3D MHD Stellar Atmosphere Models

Zazralt Magic and Åke Nordlund

Niels Bohr Institute
Copenhagen, Denmark

Overview

- Introduction
- Solar Active Region
- Coronal Heating
- Current Sheets
- Chromospheric Waves

Where are we now?

3D (M)HD stellar surface models established last 20yrs

- CIFIST-grid (Ludwig et al. 2009)
- Stagger-grid (Magic et al. 2013)

Magneto-Convection with realistic 3D radiative transfer

Equation-of-state with detailed atomic & molecular physics

Current efforts: include chromosphere & corona

- Self-consistent heating by magnetic dissipation
- Cooling by radiation and conduction

Where are we now?

3D (M)H… t 20yrs

- Cl…
- Sta…

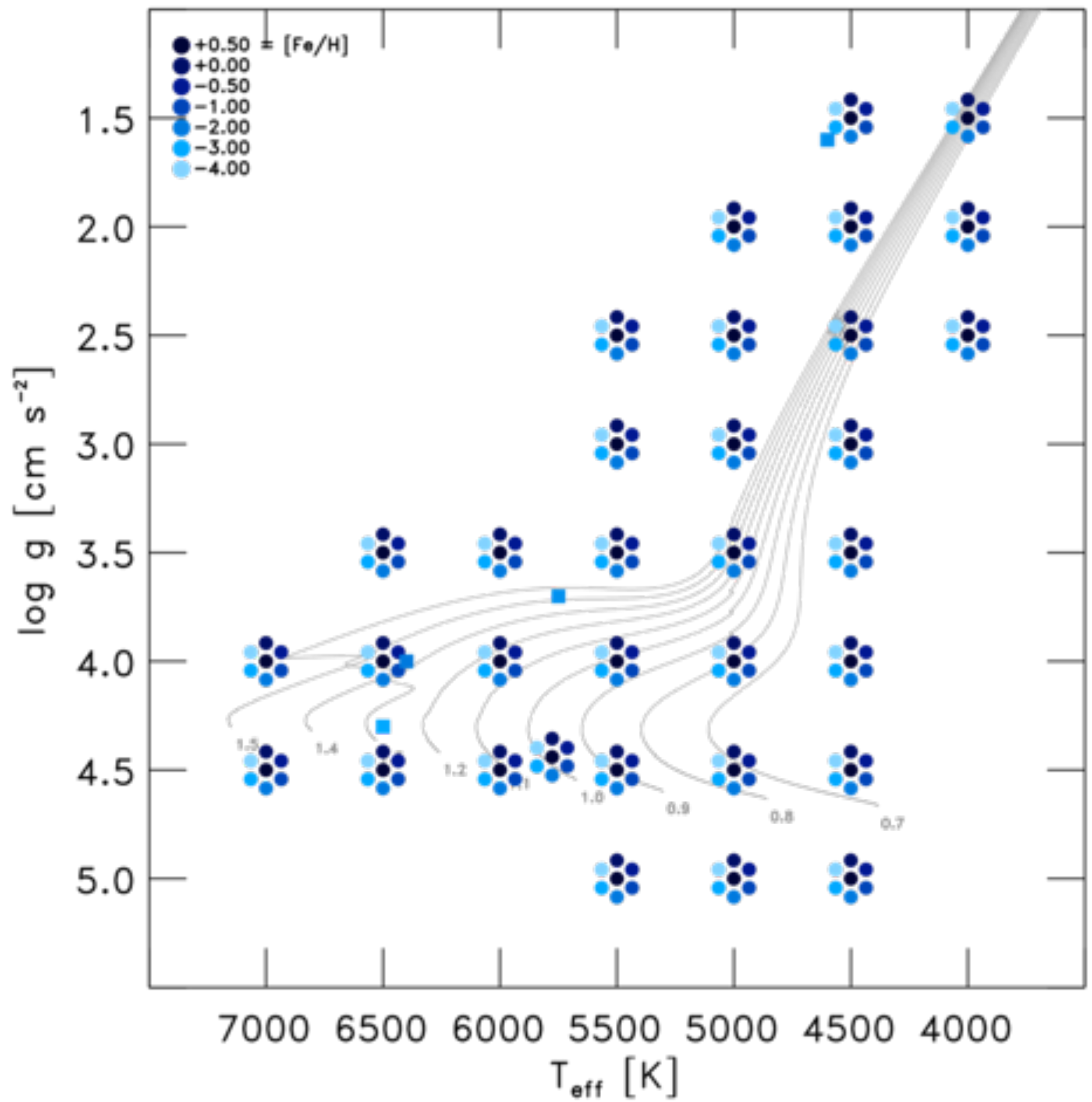
Magneto-… transfer

Equation-… lar physics

Current e…

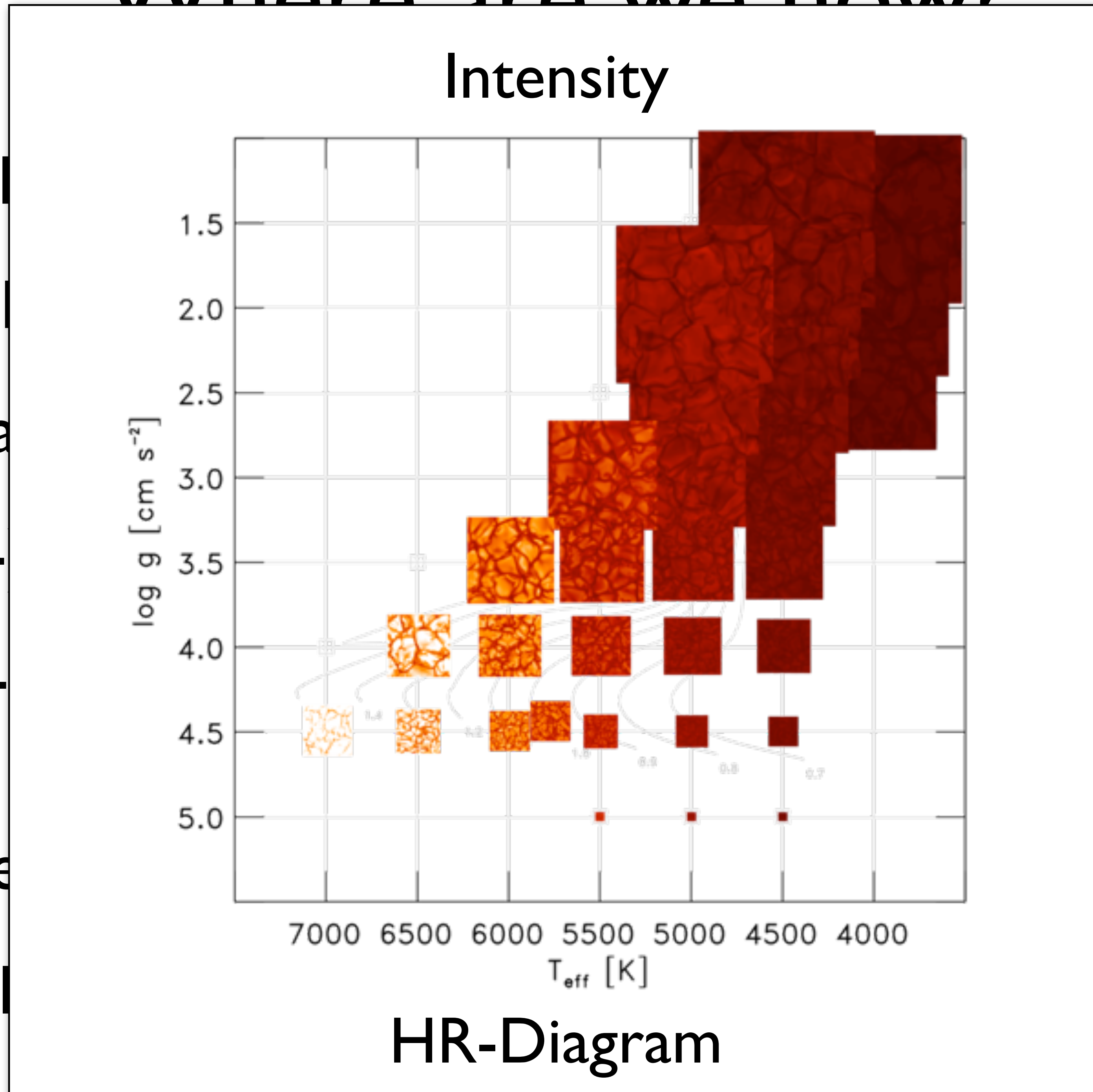
- Sel… tion
- Cooling by radiation and conduction

Stagger-grid ~ 220 models



HR-Diagram

Where are we now?



3D (M)H ... t 20yrs

- Cl
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Magneto- ... transfer

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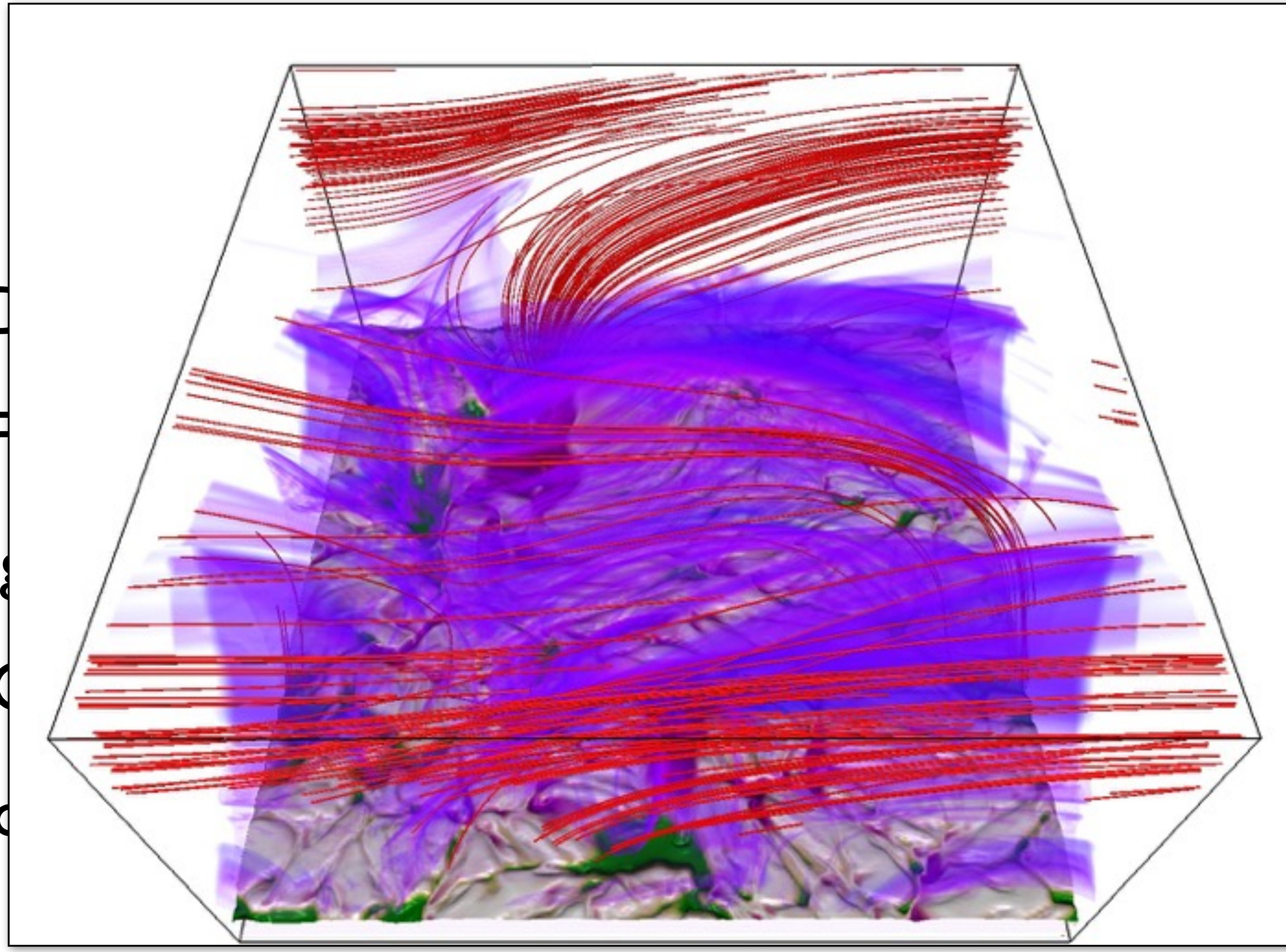
3D (M)HD

- CIF

- Stag

Magneto-C

Equation-o sics



Current efforts: include chromosphere & corona

- Self-consistent heating by magnetic dissipation

- Cooling by radiation and conduction

Motivation

Success of 3D stellar surface models:

- Observed spectral lines are accurately reproduced
- Only moderate resolution 250^3 - 500^3 necessary
- Affordable for computing grids nowadays

Success of 3D chromospheric & corona models:

- Realistic „synthetic observations“ (Oslo group)
- Reasonably affordable
- Bottleneck: high Alfven speeds

Why does 3D hydro-modelling work?

