1st Swiss SCOSTEP workshop, Oct. 4–5, 2016

Oeschger Centre, Bern

Magnetohydrodynamic Simulations at IRSOL

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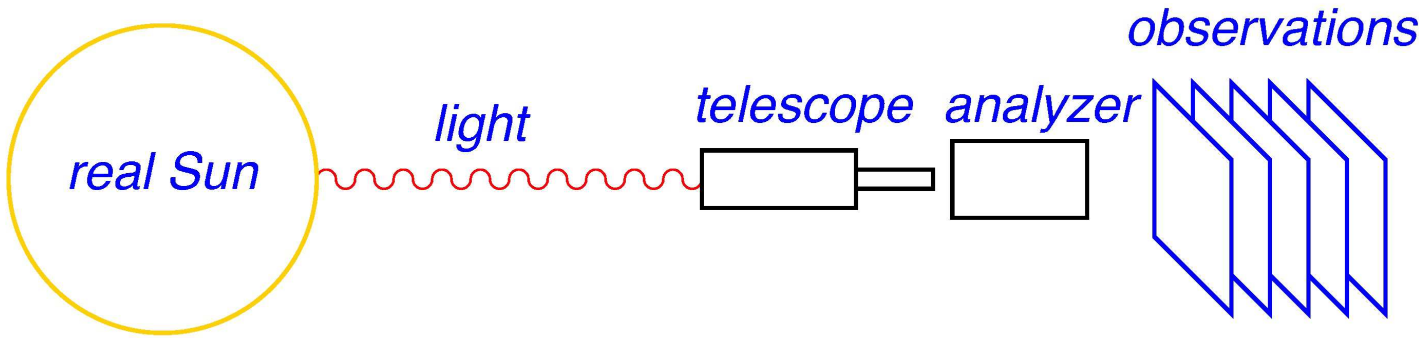
§ 1 Observations and simulations of the solar atmosphere

The solar atmosphere is in continuous turbulent motion. Light that reaches us from the Sun bears information on this dynamics and it's magnetic field. But this information is not easy to decipher. *Numerical simulations* help us to do this.



§ 1 Observations and simulations of the solar atmosphere

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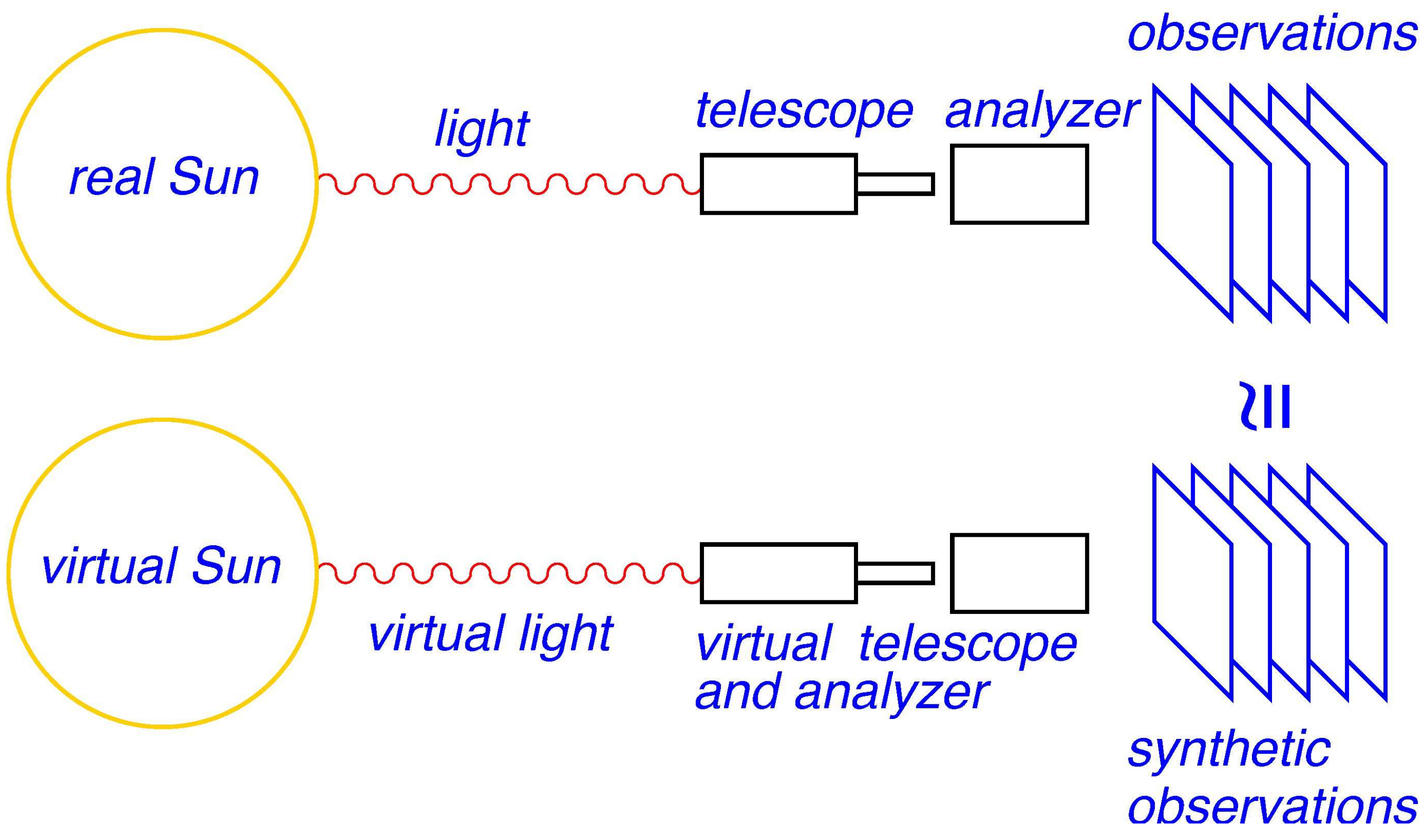
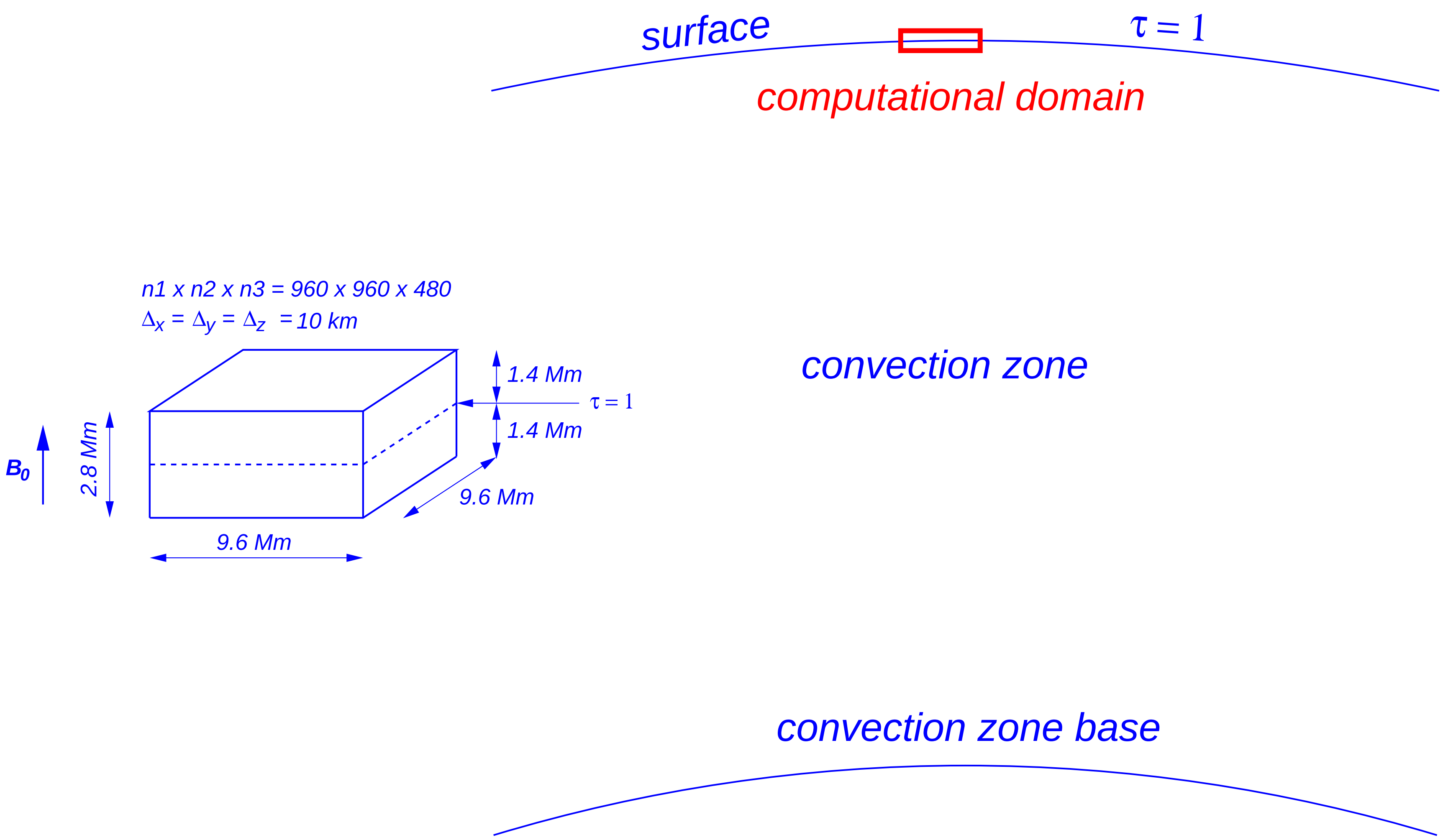
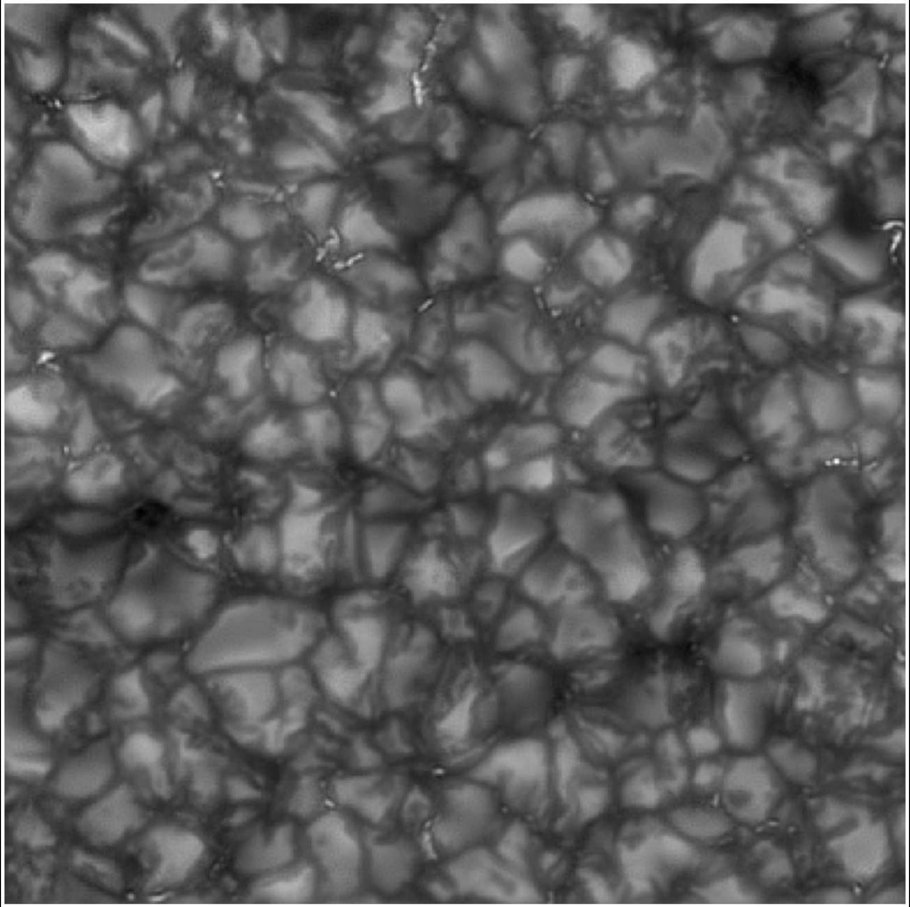


