Unipolar and bipolar flux appearance in the quiet Sun internetwork

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Introduction

- Internetwork (IN) fields are important contributors to total flux and energy budget of the solar photosphere
  - 120 Mx cm^{-2} day^{-1} (Gosic et al. 2014)
  - 1100 Mx cm^{-2} day^{-1} (Smitha et al. 2017)
  - ARs: 0.1 Mx cm^{-2} day^{-1} (Schrijver & Harvey 2014)
- Need to understand their properties and origin
- They are very different from AR fields, so origin is likely different too

- Goal: Constrain the origin of IN fields by studying their modes of appearance on the solar surface

Modes of appearance of IN flux

Bipolar pairs/clusters

Martin (1984)
Lites et al. (1996)
Martínez González et al. (2007)
Centeno et al. (2007)
Lamb et al. (2008)
Ishikawa et al. (2008)
Martínez González & Bellot Rubio (2009)
Jin et al. (2009)
Gömöry et al. (2010)
Martínez González et al. (2012)
Wang et al. (2012)
Guglielmino et al. (2012, 2021)
Fischer et al. (2018, 2019)
Gošić et al. (2022)

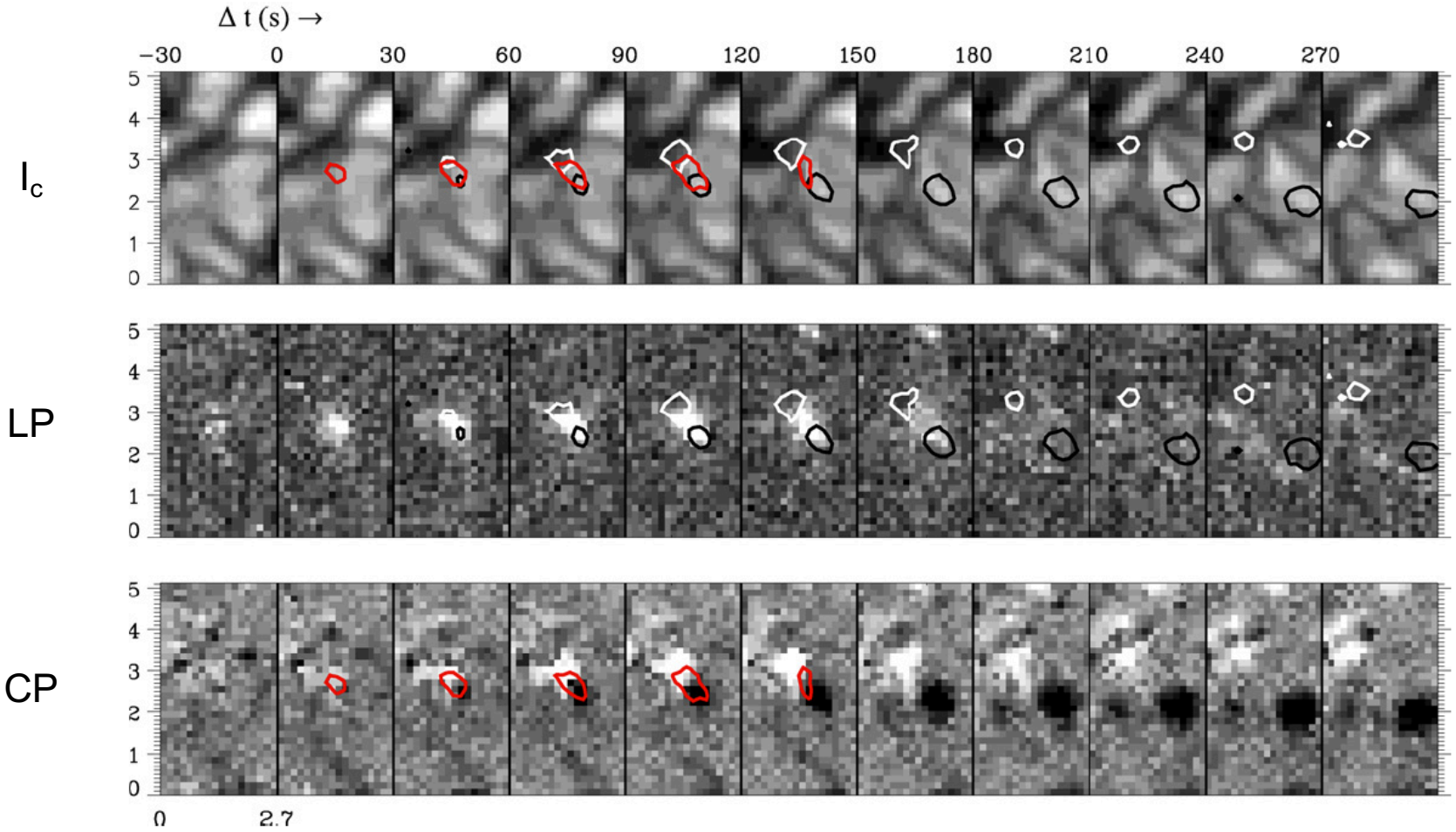
Unipolar patches

De Pontieu (2002)
Orozco Suárez et al. (2008)
Lamb et al. (2008, 2010)
Gošić et al. (2014, 2016)
Anusha et al. (2016)
Gošić et al. (2022)

Bipolar flux emergence: small-scale loops

Centeno et al., 2007, ApJ, 666, L137
Martínez González & Bellot Rubio, 2009, ApJ, 700, 1391

