

# Toward routine extraction of modeling-relevant information from photospheric boundary data

-or-

“You get what you pay for”:  
Getting Information from Photospheric SpectroPolarimetry.

**KD Leka**

Institute for Space-Earth Environmental Research  
Nagoya University, Nagoya, Japan

NorthWest Research Associates  
Boulder, Colorado, USA



NORTHWEST RESEARCH ASSOCIATES  
*"unencumbered science"*

## ***IF:***

We could

- measure all physical parameters on all scales, and
- test physical hypotheses with controlled experiments in the solar plasma,
  - ▣→ no need for modeling.

## ***But we can't. So what do models want?***

- Boundary & initialization conditions:
  - Full plasma description as  $f(\text{time, space})$ :
    - Magnetic field, currents, ionization states, densities, velocities, pressures, etc...
- Constraints
  - (kind of like medicine....)

## ***What is most generally provided (more realistic)?***

- Photospheric magnetic field
  - Line-of-sight component, or  $B$ 
    - With noise.
    - On a grid that is inappropriate for your model.
    - At one time, or a temporal cadence that is inappropriate for your model.

## Research Magnetic Field Data Availability

<i>What can we get, what do we have?</i>	Low Photosphere †	Photosphere †	Chromosphere †,‡	Low Corona †, ‡	Outer Corona / Heliosphere †,‡
Spatial Resolution	*		*	*	
Spatial Coverage					
Temporal Resolution	*		*	*	
Temporal Coverage					
Information Content	*	*	*	*	

Not all attributes necessarily simultaneously.

\*: expected to change with upcoming instrumentation

†: direct information on magnetic field

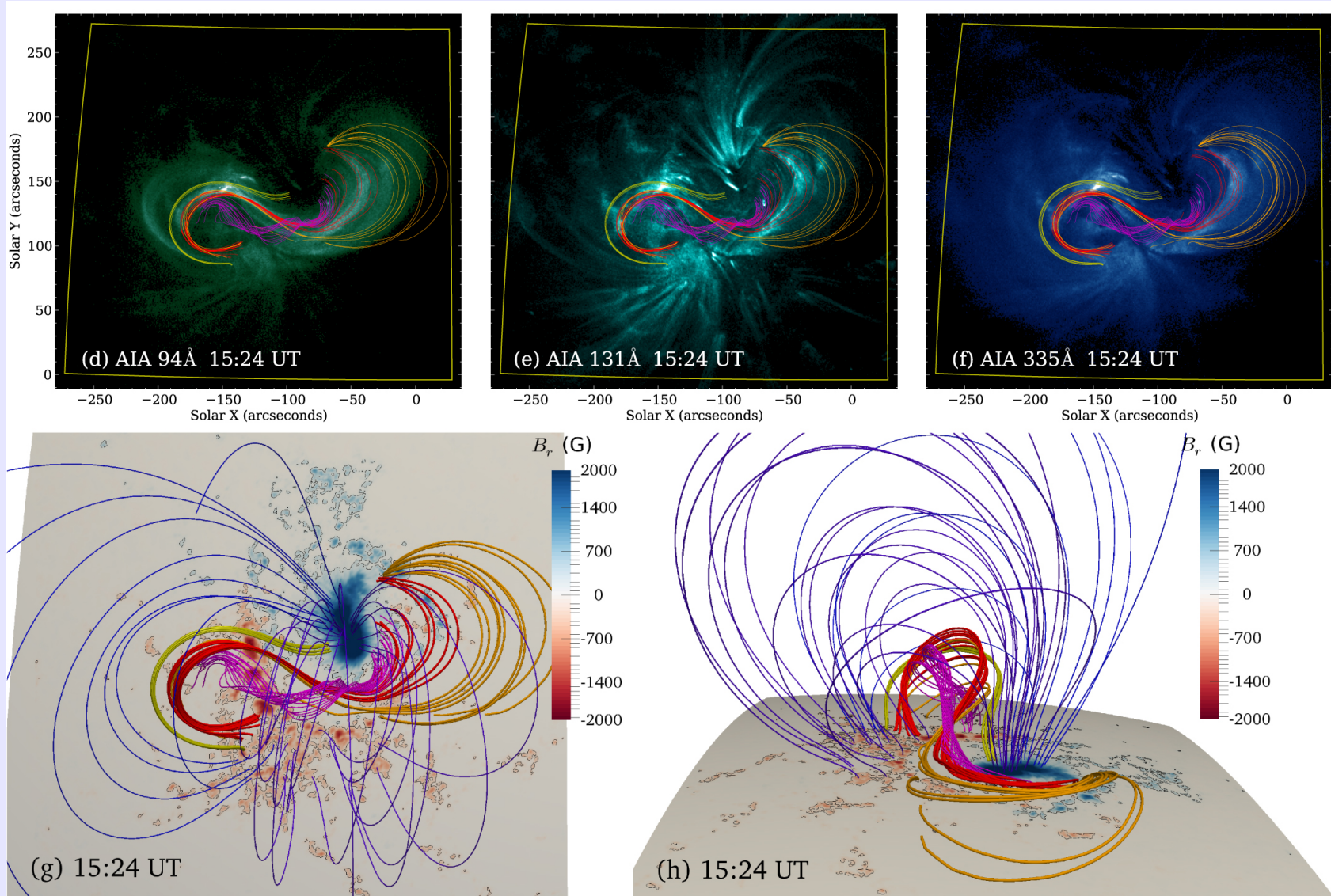
‡: indirect information on magnetic field

## How get (direct information)?

- optical, radio, IR, UV
- Zeeman effect, Hanle effect, gyroresonance / free-free emission
- Some methods: routine
  - *e.g.*, Zeeman effect well understood: basis of all photospheric “magnetograms”,
- Some methods – more experimental.
  - *e.g.*, not yet routine to acquire chromospheric field information across all chromospheric structures.

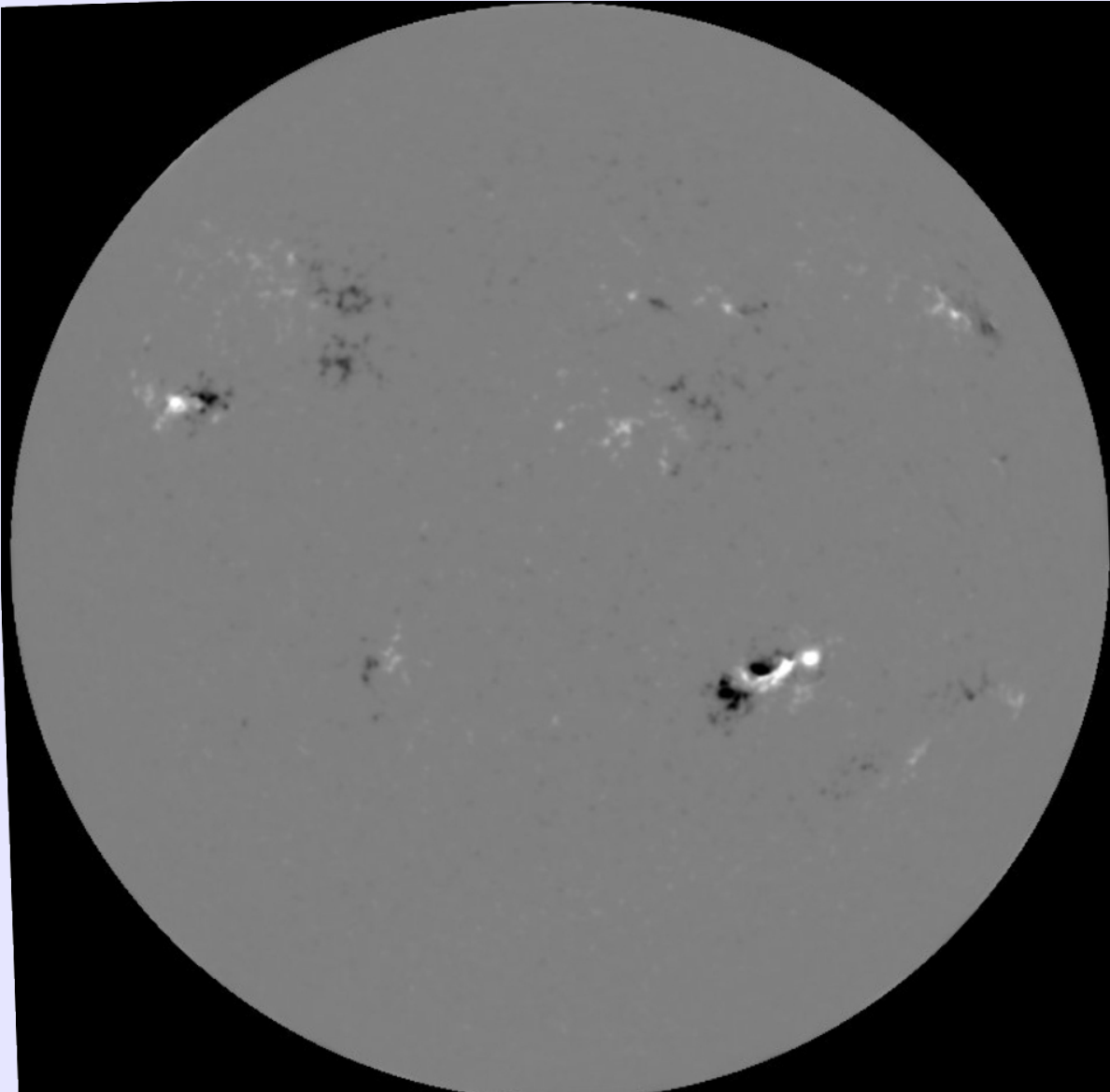
## How get (indirect information)?:

- Morphology (vs. models / extrapolations)
- ....*that's about it.*

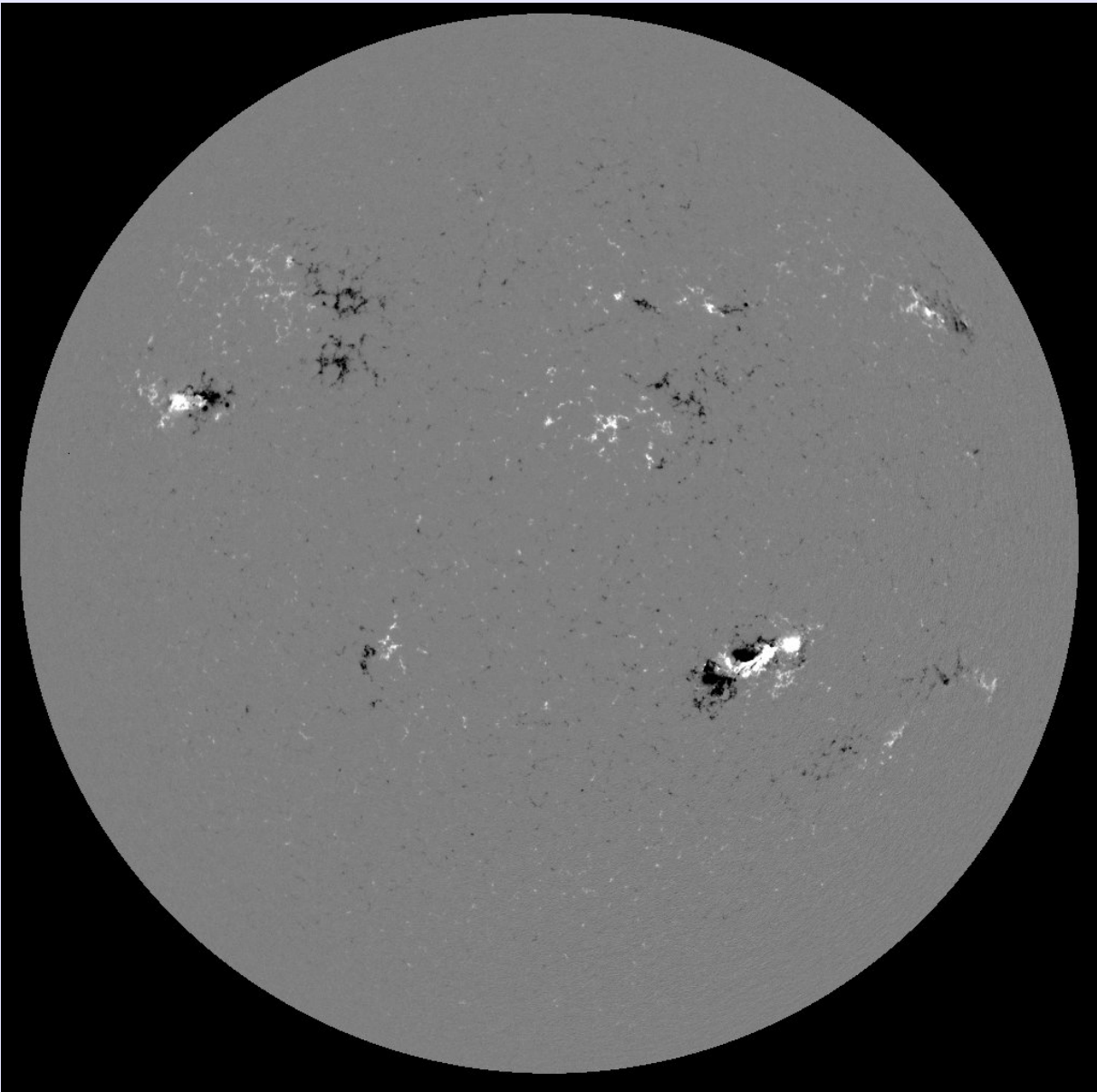


From Jiao+ 2016

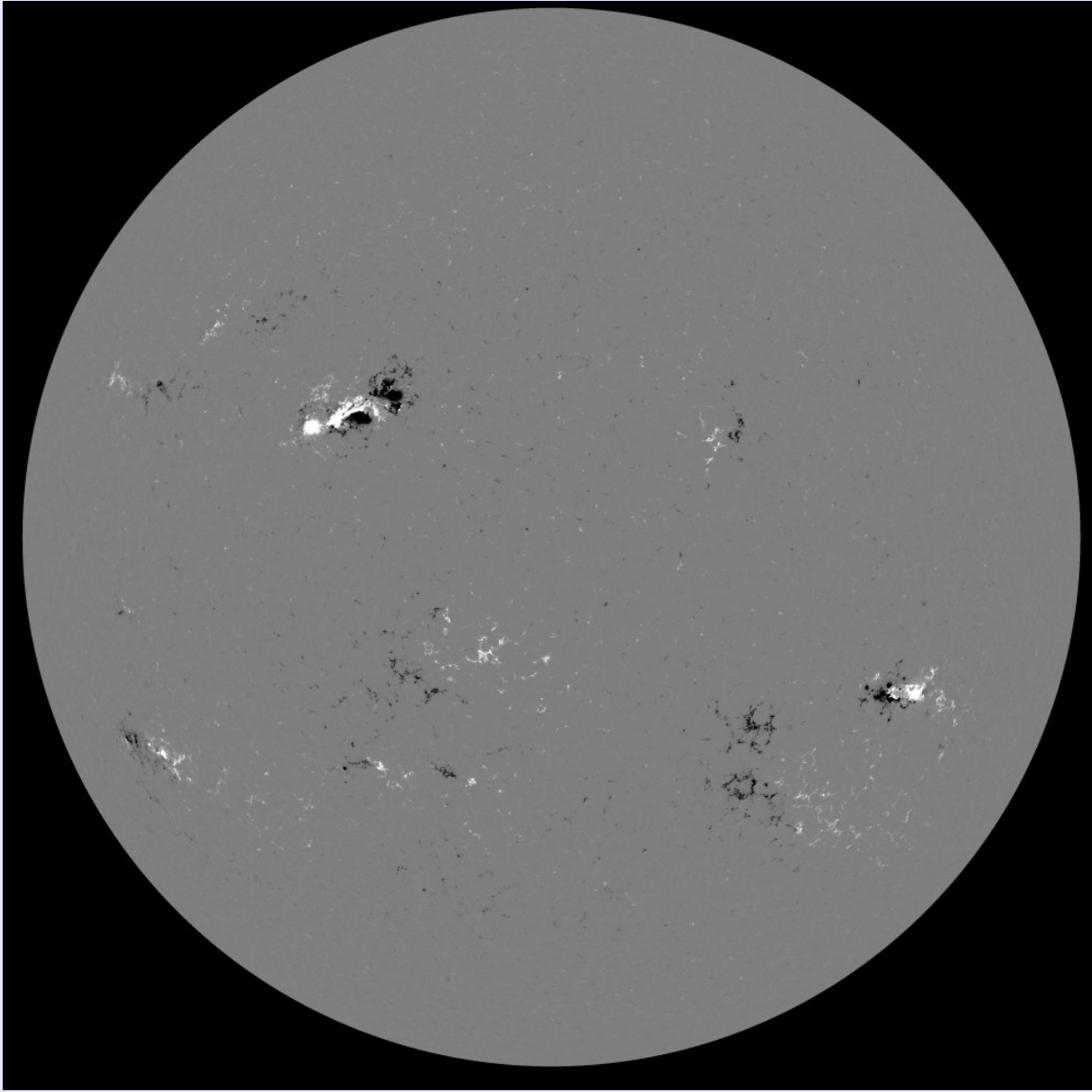
Question: Is this the photospheric magnetic field?



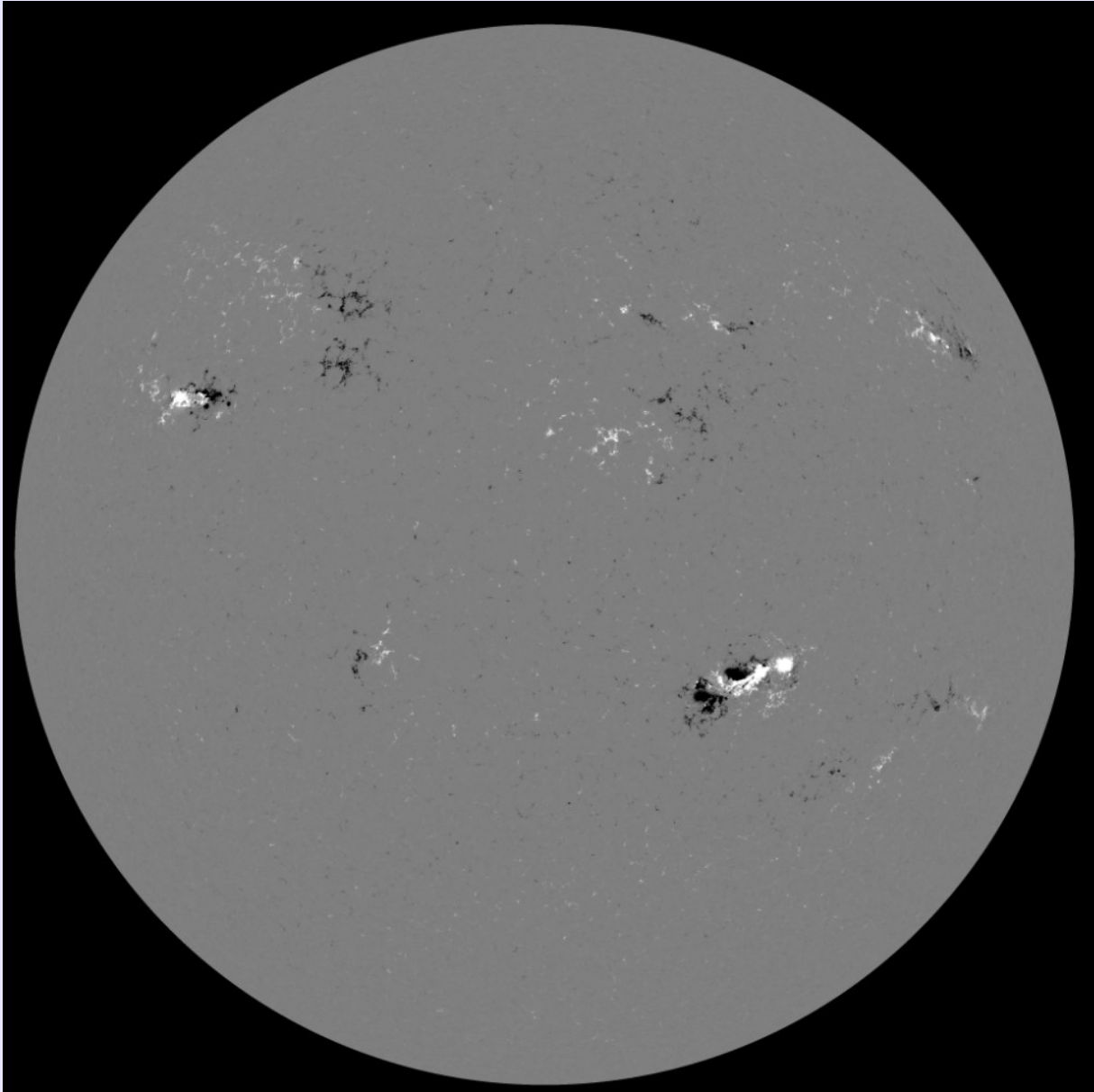
Question: Is this the photospheric magnetic field?



