Is there a turbulent cascade in the solar wind?

Roland Grappin (*LUTH, LPP*) and Gérard Belmont (*LPP*)

This lecture deals with **large scale turbulence** in the solar wind, in the inner heliosphere, ≈ 3 decades above 5s period

Several indications support slow down of interactions in the solar wind, which could make turbulence differ from standard homogeneous MHD

We review scaling, heating and (spectral) anisotropy properties

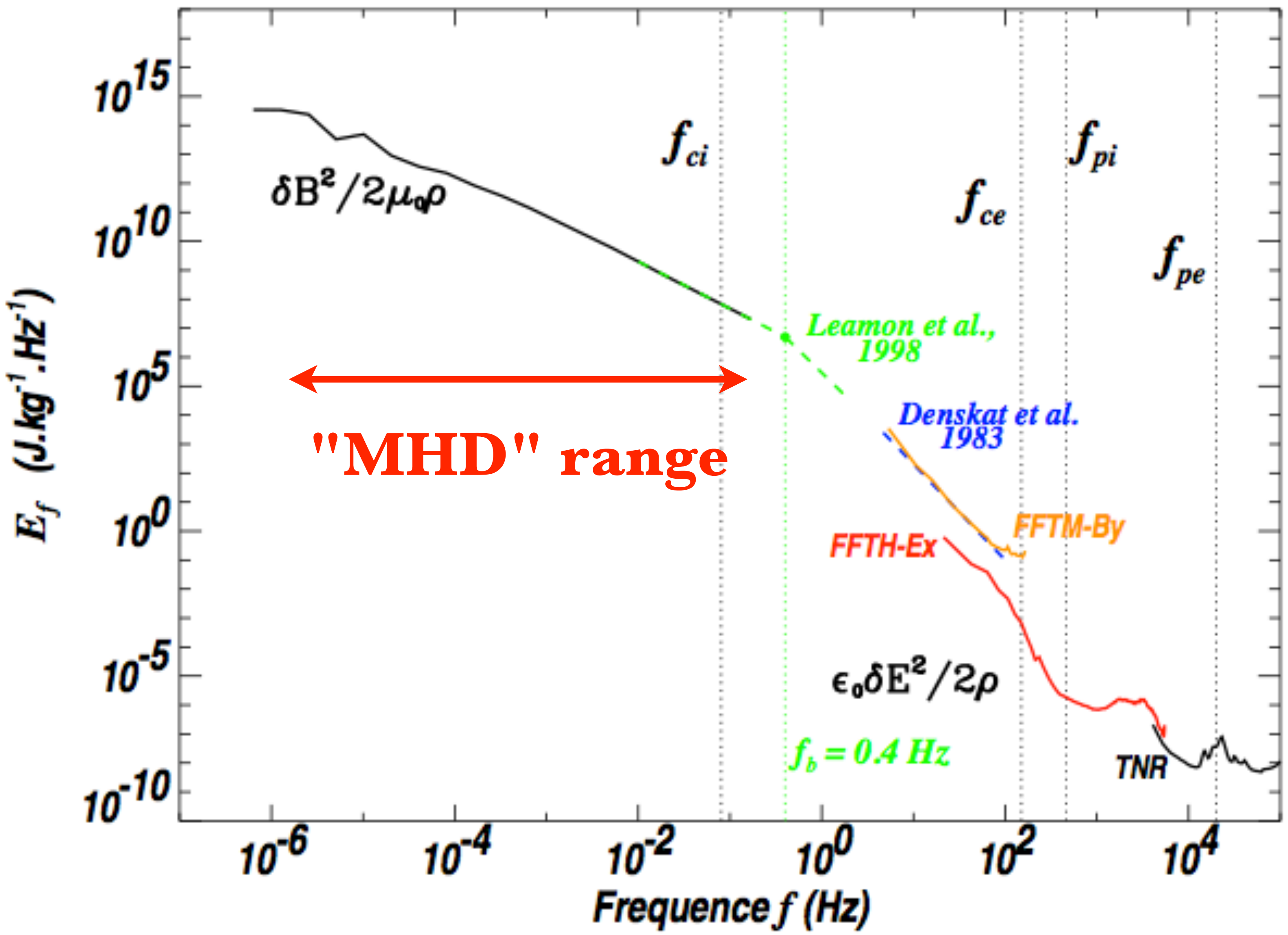
l'Observatoire de Paris | LUTH
Laboratoire de l'Univers et de ses Théories

EGU 2011

Magnetic scaling

Coleman (1968) first proposed that the observed power-law energy spectrum was the signature of a turbulent cascade

Spectral energy density per unit mass



Chadi Salem, thesis, 2000

Strong (rapid) and weak (slow) turbulence

Kolmogorov 1941 Hypothesis:
Inertial range scales with constant flux $\boldsymbol{l^\circ >> l >> l_D}$
l° = injection scale, l_D = molecular dissipation scale

Basic hypothesis: ***continuous energy flux from*** $\boldsymbol{l^\circ}$ **to** $\boldsymbol{l_D}$
$\varepsilon_l = \text{cst} = \varepsilon$ => Flux $\varepsilon \approx \mathbf{u^2/\tau = cst}$ (*)

1. **Strong coupling**
short time scale $\tau = t_{NL} = l/u$ (1A)
K41 scaling: $u^3 \approx l$; $u \approx l^{1/3}$; $u^2 = l^{2/3}$; ... $u^p \approx l^{p/3}$
Energy spectrum: $u^2 \approx kE_k$ => $\mathbf{E_k = k^{-5/3}}$ (1B)

2. **Slow coupling** (*Iroshnikov 1963, Kraichnan 1965, Boldyrev 2006*)
$B^\circ > b$, *IK version*:
long time scale: $\tau = t_{NL} B^\circ/b$ (2A)
IK scaling: $u^4 \approx l$; $u \approx l^{1/4}$; $u^2 = l^{1/2}$; ... $u^p \approx l^{p/4}$
Energy spectrum: $u^2 \approx kE_k$ => $\mathbf{E_k = k^{-3/2}}$ (2B)

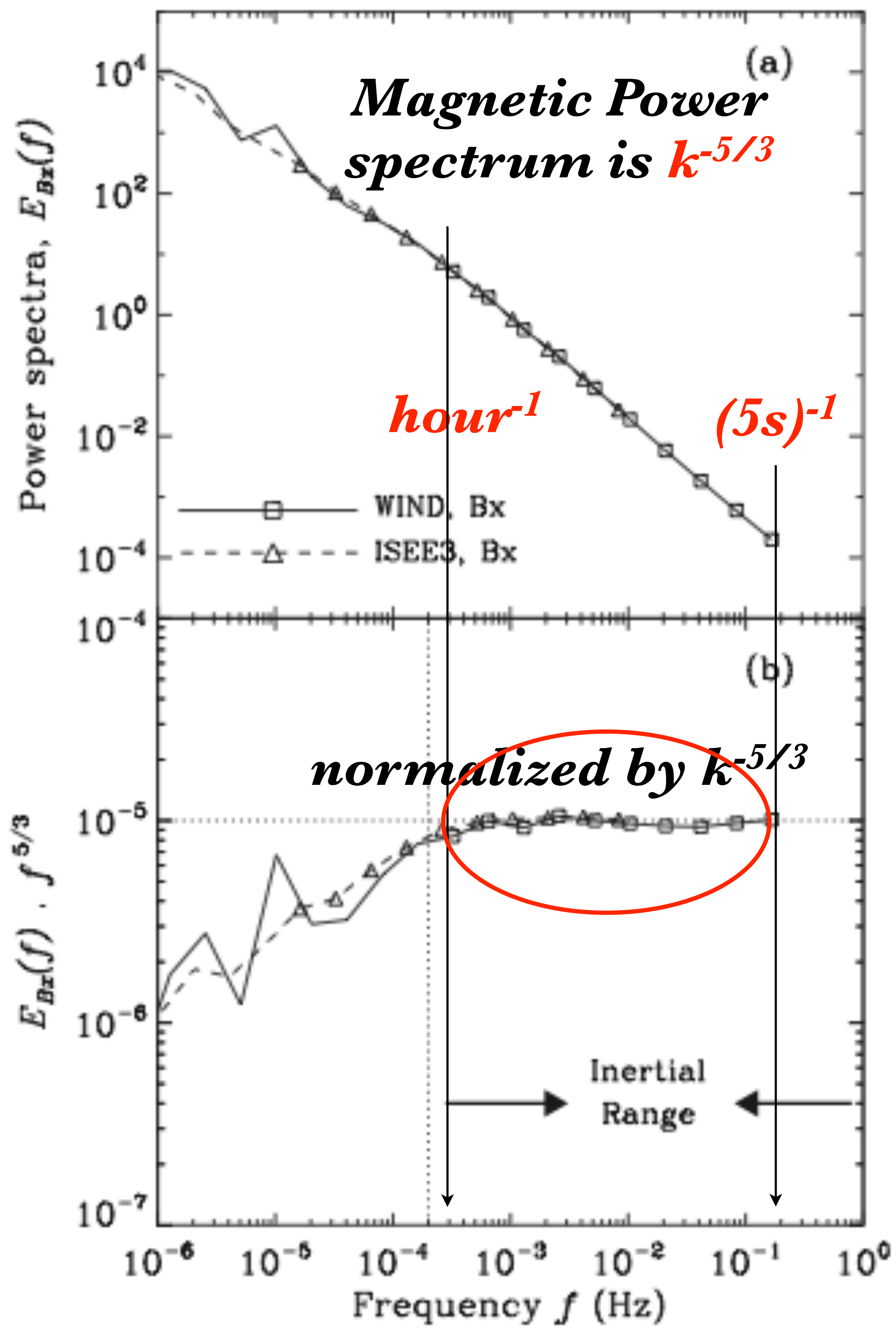
3. **Very slow coupling** (*Dobrowolny Mangeney Veltri 1980, Grappin et al 1982, 1983*)
monodirectional Alfvén waves => zero coupling

