Structure and properties of small-scale magnetic fields
Part II

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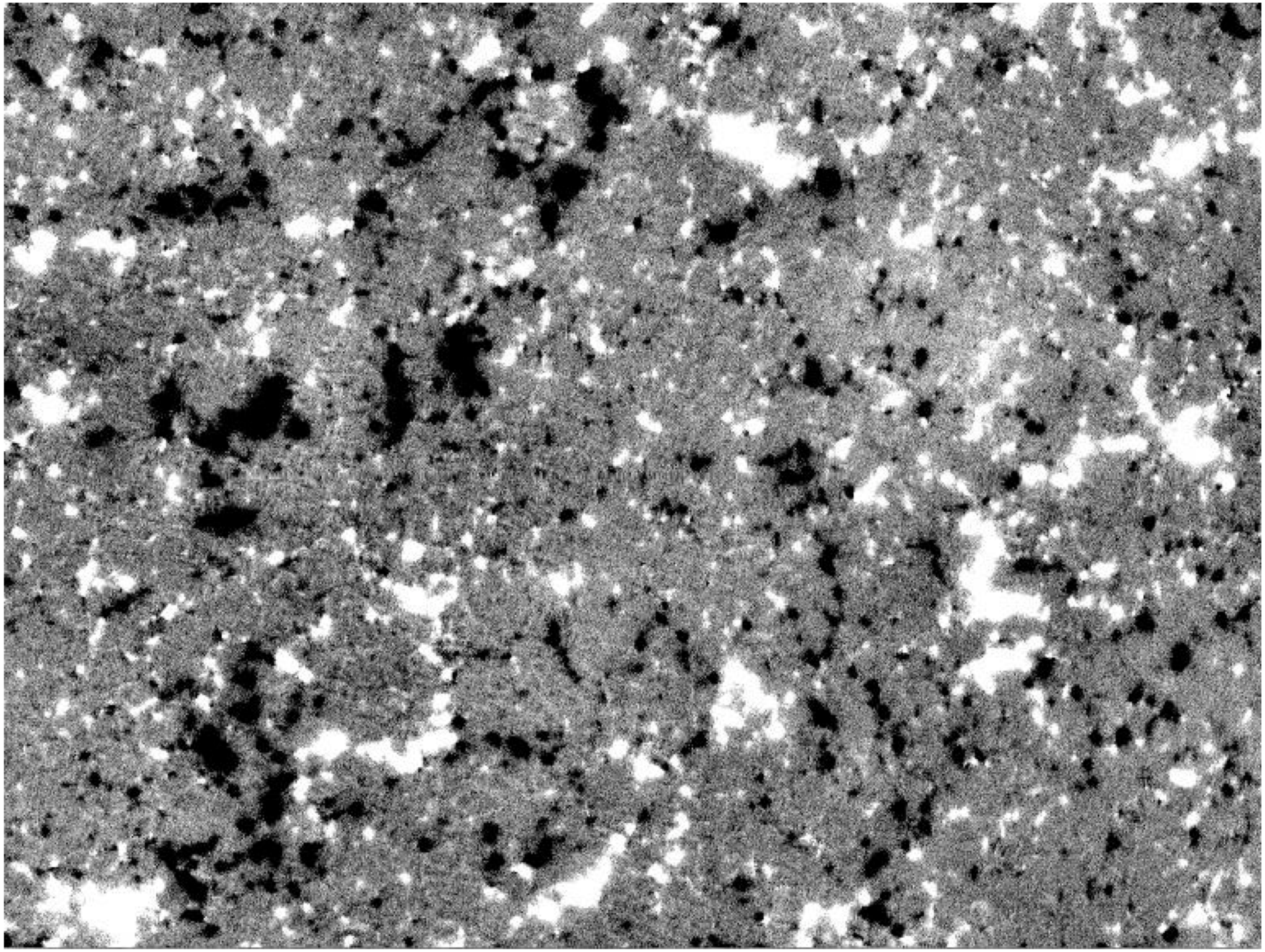
The solar internetwork

Hinode/NFI, 20 Jan 2010, FOV: 123" x 93”, cadence: 50 s

Gošić et al., 2014, ApJ, 797, 49



Small magnetic features in the interior of supergranular cells. They do not produce bright points.

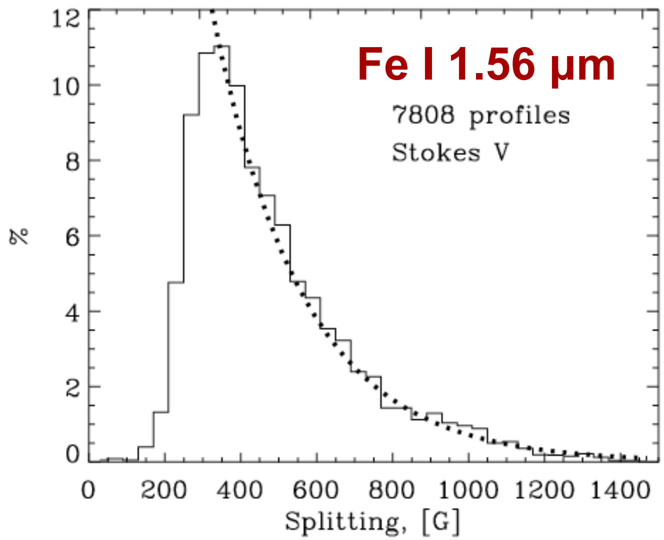
Magnetic properties of internetwork fields

- Difficult to infer because polarization signals are very weak
- Strongly affected by photon noise

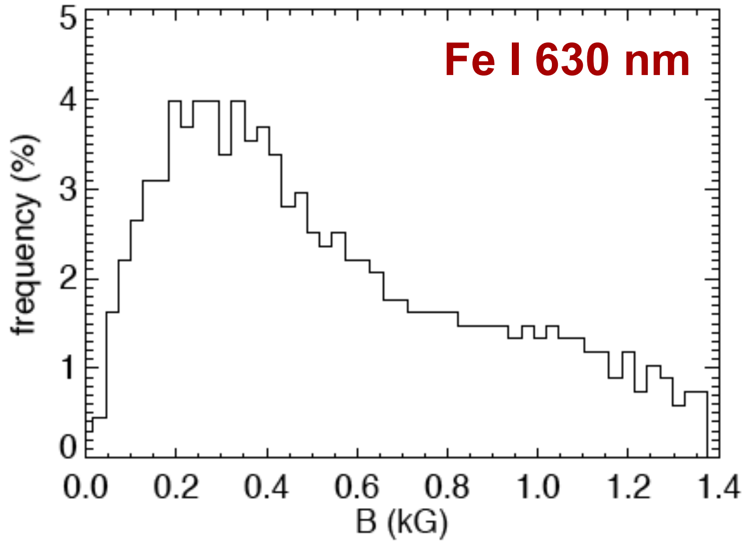
- Early determinations of the IN magnetic properties were based on spectropolarimetric measurements at low spatial resolution and different analysis techniques
  - Magnetic line ratios
  - Gaussian fits
  - MISMA inversions
  - SIR inversions
- No conclusive results
  - Near-IR lines: weak hG fields (e.g., Khomenko et al. 2003)
  - Visible lines: strong kG fields (e.g., Grossman-Doerth et al. 1996)
  - Very little information about field inclination

Field strengths from ground-based observations

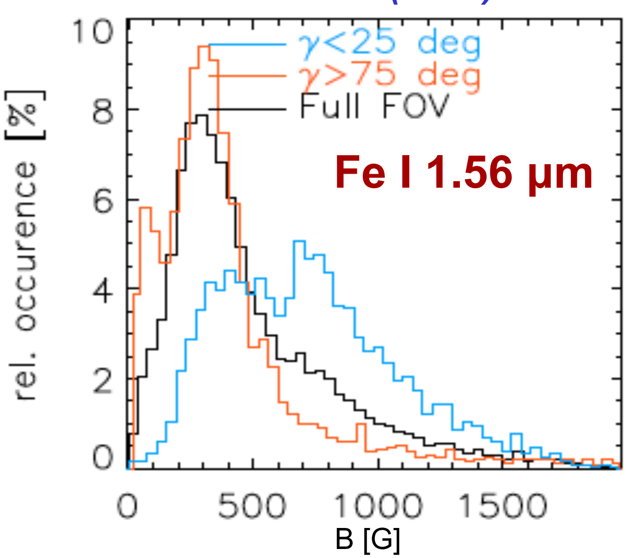
Khomenko et al. (2003)



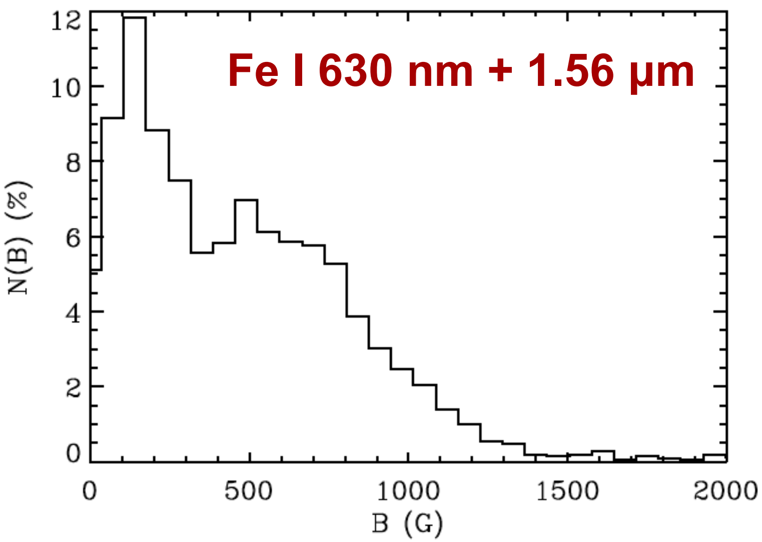
Rezaei et al. (2007)



Beck & Rezaei (2009)



Martínez González et al. (2008)



Magnetic properties of internetwork fields

- Difficult to infer because polarization signals are very weak
- Strongly affected by photon noise

- Early determinations of the IN magnetic properties were based on spectropolarimetric measurements at ~1" resolution
- No conclusive results
  - Near-IR lines: weak hG fields (e.g., Khomenko et al. 2003)
  - Visible lines: strong kG fields (e.g., Grossman-Doerth et al. 1996)
  - Very little information about field inclination

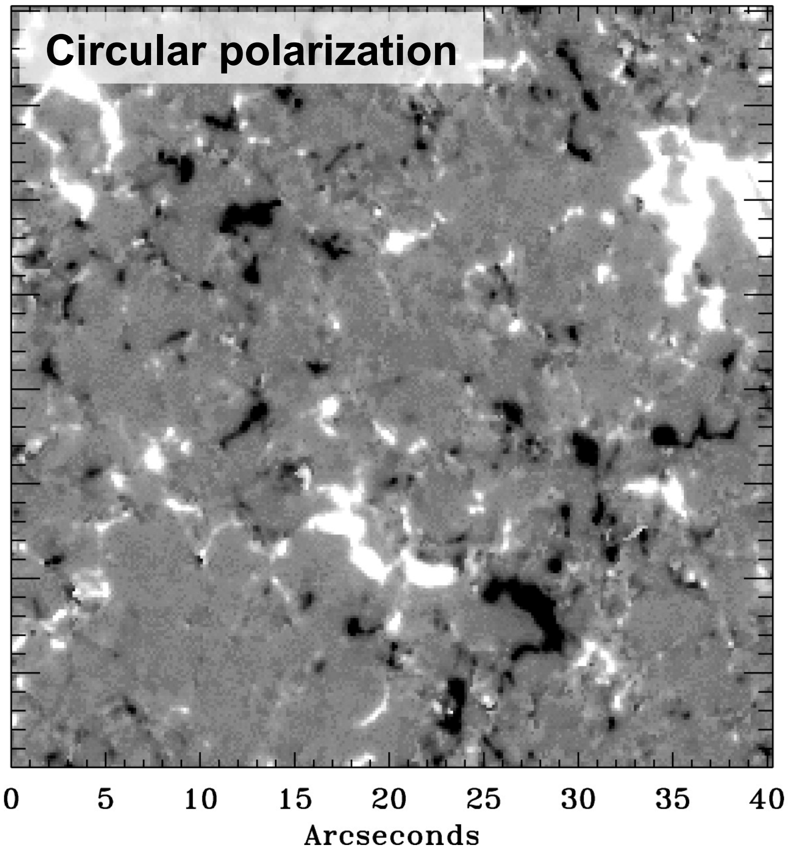
- Hinode revolutionized the field with spectropolarimetry from space at unprecedented spatial resolution and polarimetric sensitivity

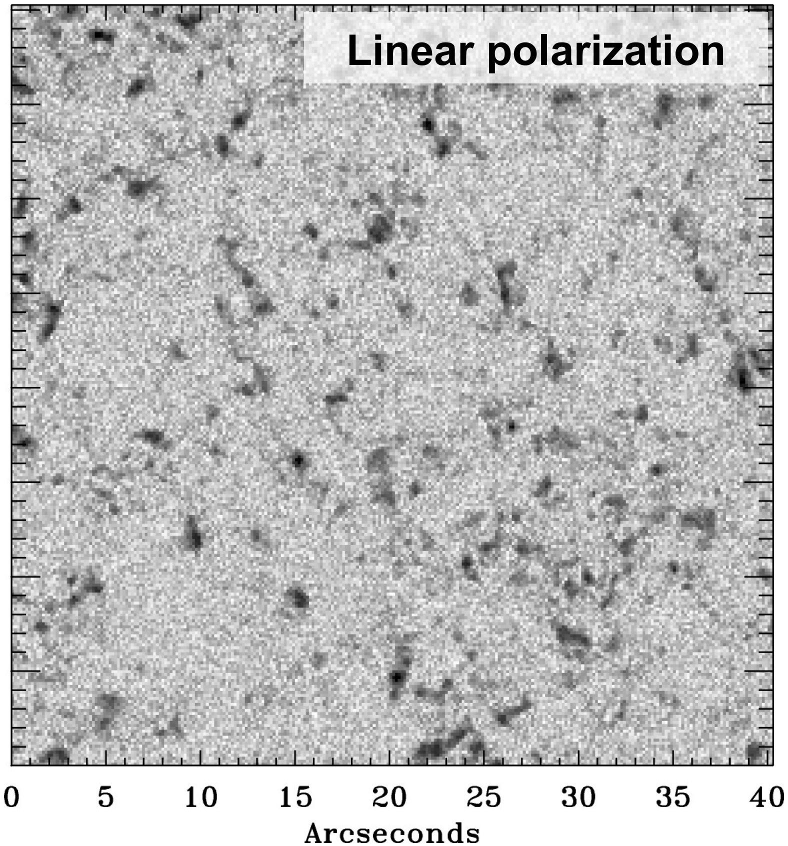
Polarization signals in the internetwork

Lites et al., 2008, ApJ, 672, 1237

Hinode/SP normal map
Noise level: 1.1 x 10^{-3} I_c

Horizontal flux density reported to be 5 times larger than vertical flux density (considering all pixels in FOV)