Hinode/SP, 25 Sep 2007



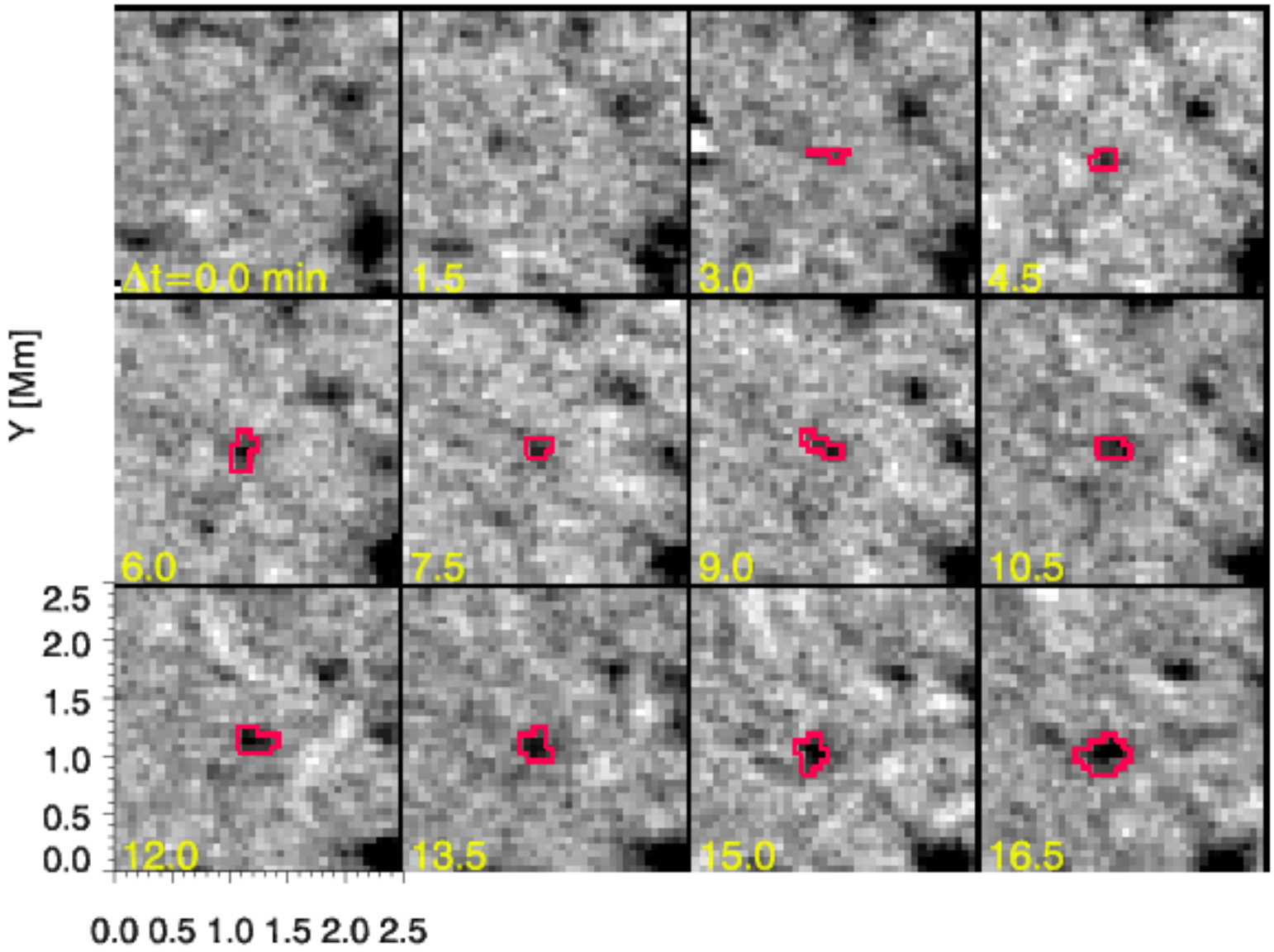
Magnetic Ω-loops emerge into the photosphere on granular scales, showing linear polarization signal in between two-opposite polarity footpoints

Small-scale magnetic loops/bipolar pairs

- May explain field strength and field inclination distributions
- May also explain magnetic topology observed in the IN, including the presence of flux above granules
- But... bipolar emergence does not seem to be the main mode of flux appearance!
  - only 6%, according to SOHO/MDI data (Lamb et al. 2008)
  - only 9%, according to SUNRISE/IMaX data (Smitha et al. 2017)

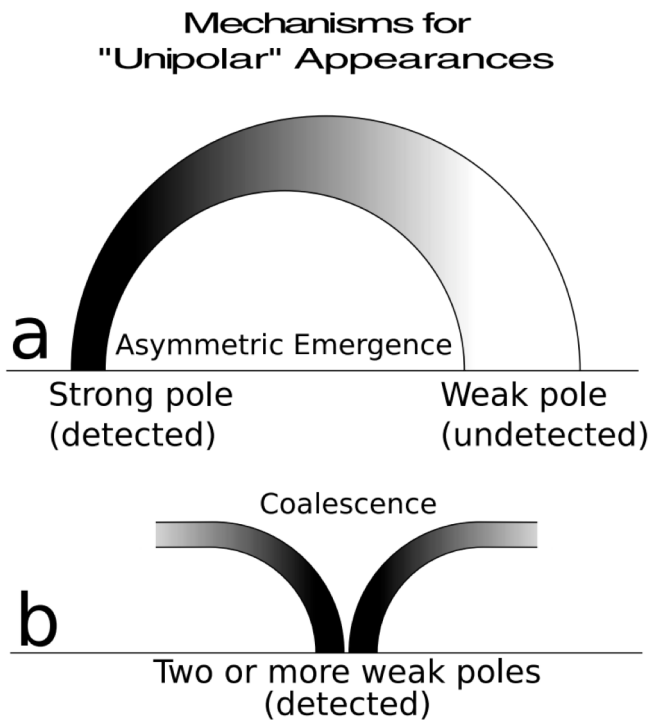
Unipolar flux appearance in the internetwork

