Surface Magnetic Features and their Evolution

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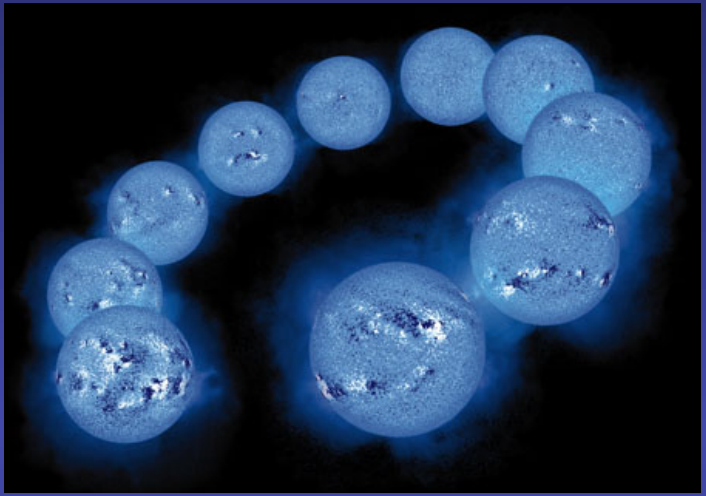
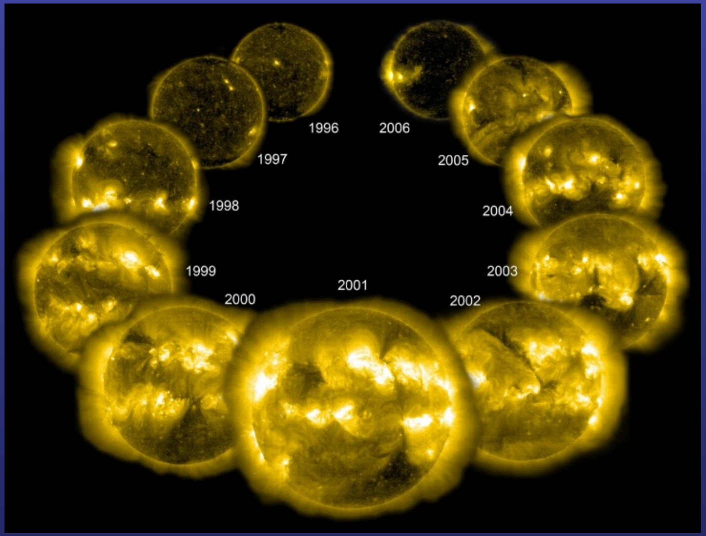
Photospheric Magnetic Fields

- Distribution/evolution of magnetic fields influences:
  - Activity in the solar atmosphere
    - e.g., flares, prominences
  - Heating of the solar atmosphere
    - e.g., solar cycle
  - The production of transients from the Sun
    - e.g., solar wind, CMEs, etc.

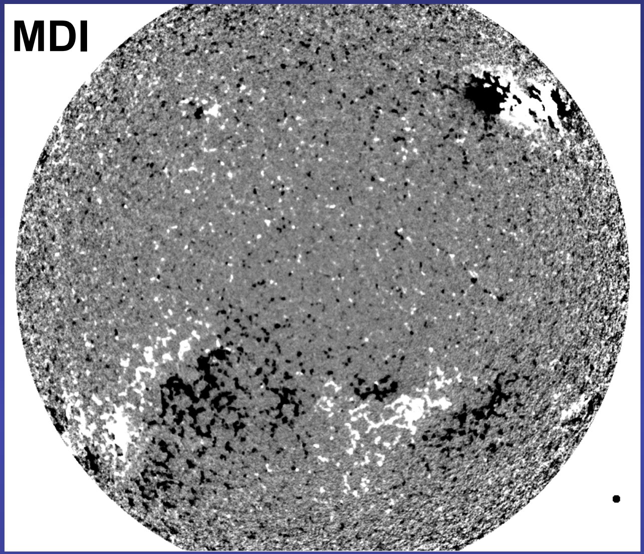
- Factors that influence the distribution & evolution of magnetic fields
  - The creation/processing of new flux
    - e.g., size & distribution of new flux features, cyclic behaviour
  - Surface processes
    - e.g., cancellation, fragmentation & coalescence



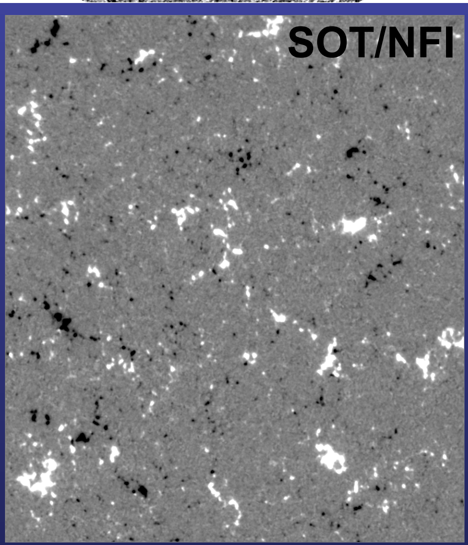


Creation of Magnetic Flux

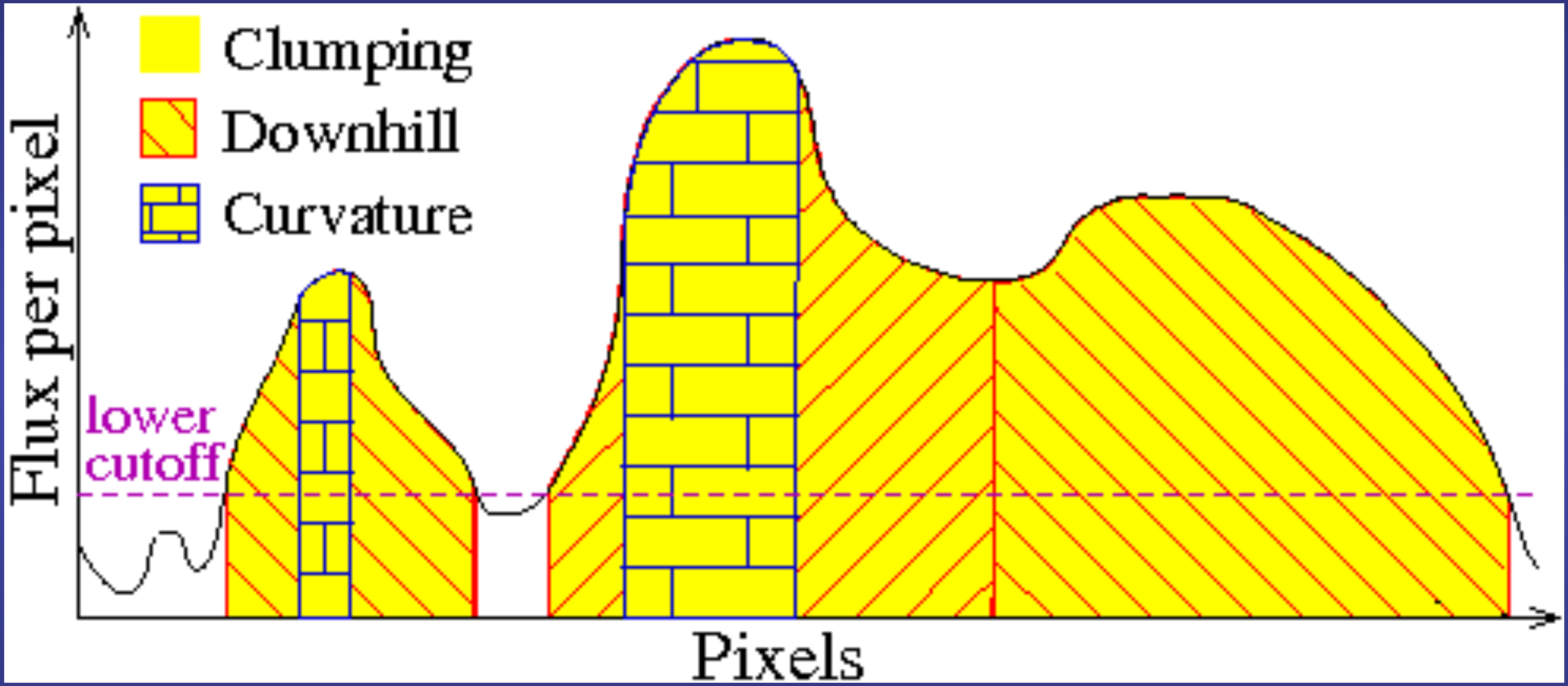
- Large-scale: Sunspot & active-regions (max flux > 10^{23} Mx):
  - Global (slow) dynamo required
  - Cyclic behaviour (period ~11/22 years)
  - Where:
    - Shear layer (tachocline) at base of convection zone



- Small-scale: Network & Intranetwork (min flux < 10^{16} Mx) [observational limit]:
  - Turbulent (fast) dynamo required
  - No cyclic behaviour
  - Operates:
    - Shear layer at top of convection zone
    - Throughout convection zone?



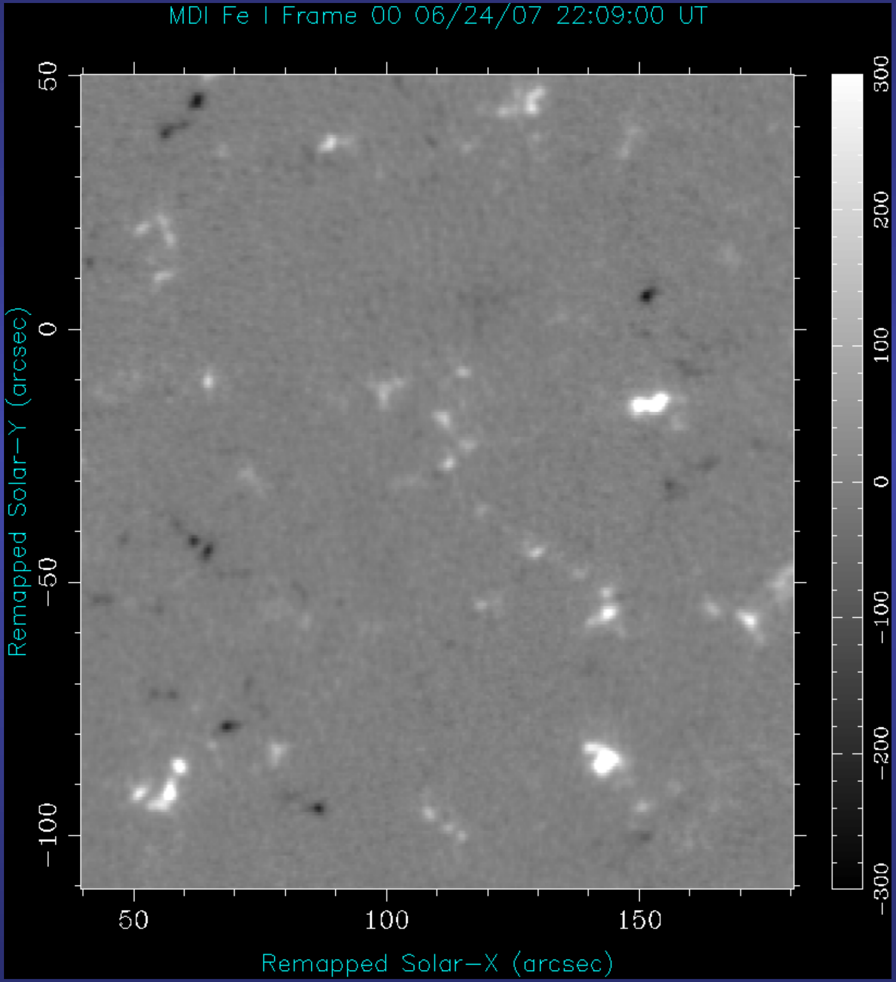
Magnetic Feature Detection Algorithms



- Feature ID methods:
  - Clumping (massifs)
  - Downhill (peaks)
  - Curvature (cores)
- Results differ between methods

Comparison of Algorithms: SOT & MDI data

- Date: 24th June 2007
- Duration: 22:09-23:08 (1 hour)
- Area: 140 arcsec x 160 arcsec
- Quiet-sun magnetograms
  - SOHO/MDI: Fe I
    - Pixel area: 0.370 arcsec^2
  - Hinode/SOT: Na-D
    - Pixel area: 0.026 arcsec^2

