The Heating & Acceleration of the Solar Wind

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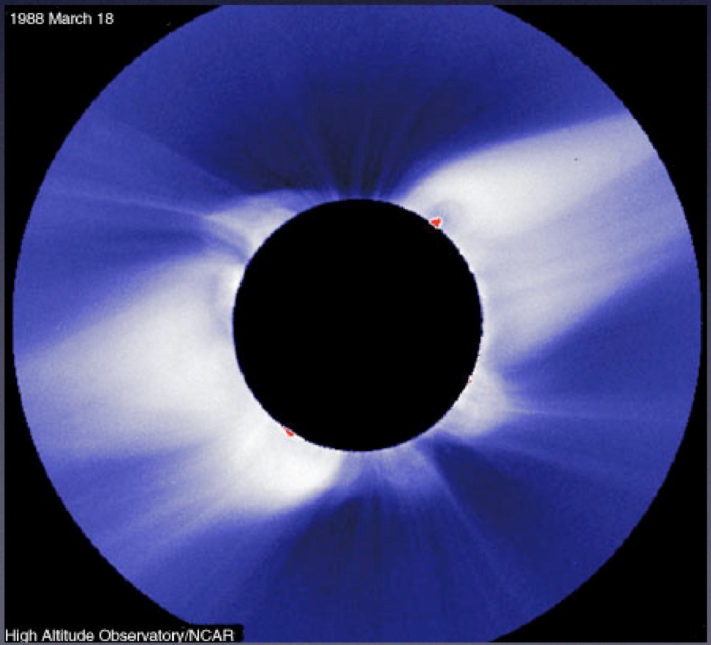
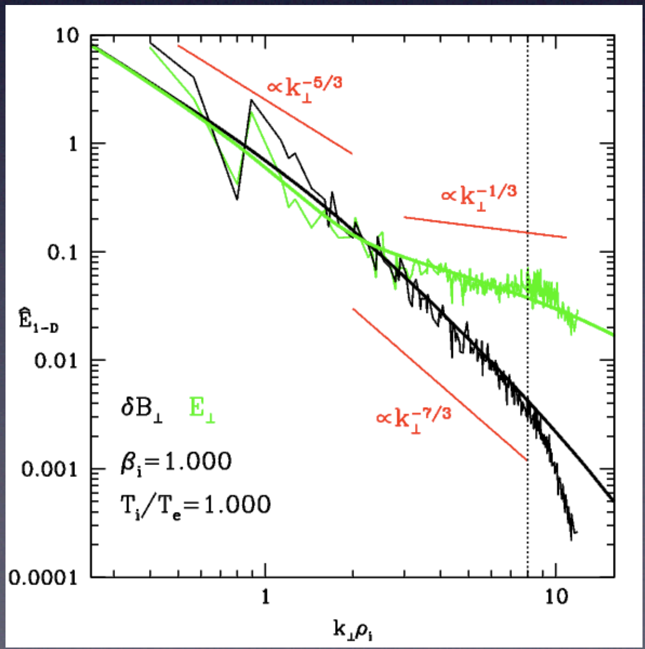




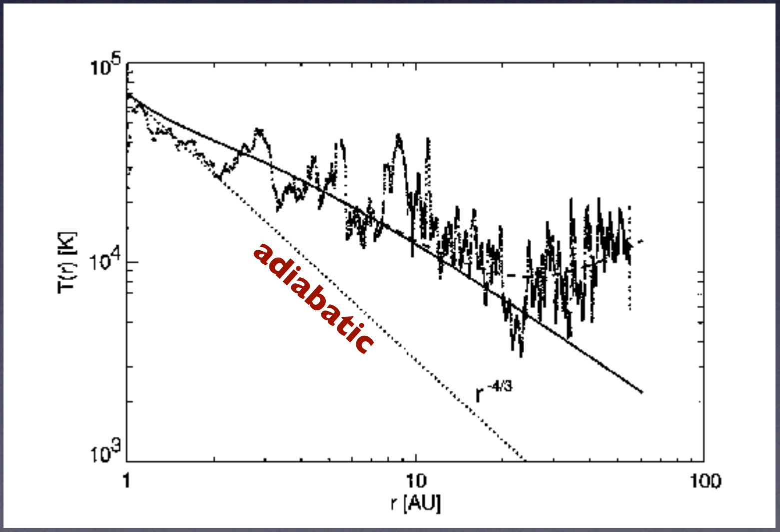
Overview

- Brief Observational & Theoretical Background
- Alfvenic Turbulence Theory (weak & strong)
  - Comparison to *In Situ* Observations at ~ AU
  - Transition to Kinetic Alfven Wave Cascade at ~ the Ion Larmor Radius
- Particle Heating by Alfvenic Turbulence
  - Comparison to the Fast & Slow Winds
  - The Puzzle of the High Frequency Cascade (or the lack thereof ....)
  - Possible Solutions

Background

- Heating required to accelerate the solar wind
  Parker 1958
- Early models invoked e$^-$ conduction but $T_p \gtrsim T_e$ in fast wind
- Local ($r \sim R_\odot$) & extended ($r \sim$ few-10^3 $R_\odot$) heating required
- Extended heating favors waves
- Alfven waves: primary observed fluctuation & least damped MHD mode in collisionless plasmas
  e.g., Belcher & Davis 1971; Barnes 1956

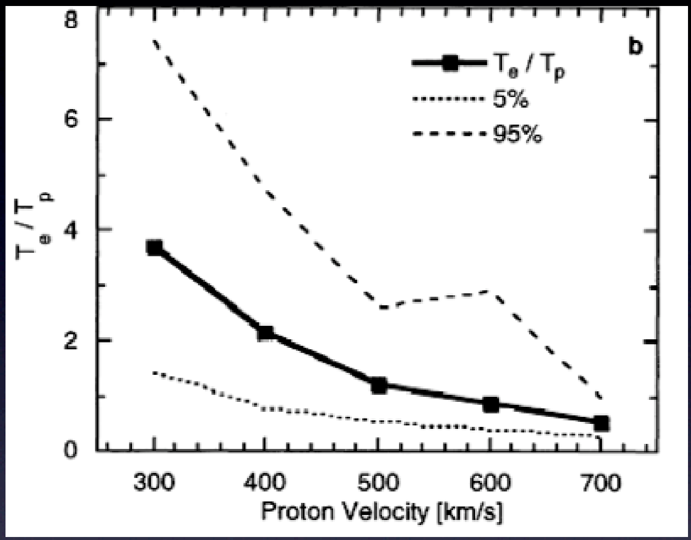
Voyager Temp Profile



Matthaeus et al. 1999

Thermodynamic Constraints on Heating

- *In situ*: must dist. btw. Fast & Slow Wind
- **Fast:** $T_{ion} \gtrsim T_p \gtrsim T_e$ & $T_{\perp,i} \gtrsim T_{||,i}$
- **Slow:** $T_e \gtrsim T_p$ & $T_{||,i} \gtrsim T_{\perp,i}$ (?)



