The Importance of Vector Magnetic Fields in Quantitative Studies of Solar Evolution

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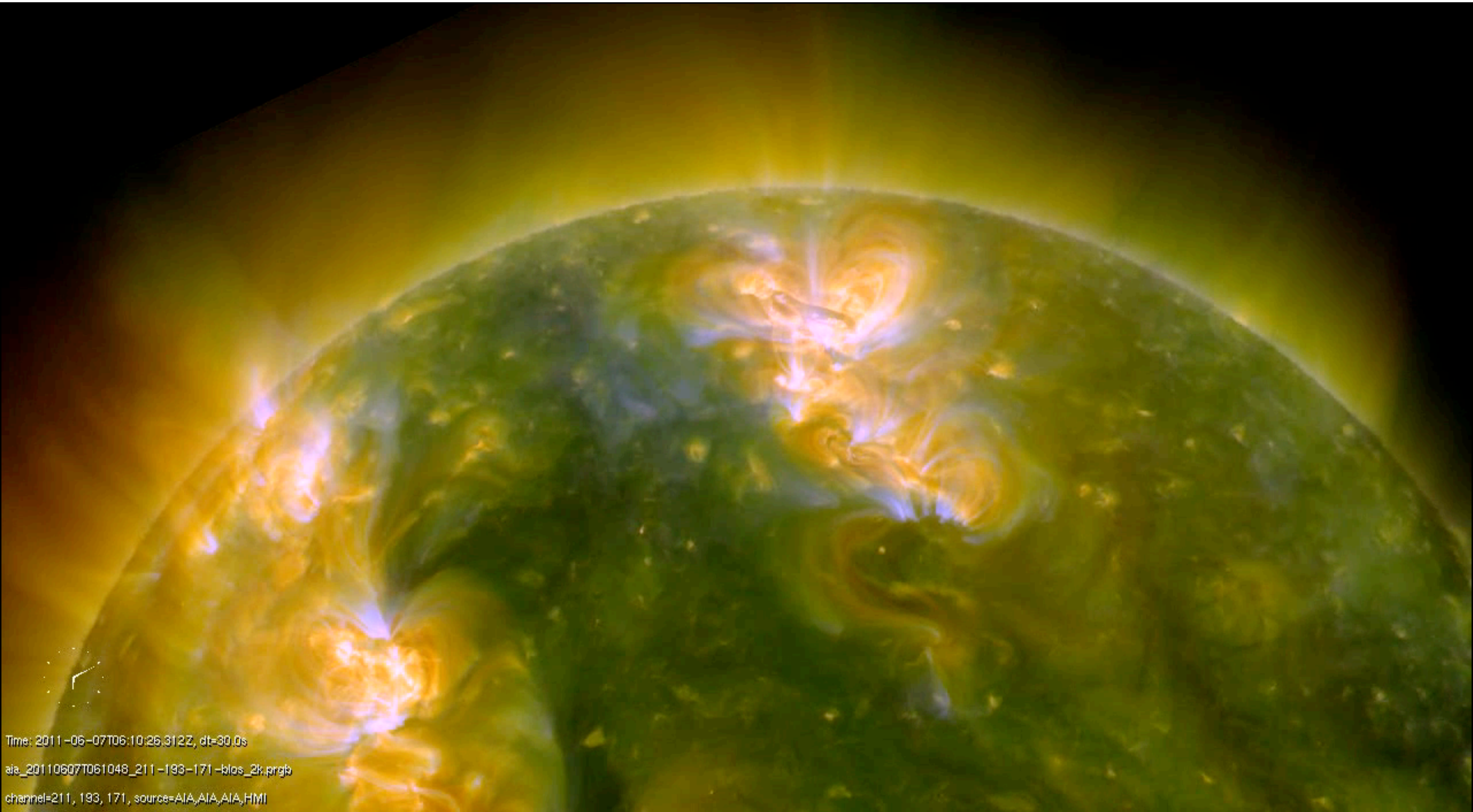
the CGEM Team

http://cgem.ssl.berkeley.edu/

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



Outline

Quantitative studies based on HMI Low-Cadence (12 min) Vector Magnetograms

- Electric fields & Poynting Fluxes
- Reconnection fluxes

Quantitative studies based on HMI High-Cadence (135s) Vector Magnetograms

- Magnetic imprints
- Lorentz forces
- Electric Currents

Data-driven models

HMI Low-Cadence Vector Data

The Helioseismic and Magnetic Imager (HMI)

- **B** & $\mathbf{V}_{\mathbf{dopp}}$ since May 1 2010
- Full disk 24 hrs/day
- dt=12 minutes, ds=360 km

Why low-cadence vector magnetograms?

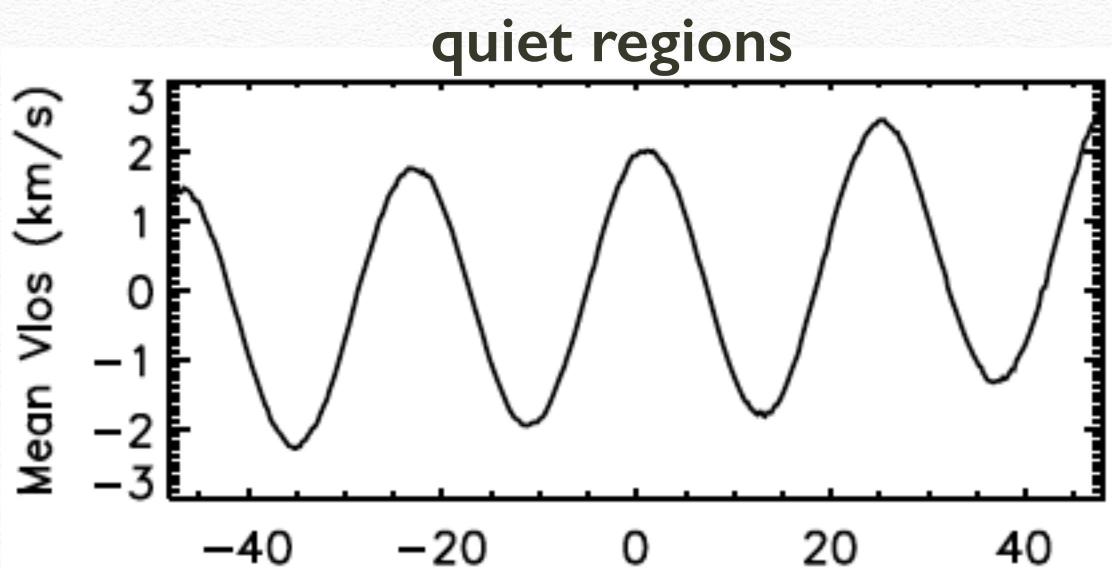
- Active-regions: v~[0.1-0.3] km/s
- Photospheric magnetic evolution is well-resolved

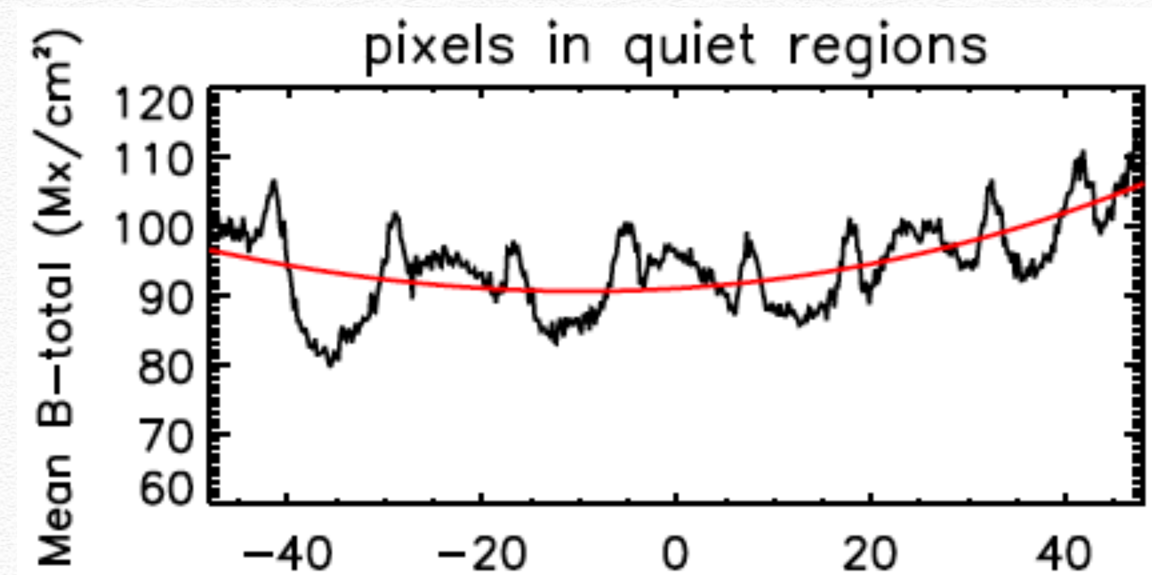
Hoeksema et. al 2014, Scherrer et al. 2012

