

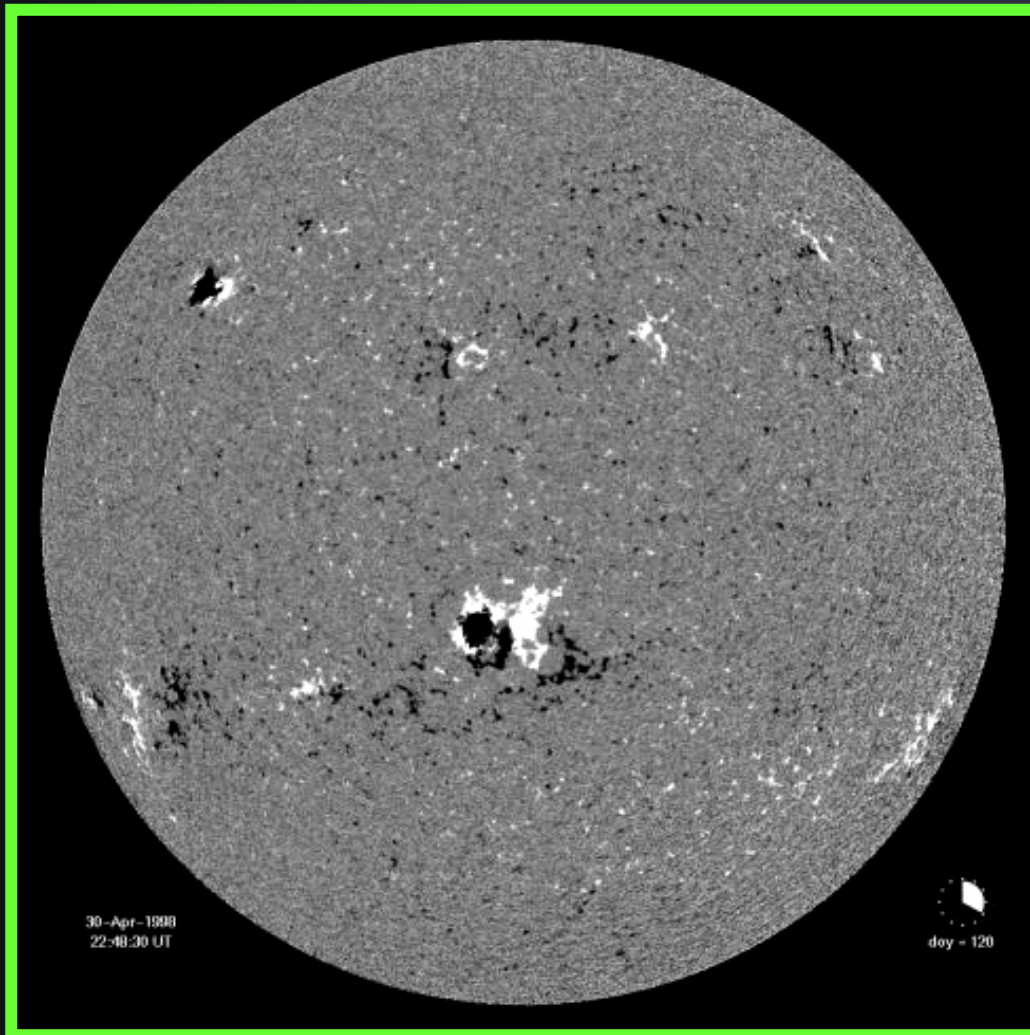
Magnetic field measured at different levels in the solar atmosphere and magnetic coupling



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Magnetic field is the source of Sun's activity, which is best visible in the outer atmosphere

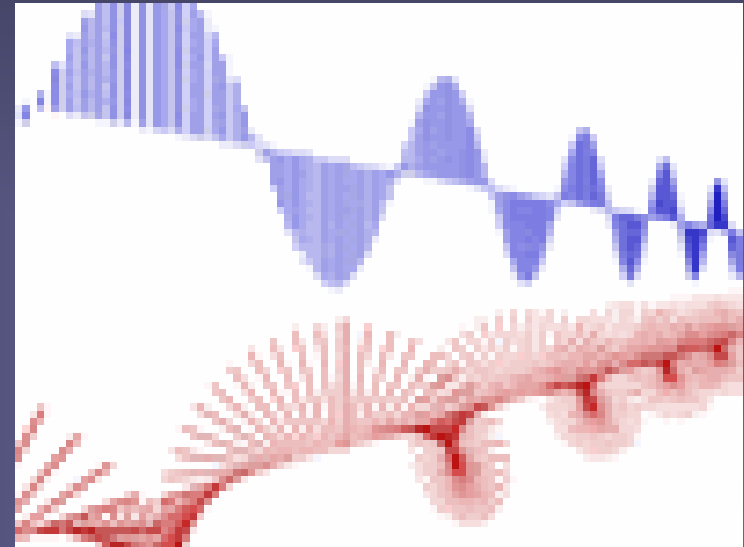


Field couples all atmospheric layers:
Need to know magnetic field from convection zone to Corona!

Major problem:
Magnetic field not well known in upper atmosphere

Measuring solar magnetic fields: techniques

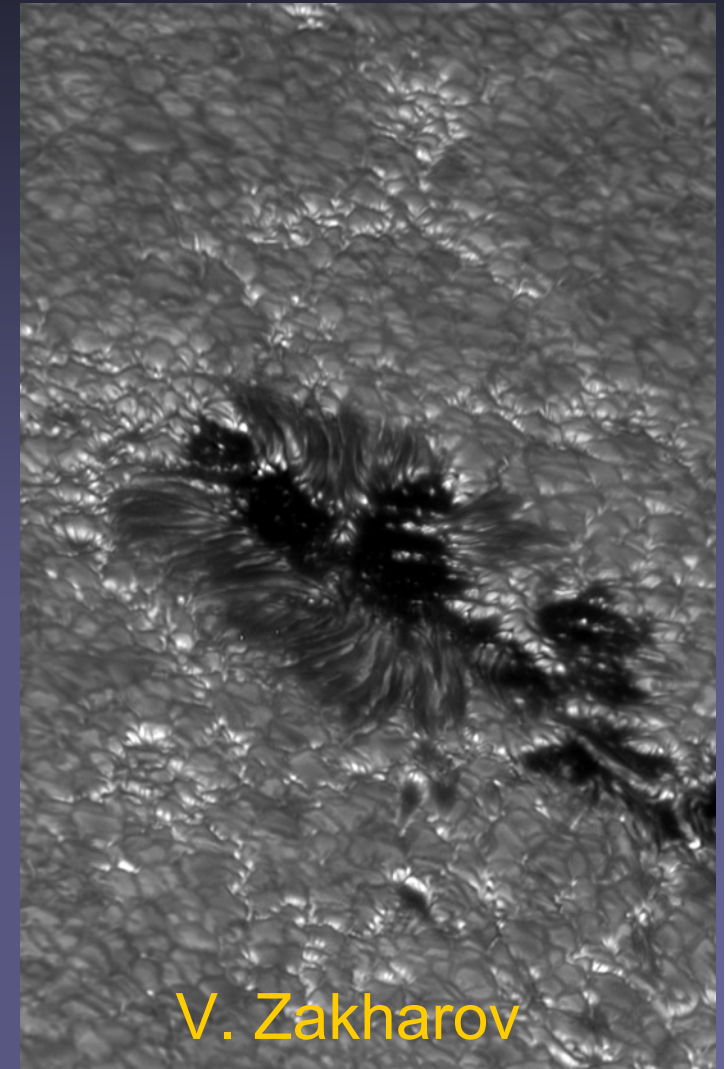
- gyroresonant emission: Radio obs. of strong fields (>250 G)
- Bremsstrahlung emission: Radio
- coronal loop oscillations: EUV, coronagraphy (Nakariakov, next talk)
- Zeeman effect: spectropolarimetric observations UV - IR
- Faraday rotation: radio obs.
- Scattering polarization: coronagr.
- Hanle effect: spectropolarimetric observations UV - IR



Polarisation!

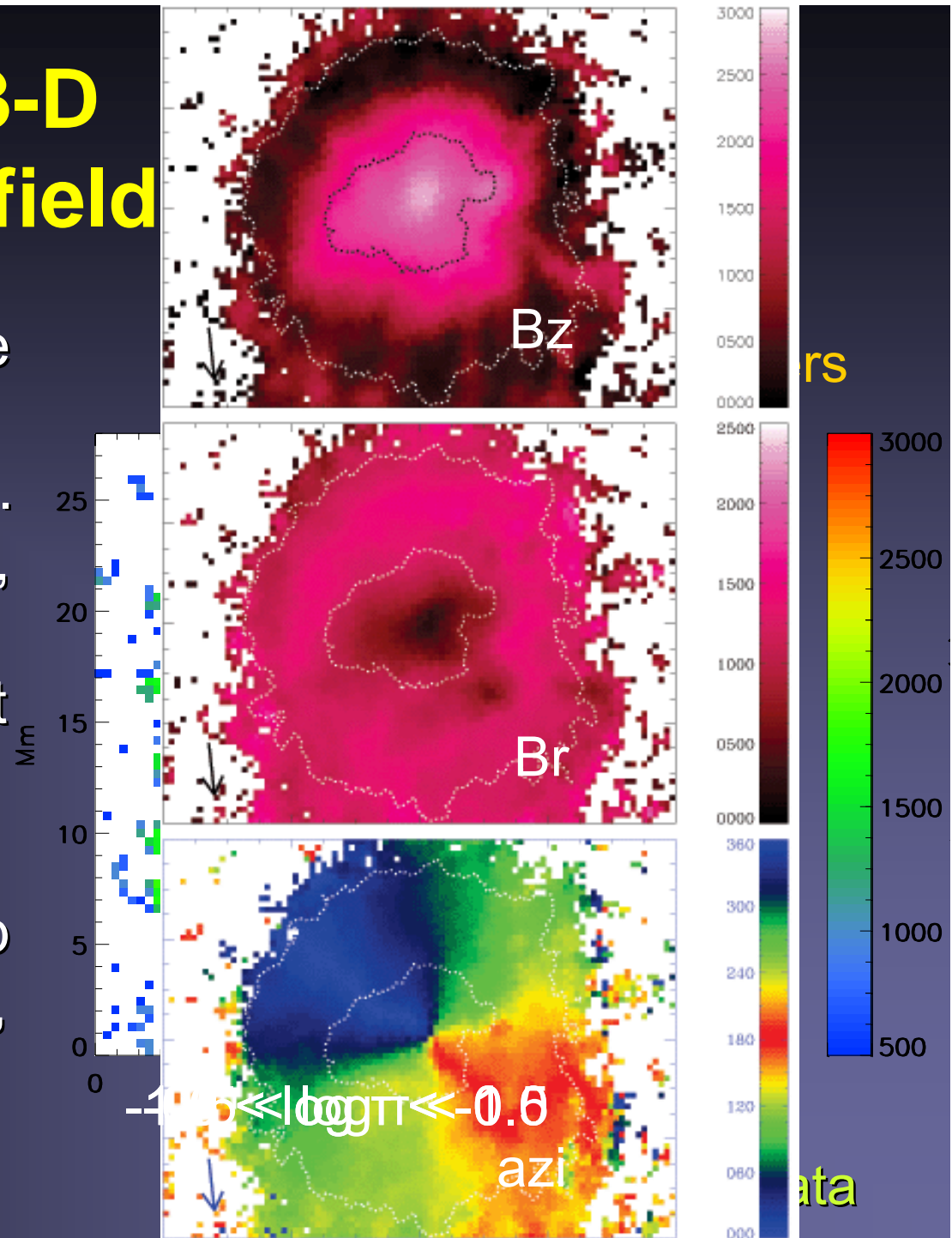
Magnetic field in photosphere

- 2 main components:
 - strong fields (flux tube fields: sunspots, faculae, network)
 - weak fields (turbulent fields)
- Measurement techniques:
 - Zeeman effect (strong fields)
 - Hanle effect (weak fields)
 - Proxies (e.g. G-band)



