National Astronomy Meeting

NAM 2013

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University of St Andrews

1-5 July 2013

Science & Technology Facilities Council

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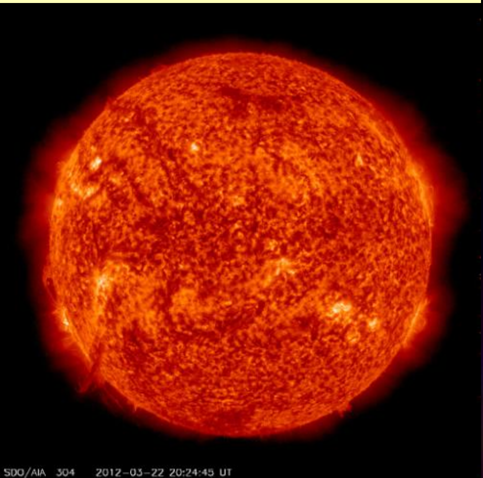
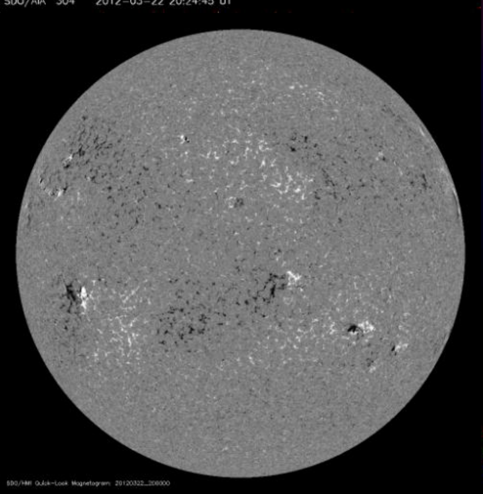
Visit St Andrews

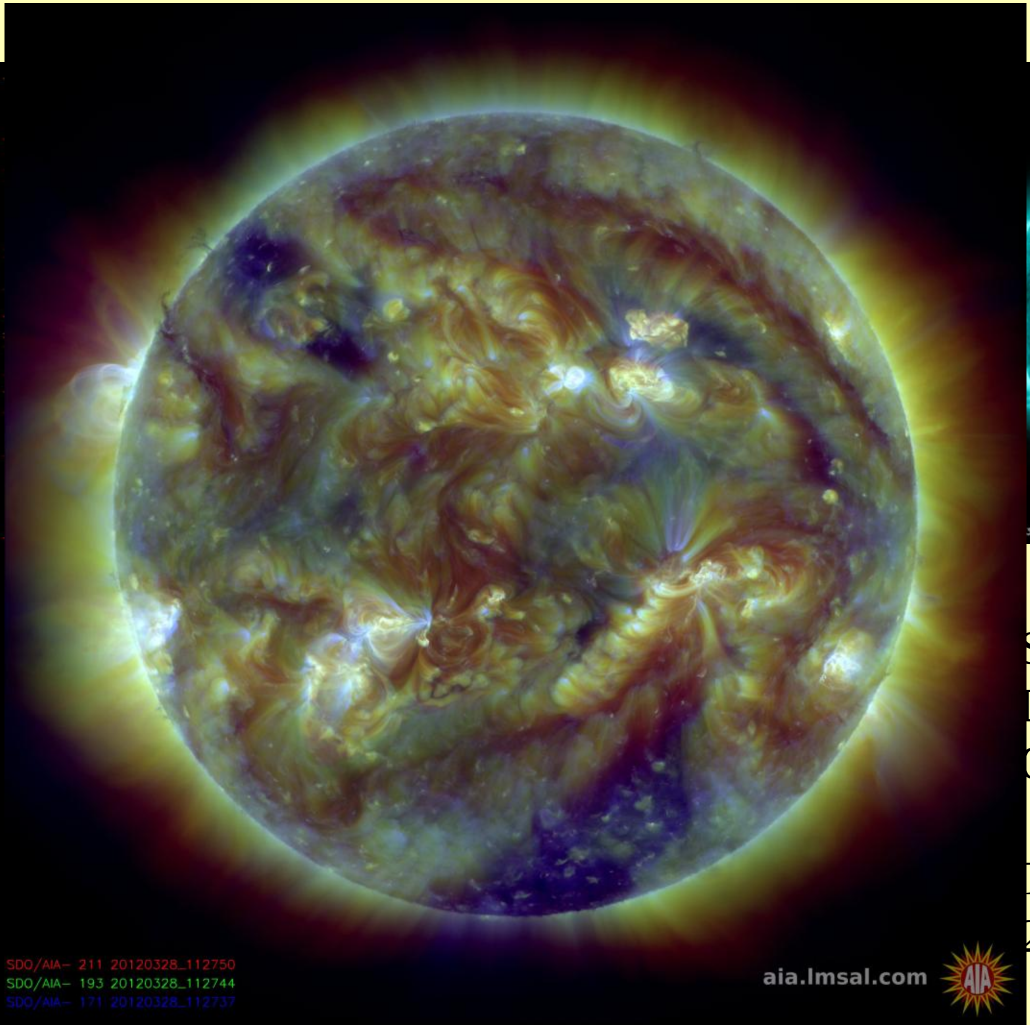
University of St Andrews

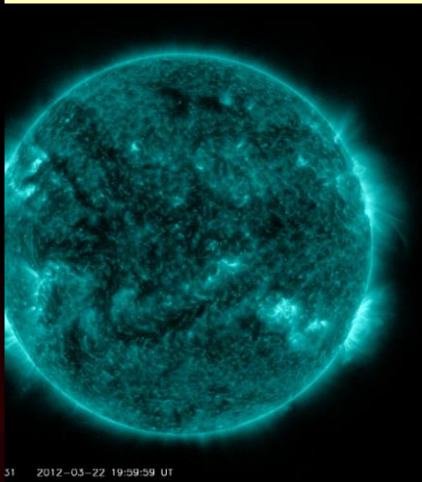
The Wonders of the Solar Atmosphere

Alan Hood
University of St Andrews









Solar Dynamics Observatory

The Sun on
22 March 2012

The Wonders of the Solar Atmosphere

What are the discoveries over the last 20 years?
Have we solved all the main problems?

1. Introduction to the Solar Atmosphere
2. Origin and evolution of magnetic field
3. Coronal Heating
4. Eruptions and CMEs
5. Flares and Particle Acceleration

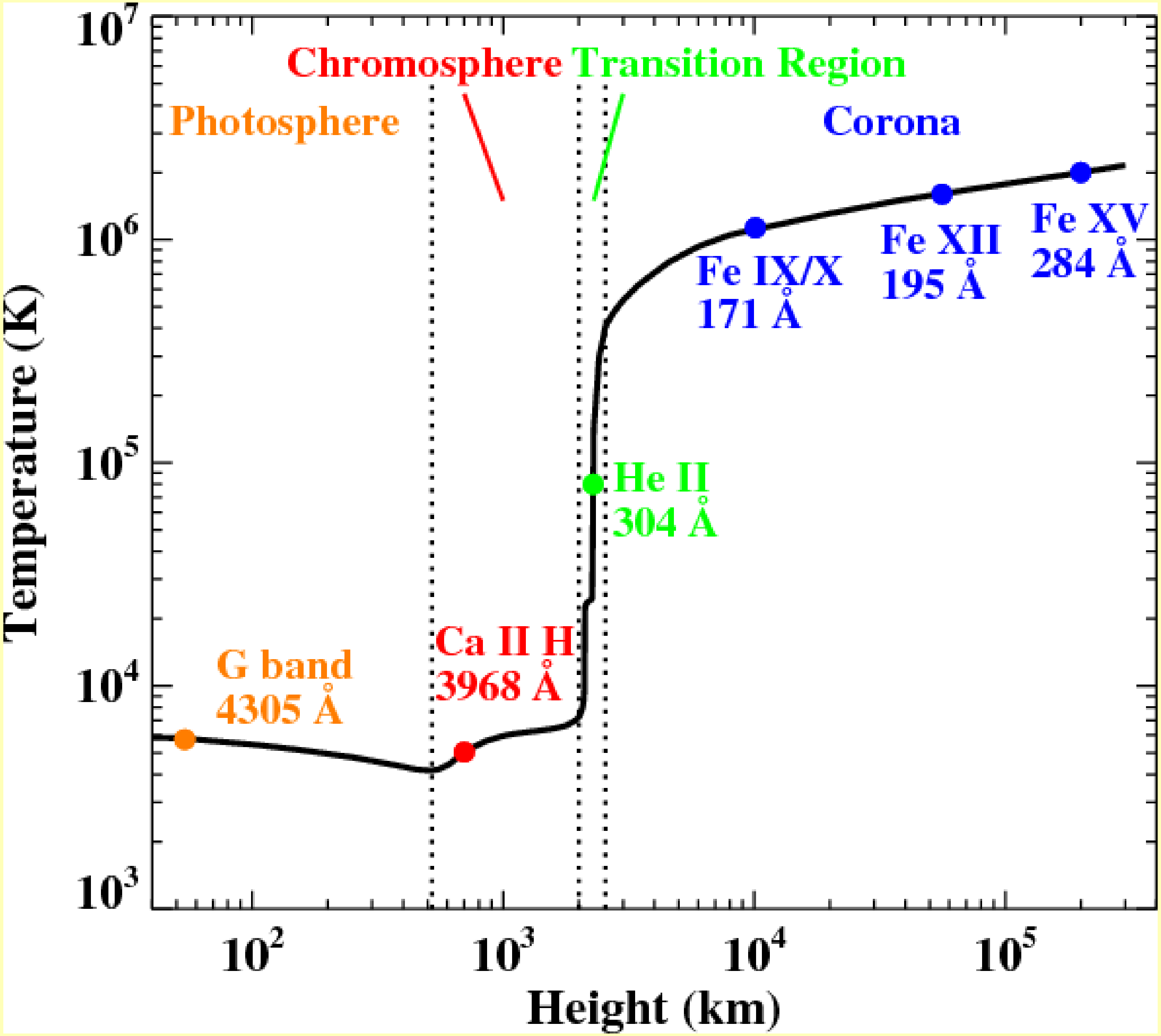
Many major research topics not included, sorry!!

Key Missions and Instruments

BISON Helioseismology (1976s, 1990s full network -) (Birmingham)
SoHO (1995 -) (helioseismology, Doppler imager,
X-ray imager, spectrometers) 12 instruments (remote and in-situ)
CDS (RAL), 3 from Germany (also USA, France, Switzerland)
TRACE (1998 – 2010) (Coronal imager)
RHESSI Flare and particle acceleration mission (2002 -) (Glasgow)
STEREO CME mission (2006 -) (RAL)
HINODE (2006 -) vector magnetogram, X-ray telescope,
Spectrometer (MSSL)
ROSA (2009 -) Rapid Oscillations instrument added to ground
based solar telescope, (Belfast)
SDO (2010 -) Magnetic field, Doppler, imagers
(full disk, 15 seconds, you miss nothing!) (RAL, UCLan)

SDO (2010): full disk every 15 seconds

1. Introduction to the Solar Atmosphere



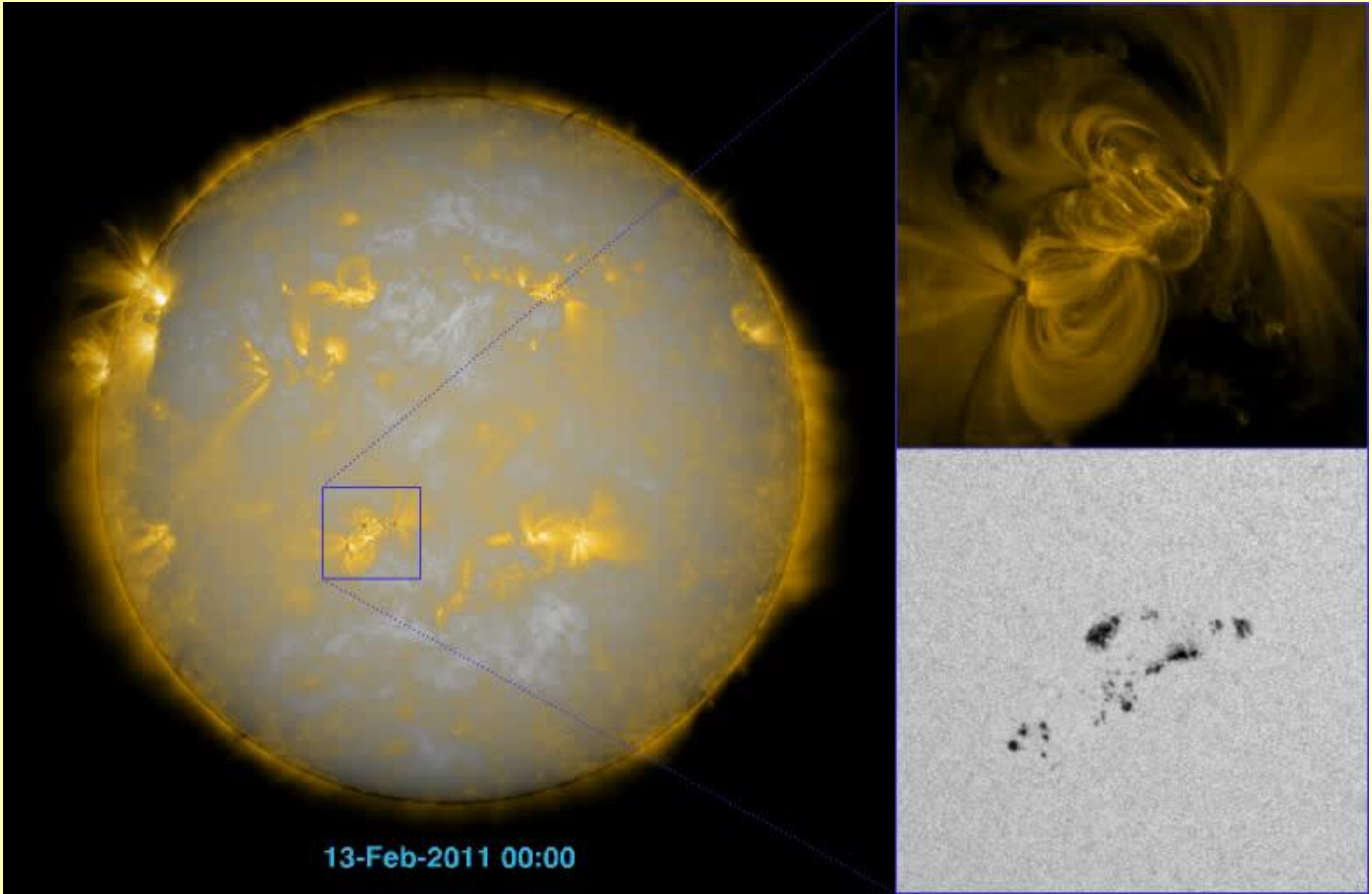
Cause and effect.

Need good T coverage.
Need magnetic field B.

Ground-based, white light and H-alpha. B in photo.

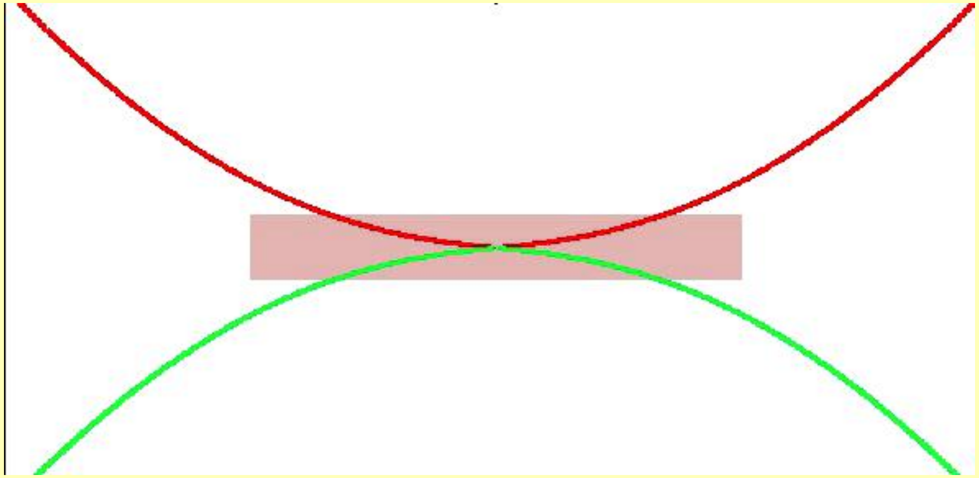
Space-based, EUV, X-ray no B in corona. Imagers or spectrometers.

Solar Magnetic Fields



Importance of the Magnetic Field

- Transports energy from interior to corona
- Supports oscillations
- Channels flows along it
- Stores energy
- Releases energy – flares/eruptions and heating



The breaking and reconnecting of field lines in 2D.
More complicated in 3D.

