An overview of synthetic spectrum generation methods. A look at the Kurucz models

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Introduction

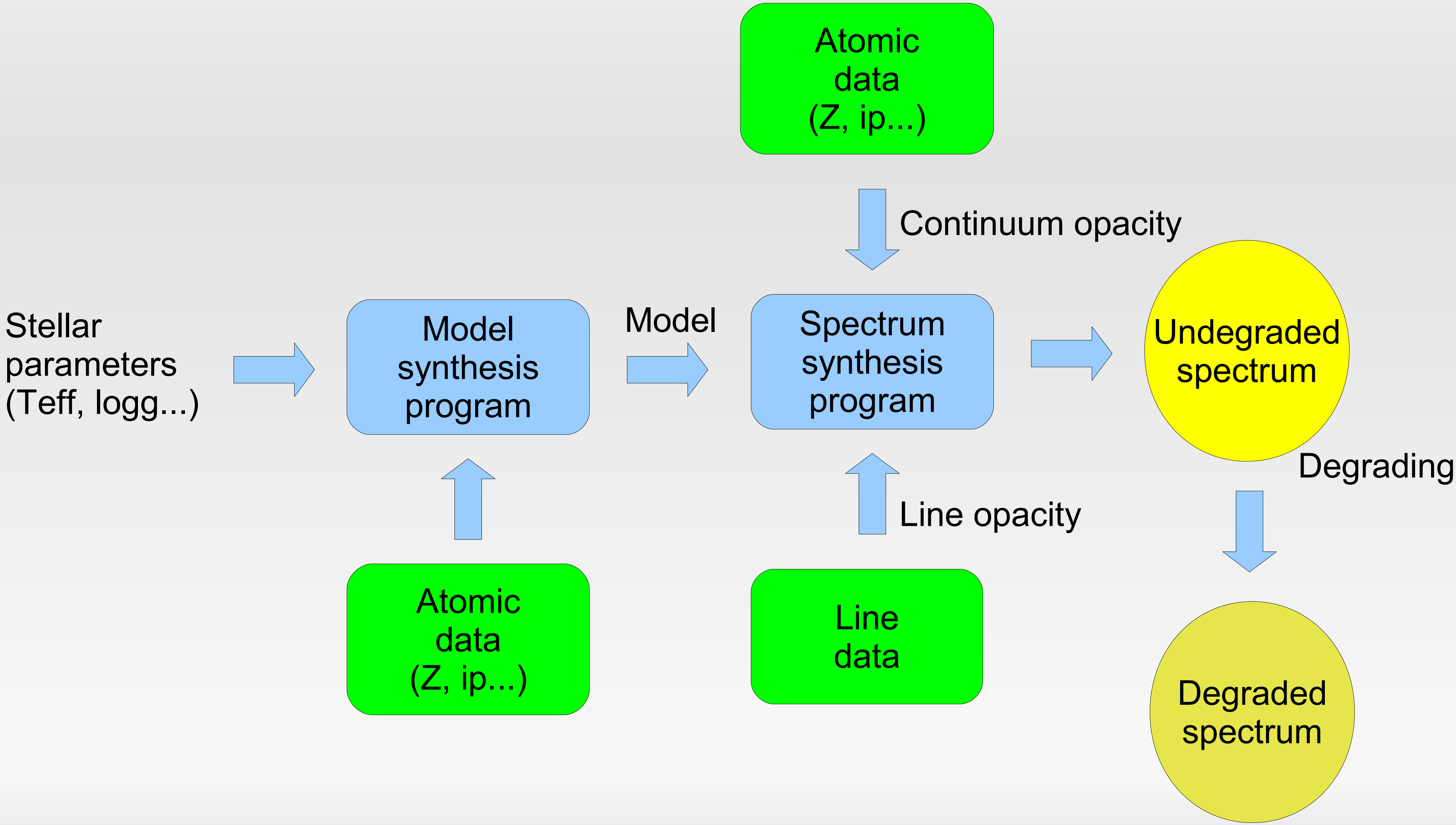
- We now have databases with hundreds of *thousands* of spectra (RAVE, SDSS), which will soon become hundreds of *millions* (GAIA).

- Manual analysis is impossible.

