PRE-ERUPTION CONDITIONS IN SOLAR ACTIVE REGIONS: O2R AND A MEANINGFUL EST ROLE

MANOLIS K. GEORGOULIS, RCAAM OF THE ACADEMY OF ATHENS

OUTLINE

- Research-to-operations (R2O) in solar eruptions
  - Data assimilation / database construction
- Solar flare (& CME) forecasting
- Parameter ranking: what works better
- Operations to Research (O2R): targeted pre-eruption observations
- A look on (the elusive) solar eruption precursors
- Conclusions

A LESSON FROM (EXO-)PLANET EXPLORATION

- ESA's CHEOPS Mission
- Mission statement (excerpt)

" CHEOPS … is the first mission dedicated to searching for exoplanet transits by performing ultra-high resolution photometry on bright stars already known to host planets …"

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- EST will feature ultra-high resolution polarimetric / imaging observations
- It can target parts of solar active regions highly likely to host eruptions

R20 IN SOLAR ERUPTIONS

- Giving basic research an operational perspective

- Fusion of expertise, long-standing and novel techniques and, of course, lots of data

R2O IN SOLAR ERUPTIONS

- Giving basic research an operational perspective

Merceret et al., SpW, 2013

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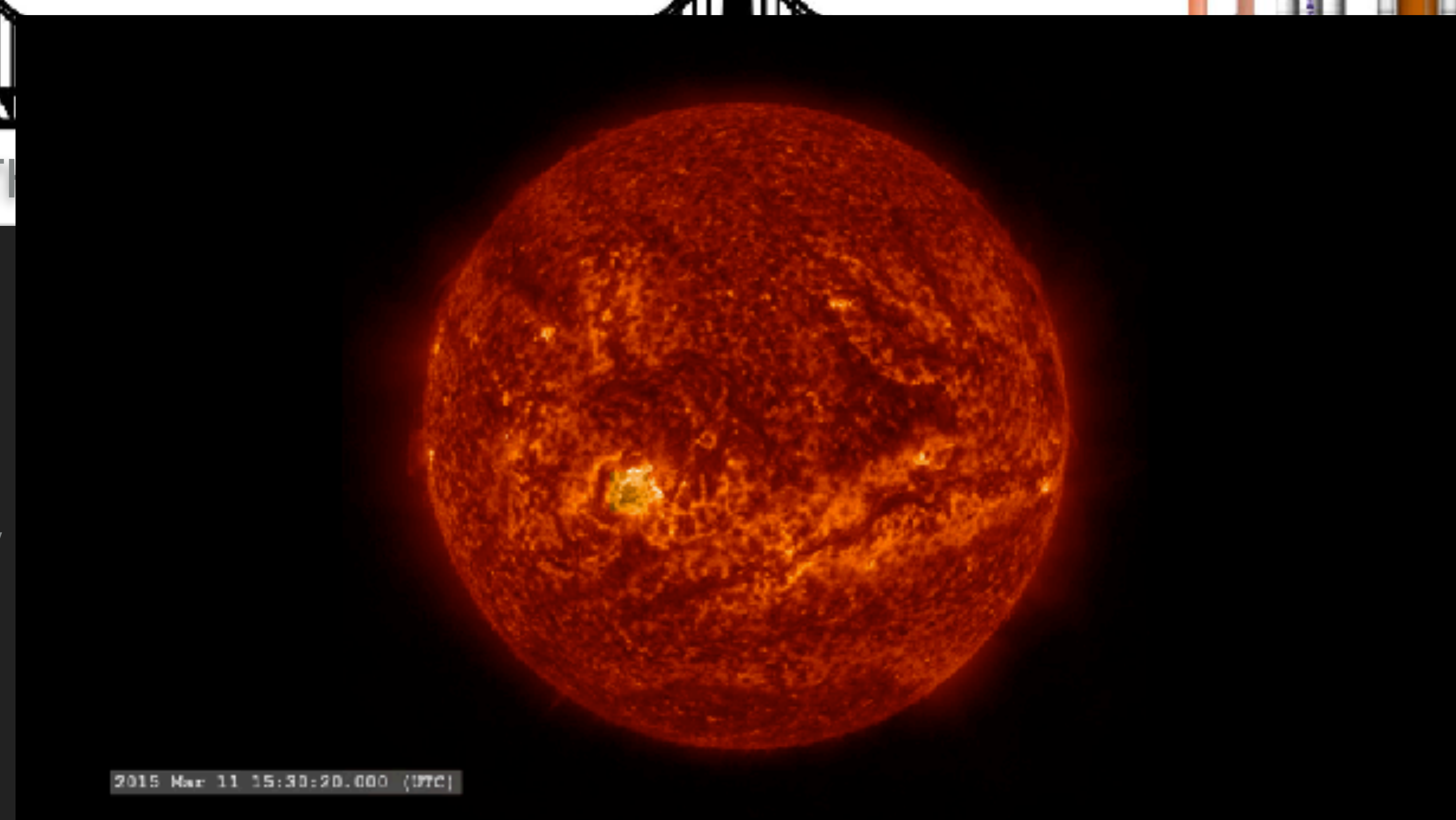
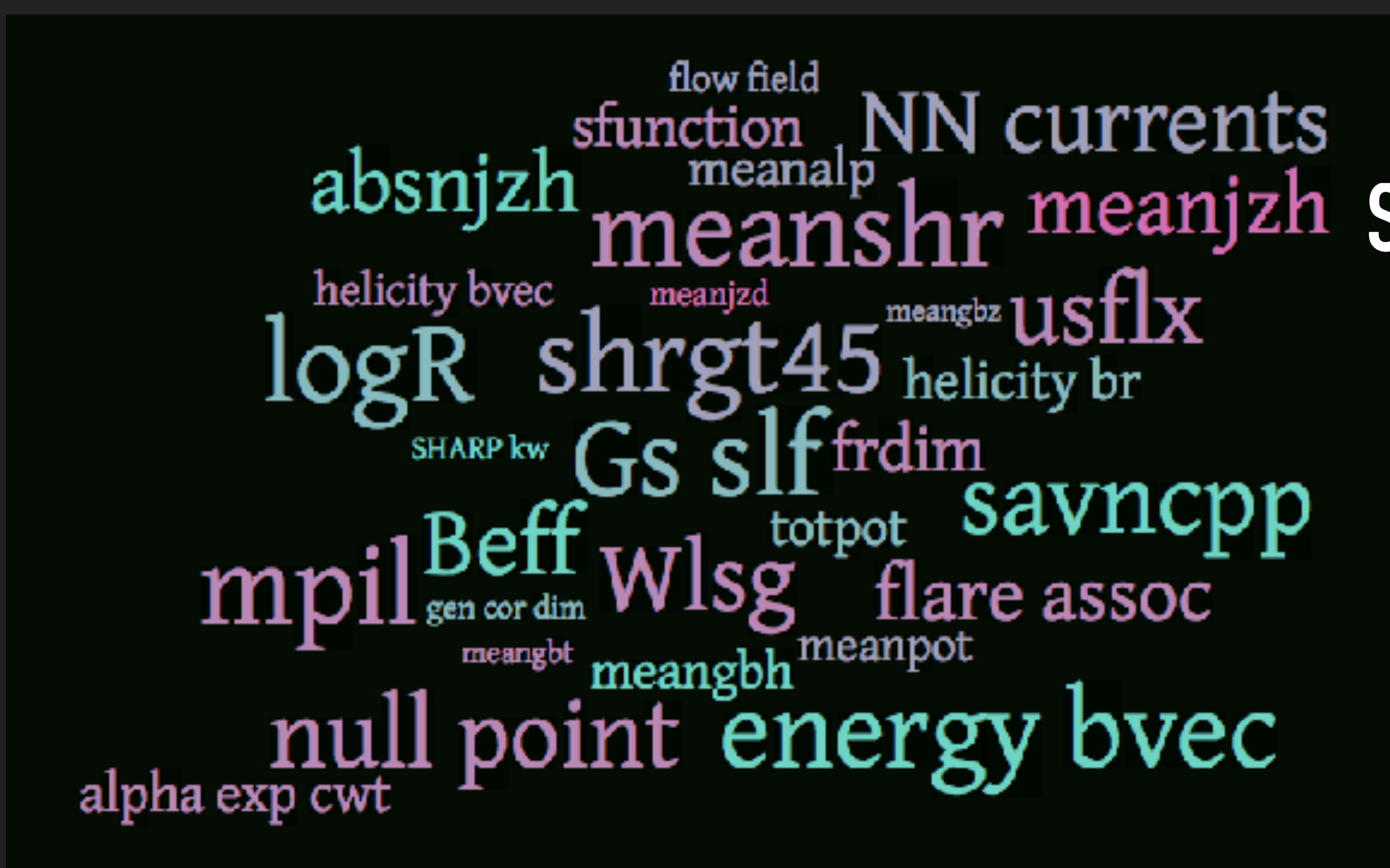
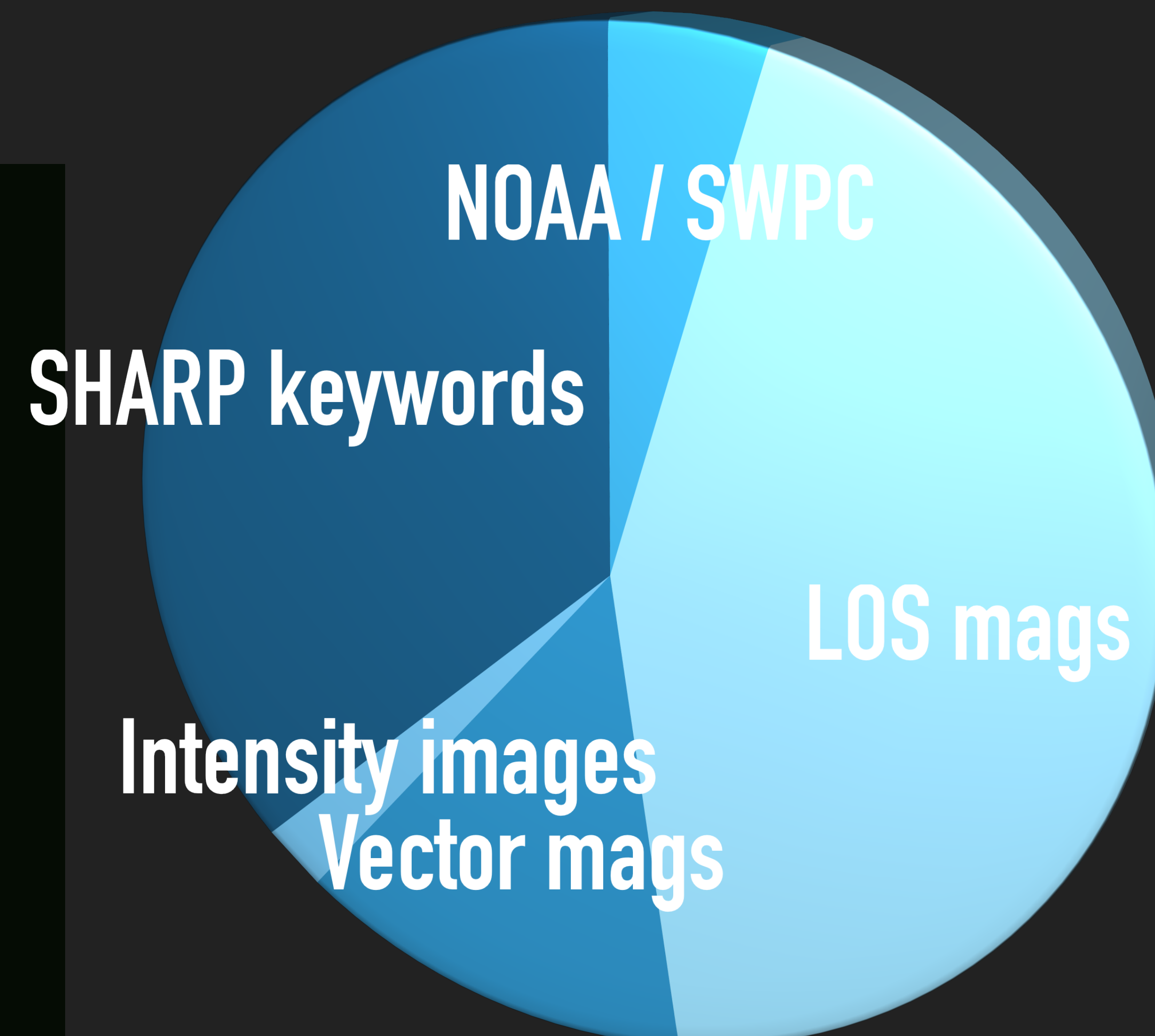


AN R2O CASE STUDY: THE EU FLARECAST PROJECT

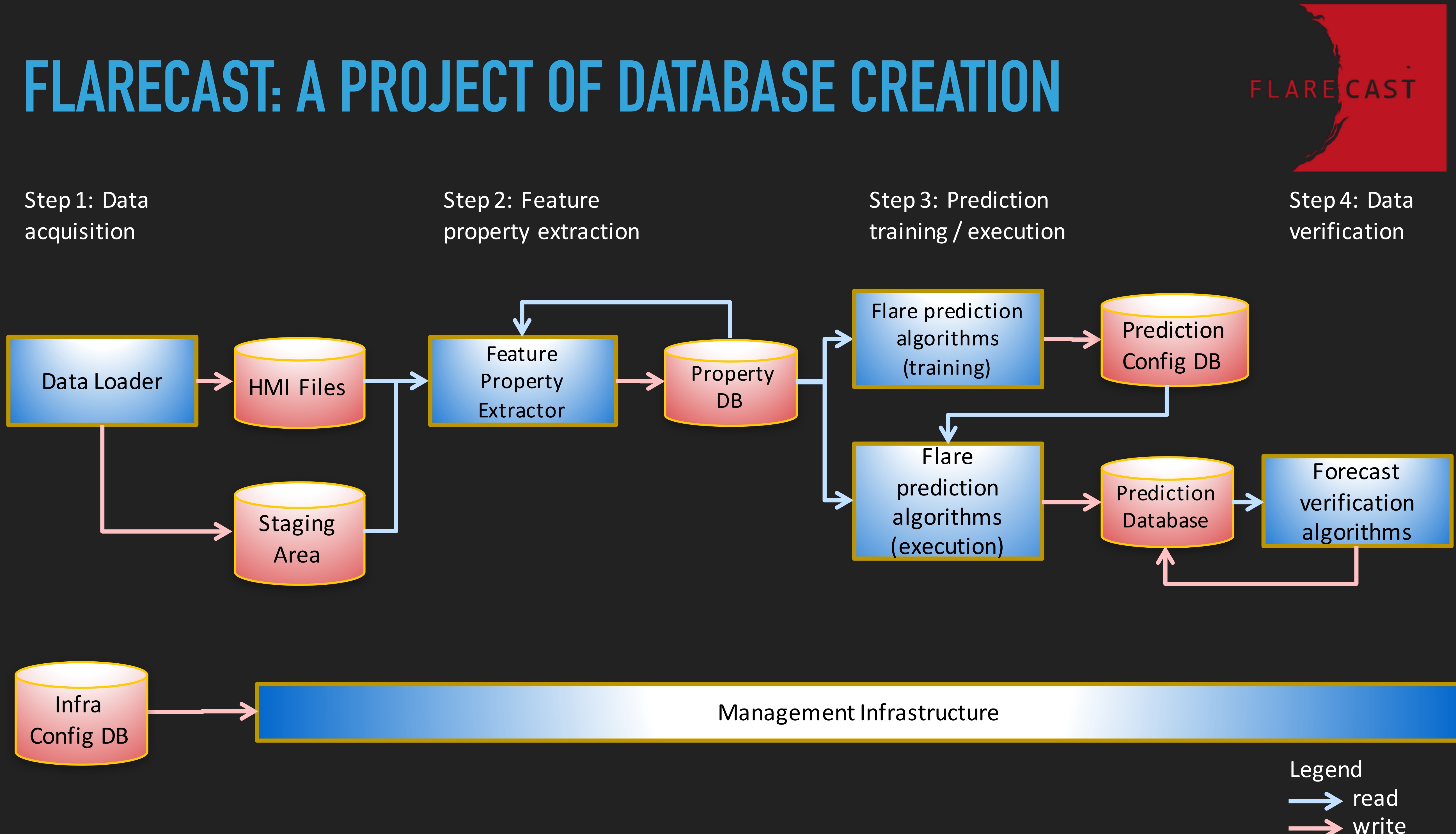
FLARECAST

- More than 100 physical parameters (predictors) extracted from each near-realtime SDO/HMI SHARP since September 2012





