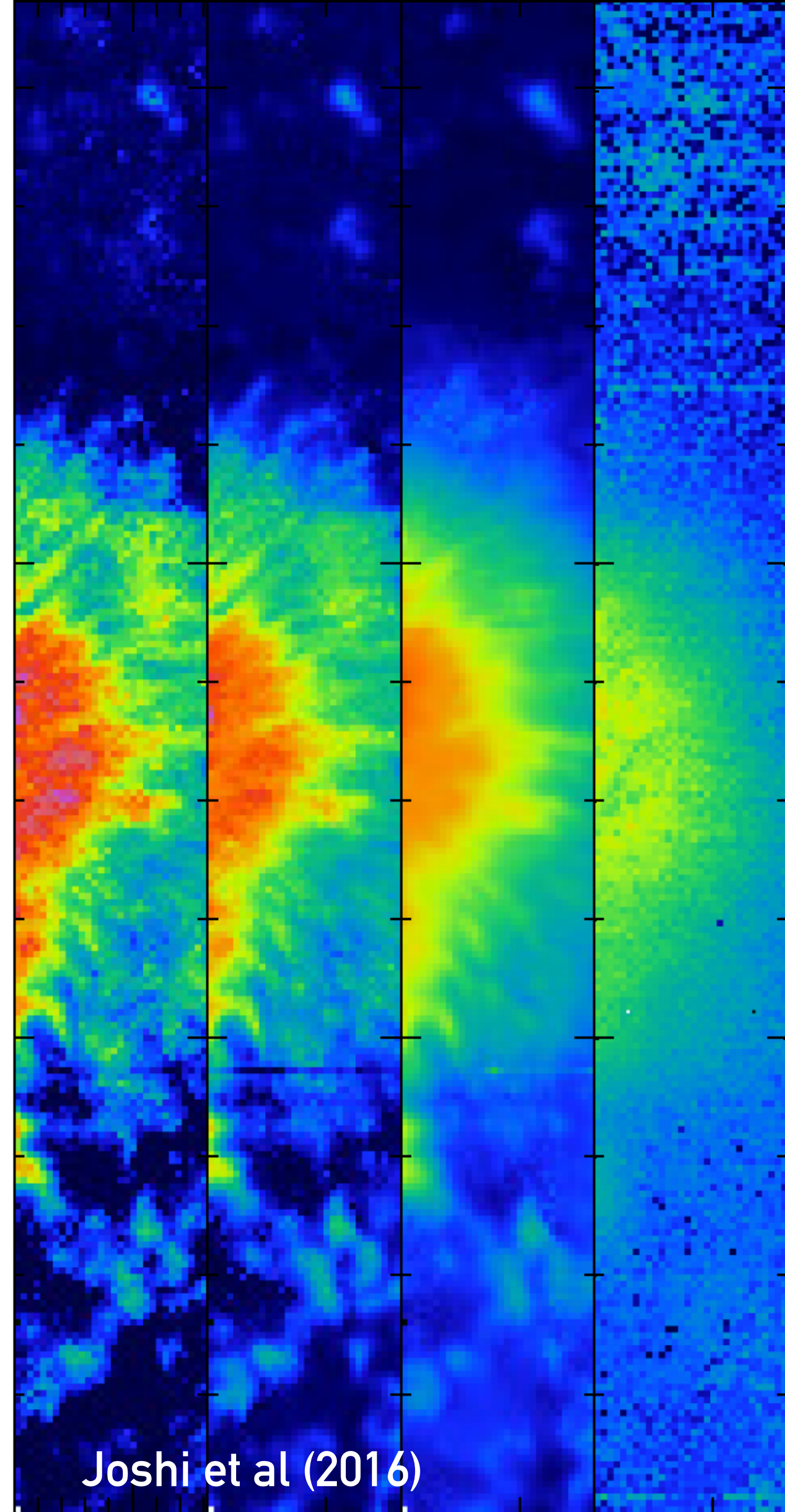


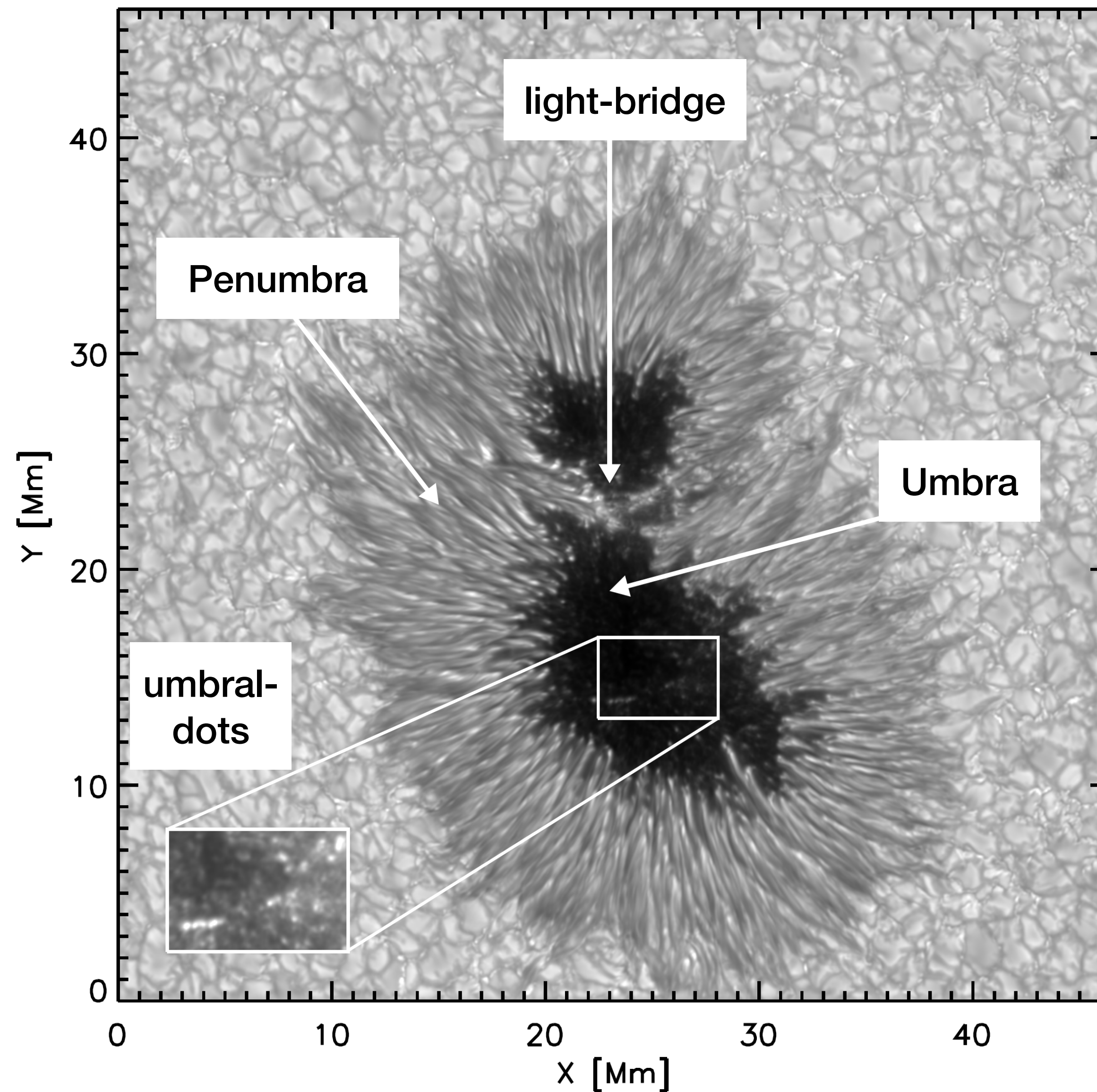
3D Sunspot Structure

Jayant Joshi

Indian Institute of Astrophysics, Bengaluru



Sunspots: photosphere



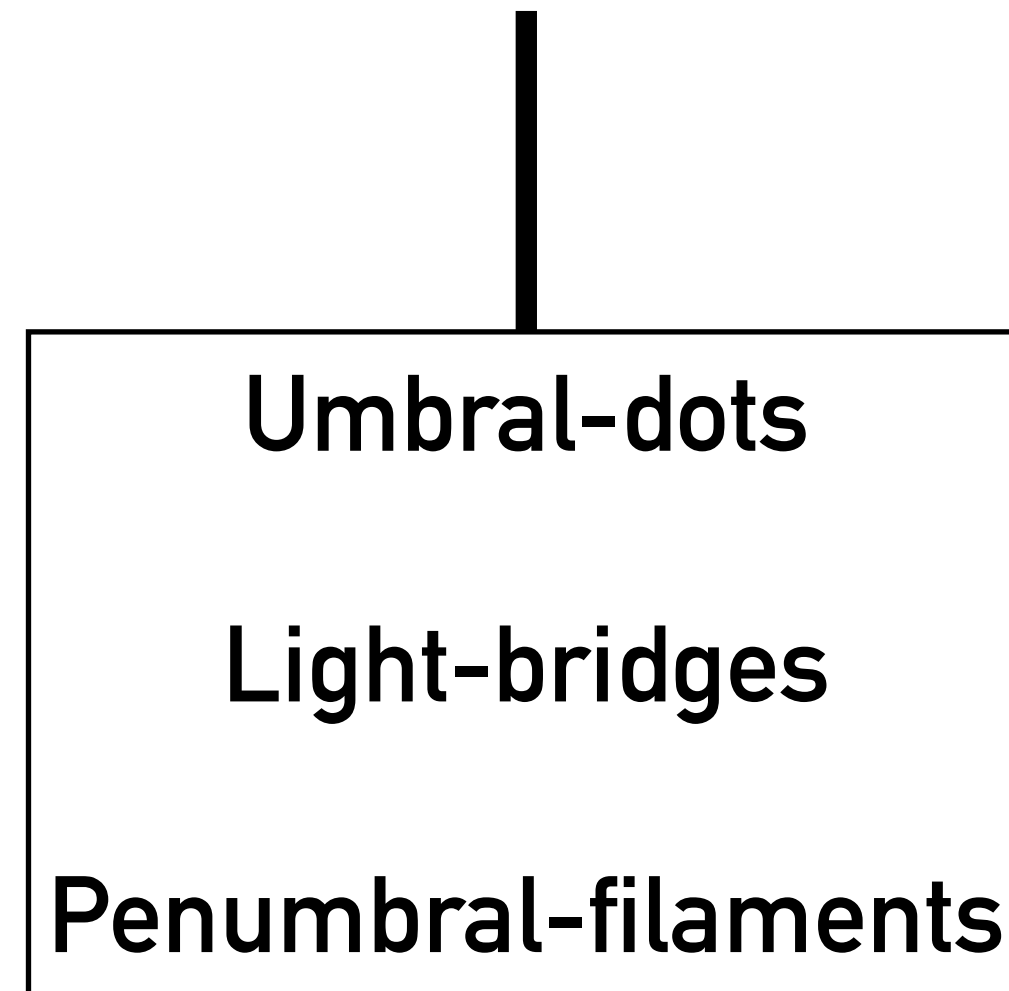
ISSS L'Aquila, 11-15 April 2022



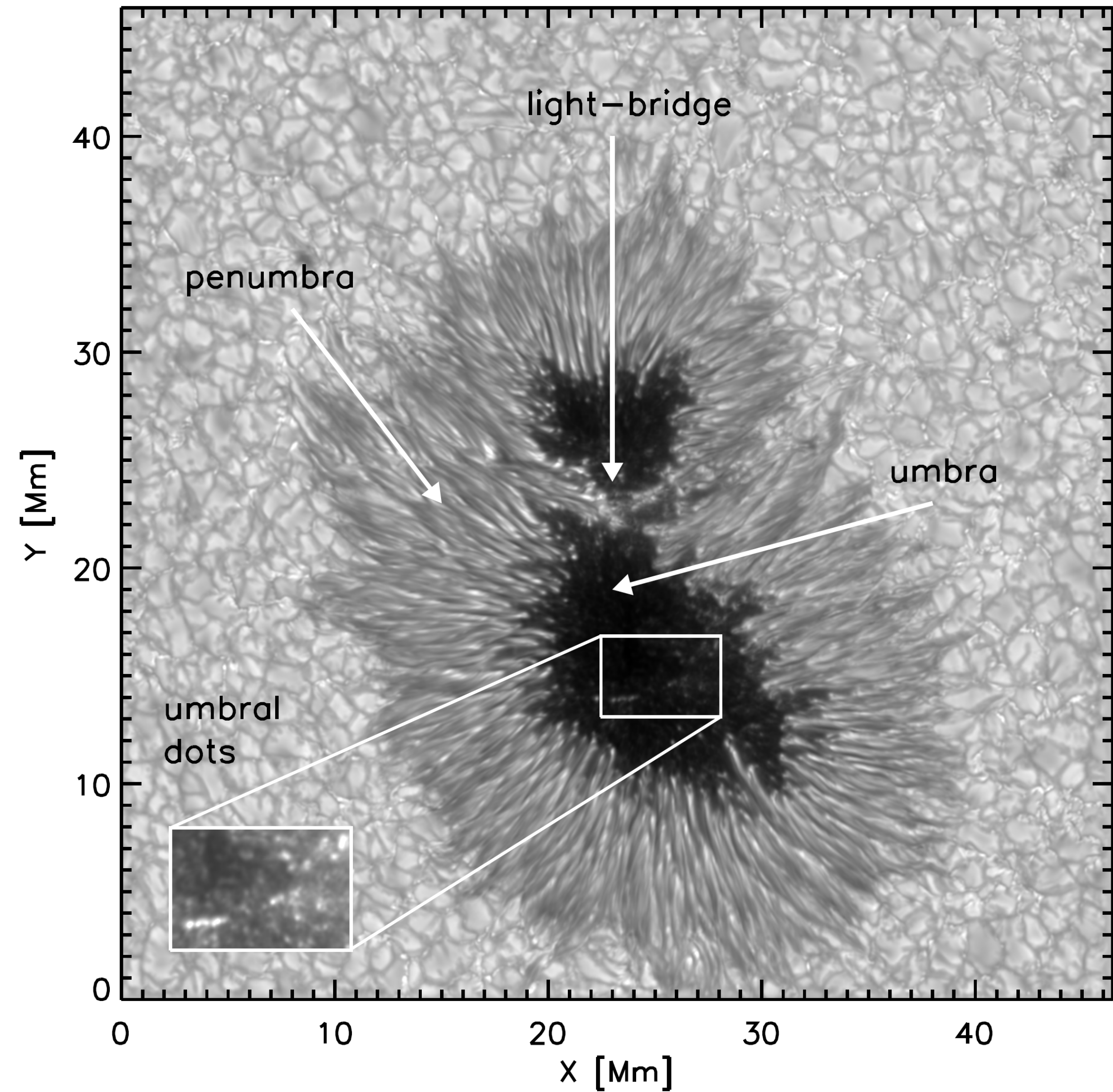
Swedish 1-m Solar Telescope

Sunspots: MHD laboratory

Origin of spatial fine
structures in sunspots
photosphere

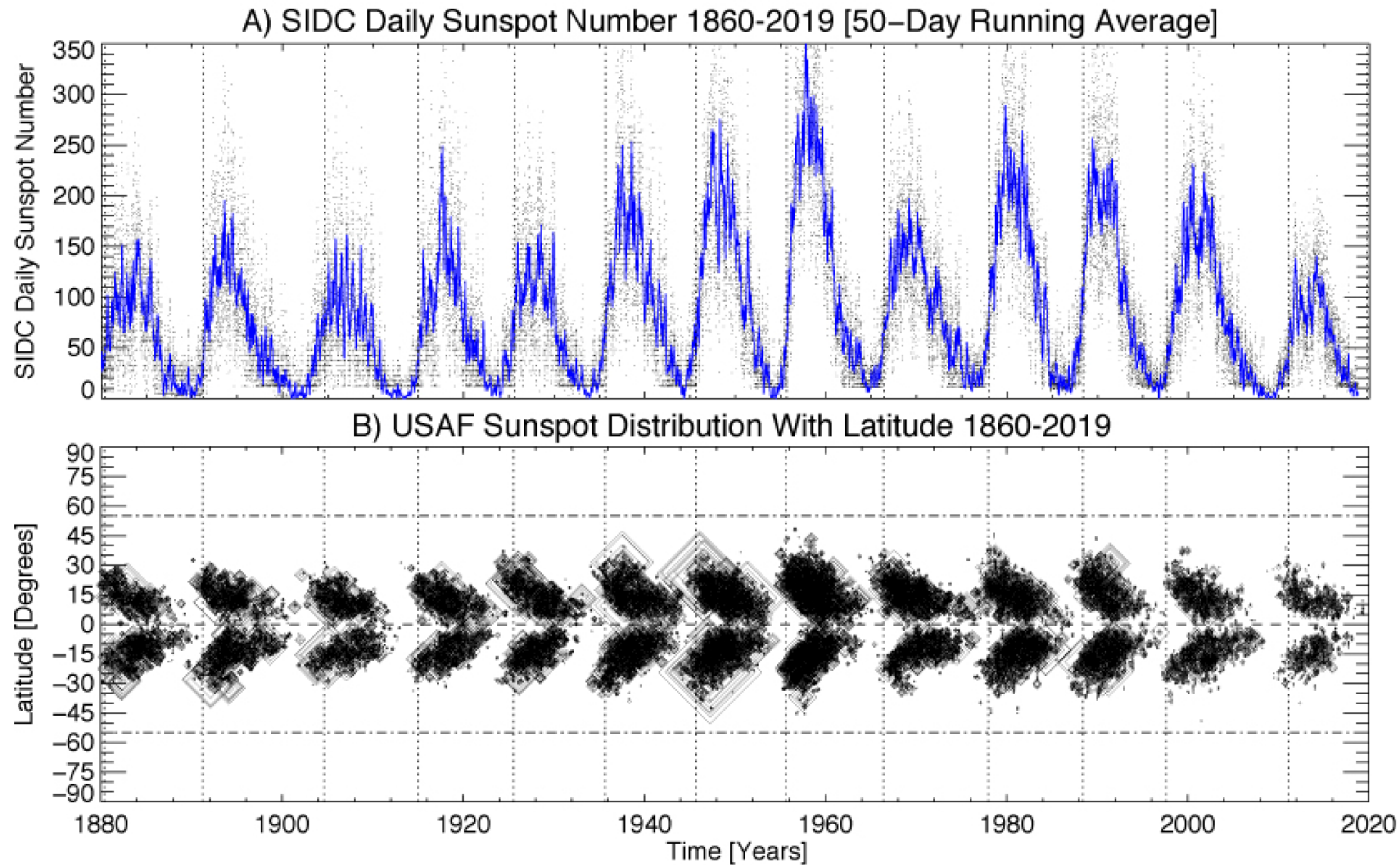


Magnetoconvection



Sunspots: MHD laboratory

Solar Dynamo and Variability



Properties of sunspots provides constraints for dynamo models

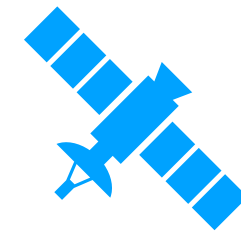
- Hale's polarity law
- Joy's law

McIntosh et al. (2021)

Sunspots: MHD laboratory

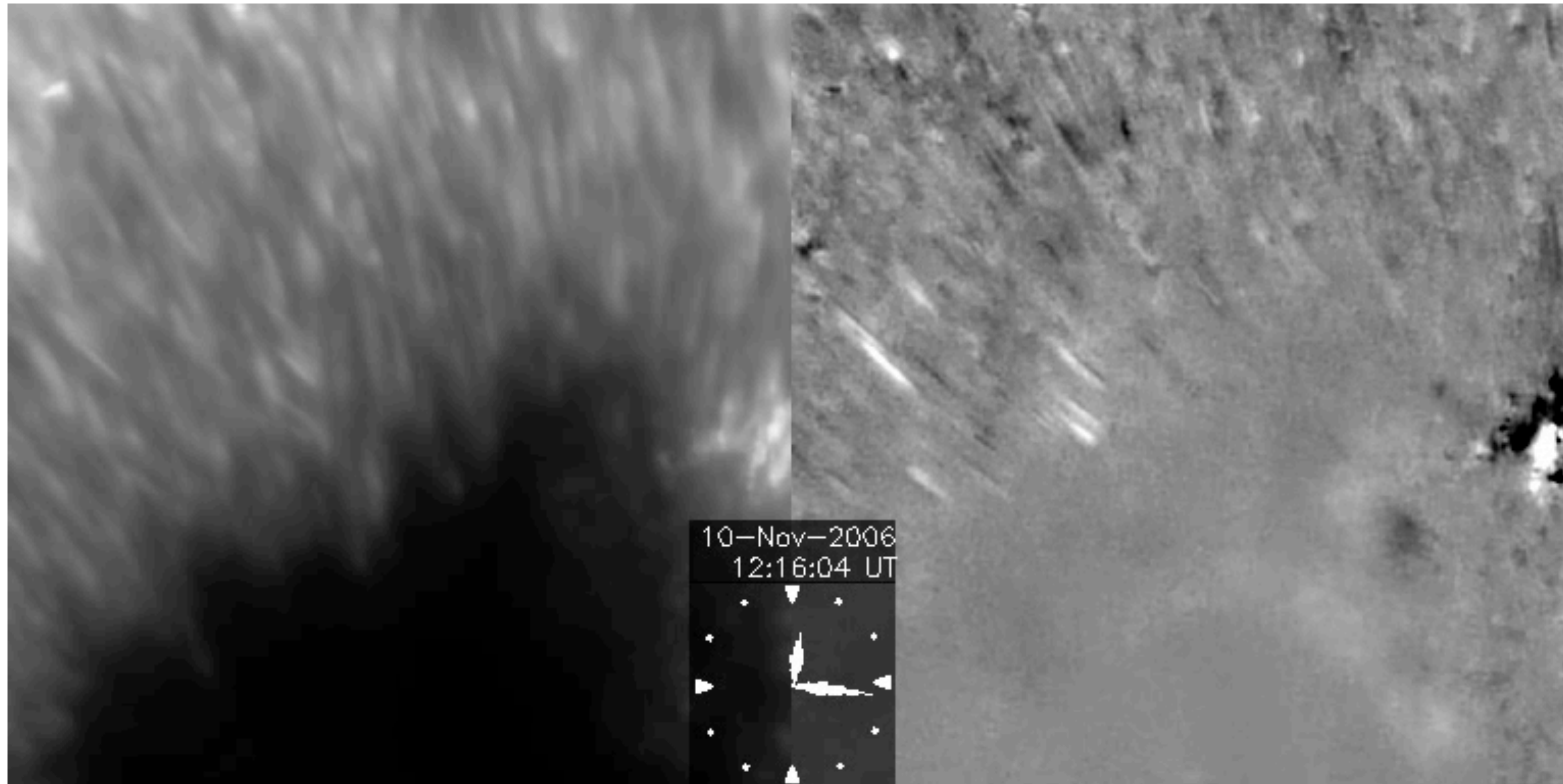
Transient dynamics

Penumbral micro-jets
Katsukawa et al. (2007)



Solar Optical Telescope / Hinode

Ca II H

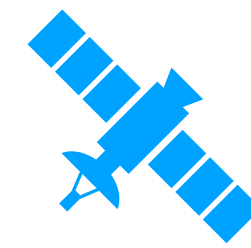


Sunspots: MHD laboratory

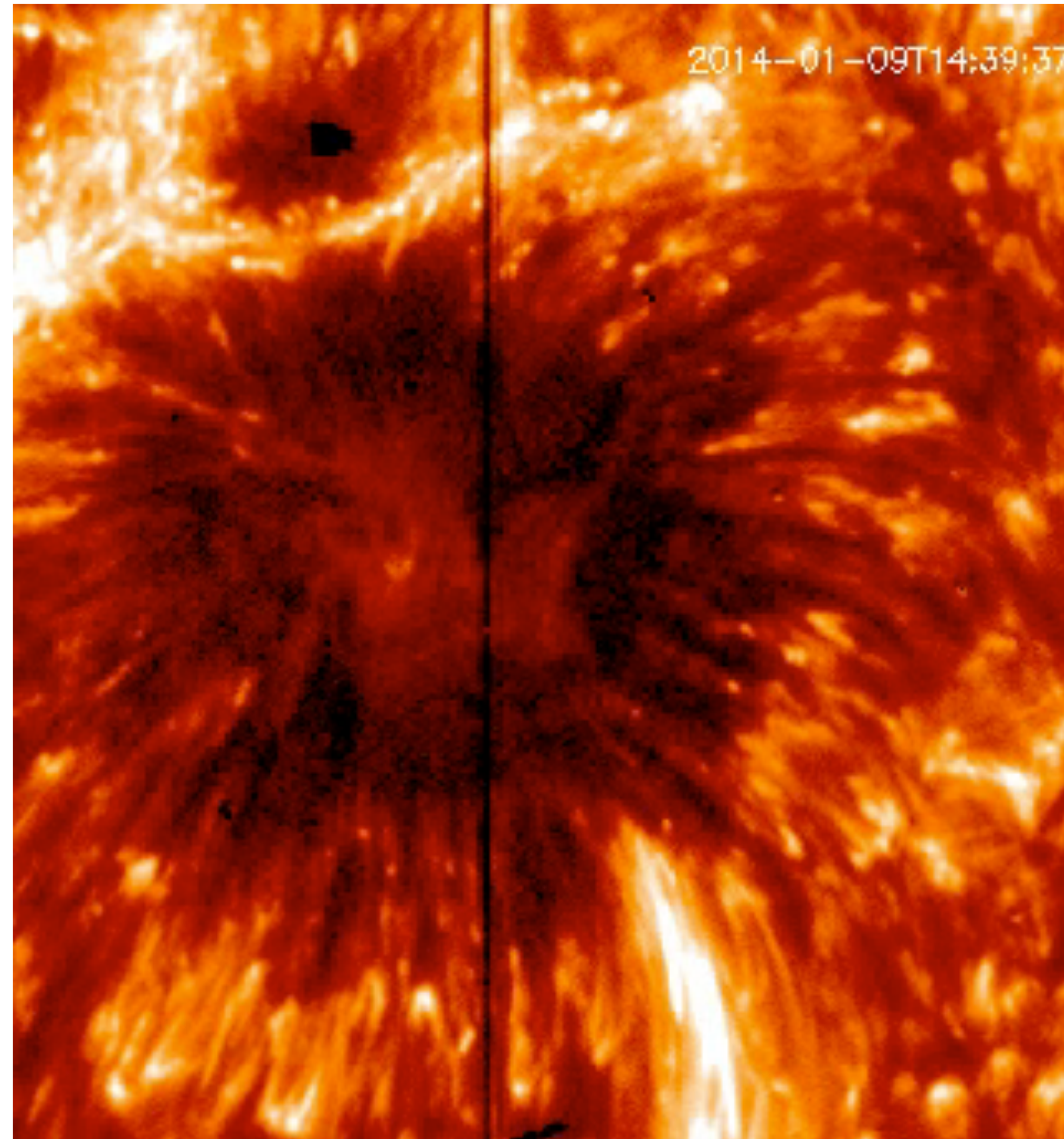
Transient dynamics

Transition region bright dots in penumbra

Tian et al. (2014)



Interface Region Imaging Spectrograph (IRIS)

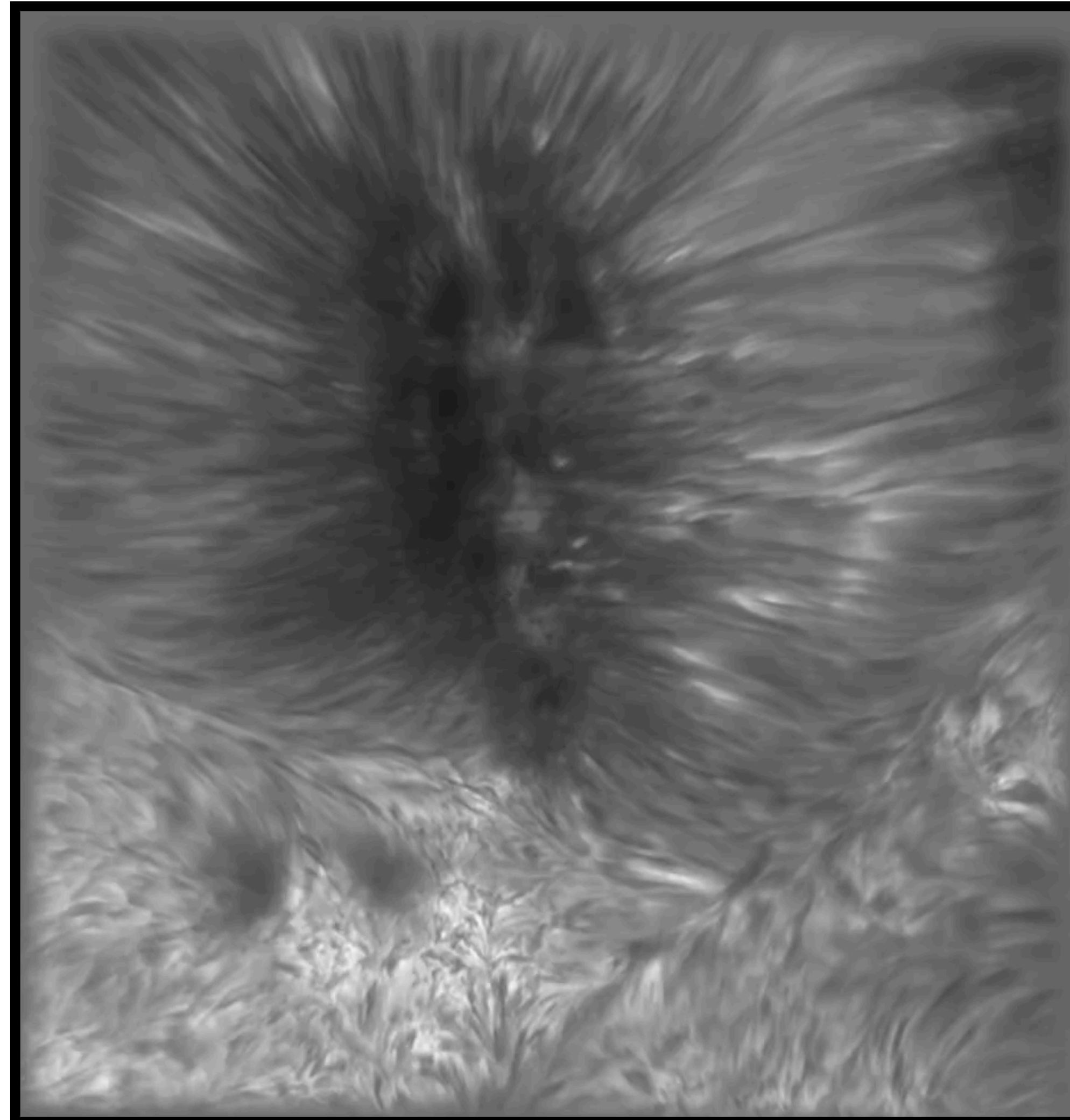


Sunspots: MHD laboratory

Transient dynamics

Ca II 854.2 nm

- Umbral flashes
- Running penumbral waves

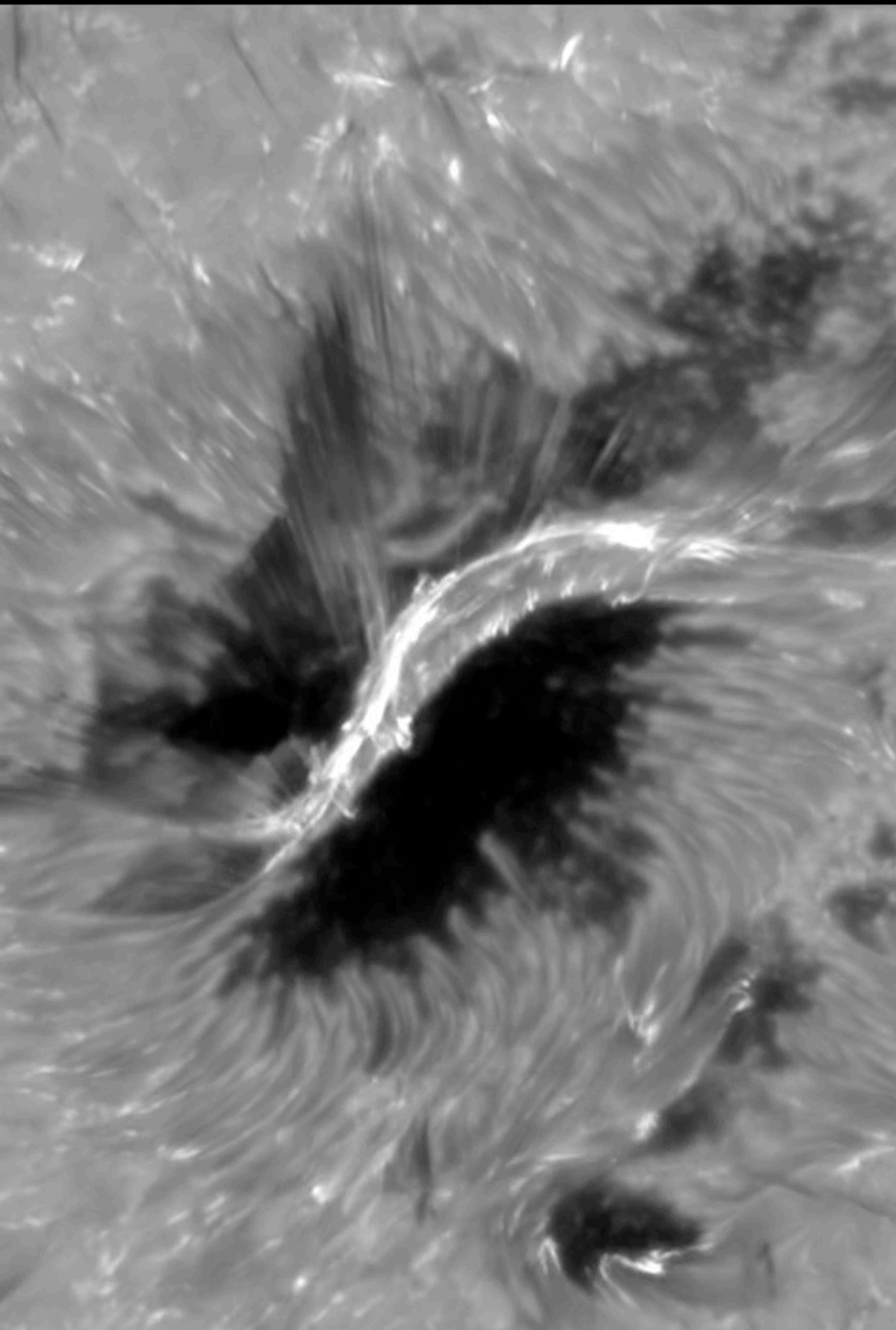
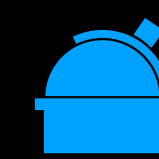


Swedish 1-m Solar Telescope

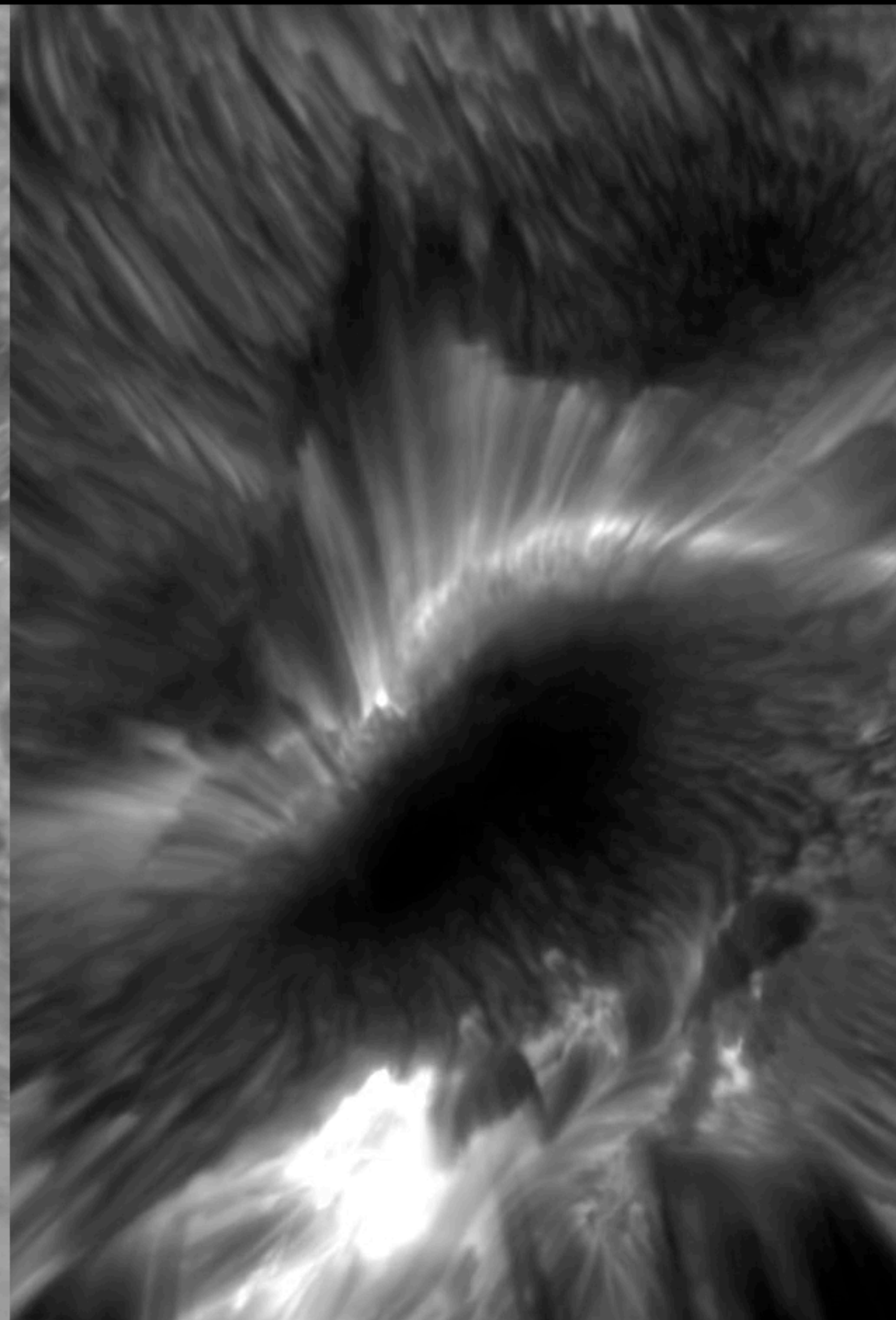
Sunspots: MHD laboratory

Transient dynamics

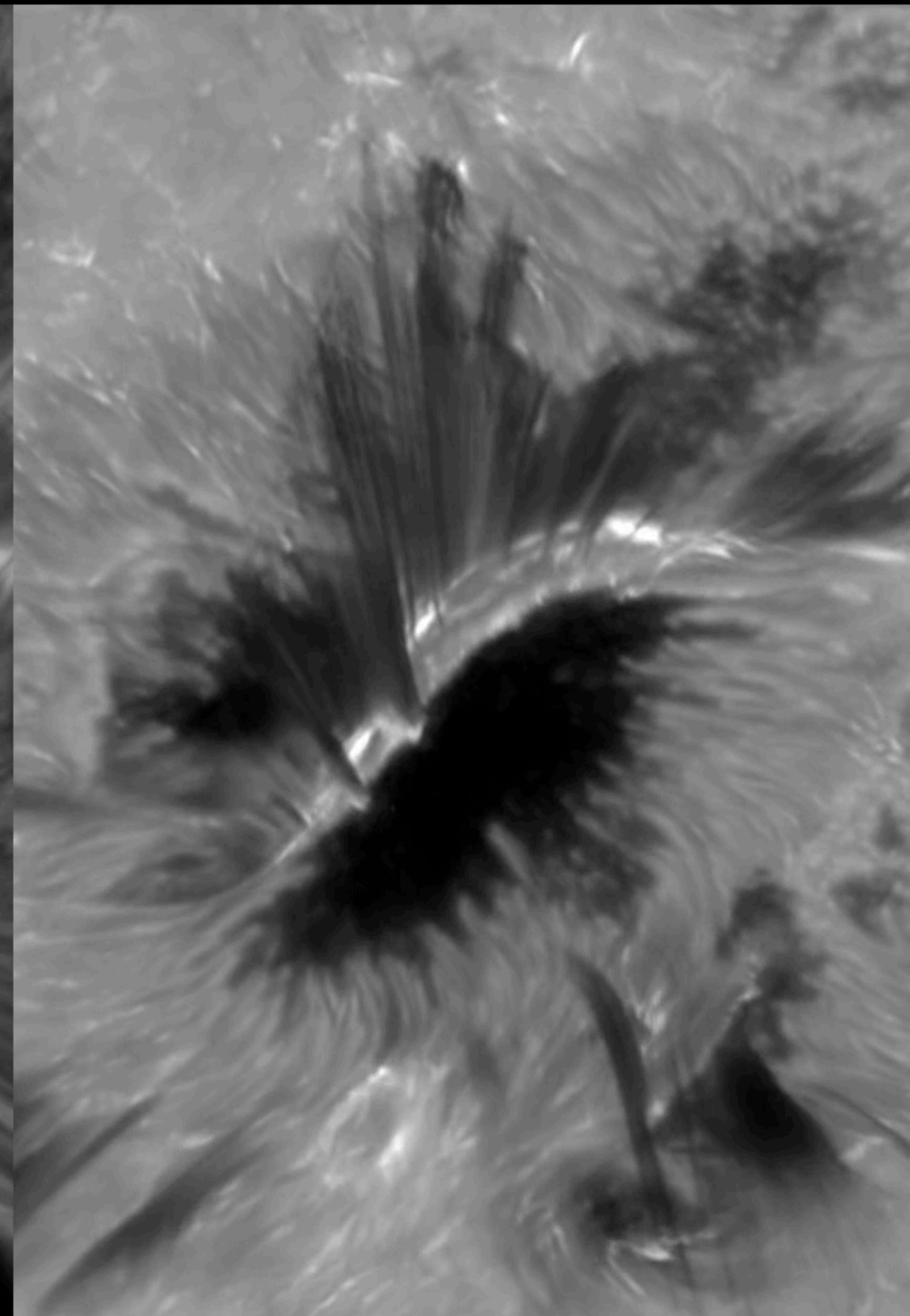
Large scale jets originating
from light-bridges



$\Delta\lambda = -860 \text{ m\AA}$



$\Delta\lambda = 0 \text{ m\AA}$
t = 08:11:54



$\Delta\lambda = +860 \text{ m\AA}$

3D Sunspot structure

Outline

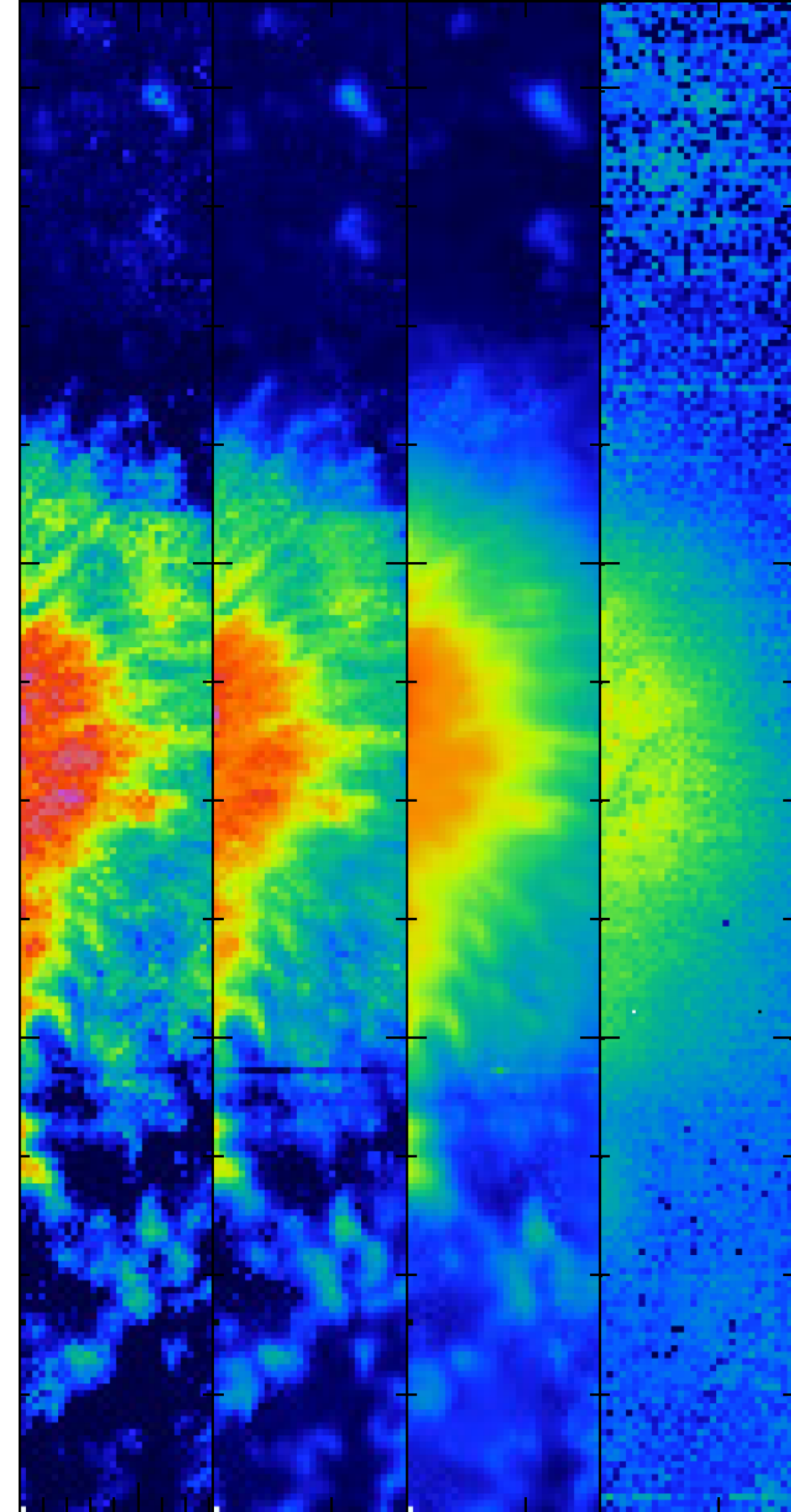
Sunspot: photosphere

- Thermal, Doppler and magnetic field structures
- Height stratifications
- Vertical magnetic field gradient
- Opposite polarity patches in penumbrae
- Inversions based on Deep Learning
- Umbra-penumbra boundary

Sunspot: chromosphere

- Magnetic field comparison with photosphere
- Vertical magnetic field gradient
- Super penumbral structure