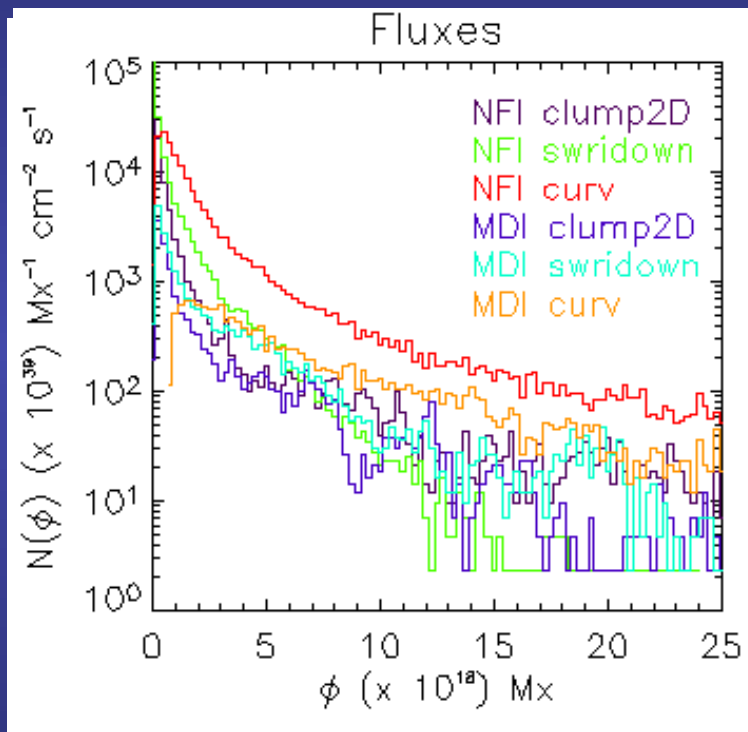


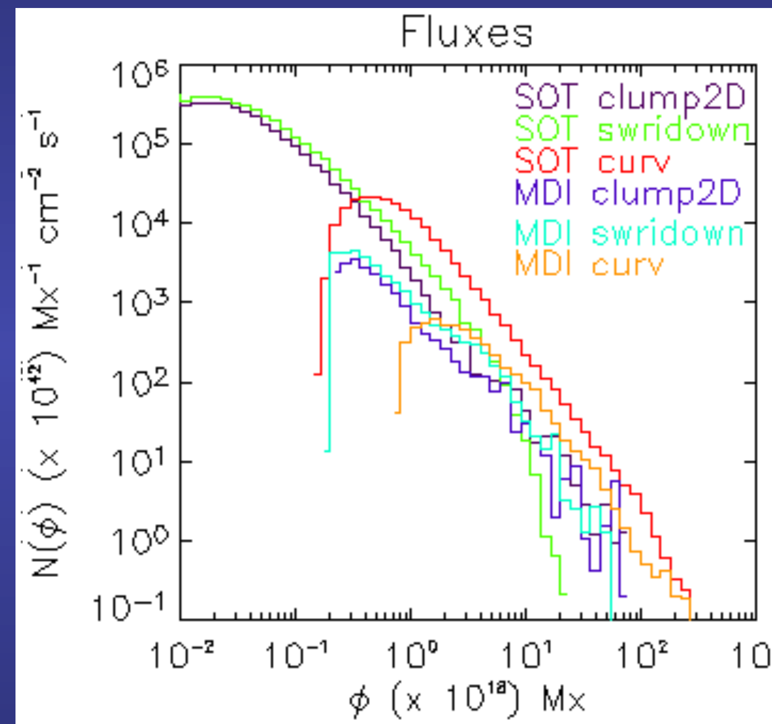
Comparison of Algorithms: Assumptions

- Assumptions:
  - Noise levels & cutoffs:
    - MDI (noise: 9.5 Mx cm^{-2})
      - lower cutoff: 28 Mx cm^{-2}, upper cutoff: 38 Mx cm^{-2}
    - SOT (noise: 6 Mx cm^{-2})
      - lower cutoff: 18 Mx cm^{-2}, upper cutoff: 24 Mx cm^{-2}
    - Flux in feature:
      - always above lower cutoff
      - above upper cutoff at sometime during feature's life
  - Minimum area: 4 pixels (curv - 9 pixels)
  - Minimum lifetime: 4 frames (4 minutes)

Comparison of Algorithms: Flux distributions

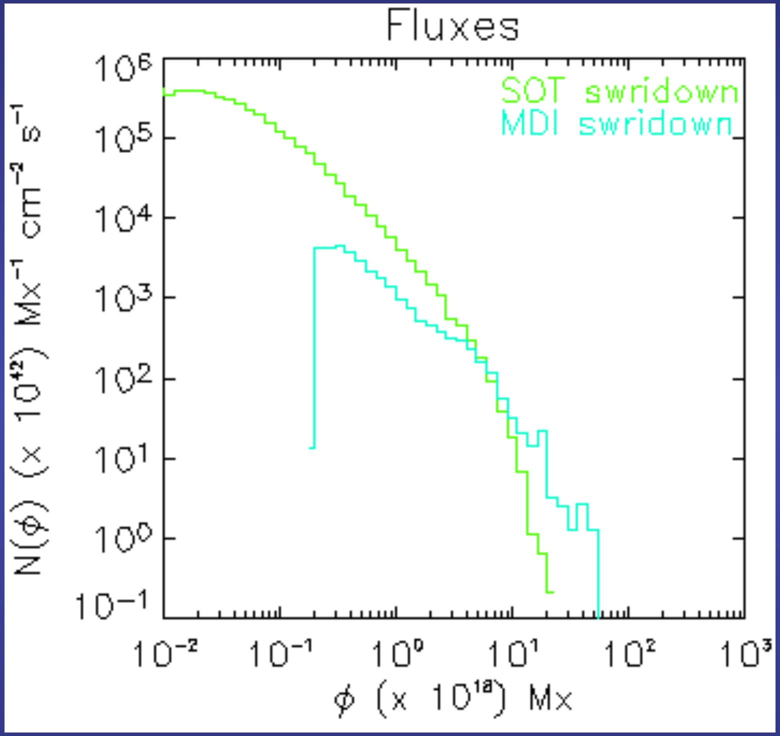
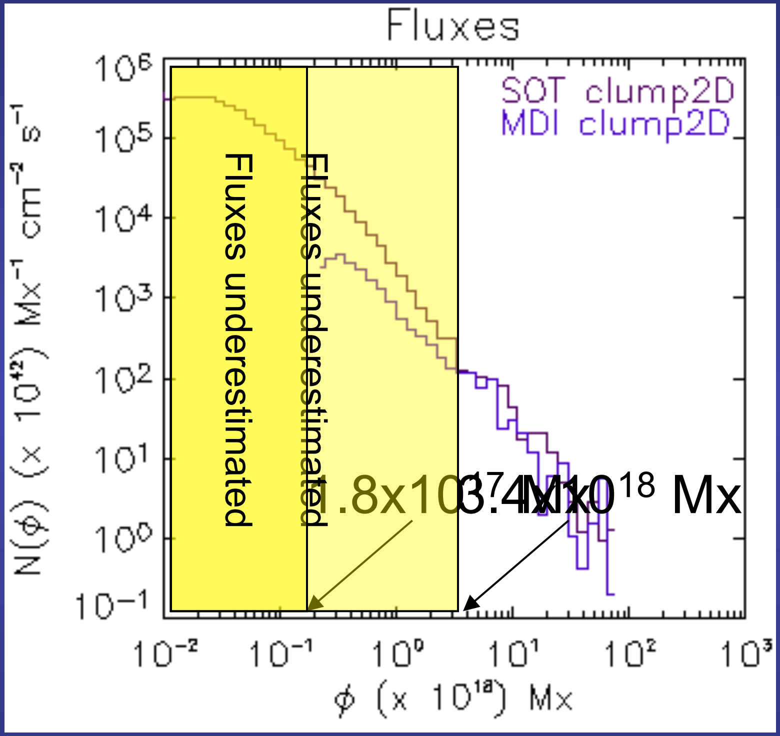
MDI flux histograms
Hinode flux histograms





- Distributions depend on feature identification method
- Tails of distributions follow power-laws
  - Are the MDI & SOT distributions the same?

Comparison of Algorithms

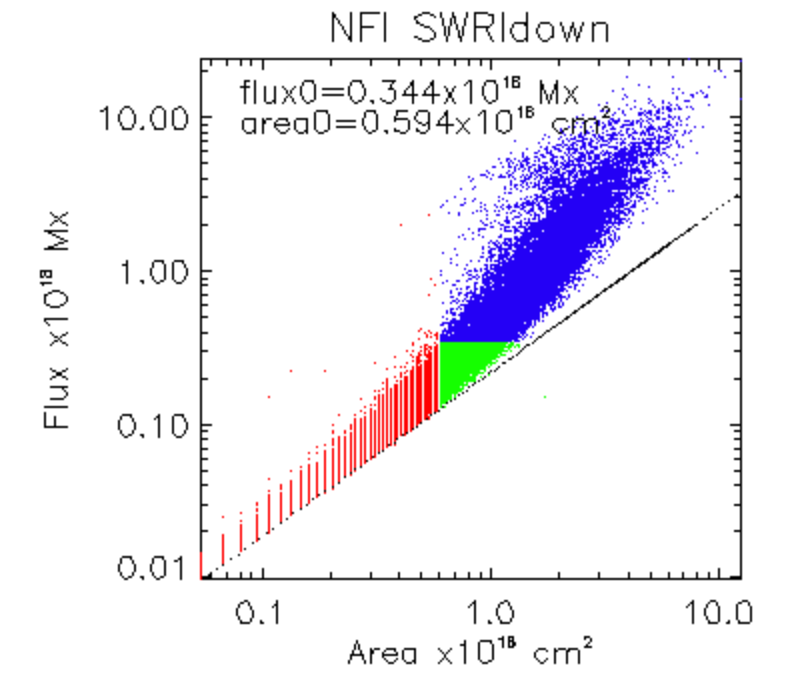
Downhill	Clumping
	

- Downhill: counts peaks
  - Higher resolution ⇒
    - More smaller features
    - Fewer large features

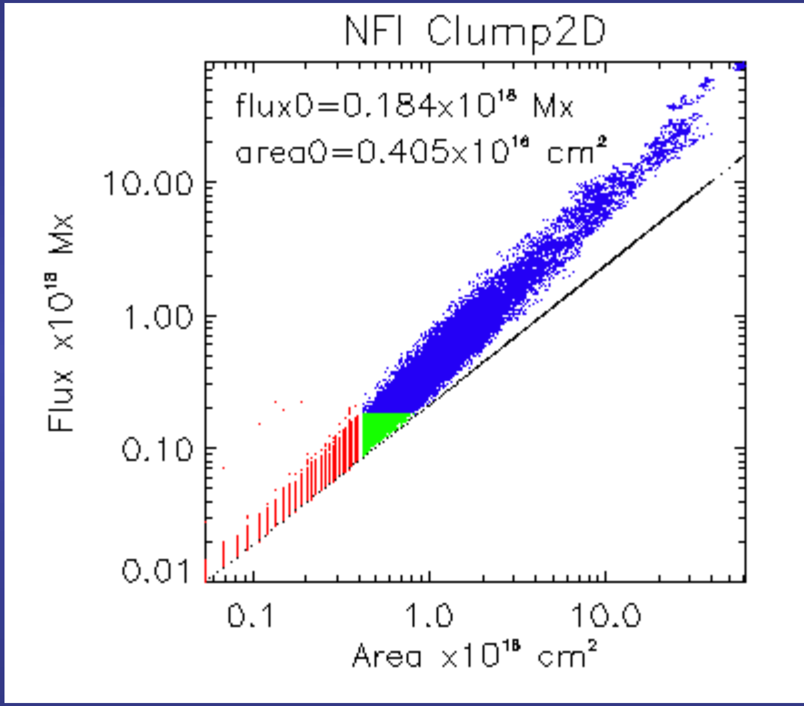
- Clumping: counts massifs
  - Higher resolution ⇒
    - More smaller features
    - Same large features