Magnetic spectrum: power-law range

At 1 AU magnetic **power-law range extends on ≈ three decades**

Wind mission from 1995 May 23 to July 23

Ch. Salem, thesis, 2000
Salem Mangeney Bale Veltri 2009



Kinetic ≠ Magnetic

Magnetic spectrum scaling as $k^{-5/3}$
Kinetic spectrum scaling as $k^{-3/2}$

Exponents ζ(p) of the structure functions:
$<\delta X(\tau)|^p> = <|X(t+\tau)-X(t)|^p> \approx \tau^{\zeta(p)}$

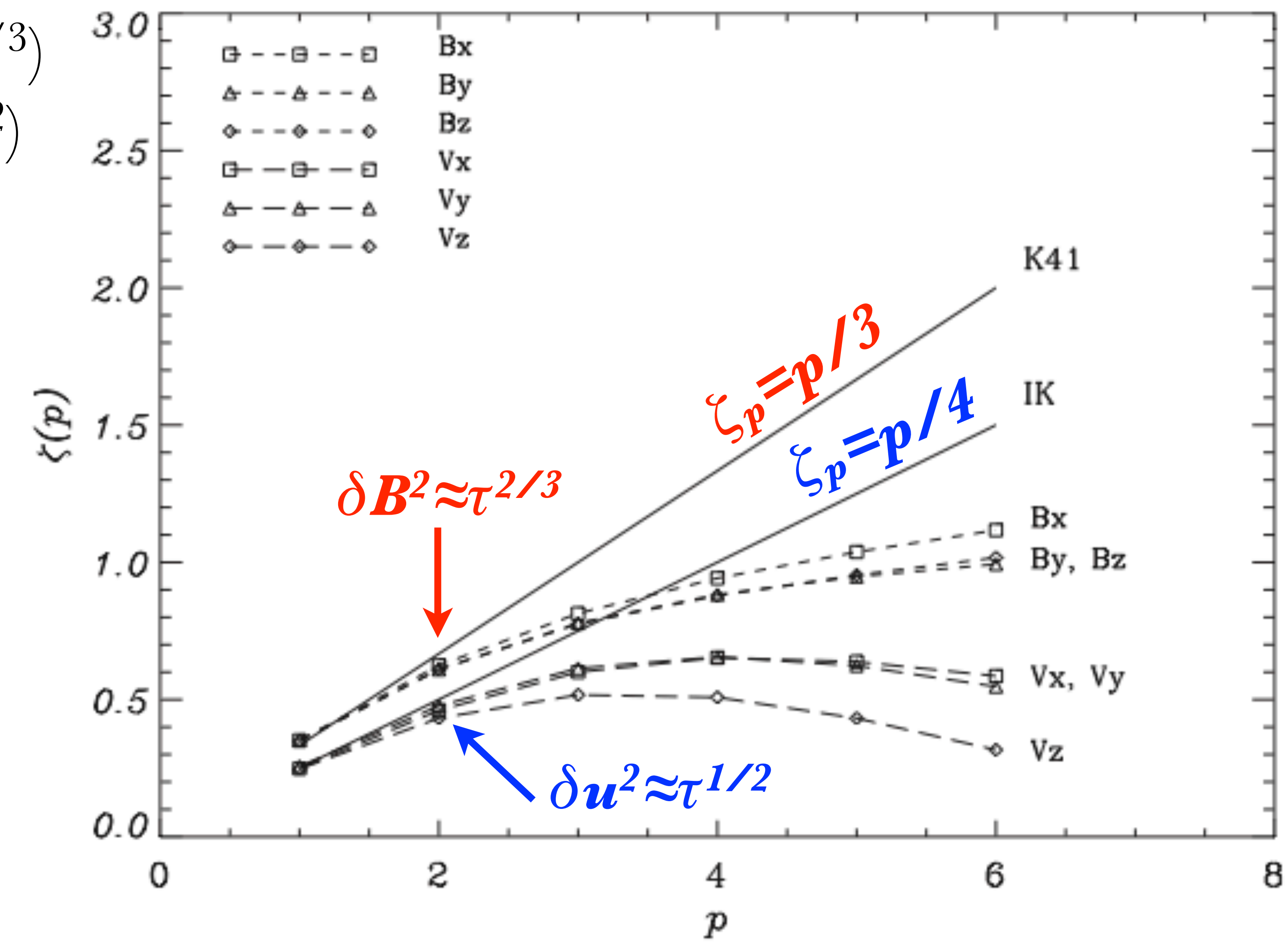
1) **Low order** moments (p=1,2)
$|\delta \mathbf{B}| \approx \tau^{1/3}$, $|\delta B|^2 \approx \tau^{2/3}$ $(E_B(k) \approx k^{-5/3})$
$|\delta \mathbf{u}| \approx \tau^{1/4}$, $|\delta u|^2 \approx \tau^{1/2}$ $(E_V(k) \approx k^{-3/2})$

2) **High order** moments (p≥3):
small exponents
<=> high intermittency
(*cf. hydrodynamic turbulence*)

Ch. Salem, thesis, 2000
Salem Mangeney Bale Veltri 2009

also Podesta et al 2006,2007

Structure function exponents ζ(p)



Pure K41/IK scaling...

Removing extreme fluctuations at all scales (≈0.4% of events)

