New generation stellar model atmospheres

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New generation stellar model atmospheres: why bother?

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Outline

- Why do we need stellar model atmospheres?
- What is stellar model atmosphere?
- What kind of model atmospheres are available today?
- New generation model atmospheres:
  - what are they and why bother?
  - if I want to use them, how do I do that?
- Final remarks

Why do we need stellar model atmospheres?

Why numerical simulations?

- In many cases: experiments technologically not possible or too expensive
- In particular in astronomy:
  - Objects far away => no *in situ* measurements
  - Extreme states of matter => often not achievable in the laboratory
  - Interpretation of observations – only with the help of theoretical models!
- Numerical simulations as important tool for the development and testing for physical theories

Sir Isaac Newton, apple tree, apple and the law of gravity.

What is stellar model atmosphere?

What should a model atmosphere do?

- Wanted: simplest model that can account for all (relevant!) observations
- A model is valid within a certain scope and within certain assumptions

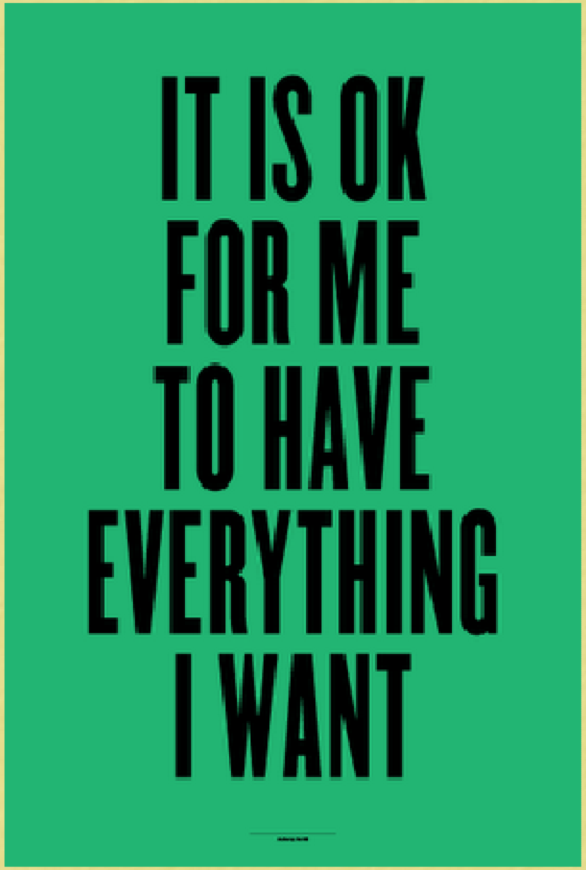
  ⇒ Do not over-interpret!!

Feasibility

- Computational costs?!
- What is affordable? What is most important?

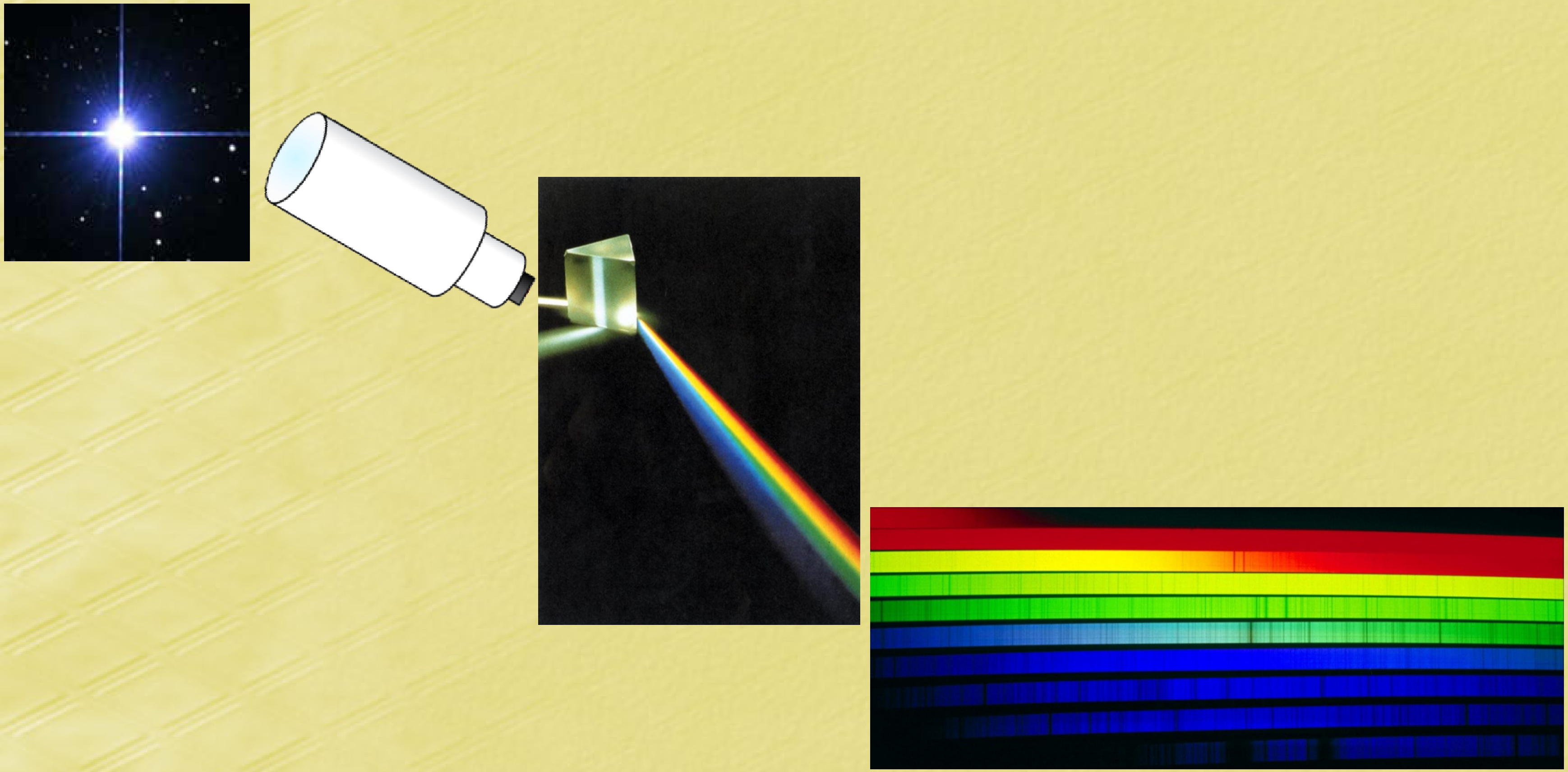
  ⇒ Compromises, compromises, …

  ⇒ Simplifications, simplifications, …



What is stellar model atmosphere?

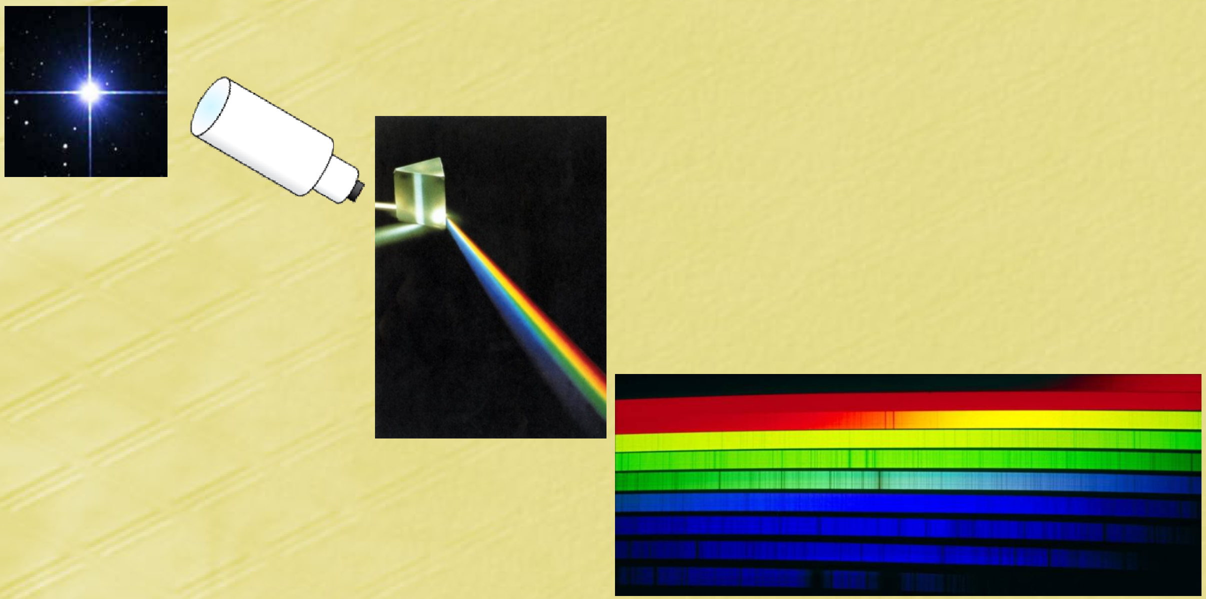
From the problem to the model (I)



What is stellar model atmosphere?

From the problem to the model (I)

- How to explain these observations?
- What are the physical processes behind?
- What do we need to realistically reproduce them in numerical model?



What is stellar model atmosphere?

From the problem to the model (II)

- Formulating the relevant physical laws:
    - Which processes need to be included?
    - Time-dependent phenomenon?
    - Spatial structure?
        - How many spatial directions necessary? 1,2,3?
        - Can symmetries be exploited to simplify the modeling?