Newbury et al. 1998

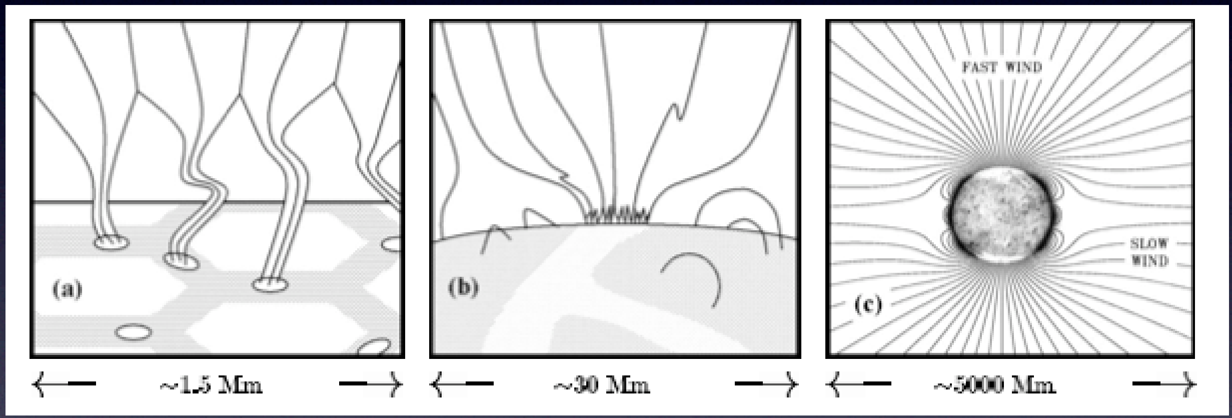
- ~1-4 $R_\odot$: constraints from UVCS/SOHO (in Coronal Holes = **Fast**)
- $T_{\perp,i} >> T_{||,i}$ (e.g., O^{5+}, p)
- $T_i >> T_p \gtrsim T_e$; preferential minor ion heating

Kohl et al. 1997. 1998; Cranmer et al. 1999

suggests ion cyclotron resonant heating

Wave Excitation/Launching

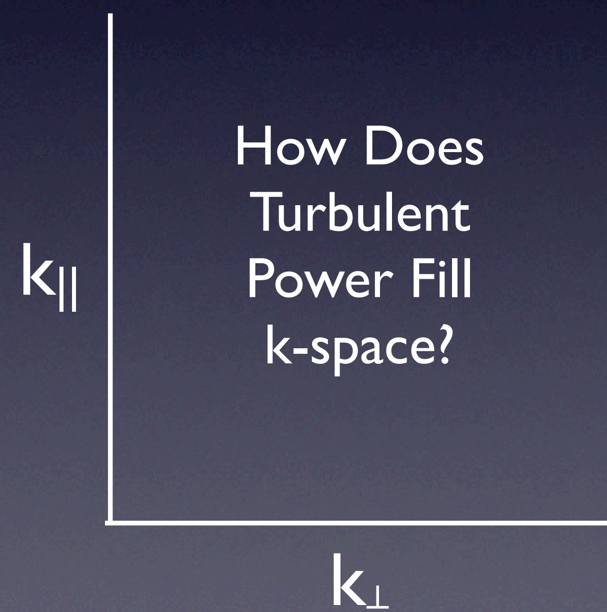
- Small-scale Magnetic Activity → High Freq. Alfven Waves
  Axford & McKenzie 1992
  - ~ Hz and higher; f^{-1} spectrum often assumed
  - damp by ion cyclotron resonance: lower freq. waves damp at larger r (lower B)



- Photospheric/Convective Motions → Low Freq. Alfven Waves
  e.g., Matthaeus et al. 1999; Cranmer & van Ballegooijen 2005
  - ~ min & shorter
  - damp by **turbulent cascade** to small scales/high frequency

MHD Turbulence

- Hydro: $P(k) \sim k^{-5/3}$
- MHD: B-field defines local direction
  - k = ??; $P(k) \sim k^{-??}$
- Focus on Incompressible MHD
  - Slow & Alfven waves
  - Balanced Turbulence



Incompressible MHD Turbulence

- View as interaction of Alfven wave packets traveling at $v = \pm v_A$ $(\omega = |k_{||}| v_A)$
  e.g., Kraichnan 1965
- a single Alfven wave packet is an exact non-linear soln of incompressible MHD
  → **turbulence requires oppositely directed waves**
  - solar wind: inward propagating waves generated by reflection of long-wavelength ($\gtrsim$ density scale-height) outward propagating waves
    e.g., Matthaeus et al. 1999; Cranmer & van Ballegooijen 2005; Verdini & Velli 2007
- **weak** turbulence: non-linear (cascade) timescale >> linear wave period

$$\omega_{nl} \ll \omega_{lin}$$

- **strong** turbulence: non-linear (cascade) timescale ~ linear wave period

$$\omega_{nl} \sim \omega_{lin}$$

Weak MHD Turbulence

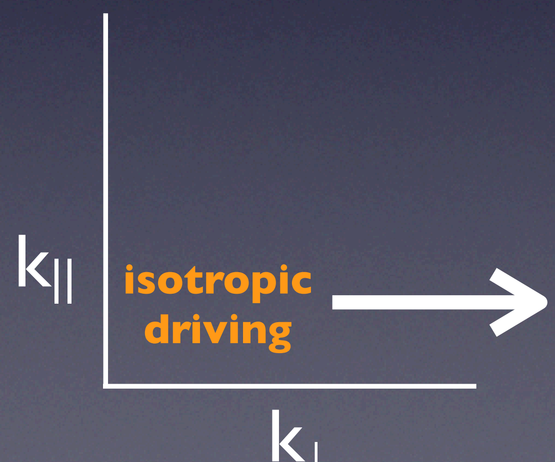
Shebalin et al. 1983; Goldreich & Sridhar 1995,1997; Ng & Bhattacharjee 1996, 1997; Galtier et al. 2000

