Exploring the Sun and its effects on the Earth's atmosphere and physical environment...

HIGH ALTITUDE OBSERVATORY

MHD Simulations of Sunspot Structure

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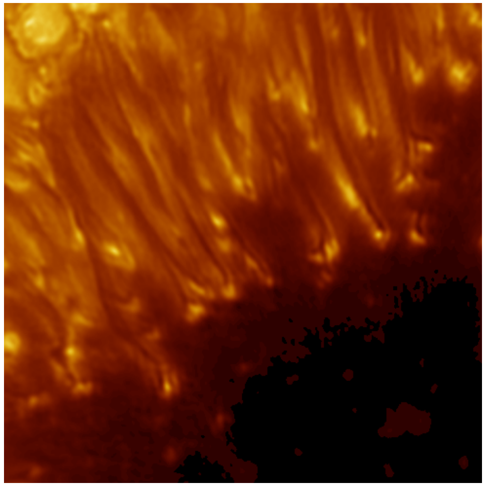
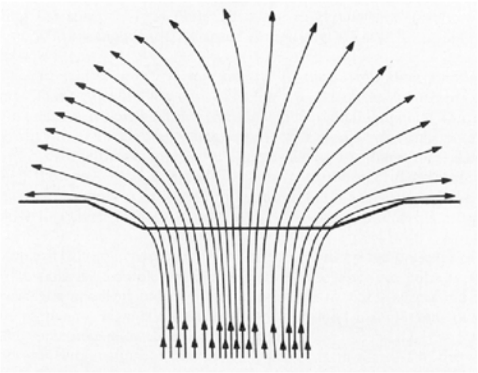
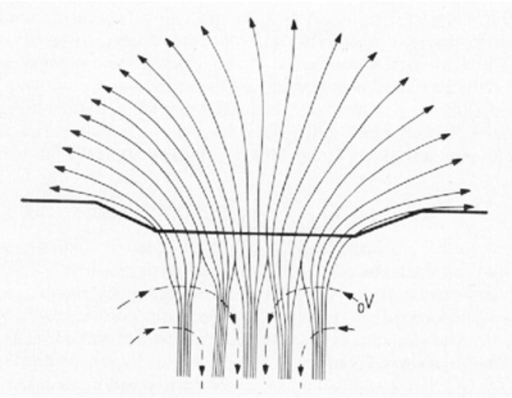
Key questions of sunspot structure

- Energy transport in sunspot
  - Umbral dots
  - Penumbral filaments
  - Light bridges
- Energy transport outside sunspot
  - Moat flows
- Subsurface structure
  - How deep? Dynamical disconnection?
  - Monolithic? Cluster of flux tubes?

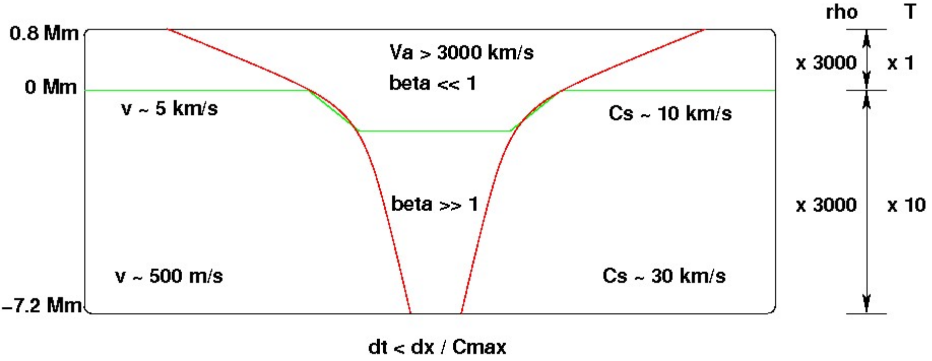


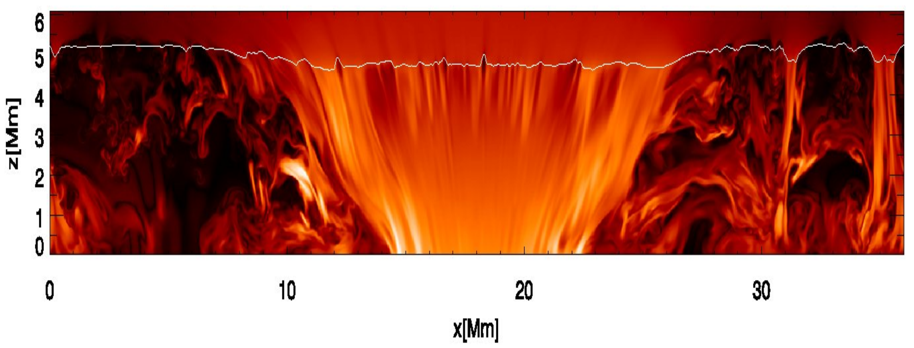
Scharmer et al. (2002)





Challenges for MHD simulations





- “Realistic physics” (MURaM code A. Vögler, MPS & HAO)
  - Multi ray radiative transfer
  - Opal equation of state
- High density contrast, large variation in plasma beta
  - Robust numerical scheme
  - Non-linear artificial diffusivities required
    - (shocks) $\Delta x\, \Delta \leftrightarrow (\Delta x)^4\, \Delta^2$ (smooth regions)
- Wide range of characteristic velocities
  - Artificial limitation of Alfven velocity (through reduction of Lorentz force)
- Large scale problem with a lot of fine structure
  - Large grid sizes required

