Stellar Parameter Determination

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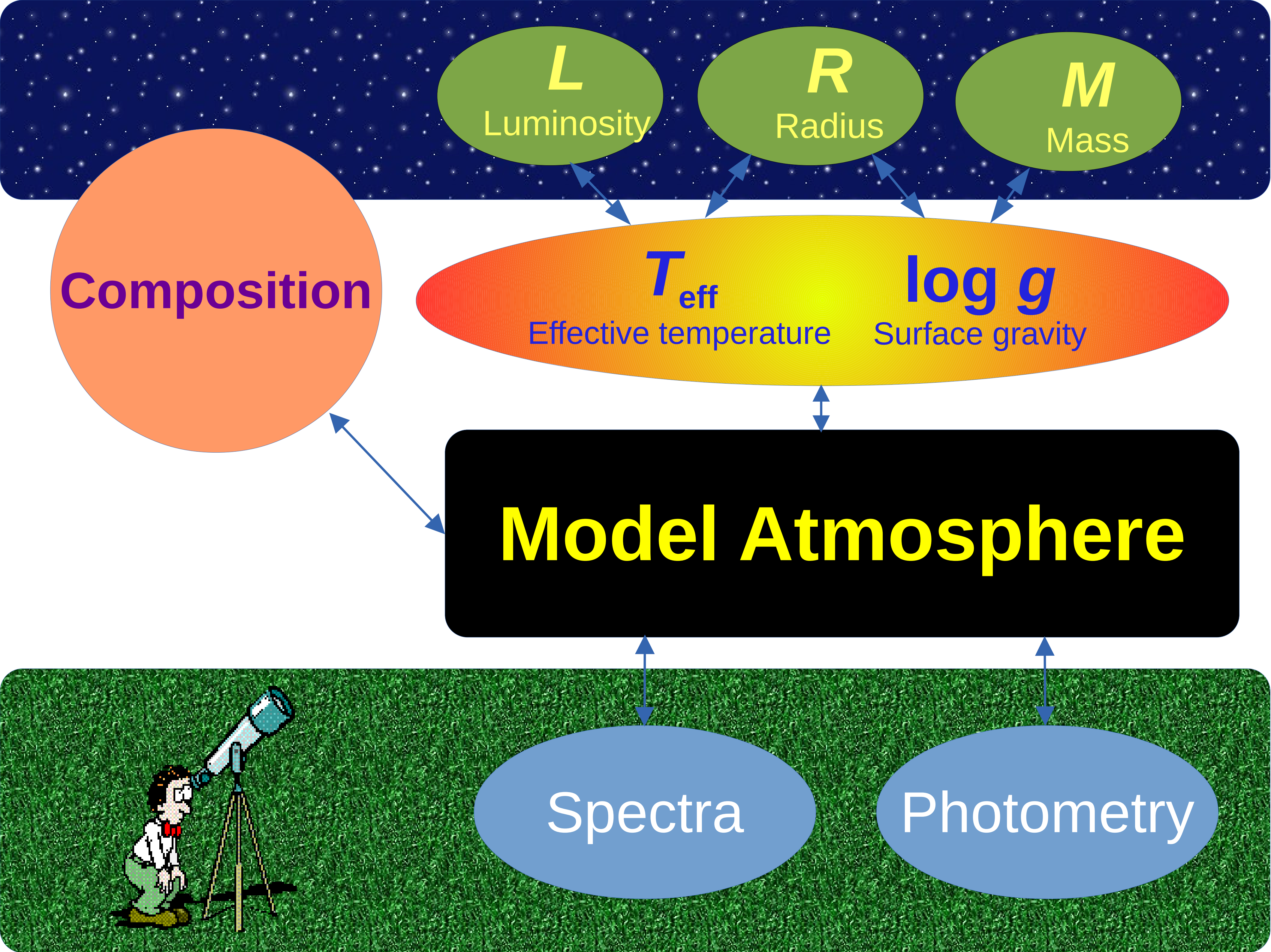


L
Luminosity

R
Radius

M
Mass

Composition

$T_{\rm eff}$
Effective temperature

$\log g$
Surface gravity

Model Atmosphere

Spectra

Photometry

Effective Temperature

$$\sigma T_{eff}^4 \equiv \int_0^\infty F_\nu \, d\nu = F_\star = \frac{L}{4\pi R^2}$$

- Temperature of a black body that gives the same total power per unit area.
- Physically related to $F_\star$ total radiant power per unit area at stellar surface.
- T_{eff} of star is temperature of blackbody with same luminosity and radius as the star

T_{eff}: Observable quantities

$$F_\star = \frac{\theta^2}{4} f_\oplus$$

- $f_\oplus$ **total** flux at earth (UV, optical, IR)
  - **Corrected for interstellar reddening**
- θ is angular diameter
  - Directly: interferometry, lunar occultations
    - **Use limb-darkening corrected values**
  - Indirectly from eclipsing binary systems with known distances (parallaxes): $\theta \propto R/d \propto R\,\pi$

.. and asteroseismology !

Surface Gravity

Surface Gravity

Stellar Density

$$g = g_{\odot} M / R^2, \rho = \rho_{\odot} M / R^3 \qquad g = R\rho = M^{1/3} \rho^{2/3}$$

- Directly given by stellar mass and radius.
  - An *indirect* measure of photospheric pressure
- Obtainable from:
  - Pairs (binary stars) R and M
  - Pulsations (astereoseismology) ρ and R
  - Planets (transits) Just ρ (but need M or R)

Fundamental Stars

- Fundamental stars can give accurate values of T_{eff} and log g for selected stars only.
    - Except for the Sun, good to no better than 1~2 %
- Composition is *not directly* measured
    - Closest is the Sun via solar system material
        - Fe 7.50 ± 0.04 (photosphere) 7.45 ± 0.01 (meteorites) Asplund et al., 2009, ARA&A, 47, 481

Everything else is model dependent!

F,G and K Reference Stars

- For example, the GAIA Benchmark Stars
  - 34 Stars with well determined parameters
    - **Not all have fundamental T_{eff} and log g.**

  - Blanco-Cuaresma et al., 2014, A&A, 566, A98;
  - Jofre et al. 2014, A&A, 564, 133

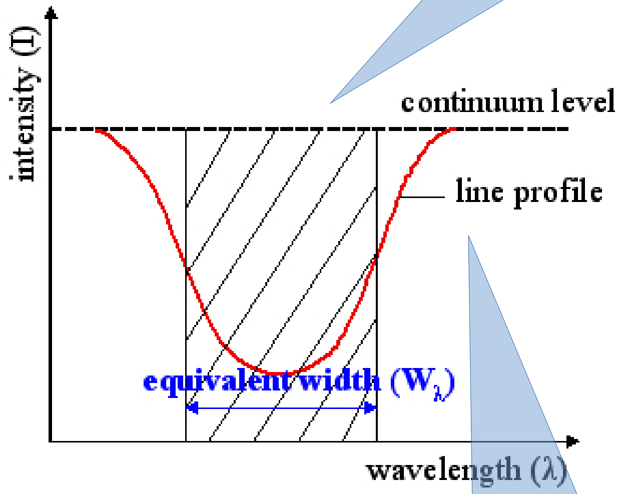
Indirect Methods

- Direct determination is usually impractical for most stars.
- Have to use indirect methods:
  - Photometric calibrations
  - Infrared Flux Method
  - Spectrophotometric flux fitting
  - Balmer Profiles
  - Line ratios
  - Equivalent Width Analysis
  - Spectrum Synthesis

Equivalent Width

- Measure of number of absorbers
  - Abundance
  - No information on profile shape
- Measure EWs of spectral lines
  - Manually
  - Automatically (ARES, DAOSPEC)

