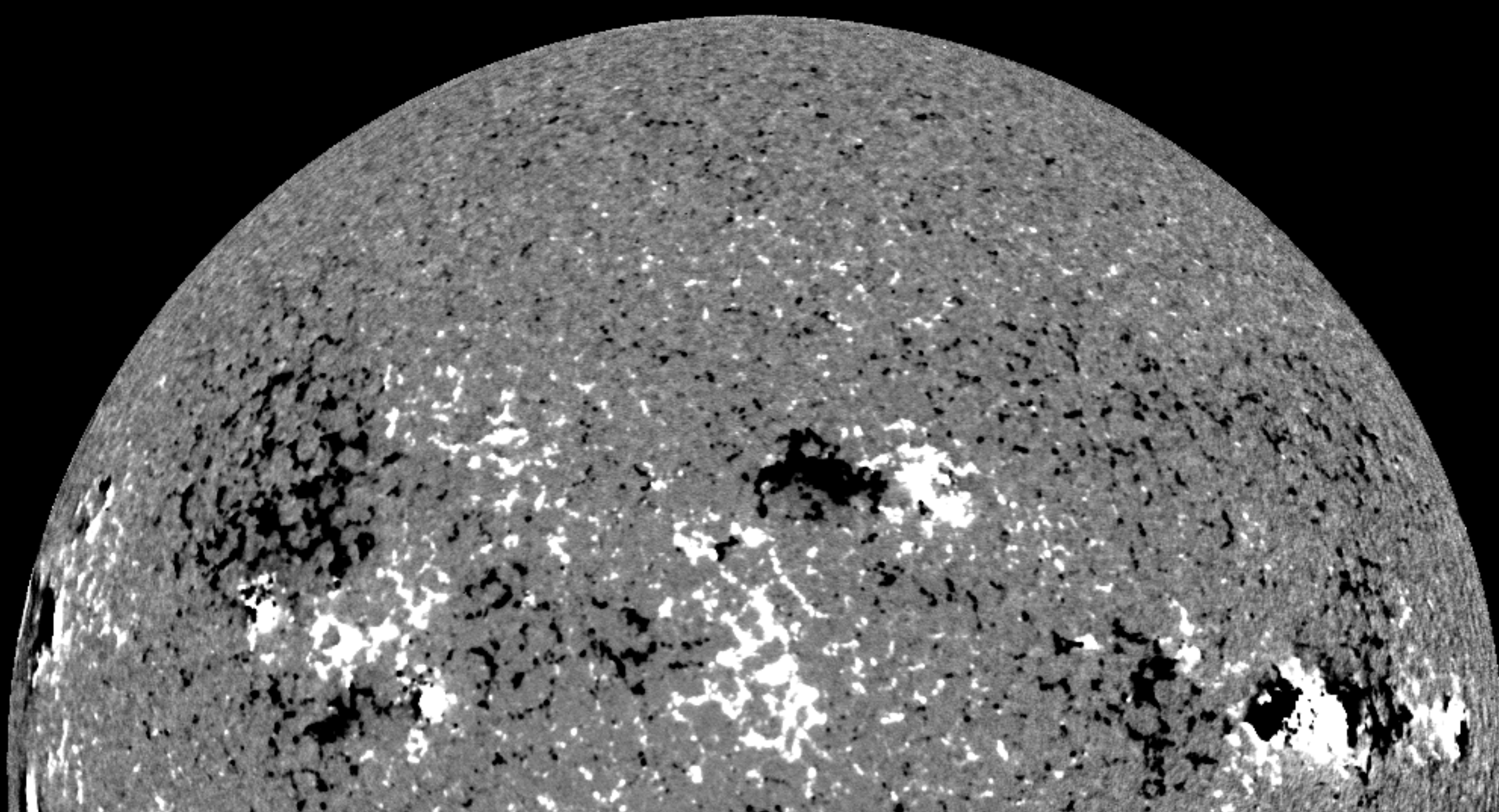
Deriving Properties of Magnetic Fields in Solar Photosphere

Maria D. Kazachenko

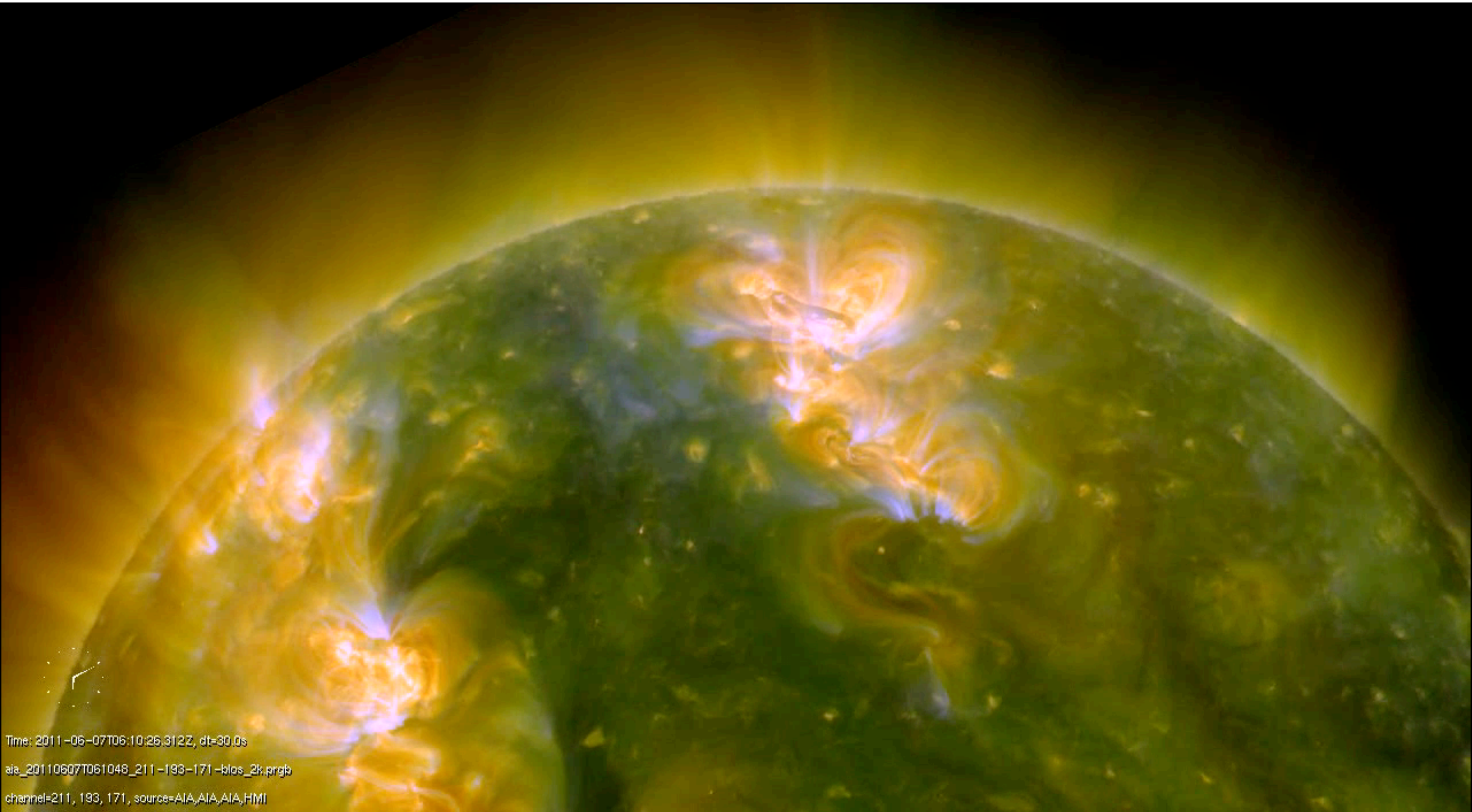
University of Colorado, Boulder — National Solar Observatory



Photosphere BLOS from HMI/SDO

COLLAGE, April 2 2020

Knowledge of Coronal Magnetic Field is Vital for Understanding Long- and Short-Term Evolution of Solar Corona



Can we use magnetic fields measured in the photosphere to understand magnetic properties of solar activity?

During next three classes we will go over methods used to derive some useful properties of evolving magnetic fields: velocity and electric fields, energy and helicity fluxes.

Outline for next three classes

- Today: magnetic fields in the photosphere; early methods to find magnetic field flows (velocity, electric fields) from these measurements.
- Next Tuesday: deriving velocity fields in the solar photosphere using more recent methods: DAVE4VM, PDFI, some ML methods; show examples of their application to solar data.
- Next Thursday: hands-on activity: applying FLCT to a sequence of HMI/SDO magnetograms to derive horizontal velocities, magnetic fluxes, helicity and energy fluxes.

Outline For Today

- Why Magnetic Fields (**B**) on the Sun Are Important?
- Where can we presently routinely measure magnetic fields on the Sun?
- What can we get from **B**?
- Tracking evolution of **B**: early methods for tracking B: tracking and inductive methods

Why Magnetic Fields Are Important?
Plasma β vs. height in solar atmosphere

Upper Corona:
Gas flows drag magnetic fields

Solar atmosphere:
Magnetic fields drag gas flows

Below photosphere:
Gas flows drag magnetic fields

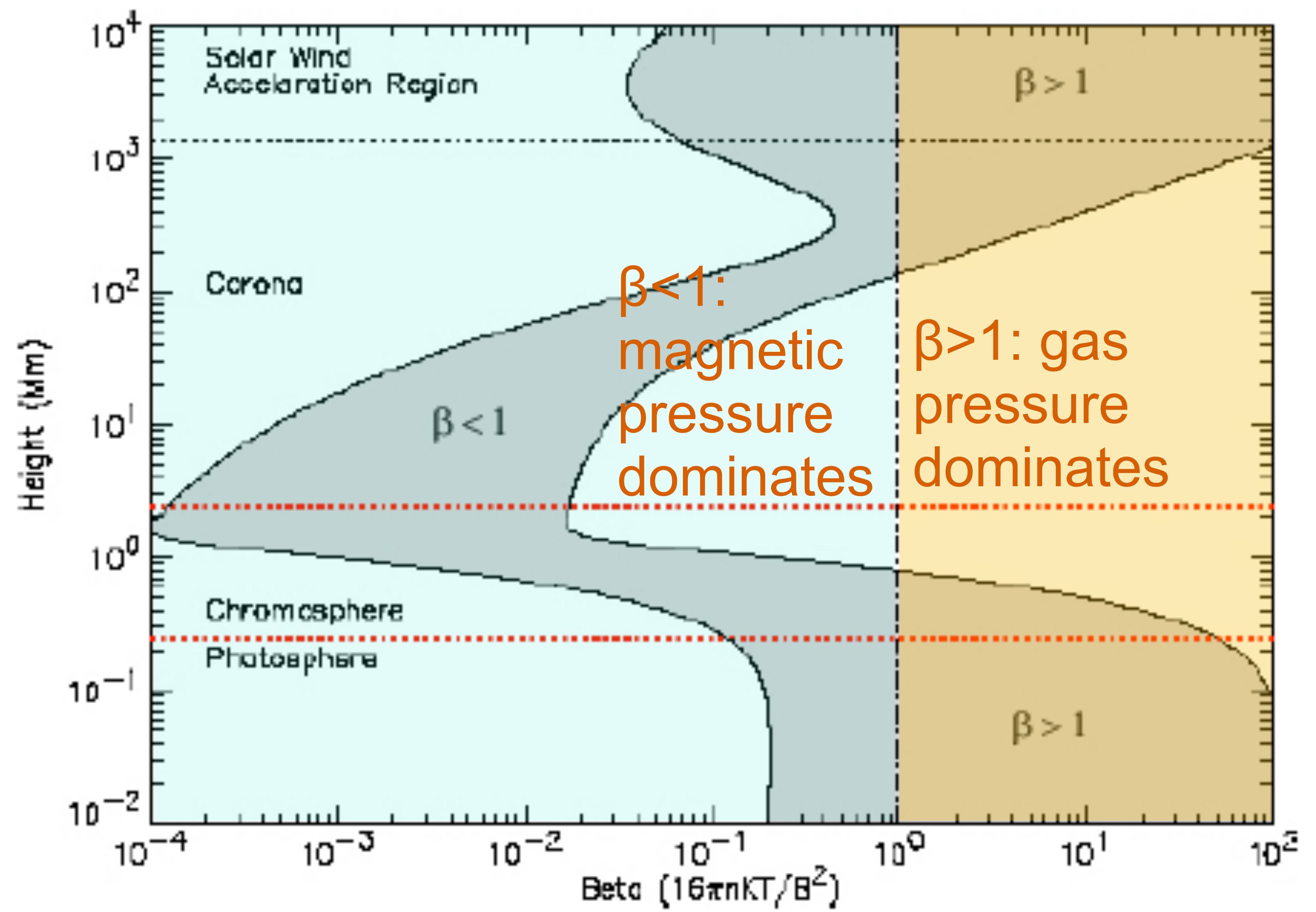


Figure 1. Ratio of gas pressure to magnetic pressure (β) as a function of height[1].

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Plasma β vs. height in solar atmosphere

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Solar atmosphere:
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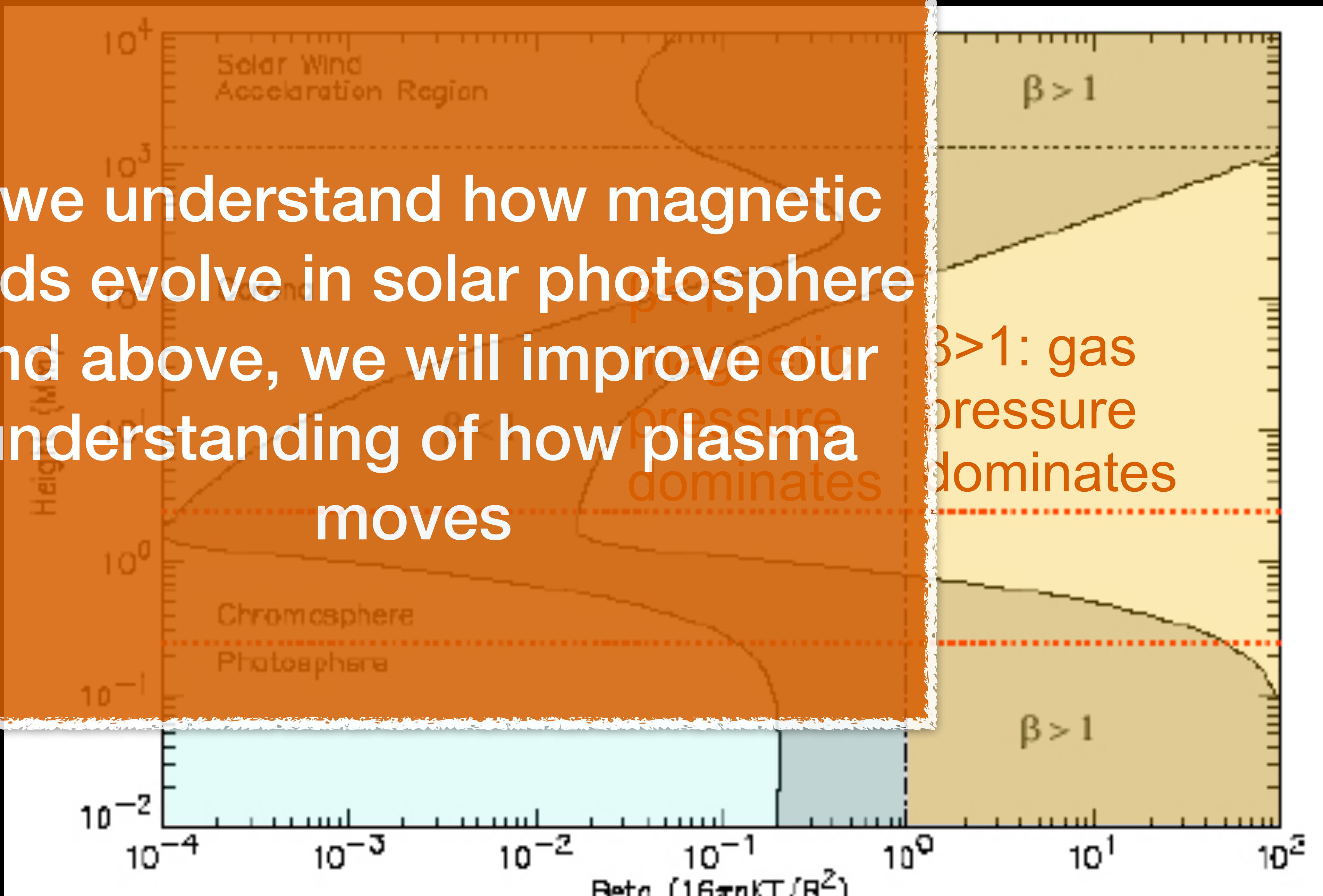
Below photosphere:
Gas flows drag magnetic fields

If we understand how magnetic fields evolve in solar photosphere and above, we will improve our understanding of how plasma moves



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Where Does CME & Flare Energy Come From?

From the low-corona magnetic field!

Table 1. Energy Requirements for a Moderately Large CME

Parameter	Value
Kinetic energy (CME, prominence, and shock)	10^{32} ergs
Heating and radiation	10^{32} ergs
Work done against gravity	10^{31} ergs
Volume involved	10^{30} cm^3
Energy density	100 ergs cm^{-3}

Table 2. Estimates of Coronal Energy Sources

Form of Energy	Observed Average Values	Energy Density ergs cm^{-3}
Kinetic ($(m_p n V^2)/2$)	$n = 10^9$ cm^{-3}, $V = 1$ km s^{-1}	10^{-5}
Thermal (nkT)	$T = 10^6$ K	0.1
Gravitational ($m_p ngh$)	$h = 10^5$ km	0.5
Magnetic ($B^2/8\pi$)	$B = 100$ G	400

Forbes 2000

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If we understand how magnetic fields evolve in solar photosphere and above, we will improve our understanding of flares and CMEs

Forbes 2000

Why Magnetic Fields Are Important?

- All solar activity, active regions and the quiet Sun, reflect evolution of magnetic fields;
- Magnetic fields observed in the photosphere are generated in the Sun’s interior, extending into the photosphere and the atmosphere => Measurements in the photosphere provide insight of **B** in the interior;
- Measurements in the photosphere provide insight of **B** in the corona; how magnetic energy is stored and released in solar atmosphere.

Where Can We Measure Magnetic Fields on the Sun?