Hydrodynamic turbulence $\Rightarrow$ Kolmogorov scaling

- Hydrodynamic dissipation enters turbulent regime
- Requires only marginally resolved turbulent cascade

Why does 3D coronal modelling work?

MHD "turbulence" $\Rightarrow$ *fast reconnection!*

- Empirically: it works, despite HUGE range-of-scale error!

  We know for a fact that fast reconnection works in 3D, otherwise detailed (Oslo-type) modelling would be WAY off !

- Reason: "turbulent" scaling of magnetic dissipation

  cf. Galsgaard & Nordlund 1996, Lazarian & Vishniac 1999, …

Stagger-code

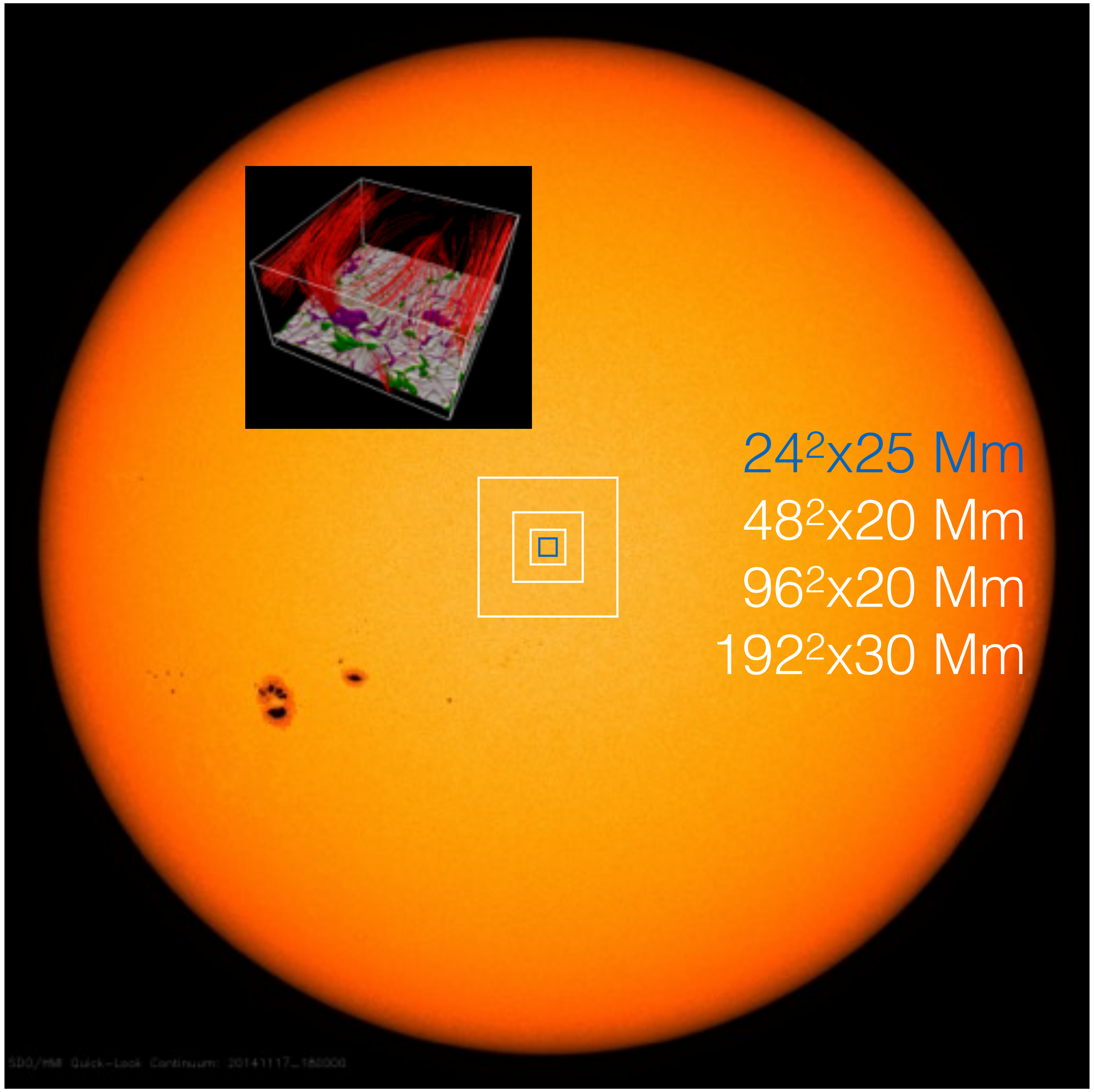
Stein & Nordlund 1998

$$
\begin{aligned}
\partial_t \rho &= -\vec{\nabla} \cdot (\rho \vec{u}) \\
\partial_t \rho \vec{u} &= -\vec{\nabla} \cdot (\rho \vec{u}\vec{u} + \tau_{ij}) \\
&\quad -\vec{\nabla} P_{\mathrm{th}} - \rho \vec{g} + \vec{j} \times \vec{B} \\
\partial_t e &= -\vec{\nabla} \cdot \left(e\vec{u} - \rho\kappa \hat{\vec{B}}(\hat{\vec{B}} \cdot \vec{\nabla})T \right) \\
&\quad -P_{\mathrm{th}} \vec{\nabla} \cdot \vec{u} + q_{\mathrm{rad}} + q_{\mathrm{visc}} + q_{\mathrm{mag}} \\
q_{\mathrm{rad}} &= 4\pi\rho \int_\lambda \kappa_\lambda \left(J_\lambda - S_\lambda \right) d\lambda \\
q_{\mathrm{rad}} &= \Lambda(T)\rho^2 \; [\text{in the corona}] \\
q_{\mathrm{mag}} &= \vec{E}_{\mathrm{diff}} \cdot \vec{j} \\
\vec{E} &= \vec{E}_{\mathrm{diff}} - \vec{u} \times \vec{B} \\
\vec{j} &= \vec{\nabla} \times \vec{B}
\end{aligned}
$$

- Solving the time-dependent radiative-MHD equations
- Convection emerges self-consistently, from first principles
- B-field coupling via Lorentz force and magnetic dissipation
- Box-in-the-star setup

Stagger-code

Stein & Nordlund 1998



$24Mm^2$ x 25.4Mm
504^2x500 48km, 4.3Gb
1008^2x500 24km, 18Gb

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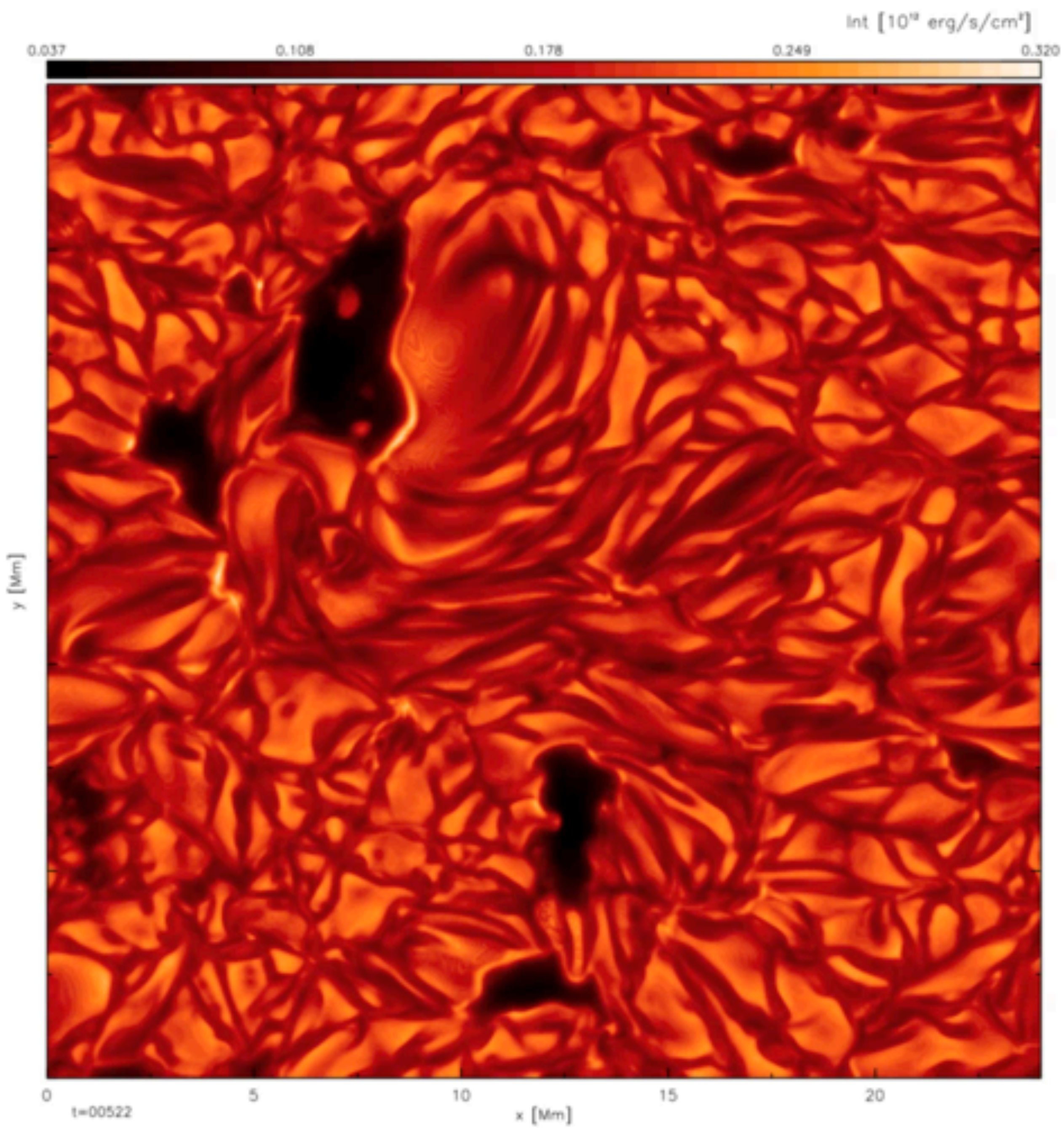
Solar Active Region



