Sunspots

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Introduction

Two magnetic components

Net Circular Polarization

Supersonic/superalfvénic velocities

Convection and penumbral/umbral brightness

Field-free convection ?

Summary and conclusions

Some recent reviews

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Introduction
Two magnetic components
Net Circular Polarization
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Field-free convection ?
Summary and conclusions

The abstract was a little bit too ambitious: it's not easy to review Sunspots in 20 minutes ...

- Solanki, S.K. 2002. Sunspots: An overview; Astronomy & Astrophysics Review, 11 (2-3), 153
- Rempel, M. & Schlichenmaier, R. 2011. Sunspot Modeling: From simplified models to radiative MHD simulations; Living Reviews in Sol. Phys., 8, 3
- Borrero, J.M. & Ichimoto, K. 2011. Magnetic structure of Sunspots; Living Reviews in Sol. Phys., 8, 4

Summary

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Introduction
Two magnetic components
Net Circular Polarization
Supersonic/superalfvénic velocities
Convection and penumbral/umbral brightness
Field-free convection ?
Summary and conclusions

A totally unbiased  list of the most important fidings in the last decade:

- Two basic magnetic components in Sunspots
- Origin of the net circular polarization in Sunspots
- Supersonic/superalfvénic Evershed flow
- Convection and penumbral/umbral brightness
- Field-free convection ?
- Summary and conclusions

Two magnetic components in the penumbra: 1”

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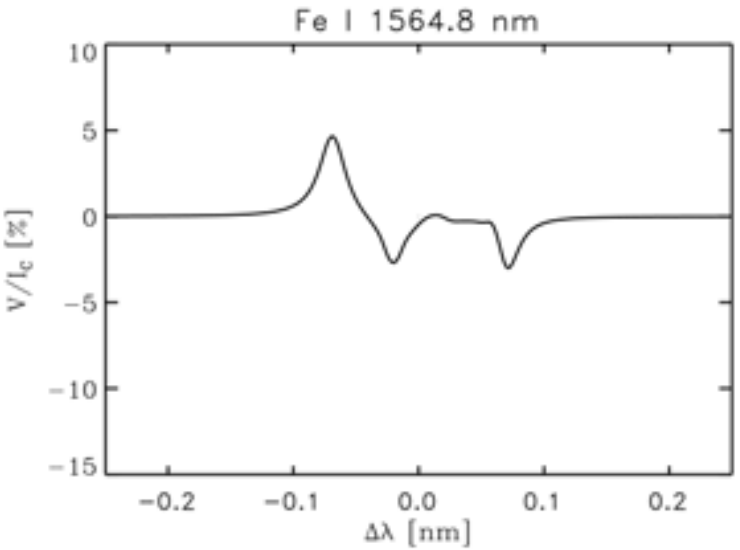
Introduction
Two magnetic components
Net Circular Polarization
Supersonic/superalfvénic velocities
Convection and penumbral/umbral brightness
Field-free convection ?
Summary and conclusions



- Multi-lobe Stokes *V* profiles detected with Fe I 1654 nm and Ti I 2231 nm
- Signature of two magnetic components coexisting within 1”

Borrero et al. 2005, A&A, 436, 333

Rüedi et al. 1999, A&A, 348, L37

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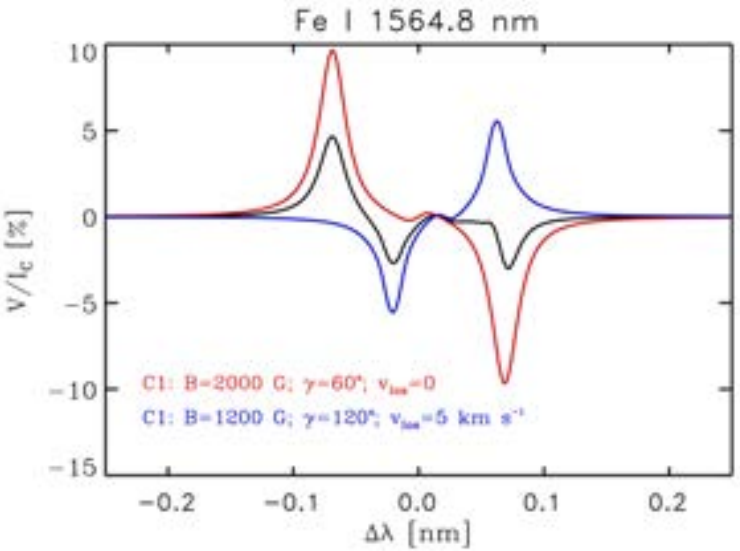
Introduction
Two magnetic components
Net Circular Polarization
Supersonic/superalfvénic velocities
Convection and penumbral/umbral brightness
Field-free convection ?
Summary and conclusions



- Component 1: strong, vertical field, no velocities
- Component 2: weaker, horizontal field†, Evershed flow

Borrero et al. 2005, A&A, 436, 333

Rüedi et al. 1999, A&A, 348, L37

† yields opposite polarities, $\gamma > 90^\circ$, when observing off disk-center

Two magnetic components in the penumbra: 0.3”

