An ocean of inclined magnetic fields in the very quiet Sun

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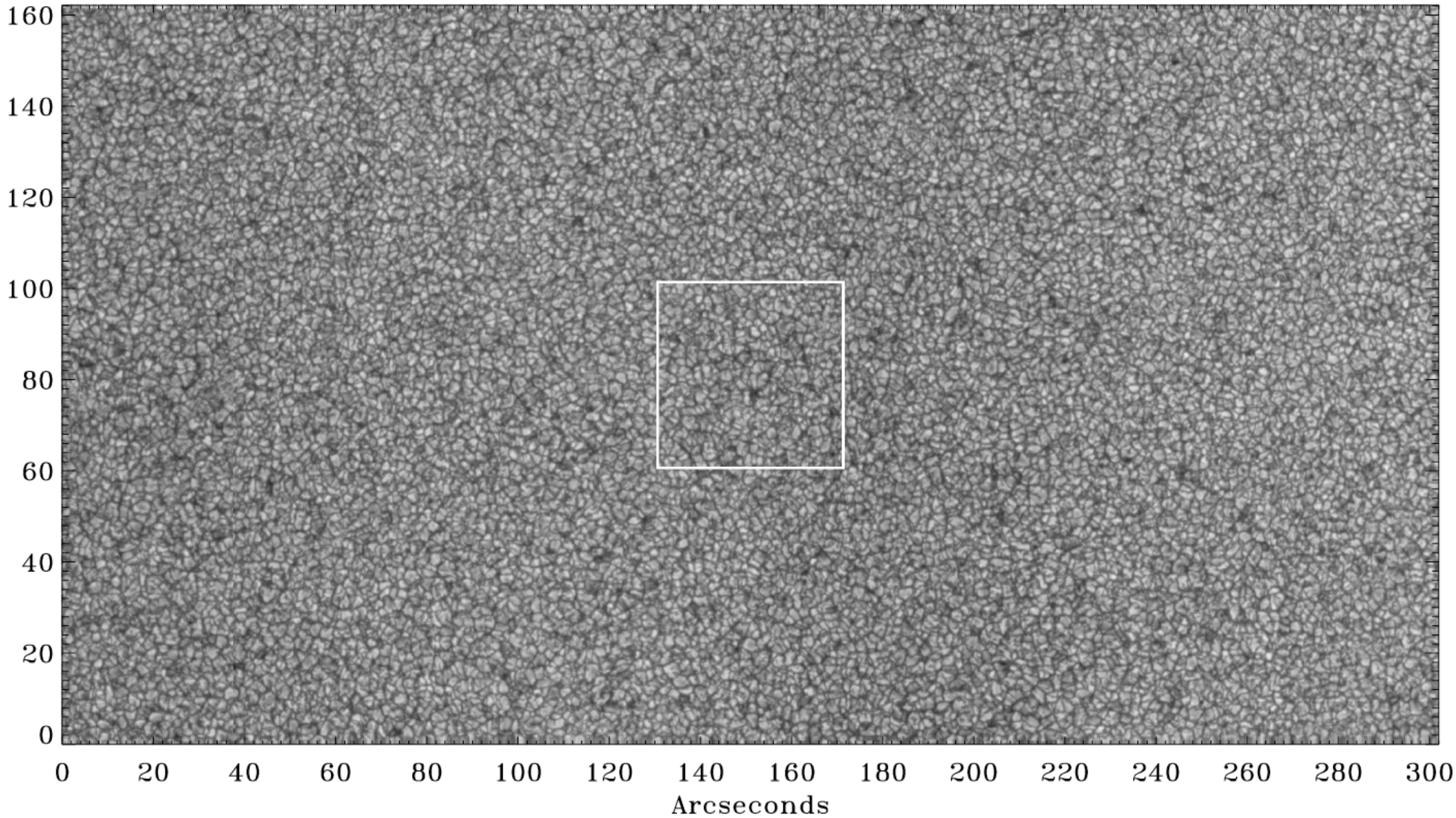
For more details see: ***Bellot Rubio & Orozco Suárez, 2012, ApJ, 757, 19***

The quiet Sun



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

Hinode/SP normal map, Fe I 630 nm
Spatial resolution: ~0.3 arcsec

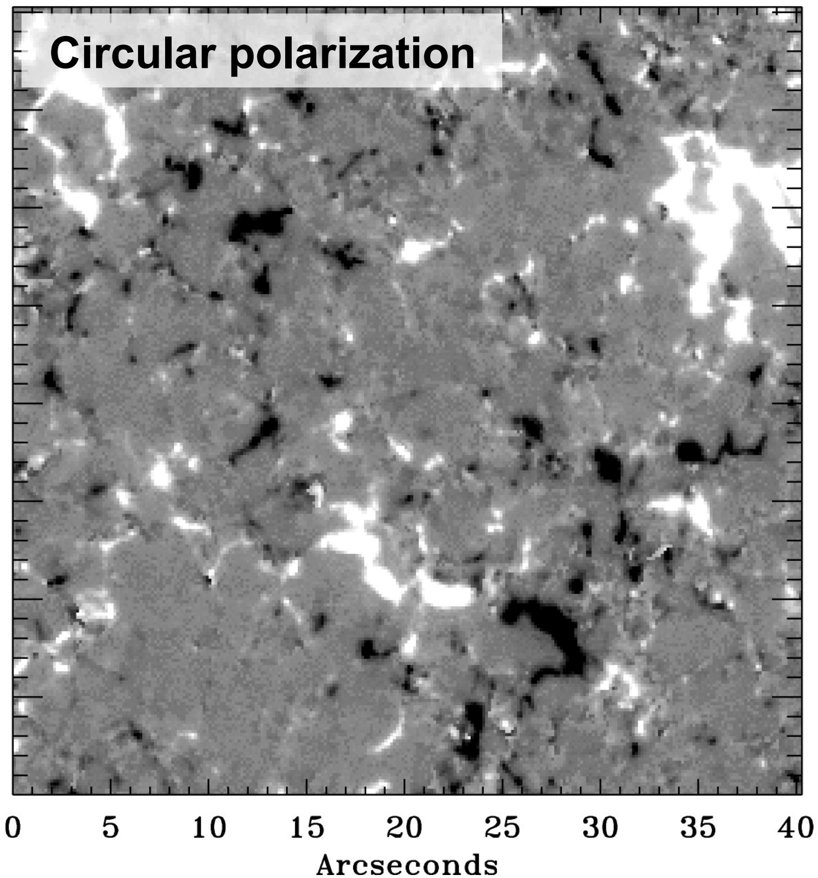
Integration time: 4.8 s
Noise level: 1.1 x 10^{-3} I_c

