Simulations of magnetohydrodynamics and CO formation from the convection zone to the chromosphere

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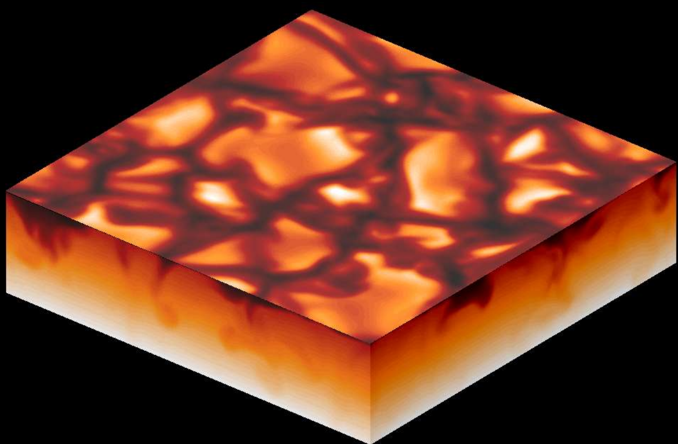
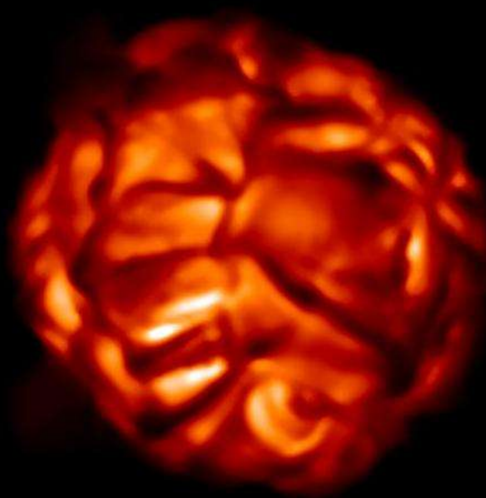
KIS

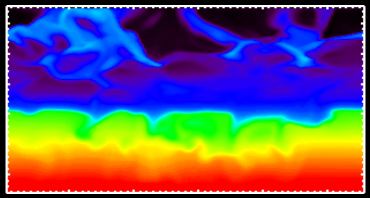
Radiation magnetohydrodynamics code



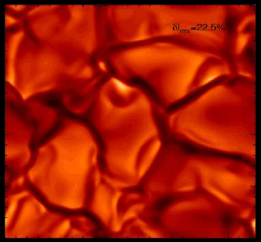
CO⁵BOLD



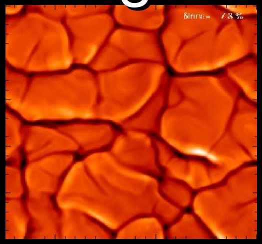
Sun



A-star



red giant

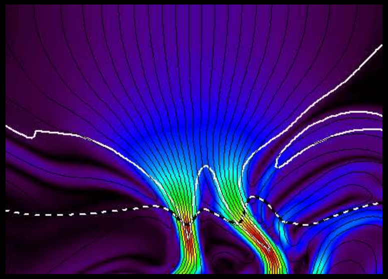


supergiant

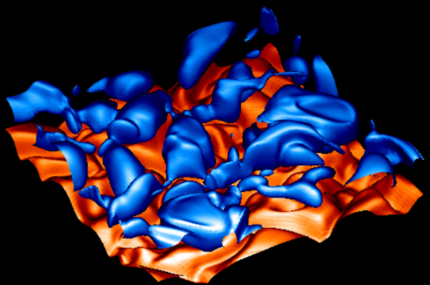
whole star

in a box

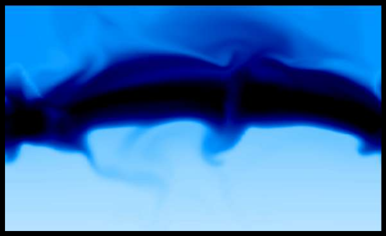
MHD



CHEM



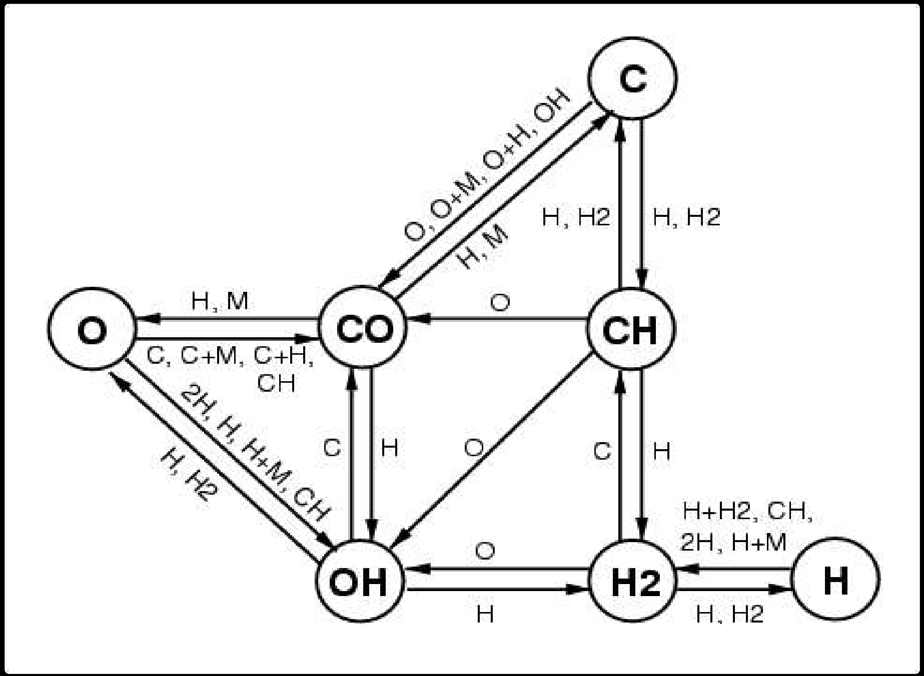
HION



DUST

Chemistry

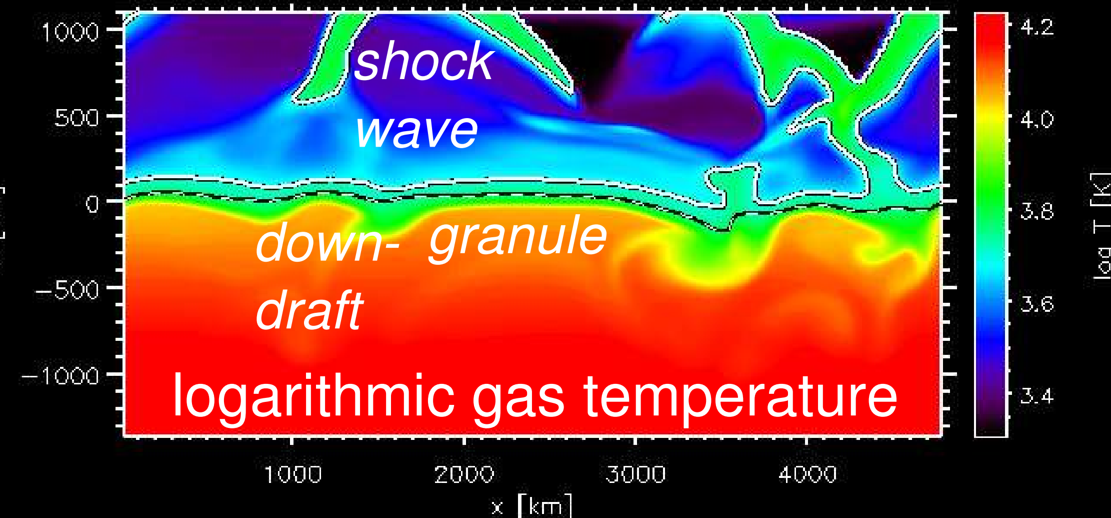
- detailed time-dependent chemistry as part of 2D/3D radiation hydrodynamic simulations using **CO⁵BOLD** (Freytag et al. 2002)
- changes due to advection with flow field and chemical reactions
- chemical reaction network:
  - 7 chemical species H, H_2, C, O, CO, CH, OH plus representative metal M (≥He)
  - 27 chemical reactions

