Modeling Polarization in Stellar Atmospheres

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Polarization in spectral lines

Polarization: **Maximum available information** on an astrophysical object.

In this talk: Among other processes affecting a continuous spectrum (Thomson/Rayleigh scattering, dust grains, …) the **resonance fluorescence** is of particular interest due to diverse sensitivity of spectral line polarization to various physical processes (optical pumping due to **anisotropic illumination**, **Zeeman** & **Hanle** effects, **collisional (de)polarization**, …).

On stellar atmosphere modeling

The goal of numerical modeling/simulation: To make **a ``copy'' of a complex real object** (of its essential properties) **in a computer**. Useful for systems whose complexity is otherwise impossible to maintain by using other approximations.

Input: Observations, theory of elementary processes, and boundary conditions.

The physical conditions in stellar atmospheres vary dramatically **from star to star** and **within the atmosphere of any single star.**

Different conditions → Different modeling methods, different approximations and even different physical theories → Different methods for different parts of an atmosphere of a given star.

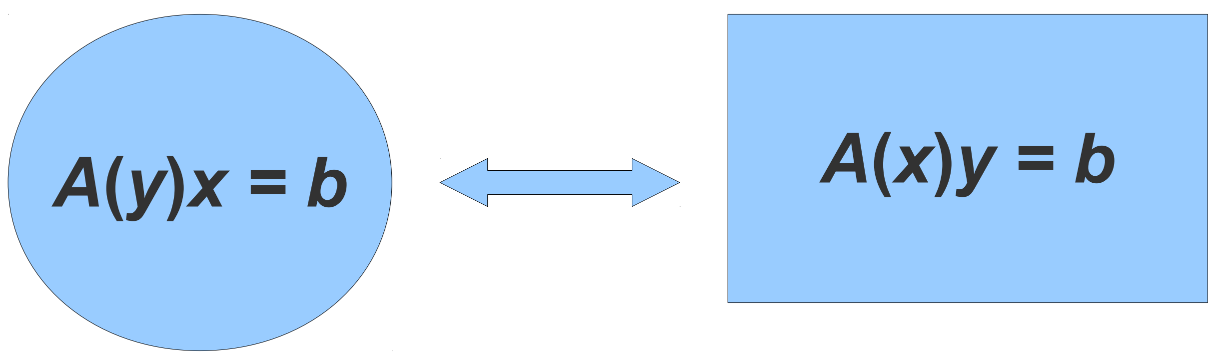
Introduction: The Non-LTE problem

In between the extremes...

1) LTE
2) non-LTE
3) Optically thin medium

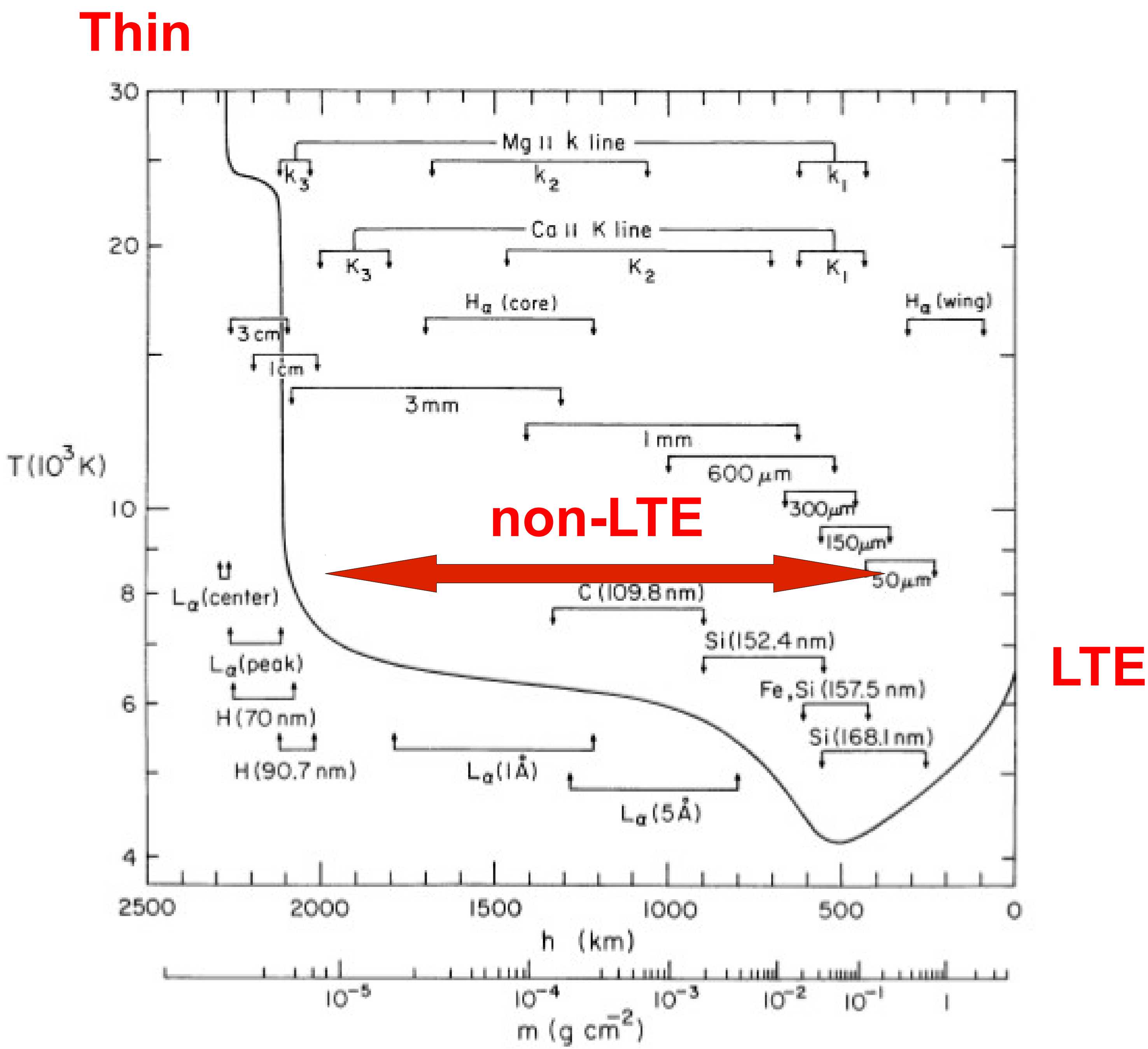
1 & 3: Immediate forward synthesis of spectra.

2: Self-consistent solution needed due to non-local coupling of matter via radiation. **Intrinsically non-linear problem requiring iterative solutions**.



Polarization included? → **Non-LTE problem of the 2nd kind**

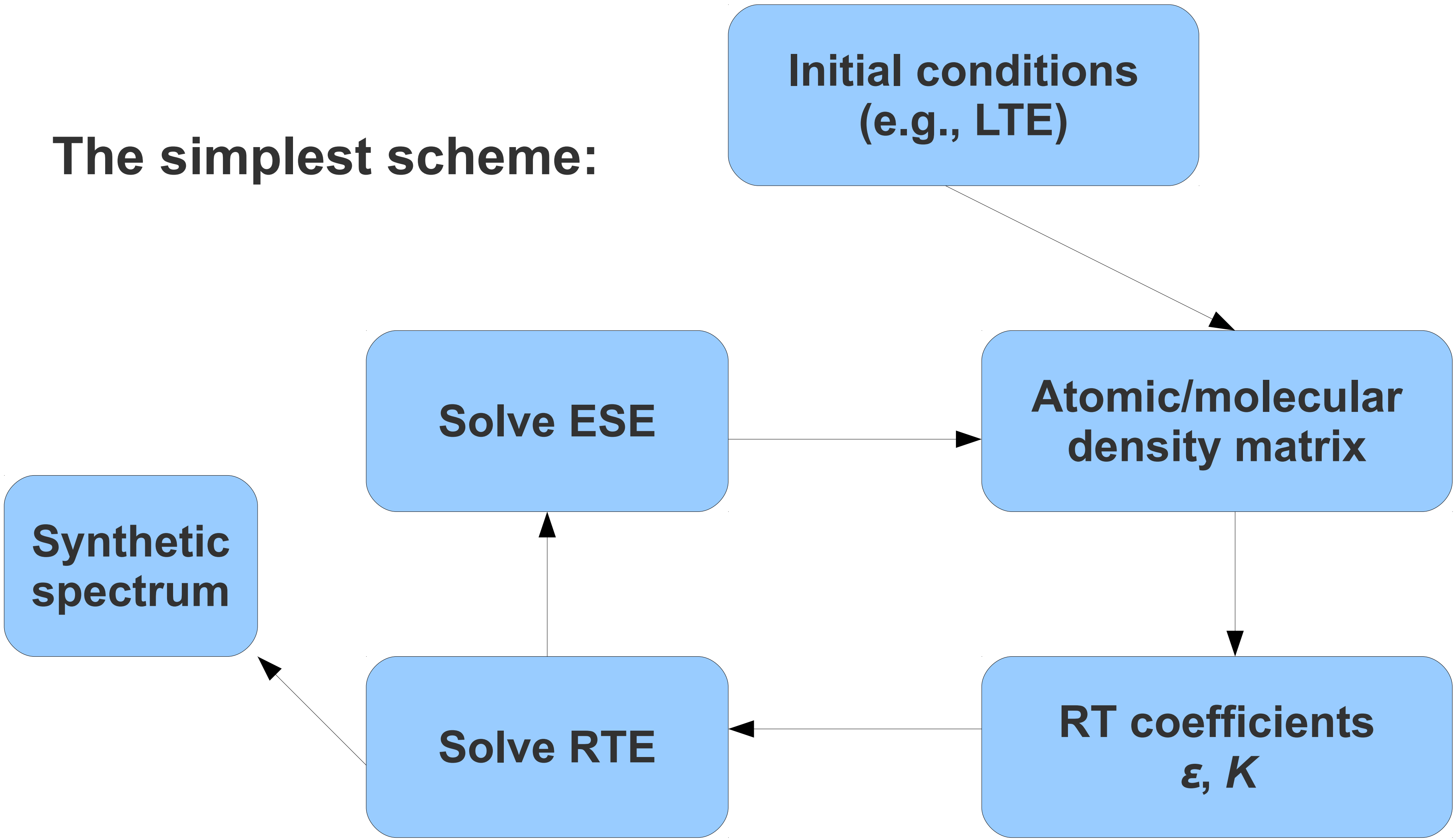
A 1D example: The quiet solar atmosphere