Hinode/NFI longitudinal magnetograms, 30 s cadence



Unipolar flux appearance in the internetwork

- Serious problem: where is the opposite-polarity flux (div **B** = 0)?
- It must be a detection problem!



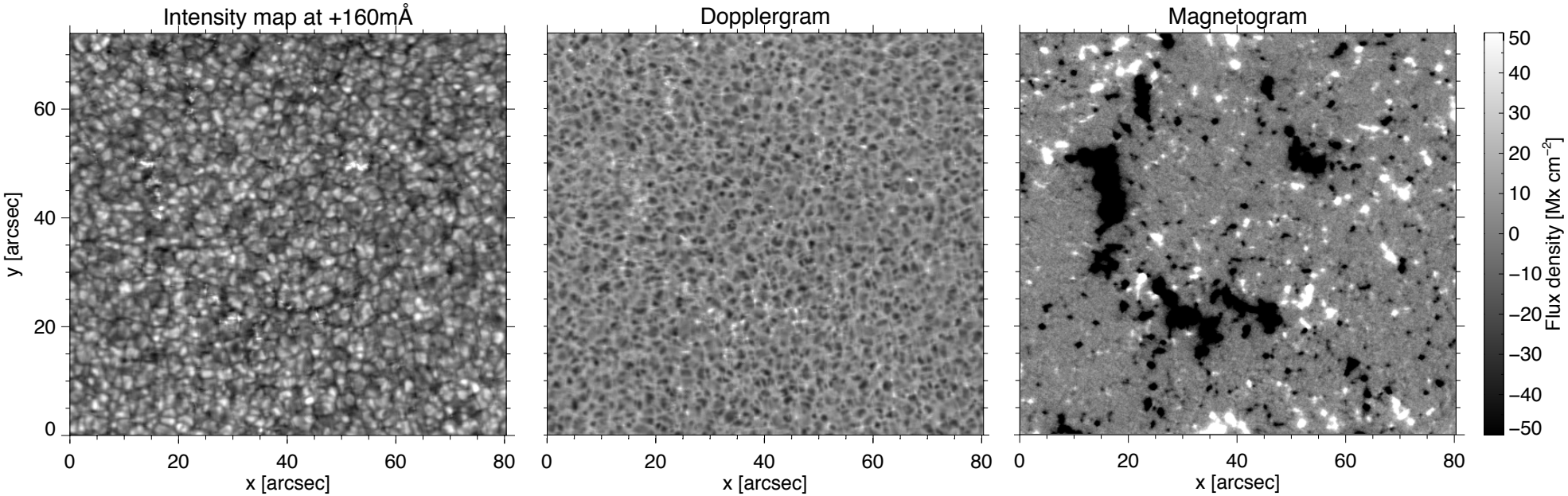
Lamb et al. (2008)

Hinode/NFI observations

HOP 151. Long-duration Hinode/NFI magnetogram sequence

- Stokes I and V filtergrams in Na I 5896 ± 160 mÅ
- High cadence: 90 s
- Low noise level: 4 G
- Long duration: 40 hr

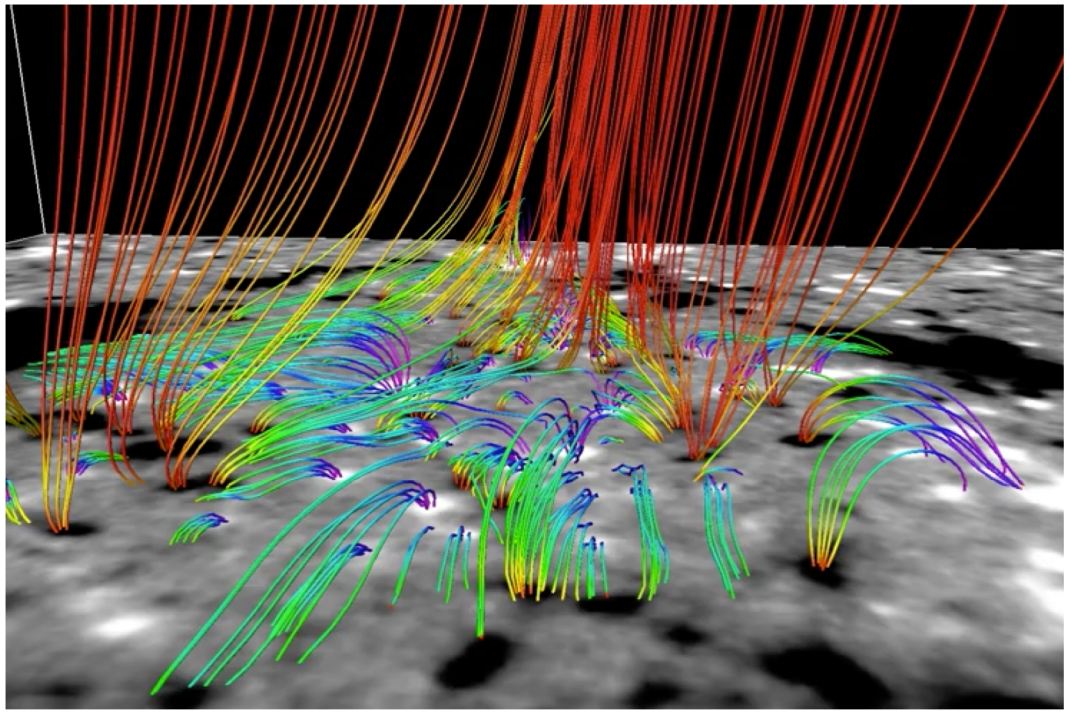
Continuous monitoring of a supergranular cell at disk center, 2-3 Nov 2010



