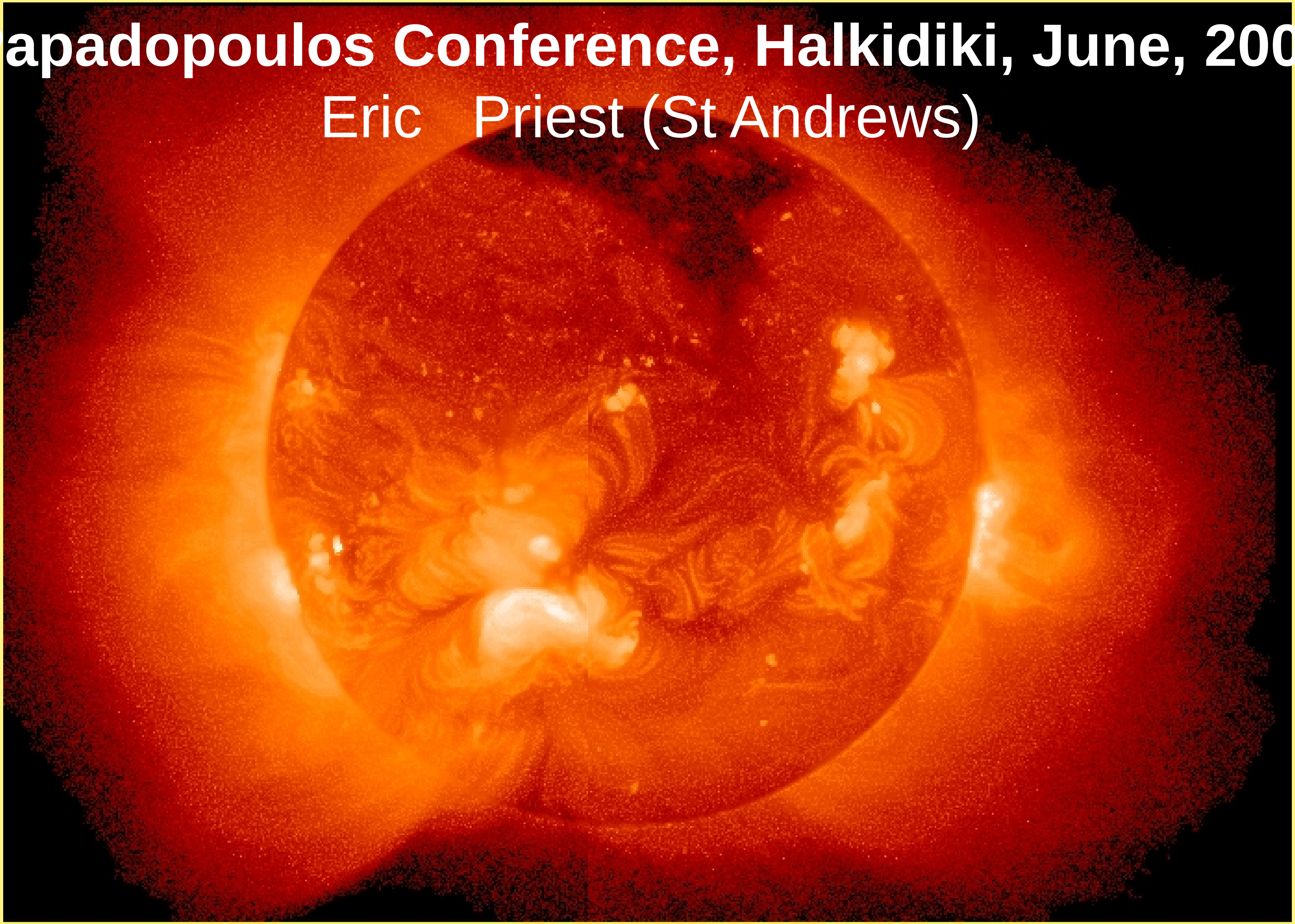
NONLINEAR PLASMA PHYSICS of the SOLAR CORONA

(Papadopoulos Conference, Halkidiki, June, 2009)

Eric Priest (St Andrews)



Introduction: Dennis Papadopoulos

PhD Maryland 1968 --> NRL 10 years --> Maryland University

(I - 1969 - coll^{less} shocks - plasma complic^{d} --> MHD!)

* Dennis: microscopic plasma astrophysics:
revolutionary ideas:

* strong turbulence in beam-plasma interactions
--> understand type III radio bursts

* anomalous transport & resistivity in ionosphere

* Collisionless shocks -->
Earth's bow shock - heat ions
Supernova shocks - heat electrons
(at high M_A by 2 stream instab^{y})

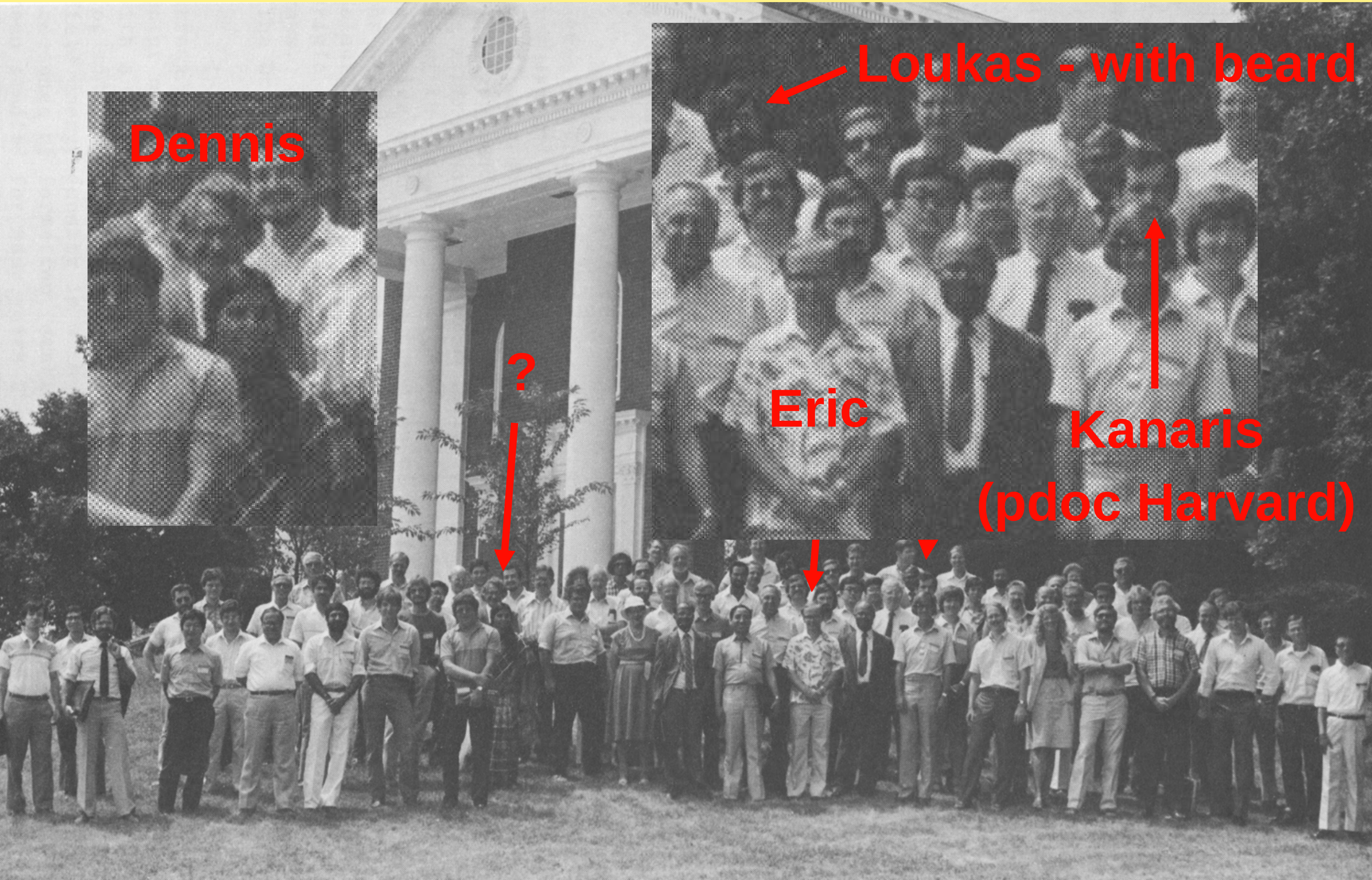
Approach: * **Use state of art computing**

* **Highly creative ideas**

IAU Symposium, Maryland, 1979

(Dennis - invited review on physics of type III radio bursts)

Symposium, Maryland, 1983



Loukas Vlahos

PhD Maryland 1979 with Kundu & Dennis P

-> army -> Maryland (1981-1985) -> Thessaloniki

Annecy SMY Workshop (1981)

I and student Peter Cargill (Ph D 81) met Loukas

--> Boulder 1982-84

Loukas persuaded Peter
--> Maryland 1984-1992 , NRL -1996 --> IC 1996

Parents: hope children fall into good company !

Peter <--> Dennis P

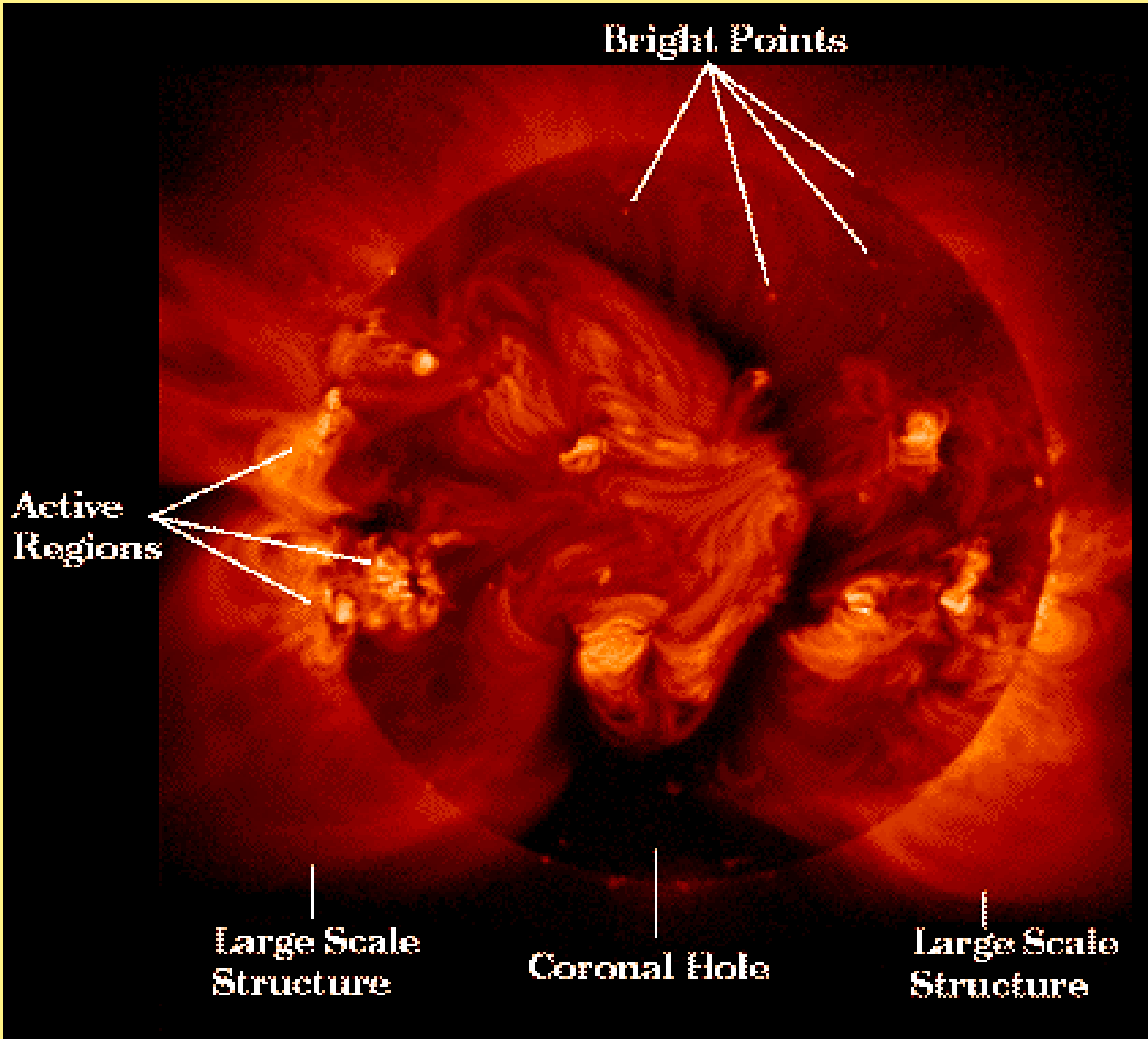
"Dennis taught me all I know about kinetic plasma phys."

