Stellar and Galactic Archaeology with Bayesian Methods

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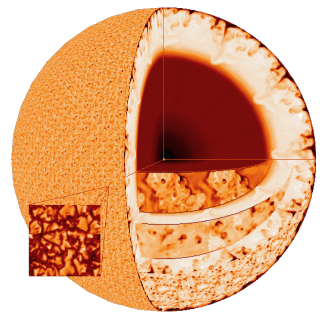
Spectroscopy
temperature, surface gravity,
chemical abundances: Li, Be,
Be,CNO, a-group, Fe-peak,
s-r process, U,Th

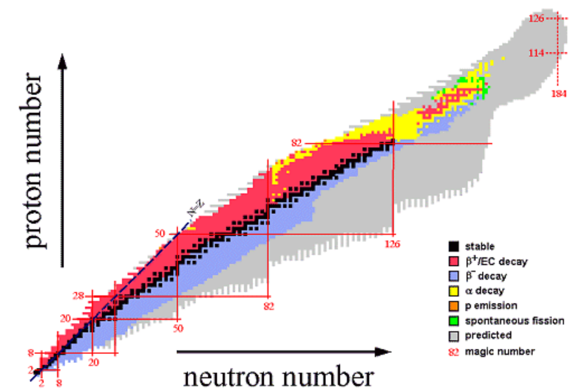
+ rotation velocity
+ activity
+ radial velocity
+ mass, age
+ distances

- **abundance trends**
- **chemo-dynamic correlations**
- **age-, mass-metallicity relations**
- **metallicity gradients**

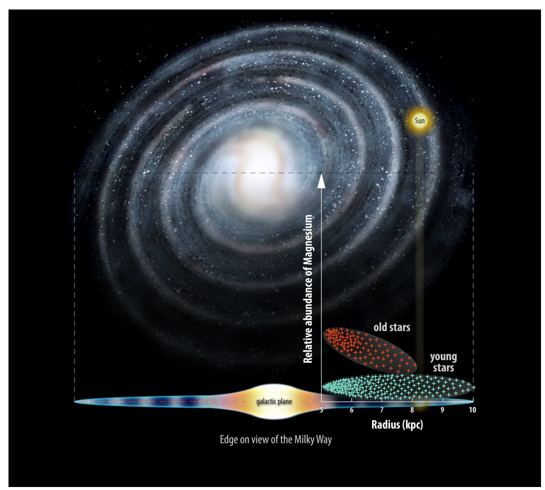
Physics of stars



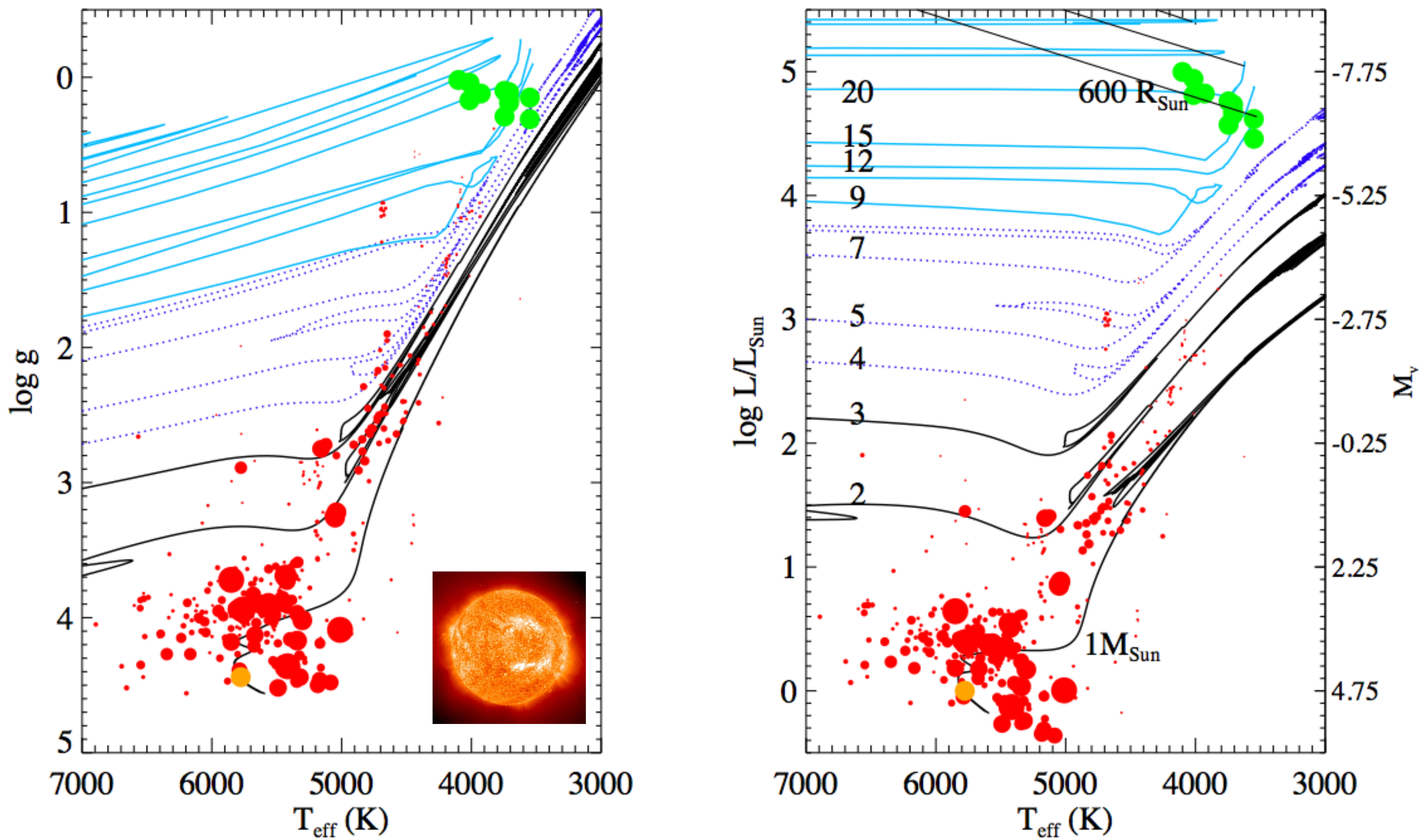
Nucleosynthesis and the origin of chemical elements



Galactic archeology and the first stars



Chemical evolution of galaxies

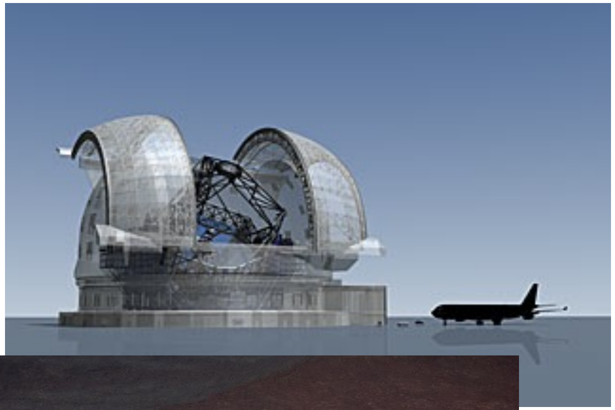


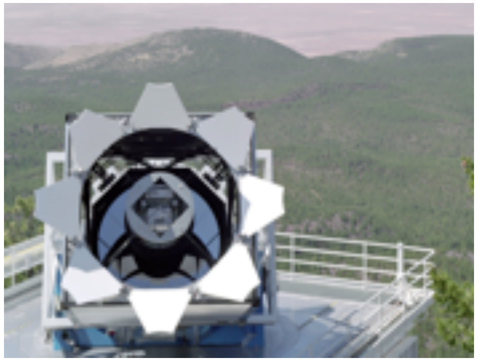
log g
0
1
2
3
4
5
7000
6000
5000
4000
3000
T_eff (K)
log L/L_Sun
5
4
3
2
1
0
20
15
12
9
7
5
4
3
2
600 R_Sun
1M_Sun
-7.75
-5.25
-2.75
-0.25
2.25
4.75
M_v

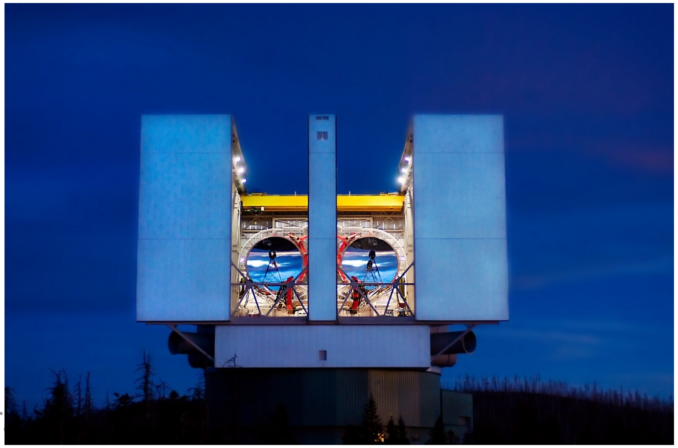
Major progress in observations in the past 10 years:
VLT's and, soon, ELT's

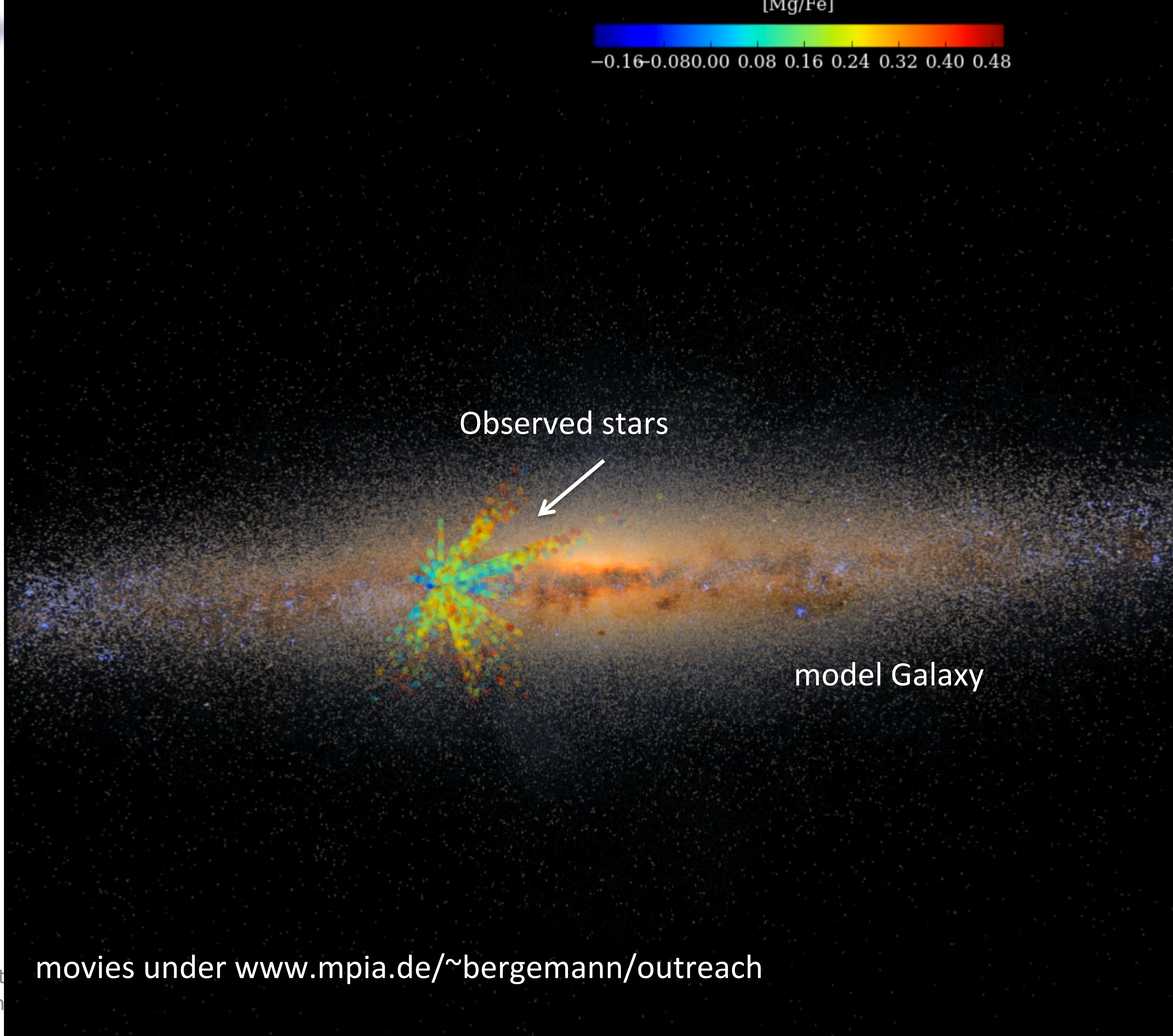
Ongoing large-scale stellar spectroscopic surveys:
SDSS (Apogee, SEGUE), RAVE, Gaia-ESO, GALAH

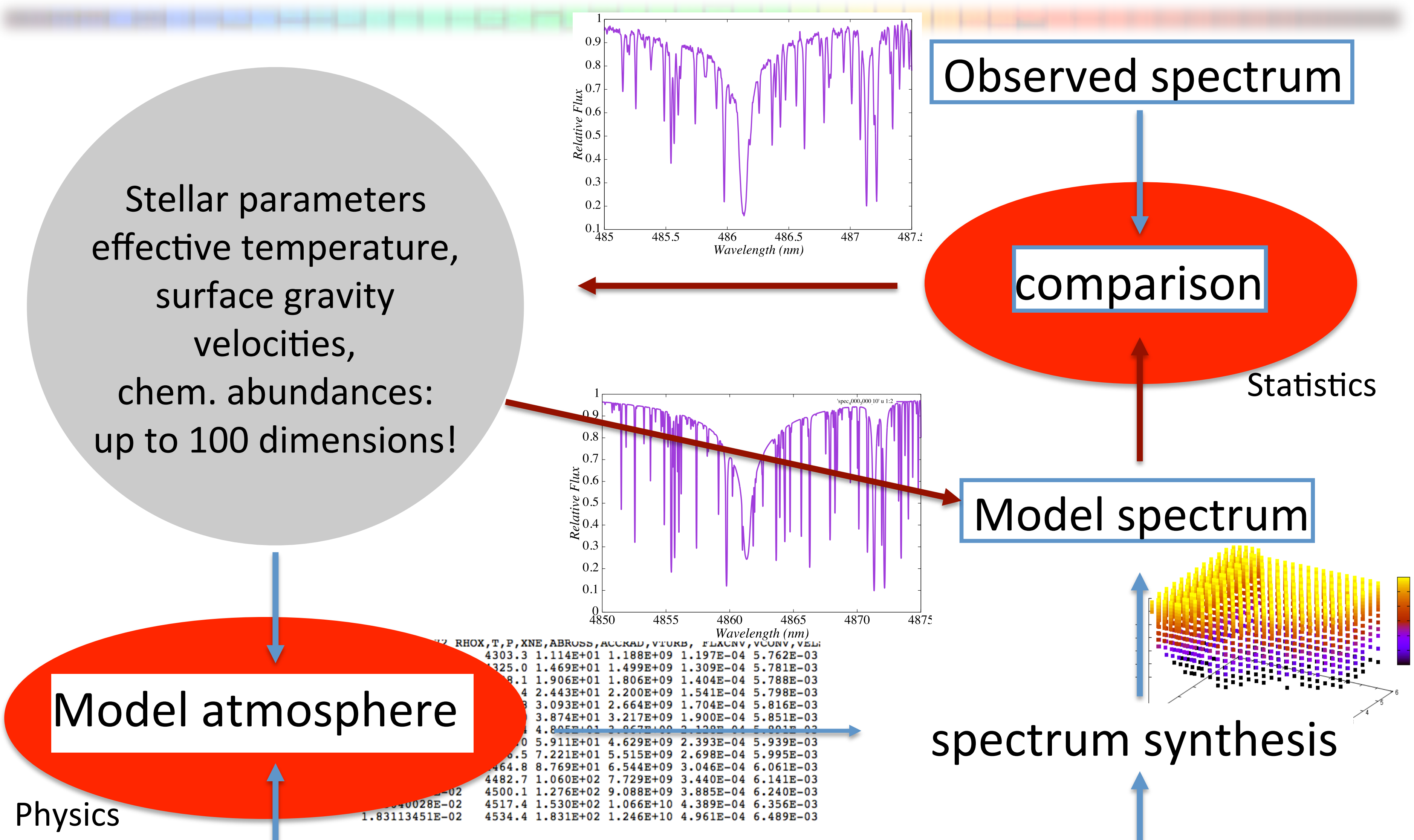
Future:
4MOST (20 million spectra, optical),
MOONS (IR)





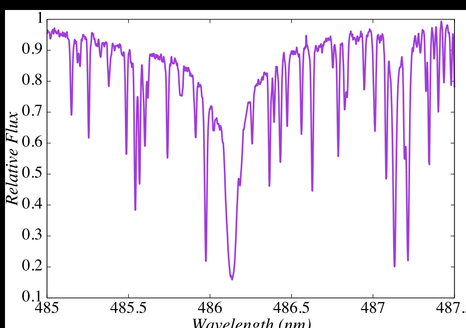



[Mg/Fe]
−0.16 −0.08 0.00 0.08 0.16 0.24 0.32 0.40 0.48
Observed stars
model Galaxy
movies under www.mpia.de/~bergemann/outreach



Basic model atmosphere theory: non-LTE (NLTE), 3D hydrodynamics, magnetic fields, winds, sphericity, molecular opacities, binarity, chromospheres, etc

What are the physical conditions of the most likely model?



?