Statistical properties of umbrae

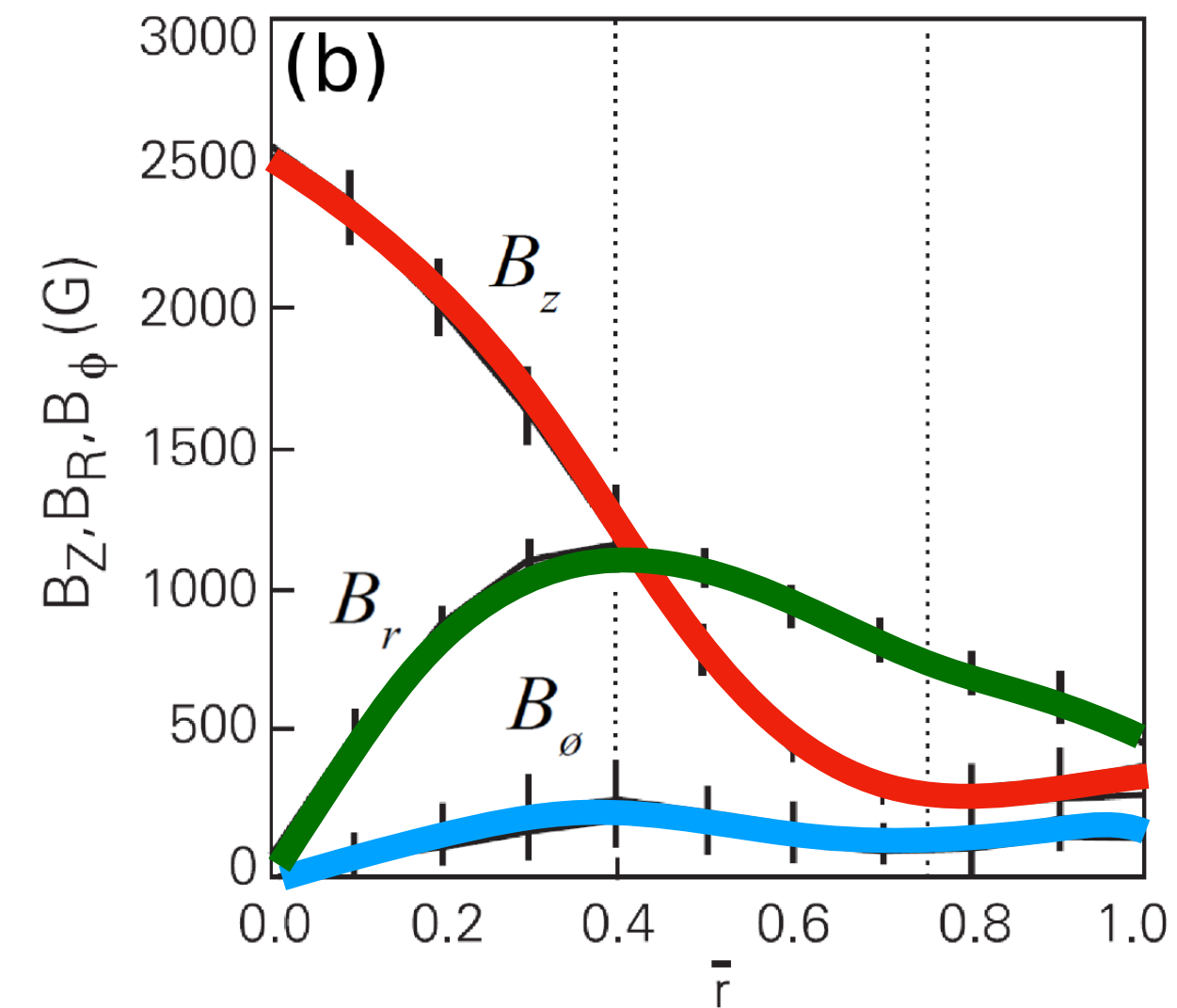
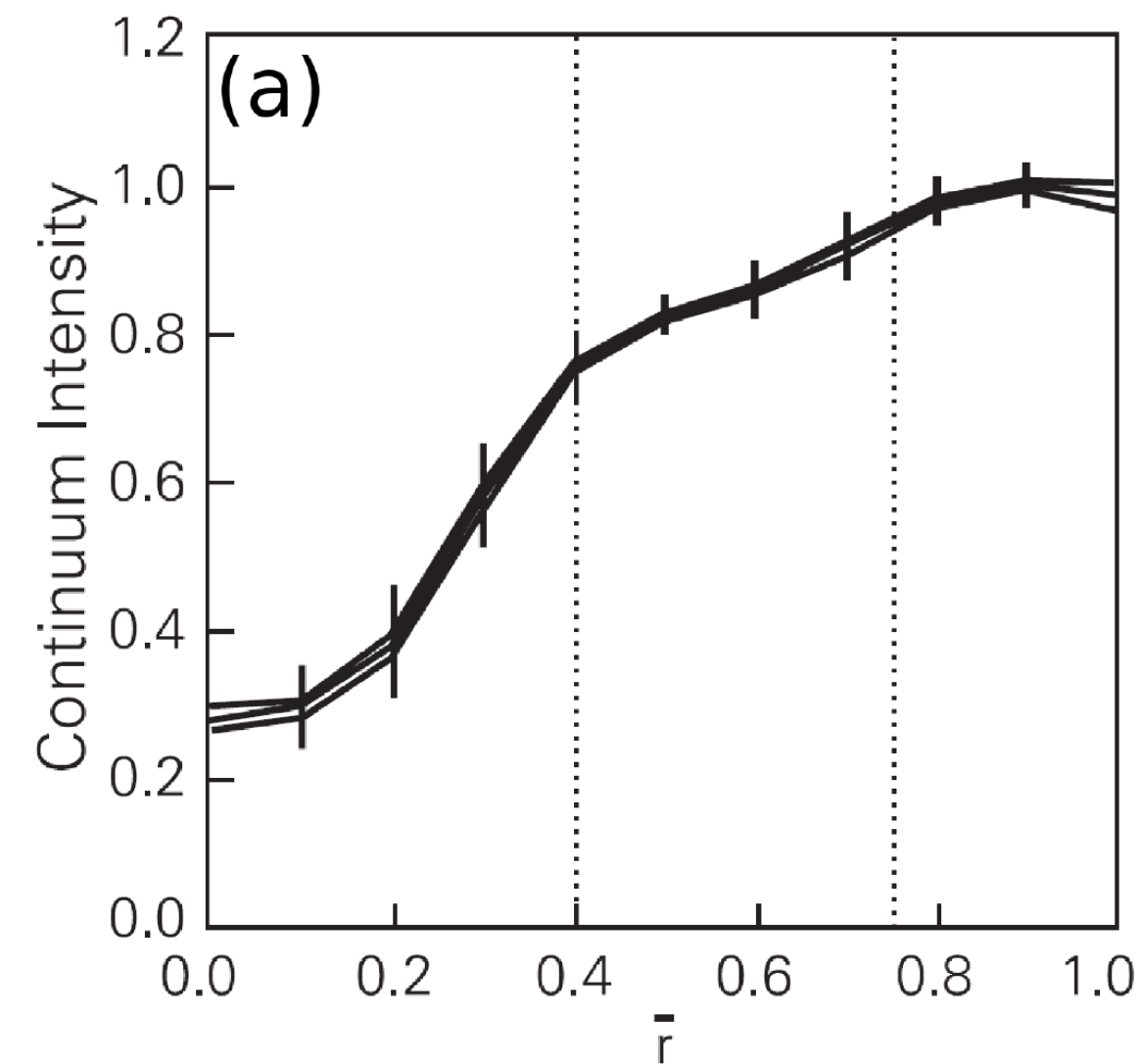


Magnetic field of sunspots: photosphere

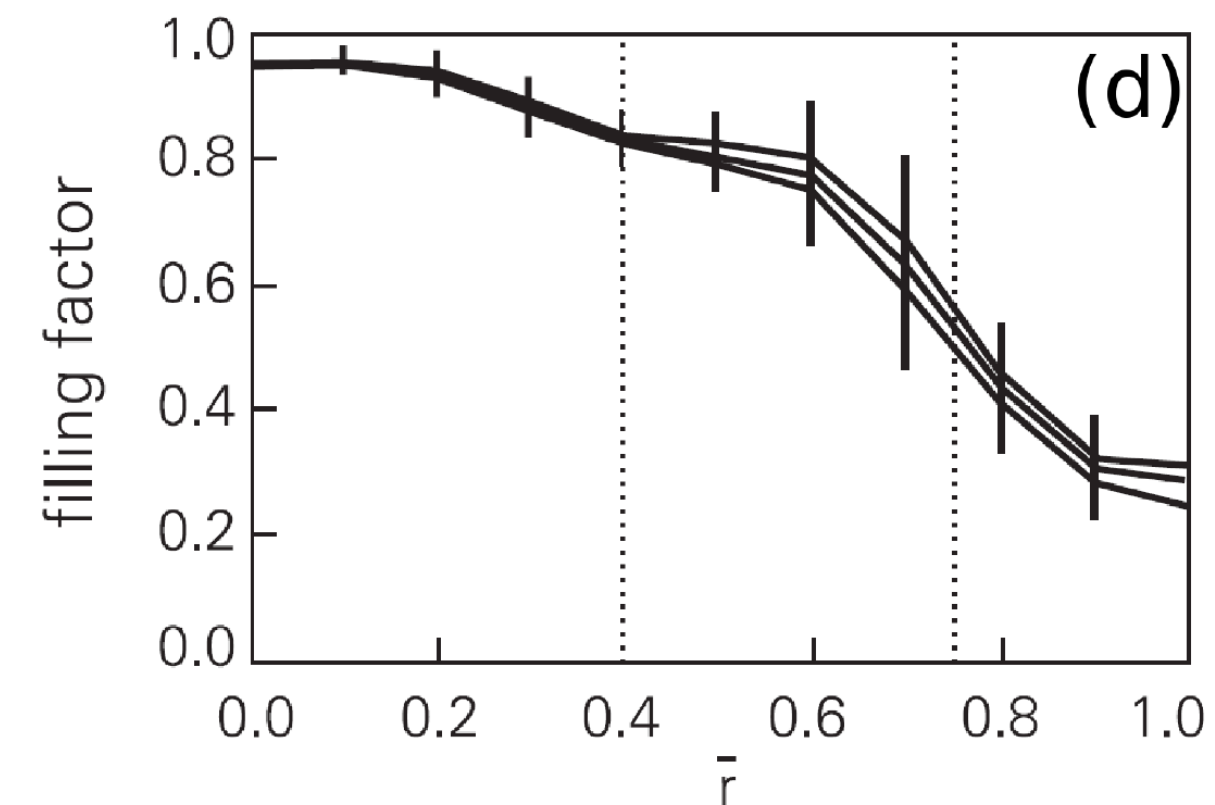
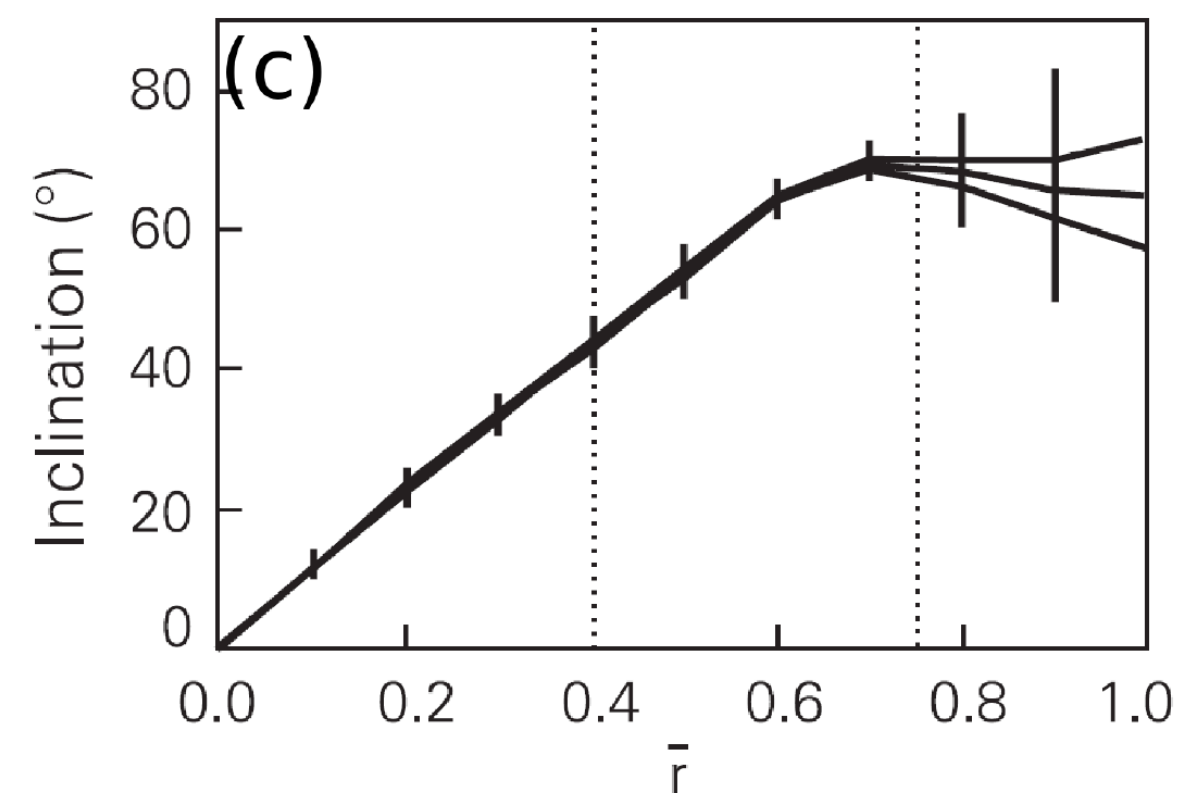
Radial properties

Analysis of 16 sunspots

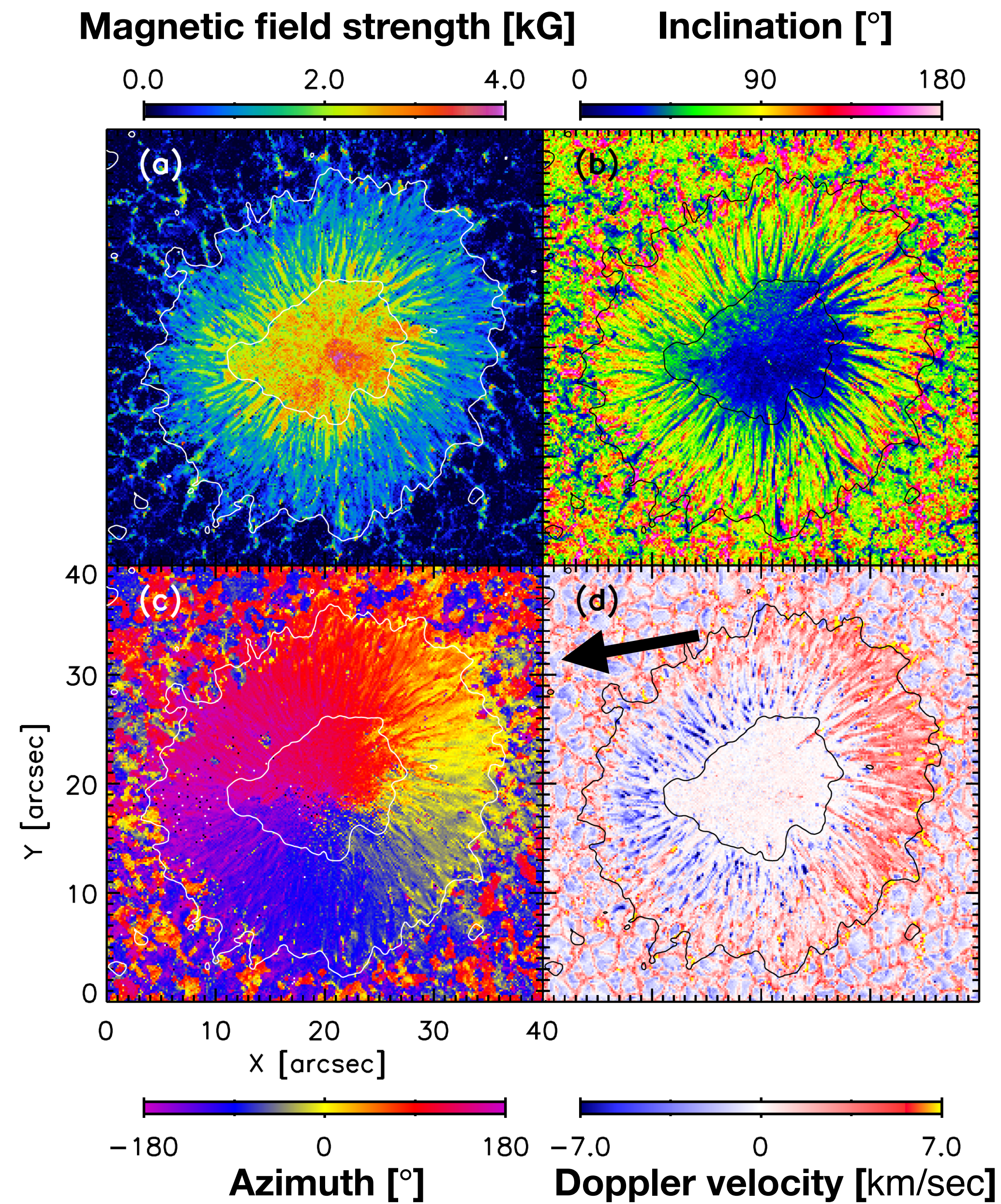
Keppens and Martinez Pillet (1996)



B_z - Vertical
 B_r - Radial
 B_ϕ - Azimuthal



Magnetic field of sunspots: photosphere

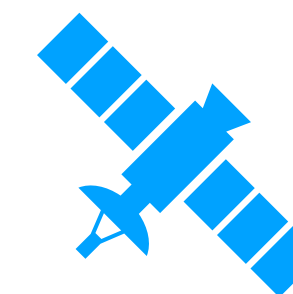


Filamentary structure

Spatially coupled inversions

Joshi (2014), PhD thesis

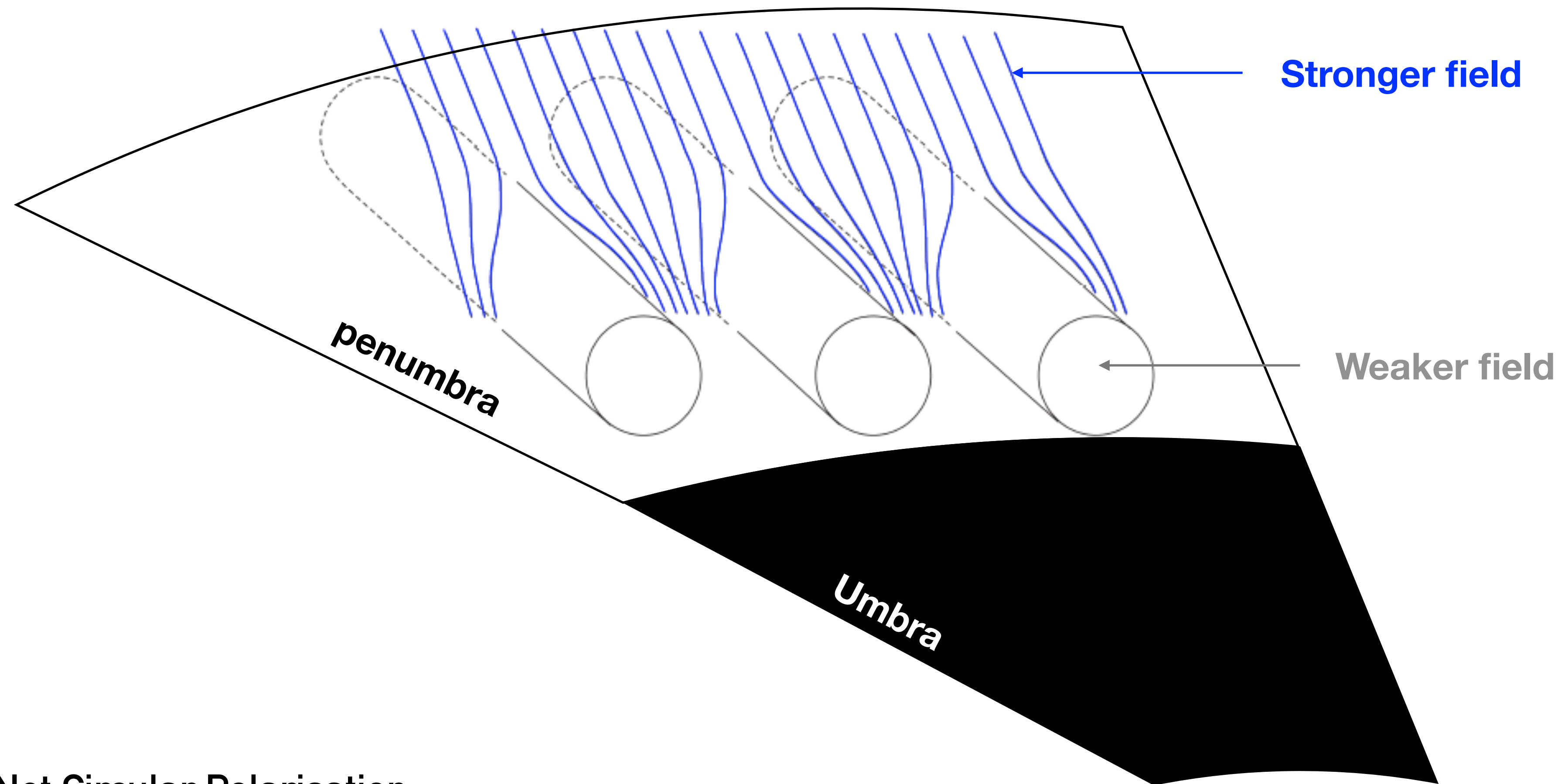
Solar Optical Telescope / Hinode



Magnetic field of sunspot penumbrae: photosphere

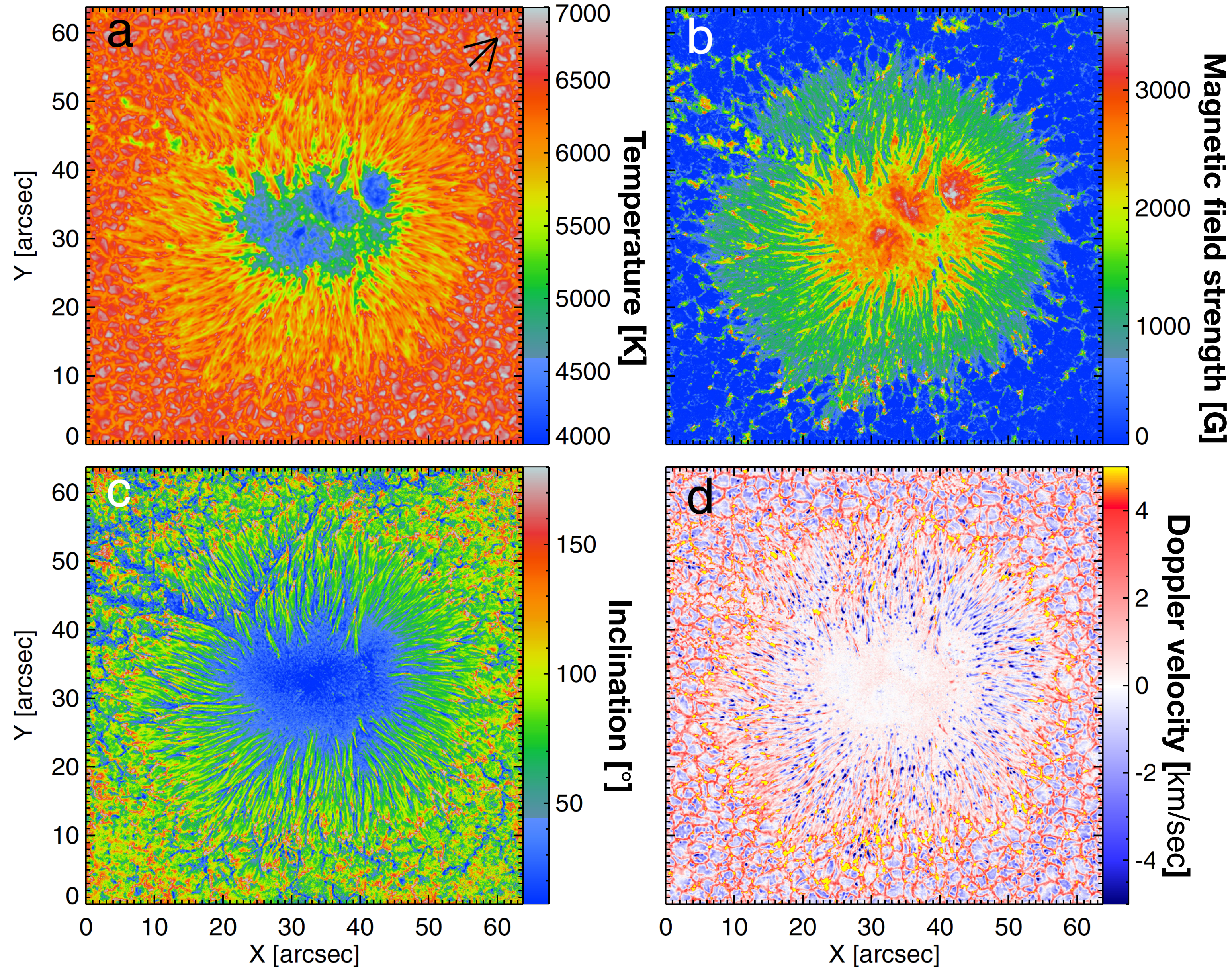
Uncombed model

Solanki and Montavon (1993)



Analysis of Net Circular Polarisation

Magnetic field of sunspots: photosphere



Filamentary structure

Spatially coupled inversions

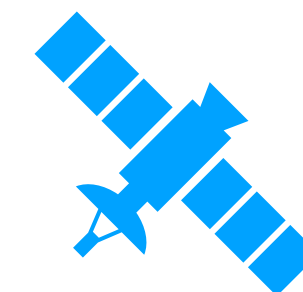
van Noort (2013)

Fe I 6301.5 & 6302.5 Å

Sunspot at the disk centre

Tiwari et al. (2015)

Solar Optical Telescope / Hinode



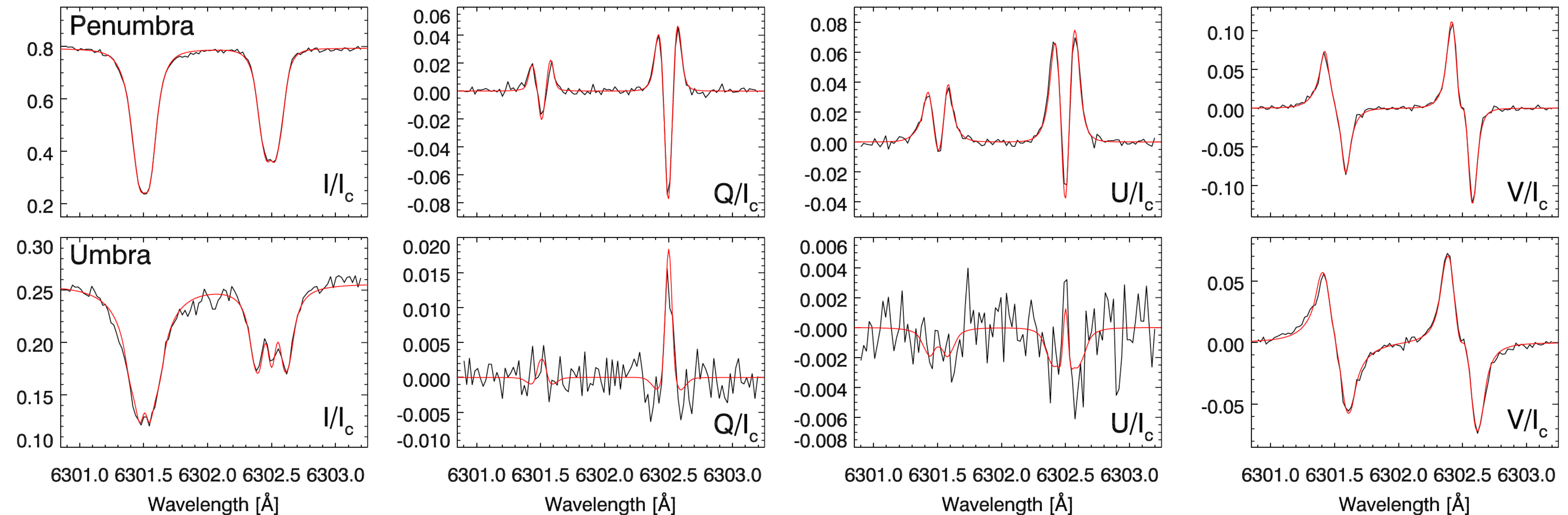
Magnetic field of sunspots: photosphere

Spatially coupled inversions

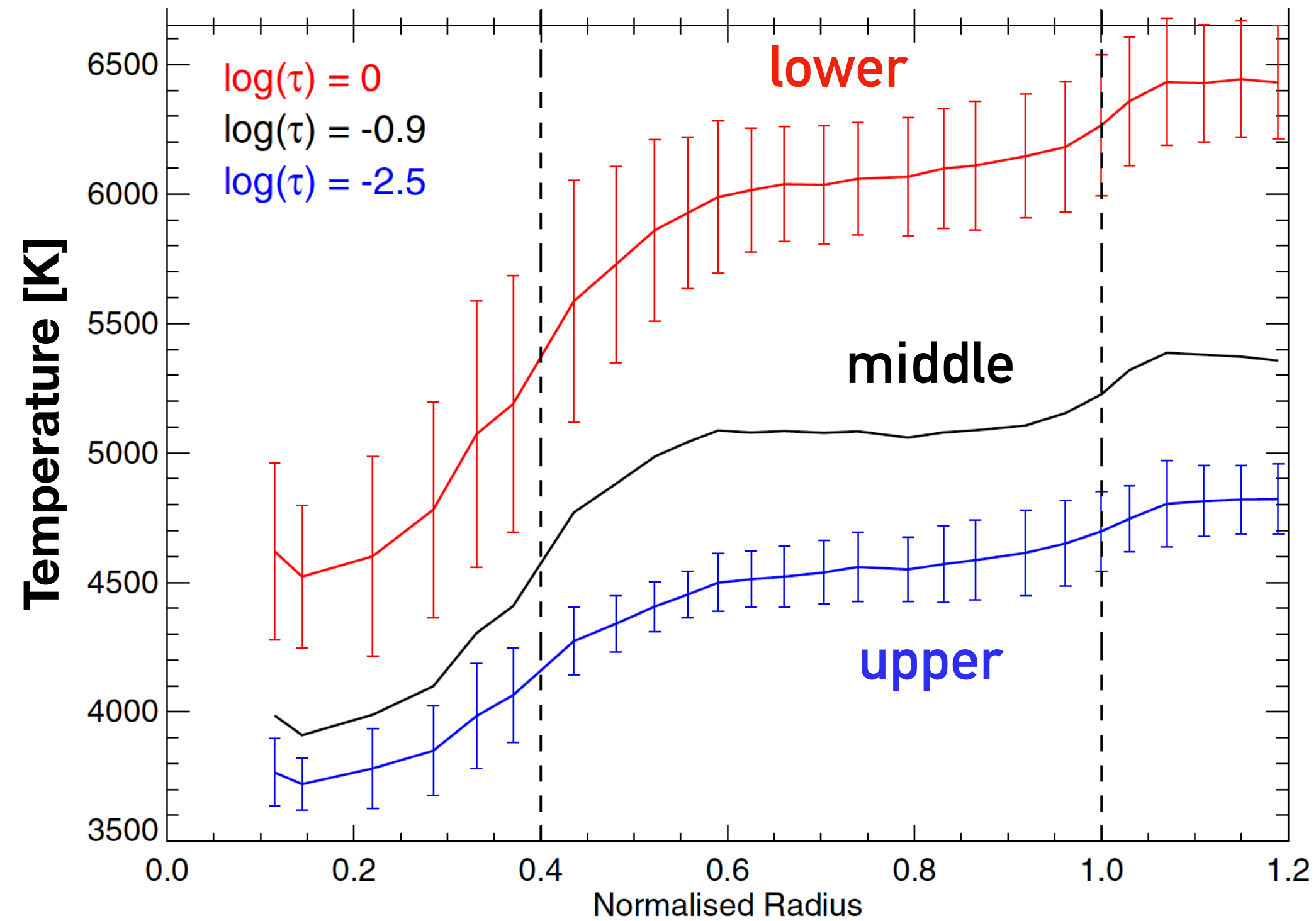
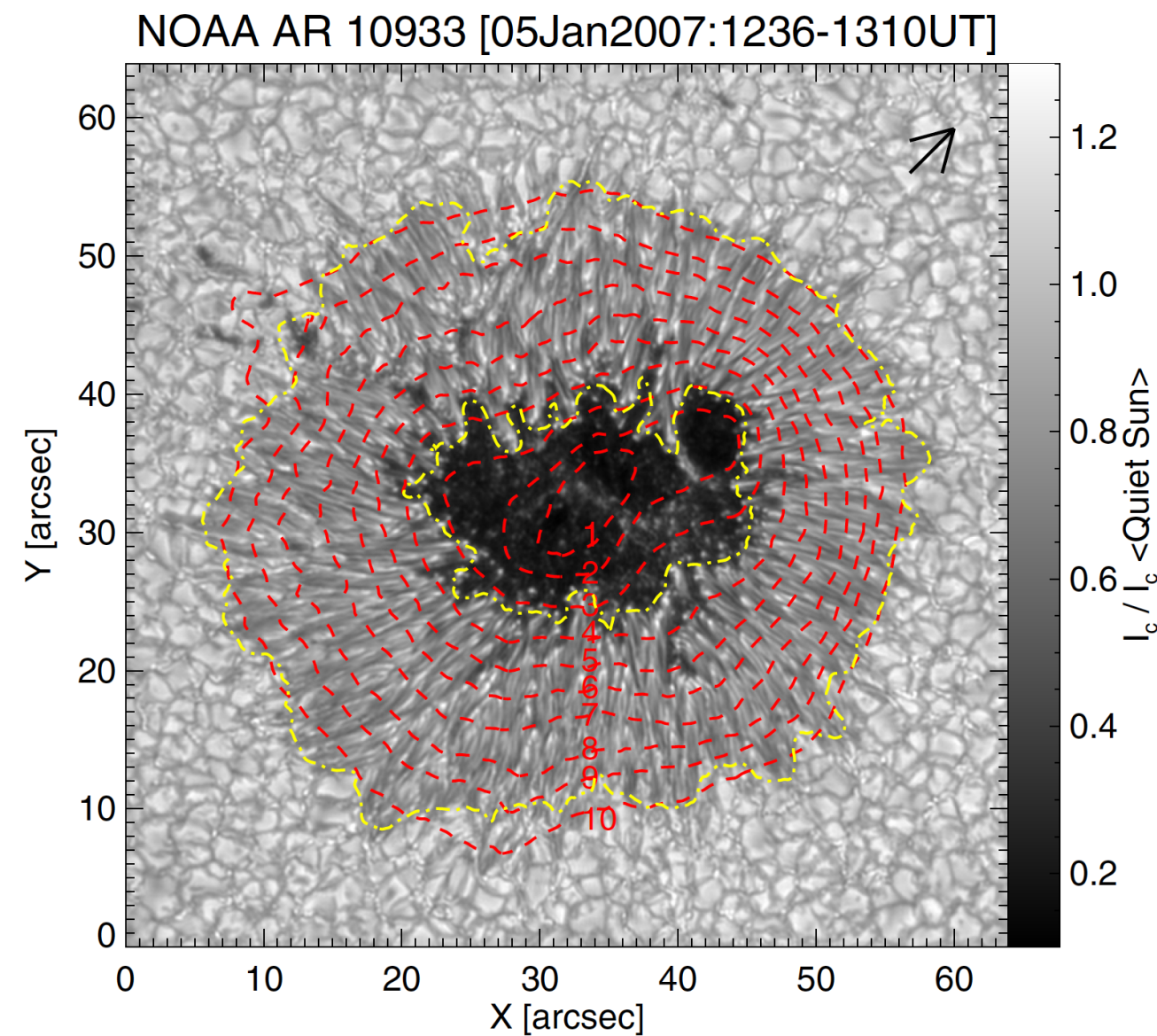
van Noort (2013)

Fe I 6301.5 & 6302.5 Å

Tiwari et al. (2015)



Magnetic field of sunspots: photosphere



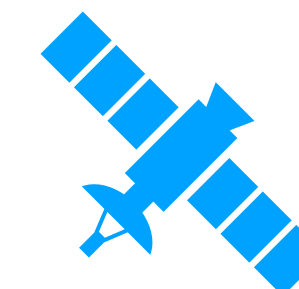
Filamentary structure

Spatially coupled inversions

van Noort (2013)

Fe I 6301.5 & 6302.5 Å

Sunspot at the disk centre

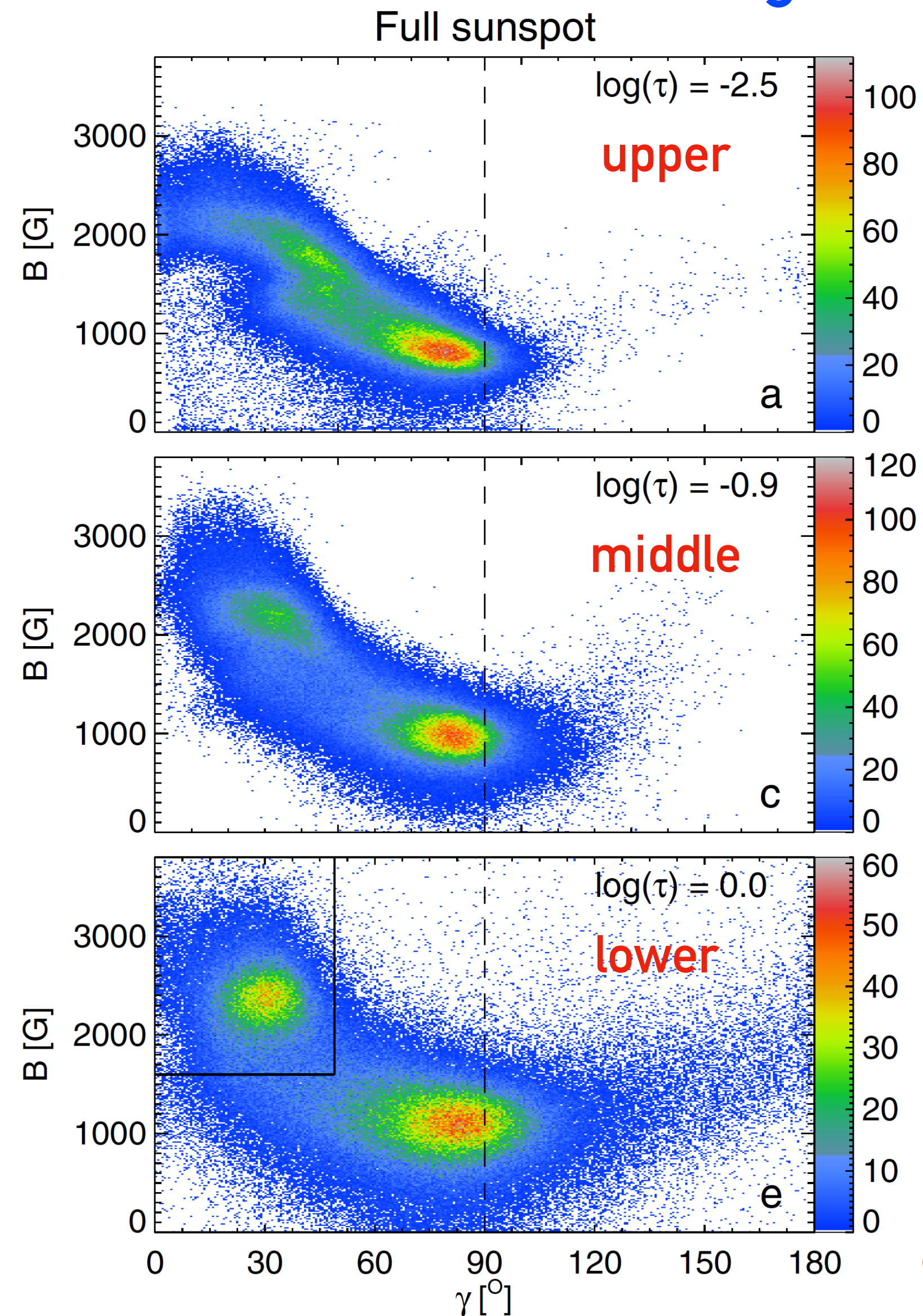


Tiwari et al. (2015)

Solar Optical Telescope / Hinode

Magnetic field of sunspots: photosphere

Inclination vs field strength



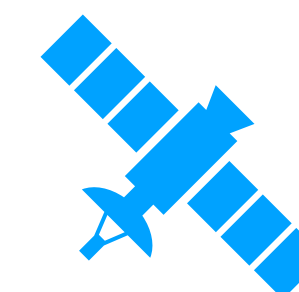
Spatially coupled inversions

van Noort (2013)

Fe I 6301.5 & 6302.5 Å

Sunspot at the disk centre

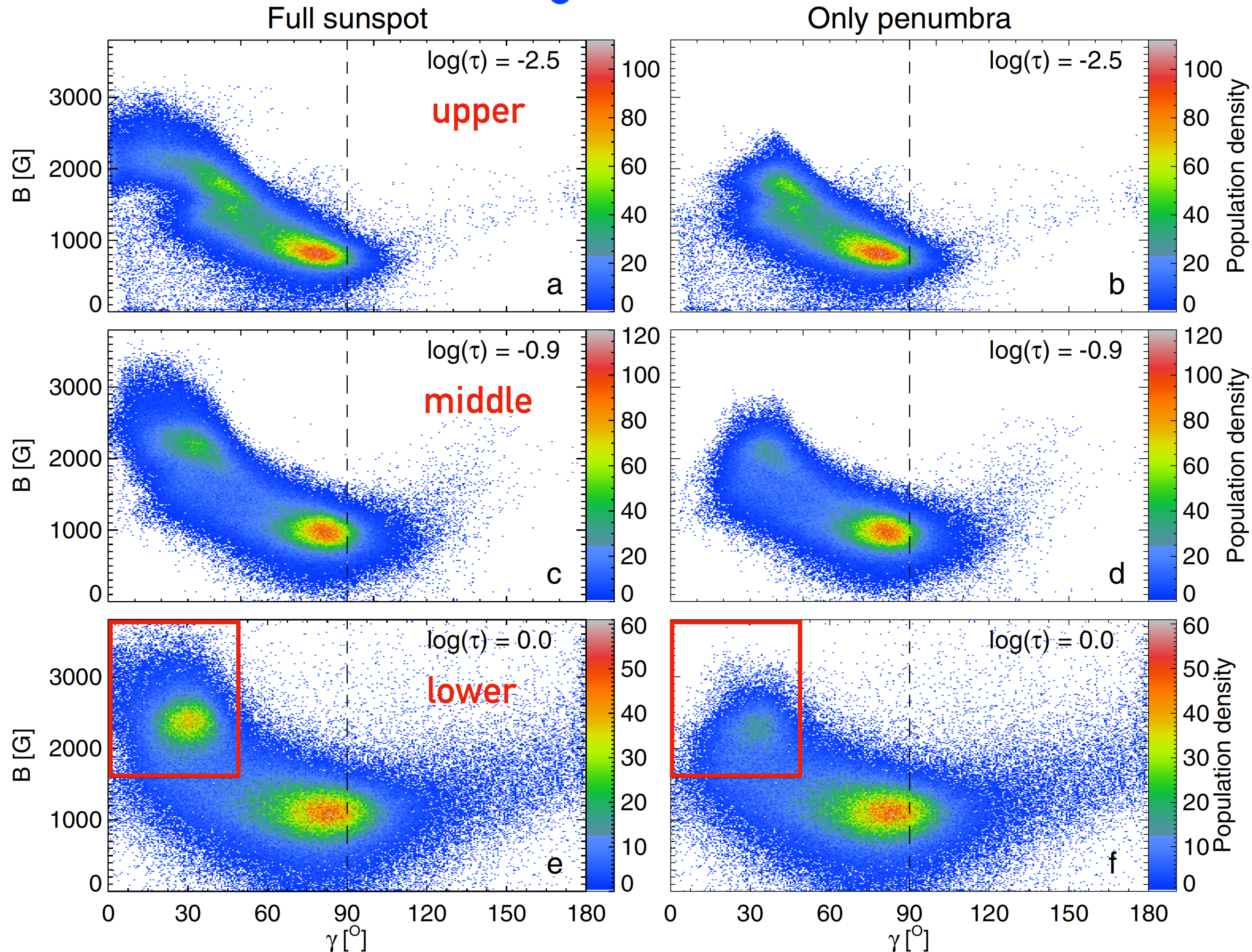
Tiwari et al. (2015)



Solar Optical Telescope / Hinode

Magnetic field of sunspots: photosphere

Inclination vs field strength



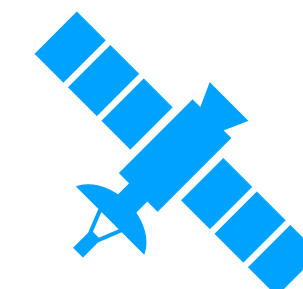
Spatially coupled inversions

van Noort (2013)

Fe I 6301.5 & 6302.5 Å

Sunspot at the disk centre

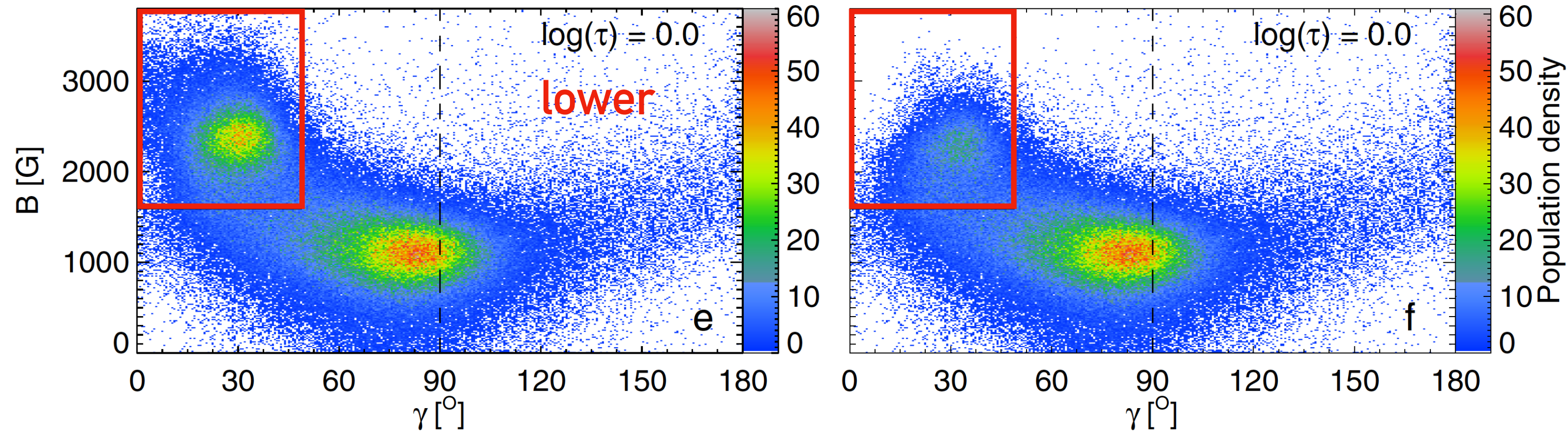
Tiwari et al. (2015)



Solar Optical Telescope / Hinode

Magnetic field of sunspots: photosphere

Inclination vs field strength



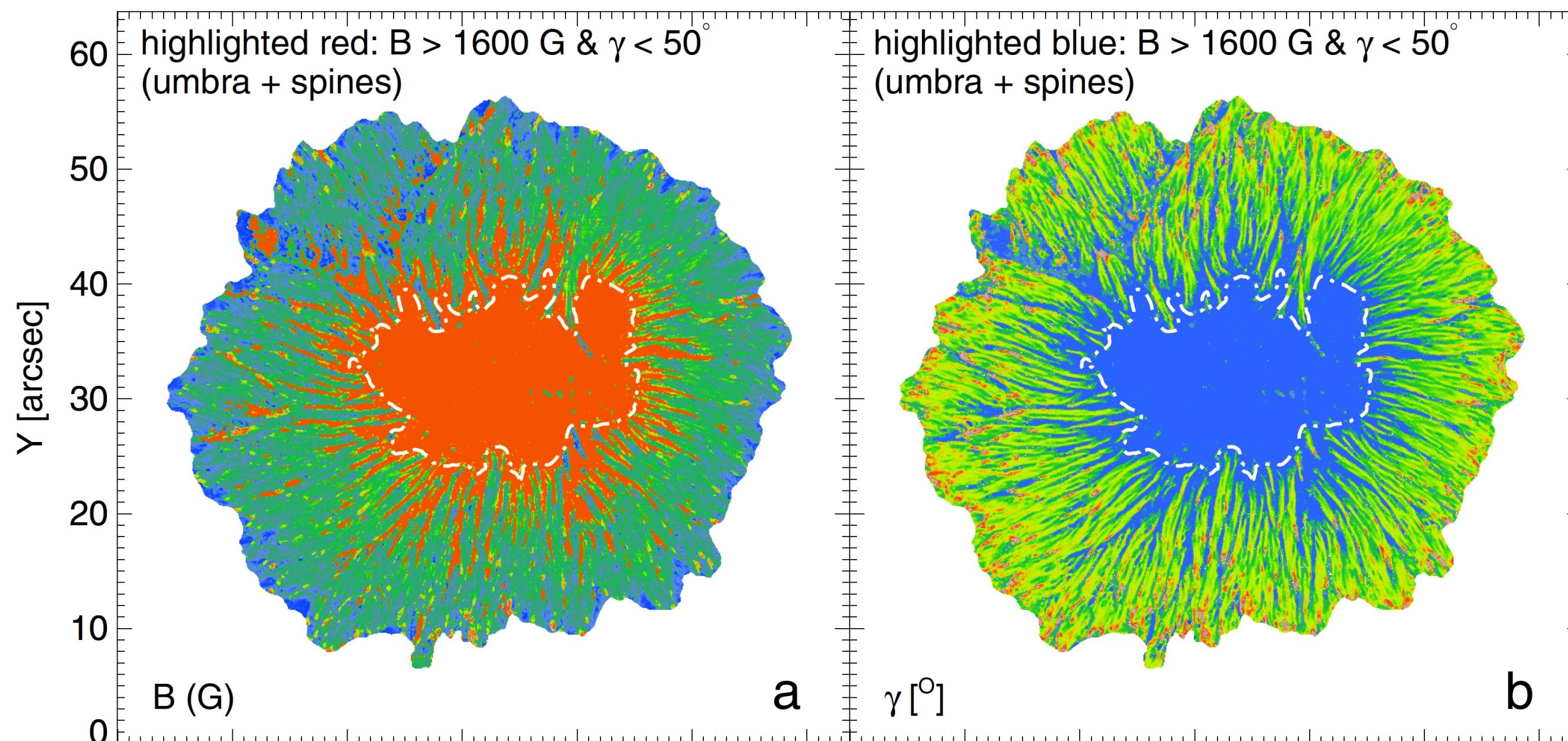
A&A 583, A119 (2015)