Under-estimation of Fluxes & Areas

Downhill

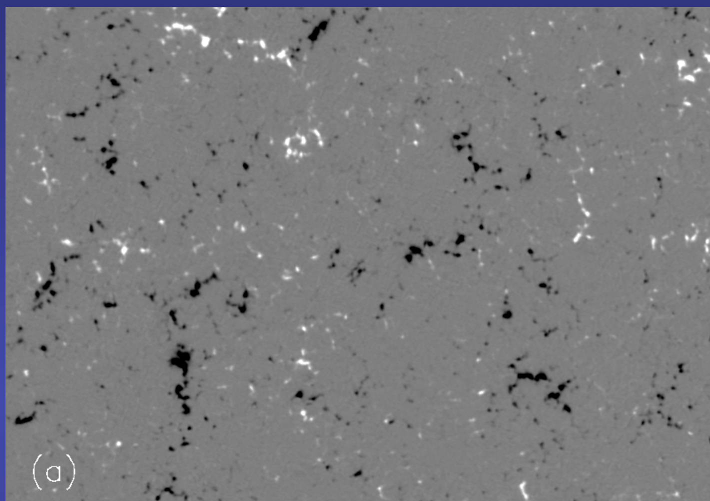


Clumping

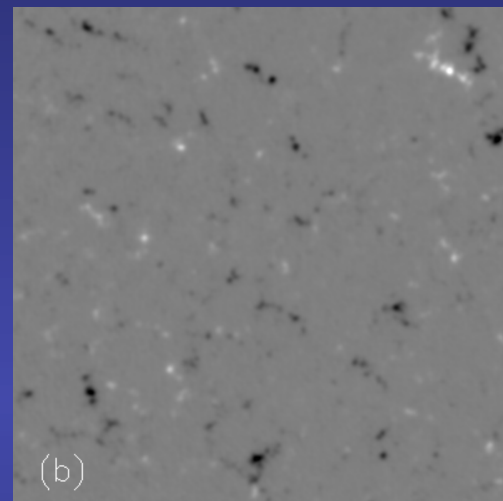


- Lower flux cutoff ⇒ fluxes & areas of small fragments under-estimated
- Blue fluxes used to determine distribution of fluxes

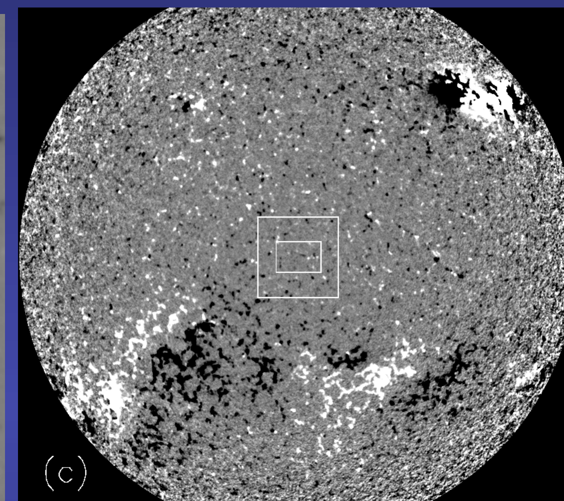
Photospheric Magnetic Field Observations



SOT/NFI 06/2007



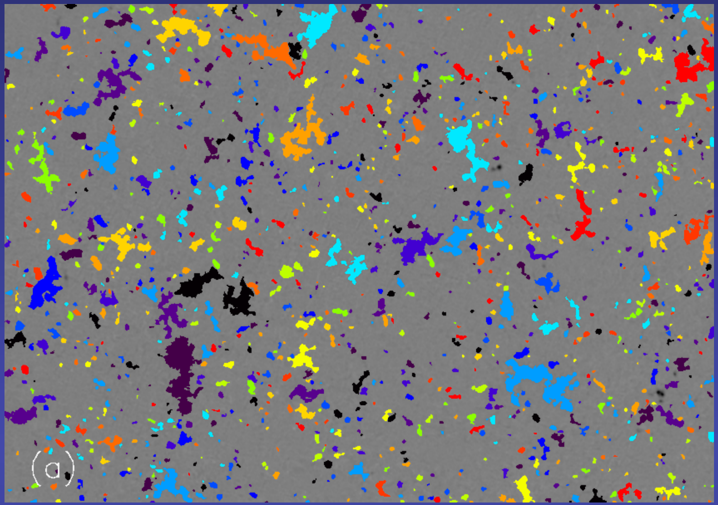
MDI HR 10/2005



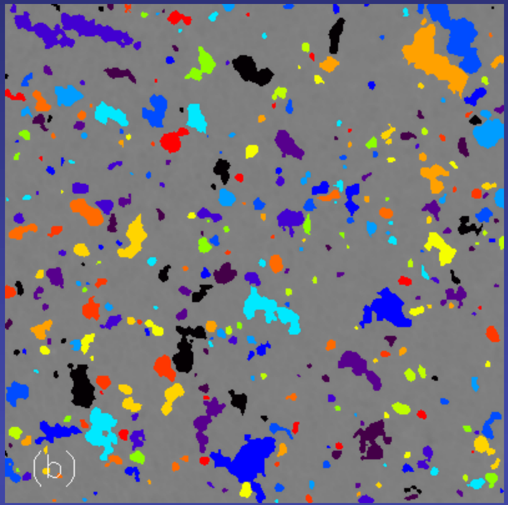
MDI FD 05/1998

- Compare fluxes of feature fluxes over solar cycle:
  - data from different instruments used
  - so use clumping method to detect features

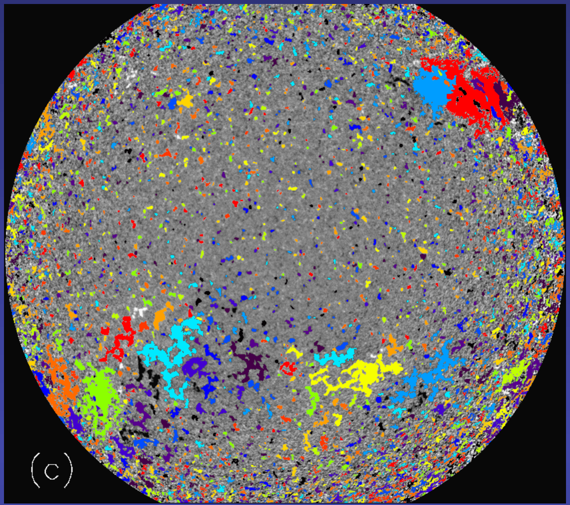
Magnetic Flux Features (Flux Massifs)



SOT/NFI 06/2007



MDI HR 10/2005

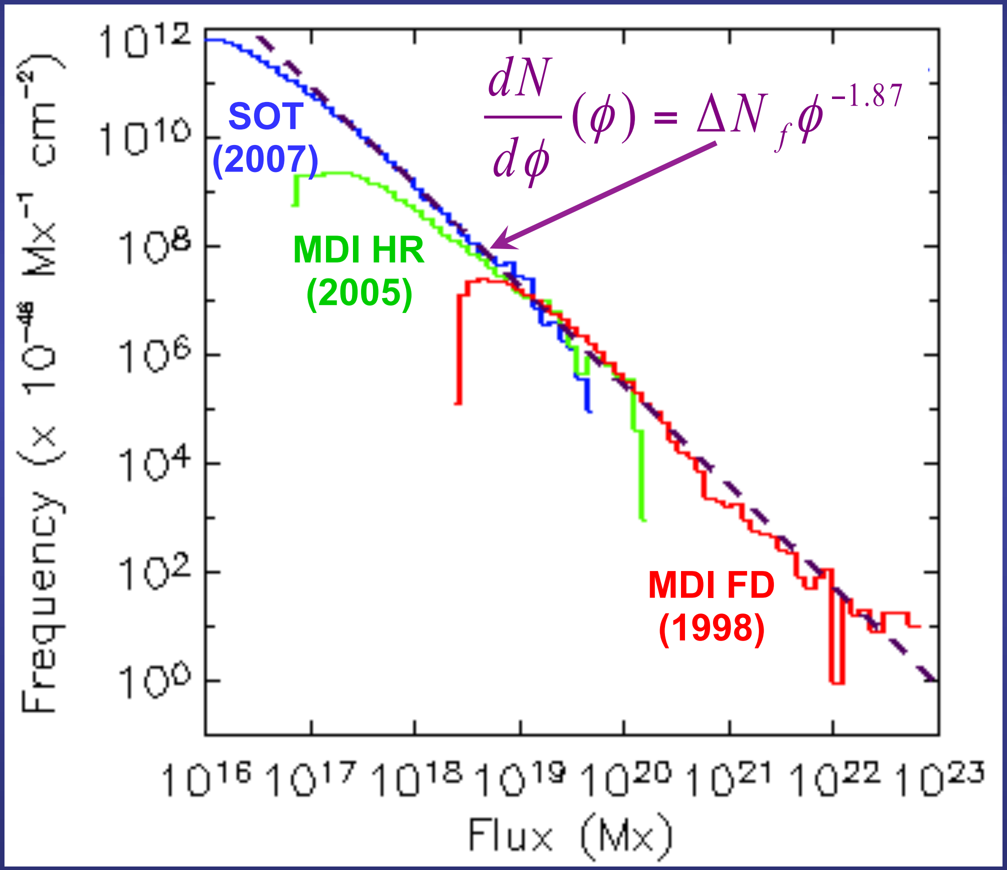


MDI FD 05/1998

	Duration (hrs)	Cadence (mins)	Area (arcsec^2)	No. of Features	Mean Flux ($\times 10^{18}$ Mx)
SOT/NFI 07	5	1.5	141 x 162	251205	0.33
MDI HR 05	17	5	246 x 246	71652	4.90
MDI FD 98	11	5	$< 60^\circ$	429256	101.13

Distribution of Fluxes

- Frequency of feature fluxes at any instance in time:
  - Power-law between $10^{17} - 10^{23}$ Mx
  - Slope of power-law
    - $\alpha_{feature} = -1.87$



Instruments: Hinode/SOT/NFI
SOHO/MDI (HR)
SOHO/MDI (FD)

Parnell et al. (2009)

Distribution of Fluxes

- Frequency of feature fluxes at any instance in time:
  - Power-law between 10^{17} – 10^{23} Mx
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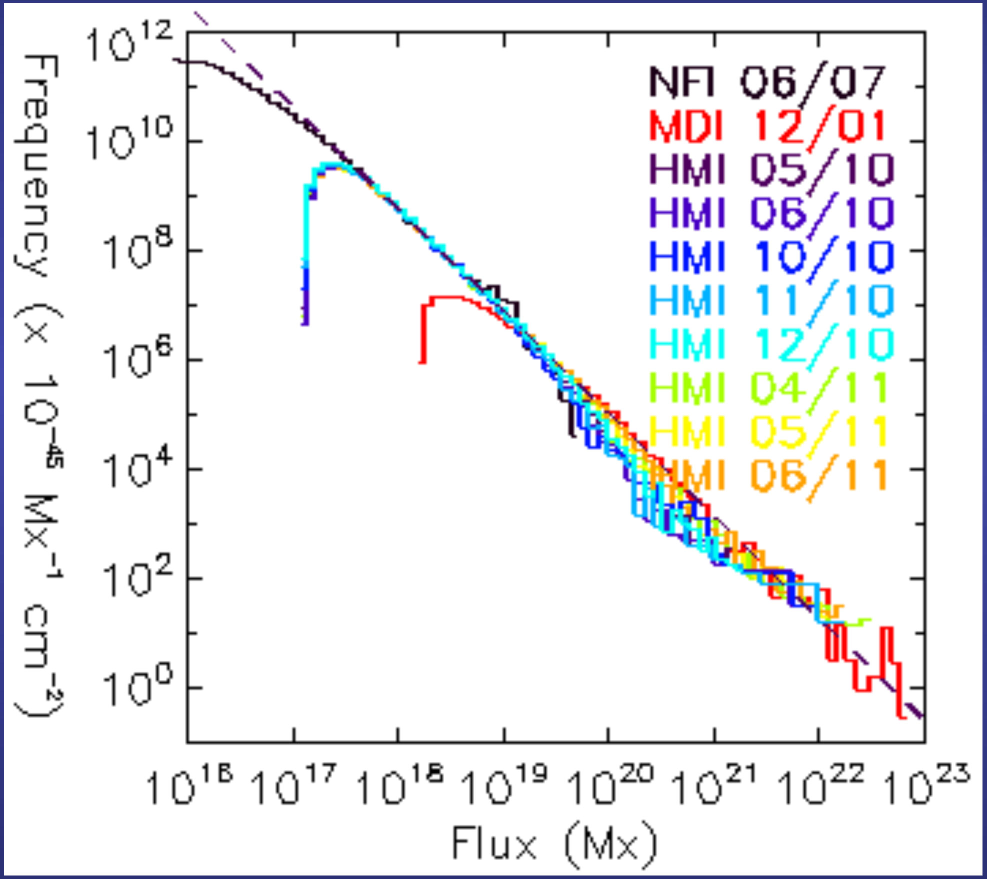


