Convection and the Origin of Evershed Flows

Göran Scharmer

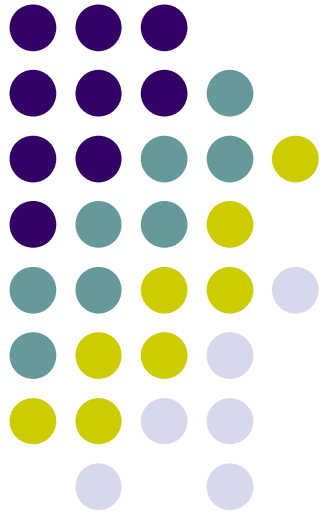
Inst. for Solar Physics, Royal Academy, Stockholm

Åke Nordlund

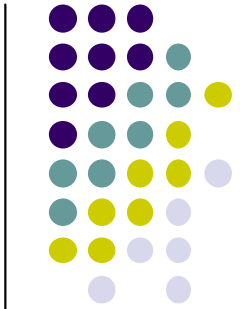
Niels Bohr Institute, University of Copenhagen

with

Tobias Heinemann and Henk Spruit



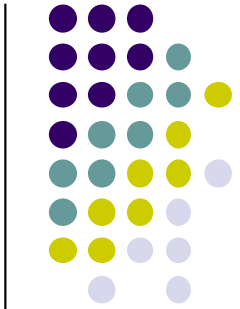
Summary of main points



- Realistic 3-D numerical models have by now essentially revealed
  - the **structure of the penumbra**, and
  - the **origin of the Evershed effect**

- Still remaining is to establish the details that quantitatively determine
  - the **penumbra luminosity**
  - the **filament widths, lengths & filling factors**
  - the **amplitude & filling f of the Evershed flow**

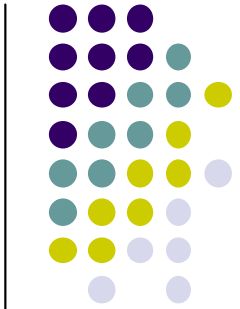
Provokative :-? No, not really!



- Qualitative agreement btw. 3-D MHD simulations with detailed and realistic physics from two groups
  - Heinemann et al 2007
  - Rempel et al 2008

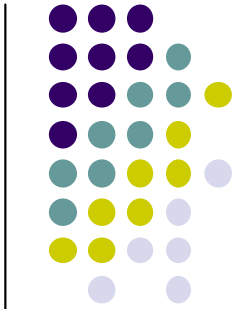
- Quantitative values depend on properties that were uncalibrated or not yet optimal:
  - Mainly the sunspot plasma beta at depth
  - Partly limited numerical resolution
  - Partly limited model size (periodicity)

Comparing sims and obs



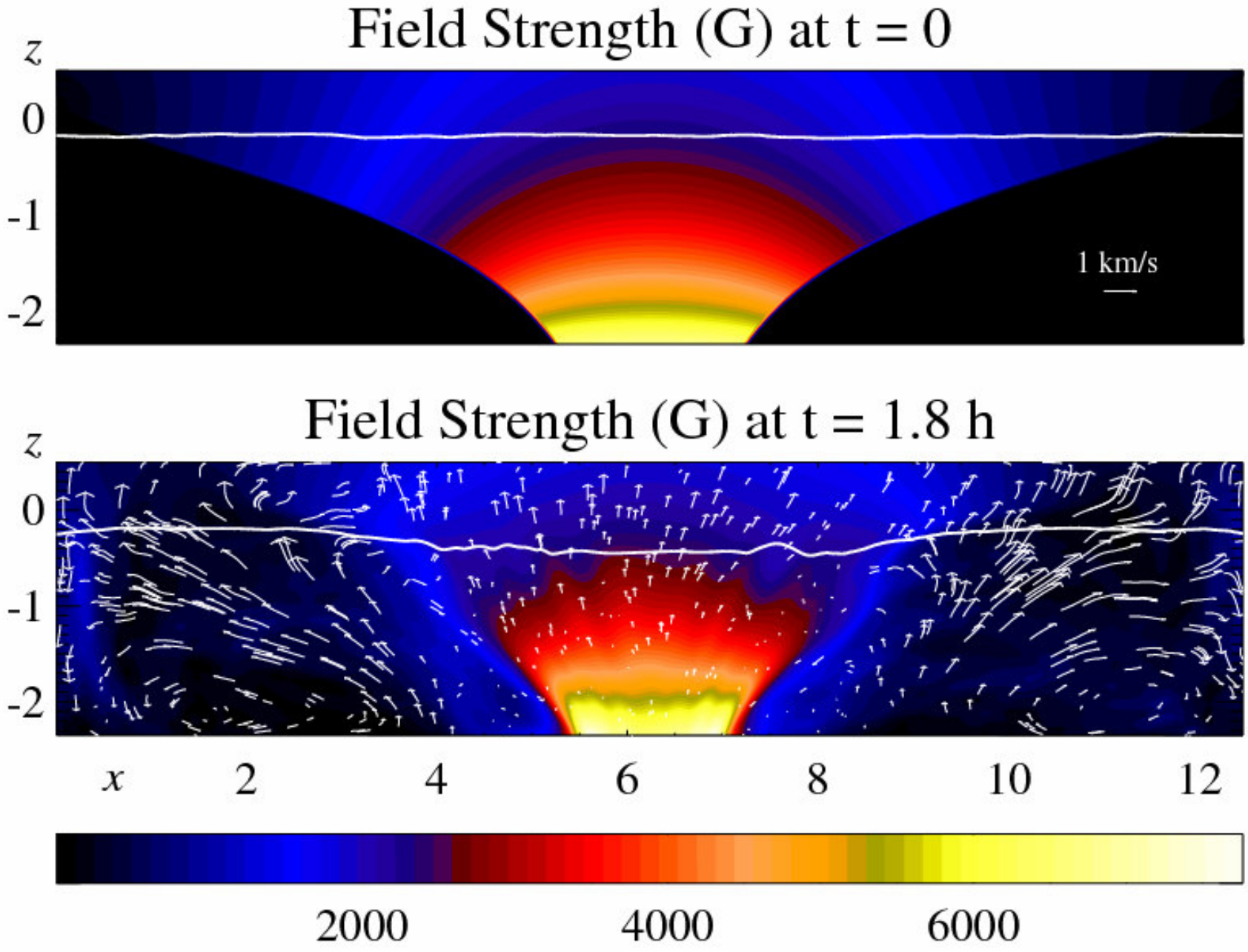
- The only safe way is to do forward comparisons!
  - Compute synthetic signals from model snapshots
  - Taking values at tau=1 is only a proxy
    - Line contribution functions are generally broad!
  - Make sure to use realistic instrument profiles
    - Empirically established point-spread-functions preferred!