Summary of MHD Equations

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\mathbf{v} \times \mathbf{B}\right) - \nabla \times (\eta \nabla \times \mathbf{B}),$$ Induction

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \mathbf{v}\right) = 0,$$ Mass continuity

$$\rho \frac{\partial \mathbf{v}}{\partial \mathrm{t}} + \rho\left(\mathbf{v} \cdot \nabla\right)\mathbf{v} = -\nabla p + \mathbf{j} \times \mathbf{B} + \rho \mathbf{g} + \rho \nu \nabla^2 \mathbf{v},$$ Motion

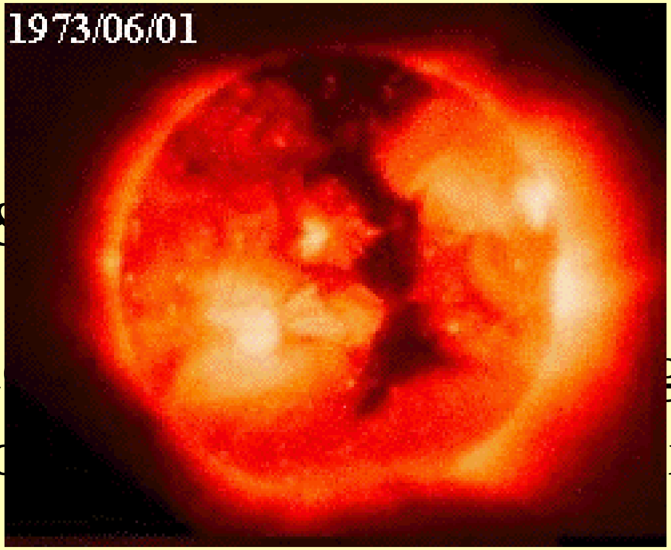
$$\frac{\rho^\gamma}{\gamma - 1} \frac{D}{Dt}\left(\frac{p}{\rho^\gamma}\right) = \nabla \cdot \left(\kappa \nabla T\right) - \rho^2 Q(T) + \frac{j^2}{\sigma} + H,$$ Energy

$$p = \frac{\rho \Re T}{\tilde{\mu}},$$ Gas law,

$$\nabla \cdot \mathbf{B} = 0.$$

Basic MHD Theory:

1980s: Equilibria – potential fields, Waves - uniform media (few observations), Instabilities (only linear), Reconnection (2D simple)



Now:

- Enormous advances &

- Equilibria – Nonlin gnier, Mackay, Yeates]
  - nature c ig]

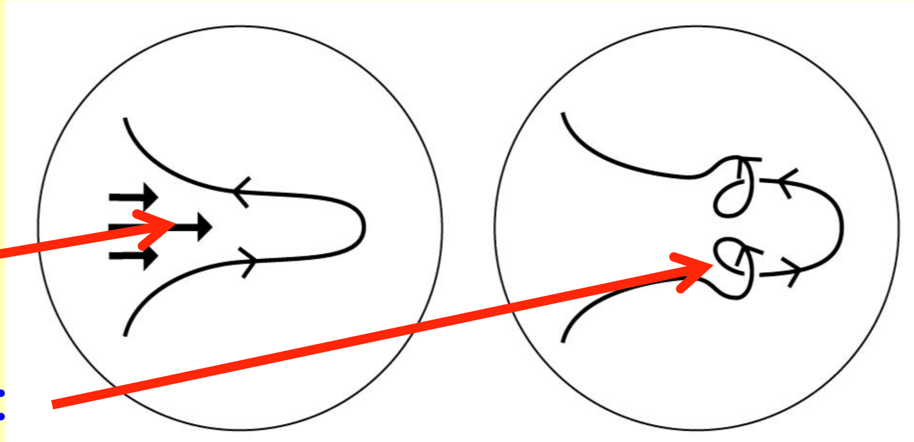
- Waves – 3D non-uniform fields, nonlinear
  [Nakariakov/Verwichte/Erdelyi/Ballai/Ruderman/De Moortel/Taroyan……..]

- Reconnection – 3D at special locations, nulls, separators, QSLs
  [Pontin/Wilmot-Smith/Parnell/Browning]

2. Origin and Evolution of Magnetic Field

Old Dynamo:

B generated through conv^n zone



B_{tor} from B_{pol} by diff. rotation:

B_{pol} from B_{tor} by turb^t cyclonic conv^n:

model by $\nabla \times (\alpha \mathbf{B})$ (Parker, 55b)

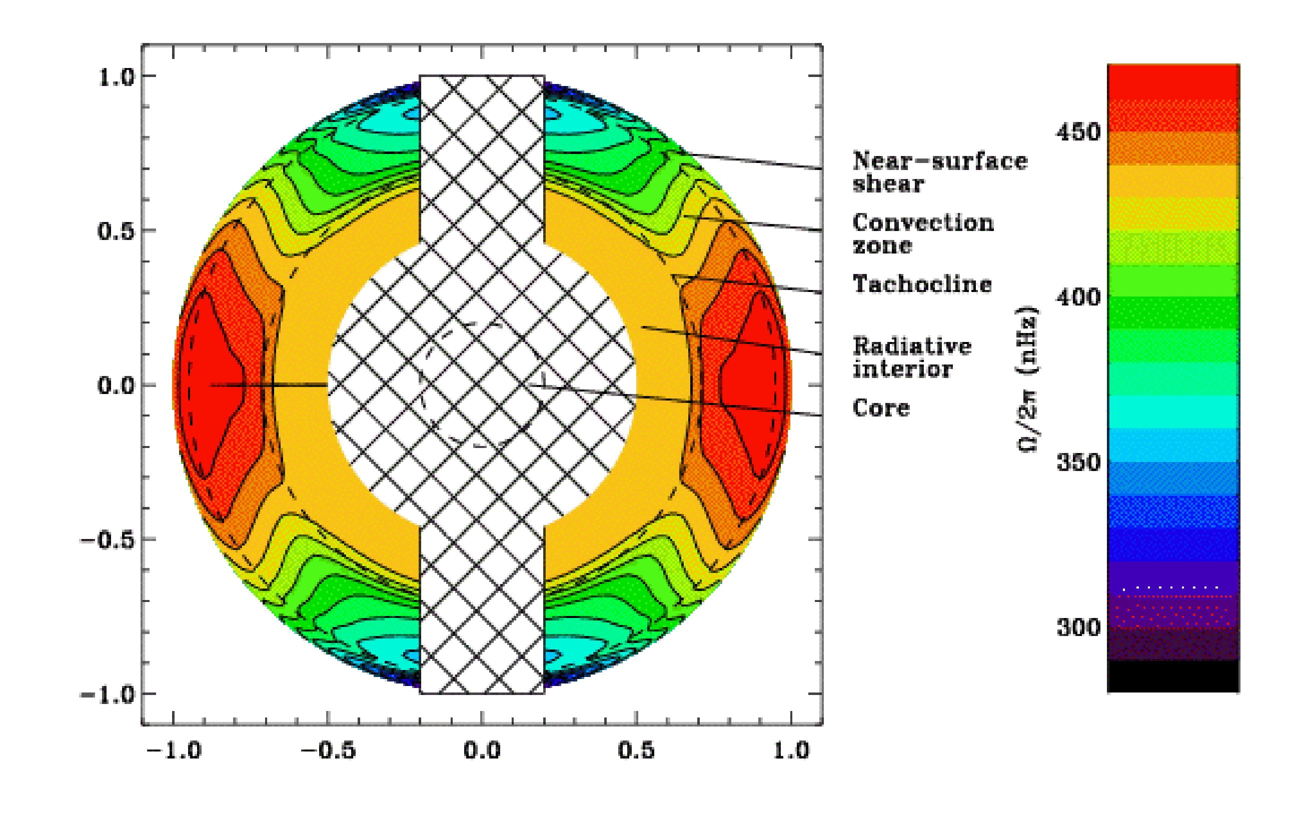
Formal derivation as mean-field theory (Steenbeck et al, 66)

Not what is happening.

Solar interior from helioseismology

Results from BISON (Birmingham), GONG and SOHO/MDI

Strong shear layer at the base of the convection zone - Tachocline

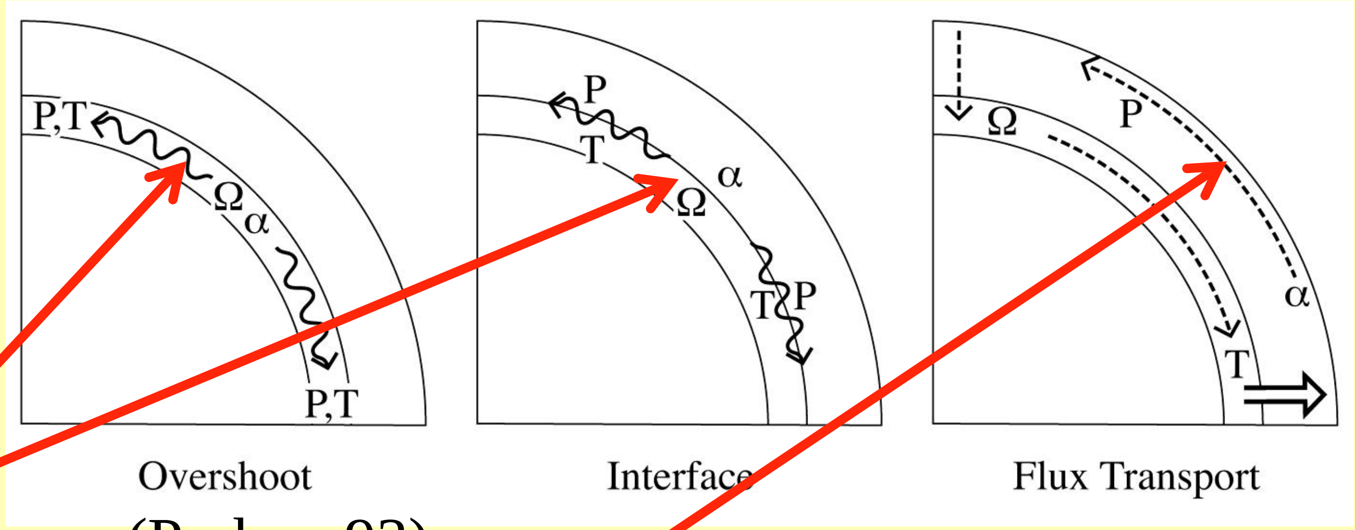


Contours of constant rate of rotation.

Hashed region unreliable results

Since 1990's: (Leeds, Cambridge, Newcastle)

B_{tor} þ B_{pol} at tachocline



- **Tachocline dynamo** (Parker, 93)

or at solar surface in

- **Flux transport dynamo** (Choudhuri et al, 95)

Future (Interior):

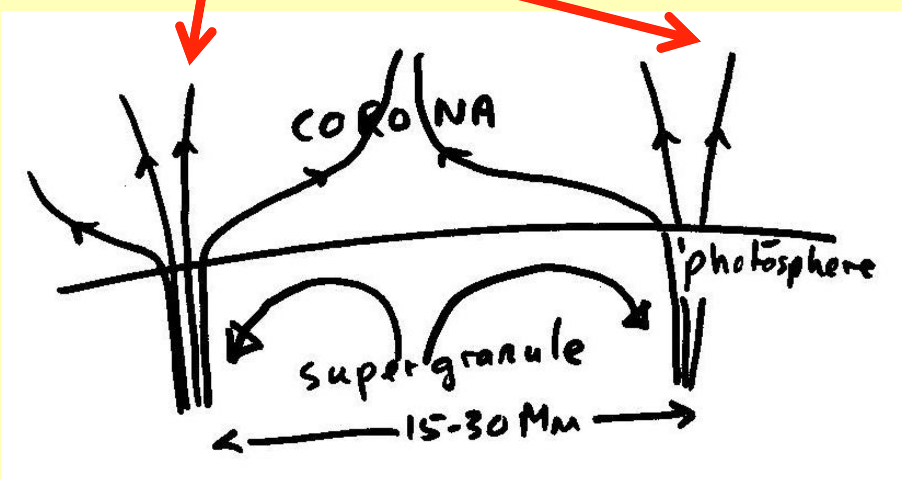
- more constraints from helioseismology
- reassess mean-field theory by numerical simulations (Proctor, Hughes)
- develop realistic tachocline & surface dynamo models (Tobias)
- explore role of magnetic buoyancy instabilities (Hughes)

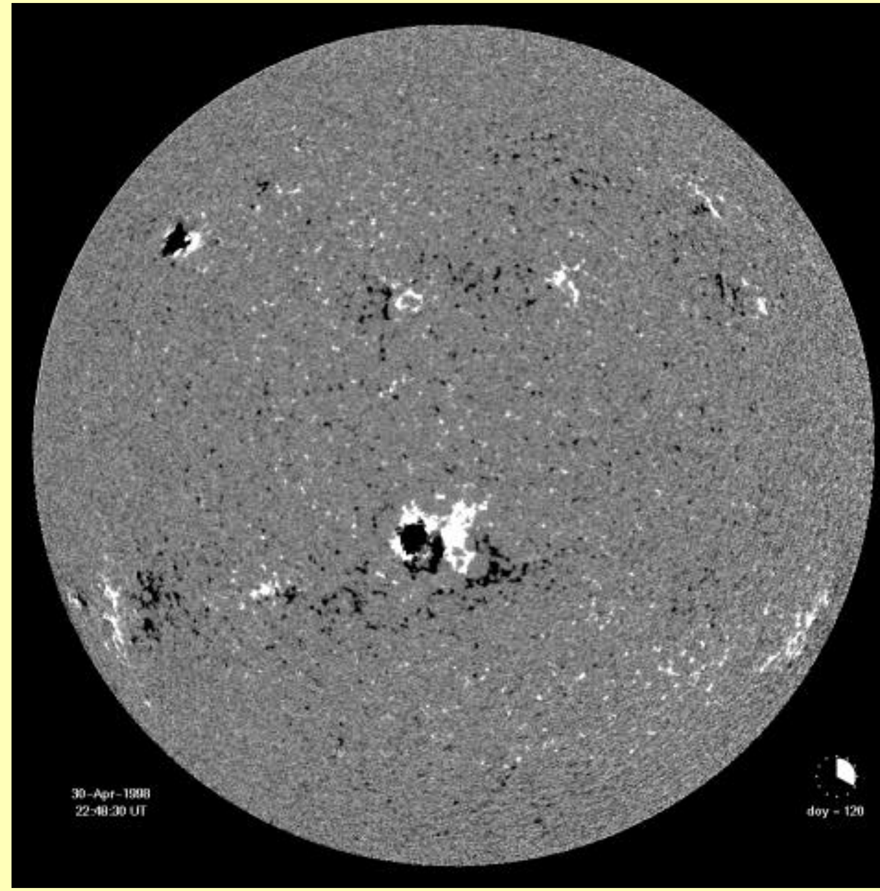
Internal Field Emerges at the Photosphere

1980s/90s: picture outside a.r.

B vertical – mainly edges supergran.

from side



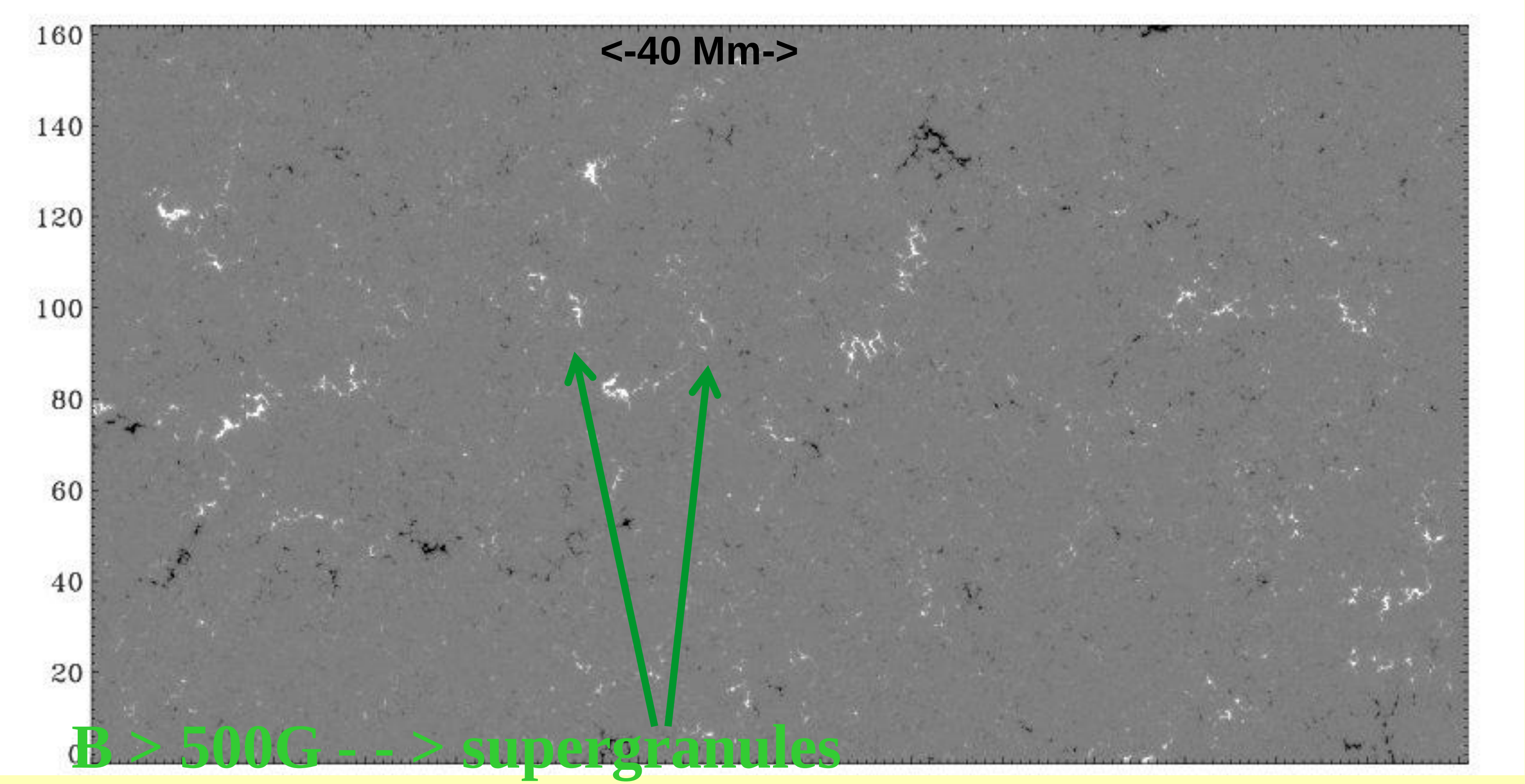


← 700 Mm →

Month of May

Now for things only learnt from 2005 onwards!!

