Our Dynamic Sun

by Eric Priest (St Andrews)

Hannes Alfvén Medal Lecture (April 25, 2017)

0. INTRODUCTION Our Sun

Object of beauty

- Central to existence of **life**

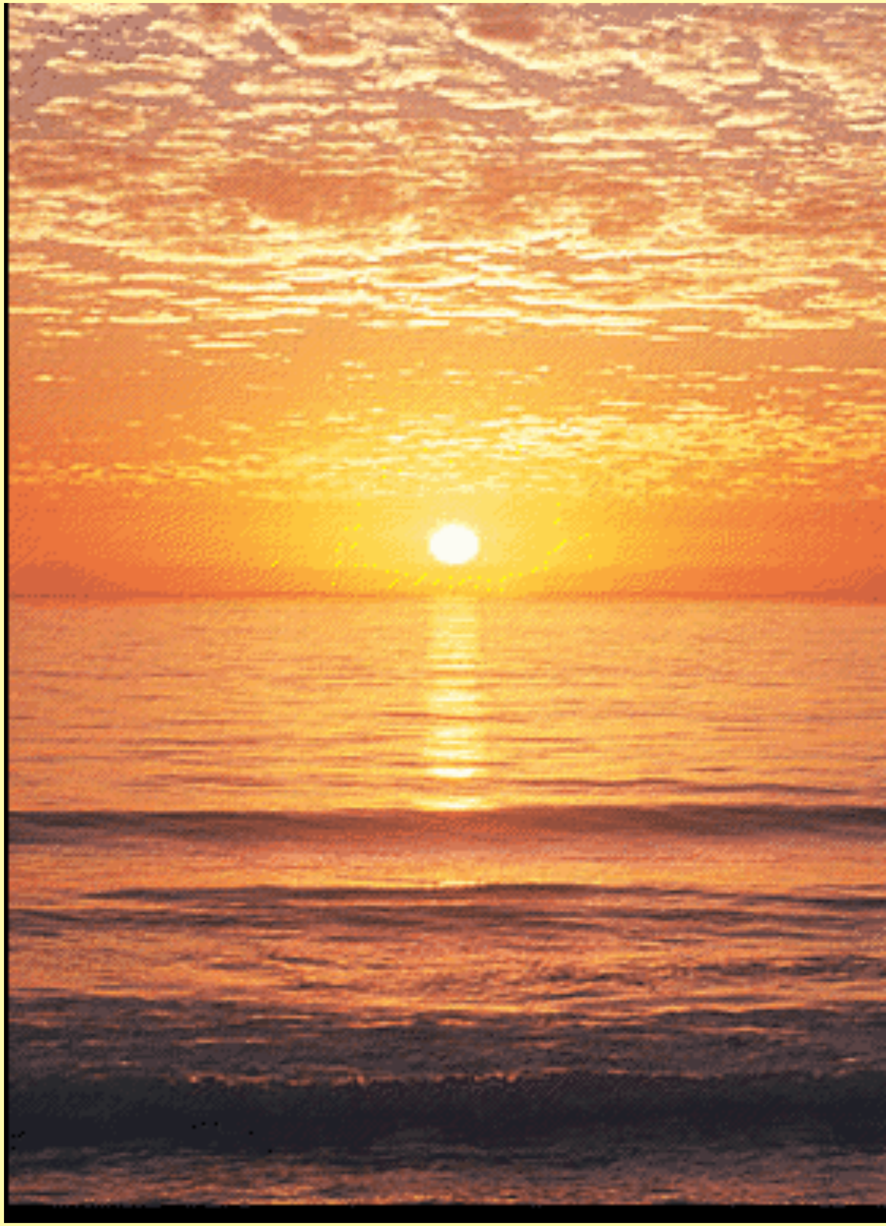
-- > climate, space weather

[Haberreiter, Pulkkinen.....]

- Key for **astronomy**

-- fund[l] cosmic processes

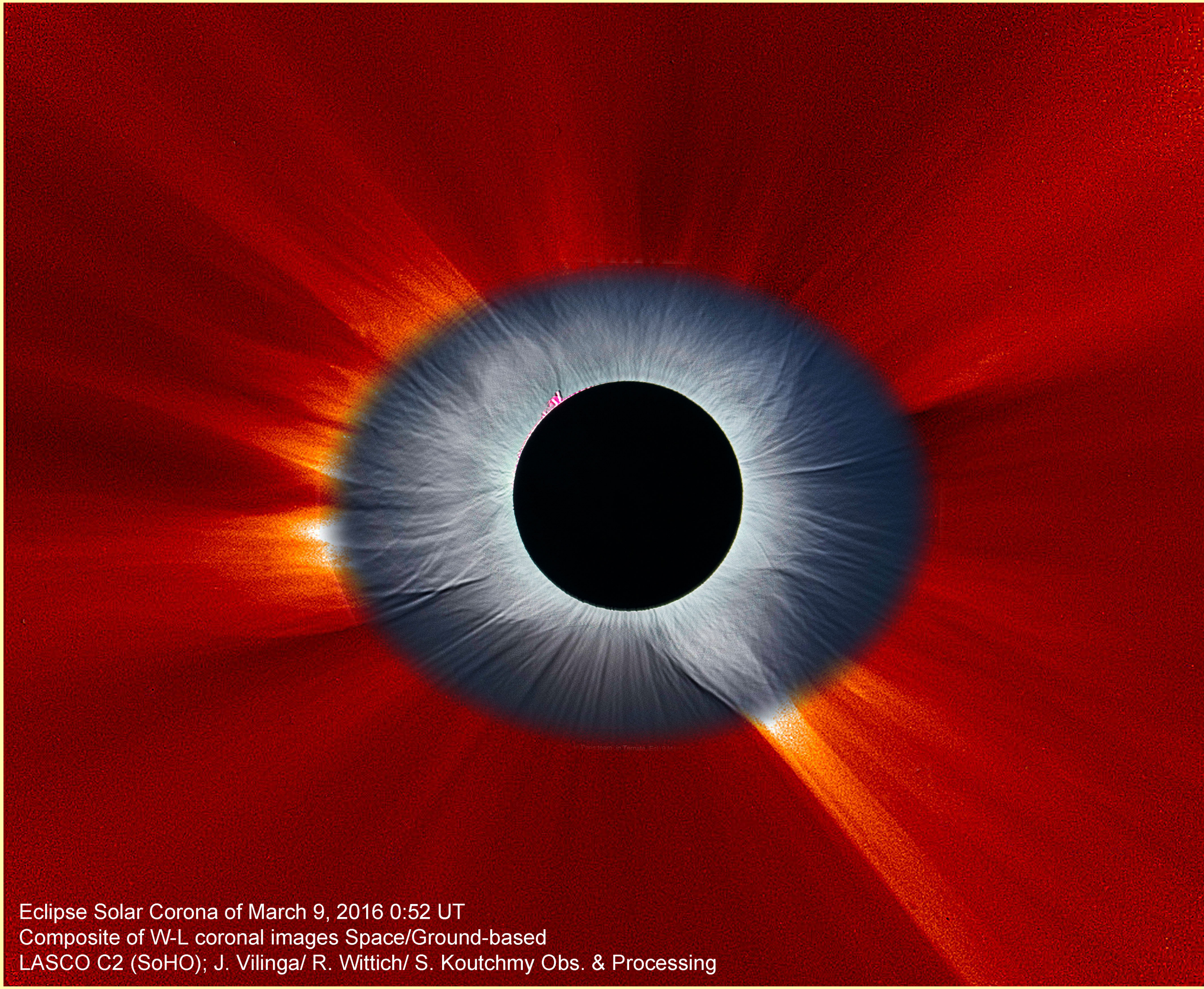
But basic properties mystery



These properties caused by magnetic field

Sun is **plasma** rather than normal gas,

so **coupled** (intimate, subtle way) **to magnetic field**



Interaction Plasma/Mag^c Field:

Equations of Magnetohydrodynamics (MHD)

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B}$$

equation of motion

$$\mathbf{j} = \nabla \times \mathbf{B}/\mu$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

induction equation

$$\eta = \frac{1}{\mu \sigma}$$

magnetic diffusivity

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho\ \mathbf{v}) = 0$$

mass continuity

$$p = R \rho T$$

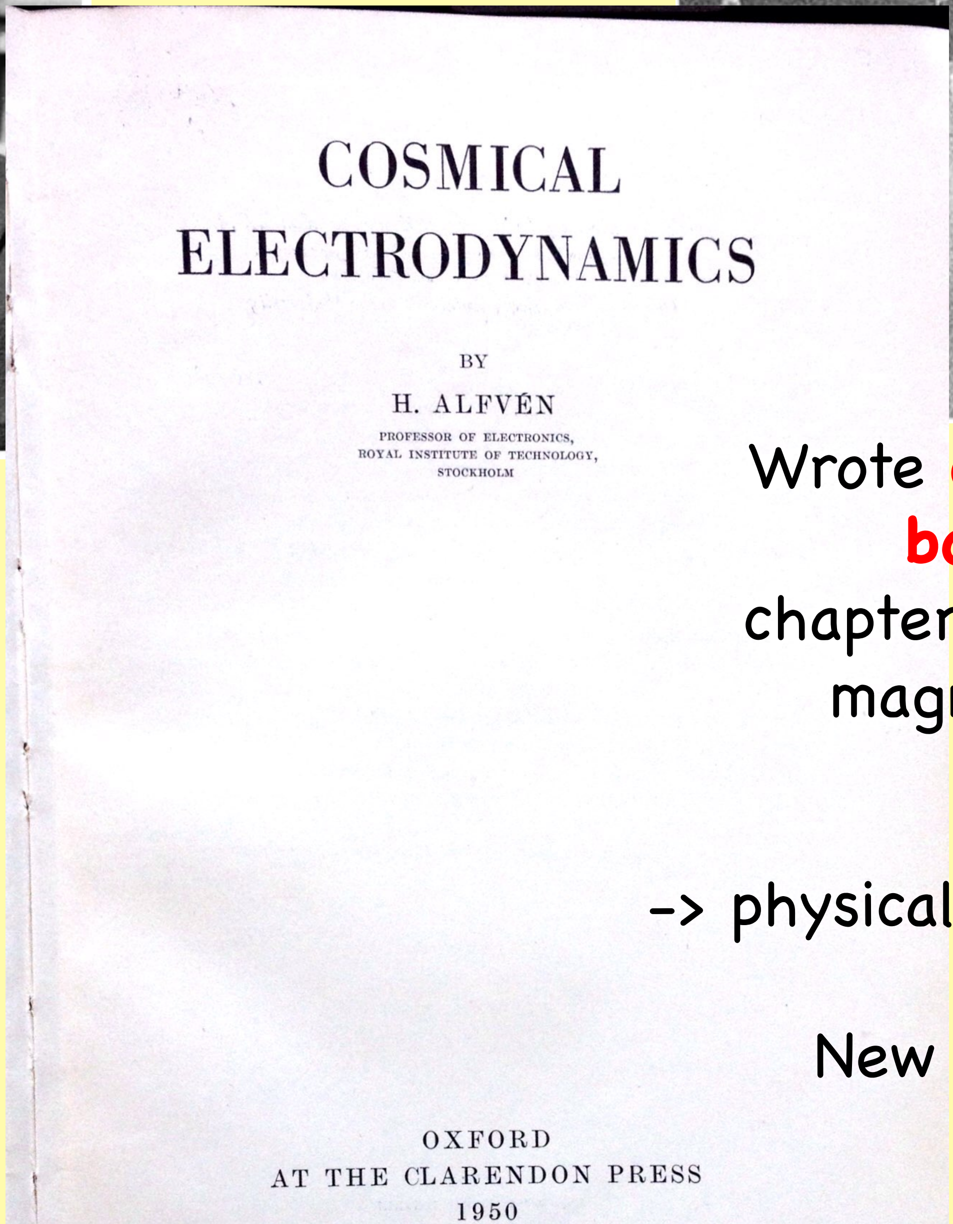
perfect gas Law

$$\frac{d}{dt}\left(\frac{p}{\rho^{\gamma}}\right) = \frac{j^2}{\sigma} + conduction + radiation + heating$$

energy equation

Beautiful!

Alfvén



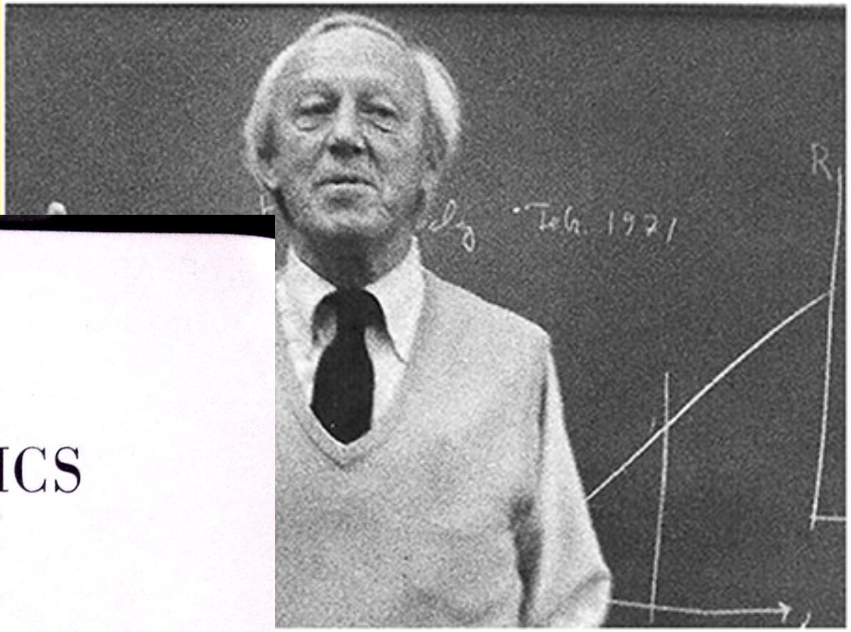
COSMICAL
ELECTRODYNAMICS

BY

H. ALFVÉN

PROFESSOR OF ELECTRONICS,
ROYAL INSTITUTE OF TECHNOLOGY,
STOCKHOLM

OXFORD
AT THE CLARENDON PRESS
1950



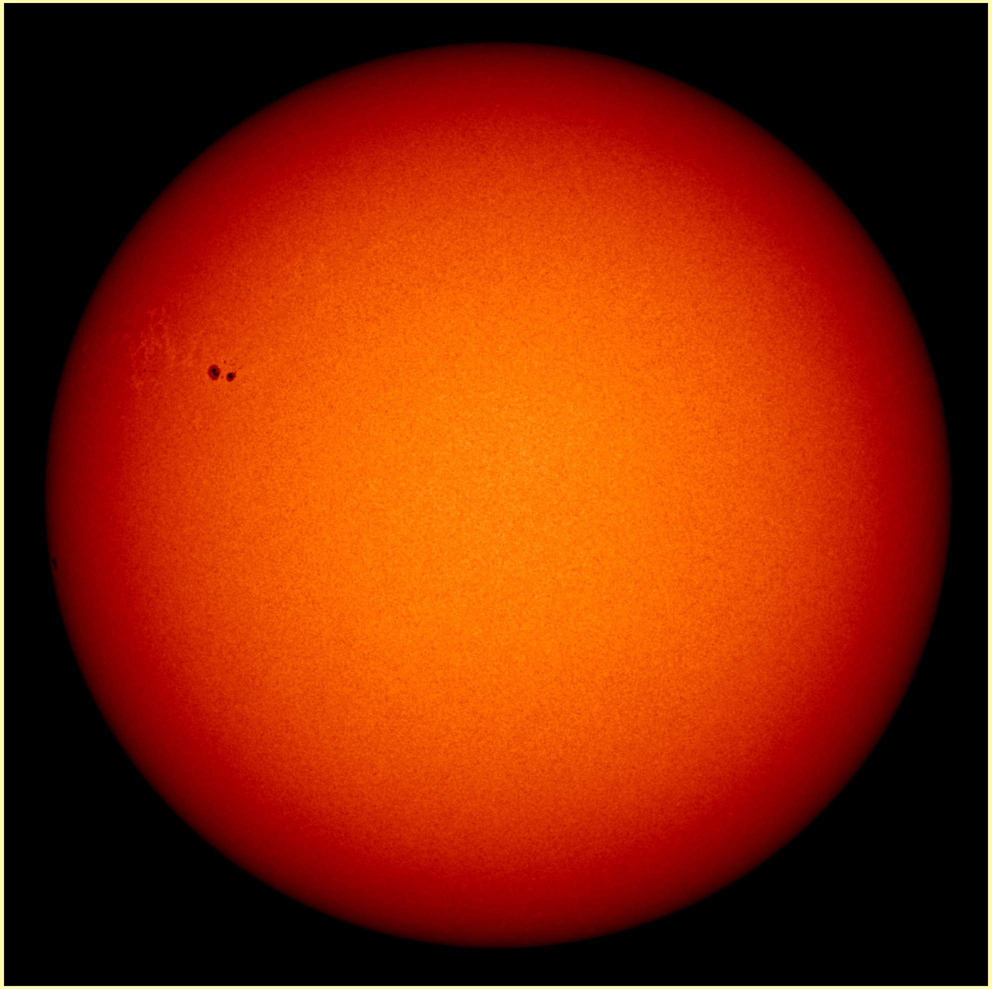
Early **pioneer** using MHD ideas (frozen flux, MHD waves)

Wrote **ground-breaking book (1950) -** chapters on solar physics, magnetic storms & aurorae

-> physical insight from obs^{ns}

New obs^{ns} revolutionised understanding

THE SUN

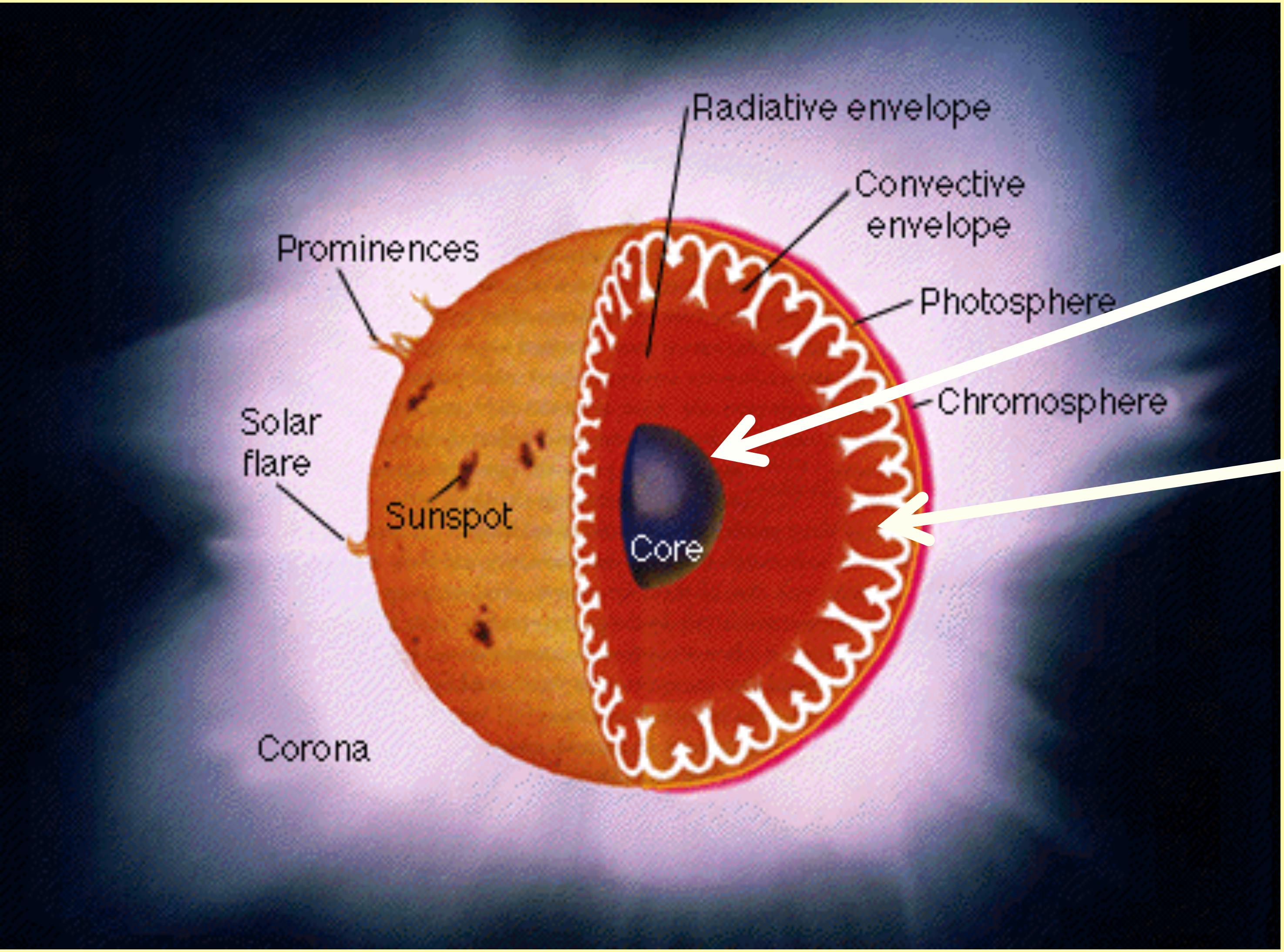


[from Solar Dynamics Observatory (SDO)]

Ball of plasma held together by gravity

radius – **700 Mm** (earth 6 Mm)

Overall Structure



Interior:

Core

Convection zone ($> 0.7\ R_0$)

Atmosphere: Photosphere, Chromosphere (10^4K), Corona (10^6K)

Share excitement of solar physics –

overview of progress from theory & observations since Alfven's Nobel Prize (1970)

1. Solar Interior
2. Photosphere
3. Chromosphere & Transition Region
4. Prominences
5. Coronal Heating
6. Solar Wind
7. Solar Flares & Coronal Mass Ejections

1. The Interior

1970:

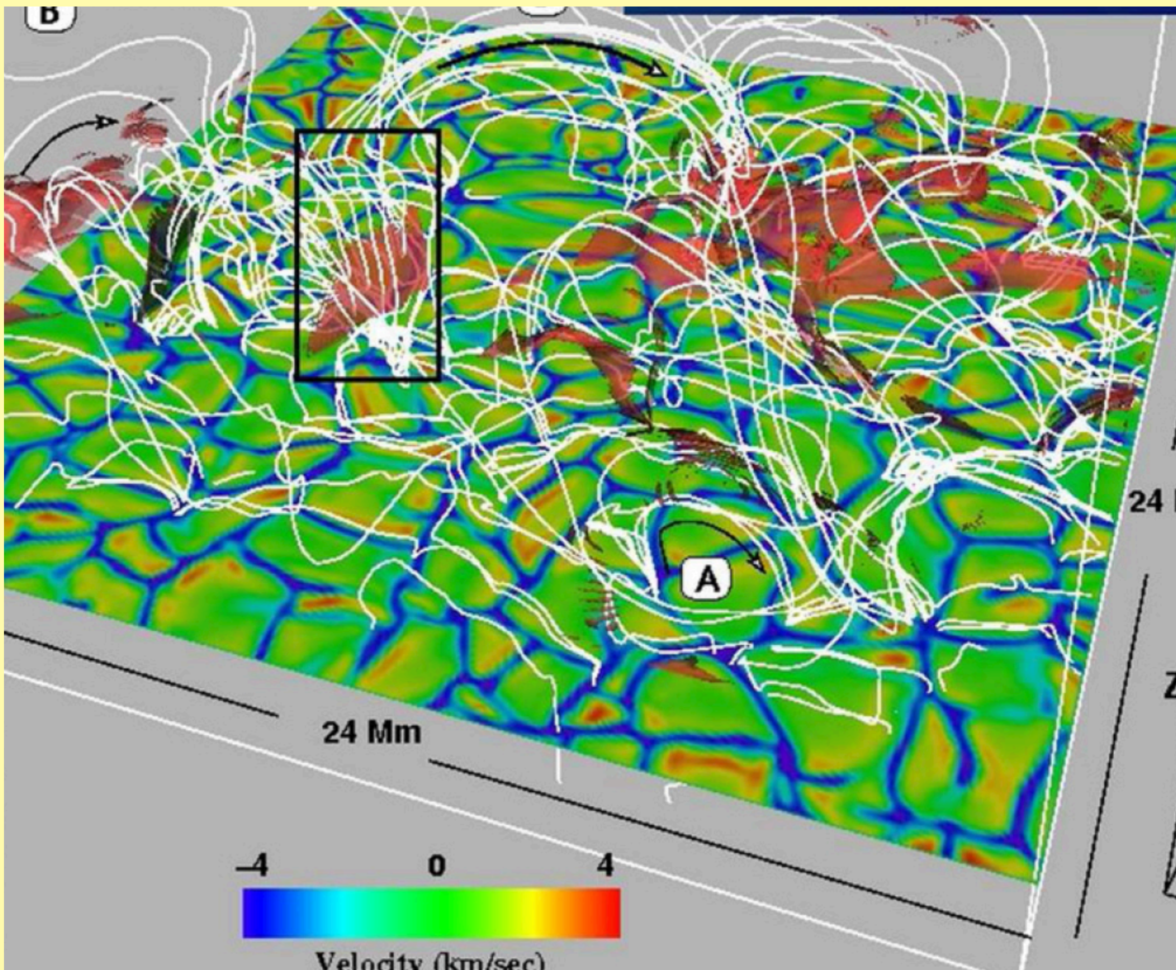
Internal T(r) – based on theory

B of sunspots – Alfvén: MHD waves generated in the core as magnetic rings

Now:

generated by **dynamo,** rise by magnetic buoyancy

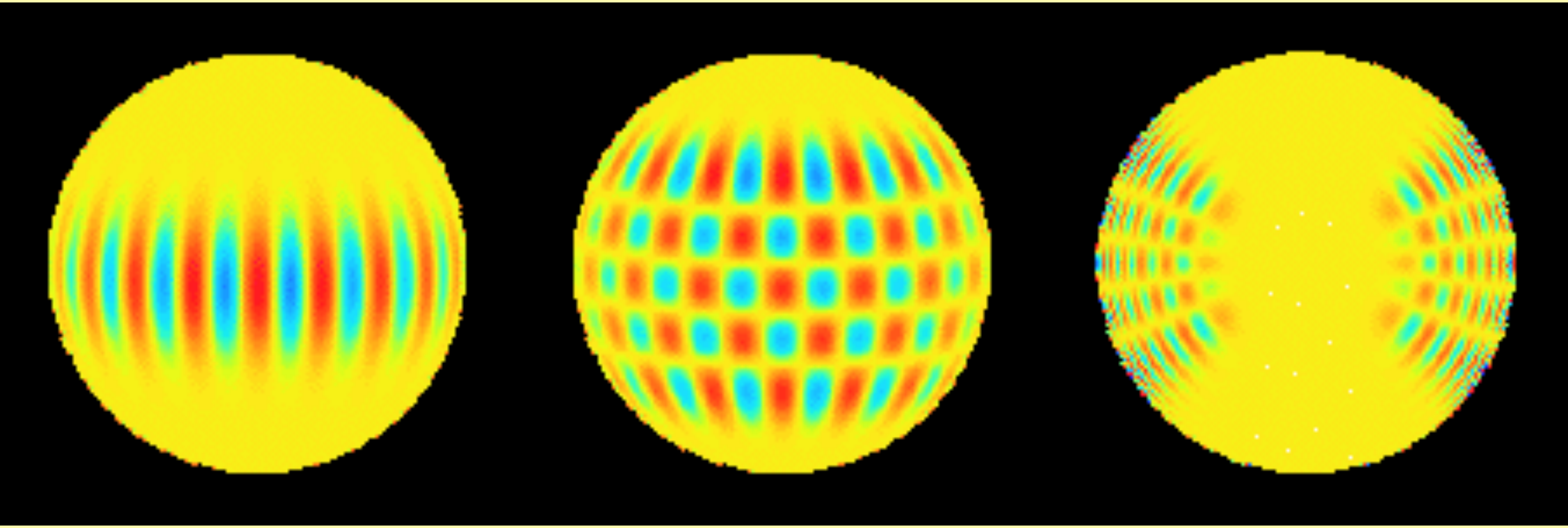
magnificent numerical experiments on rise flux through surface:



[e.g., Archontis & Hansteen]

Now:

Sun oscillates in different normal modes



several million now discovered

solar seismology

-- > T(r) of Interior

+ Internal Rotation

Vertical cut

pole

Observe at surface:

* equator > pole

Expect:

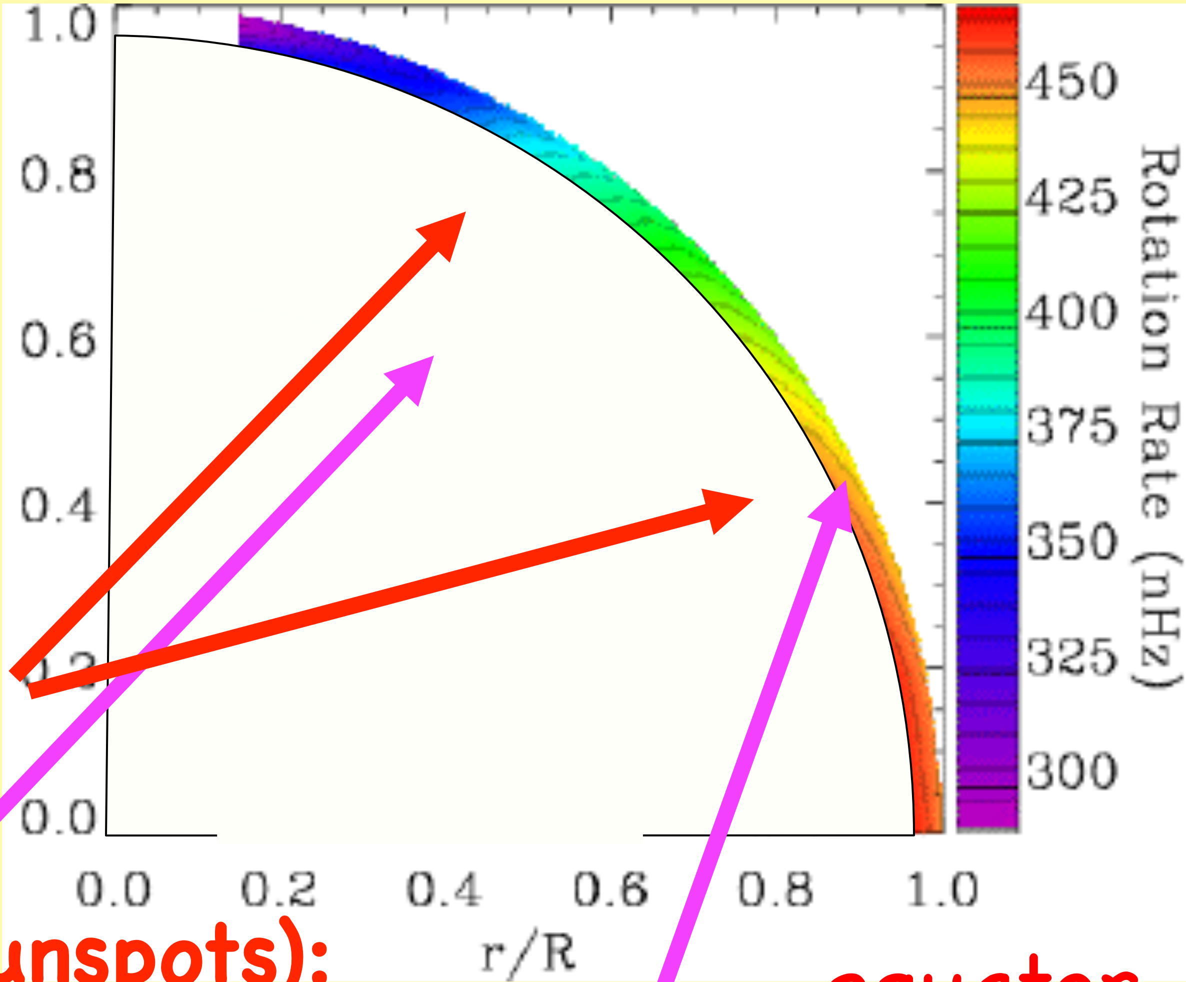
* const. on cylinders
* B generated

throughout conv. zone

Surprise:

-- const on radial lines

-- intense shear layer

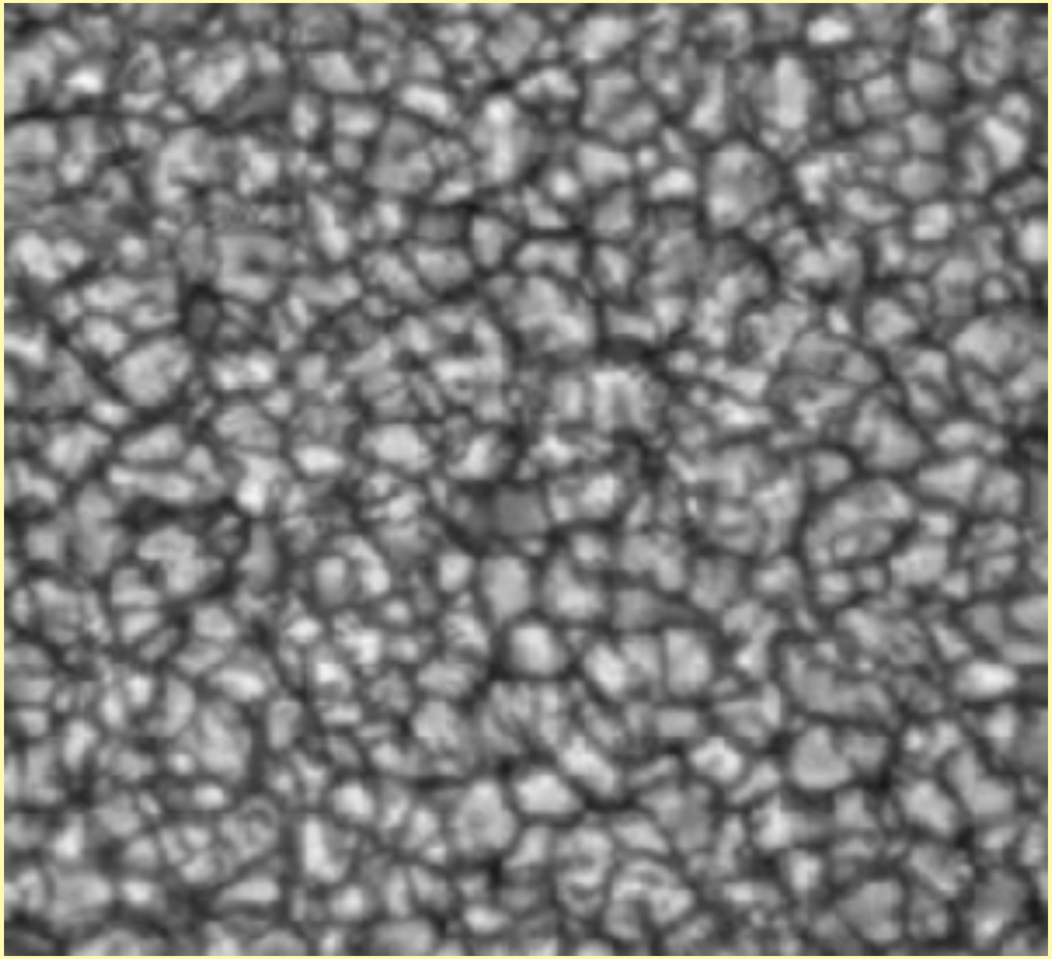


- site dynamo (sunspots):

equator

-- also near surface - ?? small-scale dynamo

2. Photosphere



Temperature 6000 K

Covered with **turbulent convection cells:**
"**Granulation**"
(1 Mm)
"**Supergranulation**"
(15-30 Mm)

Map Magnetic Field in Photosphere

white – towards, black -- away

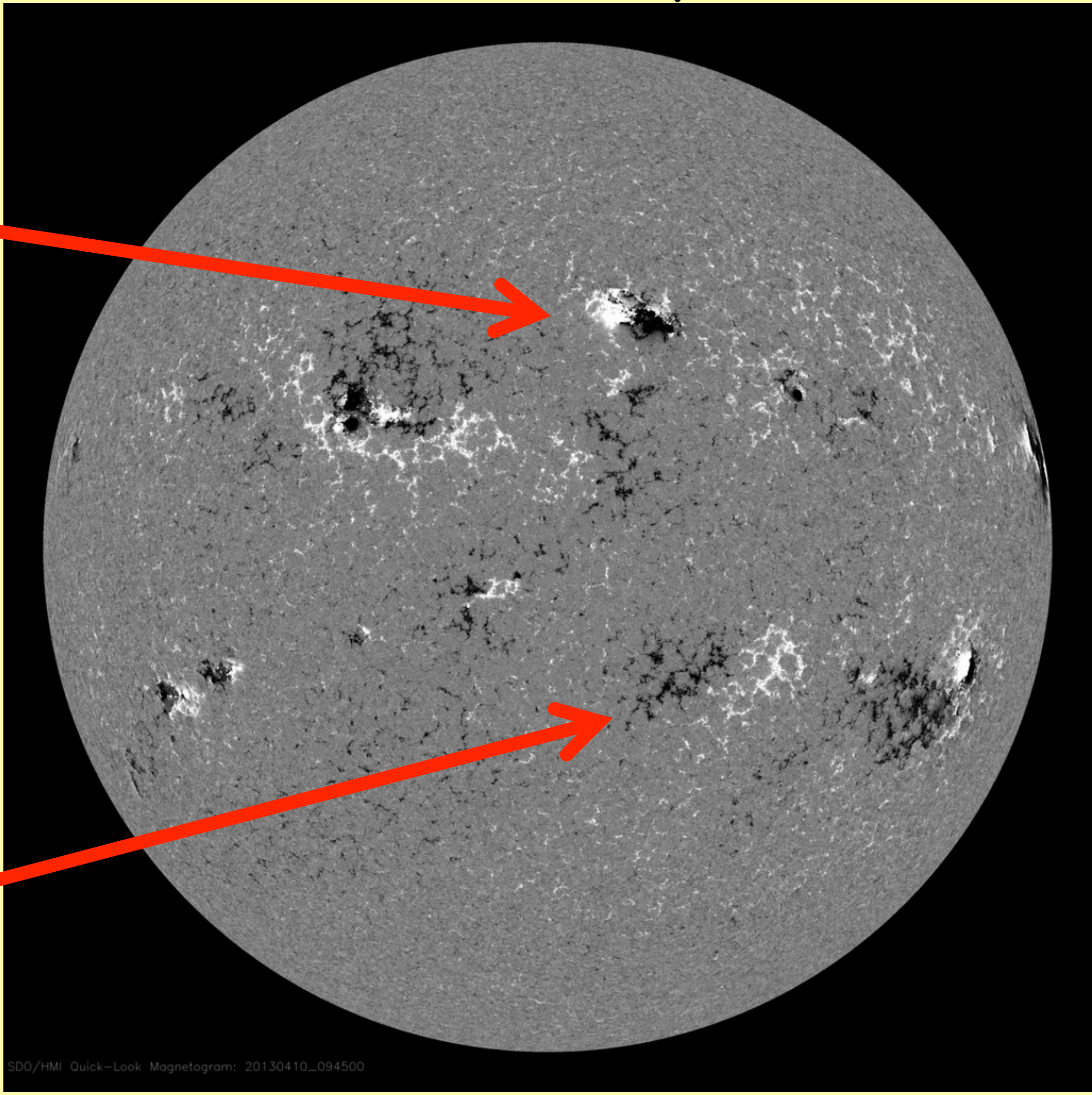
Bipolar
"Active Regions"
around sunspots

1970:

Alfvén: weak global bipolar B outside a.r

90's:

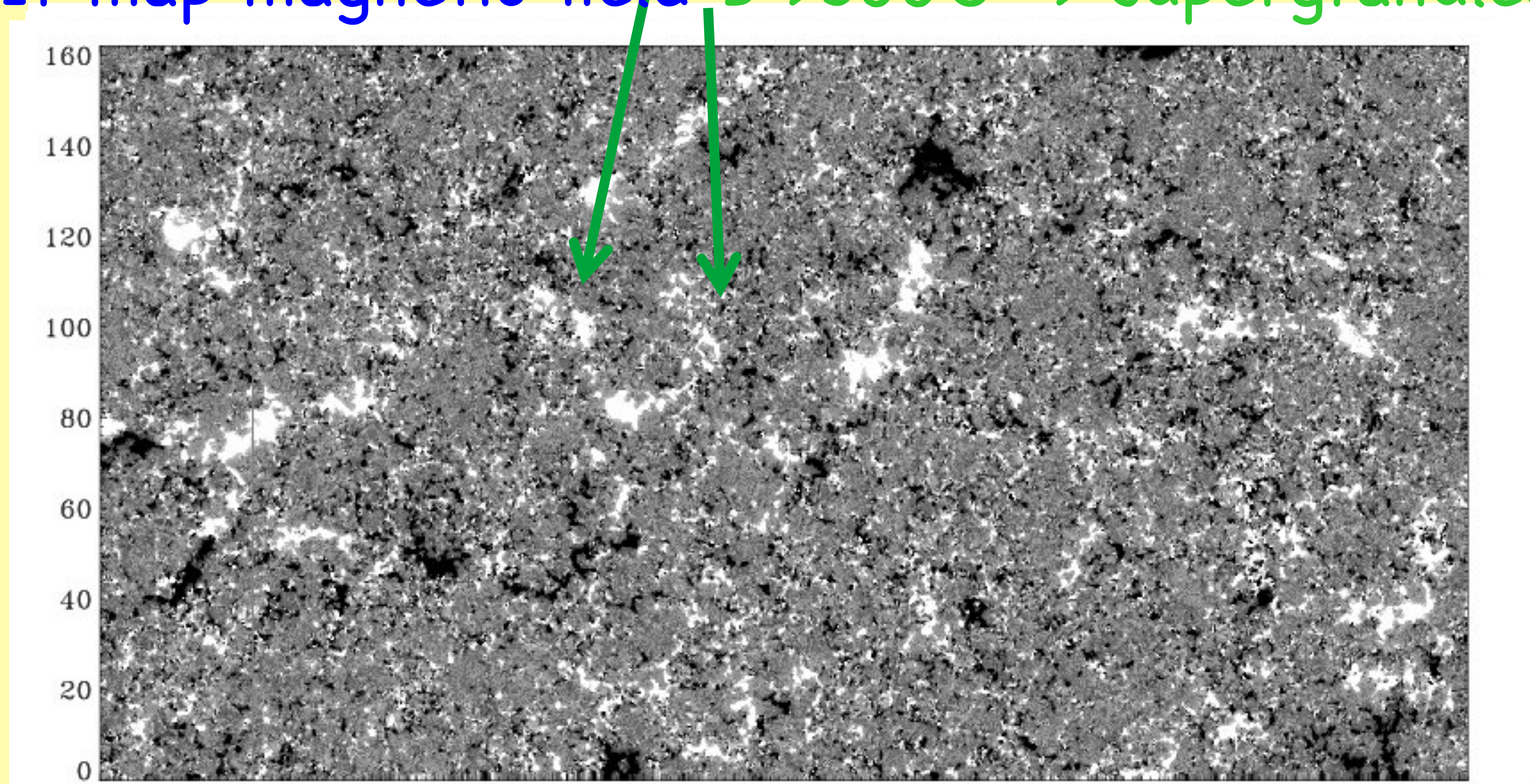
strong magnetic fields at edges of supergranules



← 700 Mm →

Now:

If map magnetic field B >500G -> supergranules



But if reduce threshold for vertical flux, see more (B > 100G) and more (B > 25 G) vertical flux

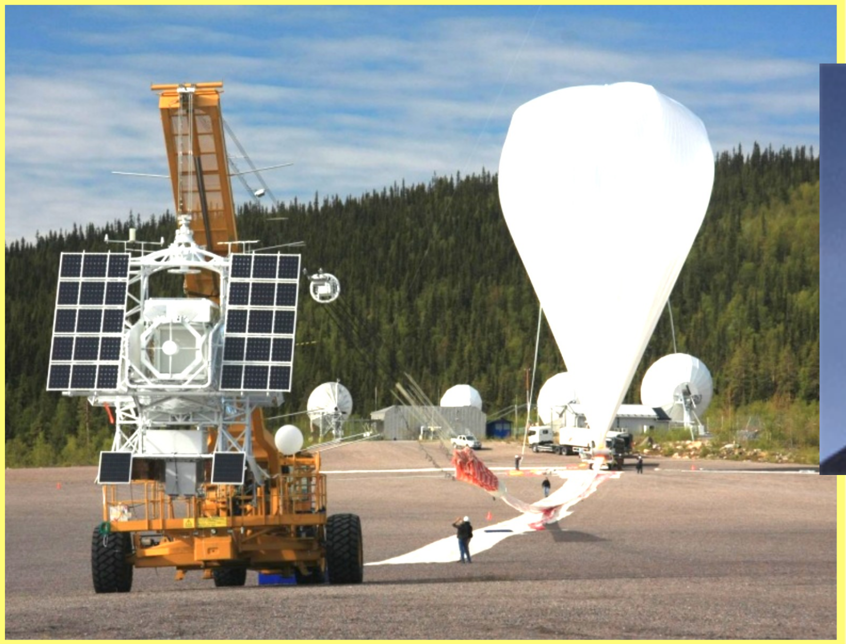
-> coronal field much more complex than thought

between granules

[Lites, Hinode]

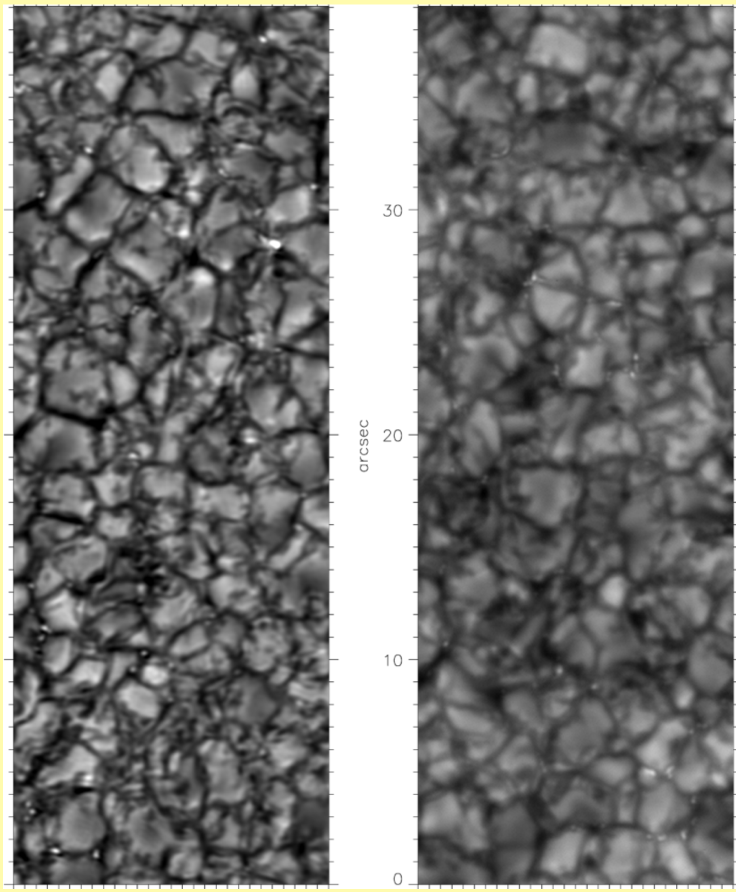
Best resolution photospheric B:

Sunrise Balloon Mission (Solanki et al)



Resolution 100 km -- >

Resolved kG fields



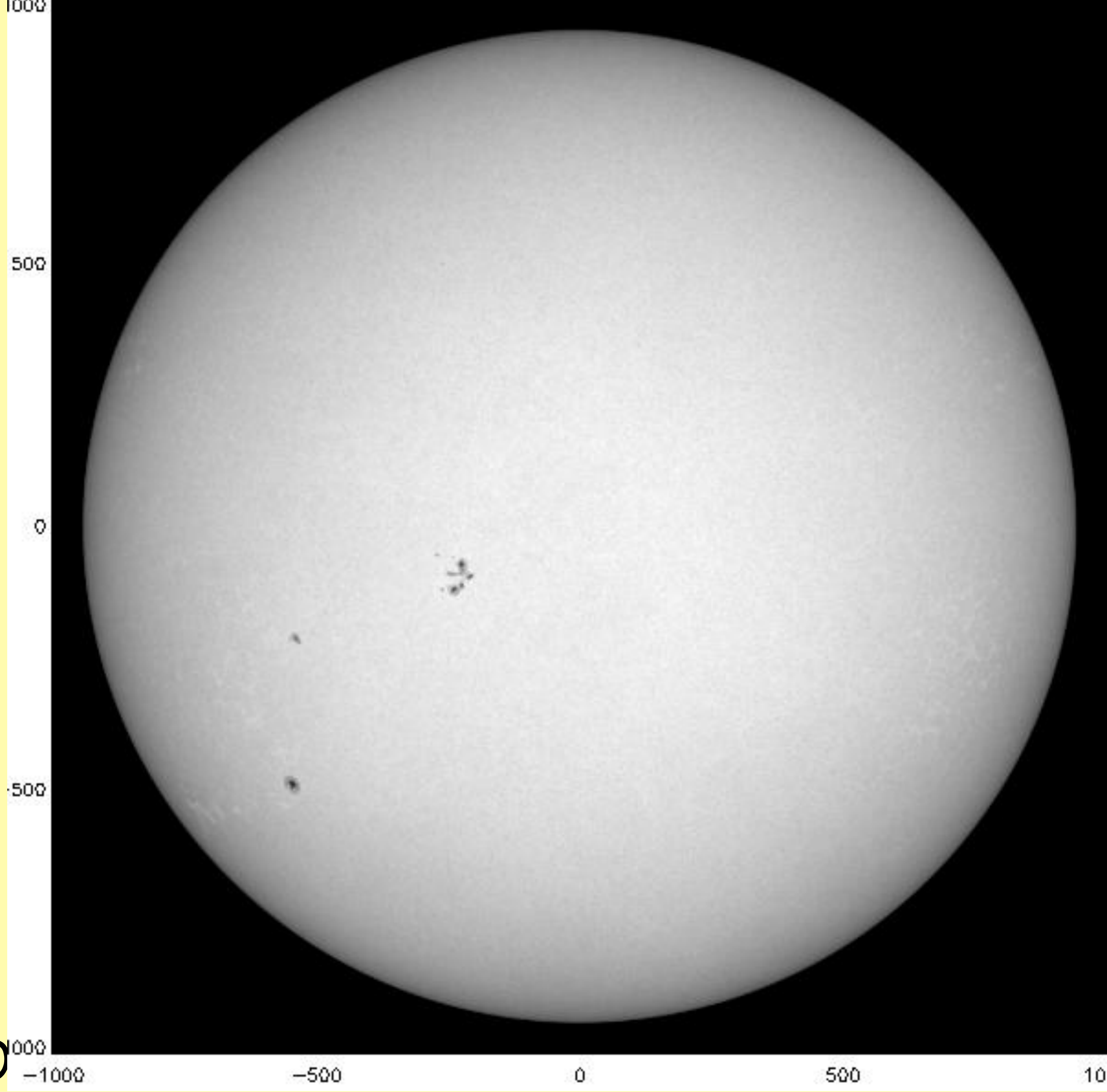
Sunrise Hinode

Now:

Amazing images from Swedish Solar Telescope (SST) La Palma:

[Luc Rouppe Van Der Voort]

