Quiet-Sun Magnetism

... from an observer's perspective ...

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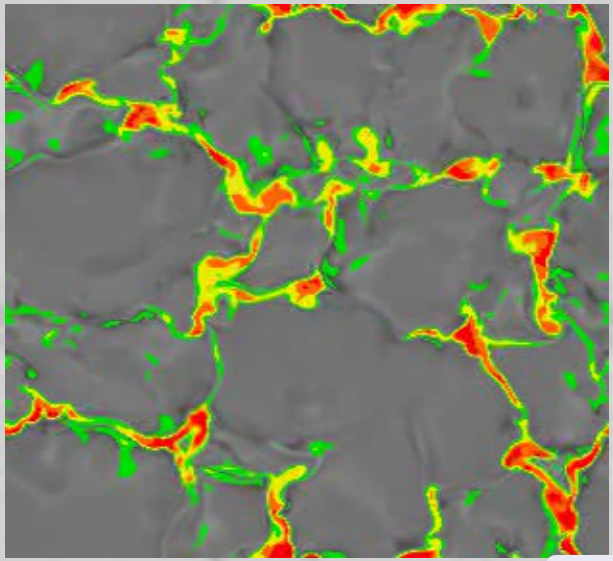
MAX-PLANCK-GESELLSCHAFT

5th international workshop on
small-scale solar magnetic fields
Bairisch-Kölldorf, Austria
April 21-24 2015

MPS

Relevance

- QS magnetism covers $>$99% of solar surface (even during maxima)
- crucial to understand the solar global magnetism
- local (surface) dynamo or cascade from global dynamo?



M. Rempel

Observations

Tool: spectropolarimetry (Zeeman & Hanle)

- weak signals $\rightarrow$ difficult detection; different sensitivity for transverse and longitudinal fields
- small scales $\rightarrow$ cancellation

$\longrightarrow$ difficult measurement!

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The consequence

- disagreement about magnetic field strength
- disagreement about angular distribution
- disagreement about μ-dependence
- disagreement about temporal behavior over activity cycle

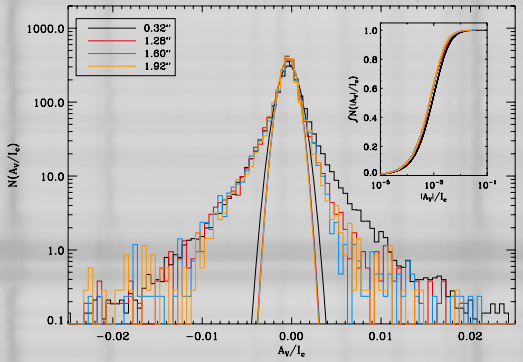
Statistical properties: spatial coherence

Martínez González et al. (2010)

spatial coherence increases with magnetic flux

- small-scale (below 100 km): weak, dynamic, intermittent, stochastic
- “flux-tubes”: organized on granular scales, longer lived, loop-forming

(also: López Ariste et al., 2006; Stenflo, 2010; Lagg et al., 2010; Ishikawa & Tsuneta, 2010)



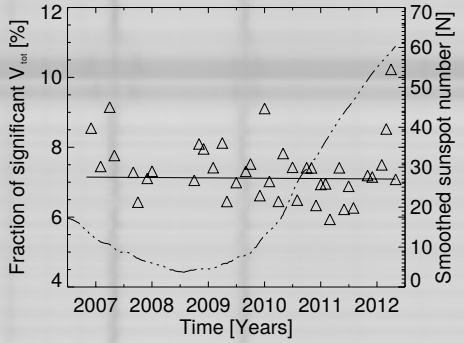
Stokes V Amplitude (A_V) histogram: Gaussian core (80%) independent on spatial resolution.

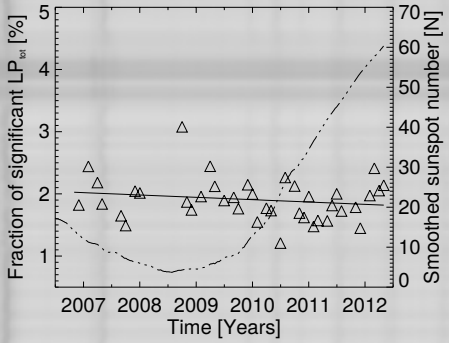
Statistical properties: correlation with activity cycle

Hinode long-term study (Buehler et al., 2013)

- careful consideration of instrumental effects
- no cycle dependence for $B_{||}$ and $B_{\perp}$

(also: Shchukina & Trujillo Bueno, 2003; Faurobert et al., 2001; Kleint et al., 2010)





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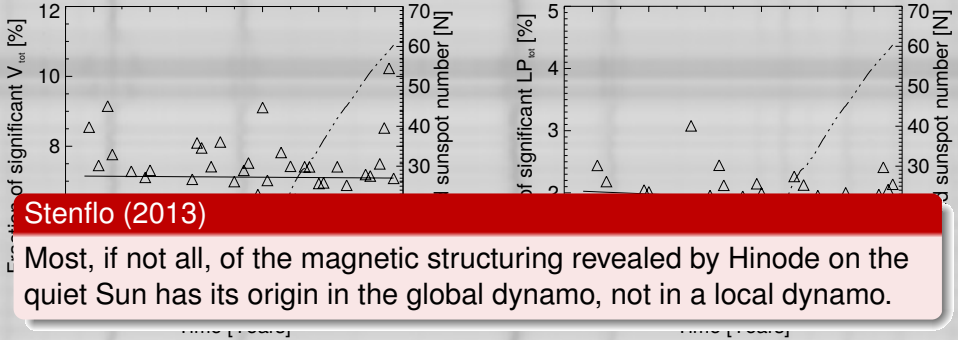


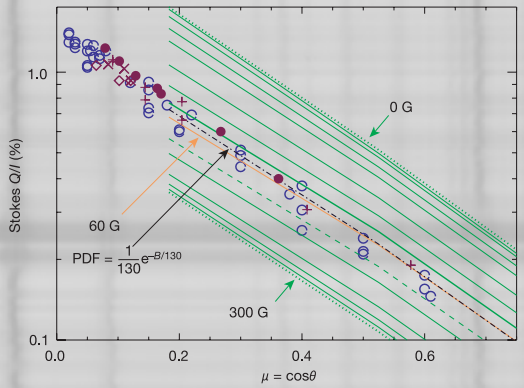
Stenflo (2013)

Most, if not all, of the magnetic structuring revealed by Hinode on the quiet Sun has its origin in the global dynamo, not in a local dynamo.

QS fields: Strength

Recent results: QS magnetic field strength (Hanle)

- Faurobert-Scholl et al. (1995): ≈30 G
- Bommier et al. (2005): 40–55 G
- Trujillo Bueno et al. (2004): 130 G
- Berdyugina & Fluri (2004): 15 G
- Asensio Ramos & Trujillo Bueno (2005): 10 G
- Shapiro et al. (2011): 40–82 G
- Kleint et al. (2010): 3-8 G (@5″)



Hanle depolarization in Sr I 4607

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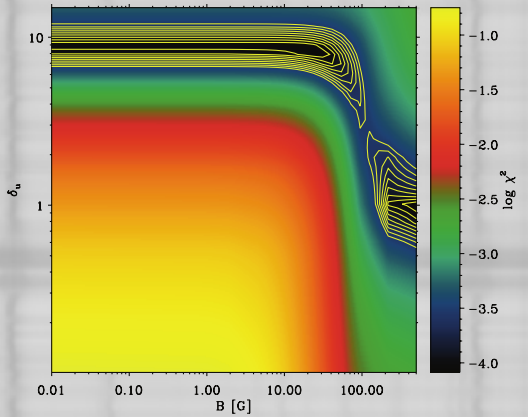

Depolarization of rotational levels of MgH lines (δ_U = coll. depol. rate)

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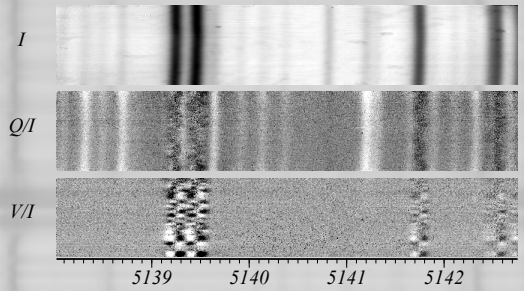
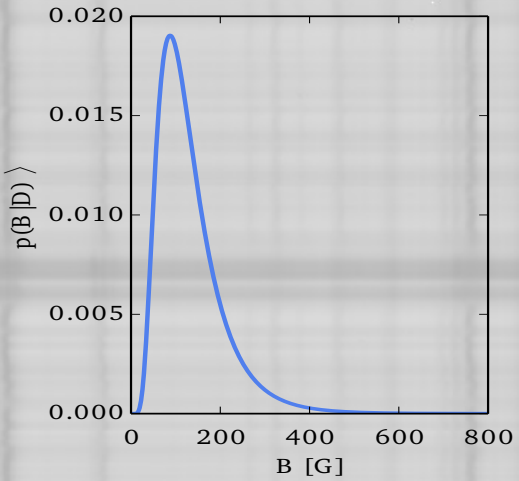


Synoptic program in C_2 line (2 triplets) and 3 FeI lines

Large discrepancies: a matter of the data?