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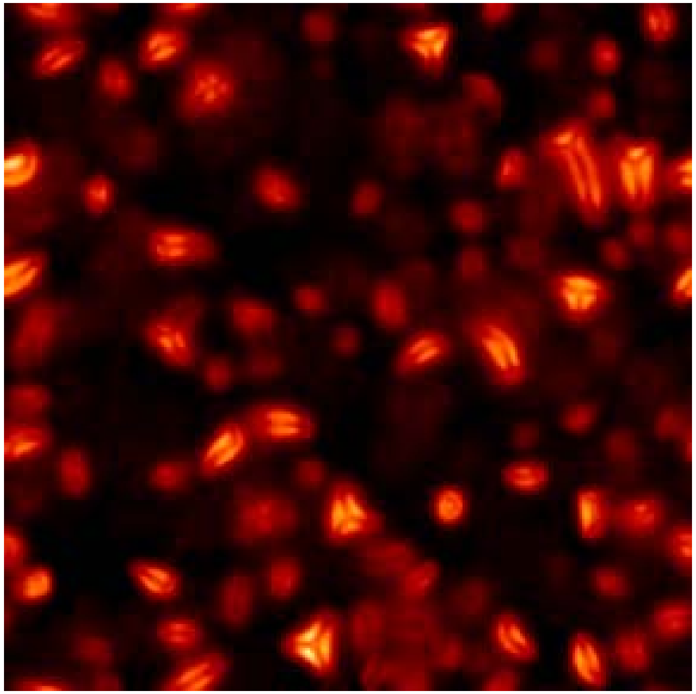
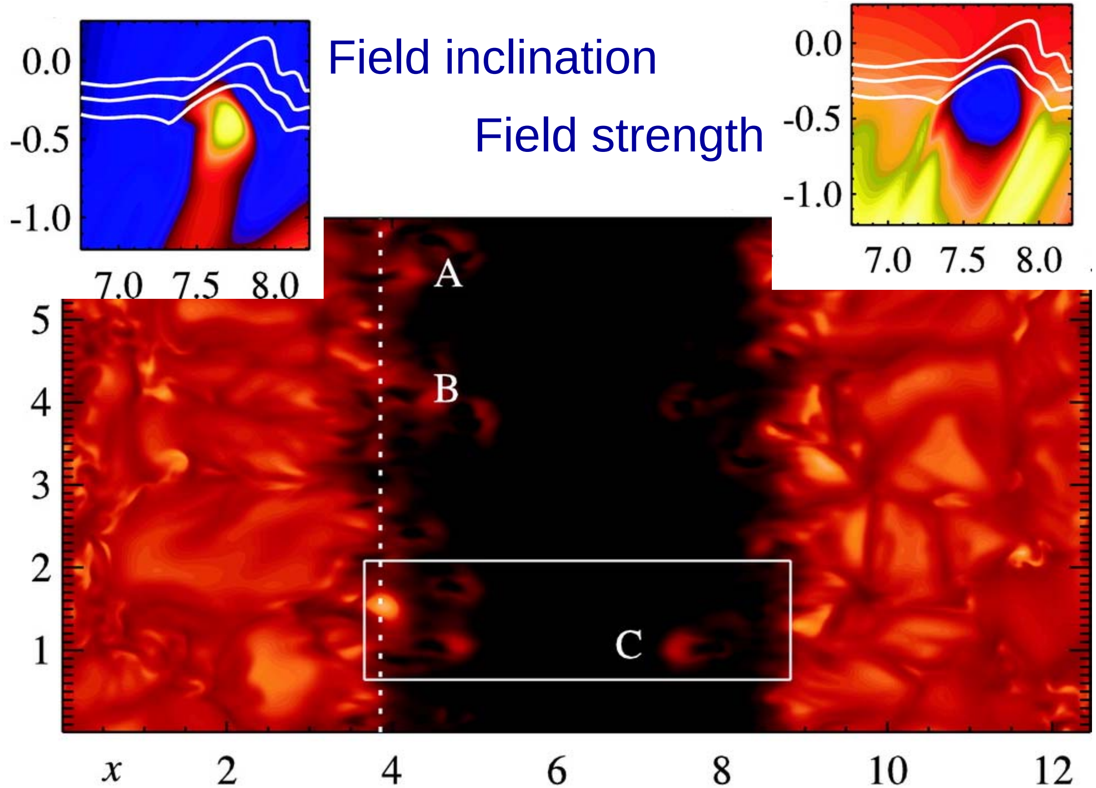
Previous work





Local-box simulation of a small volume (6 Mm×6 Mm×1.6 Mm) in a sunspot umbra (Schüssler & Vögler, 2006)

- Umbral dots with dark lanes

First attempt penumbra: Heinemann et al. (2007)
12 Mm×6 Mm×3 Mm

- Short filaments with dark lanes, weakened inclined field
- Horizontal flows of magneto-convective origin (Scharmer 2008)

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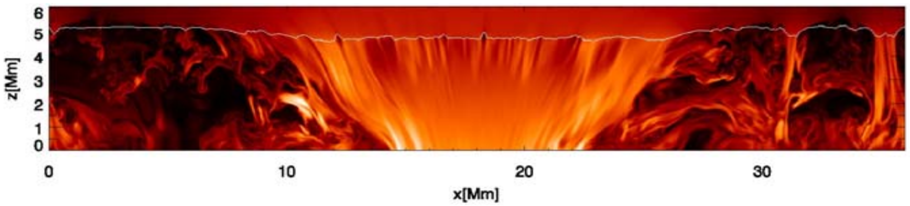
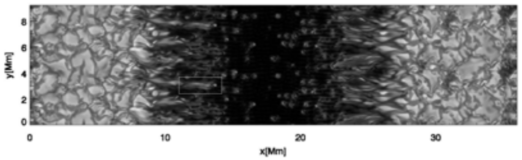
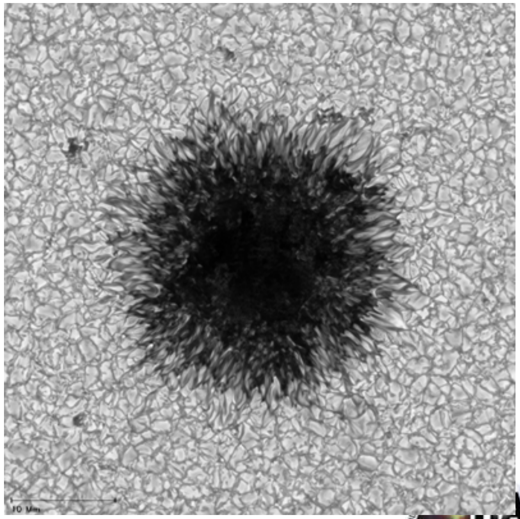
Simulation setup