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \vec{v})$$

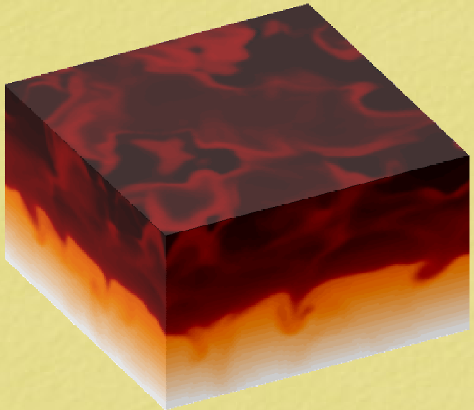
$$\frac{\partial \rho \vec{v}}{\partial t} = -\rho (\vec{v} \cdot \nabla) \vec{v} - \nabla P - \rho \vec{\nabla} \Phi$$

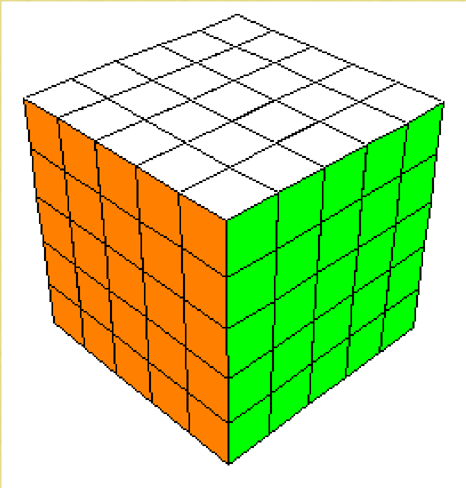
$$\frac{\partial \rho \varepsilon_{ik}}{\partial t} = -\nabla \cdot \left[(\rho \varepsilon_{ik} + P) \vec{v} \right] - \rho \vec{v} \cdot (\vec{\nabla} \Phi) + Q_{rad}$$

What is stellar model atmosphere?

From the problem to the model (III)

- Choice of the physical model size – the computational box:
  - How big must the computational box be to capture all important effects?
  - Example: fine-structure of the Sun: at least a few granules in each horizontal direction
- Discretization:
  - Solution of the physical equations at discrete grid location (or in grid cells)
  - Numerical grid:
    - geometry? boundary conditions?
    - adaptive mesh – more grid points where necessary?
    - how many grid points?

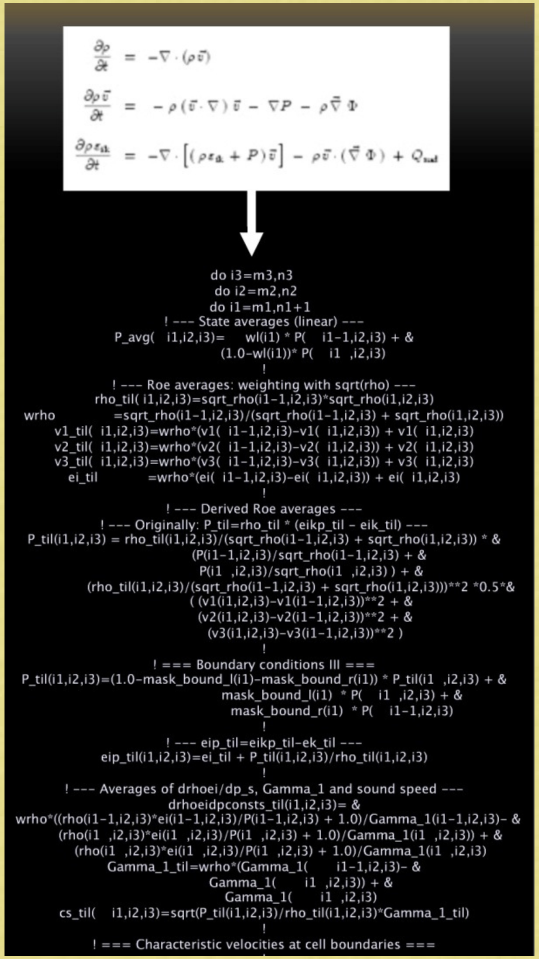




What is stellar model atmosphere?

From the problem to the model (IV)

- Development of a computer code:
  - Needed: fast and numerically stable solution methods
  - Approximations and simplifications often necessary, for instance:
    - Pre-computed look-up tables for the equation of state
    - Multi-group opacities for the radiative transfer
    - And much more… ☺



What kind of model atmospheres are available today?

Classical approach: 1D stellar atmosphere models

- Computationally easily tractable:

  ⇒ enable to include many physical processes in detail

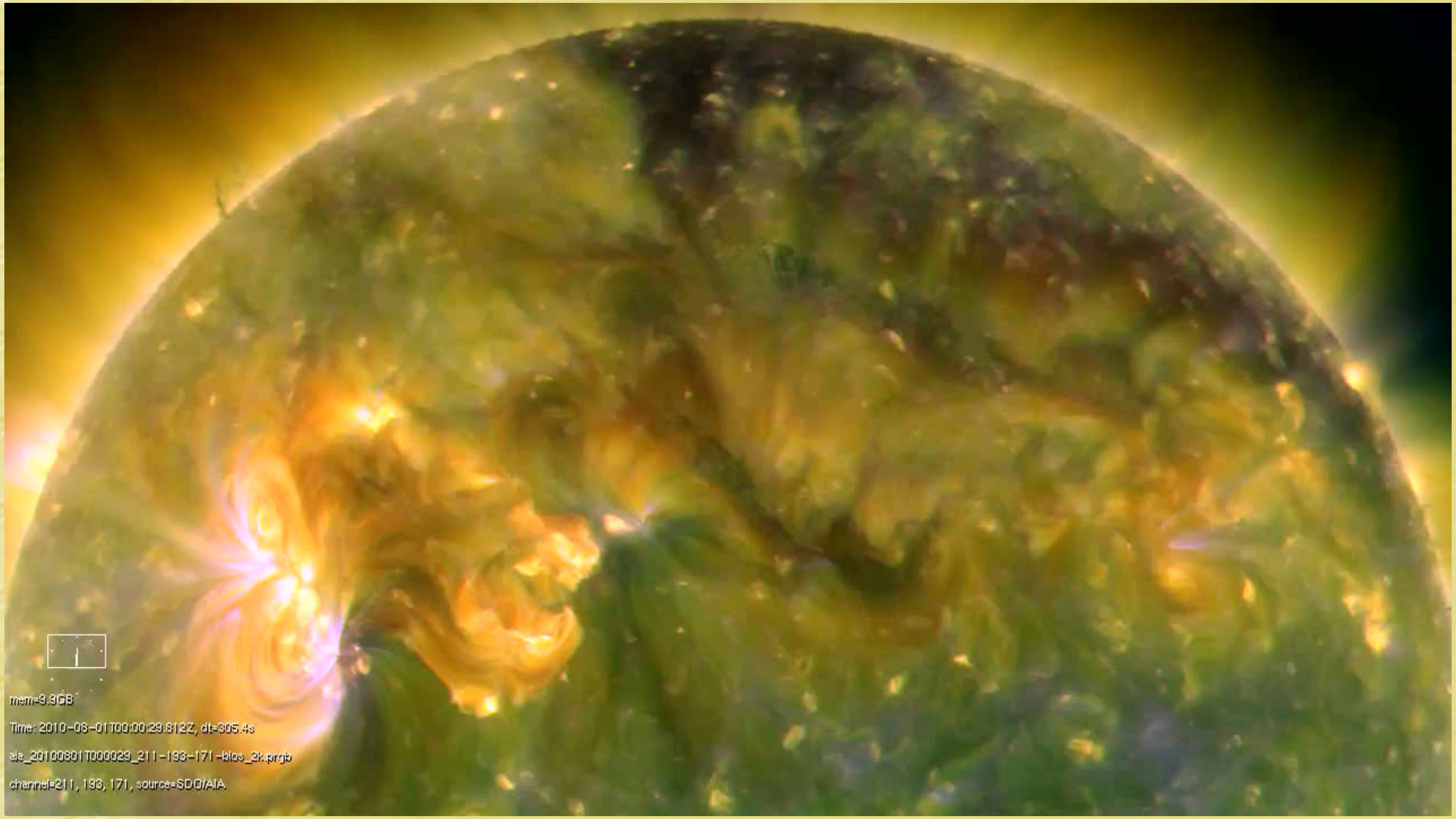
  ⇒ computation of large grids of stellar model atmospheres possible (ATLAS, MARCS, PHOENIX)
- Because of stationary and 1-dimensional nature – limitations, simplifications, and compromises:
  - simplified treatment of non-stationary phenomena (e.g., convection)
  - no possibility to account for 2D or 3D effects

  ⇒ no spatial inhomogeneities, plane-parallel stratification, etc.

Nevertheless, standard workhorses today!

What kind of model atmospheres are available today?

Real stars are not stationary nor one-dimensional!



Solar Dynamics Observatory (SDO) view of the Sun.

What kind of model atmospheres are available today?