FLARECAST: A PROJECT OF DATABASE CREATION



- Among which the Property database

THE FLARECAST PREDICTION TASKS

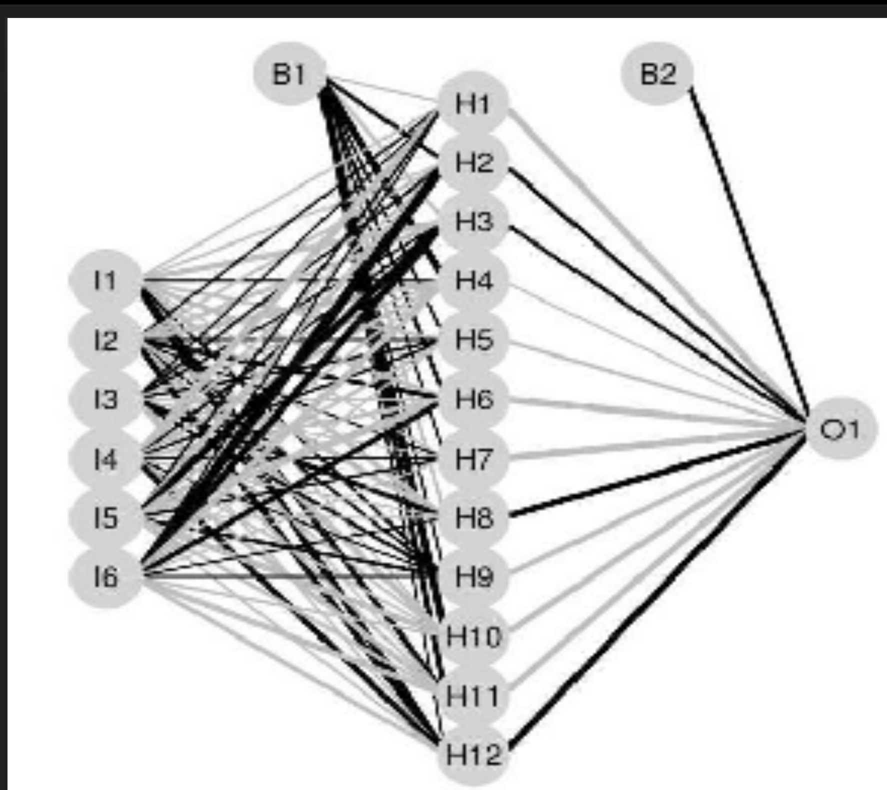
- 29 prediction methods (21 machine learning; 8 statistical)

- ❑ Statistical
- ❑ Supervised learning
- ❑ Unsupervised learning
- ❑ Timeseries analysis

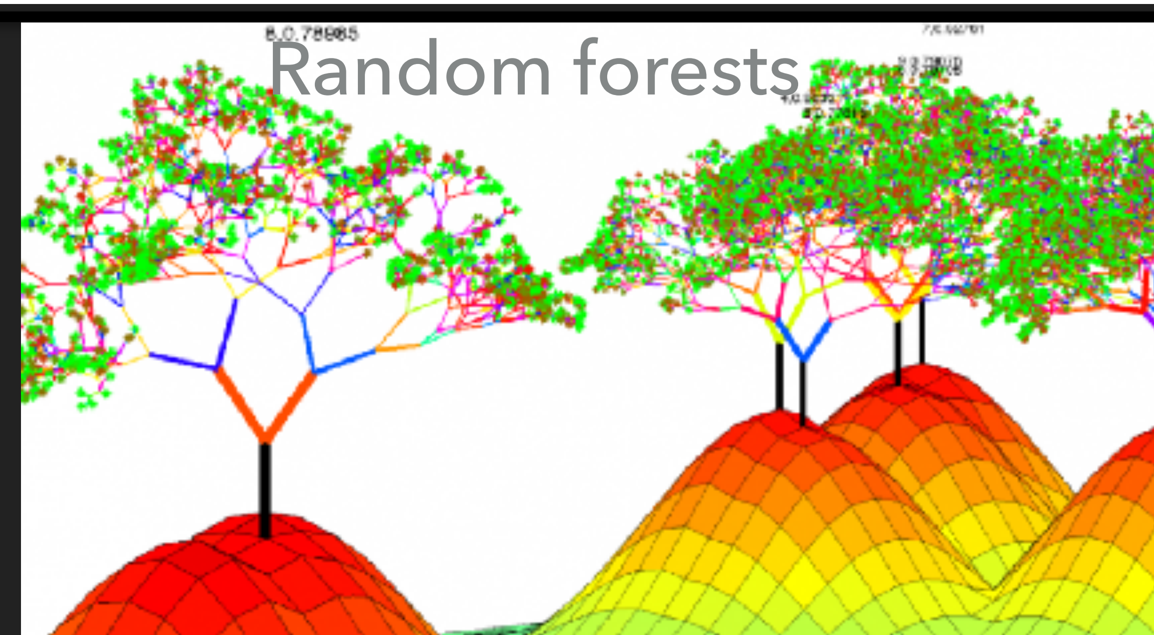
(green)	Non machine-learning
(red)	Machine-learning
(purple)	Timeseries (not implemented in this release of FLARECAST)

Machine Learning:

- Standard
- Advanced
- Innovative

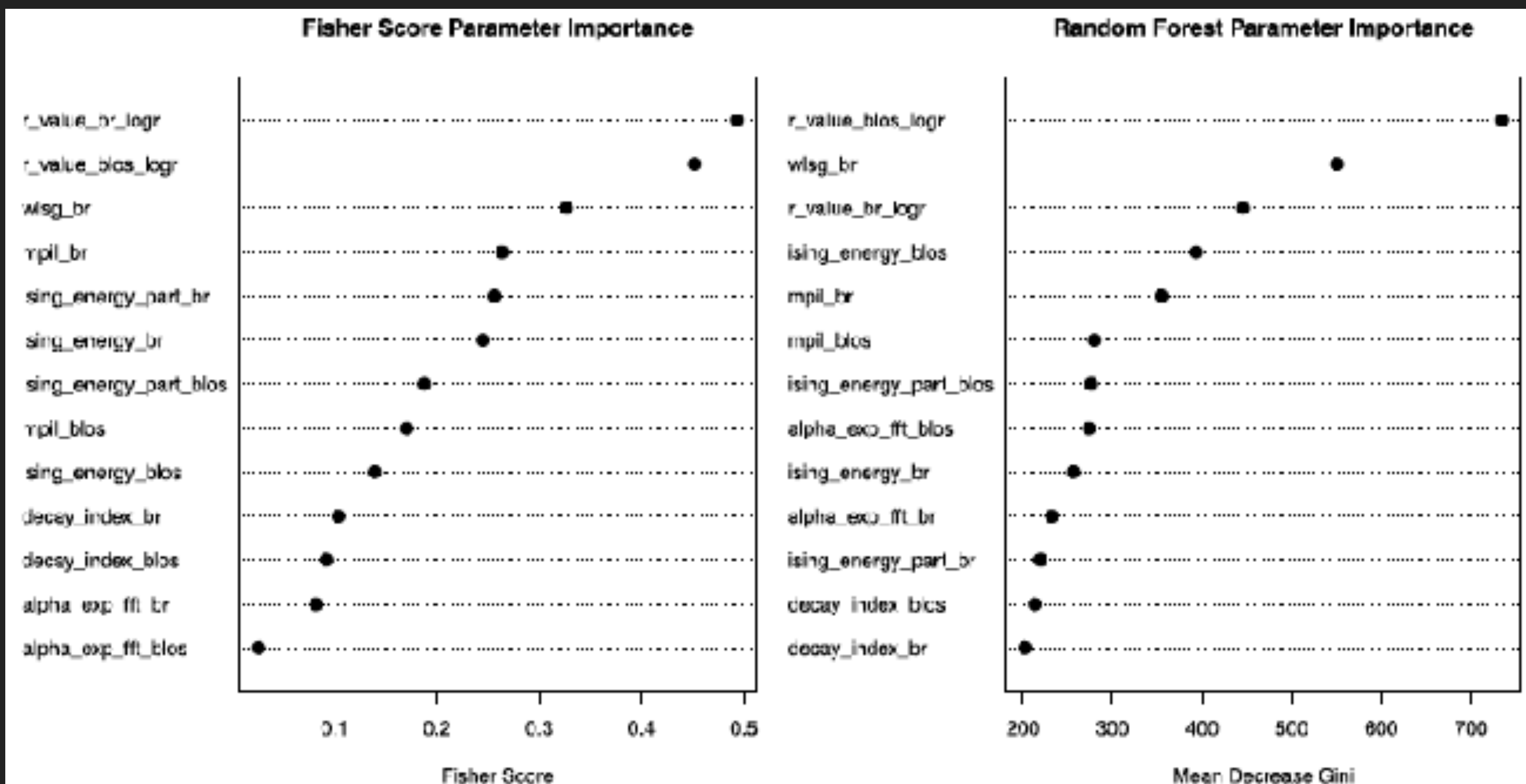


Multi-layer perceptron

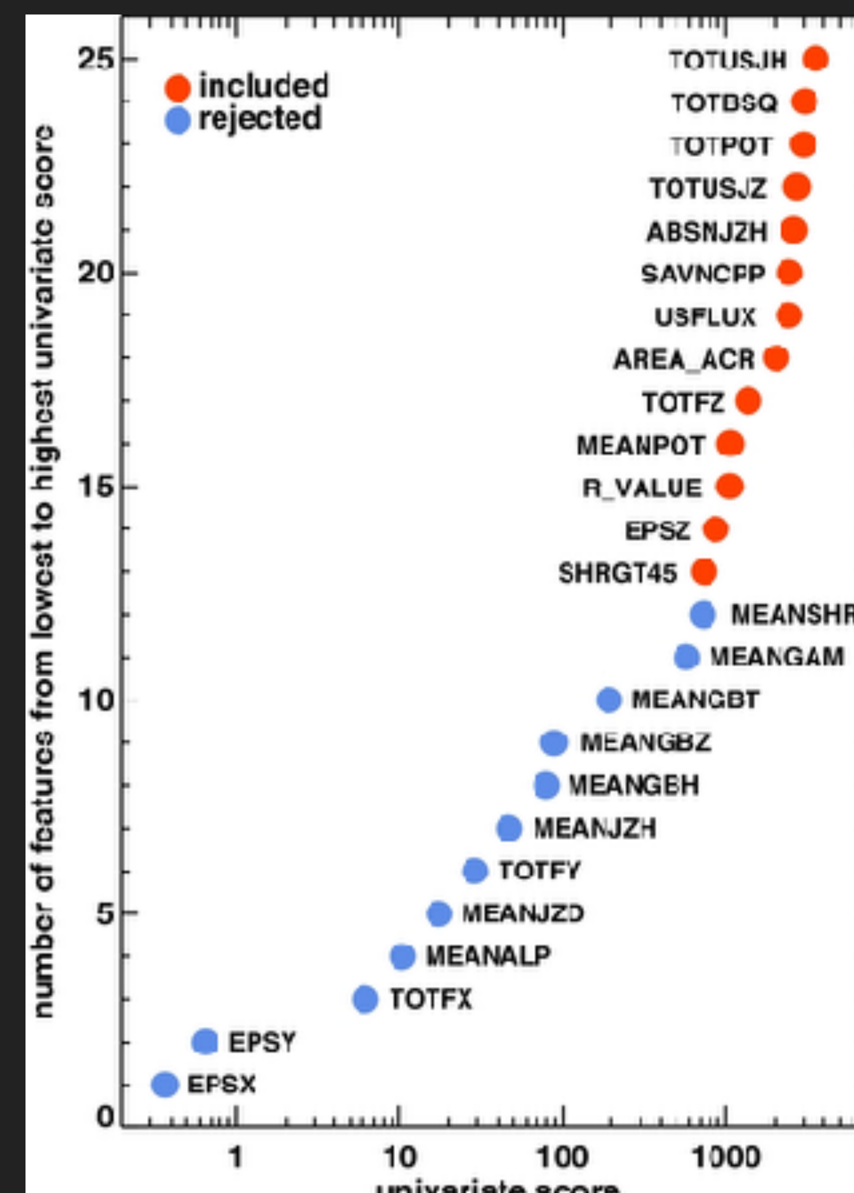


Random forests

HOWEVER, AI (MACHINE LEARNING) ALLOWS PARAMETER RANKING



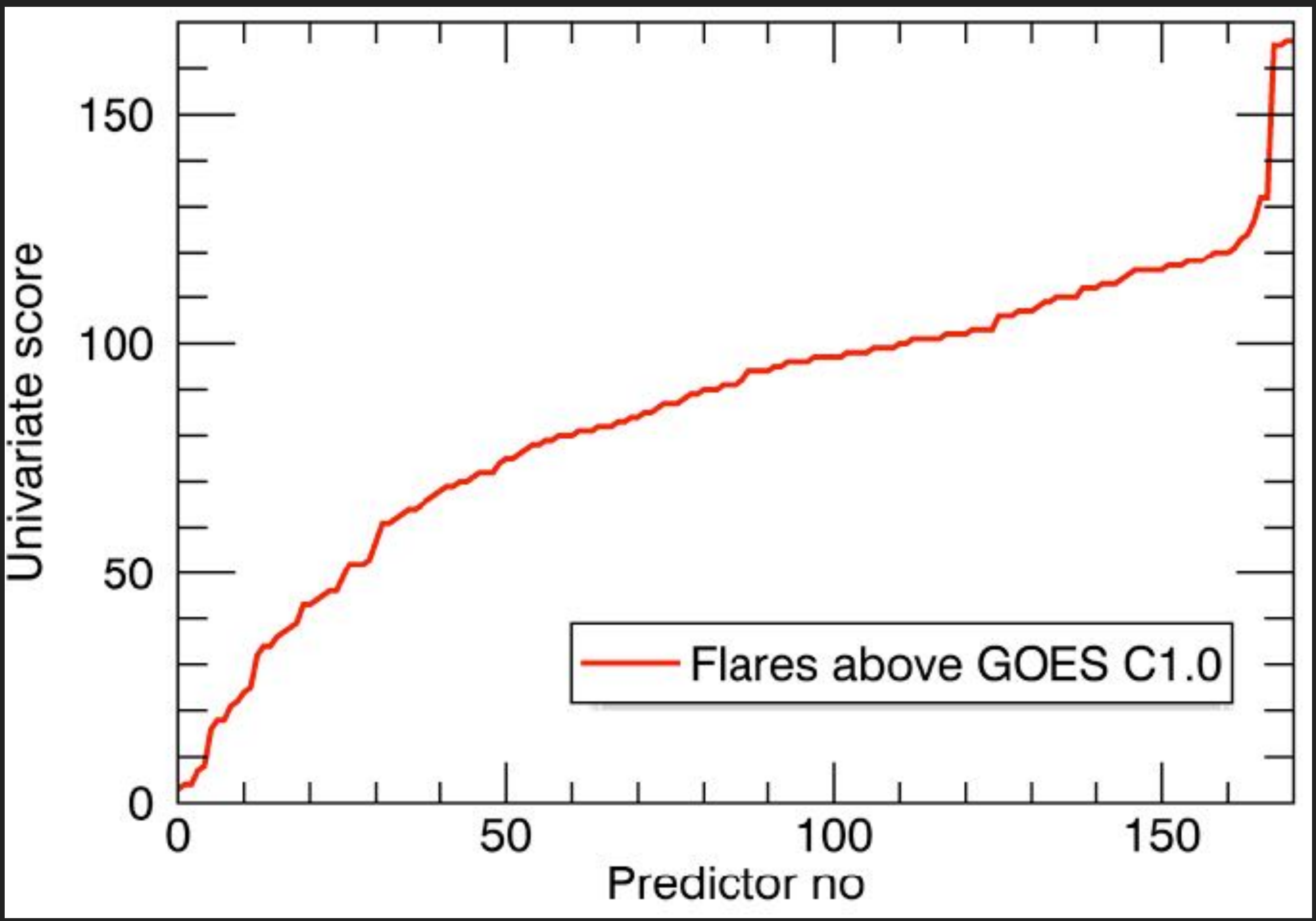
Bobra & Couvidat, ApJ, 2015: Ranking based on univariate Fisher score



Florios et al., SoPh, 2018 : Ranking with respect to Fisher score and Gini index

- Clearly, some parameters work better than others

RANKING OF PARAMETERS VARIES FOR DIFFERENT SETTINGS



- Ranking of 171 predictors with respect to their univariate score (low to high)
- Prediction of flares of class C1.0 and above