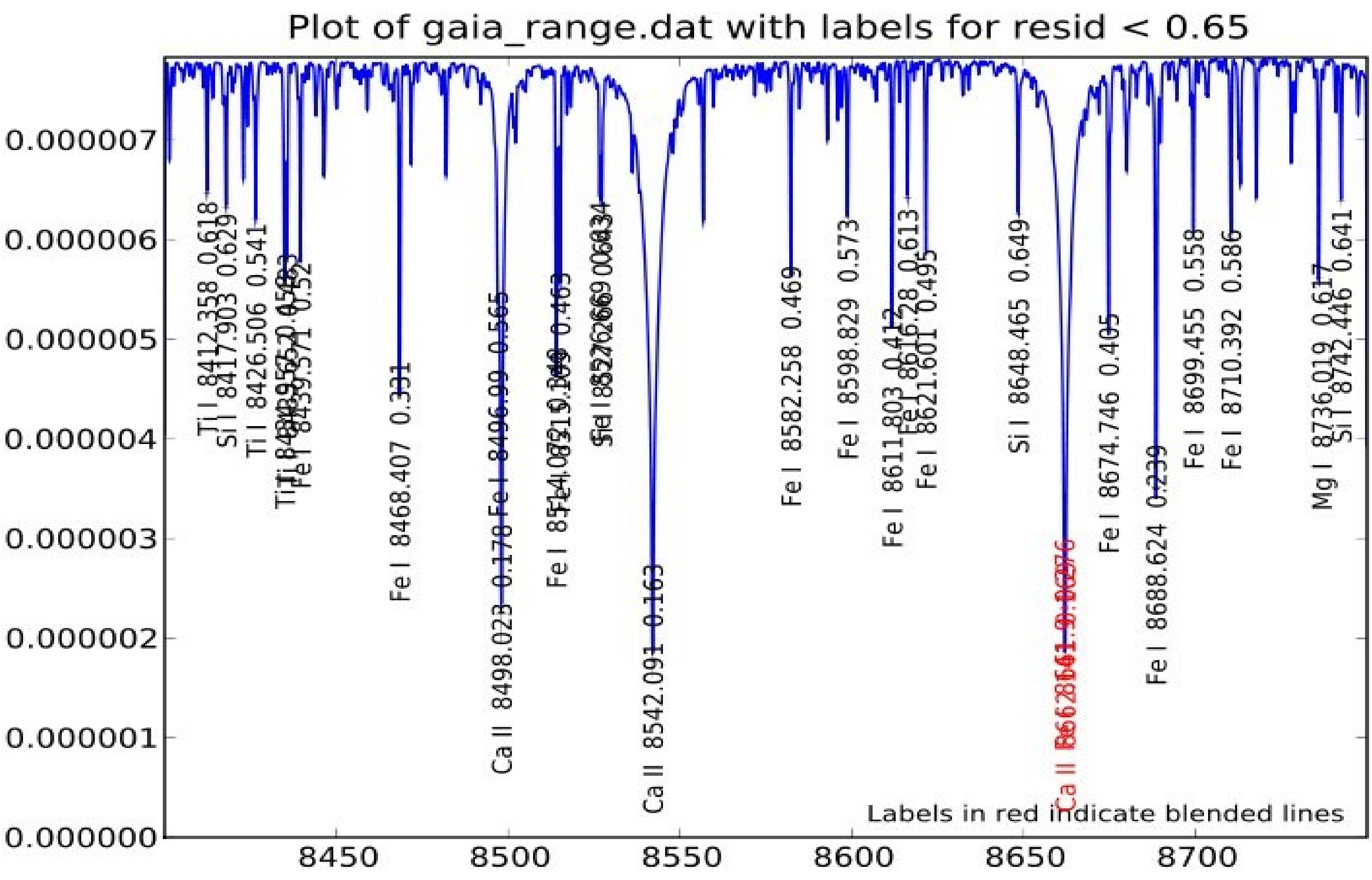
- Therefore, we need highly efficient techniques to automatically extract physical parameters from observed spectra.

- The most obvious: compare observations with a database ("grid") of synthetic spectra.

The process of creating spectra



A synthetic spectrum Teff=5500, logg = 4.5, [M/Mo] = 0



Current trends: 1D vs 3D

- 1D models use a precalculated solution of the ERT with tabulated opacities to compute line shape.
- Fast and reliable
- Static
- Don't account for some of the interesting physics: convection (→ errors in Teff) and time-dependent phenomena.
- Need for "fudge" parameters (e.g. for turbulence)

Current trends: 1D vs 3D

- 3D models solve the full hydrodynamic problem (equations of conservation of mass & energy) with tabulated opacities.