- Photosphere: both line-of-sight (LOS) and vector magnetic fields

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- Chromosphere: extremely hard, very few LOS measurements
- Solar Corona: extremely hard, very few LOS measurements

Summary: We have decent measurements of B in the photosphere; but not in the chromosphere/corona;

DKIST instruments

HMI: 0.5 arcsec = 360 Km; DKIST: 0.025'' = 20 km, 20 times better resolution

	Visible Broadband Imager, VBI	**Visible Tunable Filter, VTF**	**Visible SP, ViSP**	**Diffraction-Lim. Near IR SP DL-NIRSP**	**Cryogenic Near IR SP, Cryo-NIRSP**
ds, ''	0.011	0.028	-	0.03'' - 0.464	0.5 (cor) 0.15 (disk)
dt, s	3.2	0.8-13	10	0.001 (disk) 1 (cor)	>0.1
Band, nm	380-850	520-870	380-900, 3 bands	500-2500 1 vis, 2 NIR	1000-5000
FOV, '	2 x 2 square	1' - circle	2 x 2 square	2 x 2 & 2.4 - 27,	4 x 3 (cor) 1.5 x 1.5 (disk)
Location	I, phot-chrom	IQUV phot-chrom	IQUV B, phot-chrom	B, phot.chrom-cor.	B, corona, hel/sph <1.5 Rsun
PI	F. Voger	O. von der Luhe	R. Cassini	H. Lin	J. Kuhn
Science	Hires imaging in lines, 20 km	High ds/dt narrow band imaging, doppler, vh, B	Simult. **B** at different heights, no spatial info	B in phot/cor. imaging	B in high corona

Could be used simultaneously, mosaicing

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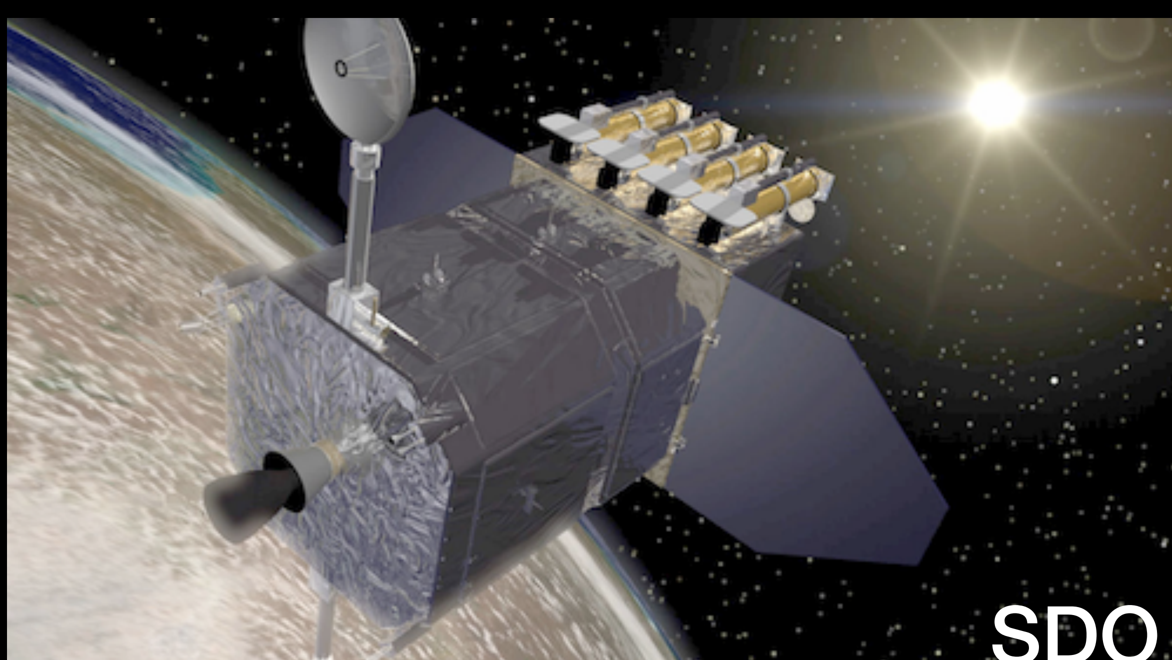
B from DKIST:

- B on disk: phot. & chromosphere; ds~20km;
- B on limb: corona; ds~300km;

+ super high dt and ds
+ B in phot., chrom., corona;
+ revolutionary new science!
  - limited FOV
  - limited duration
  - complex inversion;

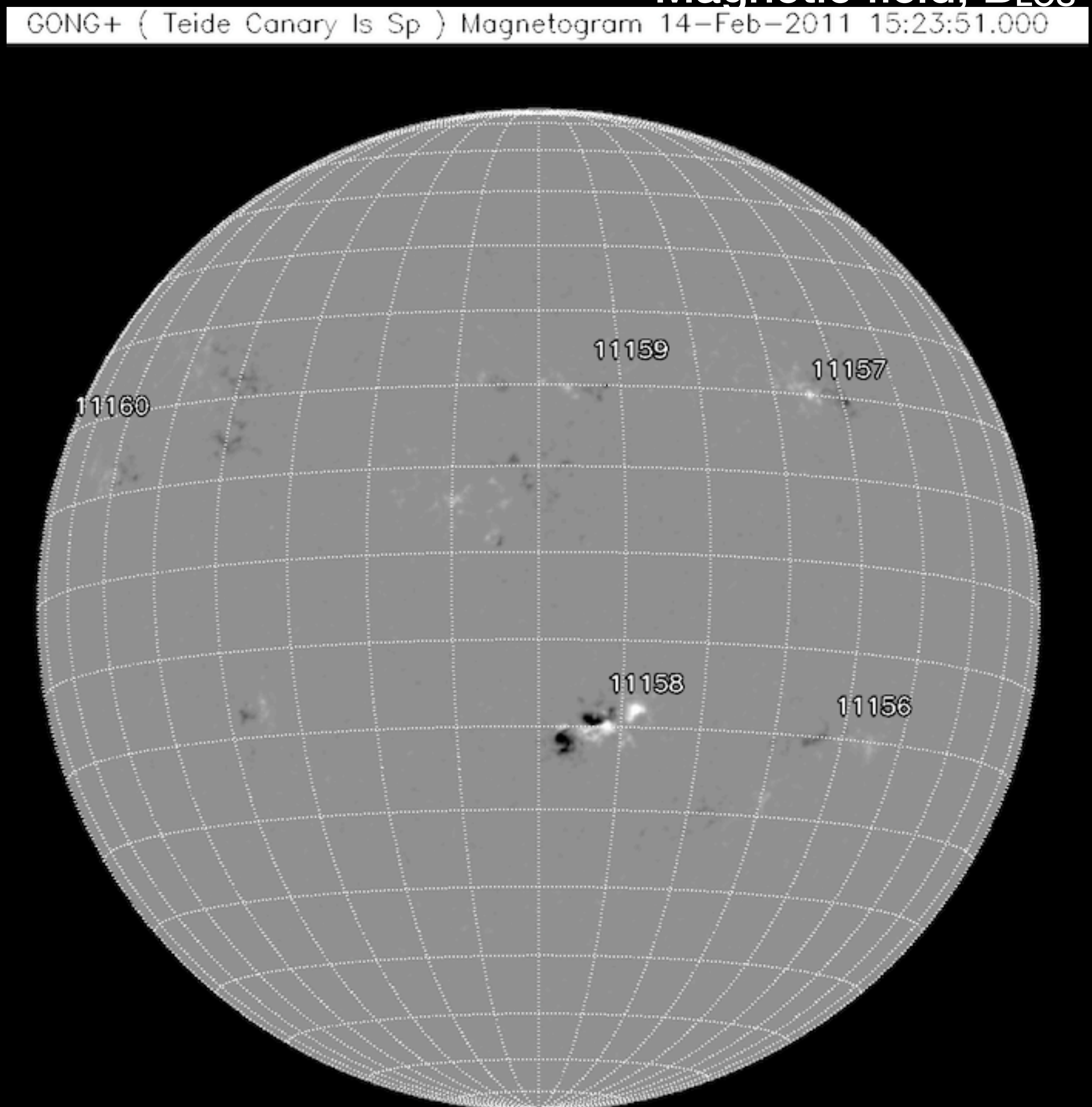
Let’s look at some examples of present day magnetic field measurements:

1) Most routine: HMI/SDO
2) Highest resolution: IMaX/SUNRISE



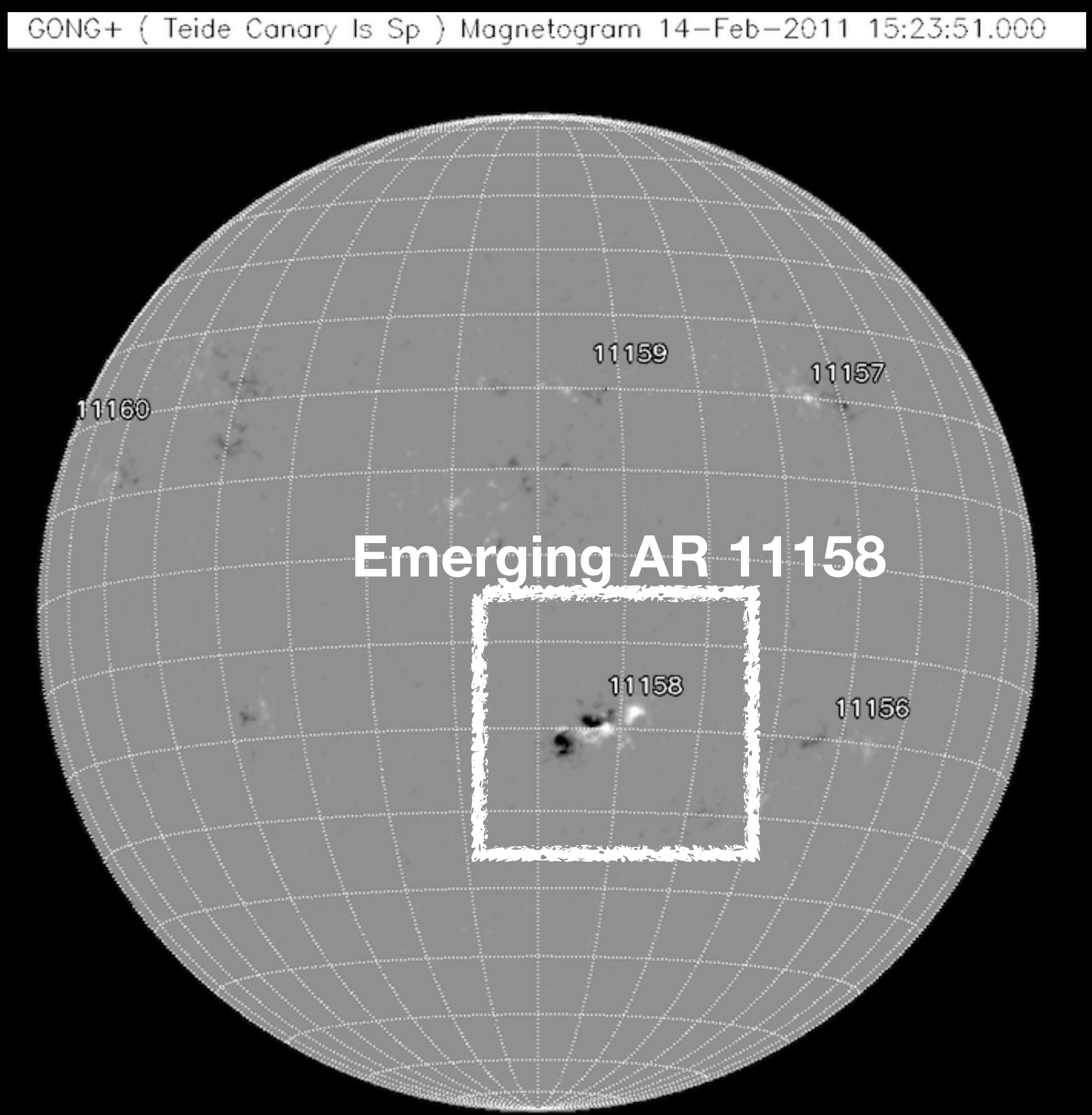
Photosphere: Magnetic Fields in an Active region: Ground-based LOS magnetogram from GONG+ on Feb. 14 2011

Magnetic field, B_{LOS}

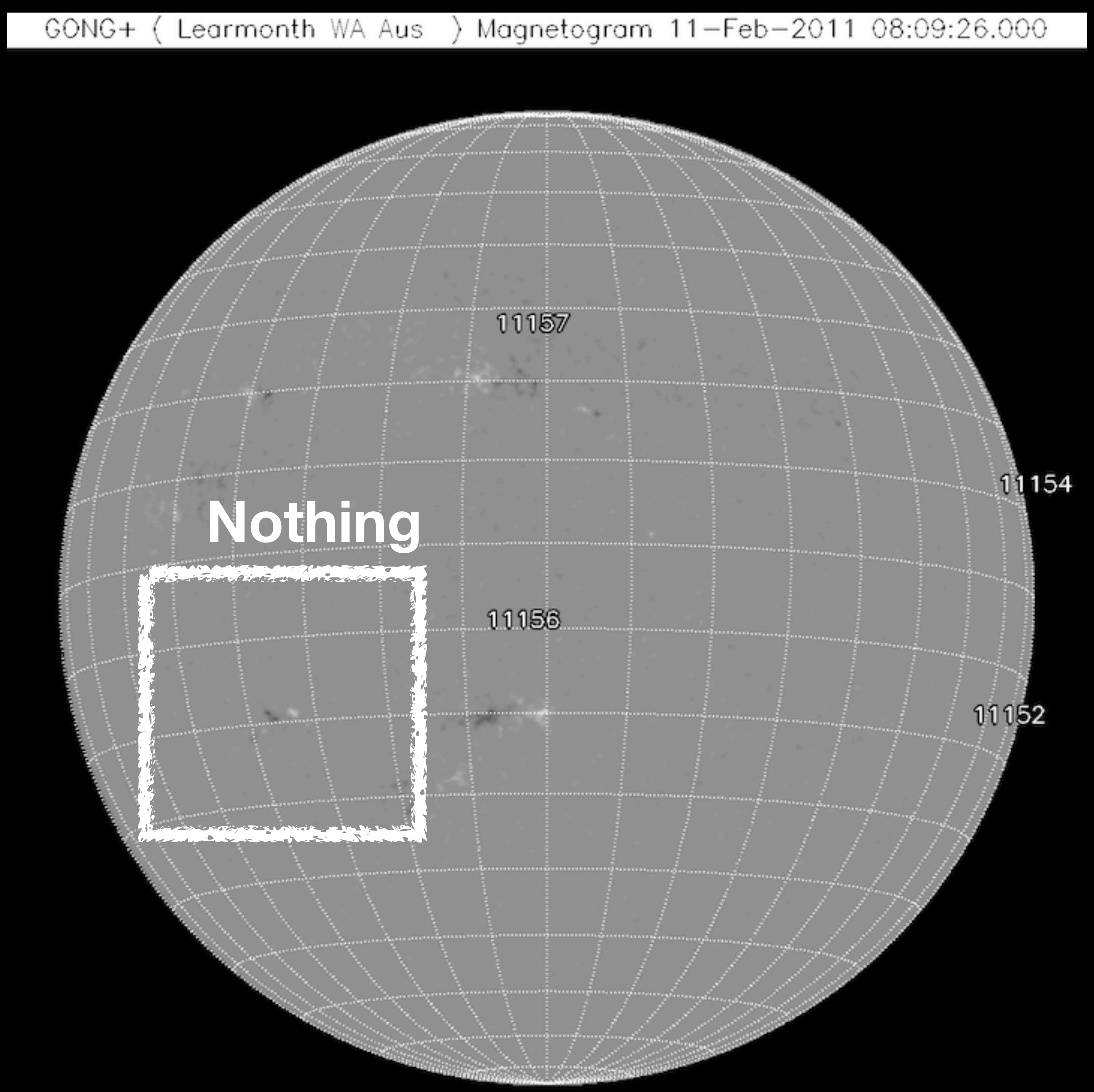


Photosphere: Magnetic Fields in an Active region: Ground-based LOS magnetogram from GONG+ (Canary Islands) on Feb. 11 and Feb 14 2011

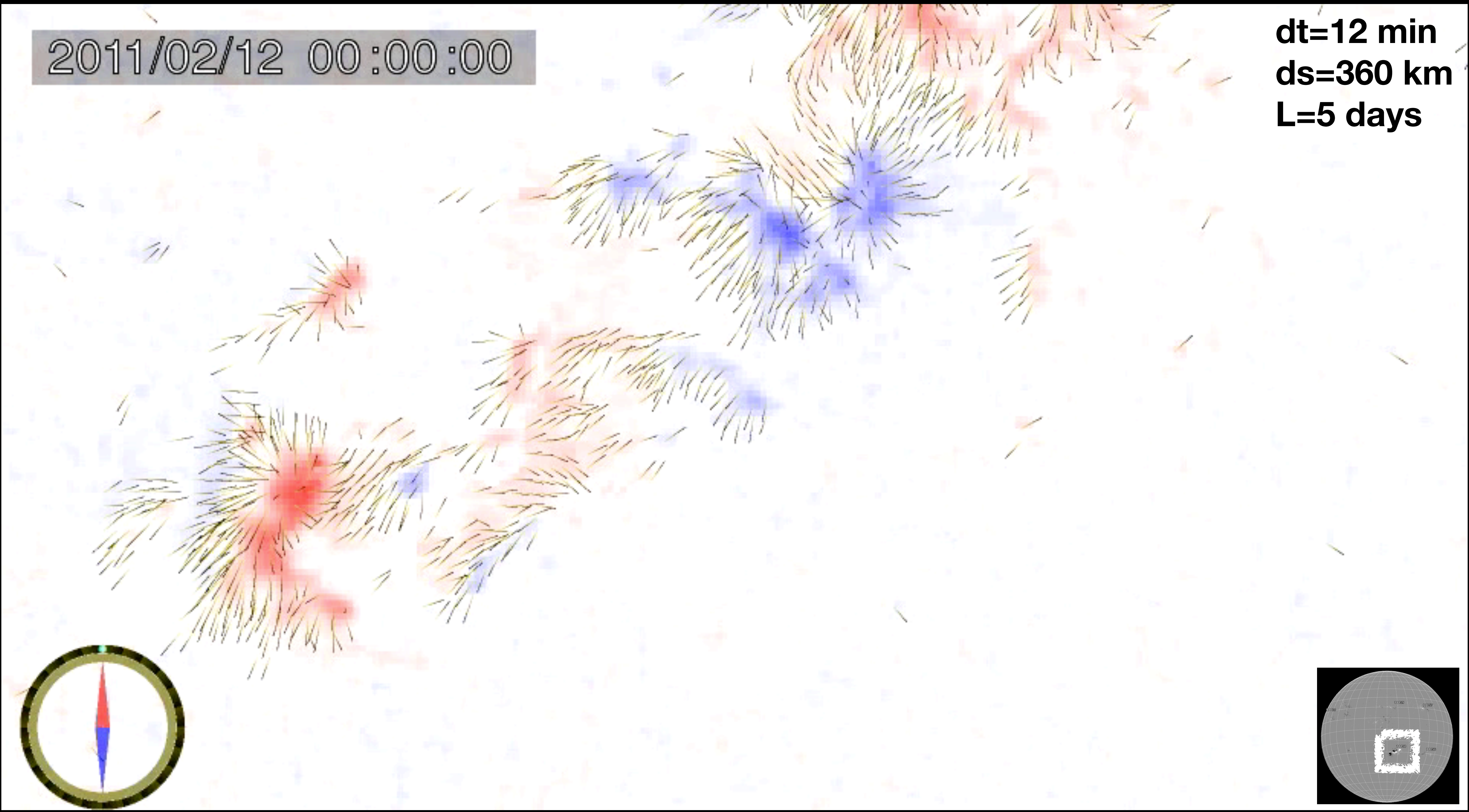
Same AR1158 we have seen



Three days earlier….