Main references

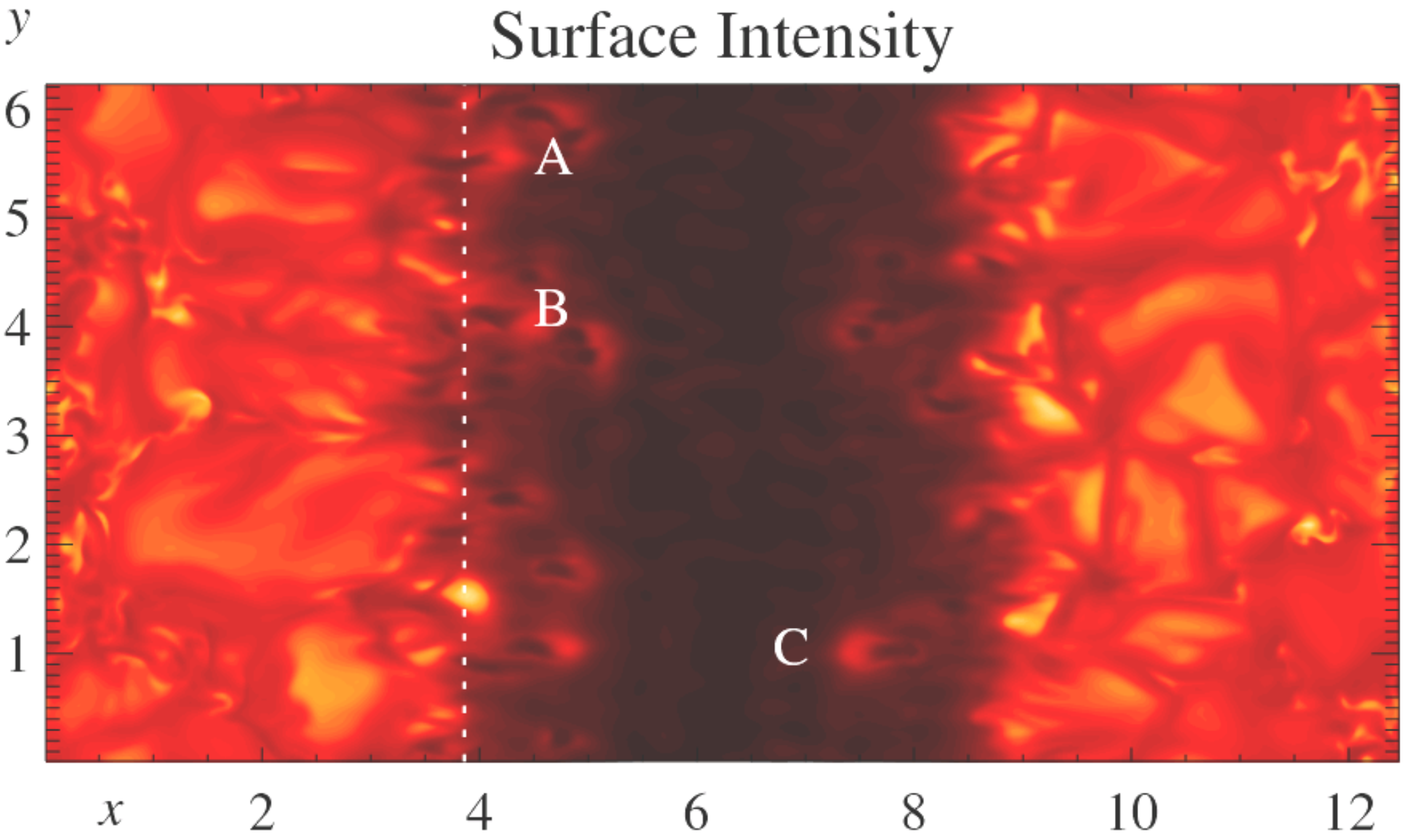


- Scharmer, Nordlund & Heinemann 2008
  - ”Convection and the origin of Evershed flows in sunspots” (ApJL 677, 149)
- Heinemann, Nordlund, Scharmer & Spruit 2007
  - ”MHD simulations of penumbral fine structure” (ApJ 669, 1390)
- Rempel, Schüssler & Knölker 2008
  - ”Radiative MHD simulations of sunspot structure” (ApJ, in press; arXiv:0808.3294v2)
- Ichimoto et al 2007
  - ”Fine structure of the Evershed effect, observed with Solar Optical Telescope aboard Hinode” (PASJ 59, 593

Cross section of model

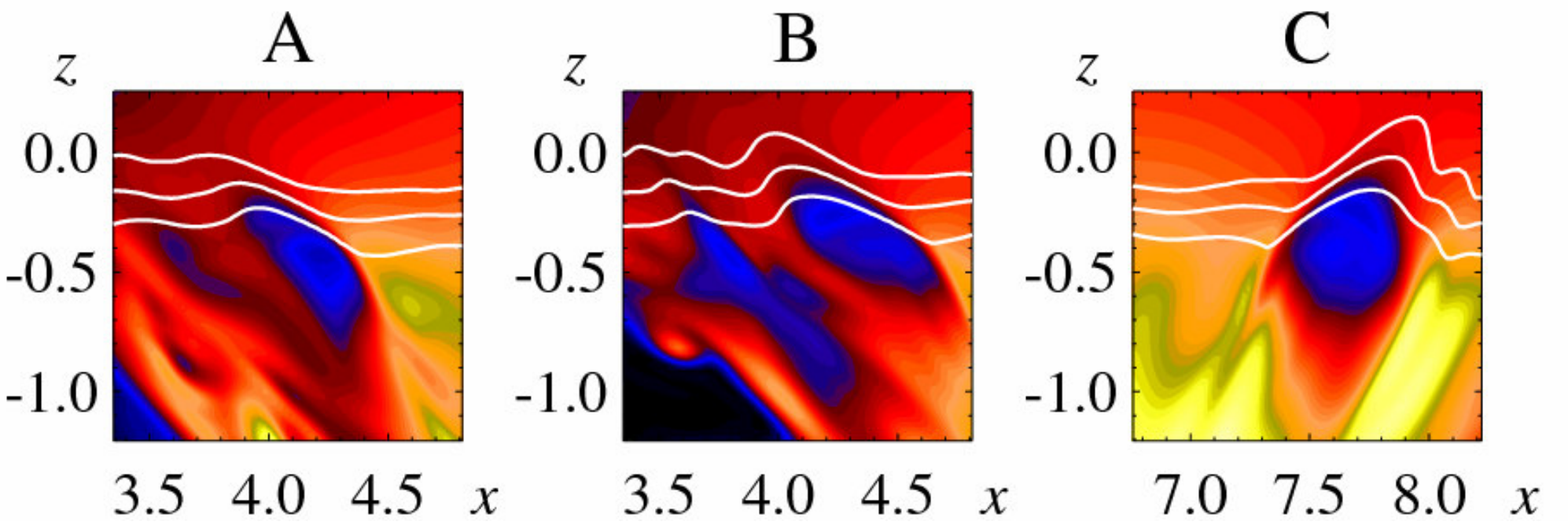


Snapshot, with dark filaments



Heinemann, Nordlund, Scharmer & Spruit 2007
Scharmer, Nordlund & Heinemann 2008

Zoom in on dark filaments, from the side



Rempel et al 2008

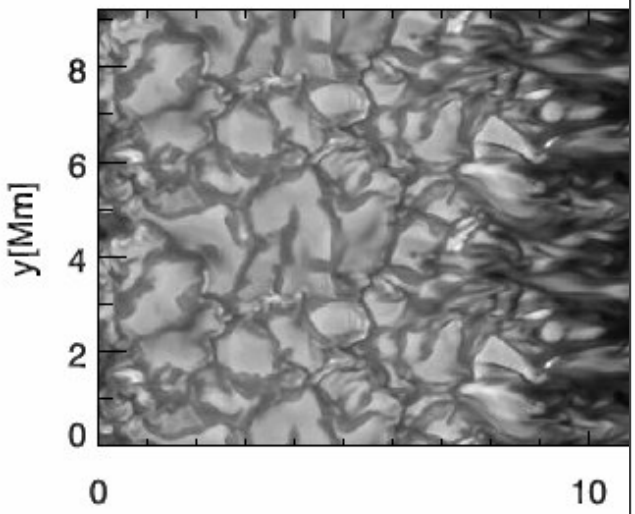


FIG. 1.— Continuum intensity image at 630
umbral dots and penumbral filaments have pe
filaments reach lengths of 2–3 Mm. The white

