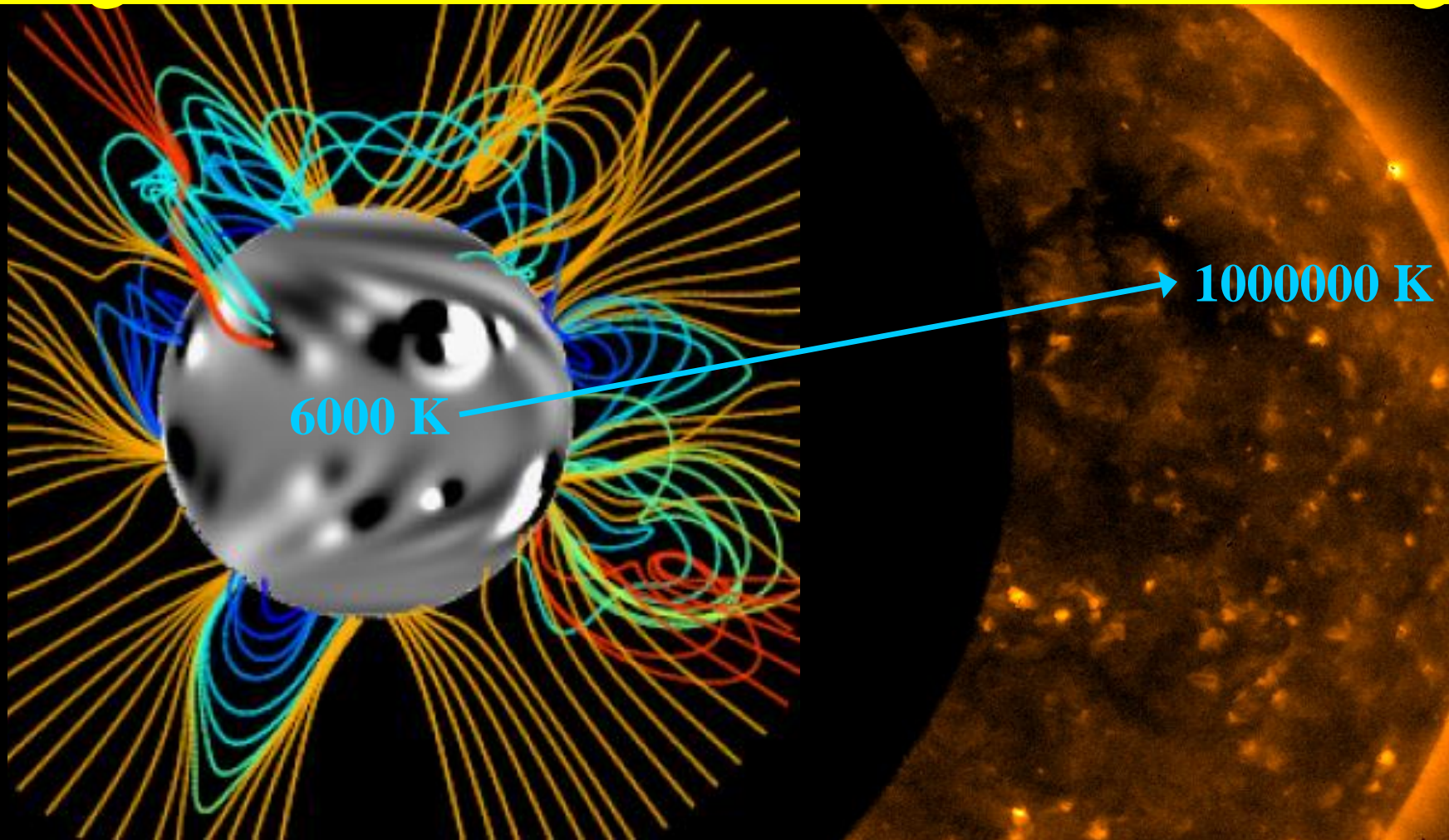


Magnetic Fields & Solar Coronal Heating



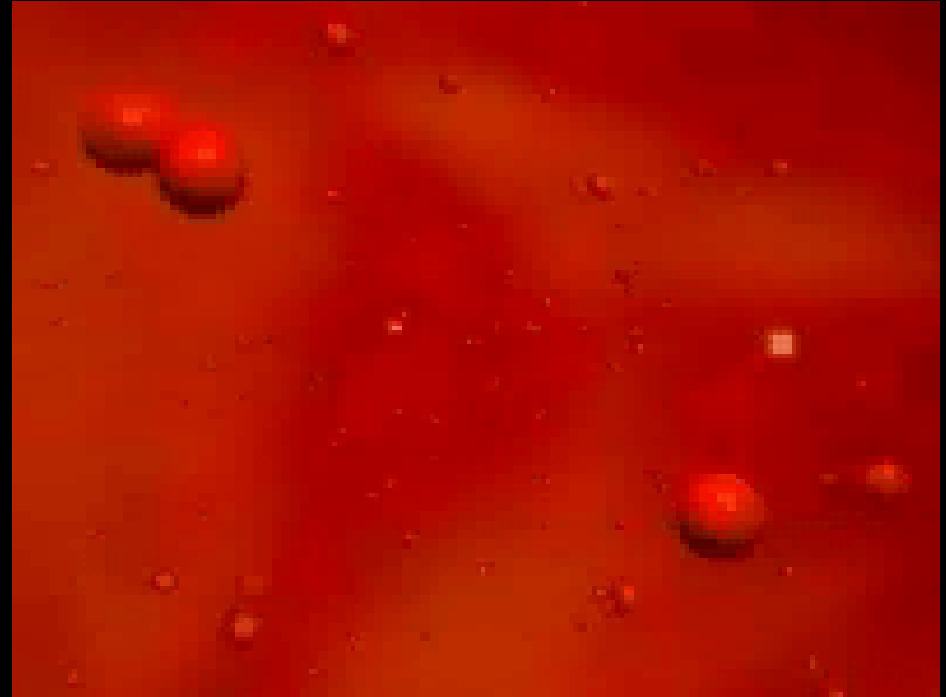
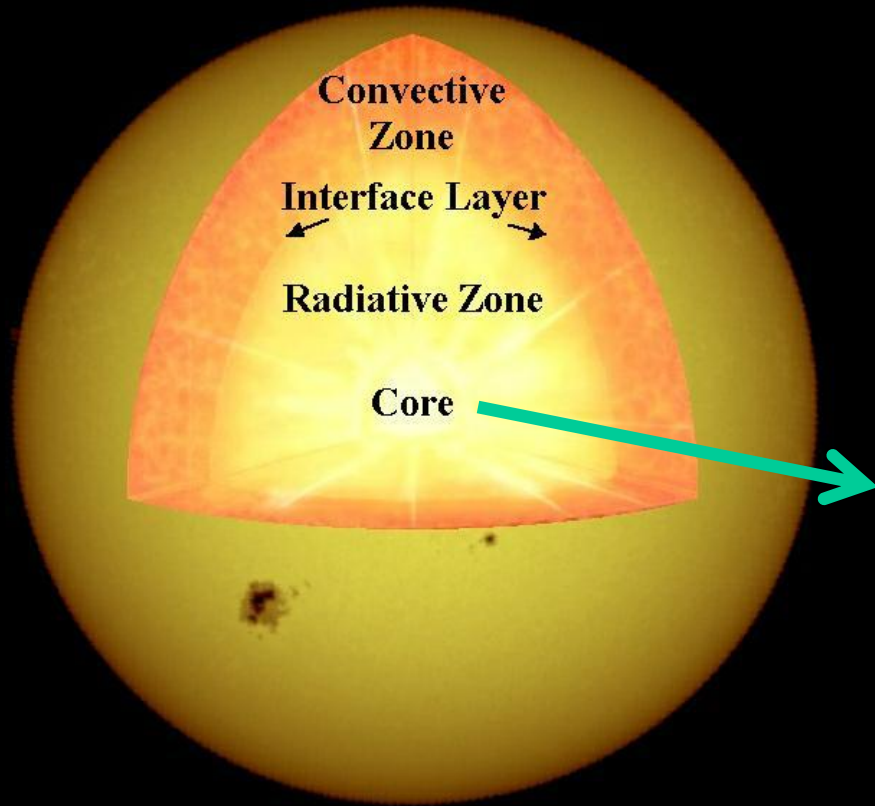
6000 K