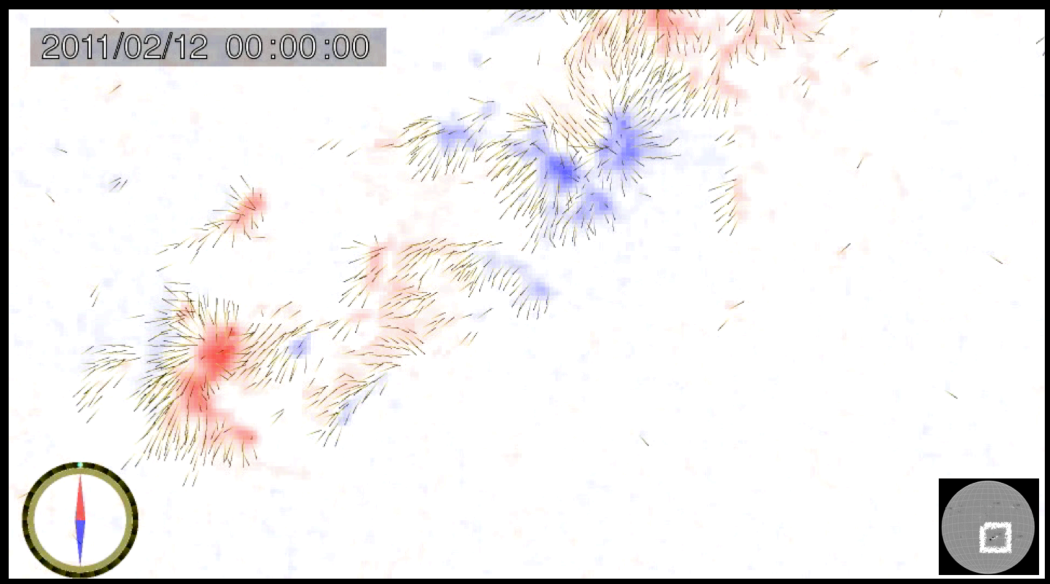
Vector B_{phot} in this Active region: from HMI/SDO (Helioseismic and Magnetic Imager / Solar Dynamics Observatory, 2010)

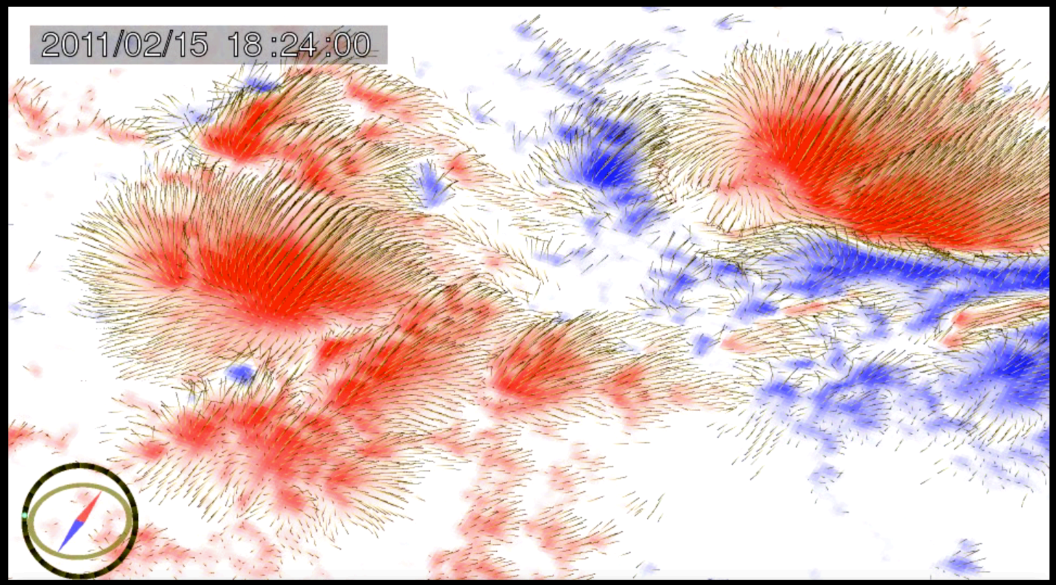


NOAA AR 11158 evolution

Red - $B_z>0$; blue - $B_z<0$, arrows - B_h

Magnetic fields at AR scale

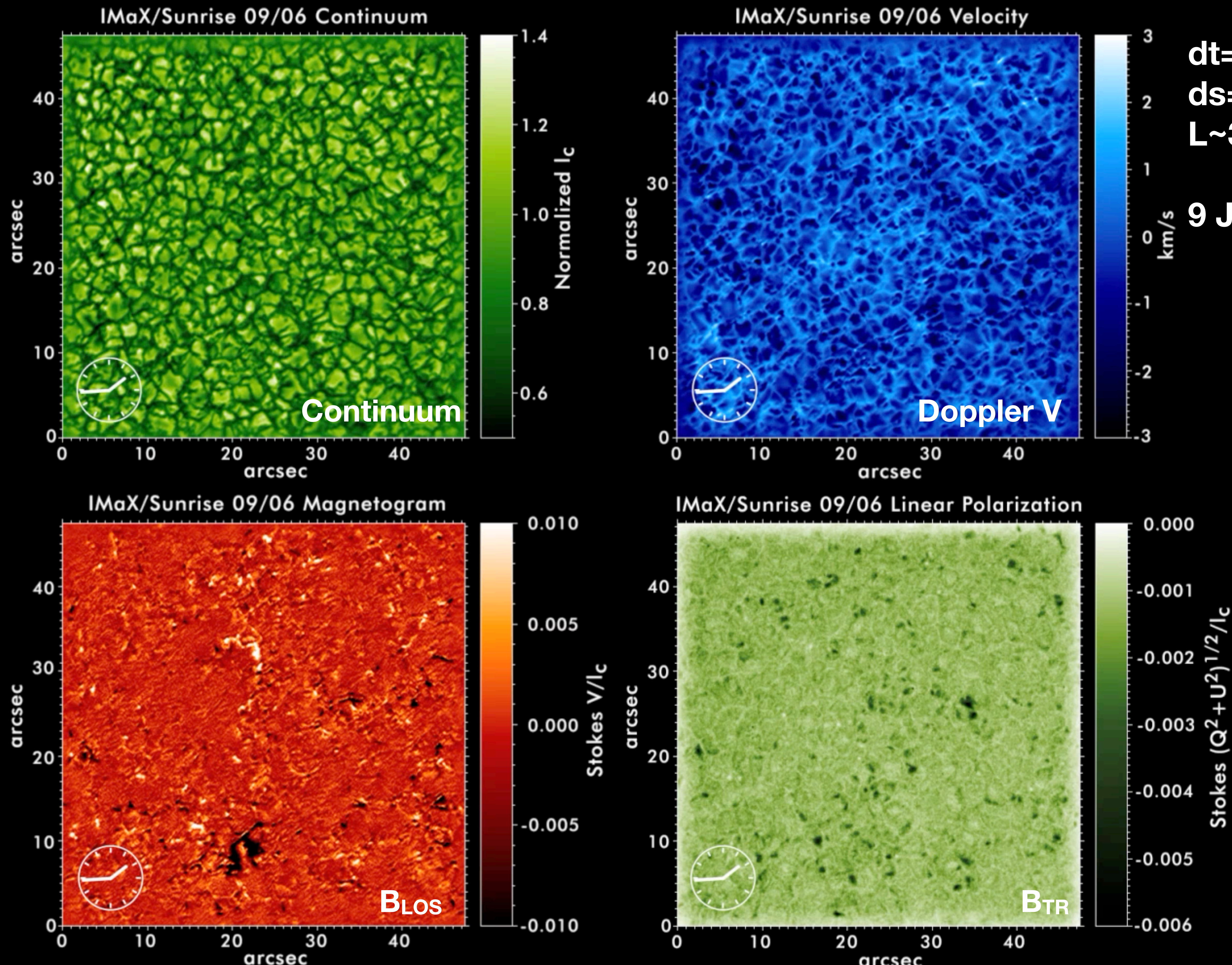




- Highly dynamical
- Emerge, cancel
- Rotate, shear
- All this dynamics contributes into storage of magnetic energy in the coronal magnetic field; solar eruptions
- We will learn more about AR magnetic fields during the hands-on exercise

Red - $B_z>0$; **blue** - $B_z<0$, arrows - B_h

Photosphere: Magnetic Fields in the Quiet Sun (Sunrise/IMaX)



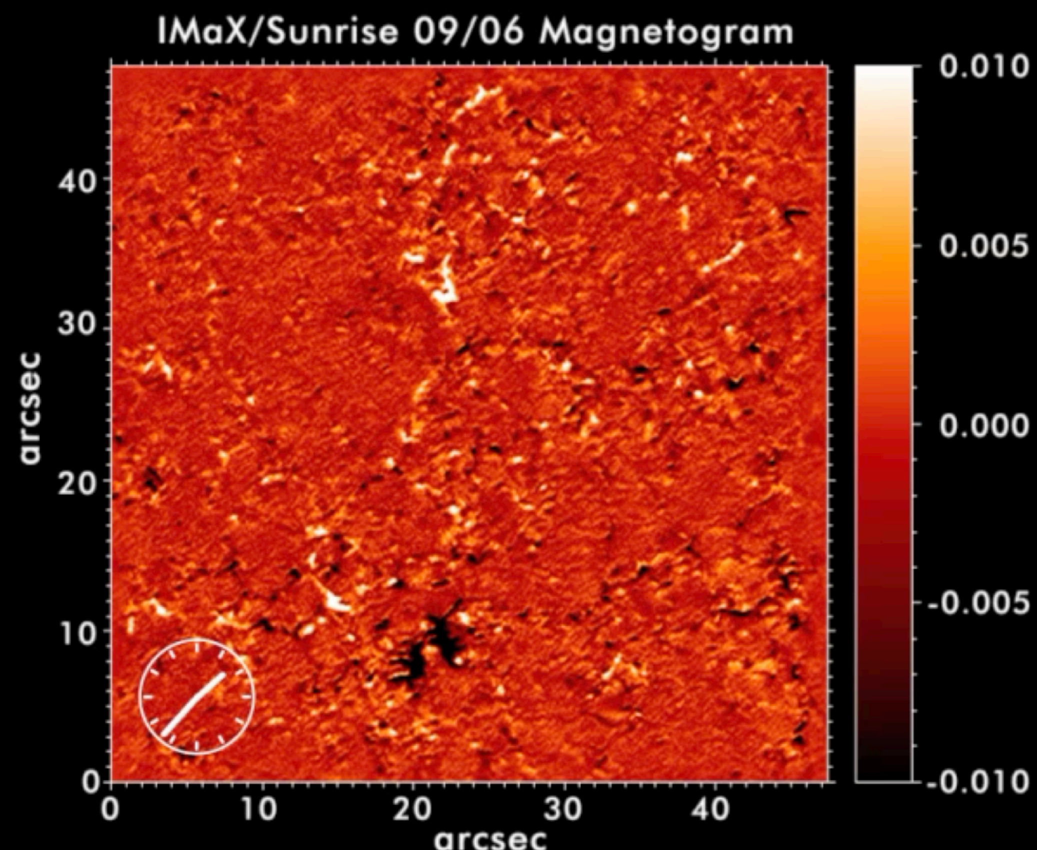
dt=10 sec
ds=40 km
L~30min

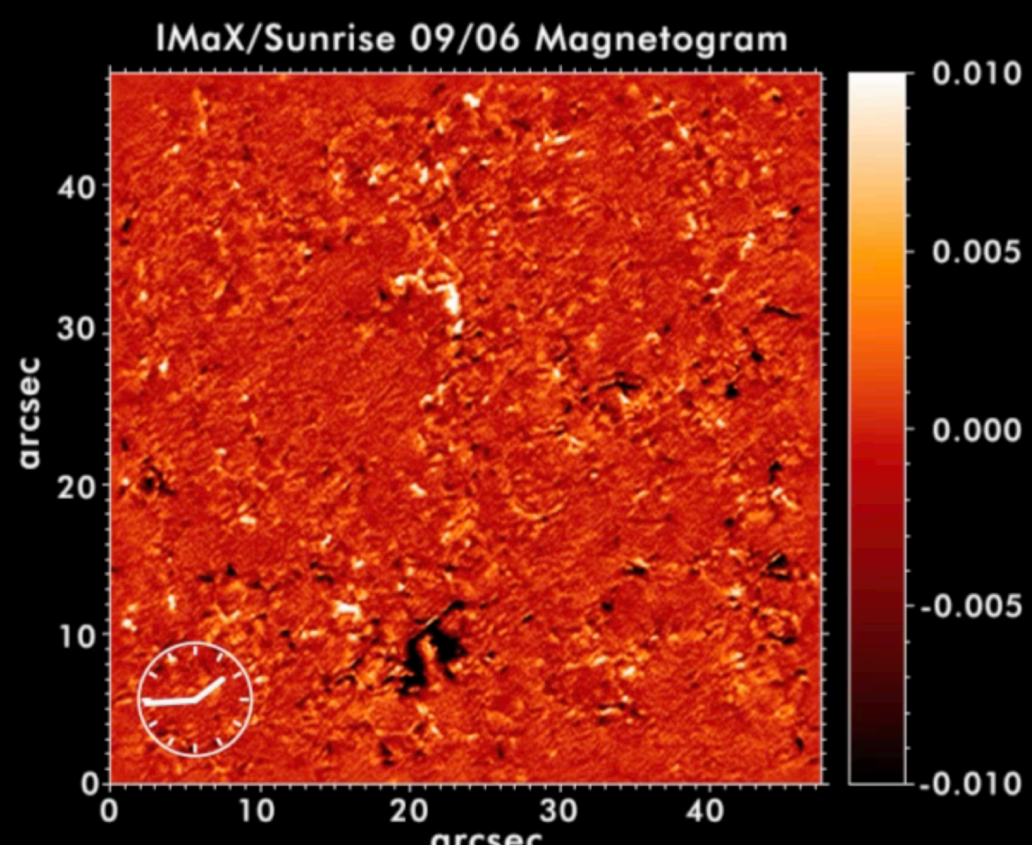
9 June 2009

White - $B_z>0$; Black - $B_z<0$,

Imaging Magnetograph eXperiment (IMaX)

Magnetic fields at quiet sun scale





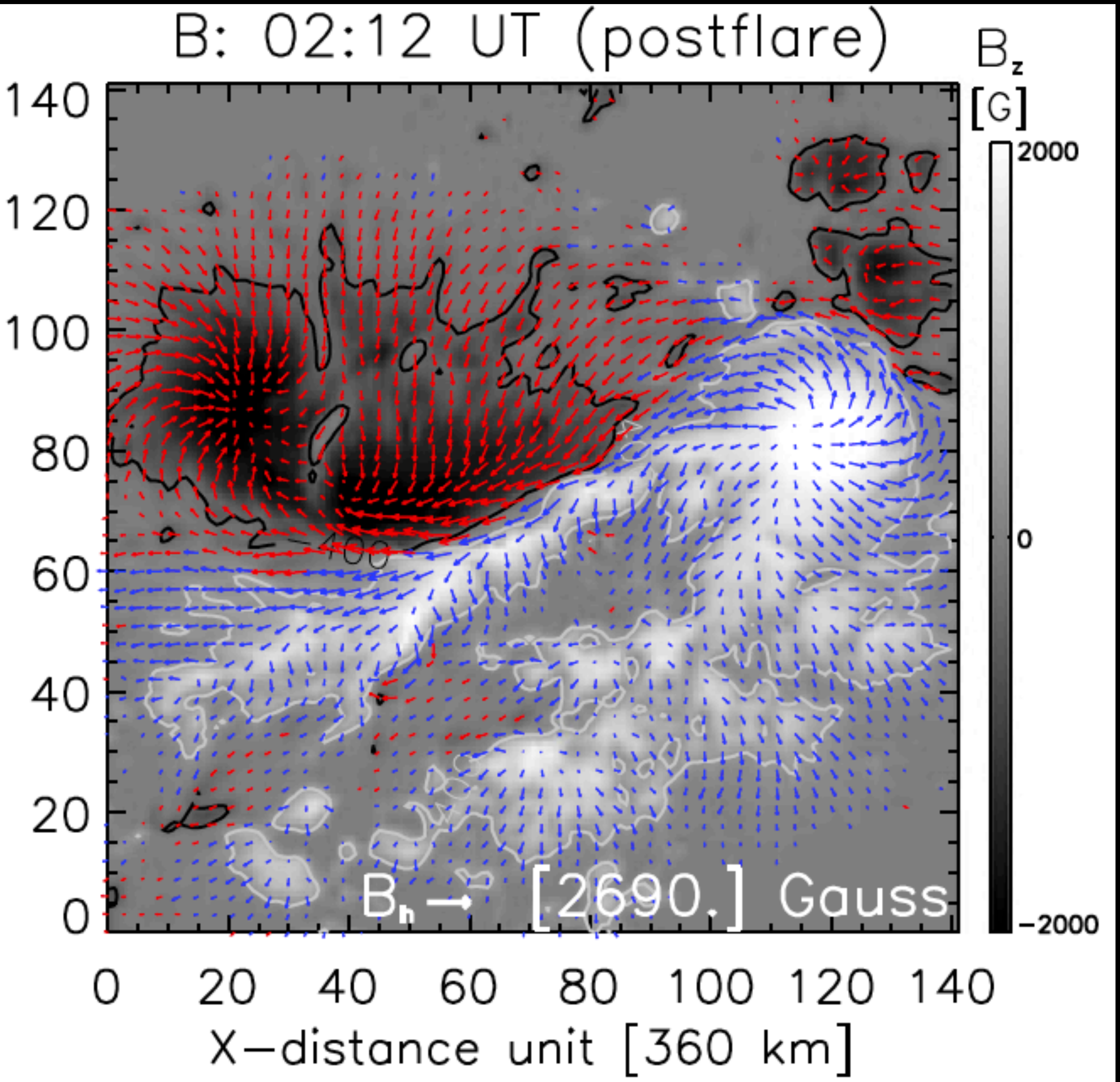
- Highly dynamical
- Emerge, cancel
- Rotate, shear
- All this dynamics contributes into storage of magnetic energy above on the smallest scales.
- Related to coronal heating?

Ok, imagine we measured magnetic field **B**(x,y) at the photosphere.

What physical properties (variables) can we derive from B=(Bx,By,Bz)?

I will give you a minute to let leave your answers in the zoom chat.

What can we get from $B=(B_x,B_y,B_z)$?