Same instrument: Hinode SOT/SP (Zeeman)

- Asensio Ramos & Martínez González (2014): < 275 G
- Orozco Suárez et al. (2007): $B_v = 9.5$, $B_h = 11.3$
- Lites et al. (2008): $B_v = 11$, $B_h = 55$
- Stenflo (2010): bimodal (B_v = 5-10; 1 kG)



Bayesian analysis of Hinode SOT/SP data

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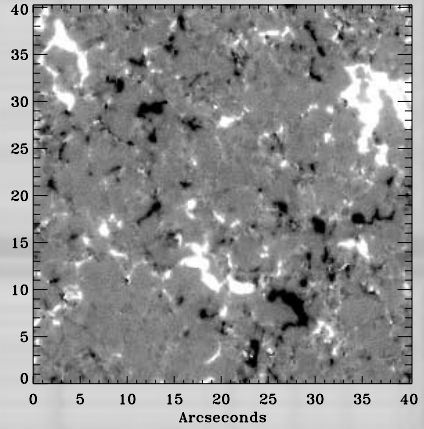

Deep mode scans Hinode SOT/SP

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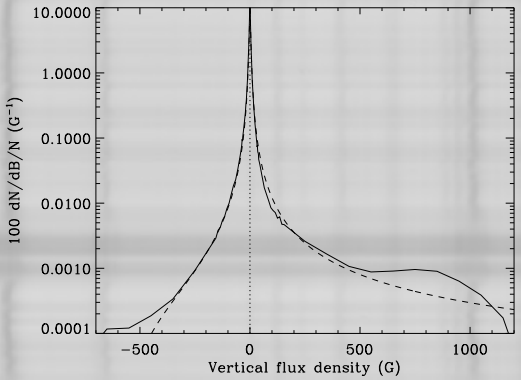


Magnetic dichotomy with two distinct populations

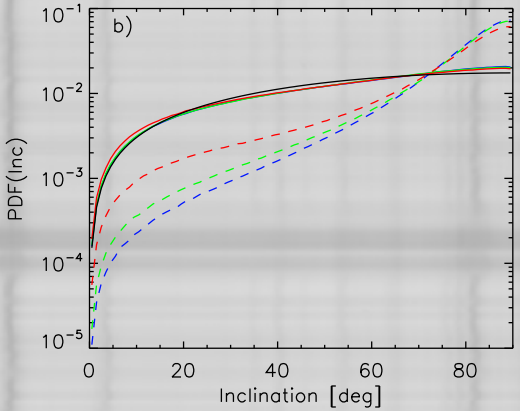
QS fields: Orientation

Local turbulent dynamo

- MHD: $P(\gamma) \propto \sin\gamma$
  (e.g. Vögler & Schüssler, 2007)
- height dependent
  (Rempel, 2014)

Measurements

- isotropic + horizontal peak
- isotropic
- mainly horizontal
- isotropic + vertical peak
- bimodal



solid: $\log\tau = 0$, dashed: ≈450 km

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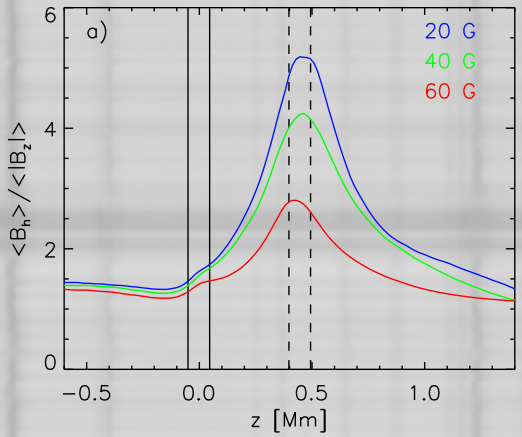

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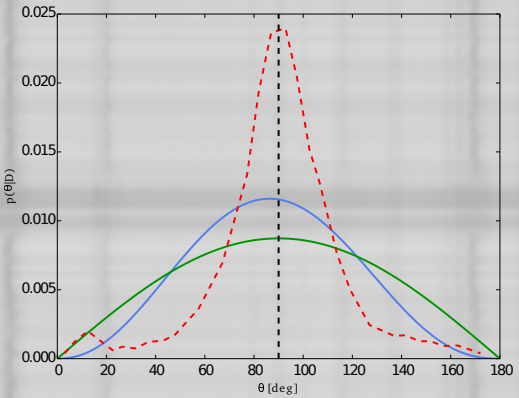

Asensio Ramos & Martínez González (2014)

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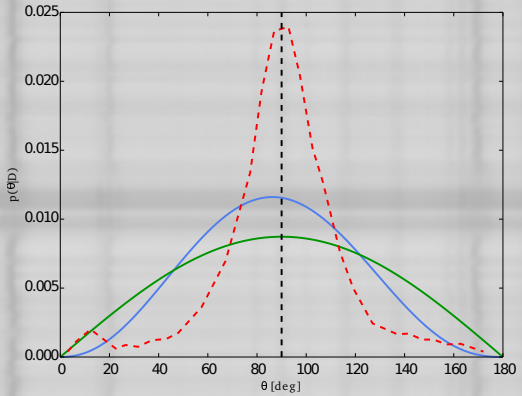

Martínez González et al. (2008); Asensio Ramos (2009)

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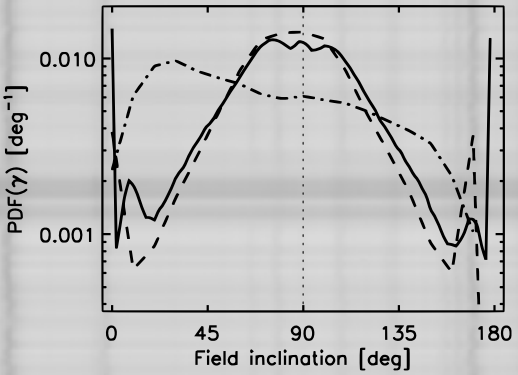

Orozco Suárez et al. (2007); Orozco Suárez & Bellot Rubio (2012); Lites et al. (2008)

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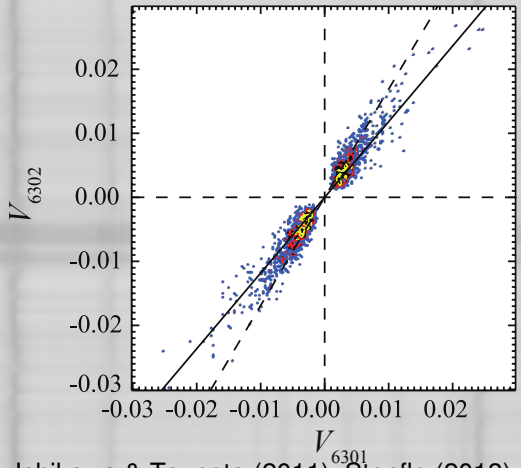

Ishikawa & Tsuneta (2011); Stenflo (2013)

Occurrence on solar disk

Assumption

if $P_\gamma \neq f(\mu) \Rightarrow$ isotropic distribution

Studies

- Martínez González et al. (2008): same signals at all μ-angles
- Borrero & Kobel (2013): B more horizontal at $\mu = 1$ than $\mu = 0.7$
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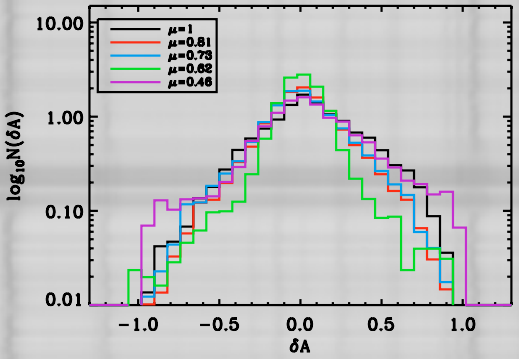

