Quiet-Sun Magnetism

A New Perspective from GRIS / GREGOR

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and the GRIS team[1]

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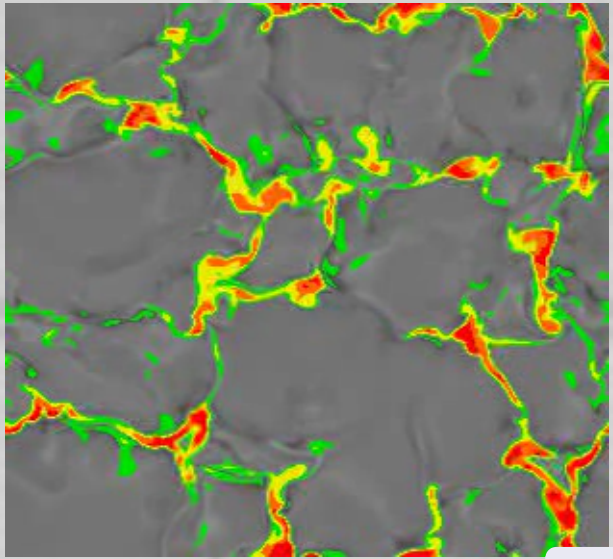
Coimbra Solar Physics Meeting

Ground-based Solar Observations
in the Space Instrumentation Era

Oct 5 – 9 2015, Coimbra

Relevance

- QS magnetism covers >99% of solar surface (even during maxima); 15% in inter-network
- crucial to understand the solar global magnetism
- local (surface) dynamo or cascade from global dynamo?



M. Rempel

Observations

Tool: spectropolarimetry (Zeeman & Hanle)

- weak signals $\rightarrow$ high sensitivity required
- small scales $\rightarrow$ high spatial resolution required

$\longrightarrow$ difficult measurement!

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$\longrightarrow$ difficult measurement!

The consequence

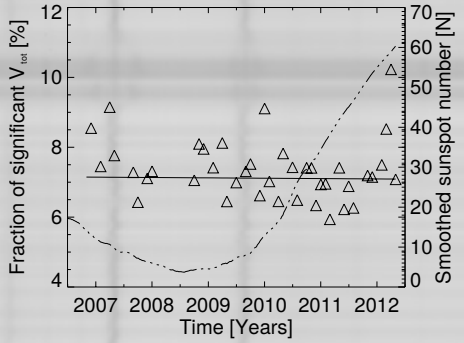
- disagreement about magnetic field strength
- disagreement about angular distribution
- disagreement about temporal behavior over activity cycle

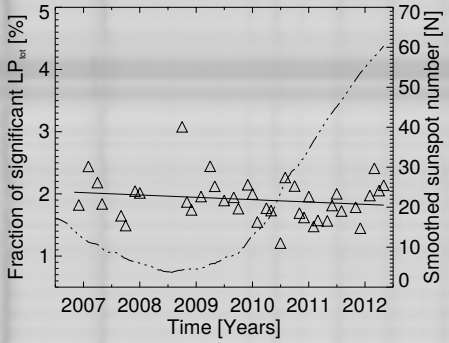
Statistical properties: correlation with activity cycle

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

- careful consideration of instrumental effects
- no cycle dependence for B_h and B_v

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





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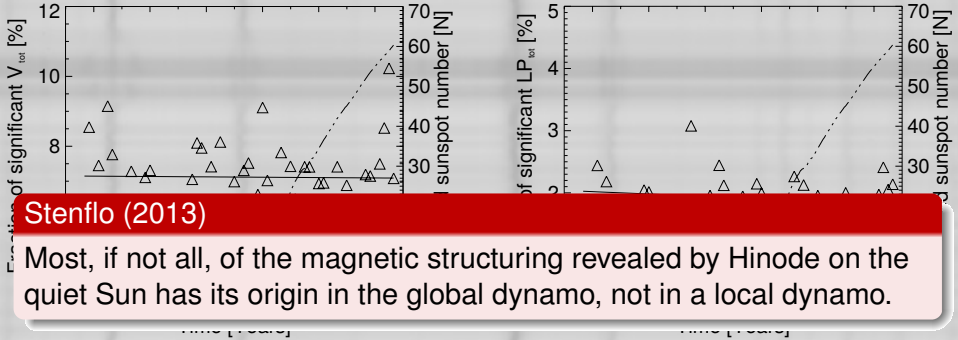


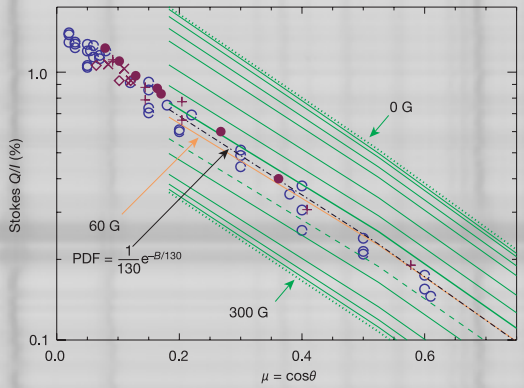
Stenflo (2013)

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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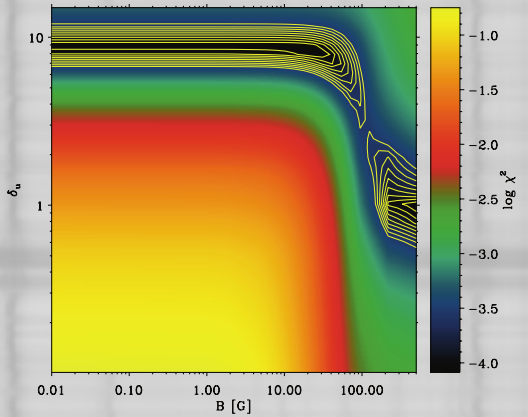

Depolarization of rotational levels of MgH lines (δ_U = coll. depol. rate)

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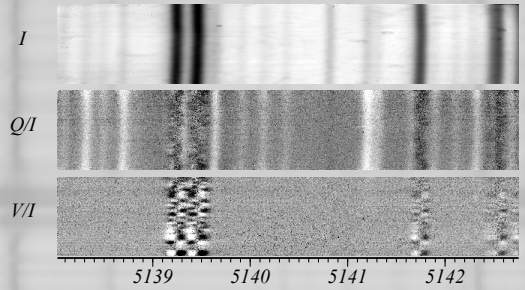
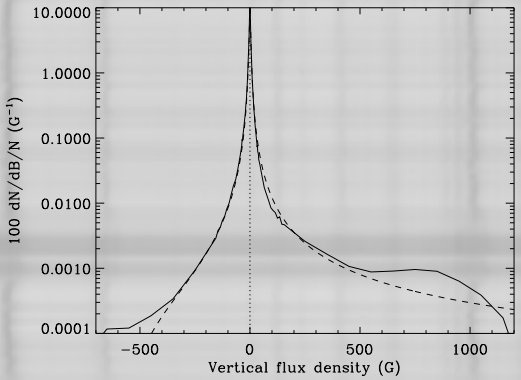


Synoptic program in C_2 line (2 triplets) and 3 FeI lines

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



Magnetic dichotomy with two distinct populations

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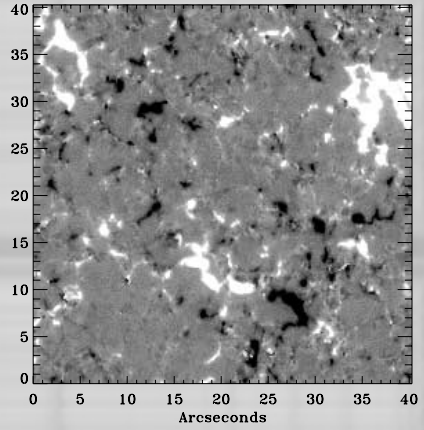

Deep mode scans Hinode SOT/SP

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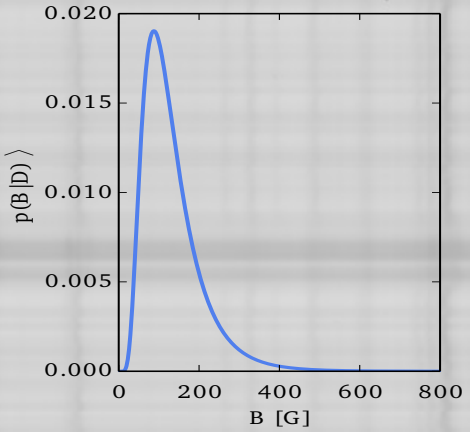
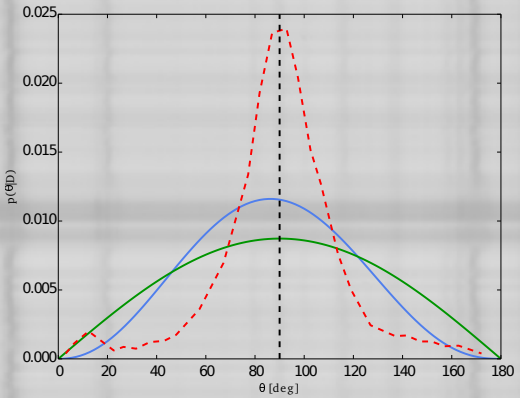