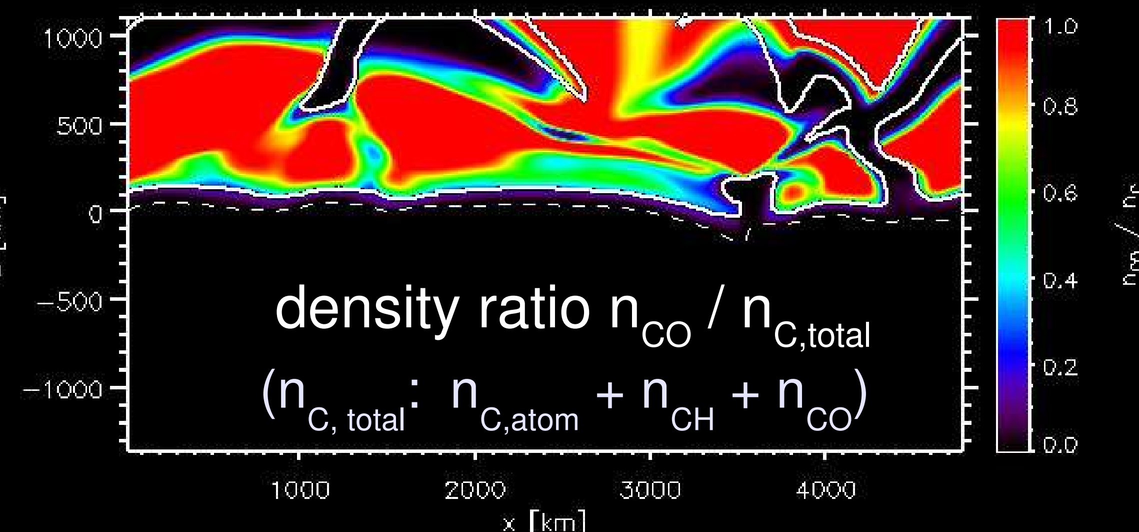


2D model for carbon monoxide

- vertical extent: upper convection zone to middle chromosphere (-1360 to 1140 km, z=0 km $\triangleq$ τ = 1)
- horizontal extent: 4800 km
- duration: ~ 1 day

- CO found above low photosphere
  - large fraction of C atoms is bound in CO
- exception: hot chromospheric shock waves:
  - gradual dissociation of CO at the fronts (due to finite dissoc. time-scales)
  - no CO in shocks
  - gradual formation in post-shock regions

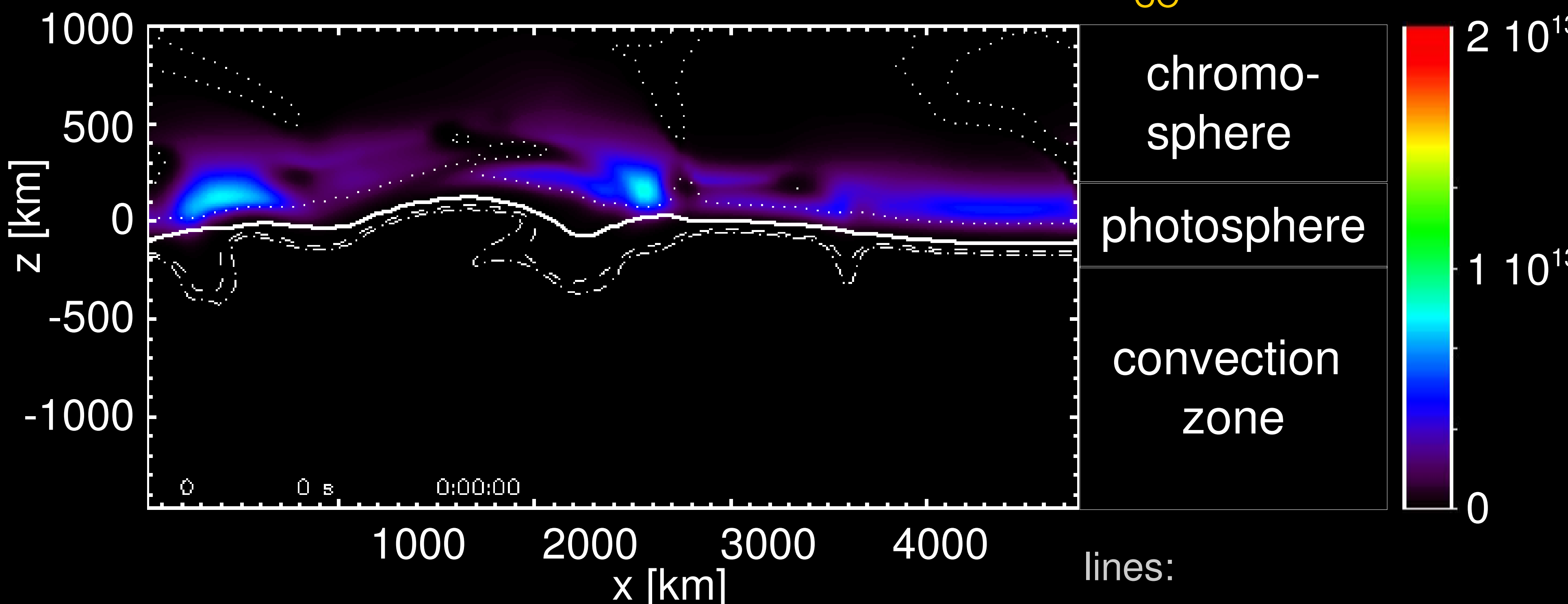




(solid: T = 5000 K, dashed: optical depth unity)