1. Observations and simulations of the solar atmosphere (cont.): nMBPs

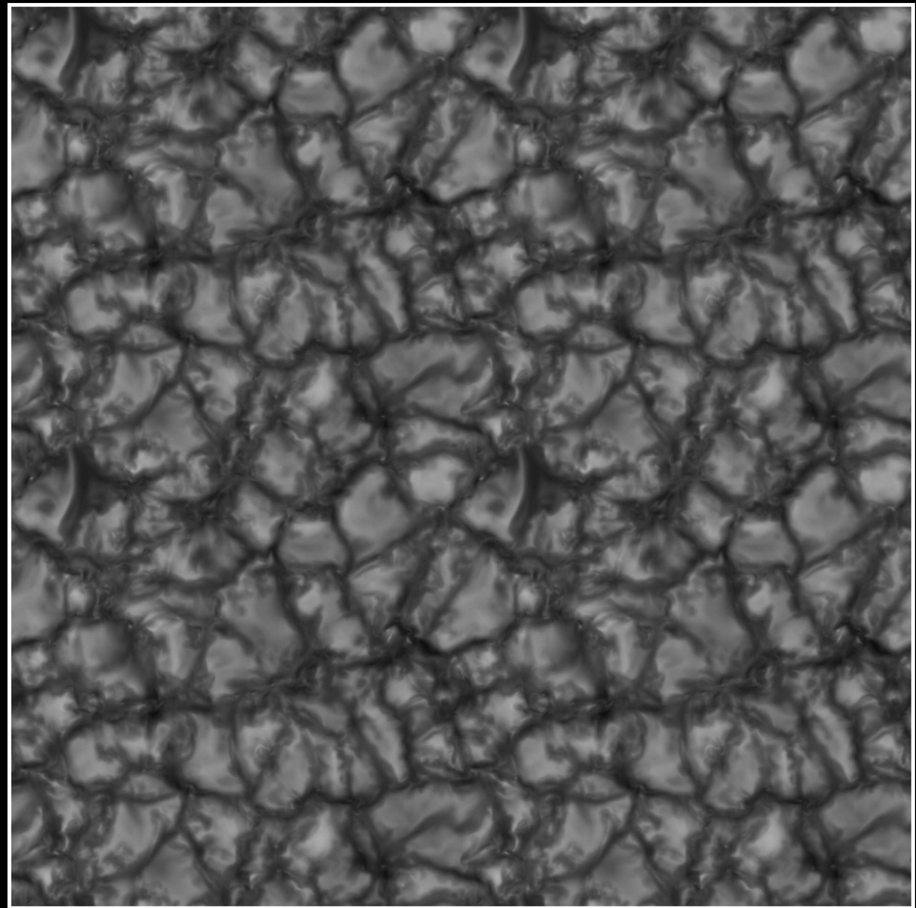


Size of a typical three-dimensional computational domain in comparison with the size of the Sun.