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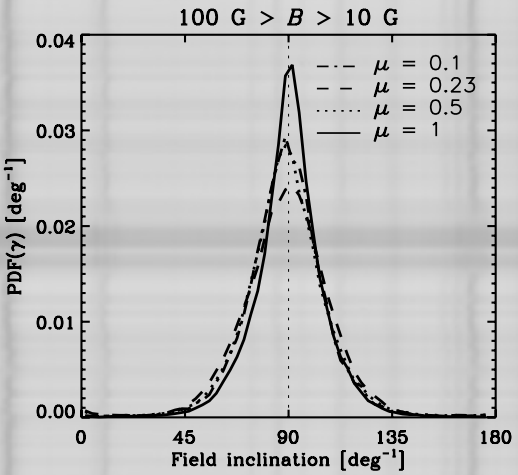

Summary of observations

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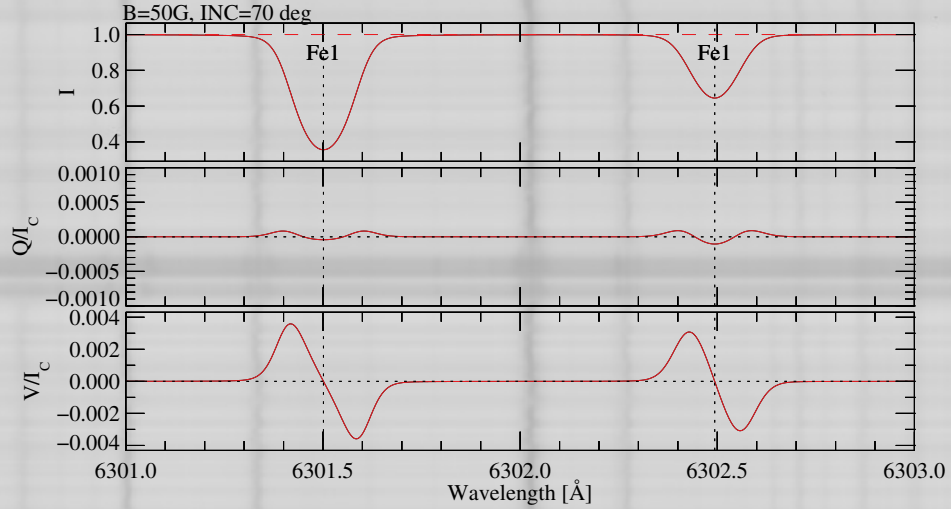
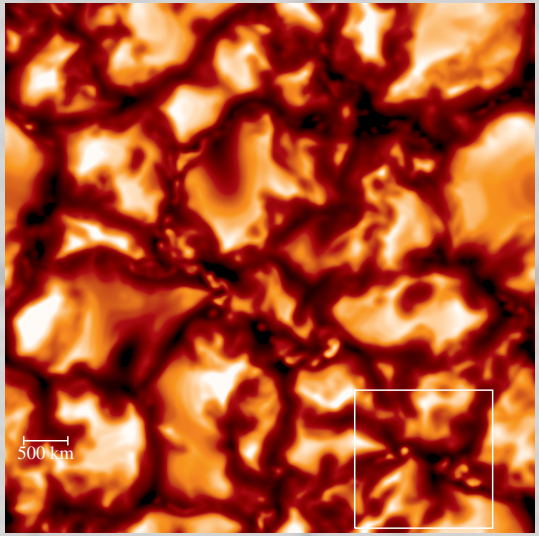
Sensitivity of polarimeters



Unresolved Stokes signals – signal cancellation



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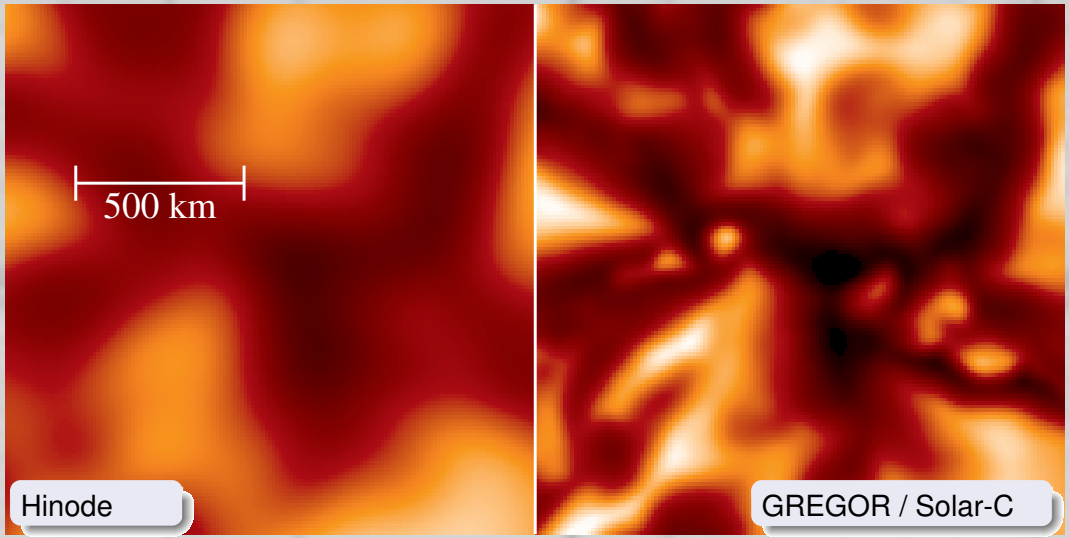

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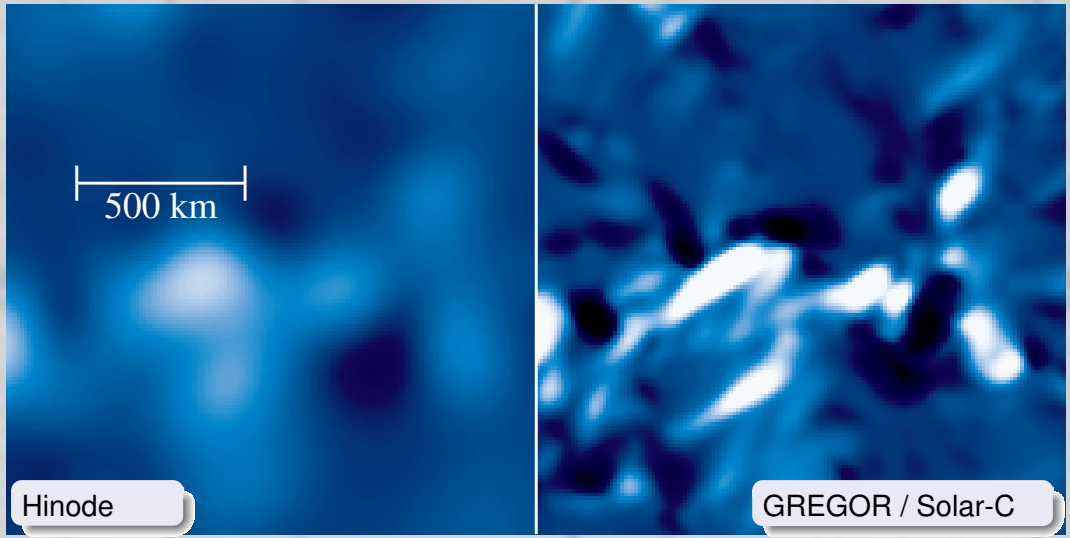


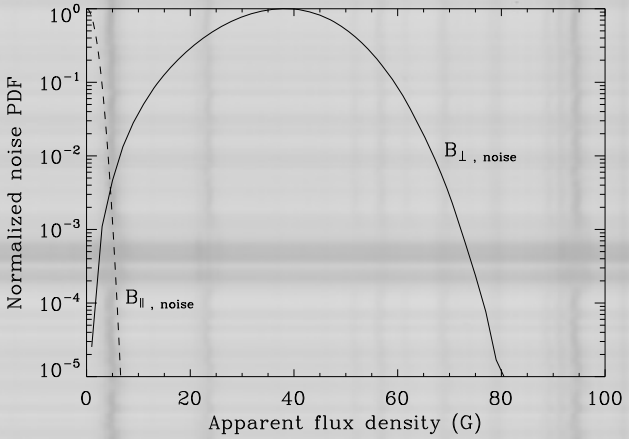
Bias introduced by Zeeman effect

weak-field limit

$$B_{||} \propto V$$
$$B_{\perp} \propto [Q^2 + U^2]^{1/4}$$

Stenflo (2013)

- ⇒ noise leads to more horizontal fields (disk center)
- ⇒ Gaussian noise: 25× higher in $B_{\perp}$



