Temperature anisotropy in the solar wind

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Solar wind

Solar wind

- weak collisions
- temperature anisotropies $T_\| \neq T_\perp$
- particle beams/drifting populations
- signatures of wave-particle interactions
- signatures of kinetic instabilities
- important wave activity/turbulence

Instabilities driven by $T_{\|s} \neq T_{\perp s}$

Linear Vlasov-Maxwell system in the long-wavelength, low-frequency limit

- Mirror instability with the threshold

$$\sum_s \beta_{s\perp}\left(\frac{T_{s\perp}}{T_{s\|}} - 1\right) > 1 + \frac{\left(\sum_s \rho_s \frac{T_{s\perp}}{T_{s\|}}\right)^2}{2\sum_s \frac{\rho_s^2}{\beta_{s\|}}}$$

  different from MHD-CGL prediction

- Fire hose instabilities with the threshold

$$\beta_{\|} - \beta_{\perp} > 2$$

  as in MHD-CGL

Full linear Vlasov-Maxwell system

$T_{\|p} < T_{\perp p}$

Proton cyclotron instability

- LH circular polarization
- cyclotron resonance
- $\Re\omega \lesssim \omega_{cp}$
- wavelengths $\sim c/\omega_{pp}$

Mirror instability

- linear polarization $\delta\boldsymbol{B} \cdot \boldsymbol{B}_0 \neq 0$
- Landau resonance
- $\Re\omega = 0$
- threshold for $k \to 0$

$T_{\|p} > T_{\perp p}$

Parallel fire hose

- RH circular polarization
- anomalous cyclotron resonance
- $\Re\omega \sim \omega_{cp}$
- wavelengths $\sim c/\omega_{pp}$

Oblique fire hose

- linear polarization $\delta\boldsymbol{B} \perp \boldsymbol{B}_0$
- both cyclotron resonances
- $\Re\omega = 0$
- wavelengths $\sim c/\omega_{pp}$

Both fire hoses unstable even for $\beta_{\|} - \beta_{\perp} < 2$

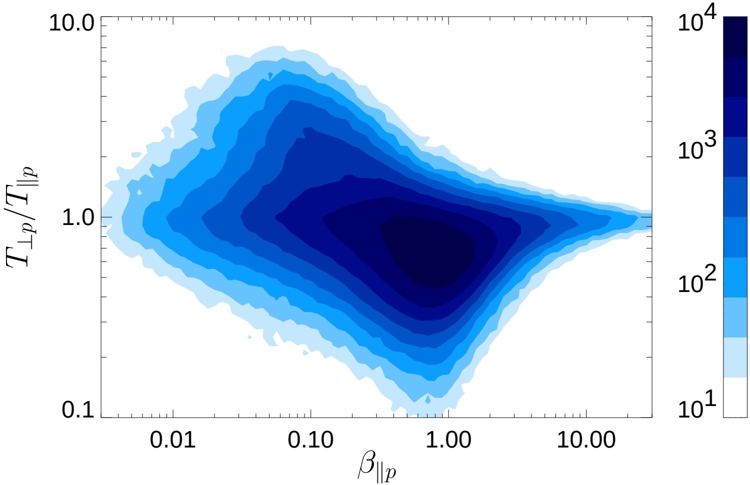
WIND/SWE observations

Wind spacecraft, 1995–2001

- two Faraday Cup instruments in the Solar Wind Experiment (*Kasper et al.*, 2002; 2006)
- + Magnetic Field Experiment
- non-linear least-squares fitting – assuming bi-Maxwellian (core) proton distribution function
    - proton density
    - proton temperatures $T_{\|p}$ and $T_{\perp p}$
    - parallel beta $\beta_{\|p}$

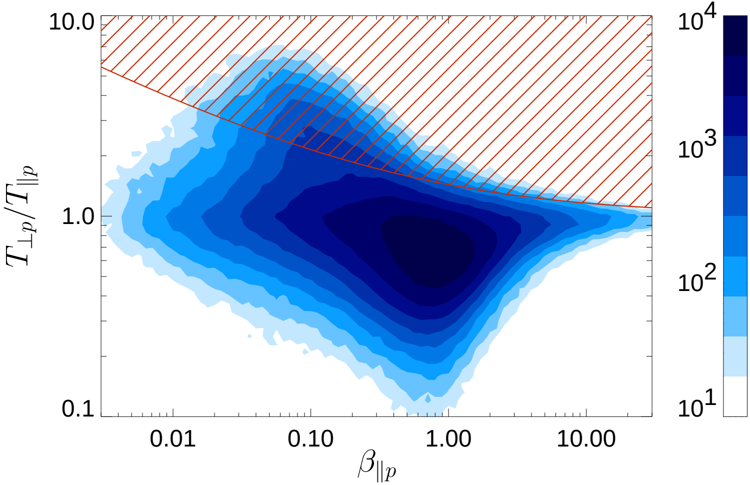
Slow solar wind proton anisotropy at 1 AU

