Quiet-Sun Magnetism

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

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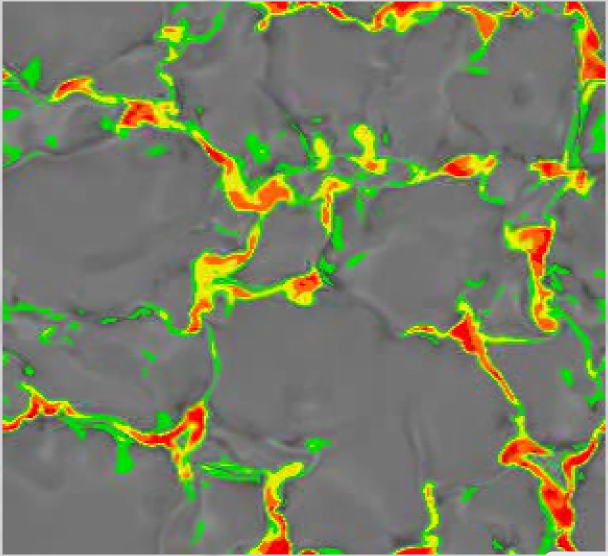
MAX-PLANCK-GESELLSCHAFT

ISSI workshop Hi-res chromosphere
July 20-24 2015
Bern

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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$\longrightarrow$ difficult measurement!

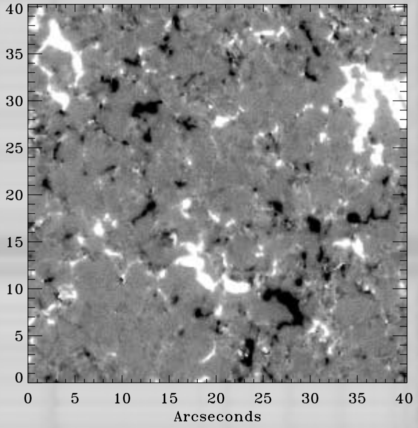
The consequence

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

What is the distribution of field strengths in the QS?

Same instrument: Hinode SOT/SP (Zeeman)

- 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)
- Asensio Ramos & Martínez González (2014): < 275 G



Deep mode scans Hinode SOT/SP

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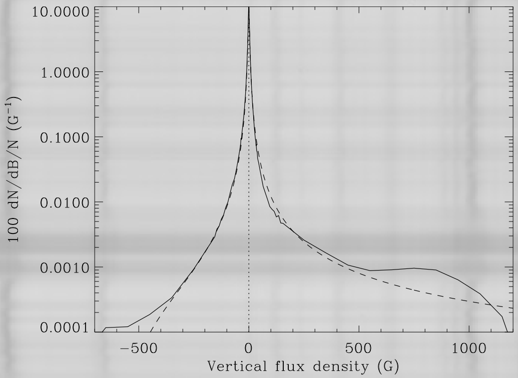

Magnetic dichotomy with two distinct populations

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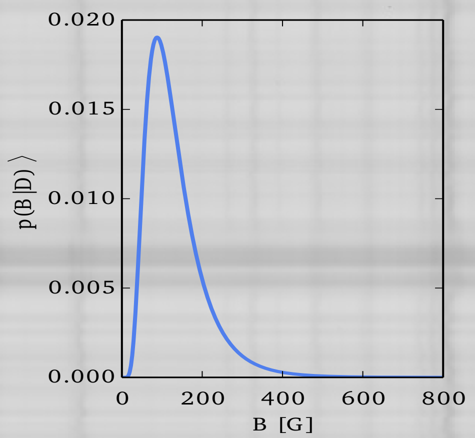
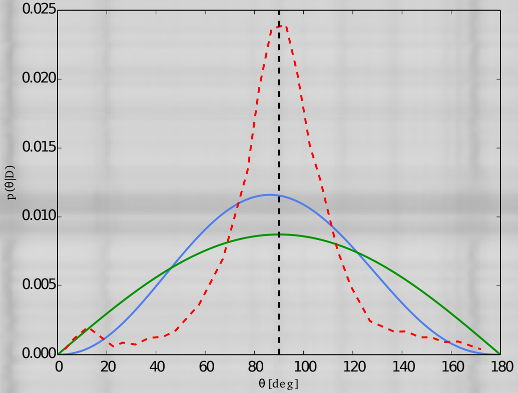


Bayesian analysis of Hinode SOT/SP data

QS fields: Orientation

Measurements

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



Asensio Ramos & Martínez González (2014)

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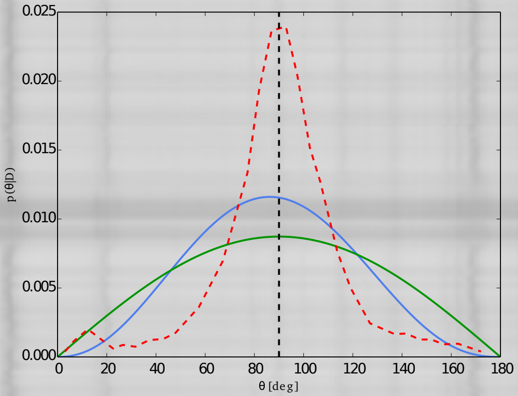

Martínez González et al. (2008); Asensio Ramos (2009)

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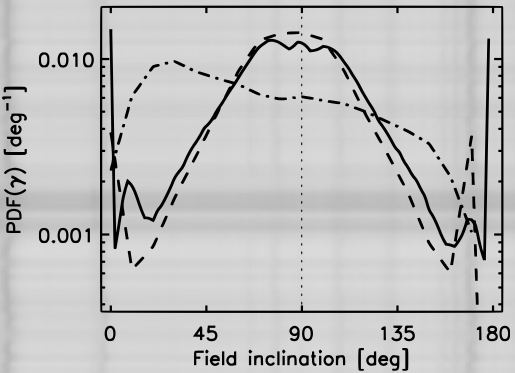

Orozco Suárez et al. (2007); Orozco Suárez & Bellot Rubio (2012); Lites et al. (2008)

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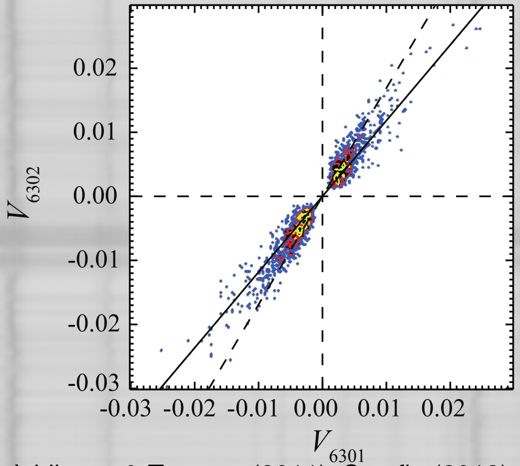

Ishikawa & Tsuneta (2011); Stenflo (2013)

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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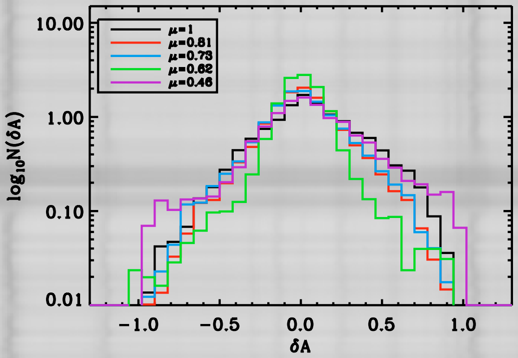

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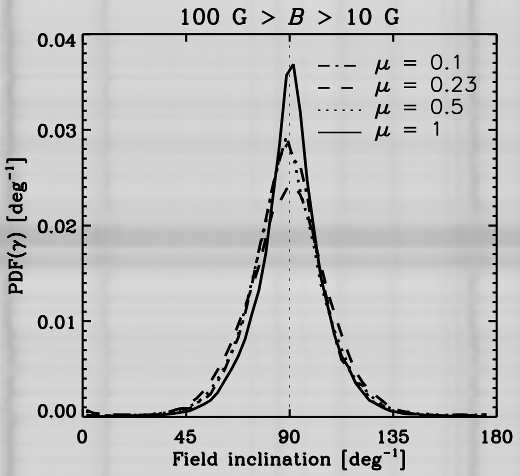