Bayesian analysis of Hinode SOT/SP data

QS fields: Orientation

Measurements

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



Martínez González et al. (2008); Asensio Ramos (2009); Asensio Ramos & Martínez González (2014)

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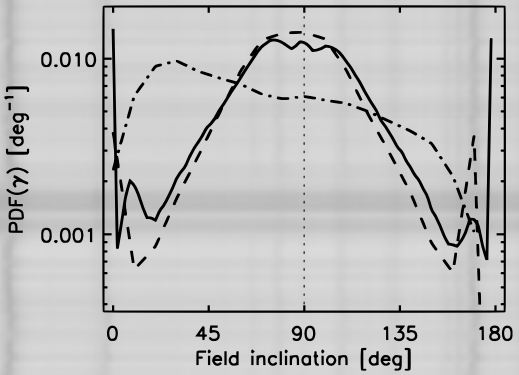

Orozco Suárez et al. (2007); Orozco Suárez & Bellot Rubio (2012); Lites et al. (2008)

Summary angular distributions (Tab. 2 from Steiner & Rezaei, 2012)

no.	authors	instrument/ simulation	line [nm]	angular distribution	$\langle B^{\mathrm{T}}_{\mathrm{app}} \rangle / \langle B^{\mathrm{L}}_{\mathrm{app}} \rangle$
1	Lites et al. (2007, 2008)	SOT/SP	630	predominantly horizontal	5
2	Orozco Suárez et al. (2007)	SOT/SP	630	predominantly horizontal	2.1
3	Martínez González et al. (2008)	VTT/TIP	1560	isotropic distribution	—
4	Beck & Rezaei (2009)	VTT/TIP	1560	predominantly vertical	0.42
5	Asensio Ramos (2009)	SOT/SP	630	isotropic for weak f elds	—
6	Danilovic et al. (2010)	SOT/SP	630	predominantly horizontal	5.8
7	Stenf o (2010)	SOT/SP	630	predominantly vertical	—
8	Ishikawa & Tsuneta (2011)	SOT/SP	630	predominantly vertical	0.86
9	Borrero & Kobel (2011)	SOT/SP	630	undeterminable	—
10	Borrero & Kobel (2012)	SOT/SP	630	non-isotropic	—
11	Steiner et al. (2008)	h20	630	predominantly hor-	4.3 (2.8)
		v10	630	izontal	1.6 (1.5)
12	Danilovic et al. (2010)	C mf=3	630	predominantly hor-	9.8 (3.5)
		C+B_{ver}	630	izontal	4.2 (2.6)

Summary of observations

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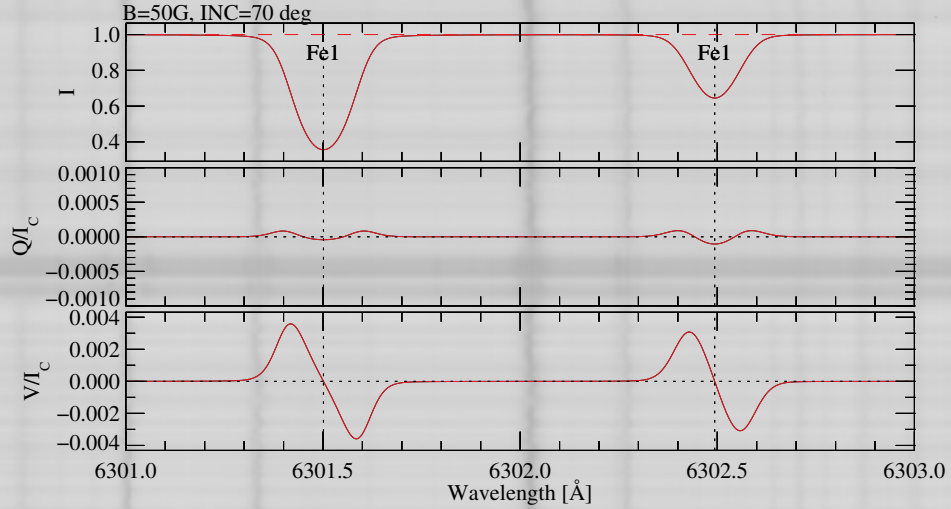
Reason 1: Sensitivity of polarimeters



Reason 2: Bias introduced by Zeeman effect

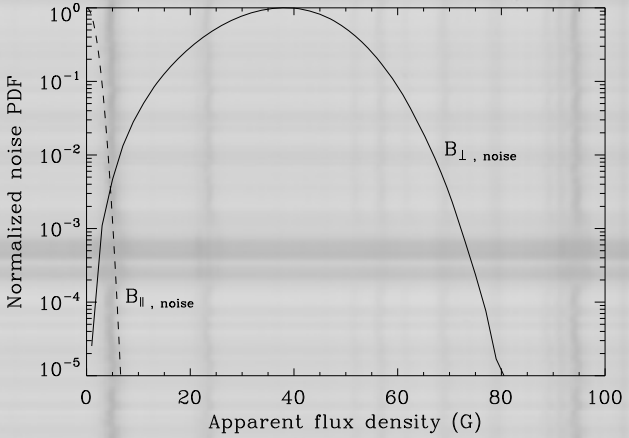
weak-field limit

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

(w.r.t. line-of-sight)

Stenflo (2013)

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



Hinode SOT/SP example

Reason 3: Height dependent B_v & B_h

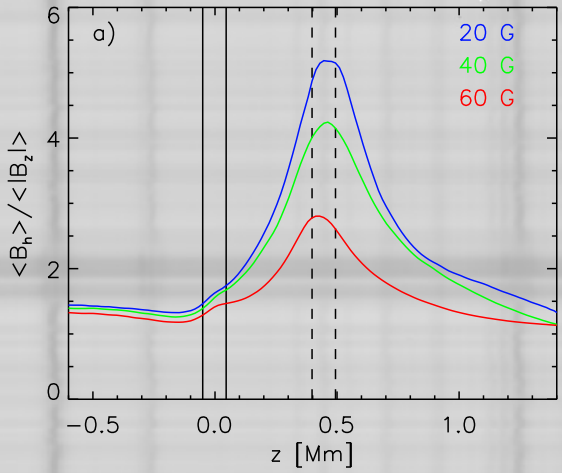
B_v vs. B_h

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)



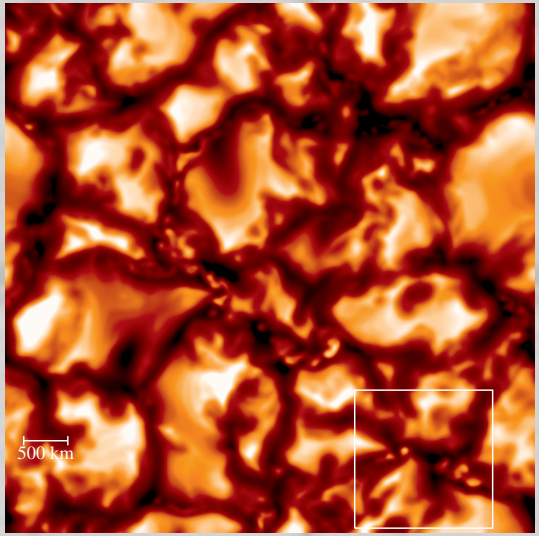
Rempel (2014)

Reason 4: Methods for QS diagnostics

Analysis methods

- Zeeman vs. Hanle
- selection of profiles (σ-level)
- inversions
  - ME vs. height dependent
  - filling factor
- direct techniques (e.g. line ratio)

Reason 5: Unresolved Stokes signals – signal cancellation



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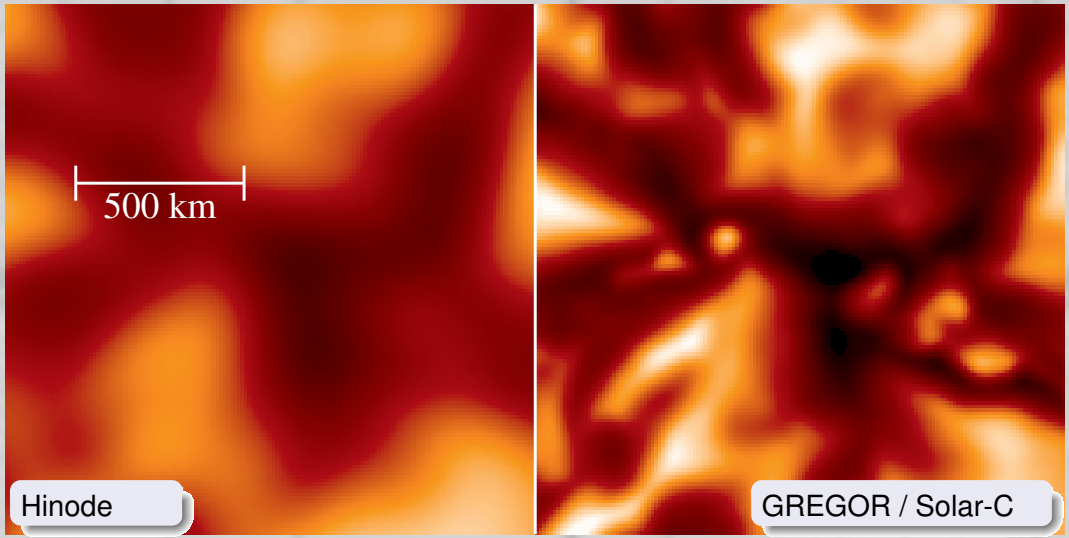