WIND/SWE data $v_{sw} < 600$ km/s



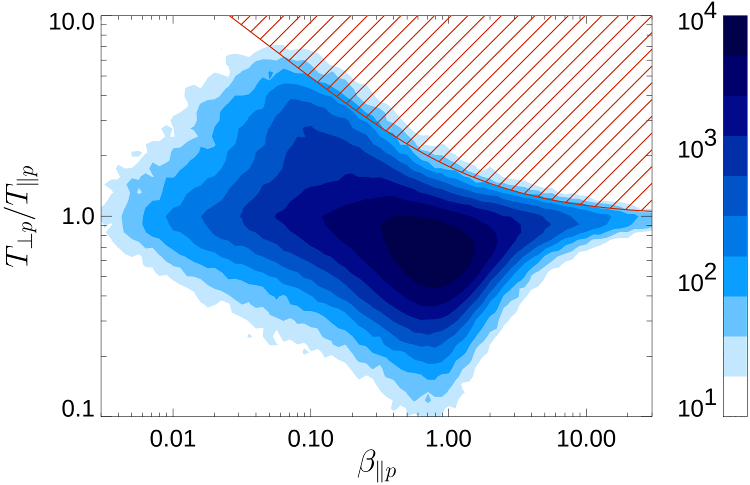
Slow solar wind vs linear theory I

Proton cyclotron instability ($\gamma_{\max} \geq 10^{-3}\omega_{cp}$)



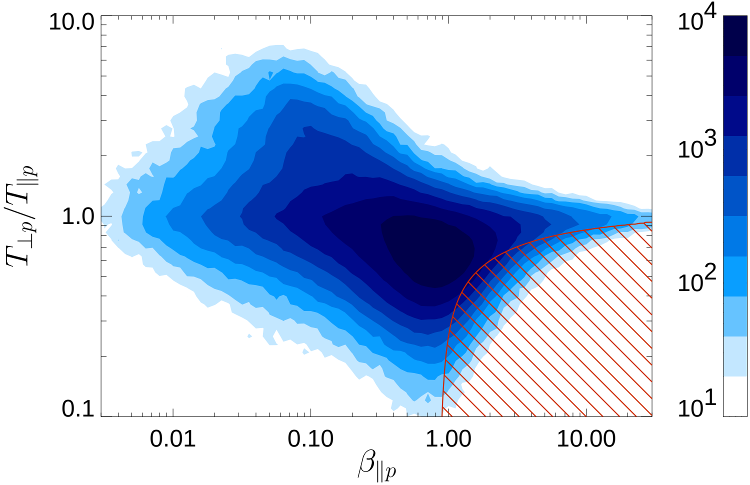
Slow solar wind vs linear theory II

Mirror instability ($\gamma_{\max} \geq 10^{-3}\omega_{cp}$)



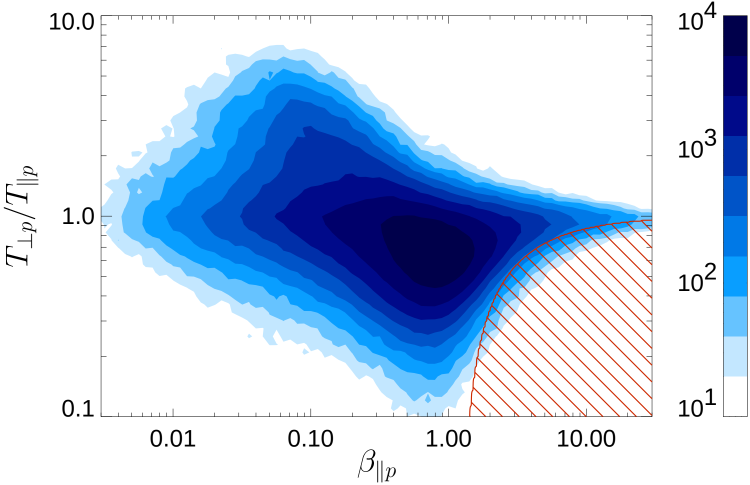
Slow solar wind vs linear theory III

Parallel fire hose ($\gamma_{\max} \geq 10^{-3}\omega_{cp}$)