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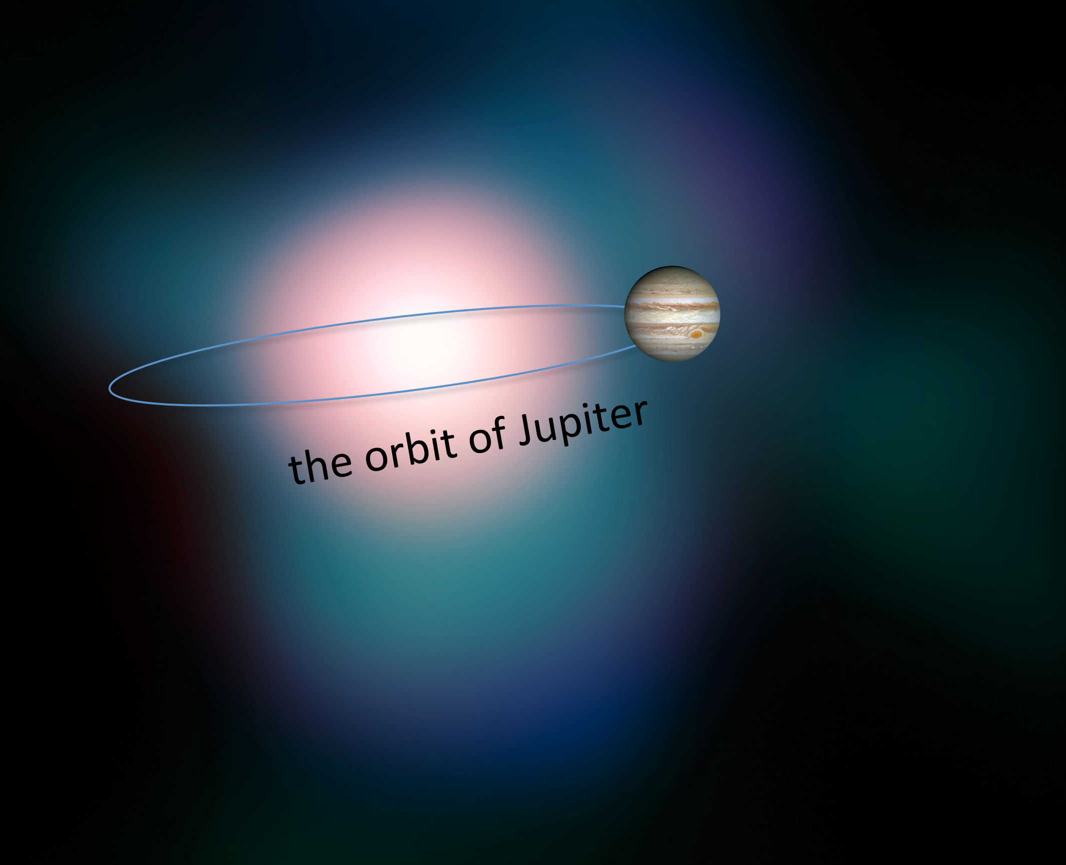
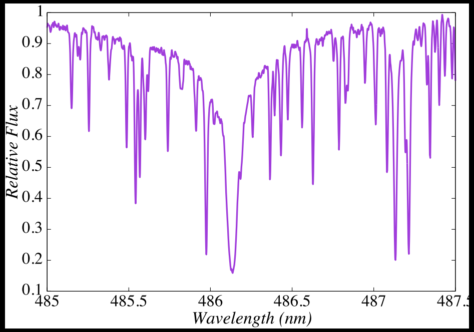


What are the physical conditions of the most likely model?



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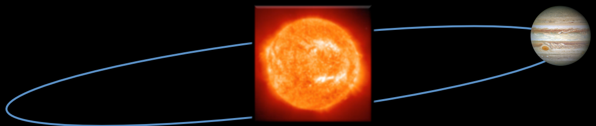


What are the physical conditions of the most likely model?

- all observed stars are point sources
- observed spectra are not perfect -> noise + data reduction problems
- stellar models are not perfect
- stellar spectra are in reality not so different → parameter degeneracies and correlations

The physical challenge

1. What is a good stellar model?

2. What type of physics can we afford computationally?

The statistical challenge

1. What is the best-fit stellar model?

2. Do we have prior knowledge from previous or complementary experiments?

Even the best observed spectra
are worth nothing
without good model comparison methods

Max-Likelihood Spectroscopy

'observed' spectrum → the goal is to estimate **T_{eff}, log(g), and metallicity** of a star

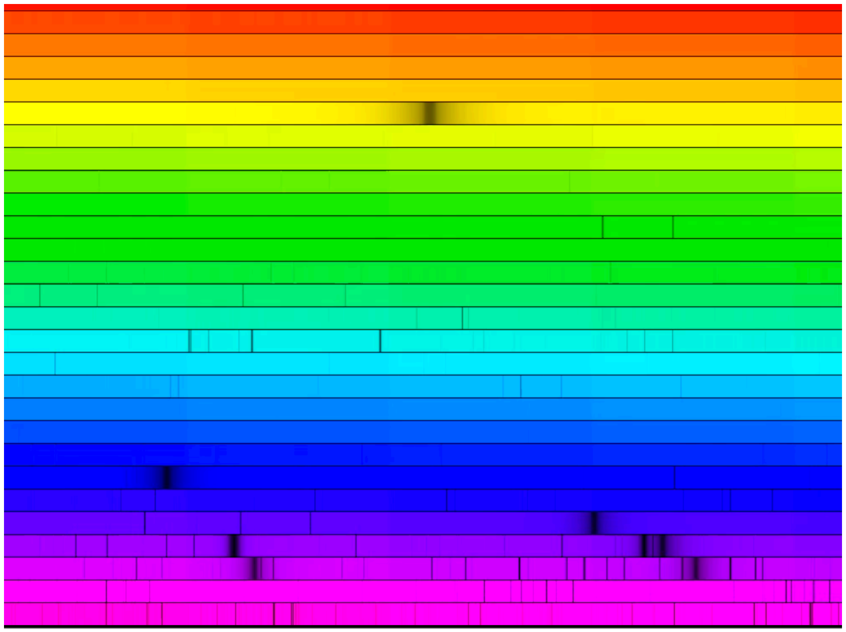
What if we rely only on the classical approach: maximum-likelihood ***L***?

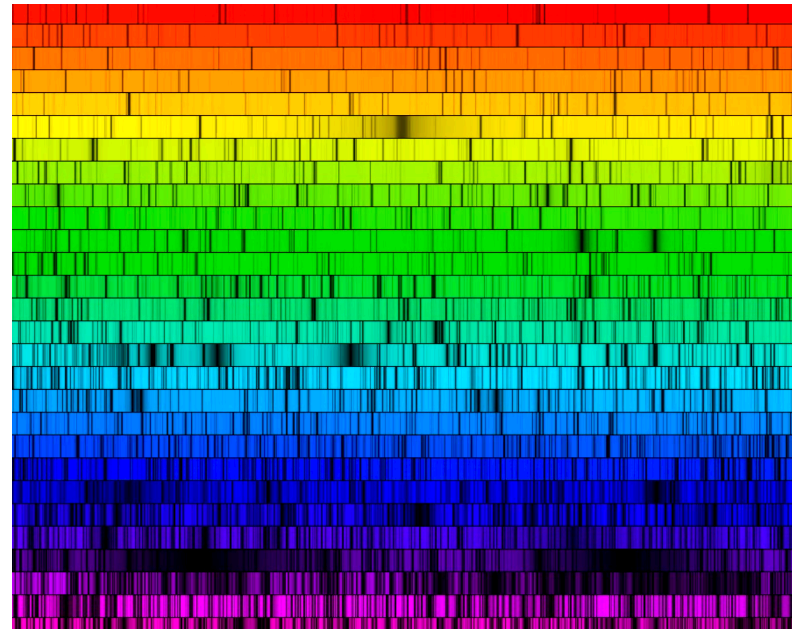
$$L \sim exp(-\chi^2/2)$$

$$\chi^2 = \sum_j \left(\frac{D_j^{\rm obs} - D_j(\,{\rm Teff, logg,}\ \ {\rm Z})^{\rm theor}}{\sigma_j} \right)^2$$

where D_j , j = 1… n are observables, i.e., spectrum in a given frequency bin

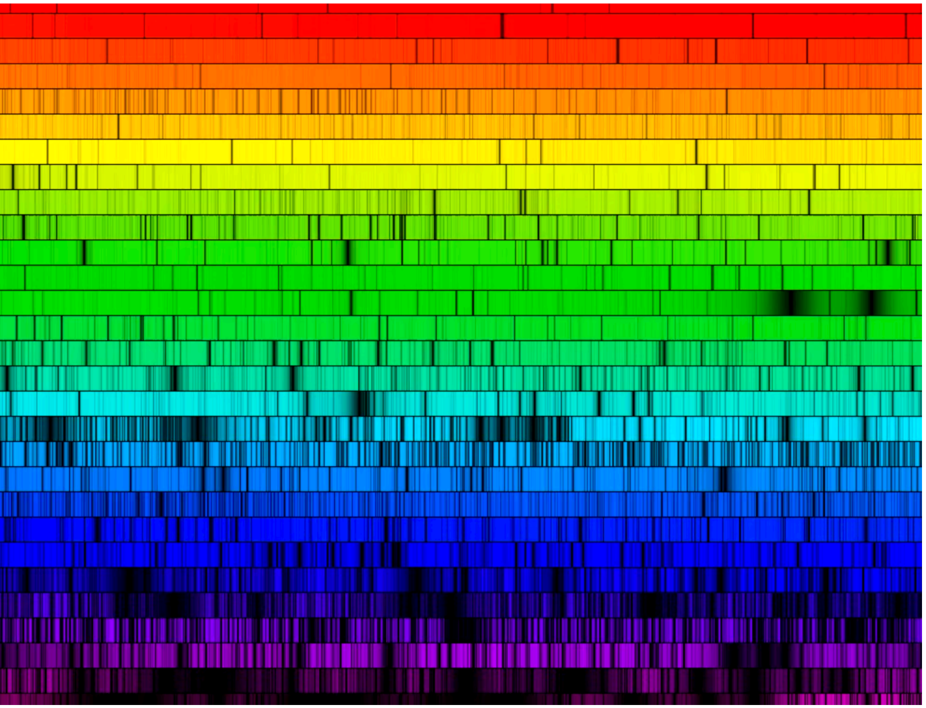
However, L attains its global maximum only if for each model characterized by [T_{eff}, log(g), [Fe/H]] there is a unique model spectrum

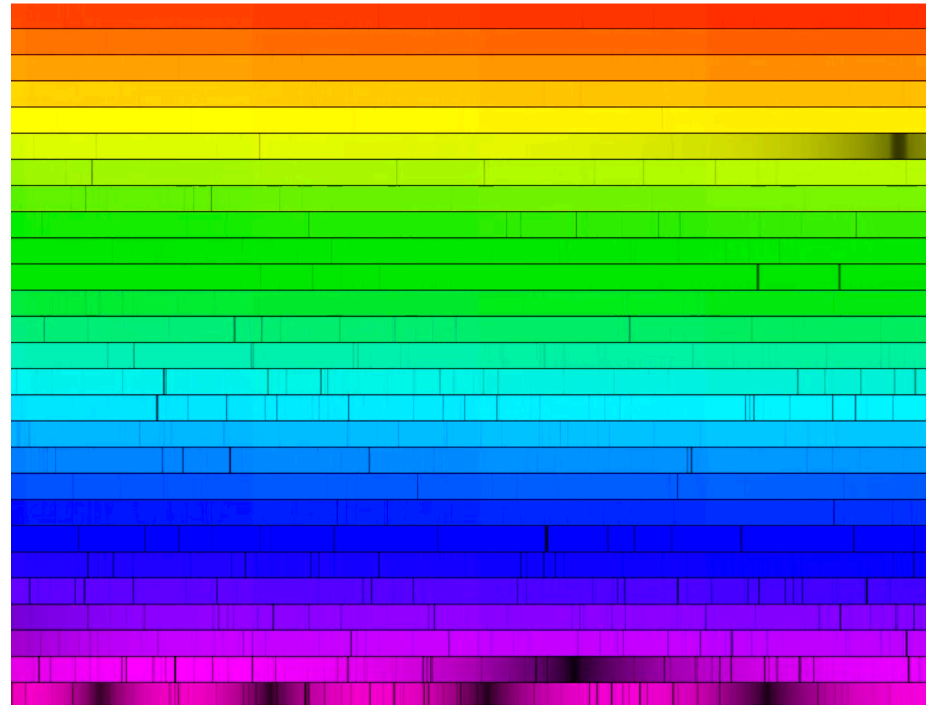




Metal-free star → Metal-rich star

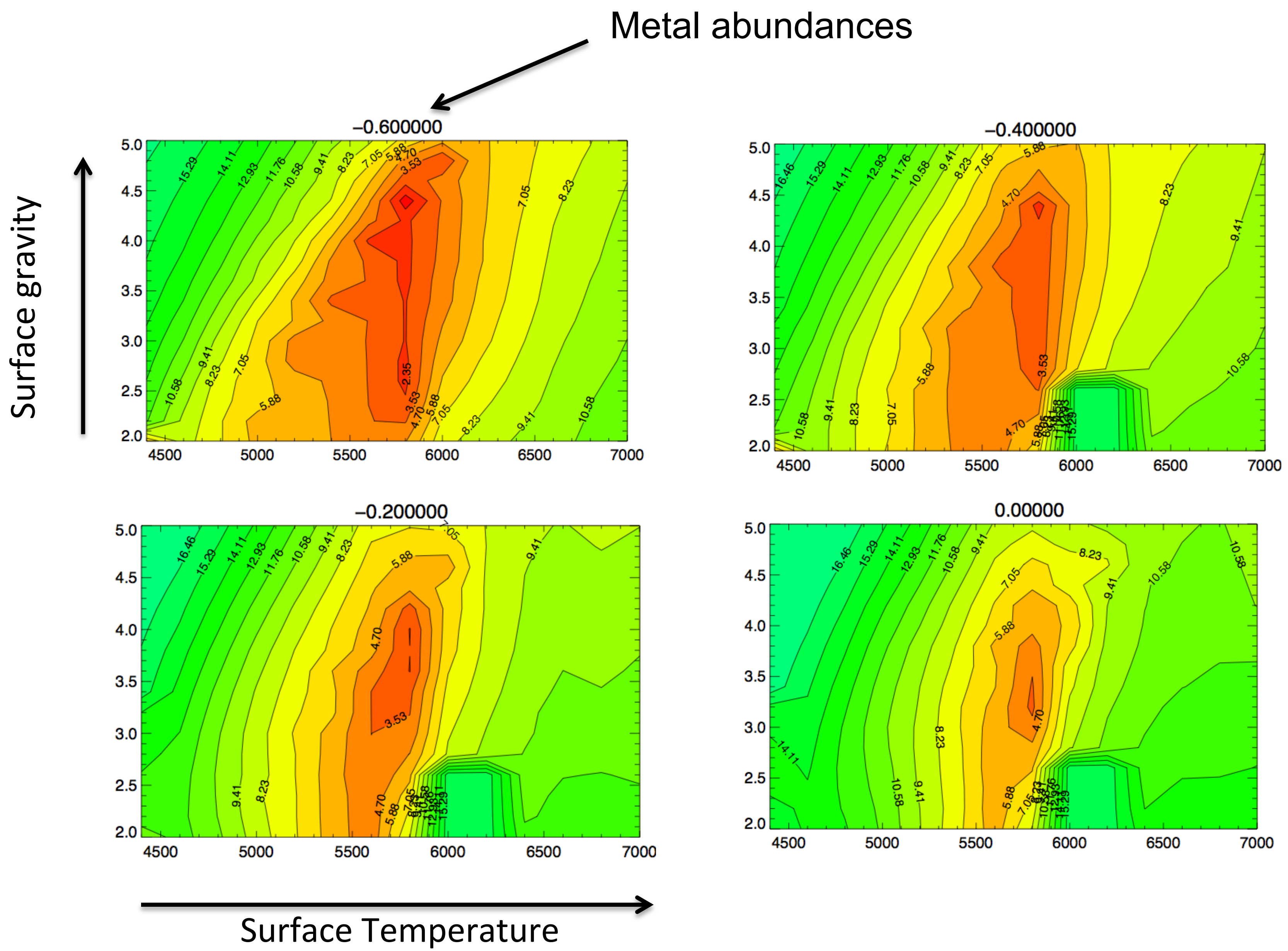
movies under www.mpia.de/~bergemann/outreach



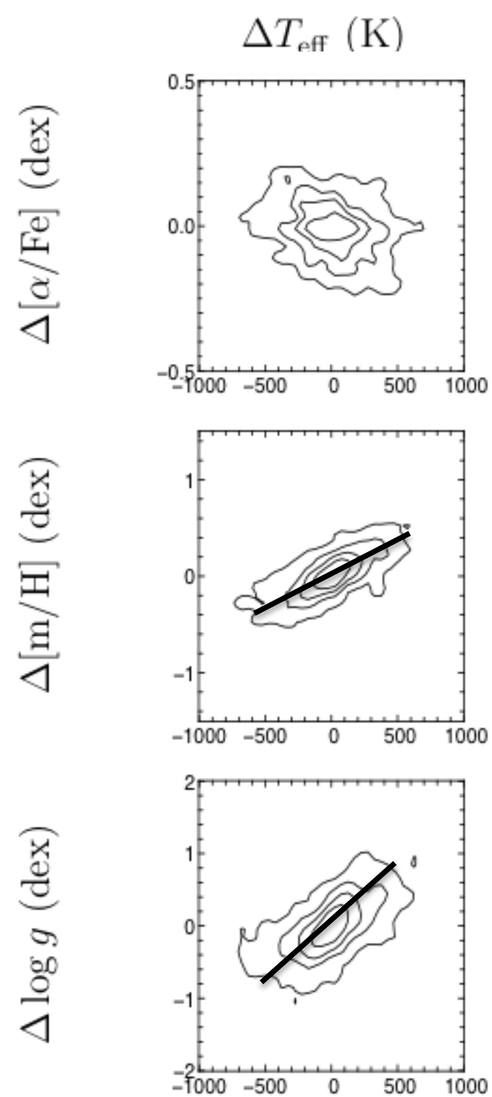


Cold star → Hot star

movies under www.mpia.de/~bergemann/outreach


Metal abundances
Surface gravity
Surface Temperature
−0.600000
−0.400000
−0.200000
0.00000
5.0
4.5
4.0
3.5
3.0
2.5
2.0
4500
5000
5500
6000
6500
7000

Max-Likelihood stellar parameters



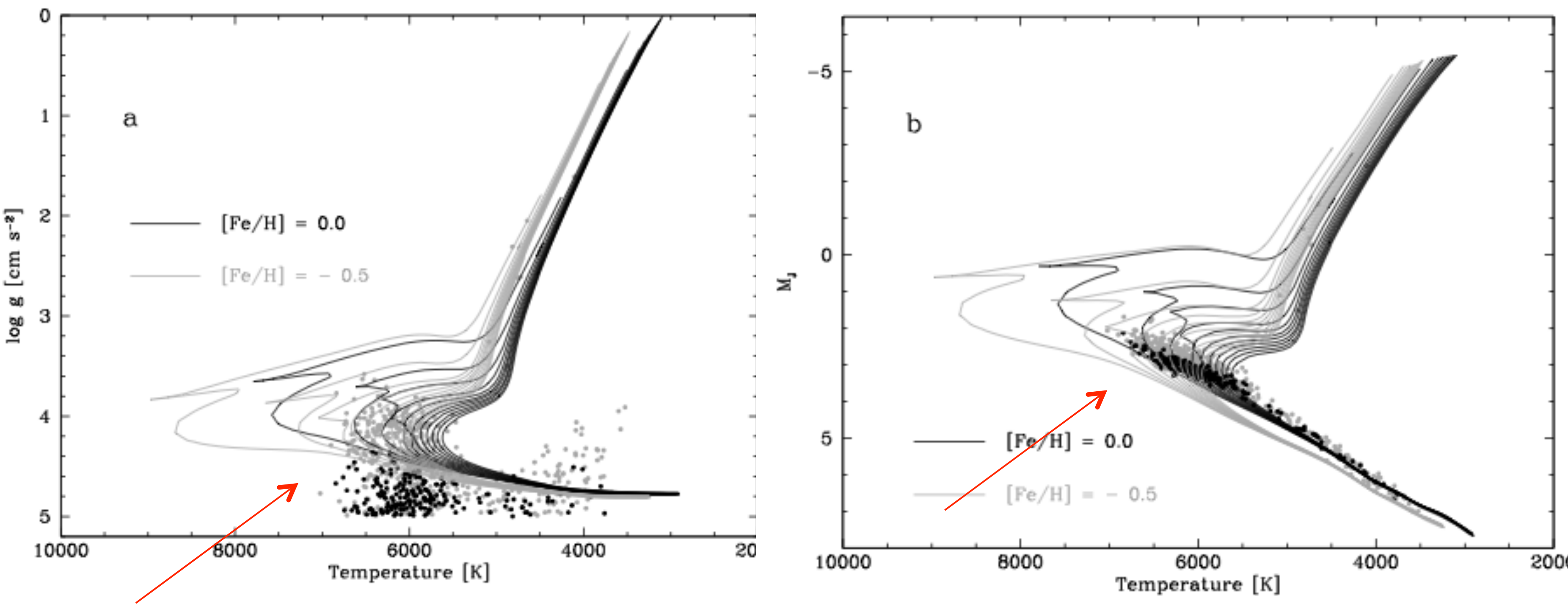
The contours contain 30,50,70,90% of the data.