Inversions: 3-D photospheric field

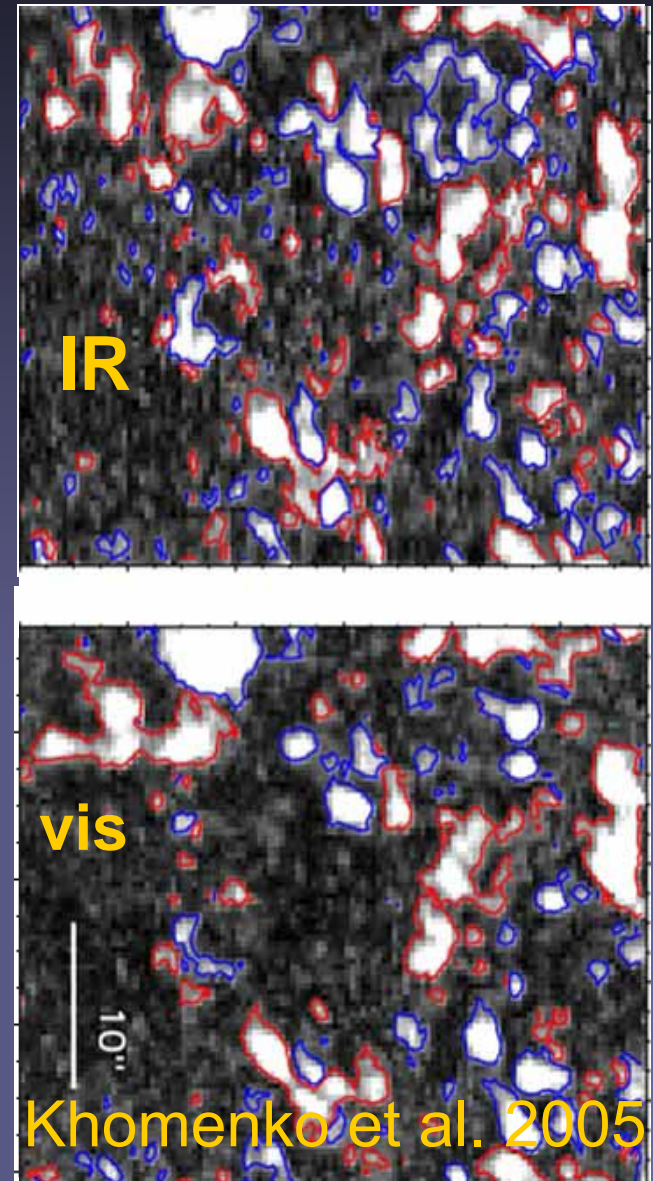
- Inversion codes deduce $B(x,y,z)$ from Stokes profiles (e.g., Auer et al. 1977, Keller et al. 1990, Ruiz Cobo & Del Toro 1992, Socas Navarro et al. 1998).
- E.g.: 3-D structure of B in sunspot (Westendorp Plaza et al. 1997, 2001, Mathew et al. 2003).



Quiet Sun fields: weak or strong?

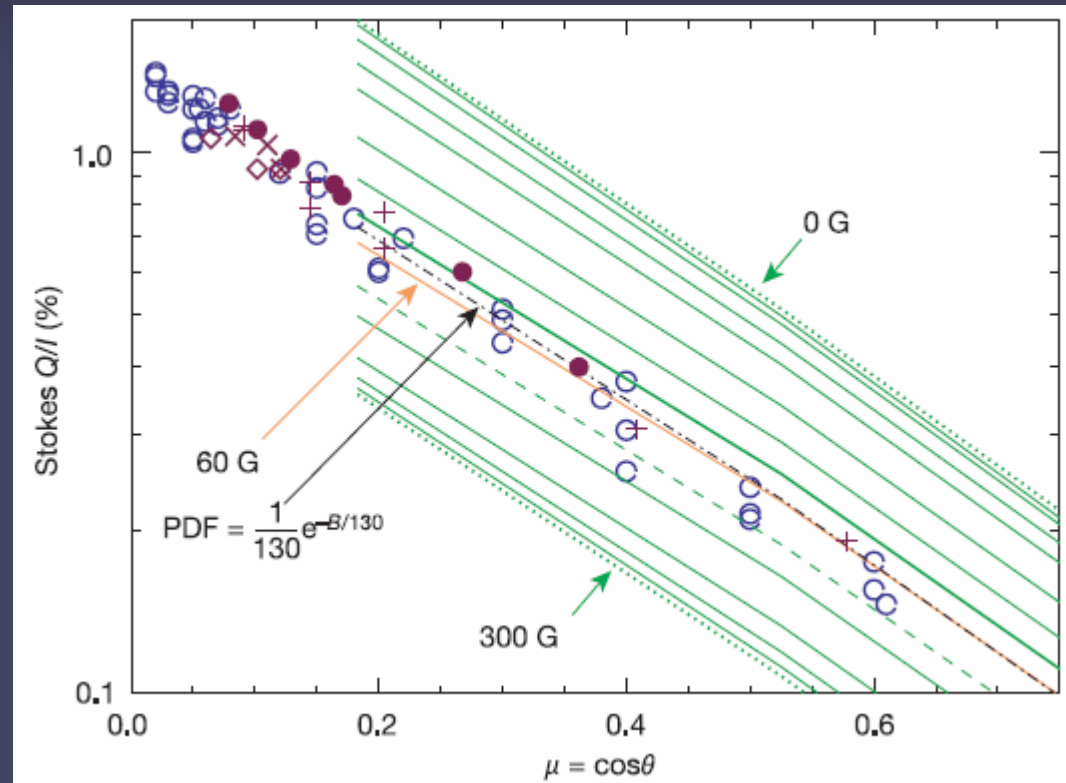
Hot topic: controversial results

- **Network:** kG fields (Stenflo 73)
- **Internetwork:** Results depend on technique
 - Zeeman in visible: mainly strong (kG fields, i.e flux-tube like)
 - Zeeman in IR: weak (<500 G)
 - Hanle: large flux in turbulent B
- **Comparison visible vs. IR**
 - Systematic errors when inverting Fe I 6302 & 6301 (Collados et al.)



Hanle measurements

- Depolarisation of Sr I resonance line gives $\langle B \rangle = 40\text{-}60$ G hidden turbulent field (Trujillo Bueno et al. 2004)
→ less magnetic energy density than the strong field.
- Trujillo Bueno et al.: if exponential PDF of magnetic field obtained from simulations is used, then the weak internetwork field magnetic energy density is larger than that in the network field (flux tube field).



