Turbulence and Complexity throughout the Heliosphere

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CUA/Physics & NASA/GSFC

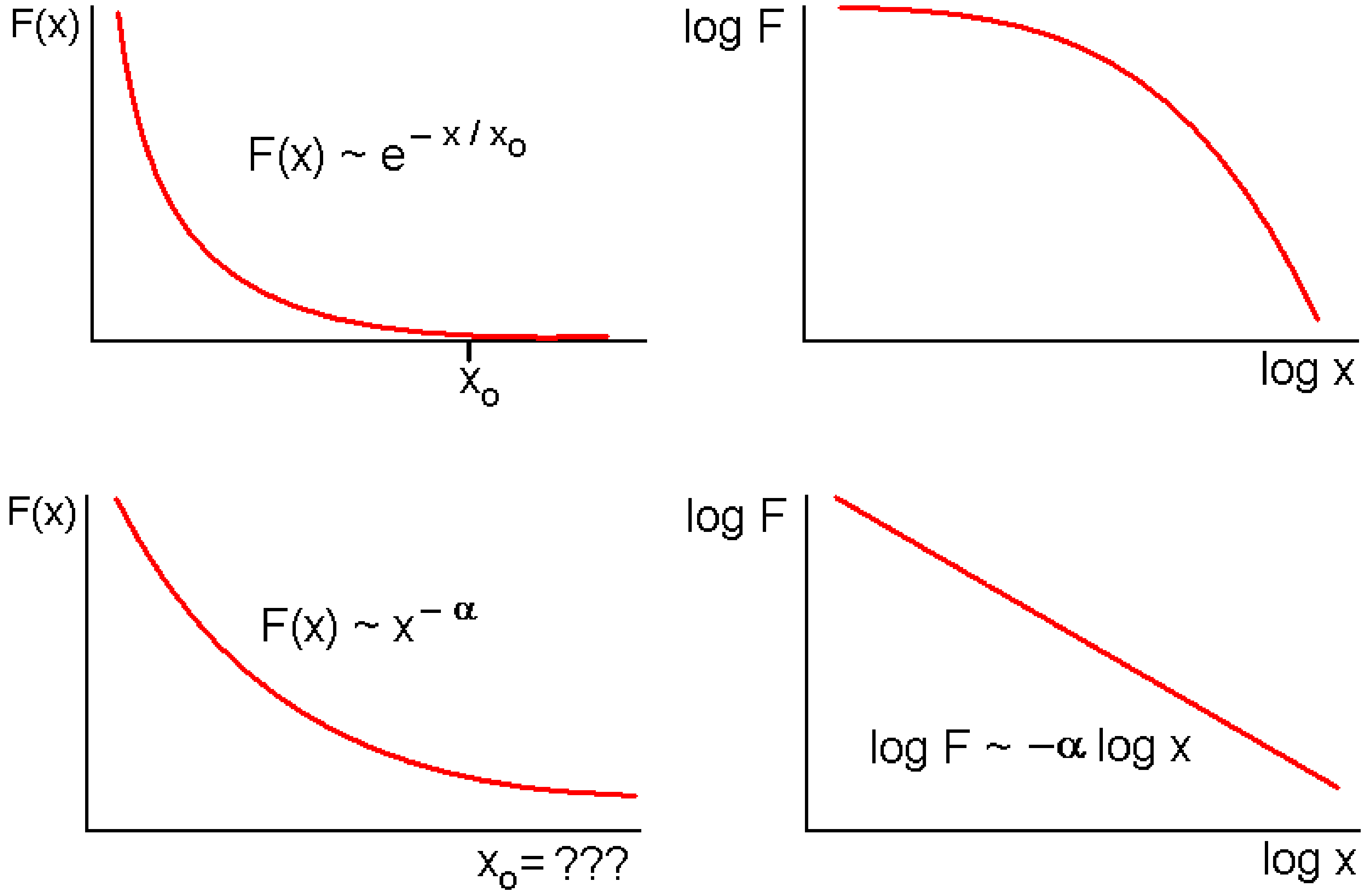
Introduction

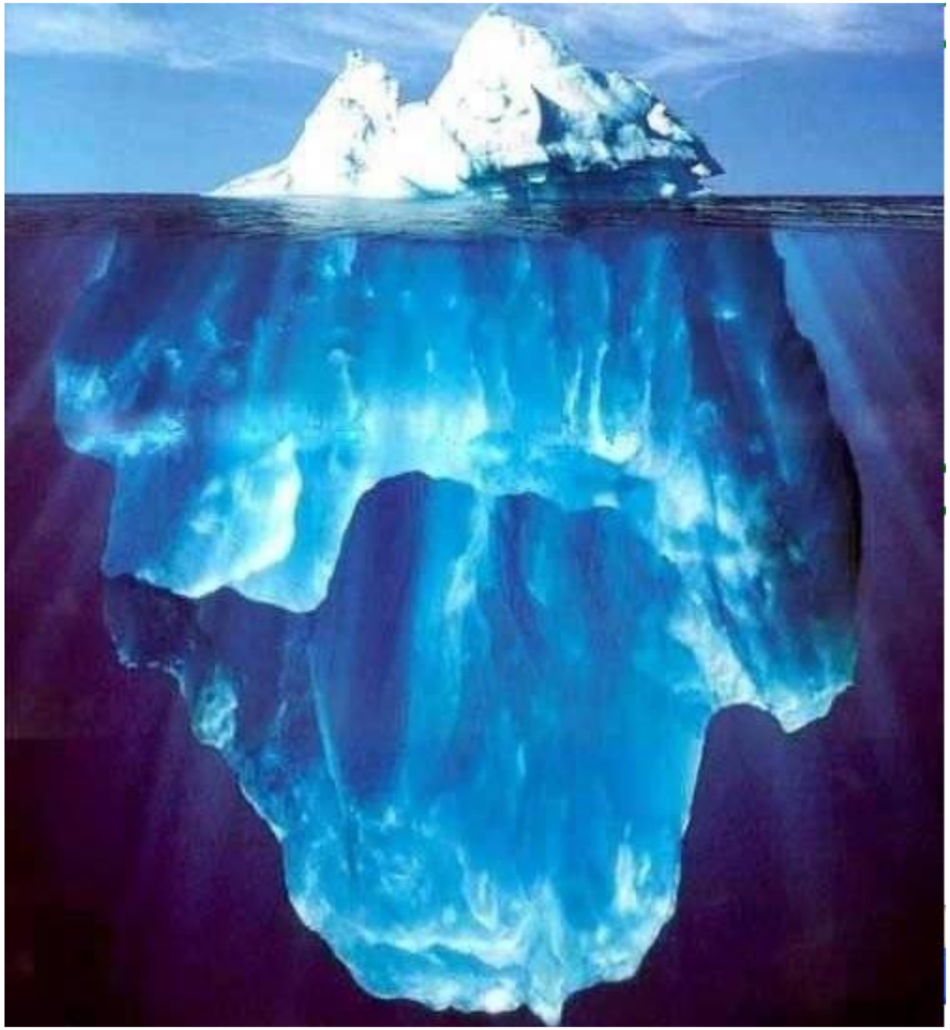
THE “INCONVENIENT TRUTH”:

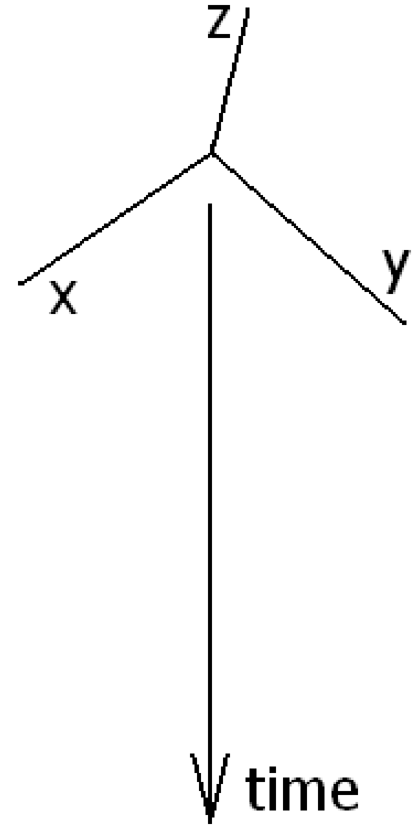
multiscale stochastic space environment

	Solar Wind	Magnetosheath	Magnetotail
Re	1×10^{14}	1×10^{12}	5×10^{12}
Re_m	3×10^{14}	1×10^{13}	1×10^{13}

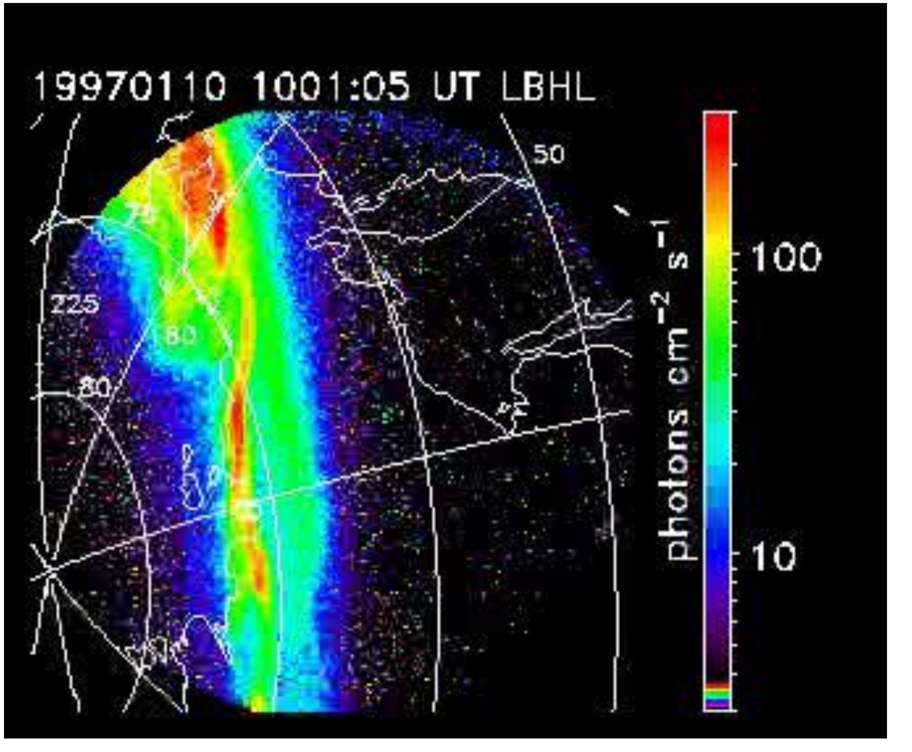
J Borovsky, H. Funsten JGR 2003


F(x)
F(x) ~ e^{− x / x_o}
x_o
log F
log x
F(x)
F(x) ~ x^{− α}
x_o = ???
log F
log F ~ −α log x
log x




z
x
y
time

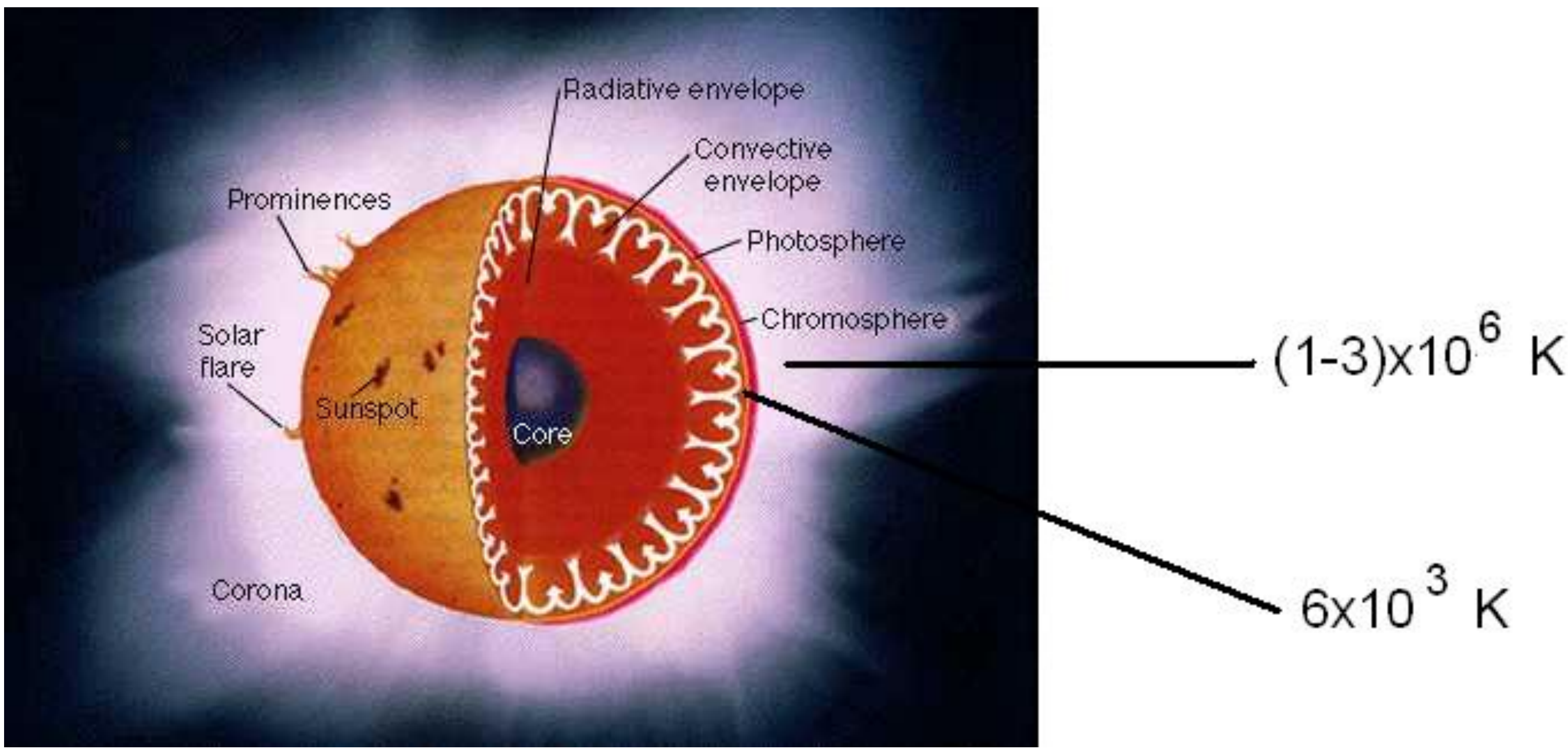
Multiscaling in space plasmas



Why should we care ?

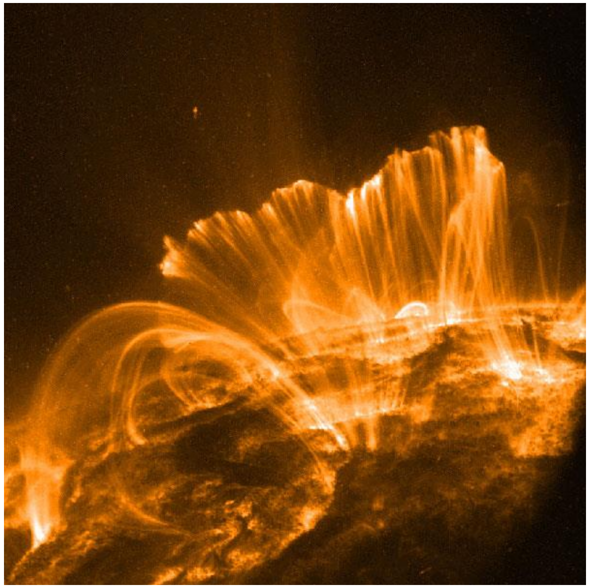
Sun

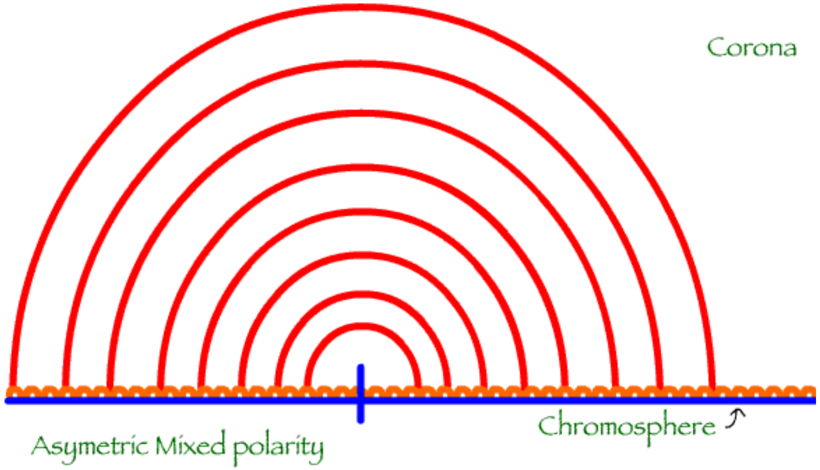
Structure of the Sun and the coronal heating problem



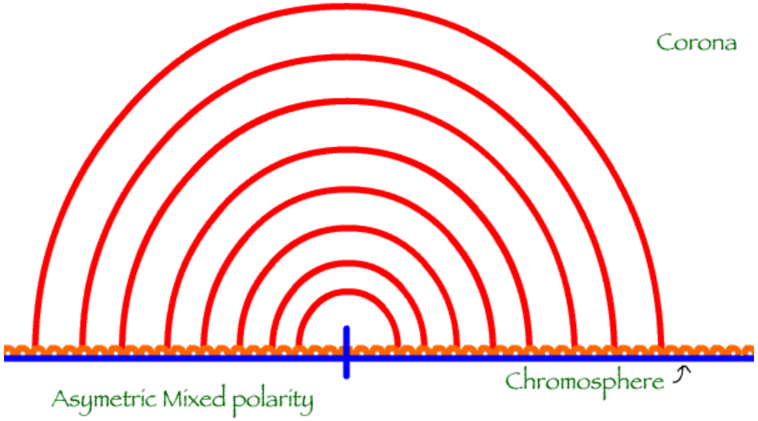
Examples of non-potential coronal structures