Inversion of Hinode/SP data at high resolution

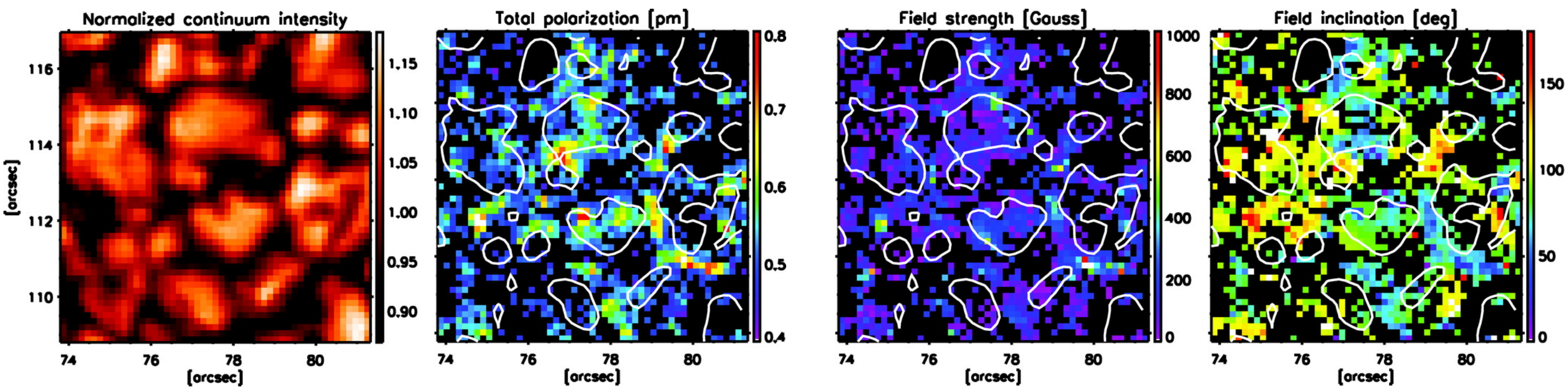
- Milne-Eddington atmospheres
  - Source function is linear with optical depth
  - Magnetic field vector/LOS velocity are constant with optical depth
- Simple model
  - High spatial resolution data, so one magnetic atmosphere in the pixel
- Accounting for telescope diffraction
  - Local stray-light profile (Orozco Suárez et al. 2008)
- Only pixels with Q, U or V above 4.5 times the noise level

- All four Stokes parameters fitted simultaneously
- Consistent inference of vector magnetic fields
- Avoids problems associated with classical inferences
- But: cannot reproduce asymmetric profiles

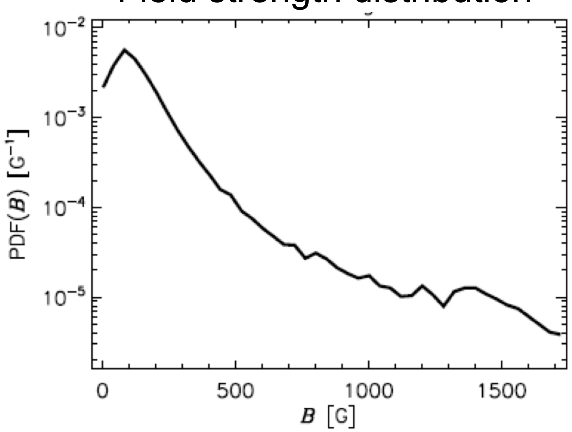
Magnetic properties of internetwork fields

Orozco Suárez et al., 2007, ApJ, 670, L61

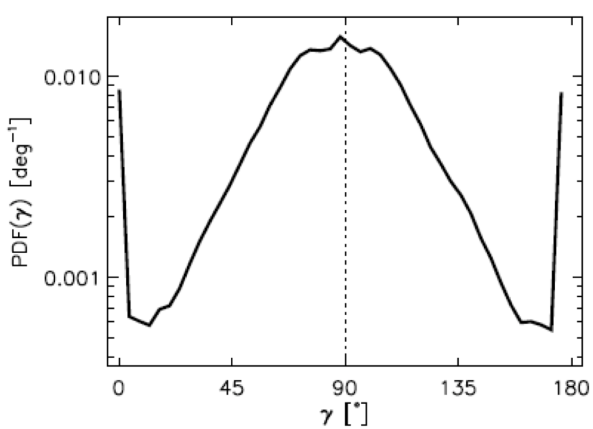
Hinode/SP normal map + ME inversion (~600 000 individual pixels)



Field strength distribution



Inclination distribution

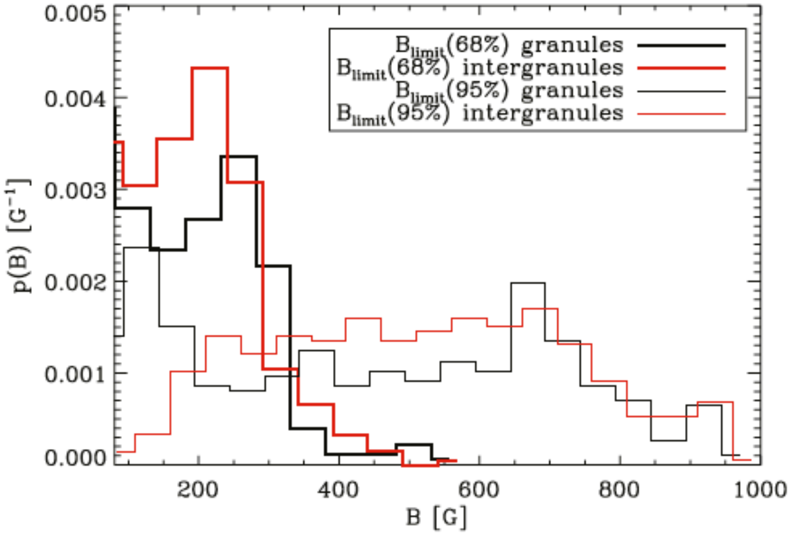


Internetwork fields are *weak and highly inclined*
(peaks at ~100 G and 90°)

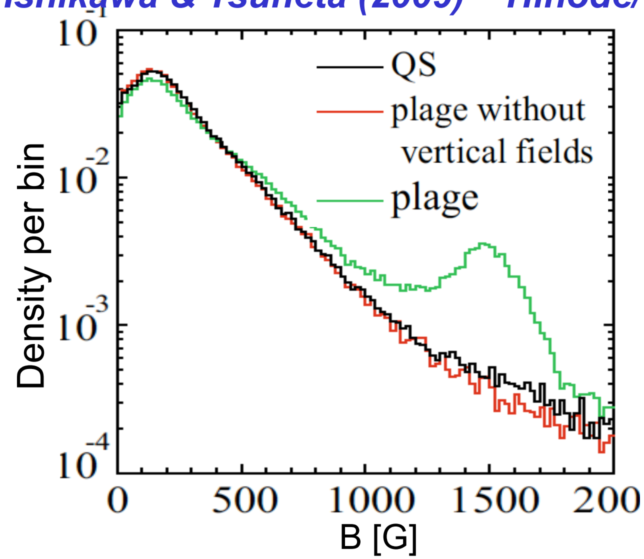
Confirmed by, e.g., Martínez González et al. (2008), Ishikawa & Tsuneta (2009), Beck & Rezaei (2009), Asensio Ramos & Martínez Gonzalez (2014)

Magnetic properties of internetwork fields

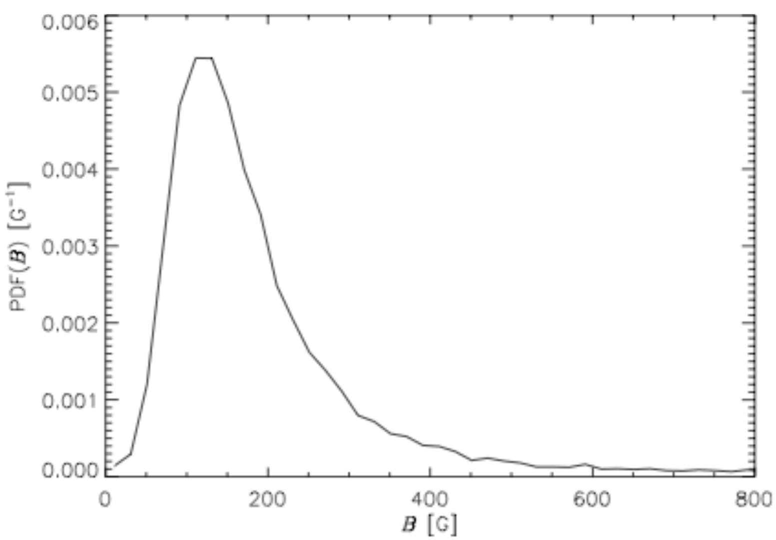
Asensio Ramos (2009) – Hinode/SP



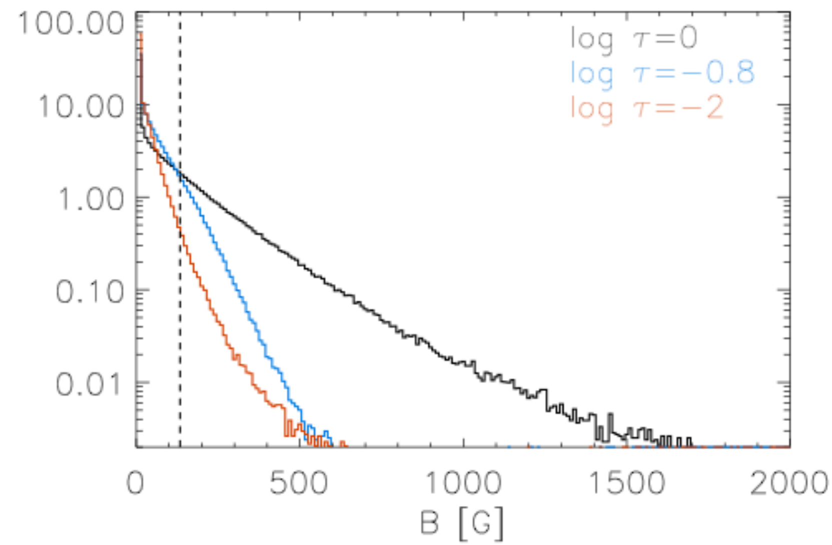
Ishikawa & Tsuneta (2009) – Hinode/SP



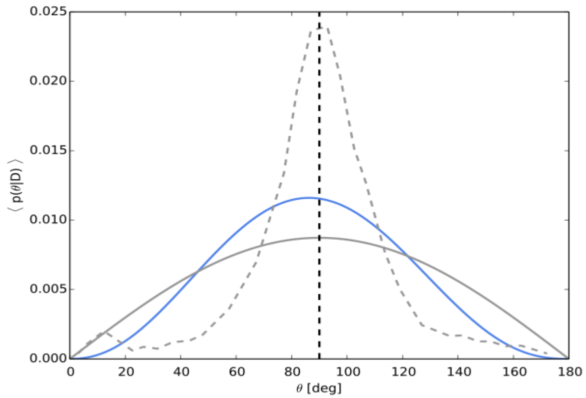
Bellot Rubio et al. (2012) – Hinode/SP



Danilovic et al. (2016) – Hinode/SP

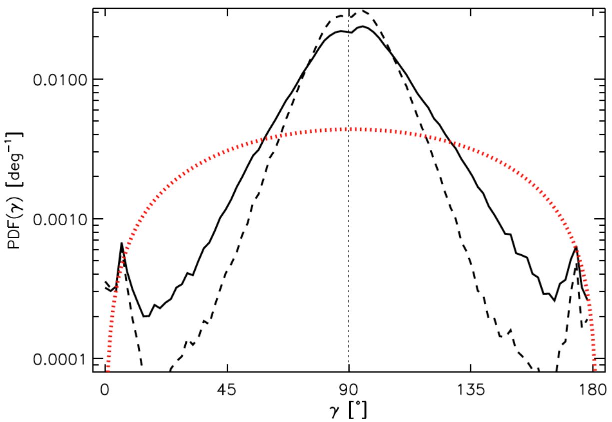


Magnetic properties of internetwork fields



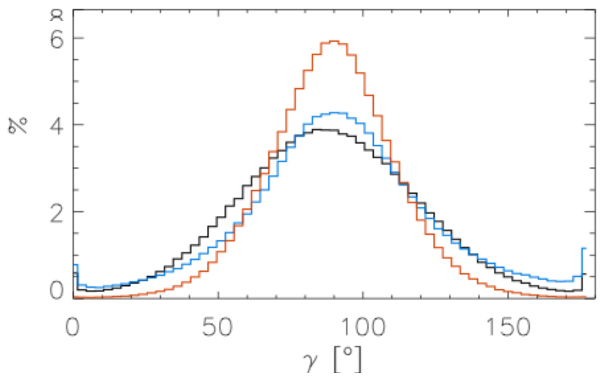
Asensio Ramos et al (2014) – PROBABLY ISOTROPIC

Blue: Hierarchical analysis of SP normal map
Dashed: ME inversion by *Bellot Rubio et al. (2012)*
Solid: isotropic distribution



Orozco Suárez et al. (2007, 2012) – PROBABLY NOT ISOTROPIC

Solid: ME inversion of SP normal map
Dashed: ME inversion of high SNR map
Dotted: isotropic distribution



Danilovic et al (2016) – PROBABLY NOT ISOTROPIC

Black: 2D inversion of SP normal map, log tau=0
Blue: log tau= -0.8
Red: log tau= -2.0

Magnetic properties of internetwork fields

- What is the exact shape of the inclination distribution?
- Noise in Stokes Q and U artificially increases field inclination (e.g., Borrero & Kobel 2011)