- non-linear time >> linear wave period ~ $(|k_{||}|\ v_A)^{-1}$
  - Momentum & Energy Conservation →

$$\vec{k}_1 + \vec{k}_2 = \vec{k} \qquad \omega_1 + \omega_2 = \omega$$

→ $k_{||,1} - k_{||,2} = k_{||}$ & $k_{||,1} + k_{||,2} = k_{||}$

- **$k_{||}$ cannot increase: energy flows in the perp. direction**



Strong MHD Turbulence

Higdon 1984; Goldreich & Sridhar 1995

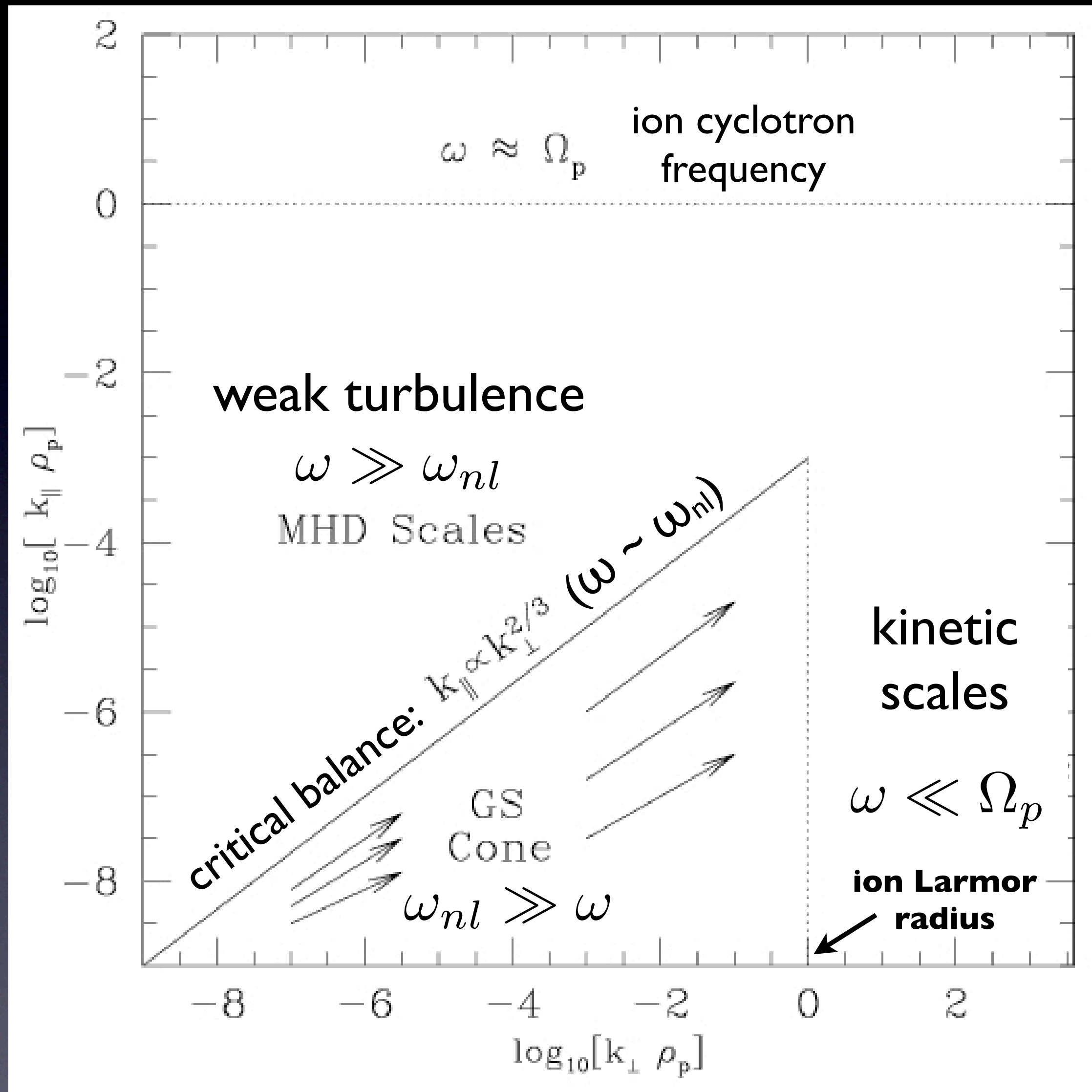
- non-linear interactions ~ $(\mathbf{v}\cdot\nabla)\mathbf{v}$
- $\omega_{nl} \sim k_\perp \delta v_\perp$ ↑ during weak turb.; $\omega_{lin} = |k_{||}|\, v_A$ unchanged
- **weak turbulence becomes strong: $\omega_{nl} \sim \omega_{lin}$**
  - "critical balance": assume turbulence maintains $\omega_{nl} \sim \omega_{lin}$
    Goldreich & Sridhar 1995

$$\rightarrow E(k_\perp) \propto k_\perp^{-5/3} \rightarrow \delta v_\perp \propto k_\perp^{-1/3}$$

Anisotropic Kolmogorov

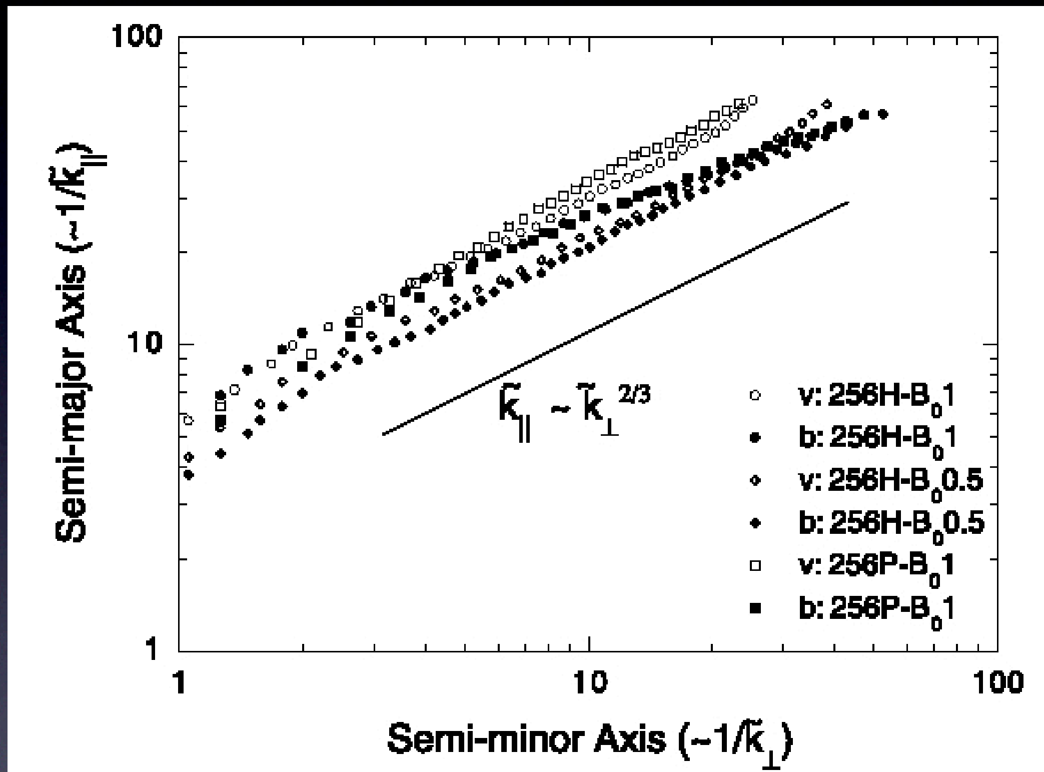
$$\text{critical balance} \rightarrow k_{||} \propto k_\perp^{2/3}$$