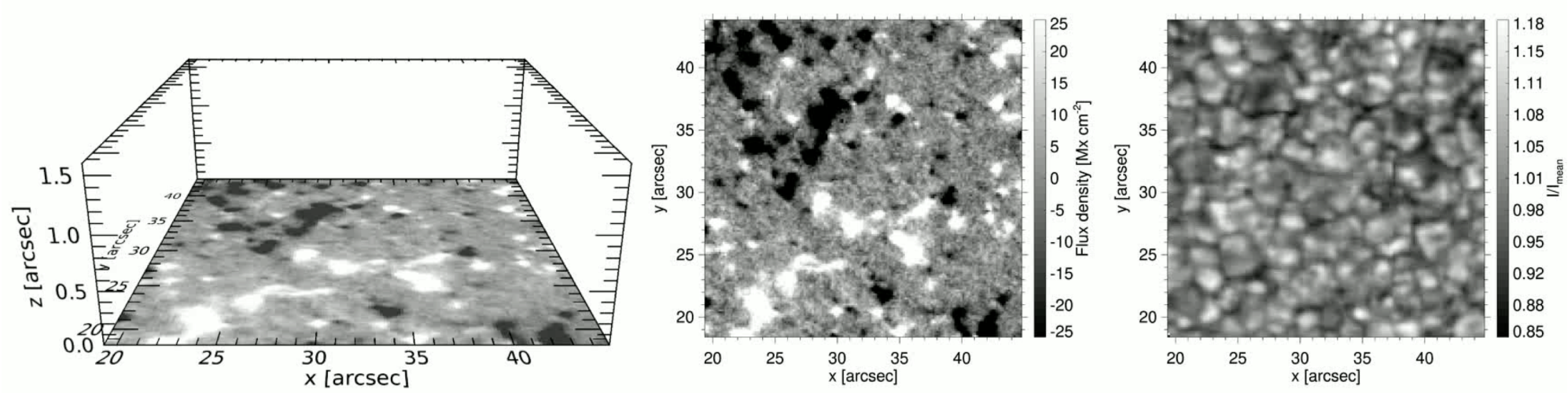
Identification of bipolar features

- We use the NFI data to identify bipolar features
- The two footpoints must
  - appear close in space and time
  - appear at the edges of the same granule
  - have approximately the same flux content
  - separate from each other following straight trajectories
  - be magnetically connected according to a magnetofrictional simulation
- Flux features tracked within supergranule (time evolution)

Magnetofrictional simulation of HOP 151 data.
Code by Cheung & DeRosa (2012)