- They are better.

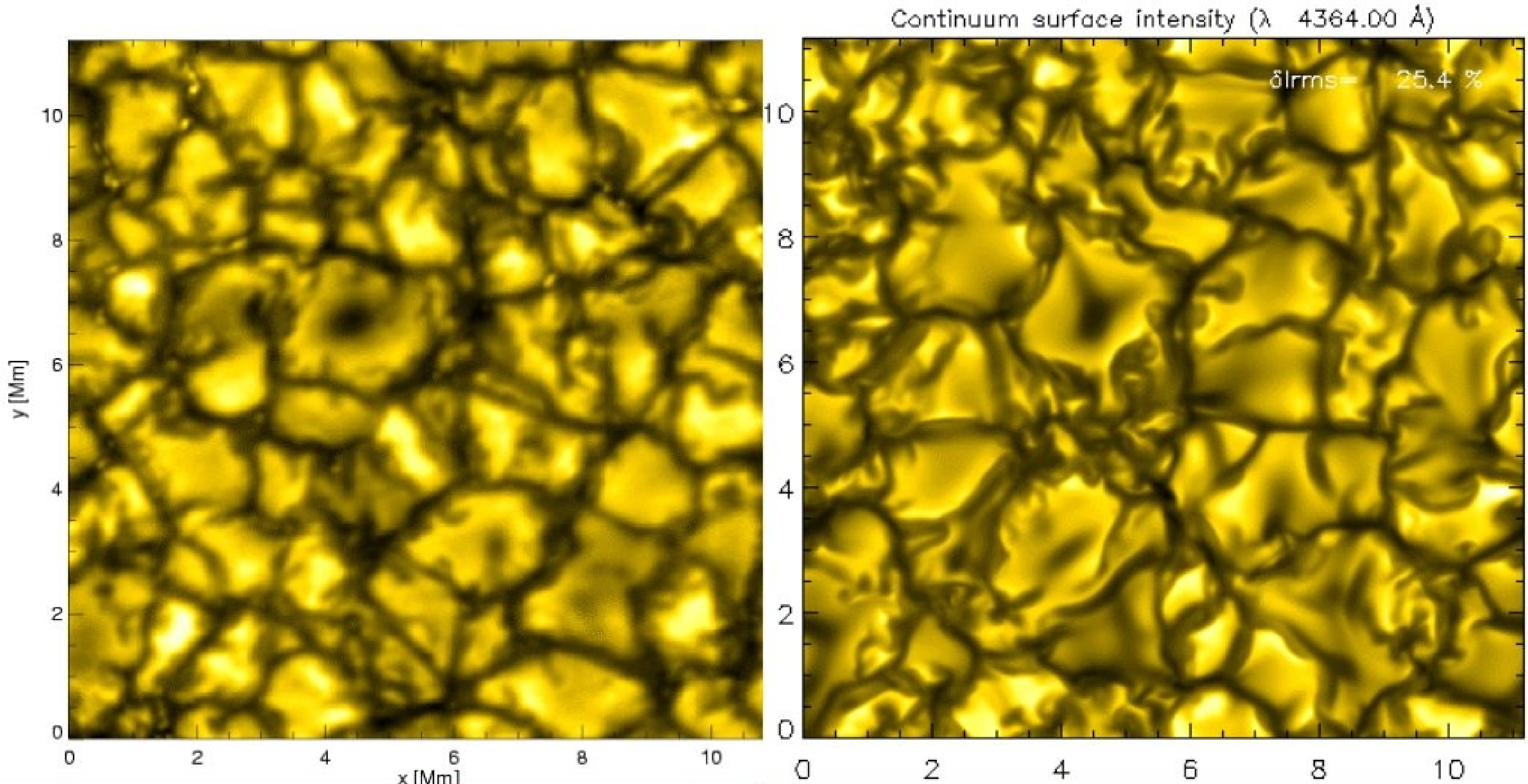
- Time-dependent solutions.

- Physics "emerge" naturally, without need for "fudge" parameters.

- Very slow, unsuitable for large-scale work (15 min/line!).

- Highly nonlinear problem.