1. Observations and simulations of the solar atmosphere (cont.)

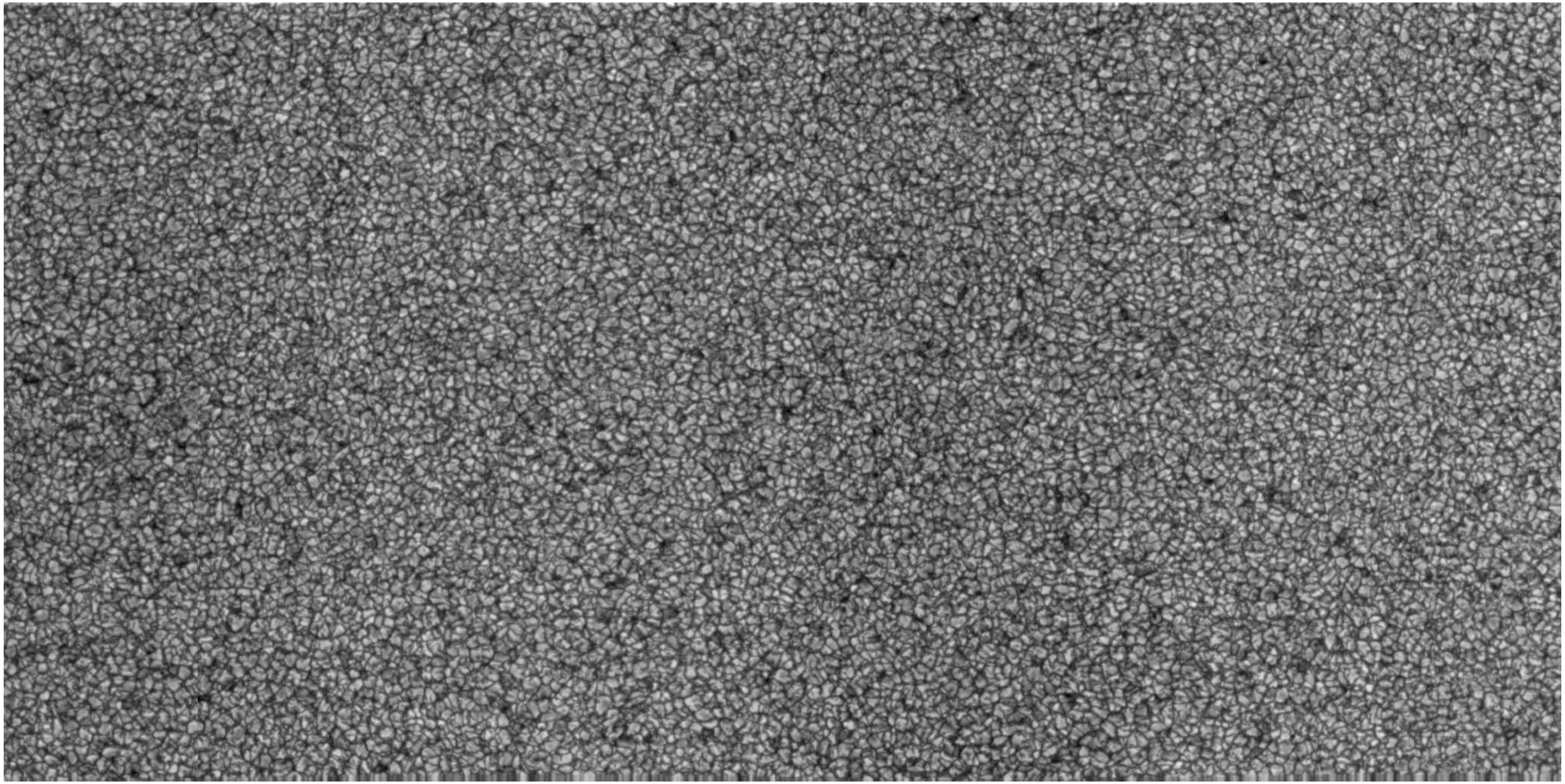


Observation of the solar surface



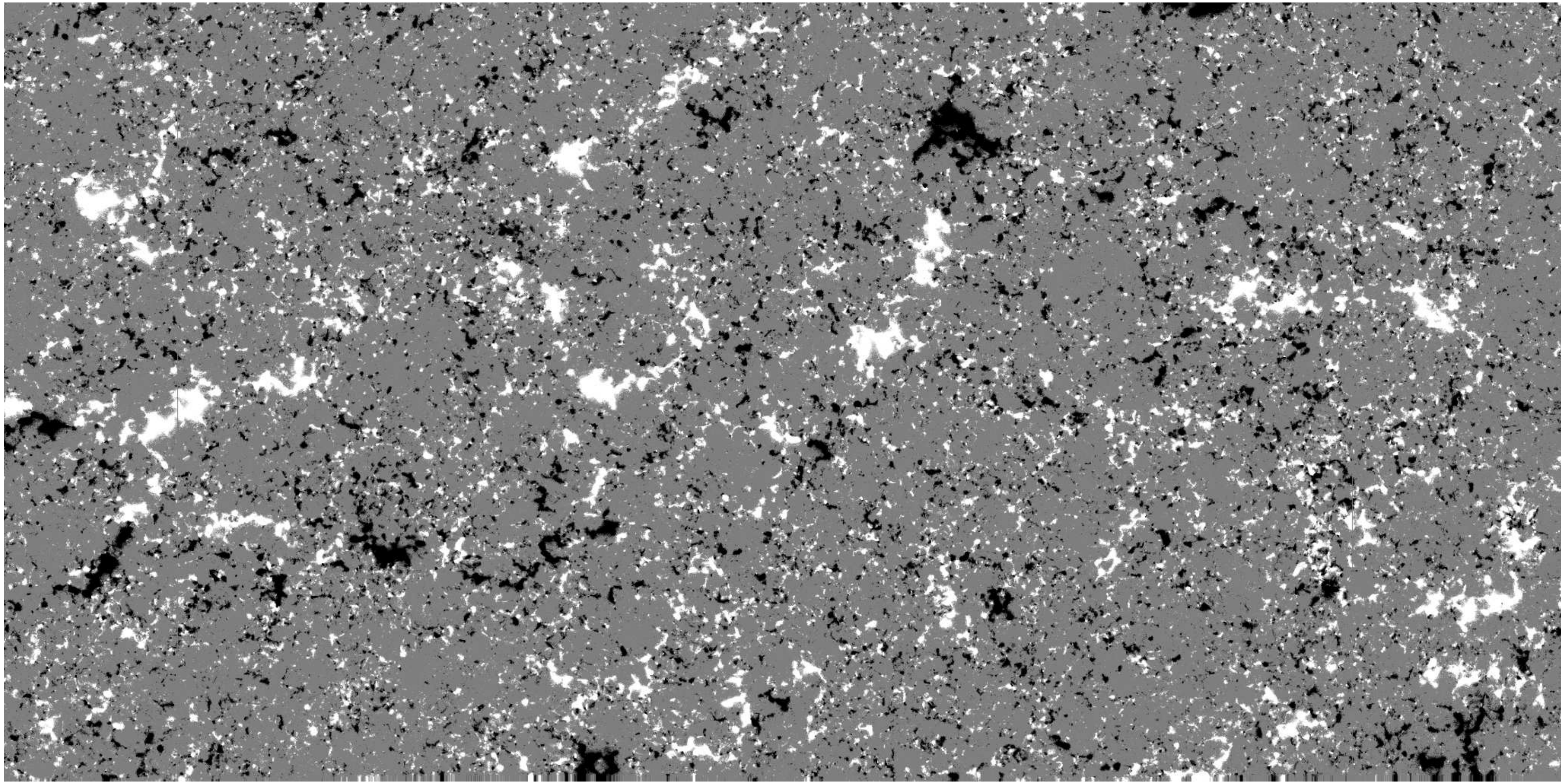
Numerical simulation

§ 2 Example 1: Interpretation of polarimetric signals



Continuum intensity at 630 nm over a field of view of $302'' \times 162''$ recorded with Hinode/SOT/SP. 2048 slit positions. From *Lites et. al. 2008, ApJ 672, 1237*

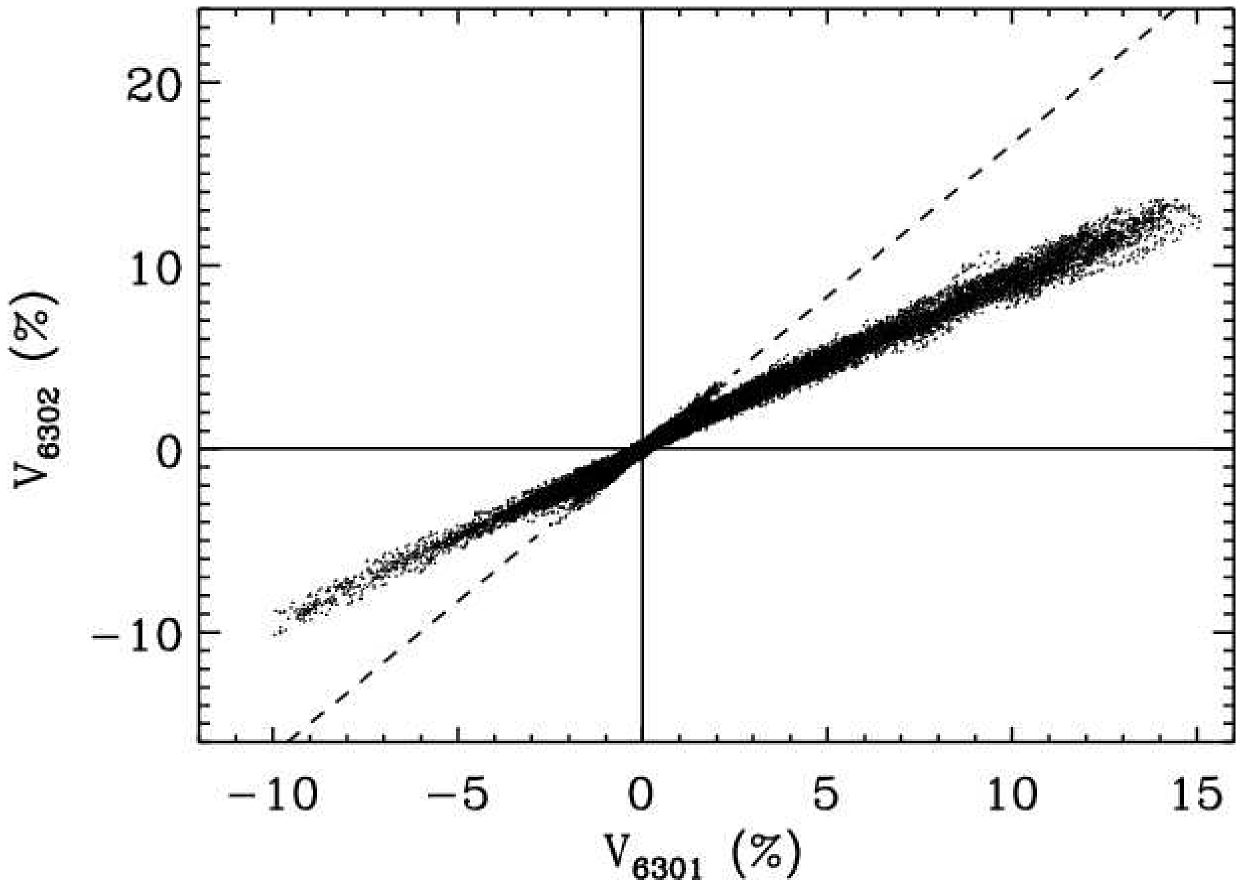
2. Example 1: Interpretation of polarimetric signals (cont.)



Apparent vertical magnetic flux density, $B^{\mathrm{L}}_{\mathrm{app}}$, of the quiet Sun over a field of view of $302'' \times 162''$. 2048 steps to 4.8 s. Maps of Fe I 630.15 and 630.25 nm.

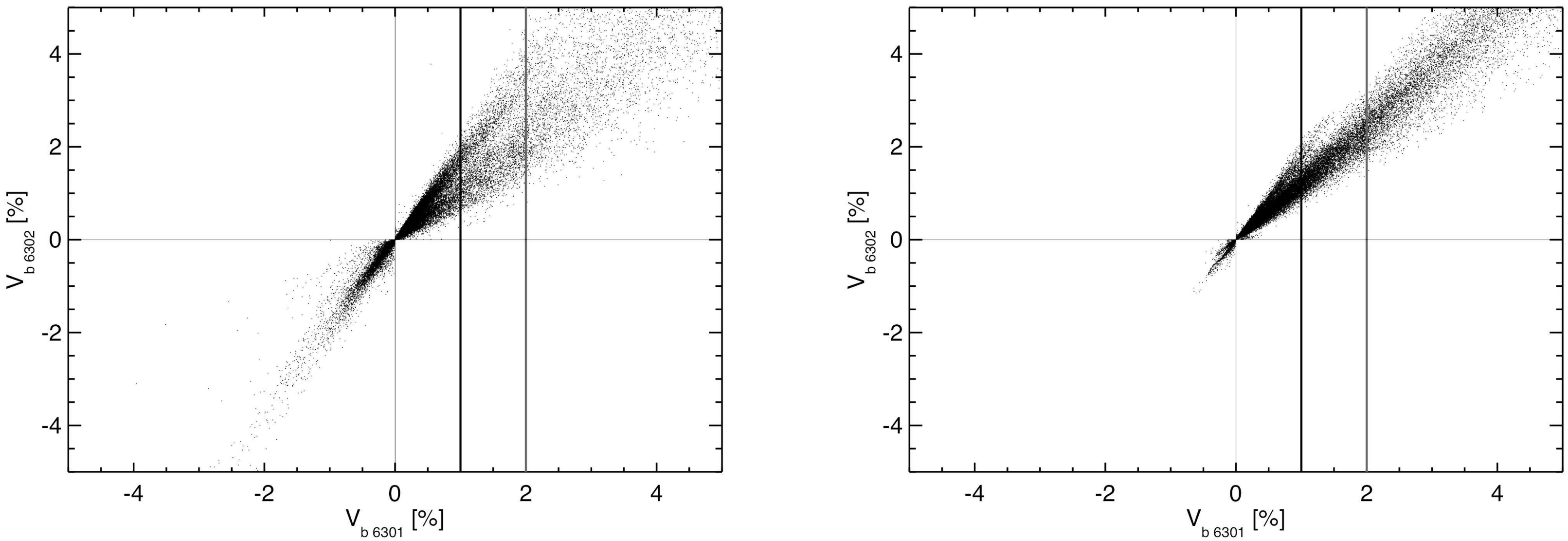
From *Lites et. al. 2008, ApJ 672, 1237*