CO distribution in 2D model

vertical cross-section: absolute CO number n_{CO}



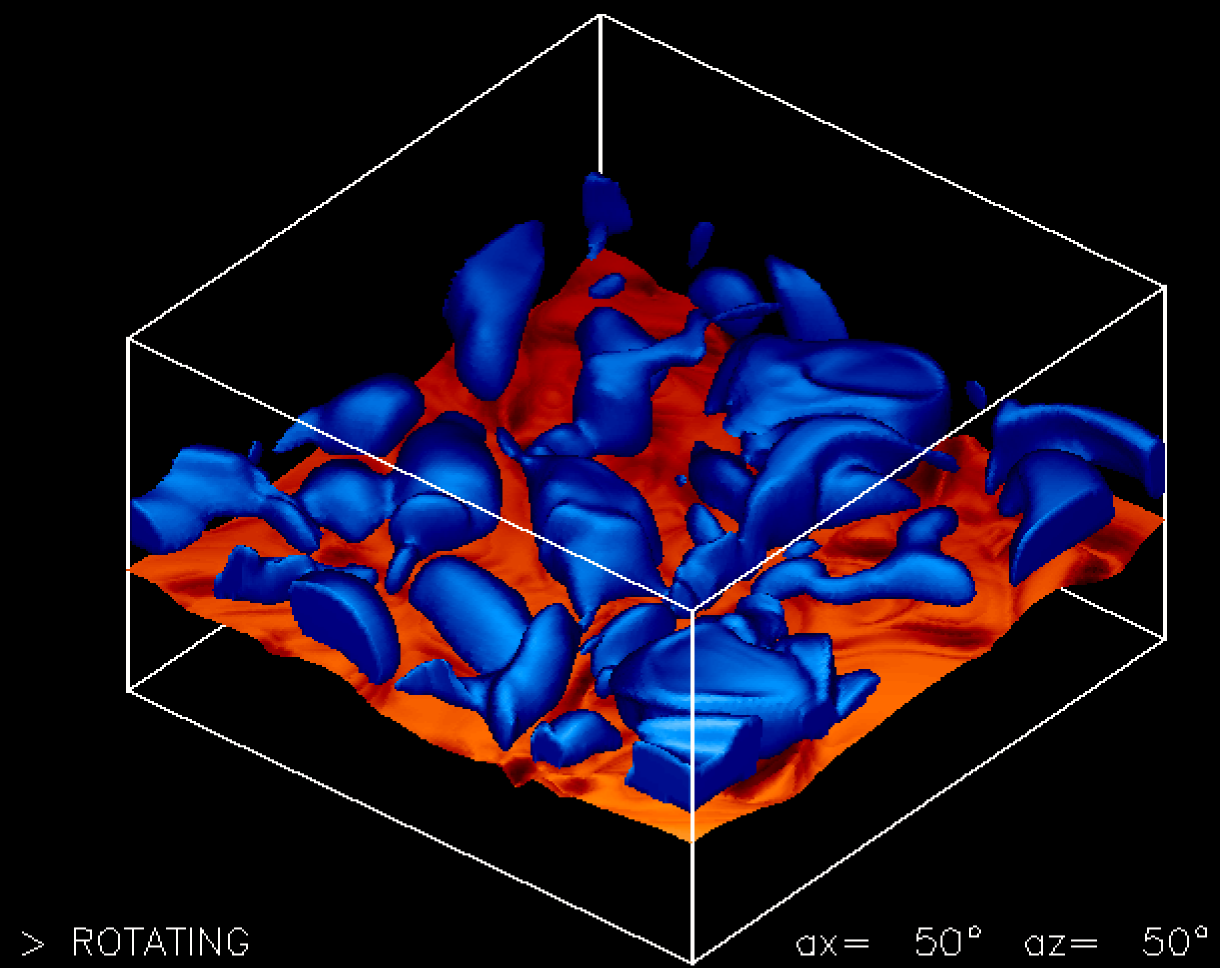
lines:
optical depth unity (solid)
iso-thermals for
5000 K (dotted),
8000 K (dashed),
10 000 K (dot-dashed)

CO mostly located in the cool regions in the middle photosphere (mapping reversed granulation)!

- peak at z=150 km
- qualitatively similar to former works (Uitenbroek 2000, Asensio Ramos et al. 2003)

3D CO model

CO “clouds” above granule interiors

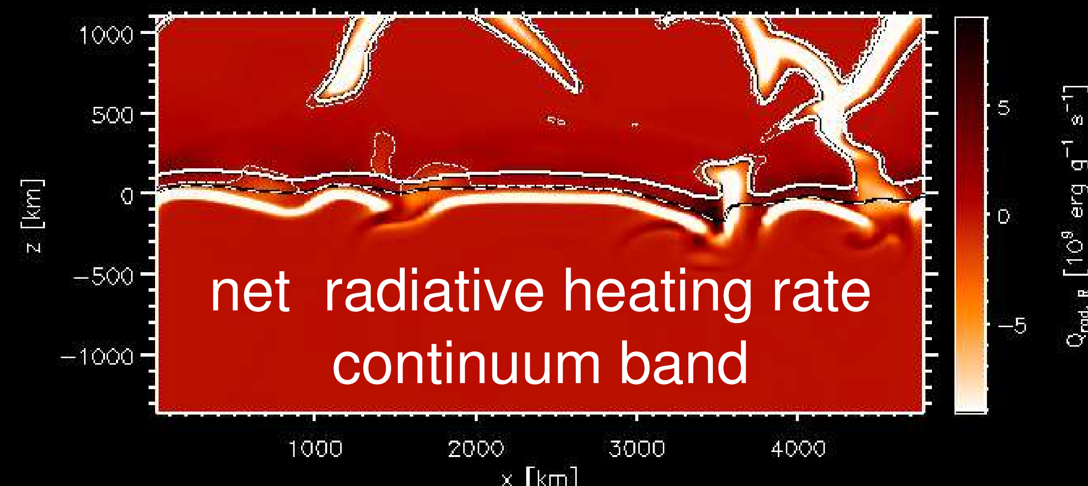


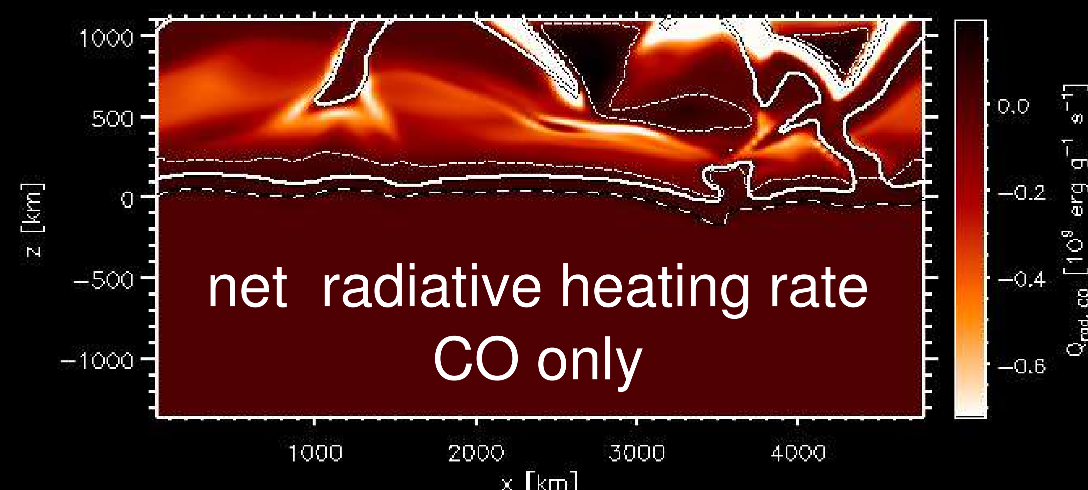
red: iso-surface optical depth $\tau = 1$