1000000 K

Dibyendu Nandy ~ ~
Ramanujan Fellow (Govt. Of India)
IISER-Kolkata

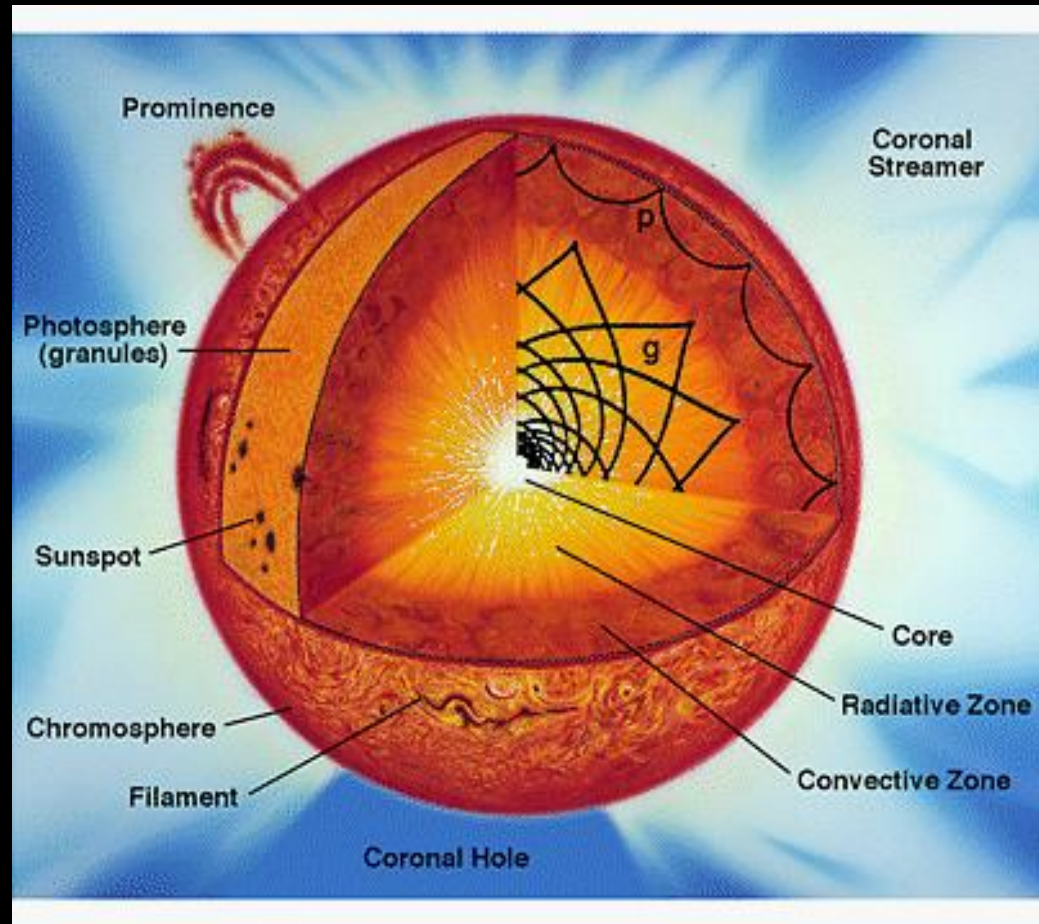


Window to the Solar Interior: Energy Generation



- Energy is generated in the center through nuclear fusion reaction which fuses atoms of Hydrogen to form Helium (with a mass-loss)
- Every second, the Sun turns a billion tons of H to He (10^{35} ergs/s)

Window to the Solar Interior: Plasma Motions



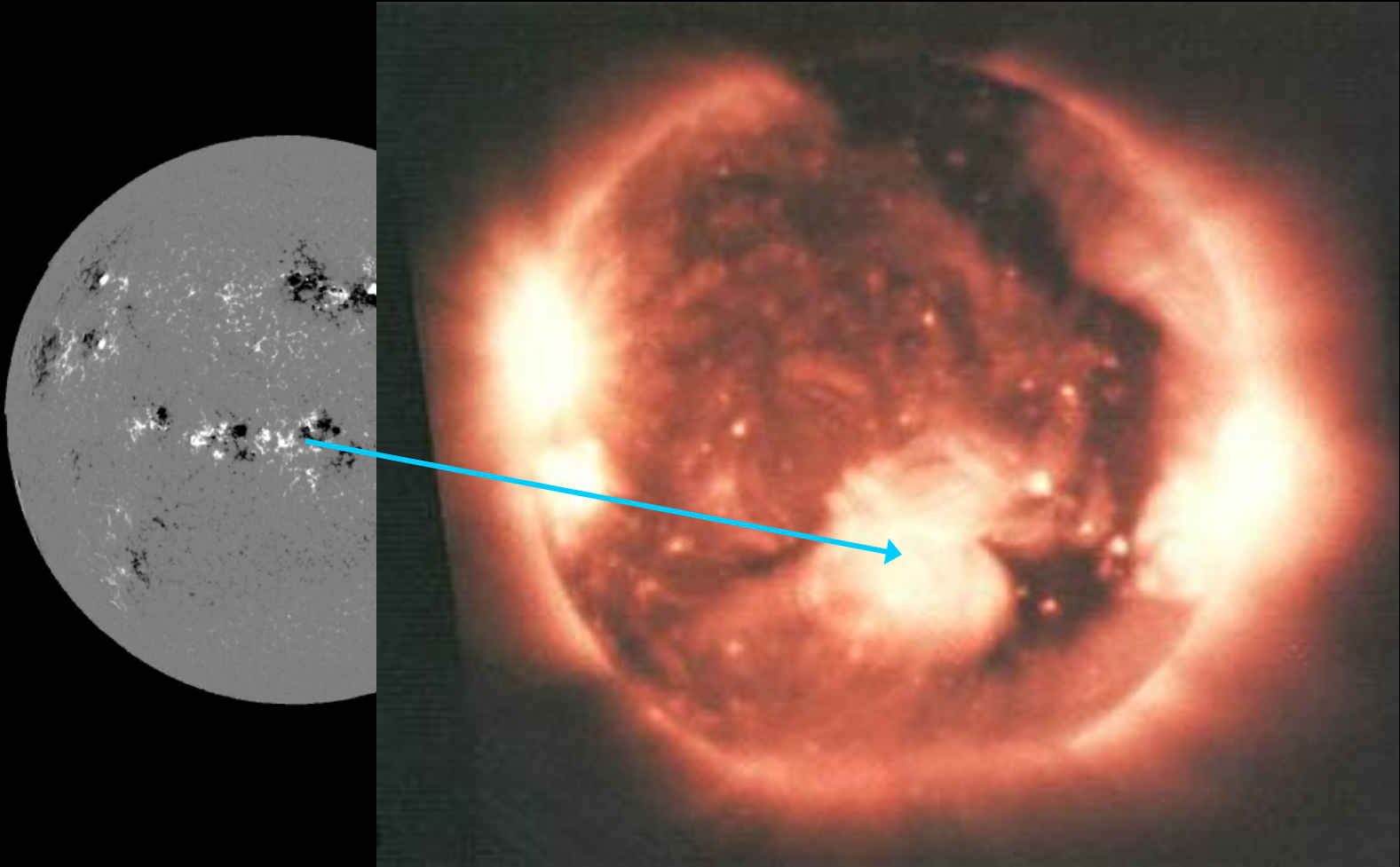
- Interior temperature exceeds a million degrees
- Matter exists in the plasma state (highly ionized)
- Convection occurs inside the sun
- The energy of convection creates magnetic fields