Small errors in continuum can lead to relatively large errors in EW



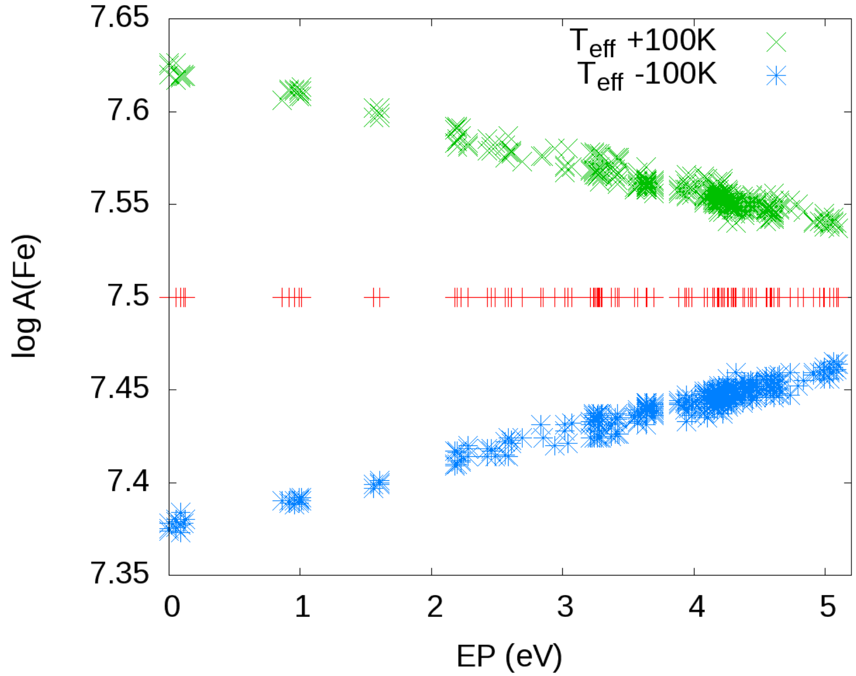
$$W_\lambda = \int_0^\infty \left(1 - F_\lambda / F_0\right) d\lambda$$

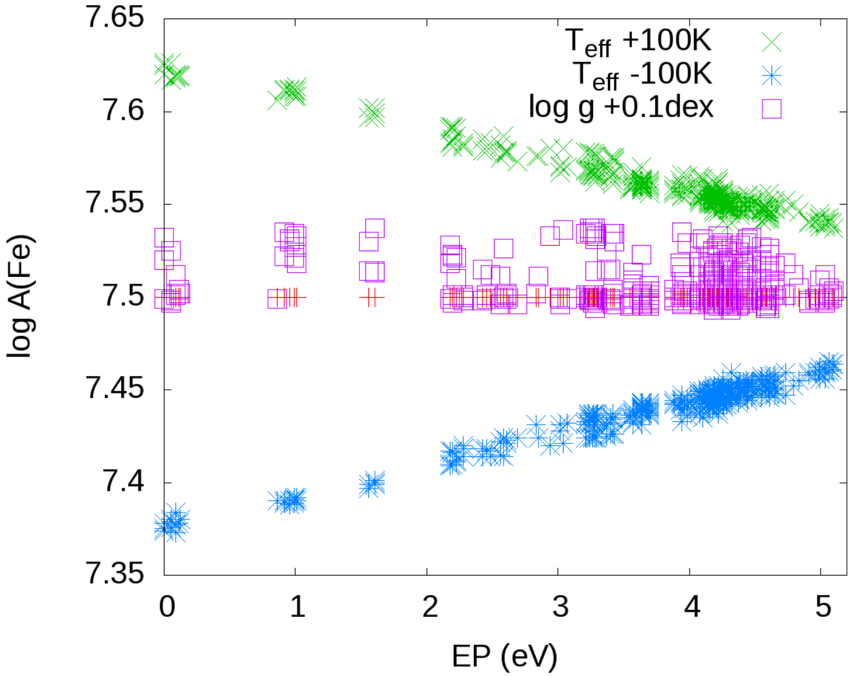
- Avoid strong lines with wings
  - Profile truncation leads to underestimated EW

Metal Line Diagnostics

- log A versus Excitation Potential (T_{eff})
  - Abundances from the same element should agree for all excitation potentials, i.e. no trend
- log A versus EW (microturbulence)
  - Adjust V_{micro} until no trend with EW
- Ionization Balance (log g)
  - Average log A obtained from differing ionization stages of the same element must agree
    - Fe I/Fe II ratio can be used as a T_{eff} – log g diagnostic

Effect of changing parameters





Simulation
Base model
T_{eff} = 6000 K
log g = 4.5
log A(Fe) = 7.50

Fe I lines (not pressure sensitive in Solar-type stars)
Wavelength range 5000-6000Å
5 < EW < 100 mÅ (avoid very weak or saturated lines)

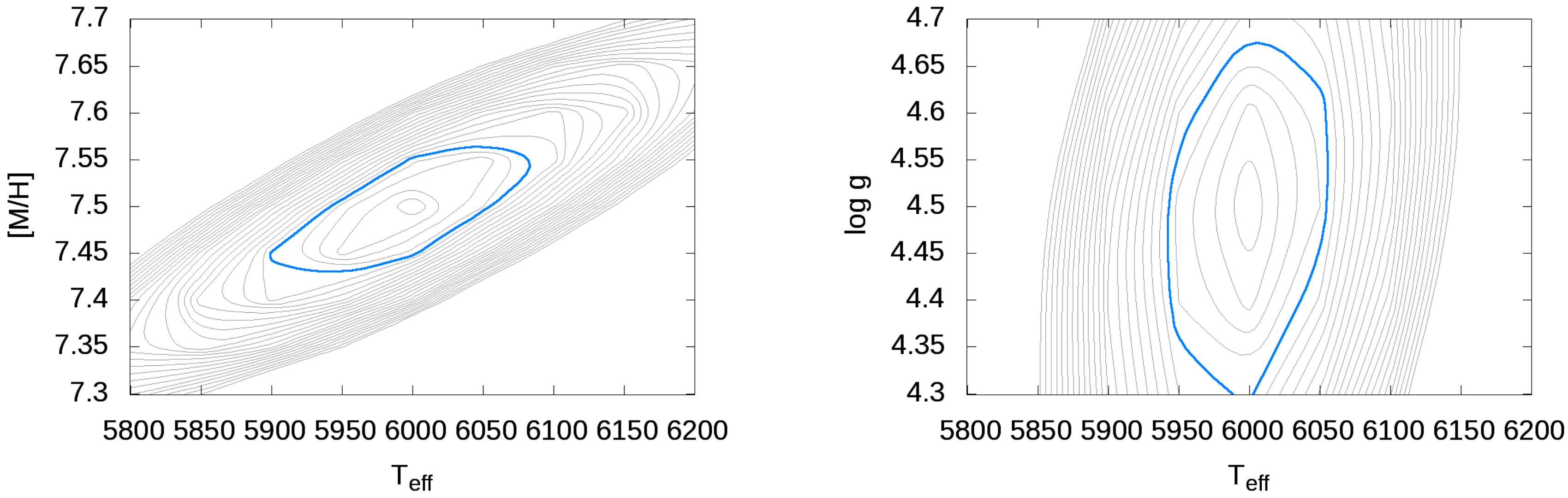
Spectral Fitting

- Measuring equivalent widths might not always be practical.
  - Blending, high rotation, etc.

- Take all or selected parts of spectrum
- Vary input parameters and calculate synthetic spectrum.
- Fit best fitting solution (minizimize χ^2)
  - Error estimates are usually just internal precision

What about missing or incorrect line data?

