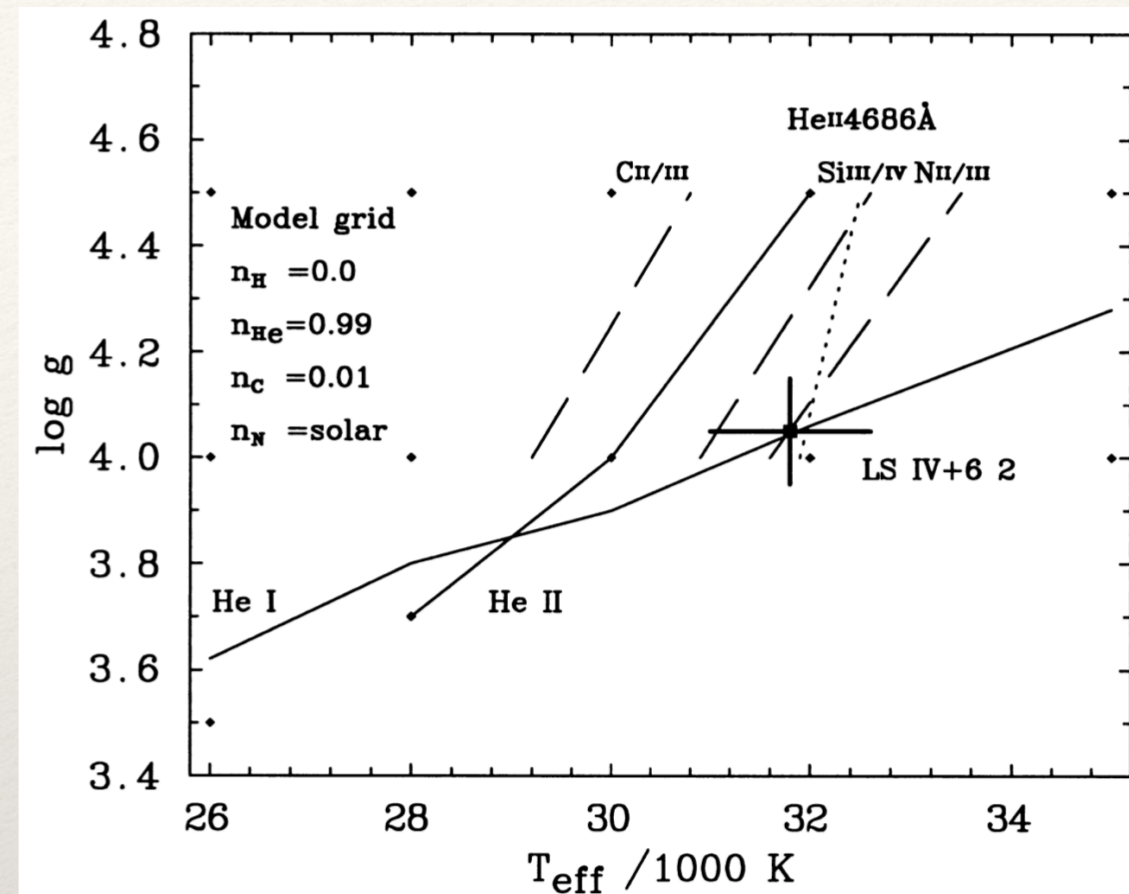
Fine analysis I: line-by-line

- ❖ 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 $g(T_{\text{eff}})$ 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_{eff} , g , compute abundance n_{ijk} from W_λ
- ❖ For element i (eg carbon) construct $\langle n_{ij} \rangle$ and $\langle n_{ij+1} \rangle$ and compare for fixed g and several T_{eff} , to find ionisation equilibrium $T_{\text{eff}}(g)$. Repeat for other elements.
- ❖ Determine best values for T_{eff} and g satisfying above criteria.