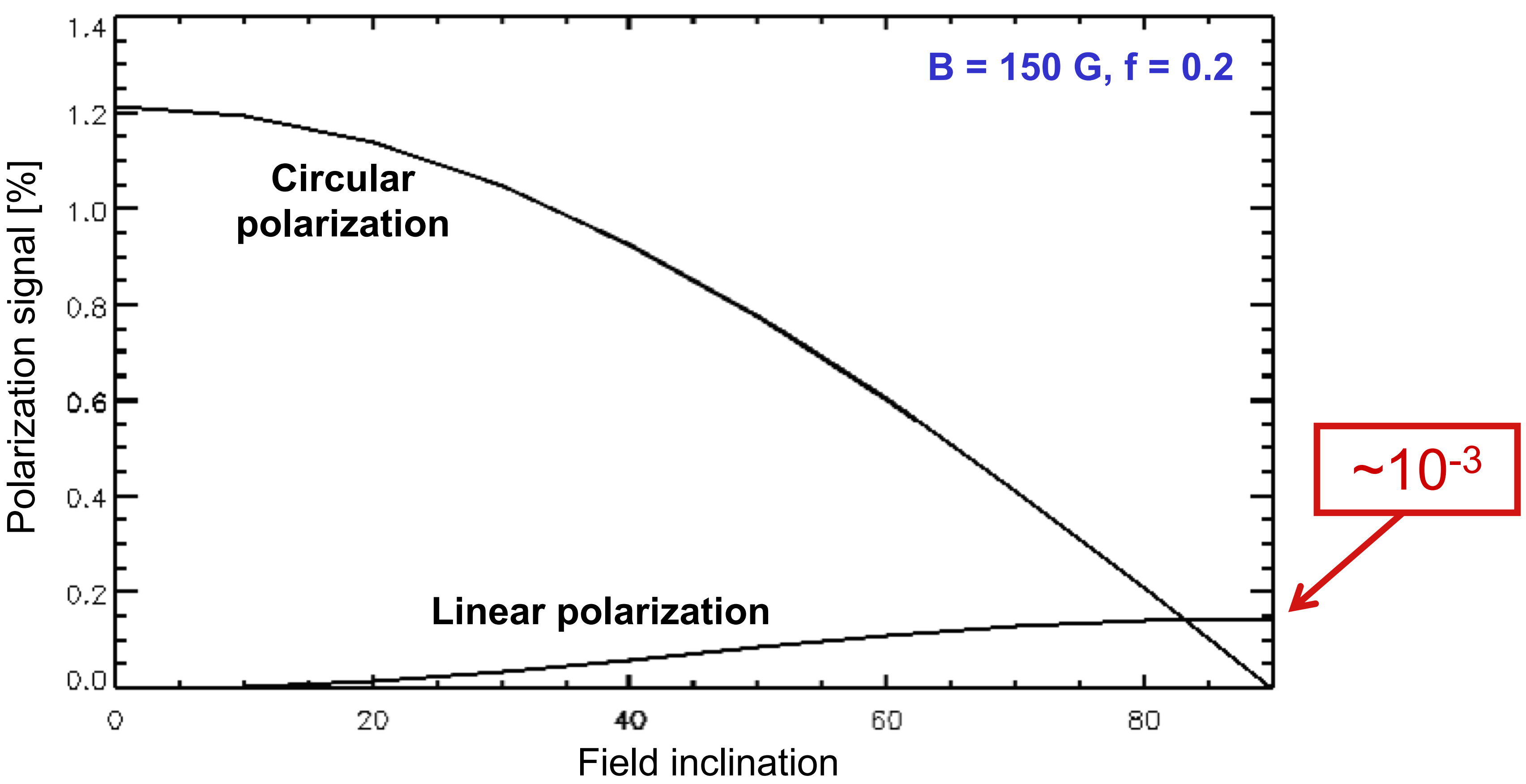
- Only a small fraction of the pixels in Hinode/SP normal maps show polarization signals well above the noise level
  - 26.0% have Stokes V amplitudes larger than 4.5 σ
  - 2.1% have Stokes Q or U amplitudes larger than 4.5 σ

- It is essential to include linear polarization signals to constrain the field inclination and therefore the vector magnetic field

Why don't we see linear polarization everywhere?

$$V \propto f\, B \cos\gamma$$

$$Q,U \propto f\, B^2 \sin^2\gamma$$



Goal: reduce noise

Lites et al., 2008, ApJ, 672, 1237

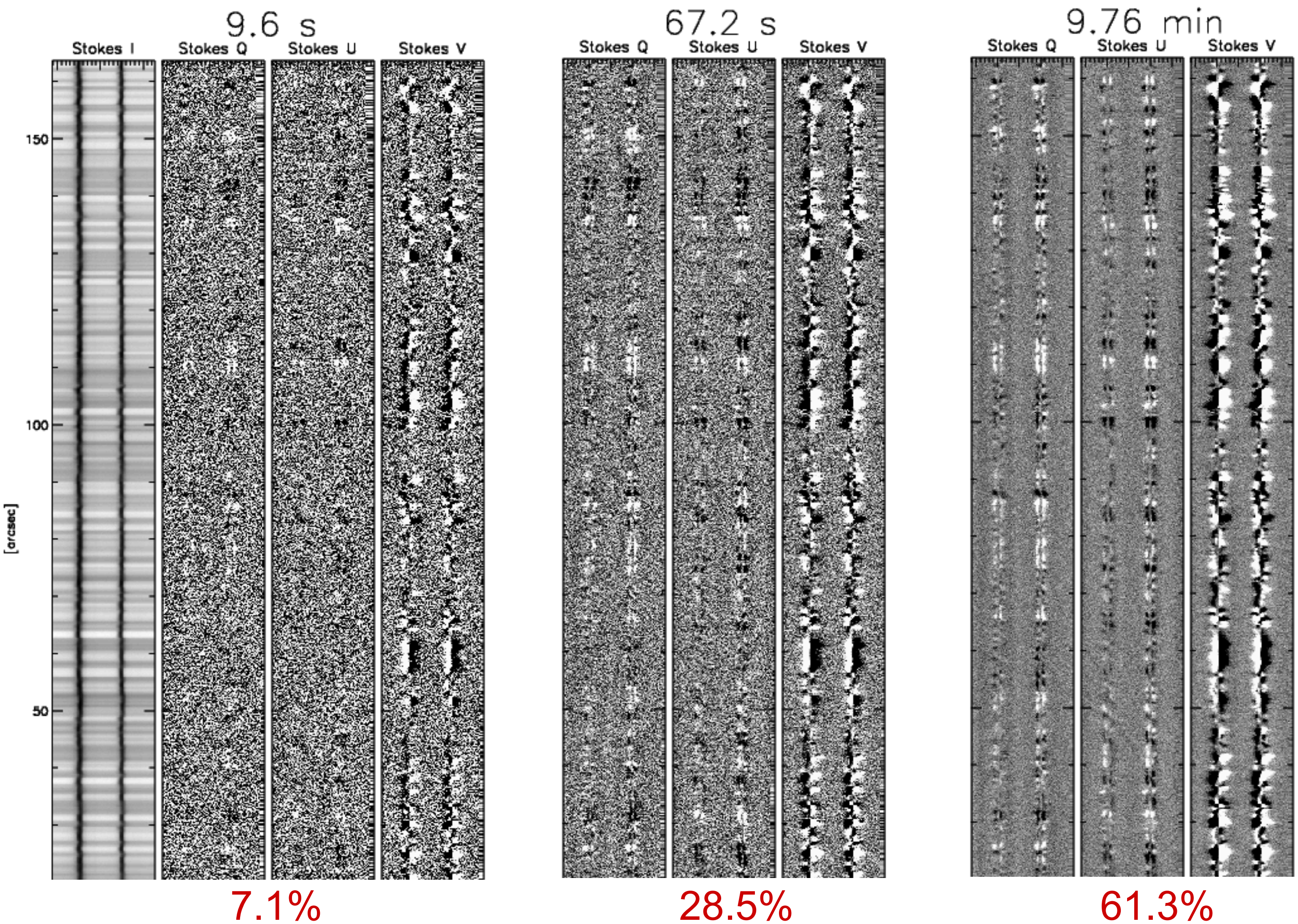
Hinode/SP **deep-mode observations**
Integration time: 9.6 s

February 27, 2007
Fixed slit position at disk center
Time sequence duration: 1 hr 51 min

Effective integration time of 67.9 s achieved by adding 7 consecutive slits

Pushing the polarimetric sensitivity to a limit

Bellot Rubio & Orozco Suárez, 2012, ApJ, 757, 19

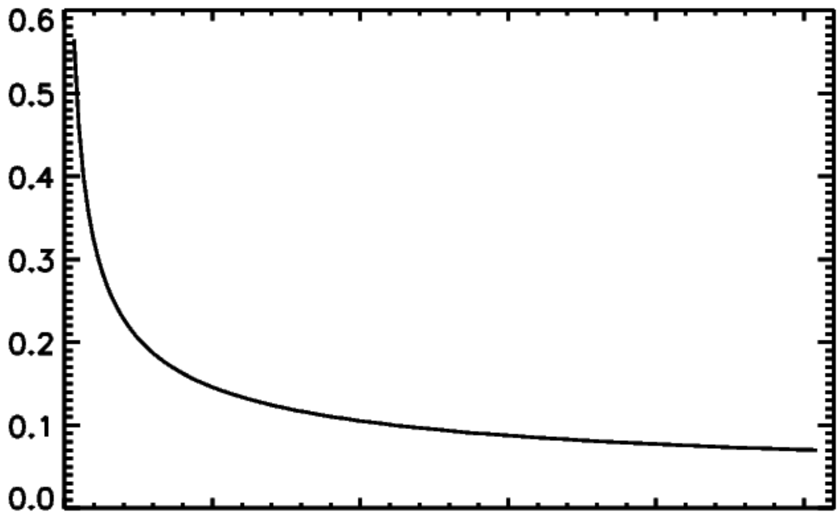


Fraction of pixels with linear signals vs integration time in Hinode/SP sit-and-stare observations

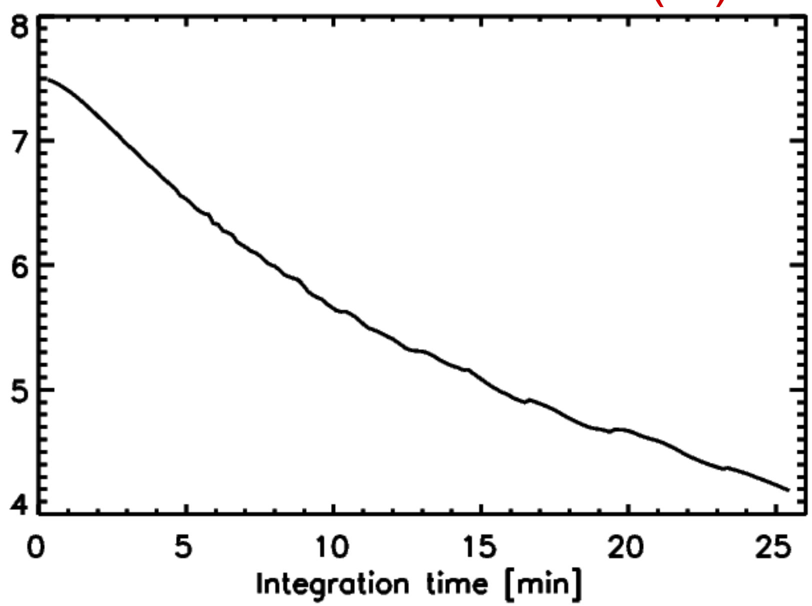
Pushing the polarimetric sensitivity to a limit

Bellot Rubio & Orozco Suárez, 2012, ApJ, 757, 19

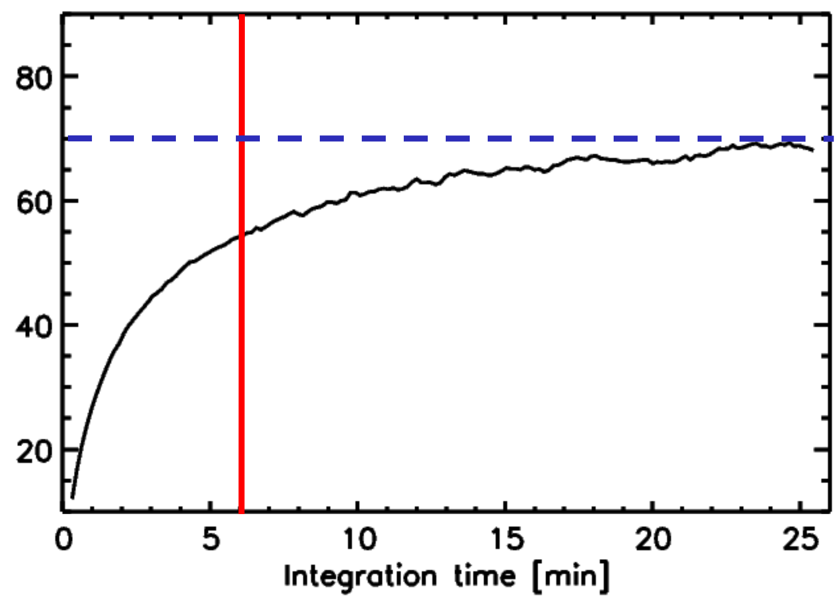
Noise level (x 10^{-3} I_c)



Granulation contrast (%)