2. Example 1: Interpretation of polarimetric signals (cont.): Stokes V line ratio

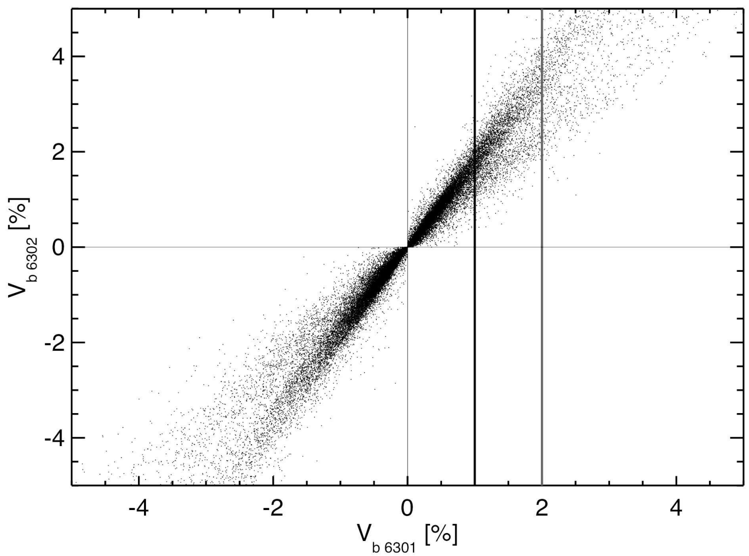


Scatter plot of the blue lobe Stokes-V amplitudes of the 6302.5 Å line vs. the 6301.5 Å line as *observed with Hinode/SOT/SP*. The dashed line is the regression relation expected for weak magnetic fields. We identify two populations of points. From *Stenflo (2011) A&A 529 A42*.

2. Example 1: Interpretation of polarimetric signals (cont.): simulation data



Scatter plot of the Stokes-V line ratio from the simulation. *Left:* full resolution; *Right:* degraded with the SOT/SP point spread function. From *Steiner & Rezaei (2012)*.

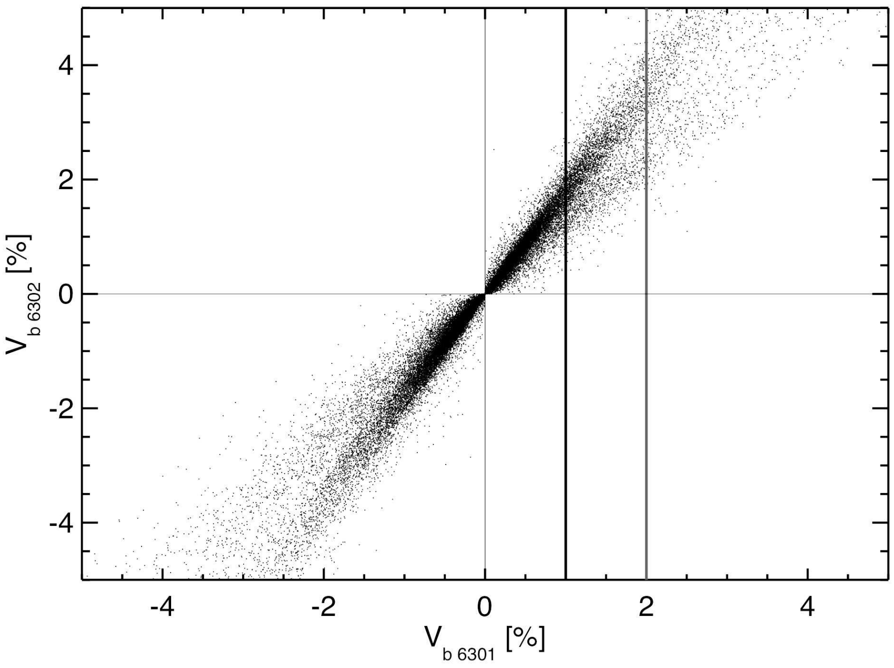


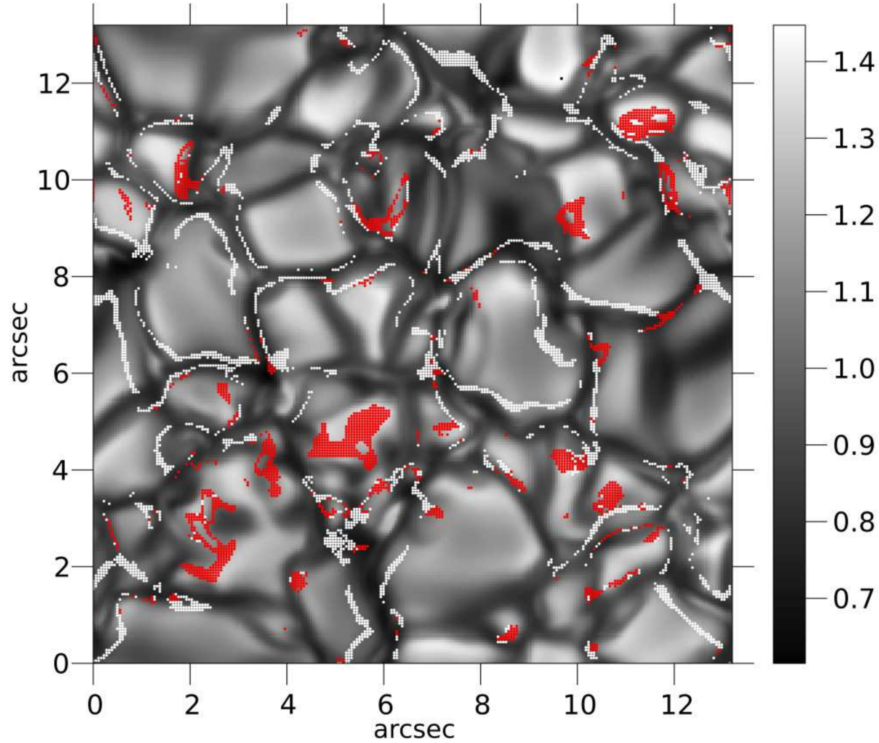
Scatter plot of the Stokes-V line ratio from a mixed polarity simulation.

"It is nice to know that the computer understands the problem, but I would like to understand it too."

Attributed to E.P. Wigner

2. Example 1: Interpretation of polarimetric signals (cont.)





From *Steiner & Rezaei (2012)*

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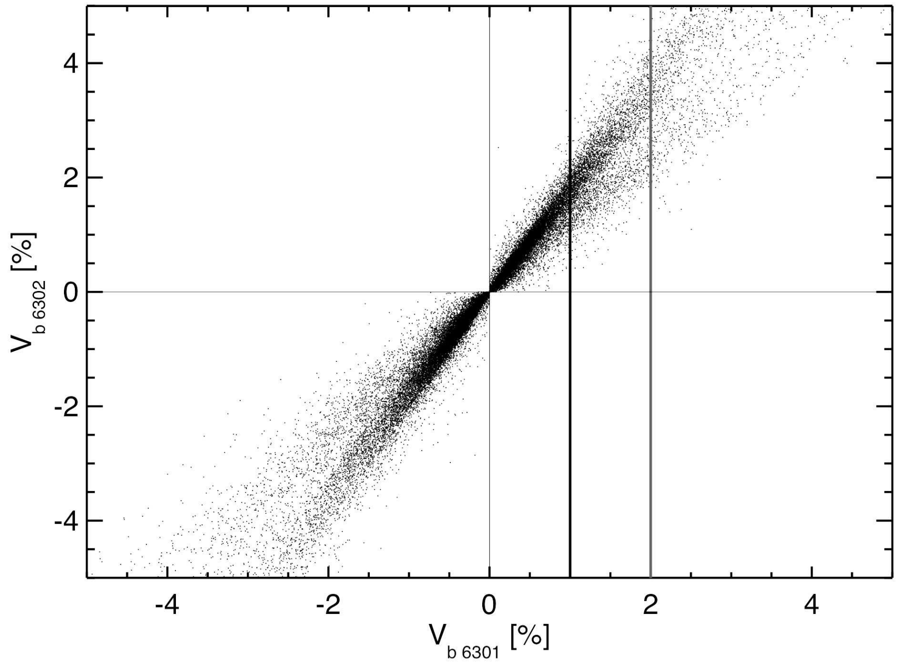
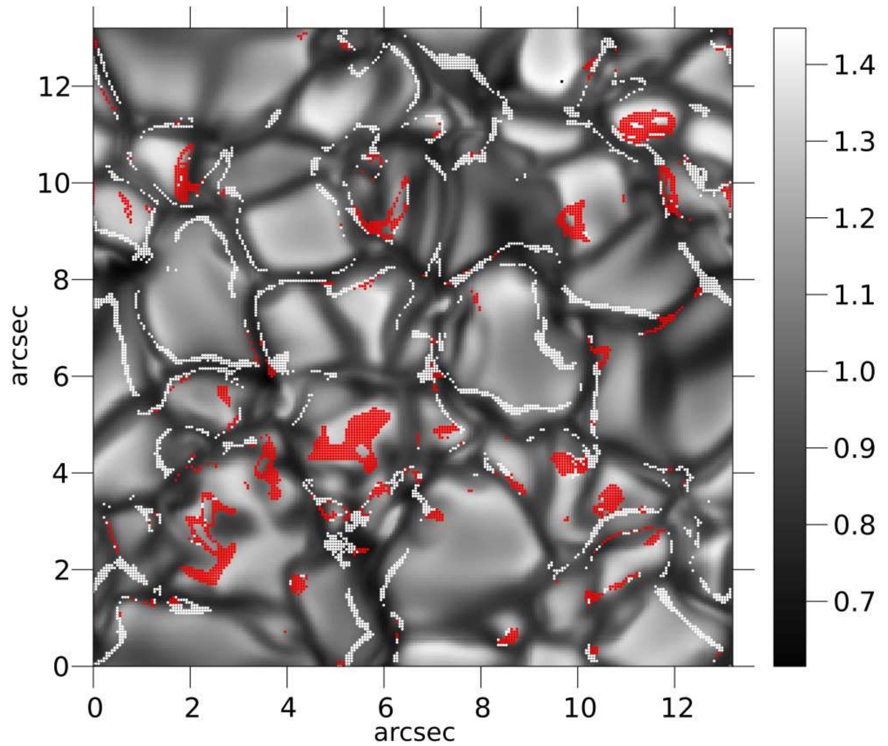