SST Observation and Numerical Simulation



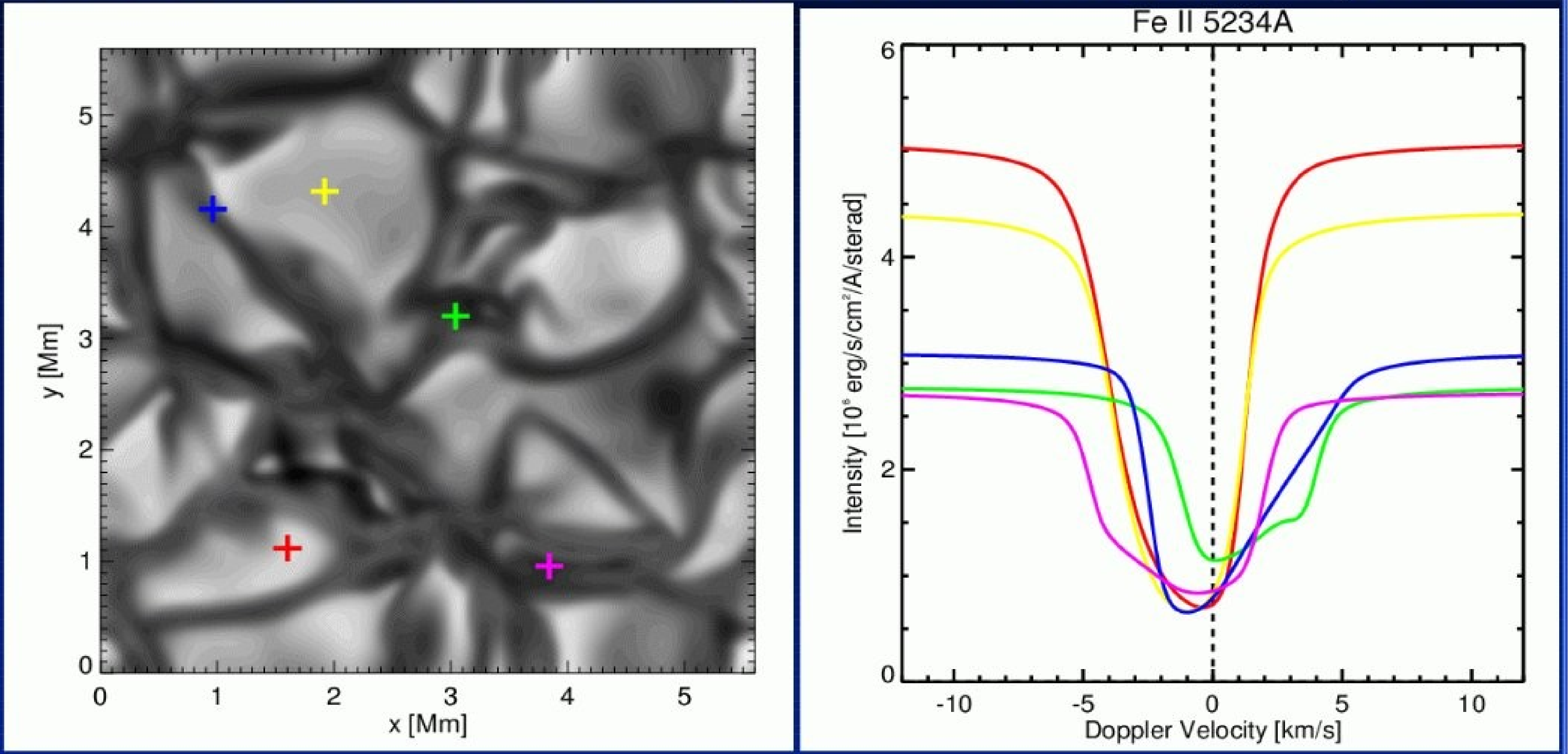
SST: 15″×15″, λ 4364 Å

(Courtesy Mats Carlsson 2004)