Instruments: Hinode/SOT/NFI
SOHO/MDI (FD)
SDO/HMI

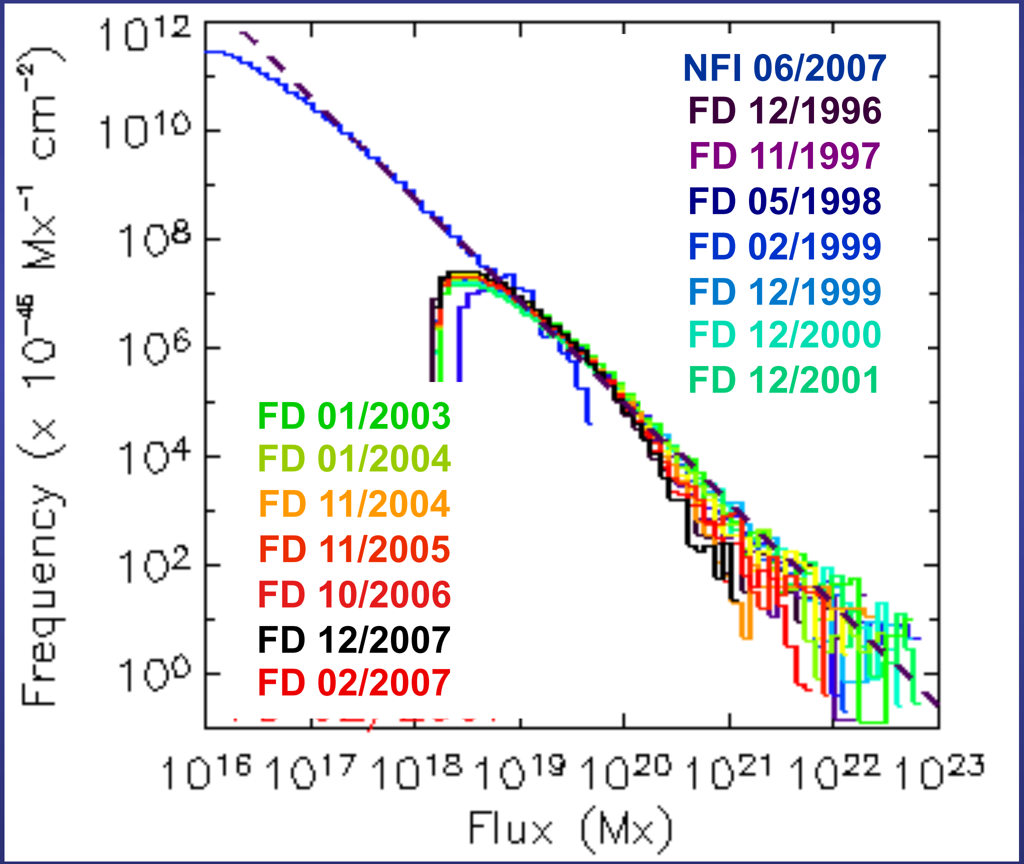
Parnell et al. (2012, in preparation)

Distribution of Fluxes (1996-2008)

- Frequency of feature fluxes at any instance in time:
  - Power-law between $10^{17} - 10^{23}$ Mx
  - Slope of power-law
    - $\alpha_{feature} = -1.87$

$$\frac{dN}{d\phi}(\phi) = \Delta N_f \phi^{-1.87}$$

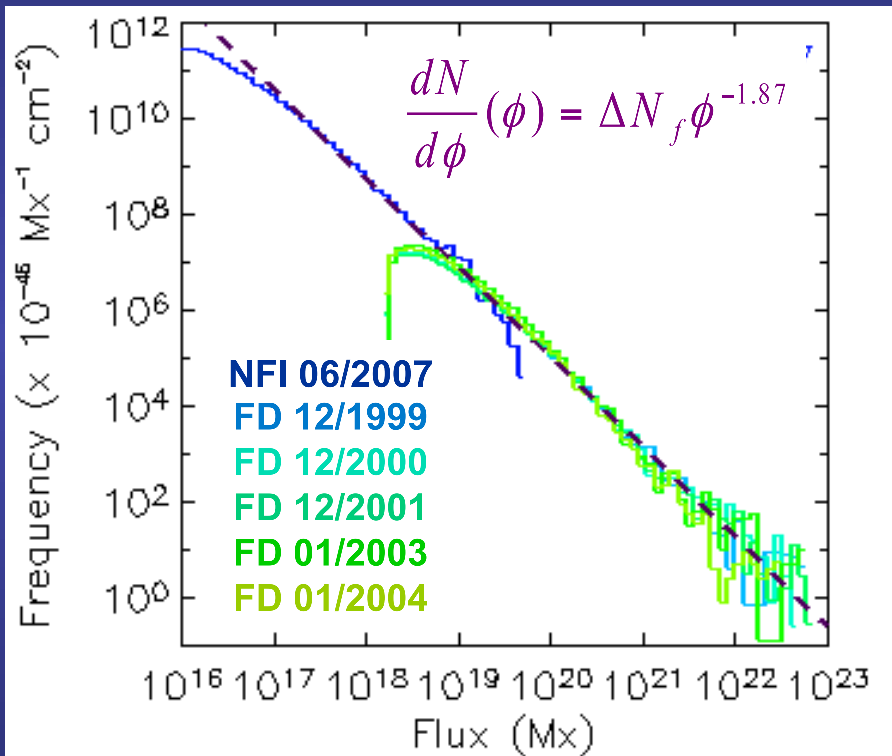
Instruments: Hinode/SOT/NFI
SOHO/MDI (FD)



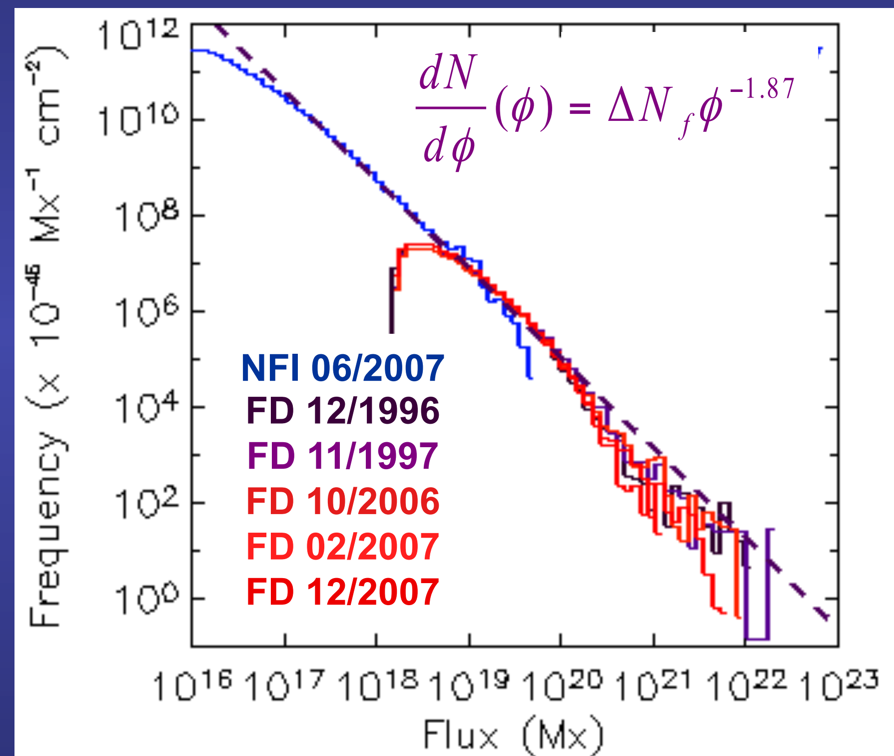
Parnell et al. (2012, in preparation)

Distribution of Fluxes

Solar Maximum



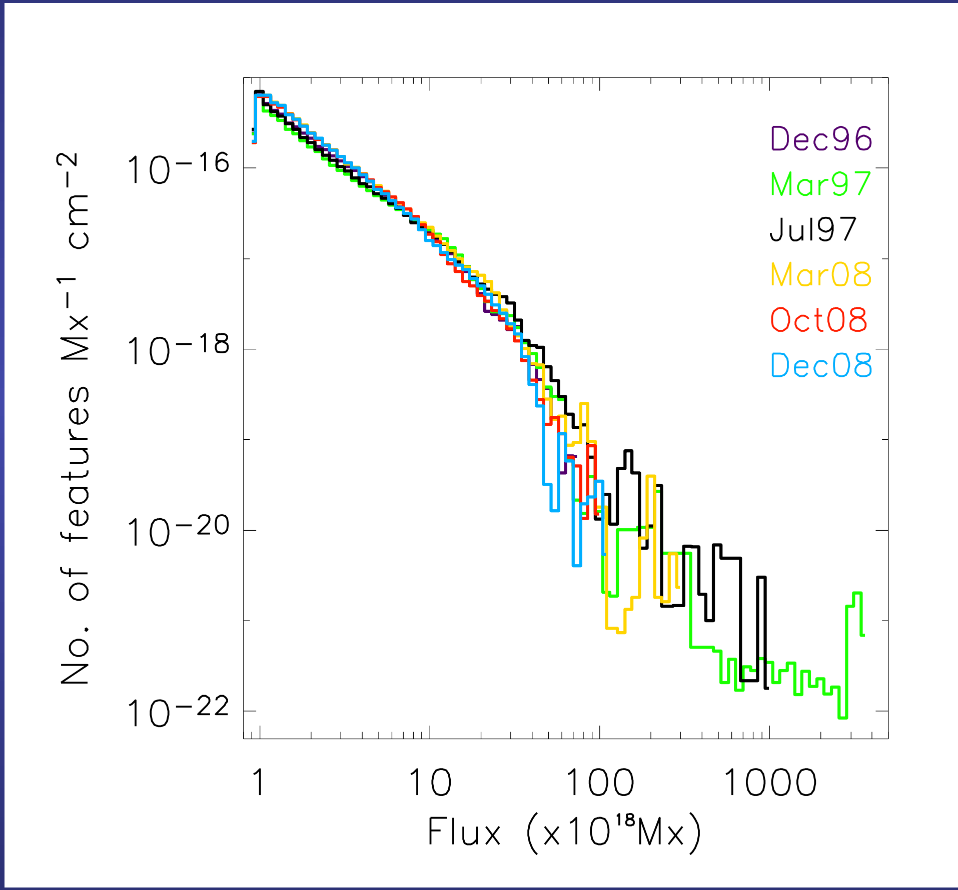
Solar Minimum



Numbers of 10^{20} Mx fluxes decrease at solar minimum
Largest flux at solar minimum ~ 10^{22} Mx

Minima: Cycle 22/23 vs Cycle 23/24

- **Flux distribution:**
  - **Slope the same**
  - **Numbers the same**
  - **Maximum flux less.**
    - **Dec 96: 10^{20} Mx**
    - **Jul 97: 10^{21} Mx**
    - **Mar 08: $4x10^{20}$ Mx**
    - **Dec 08: 10^{20} Mx**
  - **Indicates residual active-region flux lost by 2008**



Implications of Flux Distribution

- Distribution of feature fluxes:
  - Power-law between $10^{17} - 10^{23}$ Mx
  - Slope of power-law
    - $\alpha_{feature} = -1.87$

- ⇒ ***mechanism generating magnetic features is scale-free***

- Possible scenarios:

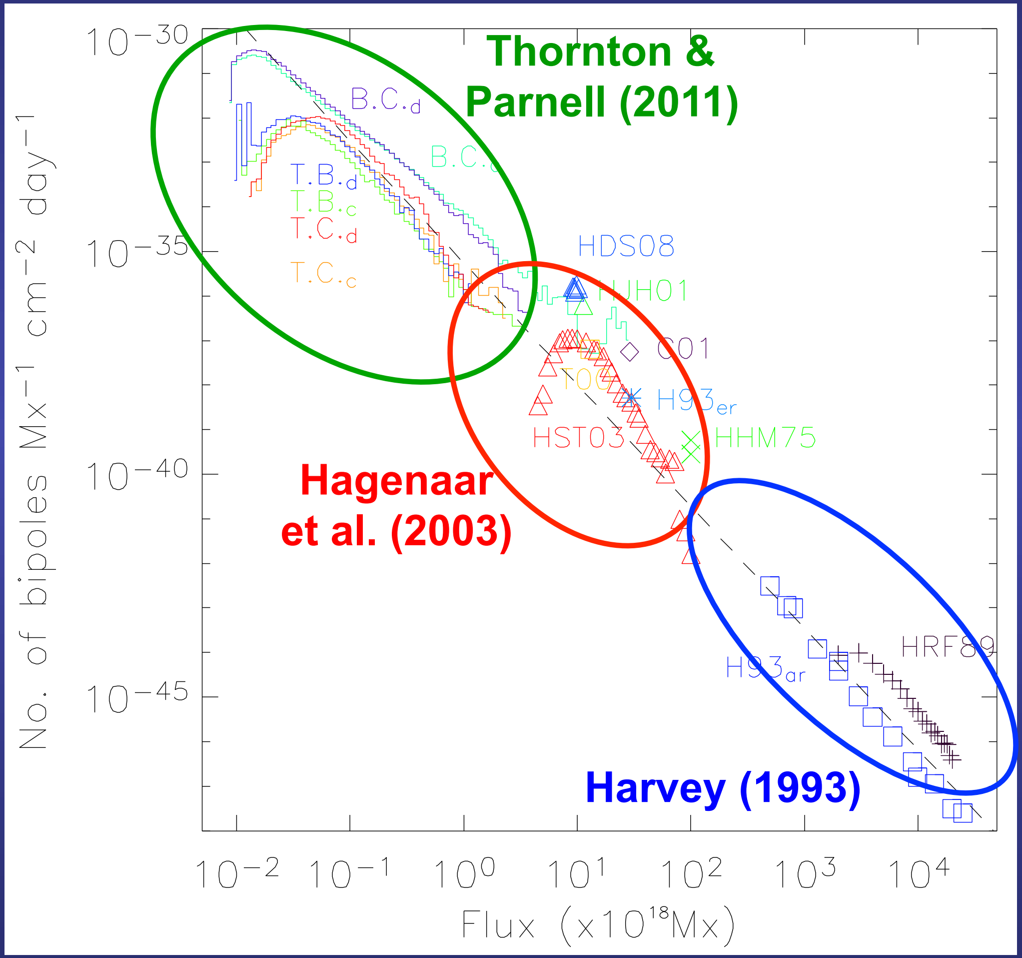
1. Process creating new flux features is scale-free?