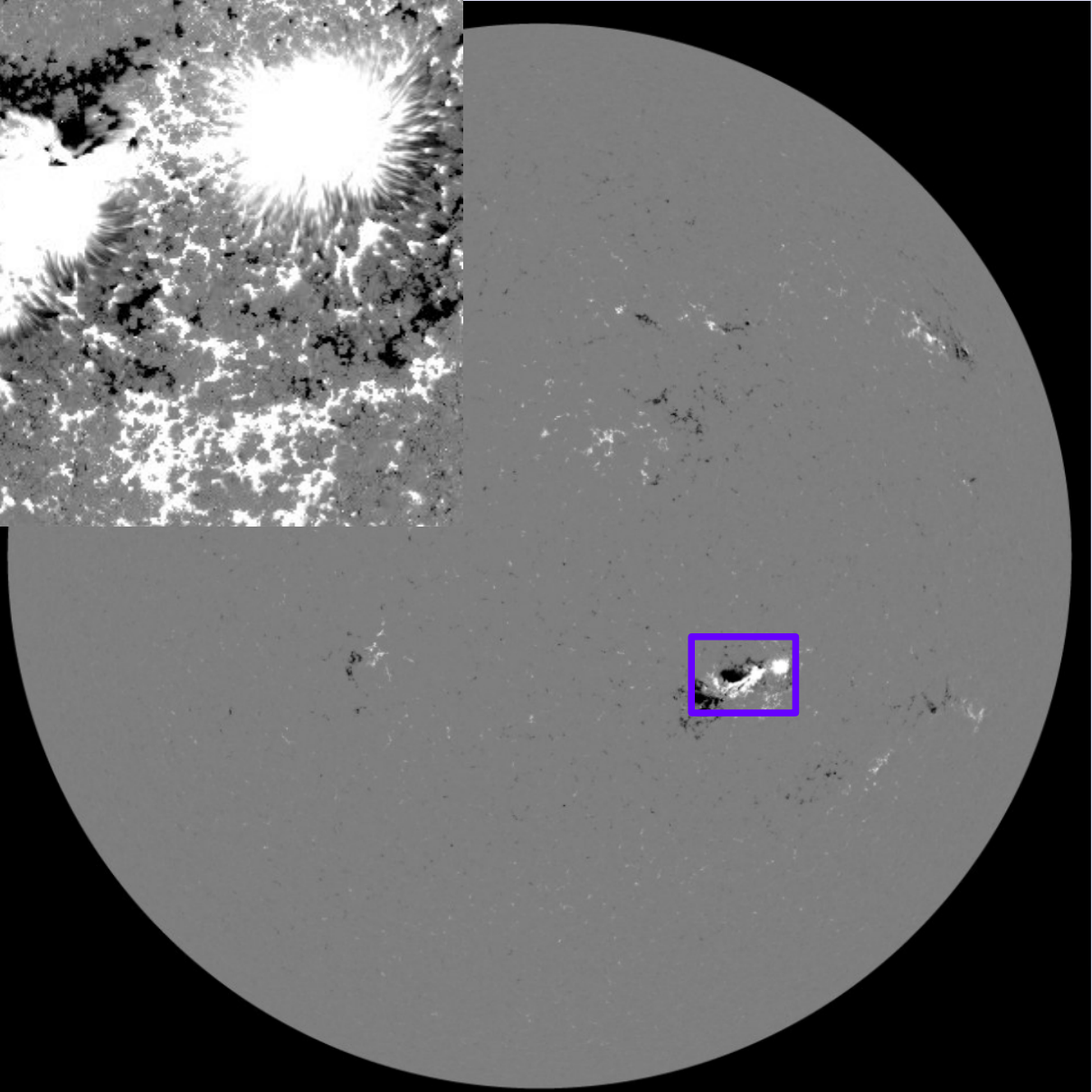
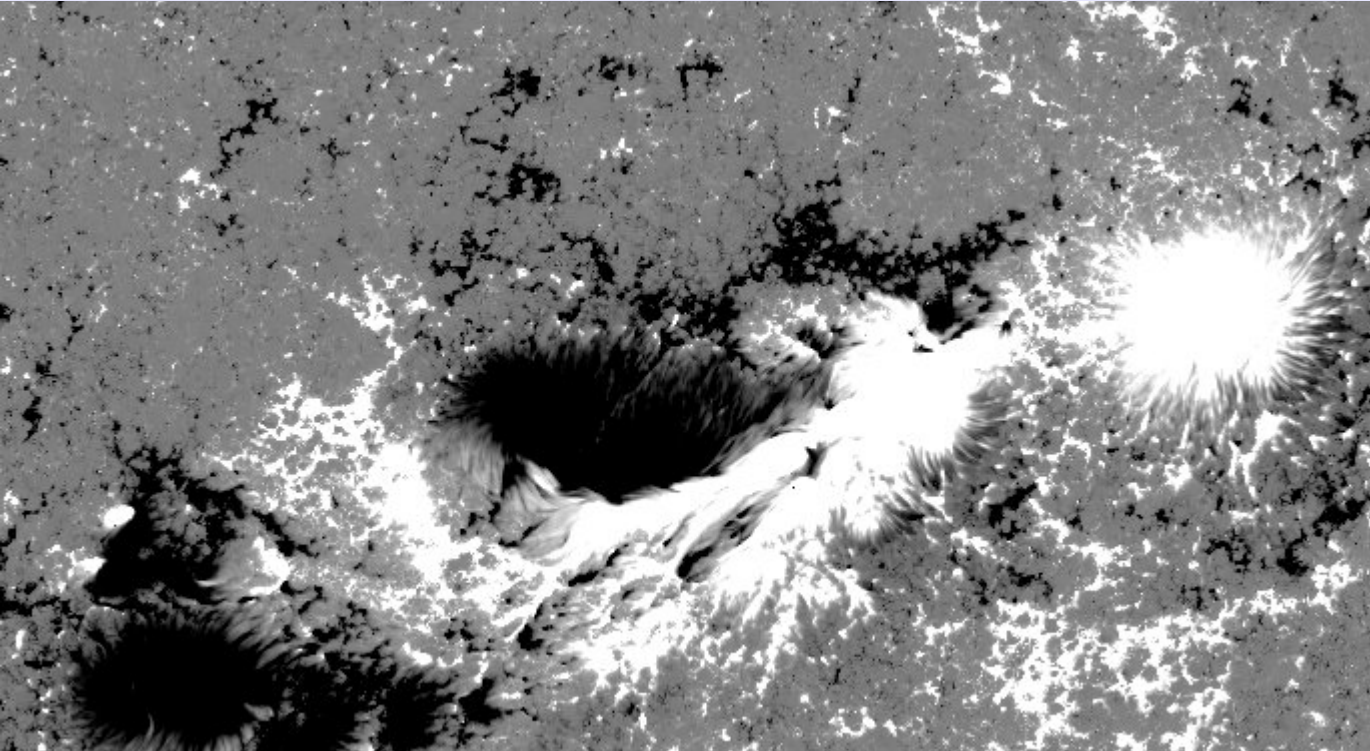
Question: Is this the photospheric magnetic field?



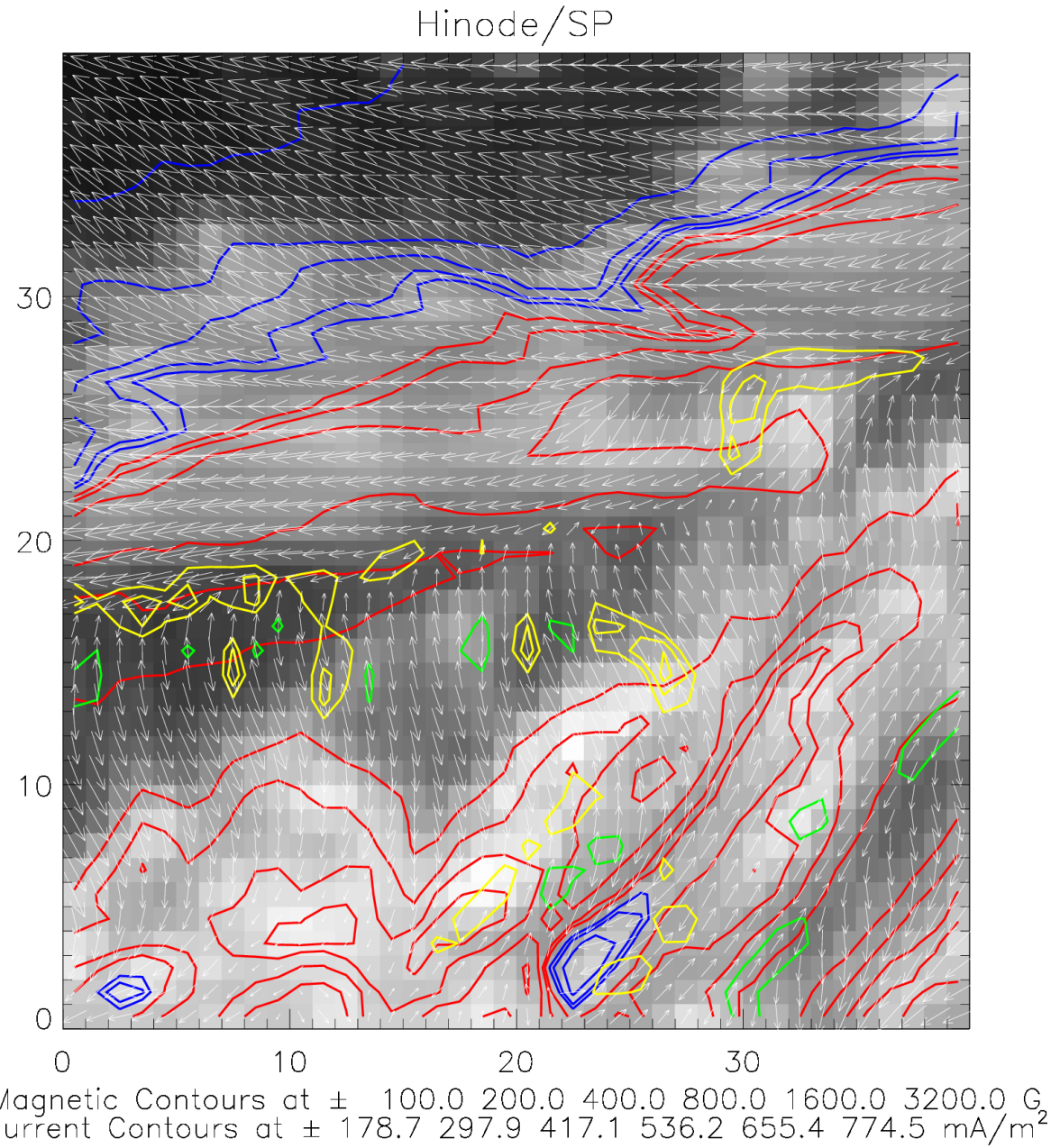
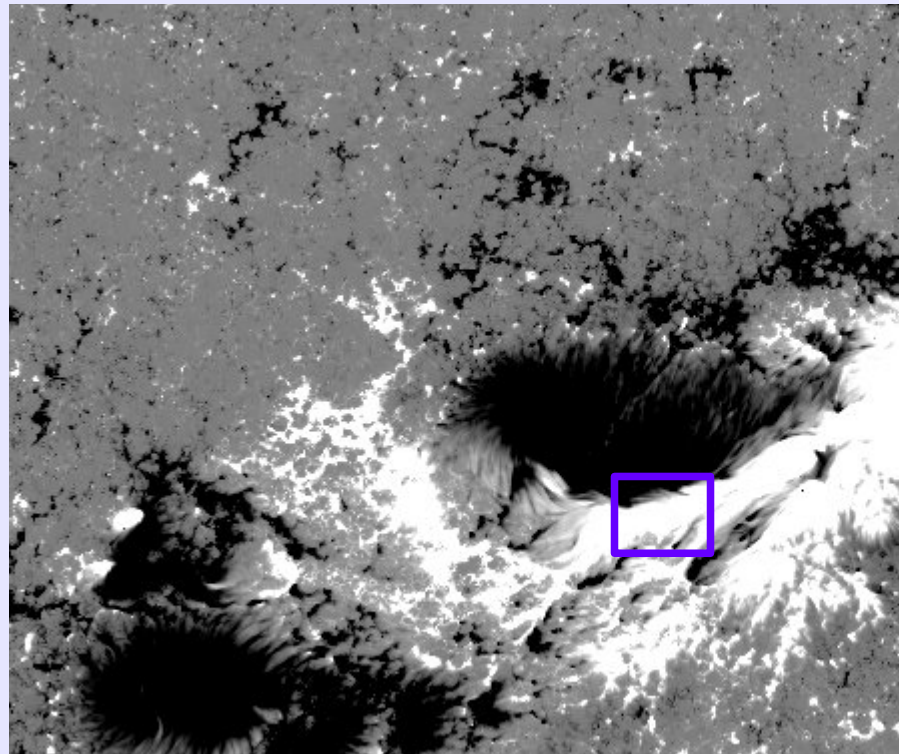
Question: Is this the photospheric magnetic field?



Question: Is this the photospheric magnetic field?

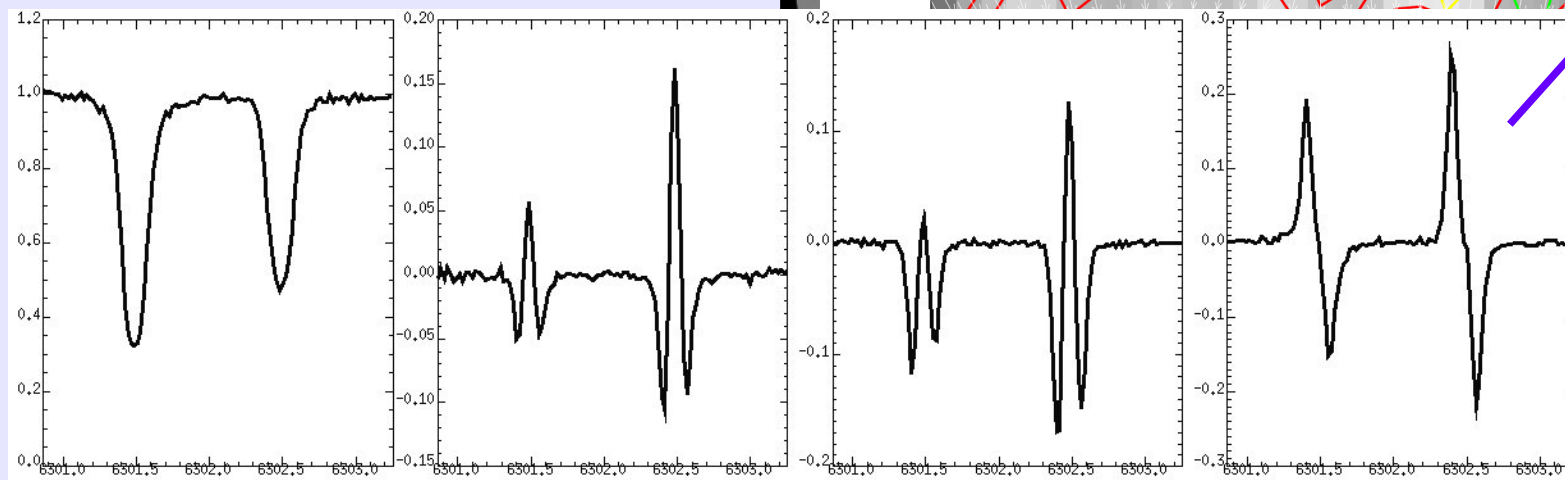
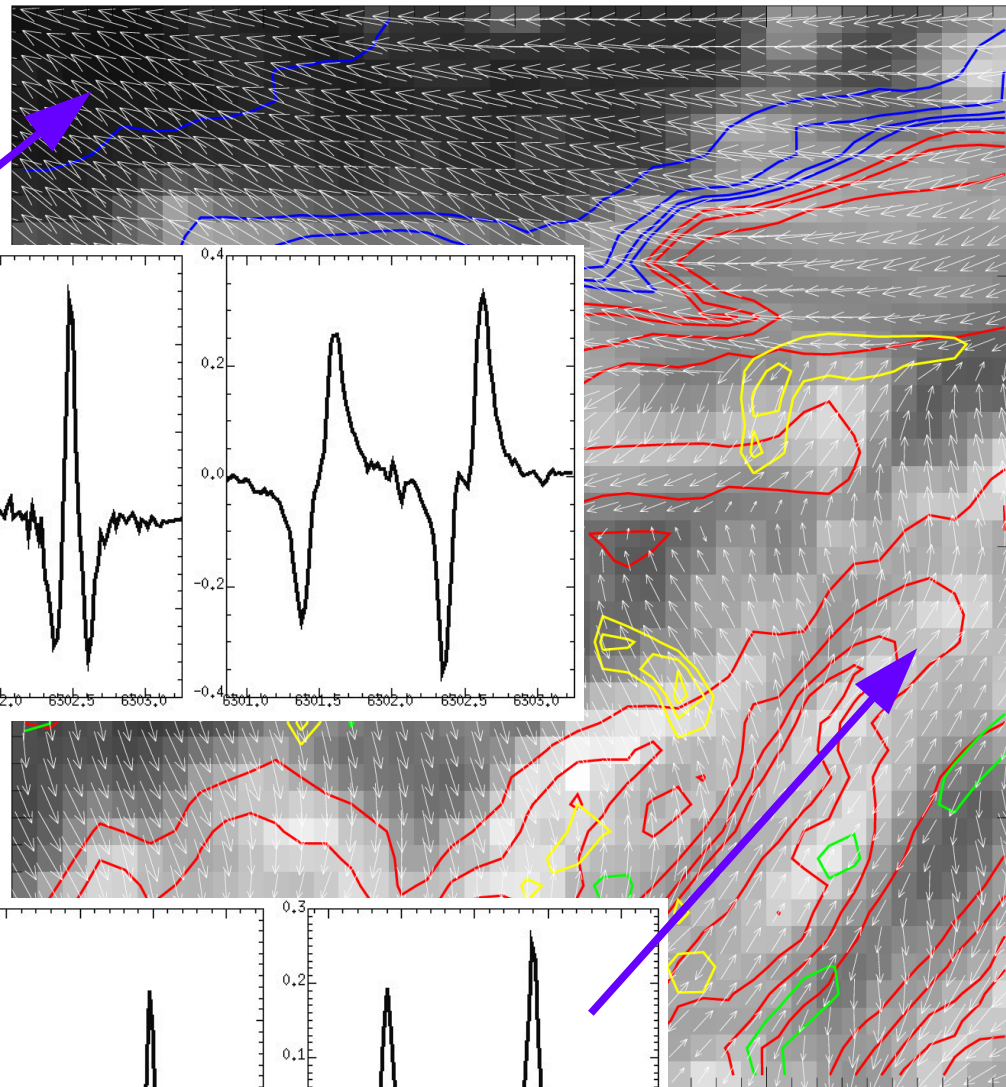
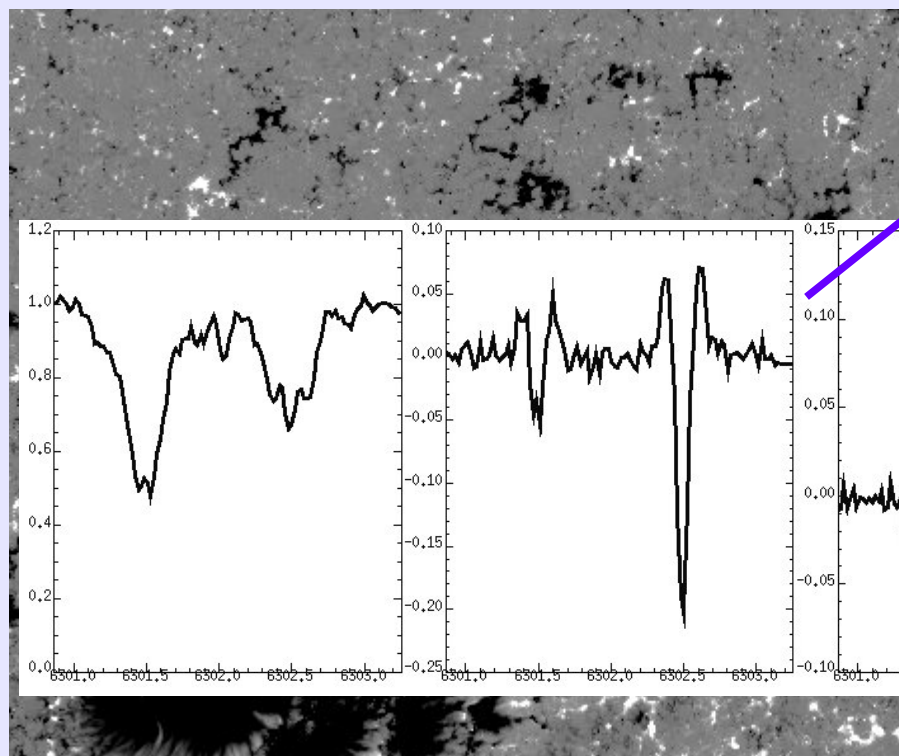