→ Consider the simulation PDFs more carefully

Radiation-MHD Simulations of small-scale magnetic fields

Continuum Intensity

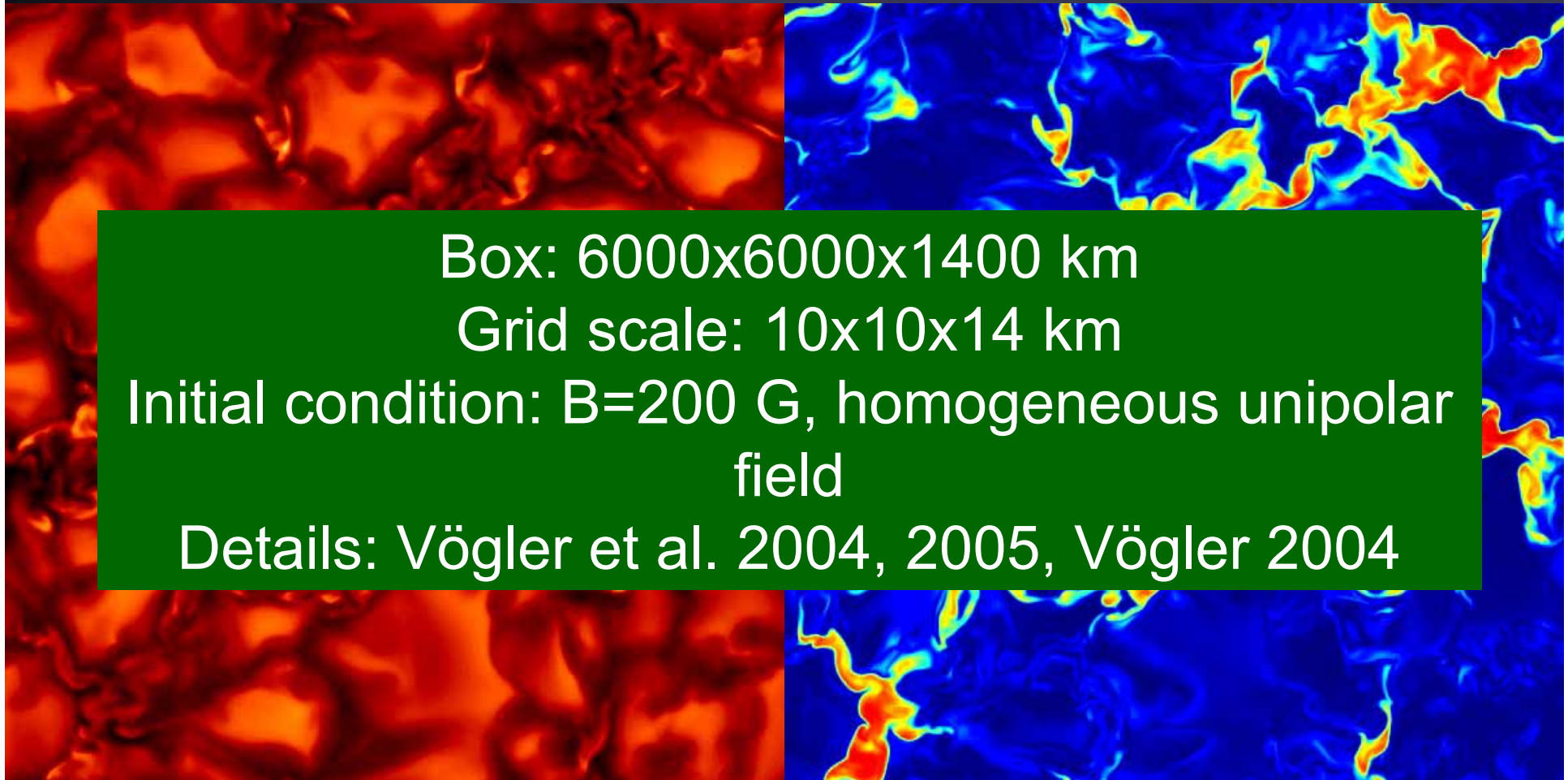
Magnetic field

Box: 6000x6000x1400 km

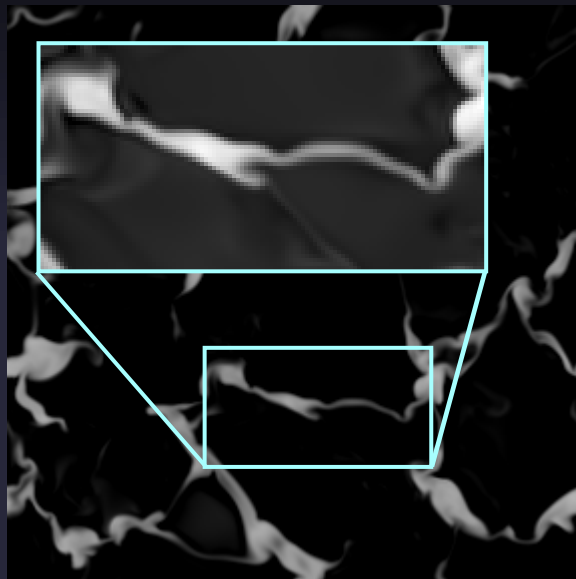
Grid scale: 10x10x14 km

Initial condition: $B=200$ G, homogeneous unipolar field

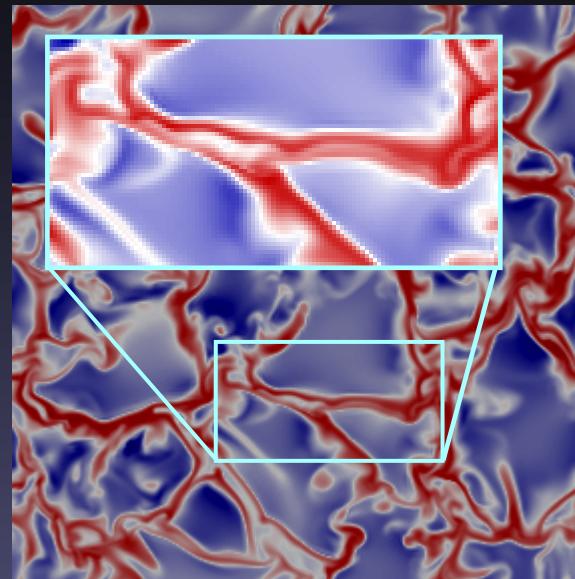
Details: Vögler et al. 2004, 2005, Vögler 2004