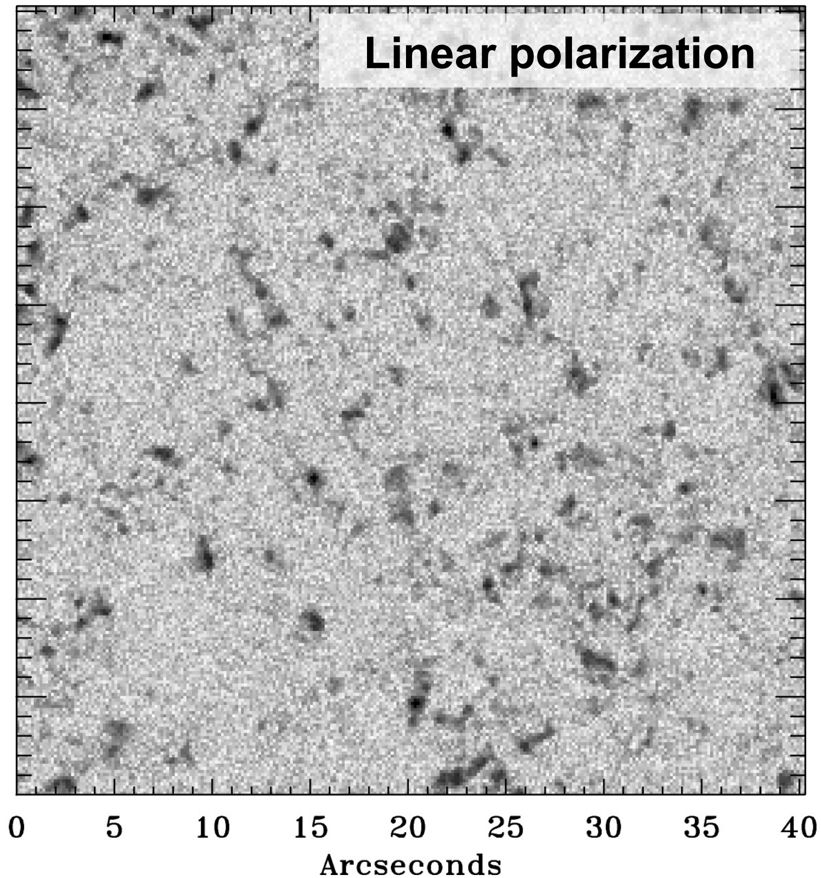
Polarization signals in the internetwork

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

Horizontal apparent flux density reported to be 5 times larger than vertical apparent flux density