- Boundary conditions
  - Periodic horizontal boundaries
  - Vertical field (bottom), potential field (top)
  - Open bottom boundary, closed in strong field regions
  - Closed top boundary
- Initialization with self-similar monolithic field



- Two geometries:
  - 'slab'
    - Focus on details
    - Fine structure
  - 'round spot'
    - Focus on large scale
    - Moat flows





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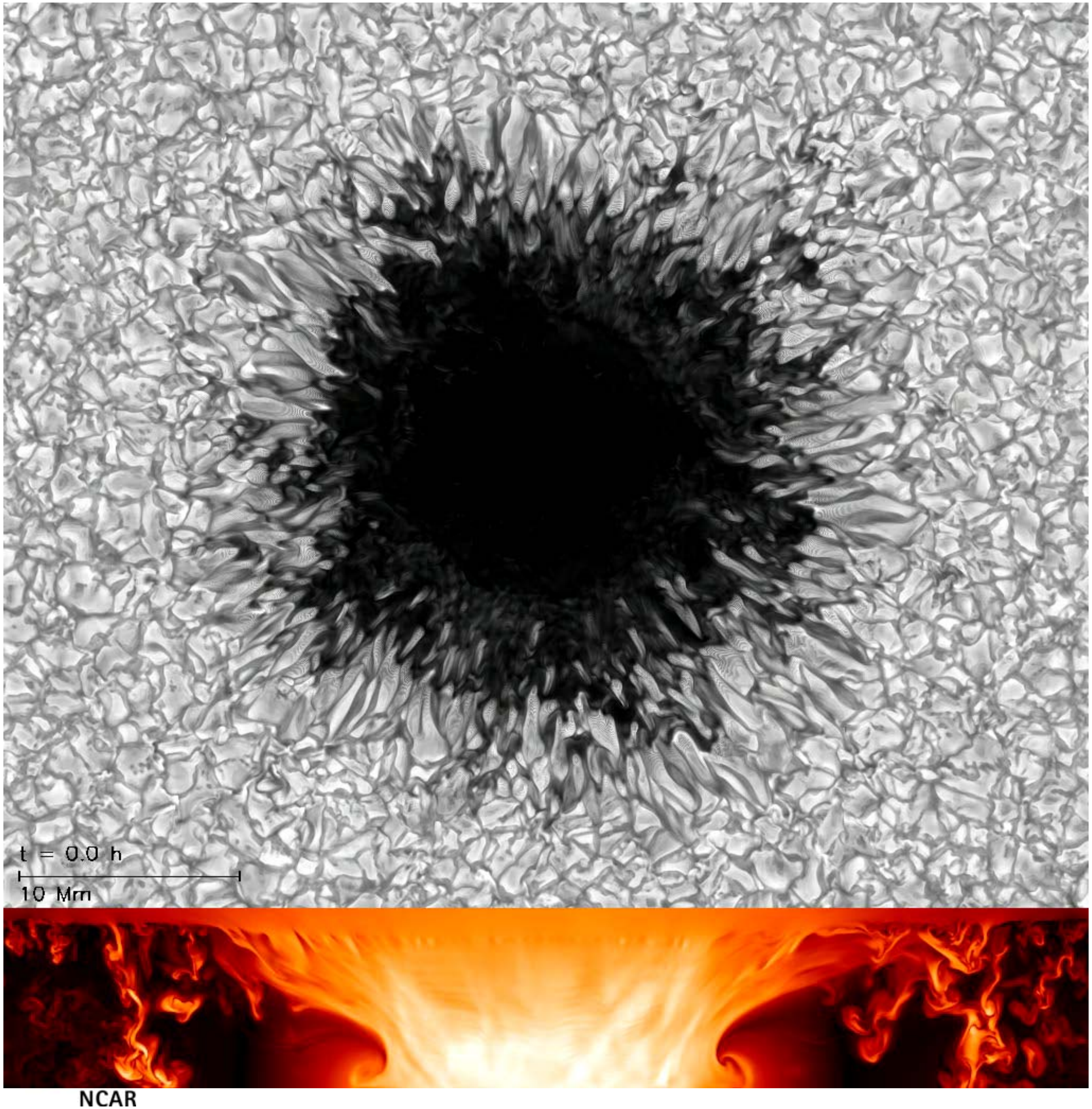
25 Mm spot in 50x50x8 Mm box



Field strength:
- ~3500 G (center)