A correlation between the error in two parameters indicates that a systematic error in one parameter influences the result in the other:

Δ log(g) = 1 dex → ΔT_{eff} = 1000 K

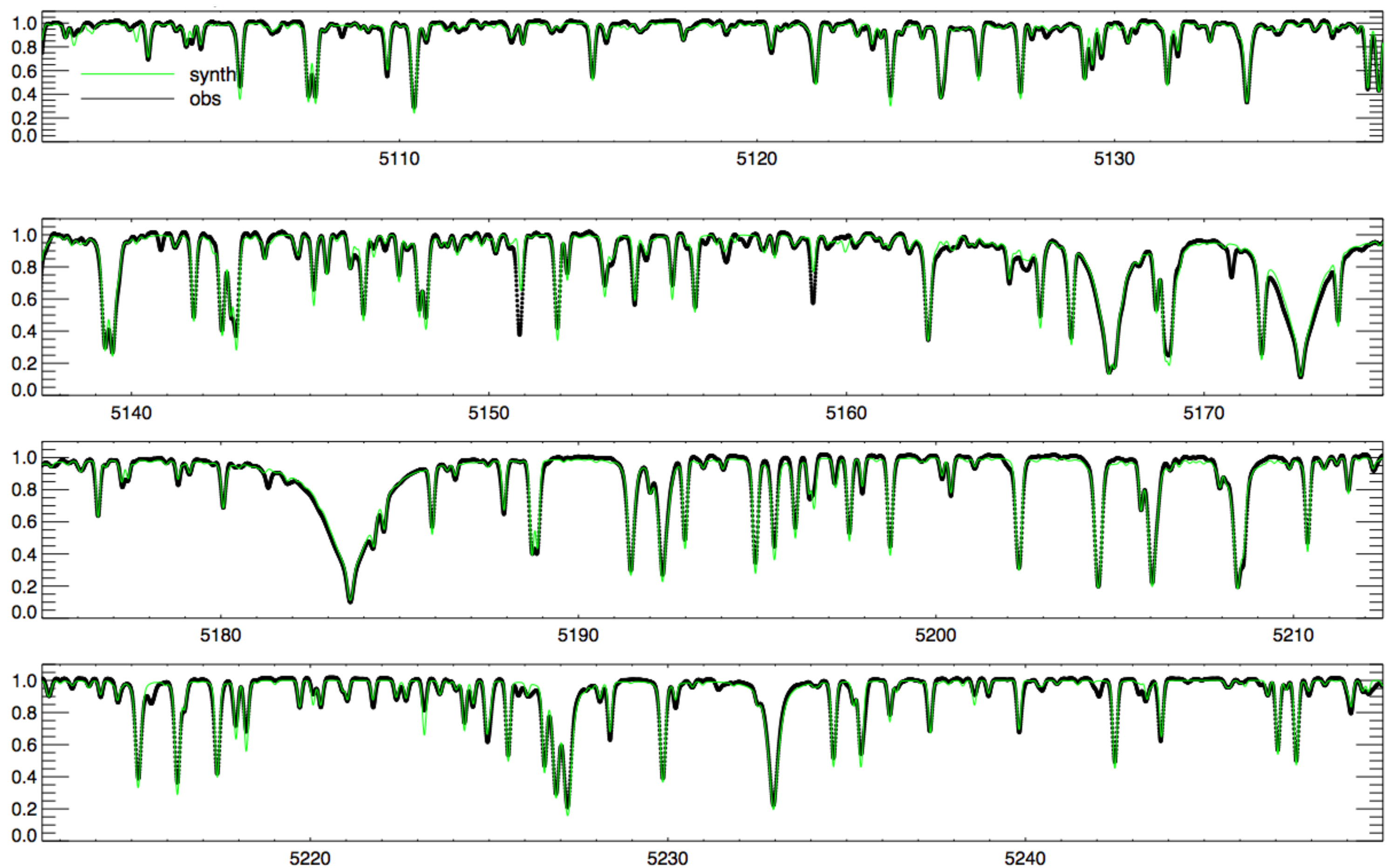
‘Orthodox’ (standard) methods are suitable:

- selection effects lead to major biases
- *imperfect* data often disregarded
- parameter degeneracies caused by physical limitations of the models
- correlated errors, …
- often there is just not enough information in the observed spectrum

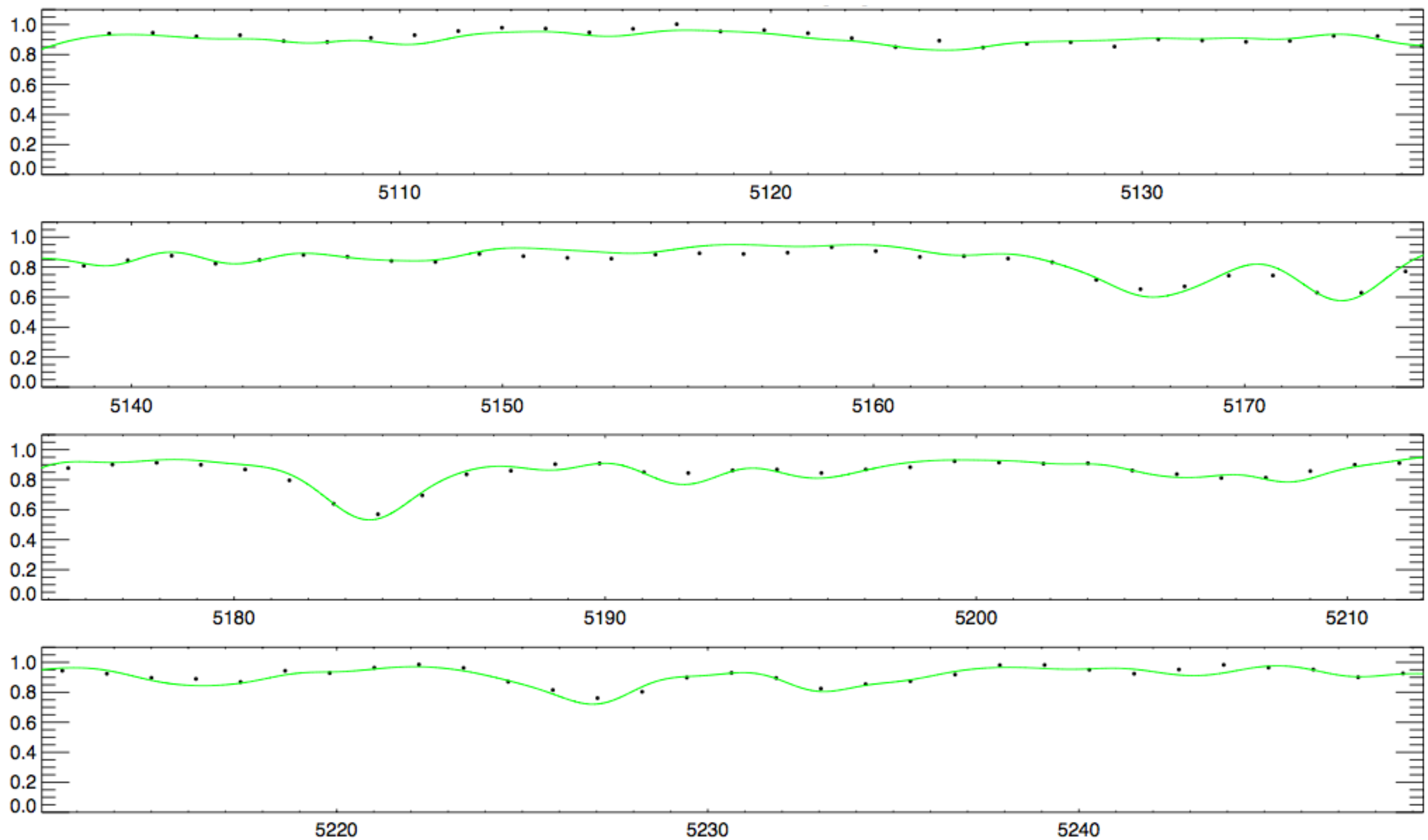


Ad-hoc ‘correction’ of stellar parameters using stellar models

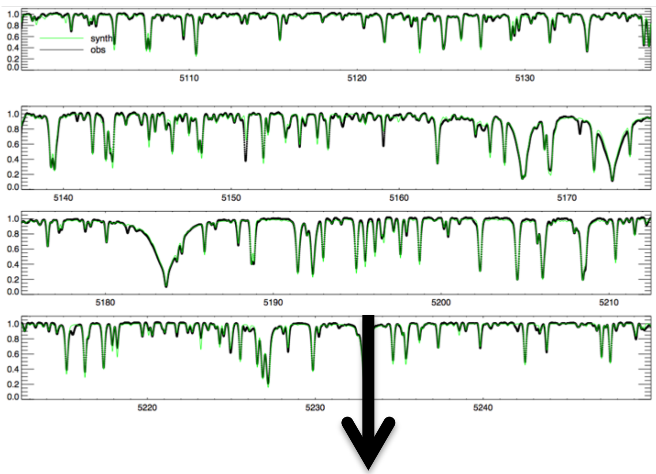
R ~ 200 000, the spectrum of the Sun



R ~ 2000, the SDSS spectrum of a solar-like 'twin'

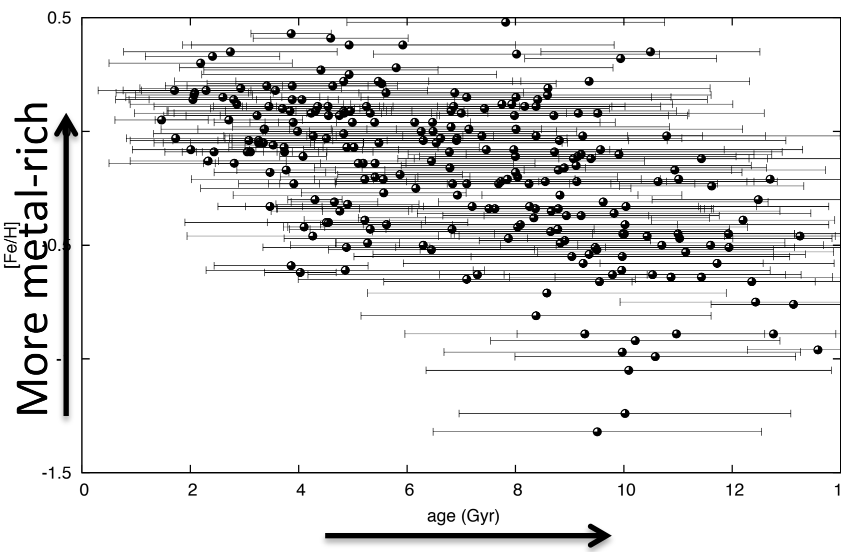


At low R and S/N most of spectral information is washed out

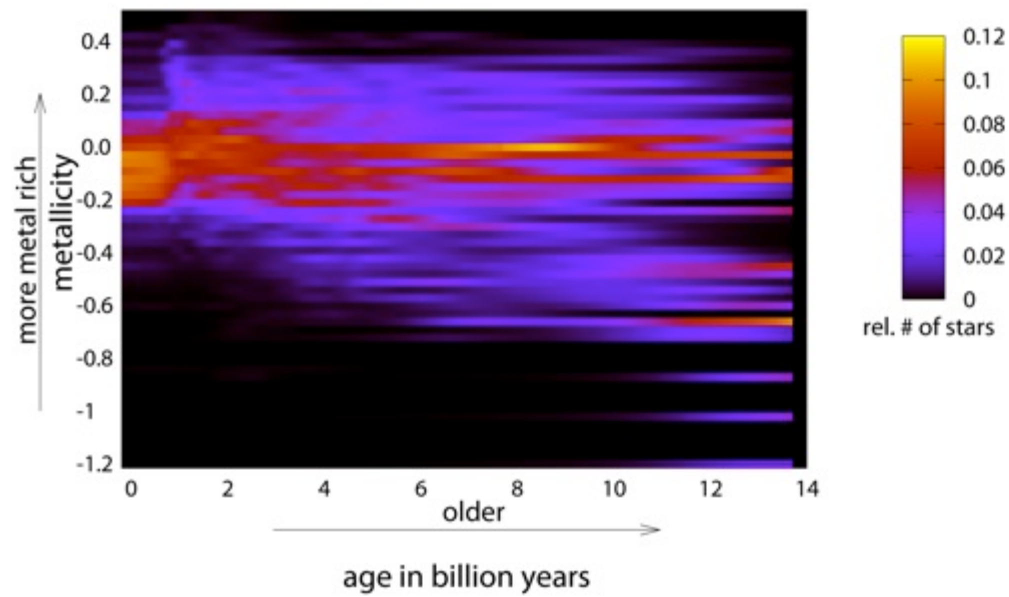


High-resolution observations

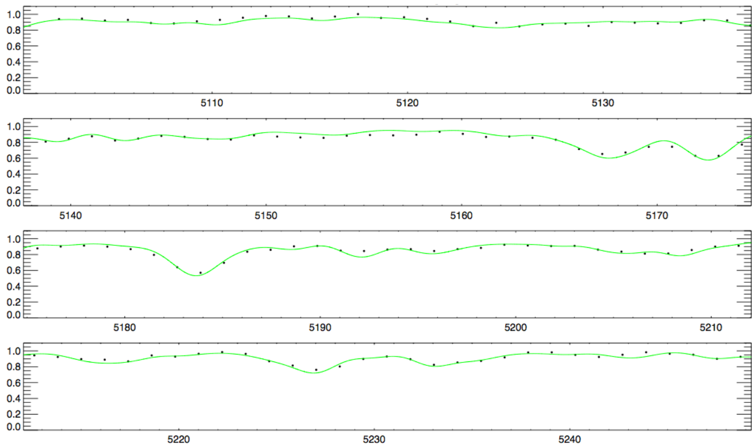
The Milky Way disk

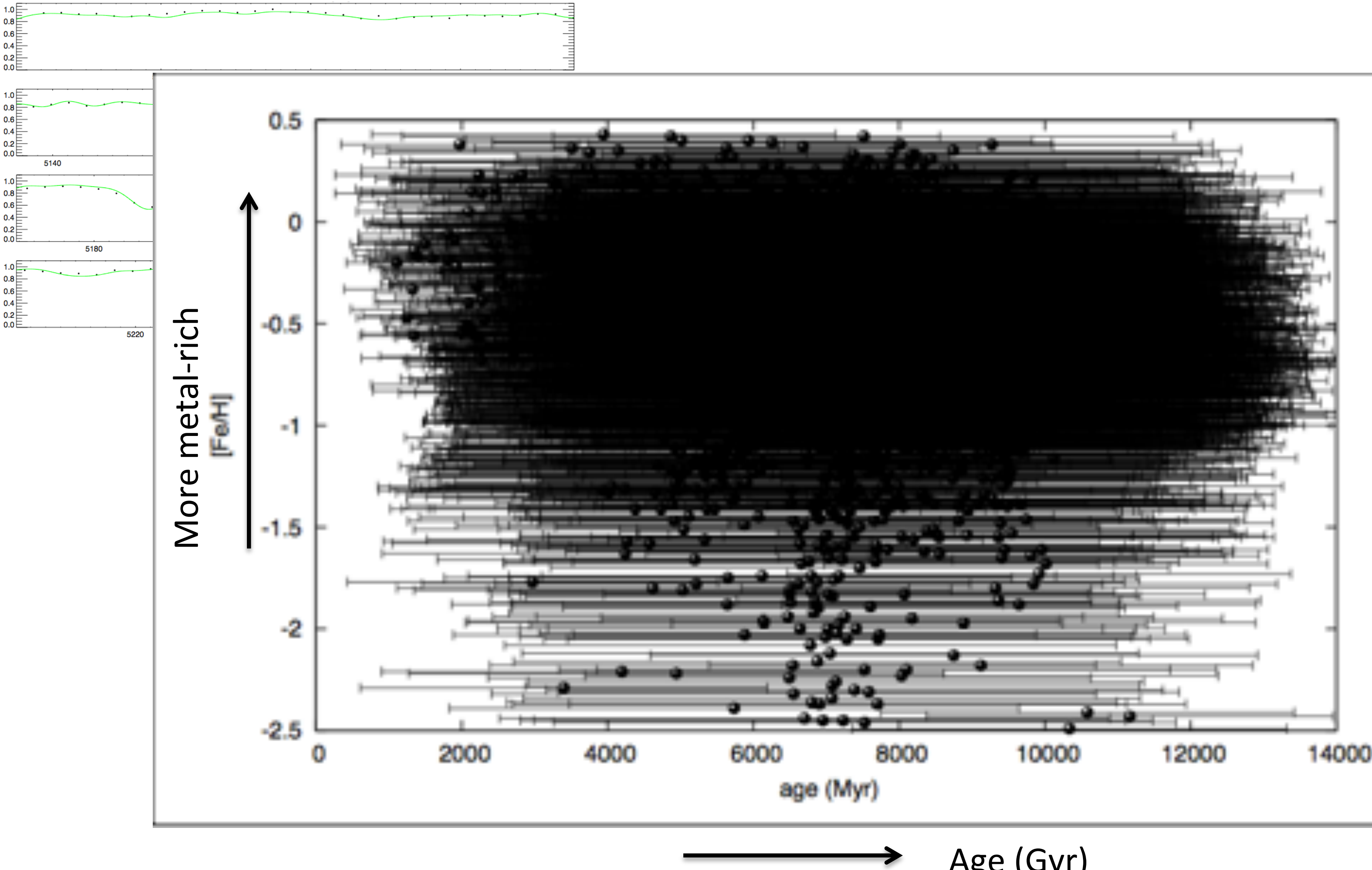


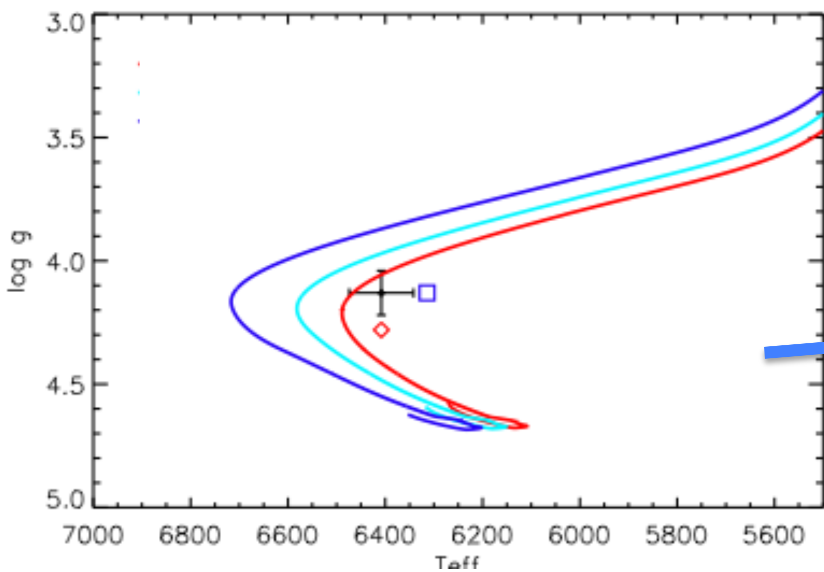
Age (Gyr)