Magnetic flux

$$\Phi = \int |B_n| \, dS,$$

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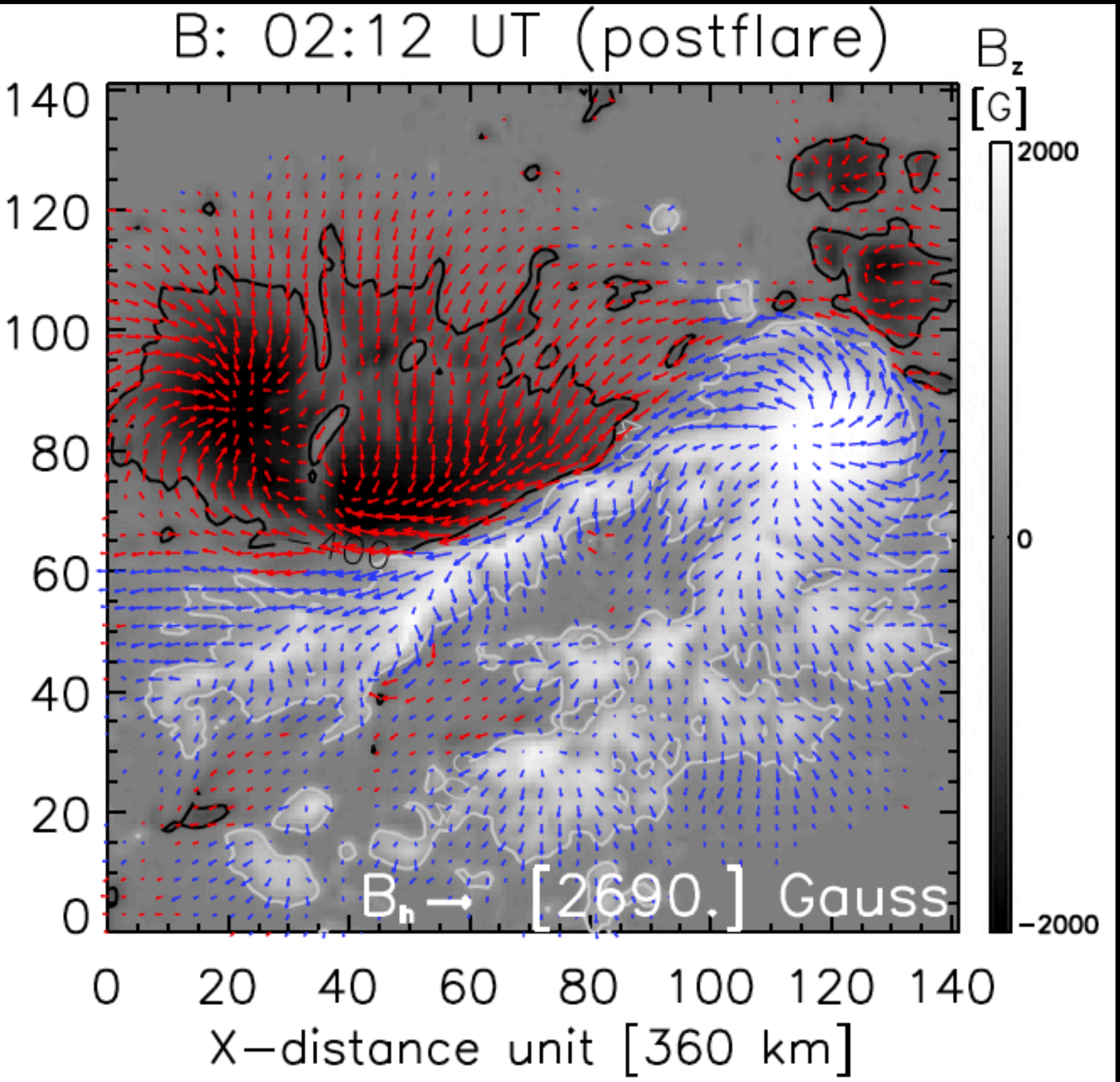

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$$J_z(x, y, t) = \frac{1}{\mu_0} \nabla \times B_h$$

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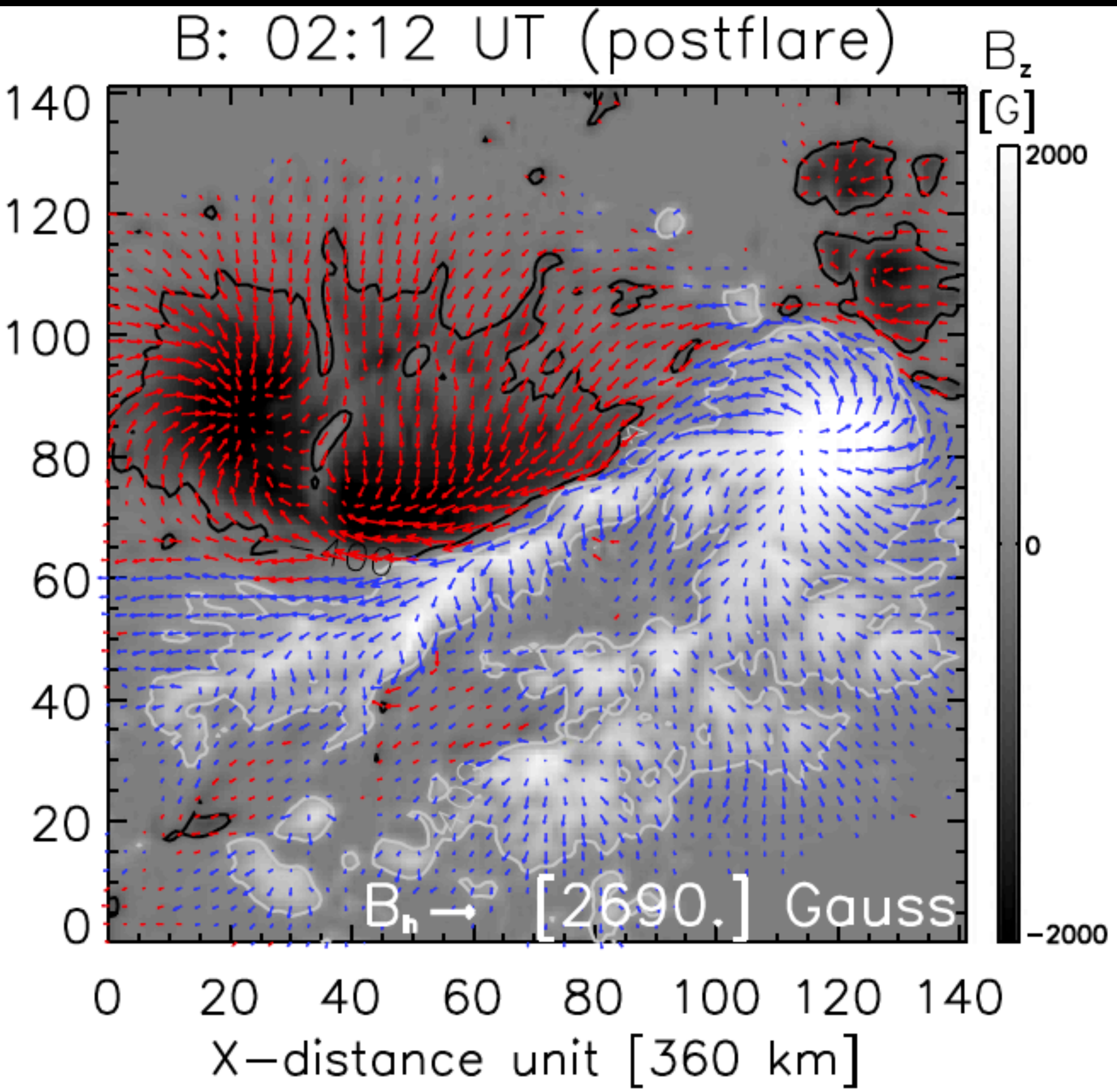

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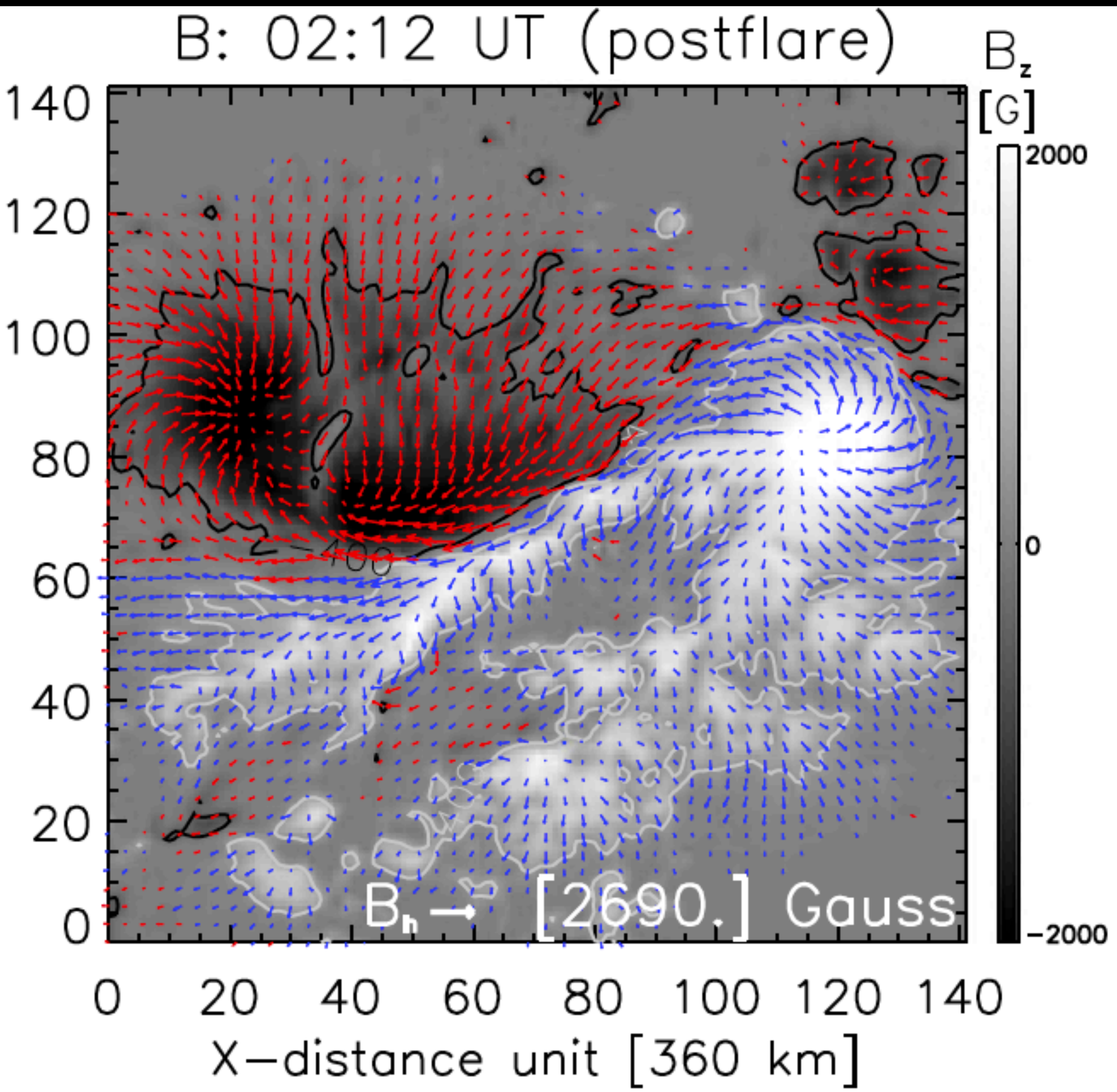

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Electric field

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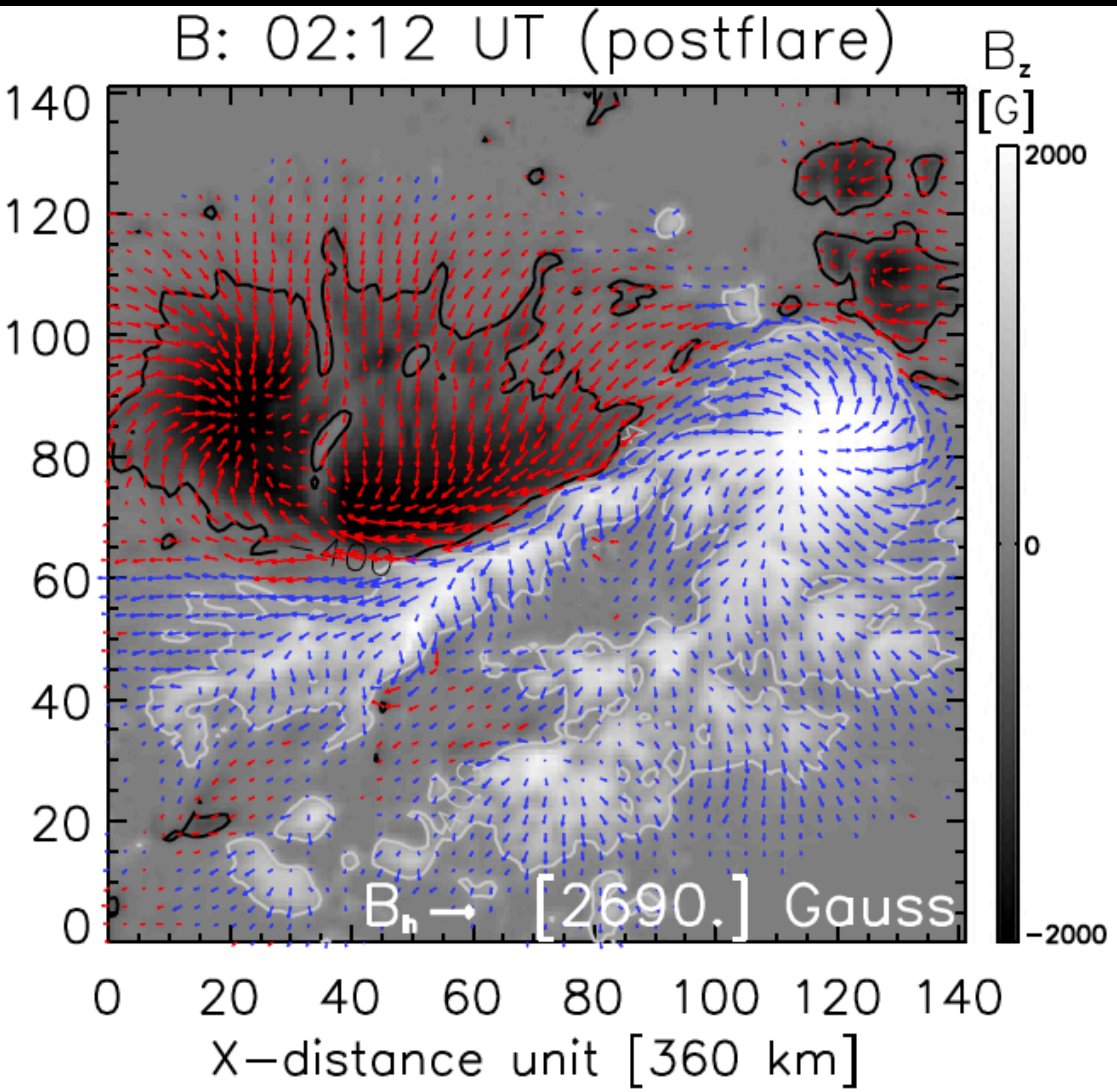
What can we get from $B=(B_x,B_y,B_z)$?



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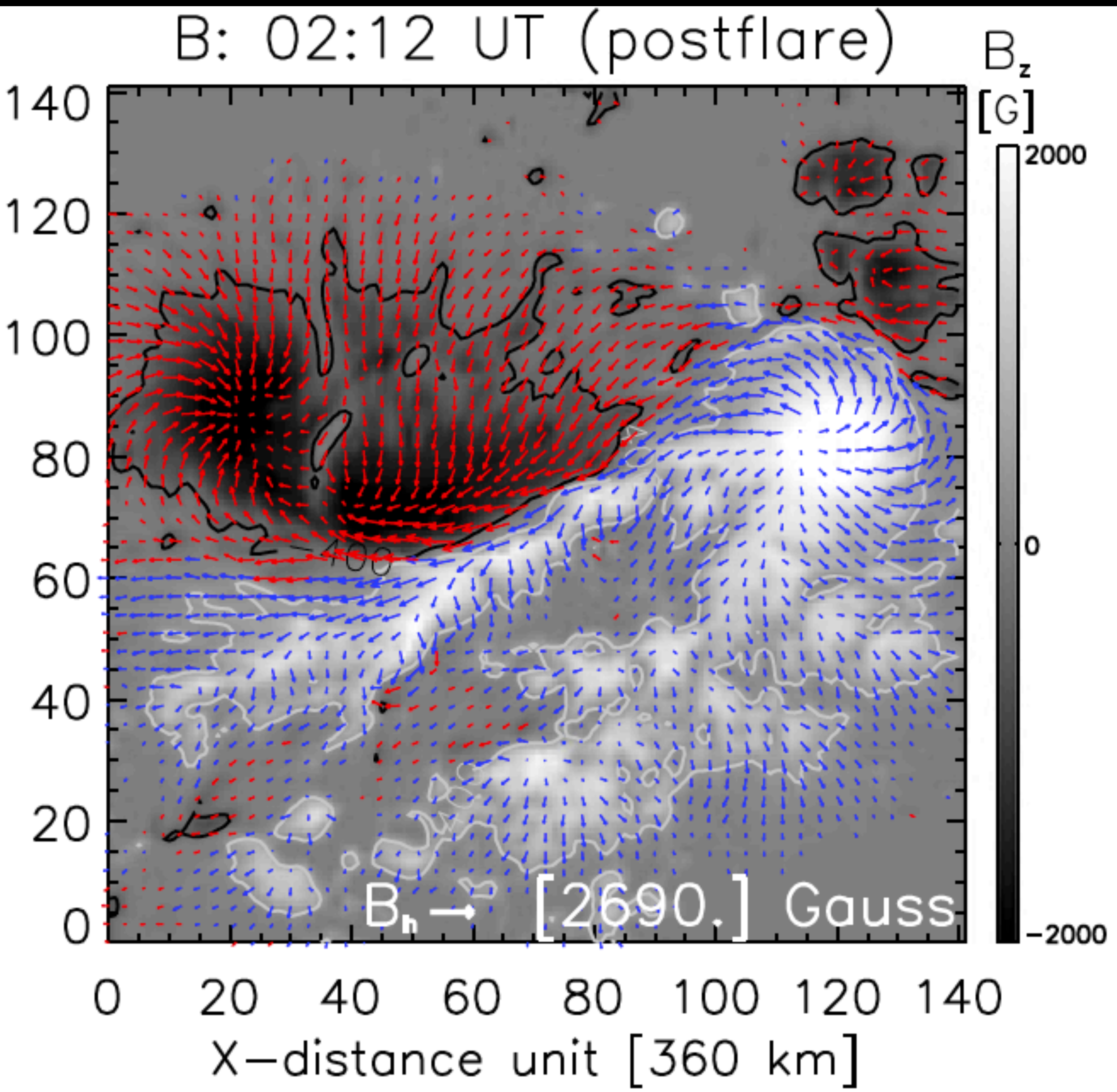

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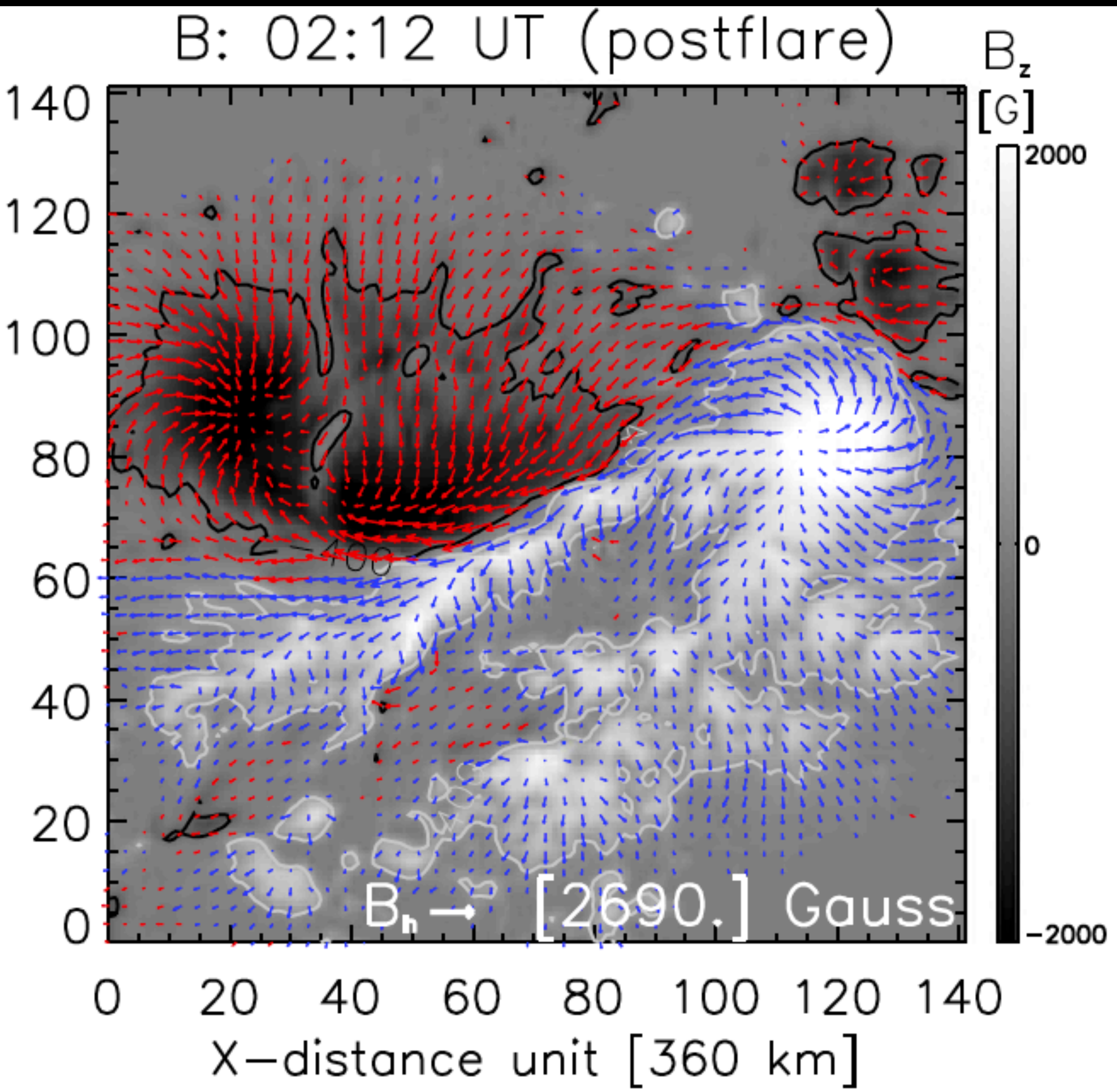
Helicity flux

$$\left(\frac{dH_R}{dt}\right) = -2 \int (\mathbf{A}^{\mathrm{P}} \times \mathbf{E}) \cdot \hat{z} \, da$$

Magnetic shear

What can we get from $B=(B_x,B_y,B_z)$?



