Proton fire hose instabilities in the expanding solar wind

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Solar wind

Solar wind ions:

- Weak collisions
- Non Maxwellian distribution functions
- Temperature anisotropies $T_{\|} \neq T_{\perp}$
- 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 $T_{\|p} < T_{\perp p}$

Parallel proton cyclotron instability

- left handed circular polarization
- cyclotron resonance
- $\Re\omega \lesssim \omega_{cp}$

Oblique mirror instability

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

Full linear Vlasov-Maxwell system $T_{\|p} > T_{\perp p}$

Parallel fire hose

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

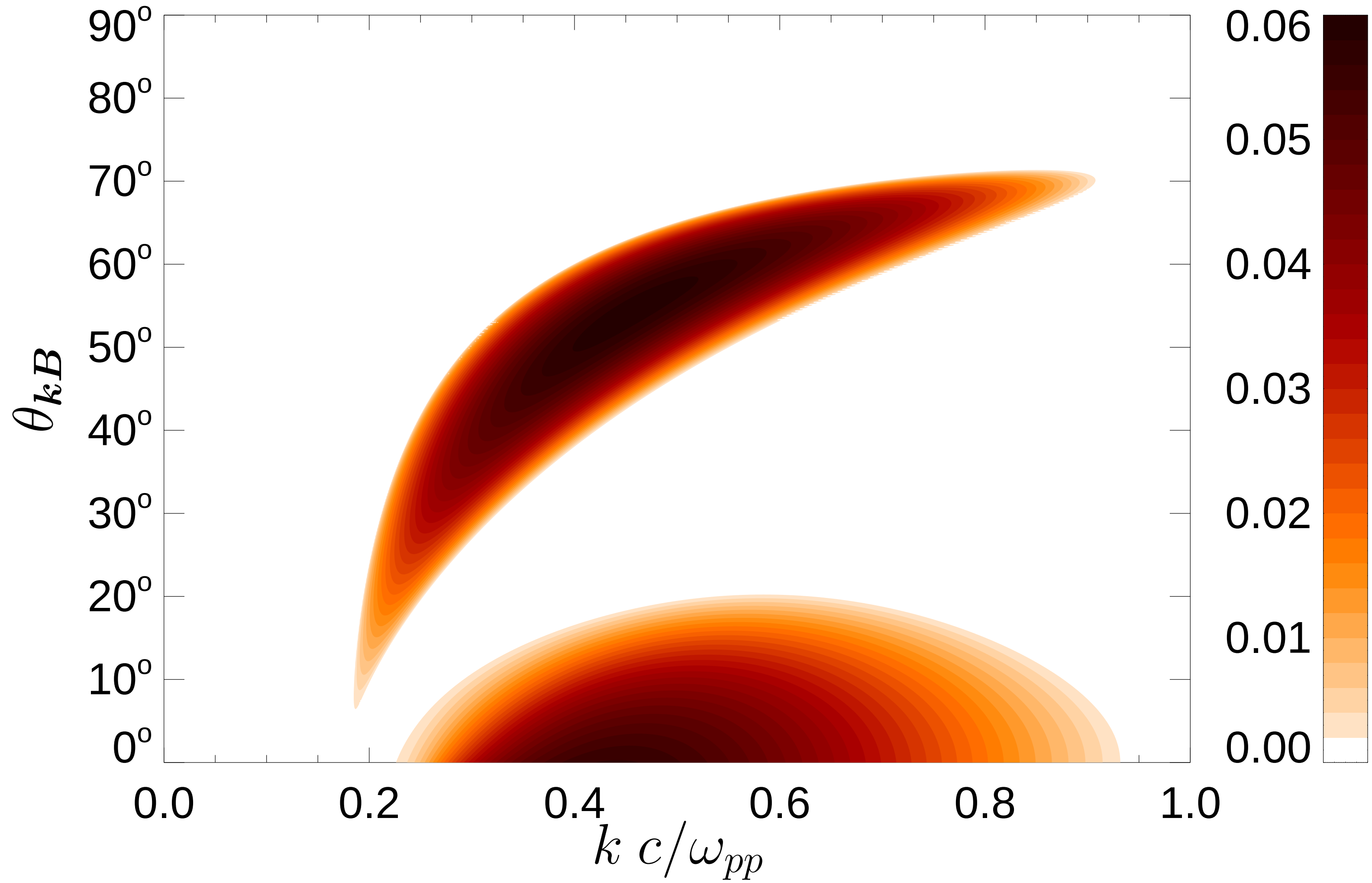
Oblique fire hose

- 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 $\beta_\| - \beta_\perp < 2$