Spatially coupled inversions

van Noort (2013)

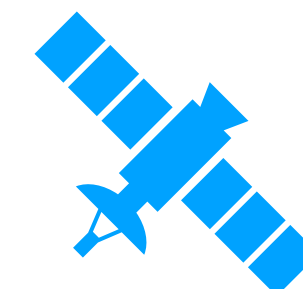
Fe I 6301.5 & 6302.5 Å

Sunspot at the disk centre



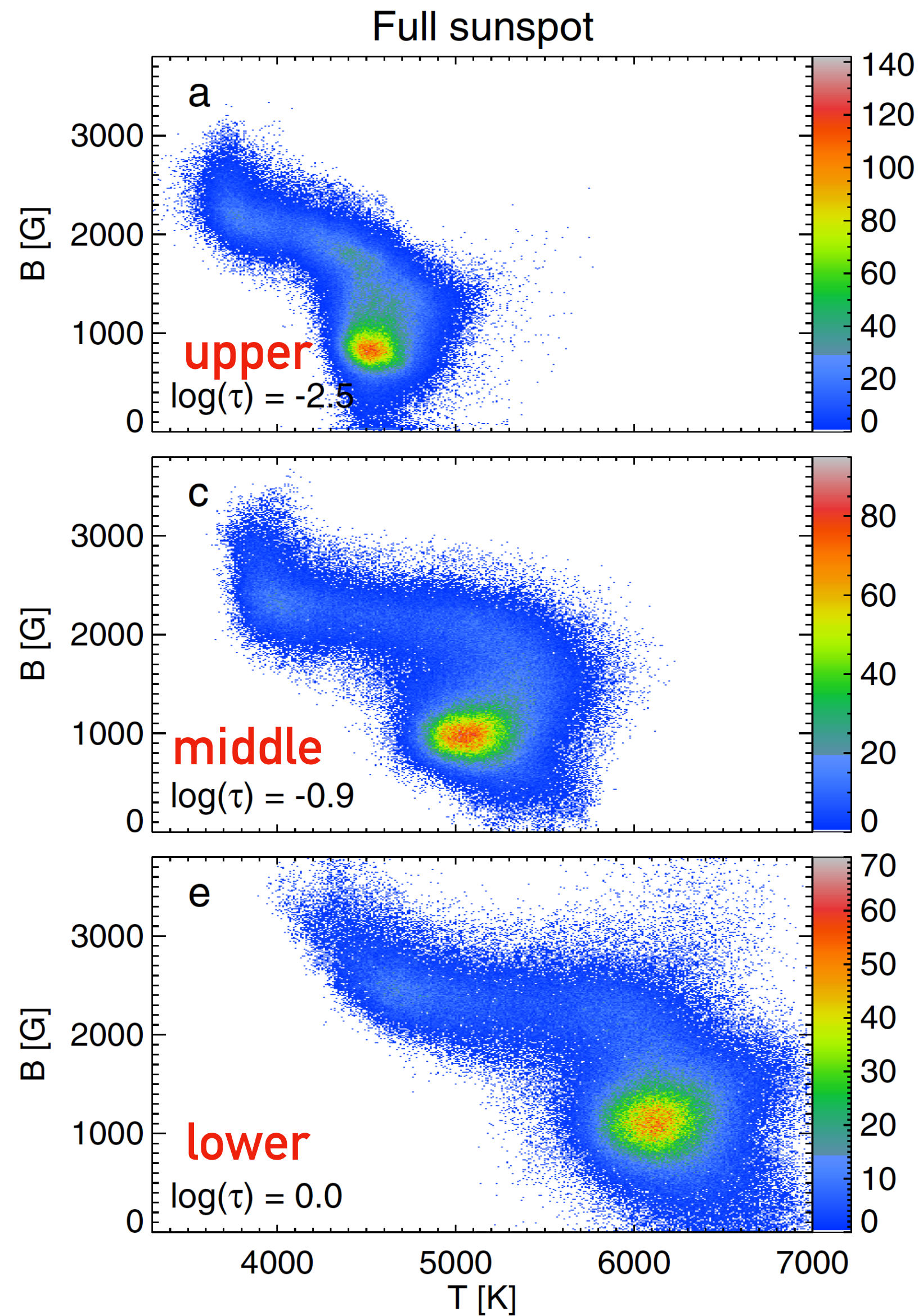
Tiwari et al. (2015)

Solar Optical Telescope / Hinode



Magnetic field of sunspots: photosphere

Temperature vs field strength



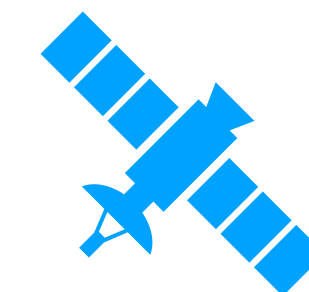
Spatially coupled inversions

van Noort (2013)

Fe I 6301.5 & 6302.5 Å

Sunspot at the disk centre

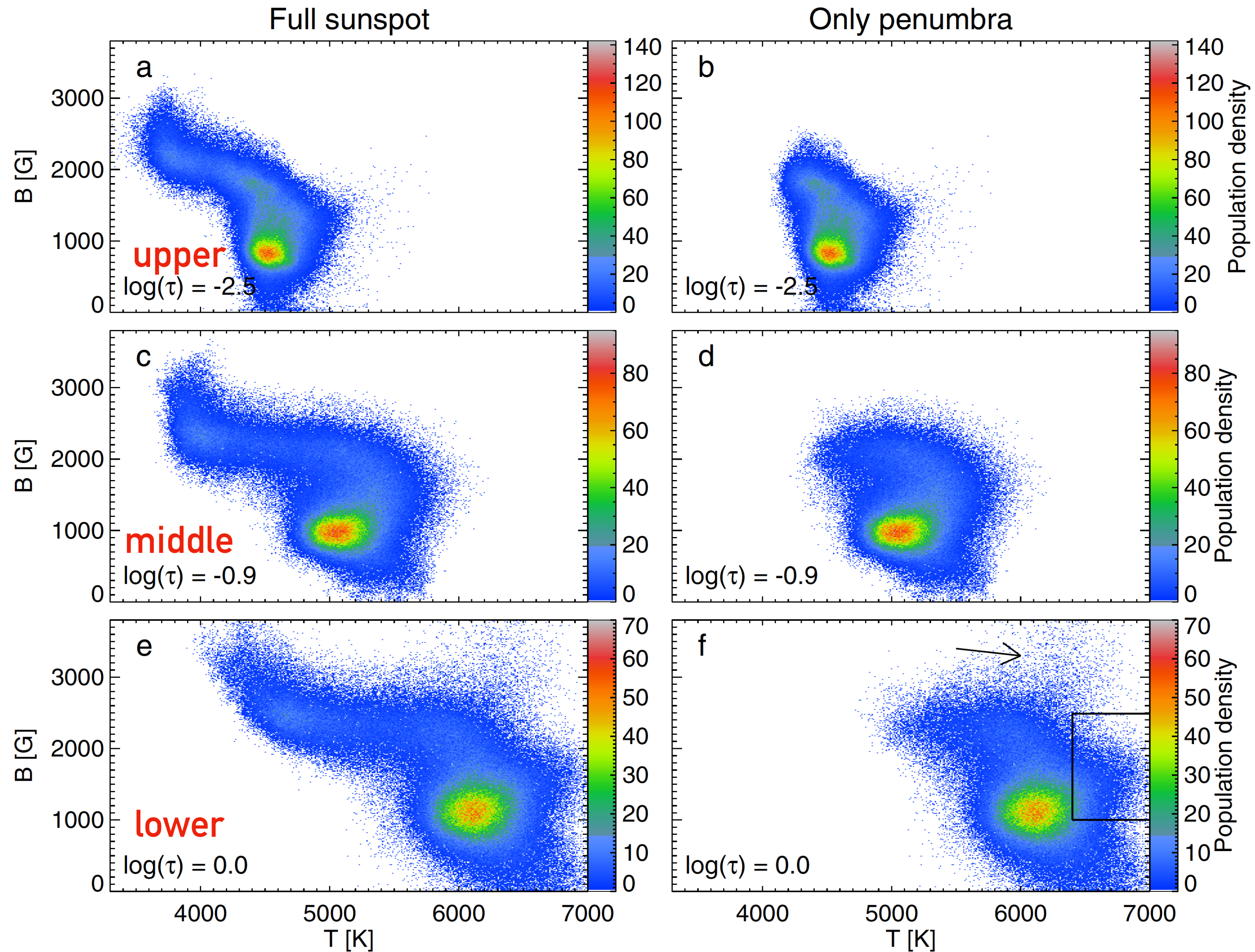
Tiwari et al. (2015)



Solar Optical Telescope / Hinode

Magnetic field of sunspots: photosphere

Temperature vs field strength



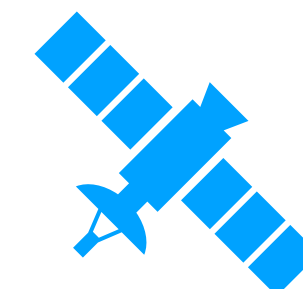
Spatially coupled inversions

van Noort (2013)

Fe I 6301.5 & 6302.5 Å

Sunspot at the disk centre

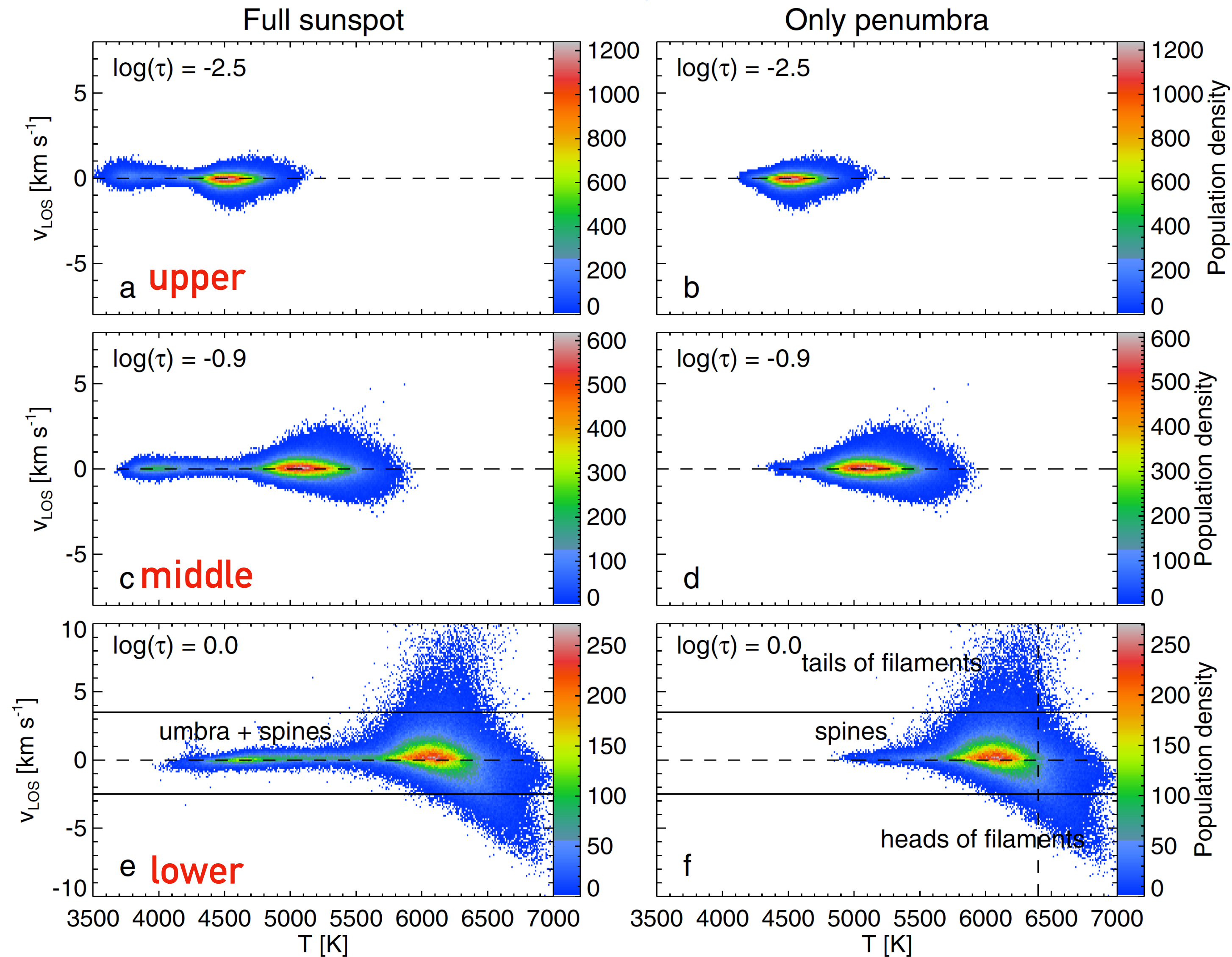
Tiwari et al. (2015)



Solar Optical Telescope / Hinode

Magnetic field of sunspots: photosphere

LOS Velocity vs field strength



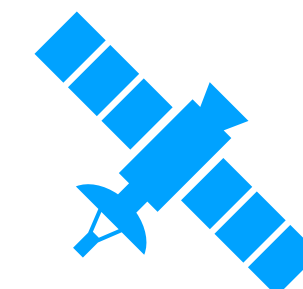
Spatially coupled inversions

van Noort (2013)

Fe I 6301.5 & 6302.5 Å

Sunspot at the disk centre

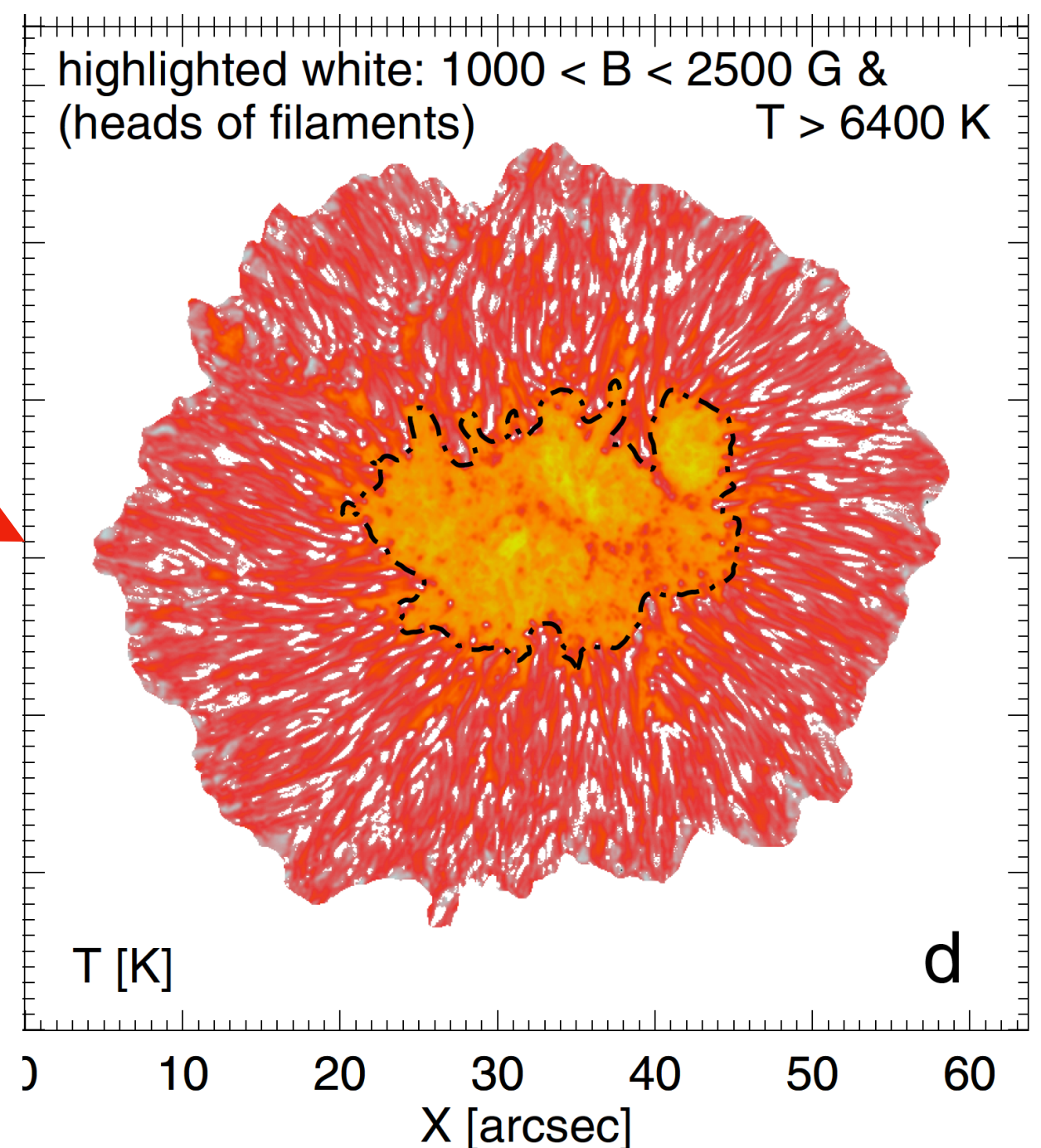
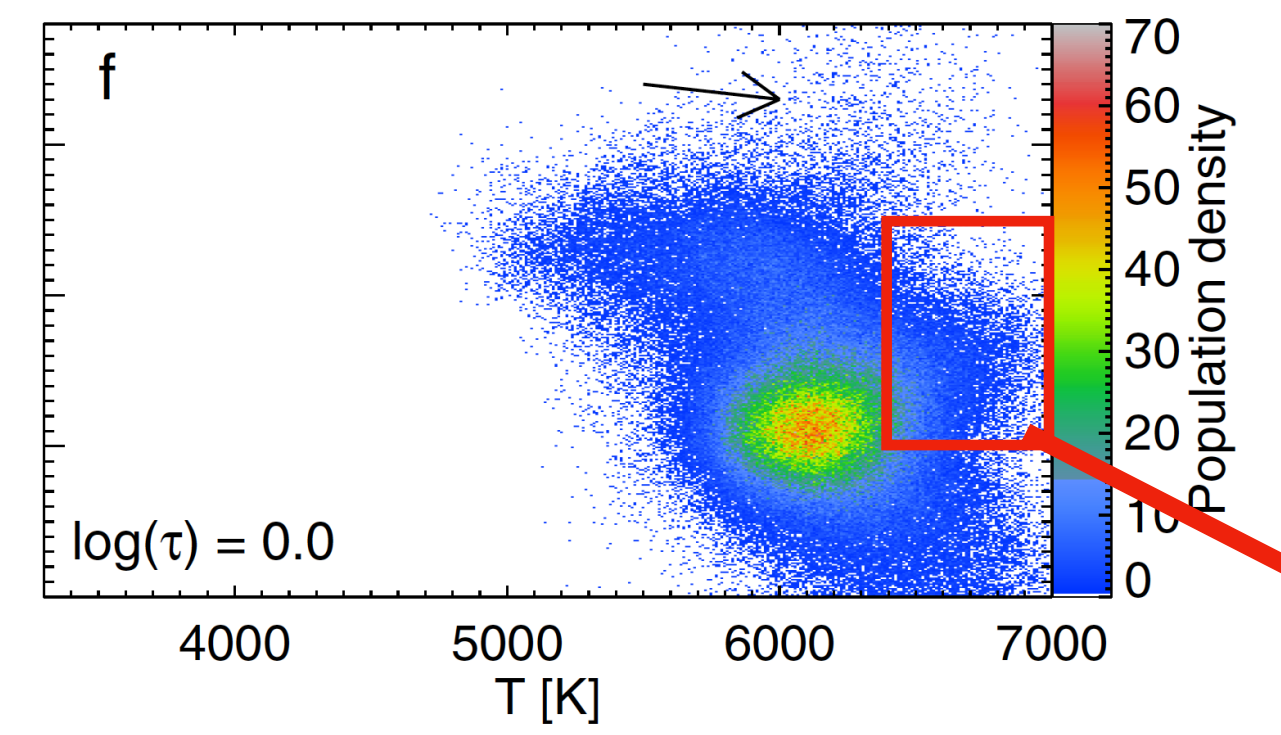
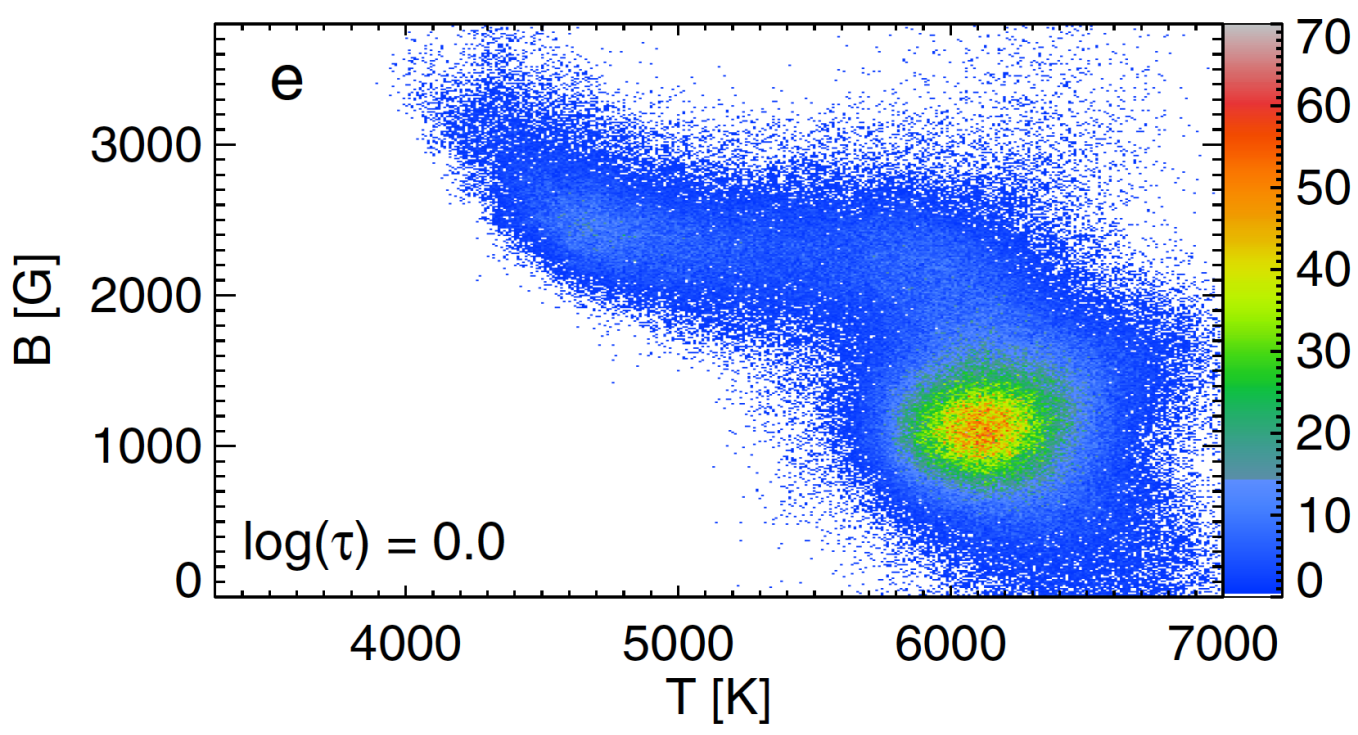
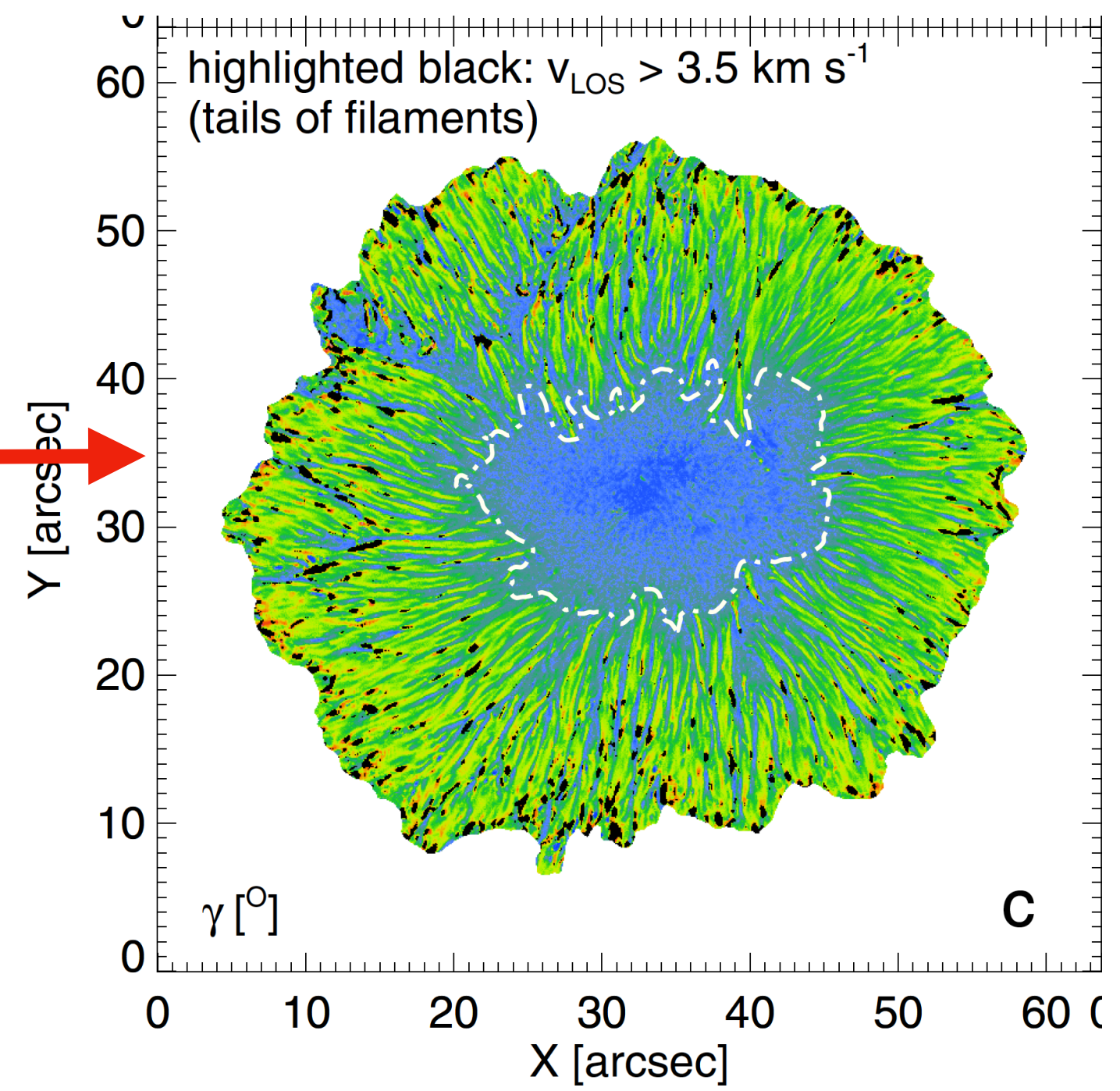
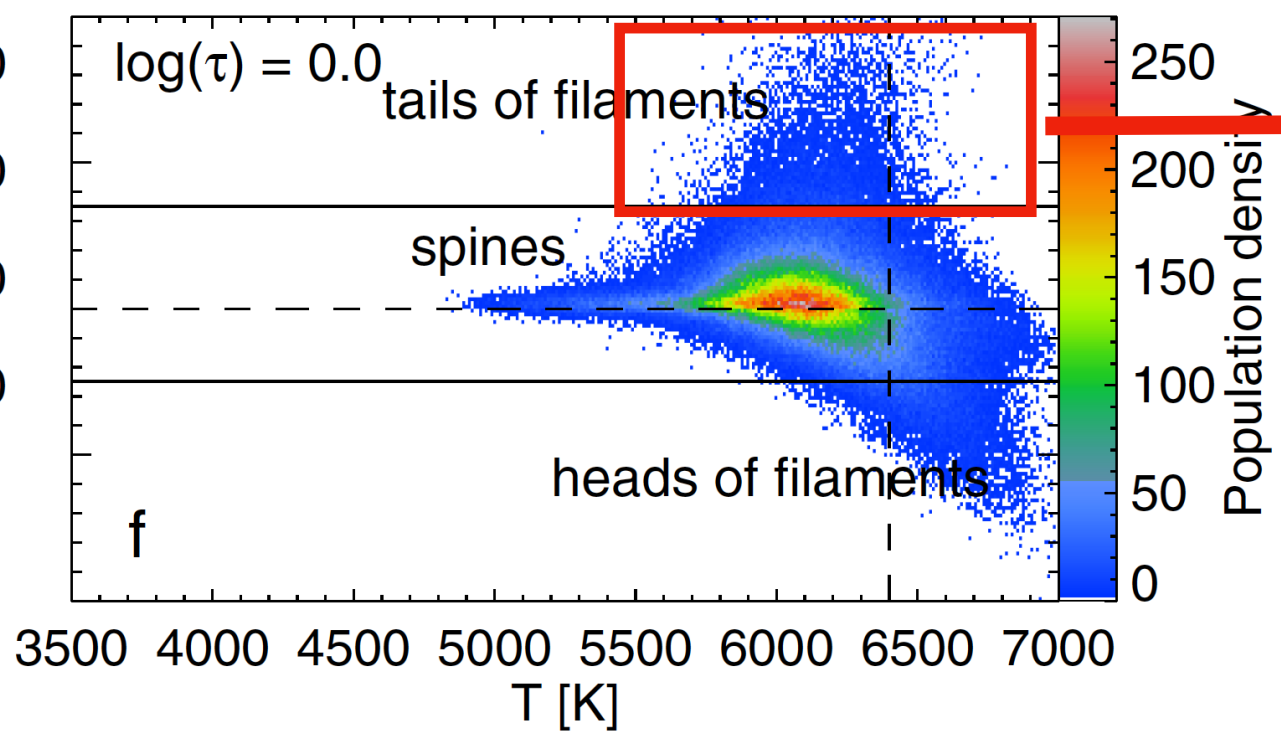
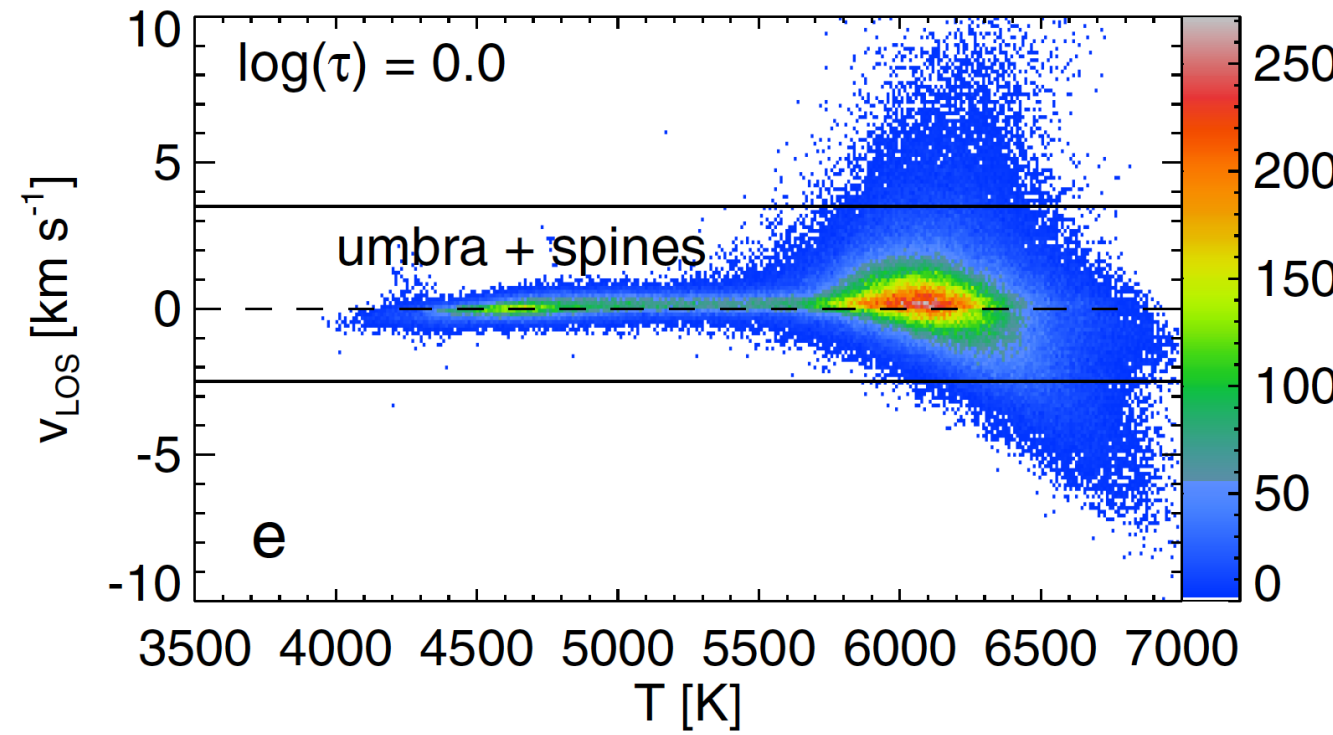
Tiwari et al. (2015)



Solar Optical Telescope / Hinode

Magnetic field of sunspots: photosphere

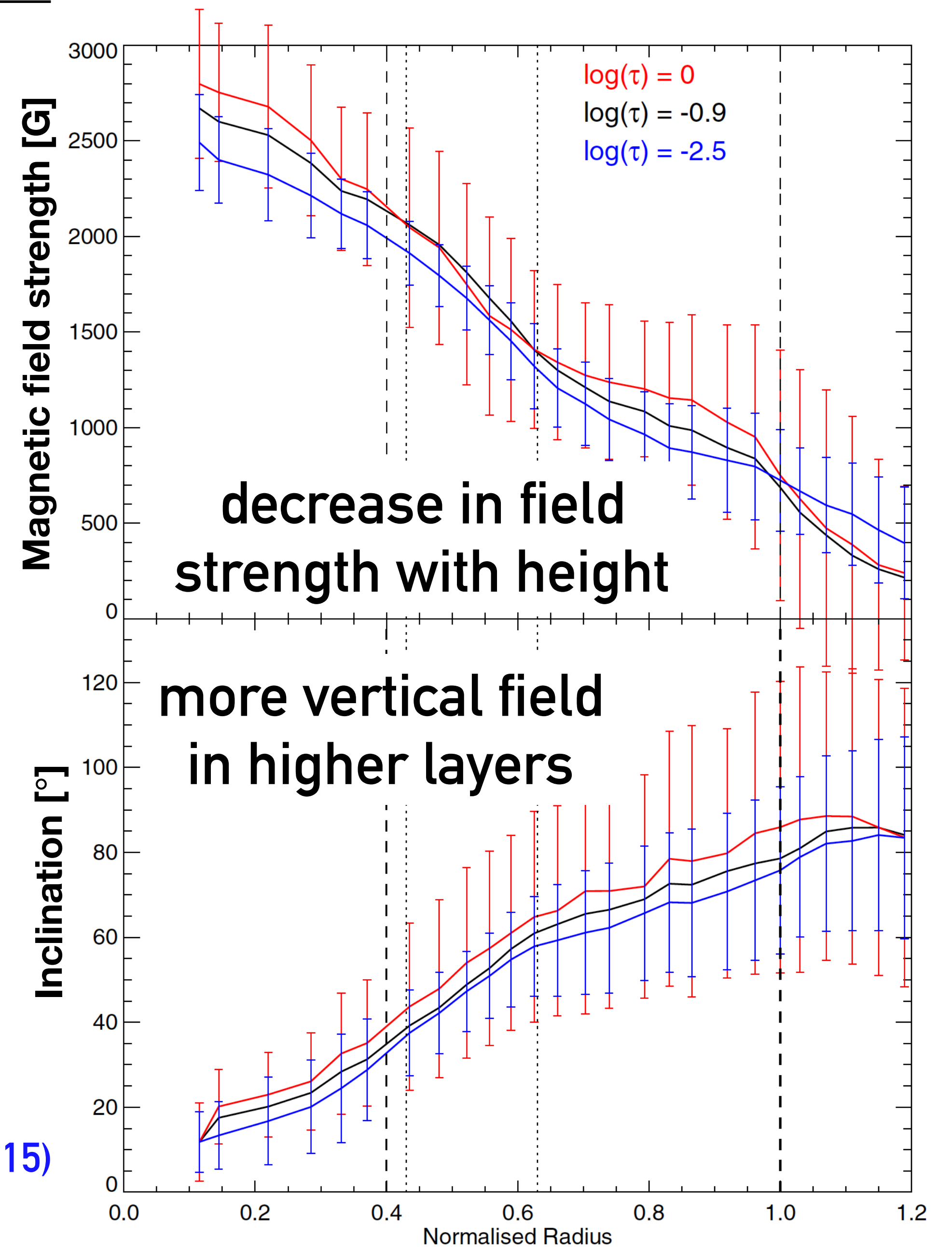
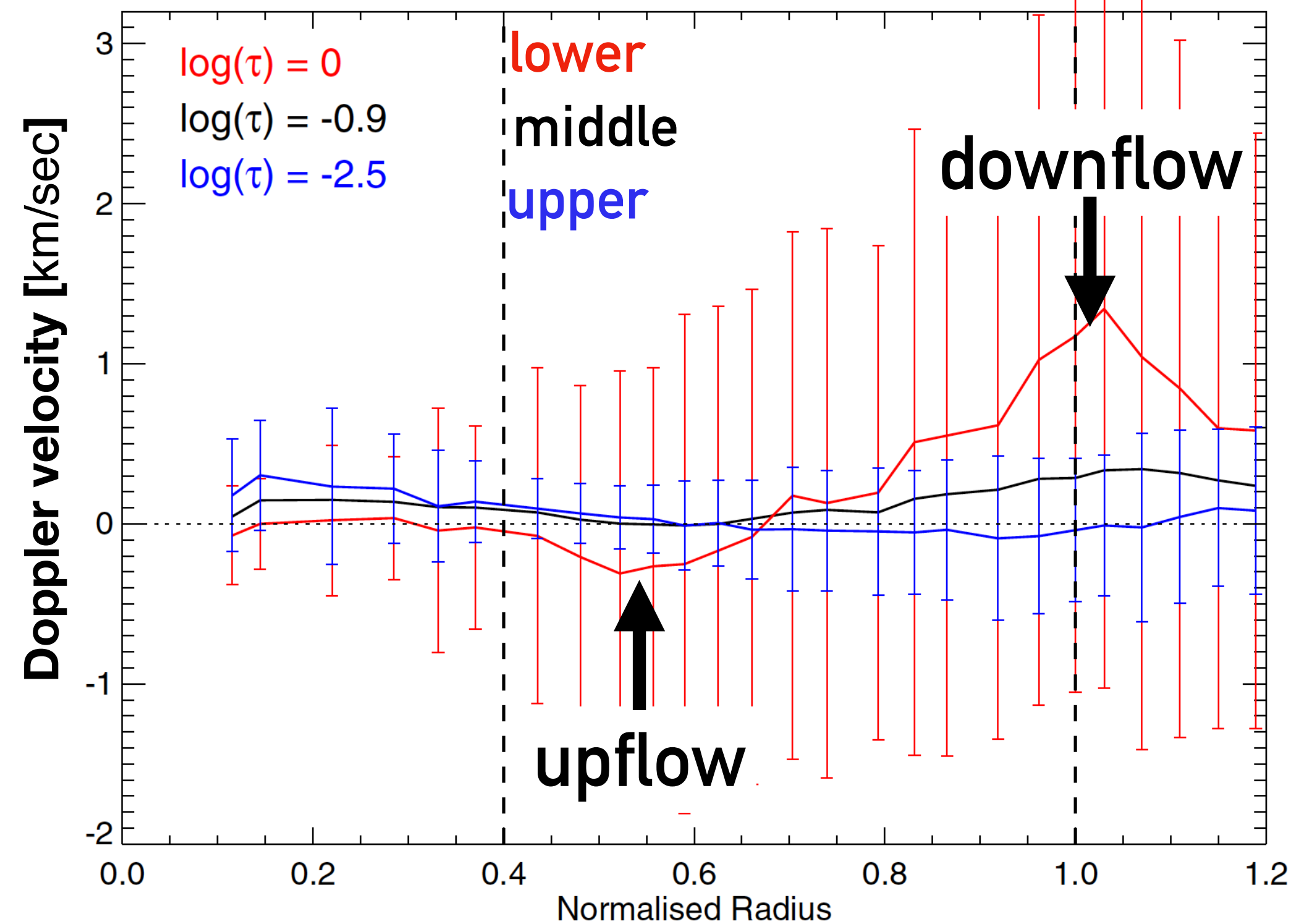
LOS Velocity vs field strength



Tiwari et al. (2015)

Magnetic field of sunspots: photosphere

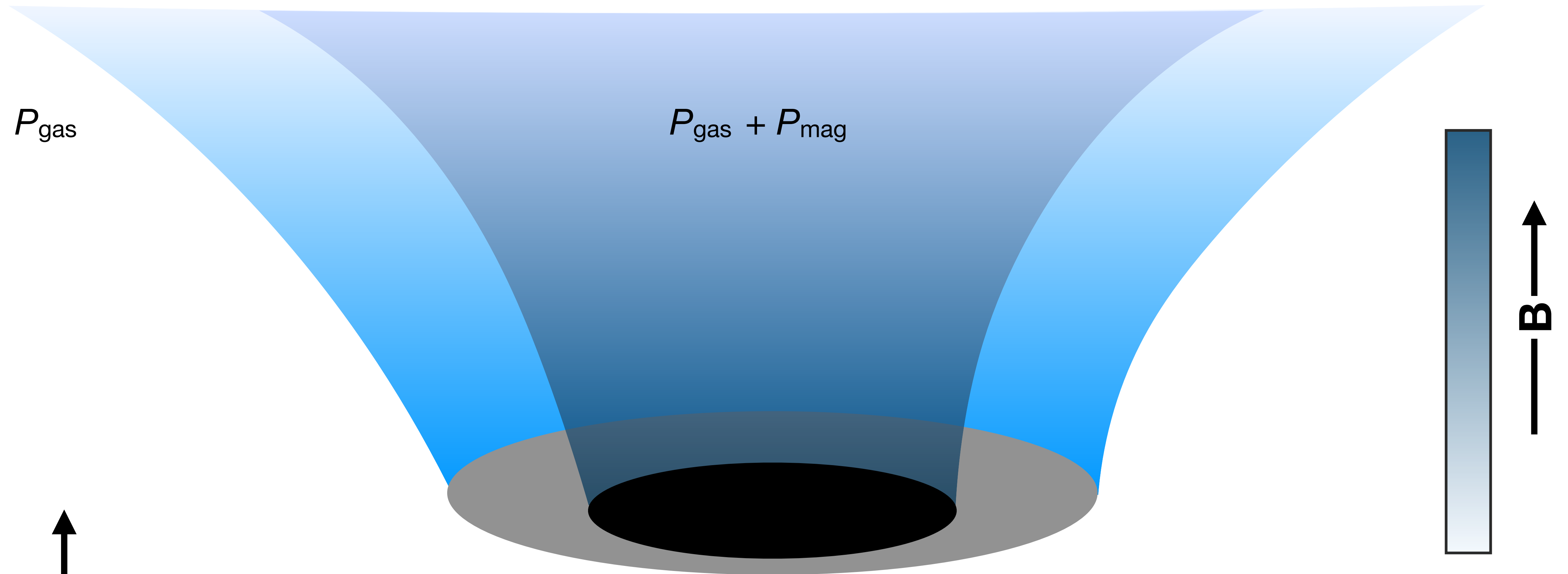
Radial properties



Tiwari et al. (2015)