Data credit: Michele Piana et al., UNIGE

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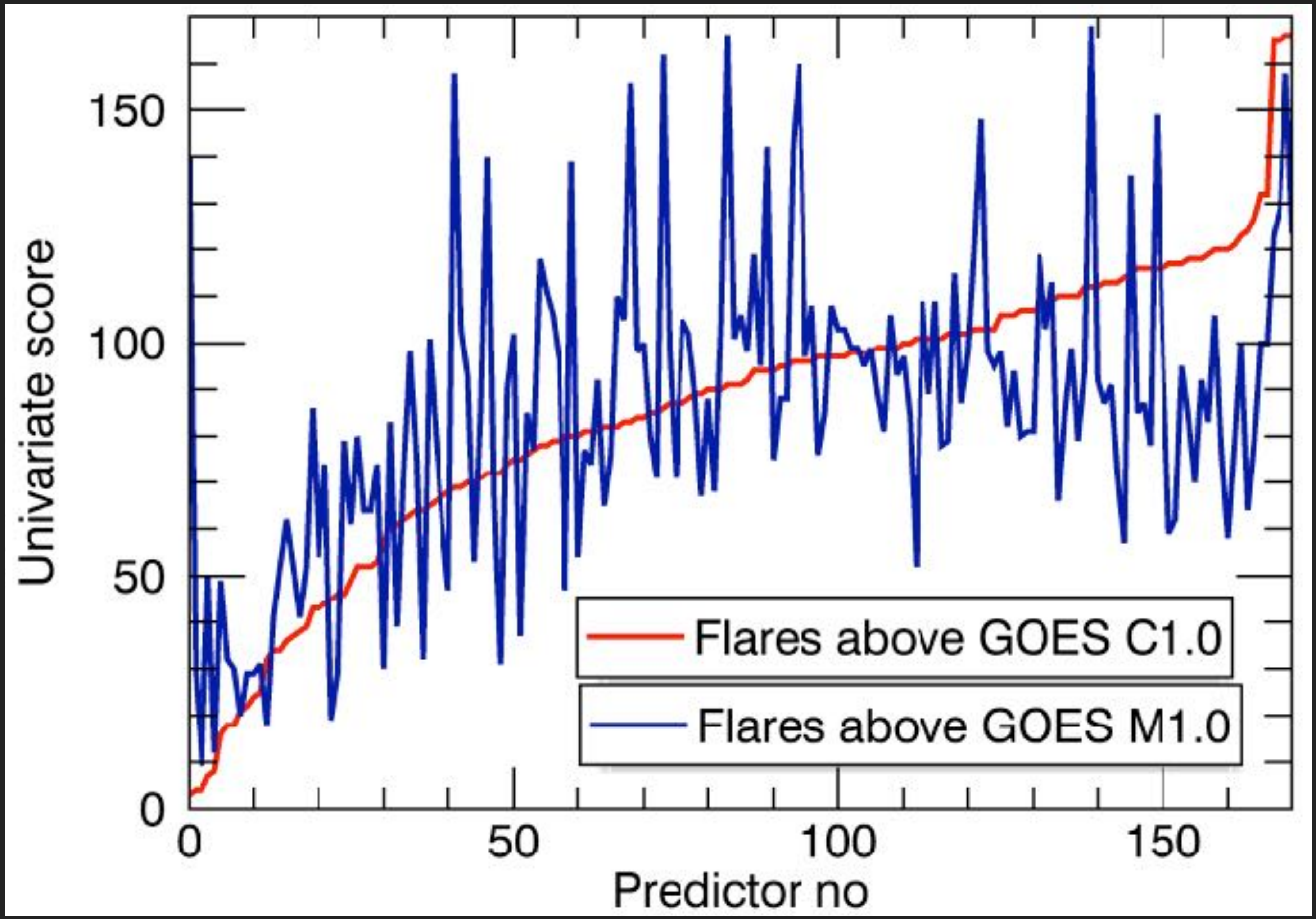

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- Prediction of flares of class C1.0 and above
- Prediction of flares of class M1.0 and above

Data credit: Michele Piana et al., UNIGE

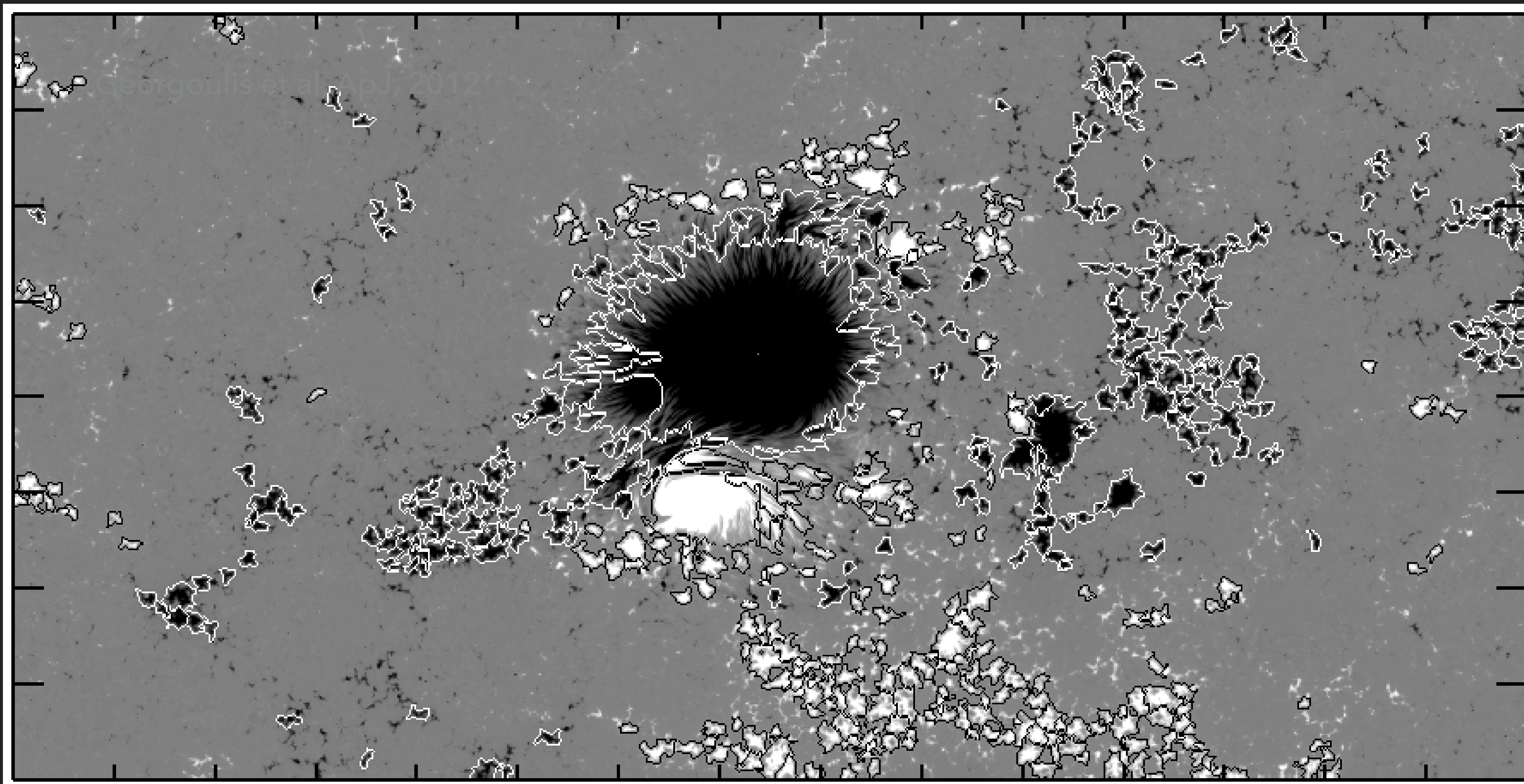
THE O2R QUESTION TO ASK: WHY DO SOME PARAMETERS WORK BETTER THAN OTHERS?

- Clearly, some parameters work better than others – different, for different settings, but there is a hierarchy of importance

THE O2R QUESTION TO ASK: WHY DO SOME PARAMETERS WORK BETTER THAN OTHERS?

- Clearly, some parameters work better than others – different, for different settings, but there is a hierarchy of importance
- **Questions to ask:**
  - What is the physics of these parameters vs. the physics of parameters that do not work?
  - How are these parameters calculated?
  - Can they be observed with EST, a non-operational (SWx-wise) instrument?
  - What can we learn by aiming to calculate these parameters at high spatial resolution / high cadence?

EXAMPLE I: NON-NEUTRALIZED ELECTRIC CURRENTS



Rather than integrating the vertical current density over all pixels for the total current, integrate over different polarity patches

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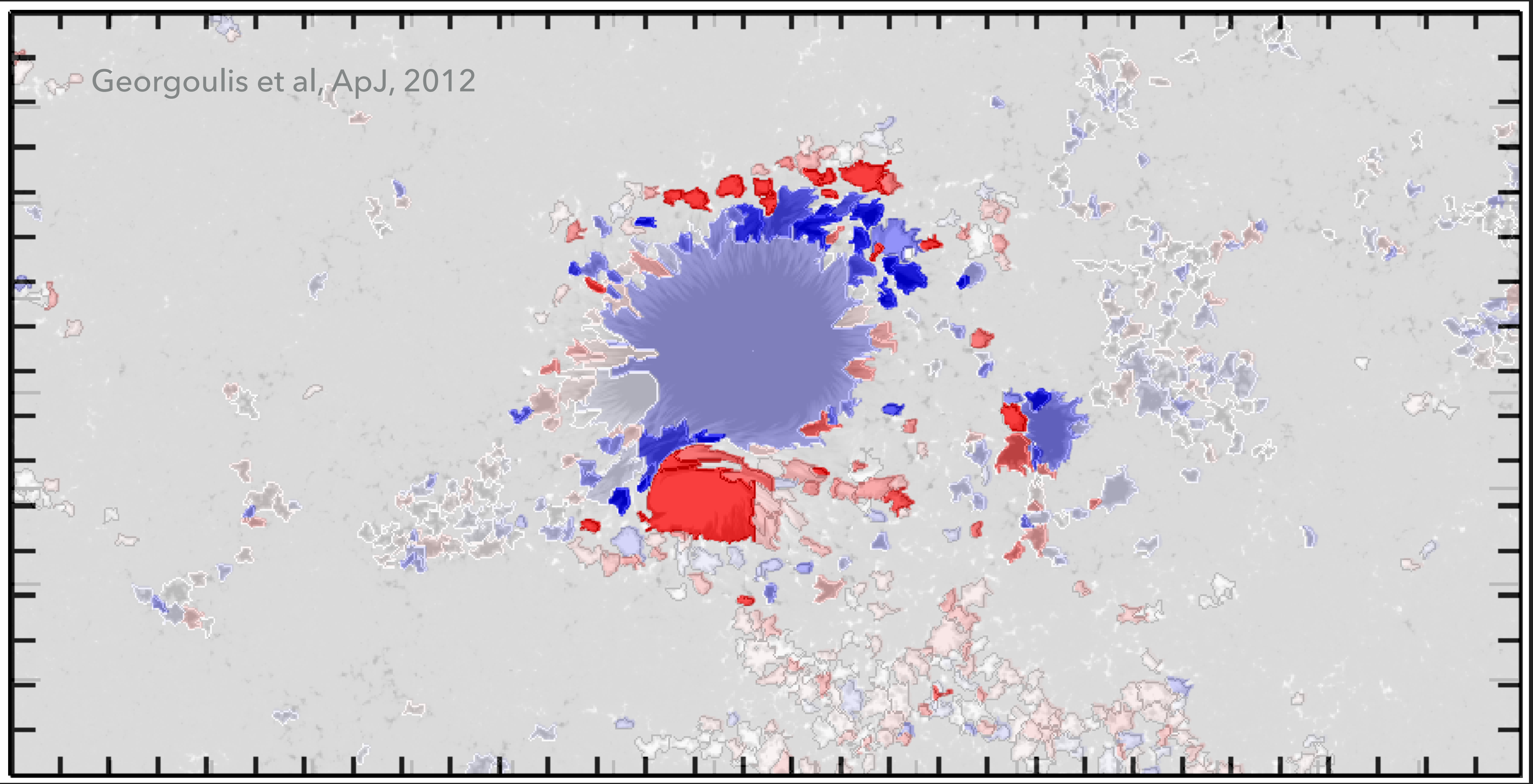

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HOW ARE THESE ELECTRIC CURRENTS CALCULATED?

$$Inet^{\pm} = \sum_{i=1}^{N} s_i^{\pm} I_i$$

Net current per polarity

Total current per magnetic partition i

$$I_i = \frac{c}{4\pi} \int_{S_i} \nabla \times \bar{B} \cdot \hat{n} dS_i = \frac{c}{4\pi} \oint_{C_i} \bar{B} \cdot d\ell_i$$

filtering out different-polarity partitions

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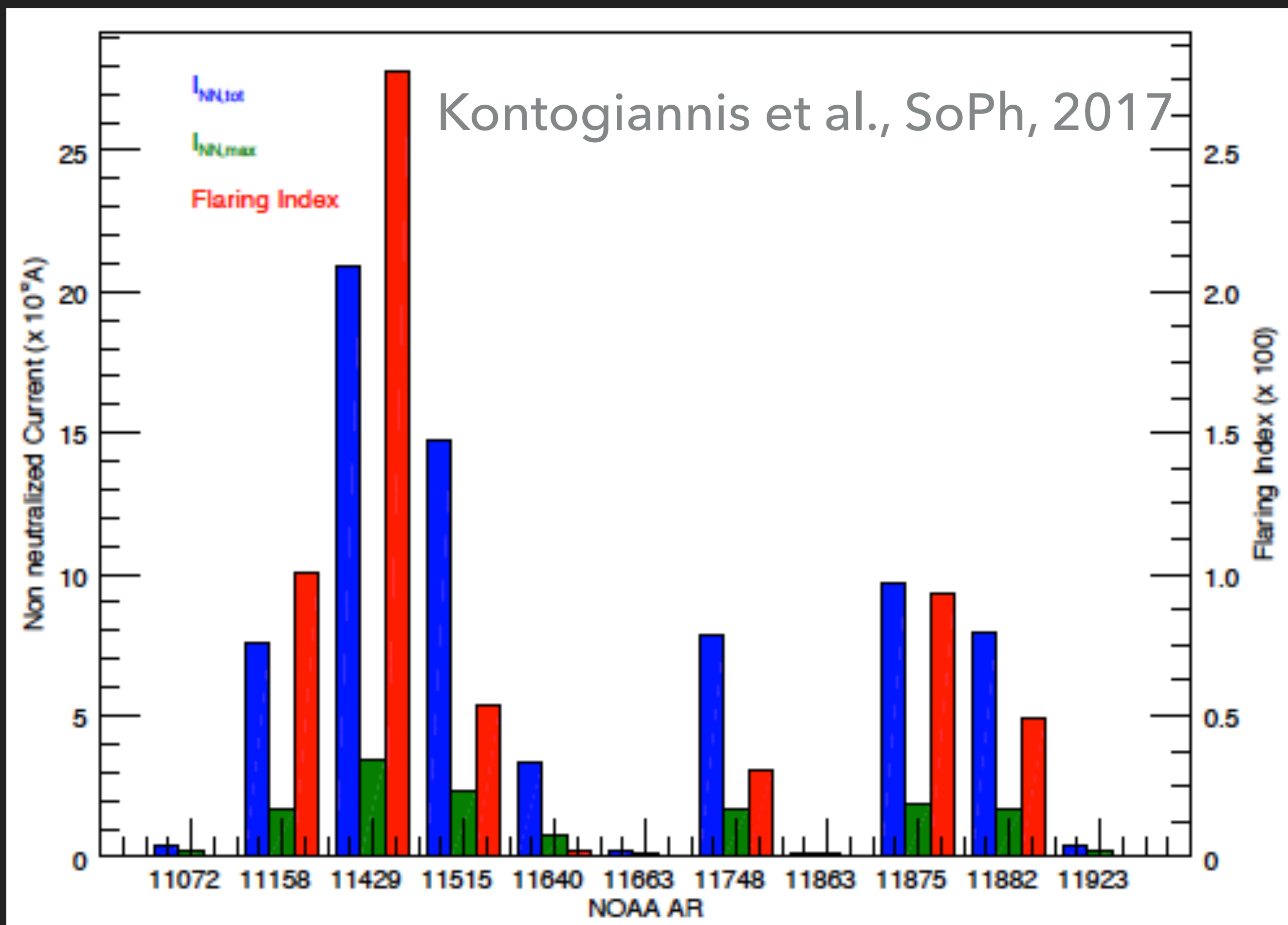