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



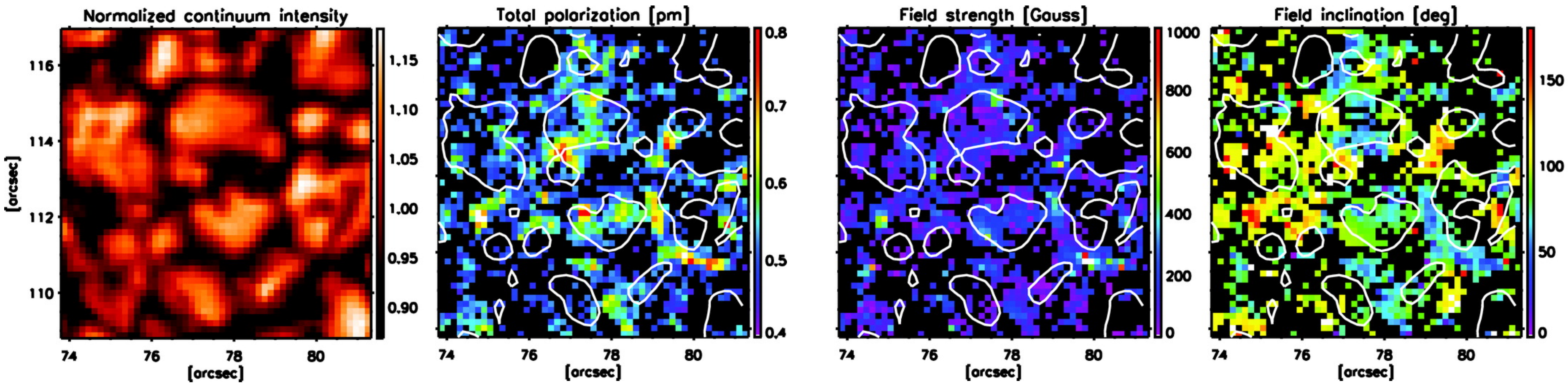


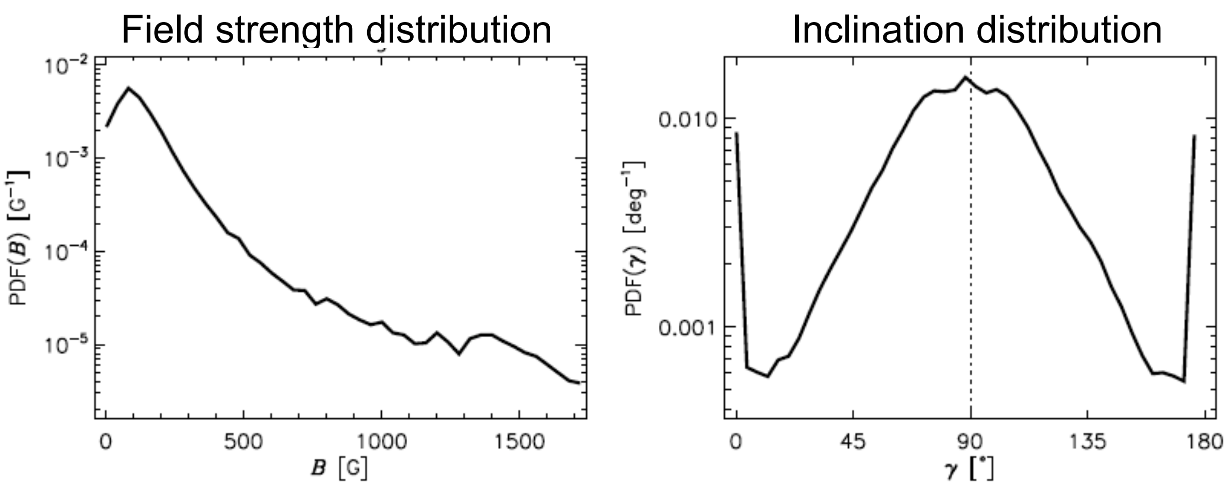
Similar maps derived by Beck & Rezaei (2009) using TIP and AO at German VTT in Tenerife

Internetwork fields from Hinode/SP data

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

One-component ME inversion (~600 000 pixels)





Internetwork fields are *weak and highly inclined* (peaking at ~100 G and 90º, respectively)

Problems

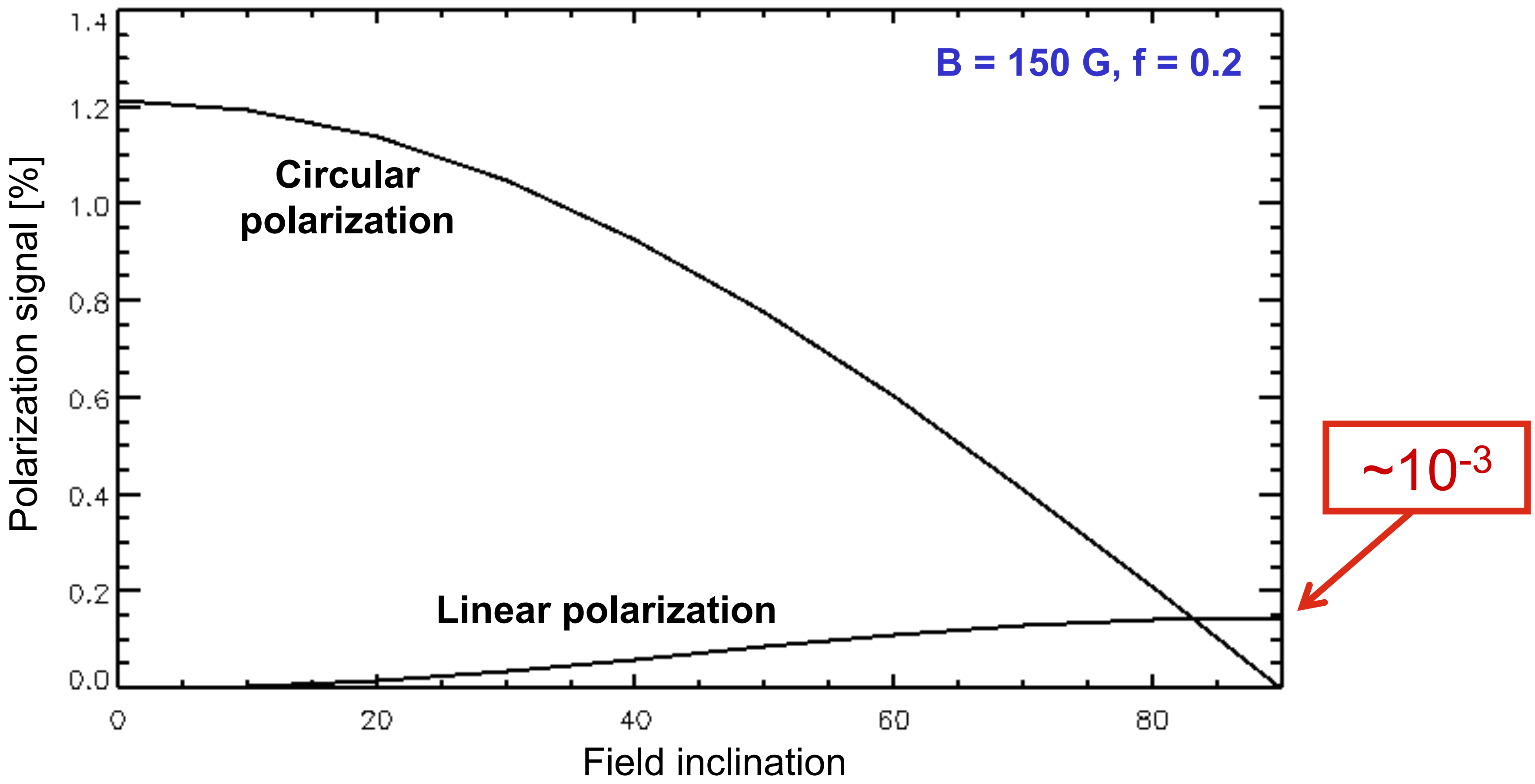
- Only a small fraction of the pixels show signals well above the noise level:
  - 26.0% have Stokes V amplitudes larger than 4.5 sigma
  - 2.1% have Stokes Q or U amplitudes larger than 4.5 sigma

