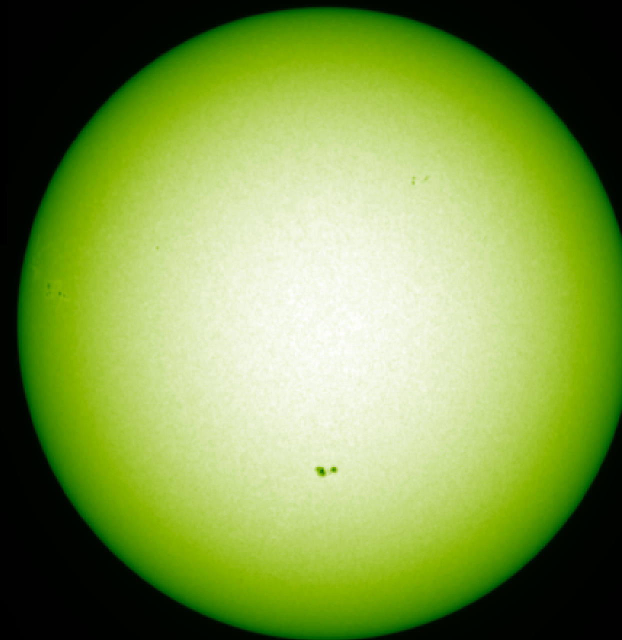
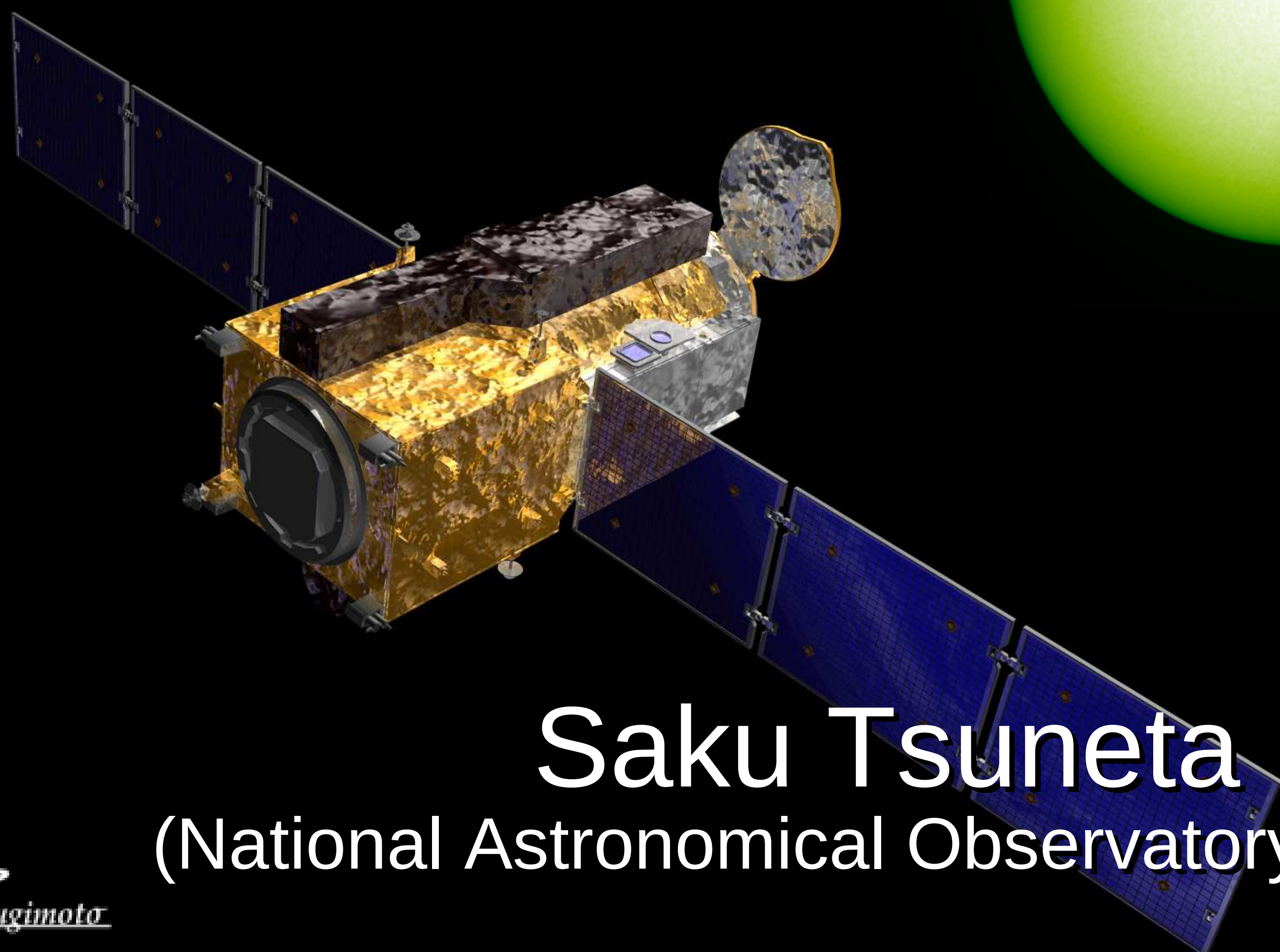
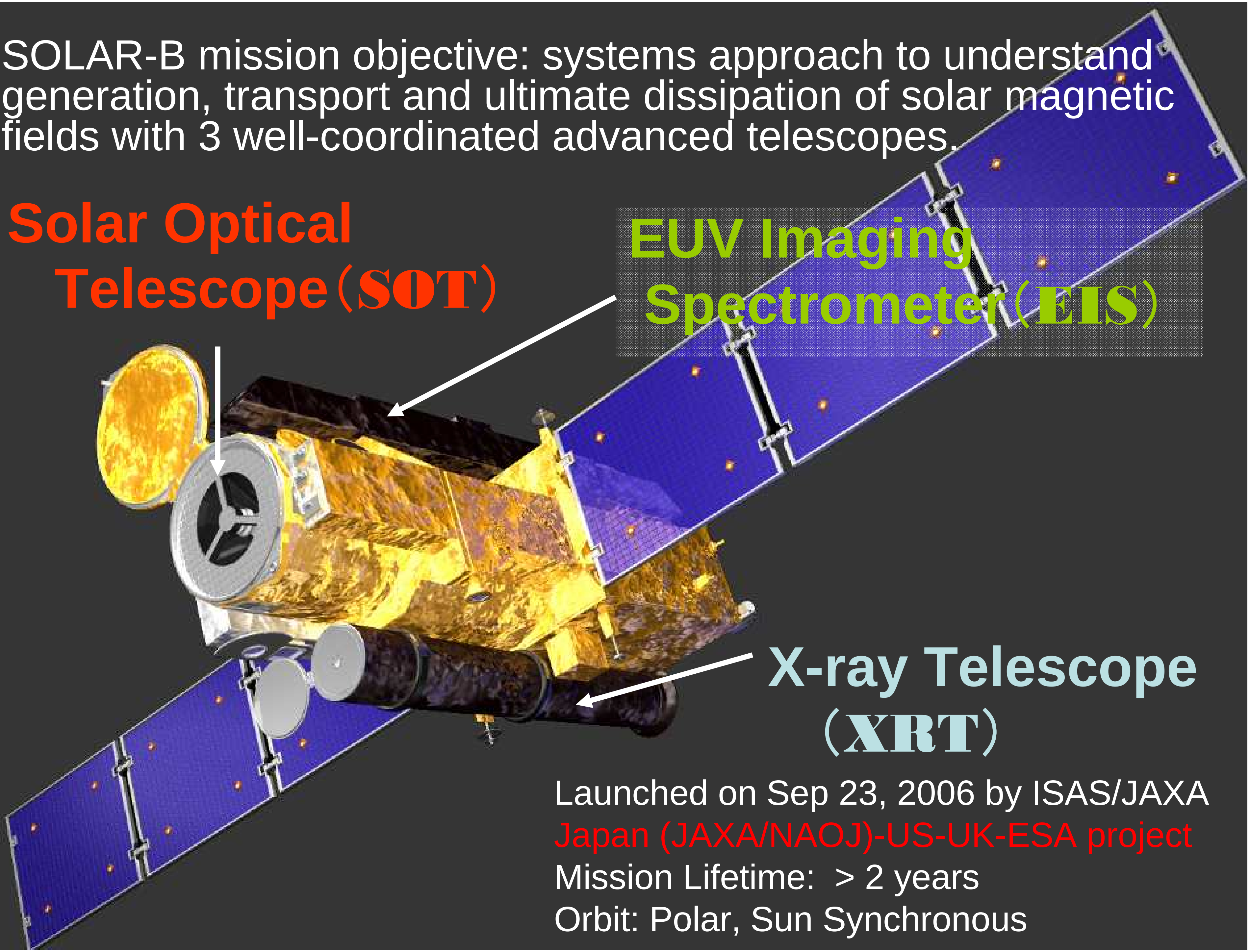
Dynamics of the Solar Atmosphere Revealed by Hinode





Saku Tsuneta
(National Astronomical Observatory of Japan)

SOLAR-B mission objective: systems approach to understand generation, transport and ultimate dissipation of solar magnetic fields with 3 well-coordinated advanced telescopes.



Launched on Sep 23, 2006 by ISAS/JAXA

Japan (JAXA/NAOJ)-US-UK-ESA project

Mission Lifetime: > 2 years

Orbit: Polar, Sun Synchronous

Hinode discoveries

Chromospheric transition region jets due to reconnection

Waves along spicules

Penumbral micro-jets

Magnetic velocity Fluctuation

Local dynamo process

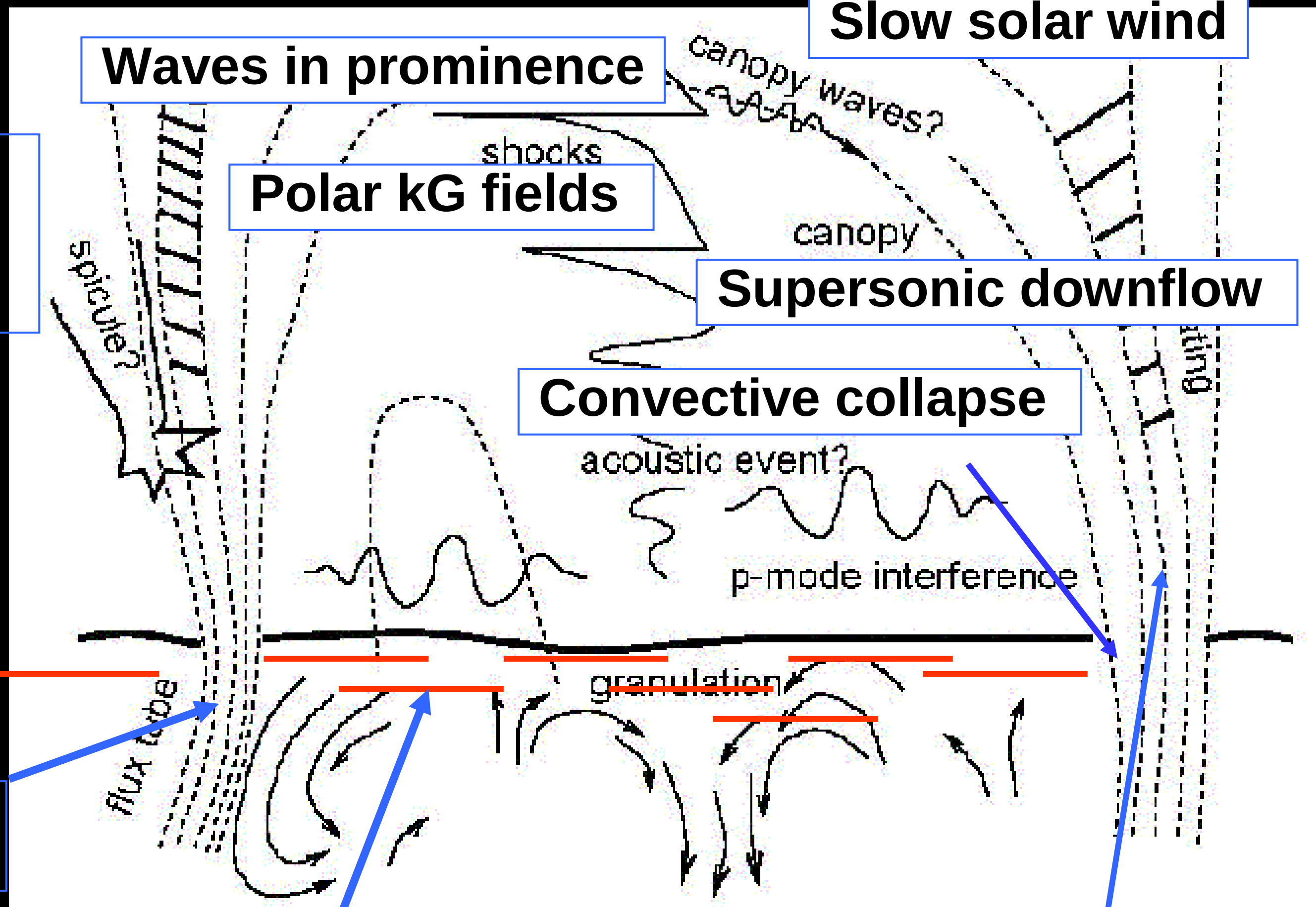
Waves in prominence

Polar kG fields

Slow solar wind

Supersonic downflow

Convective collapse

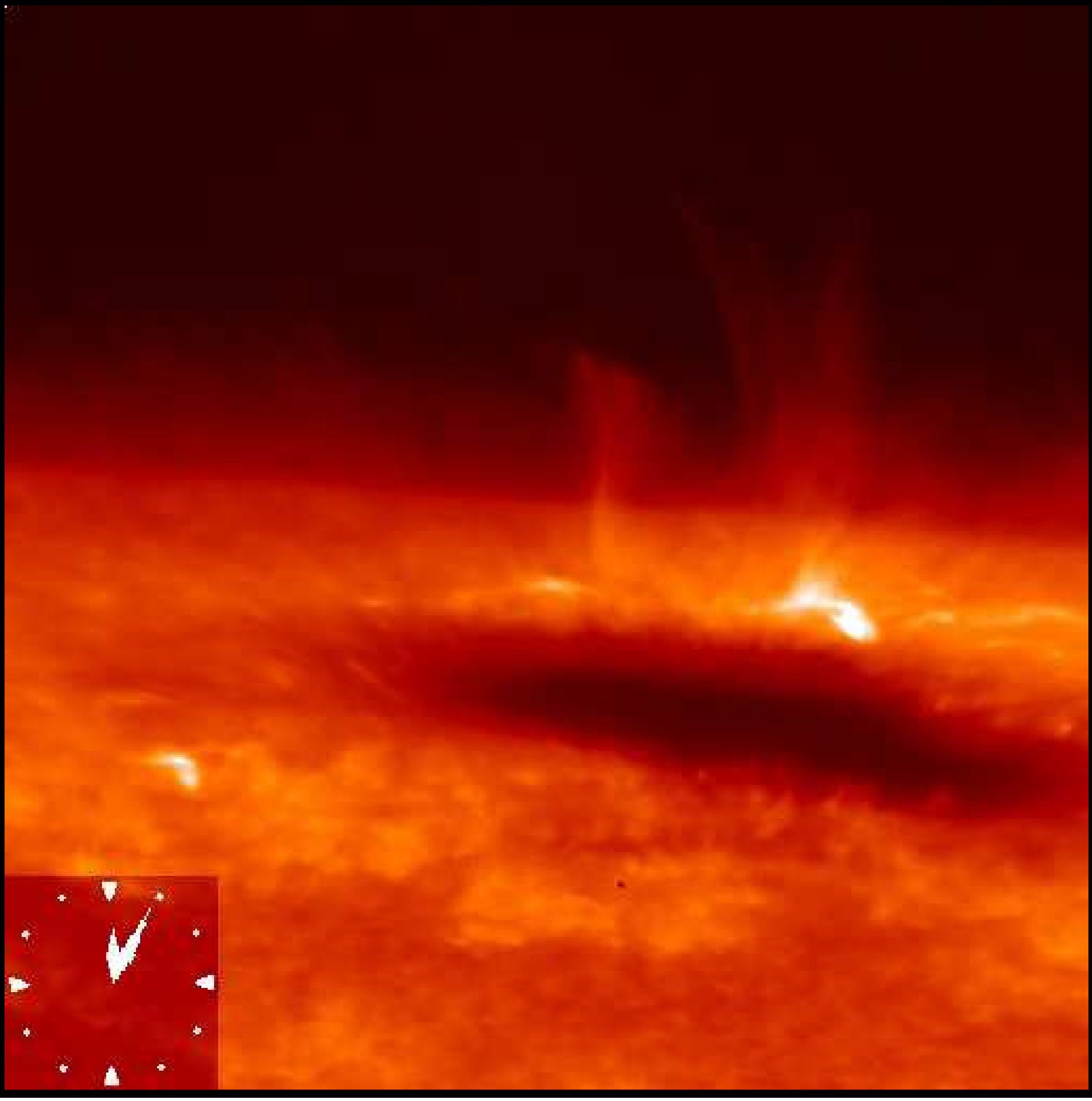


Ubiquitous Horizontal fields

High coronal turbulence

Rutten, R., ASP-CS, 184, 181, 1999

Chromosphere more dynamic than expected!