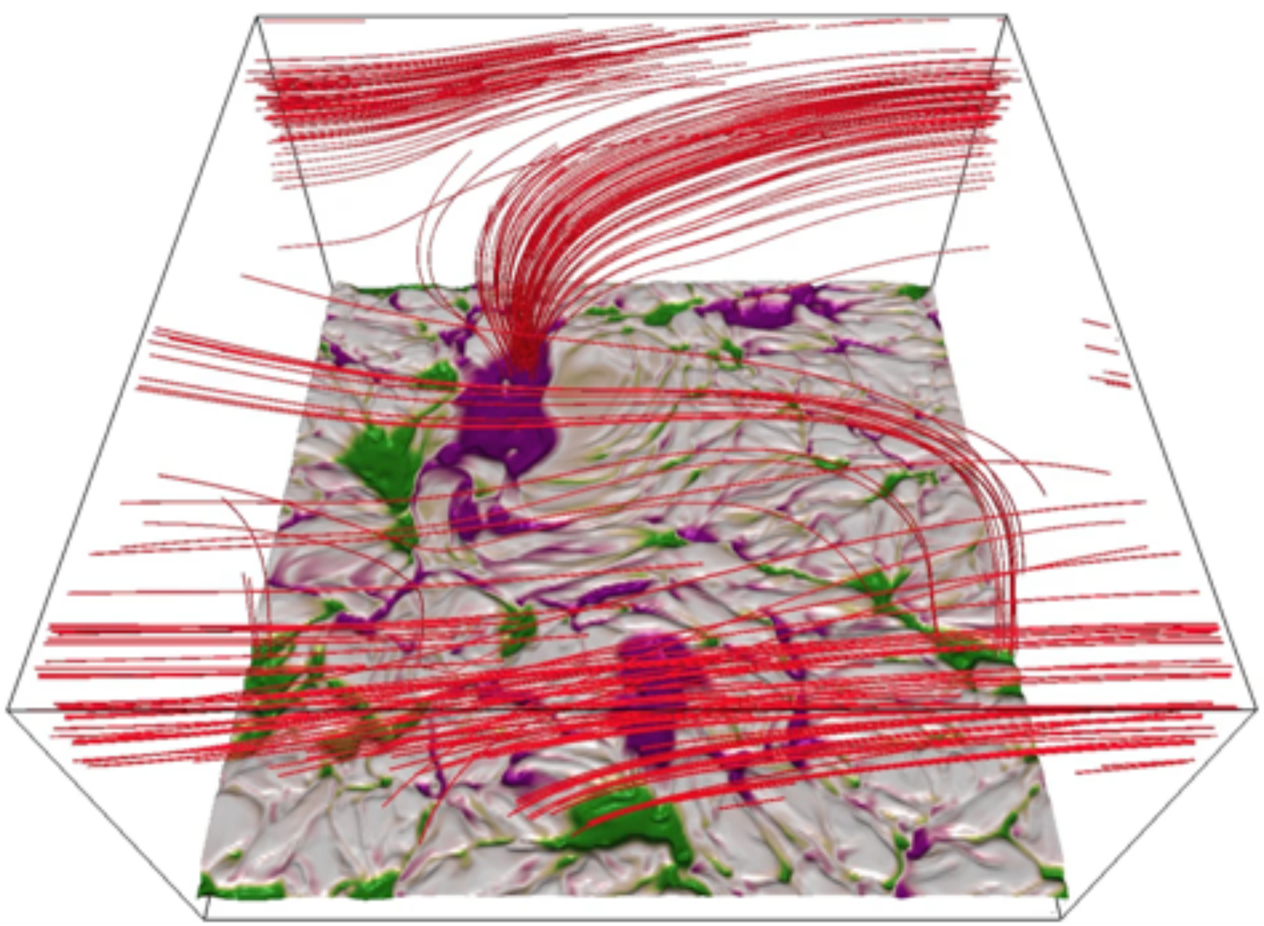
Bolometric intensity (8 min)

Stein et al. 2011

- Flux emergence of kG fields concentrations due to convective motions
- Formation of bipolar coronal loops, visible as small sun spots
- Strong Lorentz interactions between velocity and magnetic field in the photosphere $\beta \sim 1$
- Complexity emerges from first principles physics

Solar Active Region

Stein et al. 2011



Optical Surface and
B-field streamlines

- Flux emergence of kG fields concentrations due to convective motions
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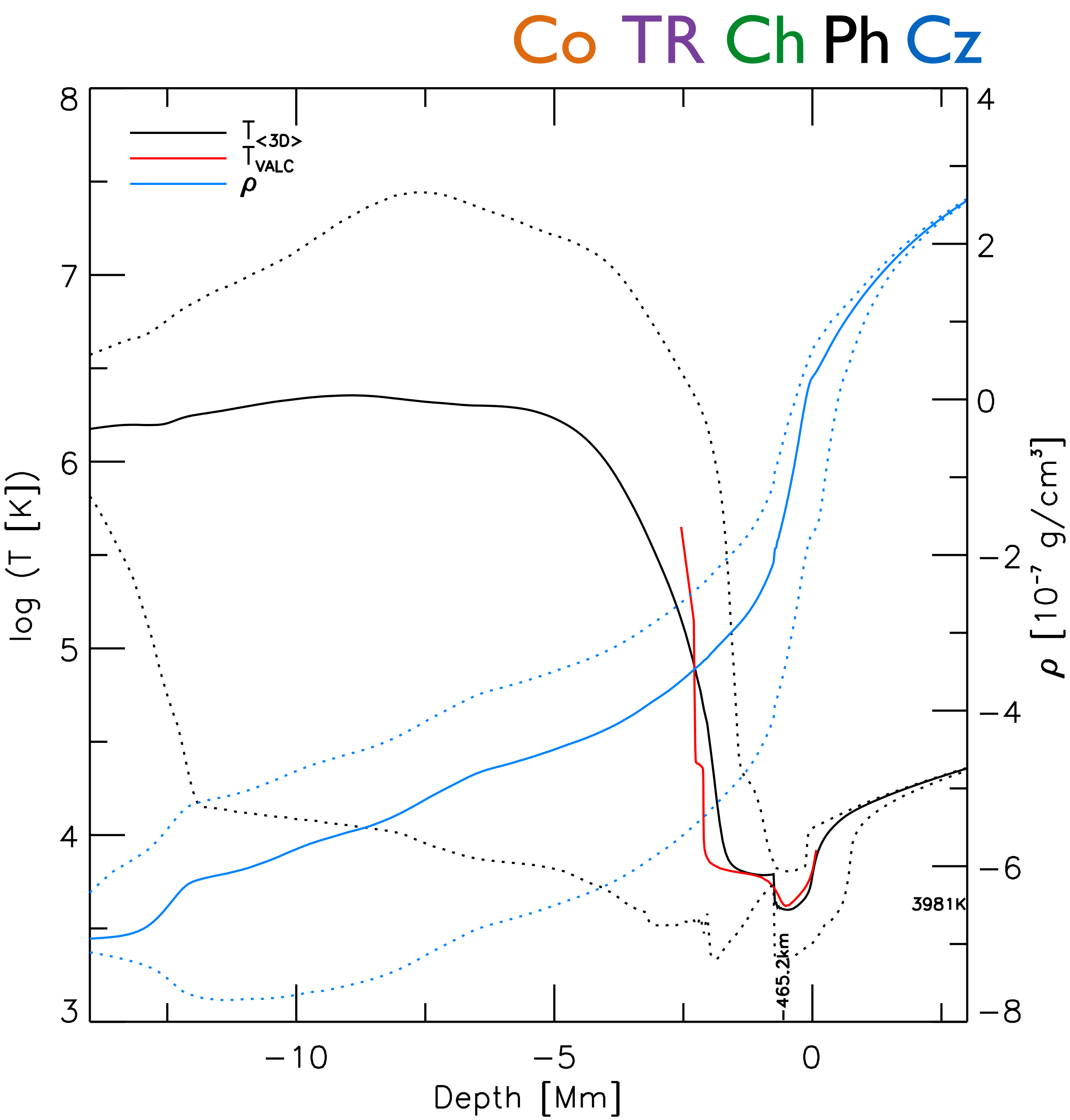
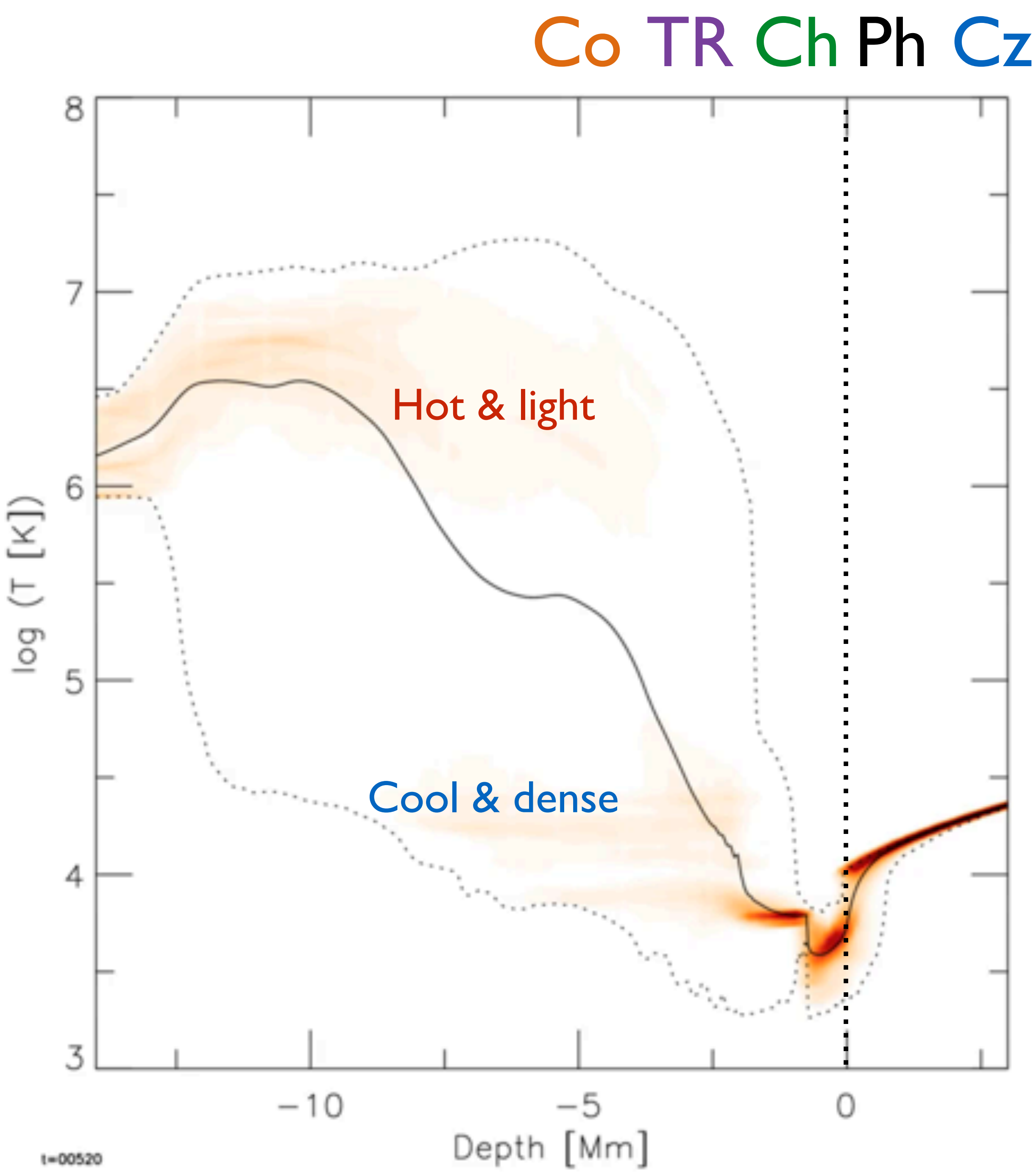
Stratification



Mean temperature and density

- Driving photospheric and convection zone layers
- Cool chromosphere with temperature minimum
- Transition region with heating to extreme high temperatures
- Hot corona, which is highly dynamical with high and low temperatures
- Comparable to observations