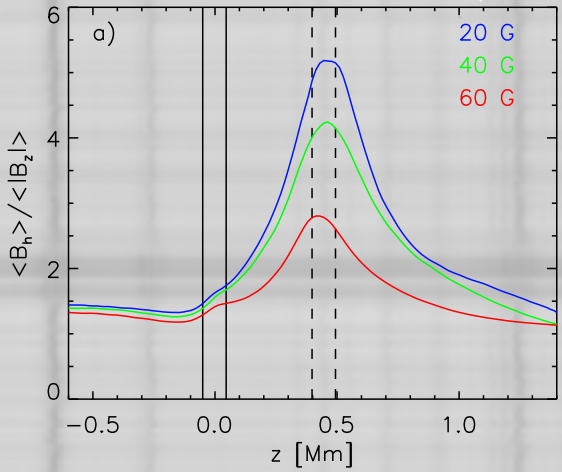
Hinode SOT/SP example

Height dependent B⊥ & B$_{||}$

B$_\perp$ vs. B$_{||}$

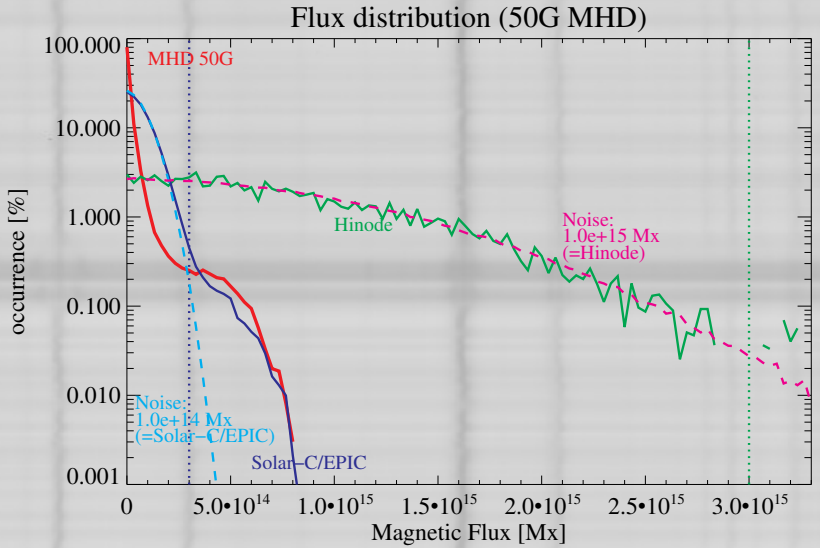
depends strongly on

- spectral line selection
- analysis method (height dependent inversion vs. ME)
- heliocentric angle (higher opacity at limb)



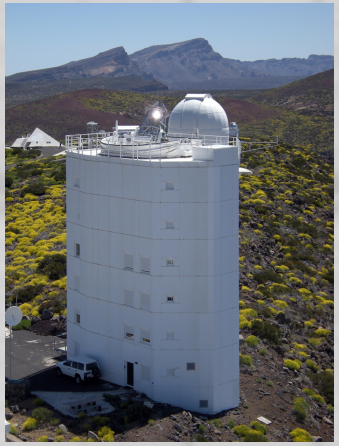
Rempel (2014)

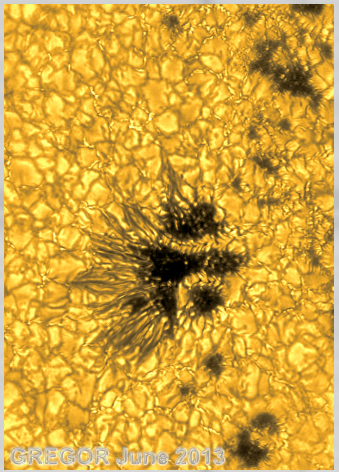
Solution: new instrumentation (Solar-C / GREGOR / DKIST)

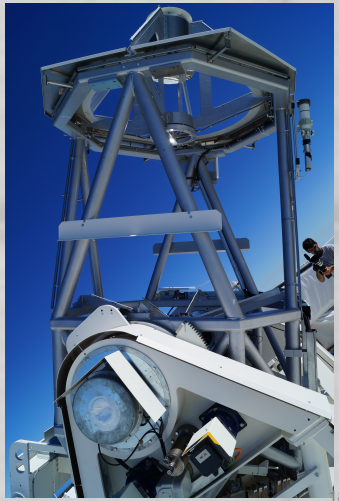


A biased view

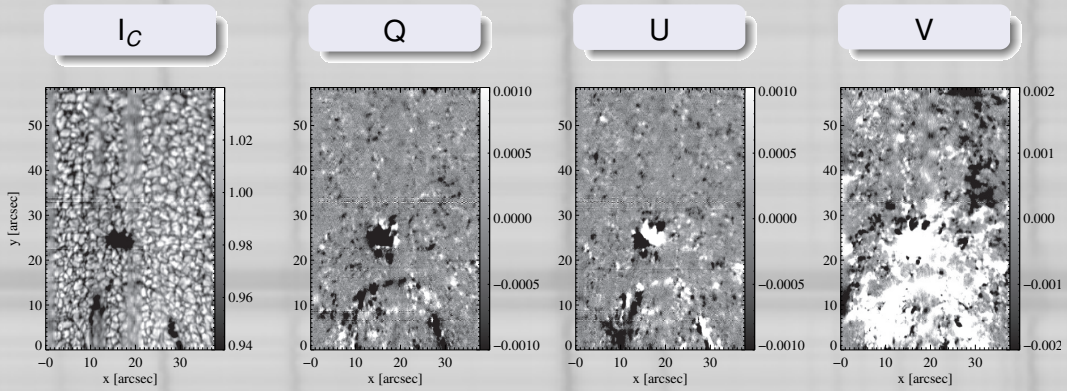
Recent results from GREGOR / GRIS







Scan of pore with quiet sun region (2014-Sep-08)

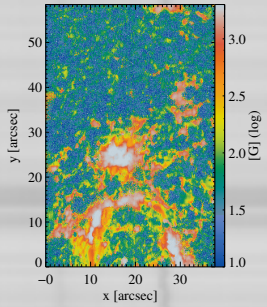


- x, y = 455″, 247″ ($\mu = 0.84$)
- exp. time: 1 s/pixel and mod. state
- noise level (unbinned): $4 \cdot 10^{-4}$ I_C

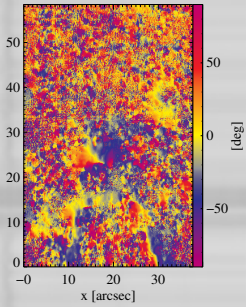
- $\lambda/\Delta\lambda \geq 150000$, 40 mÅ sampling
- spatial resolution: 0.″35 (close to diff. limit), sampling: 0.″126

Scan of pore with quiet sun region (2014-Sep-08)

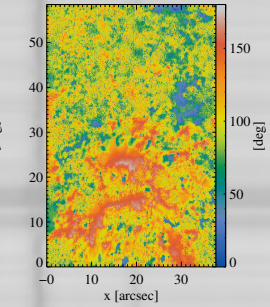
B



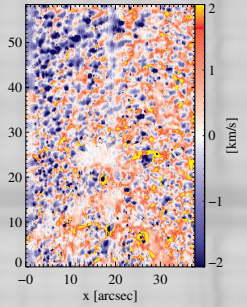
AZI



INC



v_{LOS}



Inversion setup

- Milne Eddington in 6 Fe I lines

  15631 – 15665 Å, line strength as free parameter

- free parameters

  $B, \phi, \gamma, v_{LOS}, v_D, a, S_1, \eta_0, \alpha$

- global straylight (broad PSF wings)

Scan of pore with quiet sun region (2014-Sep-08)

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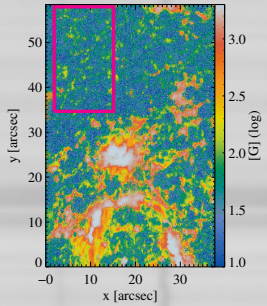

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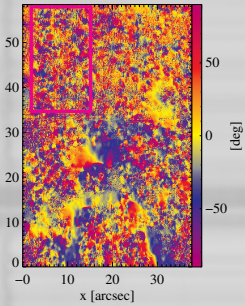

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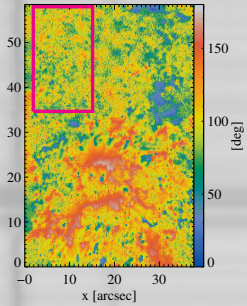

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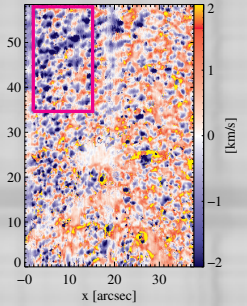