The non-LTE loop

Theoretical framework: A **multilevel theory of spectral line polarization** (Landi Degl'Innocenti & Landolfi, 2004).

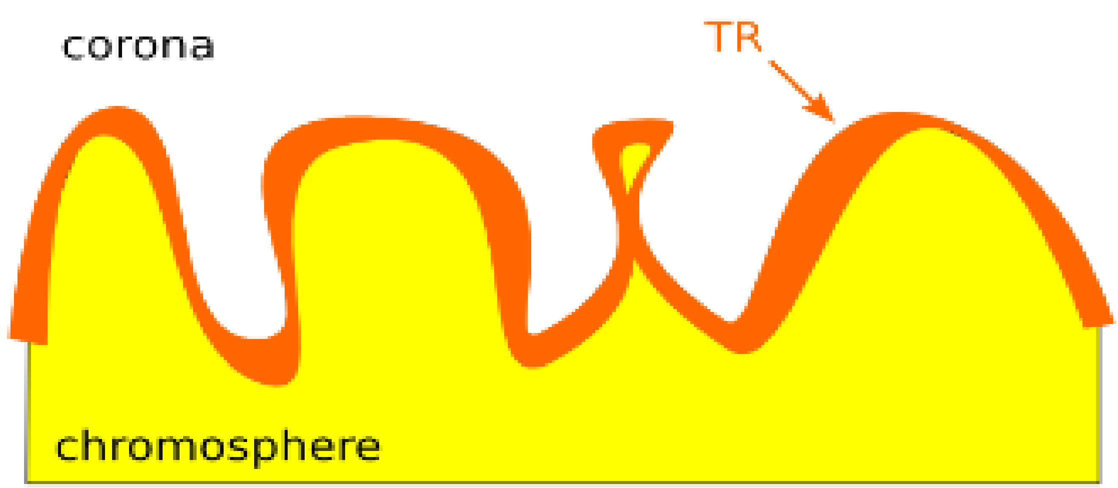
The simplest scheme:



Why do we need 3D?

1D:

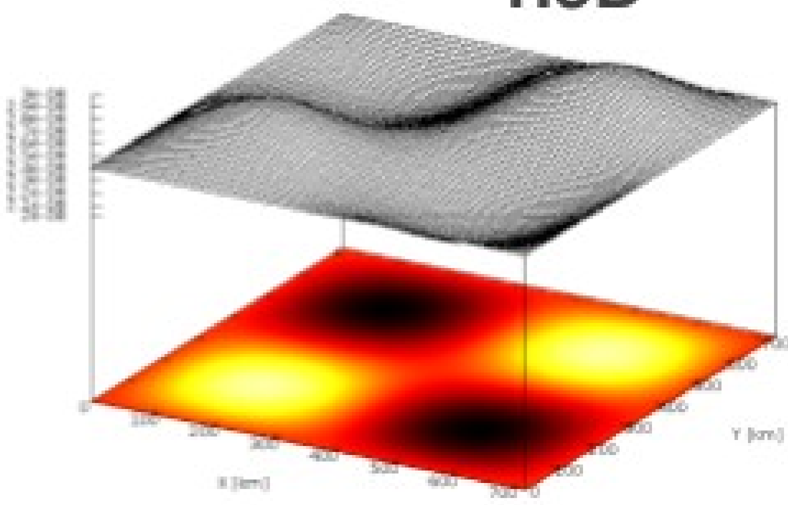
More realistically:

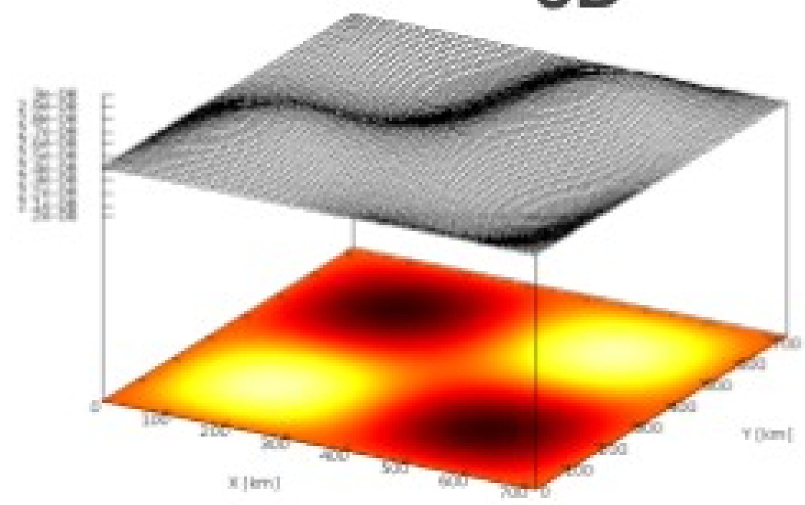


Why do we need 3D? An example of Lyα

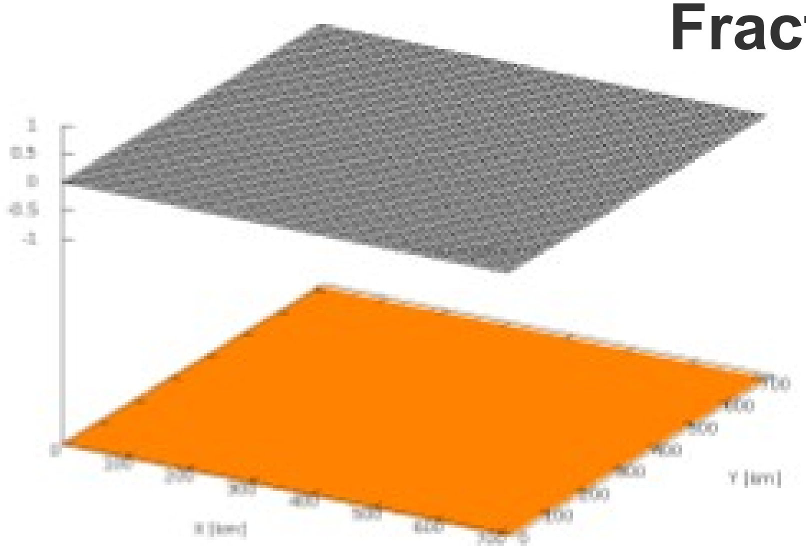
1.5D **3D**

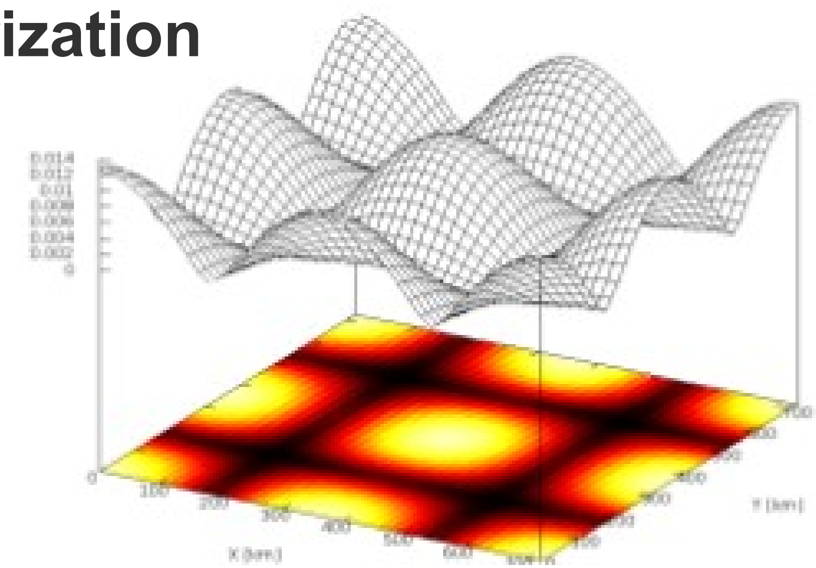
Intensity





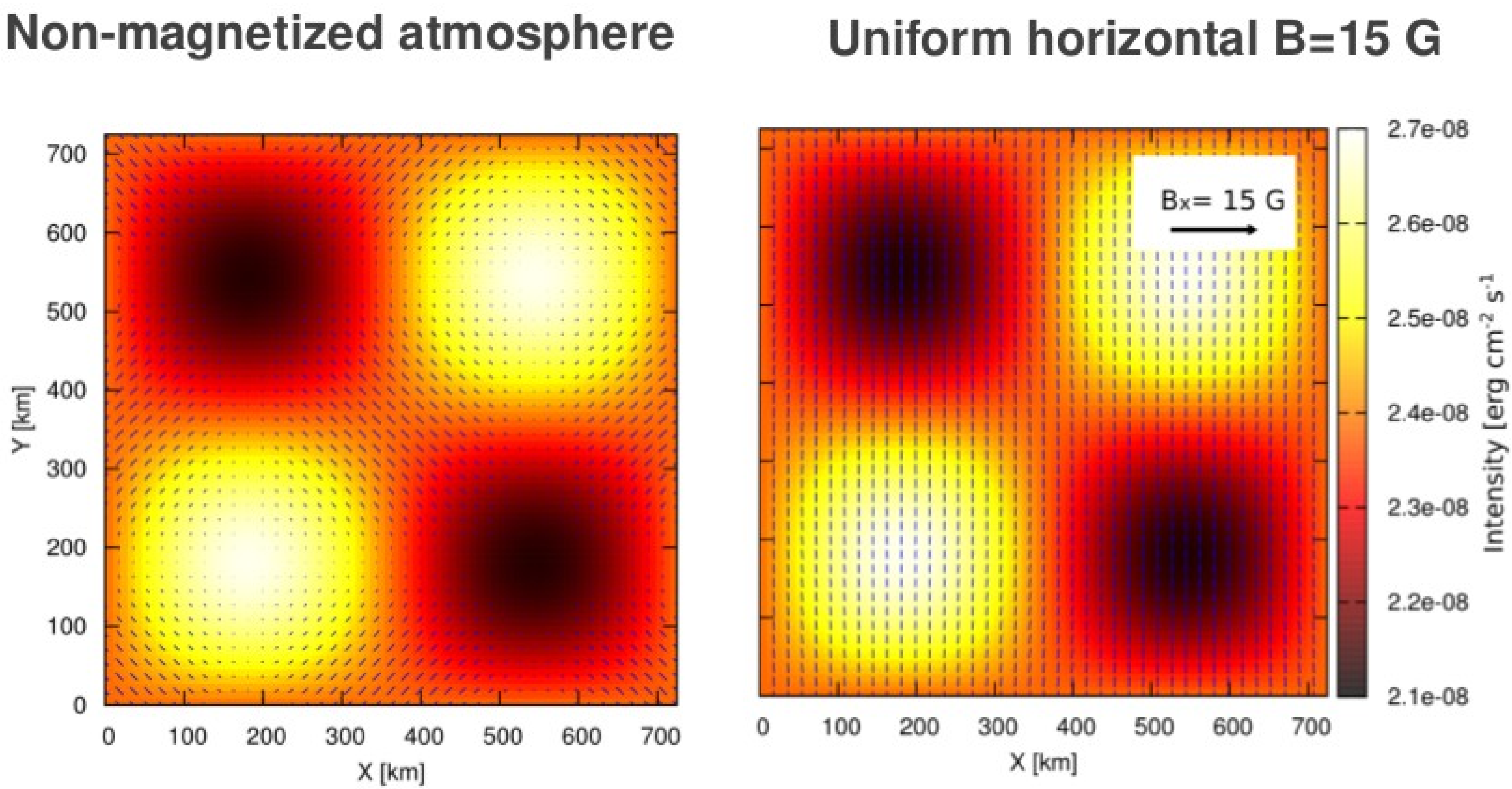
Fractional polarization





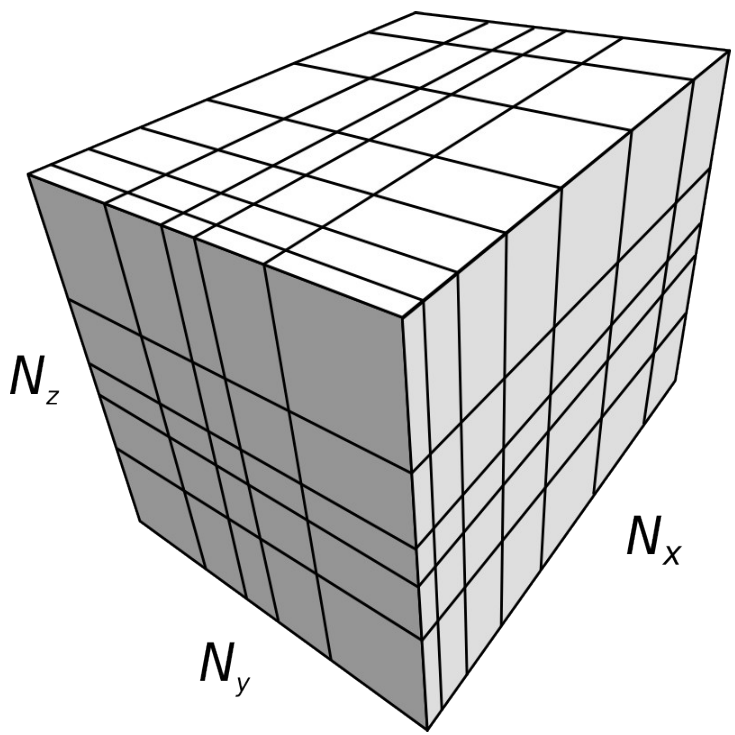
Symmetry-breaking effects can only appear in 2D & 3D

The action of the Hanle effect



In reality: **Much more complicated**

Non-LTE modeling in practice: The rectilinear grids

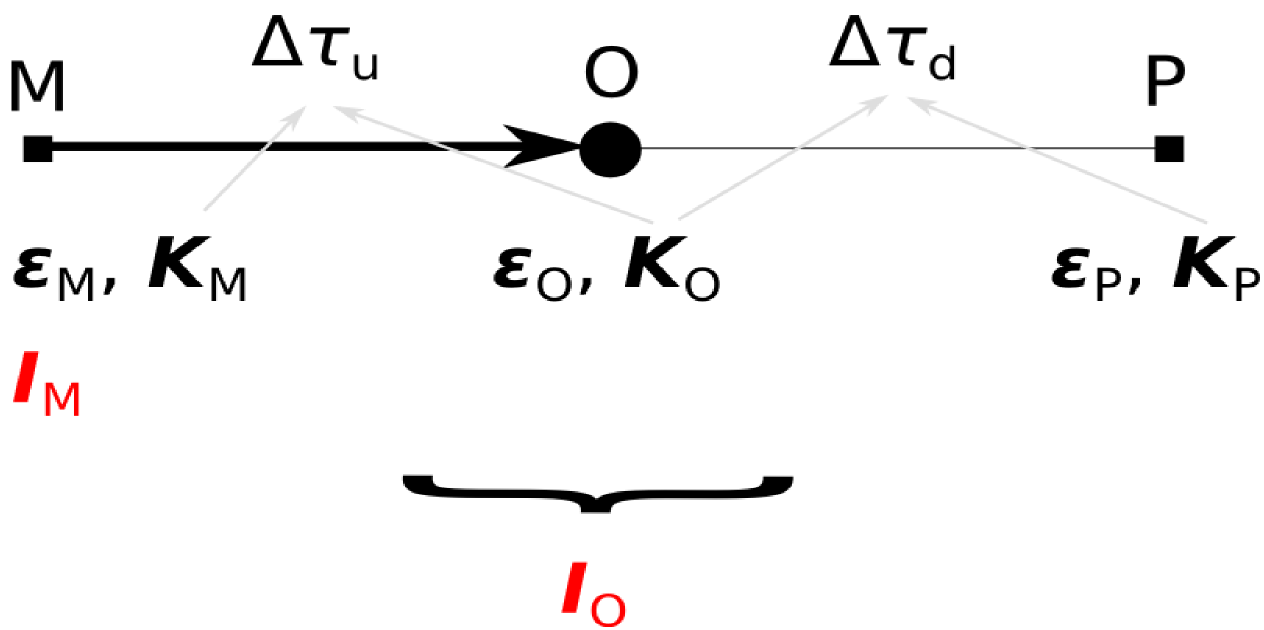


Every mesh point: density matrix, macroscopic velocity vector, magnetic field, mean radiation field tensors, temperature, …

Advantages:

- Simple representation
- Easy parsing in FS
- Periodic boundary conditions are easily implemented
- Straightforward acceleration via MG

The formal solution of RTE: The art of interpolation



$$\boldsymbol{I}_O = \boldsymbol{I}_M e^{-\tau_{MO}} + \int_O^M \left[\frac{\boldsymbol{\epsilon}}{\eta_I} - \left(\frac{\boldsymbol{K}}{\eta_I} - \mathbf{1} \right) \boldsymbol{I} \right] e^{-(\tau - \tau_O)} \, d\tau$$