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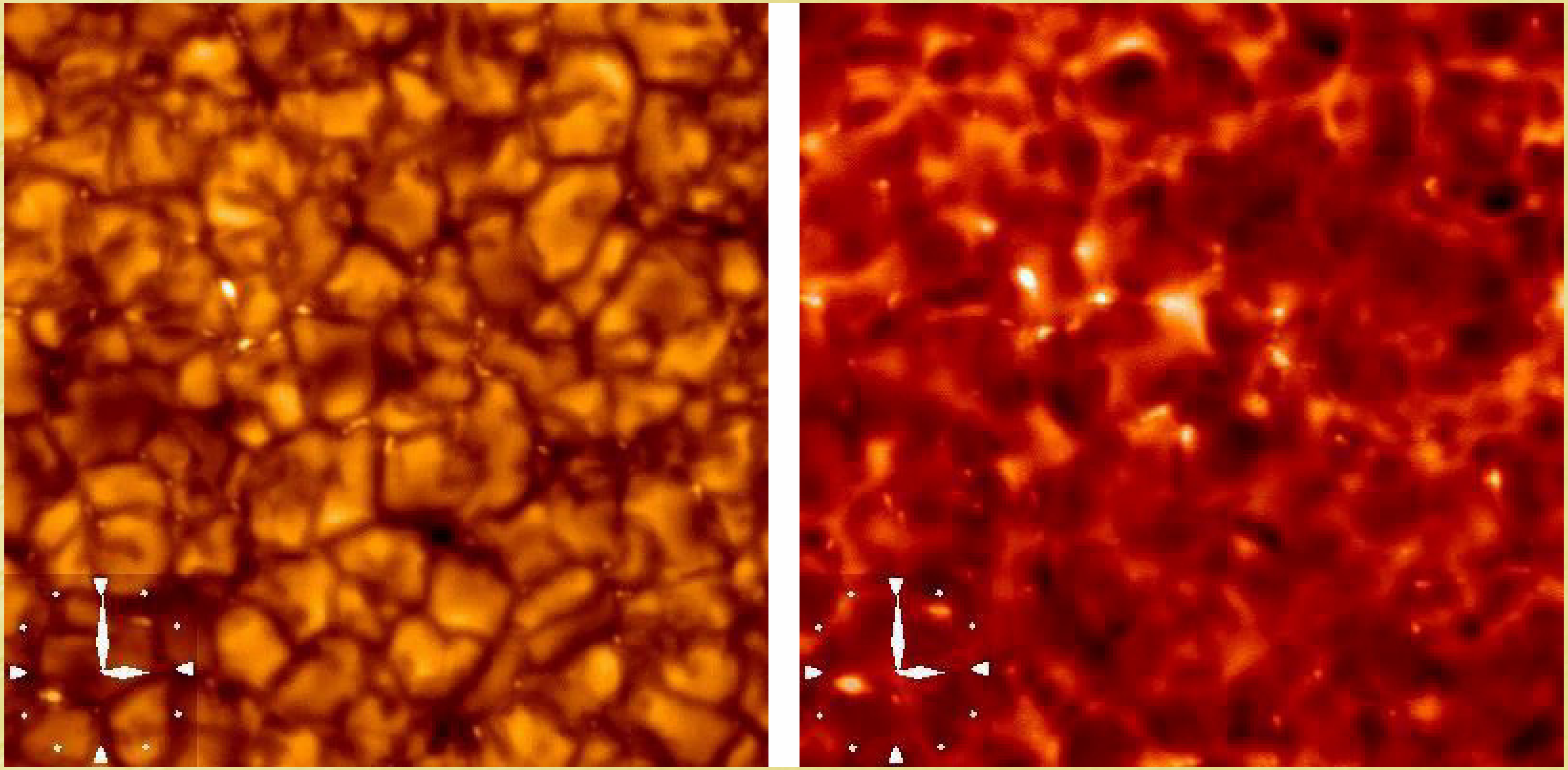
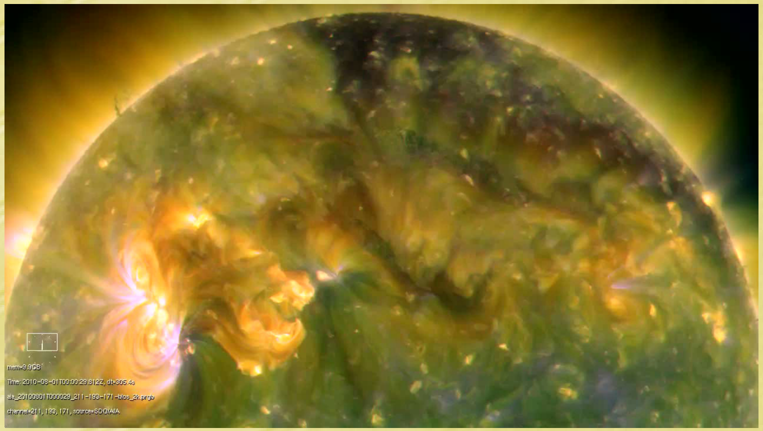


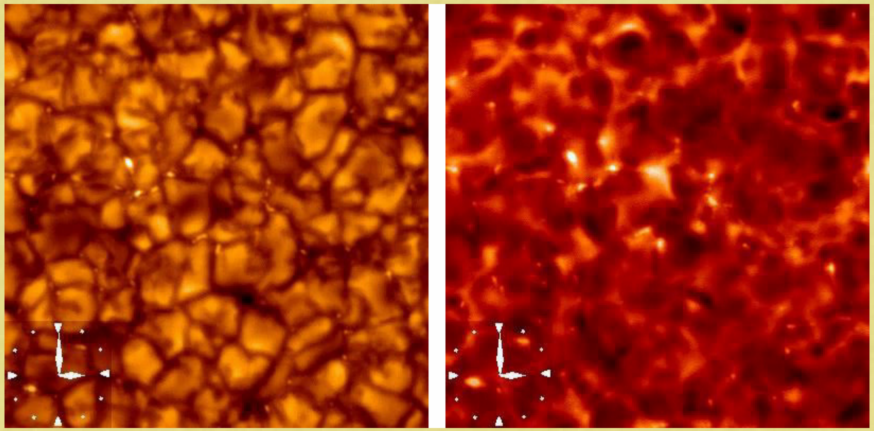
Quiet Sun: in the G-band (430 nm, left) and Ca II H band (397 nm, right; SOT/HINODE).

What kind of model atmospheres are available today?

Real stars are neither stationary nor one-dimensional!

- High-resolution observations of the Sun demonstrate: variability on a multitude of spatial and temporal scales!
- 3D hydrodynamical approach necessary!

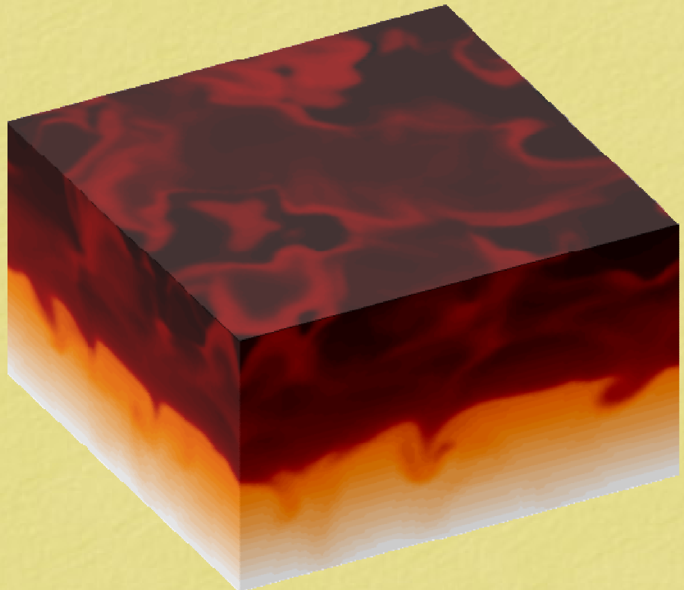




What kind of model atmospheres are available today?

New generation stellar model atmospheres: 3D hydrodynamical models

- Numerical solution of:
  - (magneto-)hydrodynamics
  - radiative transfer
  - “realistic” equation of state and opacities
  - advancing simulation in time step by step
  - result: time sequence of 3D snapshots (containing primary variables, e.g., *ρ, e, vx, vy, vz*) and auxiliary data

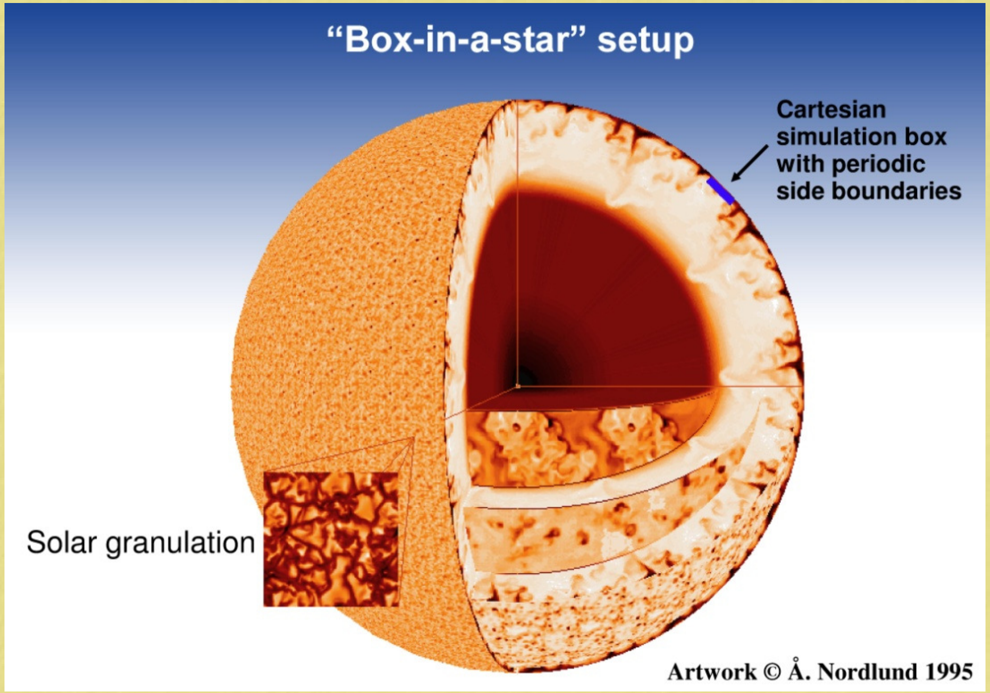


Temperature distribution in the 3D hydrodynamical model atmosphere (Wdemayer-Boehm et al. 2007).

What kind of model atmospheres are available today?

What is different with respect to classical 1D models?