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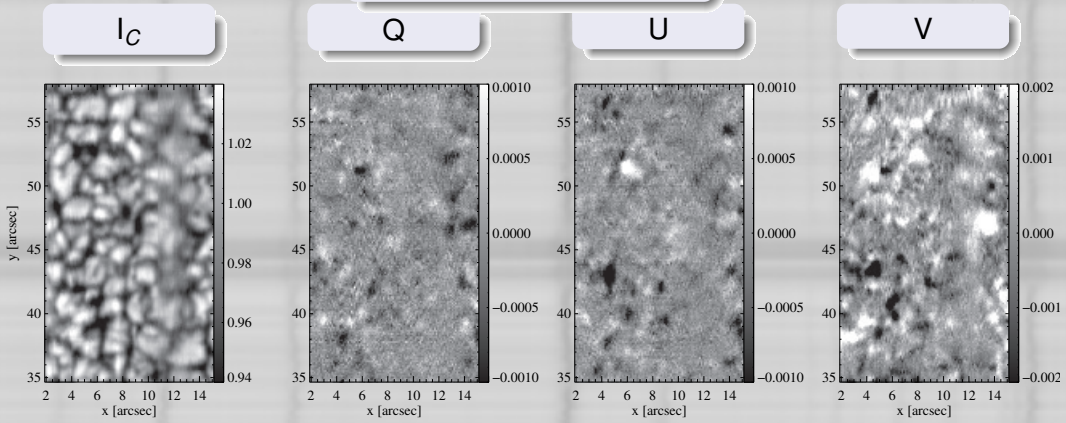
Very quiet sun region (2014-Sep-08)

All pixels



Very quiet sun region (2014-Sep-08)

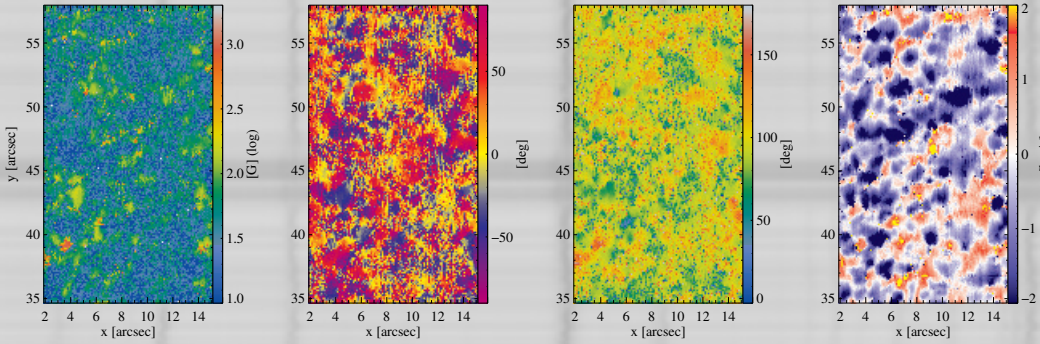
All pixels

B

AZI

INC

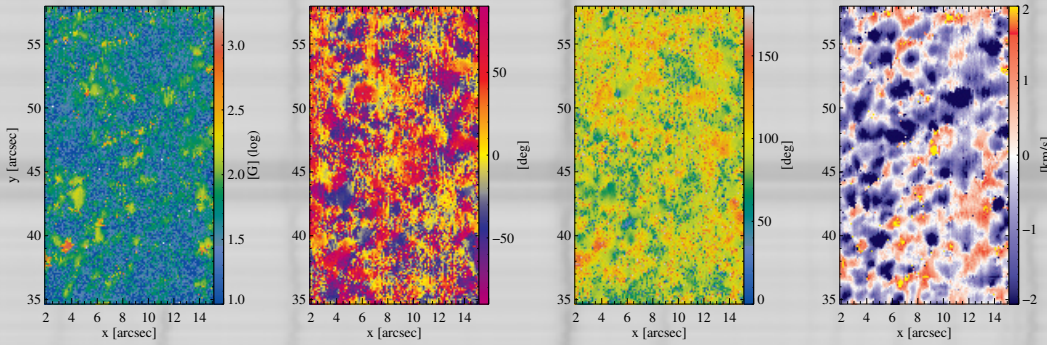
v_{LOS}



Very quiet sun region (2014-Sep-08)

All pixels

B AZI INC v_{LOS}

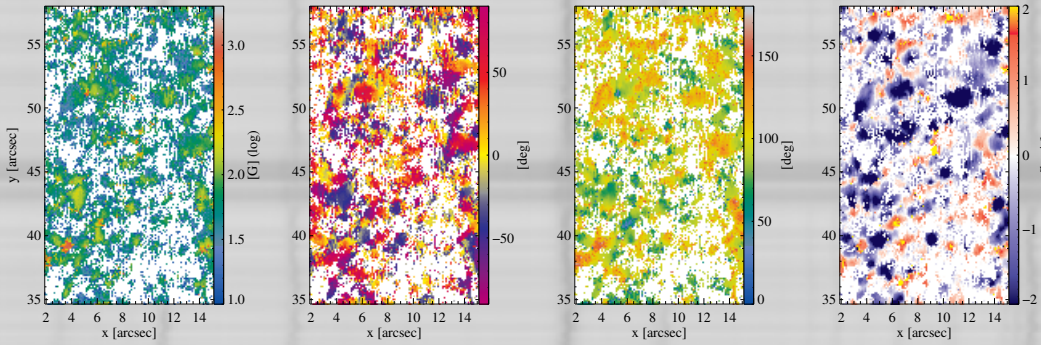


remove all pixels with low signals
Survival of IG lanes or granules?

Very quiet sun region (2014-Sep-08)

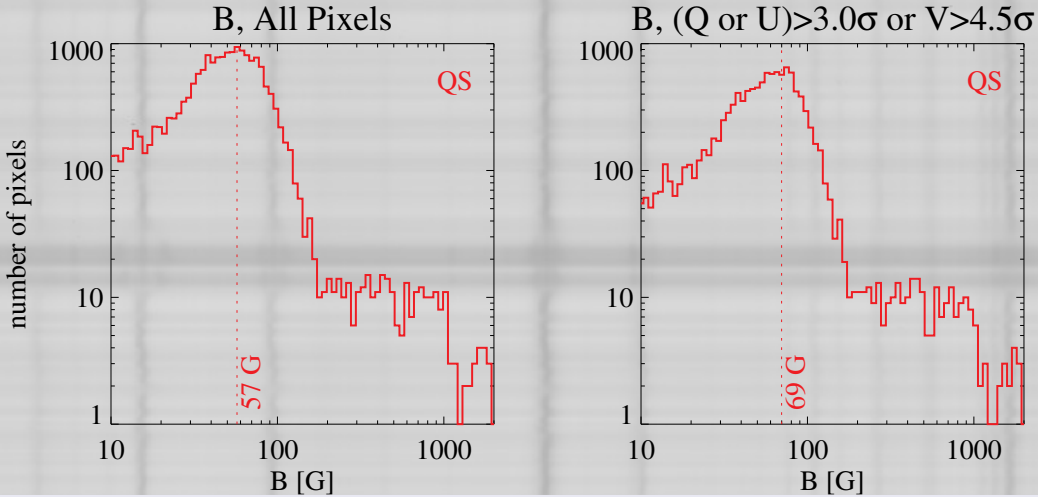
$$[(Q \vee U) > 3\sigma] \vee [V > 4.5\sigma]$$

B AZI INC ^{V}LOS



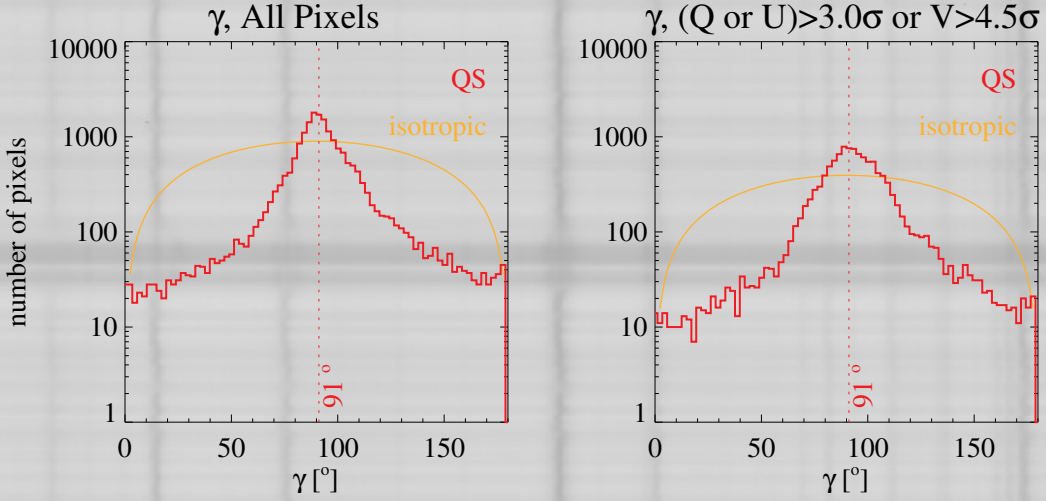
Mainly granules!
... and some IG lanes

Histogram: Magnetic Field Strength (Very quiet region, 40–50 Mx cm^{-2})