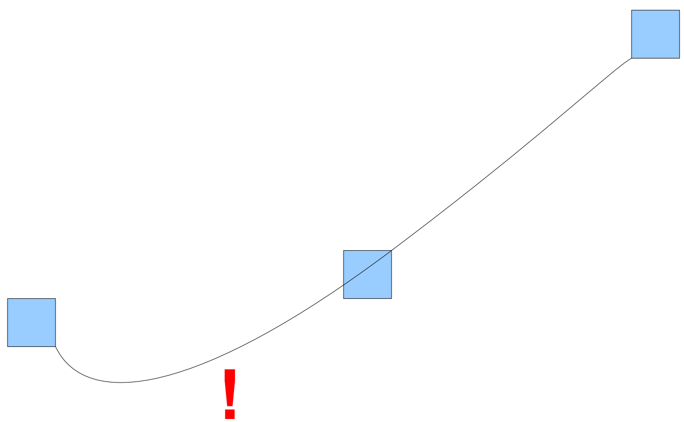
Assume $\boldsymbol{S} = \boldsymbol{\varepsilon}/\eta_I$ varies as
a) a parabola between MOP or
b) as a quadratic/cubic Bezier curve between MOP
and $(\boldsymbol{K}/\eta_I\text{-}\mathbf{1})\boldsymbol{I}$ varies linearly between MO

→ RTE can be formally integrated to obtain ***Io***
and the **Lambda diagonal** (Rybicki & Hummer 1992)

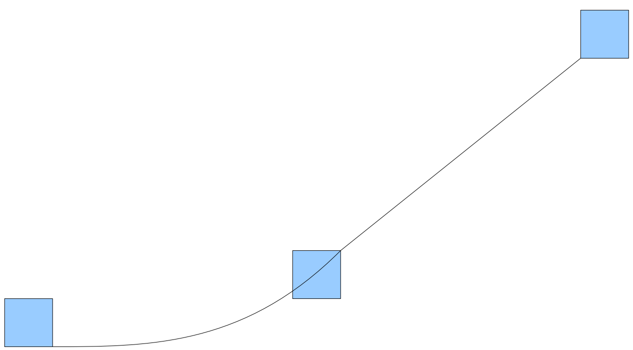
The advantages of monotonic Bezier interpolation

If the physical properties are not sufficiently sampled (this occasionally happens in the 3D models), the monotone interpolation assures physical results:

Quadratic interpolation

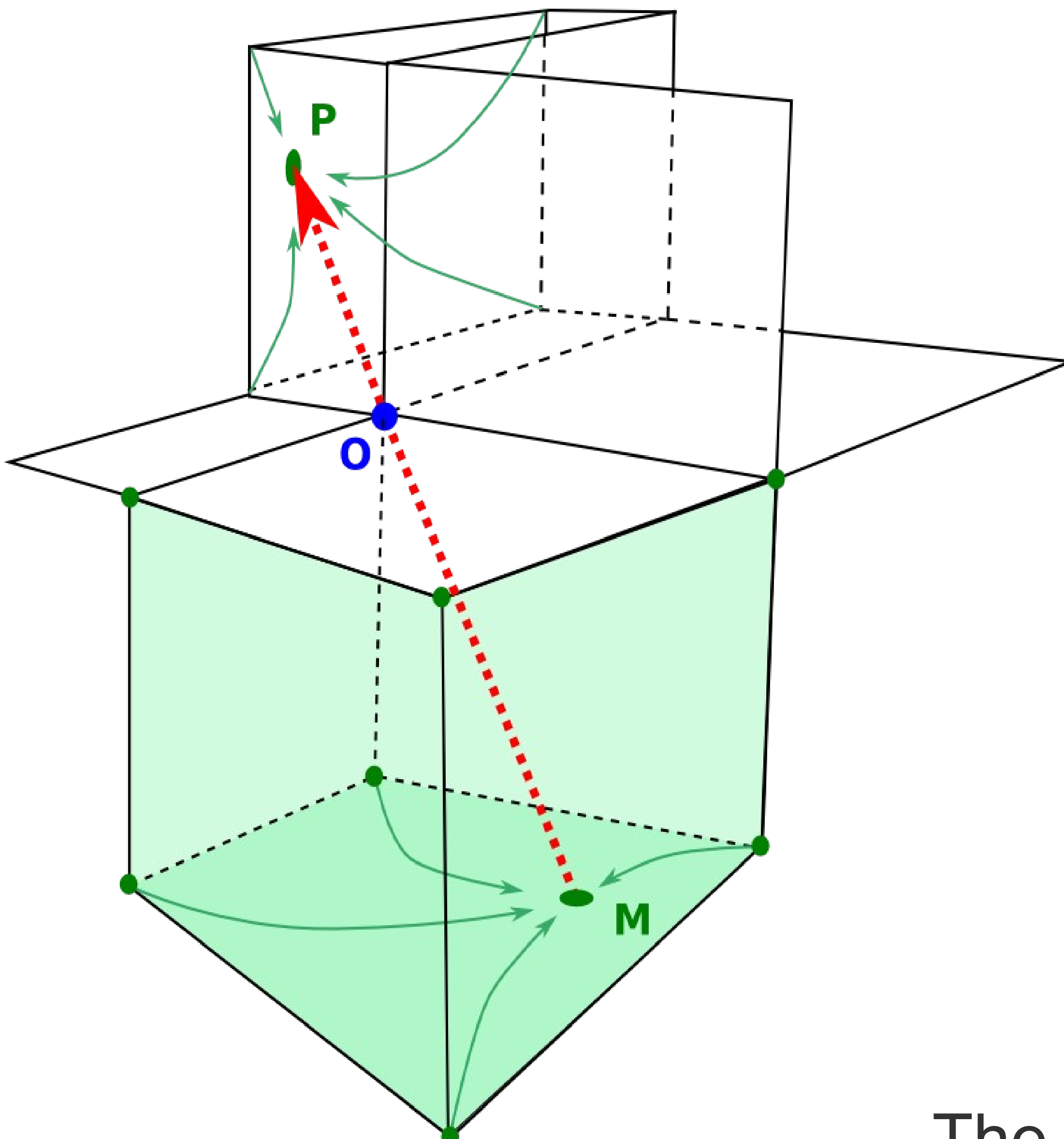


Quadratic Bezier interpolation



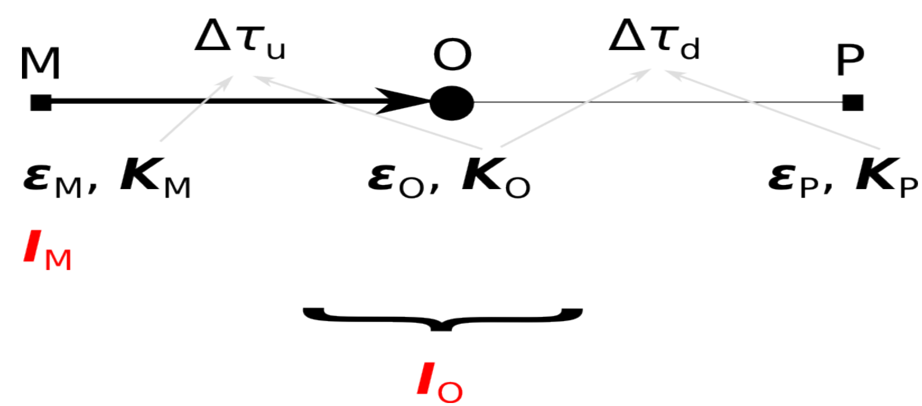
Moreover: The diagonal of the Lambda operator is always **between 0 and 1** (in general not true with parabolic interpolation in 3D) → **More stable solver**

Formal solution in 3D: The short characteristics



Short characteristics
(Kunasz & Olson 1988):