1. Introduction - The Corona

Yohkoh
(5 arcsec):
a dynamic magnetic world

- subtle interactions B & plasma

Coronal holes,
Loops,
X-ray bright pts



In Corona:

*** Fundamental aspects plasma physics** --

Dennis P (& students) ground-breaking contributions:

Particle acceleration, shock waves, instabilities, waves, reconnection

*** Subtle coupling:**

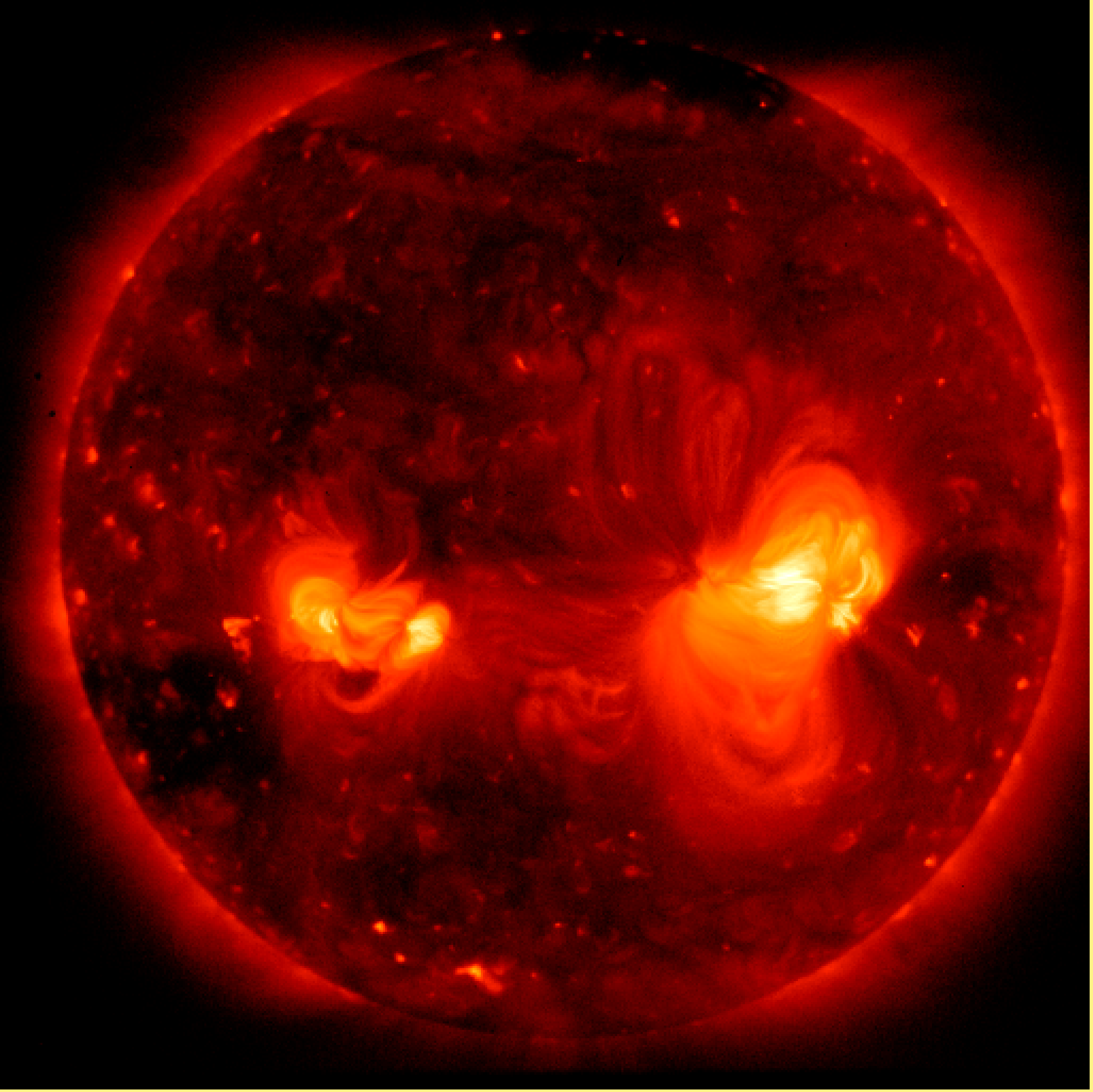
macroscopics (MHD) <---->

microscopics (kinetic plasma physics)

* MHD: global environment --

Microscopics --

transport coefficients & particle acceleration



Hinode (1 arcsec)

Stunning detail on structure & dynamics

How is corona heated?

Waves or reconnection?

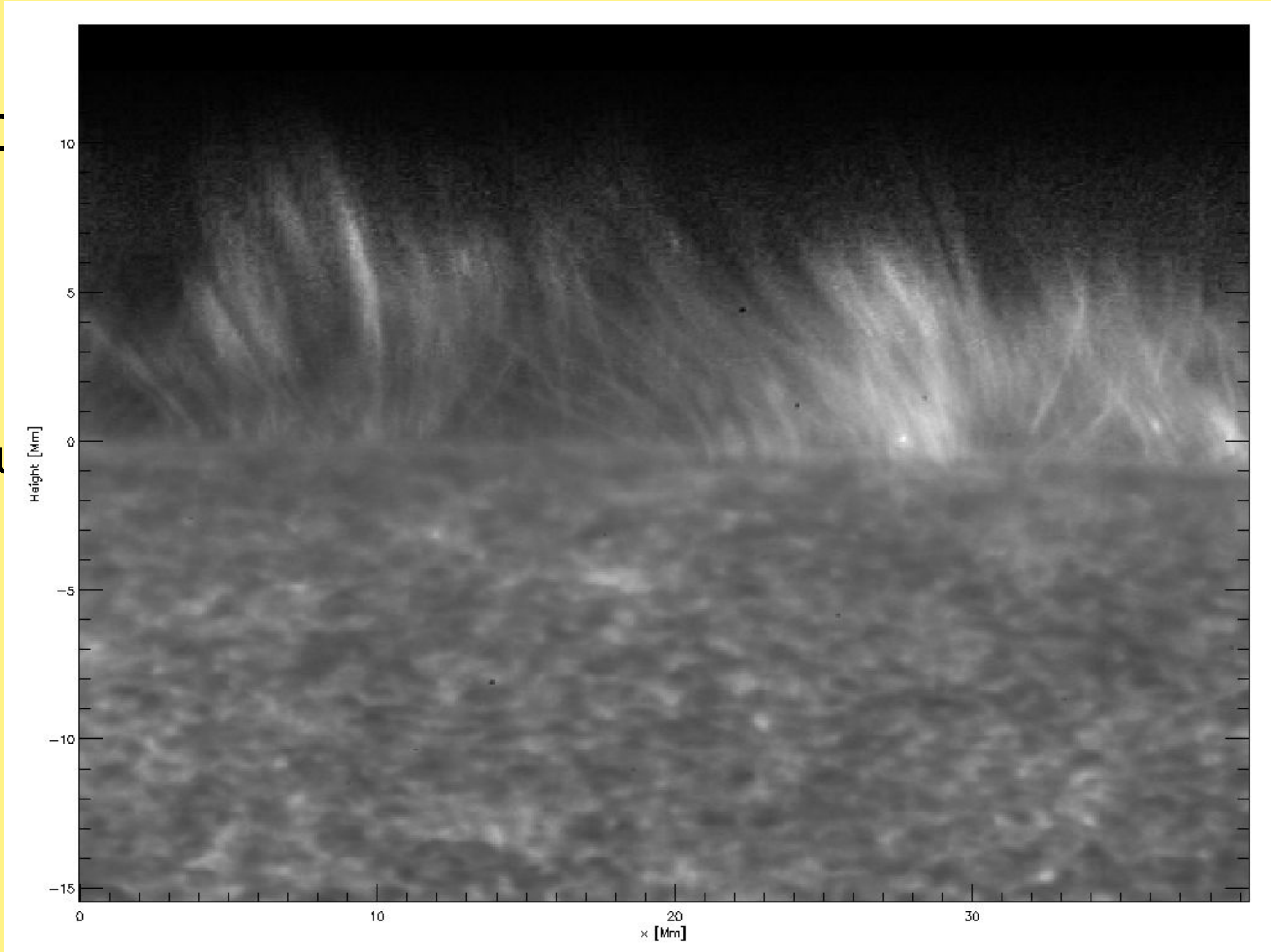
- Low-freq. waves in loops [TRACE] -too weak to heat

- Hinode --

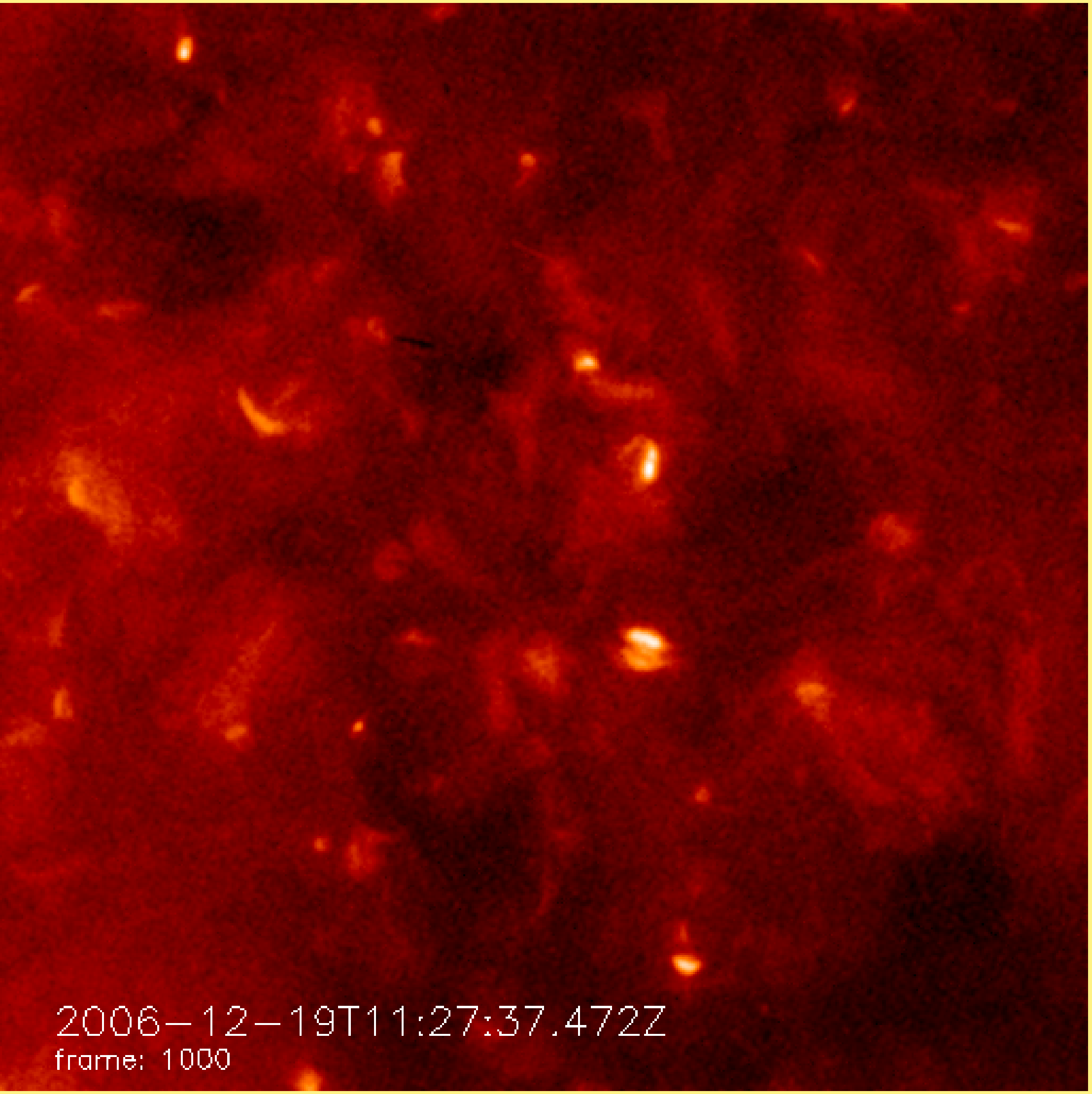
Chromospheric
Spicules
swaying

[Hansteen, Suematsu

--?? Solar wind/
coronal heating



Reconnection - most likely in low corona



[30-sec cadence, 12-hour duration]

Quiet Sun:
[XRT on Hinode]