Question: Is this the photosphere

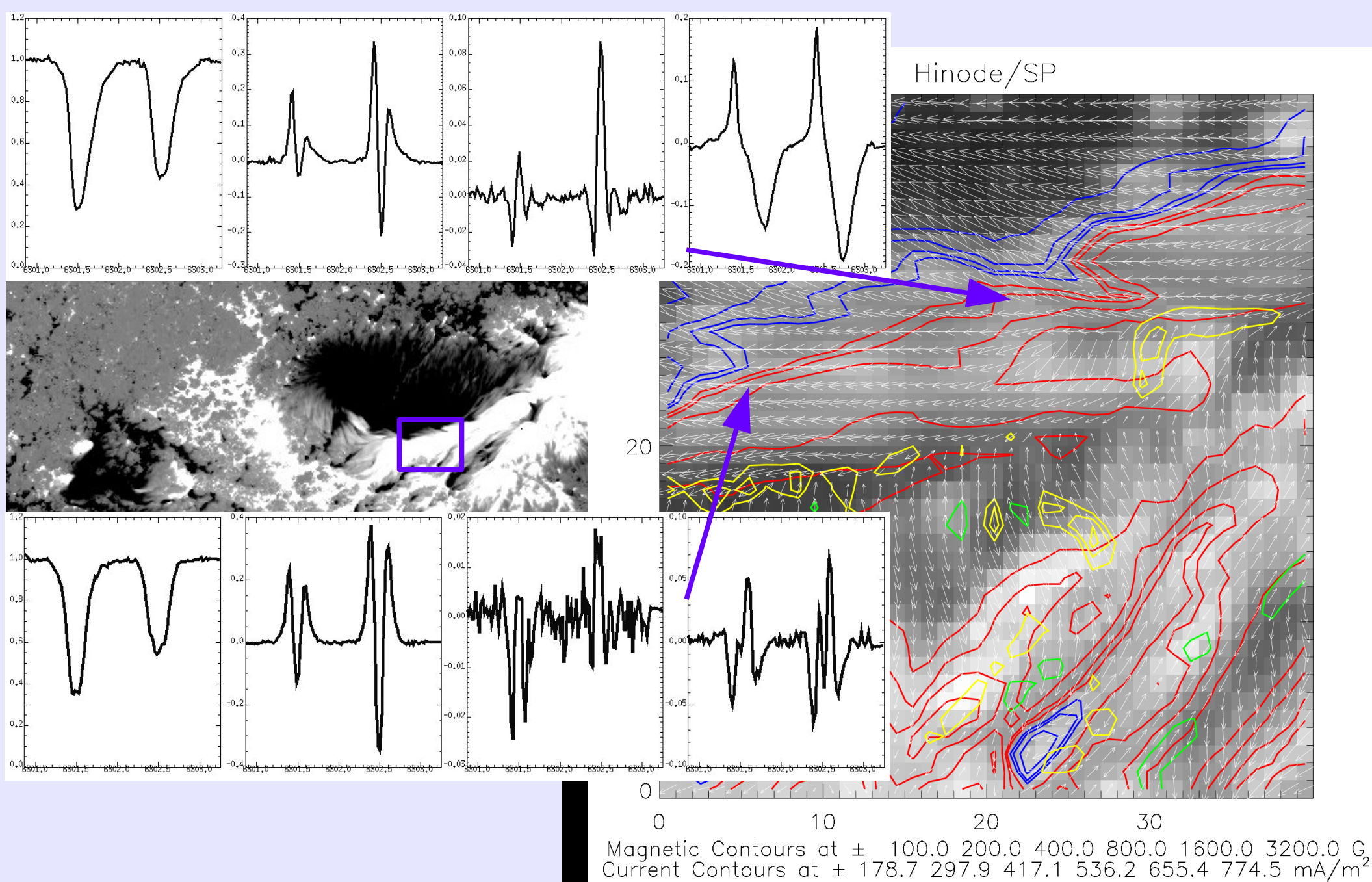


Question: Is this the photosphere

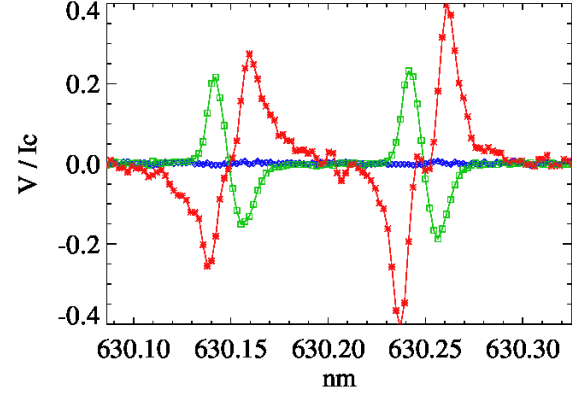
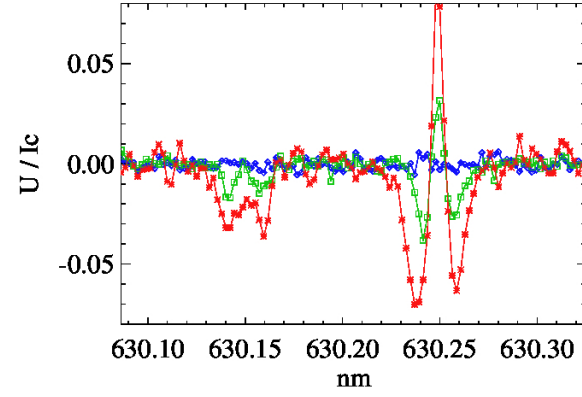
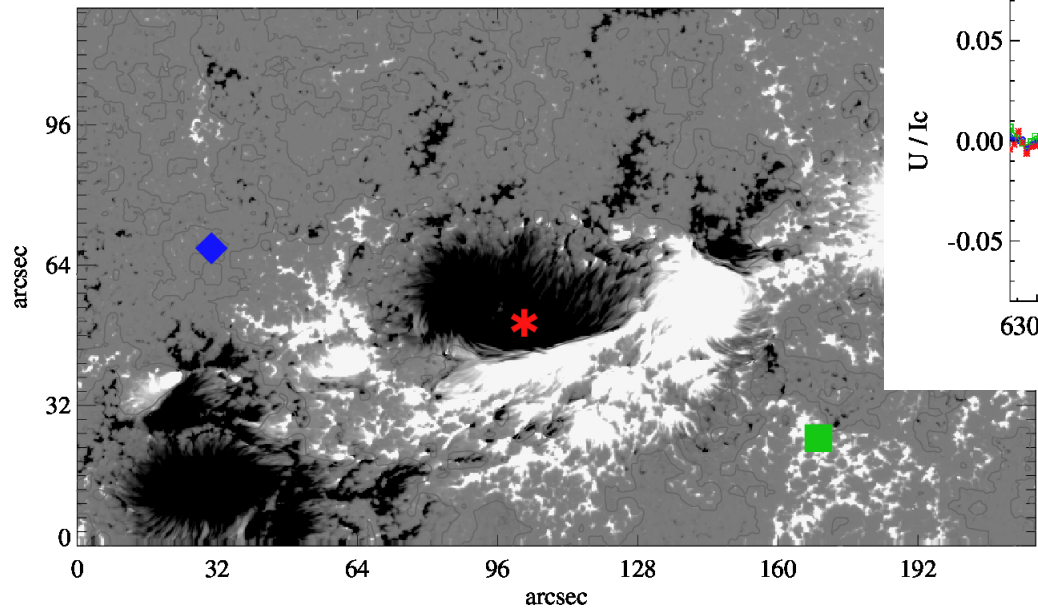
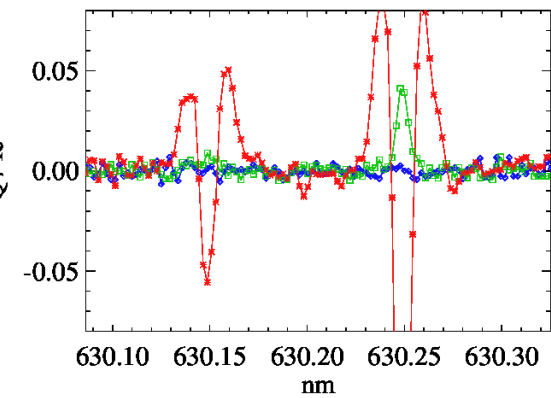
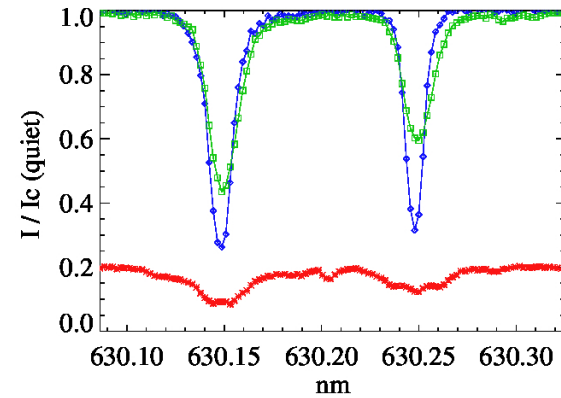
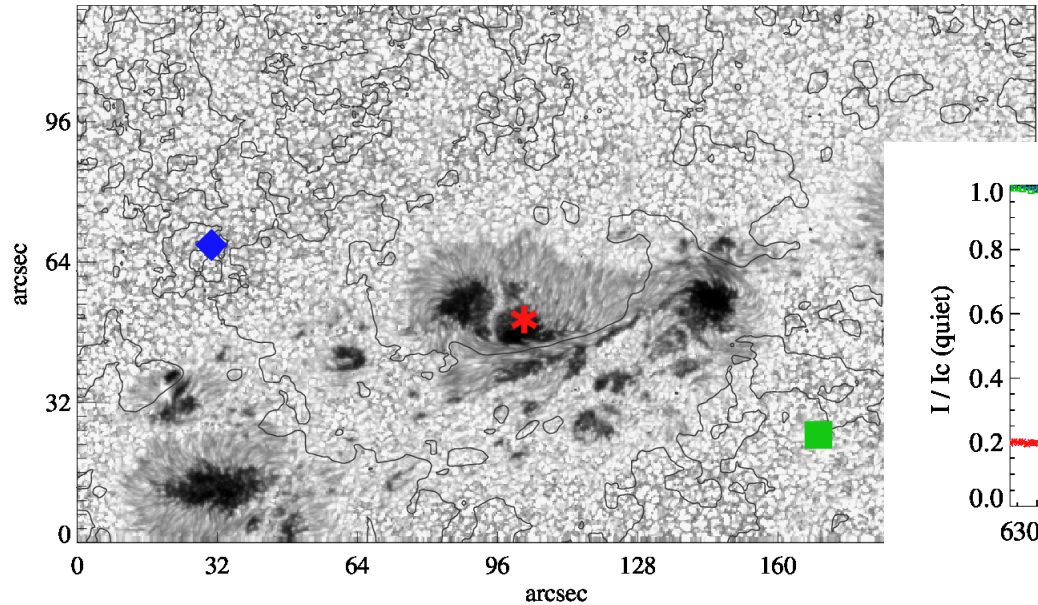
Hinode/SP



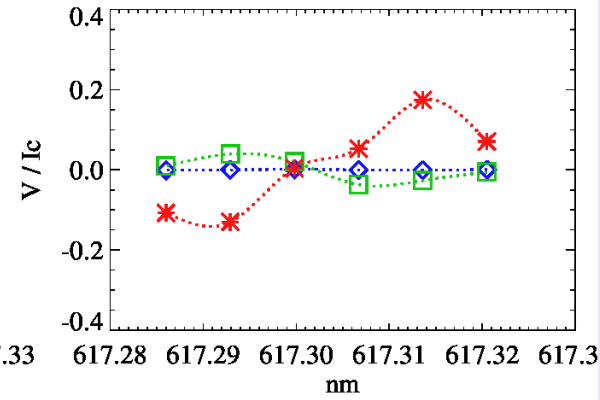
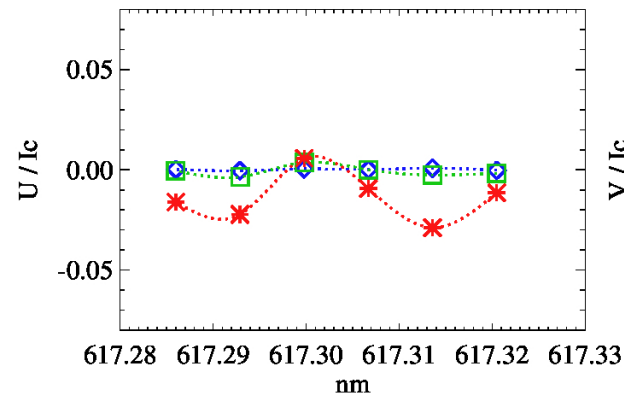
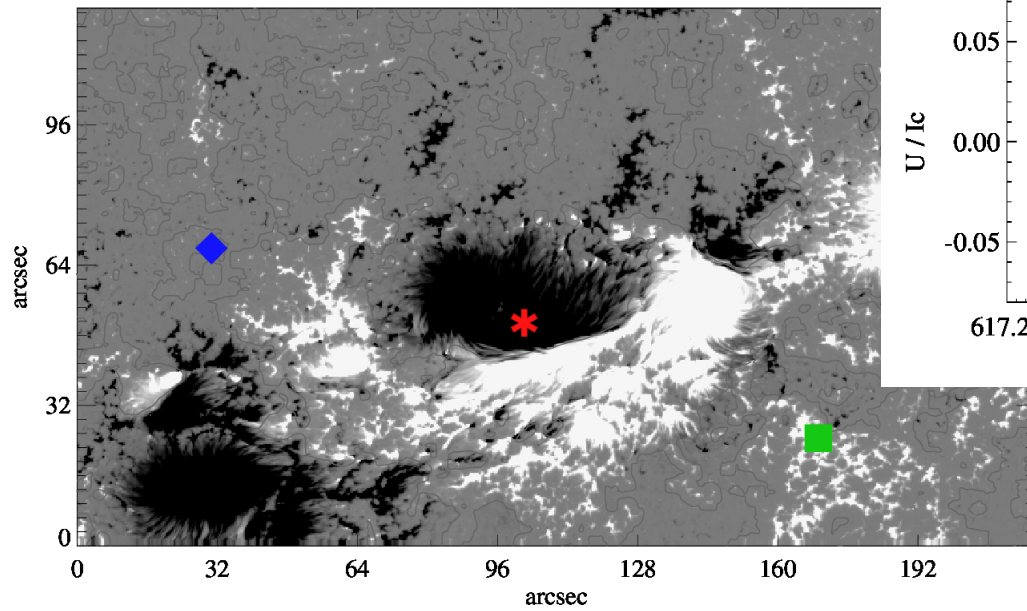
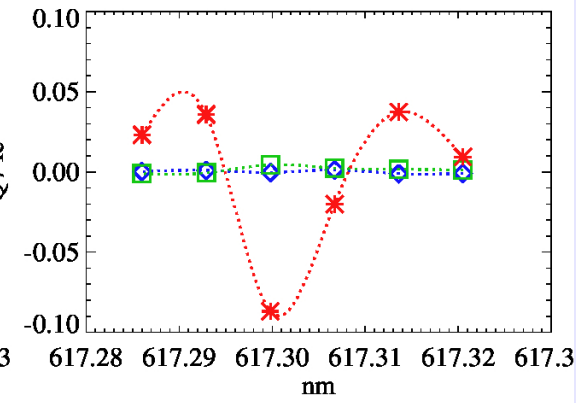
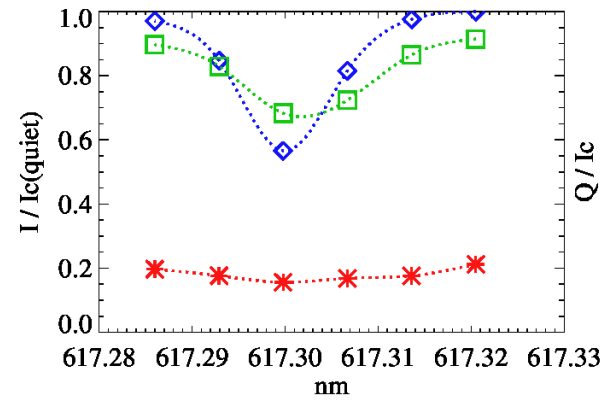
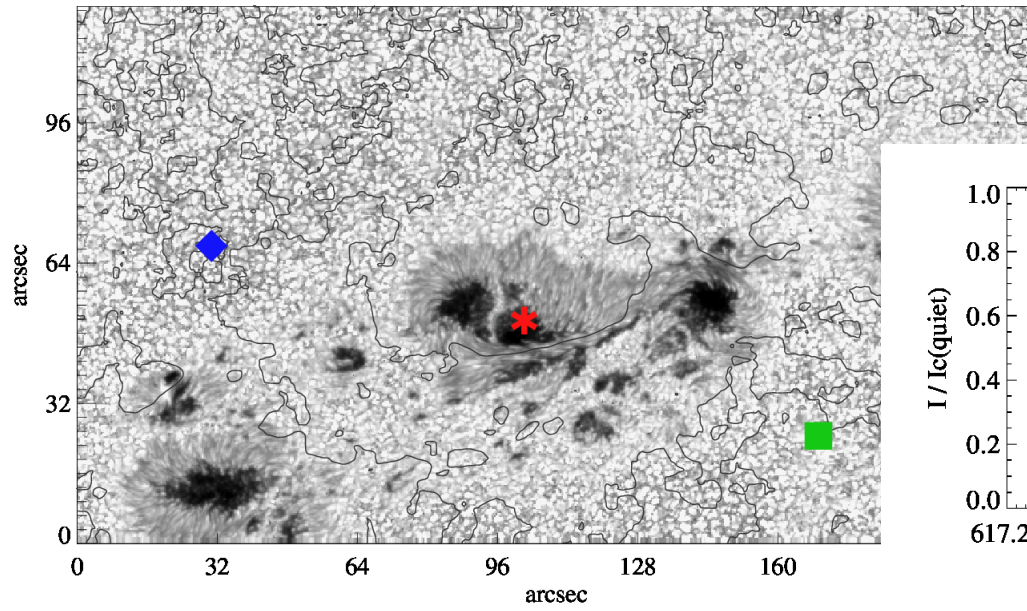
30  
800.0 1600.0 3200.0 G  
36.2 655.4 774.5 mA/m<sup>2</sup>



From Barnes & Leka 2017

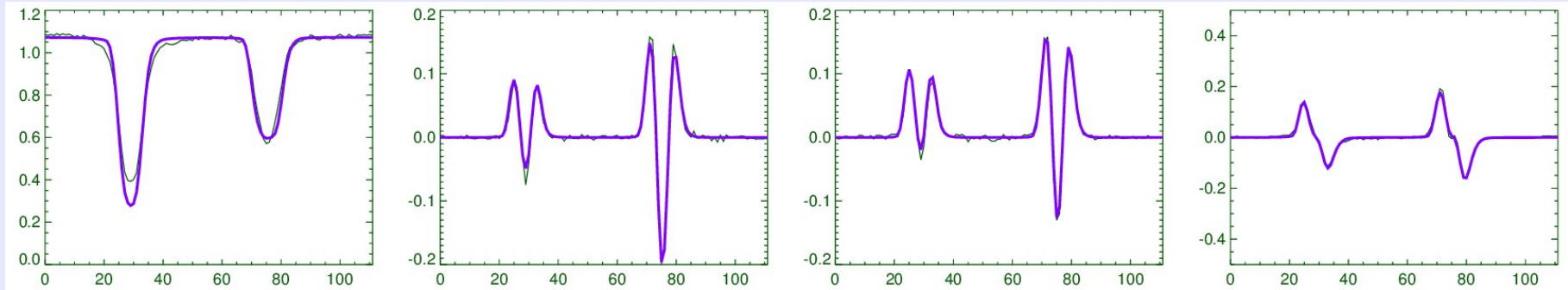


From Barnes & Leka 2017



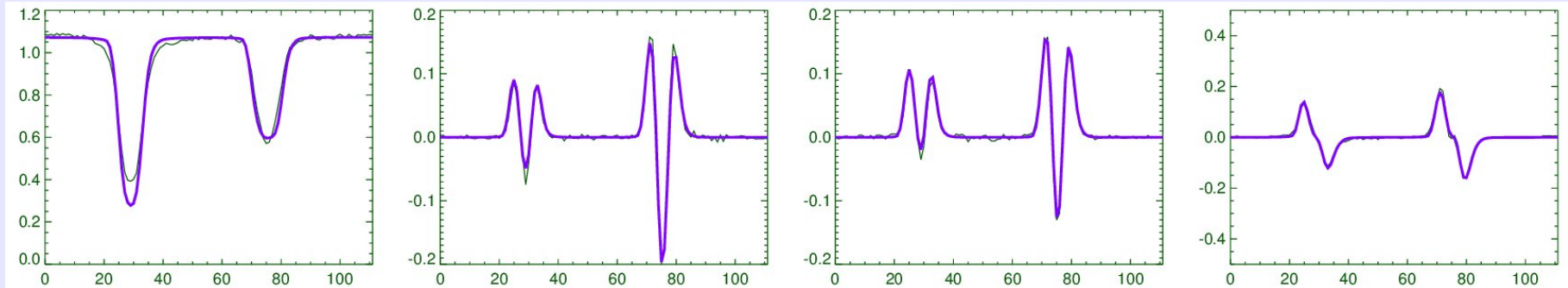
→ Invert / Fit to model to estimate  $B_{\perp}$

*Sometimes it works*

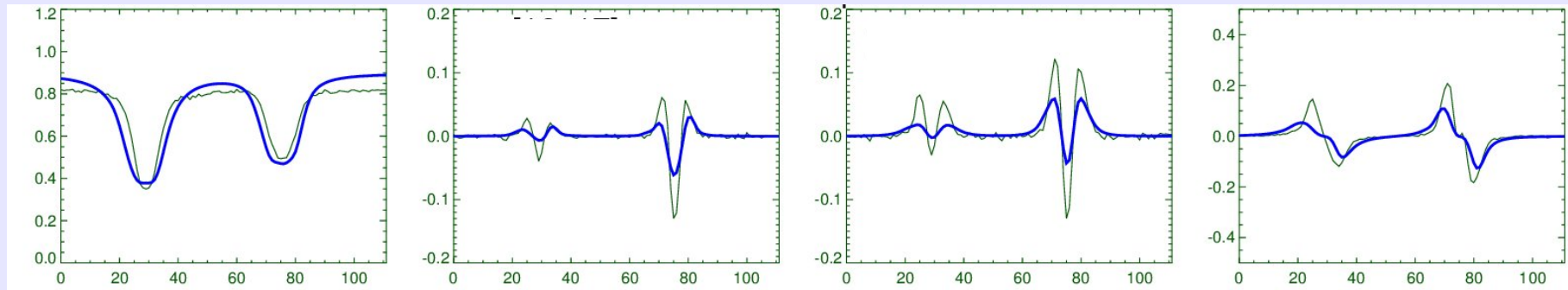


→ Invert / Fit to model to estimate  $B_{\perp}$

*Sometimes it works*



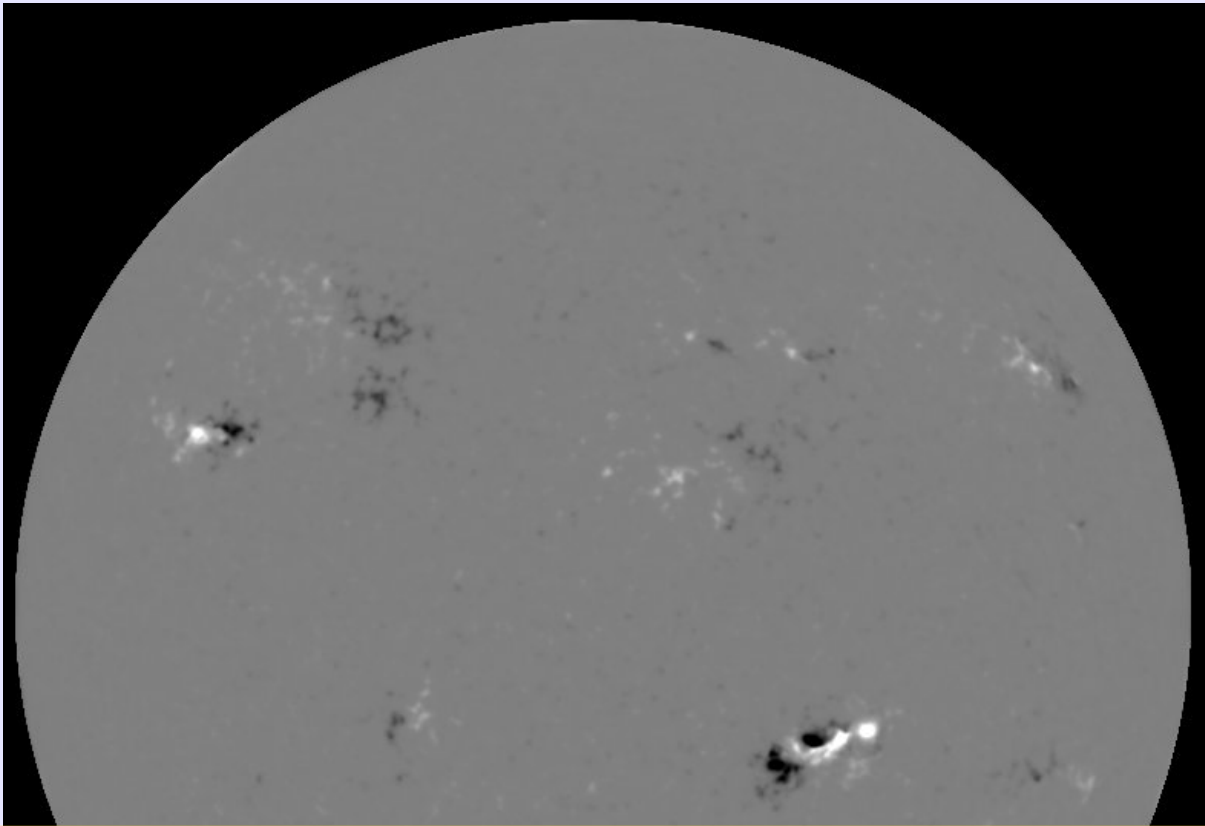
*Sometimes it does not...*



Milne-Eddington inversion (most common):

- Between 8 – 11 parameters fit, strong assumptions.
- Returns a good “average” over pixel area and optical depth.