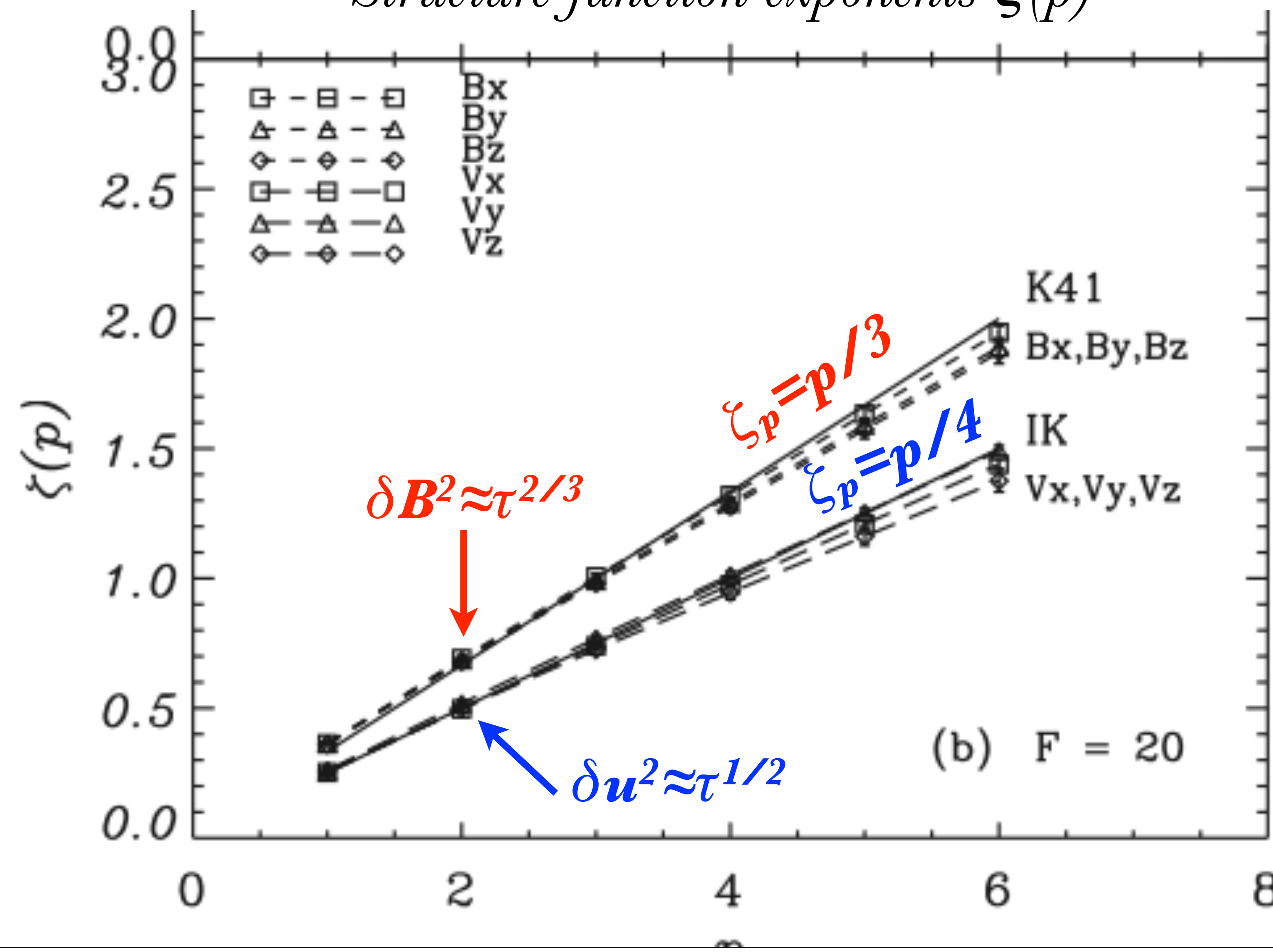
=> *removes intermittency*

=> **pure K41/IK scaling**

$|\delta \mathbf{B}|^p \approx \tau^{p/3}$

$|\delta \mathbf{u}|^p \approx \tau^{p/4}$

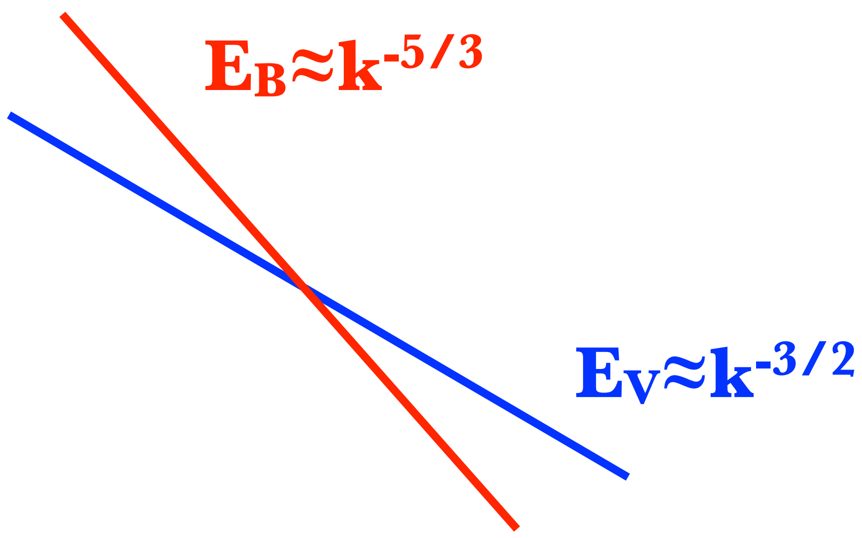
Structure function exponents ζ(p)



Salem Mangeney Bale Veltri 2009

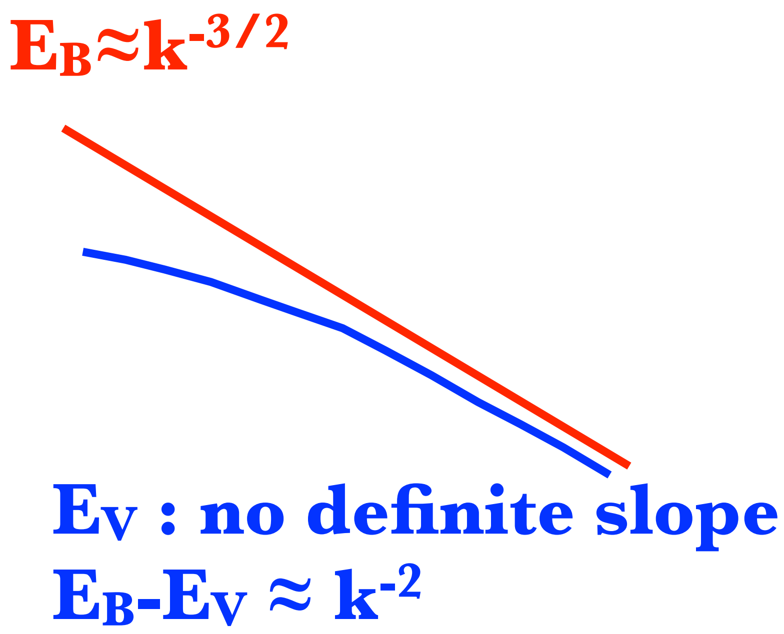
Summary

Observations



Wind mission
Salem et al 2009

Incompressible MHD simulations

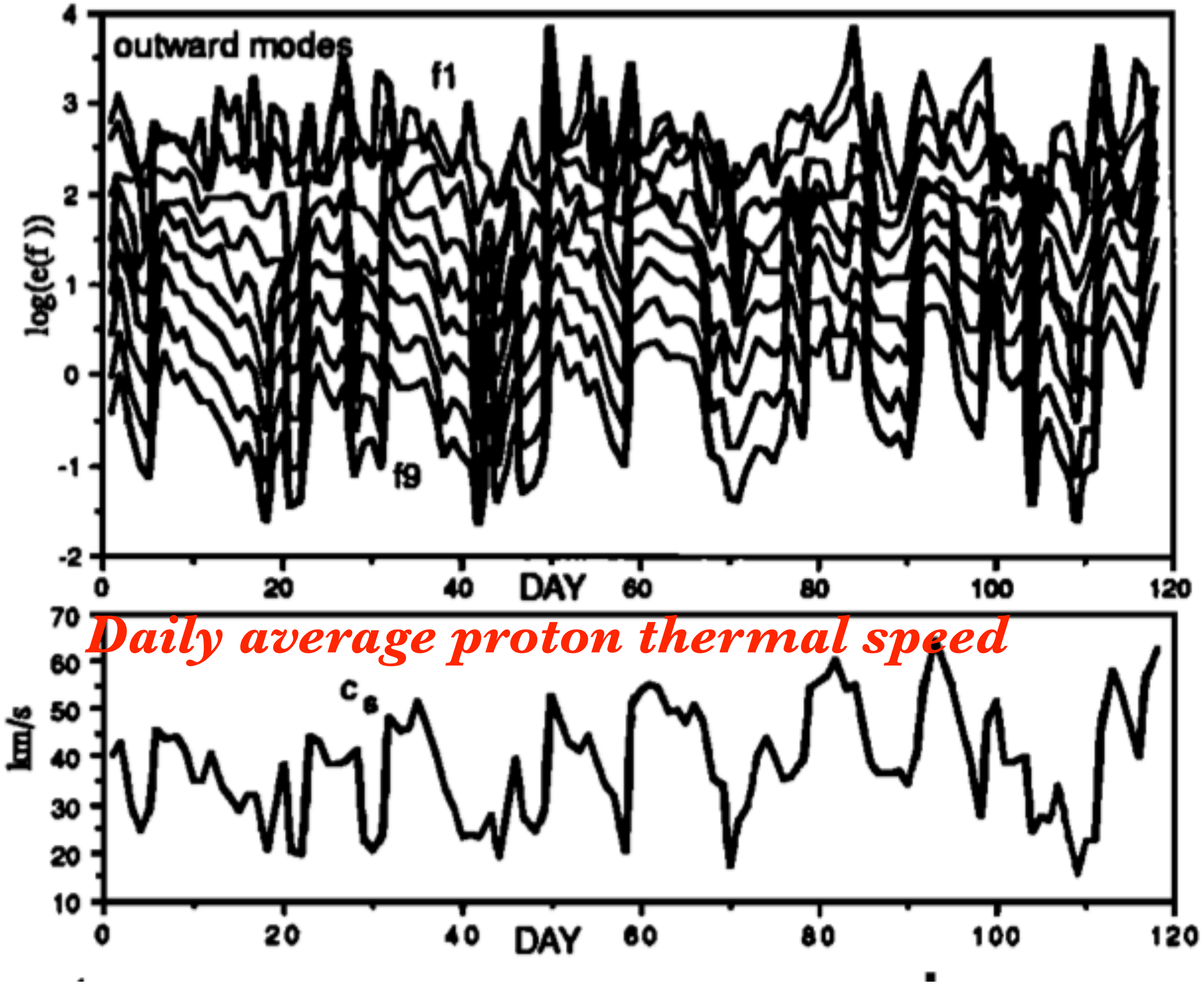


Periodic MHD 3D simulations with mean field
Müller Grappin 2005
Closure models
Grappin et al 1983

But turbulent properties at 1 AU are not invariable: they vary with proton temperature