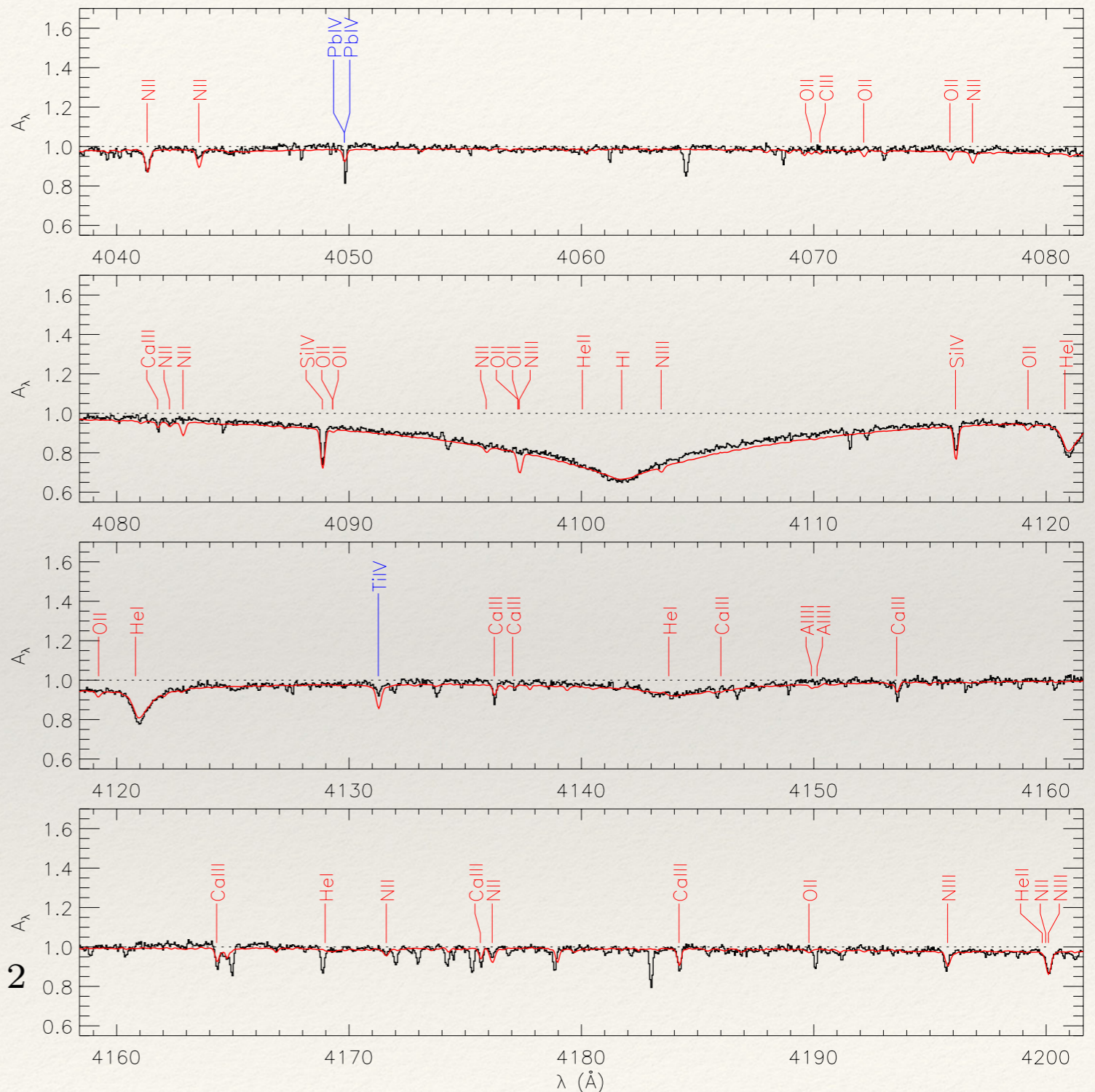


- ❖ Compute 'final' model atmosphere with T_{eff} , g and n_{i0}
- ❖ Compute all n_i from W_λ

Fine analysis II: synthesis

- ❖ Compute model atmosphere with T_{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

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



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_{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_{eff} , $\log g$, $v \sin i$.
- ❖ 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-resolution 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