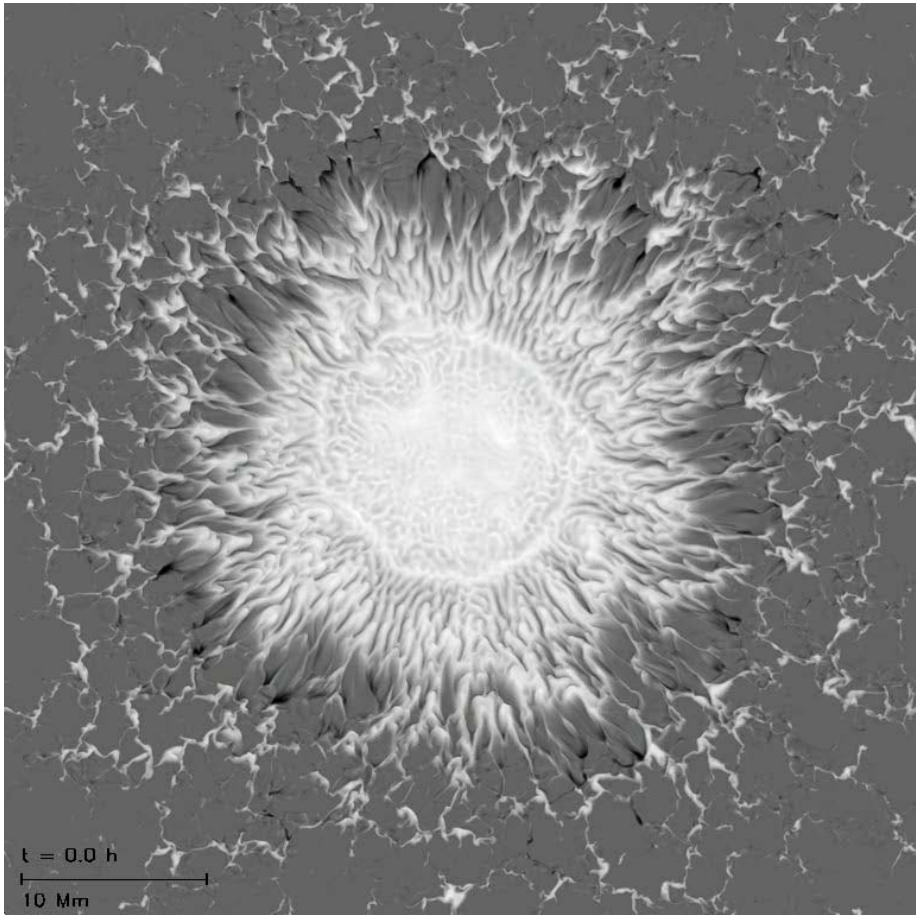
Flux:
- $\sim 1.5 \times 10^{22}$ Mx

Size:
- 1024x1024x256

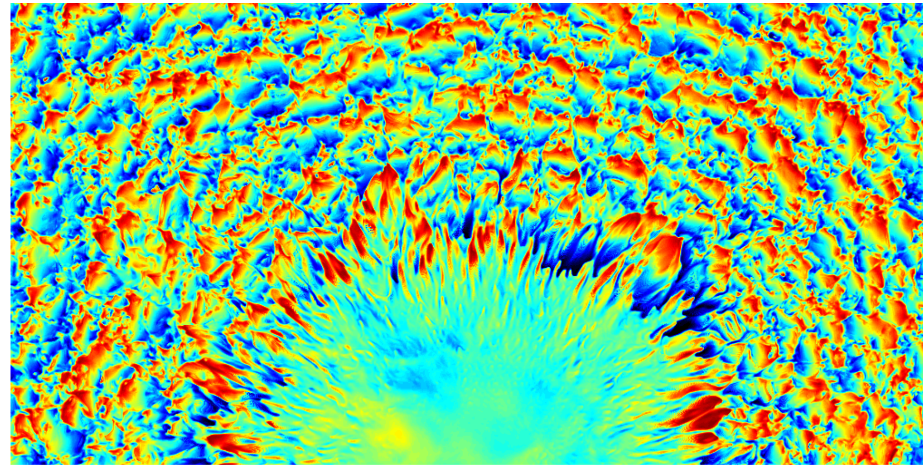
Resolution:
- 48x48x32 km

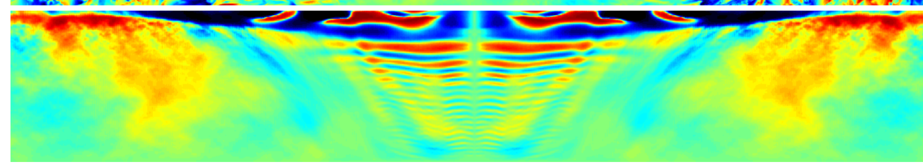
Speed:
- 20 times slower than reality
- (512 x IBM power 6)

Vertical field @ tau=1



Flow @ tau=1 (+/- 5 km/s)





Azimuthally averaged (+/- 500 m/s)

- Moat flow ~ 250 - 500 m/s
- Ring of weak inflow near spot
  - Feature likely to disappear for fully developed penumbra
- Wave propagation in umbra and penumbra
  - Amplitude most probably too strong