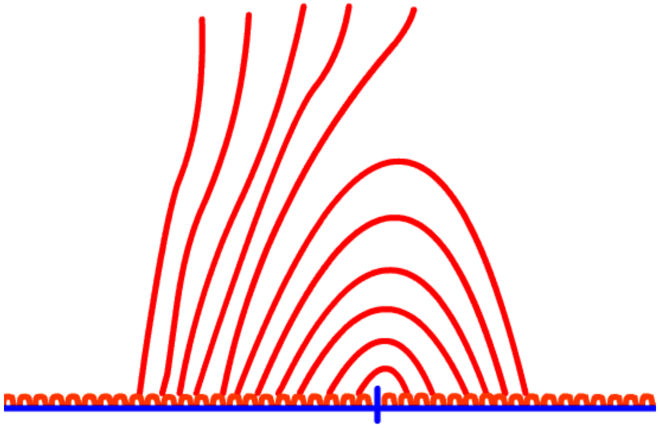
TRACE loop arcade





Convergent flow

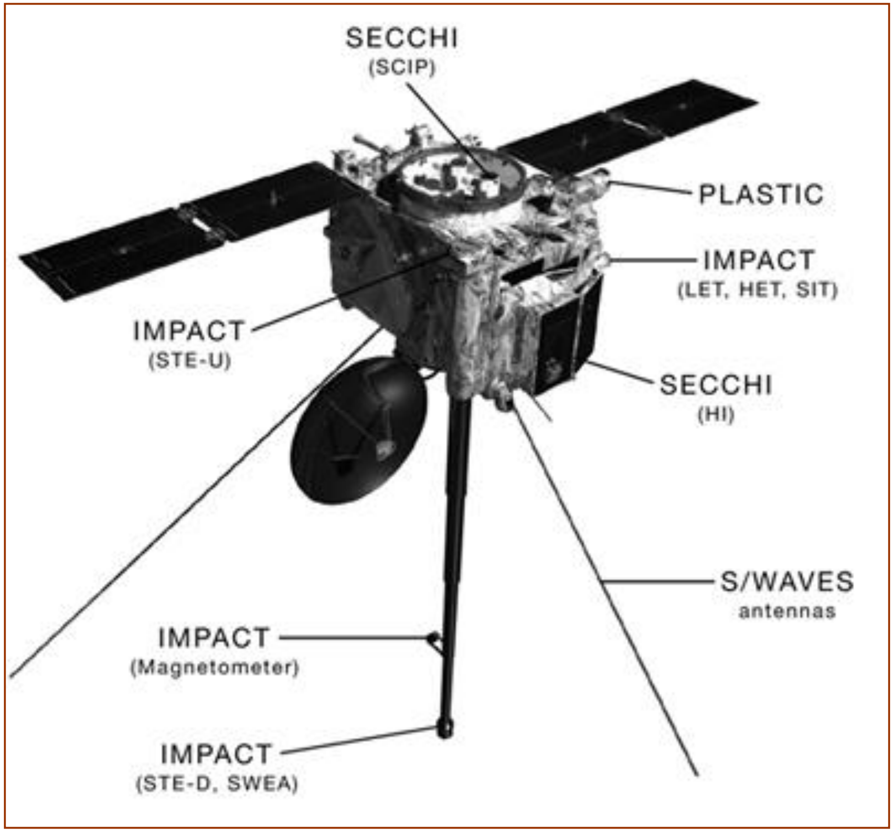




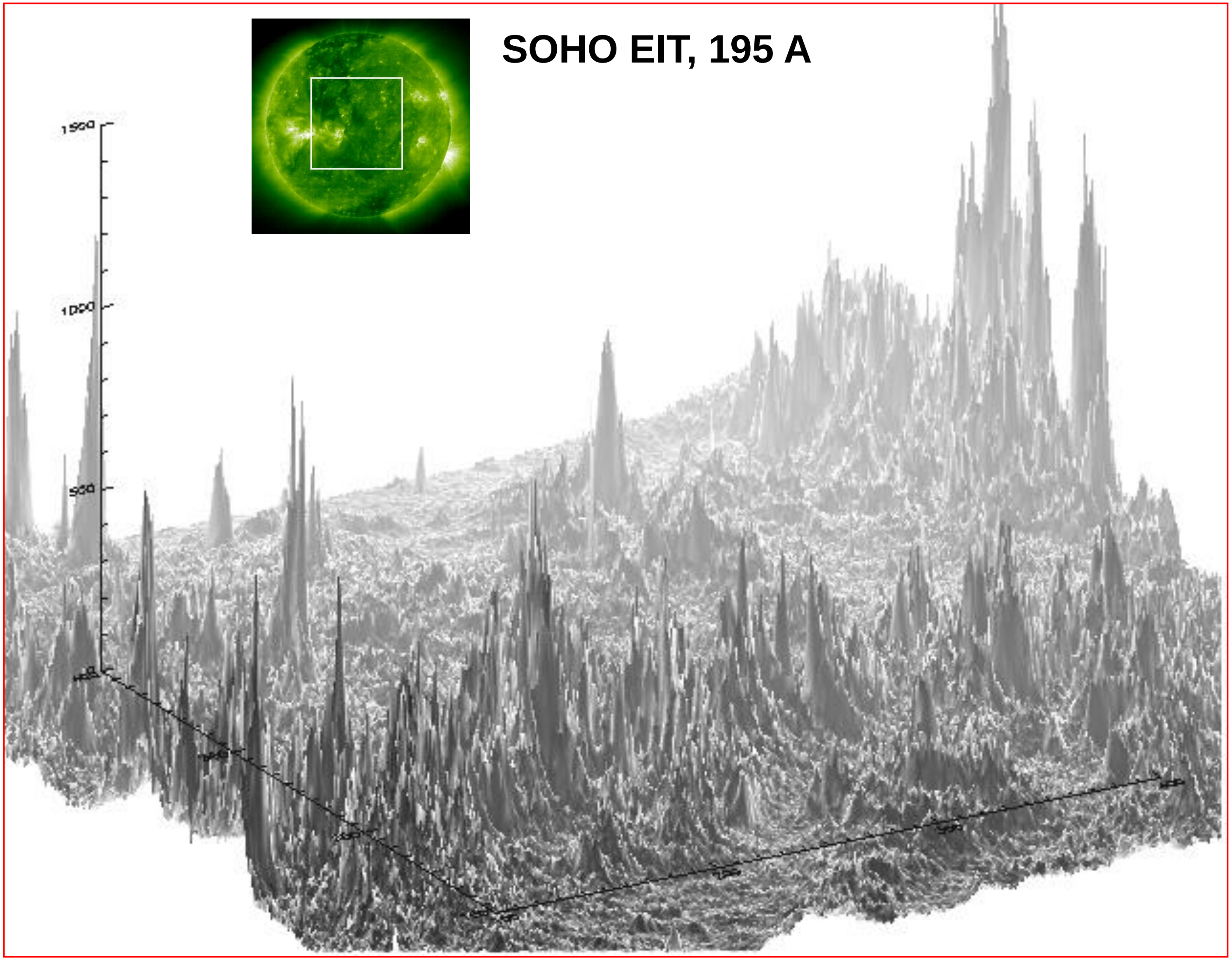
Differential rotation

Neutral line + coronal hole

Solar and Heliospheric Observatory (SOHO) and *Solar TErrestrial RElations Observatory* (STEREO) spacecraft



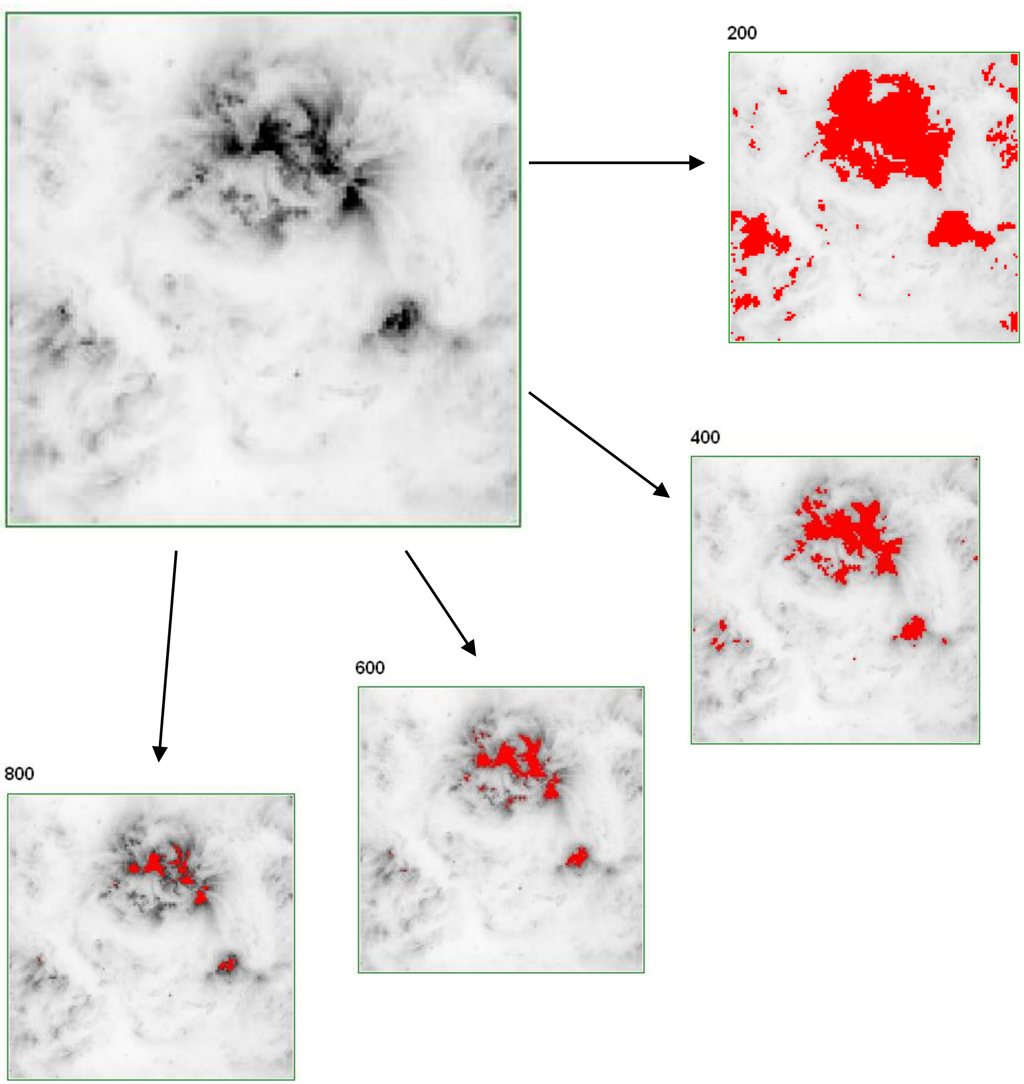
Multiscale intermittency in the solar corona : SOC or turbulence?

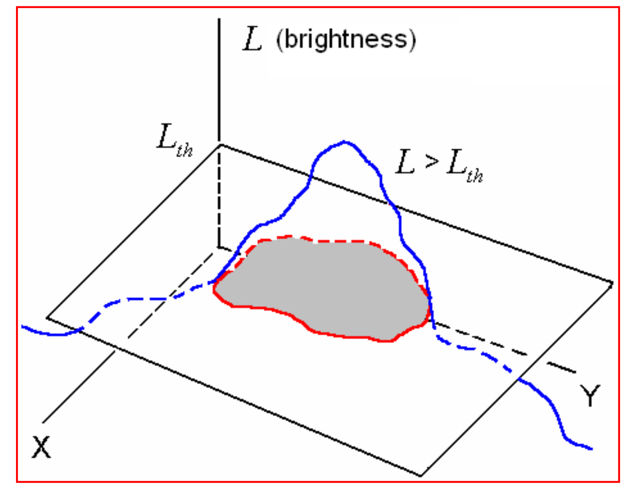


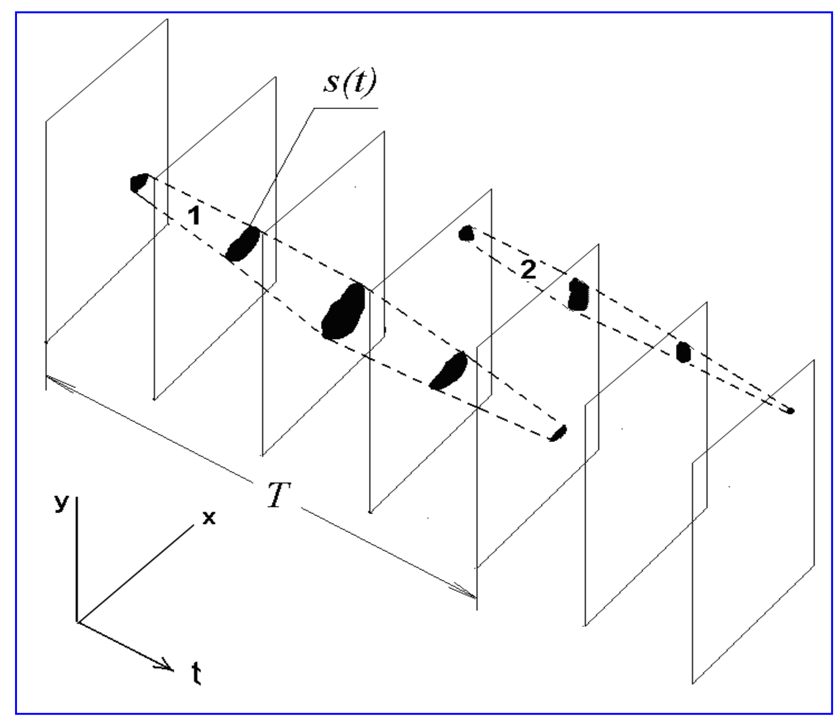
Uritsky, V.M., M. Paczuski, D. Davila, and S. I. Jones, *PRL*, 99(2), Art. No. 025001, 2007.

Spatiotemporal tracking of multiple active regions in SOHO EIT images (195 A)

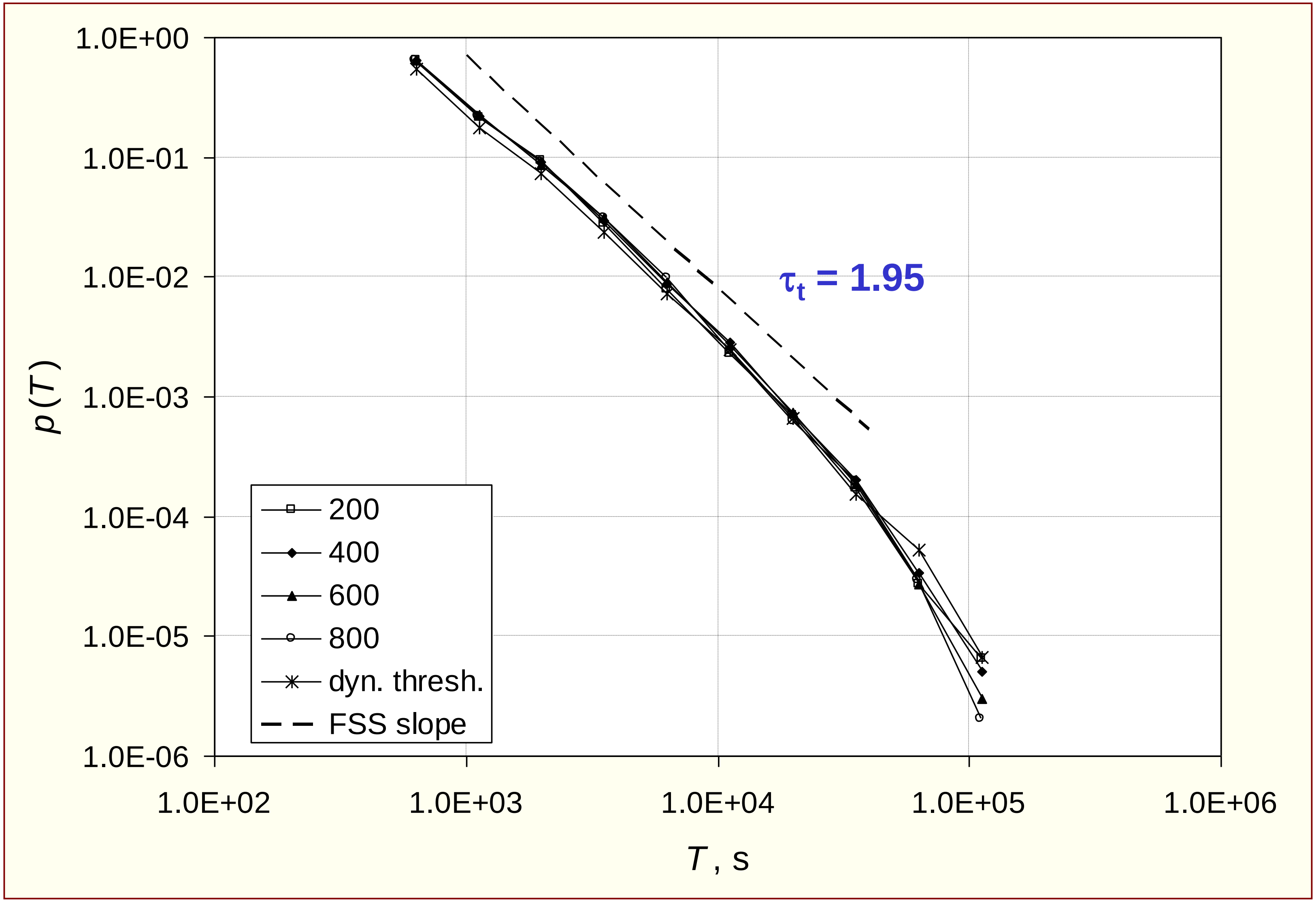
A view of active regions' geometry at different activity thresholds



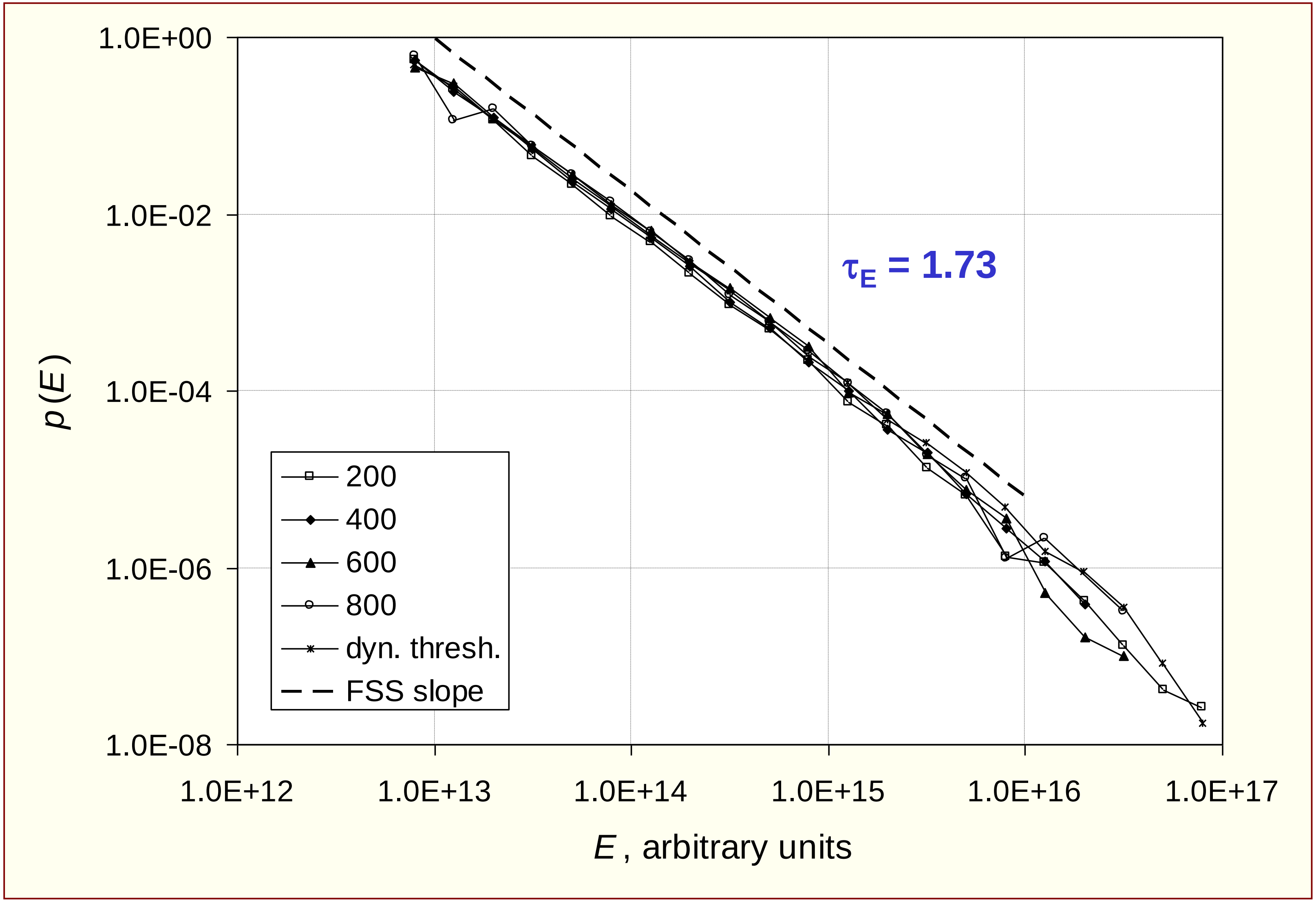




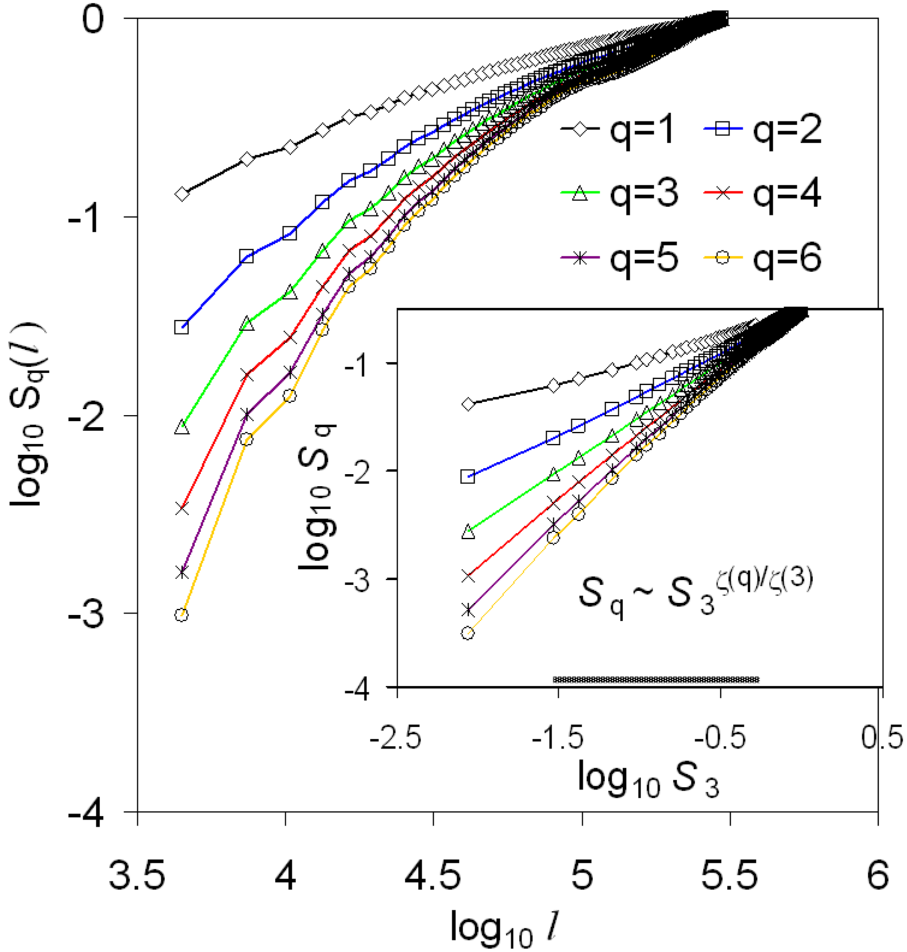
Lifetime probability distributions of coronal active regions