Simulation: 400×400×165 cells

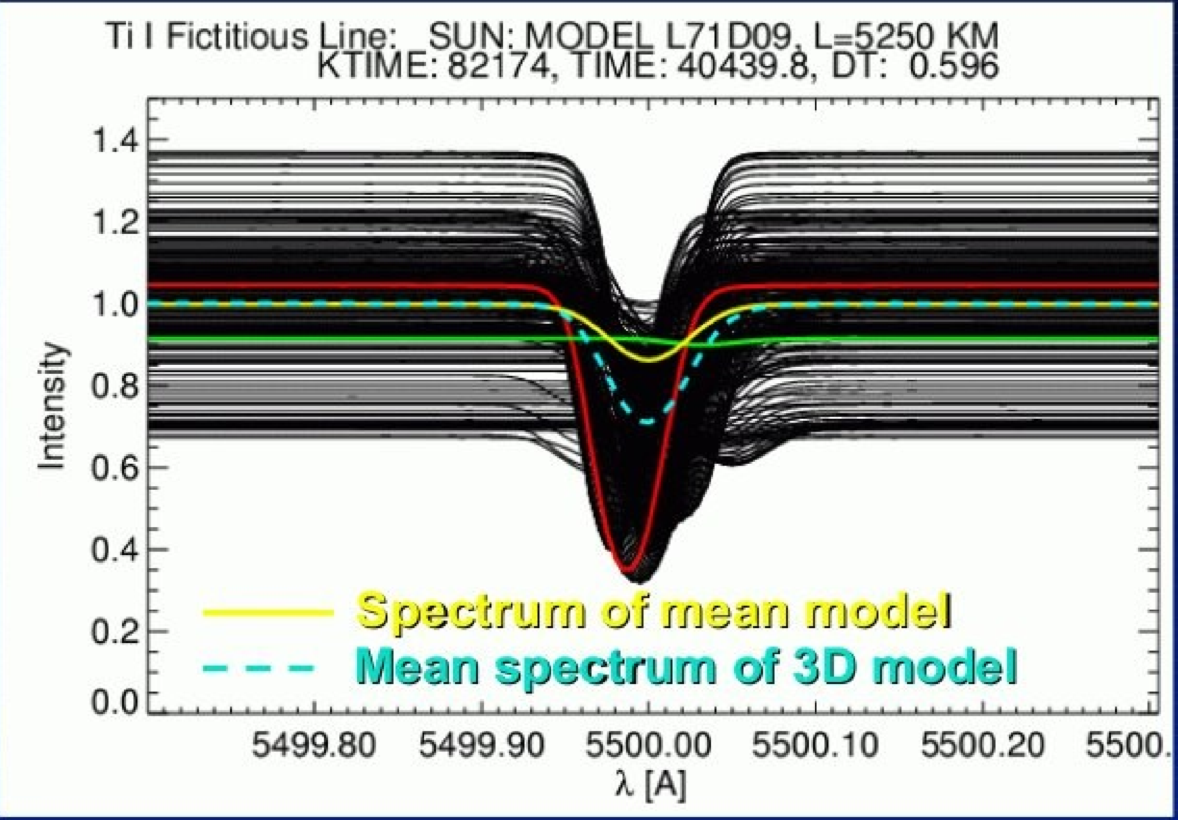
(Steffen 2004)

Line formation in inhomogeneous stellar atmospheres



Large spatial variation of emergent line profiles

Line formation in inhomogeneous stellar atmospheres



The space-time averaged 3D spectrum is **NOT** the same as the **spectrum of the space-time averaged 3D atmosphere !**

Line formation *non-linear* ⇨ 3D abundance corrections

1D models: PP vs Spherical

At the core of every 1D model is the Equation of Radiative Transfer:

$$\cos\theta \frac{\partial I_\nu}{\partial \tau_\nu} - \frac{\sin\theta}{\tau_\nu} \frac{\partial I_\nu}{\partial \theta} = I_\nu - S_\nu$$

Spherical approximation

$$\cos\theta \frac{dI_\nu}{d\tau_\nu} = I_\nu - S_\nu$$

Plane-parallel approximation (thin photosphere, homogeneous layers)

$d\tau_\nu = \kappa_\nu \rho \, dr$ is the optical depth of the medium.

PHOENIX (Hautschild)

- Developed by P. Hautschild (H. Sternwarte);
- plane-parallel or spherical, heavily NLTE.
- static or (up to relativistic!) expanding media;
- opacity for ca. 592 million lines (42 atomic, 550 molecular);
- <u>Code not available</u>; must run on his computers.

http://www.hs.uni-hamburg.de/EN/For/ThA/phoenix/index.html

MARCS

- Developed by B. Gustafsson et al (University of Uppsala);
- plane-parallel or spherical, LTE.
- only pre-calculated models and low-res fluxes! You have to calculate spectra with your own software;
- roughly comparable with Kurucz models;
- Code not available.

http://marcs.astro.uu.se/

The Kurucz "family"

- Developed by R. Kurucz (Harvard) in the early 70s; precursor of several modern methods.
- Plane-parallel, (mostly) LTE models. Many simplifications to optimize code for speed.
- Metallicities scaled to solar (ATLAS 9) or individually changeable (ATLAS 12).
- Large line database (162 million lines!).
- All code and data publicly available. Active community with several support mailing lists.
- Scarce documentation, confusing I/O, non-standard code . . .

http://kurucz.harvard.edu/

Creating a Kurucz model

Integrating the ERT gives us several magnitudes as a function of depth in the photosphere.