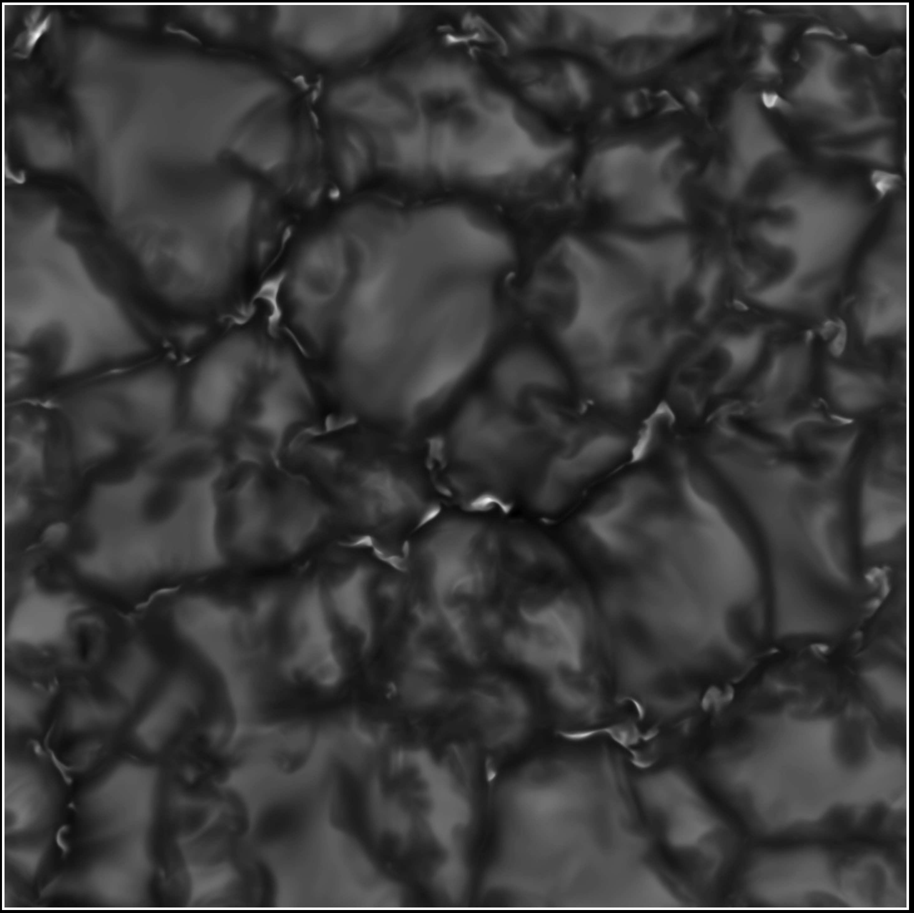
From *Steiner & Rezaei (2012)*

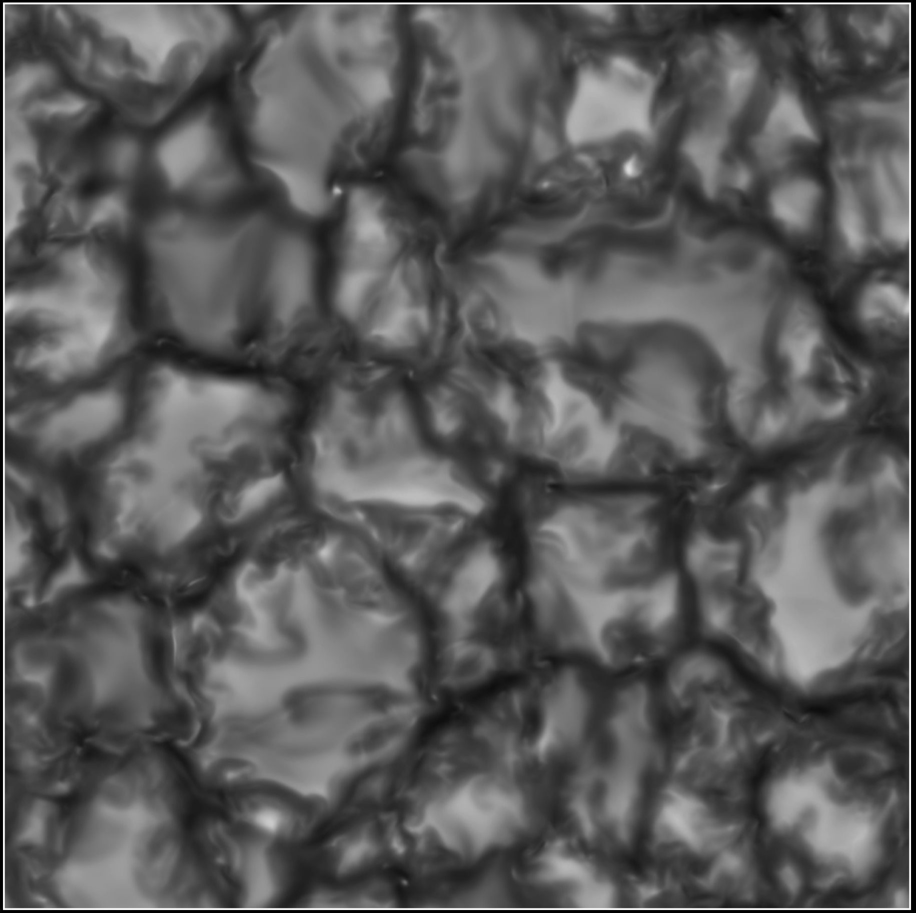
Conclusion: The two populations can be explained in terms of weak (hectogauss) magnetic fields. *Numerical simulations are indispensable for the correct interpretation.*

Maurizio Nannucci, Neon installation in the court of the Museo Novecento, Florence

§ 2 Example 2: The ‘discovery’ of non-magnetic bright points

Bolometric intensity maps





Computations: *Centro Svizzero di Calcolo Scientifico*

With magnetic fields:
Magnetohydrodynamic simulation.

Without magnetic fields:
Hydrodynamic simulation

Courtesy,
F. Calvo.

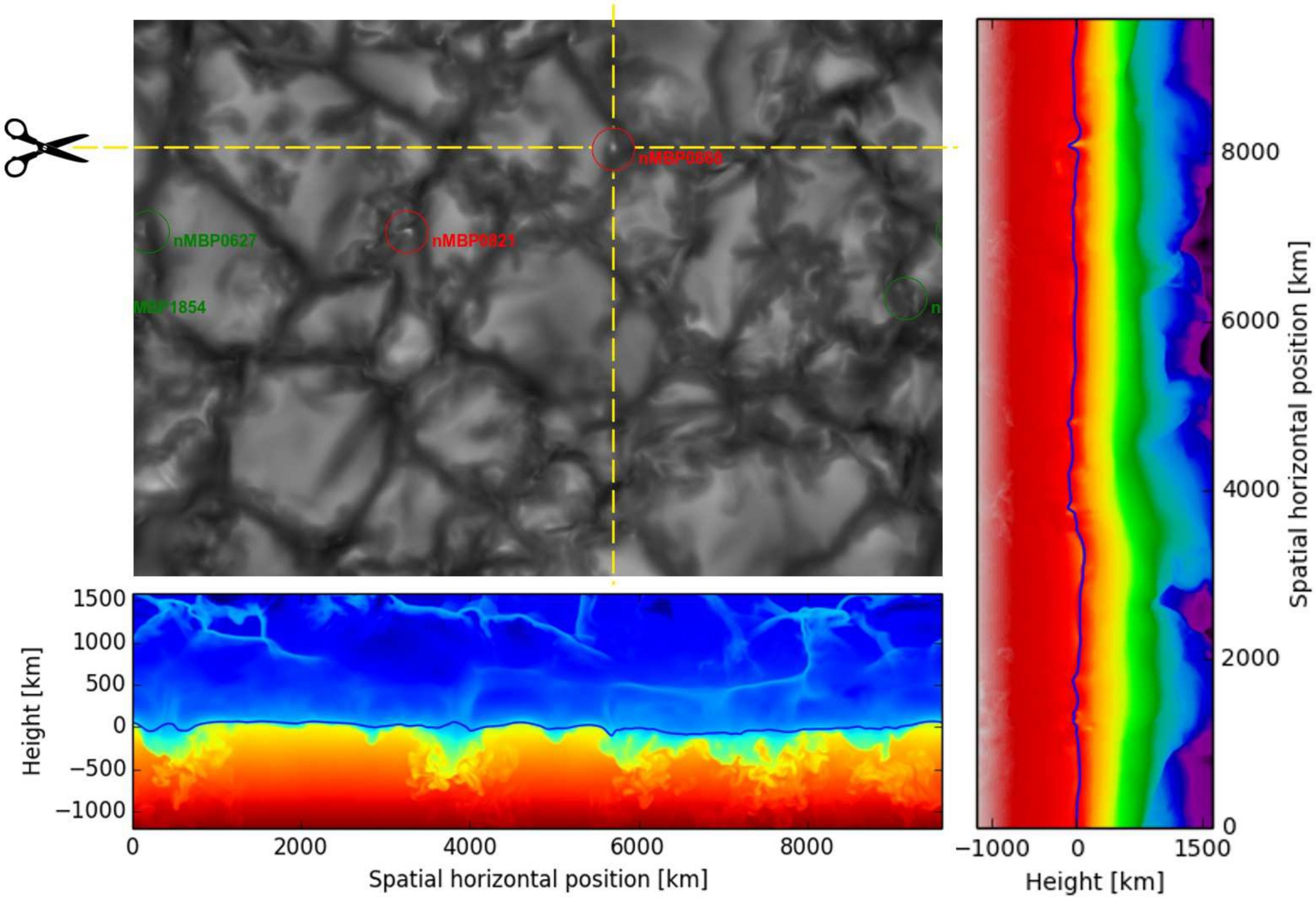
Piz Daint/Piz Dora at CSCS in Lugano

Piz Dora is a Cray XC40 with 30 144 cores (24 cores per node, 1256 nodes).