HMI Orbital Motion

Relative SDO-spacecraft-Sun velocity varies by ±3 km/s each day

Introduces orbital artifacts in the HMI data

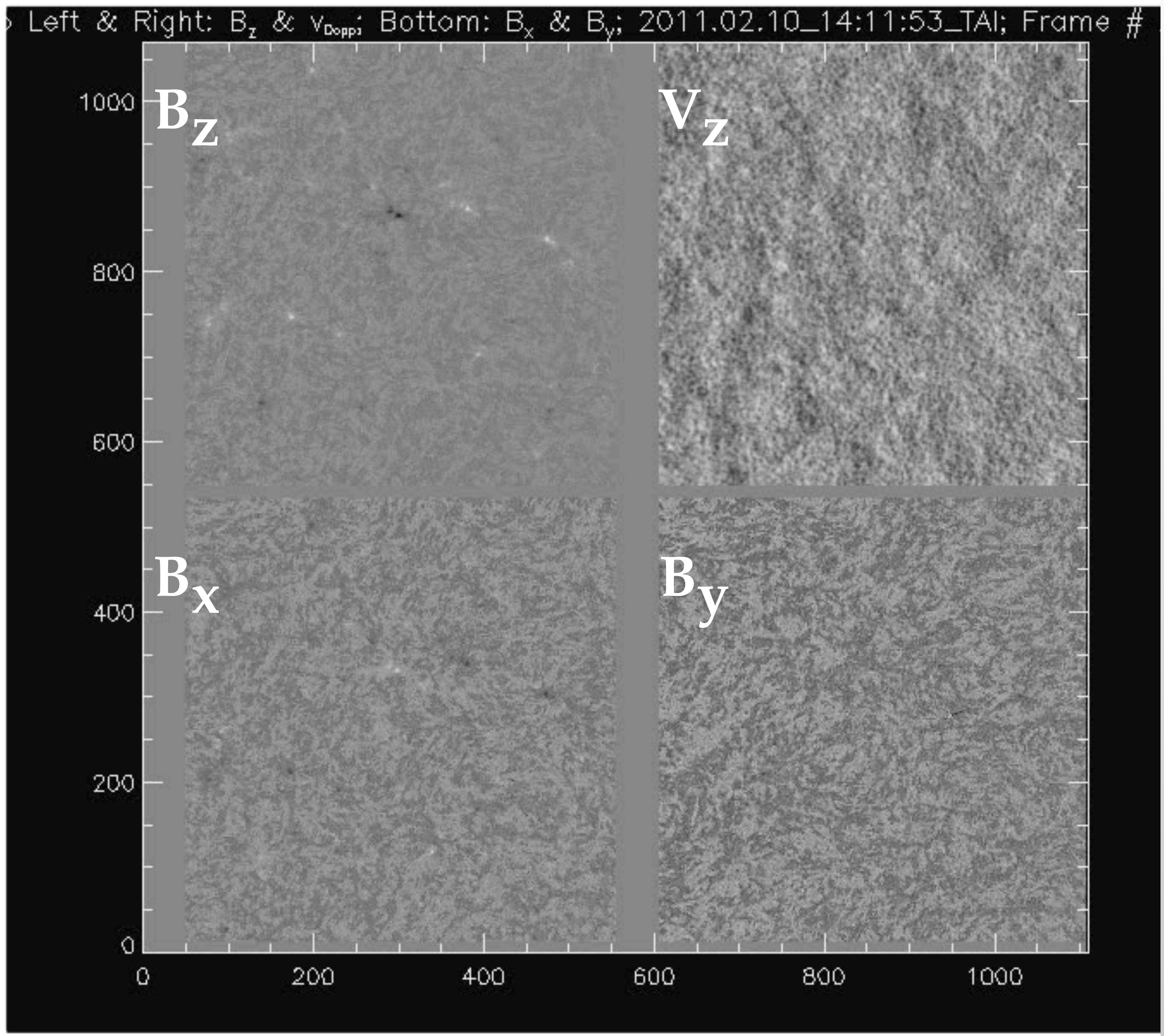




Hoeksema et al. 2014

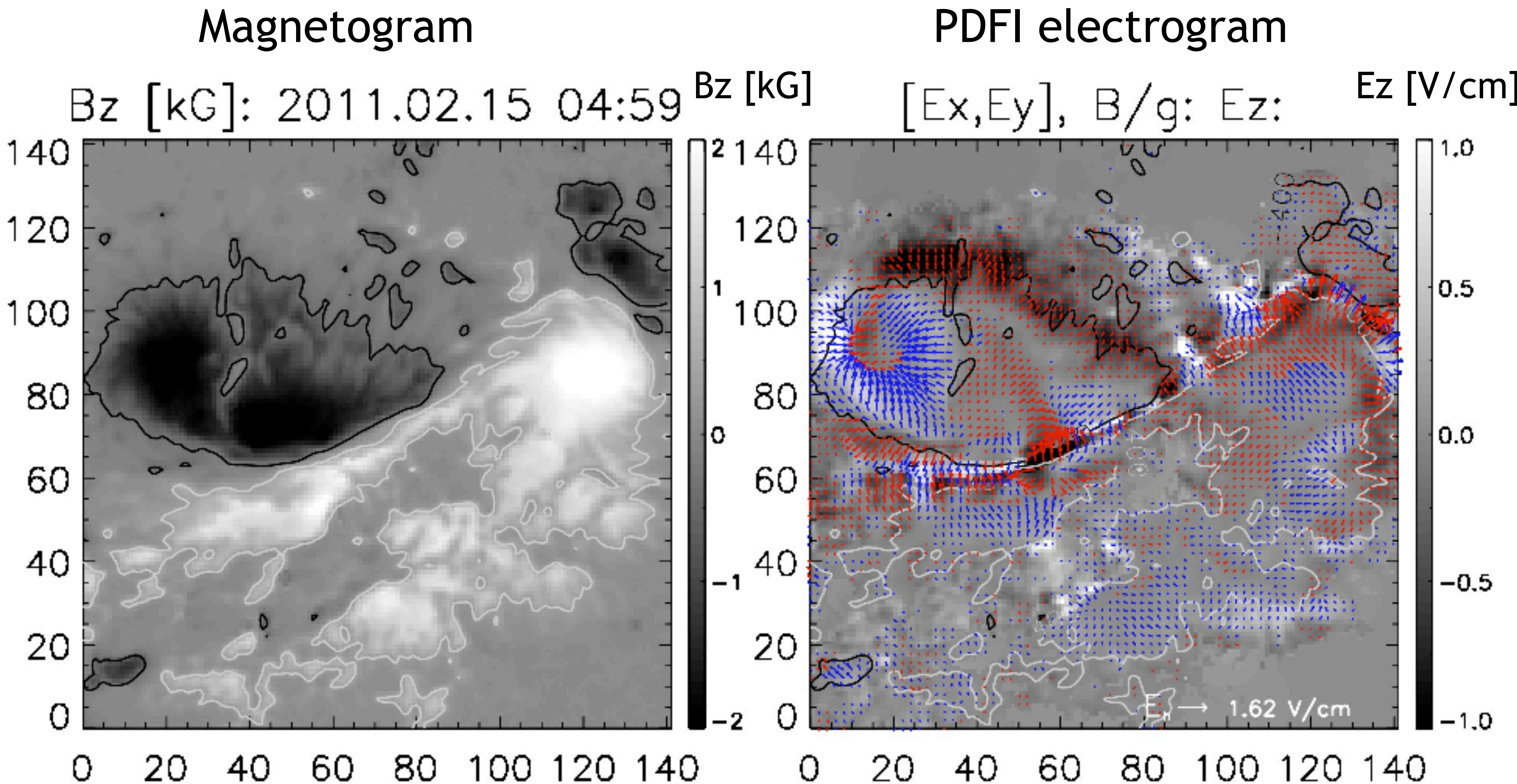
Ongoing correction efforts: P. Scherrer, T. Hoeksema and the HMI team; Schuck, Antiochos, Leka, Barnes, ApJ, 2016.

HMI Low-Cadence B and Vz in AR11158



Low Cad: Electric Fields, Energy Fluxes, Rec. fluxes High Cad: Imprints, Lorentz Force, Currents Data-Driven Simul.

Observed Magnetic Field and Derived Electrogram: Evolution



Kazachenko et al. 2015

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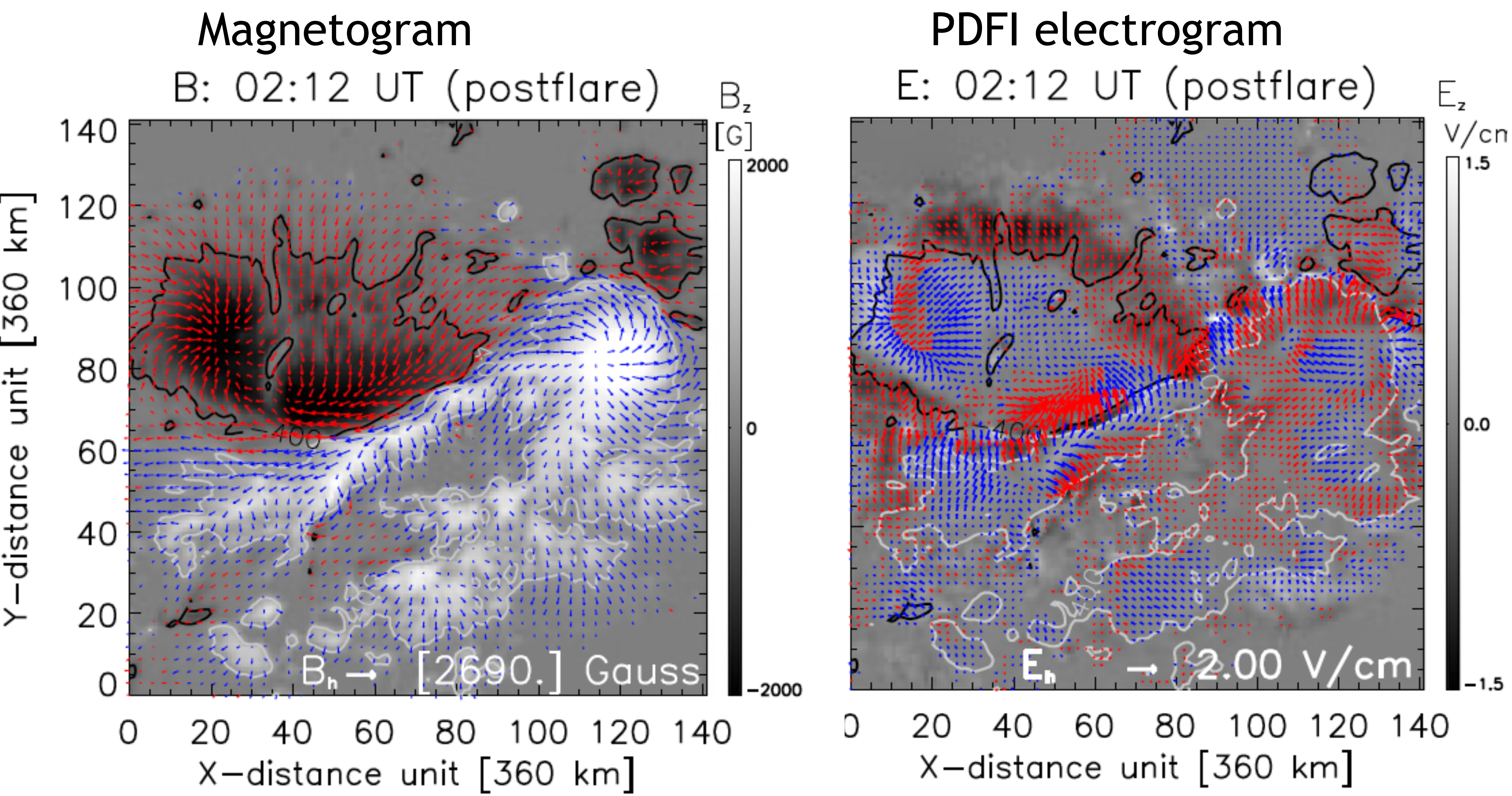
Observed Magnetic Field and Derived Electrogram: One Snapshot