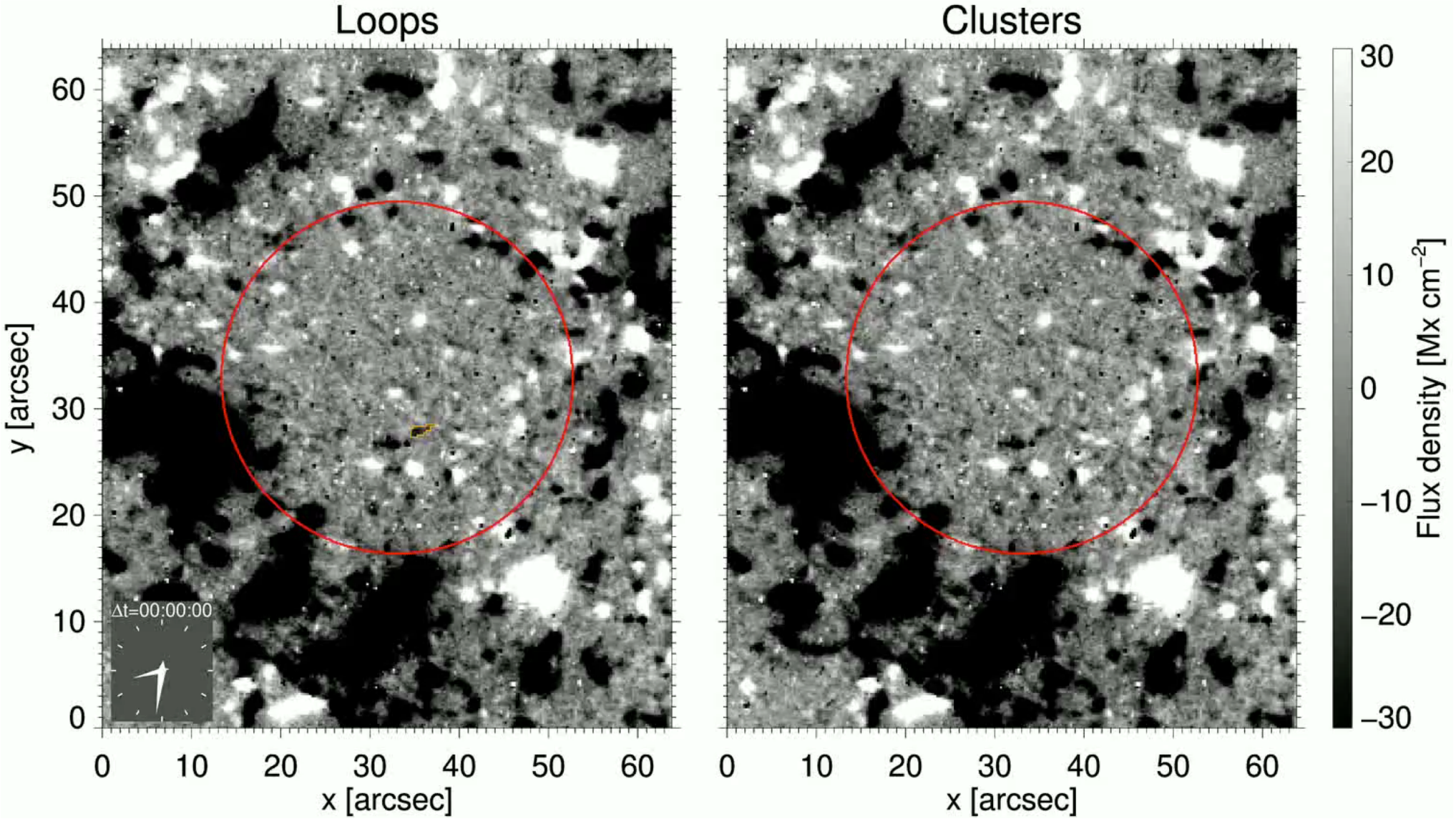


Example of small-scale IN loop



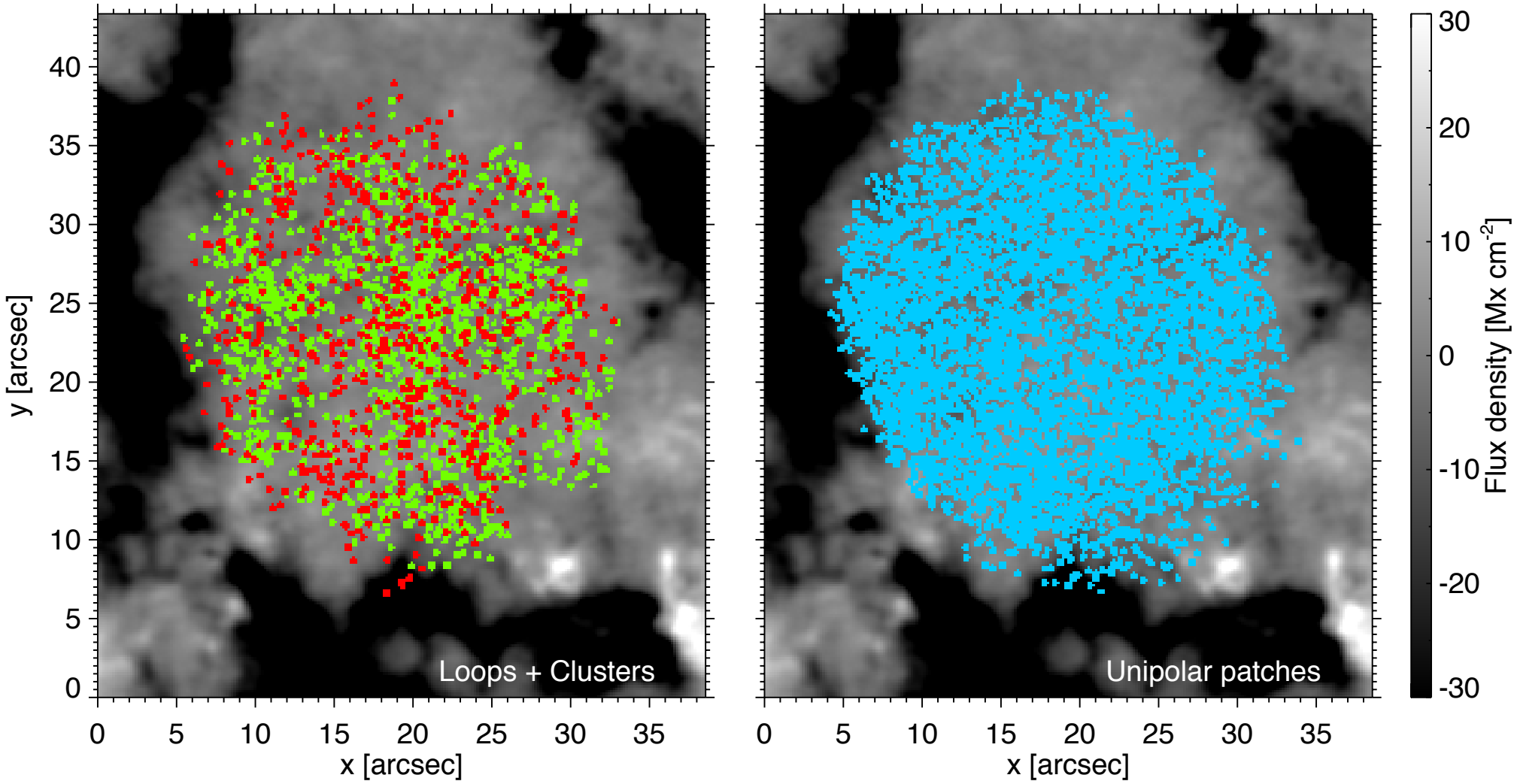
- Loop footpoints detected for 80 and 105 min, respectively
- Magnetofrictional simulation shows connectivity for the first ~40 min
- Loop expands and rises in the atmosphere
- Reaches an altitude of 1 Mm (lower chromosphere)