χ^2 Correlations



- Correlation between [M/H] and T_{eff}
- Weak sensitivity to log *g*

Simulation
Base model
T_{eff} = 6000 K
log g = 4.5
log A(Fe) = 7.50

Generated with all lines with EW >5mÅ
in wavelength range 5000-6000Å

Assumed S/N 100:1 for χ^2 calculation

A complex stellar recipe

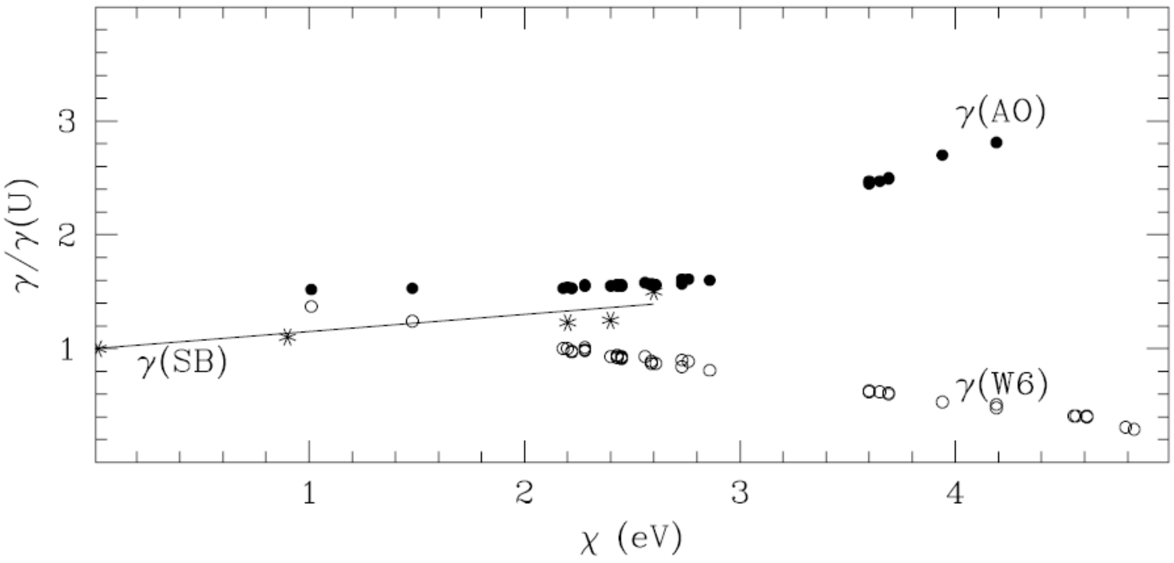
- **Atomic/Molecular data**
  - Log *gf*, damping constants, missing/bad lines, hyperfine structure, isotopes
- **Atmospheric Physics**
  - NLTE, convection, turbulence, spots, abundance clouds
- **Modelling Code internals**
  - Partition functions, continuous opacities, numerical precision
- **Analysis Methods**
  - Equivalent widths, profile fitting, choice of lines and wavelength regions
- **Data Quality**
  - S/N, scattered light, continuum normalisation, telluric/interstellar lines
- **Stellar properties**
  - Binarity, variability

Plus other ingredients!

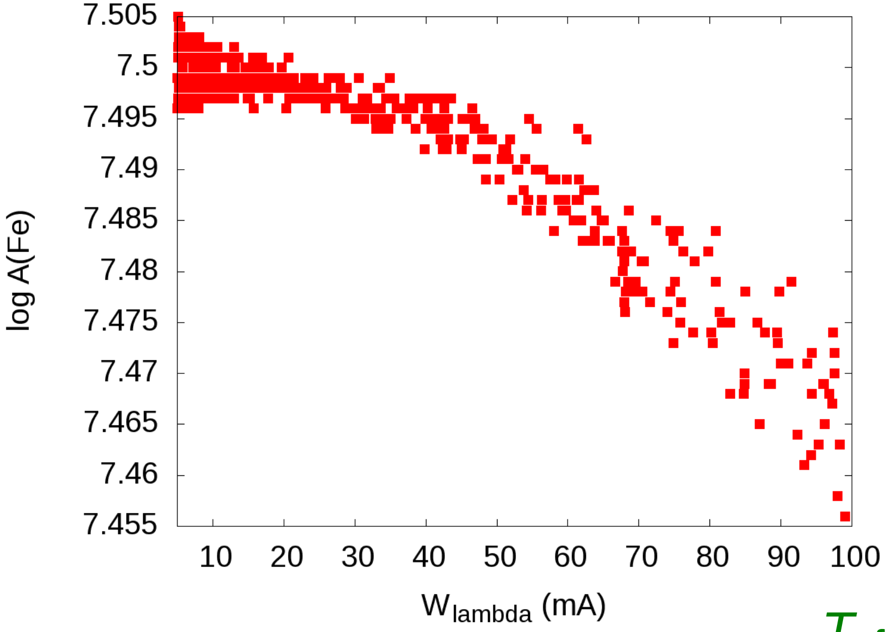
Pedagogical Heuristic Simulations

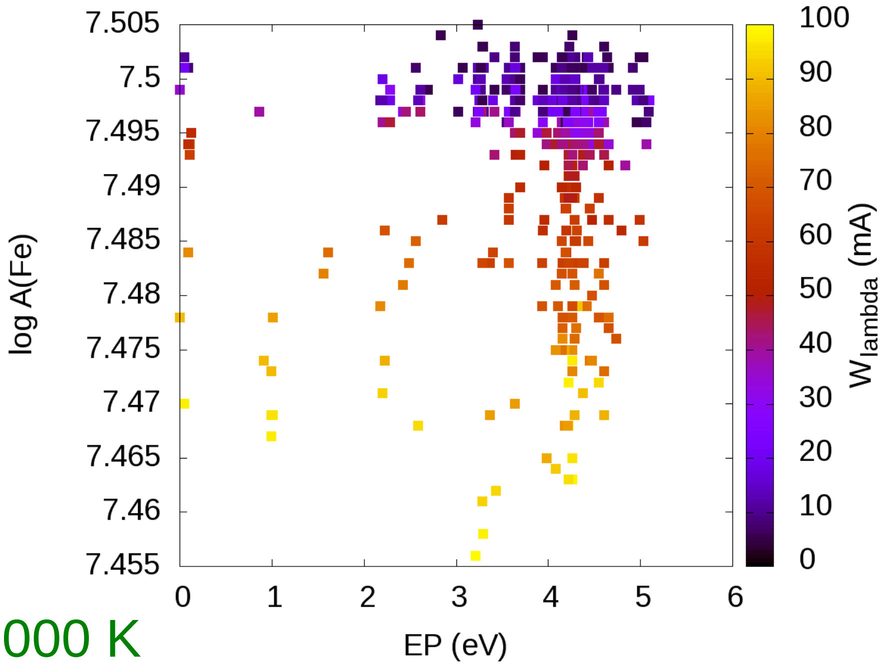
Collisional Broadening

- Ryan 1998 (A&A, 331, 1051)
  - Even weak lines can be affected by damping
  - Damping errors depend on excitation potential
    - errors in v_{mic} and T_{eff}



Effect of damping





T_{eff} = 6000 K

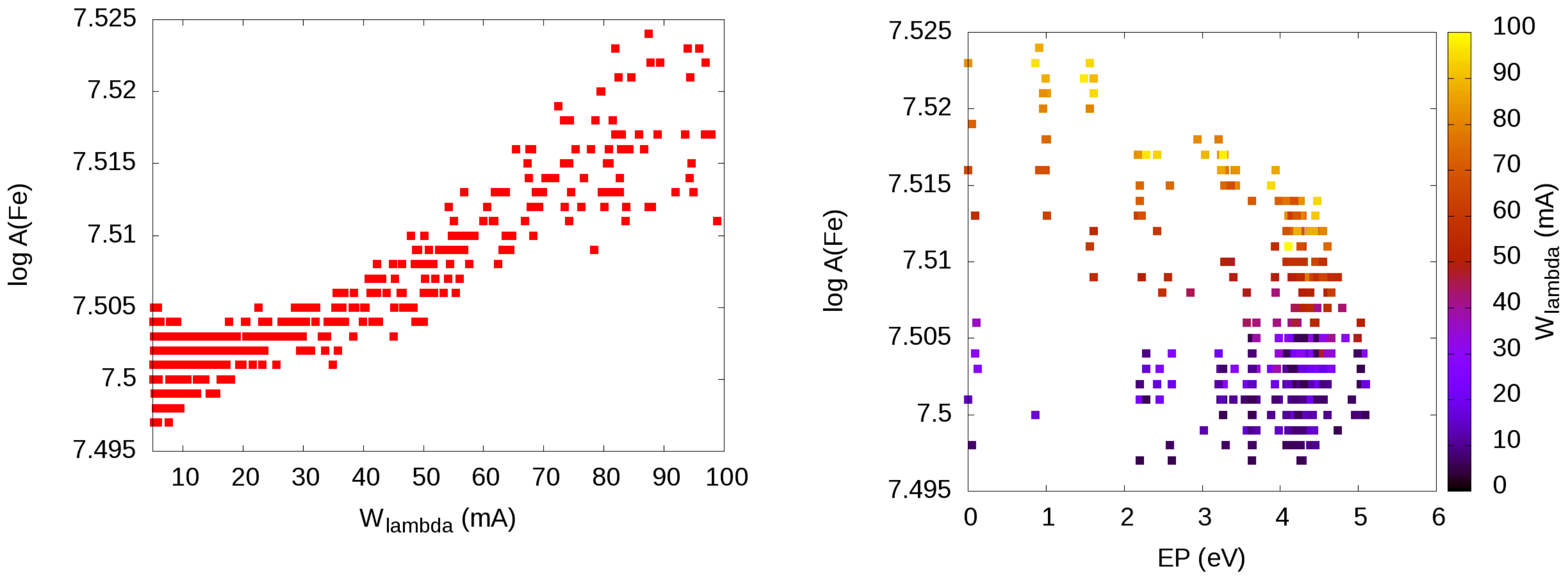
Log g = 4.5

- Effect of +20% error in van der Waals damping constant
  - could lead to errors in microturbulence and T_{eff}

Astrophysical *gf* values

- Line data is often inaccurate or missing
- Take spectrum of star with known properties and adjust synthesis line data until fits
  - Usually the Sun for late-type stars
  - Assume abundances are known
  - Mostly adjust just oscillator strengths (*gf* values)
- Widely-used and can give good results
  - **But** values do depend on model and assumed parameters.
    - Damping constants, microturbulence, convection, ...