From the Deep and into Light: The Journey of Magnetic Fields



- Sunspots & active regions originate from deep seated magnetic fields
- Magnetic fields primarily responsible for existence of stellar coronae
- Is at the heart of solar dynamic activity

Historical Views of the Sun's Corona: The Skylab Mission



- Skylab (1973-1979); Wernher von Braun, Project Horizon...
- Solar X-ray telescope: Provided detailed views of coronal structures
- Corona brightest over active regions; loops; coronal holes

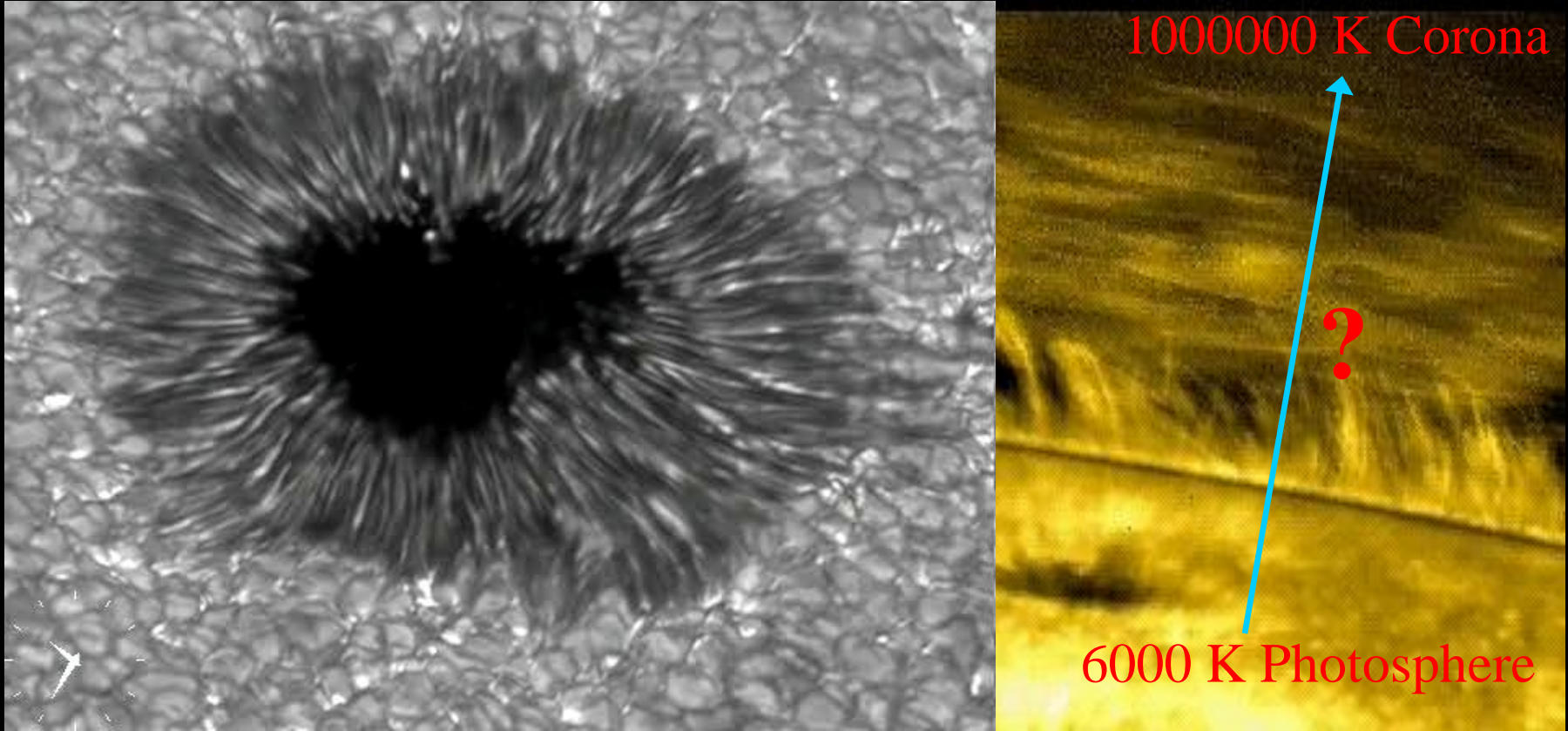
Solar Active Regions and the Million Degree Solar Corona



2002/05/16 09:18

- Decades of observations show coronal heating linked to magnetism
- Less than 2% of solar surface, provide about 50% of heating
- But what is the role of magnetic fields?

Sunspots: Connecting the Interior to the Atmosphere



- Surface of the Sun is constantly churning (turbulent convection)
- Magnetic footpoint motions, plasma jets and waves channelize energy
- Magnetized plasma relaxation via reconnection liberates energy
- But what are the relative roles, which is the dominant source?

Energetic Considerations: Some Number Crunching

- Estimates show energy flux requirement for AR coronal heating to be $\sim 10^7$ ergs / cm² / s (Withbroe & Noyes 1977)
- Annihilating a Solar AR through Magnetic Reconnection
(Assume cylindrical flux tube, $B \sim 1000$ G length-scale $\sim 10,000$ Km)

Energy Release: $B^2 / 8\pi \pi r^2 L = 10^{33}$ ergs

Can sustain AR corona for 100 days – more than sufficient!

- However, we know that active region magnetic field are not totally annihilated – so the thought experiment above does not work...

Coronal Heating – Theoretical Considerations

Coronal Heating Requirement: $\sim 10^7$ ergs / cm² / s
(Schwarzschild 1948; Schatzman 1949)

In astrophysics...

Uzdensky (2006, astro-ph/0607656)

... the most important reconnection mechanism in Astrophysics invokes waves, a certain type of waves, in fact. Called *handwaves* (See Fig 1).



Fig. 1.— Main Reconnection Mechanism in Astrophysics.

Coronal Heating – Theoretical Considerations

Coronal Heating Requirement: $\sim 10^7$ ergs / cm² / s
(Parker 1973, 1983, 1988)

DC heating (Stress/Shear Buildup)

- When footpoint motions slow
- Magnetic reconnection, current sheet formation and dissipation
- Poynting Energy flux (E/area/time) = $v B^2/4\pi \sim 10^8$ ergs / cm² / s
(B ~ 100 G, v $\sim 10^5$ cm/s)
- Adequate energy flux, viable,
- But how is the stored shear and stress released through relaxation?