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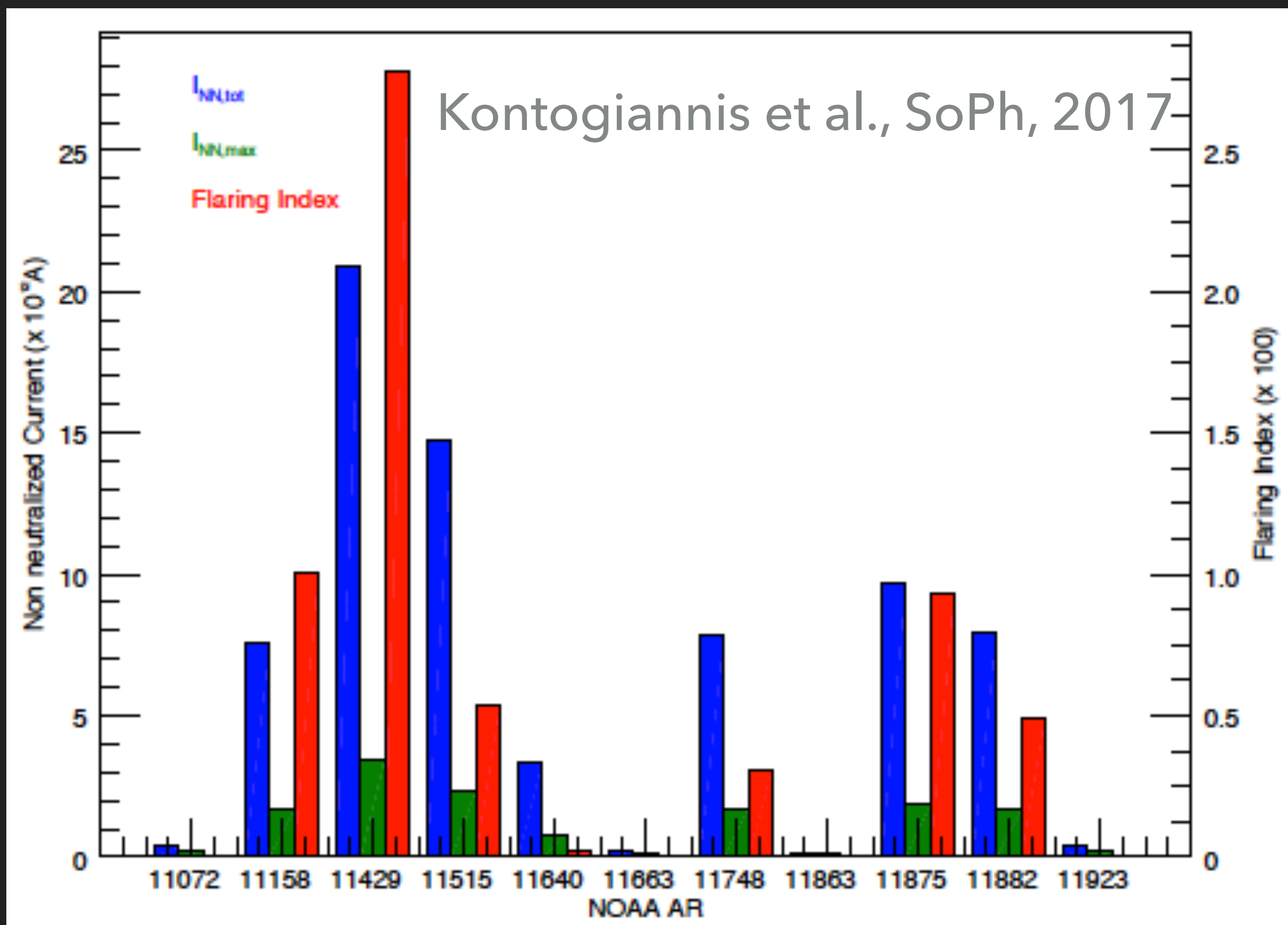

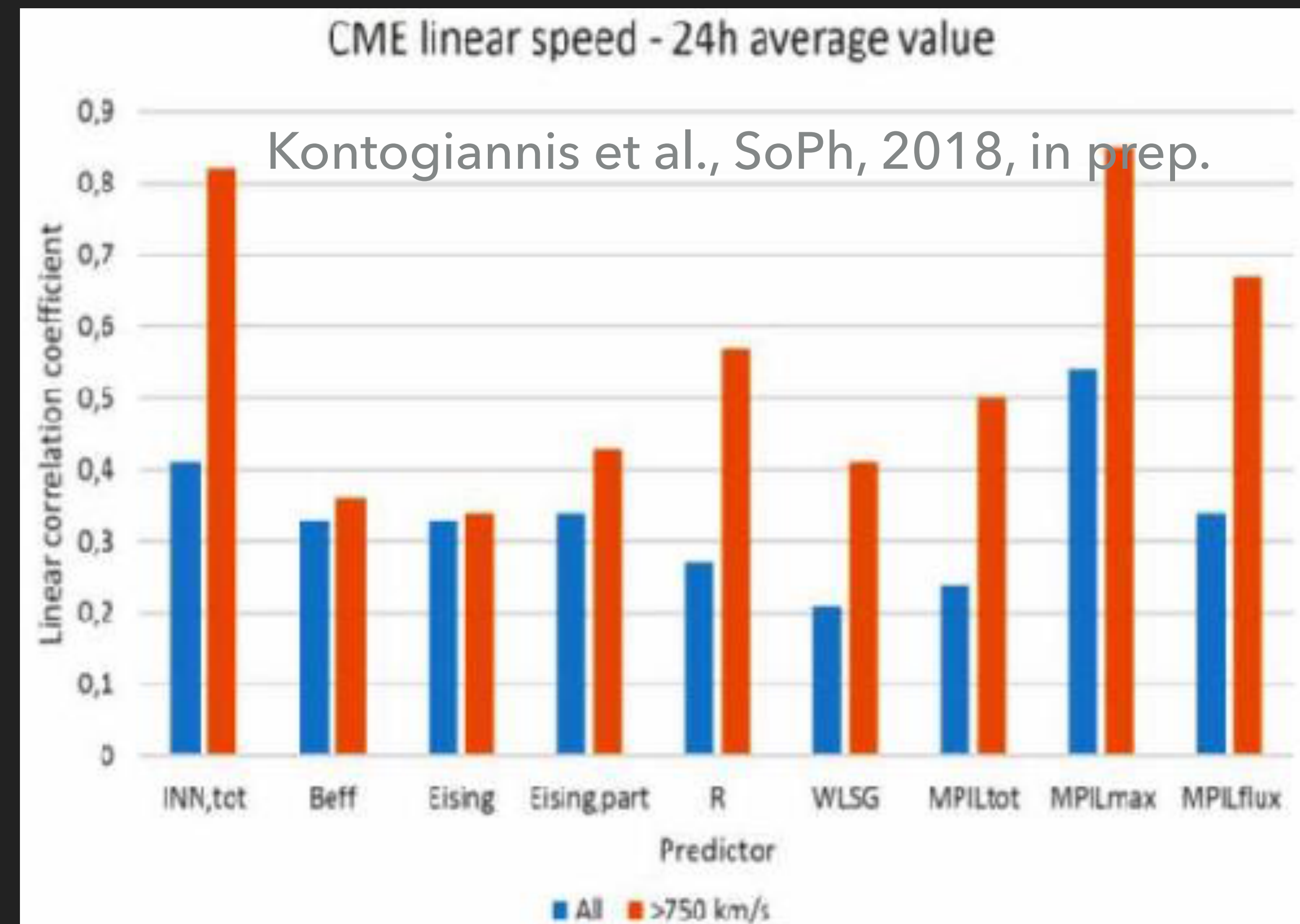

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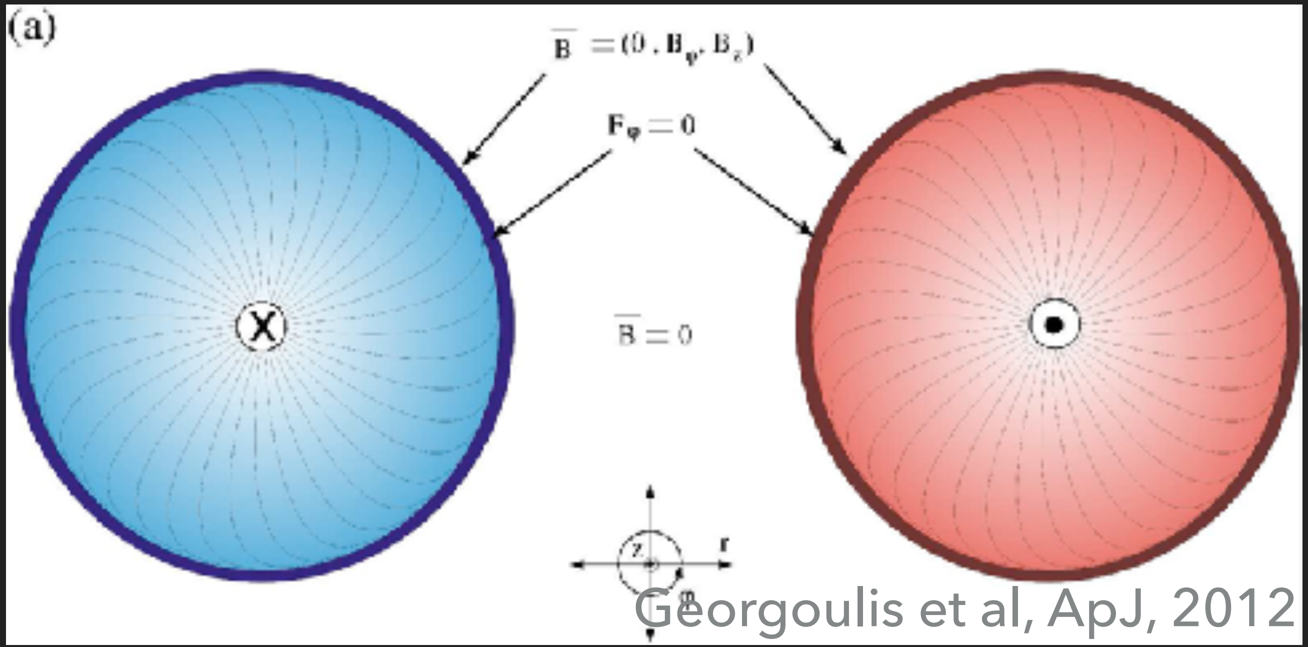

Georgoulis et al, ApJ, 2012

- Azimuthal Lorentz force on edges of flux tube footpoints embedded in field-free space:

$$F_\varphi \approx \frac{B_n}{4\pi}\left(-\frac{1}{r}\frac{\partial B_n}{\partial \varphi} + \frac{\partial B_\varphi}{\partial n}\right)$$

(purely magnetic tension)

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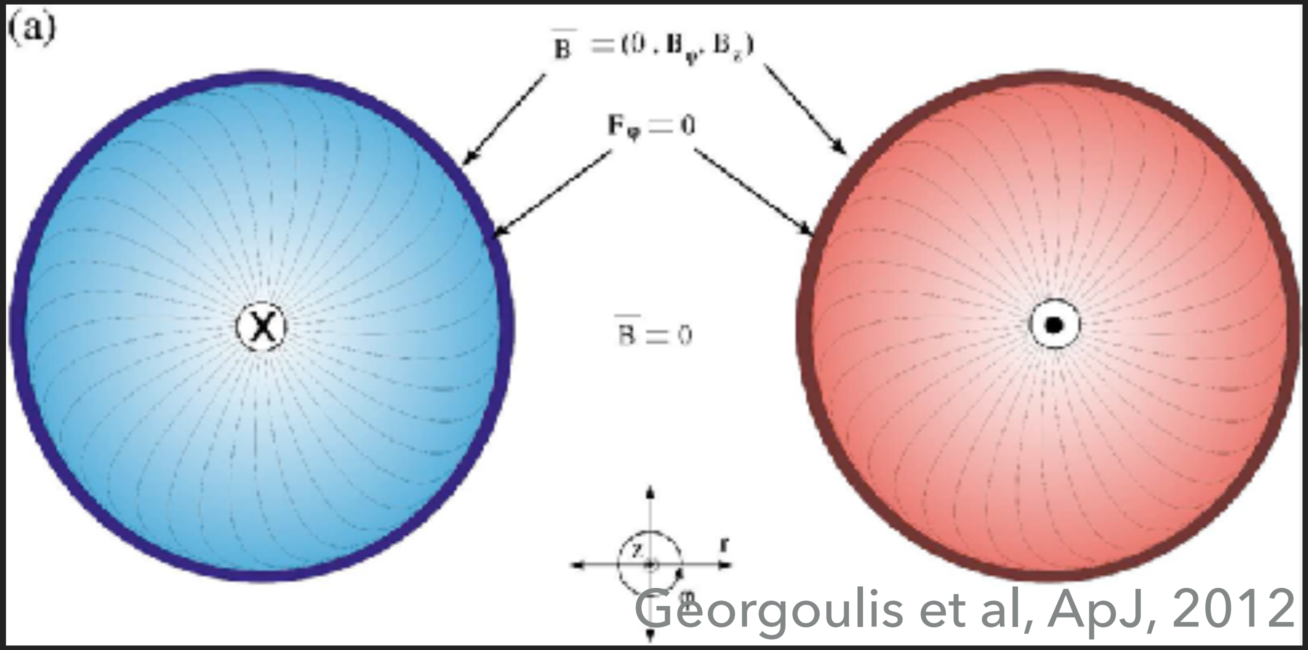

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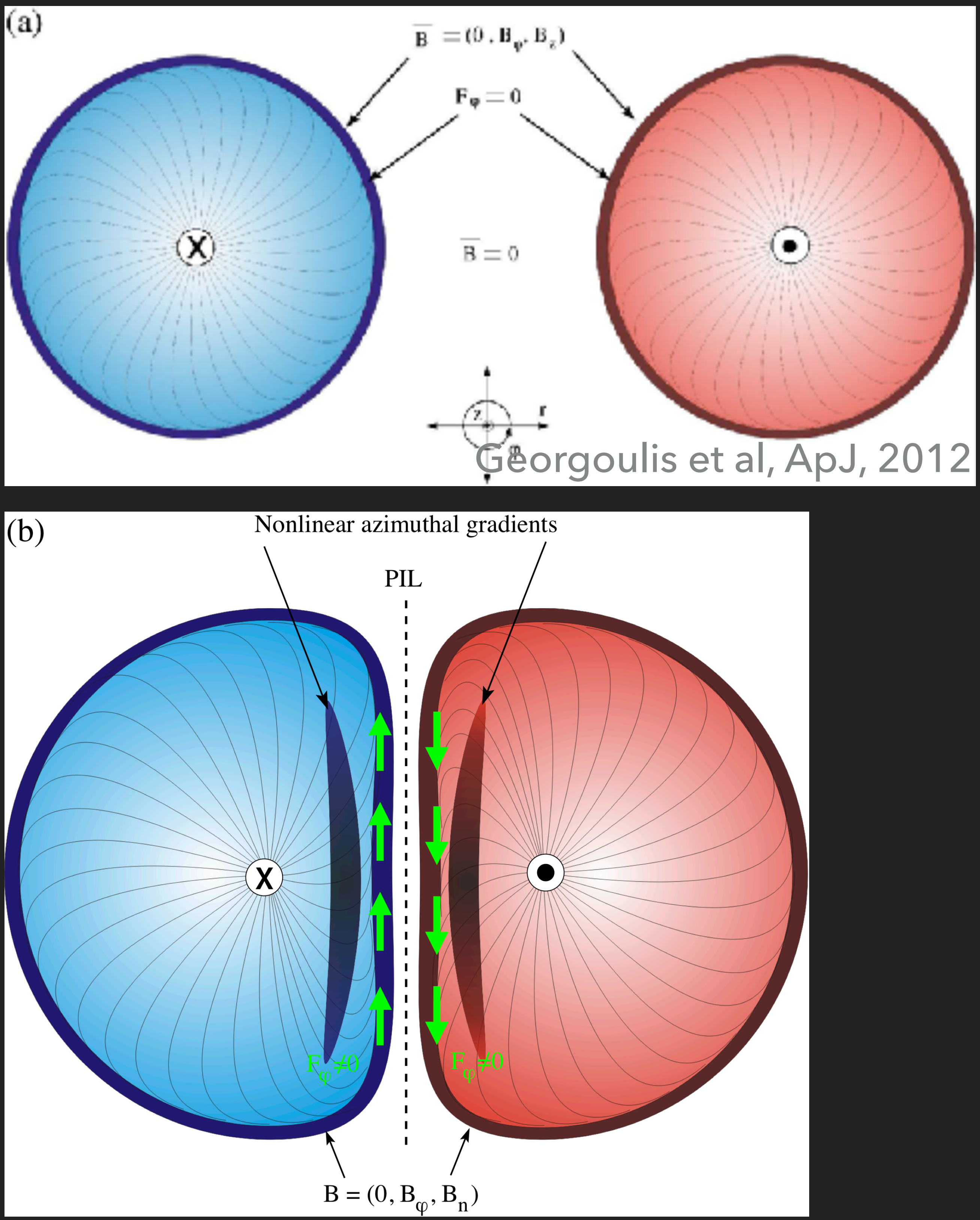