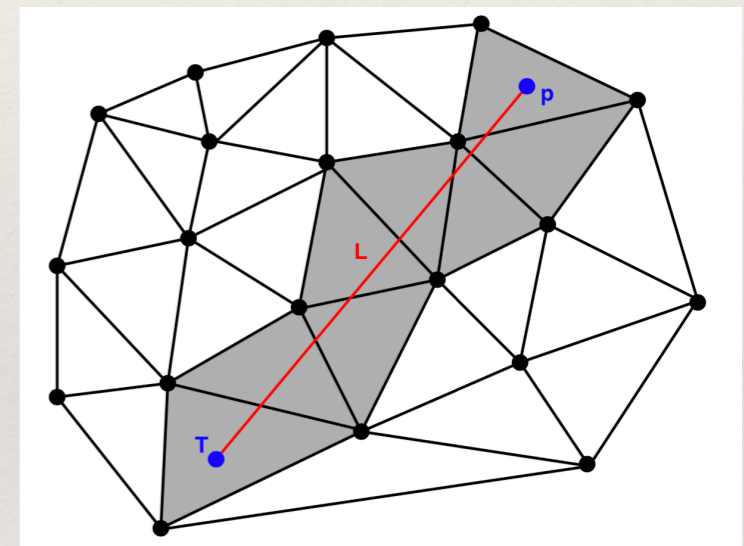
# Run Spectrum in line-mode to get list of equivalent widths
# Edit the ".spc" file to give better abundances
Spectrum.sh ../h80he20xxx/t390g600xxx.q gf_subaru.lte j0825_ewcalc_vt02.spc
j0825_eqwids
rm j0825_eqwids.fcon. j0825_eqwids.flux