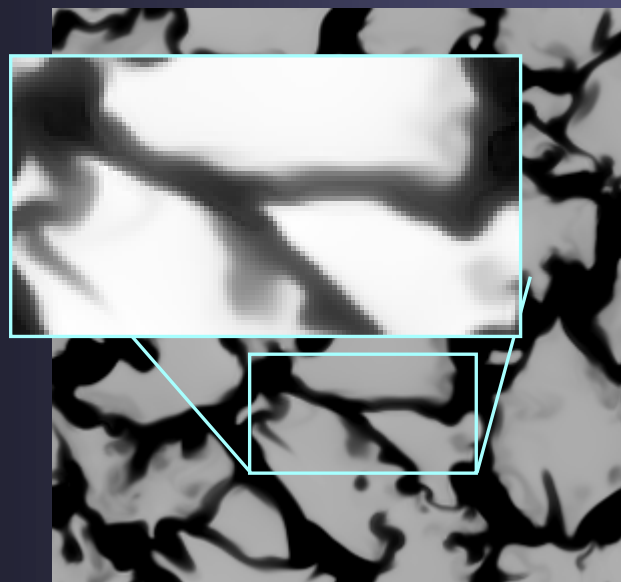
B_z



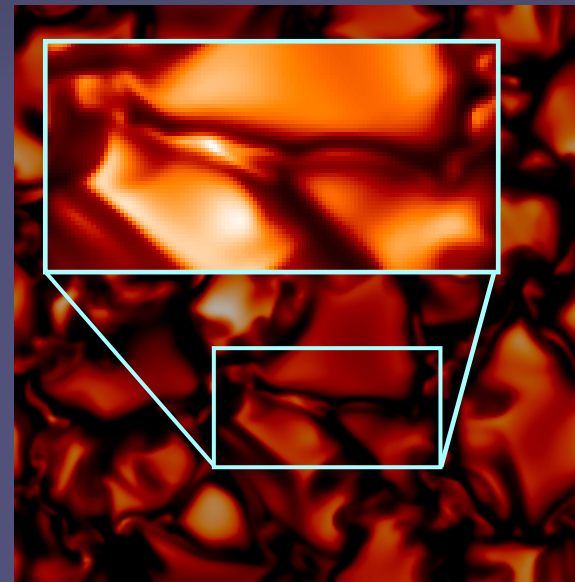
v_z



Magnetic
Element:
Magnetic
Flux
Sheet



T



I_c

horizontal cuts near surface level

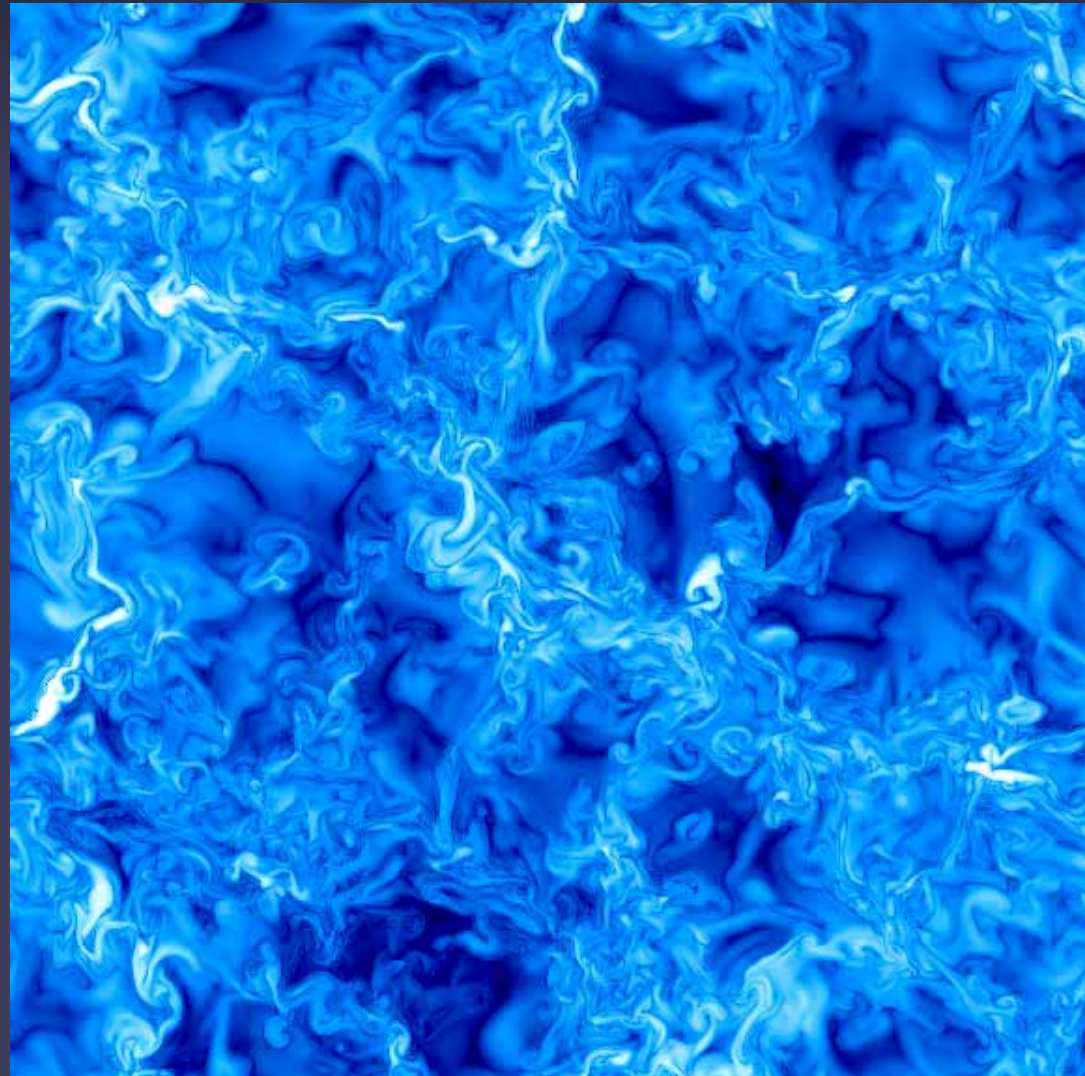
Vögler et al. 2003

Radiation-MHD Simulations of small-scale magnetic fields

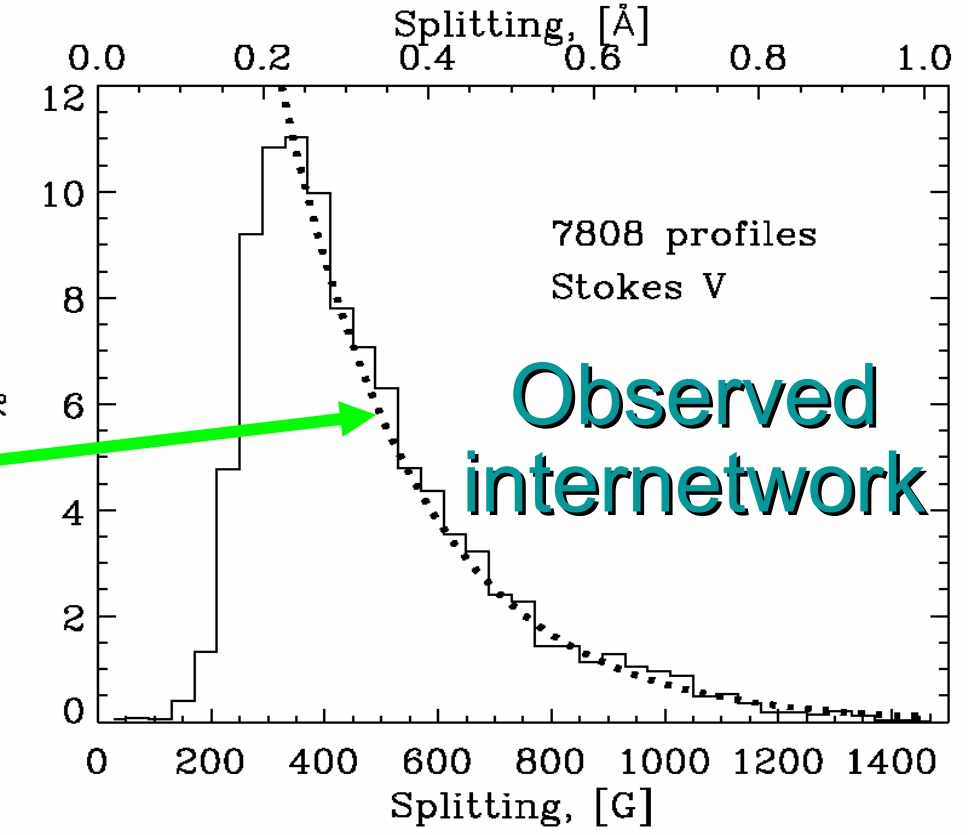
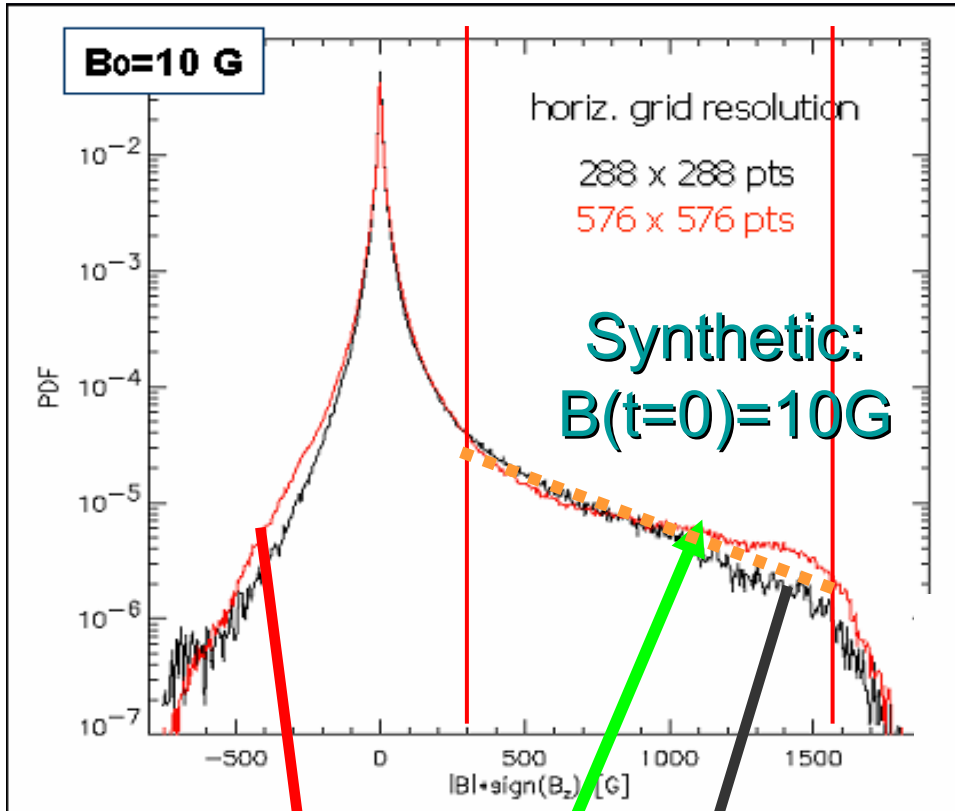
Log(|B|) for a homogeneous initial field of 10 G.

Brighter is stronger field.

Complex PDF of B shows more or less exponential drop-off at large B values.



Synthetic vs. Observed Field Strength PDFs (Probability Distribution Functions)



Exponential distribution over the field strength range covered by 1.56 μm observations

red: 10 km

black: 20 km

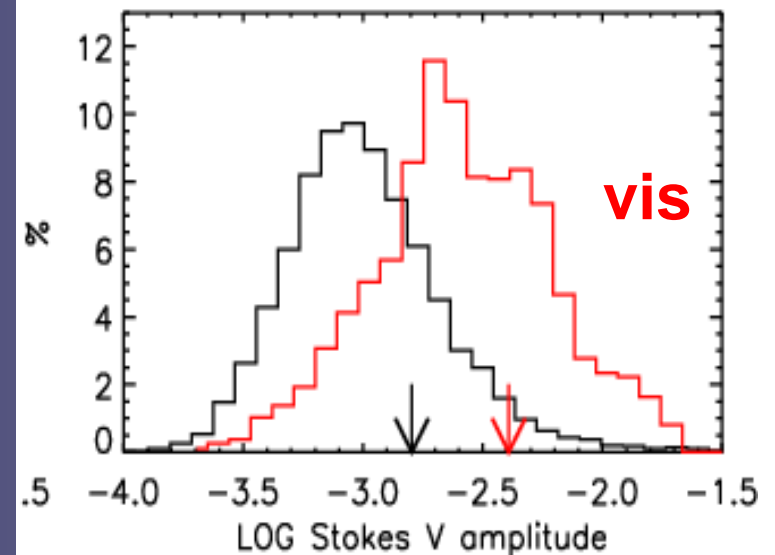
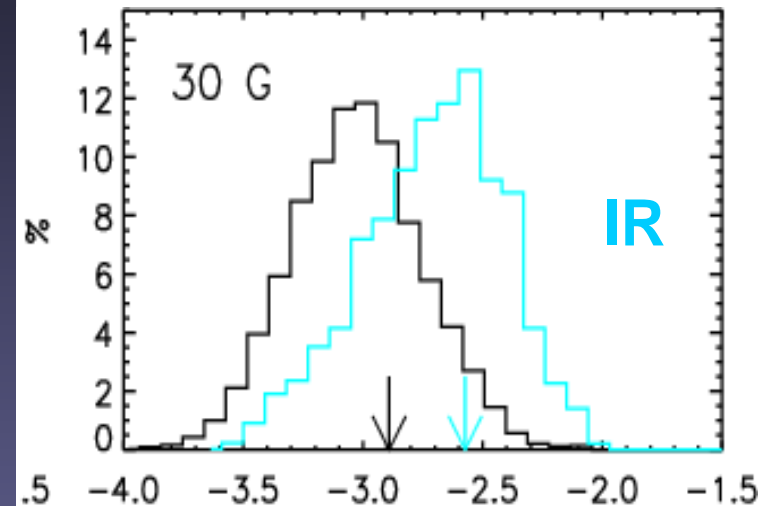
Vögler et al. 2005,
Khomenko et al. 2003

Quiet Sun fields: weak or strong?

- Internetwork: comparison with simulations:
 - Compare distribution of Stokes V amplitudes of simultaneously measured visible and IR lines with same quantity from simulations
 - vis & IR lines reproduce simulations for $\langle B \rangle = 20\text{G}$

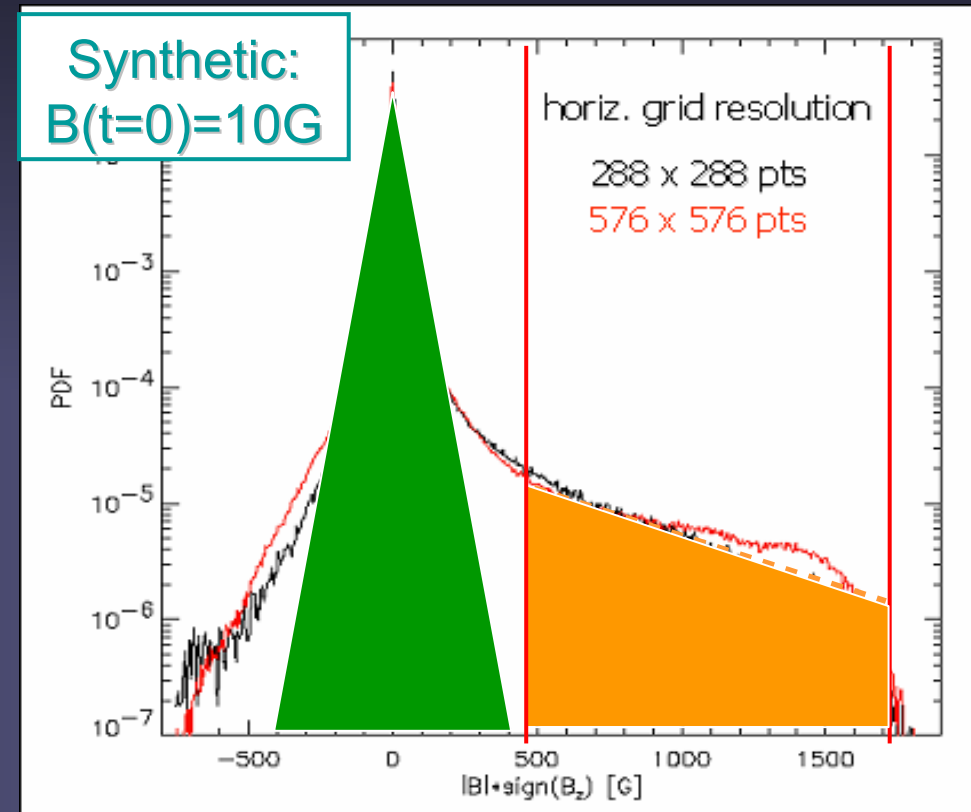
Khomenko et al. 2005

blue/red: simul, black: obs.



Quiet Sun fields: why are they of interest for magnetic coupling?

