Stellar Atmospheric Parameters … for late-type stars

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Overview

- Relevant parameters
- Methods
- Automatic tecniques
- Solutions for massive surveys

Relevant atmospheric parameters

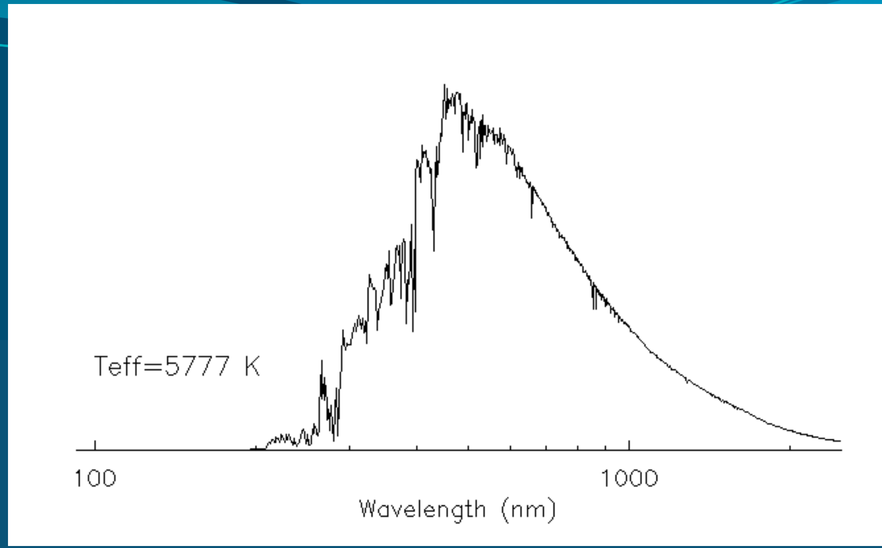
- These are those needed for interpreting spectra
- Usually: Teff, logg, [Fe/H]
- Sometimes: R, [illegible], [illegible], E(B-V), *v sin i*
- Largely ignored, but sometimes needed: [C/Fe], [[illegible]/Fe], **B**,…

Teff

- $F = \sigma T_{eff}^4$
- $F R^2 = f d^2$
- Can be directly determined from bolometric flux measurements f and angular diameters (2R/d)

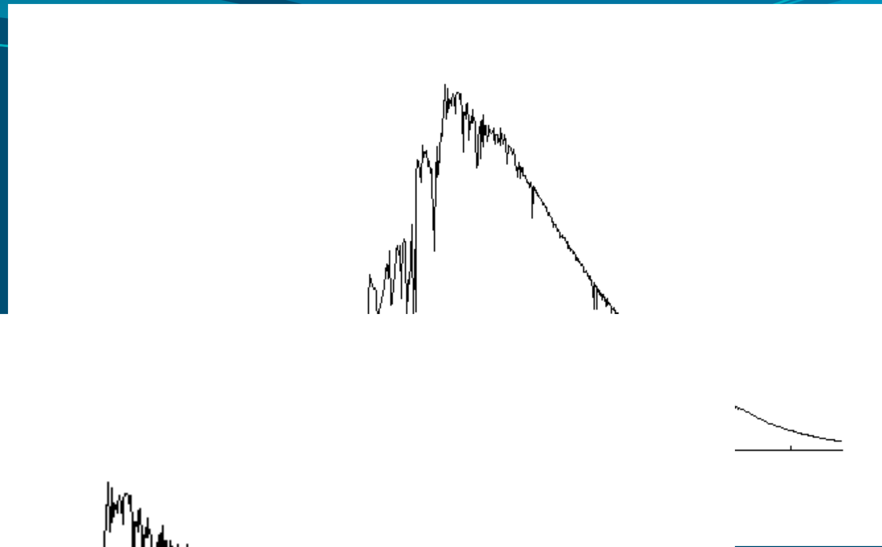
  hard but spectacular progress recently
- Photometry: model colors, IRFM
- Spectroscopic: line excitation, Balmer lines
- Spectrophotometric: model fluxes

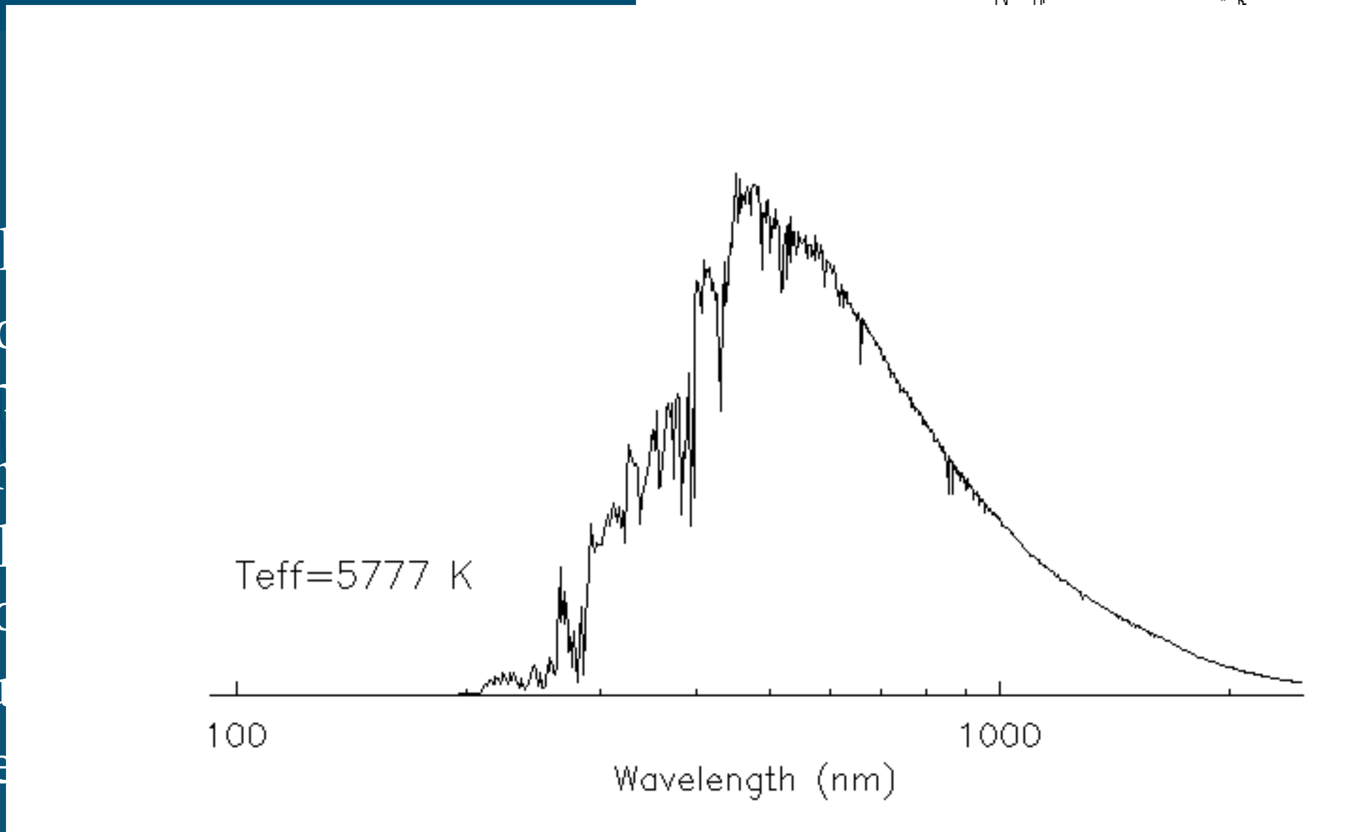
Teff • IRFM



- Multiple implementations
  Oxford (Blackwell+) 80s, Alonso+ 90s, Ramírez& Meléndez / González-Hernández+ / Casagrande+ 00s
- Fairly model independent
- Scales in fair agreement on the metal-rich end but conflicts for halo turn-off stars
- Issues know for cool (K and beyond) spectral types
  (see Allende Prieto+ 04, S4N)
- Now in good shape based on solar-analog calibrations

Teff • IRFM





- Mul
  Oxf… ez /
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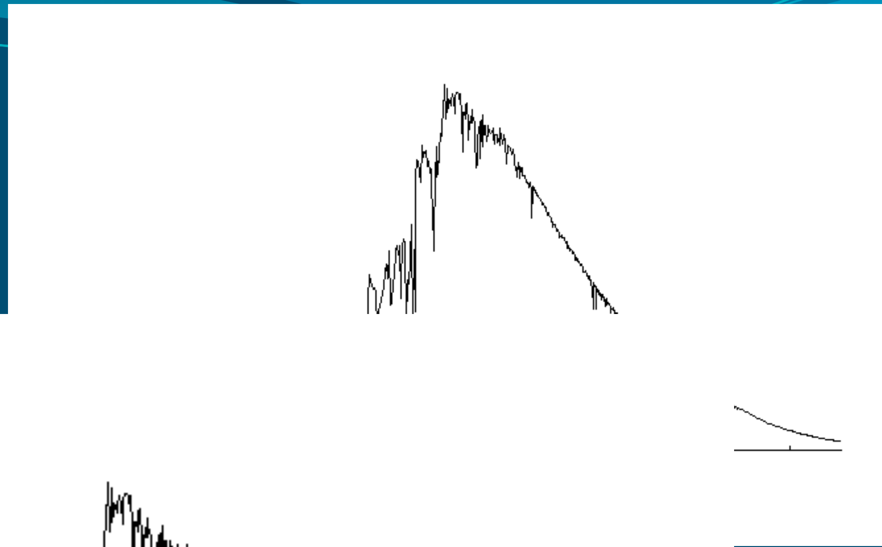
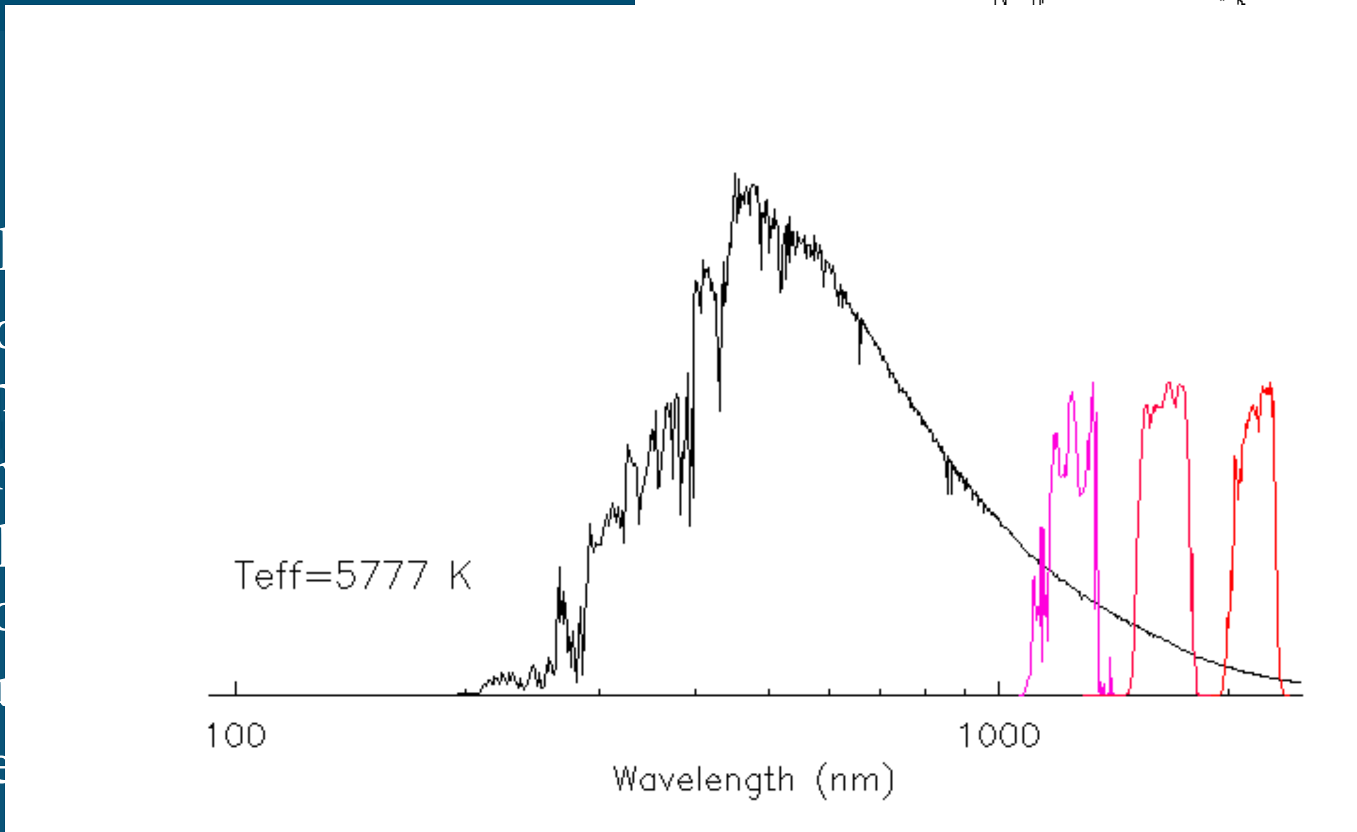
Teff • IRFM