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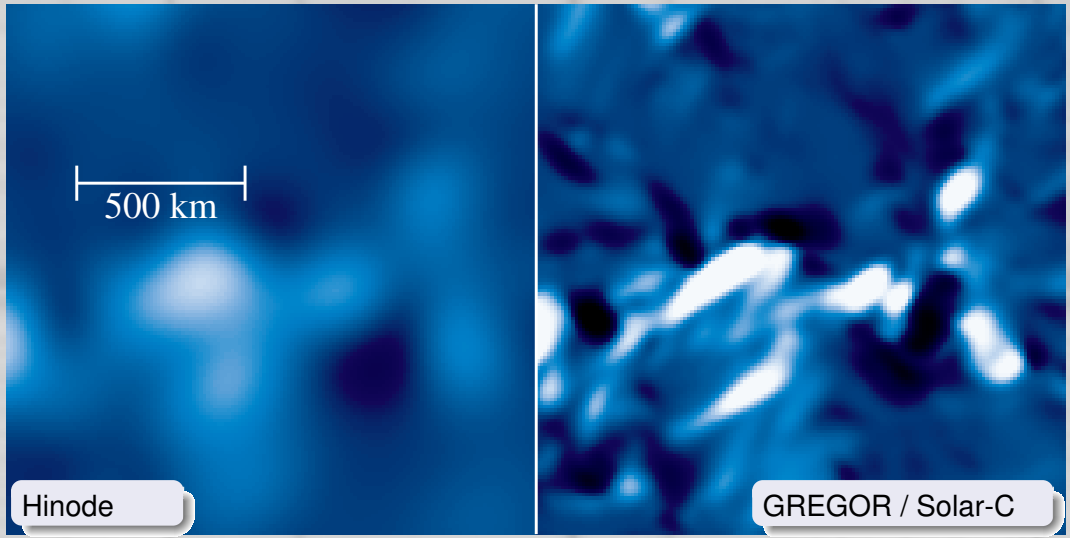
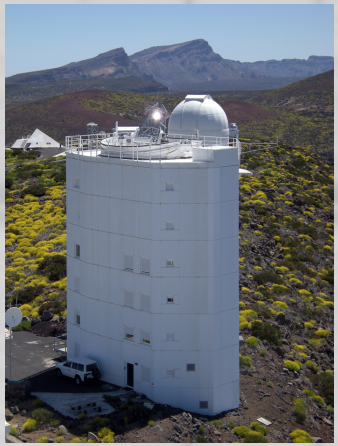
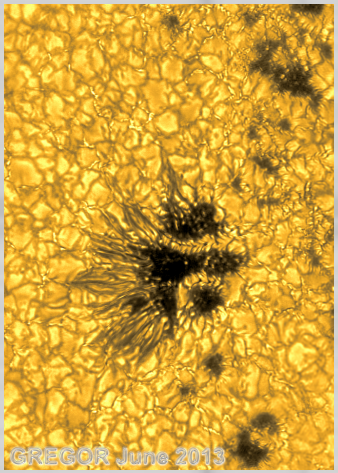
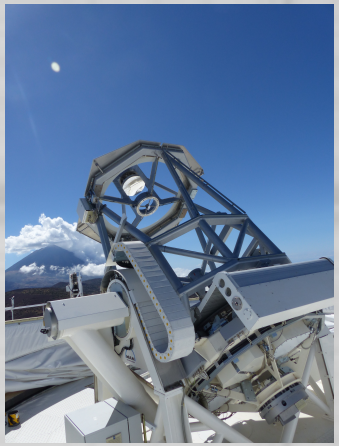


Solution: Improved instrumentation?

Recent results from GREGOR / GRIS



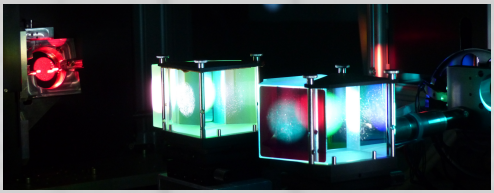


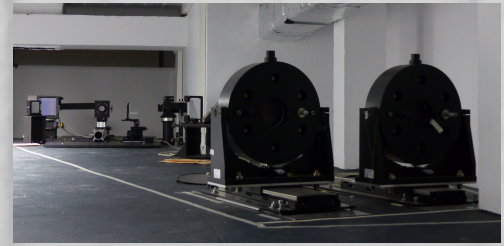


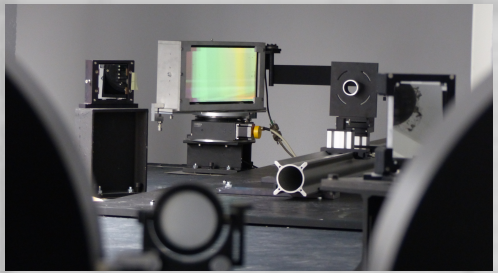
GREGOR Infrared Spectrograph (GRIS; Collados et al., 2012)

GRIS fact sheet

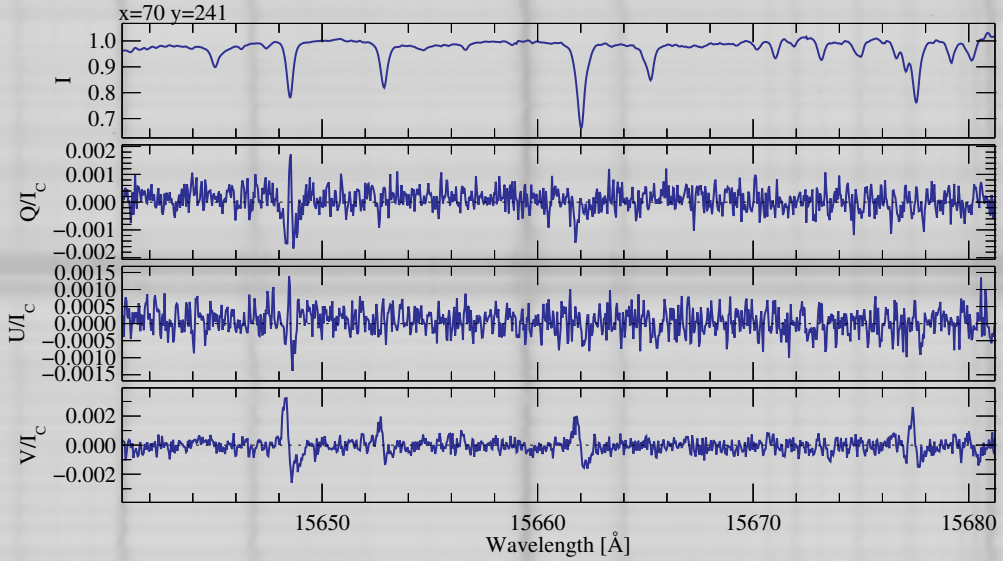
- Czerny-Turner
- sensitivity $< 10^{-4}$
- $\lambda/\Delta\lambda \approx 120\,000$ (@1.56 μm)
- Rockwell TCM-8600 1k$\times$1k (LN-cooled)
- 2 calibration units (F2 & Coudé train exit)