- Solution of 3D radiation-hydrodynamics equations in 3D Cartesian space

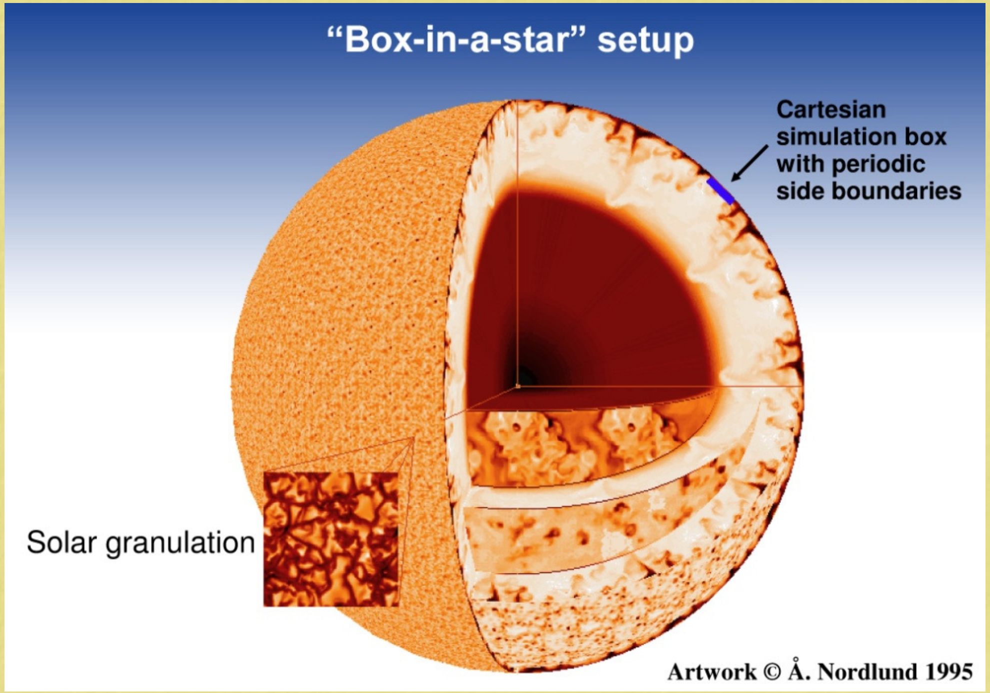


Schematic model of Solar granulation. Blue bar indicates the approximate position of the 3D RHD model simulation box (after M. Steffen).

What kind of model atmospheres are available today?

What is different with respect to classical 1D models?

- Solution of 3D radiation-hydrodynamics equations in 3D Cartesian space
- No *apriori* assumptions about stellar velocity fields



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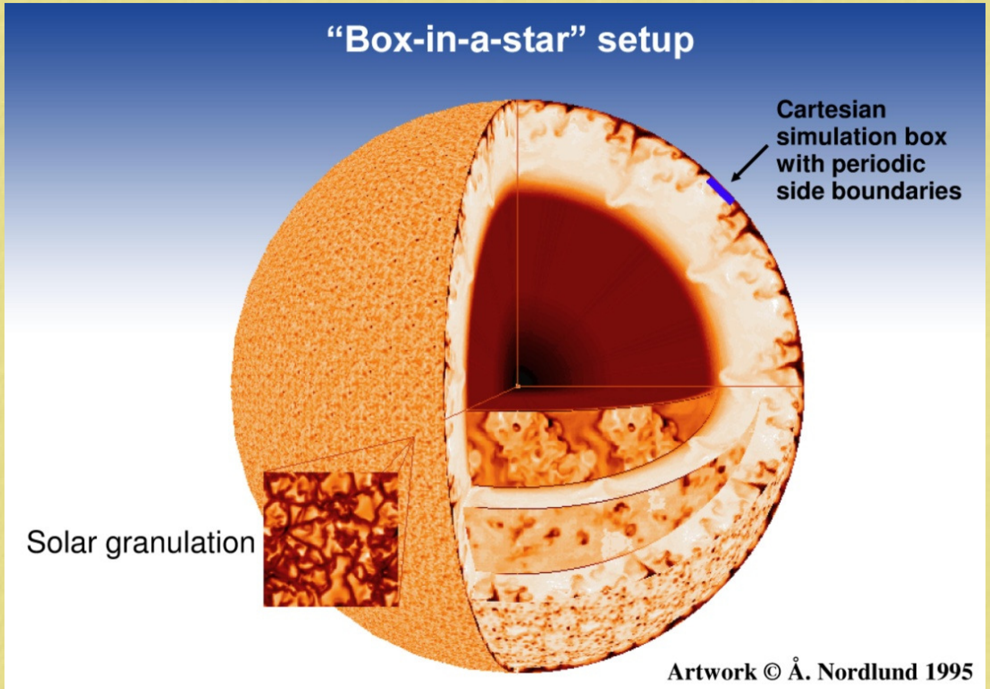
What kind of model atmospheres are available today?

What is different with respect to classical 1D models?

- Solution of 3D radiation-hydrodynamics equations in 3D (Cartesian) space
- No *apriori* assumptions about stellar velocity fields
- Significantly higher computational costs: simplifications with respect to 1D
- Both global and local models



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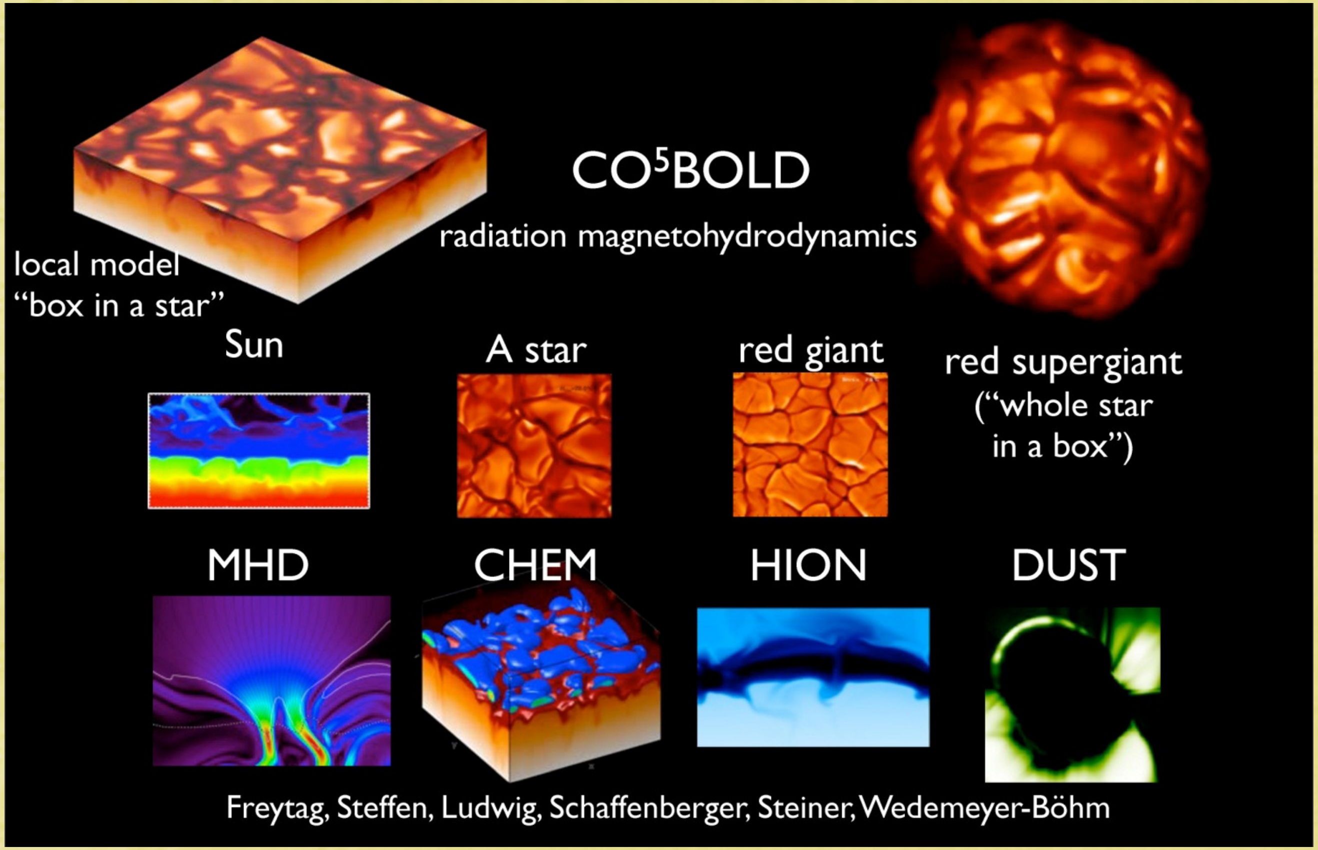
What kind of model atmospheres are available today?

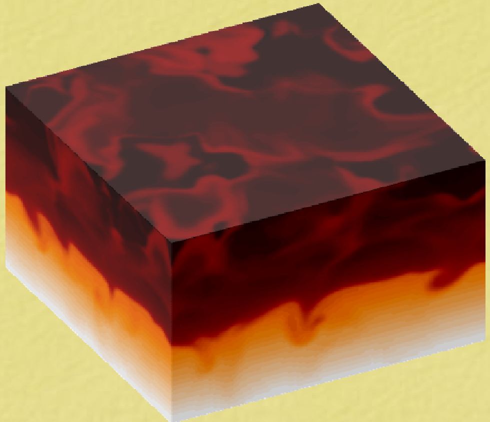
Example: CO^5BOLD radiation magnetohydrodynamics model atmosphere code

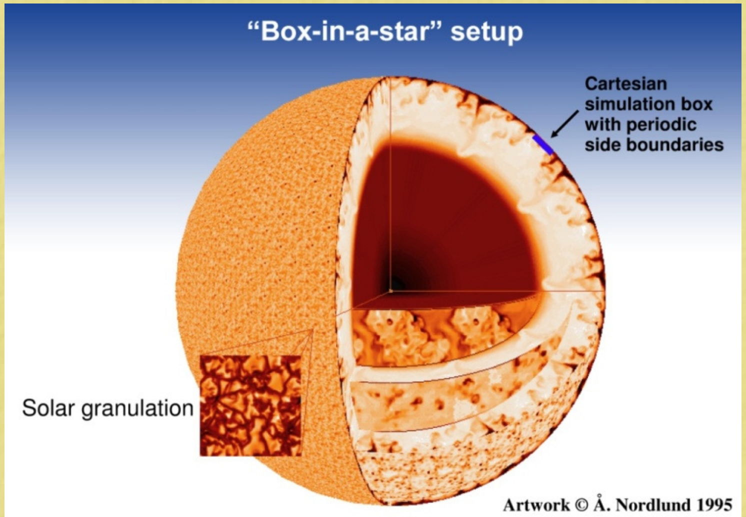


What kind of model atmospheres are available today?