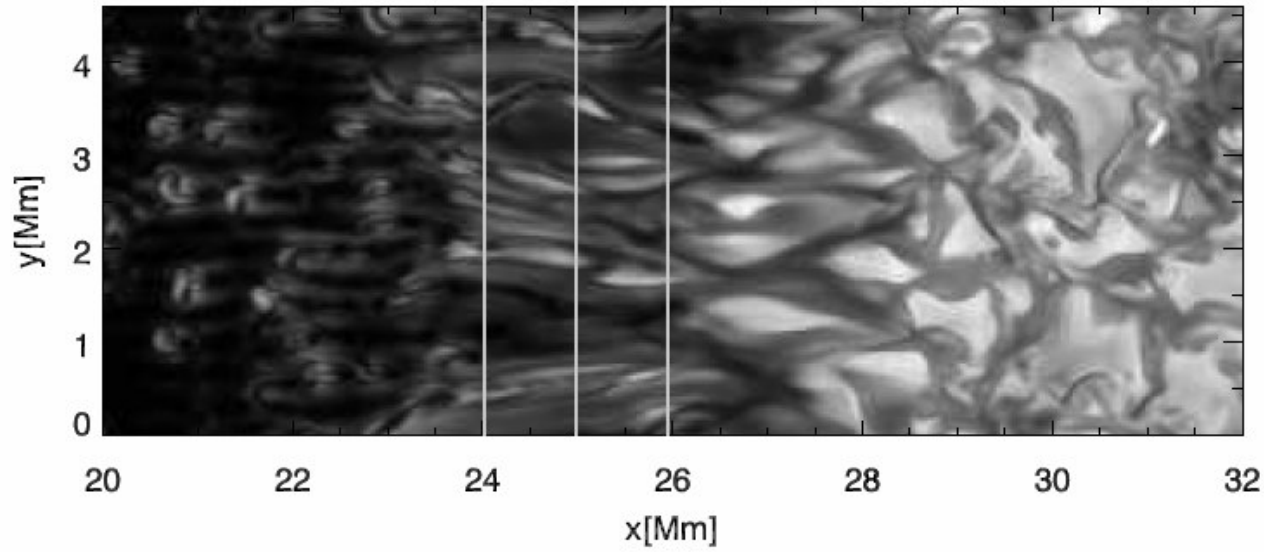
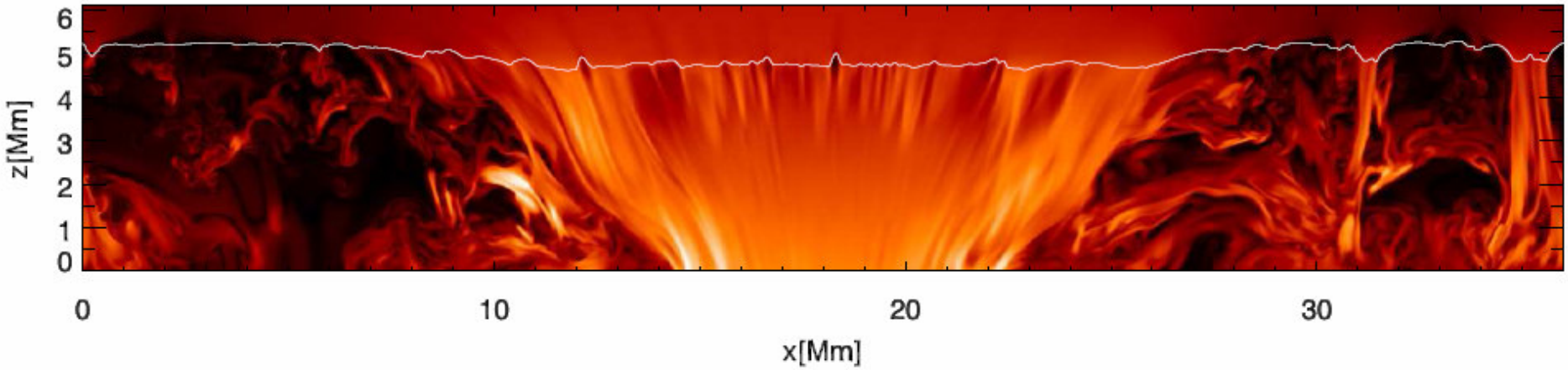
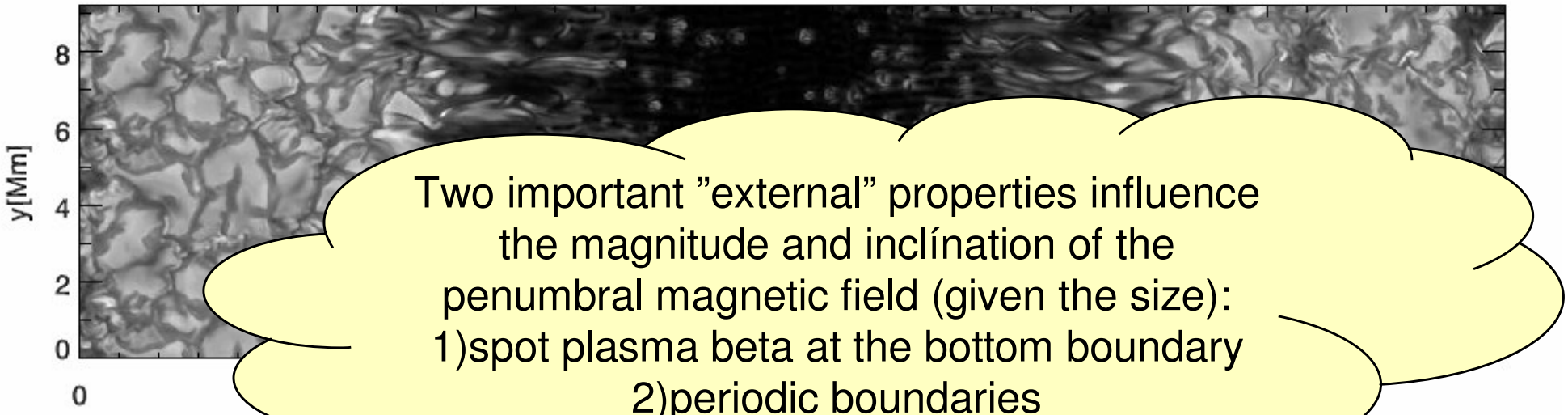


FIG. 4.— Continuum intensity image showing details of penumbral filaments. The vertical lines indicate the positions of the vertical cuts presented in Fig. 5.