Zoom from full disk by factor 100

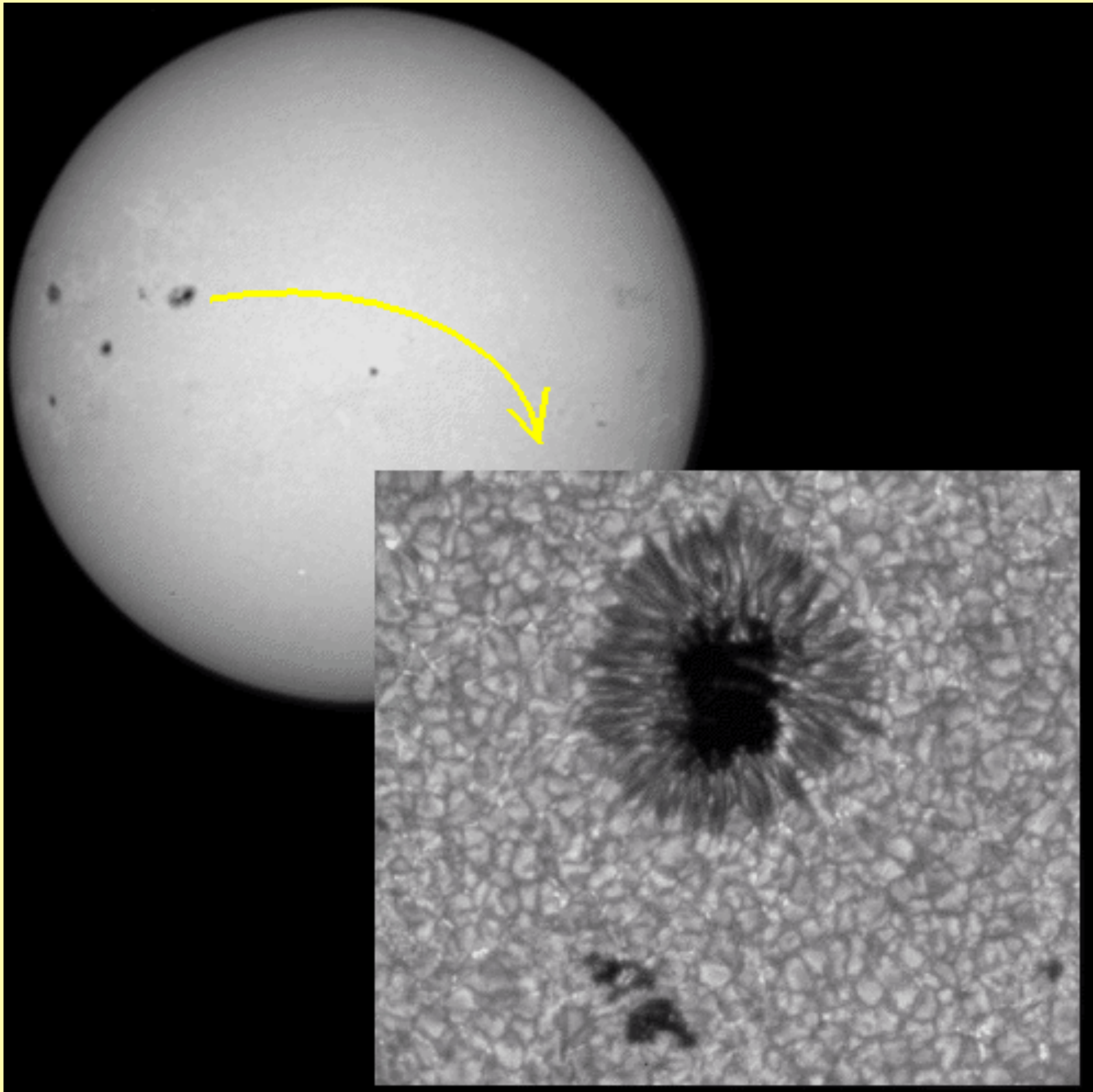


Sunspots

locations of strong vertical magnetic flux tubes

Dark because cool

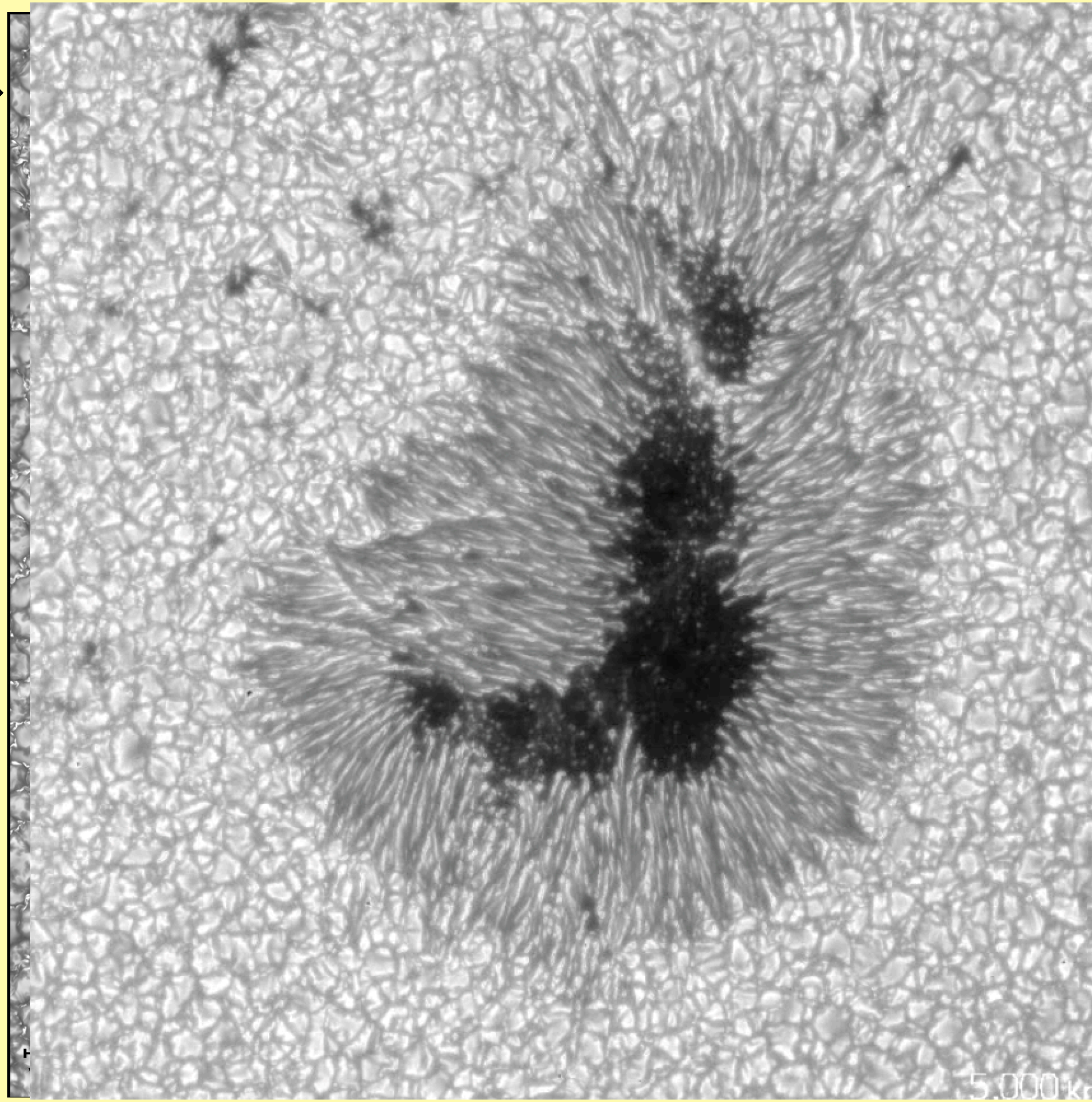
- because magnetic field stops granulation



Observations →
fine structure

computational model
[Rempel]
- highly realistic

→ natural result of
convection in a magnetic field

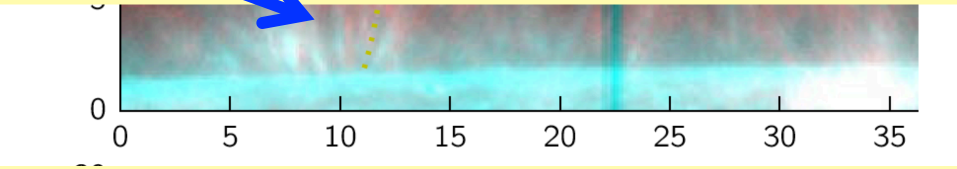


3. Chromosphere: IRIS satellite – dynamic jets

Spicules –

(i) heated to tr temps,
as they rise

(ii) and are twisted
[De Pontieu et al]

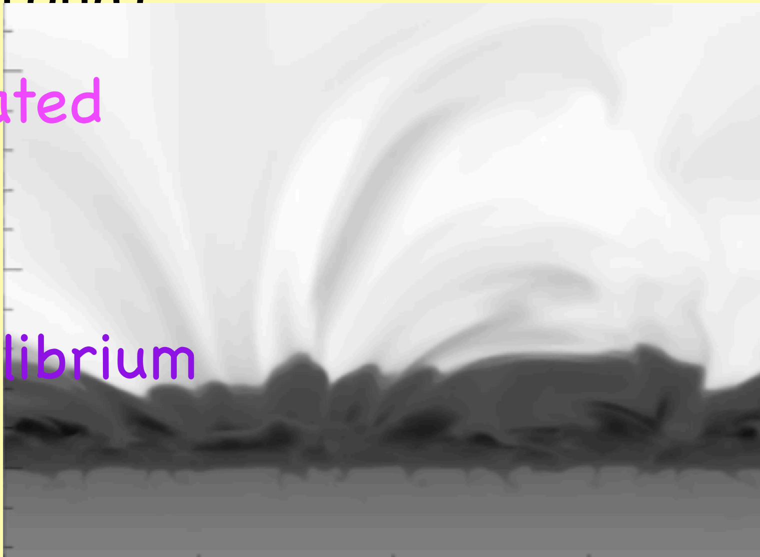


[LR van der Voort]

? contribution of jets to
solar wind: unknown?

Best 3D radiative MHD code (BIFROST)
[developed by Hansteen, Carlsson, Gudiksen]

– model complex transition (photo -> corona)

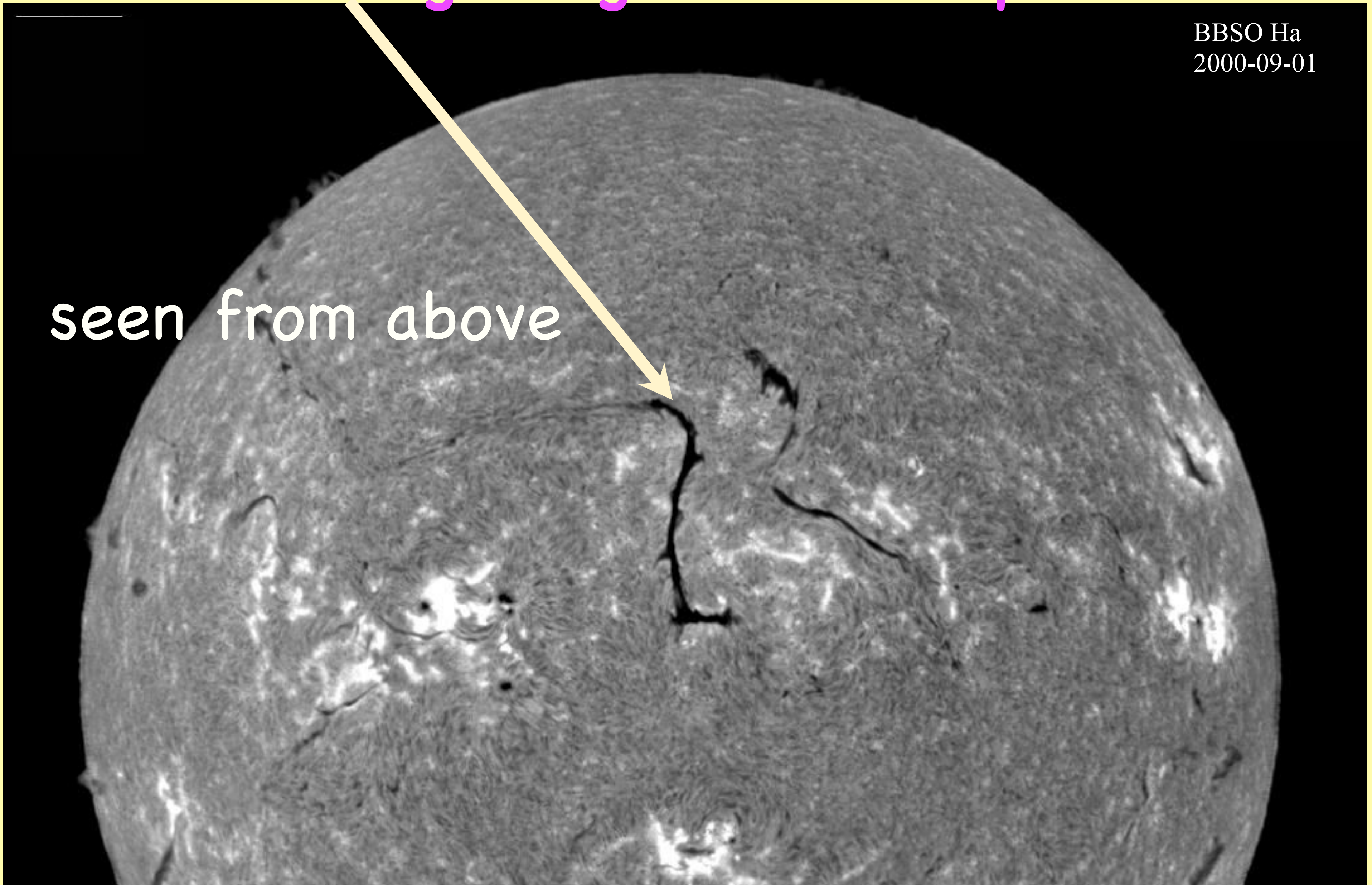


- forces: pressure -> magnetic-dominated
- plasma: neutral -> fully ionised
- radiation: optically thick -> thin
- therm^c state: local equil^m -> nonequilibrium

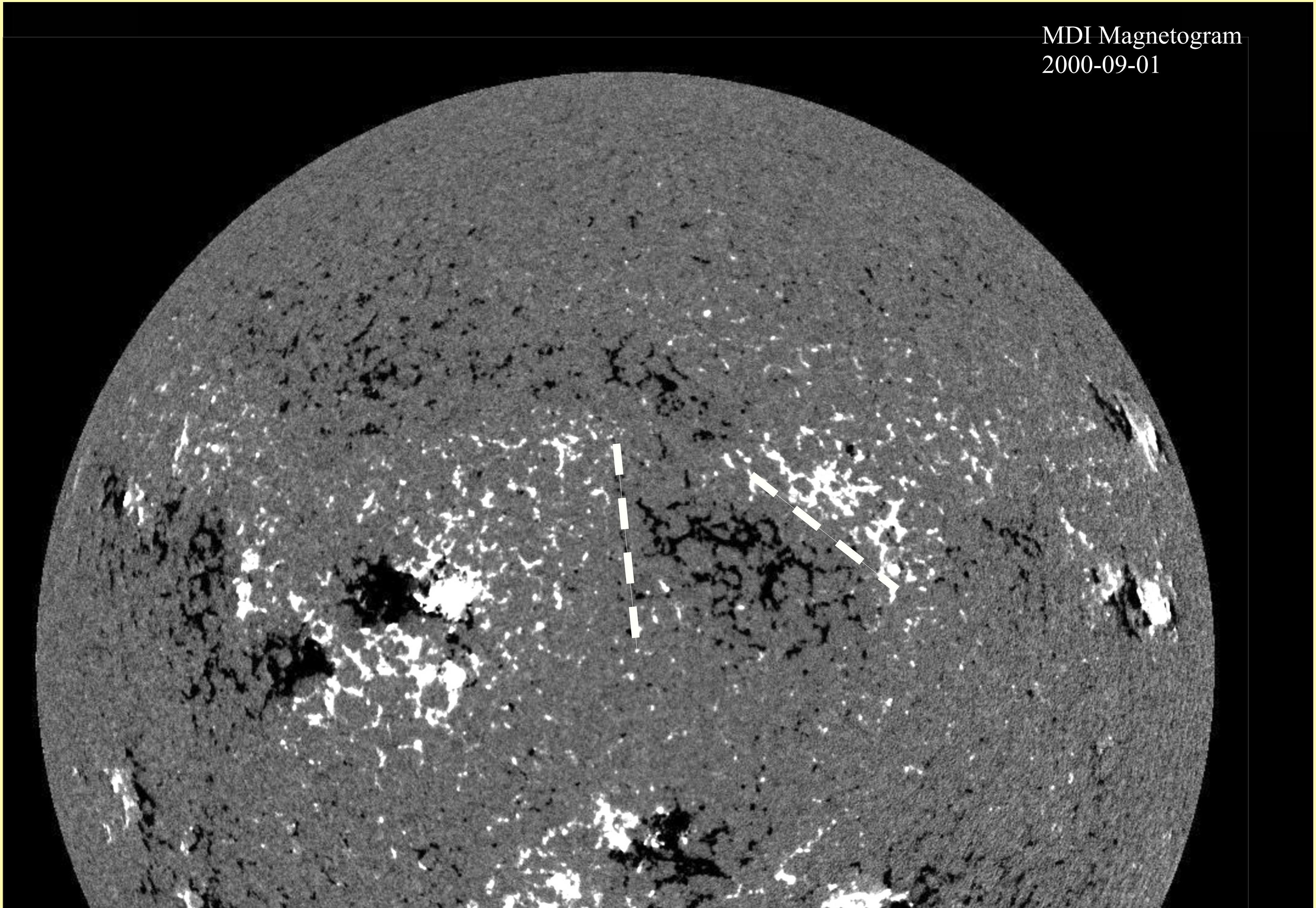
– new insights nature connections
photosphere-corona

4. Prominences – Alfvén: electrical discharges

Now: huge magnetic flux ropes

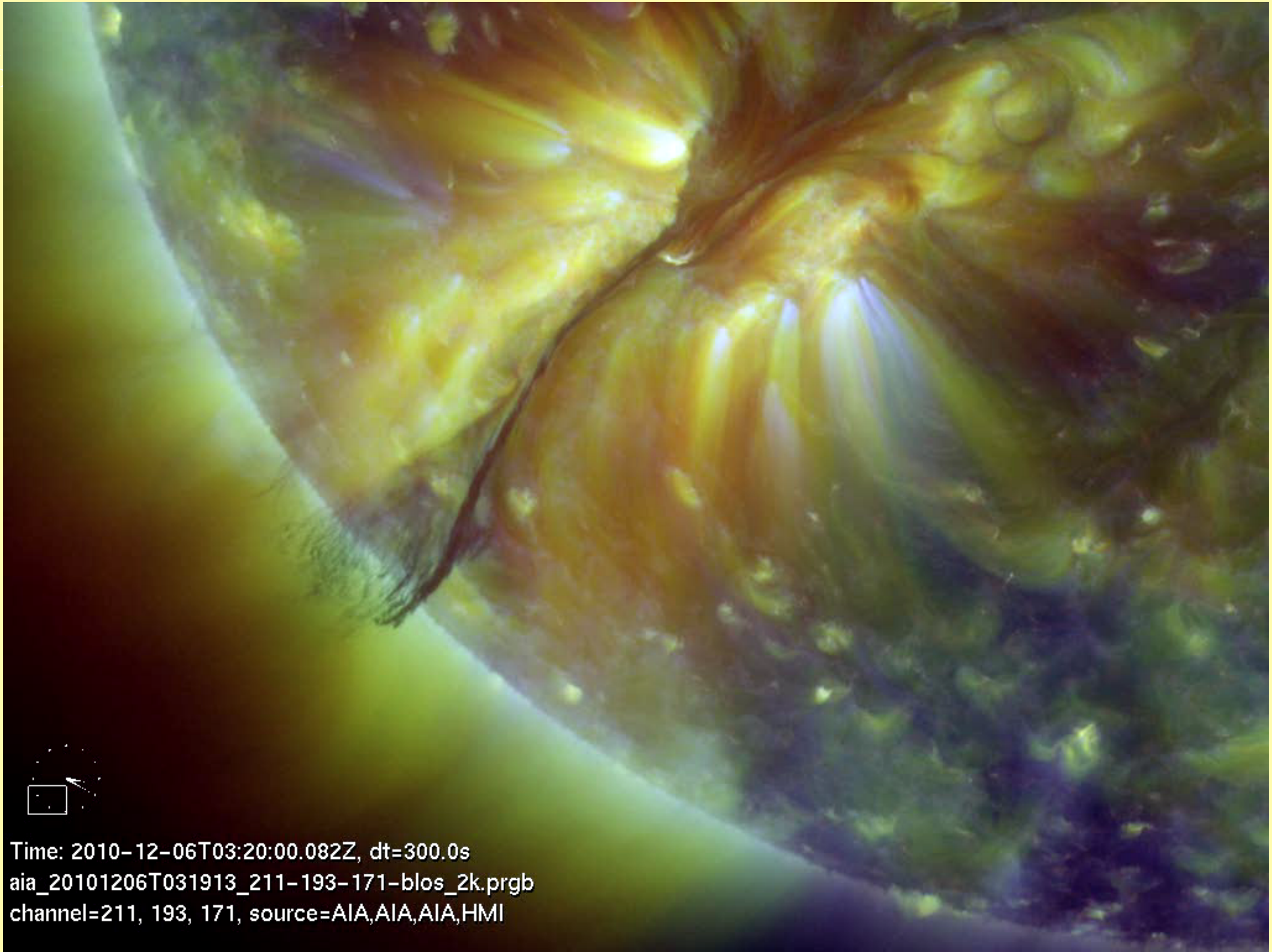


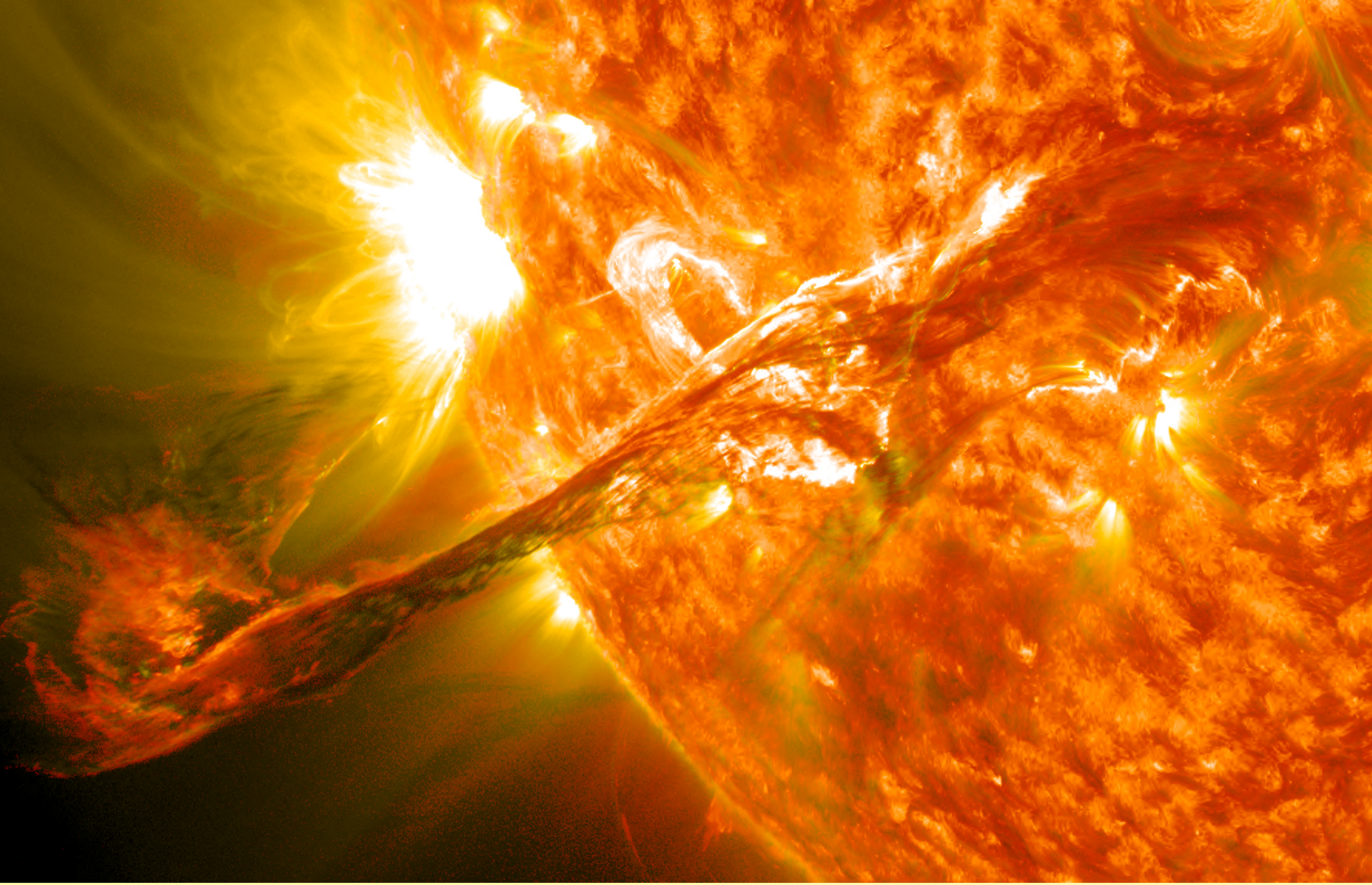
Lie above boundary between + & – "Polarity Inv^n Line"