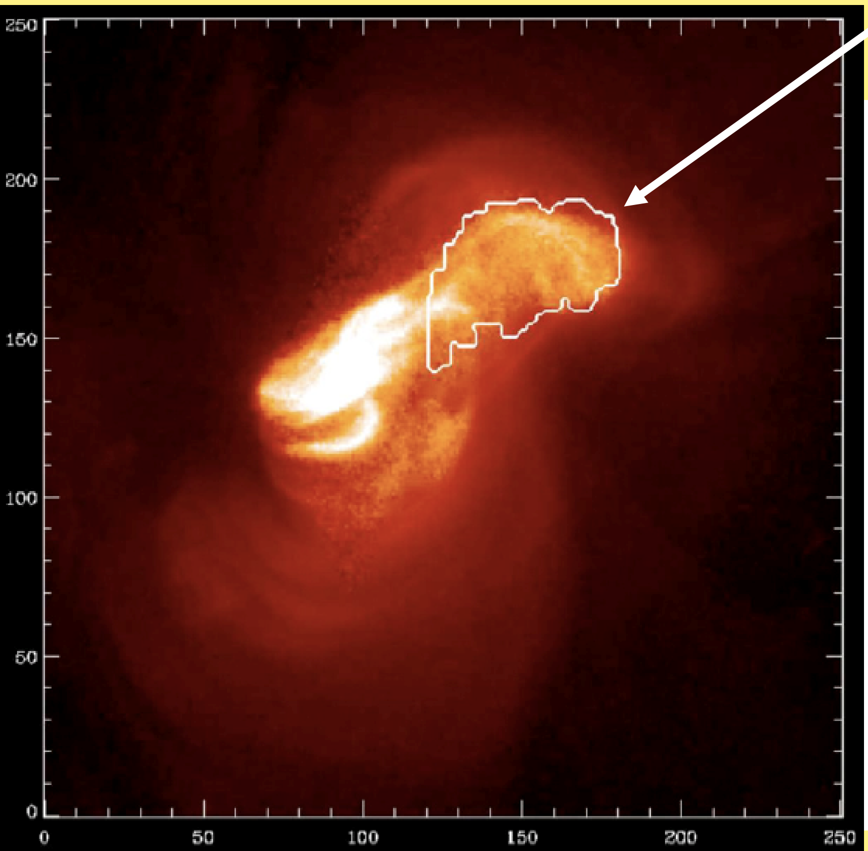
Many brightenings

X-ray bright points -
above emerging and/or
cancelling fields
in photosphere

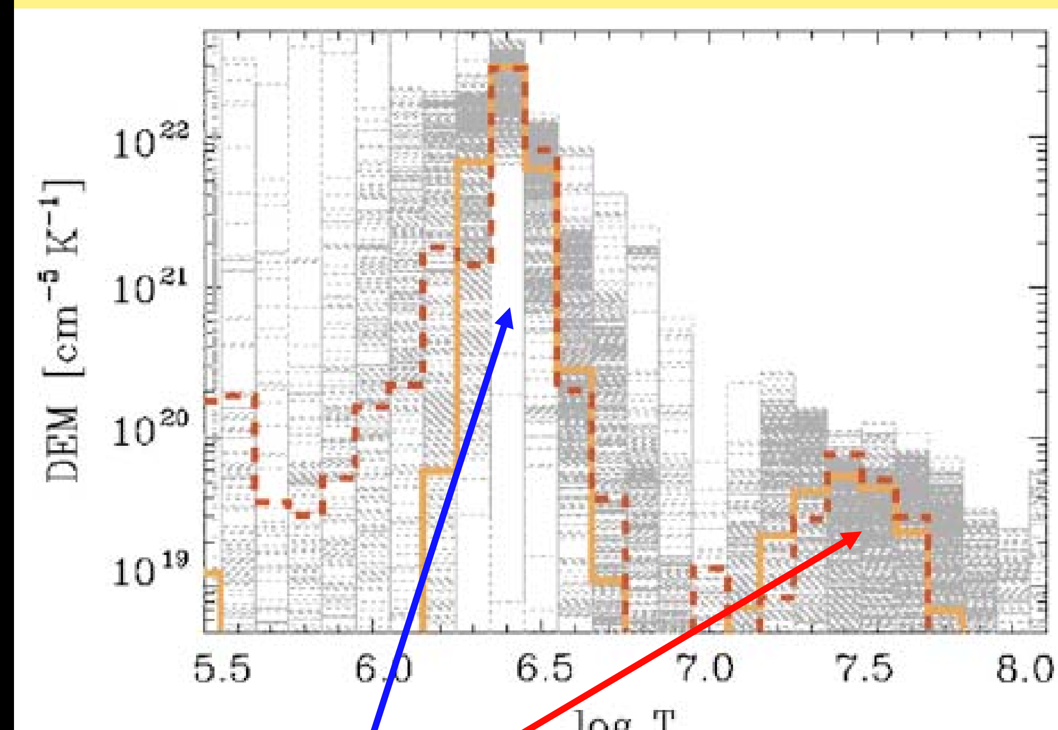
Hinode XRT - active region

(Schmeltz et al, 2009; Reale et al, 2009)

Observations inside white region



Differential emission measure



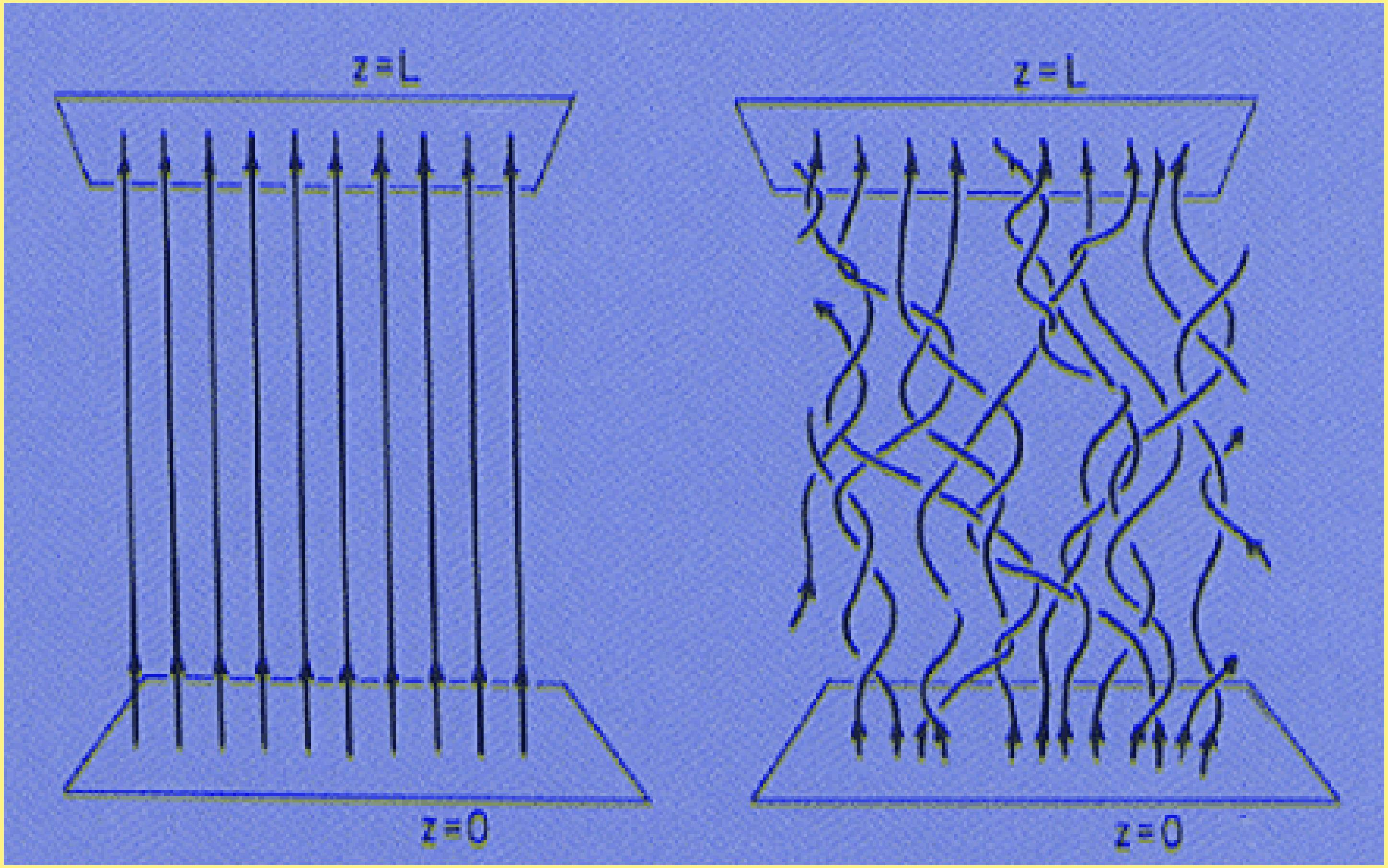
Normal active region emission at 3 MK

Plus emission (peak?) at 10-30 MK (?nanoflare

2.Coronal Heating Models

Parker's classical Nanoflare Model

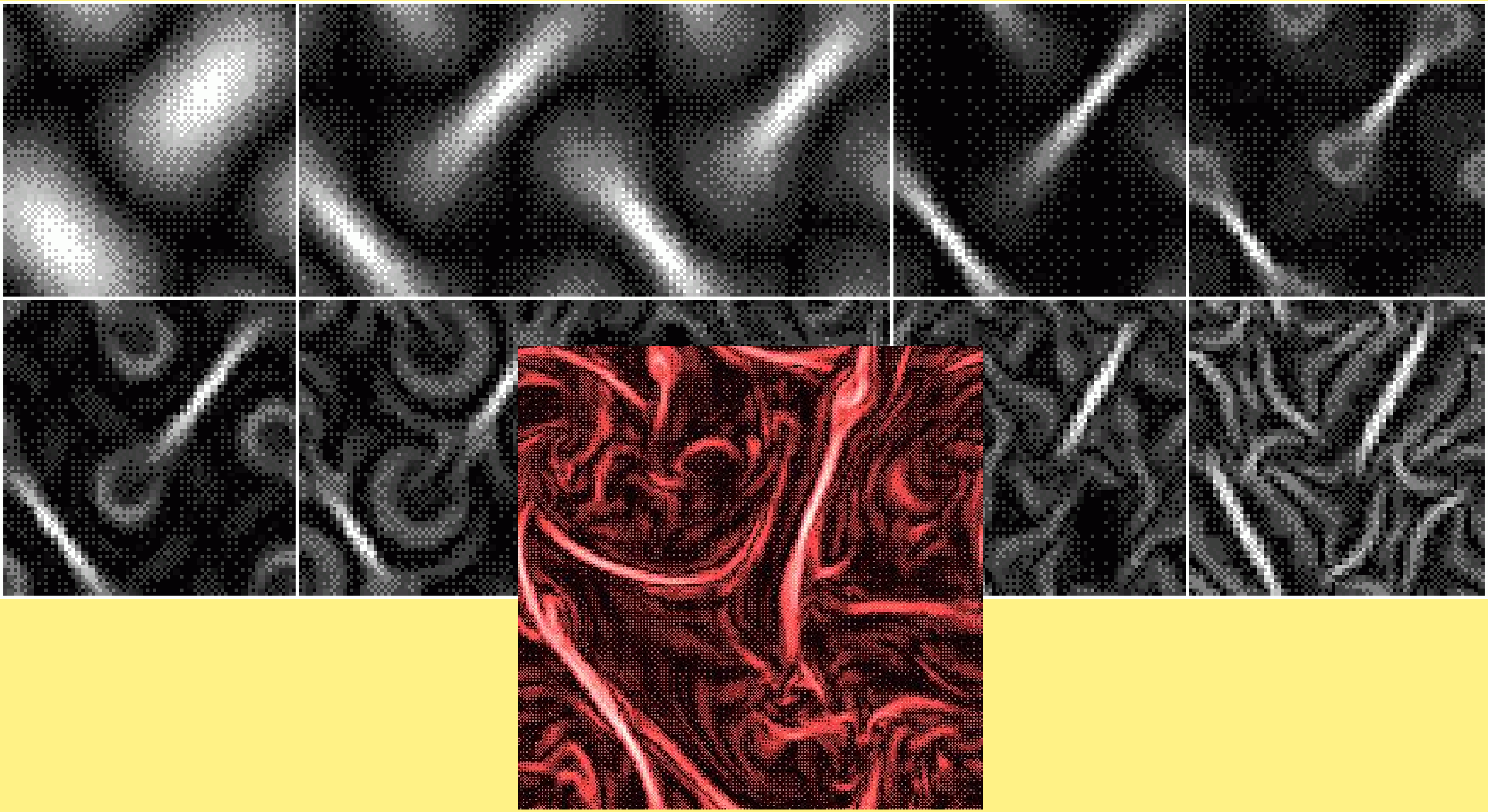
by braiding (1972)



Initial B uniform / motions braiding

Numerical Experiment (Galsgaard)

Braiding --> Current sheets grow --> turb. recon.