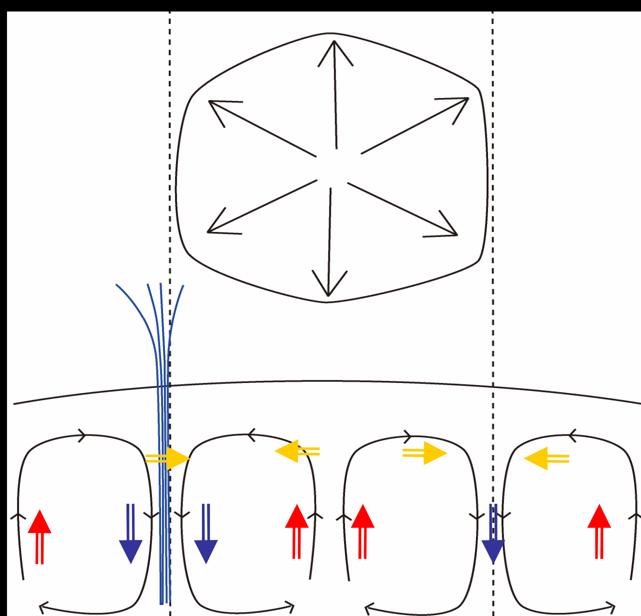
Four topics from Hinode

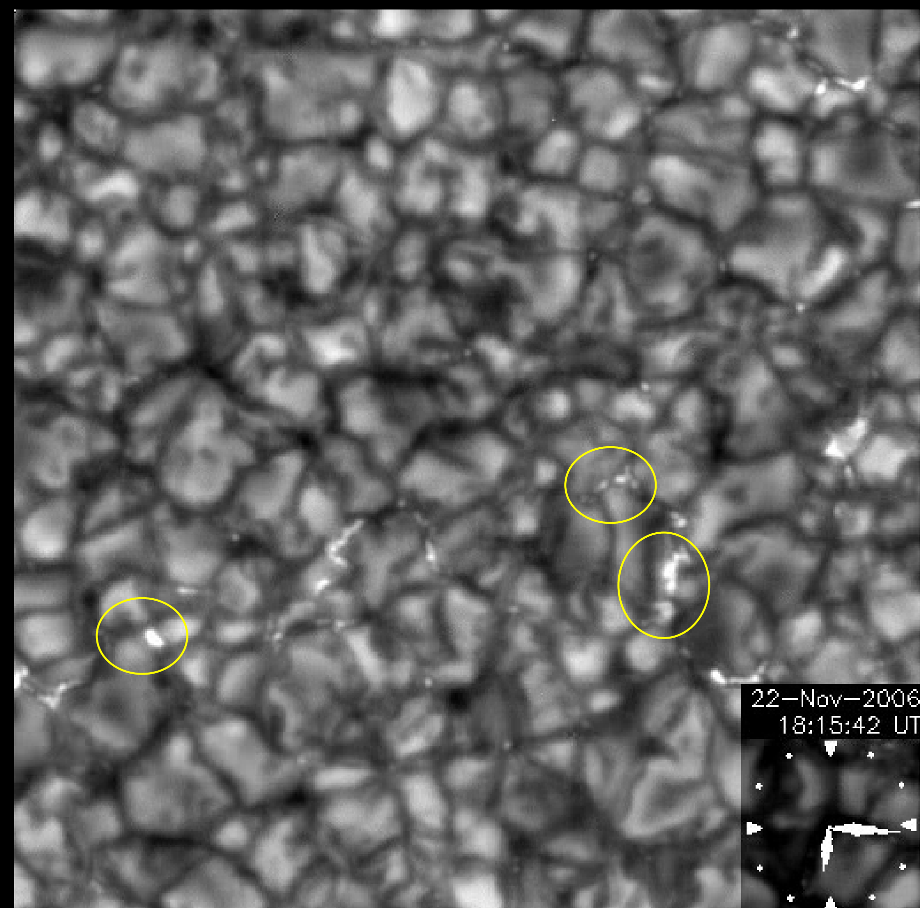
- *Ubiquitous horizontal field* (Ishikawa and Tsuneta, 2008, A&A, to be submitted)
- *Emergence of large scale horizontal flux rope* (Okamoto et al 2008, ApJL)
- *kG polar field* (Tsuneta et al 2008, ApJL, submitted)
- *Convective collapse* (Nagata et al 2008, ApJL)

Ubiquitous horizontal fields

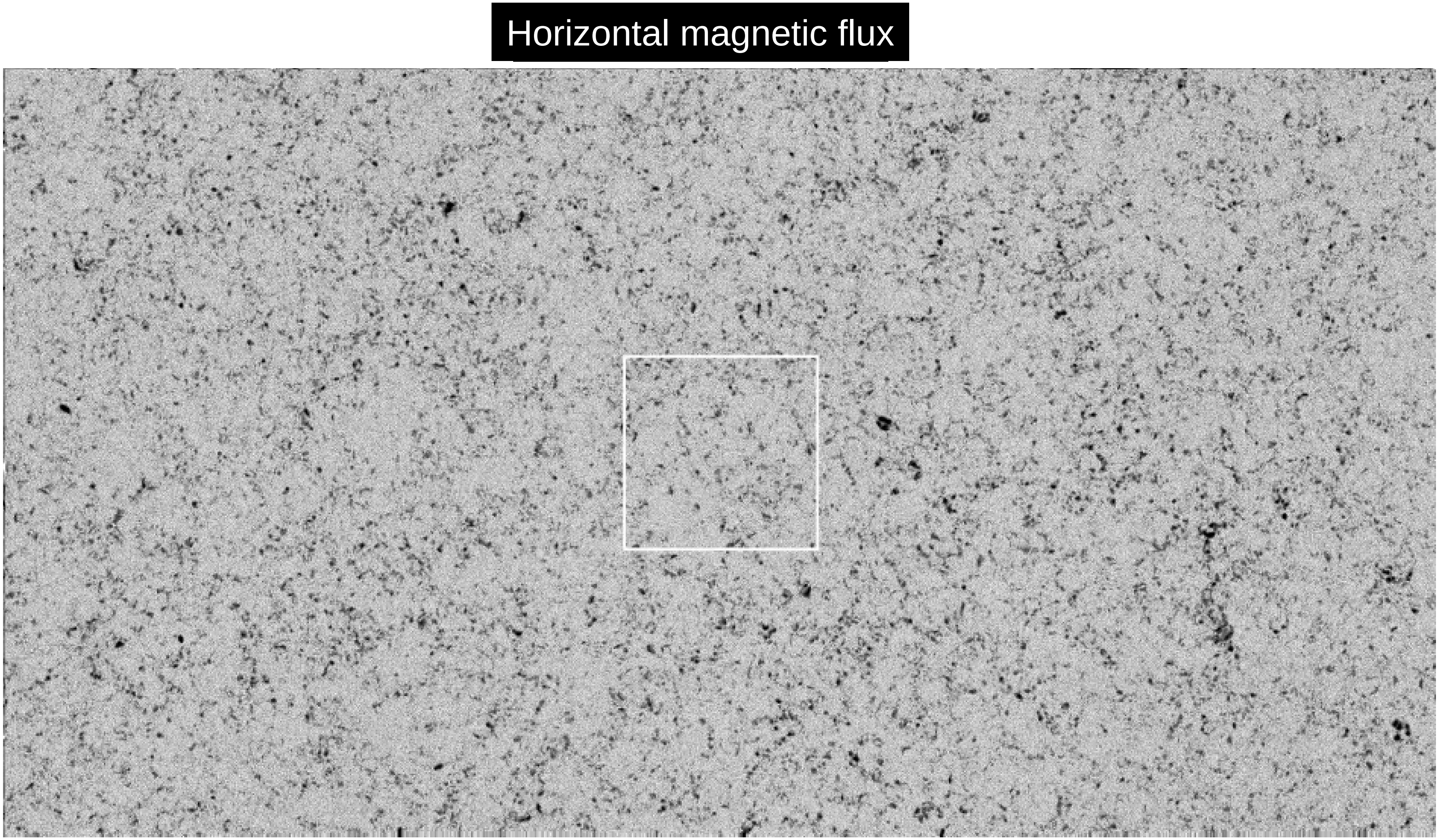
The paradigm
Ubiquitous *vertical* fields

- Both polarities
- Strong kG magnetic fields
- Located in inter-granules





Ubiquitous horizontal magnetic field discovered with Hinode

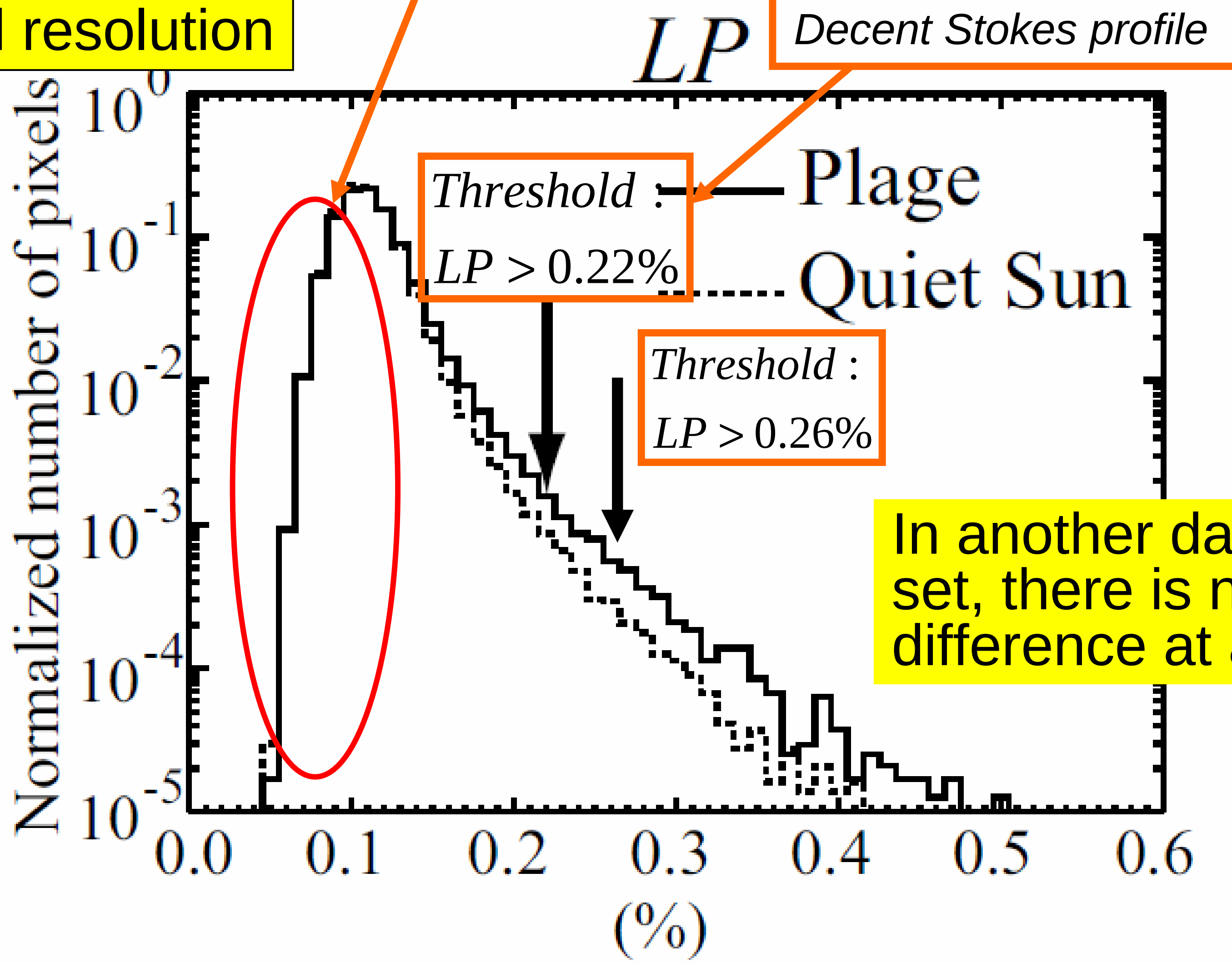


Lites et al. (2007), Orozco et al (2007)