Stratification



Temperature histogram

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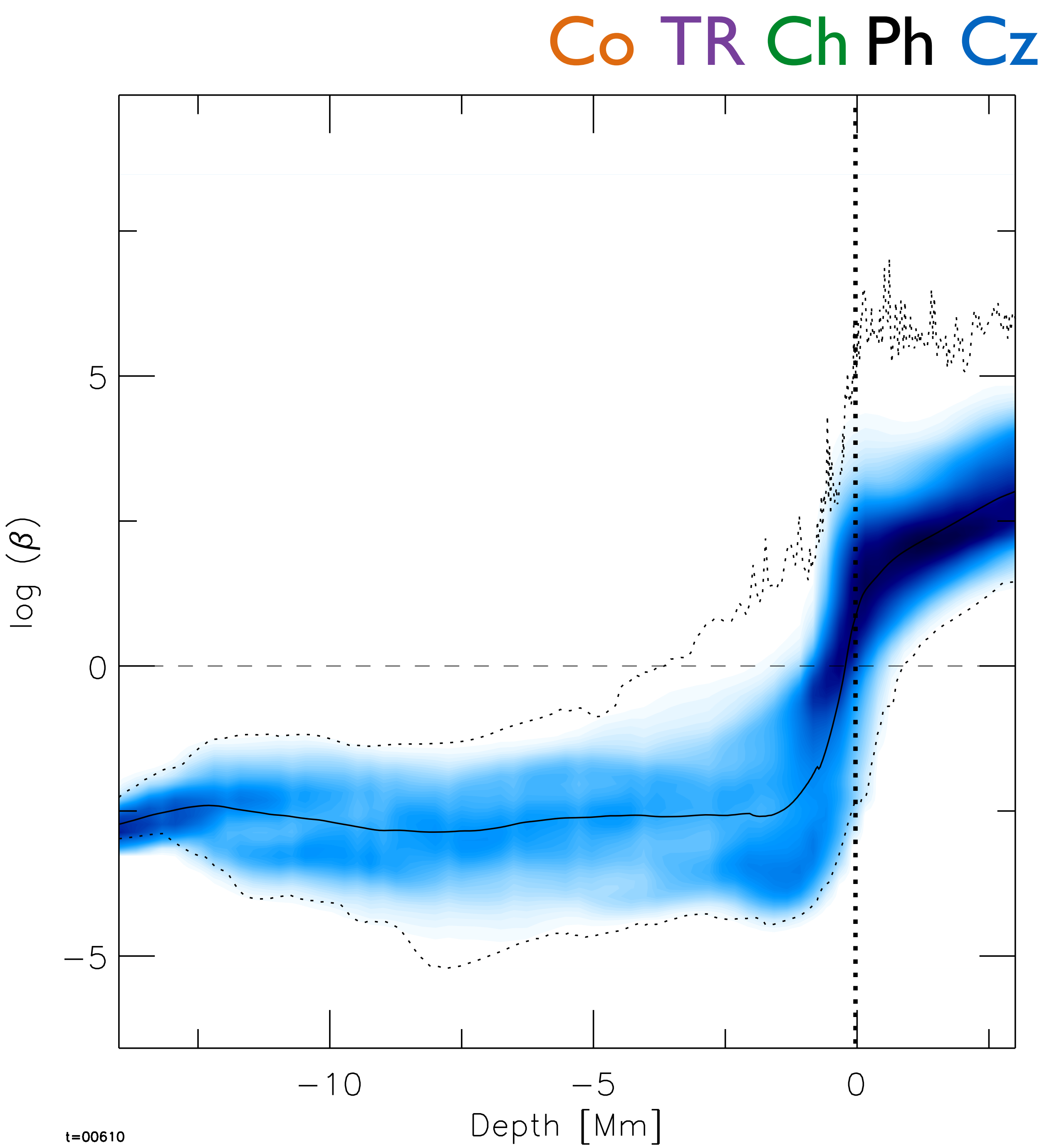
Stratification



Plasma β

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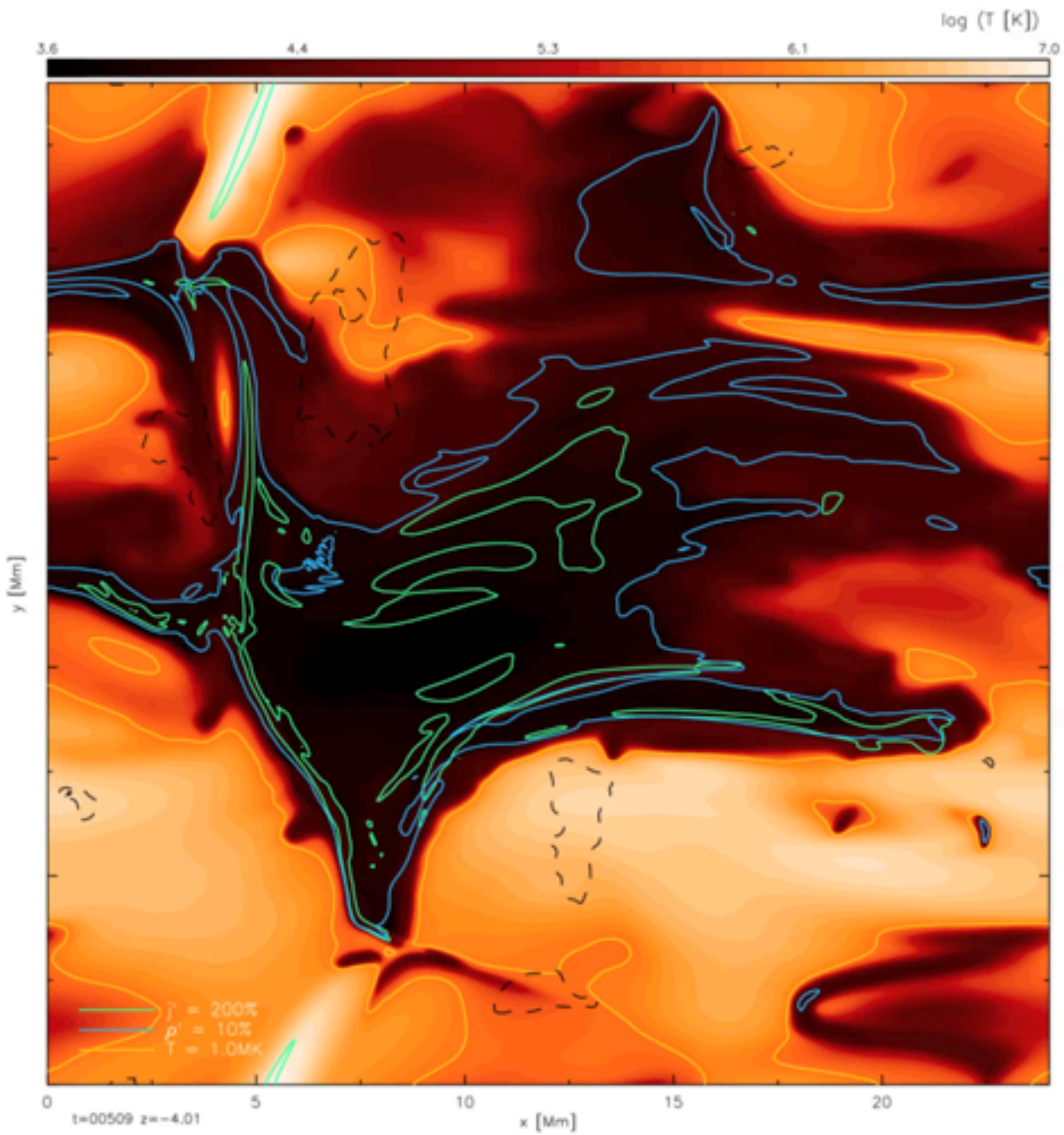
Hot Corona

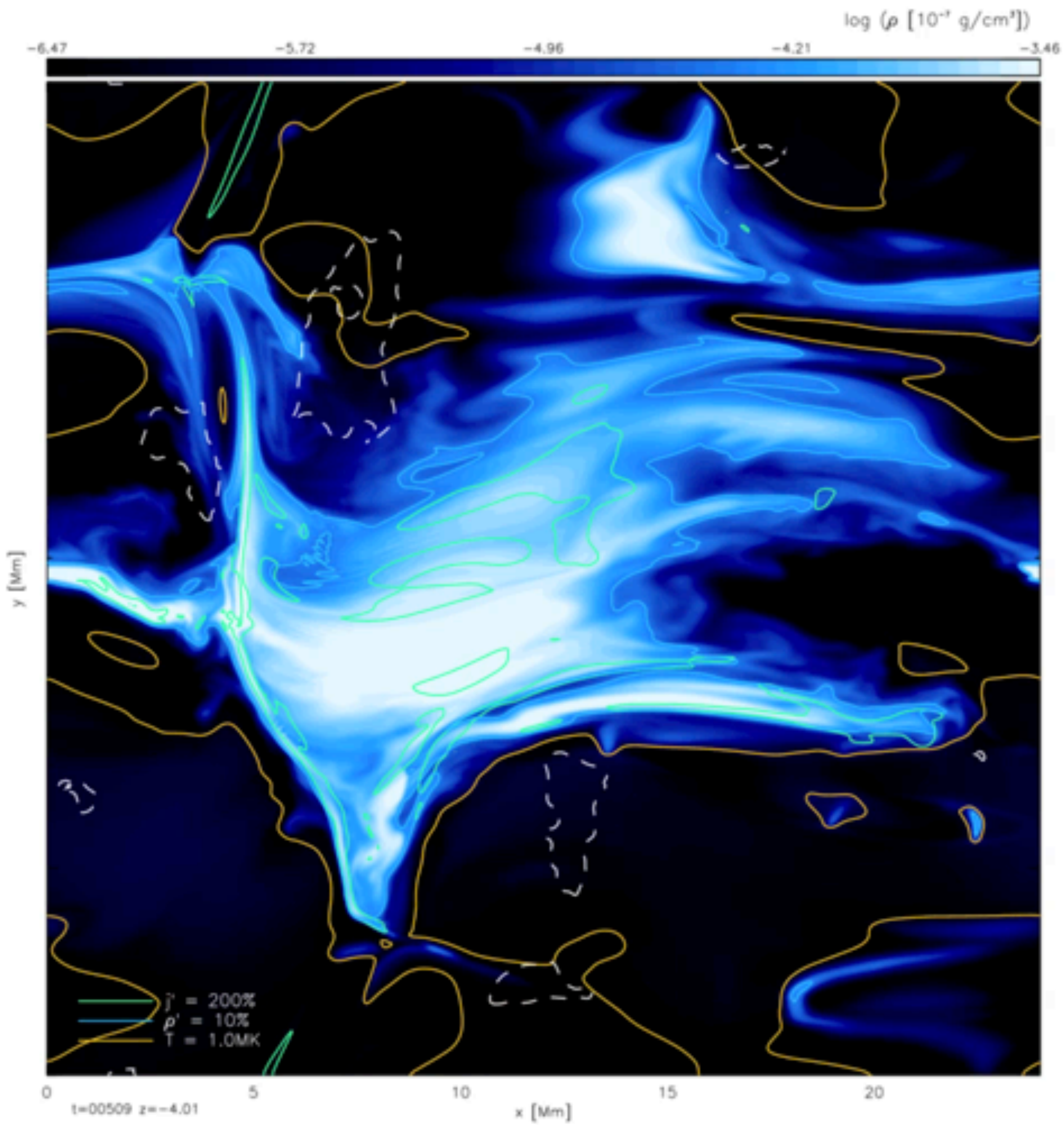


- Highly bimodal state with high/low temperatures and low/high density
- Extreme hot coronal loops with very low density and significant p_{mag}
- Cool and dense internetwork