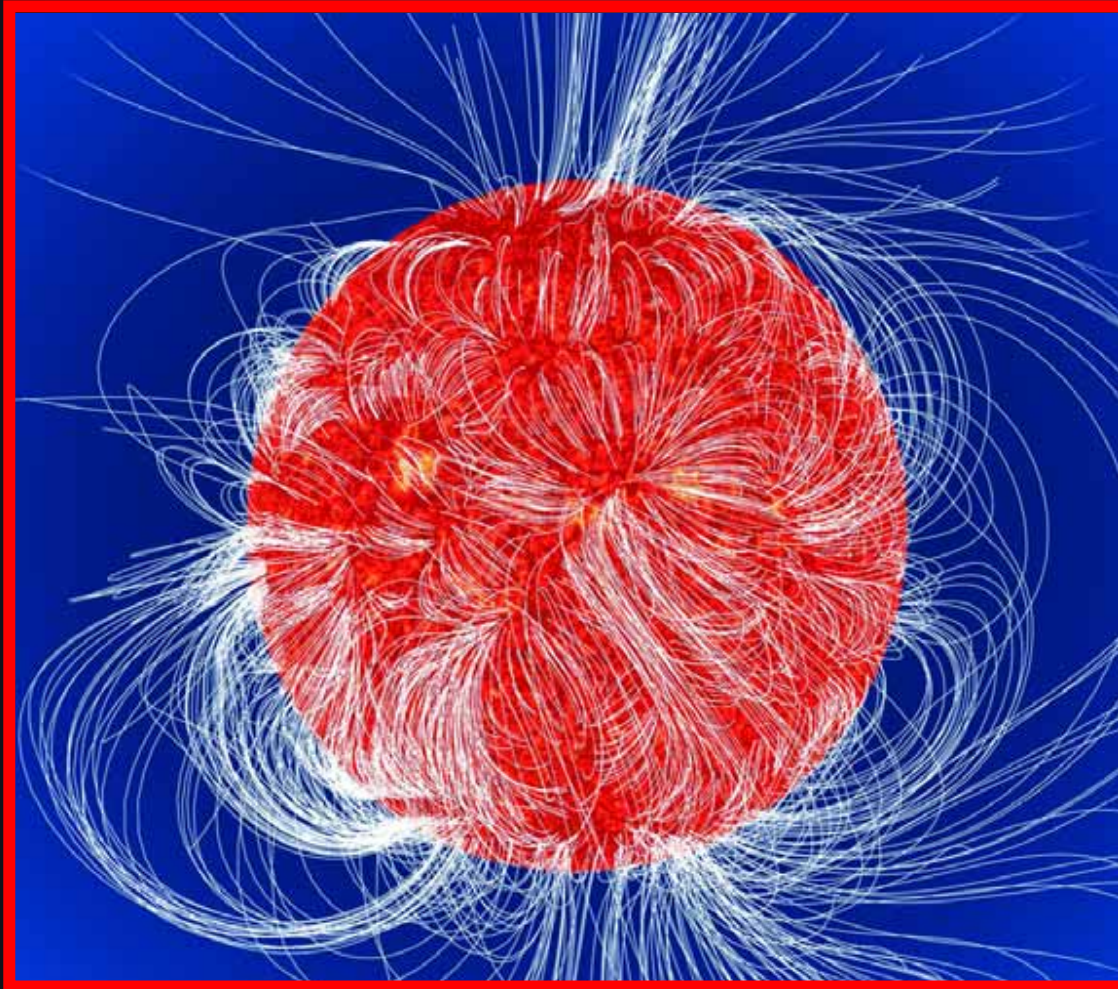
- Hanle effect interpreted in terms of exponential PDF (based on MHD simulations) gives larger energy in internetwork than in network field (Trujillo et al 04)
- Actual MHD PDF shows 2 distinct regimes:



- Rapid drop at weak fields: turbulent field
- Slow drop at strong fields: flux-tube-like fields

➔ Most of the magnetic energy is in the strong flux-tube field

Extrapolations of magnetic field from photospheric magnetograms



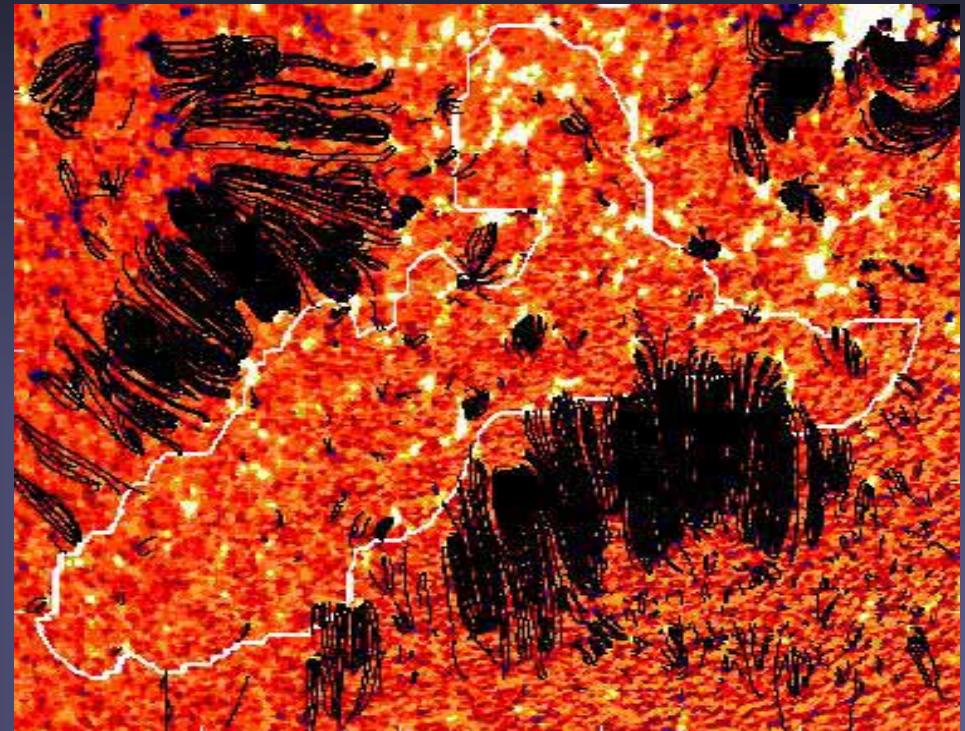
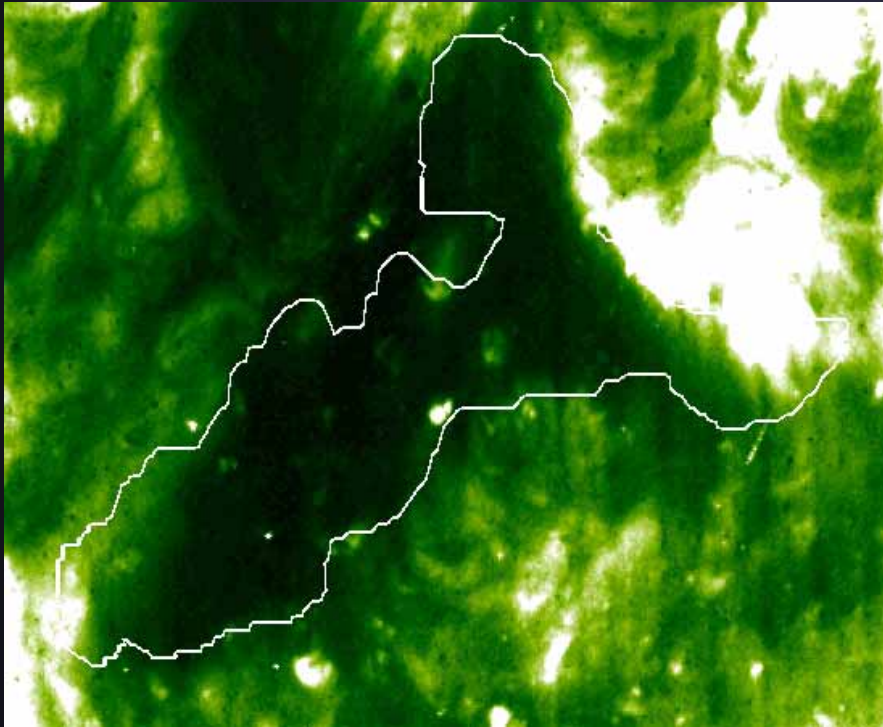
Wiegelmann 2005

Important help for knowing magnetic field in corona

Hurdles:

1. 180° ambiguity in vector field
2. Field not ff in photosphere, etc.
3. Large resources needed for realistic extrapolations

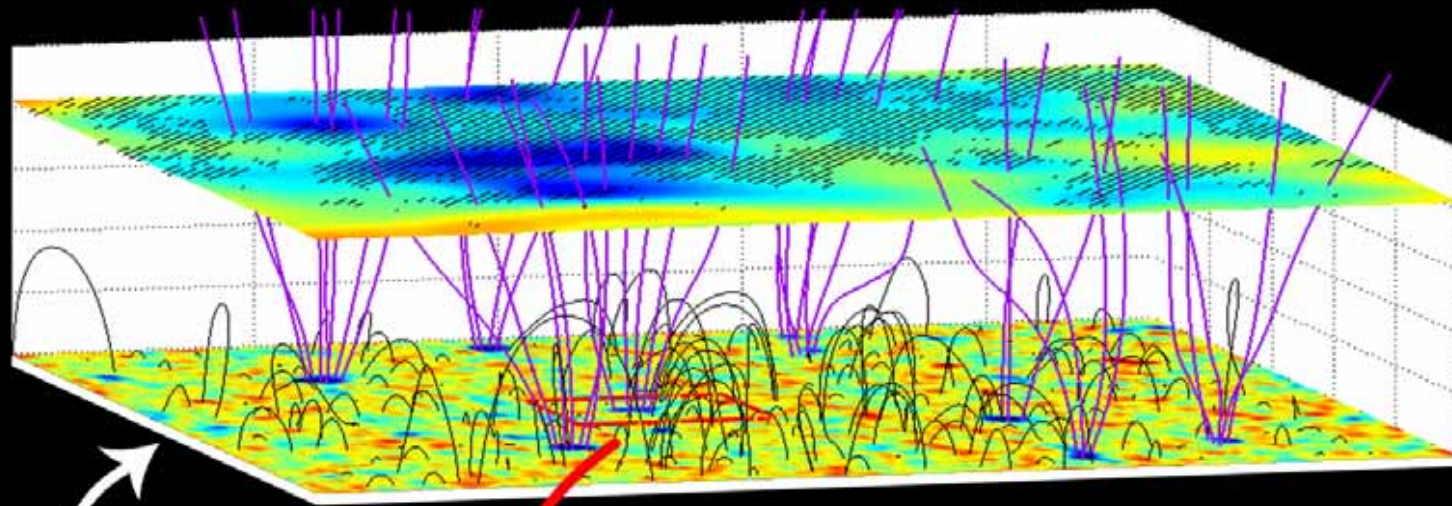
Why are Coronal Holes not visible at transition region temperatures?