1192 nodes have 64 GB RAM each, the remaining 64 nodes have 128 GB RAM.

2. Example 2: The ‘discovery’ of non-magnetic bright points (cont.)

Slices across a non-magnetic bright point (nMBP0868)



Courtesy, *F. Calvo, IRSOL.*

Emergent intensity I (*top left*), temperature T (*bottom*), density $\log(\rho)$ (*right*)

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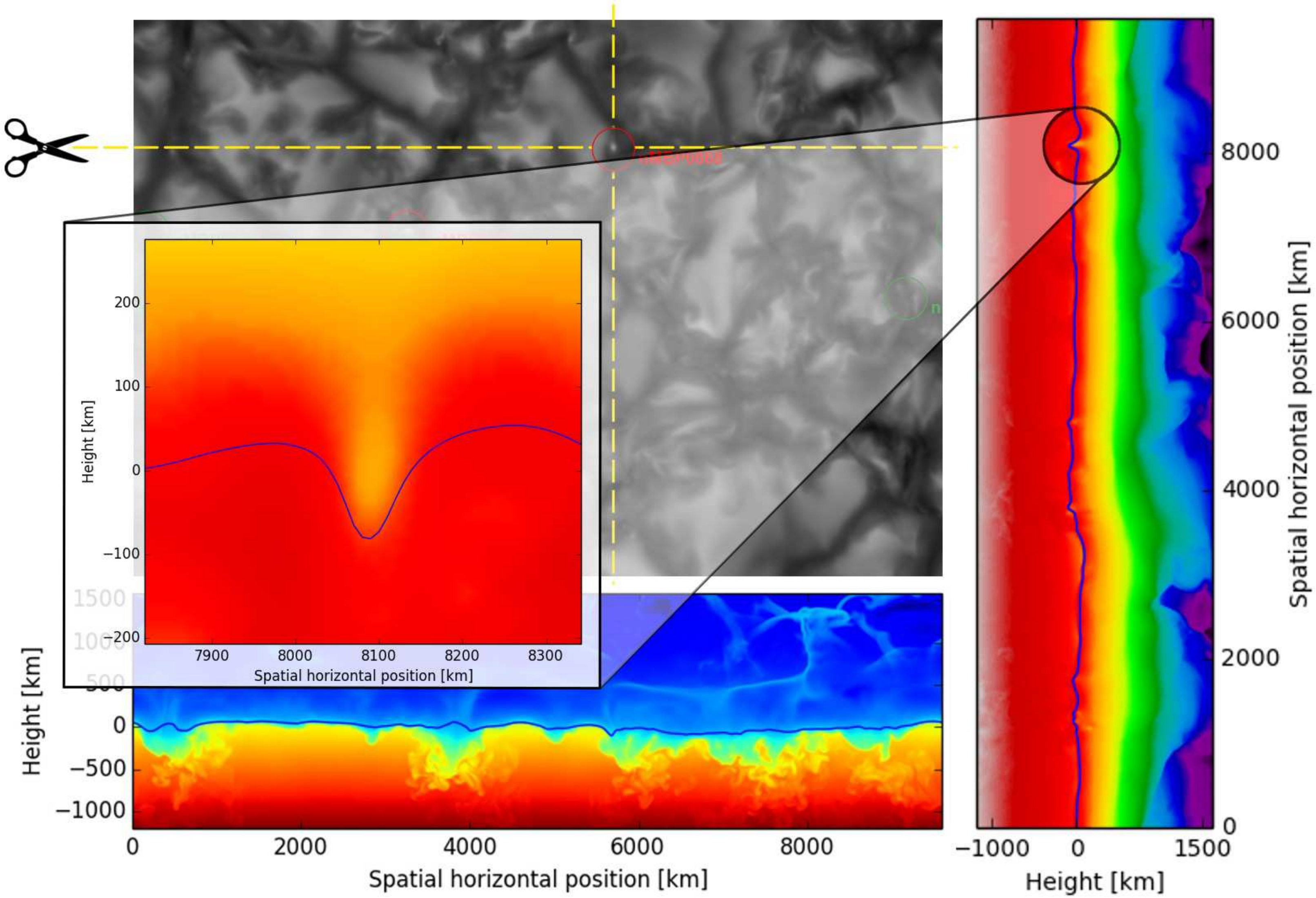

Courtesy, *F. Calvo, IRSOL.*

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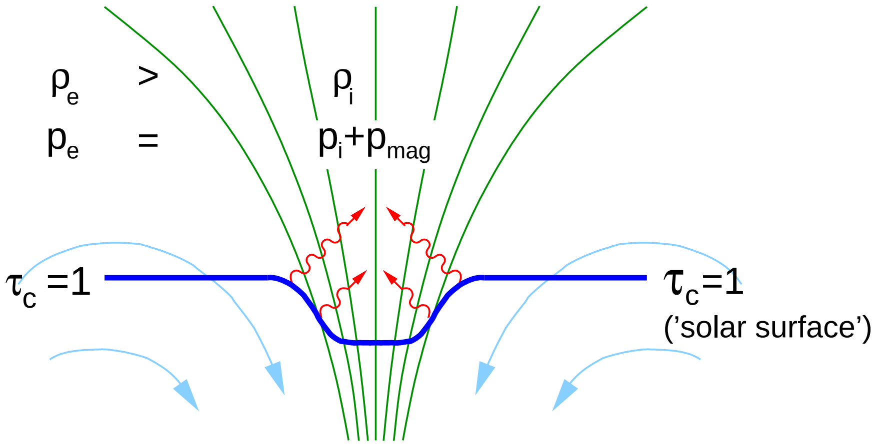
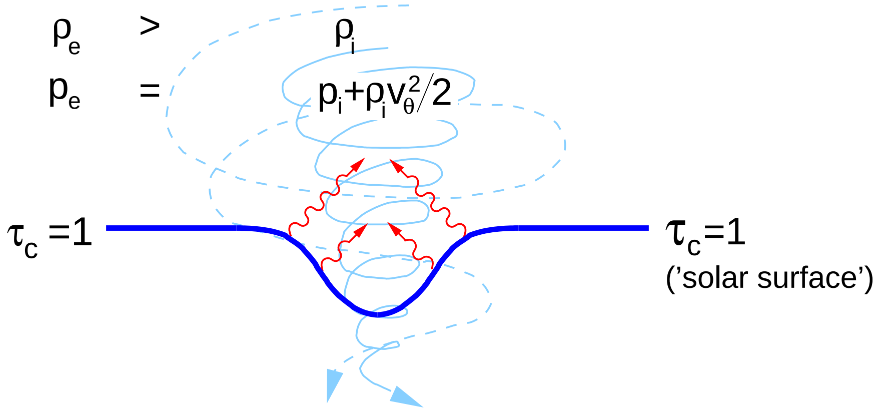
2. Example 2: The ‘discovery’ of non-magnetic bright points (cont.)



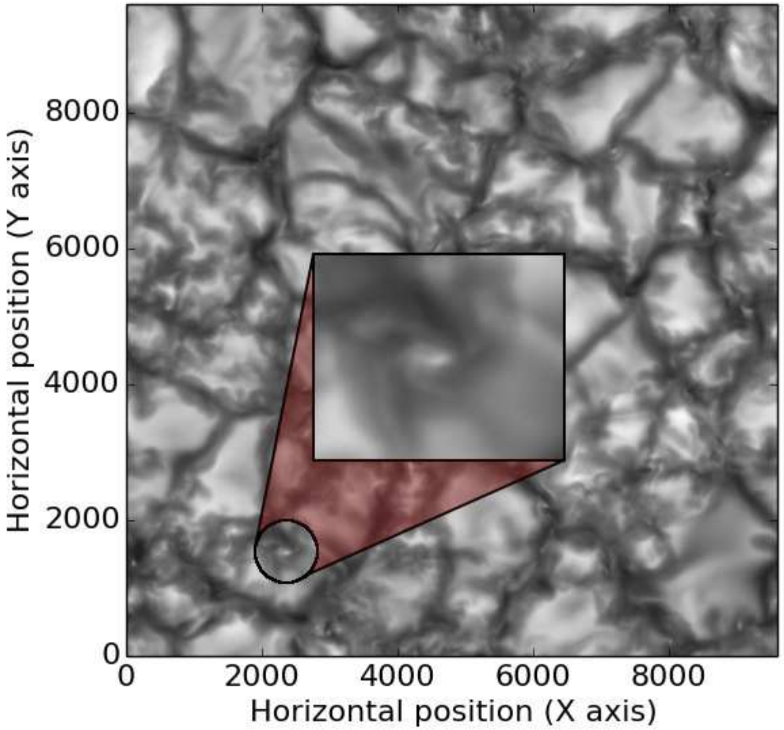


Magnetic flux sheet. Depression due to magnetic pressure.