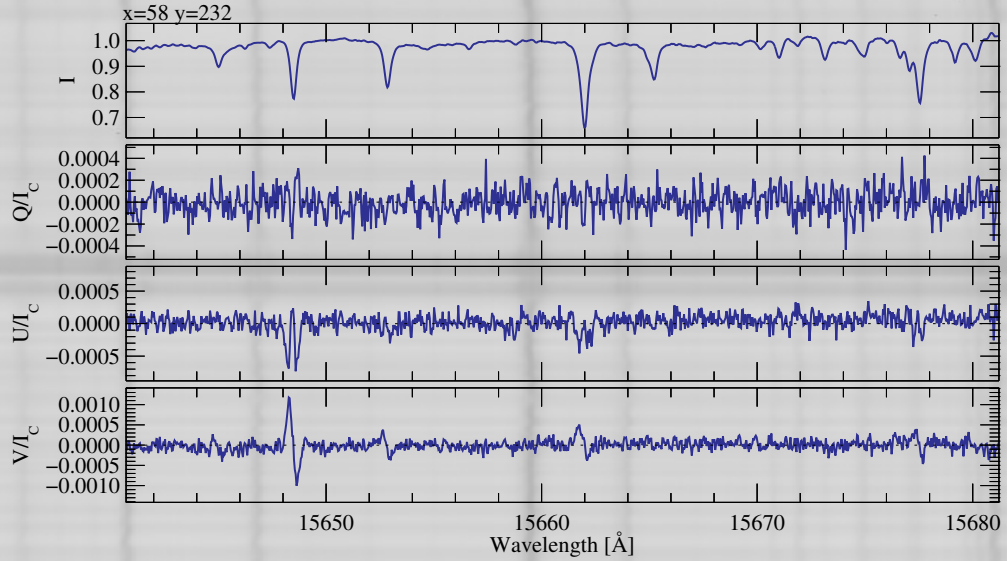




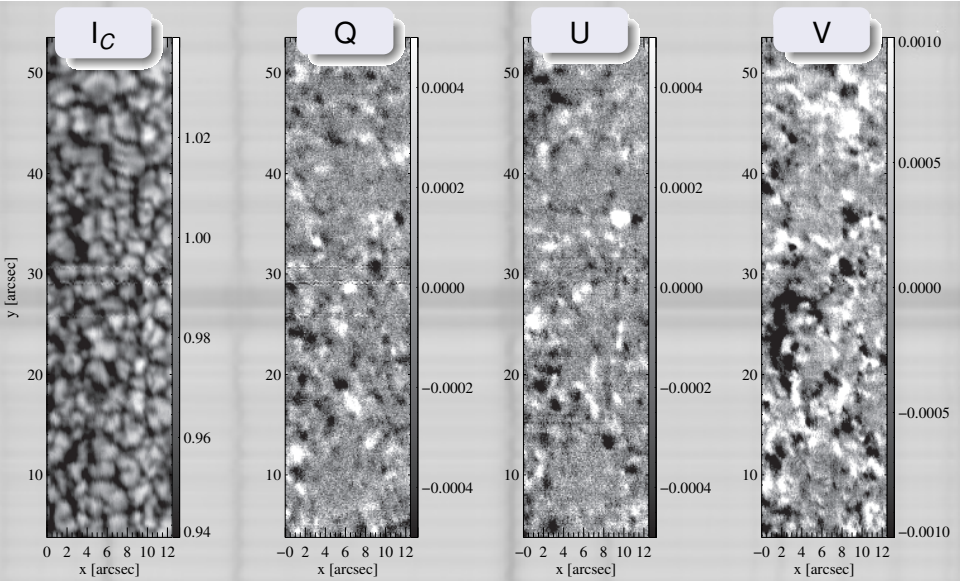
Stokes Profiles: Granule (TP) unbinned (=0.″126 pixel, noise level: $4 \cdot 10^{-4}$)



Stokes Profiles: Granule (TP) 4×4 binned (=0.″50 pixel, noise level: $1.7 \cdot 10^{-4}$)



Scan of quiet sun region (2015-Sep-15)



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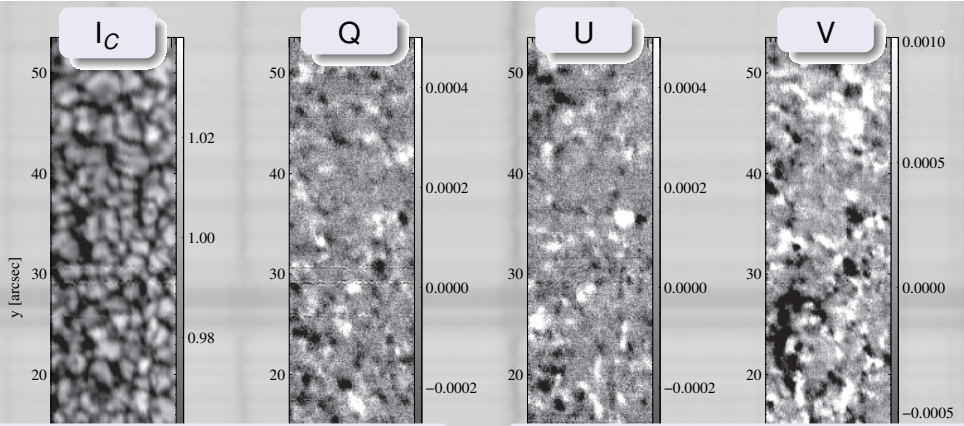

- disk center
- exp. time: 4.8 s/slit (8 s cadence)
- noise level (unbinned): $4 \cdot 10^{-4}\ I_C$

- $\lambda/\Delta\lambda \geq 120\,000$, 40 mÅ sampling
- spatial resolution: 0.″35 (diff. limit 0.″26), sampling: 0.″126

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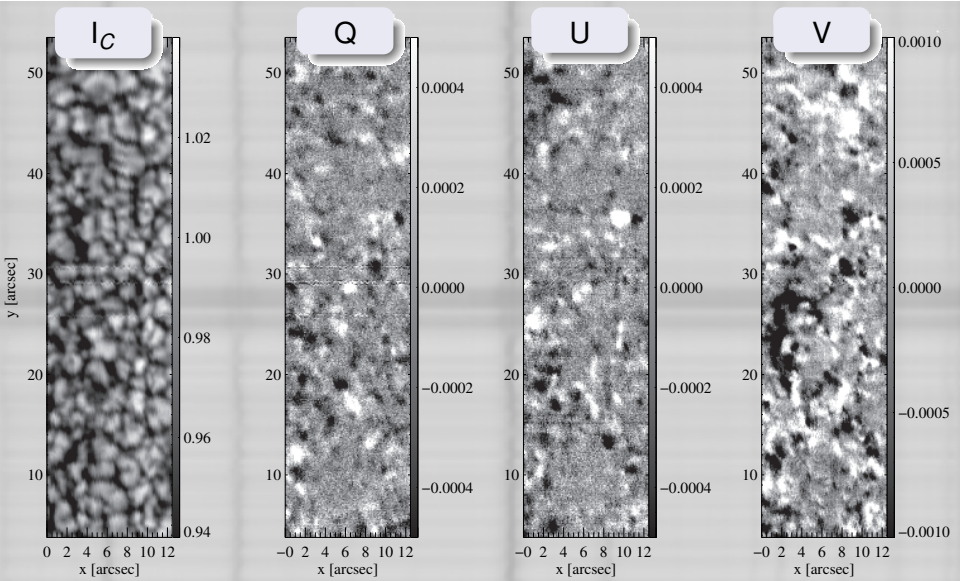

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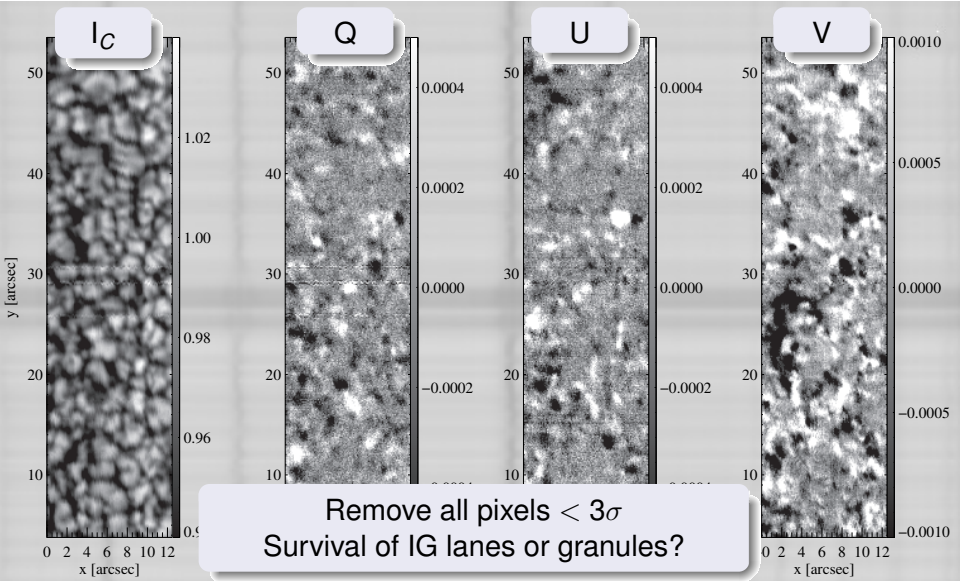
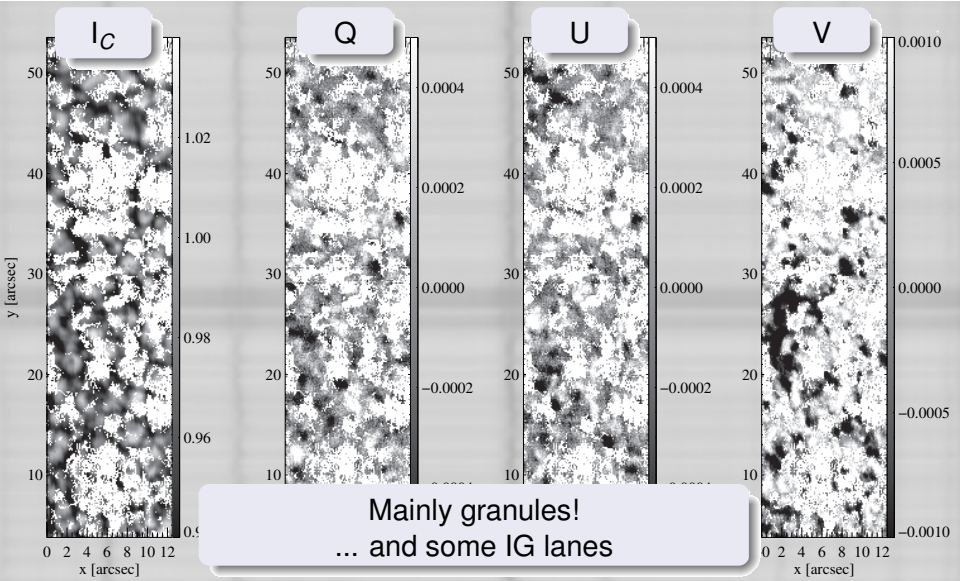