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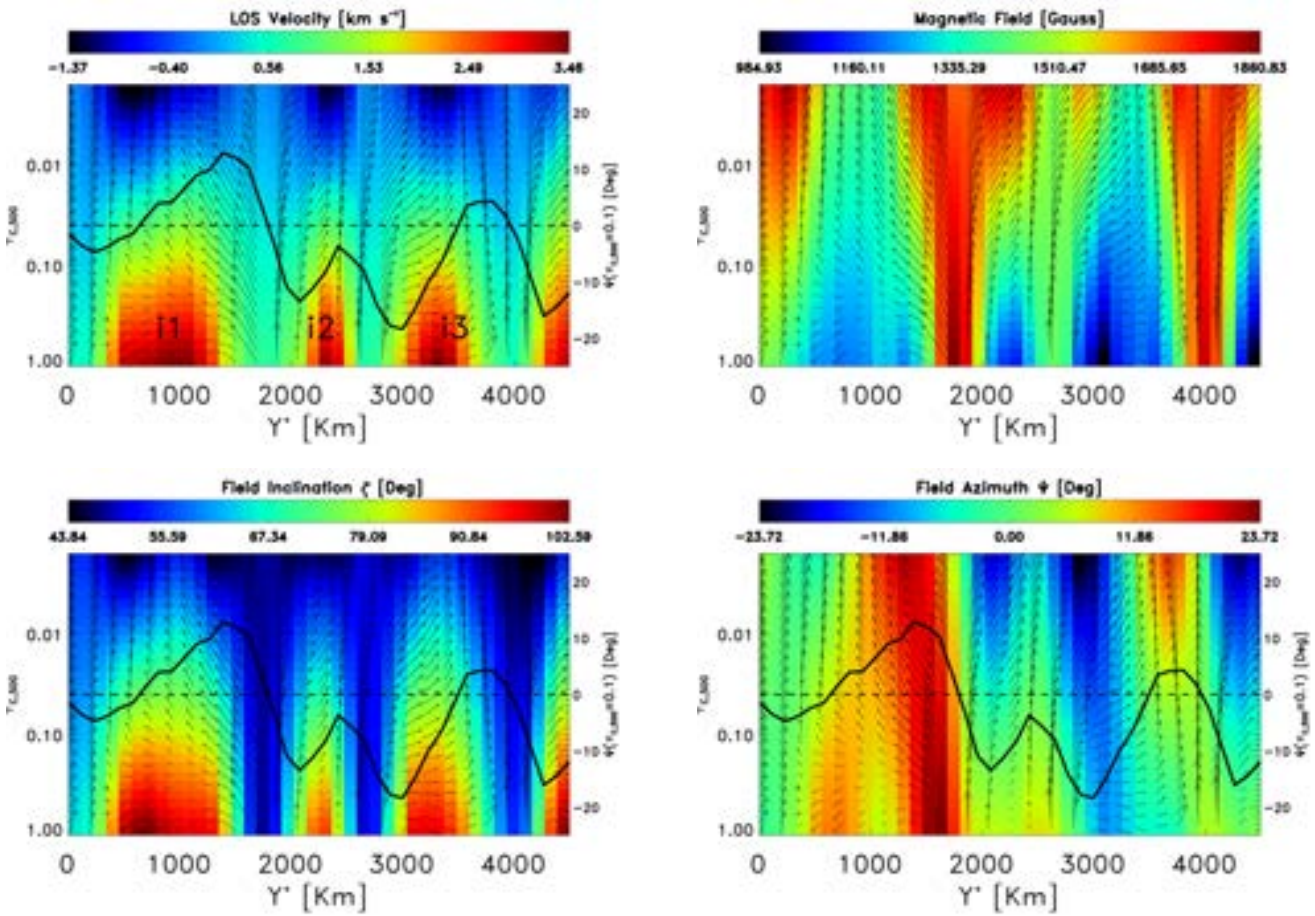
Introduction
Two magnetic components
Net Circular Polarization
Supersonic/superalfvénic velocities
Convection and penumbral/umbral brightness
Field-free convection ?
Summary and conclusions

- Two components are now spatially resolved



Borrero et al. 2007, A&A, 481, L13

Two components in the penumbra: MHD simulations

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Introduction
Two magnetic components
Net Circular Polarization
Supersonic/superalfvénic velocities
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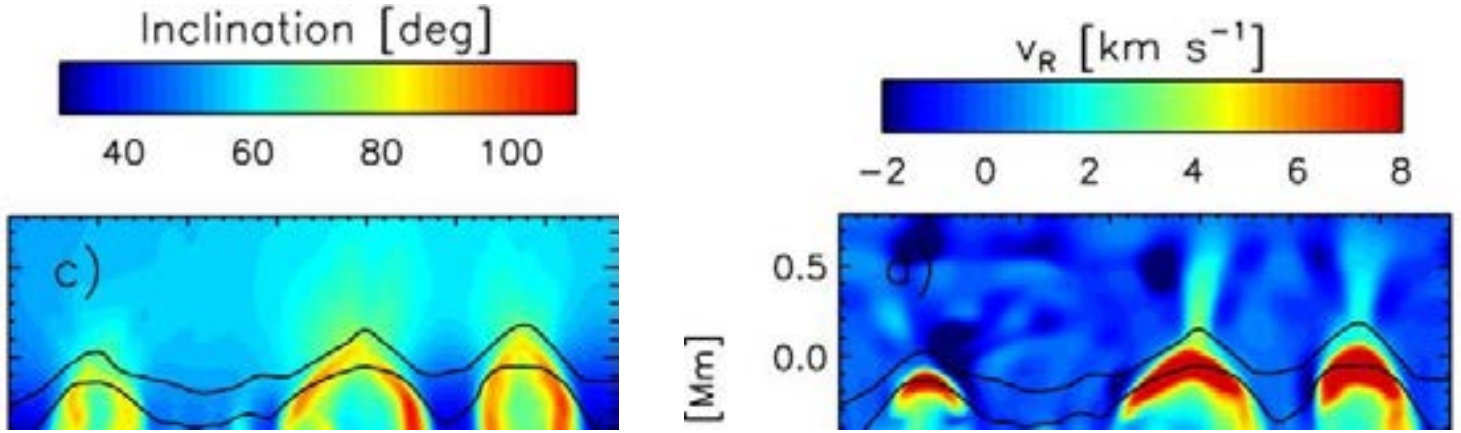
Field-free convection ?
Summary and conclusions