Scale-Dependent Anisotropy



ω ≈ Ωp
ion cyclotron frequency
weak turbulence
ω ≫ ωnl
MHD Scales
critical balance: k∥∝k⊥^2/3 (ω ~ ωnl)
GS Cone
ωnl ≫ ω
kinetic scales
ω ≪ Ωp
ion Larmor radius
log10[k∥ ρp]
log10[k⊥ ρp]

MHD Simulations Support the Goldreich-Sridhar (GS) Model



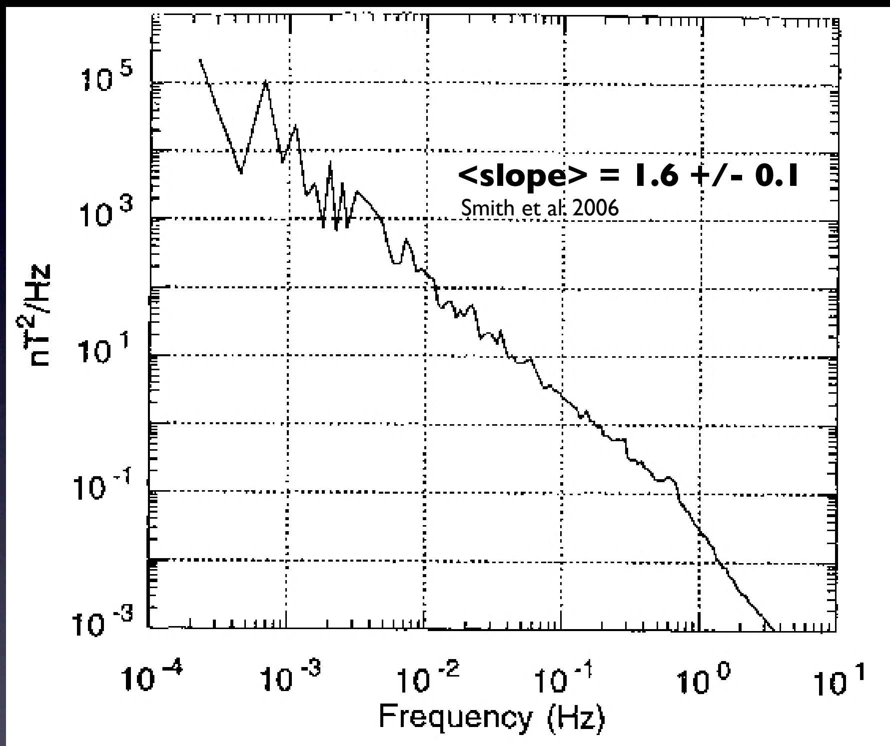
Cho & Vishniac 2000

Compressible Sims show that Alfven & Slow Modes Follow the GS Cascade

Some Fast Mode Energy Cascades to High Freq

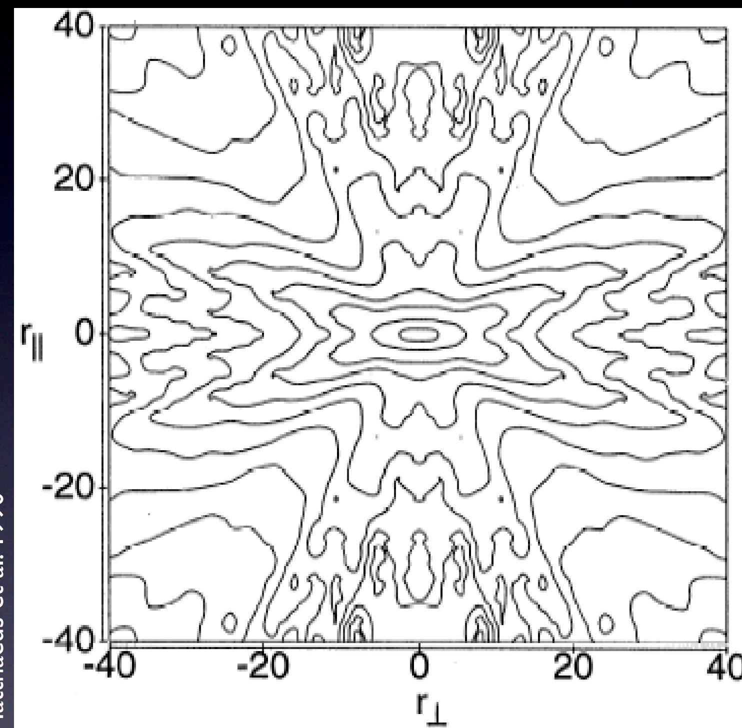
Cho & Lazarian 2003; see also Chandran 2005

Solar Wind Fluctuations



Goldstein et al. 1995

Magnetic field power spectrum consistent w/ Kolmogorov (above the ion Larmor radius)



Matthaeus et al. 1990

~ 90% of the Energy in ⊥ fluctuations

~ 10% in || fluctuations

slow wind: more ⊥ fluctuations

fast wind: more || flucuations

Dasso et al. 2005

Towards the Dissipation Range: The Transition to a Kinetic Alfven Wave Cascade at ~ ρ_i