Summary of observations

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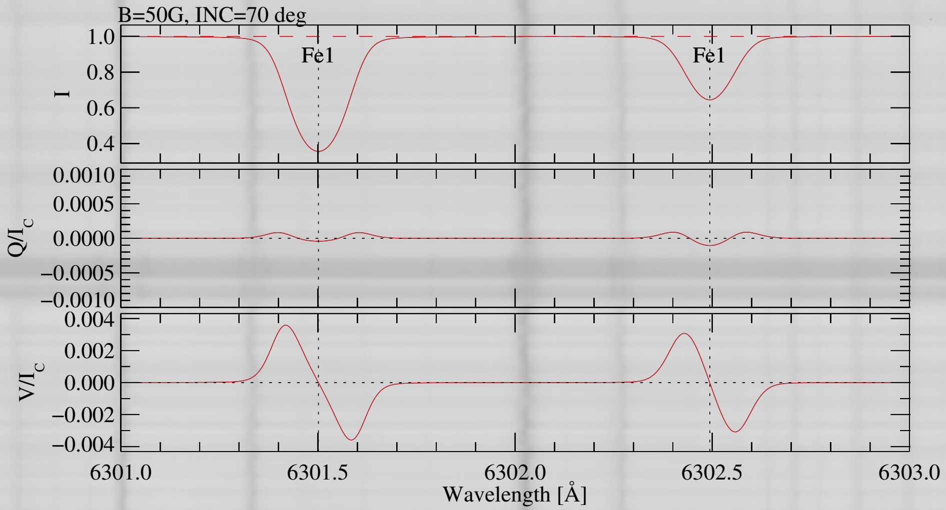
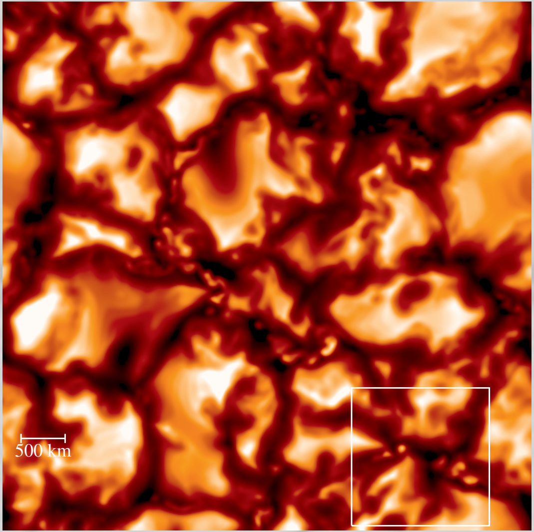
Sensitivity of polarimeters



Unresolved Stokes signals – signal cancellation



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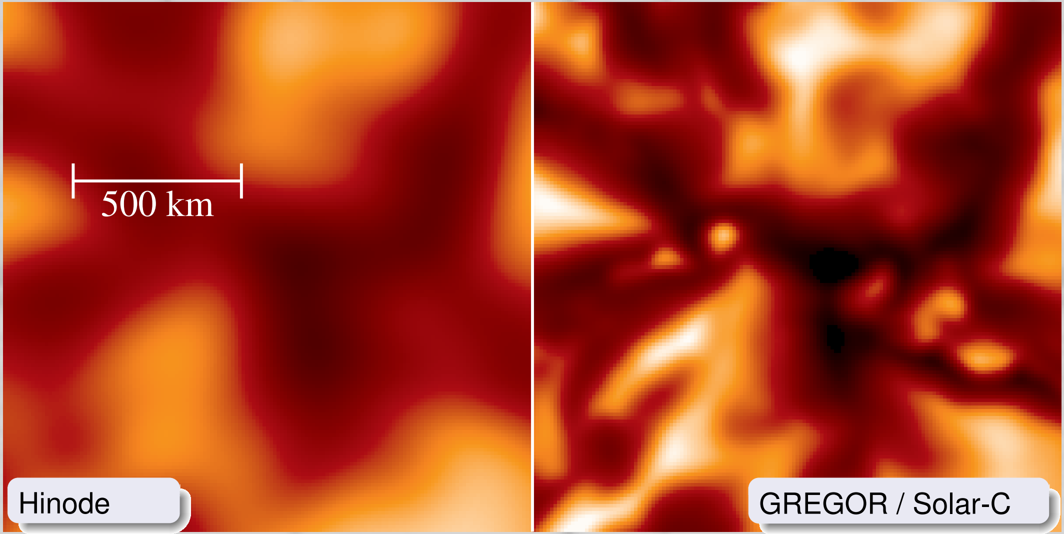

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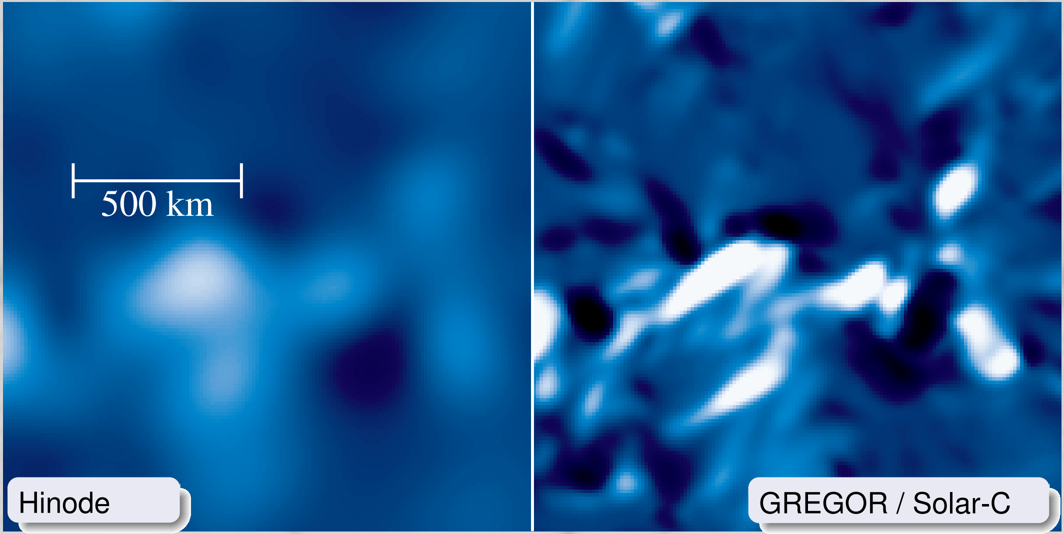


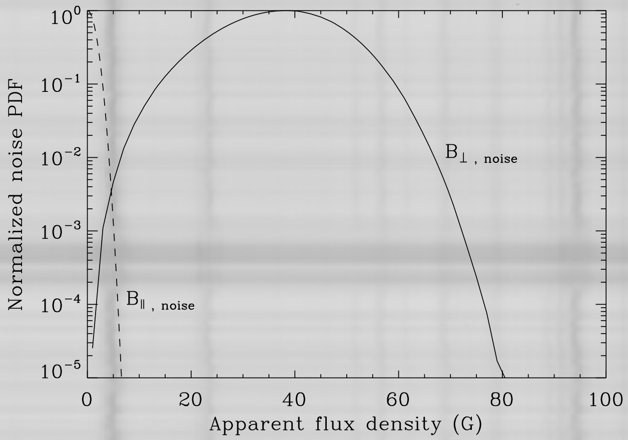
Bias introduced by Zeeman effect

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)
- ⇒ apparent flux: $25\times$ higher in $B_{\perp}$ non-Gaussian



Hinode SOT/SP example

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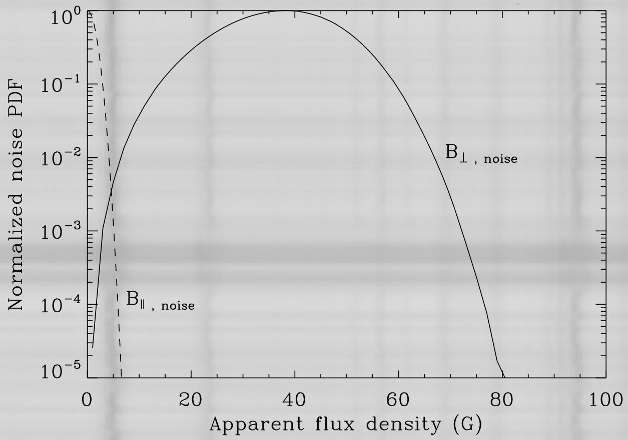
Stenflo (2013)

Histograms of the noise in the deep-mode Hinode SOT/SP observations, converted from polarization to field-strength units using the weak-field approximation. The measured polarization noise is Gaussian with standard deviations 0.035% for Stokes Q and U, 0.047% for V . Although the noise in the linear polarization is smaller, it translates to much larger apparent field strengths $B_{\perp}$,noise than the apparent field strengths $B_{||}$,noise of the circular polarization.