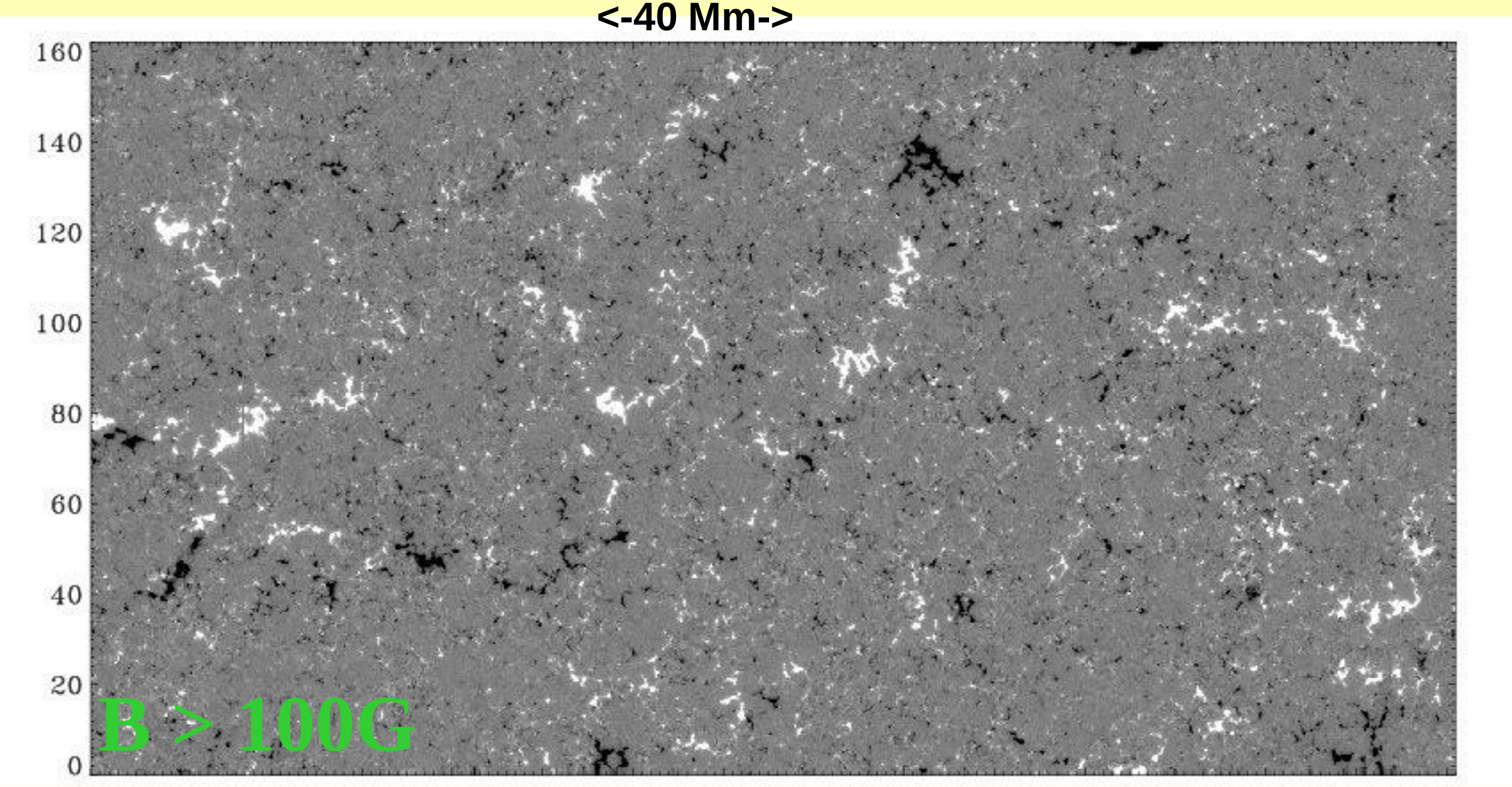
Hinode magnetograms: at low resolution



B > 500G - - > supergranules

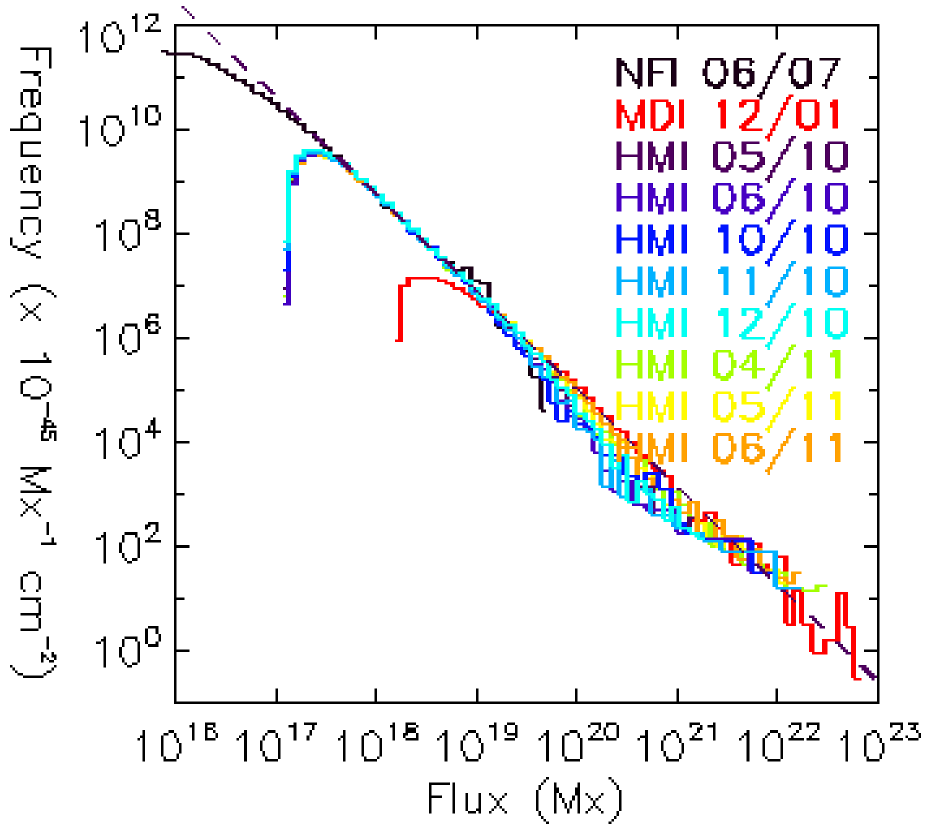
Hinode magnetograms: at low resolution

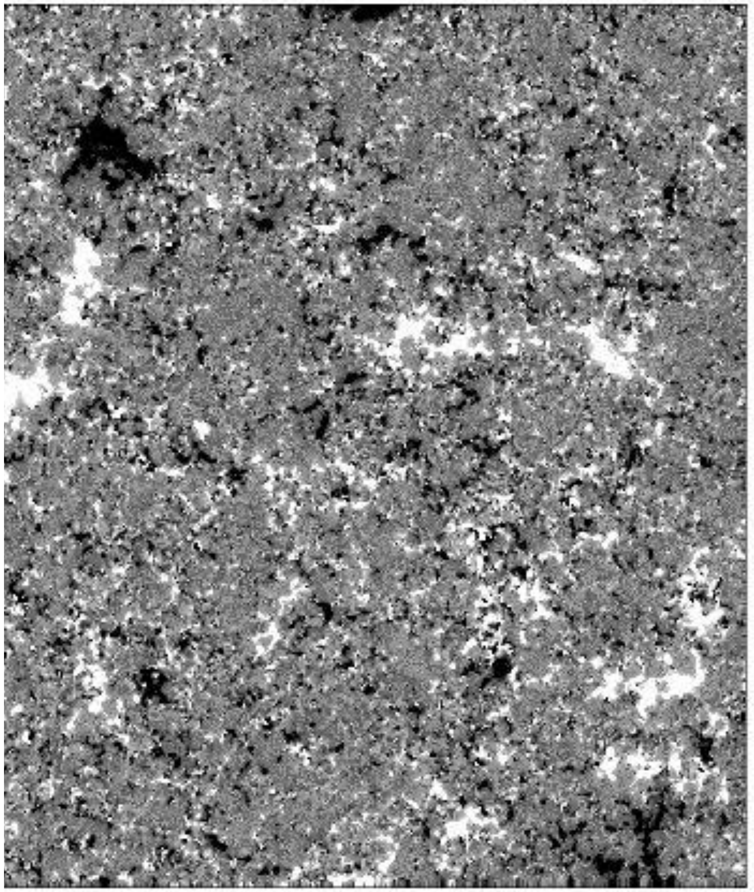
BUT, lower threshold for vertical flux -> more flux



Hinode magnetograms: at low resolution – A Magnetic Carpet

BUT, lower threshold for vertical flux -> more flux



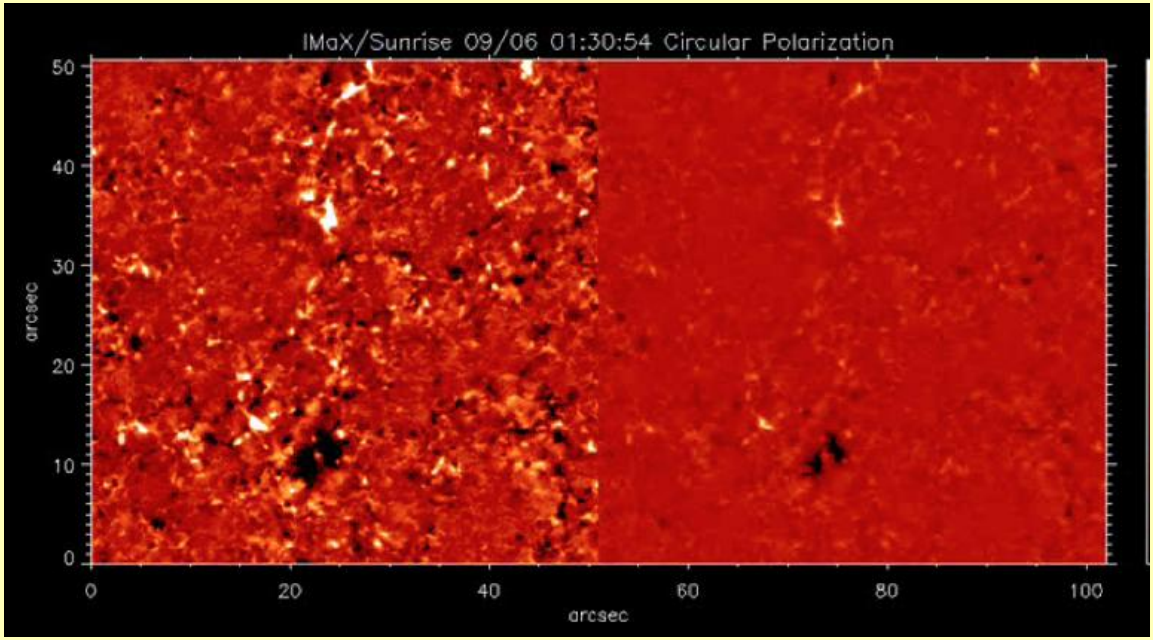


- vertical flux between granules (power law distribution, Parnell)
- coronal field **much more complex** than thought (implications for dynamo and heating).

Sunrise Balloon Flight
(PI – Max Planck Solar System Research Lindau)

- Resolved kG fields
- much smaller flux
  [by factor ten to 2 10^{15} Mx]
- 10 x more features than Hinode

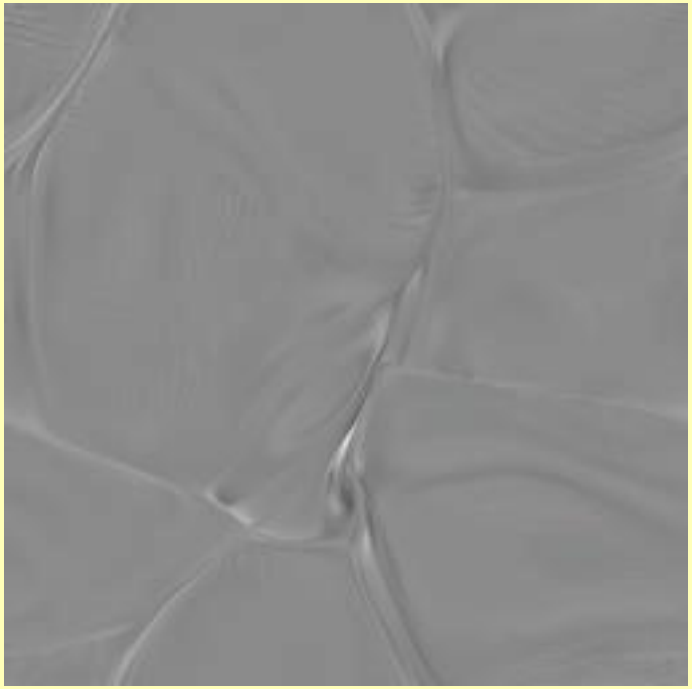
- More power in high-freq acoustic waves
  [1/2 – 3 min] on small scales
  [1/2 chromosphere heat requirement]



Sunrise Hinode

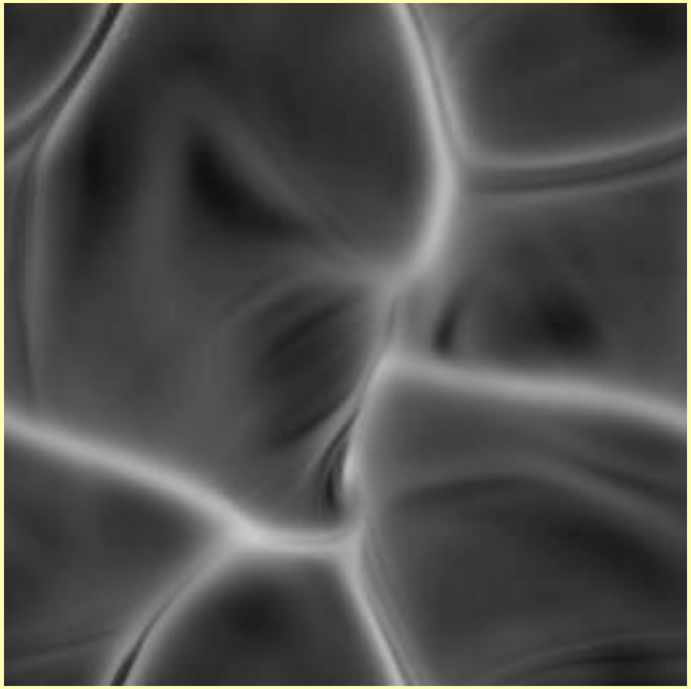
Now zoom into granule scales to study evolving magnetic carpet

Only top part of convection zone (Tobias)