Linear predictions ($\beta_{p\parallel} = 2.8$, $T_{p\perp}/T_{p\parallel} = 0.4$)

Unstable regions for fire hoses $\gamma = \gamma(k, \theta_{kB})$



WIND/SWE observations

Wind spacecraft, 1995–2001

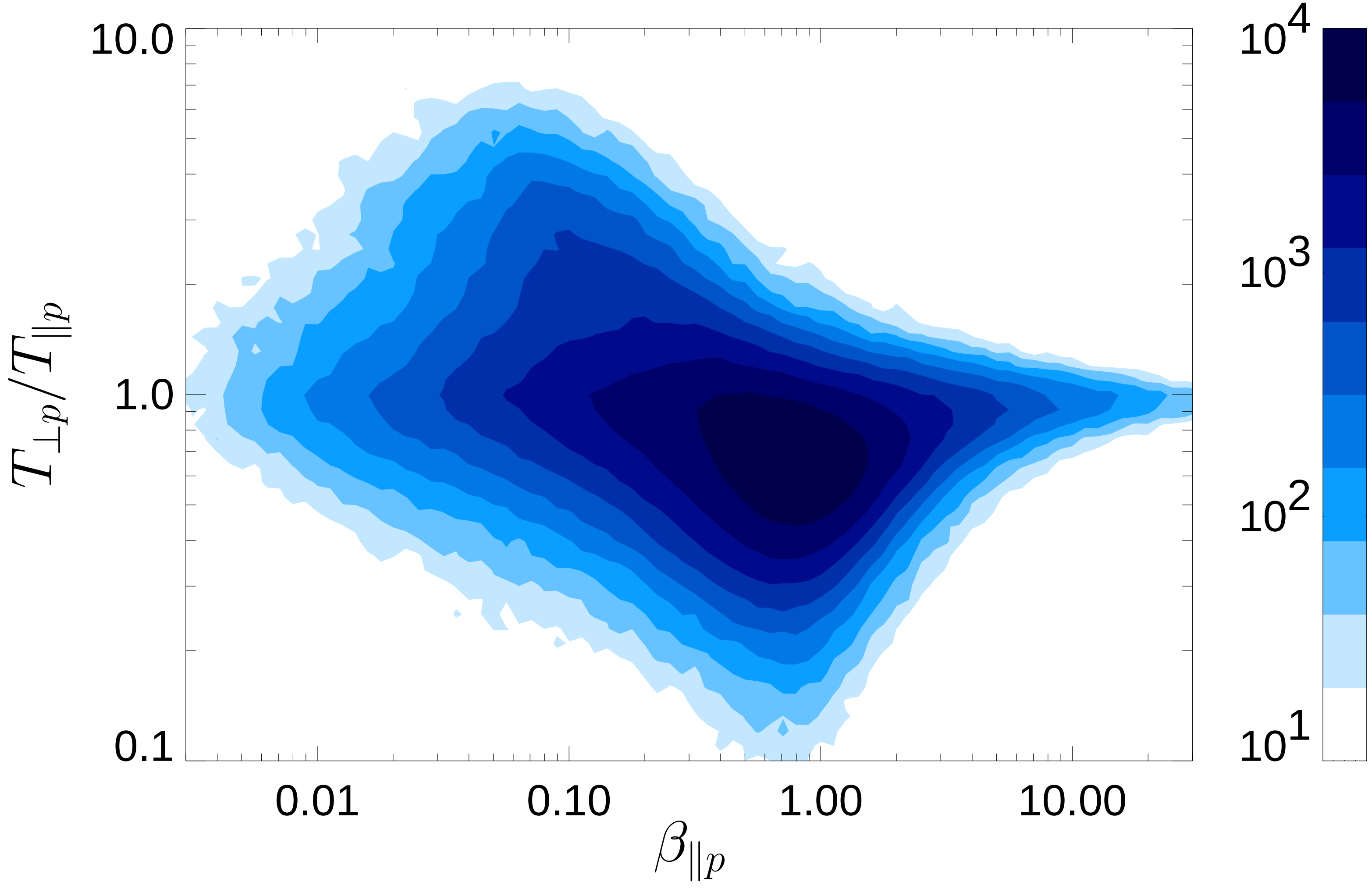
- two Faraday Cup instruments in the Solar Wind Experiment (*Kasper et al.*, 2002; 2006)