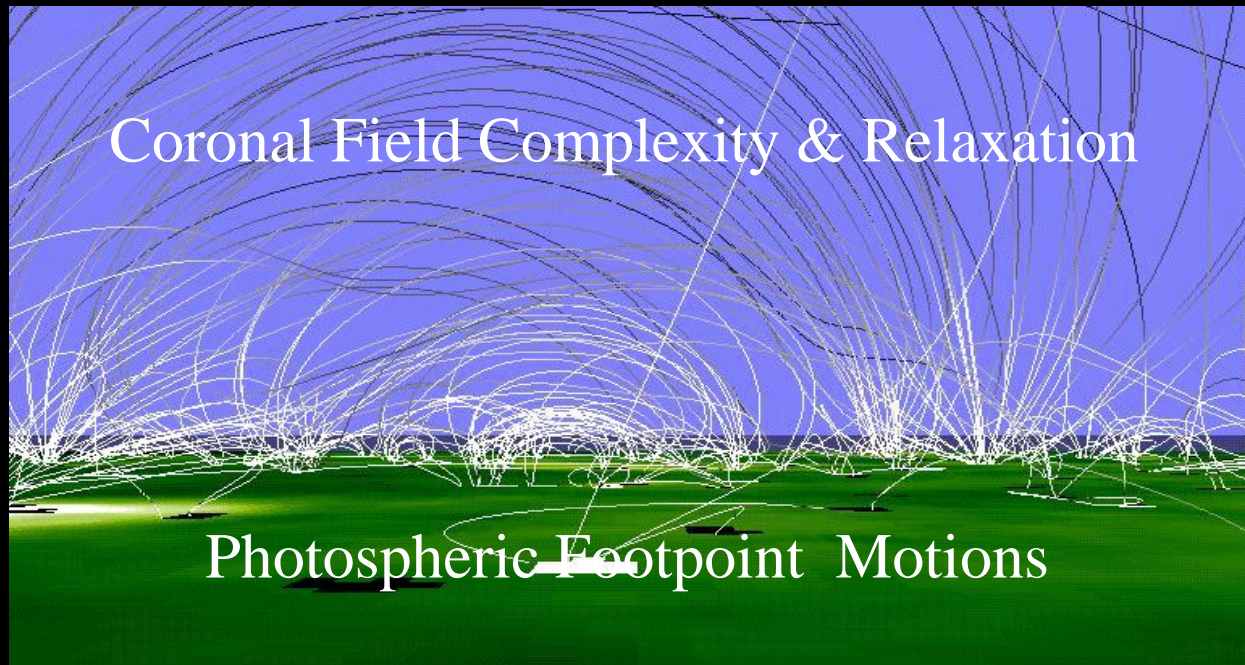
How Force-Free Magnetized Plasma's Relax: Taylor's Conjecture

- Magnetic fields in a low β (ratio of gas to magnetic pressure) plasma (for example, the solar corona) self-organizes to remove unbalanced magnetic stresses
- In the ideal MHD limit, during this evolution of the magnetized plasma towards a minimum energy state, the total magnetic helicity of the system ($\int \mathbf{A} \cdot \mathbf{B} \, dV$) remains invariant and the final magnetic field configuration is a force-free field (Woltjer 1958) satisfying $\nabla \times \mathbf{B} = \alpha(x,y)\mathbf{B}$ (α is related to magnetic twist)
- Taylor (1974) proposed that in a plasma of small, but finite resistivity, magnetic fields relax to a minimum energy state still subject to the constraint that the total magnetic helicity is conserved. However, in this case, the final state is a *linear* force-free field, with α constant from one field line to another, satisfying the equation

$$\nabla \times \mathbf{B} = \alpha \mathbf{B}$$

- Taylor's theory explained the phenomenon of reversed field pinch in laboratory plasma experiments and found applications in spheromaks

Taylor's Relaxation in Astrophysical Plasmas: Coronal Heating



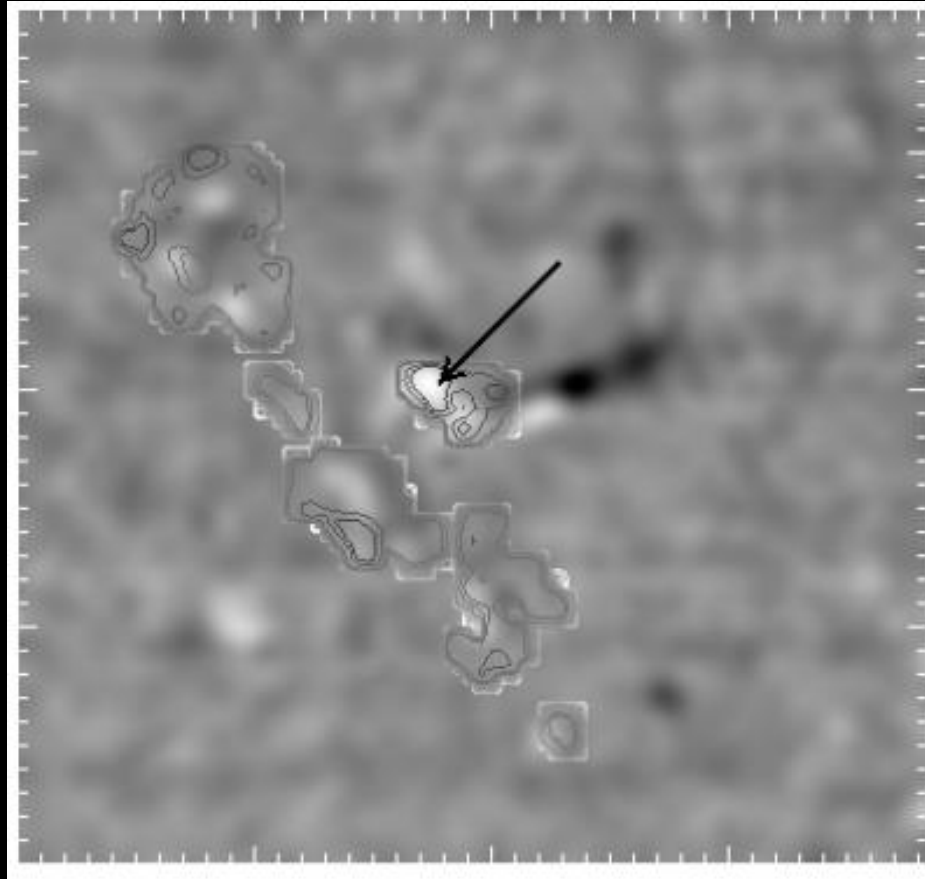
- Starting with Heyvaerts and Priest (1984), Priest and co-investigators adapted Taylor's hypothesis to coronal heating; coronal field evolves through series of linear force-free states, in response to being driven to non-linear states by footpoint motions
- Energy available for heating: Difference between linear and non-linear states
- Theories also suggest that the evolution of twist through magnetic reconnection is a hyper-diffusive process (Bellan 2000; Diamond & Malkov 2003), i.e., driven by the non-uniformity of the twist distribution itself

Observational Investigations:

Plasma Relaxation, Flaring Activity and Coronal Heating

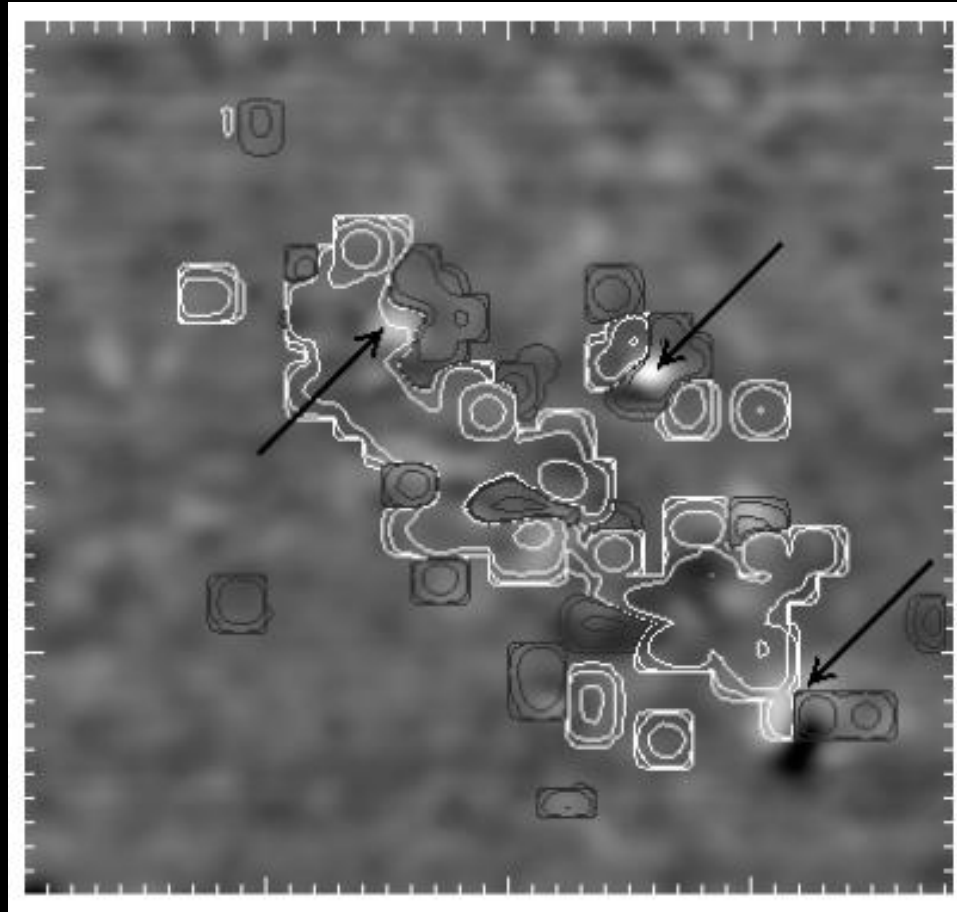
- Students & Collaborators: Micheal Hahn, Stacy Gaard, Dick Canfield, Dana Longcope, Soumitra Hazra and B. Ravindra
- Observations of magnetic field characteristics, in particular twist of solar ARs, flare diagnostics, coronal X-ray luminosity measurements
- Vector magnetic fields (HSP, Hinode-SOT)
- MCCD H α telescope (impulsive, initiation phase of flares)
- GOES X-ray sensors (Flare energy calculation)
- Yohkoh, Hinode-XRT (coronal X-ray emission)

Twist Gradient Influences Flare Initiation (Hahn et al. 2005)



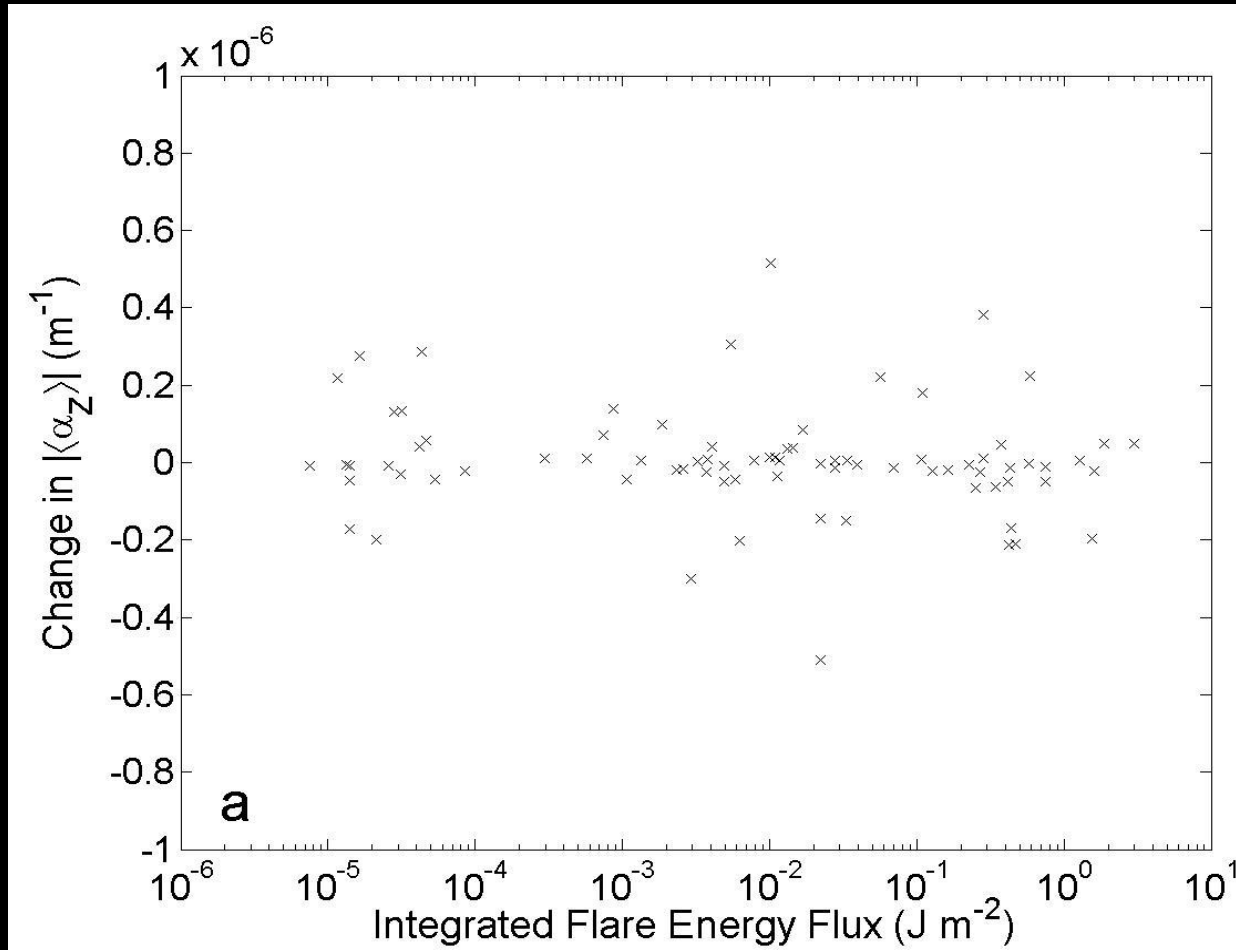
Contours of the gradient in twist $\text{grad}[\alpha_z(x,y)]$ from a pre-flare HSP vector magnetogram of AR 6919 (started on 15 November, 1991 at 21:05UT) overlaid on the corresponding gray-scale MCCD $H\alpha$ start-of-flare blue-wing flare intensity enhancement $[I_{H\alpha}(x,y)]$ image (taken the same day at 22:32:04 UT). The scale of the image is 161 by 150 Mm. Darker contours denote stronger gradients. **The black arrow marks the region of brightest intensity enhancement in $H\alpha$ emission showing it to be co-spatial with the strongest gradient in twist.**