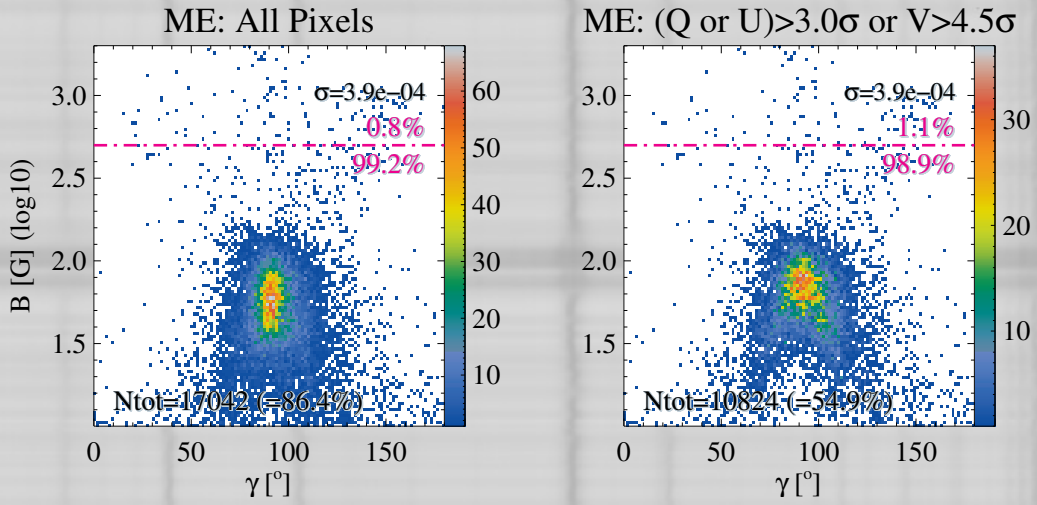


Hinode based studies: 10–50 G

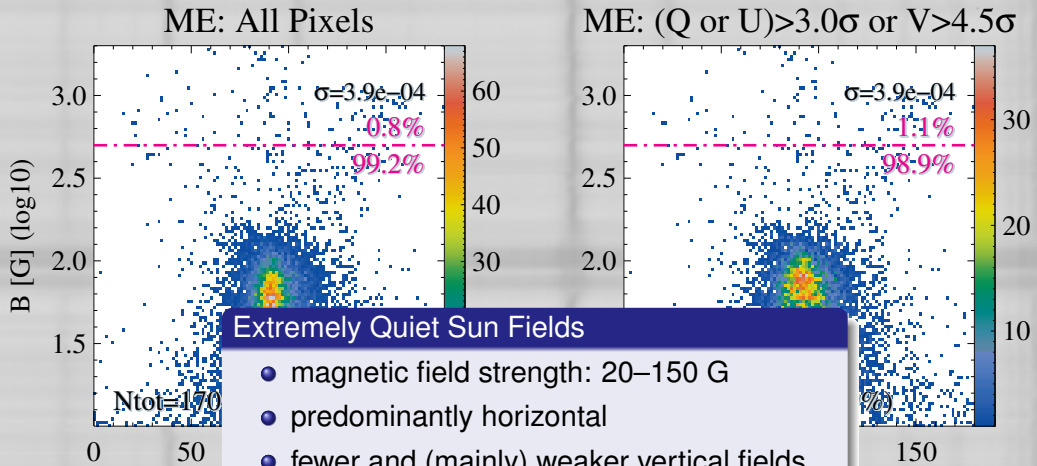
Histogram: Magnetic Field Inclination (Very quiet region, 40–50 Mx cm^{-2})



2D-Histogram: B vs. γ (Very quiet region, 40–50 Mx cm^{-2})



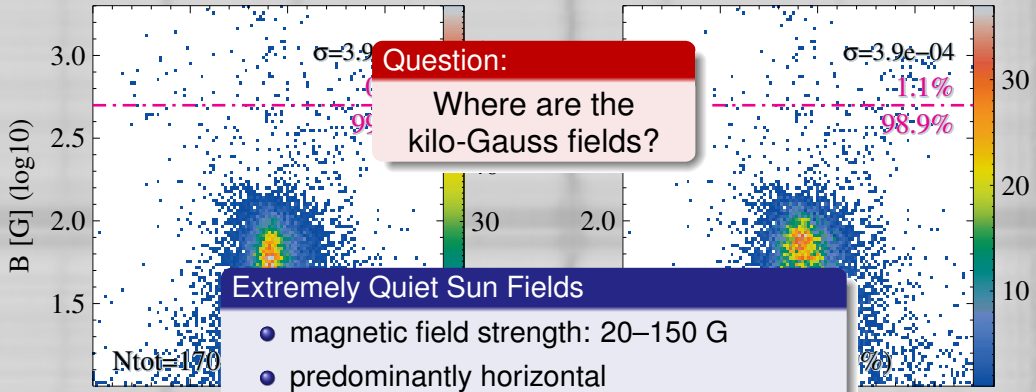
2D-Histogram: B vs. γ (Very quiet region, 40–50 Mx cm^{-2})



Extremely Quiet Sun Fields

- magnetic field strength: 20–150 G
- predominantly horizontal
- fewer and (mainly) weaker vertical fields
  resulting from tiny Stokes V signals

2D-Histogram: B vs. γ (Very quiet region, 40–50 Mx cm^{-2})



Question:

Where are the kilo-Gauss fields?

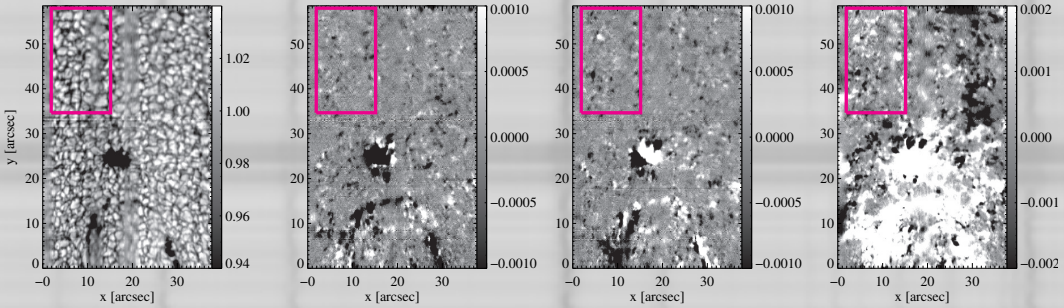
Extremely Quiet Sun Fields

- magnetic field strength: 20–150 G
- predominantly horizontal
- fewer and (mainly) weaker vertical fields
  resulting from tiny Stokes V signals