Rempel 2011, ApJ, 729, 5

Two components in umbra, penumbra and light bridges

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Introduction
Two magnetic components
Net Circular Polarization
Supersonic/superalfvénic velocities
Convection and penumbral/umbral brightness
Field-free convection ?
Summary and conclusions

Two components:

- Component 1: strong, vertical field, no velocities
- Component 2: weaker, horizontal field, Evershed flow
- $A_1 \approx A_2$

Two components can also explain:

- Umbra/UD: $A_1 \gg A_2$
- Light bridges: $A_1 \ll A_2$

Origin of the Net Circular Polarization in Sunspots

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Introduction
Two magnetic components
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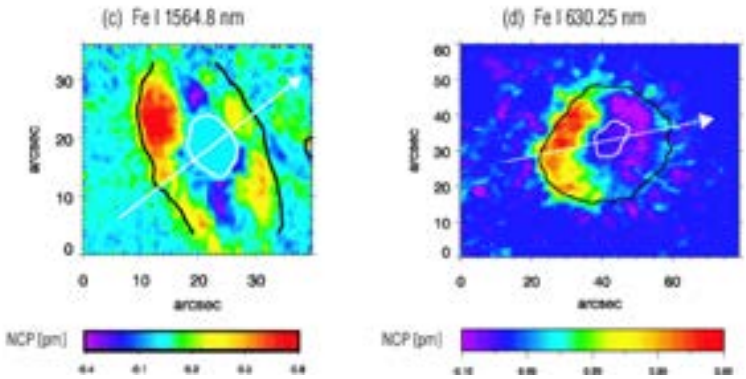
$$\mathrm{NCP} = \int V(\lambda)\mathrm{d}\lambda$$

- NCP$\neq 0$ only if variations along the light-of-sight in **B** and v_{los} are present: Landoldi & Landi Degl'Innocenti 1996, SoPh., 164, 191



- Some early attempts to explain the NCP in Sunspots
  1. Sánchez Almeida & Lites 1992, ApJ, 398, 359
  2. Solanki & Montavon 1993, A&A, 274, 478
  3. Martínez Pillet 2000, A&A, 361, 734
  4. Müller et al. 2002, A&A, 393, 305
  5. Schlichenmaier et al. 2002, A&A, 381, L77

Two component model and NCP

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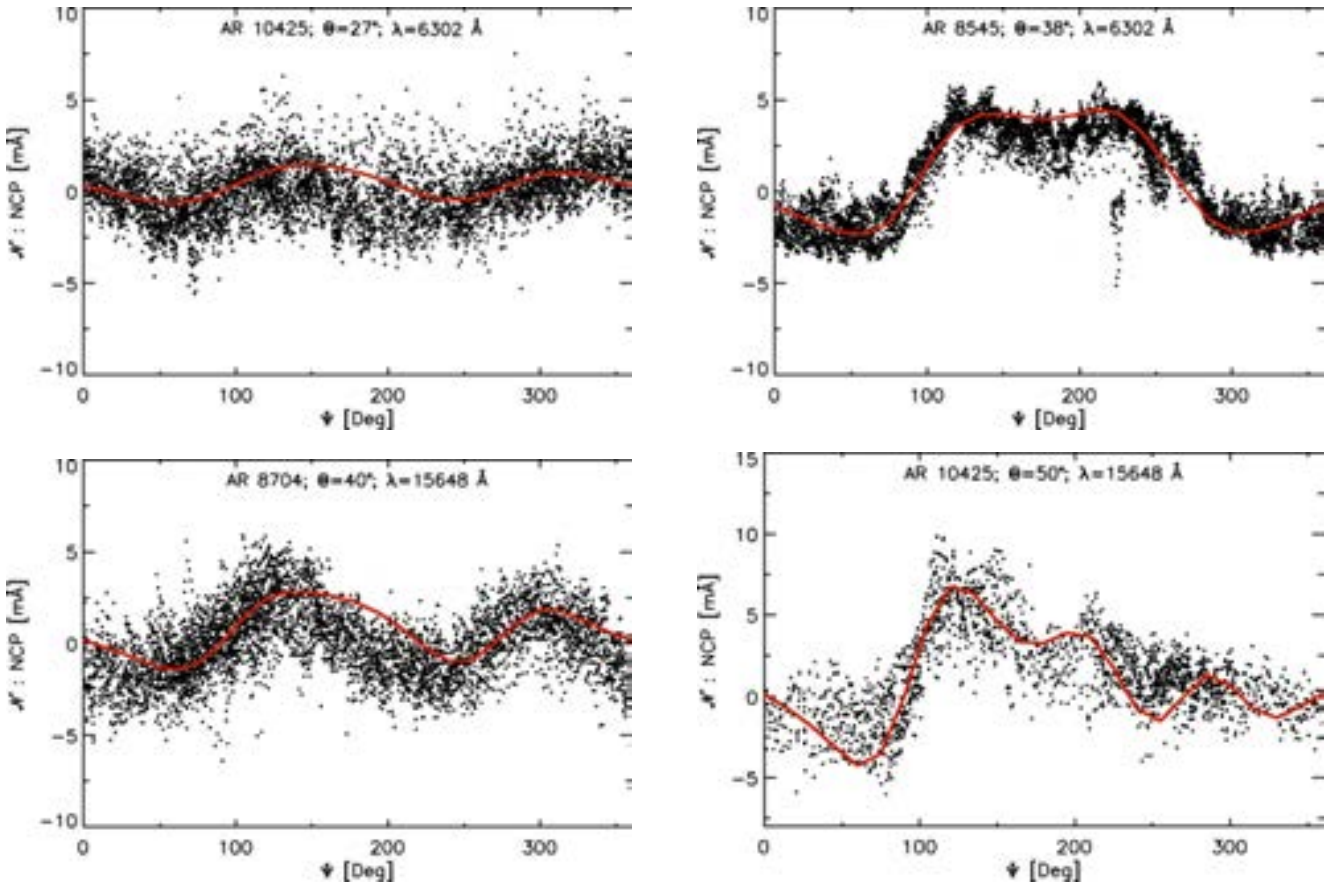
Introduction
Two magnetic components
Net Circular Polarization
Supersonic/superalfvénic velocities
Convection and penumbral/umbral brightness
Field-free convection ?
Summary and conclusions