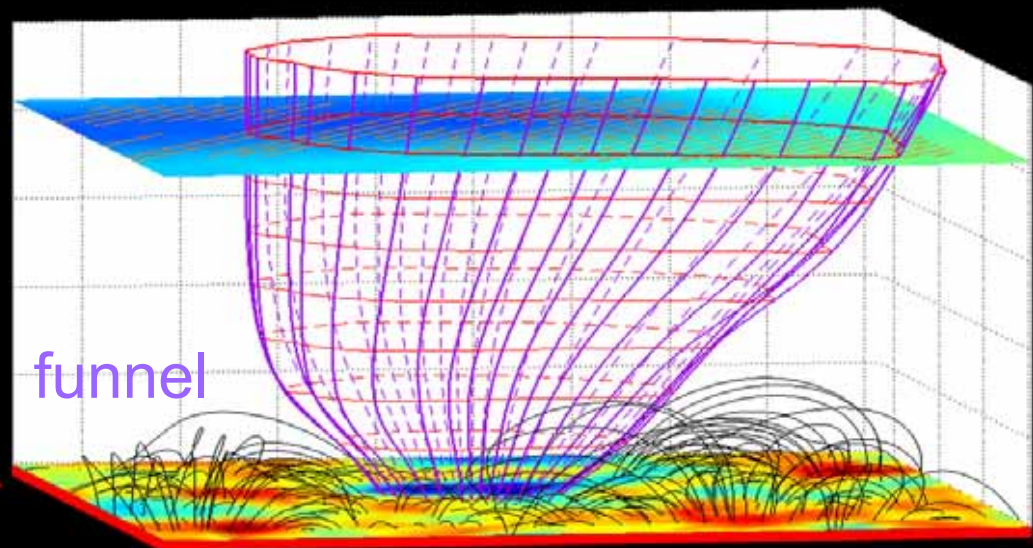
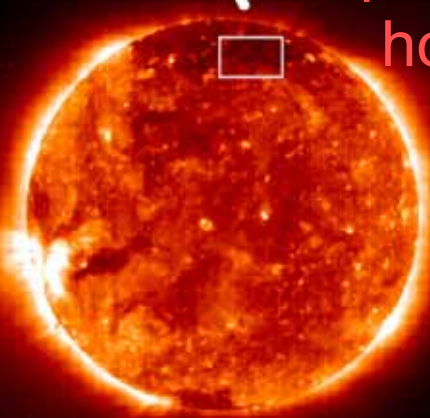
CH and QS in EIT Fe XII & MDI + overlaid magn. loops (for $B > 20G$): Many more long loops in QS than in CH. Small loops equally present in both regions. $T \sim L^{1/3}$: hot loops depleted in CH, cool loops equally present in QS and CH

Wiegelmann+Solanki 2004

B in fast solar wind source region



polar hole



funnel

Tu, et al., Science, 2005

Chromospheric magnetism

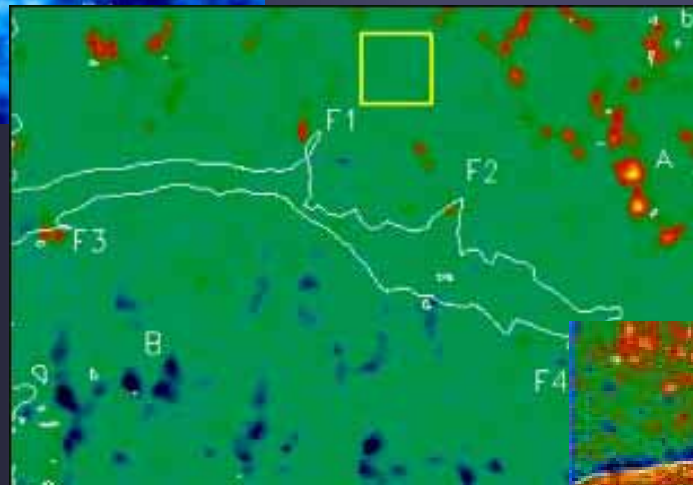
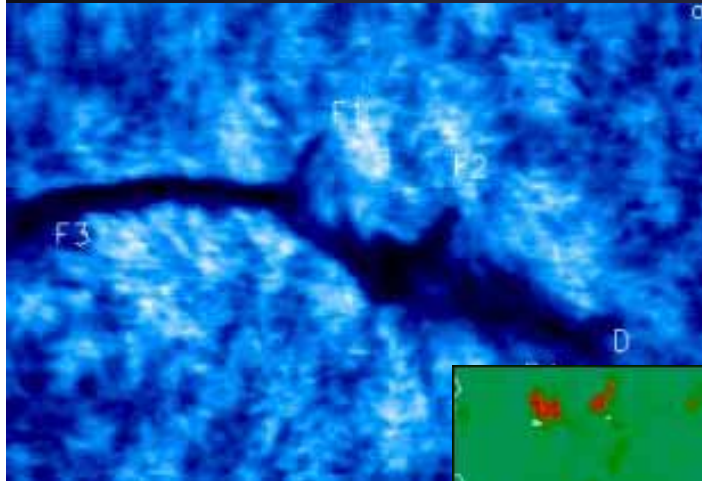
■ Zeeman effect:

- H β from Huairou observatory (many papers by H. Zhang and his group)
- Ca IR triplet (Socas Navarro & co-workers)
- He 10830 (Harvey & Hall 1971, Rüedi et al., Penn & Kuhn, Solanki et al., Socas Navarro et al)
- Na I D lines (Eibe et al. 2002)

■ Hanle effect:

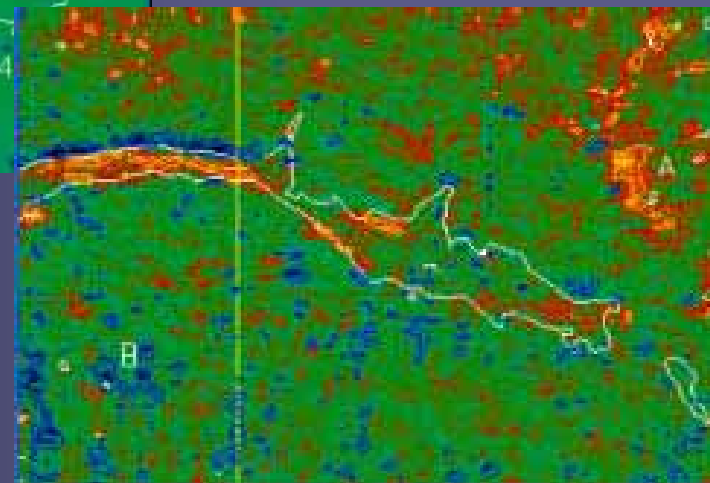
- Ca I and Sr II lines (Bianda et al.)
- He 10830 (Trujillo Bueno et al., Lagg et al.)

Measurements in Chromosphere & Photosphere



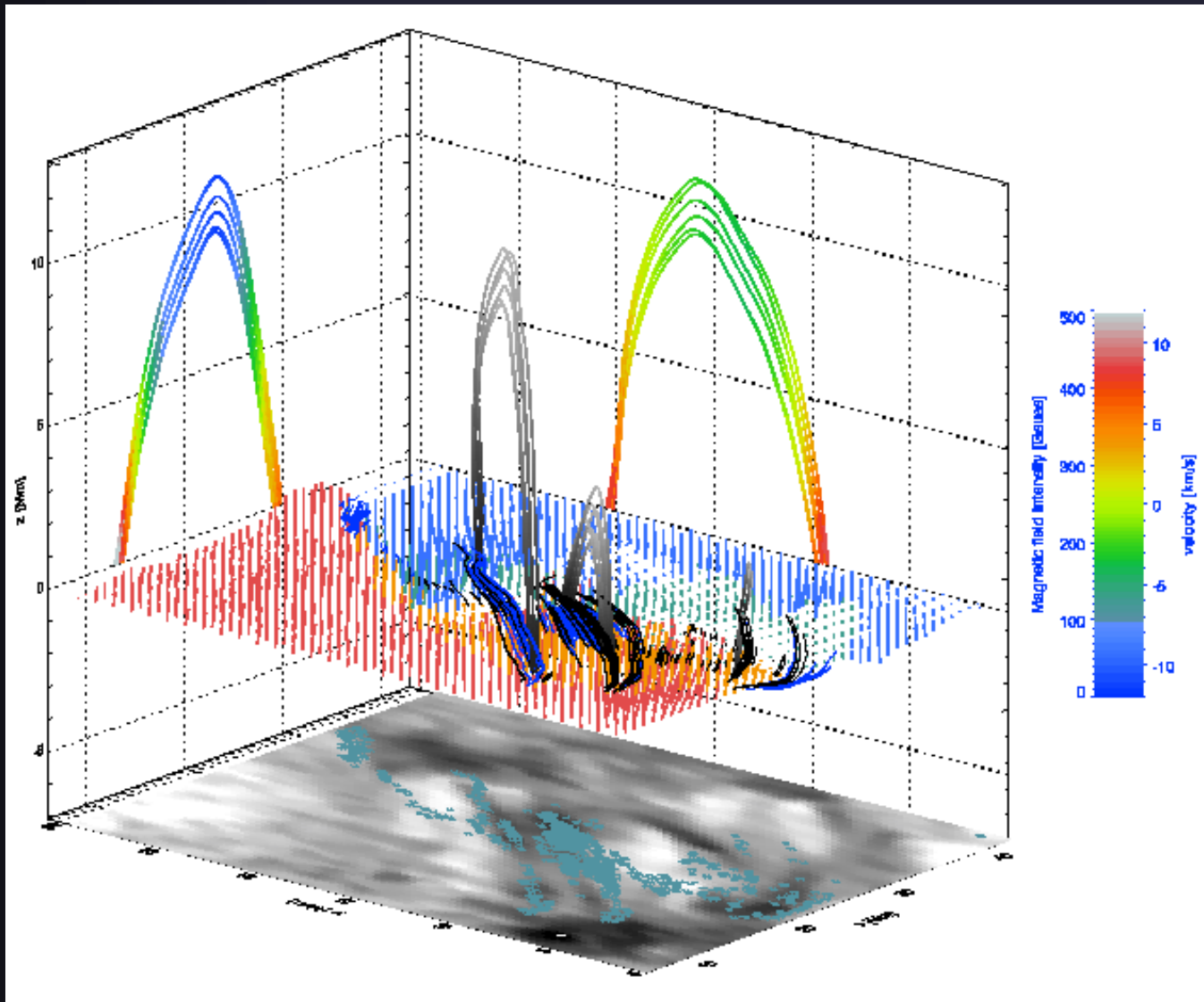
Bao & Zhang (2003):

- chromospheric magnetic field from H β filament
- LOS-field: 40-70 G
- evidence for twisted magnetic configuration inside the filament



Solar Magnetic Field
Telescope in Huairou Solar
Observing Station

Structure of Magnetic Loops



Magnetic loops deduced from measurements of He I 10830 Å Stokes profiles in an emerging flux region.