blue: iso-surface CO number density $n_{CO} = 4\ 10^{12}\ cm^{-3}$

Radiative cooling via CO lines

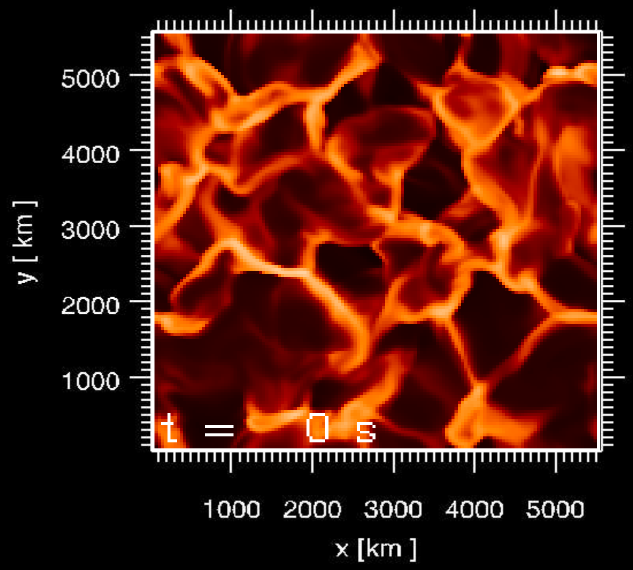
- two opacity bands: (adapted routines by Steffen & Muchmore (1988))
  1) continuum band with Rosseland mean opacity κ_R (IR excluded)
  2) infrared (IR) band at 4.7 μm with Rosseland mean opacity and additional CO line opacity $\kappa_R + \kappa_{CO}$
- solution of radiative transfer eq.
- → net radiative heating rate Q_{rad}
- → enters the energy equation
  - $Q_{rad} > 0$: absorption
  - → radiative heating (black)
  - $Q_{rad} < 0$: emission
  - → radiative cooling (white)
- Additional cooling at shock fronts but continuum band contributes much more than CO band!





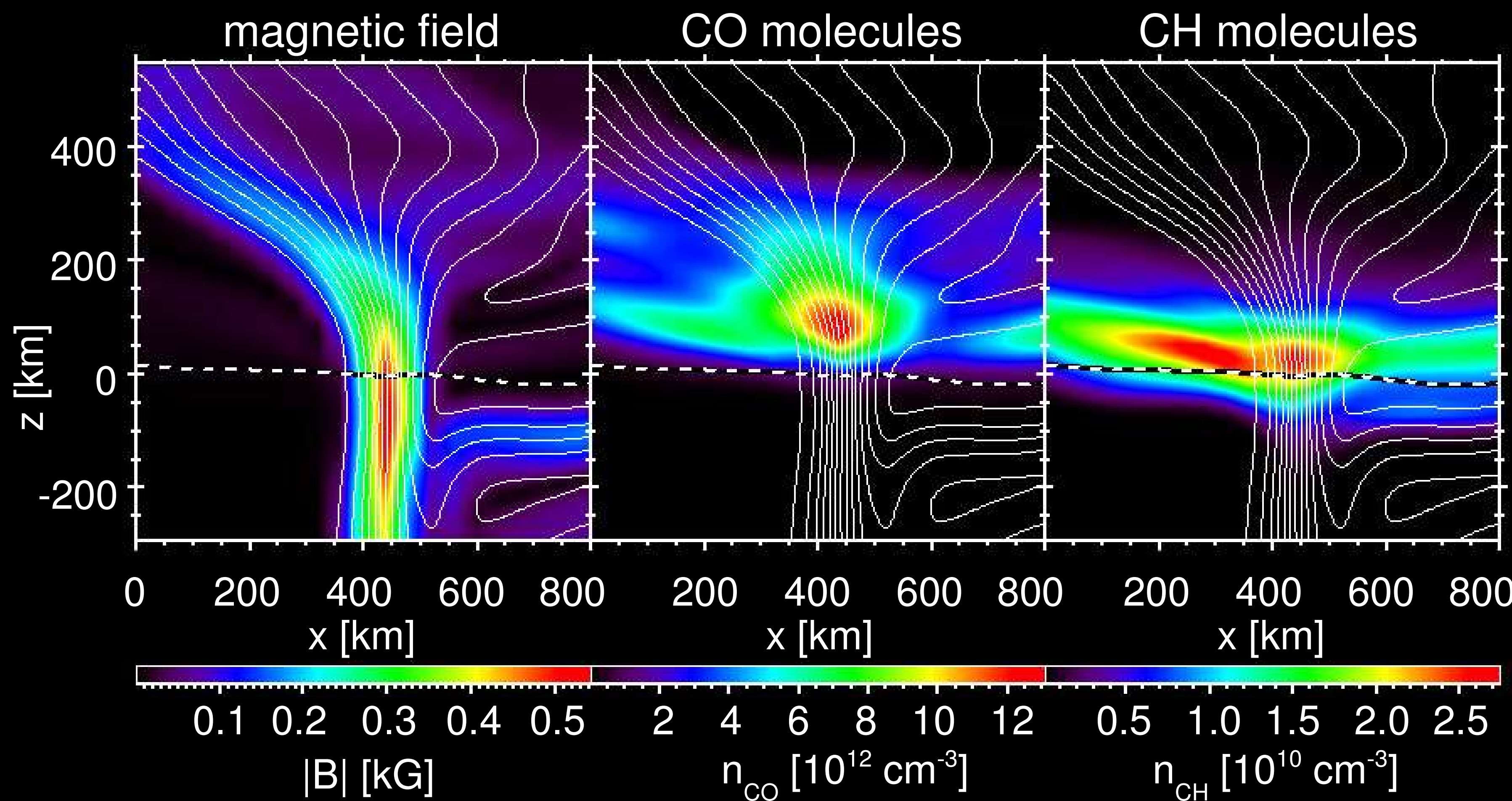
CO Conclusions

- CO cooling time-scales longer than hydrodynamical time-scales (similar to the results by Steffen & Muchmore (1988))
- ➔ atmosphere cannot relax to cool state
- ➔ average temperature reduced by ~100 K only
- ➔ **No thermal bifurcation of the solar atmosphere due to CO!**
- BUT: **CO mostly located in cool regions of reversed granulation in the middle photosphere**
- ➔ exists as part of an inhomogeneous dynamic atmosphere with co-existing hot and cool regions
- **Thermal "bifurcation" is due to interaction of propagating shock waves!**
- ➔ see **3D chromosphere model** by Wedemeyer et al. (2004, A&A 414, 1121)



gas temperature at z = 1000 km (horizontal cross-section)