Prominences usually stable – but can erupt

AIA
2010

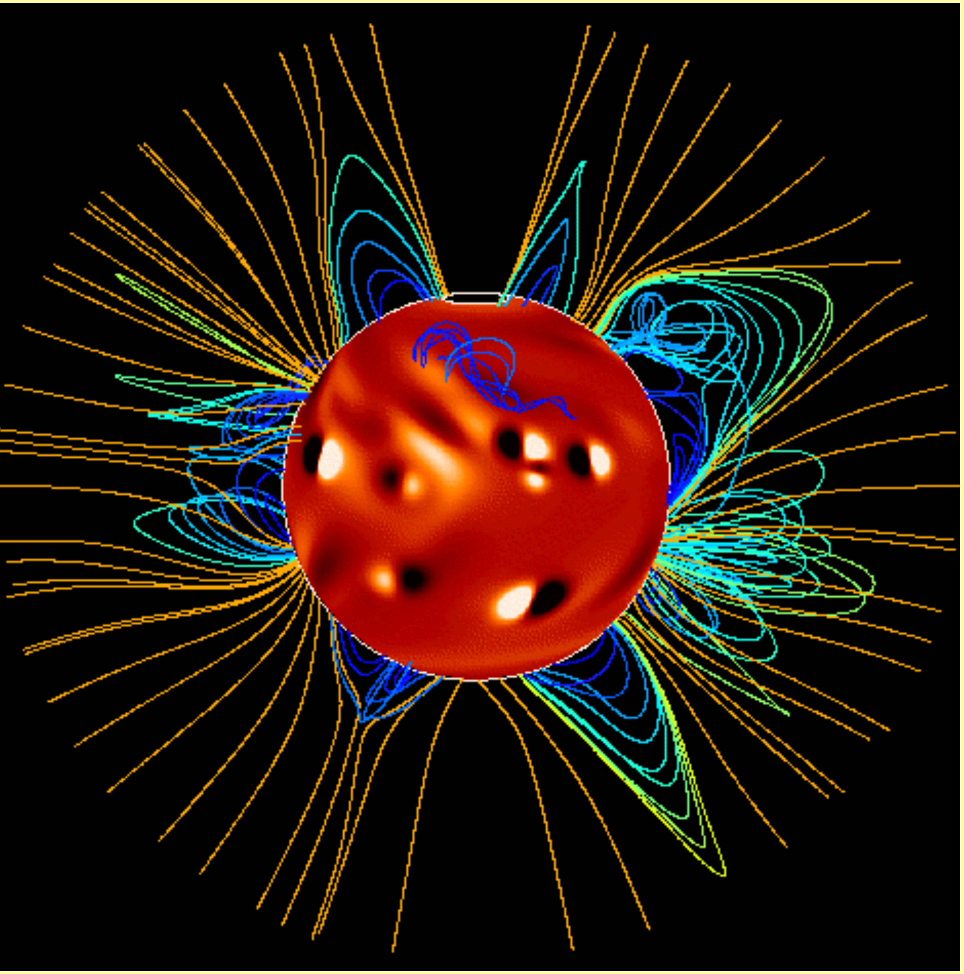




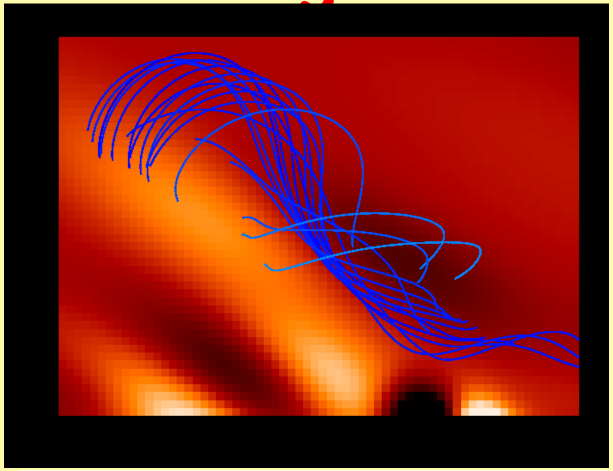
Eruptions are associated with CMEs;
– if from active region -> **solar flare**

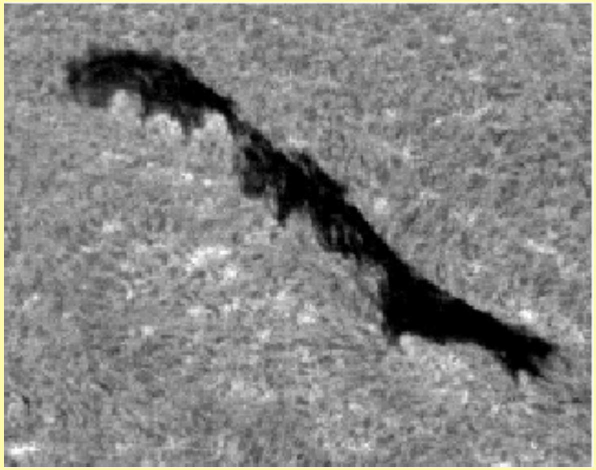
Model global coronal magnetic field [Mackay]

evolves in response to observed surface motions (diff^{l} rot^{n}, meridional flow, diffusion) + flux emergence



→twisted mag^{c} flux ropes



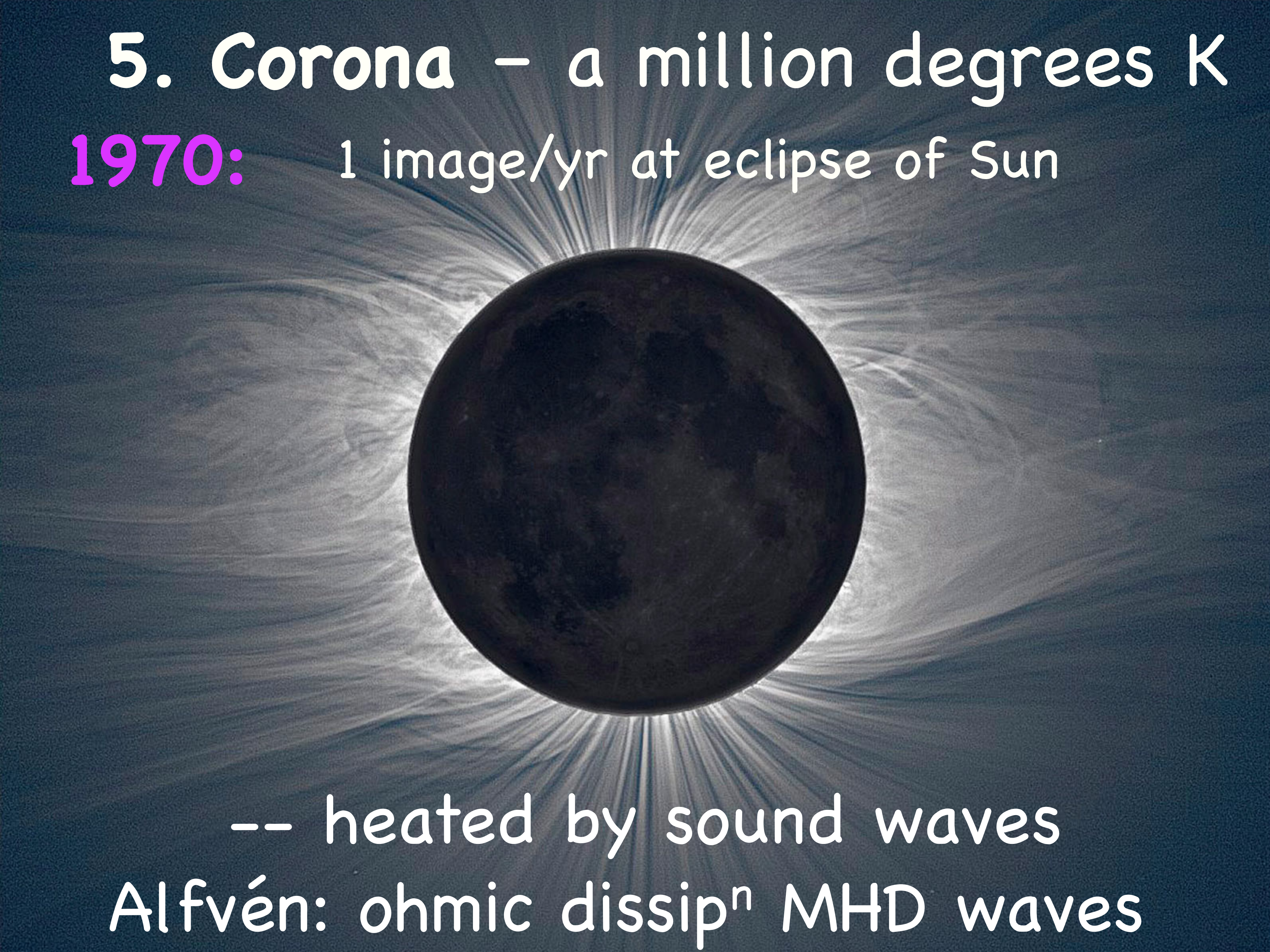


⟹

predict most prom. locations, eruptions of most cme's

5. **Corona** – a million degrees K

1970: 1 image/yr at eclipse of Sun

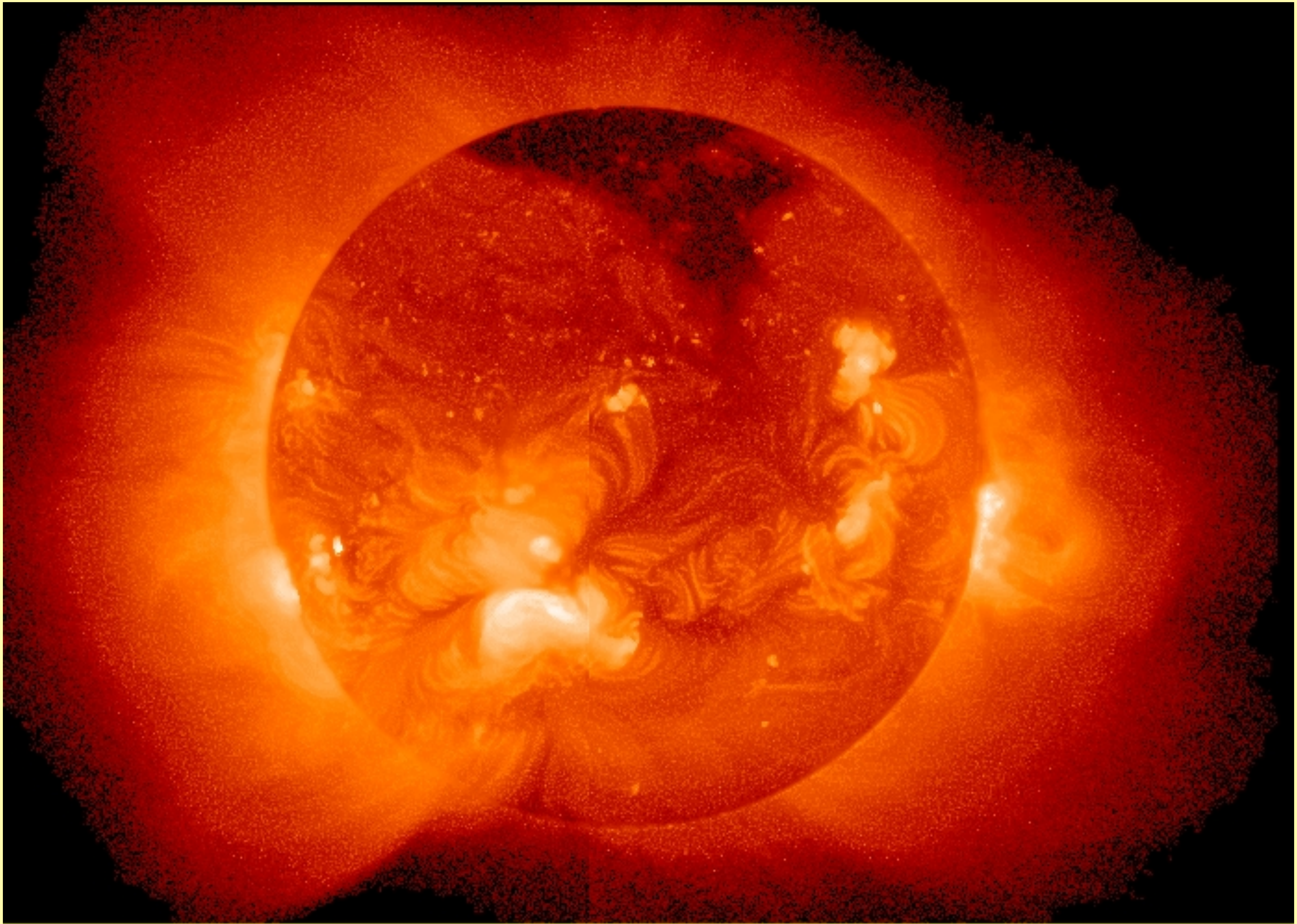


-- heated by sound waves

Alfvén: ohmic dissip^{n} MHD waves

Now: corona direct (x-rays/euv)

we know it is heated by magnetic field



Magnetic Reconnection - Differences 2D & 3D

(i) Structure of Null Point

In 2D, a null forms an X or an O-point

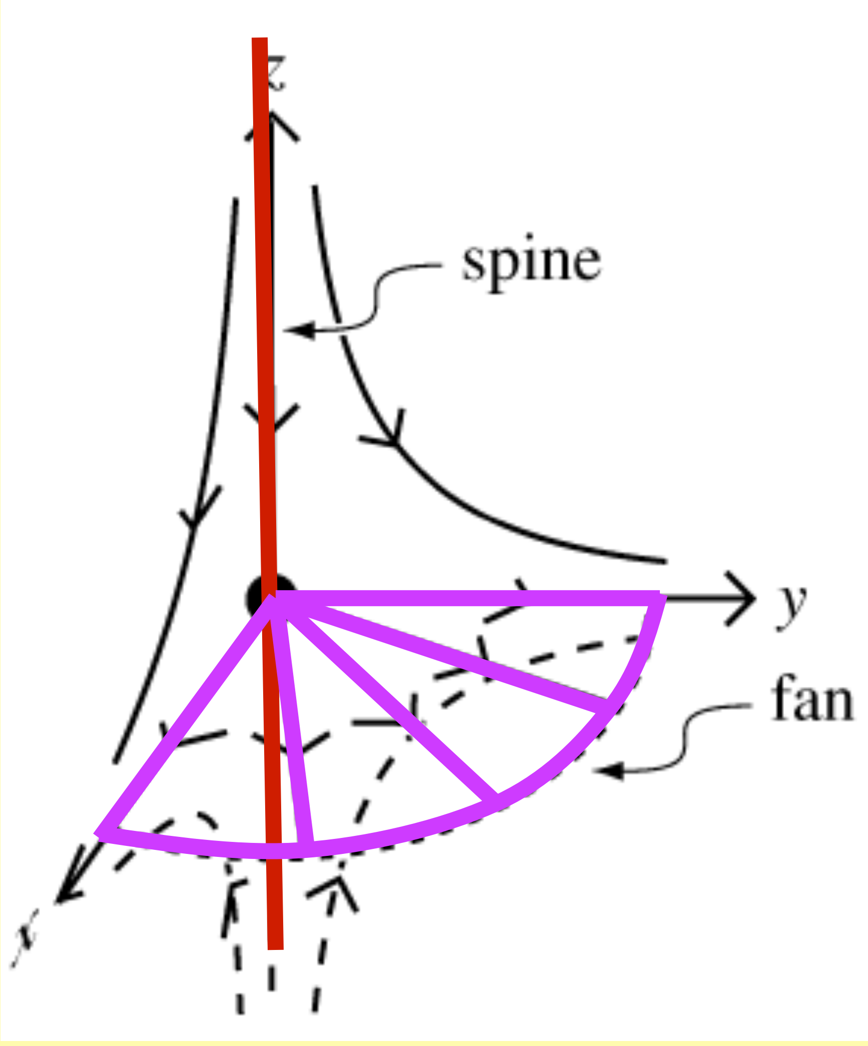
In 3D, simplest

$$\mathbf{B} = (x, y, -2z)$$

2 families of field lines
link to null point:

Spine Field Line

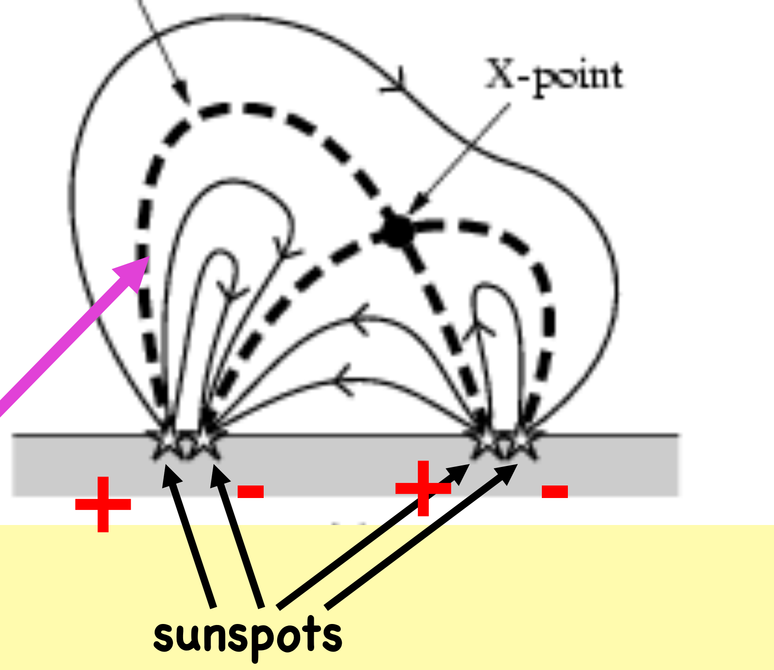
Fan Surface



(ii) Magnetic Topology

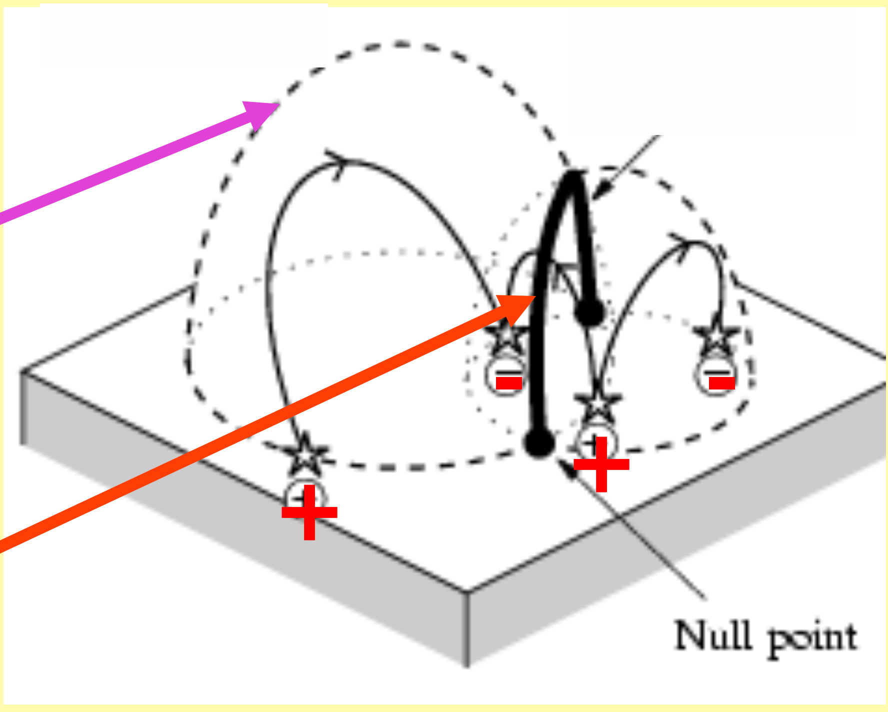
4 spots + – + –:

In 2D: X-pt – B lines from it form **"separatrix" curves**

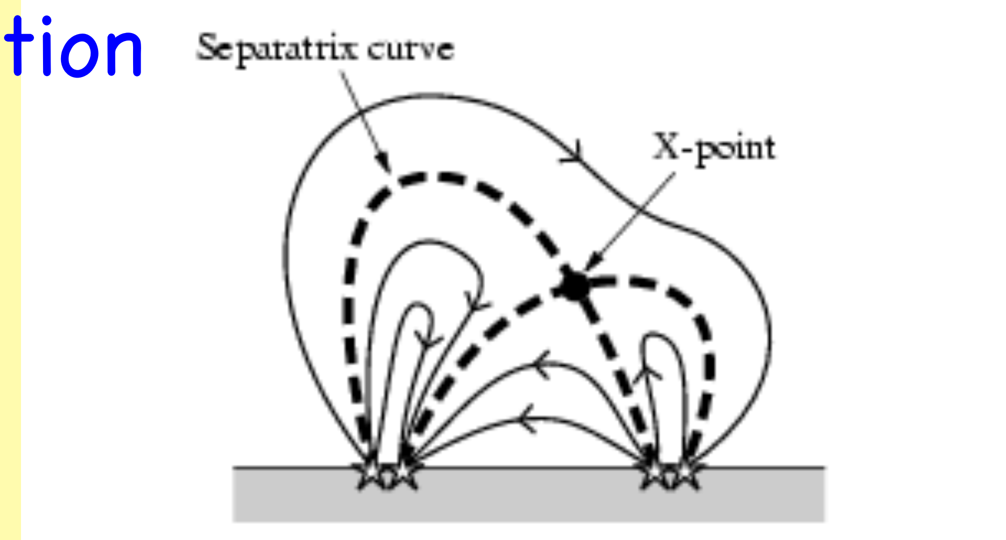


In 3D: 2 null points → **separatrix (fan) surface** from each → domes

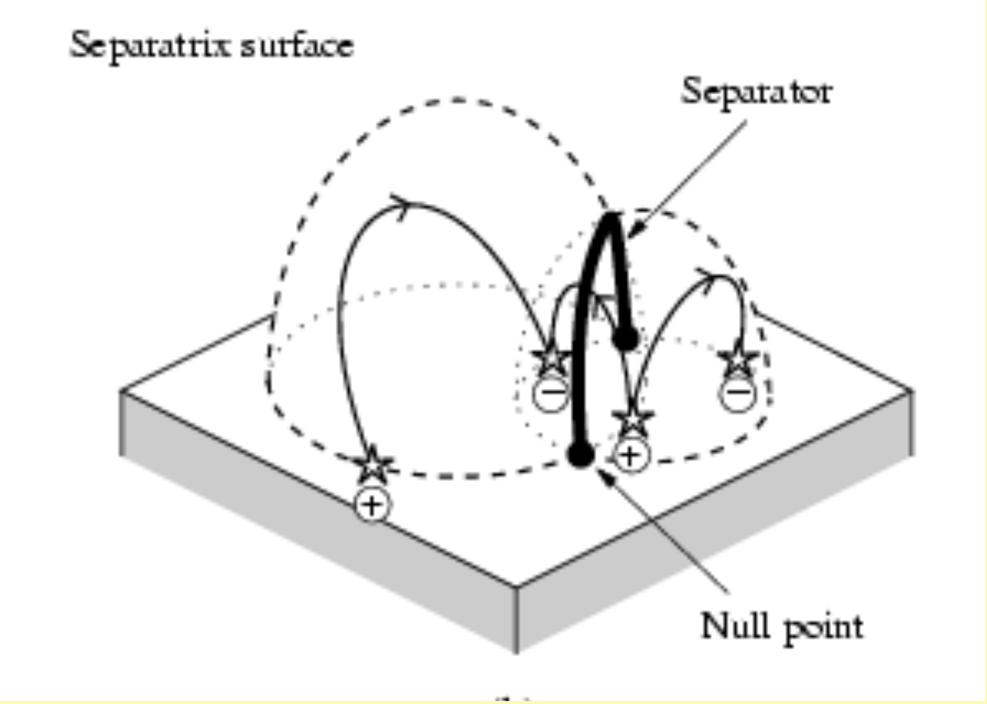
-- intersect in **separator**



(iii) Magnetic Reconnection

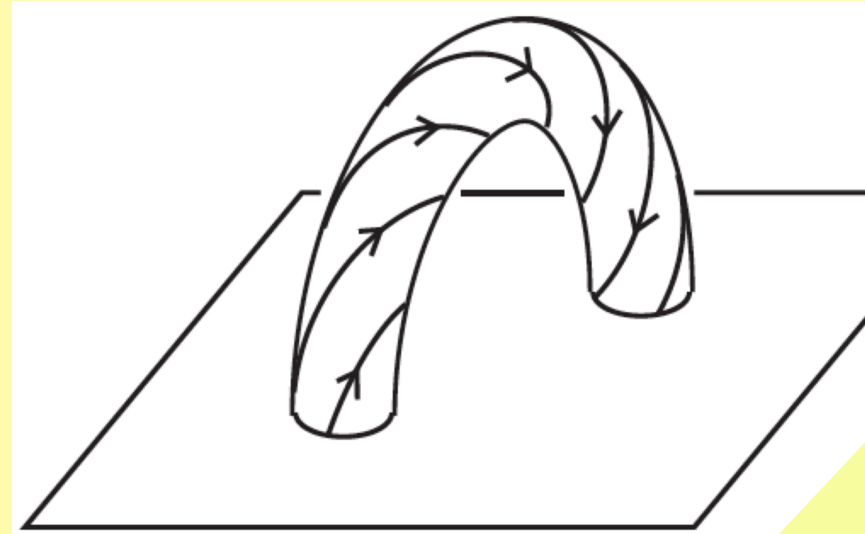


In 2D, reconnection at X transfers flux from two 2D regions to two others.



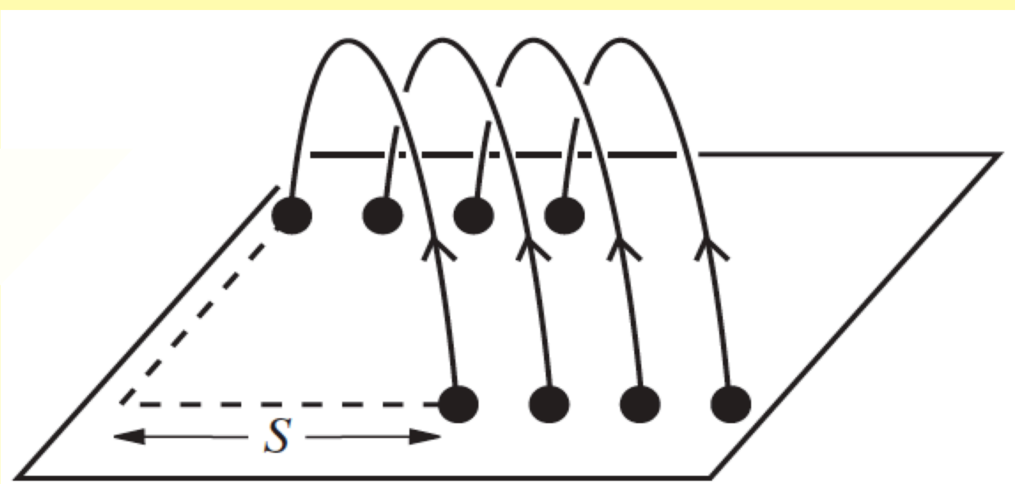
In 3D, reconnection at **separator** transfers flux from two 3D regions to two others.