Hinode SOT/SP example

Height dependent B⊥ & $B_{||}$

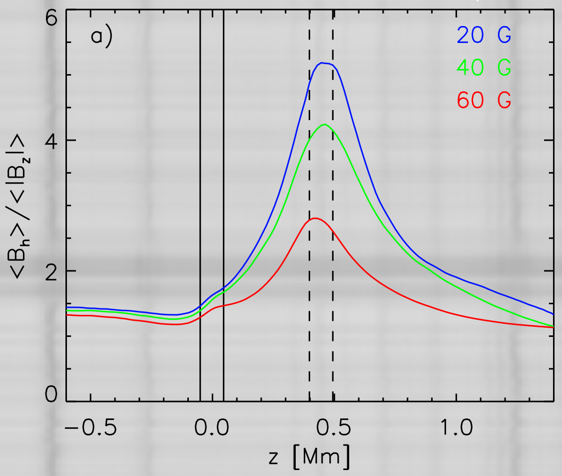
$B_\perp$ vs. $B_{||}$

depends strongly on

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

Local turbulent dynamo

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



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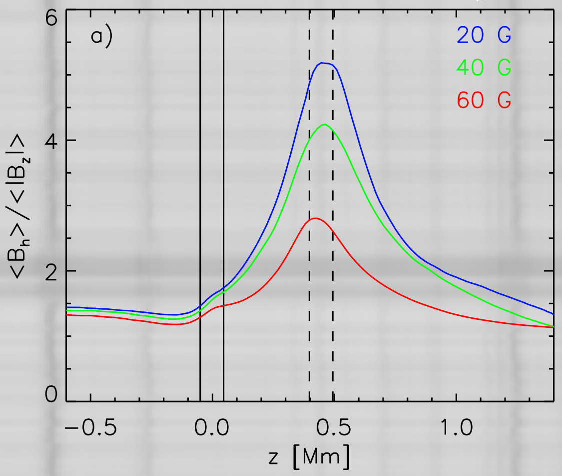

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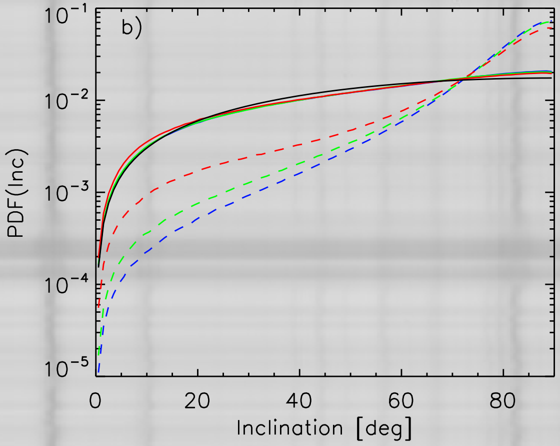
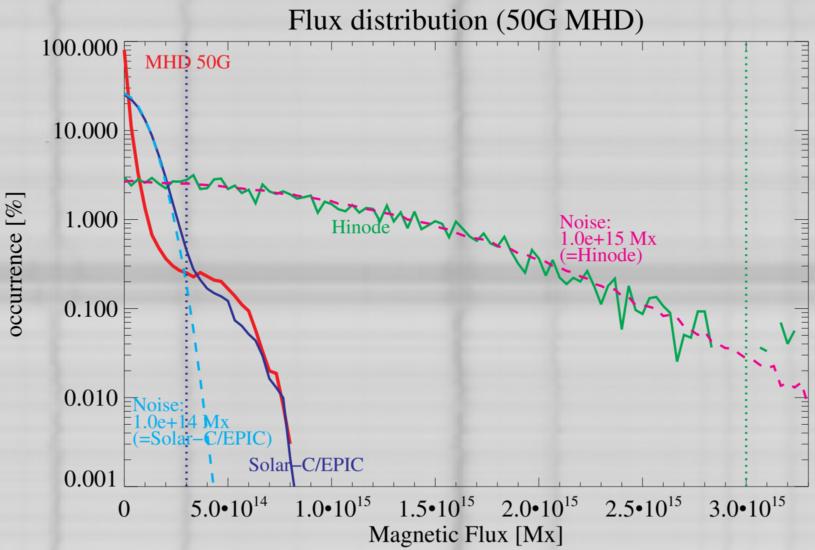


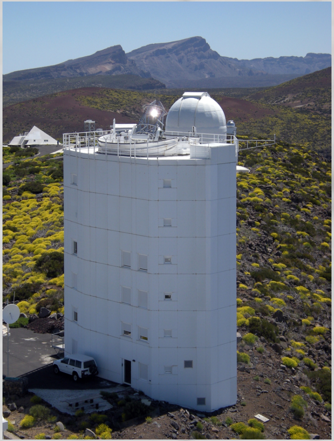
solid: $\log\tau = 0$, dashed: ≈450 km

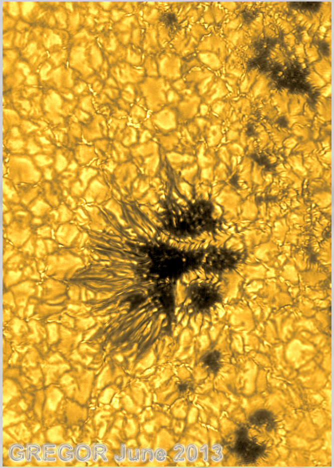
Solution: new instrumentation (Solar-C / GREGOR / DKIST)