Emergence of bipolar features



Associate loop footpoints or flux cluster patches are shown with same-color contours

Location of appearance of new IN patches



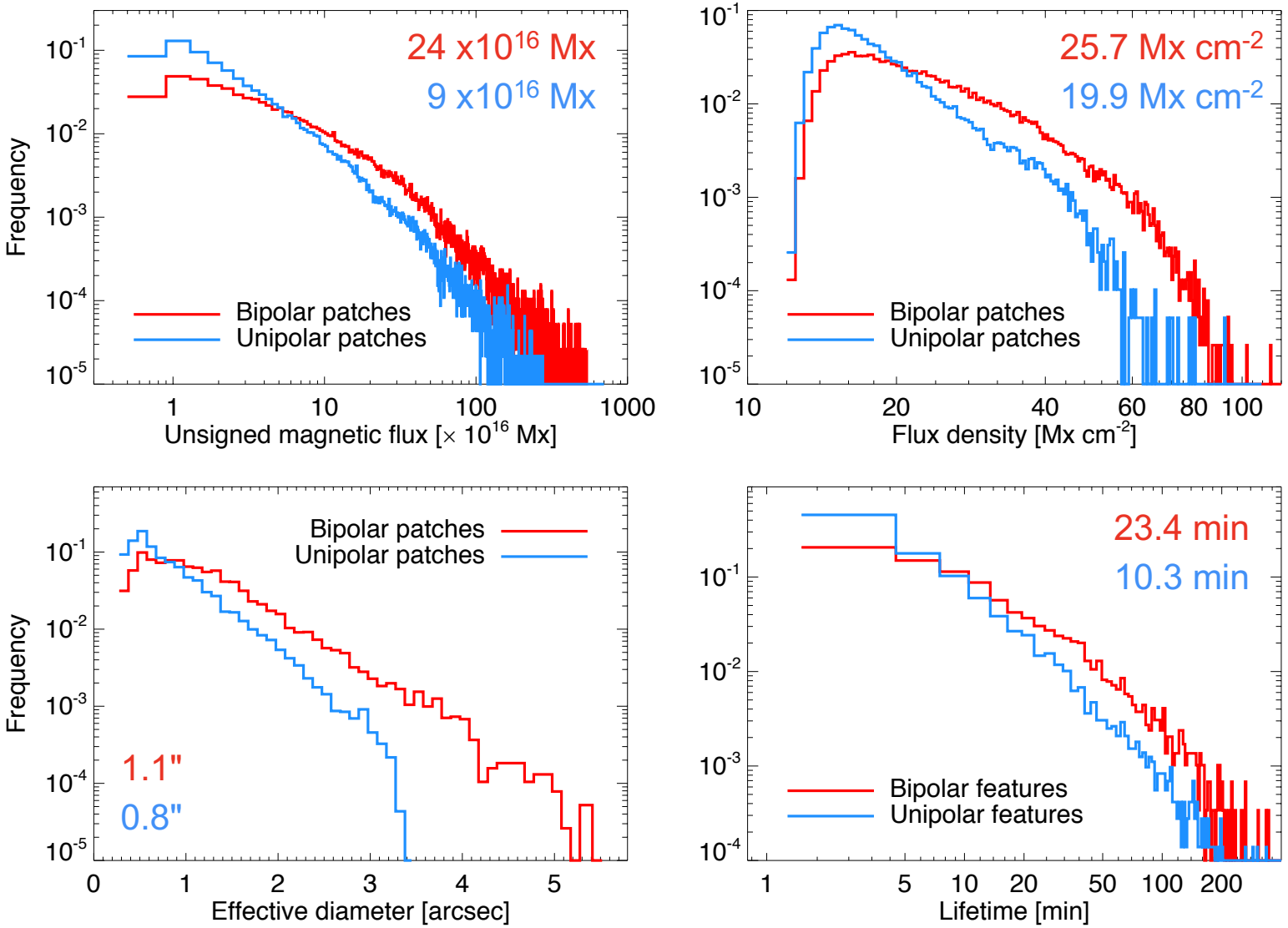
- Unipolar and bipolar features appear uniformly inside the supergranular cell
- Dead calm areas exist on mesogranular timescales (Martínez González et al. 2012), but we don't see them on supergranular timescales (~25 hours)

Properties of unipolar and bipolar IN patches

	Unipolar	Bipolar
Total number of features	7288	3270
Total number of patches	46,046	40,686
Number of positive patches	19,486	19,173
Number of negative patches	26,560	21,513
Mean unsigned flux (10^{16} Mx)	9.2	24.1
Positive patches (10^{16} Mx)	8.3	25.9
Negative patches (10^{16} Mx)	9.9	22.4
Mean flux density (Mx cm^{-2})	19.9	25.7
Mean effective diameter (arcsec)	0.8	1.1
Mean lifetime (minutes)	10.7	23.4