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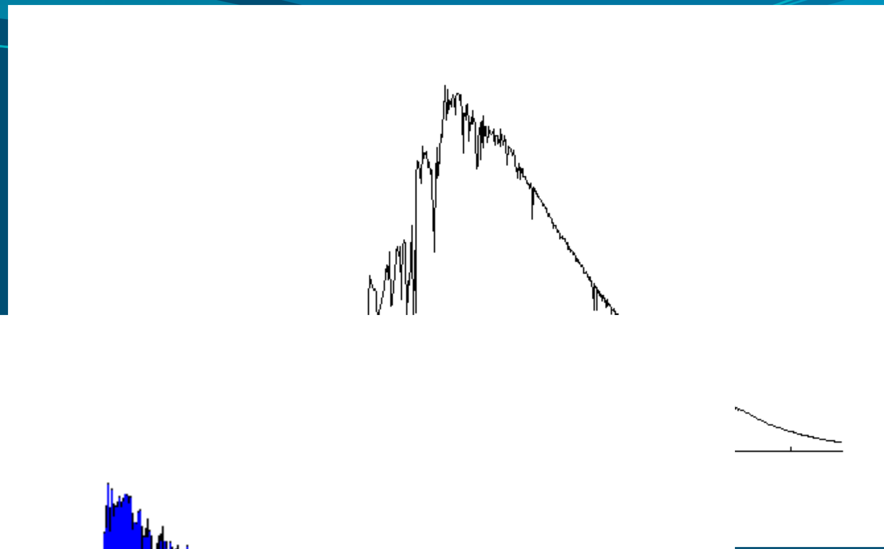

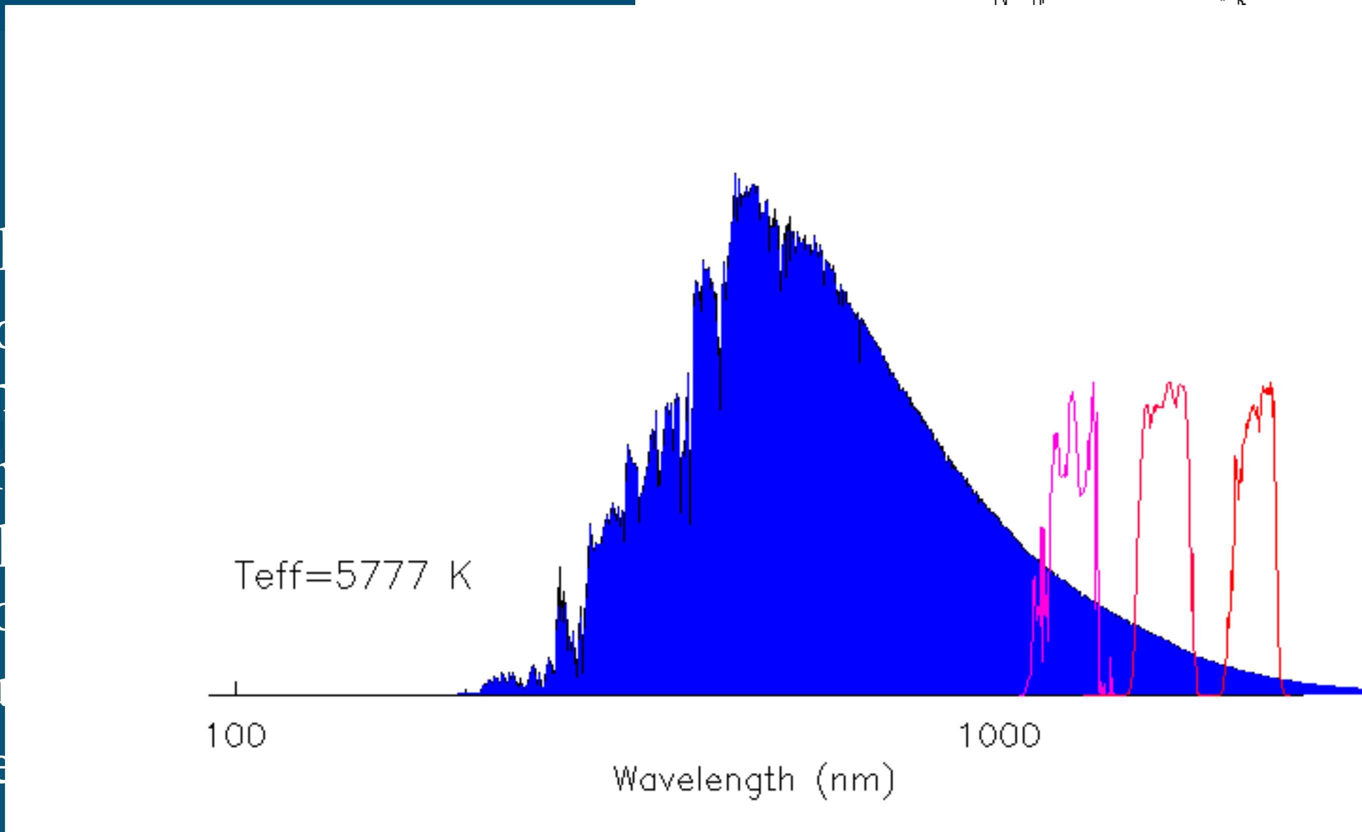

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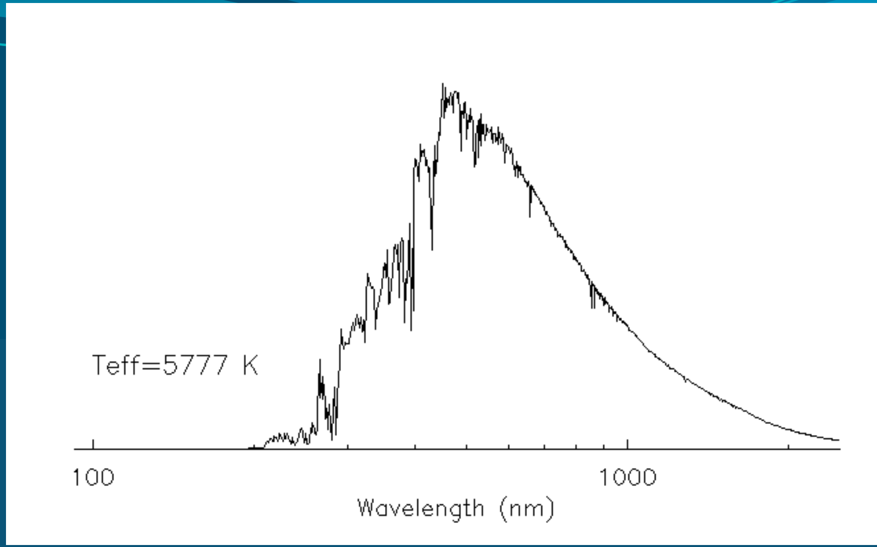

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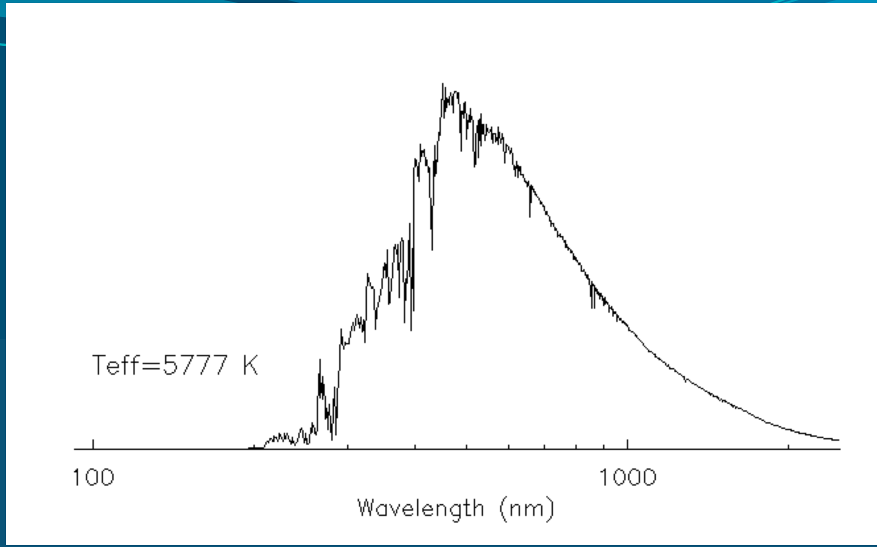

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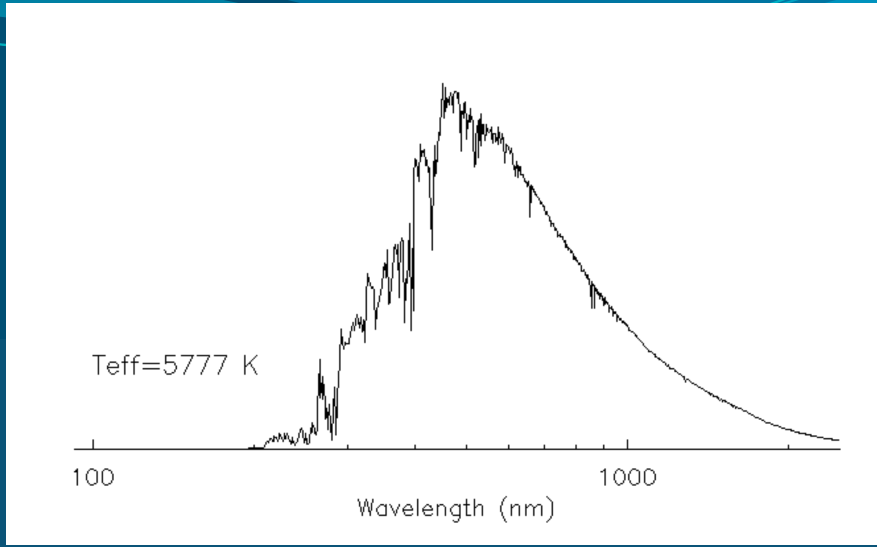

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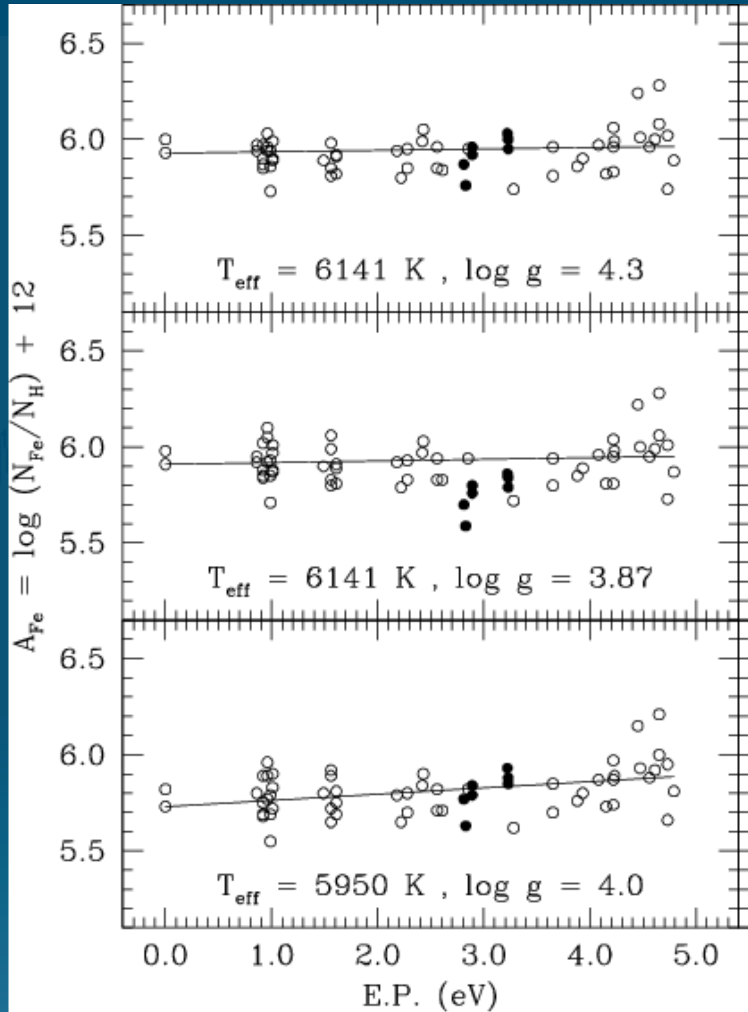
Teff • weak-line excitation

- Classical method
  lines of different formation depth (excitation energy) are very sensitive
- Model dependent: <T([illegible])>, turbulence, NLTE
- Observationally friendly