Kazachenko et al. 2015

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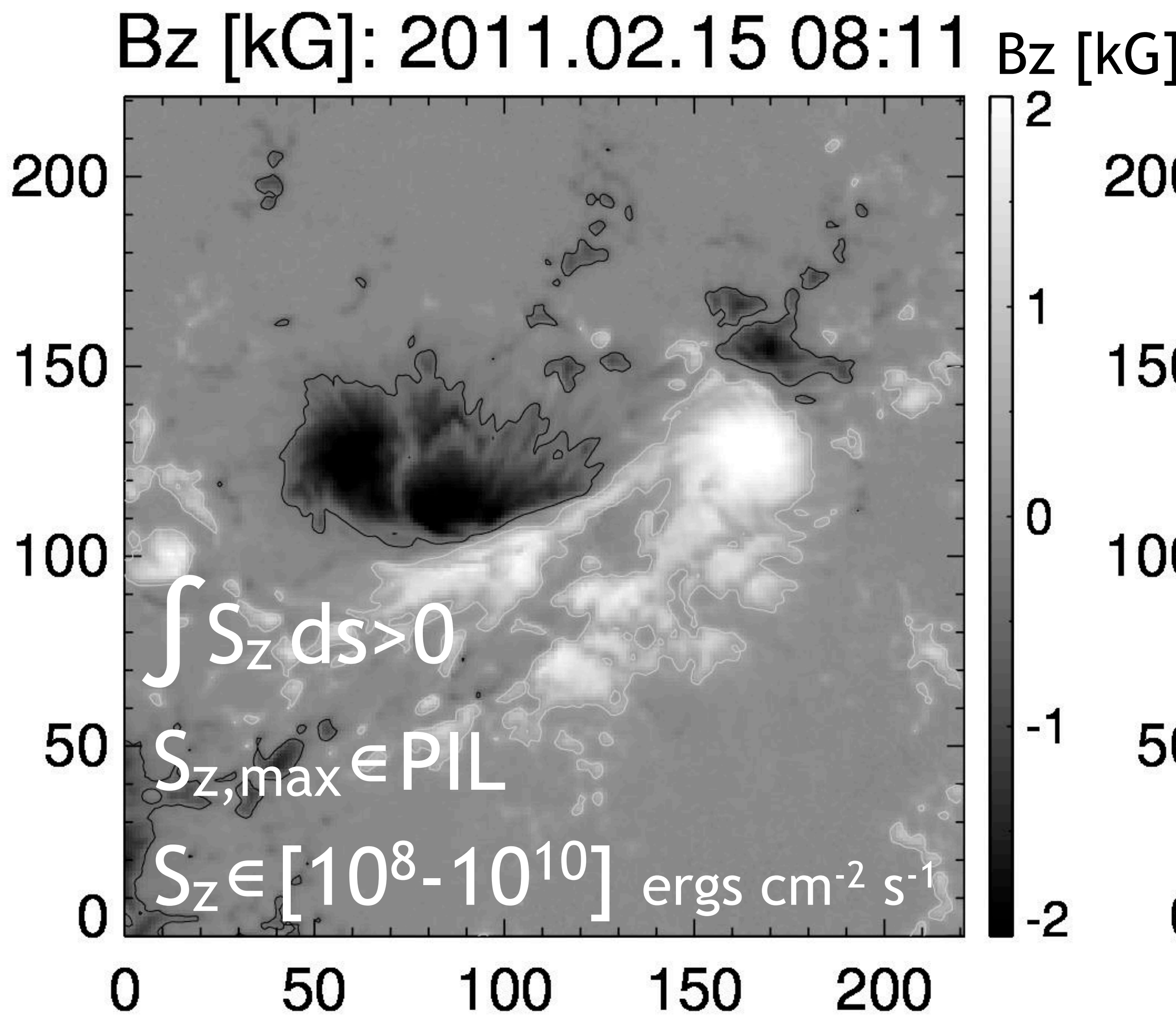
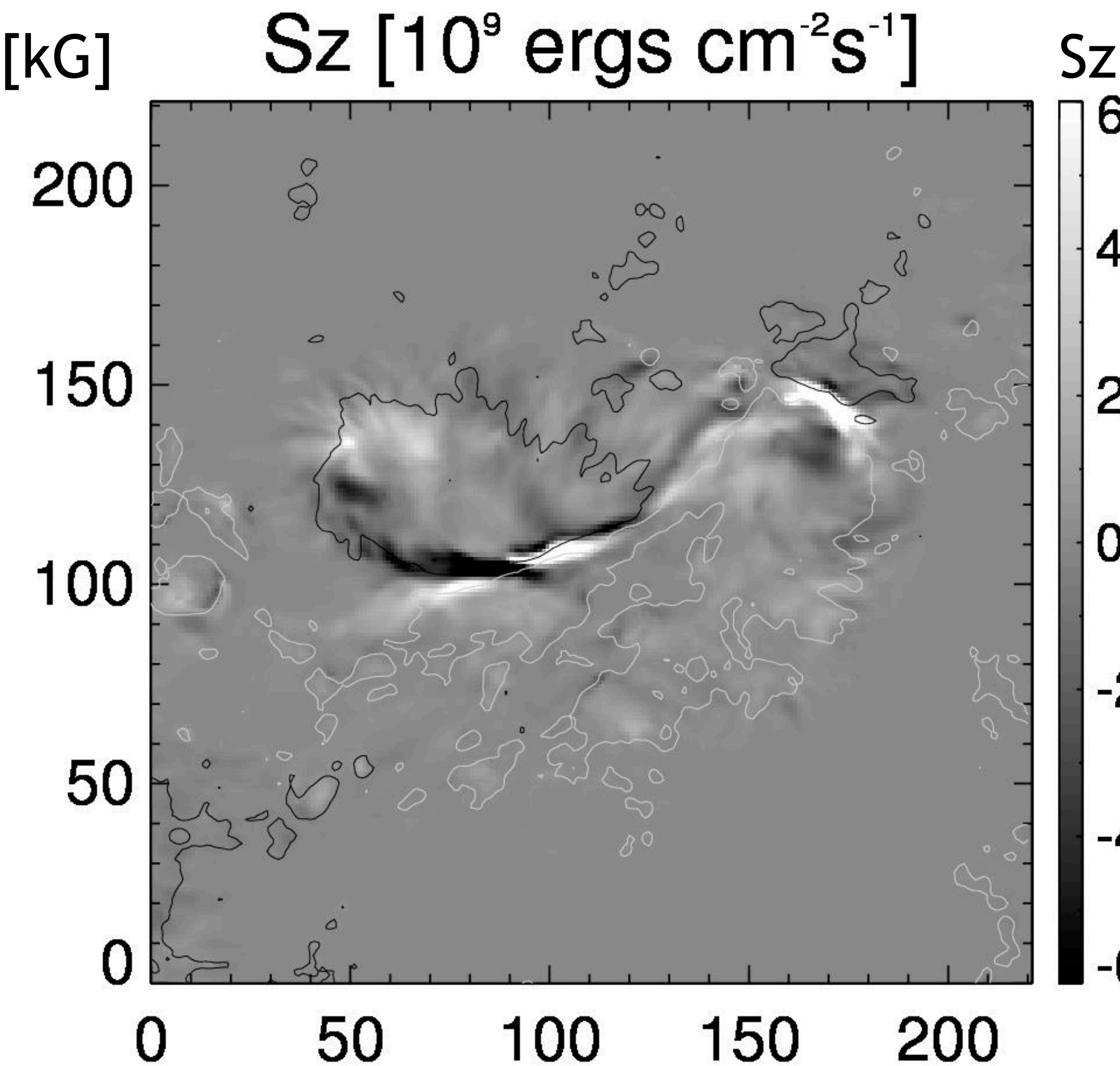
Observed Magnetic Field and Derived Energy Flux

Vertical magnetic field



Vertical Poynting flux



Kazachenko et al. 2015

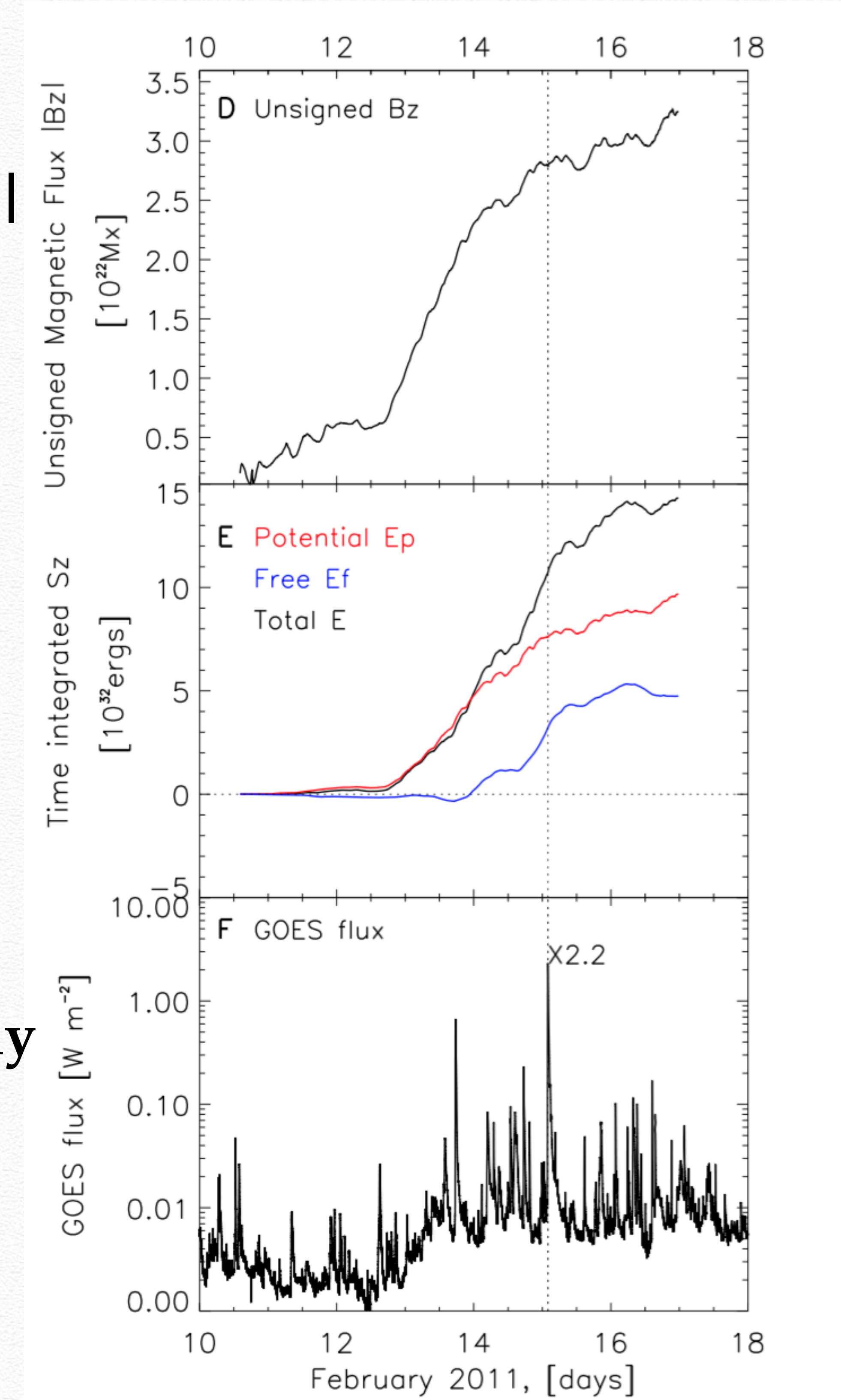
Area Integrated Poynting Flux and Relative Helicity