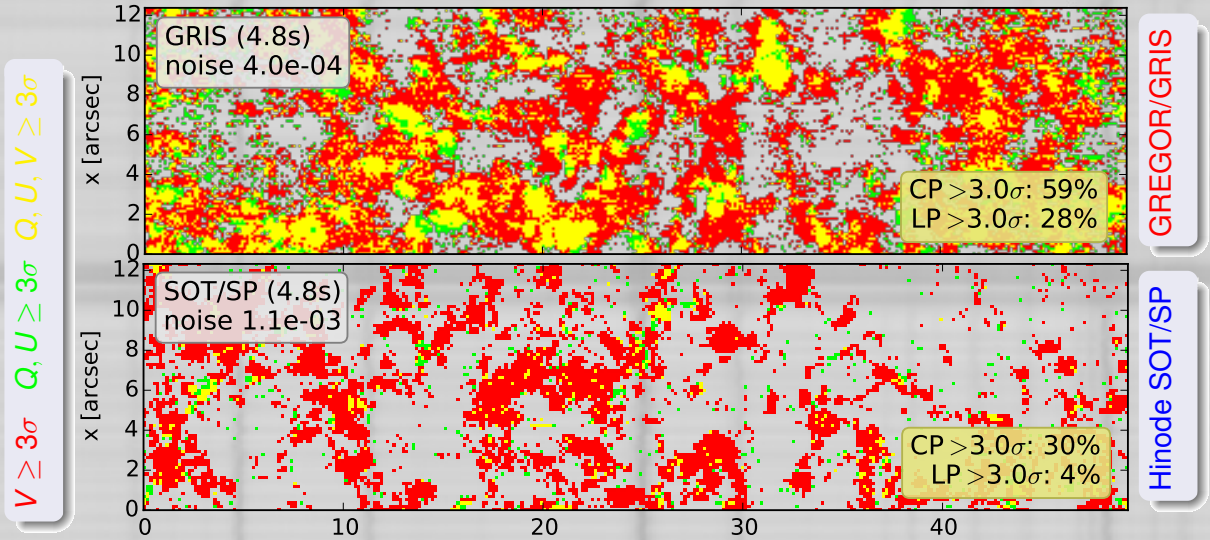
Remove all pixels $< 3\sigma$
Survival of IG lanes or granules?

Scan of quiet sun region (2015-Sep-15)



Mainly granules!
... and some IG lanes

Comparison: GRIS vs. SOT/SP



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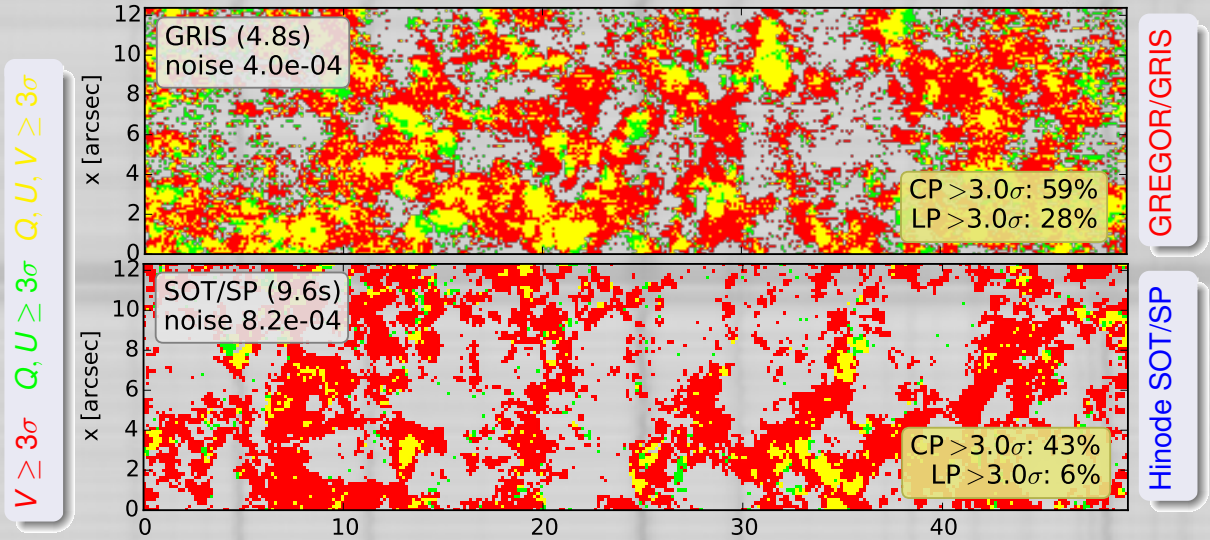

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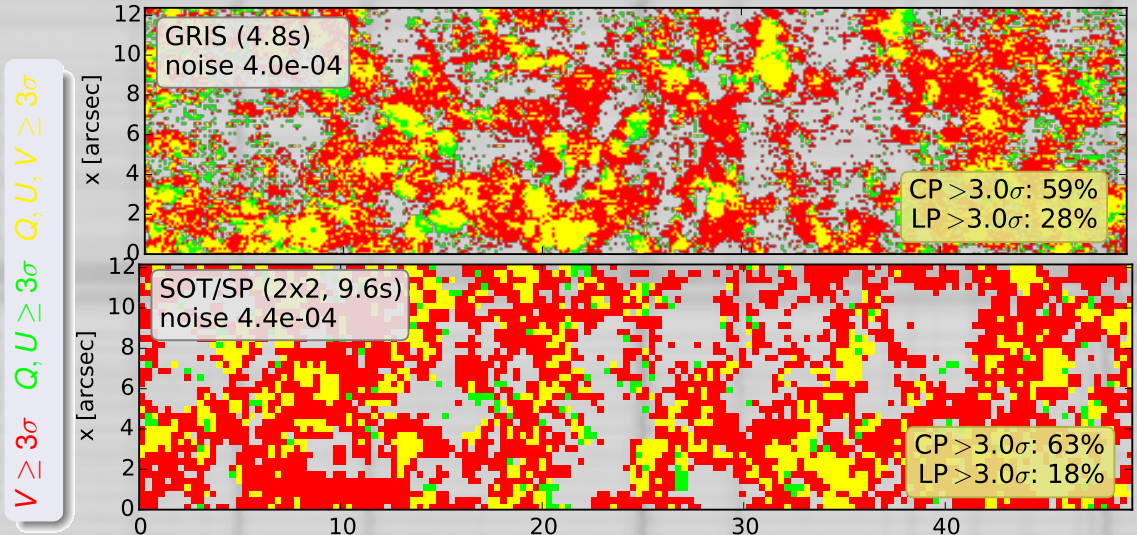

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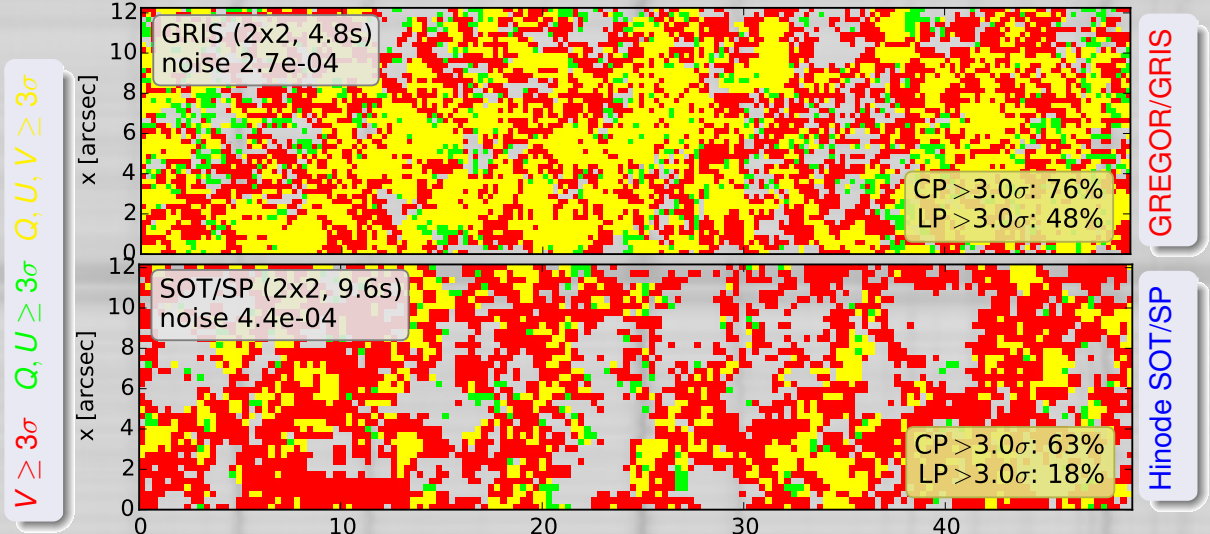
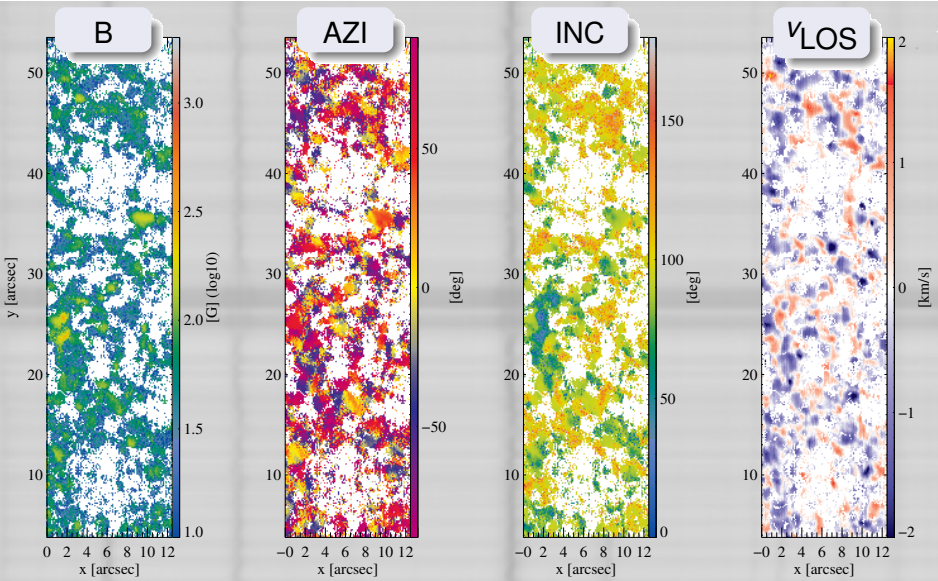