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Lorentz force

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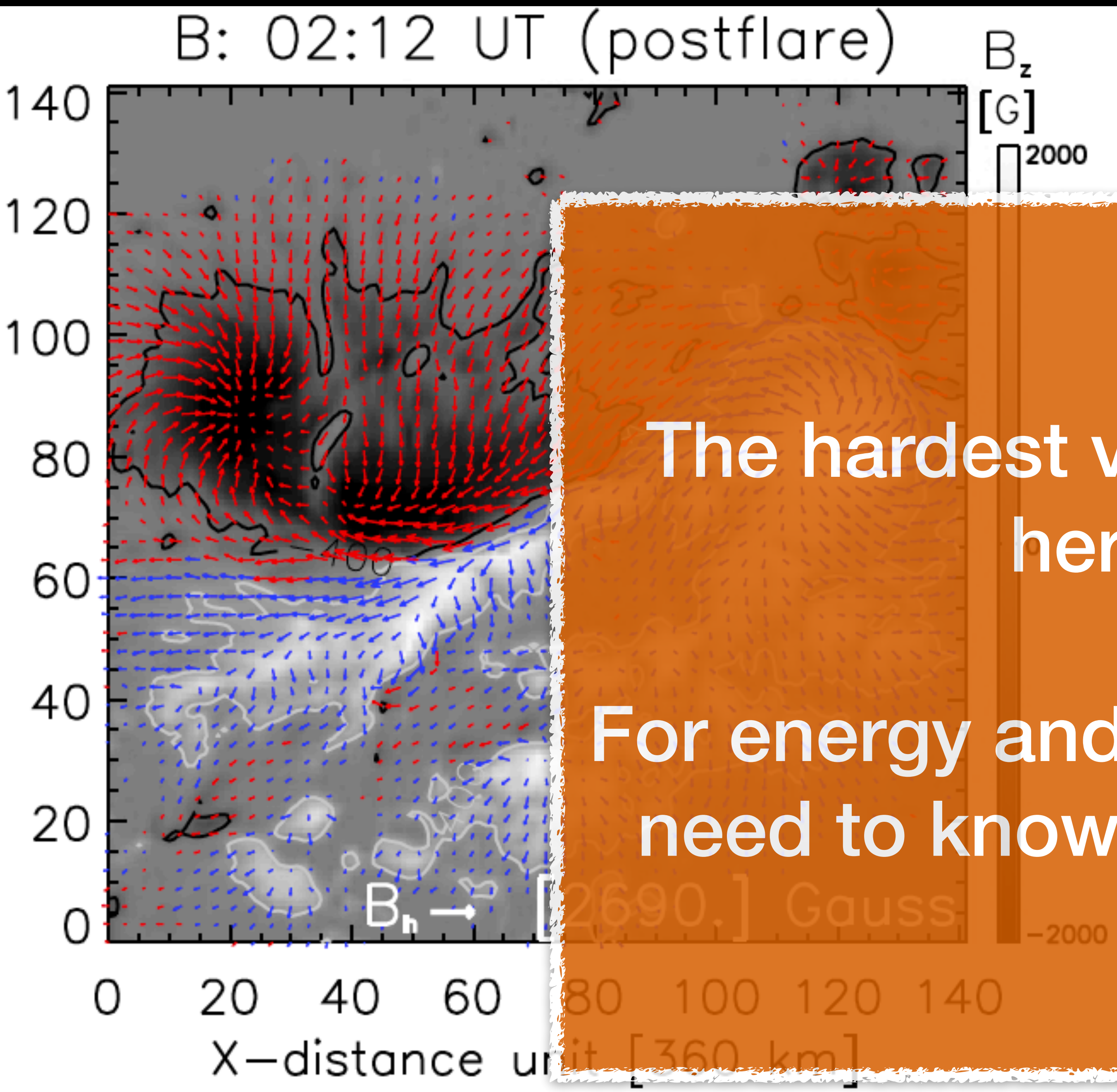

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The hardest variable to derive here is E.

For energy and helicity fluxes we need to know electric fields E;

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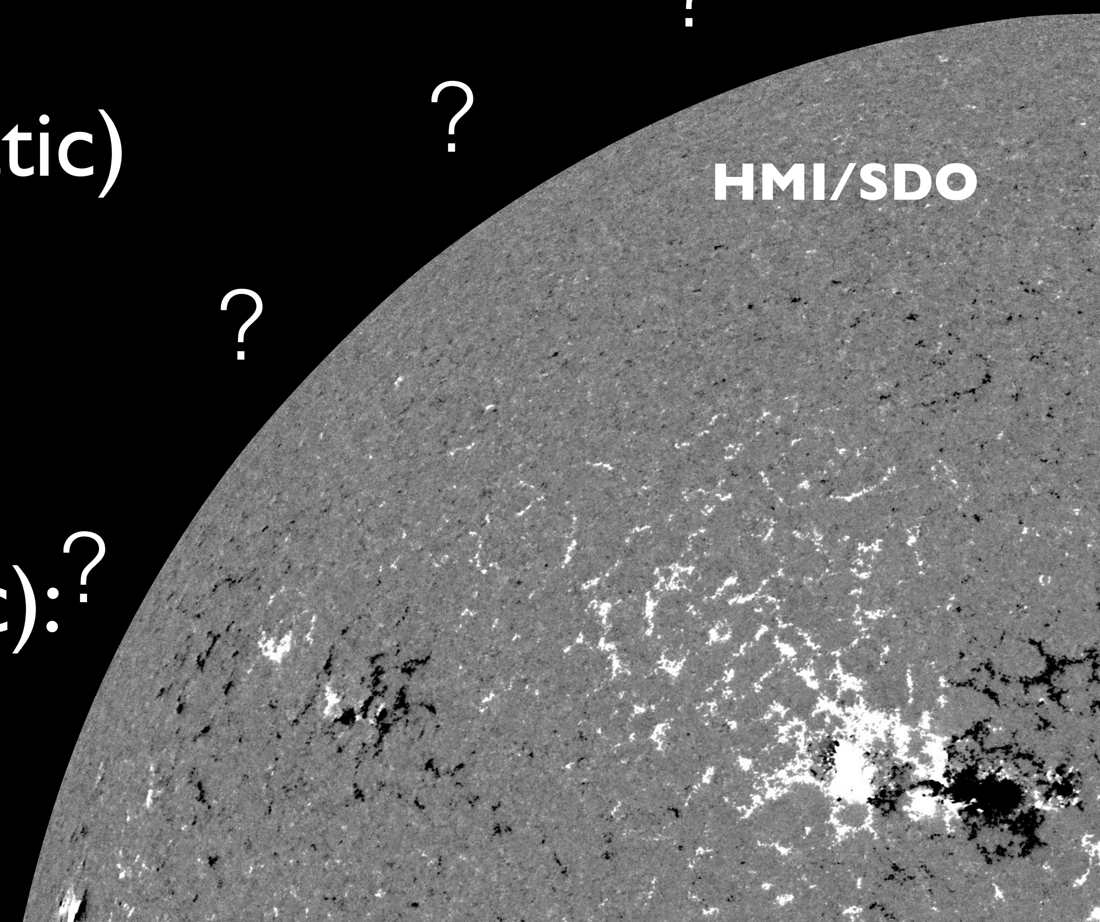
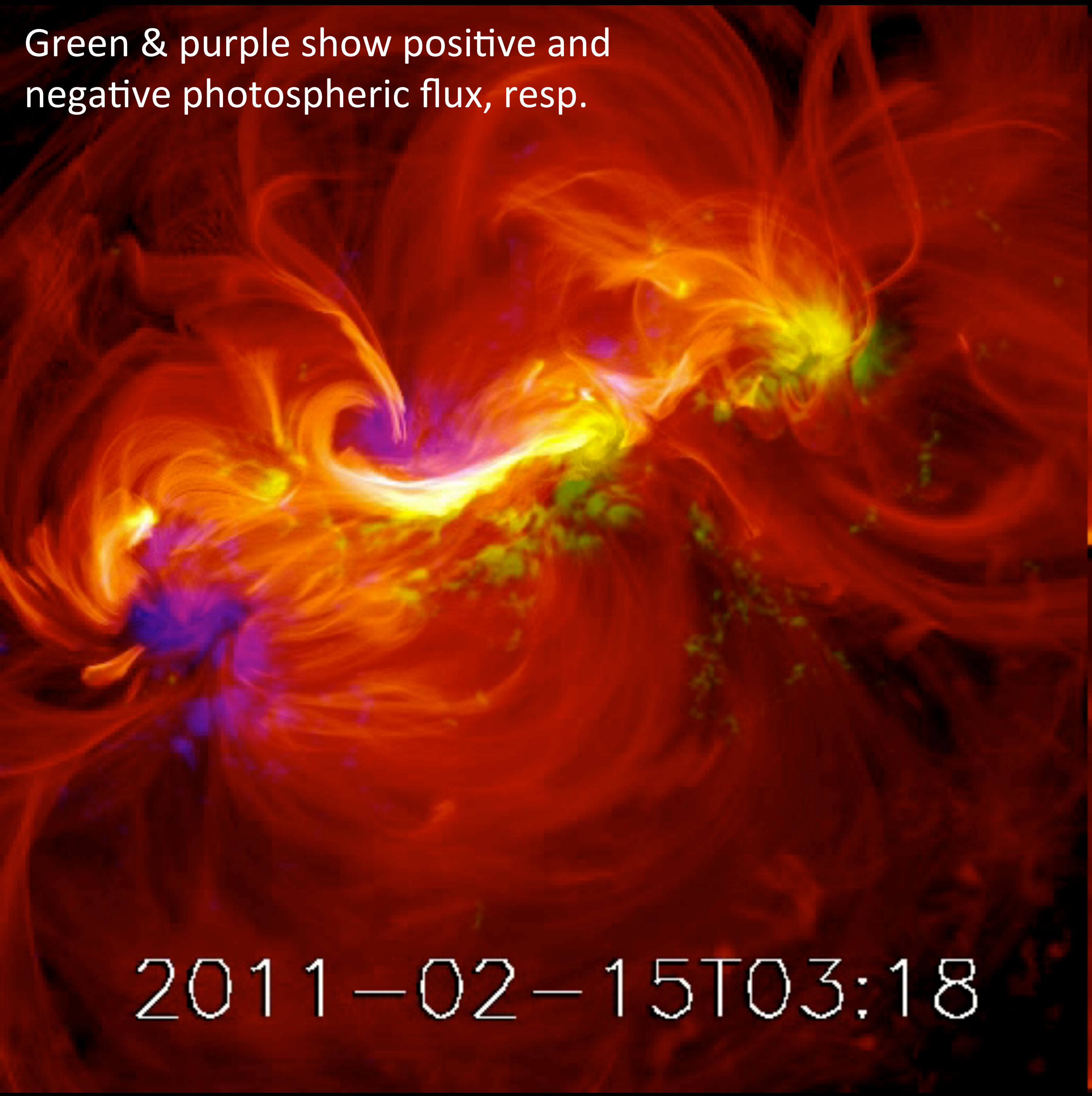
What else can we get from $B=(B_x,B_y,B_z)$?

- Magnetic fields at the photosphere could be used to improve forecasting of solar flares

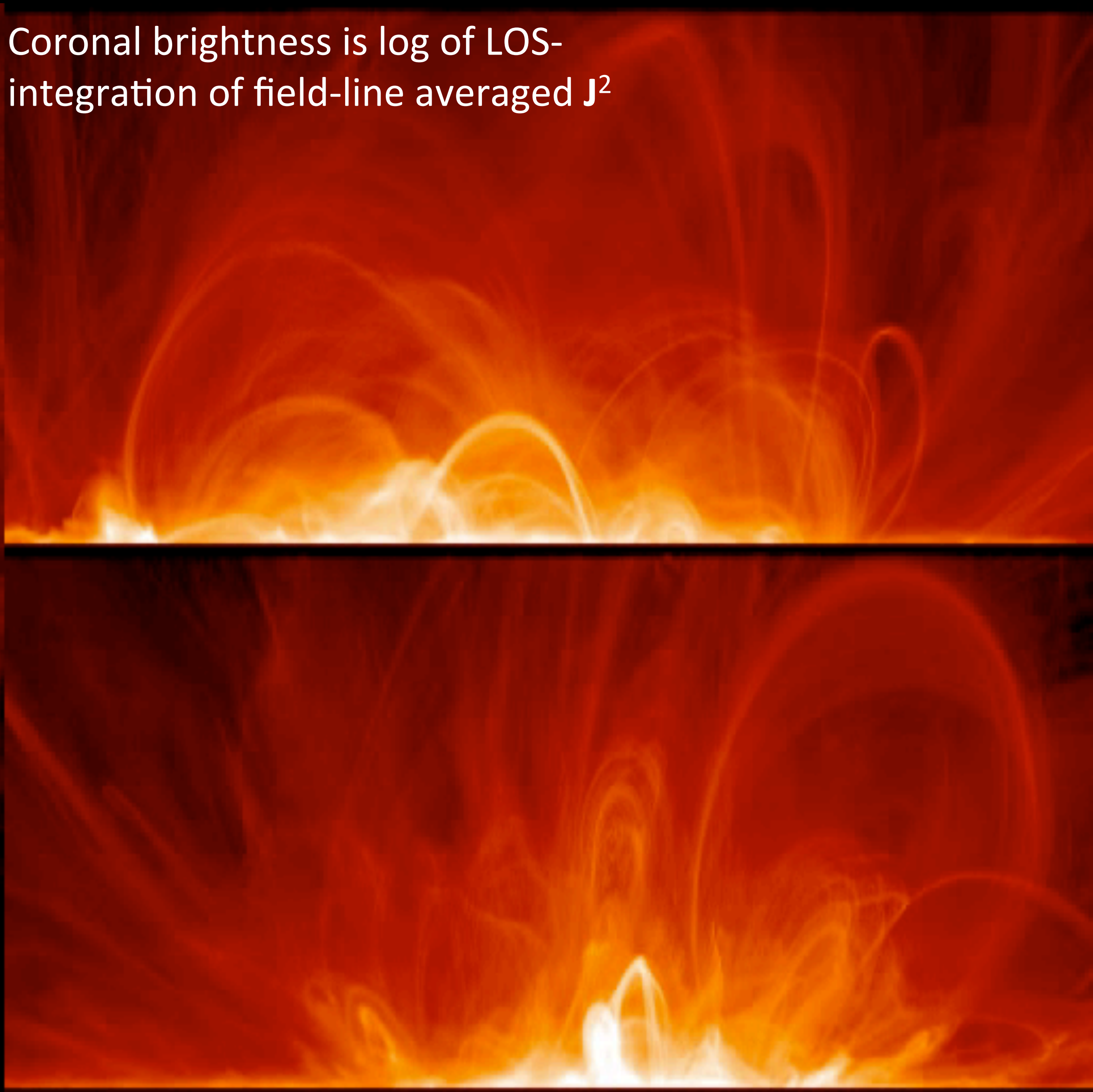
- Magnetic fields at the photosphere could be used to find magnetic fields above in the corona:
  - Potential field extrapolations (static)
  - Non-linear force-free fields extrapolations (static)
  - Data-driven simulations (dynamic): force-free of full MHD



Example Coronal Field Model of AR 11158
Driven by Photospheric **B** and derived **E**



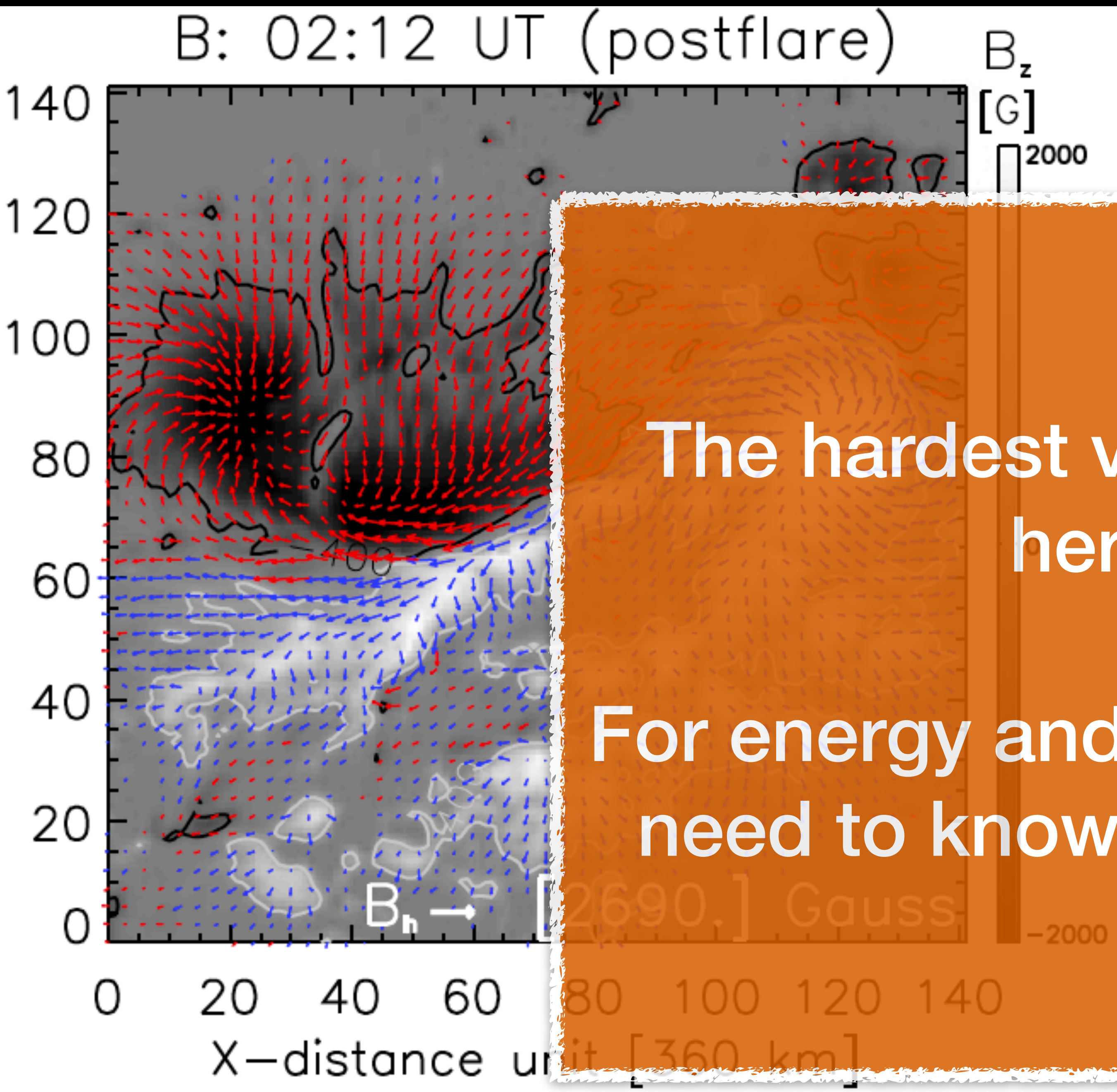
Green & purple show positive and negative photospheric flux, resp.