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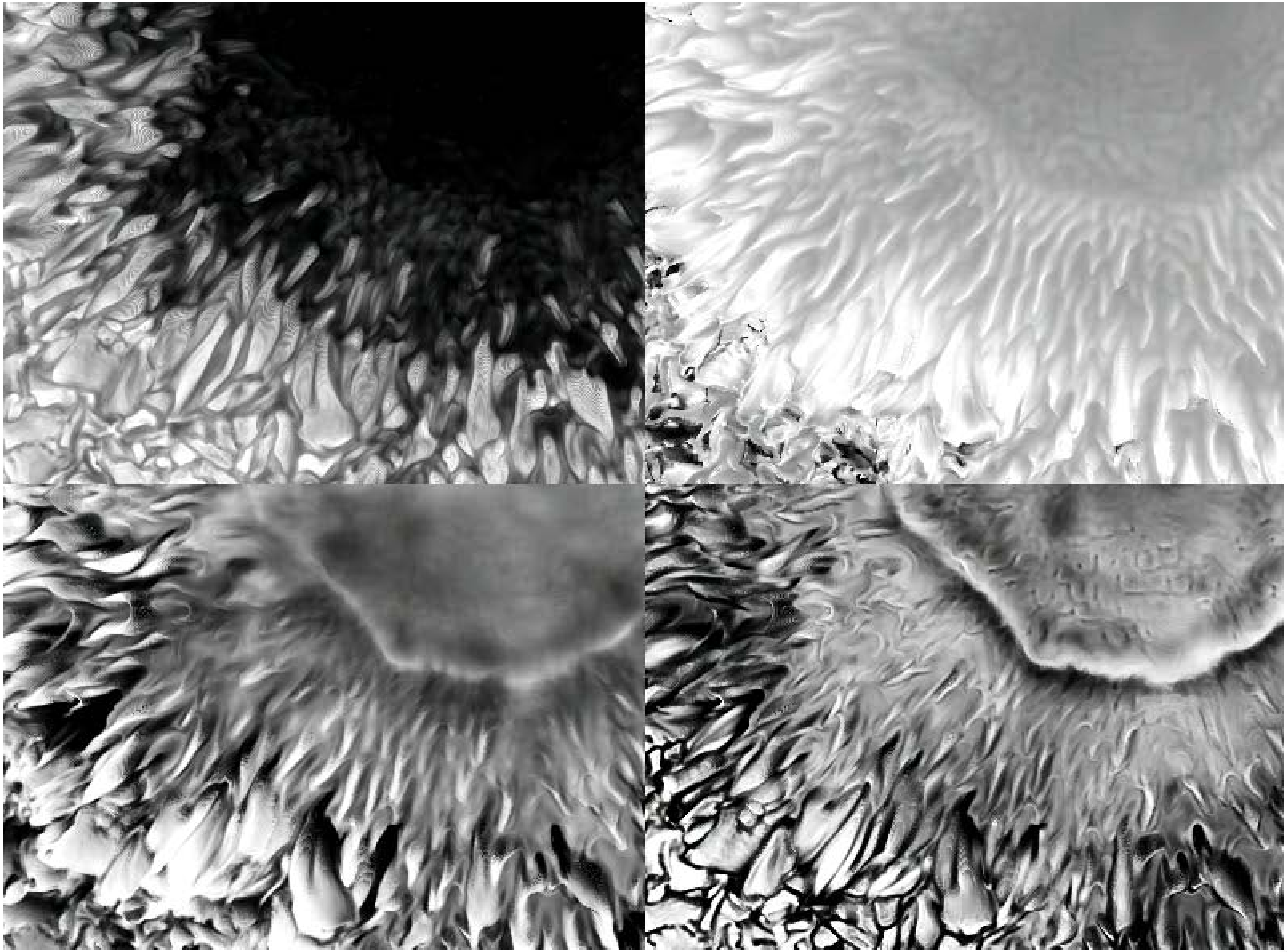
Intensity

Inclination (white: horizontal)



Radial velocity (white:outflow)

Vertical velocity (white: upflow)