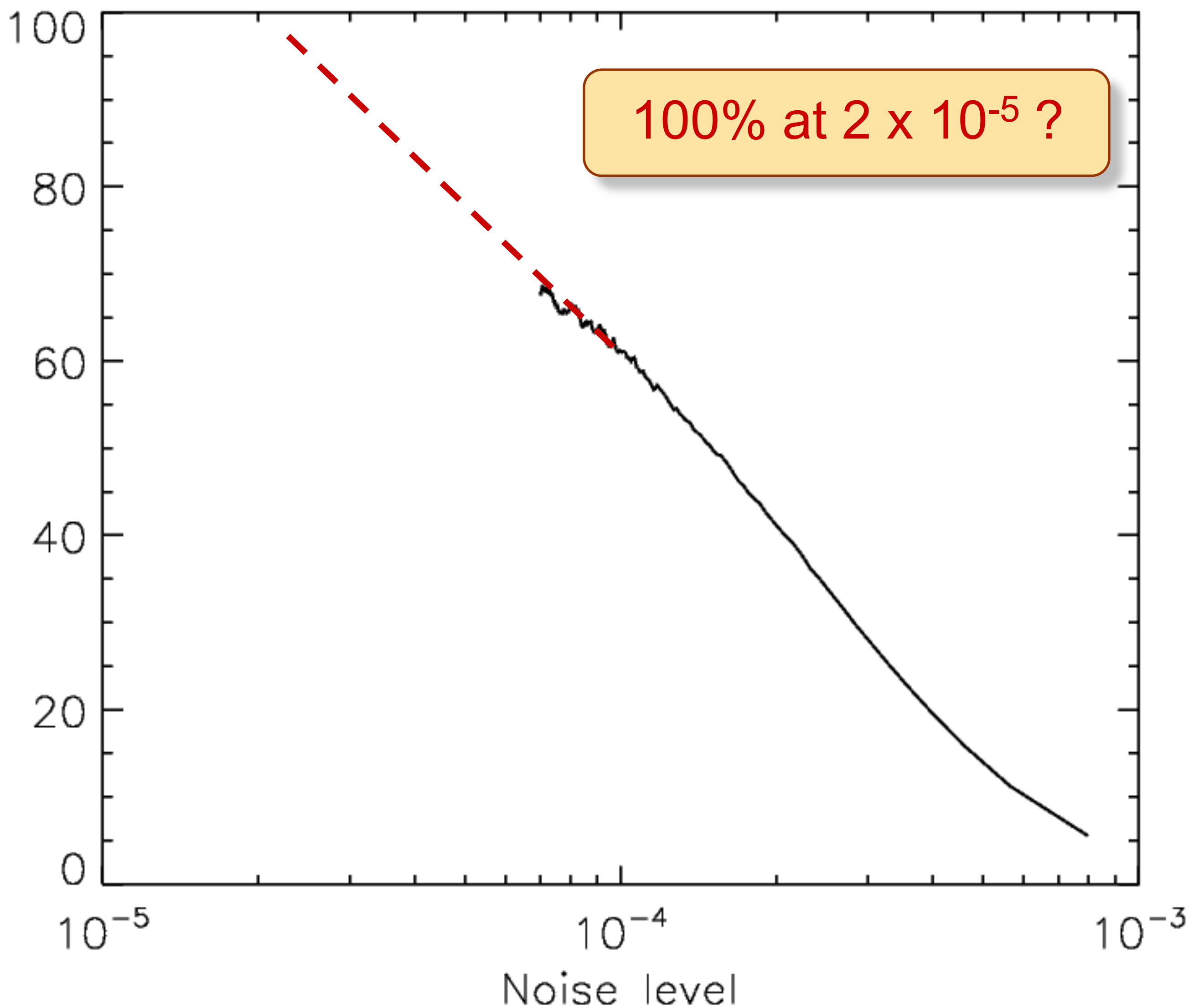
Fraction of FOV with Q or U > 4.5σ



Pushing the polarimetric sensitivity to a limit

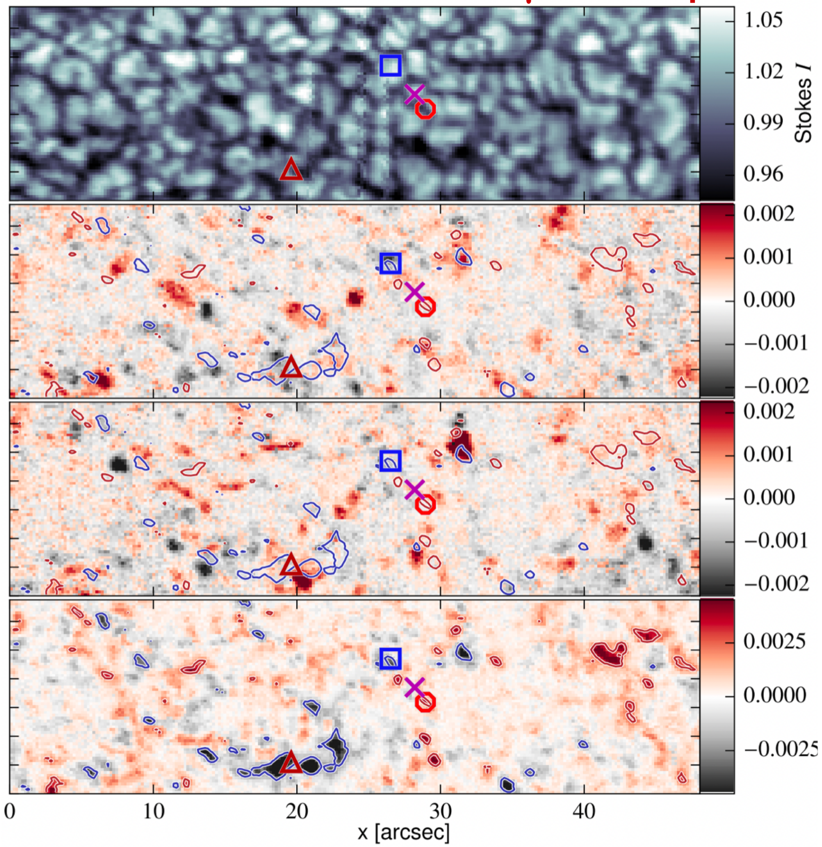
Bellot Rubio & Orozco Suárez, 2012, ApJ, 757, 19

Fraction of FOV with Q or U > 4.5σ

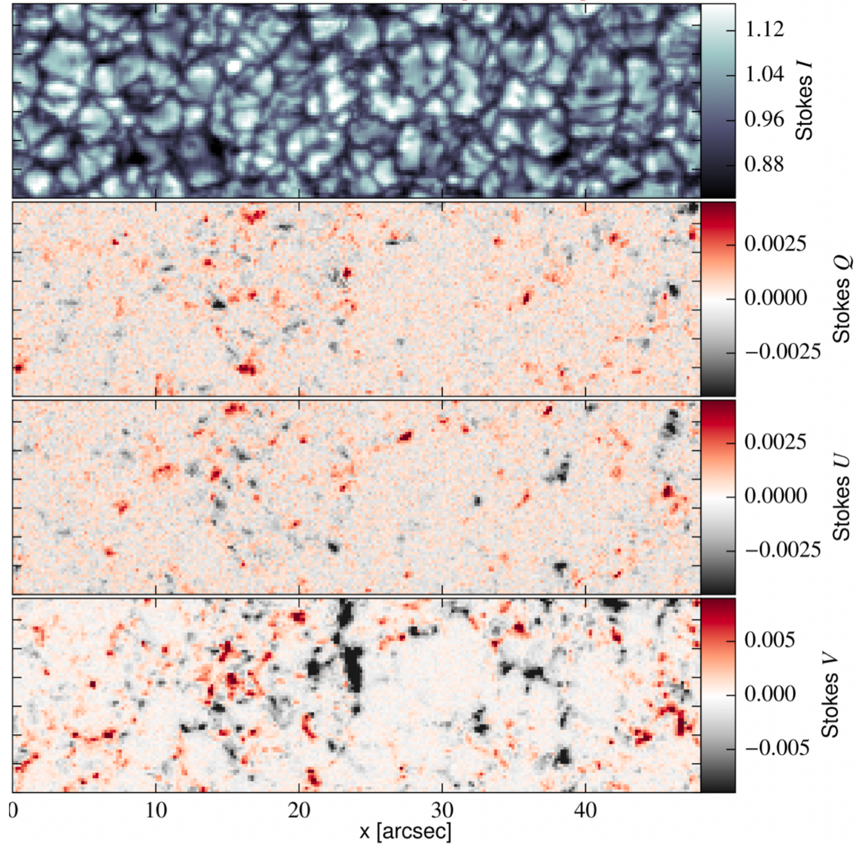


Recent results in near-infrared lines

GREGOR/GRIS 1.56 μm map



Hinode/SP deep map



Stokes V>4σ: 57.0% FOV
Stokes Q,U>4σ: 18.4% FOV

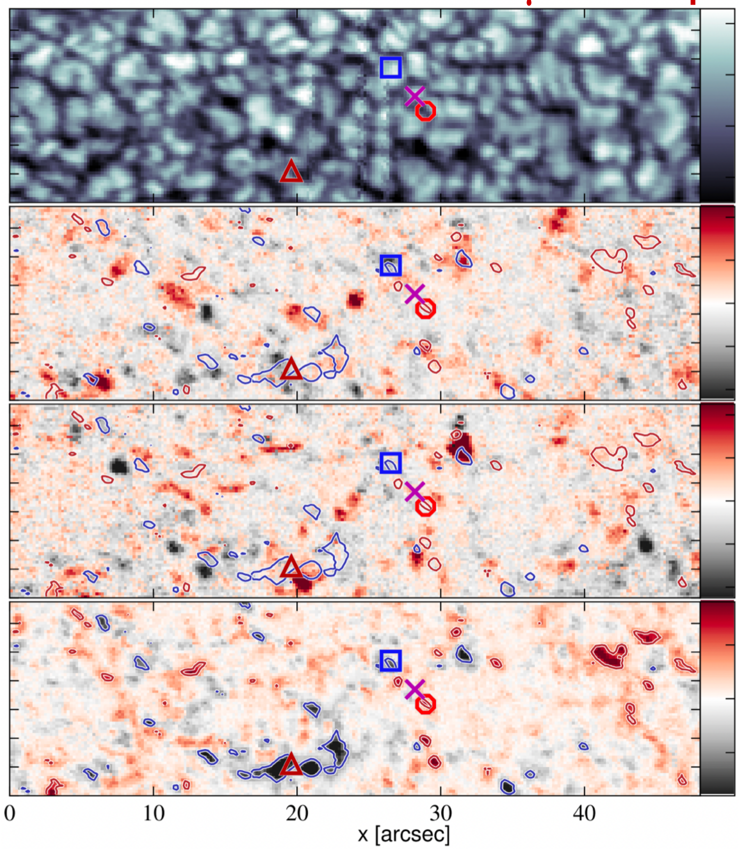
Stokes V>4σ: 37.1% FOV
Stokes Q,U>4σ: 4.2% FOV

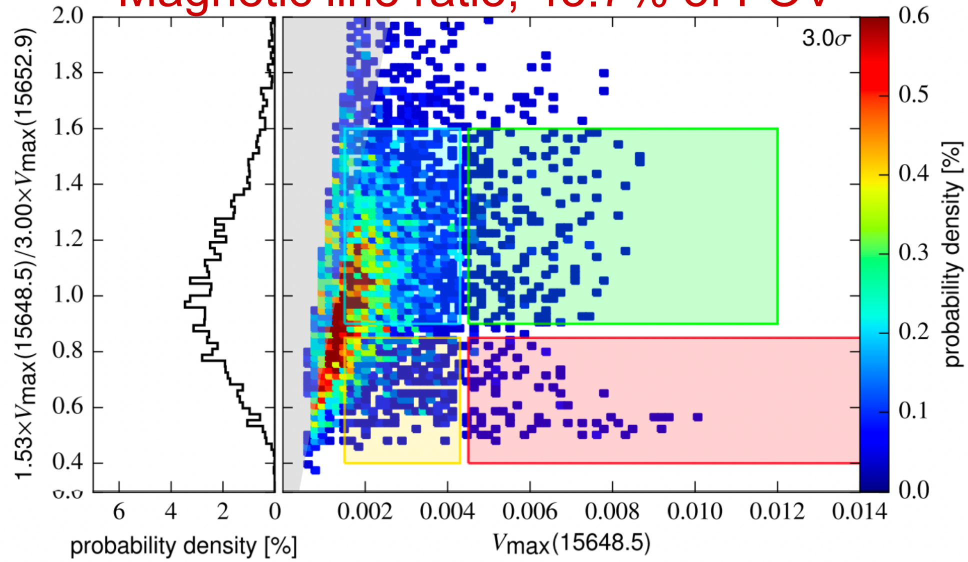
($\sigma = 4 \times 10^{-4}$ Ic)

Lagg et al., 2016, A&A, 596, A6

Recent results in near-infrared lines

GREGOR/GRIS 1.56 μm map

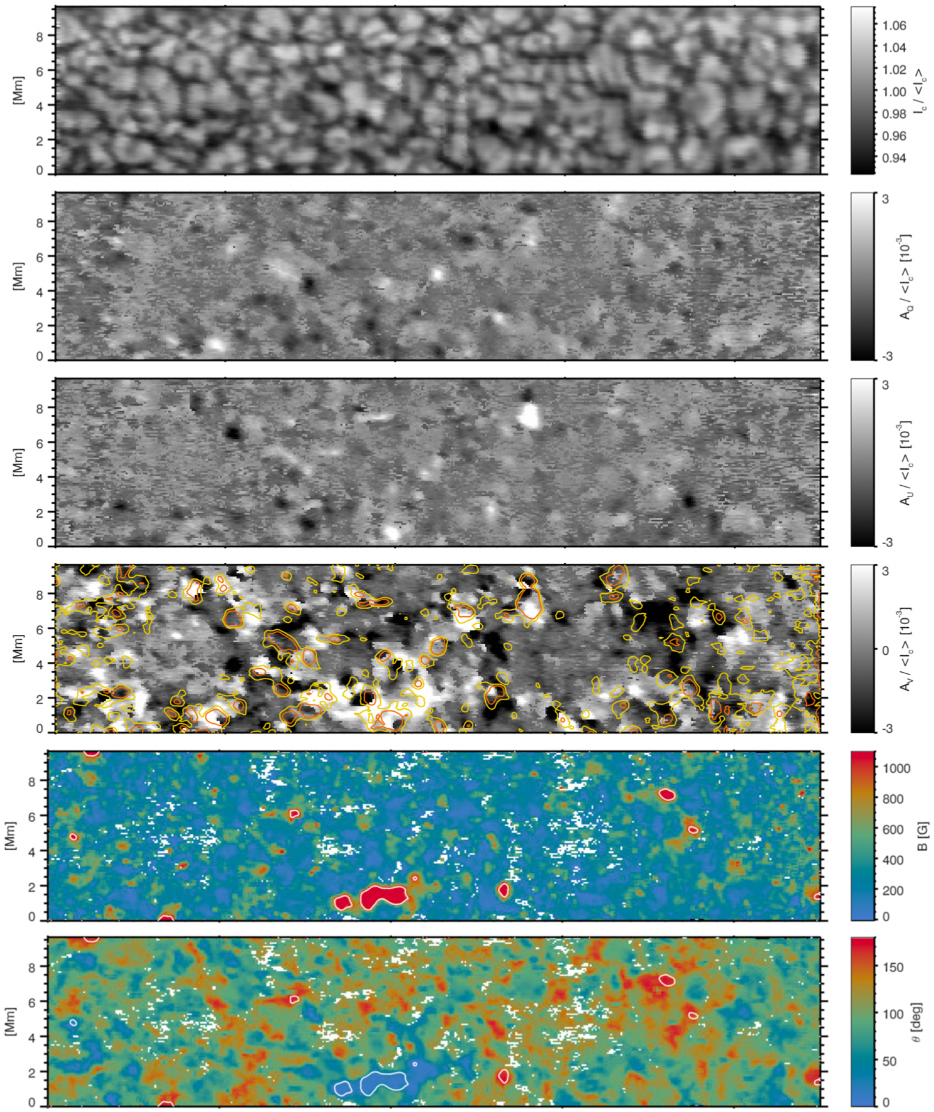




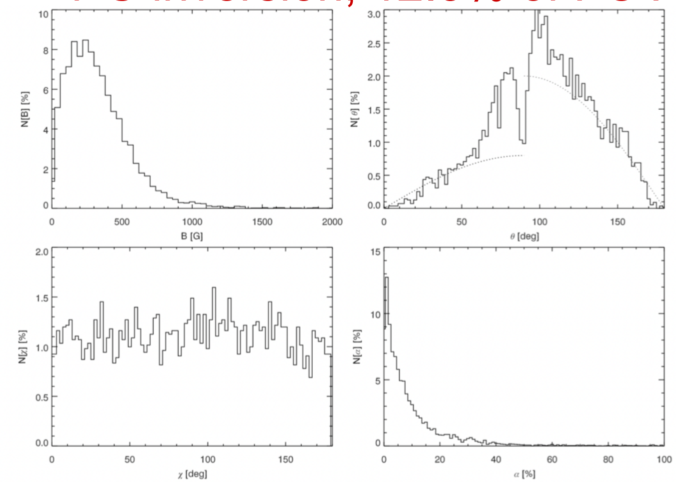
The line-ratio method applied to the Fe I 1.56 mm profiles indicates that most of the analyzed pixels harbor weak fields (magnetic line ratios > 0.6)