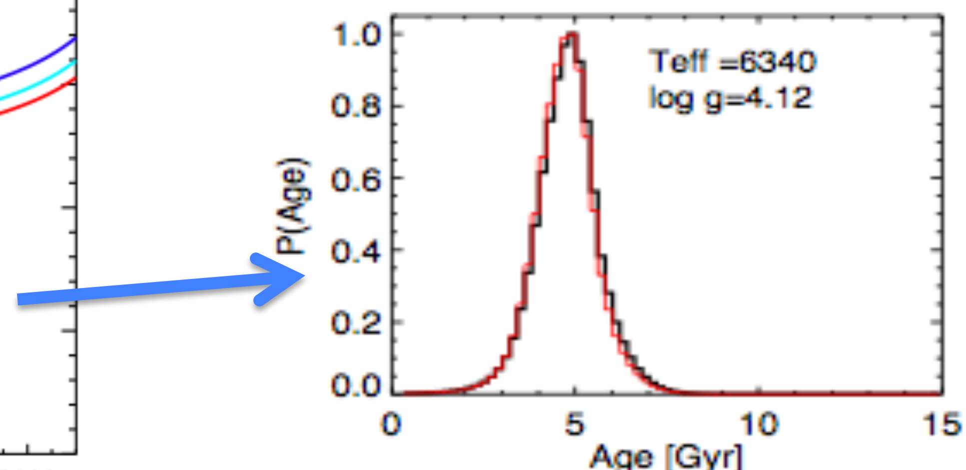


Schönrich 2010

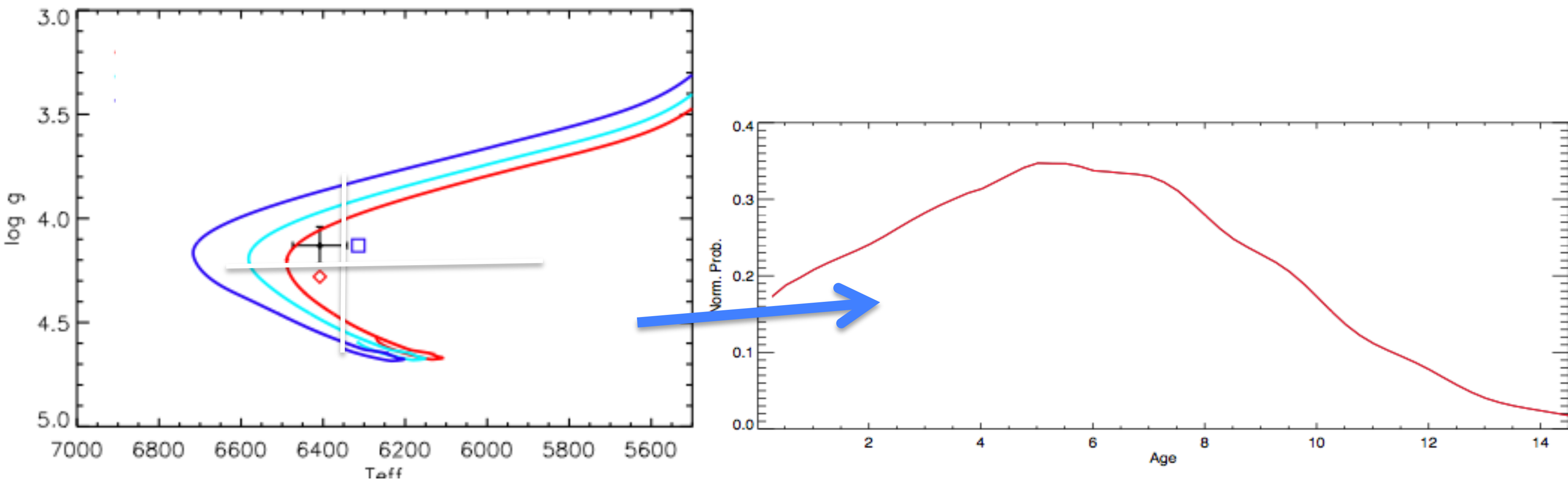

5110
5120
5130
5140
5150
5160
5170
5180
5190
5200
5210
5220
5230
5240


0.5
0
-0.5
-1
-1.5
-2
-2.5
[Fe/H]
0
2000
4000
6000
8000
10000
12000
14000
age (Myr)
More metal-rich
Age (Gyr)





Small errors (high-quality data) → well-defined PDF



low-quality data → blurred or multi-component PDF

Bayesian model testing

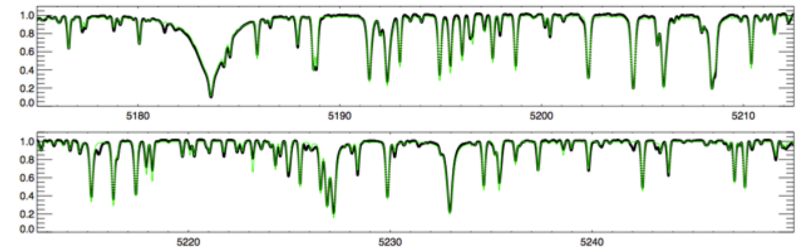
Complementary experiments

large stellar surveys observe <u>millions of stars</u>

spectroscopy:

Sloan Digital Sky Survey, Gaia-ESO, Apogee…

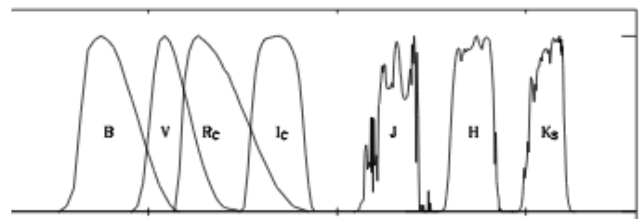
→ stellar spectra: Luminosity, Temperature



photometry:

VISTA, 2MASS, PS1, Skymapper … →

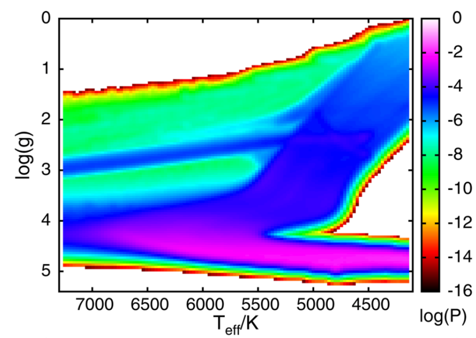
magnitudes in different filters:

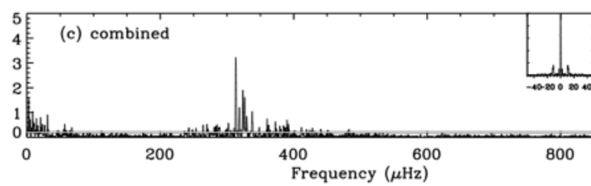


asteroseismology, stellar evolution:

CoRoT, Kepler →

mass, age of a star





astrometry:

Hipparcos, Gaia (launched 2013) →

distances

Maria Bergemann

Bayesian model testing

Stellar Spectroscopy

Bayesian spectroscopy

1) In our context, the 'core' parameter space is defined by:
metallicity (expressed by iron abundance), effective temperature, and surface gravity

T_{eff}, log g, [Fe/H]

2) Their plausibility is estimated based on the information contained in:

- observed stellar spectra
- model stellar spectra
- stellar evolution models (not all luminosities, masses, and ages are possible)
- parallaxes, photometry (constraints on log g (π) and L (color))
- WMAP → constraints on the max age

a set of parameters $\boldsymbol{X} = X_1, \ldots, X_n$

a set of observations $\boldsymbol{O} = O_1, \ldots, O_m$

The goal is to construct a full posterior PDF in all parameters

$$P(\boldsymbol{X}|\boldsymbol{O}) = \frac{P(\boldsymbol{X})}{P(\boldsymbol{O})} P(\boldsymbol{O}|\boldsymbol{X}),$$

The goal is to construct a full posterior PDF in all parameters

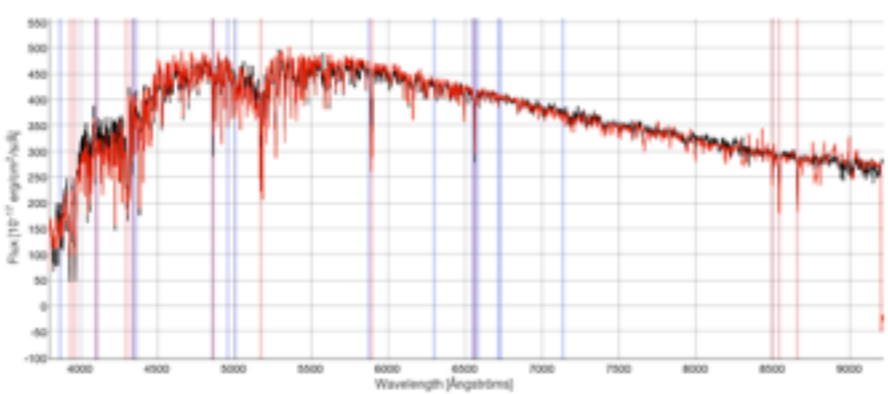
distances
Hipparcos mission
GAIA

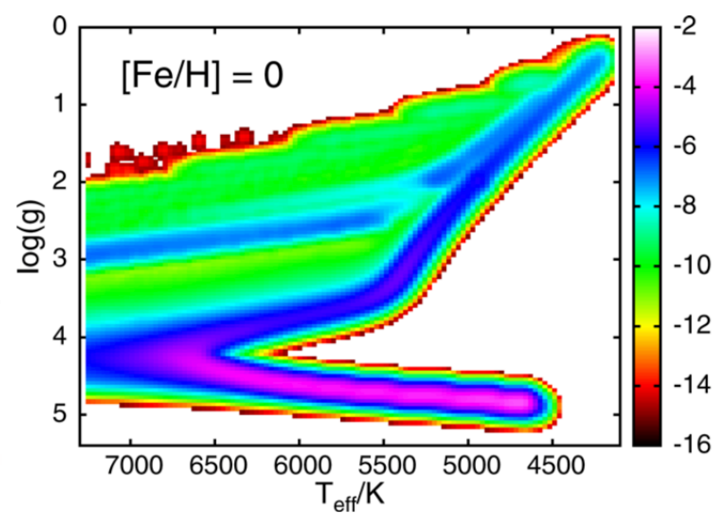
$$P(R|O_{sp}, O_{ph}) \sim P(O_{sp}|R) \cdot P(O_{ph}|R) \cdot P_{mod}(R) \cdot P_{pr}(R) \cdot P_{i,ph,astr}$$

Spectra + photometry
SDSS

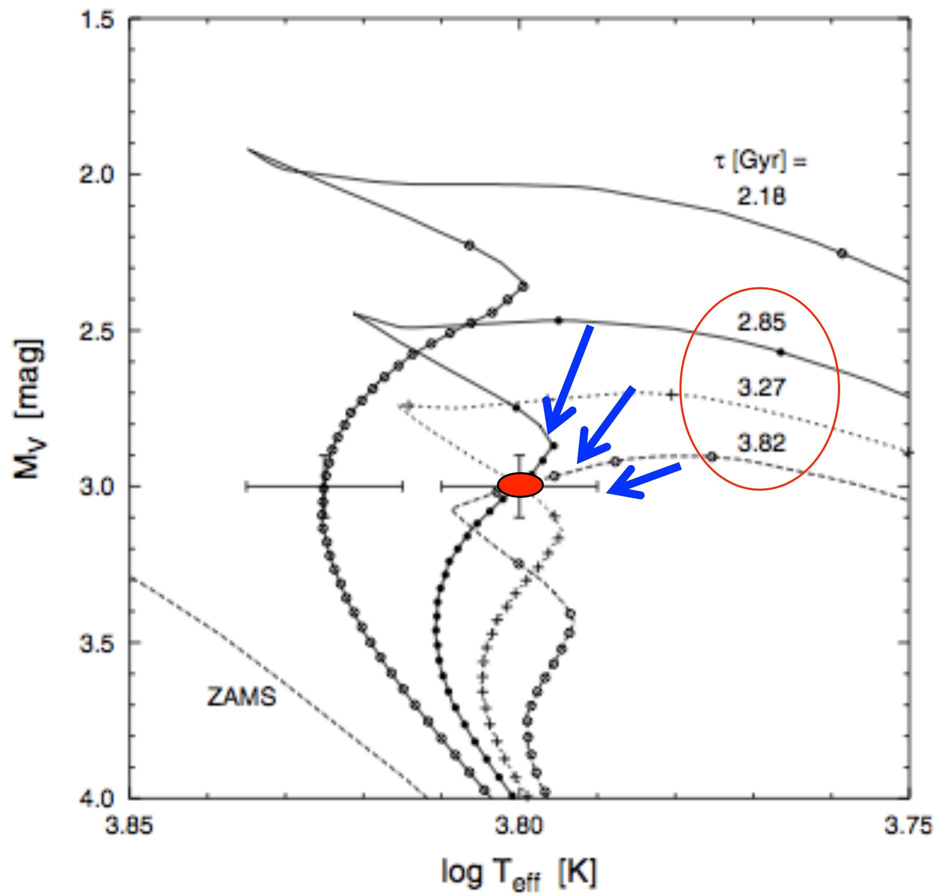
stellar evolution models

IMF, age-metallicity prior





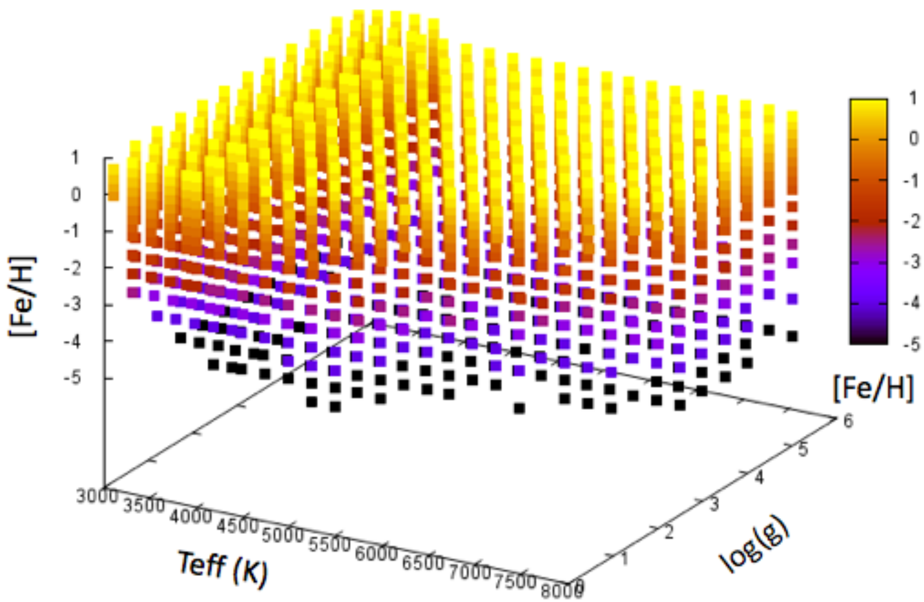
L(max) attains its global maximum for **all** three isochrones!

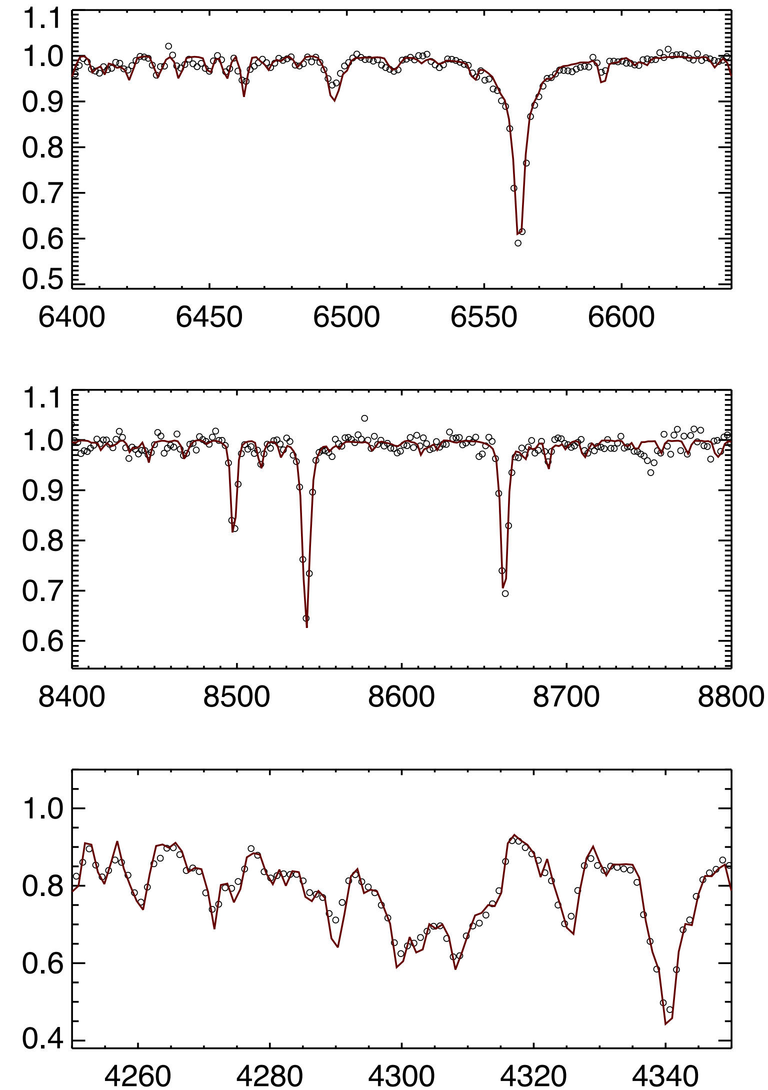


In standard *L(max)* approach, ages suffer from a 'terminal age bias', i.e., short-lived evolution stages get **un-physically** high probability.