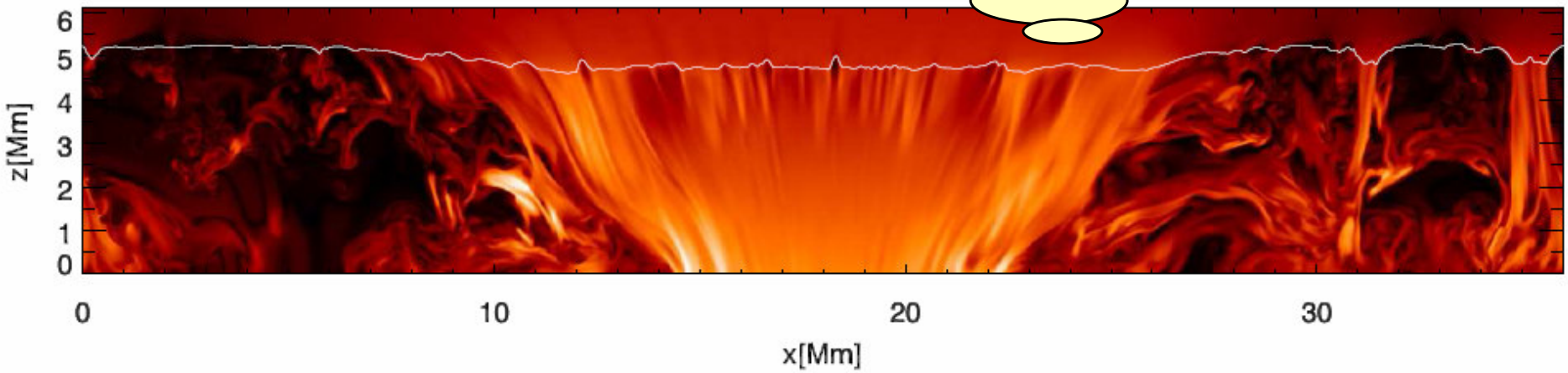


Rempel et al 2008

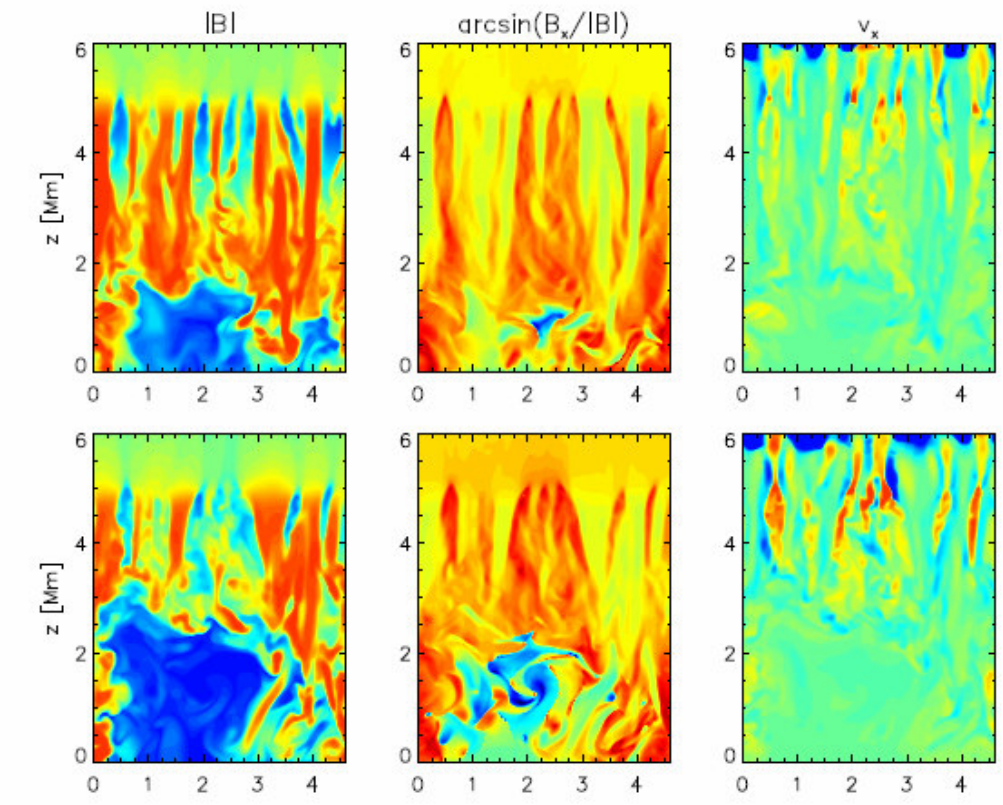


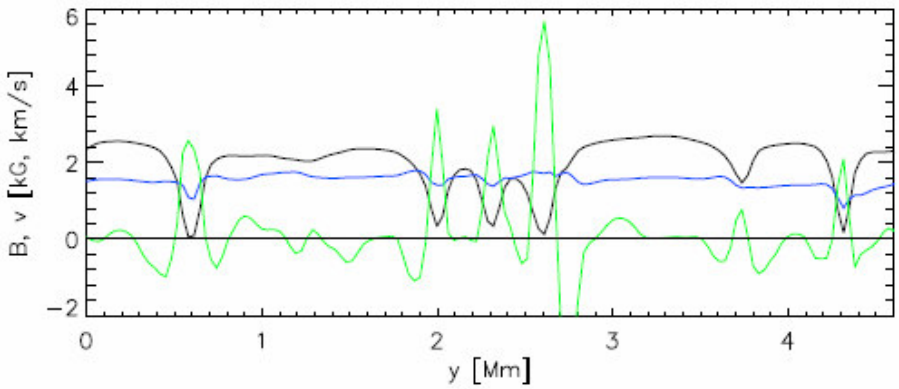
Two important ”external” properties influence the magnitude and inclínation of the penumbral magnetic field (given the size):
1)spot plasma beta at the bottom boundary
2)periodic boundaries

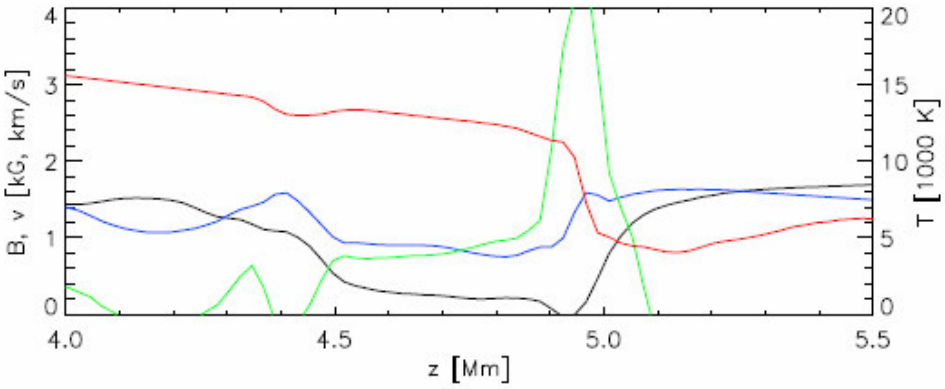
FIG. 1.— Continuum intensity image at 630 nm of the simulated sa… ment (doubled in the y-direction). The bright umbral dots and penumbral filaments have peak intensities between 40% and 90… e value outside the spot. The penumbral filaments reach lengths of 2–3 Mm. The white frame indicates the filament stu… 3.2.