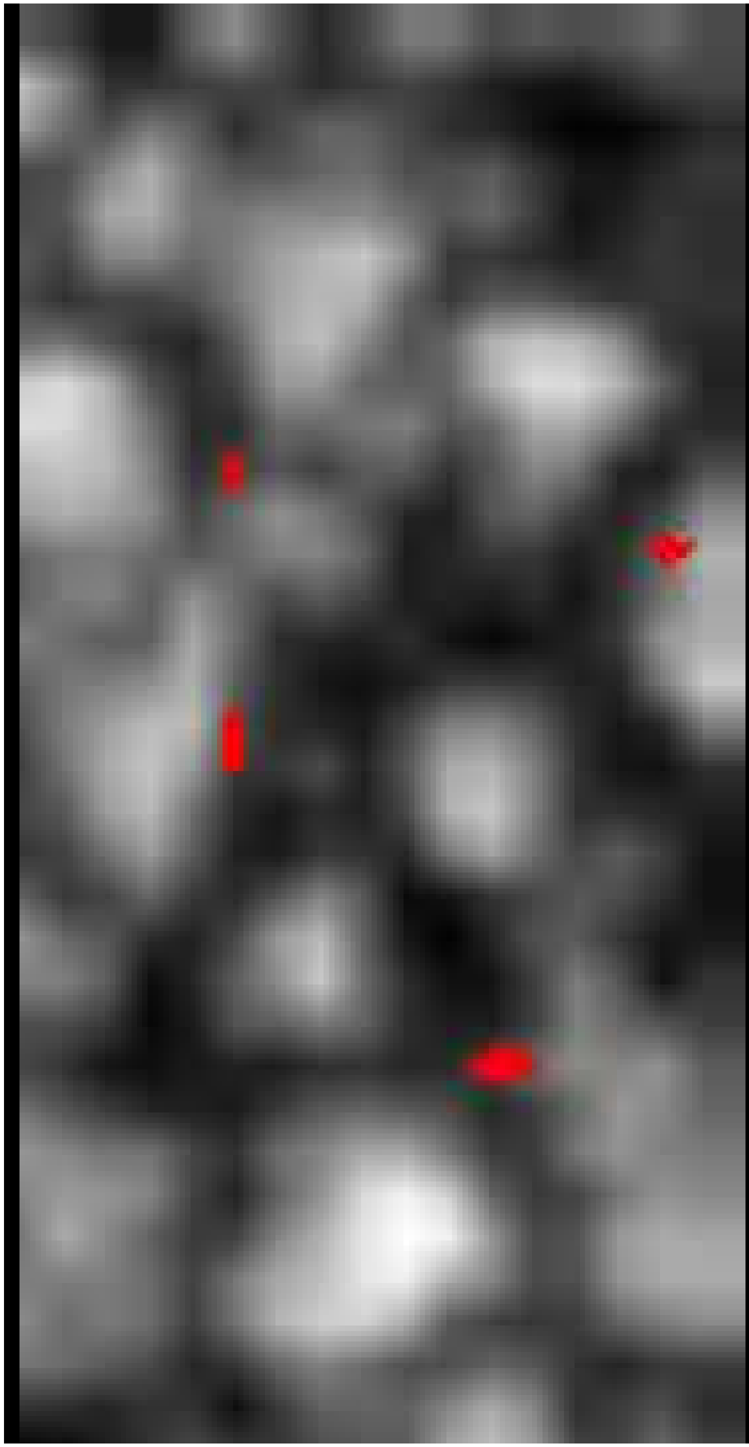
THMF Linear polarization PDF
no difference between plage and QS

Skinny SP FOV
to have 30 sec
temporal resolution

Noise dominant



In another data set, there is no difference at all.

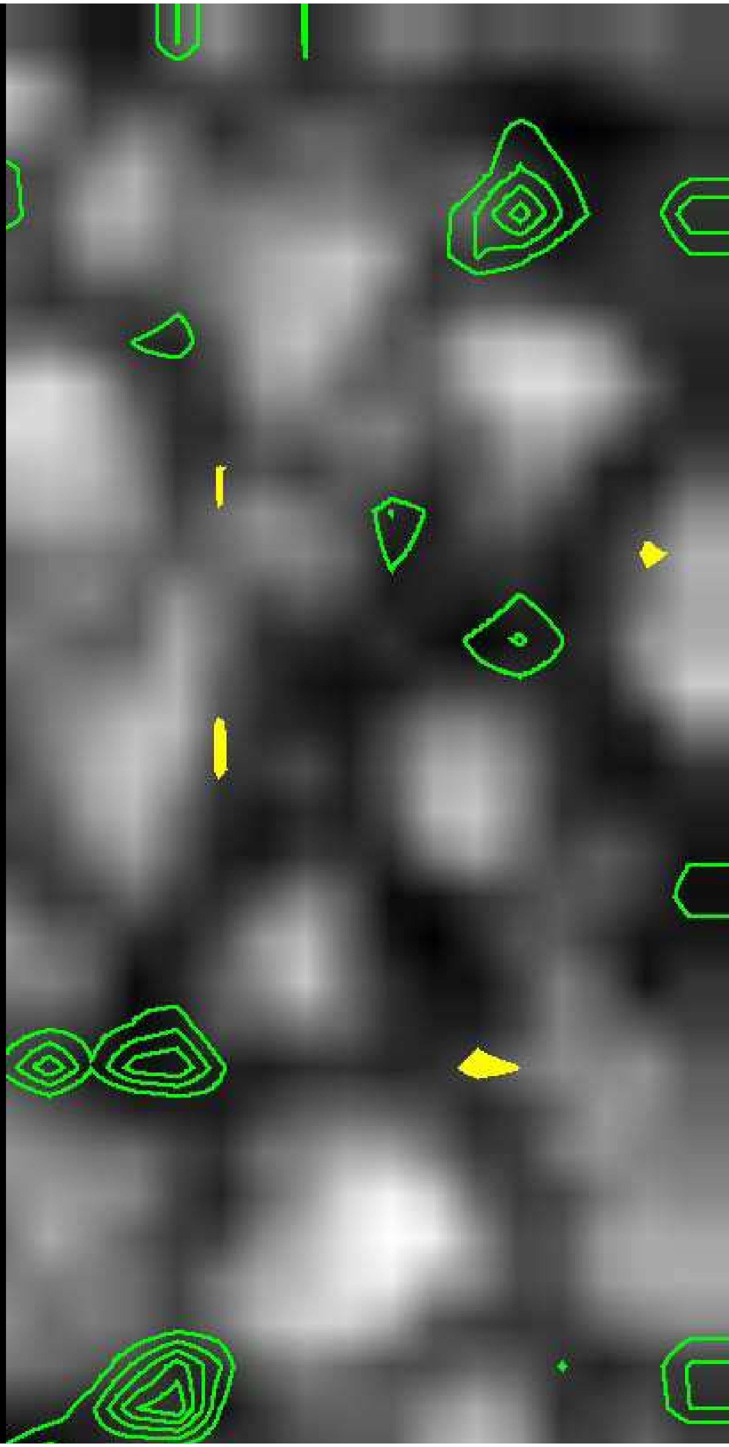


Horizontal field is highly transient!

Transient Horizontal Magnetic Field (THMF)

Centeno et al. ApJL 2007
Ishikawa et al A&A 2008

- Sun center Quiet Sun
- Stokes-Q/U (horizontal field) Red
  LP threshold: 0.18%



Horizontal field is highly transient!

Transient Horizontal Magnetic Field (THMF)

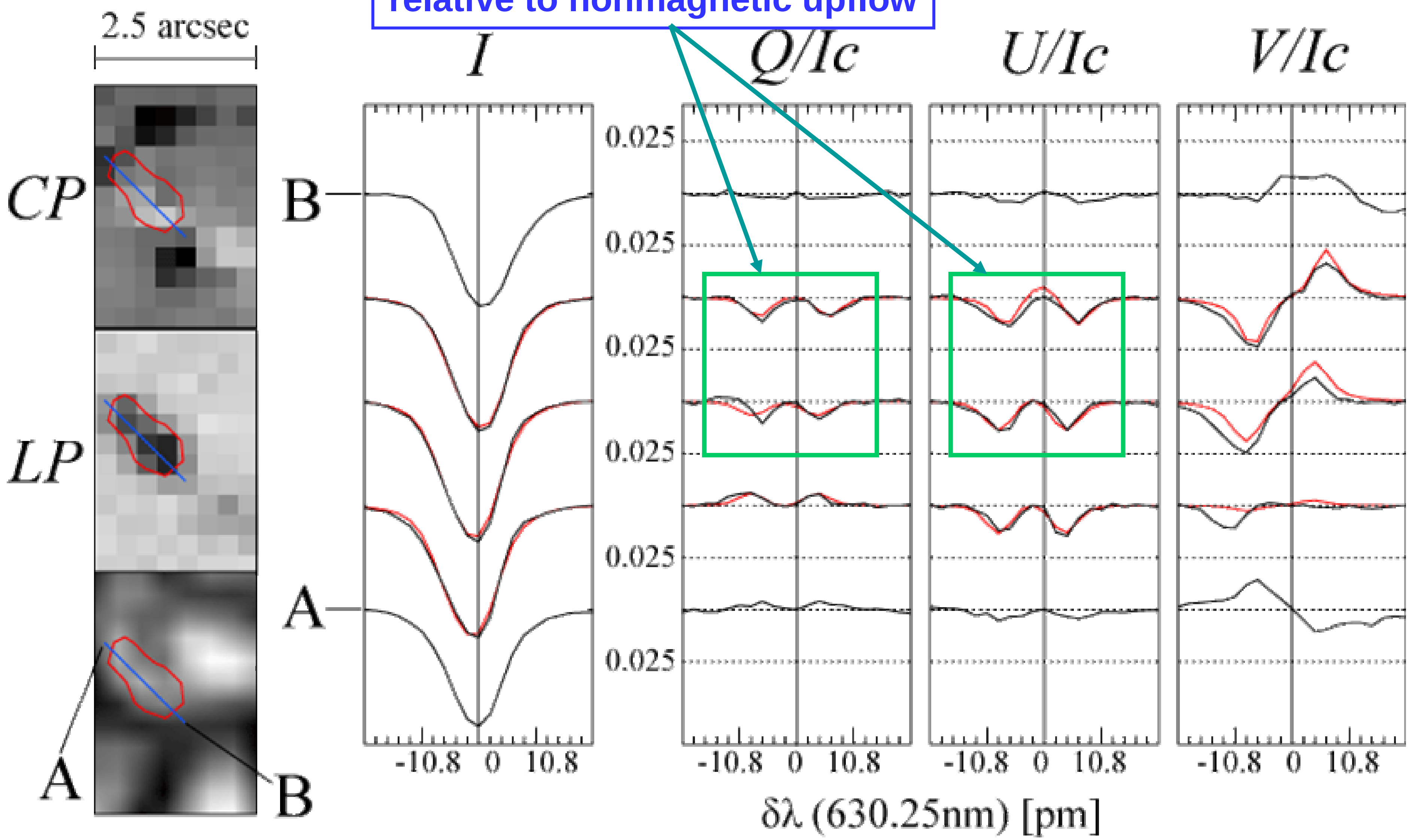
Centeno et al. ApJL 2007
Ishikawa et al A&A 2008

- Sun center Quiet Sun
- Stokes-V (vertical field) Green
- Stokes-Q/U (horizontal field) Yellow
- Threshold: CP:0.3%, LP:0.18%

HF rises with nonmagnetic convective flow

Small upward motion
relative to nonmagnetic upflow

Ishikawa et al 2008



THMF occurrence rate in plage and quiet Sun

$$Threshold:$$
$$LP > 0.22\% \,\&\, Area \geq 3\,pixels$$

- Plage region
  - 51 events for 40 min
  - Usable area : 84% (16% occupied by stable vertical fields)
  - *Occurrence rate : 0.025 events/sec*
- Quiet sun
  - 45 events for 60 min
  - Usable area : 100%
  - *Occurrence rate : 0.0125 events/sec*
- *Occurrence rate in the plage region is twice as that in the quiet sun, though the vertical flux has a factor of 8 difference.*

Very high occurrence rate indicates HF reservoir in the shallow convection layer

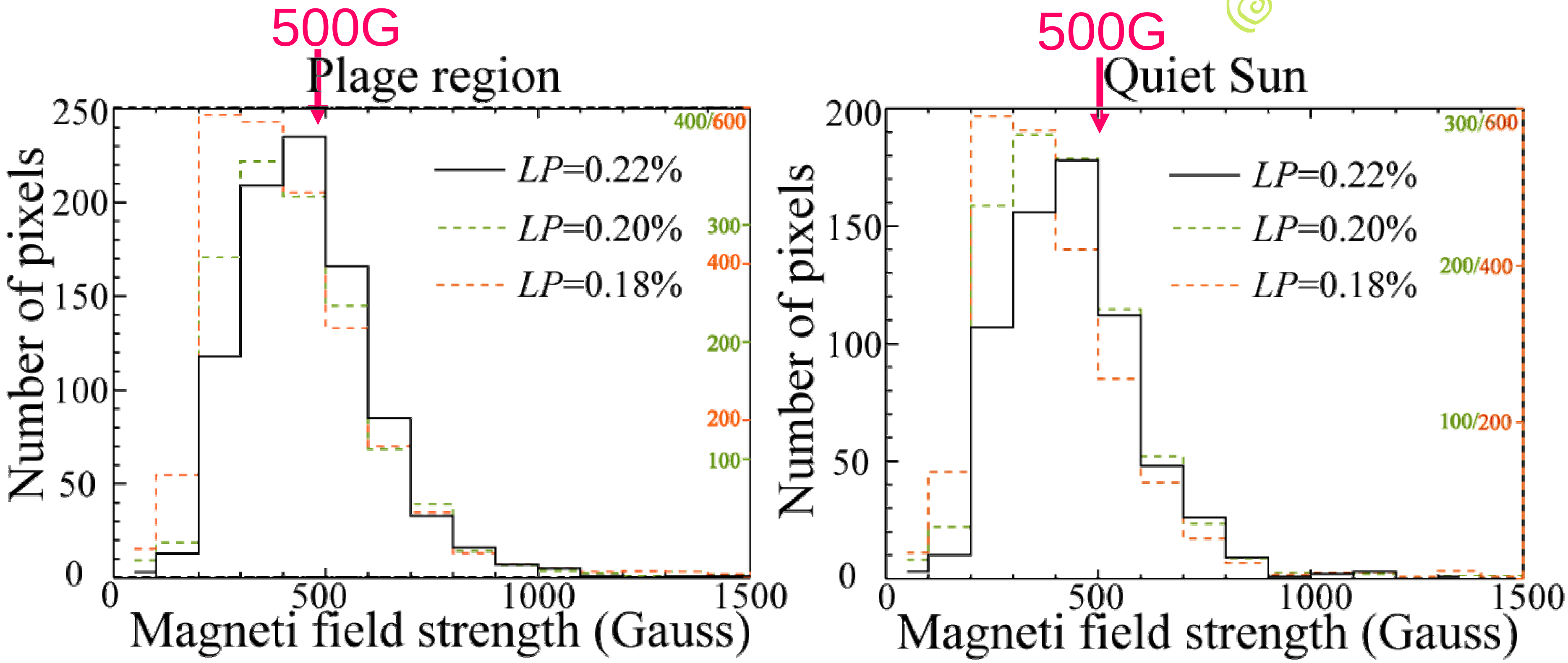
- Observation
  - 51 events in the plage region for 40 min

  1 event /47 sec
- Assumption: *all the granules have the horizontal fields uniformly in their flow pattern. HFs move with granular motion, and appear occasionally as THMFs.*
  - 152 granules in the area used for analysis (2.5”×137”)
  - Turnover time of a granule: 1000 sec
    (velocity:～2km/s, width & height of a granule:～500km)

  1 event /6.6 sec(=1000sec/152 graunues)

➢ **More than 10% of the granules have the embedded horizontal fields.**
➢ **There may be a rich reservoir for the horizontal fields below the photosphere.**