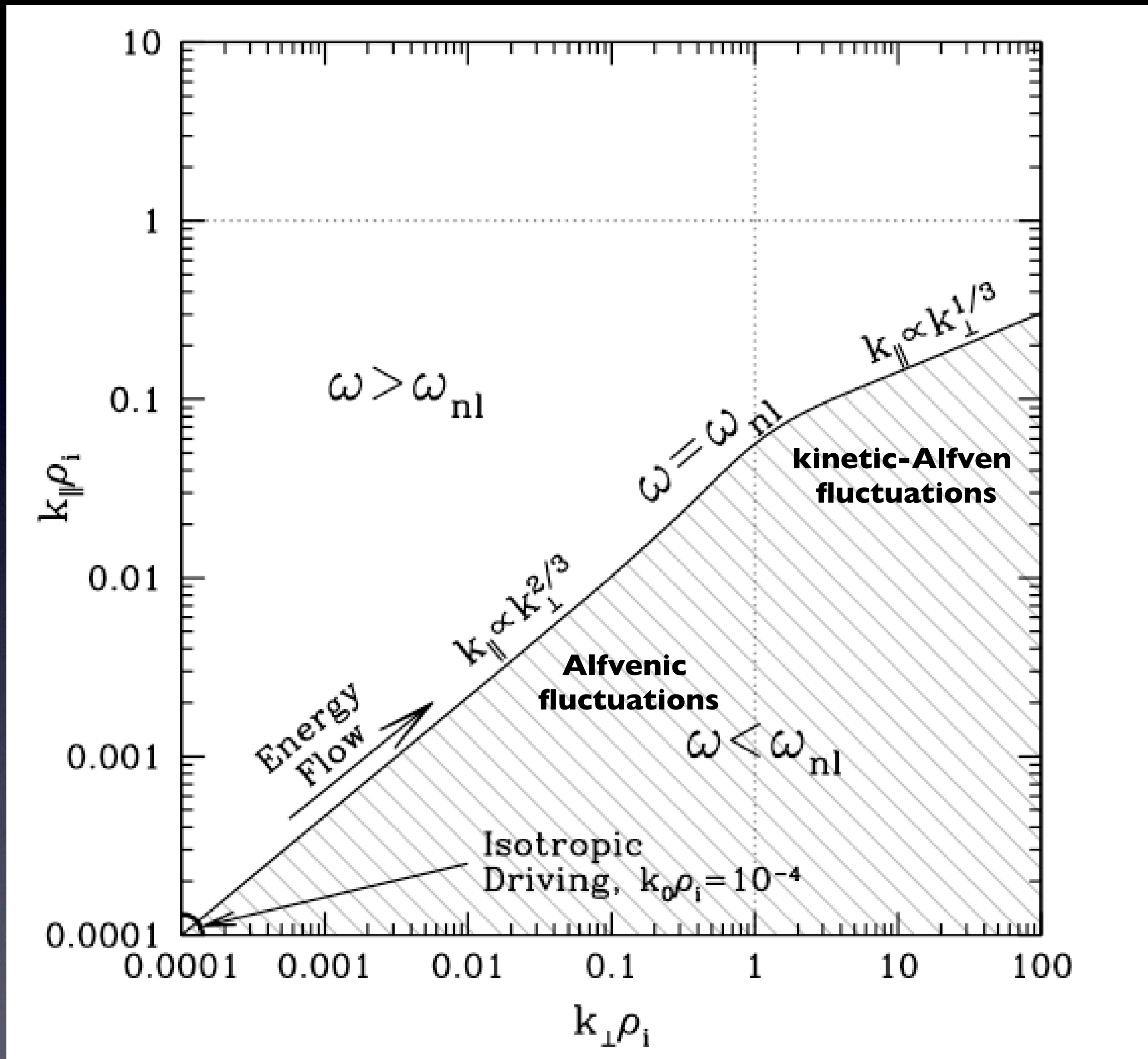
$$\text{at } \mathbf{k}_\perp \rho_\mathbf{i} \simeq \mathbf{1},\ \frac{\omega}{\mathbf{\Omega_i}} \simeq \left(\frac{\rho_\mathbf{i}}{\mathbf{L}}\right)^{\mathbf{1/3}} \beta_\mathbf{i}^{-\mathbf{1/2}} \quad \mathrm{L} \equiv \text{ outer scale of turbulence}$$

- Solar Wind at 1 AU: $\omega/\Omega_i \simeq 0.04$ at $k_\perp \rho_i \simeq 1\,(\mathrm{L} \simeq 10^{11}$ cm)
- Corona at ~ 2 $R_\odot$: $\omega/\Omega_i \simeq 0.03$ at $k_\perp \rho_i \simeq 1\,(\mathrm{L} \simeq 10^{9}$ cm)

(fluctuations already anisotropic atthe outer scale)

- $k_\perp \rho_i \gtrsim 1$ & $\omega \lesssim \Omega_i$, Alfven waves → Kinetic Alfven Waves (KAWs)