Vertical Bz

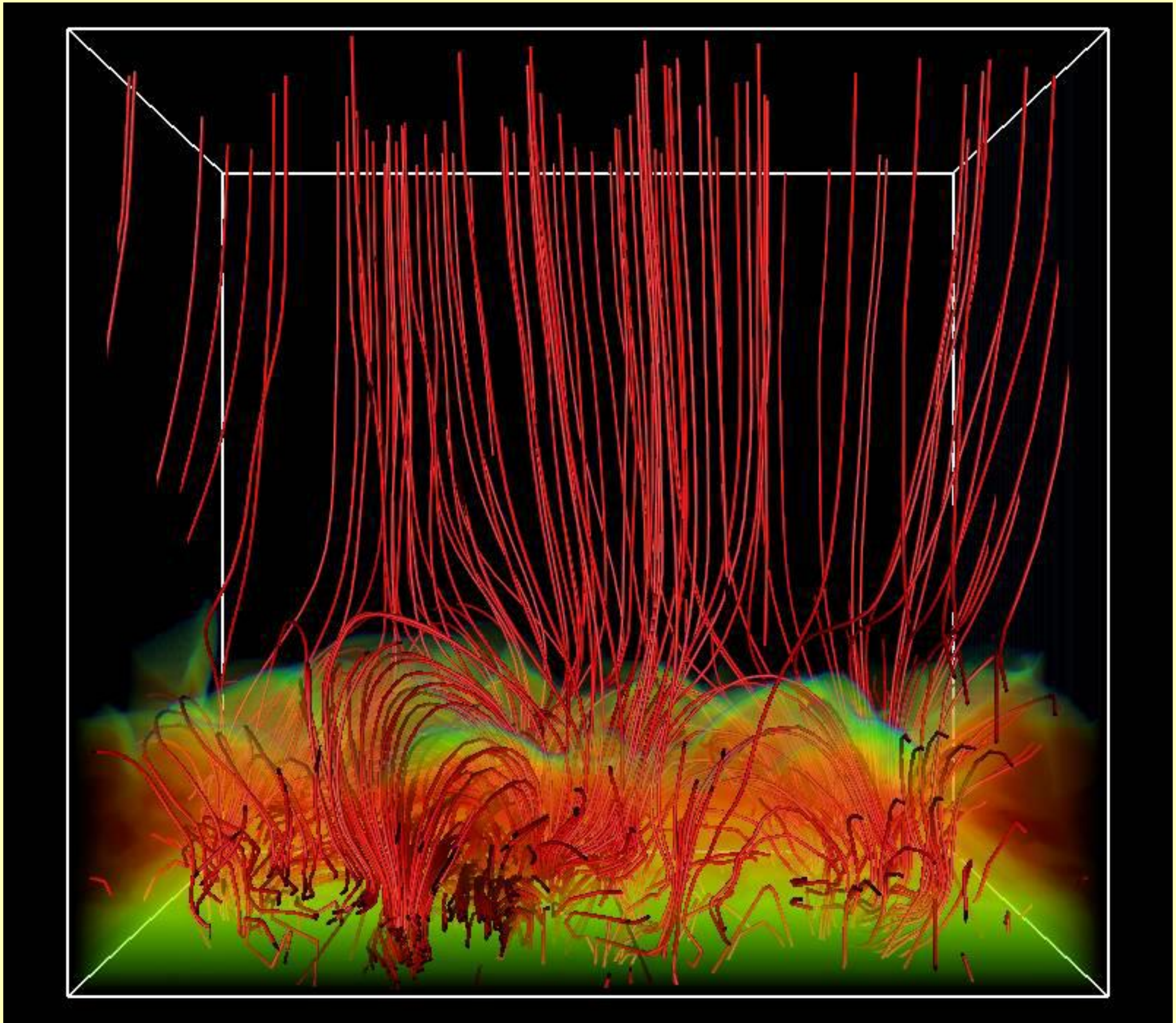
White positive, black negative



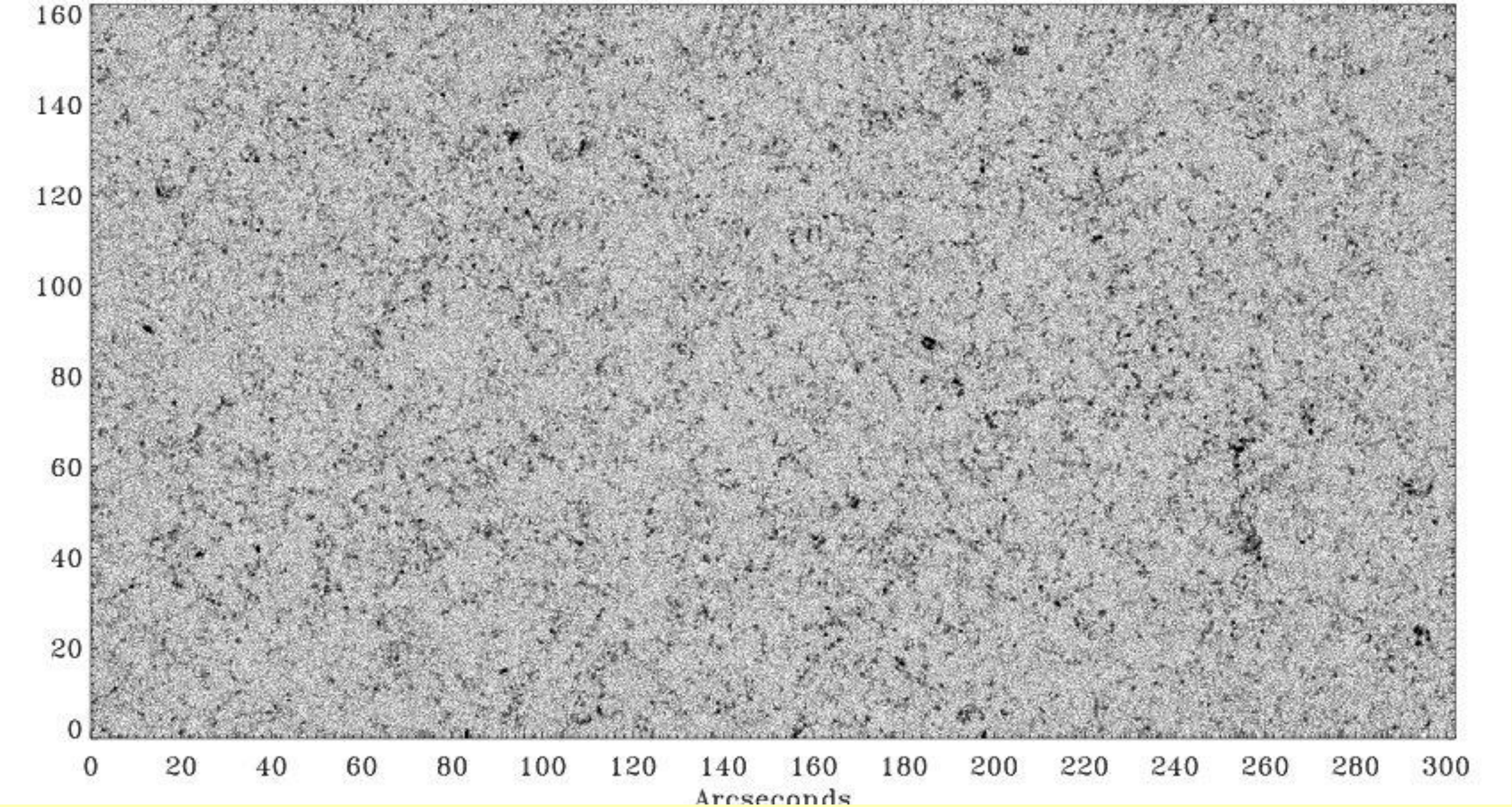
Vertical velocity vz

White down, black up

Effect of convection on a vertical field (Oslo group)



Another major surprise!
Horizontal Magnetic Field

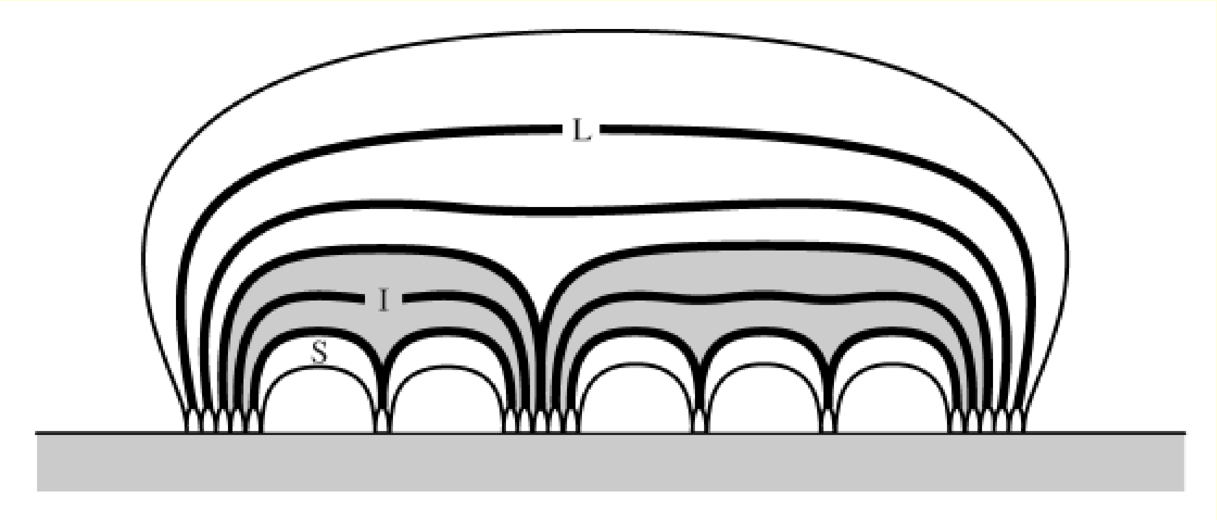


[B>200G]

Hinode: horizontal fields – edges granules

Coronal loops (outside active regions) are more complex

Coronal Tectonics Model (Priest, Heyvaerts, Title, 2002)

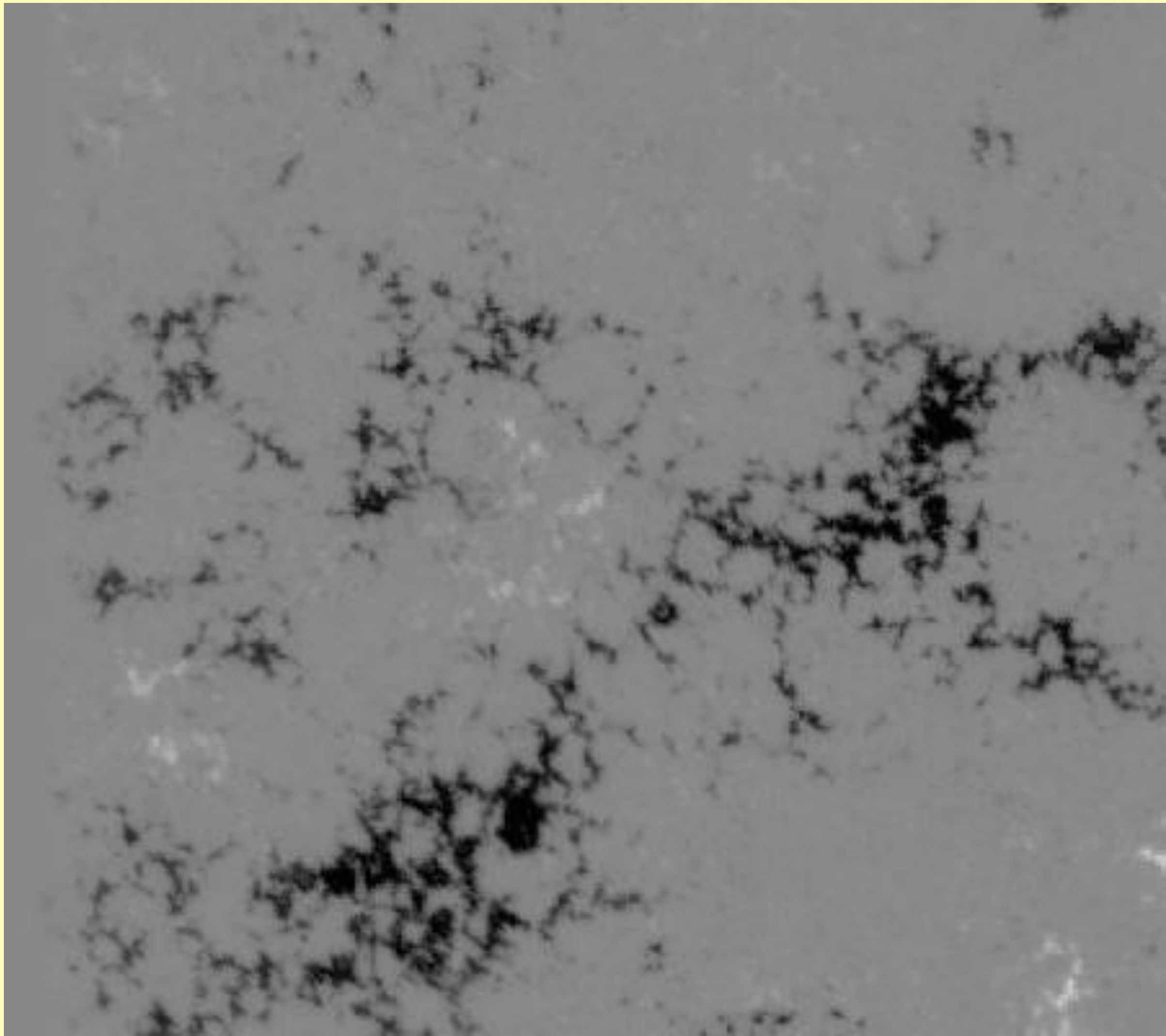


- Flux from each source separated by separatrix surfaces (& QSLs).
- Separatrix surfaces – discontinuities – current sheets
- Form in response to flux emergence, cancellation, motion

Flux Emergence: Modelling the dynamic formation of active regions

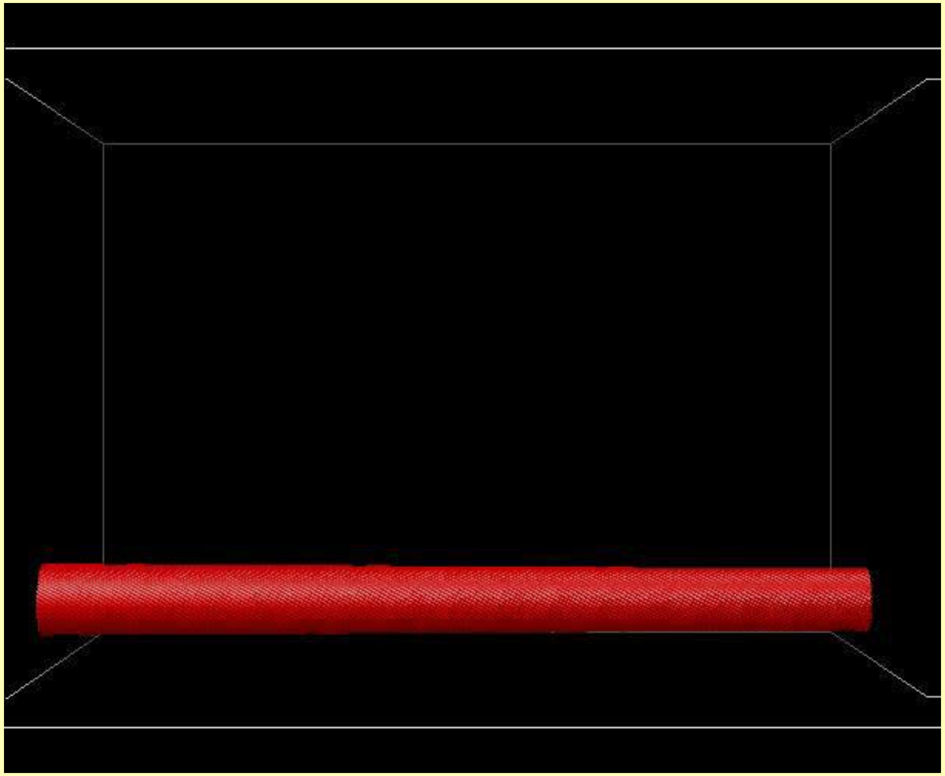
Theory: Warwick, St Andrews; Observations: MSSL, UCLan

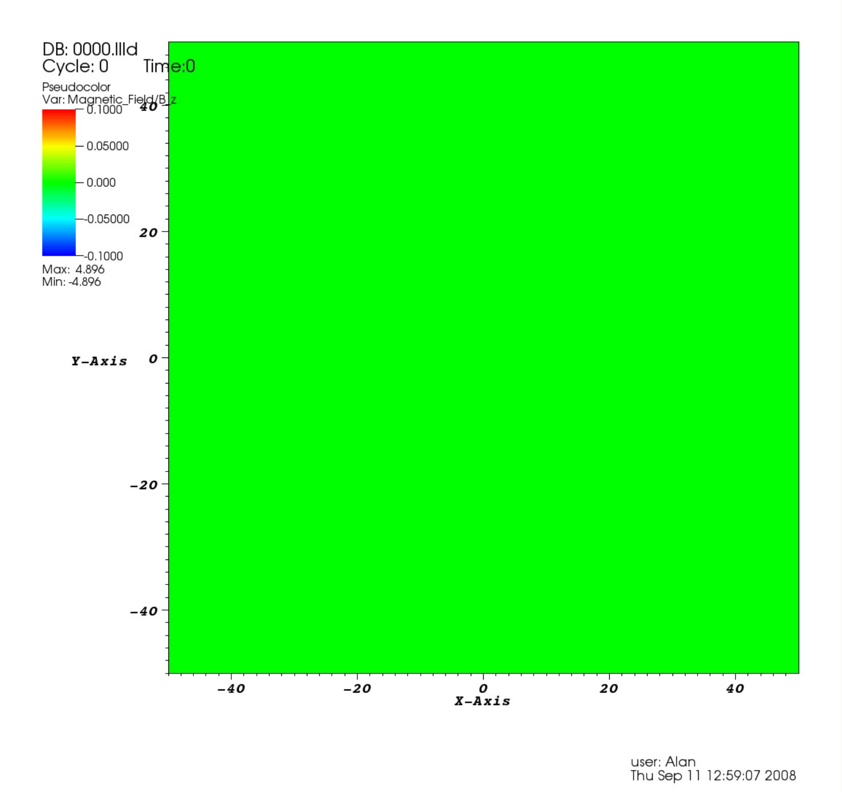
Hinode:



EIS: outflows from both edges. Slow solar wind? (Harra)

How to model emerging fields?
Cylindrical buoyant loop
(Archontis, Arber, MacTaggart, Murray)