Jørgensen & Lindegren 2005

run over the full multi-D grid of spectroscopic models

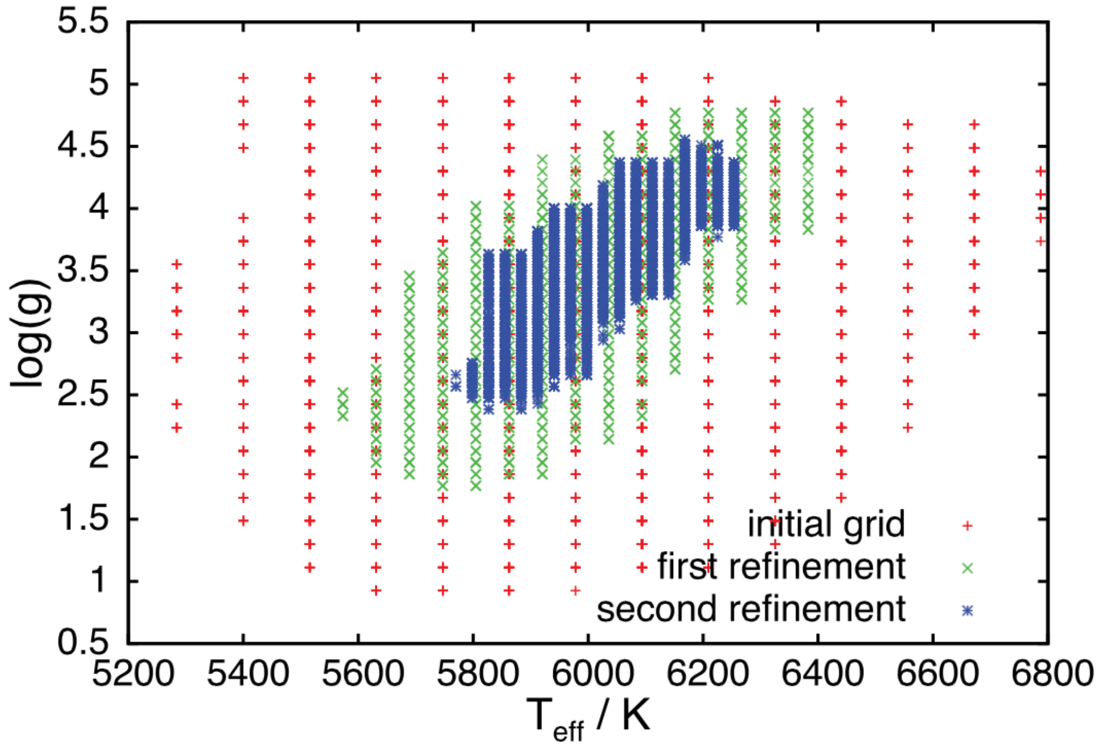




$$\chi^2 = \sum_j \left(\frac{D_j^{\rm obs} - D_j(\ {\rm Teff, logg,}\ \ {\rm Z})^{\rm theor}}{\sigma_j} \right)^2$$

Schoenrich & Bergemann 2014, MNRAS, 443

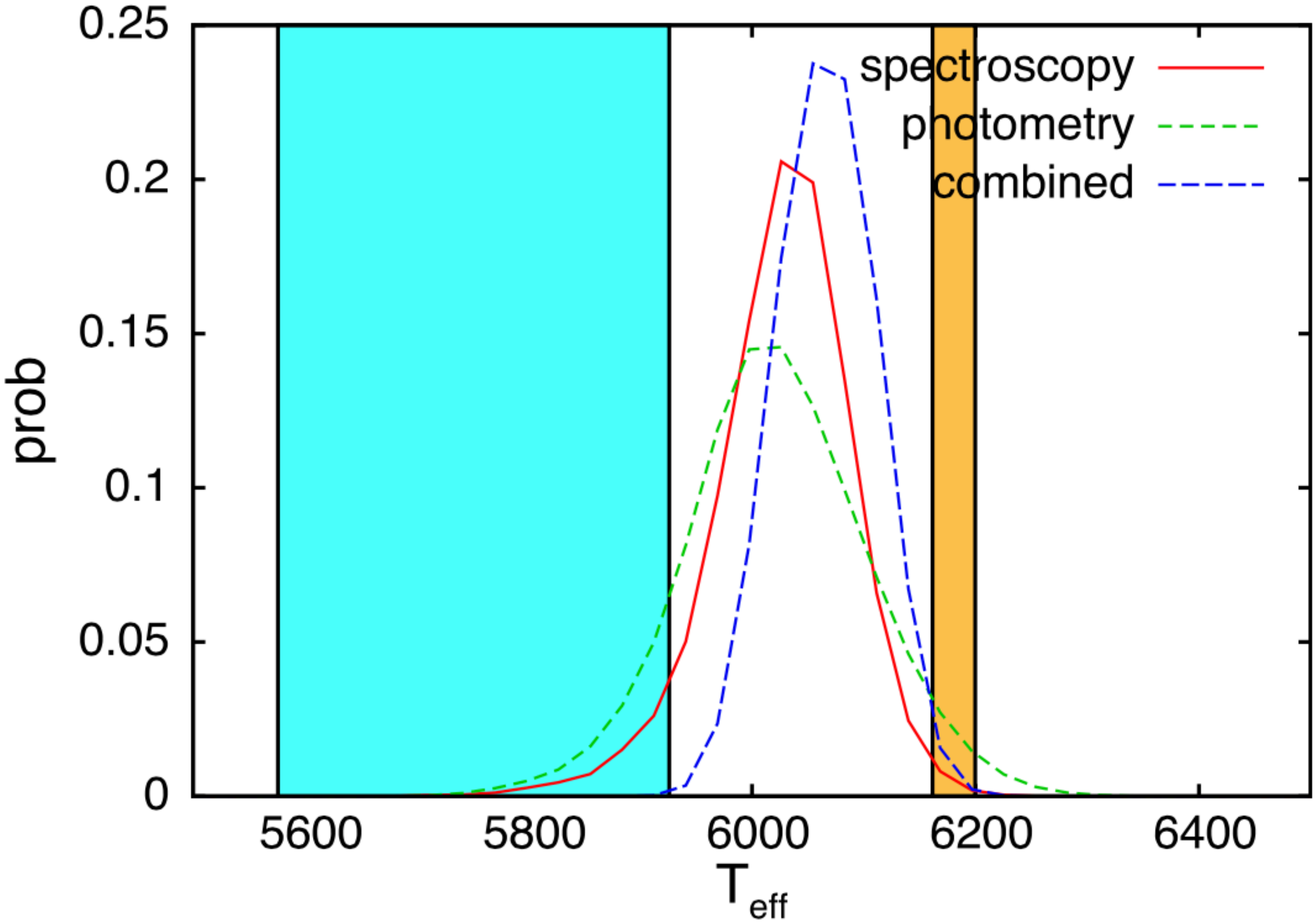
use adaptive, iteratively refined mesh guided by photometry + prior



Final values of Teff, log(g), [Fe/H]:

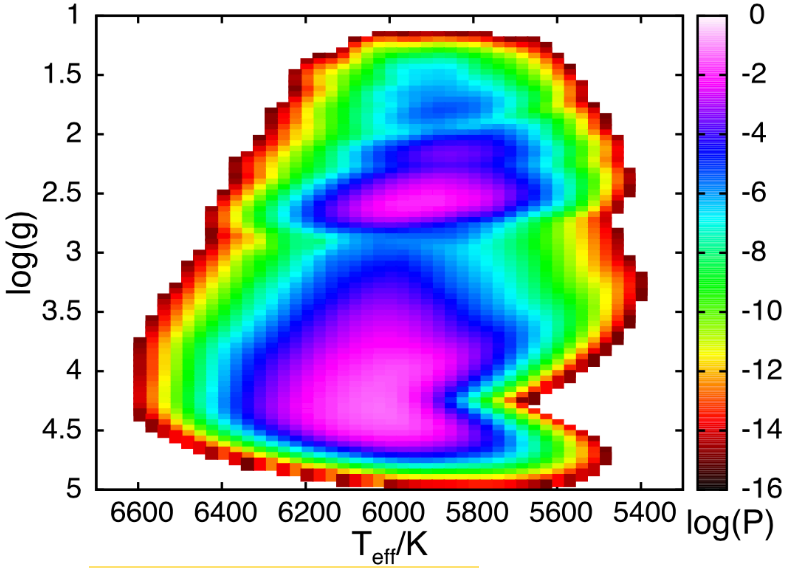
$$P(X_j|\boldsymbol{O}) = \int \int P(X_1, \ldots, X_n|\boldsymbol{O})\,\mathrm{d}x_1 \ldots \mathrm{d}x_{j-1}\,\mathrm{d}x_{j+1} \ldots \mathrm{d}x_n.$$

Results

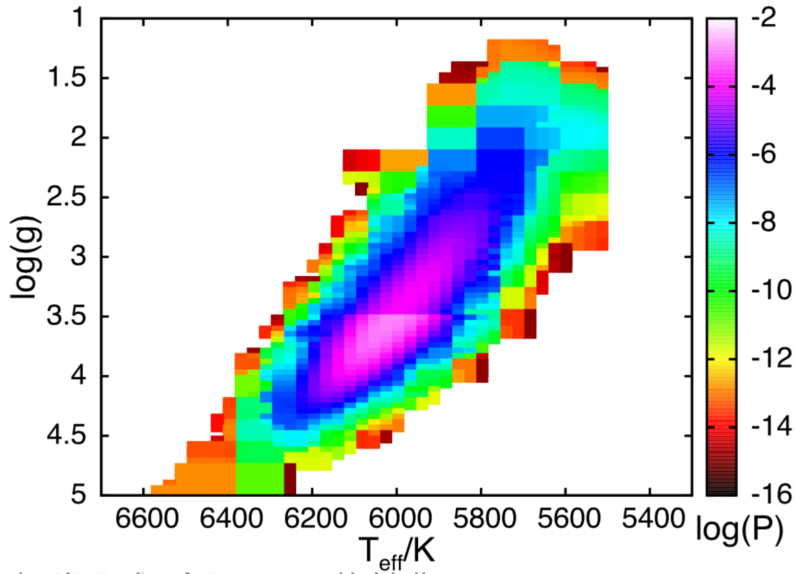


spectroscopy
photometry
combined
prob
0.25
0.2
0.15
0.1
0.05
0
5600
5800
6000
6200
6400
T_{eff}