Example: CO^5BOLD model atmosphere code

- Numerical solution of:
  - radiation magnetohydrodynamics (LTE, opacity binning)
  - “realistic” equation of state and opacities (MARCS opacities)
  - result: time sequence of 3D snapshots (containing primary variables, *ρ, e, vx, vy, vz, Bx, By, Bz*) and auxiliary data
- Both local (“box in a star”) and global (“star in a box”) model atmospheres



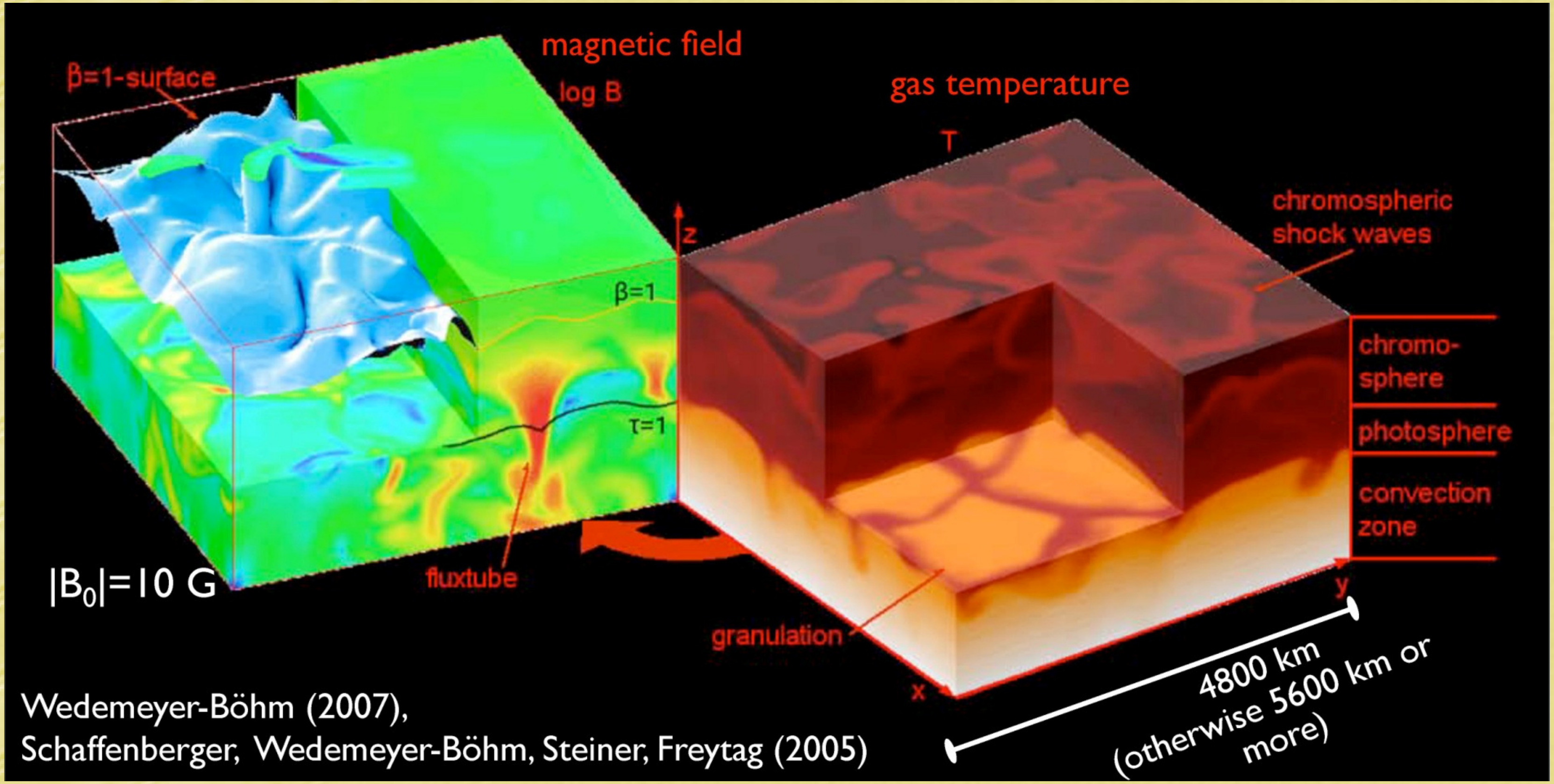


Schematic model of Solar granulation. Blue bar indicates the approximate position of the 3D RHD model simulation box.

What kind of model atmospheres are available today?

Local CO^5BOLD models

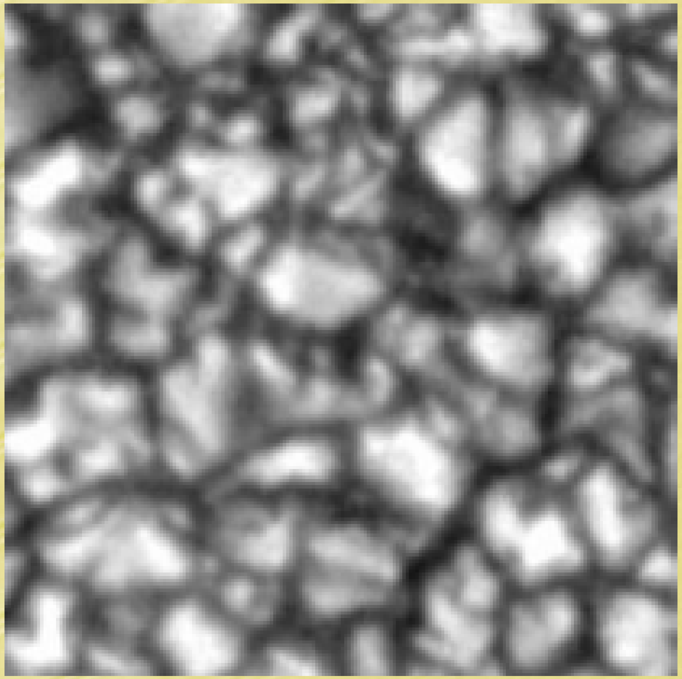
- Top of convection zone, photosphere, and chromosphere

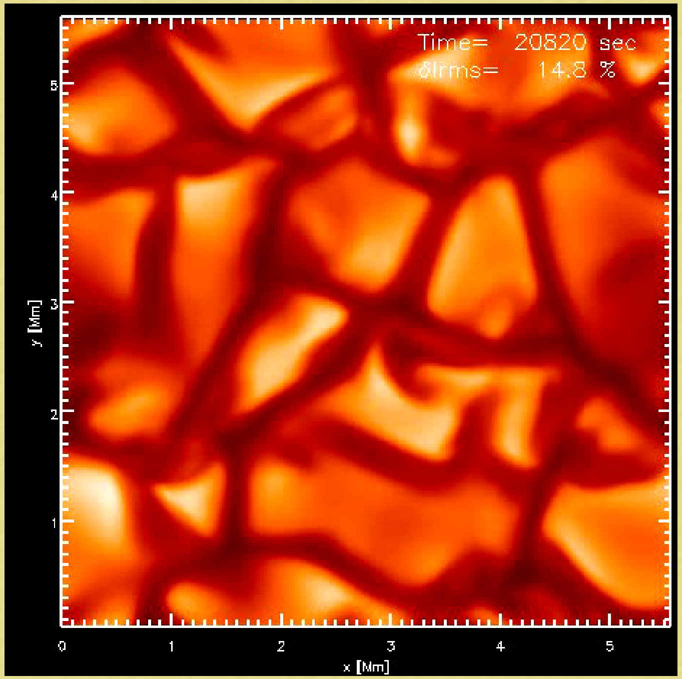


New generation stellar model atmospheres: why bother?

What can the 3D hydrodynamical models provide beyond the classical 1D view? Example I

- Effects of radiation and velocity fields on the atmospheric structures: stellar granulation