   or

2. Surface processes **after** emergence dominate (e.g. fragmentation, merging, cancellation)?

Distribution of Emerged Flux Features

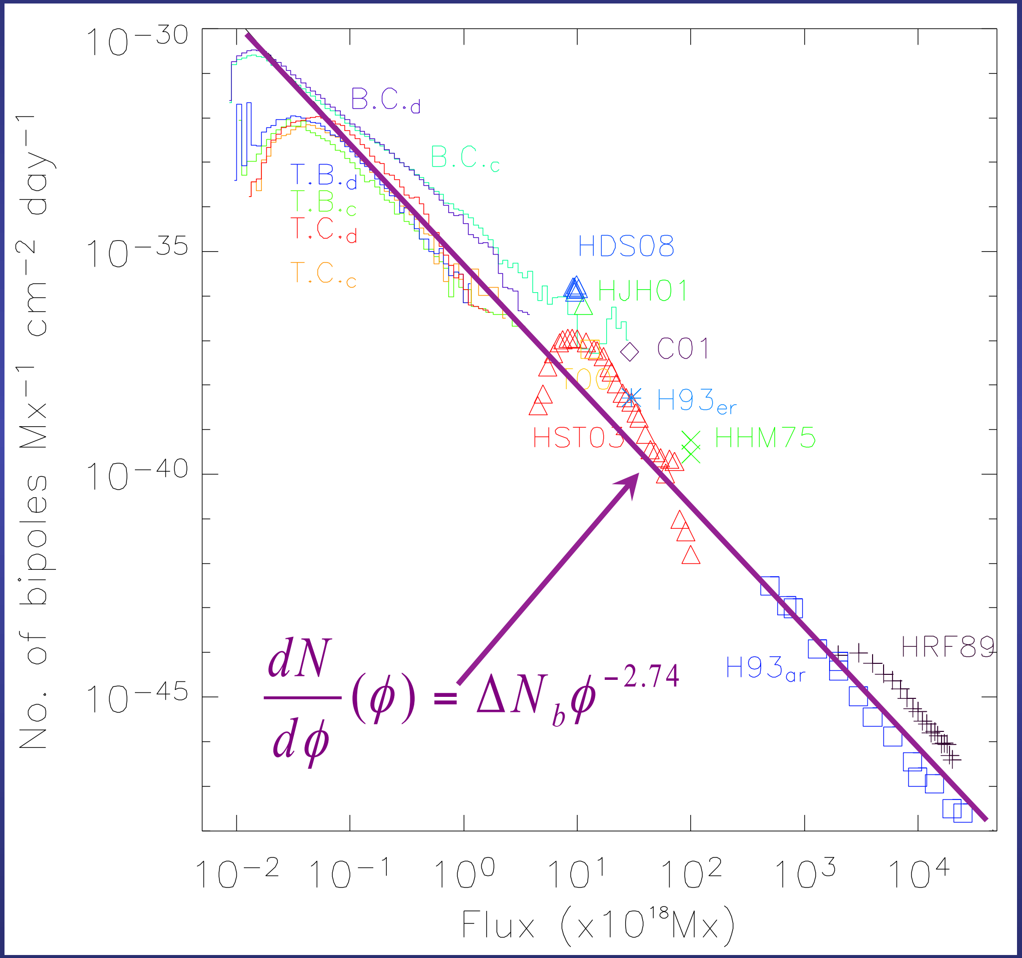
- **Frequency of peak emerged fluxes per day:**



Thornton & Parnell (2011)

Distribution of Emerged Flux Features

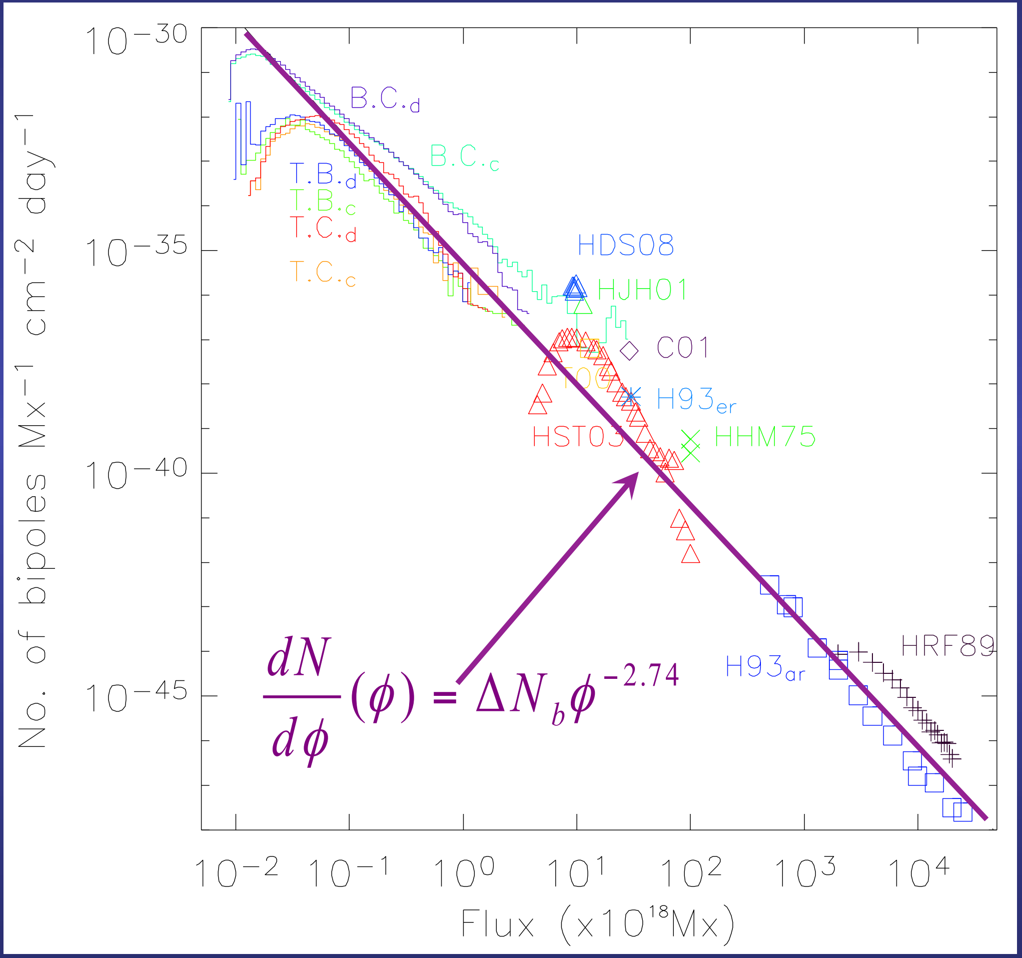
- **Frequency of peak emerged fluxes per day:**
  - **Power-law between $10^{16} – 10^{23}$ Mx**
  - **Slope of power-law**
    - **$\alpha_{emergences}$ = -2.74**



Thornton & Parnell (2011)

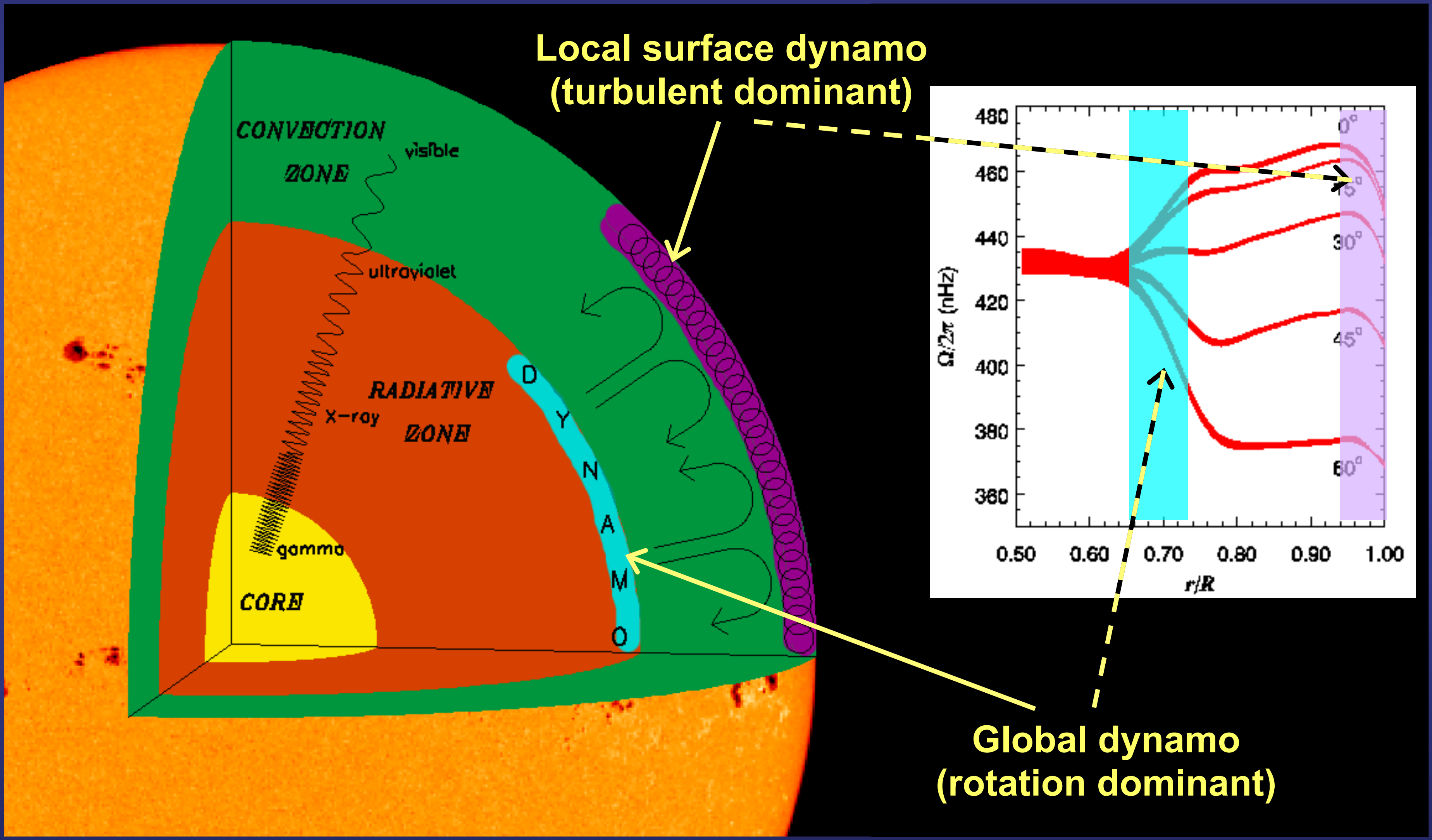
Distribution of Emerged Flux Features

- Frequency of peak emerged fluxes per day:
  - Power-law between $10^{16} – 10^{23}$ Mx
  - Slope of power-law
    - $\alpha_{emergences}$ = -2.74
- Power law ⇒ ***generation of emerging features is scale free***