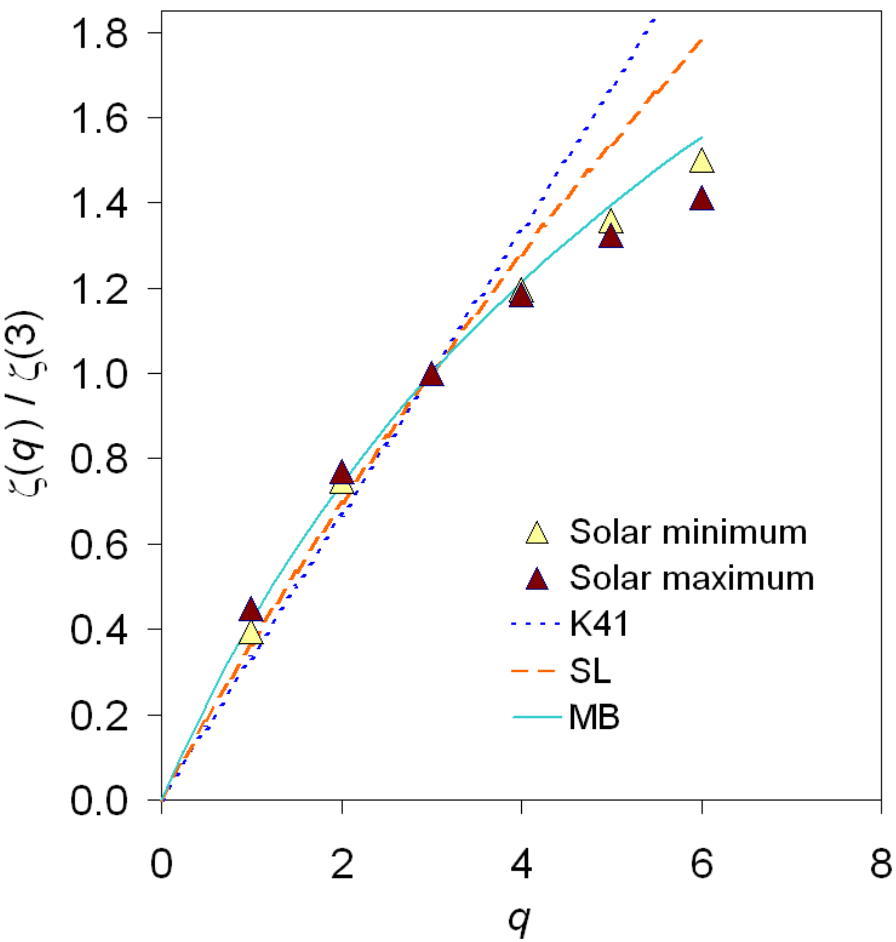


Probability distributions of coronal active regions over integrated luminosity

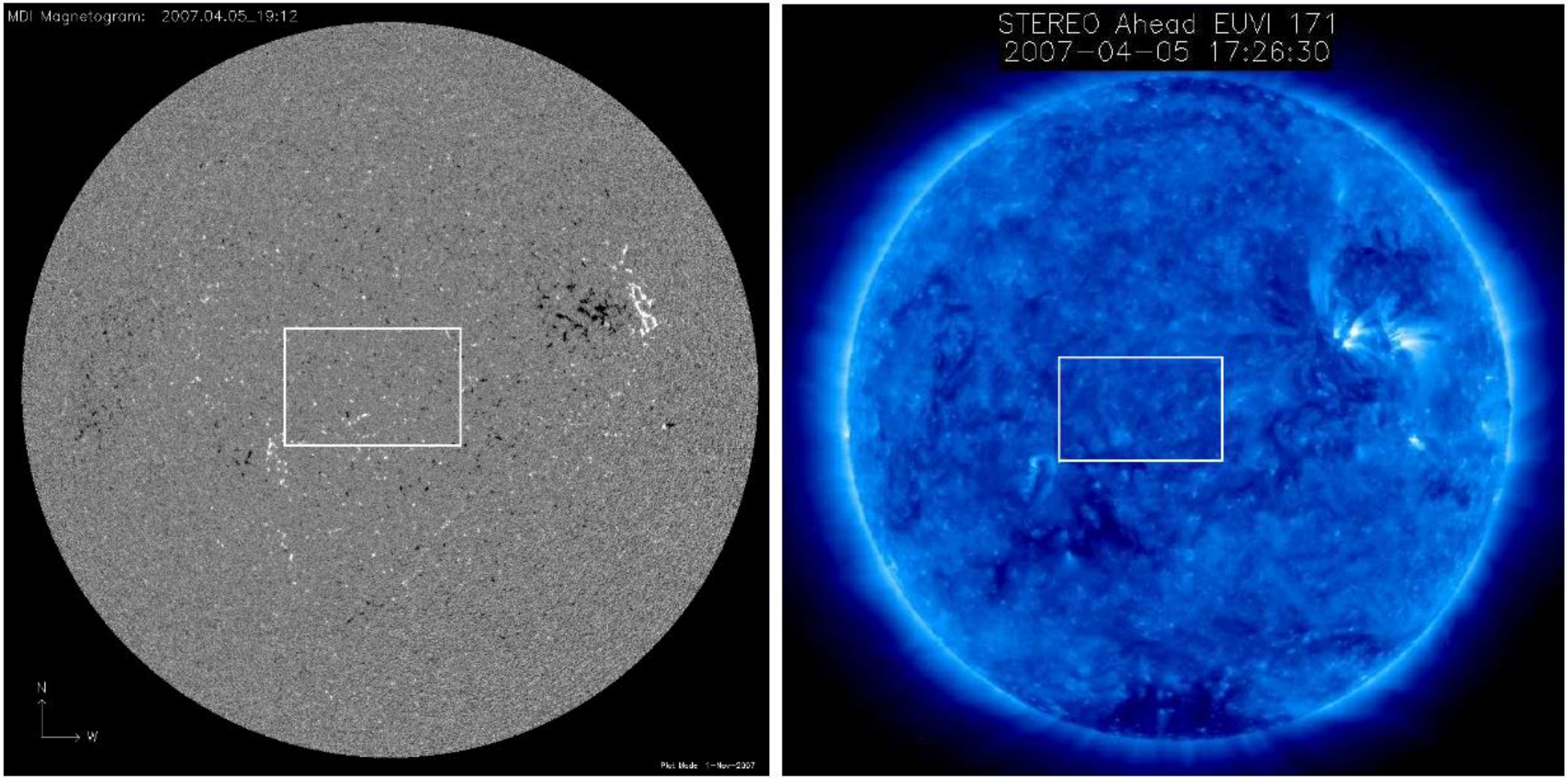


Spatial scaling of high-order structure functions of SOHO EIT images

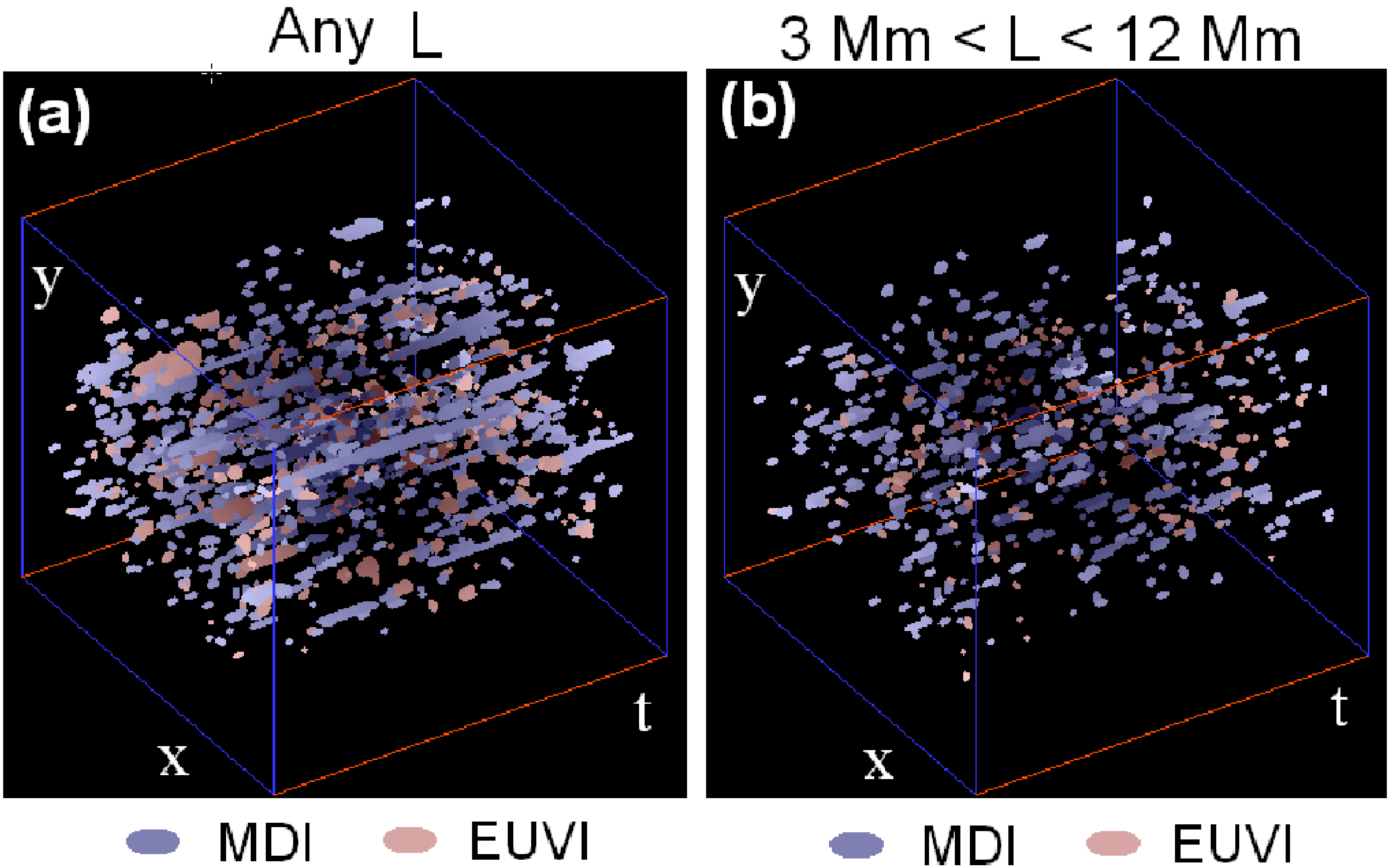




Full-disk SOHO MDI magnetogram (left) and STEREO EUVI image (right) showing the studied quiet solar region.

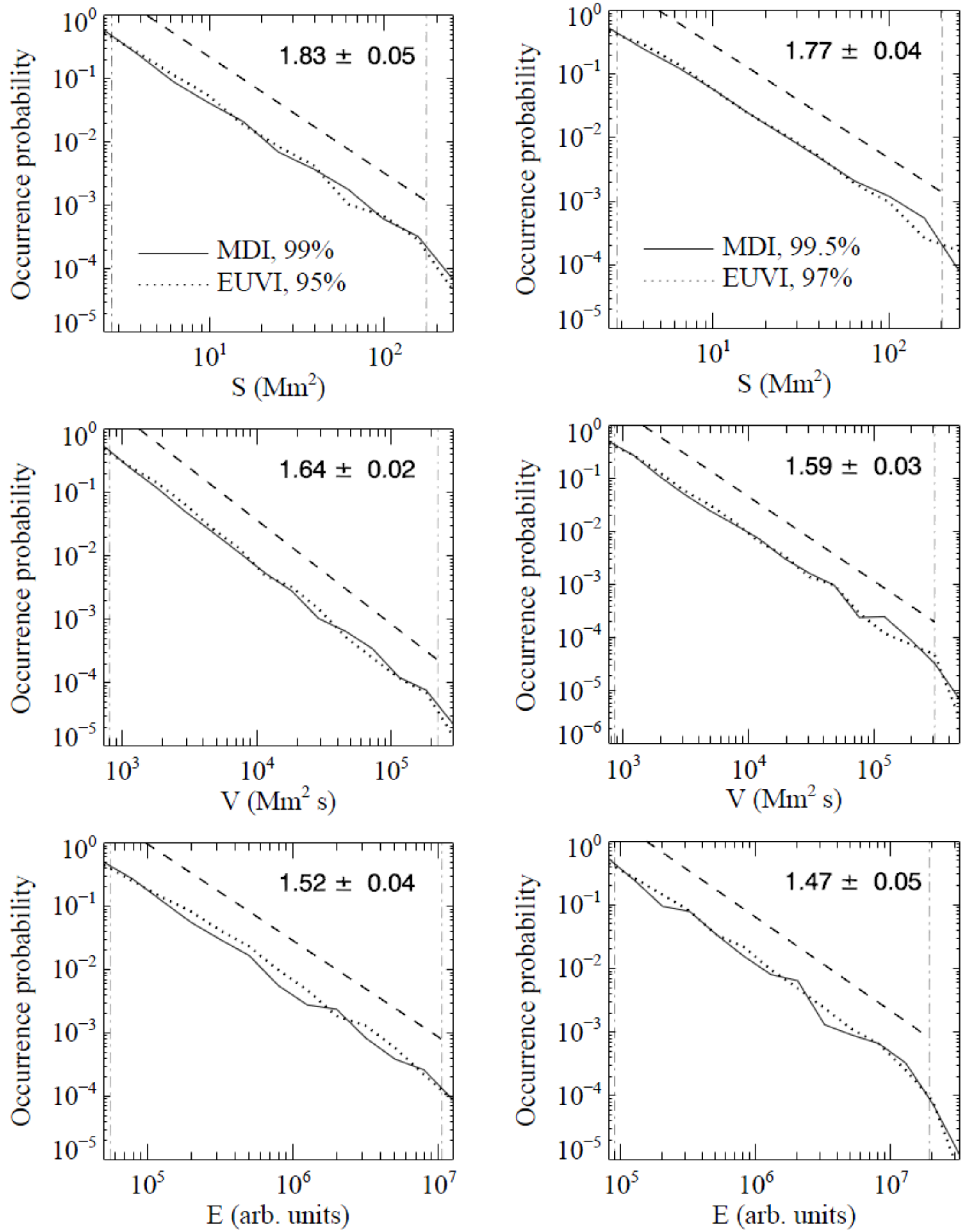


Spatiotemporal plots showing about 1/4 of the photospheric (MDI) and coronal (EUVI) events detected at respectively p = 99% and 95% percentile levels.



Comparison of probability distributions of photospheric and coronal events obtained for two combinations of thresholds yielding comparable numbers of detected events in each data sets.

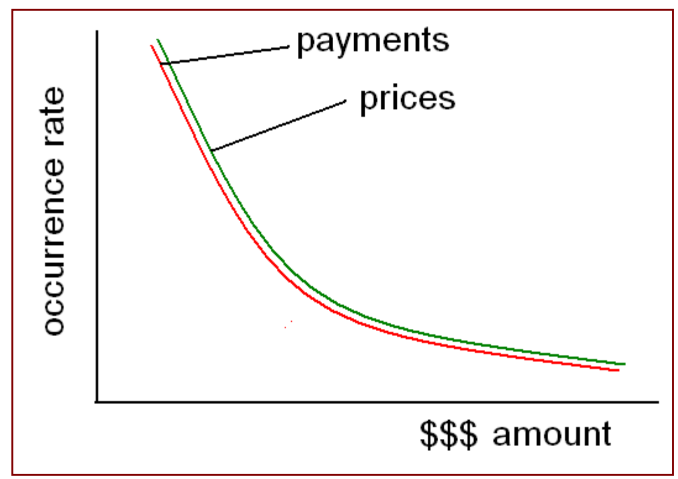
p	MDI threshold	EUVI threshold
95.0 %	13.5 ($n = 38242$)	202 ($n = 4124$)
97.0 %	17.3 ($n = 19114$)	217 ($n = 3005$)
99.0 %	32.3 ($n = 5912$)	258 ($n = 1269$)
99.5 %	42.0 ($n = 3410$)	292 ($n = 686$)



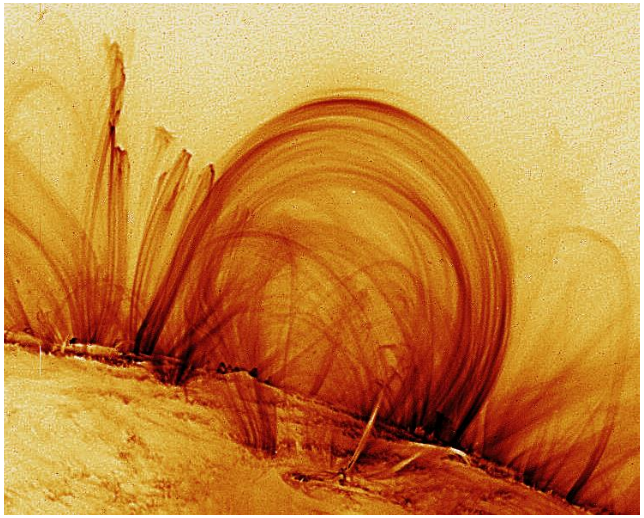
Energy budget (photosphere)

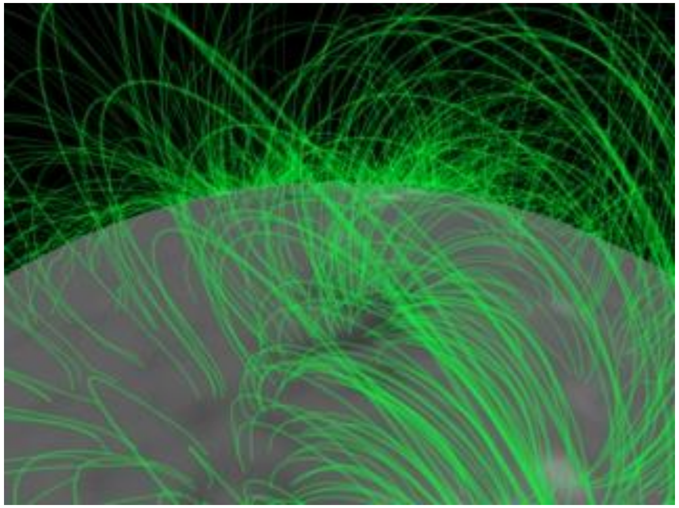
			Expense Category	Amount
		7543580500	Auto Related	$39.56
		EATON	Groceries	$57.17
		GPAYMENT	Clothing	$5.58
9/13/2013	Purchase	PAYPAL *FMYHFG	Miscellaneous	$0.99
9/13/2013	Purchase	WHOLEFDS SSP 10118	Groceries	$16.59
9/11/2013	Purchase	PAYPAL *SMARZOUKSHO	Legal And Professional	$25.99
9/11/2013	Purchase	PAYPAL *CMHOFF1	Legal And Professional	$15.99
9/12/2013	Purchase	WASH METRORAIL	Work Related	$20.00
9/9/2013	Purchase	KMART 3796	Household	$89.00
9/8/2013	Purchase	TUESDAY MORNING # 0624	Groceries	$79.47
9/8/2013	Purchase	KMART 4399	Household	$63.57
9/8/2013	Purchase	THE HOME DEPOT 2558	Home Repair	$22.70
9/9/2013	Purchase	PAYPAL *KIMBERLYBRA	Legal And Professional	$9.98
9/8/2013	Purchase	PAYPAL *PRECOCIOUS	Legal And Professional	$9.05
9/9/2013	Purchase	GIANT FOOD INC #336	Groceries	$12.98
9/9/2013	Purchase	TARGET 00014159	Groceries	$52.90
9/7/2013	Purchase	PAPA JOHN'S 00722	Dining Out	$10.60
9/7/2013	Purchase	H MART WHEATON	Groceries	$44.43
9/5/2013	Purchase	PAYPAL *HANNONC65	Legal And Professional	$4.25
9/5/2013	Purchase	PAYPAL *JEMERI5	Legal And Professional	$13.06
9/6/2013	Purchase	WHOLEFDS SSP 10118	Groceries	$10.12
8/29/2013	Purchase	ARAMARK CATHOLIC UNIVERSI	Dining Out	$7.90
8/31/2013	Credit Voucher	SHOE DEPT 0567	Clothing	-$26.48
9/3/2013	Purchase	PAYPAL *J7E7N	Legal And Professional	$7.48
9/3/2013	Purchase	PAYPAL *BELLABELLY	Legal And Professional	$3.65
9/3/2013	Purchase	PAYPAL *JBWHALE	Legal And Professional	$8.59
9/3/2013	Purchase	ARAMARK CATHOLIC UNIVERSI	Dining Out	$5.42
9/3/2013	Purchase	WASH METRORAIL	Work Related	$90.90

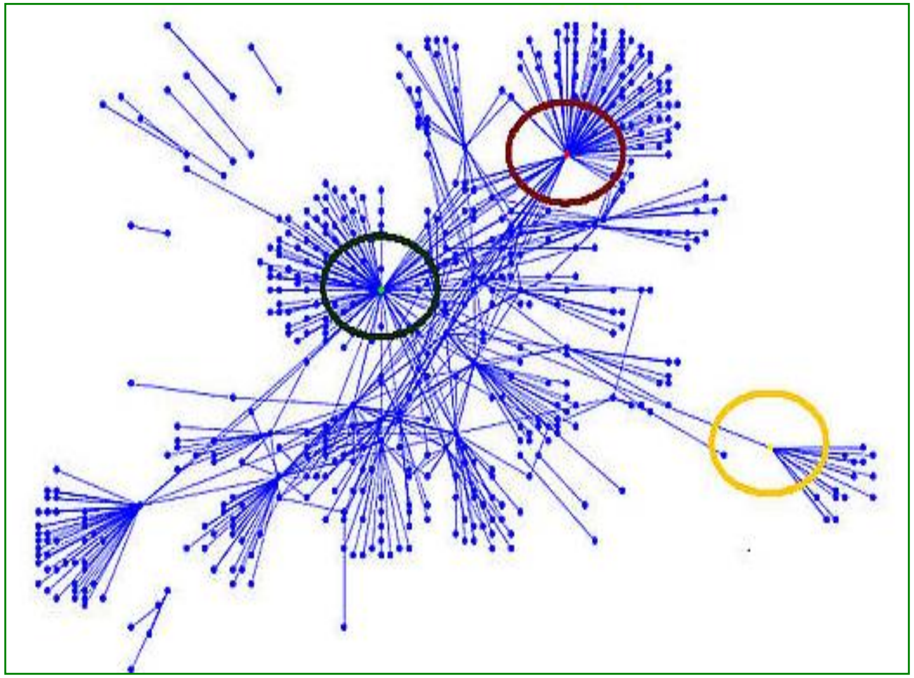
Energy dissipation (corona)