Lagg et al., 2016, A&A, 596, A6

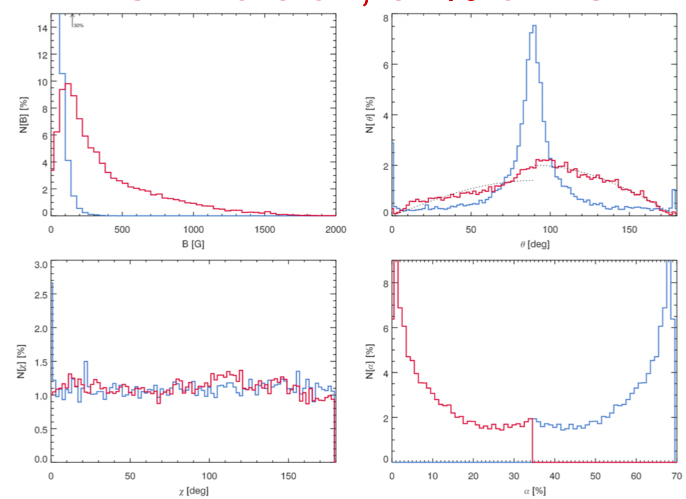
Recent results in near-infrared lines



1-C inversion, 12.3% of FOV



2-C inversion, 51% of FOV



Martínez González et al., 2016, A&A, 596, A5

Internetwork magnetic fields: current understanding

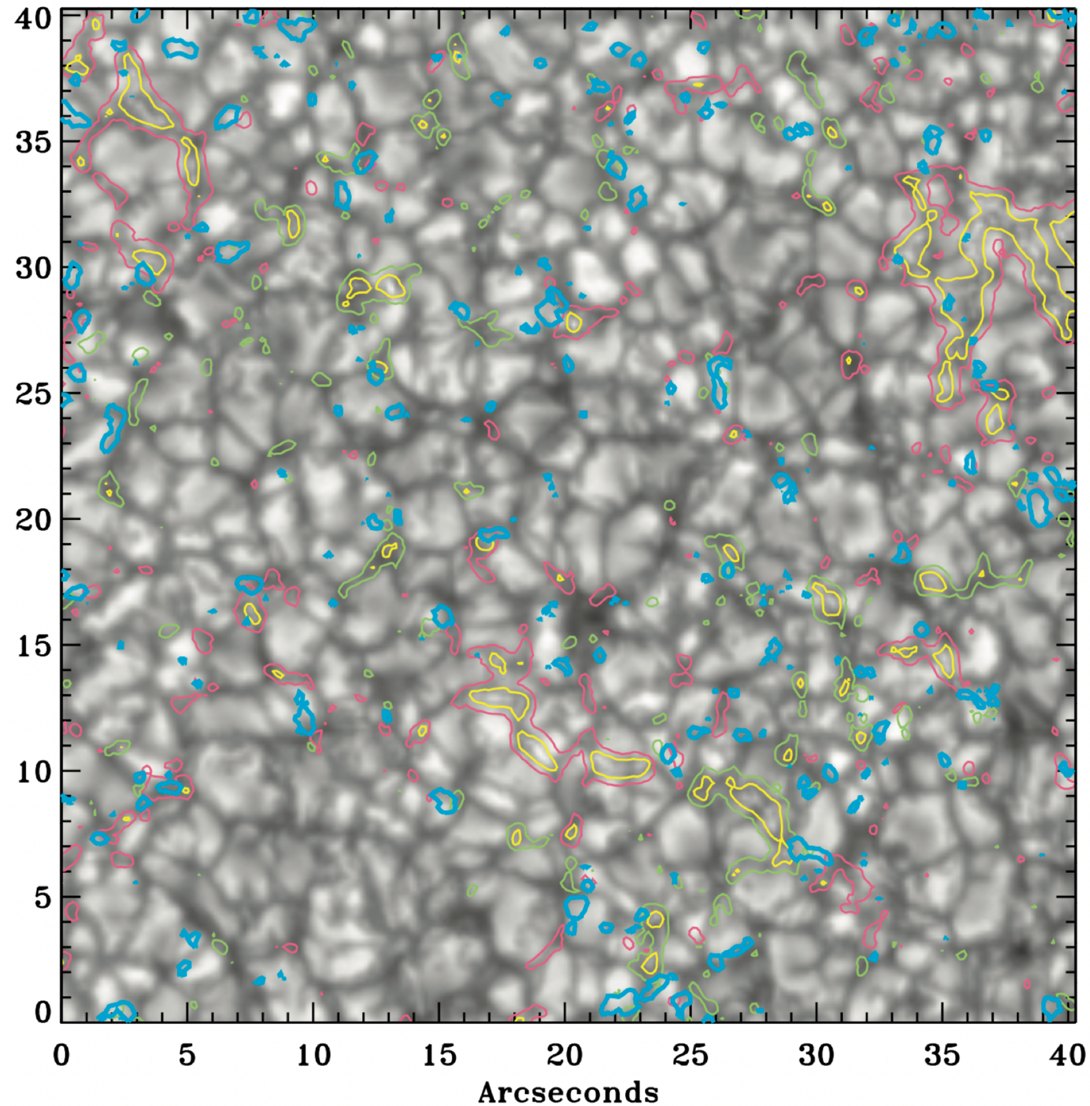
- Field strength and field inclination distributions important for
  - estimating magnetic energy and flux carried by IN fields
  - assessing contribution to magnetic network
  - quantitative comparisons with numerical MHD simulations

- Fields are weak (hG) for the most part
- Highly inclined, showing a peak at 90 degrees
  - The whole range of inclinations is observed
  - Isotropic distribution indicated by some analyses, but not confirmed

- What is the origin of these highly inclined fields?
- Need to understand magnetic topology in the QS

Origin of inclined IN fields

Lites et al, 2008, ApJ, 672, 1237
Hinode/SP normal map

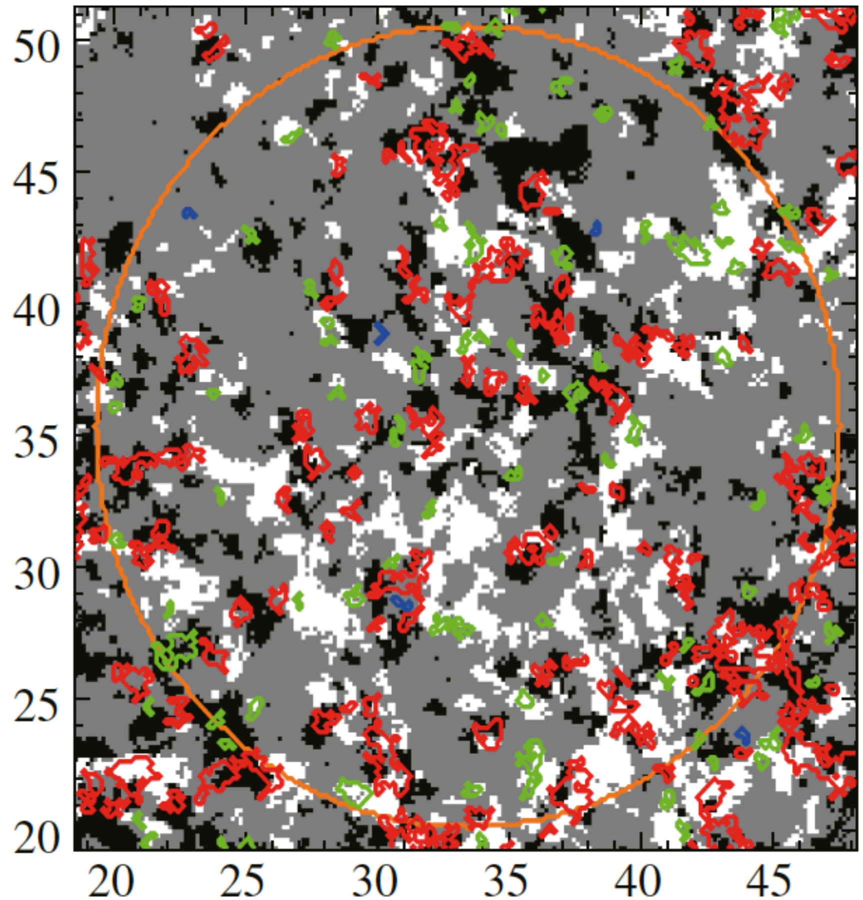


Red: positive circular polarization
Green: negative circular polarization
Blue: linear polarization

Origin of inclined IN fields

Ishikawa & Tsuneta, 2011, ApJ, 735, 74
Hinode/SP normal map

Red: "bipolar" linear polarization patches
Green: "unipolar" linear polarization patches



- 53% of the strong linear polarization patches occur between circular signals of opposite polarity
- 43% associated with circular polarization of one sign only
- 4% not associated with circular polarization signals

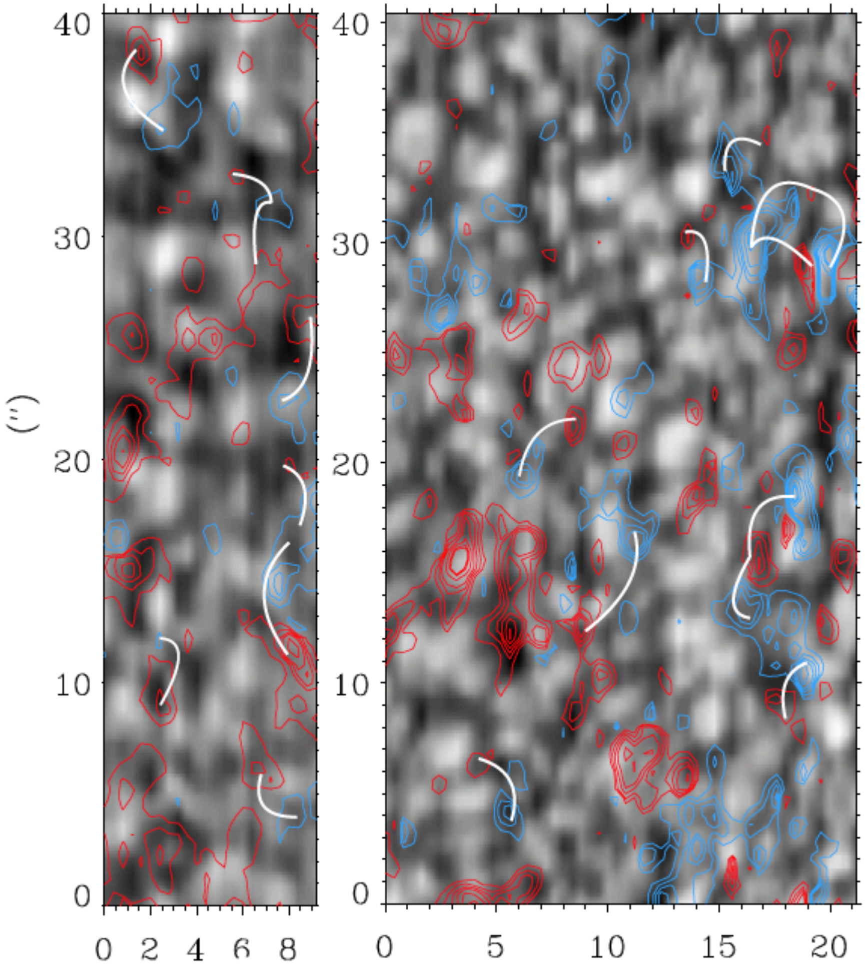
Half of the linear polarization patches compatible with loop-like magnetic topology

Small-scale magnetic loops in the IN

Martínez González et al., 2007, A&A, 469, L139

Many opposite-polarity elements of the IN are connected by short, low-lying magnetic loops

TIP@VTT, contours: positive/negative polarity



- *Horizontal Internetwork Fields* discovered by Lites et al. (1996)
- Transient (~ 5 min), compact (~1"), weak (< 600 G)
- Associated with blueshifts

Modes of appearance of IN fields

Using time sequences, IN magnetic elements are observed to appear on the solar surface in two flavors

Bipolar pairs/clusters

Martin (1984)
Lites et al. (1996)
Martínez González et al. (2007)
Centeno et al. (2007)
Lamb et al. (2008)
Ishikawa et al. (2008)
Martínez González & Bellot Rubio (2009)
Jin et al. (2009)
Gömöry et al. (2010)
Martínez González et al. (2012)
Wang et al. (2012)
Guglielmino et al. (2012, 2021)
Fischer et al. (2018, 2019)
Gošić et al. (2022)

Unipolar patches

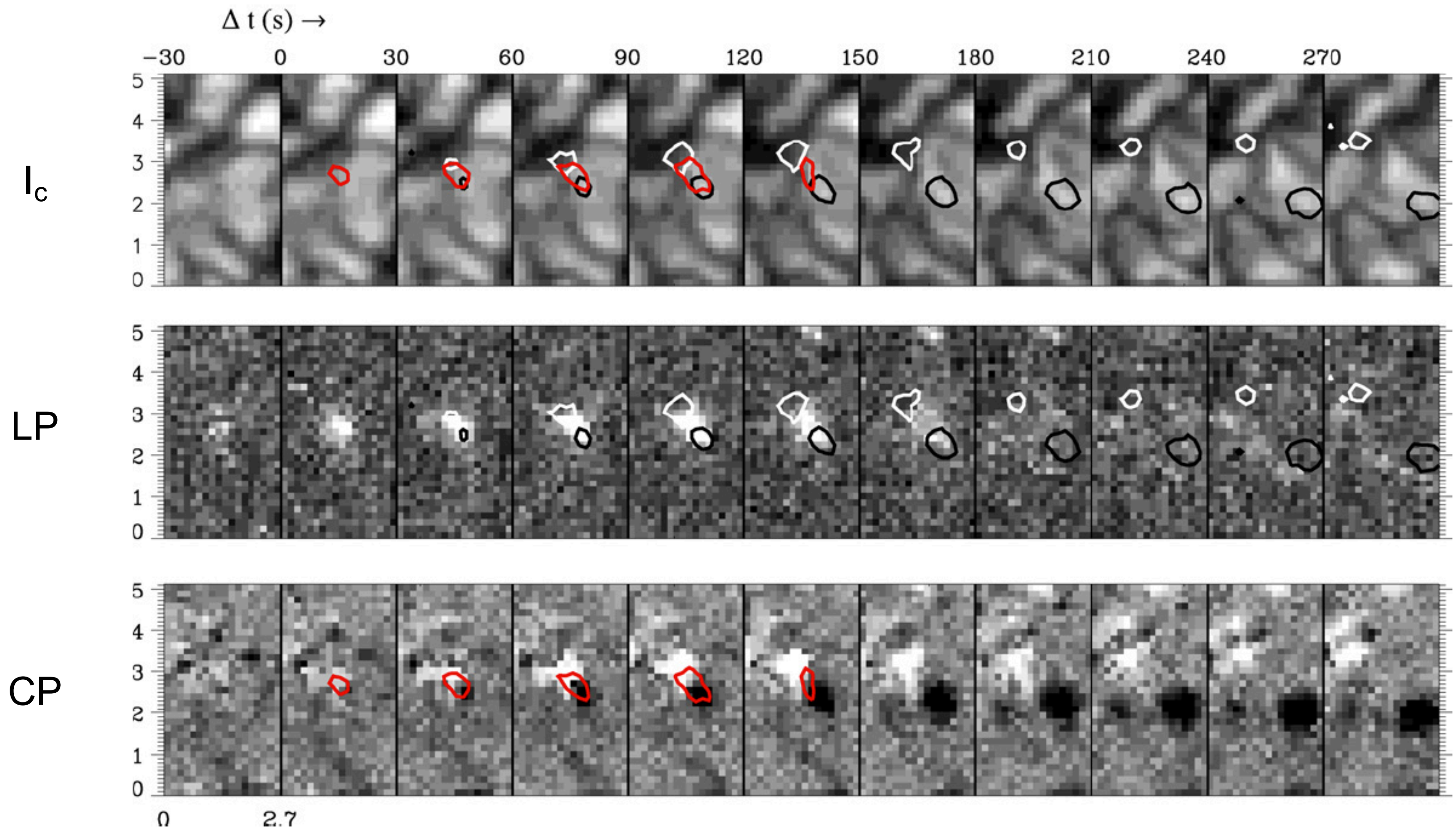
De Pontieu (2002)
Orozco Suárez et al. (2008)
Lamb et al. (2008, 2010)
Gošić et al. (2014, 2016)
Anusha et al. (2016)
Gošić et al. (2022)