Active Region as a Nonlinear Driven Dissipative System (Vlahos, 2008):

* **Photospheric flux** elements: power-law distribution (N = $F^{-1.85}$)

[percolation model, Vlahos etal 1982]

* **In corona,** observed nanoflares have power-law distribution --

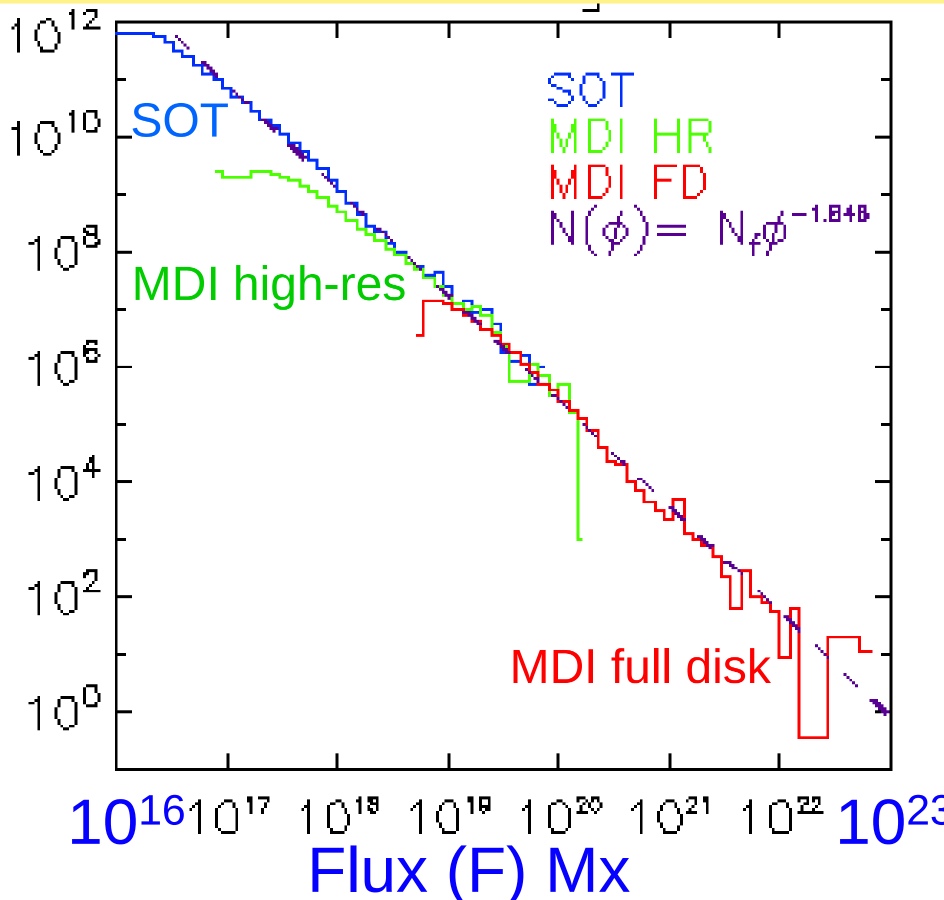
-- active region is in **SOC** (self-organised critical) state,

as current sheets form at all scales and reconnect.

* --> **stochastic acceleration** of p'cles in fractal E's

[Isliker et al, 1998; Isliker & Vlahos, 2003; Vlahos et al, 2004; Turkmani et al, 2006; Chapman, 1998..2009]

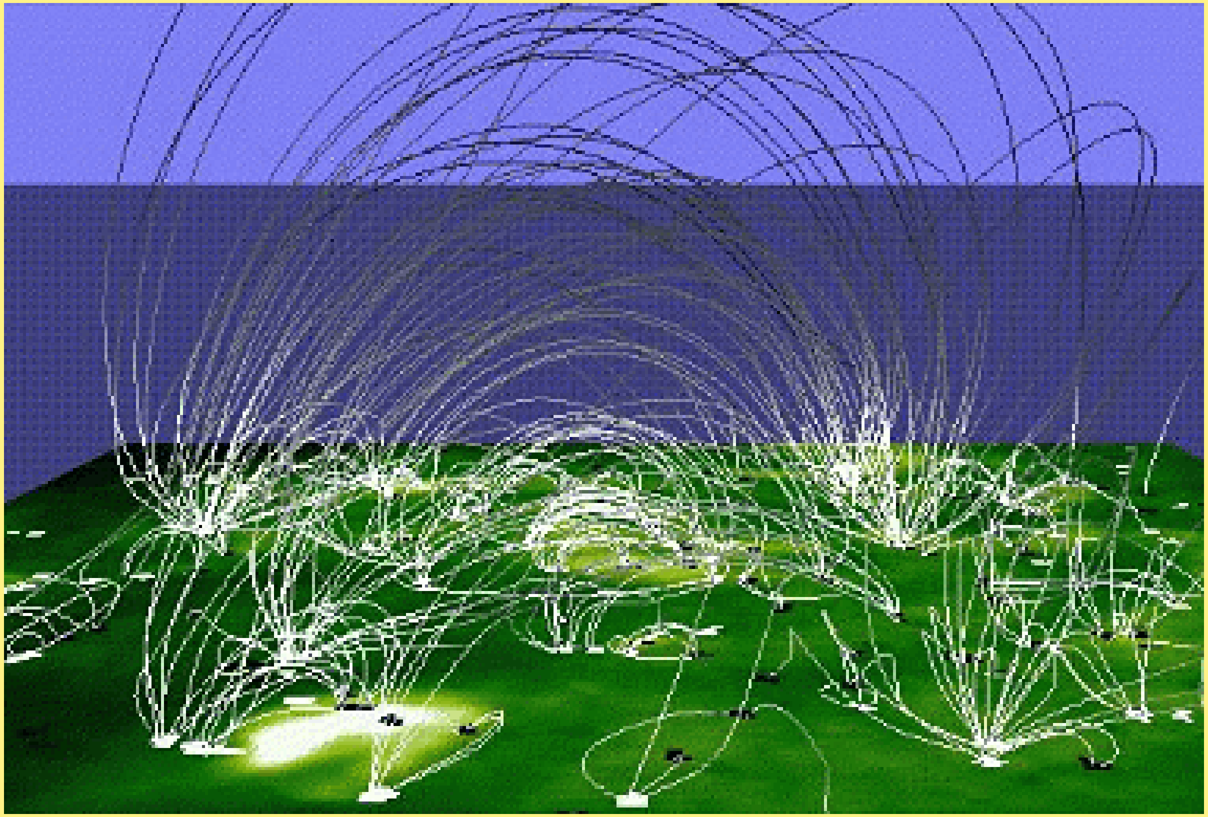
Hinode + SOHO (Parnell 2009):



3. Coronal Tectonics Model

(development of Parker's model)

3.1 Effect "Magnetic Carpet"



Magnetic sources in surface are concentrated

From observed magnetograms - construct coronal field lines

- each source connects to 8 others

- most close low down

Time for all field lines to reconnect

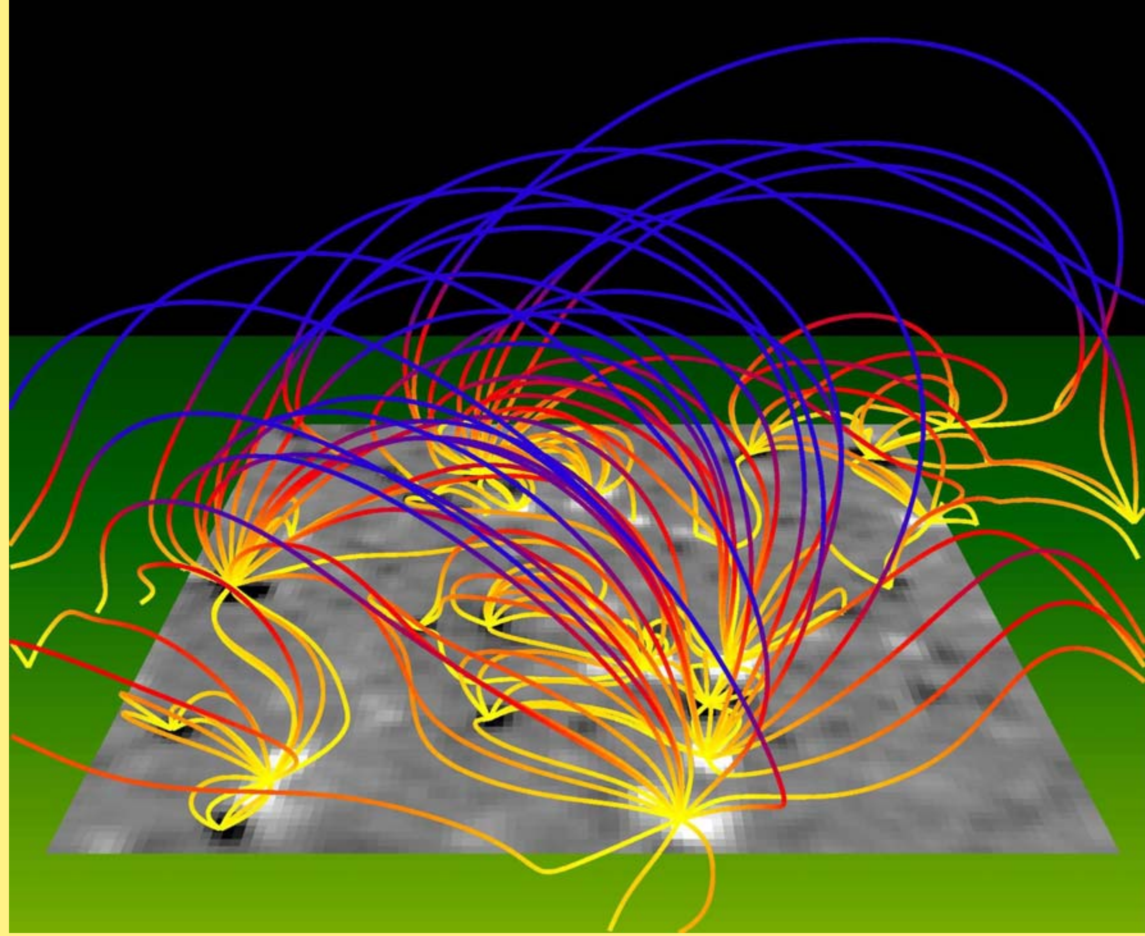
only 1.5 hours

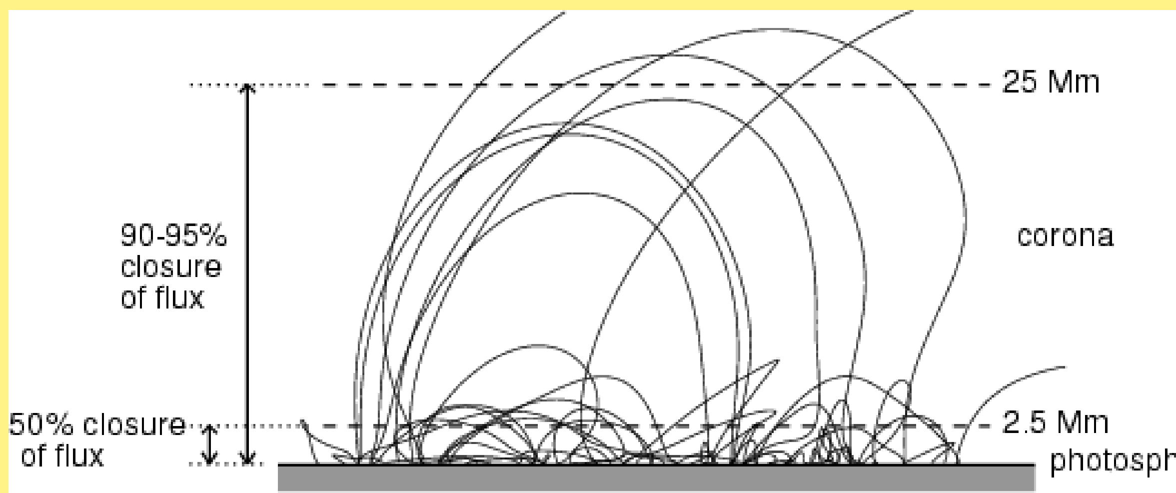
→ more complexity & heating low down

(Close et al)