Understanding multiscale topology of coronal magnetic network

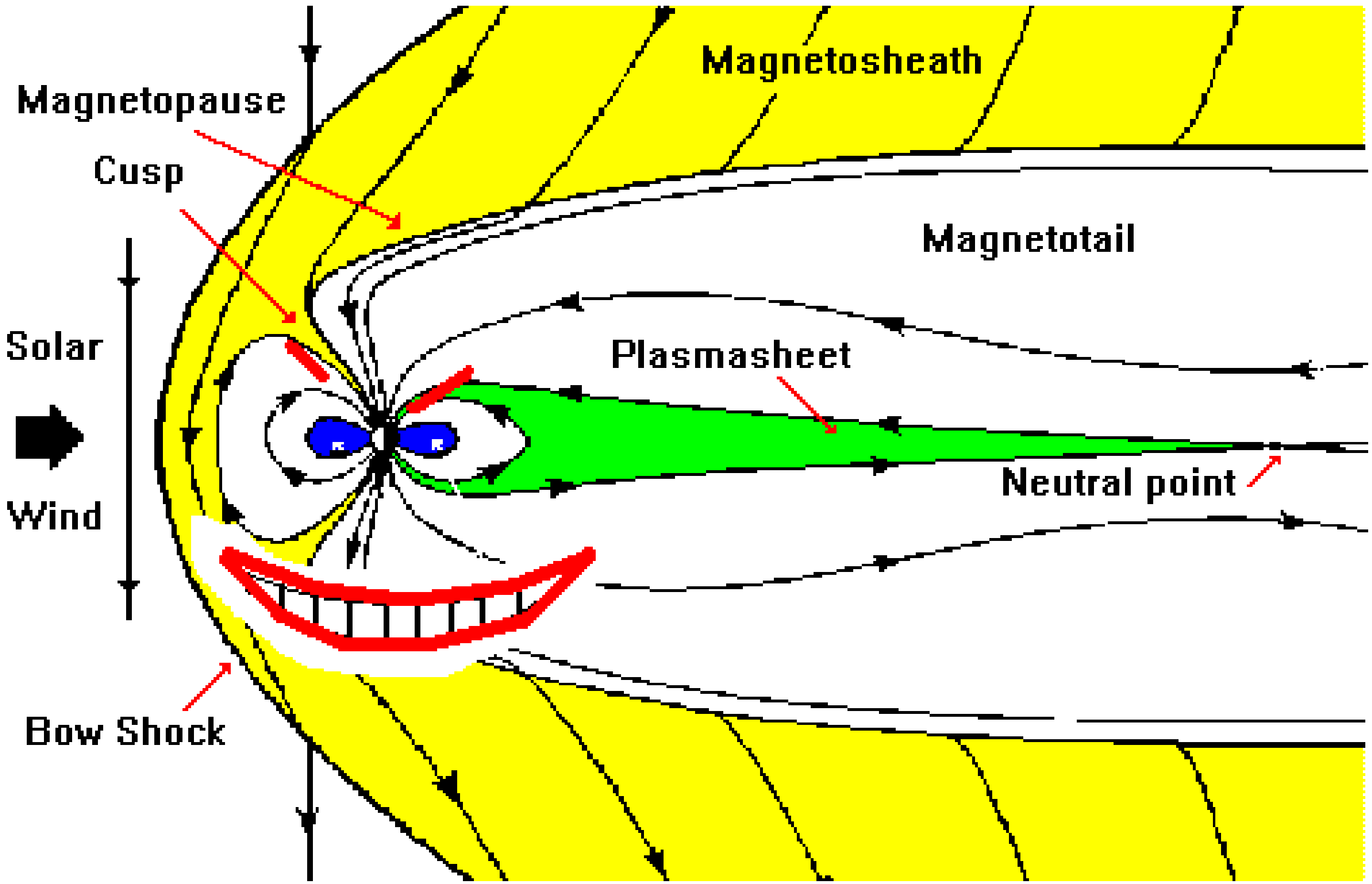




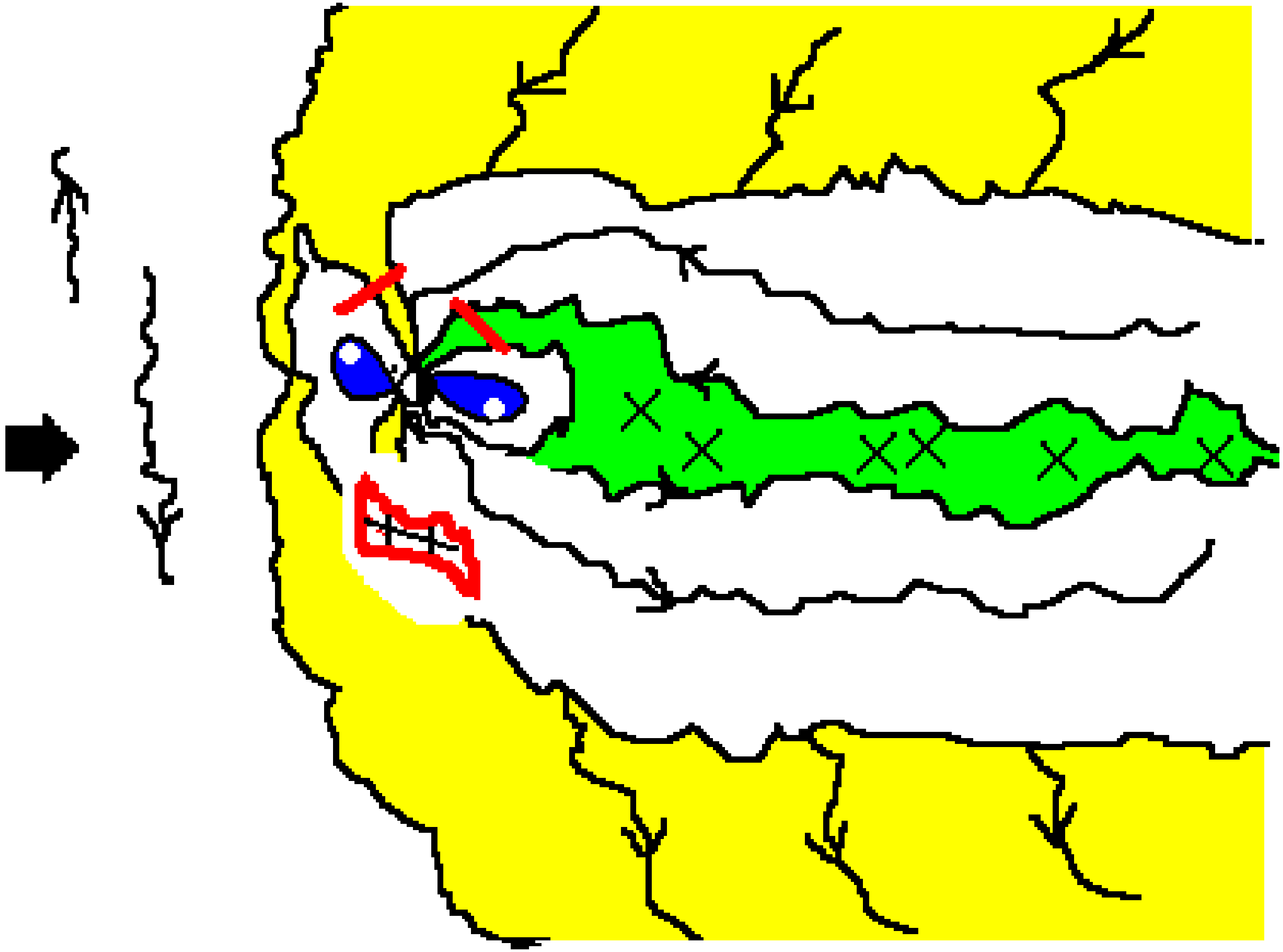


Earth’s magnetosphere

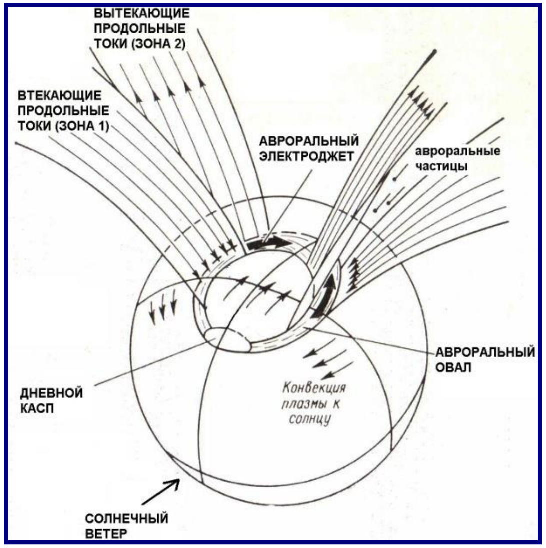
Happy dreams…

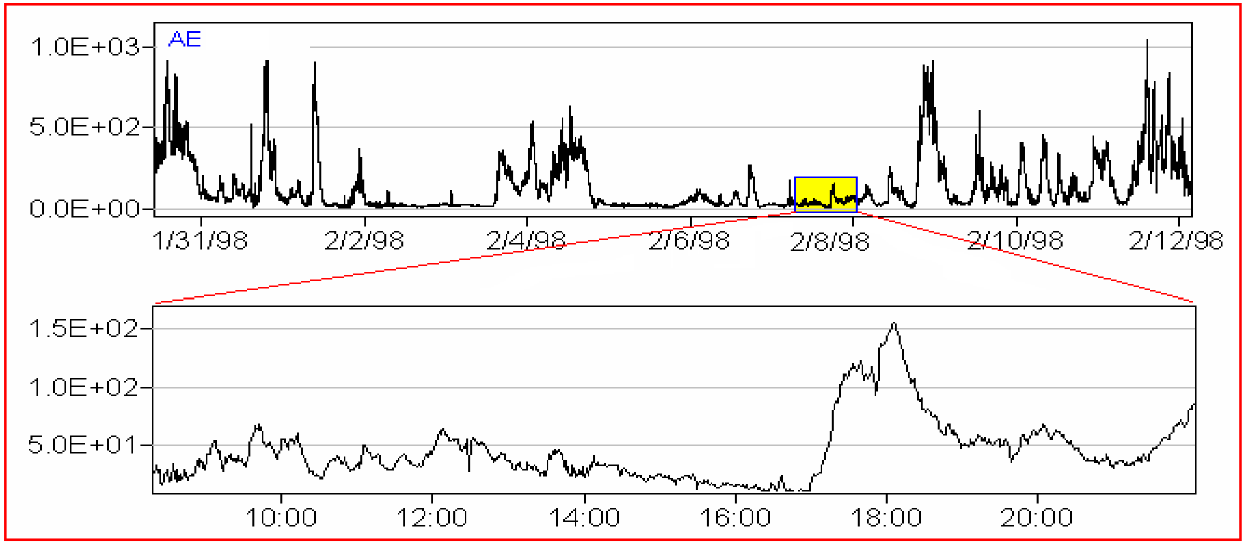


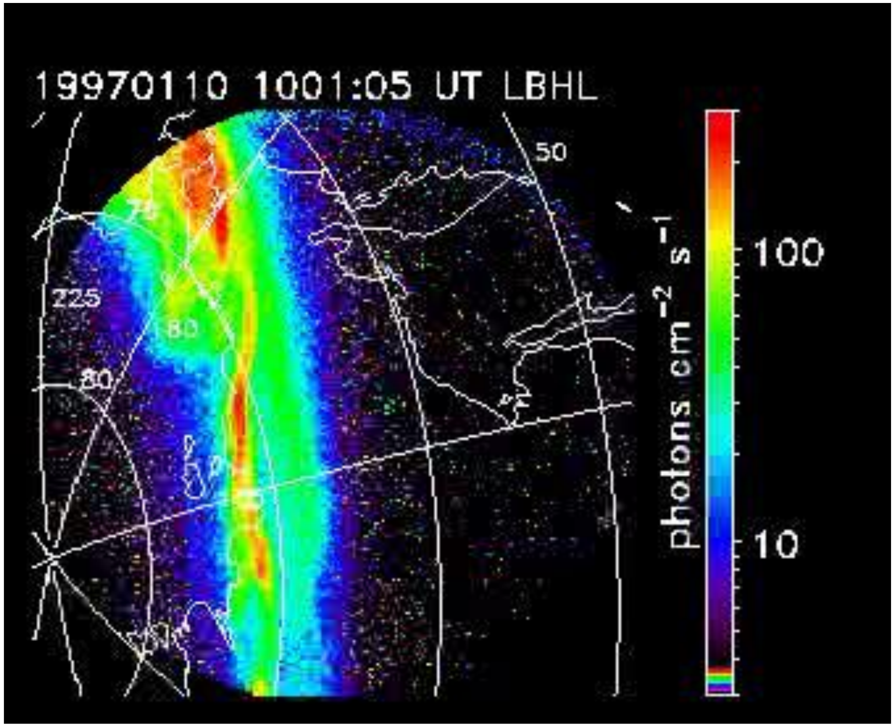
… and harsh reality



Multiscale organization of geomagnetic activity



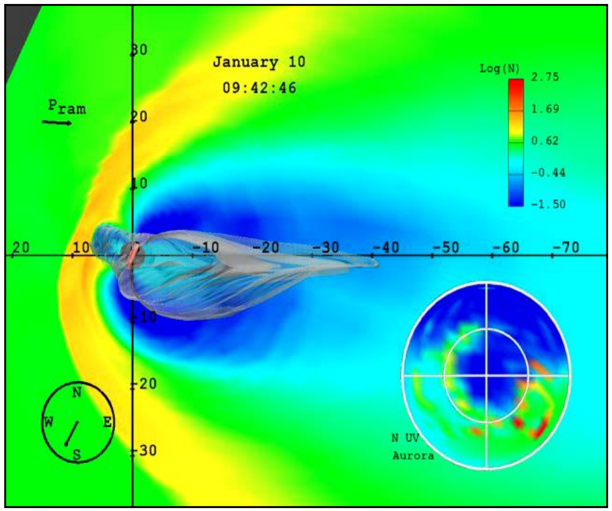


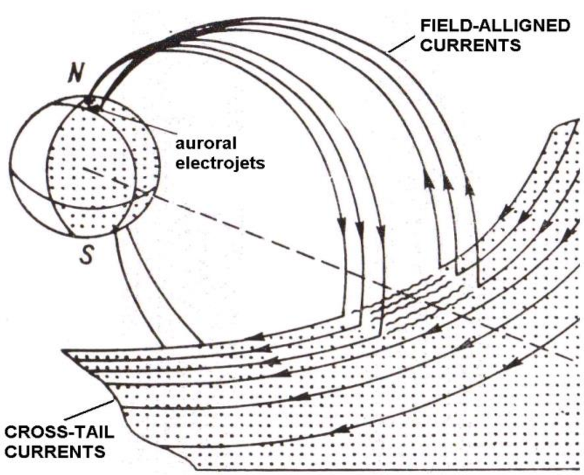


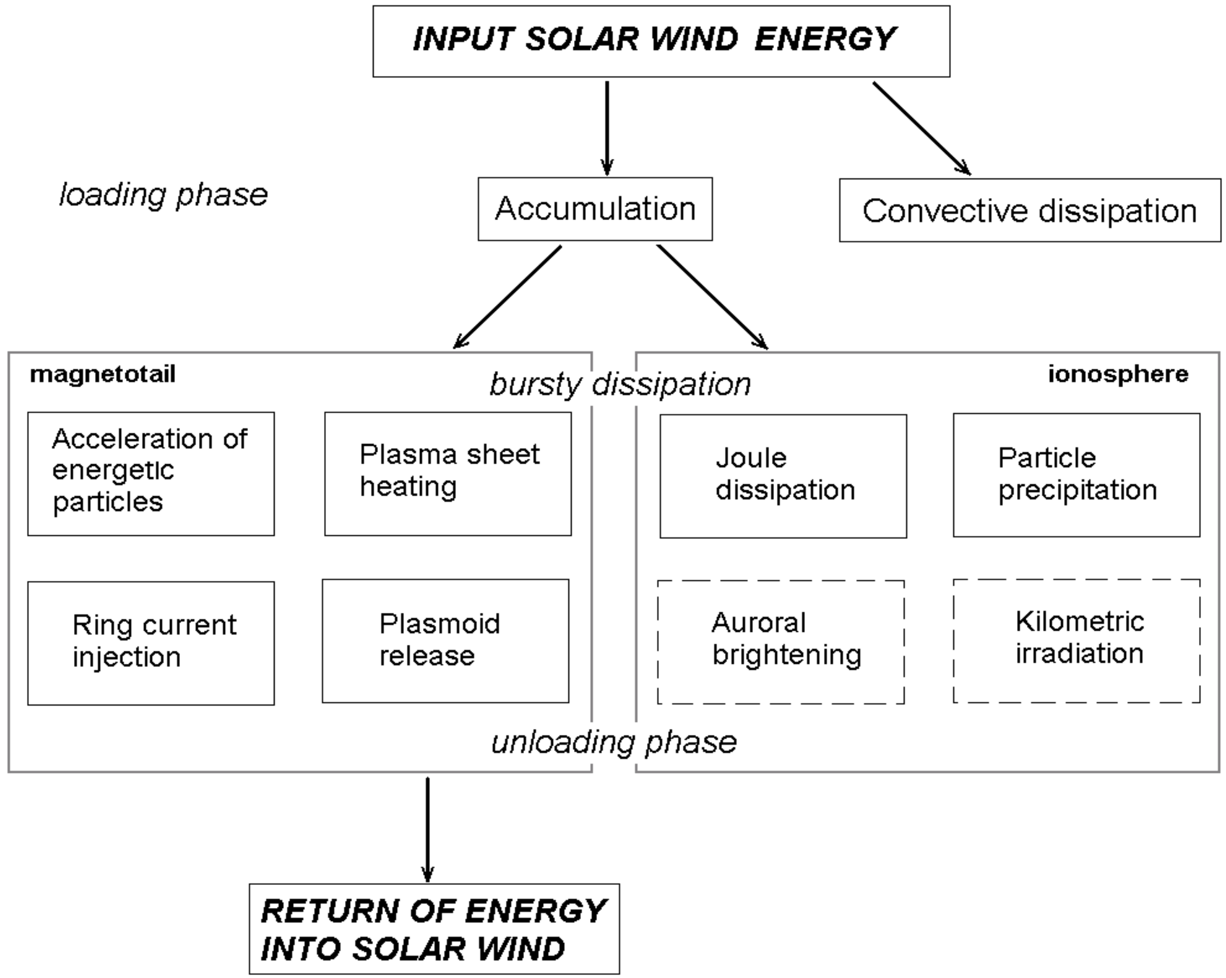
<u>Hierarchy of magnetospheric disturbances</u>

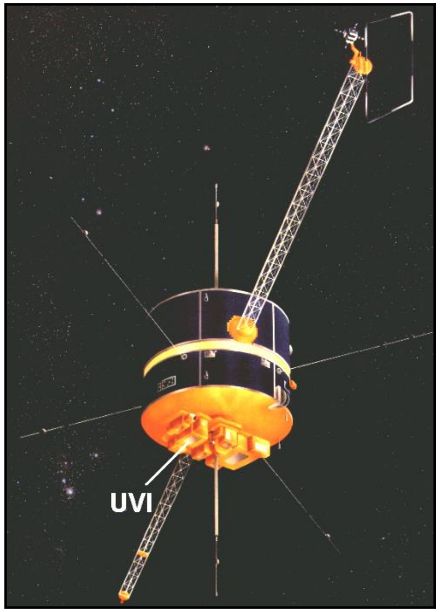
- **Geomagnetic storms**
- **Full-size substorms**
- **Substorm activations**
- **Pseudo-breakups**
- **Bursty bulk flows (BBFs)**
- **Impulsive structure of BBF events**
- **Plasma turbulence**

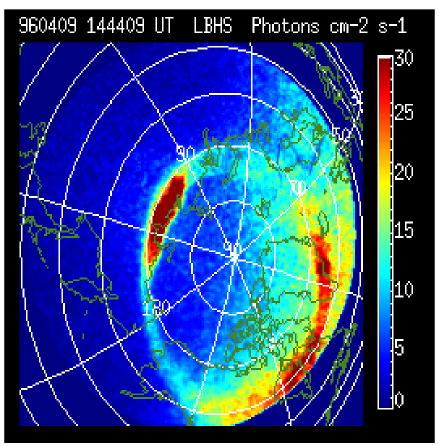
Earth's magnetosphere as an open nonlinear dissipative system