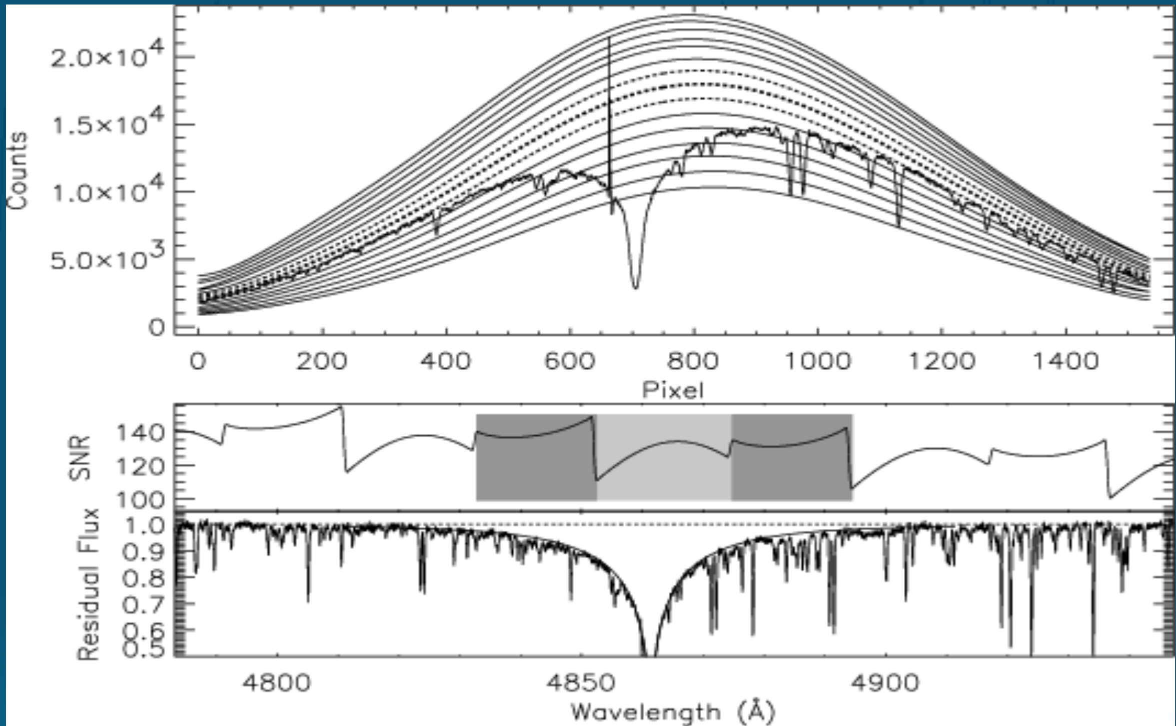


Teff • Balmer lines

- Perfected by Fuhrmann+ in the 90s

Teff • Balmer lines

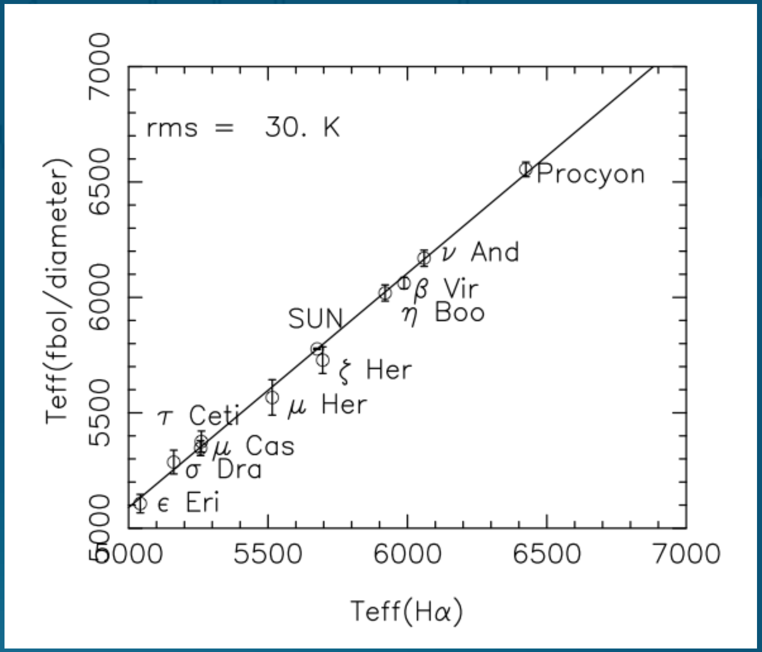
- Perfected by Fuhrmann+ in the 90s
- Applied to echelle spectra by Barklem+



Teff • Balmer lines

- Perfected by Fuhrmann+ in the 90s
- Applied to echelle spectra by Barklem
- Improved theoretical broadening calculations -- see poster and upcoming paper by Cayrel+

Main remaining issue is the effect of convection on the thermal atmospheric structure -- need 3D or an external calibration



But NLTE effects may be involved (Barklem 2007)

Teff • spectrophotometry

- Combines photometry and spectroscopy
- Hard to get very high-quality spectra (<2-3%). Need space observations to access the UV
- Great progress in the last decade (Bohlin+ Cohen+)
- HST flux calibration based on Oke V scale plus hot DA WD models. Consistency all around with Vega and solar analogs
- ACCESS (Kaiser+ 2011)

Teff • spect

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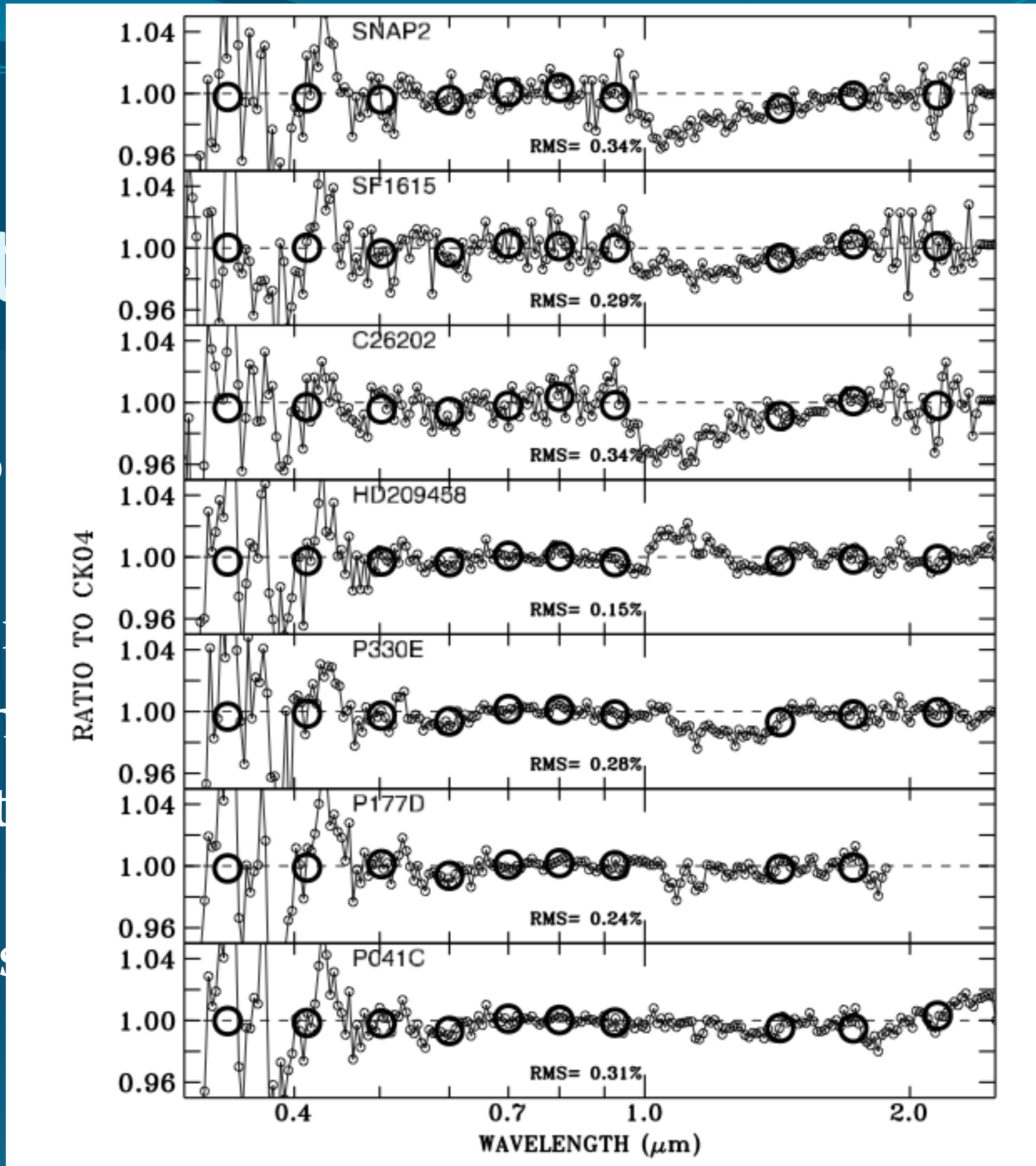
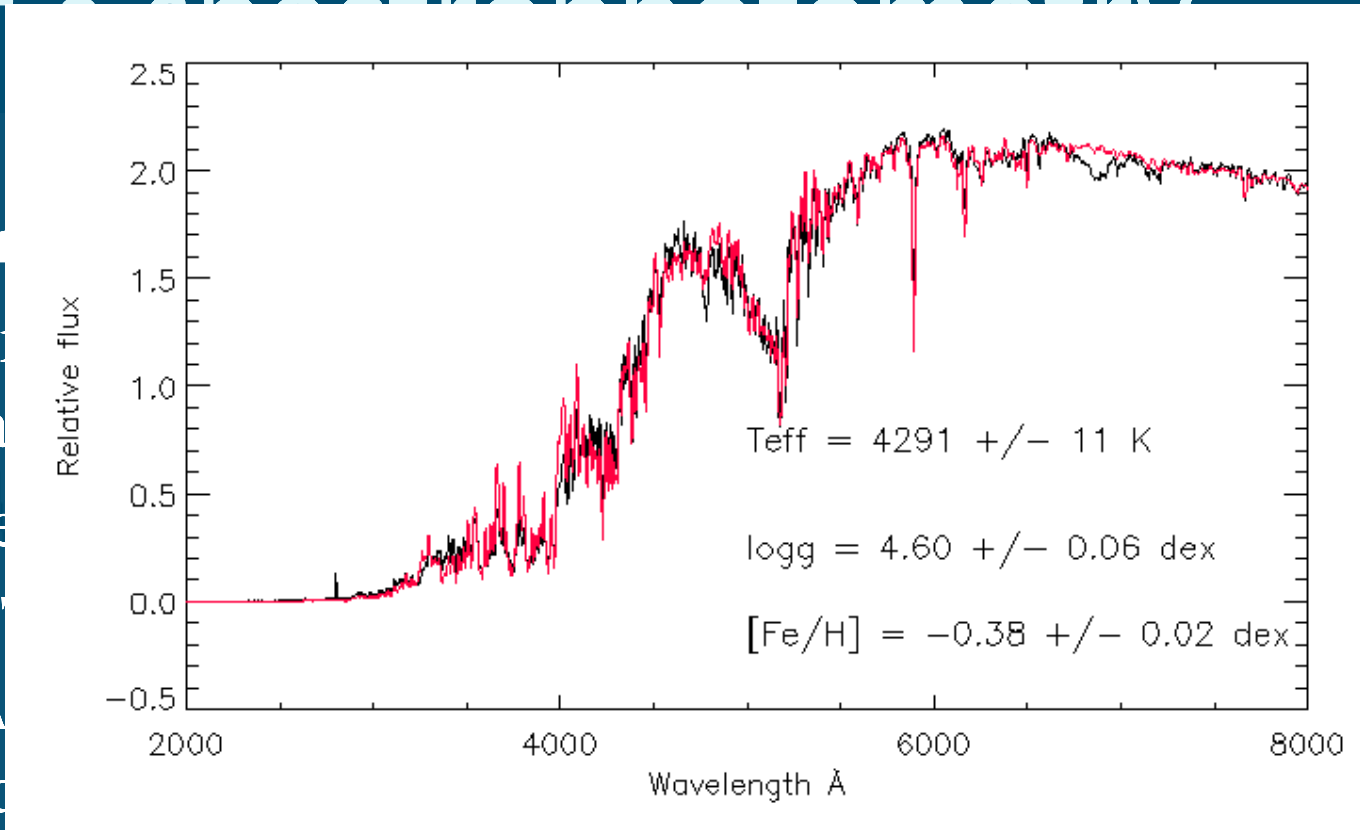
- Hard to get very space observatio
- Great progress in
- HST flux calibrat DA WD models. and solar analogs