strong Alfven wave turbulence → strong KAW turbulence

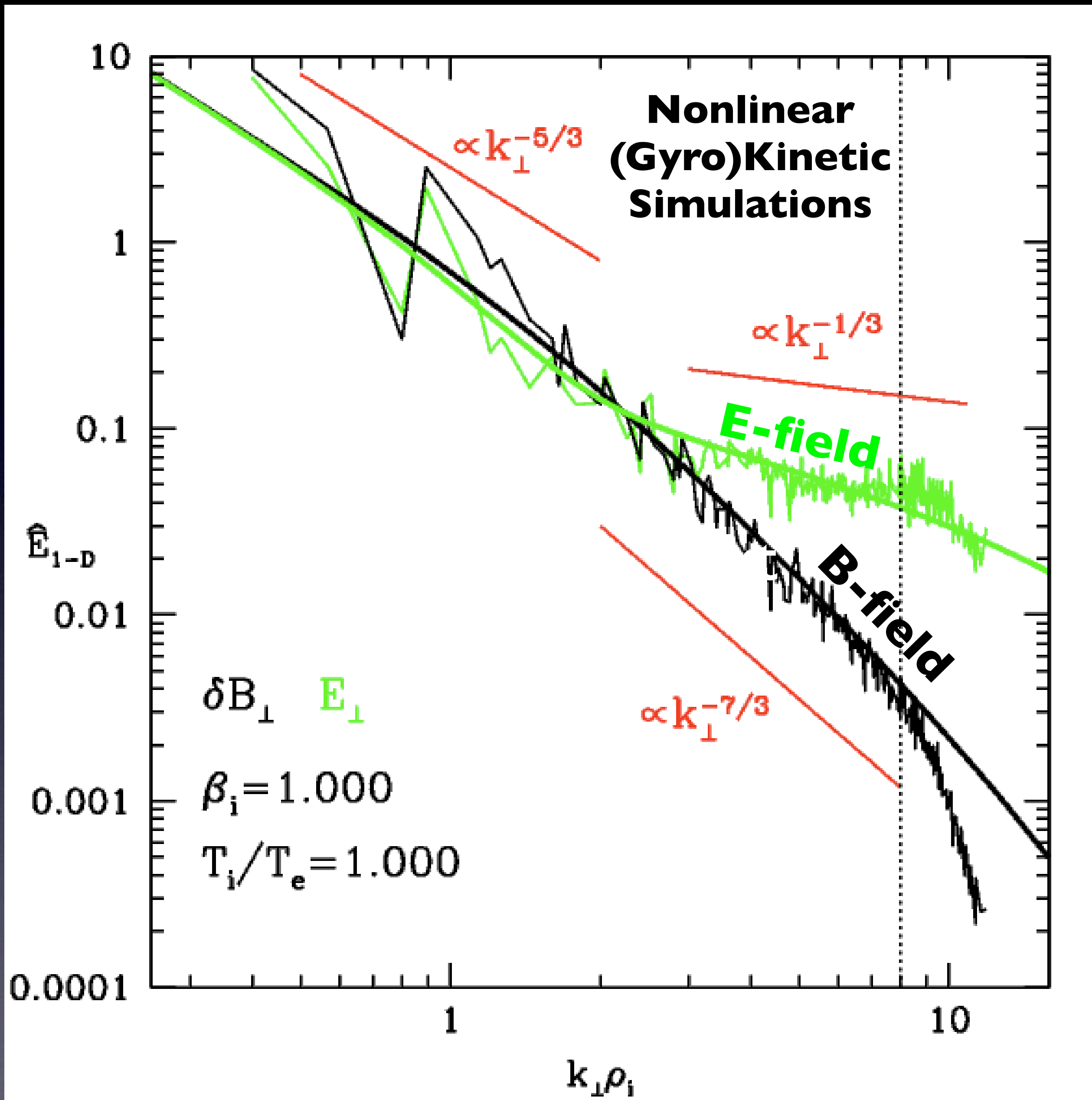


Strong KAW Turbulence (sans damping)

$$E_B \propto k_\perp^{-7/3}$$

$$k_\parallel \propto k_\perp^{1/3}$$

Biskamp et al. 1999;
Cho & Lazarian 2004;
Schekochihin et al. 2007



Howes et al. 2008

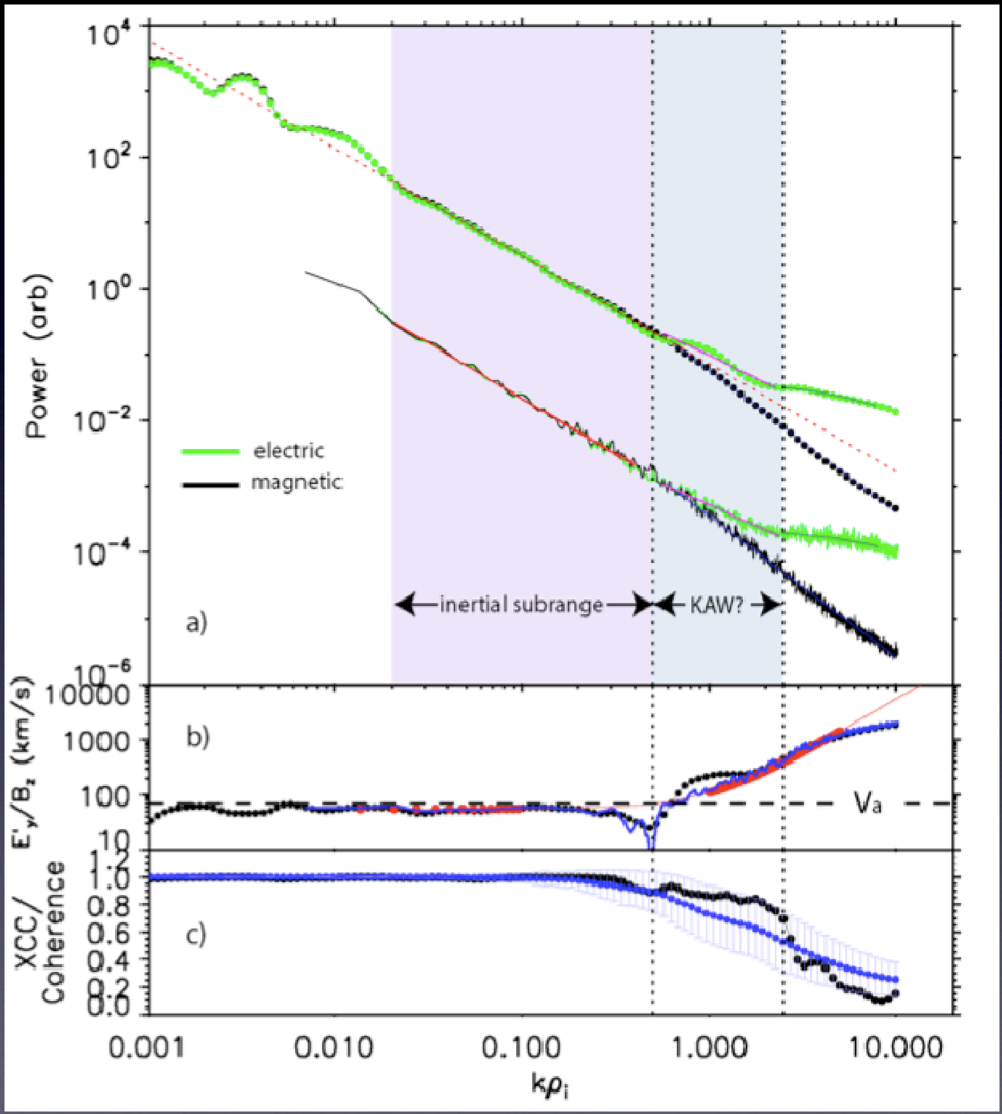
anisotropic
low frequency
turbulence
both above &
below ρ_i can be
quantitatively
modeled using a
low freq. expansion
of the Vlasov eqn

Howes et al. 2006; Schekochihin et al. 2007

“gyrokinetics”