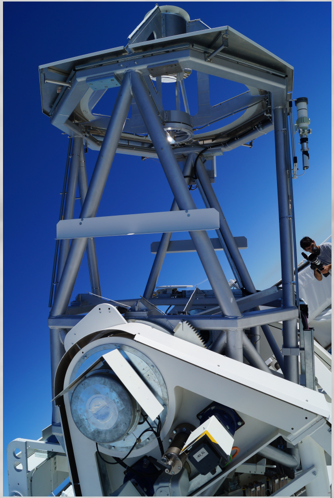


A biased view

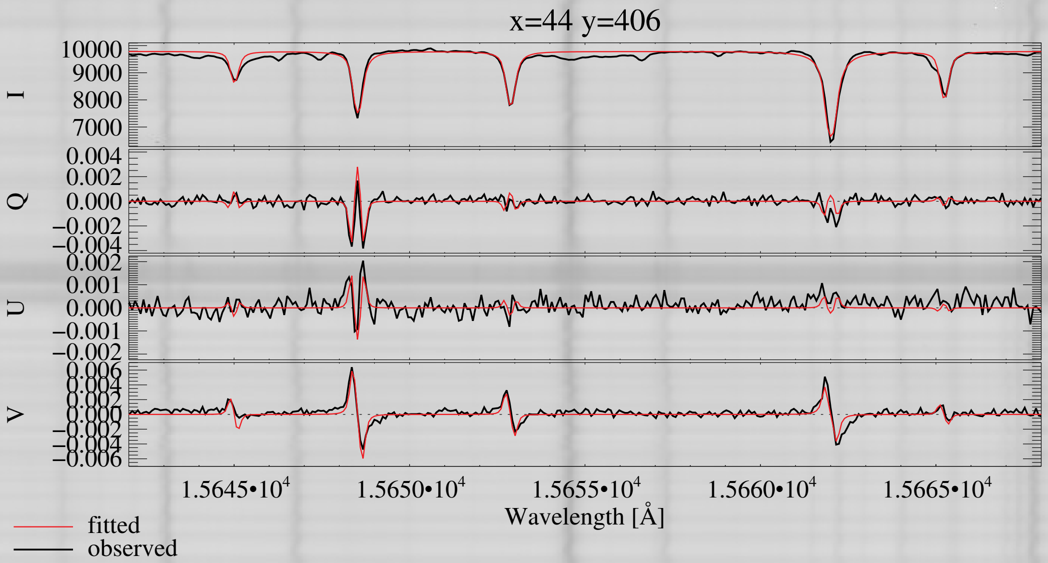
Recent results from GREGOR / GRIS



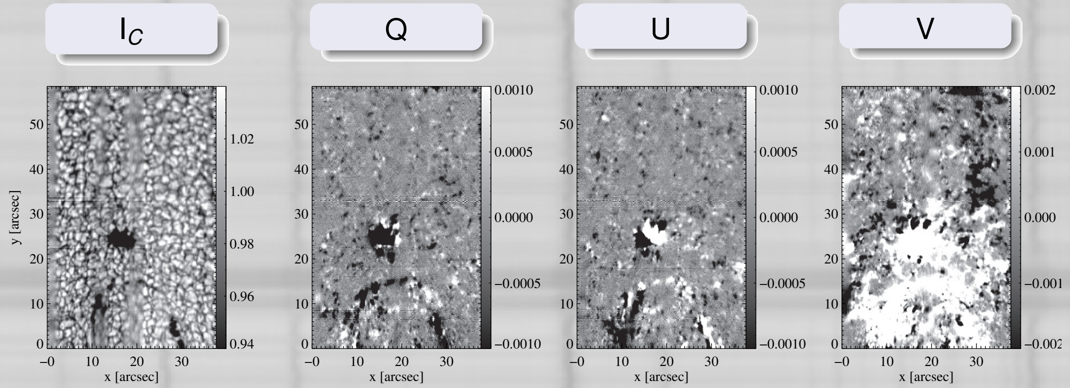




Stokes Profiles: Granule (TP) $> 3\sigma$



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

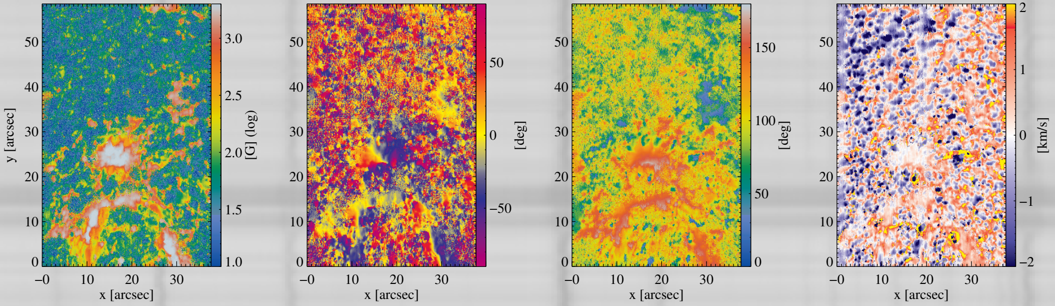


- x, y = 455″, 247″ ($\mu = 0.84$)
- exp. time: 1 s/pixel and mod. state
- noise level (unbinned): $4 \cdot 10^{-4}$ I_C

- $\lambda/\Delta\lambda \geq$ 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

  $B, \phi, \gamma, v_{\mathrm{LOS}}, v_D, a, S_1, \eta_0, \alpha$
- global straylight (broad PSF wings)

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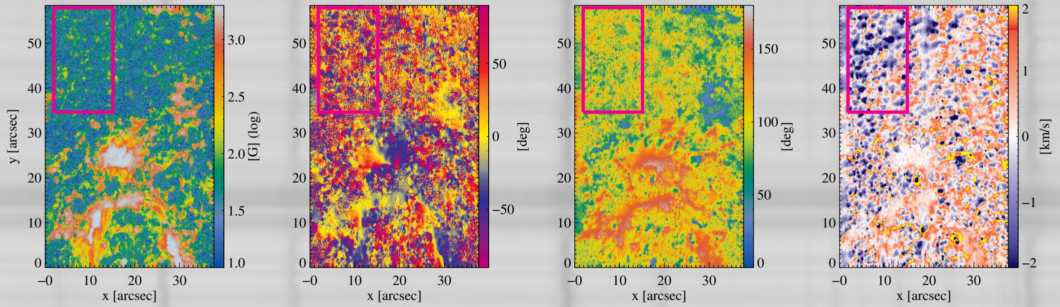

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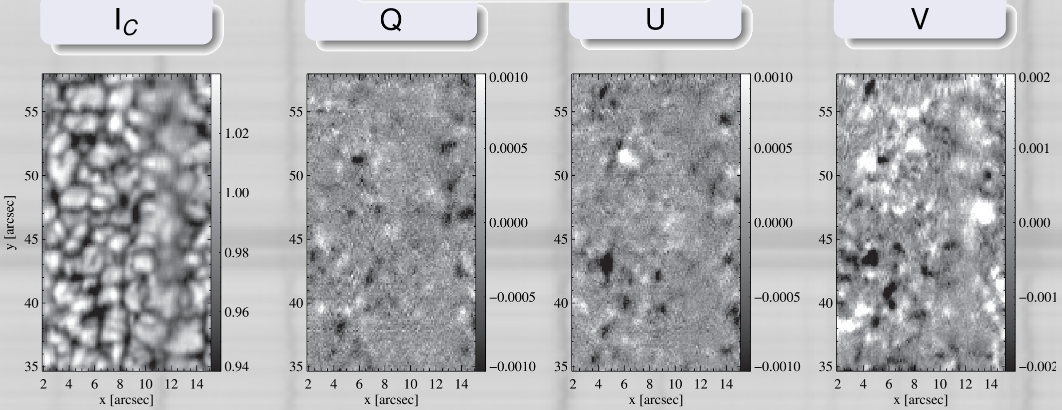
Very quiet sun region (2014-Sep-08)

All pixels



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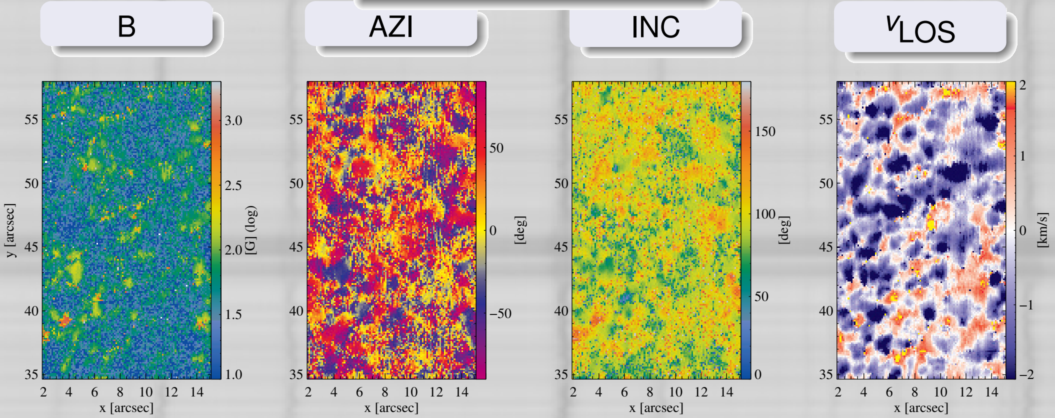

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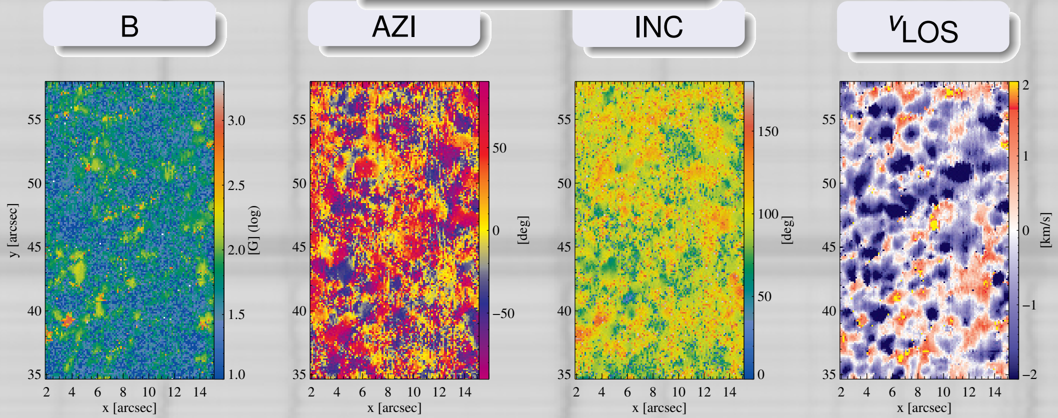
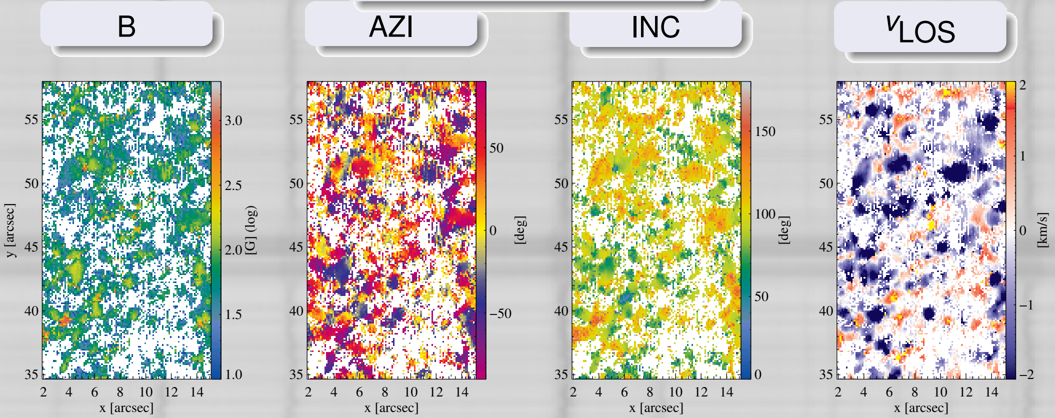


remove all pixels with low signals
Survival of IG lanes or granules?