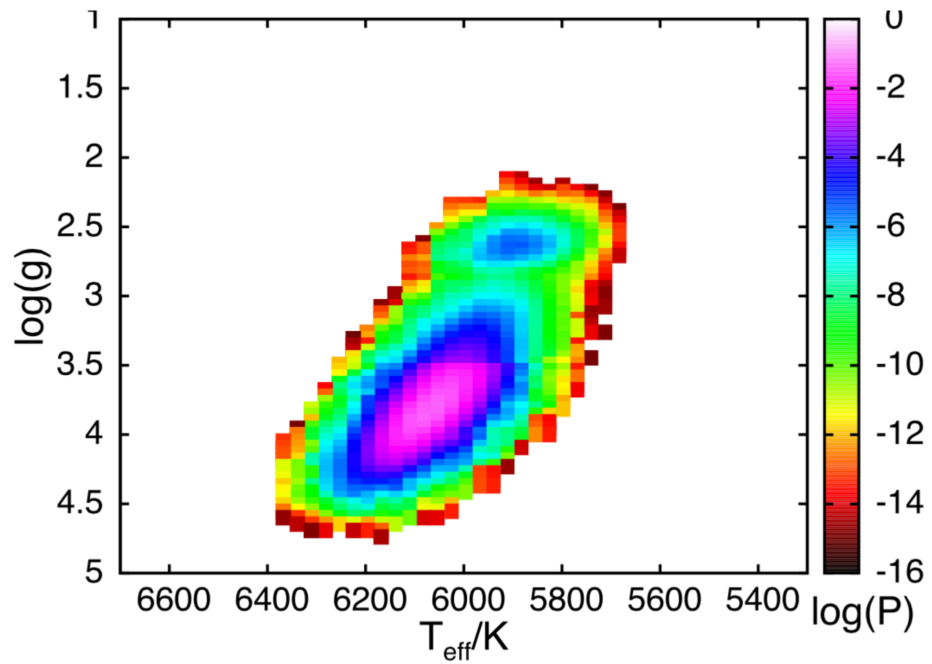
Photometric PDF



Spectroscopy PDF

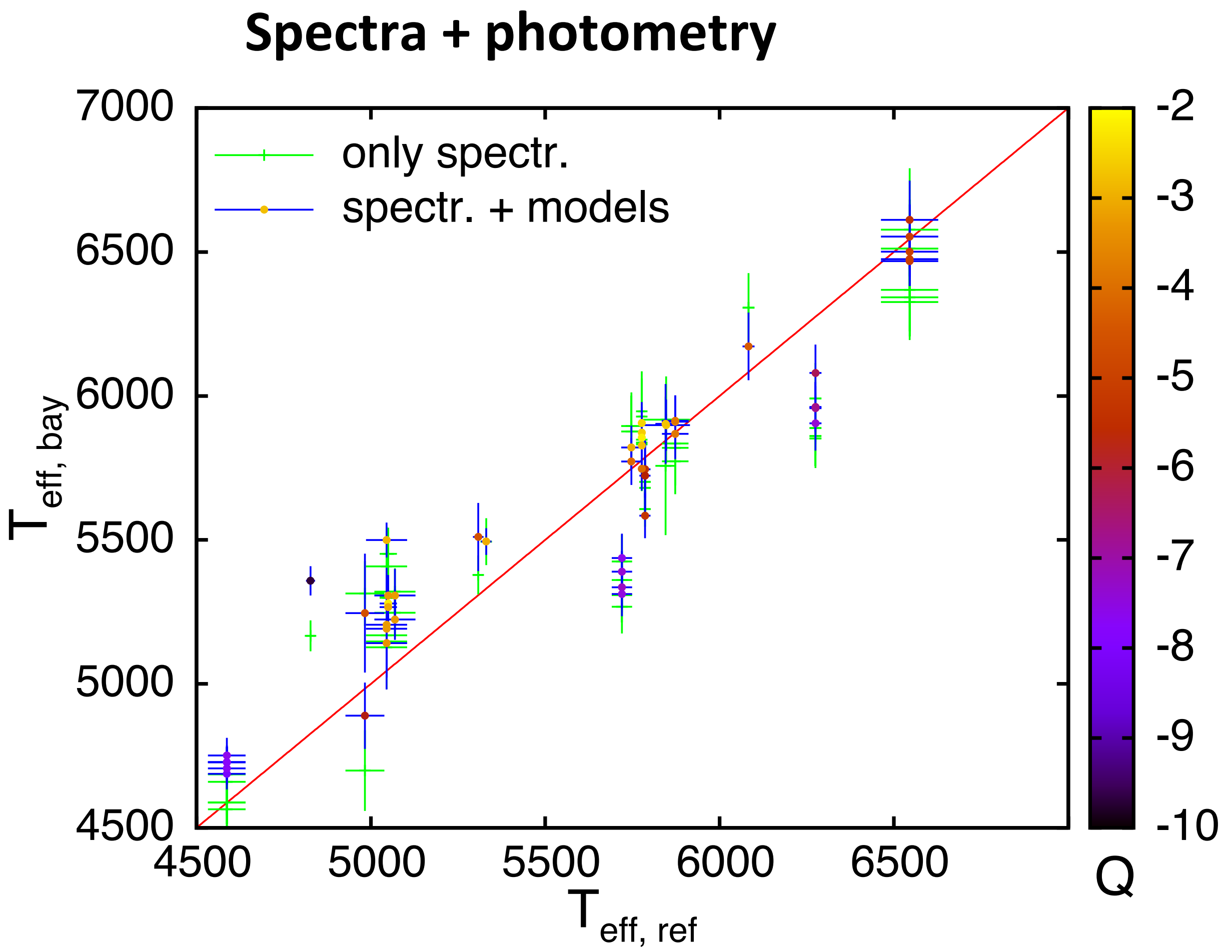


Final combined PDF

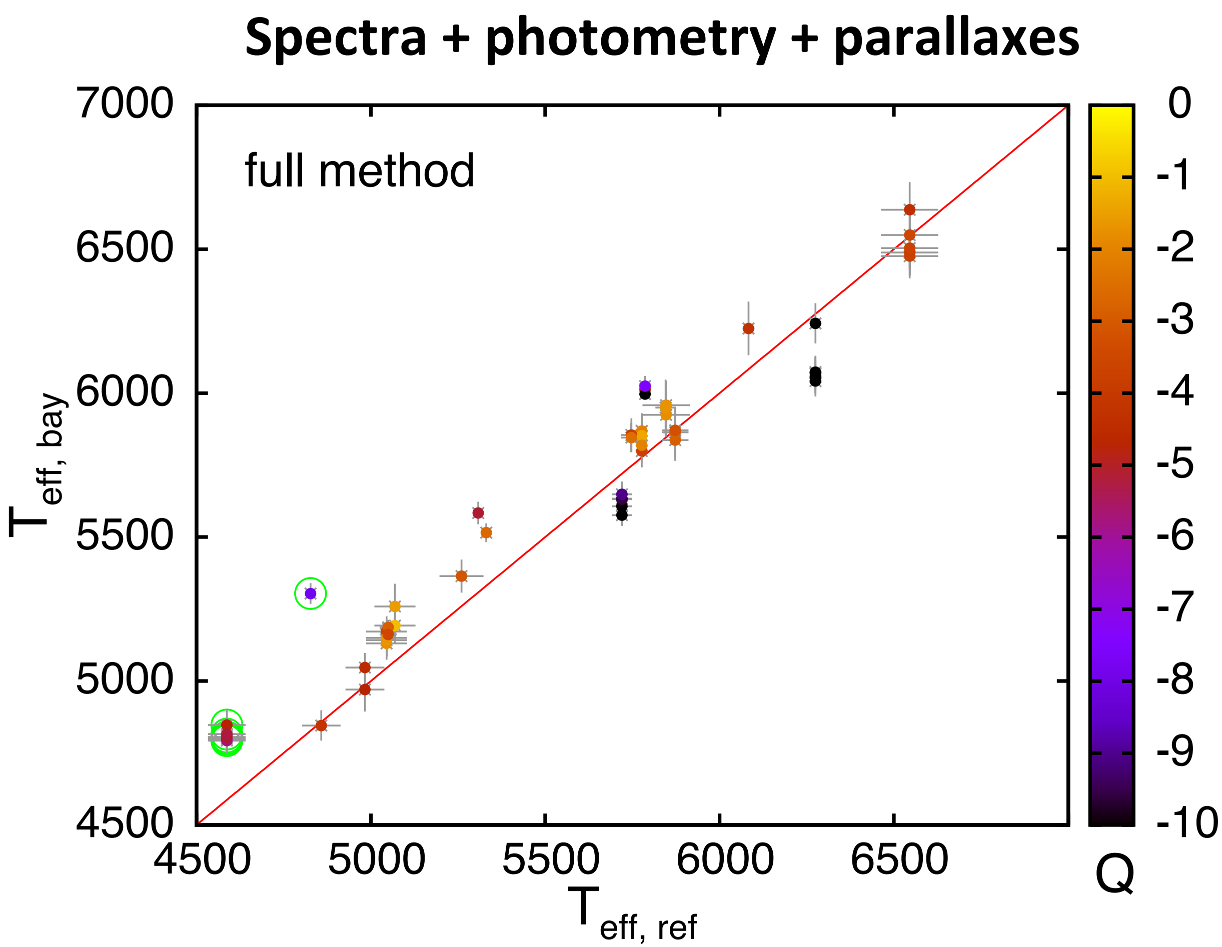


Schoenrich & Bergemann 2014, MNRAS, 443

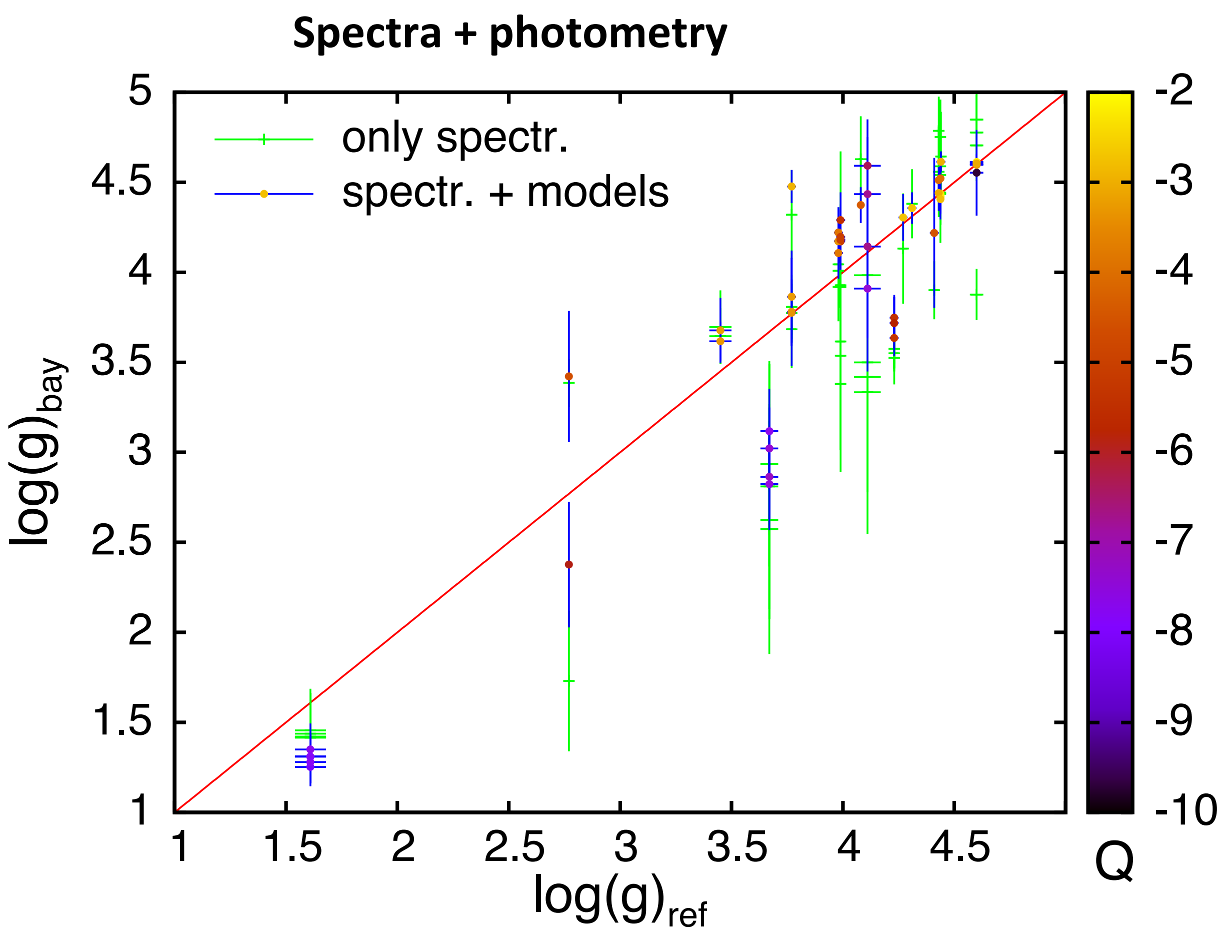
Bayesian Teff



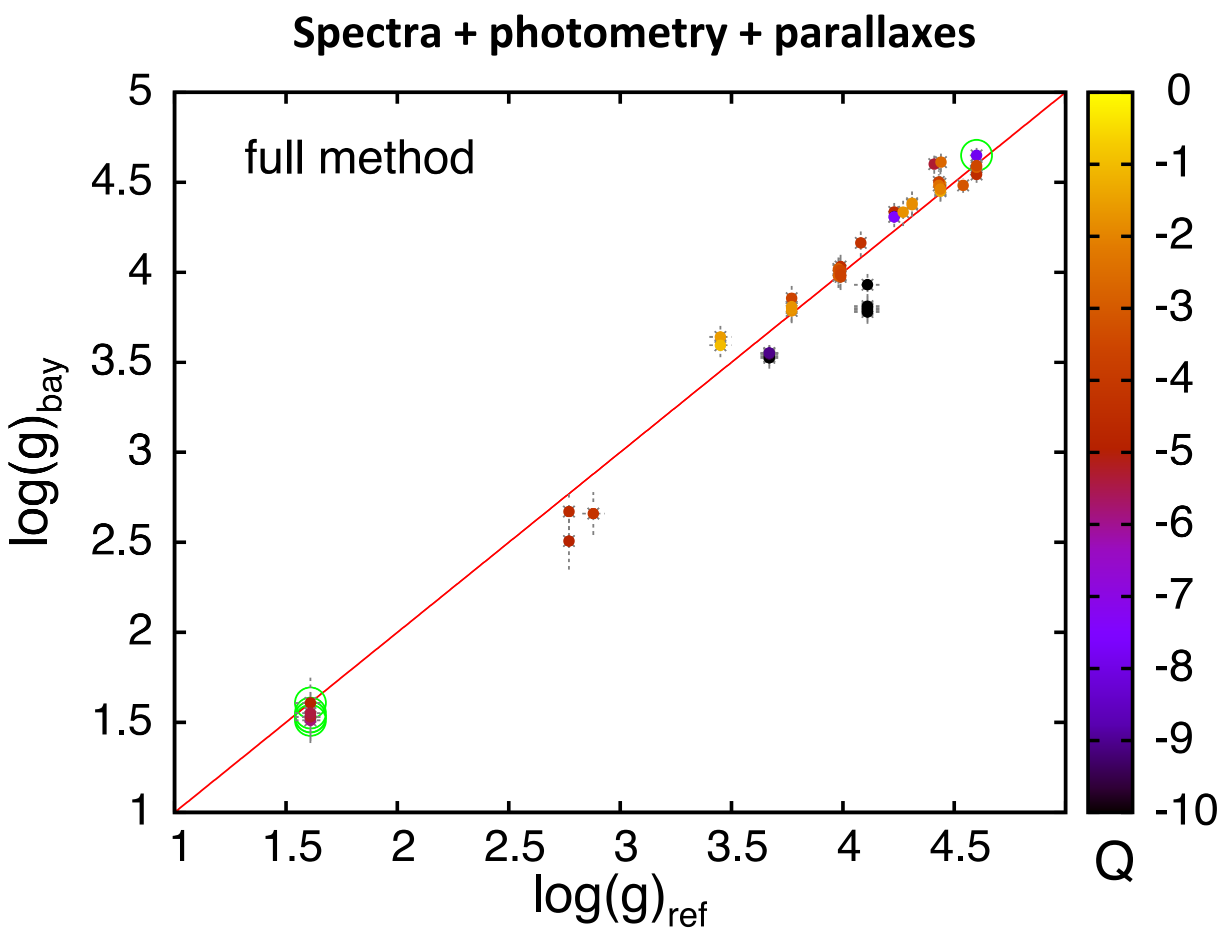
Bayesian Teff



Bayesian gravity



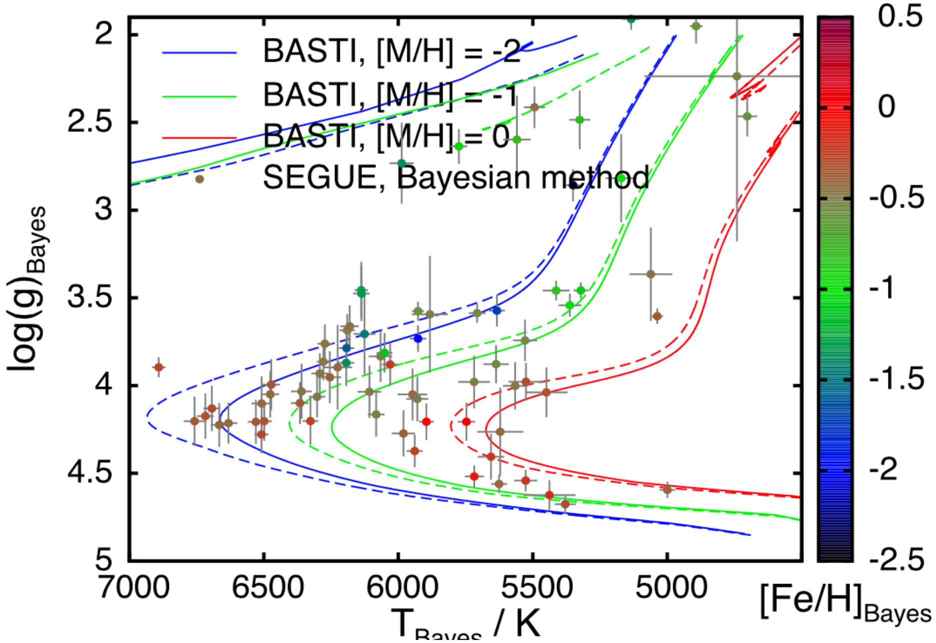
Bayesian gravity



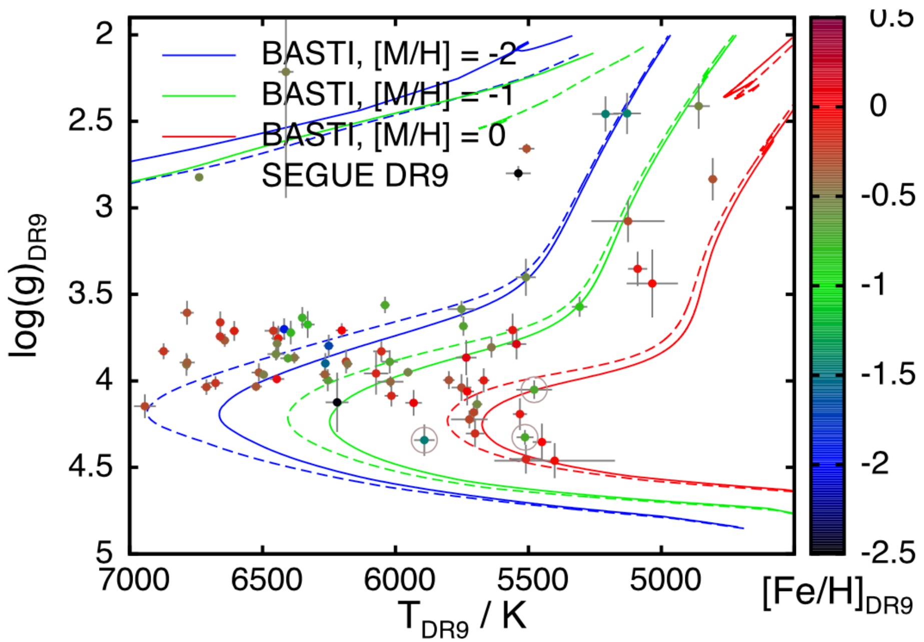
Schoenrich & Bergemann 2014

Stars from Sloan Digital Sky Survey

Bayesian



Spectroscopic only



Schoenrich & Bergemann 2014, MNRAS, 443

Bayesian: summary

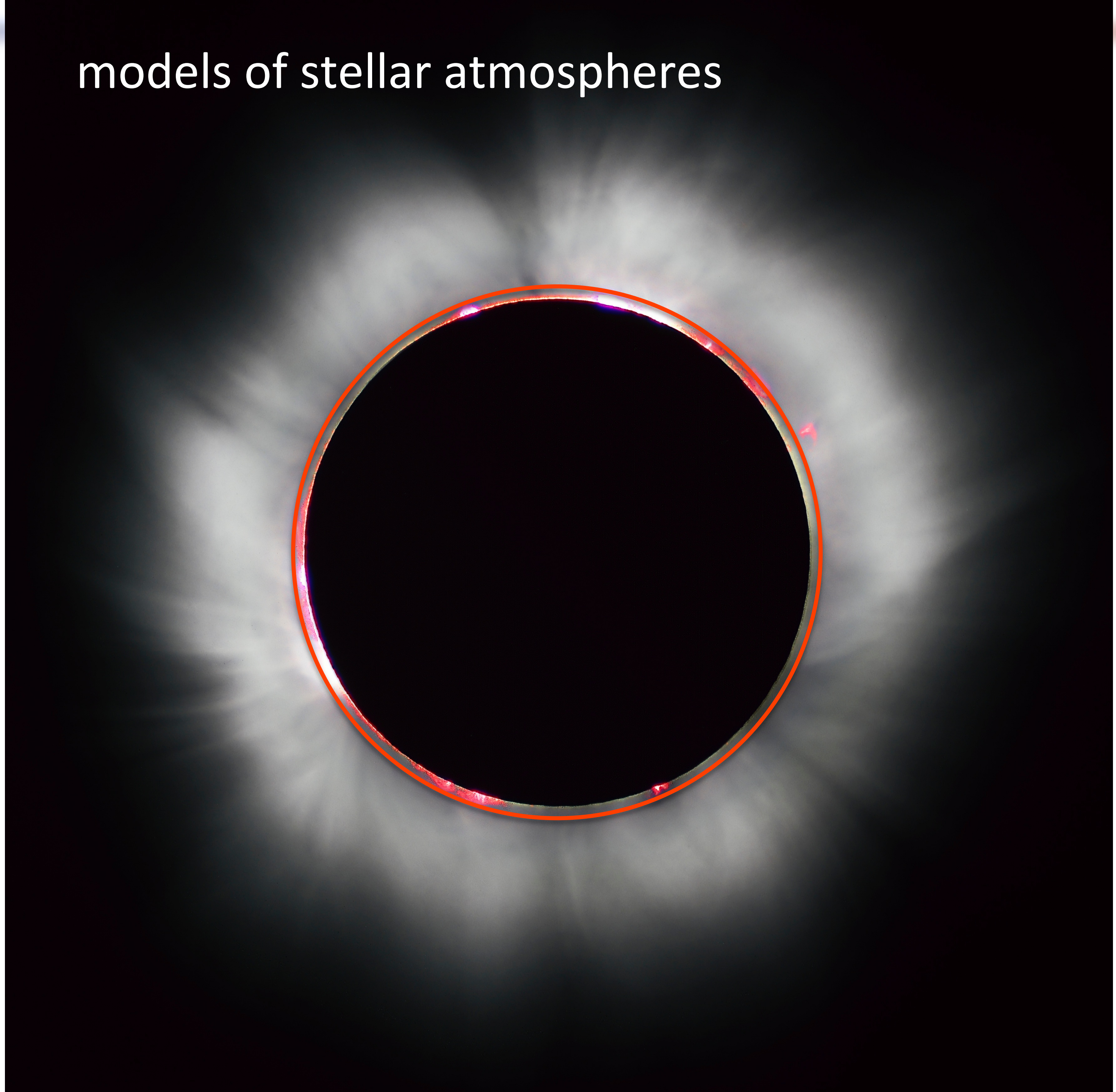
✓ Pros

- All parameters (stellar parameters, distances, ages) within one single, consistent analysis
- Automatic detection of pathologic (or interesting...) cases
- Ability to quantify systematic shifts/errors

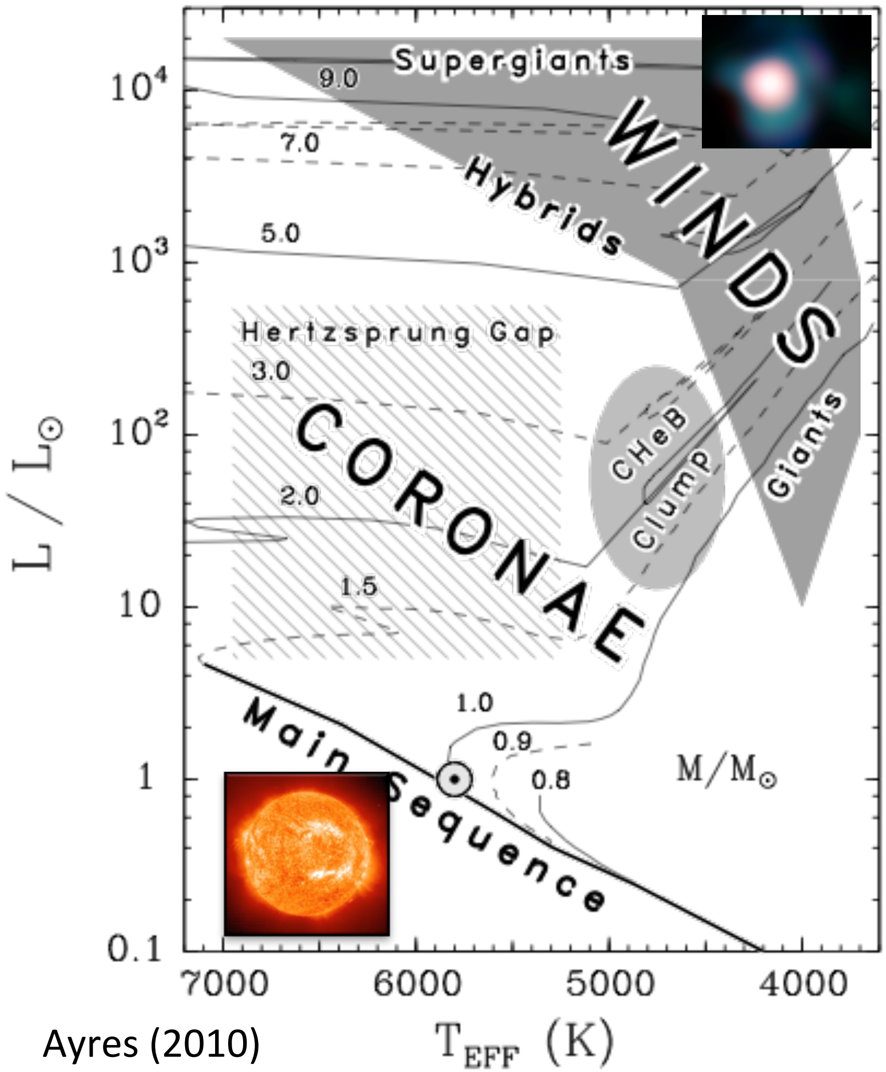
✓ Cons

- The analysis scheme is too rigid: we cannot handle objects with physical properties that are not within the pre-computed model grids
- expanding the basic parameter set is expensive 3D → 4D (?) .. We need 30
- Inclusion of priors – all stellar populations are different (the rate of star formation, IMF?)