| Bz |

Sz

X-ray

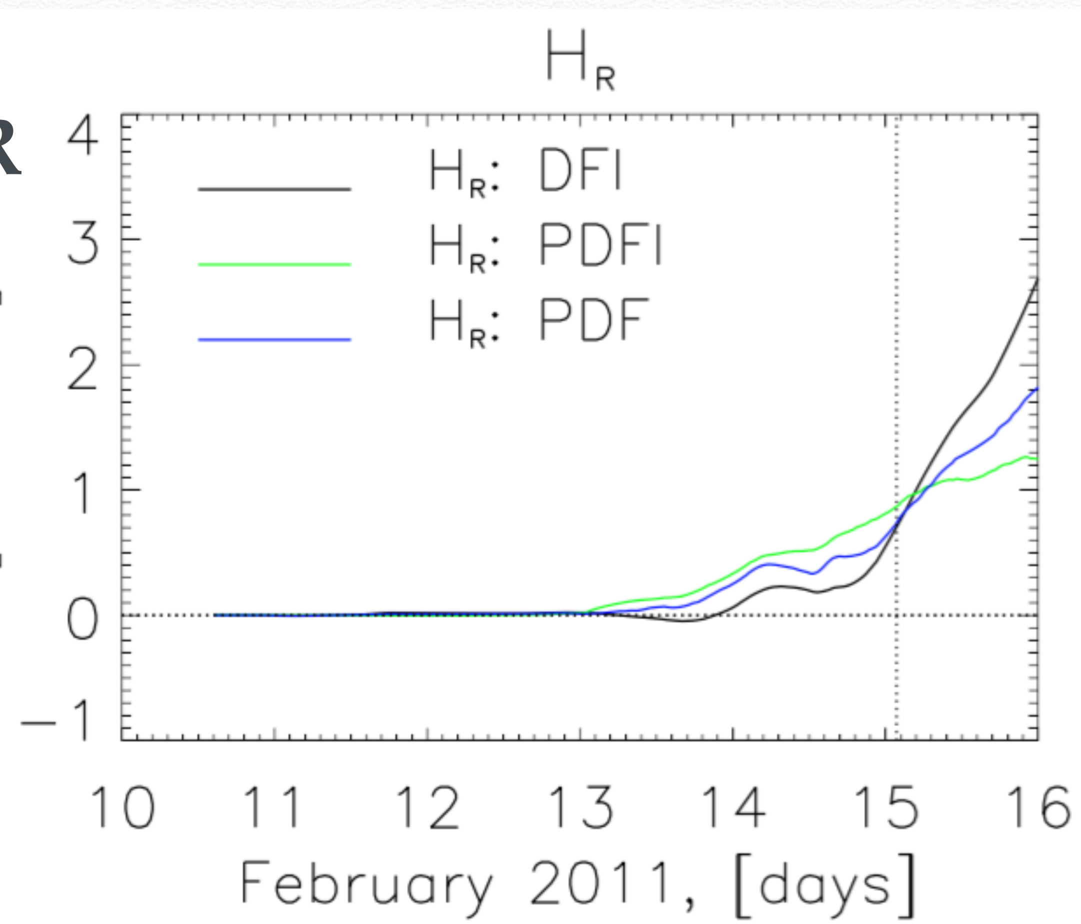
flux



Left: magnetic flux (*top*), integrated Poynting flux (*middle*) and GOES flux (bottom) evolution in AR 11158.

Bottom: helicity flux flux evolution in AR 11158 (from DFI and PDFI approaches)

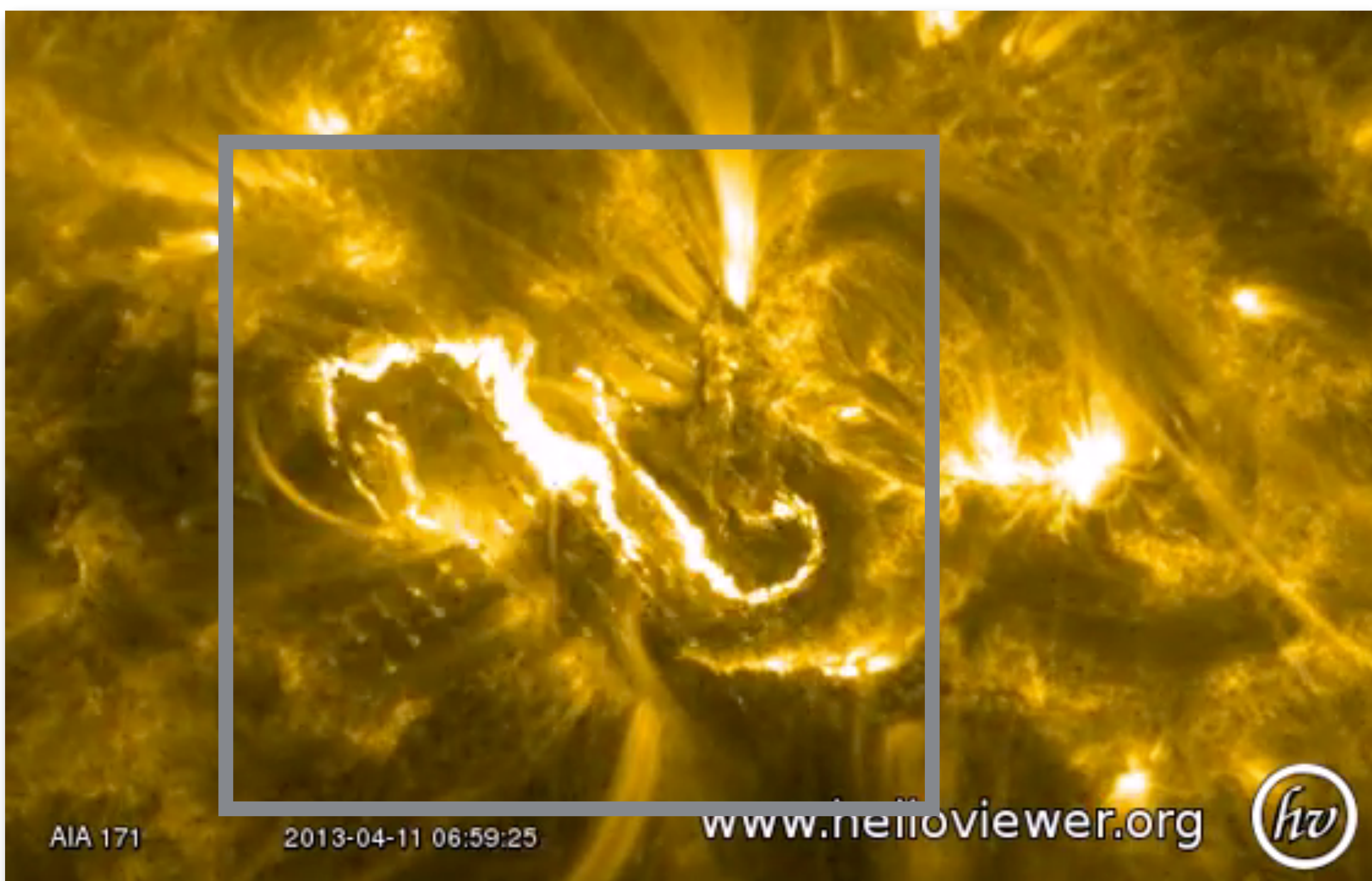
H_R



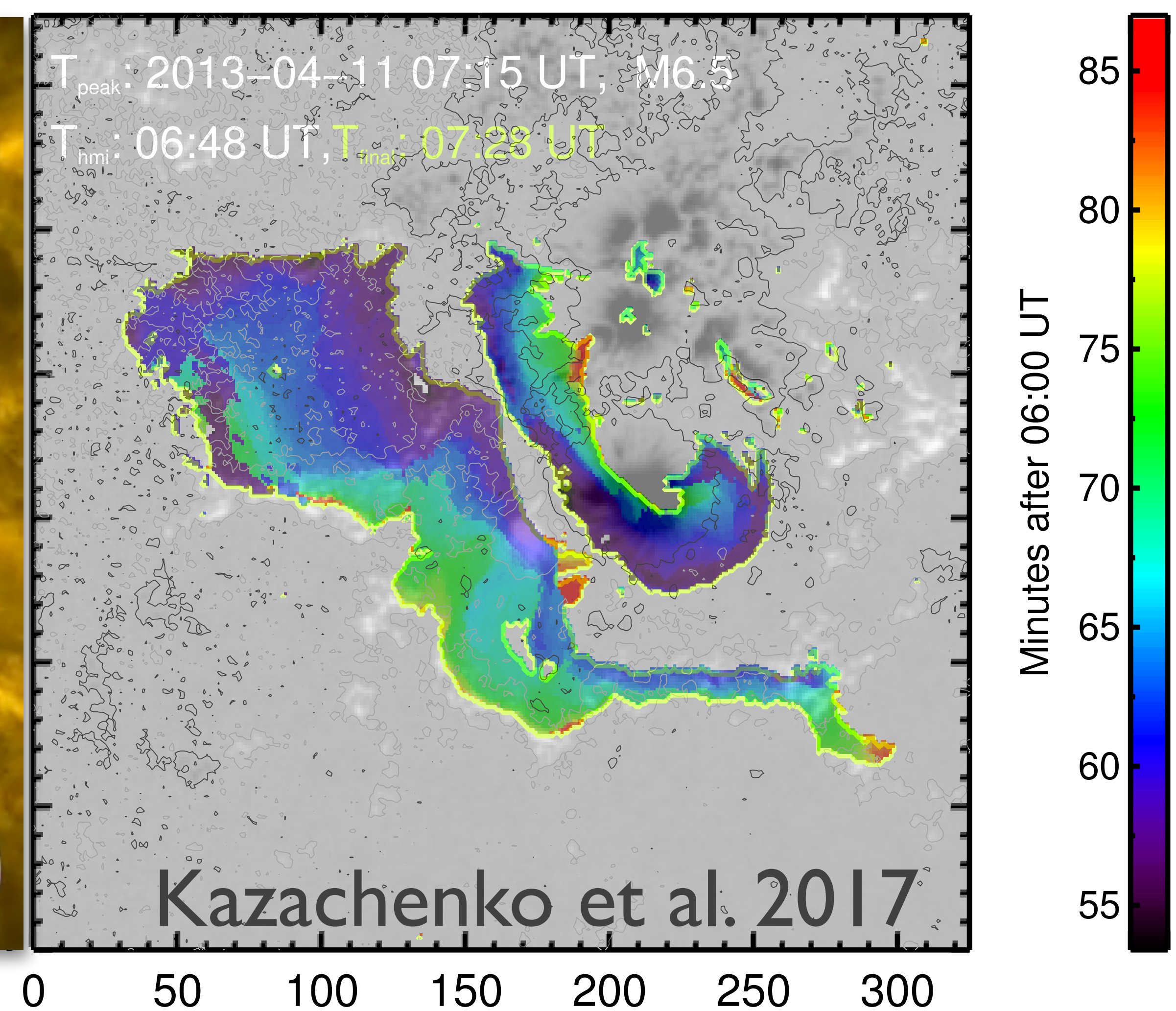
Properties of Reconnecting Magnetic Fields

Flare ribbons are the footpoints of reconnected field lines!