Astrophysical *gf* Systematics

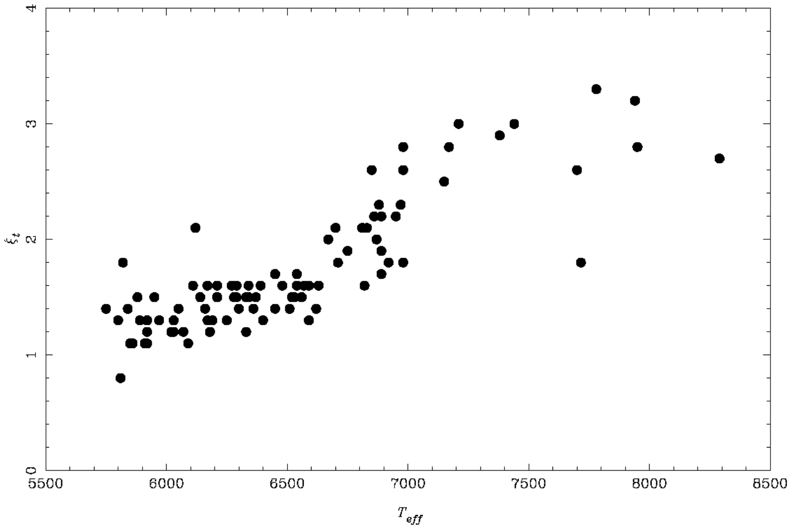


- Astrophysical *gf* values created at 6000 K but with +20% error in van der Waals damping.
  - Plots show difference in at 6500 K.

Microturbulence

Not need in 3-d simulations

- A ***free*** parameter introduced to ensure that abundances from weak and strong lines agree
- Extra source of line broadening
  - added to thermal broadening
  - Small scale motions within the atmosphere



Smalley 2004, IAUS 224, 131 based on Gray et al. 2001, AJ, 121, 2159

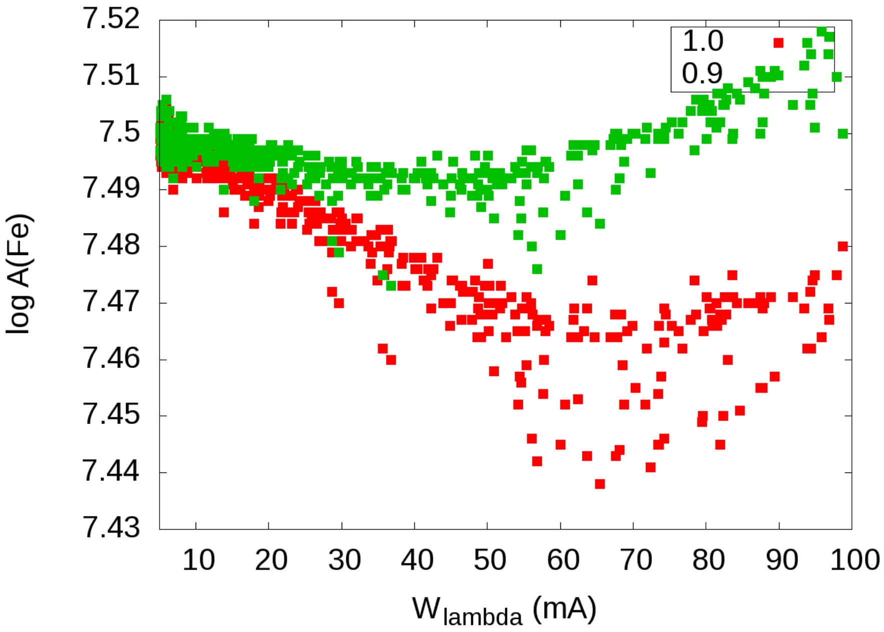
- Microturbulence varies with T_{eff}
  - increases with increasing temperature
  - peaking around mid-A type

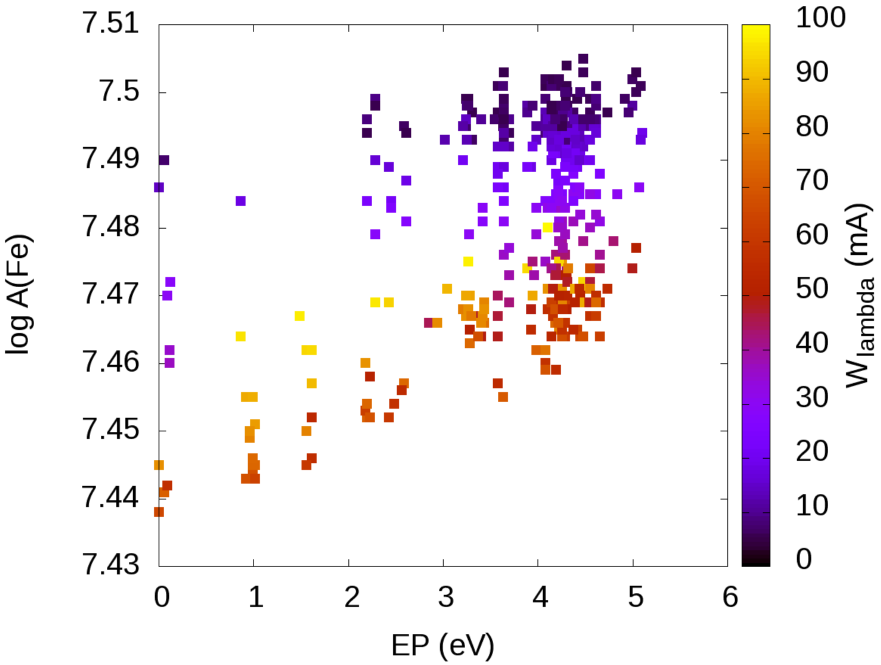
Solar Microturbulence Value

- Edvardsson et al. 1993 (A&A, 275, 101) 1.15 km/s
- Bruntt et al. 2010 (MNRAS, 405, 1907) 0.95 km/s
- Valenti & Fischer 2005 (ApJS, 159, 141) 0.85 km/s
- Santos et al. 2004, (A&A, 415, 1153) 1.00 km/s
- Magain 1984 (A&A, 134, 189) 0.85 km/s (centre of solar disk)
  - From Blackwell et al. 1984, (A&A,132, 236) using Holweger & Mueller 1974, (SoPh, 39, 19) Solar model

Which to use in Astrophysical *gf* determination?