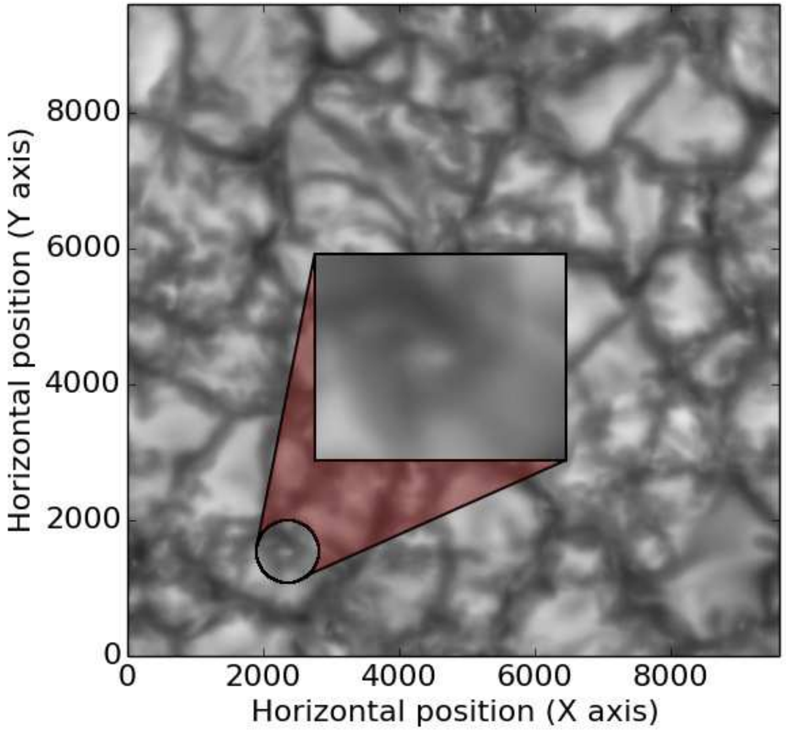
Swirl. Depression due to centrifugal force.

In both cases is the ‘hot wall effect’ responsible for the enhanced radiation from the depression.

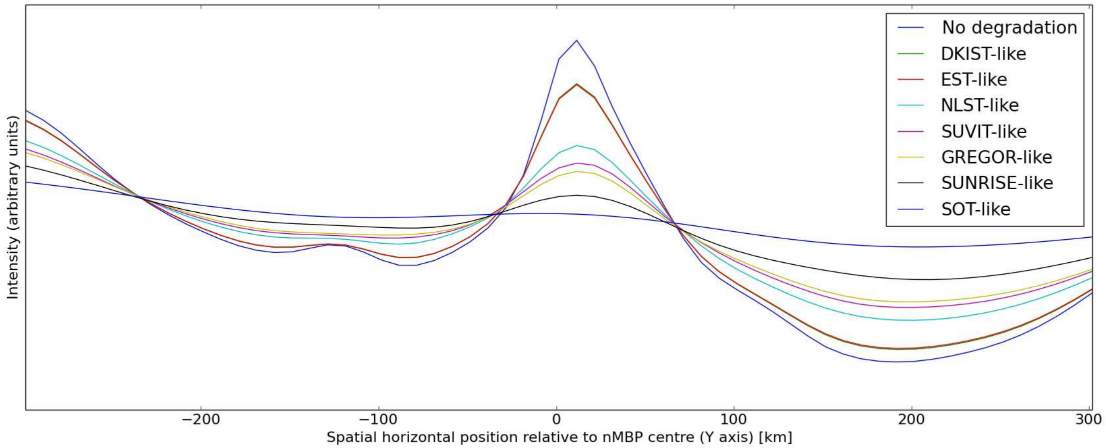
2. Example 2: The ‘discovery’ of non-magnetic bright points (cont.)



full resolution



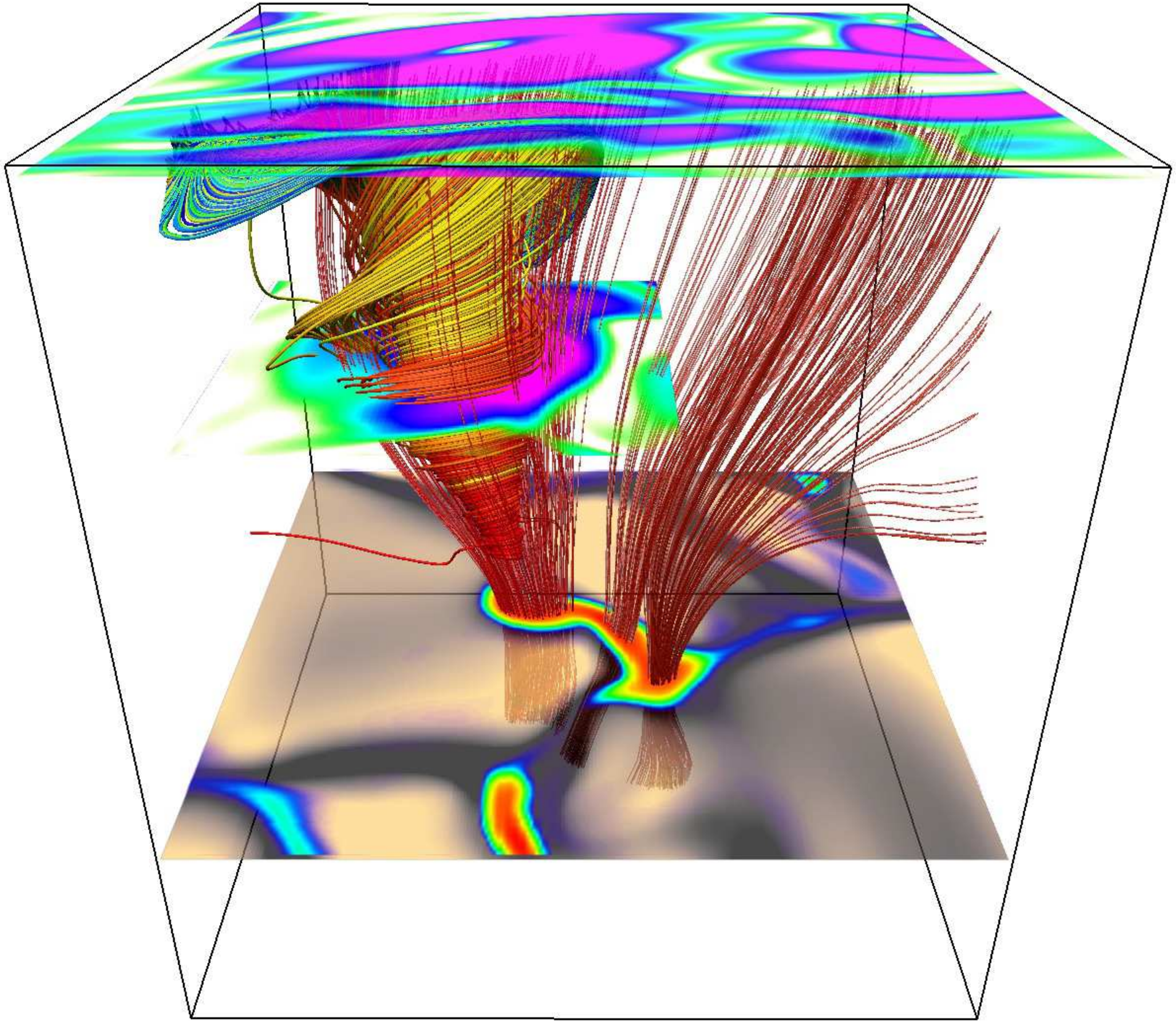
Gregor resolution



Intensity contrast across a non-magnetig bright point as observed with different telescopes.