M6.5 flare, AIA 171



Ribbon evolution over Br contour



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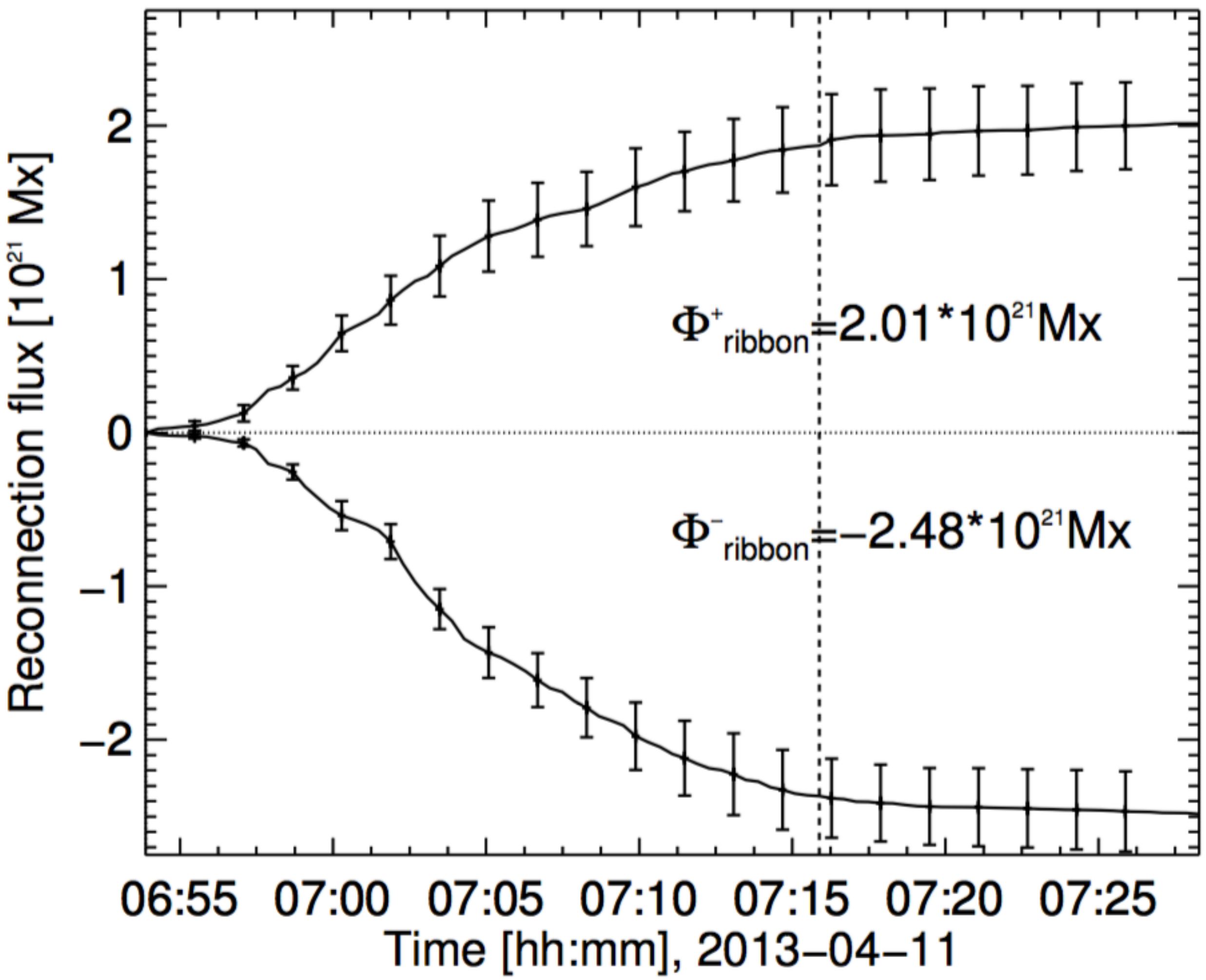
Properties of Reconnecting Magnetic Fields

Flare ribbons are the footpoints of reconnected field lines!

Reconnected Flux $$\Phi_{\rm ribbon} = \int |B_n| dS_{\rm ribbon},$$



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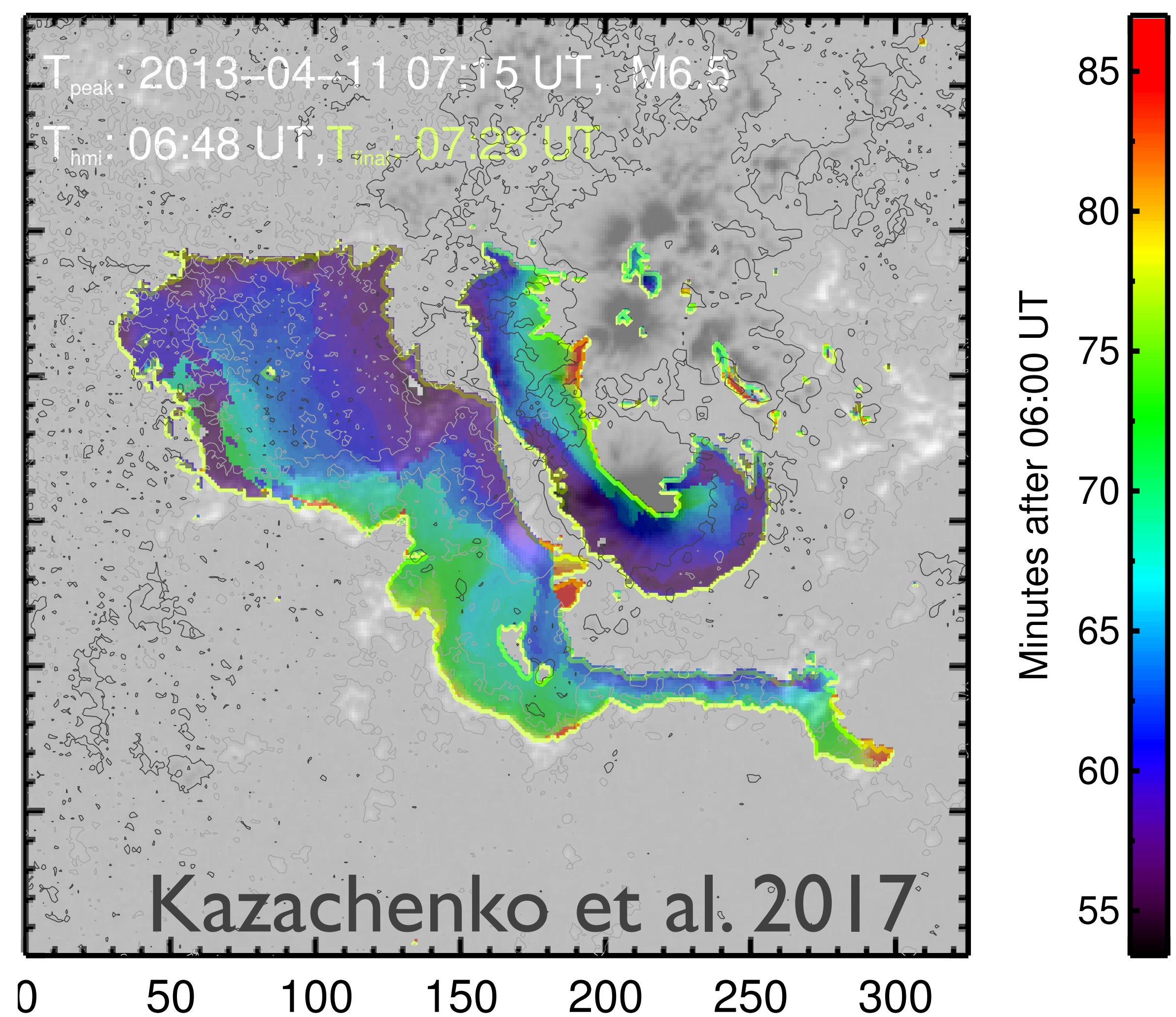

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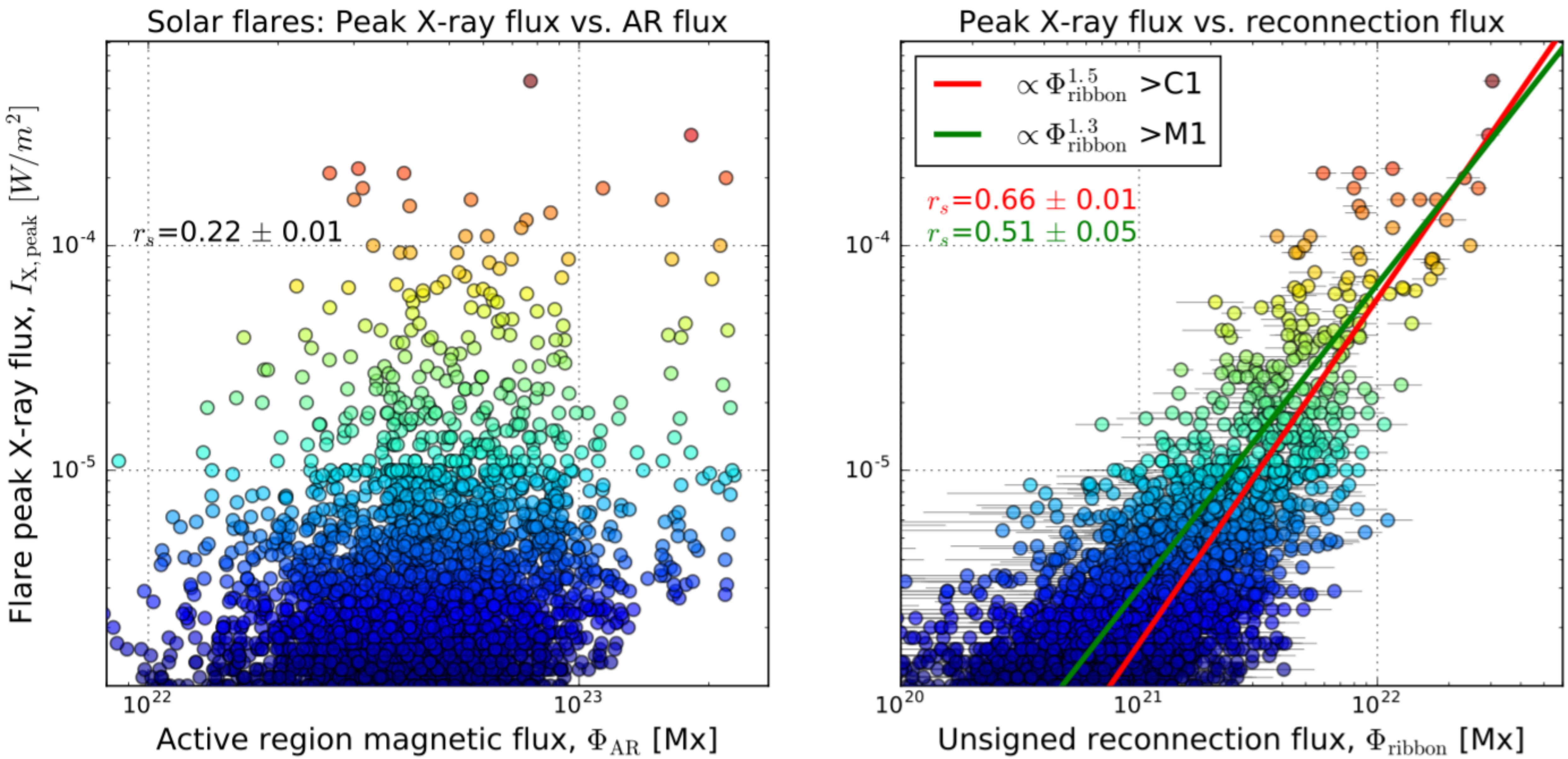
Properties of Reconnecting Magnetic Fields