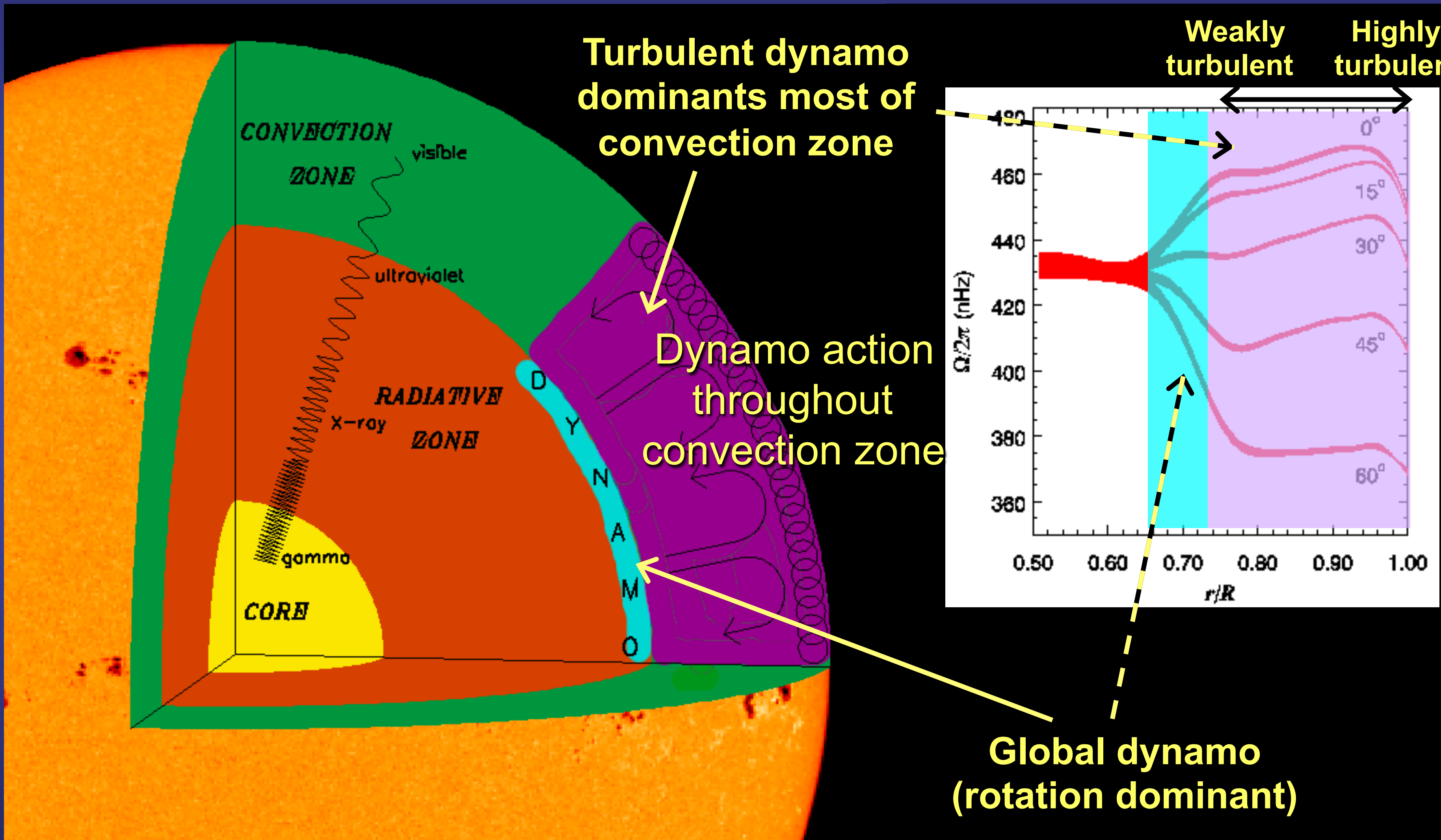


Thornton & Parnell (2011)

Solar Dynamo

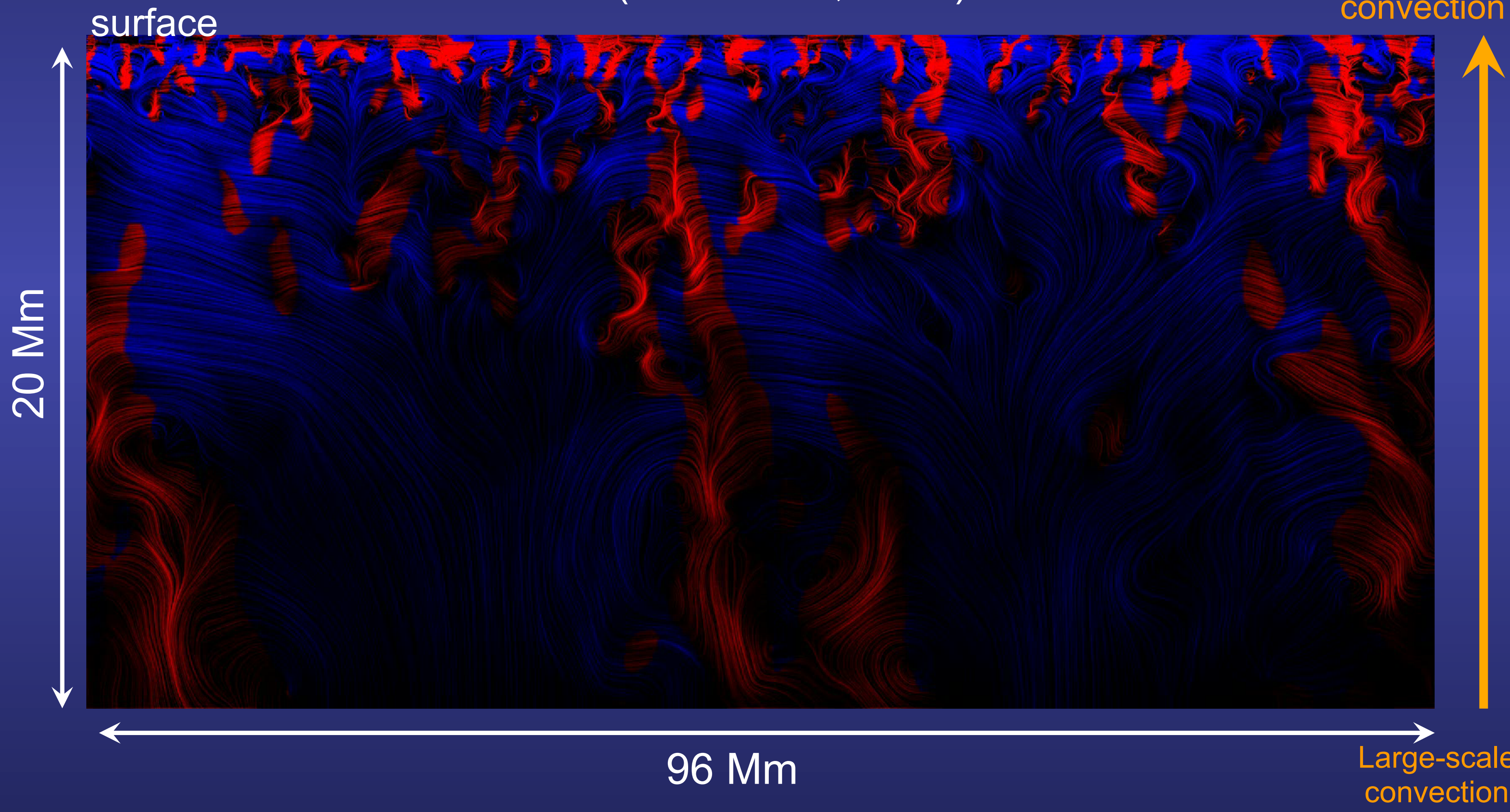


Solar Dynamo



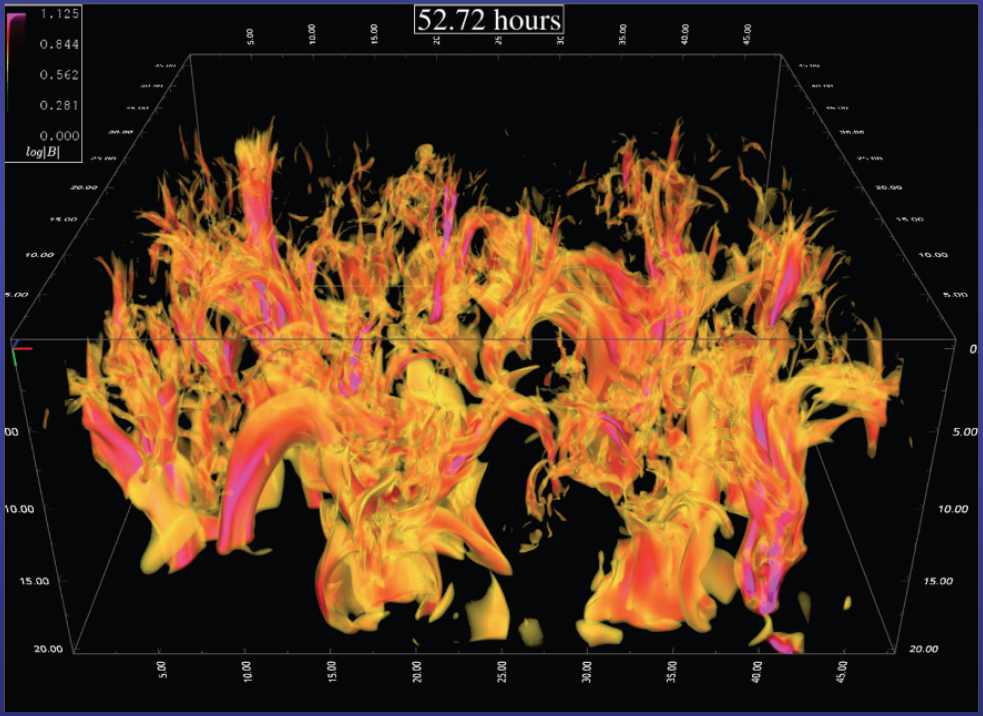
Convection Zone

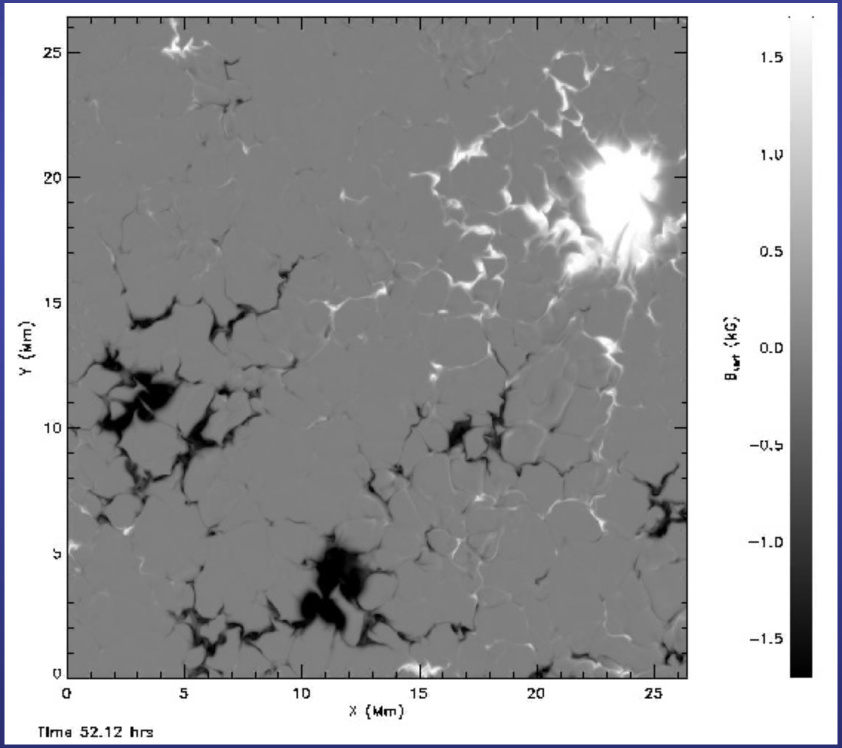
- Simulation of convection (Stein et al., 2006)