ME-results of quiet sun region (2015-Sep-15)



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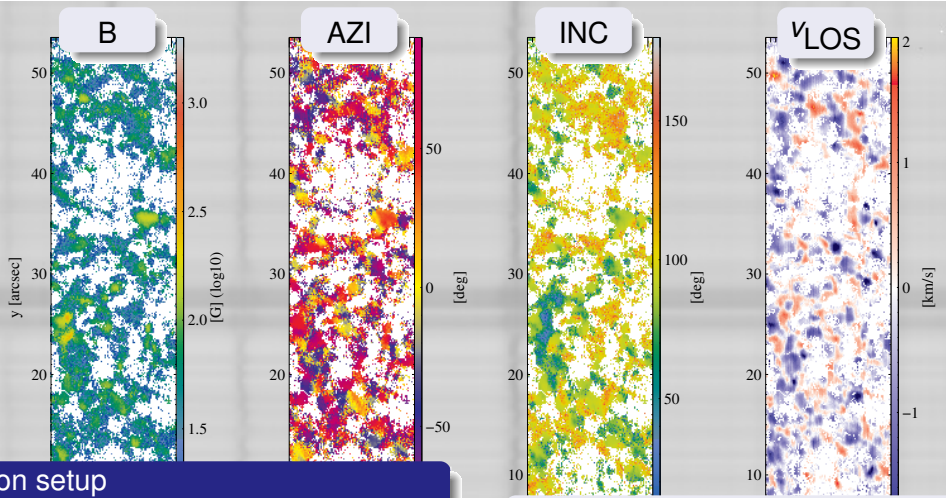


Inversion setup

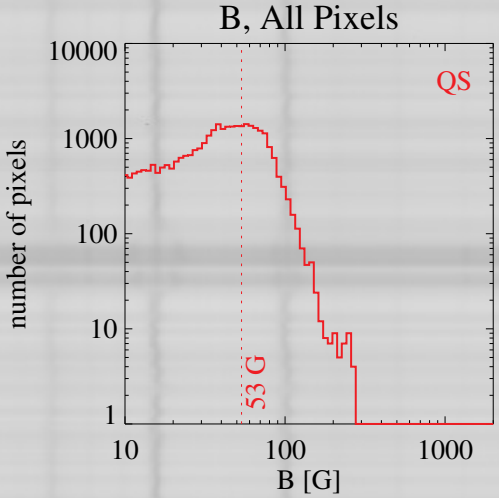
- Milne Eddington in 6 Fe I lines

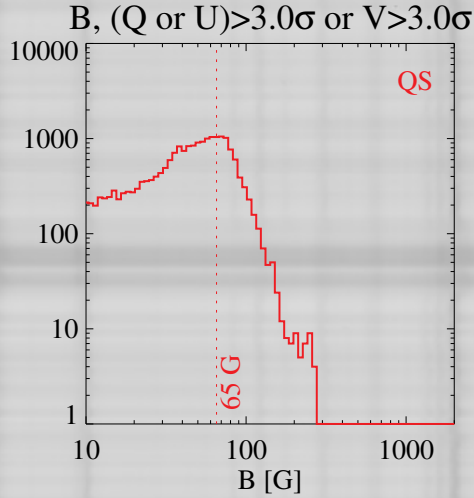
  15631 – 15665 Å, line strength as free parameter

- 8 free parameters

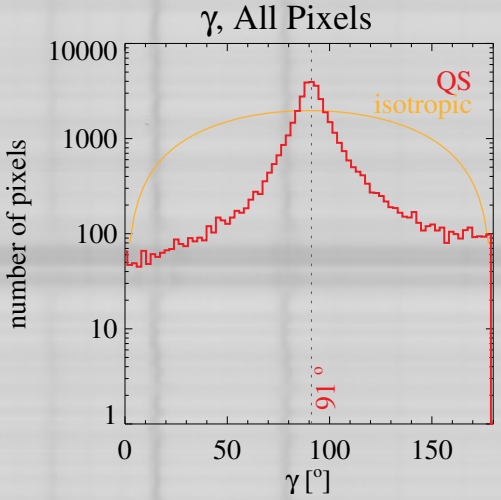
  $B, \phi, \gamma, v_{LOS}, v_D, a, S_1, \eta_0$

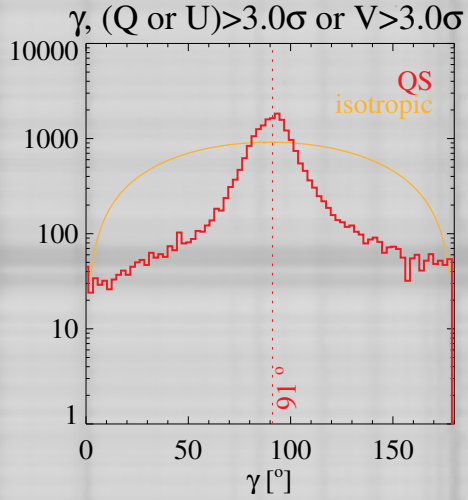
Histogram: Magnetic Field Strength



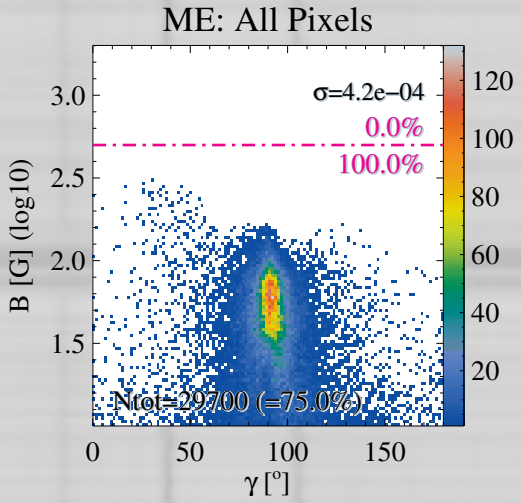


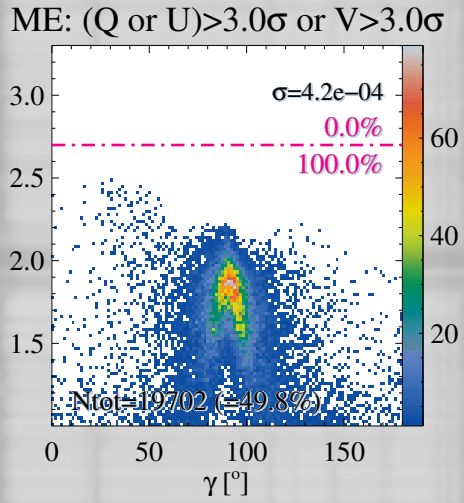
Histogram: Magnetic Field Inclination





2D-Histogram: B vs. γ

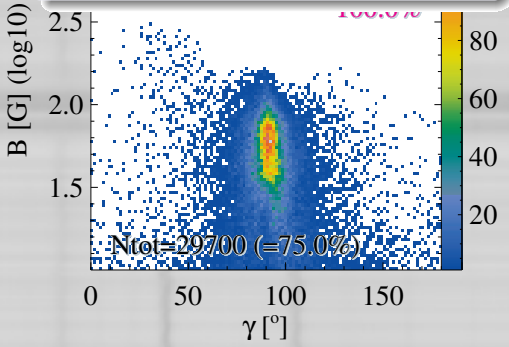


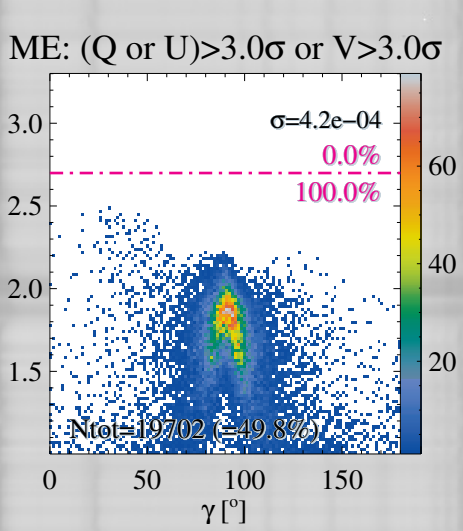


2D-Histogram: B vs. γ

Quiet Sun Fields

- strength: 20–150 G
- mainly horizontal
- few and weak vertical fields





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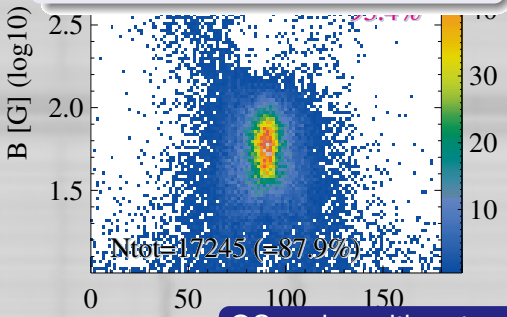