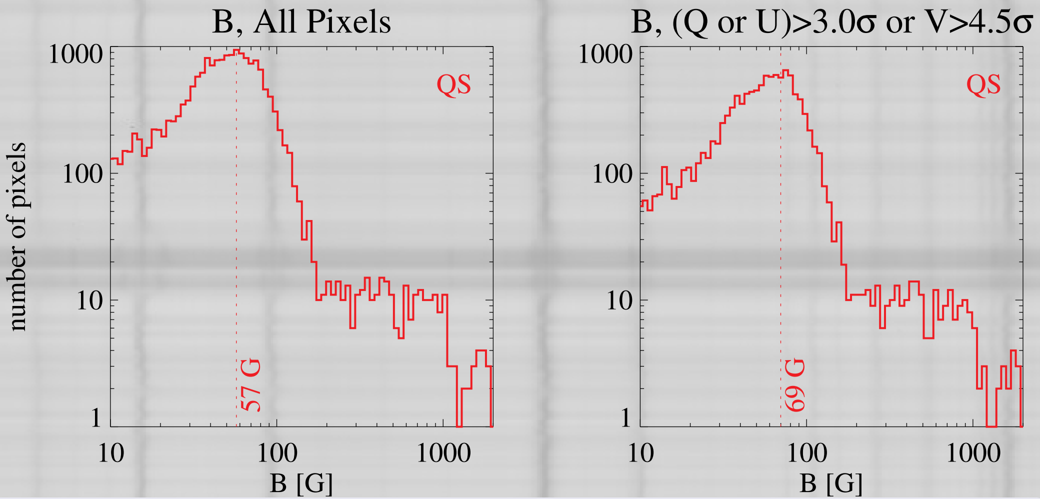
Very quiet sun region (2014-Sep-08)

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



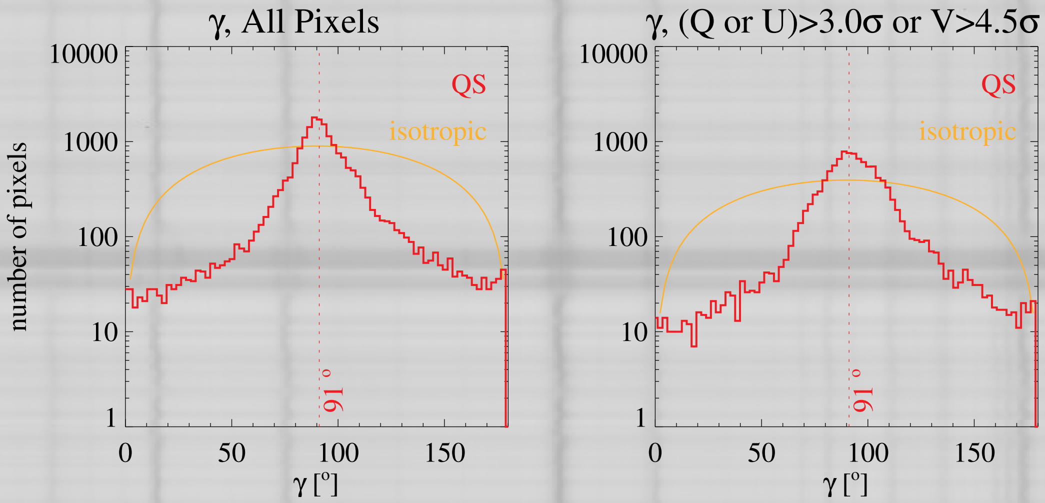
Mainly granules!
... and some IG lanes

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

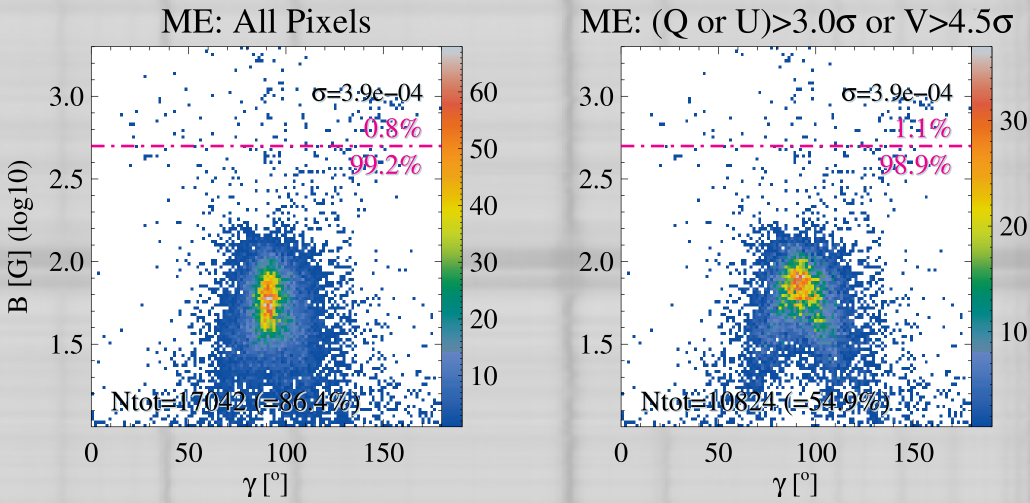


Hinode based studies: 10–50 G

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



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



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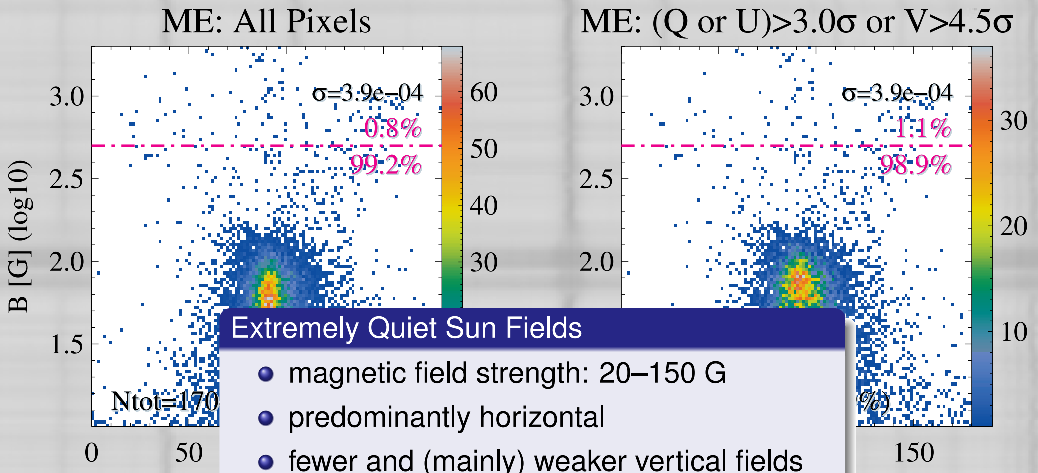
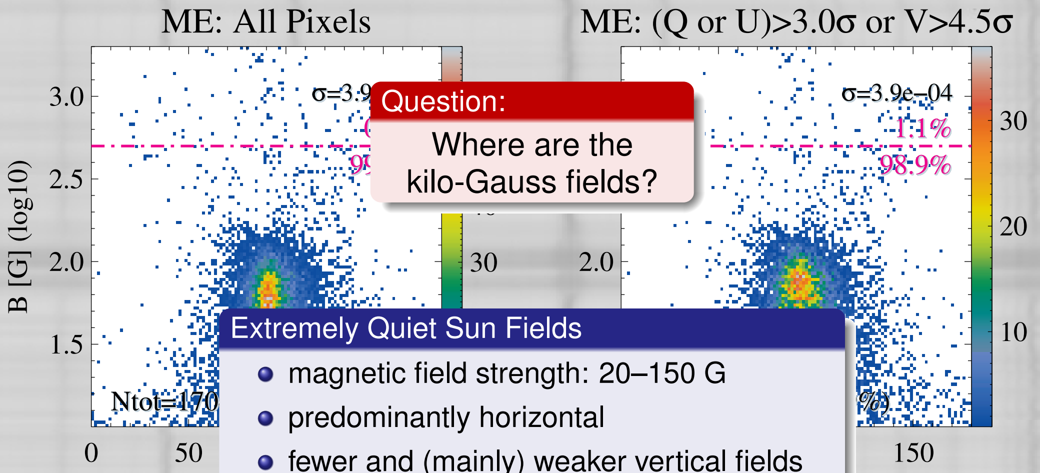