Solar analogs observed
With STIS compared with solar-like Kurucz models

Teff

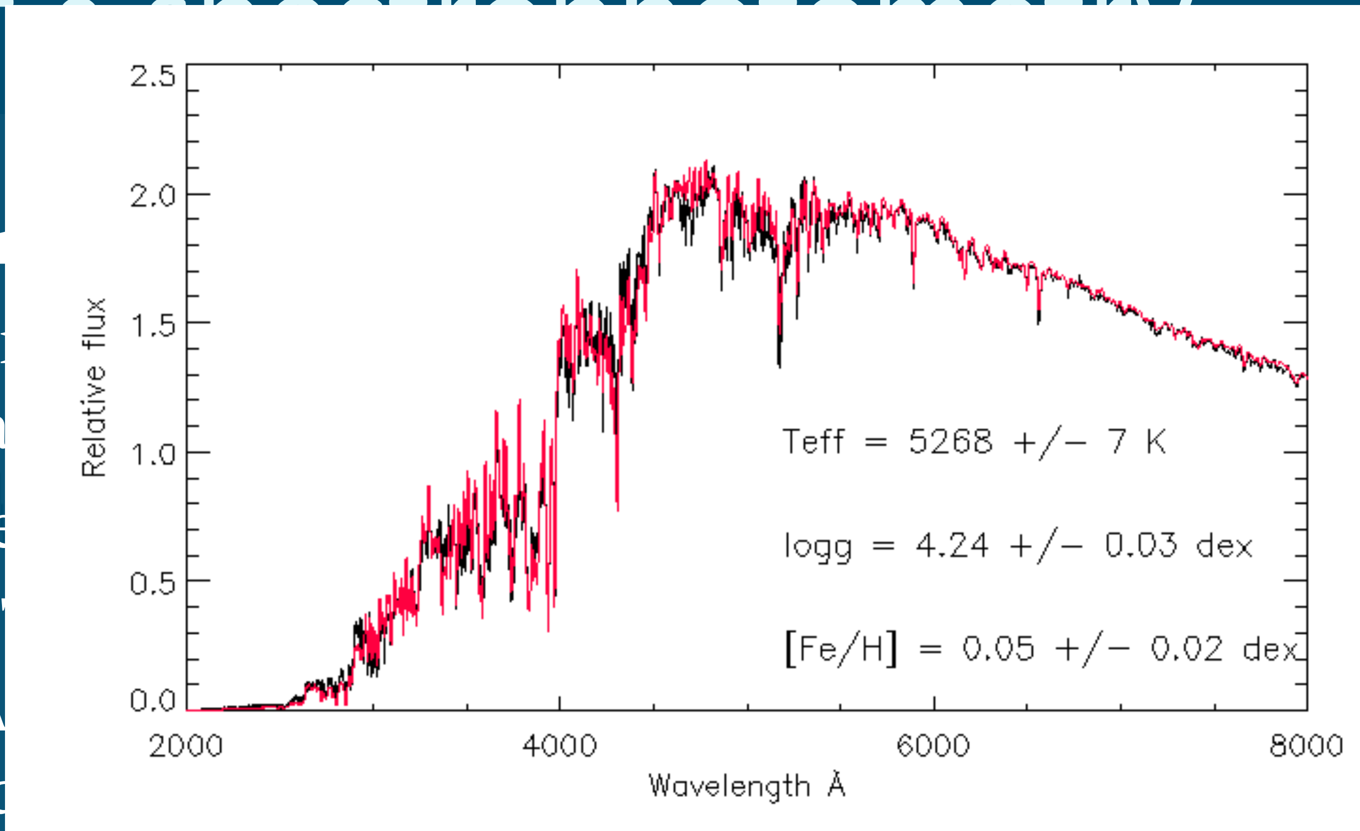
- Co
- Ha eed
  spa
- Gre n+)
- HS not
  DA ega
  and



HD 201091 (Observations from STIS NGSL)

Teff

- Co
- Ha... eed
  spa
- Gre... n+)
- HS... not
  DA... ega
  anc



HD 10780 (observations from STIS NGSL)

logg

- Gravitational field compresses the gas giving a nearly exponential density structure (pressure)
- Hard to get with accuracy: the spectrum is only weakly sensitive to gravity
- Photometry: ionization edges (Saha), molecular bands, or damping wings of strong metal lines
- Spectroscopy: ionization balance (e.g. Fe/Fe^{+}) or collisionally-dominated line wings
- Stelar structure models (luminosity)

Logg • Photometry

- Intermediate or narrow band filters (Strömgren, Mg 520 nm) taking advantage of pressure-sensitive features

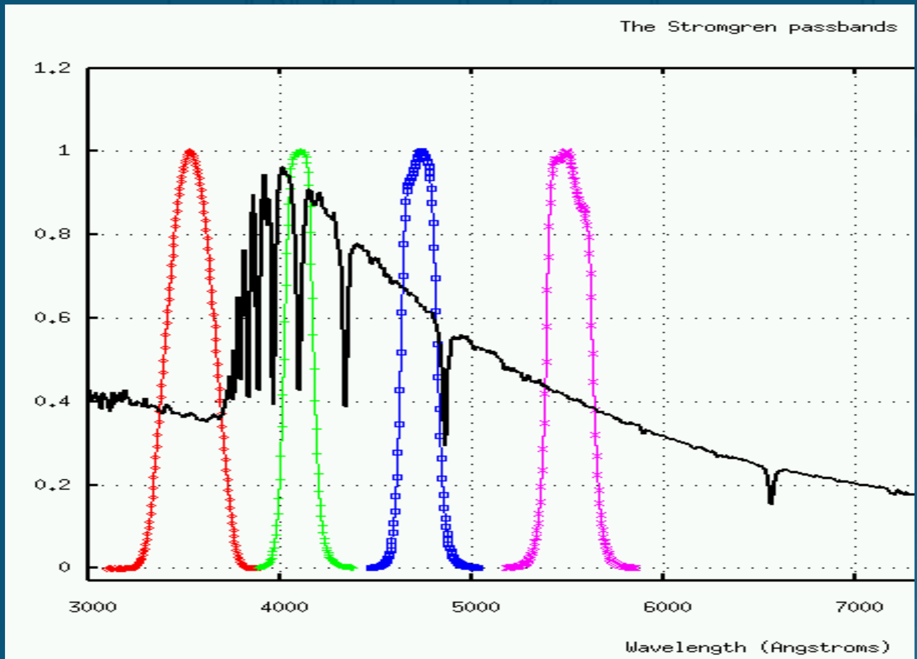
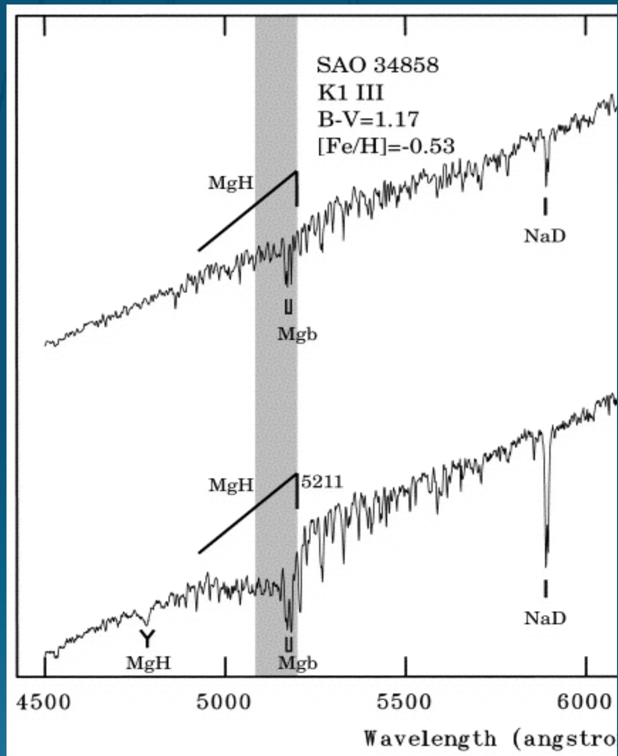


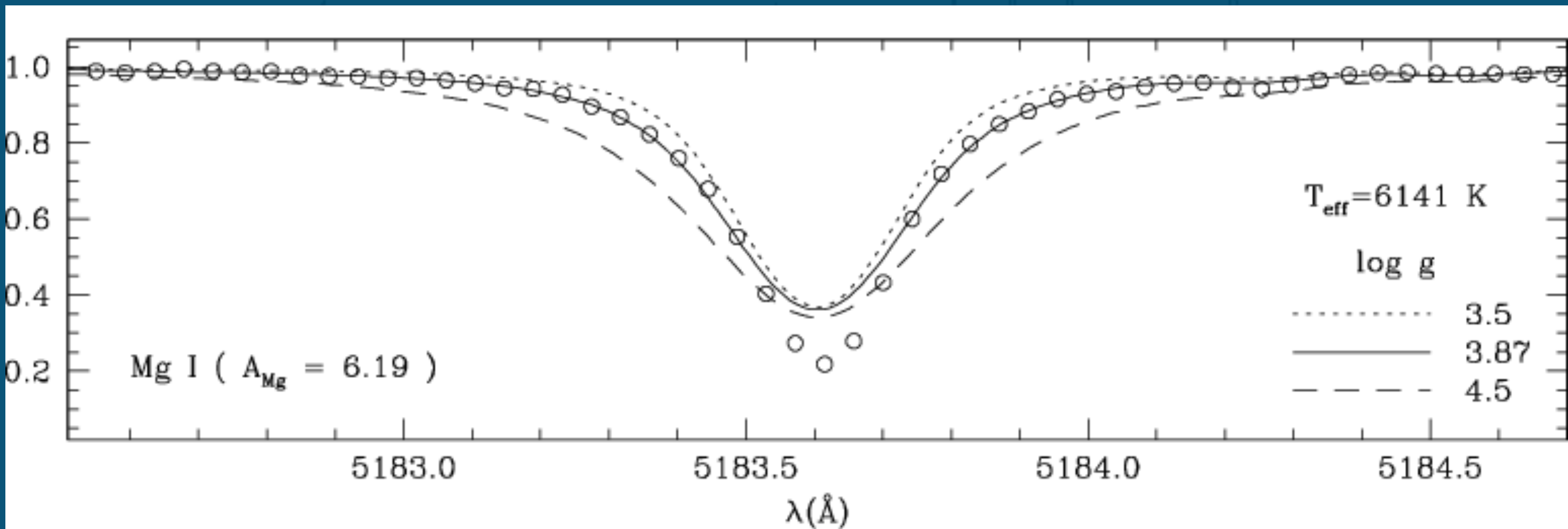
Image: Michael Richmond

Majewski + 2000



Logg • Spectroscopy

- Ionization balance: model dependent
- Strong lines (Na D, Mg b, Ca II IR triplet…)



Ramirez+ 2006

Logg • Stellar structure

- Need good luminosity determination (i.e. distance)
- Relies on interior models, fairly reliable but with caveats (solar conumdrum, convection recipes, difusion)
- Need M and R, not age
- Now statistically solid (Reddy+ 03, Jørgensen & Lindegren 05, Pont & Eyer ...)

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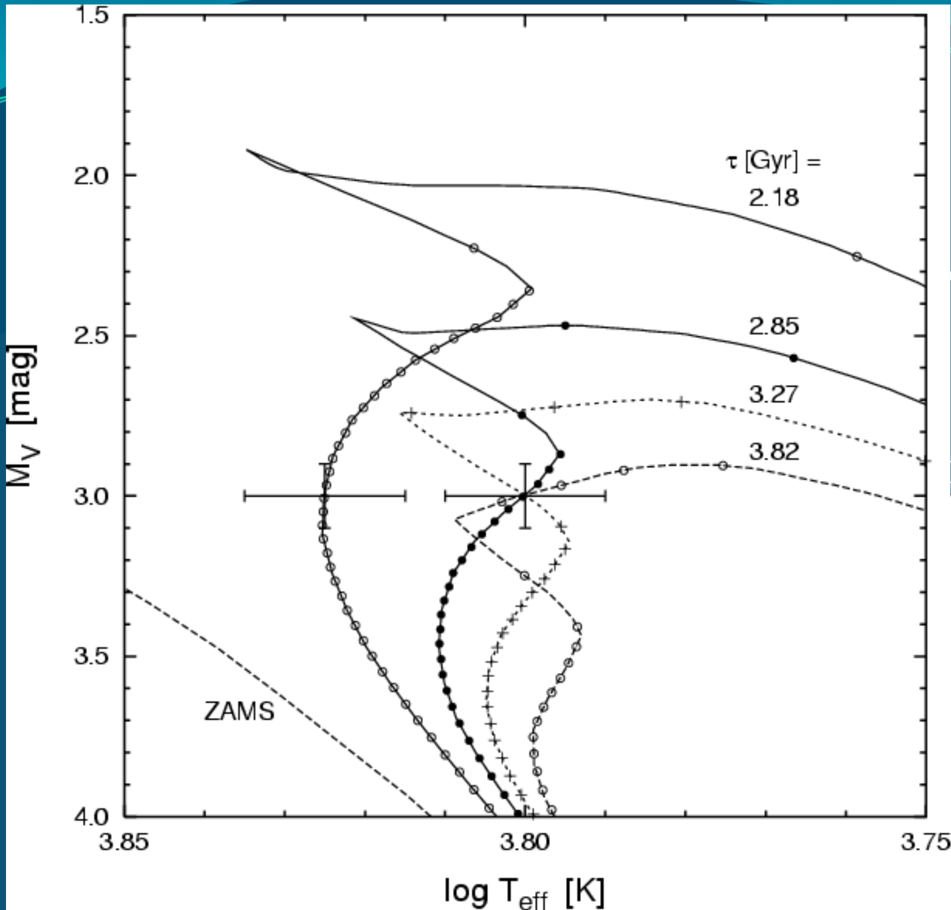

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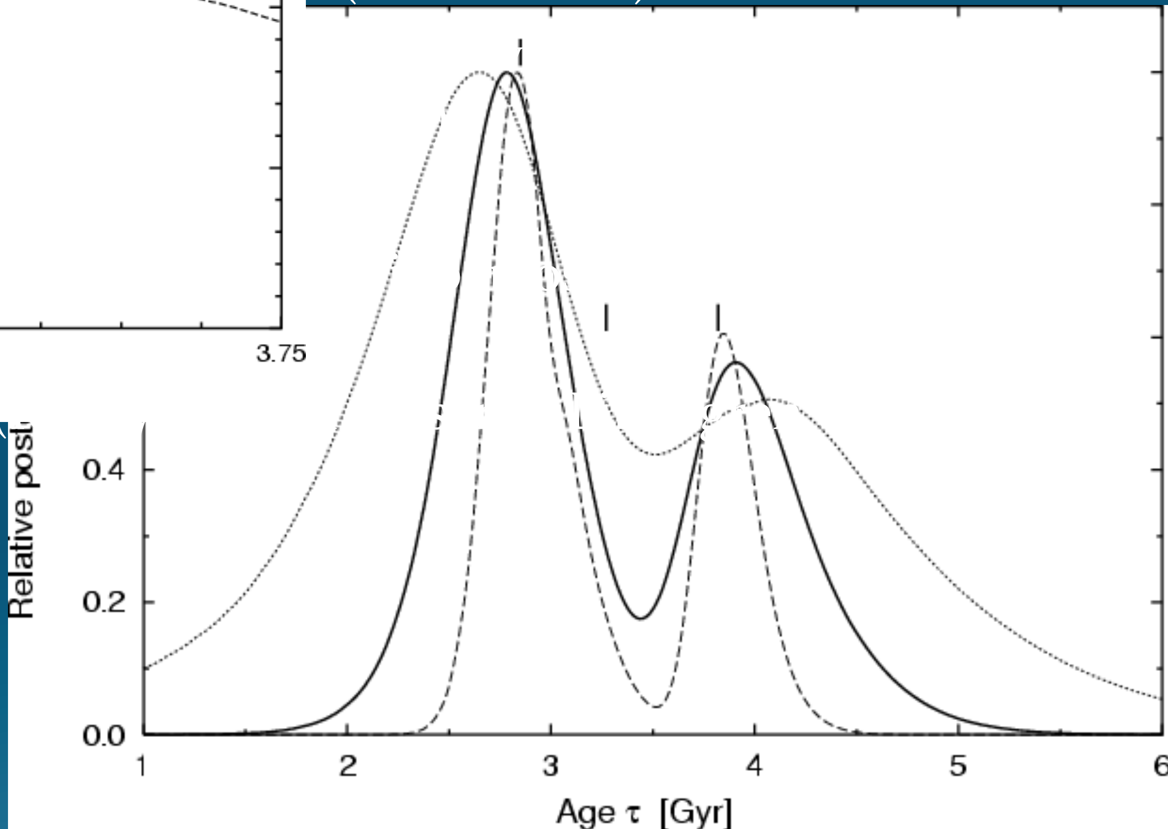
Eyer ...)