Temperature in the lower corona at 4 Mm

T = 1MK
ρ' = 10%
j' = 200%

Hot Corona



Density in the lower corona at 4 Mm

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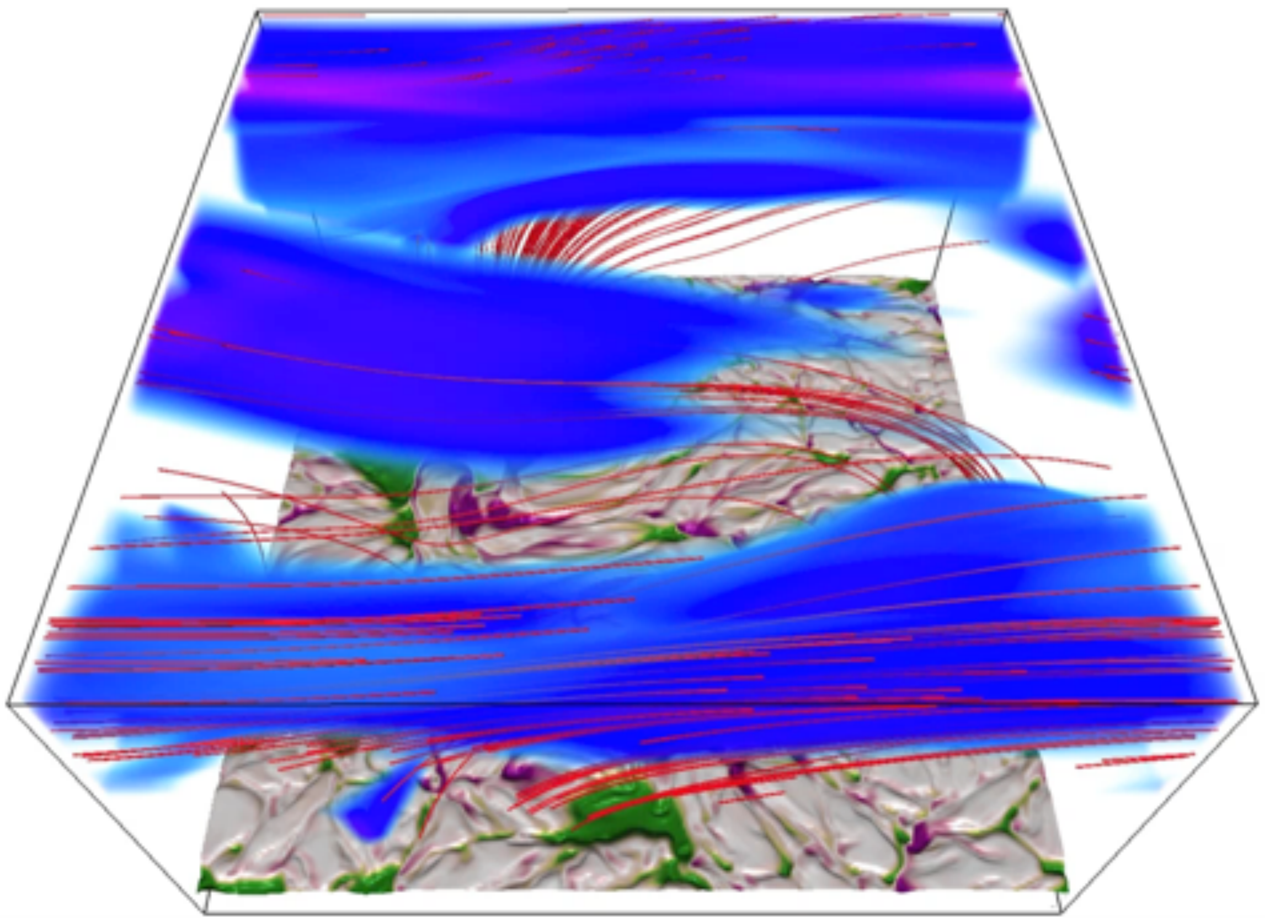

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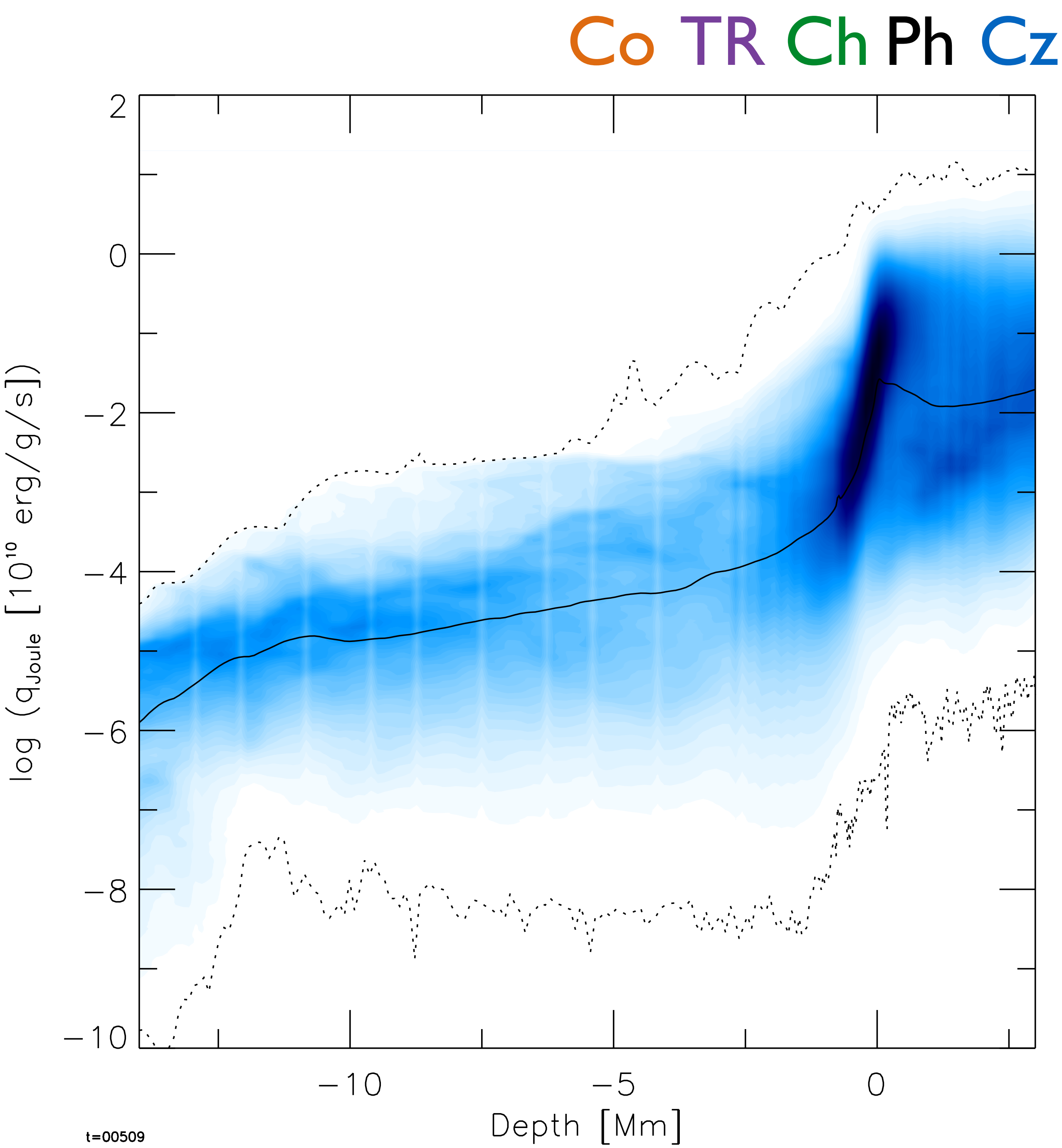
High temperatures

Coronal Heating



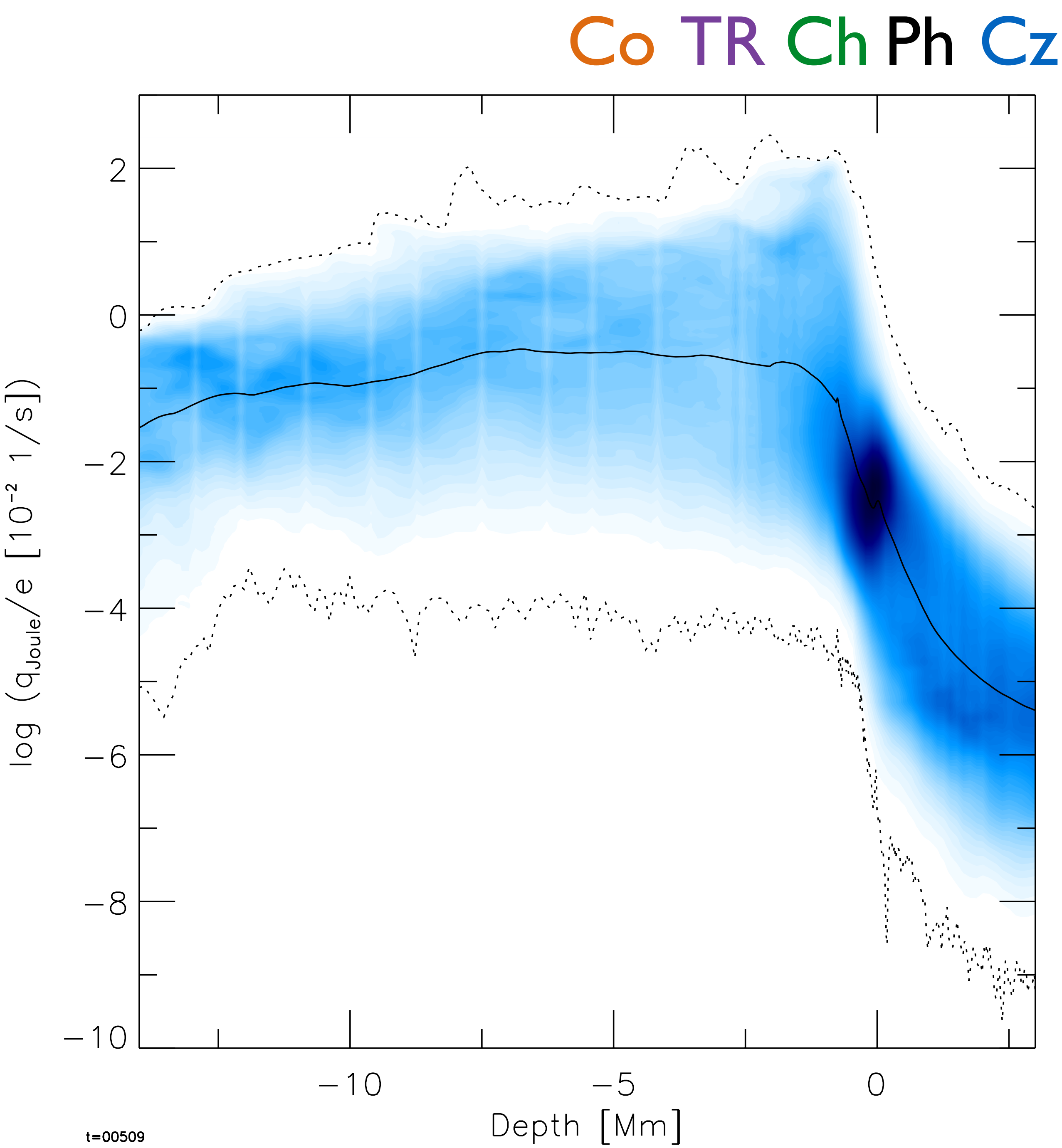
Magnetic dissipation

Galsgaard & Nordlund 1996

- $\langle w_{\mathrm{Lorentz}} \rangle \rightarrow \langle q_{\mathrm{mag}} \rangle$
- Convective photospheric motions build magnetic stress
- Release of magnetic stress by magnetic dissipation
- Heating in coronal loops with very low density