Processing of Flux by Convection Zone

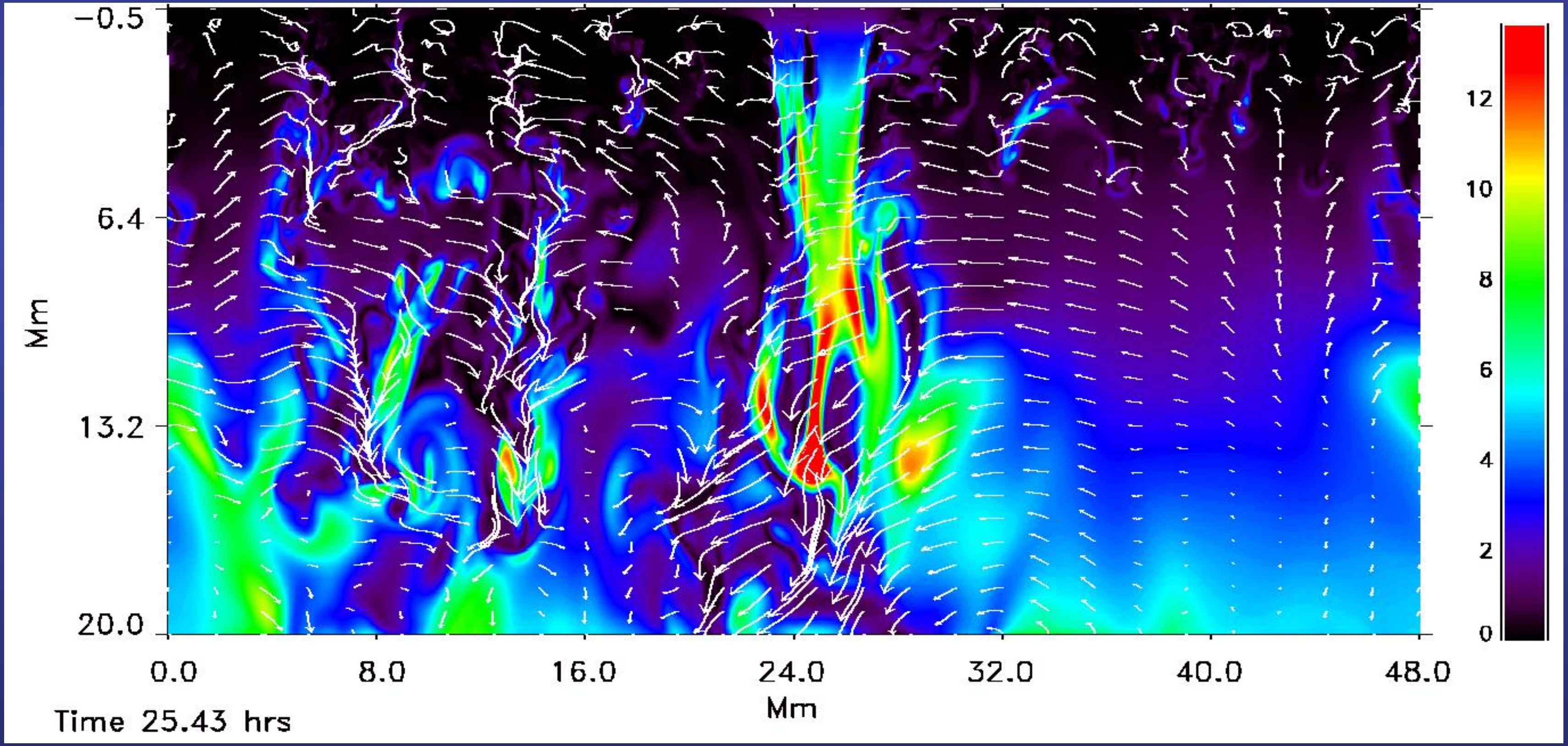
- Small-scale feature & active regions can be created without an initial flux tube (Stein & Nordlund, 2012)



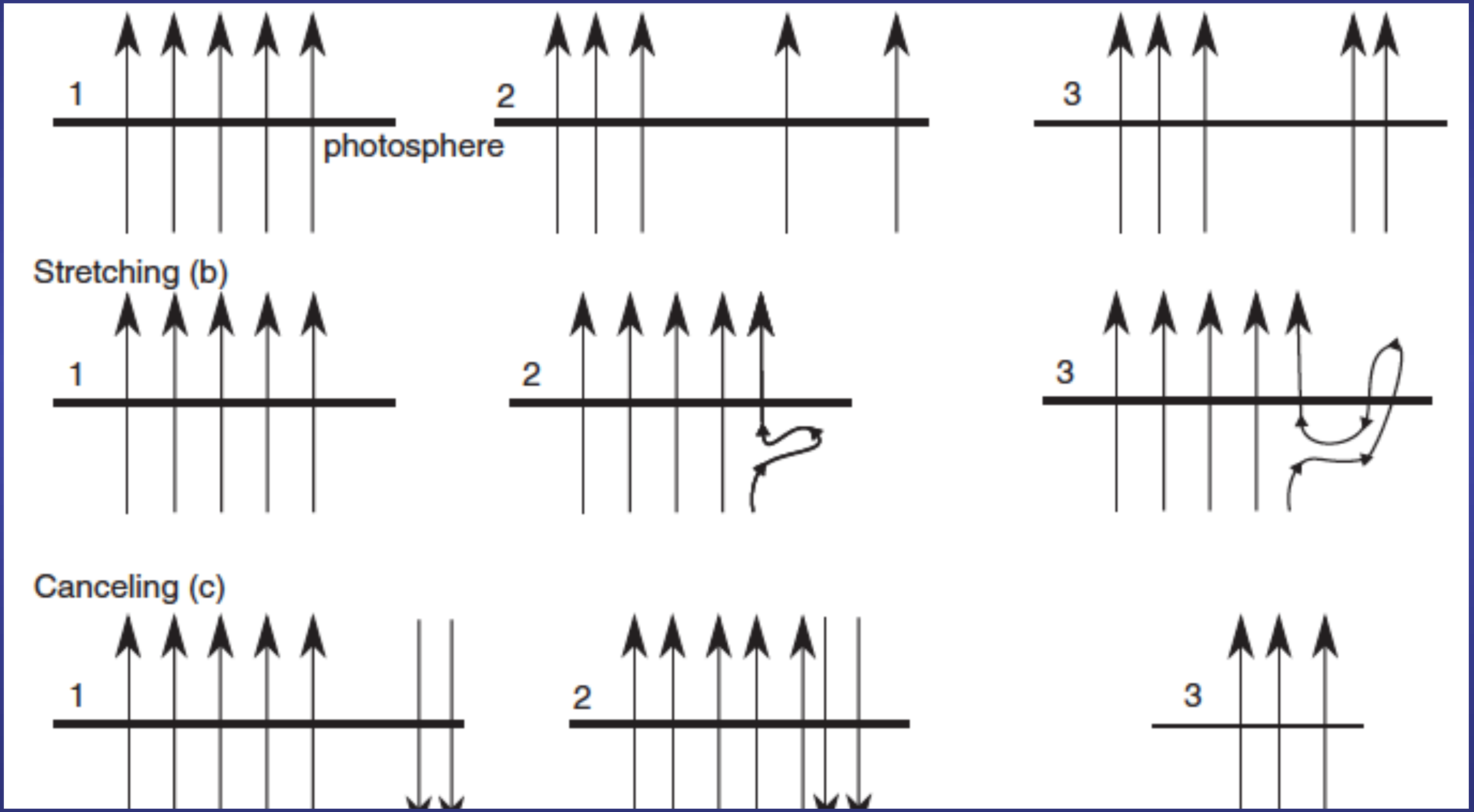


Processing of Flux in Convection Zone

- Simulations of convection have shown that small & large scale magnetic features may be created (Stein & Nordlund, 2012)



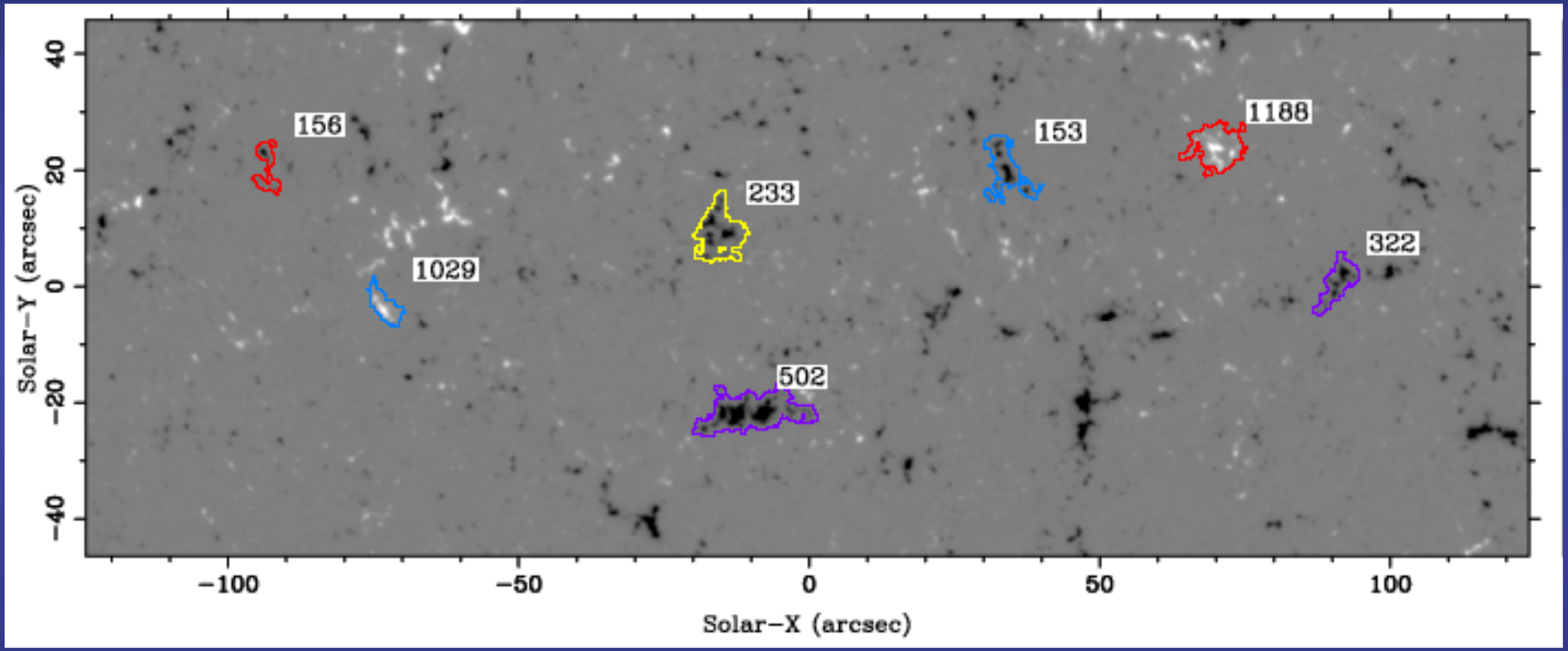
Are there more Magnetic Features about Network Concentrations?



- Three mechanisms that could result in an increase in features near a network concentration

Lamb et al. (2014)

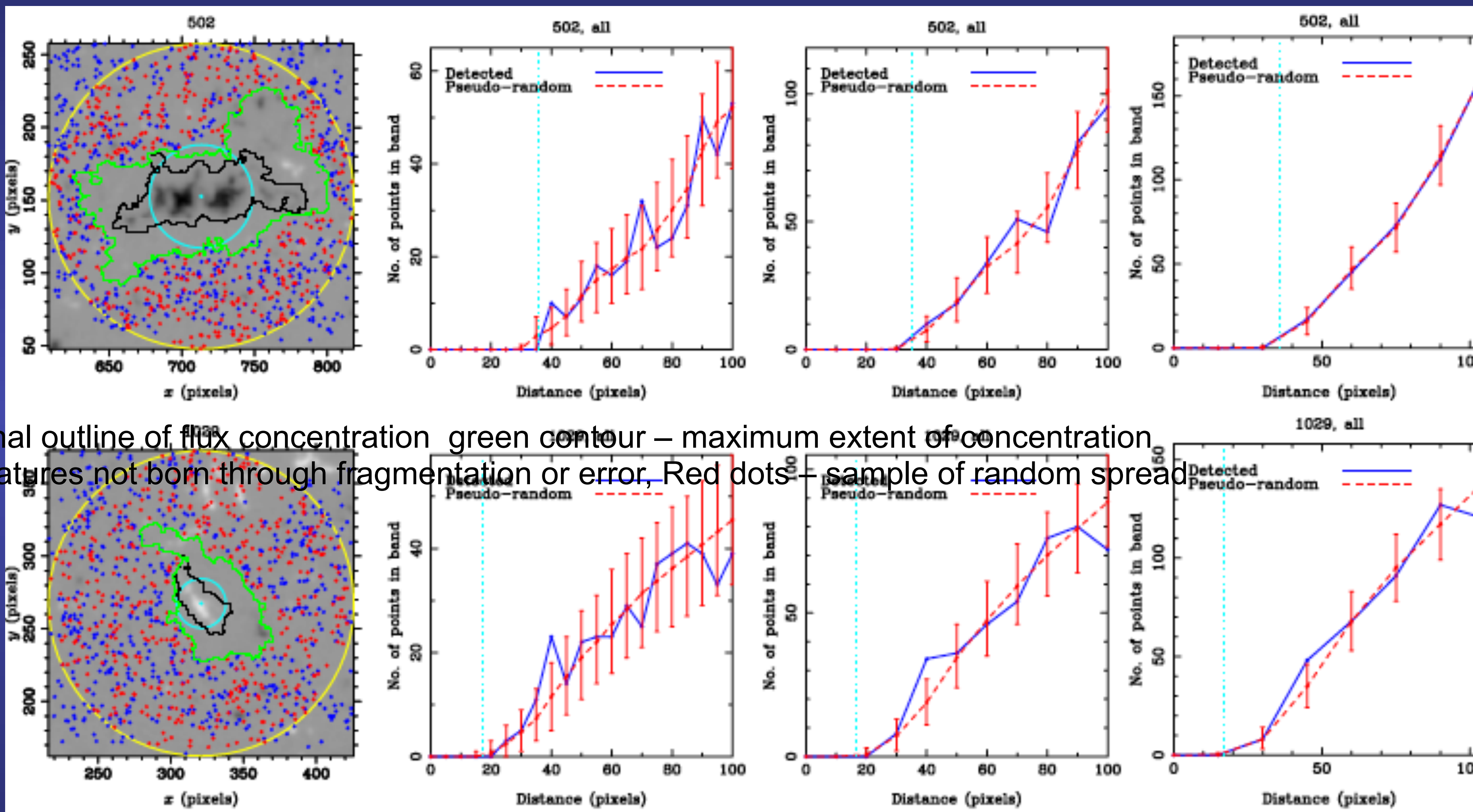
Investigate Feature Numbers about Network Concentrations