Flares Originate at Chirality Inversion Lines (Hahn et al. 2005)



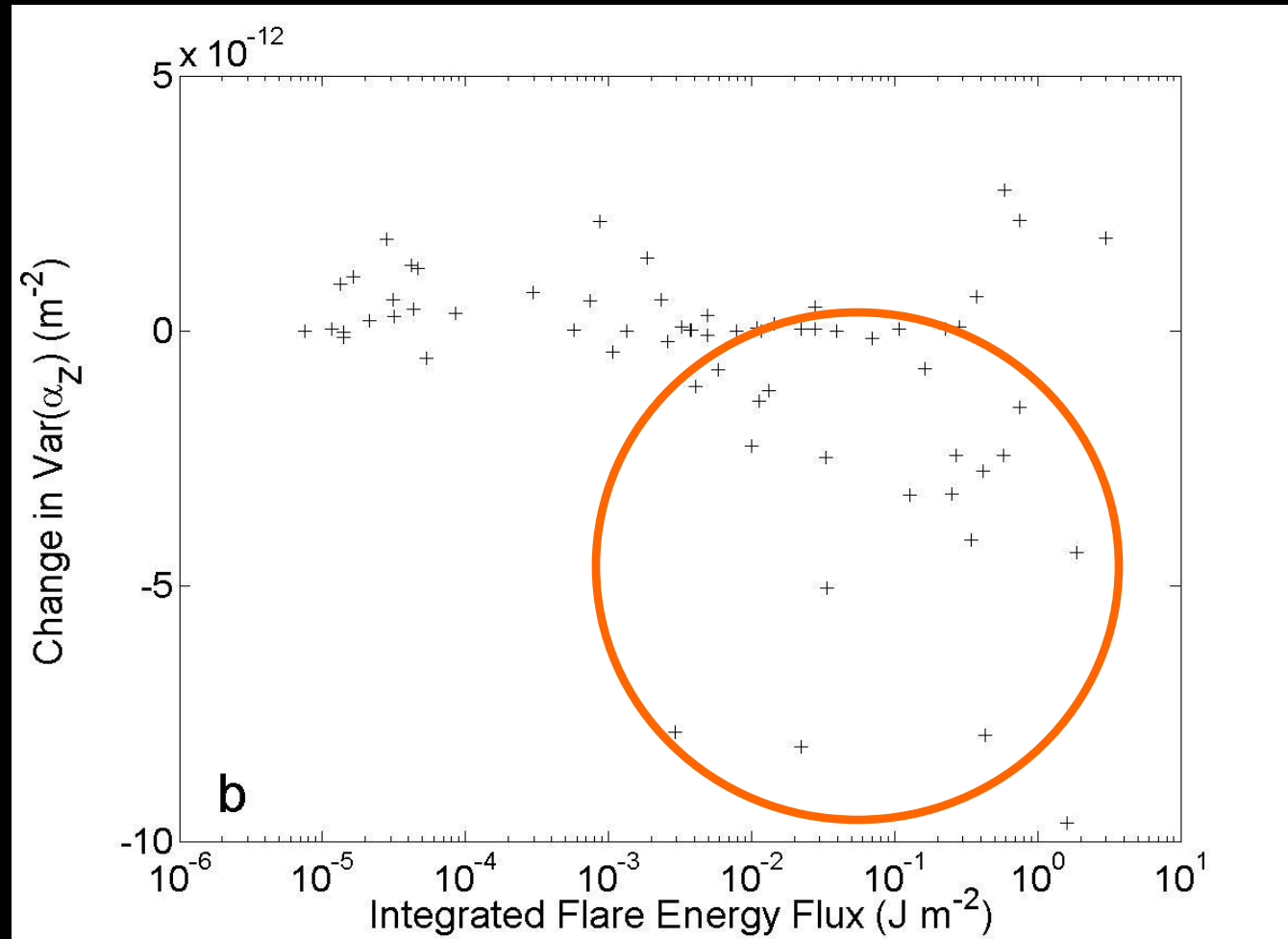
Contour map of the twist distribution $\alpha_z(x,y)$ from a pre-flare HSP vector magnetogram of AR 6982 (started at 28 December, 1991 at 18:42UT) overlaid on the corresponding gray-scale MCCD H α start-of-flare blue-wing intensity enhancement [$I_{H\alpha}(x,y)$] image (taken the same day at 21:07:34 UT). The scale of the image is 159.94 by 148.67 Mm. White contours connect regions with same value of positive twist and black contours for negative twist. **The black arrows point to regions of strong H α emission associated with the start of the flare, showing them to lie close to chirality (twist) inversion lines.**

Evolution of Twist in Flaring Active Regions (Nandy et al. 2003)



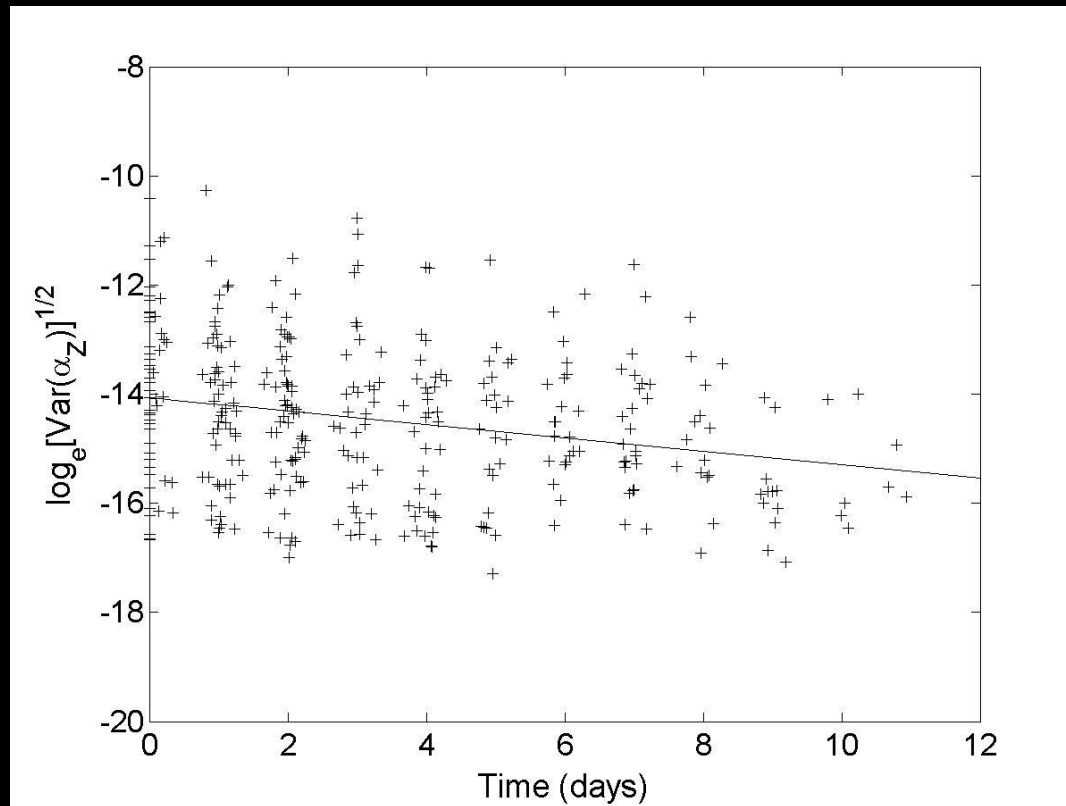
- Mean of the local α (twist) distribution is not connected with flare productivity and does not change at statistically significant levels