- Explanation of the spatial distribution in sunspots using a 2-component model



Borrero et al. 2007, ApJ, 666, L133

Borrero & Solanki 2010, ApJ, 709, 349

Supersonic/superalfvénic Evershed flow

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Introduction
Two magnetic components
Net Circular Polarization
Supersonic/superalfvénic velocities
Convection and penumbral/umbral brightness
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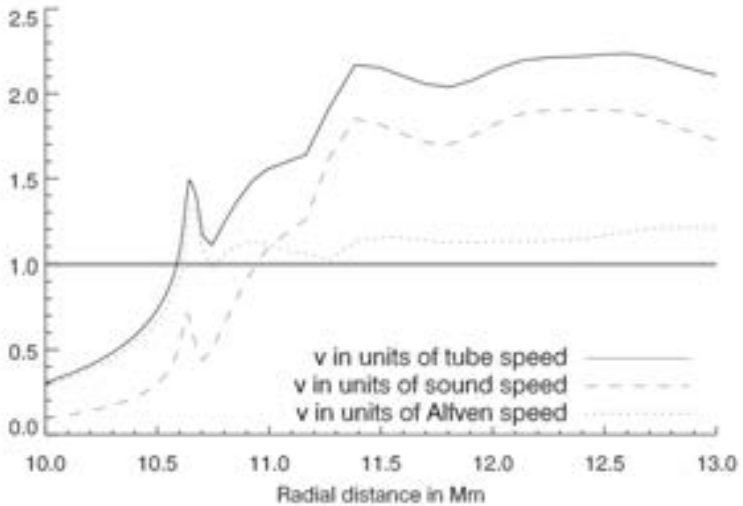
Summary and conclusions

Theoretically proposed by:

- Siphon-flows: Montesinos & Thomas 1997, Nature, 390, 485
- Moving tubes: Schlichenmaier et al. 1998, 337, 897



Schlichenmaier 2002, AN, 323, 303

Supersonic/superalfvénic Evershed flow

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Introduction
Two magnetic components
Net Circular Polarization
Supersonic/superalfvénic velocities
Convection and penumbral/umbral brightness
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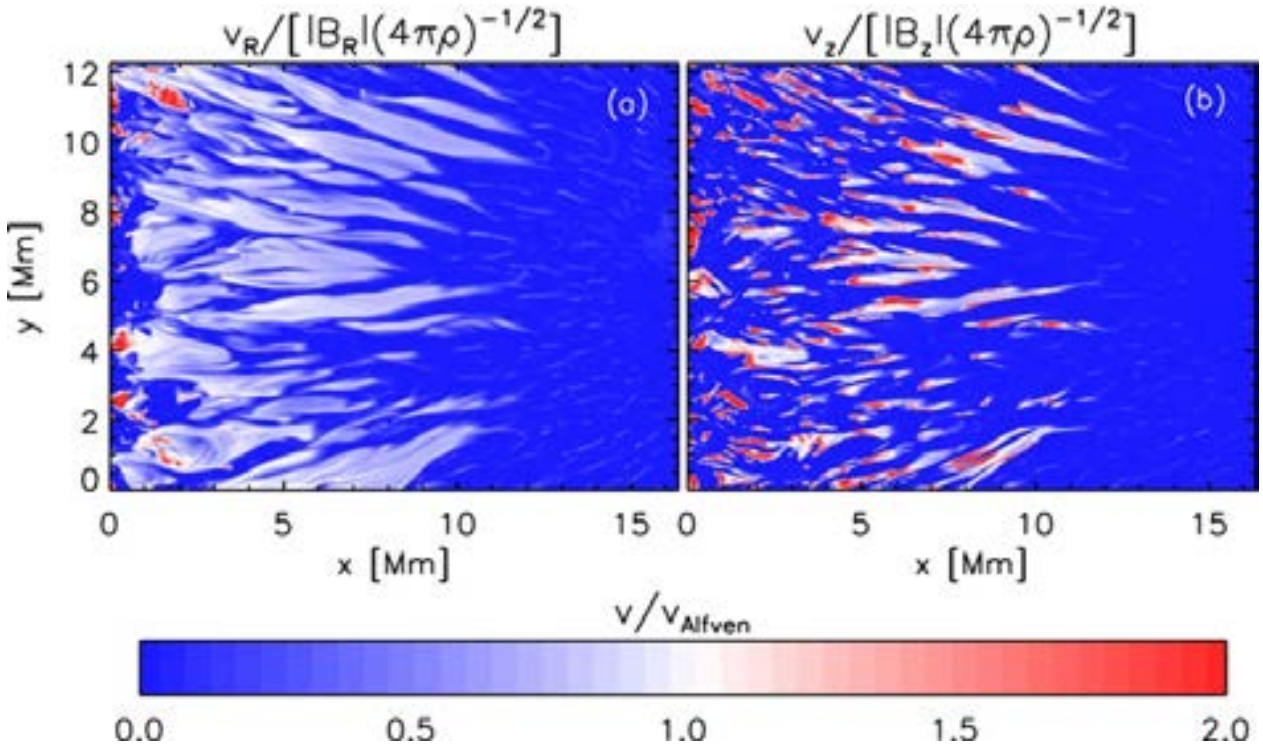
Summary and conclusions