Magnetic field of sunspots: photosphere

Vertical Gradient

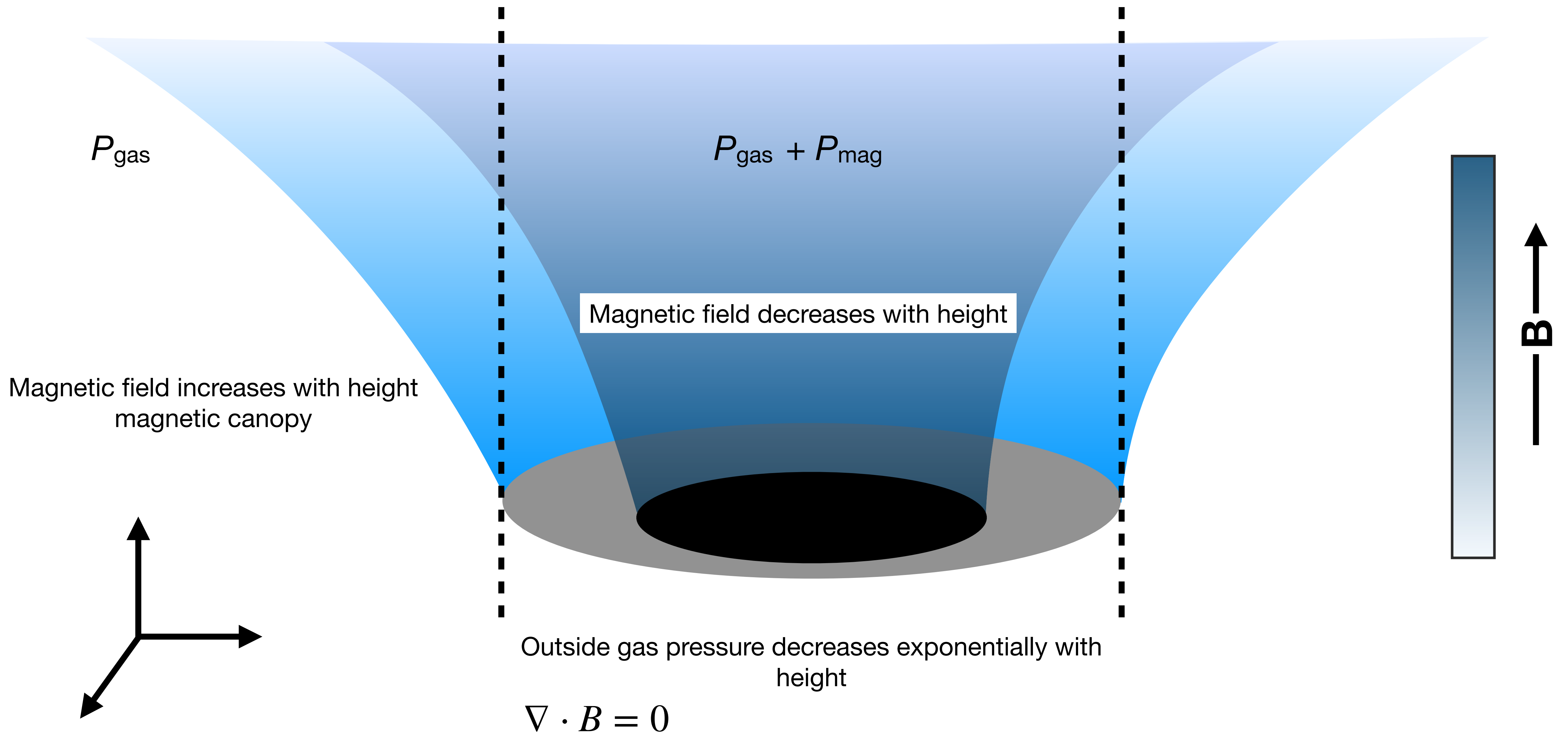


Outside gas pressure decreases exponentially

$$\nabla \cdot B = 0$$

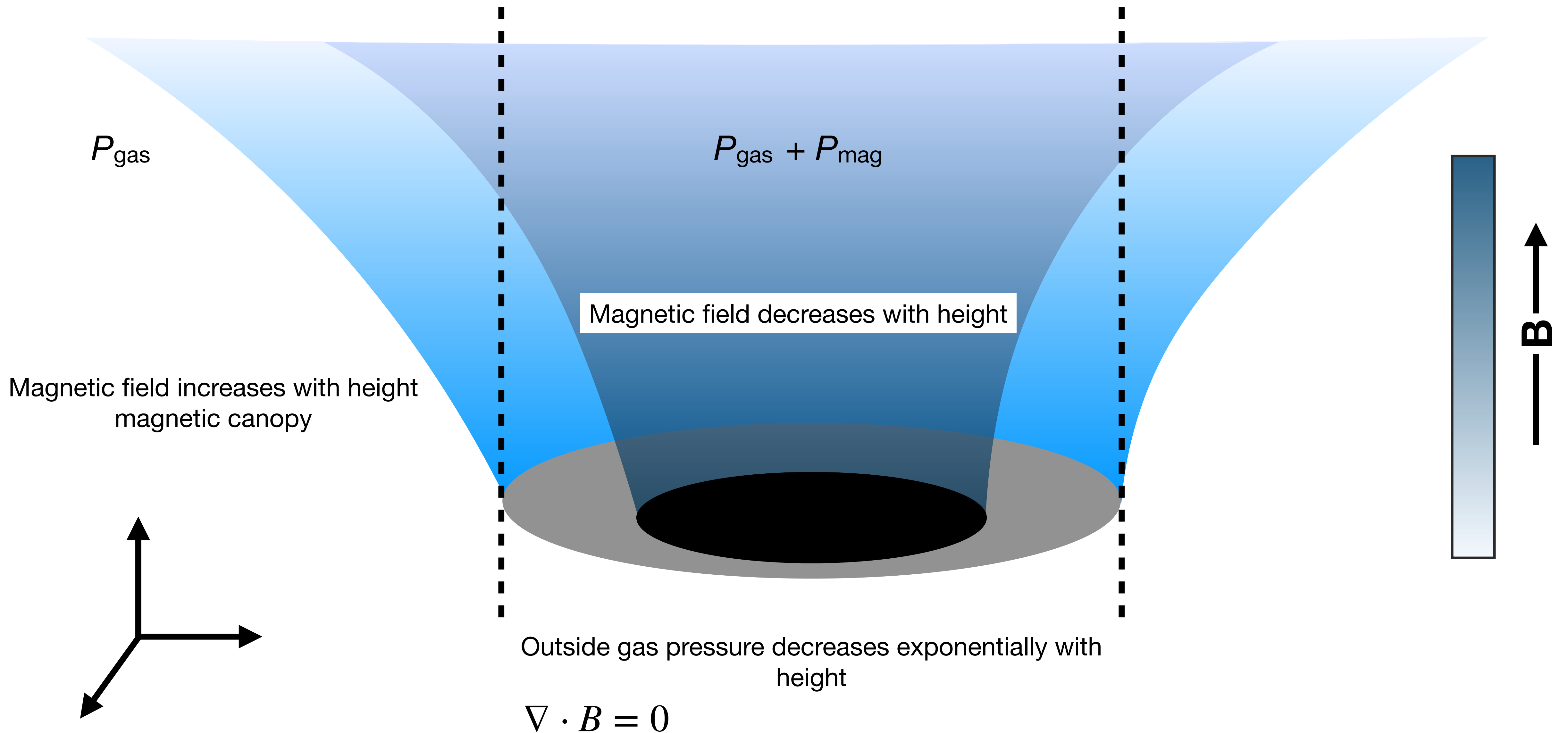
Magnetic field of sunspots: photosphere

Vertical Gradient



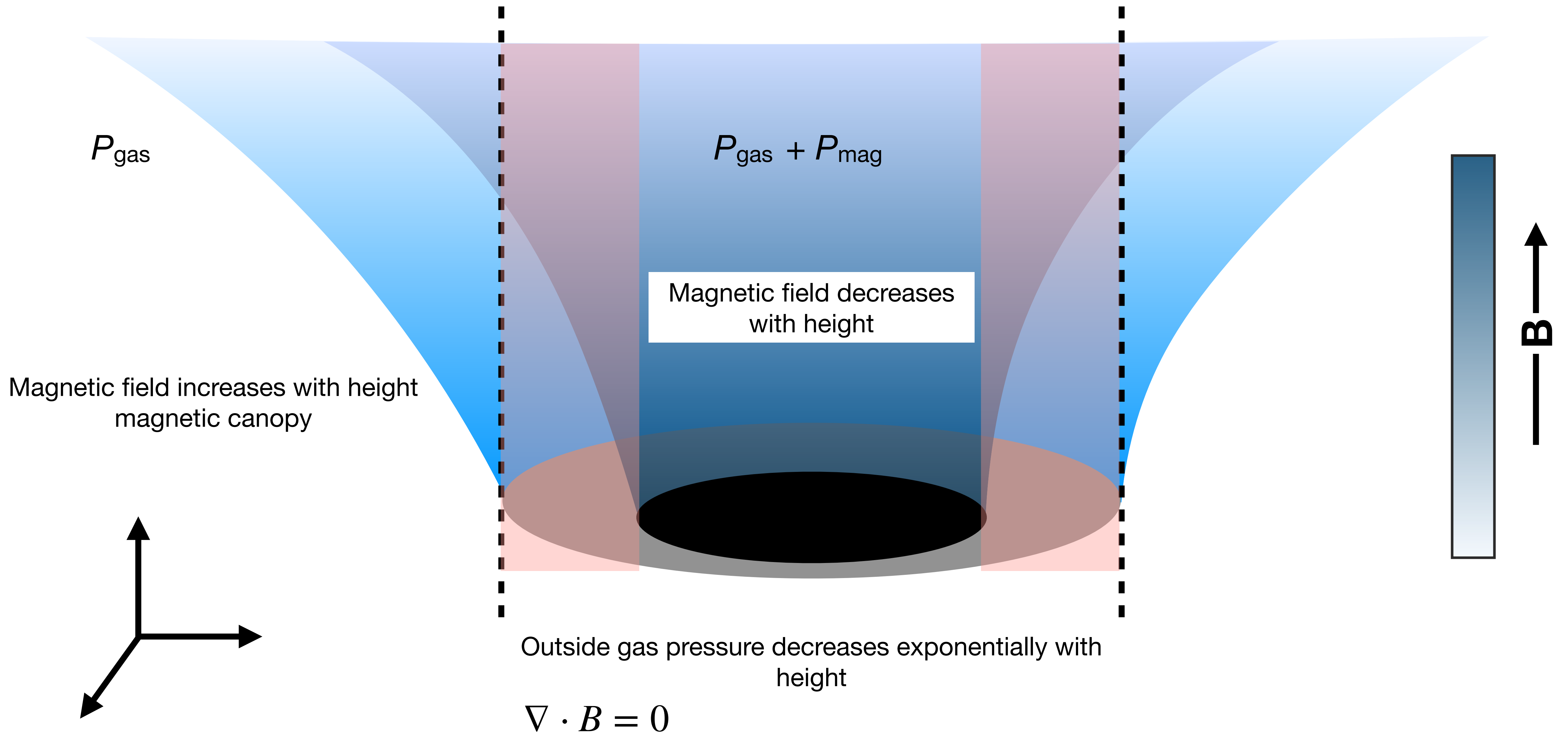
Magnetic field of sunspots: photosphere

Vertical Gradient



Magnetic field of sunspots: photosphere

Vertical Gradient



Magnetic field of sunspots: photosphere

Vertical Gradient

Different methods

- Height dependent inversions (single or multiple spectral lines)
- Using magnetic field measurements from different spectral lines with known formation height differences
- Divergence free method

$$\operatorname{div} \mathbf{B} = 0 = \frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} + \frac{\partial B_z}{\partial z}$$

$$\frac{\partial B_z}{\partial z} \approx -\frac{\Delta B_x}{\Delta x} - \frac{\Delta B_y}{\Delta y}$$

Different methods

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Magnetic field of sunspots: photosphere

Vertical Gradient

Different methods

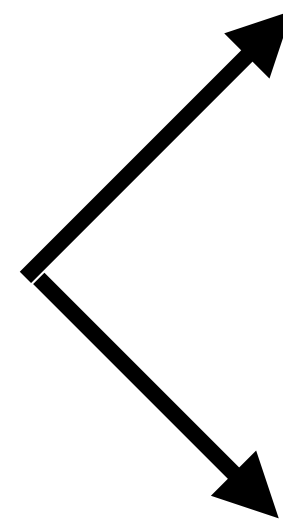
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$$\frac{\partial B_z}{\partial z} \approx -\frac{\Delta B_x}{\Delta x} - \frac{\Delta B_y}{\Delta y}$$

Different results



Solar Physics
DOI: 10.1007/.....-.....-.....-.....

The problem of the height dependence of magnetic fields in sunspots

Horst Balthasar¹

Magnetic field of sunspots: photosphere

Vertical Gradient

Different methods

- Height dependent inversions (single or multiple spectral lines)
- Using magnetic field measurements from different spectral lines with known formation heights

- Divergence free method

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$$\frac{\partial B_z}{\partial z} \approx -\frac{\Delta B_x}{\Delta x} - \frac{\Delta B_y}{\Delta y}$$

Measurements are in
optical depth scales and
not on geometrical
scales

Wilson depression

A diagram illustrating the relationship between the divergence-free method and the Wilson depression. On the left, a dashed red box contains the divergence-free method equations. An arrow points from this box to the text 'Measurements are in optical depth scales and not on geometrical scales'. Below this text is a wavy line representing the Wilson depression.

Magnetic field of sunspots: photosphere

Vertical Gradient

Balthasar (2018)

Table 1. Magnetic field gradients from the difference of photospheric spectral lines.

Author	spectral lines	umbra	penumbra
Westendorp Plaza <i>et al.</i> (2001)	Fe I 630.15 nm Fe I 630.25 nm	$-1.5 - -2 \text{ G km}^{-1}$	
Mathew <i>et al.</i> (2003)	Fe I 1564.8 nm Fe I 1565.2 nm OH 1565.19 nm OH 1565.35 nm	-4.0 G km^{-1}	
Balthasar <i>et al.</i> (2014a)	Fe I 1078.3 nm Si I 1078.6 nm	-2.0 G km^{-1} $-4.5 \text{ G km}^{-1} (\delta\text{-U})$	
Tiwari <i>et al.</i> (2015)	Fe I 630.15 nm Fe I 630.25 nm	-0.5 G km^{-1} -1.5 G km^{-1}	
Felipe <i>et al.</i> (2016)	Si I 1082.7 nm Ca I 1083.9 nm	< 0 $> 0 \text{ (LB)}$	
Joshi <i>et al.</i> (2017a)	Si I 1082.7 nm Ca I 1083.3 nm	< 0	
Verma <i>et al.</i> (2018)	Si I 1082.7 nm Ca I 1083.9 nm	-1.1 G km^{-1}	

Umbral
-0.5 - -4.0 G/km

< 0 outer PU
 > 0 inner PU
 ≈ 0
 > 0 inner PU

Magnetic field of sunspots: photosphere

Vertical Gradient

Balthasar (2018)

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Felipe <i>et al.</i> (2016)	Si I 1082.7 nm Ca I 1083.9 nm	< 0 > 0 (LB)	≈ 0
Joshi <i>et al.</i> (2017a)	Si I 1082.7 nm Ca I 1083.3 nm	< 0	> 0 inner PU
Verma <i>et al.</i> (2018)	Si I 1082.7 nm Ca I 1083.9 nm	-1.1 G km^{-1}	-0.7 G km^{-1} -1.3 G km^{-1} (EUC)

Umbral
-0.5 - -4.0 G/km

Magnetic field of sunspots: photosphere

Vertical Gradient

Balthasar (2018)

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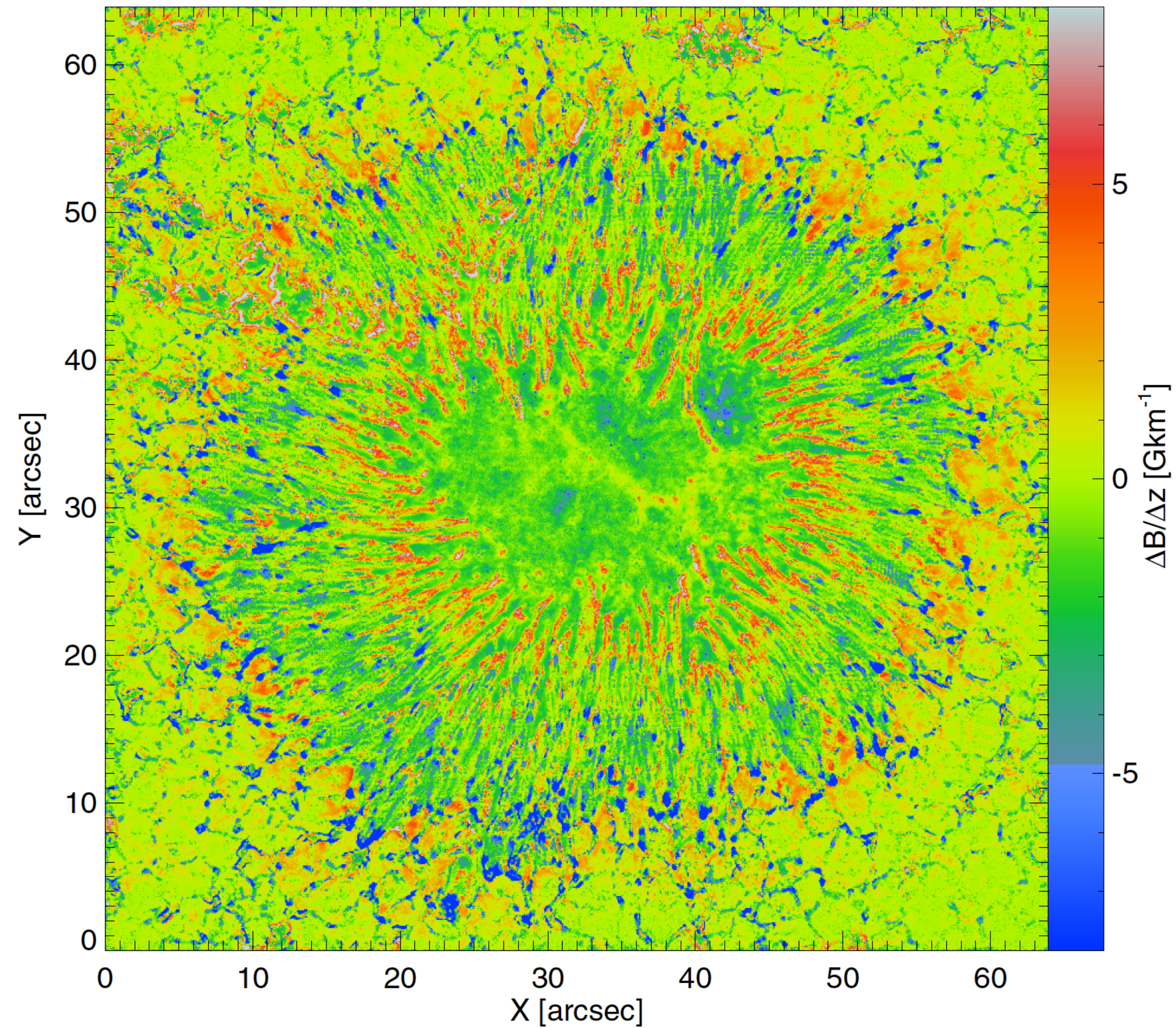
Umbra
-0.5 - -4.0 G/km

< 0 outer PU
 > 0 inner PU
 ≈ 0
 > 0 inner PU

Magnetic field of sunspots: photosphere

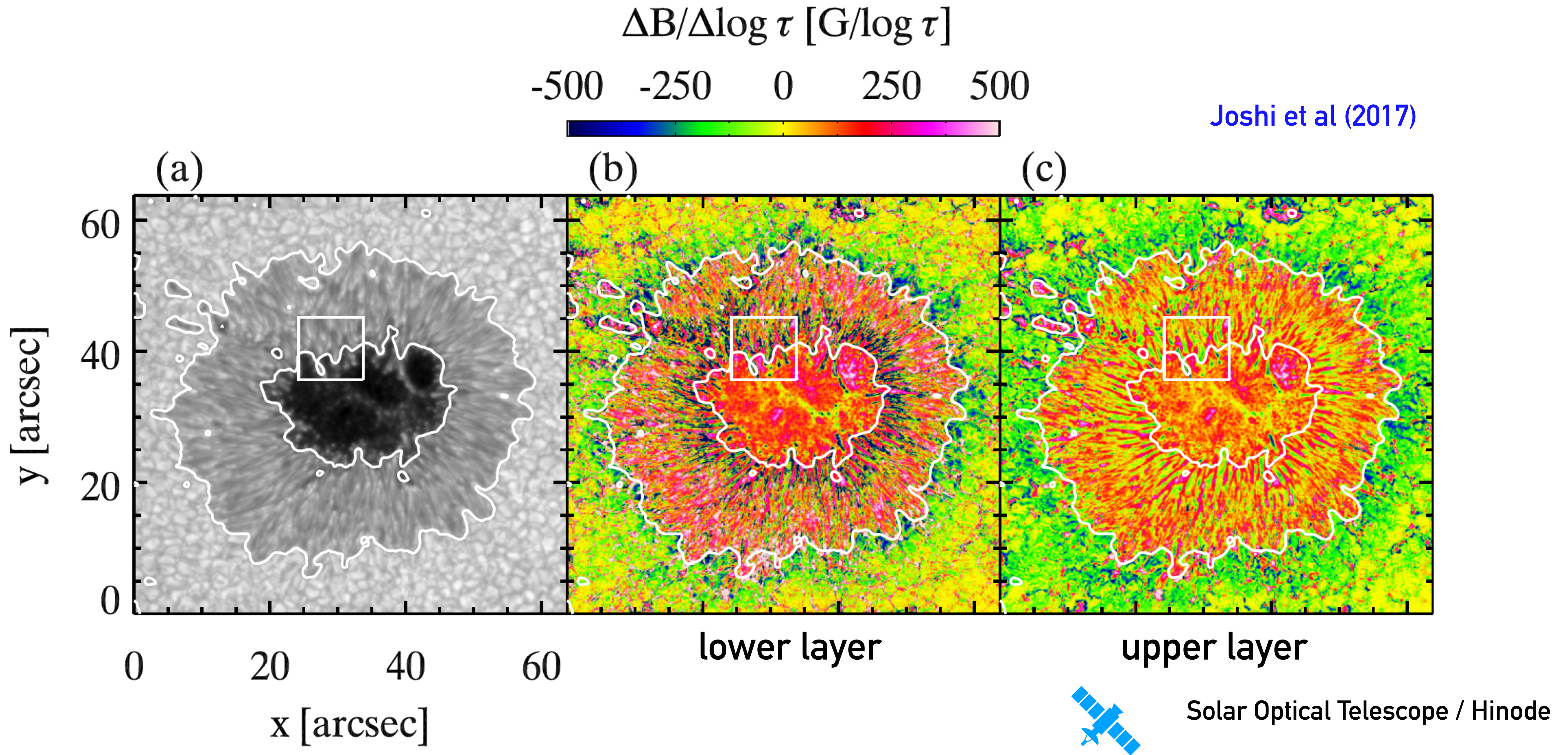
Vertical Gradient

Tiwari et al (2015)



Magnetic field of sunspots: photosphere

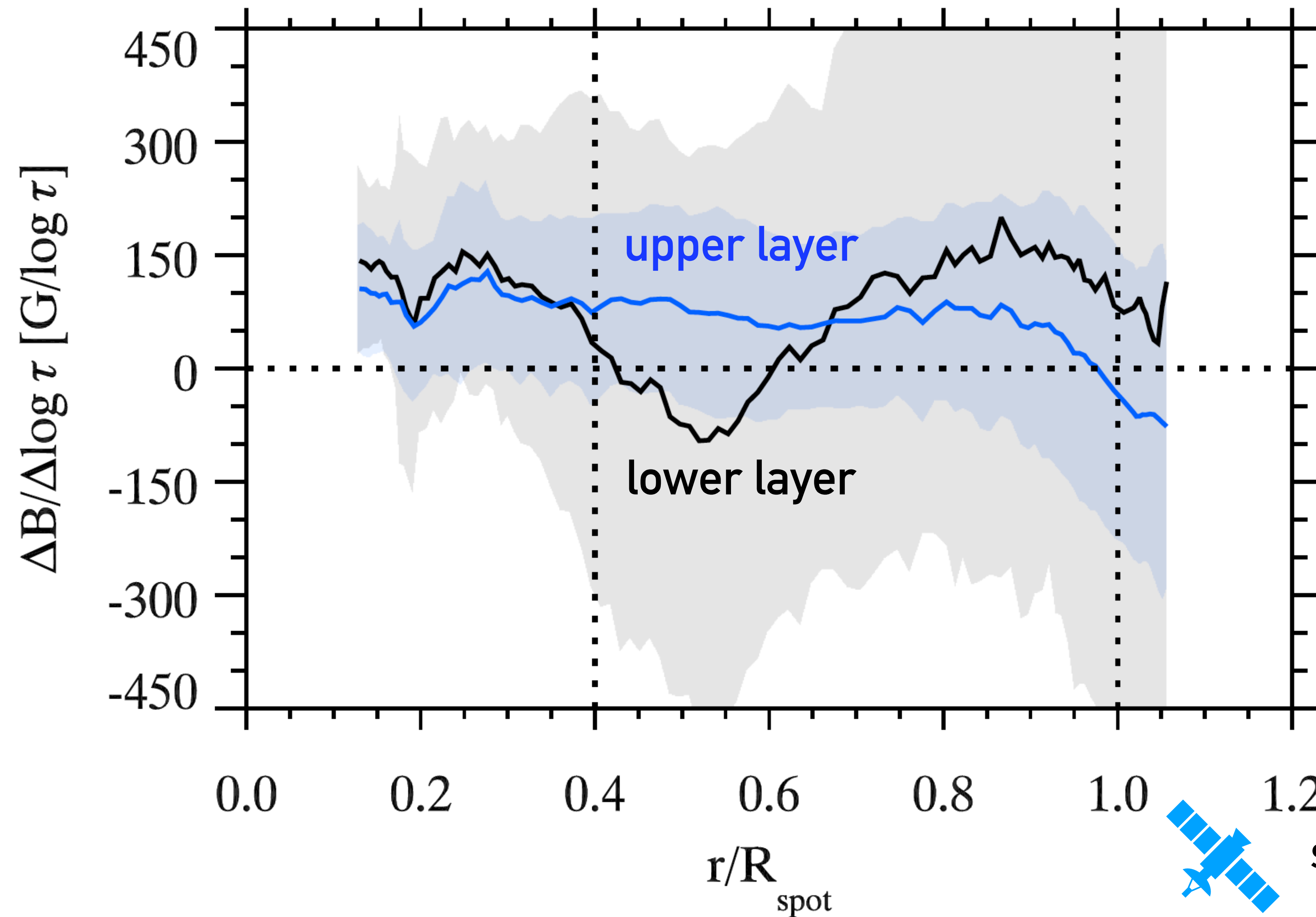
Vertical Gradient



Magnetic field of sunspots: photosphere

Vertical Gradient

Joshi et al (2017)



Solar Optical Telescope / Hinode

Magnetic field of sunspots: photosphere

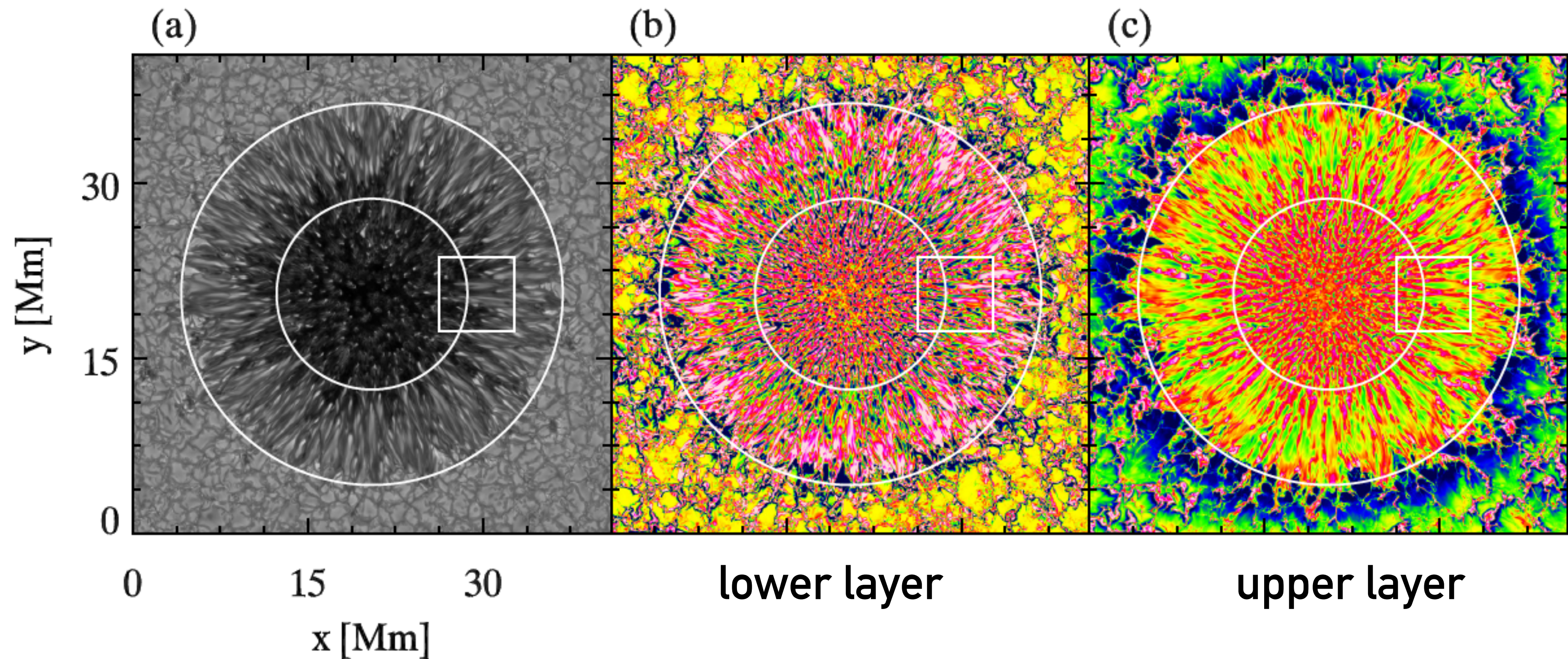
Vertical Gradient

MHD simulation
Rempel (2012)

$\Delta B / \Delta \log \tau$ [G/log τ]

-500 -250 0 250 500

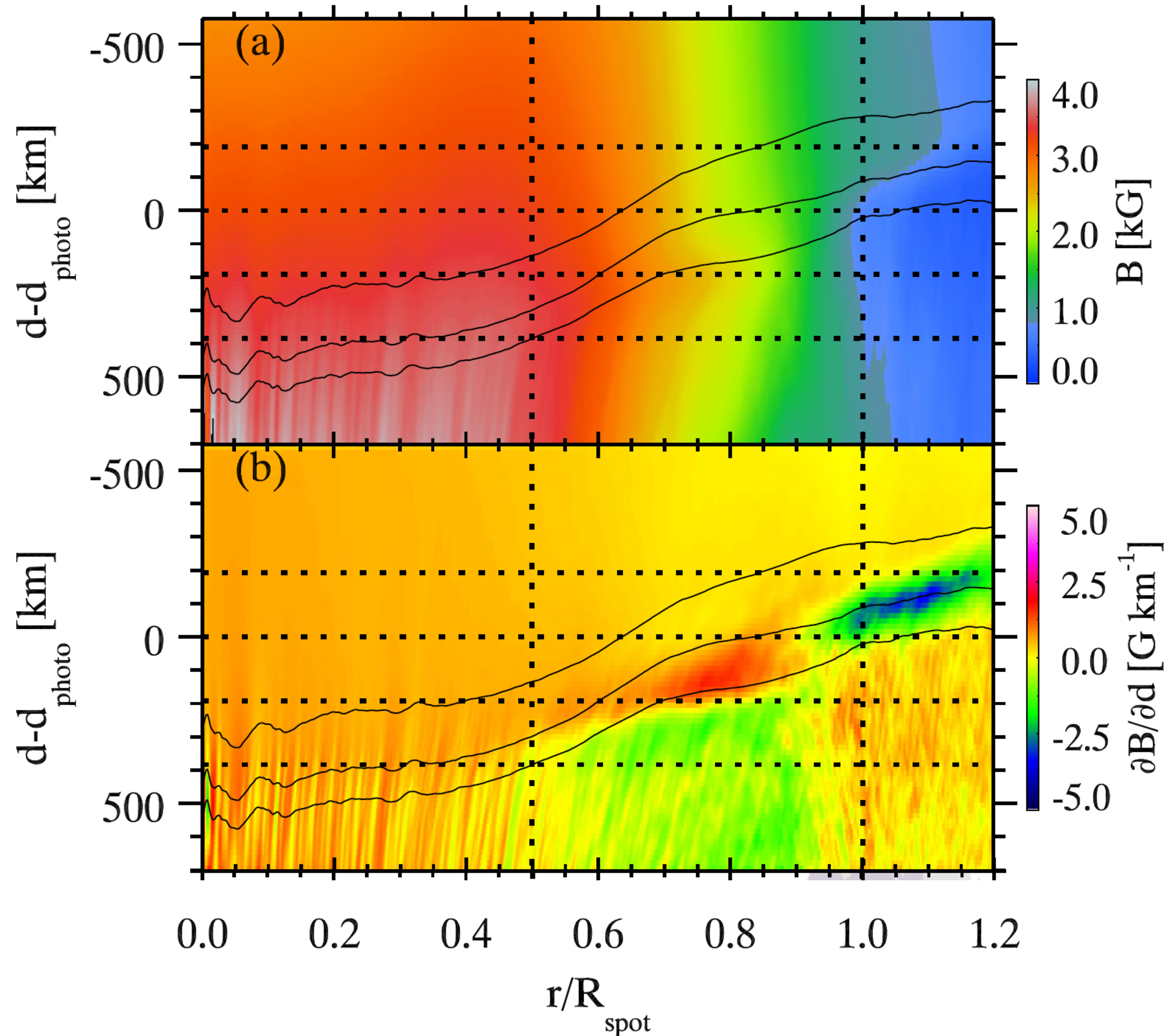
Joshi et al (2017)



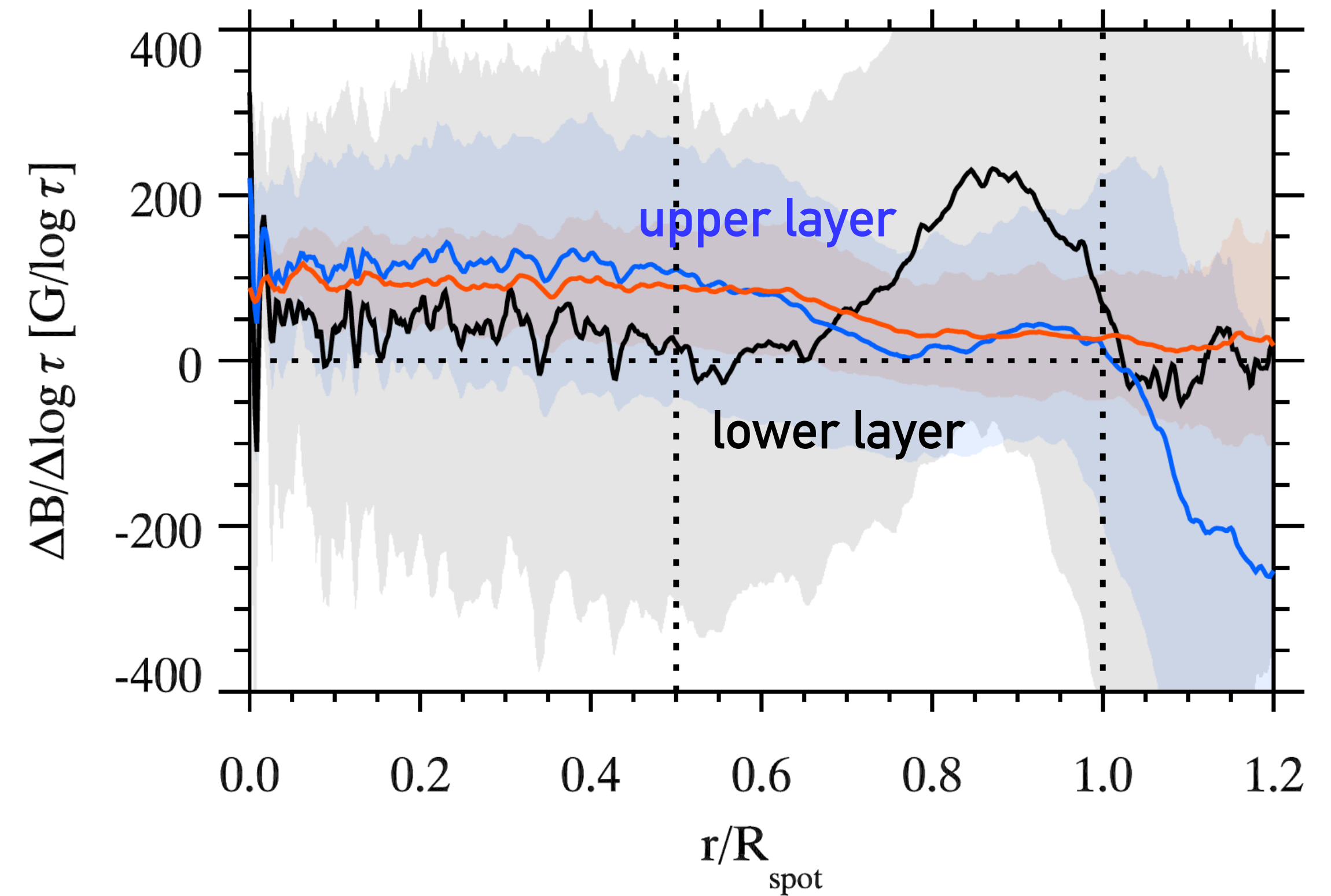
Magnetic field of sunspots: photosphere

Vertical Gradient

MHD simulation
Rempel (2012)



Joshi et al (2017)

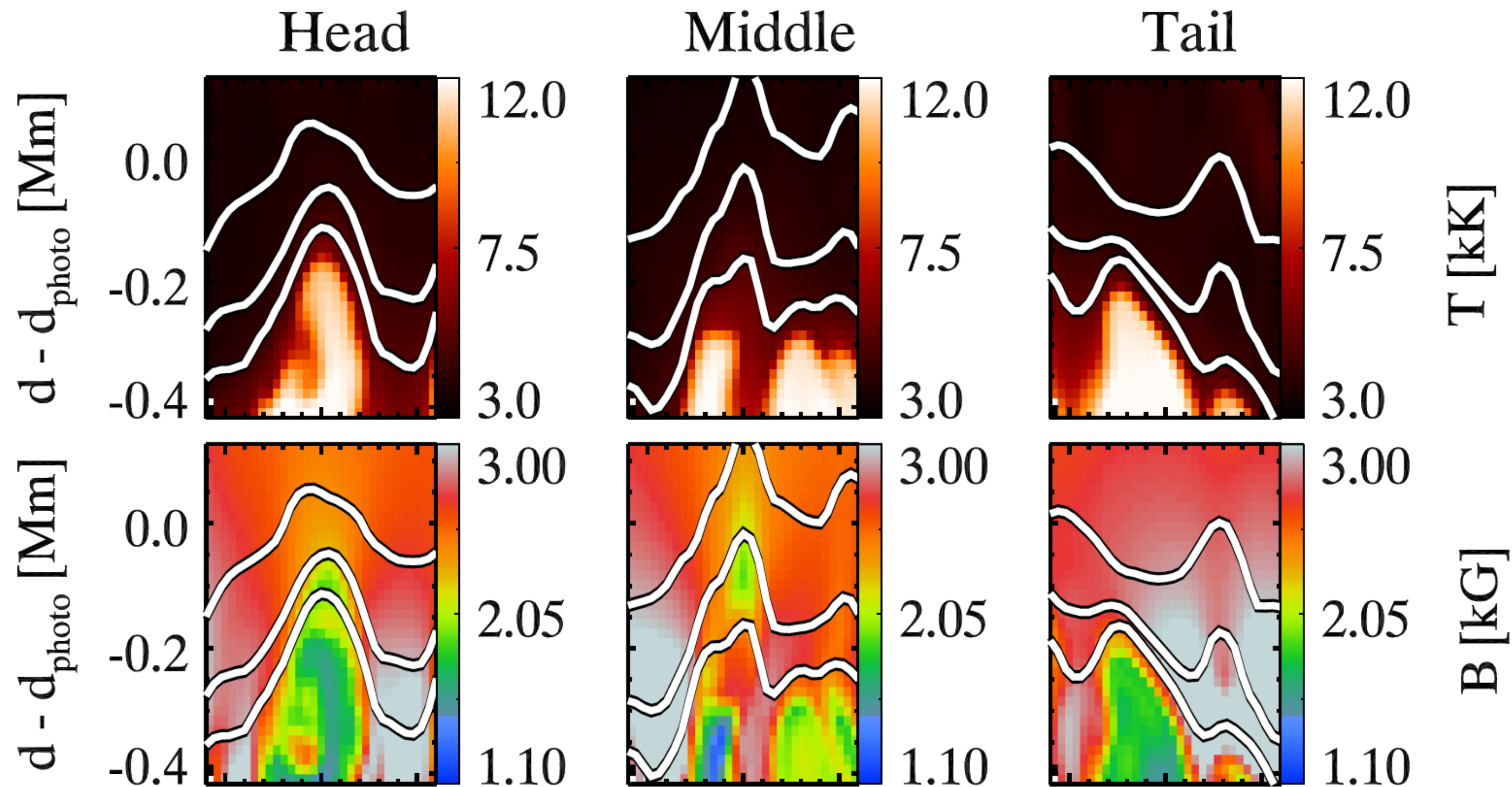


Magnetic field of sunspots: photosphere

Explanation for observed increase in the field with height in inner penumbra

Joshi et al (2017)

Corrugated surface?



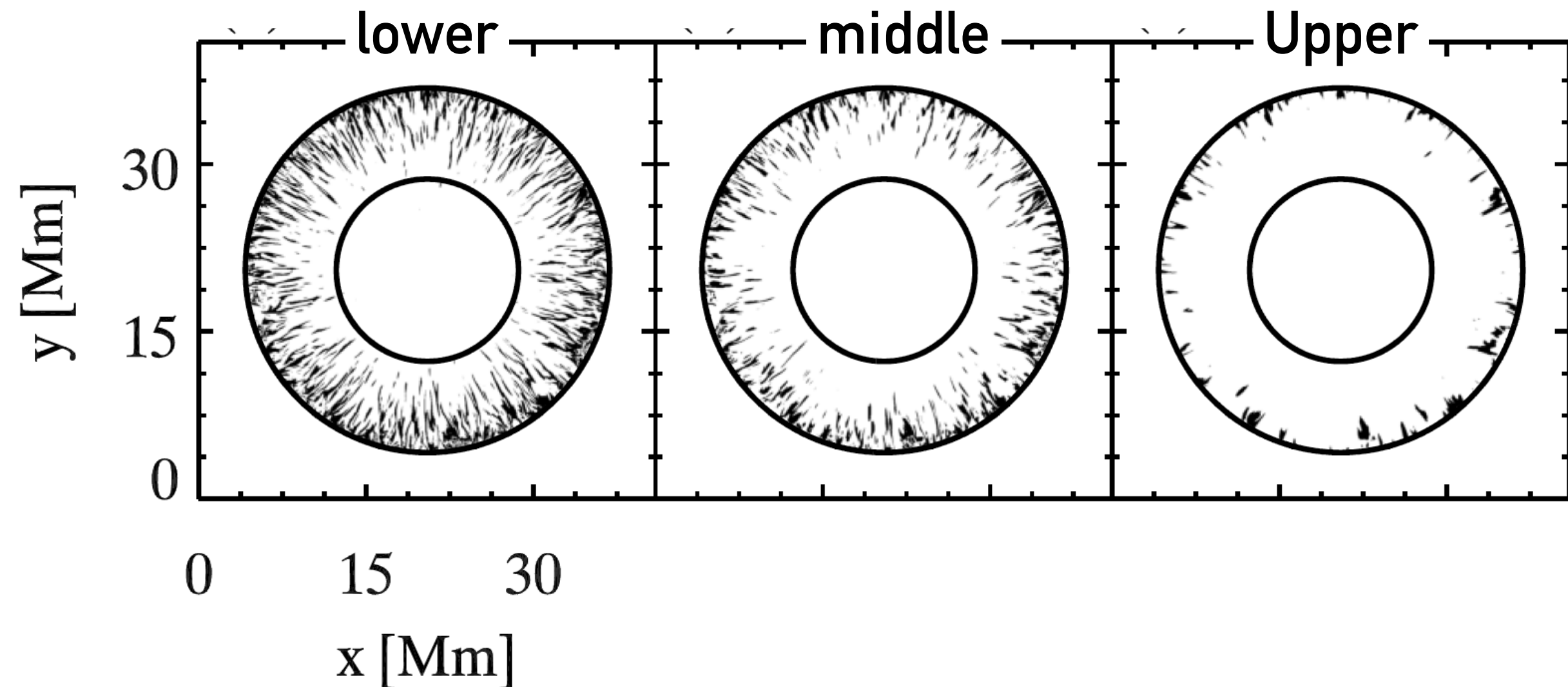
MHD simulation
Rempel (2012)

Magnetic field of sunspots: photosphere

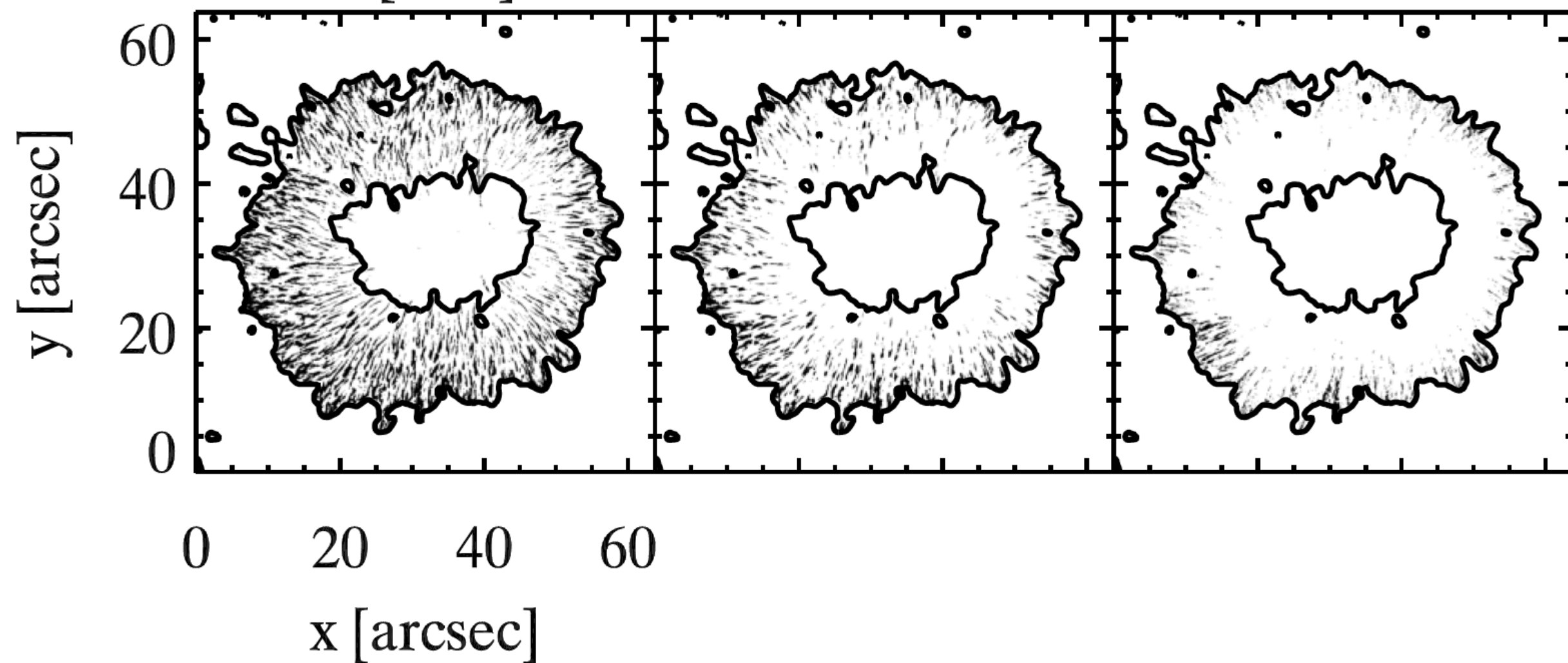
Explanation for observed increase in the field with height in inner penumbra

Joshi et al (2017)

Unresolved opposite polarity patches?