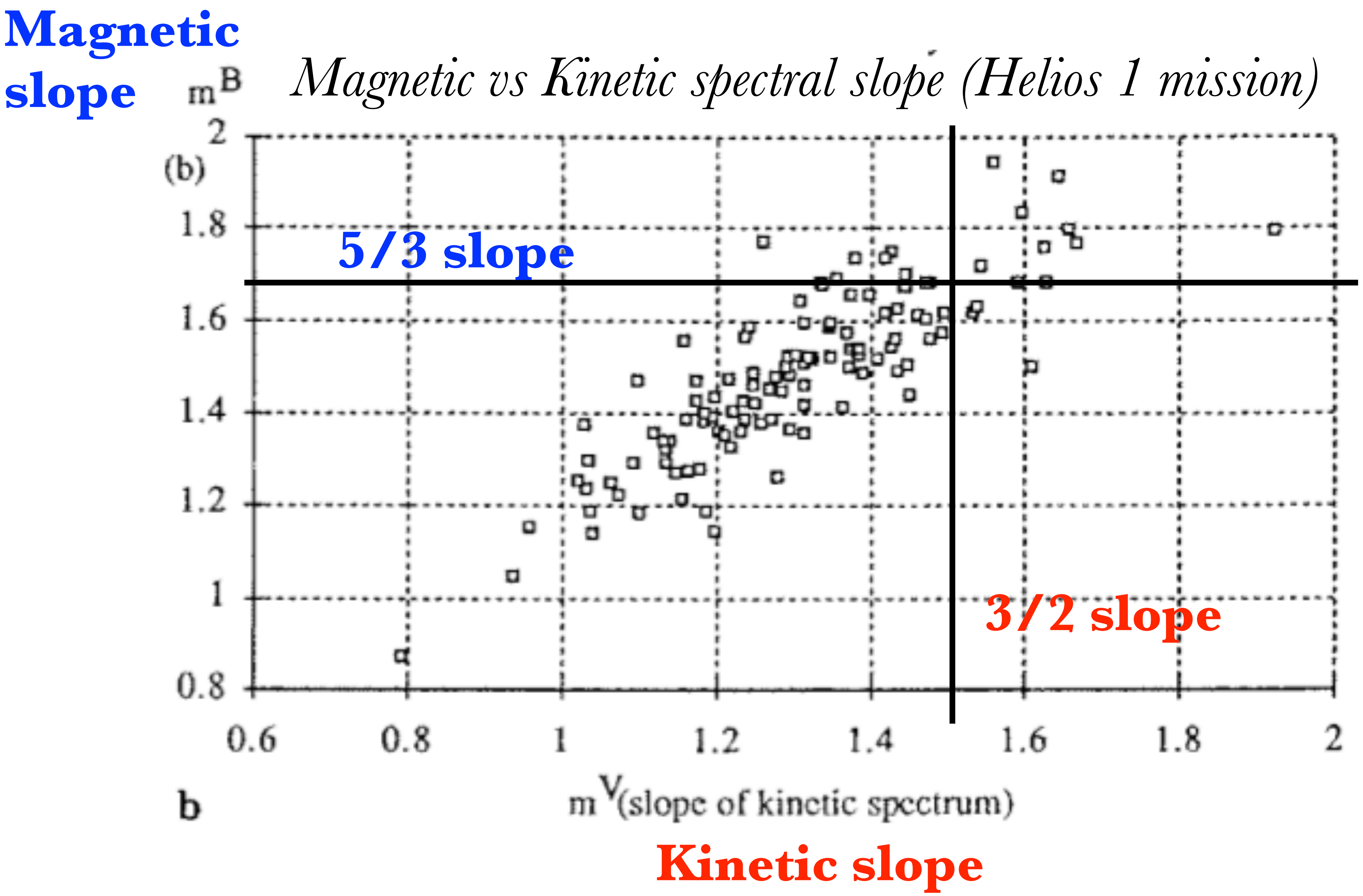
•Figure shows **nine frequency bands** from one day down to one minute
One shows outward mode energy
Magnetic energy would give the same result
•The band between hour and minute shows synchronized variations 80% correlation with proton temperature variations
• This temperature synchronized range is the **same as the 5/3 frequency range**
•Its slope is NOT constant with time: it varies ALSO with proton temperature

Daily fluctuations of spectral densities in outward Alfvén mode



Grappin Mangeney Marsch 1990

Measuring day by day scaling (Helios mission)...

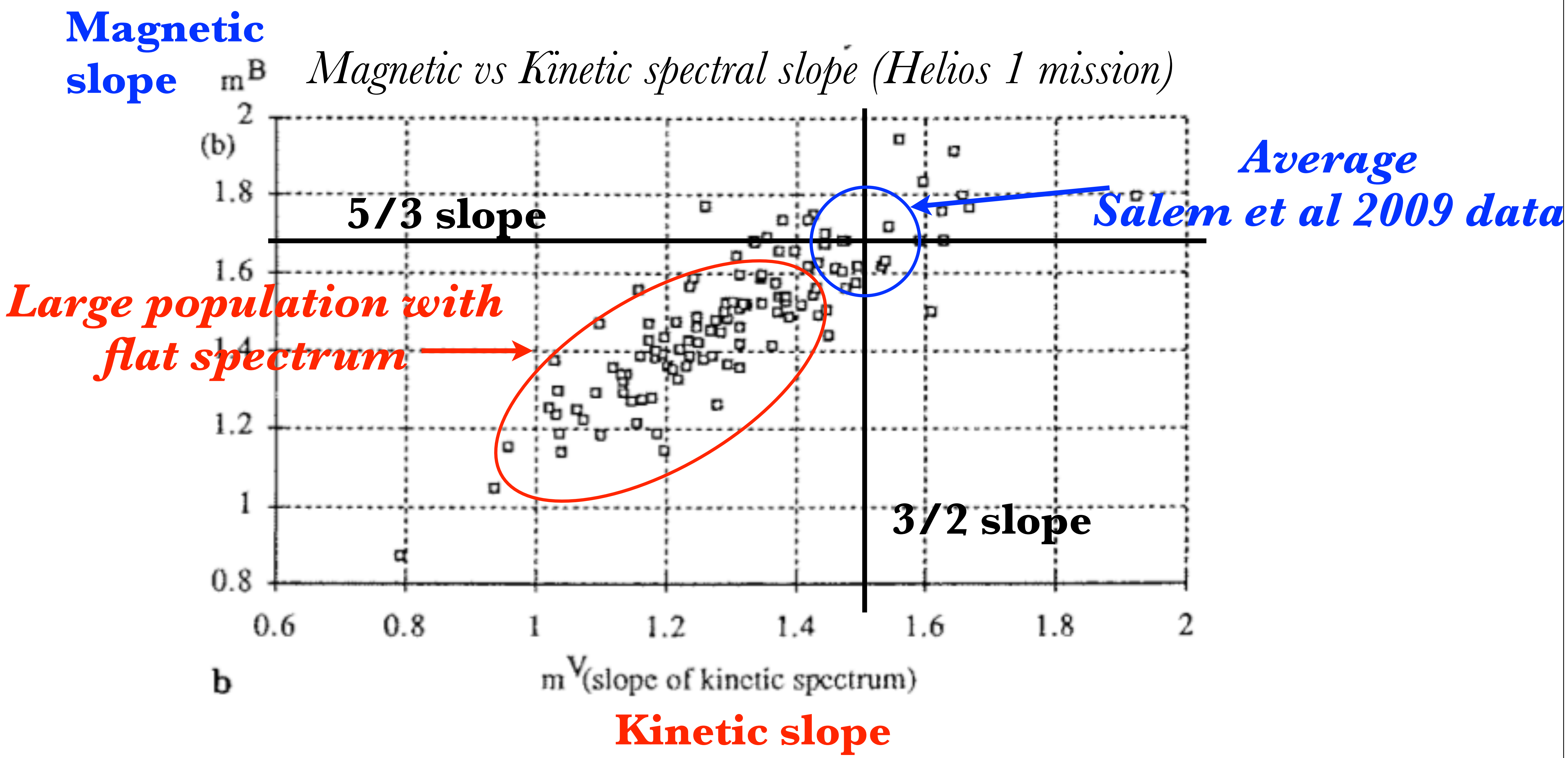


Large percentage of the population NOT in the spot (3/2,5/3)

Helios 1 mission, 118 Days of minimum solar activity 1974-1975

Grappin Velli Mangeney 1991

... shows large scatter of slopes

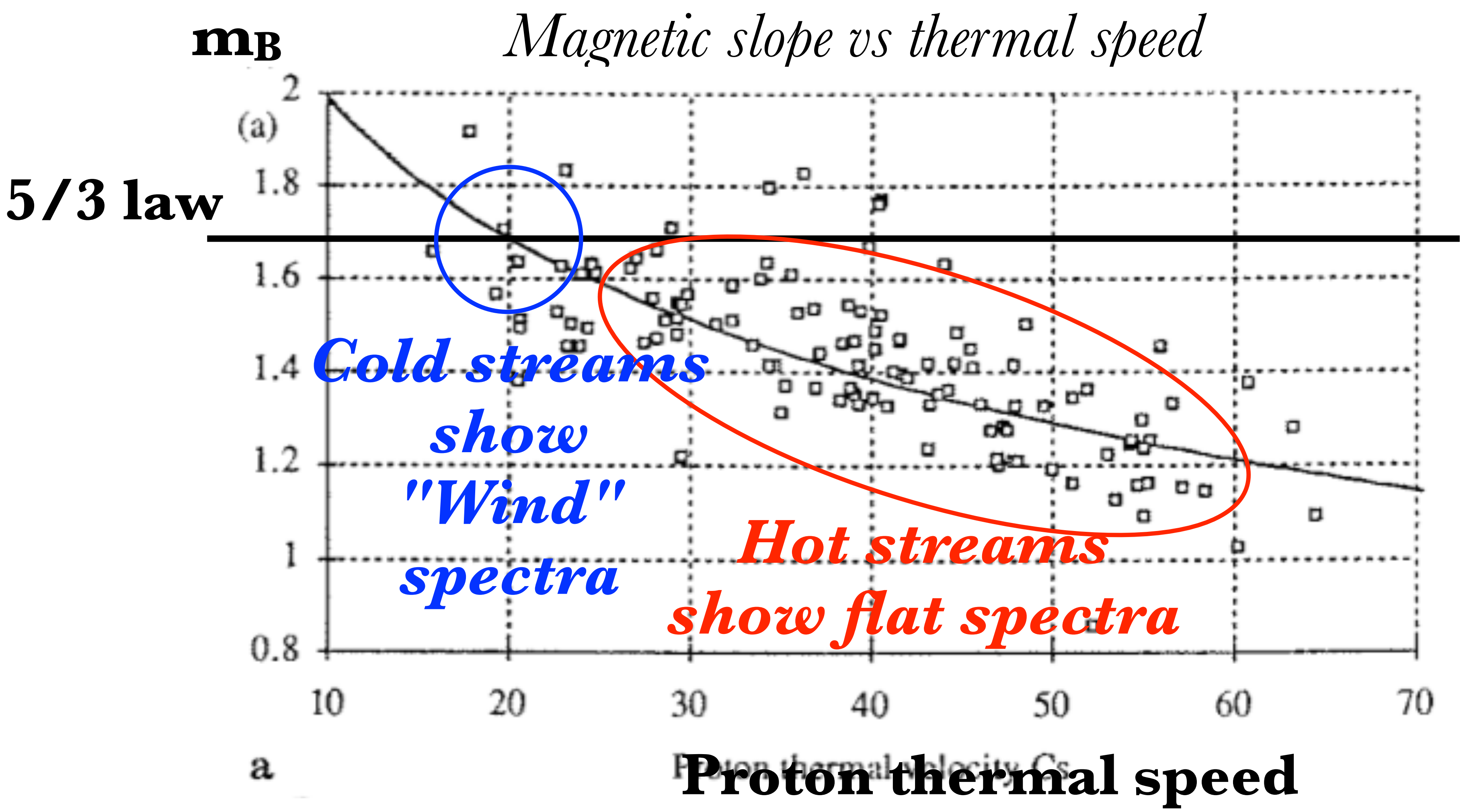


Large percentage of the population NOT in the spot (3/2,5/3)