- Seven network concentrations identified in Hinode/NFI magnetograms using SWAMIS
- Count number of small magnetic features in the very local and far-off local field about each concentration

Lamb et al. (2014)

Features about Network Concentrations



original outline of flux concentration green contour – maximum extent of concentration
etic features not born through fragmentation or error, Red dots – sample of random spread

- No evidence of increase in number of features near network concentrations
  => no evidence of small-scale ‘surface’ dynamo

Lamb et al. (2014)

Global Flux Emergence Rate

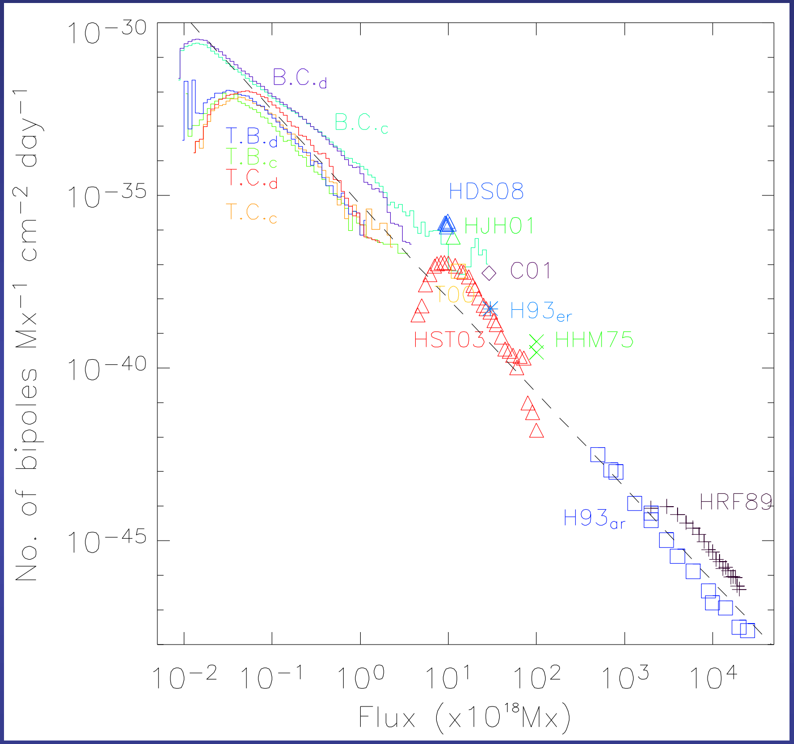
Emerged Flux distribution (Mx^{-1} cm^{-2} day^{-1}):

$$P_{emer}(\phi) = \frac{N_{emer}}{\phi_0}\left(\frac{\phi}{\phi_0}\right)^{\alpha_{emer}}$$

$$N_{emer} = 1.77 \times 10^{-14} \text{ cm}^{-2}\text{ day}^{-1}$$

$$\phi_0 = 10^{16} \text{ Mx}$$

$$\alpha_{emer} = 2.74$$



Global flux emergence rate (Mx cm^{-2} day^{-1}):

$$F_{emer}(\phi 1, \phi 2) = \int_{\phi 1}^{\phi 2} P_{emer}(\phi)\phi d\phi = \frac{N_{emer}\phi_0}{2+\alpha_{emer}}\left[\left(\frac{\phi}{\phi_0}\right)^{2+\alpha_{emer}}\right]_{\phi 1}^{\phi 2}$$

Emergence Rate vs Instantaneous Flux

Global flux emergence rates

Solar Max:

$$F_{emer}(10^{16},10^{23}) \approx 240 \ \textbf{Mx cm}^{-2}\ \textbf{day}^{-1}$$

$$\approx {}^{\dagger}1.5 \times 10^{25}\ \text{Mx day}^{-1}$$

Solar Min:

$$F_{emer}(10^{16},10^{20}) \approx 239 \ \textbf{Mx cm}^{-2}\ \textbf{day}^{-1}$$

$$\approx 1.5 \times 10^{25}\ \text{Mx day}^{-1}$$

Extra from large-scale features:

$$F_{emer}(10^{20},10^{23}) \approx 0.5 \ \textbf{Mx cm}^{-2}\ \textbf{day}^{-1}$$

$$\approx 3 \times 10^{22}\ \text{Mx day}^{-1}$$

Global instantaneous flux

Solar Max:

$$F_{emer}(10^{16},10^{23}) \approx 30 \ \textbf{Mx cm}^{-2}$$

$$\approx 1.9 \times 10^{24}\ \text{Mx}$$

Solar Min:

$$F_{emer}(10^{16},10^{20}) \approx 11 \ \textbf{Mx cm}^{-2}$$

$$\approx 7 \times 10^{23}\ \text{Mx}$$

Extra from large-scale features:

$$F_{emer}(10^{20},10^{23}) \approx 18 \ \textbf{Mx cm}^{-2}$$

$$\approx 1.2 \times 10^{24}\ \text{Mx}$$

† 10^{24} Mx day^{-1} over whole solar surface (Martínez González and Bellot Rubio, 2009)

Lifetimes of Features

Emerged flux distribution (Mx^{-1} cm^{-2} day^{-1}):

$$P_{emer}(\phi) = \frac{N_{emer}}{\phi_0}\left(\frac{\phi}{\phi_0}\right)^{\alpha_{emer}}$$

Instantaneous feature distribution (Mx^{-1} cm^{-2}):

$$P_{feat}(\phi) = \frac{N_{feat}}{\phi_0}\left(\frac{\phi}{\phi_0}\right)^{\alpha_{feat}}$$

Feature lifetimes:

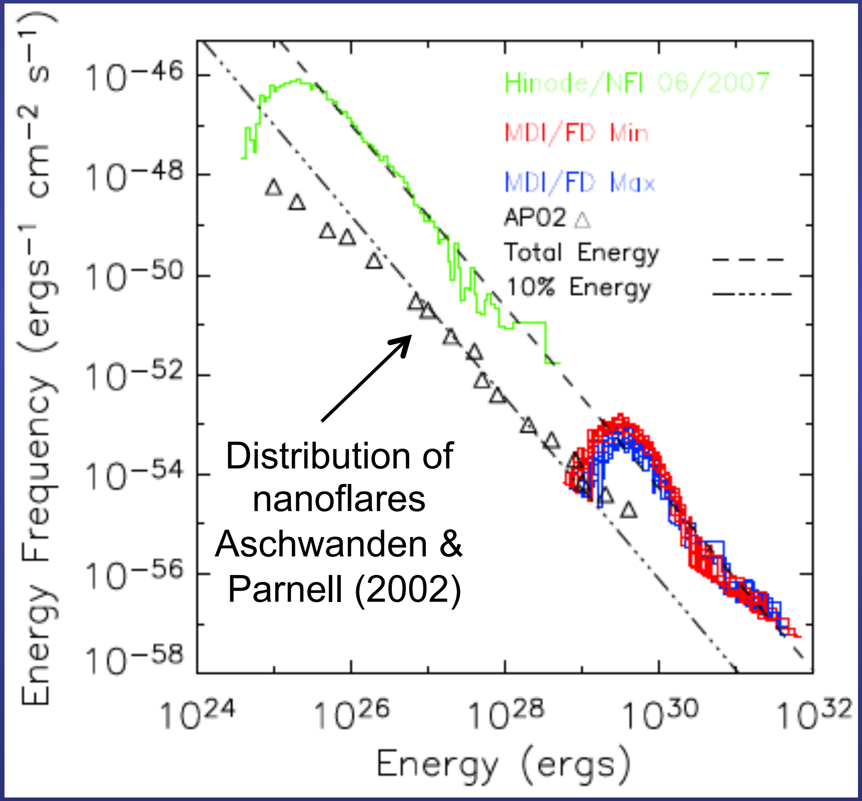
- small-scale features – short lifetimes
- large-scale features – long lifetimes

…. But the lifetimes alone cannot explain the change of slope from emerged flux to instantaneous flux

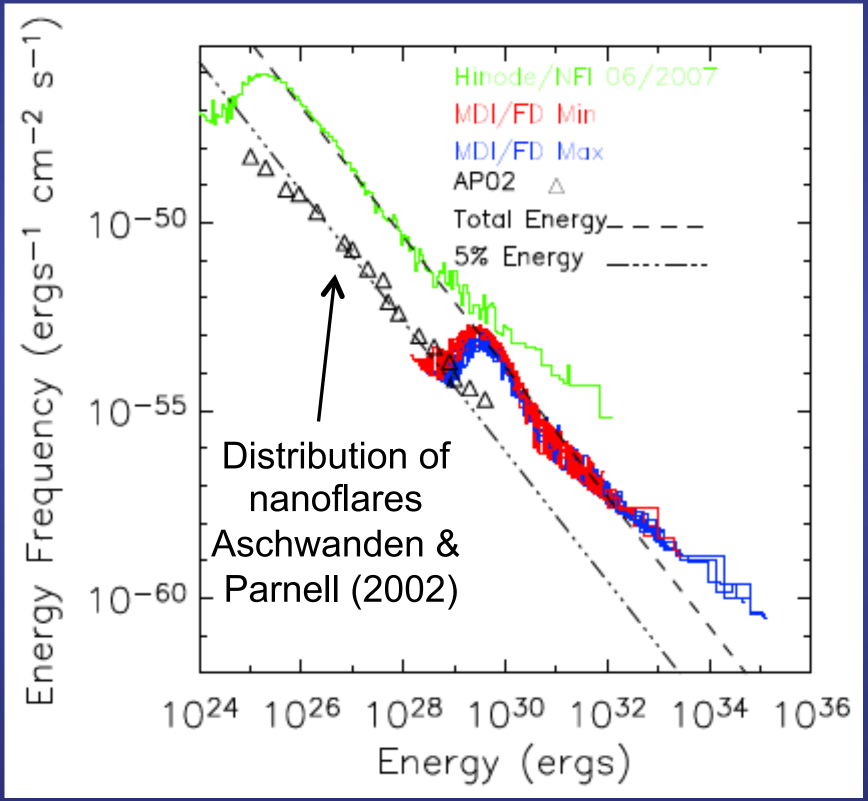
- lifetimes estimated do not match observed lifetimes

Energy from Emergence & Cancellation

Distribution of energies from emerged features



Distribution of energies from emerged & cancelled features



Conclusions

- **Flux distributions:**
  - Distribution of feature fluxes at *any instance*:
    - Power-law index: $\alpha_{features} = -1.87$
  - Distribution of peak emerged fluxes per day
    - Power-law index: $\alpha_{features} = -2.74$
  - Possible scenarios:
    - Turbulent & global dynamo coupled (turbulence decreases with depth?)
    - Convection zone plays a key role in 'processing flux'.
- **Global flux emergence rate (F_{emer}):**
  - Constant over solar cycle

    $F_{emer}(max) \approx F_{emer}(min) \approx 240$ Mx cm^{-1} day$^{-2} \approx 10^{25}$ Mx day^{-1}
  - behaviour of solar atmosphere at solar max is
    - NOT due to extra magnetic flux
    - IS due to the grouping of flux into large-scale coherent features

Conclusions 2

- Power-law distribution $\Rightarrow$ mechanism producing magnetic features is scale free.
  - Possible scenarios:
    - Turbulent and global dynamo coupled (turbulence decreases with depth?)
    - Convection zone plays a key role in 'processing flux' and determining the sizes of features observed.

- Global rate of flux emergence is constant so:
  - behaviour of solar atmosphere at solar max is
    - NOT due to extra magnetic flux
    - IS due to the grouping of flux into large-scale coherent features