- If the fields have large inclinations, why don't we see linear polarization everywhere?

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

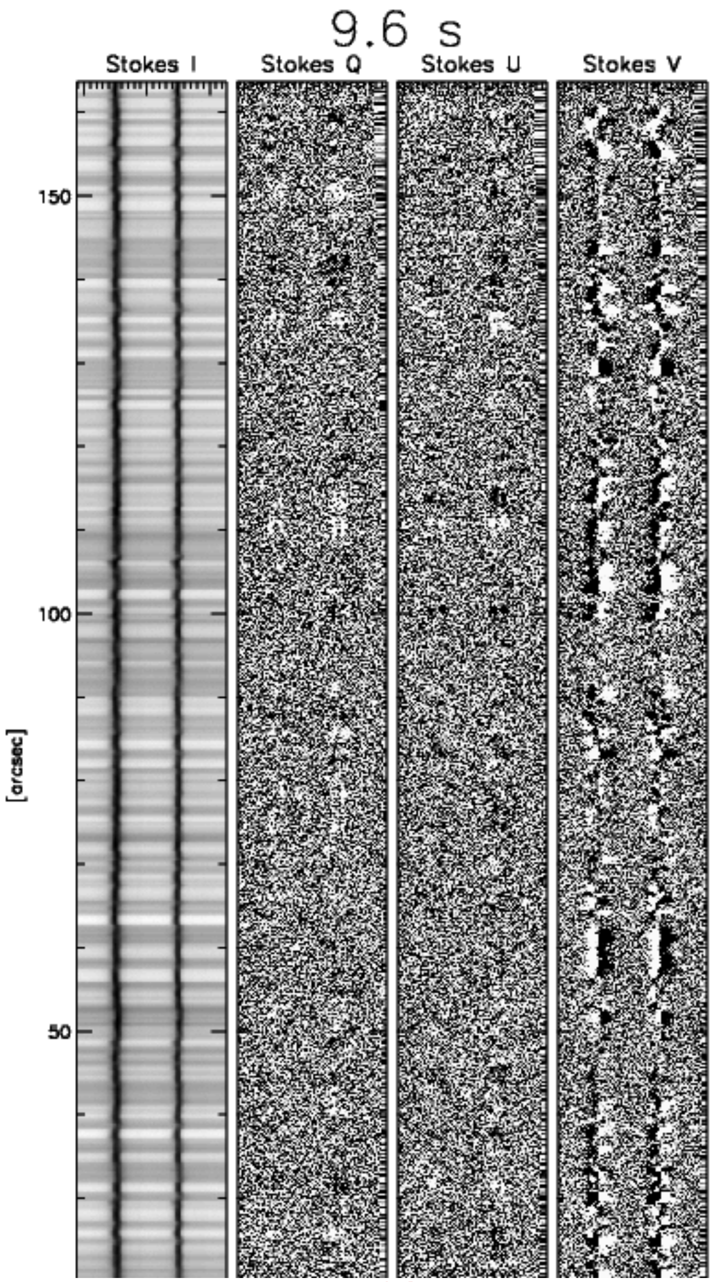
Lites et al., 2008, ApJ, 672, 1237

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

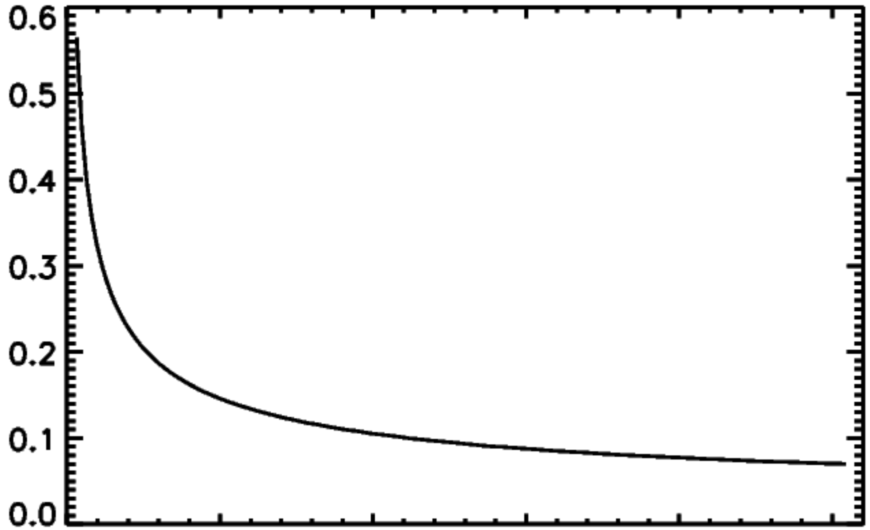
Pushing the effective integration time to a limit