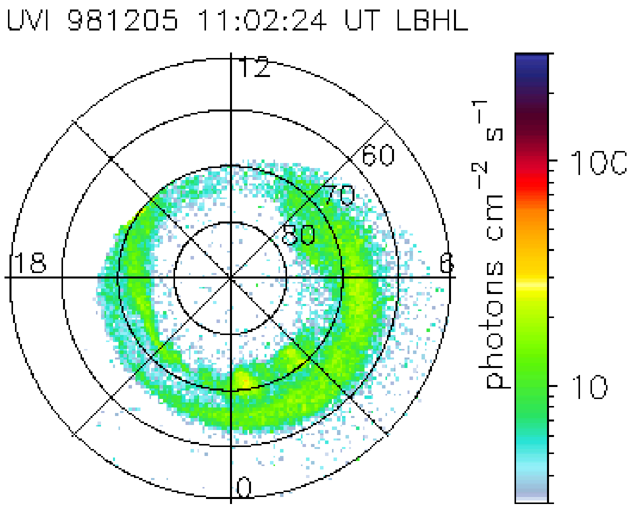


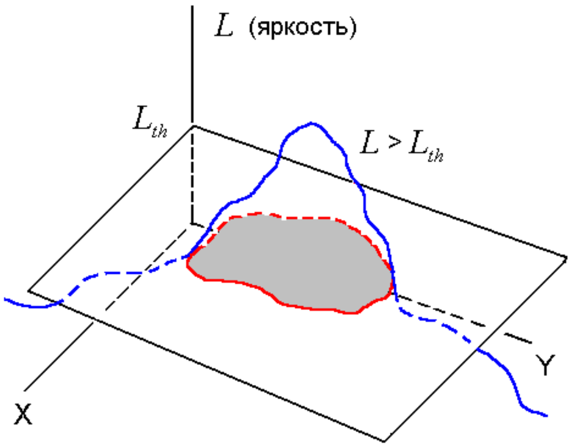


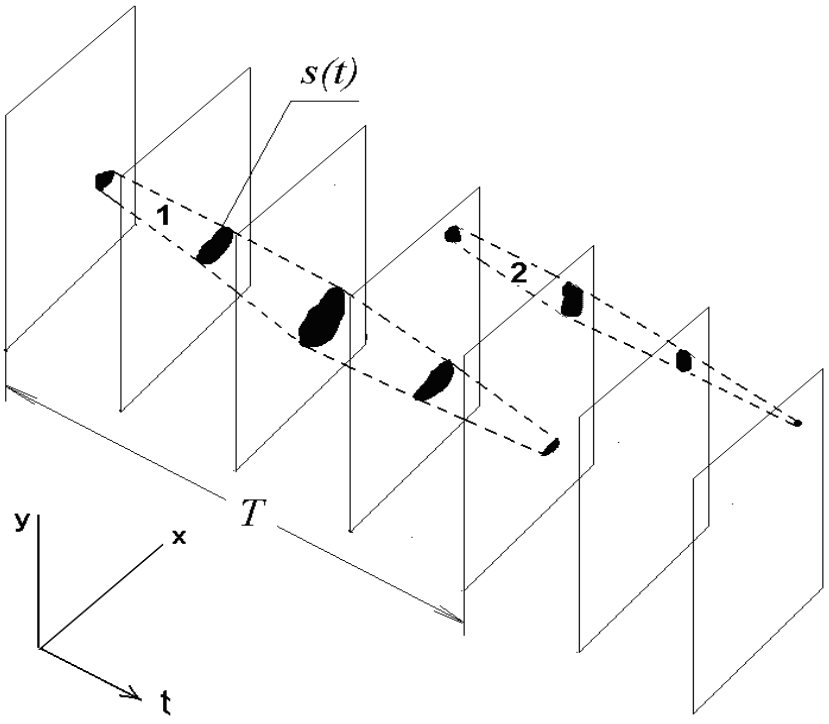


UVI filter	LBH-L (N_2) λ=160-180 nm
Integration time	36.8 s
Spatial resolution	70×70 km
Temporal resolution	184 c, 37 c
Satellite altitudes	> 6 Re
MLT range MLat range	2000 – 0400 55° – 90°
Observation periods	Jan-Feb 1997 Jan-Feb 1998
Number of processed images	~30 000

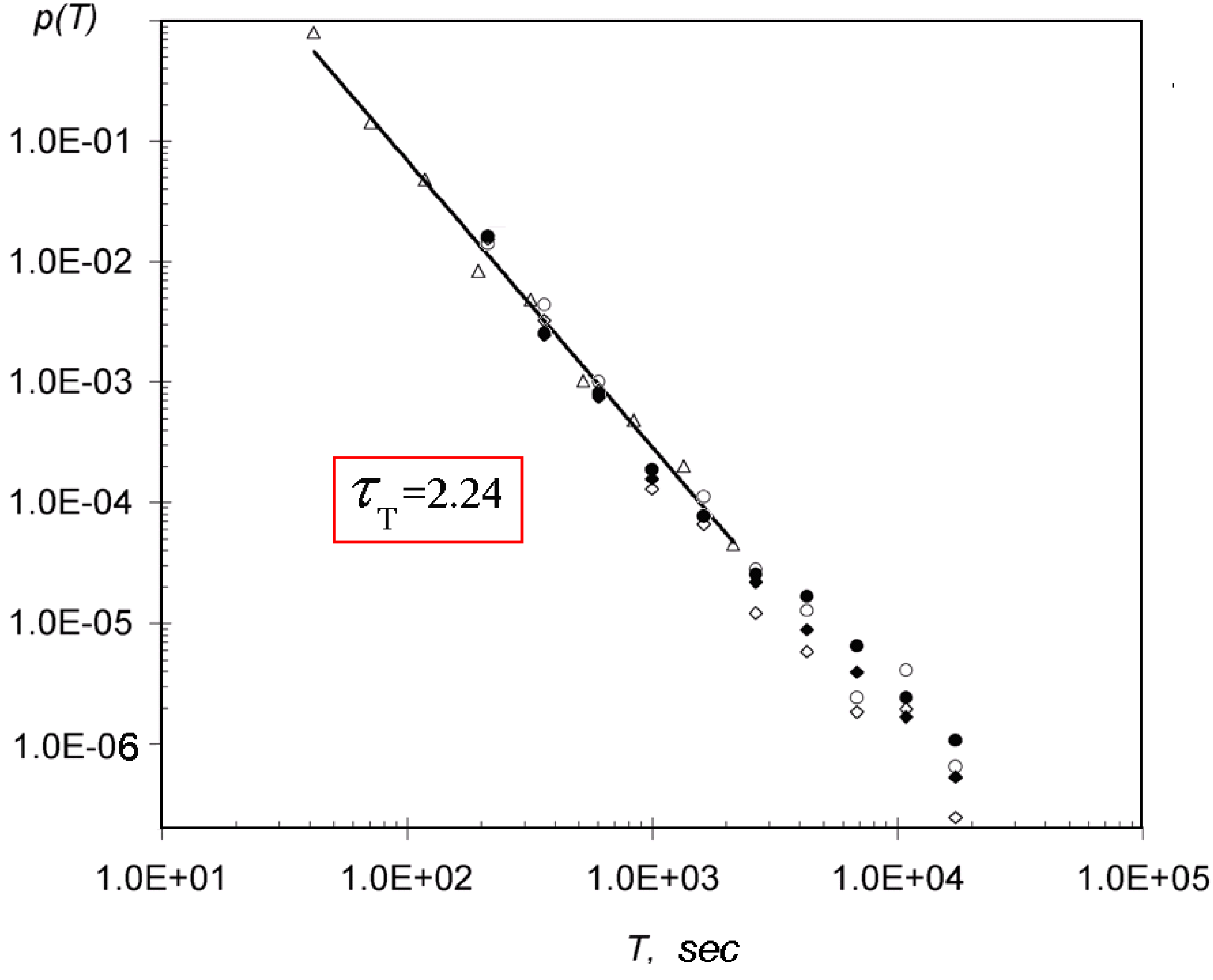
Detection and spatiotemporal tracking of active emission regions on POLAR UVI images



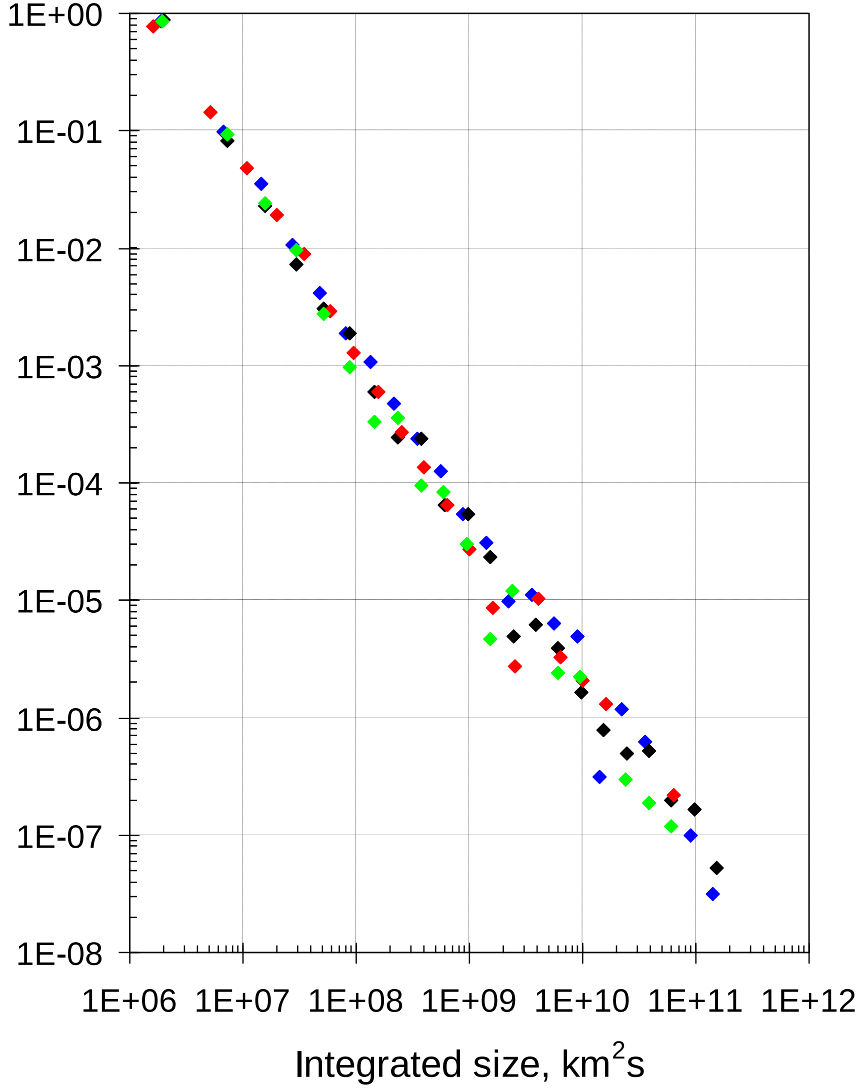


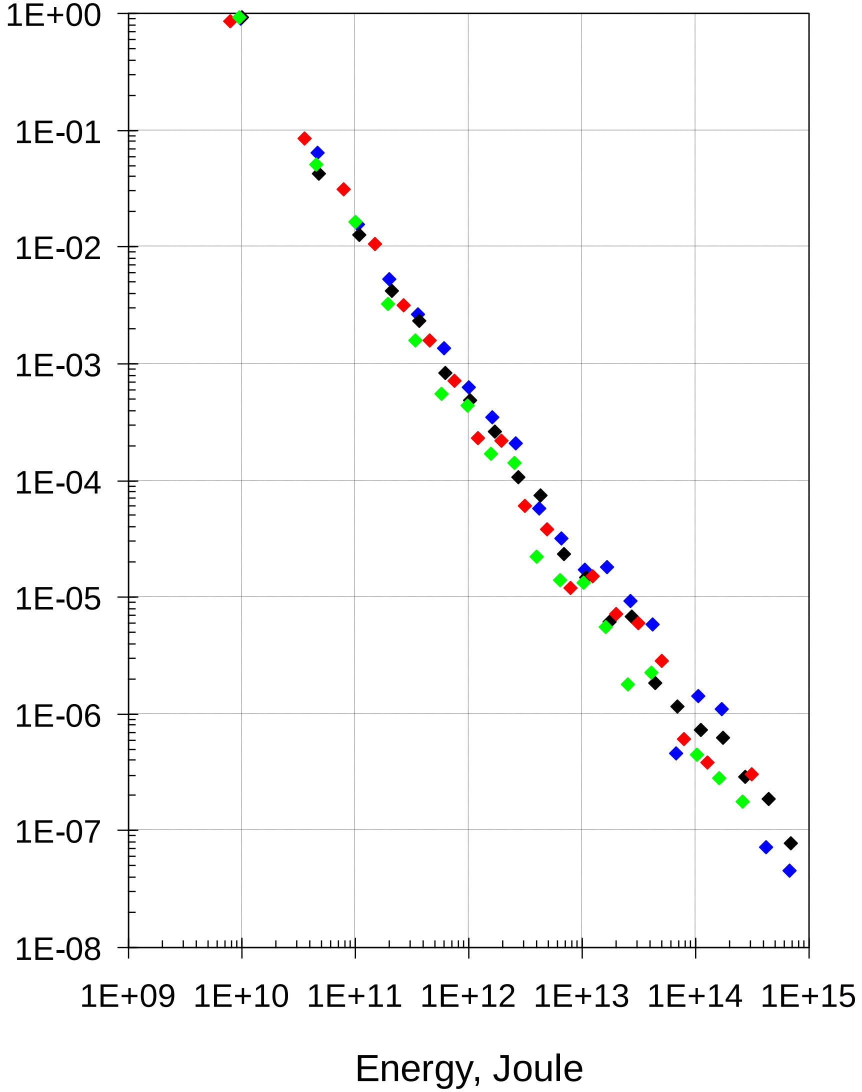


Lifetime probability distributions of auroral emission regions for different time periods and resolution



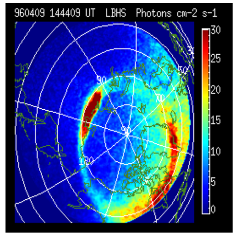
Probability distributions of emission regions of the spatiotemporal avalanche size and total energy output





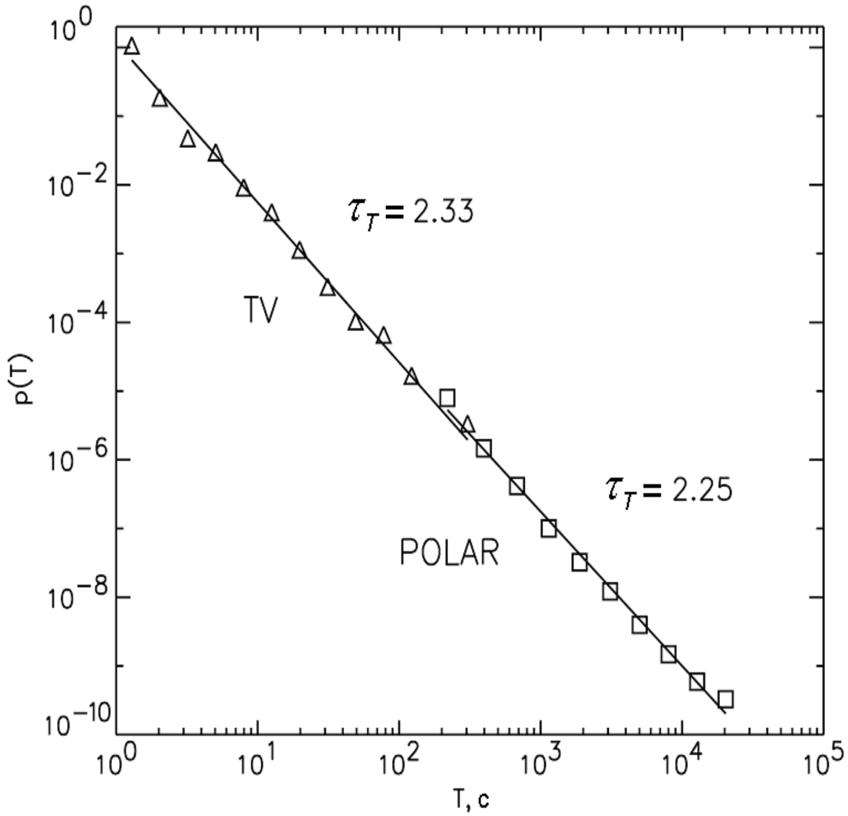
Power-law statistics of auroral emission events

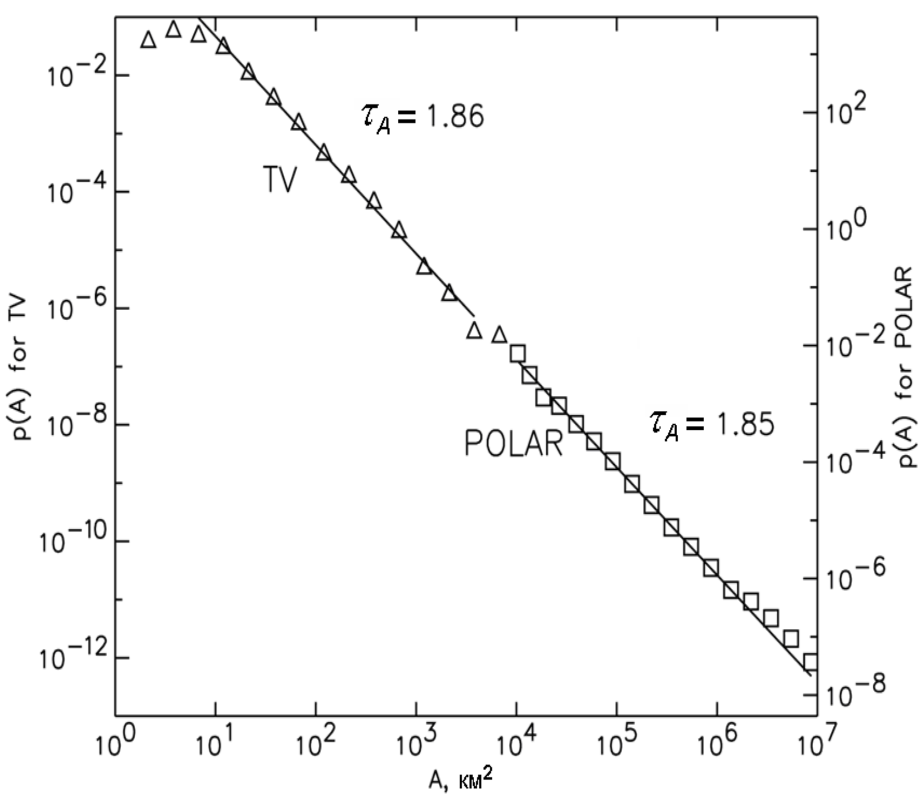
(*Uritsky et al.*, JGR 2002; *Kozelov et al.*, GRL 2004)



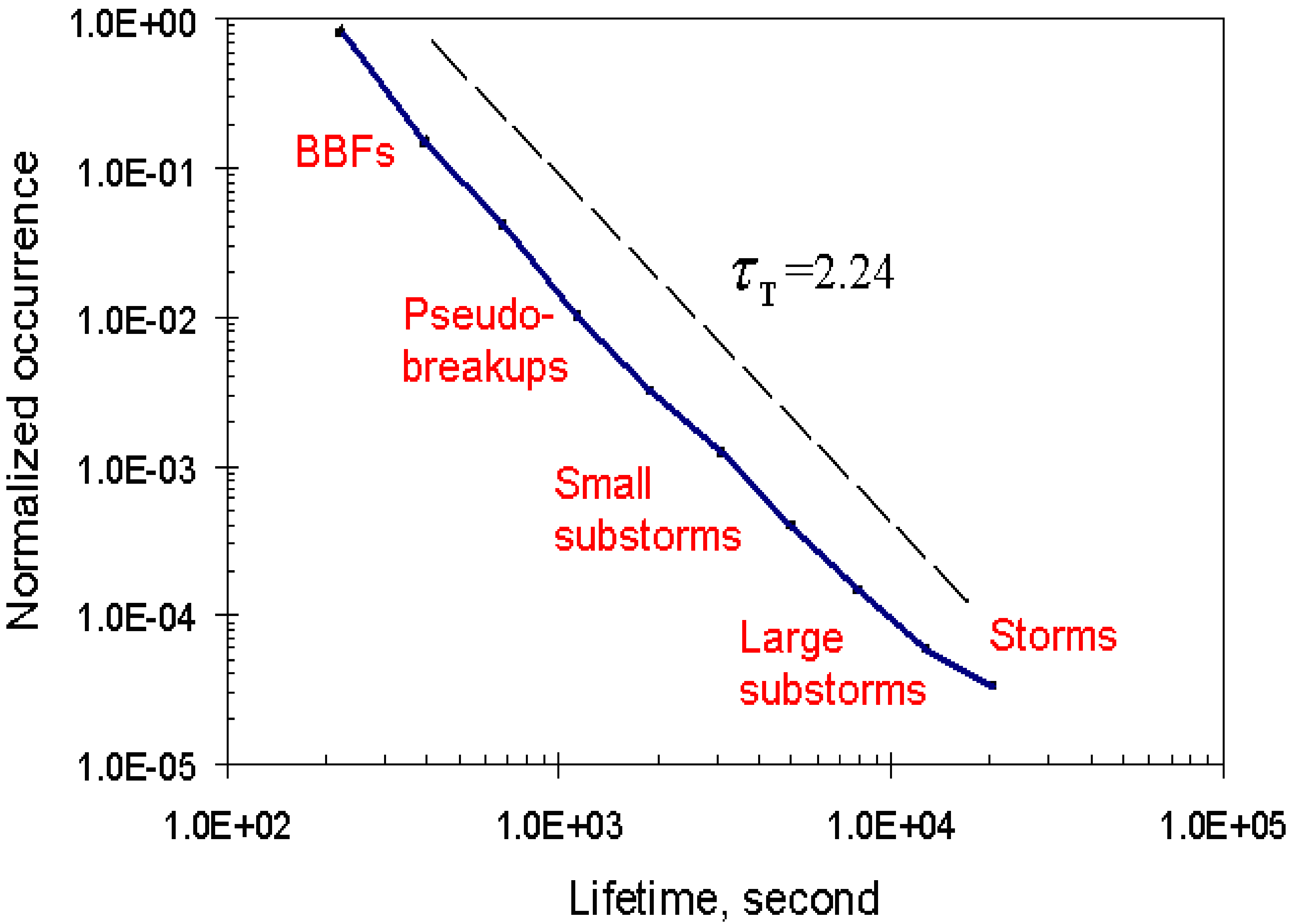
POLAR: T = 10^2 - 10^4 s, A = 10^4 - 10^7 km^2