Flux:

$$F_\nu(\tau_\nu) \equiv 2\pi \left[\int_{\tau_\nu}^{\infty} S_\nu E_2(t_\nu - \tau_\nu)\, dt_\nu - \int_0^{\tau_\nu} S_\nu E_2(\tau_\nu - t_\nu)\, dt_\nu \right]$$

where

$$E_n(x) \equiv \int_1^{\infty} \frac{e^{-xs}}{s^n}\, ds$$

is the *exponential integral* function.

Creating a Kurucz model 2

Average intensity:

$$J_\nu(\tau_\nu) = 1/2 \int_{\tau_\nu}^{\infty} S_\nu E_1(t_\nu - \tau_\nu)\, dt_\nu - 1/2 \int_0^{\tau_\nu} S_\nu E_1(\tau_\nu - t_\nu)\, dt_\nu$$

Radiation pressure:

$$P_\nu(\tau_\nu) = 1/2 \int_{\tau_\nu}^{\infty} S_\nu E_3(t_\nu - \tau_\nu)\, dt_\nu - 1/2 \int_0^{\tau_\nu} S_\nu E_3(\tau_\nu - t_\nu)\, dt_\nu$$

The source function is a kernel that contains all the information about the radiation field.

Creating a Kurucz model 3

In the presence of both absorption and scattering,

$$S(\tau)=\frac{\kappa^a}{\kappa^s+\kappa^a}B_T+\frac{\kappa^s}{\kappa^s+\kappa^a}J(\tau)$$

S depends on *J*,

but

J depends on *S*.

Solution: *iterative methods*. But, how to begin?

Creating a Kurucz model 4

Assuming the absorption coefficient κ_ν does not depend on ν , the source function can be written as

$$S(\tau)=\frac{3}{4\pi}(\tau+\frac{2}{3})F(0)$$

and

$$T=[\frac{3}{4}(\tau+\frac{2}{3})]^{1/4}T_{eff}$$

Creating a Kurucz model 5

We need to compute observables such as flux $F_n(t)$. Flux depends on source function $S_n(t)$. So:

- 1. We compute an initial S by means of a Gray model;
- 2. we use the result from the ERT to compute average intensity J, flux, etc.;
- 3. we use J to re-compute S;
- 4. we repeat the procedure until getting convergence.

Creating a Kurucz spectrum

In real atmospheres, spectral lines get broadened by different physical phenomena. Kurucz uses:

- Quantum (radiative) broadening: due to the Uncertainty Principle. Affects all lines.
- Stark broadening: Caused by protons and free electrons. Affects most lines specially in hot stars.
- Van der Waals broadening. Caused by neutral H. Affects most lines in cold stars

Creating a Kurucz spectrum 2

Broadening profiles are convolved with each other, the result being a Voigt function H(a,v), where

$$a=\frac{\Gamma_R+\Gamma_S+\Gamma_W}{4\pi\nu_D}$$

Is the width of the profile.

Creating a Kurucz spectrum 3

For each depth, Kurucz assumes that a line profile is given by

$$k_\nu = \left[\frac{\pi e^2}{mc}\frac{N}{Z}\frac{1}{\rho} gf \frac{1}{\sqrt{\pi}\Delta\nu_D}\right]\left[e^{-E/kT}\right]\left[H(a,\nu)\right]\left[1-e^{-h\nu/kT}\right]$$

All factors after the first are <1, so if the first is <0.001, the line is discarded.