Question: Is this the photospheric magnetic field?



**Answer:** *no.*

This is an estimate of the pixel-averaged line-of-sight magnetic flux from observations of the impact that said field and the surrounding atmosphere and plasma have with the transmitted light – created using hardware that imparts artifacts and software that invokes many assumptions, some of which we know are wrong.

## Further....

Models may want properties *derived* from the Photospheric Magnetic Field...

Estimating electric current:

→ Line-of-sight magnetograms: limited information ✗

→ Vector magnetograms:  $\mathbf{B}(x, y)$  ✓

→  $\mathbf{J} = \nabla \times \mathbf{B}$  ✗ (*do not have  $dB/dz$* )

→  $J_z = \nabla_h \times \mathbf{B}_h$  ✓

→ *All we need is  $dB_y/dx$  and  $dB_x/dy$ . Simple!*

Take a step back:

•  $\mathbf{B}_h$  – *how do we get this?*

→ Combination of circular and linear polarization signals.

→ Disparate signal strengths, noise.

→ Invert / Fit to model to estimate  $\mathbf{B}_\perp$

→ Use another model to determine direction

→ (that's a whole 'nother talk...)

## Further....

Models may want properties *derived* from the Photospheric Magnetic Field...

Estimating electric current:

→ Line-of-sight magnetograms: limited information ✗

→ Vector magnetograms:  $\mathbf{B}(x, y)$  ✓

→  $\mathbf{J} = \nabla \times \mathbf{B}$  ✗ (do not have  $d\mathbf{B}/dz$ )

→  $J_z = \nabla_h \times \mathbf{B}_h$  ✓

→ All we need is  $dB_y/dx$  and  $dB_x/dy$ . Simple!

Take a step back:

•  $\mathbf{B}_h$  – how do we get this?

→ Combination of circular and linear polarization signals.

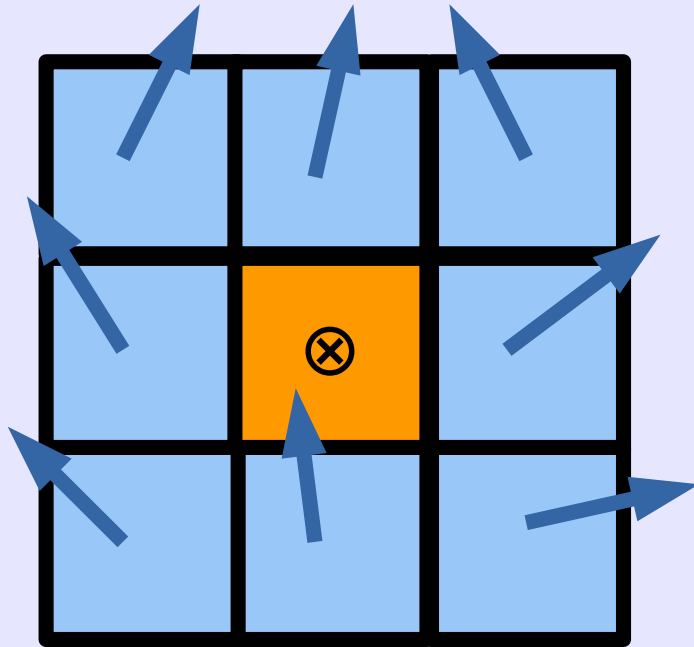
→ Disparate signal strengths, noise.

→ Invert / Fit to model to estimate  $\mathbf{B}_\perp$

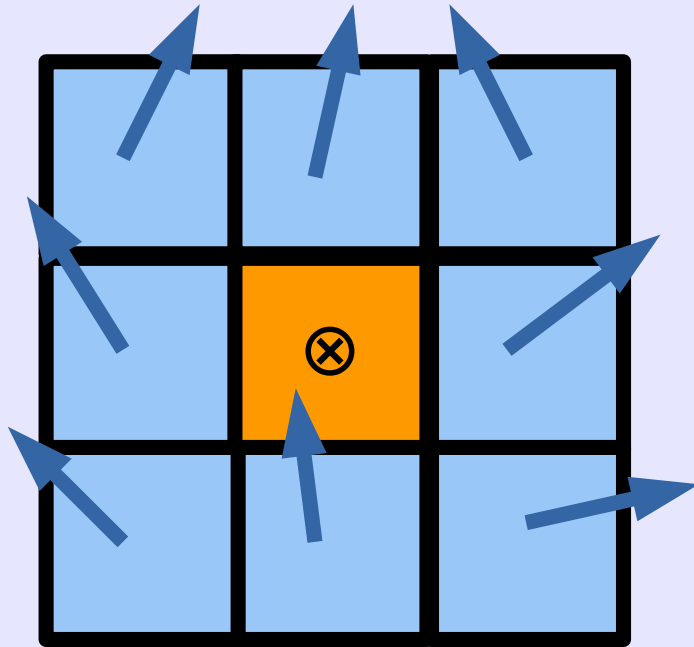
→ Use another model to determine direction

→ (that's a whole 'nother talk...)

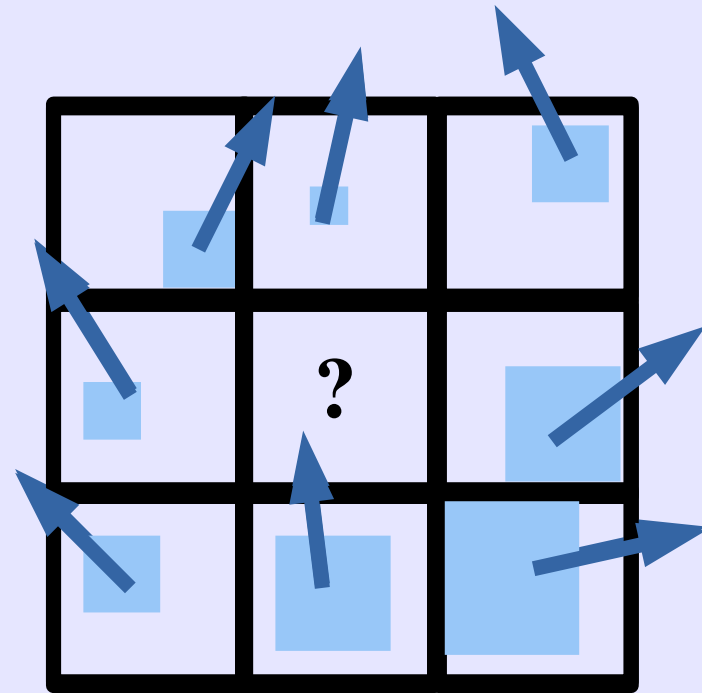
•  $d/dx, d/dy$  – can we do this?

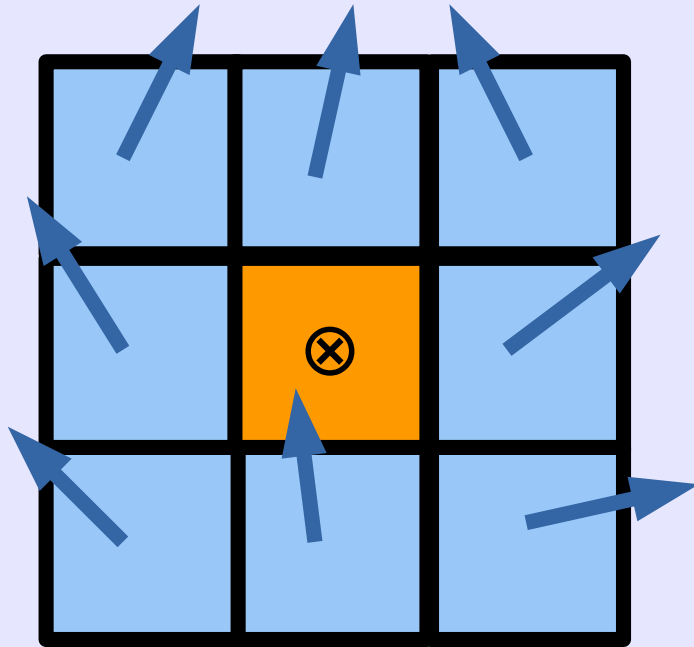


- Each pixel has a  $B_h$
- Choose your stencil,
- $J_z = \nabla_h \times B_h$  ✓



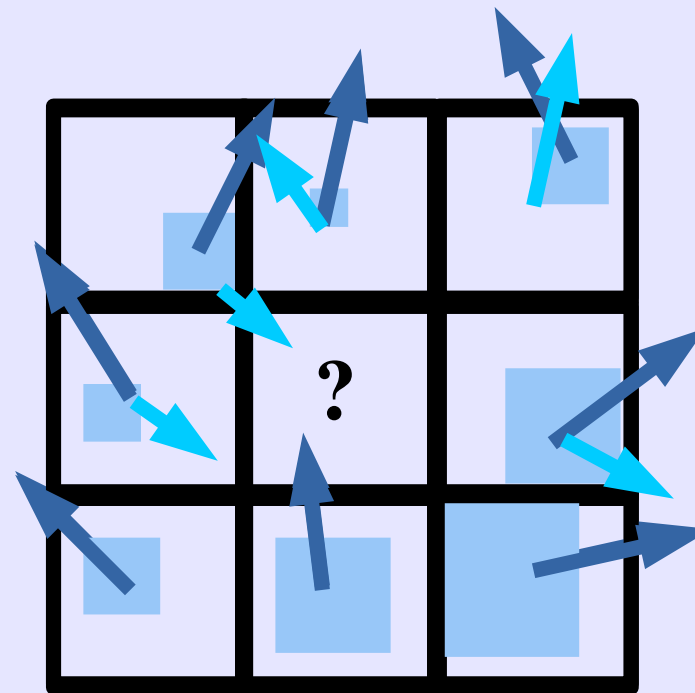
But...we aren't resolving  $Bh$





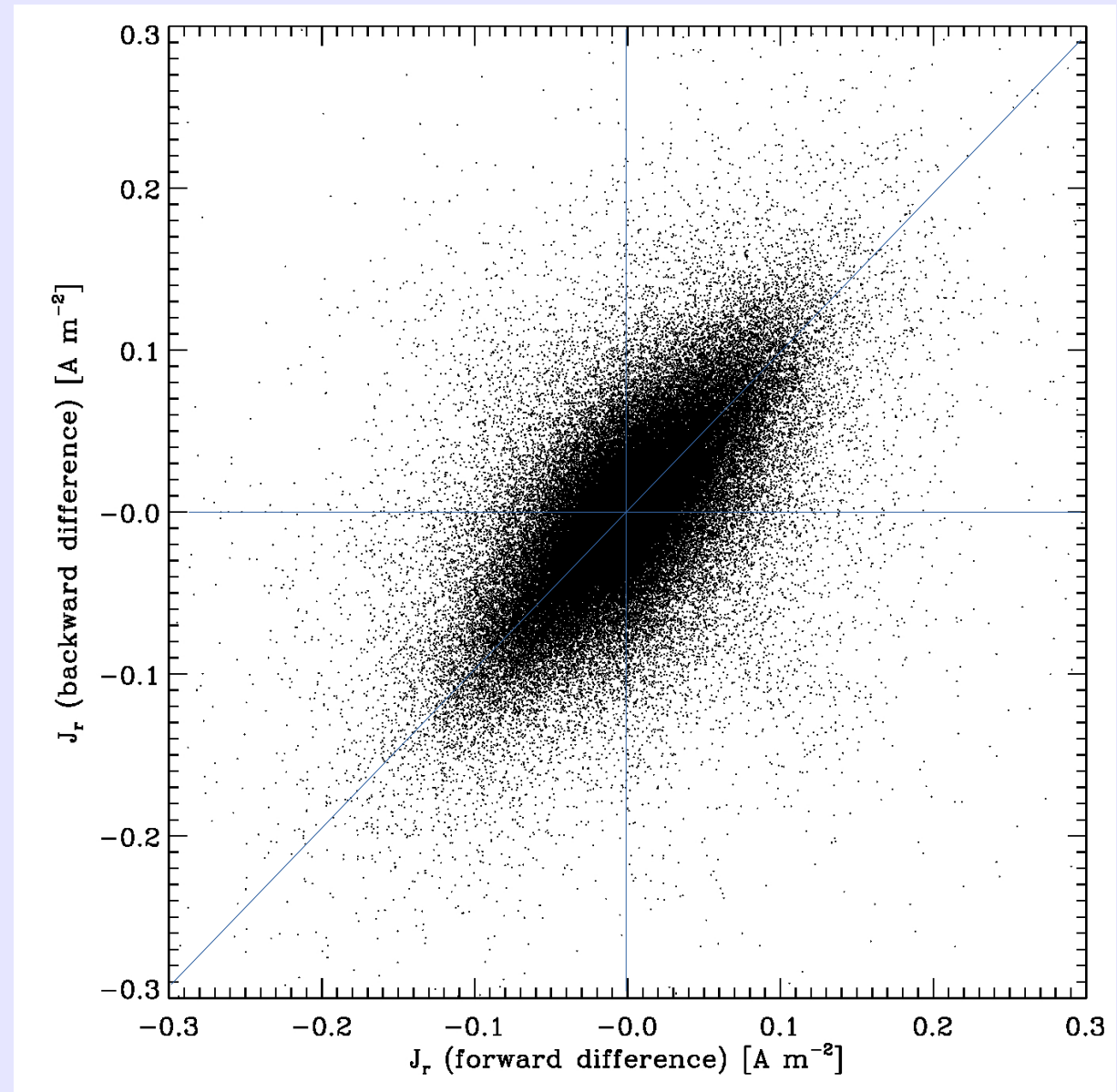
But...we aren't resolving  $Bh$

*What does a derivative mean?*



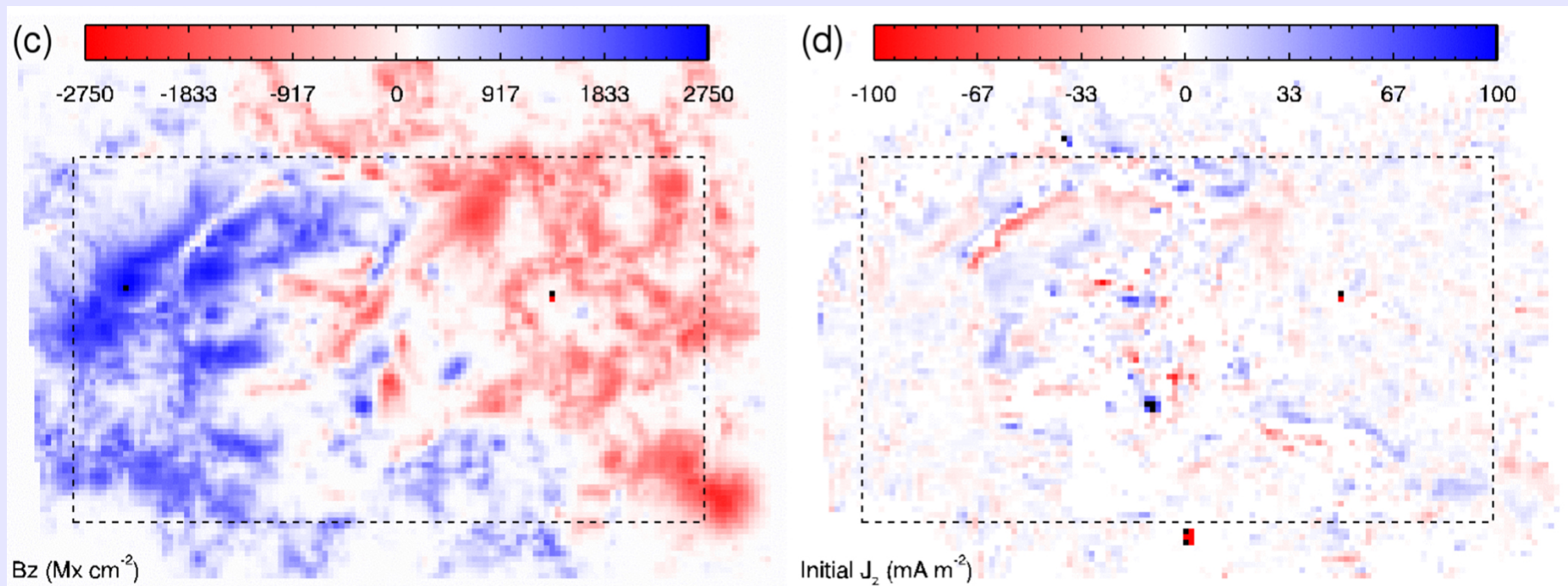
...but even the stencil matters.

- Comparison of  $J_z$  computed from Hinode/SP data using forward vs. backward derivative stencils.
- Only well-measured field is included.
- Note the *sign* can change in some instances.



From Barnes & Leka 2017

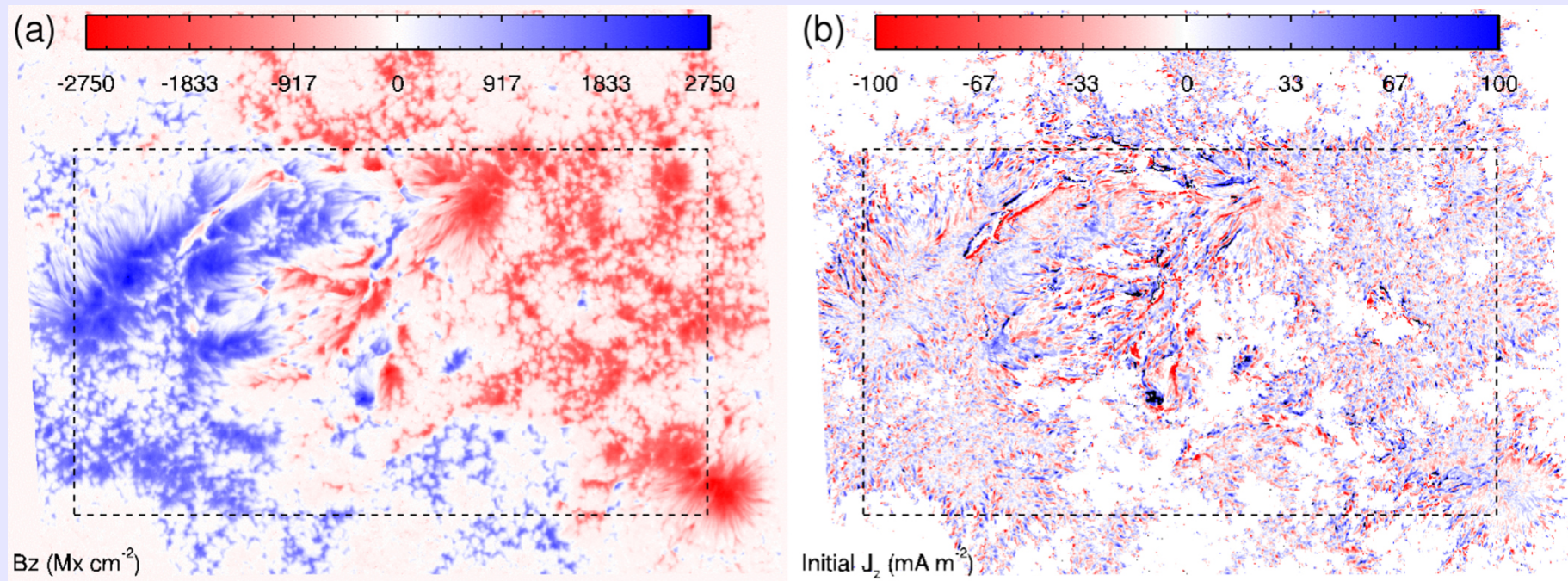
# Using the photospheric $B$ boundary: spatial resolution & resampling.