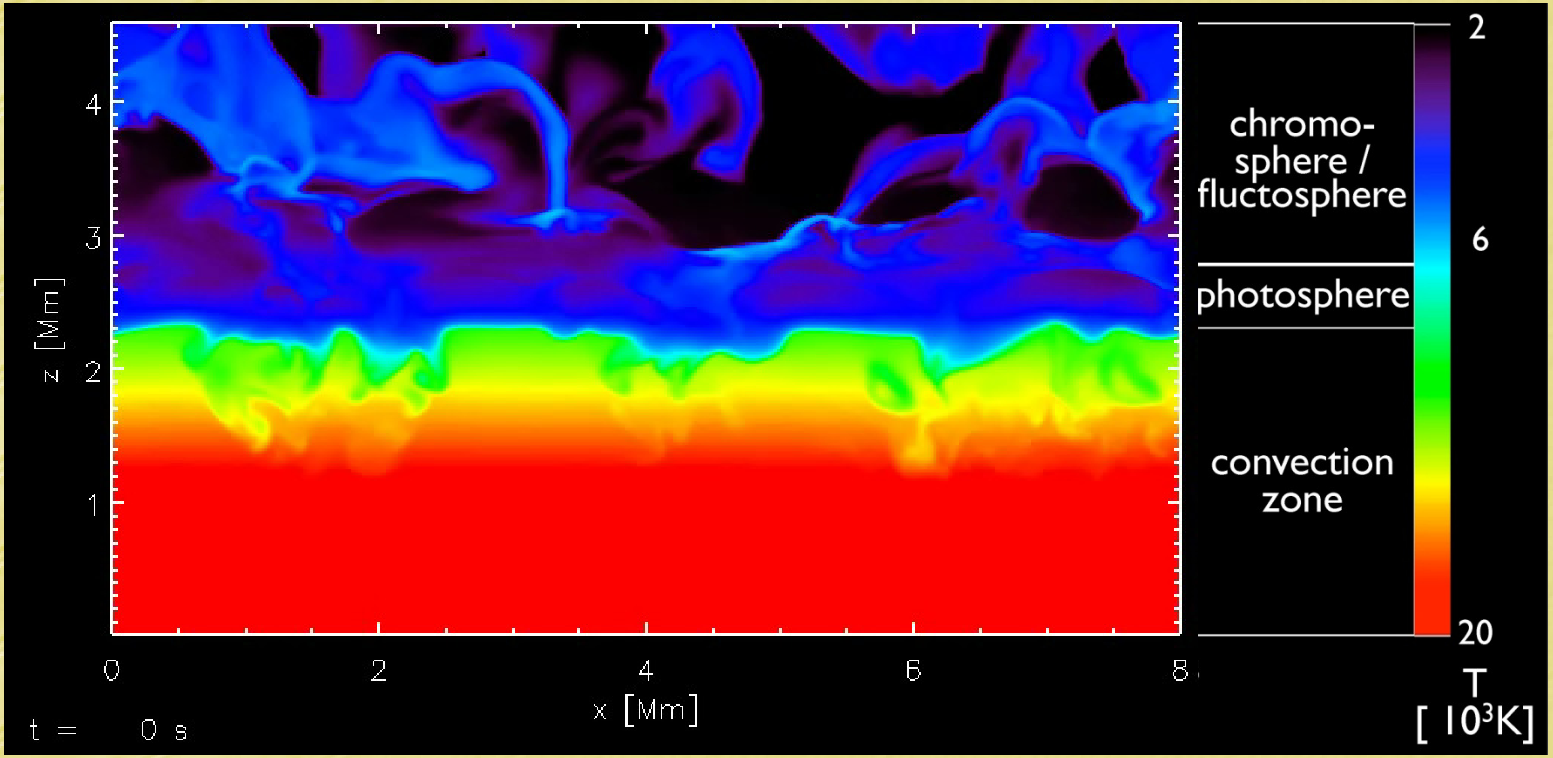


Granulation in the solar atmosphere, observations (left) and 3D hydrodynamical CO5BOLD model (right).

New generation stellar model atmospheres: why bother?

What can the 3D hydrodynamical models provide beyond the classical 1D view? Example II

- 3D hydrodynamical view of stellar photospheres and chromospheres



3D hydrodynamical CO5BOLD model of the solar atmosphere (Wedemeyer-Böhm, in prep.).

New generation stellar model atmospheres: why bother?

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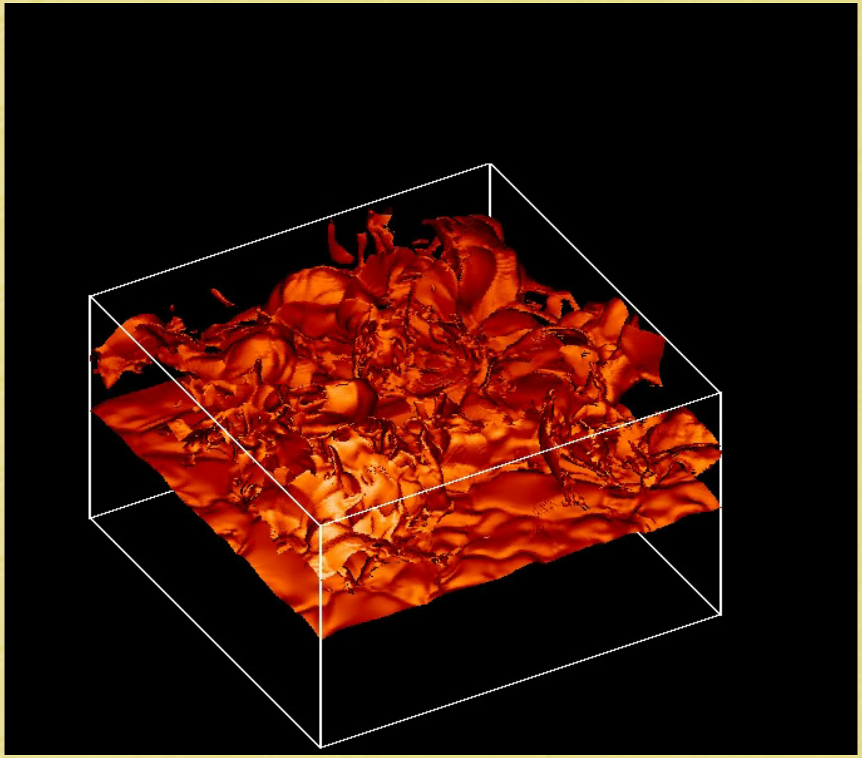
- 3D hydrodynamical view of stellar photospheres and chromospheres



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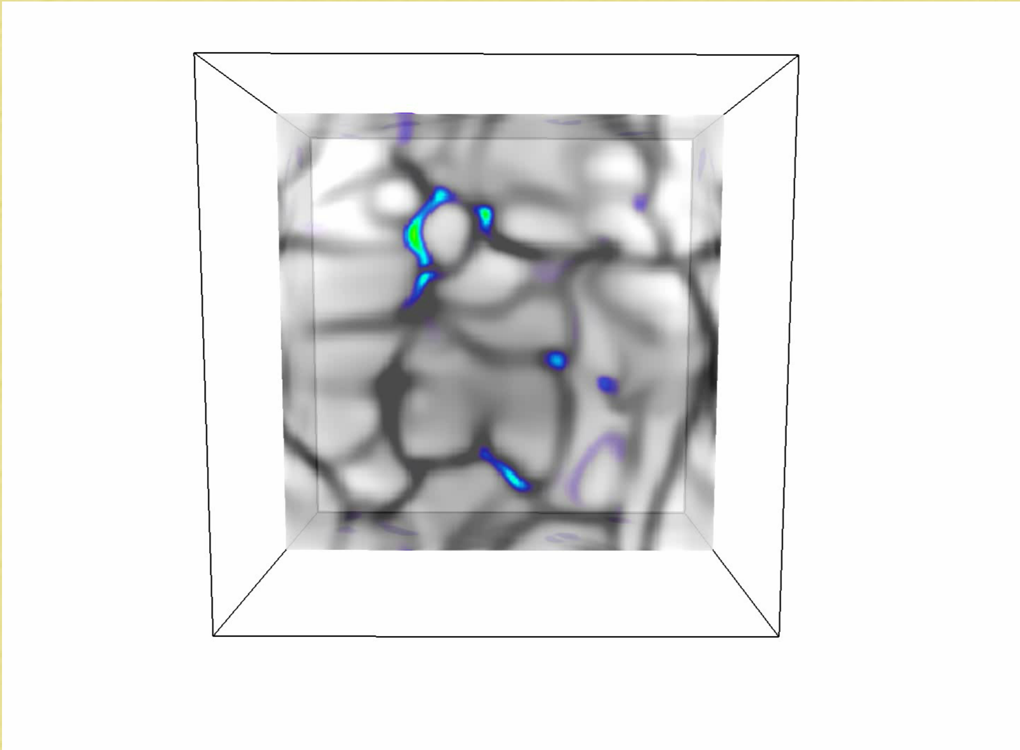
New generation stellar model atmospheres: why bother?

What can the 3D hydrodynamical models provide beyond the classical 1D view? Example III

- Evolution of magnetic structures in stellar atmospheres

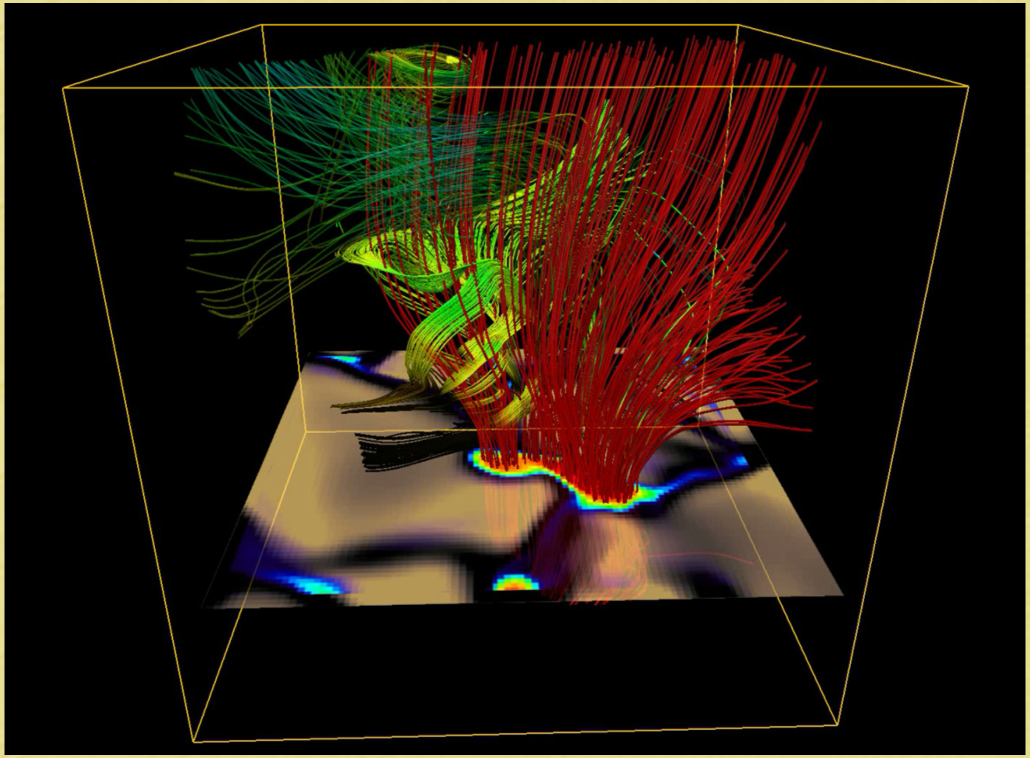


Magnetic structures in the 3D hydrodynamical CO5BOLD model of the solar atmosphere (Wedemeyer-Böhm, in prep.).

New generation stellar model atmospheres: why bother?

What can the 3D hydrodynamical models provide beyond the classical 1D view? Example III

- Evolution of magnetic structures in stellar atmospheres



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New generation stellar model atmospheres: why bother?

What can the 3D hydrodynamical models provide beyond the classical 1D view?