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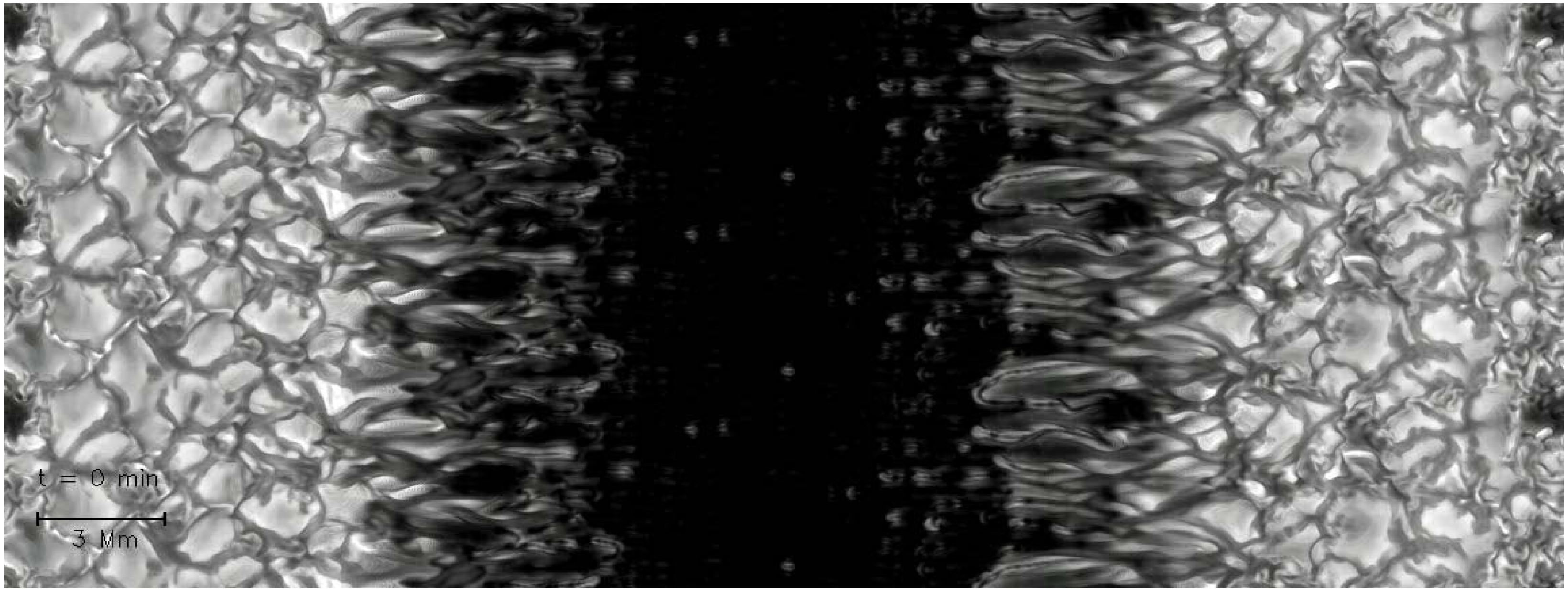
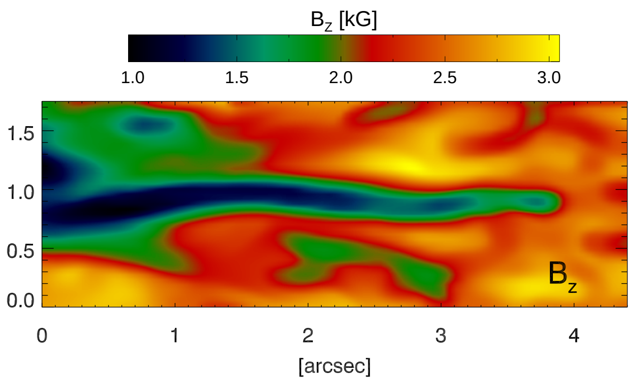
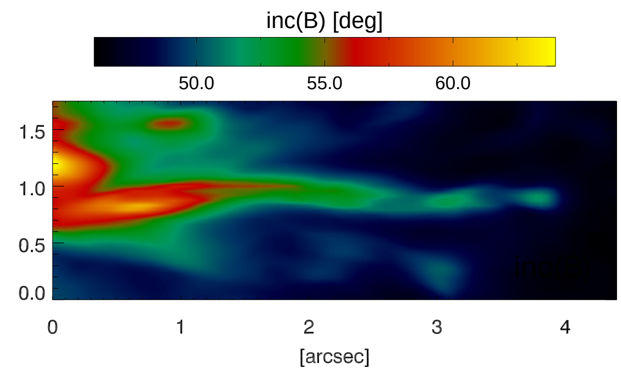
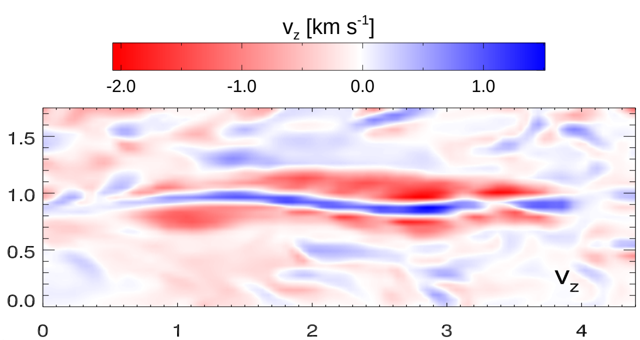
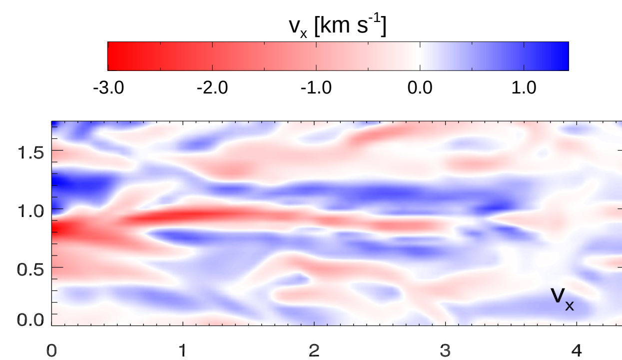

t = 0 min
3 Mm


B_z [kG]
1.0
1.5
2.0
2.5
3.0
1.5
1.0
0.5
0.0
0
1
2
3
4
[arcsec]
B_z


inc(B) [deg]
50.0
55.0
60.0
1.5
1.0
0.5
0.0
0
1
2
3
4
[arcsec]