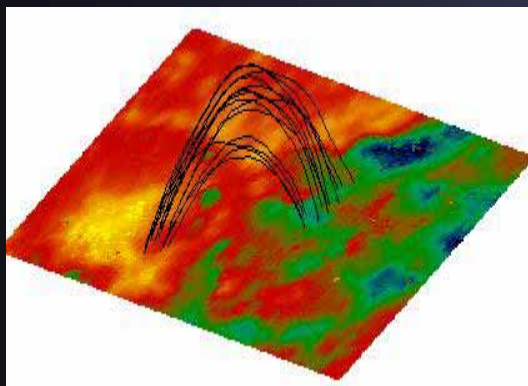
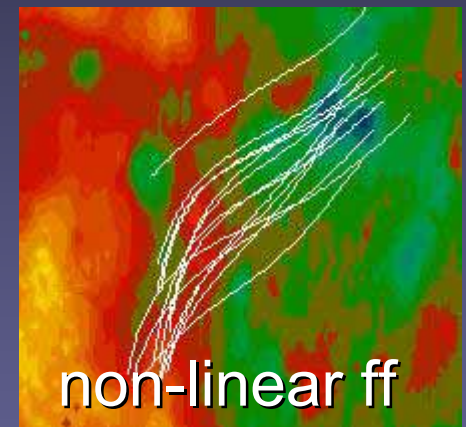
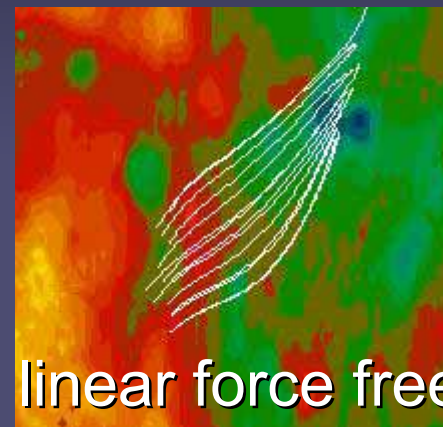
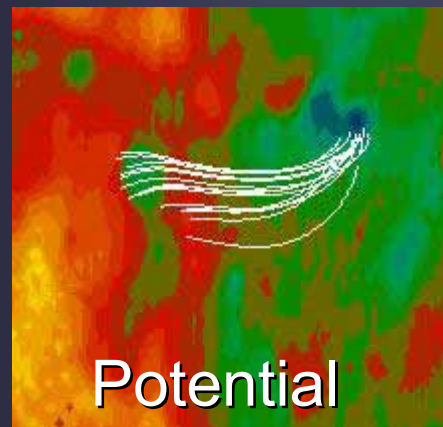
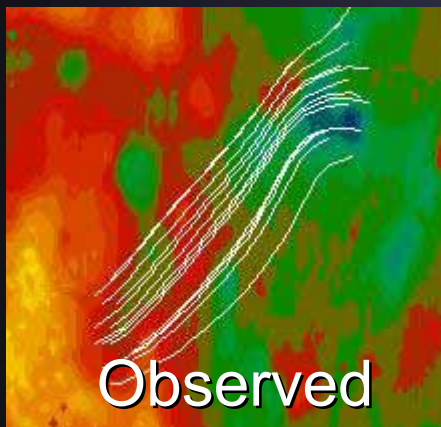
Left projection:
Field strength

Right projection:
Vertical velocity

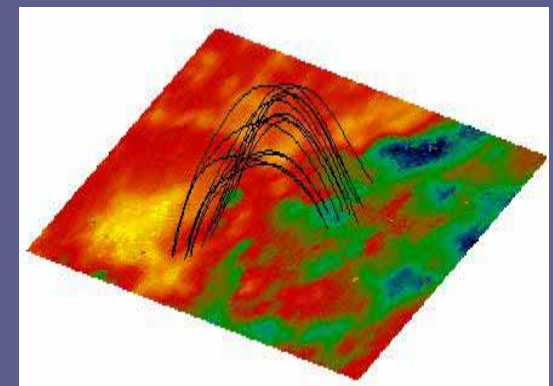
Solanki et al. 2003

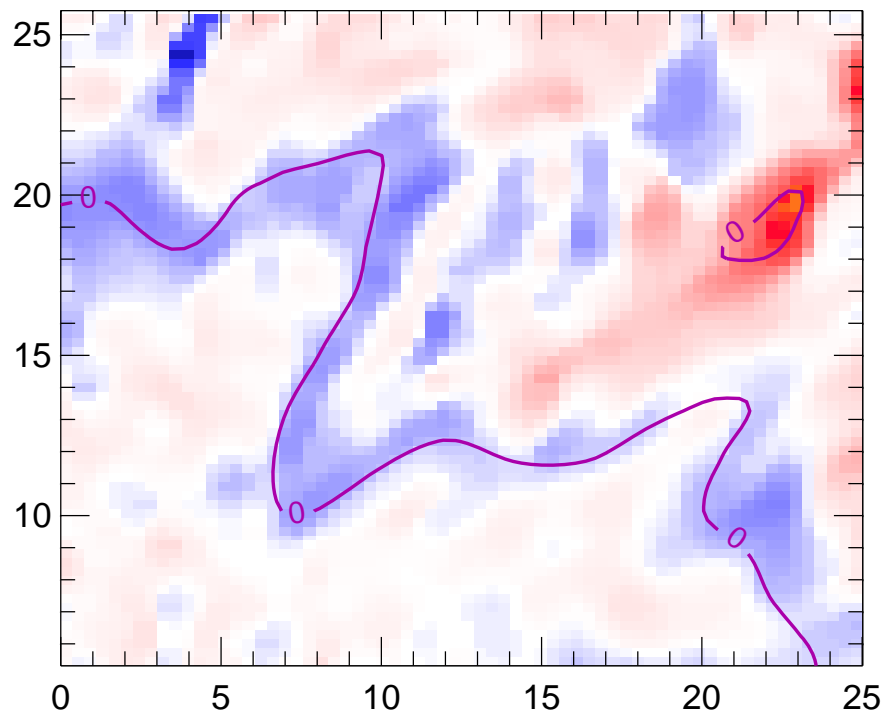
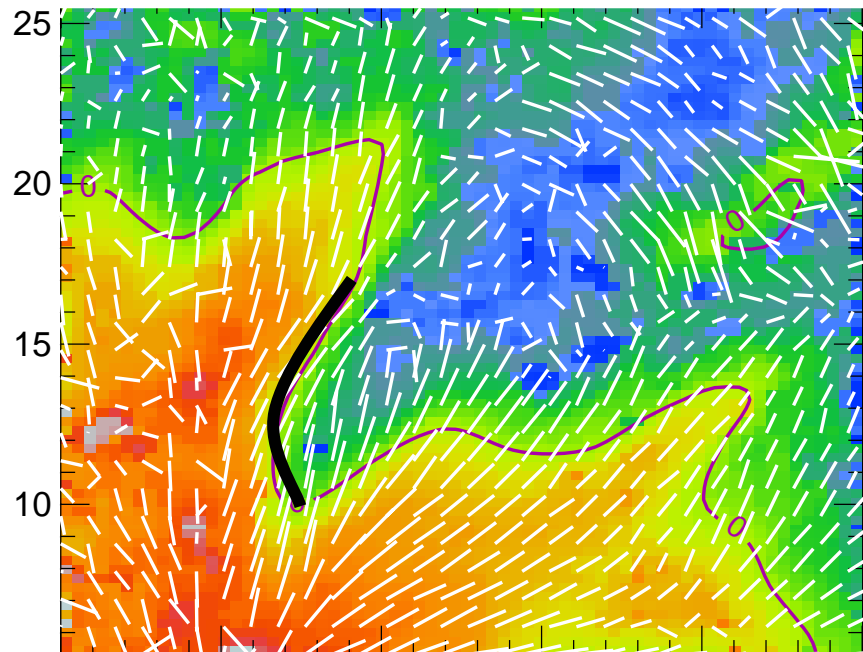
Testing Magnetic Field Extrapolations

- Non-linear force-free fields reproduce the loops reconstructed from observations better than the linear force-free ones and far better than potential fields.
- Loops harbour strong currents while still emerging.