From DeRosa+ 2015

Nice vector magnetogram:  $B_z$  on the left,  $J_z$  on the right.  
Spatial resolution  $\sim 1.25''$   
(some people call this “high resolution”)

# Using the photospheric $B$ boundary: spatial resolution & resampling.



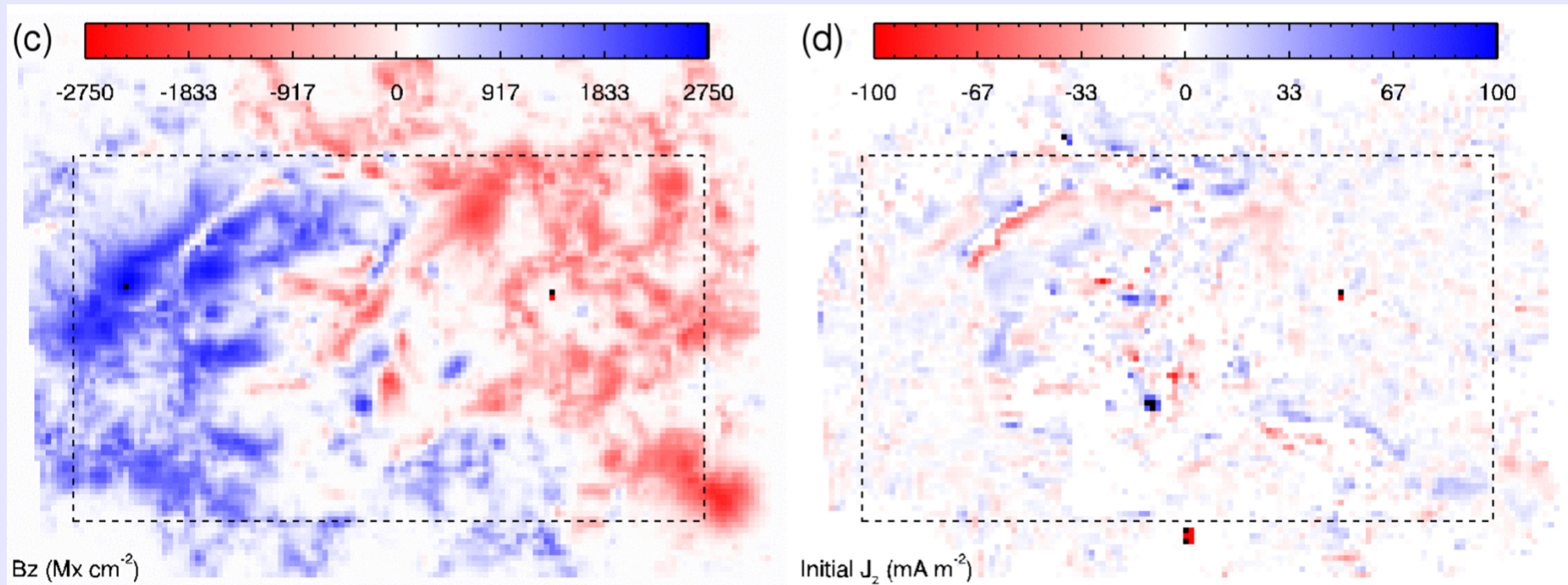
From DeRosa+ 2015

*Nicer* vector magnetogram:  $B_z$  on the left,  $J_z$  on the right.

Spatial resolution  $\sim 0.16''$

(I would call this “high resolution”)

# Using the photospheric $B$ boundary: spatial resolution & resampling.



From DeRosa+ 2015

*But that's too many pixels! I'll just bin it down to where my code will run....*

*Q: does that matter?*

# Using the photospheric $B$ boundary: spatial resolution & resampling.

**Goal:** *best* represent our best understanding of the state of the solar plasma.

**Approach:** *resample* to maintain (?):

- Field strength and characteristics
- Forces
- Currents

**Take away:** spatial resolution and “data size reduction” are *not* the same thing.

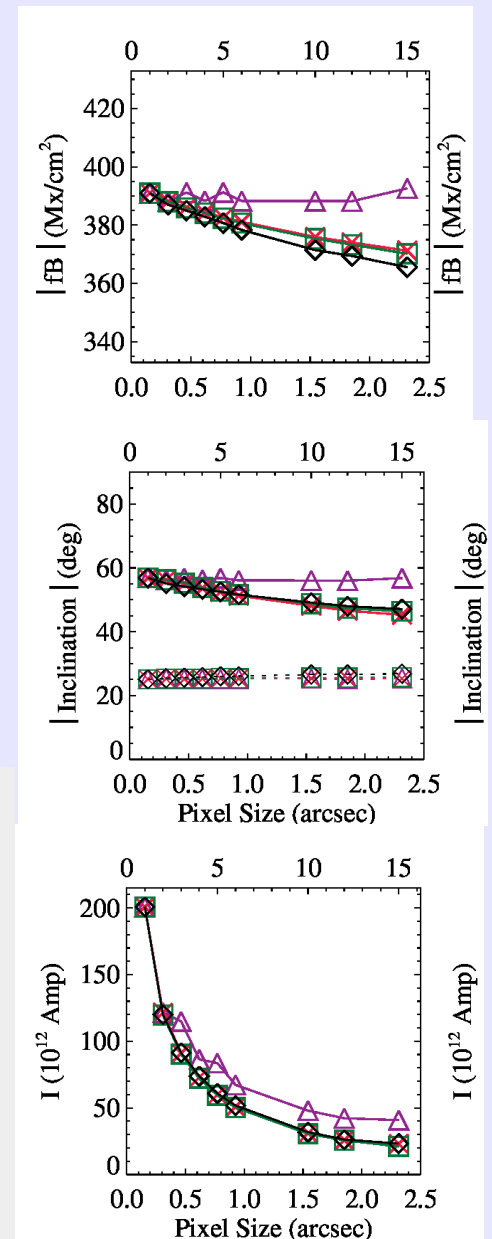
Impact of:

- spatial resolution  $\diamond$ ,
  - post-facto binning  $\square$ ,  $\times$
  - post-facto resampling  $\triangle$
- on:

*top:* average pixel flux

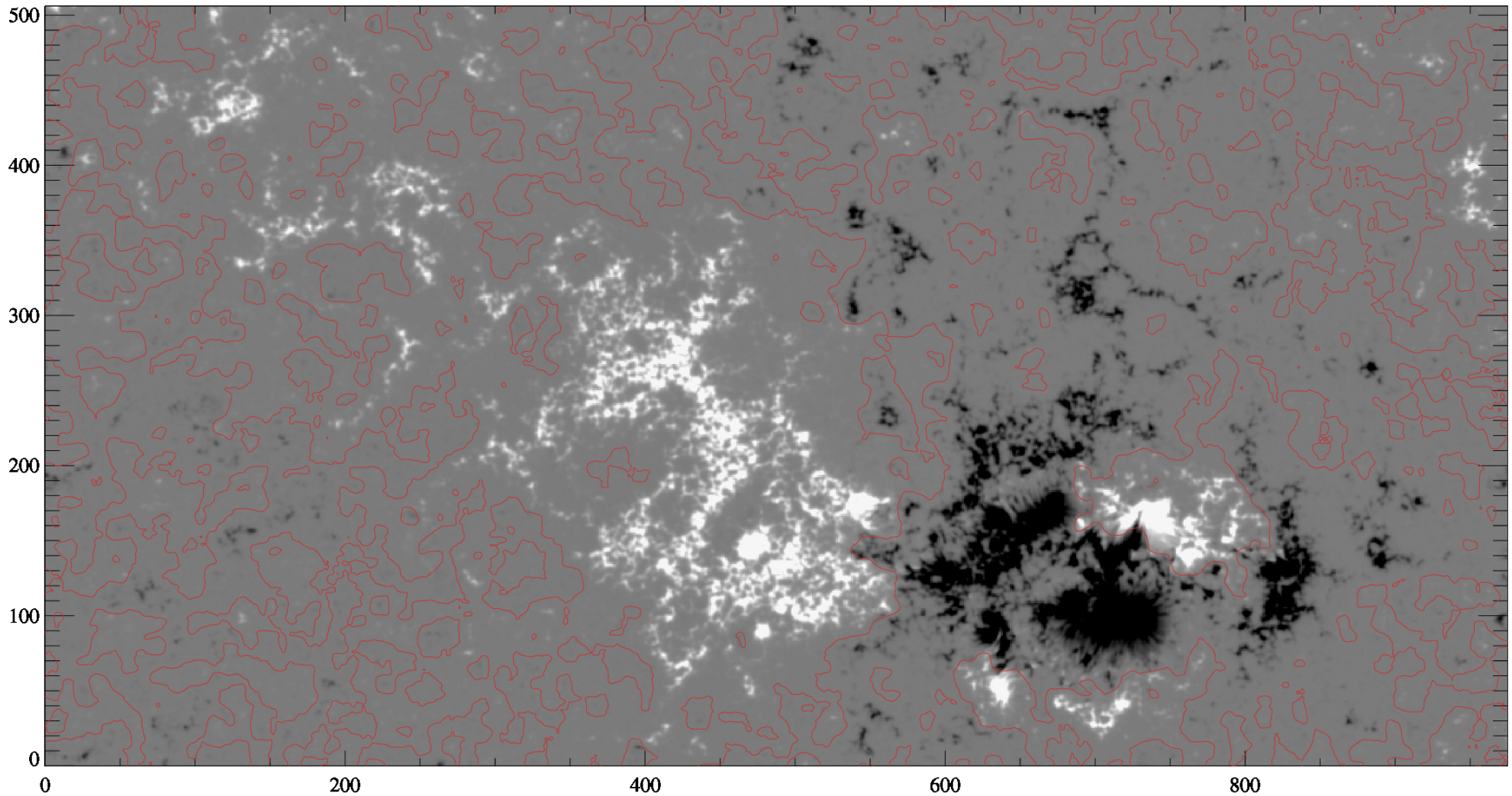
*middle:* inclination angle

*bottom:* total vertical current

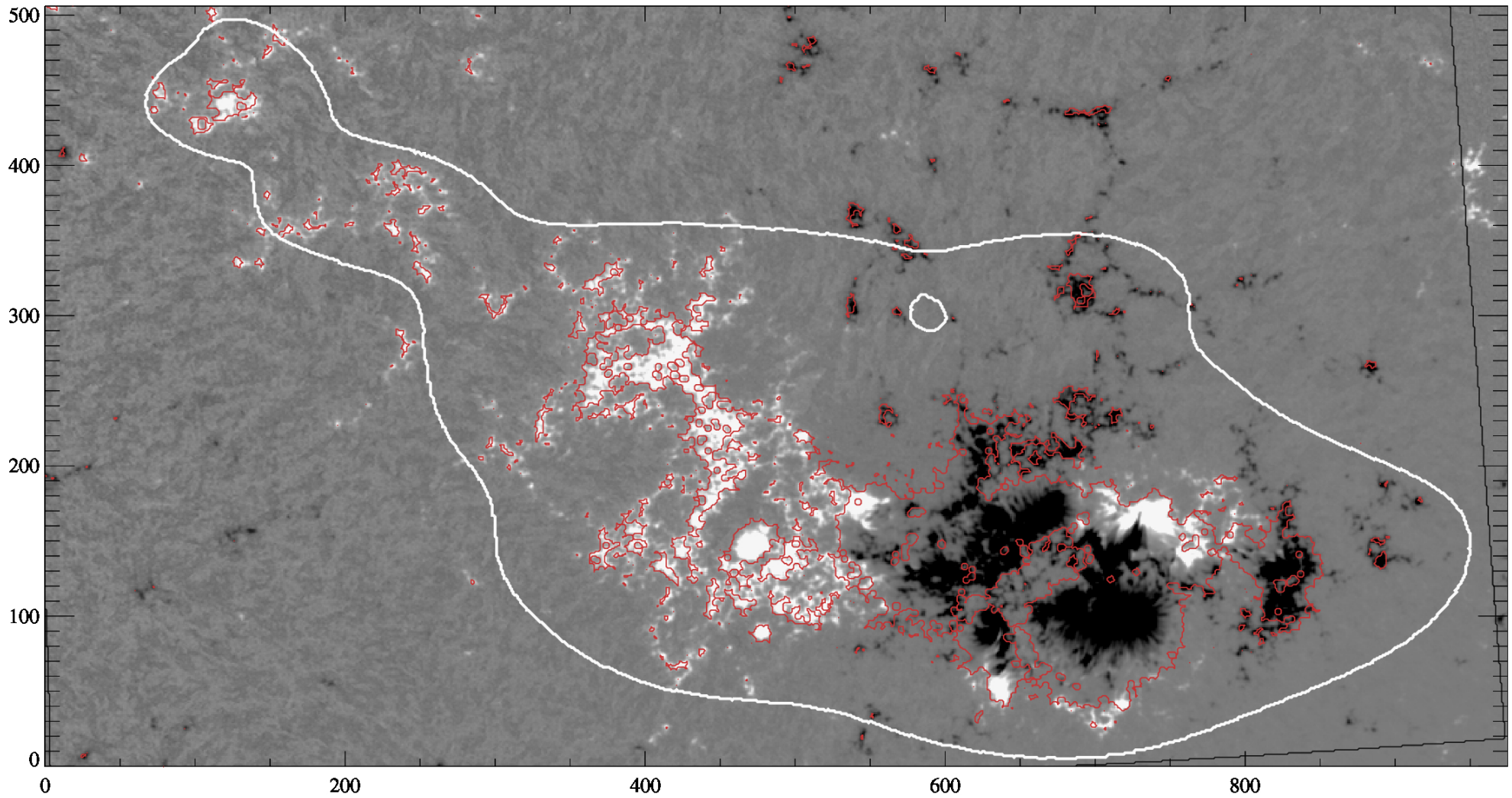


From Leka & Barnes 2011

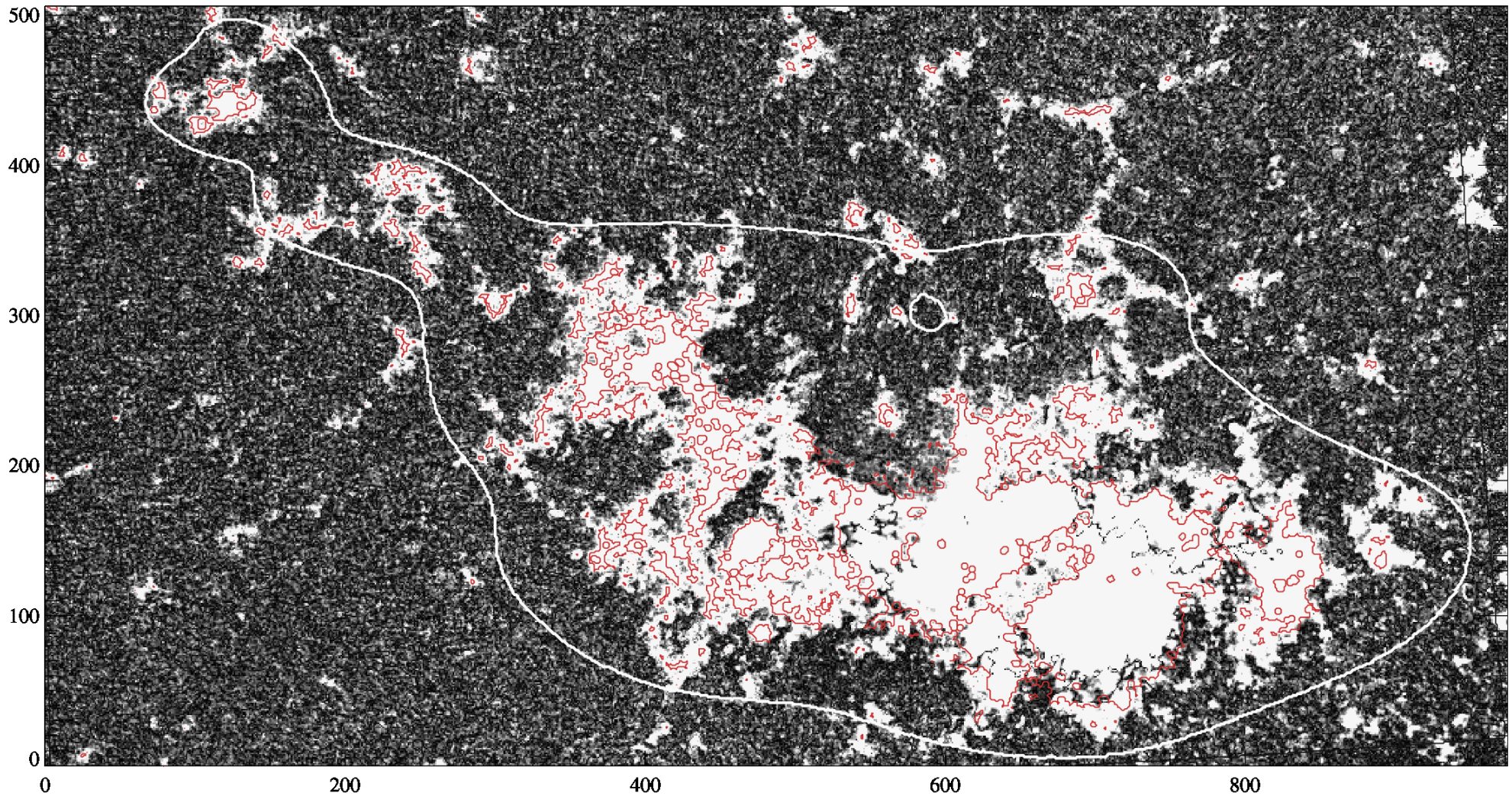
Using the photospheric **B** boundary: noise.



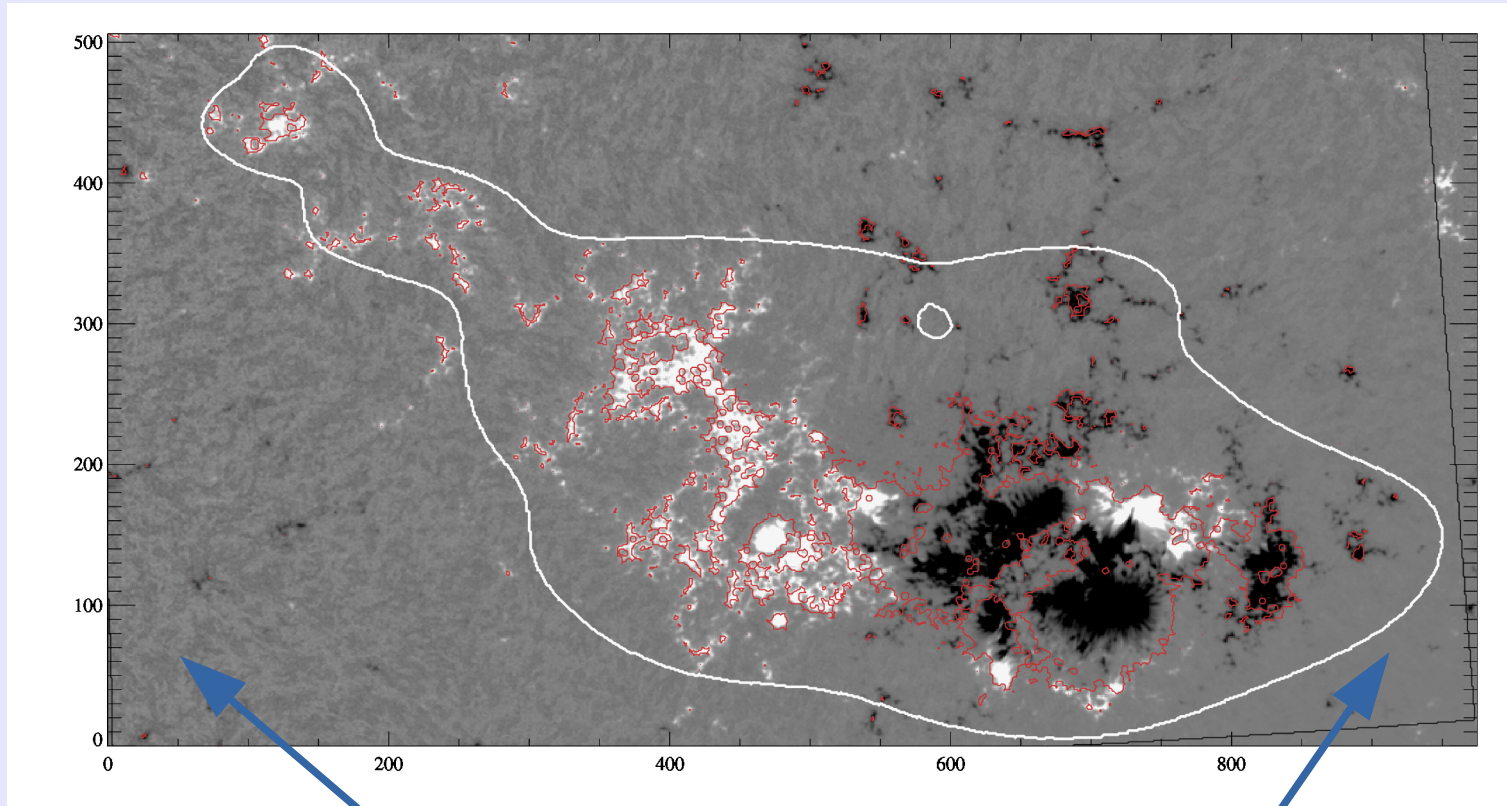
Using the photospheric  $B$  boundary: noise.



Using the photospheric  $B$  boundary: noise.



Using the photospheric **B** boundary: noise.