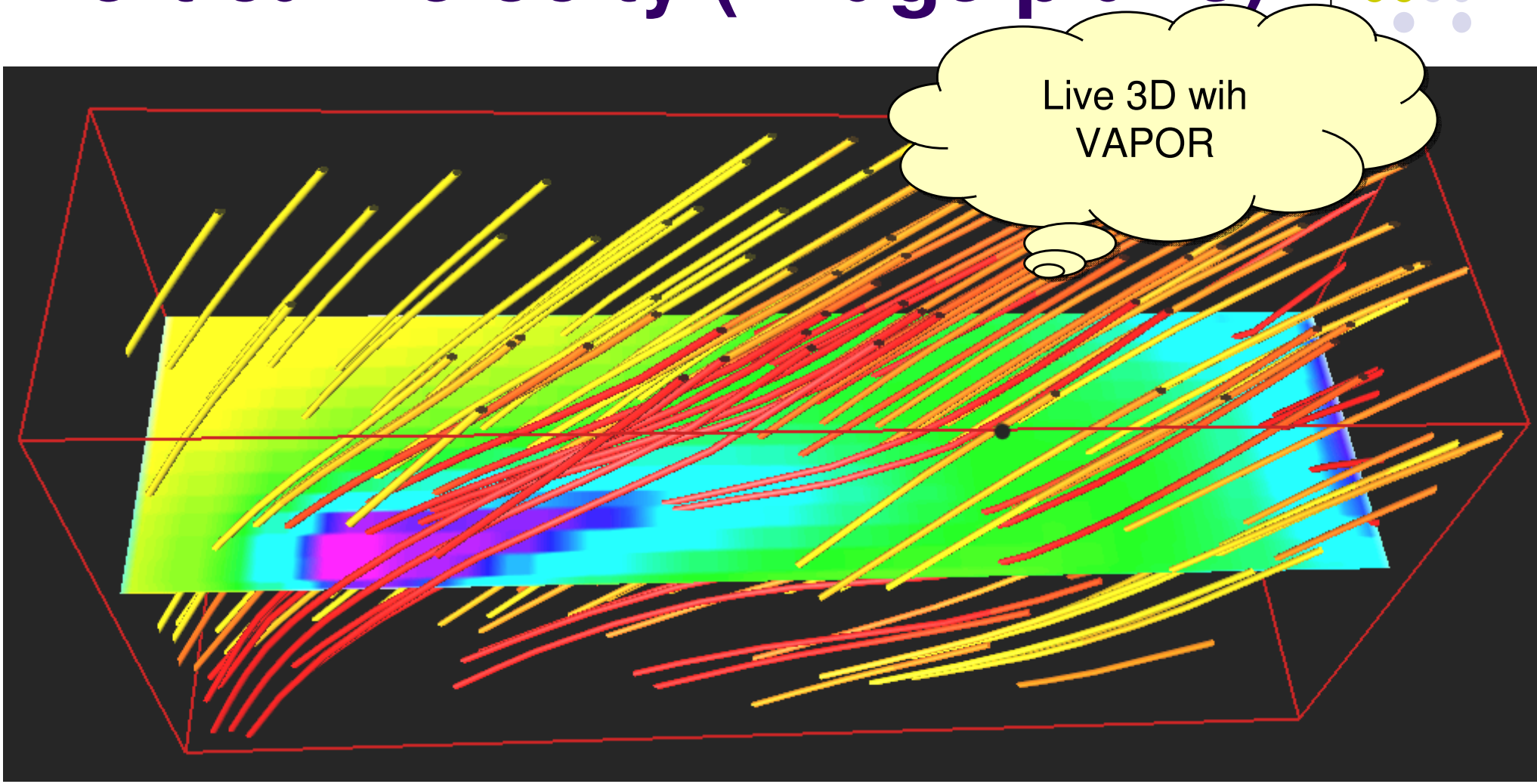
Rempel et al, cont.



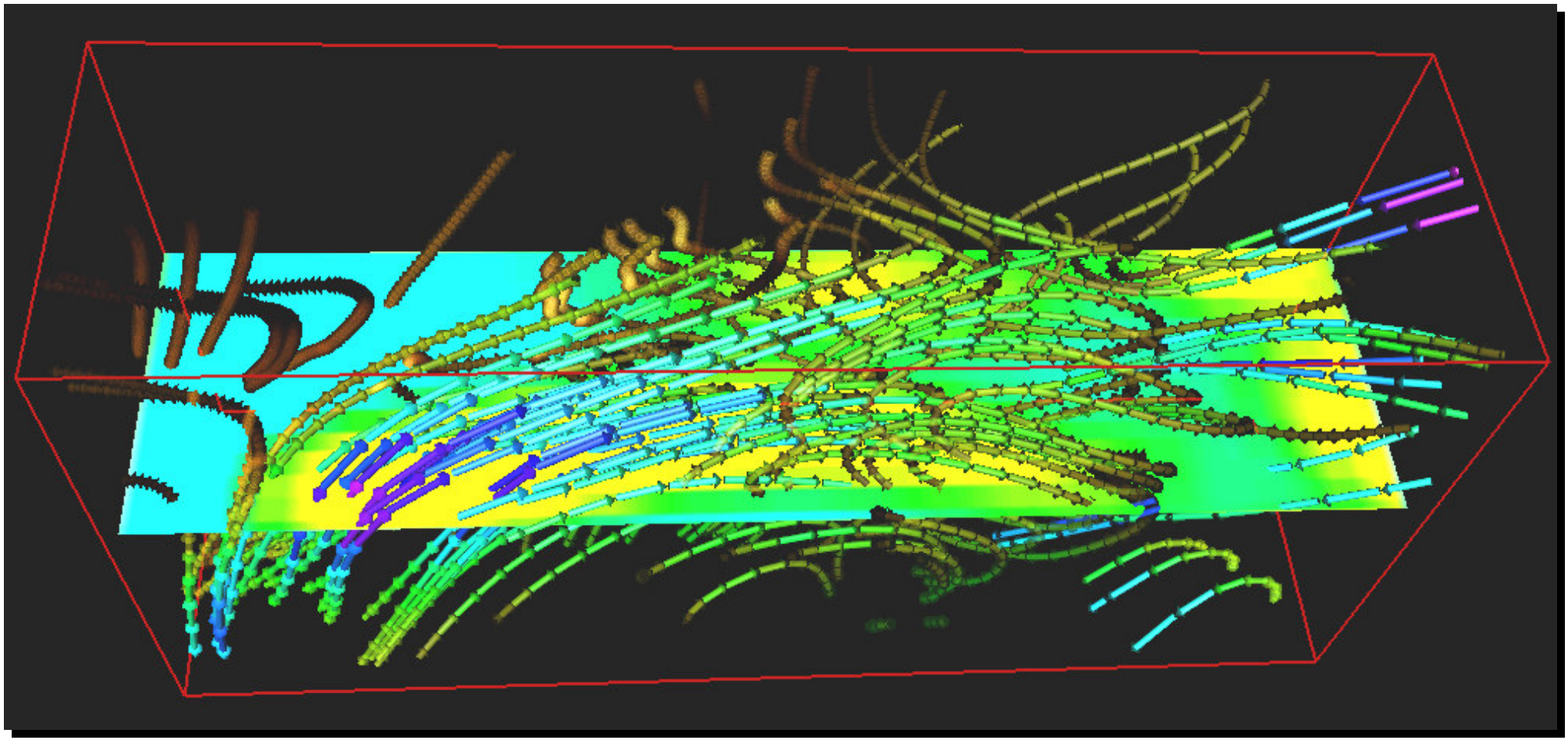




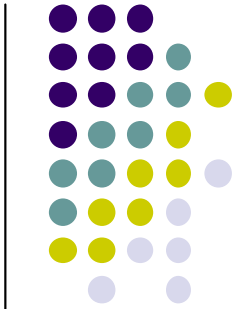
Magnetic field lines and vertical velocity (image plane)



Velocity field and magnetic field strength (image plane)

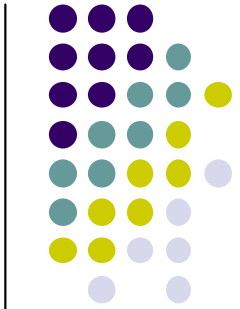


”Local” penumbra model(!)