Molecules and magnetic fields

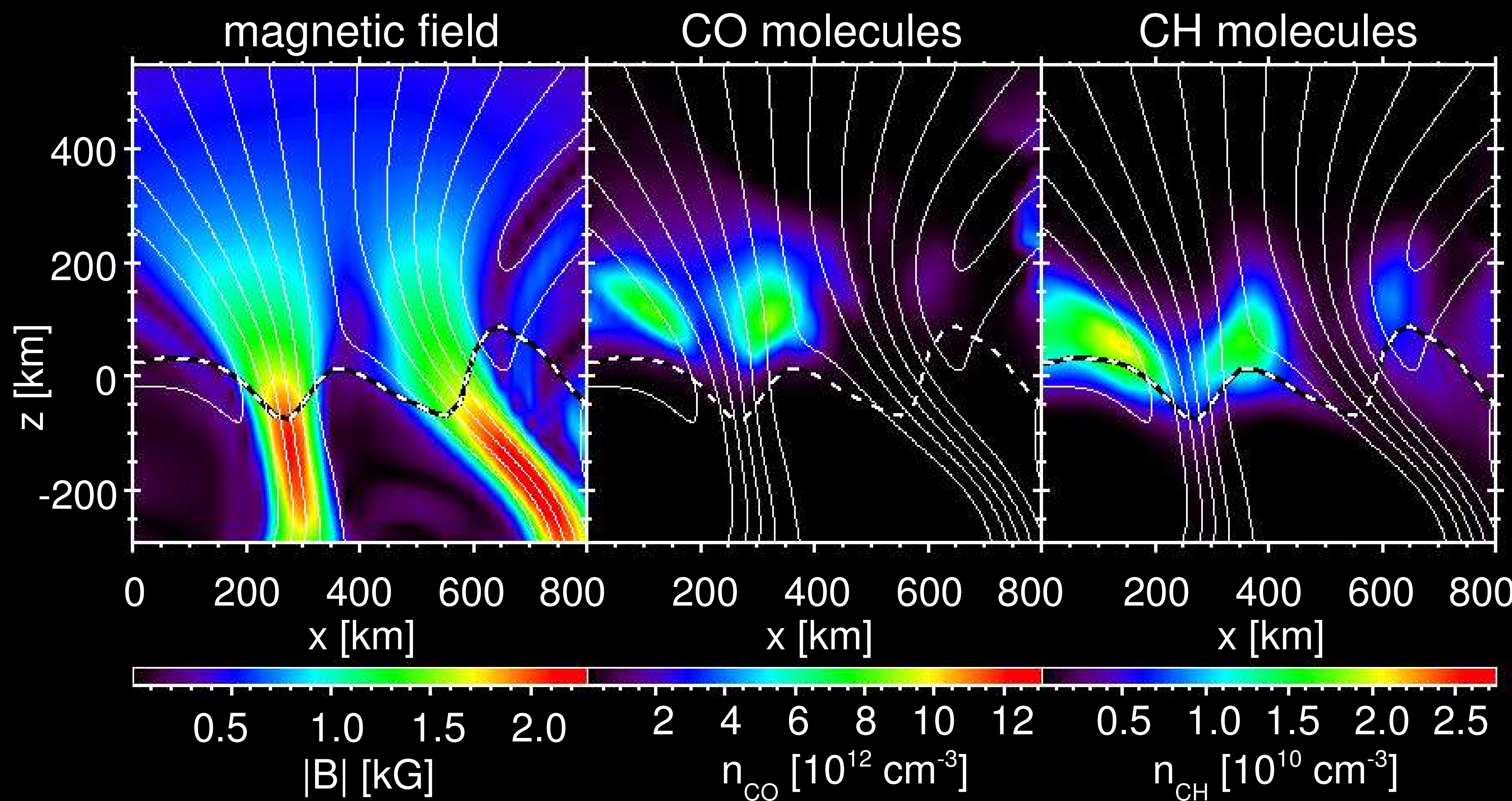


2D simulation with chemistry and magnetic fields (B_0=10 G)

Example 1: **weak** flux tube

- no “Wilson depression” ➔ no “hot walls”
- ➔ no radiative heating of flux tube atmosphere
- ➔ CH and CO enhanced even directly in flux tube

Molecules and magnetic fields



2D simulation with chemistry and magnetic fields (B_0=100 G)

Example 2: **strong** flux tubes

- "Wilson depression" ➔ "hot walls"
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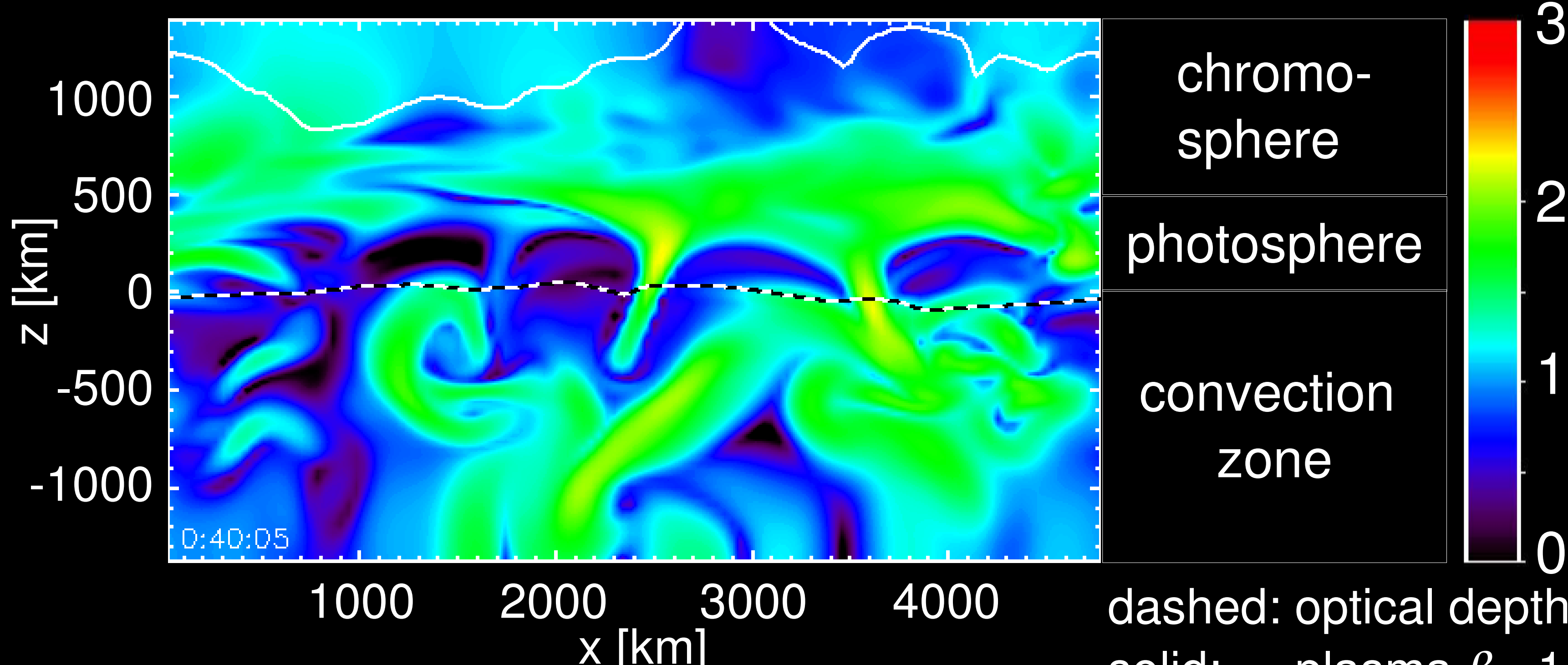
- ➔ CH and CO depleted in flux tubes