Slow solar wind vs linear theory IV

Oblique fire hose ($\gamma_{\max} \geq 10^{-3}\omega_{cp}$)



Comparison

Linear theory:

- Dominant proton cyclotron instability for $T_{\|p} < T_{\perp p}$
- Dominant parallel fire hose for $T_{\|p} > T_{\perp p}$

WIND/SWE Observations – Slow solar wind:

- Constrained by the mirror instability for $T_{\|p} < T_{\perp p}$?
- Constrained by the oblique fire hose for $T_{\|p} > T_{\perp p}$?

Discussion

Limitations

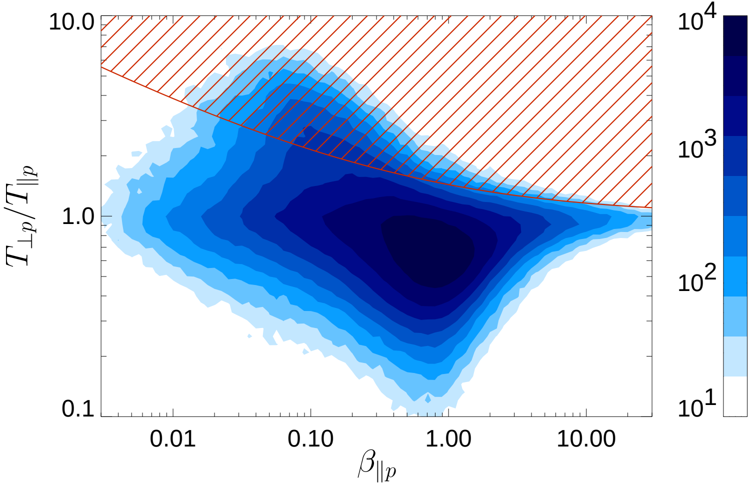
- Linear theory assumes
  - bi-Maxwellian protons
  - homogeneous, stationary medium
  - no waves

- Observations:
  - often proton core/beam distributions
  - alpha particles and other minor ions
  - important turbulence/wave activity
  - shell/quasilinear plateau distributions
  - expanding solar wind

+ nonlinear effects? $\rightarrow$ numerical simulations

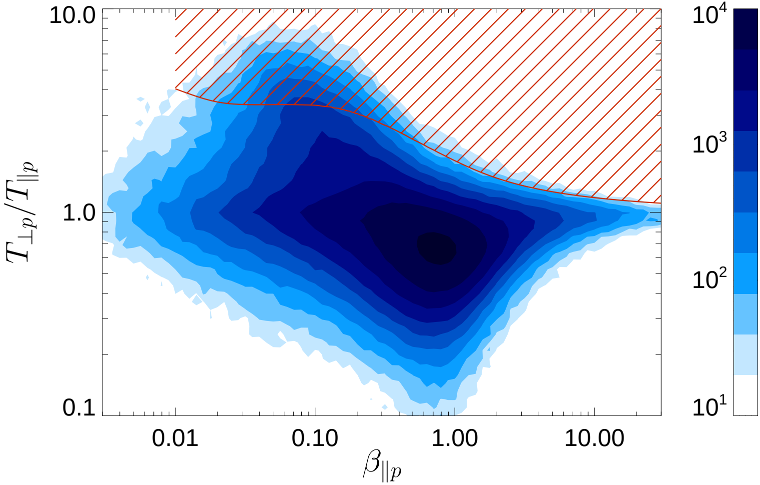
Alpha particles and cyclotron instabilities

Proton cyclotron instability ($\gamma_{\max} \geq 10^{-3}\omega_{cp}$)



Alpha particles and cyclotron instabilities

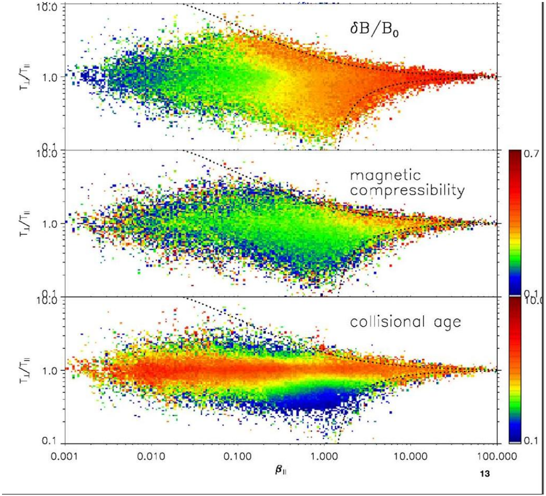
5 % of alpha particles ($\gamma_{\max} \geq 10^{-3}\omega_{cp}$)



Instability driven waves?