MHD simulation
Rempel (2012)



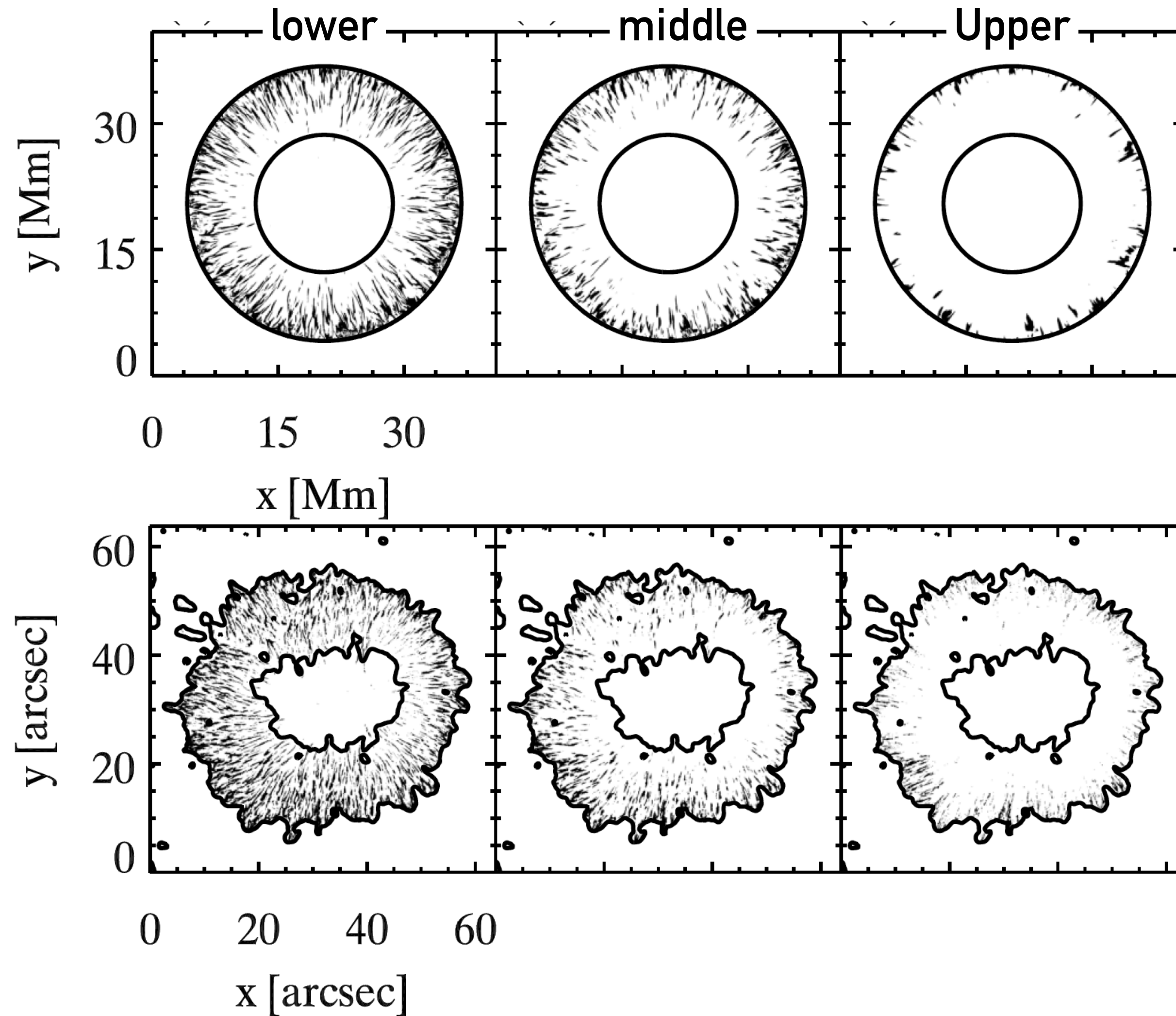
SOT/Hinode

Magnetic field of sunspots: photosphere

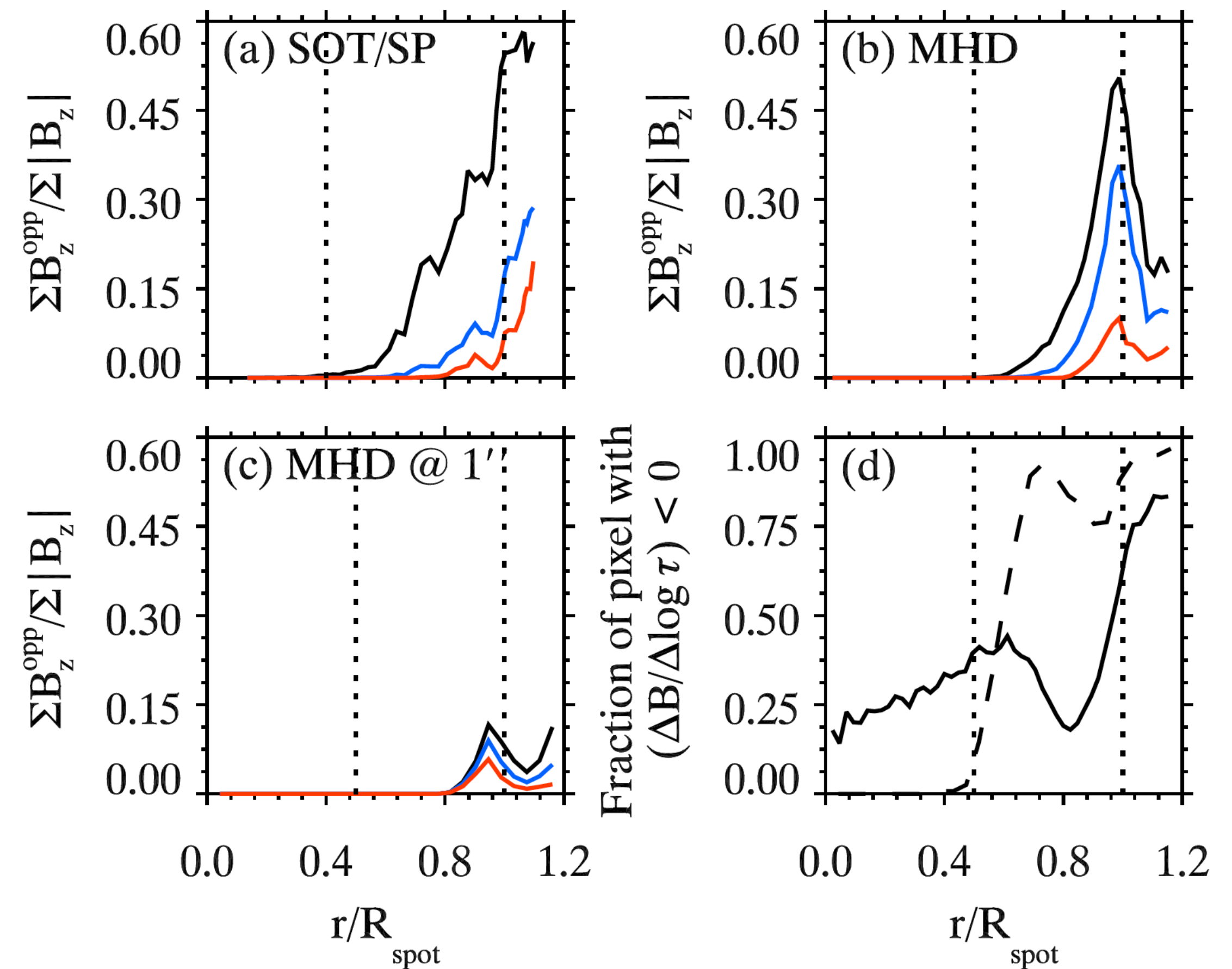
Explanation for observed increase in the field with height in inner penumbra

Joshi et al (2017)

Unresolved opposite polarity patches?



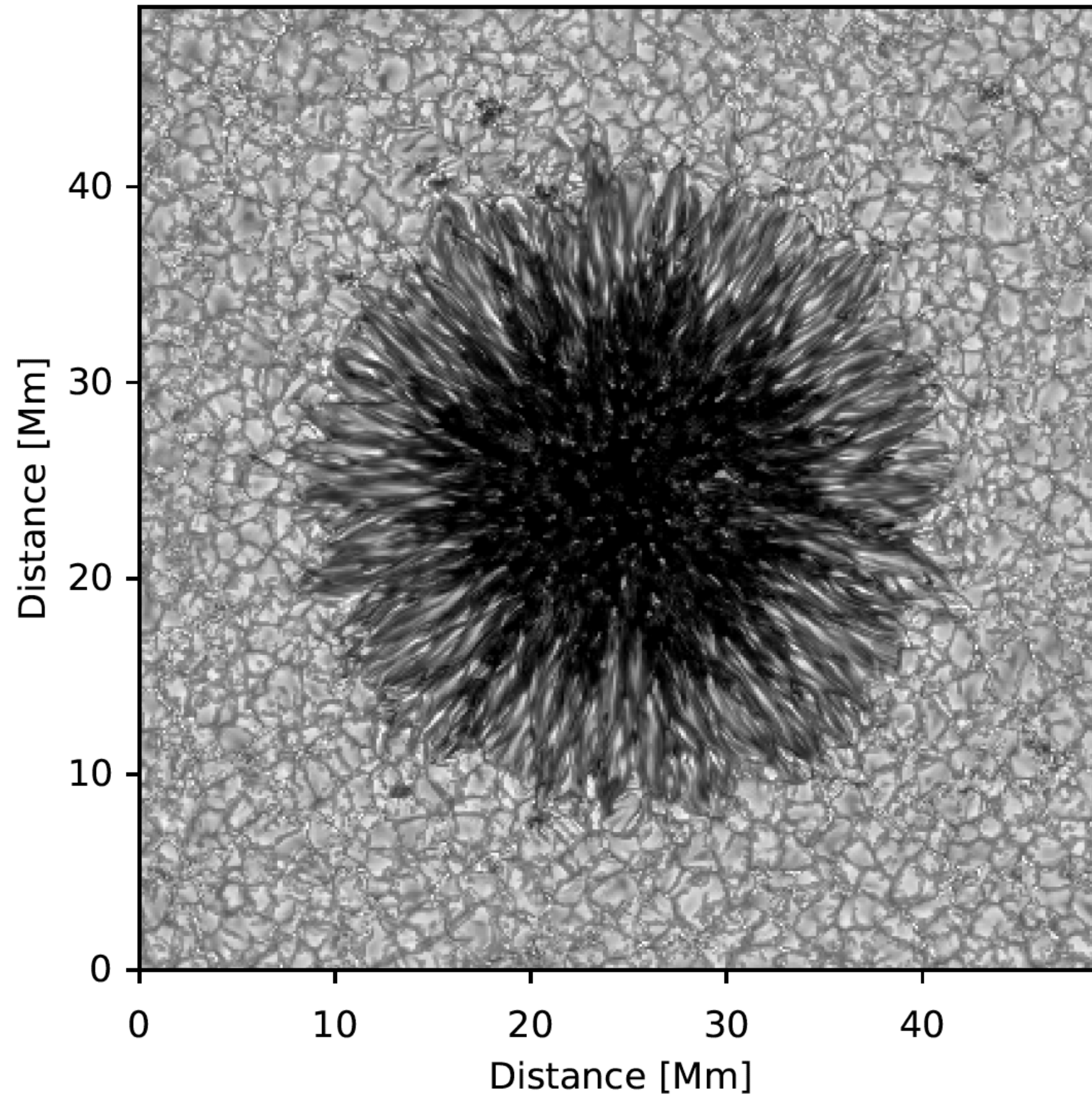
Radial distribution of opposite polarity patches



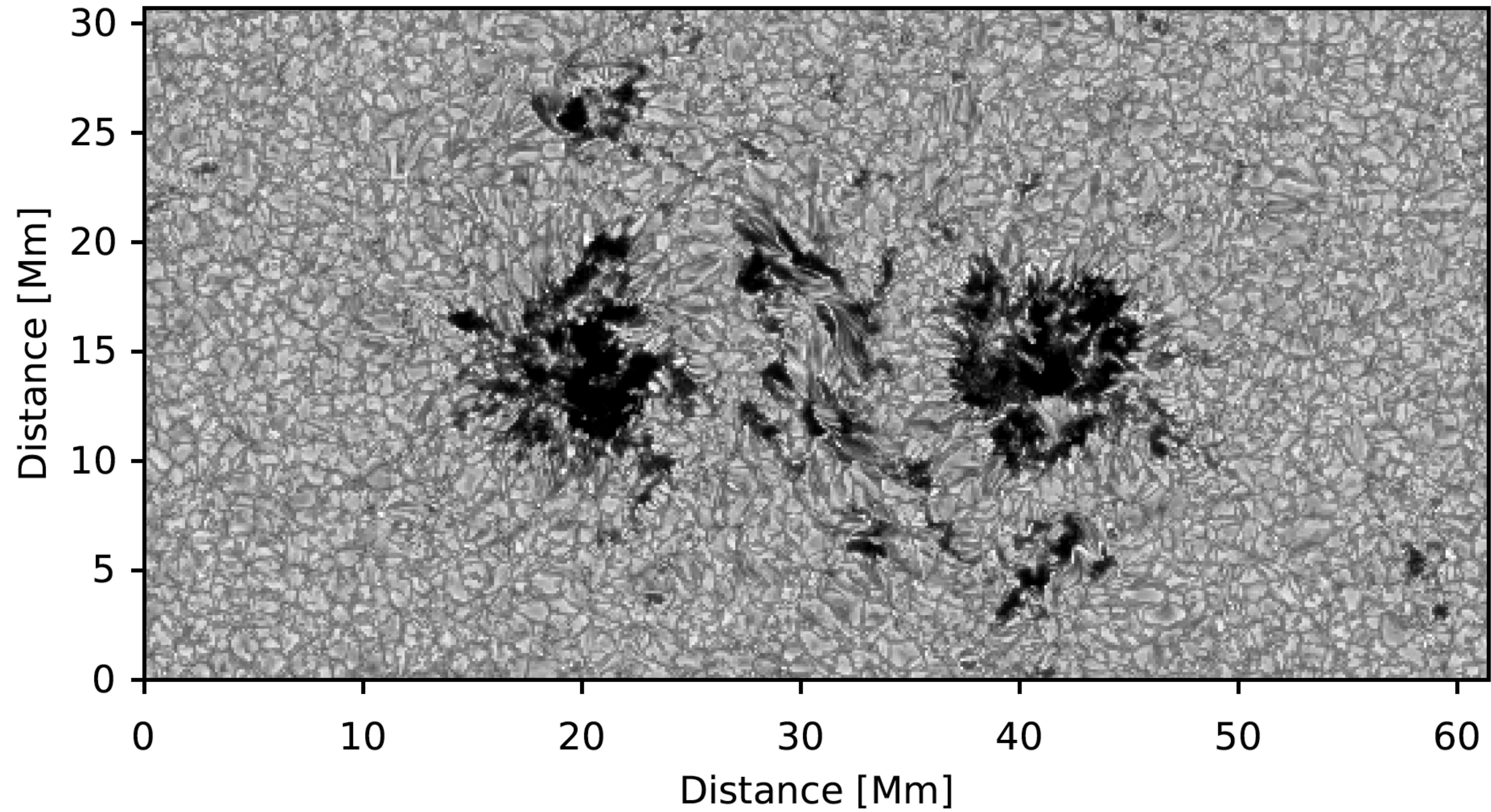
Magnetic field of sunspots: photosphere

Inversions based on Deep Learning
Convolutional Neural Network

Asensio Ramos & Díaz Baso (2019)



Rempel (2012)



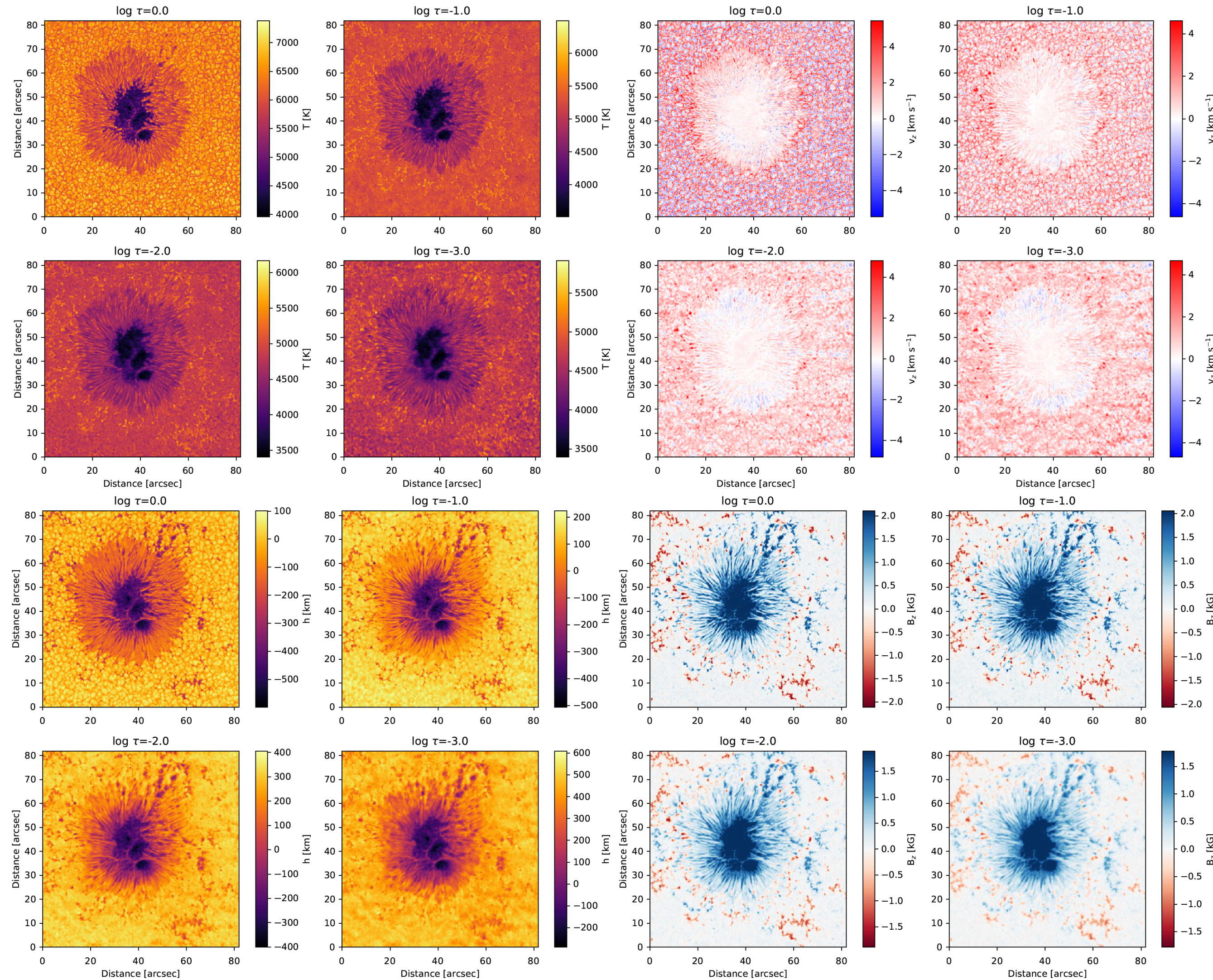
MHD simulations

Cheung et al. (2010)

Magnetic field of sunspots: photosphere

Inversions based on Deep Learning Convolutional Neural Network

Asensio Ramos & Díaz Baso (2019)



Optical depth scale

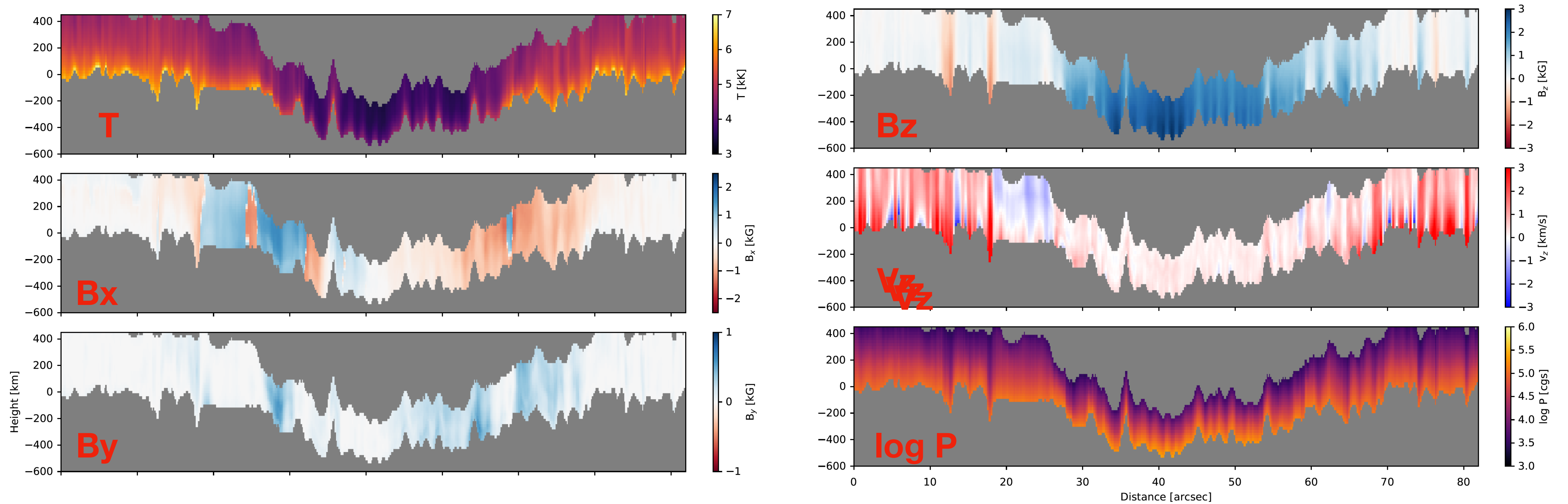
Magnetic field of sunspots: photosphere

Inversions based on Deep Learning

Convolutional Neural Network

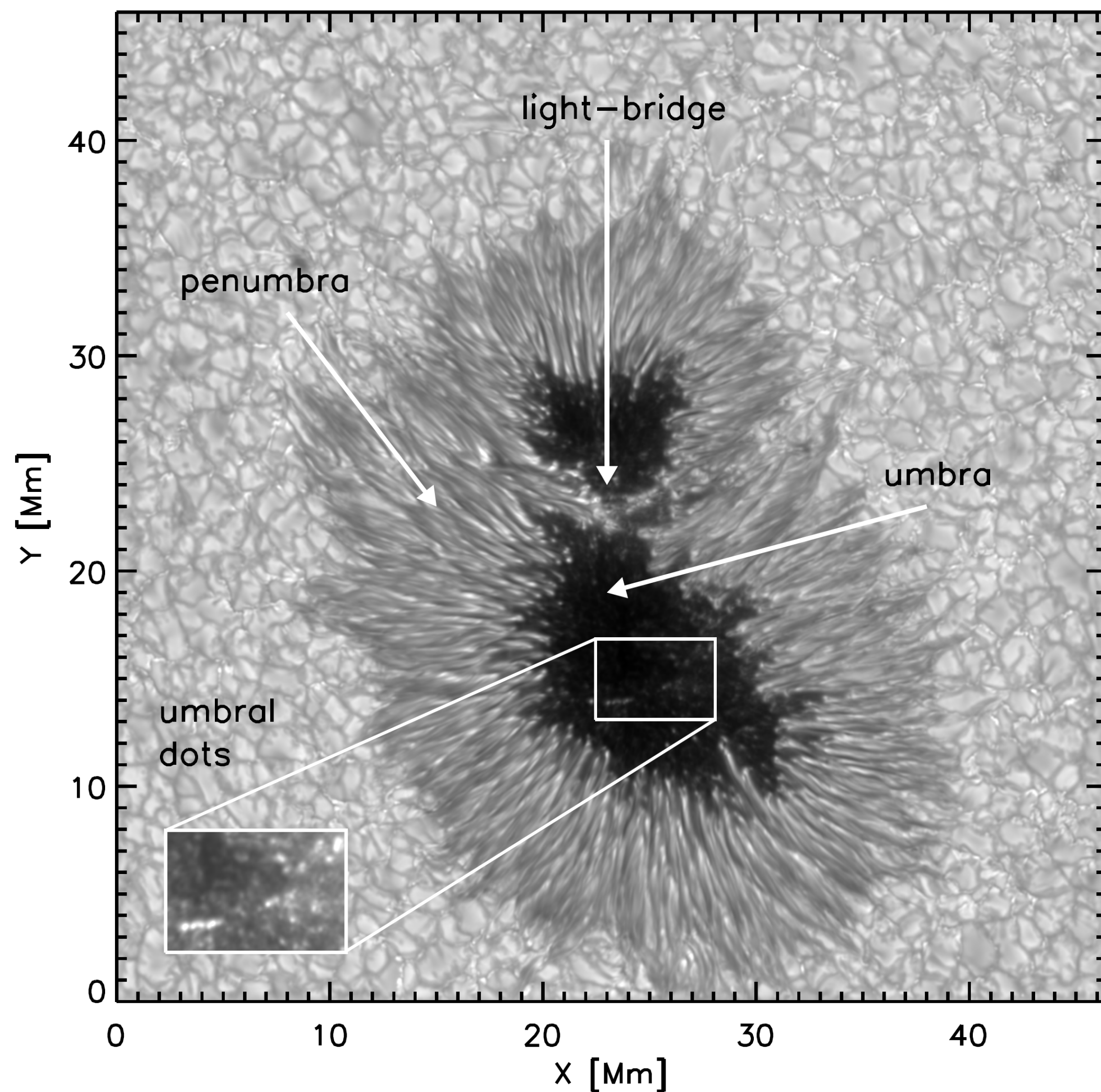
Asensio Ramos & Díaz Baso (2019)

Geometric scale

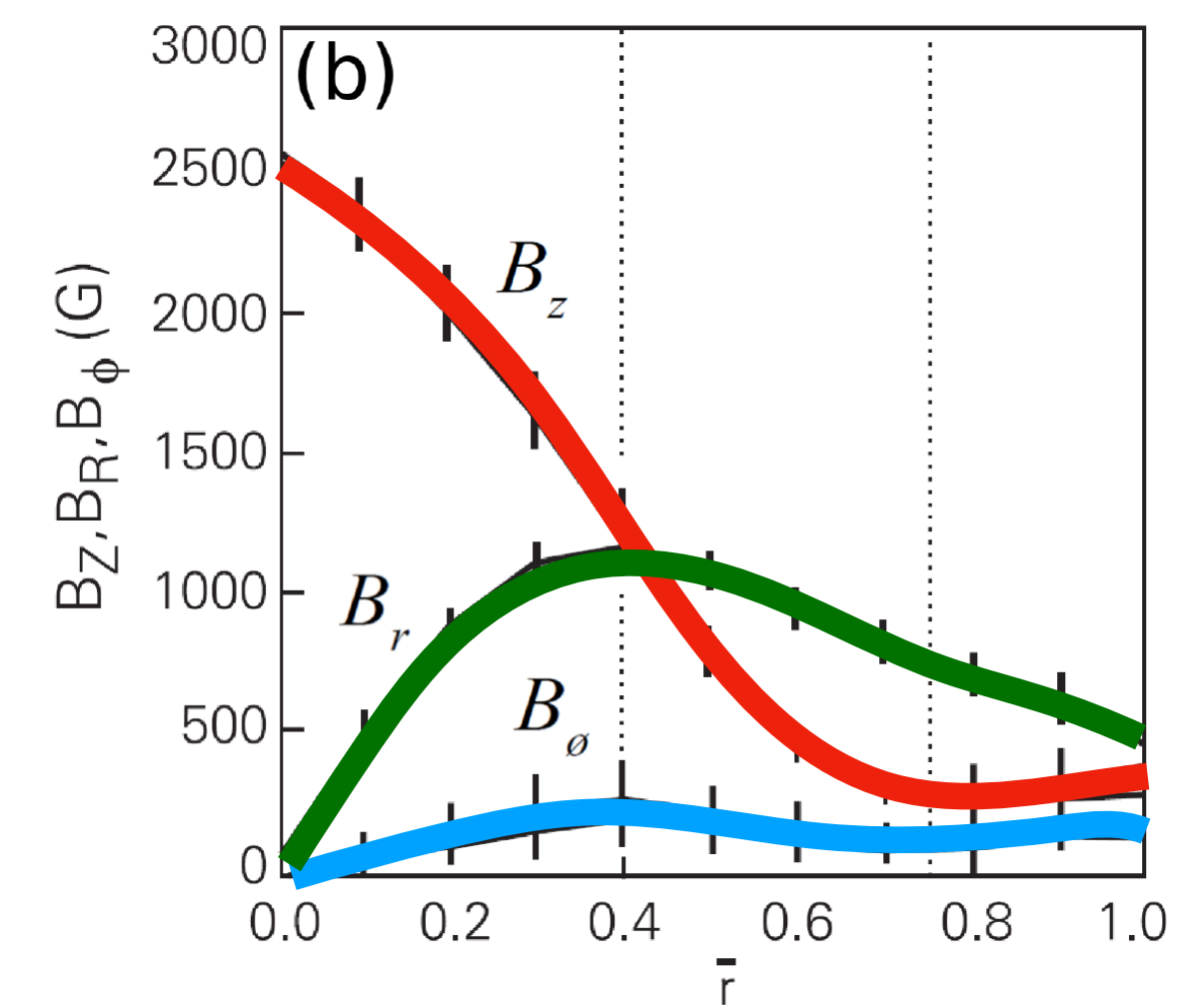
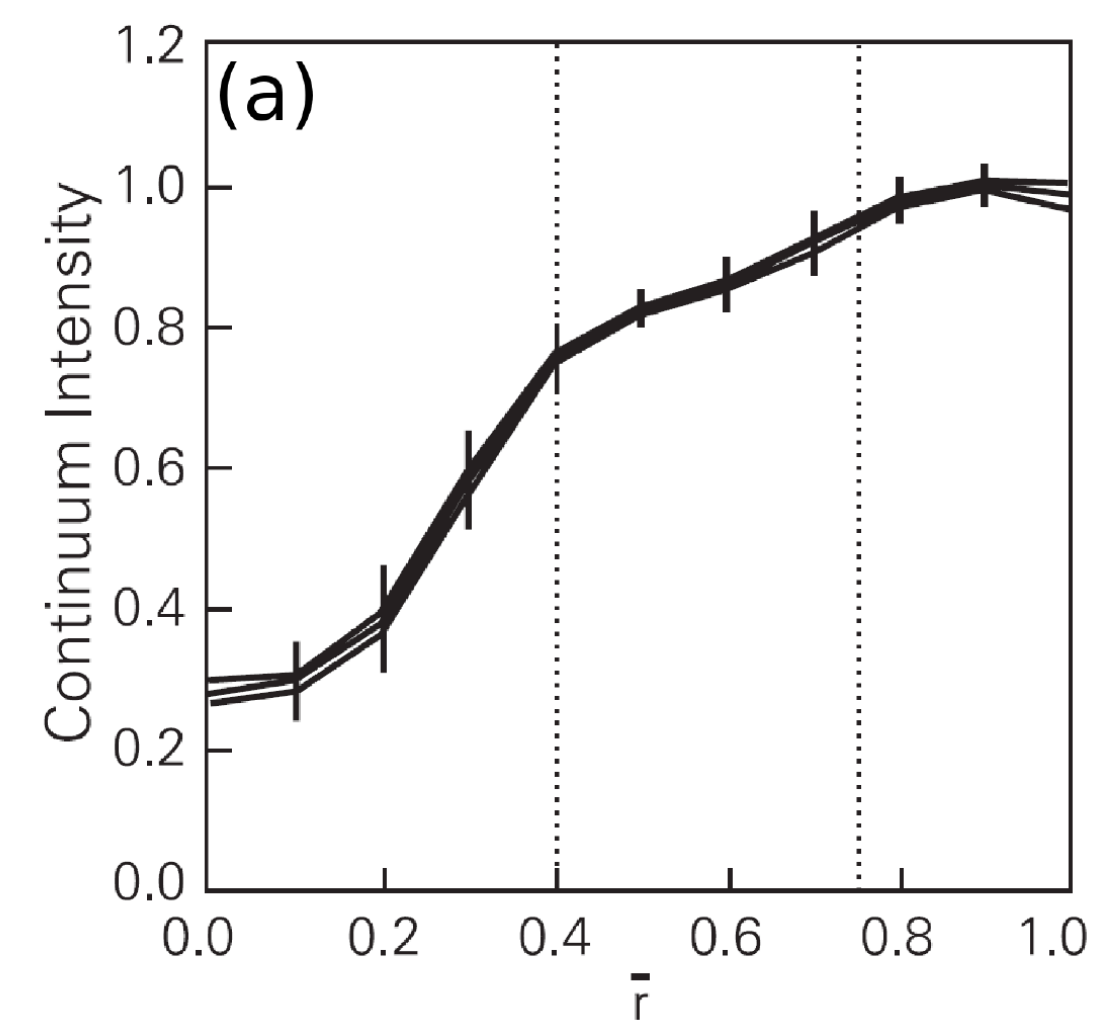


Magnetic field of sunspots: photosphere

Umbral-penumbra boundary and vertical magnetic field



Sharp intensity contrast between umbra and penumbra



Gradual change in azimuthal averages

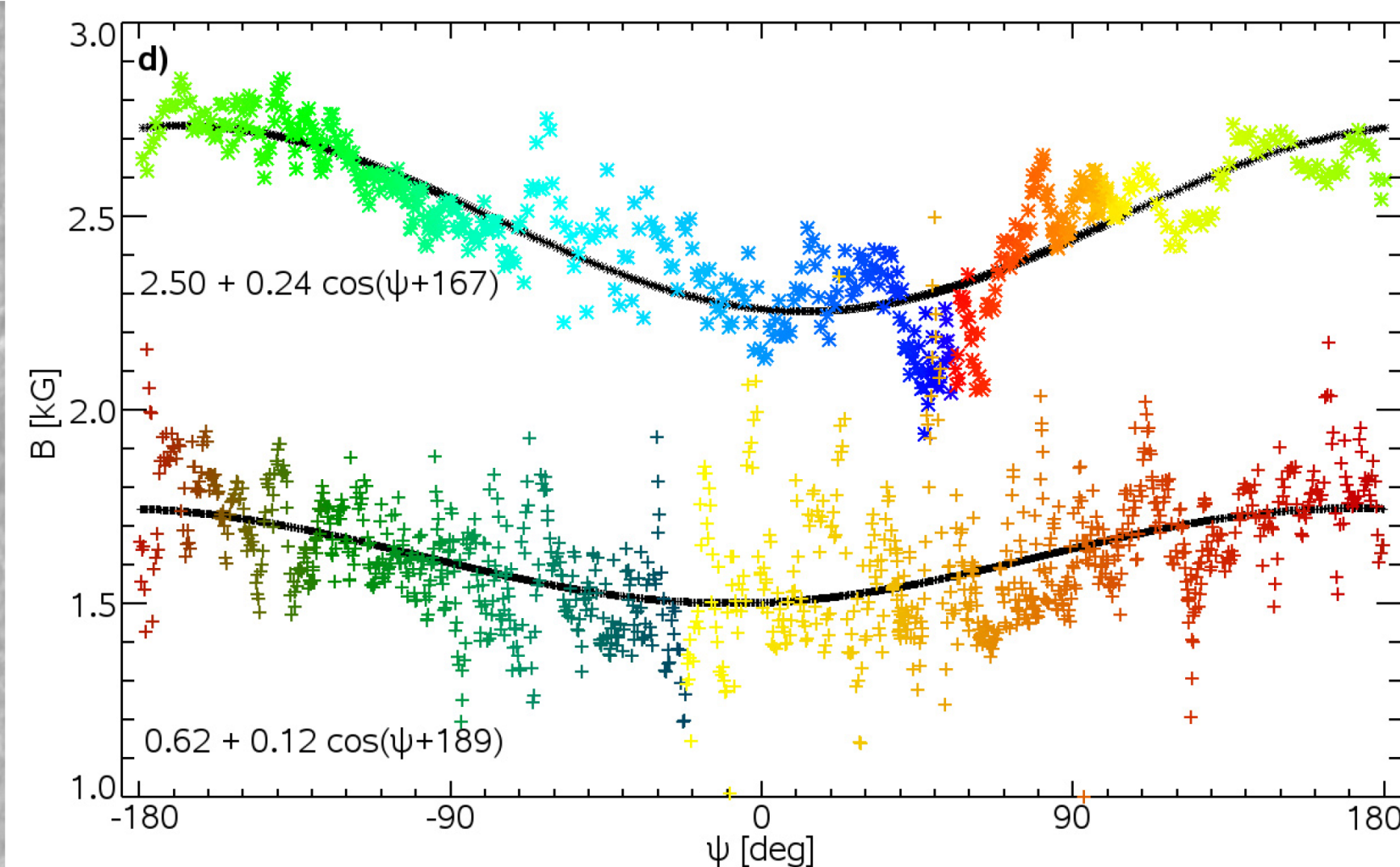
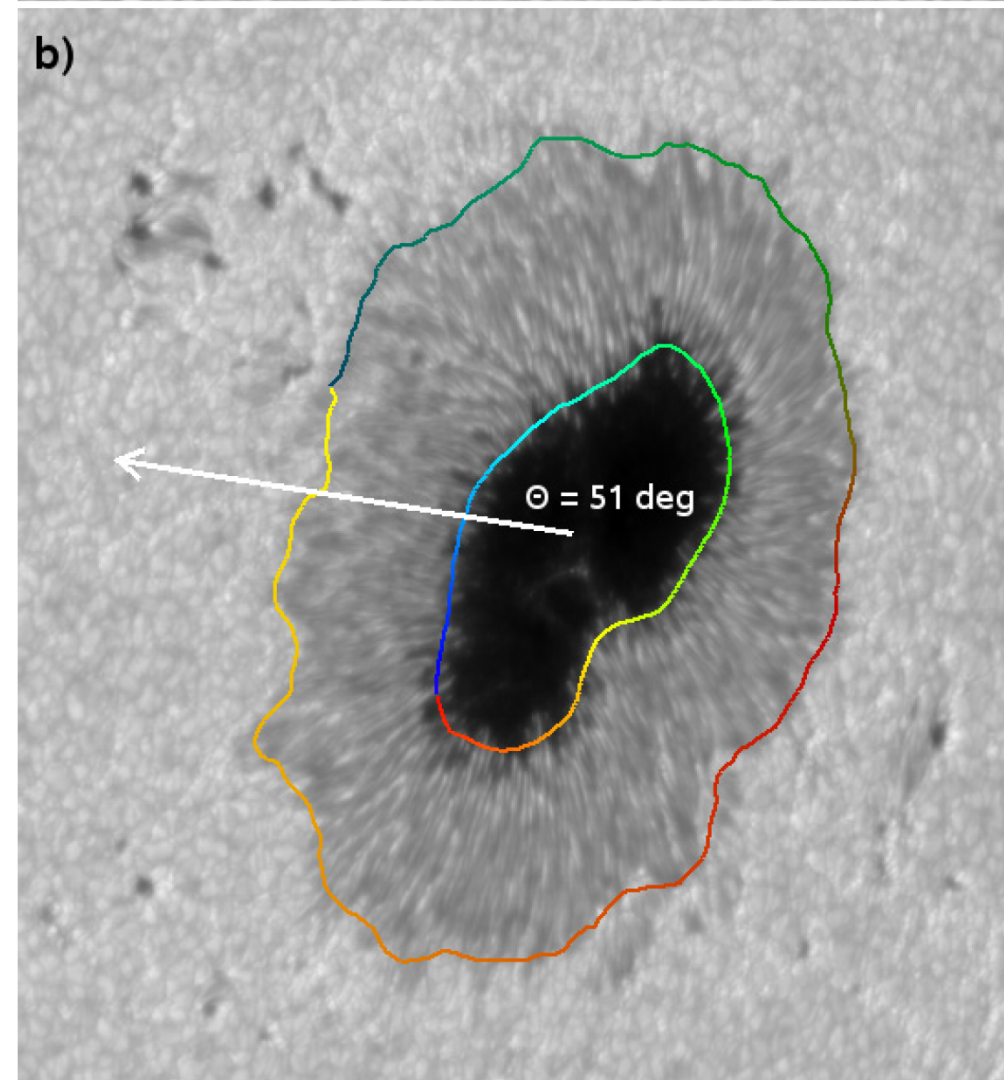
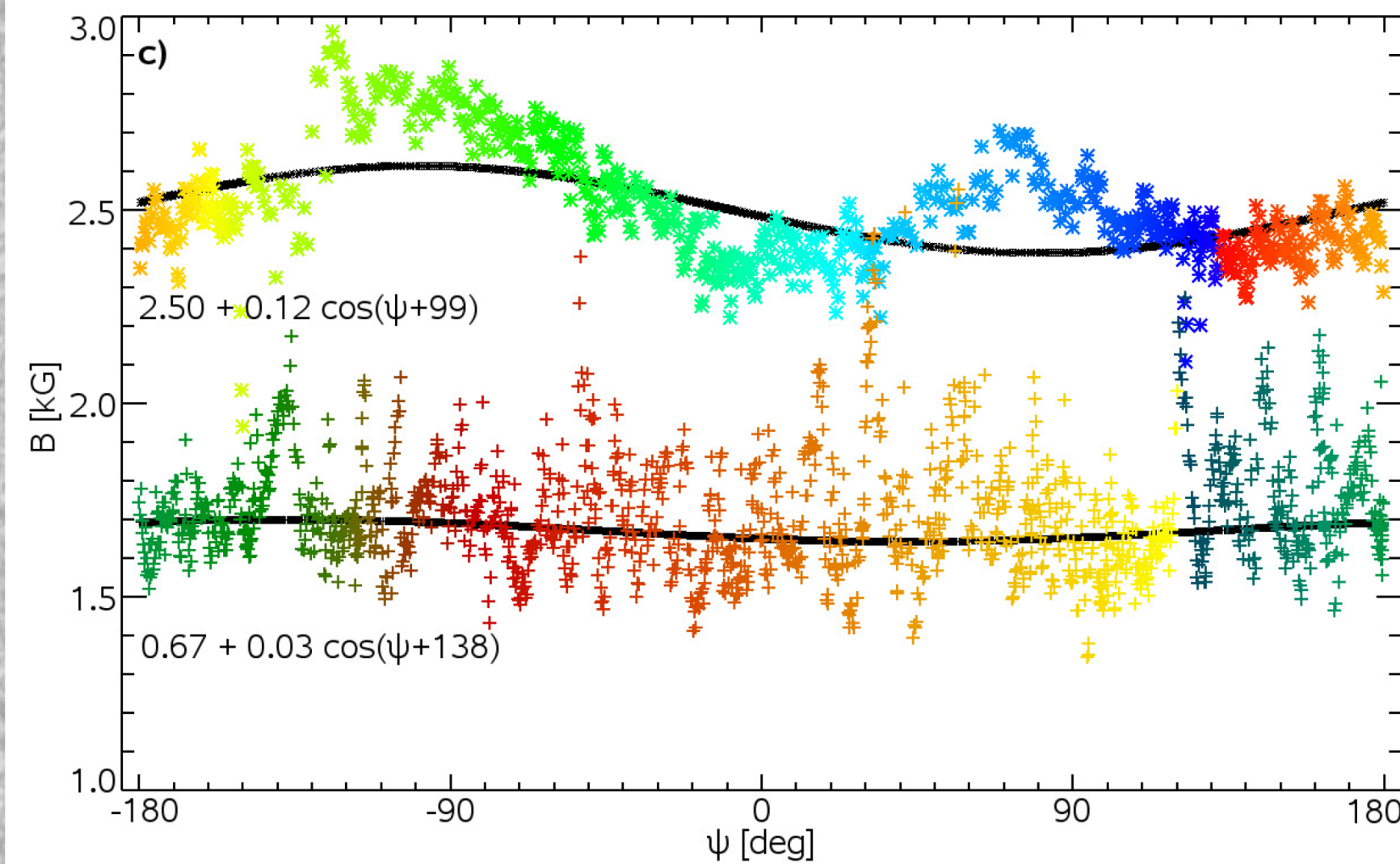
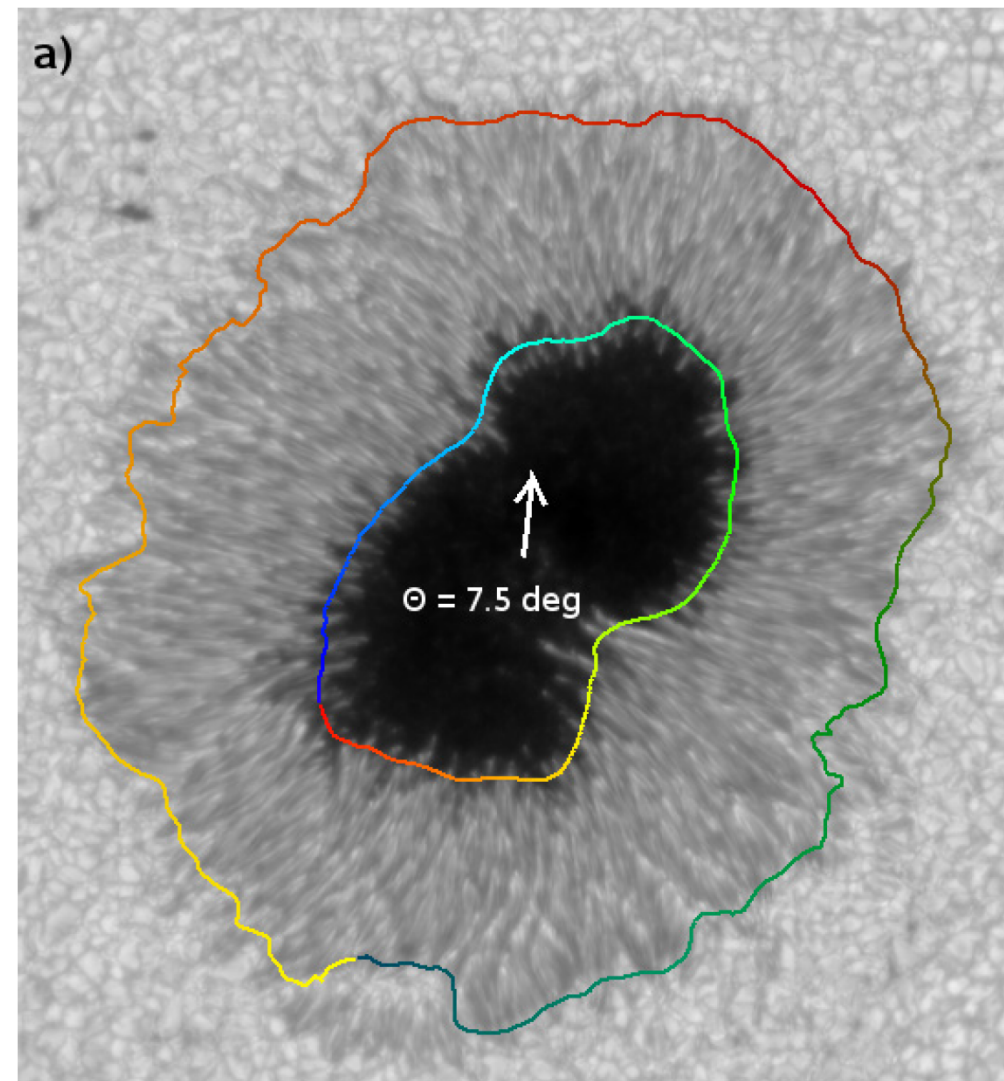
Magnetic field of sunspots: photosphere

Umбра-penumbra boundary and vertical magnetic field

Jurčák (2010)

Jurčák criterion

- Canonical value of the strength of the vertical magnetic field (**1867 G**)
- Independent of sunspot size
- Threshold for magnetoconvection



Magnetic field of sunspots: photosphere

Umbra-penumbra boundary and vertical magnetic field

A&A 639, A106 (2020)

<https://doi.org/10.1051/0004-6361/202037974>

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**Astronomy
&
Astrophysics**

No universal connection between the vertical magnetic field and the umbra-penumbra boundary in sunspots

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¹ Max-Planck-Institut für Sonnensystemforschung, Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany
e-mail: loeptien@mps.mpg.de