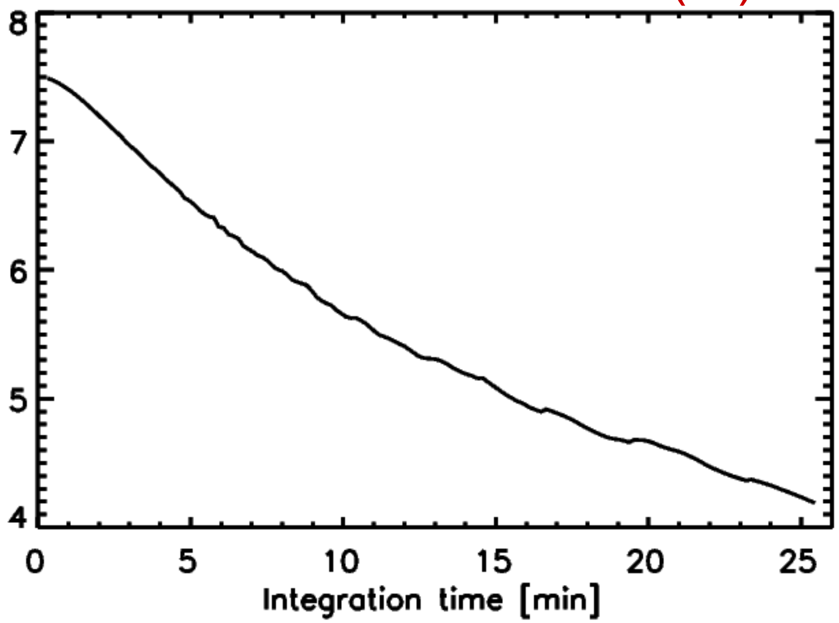
7.1%

Pushing the effective integration time to a limit

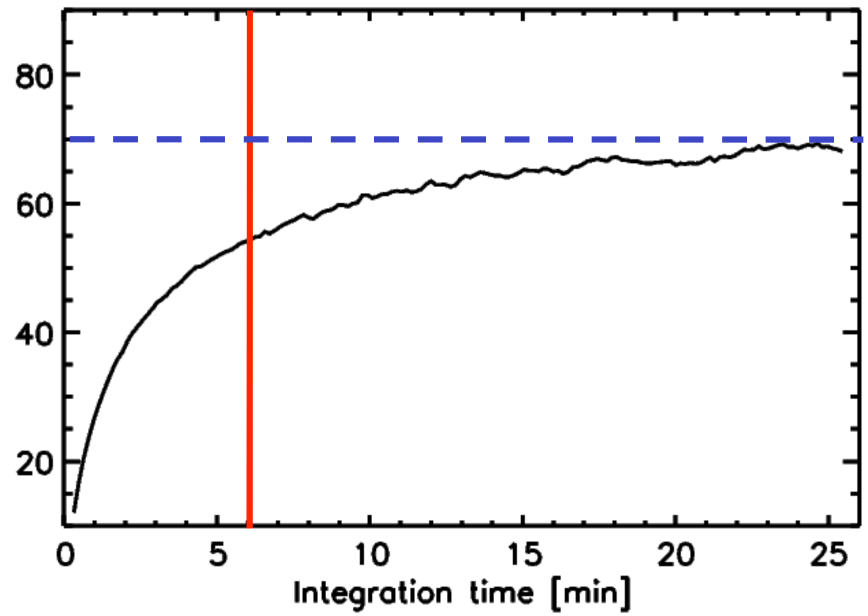
Noise level (x 10^{-3} I_c)



Granulation contrast (%)