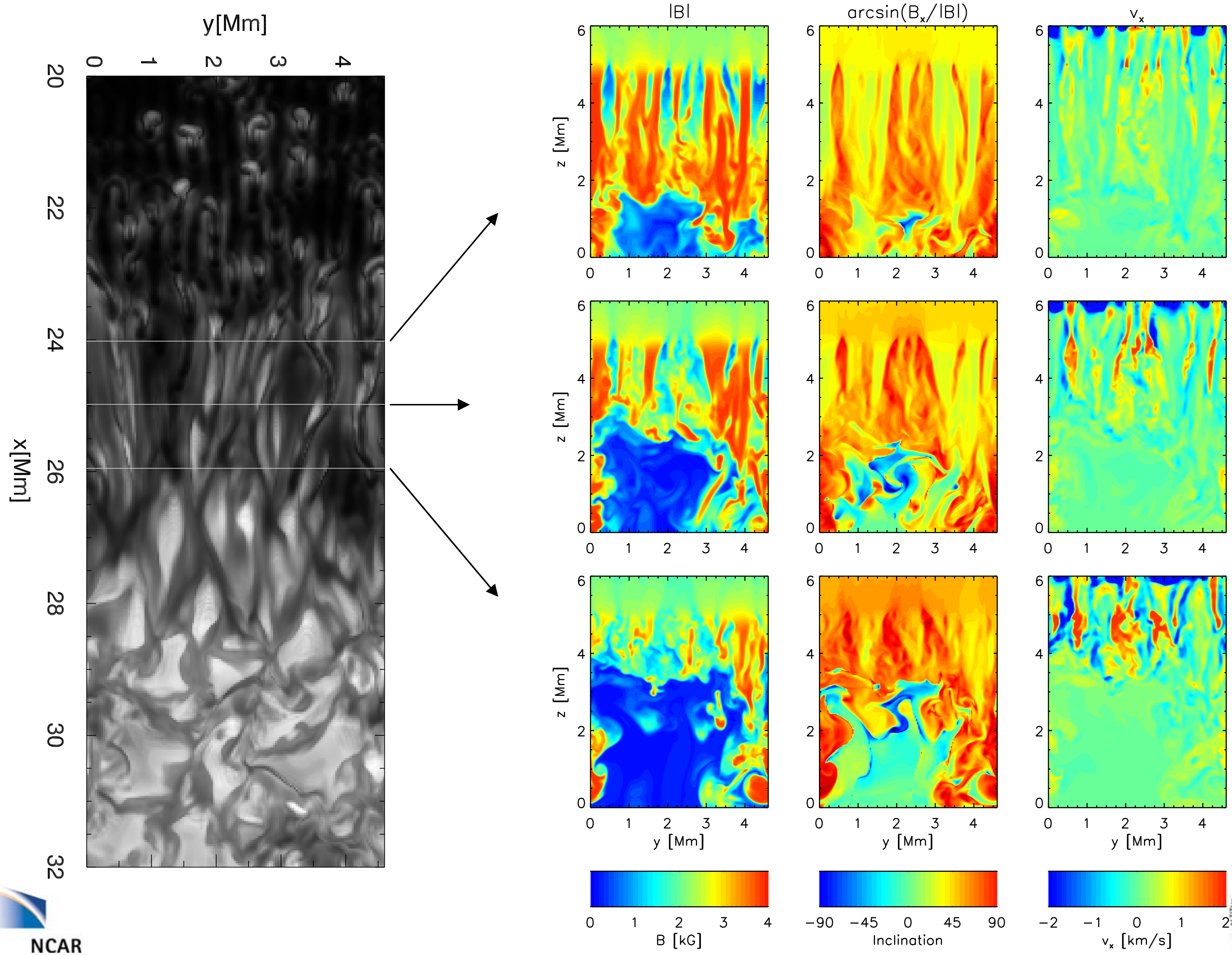
Bz, inc


v_z [km s^{-1}]
-2.0
-1.0
0.0
1.0
1.5
1.0
0.5
0.0
0
1
2
3
4
v_z


v_x [km s^{-1}]
-3.0
-2.0
-1.0
0.0
1.0
1.5
1.0
0.5
0.0
0
1
2
3
4
v_x

Vz, Vx

Vertical cuts perpendicular to filaments



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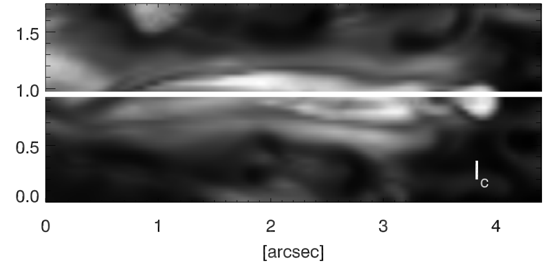
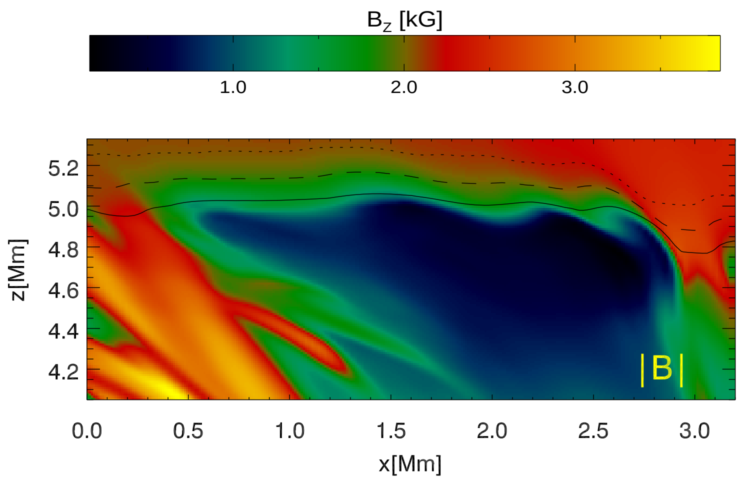
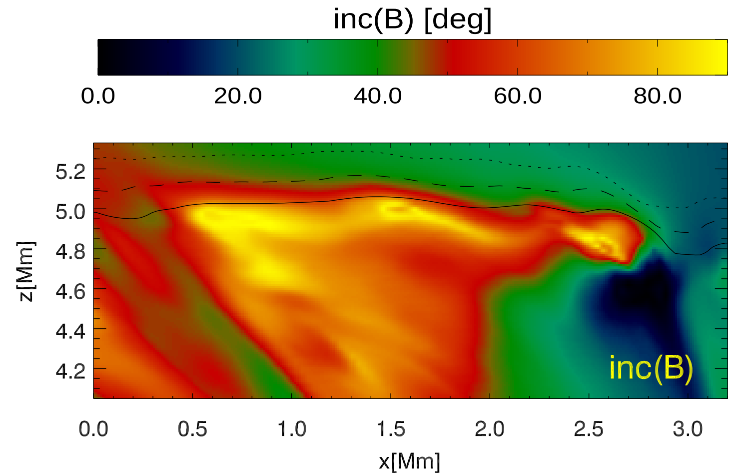
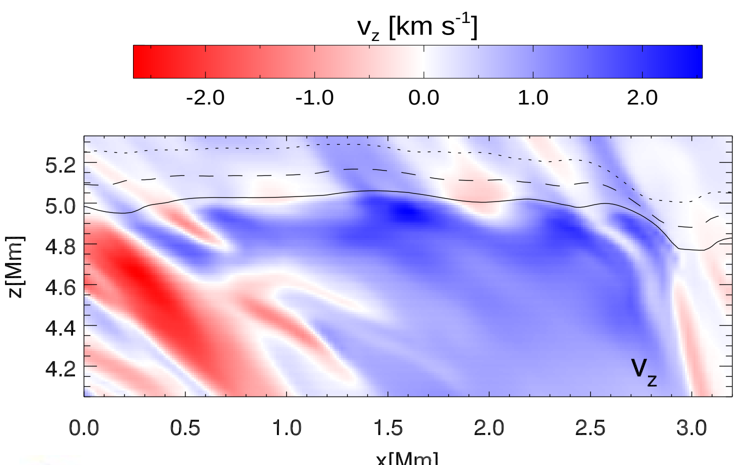
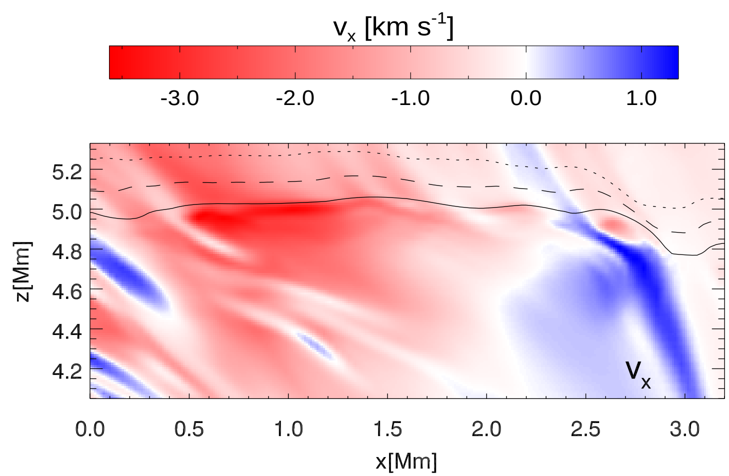
Vertical cuts along the filament