- + 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 $\beta_{\|p}$

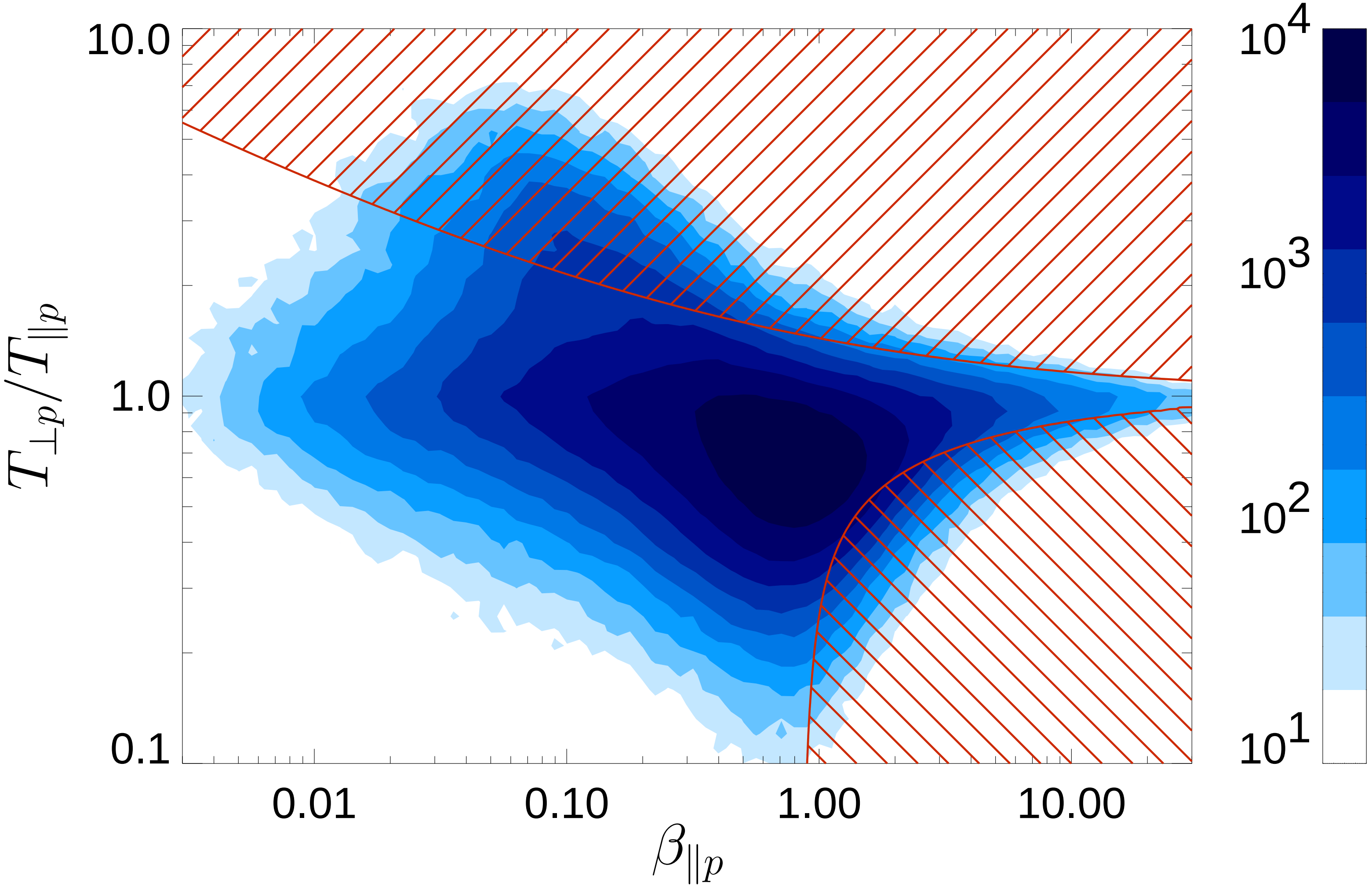
Slow solar wind proton anisotropy at 1 AU