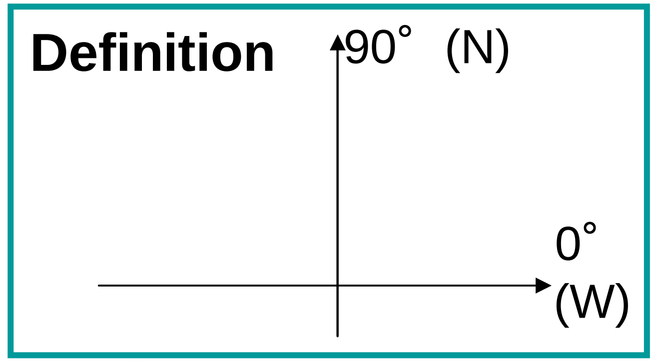
THMF Magnetic field strength PDF



- There is no difference in PDF between the plage and the quiet sun.
- The magnetic field strength is smaller than **equi-partition field (～500G).** ＊**equipartition field** : $\frac{B_e^{\,2}}{8\pi} \approx \frac{1}{2}\rho v^{\,2}$

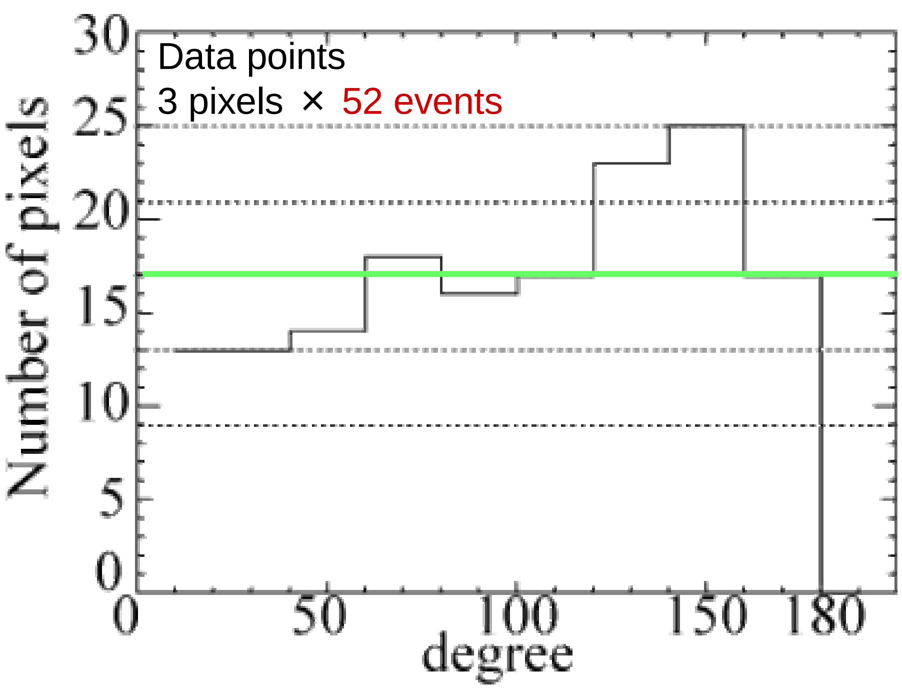
THMF directivity: there is no deviation from uniform distribution

$$Threshold: \quad LP > 0.22\% \; \& \; Area \geq 3\, pixels$$

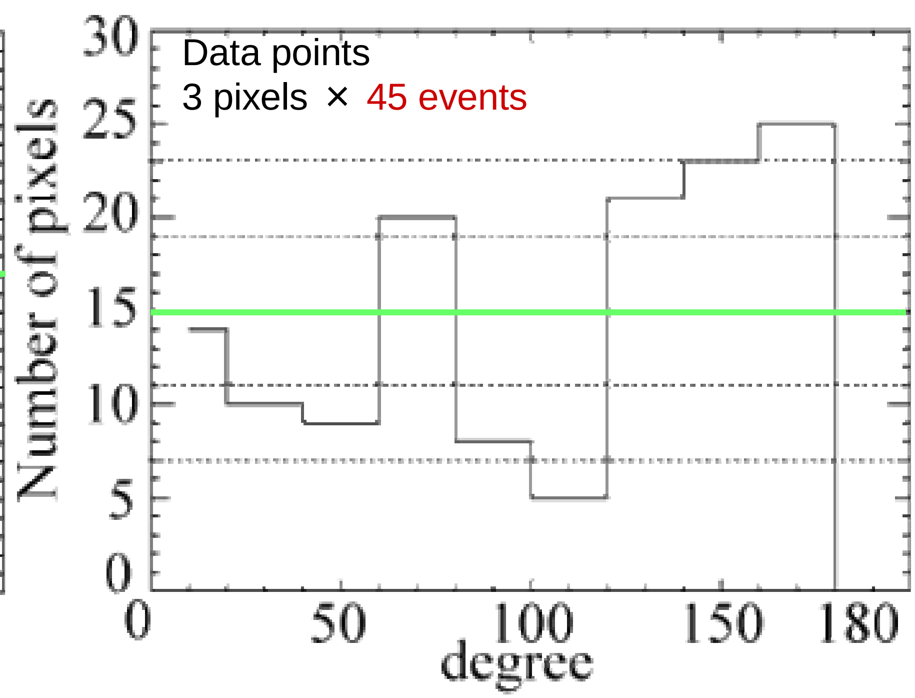


Azimuth: $\chi = \frac{1}{2}\arctan\left(U / Q \right)$

Plage region



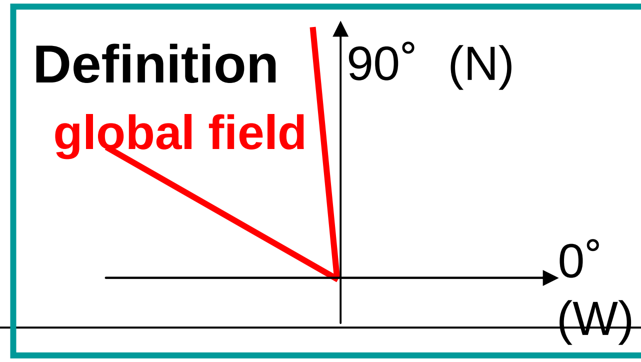
Quiet sun

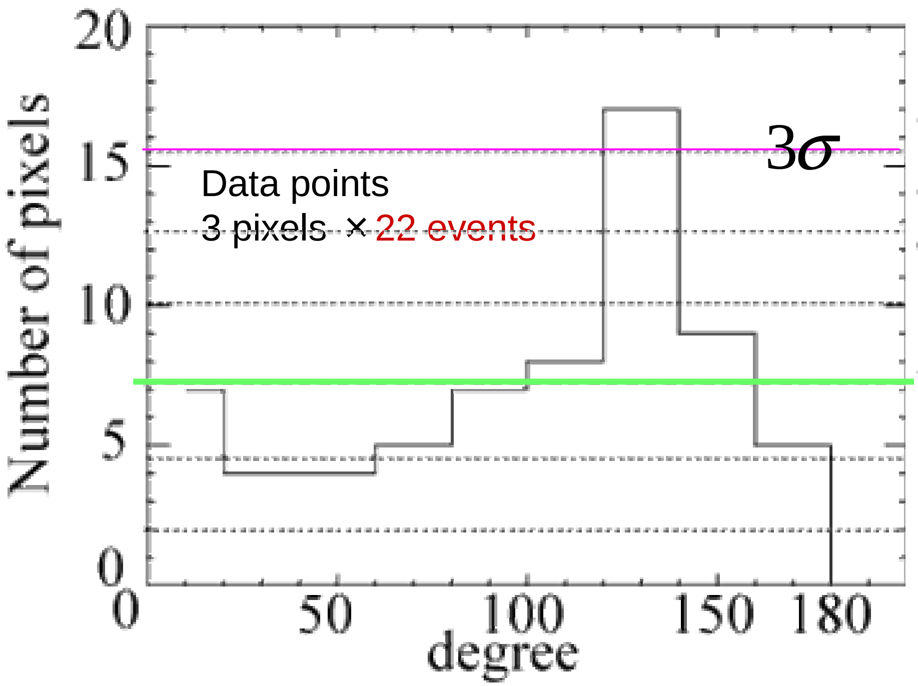


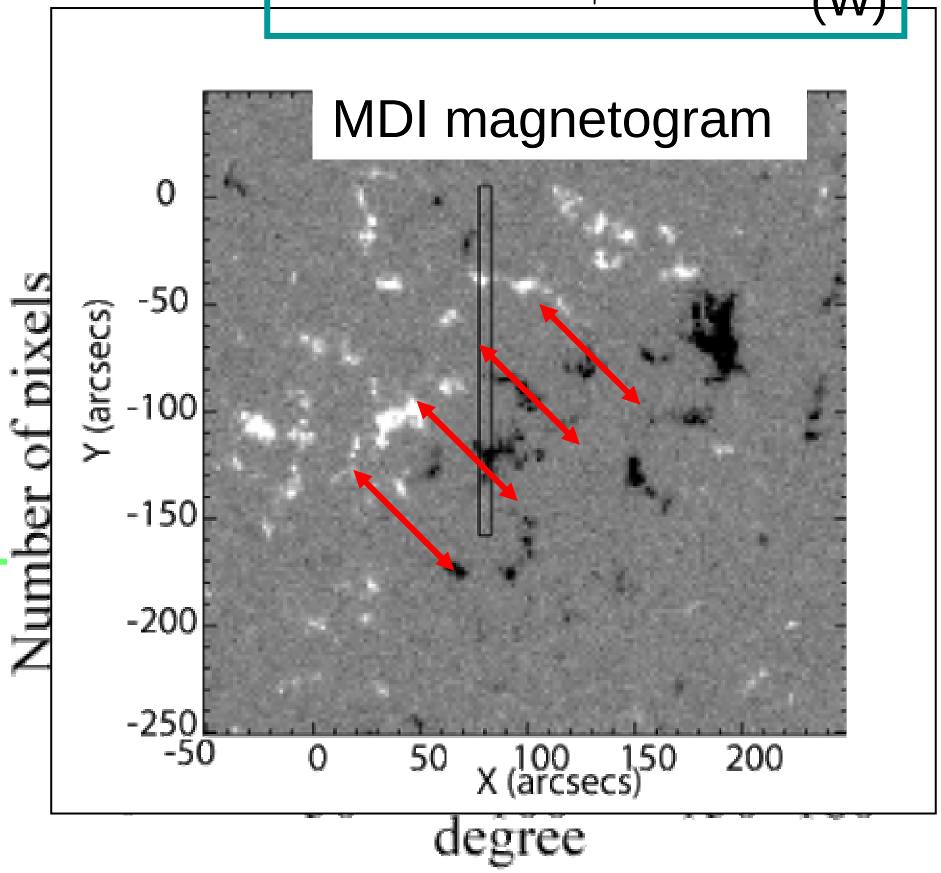
THMF with high LP have weak directivity consistent with the global polarity

$$Threshold:$$
$$LP > 0.26\% \,\&\, Area \geq 3\,pixels$$

Azimuth: $\chi = \frac{1}{2}\arctan\left(U/Q\right)$







Properties of THMF

- Receptive to convective motion
  - *Properties clearly different from emerging flux driven by Parker instability (see Ishikawa et al 2008 A&A Hinode special issue)*
- Magnetic fields strength lower than equi-partition
- Very low filling factor of 0.2 (but need correction for scattering)
- Extremely high occurrence rate
- Same occurrence rate between PL and QS in spite of x8 difference in vertical flux
- Essentially no directivity for all the event
- Directivity exist for the strong LP events, indicating influence from global fields

THMF: ○=likely, × =unlikely, △=marginal

Key obs. feature / Possibilities	Field strength <equipartition	No Directivity	Same high Occurrence rate
Active region debris	△	△	×
Failed emerging flux	○	×	×
Explosion of rising flux tube	○	△	△
Comes from vertical B	△	○	×
Local Dynamo process	○	○	○

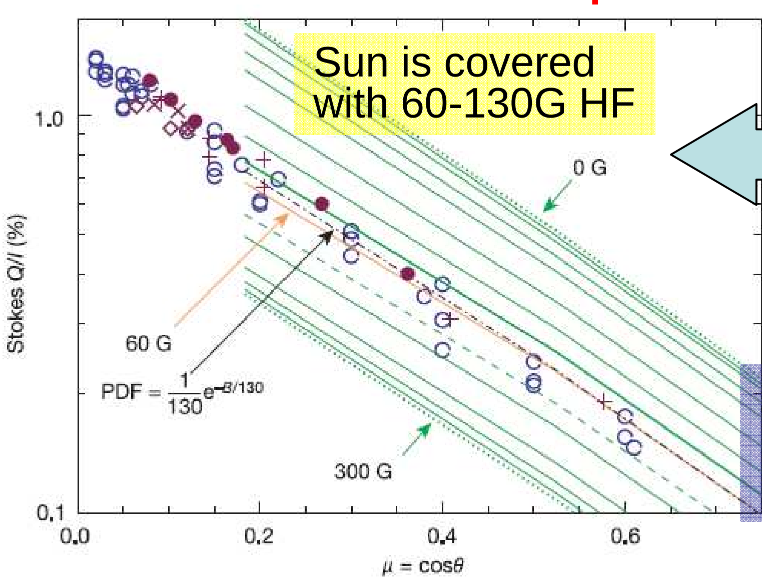
Local dynamo process
Open issues

- *Convection zone all over the sun may have statistically-stationary accumulation of HMF (reservoir).*
- If no or little dissipation (unlikely), dynamo is not needed.
- If local dynamo, what is *dissipation process*?
  - Reconnection with vertical fields?
  - Reconnection with horizontal fields?
  - Is turbulent diffusion working for HTMF?
  - In photosphere and/or in chromosphere?
- Relationship with hidden magnetism

Hinode THMF and hidden magnetism

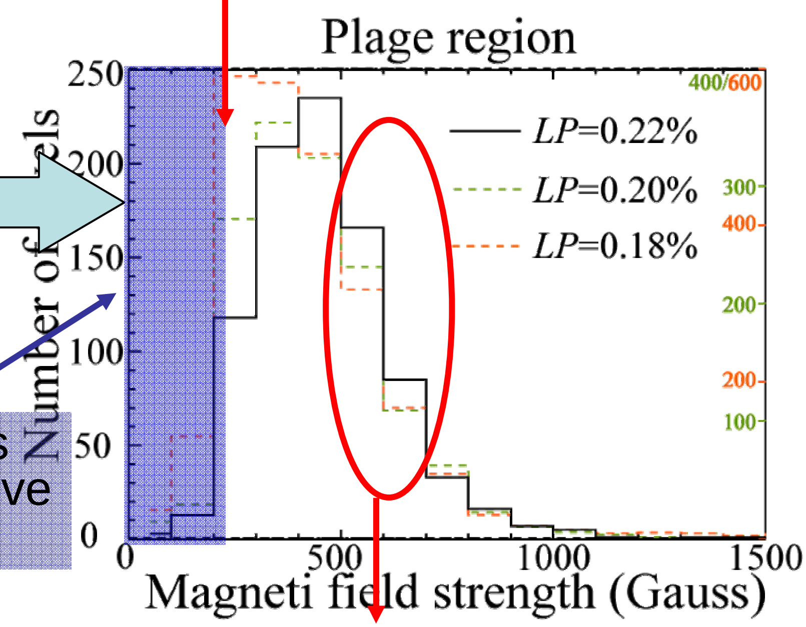
Hidden magnetism **as revealed with *Hanle effect* (Trujillo Bueno et al Nature 2004)**

Cutoff imposed by the LP threshold
An attempt to lower down the cutoff to the limit is being done.