Search for kilo-Gauss fields

All pixels

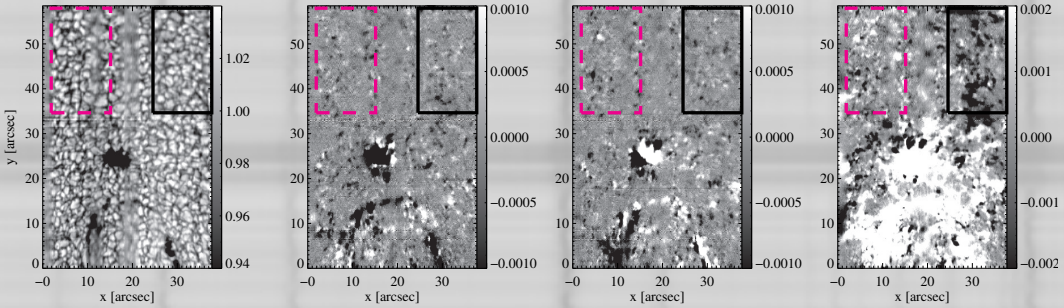
I_C Q U V



Search for kilo-Gauss fields

All pixels

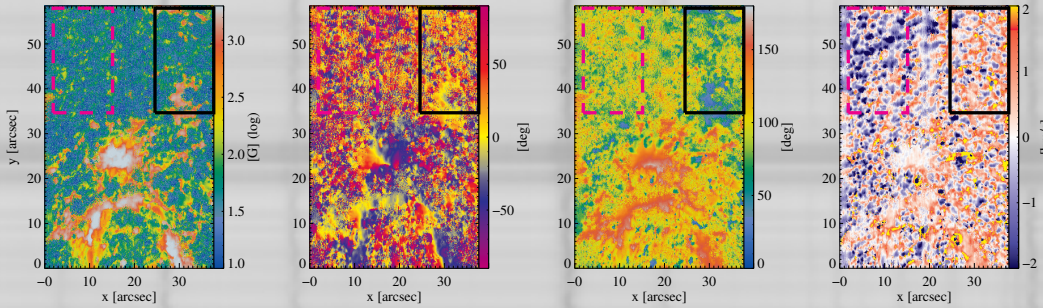
I_C Q U V



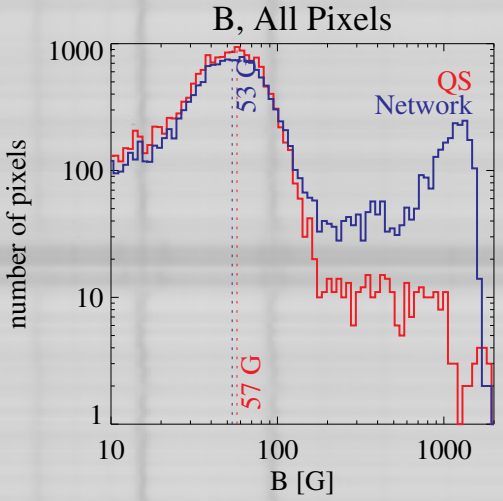
Search for kilo-Gauss fields

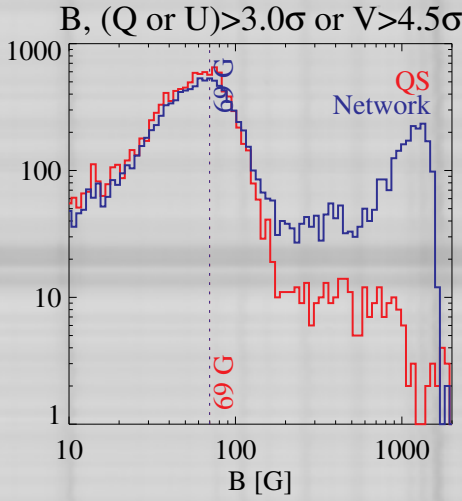
All pixels

B AZI INC v_{LOS}

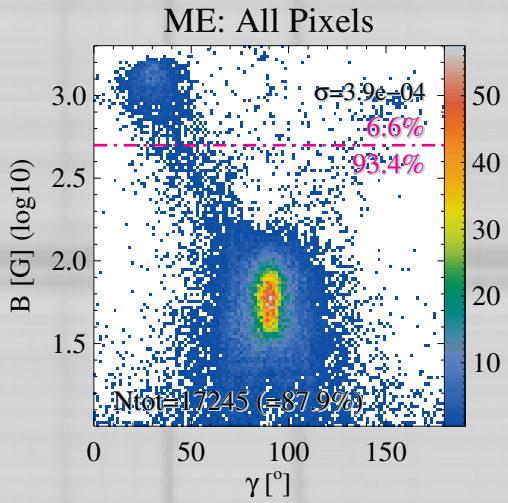


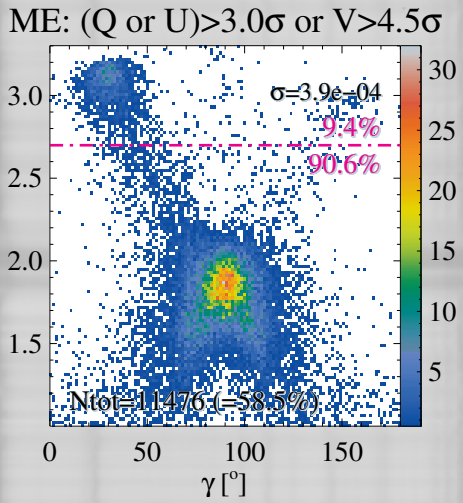
Histogram: Magnetic Field Strength (QS + network fields, $\approx$150 Mx cm^{-2})



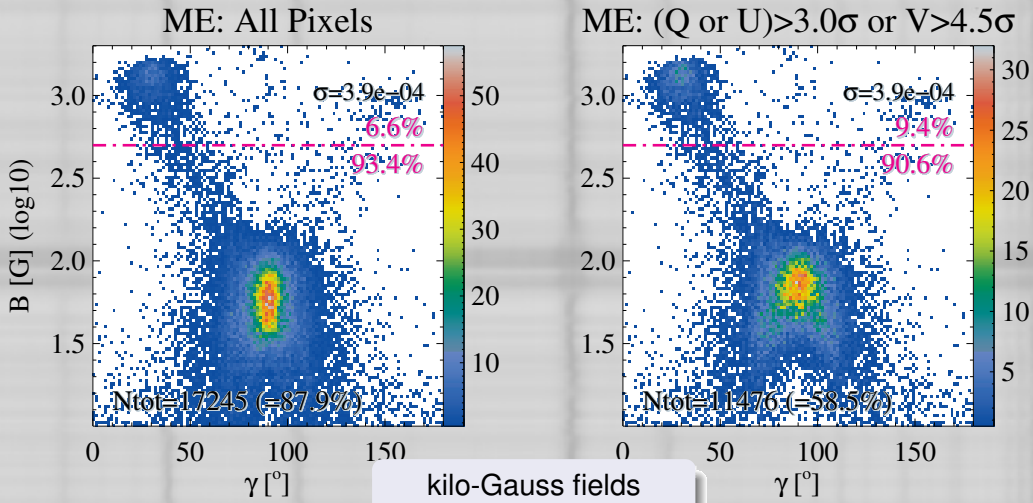


2D-Histogram: B vs. γ (QS + network fields, $\approx$150 Mx cm^{-2})



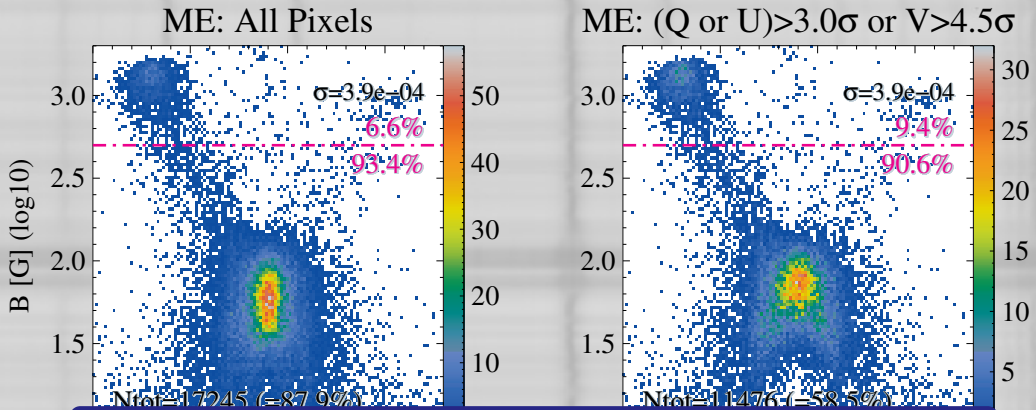


2D-Histogram: B vs. γ (QS + network fields, $\approx$150 Mx cm^{-2})



kilo-Gauss fields
in network patches

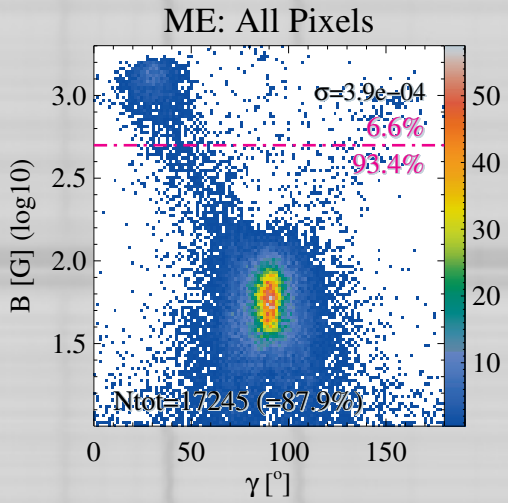
2D-Histogram: B vs. γ (QS + network fields, $\approx$150 Mx cm^{-2})