TV: T = 10^0 - 10^2 s, A = 10^1 - 10^3 km^2



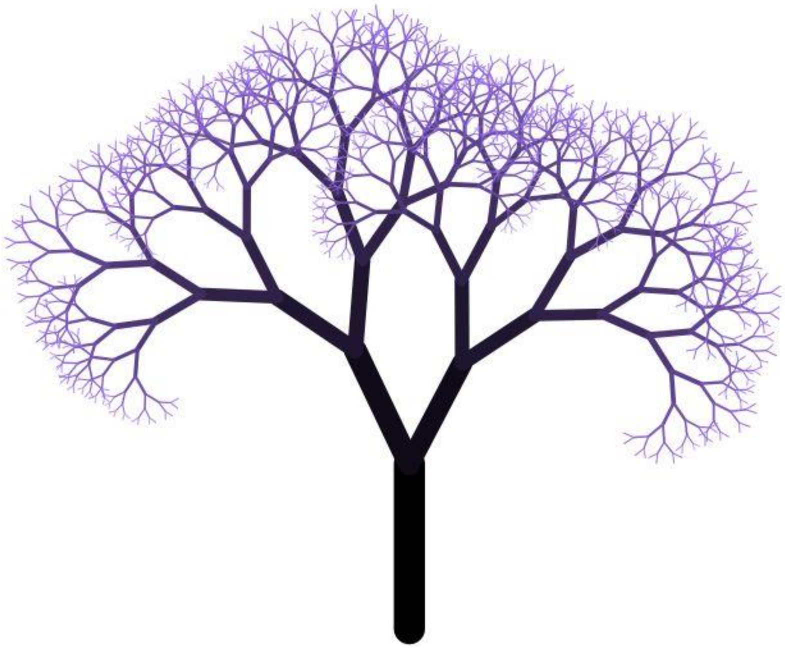


CROSS-SCALE COUPLING: continuous spectra of distinct phenomena



Modeling

Fractal models: the geometry of scale-invariance



“Smooth” treatment of multiscale systems

$$+$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{u} = 0,$$

$$\frac{\partial (\rho \vec{u})}{\partial t} + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \vec{j} \times \vec{B} + \nabla \cdot \sigma,$$

$$\frac{\partial p}{\partial t} + \vec{u} \cdot \nabla p + \gamma p \nabla \cdot \vec{u} = Q,$$

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E} = \nabla \times (\vec{u} \times \vec{B}) + \eta \nabla^2 \vec{B}.$$

$$= \;\; \ldots$$

“Smooth” treatment of multiscale systems

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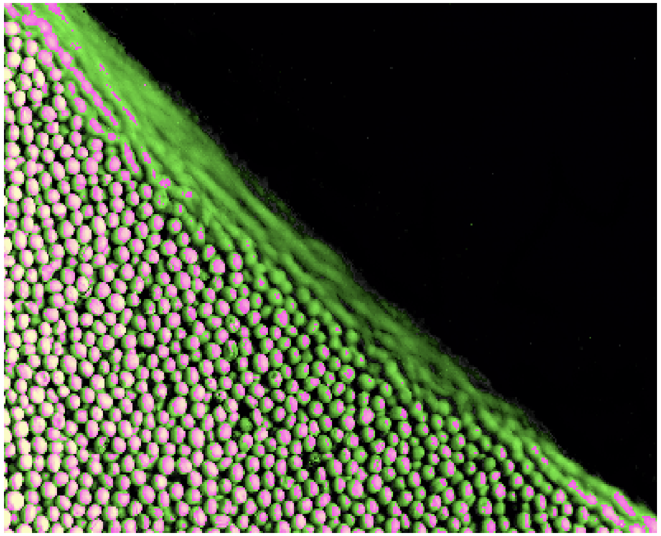
$$=$$

Two paradigms for understanding multiscale complexity

<u>Turbulence</u>

Complexity emerges as a result of fluid instabilities which typically propagate from large to small (dissipative) scales. The intermediate (inertial) range exhibits scale-free correlations in space and in time

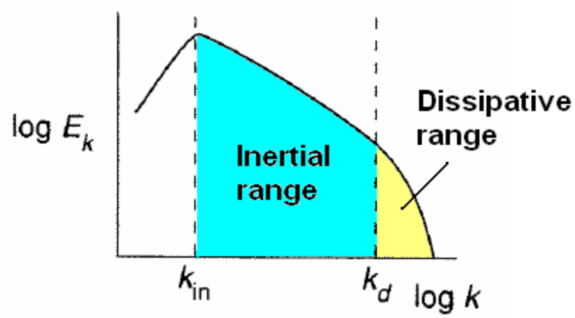
<u>Self-organized criticality</u>



Complexity results from cascades of discrete “toppling” events creating inverse cascades of energy transport called avalanches. The statistics of these events are scale-free, but the background can be uncorrelated.

Phenomenology of the turbulent spectrum

HOMOGENEOUS FLUID CASCADE
(Kolmogorov, 1941)



$$k_{in} \ll k \ll k_d$$

$$E_k = \int d\Omega_k \hat{E}_k, \quad E = \int_\infty^0 dk E_k$$
$$\epsilon_{in} = \epsilon_t = \epsilon_d := \epsilon$$

$$l_0 > l_1 > \cdots > l_N, \quad k_0 < k_1 < \cdots < k_N$$
$$l_n = k_n^{-1} = 2^{-n} l_0, \quad l_0 \sim L$$

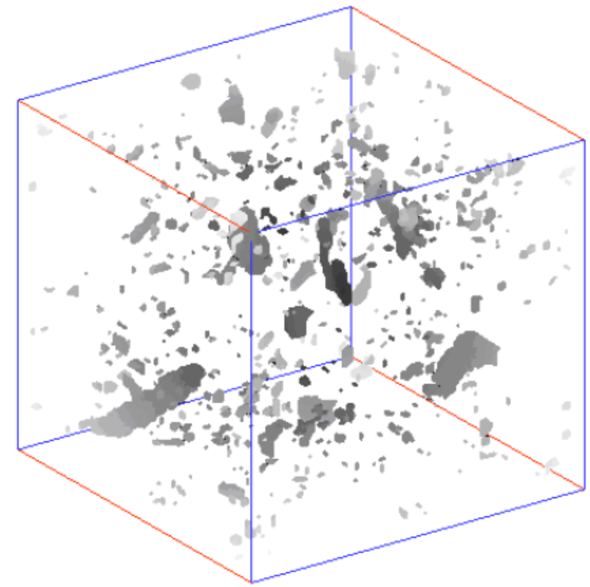
$$\tau_n \sim l_n/\delta v_n, \quad \delta v_n \equiv \delta v_{l_n}$$

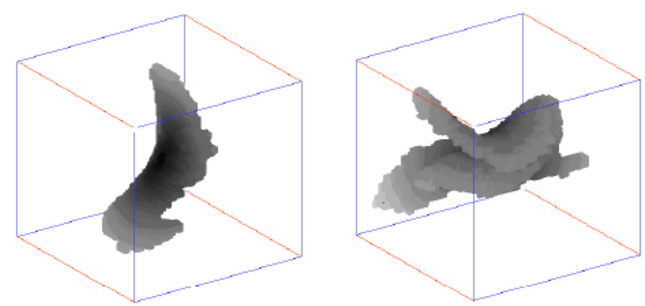
$$E_n/\tau_n \sim \delta v_n^3/l_n \sim \epsilon \;\Rightarrow\; \delta v_n \sim \epsilon^{1/3} l_n^{1/3}$$

$$\delta v_n^2 \simeq E_n \simeq \int_{k_n}^{k_{n+1}} E_k dk \simeq E_{k_n} k_n$$

$$\boxed{E_k \sim \epsilon^{2/3} k^{-5/3}}$$

INTERMITTENCY

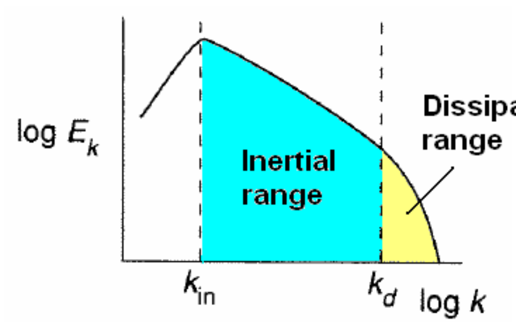




3D incompressible MHD
(Uritsky et al., *PRE*, 2010)

Phenomenology of the turbulent spectrum

HOMOGENEOUS FLUID CASCADE (Kolmogorov, 1941)



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$$E_k = \int d\Omega_k \hat{E}_k, \quad E = \int_\infty^0 dk E_k$$
$$\epsilon_{in} = \epsilon_t = \epsilon_d := \epsilon$$

$$l_0 > l_1 > \cdots > l_N, \quad k_0 < k_1 < \cdots < k_N$$
$$l_n = k_n^{-1} = 2^{-n} l_0, \quad l_0 \sim L$$

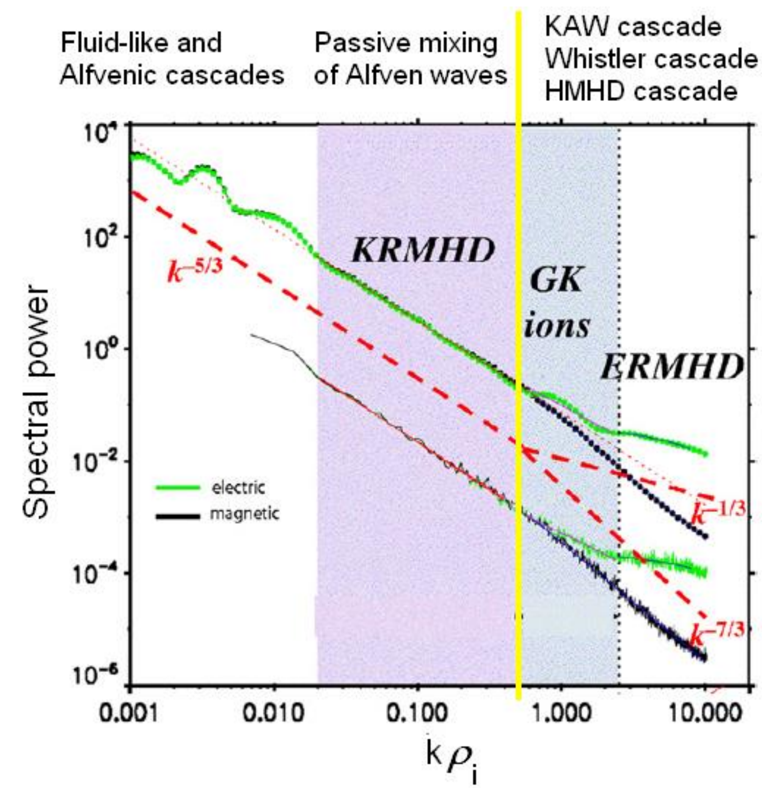
$$\tau_n \sim l_n / \delta v_n, \quad \delta v_n \equiv \delta v_{l_n}$$

$$E_n / \tau_n \sim \delta v_n^3 / l_n \sim \epsilon \;\Rightarrow\; \delta v_n \sim \epsilon^{1/3} l_n^{1/3}$$

$$\delta v_n^2 \simeq E_n \simeq \int_{k_n}^{k_{n+1}} E_k dk \simeq E_{k_n} k_n$$

$$\boxed{E_k \sim \epsilon^{2/3} k^{-5/3}}$$

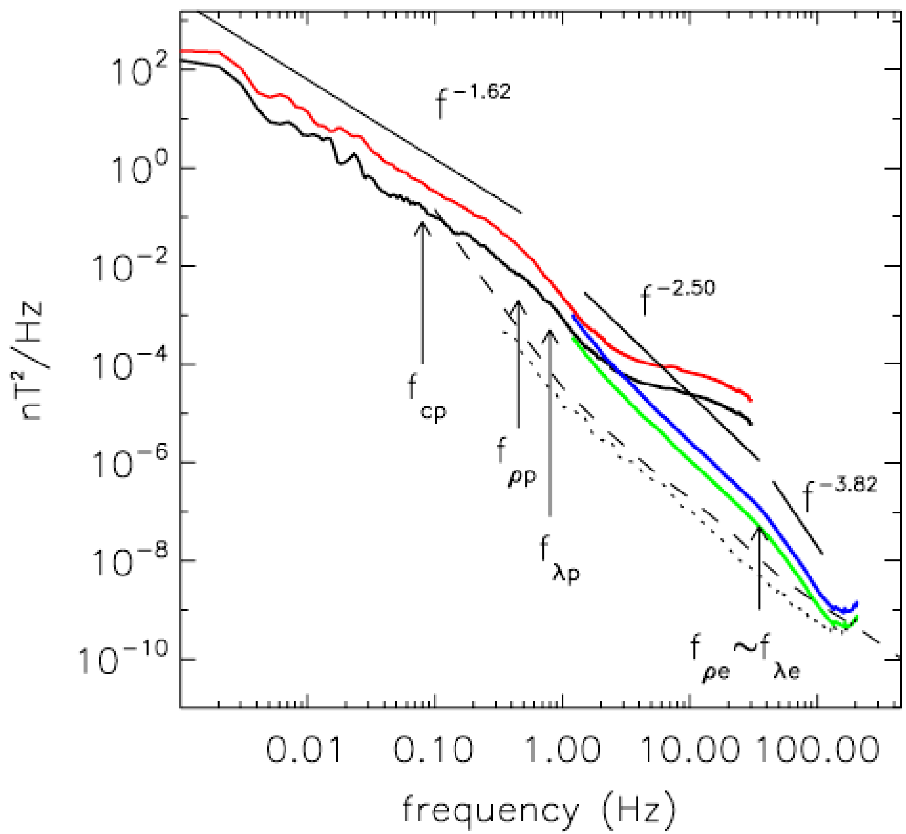
PLASMA EFFECTS AT SMALL SCALES



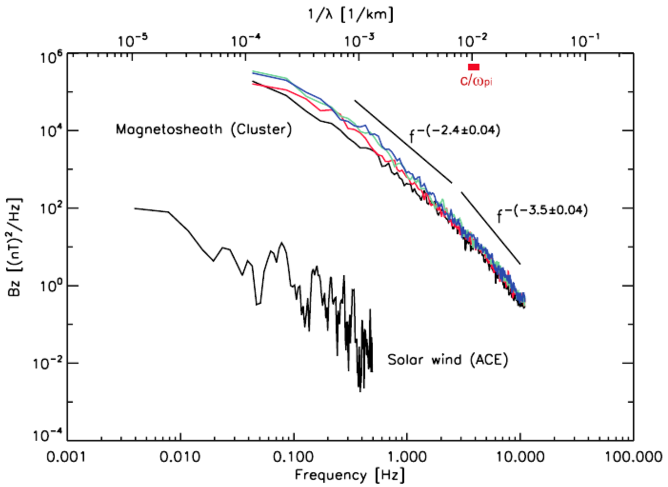
Bale et al., *PRL* 2005; Schekochihin et al., *Plasma Phys. Control. Fusion* 2007

Examples of plasma turbulence near Earth

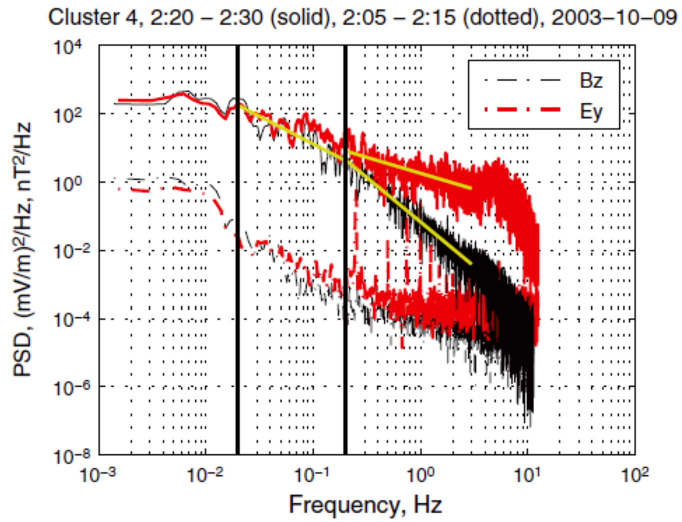
<u>Solar wind</u>
(Sahraoui et al., *PRL* 2009)



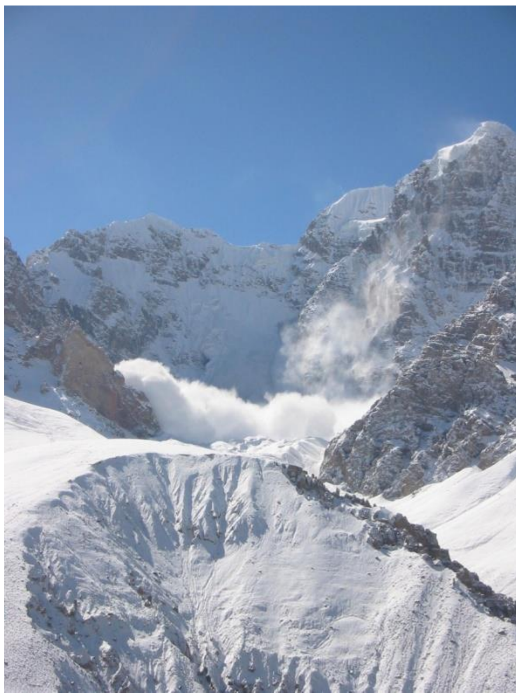
<u>Magnetosheath</u>
(Yordanova et al., *PRL* 2008)



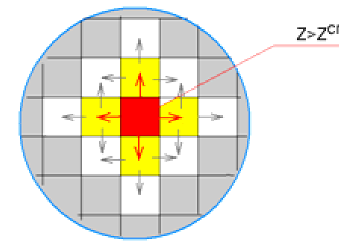
<u>Magnetotail</u>
(Eastwood et al., *PRL* 2009)



Scaling and avalanches in SOC models



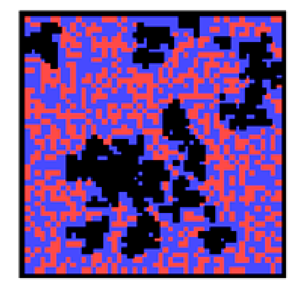
$$Z(\mathbf{i}) > Z_c \;\Rightarrow\; \begin{cases} Z(\mathbf{i}) \to Z(\mathbf{i}) + \delta Z \\ \\ Z(\mathbf{i}) \to Z(\mathbf{i}) - \sum\limits_{\mathbf{e}} \Delta Z(\mathbf{e}), \\ Z(\mathbf{i}+\mathbf{e}) \to Z(\mathbf{i}+\mathbf{e}) + \Delta Z(\mathbf{e}) \end{cases}$$



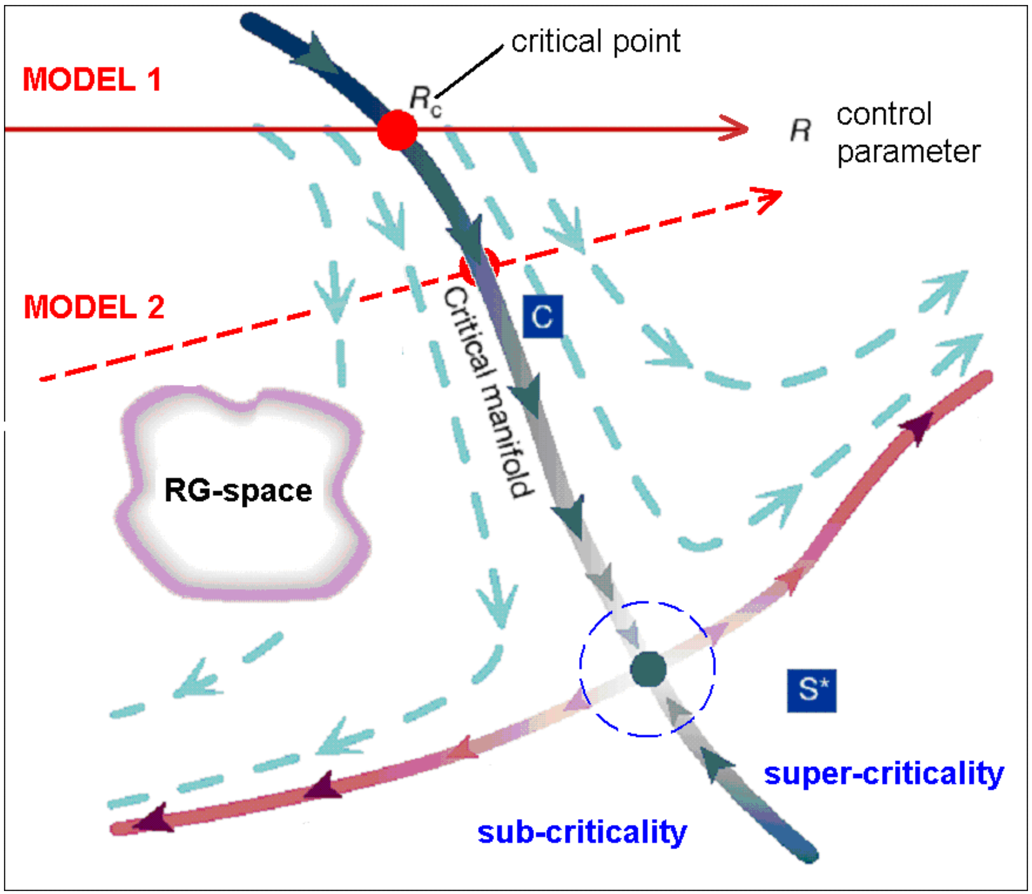
$$\Lambda = \bigcup_{t=t_0}^{t_0+T} \left(t,\, \lambda_t\right), \qquad \lambda_t = \left\{ \mathbf{i} \,\middle|\, Z_t(\mathbf{i}) \geq Z_c \right\}$$

$$S = \sum_{t=t_0}^{t_0+T} \sum_{\mathbf{i}} \theta\left(Z_t(\mathbf{i}) - Z_c\right)$$

$$E = \sum_{t=t_0}^{t_0+T} \sum_{\mathbf{i}} \left[\theta\left(Z_t(\mathbf{i}) - Z_c\right) \times \sum_{\mathbf{e}} \Delta Z_t(\mathbf{e}) \right]$$



Criticality, renormalization group, and the universality of multiscale complexity