?

Zeeman is not sensitive enough.

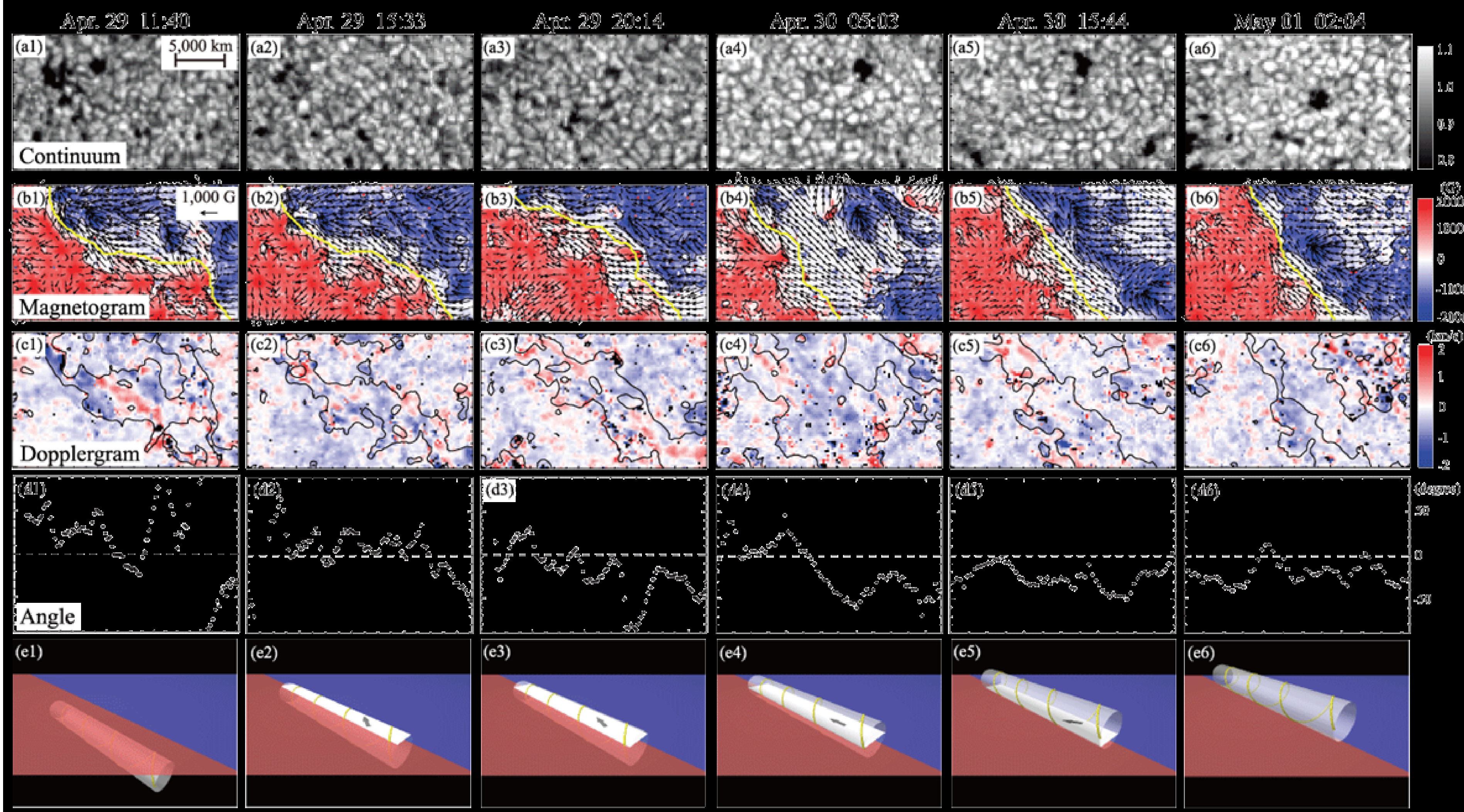


Are the THMFs tip of the iceberg for hidden magnetism?

This 400G cutoff is real, showing no kG horizontal field. Since equi-partition field increases with depth, this suggests very shallow local dynamo.

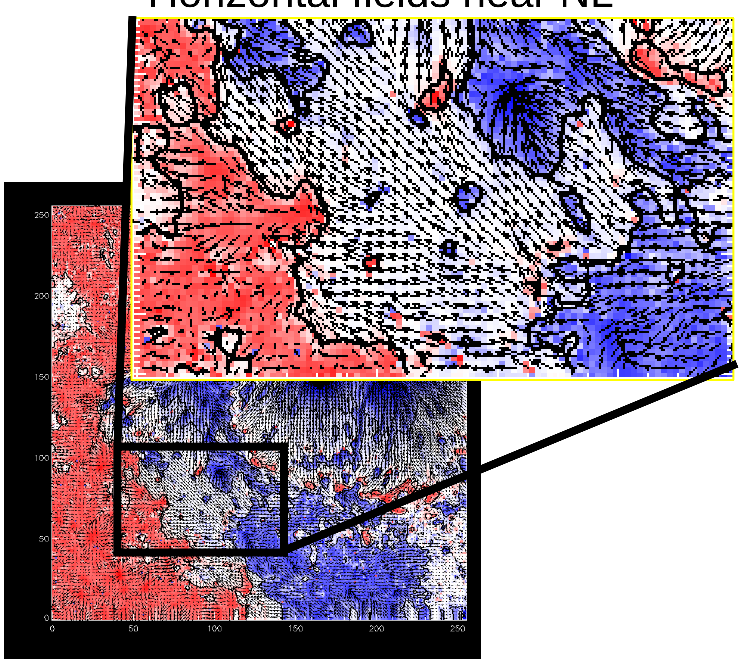
Emergence of large scale horizontal fields

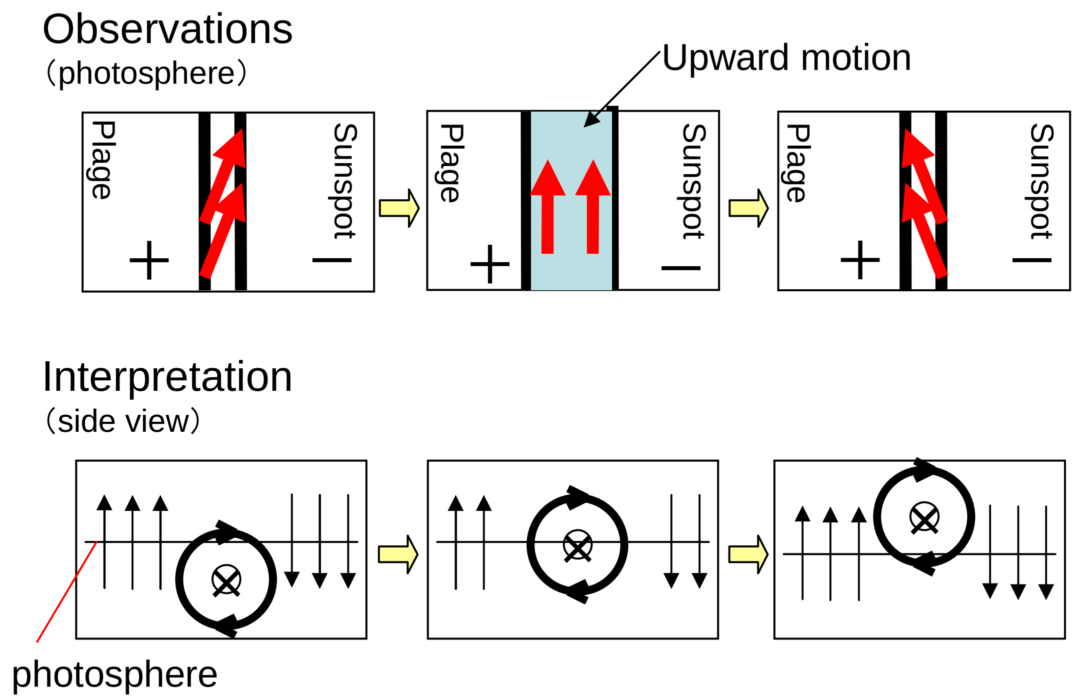
Emergence of large scale weakly helical fields

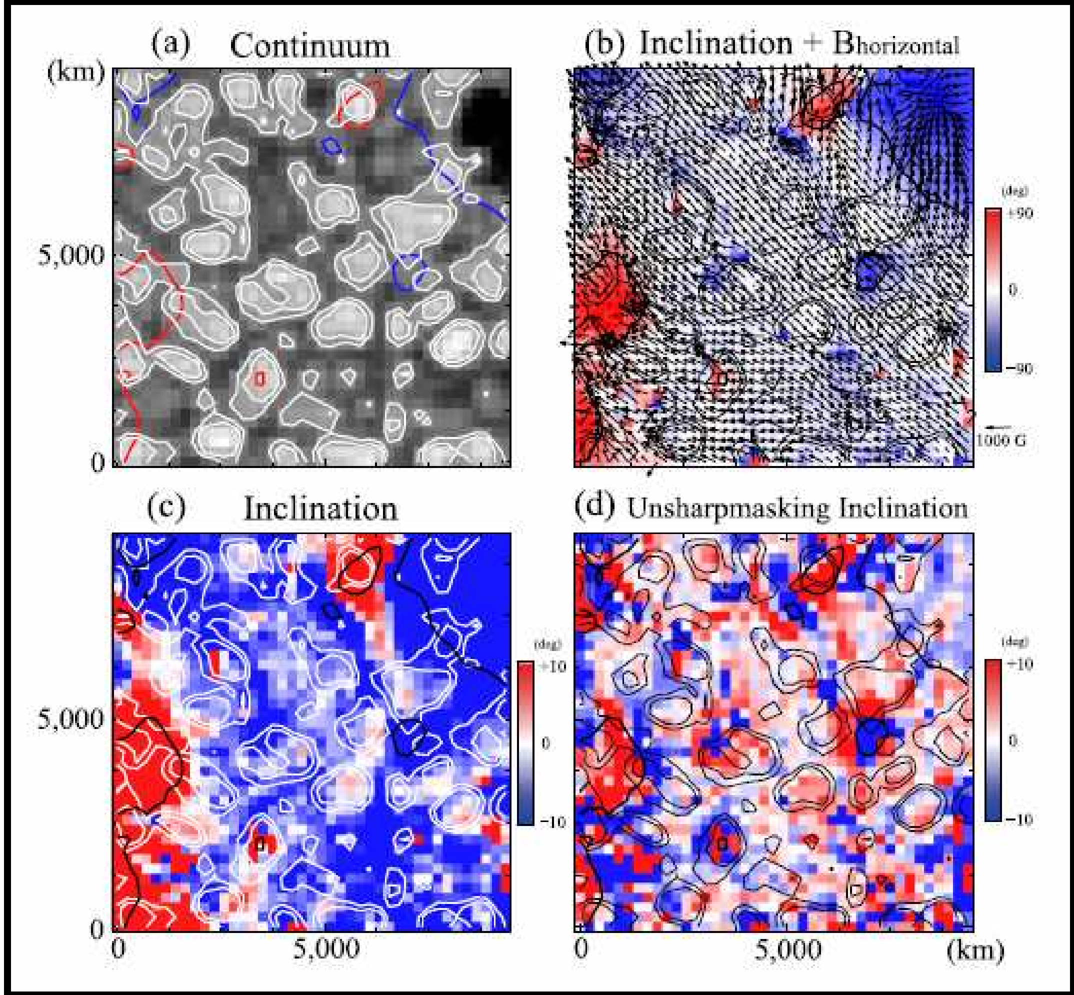


Evidence for flux rope emergence (Okamoto et al. ApJL)

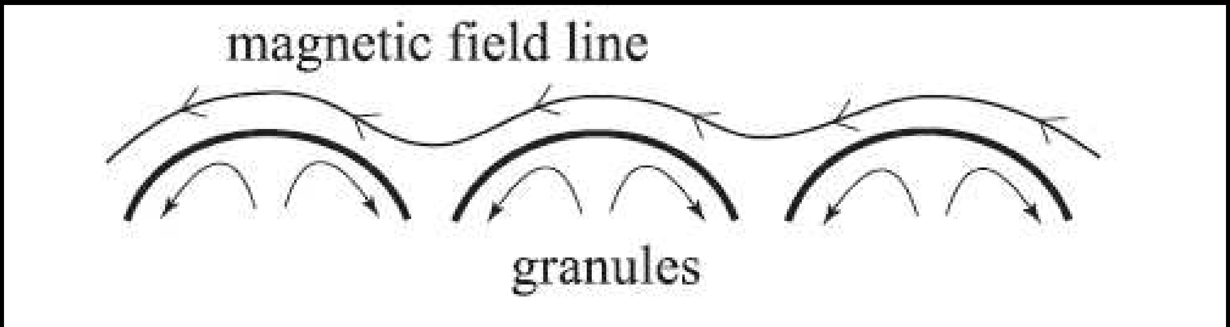
- Hinode discovery on flux rope
  - Evolution from normal to reverse horizontal fields
  - Open-close evolution of weak field region
  - Upward motion
  - Appears to affect chromospheric prominence







- Flux rope is affected by granular motion
- Is there any relationship between flux rope and HF?

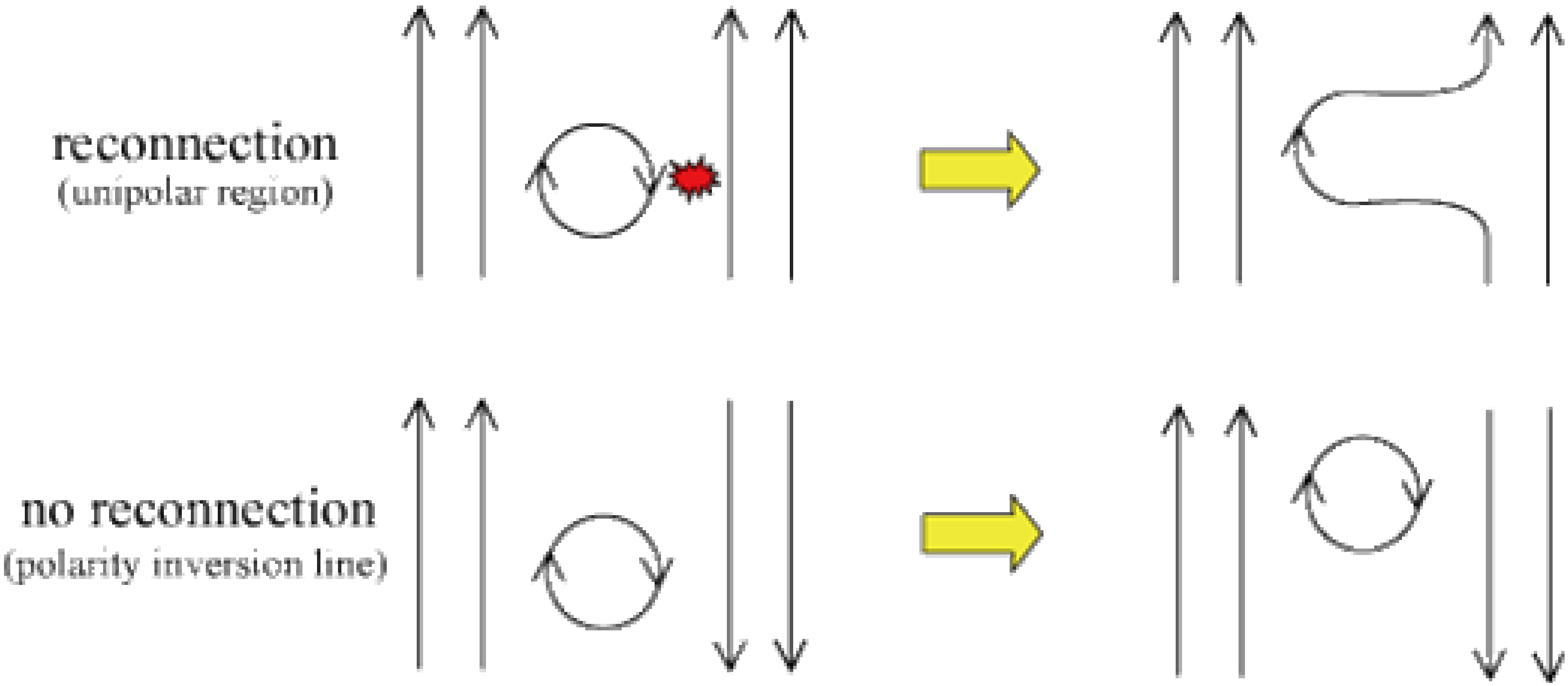


Comparison between THMF and EFR

- Transient horizontal magnetic fields
  - Field strength <400 G
  - Filling factor average 0.2
  - Location everywhere
  - Directivity essentially none
  - Occurrence rate ubiquitous
- Emerging flux rope
  - Field strength <400 G
  - Filling factor average 0.2
  - Location at PIL
  - Directivity along PIL
  - Occurrence rate unknown

Common properties

Does flux rope choose neutral line?
No, neutral line is the only channel that allows flux rope to emerge without corruption due to magnetic reconnection



Note: weakly helical

What is going on
in polar regions?