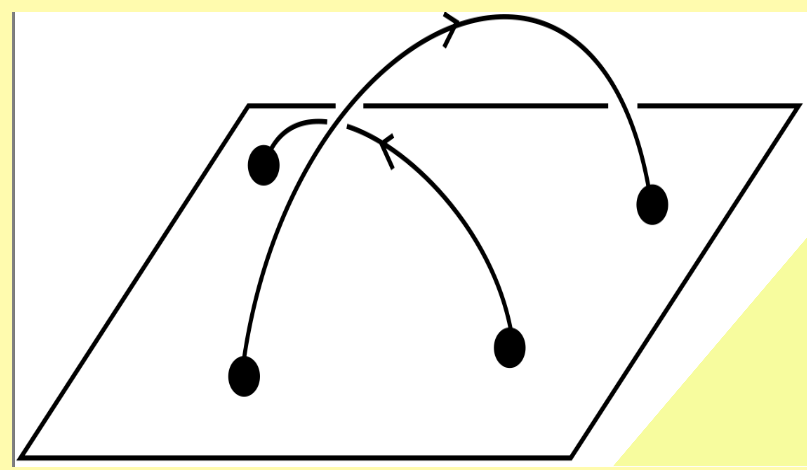
(iv) Magnetic helicity [Berger, Hornig]



A topological quantity representing

- twisting & kinking of a flux tube (**self-helicity, H_s**) plus
- linkage & knotting between diff[t] tubes (**mutual helicity, H_m**)





[Applied to CMEs by Thalmann]

Types of Reconnection:

In 2D: Reconnection at X-point well understood

In 3D: Richer – always conserves total mag. helicity

several locations where strong j grow:

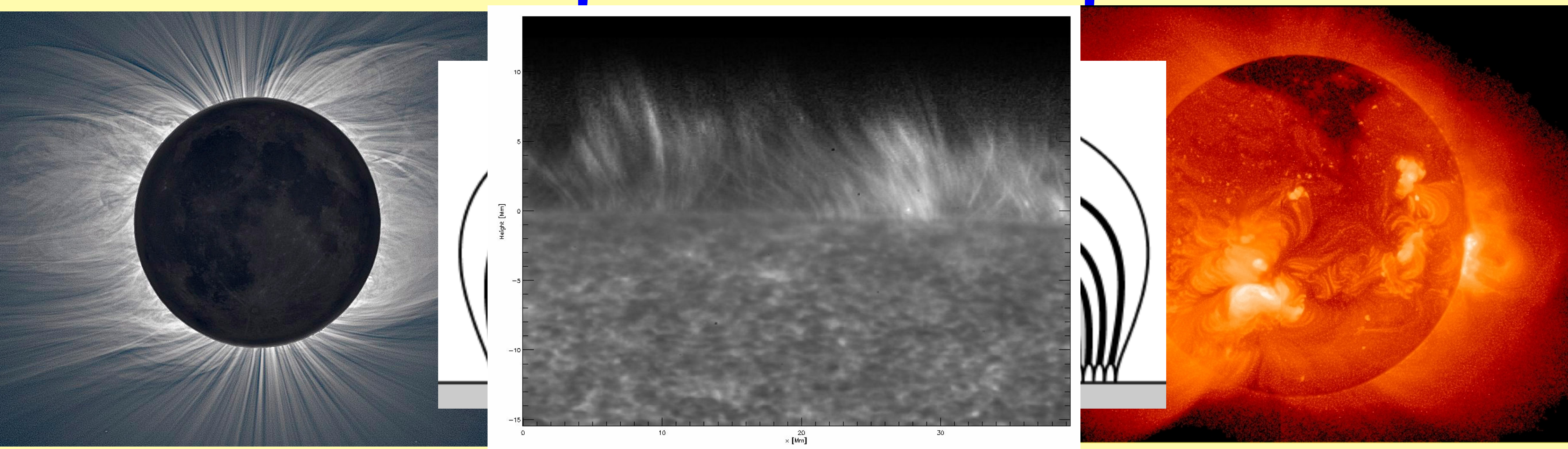
- 1. at a separator,
- 2. near a null point,
- **3. in absence of null: at "Quasi-Separator"**

Consider mapping of footpts of B-lines from 1 part of boundary to another:

If null point – ∃ separatrix, across which, sudden jump/discontinuity in mapping.

If no null, ∃ **no** separatrix, but quasi-separatrix – remnant across which mapping continuous but has steep gradient.

How heat XRBt pts, coronal loops/holes?



(a) Coronal tectonics–refinement of Parker braiding [Priest et al

- B threads solar surface in many **sources:** motions →
- **j sheets** at surfaces separating flux from each source
- →dissipate by **magnetic reconnection** in **"nanoflares"**

(b) Waves–dissipate by phase mixing/resonant absorption/coll^{less}

(c) MHD turbulence – energy cascades down to dissipation scale

[Heyvaerts & Priest; van Ballegoojen & Cranmer]

Now -many **observations** of waves, small reconn^n brightenings

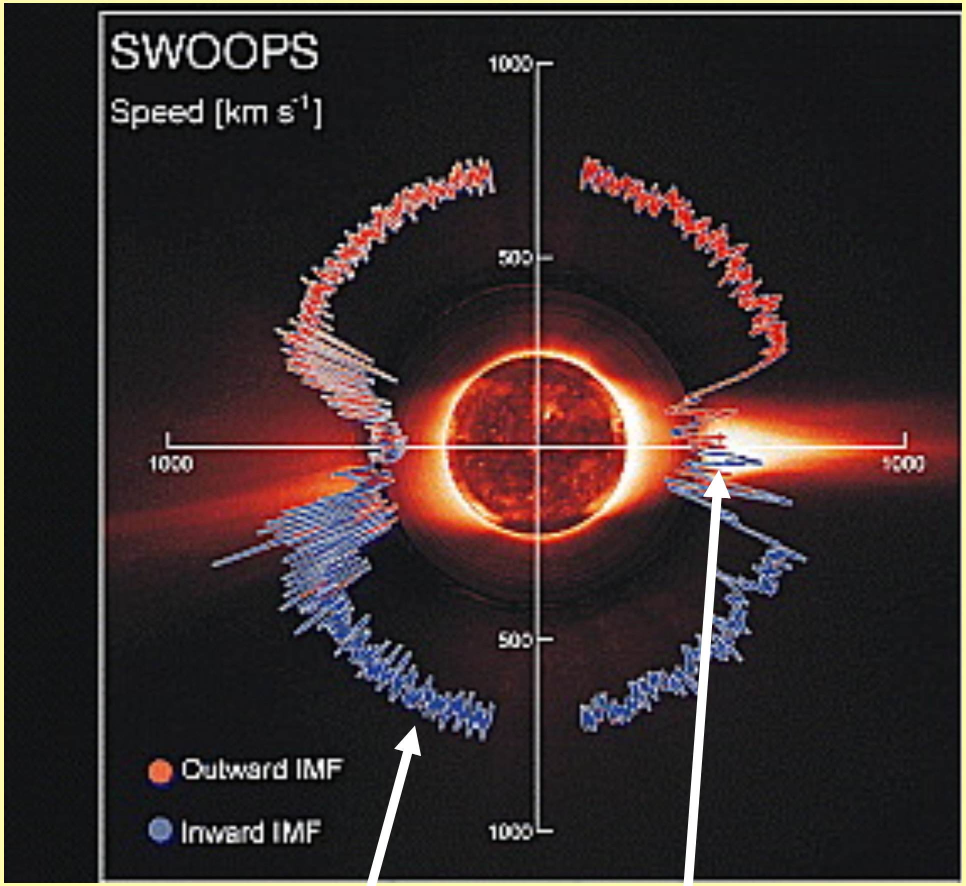
+ numerical simulations

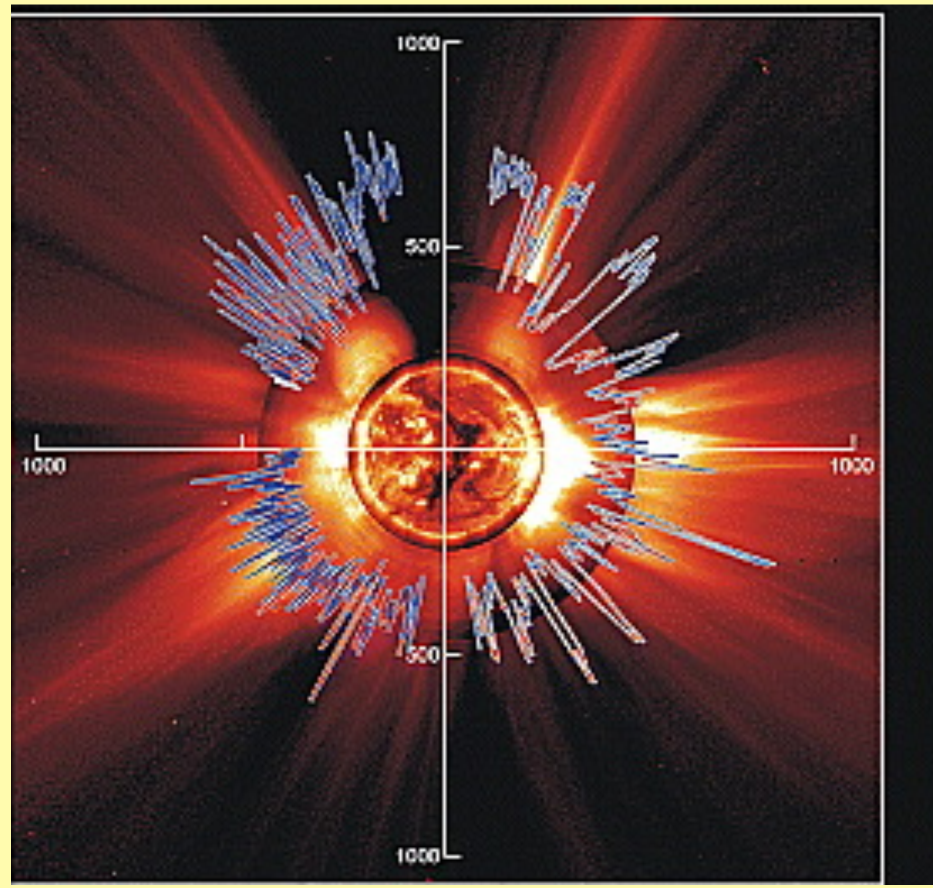
6. The Solar Wind

1970 simple Parker models sph. sym. *v(r)*

Now

Ulysses: Sunspot minimum | **Sunspot maximum**





FAST (700 km/s)
coronal holes

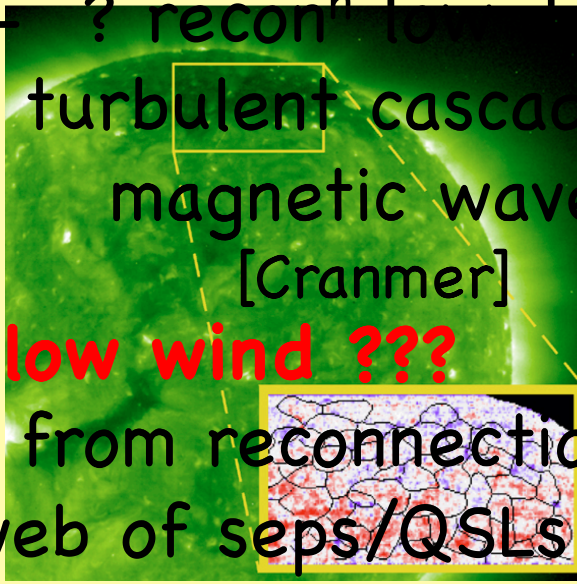
SLOW (300 km/s)
streamer belts

IRREGULAR

Fast wind originates in coronal holes in funnels

– accelerated by ?

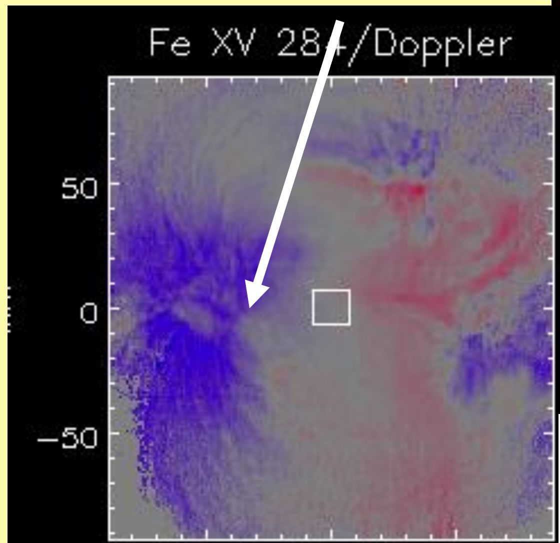
– ? recon^n low down-> turbulent cascade magnetic waves [Cranmer]



Slow wind ???

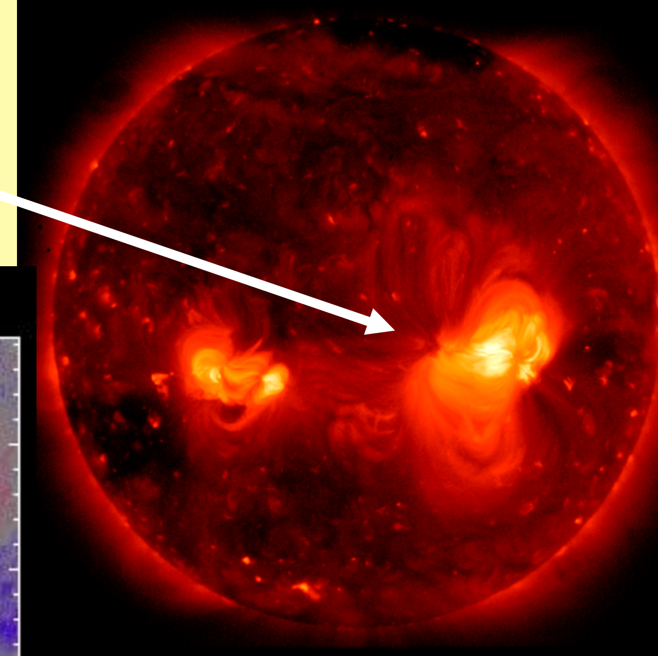
? from reconnection web of seps/QSLs near streamer boundaries

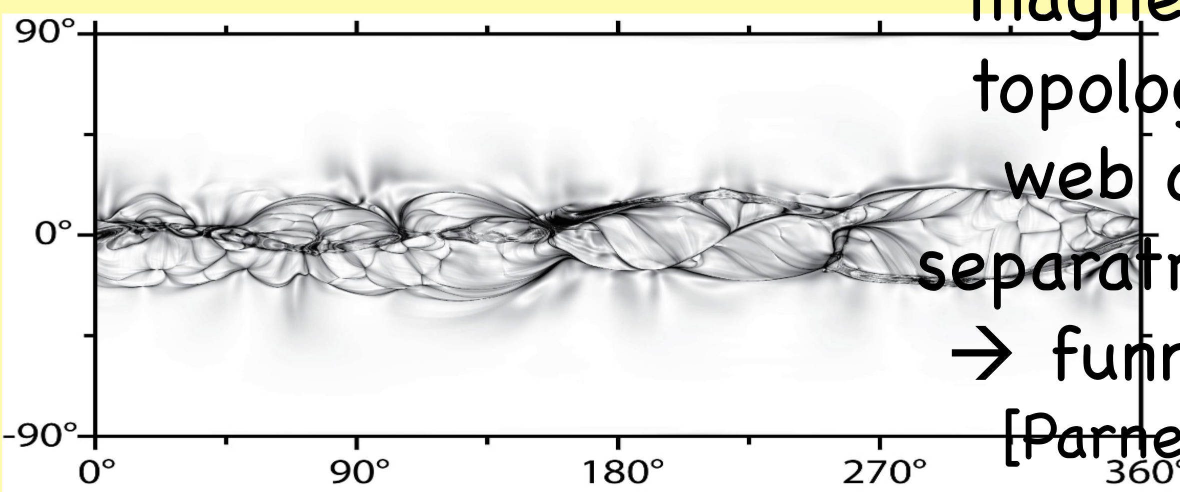
[Priest & Demoulin, Antiochos, Linker]



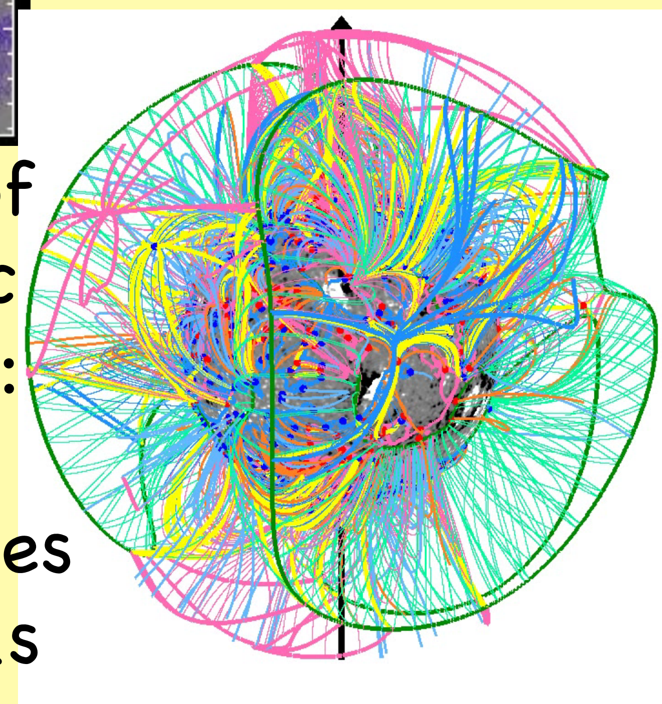
SUMER observations

Hinode observations [Sakao]





Models of magnetic topology: web of separatrices → funnels [Parnell]



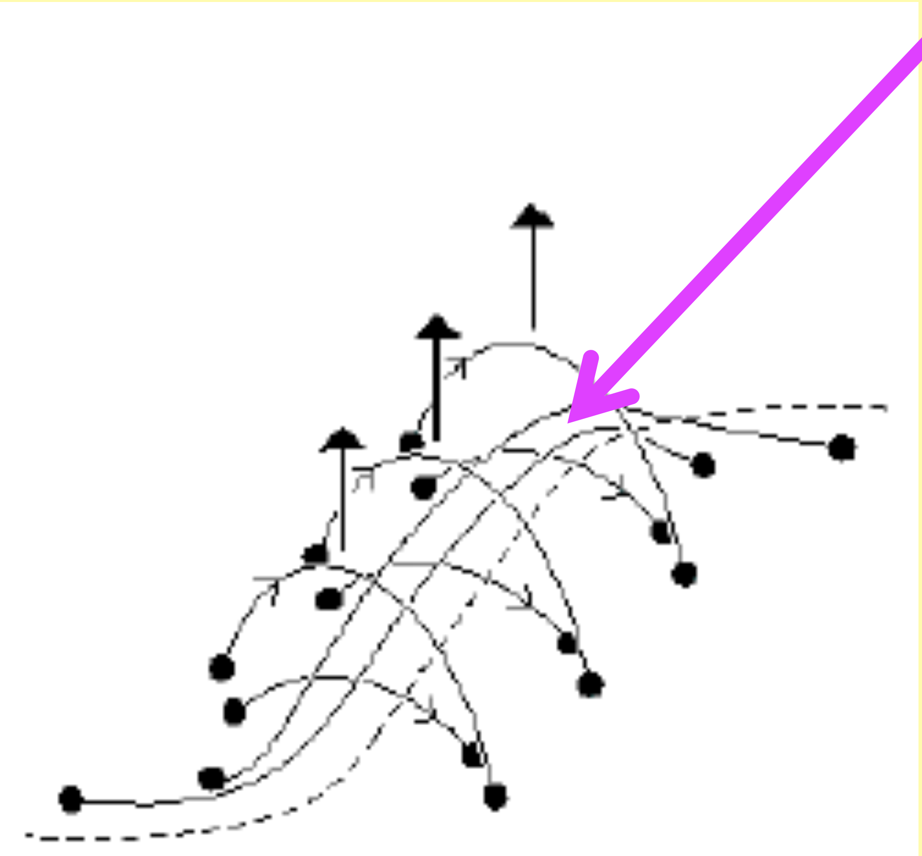
7. Solar Flares & CME's

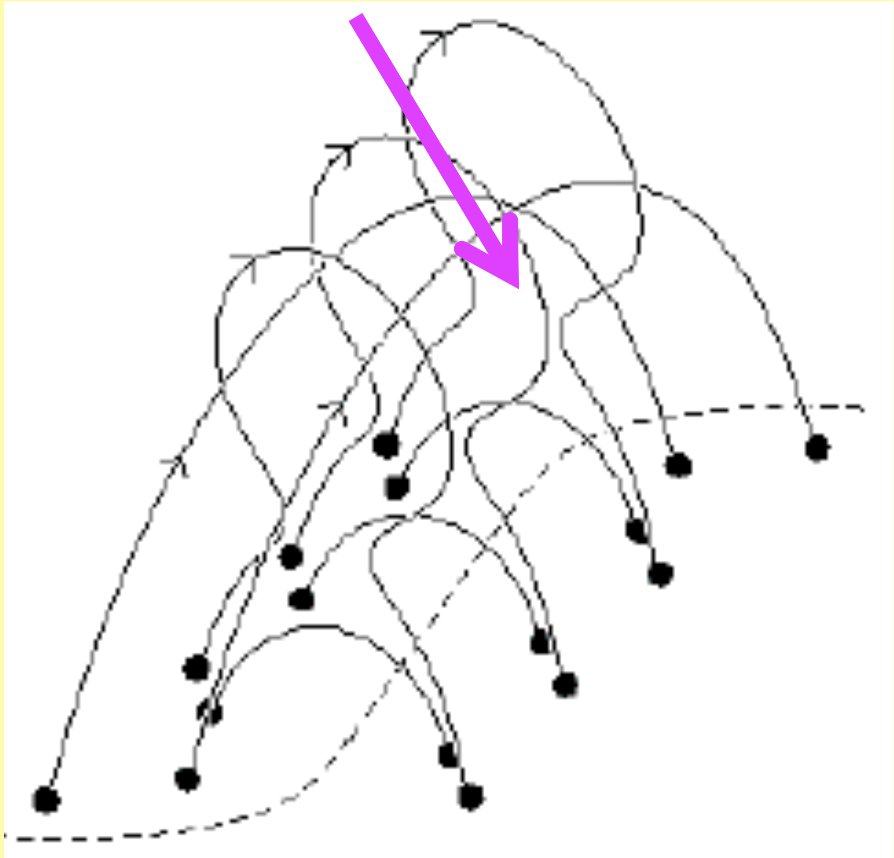
In 1970: flare = "brightening in chromosphere",

CME's had not been born

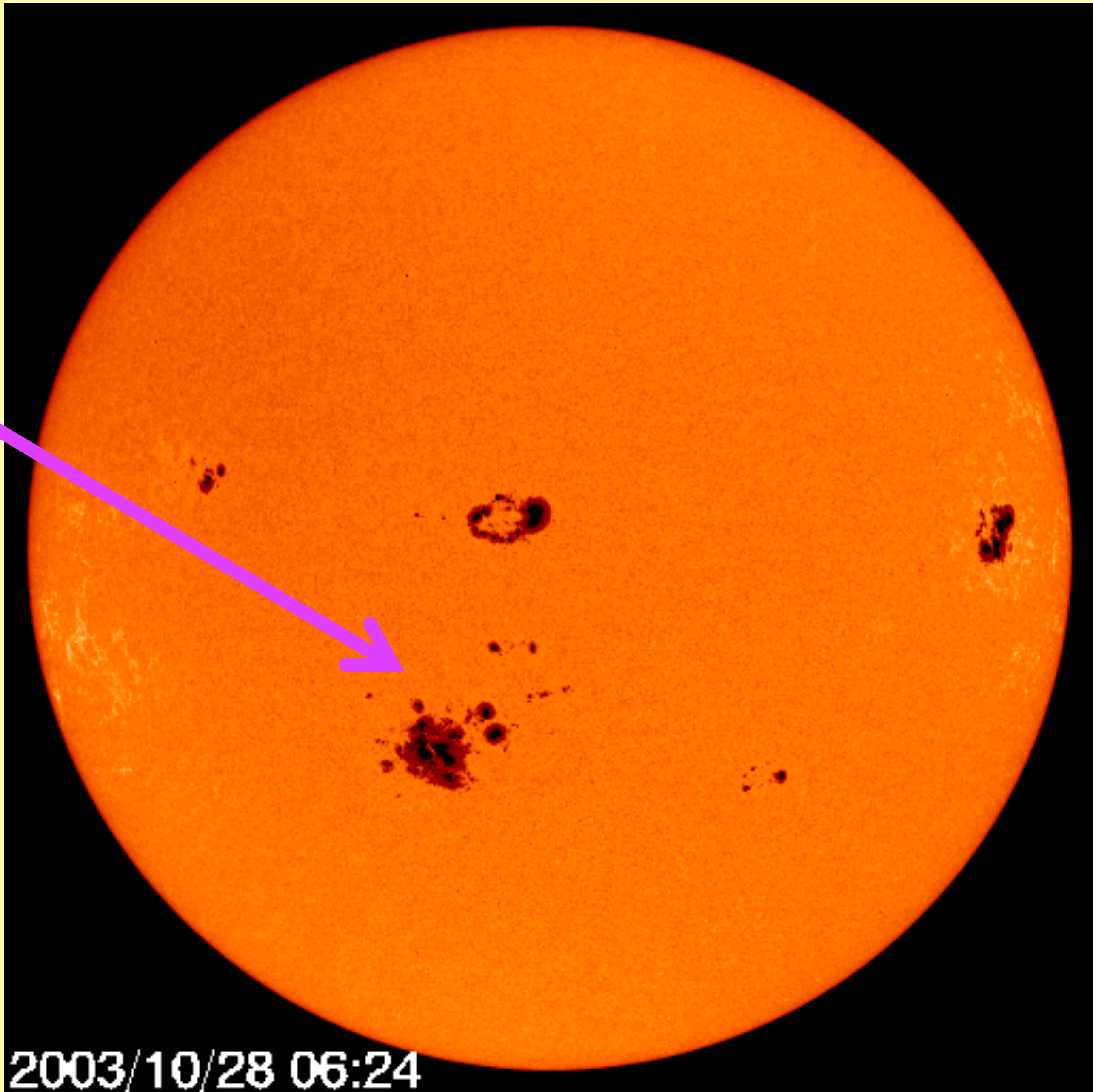
Now – core of flare in corona –

involves **eruption** of coronal magnetic flux rope **which drives reconnection below**