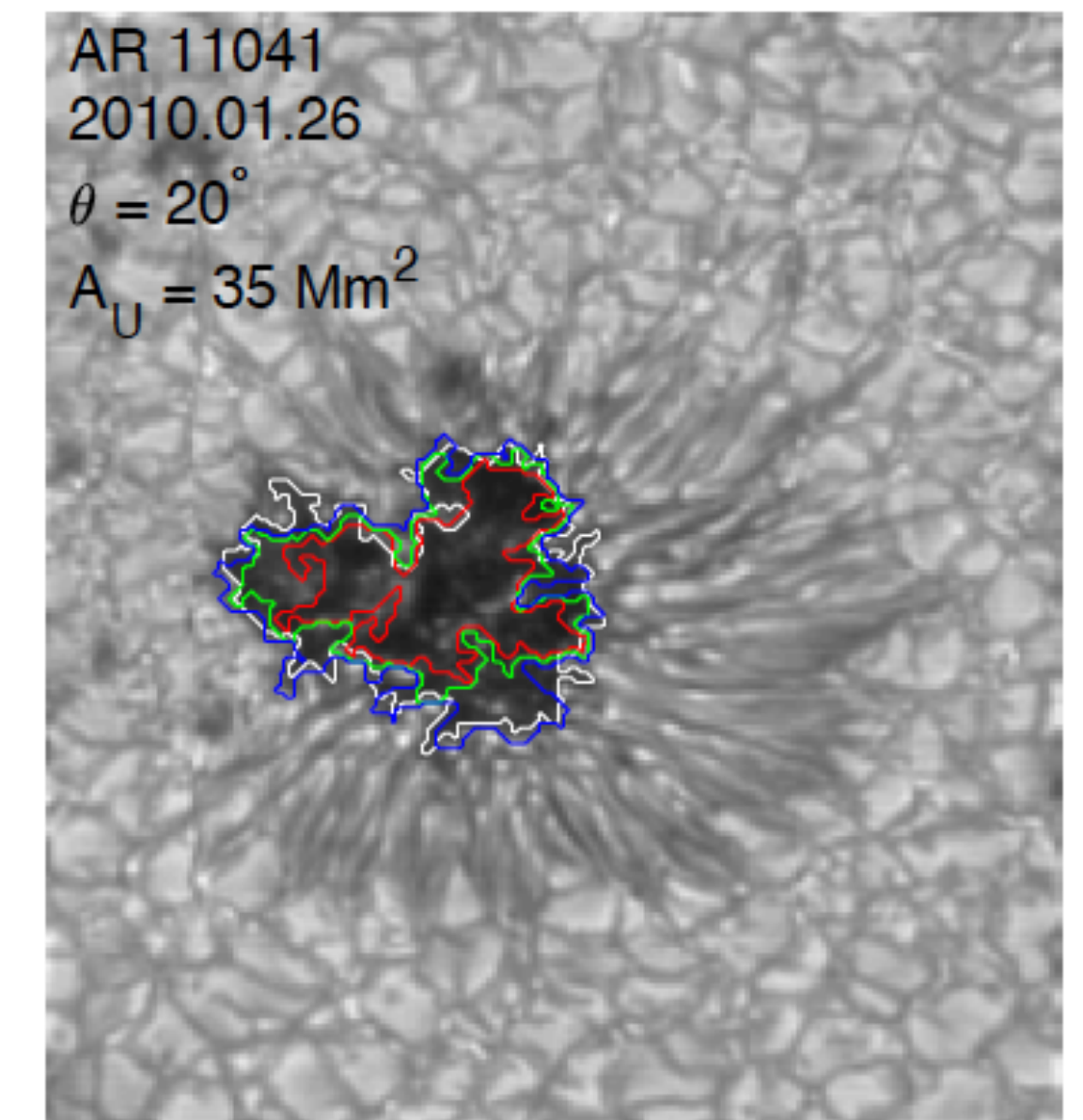
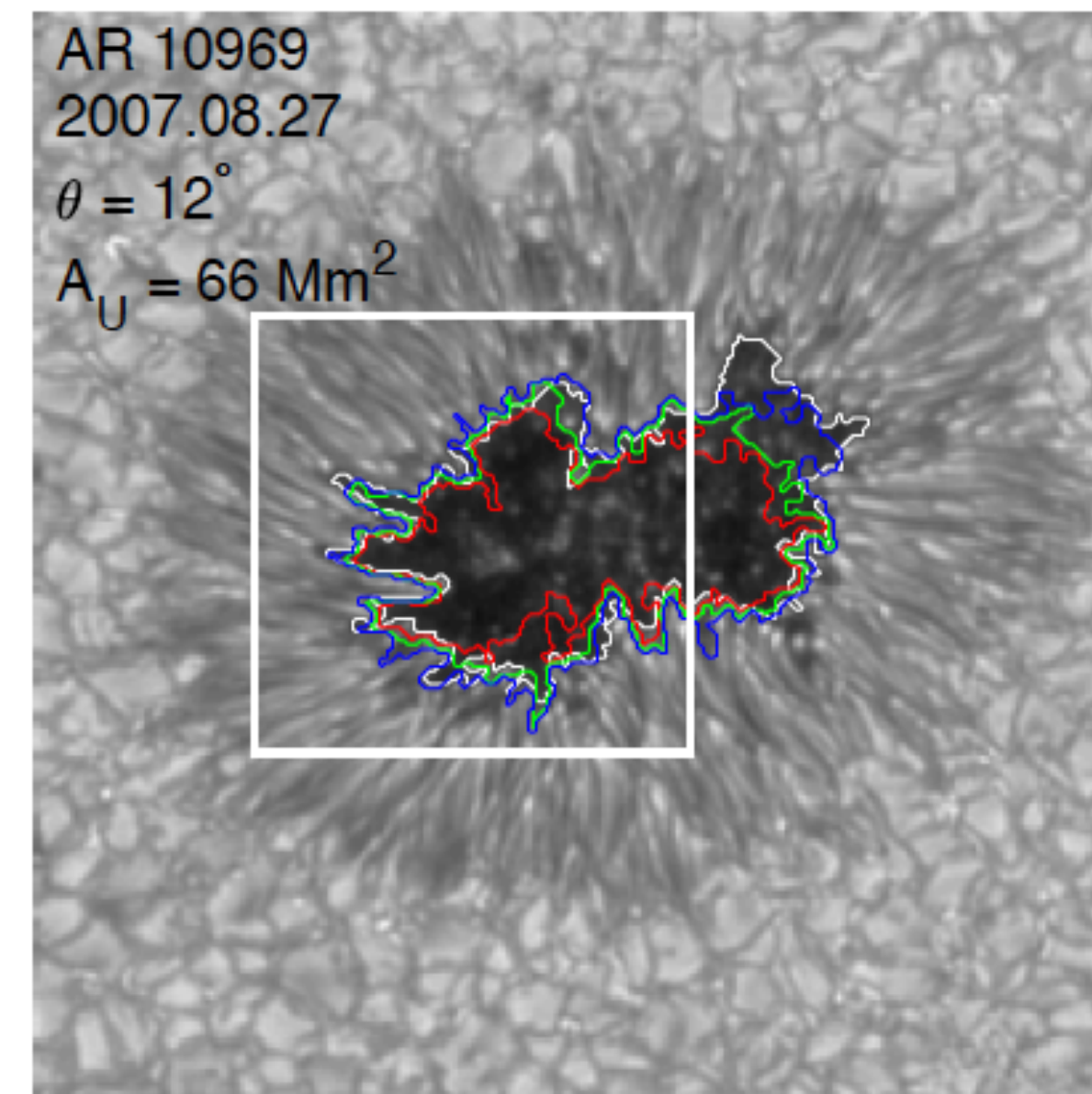
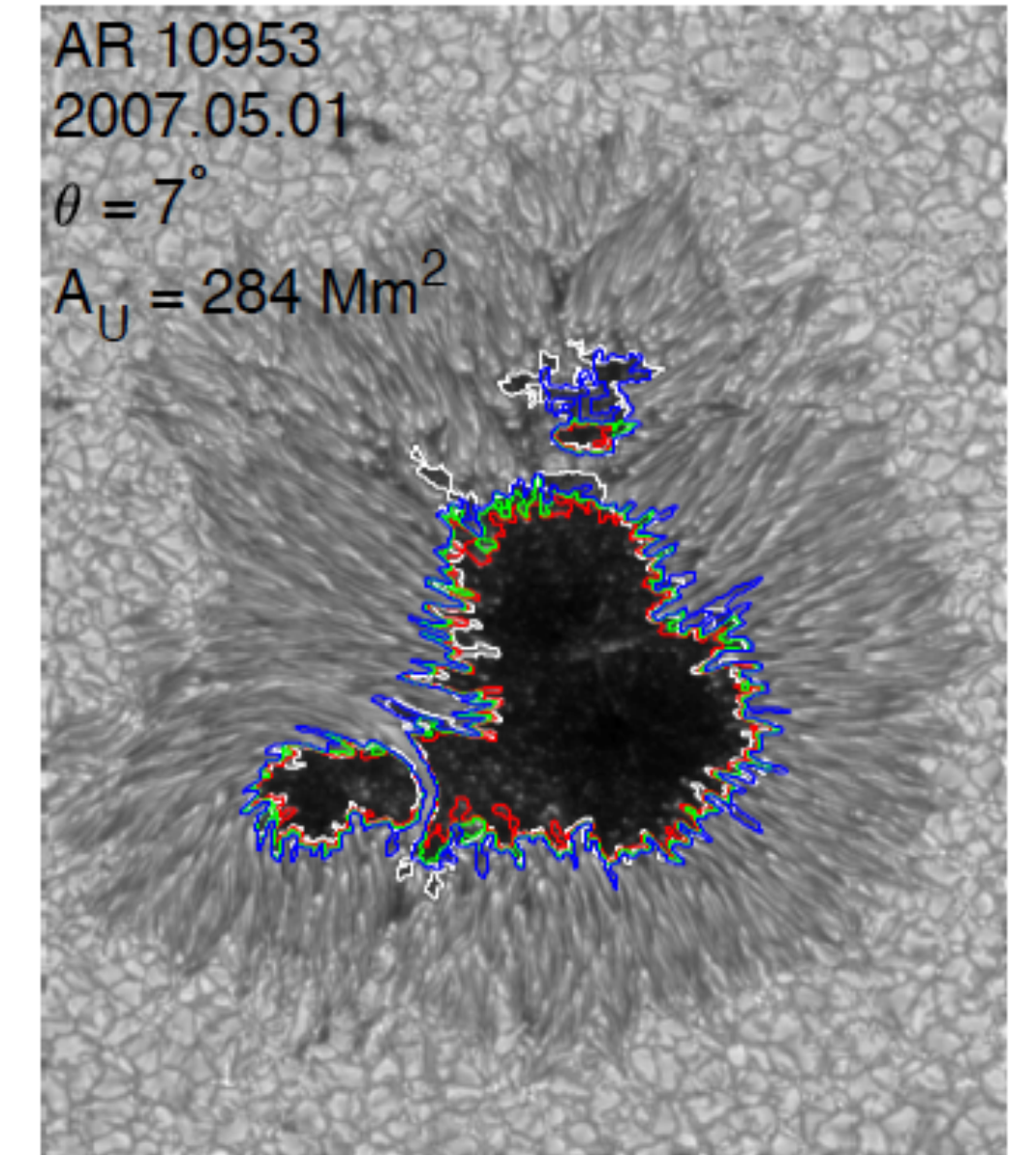
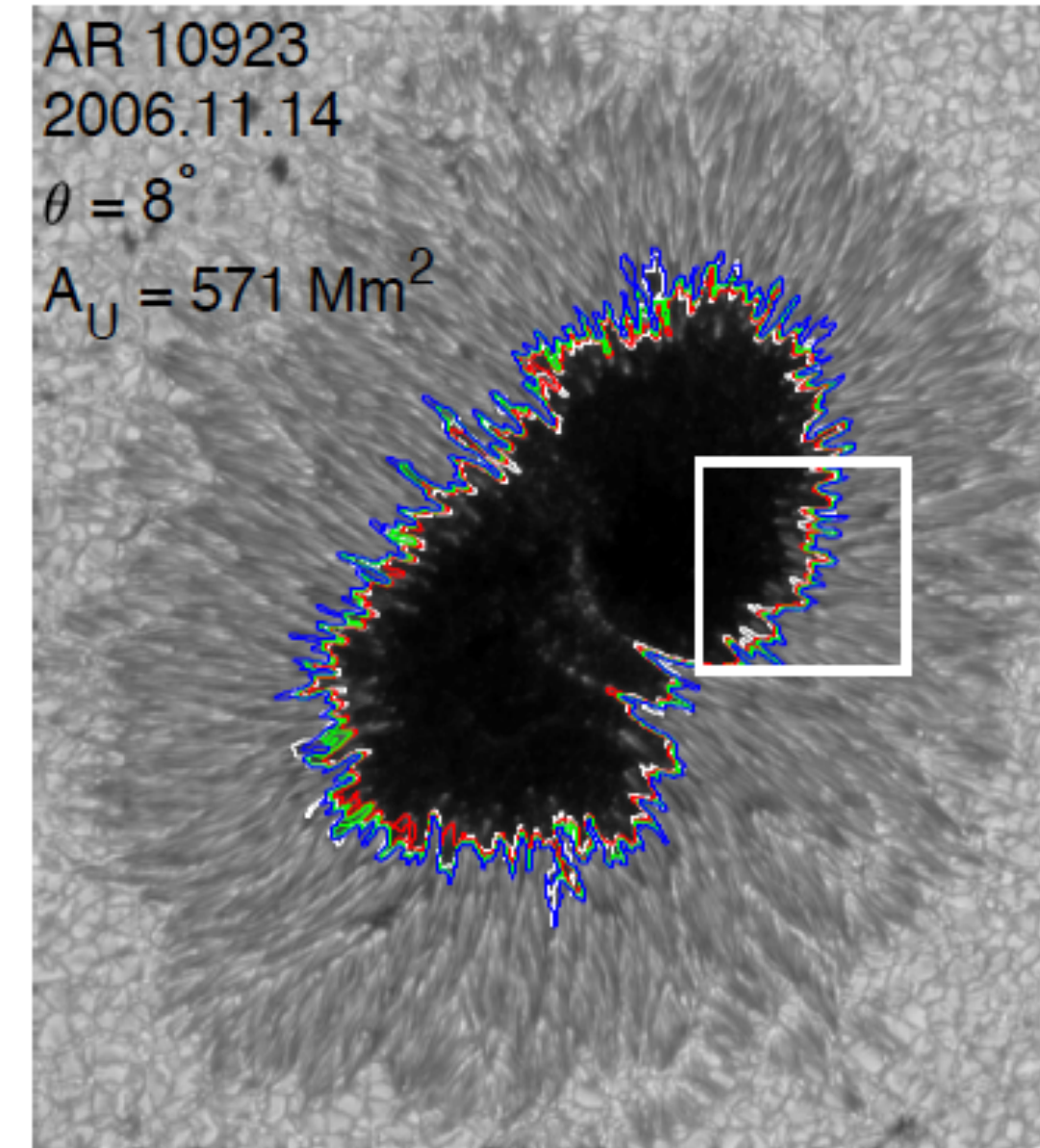
² School of Space Research, Kyung Hee University, Yongin, Gyeonggi 446-701, Republic of Korea

Magnetic field of sunspots: photosphere

Umбра-penumбра boundary and vertical magnetic field

Löptien et al. (2020)

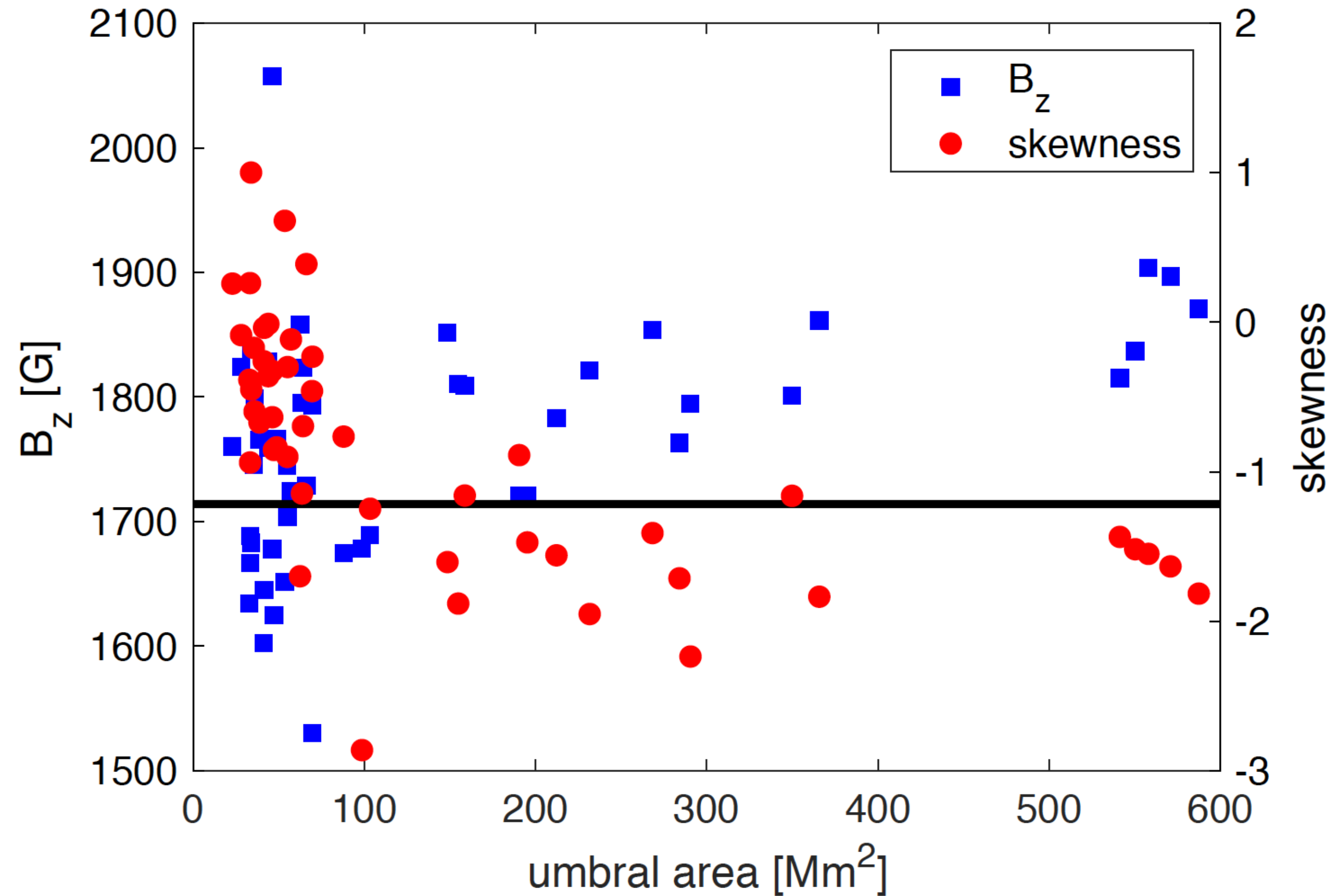
Fig. 1. Maps of the continuum intensity of selected sunspots. The white contours indicate a continuum intensity of 50% of the quiet Sun level. The other contours correspond to different strengths of the vertical magnetic field, evaluated at $\log \tau = -0.9$. Blue: 1650 G, green: 1750 G, and red: 1867 G. The white rectangles highlight regions of AR 10923 and AR 19069 that are shown in more detail later in the paper.



Magnetic field of sunspots: photosphere

Umbral-penumbra boundary and vertical magnetic field

Löptien et al. (2020)



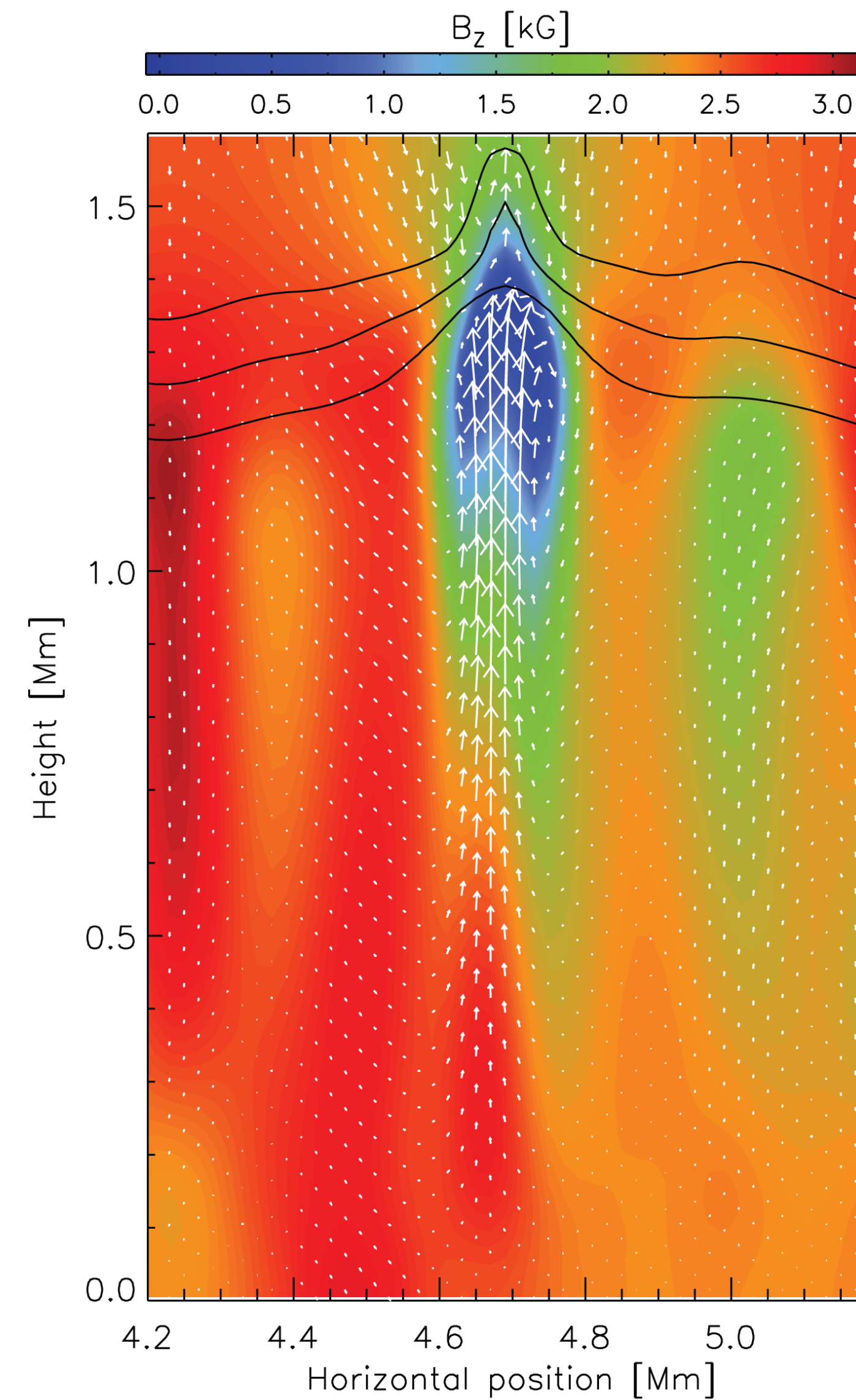
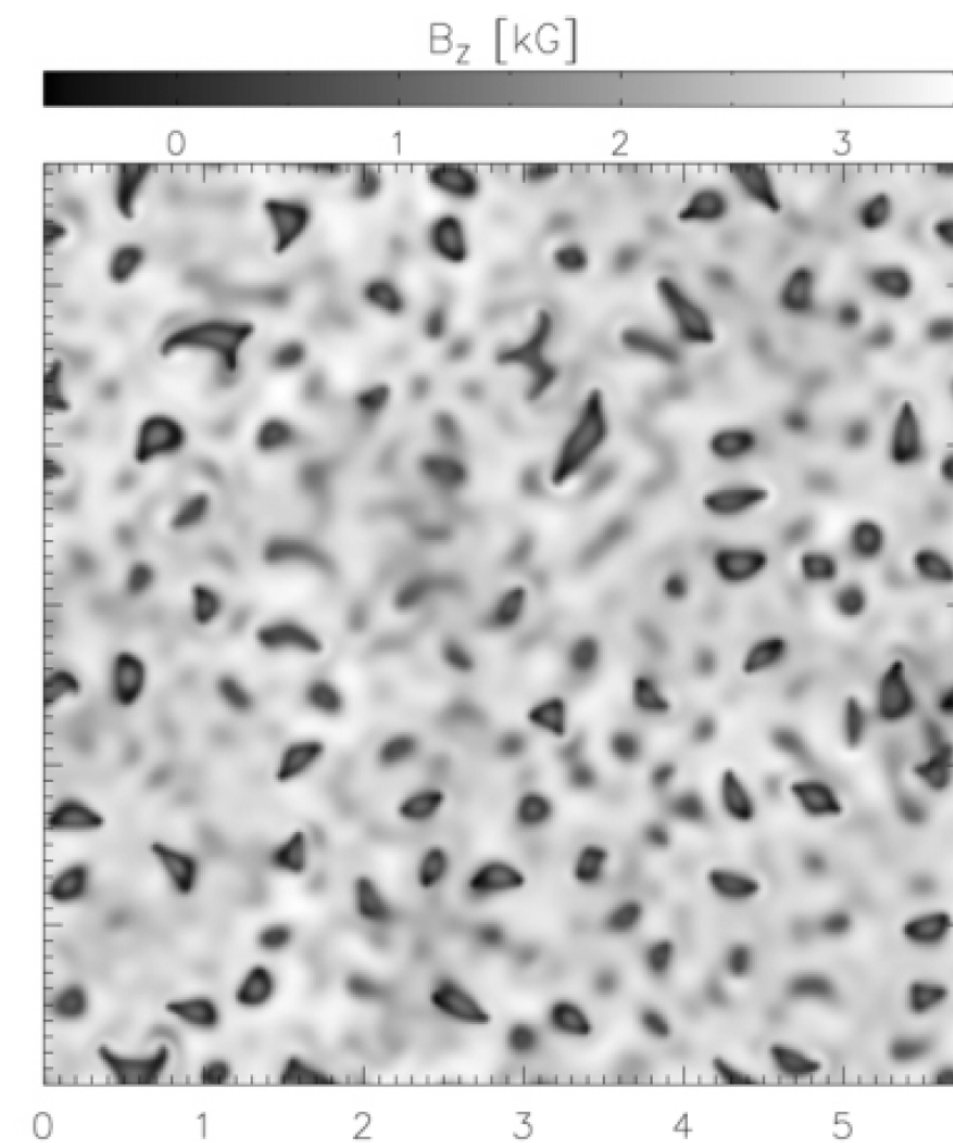
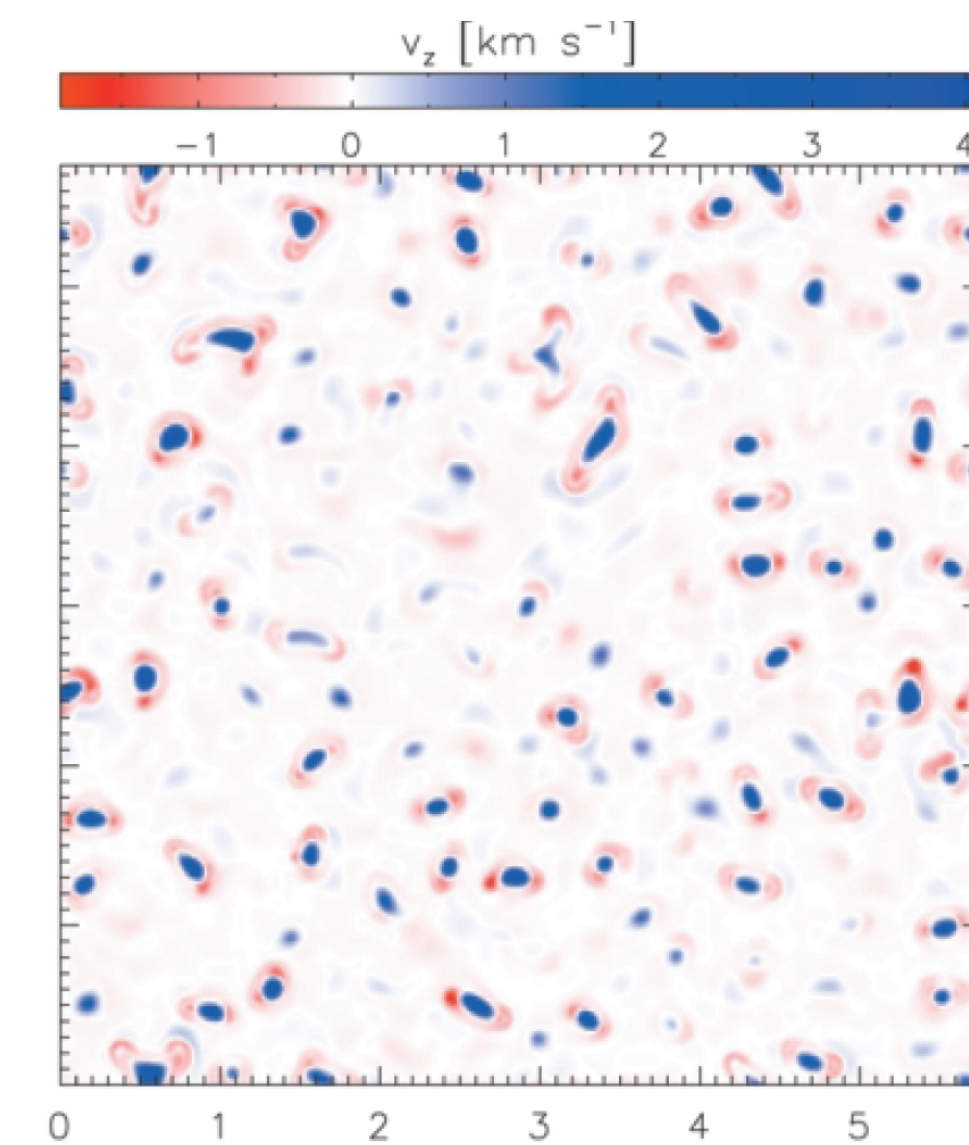
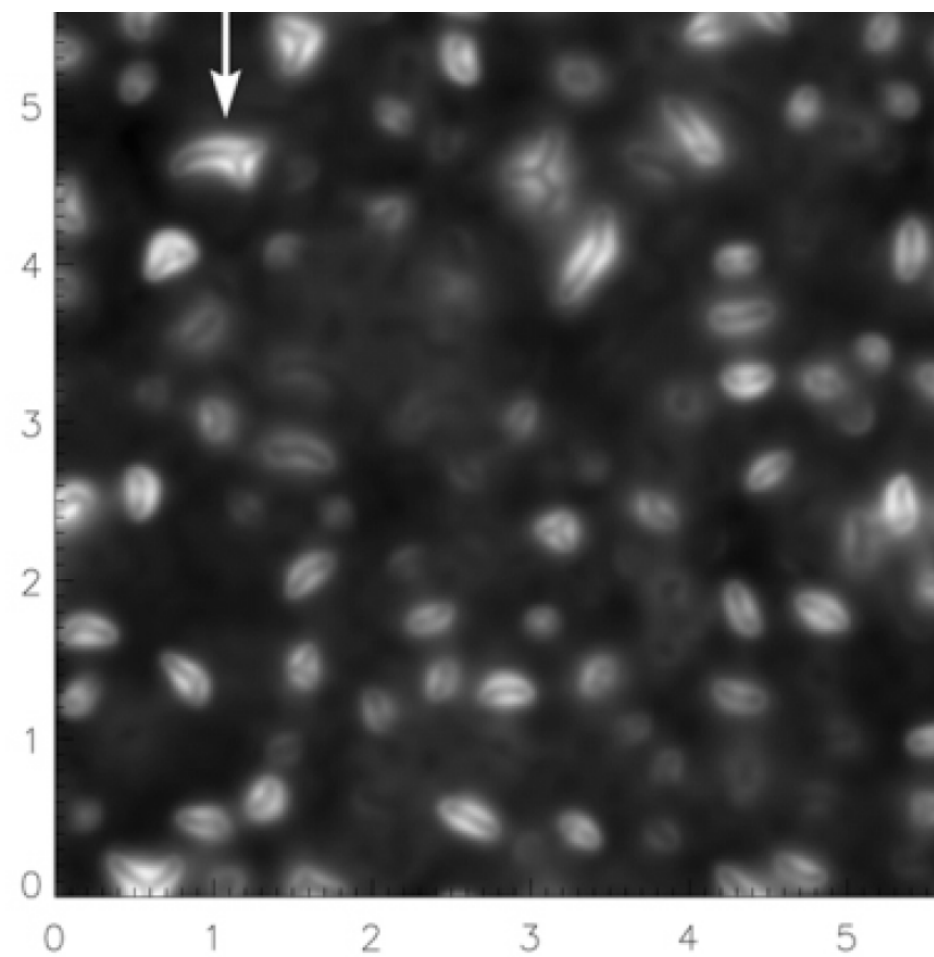
Magnetic field of sunspots: photosphere

Umbral dots

MHD simulation

Schüssler and Vögler (1997)

Magnetoconvection

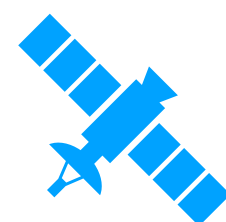
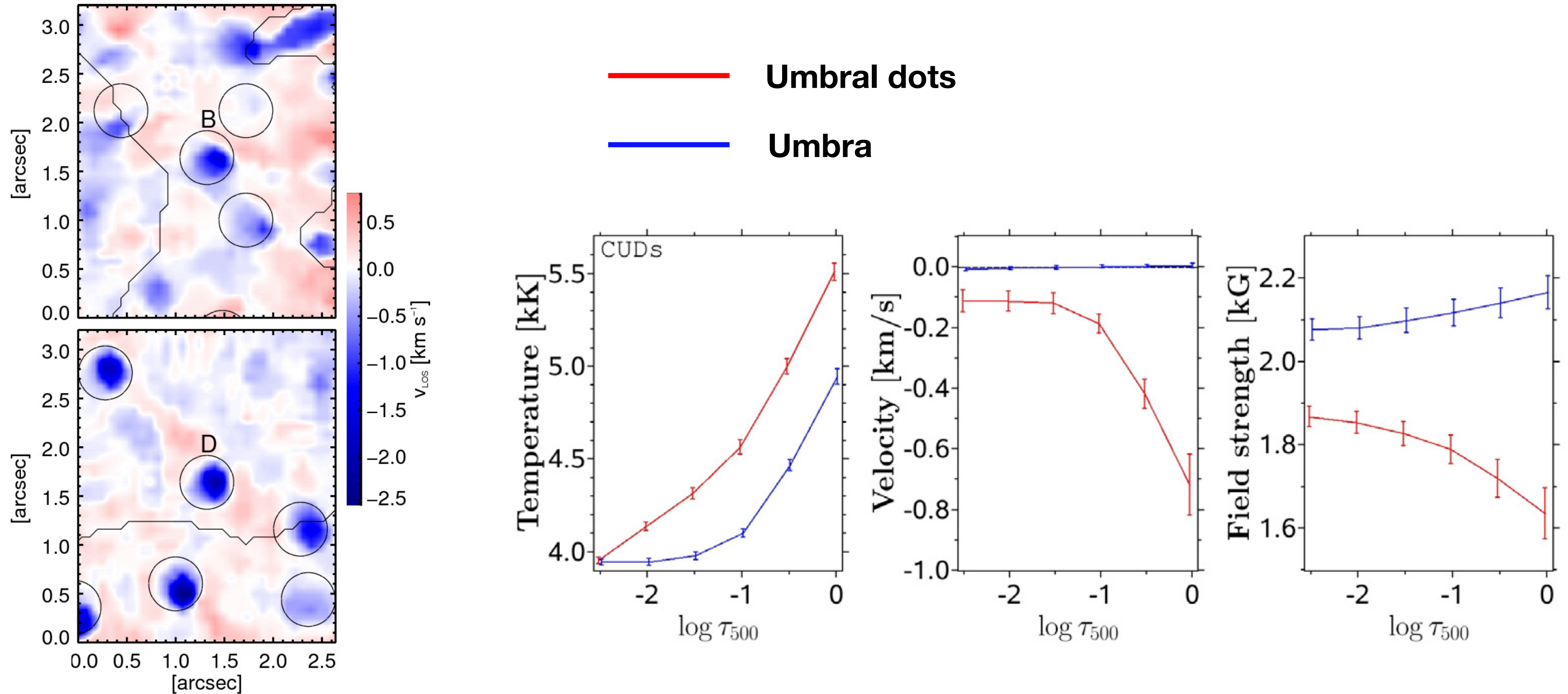


Magnetic field of sunspots: photosphere

Umbral dots

Observational evidence of magneto-convection

Riethmüller et al. (2013)



Magnetic field of sunspots: Chromosphere

Challenges to measurements of chromospheric magnetic field

- Weaker fields

Gas pressure drops by several order of magnitude
Magnetic field lines expands - weaker field

Required polarimetric accuracy - few times 10^{-4}

- Faster dynamics

Shorter exposure time

- Non local thermodynamical equilibrium (non-LTE)

Most of chromospheric spectral lines form in non-LTE condition

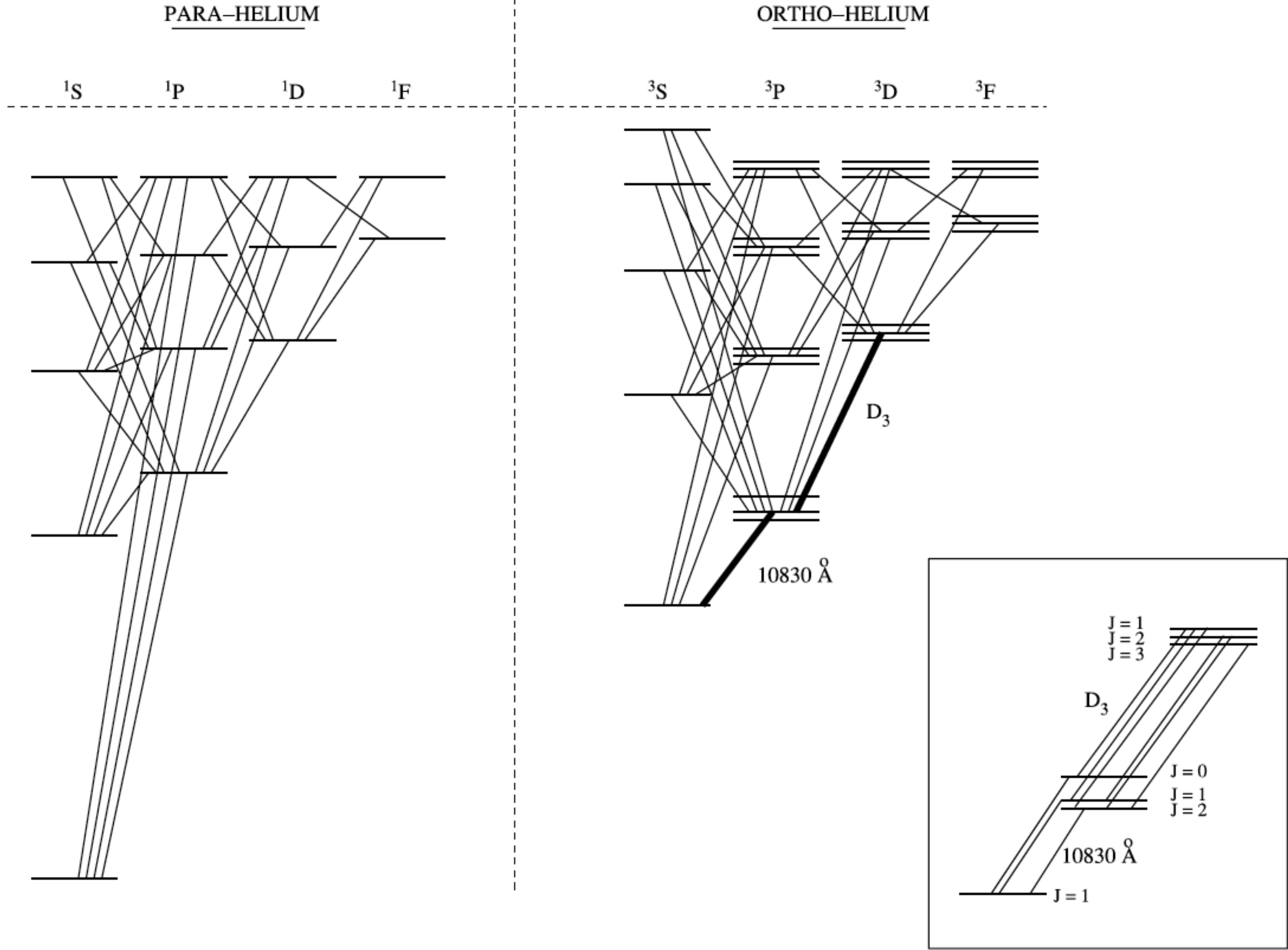
Non-LTE inversion codes - NICOLE (Socas-Navarro et al. 2015)

STiC (de la Cruz Rodríguez et al. 2016)

Exception- He I 1083.0 nm and He D3

Magnetic field of sunspots: Chromosphere

He I 10830 Å

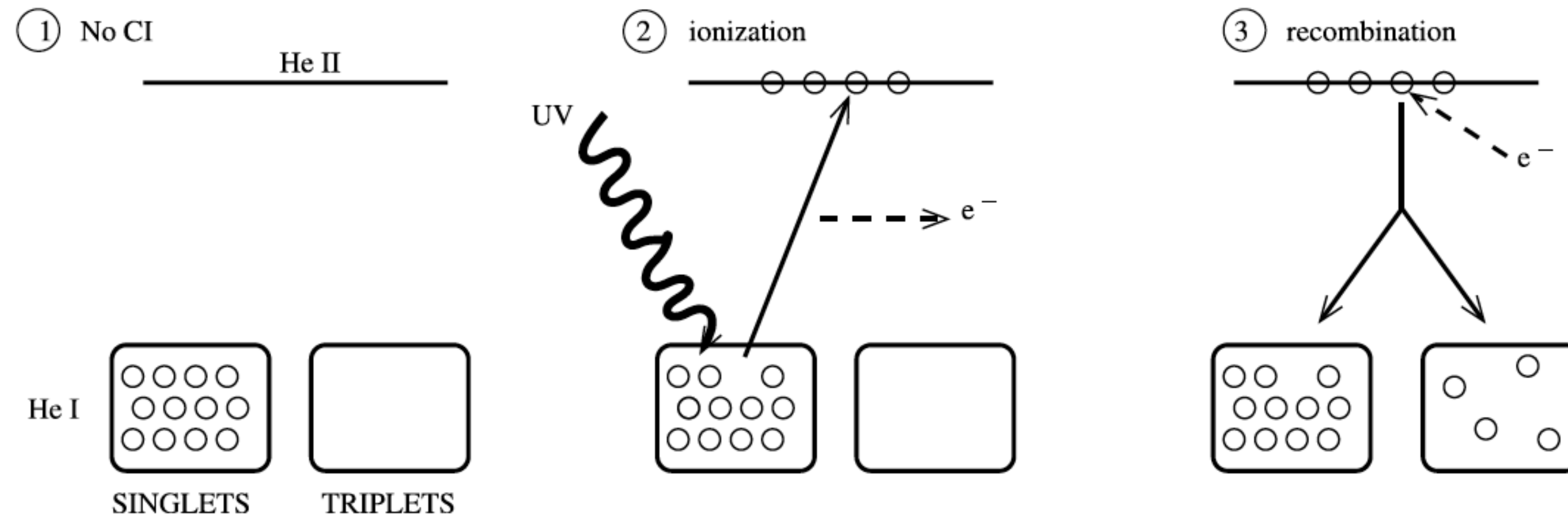


Formation of the He I D_3 and He I 10830 Å lines

Requires EUV radiation from corona to ionize helium. Subsequently, He II atoms recombine with free electron to populate the helium triplet system.