? describe structure

? nature of reconn^n

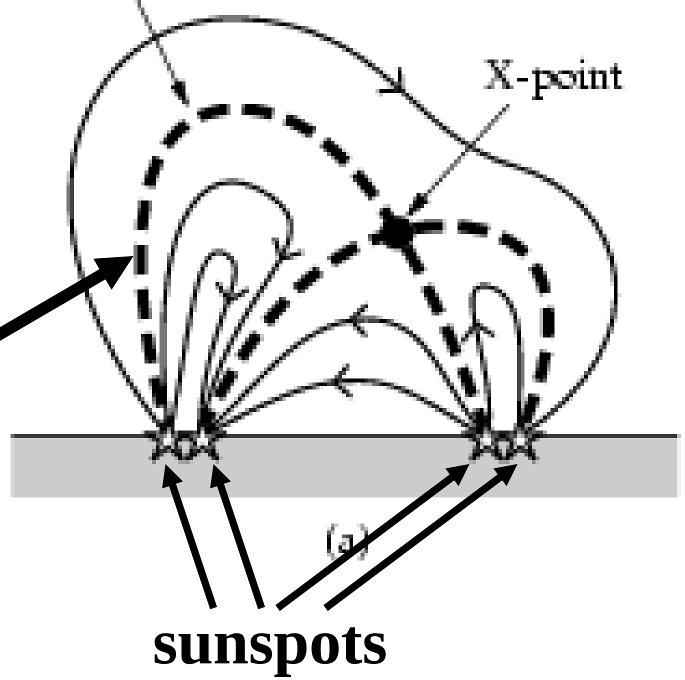




Topology of Coronal Fields - Complex

In 2D --

Separatrix curves

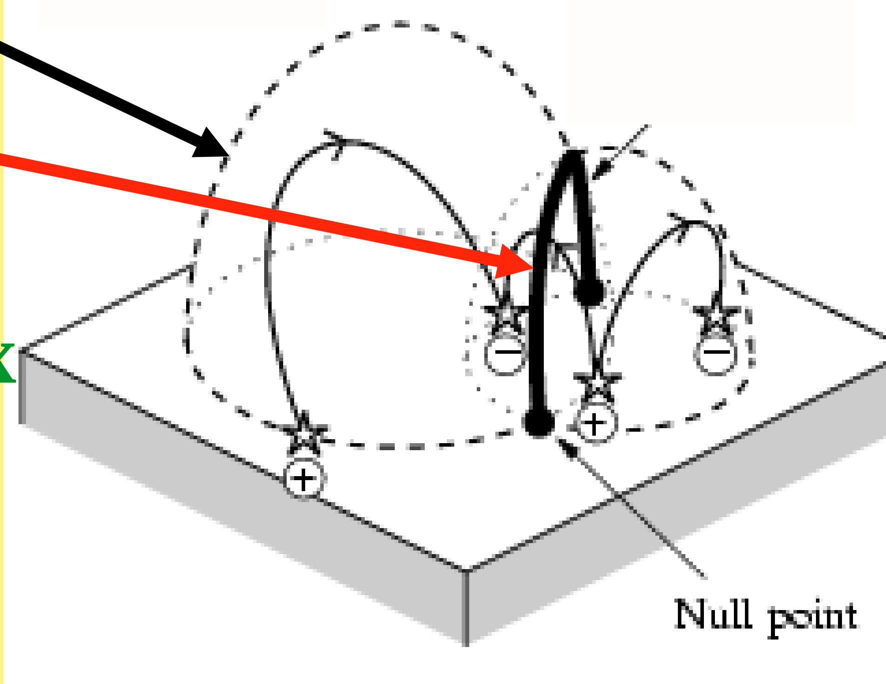


In 3D --

Separatrix surfaces

-- intersect in Separator

- Reconnection can transfer flux



In complex fields:

SKELETON-- set separatrices

3D RECONNECTION--

Many New Features

- In 2D, reconnection at **null points**, B = 0
- In 2D, magnetic lines slip through plasma --

  but change connections only at X

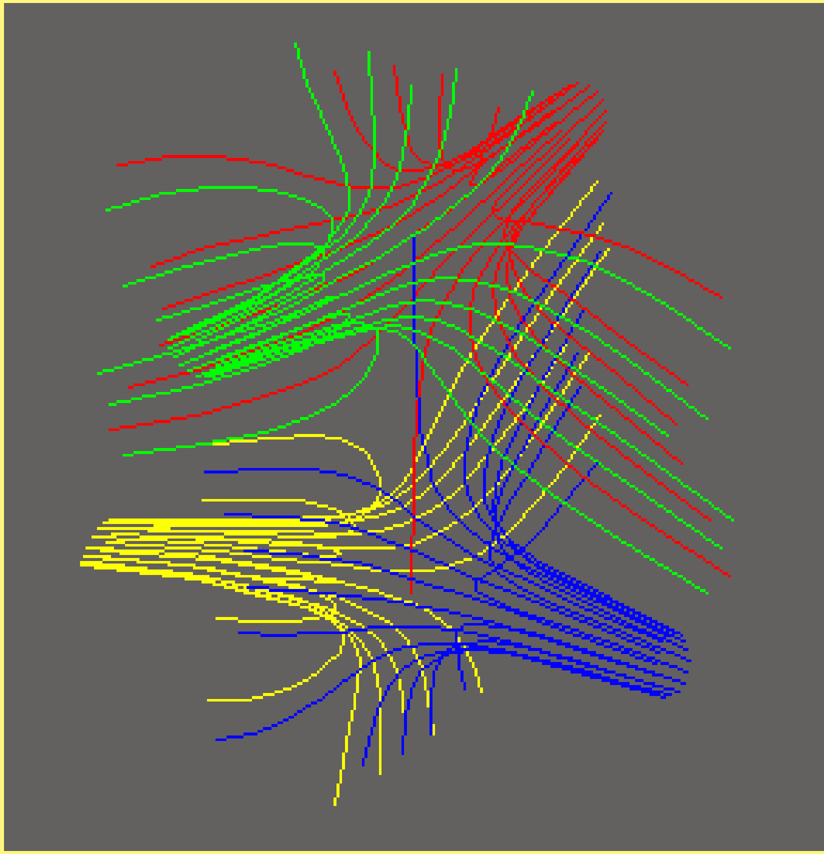
QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

- In 3D, fieldlines **continually change connections** in

3D Reconnection

can occur

at a null point **or in absence of null (QSLs)**



At Null -- 3 Types of Reconnection:

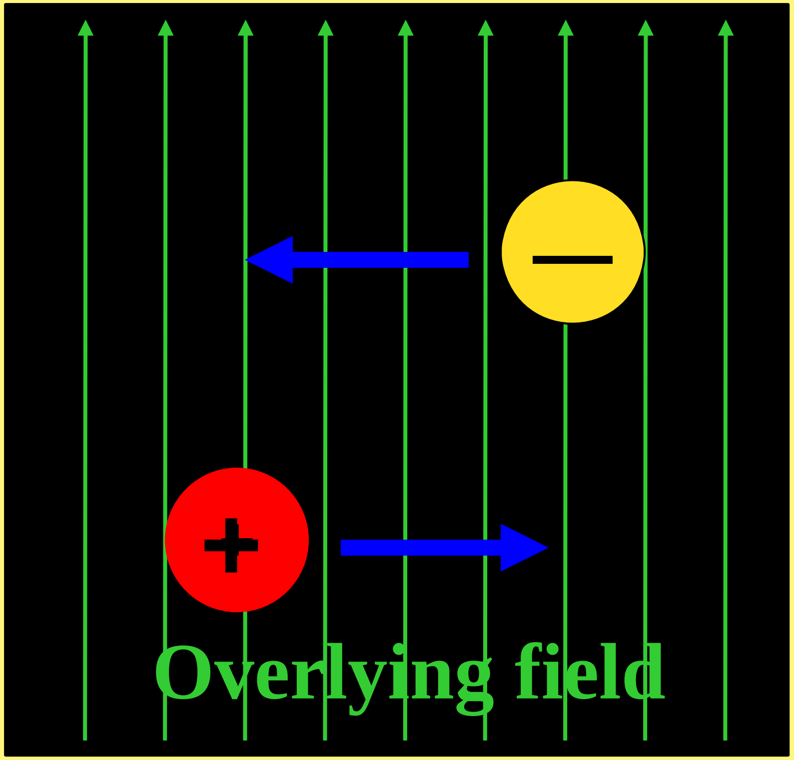
Spine reconnection

Fan reconnection

Separator reconnection

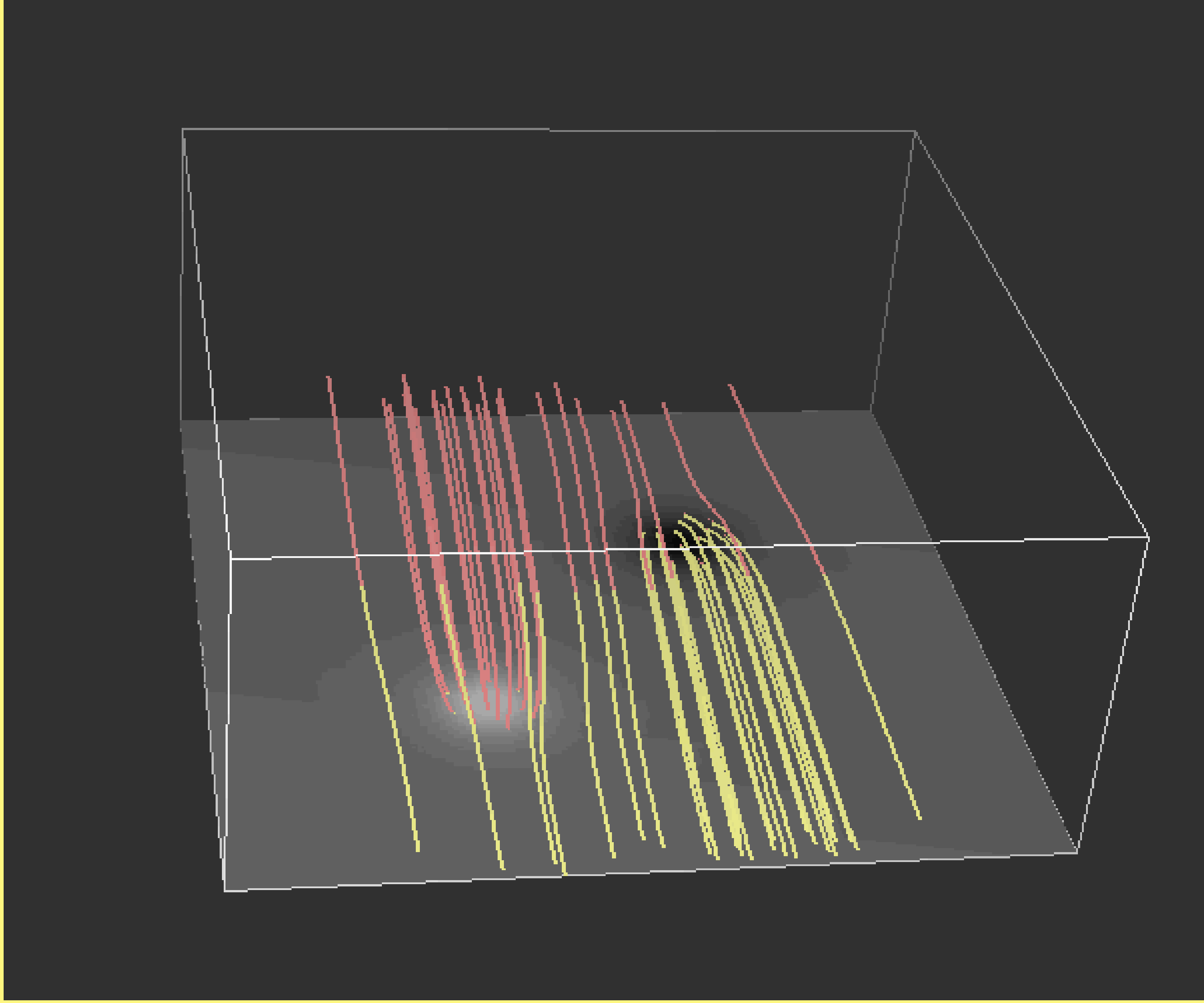
Numerical Experiment:
"Simple" binary interaction of 2 photosph^c sources

[Haynes, Parnell, Galsgaard, Priest]



- Two source fragments (of opposite polarity).
- + Overlying field
- Sources pass by each other

Numerical experiment



B-lines

Current

How does reconnection occur ?

Nulls, sep^{rs}, nonnulls?

Construct magnetic **skeleton** -- movie

- and + sources
in overlying B.

→Separatrix
surfaces.