Emergence of small-scale magnetic loops in the IN

Centeno et al., 2007, ApJ, 666, L137

Martínez González & Bellot Rubio, 2009, ApJ, 700, 1391

Hinode/SP, 25 Sep 2007



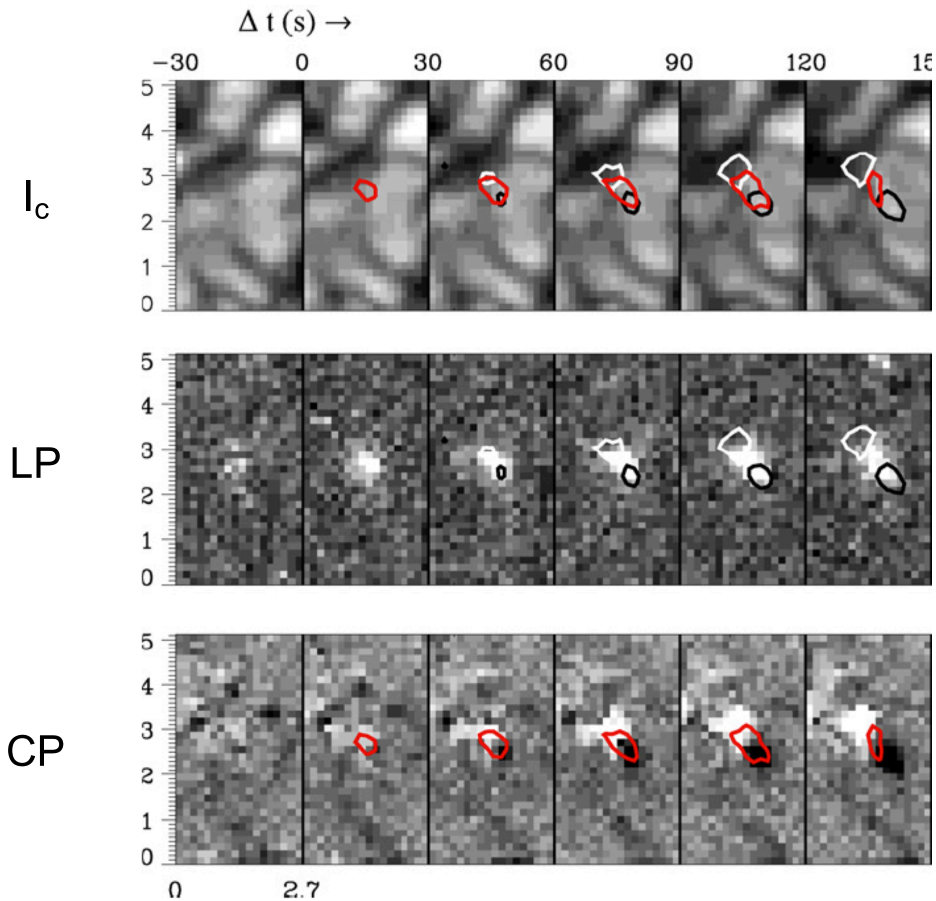
Magnetic Ω-loops emerge into the photosphere on granular scales, showing linear polarization signal in between two-opposite polarity footpoints

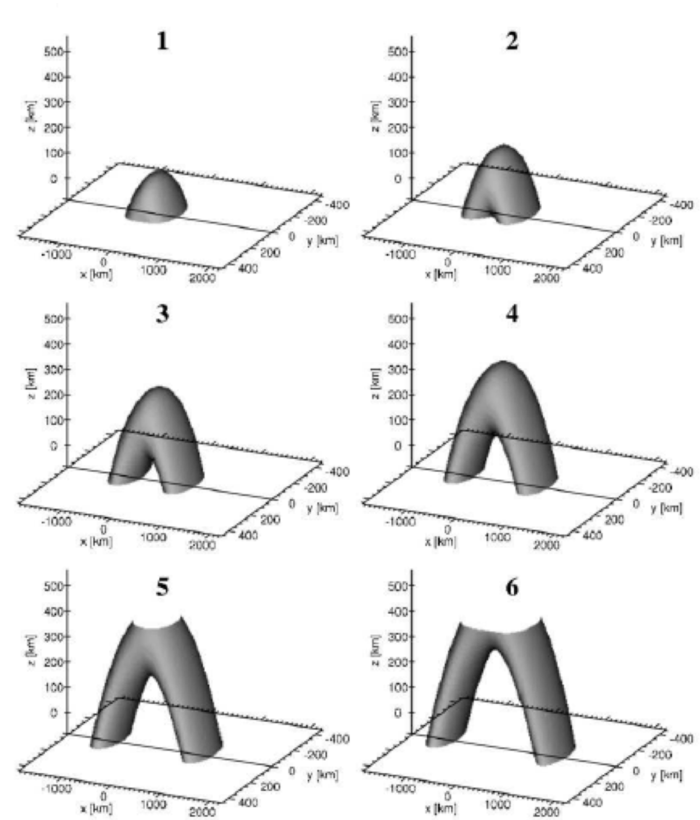
Emergence of small-scale magnetic loops in the IN

Centeno et al., 2007, ApJ, 666, L137

Martínez González & Bellot Rubio, 2009, ApJ, 700, 1391

Hinode/SP, 25 Sep 2007





Gömöry et al. (2010)

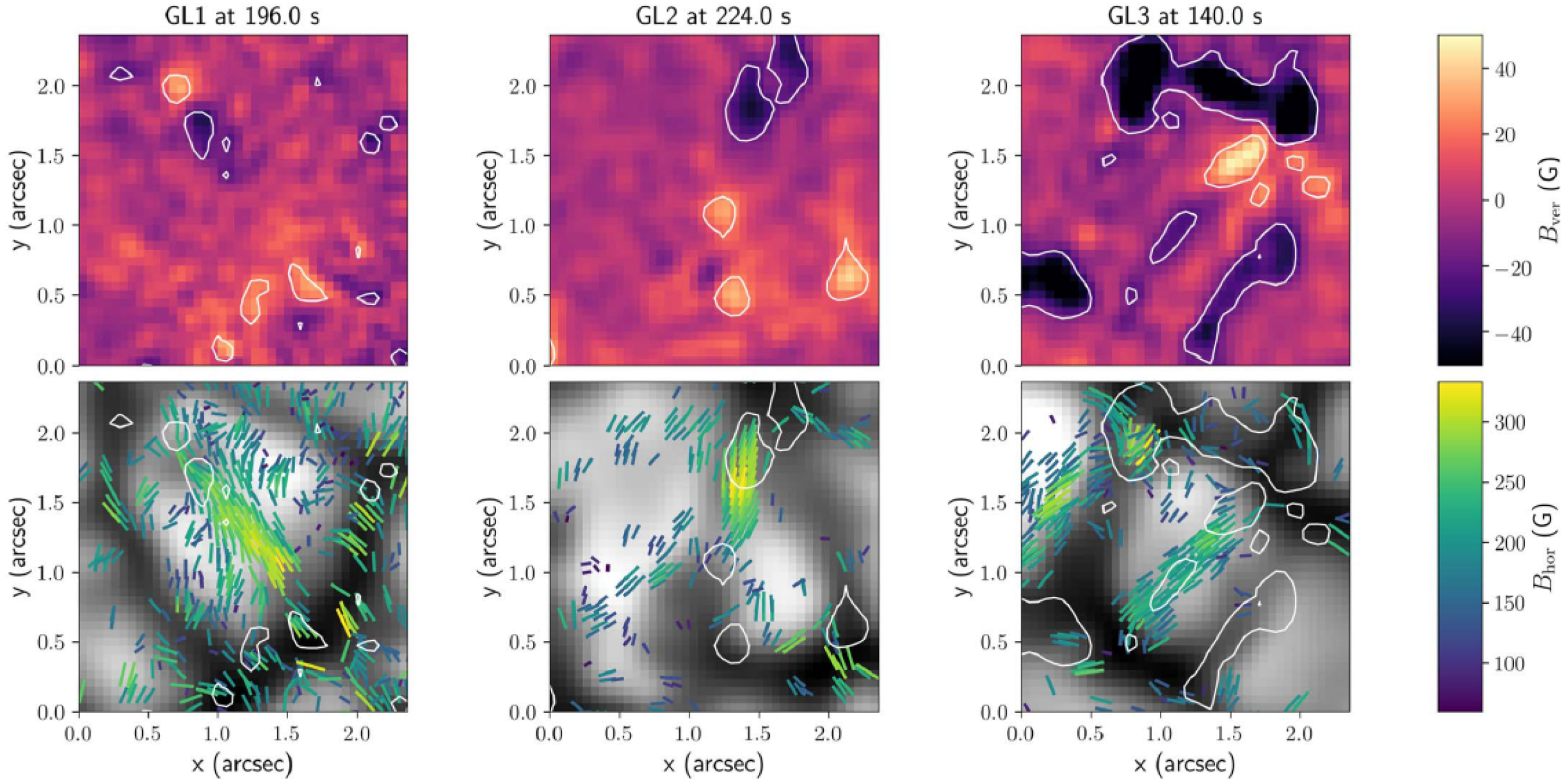
Confirmed by Ishikawa et al. (2008), Jin et al. (2009), Zhang et al. (2009), Gömöry et al. (2010)

0.02 arcsec^{-2} h^{-1} (Martínez González & Bellot Rubio 2009; Hinode/SP), 0.25 arcsec^{-2} h^{-1} (Martínez Gonzalez et al. 2012; IMaX)

Emergence of small-scale magnetic loops in the IN

Fischer et al., 2020, ApJ, 903, L10

SST/CRISP data + VFISV inversion

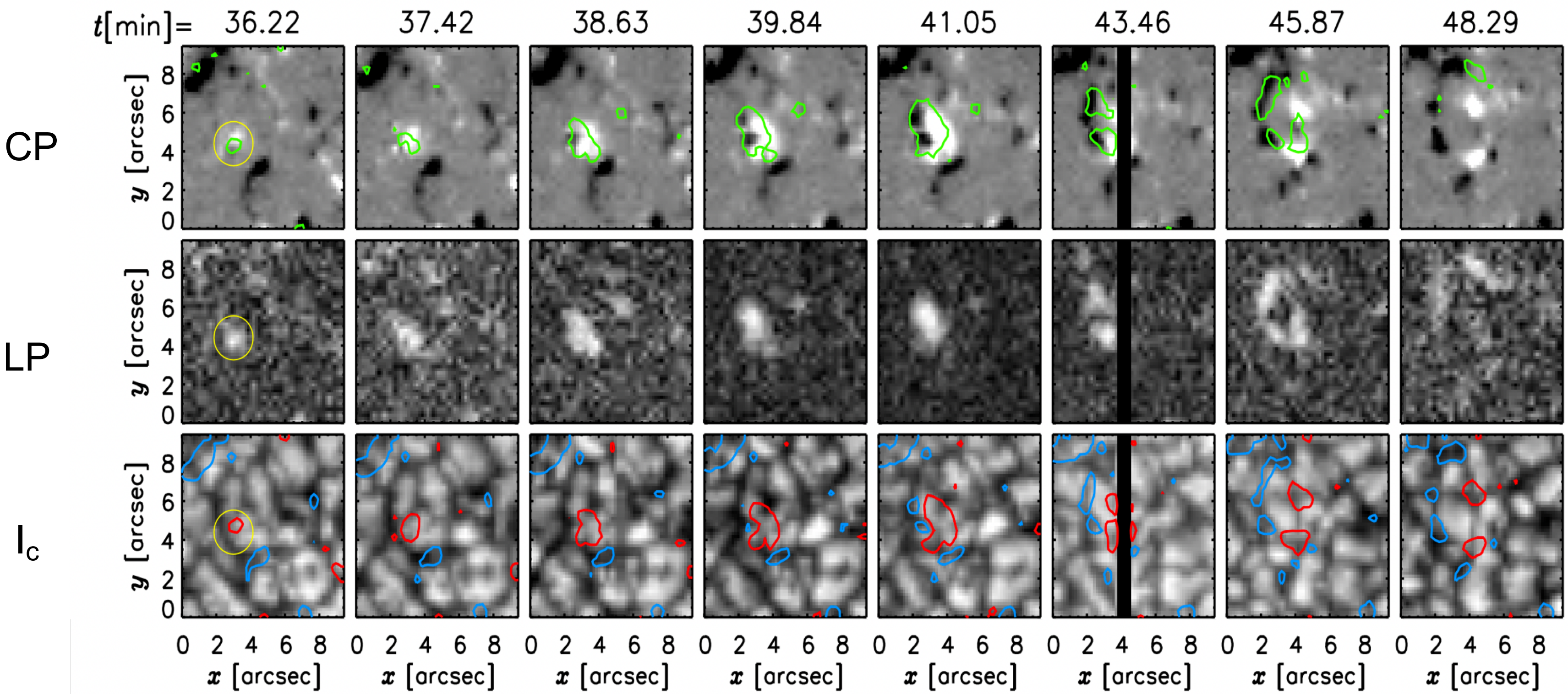


- Linear polarization seen on granular lanes, corresponding to fields of up to 300 G
- Granular lanes are produced by horizontal vortex tubes
- Mechanism can bring dispersed flux from intergranular lanes into granules and back

Emergence of small-scale magnetic sheets in the IN

Fischer et al., 2019, A&A, 622, L12

Hinode/SP normal map + SIR inversion

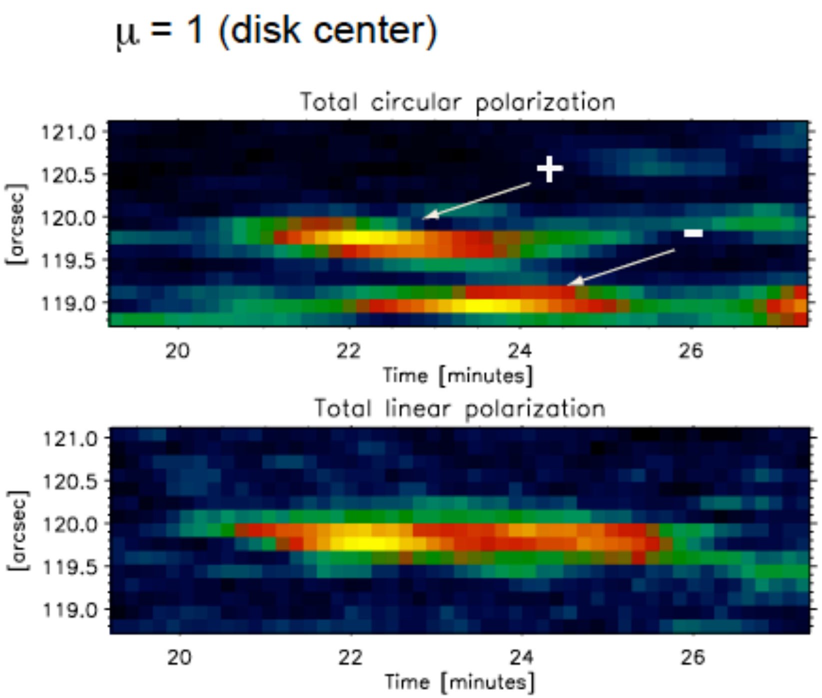


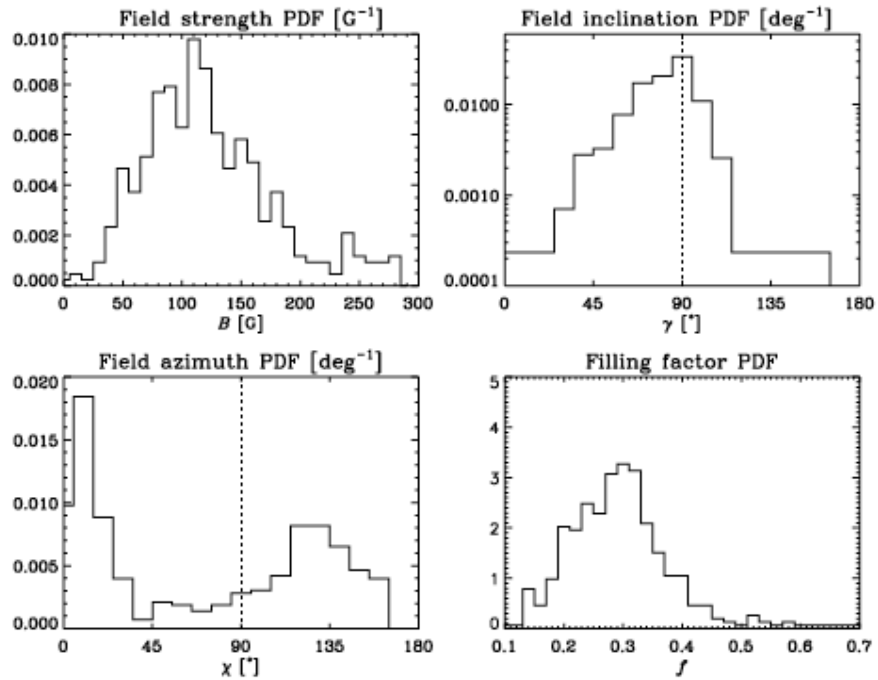
- Another type of bipolar emergence (also in simulations, Moreno Insertis et al. 2018)
- Large sheet of horizontal flux covering full granule
- Sheet fragments as it expands to the granular edges, leaving only footpoints