3D MHD model

- extent: vertical: -1400 km to +1400 km, horizontal: 4800 km
- initial magnetic field: vertical, B_0 = 10 G (≙internetwork region)
- chromosphere is highly dynamic
- propagating shock waves compress magnetic field
- ➔ fast moving filaments of enhanced field
- surface of plasma β=1 on average at z=1000 km but varies strongly

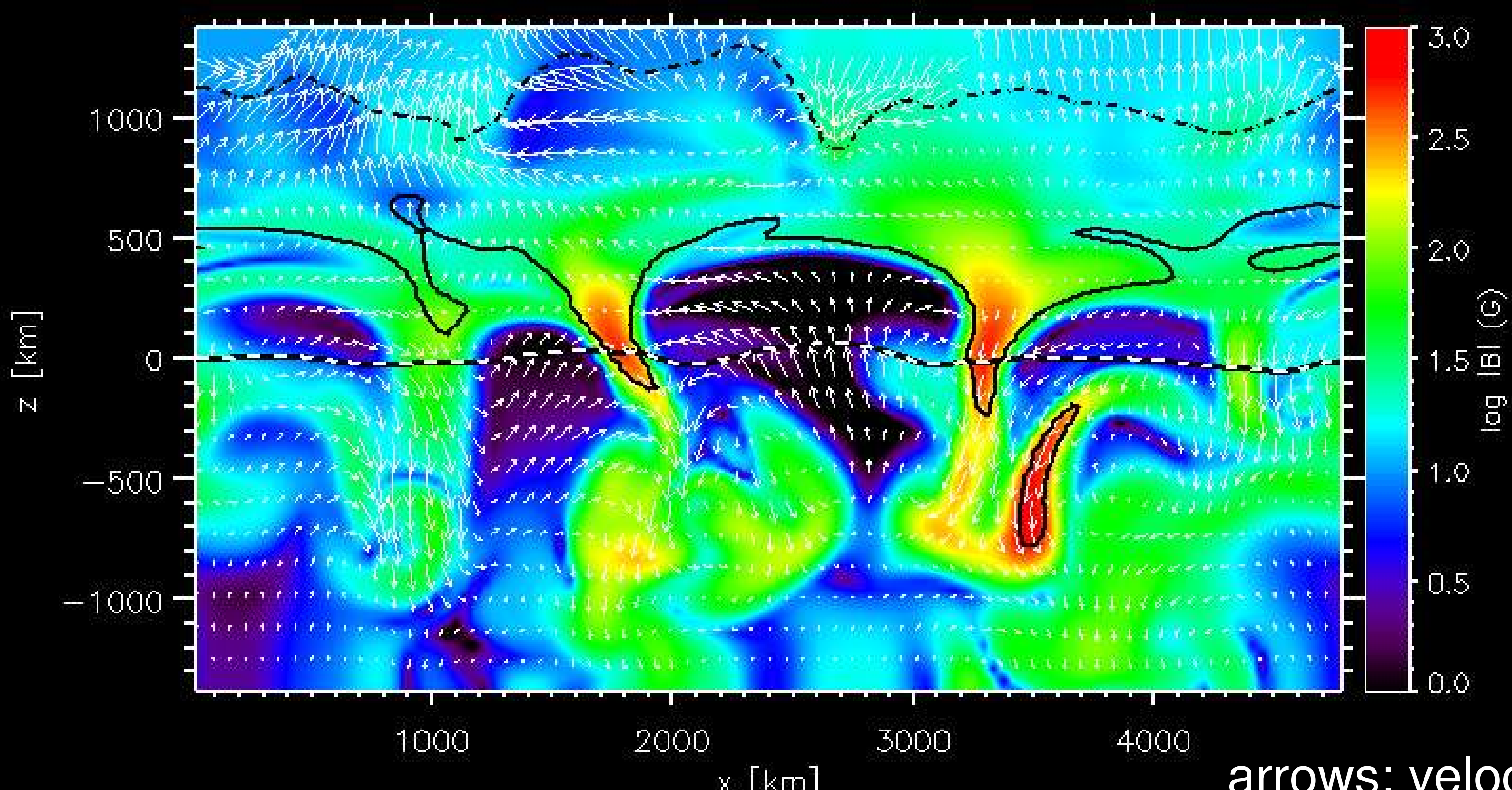
vertical cross-section: absolute field strength log |B|



dashed: optical depth unity
solid: plasma β= 1

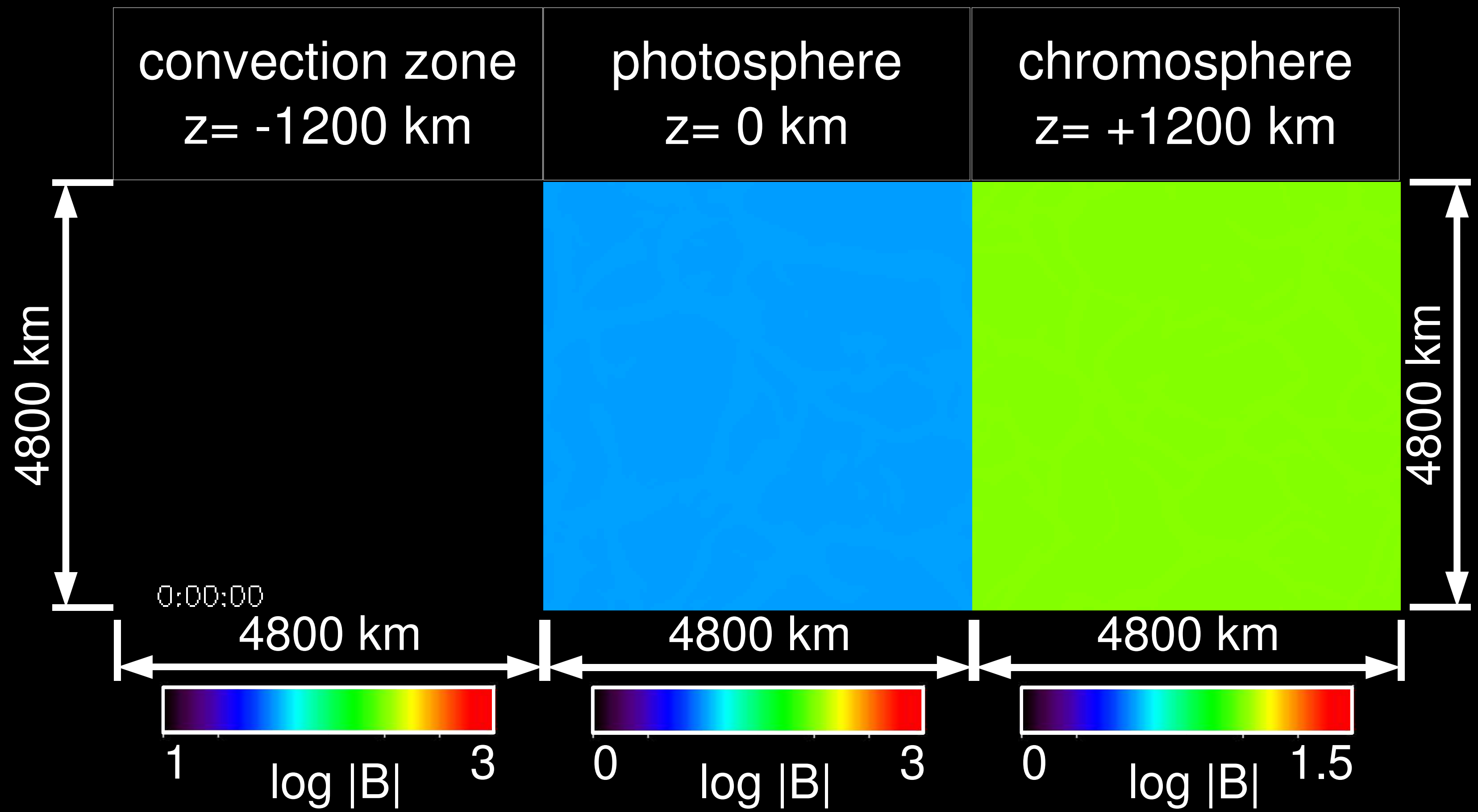
"Small-scale canopy"