Coronal Heating

Galsgaard & Nordlund 1996



Magnetic dissipation normalised by internal energy per volume

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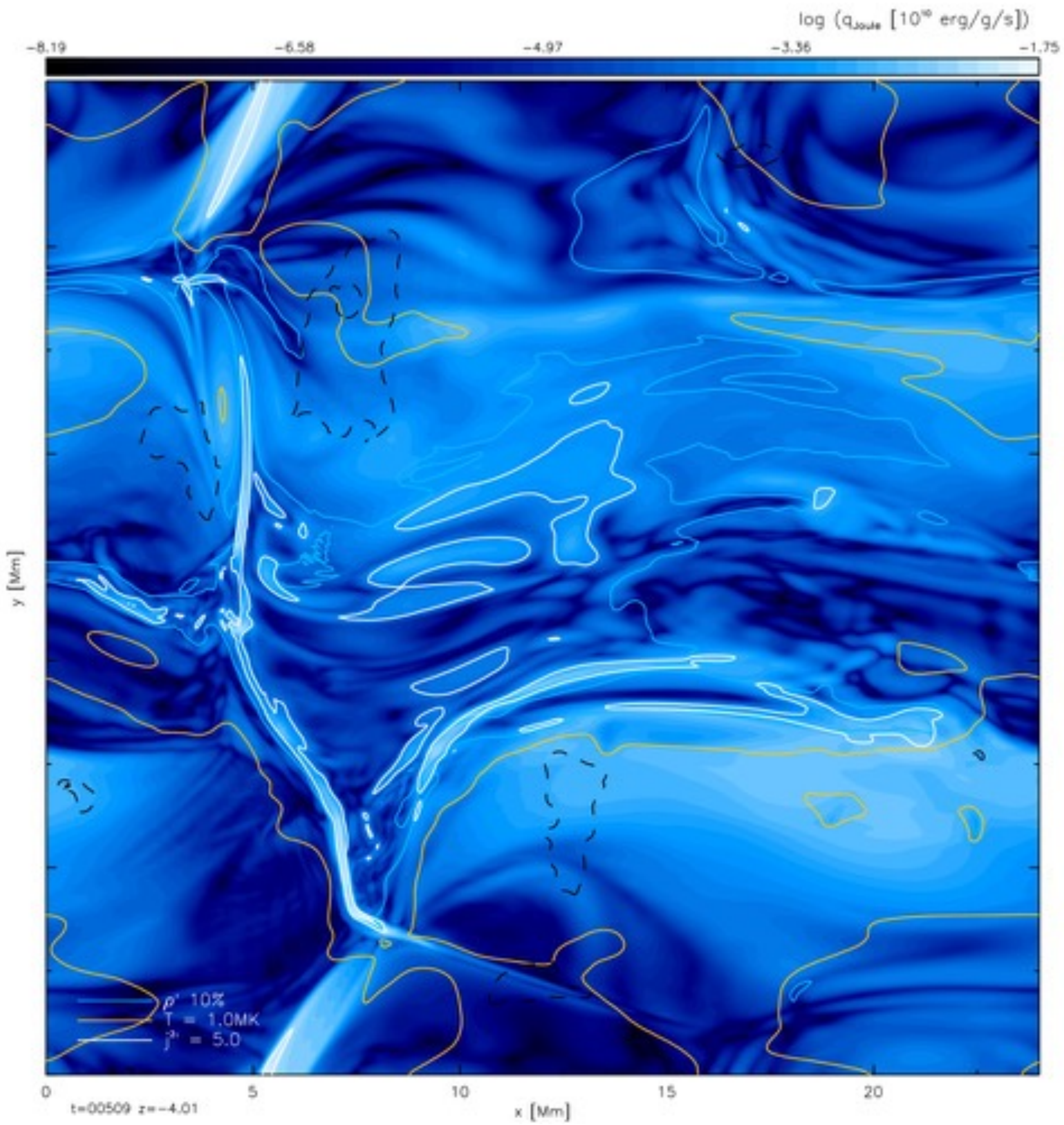
Coronal Heating

Galsgaard & Nordlund 1996



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Magnetic dissipation in the lower corona at 4 Mm

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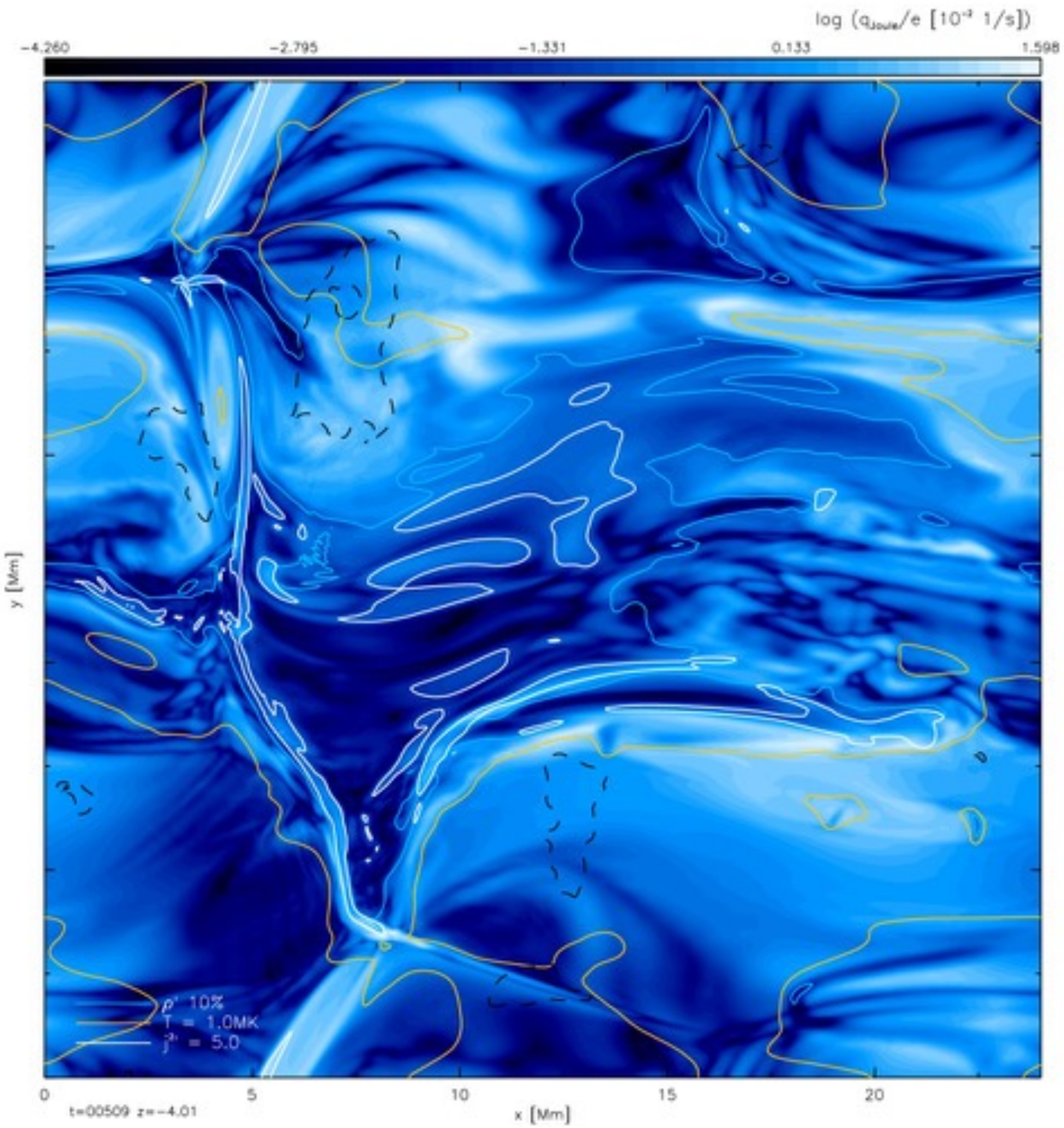
Coronal Heating



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Galsgaard & Nordlund 1996

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Why is the magnetic dissipation right?

Magnetic dissipation does not depend much on η !

- Amazing from the point of view $< Q_{Joule} = \eta J^2 >$

Not so amazing from the point of view $<Q> \sim <W>$

- The average magnetic dissipation $<Q>$ …
- … must be balanced by the average Lorentz work $<W>$

Much easier to understand why $<W>$ is $\approx$ independent of resistivity η: depends mainly on field line connectivity !

Coronal conditions

- Very high Alfven speeds relative to sound speed
- Low plasma $\beta \Rightarrow$ nearly force-free conditions
- Electric currents $\approx$ parallel to the magnetic field

$$\vec{j} = \alpha \vec{B}$$

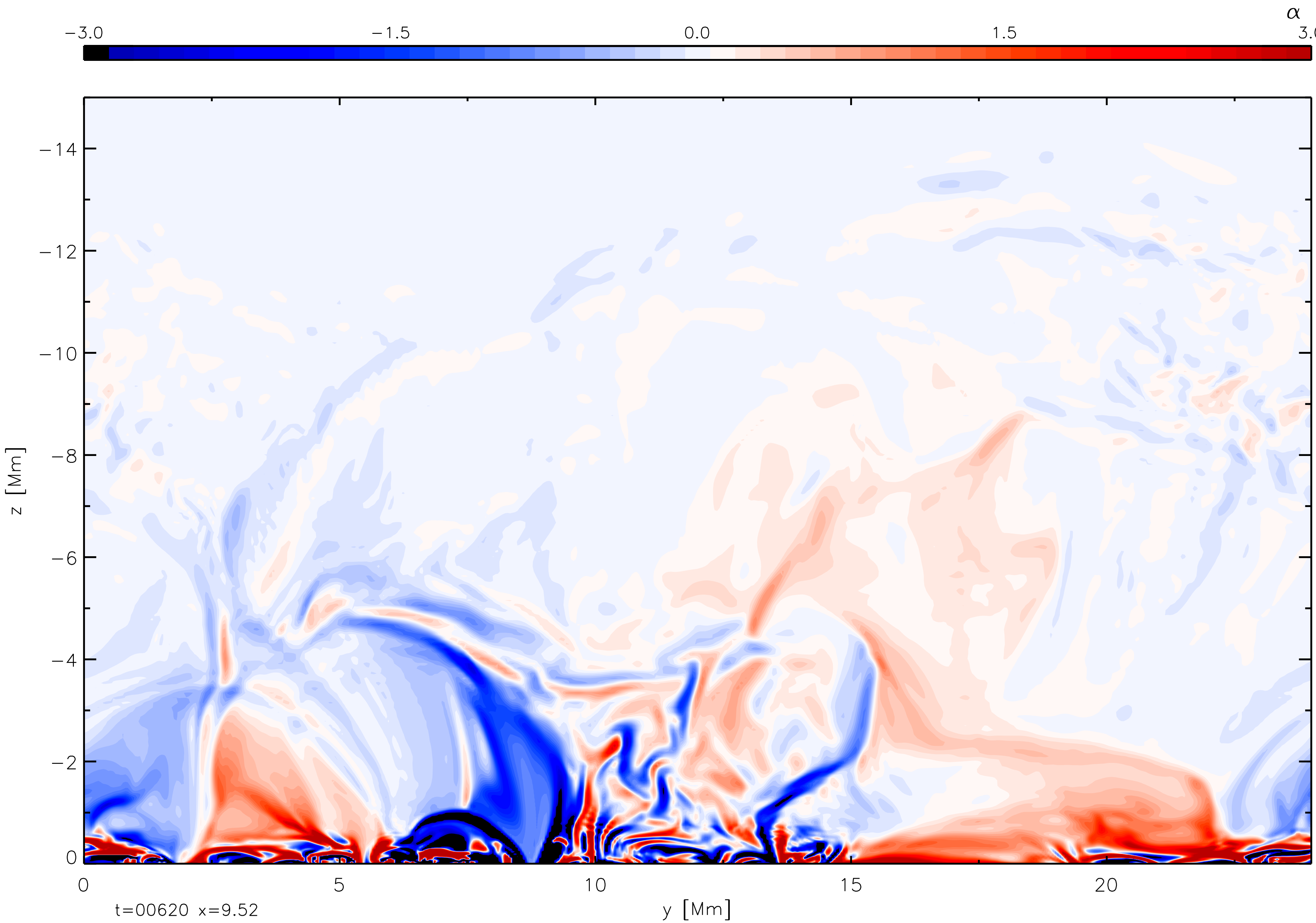
[one can show α must be constant along field lines]

But, it can vary a lot from field line to field line!