Even the best observed spectra
and good statistics
are worth nothing
without good models


models of stellar atmospheres

Basic model atmosphere theory – the models are usually trained on a given class of stars



Ayres (2010)

We do not have a single consistent set of models which describe all types of stars found in nature:

- rotate up to 100 km/s
- pulsate
- lose mass in winds
- magnetic fields (kG)
- exist as binaries or multiple systems (overlapping spectra)
- mass motions (inflows, outflows)
- Circumstellar dust shells

Classical stellar atmosphere models

- ✓ local thermodynamic equilibrium
- ✓ Hydrostatic equilibrium
- ✓ 1-dimensional
- ✓ plane-parallel → semi-infinite
- ✓ plus about **30 ad-hoc free parameters**

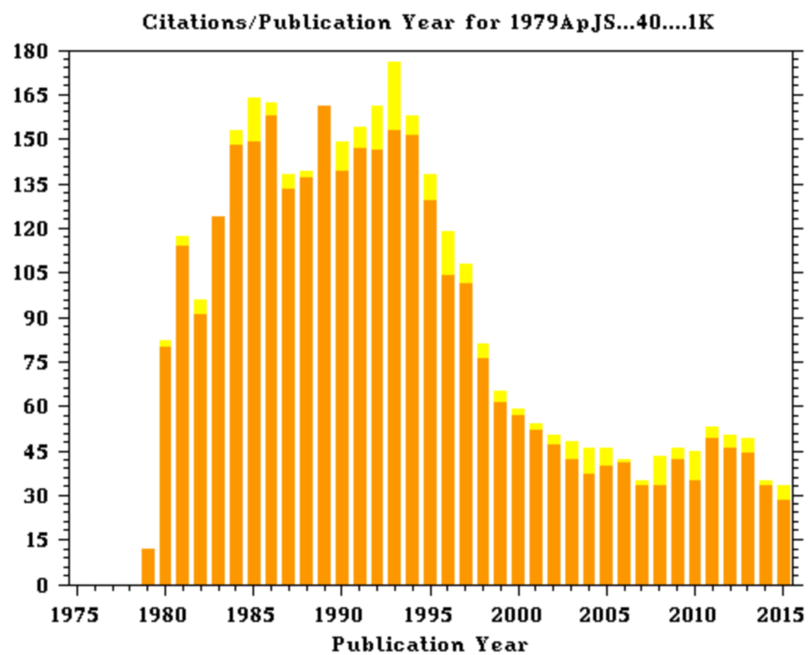
$$\cos\theta \frac{dI_\nu}{dz} = \kappa_\nu I_\nu - \eta_\nu$$

$$F = \frac{L}{4\pi R^2} = \sigma T_{\rm eff}^4,$$

$$\int_0^\infty J_\nu(\tau) d\nu = \int_0^\infty S_\nu(\tau) d\nu$$

$$\nabla P_{tot} = -\rho \frac{GM_r}{r^2},$$

$$\nabla P_{rad} = -1/c \int_0^\infty (\kappa_\nu + \sigma_\nu) F_\nu d\nu$$



~4000 citations
the most widely-used grid of stellar spectra in astronomy
Kurucz, 1979, ApJ

Kurucz+

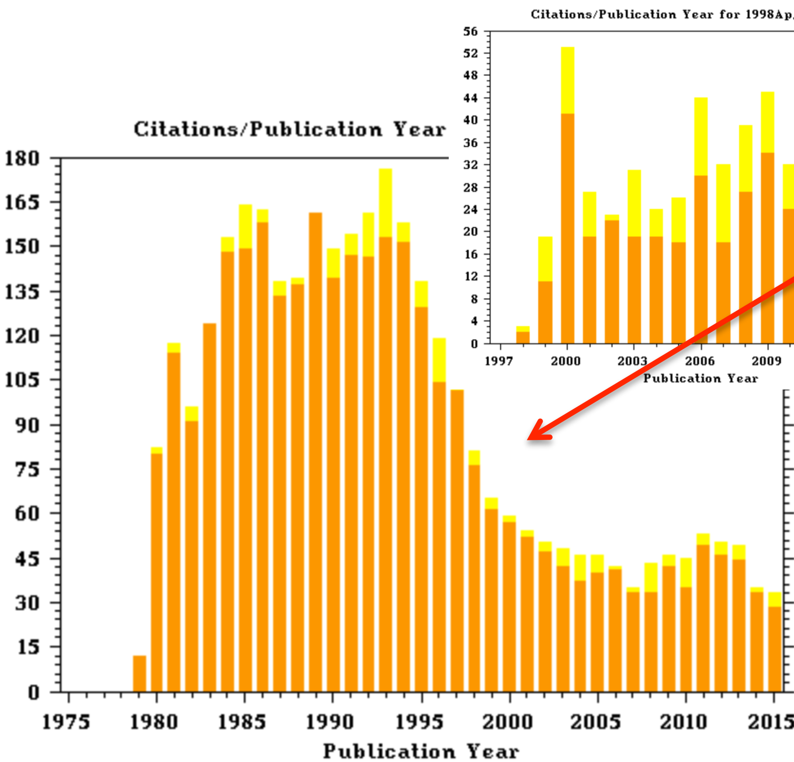
Classical stellar atmosphere models

- ✓ local thermodynamic equilibrium
- ✓ Hydrostatic equilibrium
- ✓ 1-dimensional
- ✓ plane-parallel → semi-infinite
- ✓ plus about **30 ad-hoc free parameters**

$$\cos\theta \frac{dI_\nu}{dz} = \kappa_\nu I_\nu - \eta_\nu$$

$$F = \frac{L}{4\pi R^2} = \sigma T_{\rm eff}^4,$$

$$\nabla P_{rad} = -1/c \int_0 (\kappa_\nu + \sigma_\nu) F_\nu d\nu$$



the first paper on 3D hydro-dynamical model atmospheres of stars
Stein & Nordlund, ApJ, 499, 1998

~3400 citations
the most widely-used
1D p-p grid of stellar spectra
in astronomy
Kurucz, ApJS, 40, 1979

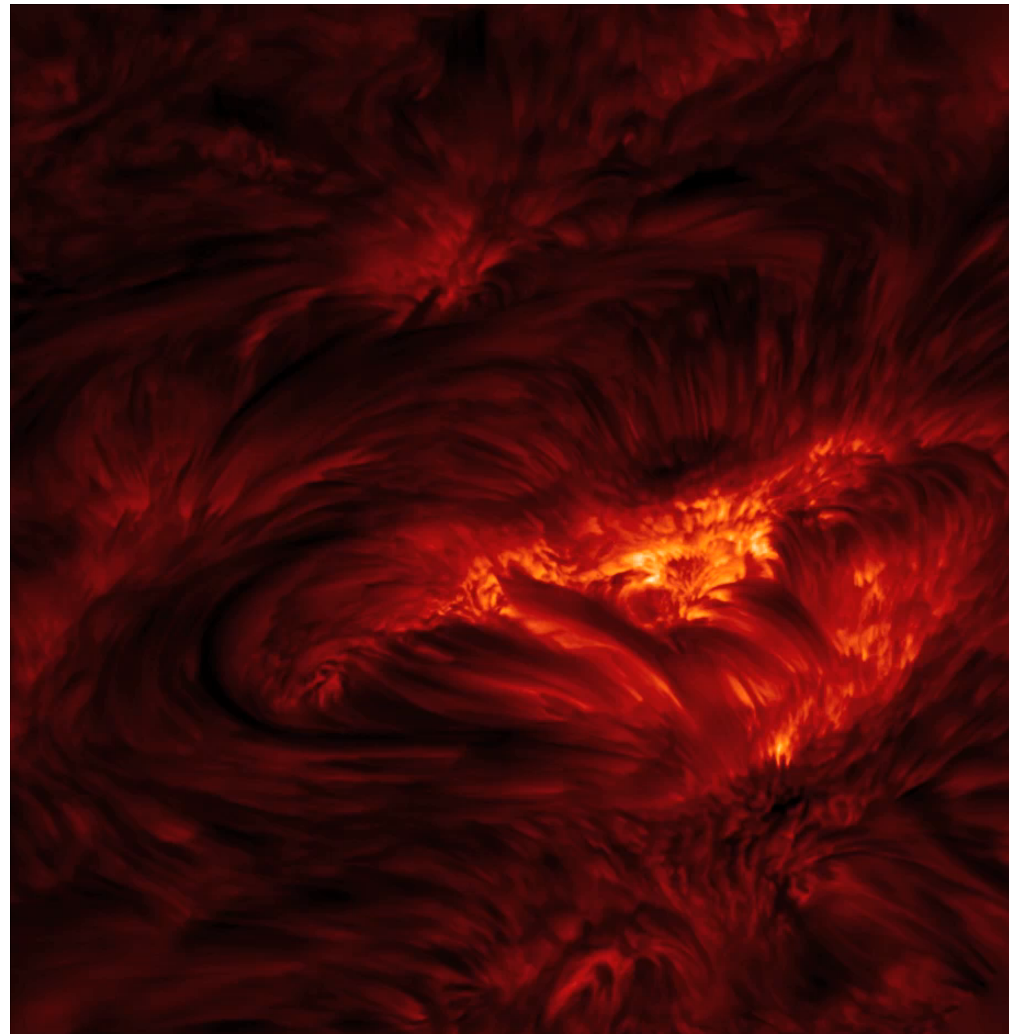
Kurucz+

- ✓ local thermodynamic equilibrium
- ✓ Hydrostatic equilibrium
- ✓ 1-dimensional
- ✓ plane-parallel → semi-infinite
- ✓ plus about **30 ad-hoc free parameters**

The observed image of the Sun
Swedish Solar Telescope (1m)

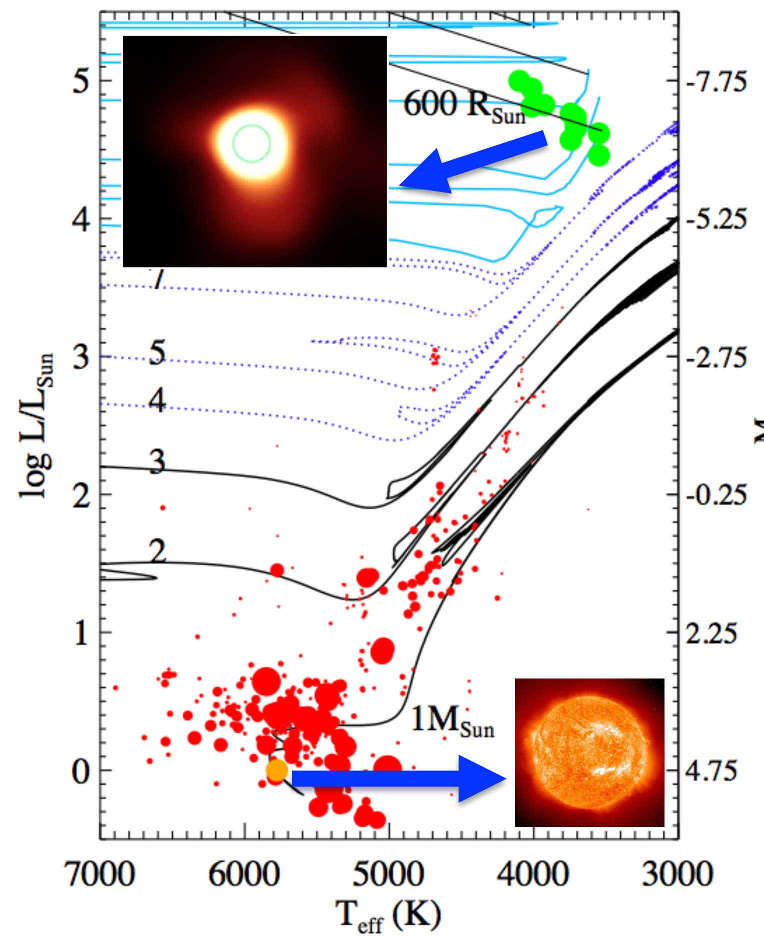
Does that work?

No



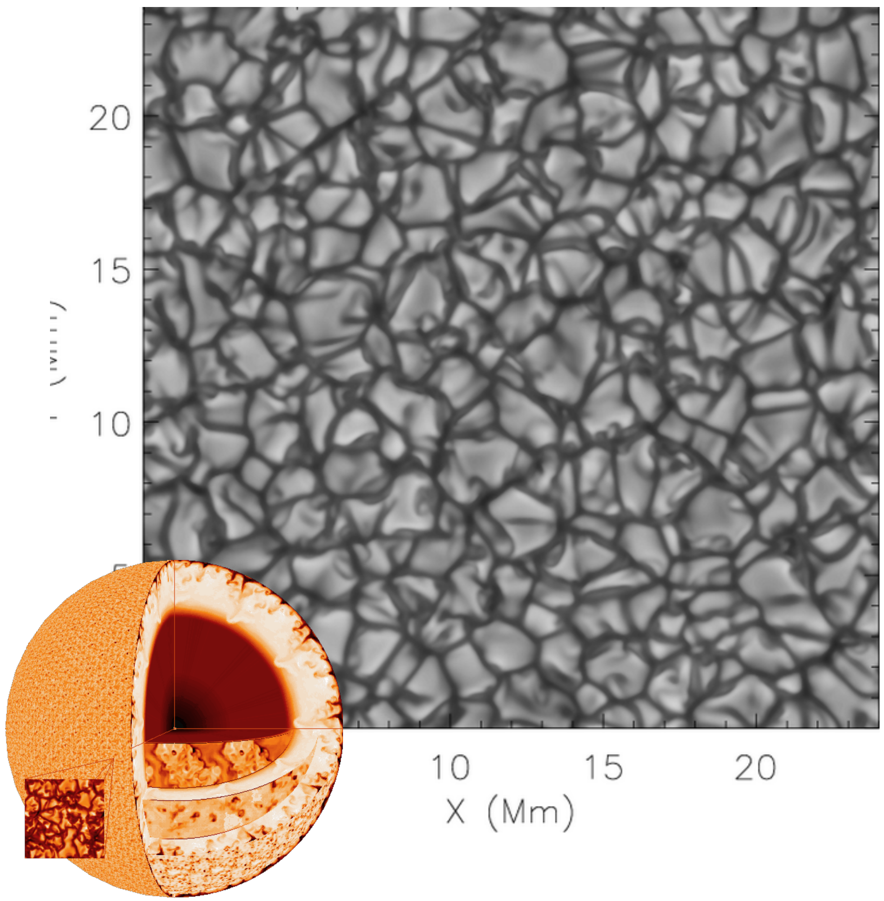
State-of-the-Art

- 3D hydrodynamics
- non-LTE (consistent treatment of the radiation field and physical state of the gas —> gas must respond to the radition loss from the surface)
- ab initio
- complete sampling of opacity sampling (up to 100 million spectral lines)
- no for unphysical calibrations ('mixing length', 'microturbulence')

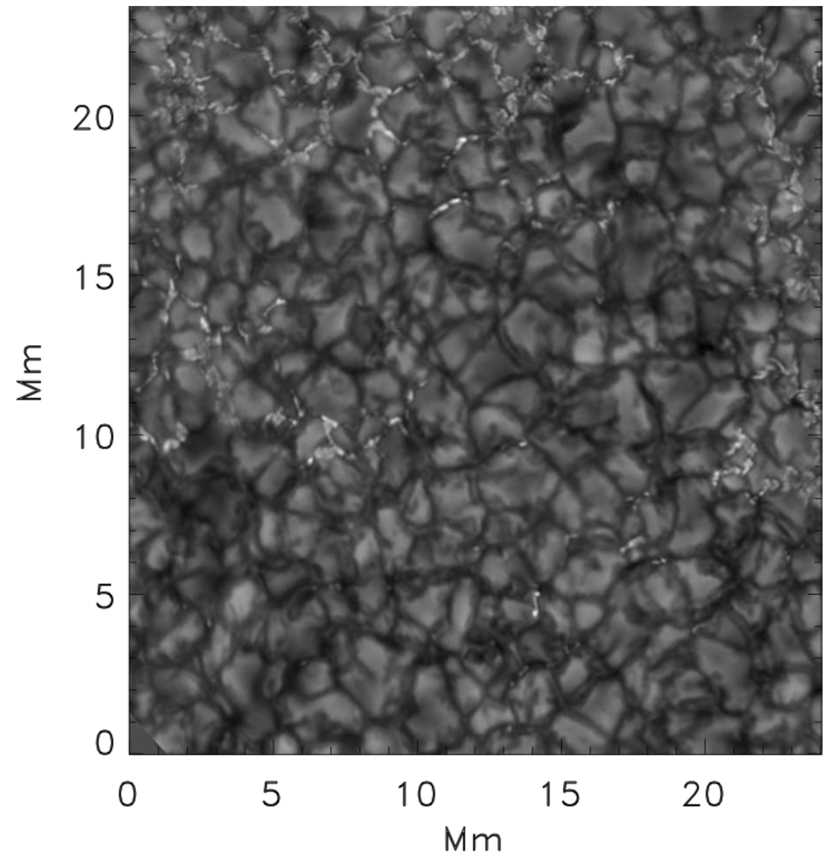


3D Hydrodynamical models

the same scales - both images 20x20 Mm (!)