- lateral flows above granule interiors
- ➔ advection of magnetic field towards intergranular lanes
- ➔ granule interiors very weak field only, virtually void
- above: flux tube funnels spread out, form a horizontally aligned field
- ➔ dynamic "small-scale canopy" (in internetwork regions)



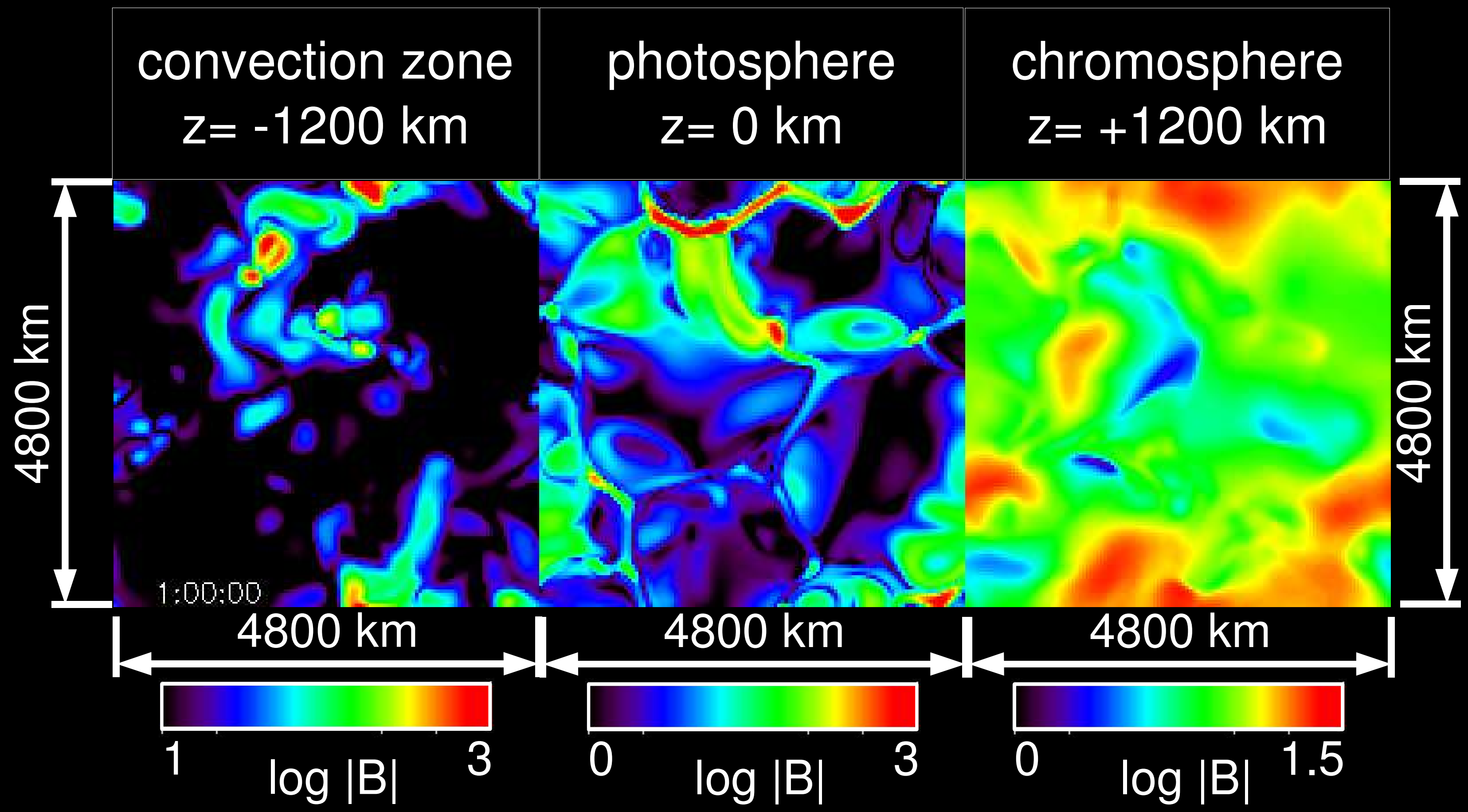
arrows: velocity field

Horizontal field distribution



- horizontal cross-section at three heights:
- chromospheric field much weaker (|B|< 50 G) than photospheric
- BUT:
    - more homogeneous
    - evolves much faster

Horizontal field distribution



- horizontal cross-section at three heights:
- chromospheric field much weaker (|B|< 50 G) than photospheric
- BUT:
  - more homogeneous
  - evolves much faster