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

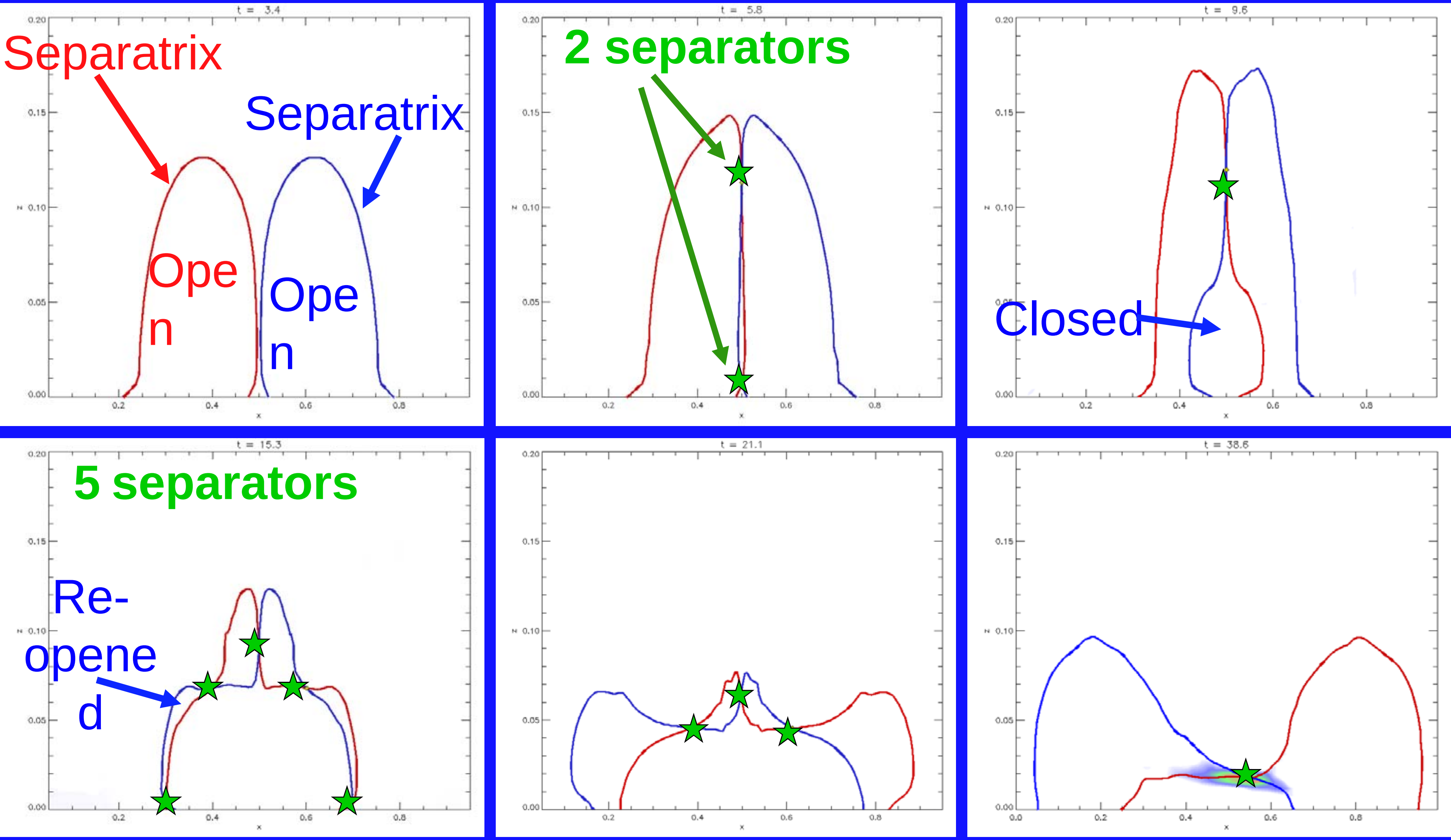
Move sources
--> flux tube
joining sources

Separator

Movie of vertical cut across skeleton

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Cross-sections of Separatrix Surfaces

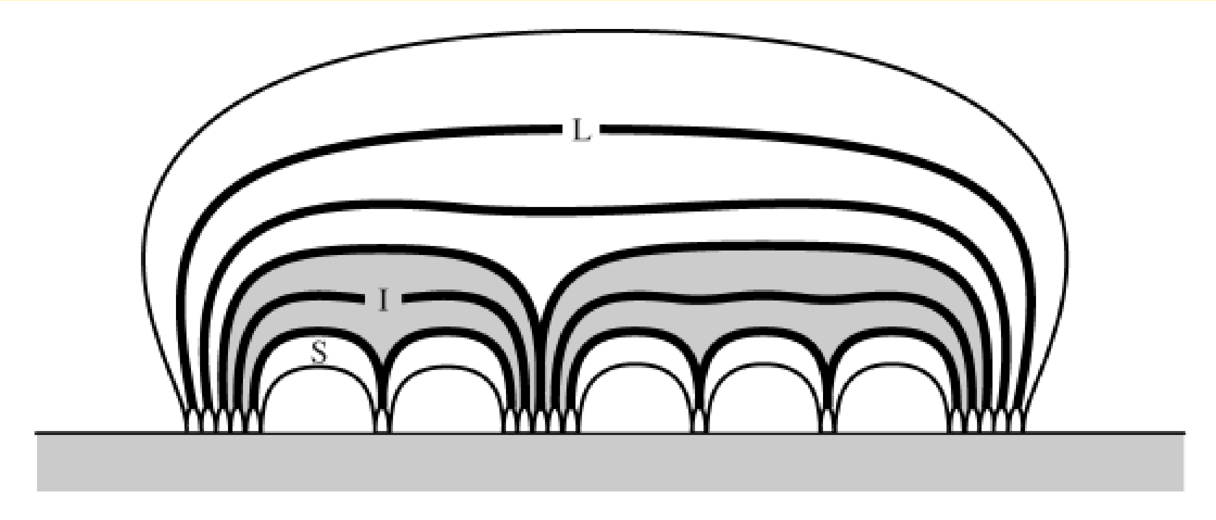


Coronal Tectonics Model

(updated version of Parker nanoflare/topological dissipation)

[Priest, Heyvaerts & Title]

- Each "Loop" --> surface in many sources
- Flux from each source separated by separatrix surfaces



- As sources move --> **J sheets on separatrices & separators** --> Reconnect --> Heat

- **Corona filled w. myriads of J sheets, heating impulsively**

Fundamental Flux Units

- **Intense tubes** (B -- 1200 G, 100 km, 3 x 10^{17} Mx)

- Single X-ray bright point --

100 sources

800 sep^{rs}, 1600 sep^{ces}

- Each TRACE Loop --

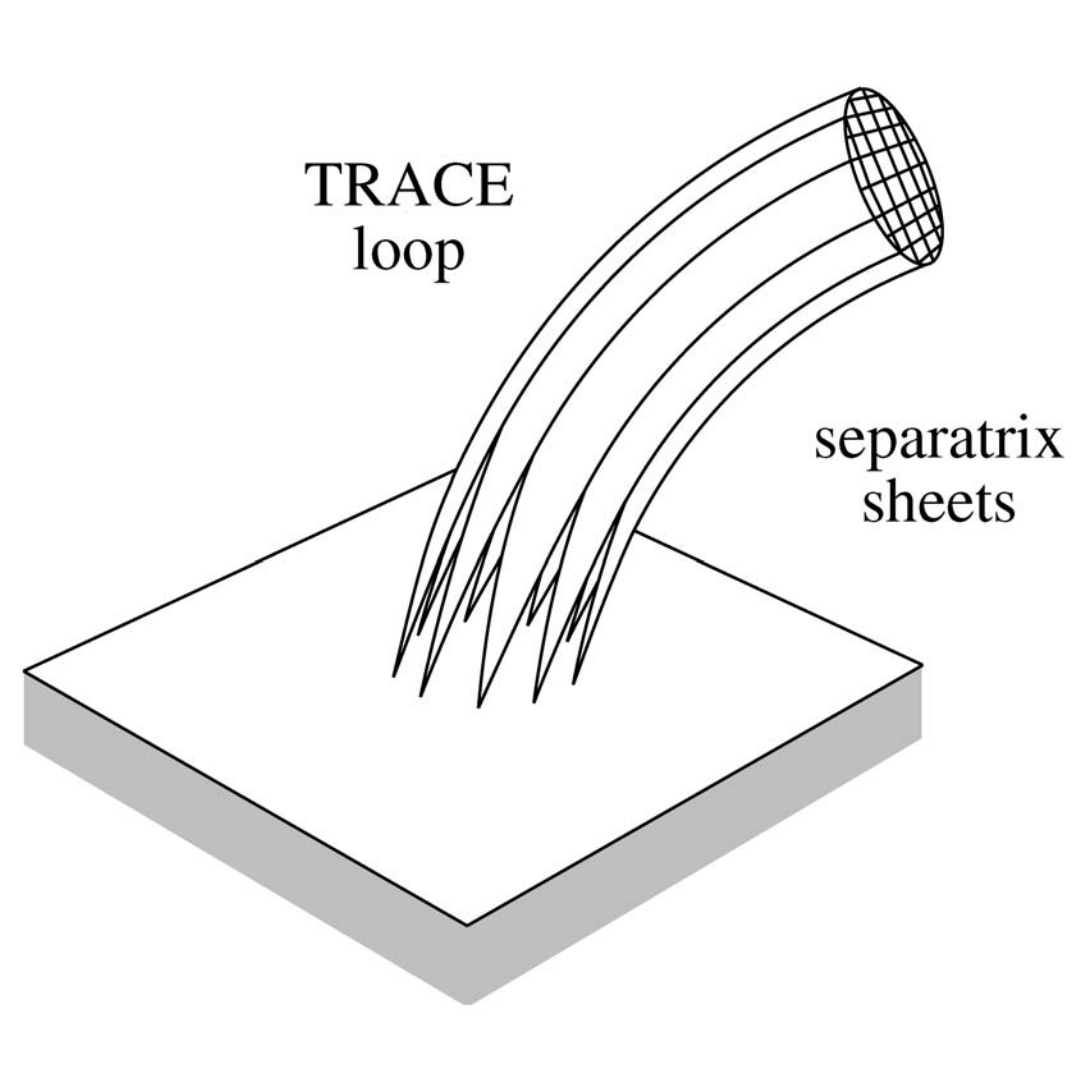
10 finer loops

80 sep^{rs}, 160 sep^{ces}

TRACE Loop

Reaches to surface in many footpoints.

Separatrices form web in corona



4. If reconnection heats corona at many sheets,

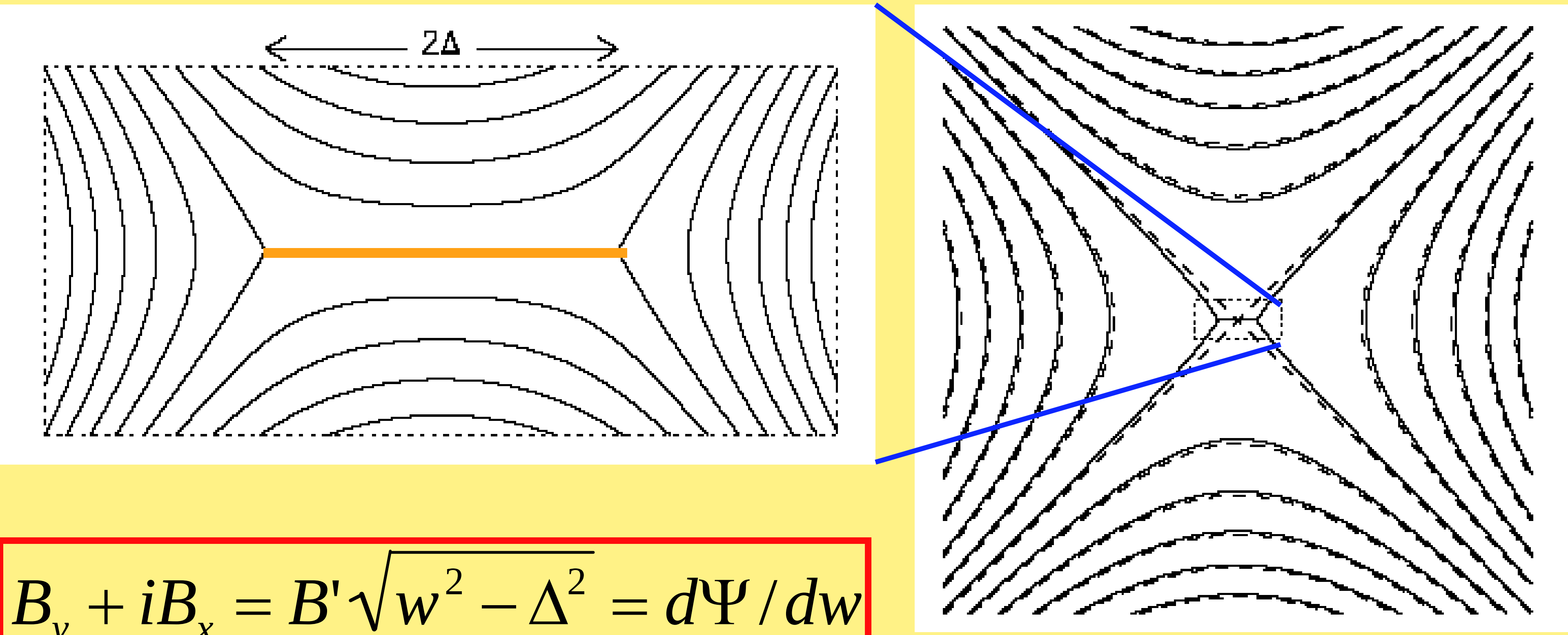
1. How does energy spread out ?