Helios 1 mission, 118 Days of minimum solar activity 1974-1975

Grappin Velli Mangeney 1991

Flat spectra are hot



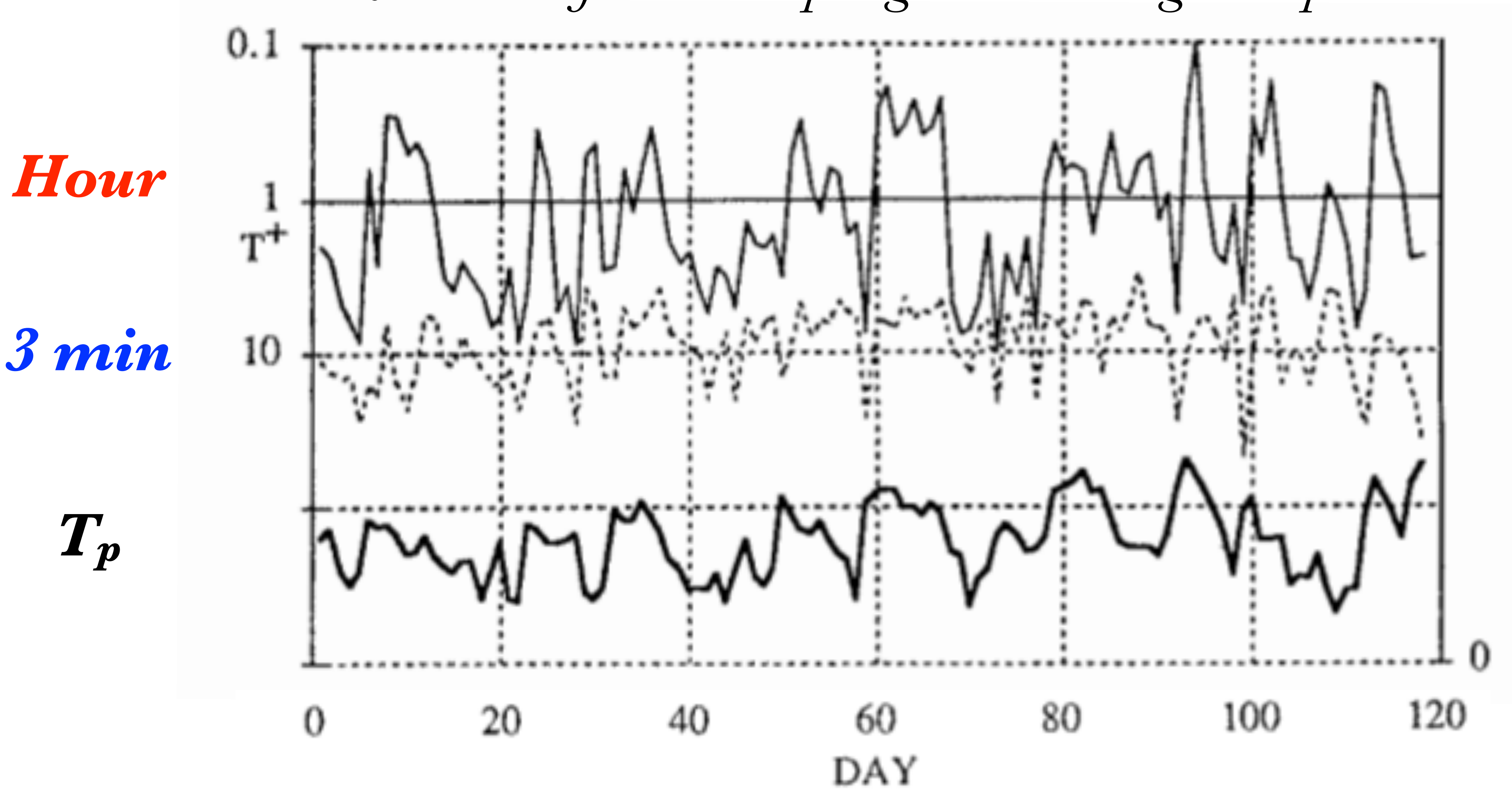
During solar minimum, the RED population is that of HOT, FAST streams which are dominant

Grappin Velli Mangeney 1991

Flat population NOT relaxed

Using **slow coupling time** as in IK: $t^* = t_{NL} \times B^\circ / b$

Number of slow coupling times during transport



=> Hour scales NOT relaxed in Hot streams

Grappin Velli Mangeney 1991

II Heating issue: trying to reveal time scales

Energy equation

$$\frac{dT_{pr}}{dr} + \frac{4}{3}\frac{T_{pr}}{r} = \frac{m_p}{(3/2)V_{SW}k_B}\epsilon$$

+ Measured gradient $\mathbf{T_p \approx 1/R^{0.9\pm0.1}}$
(from Helios mission, *Freeman et al 92, Totten et al 95*)
• → **"observed" heat flux** depending on V [km/s] and T [K]

$$\epsilon_{heat} = 3.6 \times 10^{-5} T_{pr} V_{SW} \text{ [J/(kg s)]},$$

=> Testing *two theoretical heating rates*:
• the **fast one** (K41):

$$\epsilon_{Kol} = (2\pi/V_{SW})\nu^{5/2}\left[(1+R_A)(5/3)(P_B(\nu)/\mu_0 m_p n_p)/C_K\right]^{3/2},$$

• the **slow one** (IK):

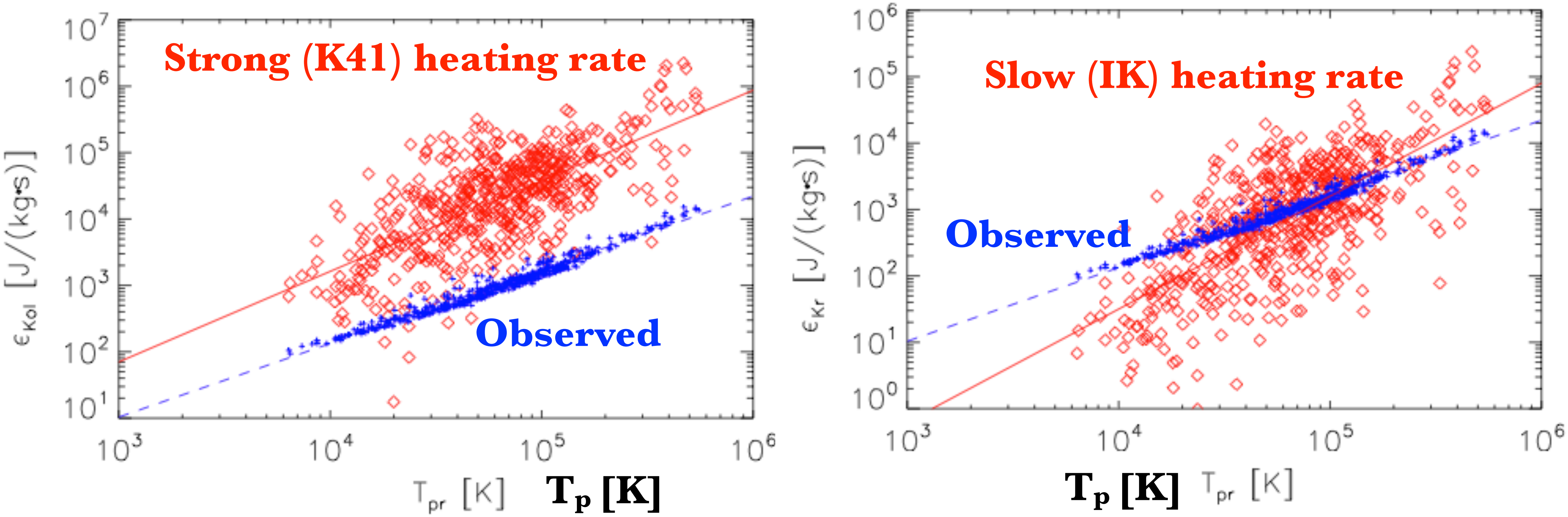
$$\epsilon_{Kr} = (2\pi/V_{SW})V_A^{-1}\nu^3\left[(3/2)(P_B(\nu)/\mu_0 m_p n_p)/A\right]^2.$$

→ 0 when V_A → 0

Vasquez Smith Hamilton MacBride Leamon 2007

Matching phenomenology and observations

Vasquez Smith Hamilton MacBride Leamon 2007



•IK phenomenology better matches "observed" heating rate,
•but temperature scaling not very good