Coronal brightness is log of LOS-integration of field-line averaged $\mathbf{J}^2$

Courtesy Mark Cheung and the Coronal Global Evolutionary Model Team

What can we get from $B=(B_x,B_y,B_z)$?



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Helicity flux

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Magnetic shear

Lorentz force

Finding Electric Fields is Hard. Why?

- Directly measure from Stark Effect? Hard!

  Wien(1916) … Foukal & Behr (1995). Some planned efforts with DKIST.

- Find E from V (horizontal velocity). Possible!
  - From Ideal MHD: **E=-VxB.**
  - But then, how to find V?
- From Faraday's Law $$\frac{\partial B}{\partial t} = -(\nabla \times cE),$$

Today we will review earliest electric field inversion methods

- Non-inductive or Tracking approaches to find V: Local Correlation Tracking (LCT, November & Simon 1988), Fourier Local Correlation Tracking (FLCT, Fisher & Welsch 2008).

- First methods that implements some form of induction equation (inductive approach): Minimum energy fit (MEF, Longcope 2004), DAVE (Schuck 2006),
$$\frac{\partial \boldsymbol{B}}{\partial t} = -(\nabla \times c\boldsymbol{E}),$$

- Comparison of early methods before we had routine vector magnetogram measurements: Welsch et al. 2007.

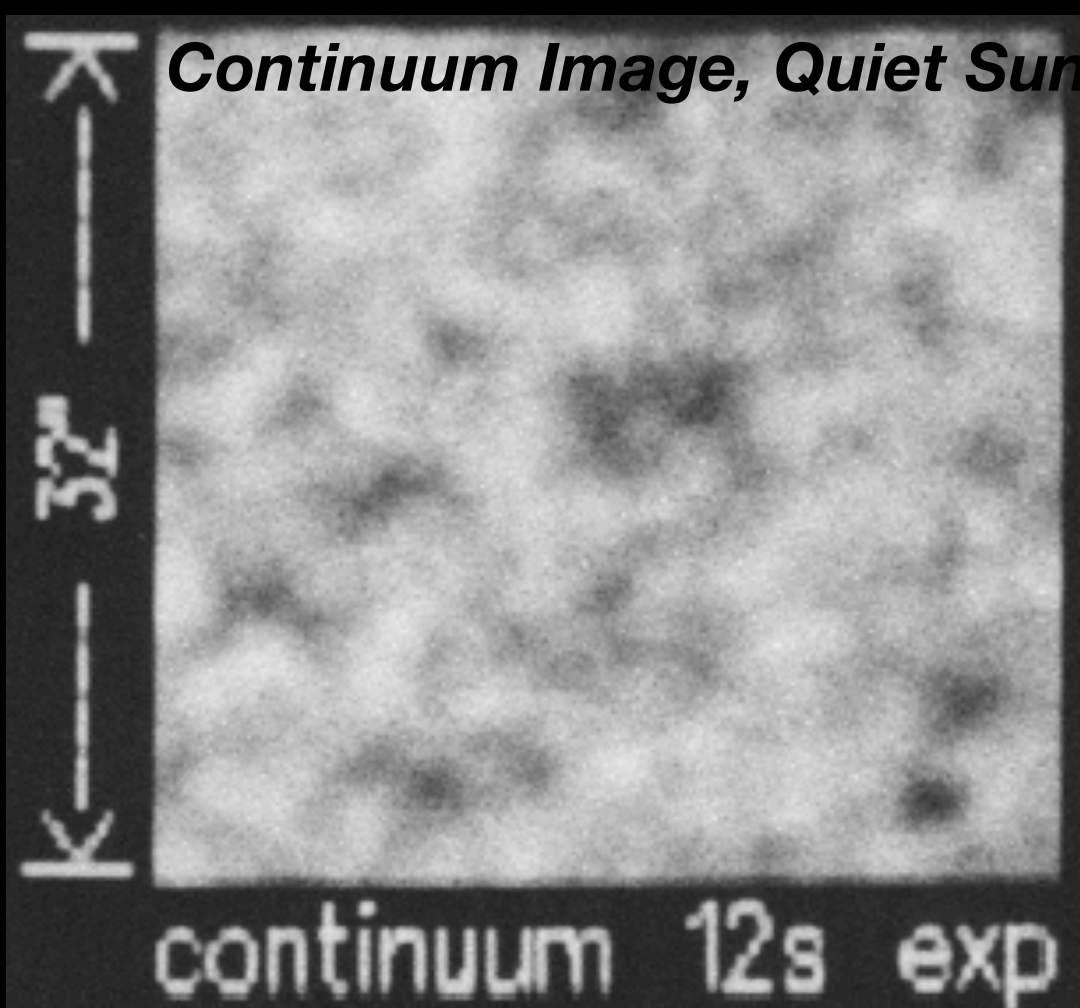
Local Correlation Tracking (LCT)

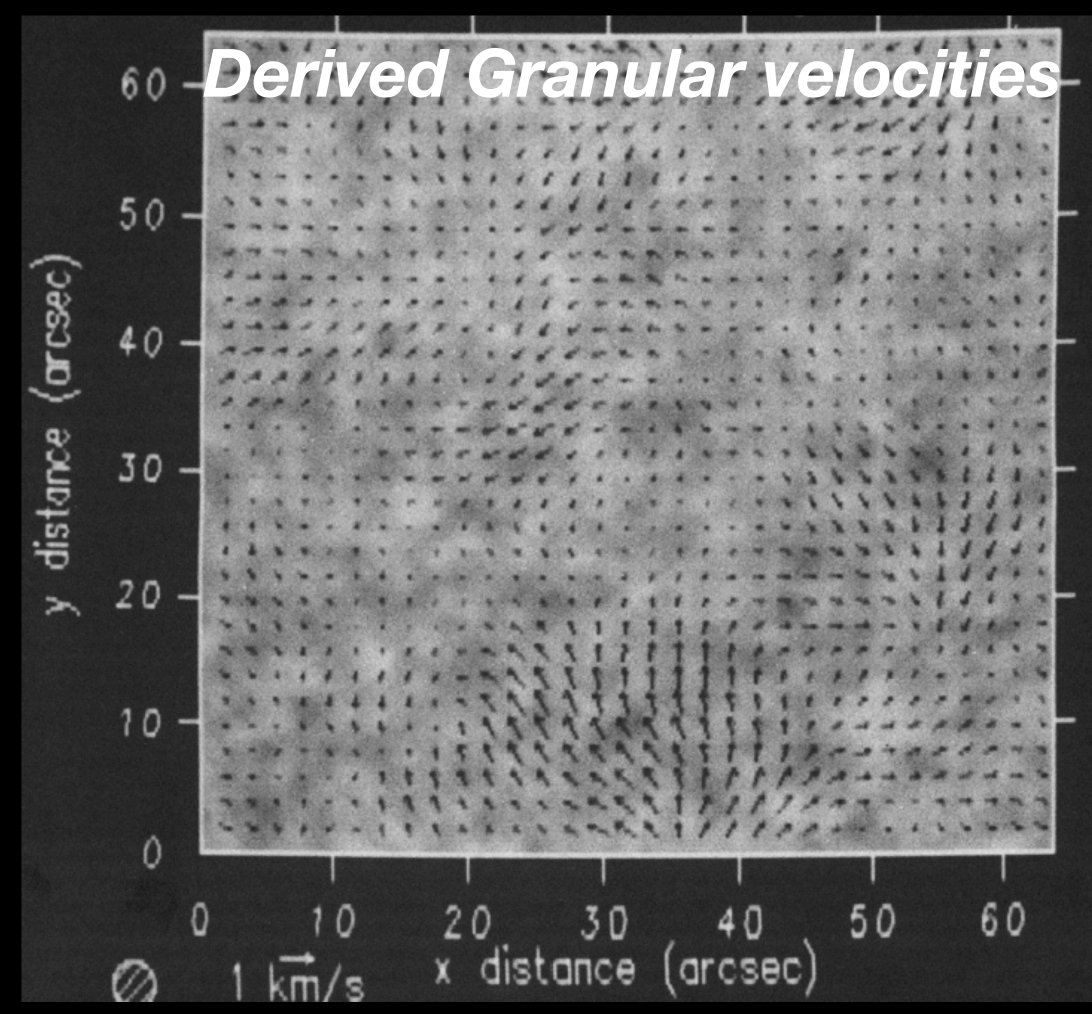
- <u>November & Simon, 1988:</u> introduced Local Correlation Tracking in Solar Physics; minimizes the merit function M to find relative displacement dx b/w I_1 and I_2 images:

$$M(\delta \mathbf{x}_i) = \sum_{p=-s}^{+s} \sum_{q=-s}^{+s} \left\{ W(p,q) \left[I_1\left(x_i + p + \frac{\delta x_i}{2}, y_i + q + \frac{\delta y_i}{2}\right) - I_2\left(x_i + p - \frac{\delta x_i}{2}, y_i + q - \frac{\delta y_i}{2}\right) \right]^2 \right\},$$

where W - apodizing function (gaussian) which weights pixels closer to x_i more heavily in the sum.

- Used white light observations of solar granulation, L=80min: Sacramento Peak Vacuum Tower Telescope to derive granular velocities;
- **<u>Results</u>**: Solar mesogranulation and super-granulation flows of 10”-40” spatial scales



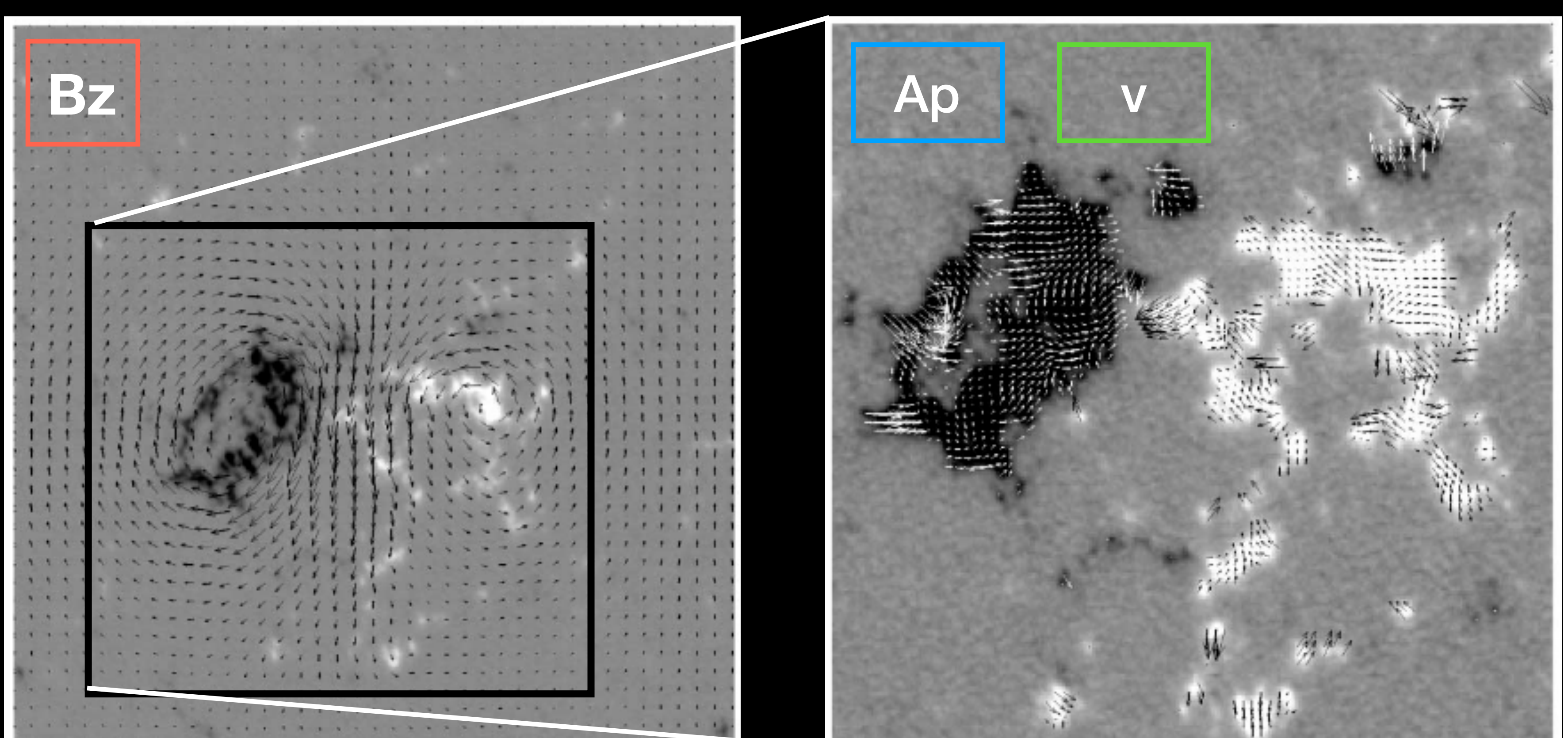


LCT: first application to a large dataset

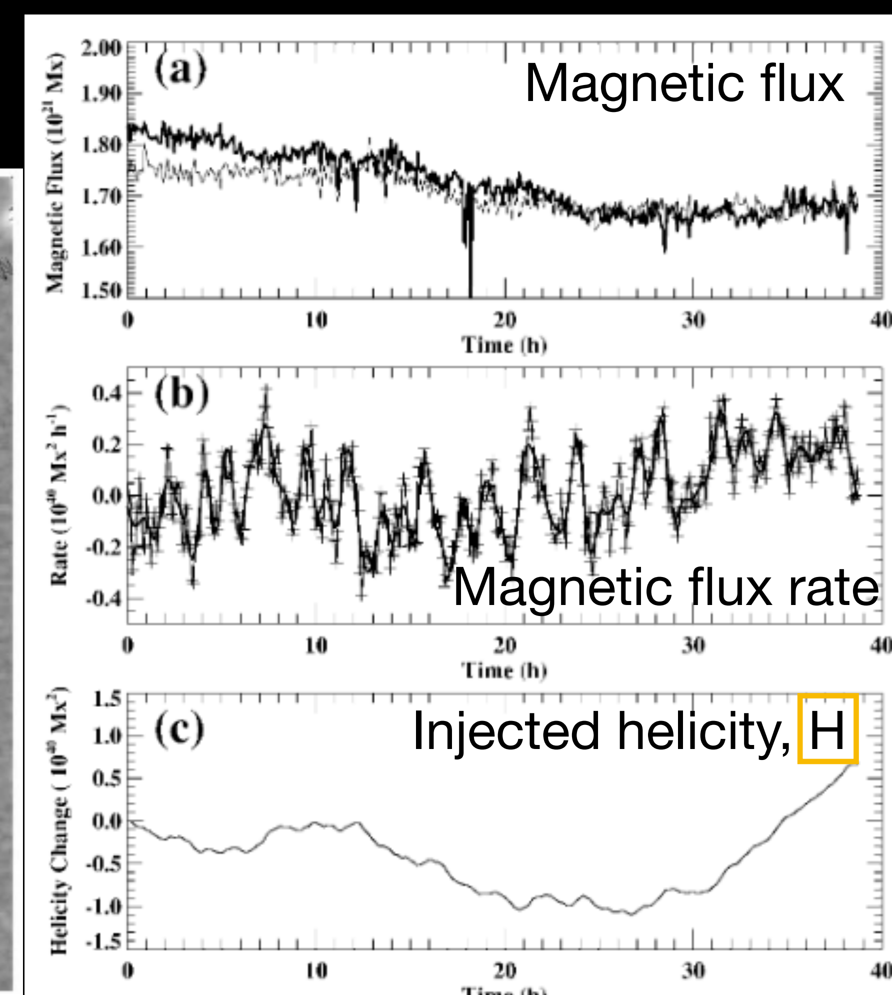
- Chae 2001: First application of LCT to MDI/SOHO LOS magnetograms;
- L=40 hrs, AR 8011, dt=96 min; ds=720km;
- Results: found rate of magnetic helicity injection to better understand role of photospheric flows in the evolution of coronal magnetic fields in solar ARs:

$$\frac{dH}{dt} = \oint 2(\boldsymbol{B}\cdot\boldsymbol{A}_p)v_z\, dS + \oint -2(\boldsymbol{v}\cdot\boldsymbol{A}_p)B_z\, dS,$$

emergence term *shear term*

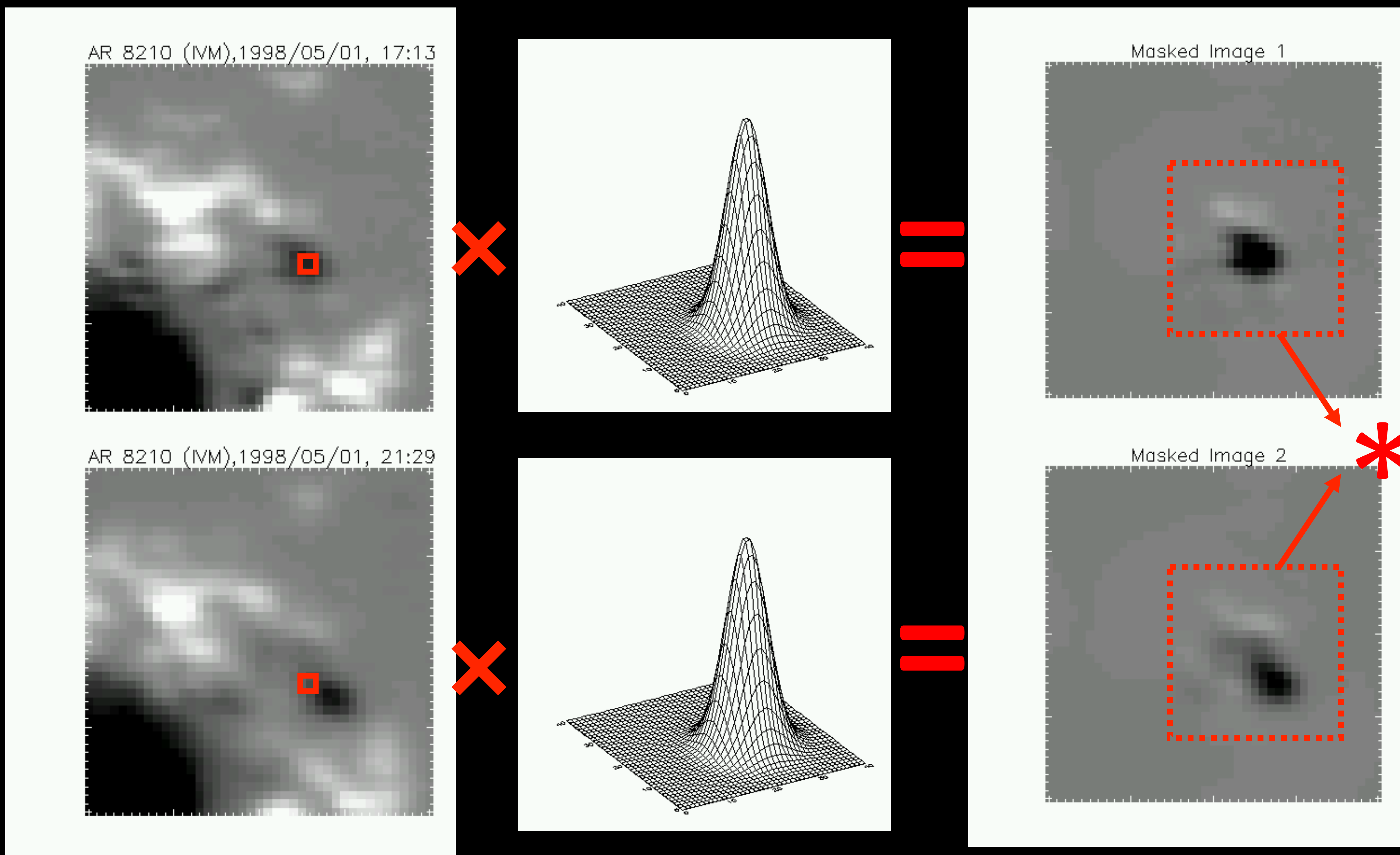


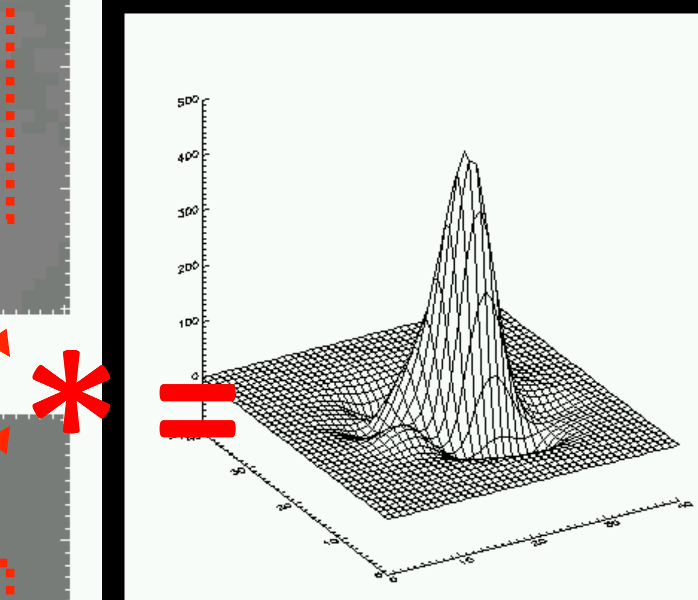
LOS B and vector potential Ap *Derived horizontal velocities*