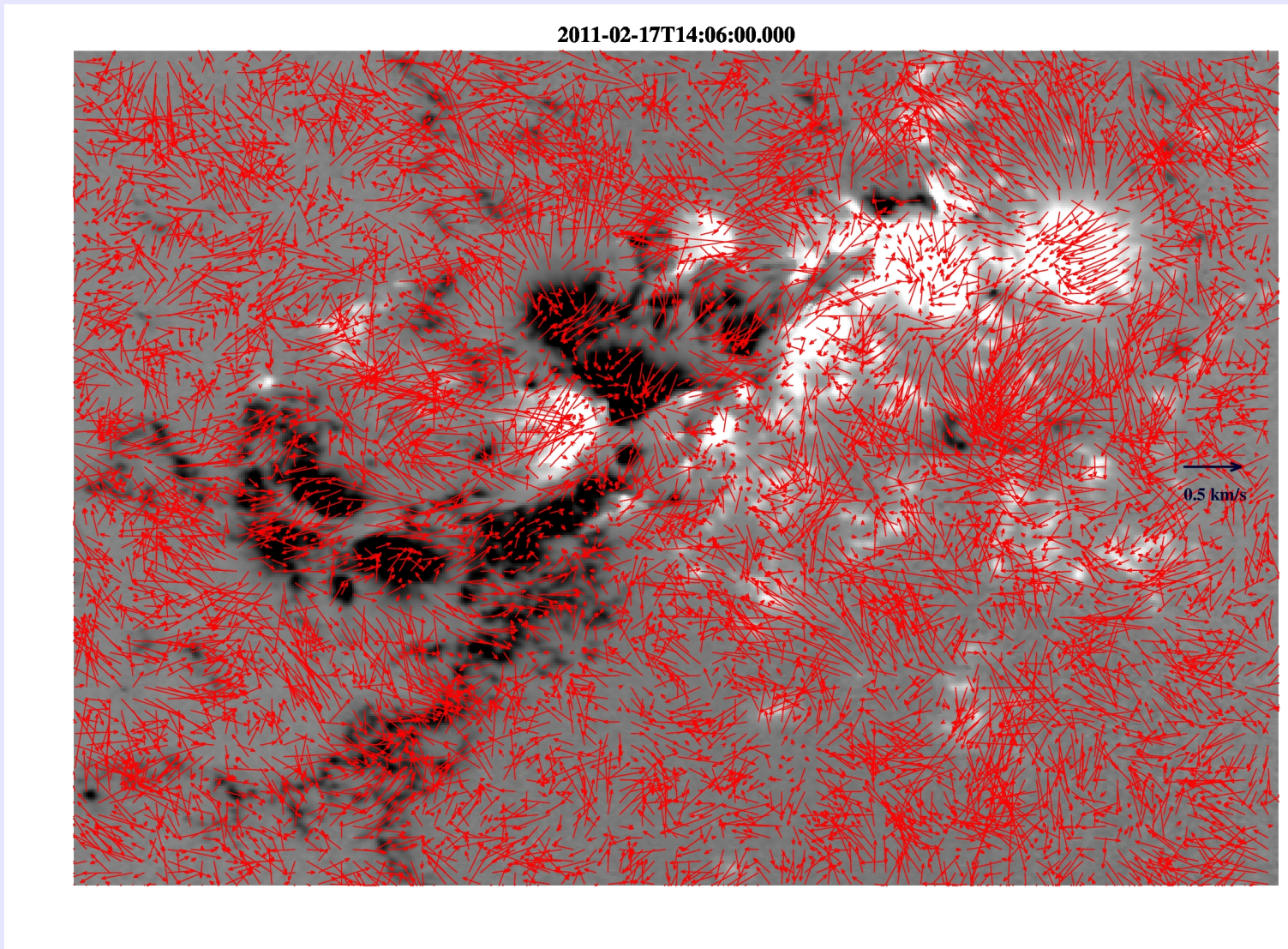
30G difference in noise level

Differences: All pixels vs.  $S/N \geq 3$  pixels:

Total flux: 50% difference

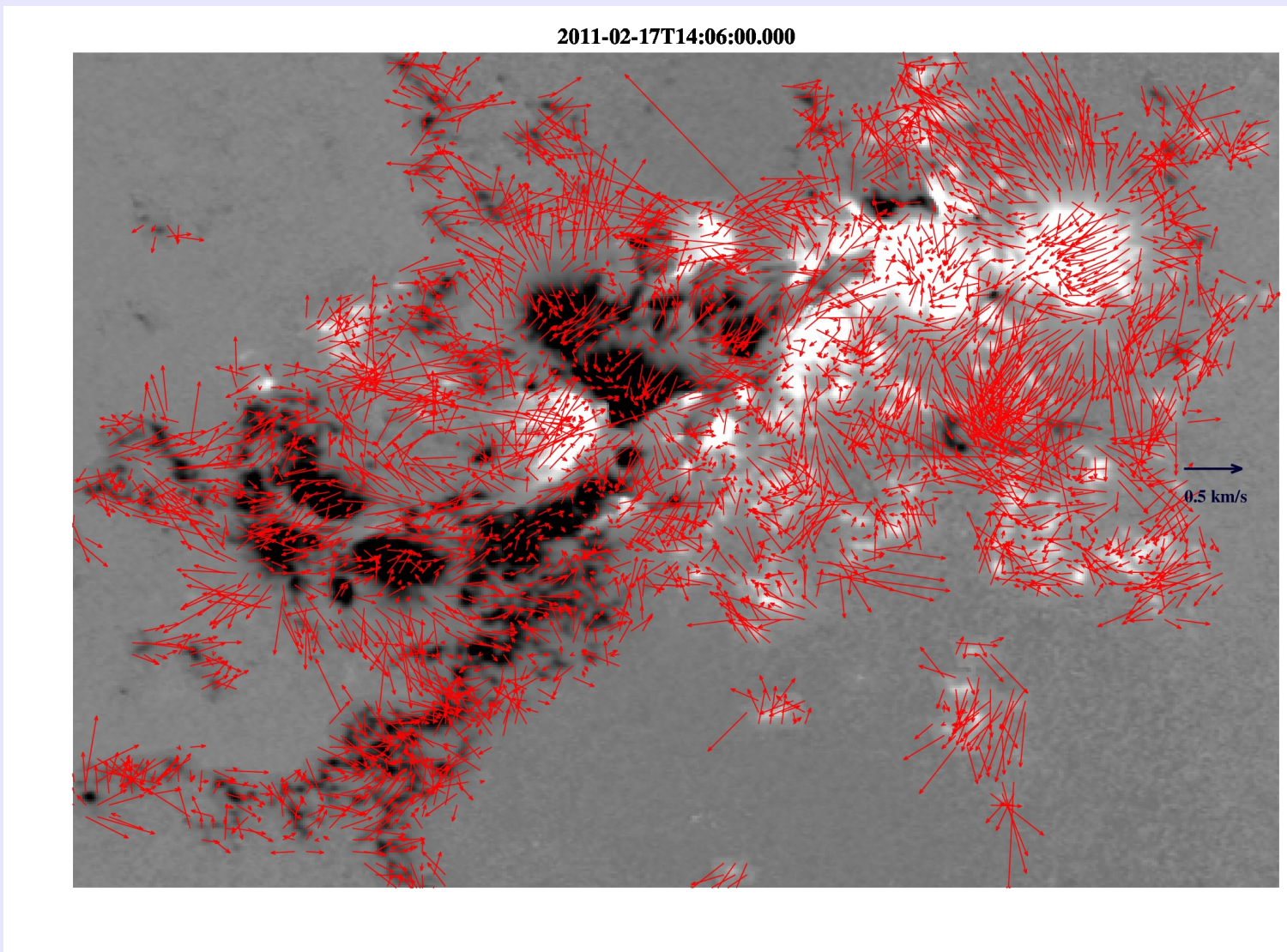
Total current: 85% difference

Using the photospheric  $B$  boundary: noise.



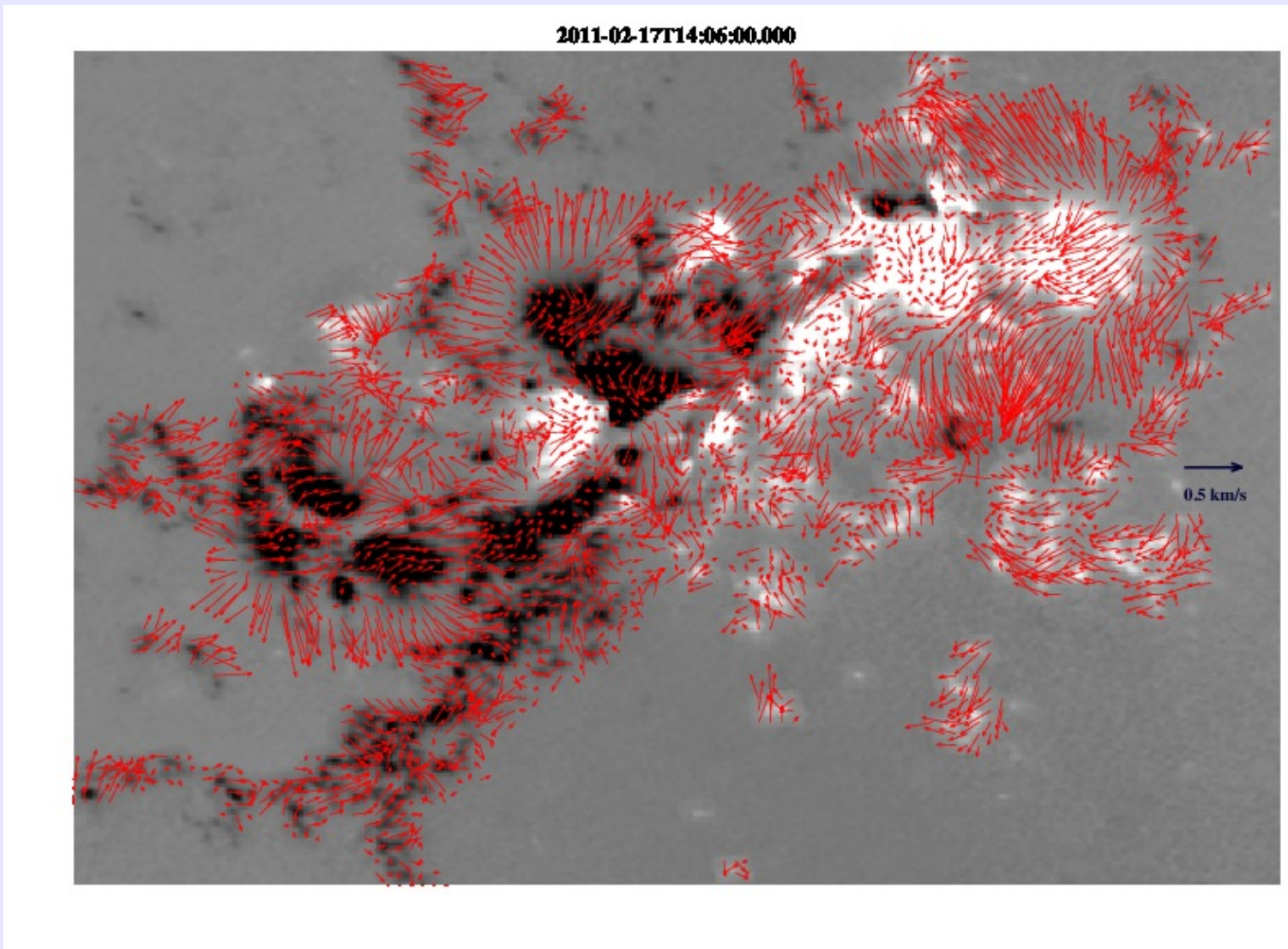
DAVE4VM output, all pixels included. Dominated by noise.

Using the photospheric  $B$  boundary: noise.



DAVE4VM output,  $\text{conf} > 60$  pixels included. Patterns visible.

Using the photospheric  $B$  boundary: noise.



DAVE4VM output,  $\text{conf} > 60$  pixels, lower effective cadence. Patterns clear.

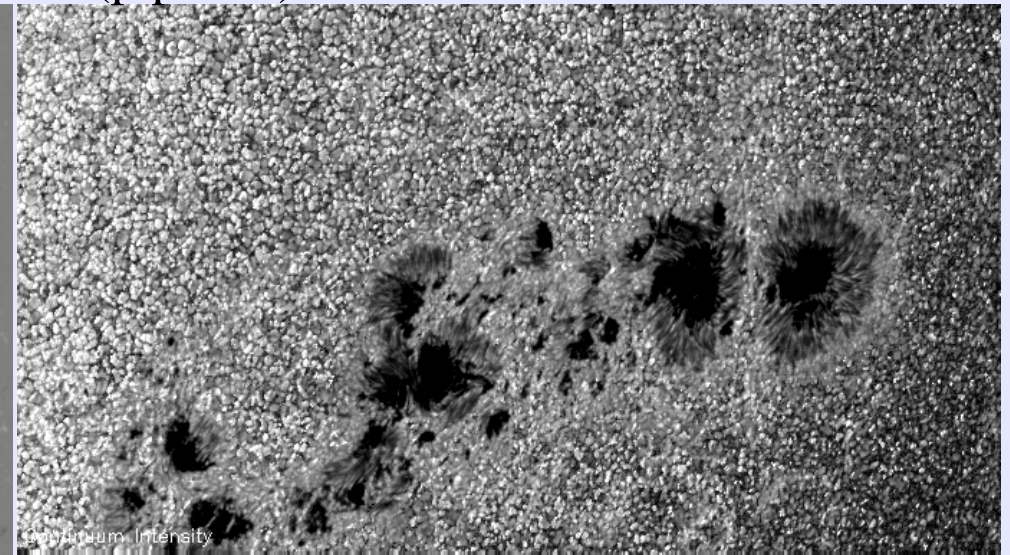
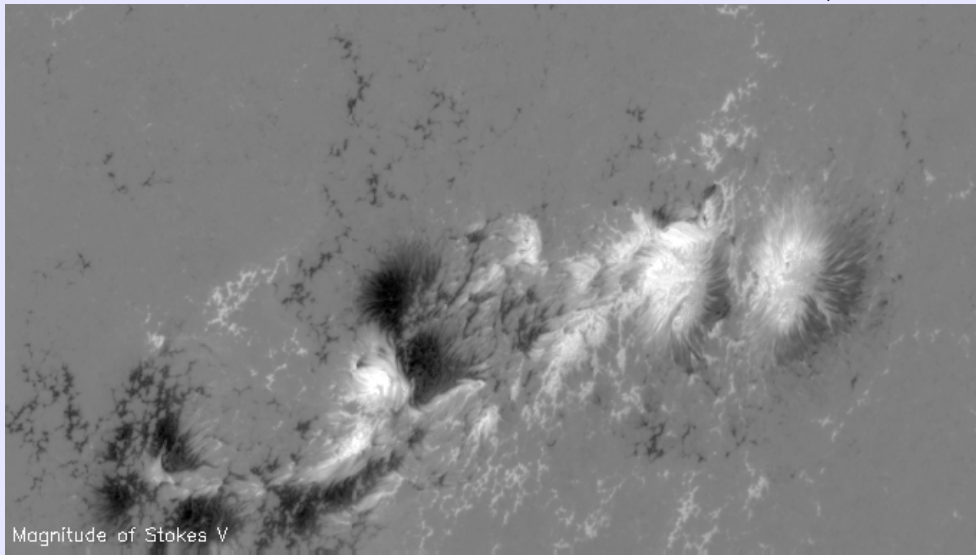
Some good news: additional information often available.

→ Even from Milne-Eddington inversions, constraints / input exist:

Stokes V

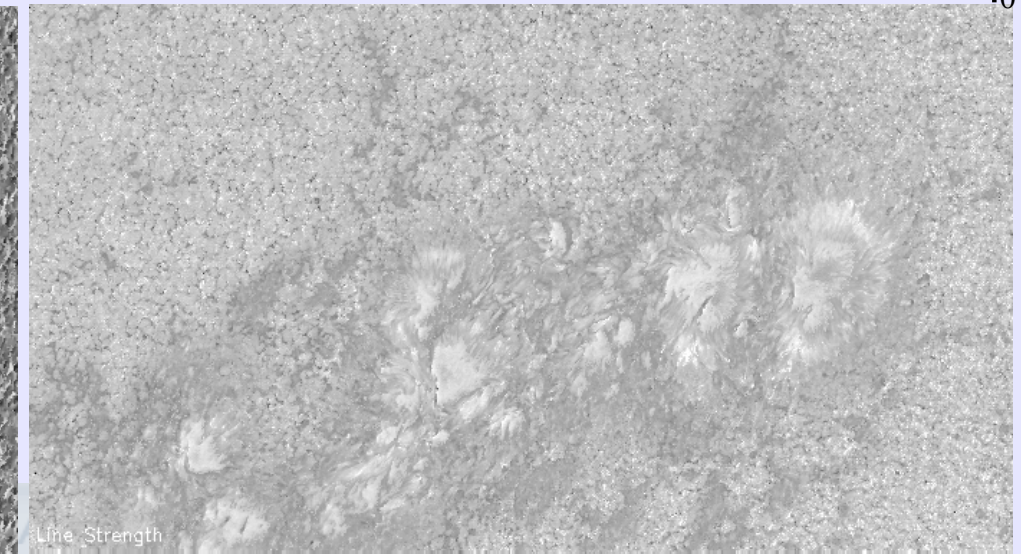
*Hinode*/SP data, MERLIN (pipeline) inversion

Continuum



630.15nm, 630.25 V<sub>Doppler</sub>

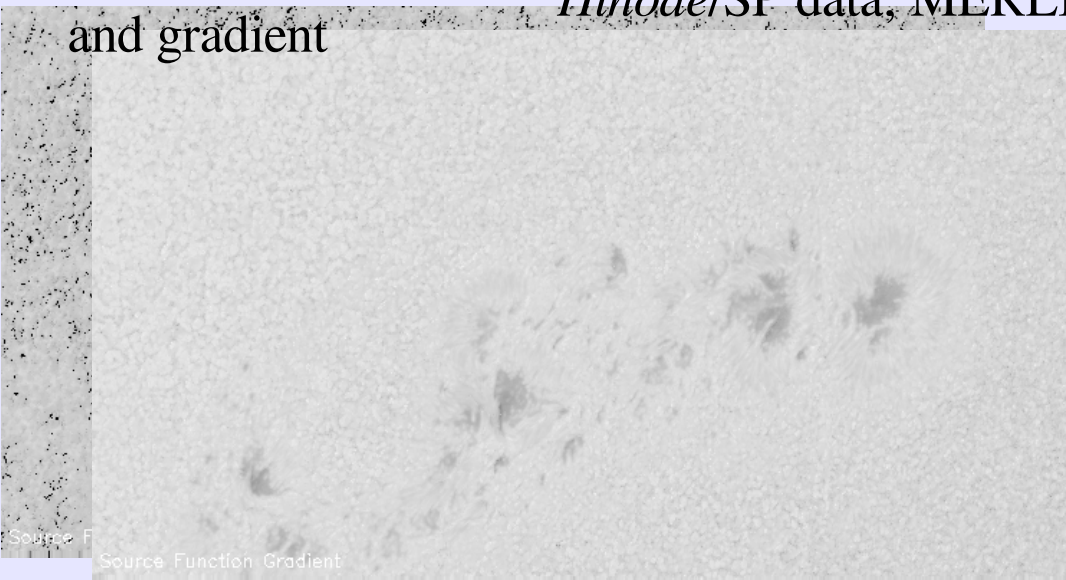
Line-to-continuum ratio  $\eta_0$



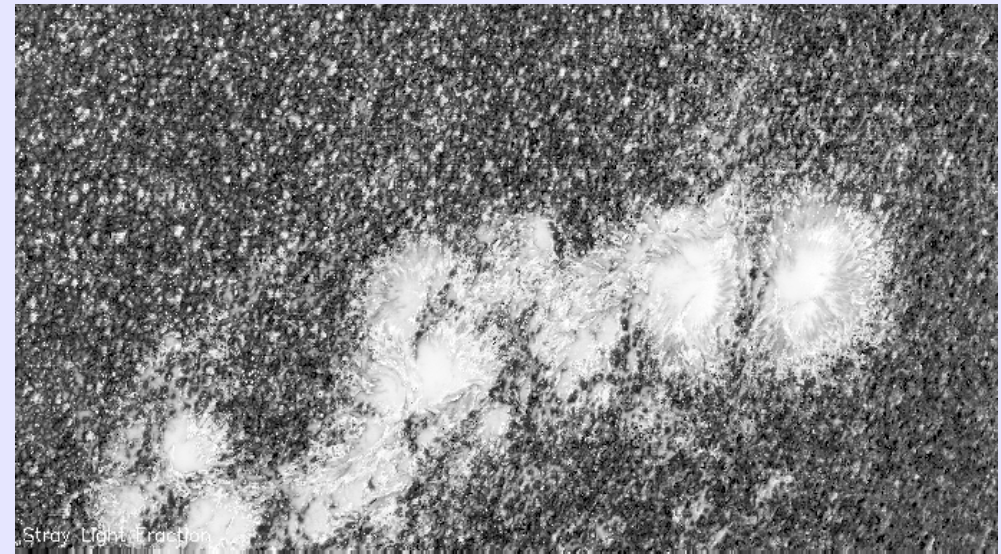
Some good news: additional information often available.

→ Even from Milne-Eddington inversions, constraints / input exist:

Source function  
and gradient

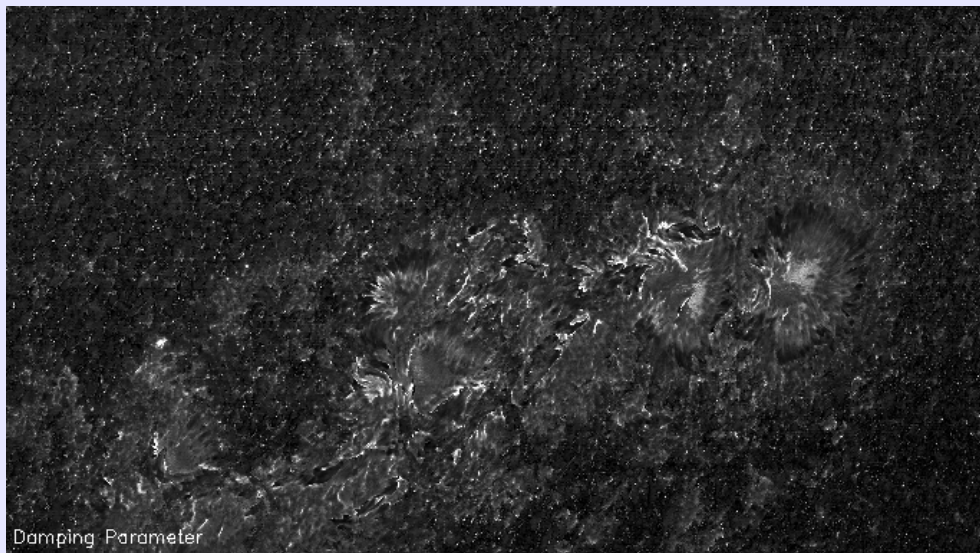


*Hinode*/SP data, MERLIN (pipeline) inversion

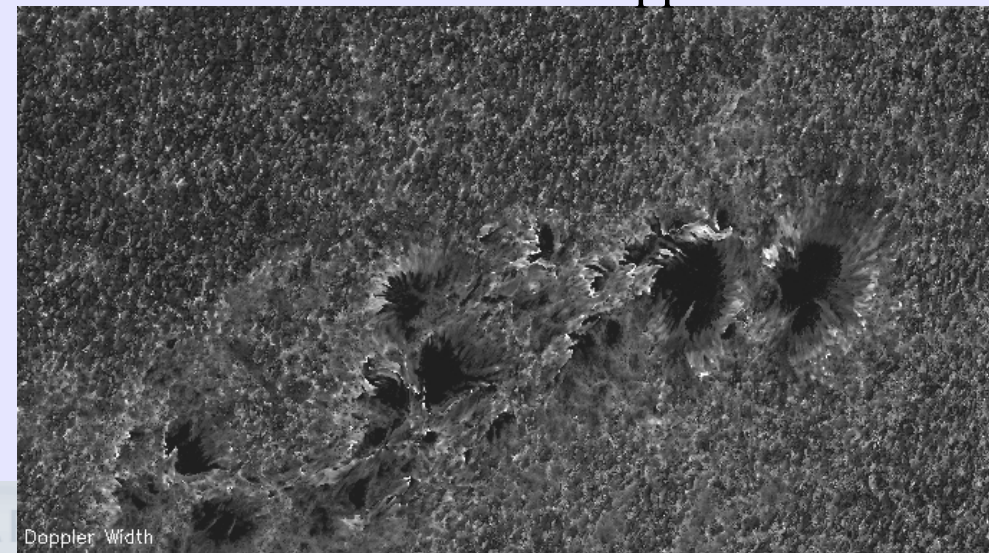


Fill Fraction

Damping Parameter



Doppler Width



Some good news: additional information often available.