Power-law scaling at criticality

$$R \to R^*$$
$$S \to S^*$$

$$F(L) = a \times F(L \times b), \quad L = \{\Delta\mathbf{x}, \Delta t, \Delta R, \ldots\}$$
$$b = 1 + \delta, \; a = 1 + \alpha\delta, \; \delta \ll 1$$

$$F(L+\delta L) - F(L) = -\alpha\delta F(L+\delta L)$$
$$\frac{F(L+\delta L) - F(L)}{\delta L} = -\alpha \frac{F(L+\delta L)}{L}$$

$$\frac{dF}{dL} = -\alpha \frac{F}{L} \quad \longrightarrow \quad F(L) \sim L^{-\alpha}$$

$$\boxed{\text{Scale-free:} \quad \alpha \neq f(\mathrm{L})}$$

***Sethna et al.*, Nature 410, 242-250, 2001**

Measuring SOC: scaling exponents and relations

Scaling relations

Avalanche critical exponents

$$\boxed{\begin{aligned} p(S) &= S^{-\tau_S} f_S(S/S_c), \quad S_c \sim L^D \\ p(E) &= E^{-\tau_E} f_E(E/E_c), \quad E_c \sim L^{D_E} \\ p(T) &= T^{-\tau_T} f_T(T/T_c), \quad T_c \sim L^z \end{aligned}}$$

Dynamical critical exponents

$$\sigma(t) = \frac{1}{N}\sum_{k=1}^{N}\left[\int_{\Lambda_k(t+t_{0k})} dV\right], \quad P_s(t) = n(t)/N$$

$$\boxed{\sigma \sim t^{\eta}; \quad P_s \sim t^{-\delta}; \quad \bar{S} = \int_{S_1}^{S_2} S\, p(S|T)\, dS \sim T^{\kappa}}$$

Fractal critical exponents

$$C(r) = \left\langle \left[\left\langle \left(w(\boldsymbol{r},t) - w(\boldsymbol{r}',t) \right)^2 \right\rangle_r \right]^{1/2} \right\rangle_t, \quad r \equiv |\boldsymbol{r} - \boldsymbol{r}'|$$

$$C(\tau) = \left\langle \left[\left\langle \left(w(\boldsymbol{r},t) - w(\boldsymbol{r},t') \right)^2 \right\rangle_\tau \right]^{1/2} \right\rangle_{\boldsymbol{r}}, \quad \tau \equiv |t - t'|$$

$$\boxed{\begin{gathered} C(r) \sim r^{\alpha}, \quad C(\tau) \sim \tau^{\beta} \\ D_F = d - \alpha, \quad D_t = 2 - \beta, \quad N(r) \sim (1/r)^{D_B} \end{gathered}}$$

$$\boxed{(\eta + 2\delta + 1)/(\eta + \delta + 1) = \tau_S}$$

$$\boxed{\eta + \delta + 1 = \kappa}$$

$$\boxed{\frac{\alpha}{\beta} = D(2 - \tau_S)}$$

$$\boxed{D = \alpha + D_B}$$

Toward realistic description of plasma turbulence

Idealized turbulence (K 41)

* direct energy cascade
* homogeneous dissipation
* energy: kinetic

Non-intermitent hydrodynamic fluids

Real SOC / turbulence

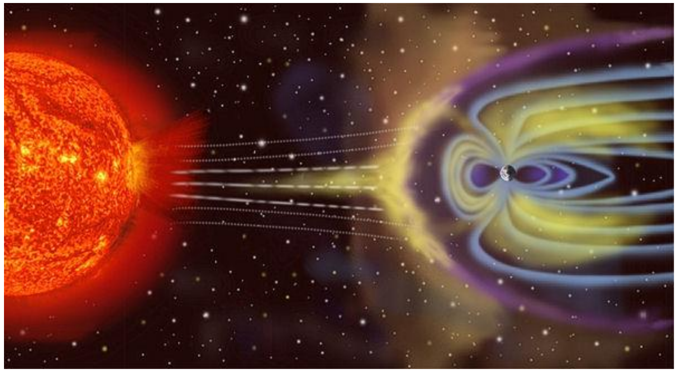
* bidirectional energy cascades
* intermittent dissipation
* strongly non-equilibrium
* energy: kinetic and potential

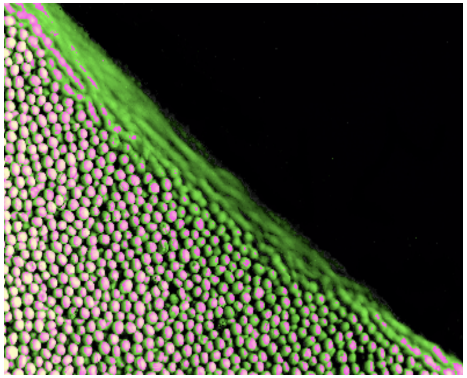
Highly-intermittent magnetized fluids
Strongly-driven avalanching systems

Idealized SOC (BTW 87)

* inverse energy cascade
* driving / dissipation rates -> 0
* no spatiall / temporal correlations
* energy: potential

Granular systems with frozen metastable configurations





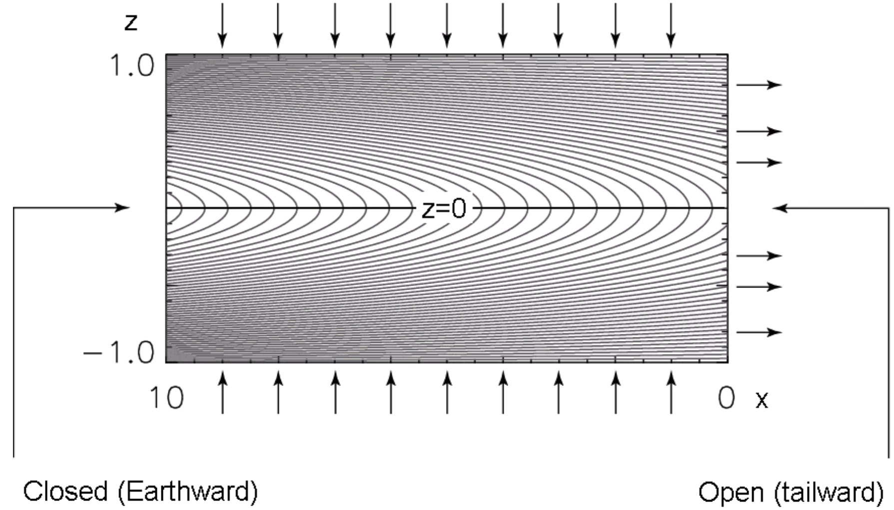
MODELING: 2-D resistive MHD model of the current sheet avalanching dynamics (A. Klimas, JGR 2004)

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

$$\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla)\mathbf{V} = -\frac{1}{4\pi\rho}\nabla A(\Delta A) - \frac{\nabla P}{\rho}$$

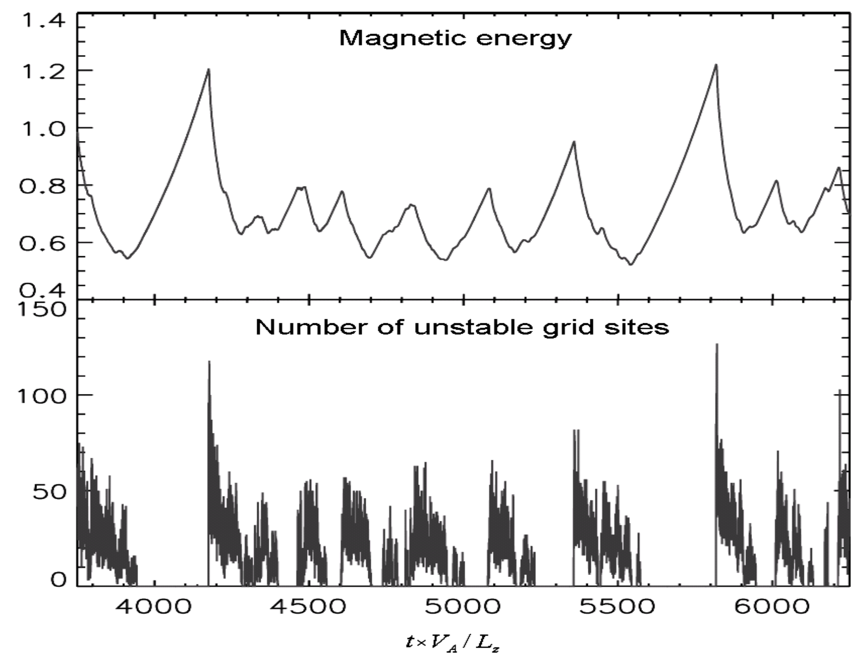
$$\frac{\partial A}{\partial t} + (\mathbf{V} \cdot \nabla) A = \underline{D}\,\Delta A$$

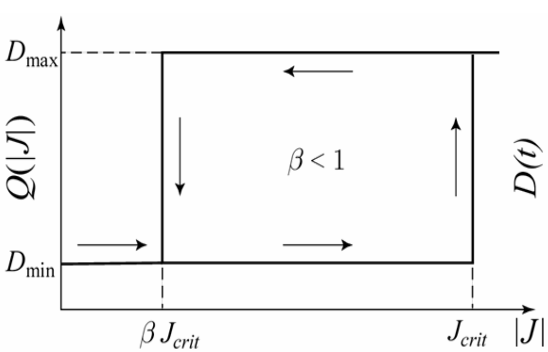
$$\left(\frac{1}{\gamma - 1}\right)\left[\frac{\partial P}{\partial t} + \mathbf{V} \cdot \nabla P\right] + \left(\frac{\gamma}{\gamma - 1}\right) P(\nabla \cdot \mathbf{V}) = \frac{1}{4\pi}\underline{D}(\Delta A)^2$$

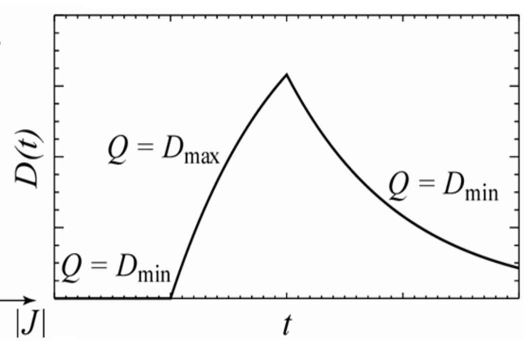


$$J \equiv J_y = -\Delta A / \sqrt{8\pi}$$

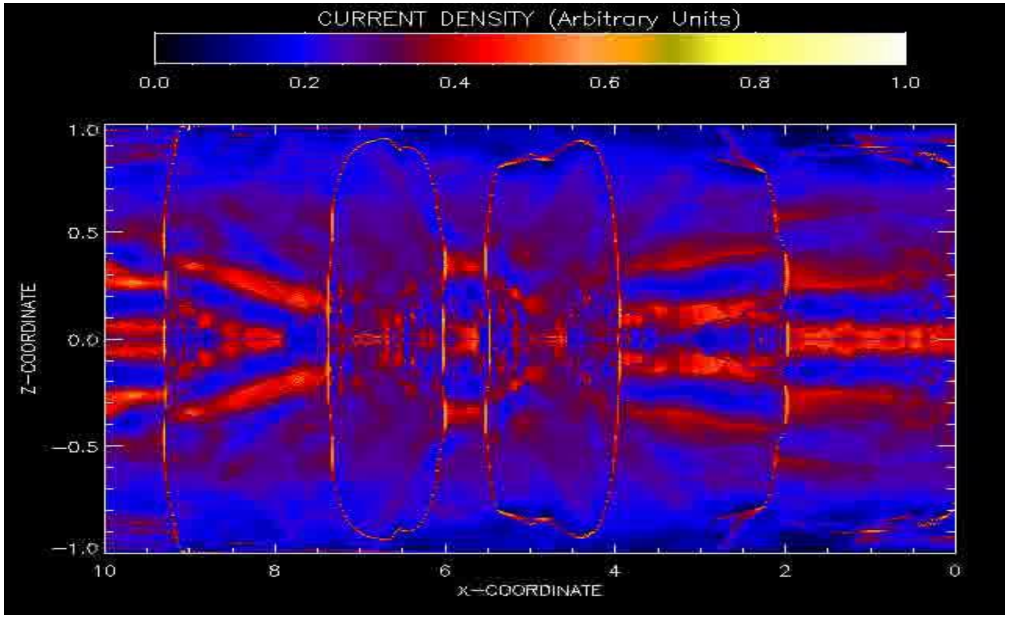
$$\frac{\partial D(z,t)}{\partial t} = \frac{Q(|J|) - D}{\tau}; \qquad Q(|J|) = \begin{cases} D_{\min} & |J| > J_c \\ D_{\max} & |J| < \beta J_c \end{cases}$$

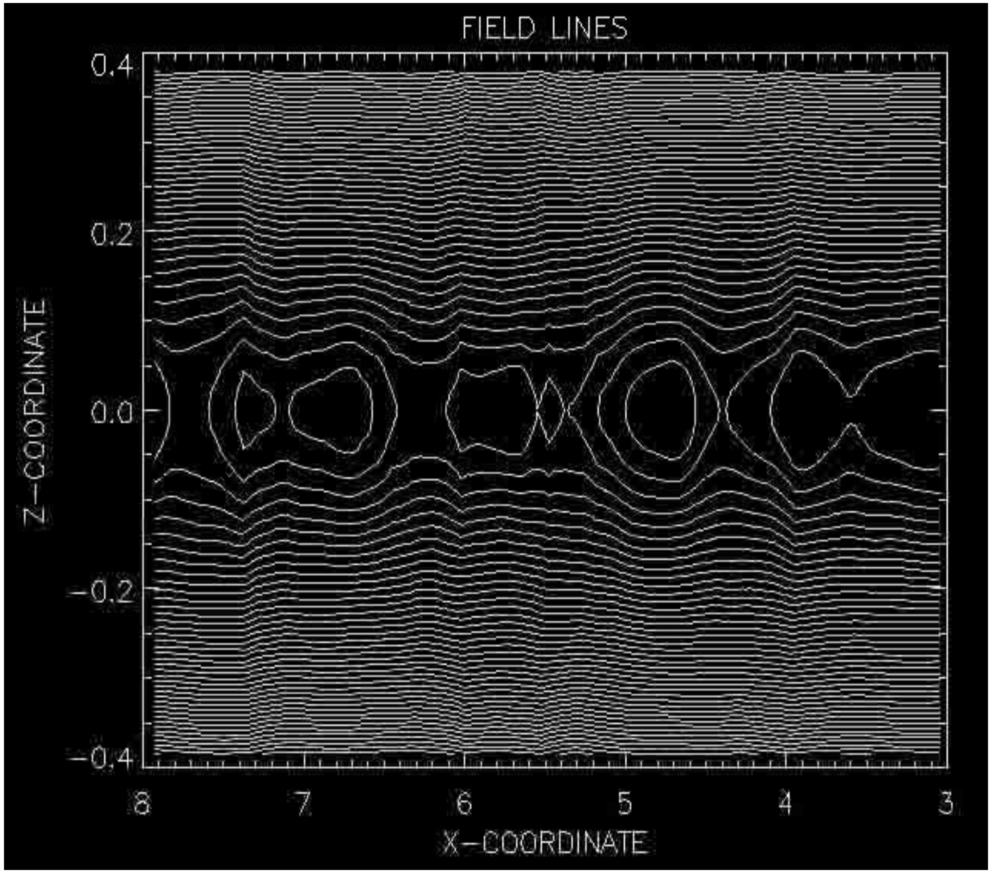


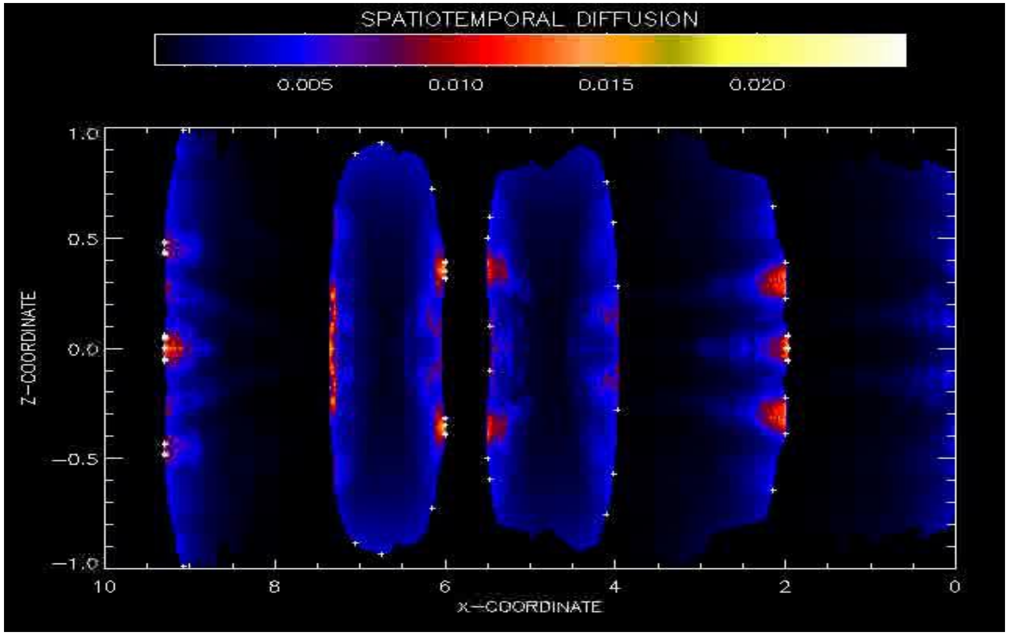


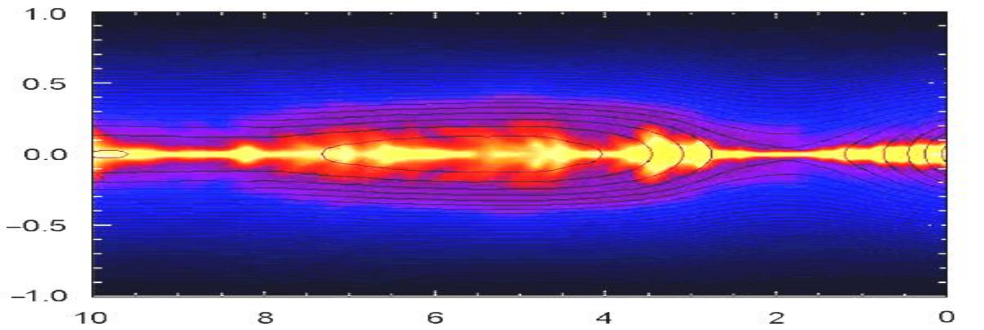


Spatiotemporal evolution of model parameters

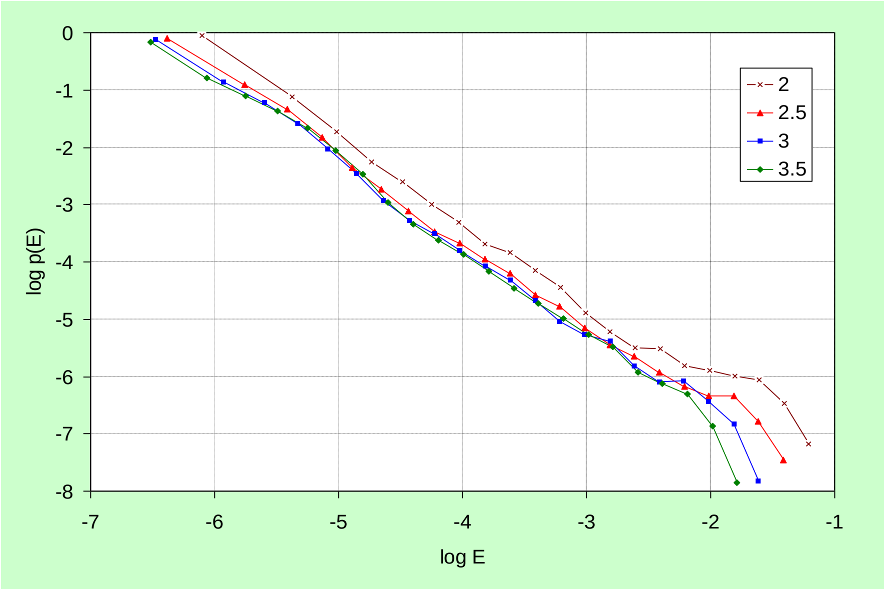


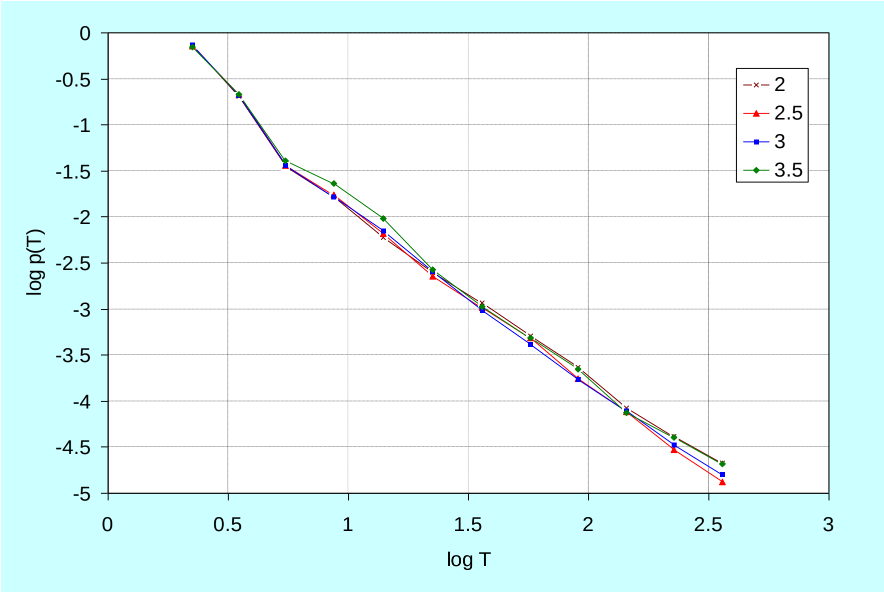


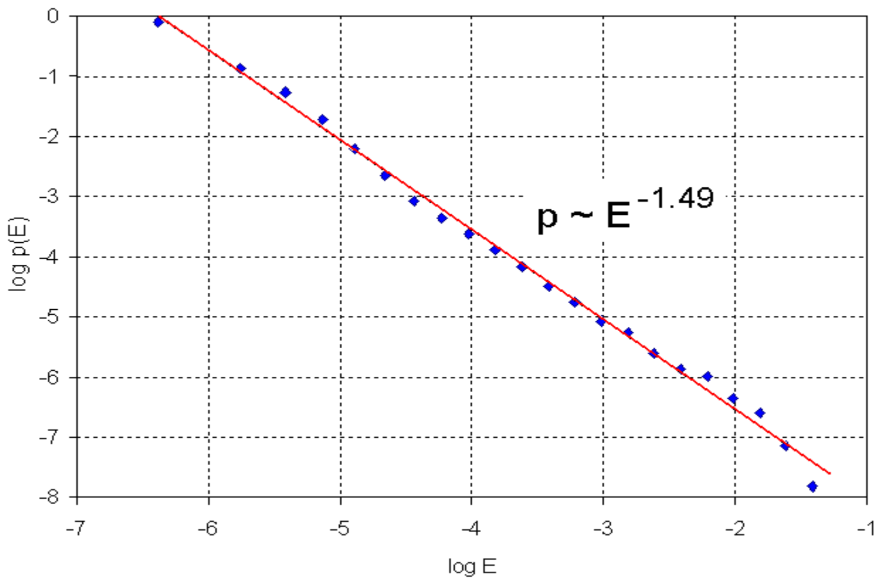


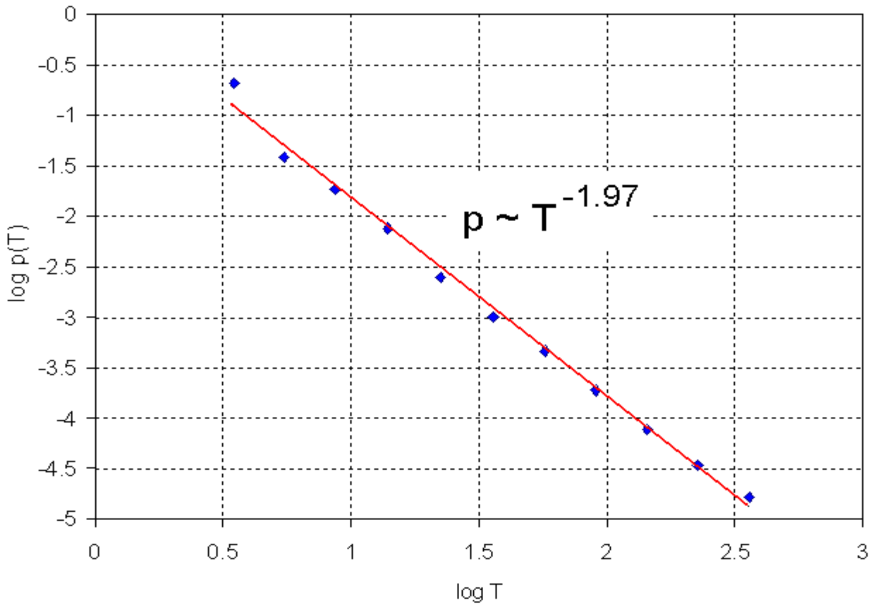


Probability distributions of anomalous resistivity regions over dissipated energy (left) and lifetime (right)