WIND/SWE data $v_{sw} < 600$ km/s (*Hellinger et al.*, 2006):



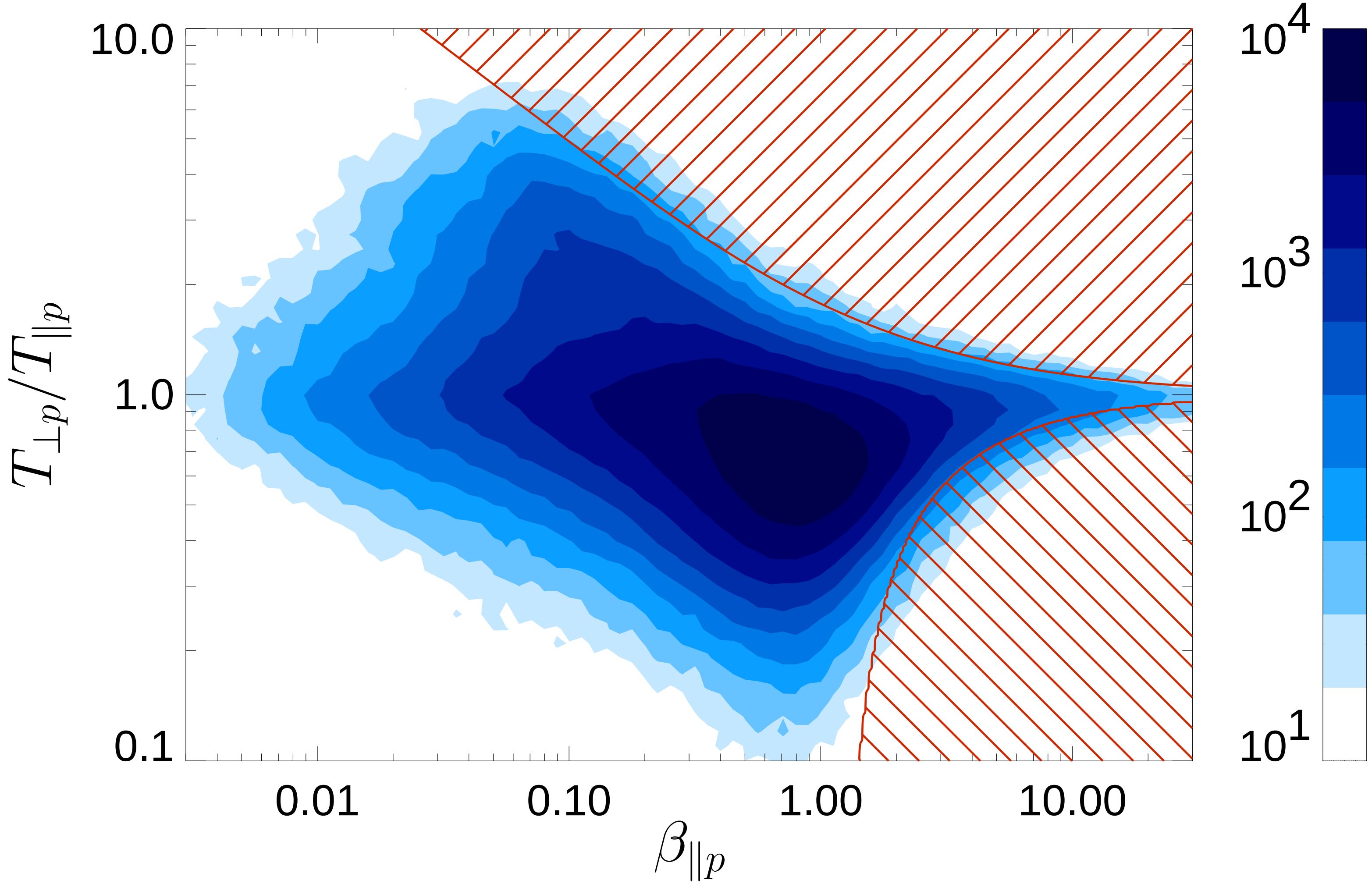
Slow solar wind vs linear theory I

Proton cyclotron & parallel fire hose $(\gamma_{\max} \geq 10^{-3}\omega_{cp})$