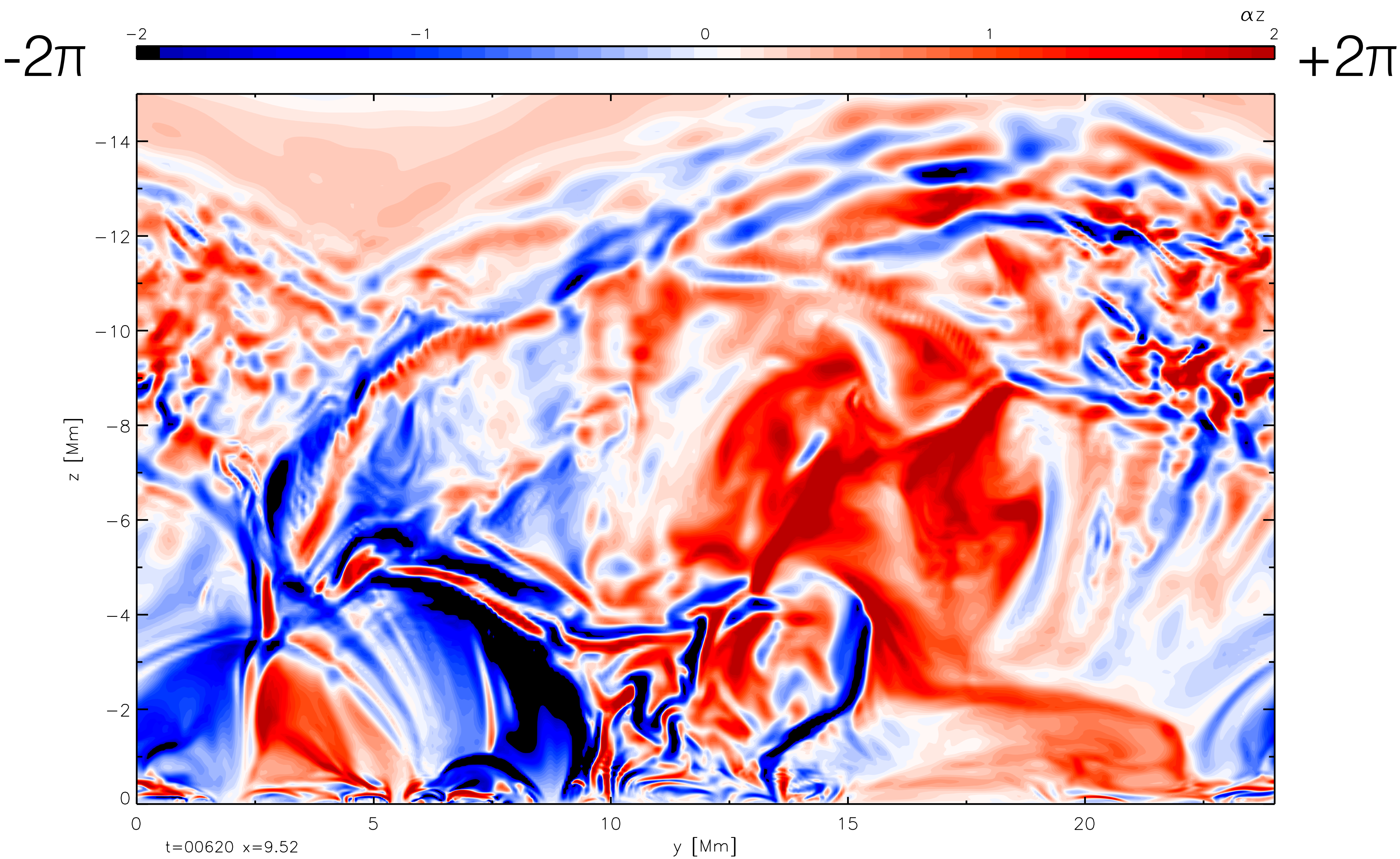
αL = total twist along field line of length L

$$\vec{j} = \alpha \vec{B}$$

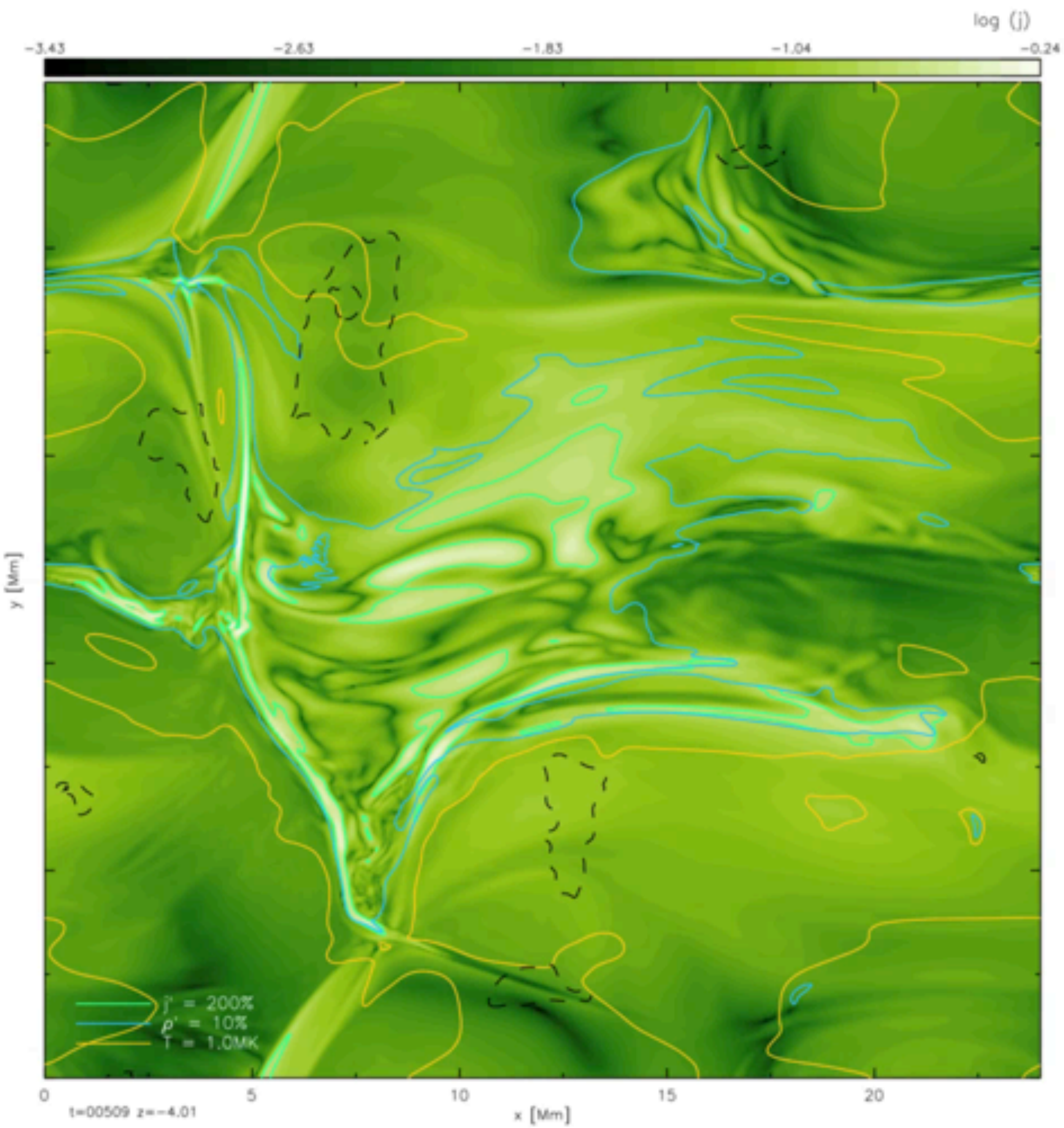
α = twist parameter [inverse length]



α times height×π



Current Sheets

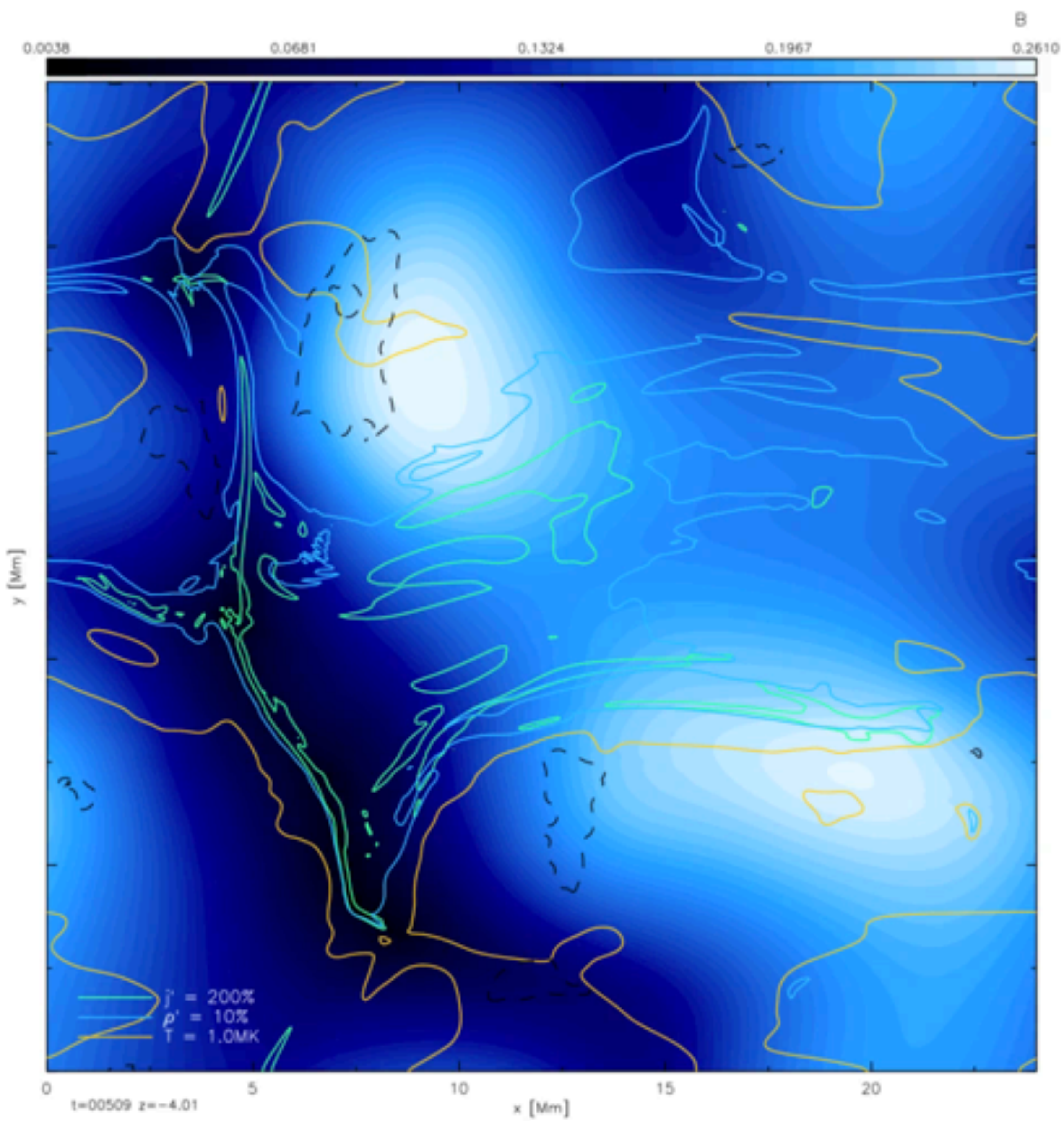


Current density in the lower corona at 4 Mm

T = 1MK
ρ' = 10%
j' = 200%

- Strongest current sheets — in terms of **absolute** current density — occurs mostly outside the coronal loops
- Actual heating is moderate in cool regions, with high density
- In low density, hot loops, absolute heating can be **smaller**