Data from *ACE mission 1998-2002*
NB Good correlation of *theoretical* heating rates with temperature
comes from good correlation of turbulent amplitude with temperature (*Grappin Mangeney Marsch 1990*)

III Anisotropy

Anisotropy of MHD turbulence with mean field

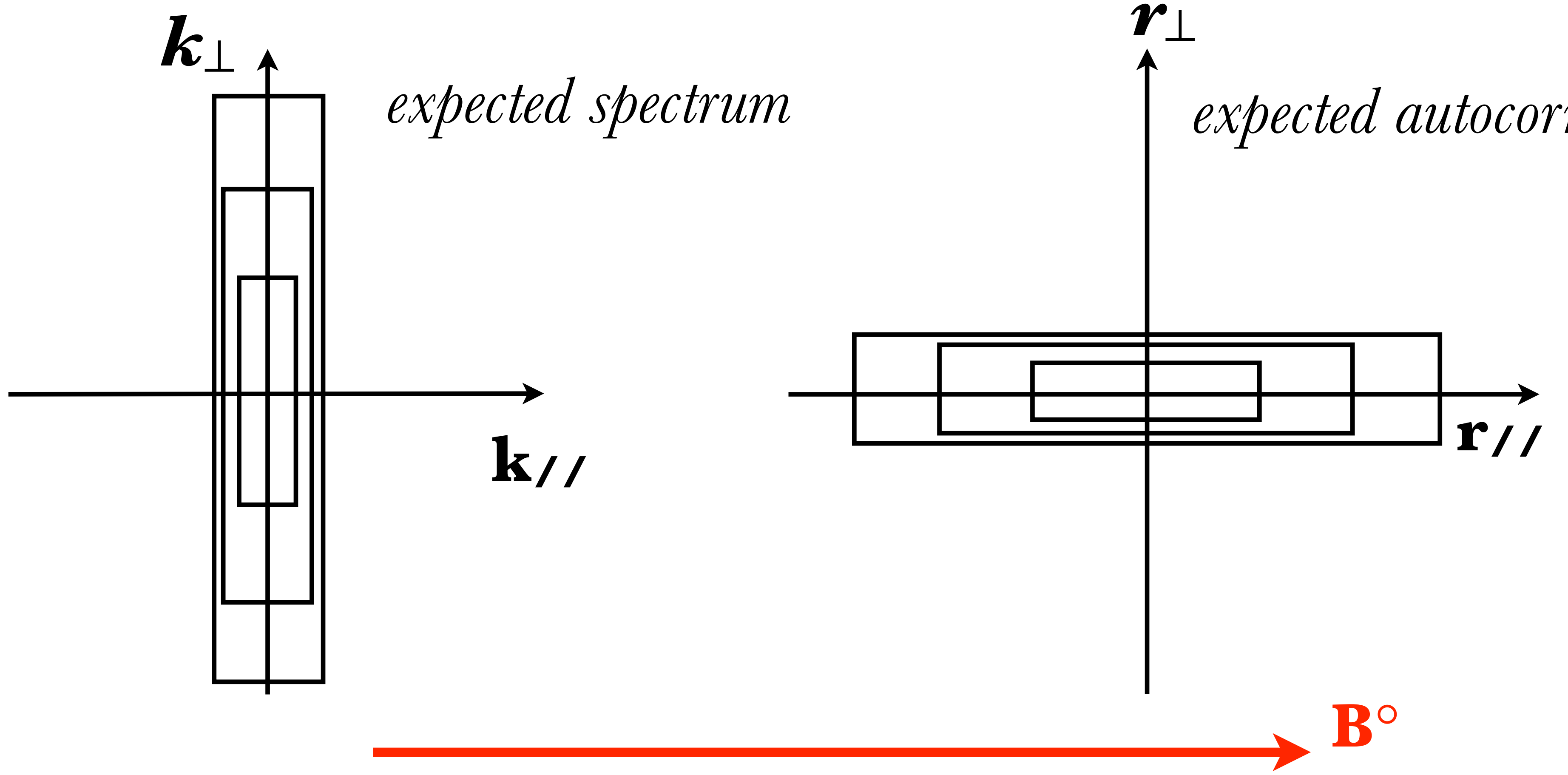
POOR NL coupling parallel to B° (weakening by phase variations)

Strauss 1976, Montgomery Turner 1981, Shebalin Matthaeus Montgomery 1983

Grappin 1986

=> Spectrum should be mainly **perpendicular to B°**

<=> Autocorrelation should be mainly **// to B°**



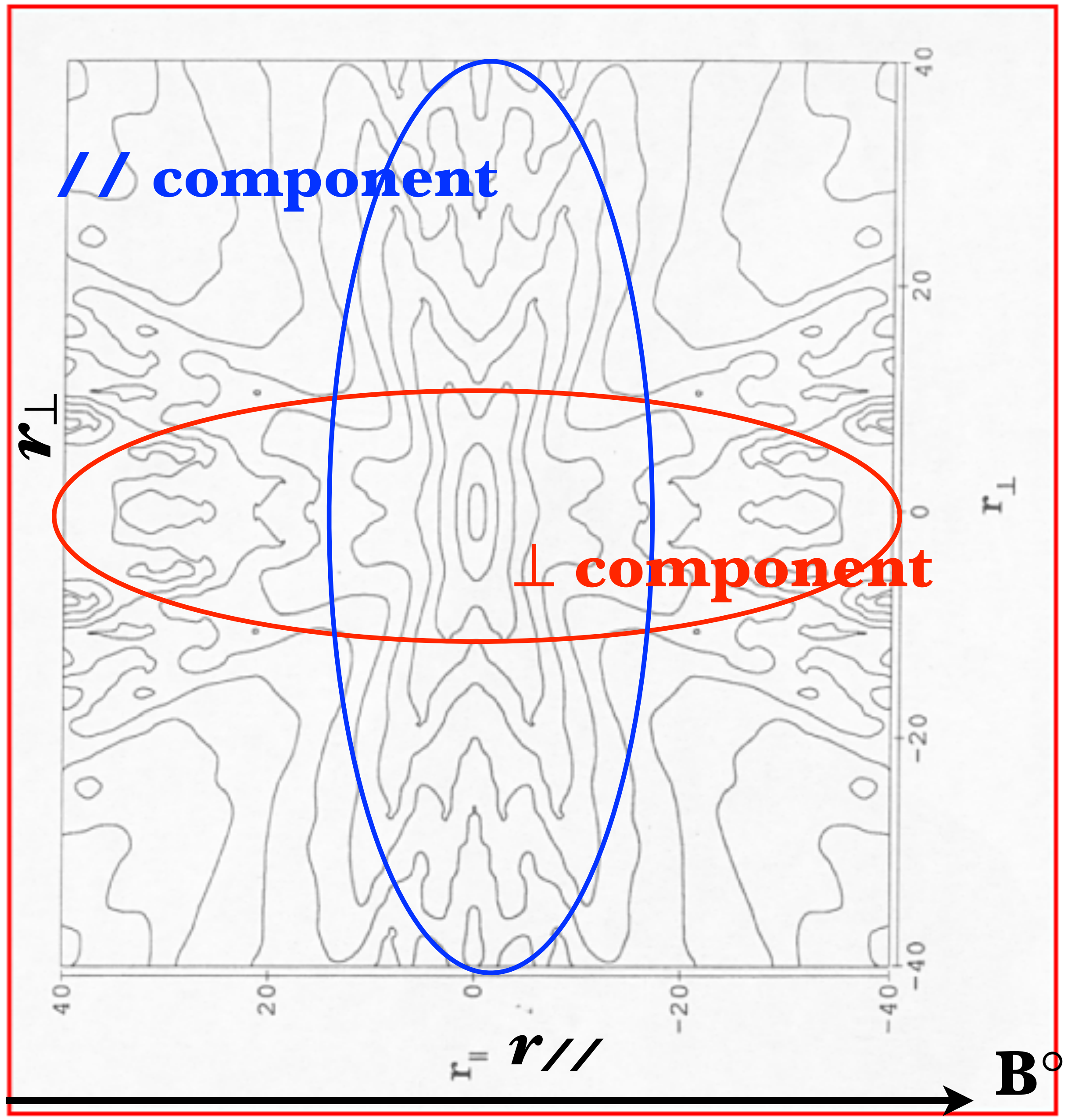
Autocorrelation ≈ isotropic !

autocorrelation <δB$_i$(**r'**) δB$_i$(**r'**+**r**)>
Units of 10^5 km (average: [3 min, 2 hours]

Conclusion
⊥ component NOT dominant at small scales

•Standard interpretation:
// component = linear waves (present from start)
⊥ component = turbulent component