In Situ Measurements in the Solar Wind

(Bale et al. 2005)



In Situ Measurements of E & B-fields with Cluster are Consistent with a transition to KAWs at small scales but *not* with the onset of ion cyclotron damping

Collisionless Damping of the Anisotropic Cascade

Quataert 1998; Leamon et al. 1998; Quataert & Gruzinov 1999; Cranmer & van Ballegooijen 2003; Gary & Nishimura 2004

- so long as $\omega \lesssim \Omega_i$
  - no cyclotron resonance
  - magnetic moment $\mu \propto T_\perp/B$ is conserved
  - $\rightarrow$ heating can only increase $T_{||}$
- cyclotron damping is strongly suppressed at $k_\perp \rho_i \gtrsim 1$

  $\rightarrow$ for cycl. damping to be impt, $\omega \rightarrow \Omega_i$ at $k_\perp \rho_i \lesssim 1$

Collisionless Damping of the Anisotropic Cascade

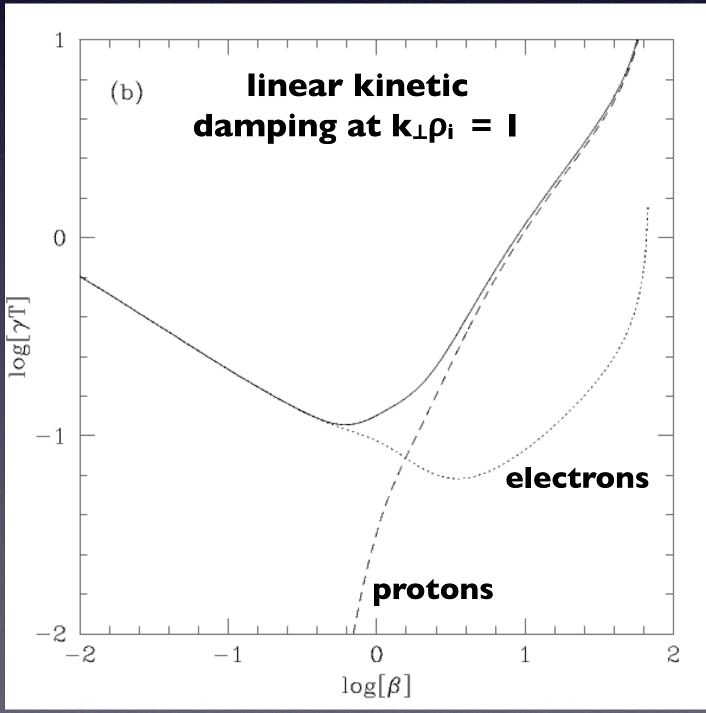
Quataert 1998; Leamon et al. 1998; Quataert & Gruzinov 1999; Cranmer & van Ballegooijen 2003; Gary & Nishimura 2004

- parallel heating via the Landau resonance: $\omega = k_{||} v_{||}$
  - both Landau damping ($\delta E_{||}$) & transit-time damping ($\delta B_{||}$)
    $\beta \lesssim 1$ $\beta \gtrsim 1$

- ***primarily e^- heating for $\beta \lesssim 10$***
  - dominant source of e^- heating

    in solar wind (?); consistent with

    $T_e \gtrsim T_p$ in slow wind



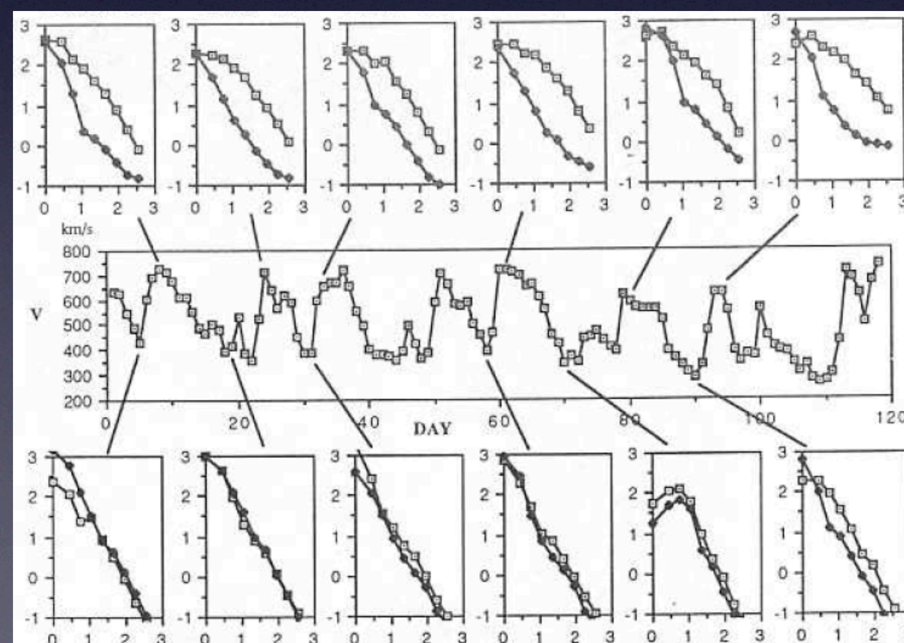
The Puzzle ...

- How to get $T_{ion} \gtrsim T_p \gtrsim T_e$ & $T_{\perp,i} \gtrsim T_{||,i}$? (Fast Wind)
  - Outer scale << Assumed Values (unlikely ...?); Coupling of KAWs to Ion Bernstein, fast waves (unlikely)

$$\mathrm{at}\ \mathbf{k}_\perp \rho_i \simeq 1,\ \frac{\omega}{\Omega_i} \simeq \left(\frac{\rho_i}{L}\right)^{1/3} \beta_i^{-1/2} \quad L \equiv \text{outer scale of turbulence}$$

  - Fast Waves Cascade to High Frequencies for β << 1 (Chandran '05)
    - but Alfvenic fluctuations dominate at ~ AU ...
  - Imbalanced Turbulence?
    - anisotropy is the same
    - cascade slows down