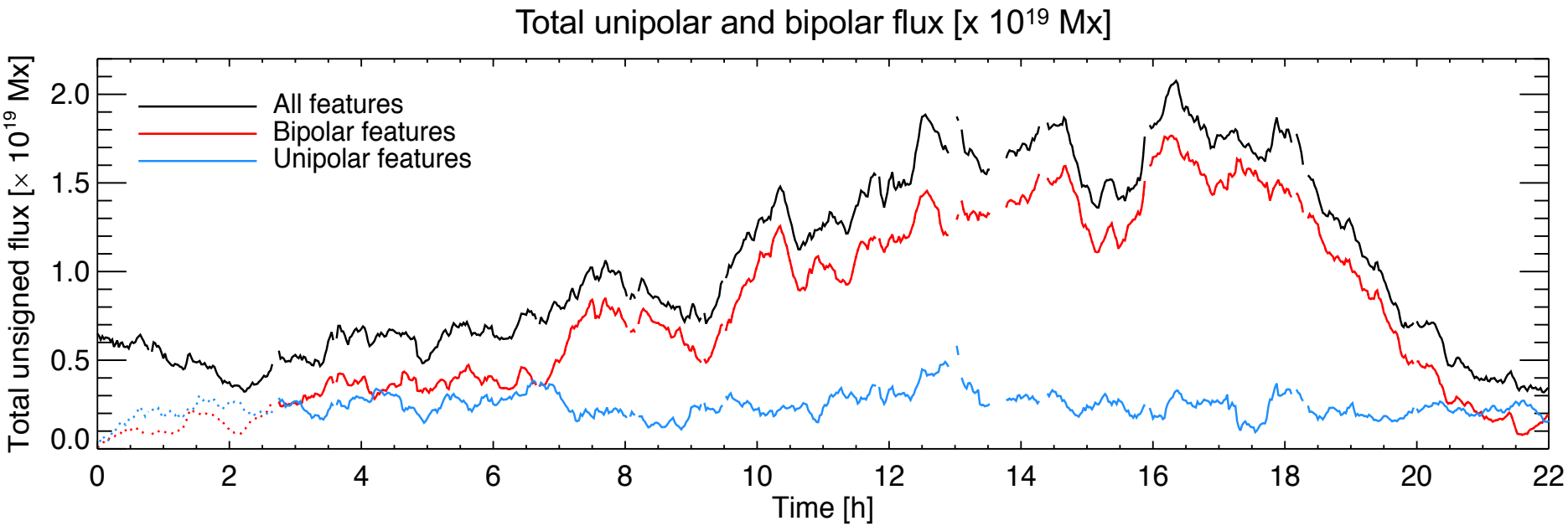
Bipolar patches tend to carry more flux per feature and have larger flux densities, sizes, and lifetimes than unipolar patches

Properties of unipolar and bipolar IN patches



Bipolar patches carry more flux and have larger flux densities, sizes, and lifetimes than unipolar patches

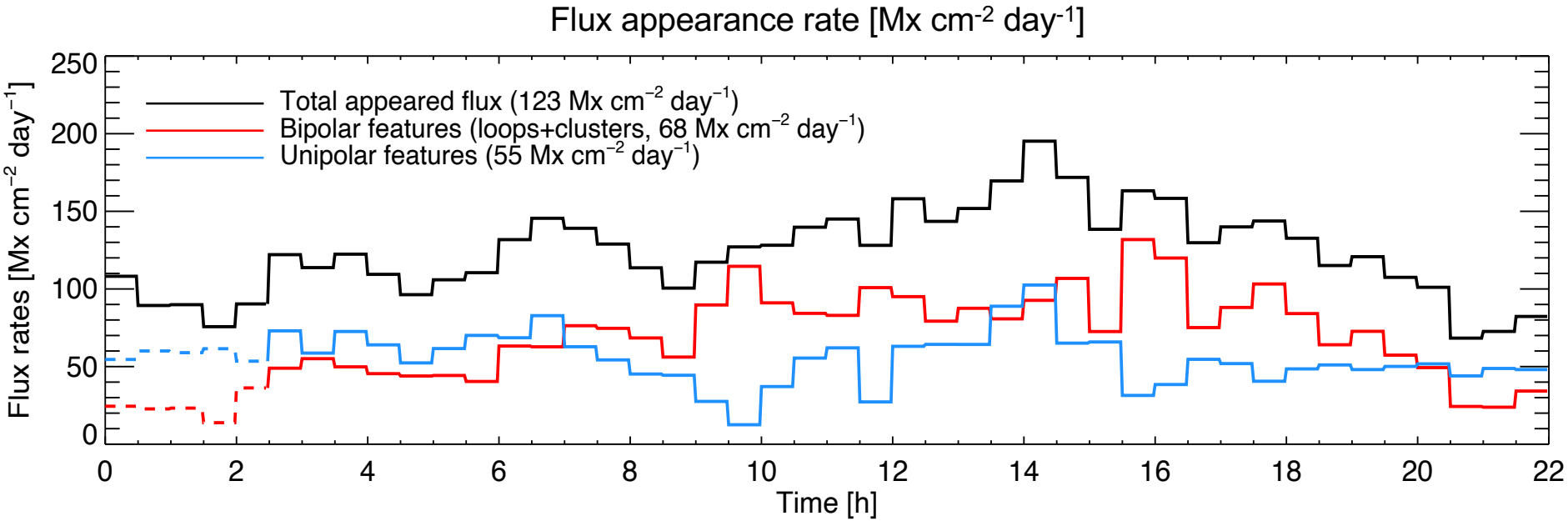
Unipolar and bipolar IN flux budget



- 72% of the total IN flux in the supergranular cell is in the form of bipolar features
- Mixed-polarity clusters provide most of the bipolar flux, 60% of total unsigned flux