3D MHD simulations also predict them:



Rempel 2011, ApJ, 729, 5

Supersonic/superalfvénic Evershed flow

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Introduction
Two magnetic components
Net Circular Polarization
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Convection and penumbral/umbral brightness
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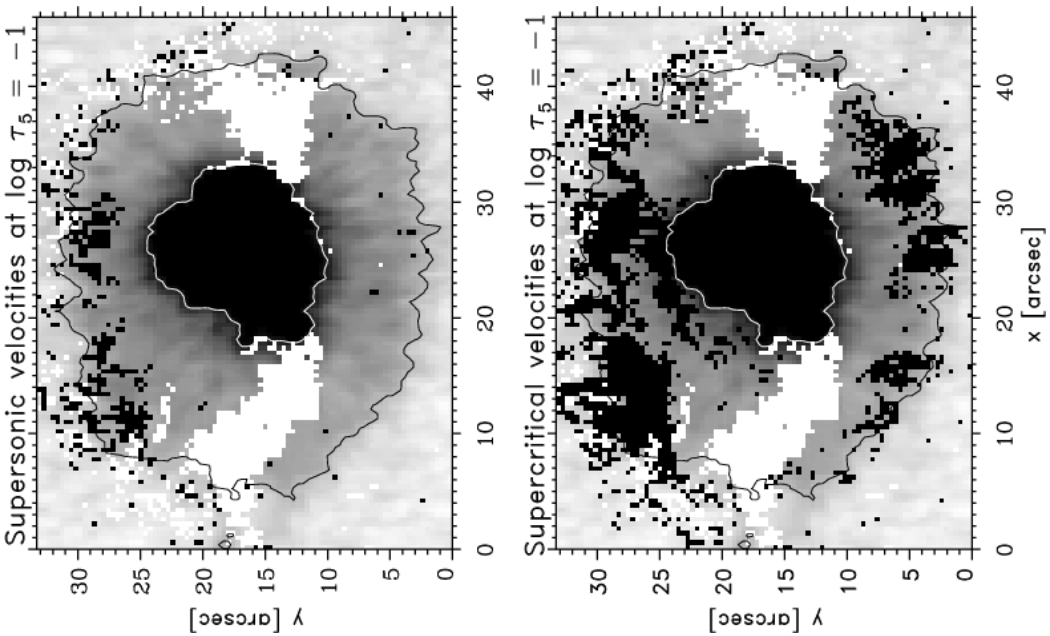
Observationally found:

- Del Toro Iniesta et al. 2001, ApJ, 549, L139
- Penn et al. 2003, ApJ, 590, L119
- Bellot Rubio et al. 2004, A&A, 427, 319
- Borrero et al. 2005, A&A, 436, 333



Bellot Rubio et al. 2004, A&A, 427, 319

Convection and penumbral/umbral brightness

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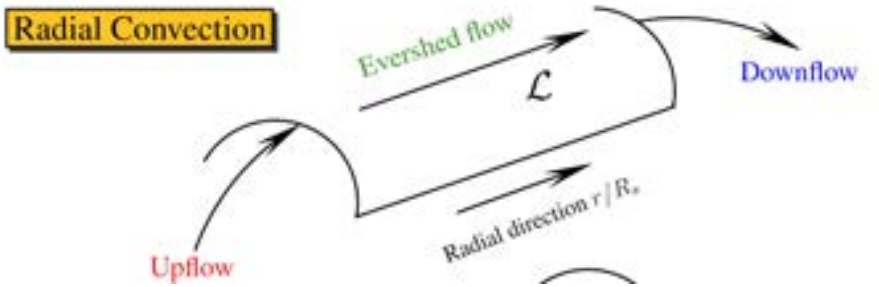
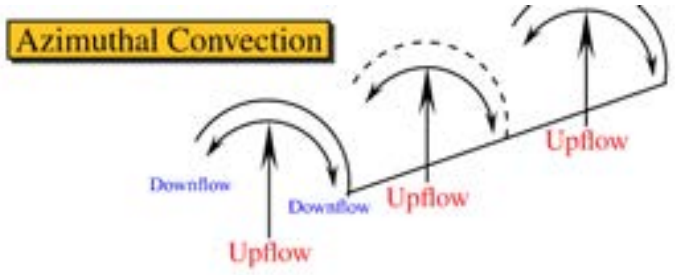
Introduction
Two magnetic components
Net Circular Polarization
Supersonic/superalfvénic velocities
Convection and penumbral/umbral brightness
Field-free convection ?
Summary and conclusions

The easiest way to explain penumbral brightness is through convection



Schlichenmaier et al. 1999, A&A, 349, 961 | Ruiz Cobo & Bellot Rubio 2008, 488, 749