MHD Conclusions

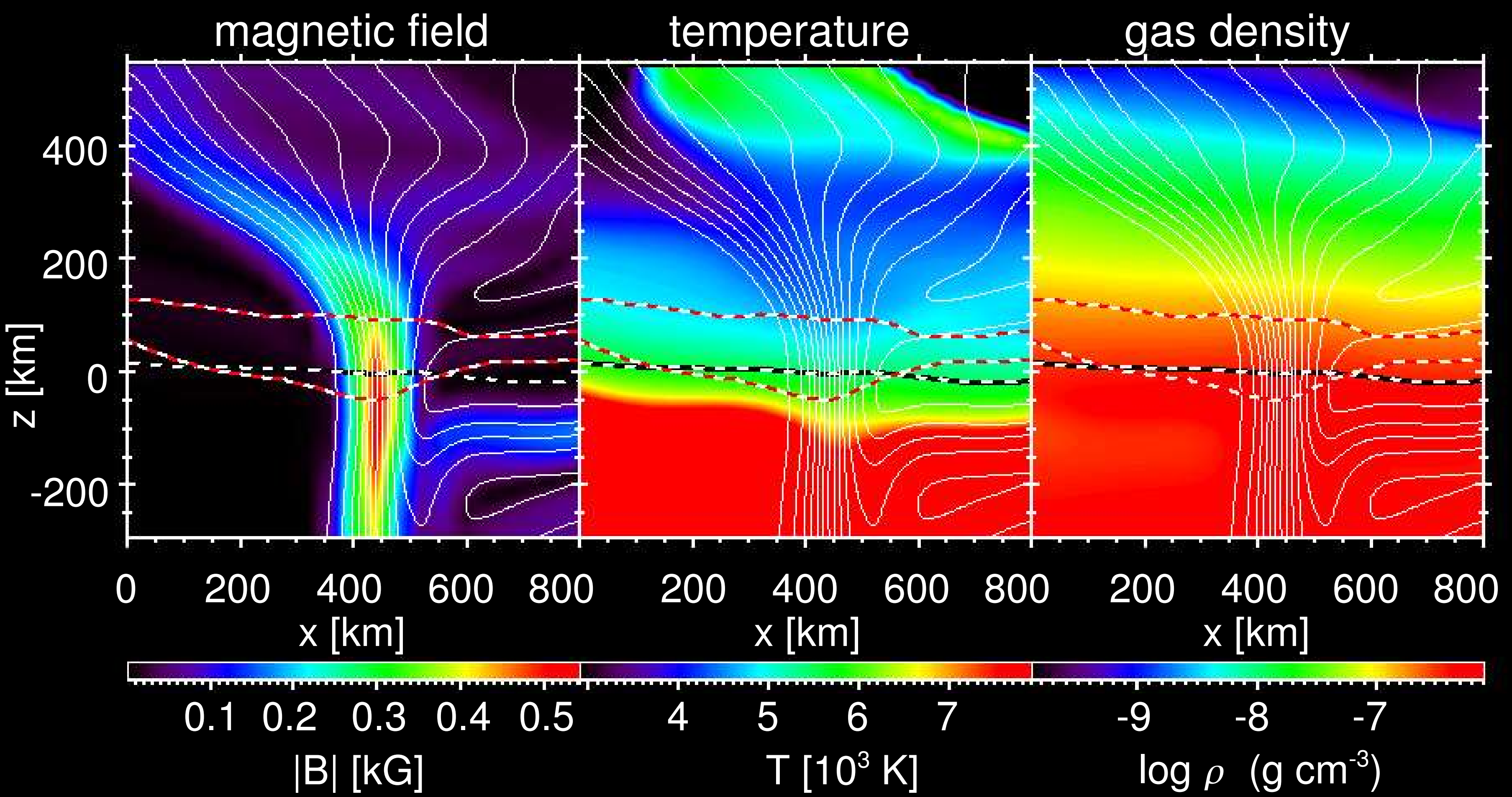
- **Magnetic field in the chromosphere is very dynamic!**
  - time-scales much shorter than in the layers below
  - rapidly moving filaments of enhanced field strength

- **surface of plasma $\beta = 1$**
  - separates the highly dynamic middle chromosphere from the slower evolving lower layers
  - height on average at z=1000 km

- **“small-scale canopy”:**
  - photospheric flows expel magnetic field from granule interiors
  - ➔ granule centres virtually void of magnetic field
  - ➔ “canopy” field above voids

Additional material

Molecules and magnetic fields



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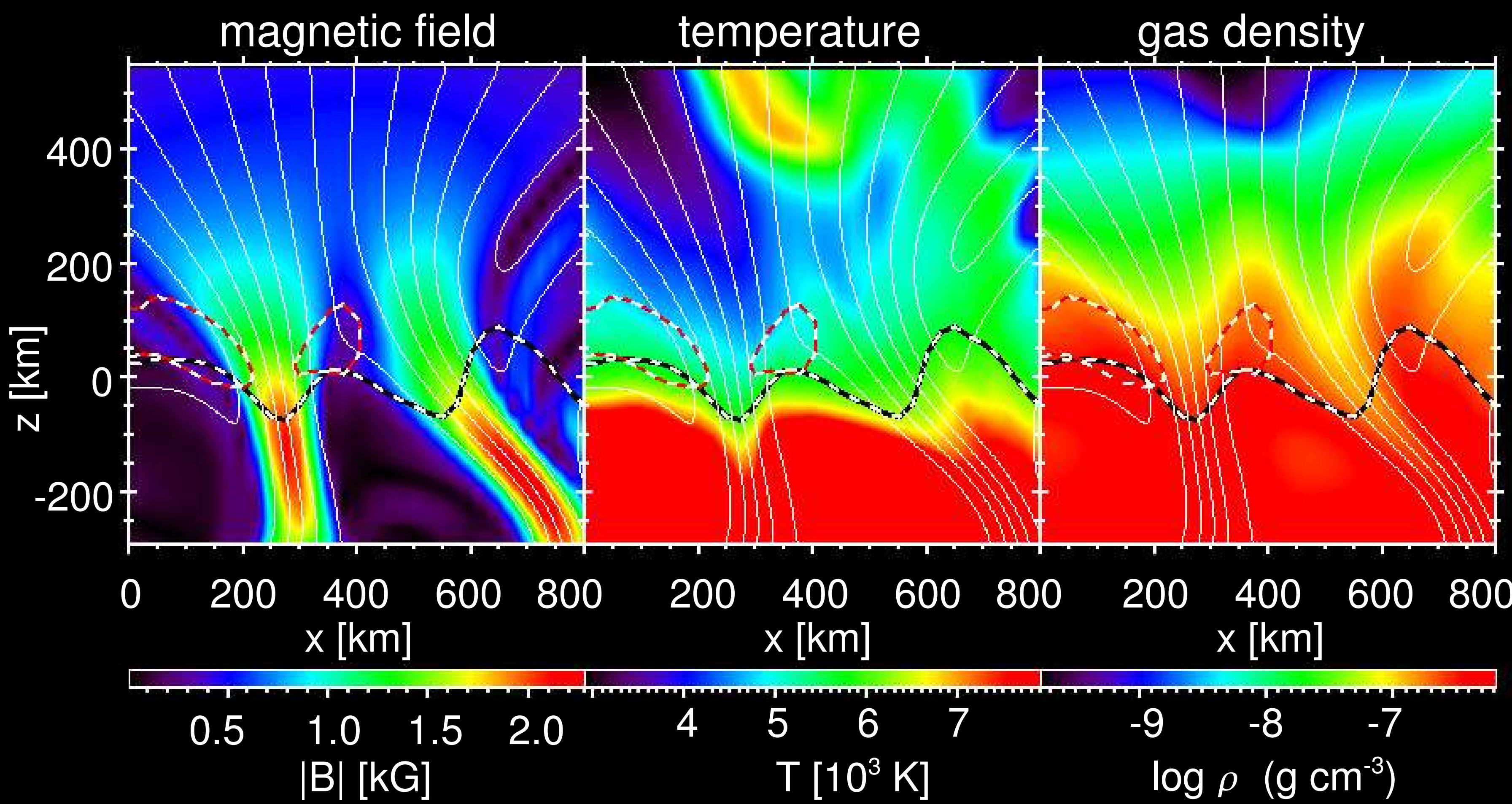
Molecules and magnetic fields



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