Origin of inclined IN fields

Orozco Suárez & Katsukawa, 2012, 746, 182

Hinode/SP deep mode map + ME inversions





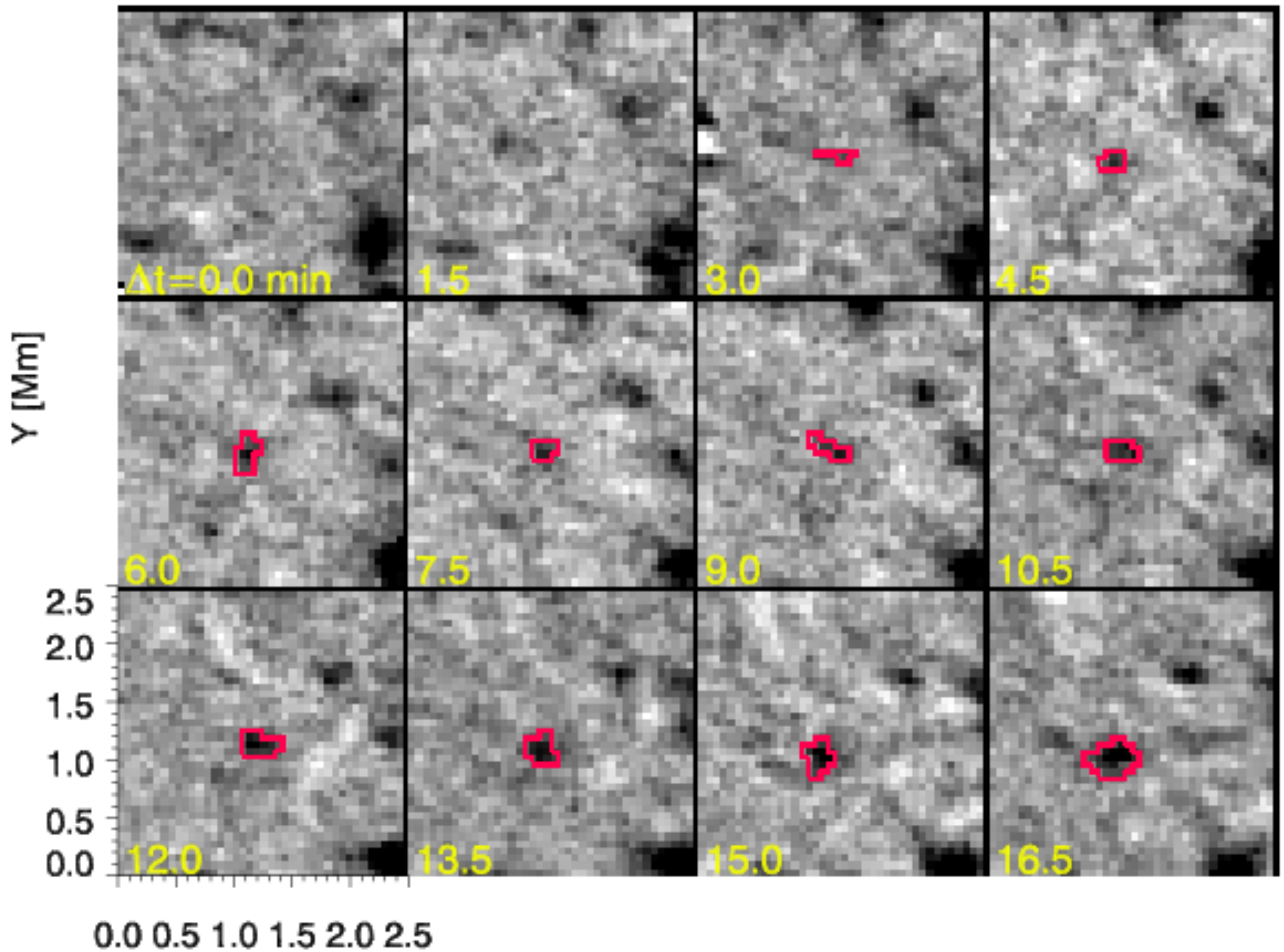
The field strength and inclination PDFs resulting from small-scale loops have similar shapes to those obtained from the inversion of full Hinode/SP maps

Small-scale magnetic loops/bipolar pairs

- May explain field strength and field inclination distributions
- May also explain magnetic topology observed in the IN, including the existence of flux above granules
- But... bipolar emergence does not seem to be the main mode of flux appearance!
  - only 6%, according to SOHO/MDI data (Lamb et al. 2008)
  - only 4%, according to SUNRISE/IMaX data (Smitha et al. 2017)

Unipolar magnetic flux appearance

Hinode/NFI longitudinal magnetograms, 30 s cadence



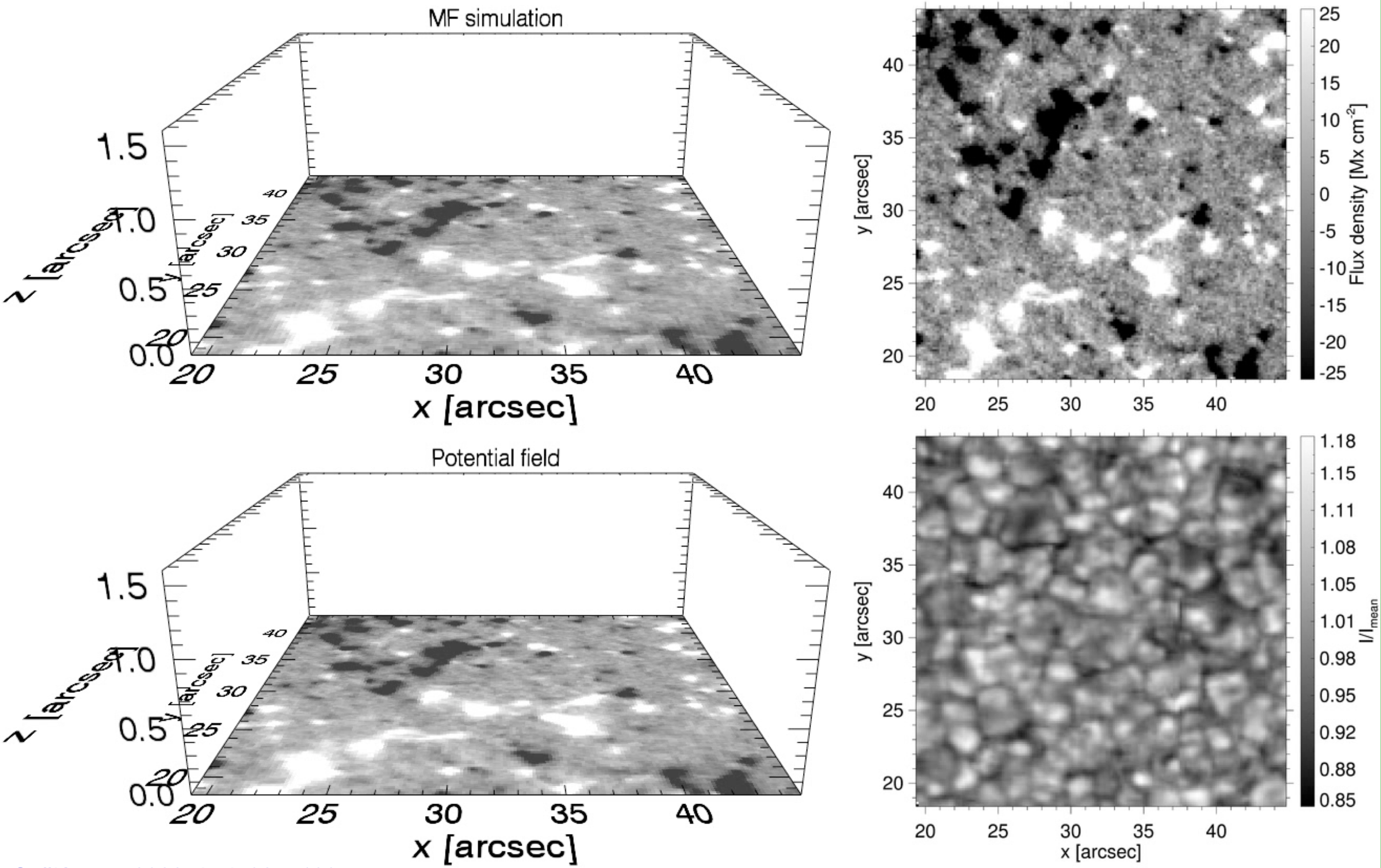
Unipolar vs bipolar flux emergence in the QS

- Unipolar appearance poses a serious problem: where is the opposite-polarity flux (div B = 0)?

- Loops are difficult to identify without full Stokes measurements

- Gošić et al. (2022) used long duration Hinode/NFI magnetogram sequences to identify bipolar features. The two footpoints must
  - appear close in space and in time
  - have approximately the same flux content
  - separate from each other following straight trajectories
  - appear at the edges of the same granule
  - be magnetically connected according to a magnetofrictional simulation

Magnetic connectivity of bipolar features



Gošić et al, 2022, ApJ, 925, 188

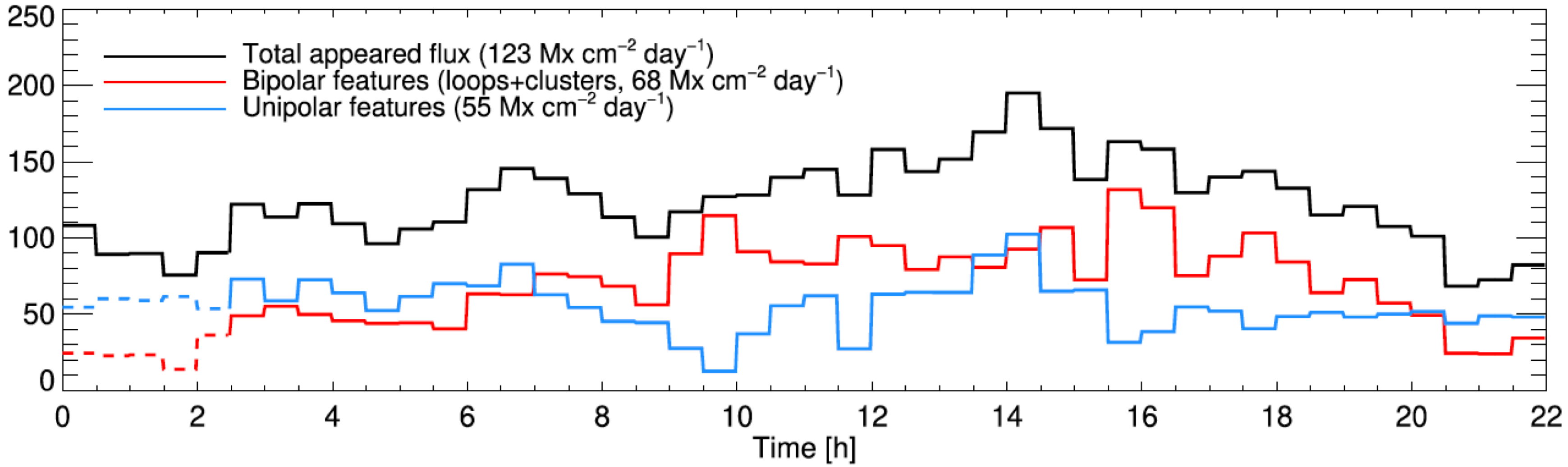
Unipolar vs bipolar flux appearance in the IN

Gošić et al., 2022, ApJ, 925, 188

Hinode/NFI Na D1 + feature tracking + MF simulation

First MF simulation of QS magnetograms

Flux rates [Mx cm^{-2} day^{-1}]