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


5.5 Optimisation

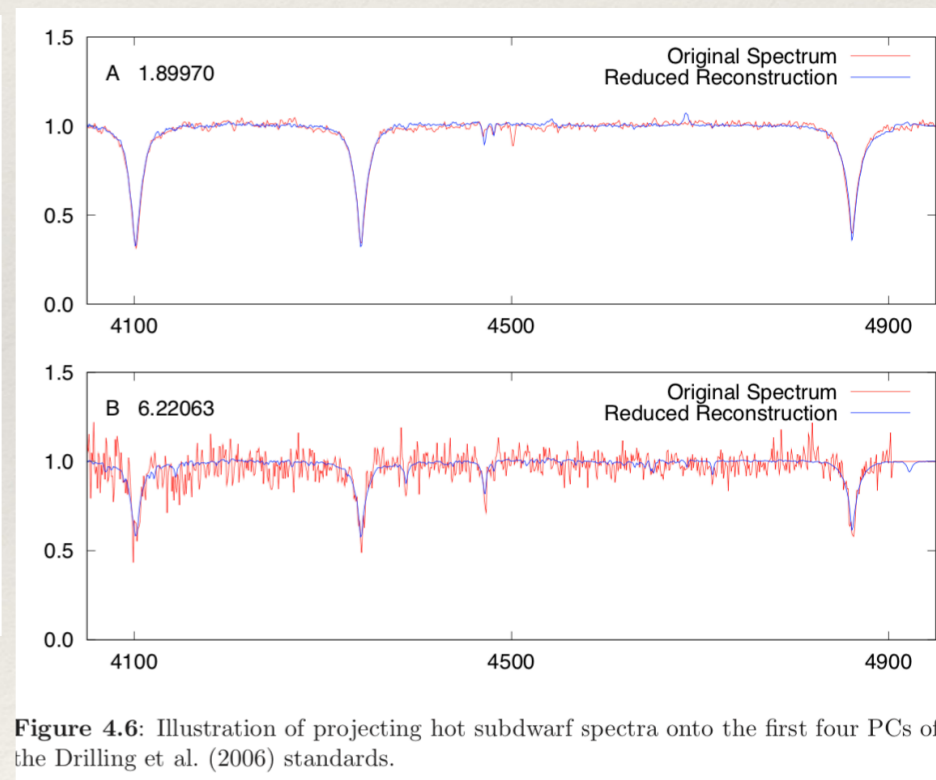
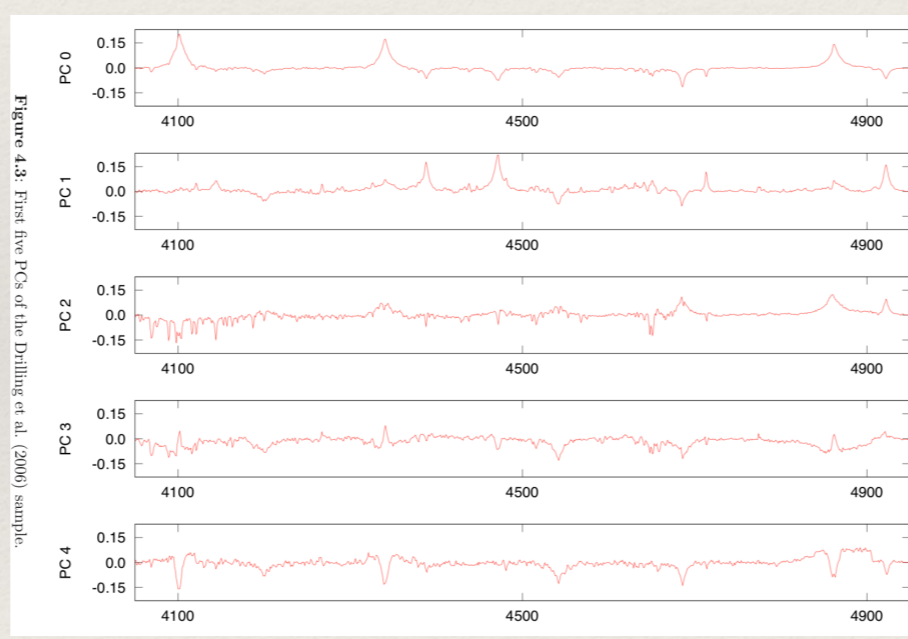
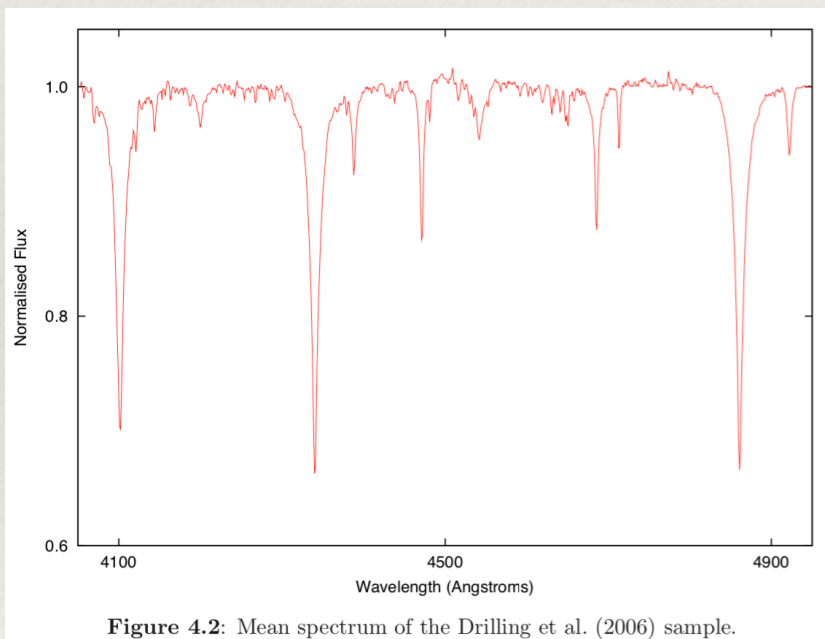
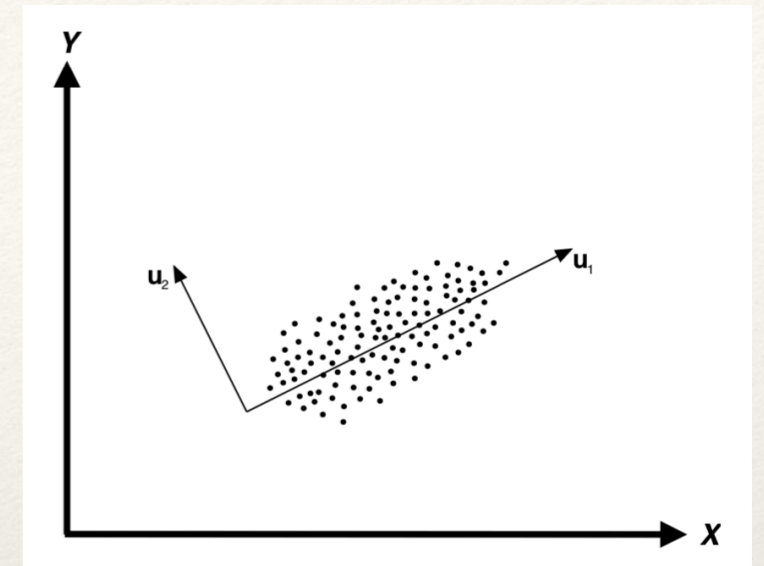
$$\chi^2 = \sum_i \left(\frac{S_{\lambda i} - s_{\lambda i}}{\delta S_{\lambda i}} \right)^2 / \sum_i \left(\frac{1}{\delta S_{\lambda i}} \right)^2$$