Magnetic field of sunspots: Chromosphere

He I 10830 Å



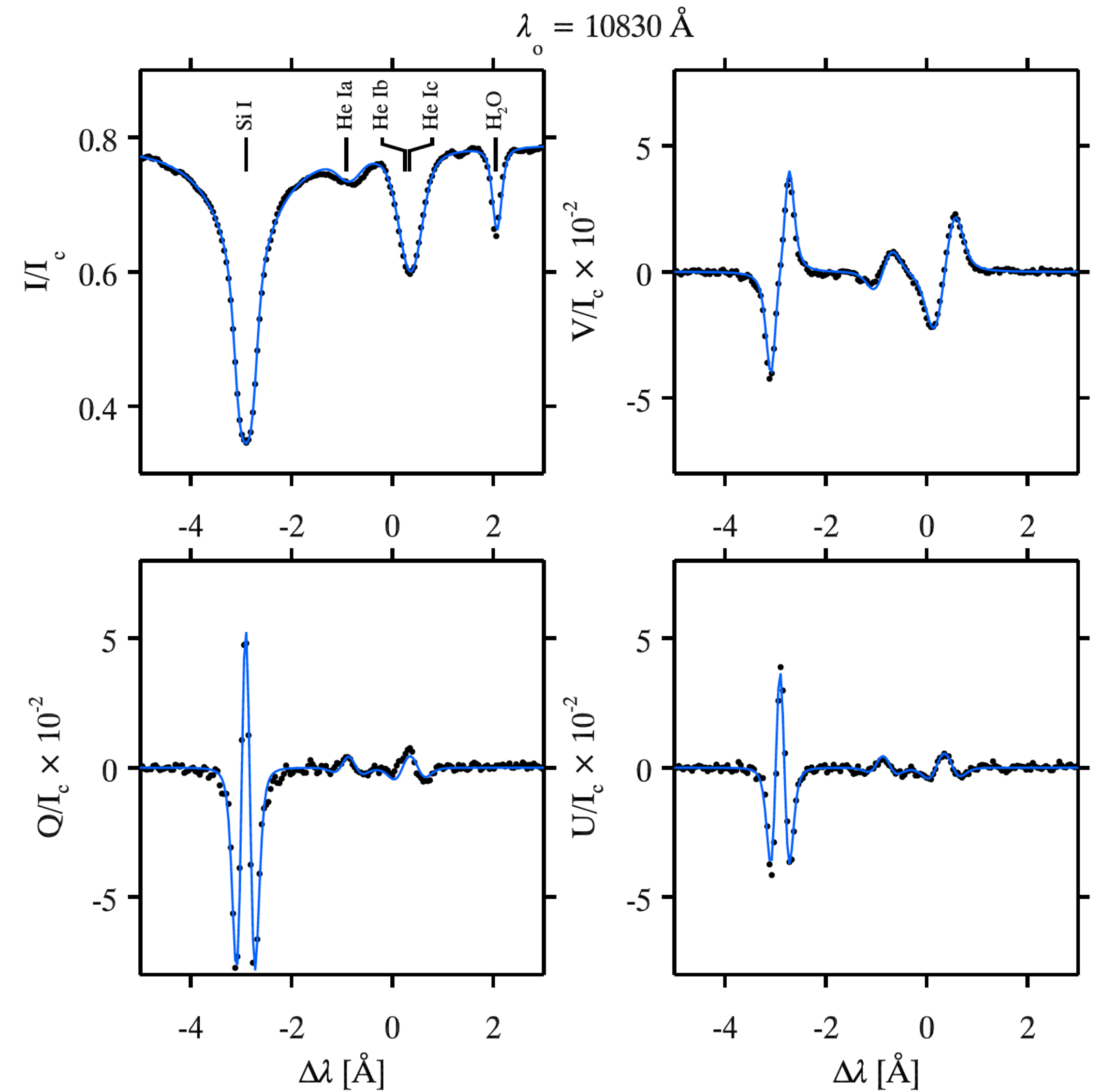
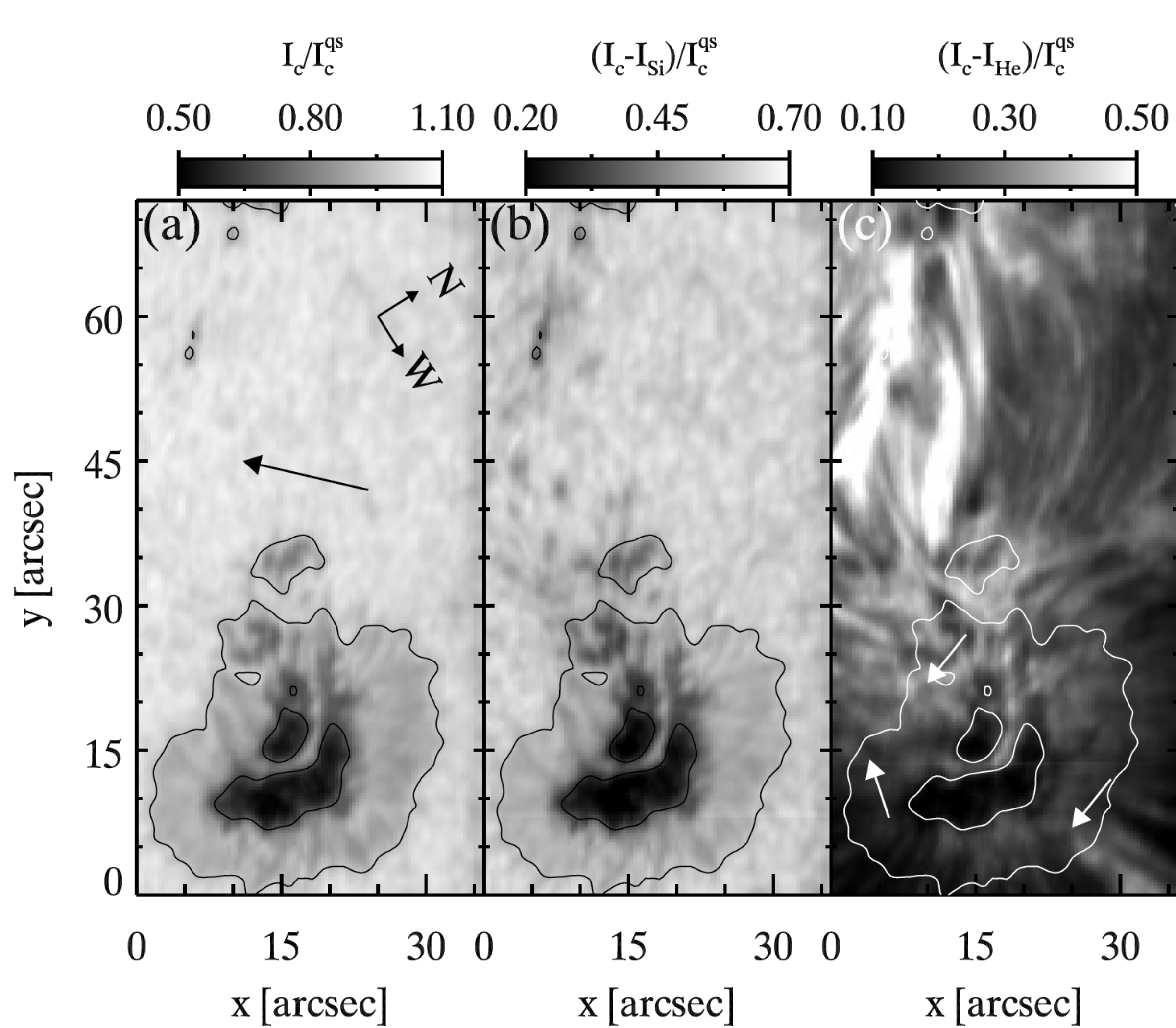
Formation of the He I D₃ and He I 10830 Å lines

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Magnetic field of sunspots: Chromosphere

He I 10830 Å

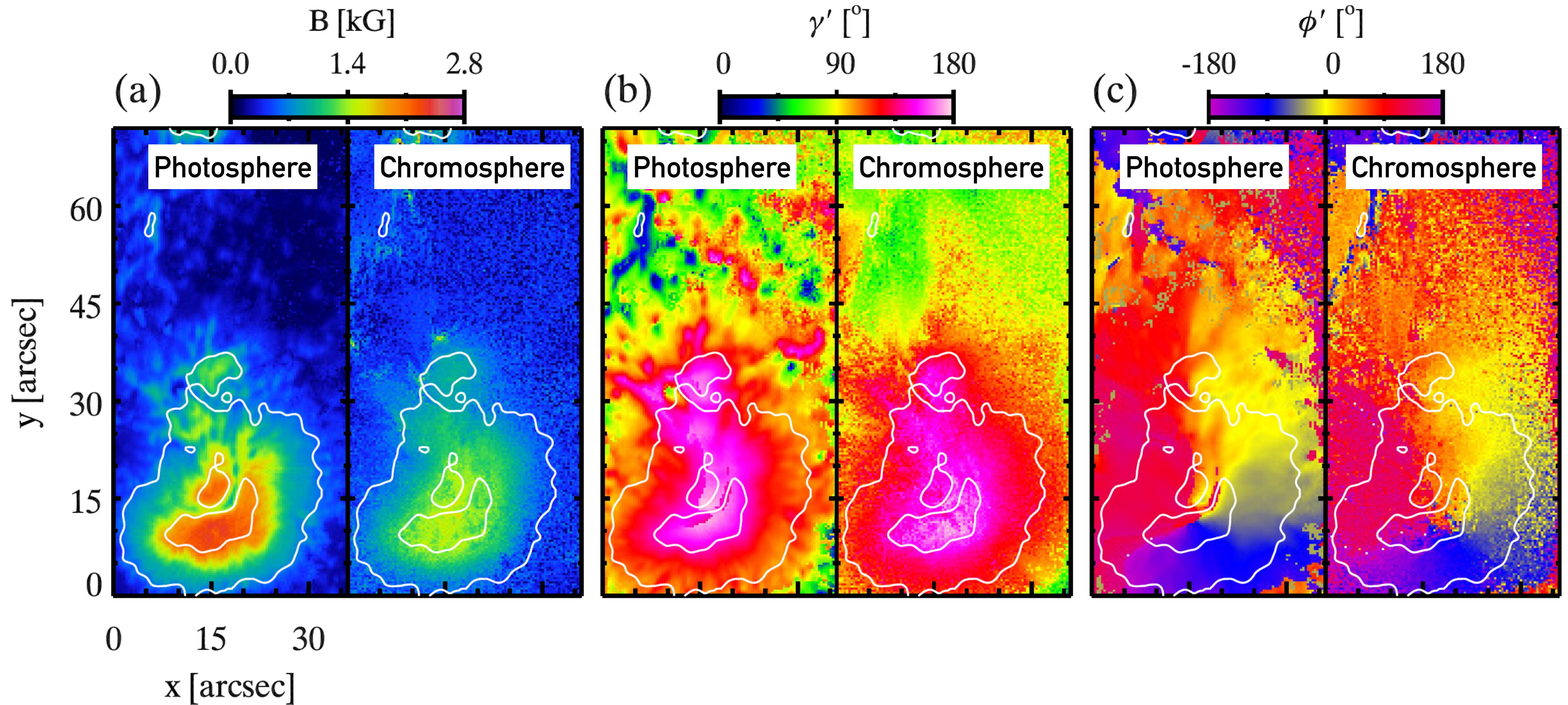
Joshi et al (2017)



Magnetic field of sunspots: Chromosphere

He I 10830 Å

Joshi et al (2017)

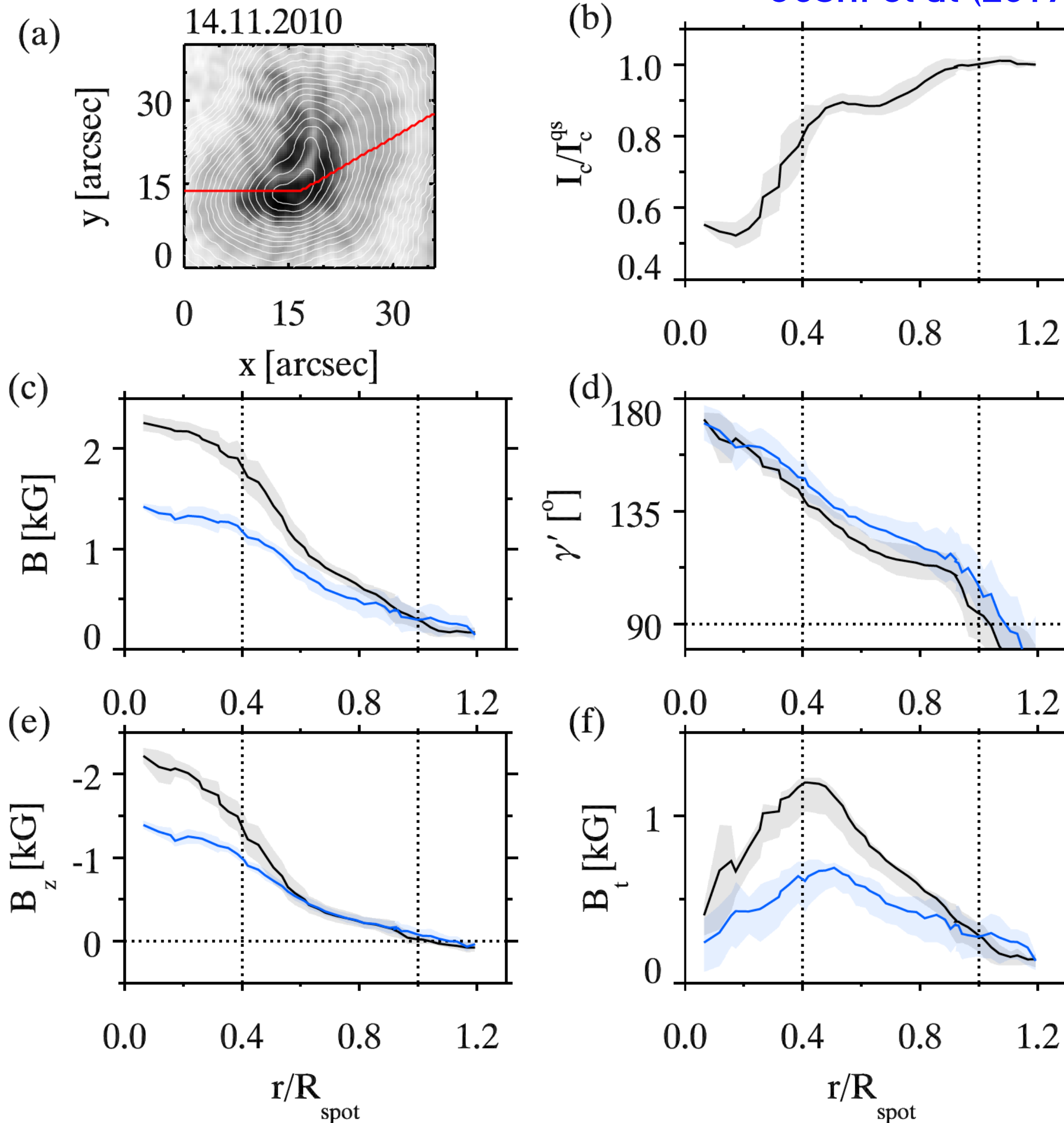


Magnetic field of sunspots: Chromosphere

He I 10830 Å

Radial properties

Joshi et al (2017)



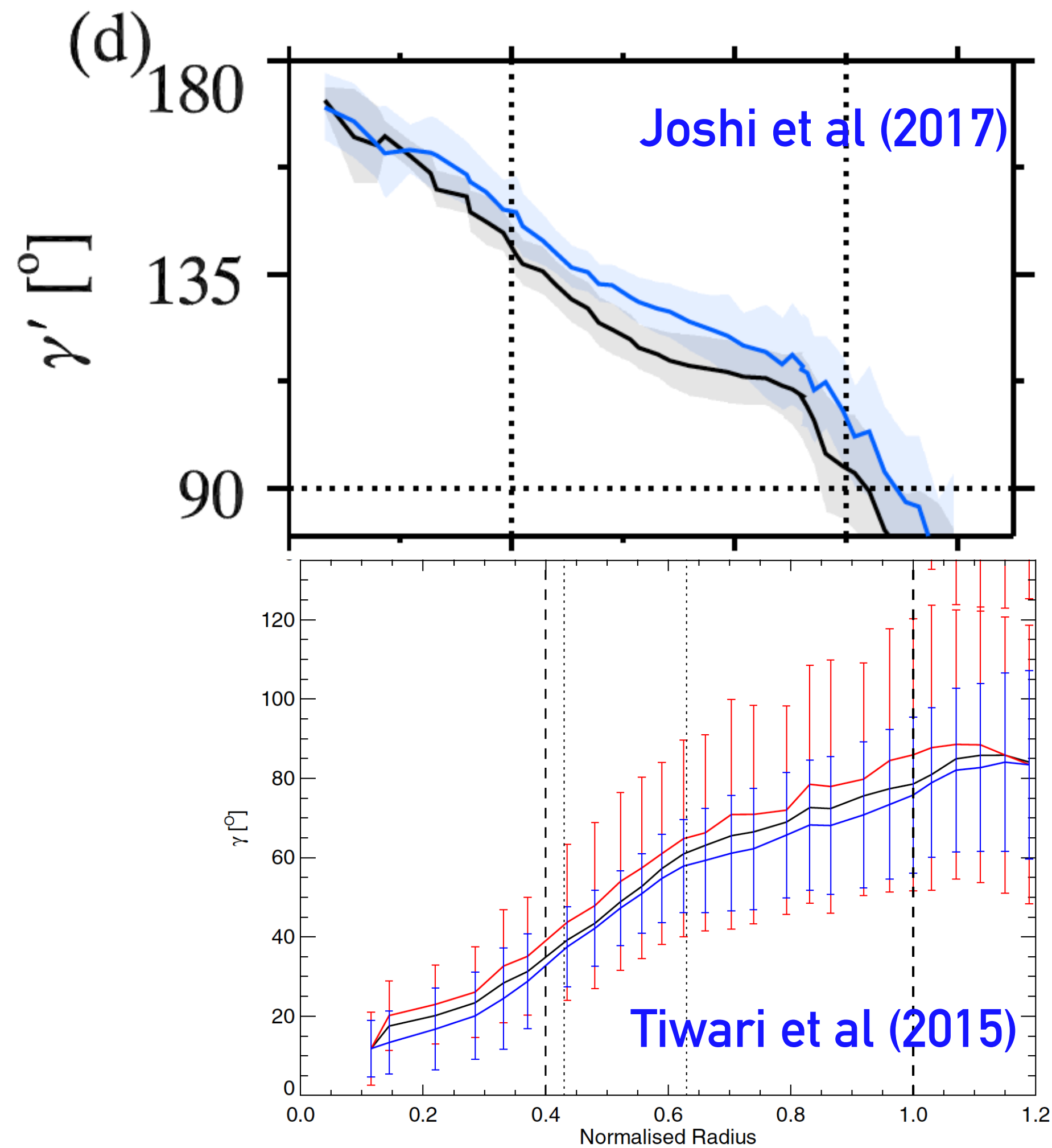
Photosphere
Chromosphere

Magnetic field of sunspots: Chromosphere

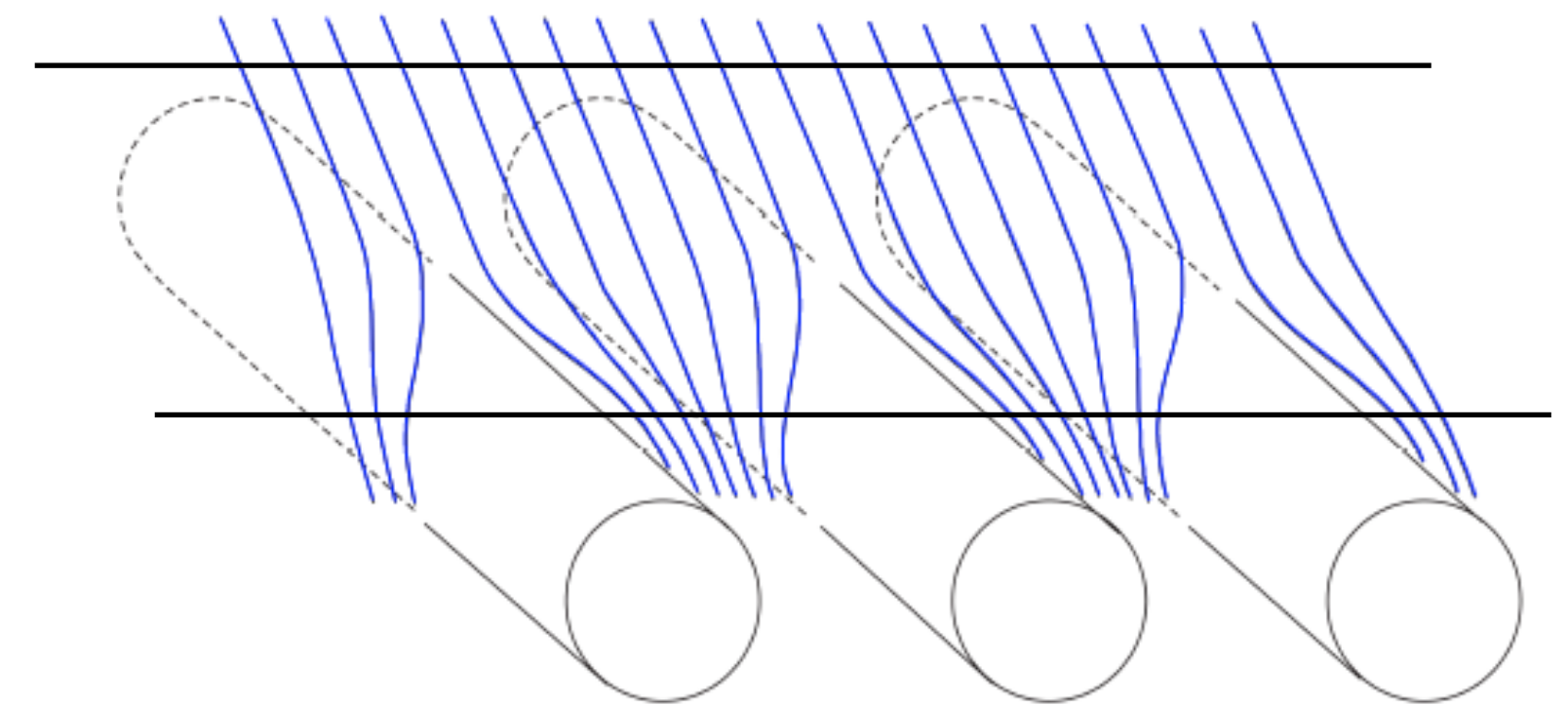
He I 10830 Å

Radial properties

Photosphere
Chromosphere



more vertical field
in higher layers

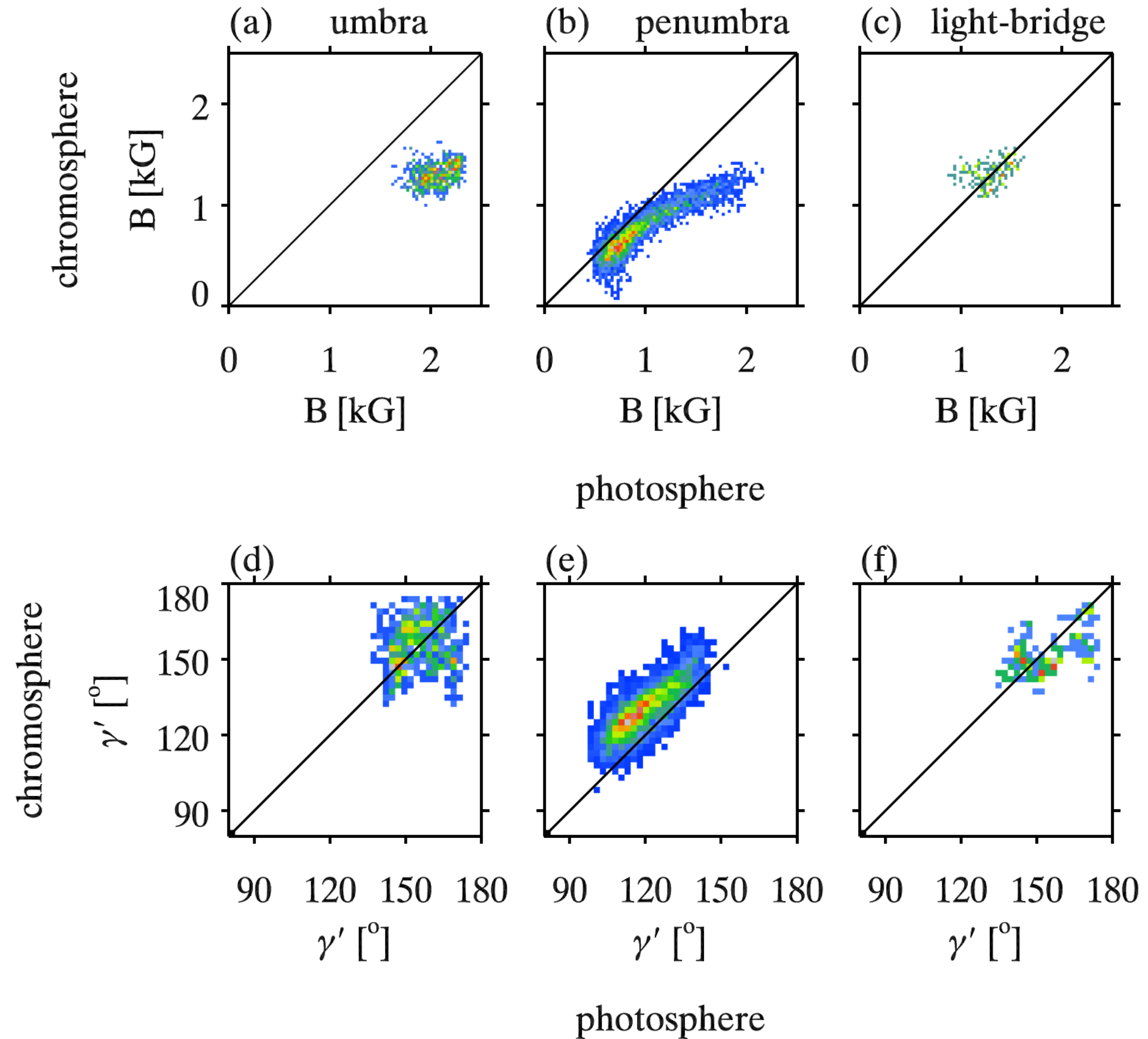
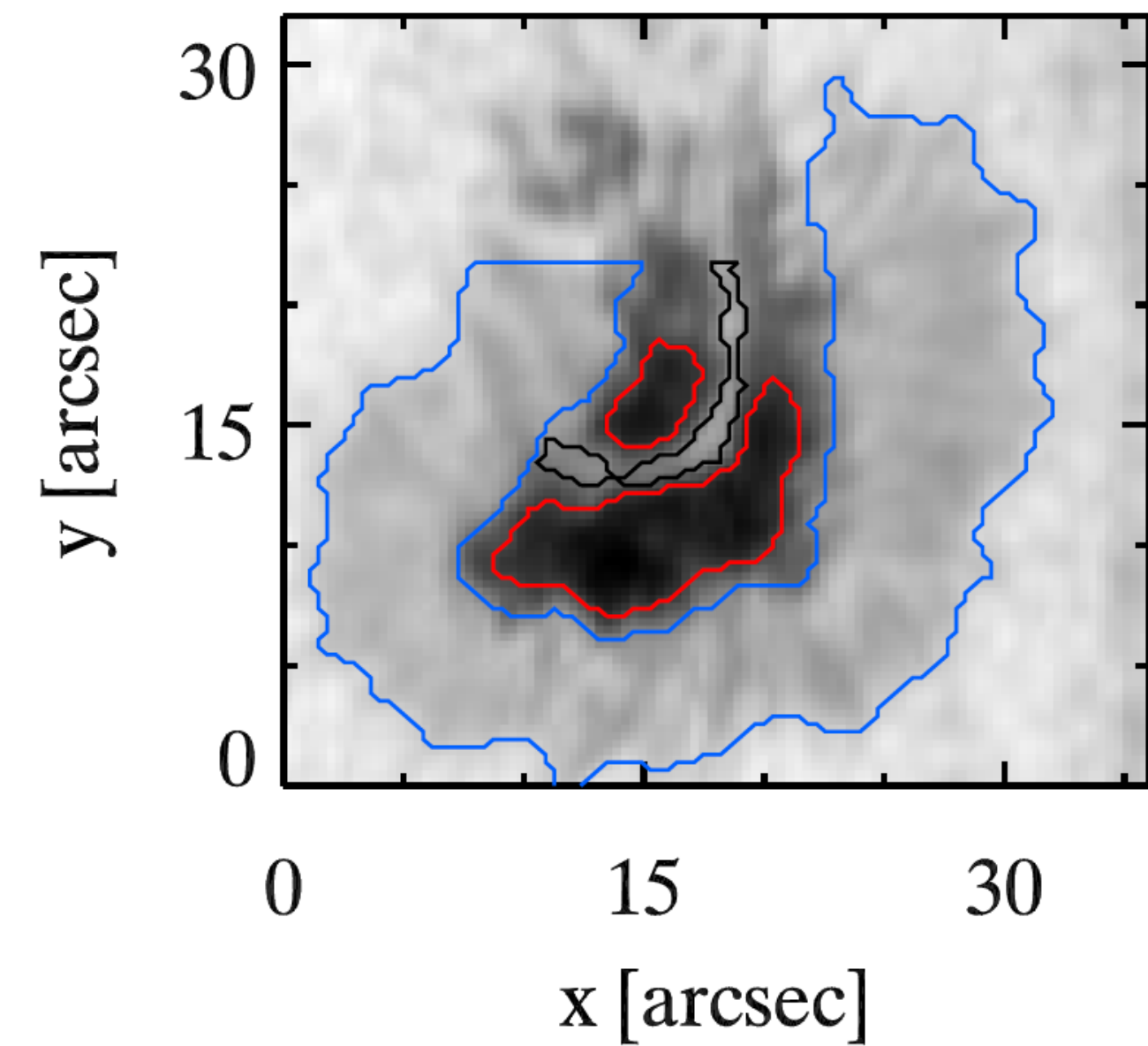


Magnetic field of sunspots: Chromosphere

He I 10830 Å

Radial properties

Joshi et al (2017)



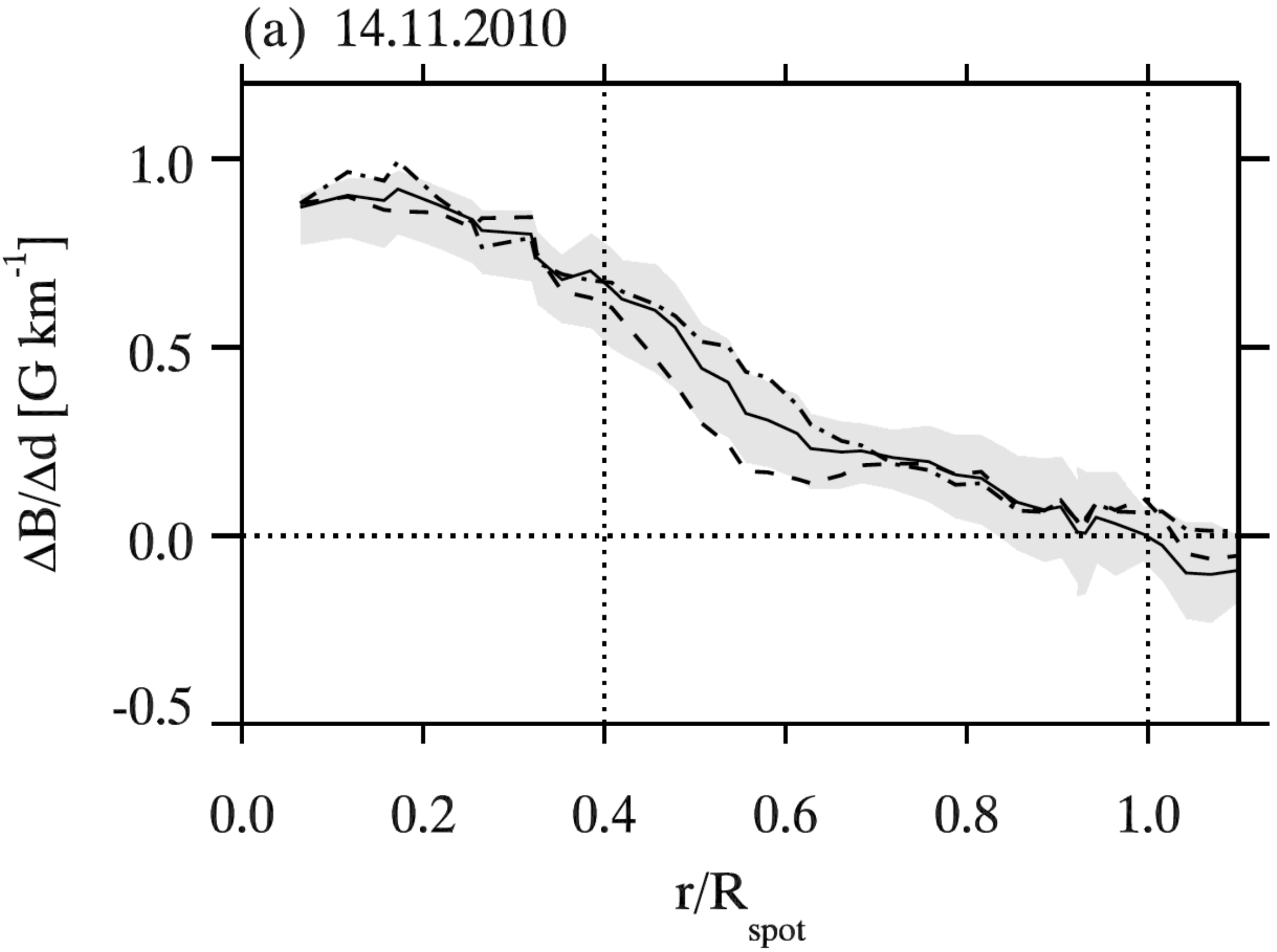
Magnetic field of sunspots: Chromosphere

He I 10830 Å

Vertical gradient

Joshi et al (2017)

No information about spatial variations in formation height



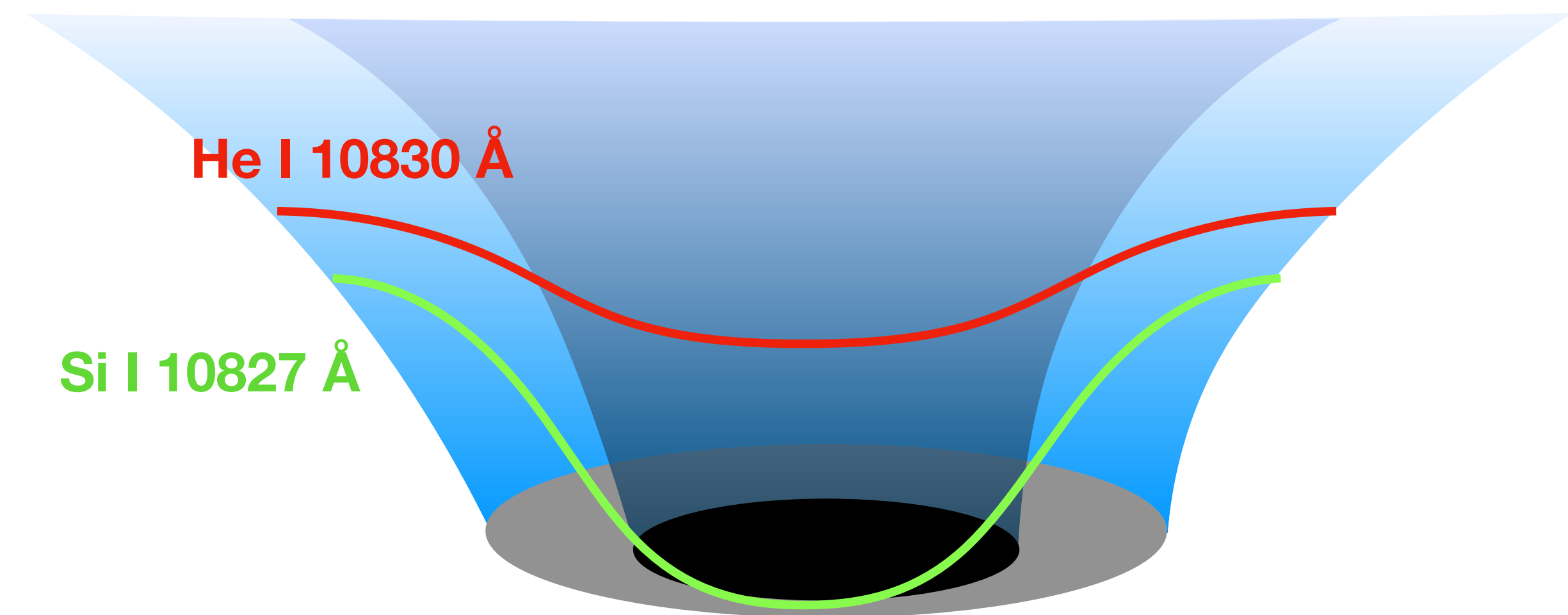
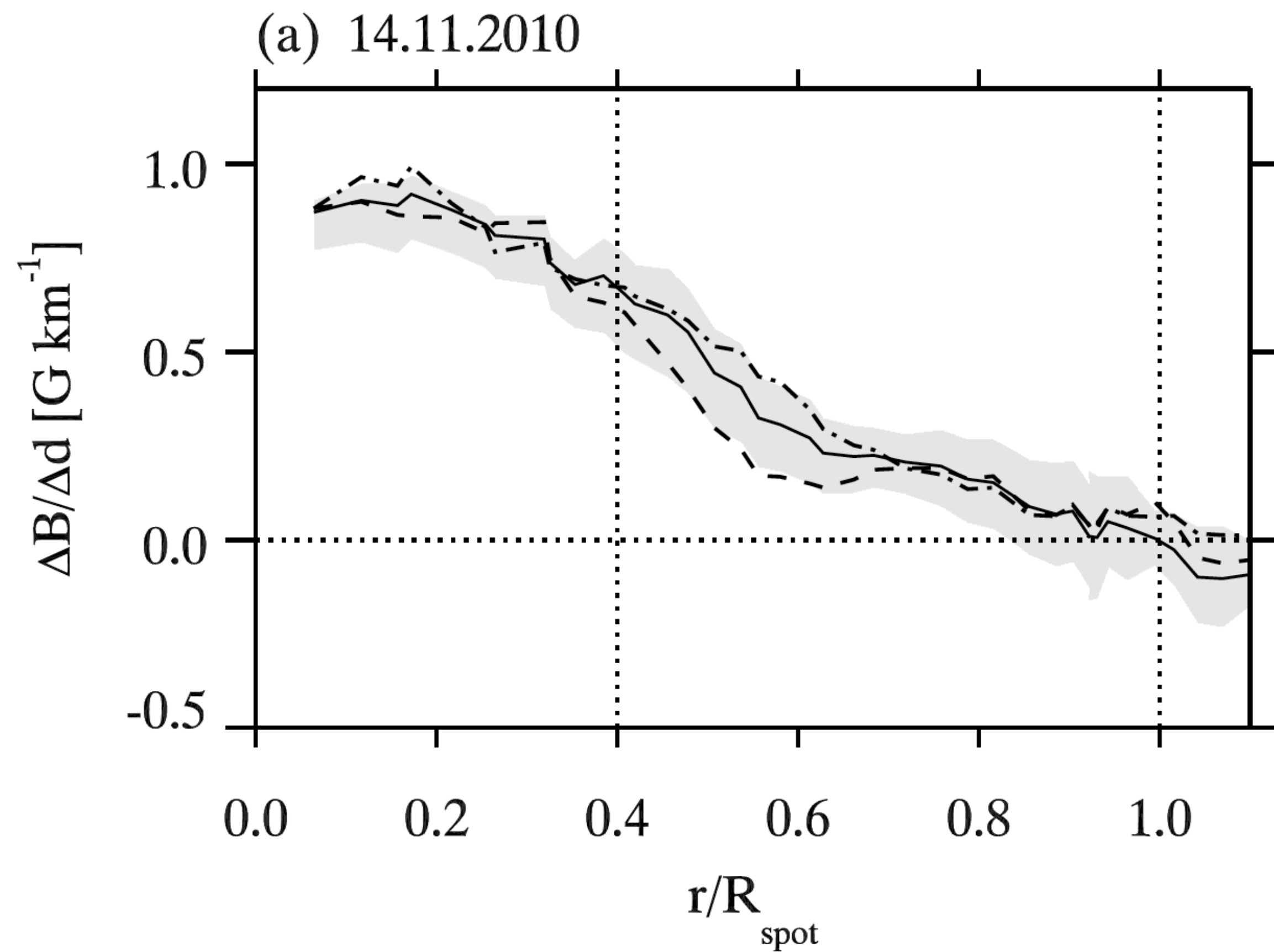
Magnetic field of sunspots: Chromosphere

He I 10830 Å

Vertical gradient

Joshi et al (2017)

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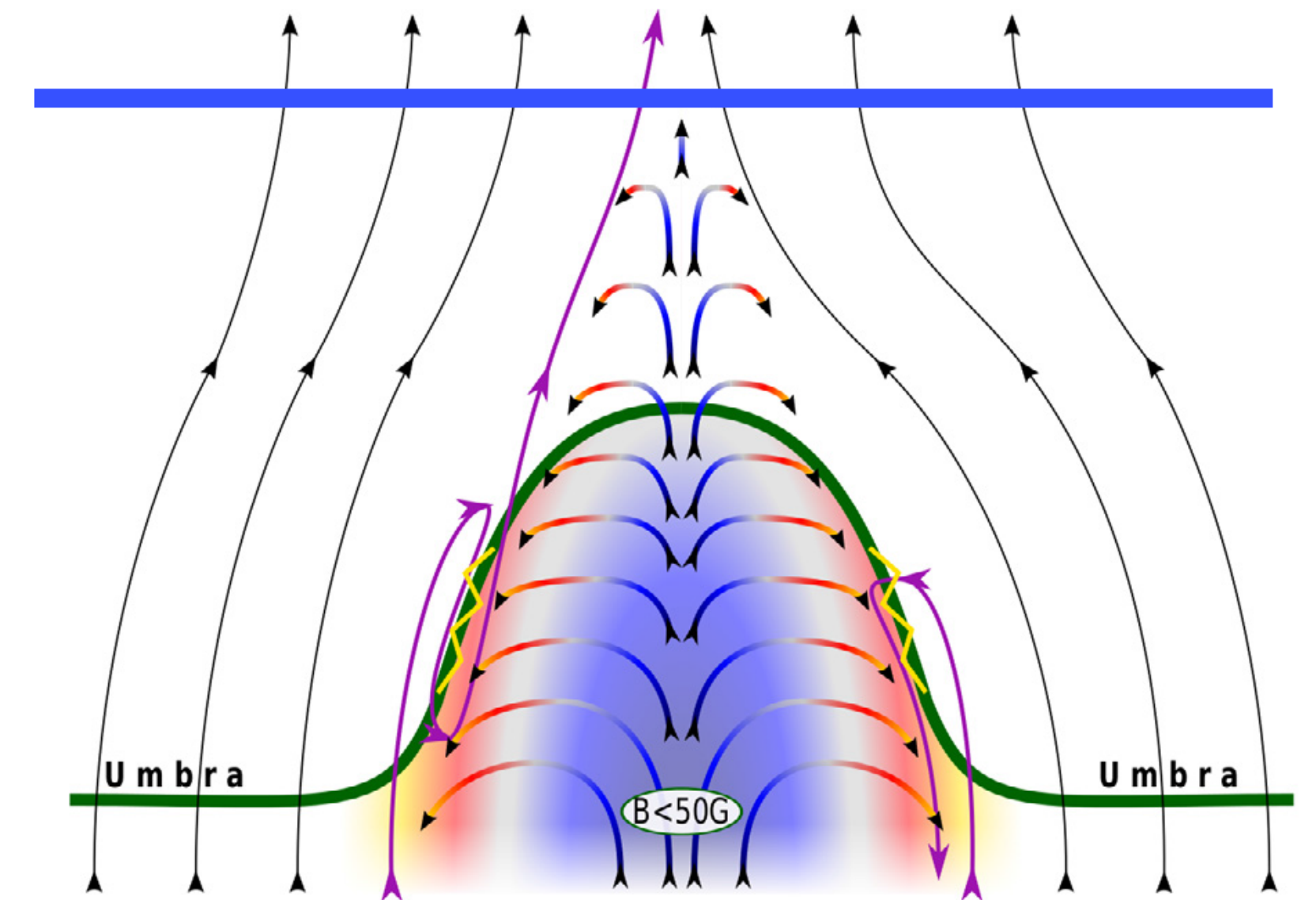
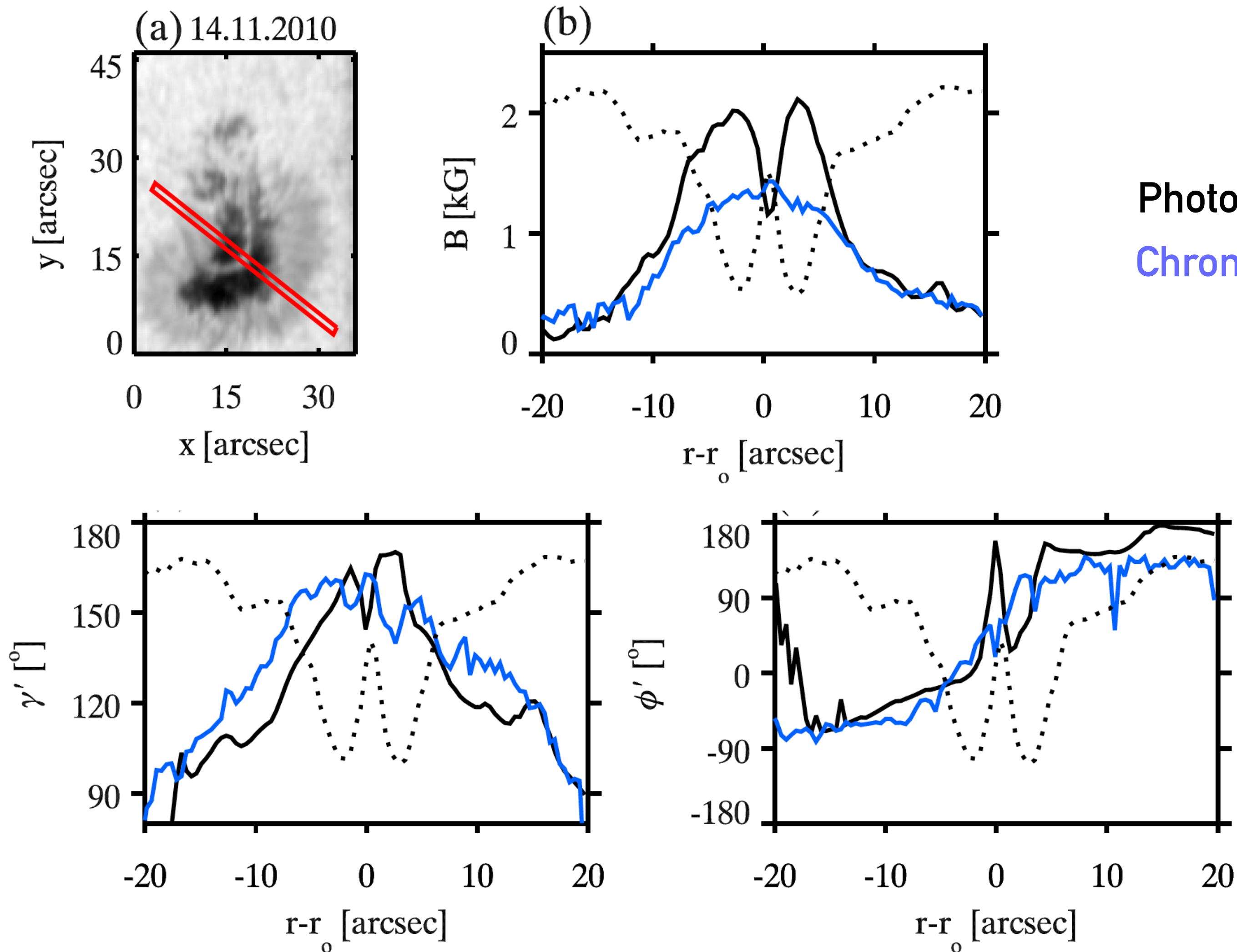


Magnetic field of sunspots: Chromosphere

He I 10830 Å

Joshi et al (2017)

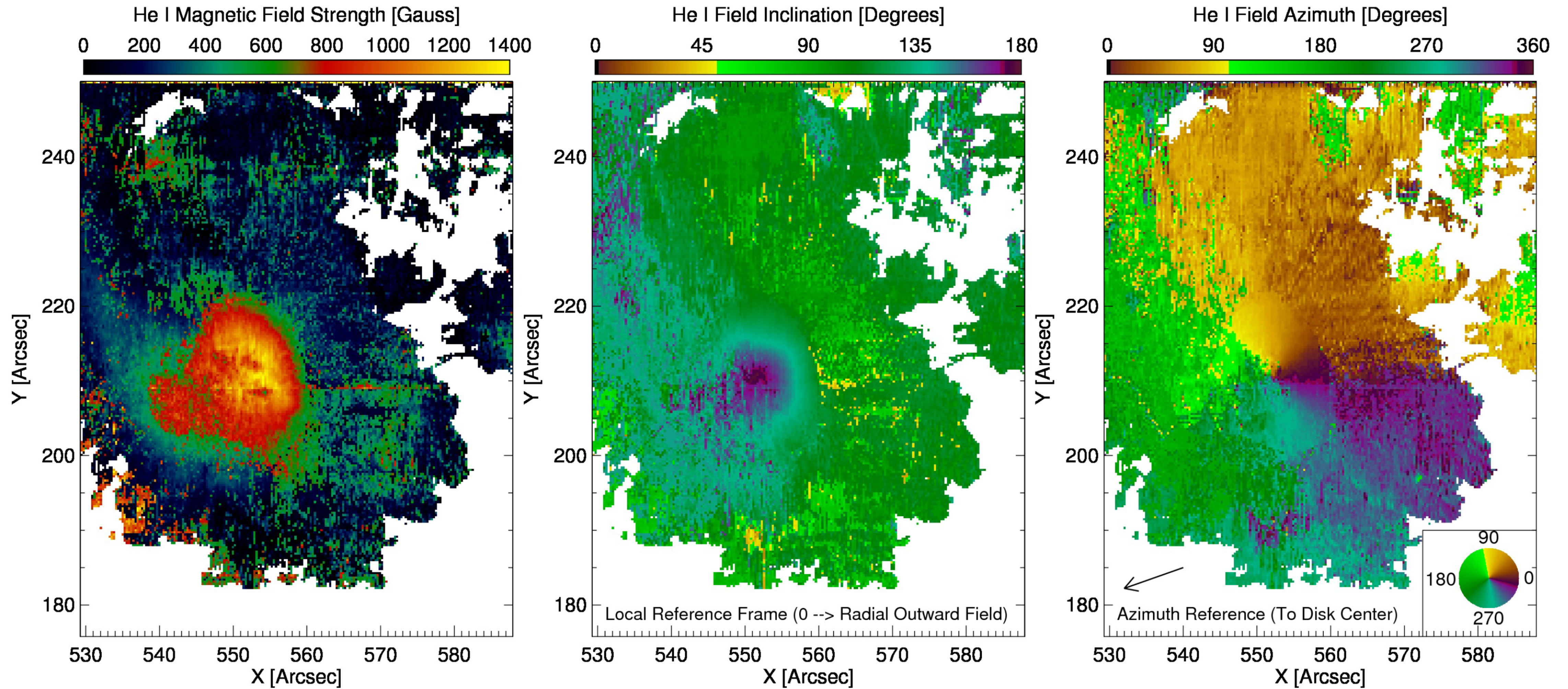
Structure of light-bridge



Magnetic field of sunspots: Chromosphere

He I 10830 Å
Zeeman+Hanle

Schad et al (2015)