RibbonDB: ~3000 solar flares



Kazachenko et al. 2017

HMI High-Cadence Vector Data

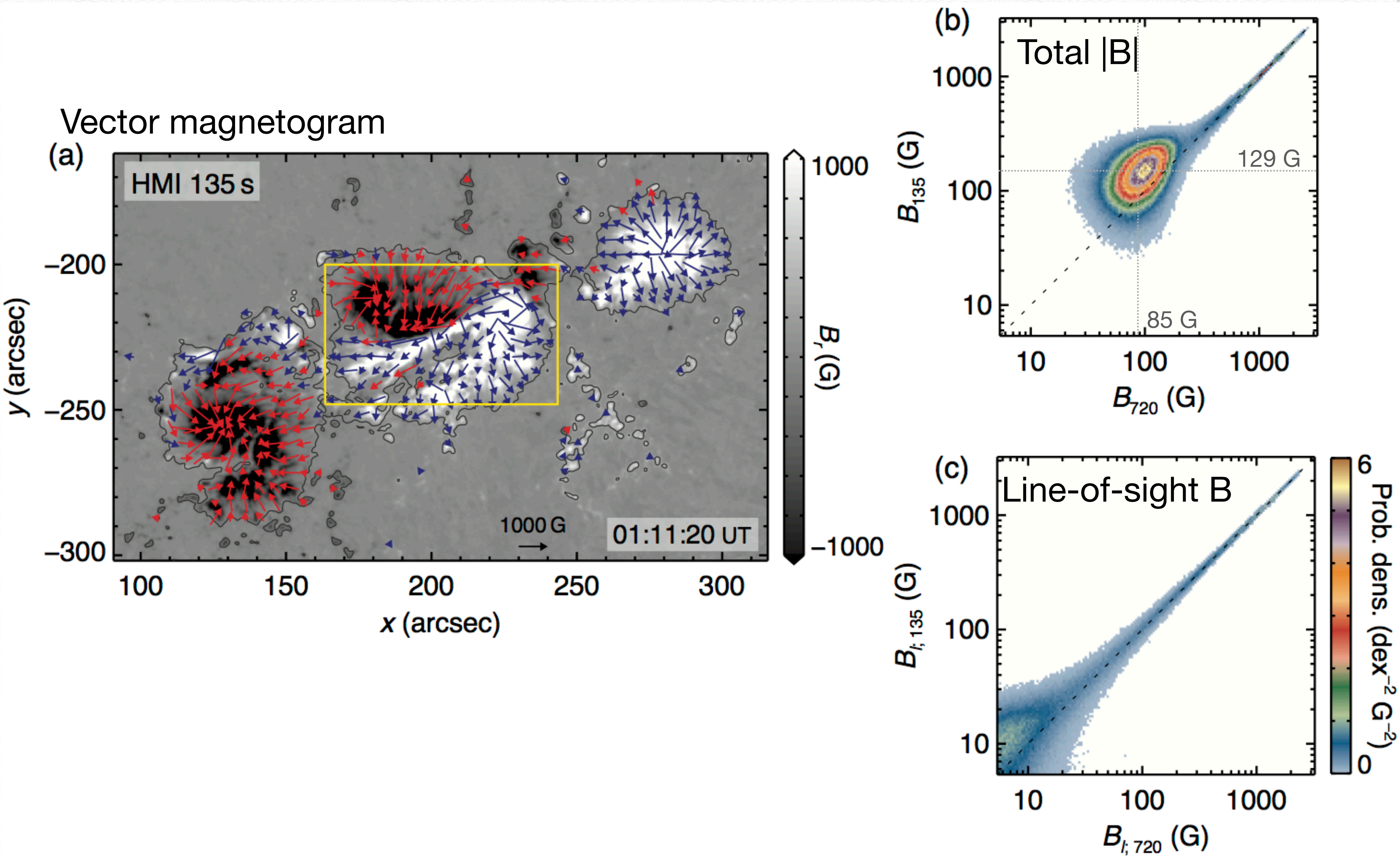
- dt=135 s (dt=90 s after Apr 2016); ds=360 km;
- Data already available for selective periods (360 h); but could be requested for any time during SDO mission. Email HMI team.

Why high-cadence vector magnetograms?

- Some types of rapid photospheric magnetic evolution is under-resolved at 12-min
- **Example**: major eruption; flux emergence

Sun et al., 2017, *ApJ*, **839**, 67

Comparison Between High- and Low-Cadence Vector Data



Low Cad: Electric Fields, Energy Fluxes, Rec. fluxes   High Cad: Imprints, Lorentz Force, Currents Data-Driven Simul.

Magnetic "Imprint" & "Transient"

During eruption photospheric field changes during minutes

Field changes: → "imprints" (permanent)

Field changes: → "transients" (temporary)

Before high-cadence HMI data:

B_{los} observations: good temporal cadence, but no vector

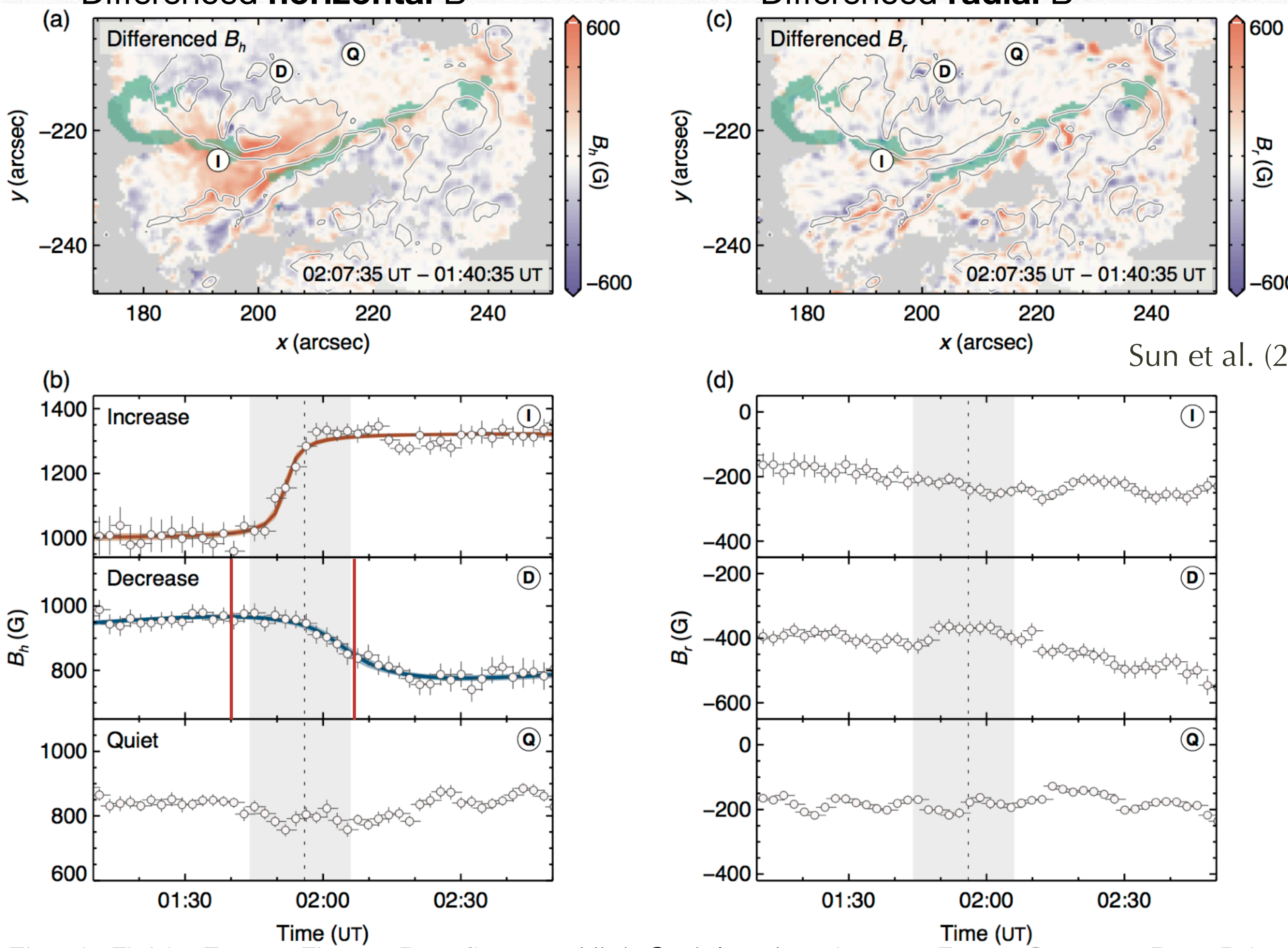
B observations: low temporal cadence

High-cadence HMI data: can clarify ambiguities

Sun et al. (2017)

Magnetic “Imprint” in AR 11158

Differenced **horizontal** B   Differenced **radial** B



Sun et al. (2017)

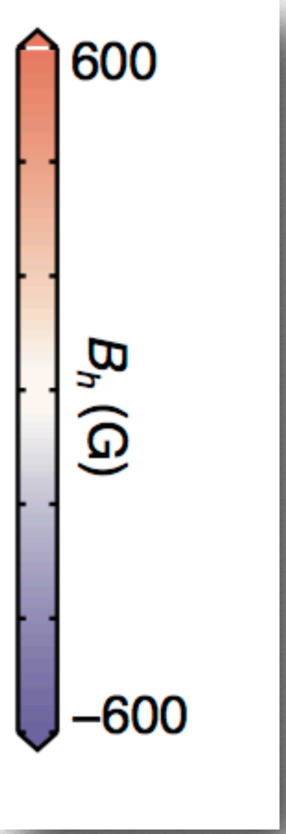
Low Cad: Electric Fields, Energy Fluxes, Rec. fluxes   <u>High Cad:</u> Imprints, Lorentz Force, Currents Data-Driven Simul.

Magnetic "Imprint" in AR 11158: Temporal Evolution

Differenced Bh

Sun et al. (2017)

increase

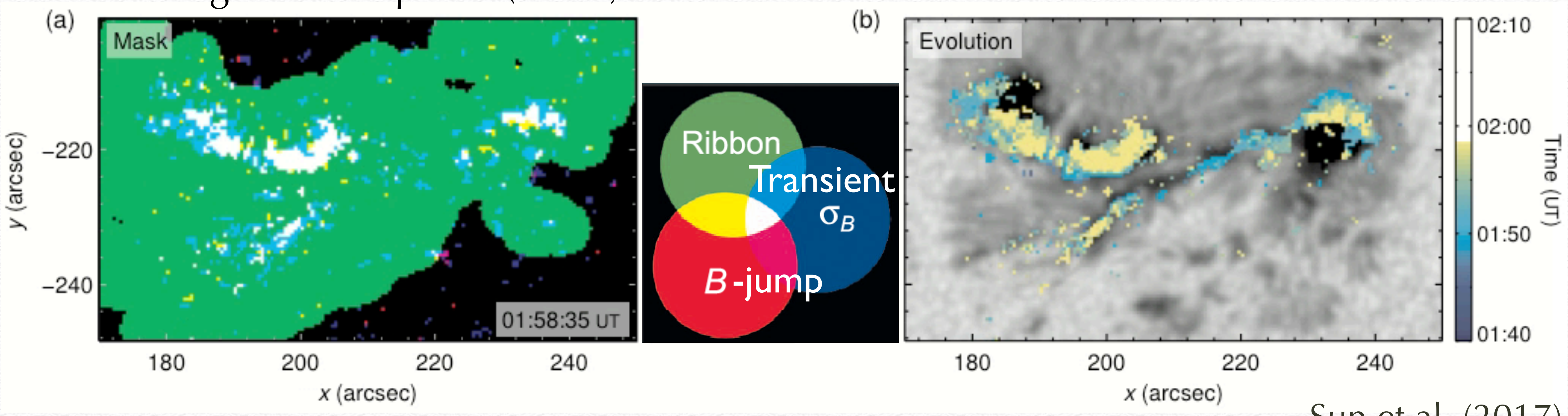


decrease

A New Method to Locate Transient Pixels

Transient Pixel: resides inside **ribbon** **(green)**
has large field uncertainty **(σ_B)**
has a jump in the signal (**B-jump**)