- Periodic ”across”
  - Fine, so are the previous models
- Periodic ”along”
  - Hm, can one do that???
    - What about the ”inclined penumbra”?!
  - Yes, one can!
    - Which proces that inclination is not essential!
- Allows studying dependence on strength and inclination of B
  - Penumbra luminosity
  - Penumbra filament properties

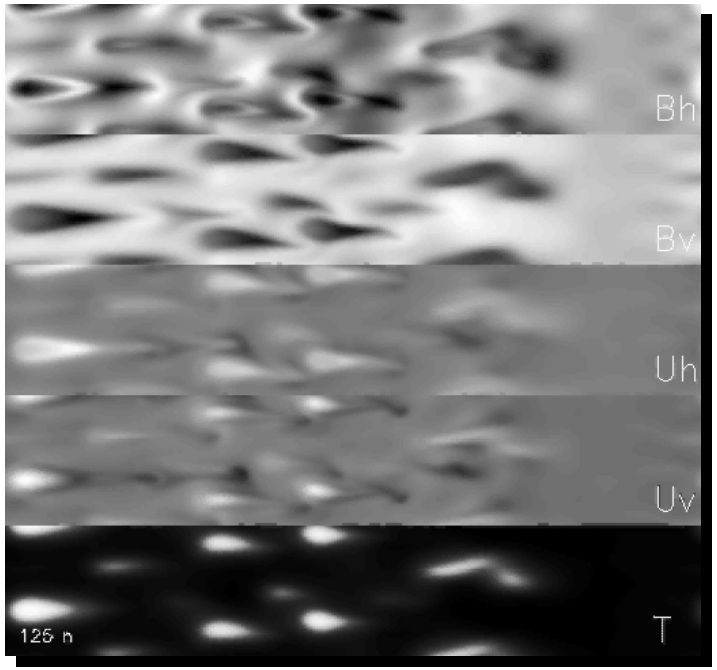
Mechanisms

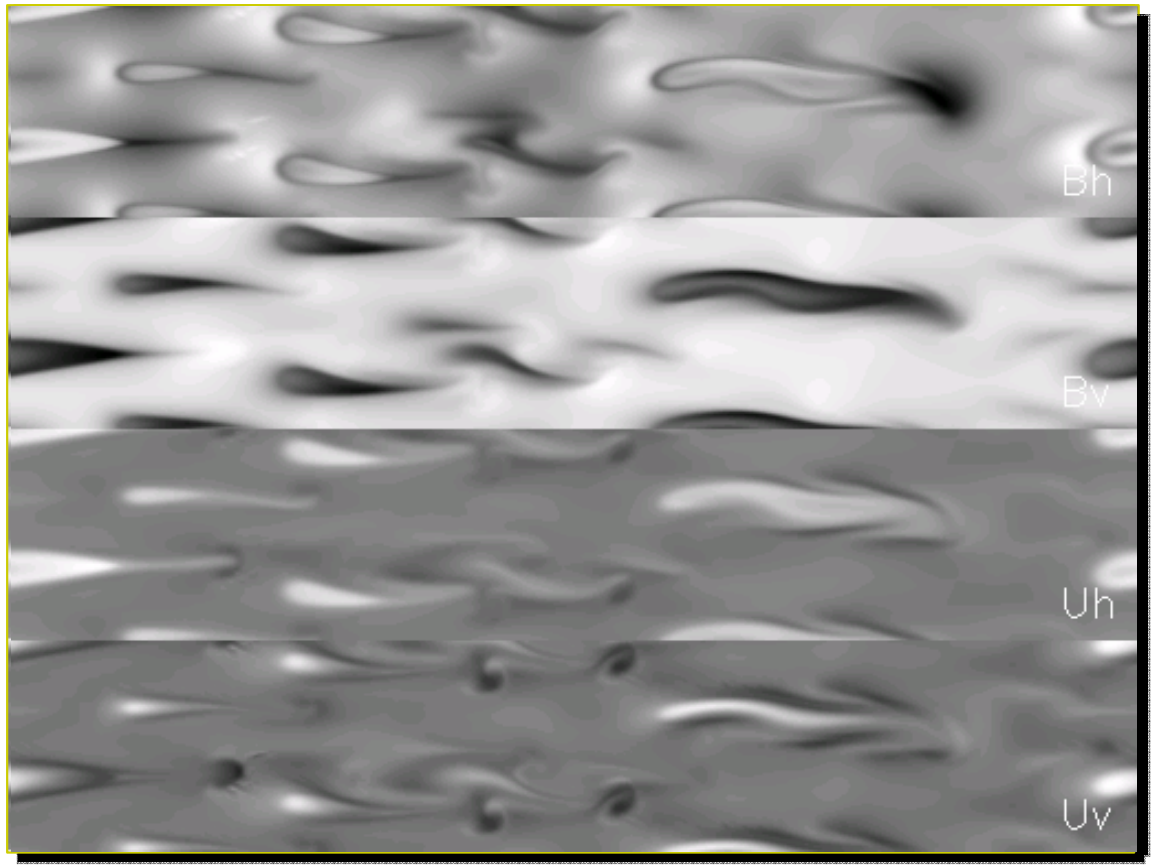


- Convection – convective instability with B
  - If suppressed the optical surface sinks until the pressure and density become large enough to allow convection
  - Average upflow must be 1-2 km/s to sustain surface luminosity
    - Models that ”pipe” that energy horizontally too far don’t work!
- Mass conservation – overturning motions
  - Diverted into the ”easiest” direction = radially outwards
  - Amplitude needs to be high; semi-2D flow (cf. 3D)