Magnetic field fluctuations, RMS over 3 s (*Bale et al.*)

- enhancements in amplitude near the thresholds
- compressible fluctuations near the mirror threshold – evidence of the mirror mode?
- more collisional protons are more isotropic



Full linear Vlasov-Maxwell system

$T_{\|e} < T_{\perp e}$

Whistler instability

- RH circular polarization
- cyclotron resonance
- $\Re\omega \lesssim \omega_{ce}$
- wavelengths $\sim c/\omega_{pe}$

Mirror instability

- linear polarization $\delta\boldsymbol{B}\cdot\boldsymbol{B}_0 \neq 0$
- Landau resonance
- $\Re\omega = 0$
- threshold for $k \to 0$

$T_{\|e} > T_{\perp e}$

(Quasi-)parallel fire hose

- LH circular polarization
- non-resonant
- $\gamma \sim \omega_{cp}$
- wavelengths $\sim c/\omega_{pe}$

Oblique fire hose

- linear polarization $\delta\boldsymbol{B} \perp \boldsymbol{B}_0$
- both cyclotron resonances
- $\Re\omega = 0$
- wavelengths $\sim c/\omega_{pe}$

Oblique fire hose unstable even for $\beta_{\|} - \beta_{\perp} < 2$

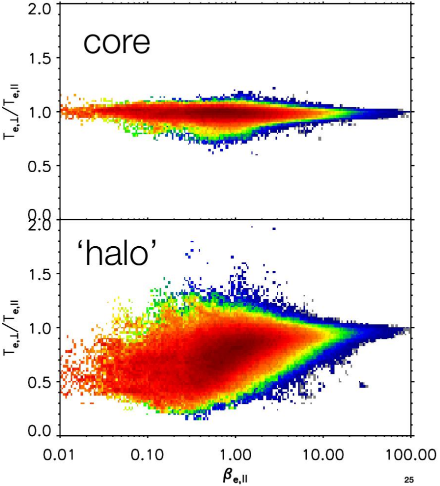
Solar wind electrons I

Solar wind electrons:

- bi-Maxwellian core
- bi-κ halo
- strahl populations

Wind/3DP observations (*Bale et al.*)

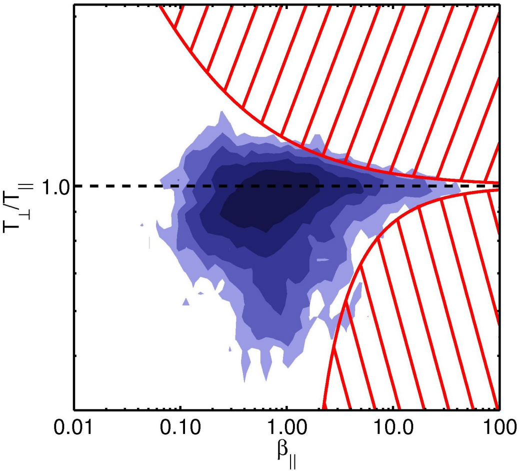
- core more isotropic
- halo – constraints by whistler and oblique fire hose instabilities



Solar wind electrons II

Helios, Cluster & Ulysses (*Štverák et al.*, 2008)

- Core electrons constrained by whistler and oblique fire hose instabilities
- Similarly for halo electrons
- role strahl?



Standard 1-D hybrid simulations

Hybrid simulation:

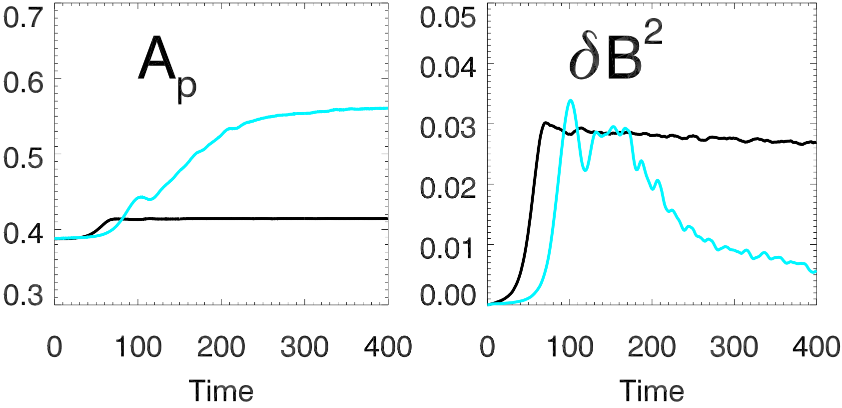
- ions – kinetic treatment (particle-in-cell method)
- electrons – massless, charge-neutralizing fluid