Spruit & Scharmer 2006, A&A, 447, 343 | Scharmer et al. 2008, ApJ, 667, L149

Convection and penumbral/umbral brightness

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Introduction
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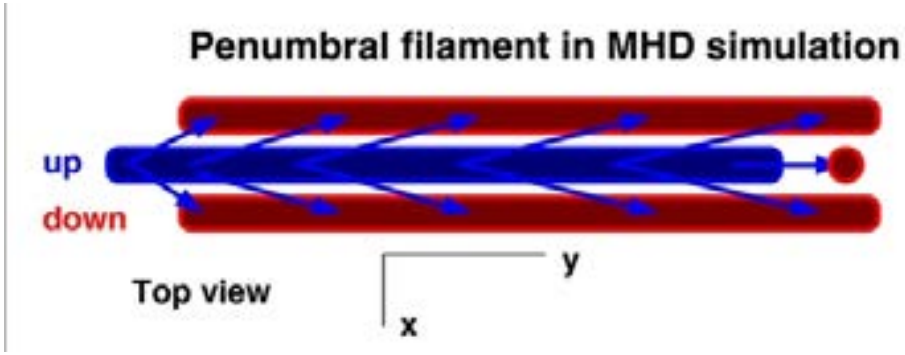
Summary and conclusions

3D MHD simulations indicate both exist, with azimuthal convection carrying most of the energy



Rempel 2012, ApJ, 750 62

Similar situation already predicted on observational grounds

- Schlichenmaier & Solanki 2003, A&A, 411, 257

Convection and penumbral/umbral brightness

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Introduction
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Supersonic/superalfvénic velocities
Convection and penumbral/umbral brightness
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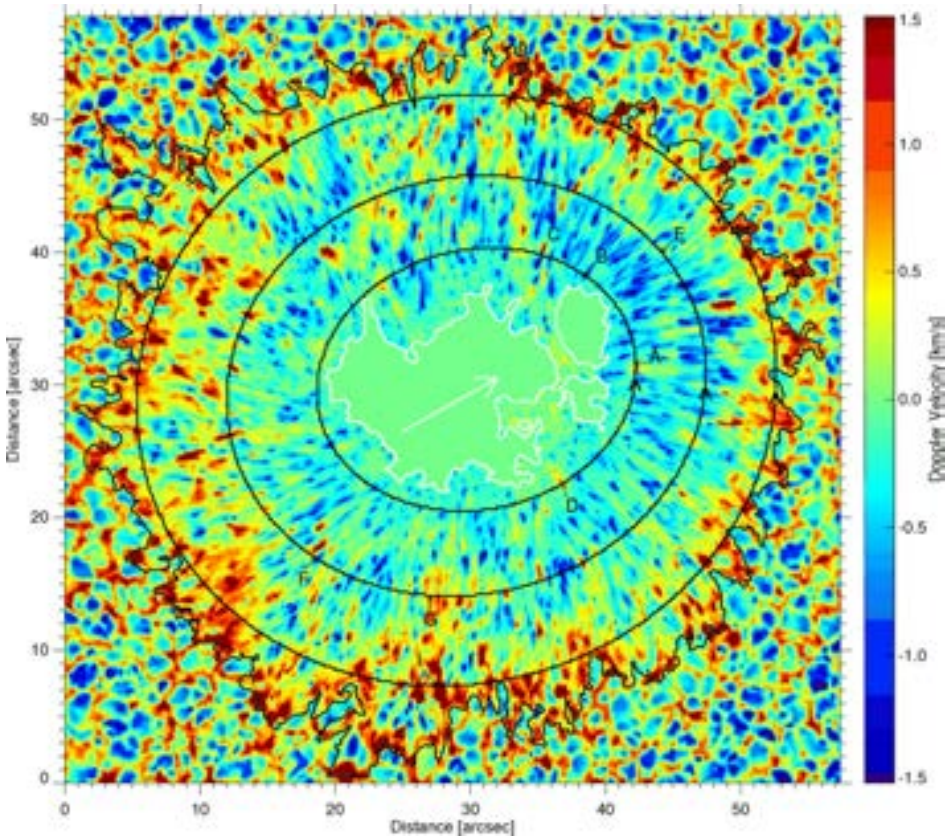
Summary and conclusions

Radial convection can be found by direct Doppler measurements



Franz & Schlichenmaier 2009, A&A, 508, 1453

Convection and penumbral/umbral brightness

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Introduction
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Net Circular Polarization
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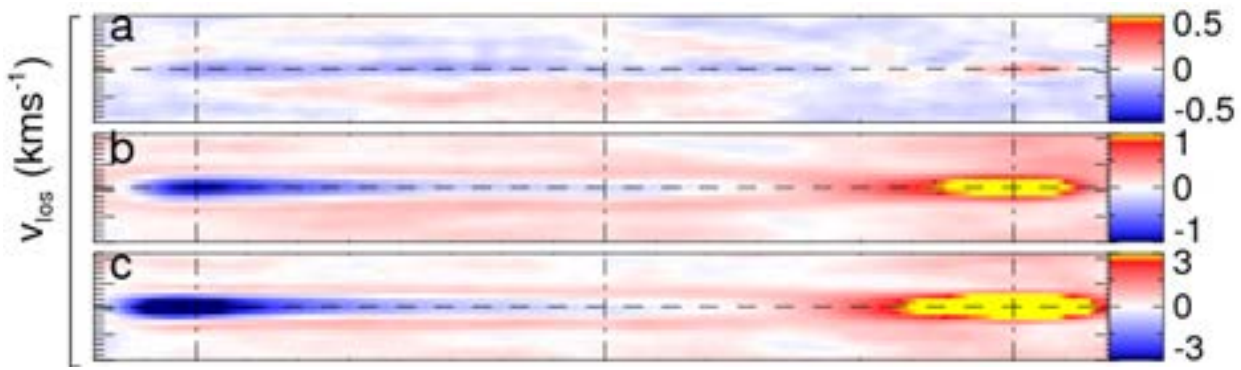
Summary and conclusions

Finding azimuhtal convection requieres very high spatial resolution

- Correcting for *straylight*: Scharmer et al. 2011, Science, 333, 316, Joshi et al. 2011, ApJ, 734, L18
- Accounting for PSF: Tiwari et al. 2013, A&A, 557, 25, Ruiz Cobo & Asensio Ramos 2013, A&A, 549, 4



Tiwari et al. 2013, A&A, 557, 25

Field-free umbral dots ?