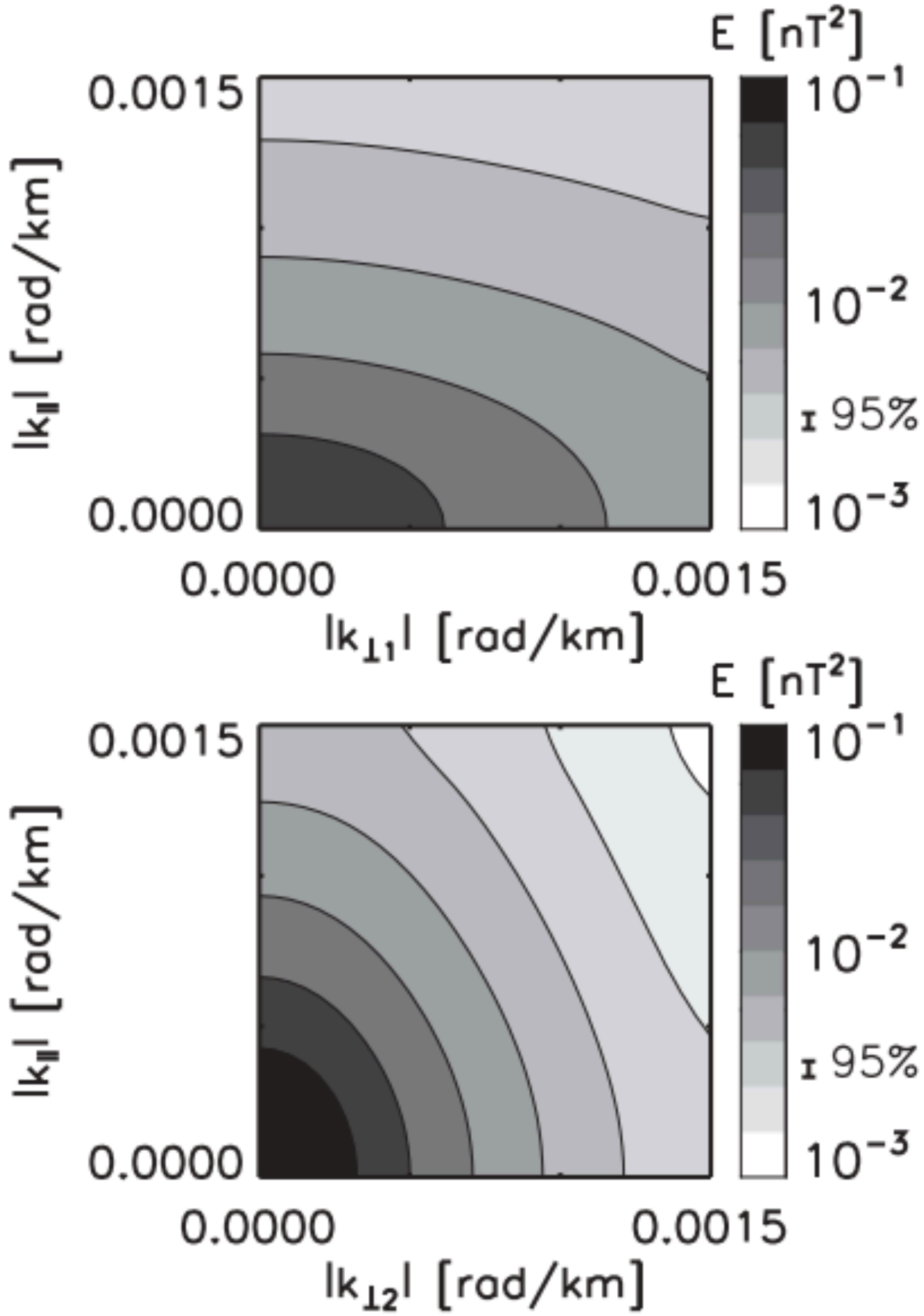
δB auto-correlation *(units 10^5 km)*



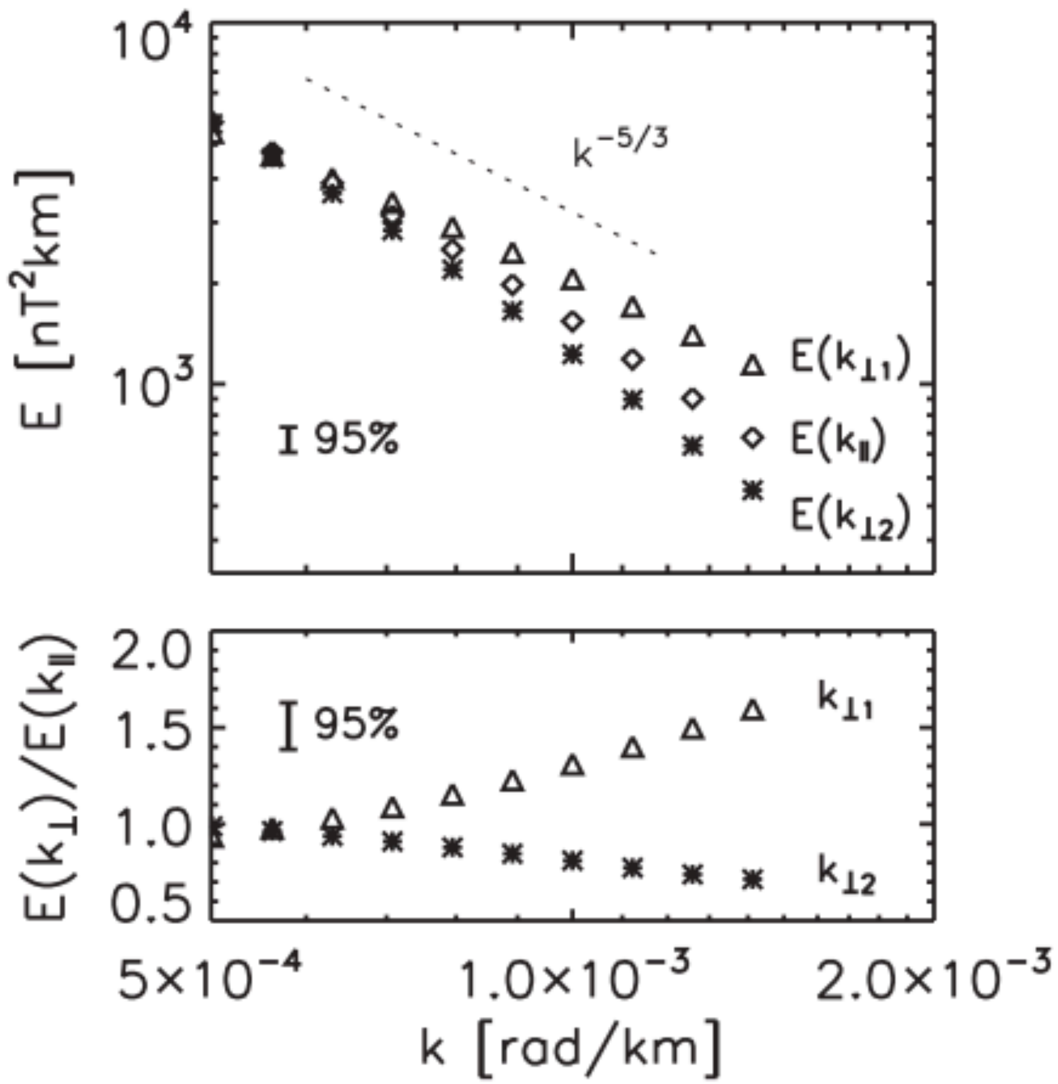
Matthaeus et al., 1990

3D spectrum still more exotic (using k-filtering)

2D cuts of energy spectrum



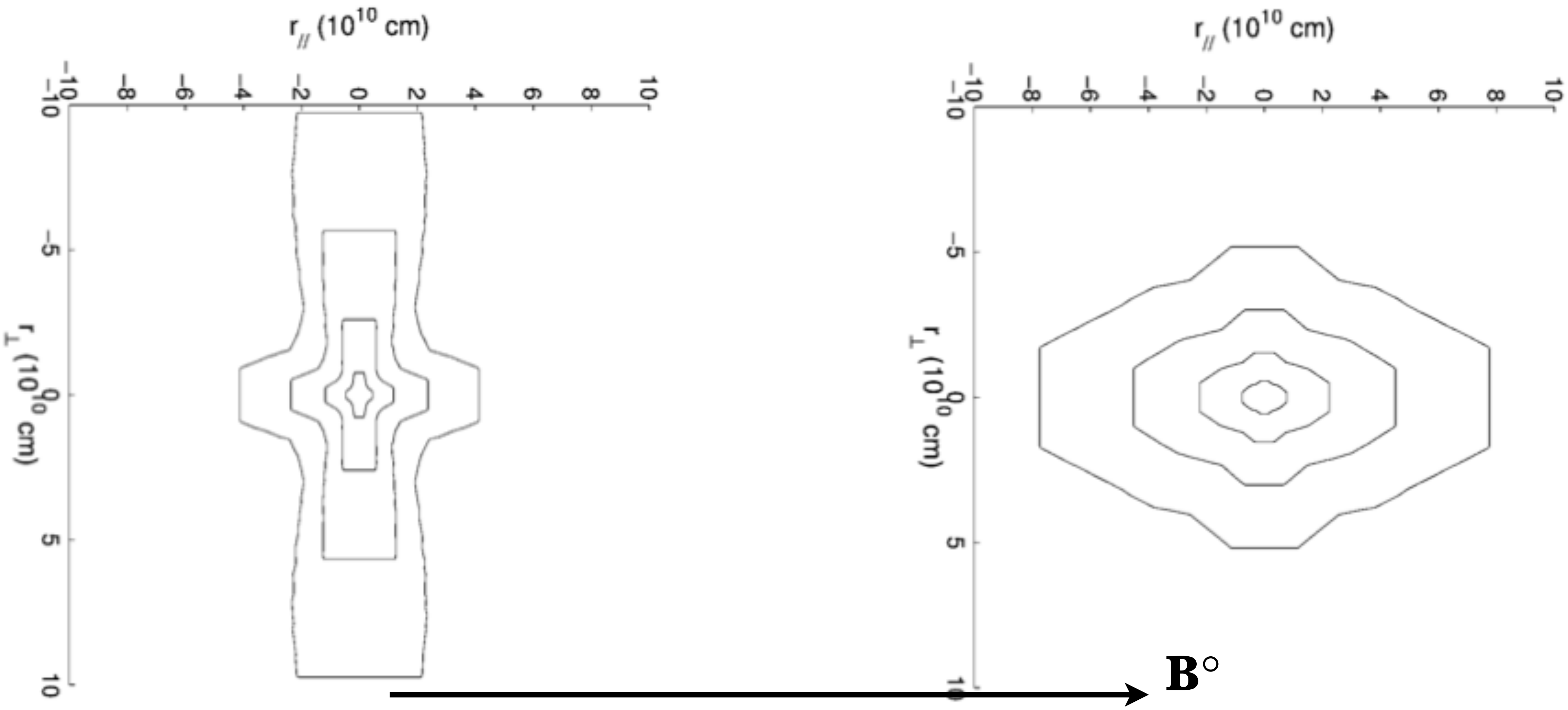
During this period of *slow* wind, the B° axis is NOT a symmetry axis
...OR there is another one...
see also *Bieber and Bieber 1999*