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



Automatisation

- ❖ Artificial Neural Networks
- ❖ Principal Components Analysis



Obtain mean spectrum,

First five PCs

and variances around the mean

of the Drilling sample

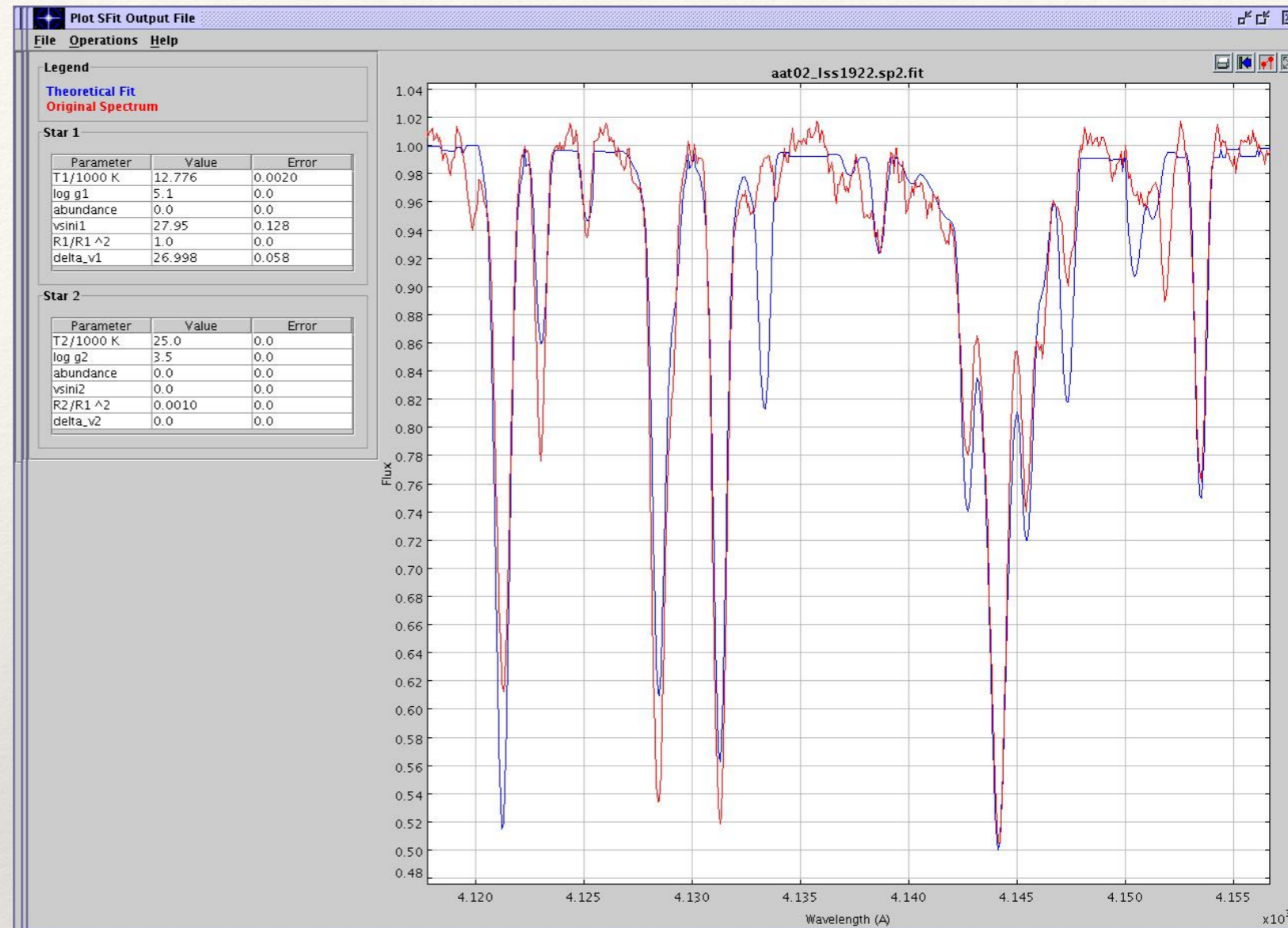
Reconstruction of spectra from PCs

Potential of PCA derived from models for analysis

ISFIT: interactive spectrum fitting

The SFIT Control File Editor interface is divided into several sections:

- Model Grid:** File Name: modelexample
- Spectrum to Fit:** File Name: aat02_iss1922.sp2, Sigma: 0.01, Instrument: 0.1 A, Velocity Drift: 0 Km/s, Cosmic: 1.01
- Fitting Method:** Algorithm selection (Levenburg, Amoeba, Genetic, Chi-Squared) with a **Configure** button.
- Configure Dialog:** Tolerance: 1.0E-3, Range: Lower: 4000, Upper: 4950.
- Parameters:** A table of parameters for Primary and Secondary stars, including Effective temperature, Surface gravity, Projected rotation velocity, Radial velocity, and Brightness contribution.
- Mask Regions:** A table with columns for Lower and Upper wavelength bounds, and buttons for Add, Remove, and Clear.



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

iSPEEC: interactive spectrum fitting

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

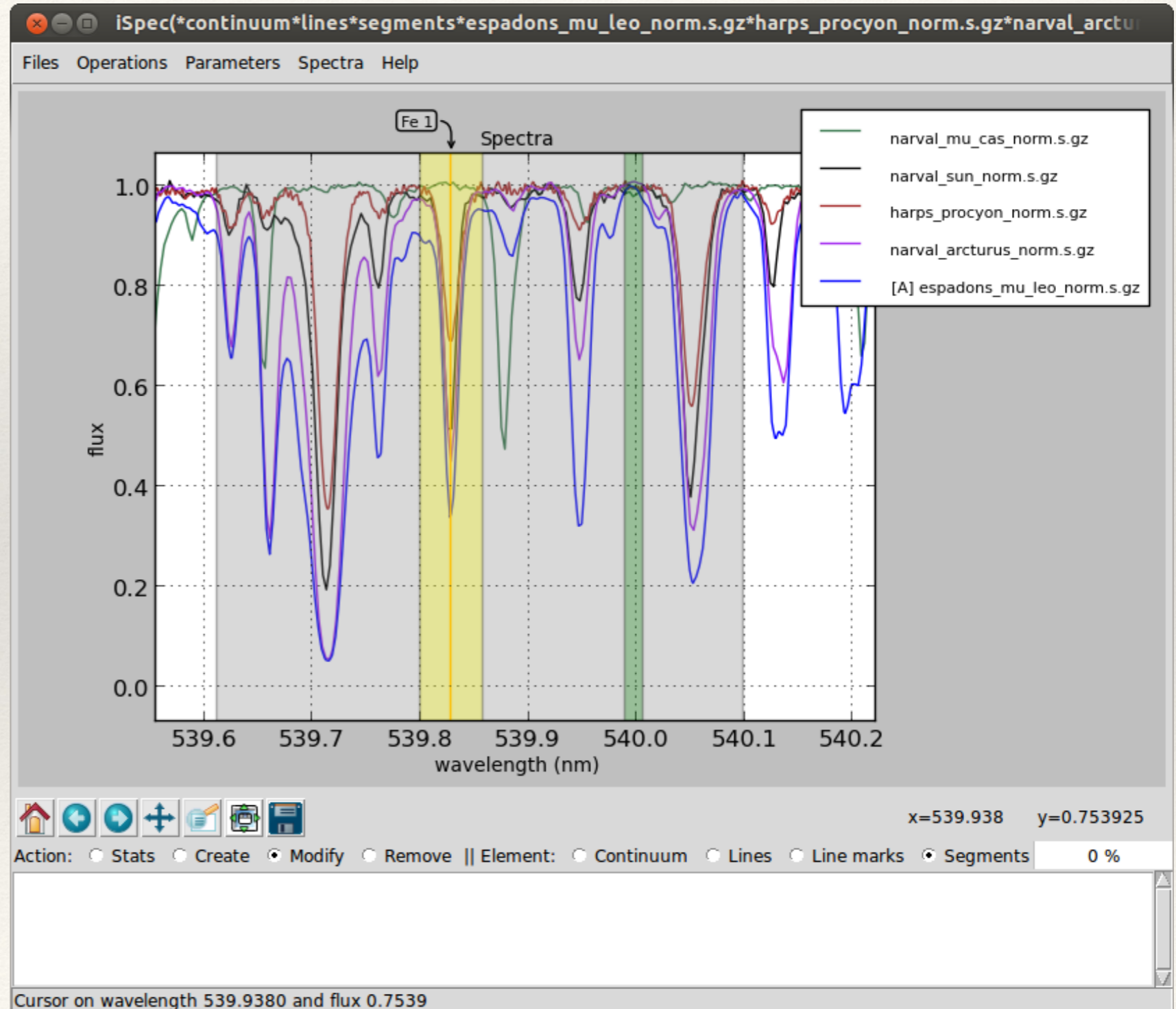
iSpec is an open source framework for spectral analysis (Blanco-Cuaresma et al. 2014a).