Slow solar wind vs linear theory II

Mirror and 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

Standard 1-D simulations

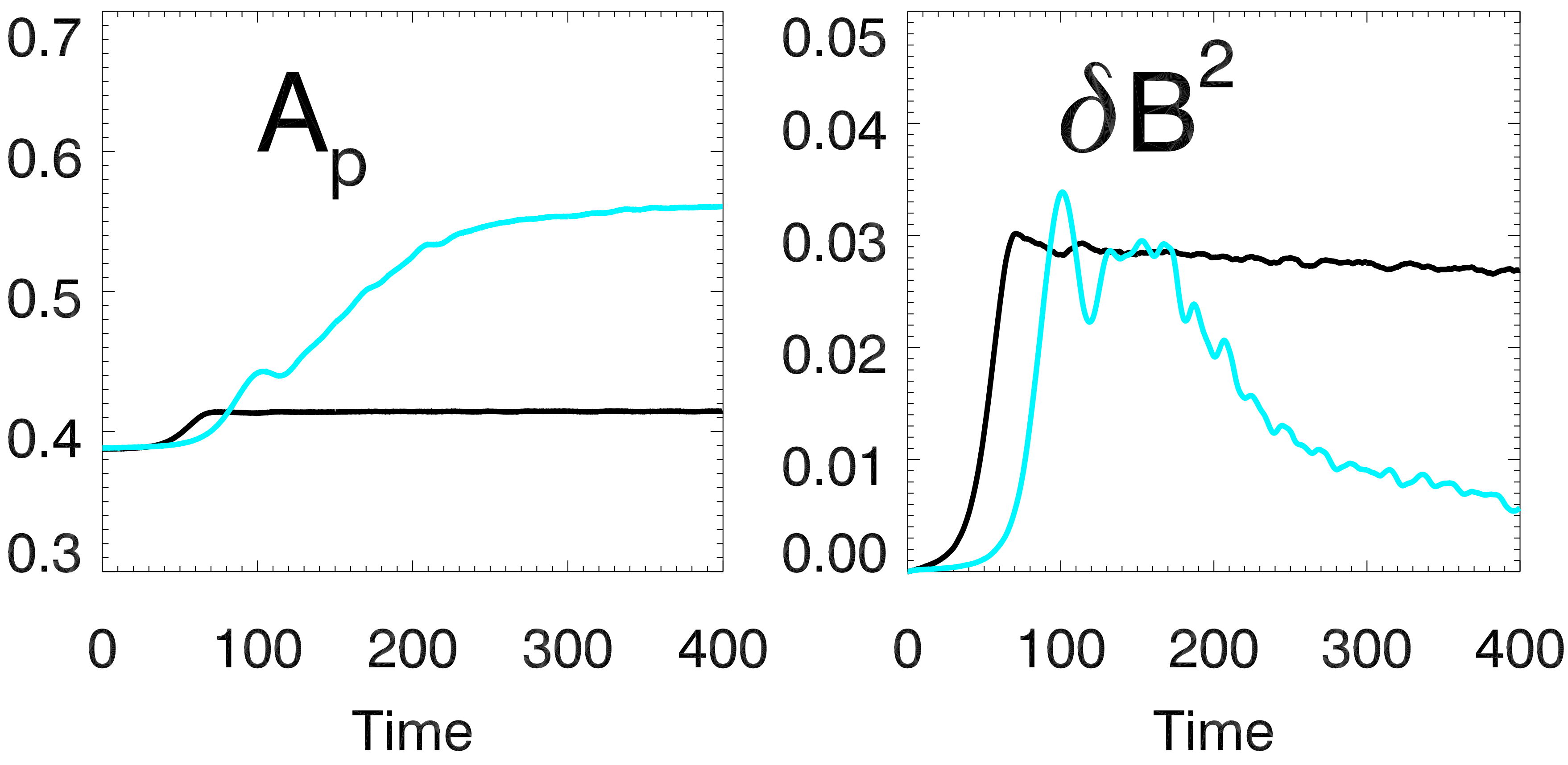
Nonlinear properties of the proton fire hose instabilities:

- 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

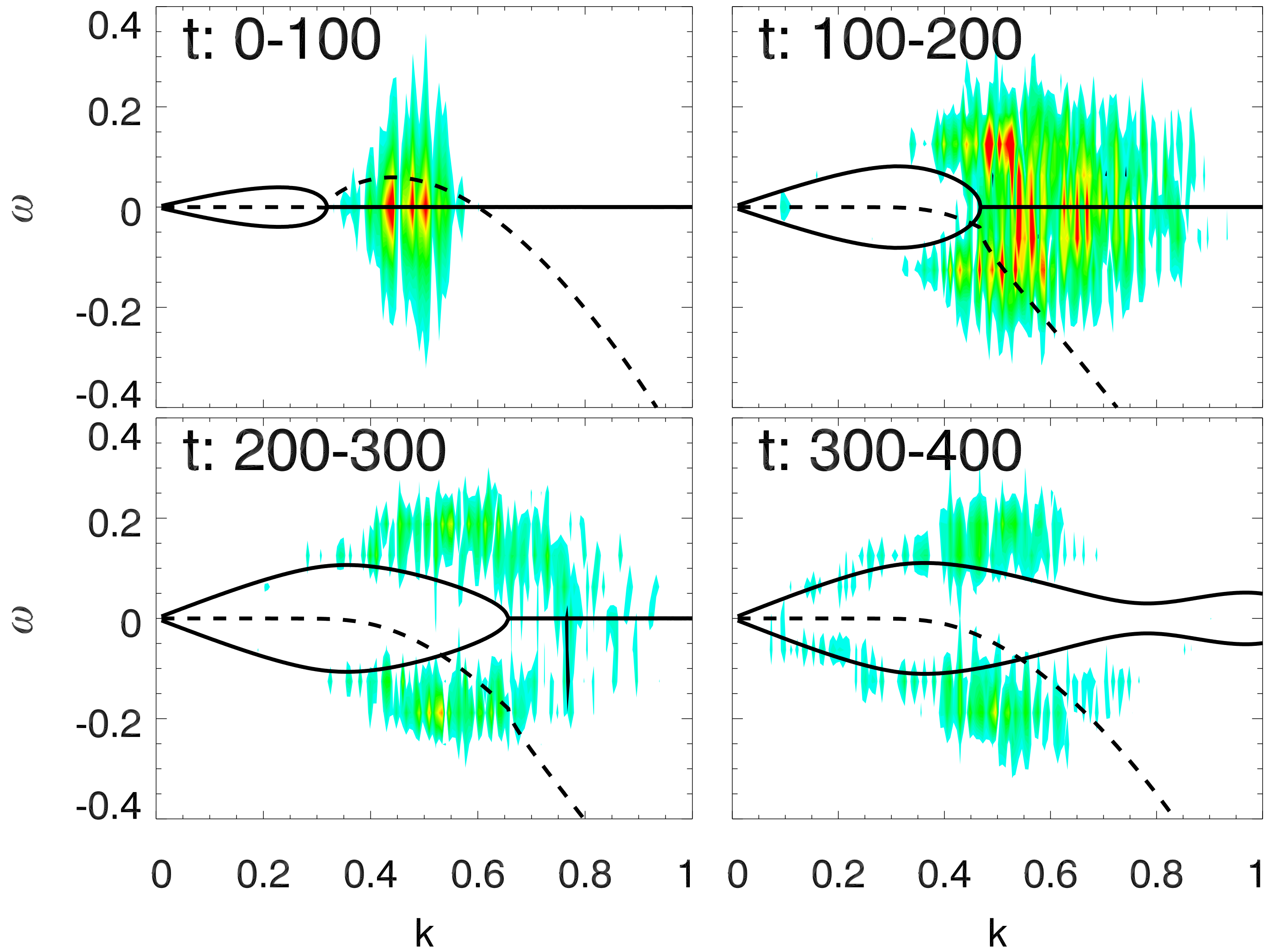
1-D hybrid simulations, $\beta_{p\parallel} = 2.8$