-- conduction along B
-- reconnection jets
-- waves across B
-- fast particles

2. If reconnection time-dependent,
how much energy liberated locally/globally?

Simple model problem
[Longcope & Priest]

Magnetic field of Current Sheet in X



$$B_y + iB_x = B'\sqrt{w^2 - \Delta^2} = d\Psi / dw$$

At large r, $B = B_0 + B_1$

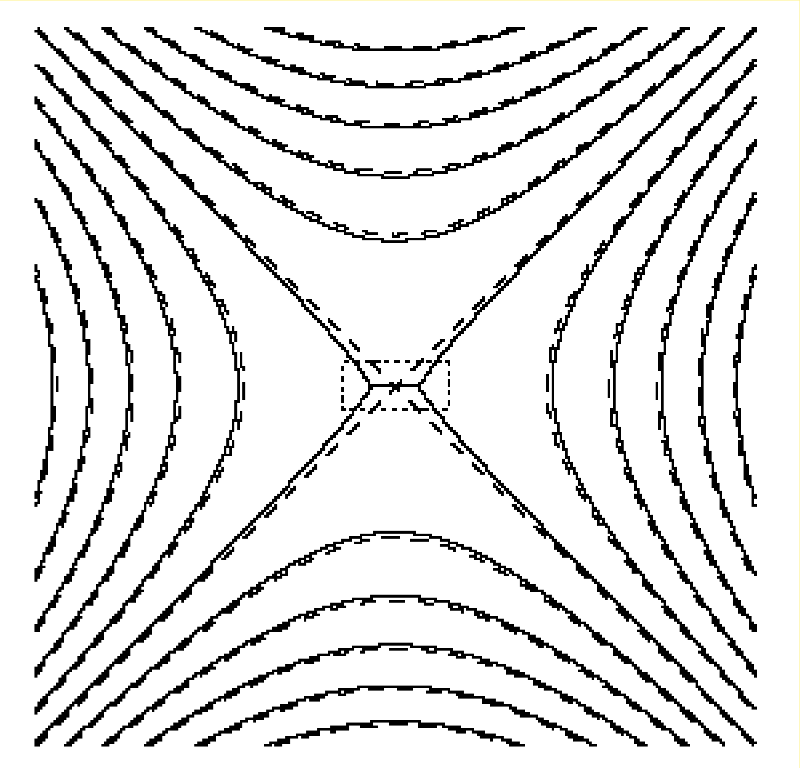
$$\boldsymbol{B_0} = -B'[y\,\hat{\boldsymbol{x}} + x\,\hat{\boldsymbol{y}}], \quad B_{1\phi} = \frac{I_0}{2\pi r} \text{ (line current)}, \quad \omega_A = \frac{B'}{\sqrt{4\pi\rho}}$$

Lots of energy far from CS

Suppose sheet reconnects

Current (I) dissipates

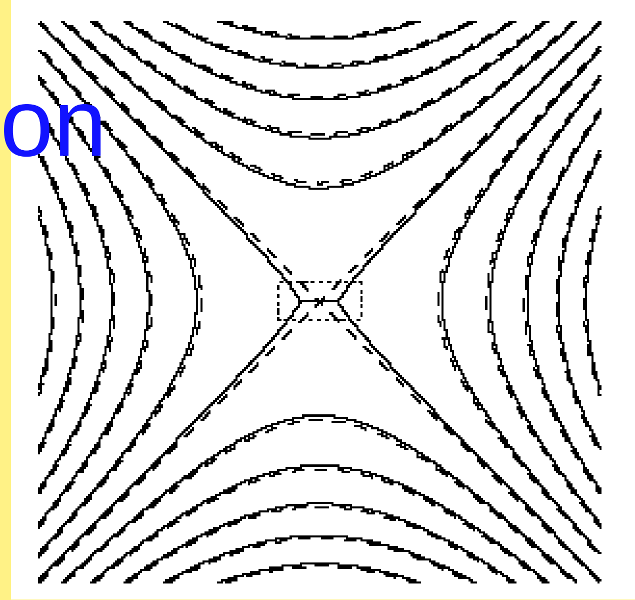
Local process but has global consequences:



Decrease **I** --> **B** must change at large distances

How ??

Model for effect of reconnection



Linearize about X-point $\mathbf{B}_0$:

$$\frac{\partial \mathbf{B_1}}{\partial t} = \nabla \times (\mathbf{v_1} \times \mathbf{B_0}) + \eta \nabla^2 \mathbf{B_1},$$

$$\rho_0 \frac{\partial \mathbf{v_1}}{\partial t} = \mathbf{j_1} \times \mathbf{B_0}.$$

$$\mathbf{B}_0 = -B'[y\hat{\mathbf{x}} + x\hat{\mathbf{y}}]$$

Assume B_1 @ t=0 is due to current sheet

η is “turned on”

current diffuses
i.e. reconnection

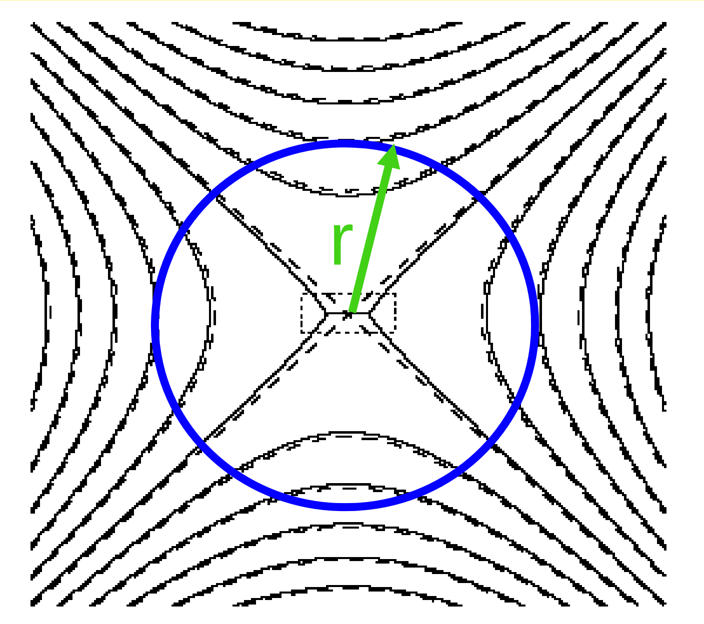
Combine equations:

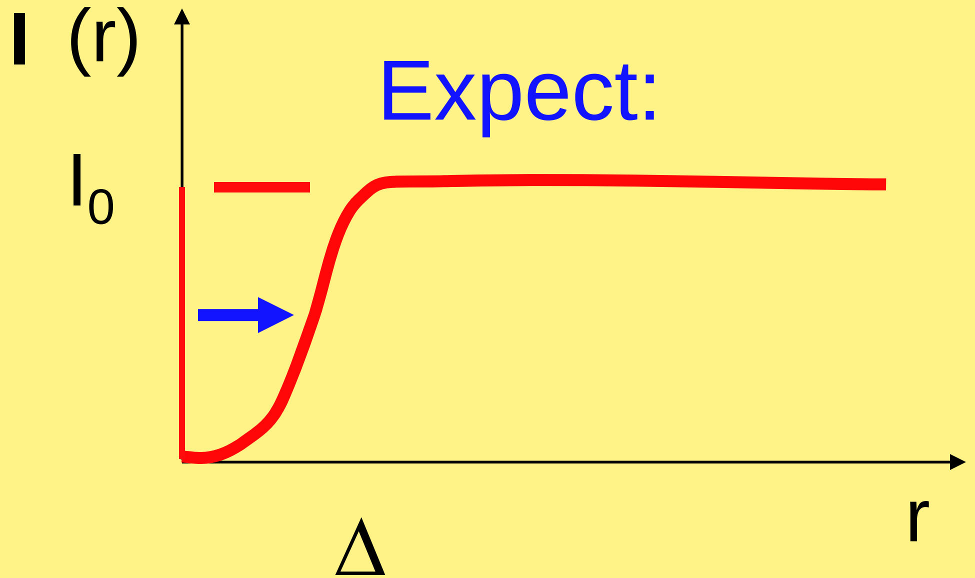
Put $rB_{1\phi} = I(r,t)$ = twice current enclosed in r

$$\frac{\partial^2 I}{\partial t^2} = \omega_A^2 r \frac{\partial}{\partial r}\left(r \frac{\partial I}{\partial r} \right) + \eta r \frac{\partial}{\partial r}\left(\frac{1}{r} \frac{\partial^2 I}{\partial r \partial t} \right)$$

wave

diffusion





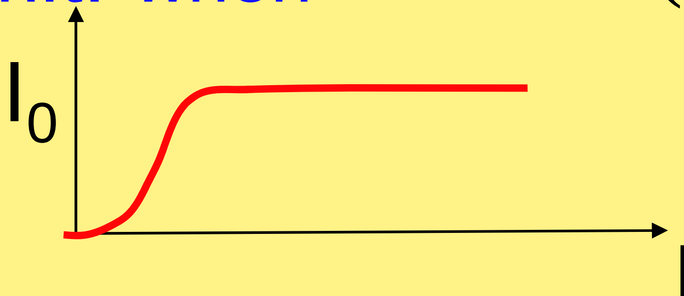
$$\frac{\partial^2 I}{\partial t^2} = \omega_A^2 r \frac{\partial}{\partial r}\left(r \frac{\partial I}{\partial r}\right) + \eta r \frac{\partial}{\partial r}\left(\frac{1}{r} \frac{\partial^2 I}{\partial r \partial t}\right)$$