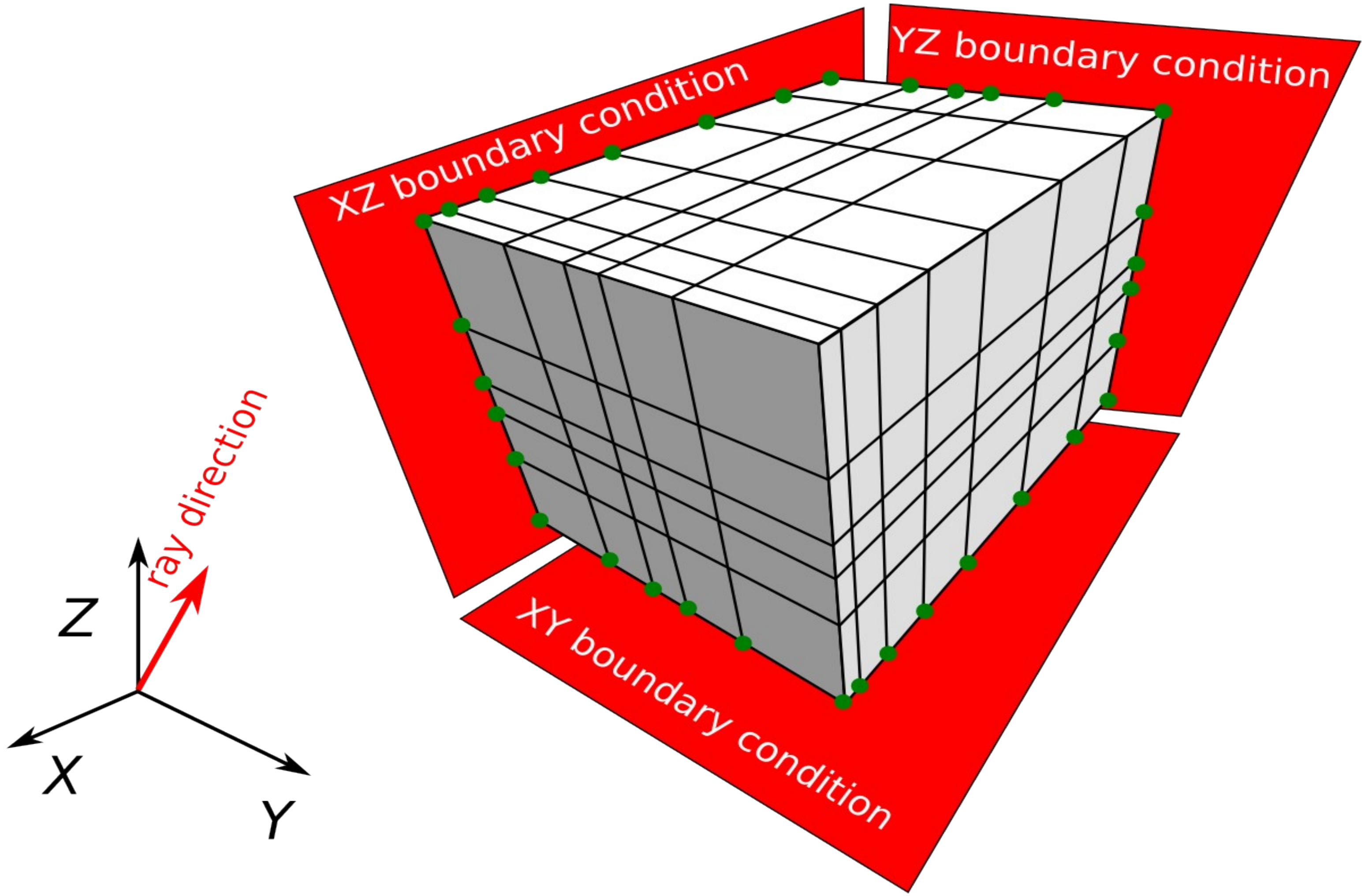
Faster than long characteristics: Scales linearly with the number of grid points



The need of I_M → **Topologically sorted grid points**

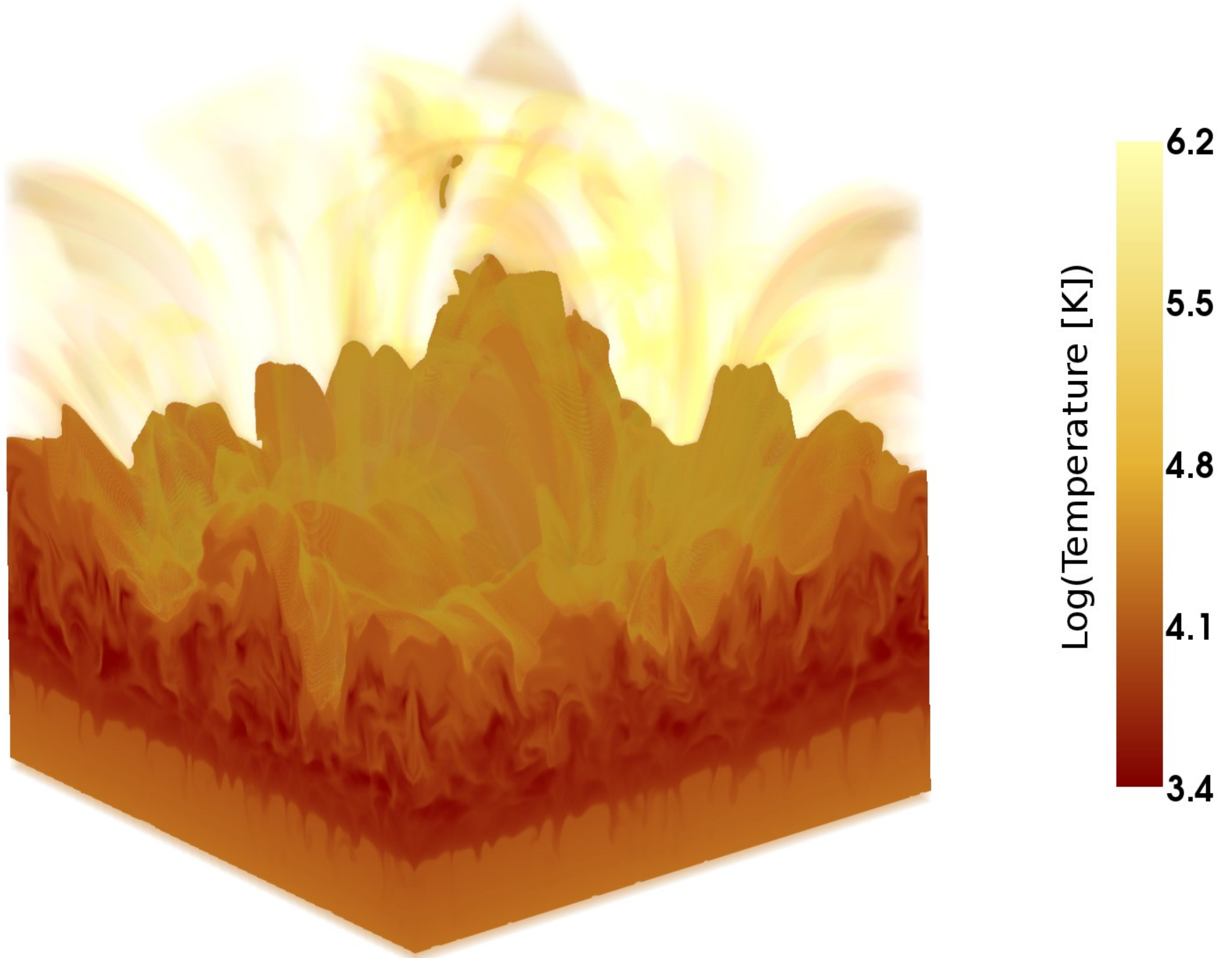
Formal solution in 3D: Parsing the grid

Rectilinear grids: Simply topologically sorted



Boundary conditions: periodic / fixed. The need of parallel solution → Storage and reuse of the emergent Stokes vector at the **periodic boundaries** between iterations.

Why Jacobi (ALI) is not sufficient in realistic problems



Leenaarts et al. (2012)

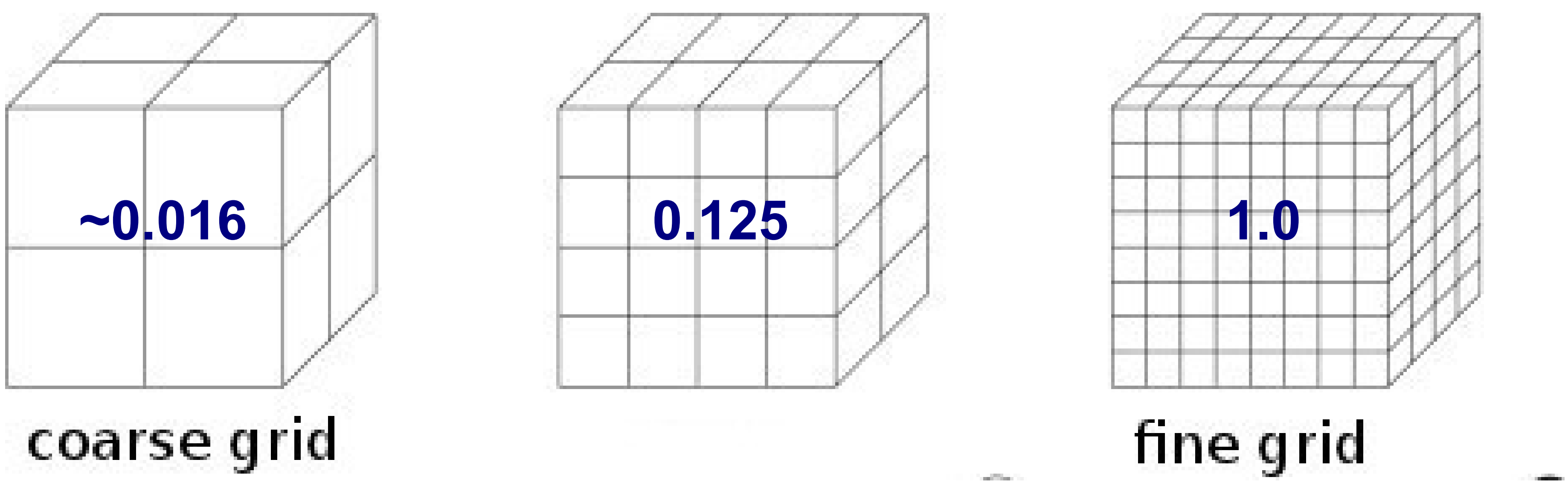
Typical **1D** problem: **~100 grid** points.