Narita Glassmeier Sahraoui Goldstein 2010

Separating fast and slow wind
(again assuming B° axisymmetry)

δB auto-correlation *(units 10^5 km)*



Fast (>500km/s) wind ***Slow (<400km/s) wind***

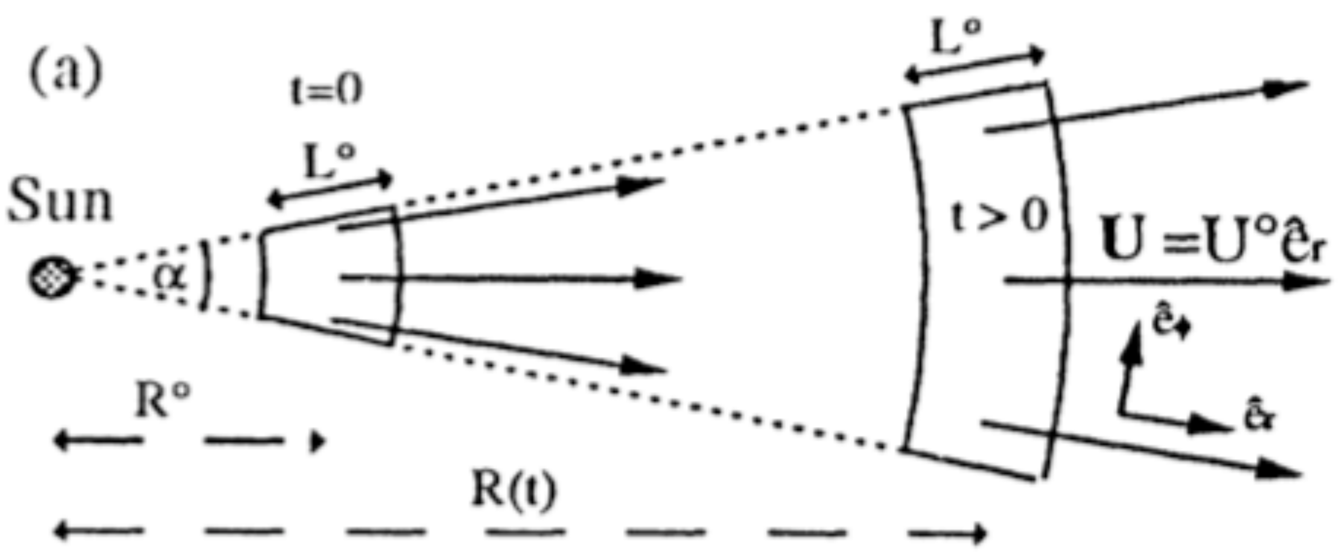
Dominance of // component ≈ Isotropy

Dasso Milano Matthaeus Smith ApJ 2005

What the wind does to spatial structures

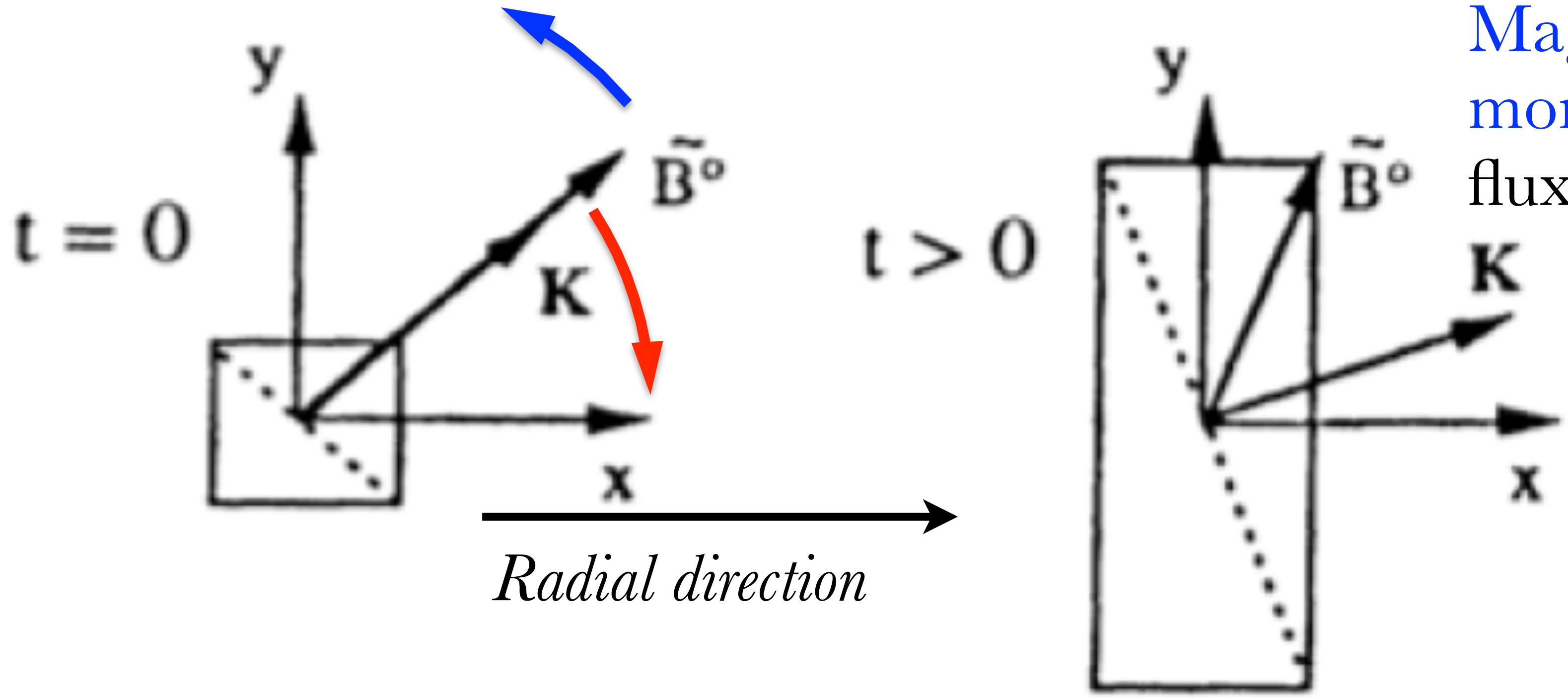
1. Expansion of the wind transforms // structures into ⊥ => **$k_\perp$ into $k_{//}$**
NB Here "//" <=> // $\hat{e}_r$, "⊥ " <=> "⊥ $\hat{e}_r$"
2. nonlinear coupling ⊥ to radial are reduced/delayed
3. Close enough to Sun, B° ≈ radial, hence **// to $\hat{e}_r$ <=> // to B°**

=> Expansion favours isotropization of spectrum



1.5D and 2.5D MHD: *Grappin Velli Mangeney 1993, Grappin Velli 1996*
Also (Hybrid): *Hellinger et al 2003, 2005*

Is there enough time ?



Magnetic field B° becomes more transverse because of flux conservation

Wave vectors k become more radial

Characteristic times

Time for cascade perp to B°: t_{NL}

Time for expansion: $t_{exp}=(\mathrm{div}U)^{-1} \approx R/(2U)$

=> 1 Day at 1AU, 0.1 Day at 0.1 AU

=> Expansion important ($t_{exp} < t_{NL}$) **only at large scales**

BUT Alfvénic turbulence in fast wind has **large effective t_{NL}** because $z^- \ll z^+$*

=> explains why // spectrum **can dominate in fast wind**

** Dobrowolny Mangeney Veltri 1980, Grappin Frisch Pouquet Léorat 1982*
Grappin Velli Mangeney 1991

Summary

1. Scaling

•Observed **average** scaling (V-slope=3/2, B-slope=5/3) differs from MHD simulations

•Hot streams show flatter spectra, with strong expansion effect

2. Heating

•Heating SLOW compared to K41 prediction

•But good match of IK heating might be coincidence, as dominant B spectrum not follows IK scaling

3. Anisotropy

• shows // component that might be made of linear waves,

• but also might result from strong expansion effects + NL

Conclusion:

•Standard Kolmogorov cascade NOT a good model: SW turbulence is a *slow process*, comparable to IK cascade

•expansion probably plays a significant role (together with Alfvénicity)

•direct 3D MHD simulations with expanding box model (*Grappin Velli Mangeney 1993*) are needed