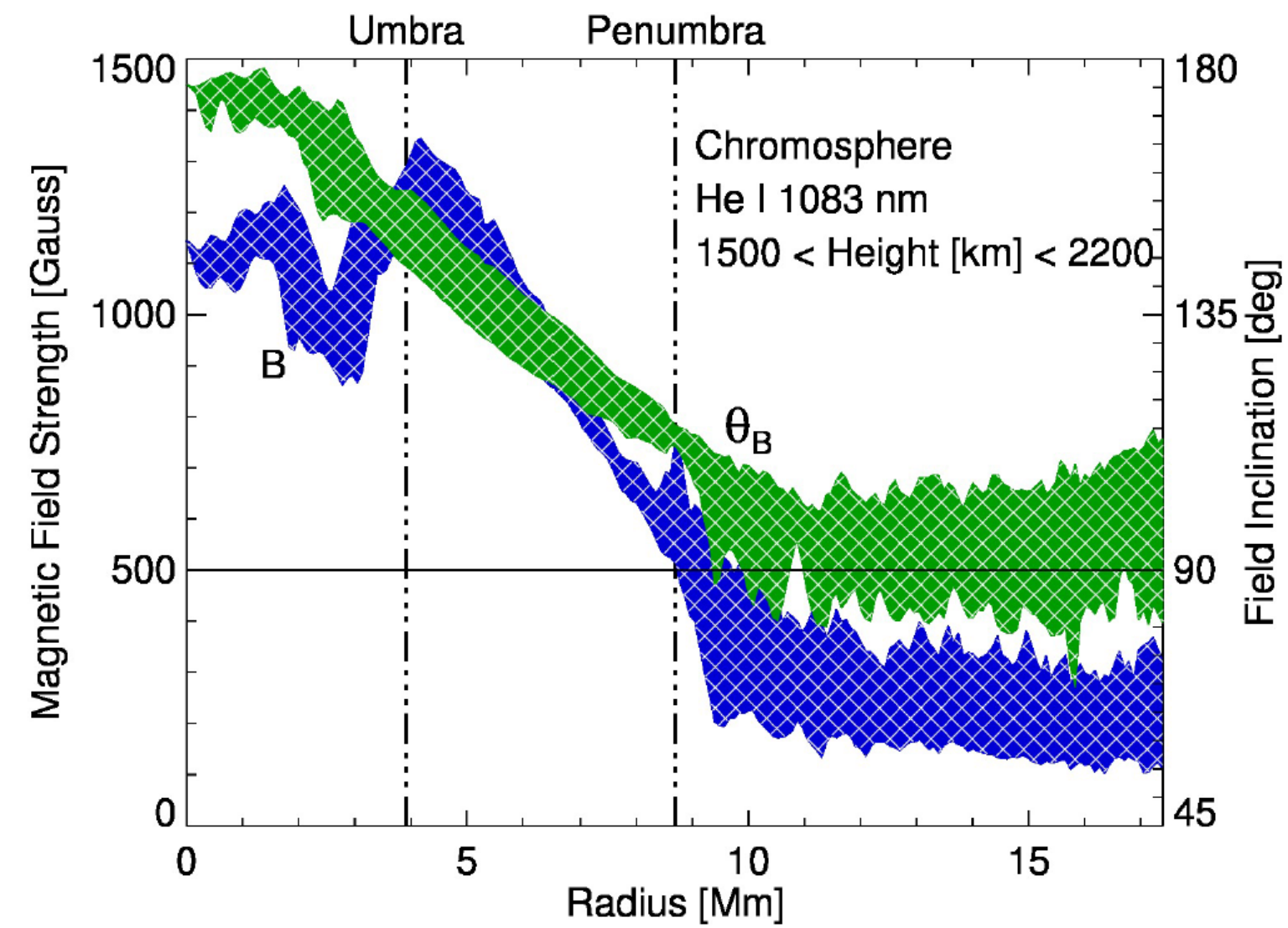
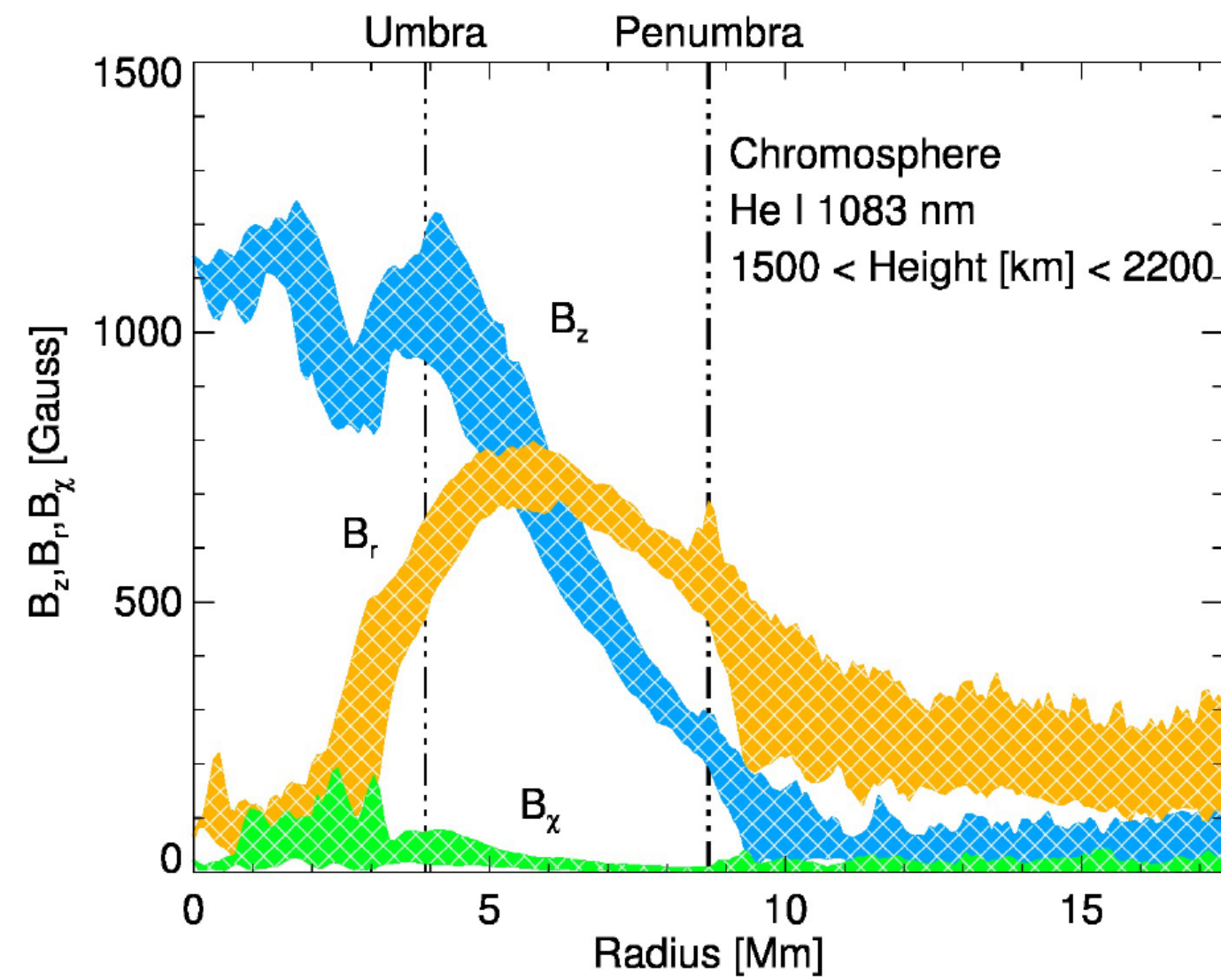


Magnetic field of sunspots: Chromosphere

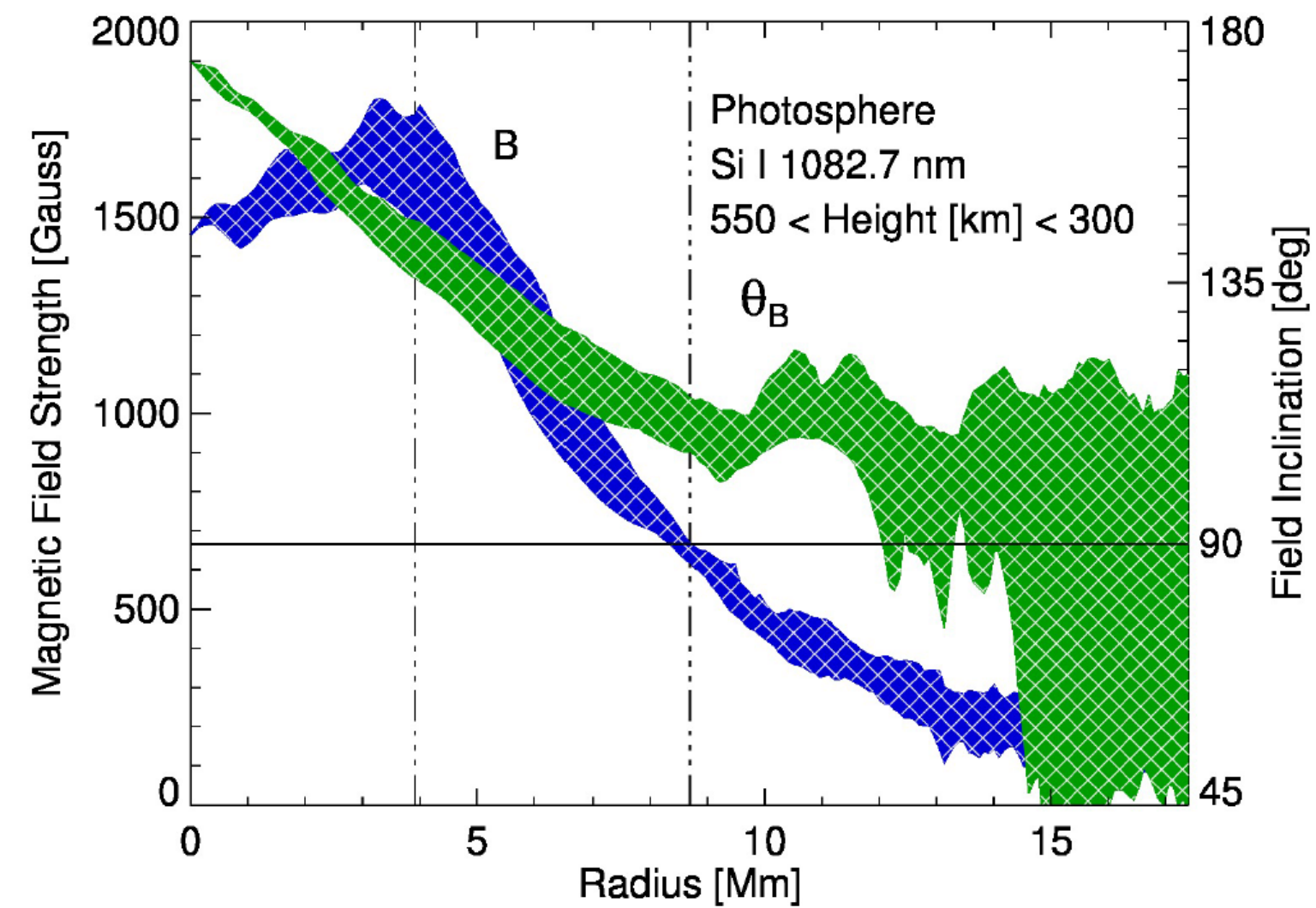
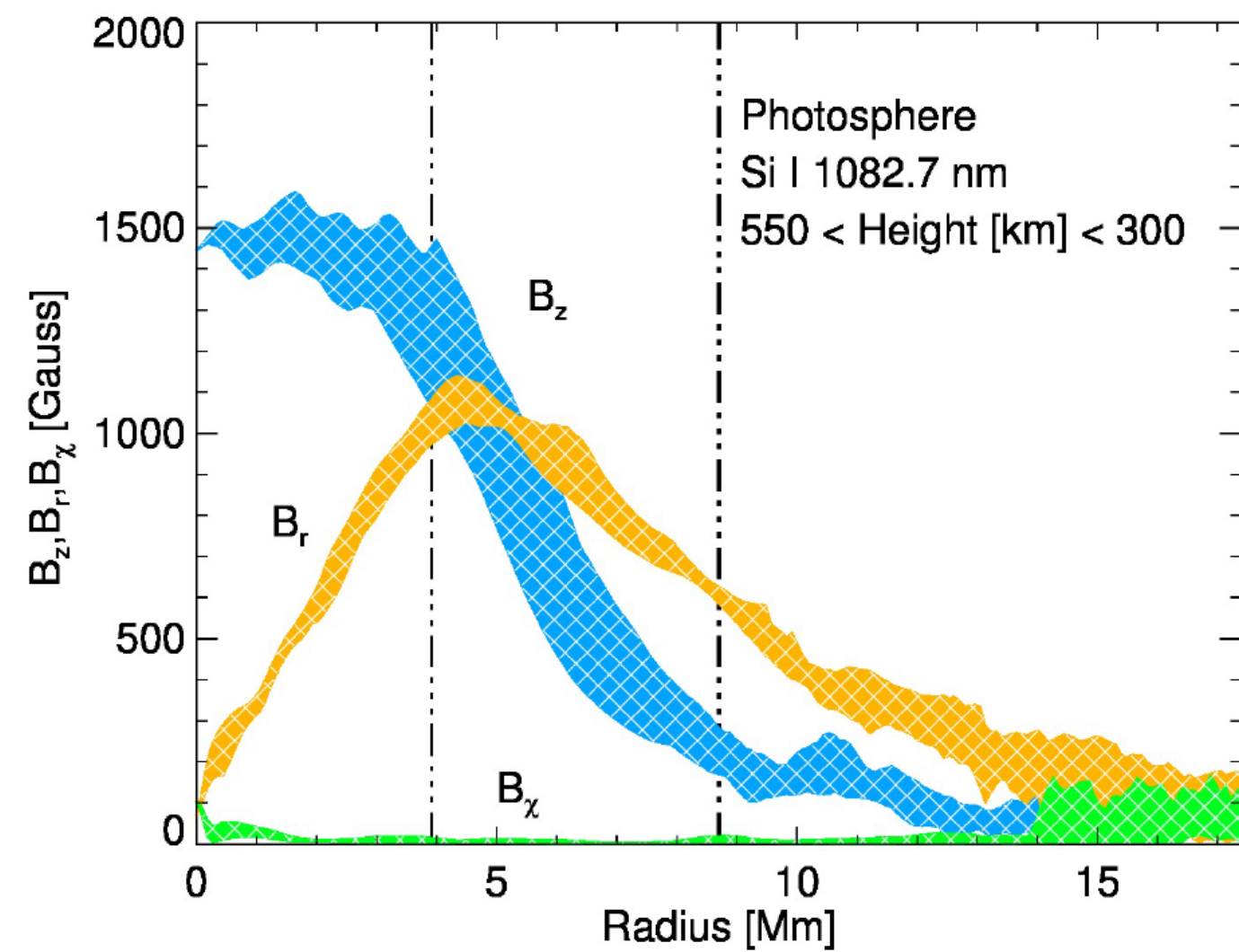
He I 10830 Å
Zeeman+Hanle

Schad et al (2015)

CHROMOSPHERE



PHOTOSPHERE

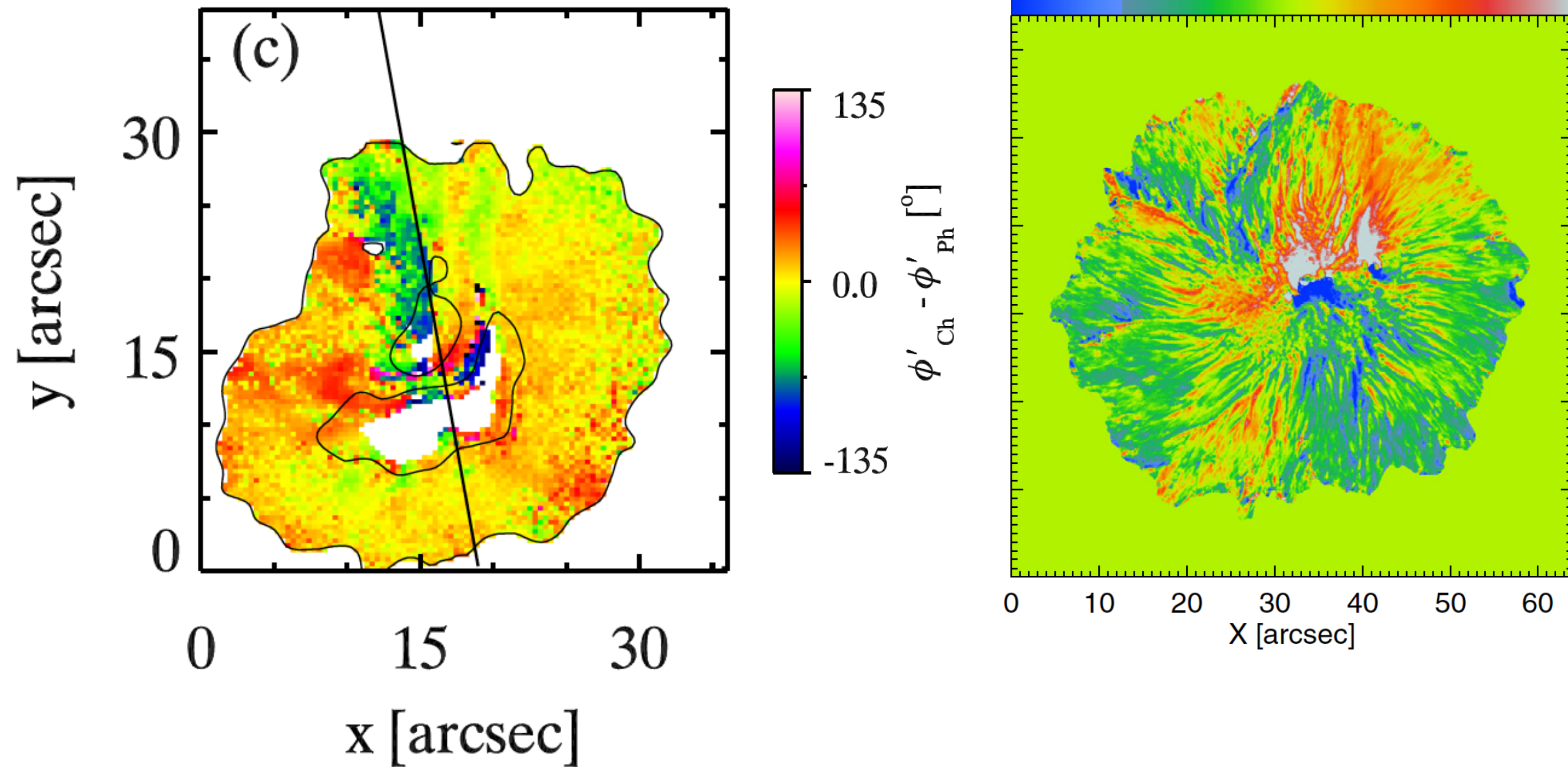


Magnetic field of sunspots: Chromosphere

He I 10830 Å

Twist

Joshi et al (2017)



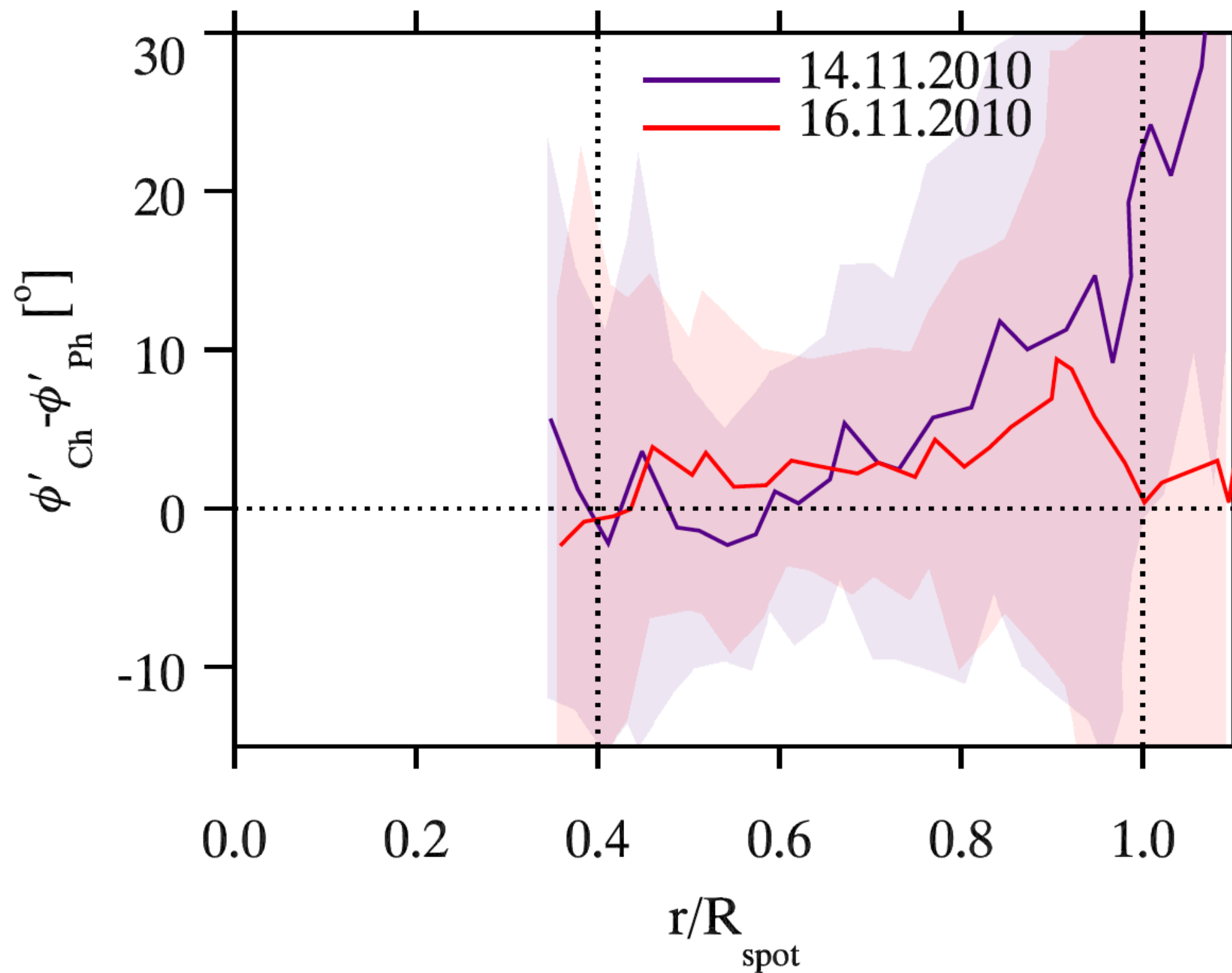
Magnetic field of sunspots: Chromosphere

He I 10830 Å

Twist

Radial variations

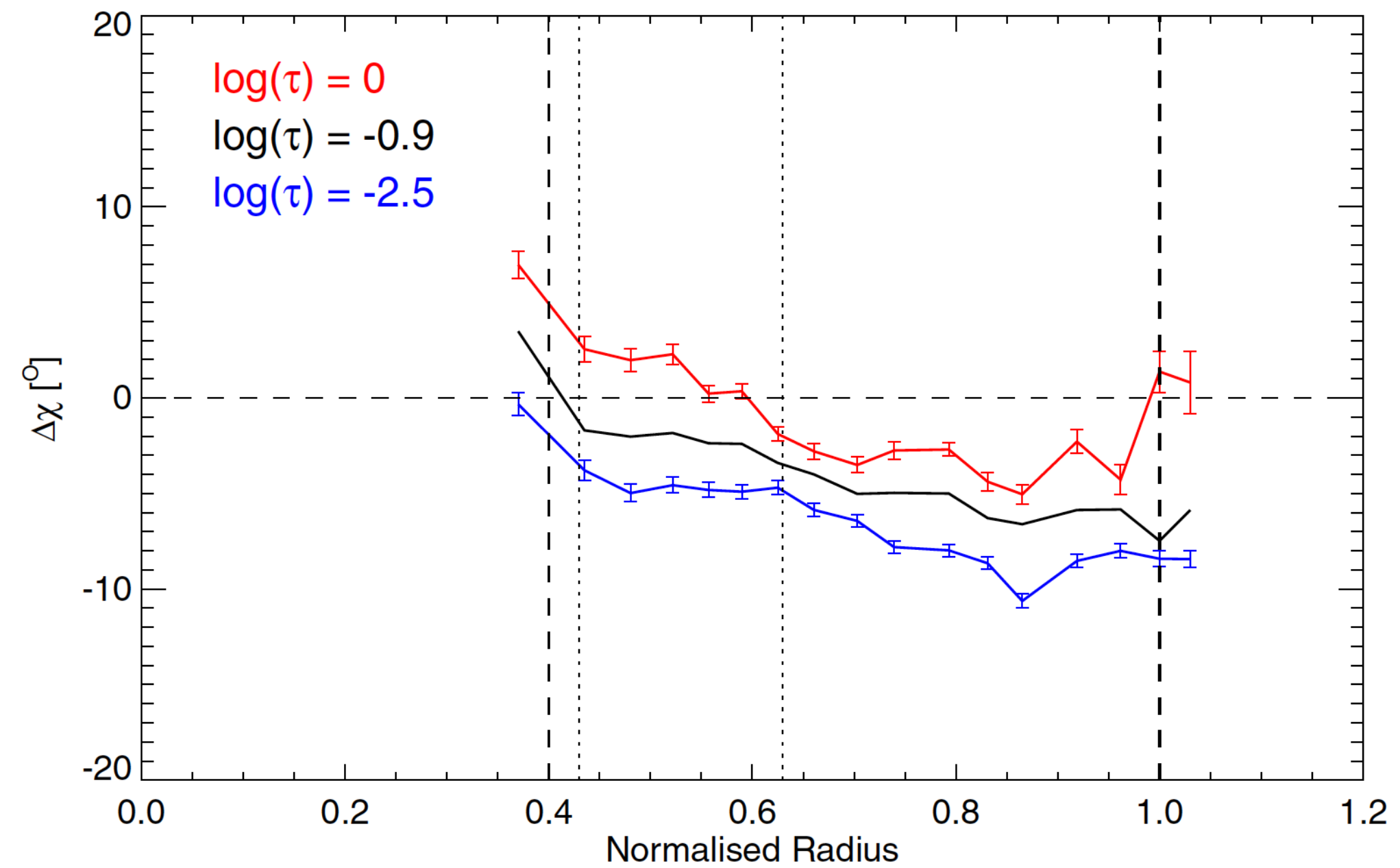
Joshi et al (2017)



Increase in the twist in outer penumbra

Coriolis force on radial flows + weaker field in outer penumbra, [Peter \(1996\)](#)

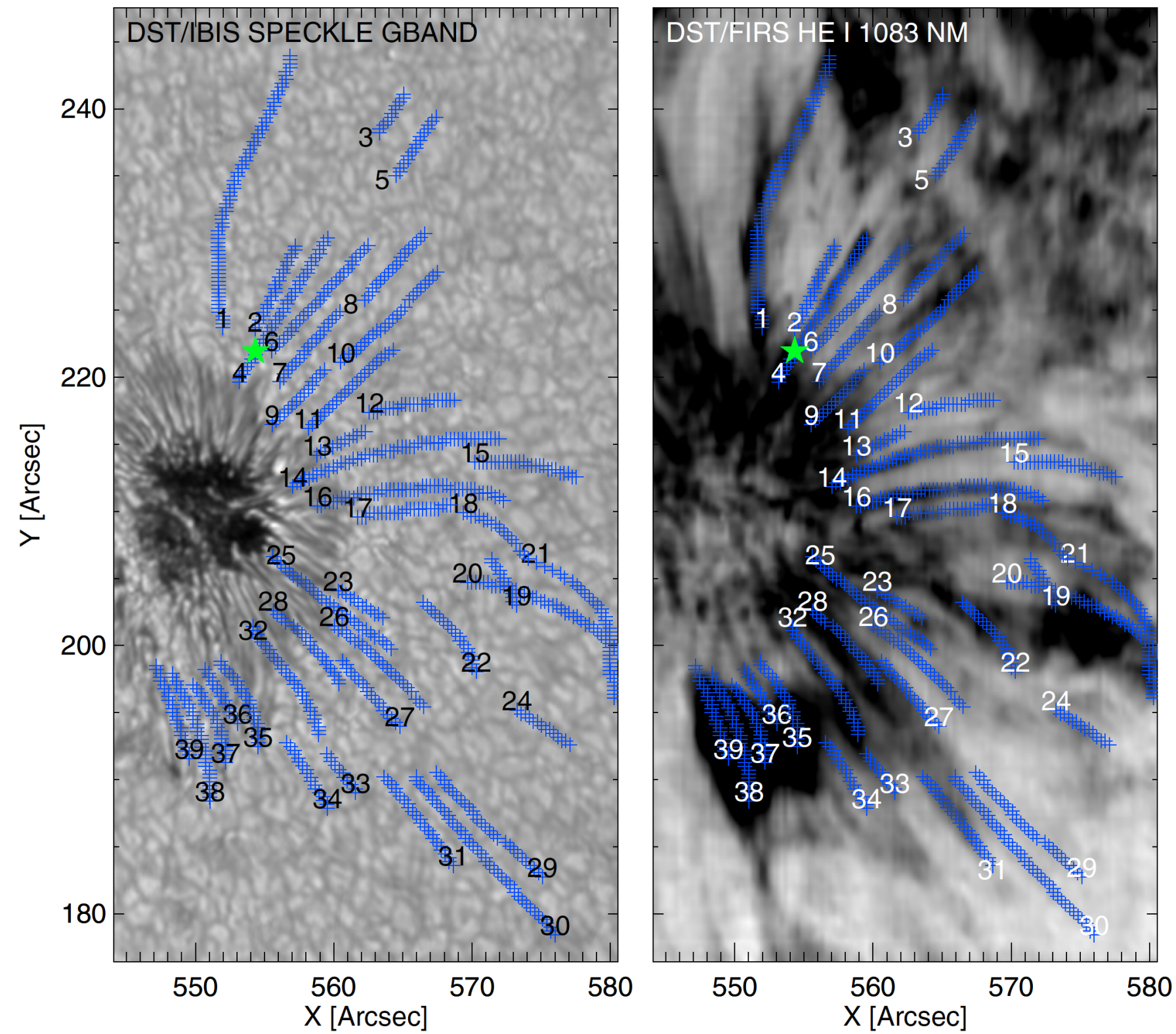
Tiwari (2015)



Magnetic field of sunspots: Chromosphere

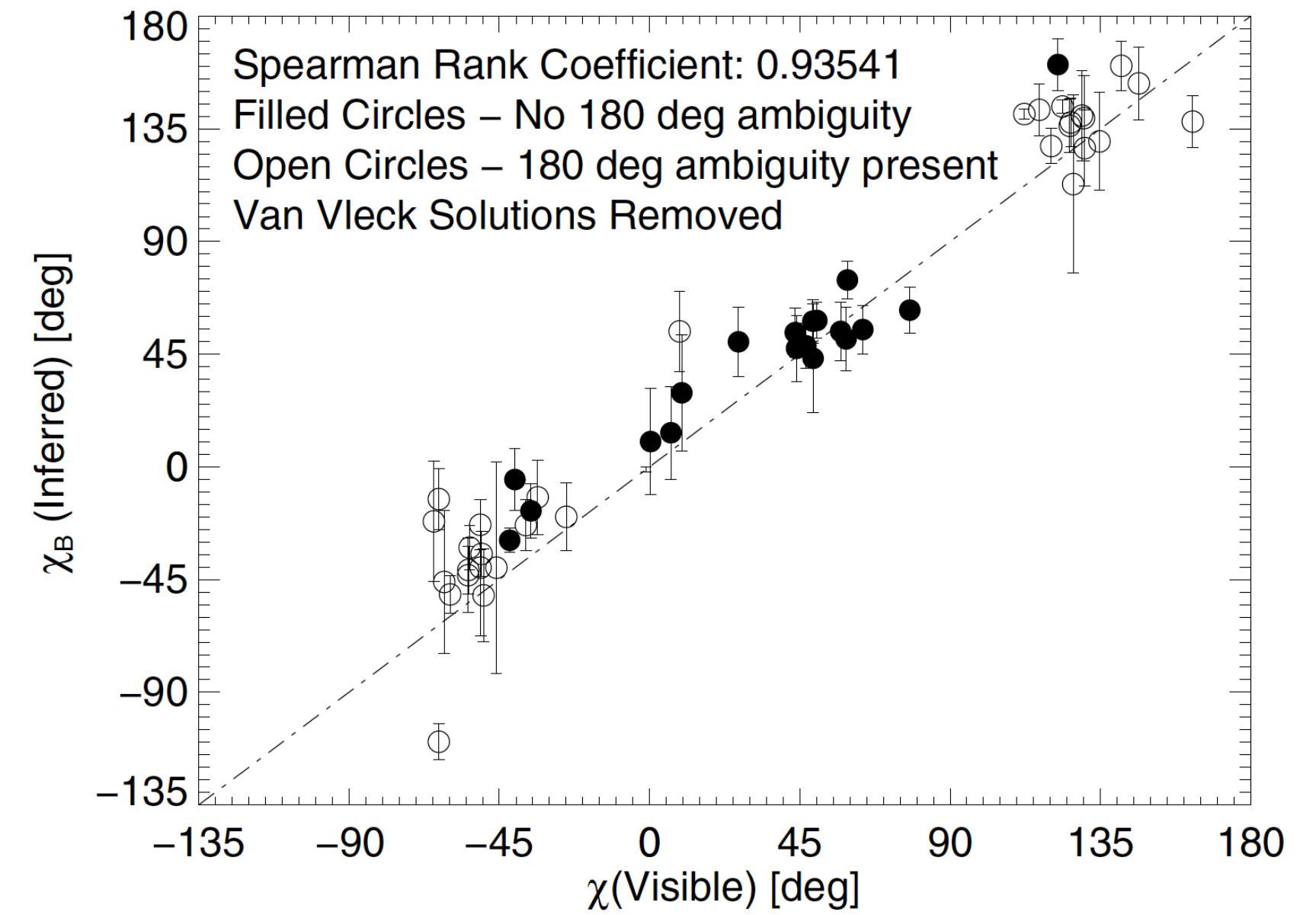
Magnetic field of fibrils/superpenumbra

Schad et al. (2013)



He I 1083.0 nm

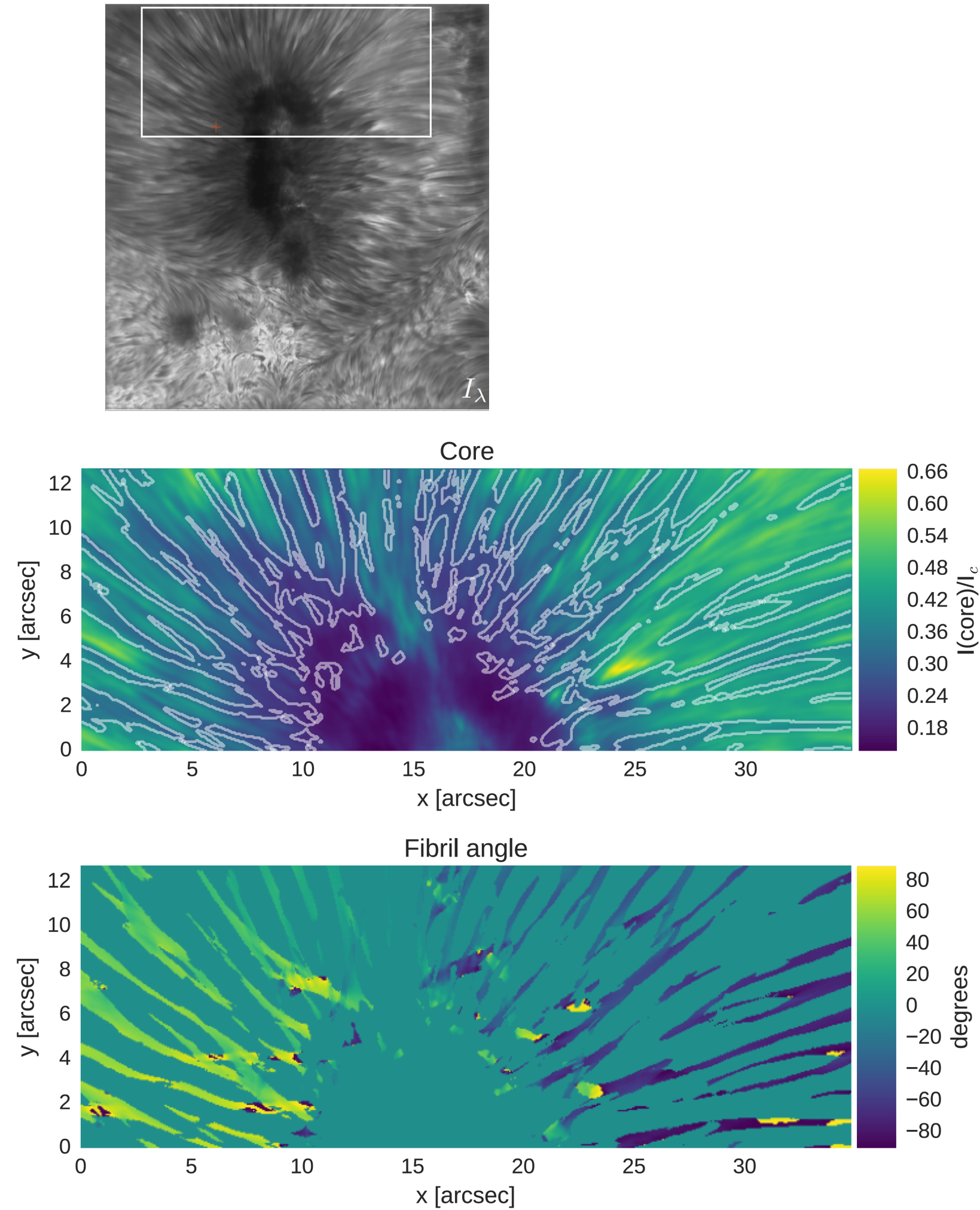
Orientation of magnetic field vs orientation of fibrils



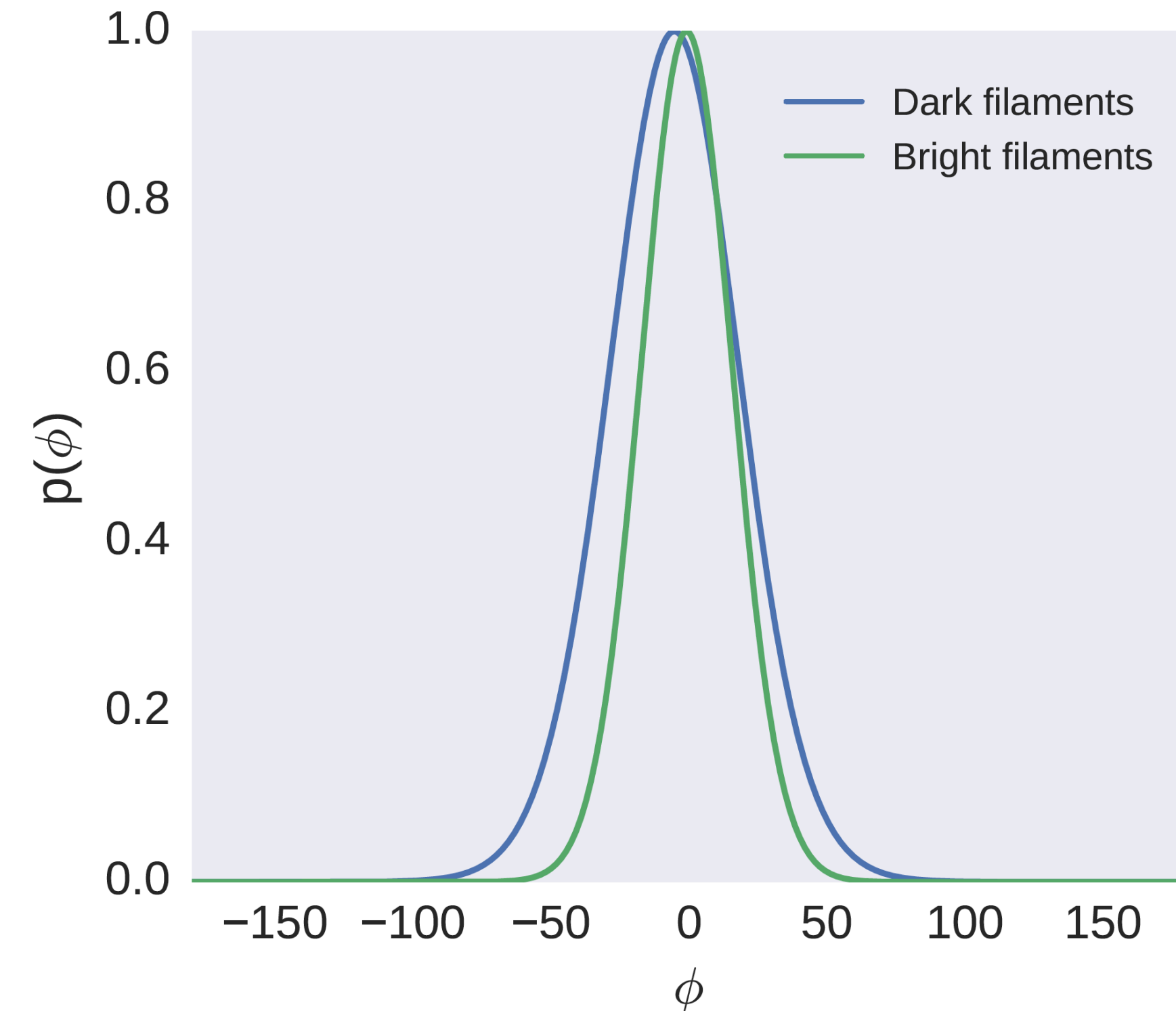
Magnetic field of sunspots: Chromosphere

Magnetic field of fibrils/superpenumbra

Asensio Ramos et al. (2017)



Bayesian hierarchical model



misalignment



Swedish 1-m Solar Telescope

Ca II 854.2 nm

ISSS L'Aquila, 11-15 April 2022

3D sunspot Structure

Outlook

Multi-line inversions to improve resolution in vertical direction

DKIST, Sunrise III

Transient dynamics and time varying stratified magnetic field

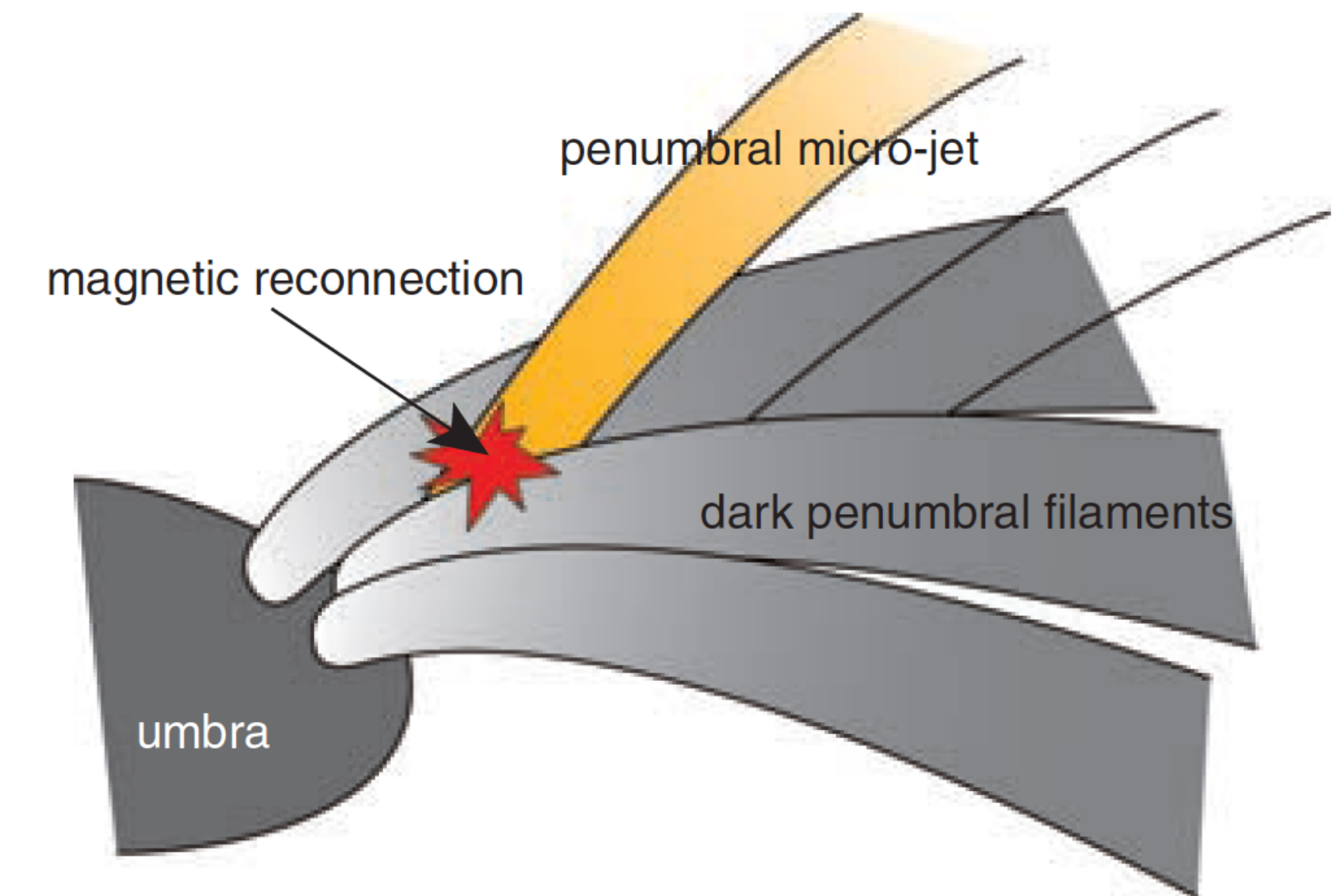
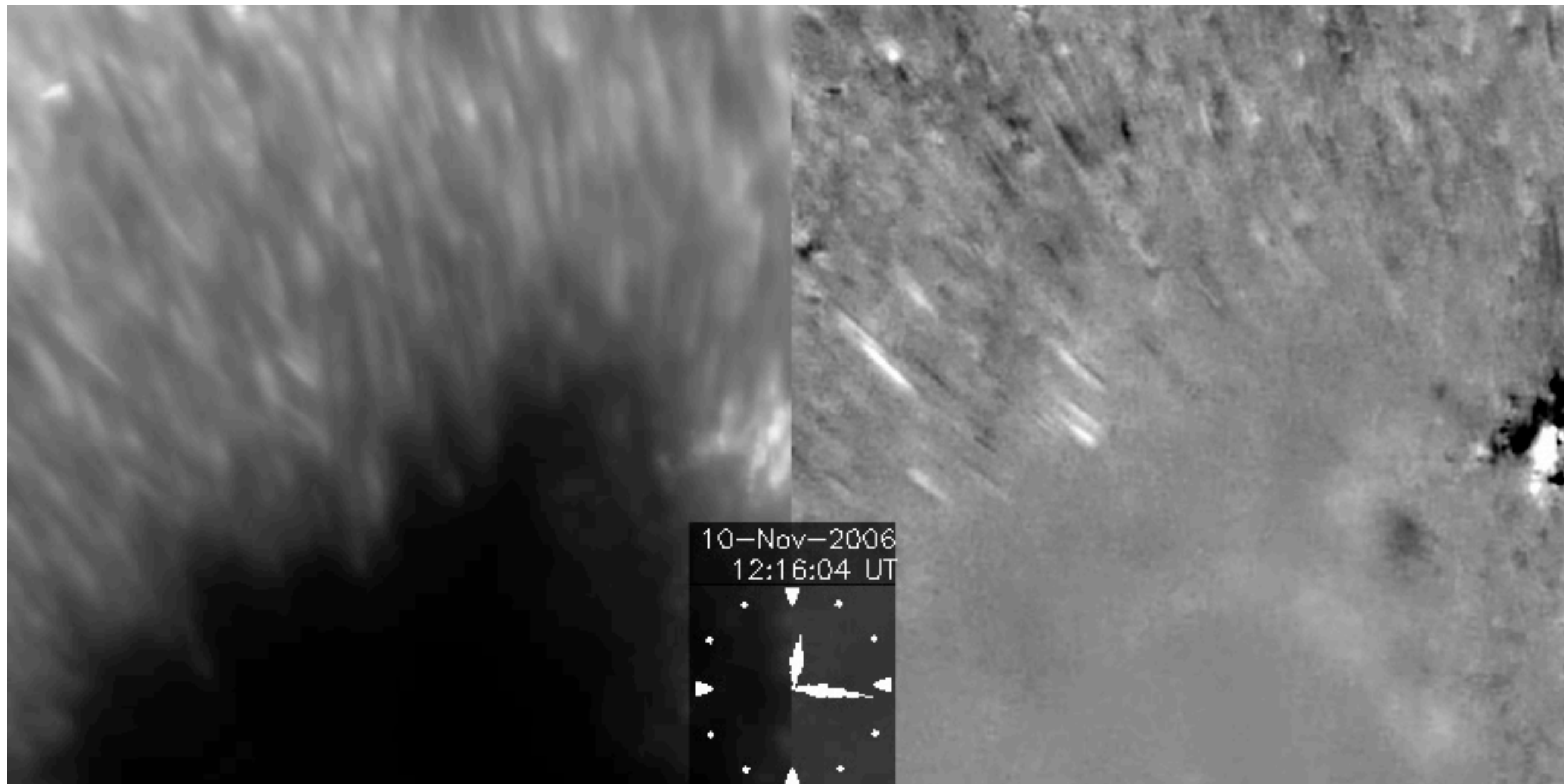
3D sunspot Structure

Outlook

Multi-line inversions to improve resolution in vertical direction

DKIST, Sunrise III

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3D sunspot Structure

Outlook

Multi-line inversions to improve resolution in vertical direction

[DKIST, Sunrise III](#)

Transient dynamics and time varying stratified magnetic field

Deep learning based inversions