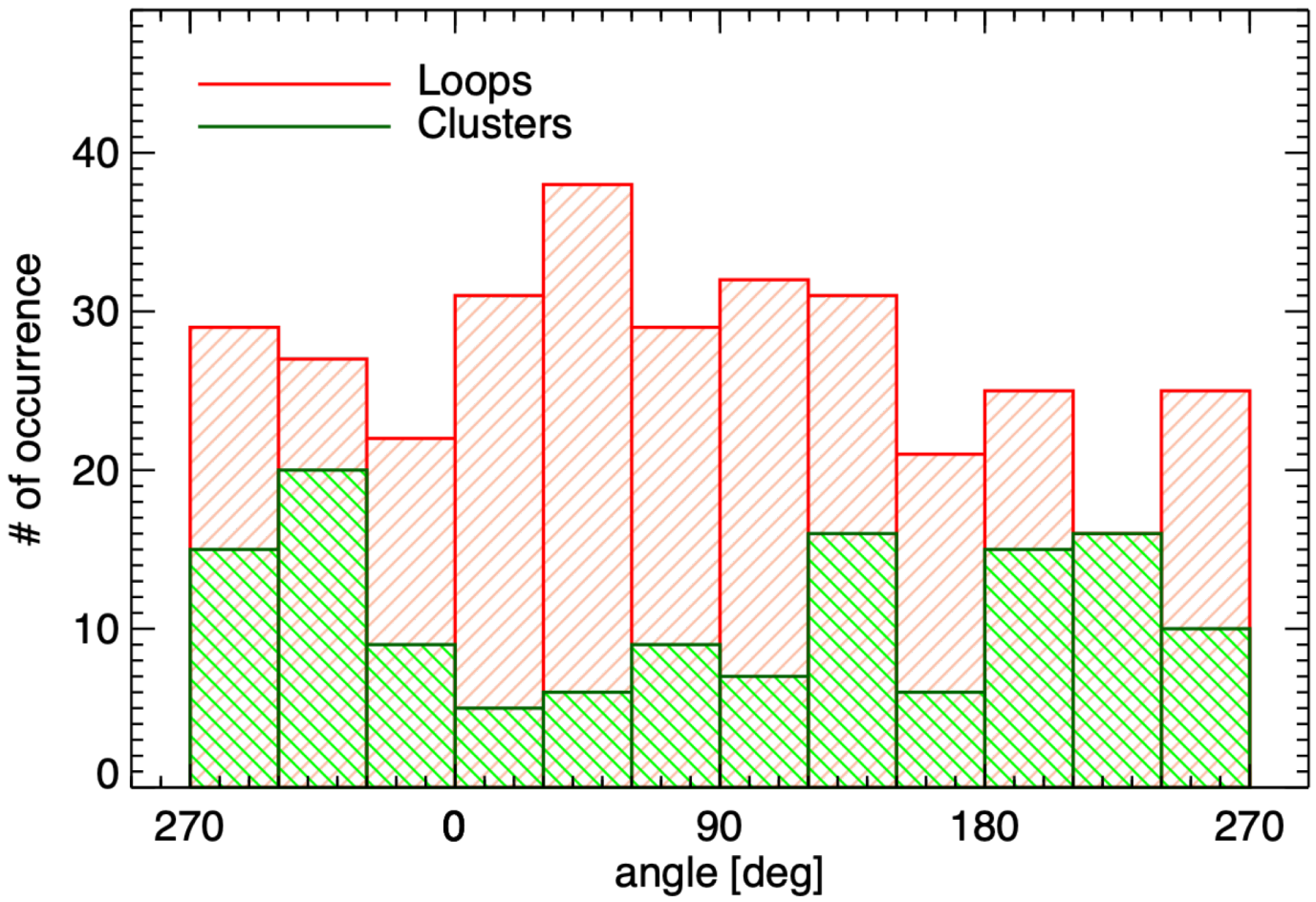
- The total unipolar flux remains more or less constant with time, unlike the bipolar flux

Unipolar and bipolar flux appearance rate



- About 55% of the IN flux appears in bipolar form
- Unipolar flux appearance rates are more stable

Orientation of IN loops and clusters



Bipolar features do not show any preferred orientation upon emergence on the surface

Summary and conclusions

- Two distinct populations of IN flux patches
  - Different physical properties
- Bipolar features
  - Contribute 72% of total internetwork flux
  - Account for 55% of total IN flux appearance rate
  - This is new flux. No preferred orientation, so local dynamo favored
- Unipolar features
  - Appear uniformly, no flux voids on supergranular timescales
  - Constant contribution to total internetwork flux
  - No new flux, but coalescence of very weak flux hidden in the noise
- Future work: detailed analysis of bipolar features in the observations

Reference: Gošić et al., ApJ, 925, 188 (2022)