Logg • Stellar structure

- Need good luminosity determination (i.e. distance)
- Relies on interior models, fairly reliable but with caveats (solar conumdrum, convection recipes, difusion)
- Need M and R, not age
- Dominated by errors in parallaxes for Hipparcos ($V<9$, $d<100$ pc) stars, but likely not the case for Gaia
- Now statistically solid (Reddy+ 03, Jørgensen & Lindegren 05, Pont & Eyer ...)

[Fe/H]

- A big oversimplification
- High sensitivity of the spectrum (can also be derived from photometry including blue/UV), but highly model dependent
- Many weak lines, good atomic data, good spectra, and a good model
- See next talk by E. Caffau

More…R, [illegible], [illegible], E(B-V), *v sin i*

- R needed for spherical models
- Micro- macro-turbulence needed for hydrostatic models
- E(B-V) needed in photometry/spectrophotometry data are involved
- Rotation cannot be ignored, but hard to disentangle from other broadening mechanisms in late-type stars

And more… [C/Fe],[[illegible]/Fe], B

- C/O can substantially alter atmospheric structure through, e.g. CO formation
- [illegible] include abundant elements (O) and important electron donors (Mg, Ca, Si)
- Magnetic fields and chemical inhomogeneities may also be important (e.g. AM stars)

General thoughts

- Photometric and spectrosphotometric methods seem robust for Teff, but beware of reddening!
- If a good parallax is available, stellar evolution models seem safe for logg
- At high metallicity, iron lines give a good handle, but beware of 3D/NLTE for metal-poor stars
- Need consistency!

Automation

- Classical analysis methods can be coded in the computer
- These will have limitations: need to reliably measure equivalent widths (EW)
- Ultimately, the use of EW is related to simplify the calculations (scalar quantities instead of arrays) but is also somewhat blind, I.e. full spectral analysis preferred

Automation II

- Optimization methods: local (gradient, Nelder-Mead…), global (metropolis, genetic algorithms…)
- Projection methods (ANN, MATISSE, PCA, SVM…)
- Bayesian methods
- But many combinations possible
- Spectral model can be calculated on the fly or interpolated
- Issues are sometimes continuum normalization, complicated PSF, large number of dimensions, degeneracies

Massive surveys

- RAVE
  (R~7500, 841-880 nm)
- SDSS-SEGUE
  (R~1800, 380-910 nm)
- SDSS-III APOGEE
  (R~30000, 1500-1700 nm)

- Gaia RVS, BP/RP
  (R~11500, 847-874 nm)
  (R<50, 300-1000 nm)

Gaia

Blue photometer:
330 – 680 nm

Red photometer:
640 – 1000 nm

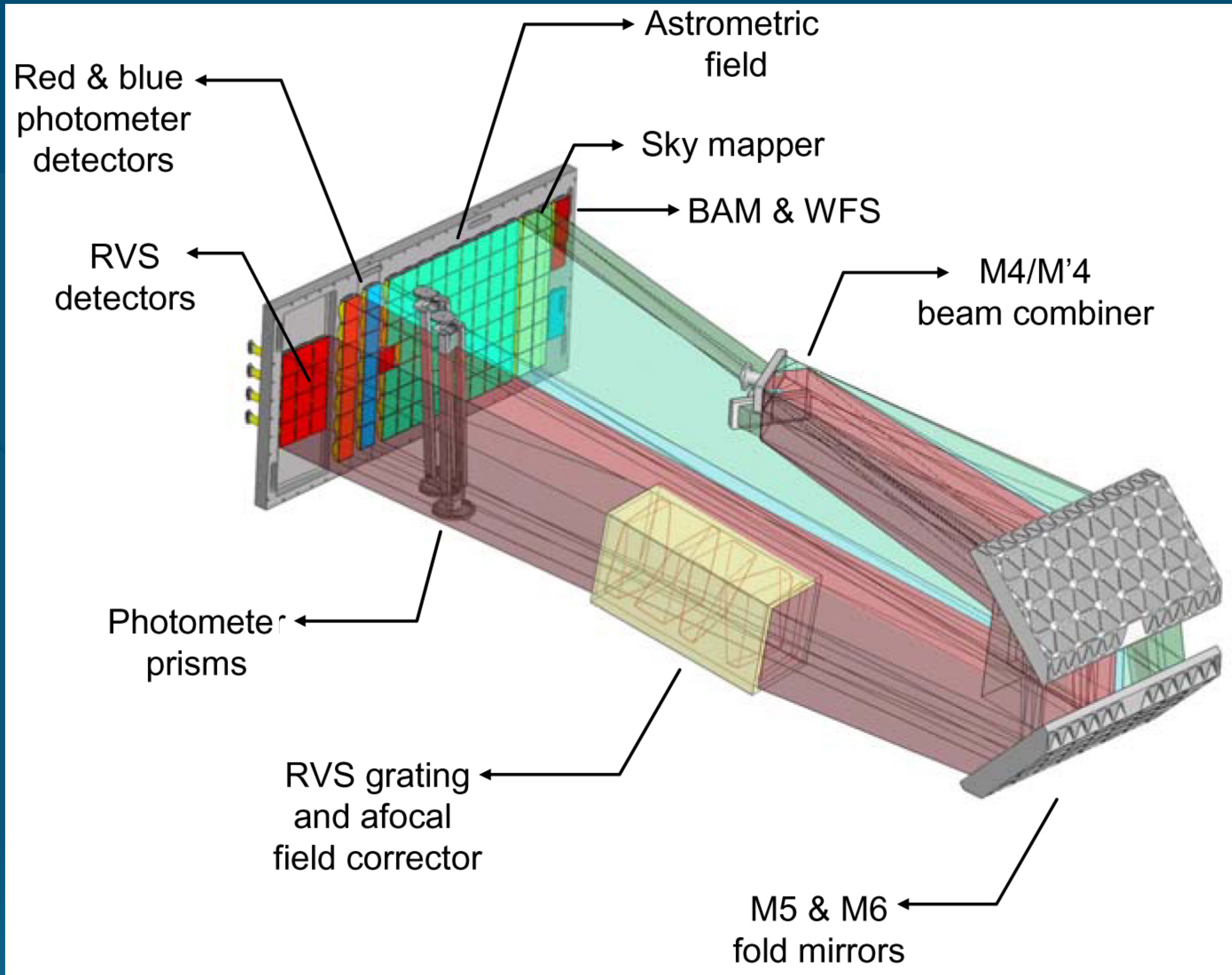
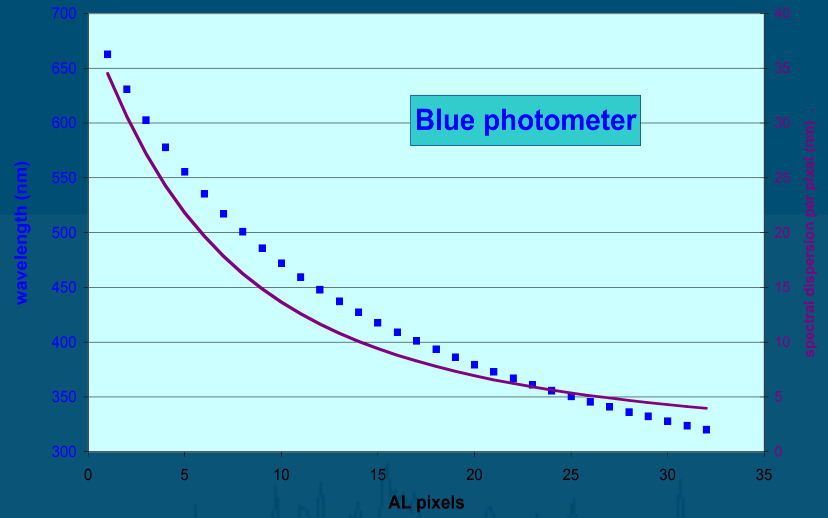
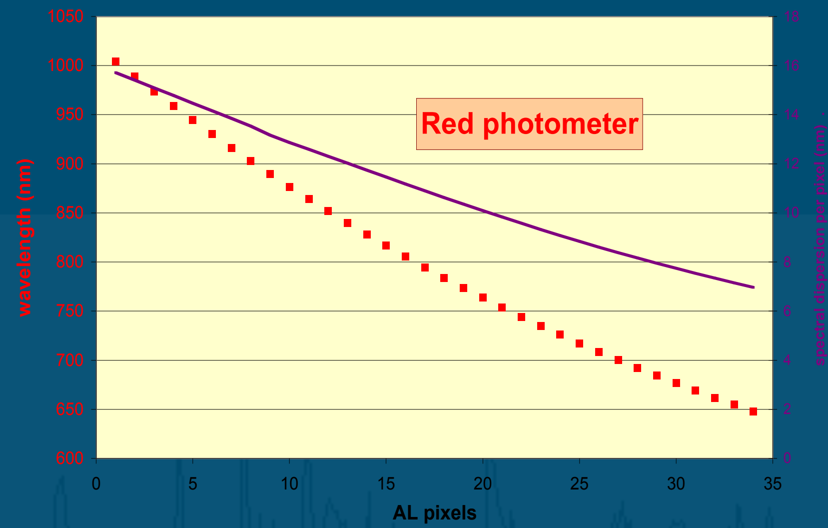
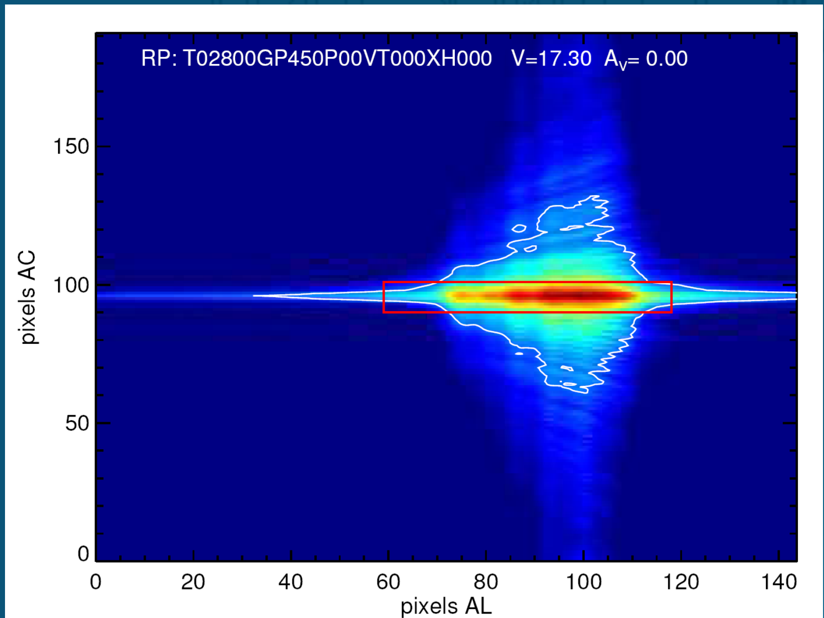