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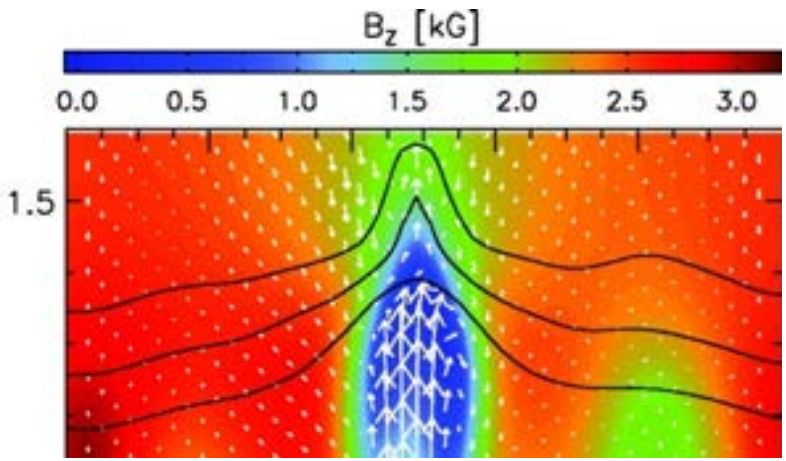
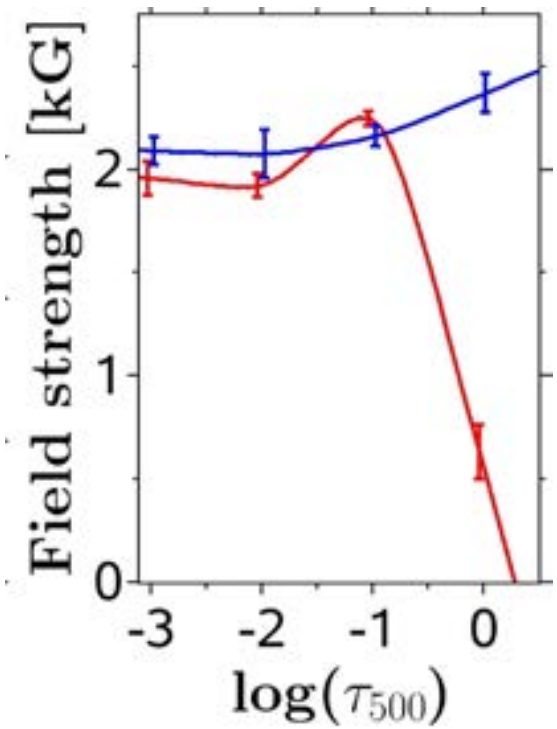
Introduction
Two magnetic components
Net Circular Polarization
Supersonic/superalfvénic velocities
Convection and penumbral/umbral brightness
Field-free convection ?
Summary and conclusions

- Umbral magnetic field is mostly vertical: $B \simeq B_z$
- Inside UDs, $B_z \rightarrow 0$ due the convective flow inside
- Therefore, in UDs: $B \simeq B_z \rightarrow 0$
- Almost field-free convection



Vögler & Schüssler 2006, ApJ, 641, L73



Riethmüller et al. 2008, ApJ, 678, L157

Field-free penumbral filaments ?

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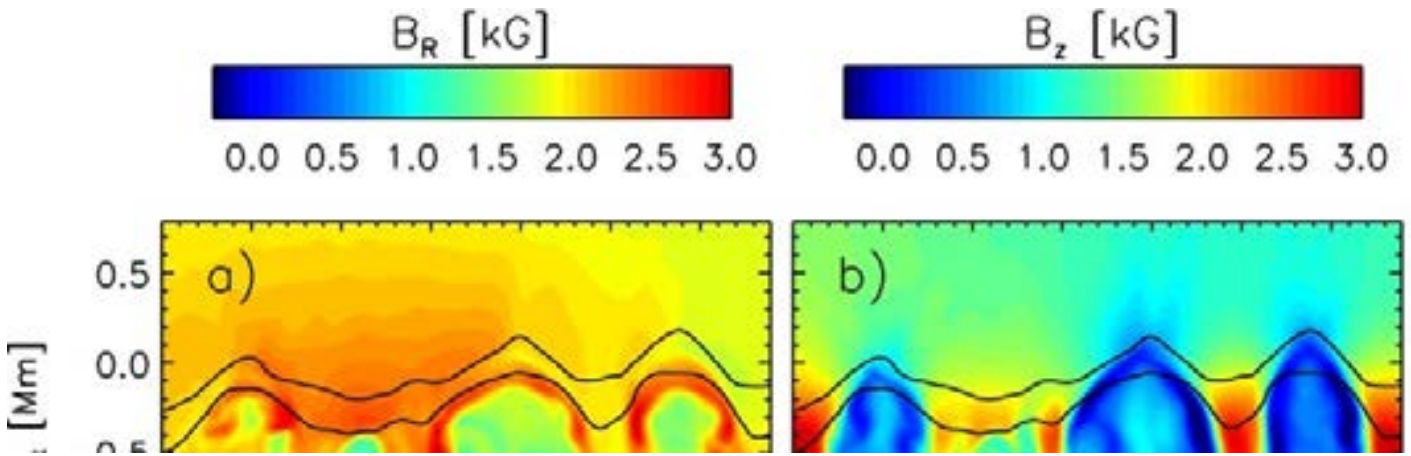
Introduction
Two magnetic components
Net Circular Polarization
Supersonic/superalfvénic velocities
Convection and penumbral/umbral brightness
Field-free convection ?
Summary and conclusions