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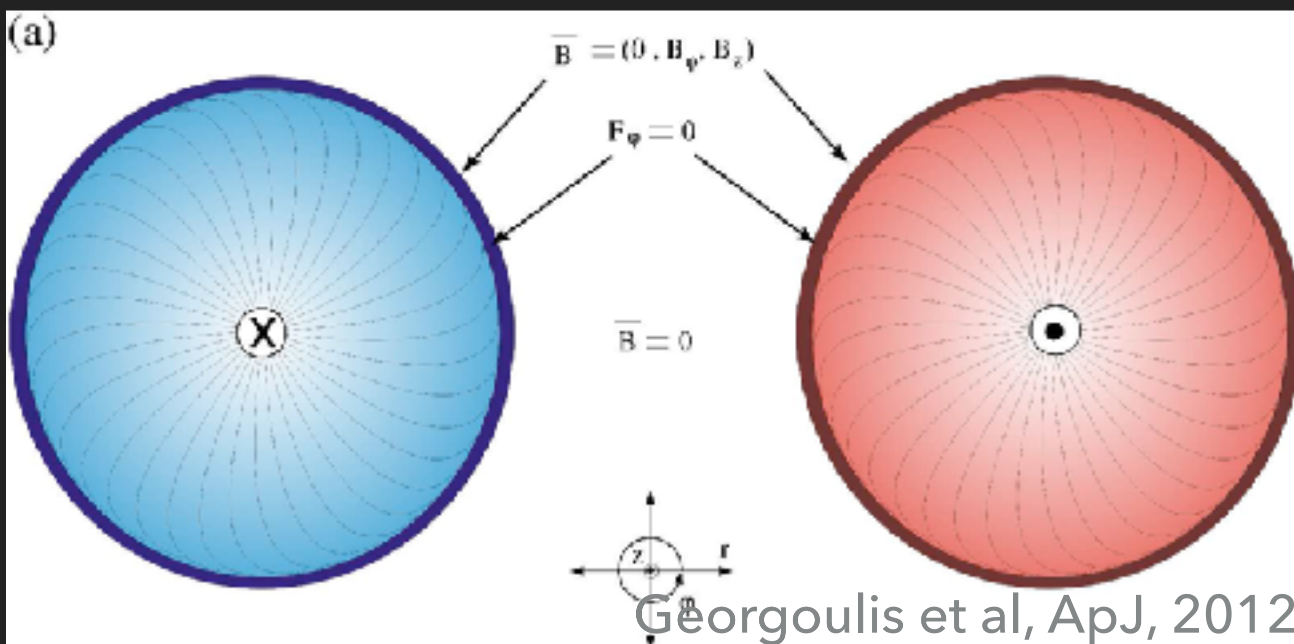

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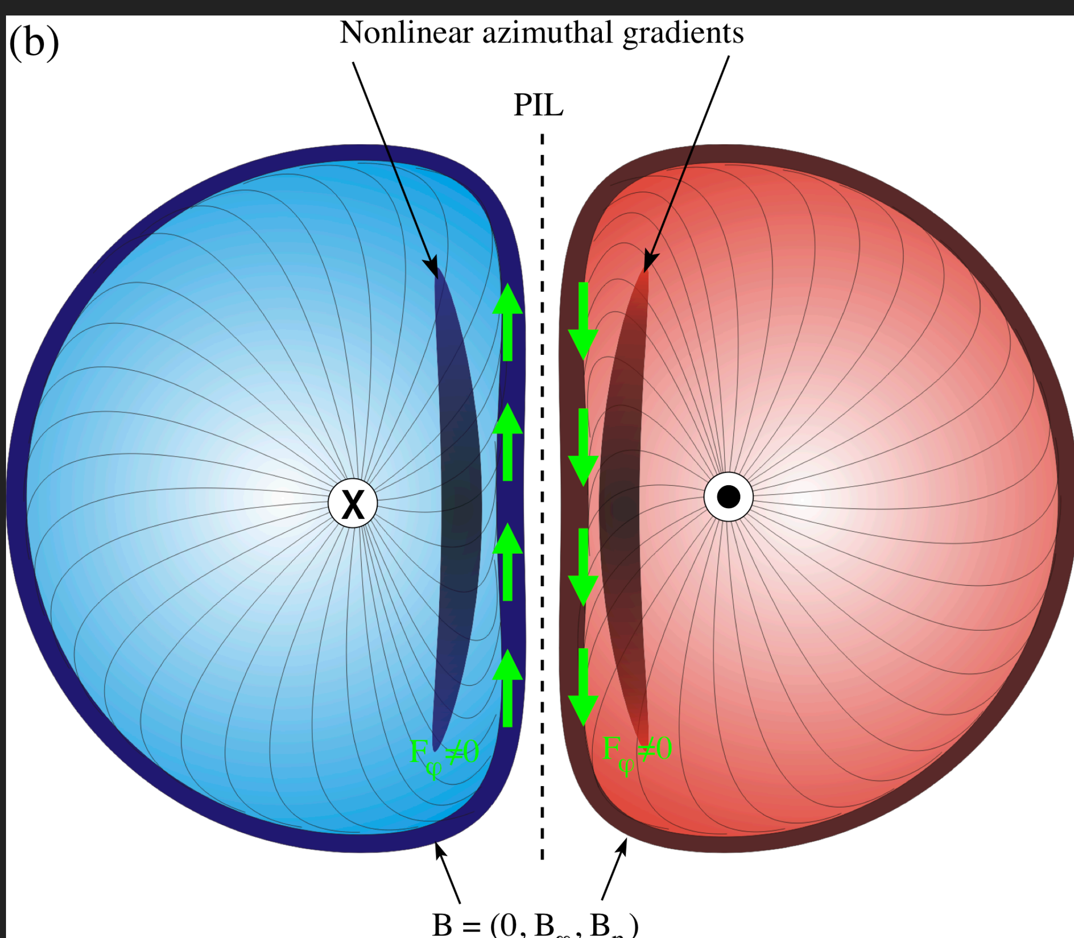

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Lorentz force appears along strong PILs when the interacting magnetic polarities <u>deform</u> as a result of this interaction

IT ALL BOILS DOWN TO CALCULATING ($\partial B_{\phi}/\partial \eta$)

- Multi-height measurements in active regions that generate strong (i.e., sheared) magnetic polarity inversion lines
- This will allow calculation of the azimuthal Lorentz force along the PIL, that can then be connected to net currents

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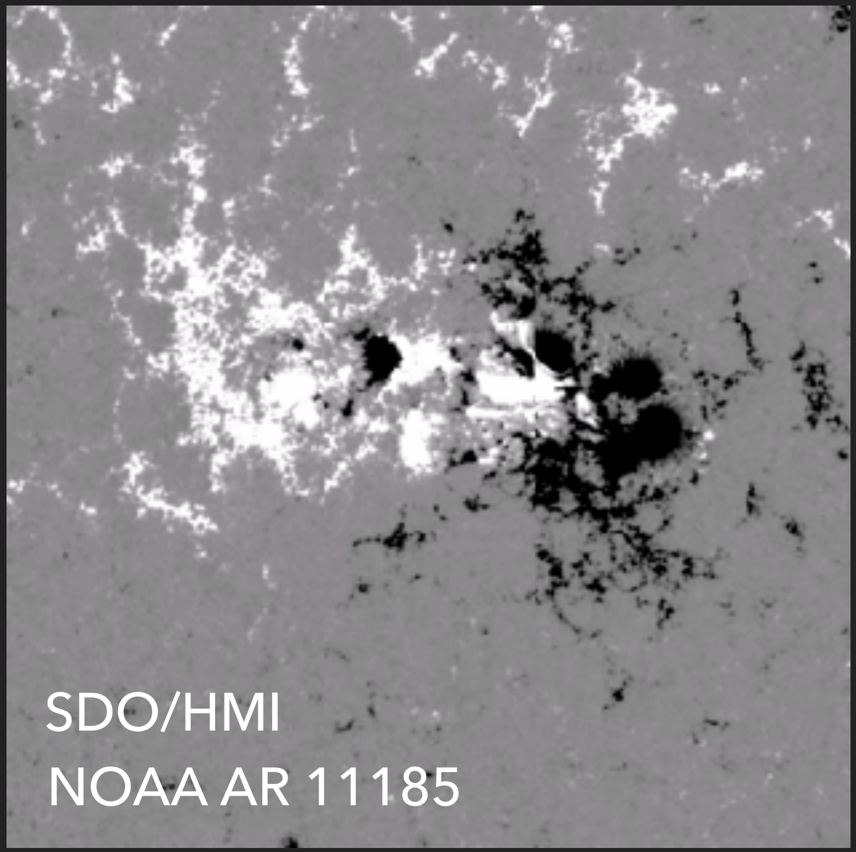

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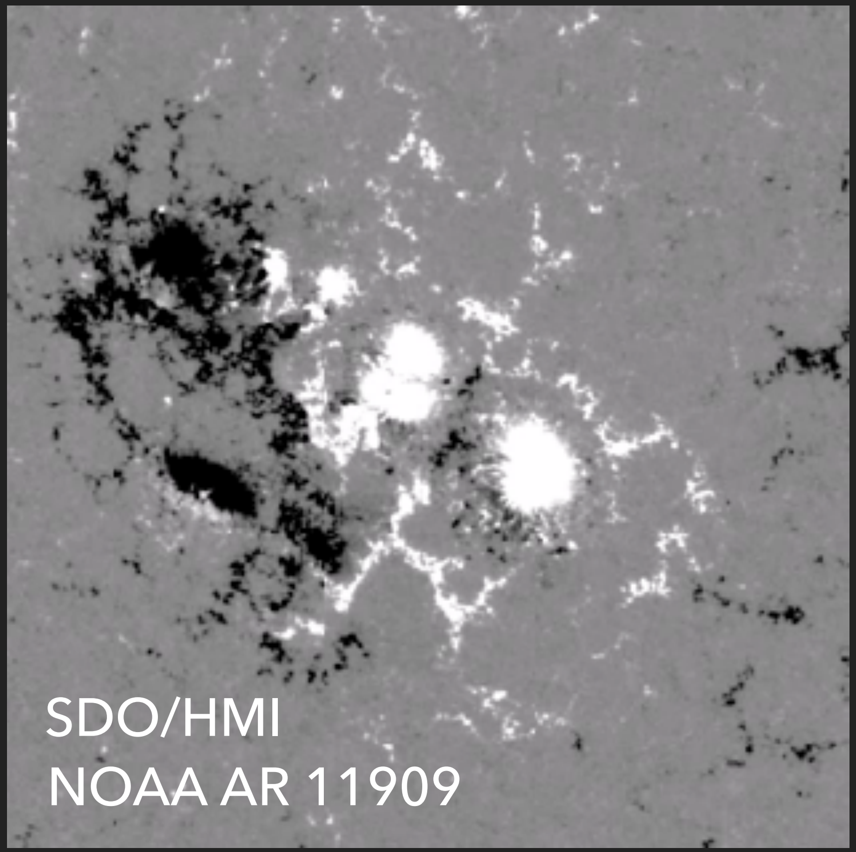

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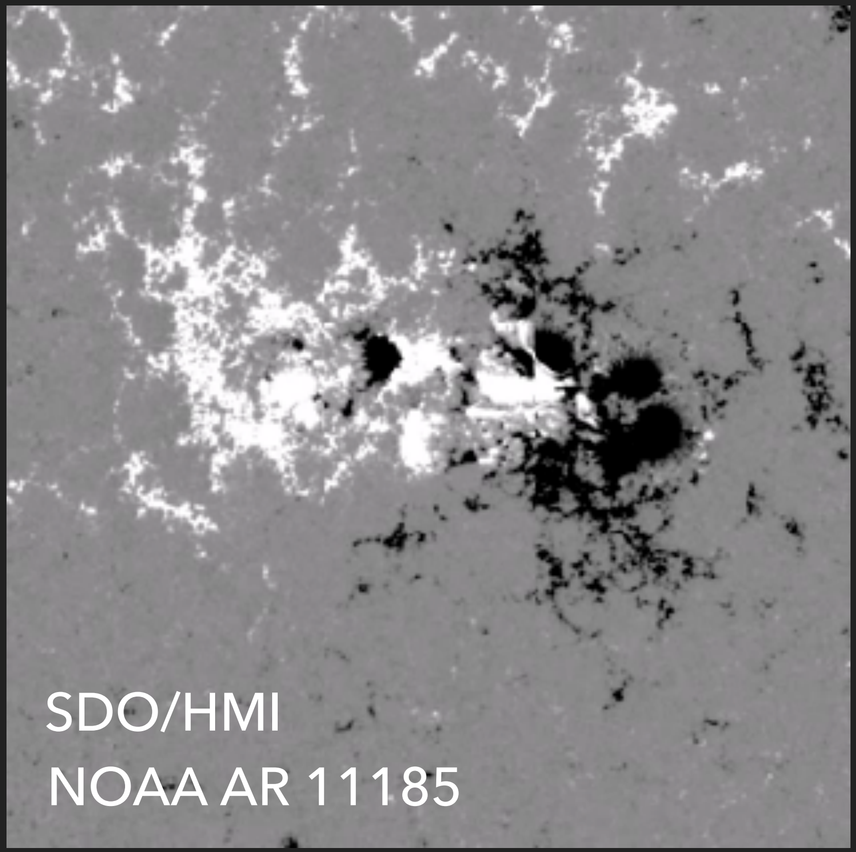

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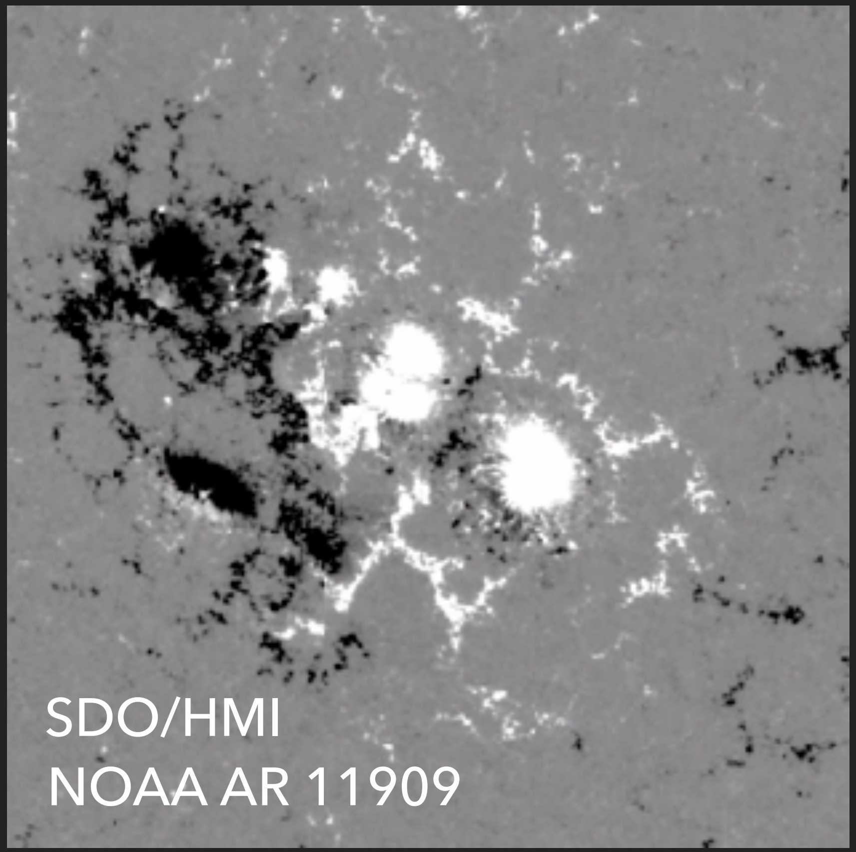

- The next question to ask : why shear?