→ Even from Milne-Eddington inversions, constraints / input exist:

- Fill fraction / scattered light fraction → unresolved structures
- Source function components → temperature (changes) constraints
- Doppler Width, Macroturbulence → temperature constraint
- Line-to-Continuum Ratio → Ionization state (temperature constraint)
- Doppler Shifts (2 lines independently) → velocity gradients
- Field parameters (2 lines independently) → magnetic field gradients

Some good news: additional information often available.

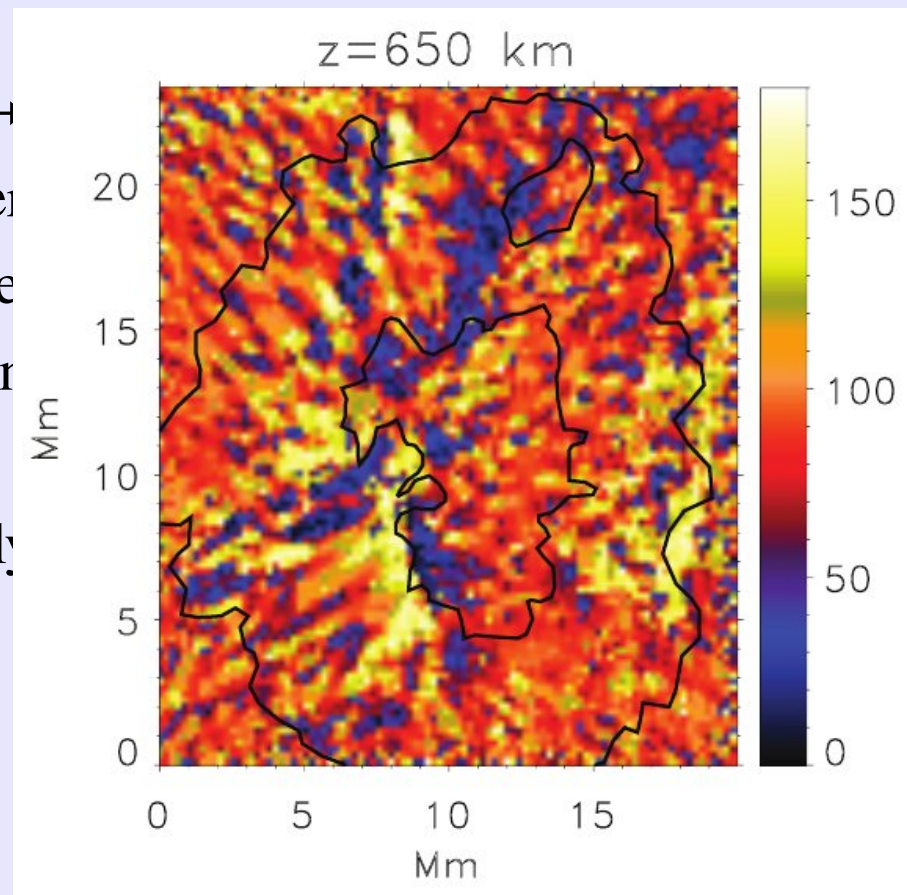
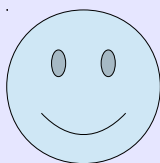
→ Even from Milne-Eddington inversions, constraints / input exist:

- Fill fraction / scattered light fraction →
- Source function components → temperature
- Doppler Width, Macroturbulence → temperature
- Line-to-Continuum Ratio → Ionization
- Doppler Shifts (2 lines independently)
- Field parameters (2 lines independently)

● More sophisticated inversion methods exist, even more are being developed. Especially useful for multi-line observations.

● Most are not yet routinely applied to full “maps” of active regions.

● People are working on that.



Angle between  $\mathbf{B}$  and  $\nabla \times \mathbf{B}$  from multi-line non-LTE inversion.

(from Socas Navarro 2005)

## **The Take-away Messages:**

Keep in mind how “measurements” are made, and the limitations, assumptions, interpolations, *etc.*: they impact your input!

## **The Take-away Messages:**

Keep in mind how “measurements” are made, and the limitations, assumptions, interpolations, *etc.*: they impact your input!

Make efforts to retain “character” of original / best observations.

## **The Take-away Messages:**

Keep in mind how “measurements” are made, and the limitations, assumptions, interpolations, *etc.*: they impact your input!

Make efforts to retain “character” of original / best observations.

Be mindful of errors and uncertainties: they impact your input!

## The Take-away Messages:

Keep in mind how “measurements” are made, and the limitations, assumptions, interpolations, *etc.*: they impact your input!

Make efforts to retain “character” of original / best observations.

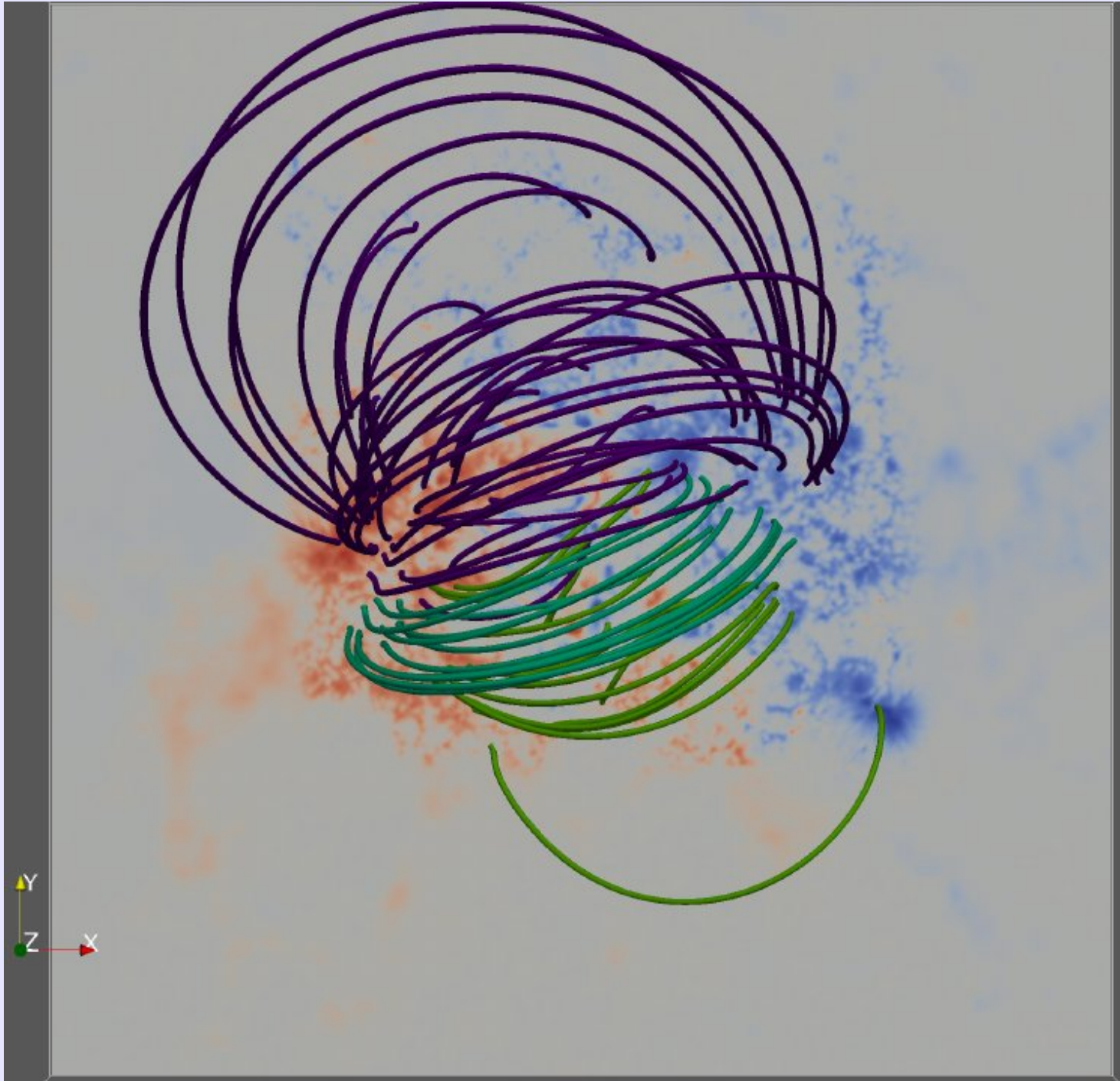
Be mindful of errors and uncertainties: they impact your input!

Utilize additional constraints: other parameters from photospheric inversions, chromospheric data, *etc.*



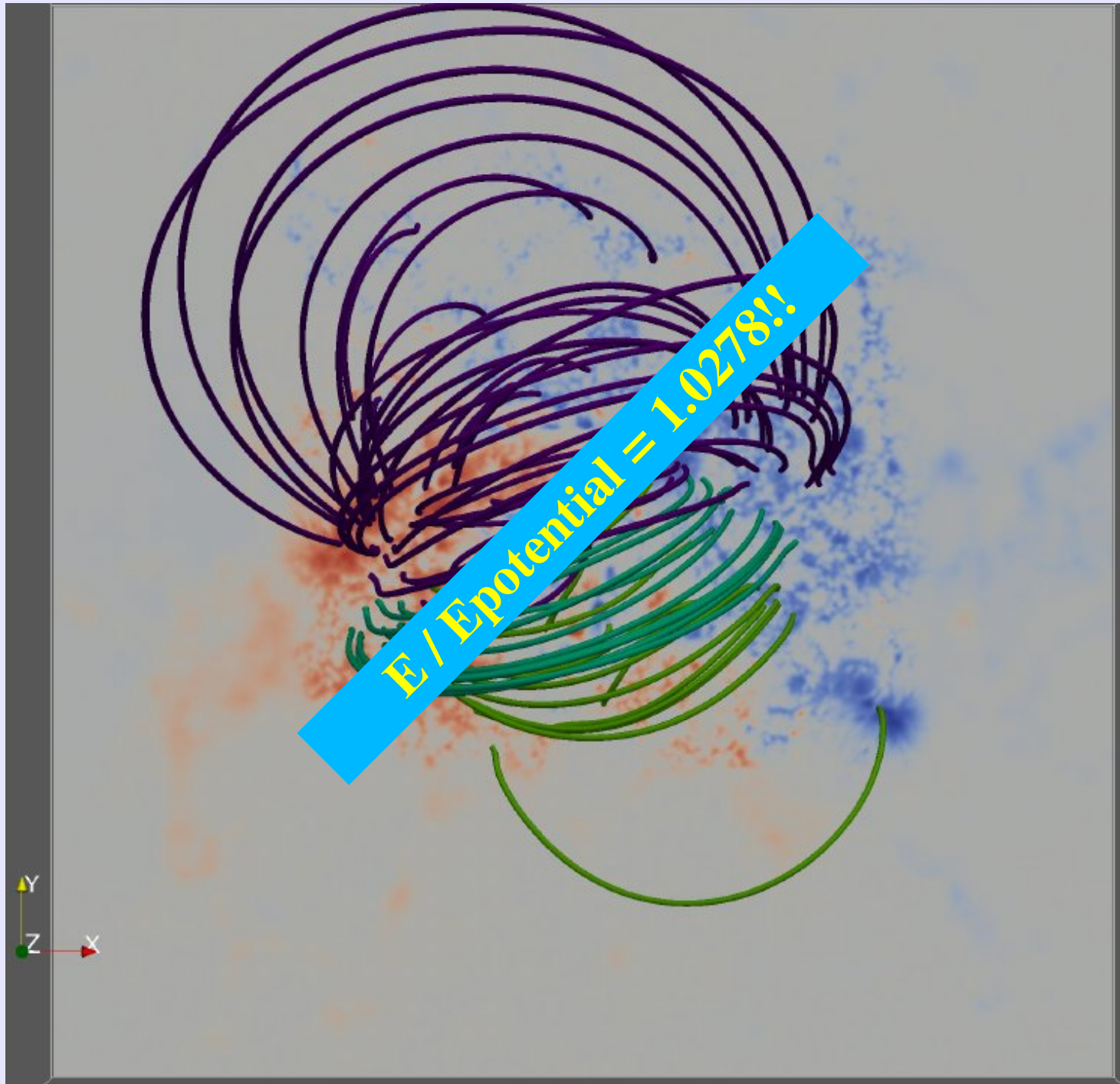
## Extra Slides

From Gilchrist, Barnes  
& Leka, in prep.

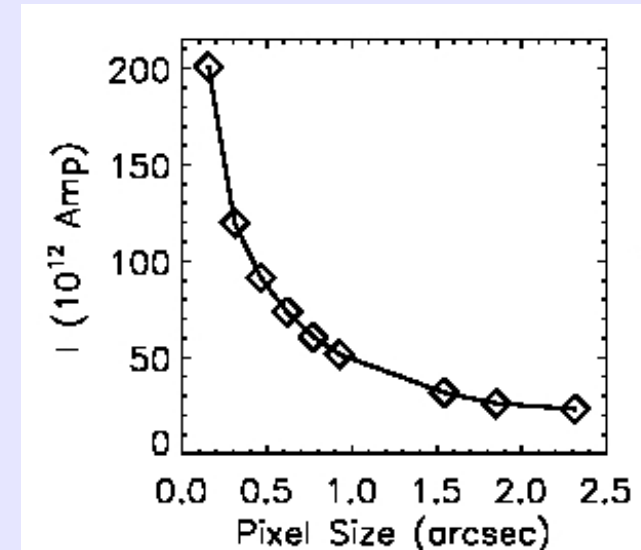
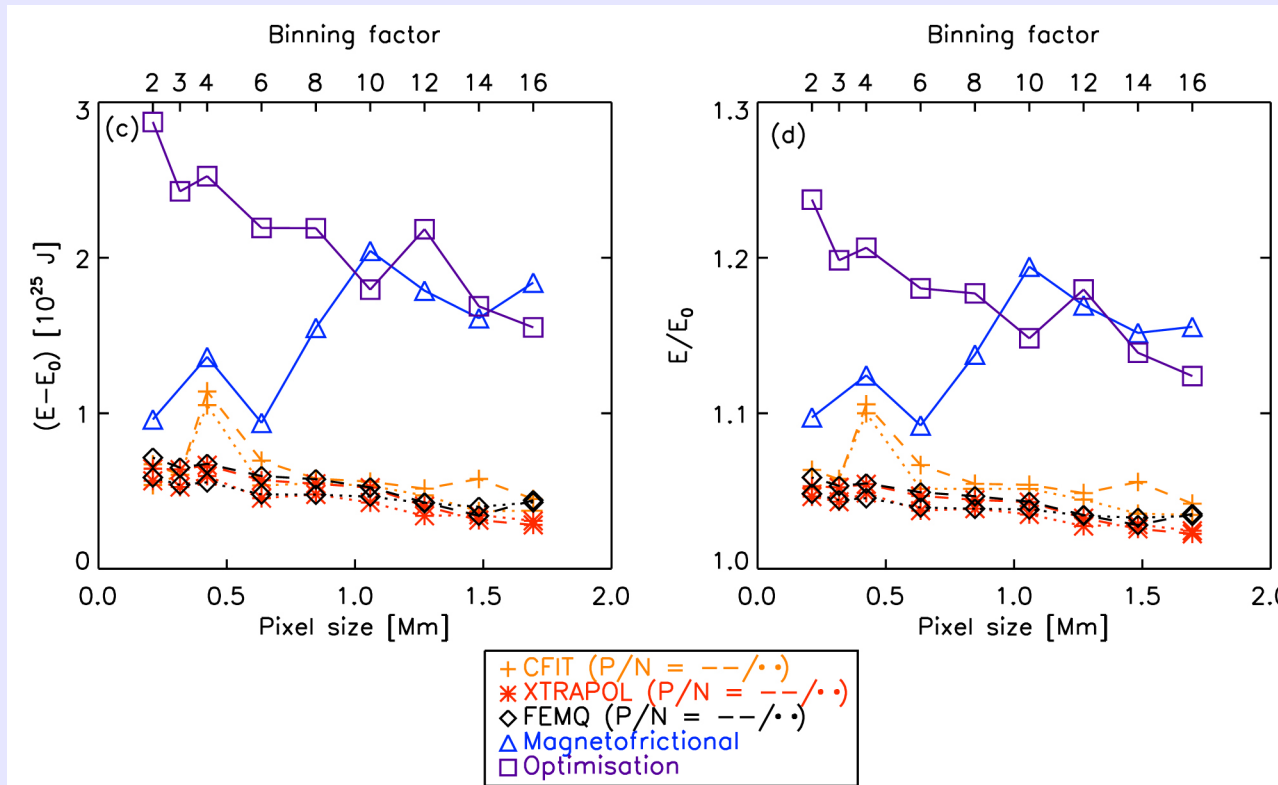


..and estimate the coronal energy available for flares, CMEs, SEPs, etc. etc.

From Gilchrist, Barnes  
& Leka, in prep.



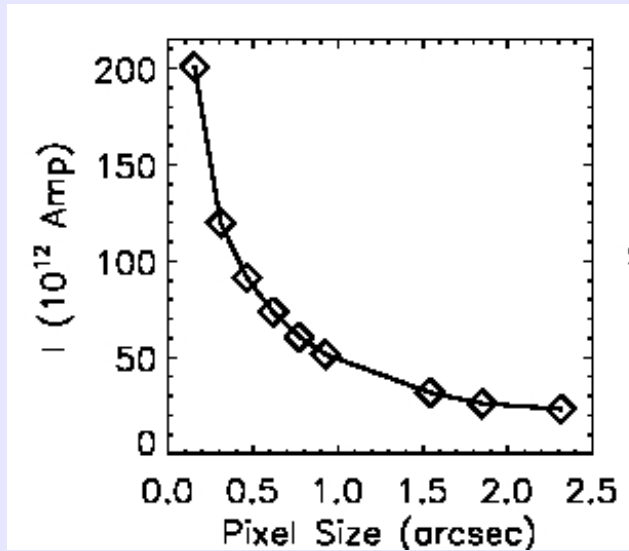
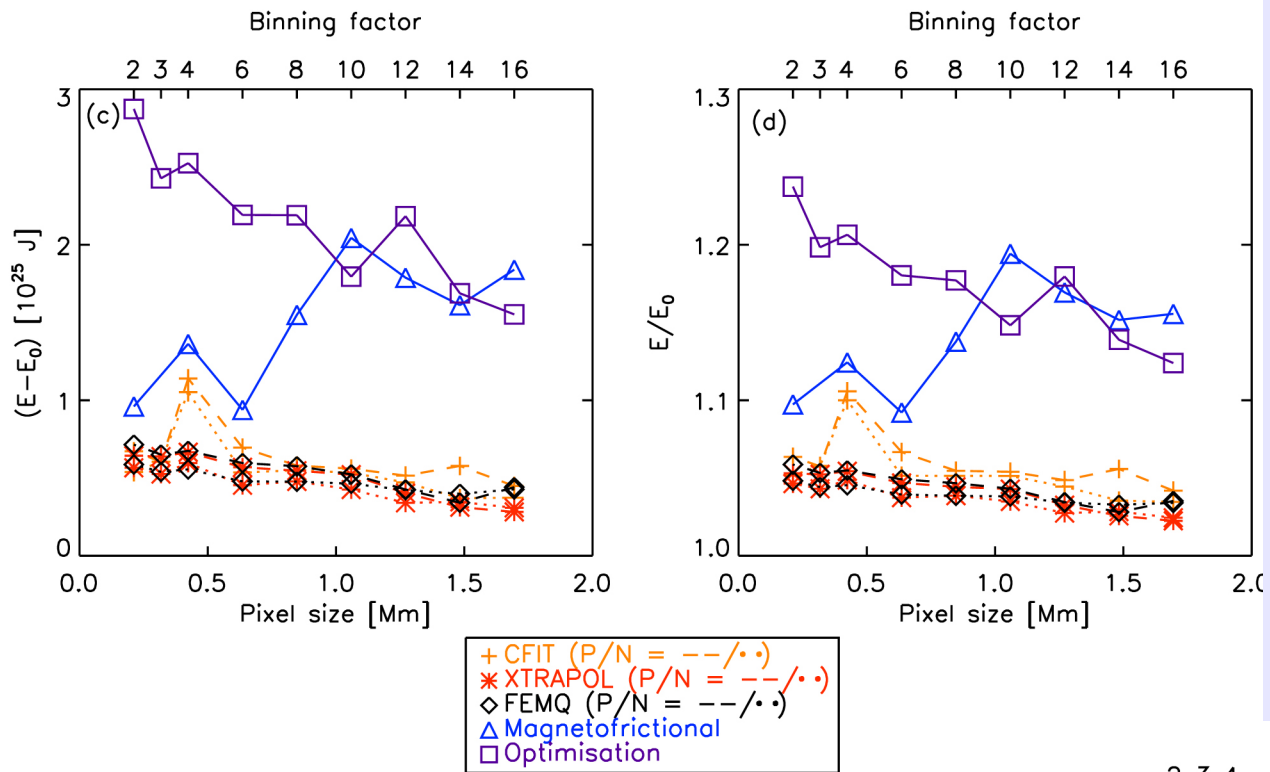
From DeRosa+2015;  
Barnes & Leka 2017



***The bad news:***

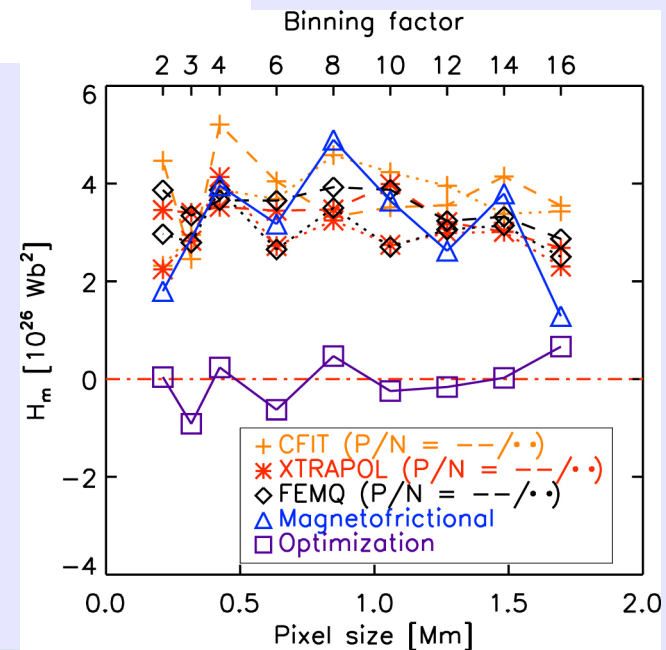
- That number depends on binning / resolution of input.