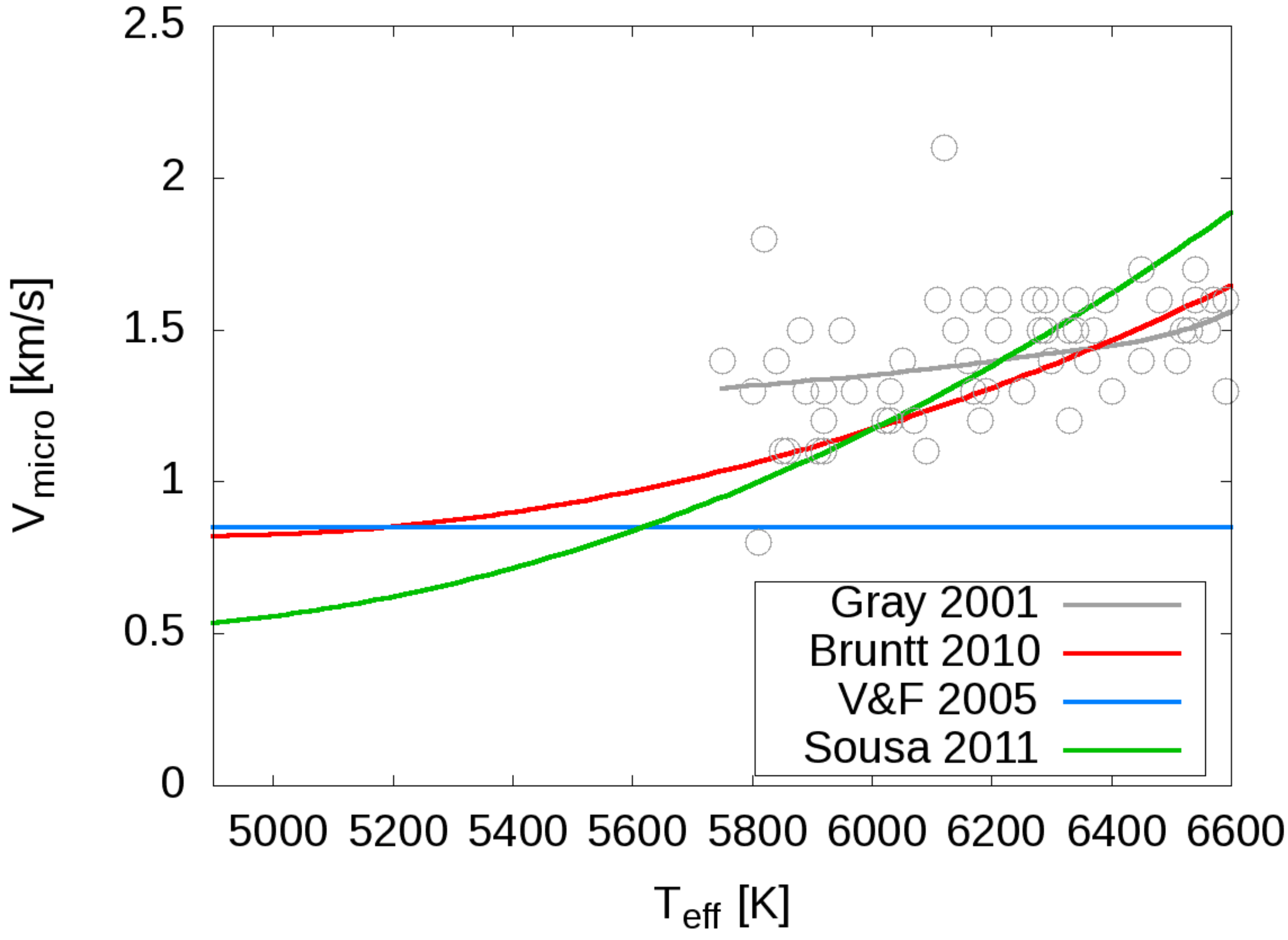
Astrophysical *gf* Systematics





- Astrophysical *gf* values created at 6000 K but with microturbulence too low by 0.1 km/s.
    - 0.9 km/s instead of "*true*" 1.0 km/s
  - Plots show difference at 6500 K

Microturbulence Calibrations



Valenti & Fischer 2005 found:

"strongly correlated values of v_{mic} and [M/H], suggesting that v_{mic} and [M/H] are partially degenerate."

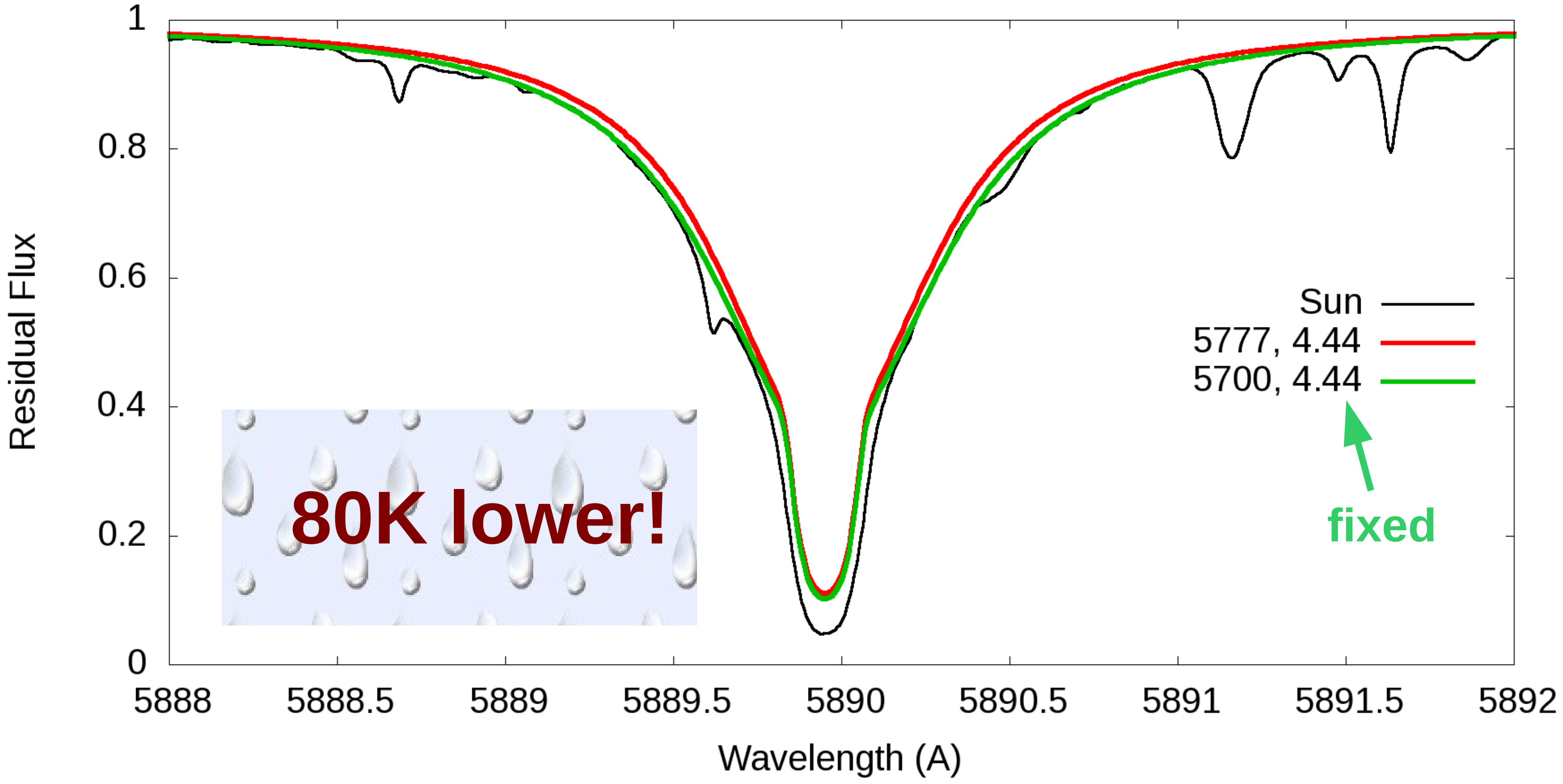
Adopted fixed value.

Gray 2001 fit by Smalley 2004, IAUS, 224, 131
Sousa 2011 is fit given in 2013, ApJ, 768, 79

Valenti & Fischer, 2005, ApJS, 159, 141
Bruntt et al., 2010, MNRAS, 405, 1907

Fixing log *g*

Planetary Transits
or
Asteroseismology



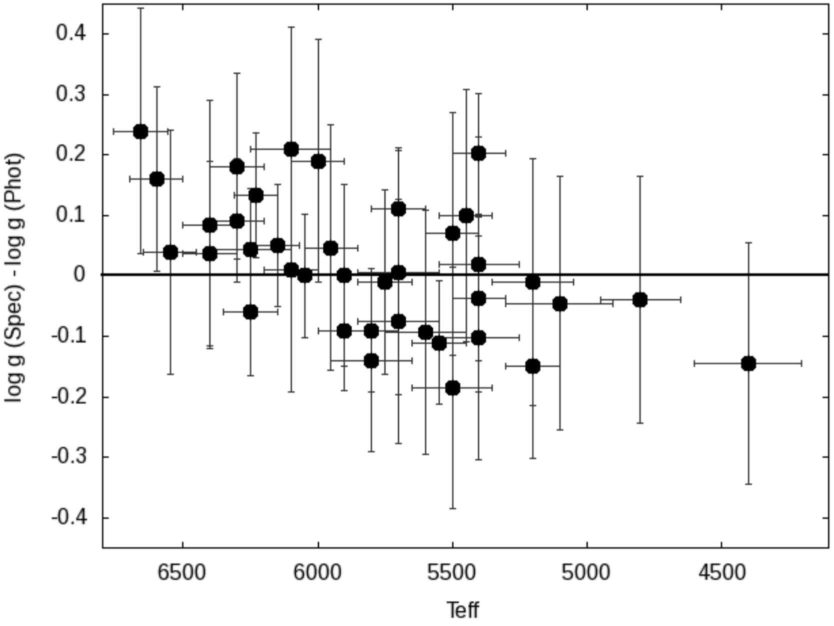
80K lower!