Extremely Quiet Sun Fields

- 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
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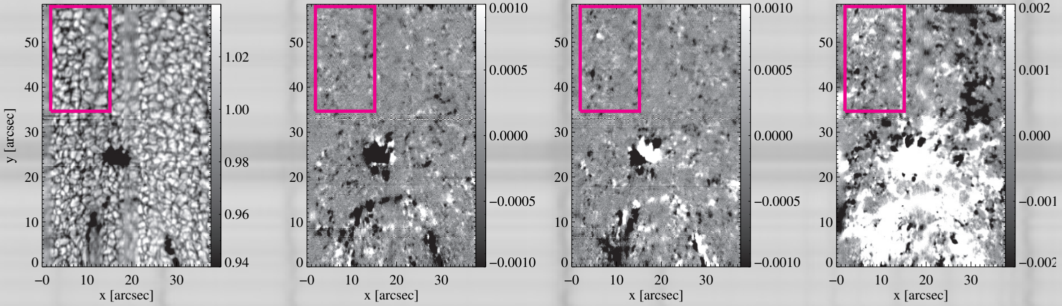
  resulting from tiny Stokes V signals

Search for kilo-Gauss fields

All pixels

I_C Q U V



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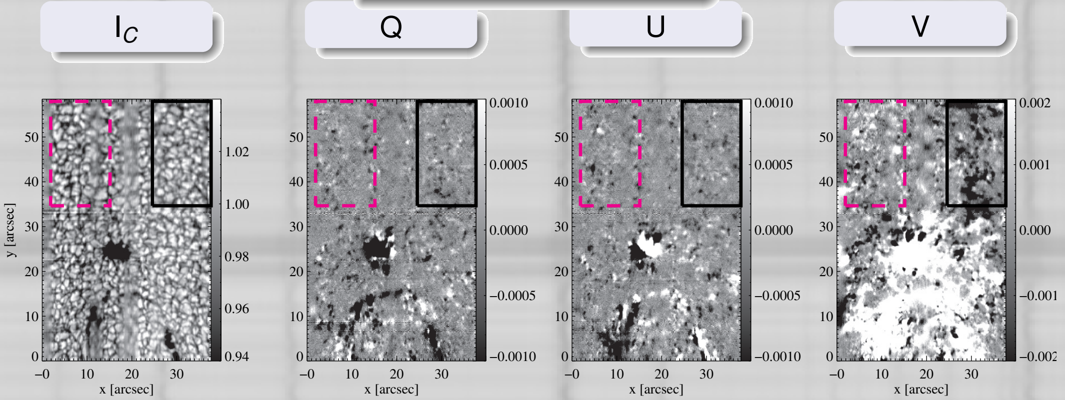

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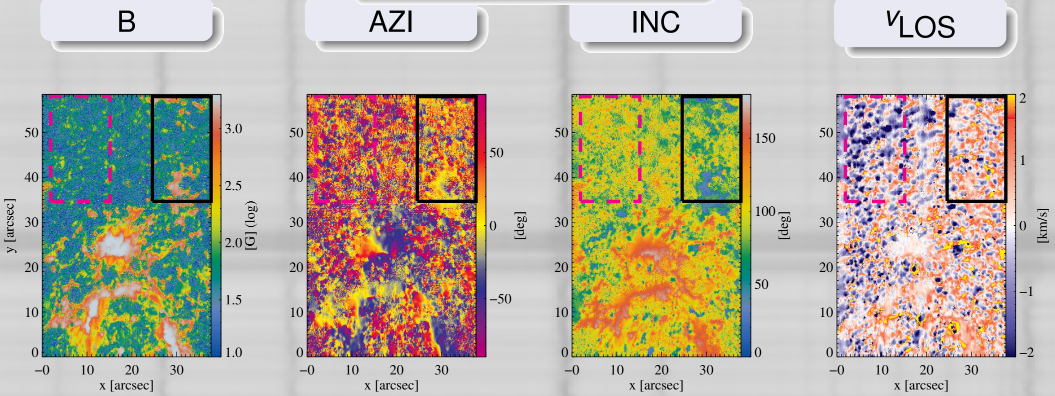
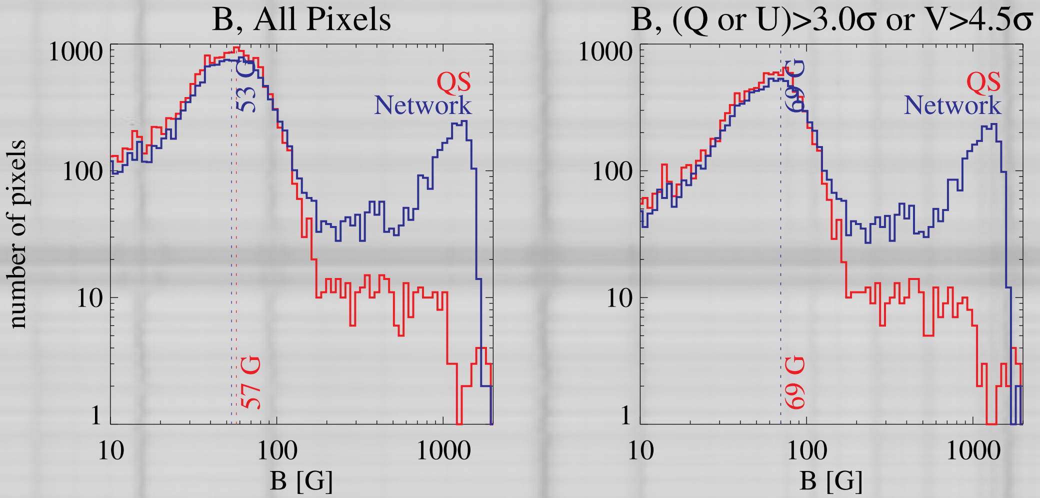
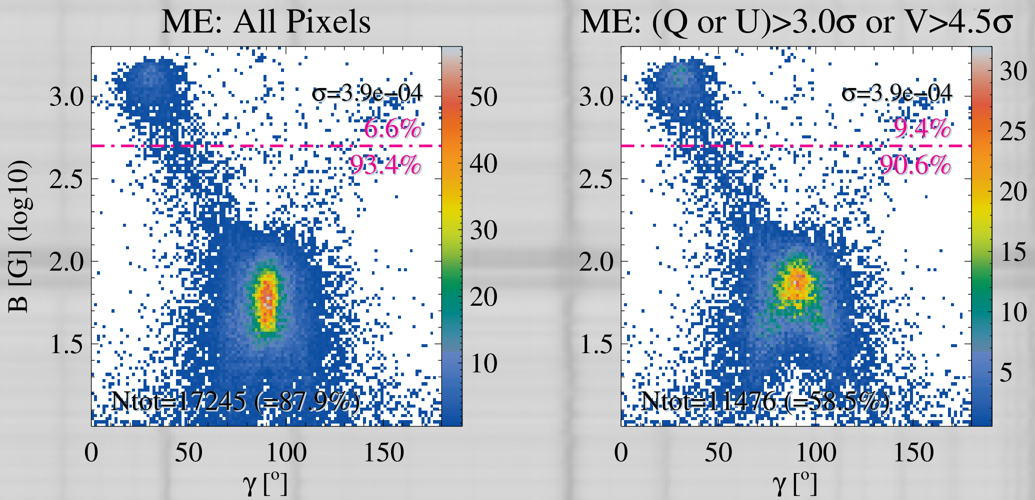