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.

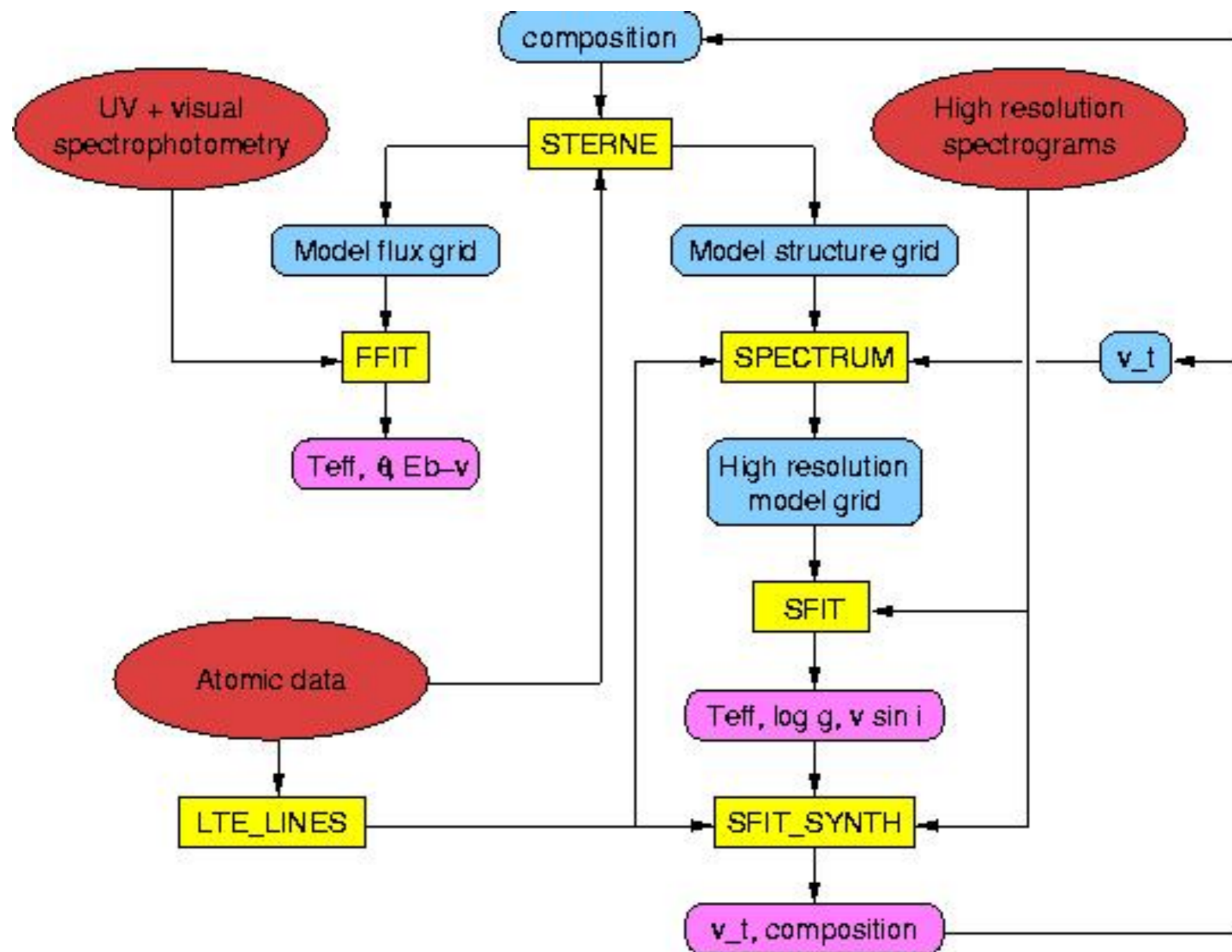


5.6 Errors

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

- ❖ 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 ...

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