fixed

Fixing log *g* can lead to incorrect other parameters

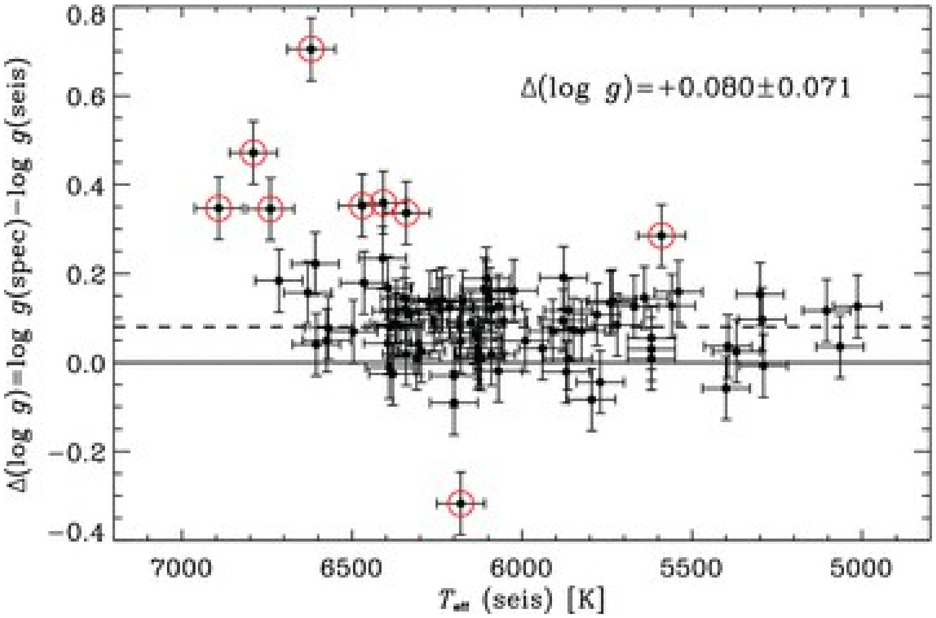
Surface Gravity from Spectroscopy

Transit log *g*



Smalley et al. 2012 A&A, 547, A61

Asteroseismic log *g*



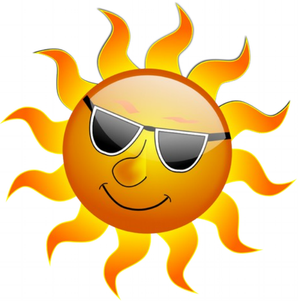
Bruntt et al. 2012 MNRAS, 423, 122

Spectroscopic log *g* can be **accurately** determined to ±0.1 dex
<u>by spectral analysis alone!</u>

Starspots

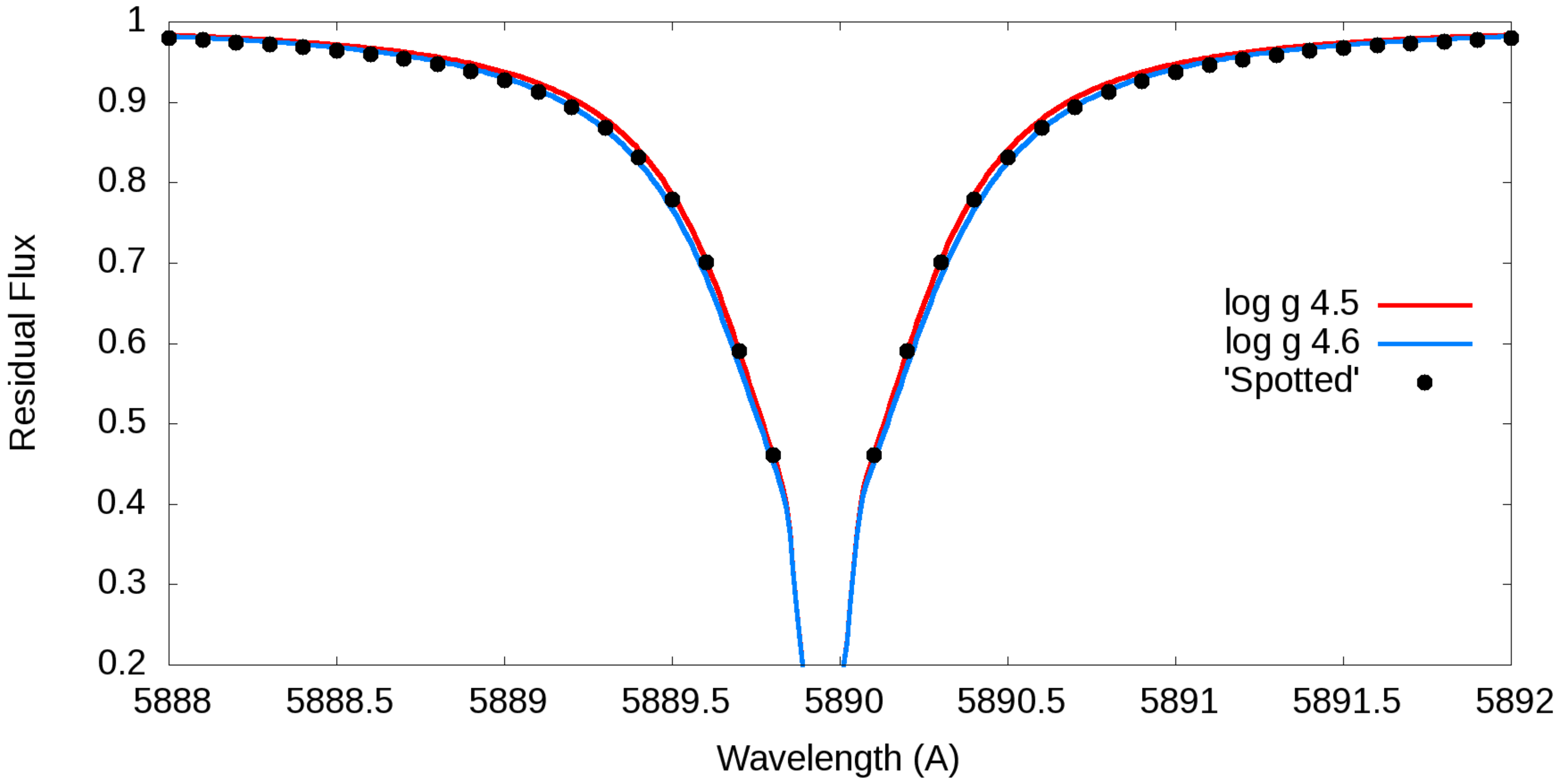
- Simulate a spotted star with 5% spot coverage.
- Take two models: T_{eff} = 6000 K and T_{eff} = 5000 K
  - Both with log g =4.5
- Generate spectra and combine 95% and 5%
- Fit with single T_{eff} model
- H_{α} gives 5950 K. Agrees with Stefan's Law:

$$\left(0.95\times6000^{4}+0.05\times5000^{4}\right)^{1/4}=5953$$



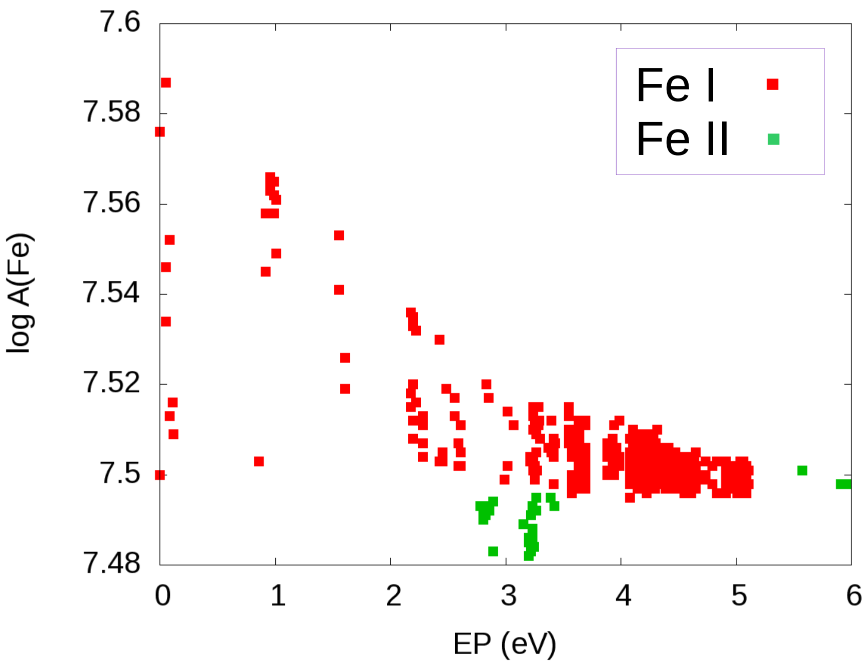
- But, what log g does Na D give?