Fourier Local Correlation Tracking (FLCT)

Welsch et al. 2004: FLCT method finds horizontal velocity V(x,y) by correlating subregions, to find local shifts:





1) For each (x_i,y_i) above $|B|_{threshold}$

2) Apply Gaussian mask at (x_i,y_i)

3) Truncate and cross-correlate in Fourier space

4) $\Delta x\ (x_i,y_i)$ is interpolated max. of correlation function

Today we will review earliest electric field inversion methods

Main Problem: derived horizontal velocity, V, is not necessarily physical

- Non-inductive or Tracking approaches to find V: Local Correlation Tracking (LCT, November & Simon 1988), Fourier Local Correlation Tracking (FLCT, Fisher & Welsch 2008).
- First methods that implements some form of induction equation (inductive approach): Minimum energy fit (MEF, Longcope 2004), DAVE (Schuck 2006),

$$\frac{\partial \boldsymbol{B}}{\partial t} = -(\nabla \times c\boldsymbol{E}),$$

- Comparison of early methods before we had routine vector magnetogram measurements: Welsch et al. 2007.

First inductive method (IM)

Kusano et al. 2002: assume ideal induction eq. $\frac{\partial \boldsymbol{B}}{\partial t} = -c(\nabla \times \boldsymbol{E}) = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}),$

1) Use B_z observations and LCT method => Vh;

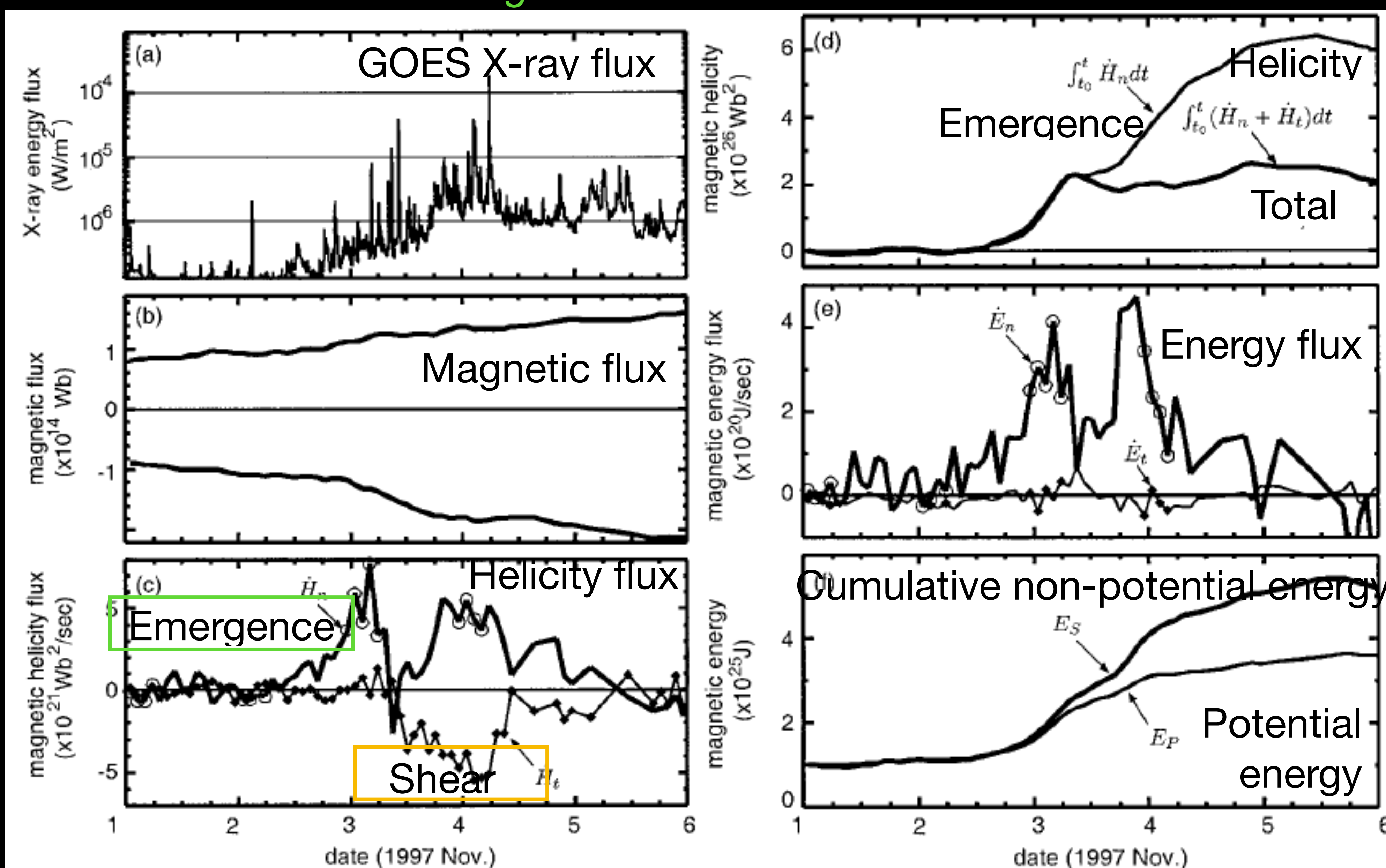
2) Use B_z, B_h, V_h & $\frac{\partial B_z}{\partial t} = \hat{\boldsymbol{z}} \cdot \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = -\nabla \cdot (\boldsymbol{v}_h B_z - v_z \boldsymbol{B}_h),$ => V_z

- Problems: Not defined in areas where $B_h = 0$.

First inductive method (IM): application

- Kusano et al. 2002: Applied to AR 8100, 1997 Nov 1, B_z from MDI/ SOHO and **B** from vector magnetograph, NAOJ;
- Results: shear and emergence terms are equally important;

$$\frac{dH}{dt} = \underbrace{\oint 2(\boldsymbol{B}\cdot\boldsymbol{A}_p)v_z\, dS}_{\text{emergence term}} + \underbrace{\oint -2(\boldsymbol{v}\cdot\boldsymbol{A}_p)B_z\, dS}_{\text{shear term}},$$



Inductive LCT Method (ILCT)

- Welsch et al. (2004) showed that FLCT flows only approximately reproduce observed dB_z/dt.
- As an alternative they suggested to use decomposition

$$\mathbf{u}B_z = -\nabla_h \chi + \nabla_h \times \psi \mathbf{z}$$

$$\frac{dB_z}{dt} = -\nabla \cdot (\mathbf{V_h} B_z - V_z \mathbf{B_h}) = -\nabla \cdot (\mathbf{u} B_z) = -\nabla \cdot (-\nabla_h \chi + \nabla_h \times \psi \mathbf{z})$$

Then χ is defined by solving Poisson equation and ψ is defined by LCT speed assuming $\mathbf{u}=\mathbf{u}^{(\mathbf{LCT})}$.

Assuming $\mathbf{V_{perp}} \cdot \mathbf{B} = 0$ we can find $\mathbf{V_{perp}}$.

Other inductive methods

- Longcope (2004): Minimum energy fit (MEF): finds smallest plasma velocities consistent with magnetograms and magnetic induction equation

- Schuck (2006): Building on differential LCT introduced differential affine velocity estimator (DAVE); finds optical flow field that is statistically consistent with the magnetic induction equation and the affine velocity profile within the window aperture (varying window size);

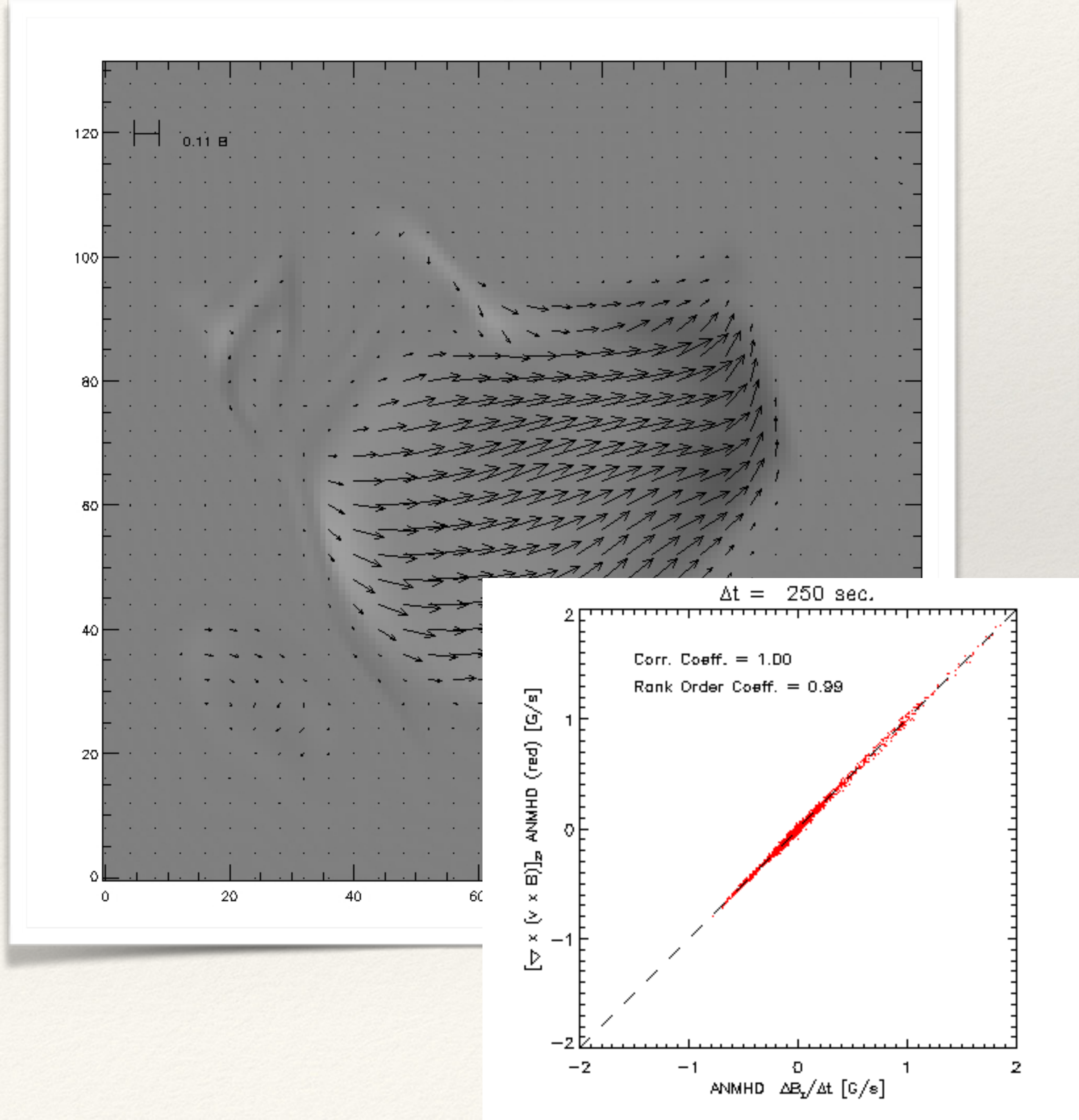
- Georgoulis & LaBonte (2006): minimum structure reconstruction method (MSR); Uses inductive and electrostatic potential decomposition;

- For excellent reviews of different methods see Welsch et al. (2007), Schuck (2006);

Accuracy of Velocity Estimates

- Welsch et al. (2007) conducted quantitative tests of accuracy using several available methods.
- They created "synthetic magnetograms" from ANMHD simulations of a bipolar magnetic region rising through a convecting medium.
- In these data, both **V** & **B** are known exactly.
- They verified that the ANMHD data were consistent with

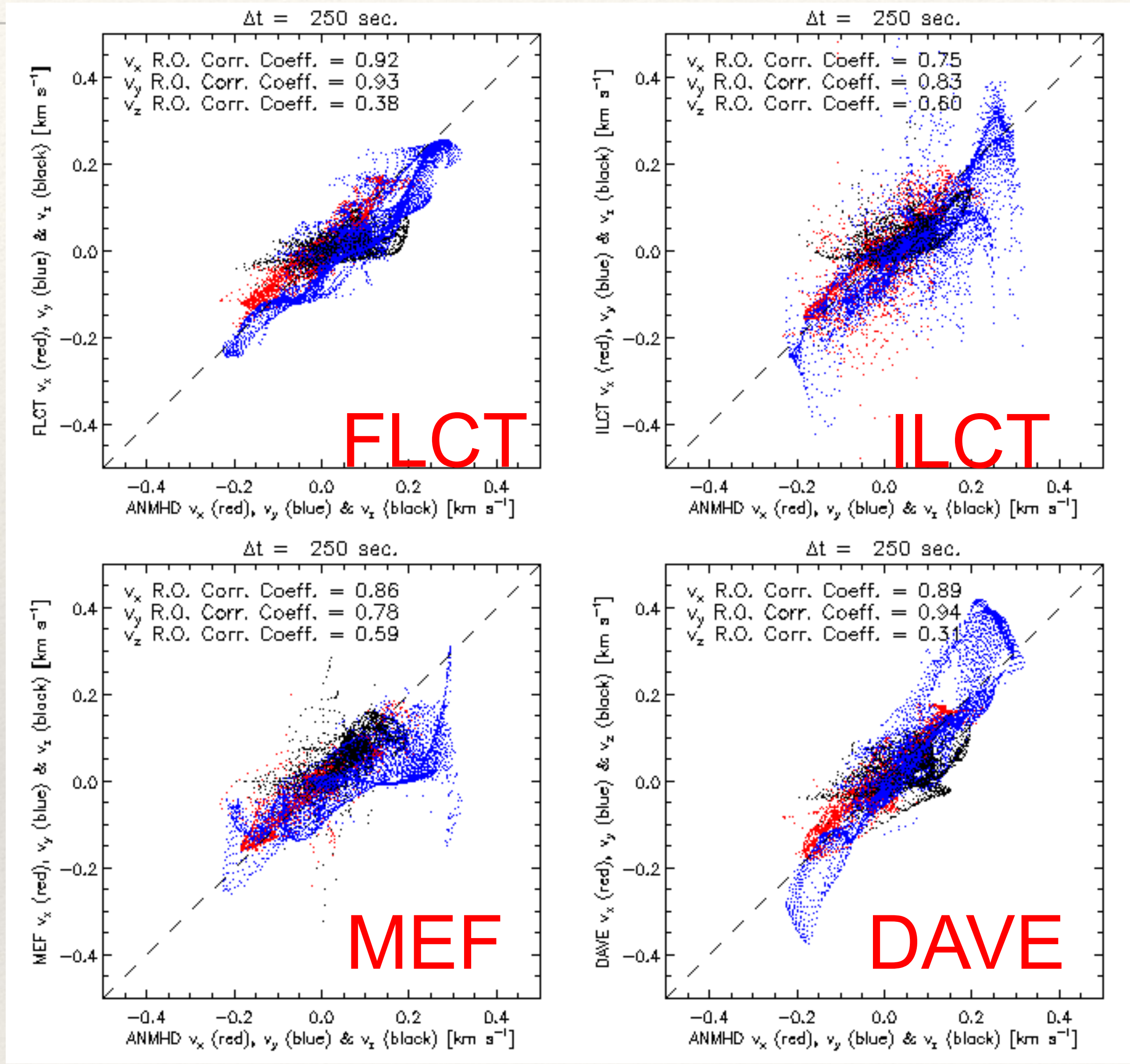
$$\partial_t B_n = \nabla \cdot (V_n \mathbf{B_{hor}} - \mathbf{V_{hor}} B_n)$$



Accuracy of Velocity Estimates

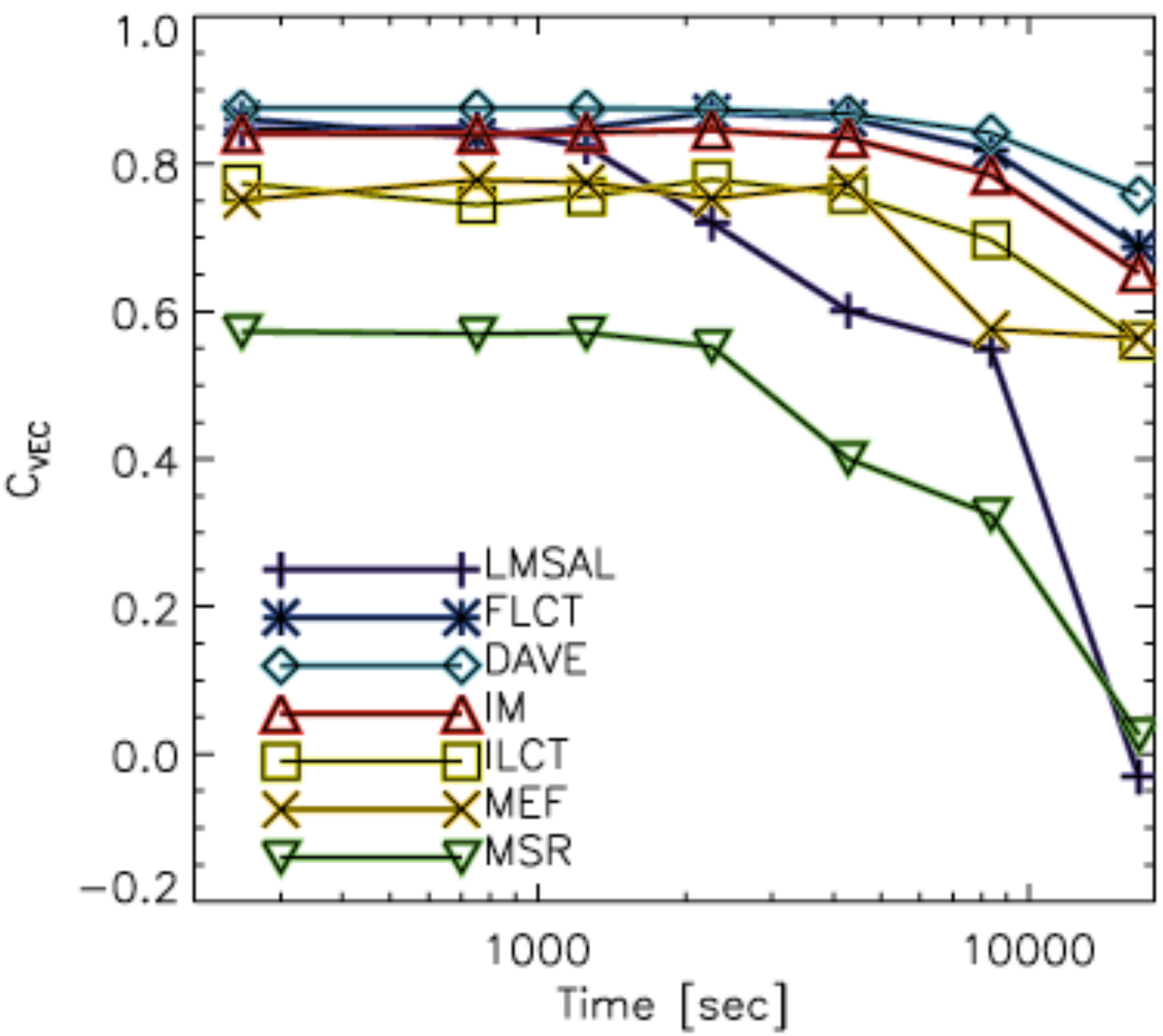
Here, I show representative results from just a few of the methods tested:

- Fourier LCT (FLCT, Welsch et al. 2004)
- Inductive LCT (ILCT, Welsch et al. 2004)
- Minimum Energy Fit (MEF, Longcope 2004)
- Differential Affine Velocity Estimator (DAVE, Schuck 2006)

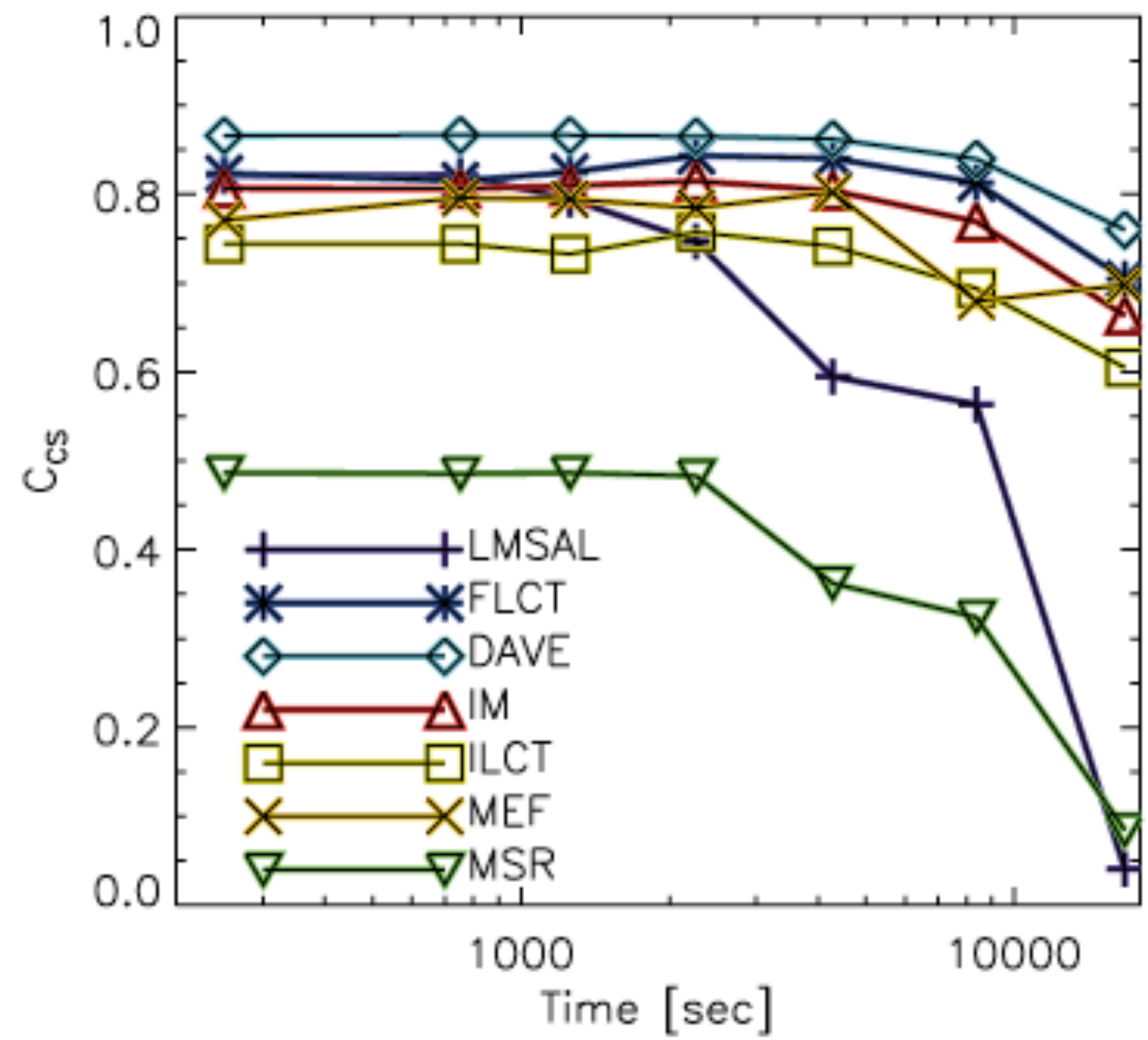


Comparison of actual ANMHD and derived velocity estimated using FLCT, ILCT, MEF, DAVE.

Comparison of different methods using ANMHD test case: velocity comparison



Vector correlation for varying cadence

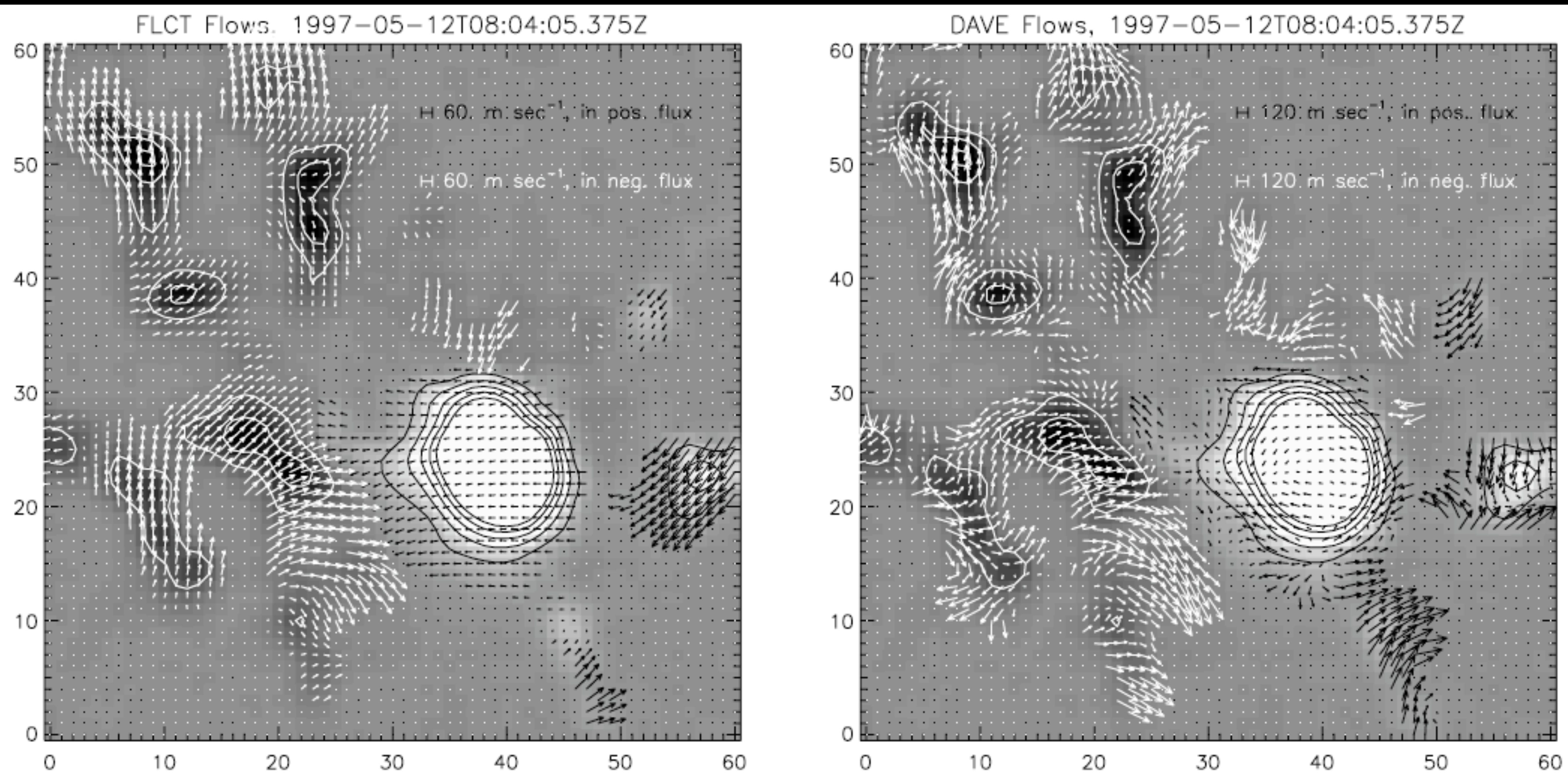


Direction correlation for varying cadenc

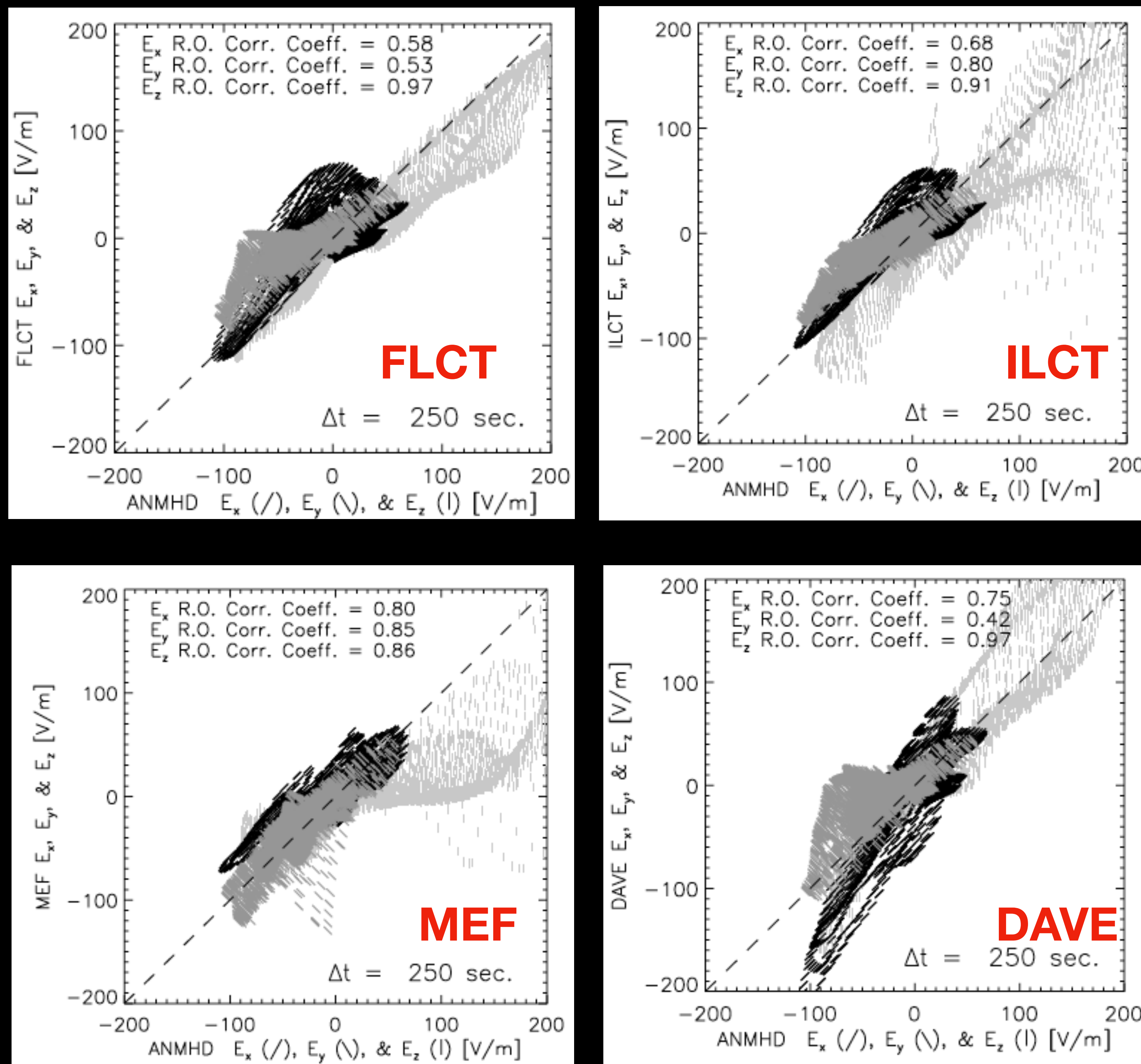
<u>Velocity reconstruction</u>: all methods did poorly, IM, FLCT, and MEF performed similarly; DAVE did slightly better;

Welsch et al. 2007

Real magnetogram: Sample maps of FLCT and DAVE flows show them to be strongly correlated, but far from identical.

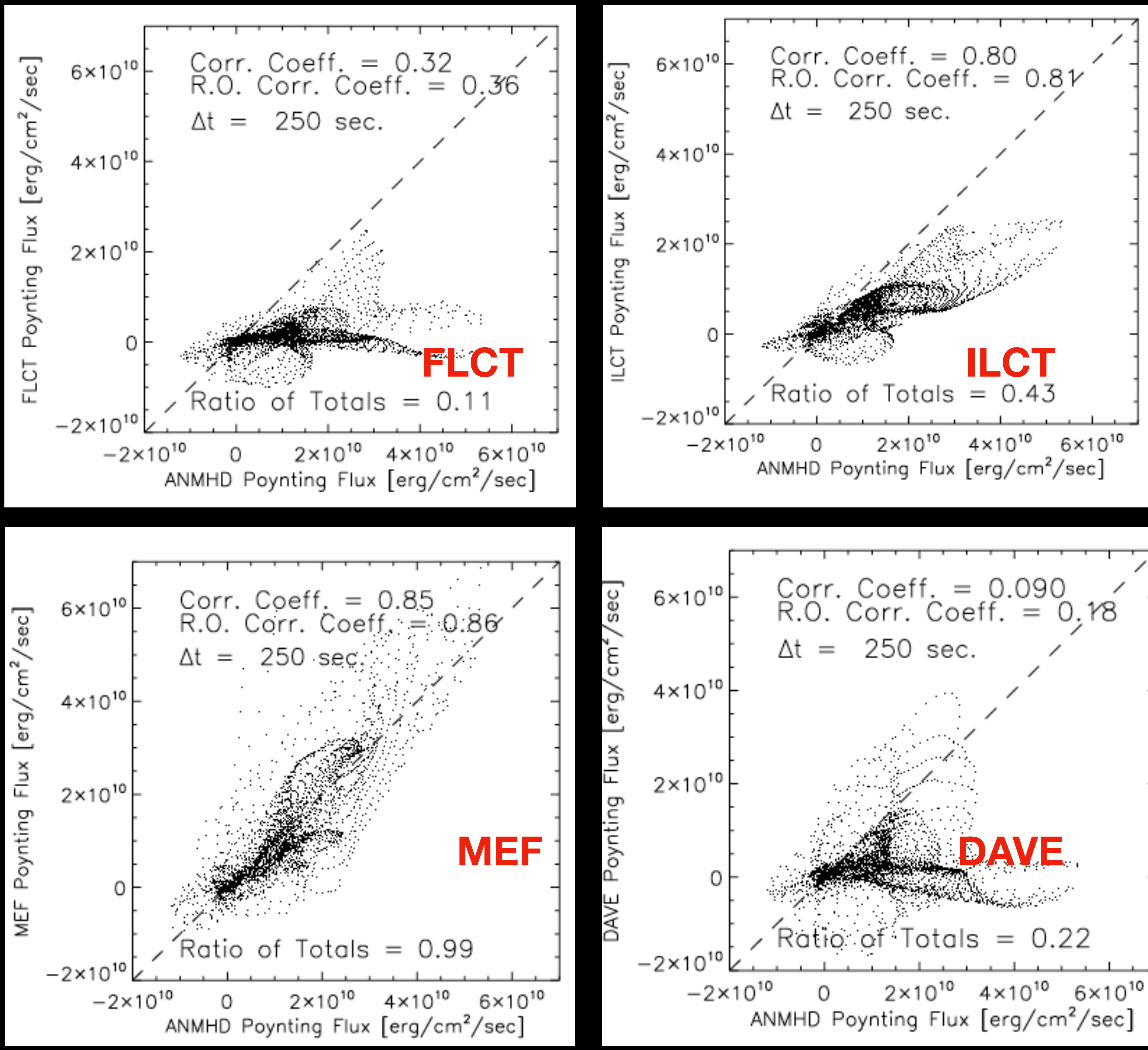


Comparison of different methods using ANMHD test case: electric fields comparison



- <u>Electric fields:</u> DAVE, FLCT, ILCT, MEF did OK.

Comparison of different methods using ANMHD test case: Poynting flux comparison



- <u>Energy and helicity fluxes:</u> MEF was the best; could be because it is most suitable physically to ANMHD test case.

Comparing performance of FLCT, DAVE, ILCT, MEF, IM etc (from Welsch et al. 2007): Summary

- Velocity reconstruction: all methods did poorly, IM, FLCT, and MEF performed similarly; DAVE did slightly better;

- Electric fields: DAVE, FLCT, ILCT, MEF did OK.

- Energy and helicity fluxes: MEF was the best; could be because it is most suitable physically to ANMHD test case.

So which inversion should we use to get horizontal velocity V or E?

Most of the described methods only used **one component of B, B_R** and the normal component of induction equation to find horizontal velocity:

$$dB_z/dt = -c[\nabla_h \times E_h]_z = [\nabla \times (v \times B)]_z$$

Now with routine vector and Doppler velocity field measurements we could solve **vector B** and induction equation:

$$dB/dt = -c[\nabla \times E] = [\nabla \times (v \times B)]$$

- Examples of methods that use vector magnetic fields:
  - DAVE4VM (Schuck et al. 2008)
  - PDFI (Fisher et al. 2020, Kazachenko et. al. 2014).

Summary

- Today we learnt: Why Magnetic Fields (**B**) on the Sun Are Important? Where can we presently routinely measure magnetic fields on the Sun? What can we get from **B**? Finding E (or V) from **B**: Tracking & Inductive methods.

- Next Tuesday: we will learn how one could derive velocity fields in the solar photosphere using vector **B and** more recent methods: DAVE4VM, PDFI and also some ML methods. I will show examples of their application to HMI data.

- Next Thursday: hands-on activity: applying FLCT to a sequence of HMI/SDO magnetograms to derive horizontal velocities, magnetic fluxes, helicity and energy fluxes.