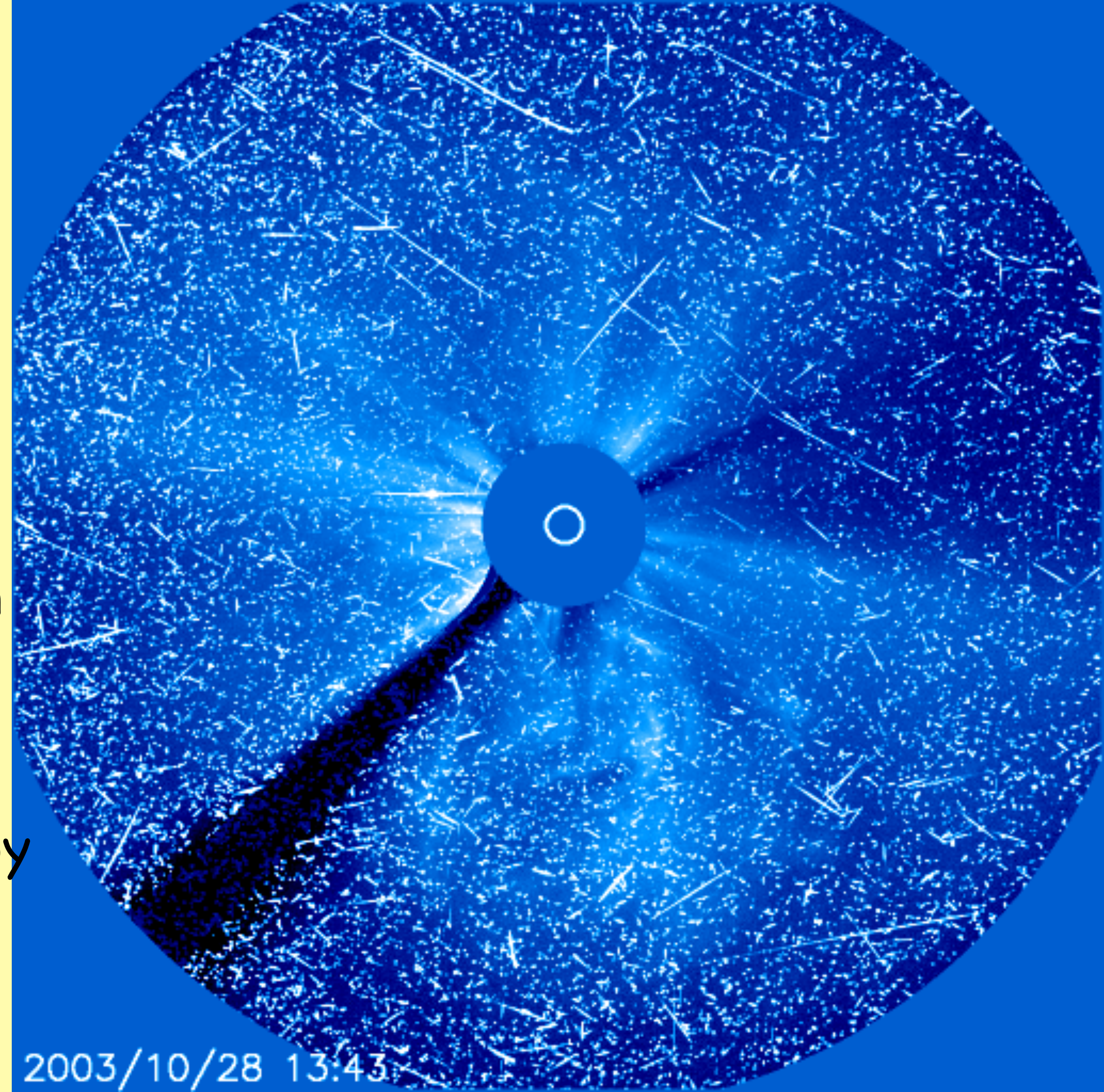
Example complex sunspots before flare



Outer Corona – eruption

1–2 days reach Earth

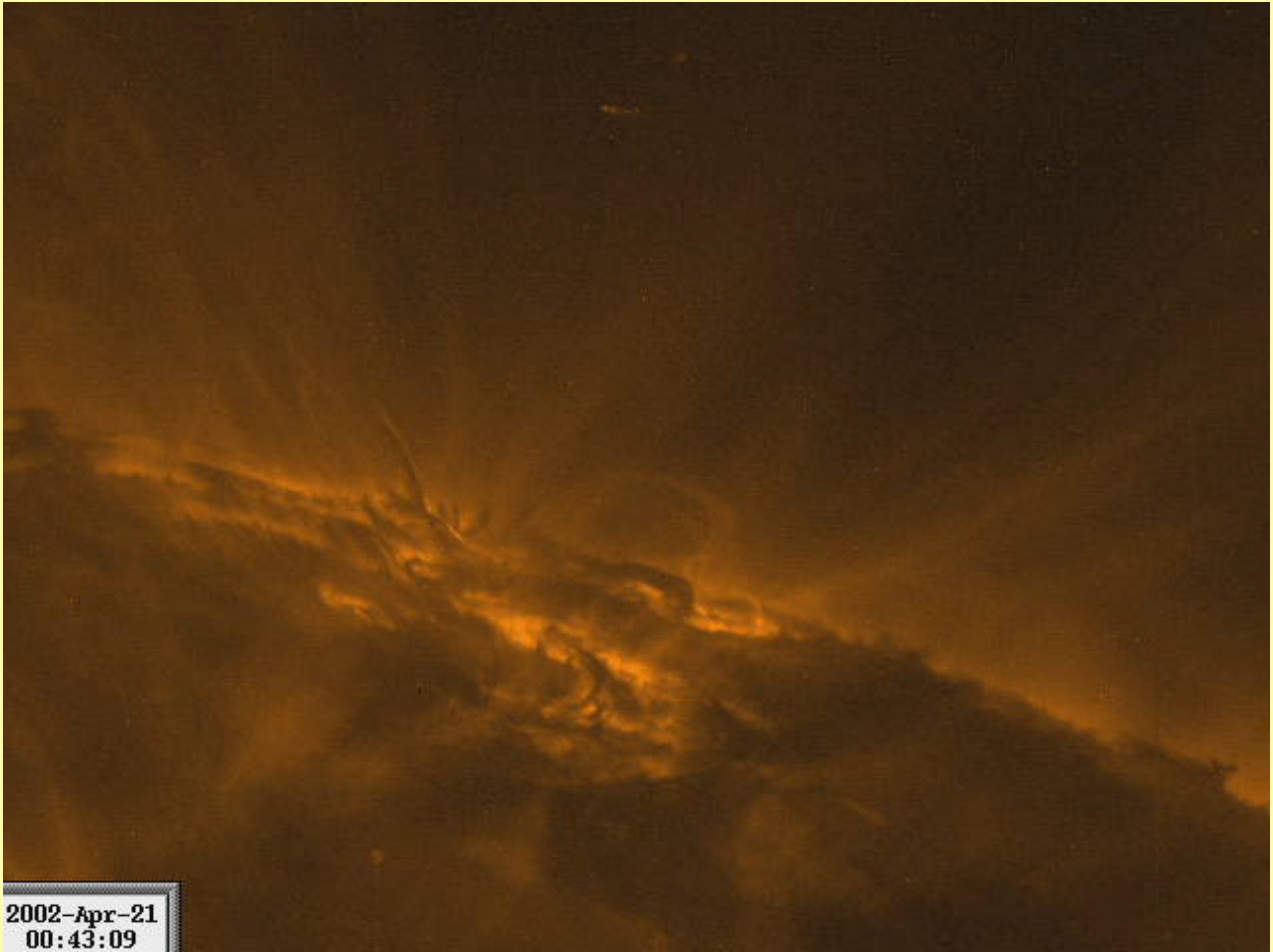
Snow – rel^c particles accelerated by reconnection & shocks [Mandraki]



Aurora in St Andrews

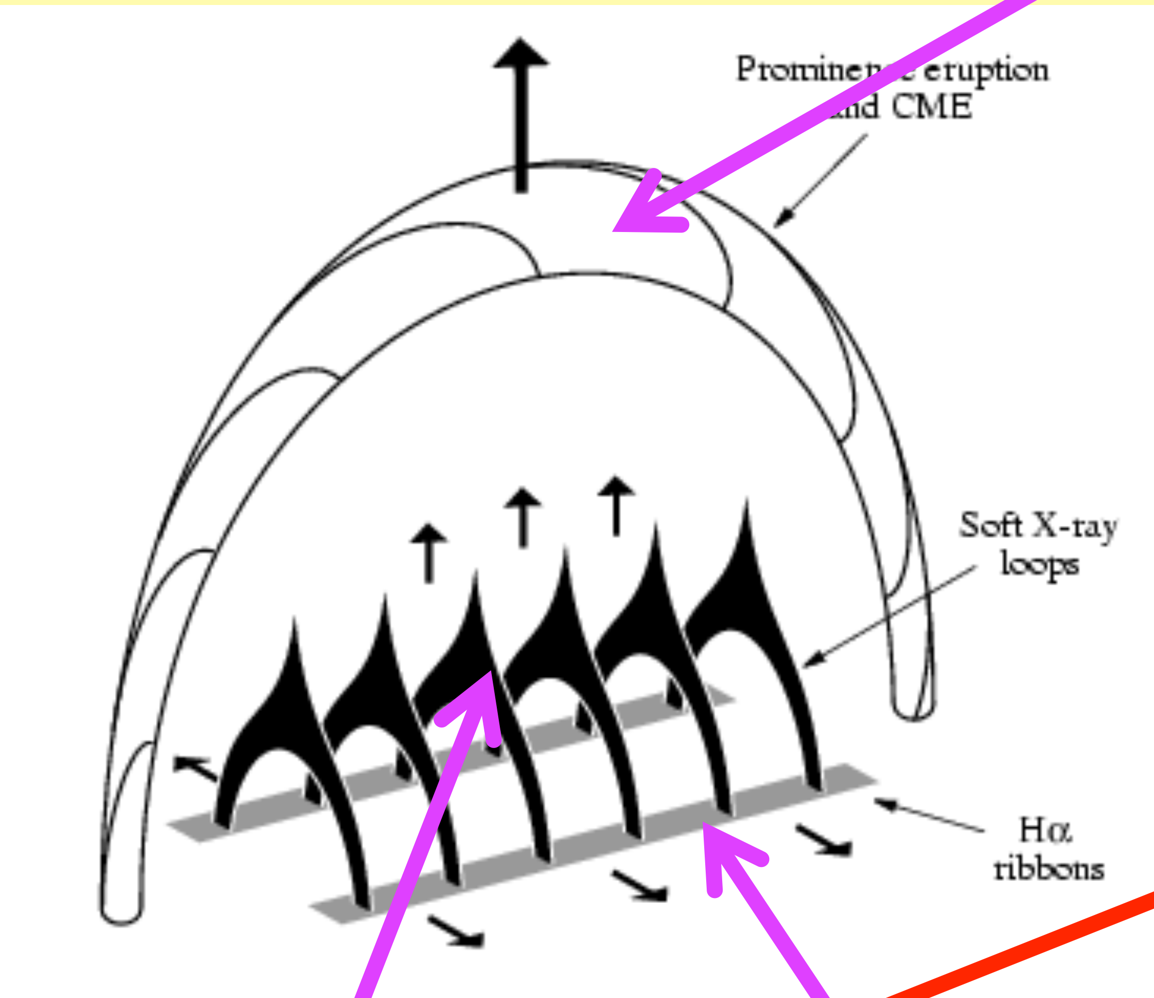
Zoom to compare images
(7 instruments on 3 satellites)

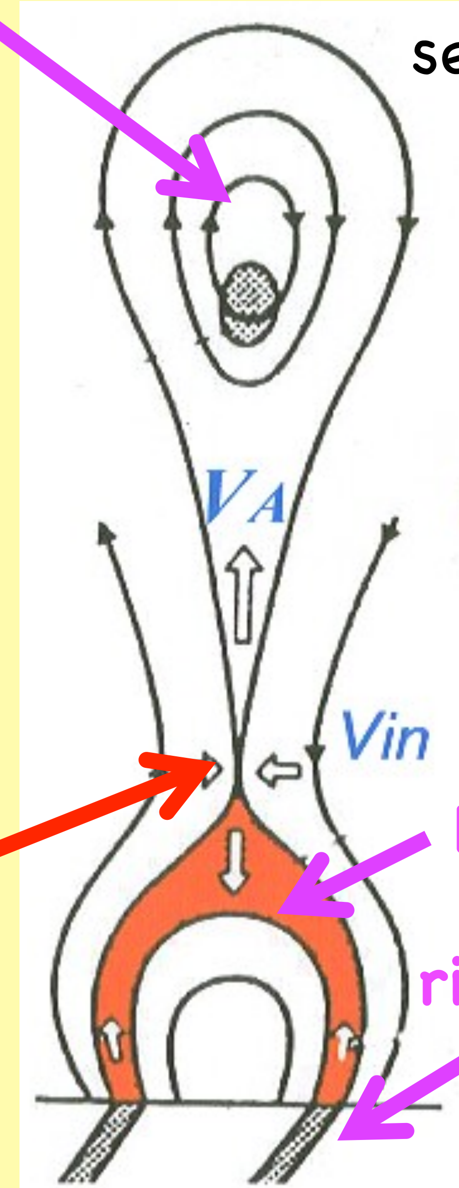
Eruption --> rising 1MK flare loops- draining



So in main phase – Flux rope

In 2D vertical section





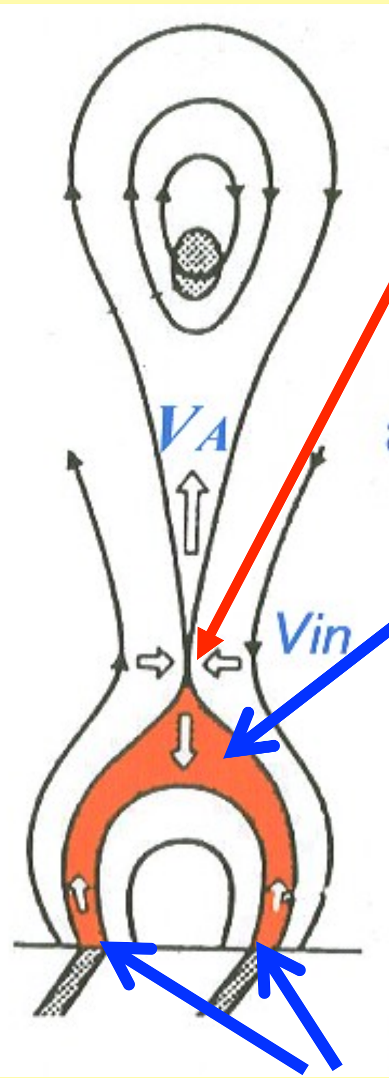
loops & ribbons

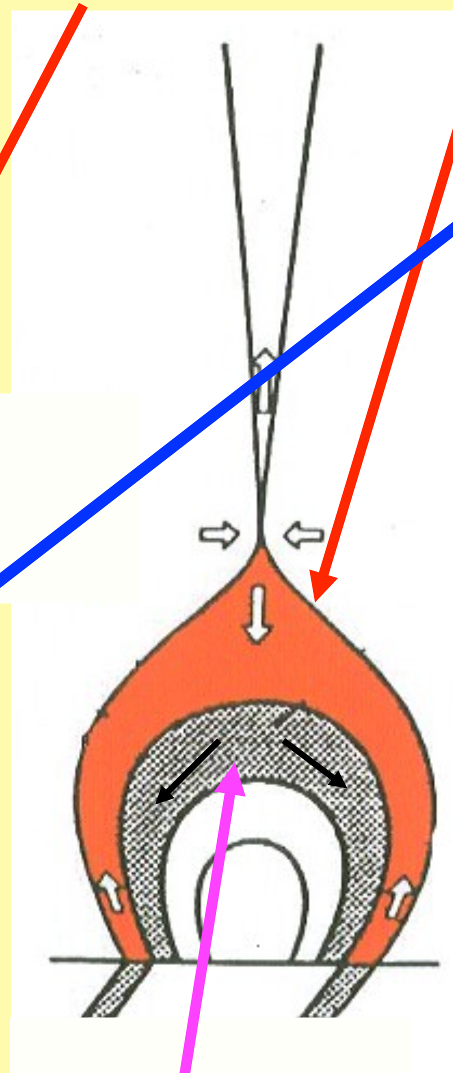
Arcade hot coronal loops + chromospheric ribbons

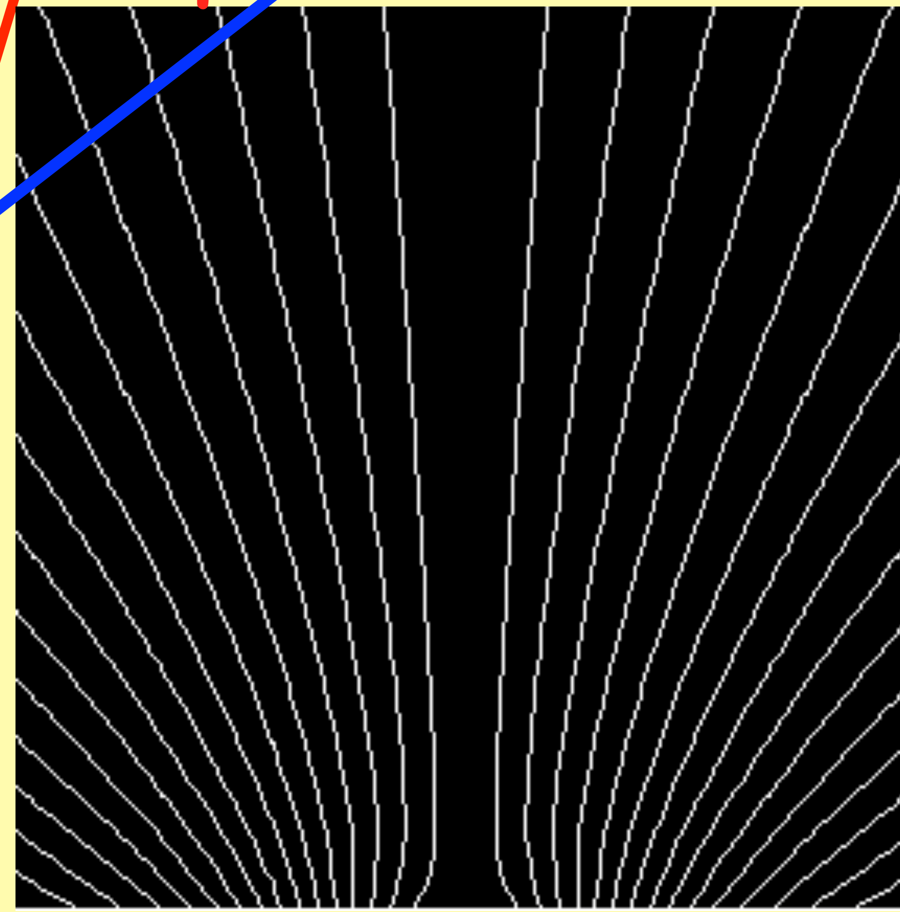
Reconnection adds magnetic flux/helicity to flux rope

Reconnection -- > hot loop

As recon continues, new loops form & heated







filled by evaporation

old loops cool & drain

Yellow – very hot

red – cooled

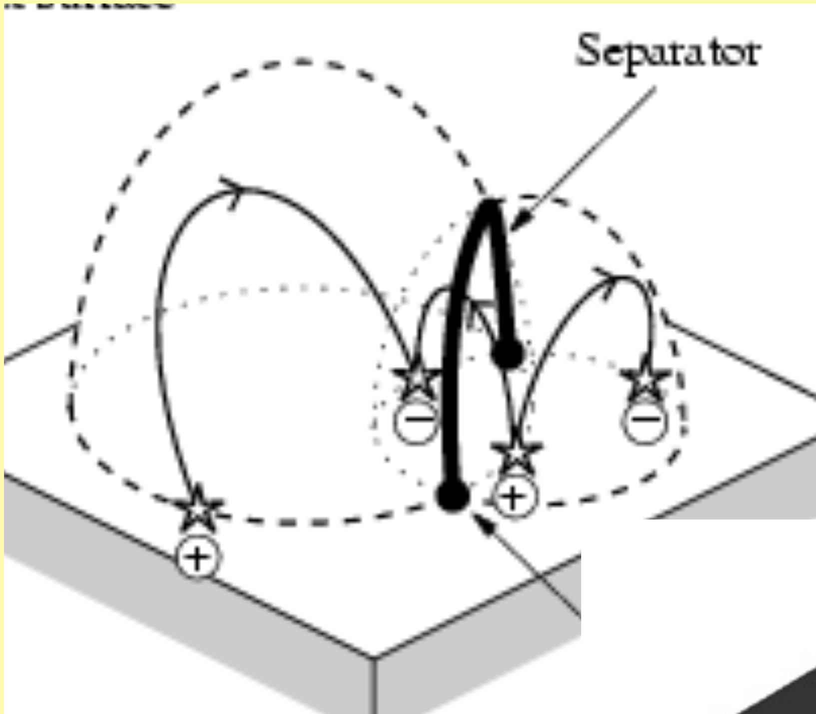
?? Kind of reconnection occurs in flare/CME ?