Evolution of Variance in Twist in Flaring Active Regions (Nandy et al. 2003)



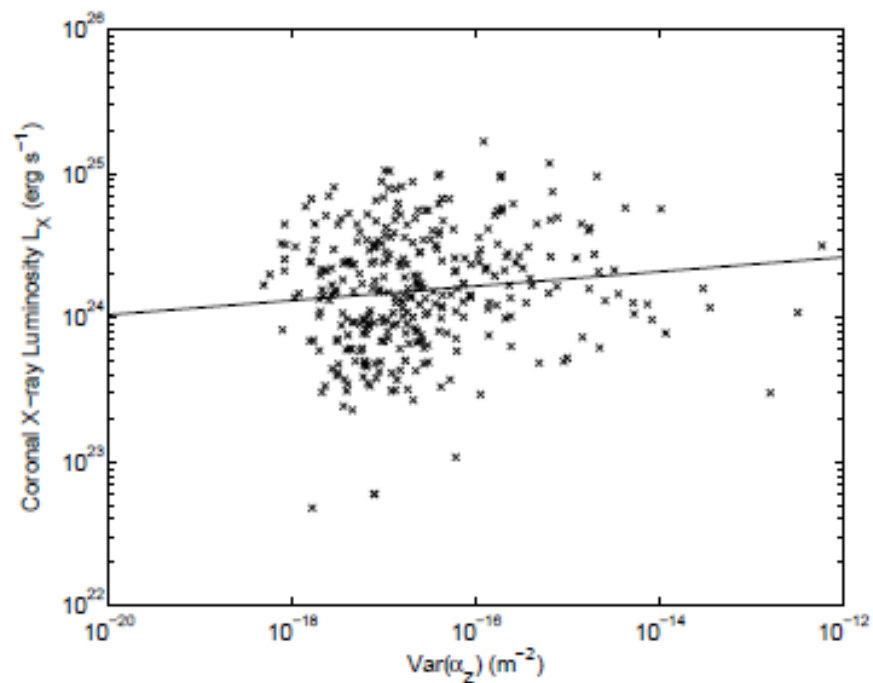
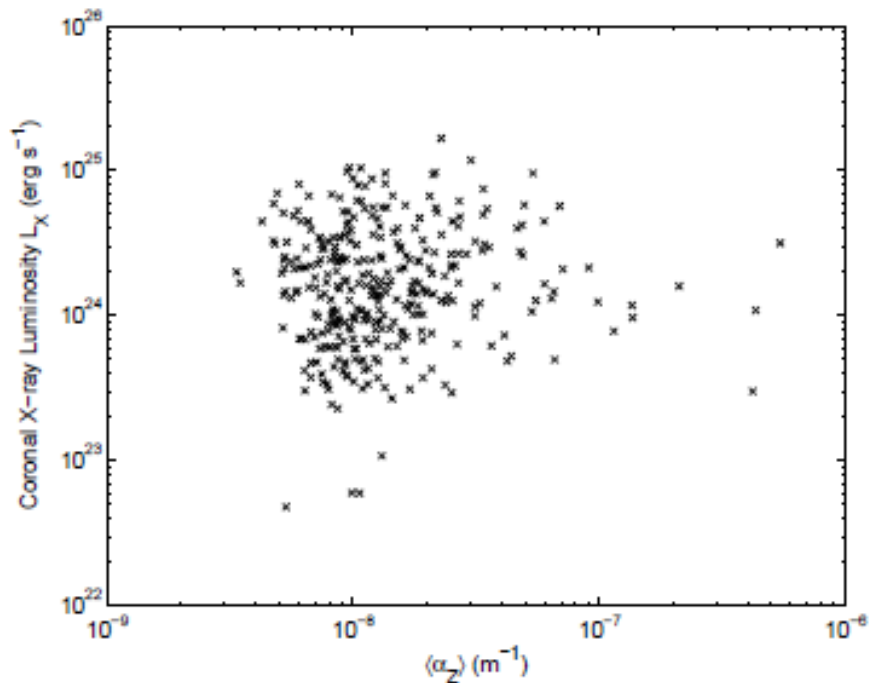
- Statistically significant correlation indicating that the variance in the α (twist) distribution decreases with increasing flare-productivity

Plasma Relaxation Timescale (Nandy et al. 2003)



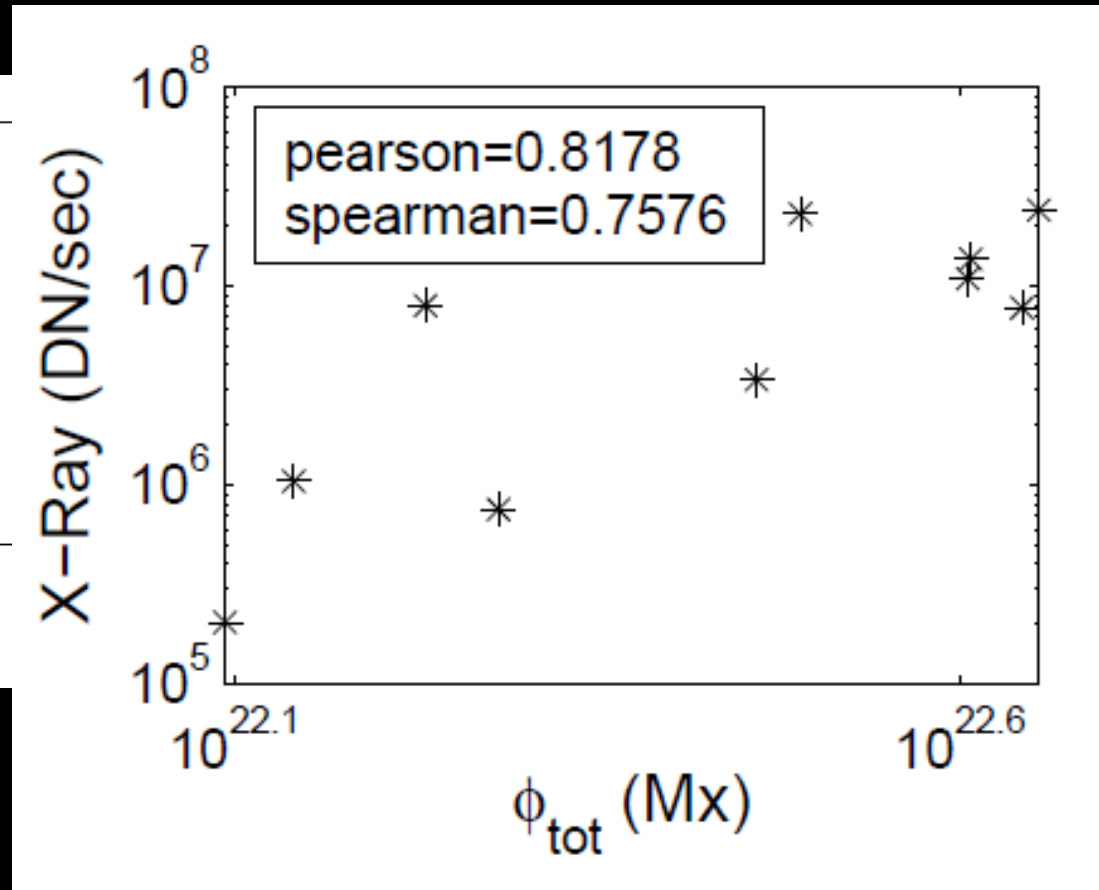
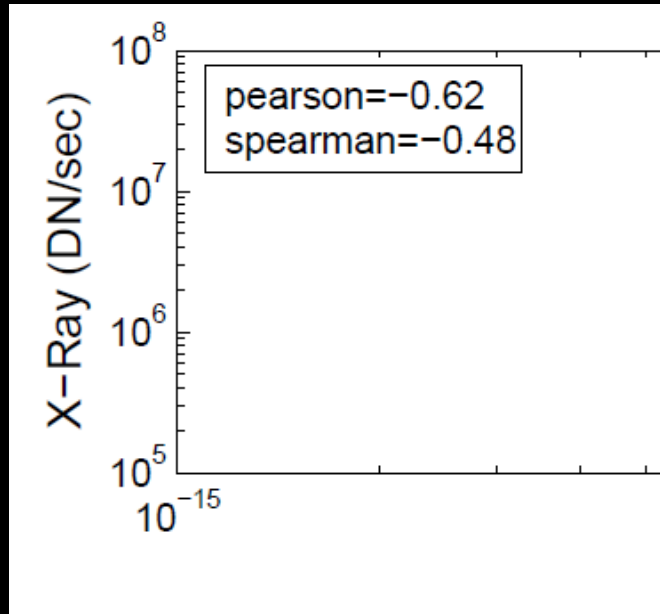
- The slope of the temporal evolution curve of $\ln[\text{Var}(\alpha)]^{1/2}$ values of these flaring active regions generates relaxation timescale $\tau = 8.1$ days
- Significant because this allows footpoint motions (timescale ~ 1 day) to build up enough stresses before release of energy
- This maximizes coronal heating (Vekstein, Priest & Steele 1991)