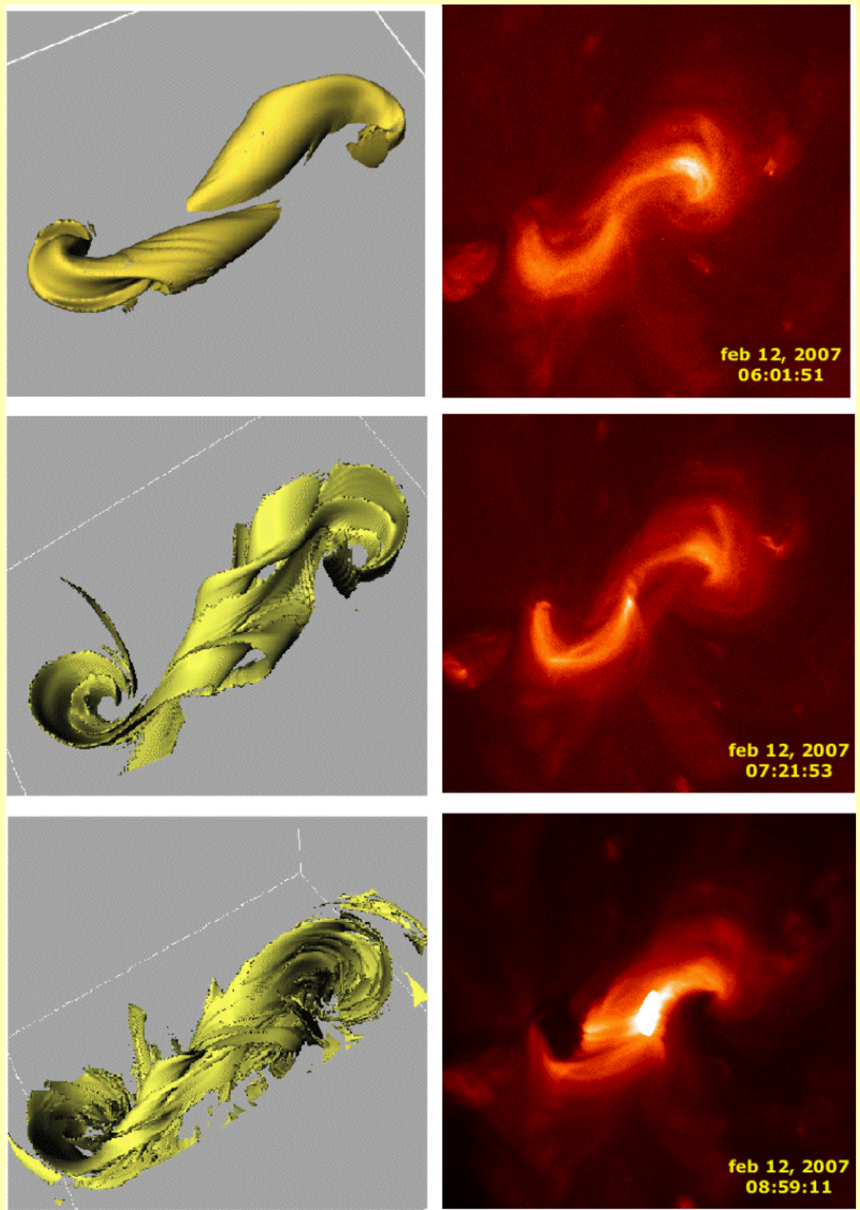




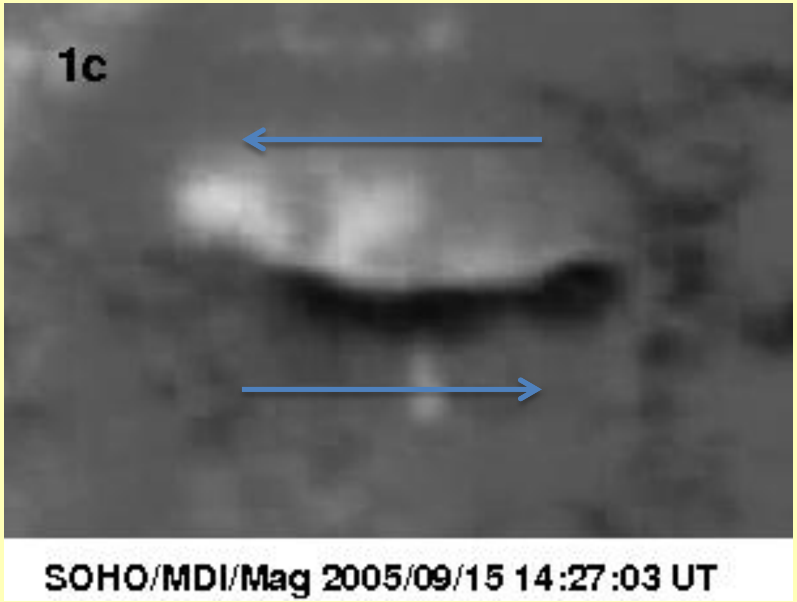
Emerging bipolar region formed sigmoid (Archontis). Eruption in both simulation and observations.

J density simulation

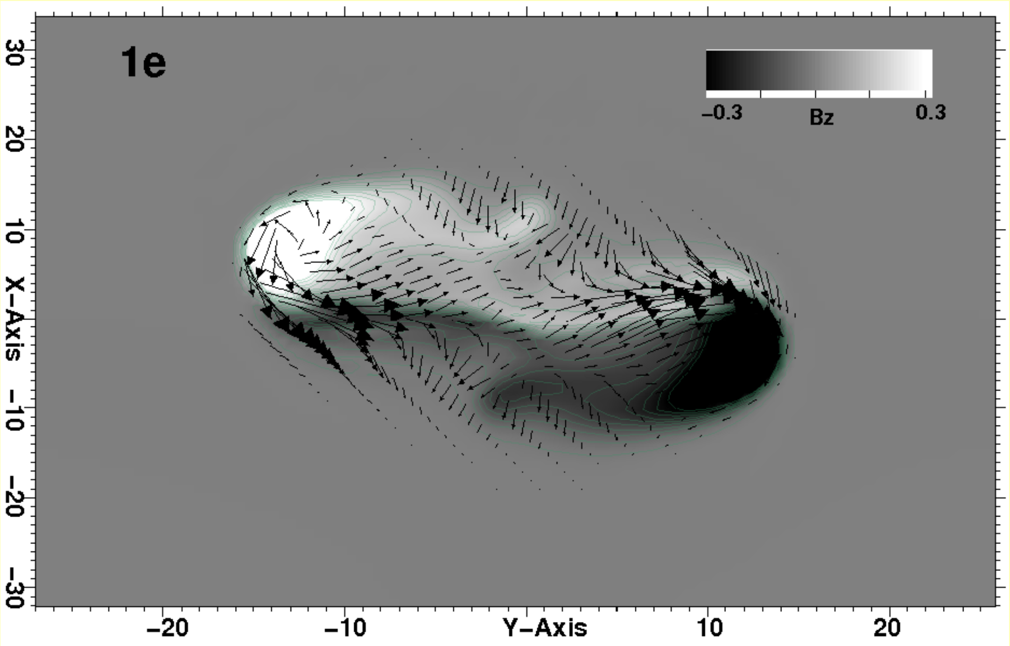
Intensity



Magnetic Tails: Bipoles formed tail structure



What about photospheric shear? Is it observed?



What about flux rope formation and ejection? Multiple events?

Do we see the adiabatic cooling seen in simulations?

Flux Emergence simulations

- Starting to get agreement with some general features.
- BUT questions remain.
- Rotating sunspots. Is it untwisting of interior loop?
- Multiple bipole emergence. How important is this?
- Outflows at edge of active regions. Is this part of solar wind?
- How does emerging field interact with coronal field?
- Importance of eruptions?
- Serpentine field emerging between main spots. How?

3. Coronal Heating

Need photospheric B field: SDO/HMI, Hinode/SOT
Need complete T coverage: SDO/AIA, Hinode/EIS/XST

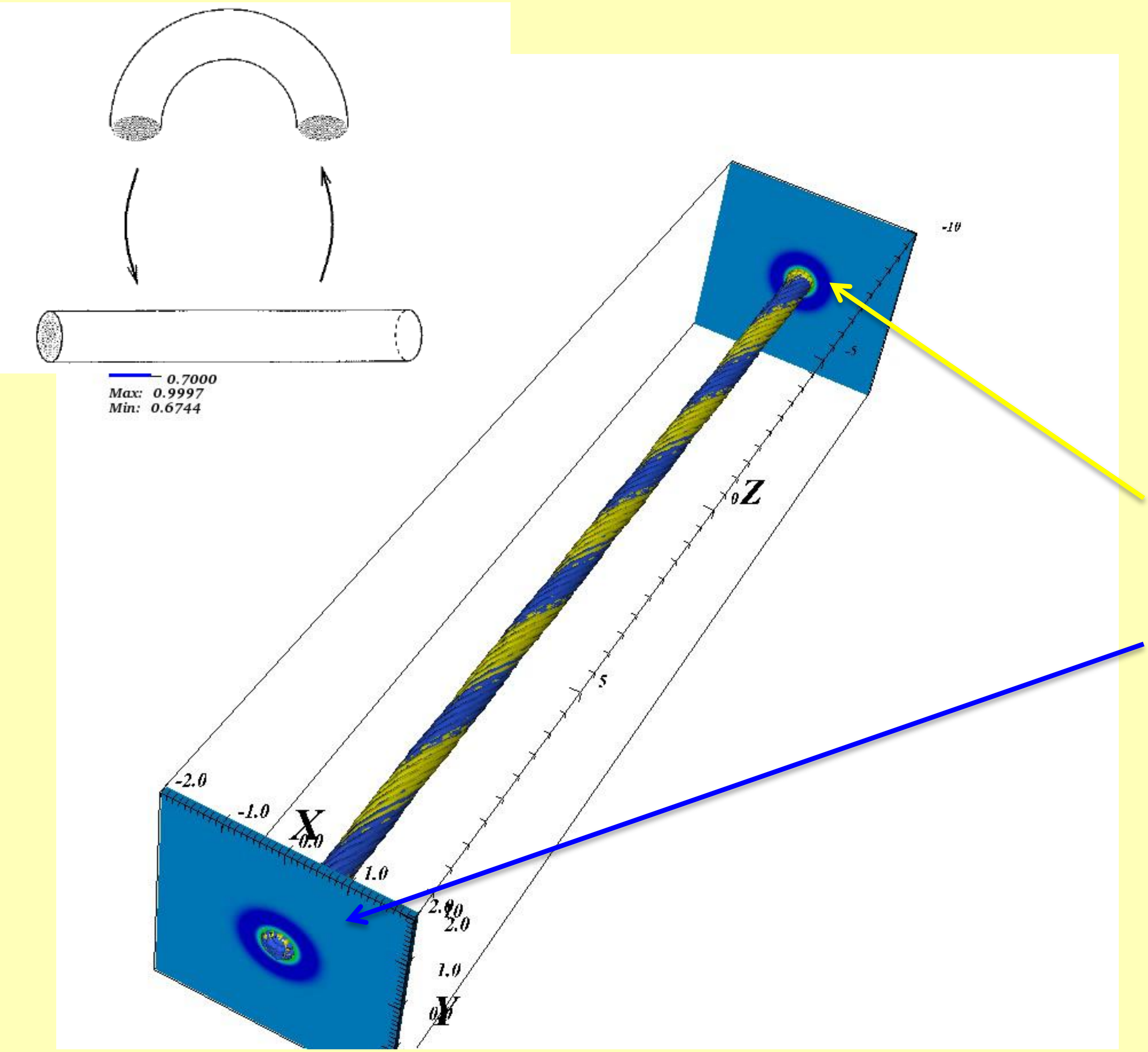
- Old (difficult) problem with some major progress.
- Heating due to magnetic field BUT exactly how?
- Current sheets – how form? – Nanoflares? (Walsh, Cargill)
- Store and release.

a) Smooth motions then instability.
b) Smooth motions but discrete B sources – magnetic carpet.
c) Complex motions – braiding.

- Waves – many observations now.
- Spicules?
- Turbulence?

- Many ideas but do any of them actually work?
- What happens to plasma?

Heating. Store and Release
MHD Instability and Relaxation
(St Andrews, Manchester, Warwick, Dundee)

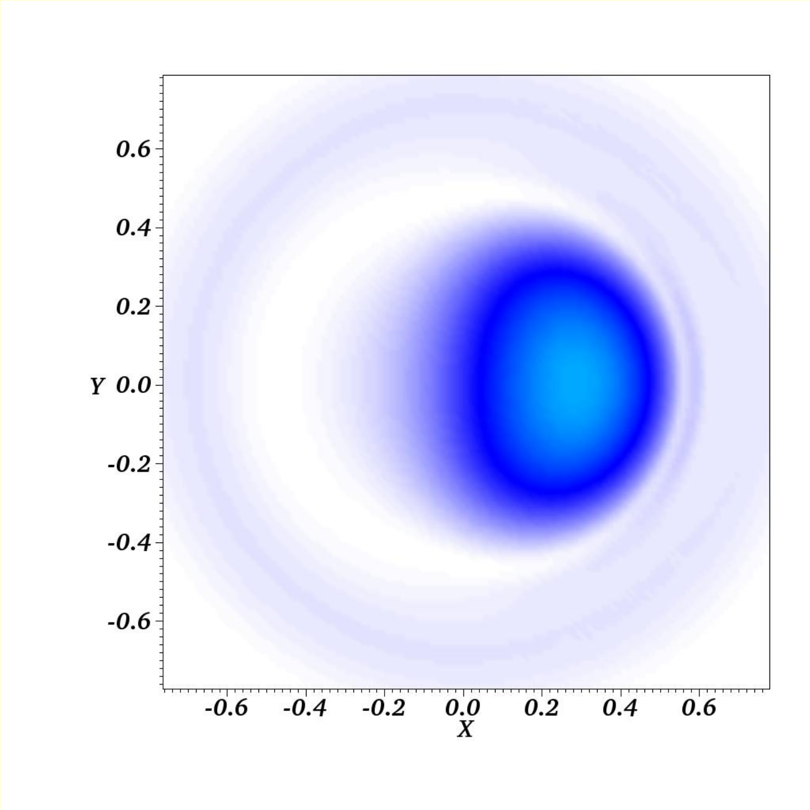


1. Instability creates j sheets
2. Reconnection heats and
3. Relaxes to simpler B.
4. T is more than enough.

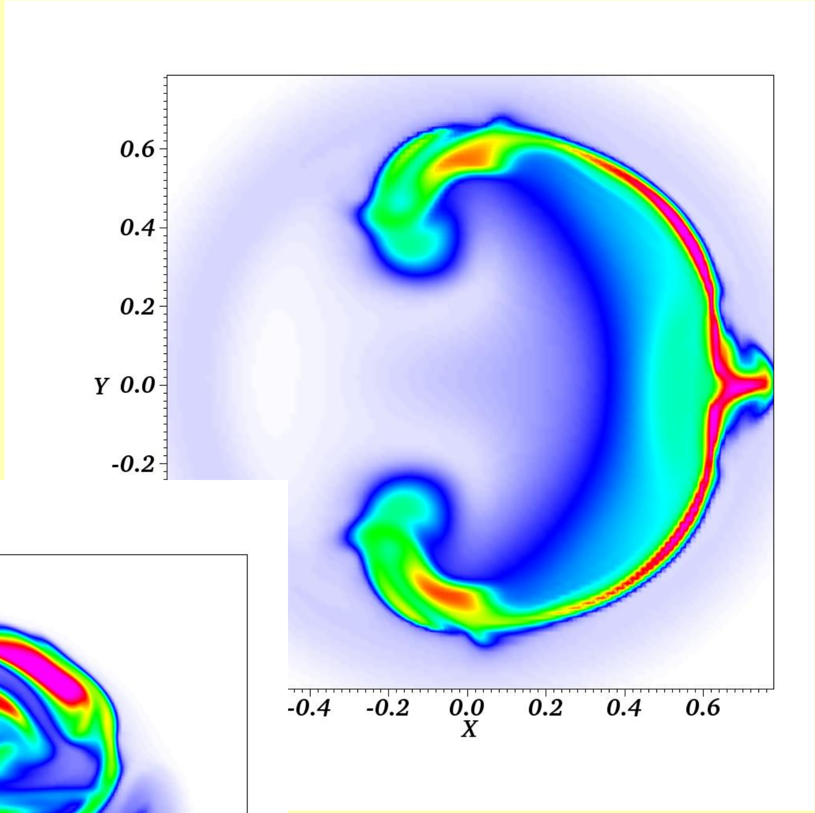
Yellow fieldlines from top axis.
Blue fieldlines from Bottom axis.