State-of-the-art MHD simulation of the solar chromosphere:
Nx ~ Ny ~ Nz ~ 500
→
125 million grid points

Each FS: **Days of CPU time** for a single spectral line (with ~200 iterations needed)

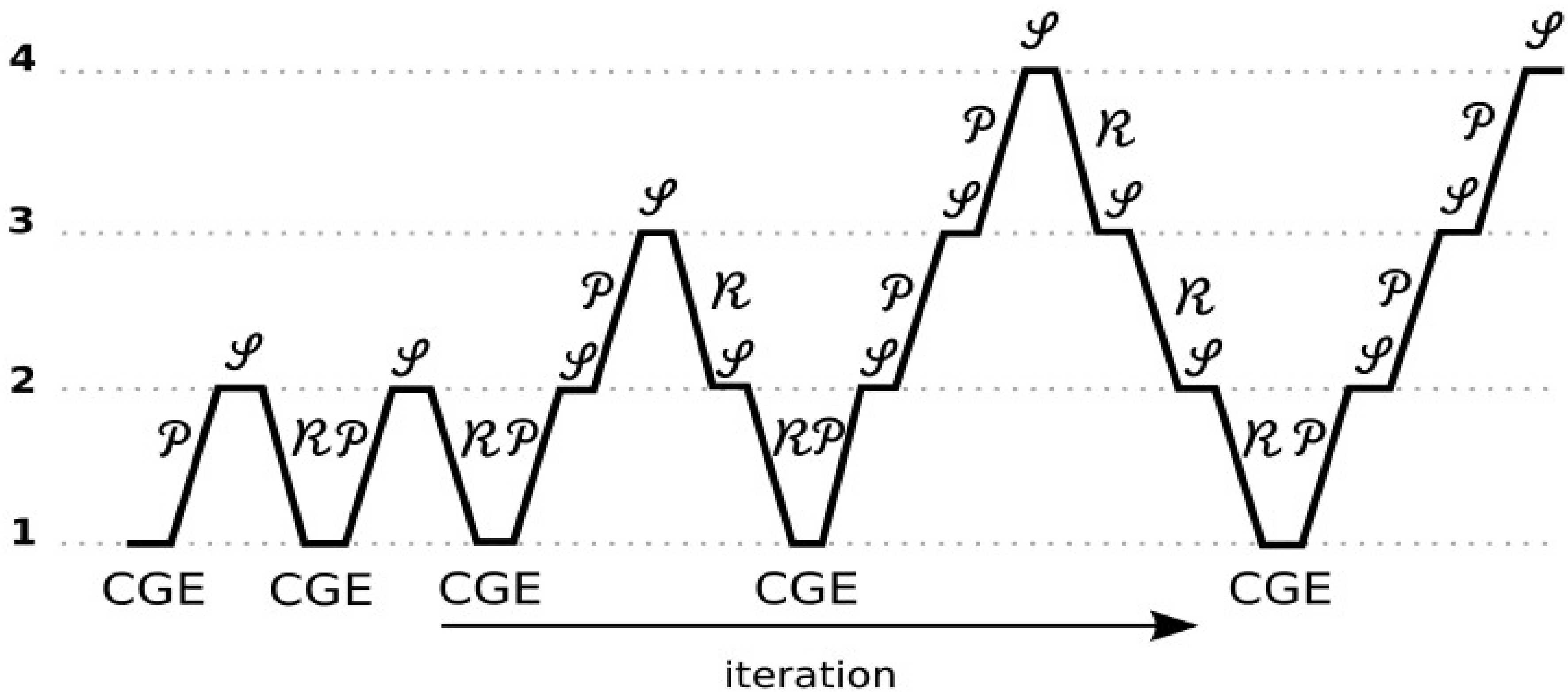
Multigrid acceleration

The standard preconditioned iterations are essentially **a smoothing process** reducing efficiently only the high-frequency error with respect to grid spacing. Convergence time: **O(*N*^2)**



Hackbush (1985), Fabiani Bendicho et al. (1997)

The nested iteration: Another factor of 2 of speedup

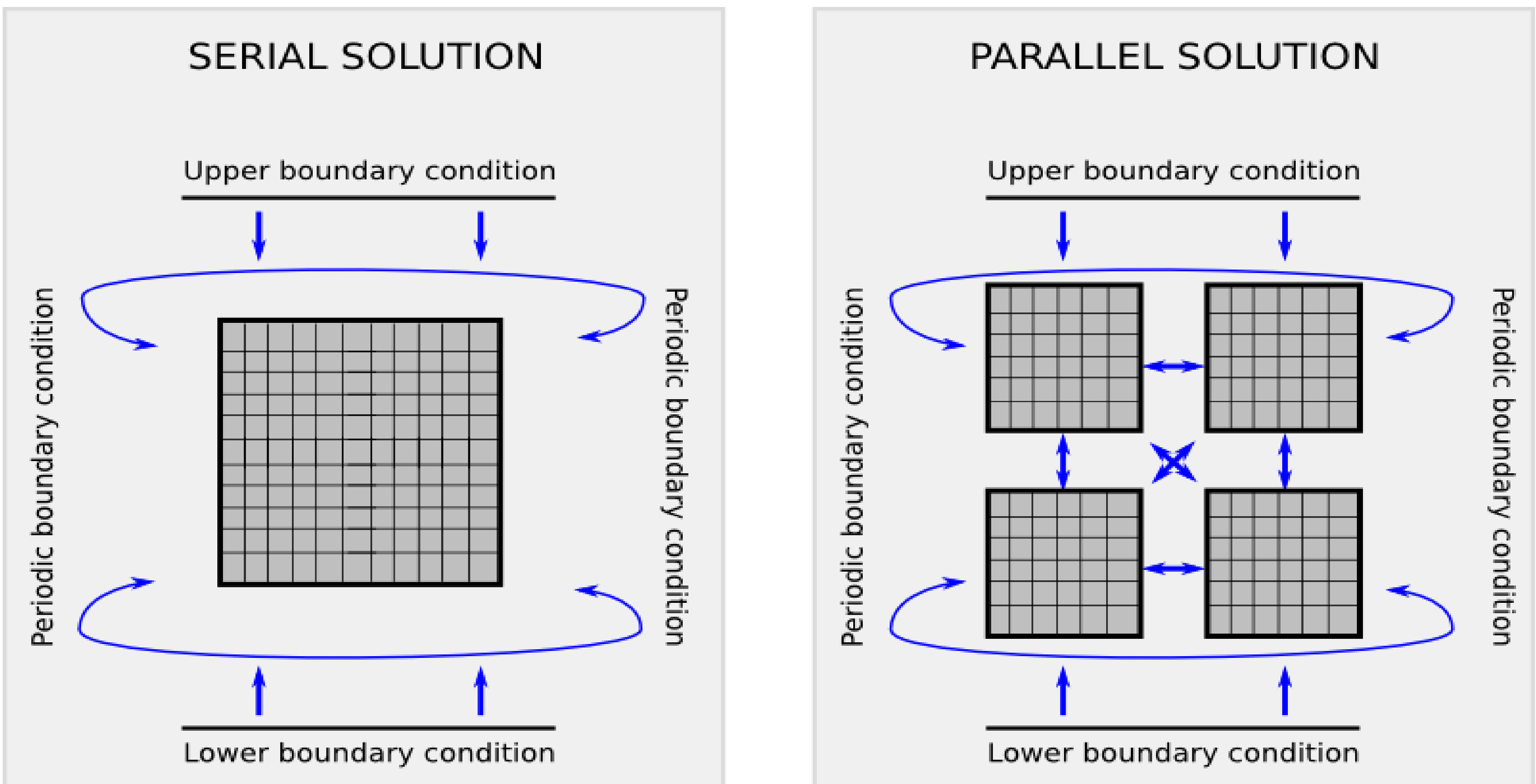


Multigrid iteration asymptotic behavior: **O(*N*) … Fixed** (and small ~ 10) **number of formal solutions** in the finest grid **independently of grid resolution + Reliable stopping criterion**

Parallelization: A necessity realistic modeling

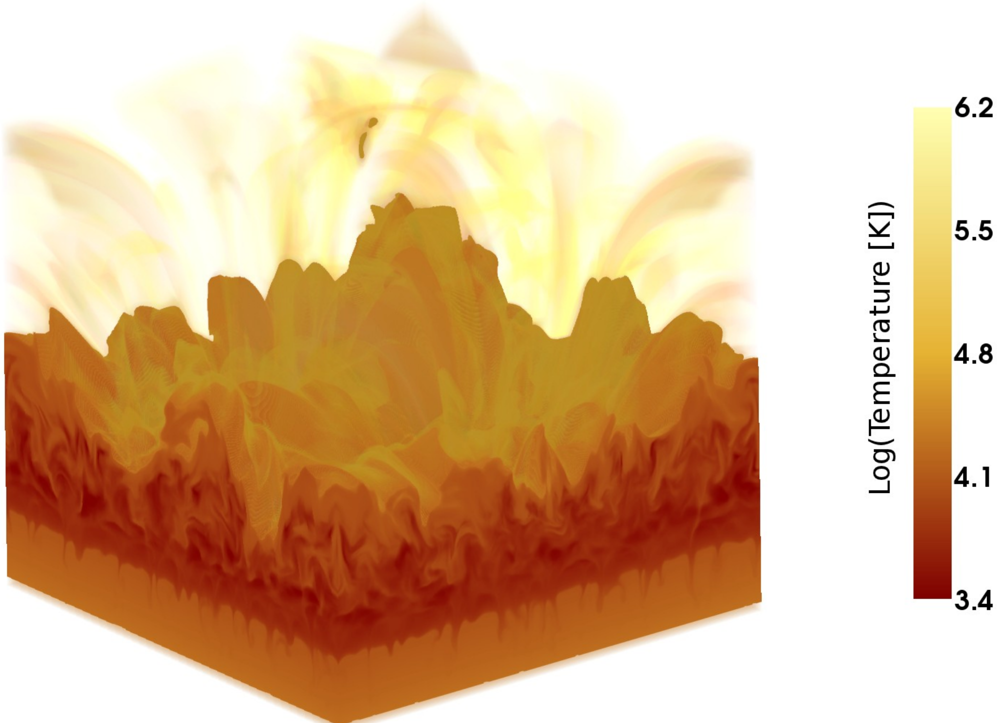
The current MHD simulations:
Synthesis of a single polarized resonance line: **~40 GB** of memory and weeks of calculation on a serial machine.