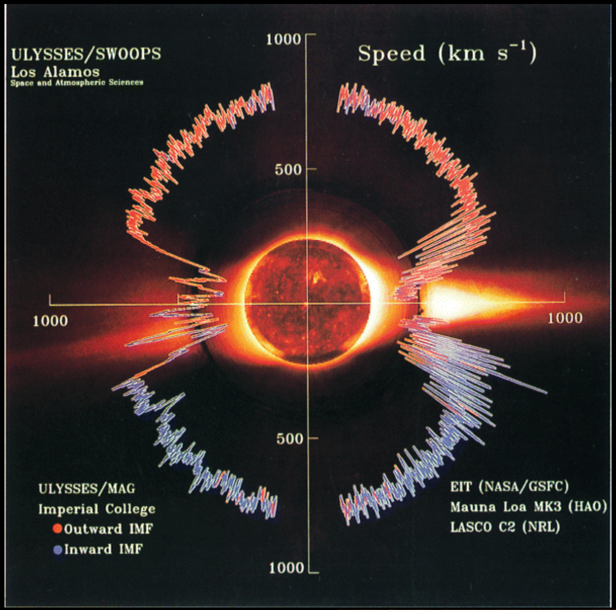
Tsuneta et al (2008)

What is going on in polar region ?

Source of fast solar wind
Location of global poloidal fields
sink of meridional flow

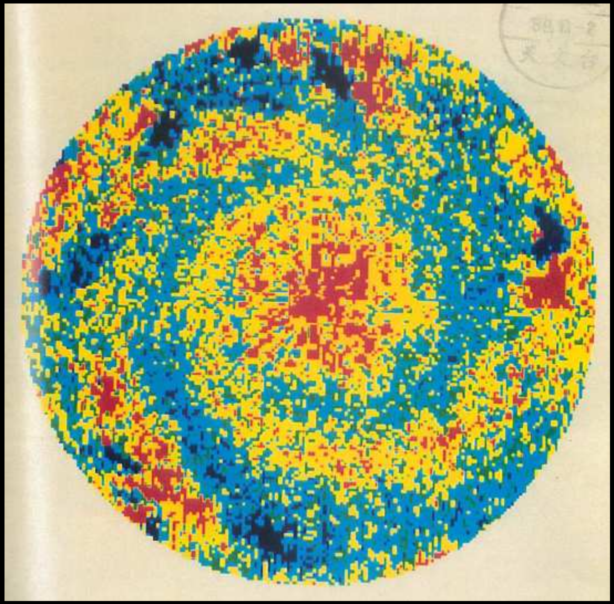
High speed solar wind

Ulysses
(McComas etal 2000)

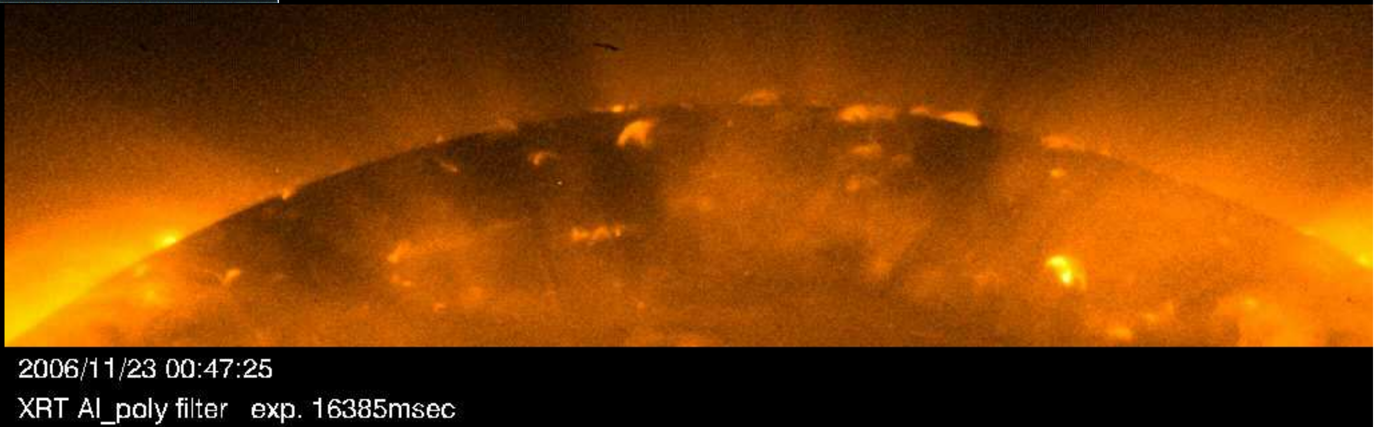


Polar fields

Kitt Peak
(Wang et al)

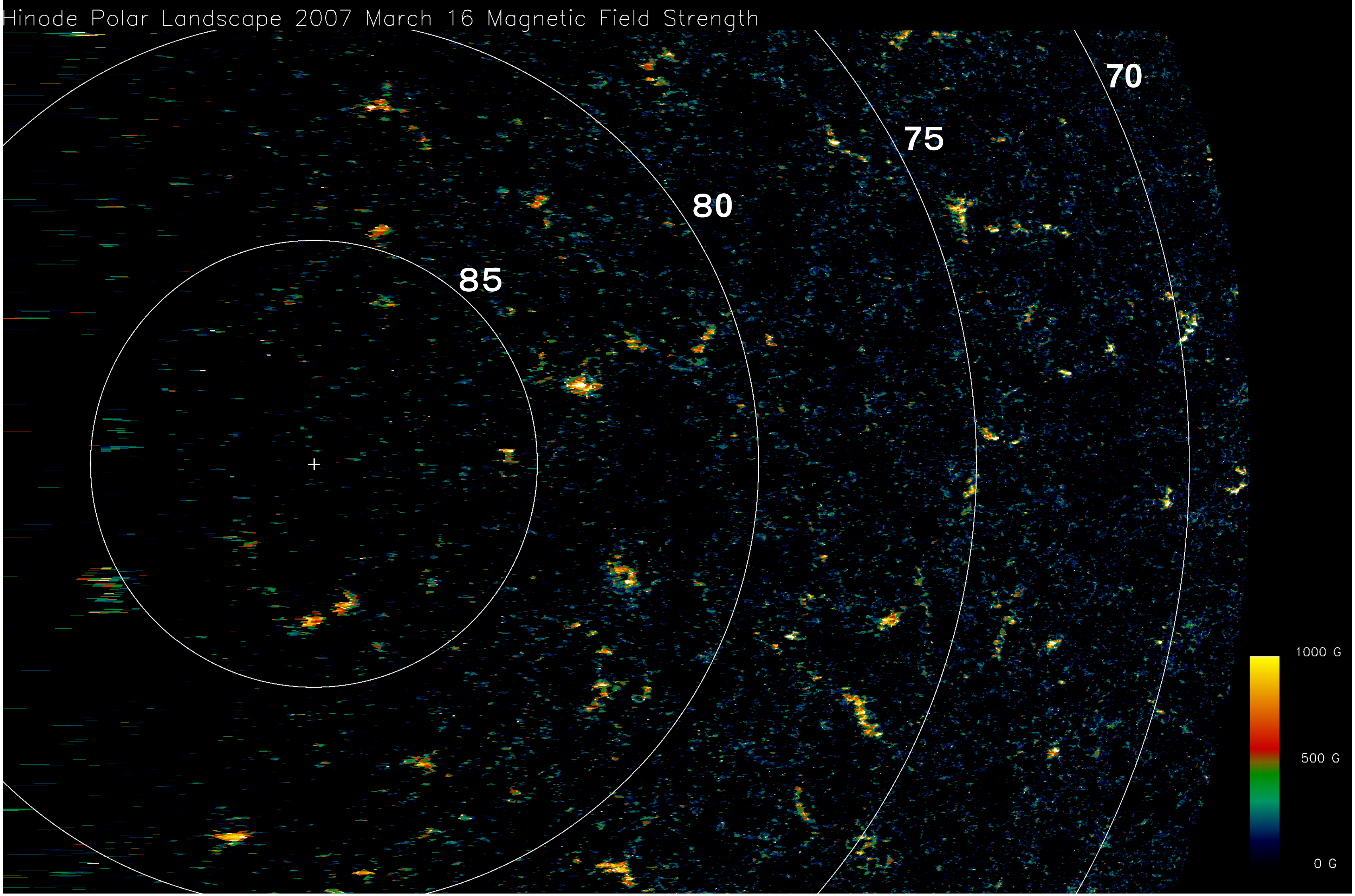


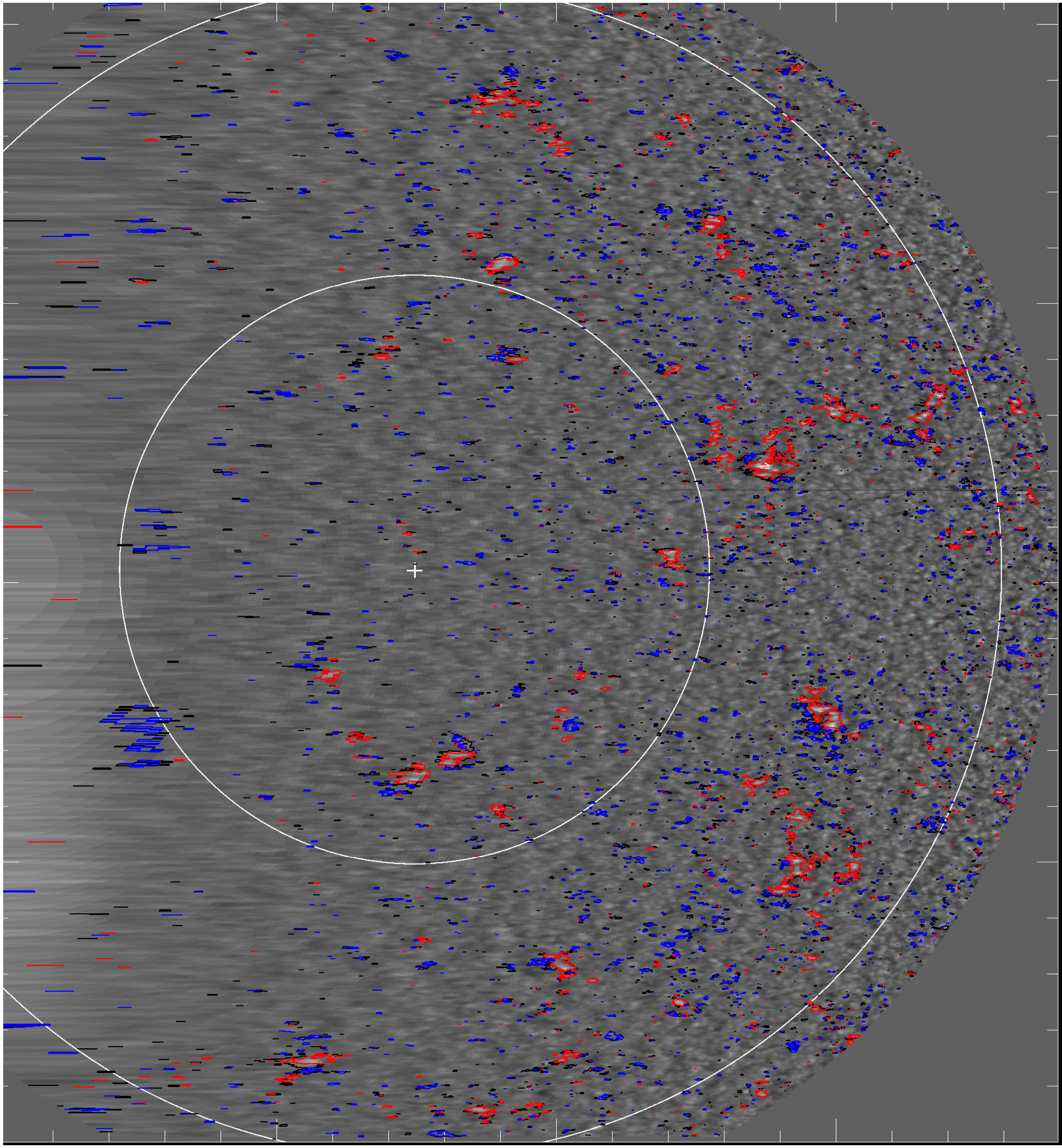
Hinode XRT
High coronal Activity in polar region