Penumbra in-a-box; resolution

- 750 x 6250 km
- resolution:
  - 24 km
  - 12 km
  - 6 km

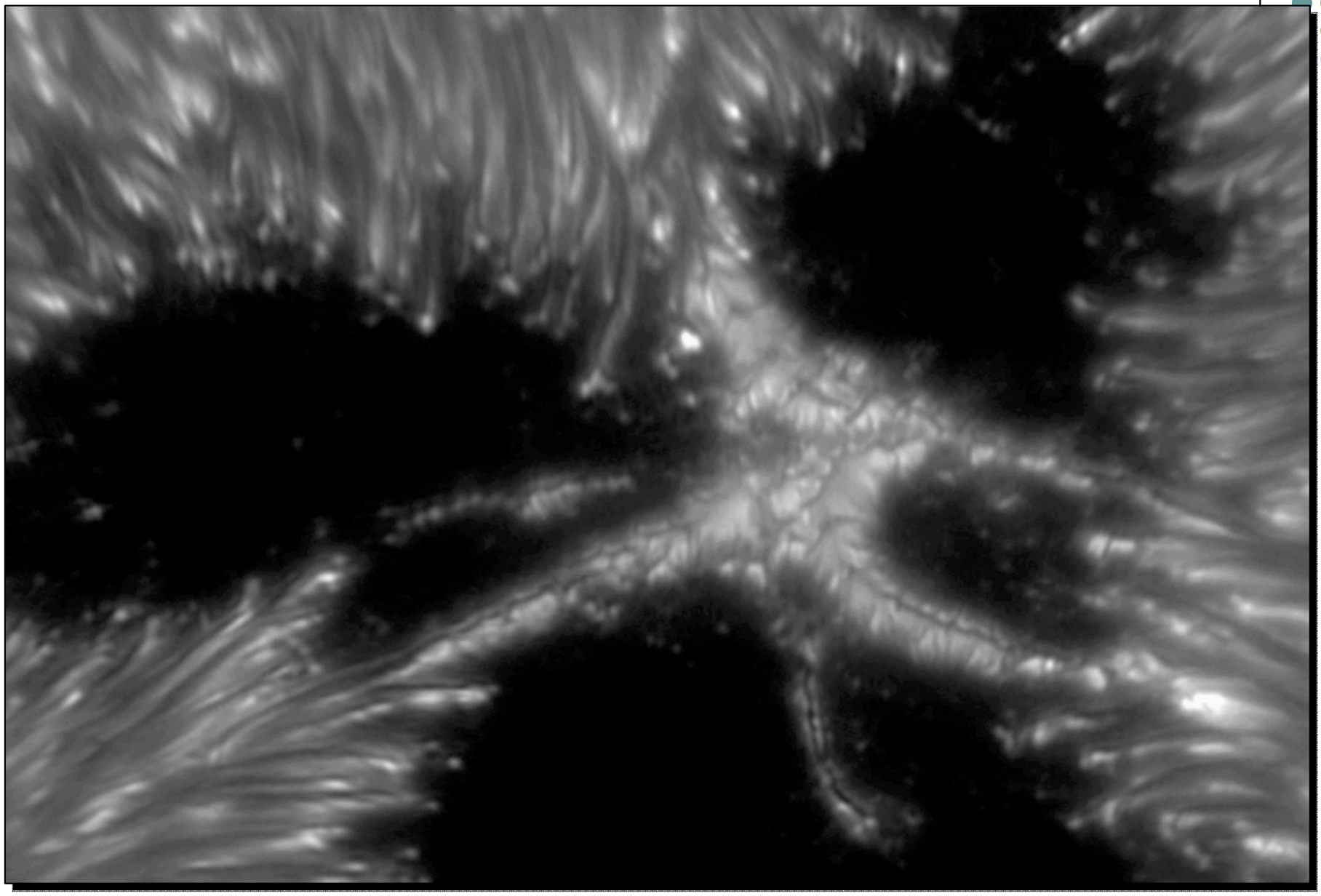




Mechanisms, cont.

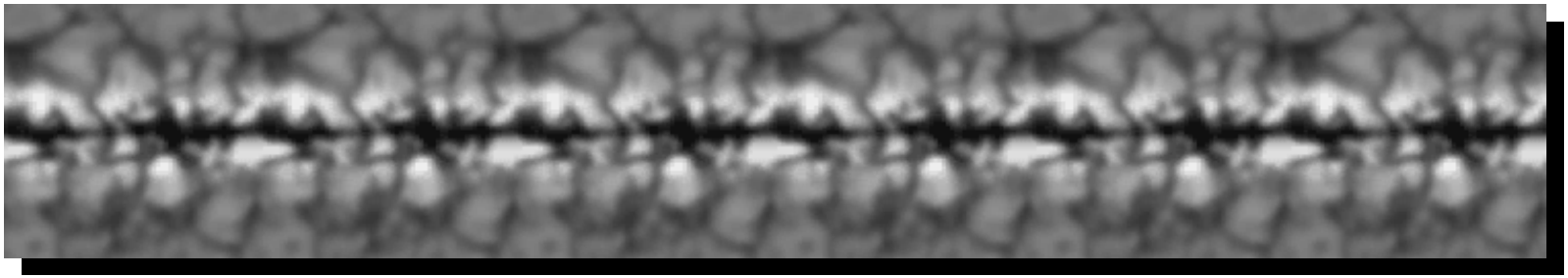
- Bending field lines down
  - Cooling increases the weight / volume with ~factor 2
    - Facilitates the bending
  - How come the force is strong enough??
    - If it wasn't the system would auto-reconfigure / sink!
- Dark cores
  - Are due to the magnetic field cusp above the filament
    - Do ***not*** correspond to downflows at filament centers!
  - Cf. umbral light bridges
    - Lites et al 2004
    - ÅN 2006, Heinemann 2006

Lites et al. 2004: 3-D structure



Sunspot lightbridge dark cores

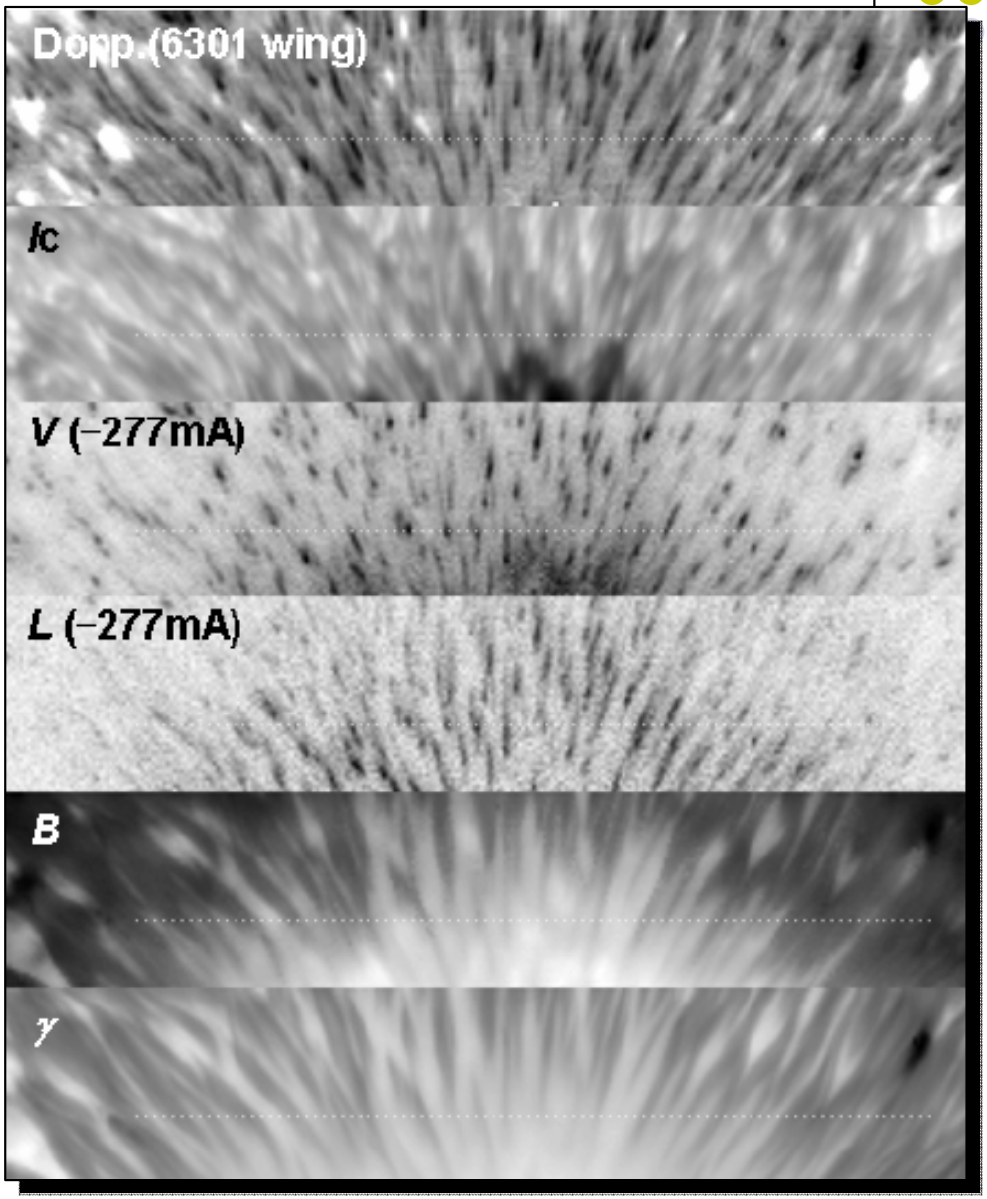
- Lightbridge simulation (ÅN 2006)