Effect of “Spot” on Na D line

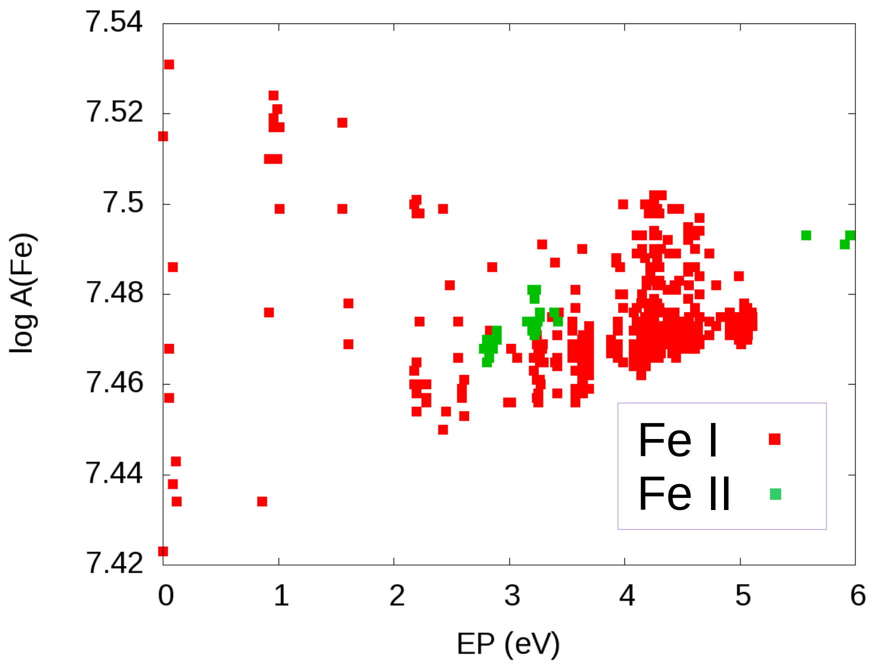


Spectroscopic log *g* overestimated in spotted stars?

Spots and EWs



T_{eff} = 5953 K, log g = 4.5



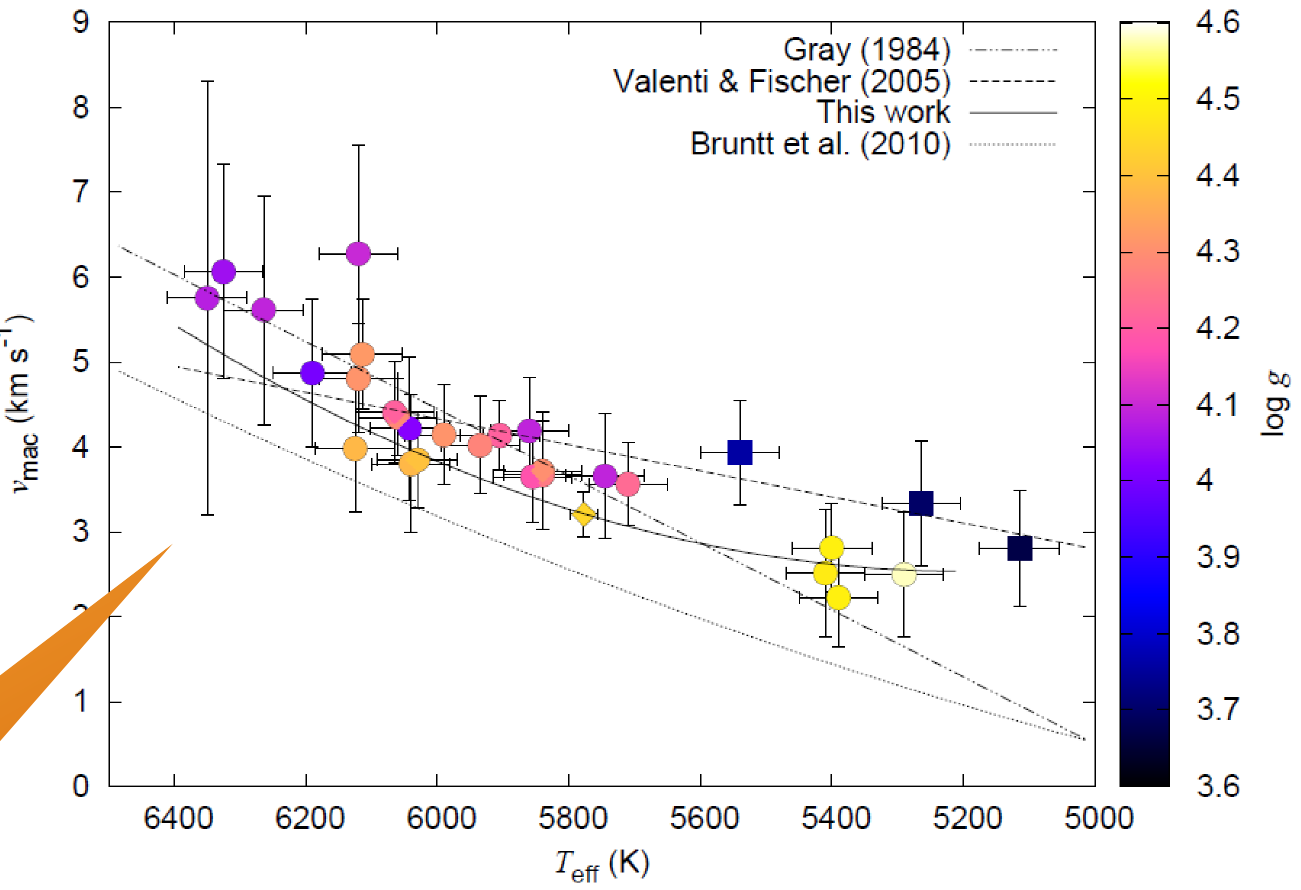
T_{eff} = 5890 K, log g = 4.42

- Effect on determination of T_{eff} and log g
  - depends on choice of lines.