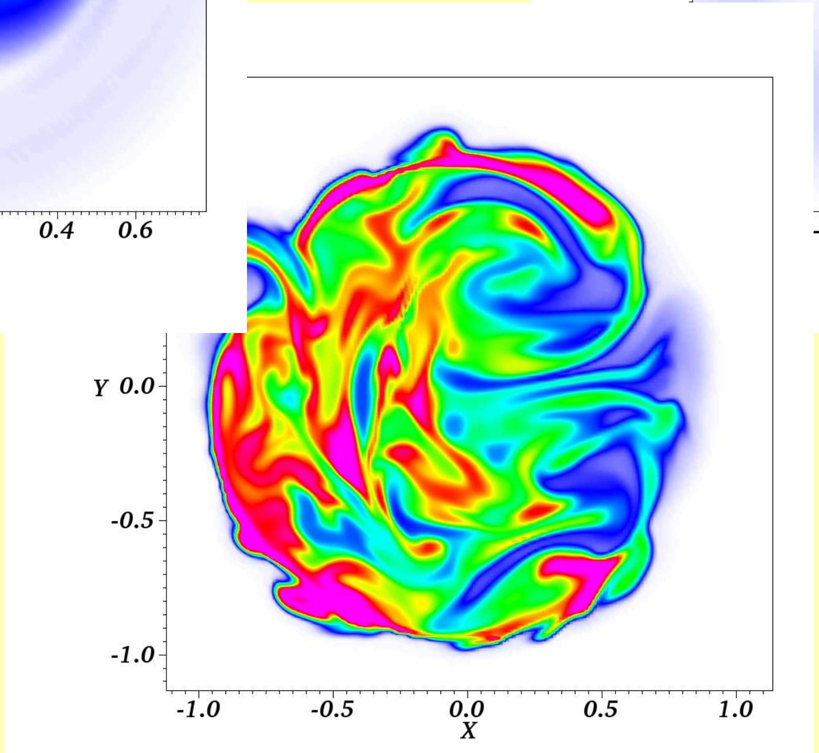
Resulting Temperature

t = 155 sec



t = 240 sec





T(red) = 15 million K
T(blue) = 0.1 million K

t = 400 sec

Heats in 100 secs.
Spreads across loop
Viable mechanism.

(Arber, Bareford, Browning, Hood)

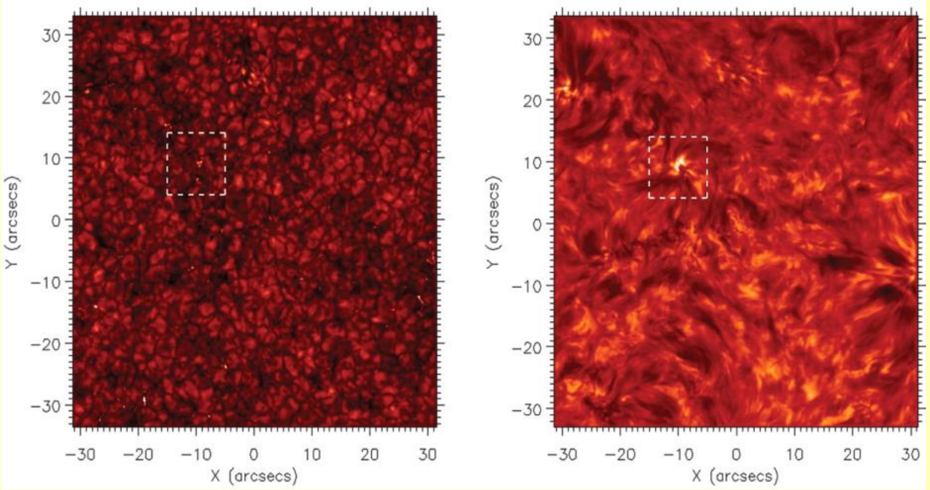
Heating by Waves
MHD Waves in the Solar Atmosphere
(St Andrews, Sheffield, Warwick, Belfast, Aberstywyth)

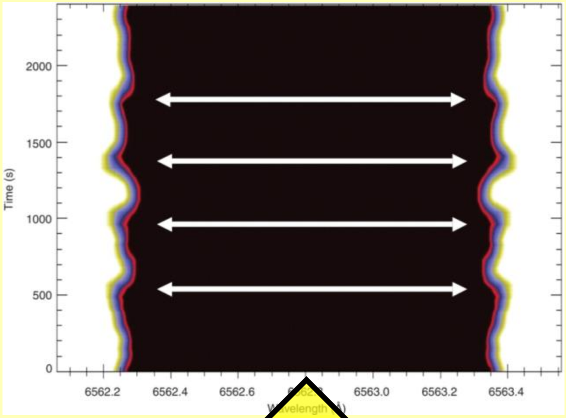
1. Theory developed over 30 years ago.
2. 30 years ago, no observations of waves.
3. Could they heat the corona?
   - Active regions
   - Quiet Sun
   - Coronal holes

Need good time cadence.
SDO – 10 second
COMP – 29 seconds
ROSA (Belfast) – 1 second (or less)

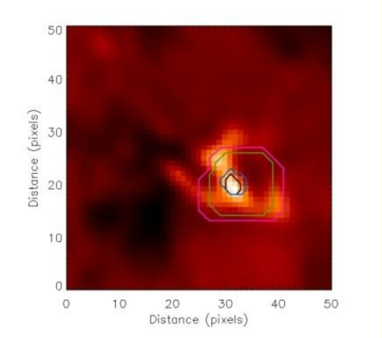
Alfvén(ic) Waves in the Chromosphere

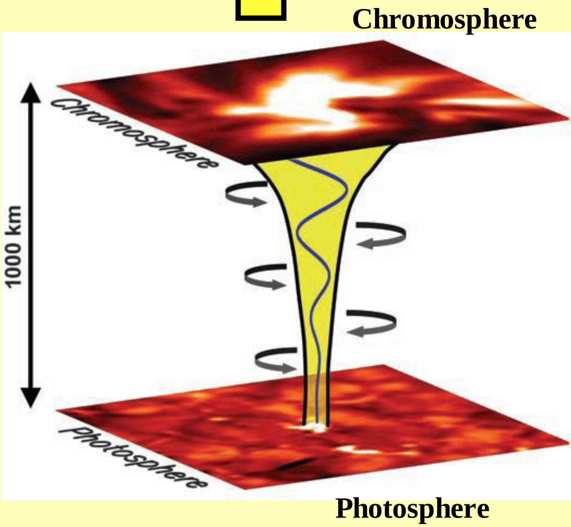
Jess et al (2009)

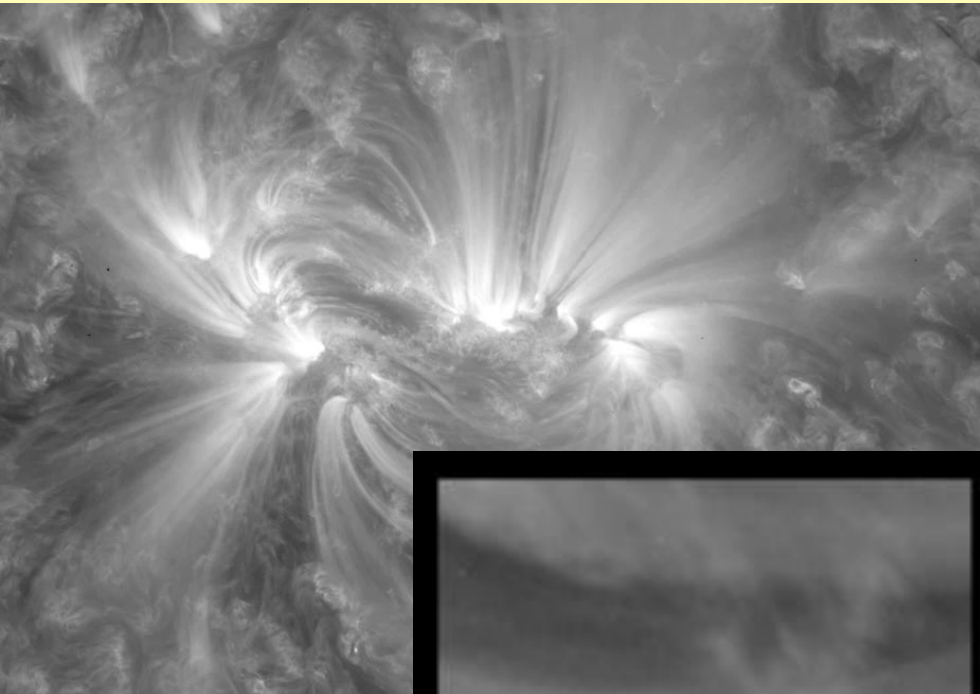




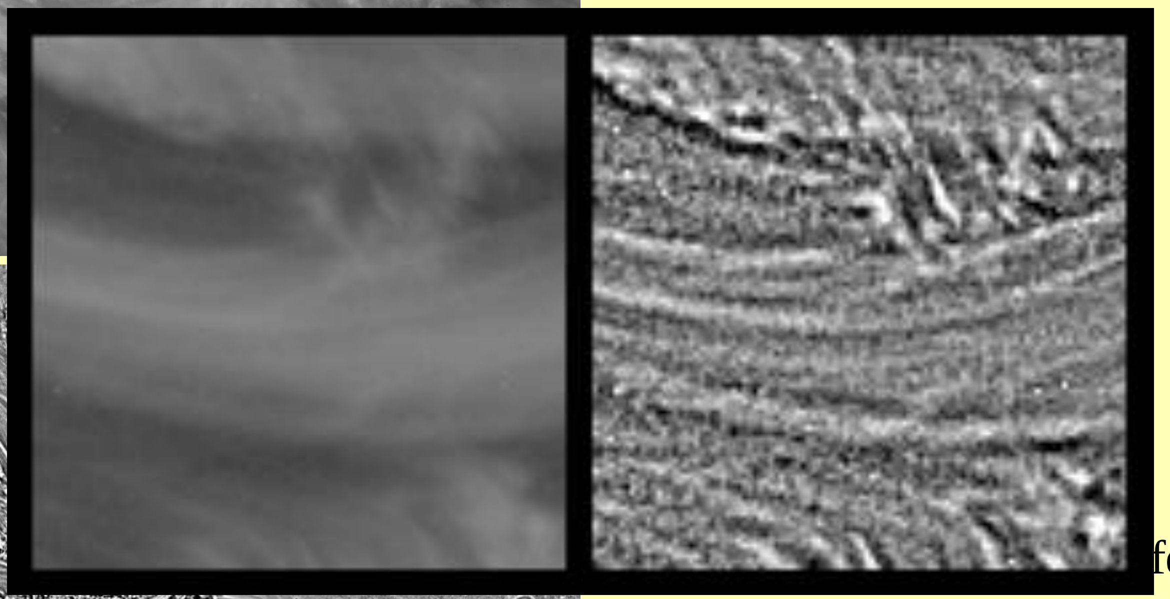
- Chromospheric bright point oscillations (SST)
- Periodic spectral line broadening; no intensity oscillations
  - Interpreted as torsional Alfvén waves
    - Frequency as a function of radius resolved
    - Chromospheric energy flux ~ 15,000 W m^{-2}
    - 1.6% of surface covered in Bright Points
      - Global average ~ 240 W m^{-2}
    - Transmission coefficient ~ 42%
      - Coronal energy flux ~ 100 W m^{-2}

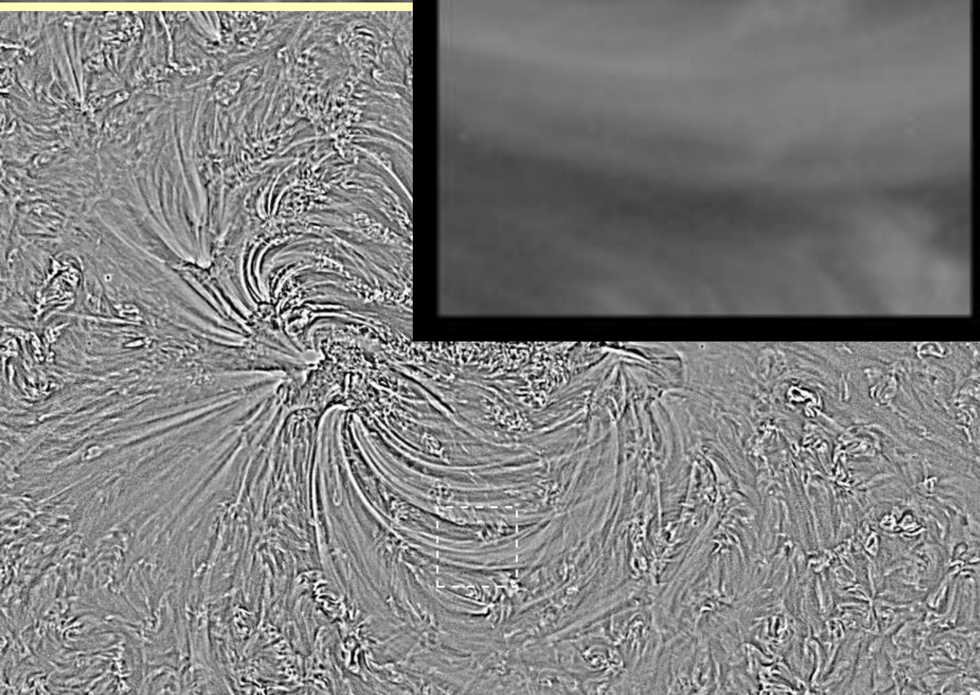






Active region – Intensity (171?)





ference

Expand up the dashed square region !!

Waves are everywhere!!

1. Significant energy in observed waves.
2. Enough to heat?
   Yes, if we can damp them quickly.
3. How do they dissipate/damp?
   Phase mixing. (St Andrews)
   Resonant absorption. (Sheffield)
   Null points. (Northumbria)
4. How does the plasma respond to the heating?
   Only just starting.

4. Coronal Mass Ejections and Eruptions (St Andrews, MSSL)

(STEREO, SoHO/Lasco, SDO)

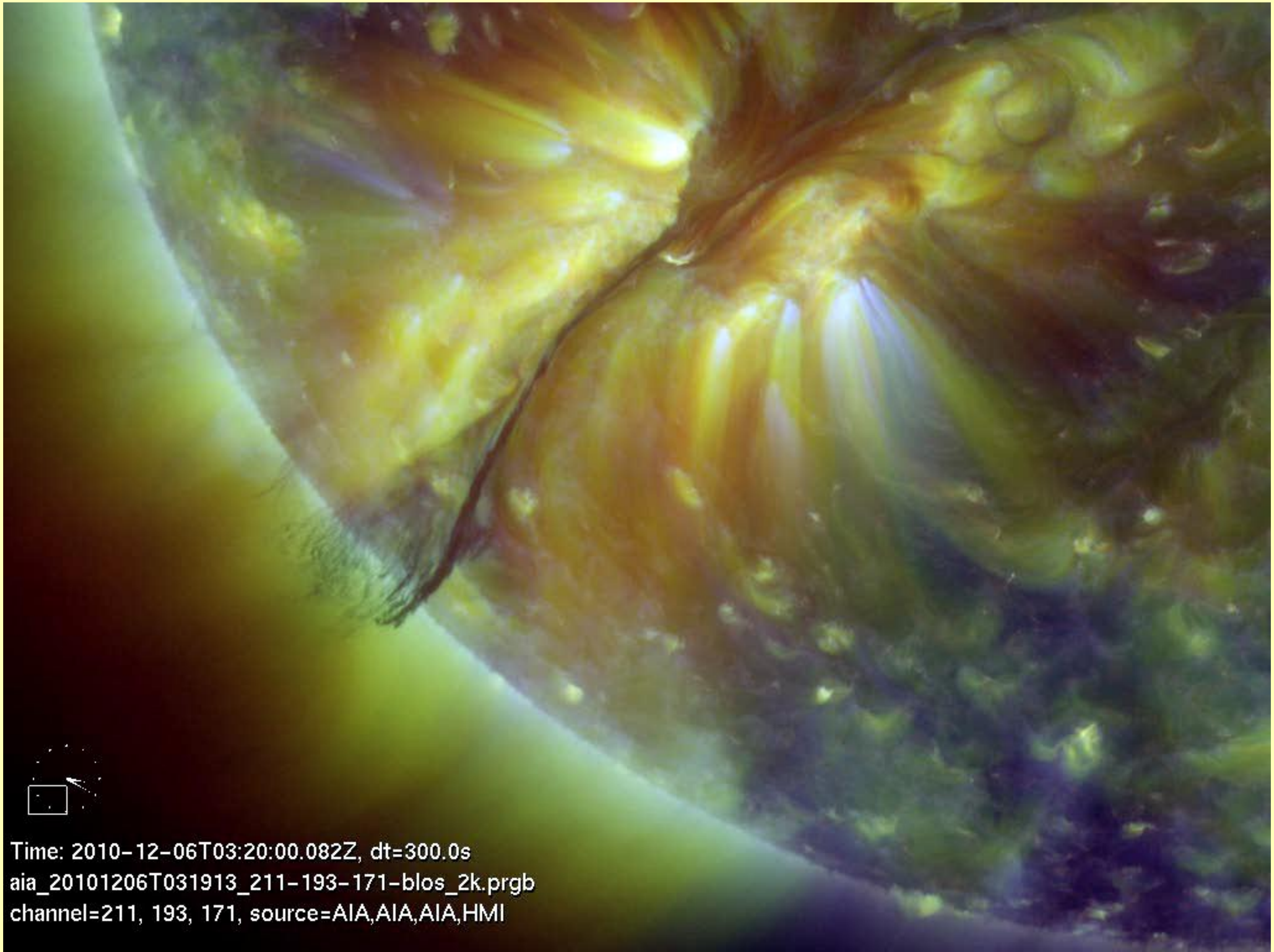
Two types of eruption

1. Quiescent prominences (large CMEs, away from sunspots)
2. Active region (higher frequency, flare related)

Model by

1. Global coronal field modelling (months)
   - Requires slow build up of non-potential B.
   - Sequences of force-free equilibria.
2. Emergence and active region interactions (day)
   - New flux, active region shearing.
   - Dynamic.