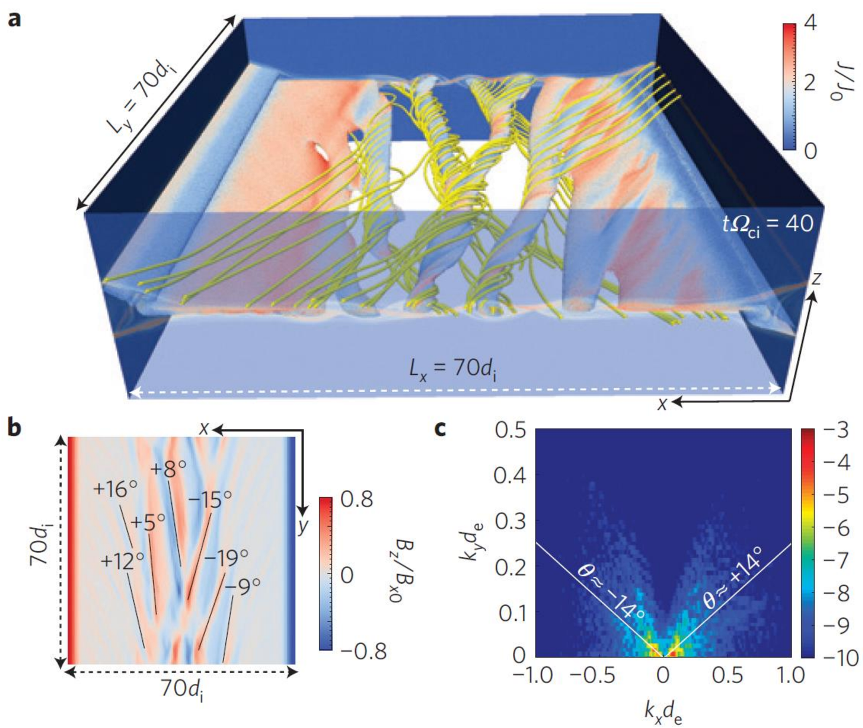


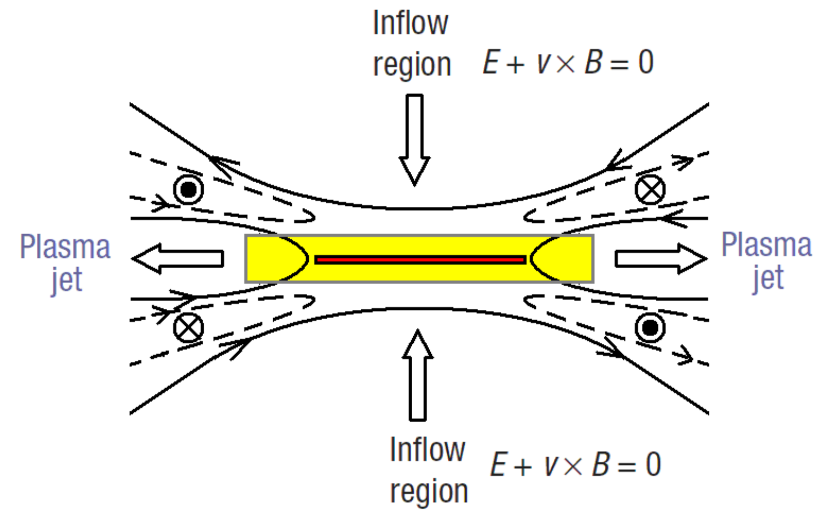


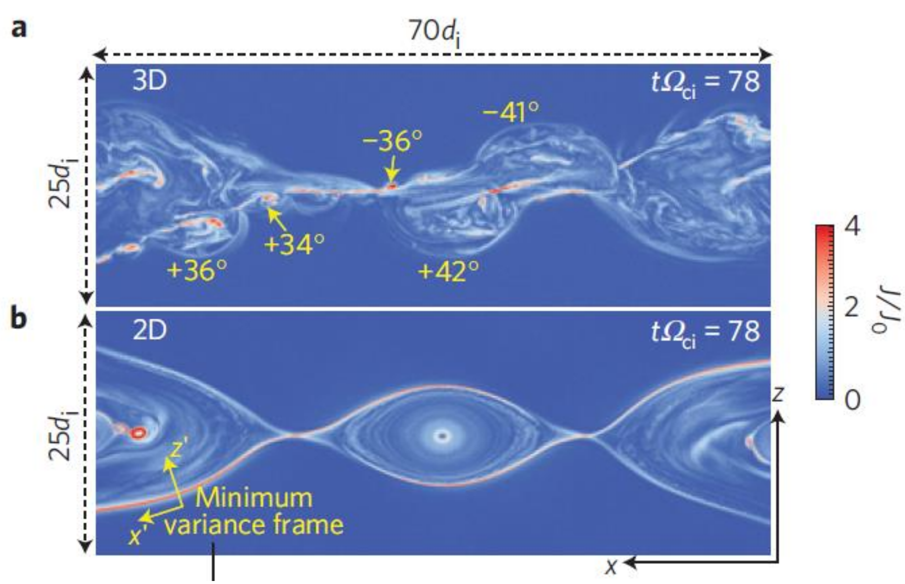




Daughton et al., Nature Phys 2011







- **What role does multiscale turbulence play?**
- **What is its fundamental physical mechanism?**
- **Does turbulence facilitate or inhibit fast Rx?**
- **Is energy conversion cominated by small or large scales?**
- **How to measure such Rx events?**

Part of complete coverage on
Netiquette

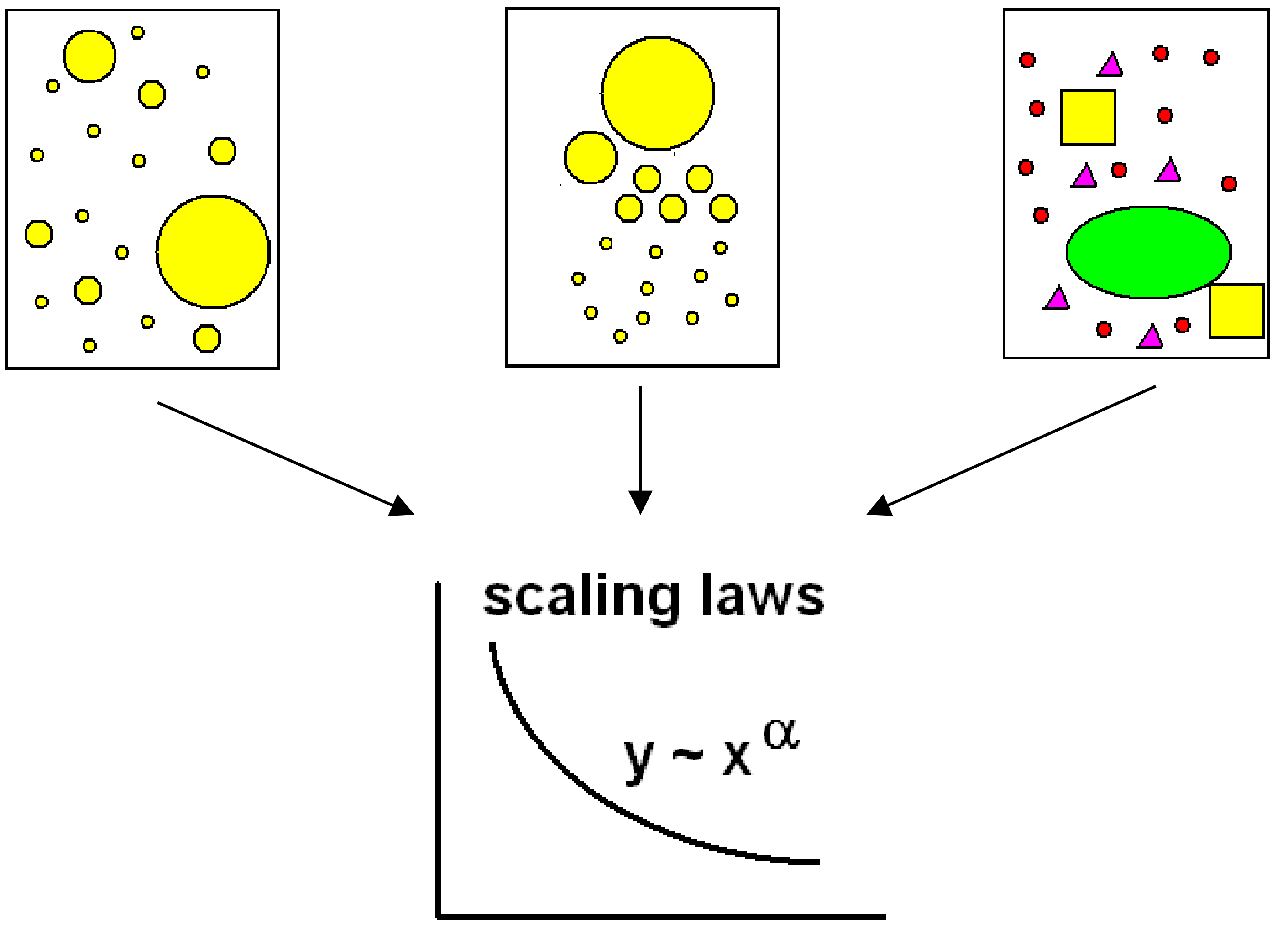
NETIQUETTE

How to reconnect and not be awkward or creepy

By **Andrea Bartz** and **Brenna Ehrlich**, Special to CNN
March 2, 2011 8:55 a.m. EST | Filed under: Social Media

Unresolved problems & future tasks

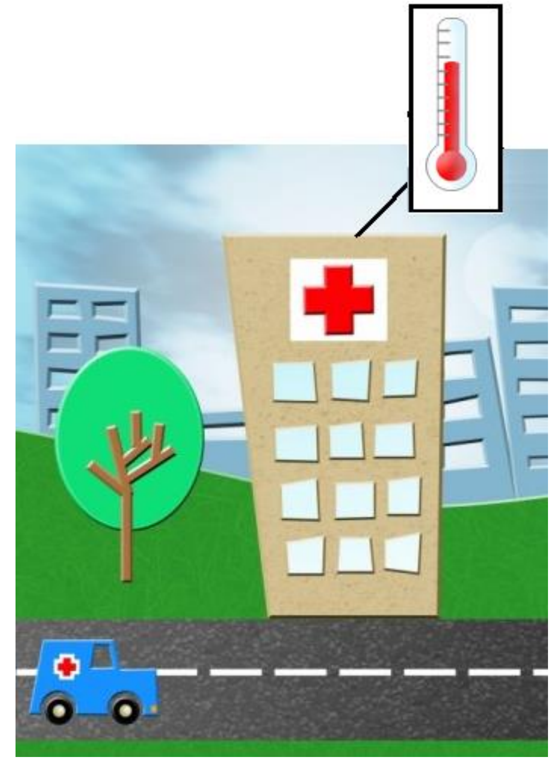
Is physics indeed scale free ?



“Mainstream” community

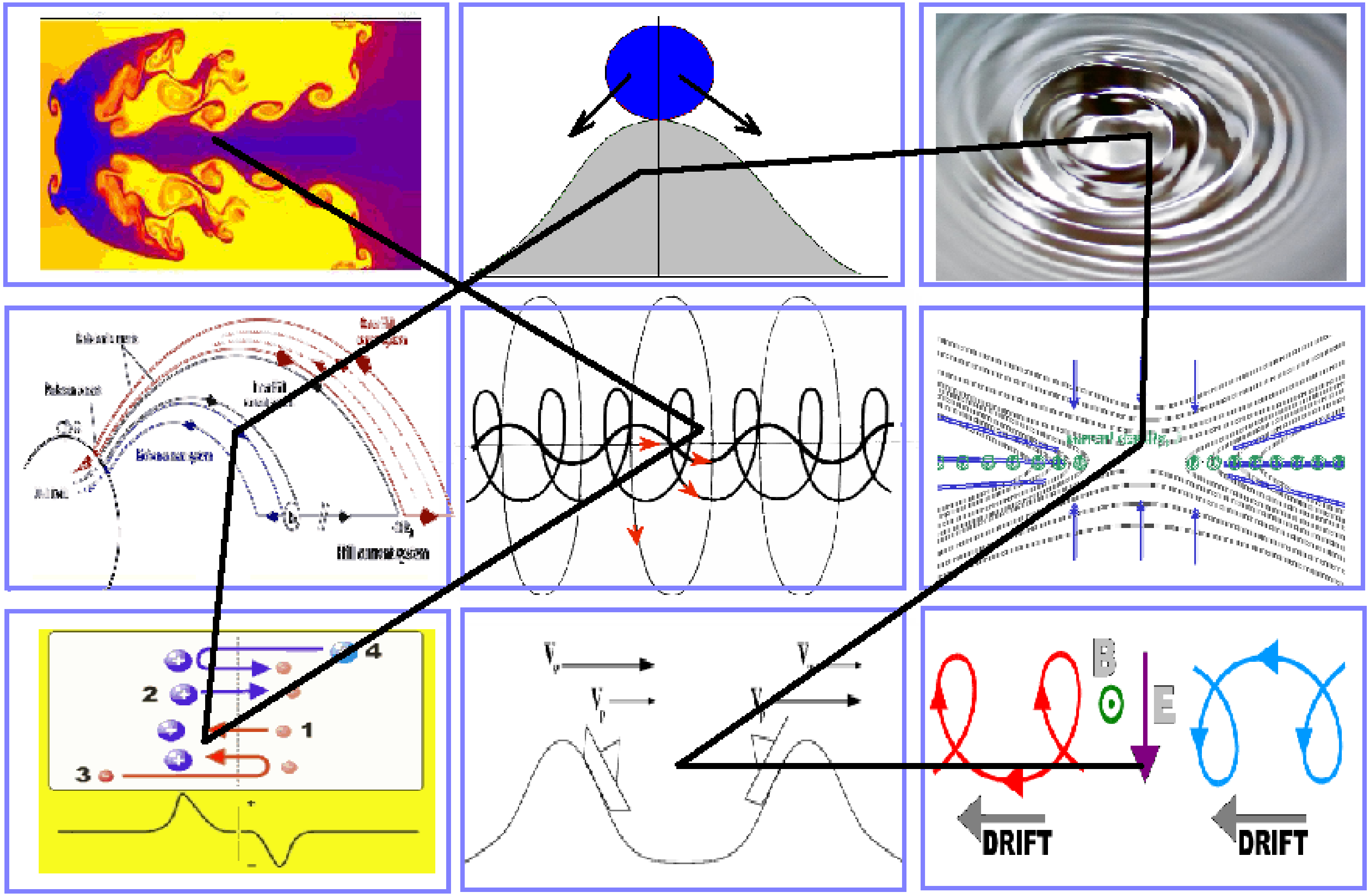
Case-by-case analysis

“Complexity” community

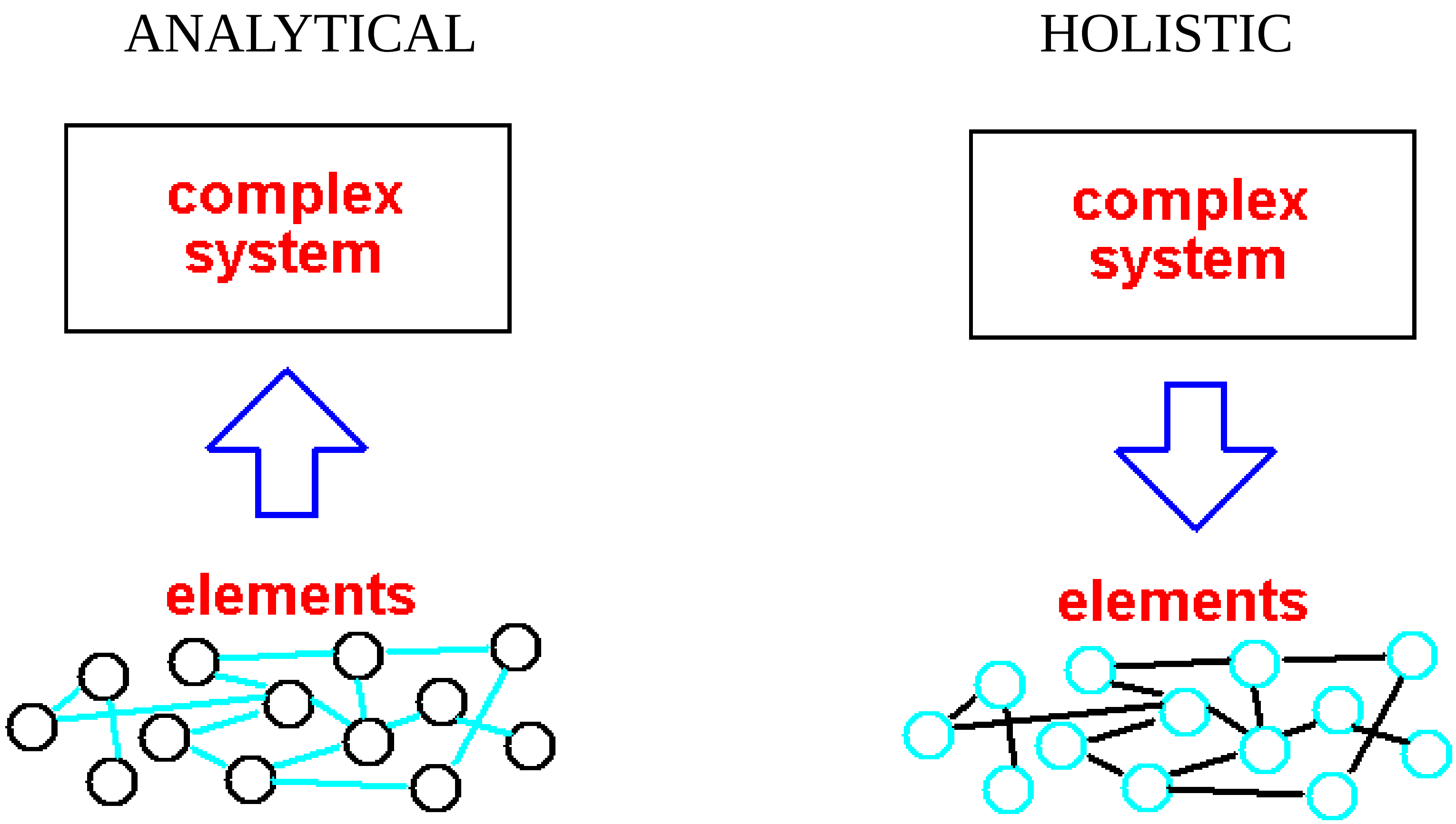


Ensemble averaging

Functional complexity of plasma behavior: the diversity of mechanisms



Two approaches to exploring complex dynamical systems



THANK YOU !