Fraction of FOV with Q or U > 4.5σ



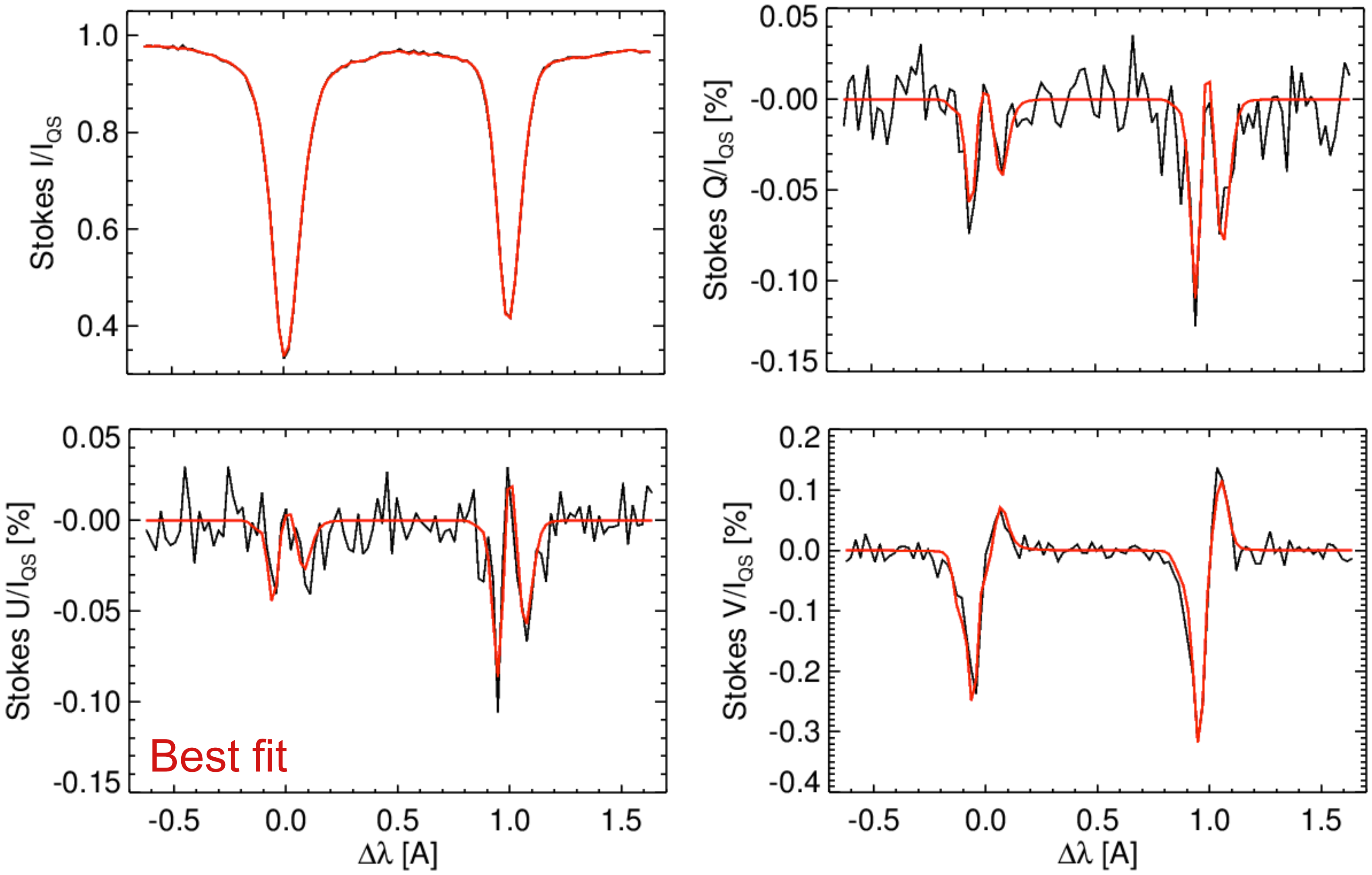
SIR inversion of ultra-deep observations

Inversion of the **6.1 minute integrations:**

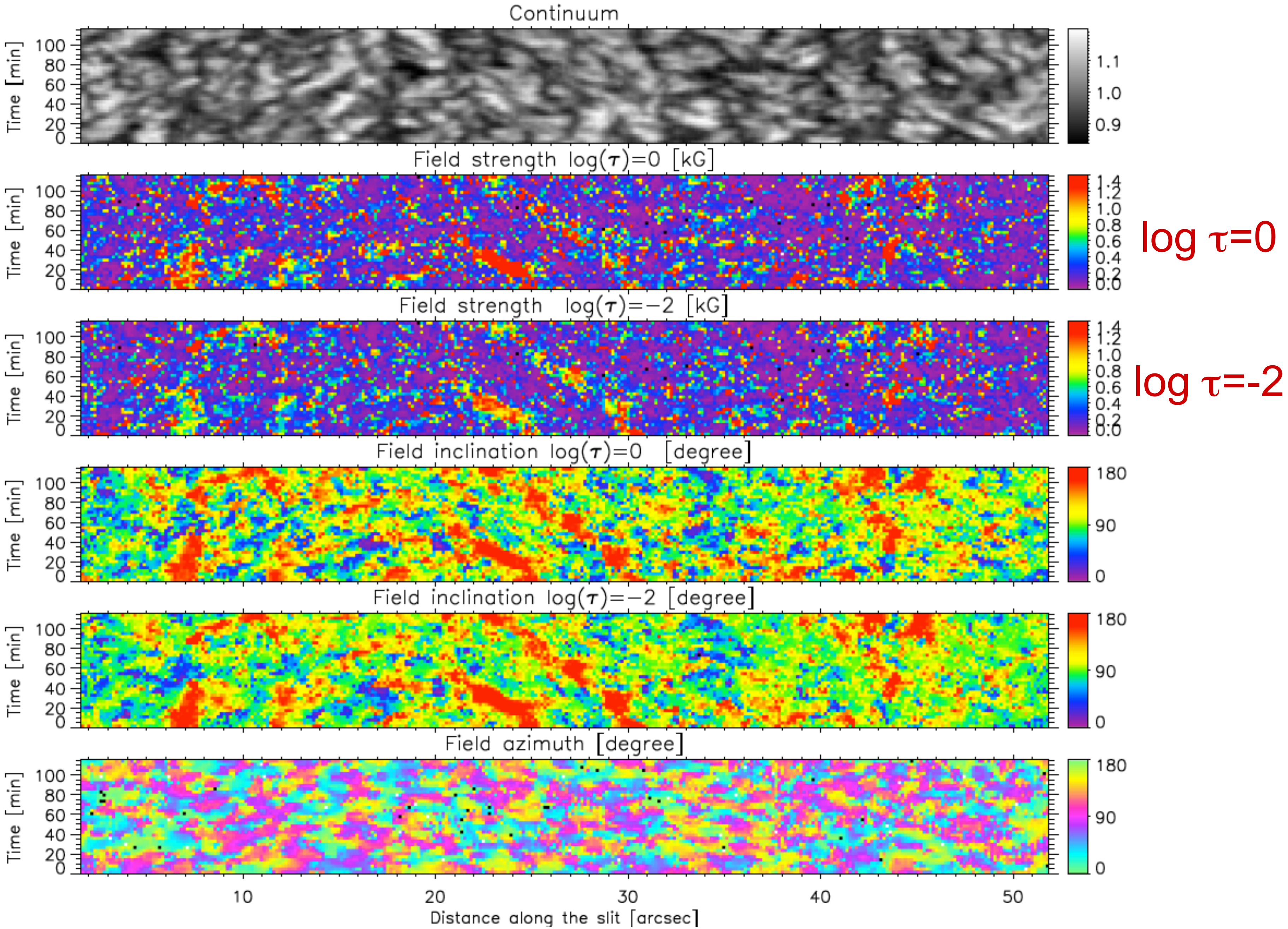
- SIR code (Ruiz Cobo & del Toro Iniesta 1992) with vertical gradients of atmospheric parameters to exploit line asymmetries
  - Five nodes for temperature
  - Two nodes for field strength, field inclination, and LOS velocity
  - Height-independent (constant) field azimuth and microturbulence
  - Magnetic filling factor (via local stray light)
  - No macroturbulence
- Use inversion results only for pixels with Stokes Q or U amplitudes well above the noise ($>4.5\sigma$): 53% surface coverage
- These pixels show both linear and circular polarization signals, making it possible to derive the vector magnetic field stratification accurately