Cirtain etal 2007

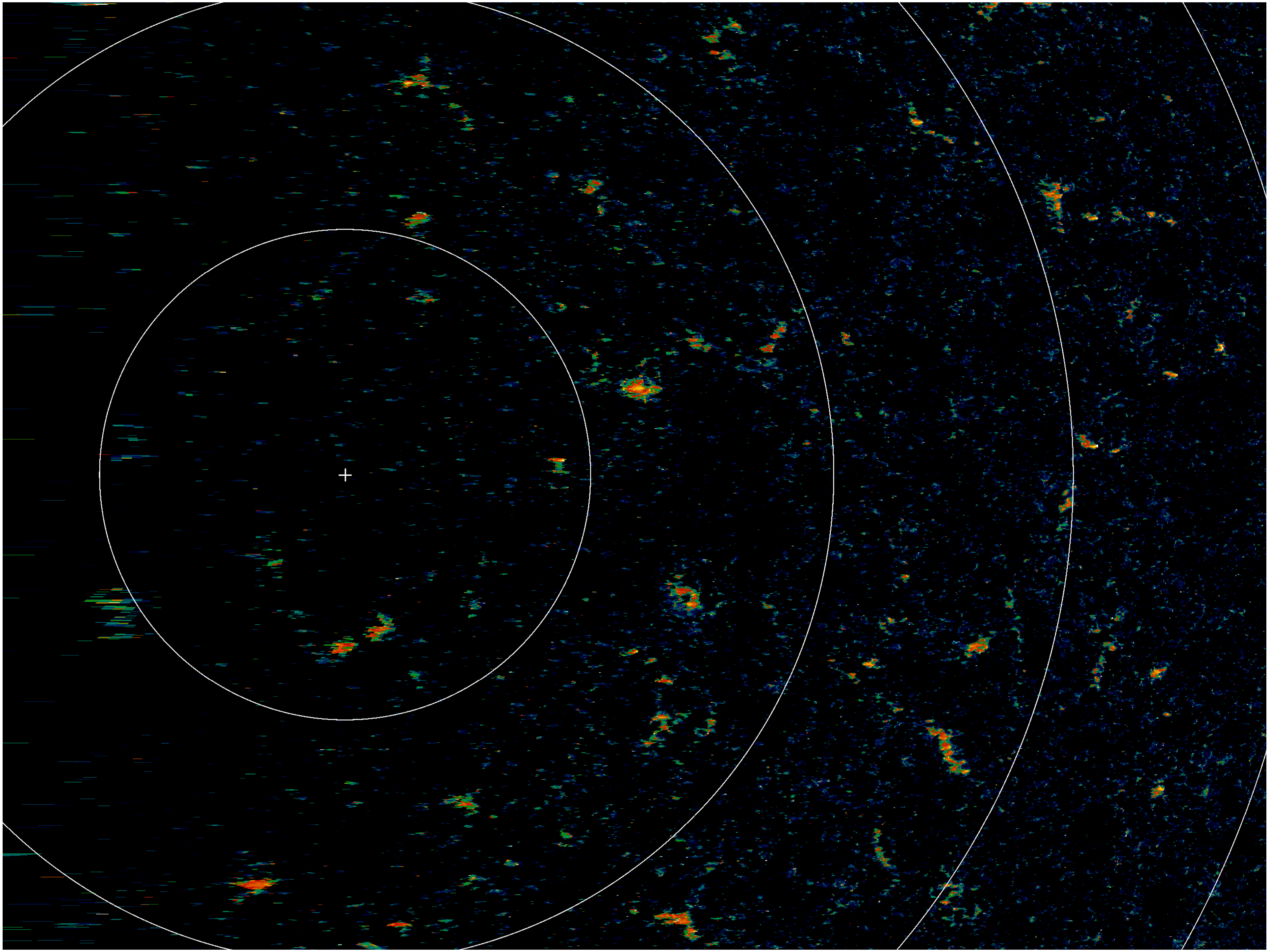
Polar landscape kG field





Red : vertical
Blue : horizontal

Polar region consists of same-sign vertical B with horizontal B

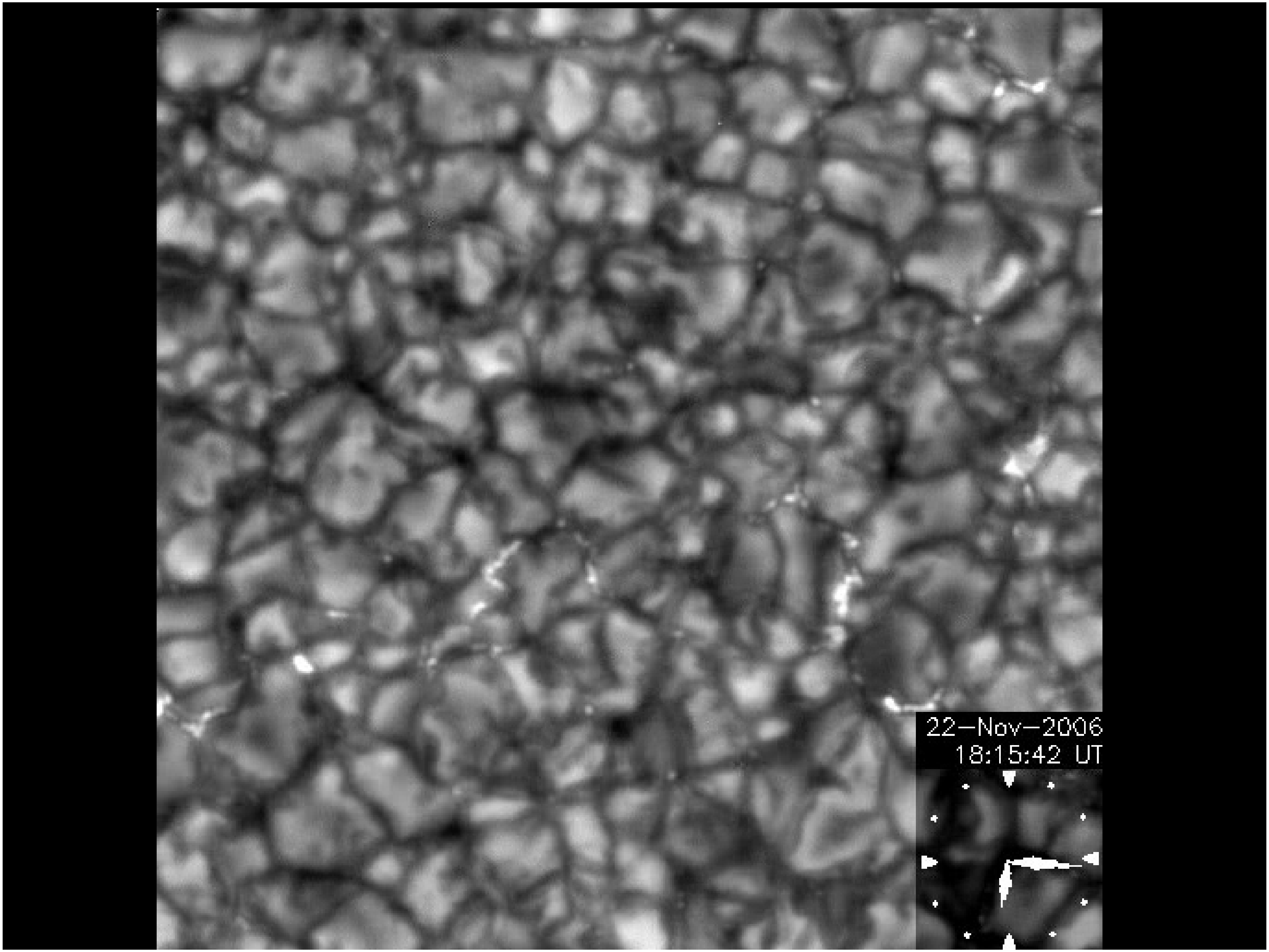


Total and average magnetic flux

- Total vertical flux 2.2-9.9 x 10^{21} Mx
- Total horizontal flux 0.4-2.0 x 10^{22} Mx
  - Magnetic fill factor (scattered light correction) causes uncertainty
  - Horizontal flux factor of 2 larger
  - Average vertical flux 10.0 G (best estimate)
- Ulysses observations
  - 2 x 10^{22} Max (above 35 degree)

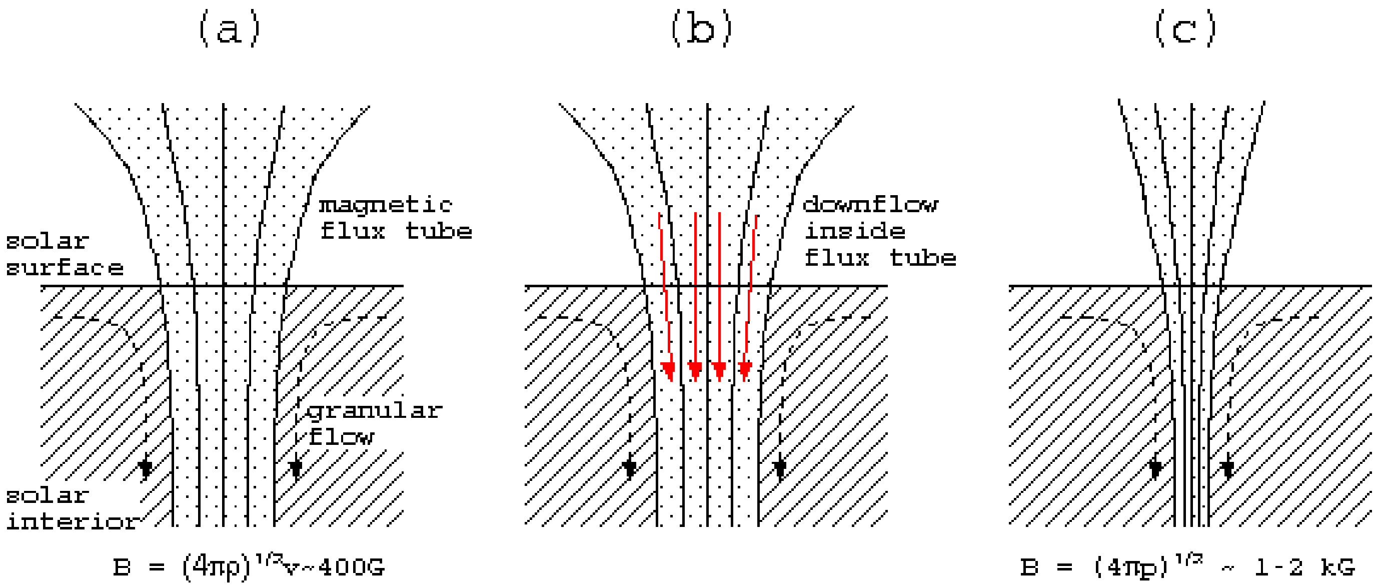
Convective collapse

Nagata et al ApJL (2008)


22-Nov-2006
18:15:42 UT

Convective Collapse and kilo-gauss flux tube formation

Parker (1978); Hasan (1985), Hasan et al. (2003), Bunte, Hasan,Kalkofen, (1983)



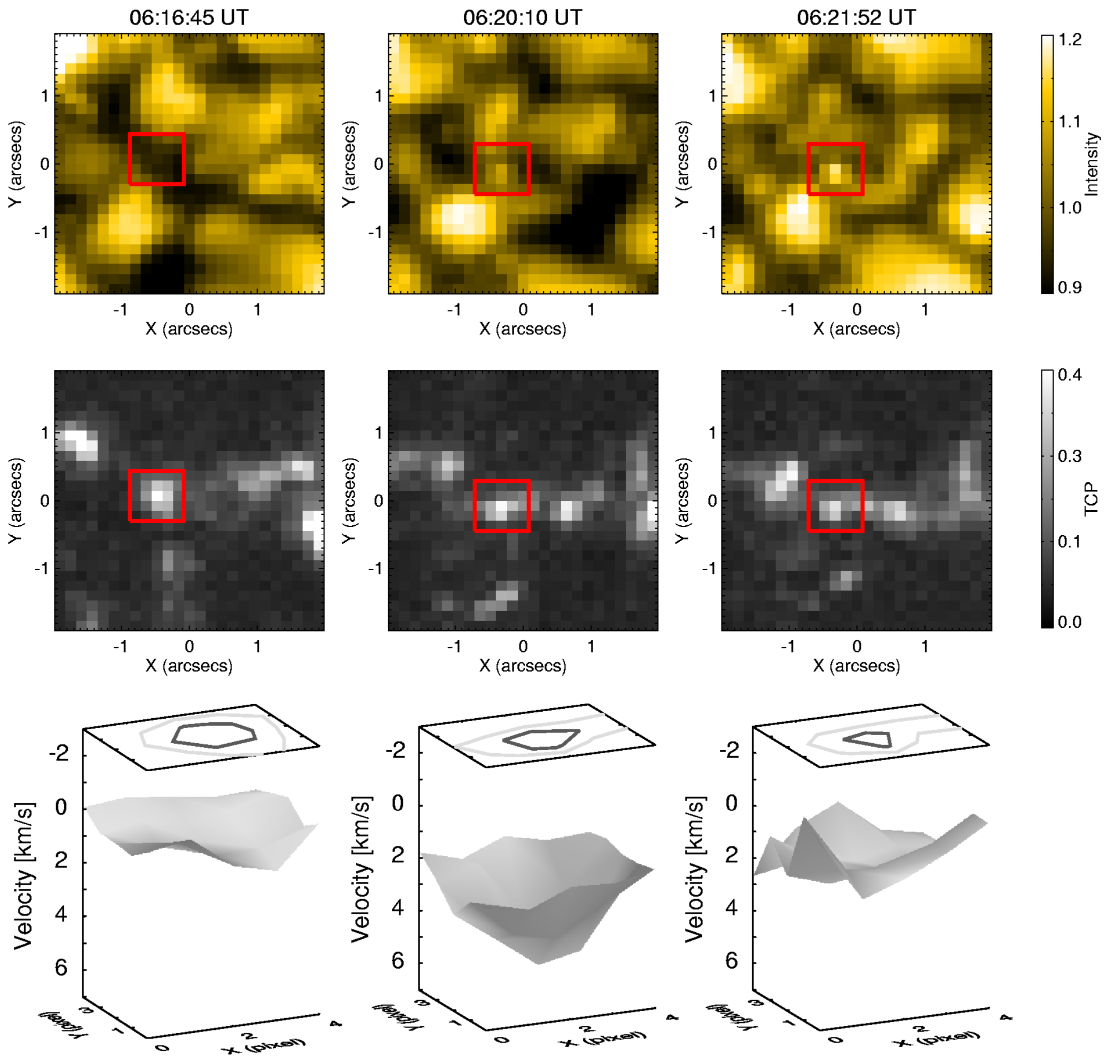
(a)As magnetic Pressure increases, heat flux from the granule decreases.

(b) Flux tube cools due to radiation loss, and down flow grows.

(c) Flux tube shrinks due to the decreased pressure inside, and then the field strength increases; kilo-gauss flux tube appears.