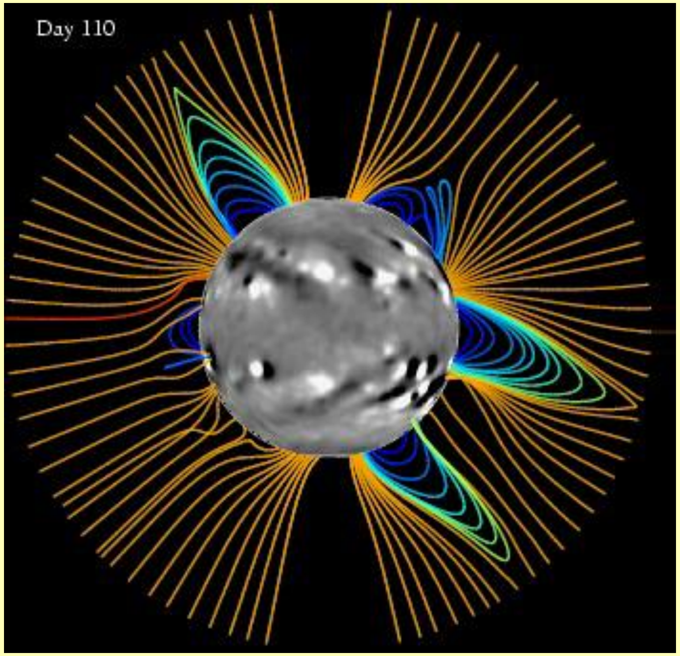
Prominence eruption: 171 – 193 - 211

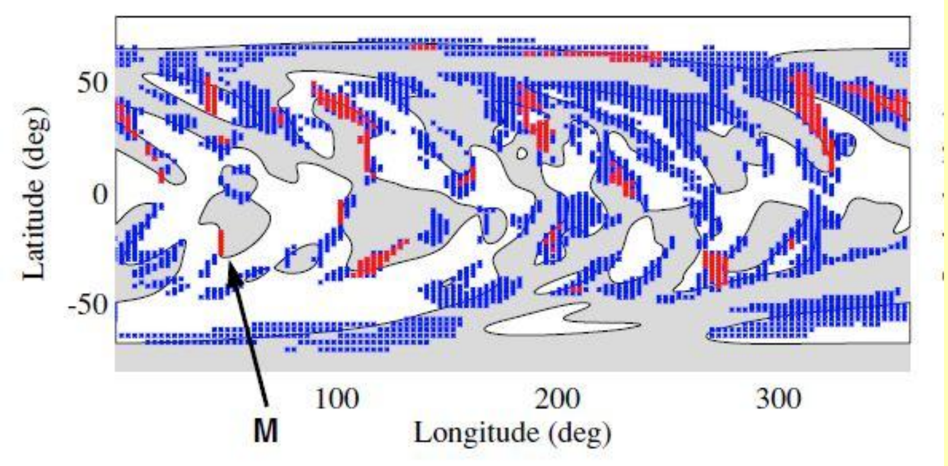


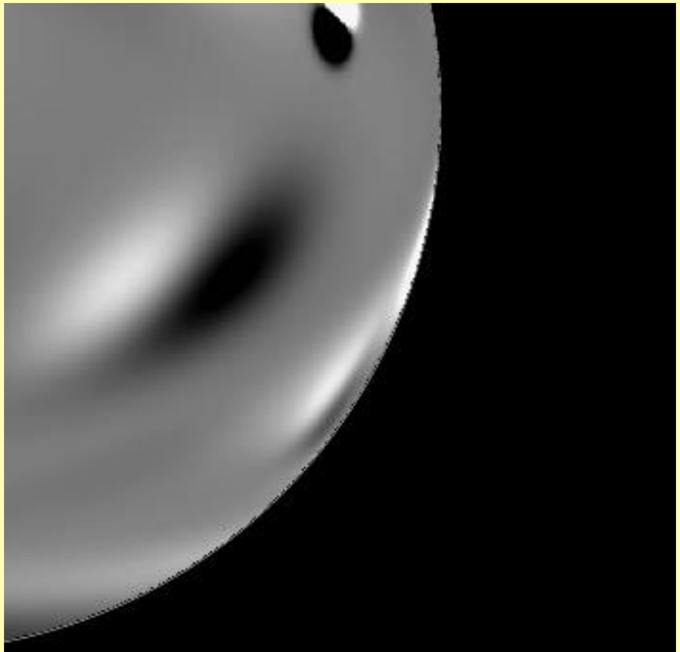
Global Non-Potential Model (Mackay, Yeates)

- Long Term simulations (months ~ years).
  - Build up free magnetic energy
- Retains memory of B interactions and J build up
- Formation of filaments/ejection of flux ropes.

6 month: May-Aug 1999







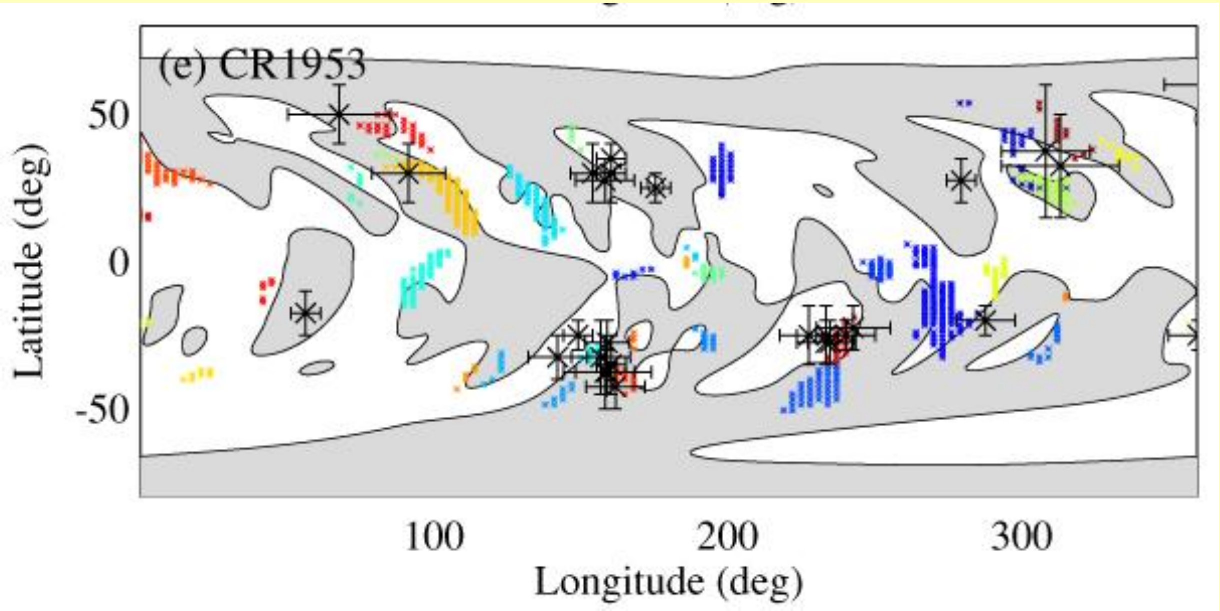
Blue stable ropes, red ejections.

Mackay et al. 2000,2006a,b
Yeates et al. 2007, 2008a,b, 2009a,b.

Comparison with Observations !

- Yeates et al. 2010: comparison of flux rope ejections and CME source locations from EIT EUV events.

4.5 months : 330 CMEs (Lasco), only 98 identified in EIT 195 Å events.



Comparison problematic.

Outcome : +ve correlation 0.49

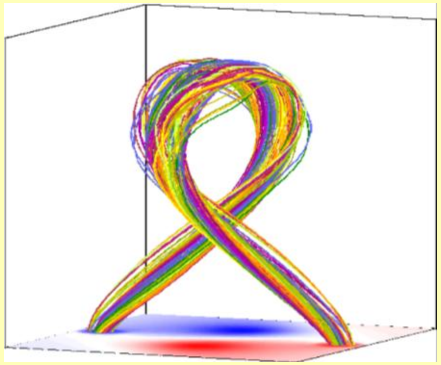
- Fits with the two types of CMEs:

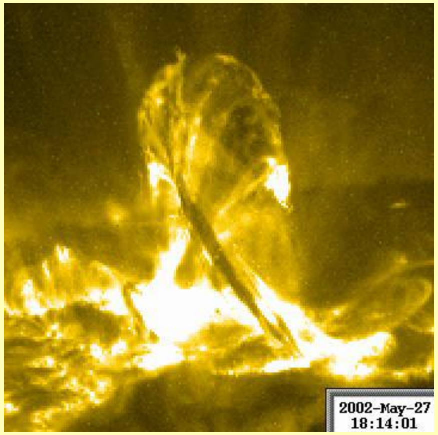
- Multiple CME mechanisms operate on different time/spatial scales.

5. Flares and Particle Acceleration

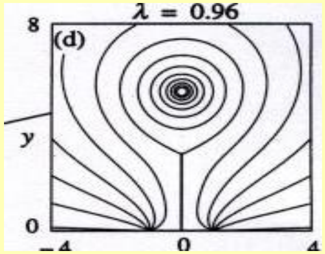
- Used to focus on how to release the energy on the timescale needed.
- Initial energy release must involve reconnection but need it to be fast enough. Ideal MHD timescales.

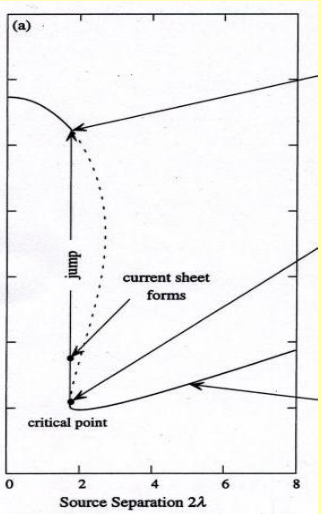
Kink instability
[Kliem,Torok, Hood]



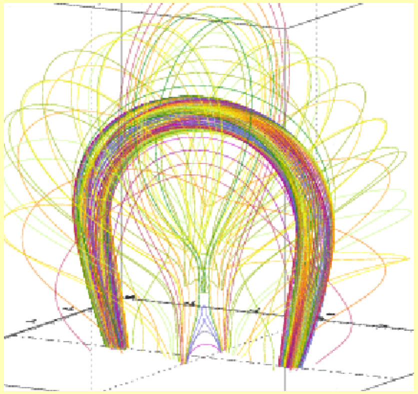


Nonequilibrium
Catastrophe
[Forbes, Priest]

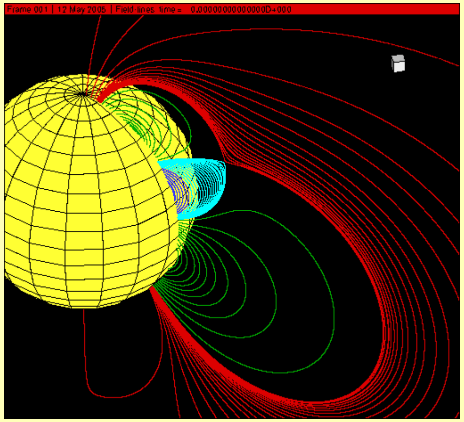




Torus
Instability
[Kliem, Torok]

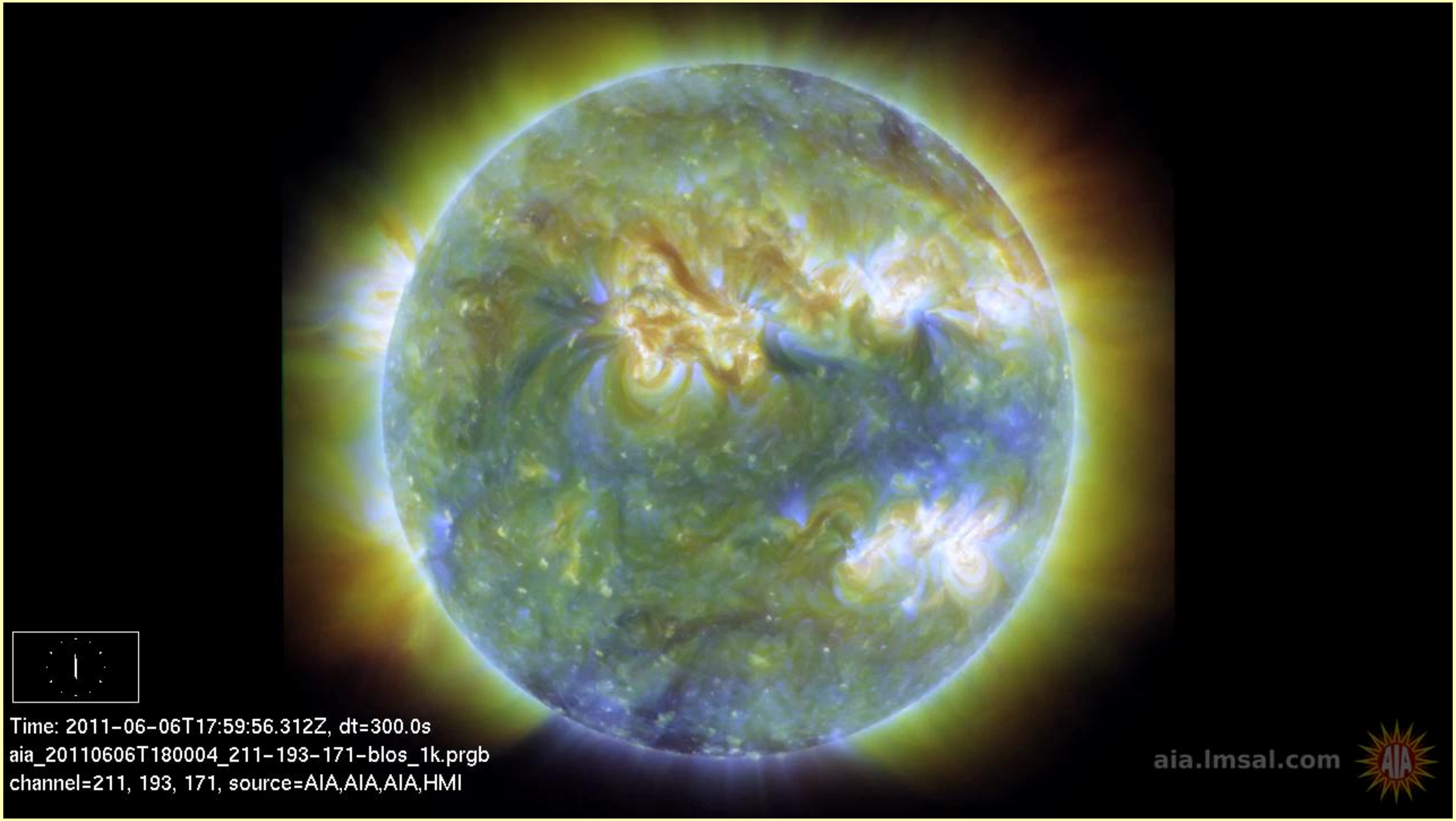


Breakout
(Antiochos)



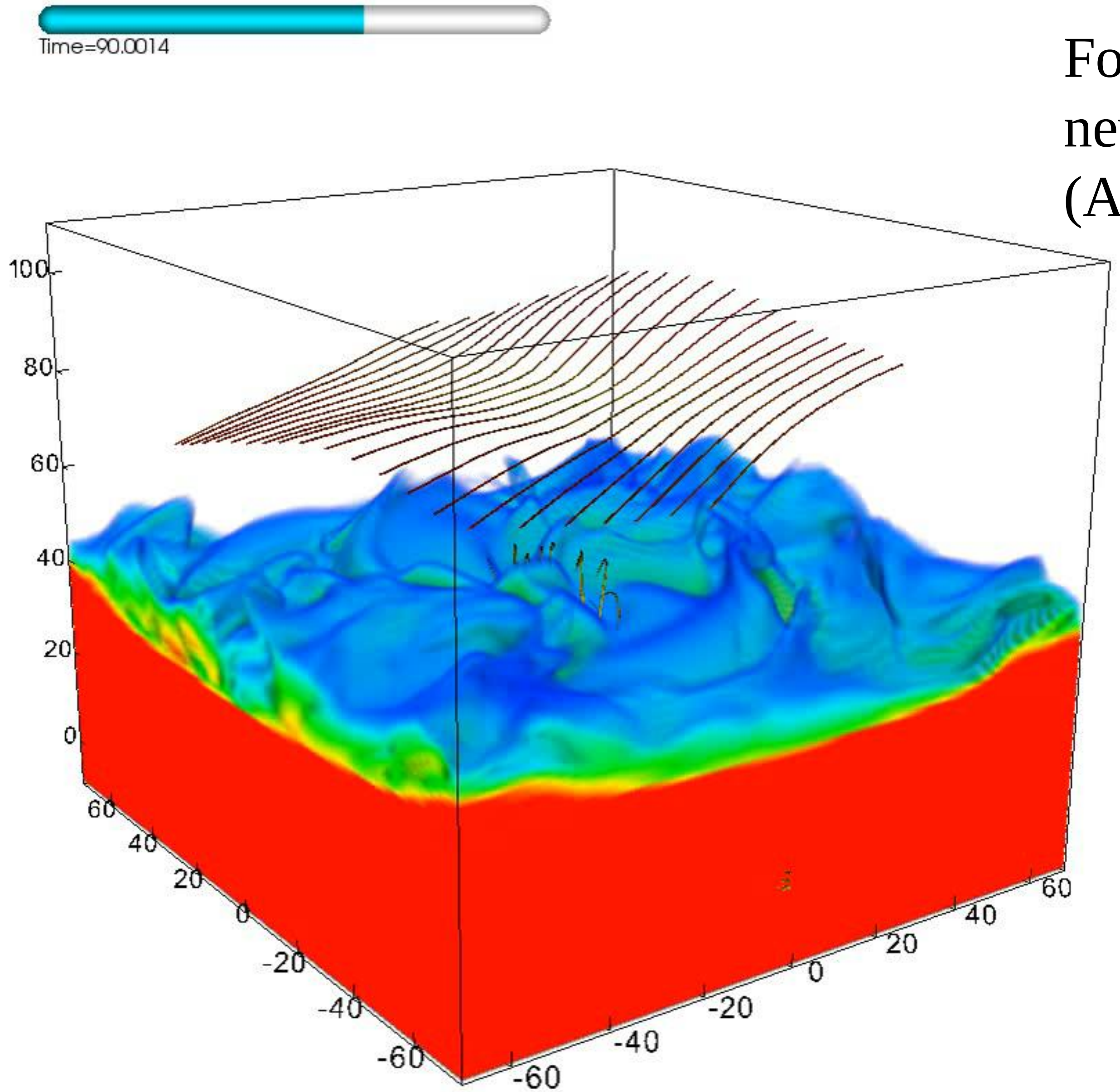
SDO – X Flare on June 2011

171, 193, 211 combined. Covers 0.6 – 1.2 million K



Eruptions from evolving Active regions.
Several flares/eruptions from lower active region.