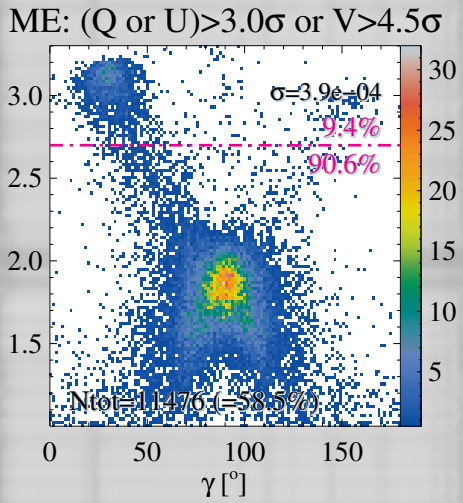


Stenflo (2010) *"... magnetic dichotomy with two distinct populations"*

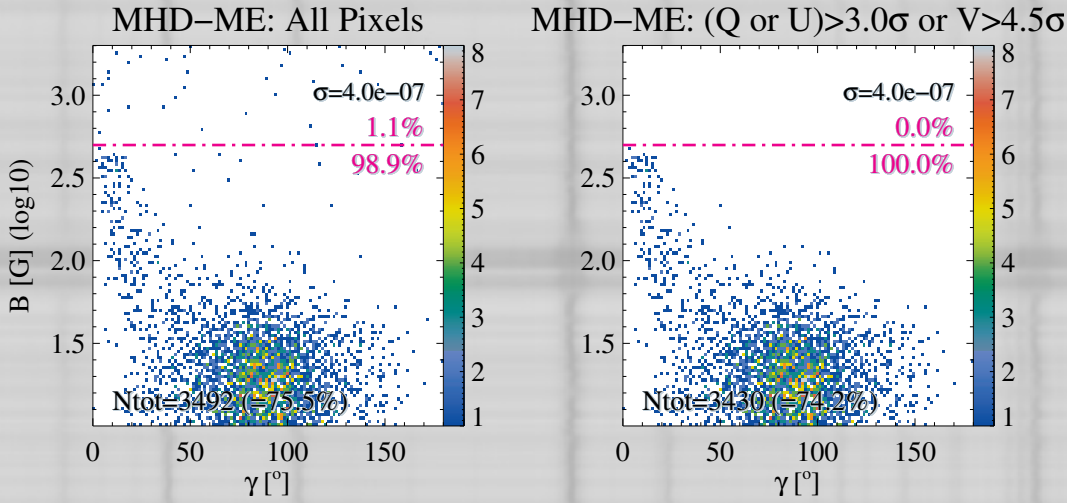
1. collapsed: kG, extremely vertical
2. uncollapsed: weak fields, asymptotically isotropic at zero flux

2D-Histogram: B vs. γ (QS + network fields, $\approx$150 Mx cm^{-2})

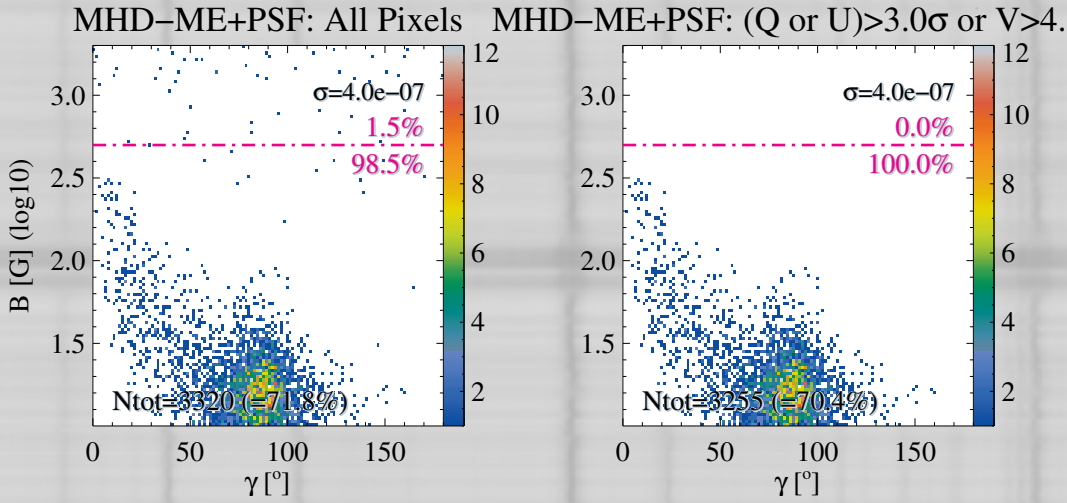




2D-Histogram: B vs. γ MHD-data



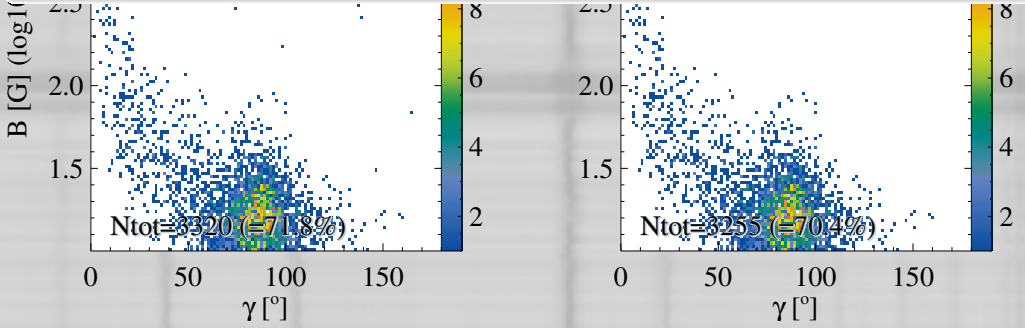
2D-Histogram: B vs. γ MHD-data



2D-Histogram: B vs. γ MHD-data

Increase of B_h:B_v from decrease in spatial res!

- $B_h \propto \sqrt{Q, U}$, $B_v \propto V$ $\Rightarrow$ $B_h^{PSF} = \sqrt{\alpha} B_h$
- PSF-convolution: reduces signal Q, U and V signal by same factor α $\Rightarrow$ $B_v^{PSF} = \alpha B_v$ $\Rightarrow$ recovered field is more horizontal!



2D-Histogram: B vs. γ MHD-data

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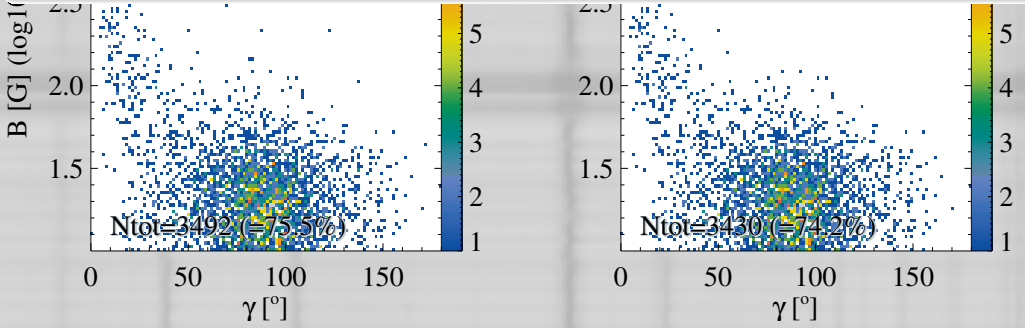

Quiet Sun & Network: GRIS results

Quiet Sun & Network Fields: two distinct populations

- prevalent horizontal (may be biased by weak signals!)
- dominated by weak fields:

inversion	$\log\tau = -0.8$	$\log\tau = 0$
ME	50–150 G	
1D	30–100 G	50–200 G
LS removed	30–100 G	80–400 G

- 2^{nd} population with mainly vertical, $>$ 1 kG fields
- kG fields only in deepest layer
- lack of hG fields & intermediate inclinations

$\rightarrow$ consistent with bimodal distribtion

Summary: Quiet Sun Magnetism

Agreement:

- crucial to understand solar magnetism

Disagreement

- dependency with level of solar activity
- strength, direction, μ-dependence

Steps toward a solution

Advances in instrumentation:

- Hi-res &pol. sensitivity (10^{-4})

$\rightarrow$ GREGOR, NST, DKIST, EST, Solar-C

Advances in analysis:

- inversions: proper treatment of straylight (“filling-factor” discussion, 2D-inversions)
- proper treatment of height-dependence
- improved modelling (Hanle)

ISSI workshop “Quiet-Sun Magnetism”: Application running...

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Stokes Profiles: Granule (TP) $> 3\sigma$