Summary

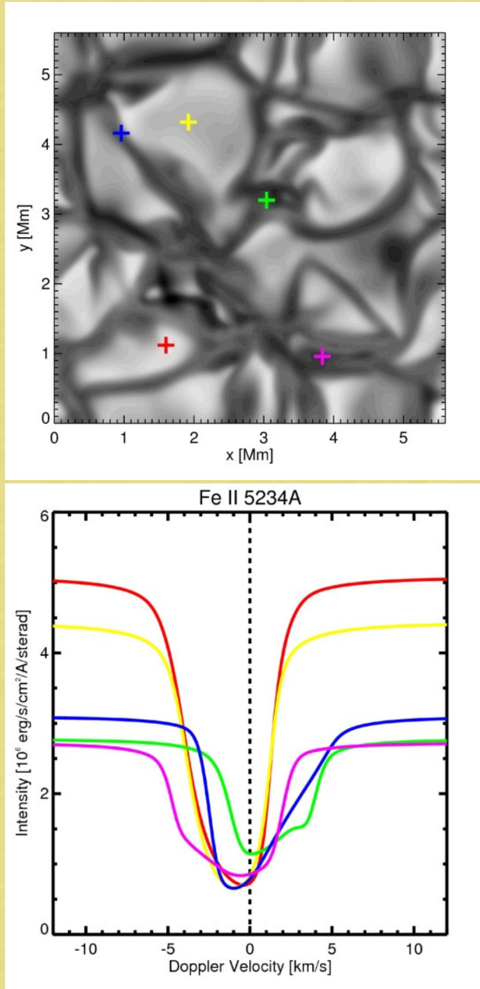
- Effects of radiation and velocity fields on the atmospheric structures
- 3D hydrodynamical view of stellar photospheres and chromospheres
- Evolution of magnetic structures in stellar atmospheres

$\Rightarrow$ **Implications on the observable properties of real stars: spectra, photometric colors, radial velocities and so on!!**

New generation stellar model atmospheres: why bother?

3D hydrodynamical effects in stellar atmospheres

- Implications on the spectral line formation:
  - Variations in line strengths, widths, shifts, asymmetries across granulation pattern
  - Non-linearities cause net effects in disk-integrated light

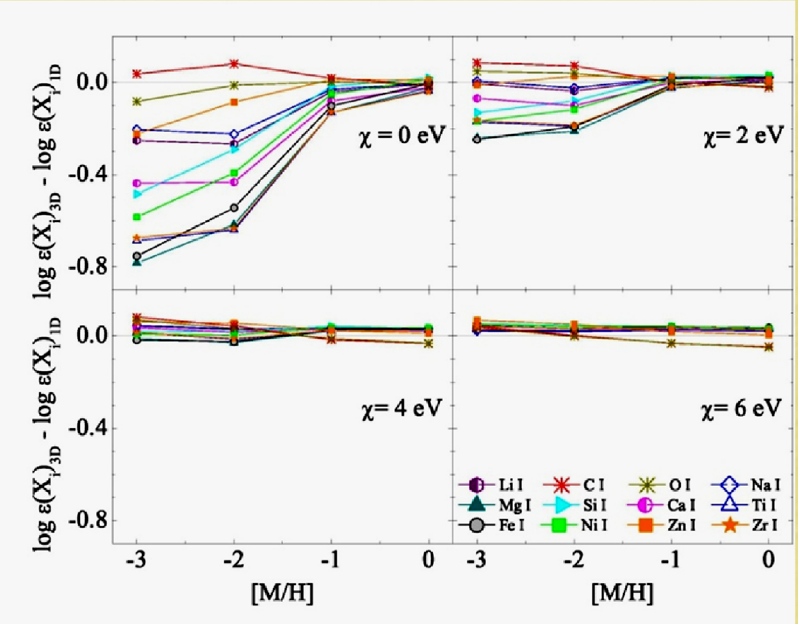


Top: surface granulation in the 3D hydrodynamical CO5BOLD model of the Sun.
Bottom: shapes of Fe II lines formed at different locations in solar atmosphere.

New generation stellar model atmospheres: why bother?

3D hydrodynamical effects in stellar atmospheres

- Implications on the spectral line formation:
    - Differences in the abundances derived with classical 1D and 3D hydrodynamical model atmospheres



3D – 1D abundance corrections for various neutral atoms characterized by various excitation potentials, plotted versus metallicity (Dobrovolskas et al. 2012, in prep.).

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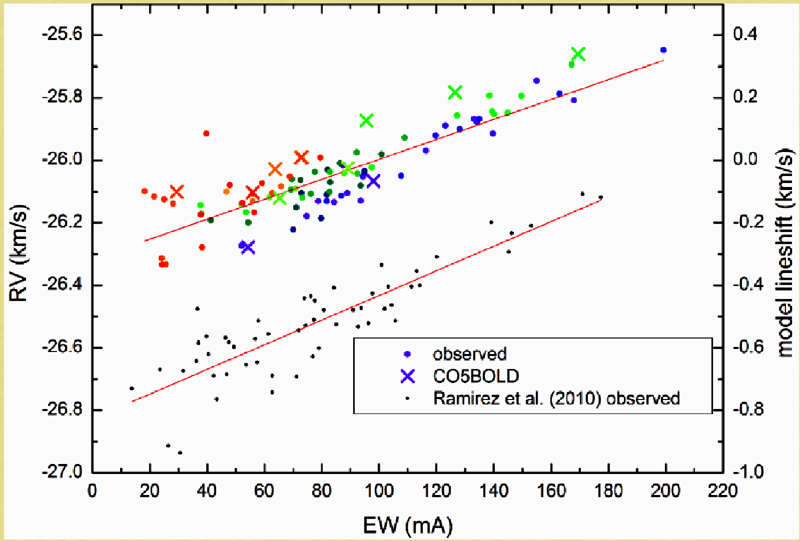
New generation stellar model atmospheres: why bother?

3D hydrodynamical effects in stellar atmospheres

- Implications on the spectral line formation:
  - Differences in the abundances derived with classical 1D and 3D hydrodynamical model atmospheres
  - Spectral line shifts: largest in case of weakest spectral lines



Measured (dots) and calculated (crosses, COBOLD models) line shifts in the atmosphere of the metal-poor giant HD 122563 (Klevas et al. 2012, in prep.).

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New generation stellar model atmospheres: why bother?

3D hydrodynamical effects in stellar atmospheres

- Implications on the spectral line formation:
  - Differences in the abundances derived with classical 1D and 3D hydrodynamical model atmospheres
  - Spectral line shifts: largest in case of weakest spectral lines
  - Different radial velocity shifts for different stars

Stellar type	$T_{\rm eff}$ [K]	$\log g$	[Fe/H]	Mass [$M_\odot$]	$R_\star$ [$R_\odot$]	$\Delta\lambda_{\rm FeI}$ [km.s^{-1}]	$\Delta\lambda_{\rm CaII}$ [km.s^{-1}]	Ref.	Symbol
Local simulations with STAGGER-CODE									
K giant	4700	2.2	0.0	…	…	−0.36	+0.29	[8]	●
K giant	4720	2.2	−1.0	…	…	−0.45	+0.23	[8]	▲
K giant	5035	2.2	−2.0	…	…	−0.58	+0.25	[8]	▼
K giant	5130	2.2	−3.0	…	…	−0.28	+0.31	[8]	♦
K giant	4630	1.6	−3.0	…	…	−0.22	+1.55	[9]	■
F star	6500	4.0	0.0	…	…	−0.75	+3.4	[10]	★
Global simulations with CO^{5}BOLD									
RSG	3430	−0.35	0.0	12	846	+0.75	−1.89	[5]	●
RSG	3660	0.02	0.0	6	386	+2.80	−7.95	[5]	★

Radial velocity shifts for Fe I and Ca II lines predicted by the 3D hydrodynamical models for different types of stars (Chiavassa et al. 2011).

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New generation stellar model atmospheres: why bother?

3D hydrodynamical effects in stellar atmospheres

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New generation stellar model atmospheres: why bother?

3D hydrodynamical effects in stellar atmospheres

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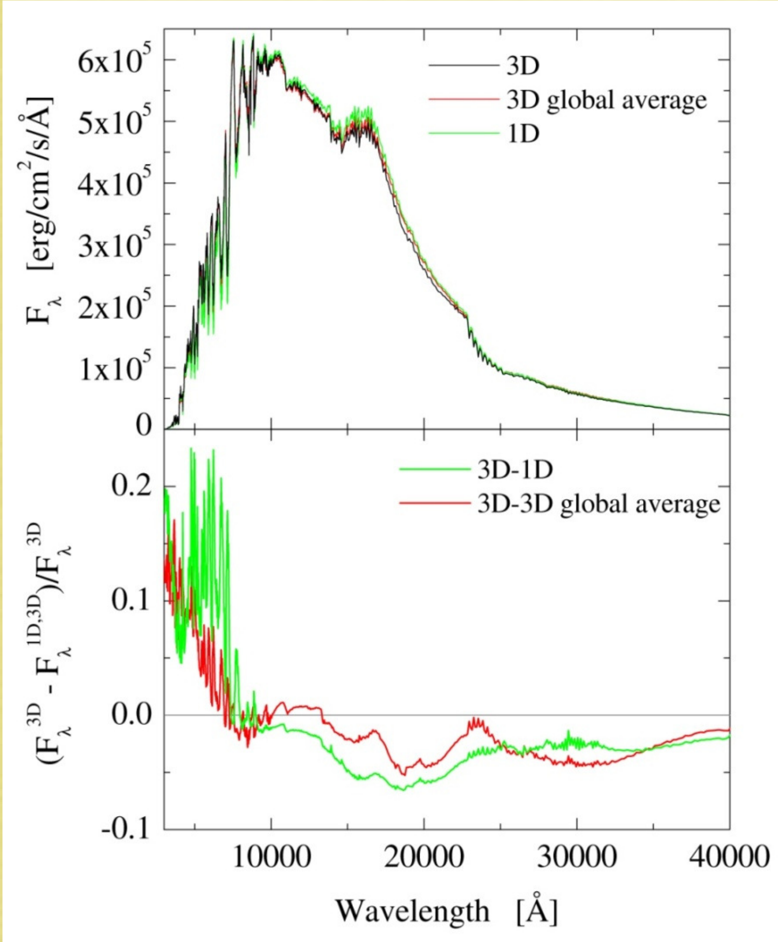
New generation stellar model atmospheres: why bother?