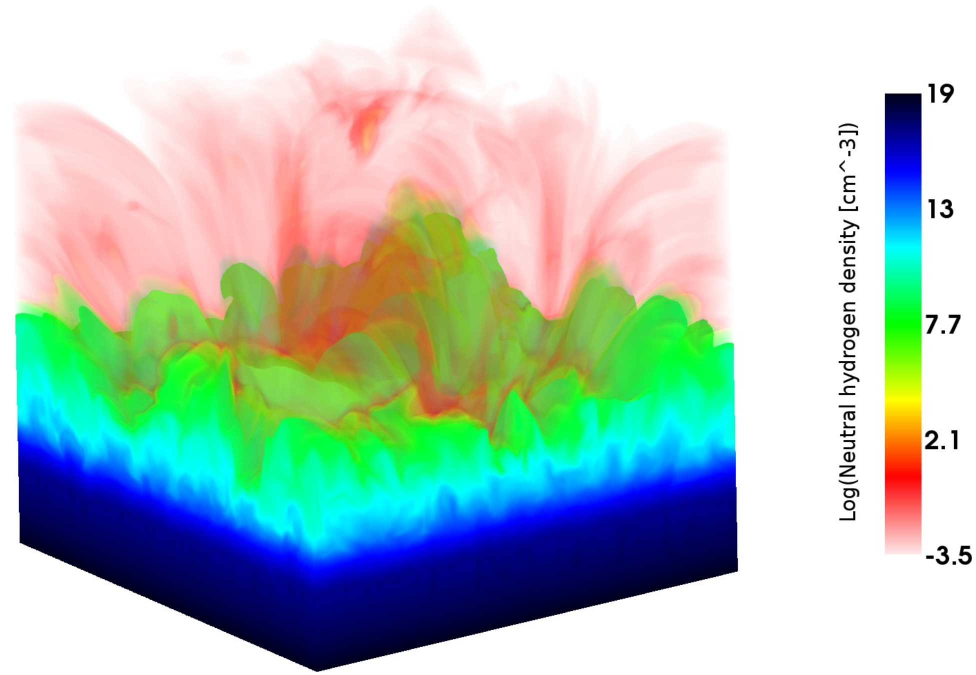
Domain decomposition:

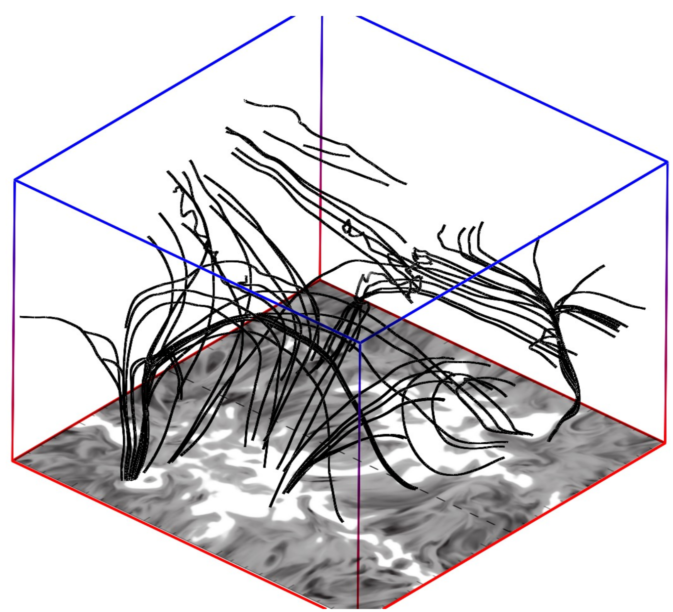


Implementation: The MPI library running on a computer cluster

Synthesis of the solar Lyα line of hydrogen







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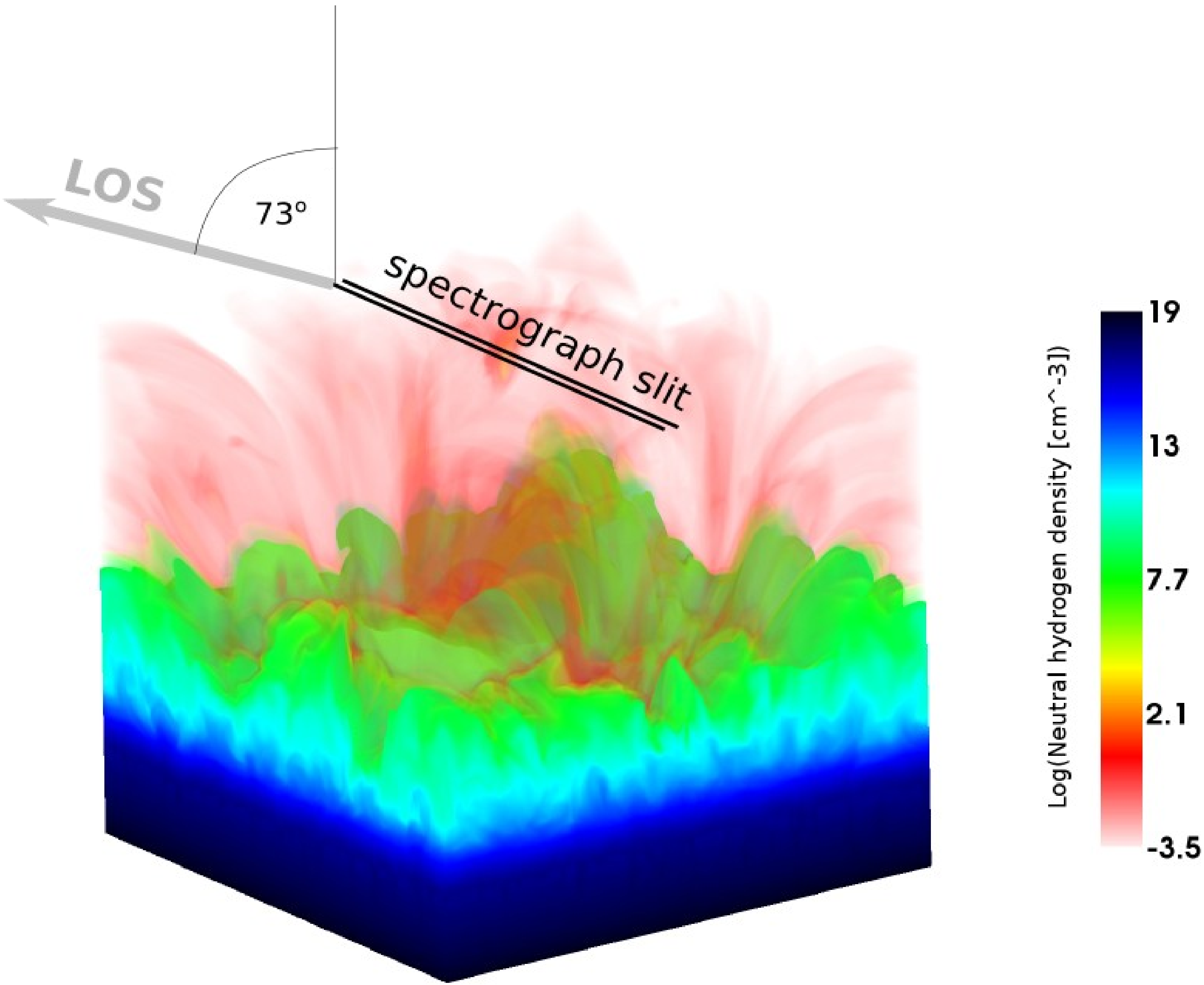
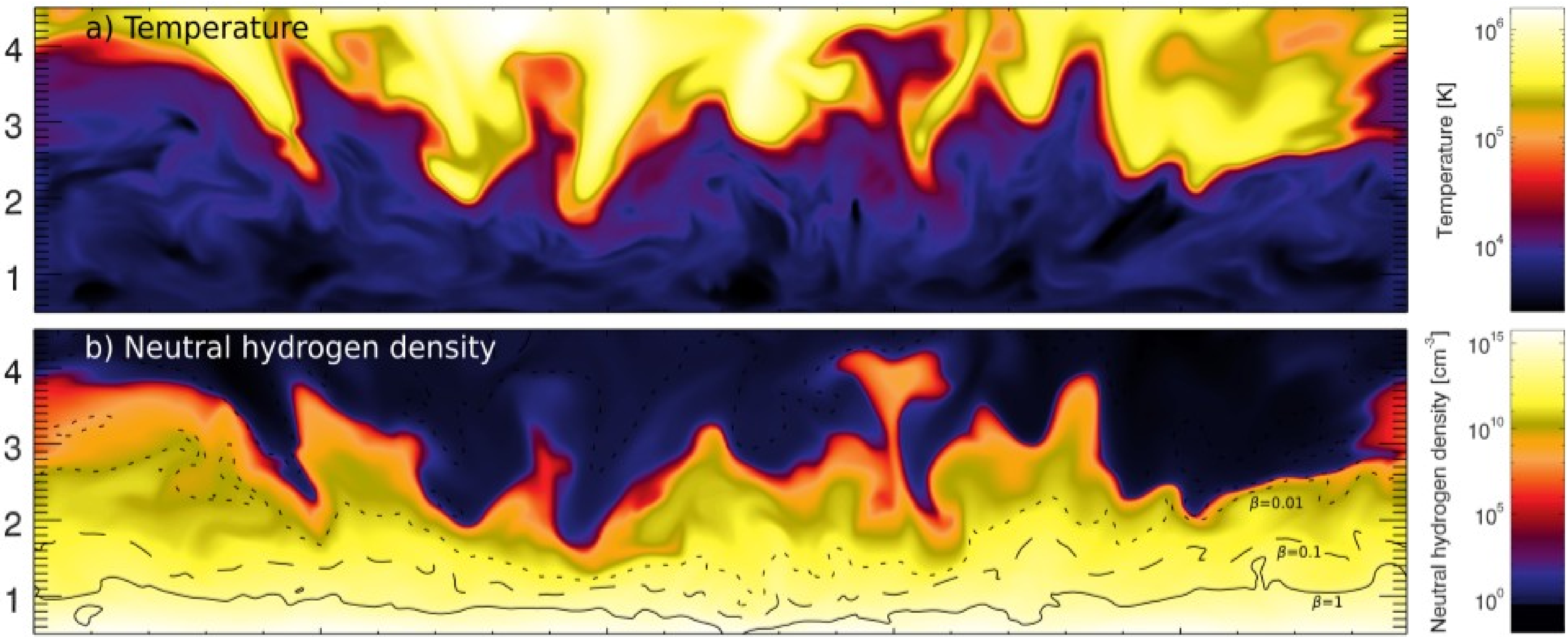
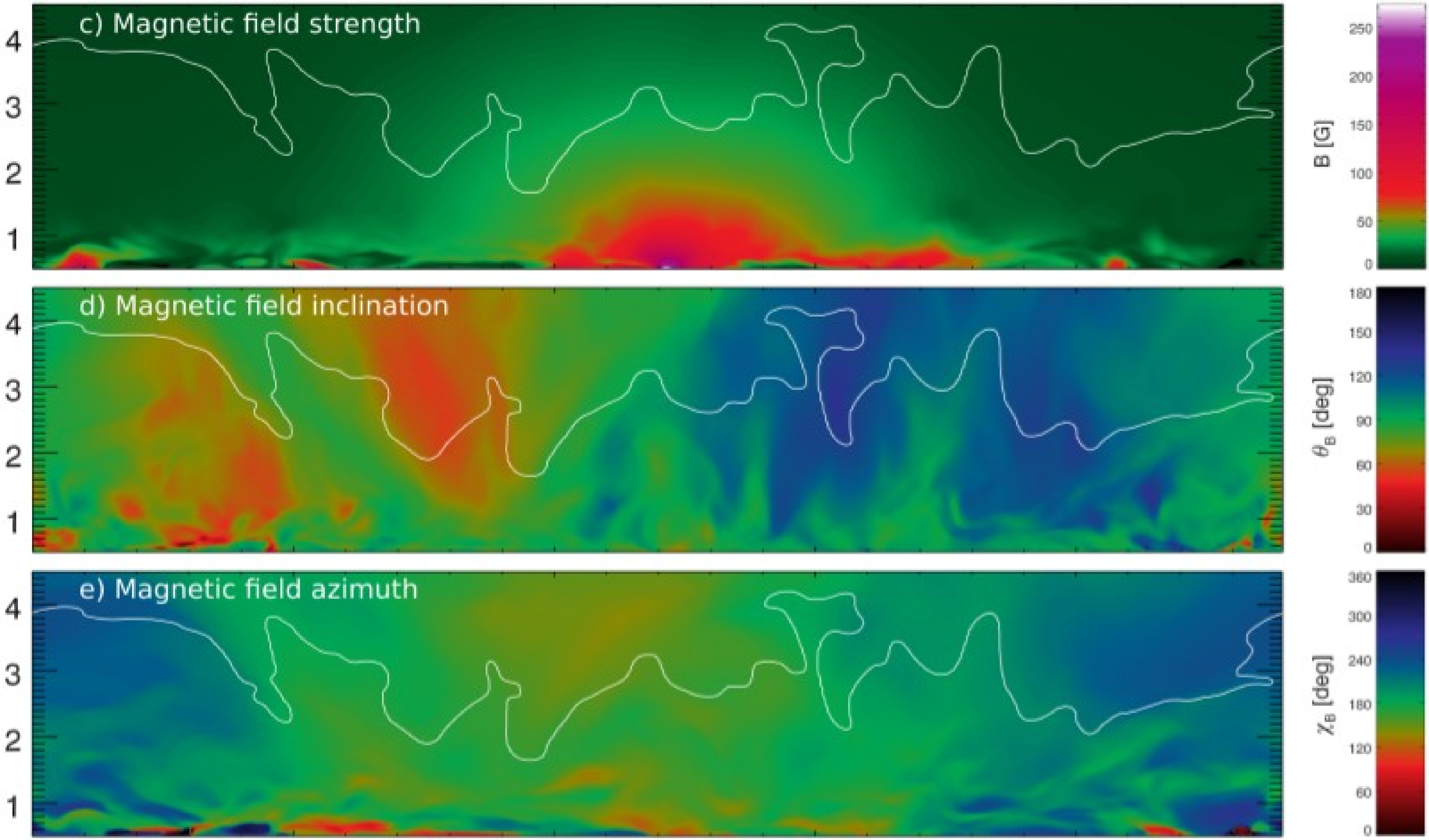


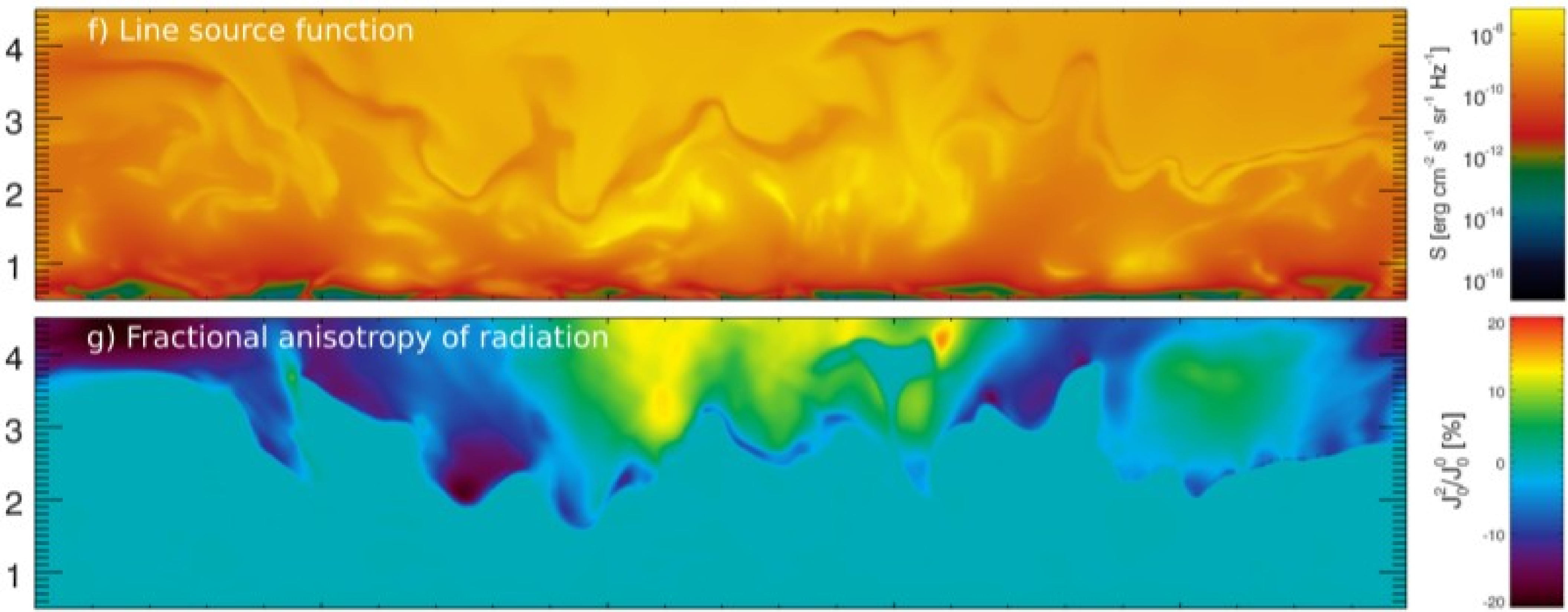
Solution in a vertical 2D slice: Temperature & neutral hydrogen desnity



Solution in a vertical 2D slice: Magnetic field



Solution in a vertical 2D slice: Lyα source function and anisotropy



The emergent spectrum