Figure courtesy EADS-Astrium

Photometry Measurement Concept





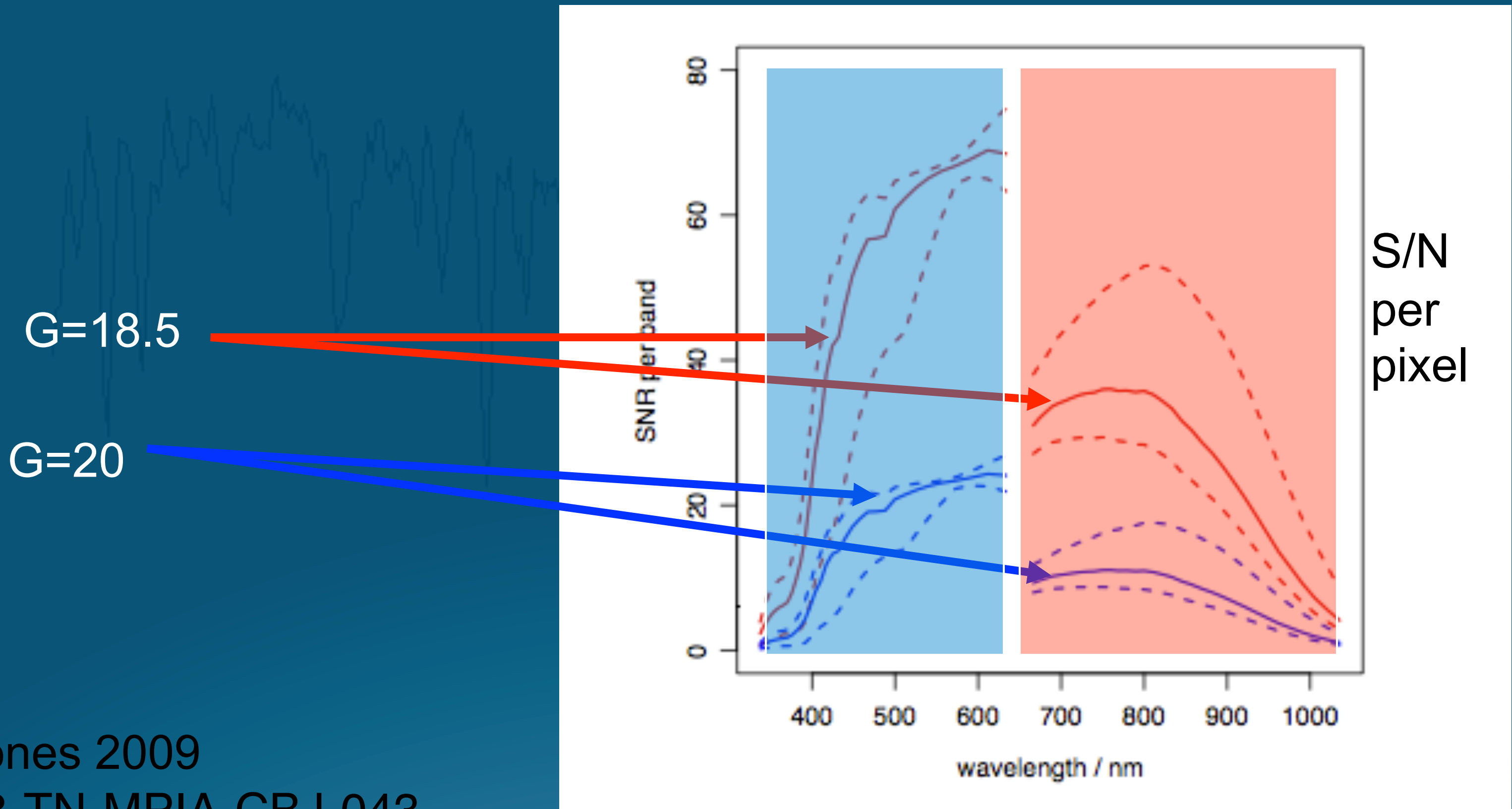


RP spectrum of M dwarf (V=17.3)
Red box: data sent to ground
White contour: sky-background level
Colour coding: signal intensity

Figures courtesy Anthony Brown

Ideal tests

- Shot, electronics (readout) noise
- Synthetic spectra
- Logg fixed (parallaxes will constrain luminosity)

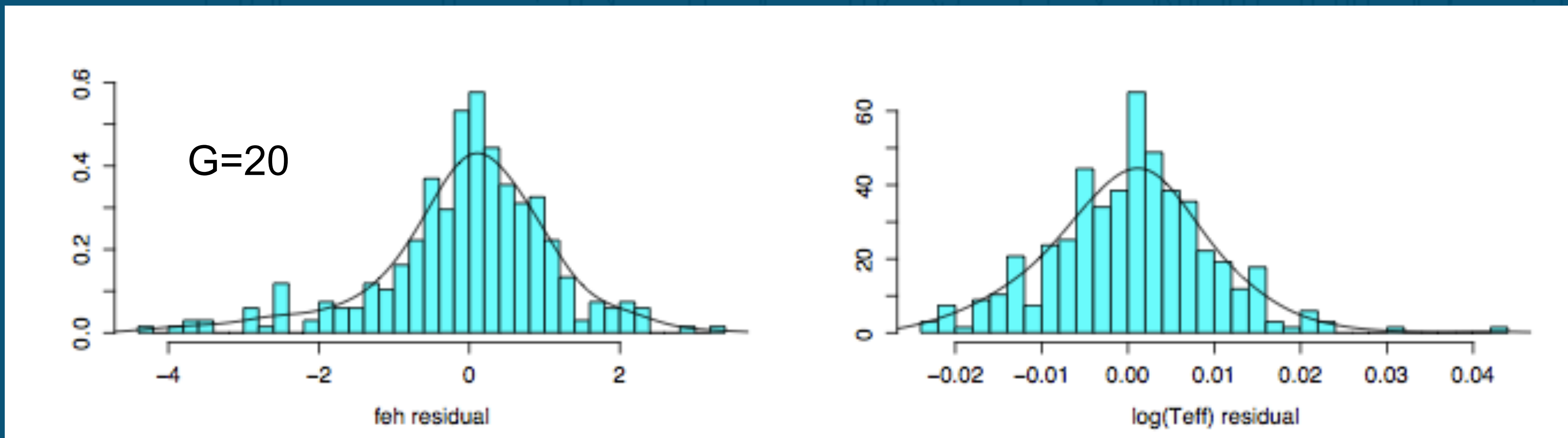


Bailer-Jones 2009
GAIA-C8-TN-MPIA-CBJ-043

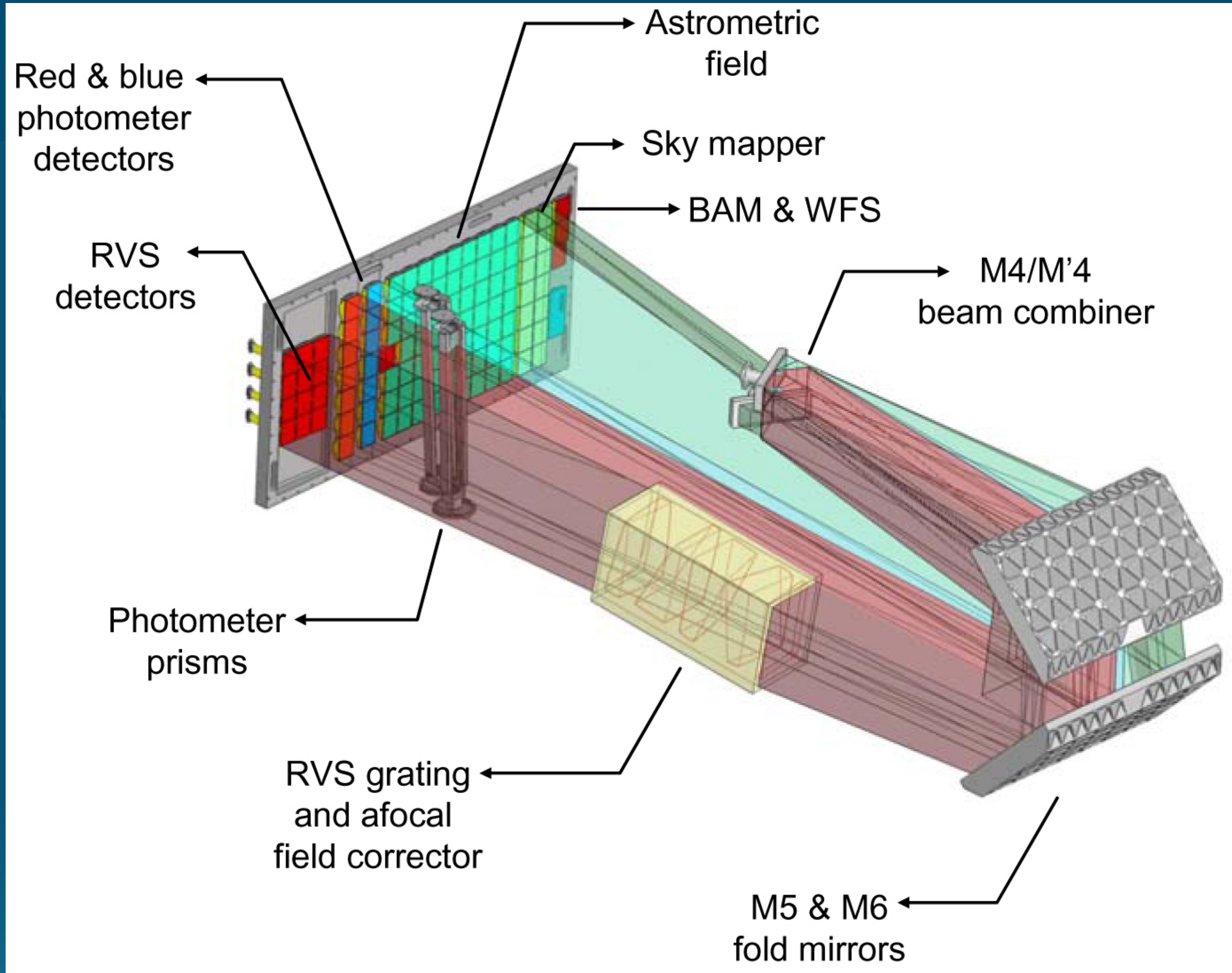
(Spectro-)photometry

- ILLIUM algorithm (Bailer-Jones 2008). Dwarfs:

G=15	σ([Fe/H])=0.21	σ(Teff)/Teff=0.005
G=18.5	σ([Fe/H])=0.42	σ(Teff)/Teff=0.008
G=20	σ([Fe/H])=1.14	σ(Teff)/Teff=0.021



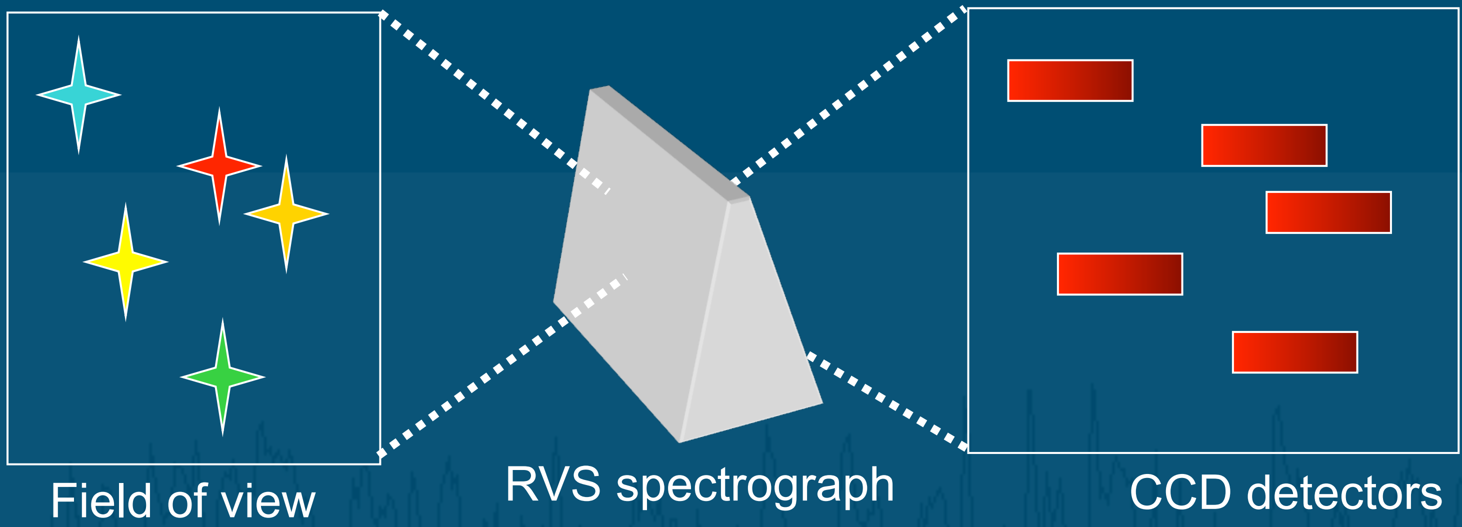
Radial Velocity Measurement Concept

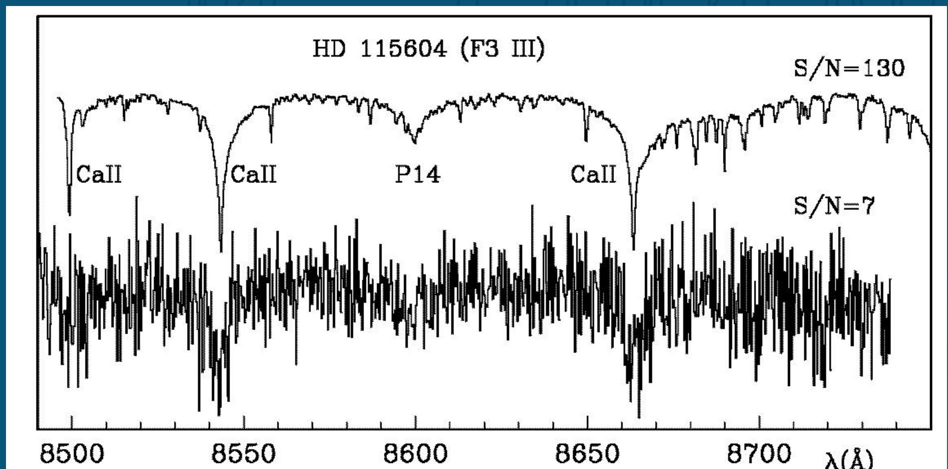


Spectroscopy: 847–874 nm (resolution 11,500)