3D hydrodynamical effects in stellar atmospheres

- Implications on the global trends in stellar spectra:
  - 3D model produces more flux than its 1D counterpart in the blue spectral region and less in the red/near-infrared

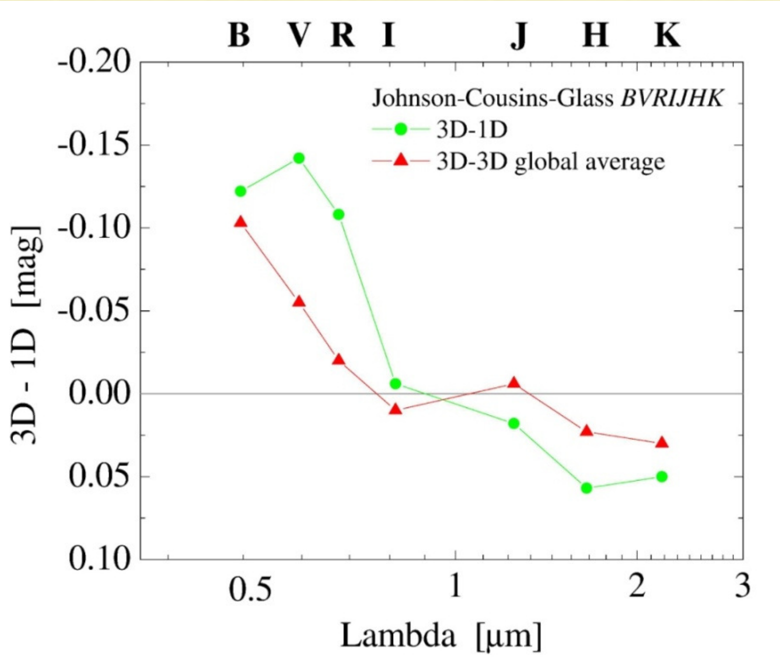


Top: Spectral energy distributions of the 3D (black), <3D> global average (red) and 1D (green) models of red giant. Bottom: differences between the spectral energy distributions: 3D–1D (green) and 3D – <3D> (red) (Kucinskas et al, in prep.).

New generation stellar model atmospheres: why bother?

3D hydrodynamical effects in stellar atmospheres

- Implications on the global trends in stellar spectra:
    - 3D model produces more flux than its 1D counterpart in the blue spectral region and less in the red/near-infrared
    - Differences in the photometric colors predicted with classical 1D and 3D hydrodynamical model atmospheres



Differences in the photometric colors: 3D–1D (green) and 3D–3D_global_average (red) (Kucinskas et al., in prep.).

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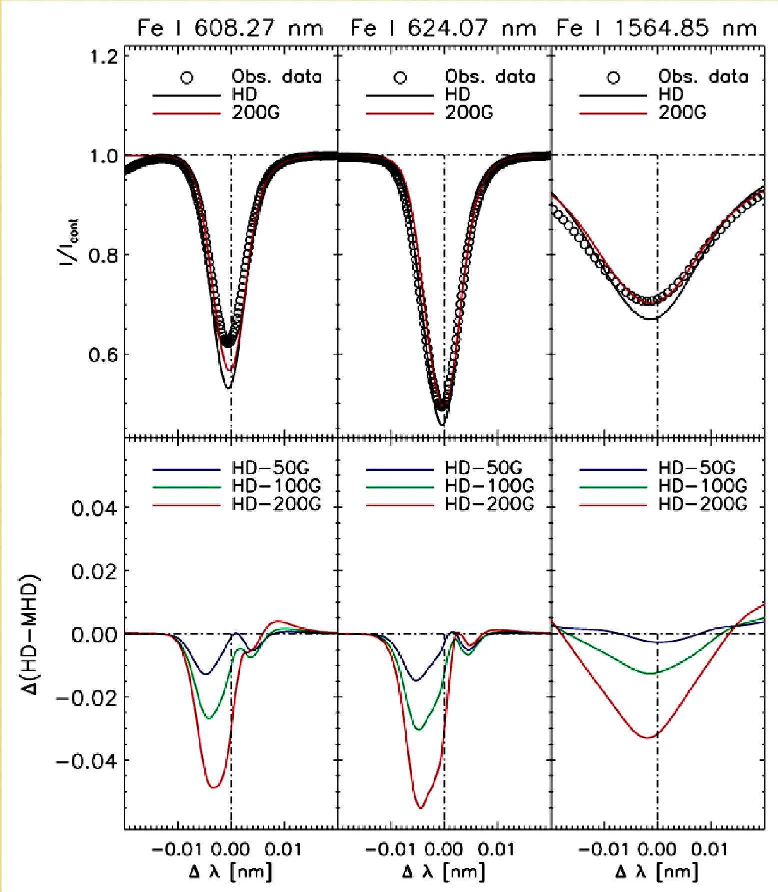
New generation stellar model atmospheres: why bother?

3D magnetohydrodynamical effects in stellar atmospheres

- MHD models of solar atmosphere :
  - Noticeable differences in Fe I line strengths predicted with the 3D MHD and pure 3D hydrodynamical model atmospheres
  - Better agreement of 3D MHD Fe I line profiles with observations



Top: observed (dots), 3D hydrodynamical (black lines), and 3D MHD (red lines) profiles of Fe I lines in the solar spectrum. Bottom: differences between the observed and theoretical line profiles (Fabbian et al. 2010).

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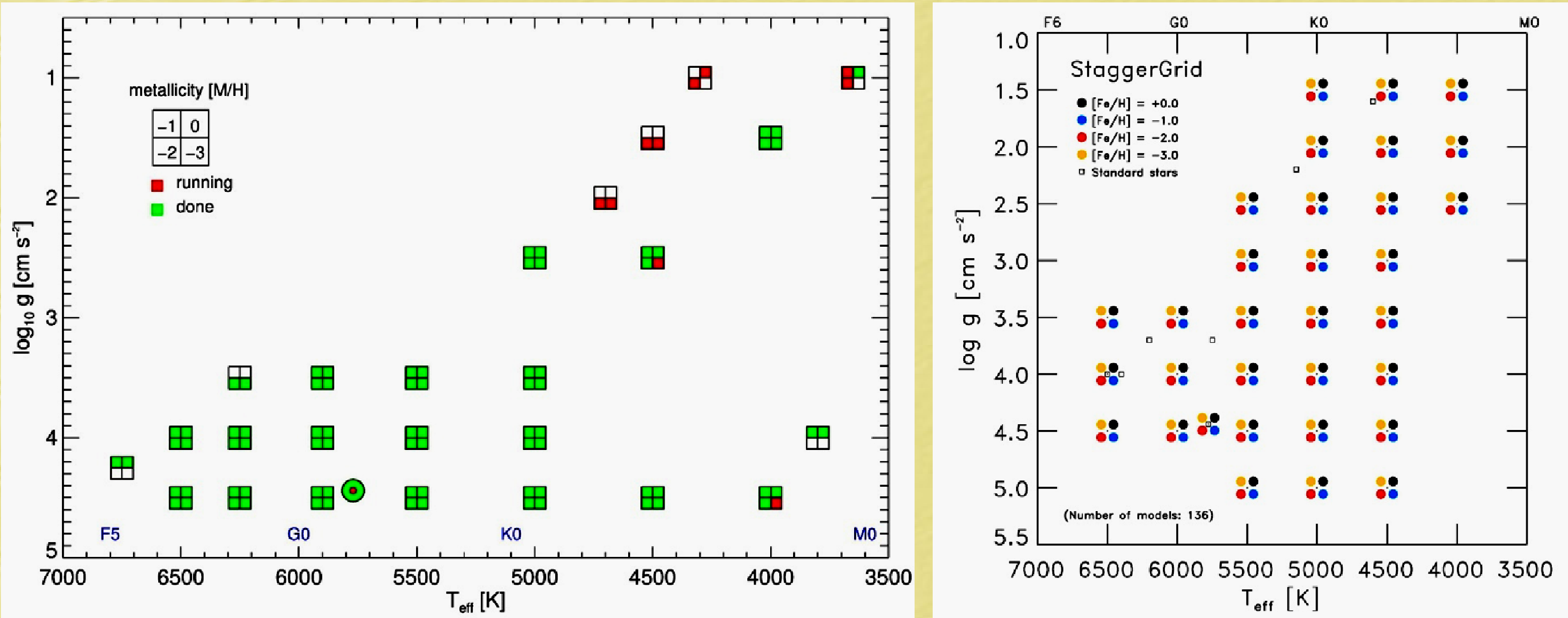
New generation stellar model atmospheres: user's perspective

3D stellar atmospheres for your work

- Grids of 3D model atmospheres are starting to appear
- Advice on possible use available from the modelers!



CO5BOLD (left, Ludwig et al. 2009) and STAGGER (right, Collet et al. 2011) grids of 3D hydrodynamical model atmospheres.

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New generation stellar model atmospheres: final remarks

- 3D (magneto)hydrodynamical model atmospheres are becoming available

  ⇒ **use them!**
- 3D (magneto)hydrodynamical model atmospheres are still experimental

  ⇒ **use with caution!!**
- ANY model atmosphere is based on a (LARGE!!) number of different assumptions, simplifications, and compromises

  ⇒ **do not over-interpret!!!**

THANK YOU!

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What kind of model atmospheres are available today?

Other 3D hydrodynamical stellar model atmospheres

- STAGGER code (REFERENCES!!)
- BIFROST code (former Oslo-STAGGER code; REFERENCES!!)
- MURAM code
- …..

⇒ enable to include many physical processes in detail

⇒ computation of large grids of stellar model atmospheres possible (ATLAS, MARCS, PHOENIX)