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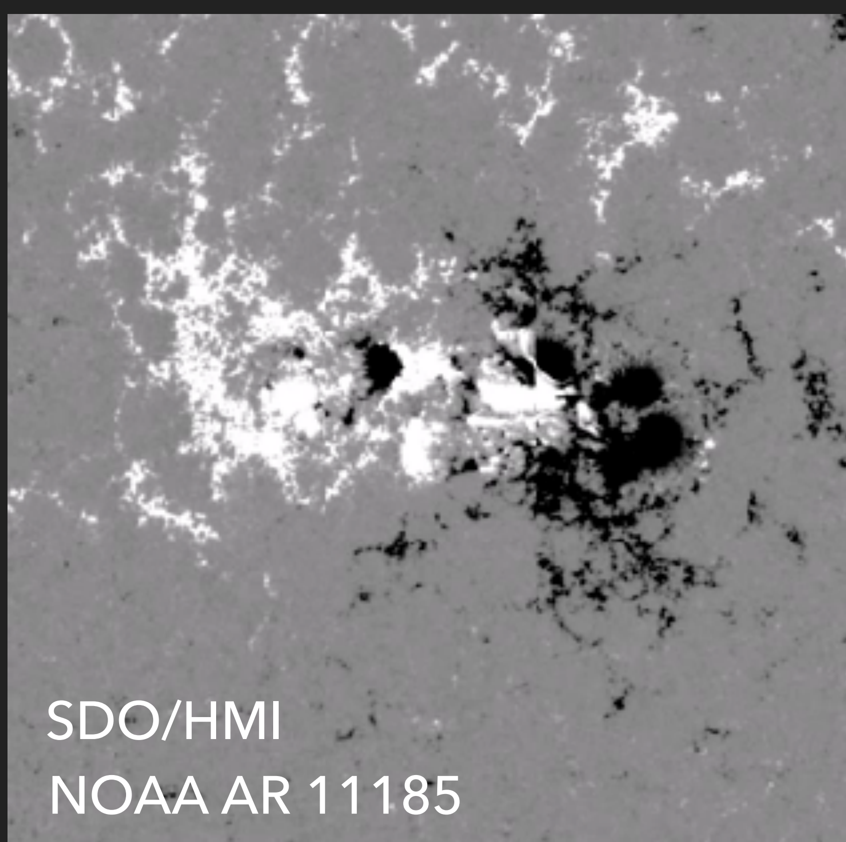

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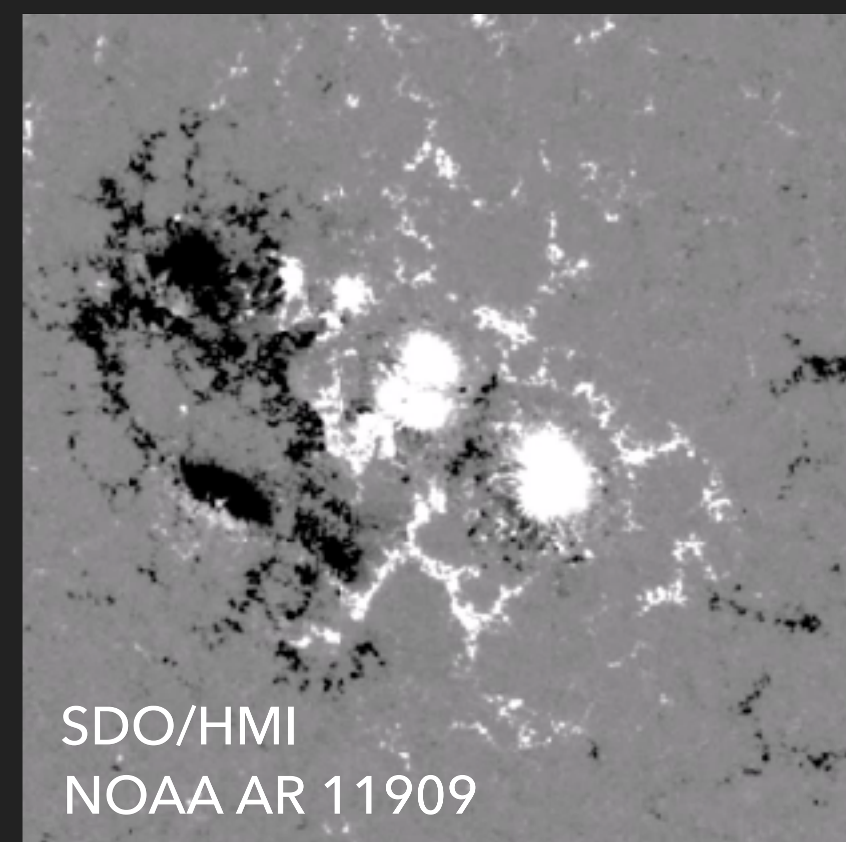
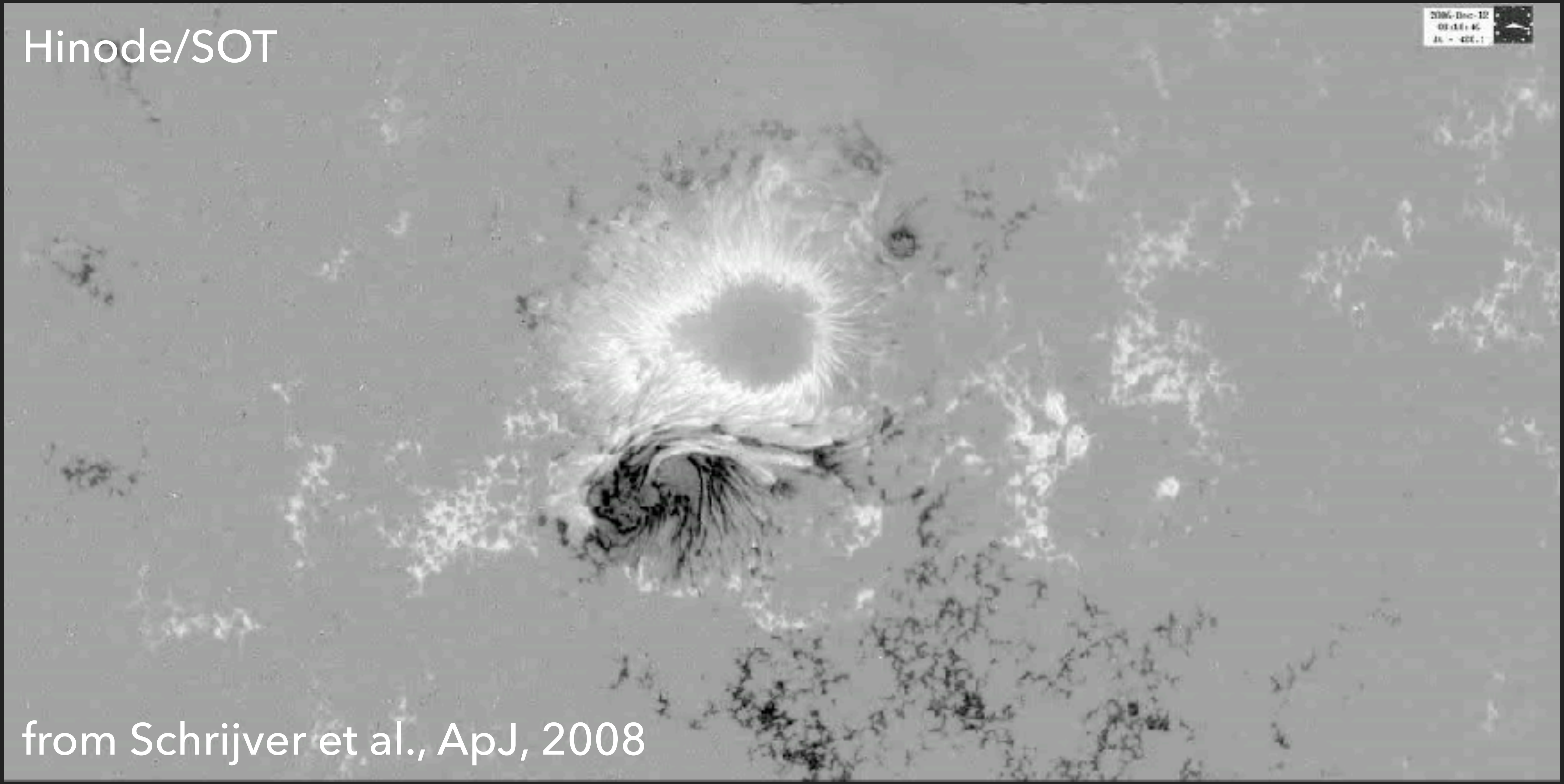


- The next question to ask : why shear?
  - With a plausible answer: check the plasma-β parameter along PIL

SHEAR ALONG MAGNETIC POLARITY INVERSION LINES



- Mean photospheric equipartition value for B-field: ~800 G, with an upper limit of ~1400 G
- B-field values along PIL in NOAA AR 10930: >1500 G sometimes >2000G

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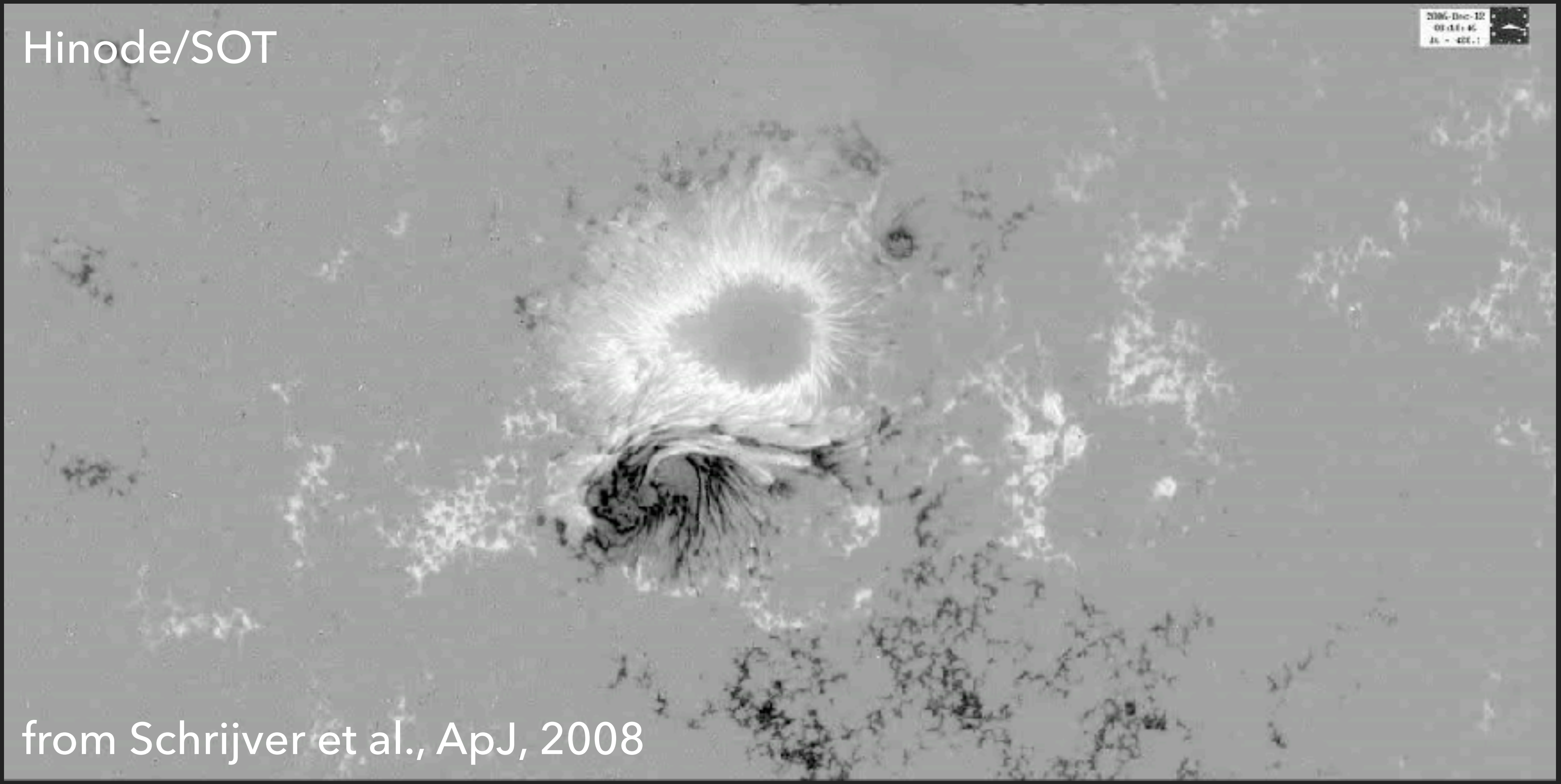

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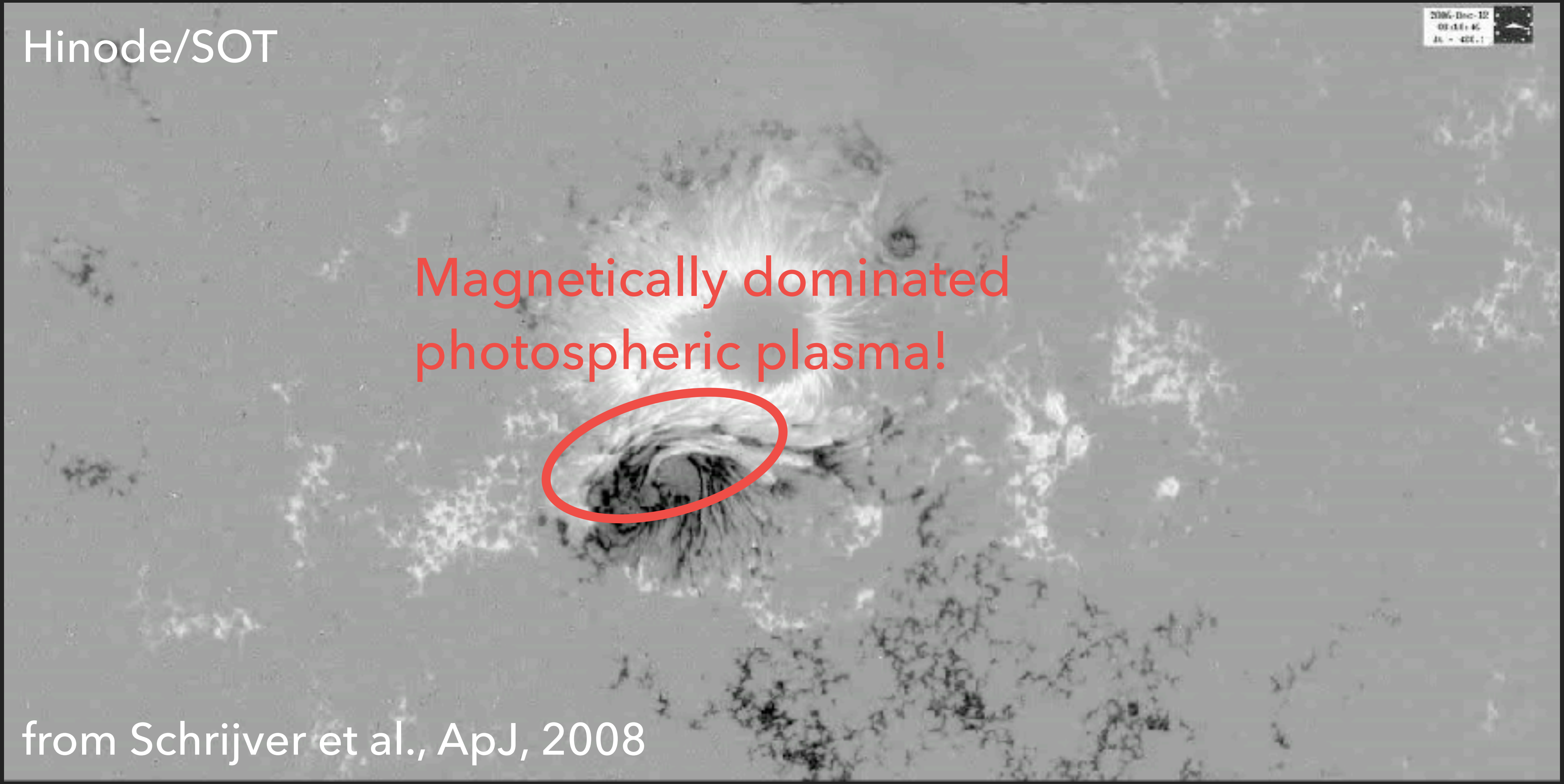