Finding transient pixels (white) Evolution of transient



Sun et al. (2017)

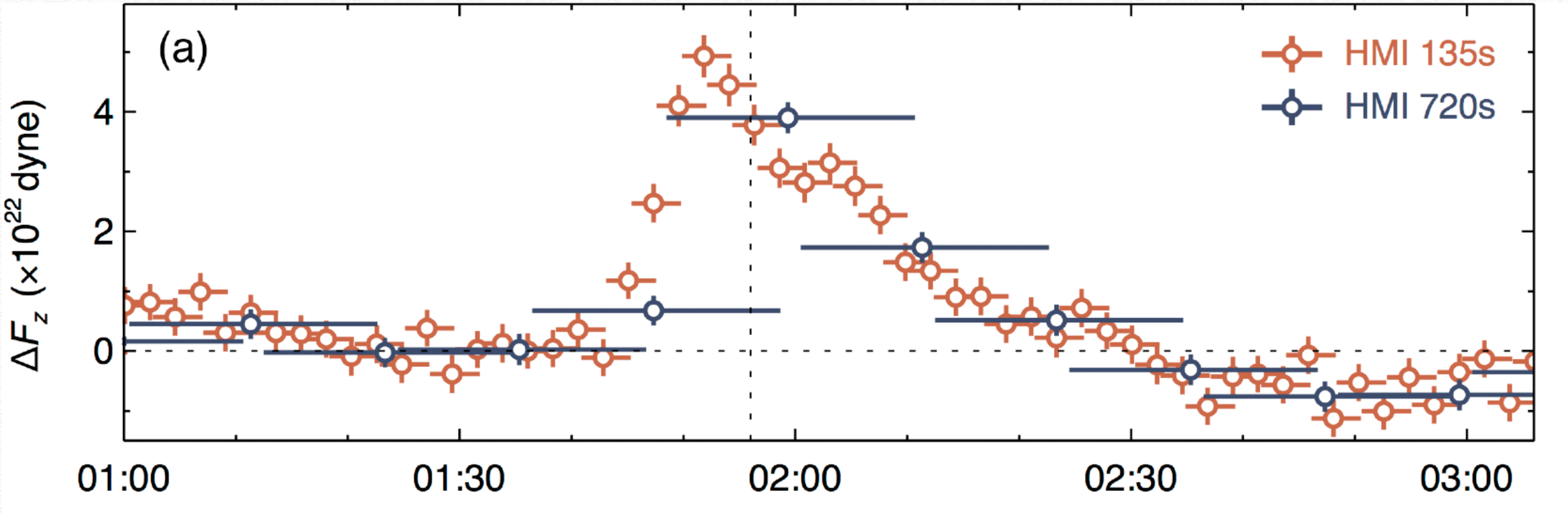
Transients

Cover 6% of strong-field pixels in AR 11158
Most of them are not colocated with imprints
Are co-spatial with white-light sources

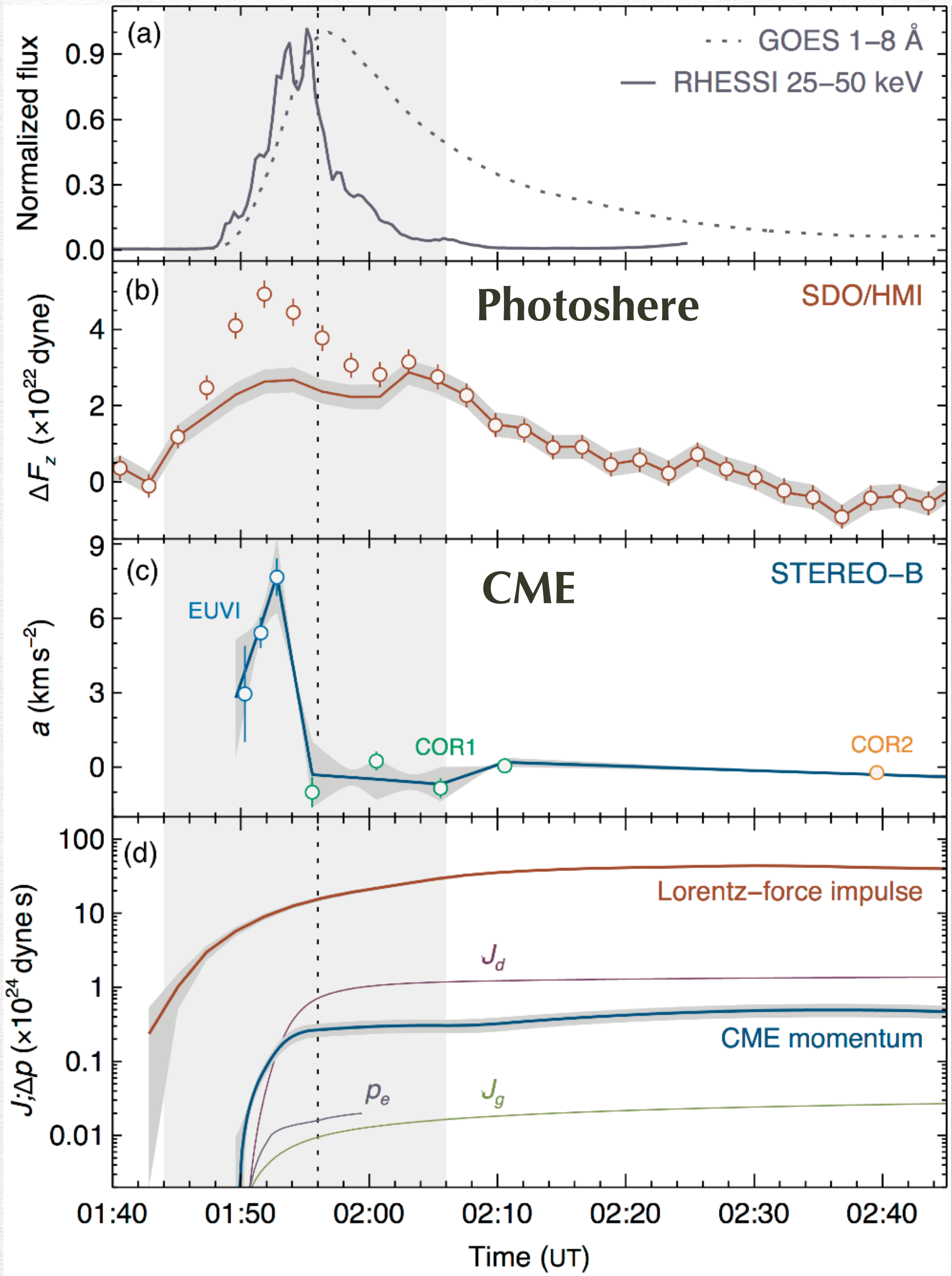
Lorentz Force Change in AR 11158

$$F_z = \frac{1}{8\pi} \int_{\text{photosph}} (B_h^2 - B_z^2) dA.$$

Sun et al. (2017)



Lorentz Force & Momentum Partition



F_z and a_{CME} co-evolve

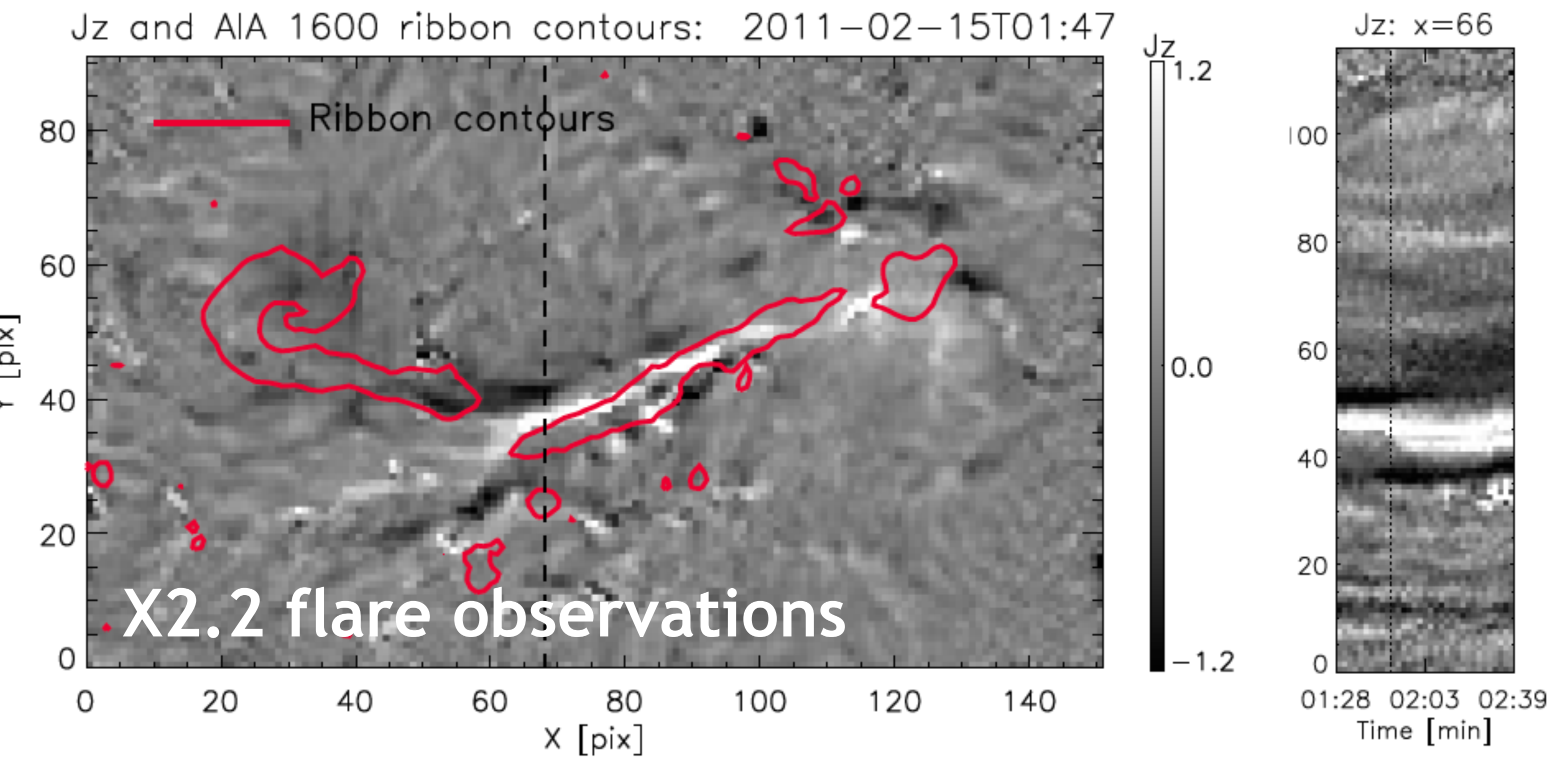
Lorentz-force impulse is **~100x** CME momentum!