→ ***less*** likely to reach ~ Ω_i

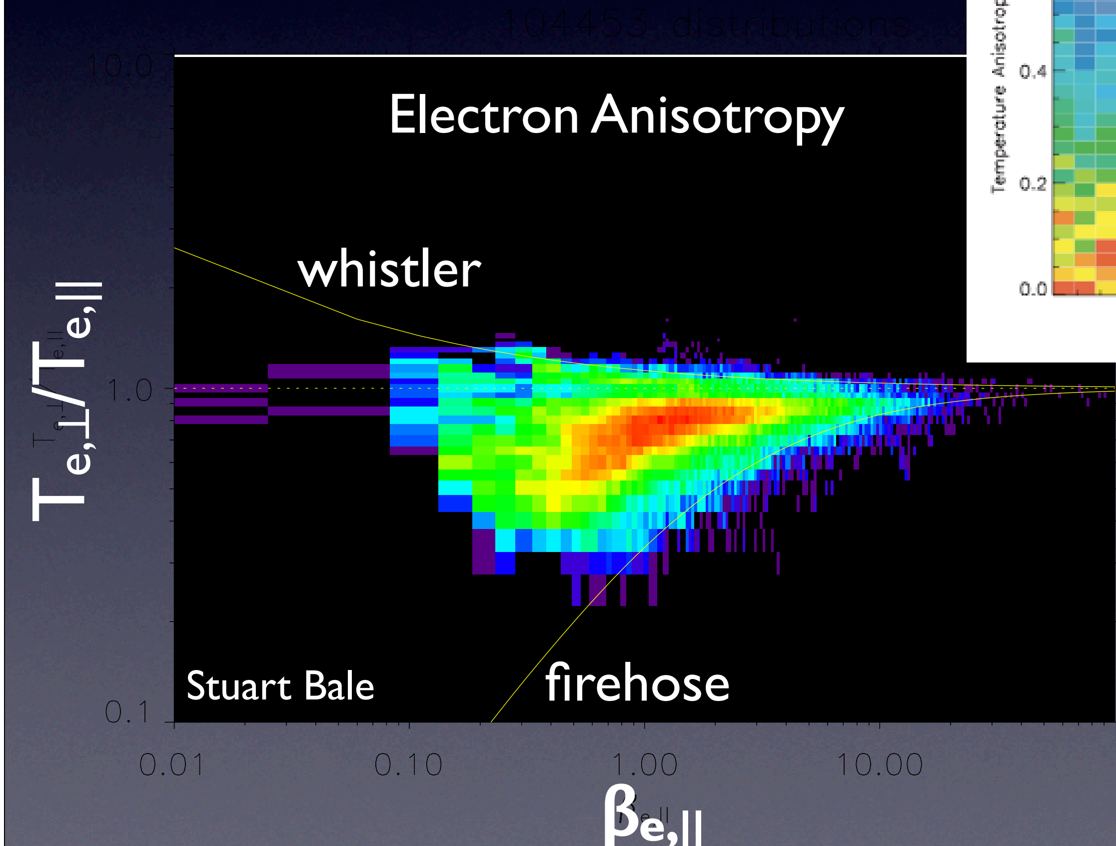


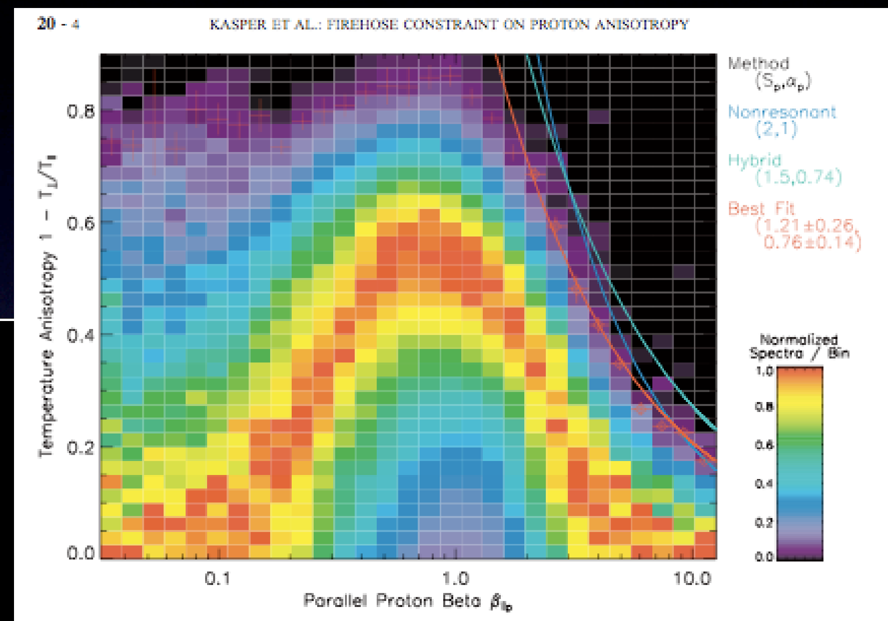
Grappin et al. 1990

The Puzzle ...

- How to get $T_{ion} \gtrsim T_p \gtrsim T_e$ & $T_{\perp,i} \gtrsim T_{||,i}$? (Fast Wind)
  - Imbalanced Turbulence: cascade slows down
    - other non-linearities impt?
    - e.g., Alfven waves steepen on a timescale $\sim \omega_{lin}^{-1} \, (B/\delta B)^2$
  - Secondary Instabilities
    - electron-ion: $T_e \rightarrow T_i$ (e.g., e- beams)
      Cranmer & van Ballegooijen 2003; Gary & Nishimura 2004
    - velocity space: $T_\perp \leftrightarrow T_{||}$

Velocity-Space Instabilities





proton || anisotropy limited by firehose

Kasper et al. 2002

Summary

- Alfvenic Turbulence is the Most Promising Source of Heating in the Extended Corona and Solar Wind
- Strong MHD Turbulence (Alfvenic)
  - ✓ Anisotropic Kolmogorov Turbulence: $\mathrm{critical\ balance} \rightarrow k_{\|} \propto k_{\perp}^{2/3}$
  - ✓ $k_{\perp}\rho_i \sim 1$: Alfven Wave Cascade → Kinetic Alfven Wave Cascade
    - ***NOT*** cyclotron damping: $\omega \sim 0.03\text{-}0.2\ \Omega_i$ even at $k_{\perp}\rho_i \sim 1$
    - Confirmed by Cluster Electric Field Measurements
  - KAW Cascade → Electron || Heating at $k_{\perp}\rho_i \sim 0.3\text{-}10$ ($\beta \sim 10^{-3}\text{-}1$)
- Puzzle: $T_{ion} \gtrsim T_p \gtrsim T_e$ & $T_{\perp,i} \gtrsim T_{\|,i}$ (Fast Wind)
  - Smaller Outer Scale? Fast Waves? Secondary Instabilities? Addtl non-linearities? Sweep + Cascade in ω? ...