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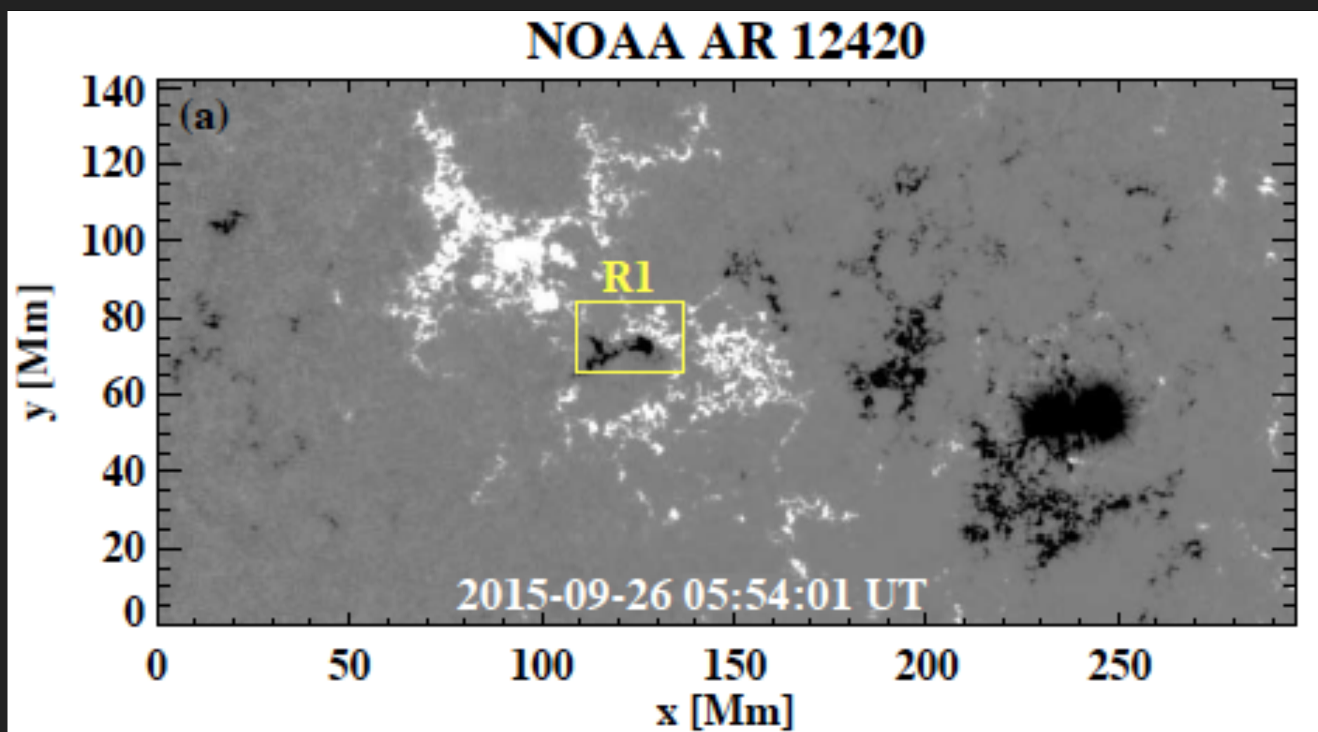
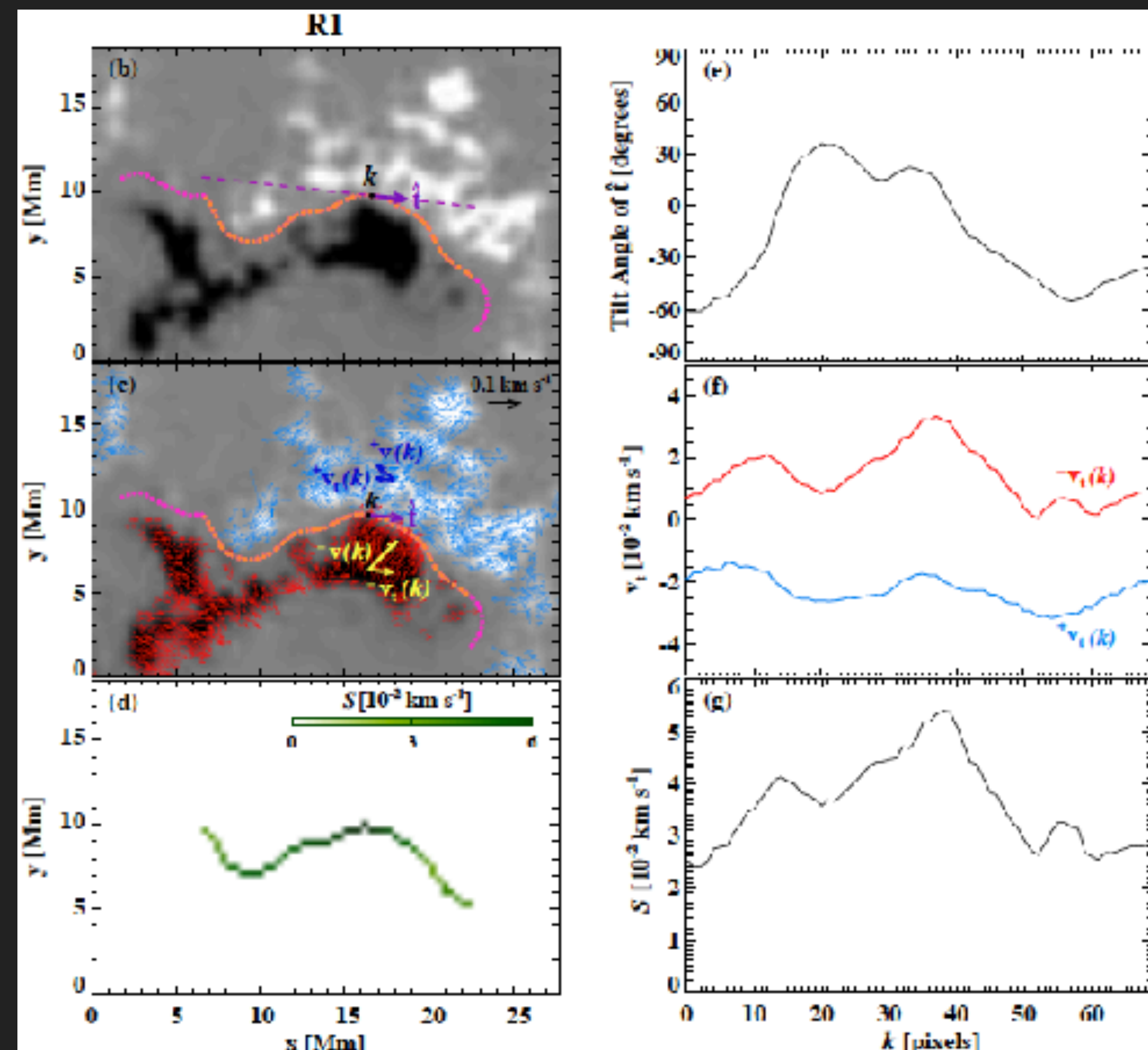
EXAMPLE II: INTEGRATED SHEAR FLOW





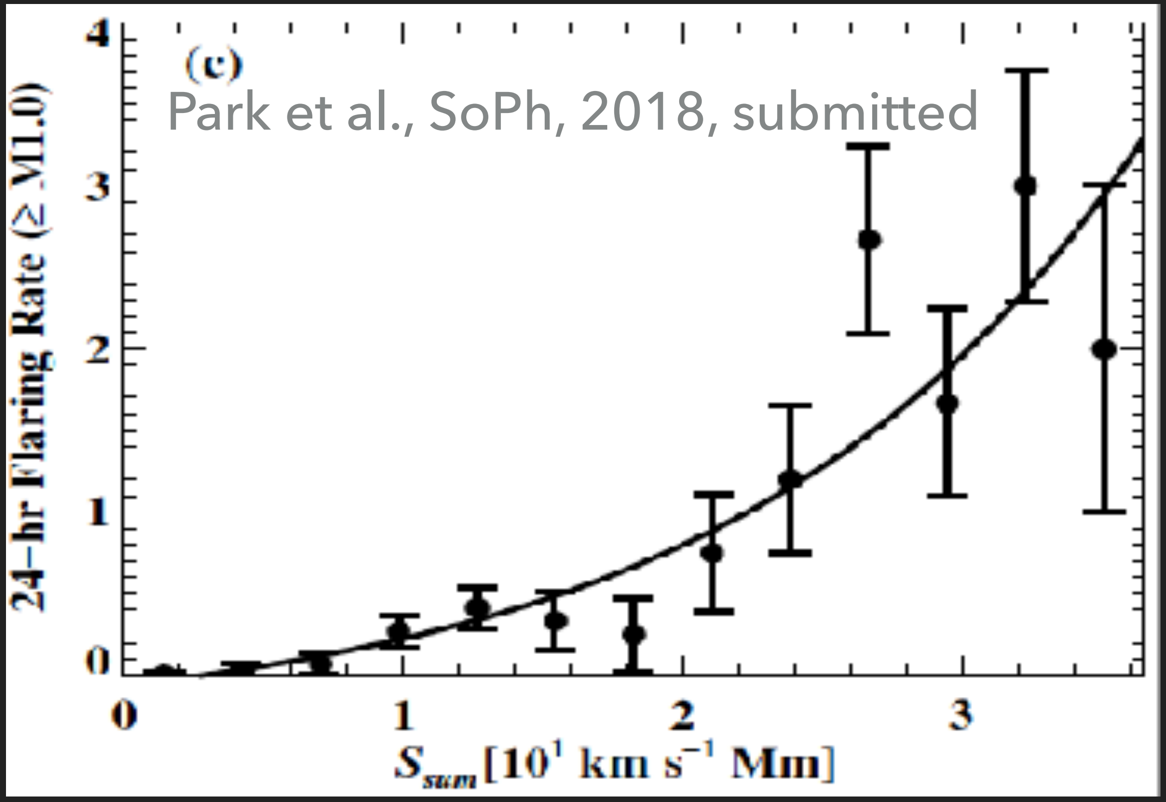
Park et al., SoPh, 2018, submitted

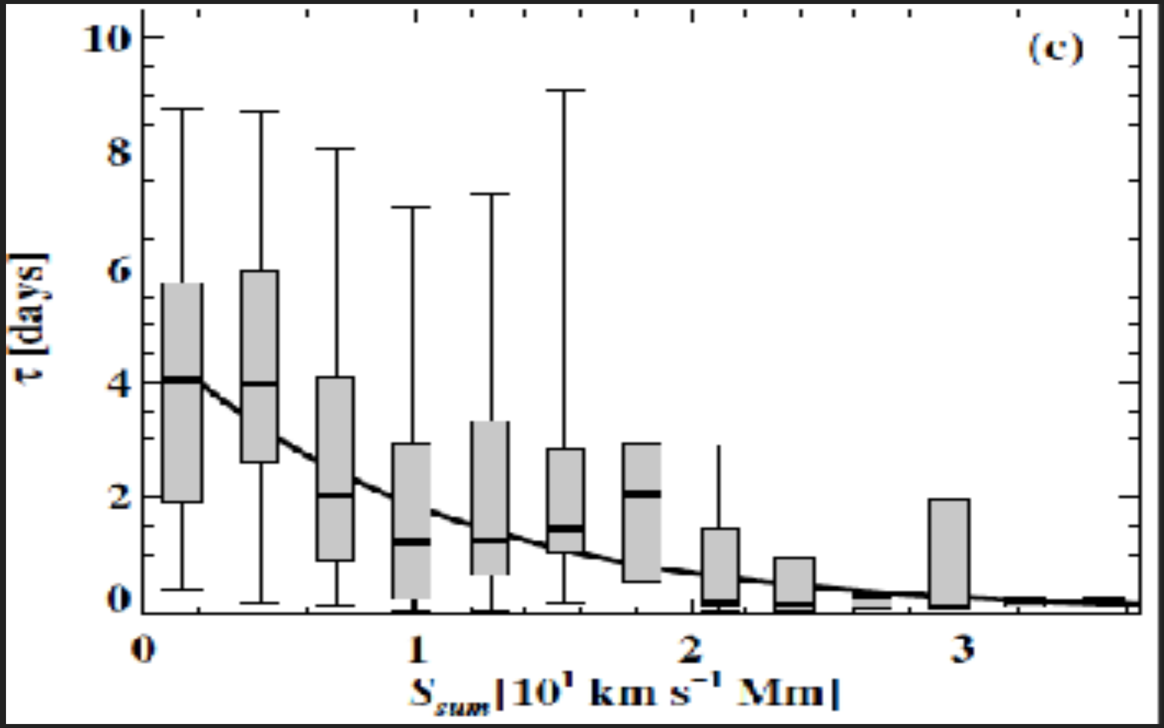
$$S_{sum} = \sum_{k=1}^{N} |^{+}\bar{v}_{t_k} -^{-} \bar{v}_{t_k}|$$

- Sum over all pixels k of the PIL
- Velocities are weighted averages of the two-polarity velocities at an area of 15 x 15 Mm^2 centered at k

PROPERTIES OF THE INTEGRATED SHEAR FLOW

- Park et al. (2018) report that:
  - the larger the S_{sum} an AR has, the more likely it is to produce flares within 24 h
  - the larger the S_{sum}, the shorter the waiting time until the next flare
  - widespread shear in PILs accounts for repeated flaring, at shorter timescales





WHAT COULD / SHOULD EST DO?

Instrument 1	FP_{VIS}, FP_{IR} — Velocity field @ photosphere / chromosphere	
Goal	Measure 2D velocity and intensity oscillations over network magnetic field concentrations	
	Requirement	Goal
Photosphere	Fe I 543.4, Fe I 709.0	
Chromosphere	Ca II H, Hα, Ba I 455.5	
FOV	20″×20″	40″×40″
Spatial resolution	0.05″	
SNR	500	1000
Integration time	1 sec	0.5 sec
Cadence	20 sec	6 minute
Notes	High resolution and high cadence in 2D field of view	

Instrument 2	IFU_{IR} — Magnetic field @ photosphere / chromosphere	
Goal	Measure 2D magnetic field vector in the photosphere and chromosphere to complement the velocity data	
	Requirement	Goal
Photosphere	Fe I 1564,	
Chromosphere	He I 1083, Ca II 854	
FOV	20″×20″	40″×40″
Spatial resolution	0.05″	
SNR	5000	10000
Integration time	2 sec	2 sec
Cadence	5 minute	2 minute
Notes	High polarimetric precision and low noise.	

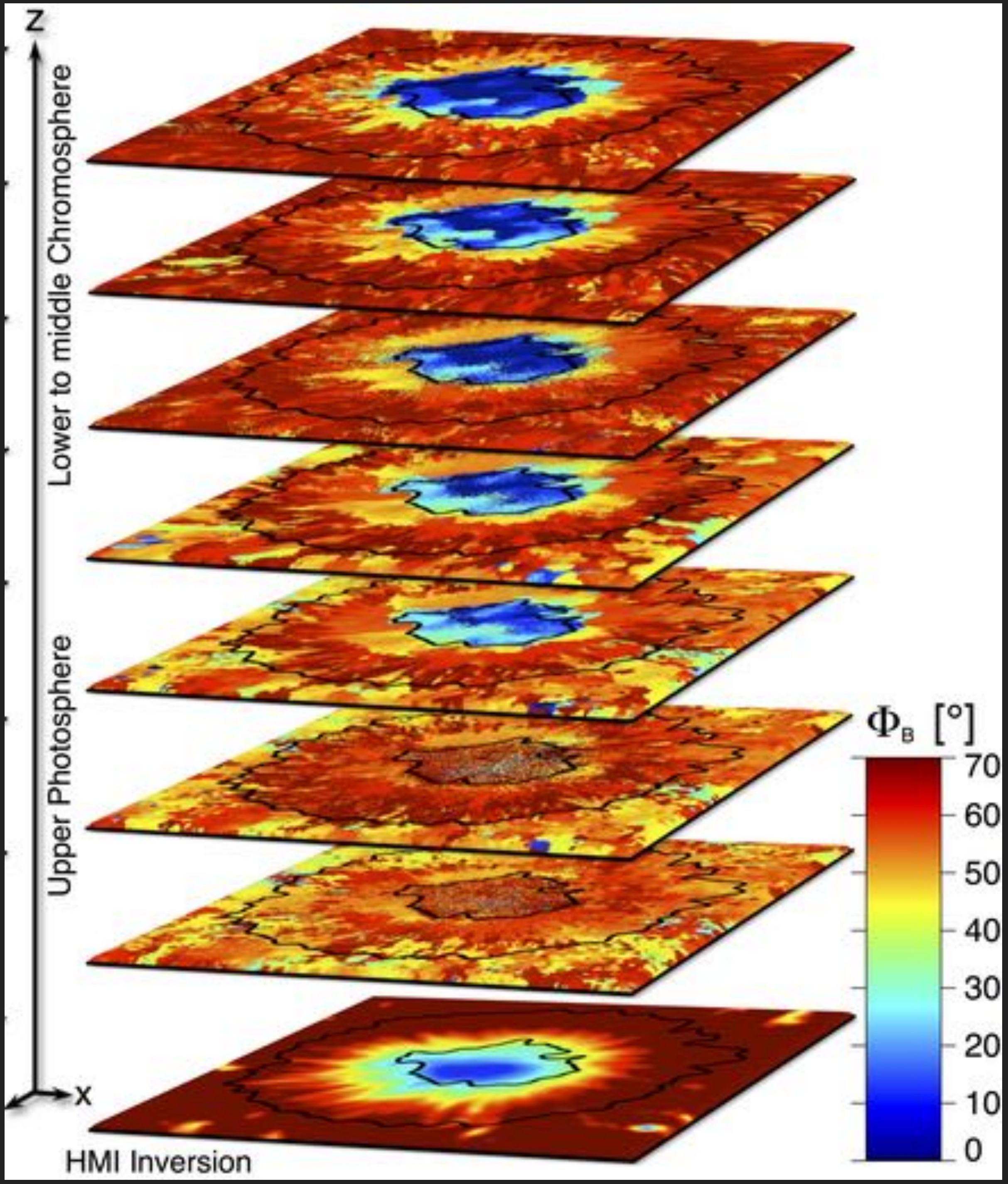
- To investigate these effects, one does not need the entire active region in the FOV
- EST does not need to predict, but to understand these phenomena:
  - Is the Lorentz force giving rise to magnetic shear?