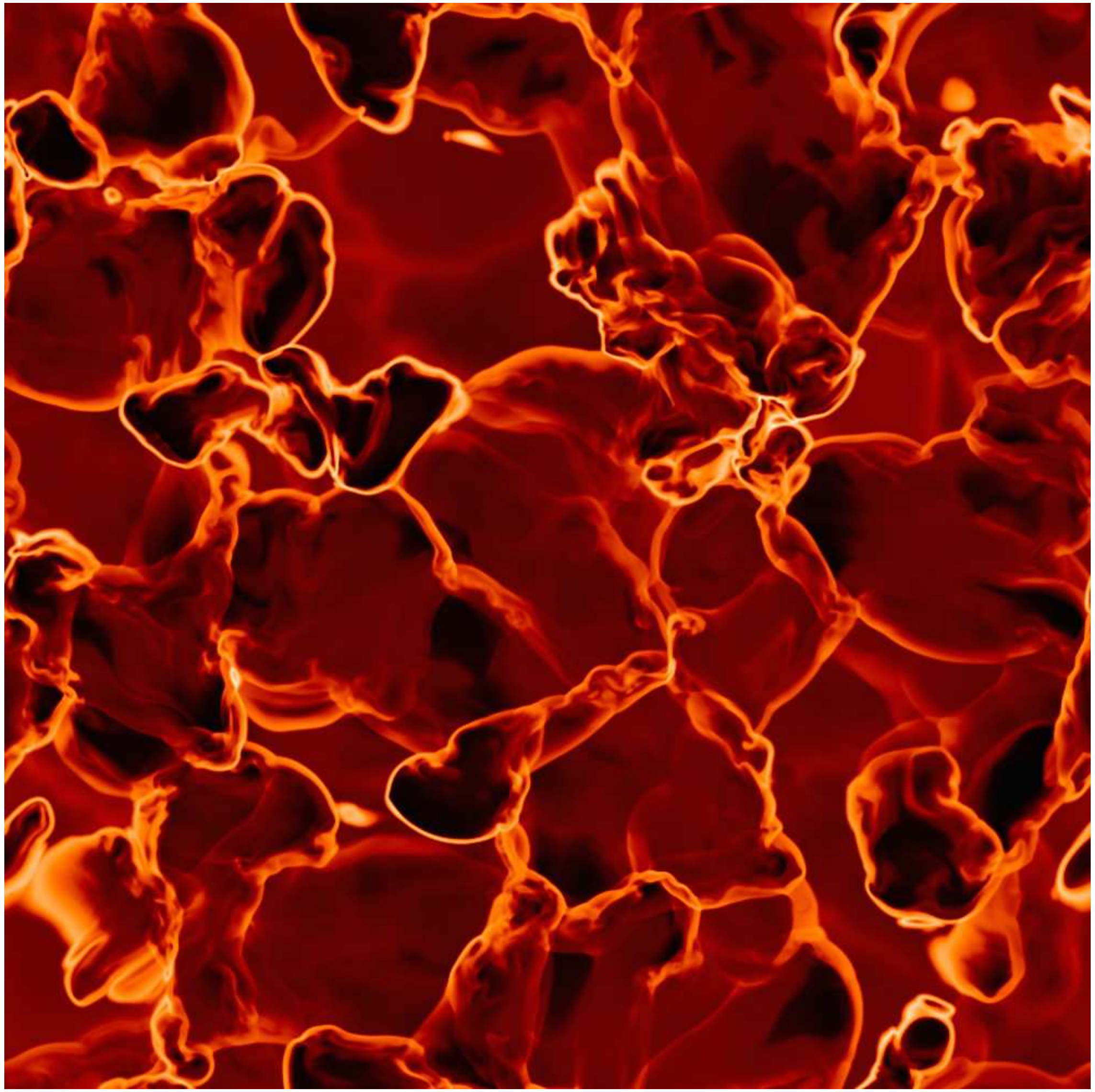
From *Calvo et al. (2016)*.

Example 2: The 'discovery' of non-magnetic bright points (cont.)



Close-up of a swirl event. The plasma flows along and co-rotates with the magnetic field (spiral streamlines). From *www.solartornado.info*.

§ 3 Polarized radiative transfer in discontinuous media



Horizontal cross-section through the chromosphere of a simulation. Colors show temperature. *Shock fronts and temperature spikes* are ubiquitous.

In a *PhD-project at IRSOL*, we test new ideas on numerical methods for polarized radiative transfer in discontinuous media (PhD-project of *Gioele Janett*).

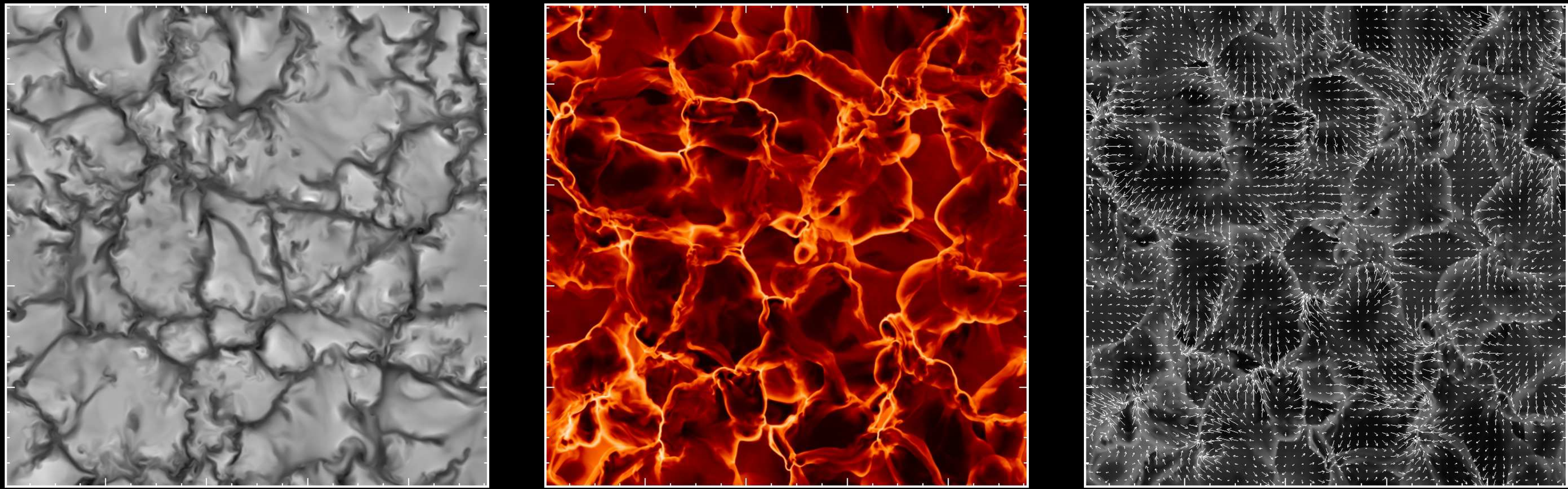
§ 4 Future directions

At IRSOL, we have now created a *series of 'high resolution' solar models* (grid size 10 km) with and without magnetic field and various initial magnetic field configurations.

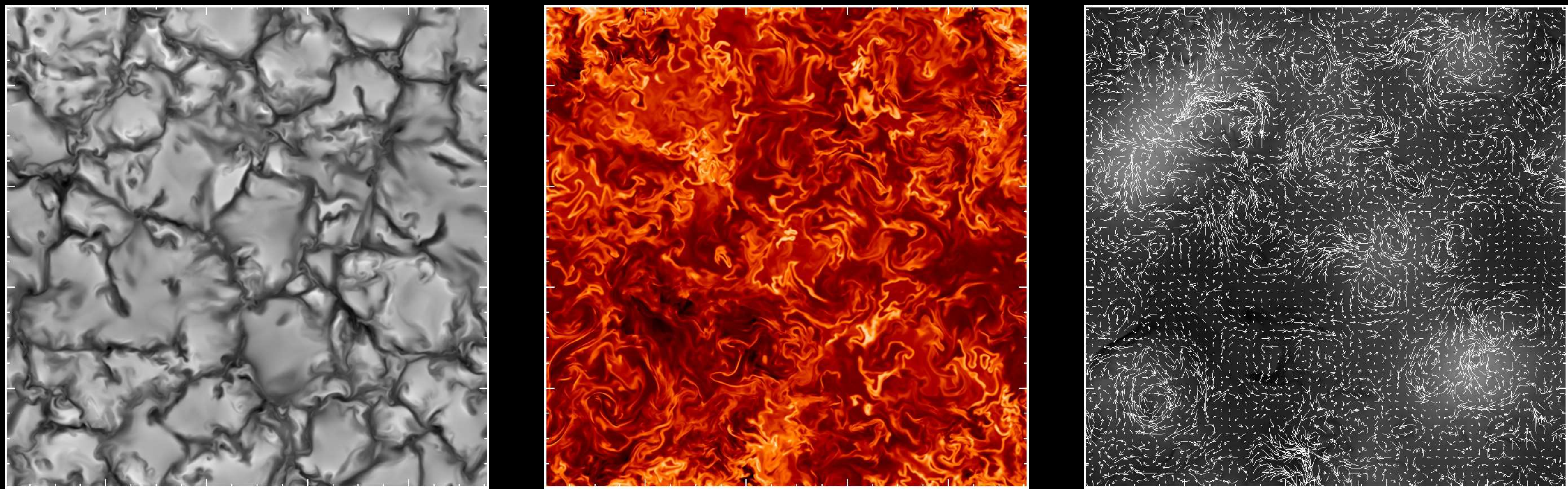
model name	solver	initial magnetic field configuration	t [h]
d3t57g45b0roefc	Roe	no magnetic field	2.0
d3t57g45b0fc	HLLMHD	no magnetic field	2.0
d3t57g45v50fc	HLLMHD	vertical, homogeneous, 50 G	2.0
d3t57g45v200fc	HLLMHD	vertical, homogeneous, 200 G	2.0
d3t57g45v50fc	HLLMHD	horizontally inflowing, 50 G	2.0
d3t57g45p200fc	HLLMHD	potential filed configuration	2.0

We can use these models for various other analyzes, e.g., on the *structure of the magnetic and velocity field in the chromosphere*.

Solar model, magnetic field-free, 9.6 x 9.6 Mm



Solar model, initial homogeneous vertical 50 G magnetic field, 9.6 x 9.6 Mm



v_z at $\langle\tau\rangle = 1 = z = 0$ T (z=1200 km) $v_{\rm hor}$ (z=1200 km)

The critical review of existing numerical methods for the integration of the radiative transfer equation for polarized light has led to interesting insights and to possibly faster and more accurate methods. We further explore the development of a *robust, fast, and accurate method for discontinuous media*. This work has already lead to the improvement of the existing RH-code. It could further lead to an new kind of *inversion code* for the recovery of highly structured atmospheres or for a robust and fast *RT module for the simulation code*. Also applications to *lines formed under NLTE* are foreseen.

Table of content

References

Calvo, F., Steiner, O., & Freytag, B.: 2016, *Non-magnetic photospheric bright points in 3D simulations of the solar atmosphere*, A&A, in press

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Steiner, O. & Rezaei, R.: 2012, *Recent Advances in the Exploration of the Small-Scale Structure of the Quiet Solar Atmosphere: Vortex Flows, the Horizontal Magnetic Field, and the Stokes-V Line-Ratio Method*, in L. Golub, I. De Moortel, and T. Shimizu (eds.), Hinode 5: Exploring the Active Sun, ASP Conf. Ser. 456, p. 3-32.

Stenflo, J.O.: 2011, *Collapsed, uncollapsed, and hidden magnetic flux on the quiet Sun*, A&A 529, A42