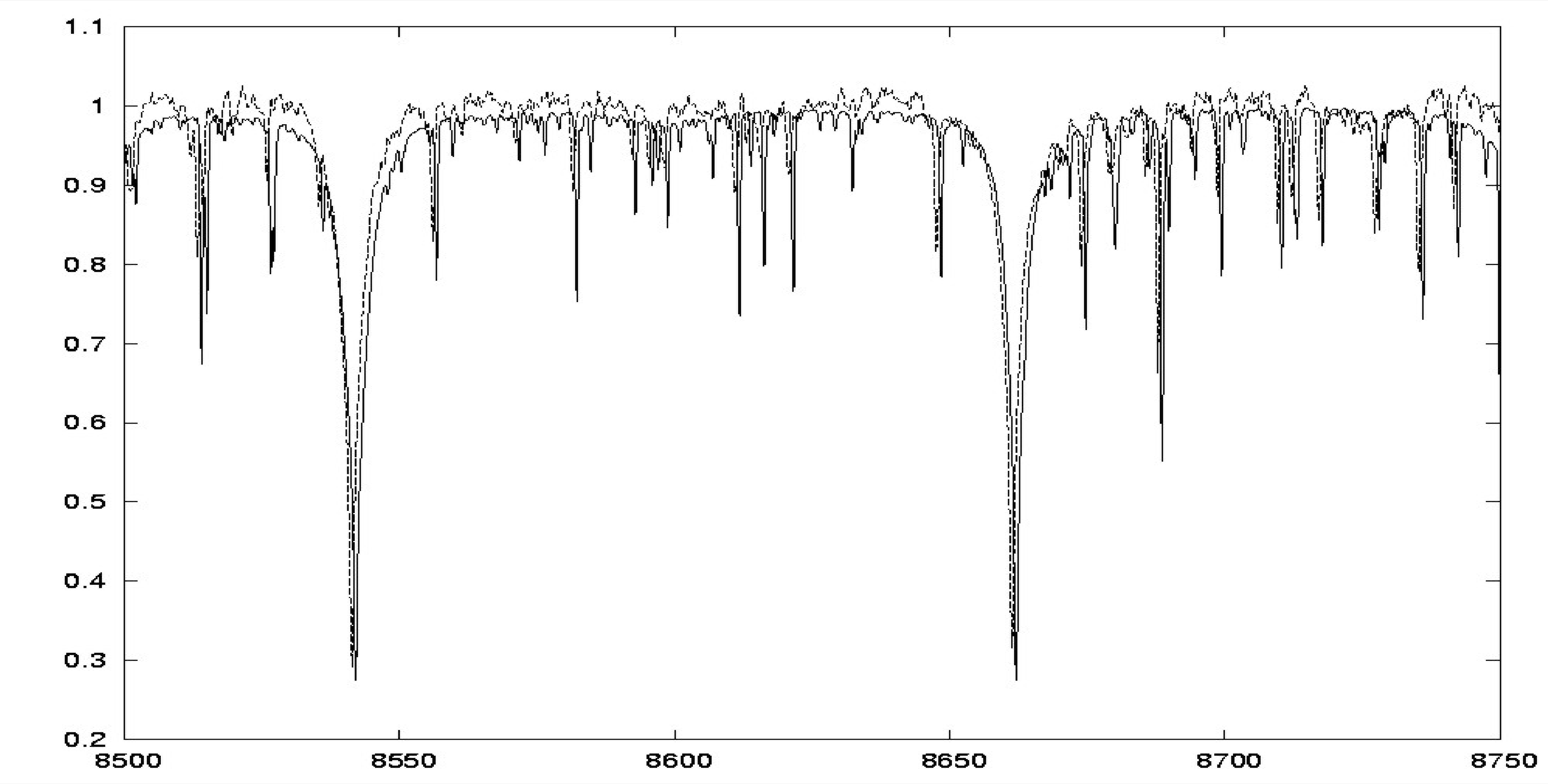
If not:

- The line is accepted and the procedure repeated;
- the continuum opacity is calculated and added;
- intensity at every wavelength is calculated, with the ERT.
- We jump to the next depth.

Creating a Kurucz spectrum 4

The spectrum is the convolved with a rotation profile and an instrumental one, to account for rotational broadening and limited instrumental resolution. The result is the final spectrum.

Kurucz spectrum vs observed



Conclusions

- Synthetic spectra are a rapidly-evolving tool for an extremely demanding task;
- The future is in full HD 3D ab-initio models; however, 1D will be mostly used for the next few years;
- There is a wide choice of 1D model/spectrum suites, but the ones whose code is public spur the most development.
- We are bound to see a lot happening in this field yet.

urtzi@escher: ~/programs/kurucz/originals/synthe

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      COMMON /BO/BO1(kw,13),XNFPO(kw,1),BO2(kw,4)
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Hvala!