SIR inversion of ultra-deep observations

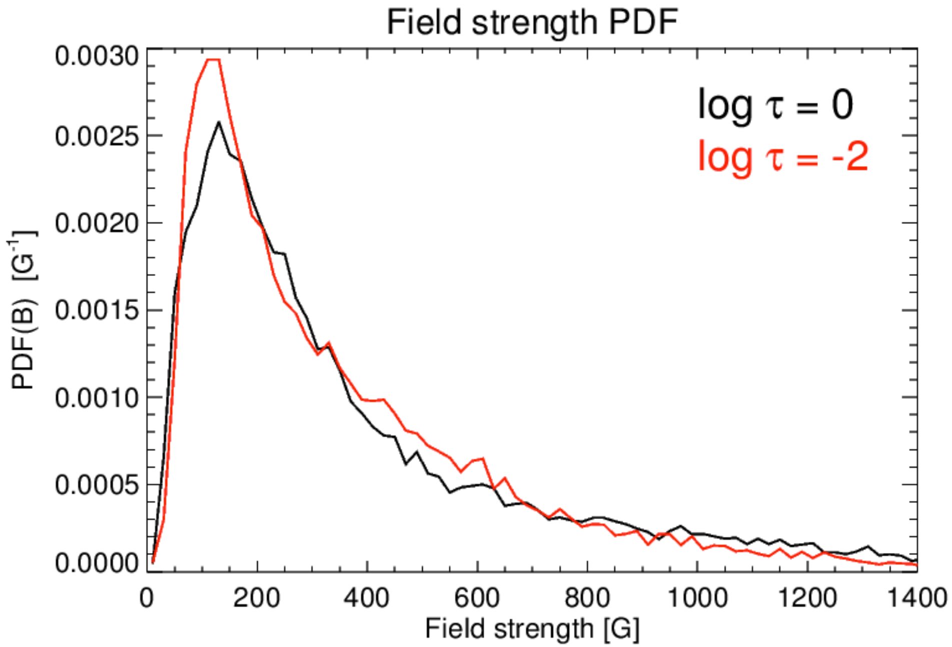
B(τ=0.1)=310 G, γ(τ=0.1)=102^o, χ=110^o, f=0.07