Figures courtesy EADS-Astrium

Radial Velocity Measurement Concept



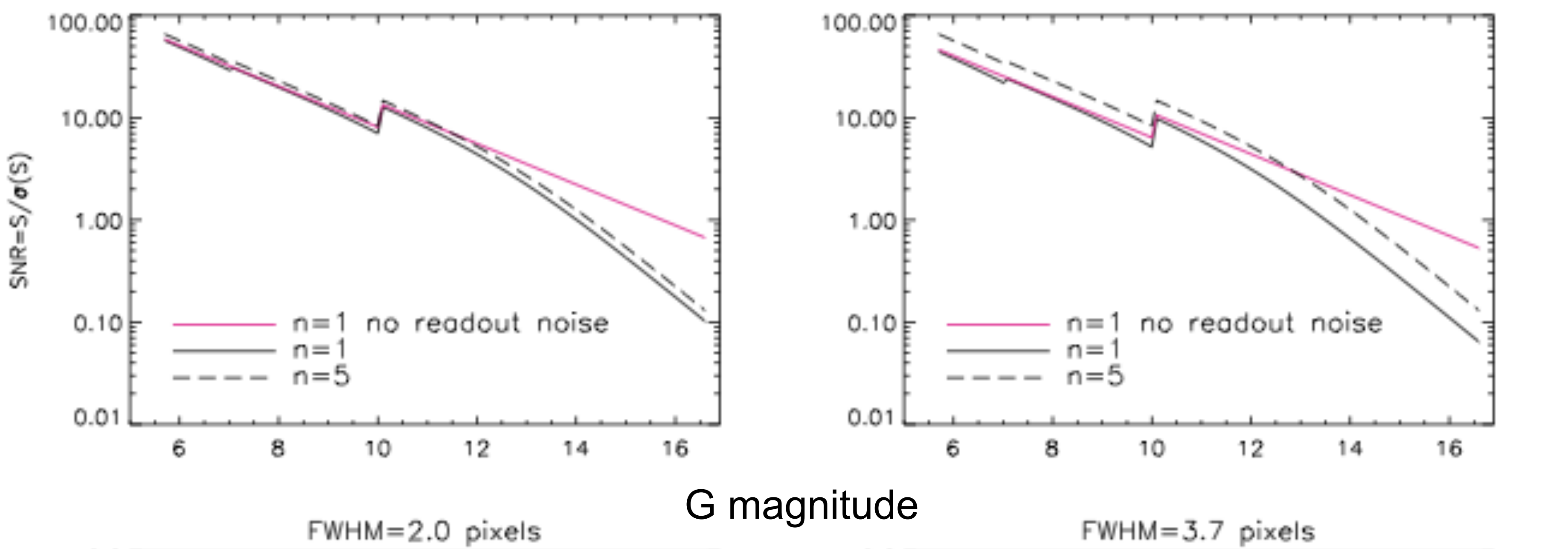


RVS spectra of F3 giant (V=16)
S/N = 7 (single measurement)
S/N = 77 (40x3 transits)

Figures courtesy David Katz

RVS S/N (per transit and ccd)

- 3 window types: G<7, 7<G<10 (R=11,500), G>10 (R~4500)
- $\sqrt{(S + rdn^2)}$
- Most of the time RVS is working with S/N<1



Allende Prieto 2009, GAIA-C6-SP-MSSL-CAP-003

RVS produce

- Radial velocities down to V~17 (10^8 stars)
- Atmospheric parameters (including overall *metallicity*) down to V~ 13-14 (several 10^6 stars)

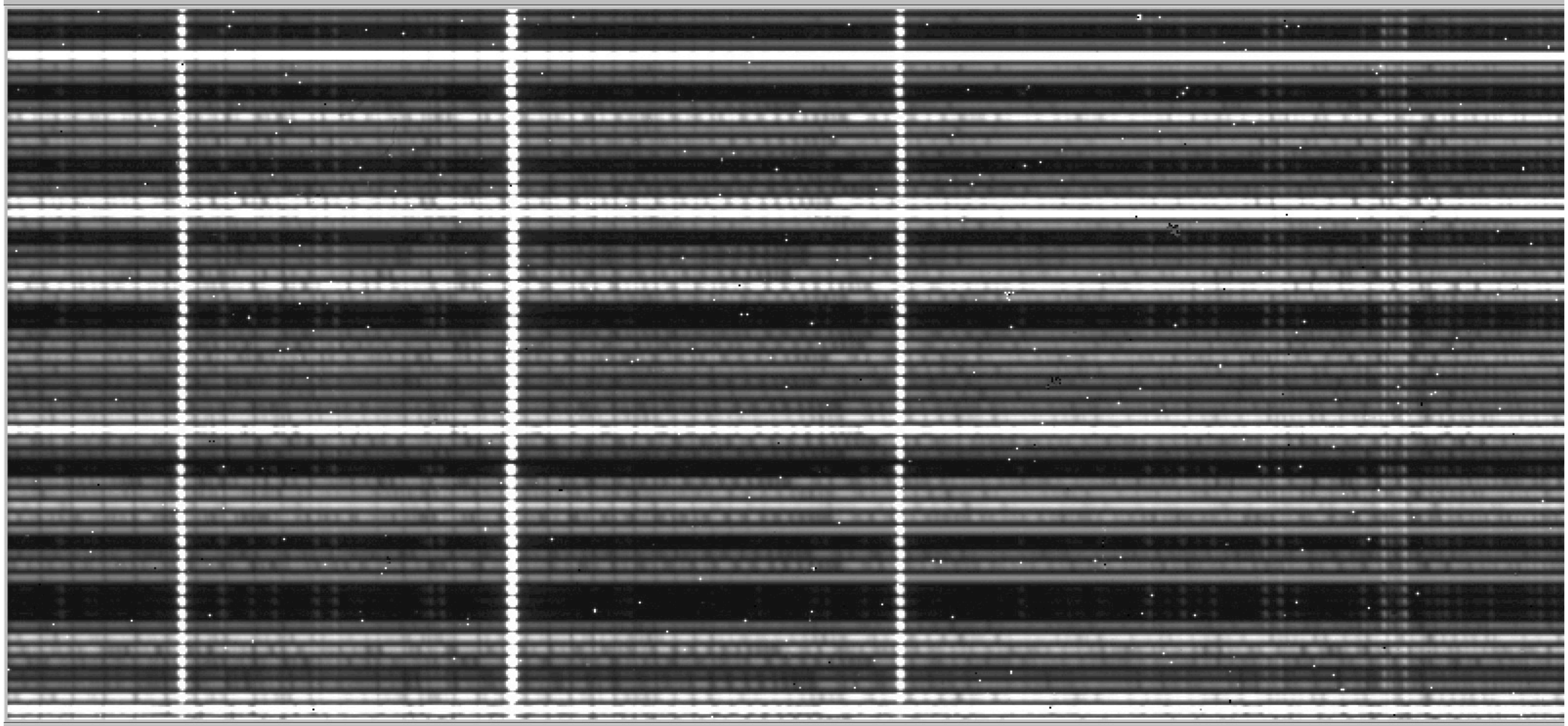
(MATISSE algorithm, Recio-Blanco, Bijaoui & de Laverny 06)

- Chemical abundances for several elements down to V~12-13 (few 10^6 stars)
- Extinction (DIB at 862.0 nm) down to V~13 (e.g. Munari et al. 2008)
- ~ 40 transits will identify a large number of new spectroscopic binaries with periods < 15 yr (CU4, CU6, CU8)

APOGEE Spectra

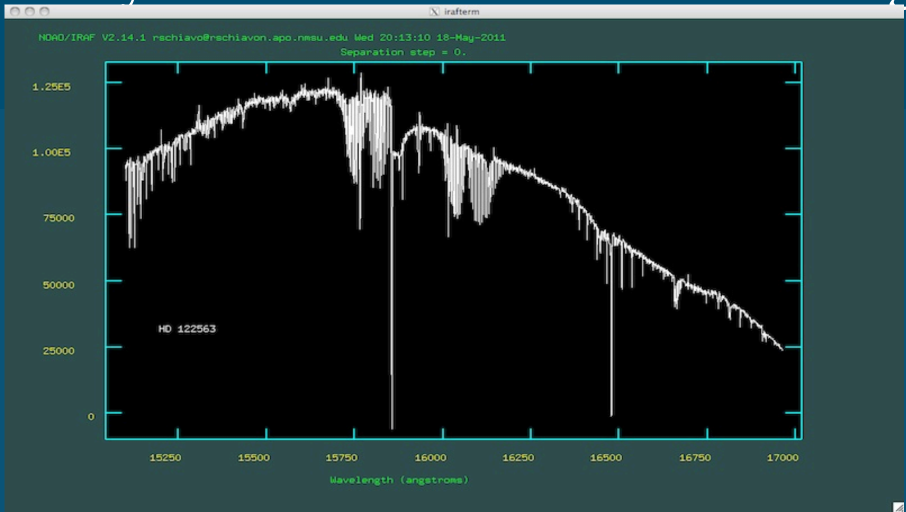
- May 11-22: First full APOGEE bright run.

Below: First APOGEE+2.5-m observations of Galactic bulge.

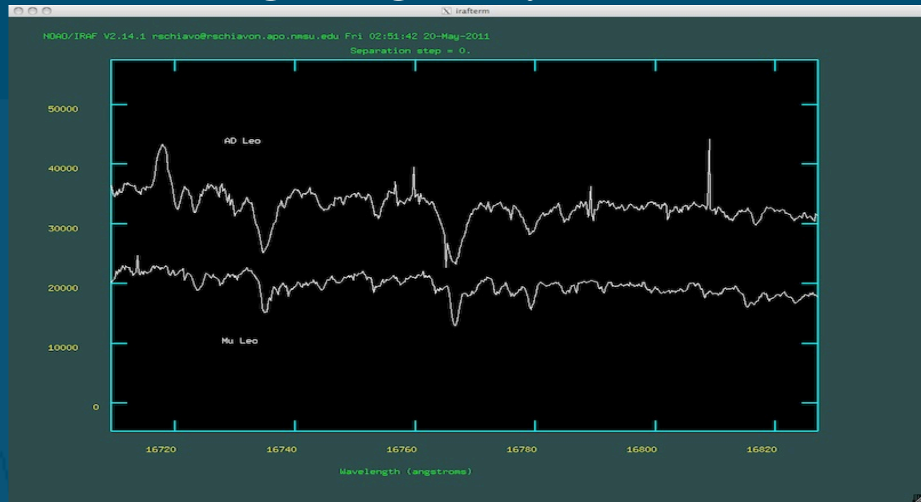


APOGEE data

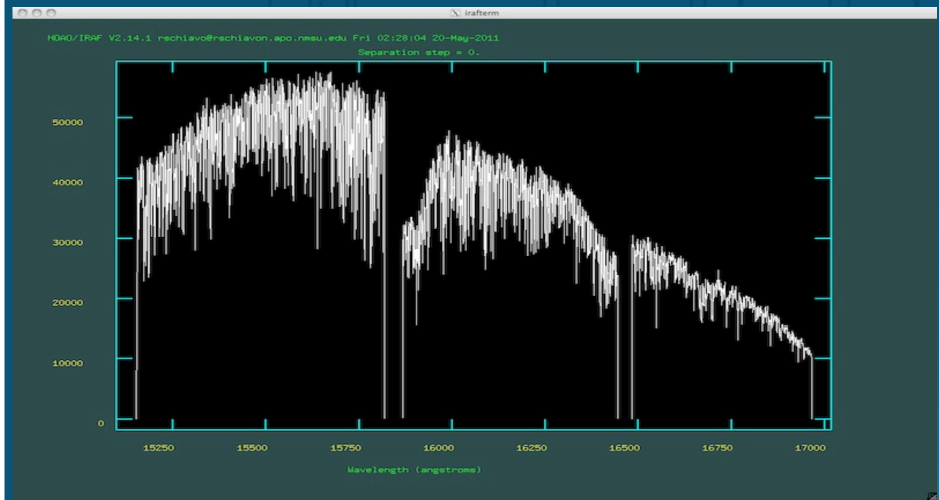
- May 11-22: First full APOGEE bright run -- rogues gallery.



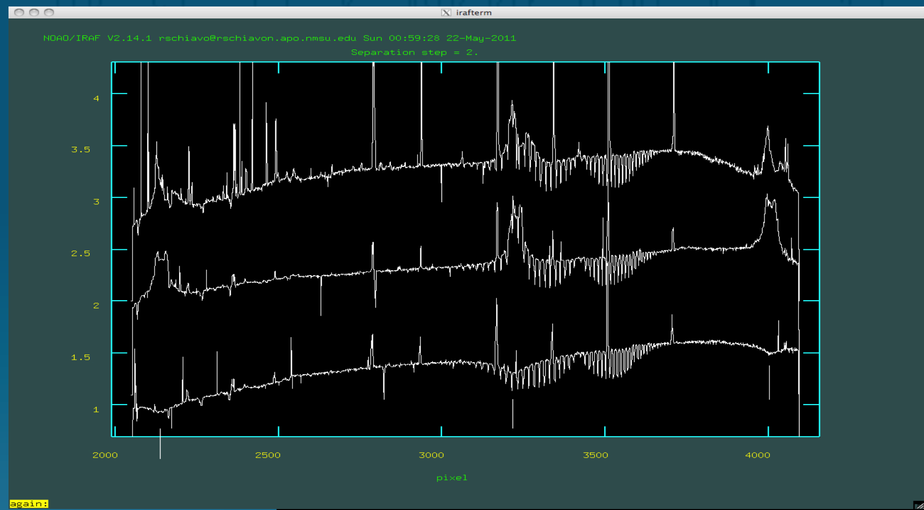
High S/N (>100) exposure of the very metal poor star HD 122563.