From DeRosa+2015;  
Barnes & Leka 2017

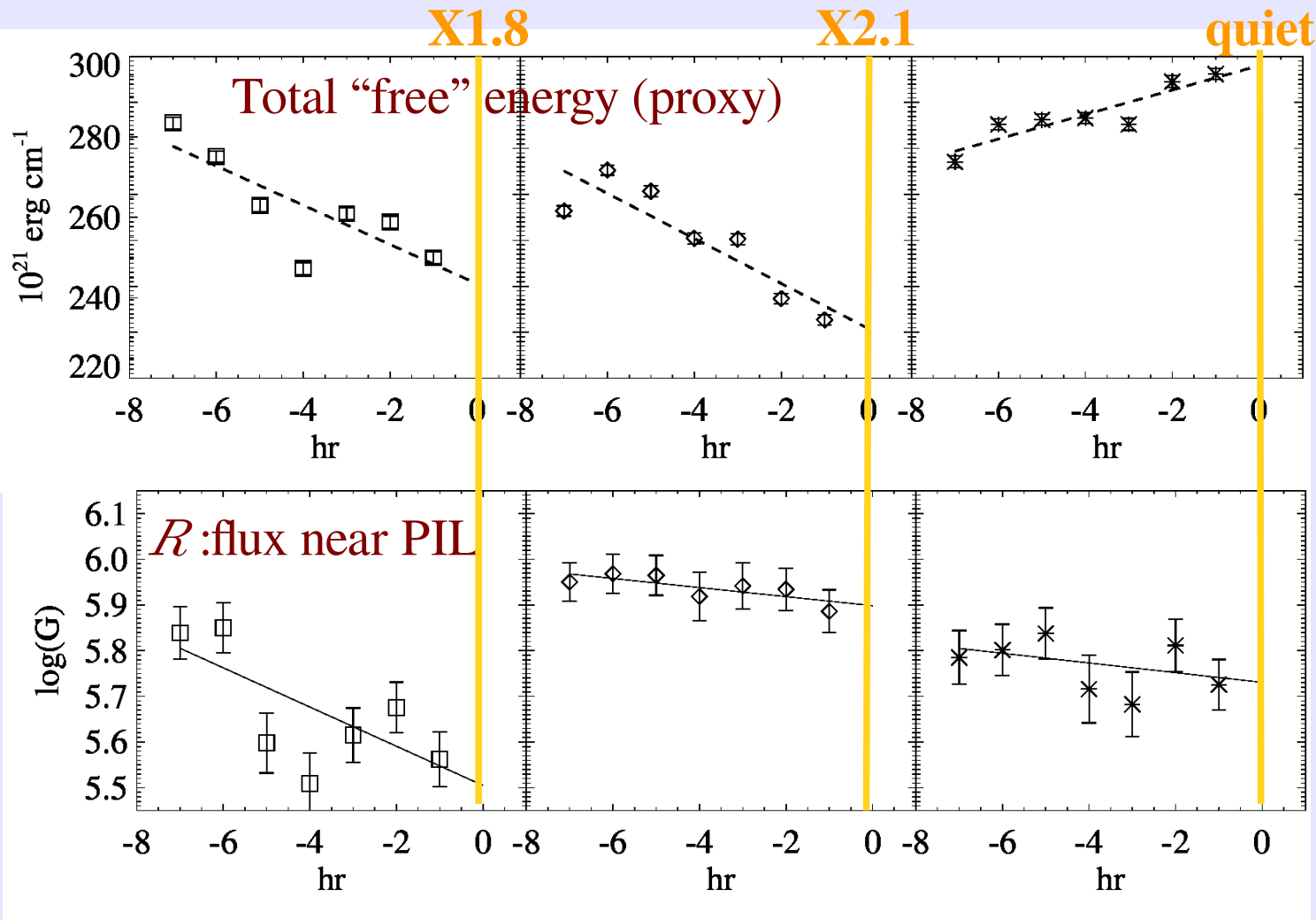


**The bad news:**

- That number depends on binning / resolution of input.
- It also depends on the method.



# Back to understanding / predicting energetic events:

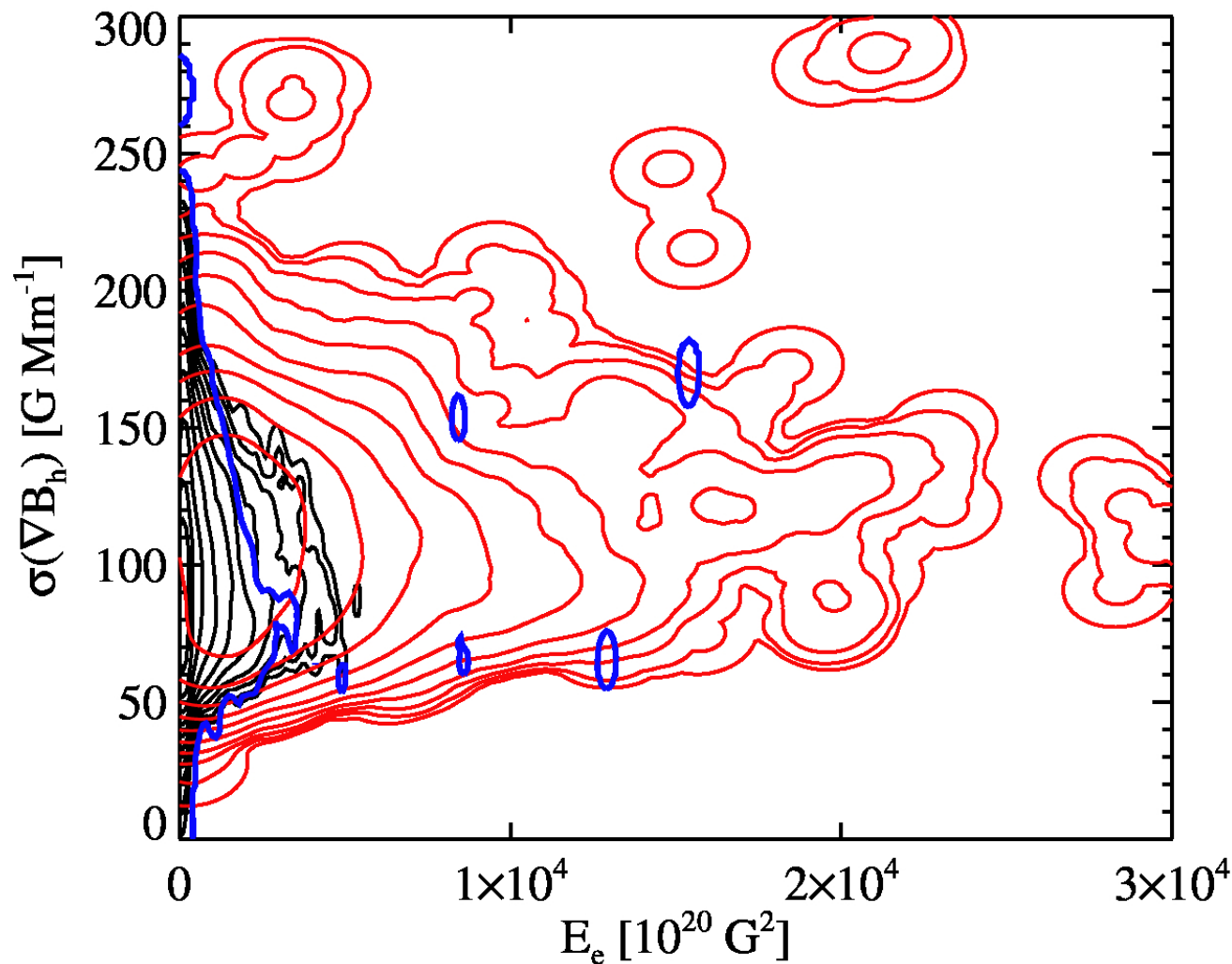


Want to use  $B$  information to understand the behavior of the solar plasma prior to energetic events.

From Leka, Barnes & Wagner 2018

Pre-event behavior of total free energy proxy (top) and the amount of flux near a Polarity Inversion Line (bottom), as indicated; third panel is prior to "no event".

## *Back to understanding / predicting energetic events:*



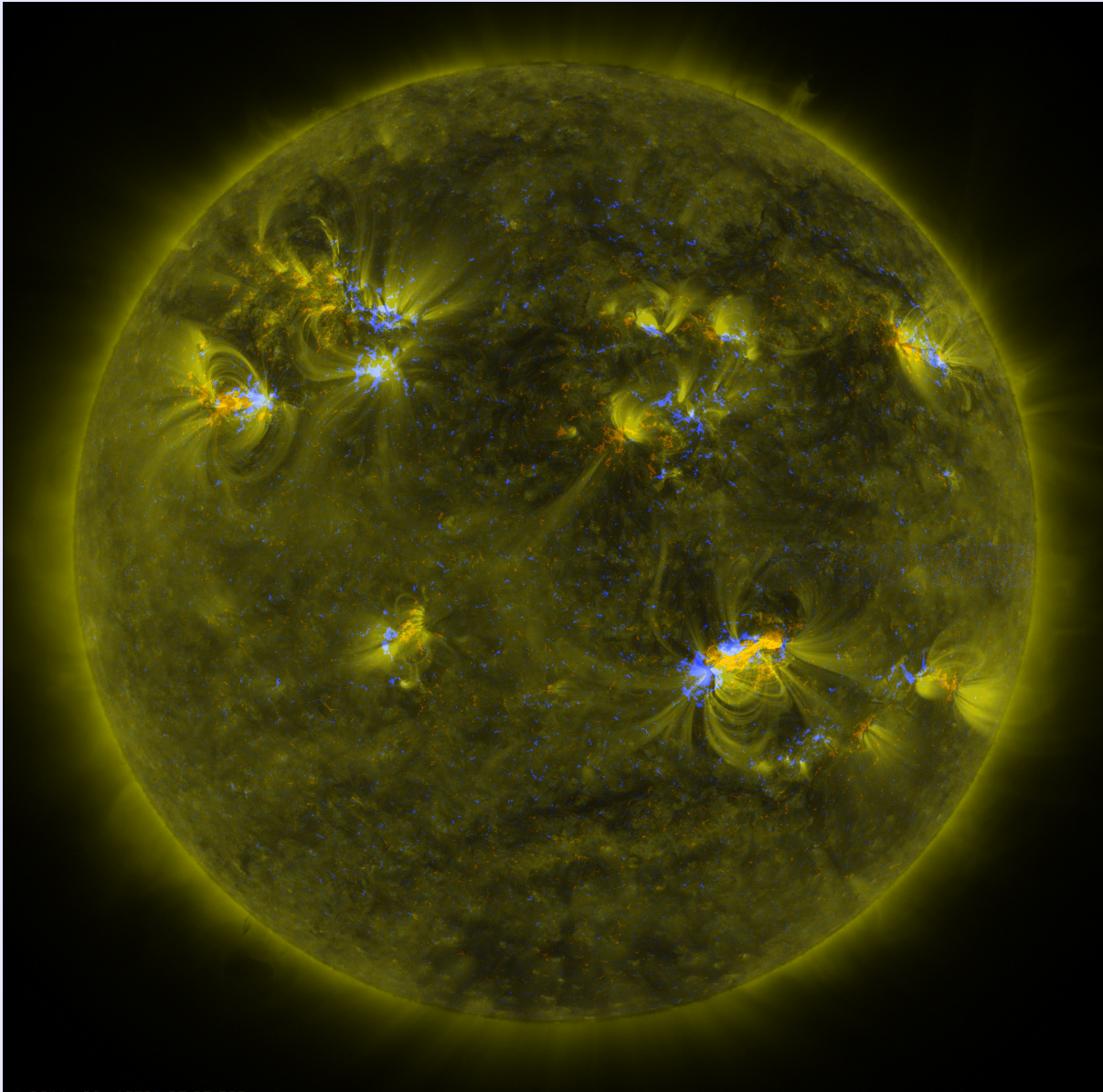
Want to use ***B*** information to understand the behavior of the solar plasma prior to energetic events.

Statistically:  
***B*** can help distinguish regions more likely to produce events.

Probability Density Functions of 65,000 **flare-productive** and flare-quiet HMI patches, with 50% probability contour for reference, in parameter-space of the standard deviation of horizontal gradients, and a free-energy proxy.

From Leka, Barnes & Wagner 2018

## Summary



### Statistically:

***B*** can help distinguish regions more likely to produce events.

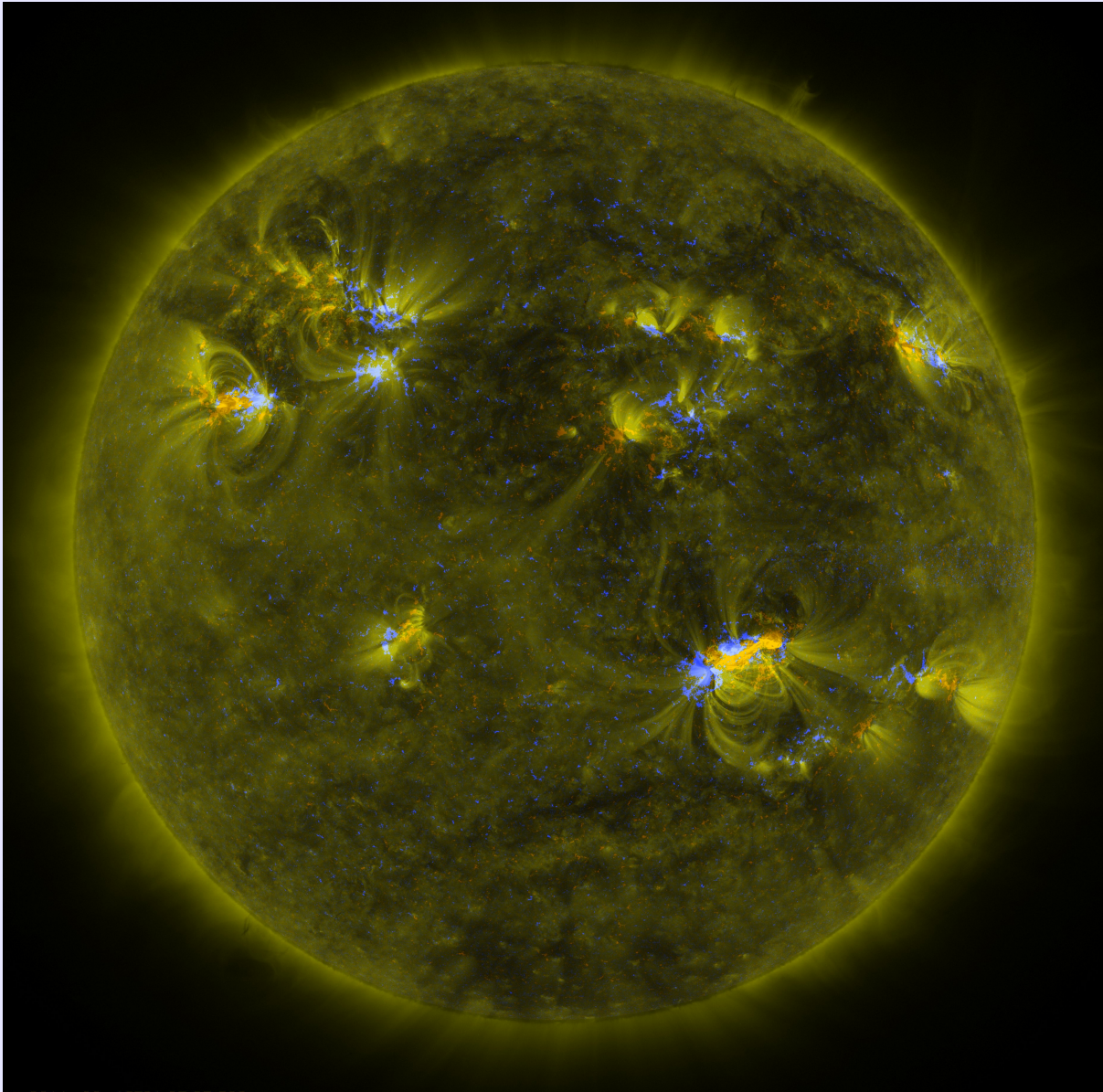
### However,

“what is the **XX**\* *here*?”

- Much *much* more difficult to answer (well).
- Values without error bars are useless.
- Not yet routinely answerable over most of the solar atmosphere.

**XX**= Magnetic field strength, direction, orientation, local gradient, current density, helicity, free energy, twist, divergence, connectivity, topology, *etc. etc.*

## Concluding Remarks



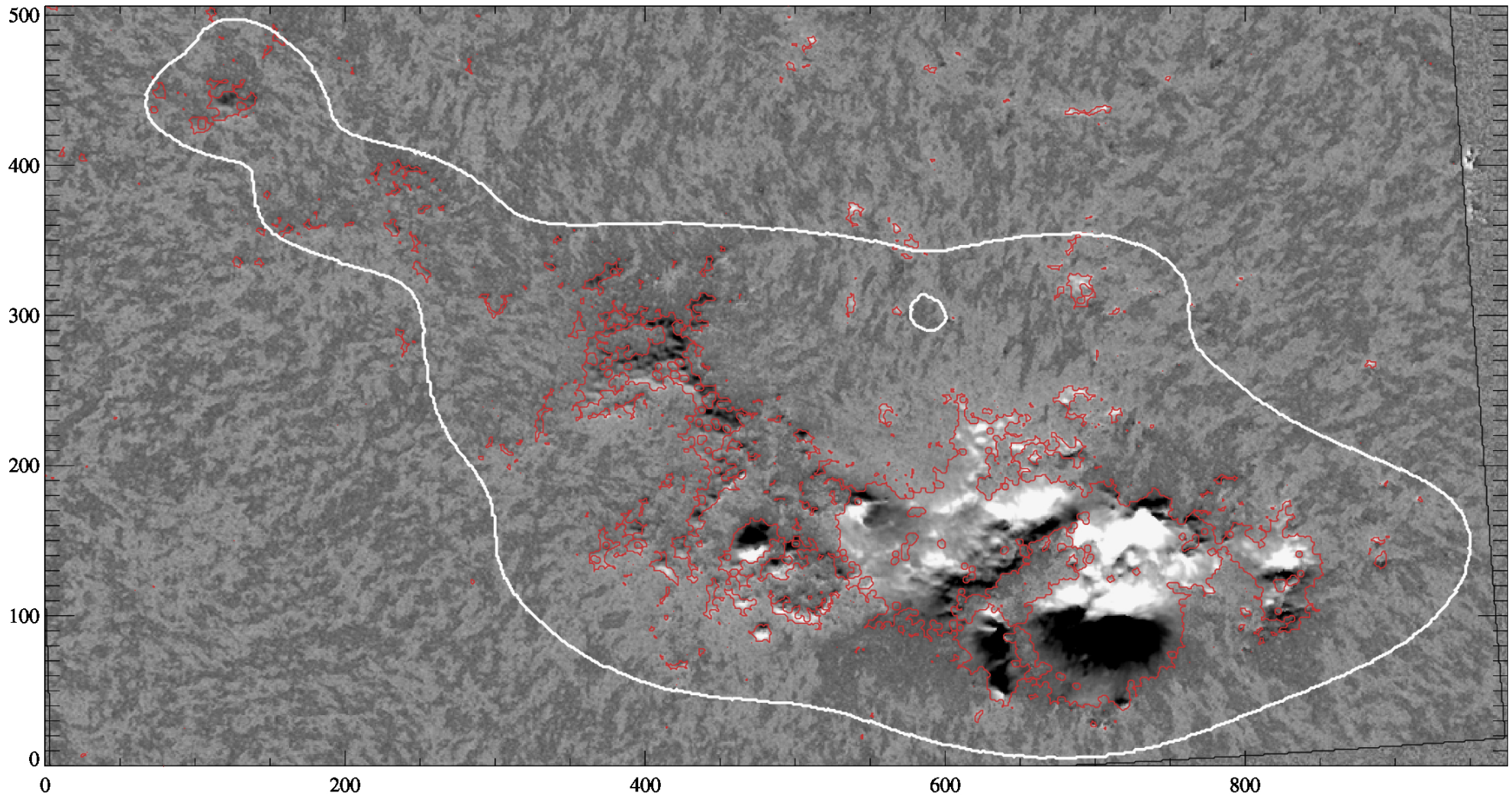
So what do we need for understanding and prediction?

1) Ability to answer “what is the **XX**\* *here*?” routinely over more of the solar atmosphere.

2) Understanding and recognition of impact that assumptions, tools, and data manipulation has on downstream results.

**XX**= Magnetic field strength, direction, orientation, local gradient, current density, helicity, free energy, twist, divergence, connectivity, topology, *etc. etc.*

Using the photospheric  $B$  boundary: noise.



Using the photospheric  $B$  boundary: noise.