Coronal Heating and Twist (Nandy 2008)



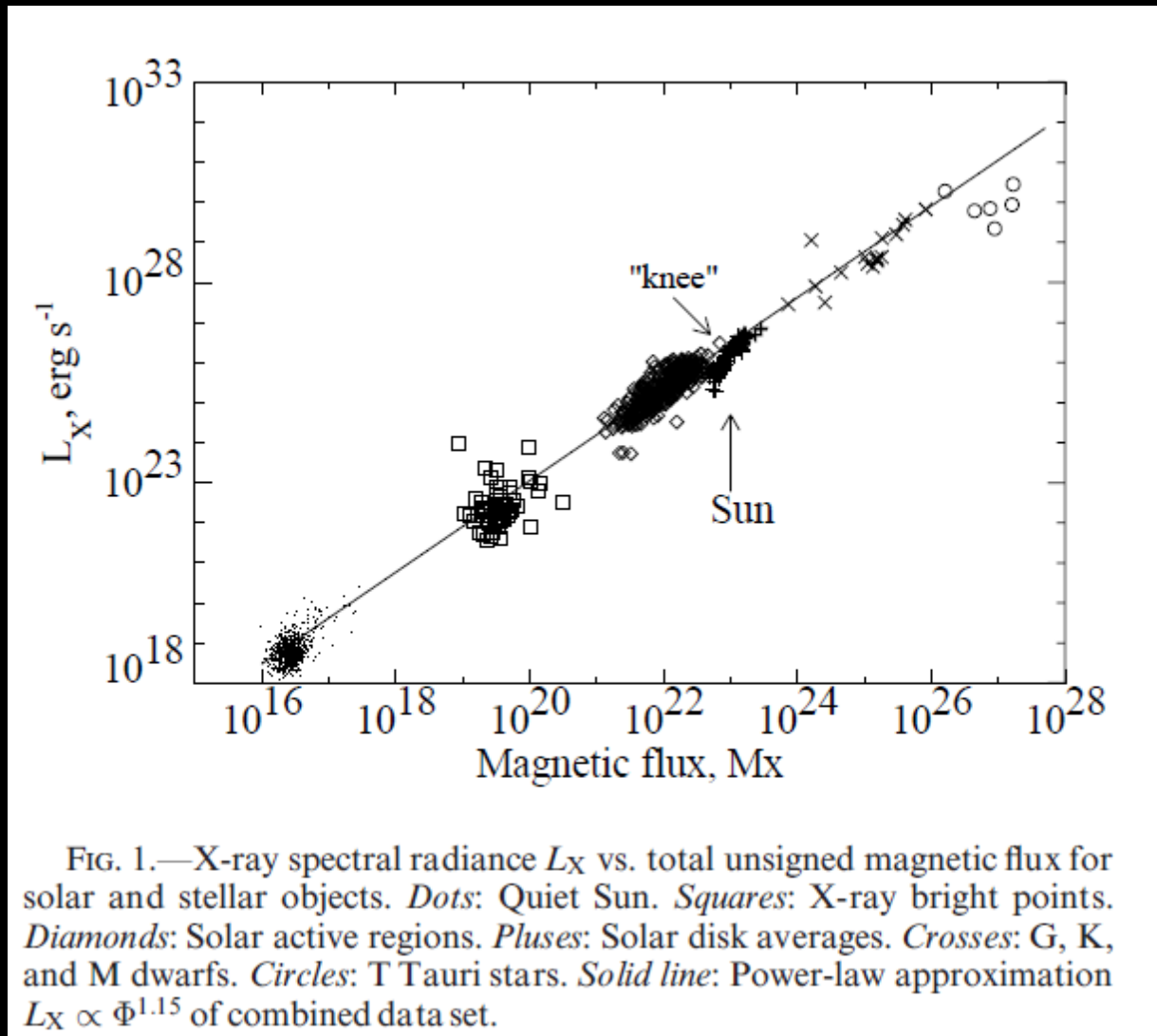
- No correlation with mean AR twist and coronal X-ray luminosity
- Statistically significant correlation between variance in AR twist and coronal X-ray luminosity
- These were Yohkoh era studies; do higher resolution observations confirm these?

Twist and Coronal Heating in High Resolution (Hazra, Nandy & Ravindra, ongoing...)



- Co-spatiotemporal data from Hinode-SOT and Hinode-XRT (limited)
- In fact negative correlation between X-ray emission and twist
- X-ray luminosity correlates best with magnetic flux
(Confirms an earlier analysis of Fisher et al. 1998)

And how about that....(Pevtsov et al. 2003)



Tells us something beautifully simple, and perhaps fundamental about coronal heating...

Summary

- Magnetic fields at heart of solar flaring activity and coronal heating
- Traditionally two main contenders: reconnection (DC) or waves (AC)
- Do not discount other mechanisms (e.g., jets; Pontieu 2011)

The Relaxation Process

- Plasma relaxation, flaring activity and coronal heating driven not by the magnitude of twist, a measure of AR non-potentiality, but by the variance in the twist distribution within magnetic configurations
- Implicates a hyper diffusive process driven by the non-uniformity of magnetic twist

The coronal heating problem is not that we do not have a mechanism for heating the corona, but that we have many likely candidates, the relative roles and underlying physics of which are still unclear

Quiz Time



Because he has found a coronal hole!

Acknowledgements

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