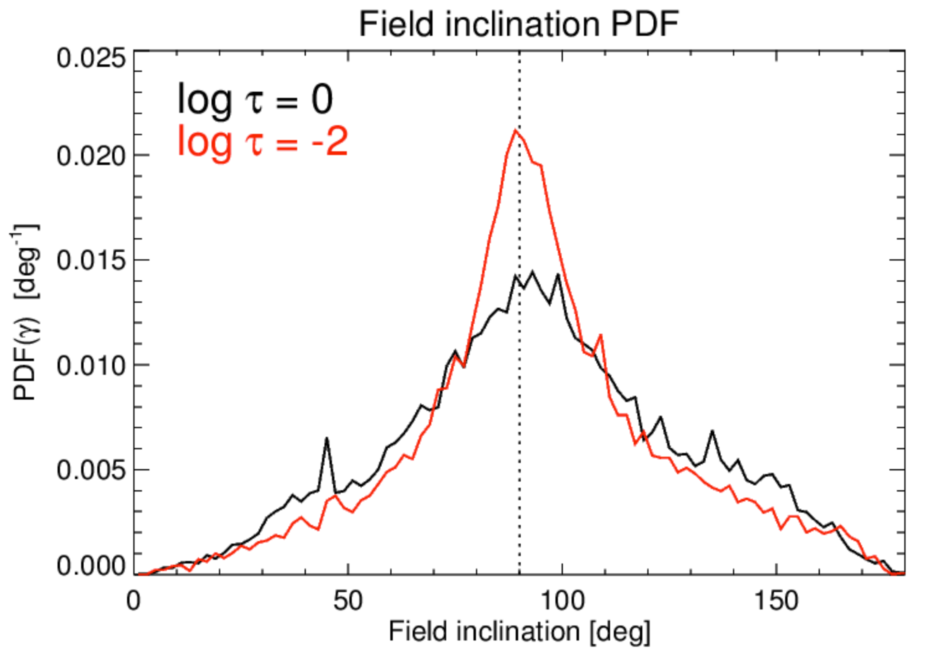


SIR inversion of ultra-deep observations



Quiet-Sun magnetism at different heights

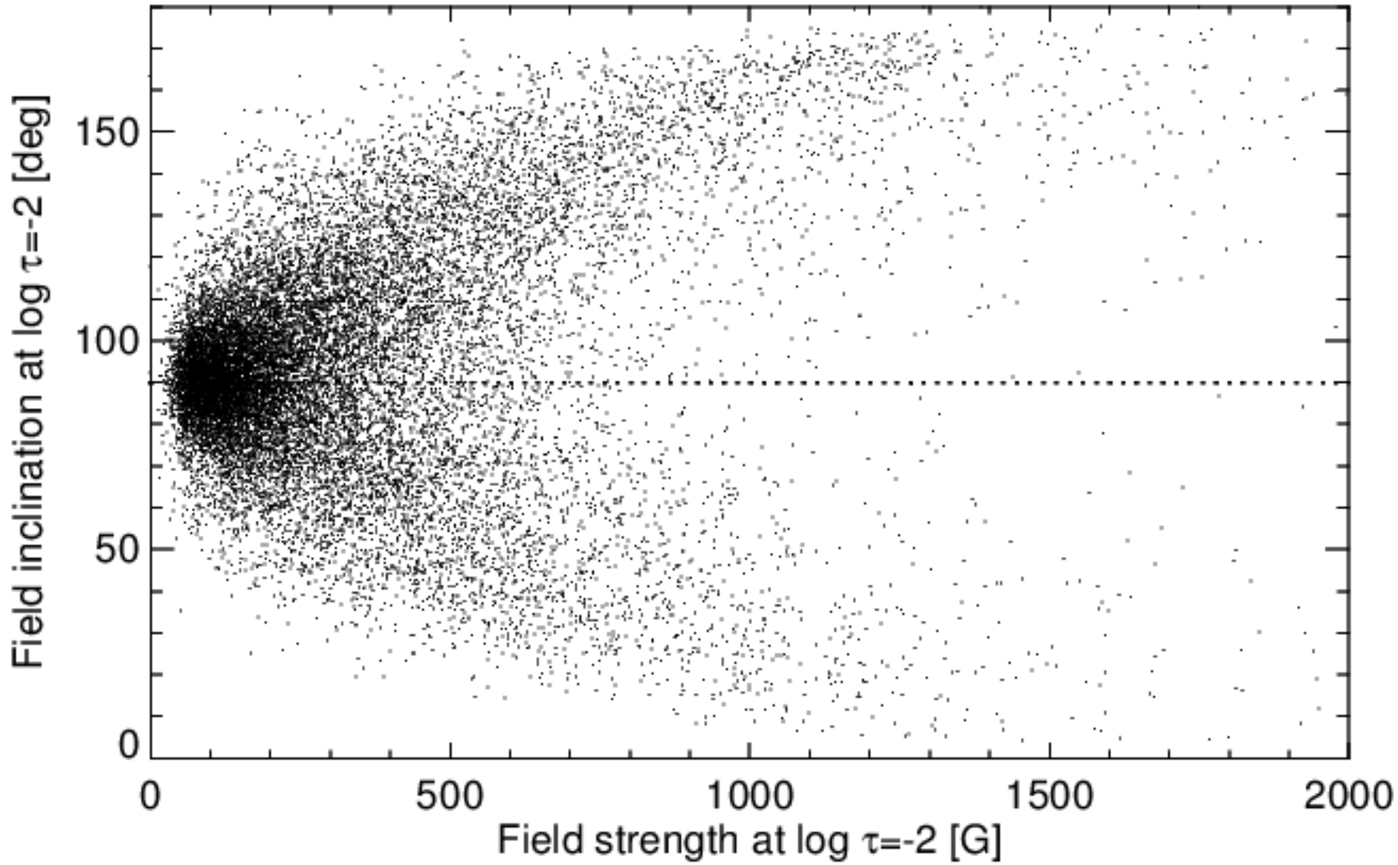




Integration time:	6.1 min
Noise level:	1.3×10^{-4} I_c
	0.2 G longitudinal, 15 G transverse
Pixel size:	0.16″
Fraction of FOV:	53%

PDFs of field strength and field inclination peak at 140 G and 90º, respectively

Ratio of horizontal to vertical field components



$\langle B_h \rangle / \langle B_v \rangle = 2.4$ at $\log \tau = 0$ and 3.4 at $\log \tau = -2$

for the weaker fields (<500 G)

(supporting findings by Lites et al. 2008, Orozco Suárez & Bellot Rubio 2012, Stenflo 2013, and simulations results by Schüssler & Vögler 2008, Steiner et al. 2008, Danilovic et al 2010)

Summary

- We detect linear polarization signals everywhere: the quiet Sun is a real ocean of inclined magnetic fields
- Properties of internetwork fields (53% of surface area):
  - Weak fields, strengths near or just below the Hanle saturation limit
  - Large inclinations
  - Isotropic distribution of azimuths
  - Fields tend to become weaker and more inclined with height
- Most likely, these are the "turbulent" fields revealed by Hanle depolarization measurements (e.g, Stenflo 1982; Faurobert-Scholl 1993; Trujillo Bueno et al. 2004)
- Larger telescopes/2D spectropolarimeters needed to follow evolution of the fields and understand their origin. Compelling scientific driver for Solar-C!