Zoomed in comparison of M dwarf (AD Leo) and M giant (μ Leo).



μ Leo, a metal-rich giant star.



Some newly d[redacted]

Data Analysis

- FERRE optimization with interpolation on a pre-computed grid
- N-dimensional f90 code
- Various algorithms: Nelder-Mead (Nelder & Mead 1965), uobyqa (Powell 2002), Boender-Rinnooy Kan-Strougie-Timmer algorithm (1982)
- Linear, quadratic, cubic spline interpolation
- Spectral library on memory or disk
- PCA compression
- Handling of complex PSF w/o compression
- Flexible: SDSS/SEGUE, WD surveys, APOGEE, STELLA, Gaia-ESO...

Abundances & Stellar Parameters

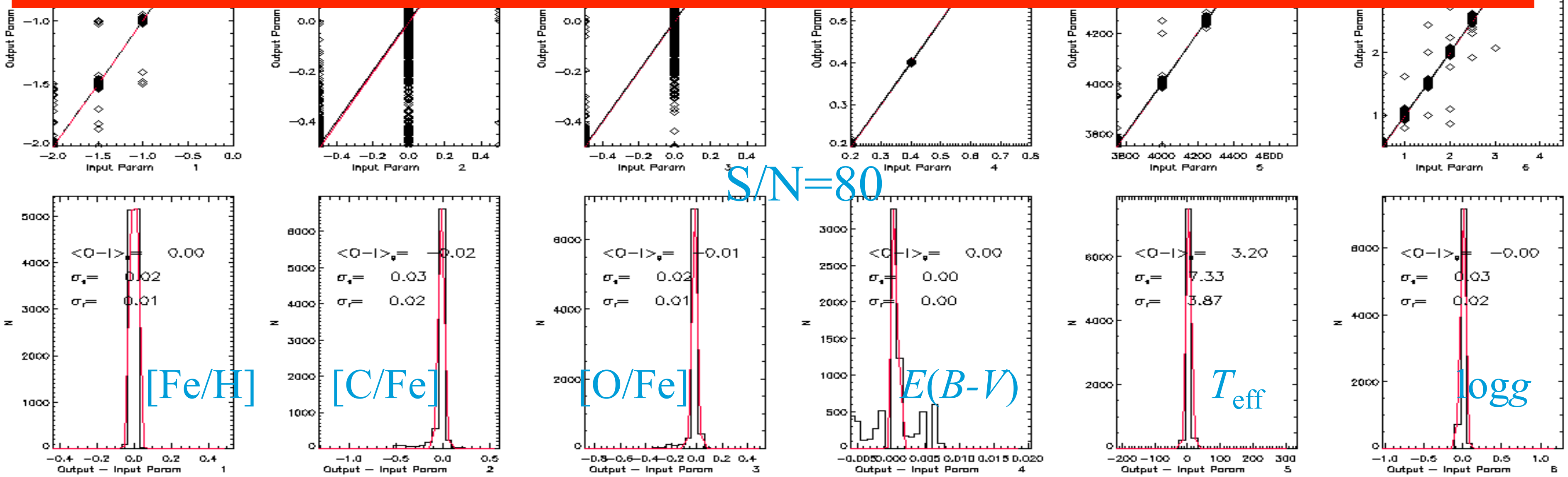
fundamental parameters:

- 3 ($T_{\rm eff}$, log g, [Fe/H])
- 4 ($T_{\rm eff}$, log g, [Fe/H], [C/Fe])
- 5 ($T_{\rm eff}$, log g, [Fe/H], [C/Fe],)
- 5 ($T_{\rm eff}$, log g, [Fe/H], [C/Fe], [O/Fe])
- 6 ($T_{\rm eff}$, log g, [Fe/H], [C/Fe], [O/Fe], E(B-V))
- 6 ($T_{\rm eff}$, log g, [Fe/H], [C/Fe], [C/Fe], [N/Fe])

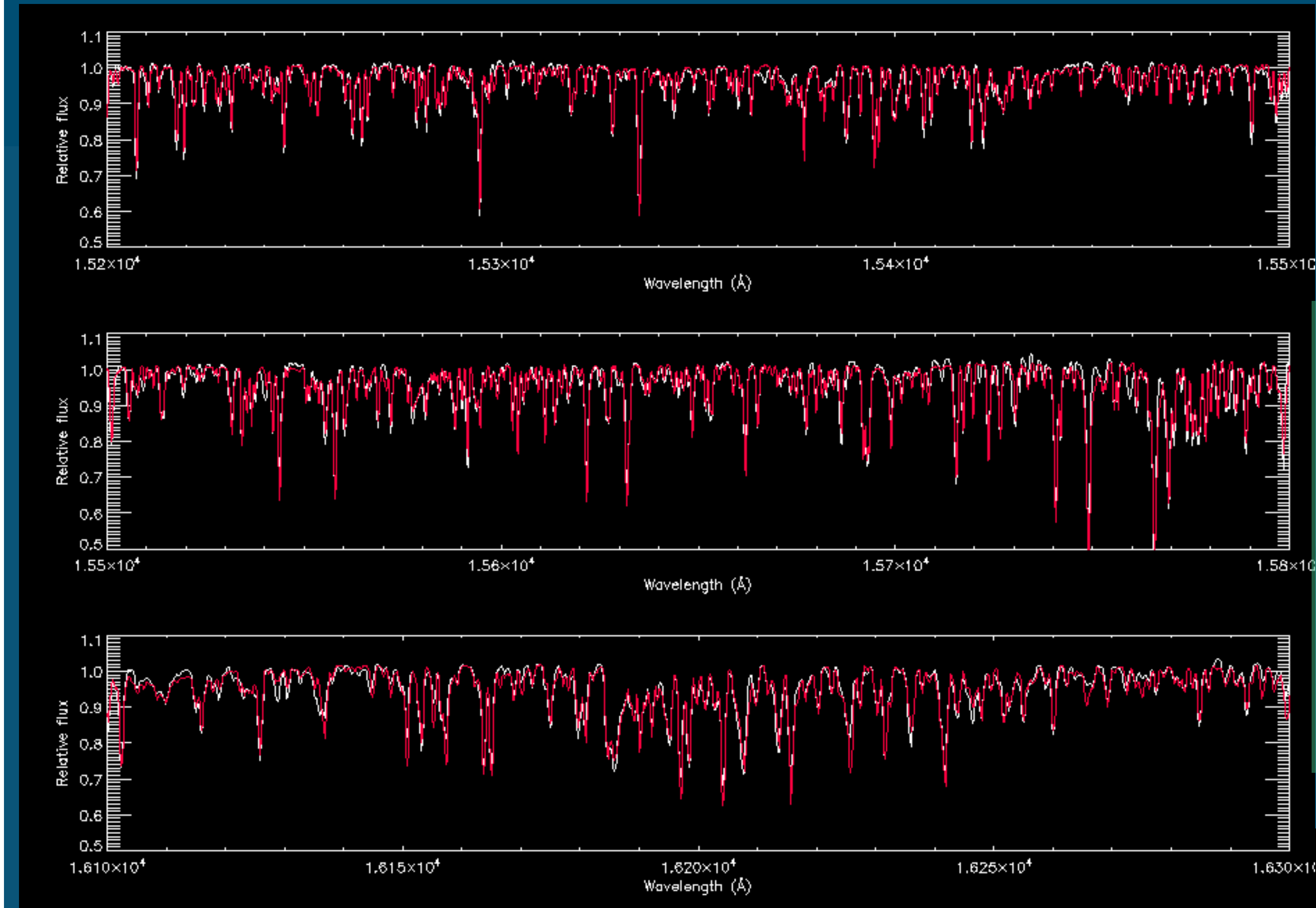
…

- For many/most targets (disk cool giants):
  - $T_{\rm eff}$, log g, Fe/H, C/Fe, N/Fe, O/Fe, maybe .
- Simplify for metal-poor stars ([Fe/H] < -1 or -2):
  - $T_{\rm eff}$, log g, Fe/H, O/Fe, maybe .
- Simplify for warmer types (G-F):
  - $T_{\rm eff}$, log g, Fe/H, C/H, maybe .

A minute/star/processor (3.5 days on 20 processors for 100,000 stars)



Abundances & Stellar Parameters



Teff=4408 K
logg=2.13
Log10([illegible])=0.33
[Fe/H]=-0.56
[C/Fe]=+0.44
[N/Fe]=+0.02
[O/Fe]=+0.50

ASPCAP Fitting the Arcturus spectrum (Hinkle et al.) smoothed to R=30,000

Closing remarks

- Significant progress has taken place in the last few years as to extracting atmospheric parameters from spectra and photometry
- We still lack a general recipe that gives the best results in all cases-- consistency checks are necessary
- 3D models and NLTE are beginning to be used, although only marginally
- Improvements in fundamental data also slow, but happening
- Automation is improving dramatically, in response to the needs of the onging/coming massive surveys

RV performance

Table 1: RVS Average Signal per HR sample

V (mag)/SpT	7 /B1V	13/G2V	13.5/K1III	12/B1V	16.5/G2V	17/K1III
G_{rvs} (mag)	7.3	12.2	12.3	12.3	15.7	15.8
mode	HR	LR	LR	LR	LR	LR
I (e^-)	1033.	34.0	31.0	31.0	1.35	1.23
σ (e^-)	32.6	7.9	7.7	7.7	5.4	5.4

V(mag)	11	13.5	17
G2V	1.6	1.7	14.5
K1III-MP	1.4	1.6	15.7

Spec. for late-type stars

1 km/s at V<13

15 km/s down to V=17

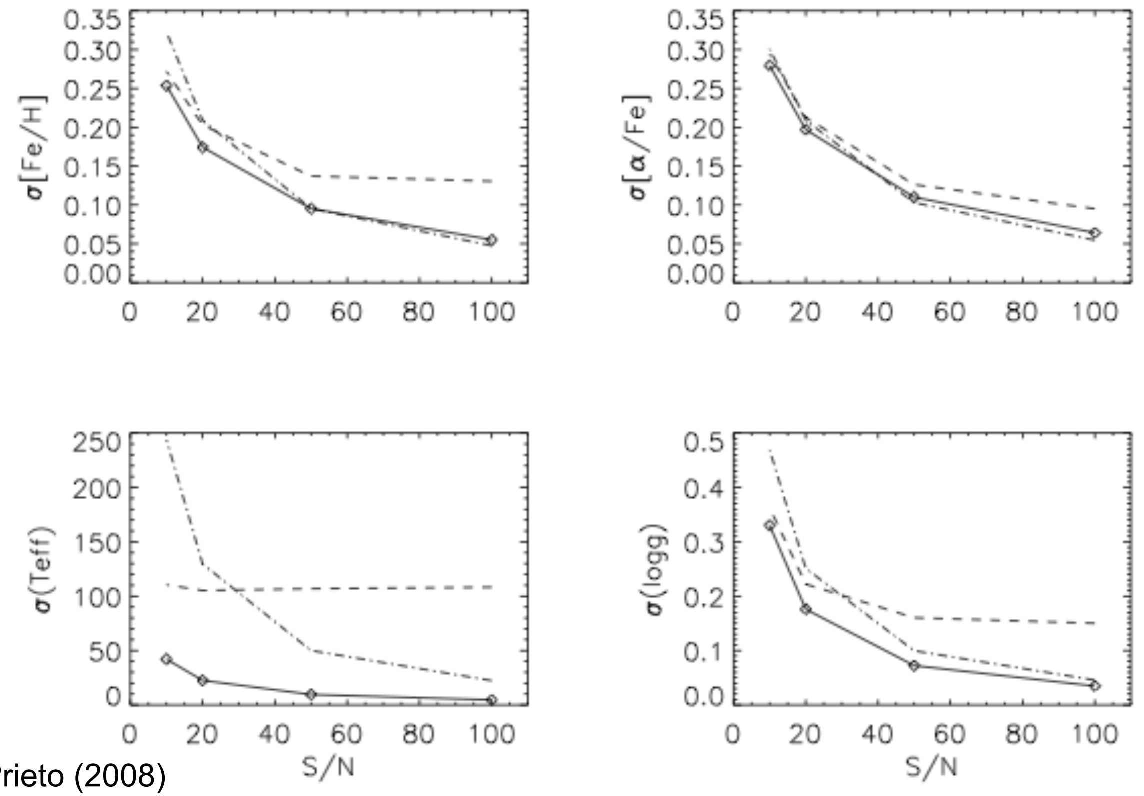
performance estimates as of 2009

Atmospheric parameters (Ideal tests)

Solid: absolute flux

Dashed: absolute flux, systematic errors (S/N=1/20)

Dash-dotted: relative flux



Allende Prieto (2008)

APOGEE Instrument

- End of April: On-site installation.