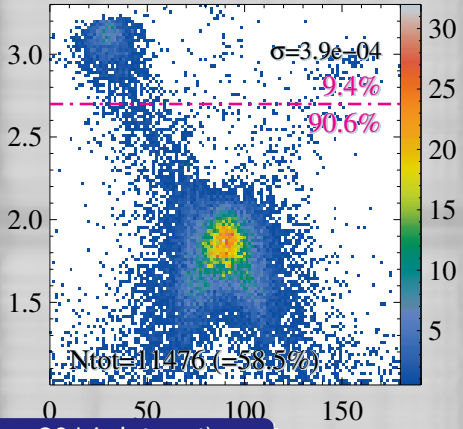

QS region with network (Sep 2014 dataset)

additional population: vertical, kG fields

2D-Histogram: B vs. γ

Quiet Sun Fields

- strength: 20–150 G
- mainly horizontal
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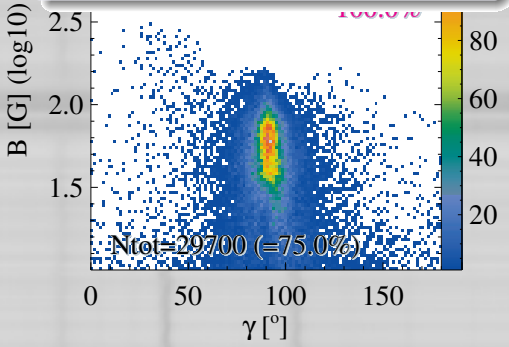
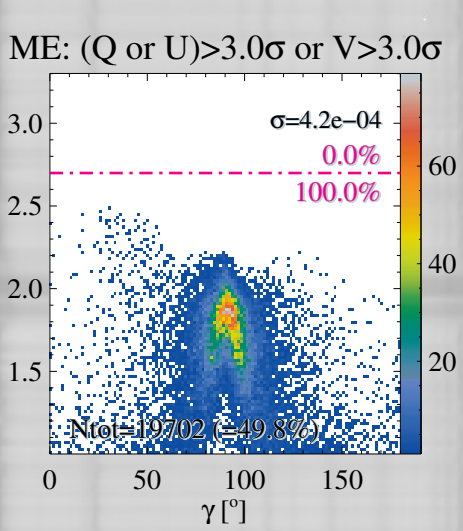
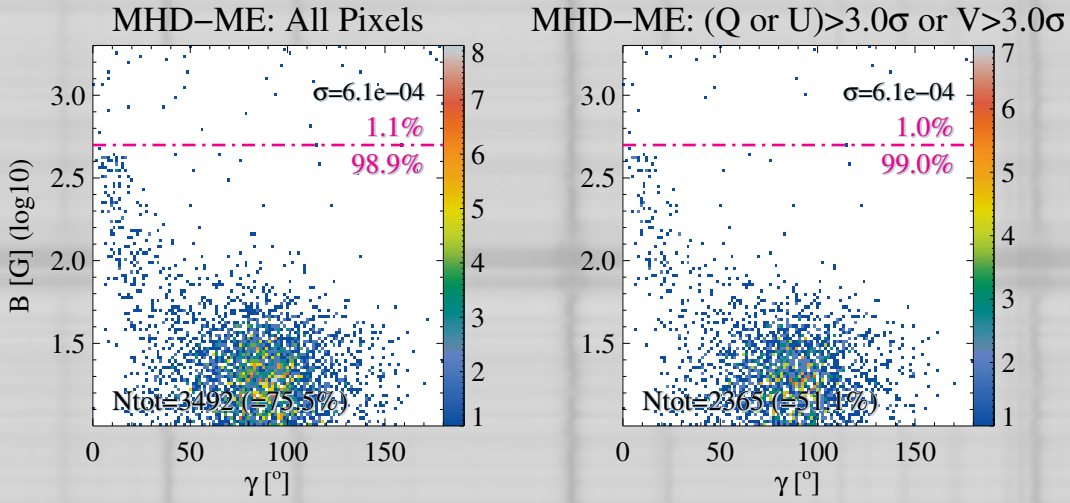




2D-Histogram: B vs. γ MHD-data



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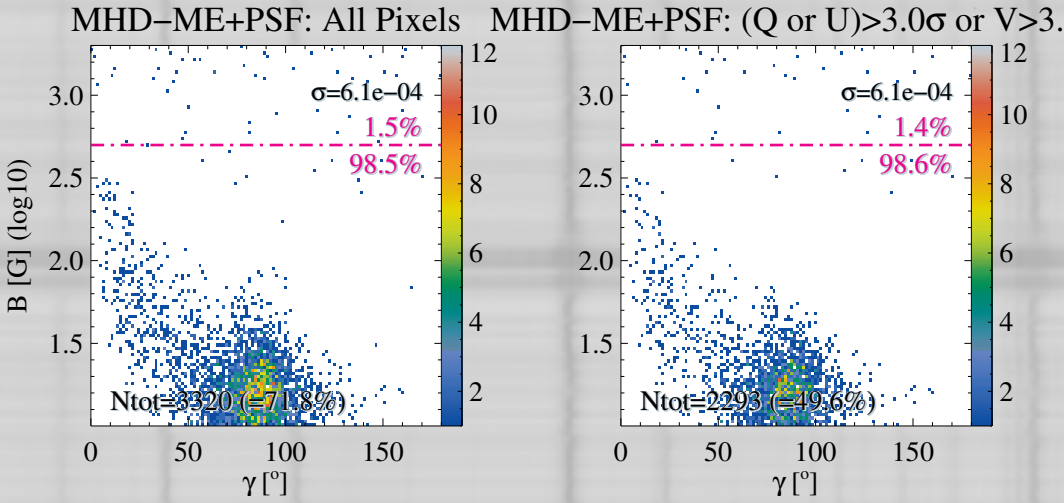
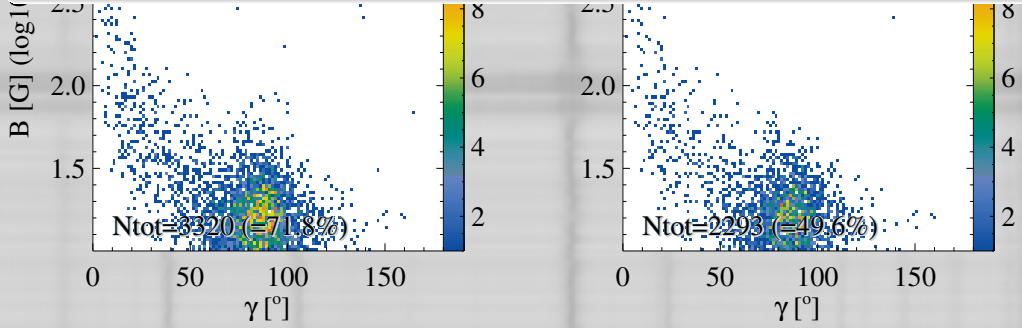


2D-Histogram: B vs. γ MHD-data

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!



Do we resolve the quiet Sun fields?