SOT-SP Observations of a kilo-gauss field strength flux tube

6 Feb. 2007 at Disk center (Quiet region)



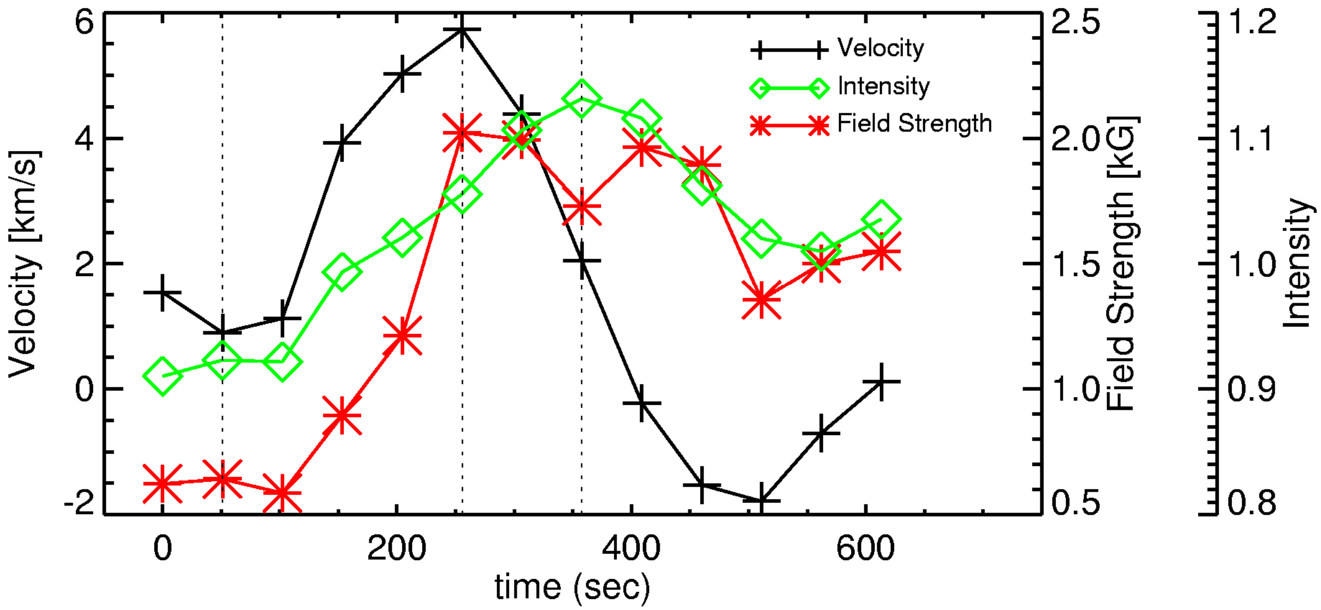
06:16:45 - No remarkable features are found on the continuum map. A magnetic feature with strong circular polarization signal is found there.

06:20:10 - A continuum bright point is clearly seen. The magnetic feature corresponding to the bright point shows a strong downflow with ~6 km/s.

06:21:52 – The continuum bright point becomes more prominent. The strong downflow has ceased. .

SOT-SP Observations of a kilo-gauss field strength flux tube

The evolution of field strength, line of sight velocity, and continuum intensity observed at the central pixel of the magnetic feature of interest; ME inversion was used.

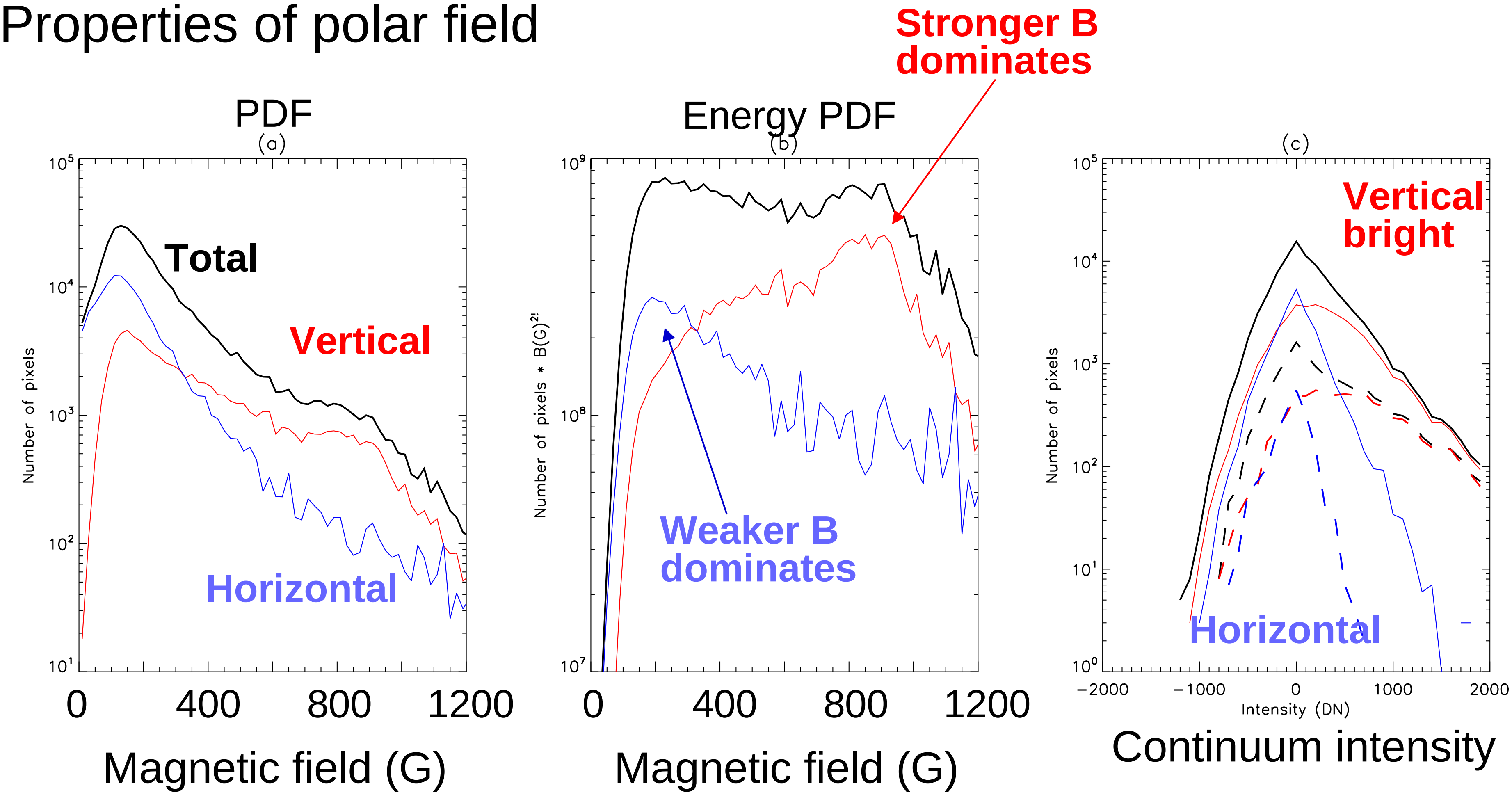


The initial field strength of ~400 G is intensified up to ~ 2000 G as the downflow grows to 6 km/s in 150 s. The field strength then remains above 1000 G throughout the sequence.

A transient upflow of ~2 km/s at the end of the sequence.

Backup slide

Properties of polar field



Interpretation

(1) Due to thermal isolation from the surroundings by the magnetic fields, the radiative cooling of a flux tube drives convective intensification, which causes a strong downflow.

(2) The field strength in the flux tube is intensified as the flux tube is evacuated with the downflow, keeping pressure balance with the surroundings

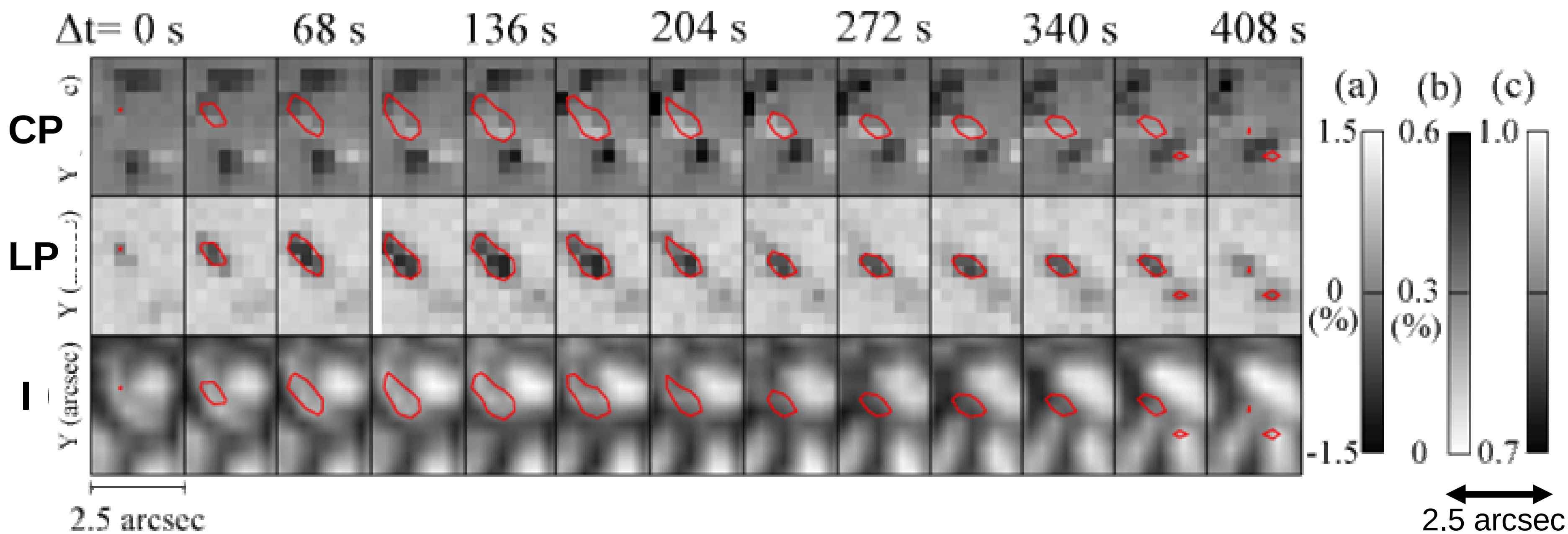
(3) The surface of unity optical depth goes down as the flux tube is evacuated, and the temperature at the surface is increased by the radiation from the surroundings whose temperature is higher than that at the higher layer; the continuum intensity consequently increases (Spruit 1976).

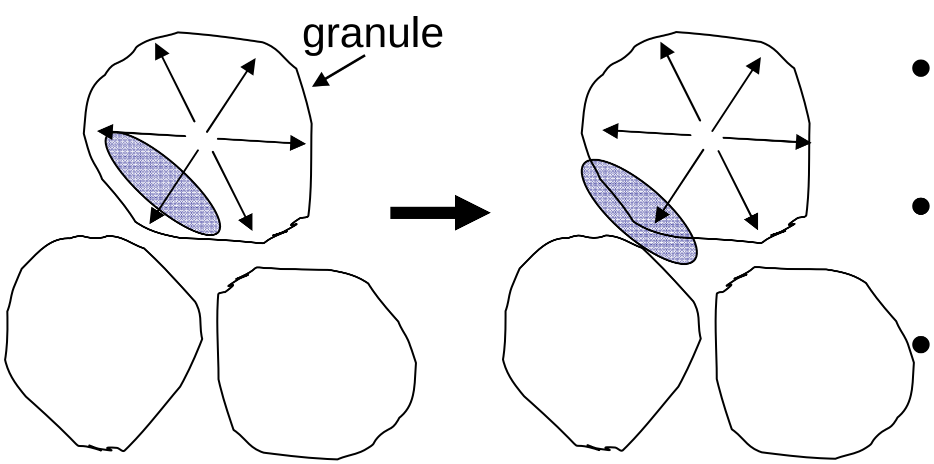
(4) The downward flow bounces back at the dense bottom layer, and the upward motion appears. Such "rebounds" have also been seen by Bellot Rubio et al. (2001) and Socas-Navarro (2005).

The Observations are naturally explained with the convective collapse model.

Horizontal fields in plage

PL Ishikawa et al (2008)
QS Centeno et al. (2007)

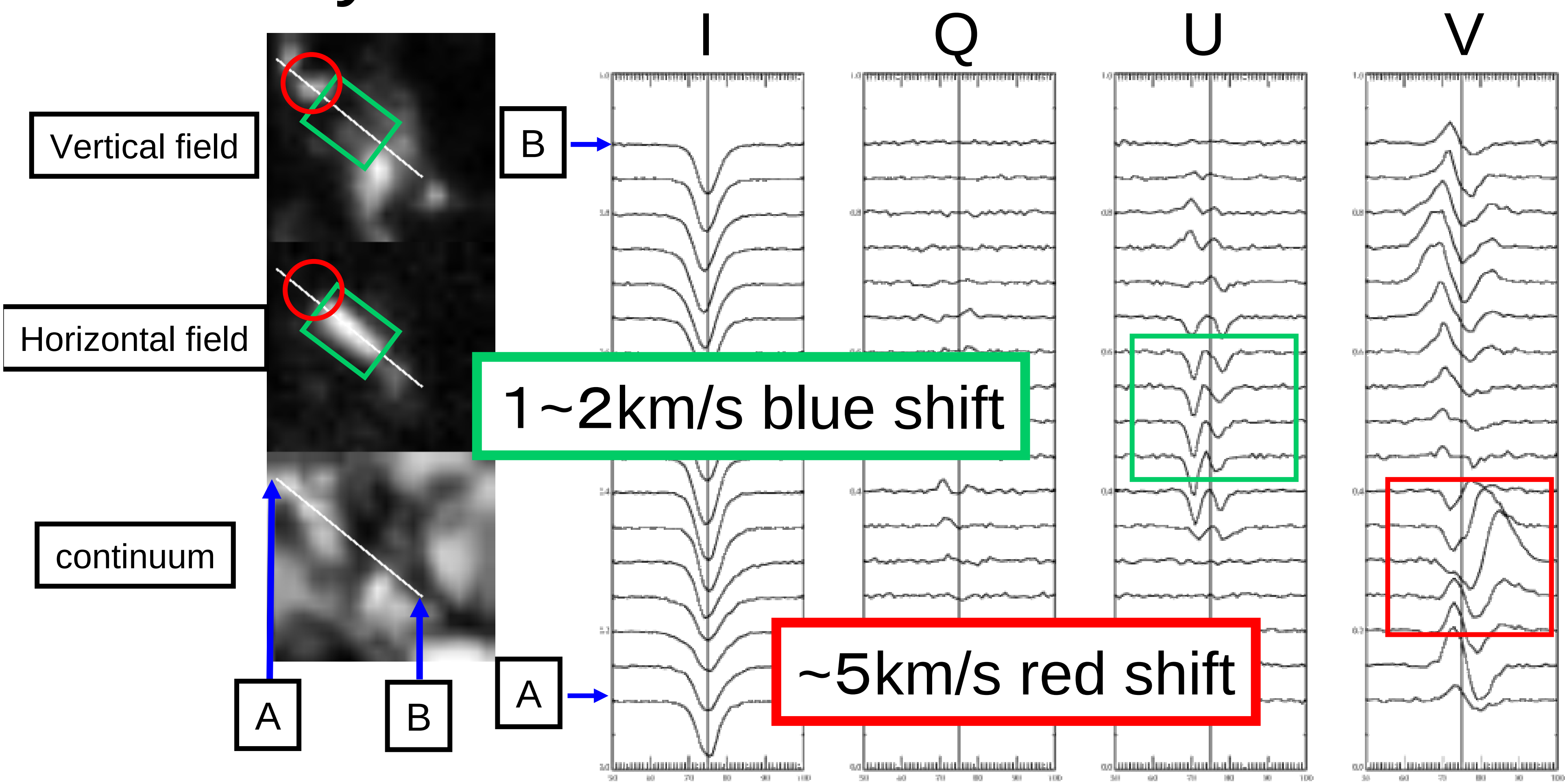




Lifetime:6min

- Receptive to the convective flow
- Horizontal magnetic fields appear in the field free regions.
- We have similar horizontal field in the quit sun (Centeno et al)

More proto-typical emerging flux only one event in the data set



- Blue shift (1~2km/s) is detected, where horizontal magnetic field is strong.
- Very strong red shift (~5km/s) at one footpoint.