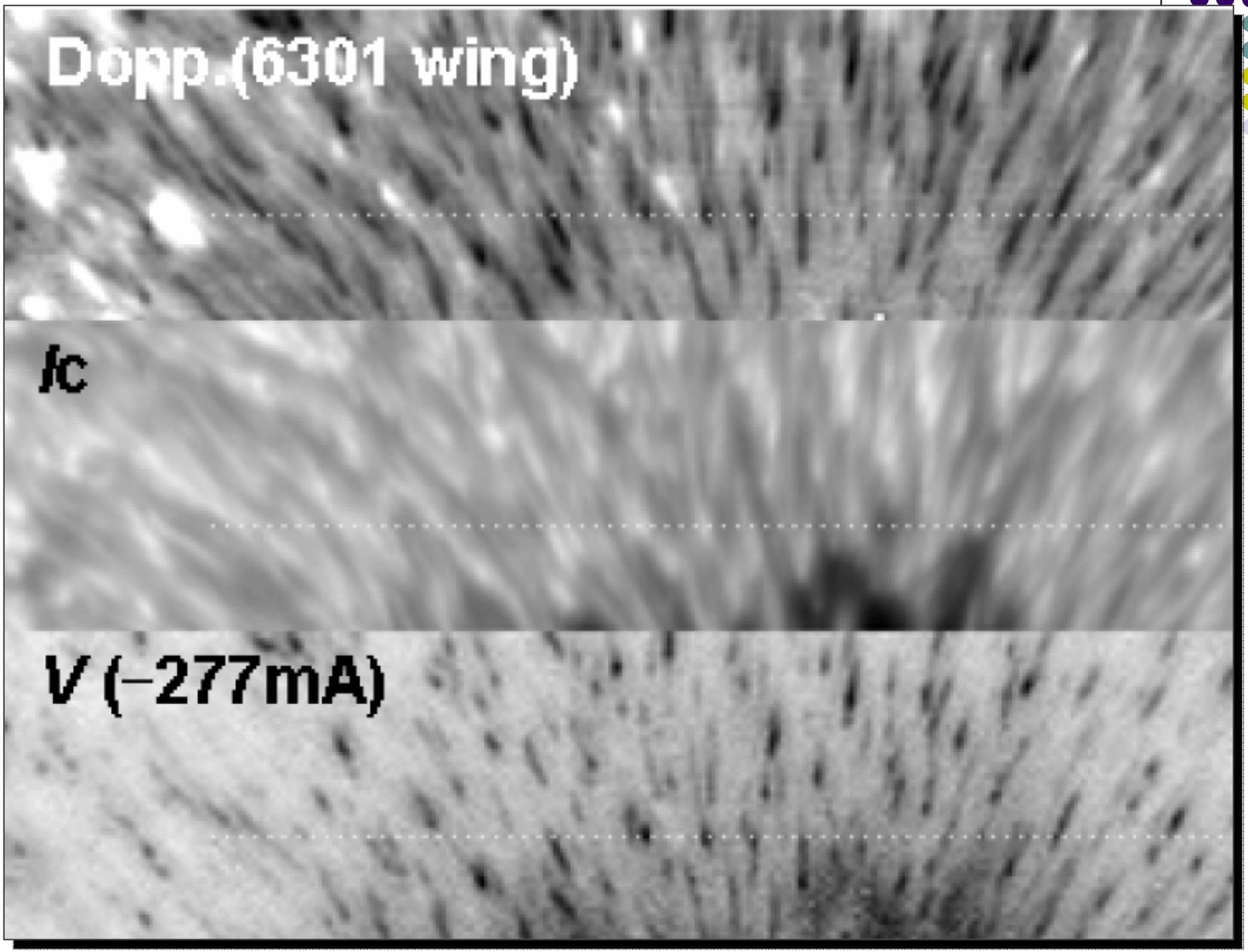


  - scale 1.5 x 1.5 x 3 Mm
  - resolution 12x12x12 km
  - with radiation and ionization

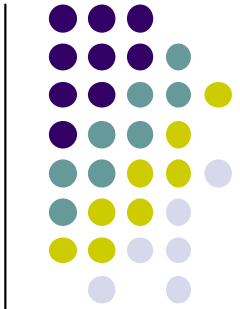
Penumbral structure, Hinode

- When observed with sufficient resolution (Hinode; Ichimoto et al 2007), the typical structure sizes in the radial direction are only a few arcseconds
  - The panel sizes are approx 35 x 6 arcsec




Dopp.(6301 wing)
Ic
V (−277mA)

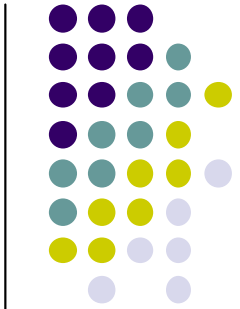
Summary of main points



- Realistic 3-D numerical models have by now essentially revealed
  - the **structure of the penumbra**, and
  - the **origin of the Evershed effect**

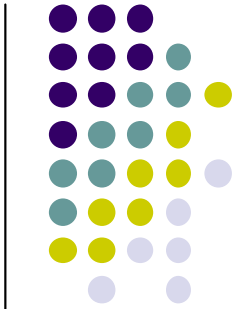
- Still remaining is to establish the detailed properties determining
  - the **penumbra luminosity**
  - the **filament widths and lengths**
  - the **amplitude of the Evershed flow**

Conclusions



- The filamentary structure of the penumbra is due to
  - Overturning convection, constrained by an inclined, strong magnetic field

- The Evershed effect is due to
  - The horizontal, top part of the convective flow, constrained to overturn mainly in the radial direction



Thanks for your attention!

Acknowledgments

The results presented here were made possible by hardware grants to ÅN from the Danish Center for Scientific Computing, and by Columbia computing resource grants to Bob Stein from NASA / NAS.

Visualizations partly done with VAPOR from NCAR.