Current Sheets



Magnetic field in the lower corona at 4 Mm

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j' = 200%

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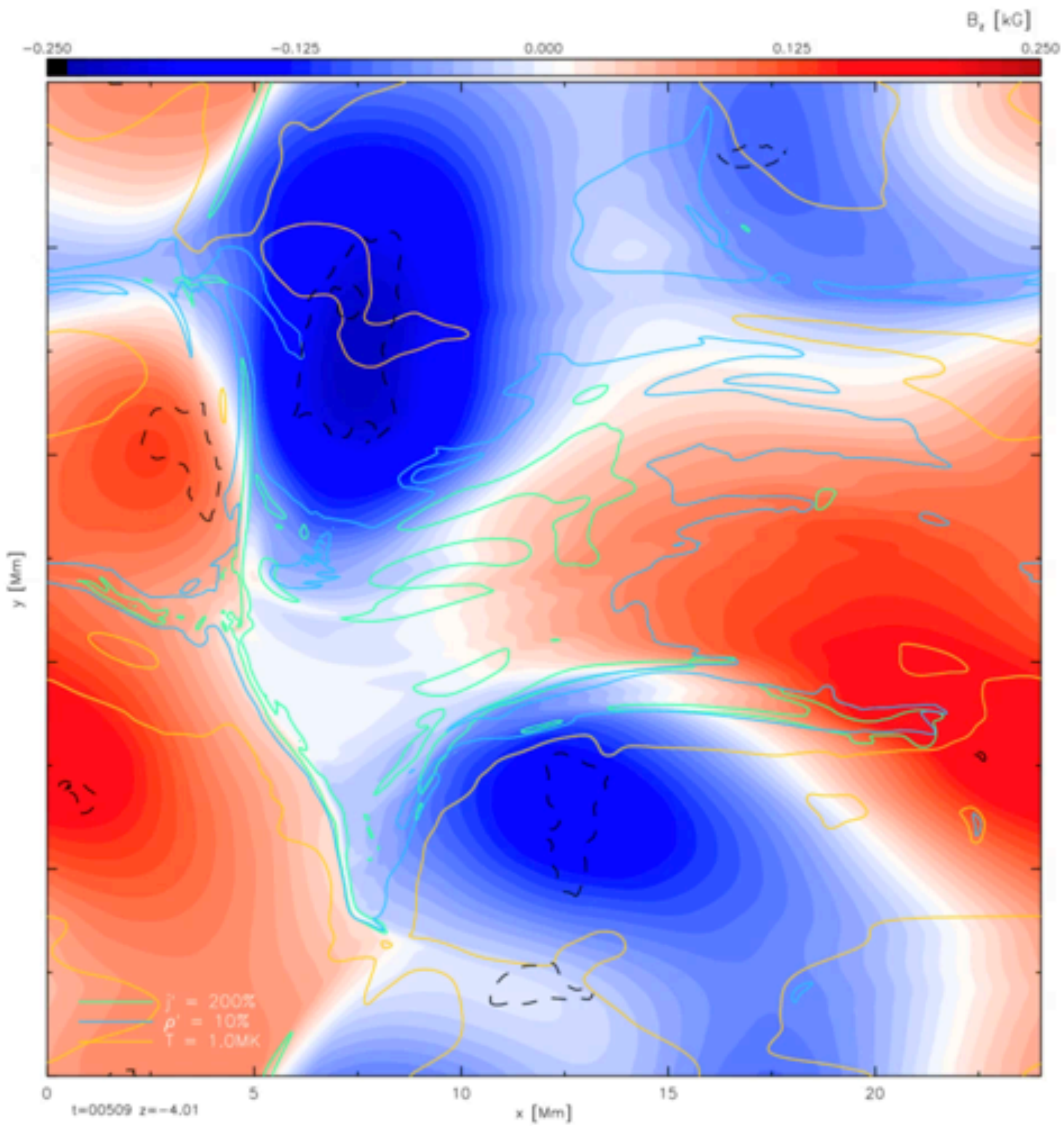
Current Sheets



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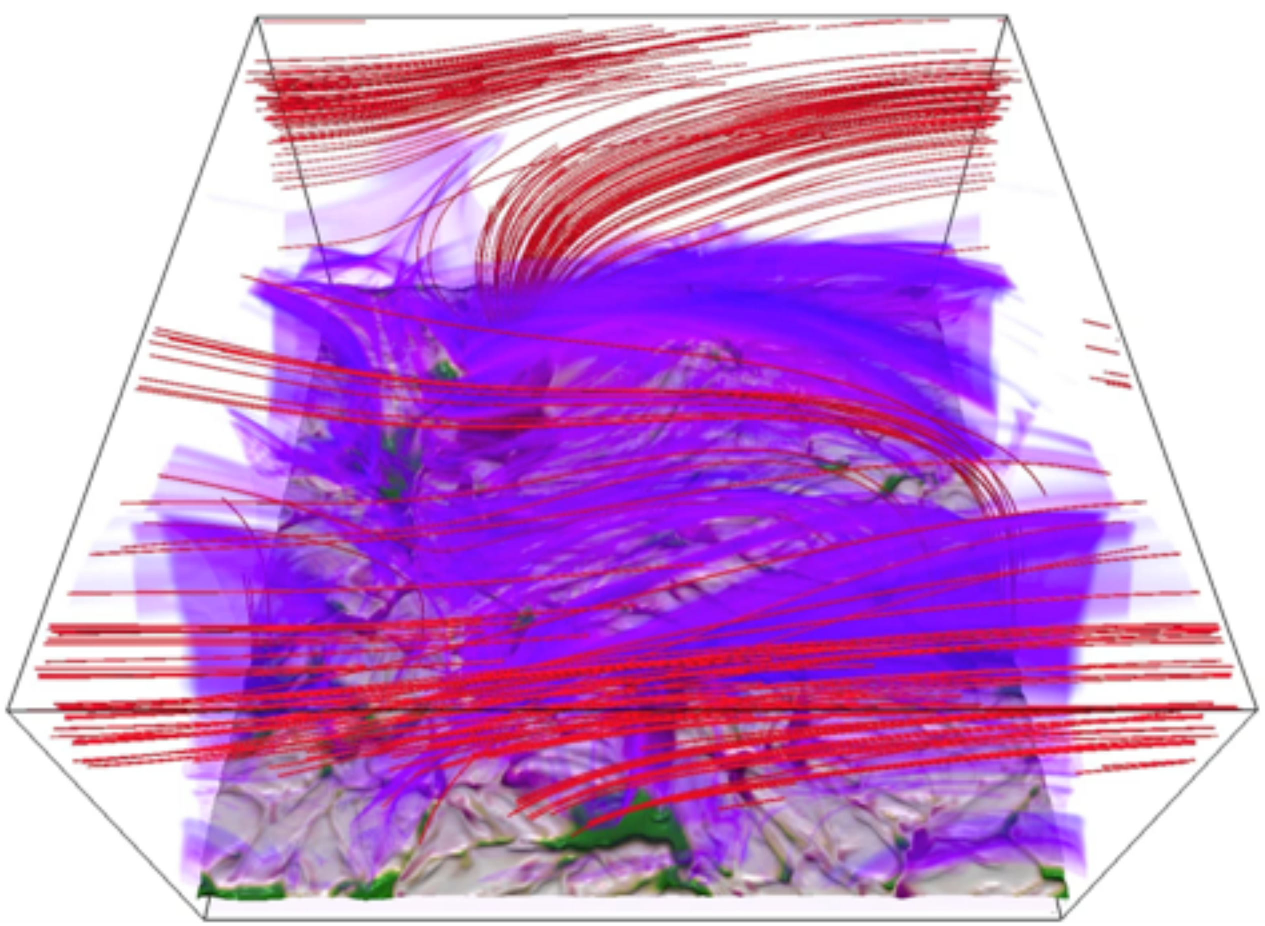
Vertical B-field in the lower corona at 4 Mm

T = 1MK
ρ' = 10%
j' = 200%

Current Sheets



Current Density

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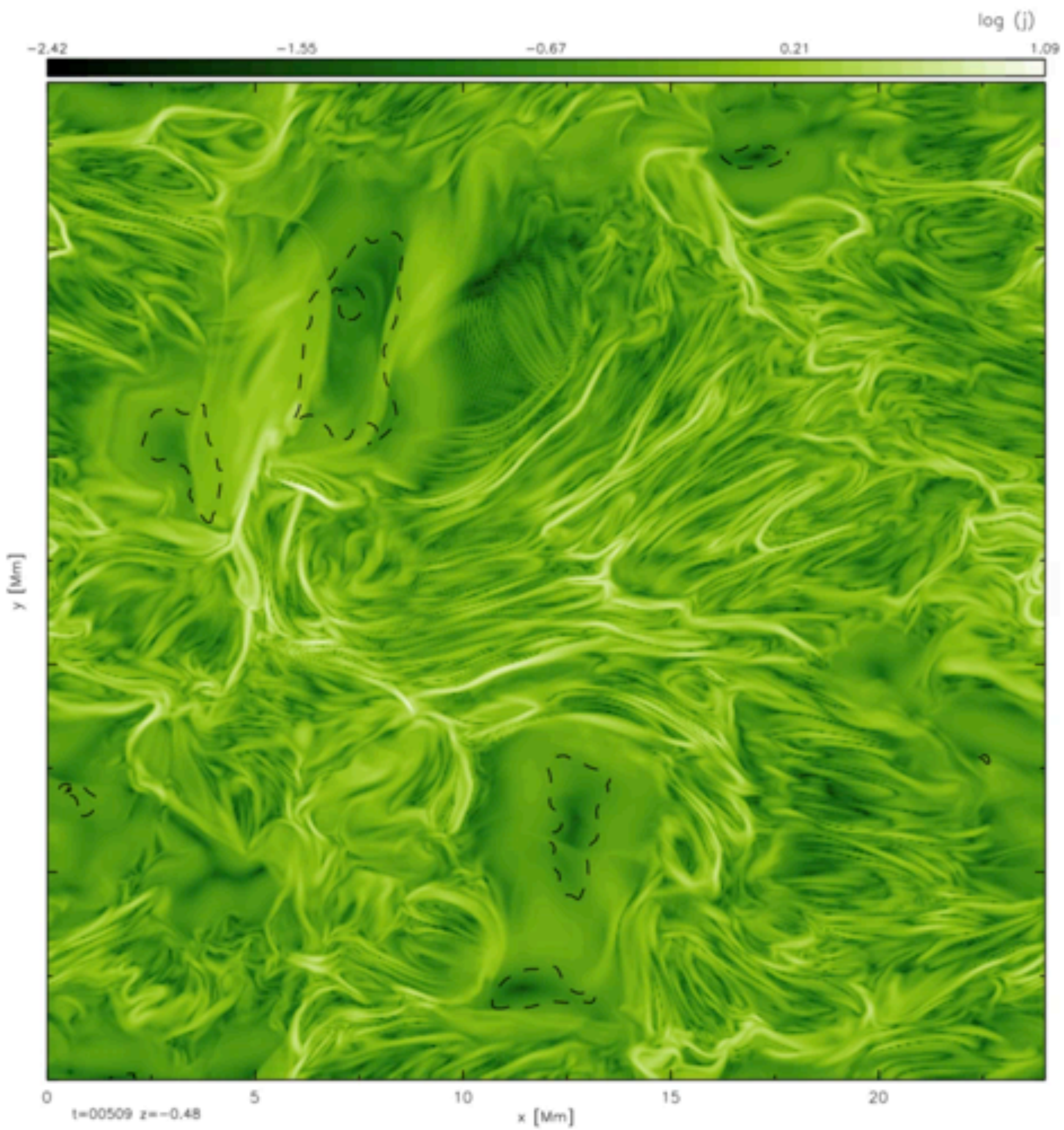
Chromospheric Waves



Current density in the lower corona at 480 km

- Ubiquitous wave activity in the chromosphere
- Confined to the dense regions and chromosphere

T = 1MK
ρ' = 10%
j' = 200%

Specific Conclusions

- Photospheric driving and consequent coronal heating from first principles
- Temperature in coronal loops > 1MK
- Development of strong current sheets mostly in the cool regions
- Chromospheric magneto-acoustic waves

General Conclusions

- Ab initio 3D MHD atmosphere modelling including corona feasible
  - cf. very detailed Oslo modelling by Viggo Hansteen tomorrow
- How can this be possible?
  - indirectly demonstrates that „fast reconnection“ works
  - AND works already at today moderate numerical resolution
- Why does fast reconnection work?
  - We have demonstrated that aL ~ unity
  - work is independent of eta
  - <W> ~ <Q> => Q „ind.“ eta => fast reconnection

Thank you