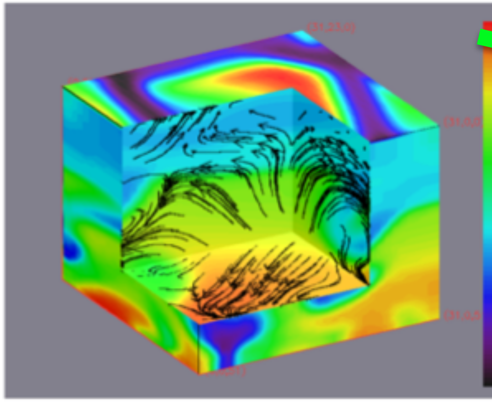


Matloch+ (2010)
(c) Asplund

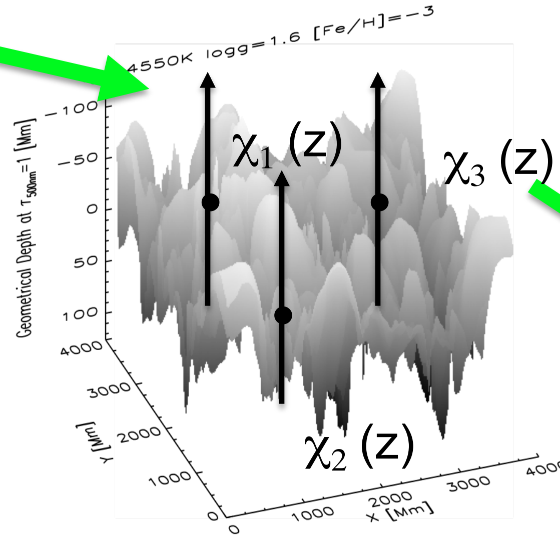


Nordlund+ (2009), observed SST

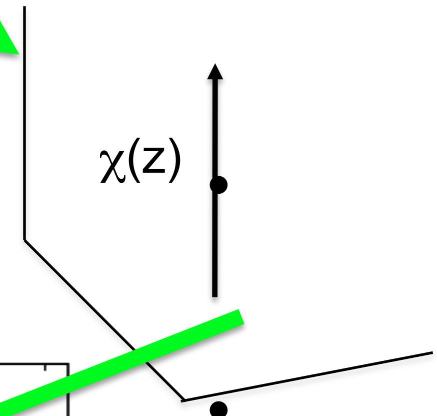
3D NLTE spectroscopy

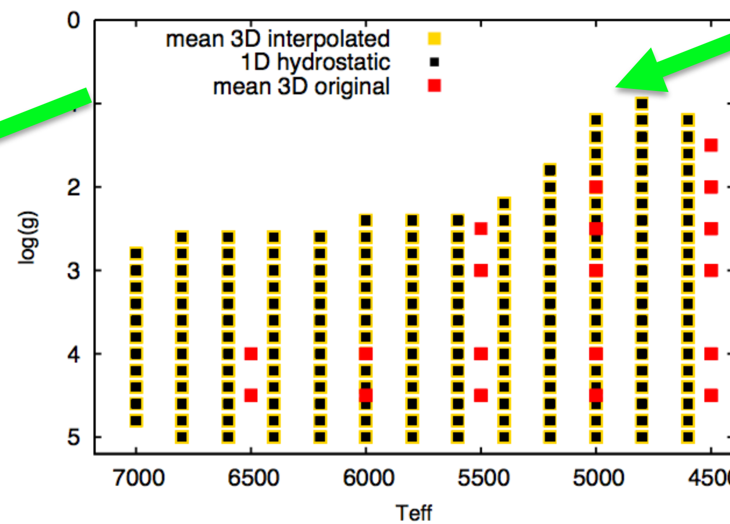


average spatially (x,y)



e.g., collapsing **opacity surface** to a single z-dependent value





3D NLTE spectroscopy

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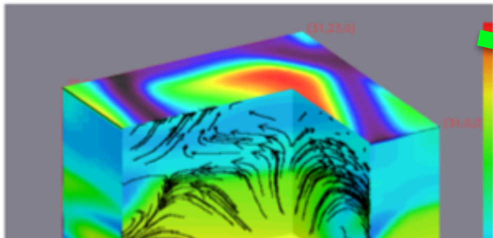

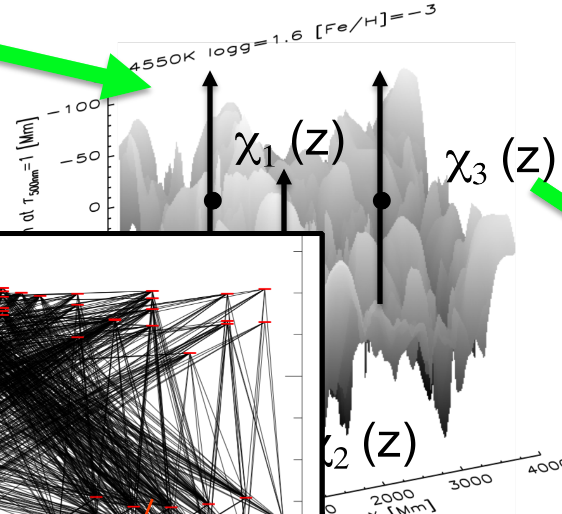

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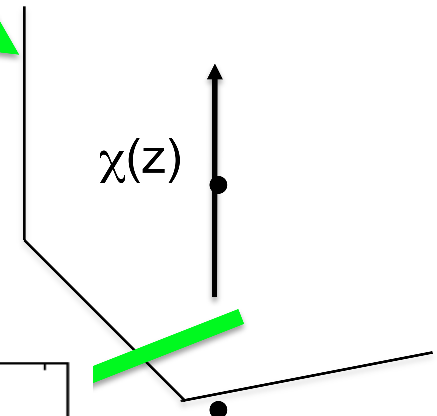
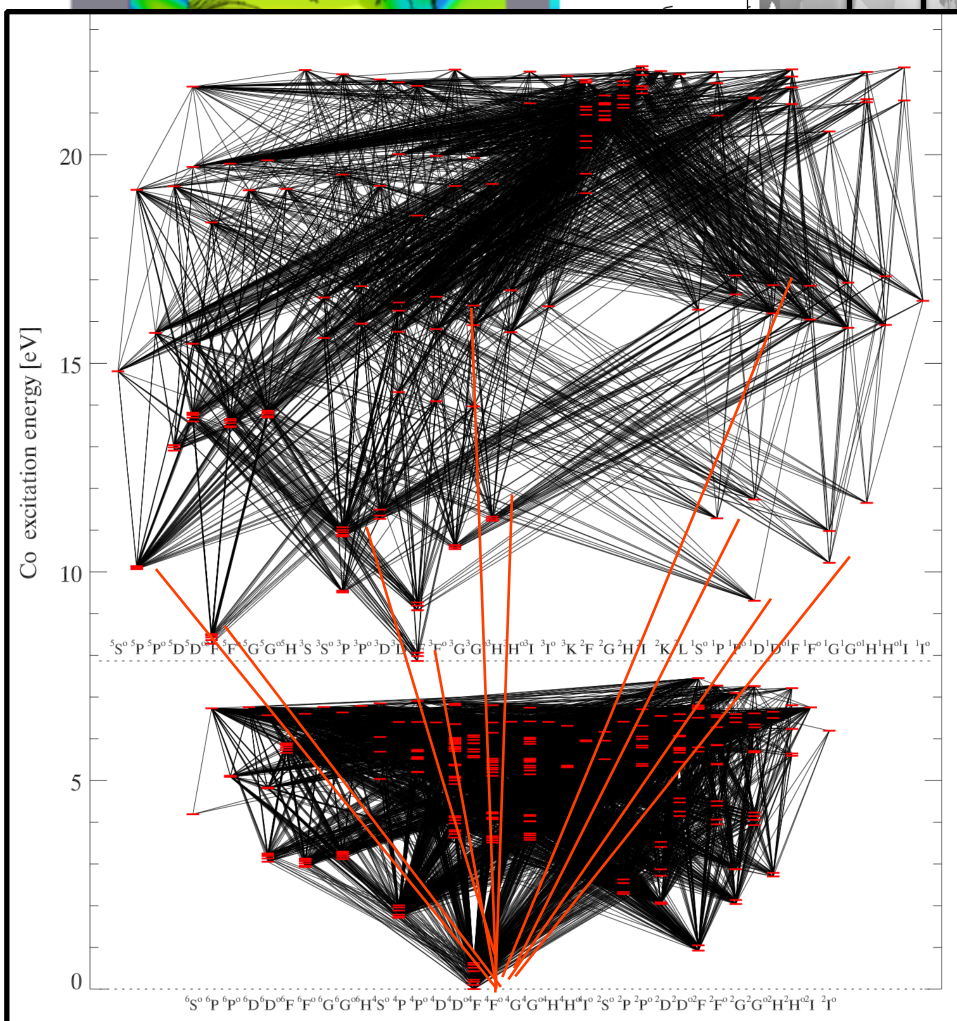
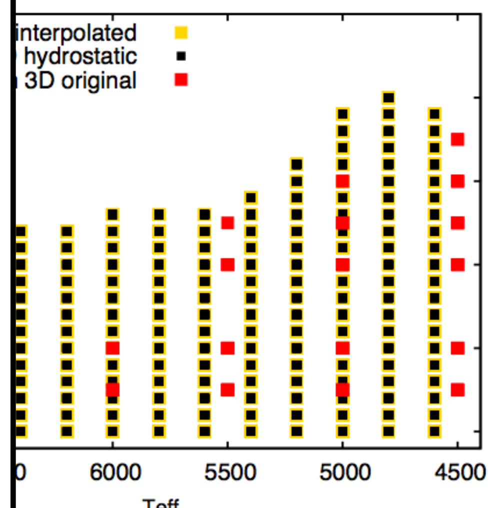


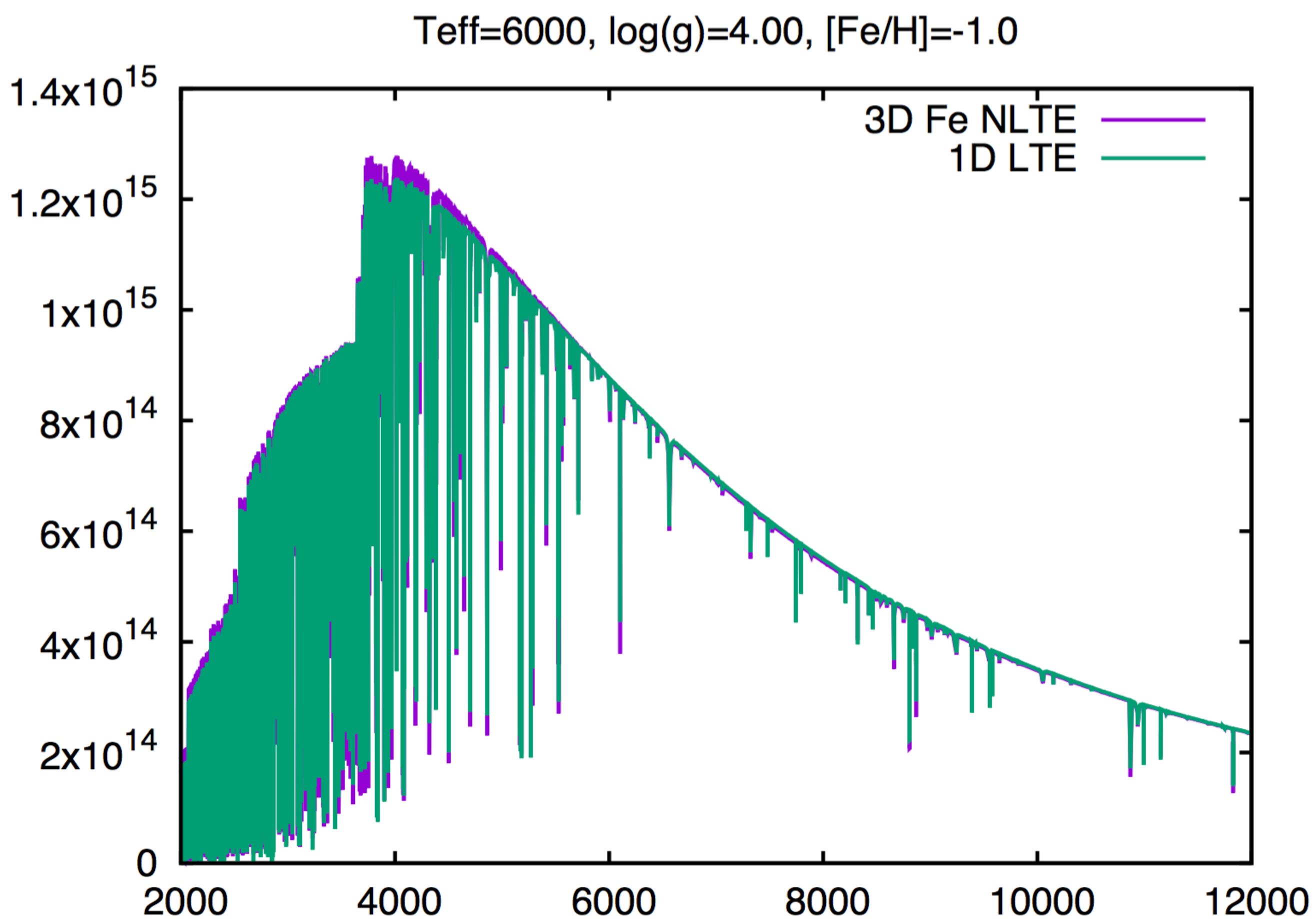




NLTE radiation transport in millions atomic lines

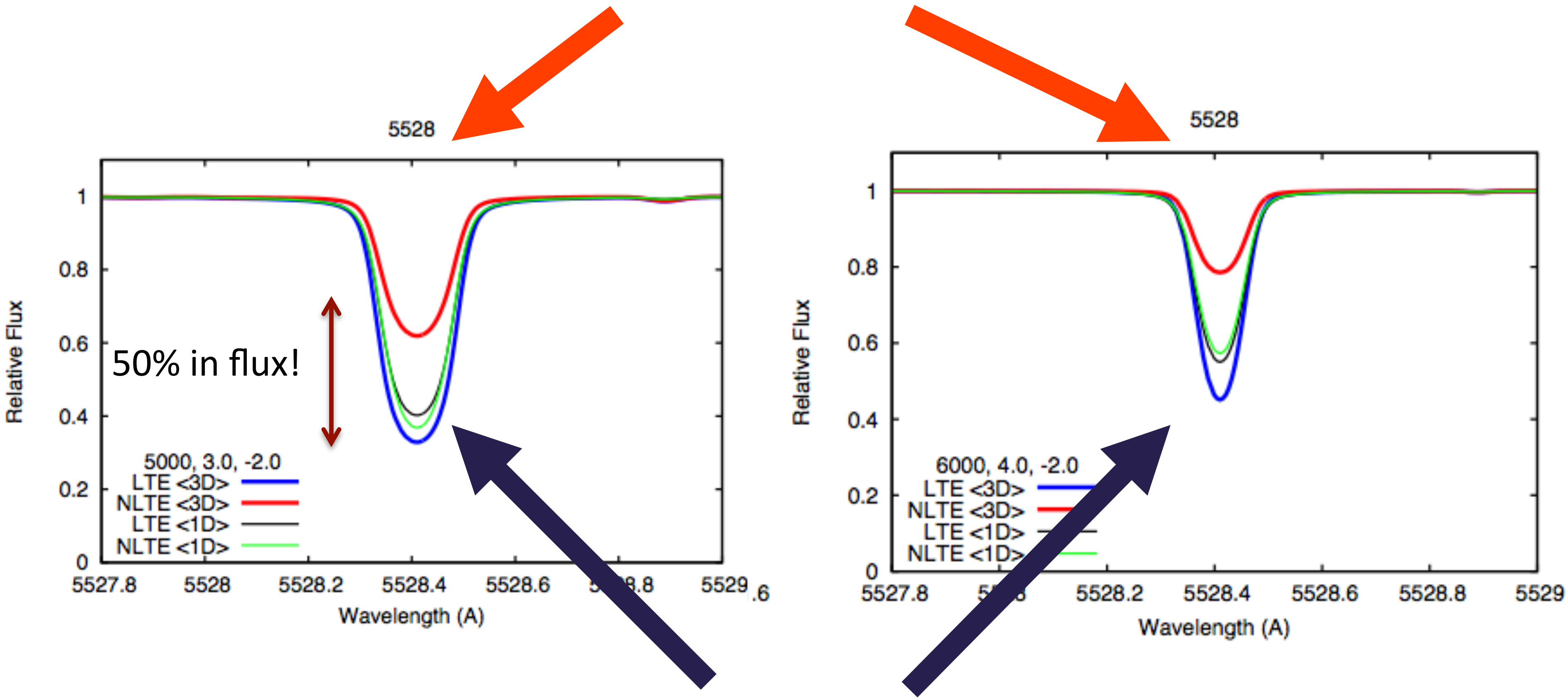
Bergemann et al. 2012

New way for survey spectroscopy with 3D NLTE



Bergemann et al. in prep.

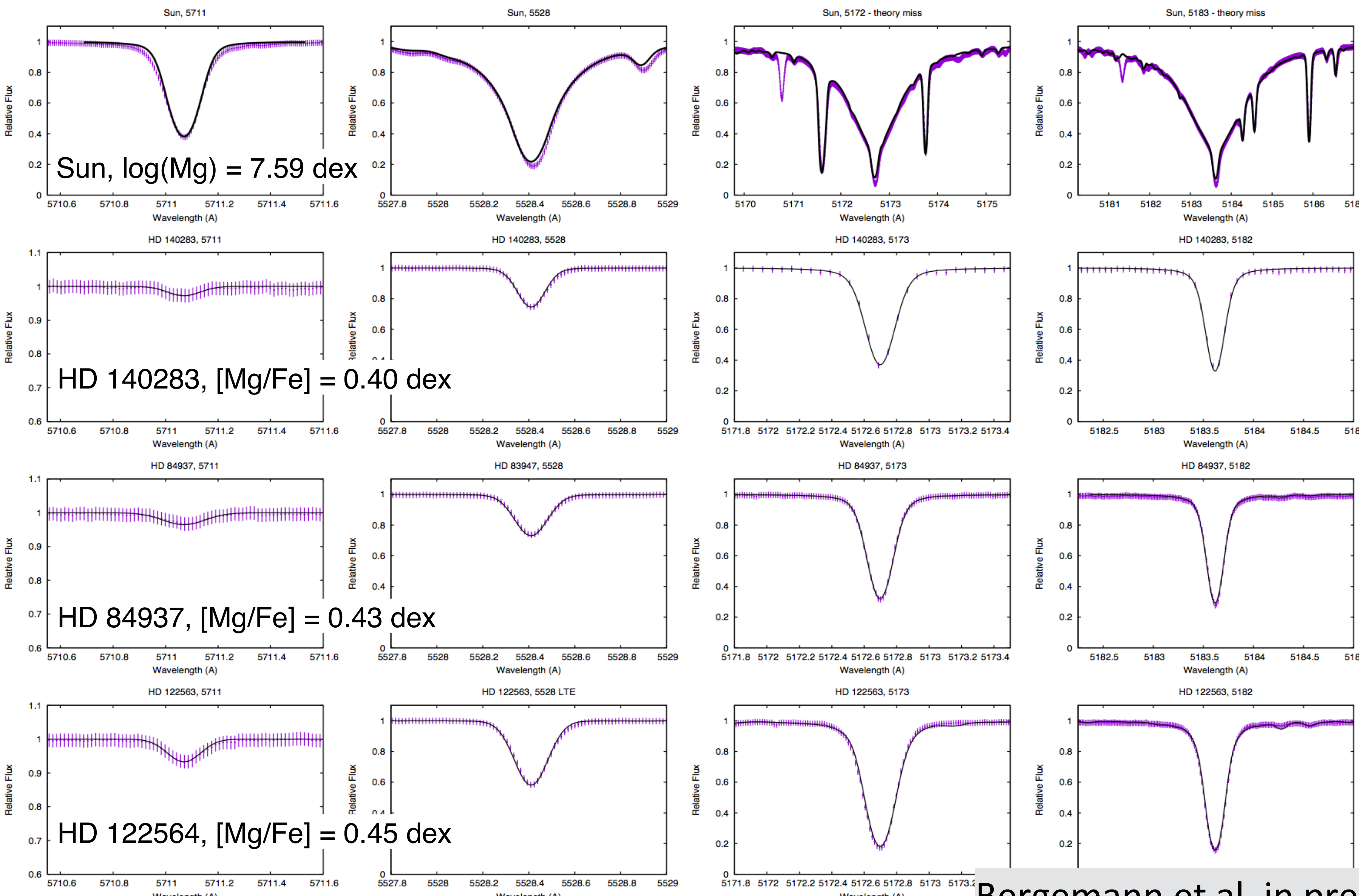
<3D> NLTE



What classical (1D LTE) models can do for us

Bergemann et al. in prep.

State-of-the-Art <3D> NLTE: no free parameters



Bergemann et al. in prep.

Summary

Stellar model atmospheres

need consistent improvements on models: 1D-3D, (N)LTE, rotation, stellar evolution

Bayesian-type (full –Prob.) schemes

- All parameters within **one single, consistent analysis**
- Automatic detection of pathologic (or interesting...) cases
- direct ability to quantify systematic shifts/errors,
  in future: reddening, distances, binary fractions, He

Good algorithms efficiently combining models and Bayesian are needed:

4MOST survey (2021) – 20 million stellar spectra with distances & kinematics (Gaia follow-up)