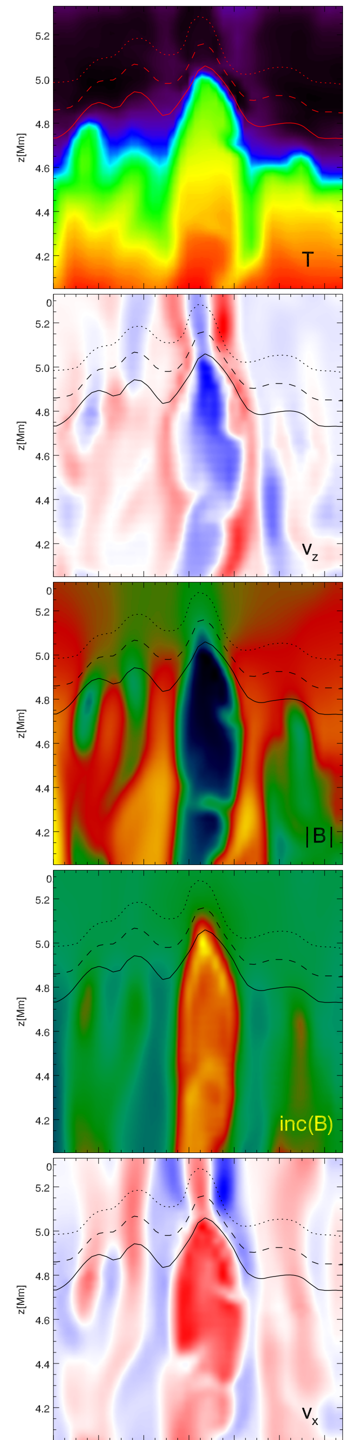






Magneto-convective origin

- Umbral dots and penumbral filaments of similar magneto-convective origin
  - Overturning convection central element
  - Elongated features in presence of horizontal field
  - No intrusion of field free plasma from outside or beneath
- Magneto-convection mode:
  - Upflow along field lines weakens field (Bx and Bz)
    - energy source: potential energy of superadiabatic stratification
    - primary energy supply mechanism
  - Overturning convection in top
    - horizontal expansion primarily weakens Bz (but not Bx!)
    - field becomes horizontal due to lack of vertical field
  - Upflow deflected by inclined field
    - horizontal outflows in central part
    - inflows possible near edge of isolated filaments, less pronounced in case of more dense filaments
  - Observations can only see the tip of the iceberg



Summary

- Separated filaments with observed properties
  - Filaments with dark cores
  - Almost horizontal field, horizontal flow of ~ 2 - 3 km/s
  - Important: horizontal flow in magnetized region (required to explain observed circular polarisation)
- No dense penumbra (yet)
  - Interface umbra/penumbra
  - Evershed flow on average too ~2 - 3 km/s, peak flows ~9 km/s
- Detailed comparison with observations not (yet) possible (see poster by R. Schlichenmaier)
  - Non-gray radiative transfer, higher resolution needed
- Observational evidence for overturning convection?
  - Ichimoto et al (2007)
    - ‘twisting’ motions in filaments
  - Rimmele (2008); Zakharov et al. (2008); Bharti et al. (2007):
    - Direct observation of overturning motions
  - Several other studies looked for signature, but couldn’t detect it

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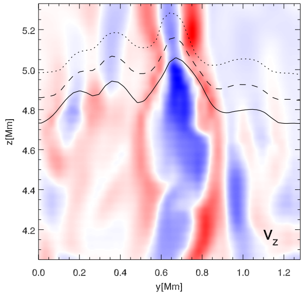
Future developments

- Numerical simulations on the scale of sunspots are feasible with the computing power available today
- High resolution runs in slab and circular geometry to further study fine structure
  - Kelvin-Helmholtz shear flow instabilities in boundary layer of plume
  - Better resolution of tau=1 level
  - Non-grey radiative transfer
  - Detailed comparison with spectropolarimetric data



- Larger runs in circular geometry
  - Deeper boxes (~16 Mm)
    - Subsurface structure of sunspots, dynamical disconnection
    - Less influence of bottom boundary on p-modes
    - Depth of moat flows
  - Wider boxes (~100 Mm)
    - Runs with interaction of mixed polarity spots
  - Artificial data for testing helioseismic inversion methods

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