HMI probes photosphere: integration includes highly stratified lower atmosphere

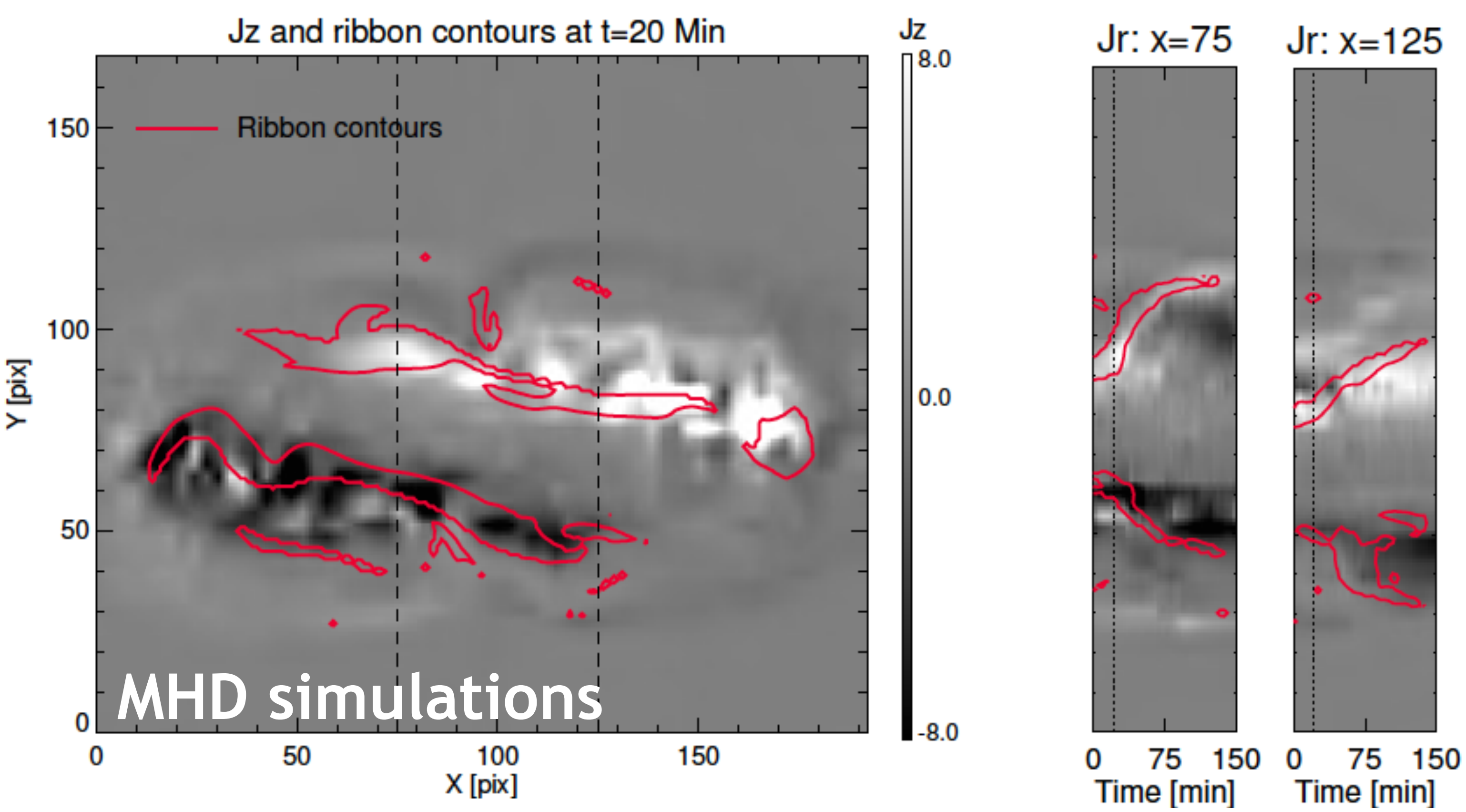
Excess Lorentz force pulls on photosphere: new mass comes into volume; its gravity offsets ΔF_z

Lorentz Force at the disk center is a proxy for the halo CME velocity which is difficult to measure.

Flare Ribbons Vs. Vertical Currents



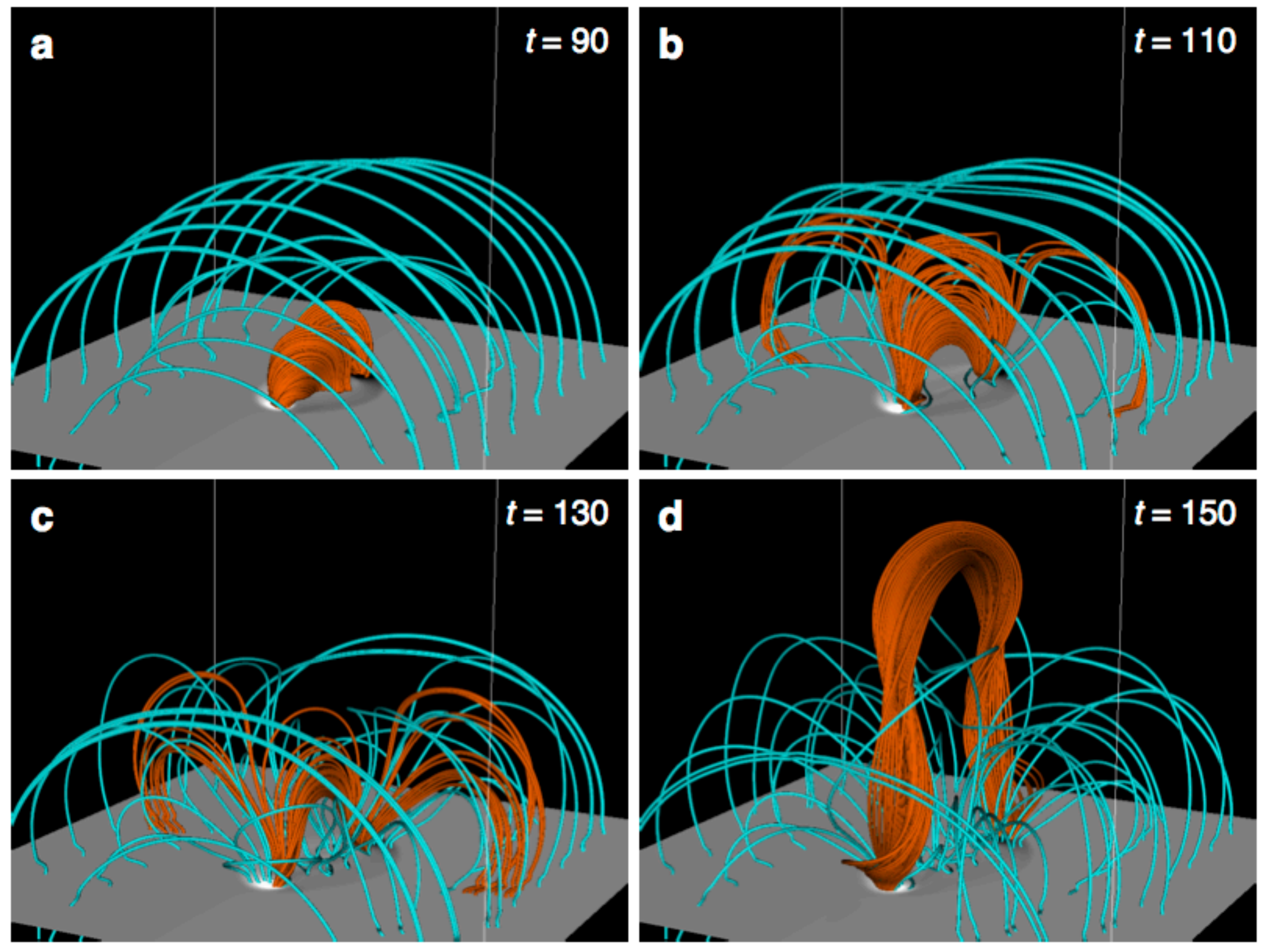
Jz (**Black**) and ribbons (**Red**) spatially (left) and as a function of time (right)



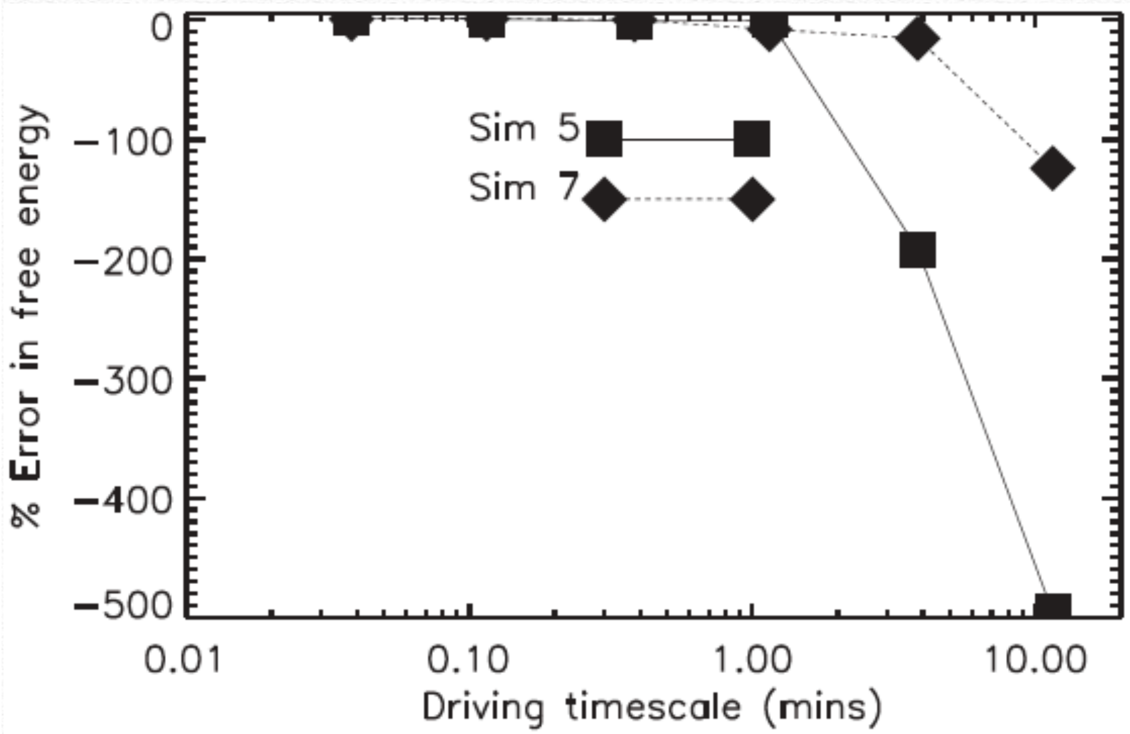
We find a spatio-temporal correlation between locations of strong Jz and ribbons

Kazachenko & Lynch in prep.

Data-Driven Models: How Are Data-driven Models Affected By a Finite Observation Cadence?



Error in the magnetic free energy as a function of the input-data cadence for a **fast emergence**



Leake et al. 2014, 2017

Properties From **B**-Observations For Data-Driven Models' Validation

- Magnetic energy (free and potential)
- Magnetic helicity
- Reconnection flux (during eruptions)
- Change in Lorentz force

Conclusions

- HMI/SDO: first routine high-quality full disk measurements of the solar vector magnetic field
- Vector magnetic fields allow us to estimate:
    - Electric fields
    - Poynting fluxes
    - Electric currents
    - Lorentz forces
    - Magnetic energy & helicity etc.
  - Drive coronal magnetic field models and validate them
- Vector magnetic fields observations are key to quantitative studies of Sun's atmosphere.

Low Cad: Electric Fields, Energy Fluxes, Rec. fluxes   High Cad: Imprints, Lorentz Force, Currents Data-Driven Simul.

Thank you!