Histogram: Magnetic Field Strength (QS + network fields, $\approx$150 Mx cm^{-2})



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



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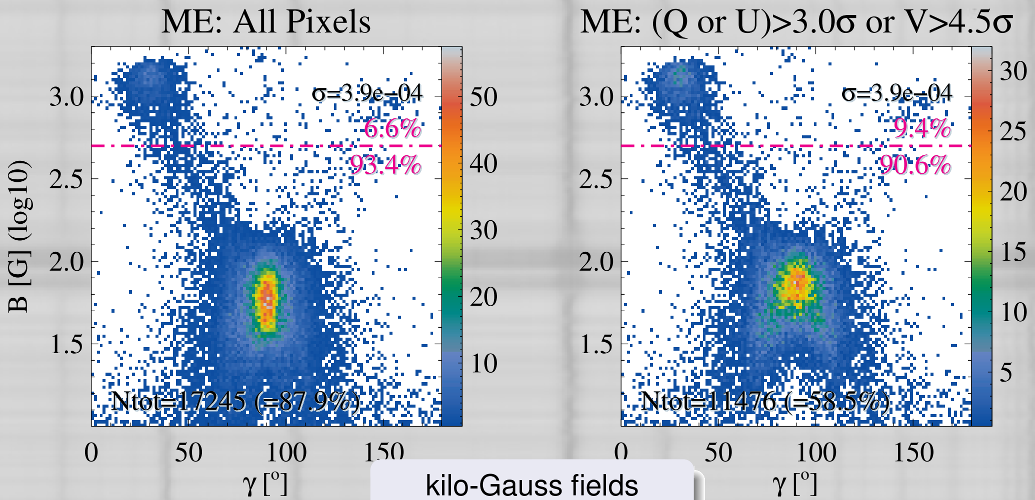
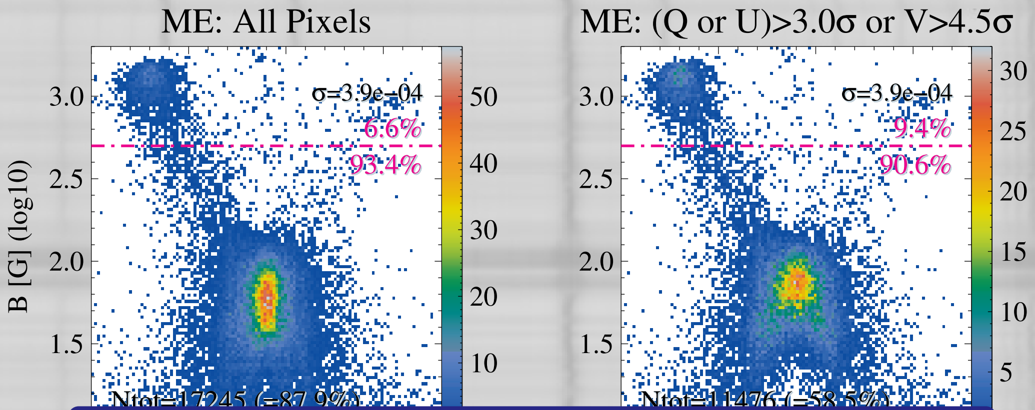


kilo-Gauss fields
in network patches

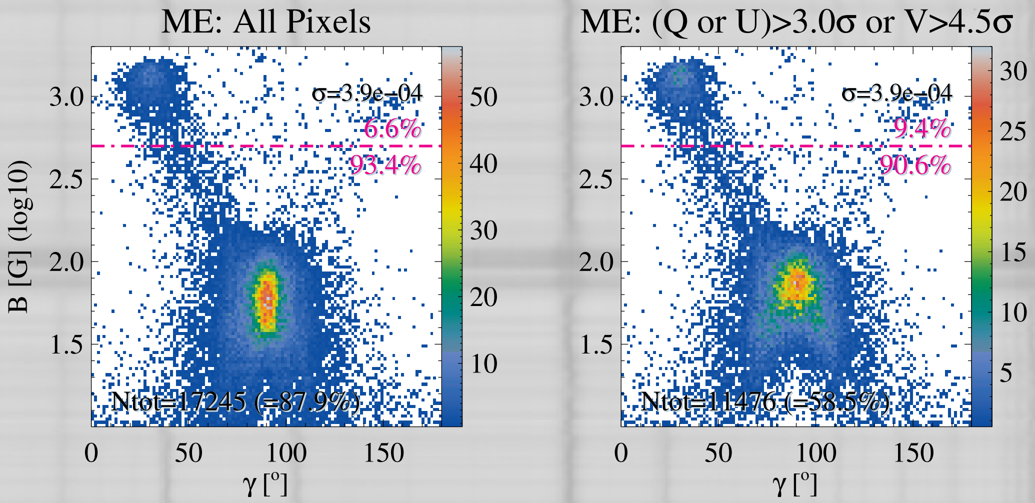
2D-Histogram: B vs. γ (QS + network fields, $\approx$150 Mx cm^{-2})



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})



Quiet Sun & Network: Is the problem solved?

Quiet Sun & Network Fields: two distinct populations

- prevalent horizontal
- 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

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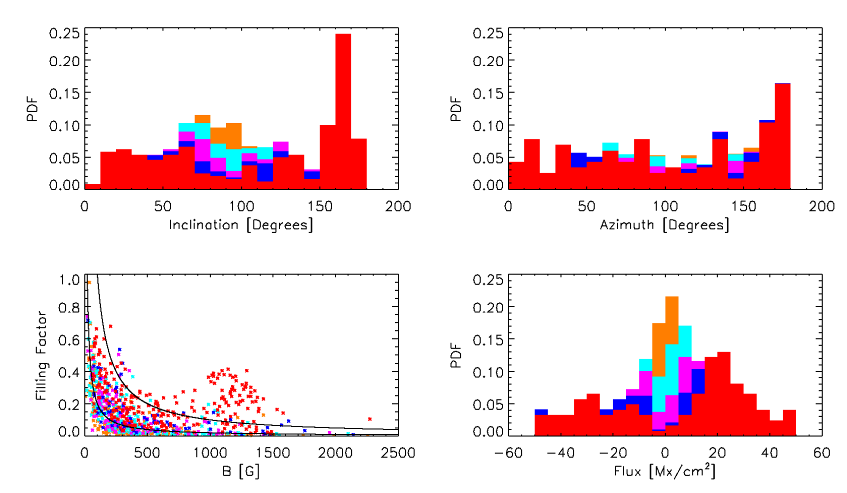
What if the fields are unresolved?



Marian Martínez González

How to proceed?

Can Hi-Res Zeeman polarimetry provide a solution?

Problems:

1. noise $\rightarrow$ more horizontal fields
2. resolution $\rightarrow$ stronger, more isotropic fields (FF)

Solution:

- noise-free data?
- larger aperture telescopes?