Magnetic Line Ratio Technique (Solanki et al., 1992)

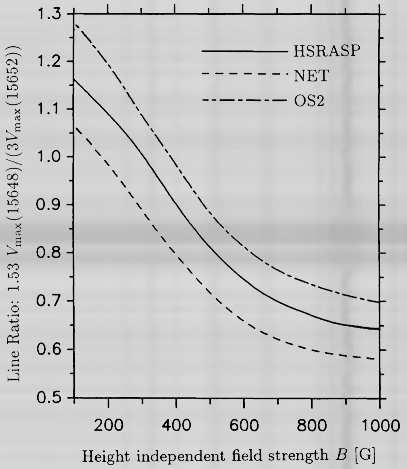
$$\mathrm{MLR} = \frac{g_{\mathrm{eff}}(15652)\, V_{\mathrm{max}}(15648)}{g_{\mathrm{eff}}(15648)\, V_{\mathrm{max}}(15652)}$$

Requiremenrts:

- spectral lines identical except for Landé factor
- 2 distinct components:
  (1) magnetized, (2) field-free

→ not fulfilled for Fe I 1.56 line pair

→ BUT: points towards right direction



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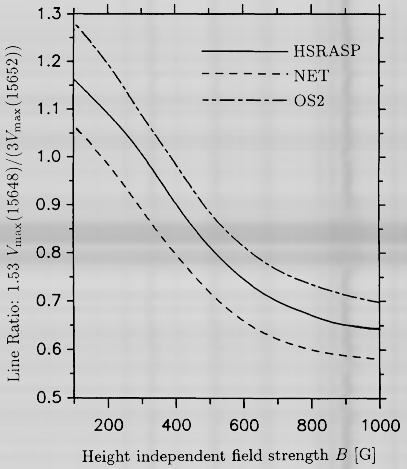

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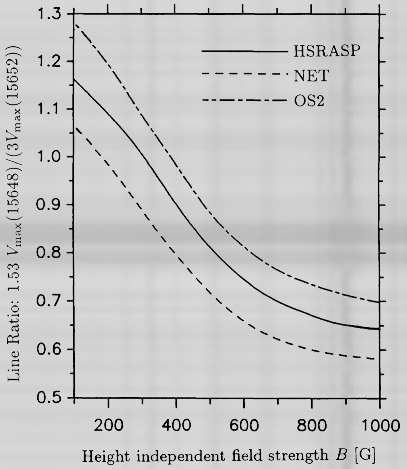
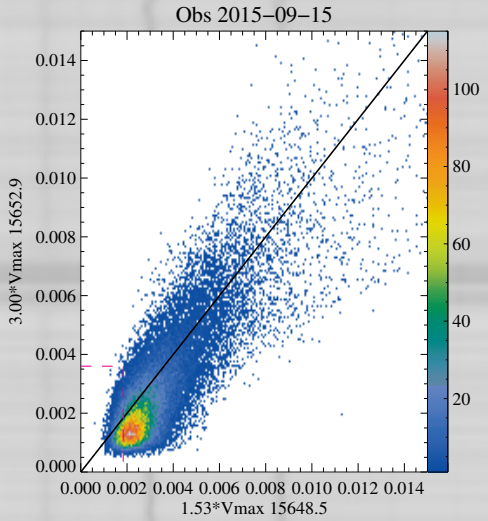
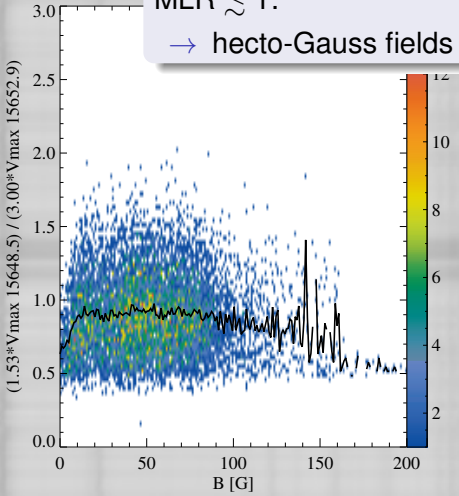


MLR for 2015-Sep-15 quiet Sun scan

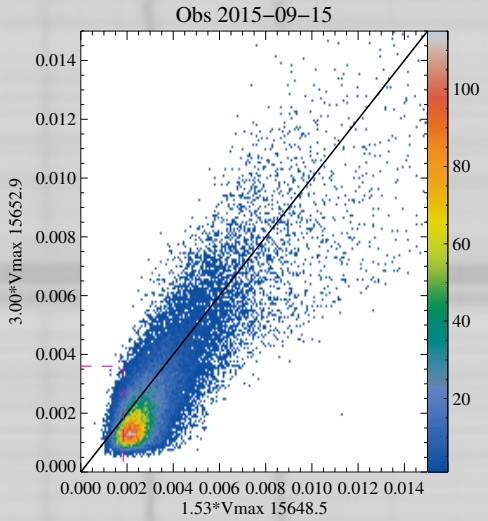


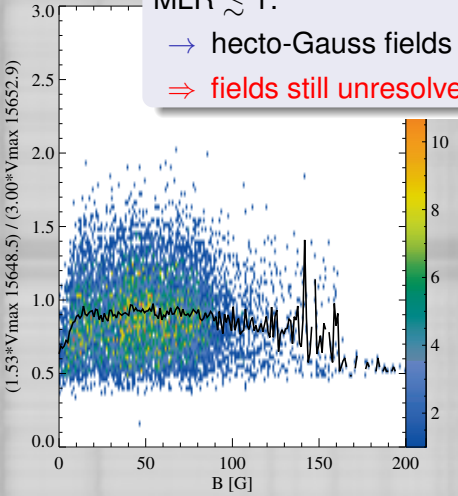


MLR $\lesssim 1$:

$\rightarrow$ hecto-Gauss fields

MLR for 2015-Sep-15 quiet Sun scan





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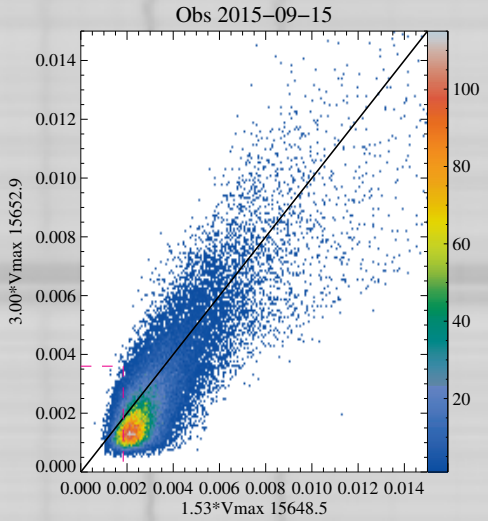

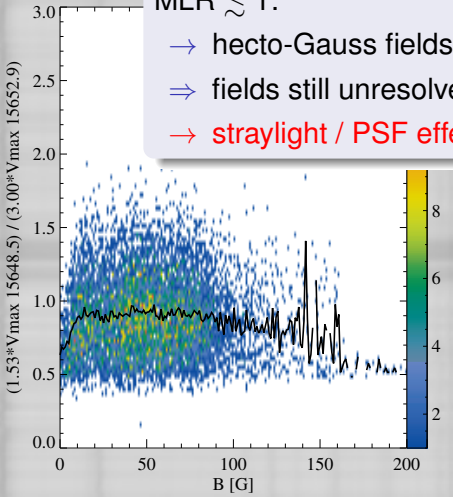

MLR $\lesssim 1$:

- $\rightarrow$ hecto-Gauss fields
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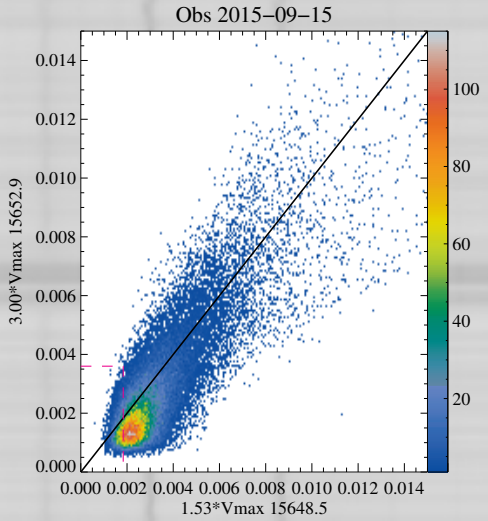

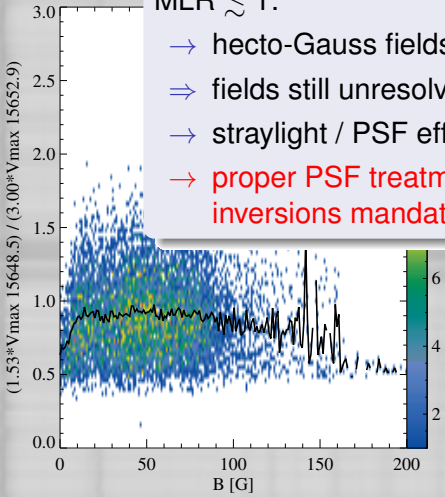

MLR $\lesssim 1$:

- $\rightarrow$ hecto-Gauss fields
- $\Rightarrow$ fields still unresolved?
- $\rightarrow$ straylight / PSF effect?
- $\rightarrow$ proper PSF treatment in inversions mandatory!

Summary: Quiet Sun Magnetism

Agreement:

- crucial to understand solar magnetism

Disagreement

- dependency with level of solar activity
- strength & direction

Steps toward a solution

Advances in instrumentation:

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

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

Advances in analysis:

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

Summary: Quiet Sun Magnetism

Agreement:

- crucial to understand solar magnetism

Disagreement

- dependency with level of solar activity
- strength & direction

GREGOR/GRIS:

closer to a solution, but not yet there...

Steps toward a solution

Advances in instrumentation:

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

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Advances in analysis:

- inversions: proper treatment of PSF / straylight (“filling-factor” discussion, 2D-inversions)
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