- Penumbral magnetic field is inclined: $B = \sqrt{B_r^2 + B_z^2}$
- Again, $B_z \rightarrow 0$ due the convective flow inside
- Therefore: $B \simeq B_r \neq 0$
- Convection within a non-vanishing magnetic field



Rempel 2011, ApJ, 729, 5

How strong is the magnetic field in the filaments ? Observations

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Introduction
Two magnetic components
Net Circular Polarization
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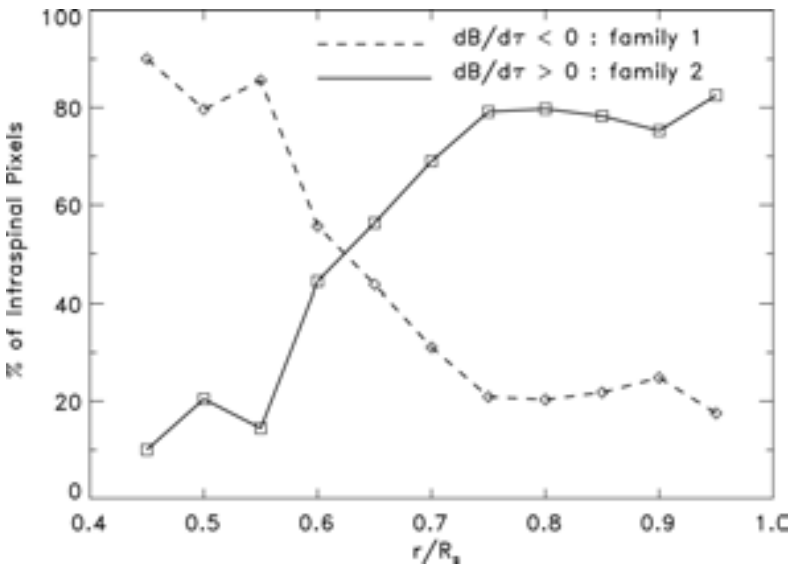
Summary and conclusions

- $B_2 \simeq 1200$ G and independent of r/R: Borrero et al. 2005 , A&A, 436, 333, Borrero et al. 2006, A&A, 450, 383
- Meanwhile the ambient field drops from $B_1 \simeq 2500$ G at $r/R = 0.4$ to $B_1 \simeq 750$ at $r/R = 1.0$
- At some radial distance: $B_2 > B_1$



- Family # 1: $B_2 < B_1$
- Family # 1: $B_2 > B_1$

Borrero & Solanki 2008, ApJ, 687, 668

How strong is the magnetic field in the filaments ? Simulations

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Introduction
Two magnetic components
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Convection and penumbral/umbral brightness
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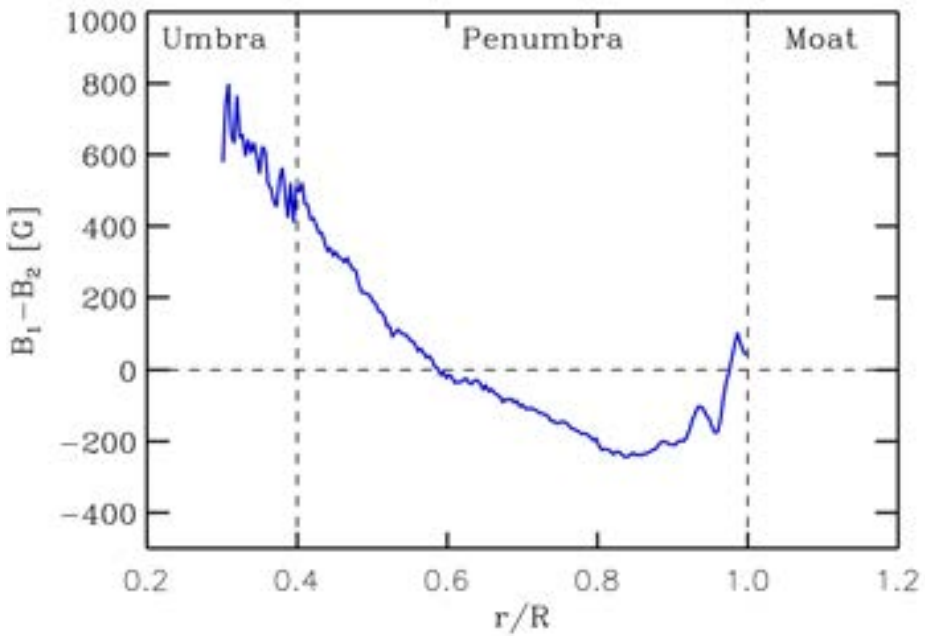
Same effect seen in 3D MHD simualtions

- $B_2 < B_1$ for $r/R < 0.6$
- $B_2 > B_1$ for $r/R > 0.6$



Courtesy of Matthias Rempel

Summary and conclusions

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Introduction
Two magnetic components
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- Two magnetic components (vertical/strong field, no velocities and horizontal/"weak" field, Evershed flow) explain (at 1") not only the penumbra, but also umbra/UDs, light bridges, and the NCP in sunspots
  - in the umbra/inner penumbra $B_1 > B_2$
  - In the mid/outer penumbra $B_1 < B_2$
- Evershed flow in # 2 is found to be supersonic / superalfvénic from the middle penumbra outwards
- At better resolutions ($\ll 1$") we see that # 2 also carries convective motions $\rightarrow$ umbral and penumbral brightness
- Convective motions redude B_z in # 2
  - convection in UDs occurs in an almost field-free enviroment
  - convection in penumbral filaments occurs within a strong† magnetic field

† magnetic energy $\simeq$ kinetic energy