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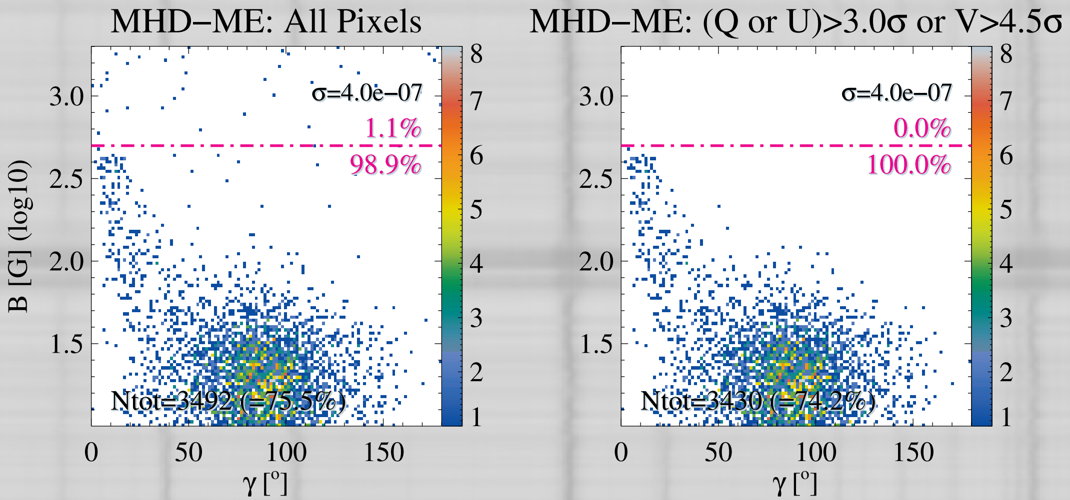
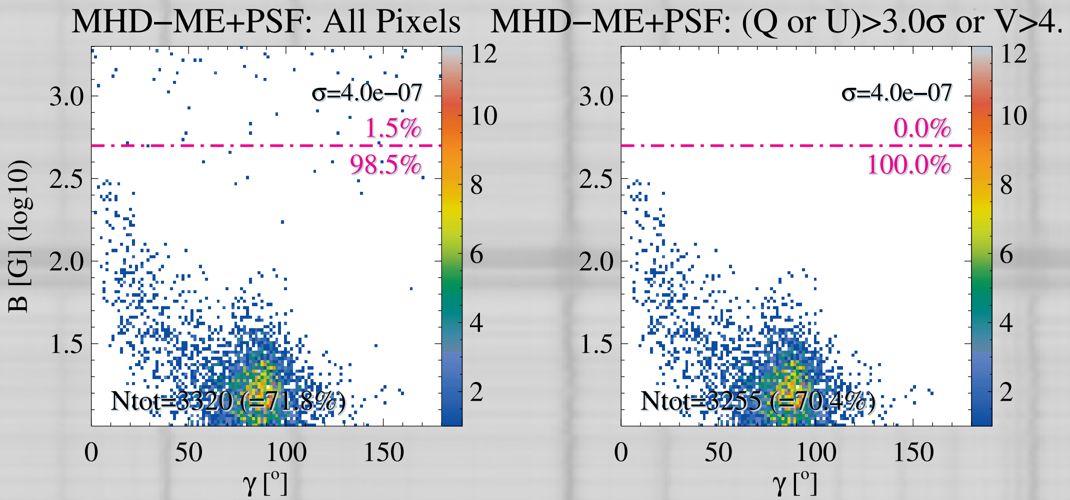
- larger aperture telescopes?

2D-Histogram: B vs. γ MHD-data



2D-Histogram: B vs. γ MHD-data

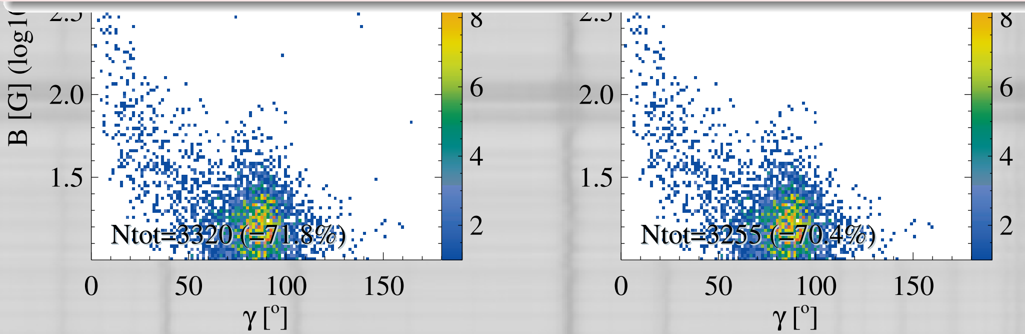


2D-Histogram: B vs. γ MHD-data

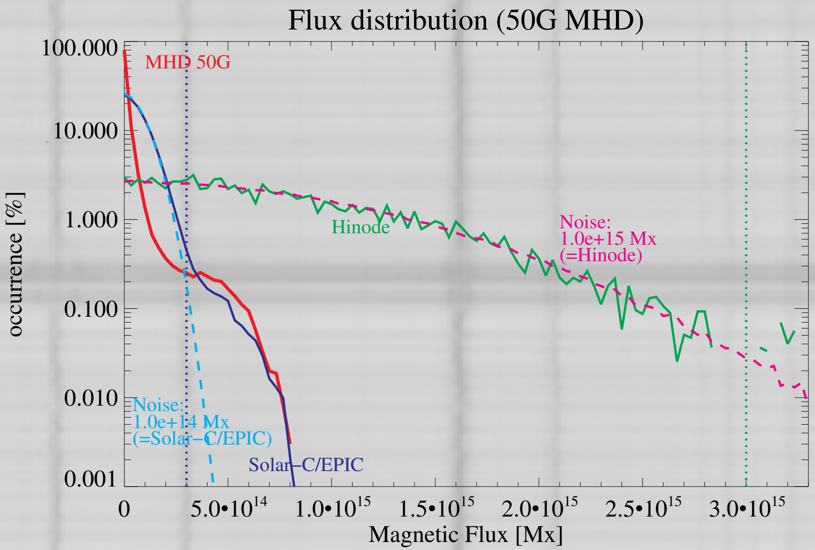
Increase of B_h:B_v from decrease in spatial res!

- $B_h \propto \sqrt{Q, U}$, $B_v \propto V$ $\Rightarrow$ $B_h^{PSF} = \sqrt{\alpha} B_h$
- PSF-convolution: reduces Q, U, V signal by same factor $\alpha < 1$ $\Rightarrow$ $B_v^{PSF} = \alpha B_v$

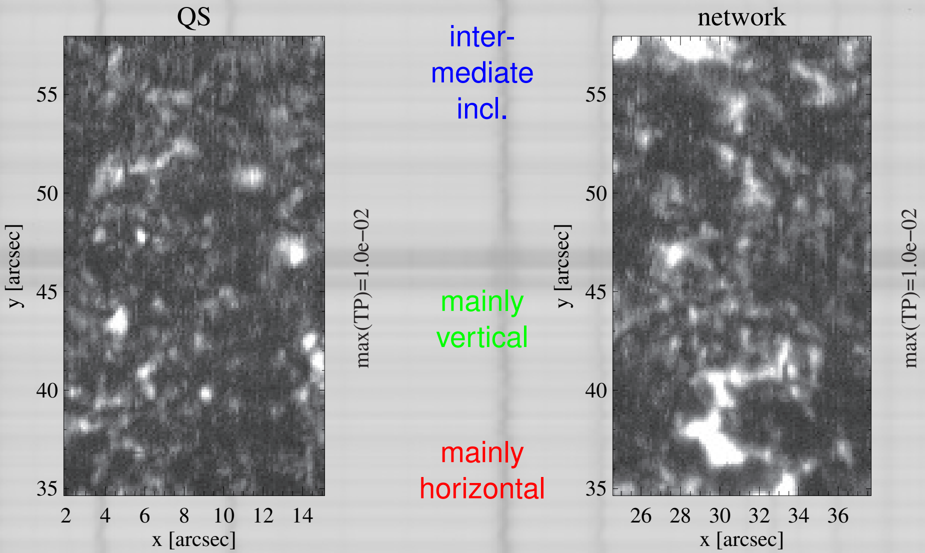
$\Rightarrow$ recovered field is more horizontal!



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



S/N Study: Stokes maps: *QUV* flags

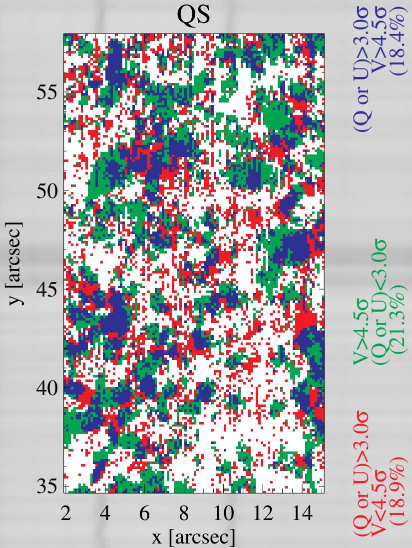


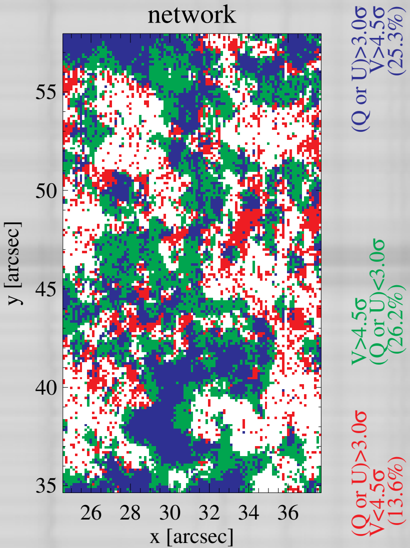
inter-
mediate
incl.

mainly
vertical

mainly
horizontal

S/N Study: Stokes maps: *QUV* flags





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