Macroturbulence

Stellar granulation

Difficult to disentangle between v sin I and macroturbulence on line profile

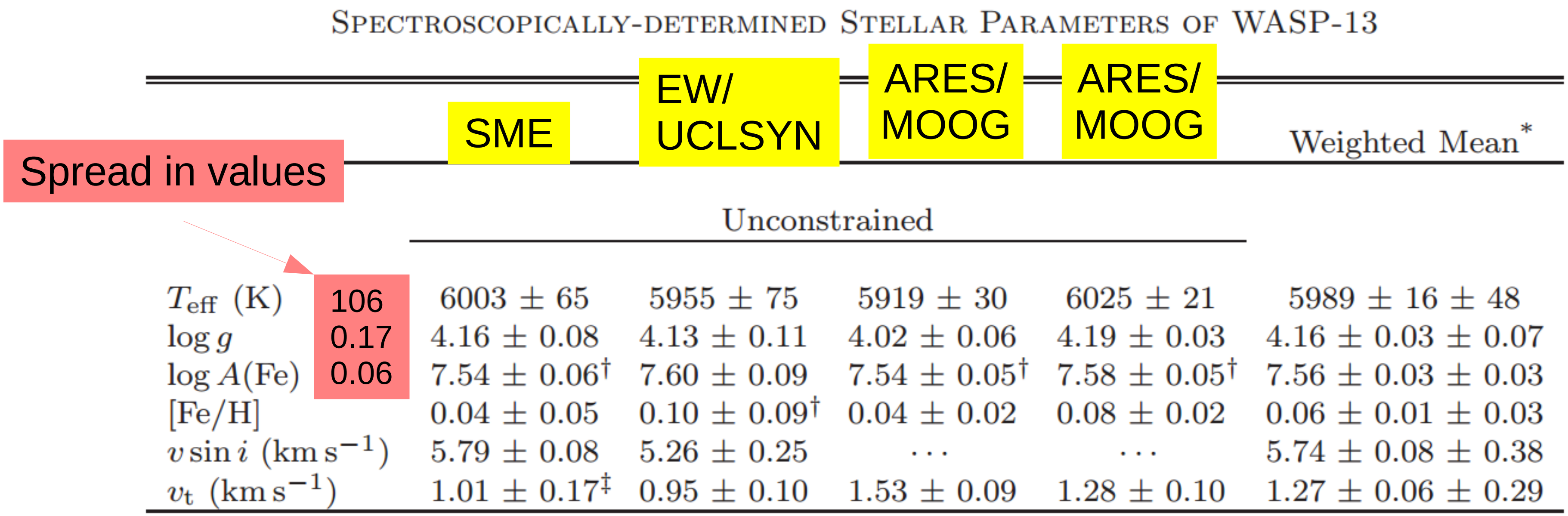


Base on v sin i from Kepler astereoseismology

Doyle et al. 2014 ArXiv 1408.3988

A few Case Studies from the Literature

WASP-13



Spectroscopically-determined Stellar Parameters of WASP-13

	Spread in values	SME	EW/ UCLSYN	ARES/ MOOG	ARES/ MOOG	Weighted Mean*
		Unconstrained				
$T_{\rm eff}$ (K)	106	6003 ± 65	5955 ± 75	5919 ± 30	6025 ± 21	5989 ± 16 ± 48
log g	0.17	4.16 ± 0.08	4.13 ± 0.11	4.02 ± 0.06	4.19 ± 0.03	4.16 ± 0.03 ± 0.07
log A(Fe)	0.06	7.54 ± 0.06†	7.60 ± 0.09	7.54 ± 0.05†	7.58 ± 0.05†	7.56 ± 0.03 ± 0.03
[Fe/H]		0.04 ± 0.05	0.10 ± 0.09†	0.04 ± 0.02	0.08 ± 0.02	0.06 ± 0.01 ± 0.03
$v \sin i$ (km s^{-1})		5.79 ± 0.08	5.26 ± 0.25	…	…	5.74 ± 0.08 ± 0.38
$v_{\rm t}$ (km s^{-1})		1.01 ± 0.17‡	0.95 ± 0.10	1.53 ± 0.09	1.28 ± 0.10	1.27 ± 0.06 ± 0.29

- H_α 5950 ± 70 K; log *g* (Transit) 4.10 ± 0.04
- SPC: 5982 ± 50 K (Torres et al. 2012, ApJ, 757, 161)
- IRFM: 5935 ± 183 K

Gómez Maqueo Chew, et al., 2013, ApJ, 768, 79

Gaia-ESO Survey

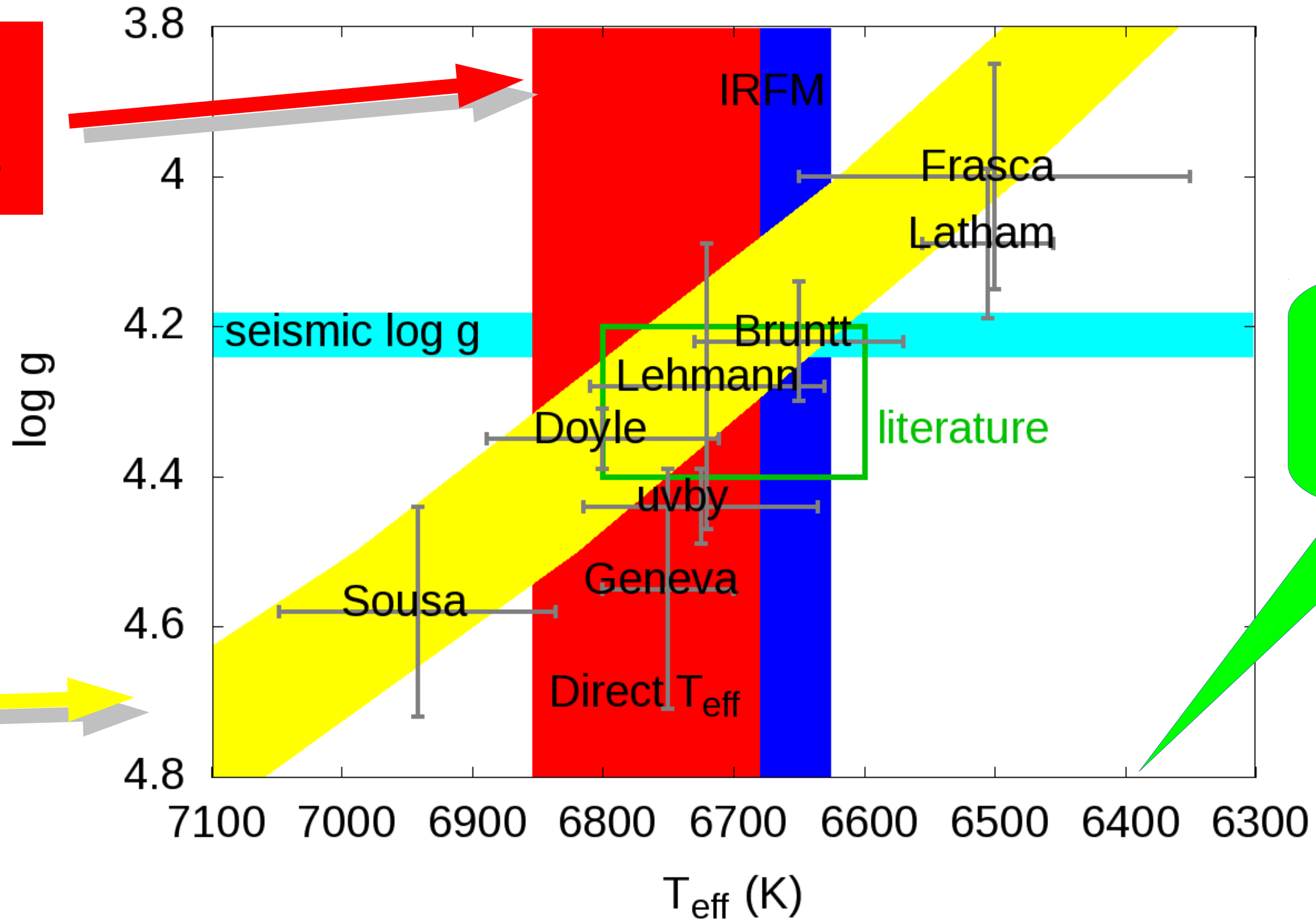
- The analysis of 1301 FGK-type stars (2014arXiv1409.0568S)
- 13 independent groups and methods
  - All using MARCS models (no Kurucz ATLAS models)
- *Method-to-method dispersion* of the atmospheric parameters
  - **T_{eff} 55 K, log *g* 0.13 dex, [Fe/H] 0.07 dex**
- *Systematic biases* are estimated to be between
  - **T_{eff} 50-100 K, log *g* 0.10-0.25 dex, [Fe/H] 0.05-0.10**
- The typical method-to-method dispersion of elemental abundances varies between 0.10 and 0.20 dex.

All spectral analysis methods are well developed and yield satisfactory results

Θ Cygni

Revised angular diameter

Fe I/Fe II Ionization balance



Original Direct T_{eff} !

Guzik et al. In prep

Summary

- Analyses should include sufficient reference stars
  - use exactly the same methods and quality of spectra.
- Use as many diagnostics as possible
  - Spectroscopic and photometric.
- Realistically the typical errors:
  - T_{eff} ± 50~100K
  - log g ± 0.1~0.2 dex
  - Abundances ± 0.05~0.10 dex

Errorbars in stellar analyses *usually* show how well the model fits to the data and **not** how good is the model.

High precision fitting to high S/N data is possible, but overall accuracy of parameters is less certain.