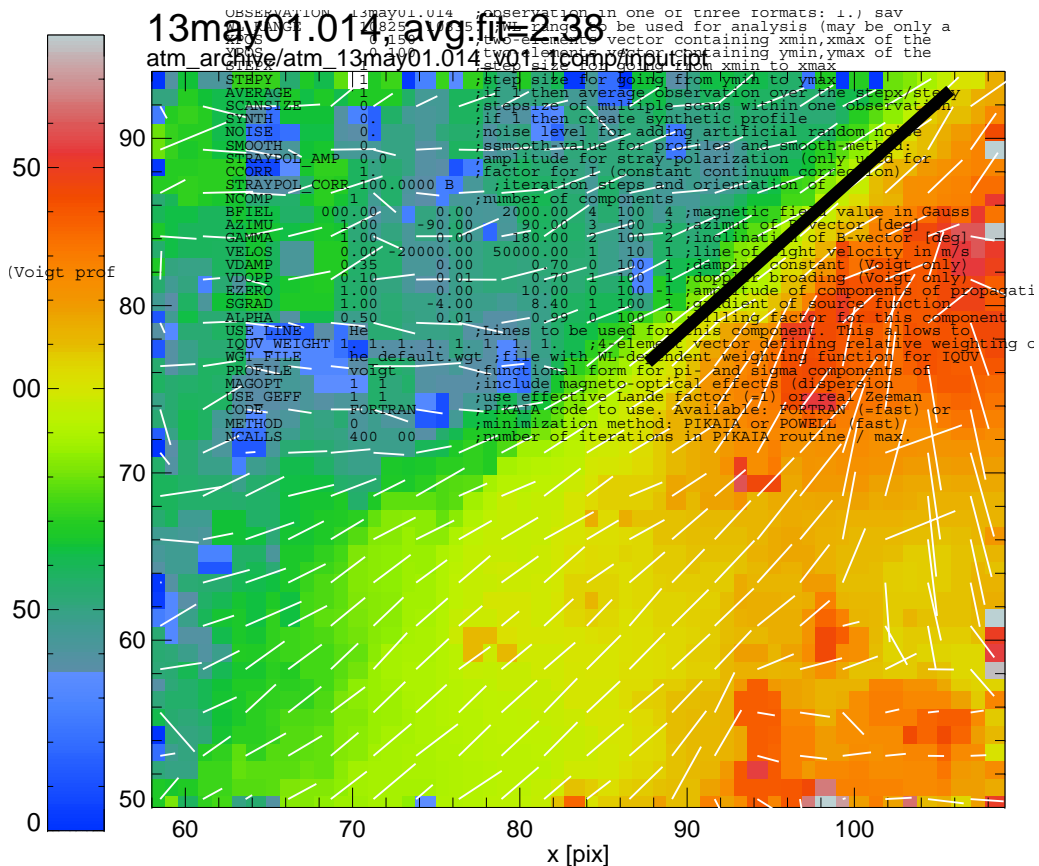
Wiegelmann et al. 2004





Current sheets
 Multiple large current sheets found, but not very common

13may01.014 avg fit=2.38
 atm_archive/atm_13may01.014_voigt/comp/output

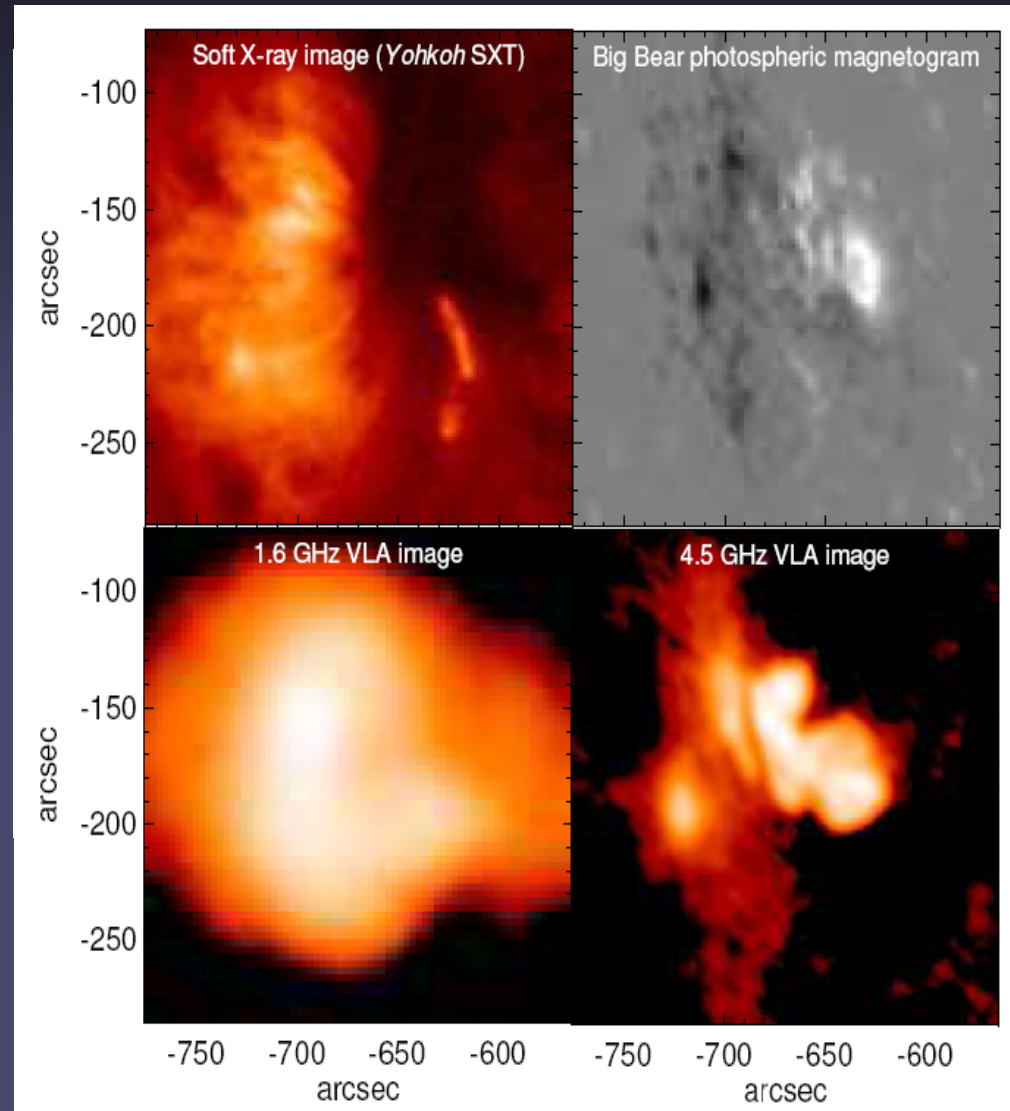


```

OBSERVATION 13may01.014 observation in one of three formats: 1.) sav
PARAMETERS 1325 parameters to be used for analysis (may be only a
SUBS 1 subselected vector containing xmin,xmax of the
XMIN 0.00 leftmost vector containing ymin,ymax of the
XMAX 100.00 rightmost vector containing xmin to xmax
STEPX 1 step size for going from ymin to ymax
AVERAGE 1 if 1 then average observation over the stepx/stepy
SCANSIZE 0 stepsize of multiple scans within one observation
SMOOTH 0 if 1 then create synthetic profile
NOISE 0 noise level for adding artificial random noise
SMOOTH 0 smooth value for profiles and smooth method
STRAYPOL AMP 0.0 amplitude for stray polarization (only used for
CCORR 1 factor for 1 (constant continuum correction)
STRAYPOL CORR 100.0000 B iteration steps and orientation of
NCOMP 1 number of components
BFIELD 000.00 0.00 2000.00 4 100 4 magnetic field value in Gauss
AZIMU 1.00 -90.00 90.00 3 100 3 azimuth of B-vector (deg)
GAMMA 1.00 0.00 180.00 2 100 2 inclination of B-vector (deg)
VELOS 0.00 -20000.00 50000.00 1 10 1 line-of-sight velocity in m/s
VDAMP 0.35 0.00 0.70 0 100 1 damping constant (Voigt only)
VDOPP 0.10 0.01 0.90 1 100 1 doppler broadening (Voigt only)
EZERO 1.00 0.00 10.00 0 100 -1 amplitude of components of propagati
SGRAD 1.00 -4.00 8.40 1 100 1 gradient of source function
ALPHA 0.50 0.01 0.99 0 100 0 filling factor for this component
USE LINE He lines to be used for this component. This allows to
IQUV WEIGHT 1 1 1 1 1 1 4 element vector defining relative weighting c
WGT FILE he default.wgt file with element weighting function for IQUV
PROFILE voigt functional form for pi- and sigma components of
MAGOPT 1 1 include magneto-optical effects (dispersion of
USE GEFF 1 1 use effective Lande factor (=1) or real Zeeman
CODE FORTRAN PIKALA code to use. Available: FORTRAN (=fast) or
METHOD 0 minimization method: PIKALA or POWELL (fast)
NCALLS 400 00 number of iterations in PIKALA routine / max
  
```

Radio Measurements

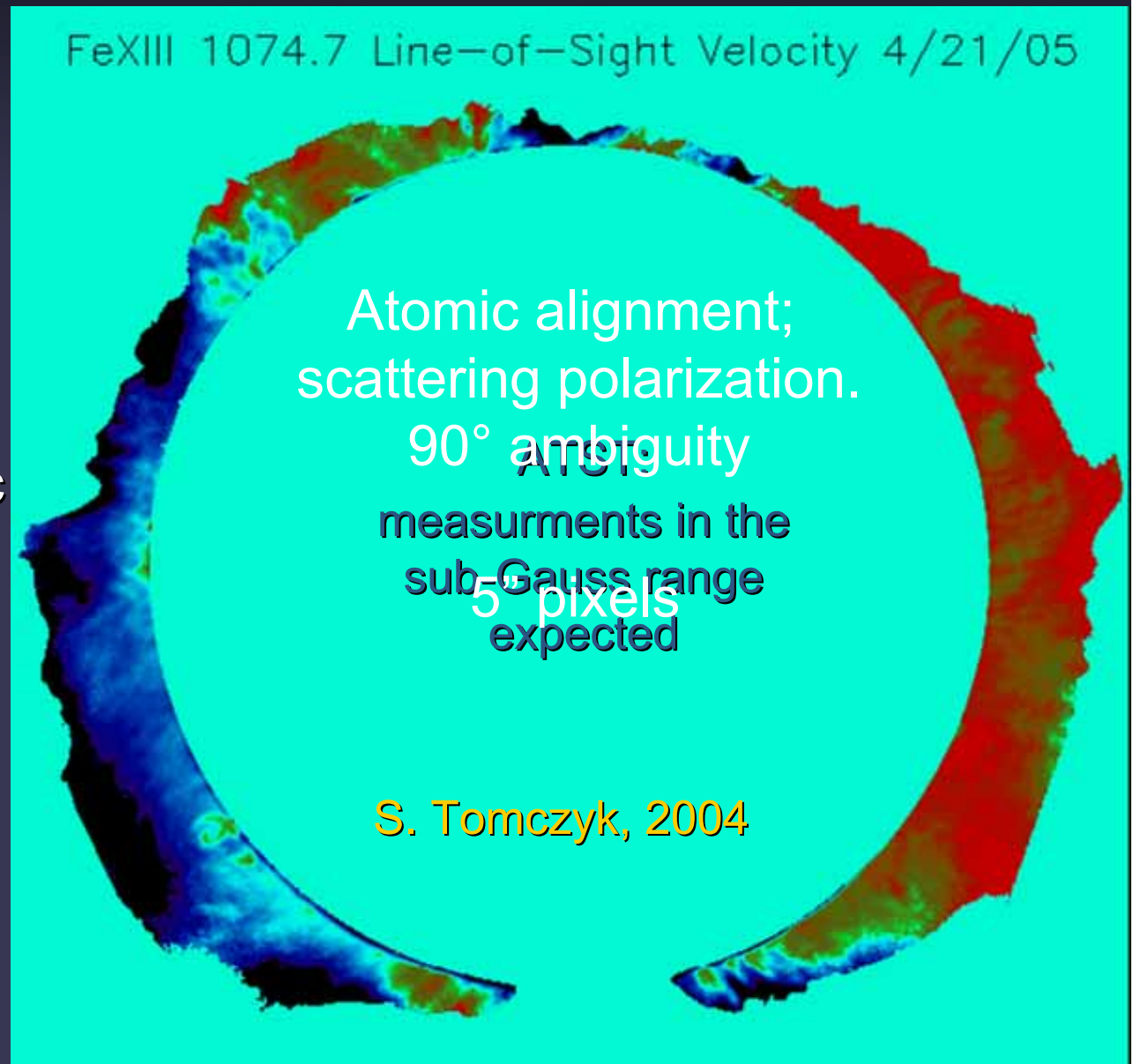
- **Bremsstrahlung:** from collisions of e^- with ions \rightarrow e^- density diagnostic tool. Polarisation: weak longitudinal B fields
- **Gyroresonance:** emission from nonrelativistic thermal plasma at low harmonics of the electron gyrofrequency, $f_B = 2.8 B$ MHz
- **Gyrosynchrotron:** emission by mildly relativistic e^- at harmonics 10-100 of the gyrofrequency
- **Plasma emission:** caused by electrostatic Langmuir waves



White (2002)

Coronal Zeeman effect

- Coronagraphic measurements in Fe XIII 1074.7 nm (Lin et al. 2000)
- Coronal Multi-channel Polarimeter: (CoMP; Sacramento Peak): IQUV
- **Problem:** LOS integration.
- **Possible solution:** vector tomography (Inhester et al.)



Conclusions

- Magnetic field measurements in photospheric layer are of a high standard
 - Still open questions: structure and strength of the field in the very quiet Sun (internetwork and turbulent field)
- Rapid recent progress in study of chromospheric magnetism
 - Many open questions: E.g., how common are chromospheric current sheets and how are they related to flares and coronal heating
- Progress in coronal field measurement needed
 - Improved radio data (FASR, 2009)
 - Development of other techniques, incl. UV Hanle effect measurements (e.g. Solanki et al. 2006)