wave

diffusion

(i) Large r (wave) limit: when $R = \ln(r/\ell_\eta) >> 1$

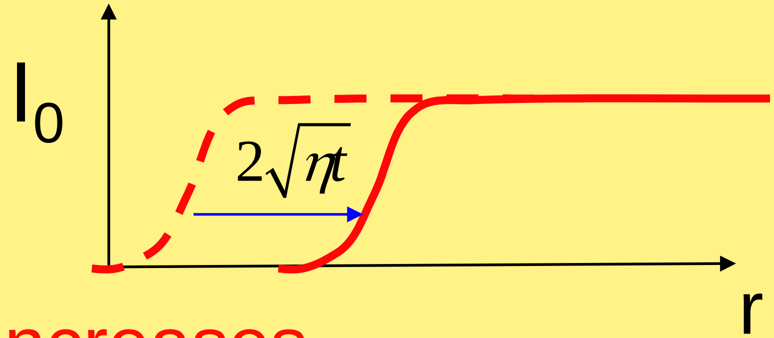
$I(R,t)=I_0-F(t-R)$



$$\ell_\eta = \sqrt{\frac{\eta}{\omega_A}}$$

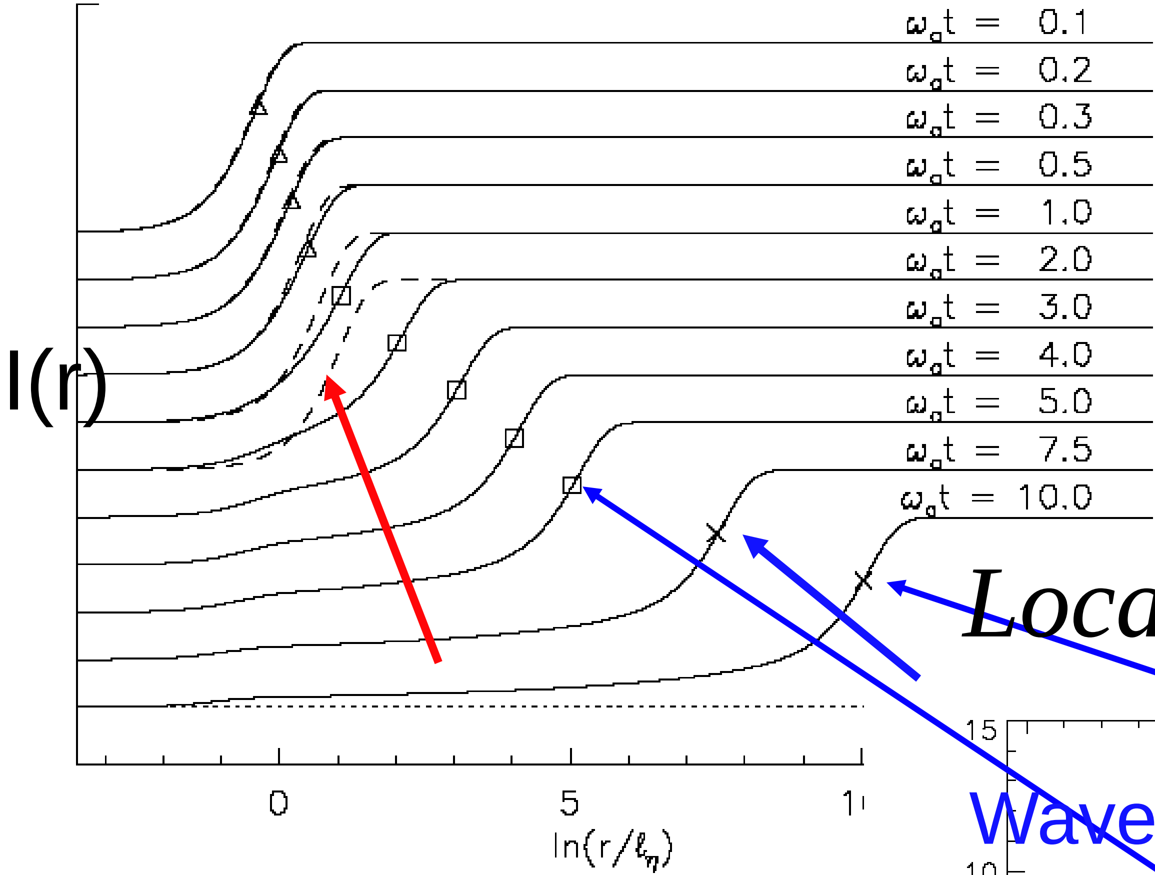
(ii) Small r (diffusive) limit:

$$I(r,t) = I_0 - I_0 \exp\left(-\frac{r^2}{4\eta t}\right)$$

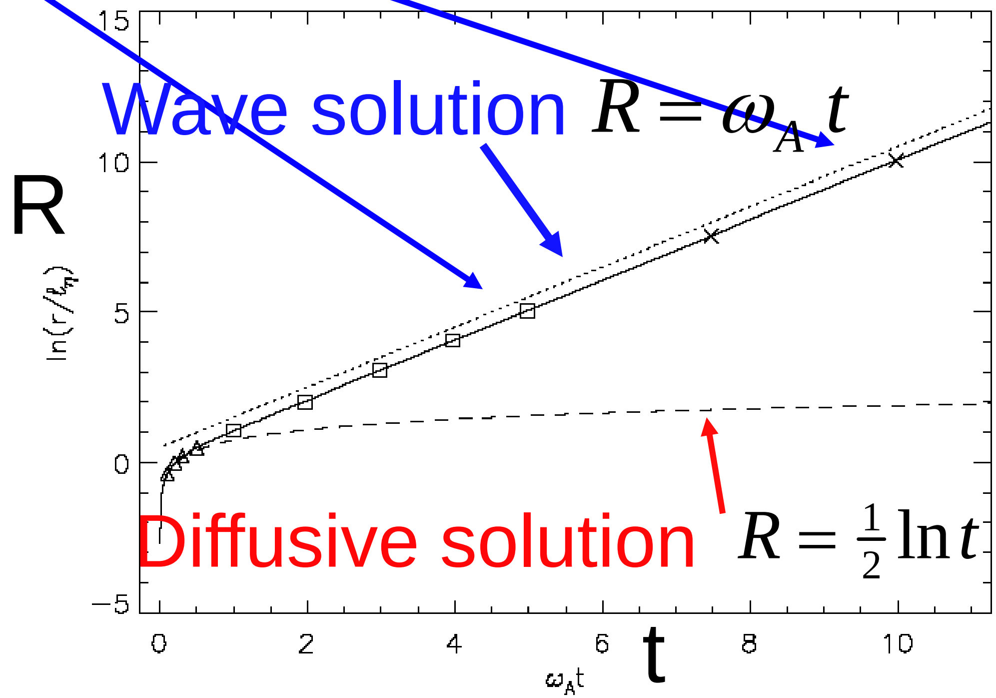


NB $j = \frac{1}{r}\frac{\partial I}{\partial r}$ --> 0 at origin as t increases

Numerical Solution

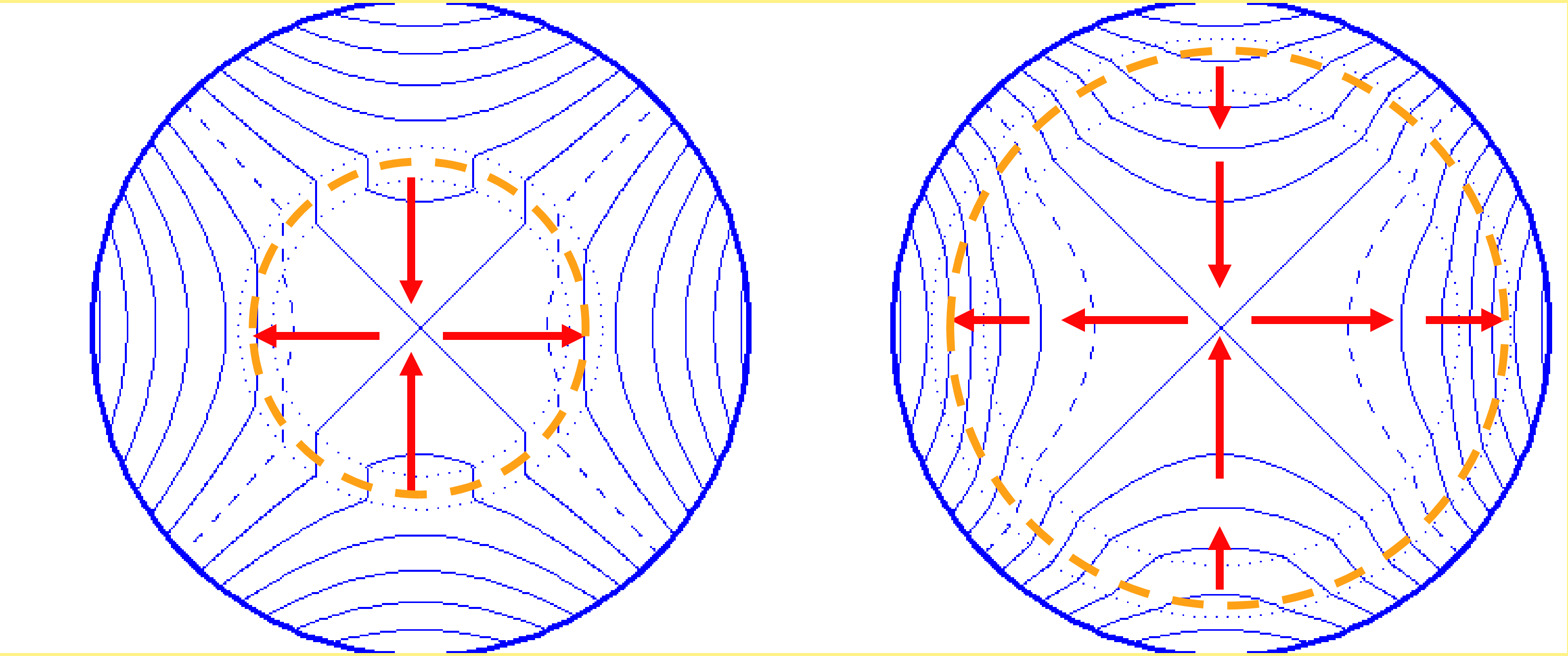


Location where $I = \frac{2}{3} I_0$

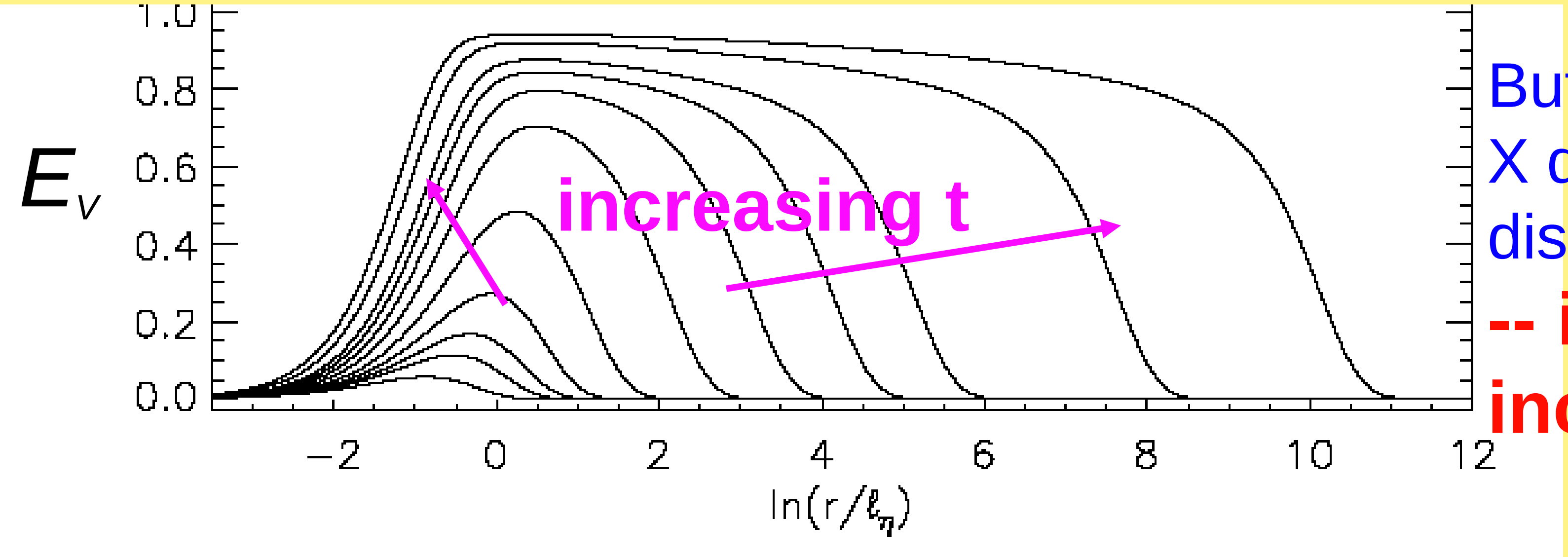


Transition:
diffusive to
wave solution

Sheath of Current propagates out



In wake of sheath a flow, assoc[d] with $E_V(r,t)\,\hat{\mathbf{z}} = -\mathbf{v}_1 \times \mathbf{B}_0$



But flow near X does not disappear

-- it slowly increases !

Resolving the Paradox - 3rd regime

At large t $(i.e.,\ t > 1/\omega_A)$

$$\frac{\partial^2 I}{\partial t^2} = \omega_A^2 r \frac{\partial}{\partial r}\left(r \frac{\partial I}{\partial r} \right) + \eta r \frac{\partial}{\partial r}\left(\frac{1}{r} \frac{\partial^2 I}{\partial r \partial t} \right)$$

Advection = diffusion

$$I(r,t) = \frac{I_0}{2\omega_A t}\left[1 - \exp\left(-\frac{\omega_A^2 r^2 t}{\eta} \right) \right]$$

$$j = \frac{1}{r}\frac{\partial I}{\partial r} = \frac{I_0 \omega_A}{\eta} \exp\left(-\frac{\omega_A^2 r^2 t}{\eta}\right)$$

$$= \frac{I_0 \omega_A}{\eta} \quad at \quad r = 0$$

Peak in j remains at X
and
produces a steady E
(indep of η)
i.e. fast reconnection

5. Summary

- **3D Reconnection** v. diff. from 2D

- **Coronal heating** **model in complementary ways:**

  -- as self-organised critical state

  -- by coronal tectonics model

  -- updated version of Parker braiding

- Response to enhanced η in current sheet (CS):

  magnetic energy --> K.E. in wave -- later dissipate.

- **But Dennis - prophet** **- far ahead of time**

need revolution, based on his ideas, to fully understand corona

w. coupling micro <--> macro