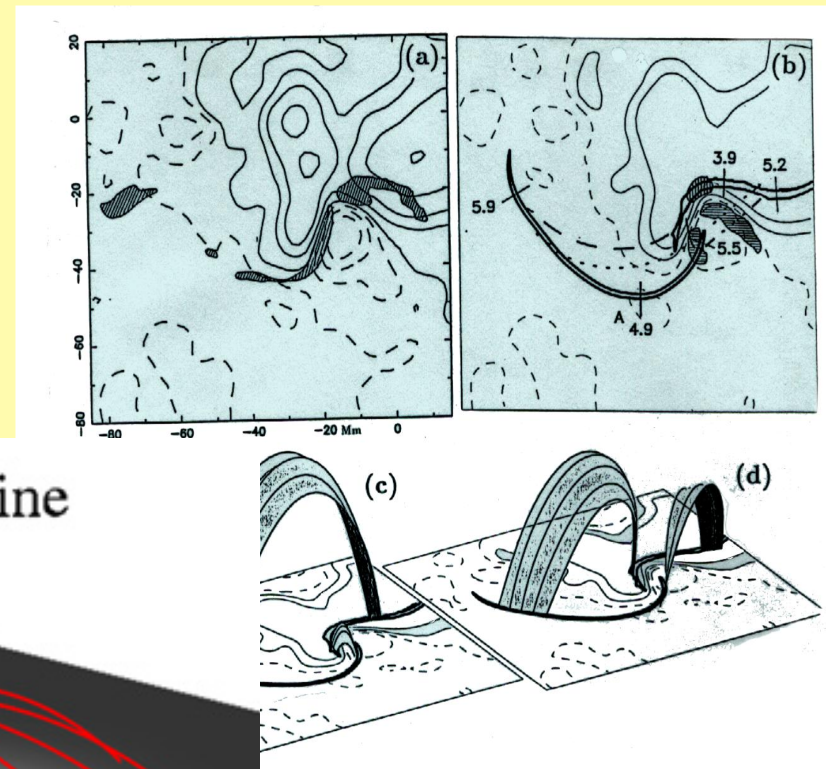
separator

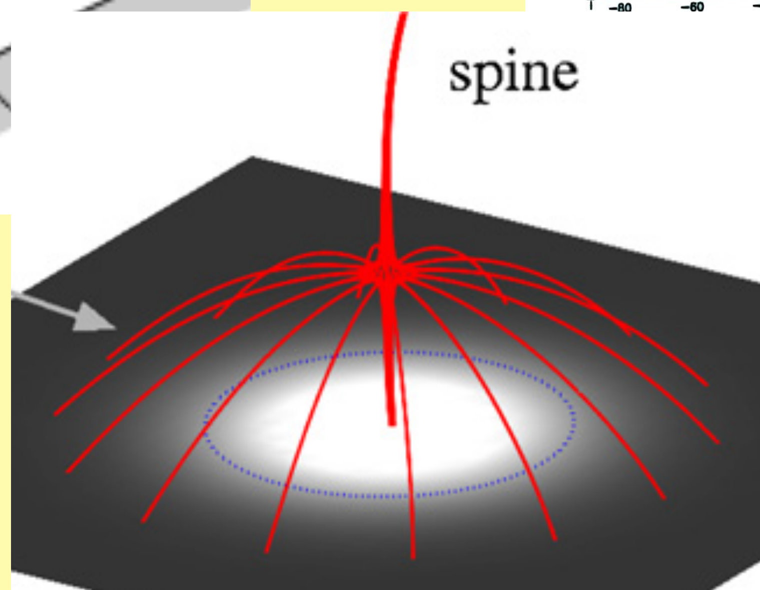
(field line joining 2 nulls)

quasi-separator

(remnant of separator when no nulls)

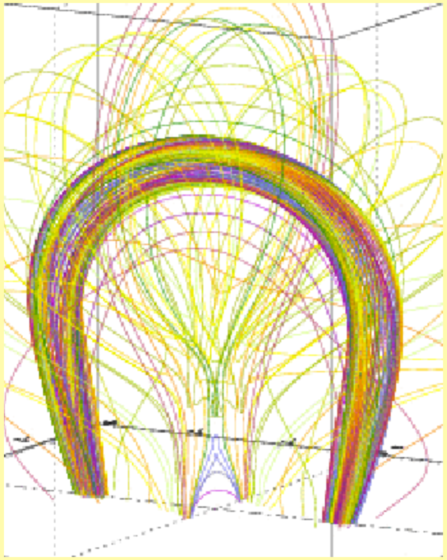


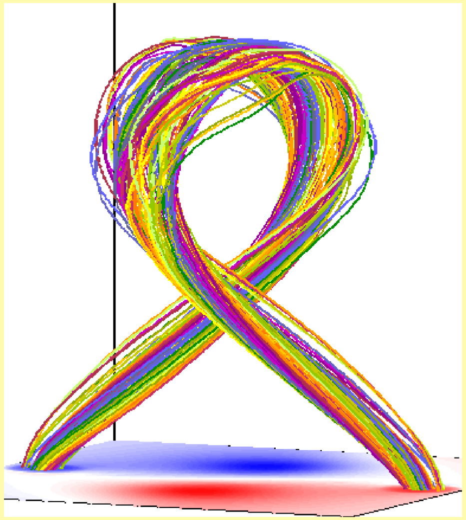




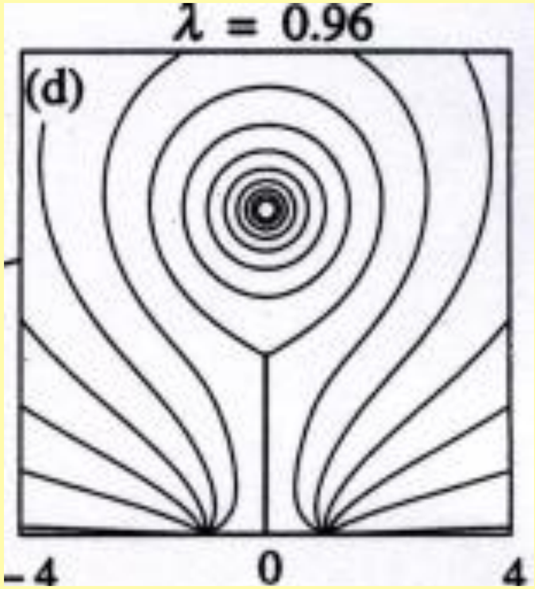
coronal null point

Cause of eruption
– torus or kink instability,



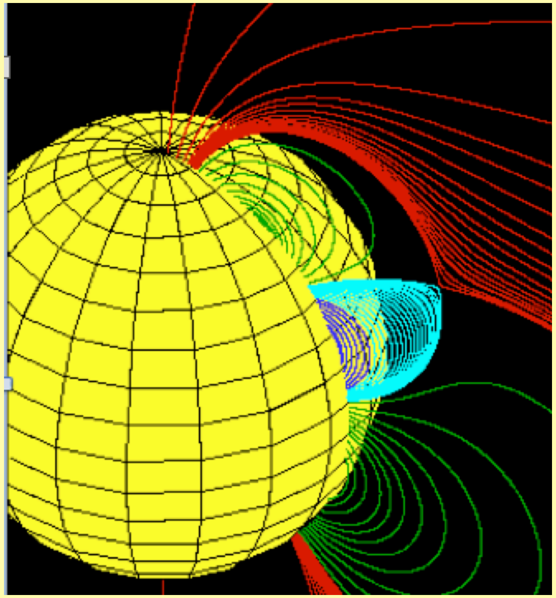


or magnetic nonequilibrium
[e.g. Chen]



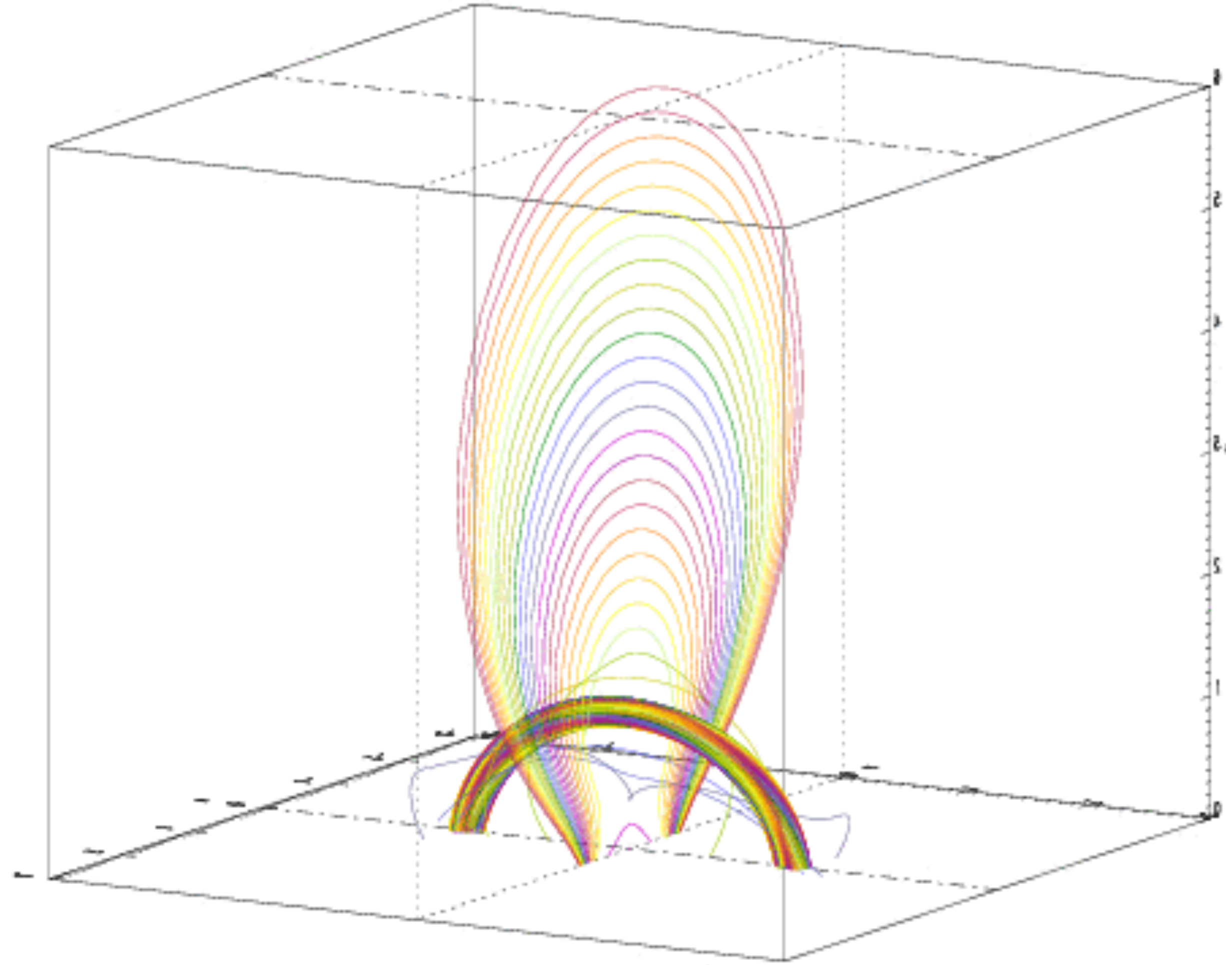
[Temmer]

or magnetic
breakout



Ex of torus instability

Eruption - -> reconnection below



?? Nature **3D reconnection in** rise phase

– bright pts, spread, create ribbons

?? How is **twist** in erupting flux rope produced

Some of twist in eruption is from initial flux tube

Suggest new way create twist [Priest & Longcope, 2017]:

(i) In rise phase, by **"zipper" reconnection**

-spreads along coronal arcade $A_+ A_- \to B_+B_-,\ C_+C_-,\ D_+D_-$

At each reconnection total magnetic helicity conserved,

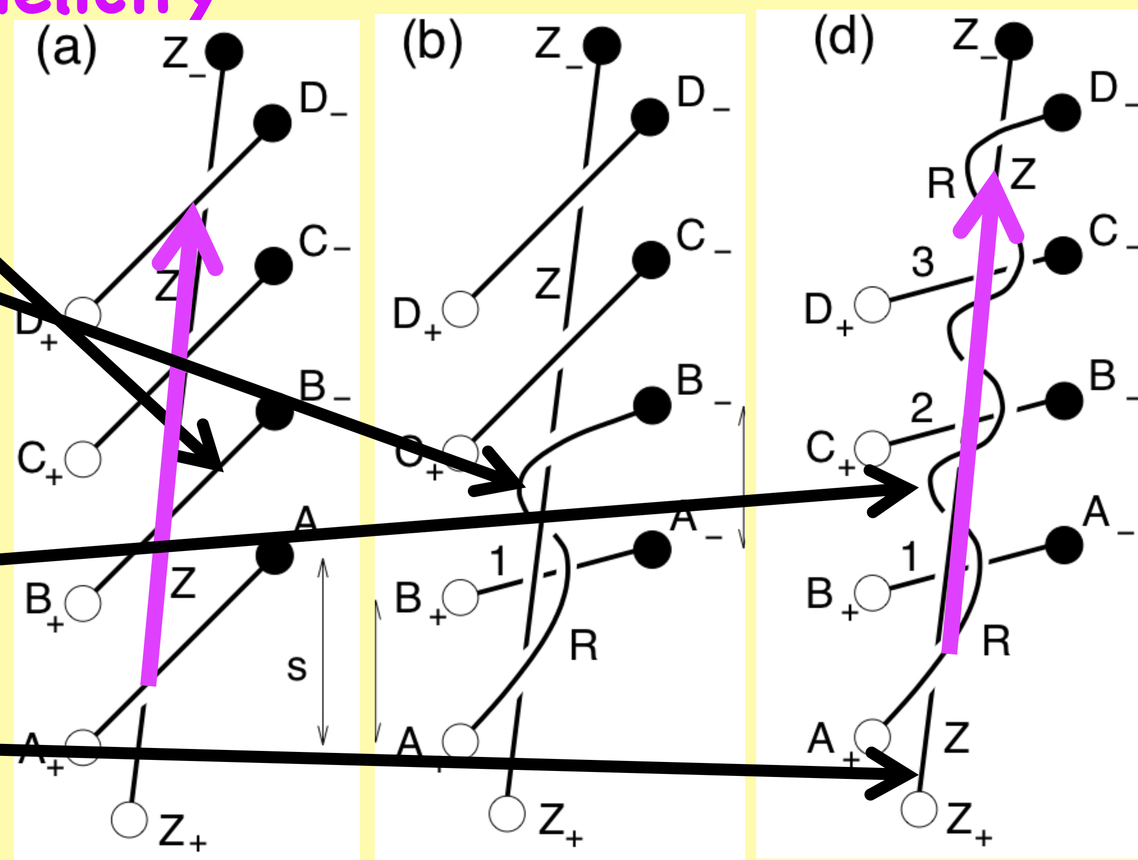
but **mutual magnetic helicity** of [inner] coronal arcade

-> self helicity of new flux rope

So zipper reconnection creates

Core of high twist

around initial tube

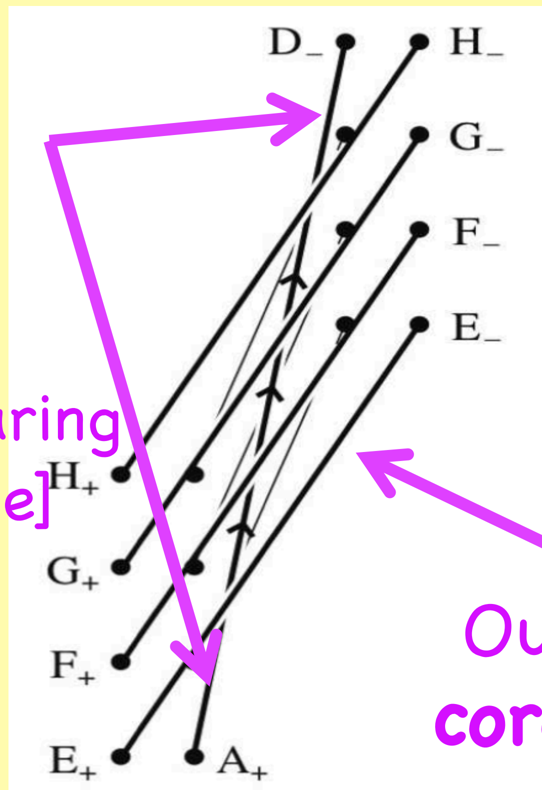


(ii) **During Main Phase,** flux tube continues to grow by quasi-2D reconnection, with mutual helicity of outer coronal arcade → self helicity of new outer part of flux rope

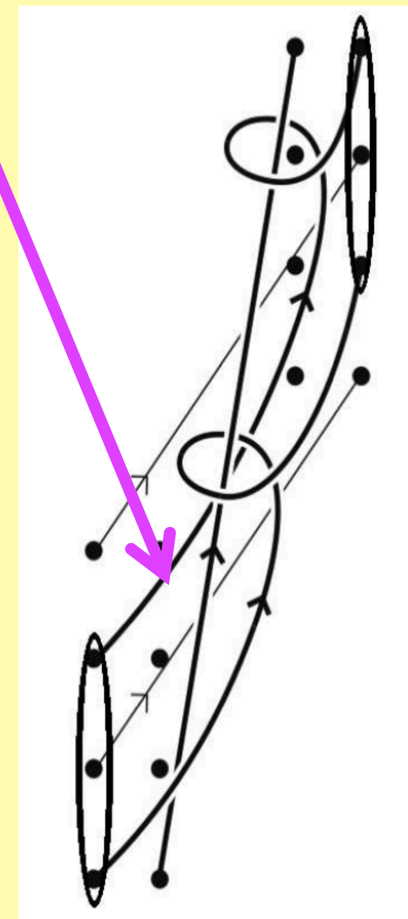
Start of main phase:

Core Flux Rope

[created during rise phase]



Outer **coronal arcade**



[cf Thalmann, Nindos, Gopalswamy...]

8. In Conclusion

- ❖ **SUN – many intriguing unsolved problems**

  – huge progress

  would have delighted Alfvén:

  ? generate magnetic field,

  ? dynamic fine-scale nature atmosphere

  ? heat corona

  ? cause of solar flares

  ? accelerate solar wind

- ❖ **Future breakthroughs – new observations**

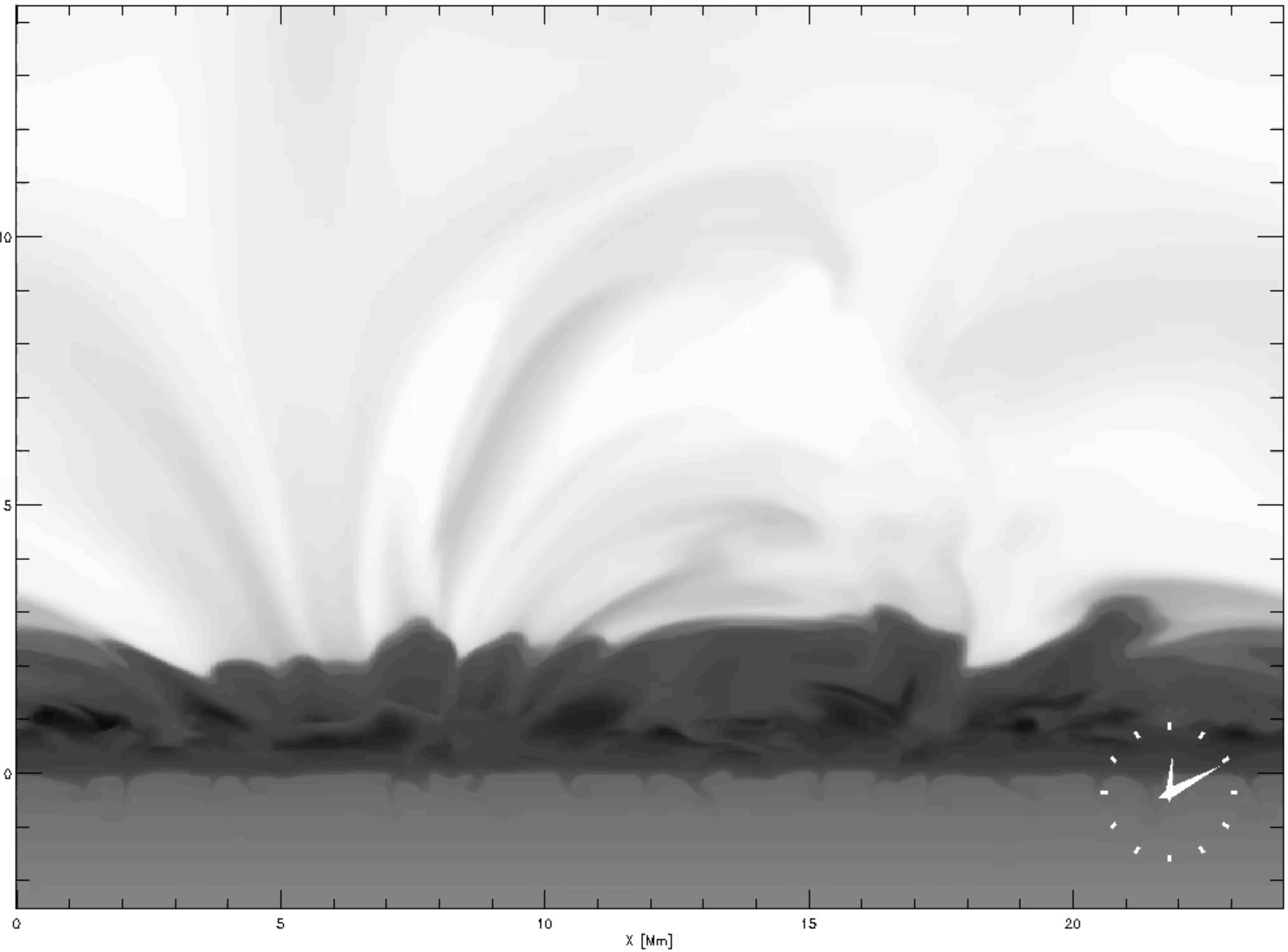
European Solar Orbiter mission (2019),

DKIST 4m telescope on Hawaii (2019),

Clever ideas/theories in spirit of Alfvén


So let's enjoy the challenge &
the beauty of the Sun

Vertical cut thro' simulation (T>100 kK white)



Corona

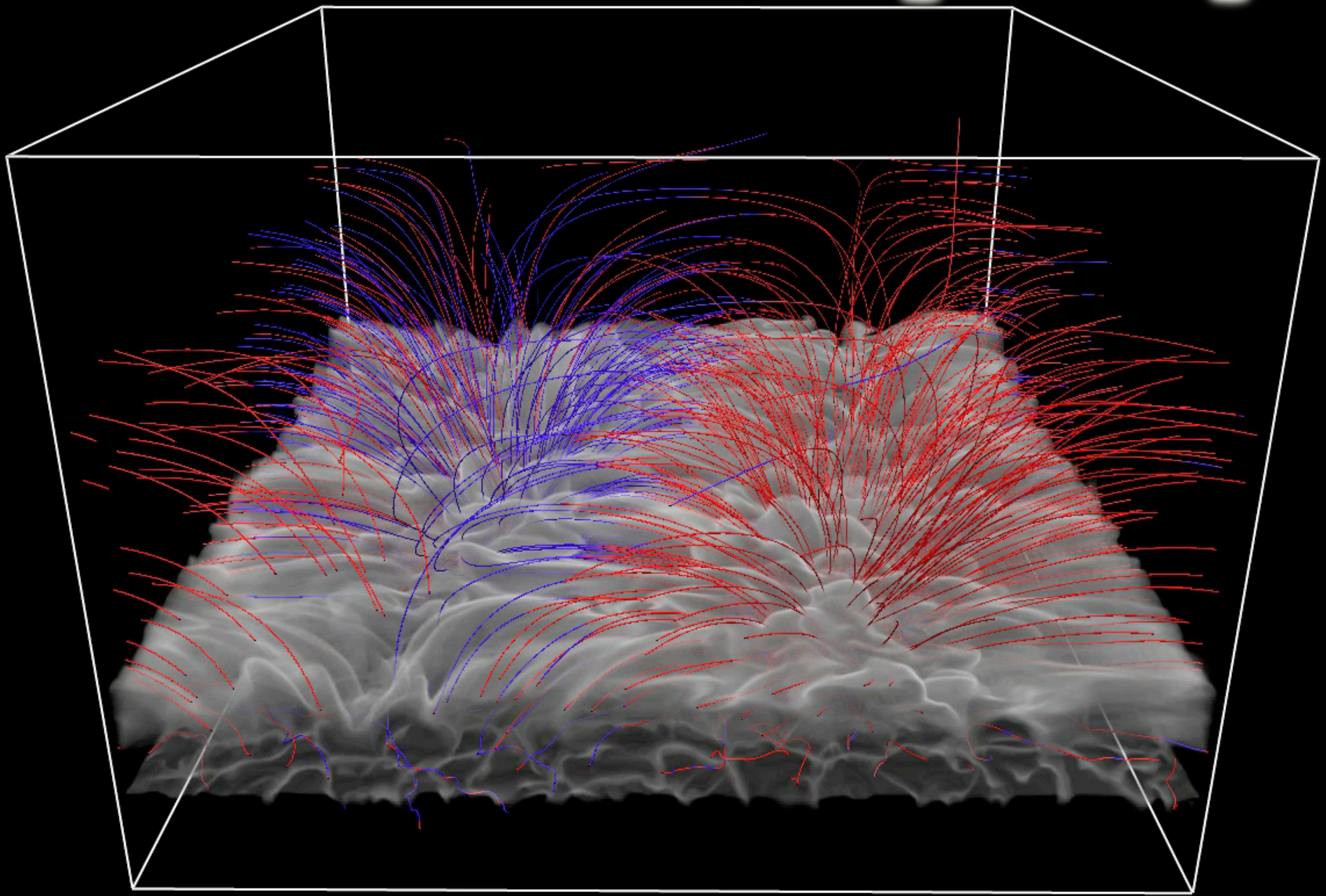
Chromo-
sphere

Photo-
sphere

Chromosphere v dynamic – heated by MHD waves

Plasma at 10,000 K

+ magnetic field lines with $B_z>0$ and $B_z<0$



Major Discoveries with Bifrost:

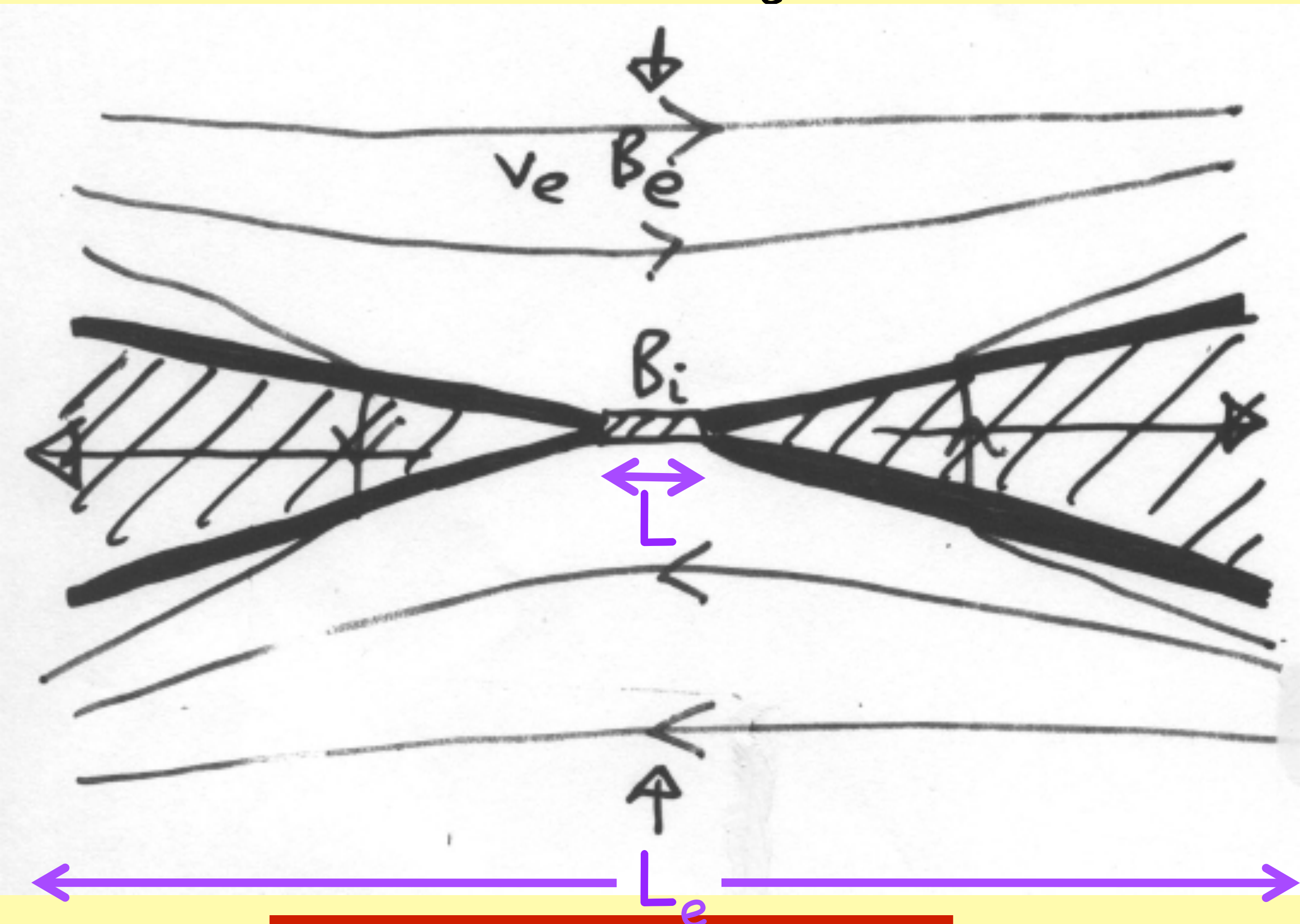
- 1st realistic model of chromosphere [Hansteen,Carlsson]
- Understanding puzzling features of chromospheric lines (Hα, Mg H&K) [Leenarts]
- Understand impact of non-equilibrium H ionization [Leenarts, Olluri]
- Understand formation of He lines such as He II 304 [Golding]
- Puzzling jets (spicules) – magnetic shock wave [Hansteen, Rouppe]