SRD OP 2.4.2 (time-dependent behavior of chromospheric jets)

OTHER RELEVANT OBSERVATIONS

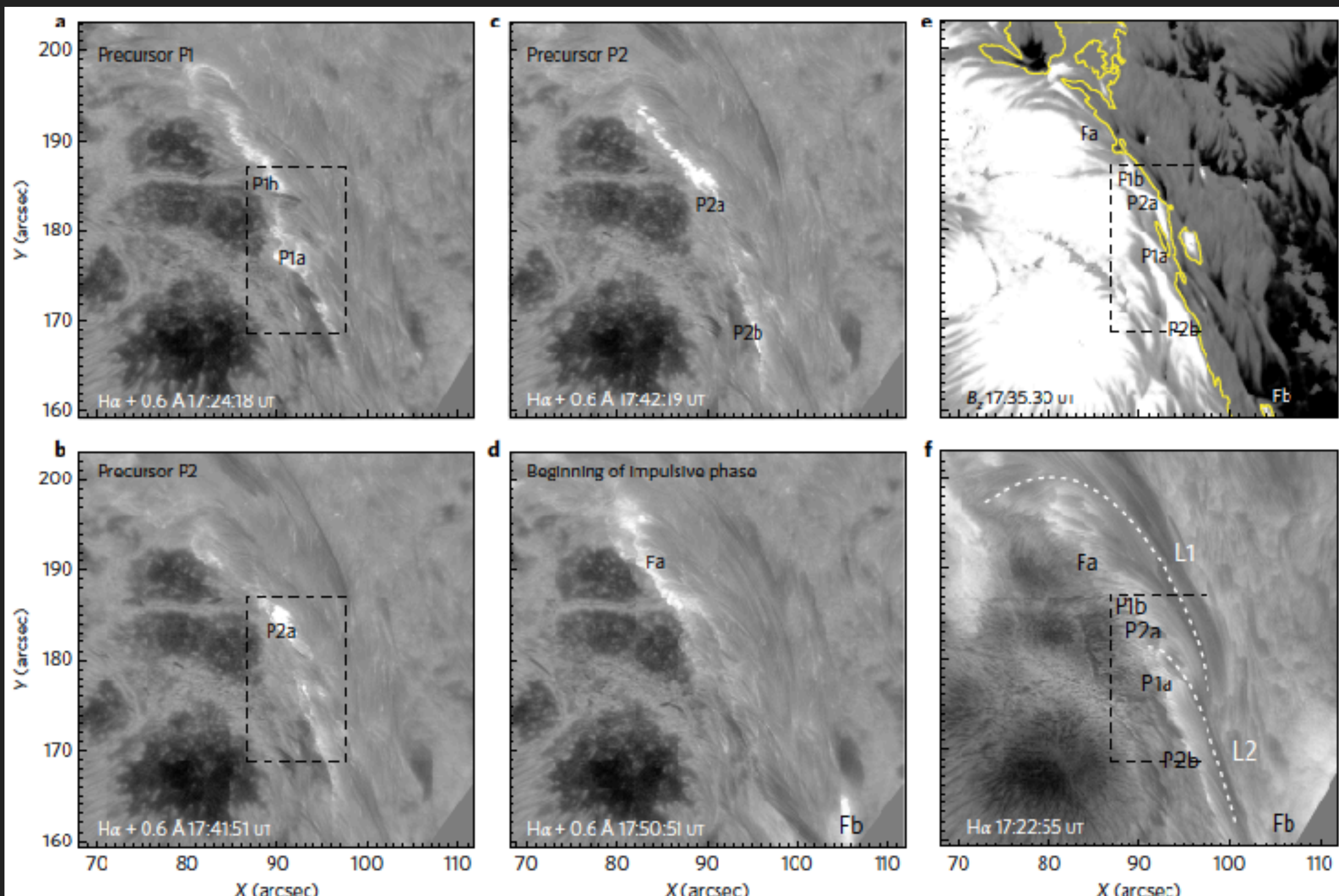
- Enabled by the joint knowledge of photospheric and chromospheric magnetic fields / velocities
  - Evaluate / compare Poynting and helicity fluxes for a quantitative assessment of the storage & release mechanism
  - Aim to resolve the azimuthal ambiguity of 180° in 3D
  - Perform measurements in the pre- and post-eruption phases at <u>both</u> chromosphere and photosphere

Zenith inclination in color scale



Credit : KIS – IBIS / DST

FUTHERMORE: ARE THERE (UNAMBIGUOUS) ERUPTION PRECURSORS?

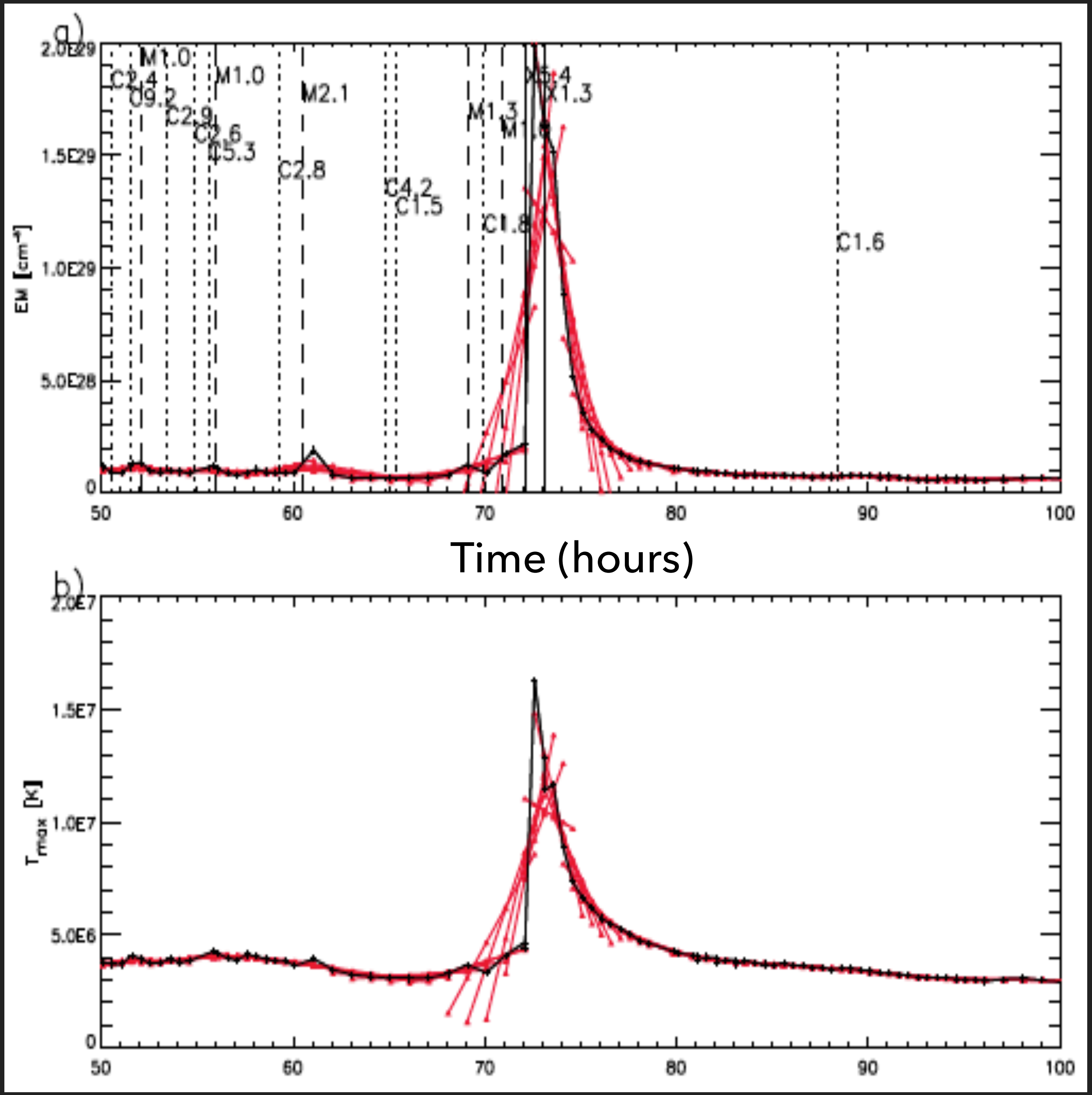


- Hα (line-center and off-band observations along with the local magnetic field
- However, it is mentioned that observed brightenings are "possibly linked to the onset of the main flare"

Wang et al., NatAst, 2017

(POSSIBLE) PRE-HEATING EVENTS IN FLARES

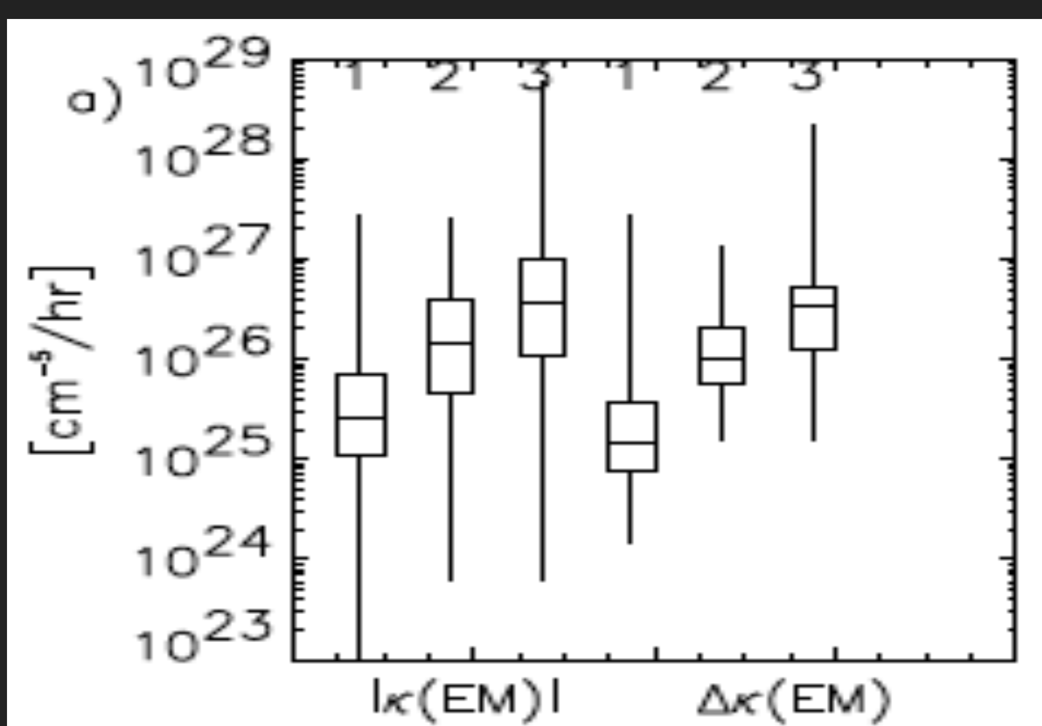
- DEM and Temperature profiles over part of the active region seem to increase tens of minutes to a couple of hours prior to the flare

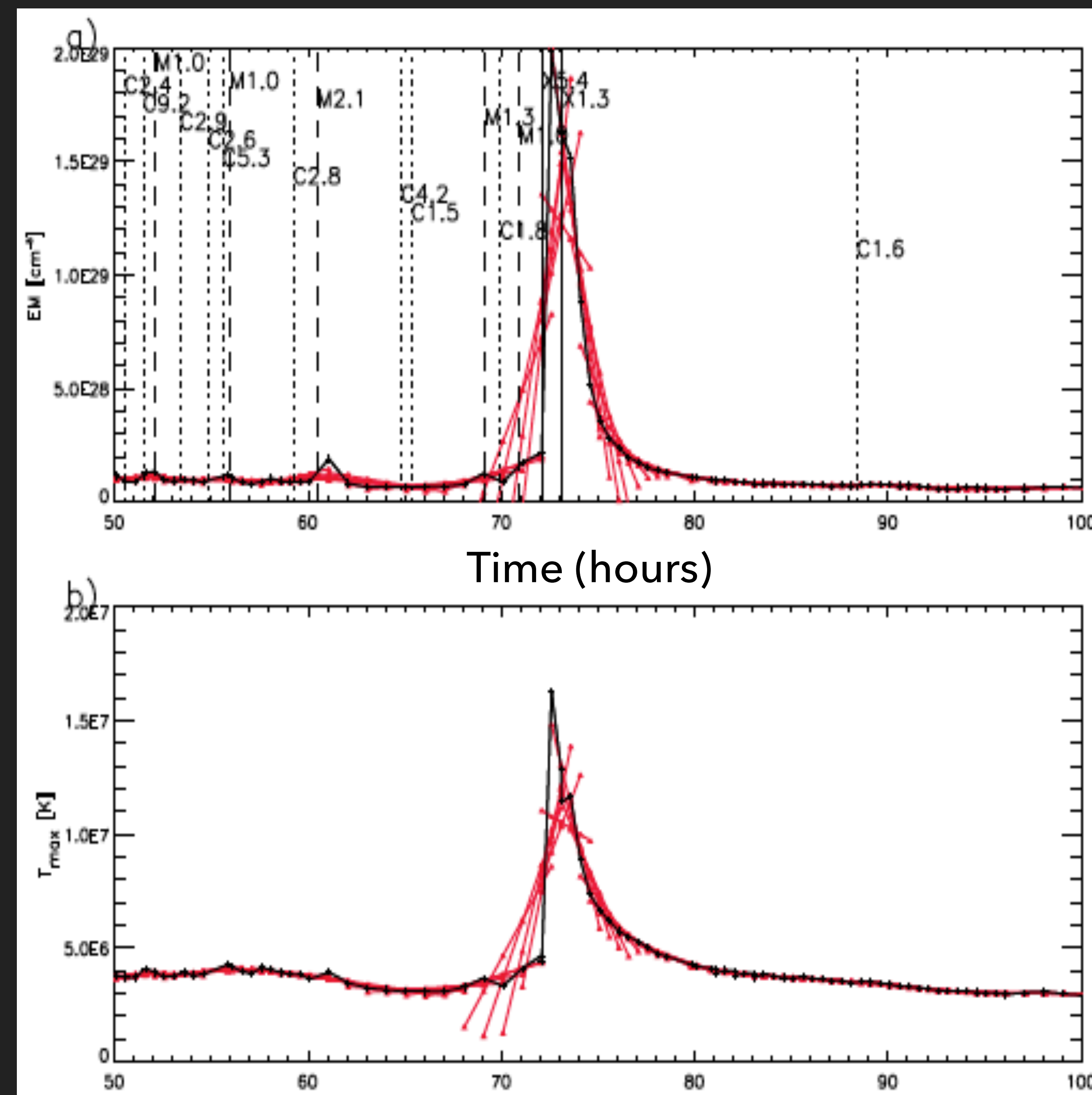


Gontikakis et al., SoPh, 2018, submitted

(POSSIBLE) PRE-HEATING EVENTS IN FLARES

- DEM and Temperature profiles over part of the active region seem to increase tens of minutes to a couple of hours prior to the flare
- This holds statistically for different active-region populations





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WHAT COULD / SHOULD EST DO?

Instrument 1	SP_vis & SP_ir	
Goal	Search for any brightening or flaring emission which could be spatially and temporally correlated with a CME. Infer the magnetic field configuration of the flux rope involved in the eruption leading to the coronal mass ejection.	
	Requirement	Goal
Photosphere	Fe I 1565	+Si I 1082.7 nm
Chromosphere	Ca II 854 nm, Hα, Ba II 455	+He I 1083 nm
Wavelength samples	15	20 for chromospheric lines
FOV	60″ × 60″	120″ × 120″
Spatial resolution	0.″05	
SNR	200	
Cadence	5 s	
Notes	Raster scans with slit parallel to the magnetic flux rope axis to look for plasma motions and for brightenings in the surroundings.	

Instrument 2	BB_vis & BB_ir	
Goal	Detect flare signatures at photospheric and chromospheric heights. Context information on the active region morphology before, during and after the flare - CME occurrence.	
	Requirement	Goal
Photosphere	G-band	+CN bandhead
Chromosphere	Ca II H line core & line wing	Hα
Wavelength samples		
FOV	120″ × 120″	As large as possible
Spatial resolution	0.″1	
SNR	> 100	
Cadence	10 s	5 s
Notes	These observations should be complemented with data acquired by coronagraphs.	

- Apparatus for observing brightenings
- Again. the RoIs for this type of brightenings are along strong PILs

The objective should be an <u>unambiguous</u> correlation between brightenings and eruptions

SRD OP 6.8.1 (CME sources and temporal relation with flares)

CONCLUSIONS

- EST can be used to understand active regions that are usual suspects for eruptions – targets of opportunity. This information is provided by existing R2O studies, hence attempting the reverse step (O2R)
- Mapping the photospheric plasma β and detecting shear could trigger the relevant observing plans
- One basically needs the variation of field with height, to estimate crucial parts or the entire Maxwell stress tensor, giving rise to the Lorentz force
- This could be combined with potential pre-eruption signals / precursors at slightly higher FOVs, but nowhere near having the entire active region in the FOV
- Immediate benefits:
  - eruption interpretation
  - the flare – CME connection
  - determining some unambiguous eruption precursors.

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- Immediate benefits:
  - eruption interpretation
  - the flare – CME connection
  - determining some unambiguous eruption precursors. **Only to ask "why" again, enabling a new level of research**