Density and Magnetic Field Lines

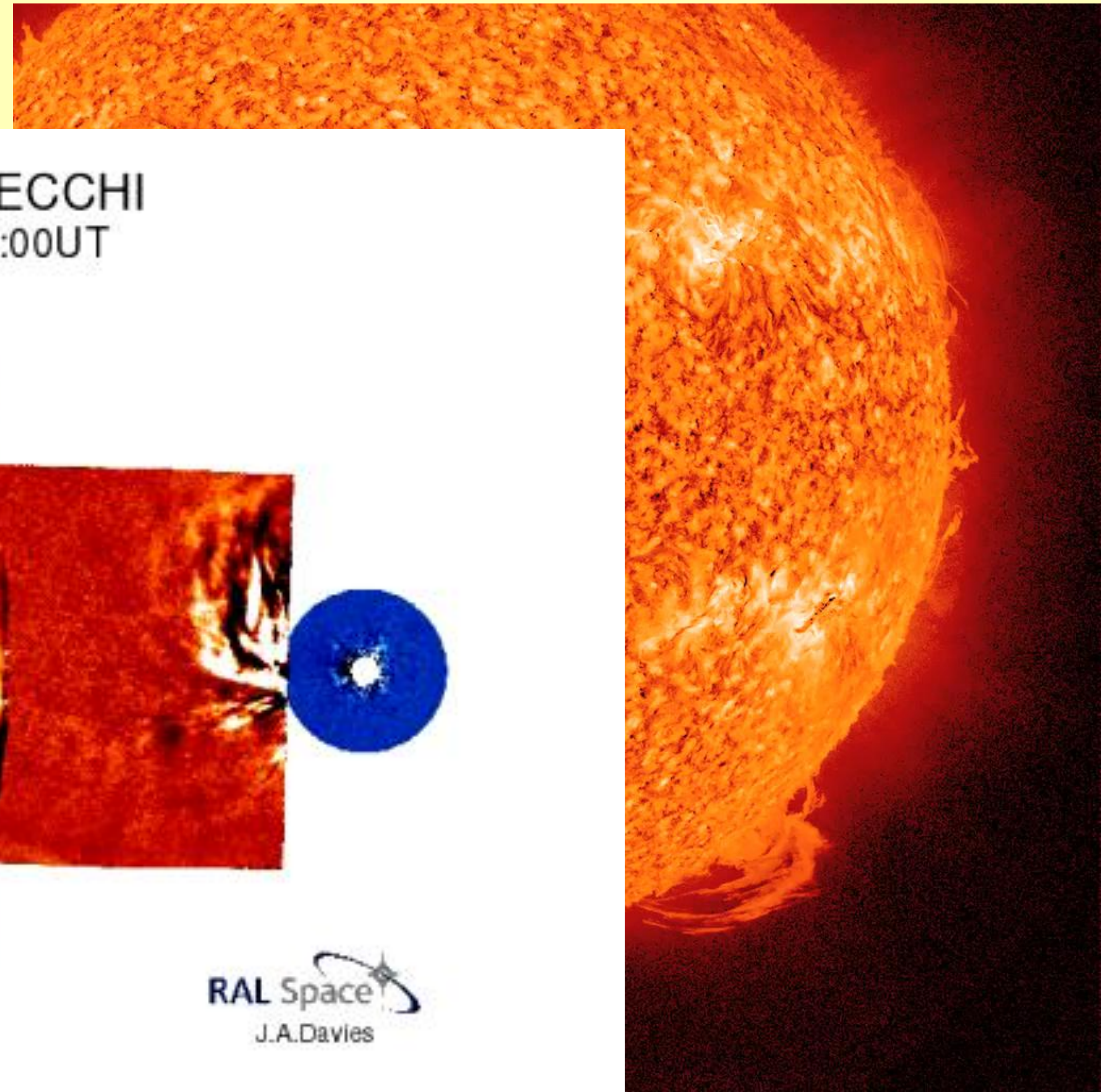


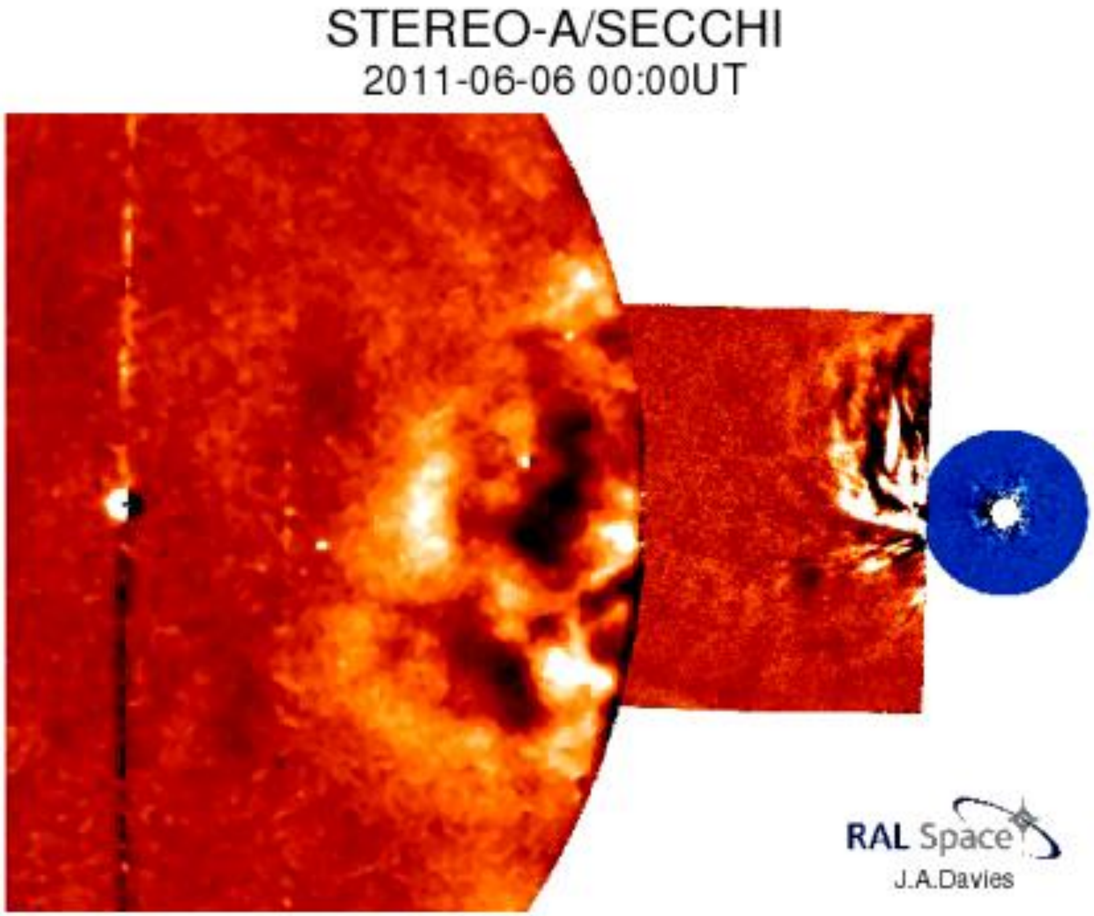
Formation of new active region (Archontis)

Eruption needs coronal B

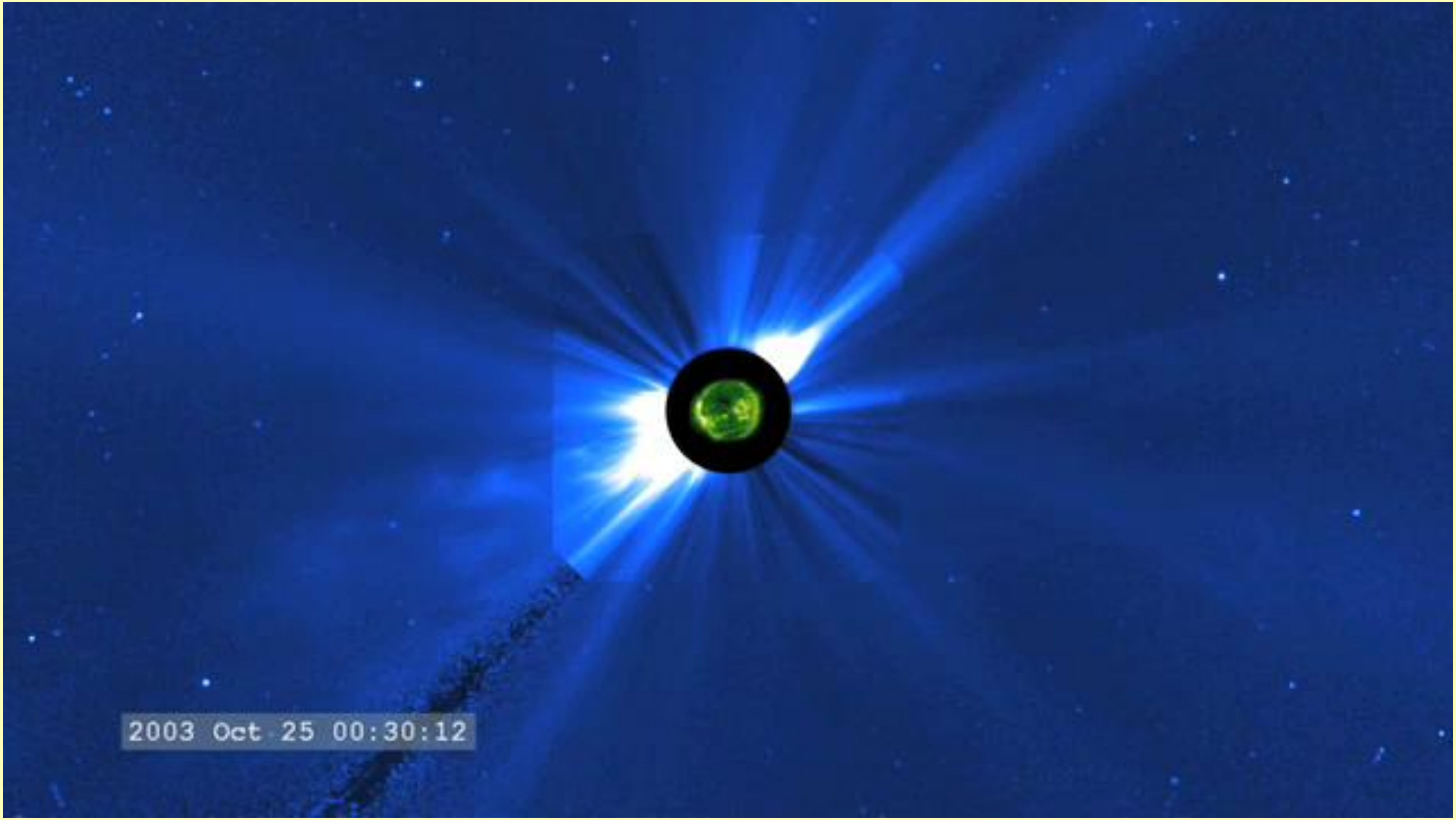
SDO and STEREO

(June 2011, X class flare)

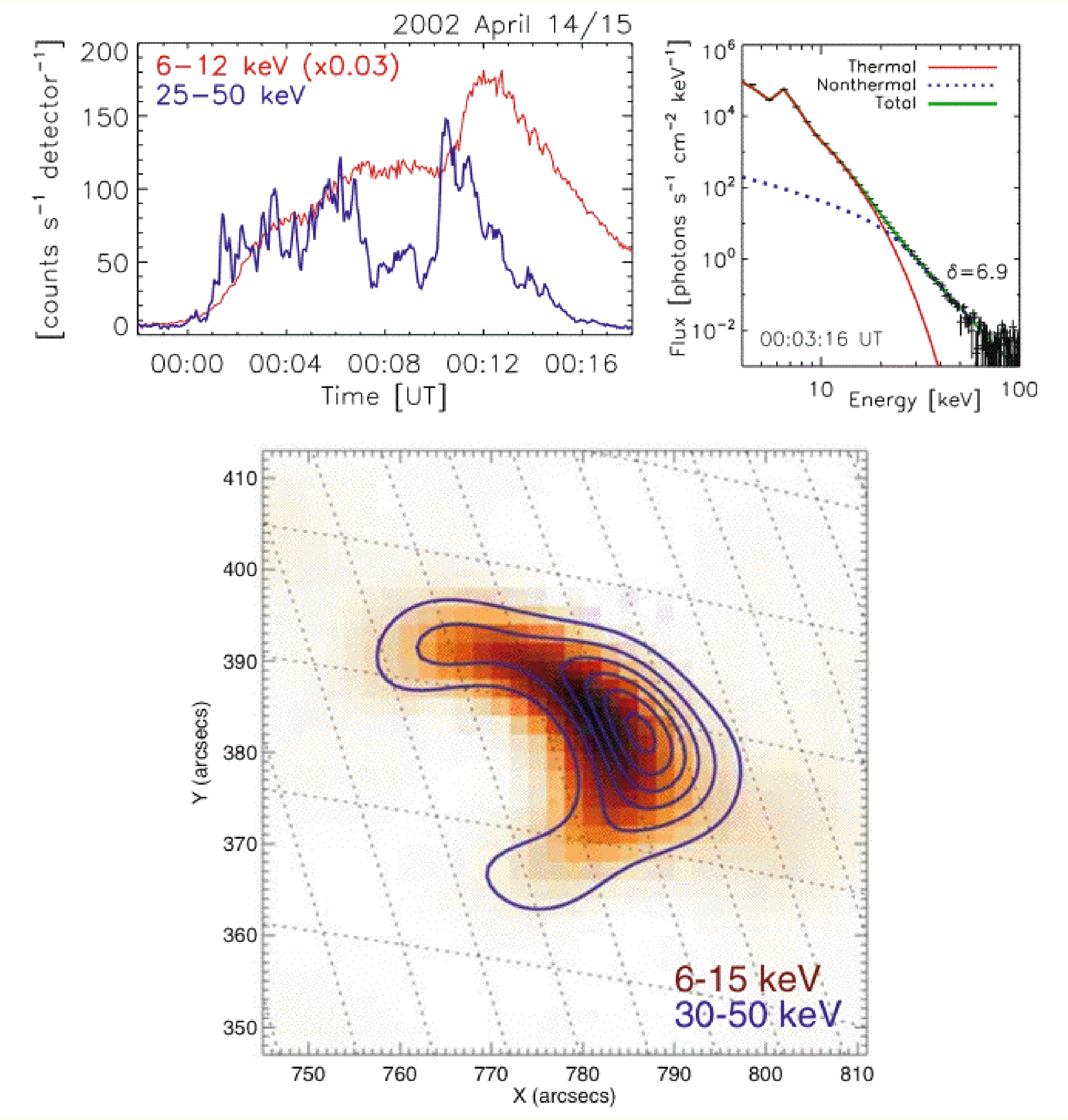




STEREO – Coronagraph
CMEs



RHESSI: Flare (Fletcher, Hudson, MacKinnon)



Hard X-ray emission during flares, normally from footpoints. Here around loop summit.

Electrons at 10 keV would correspond to T = 10^8K.

Evidence of significant particle acceleration.

50% of released energy goes into particle acceleration.

Too many electrons needed.

Major problem to explain.

Conclusions

1. Helioseismology – major success, more to come.
2. Dynamo – tachocline important, at least 2 scales?
3. Photospheric field – why so fragmented in Quiet Sun?
4. Active regions – formation through emergence and interactions
5. Heating – not just either nanoflares or waves – both likely.
6. Eruptions – long term storage, short term storage.
7. Flares – timescale for energy release/particle acceleration.