Petschek (1964)

-- 1^{st} to consider external
-- assumed v_e given > v_{SP}
-- allow $L < L_e$

- **Sheet bifurcates –**

  Slow shocks – most of energy



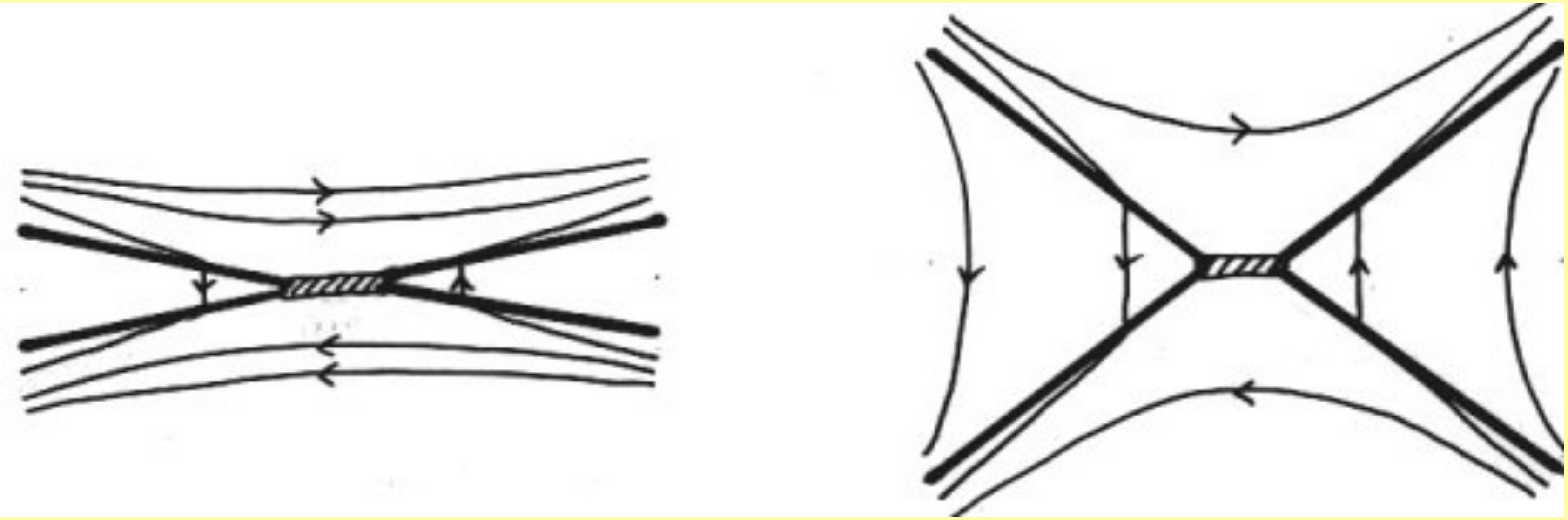
- **Reconnection speed v_e :**

any rate up to maximum

$$v_e = \frac{\pi v_A}{8 \log R_{me}} \approx 0.1 v_A$$

Note: (i) different i.c.'s -- >

different fast regimes



Almost uniform

Nonuniform

Petschek is **one particular** case

(ii) Petschek can occur if η enhanced in diff^n region

(iii) Collisionless models w. Hall effect ->

fast reconnection - rate = 0.1 v_A

(iii) In 2D: Reconnection at X-point

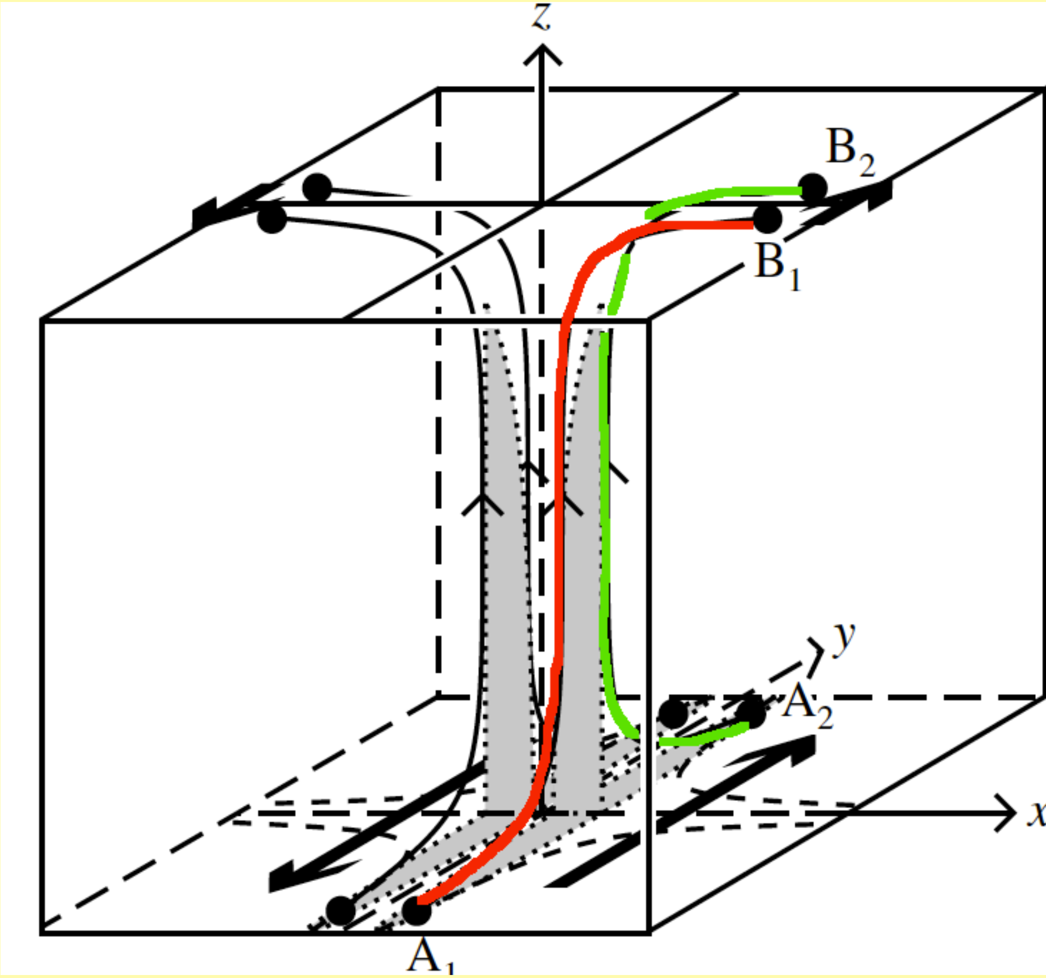
In 3D:

- 1. at a separator,
- 2. near a null point,
- **3. in absence of null:** **or**

at k.B=0 surface

Quasi-Separatrix Layer

(mapping gradient large)



e.g., X-field + B_z

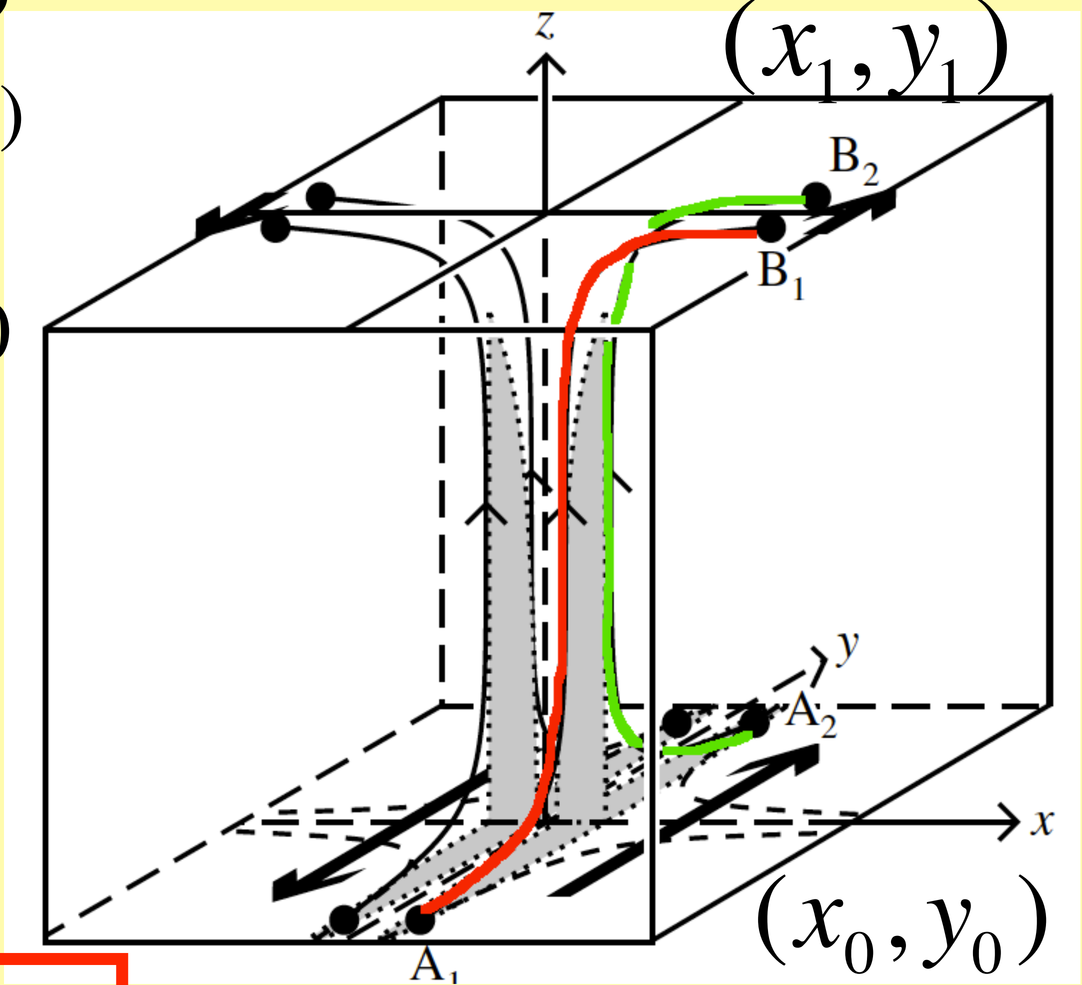
B map cont^{sy} to A

– strong gradient – flip – quasi-separator

All natural locations where strong j grow

QSL Reconnection (Priest & Demoulin)

Impose $\boldsymbol{v}$ *at* (x_1, y_1) *on top*
and deduce $\boldsymbol{v}, \boldsymbol{E}$ *at* (x_0, y_0)



$$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = 0, \quad \nabla \times \boldsymbol{E} = 0$$

$$\Rightarrow \boldsymbol{E} = \nabla \Phi, \ \boldsymbol{B} \cdot \nabla \Phi = 0,$$

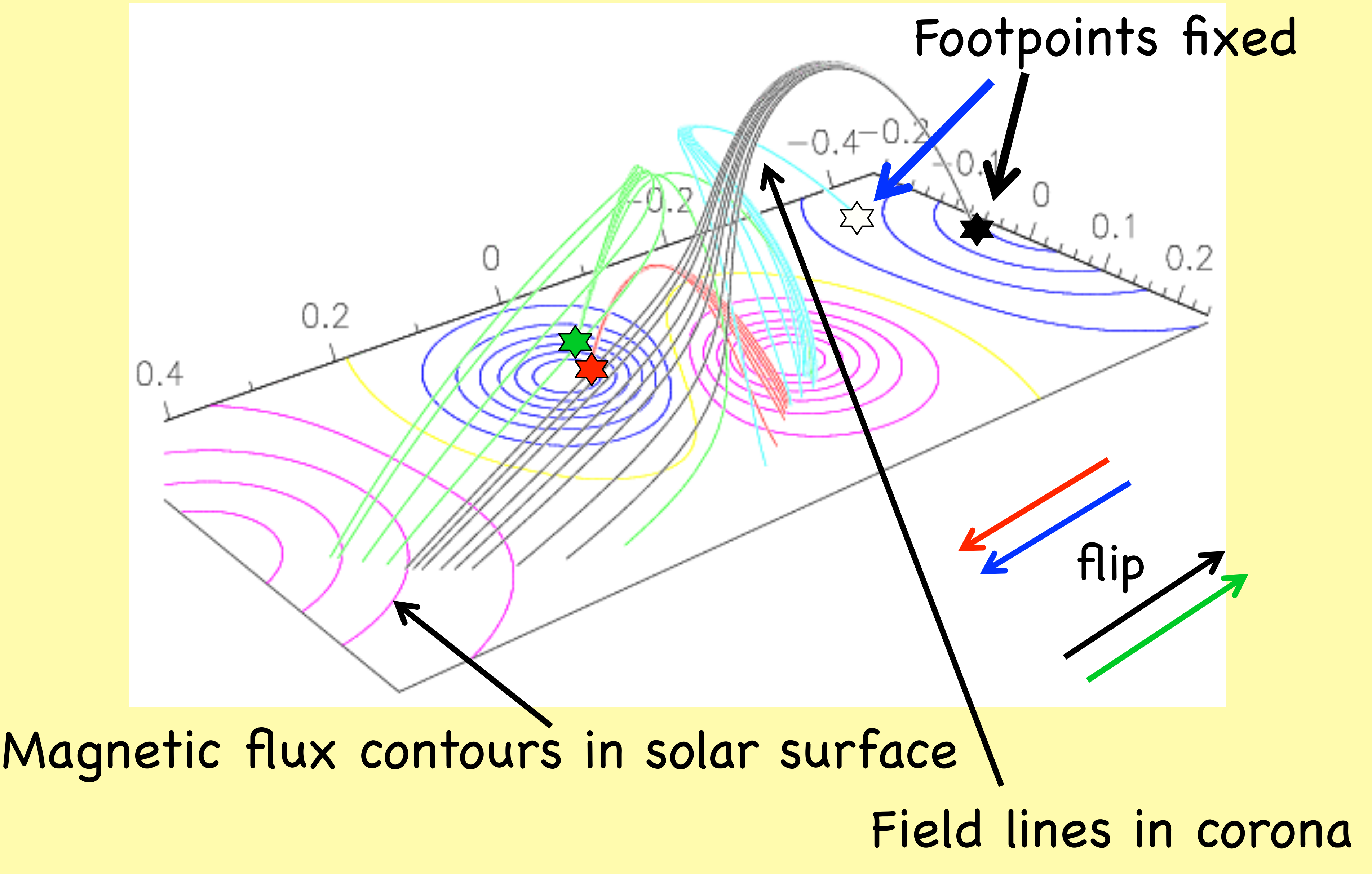
$$\boldsymbol{v} = \frac{\nabla \Phi \times \boldsymbol{B}}{B^2}$$

$$\text{Then } E_{x0} = \frac{\partial \Phi}{\partial x_0} = \frac{\partial \Phi}{\partial x_1} \frac{\partial x_1}{\partial x_0},$$

Large in QSL-flipping

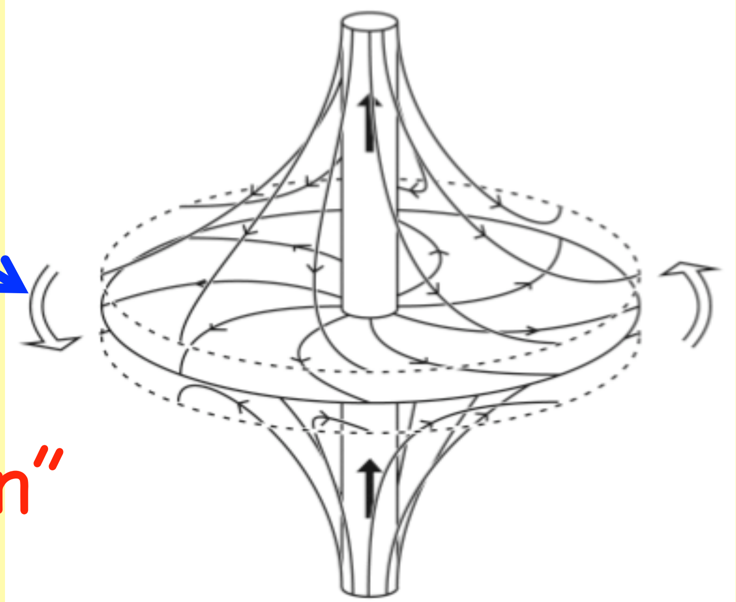
EXAMPLE of QSL reconnection with field lines flipping

(Demoulin)



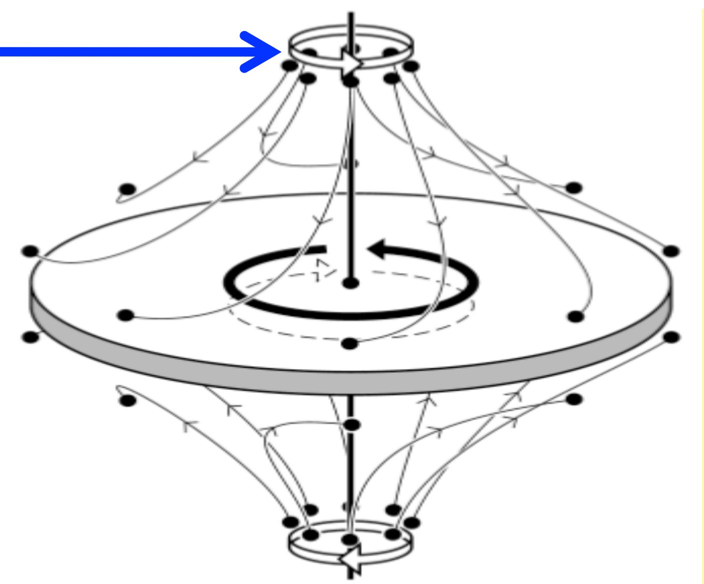
Near Null Pt, Resistive MHD experiments -- >
3 types of 3D null reconnection

- (a) Rotate edges of fan
- -- > J along spine
- Rotational B-line slippage



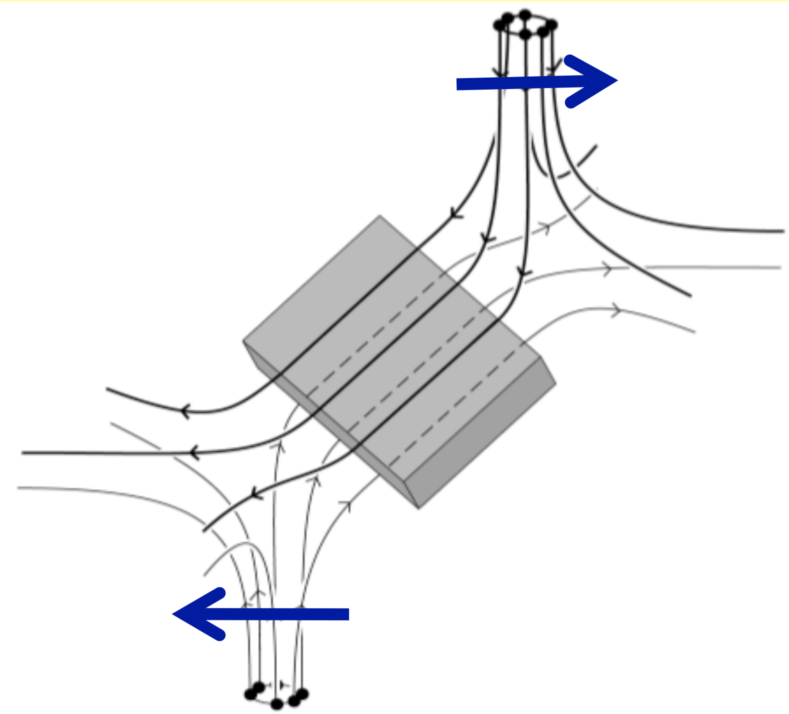
"Torsional spine reconnection"

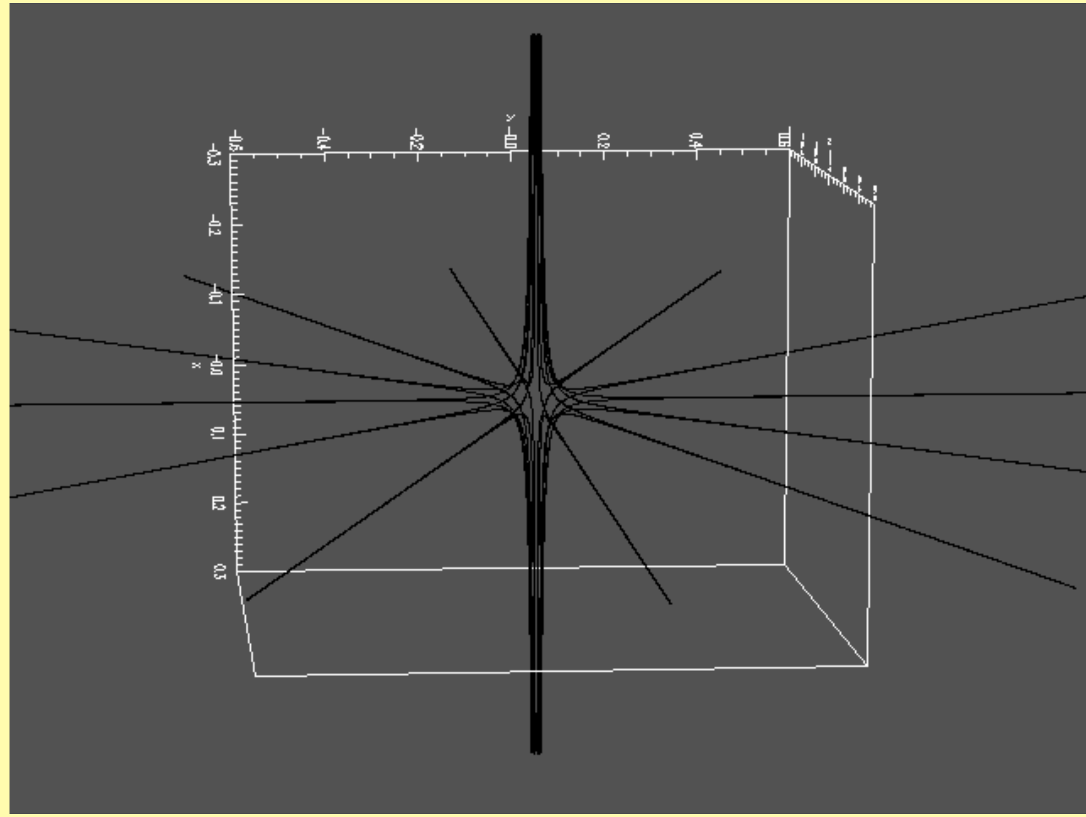
- (b) Rotate ends of spine
- drives planar J in fan
- Counter-rotation above/below fan



"Torsional fan reconnection"

(c) Shear spine or fan:



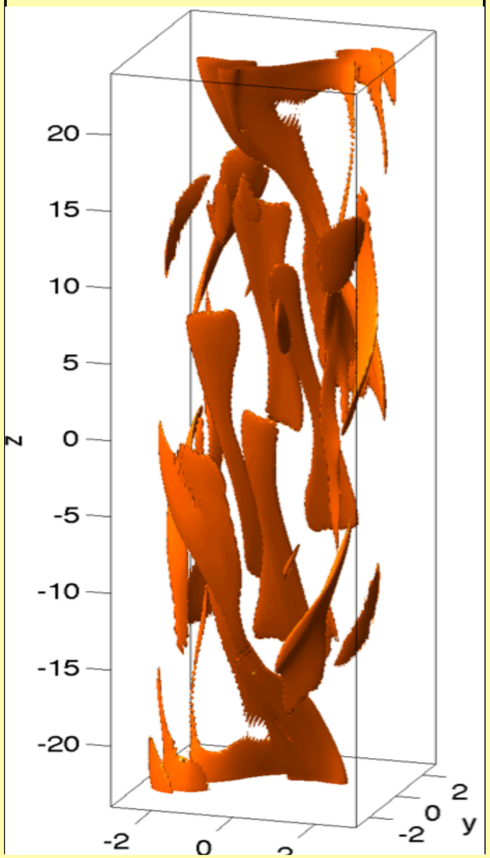


- B collapses to sheet with J (in colour) ll fan
- Flow crosses spine and fan

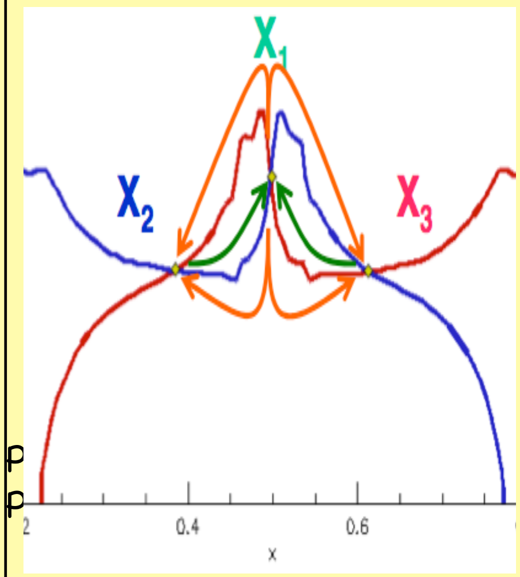
"Spine-fan reconnection"

Other General Properties in 3D

Can occur at **multiple interacting** sites [**Hornig, Galsgaard**]



Flux can be reconnected **multiple times**



Flyby experiment of Parnell
3 separators

Unlike 2D, no need for **fast** (Alfvénic) **outflows**

For **collisionless & turbulent aspects** see

Today: Buechner, Zenitani, Gomez

and later in the week
Uzdensky (**turbulent recon**)
Yamada (**particle acceler**)
Daughton (**electron region**)
Lazarian (**stochastic recon**)
………