Nonlinear properties of the proton fire hose instabilities:

- Parallel fire hose instability
  - quasi-linear saturation
  - weak reduction of temperature anisotropy
- Oblique fire hose instability
  - self-destructive evolution
  - inverse cascade of Alfvénic fluctuations
  - strong reduction of temperature anisotropy

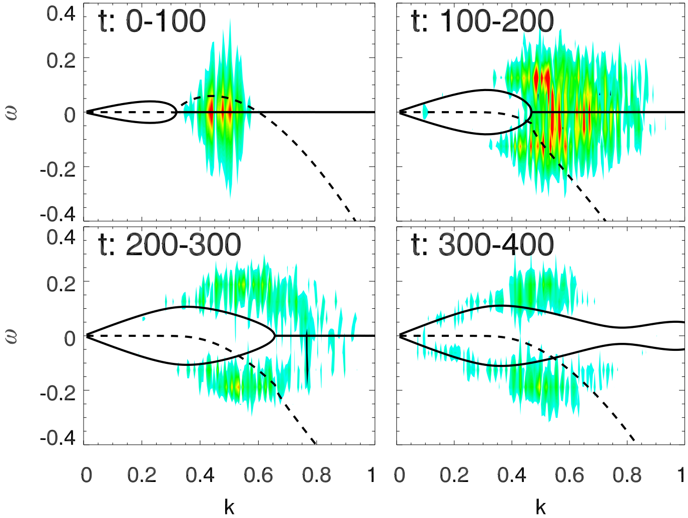
1-D hybrid simulations, $\beta_{p\parallel} = 2.8$

Evolution of $A_p = T_{p\perp}/T_{p\parallel}$ and δB^2



1-D hybrid simulations

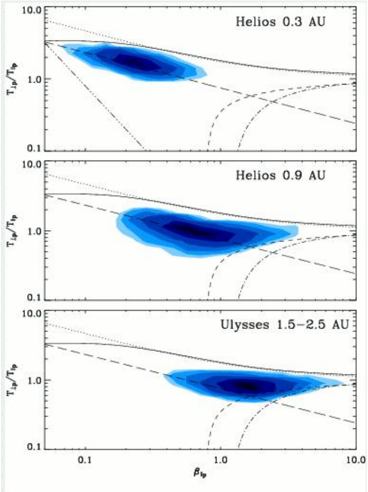
Evolution of oblique fire hose



Radial evolution in the solar wind

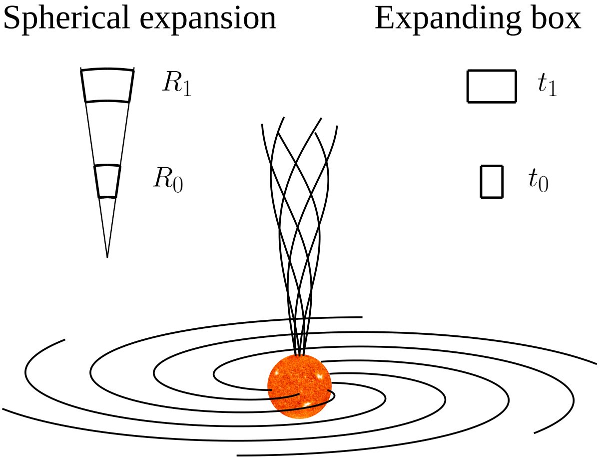
Expansion – fast solar wind (*Matteini et al.*, 2007)

- $T_{p\perp}/T_{p\|}$ decreases and $\beta_{p\|}$ increases with the distance
- evolution is not CGL
- a signature of the cyclotron heating?
- Coulomb collisions
- at larger distances controlled by fire hose instabilities



Expanding box model

Schematic view – spatial vs temporal:



Hybrid expanding box model

Solar wind expansion

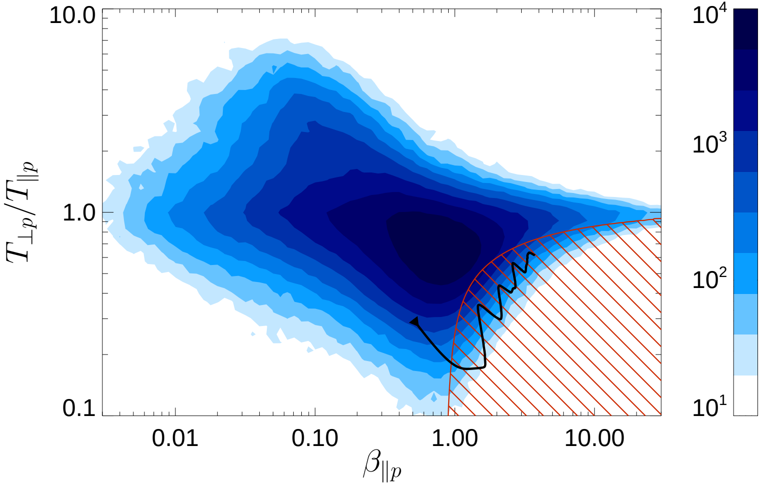
- assuming a constant solar wind velocity
- transverse scale expands linearly with time
- hybrid approximation, kinetic ions & fluid electrons

Slow expansion

- CGL evolution when no wave activity is present
- low frequency waves follow WKB
- natural generation of temperature anisotropy
- self-consistent competition between the expansion and instabilities.

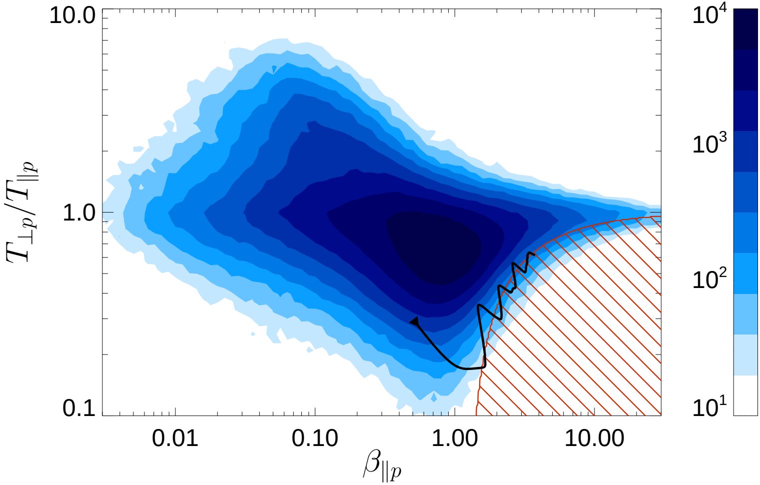
2-D Hybrid Expanding Box Simulation I

Expansion vs the parallel fire hose (cf., *Matteini et al., 2006*)



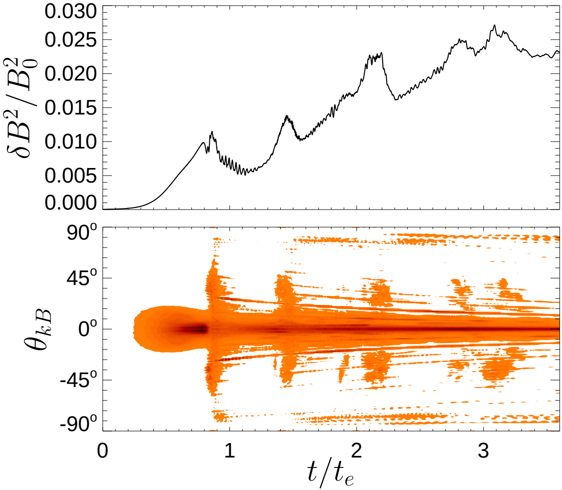
2-D Hybrid Expanding Box Simulation II

Expansion vs the oblique fire hose (*Hellinger & Travnicek, 2008*)



2-D Hybrid Expanding Box Simulation III

Evolution of wave energy



Summary

Proton temperature anisotropy

- constrained by mirror and proton cyclotron instabilities
- constrained by both fire hose instabilities.
- oblique fire hose sets the final frontier for the anisotropy
- signatures of generated waves.
- Simulation results explain the apparent discrepancy between the linear prediction and WIND/SWE observations.

Electron temperature anisotropy

- constrained by whistler and oblique fire hose instability
- observation of generated waves?