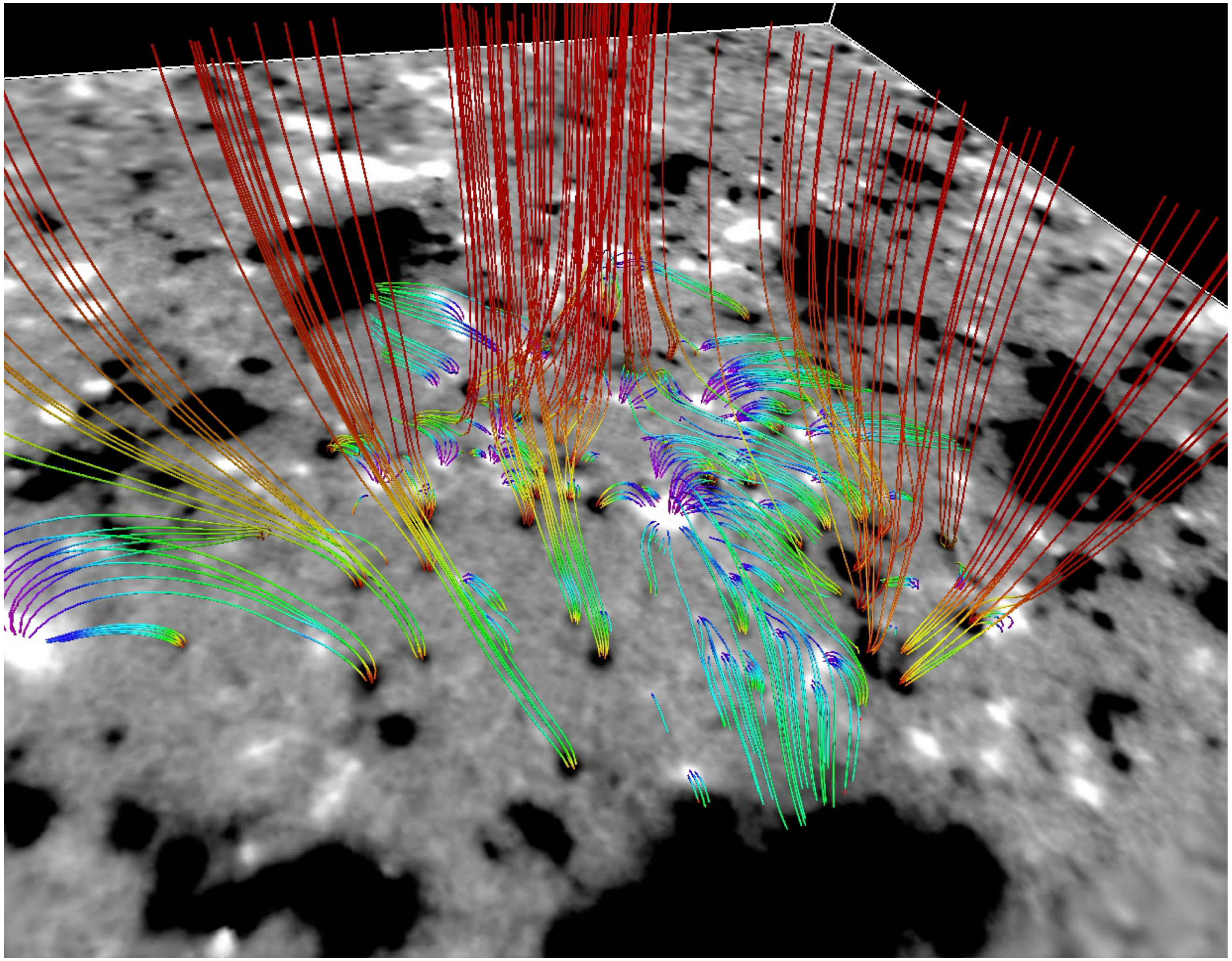


- About 55% of the IN flux appears in bipolar form
- Most of the bipolar flux is contained in clusters, with small-scale loops carrying less flux

- Still, 45% of the IN flux is observed to appear in unipolar form
- Coalescence of very weak background flux that is buried in the noise? (Lamb et al 2012)

Magnetic coupling of the quiet solar atmosphere

Magnetofrictional simulation of quiet Sun fields observed by Hinode/NFI



Gošić et al, 2022, ApJ, 925, 188

Low-lying IN loops and more vertical IN and network fields. Very frequent interactions

Magnetic coupling of the quiet solar atmosphere

- Flux emergence and subsequent surface evolution give rise to interactions between different flux systems

- Interactions can drive magnetic reconnection at multiple heights
- Important for energetics and dynamics of the atmosphere
- May explain ubiquitous chromospheric heating in the IN!

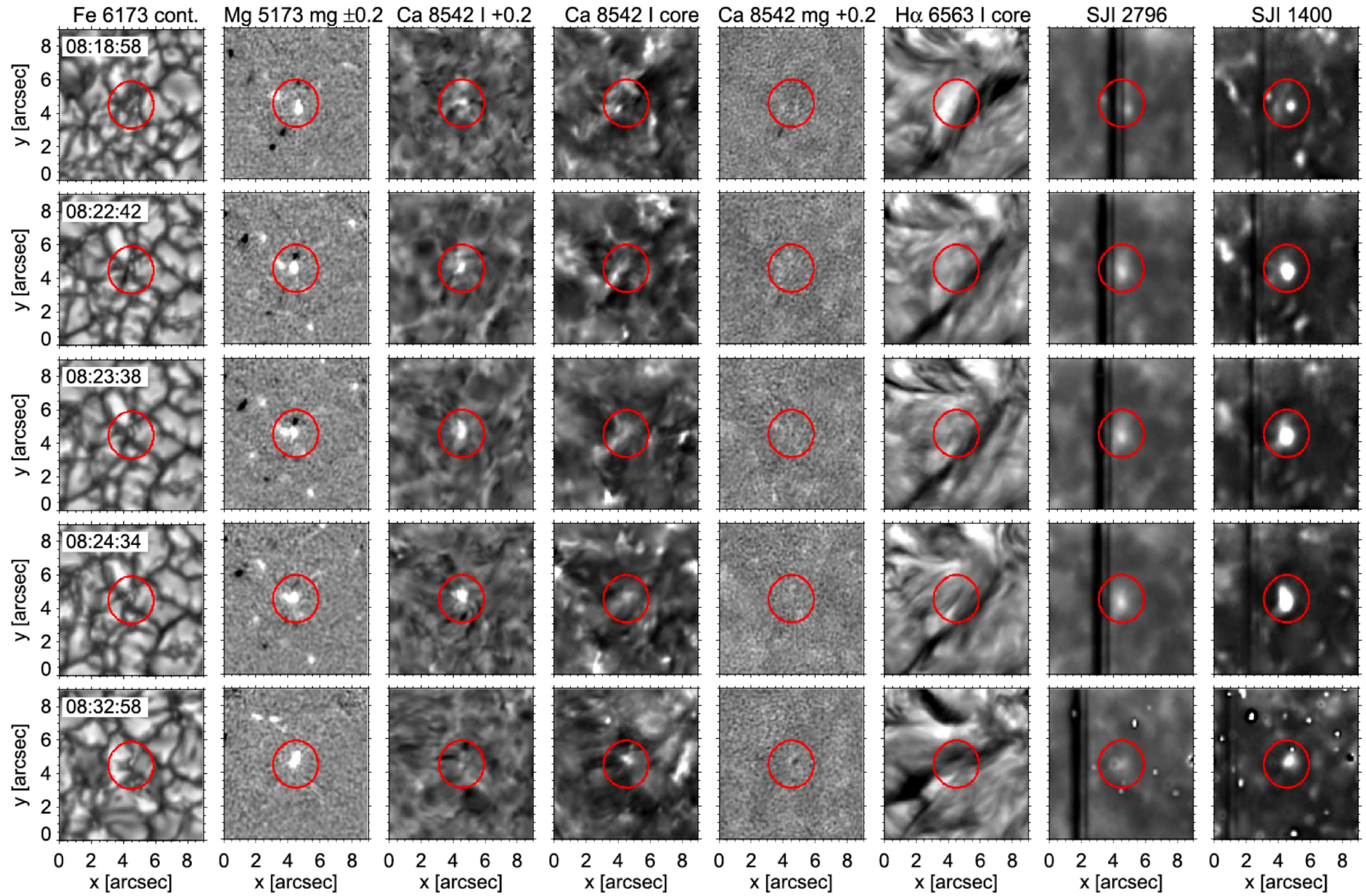
Lecture by Salvo Guglielmino on magnetic coupling

Cancellation of opposite-polarity fields

Gošić et al., 2018, ApJ, 857:48

SST/CRISP + IRIS

25% of total IN flux in Hinode/NFI data disappears by cancellation



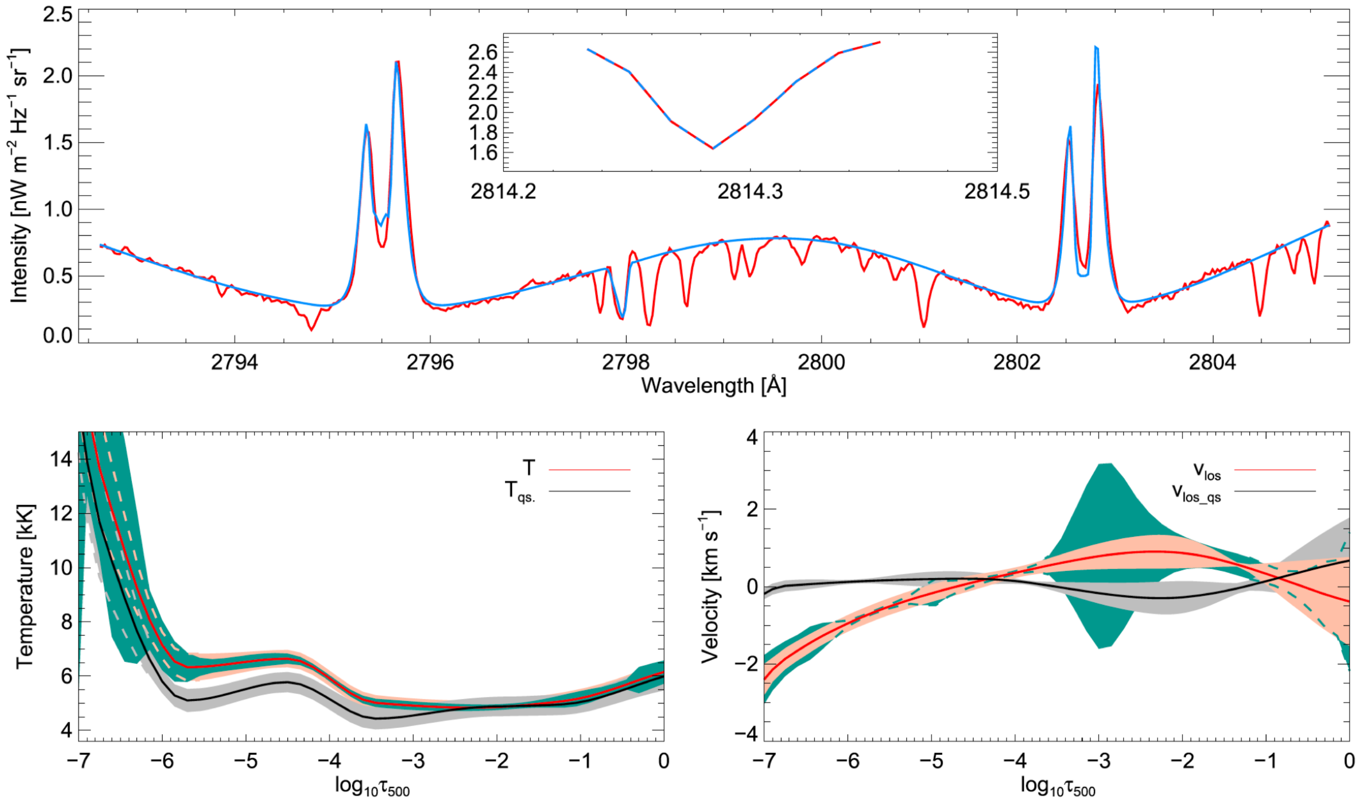
Cancellation of weak IN fields gives rise to strong small-scale brightenings in Ca II 8542 and SJI 2796/1400

Cancellation of opposite-polarity fields

Gošić et al., 2018, ApJ, 857:48

SST/CRISP + IRIS

Cancellation of opposite-polarity fields in quiet Sun internetwork



- Local temperature enhacements of up to 2000 K between log τ = -4 and -6.5, from STIC inversions
- Magnetic energy estimated to be sufficient to explain radiative losses in chromosphere locally, but not globally because of too few cancellations at the SST sensitivity

Summary

- Properties of quiet Sun fields determined at high spatial resolution
  - Individual magnetic elements can now be resolved
  - Internetwork fields are weak and highly inclined
- Magnetic topology inferred
  - Small-scale magnetic loops could explain the observed distributions
- Flux emergence/disappearance processes characterized
  - Problem posed by unipolar flux appearance partially solved
- Importance of magnetic coupling by quiet Sun fields recognized

Outlook

- Properties of quiet Sun fields –> Sensitivity
  - Extend the analysis to entire solar photosphere
  - Determine exact shape of inclination distribution
  - Study temporal evolution of fields

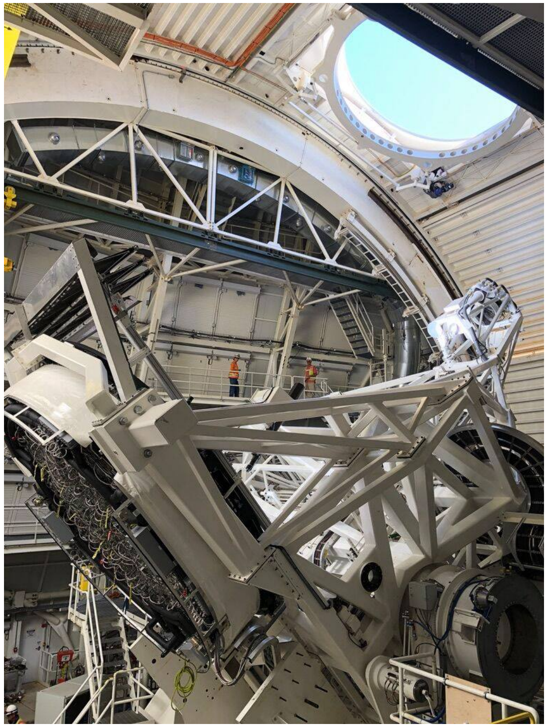
- Role of QS fields in chromospheric/coronal heating –> Multilline obs
  - Characterize surface processes, particularly flux cancellation
  - Are cancellations the signature of magnetic reconnection?
  - Quantify energy release in upper layers

- Origin of IN fields –> Sensitivity + multiline observations
  - Small-scale dynamo vs global dynamo
  - Quantative comparison of field distributions with MHD simulations
  - Time evolution - do fields appear as small-scale loops?

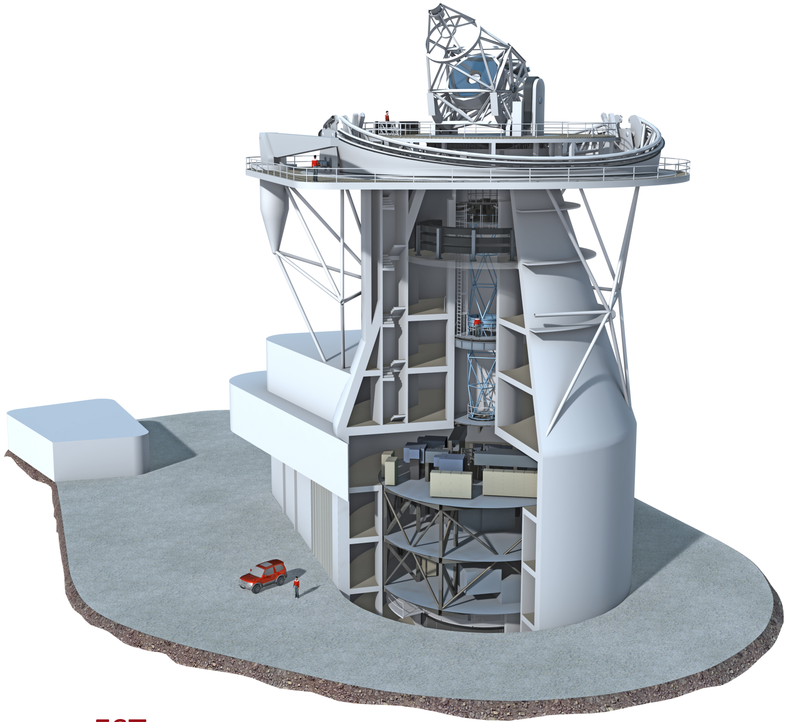
Next-generation solar telescopes

High polarimetric sensitivity and multi-line vector spectropolarimetry requires large aperture telescopes

- DKIST 4.0m aperture, first science observations in March 2021
- EST 4.2m aperture, now in preparatory phase for construction



DKIST



EST

Long-duration time
sequences over large FOVs
require space observations

Solar Orbiter PHI