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



1-D hybrid simulations

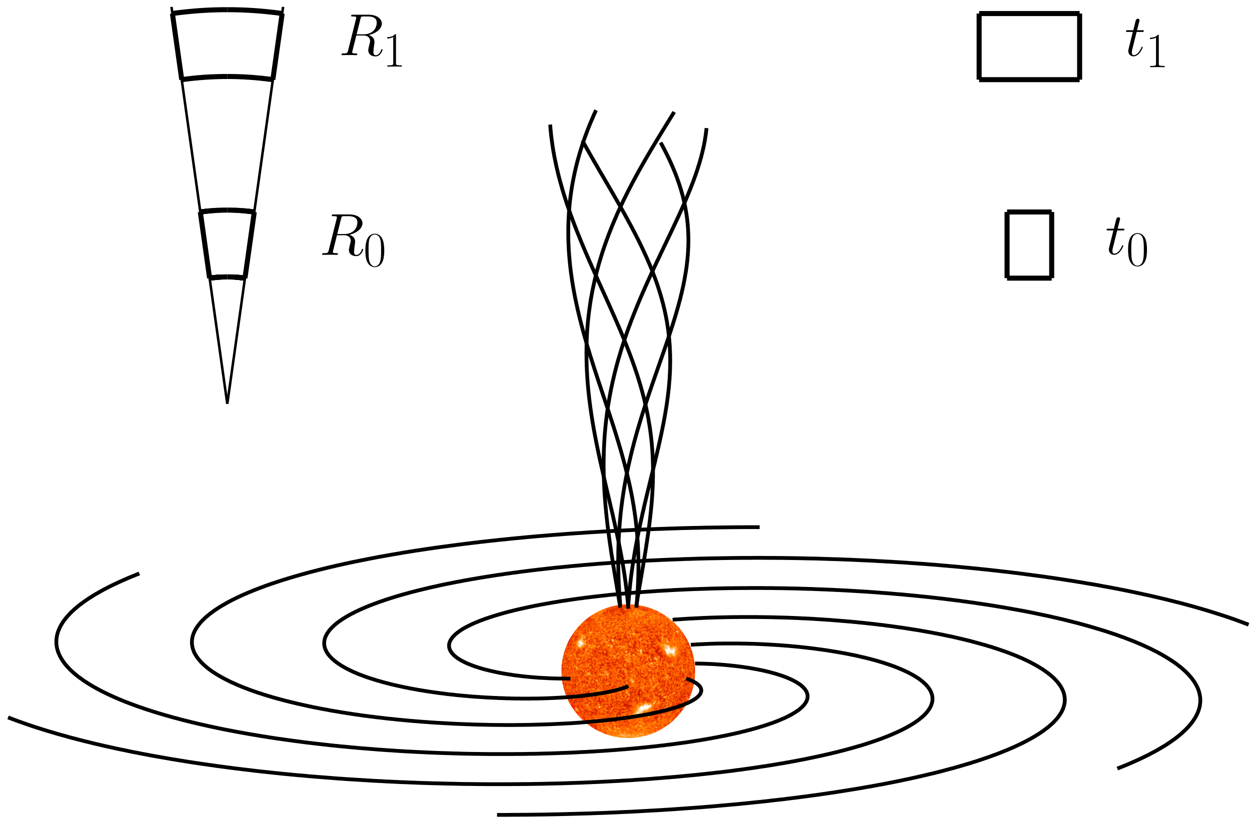
Evolution of oblique fire hose



Expanding expanding box model

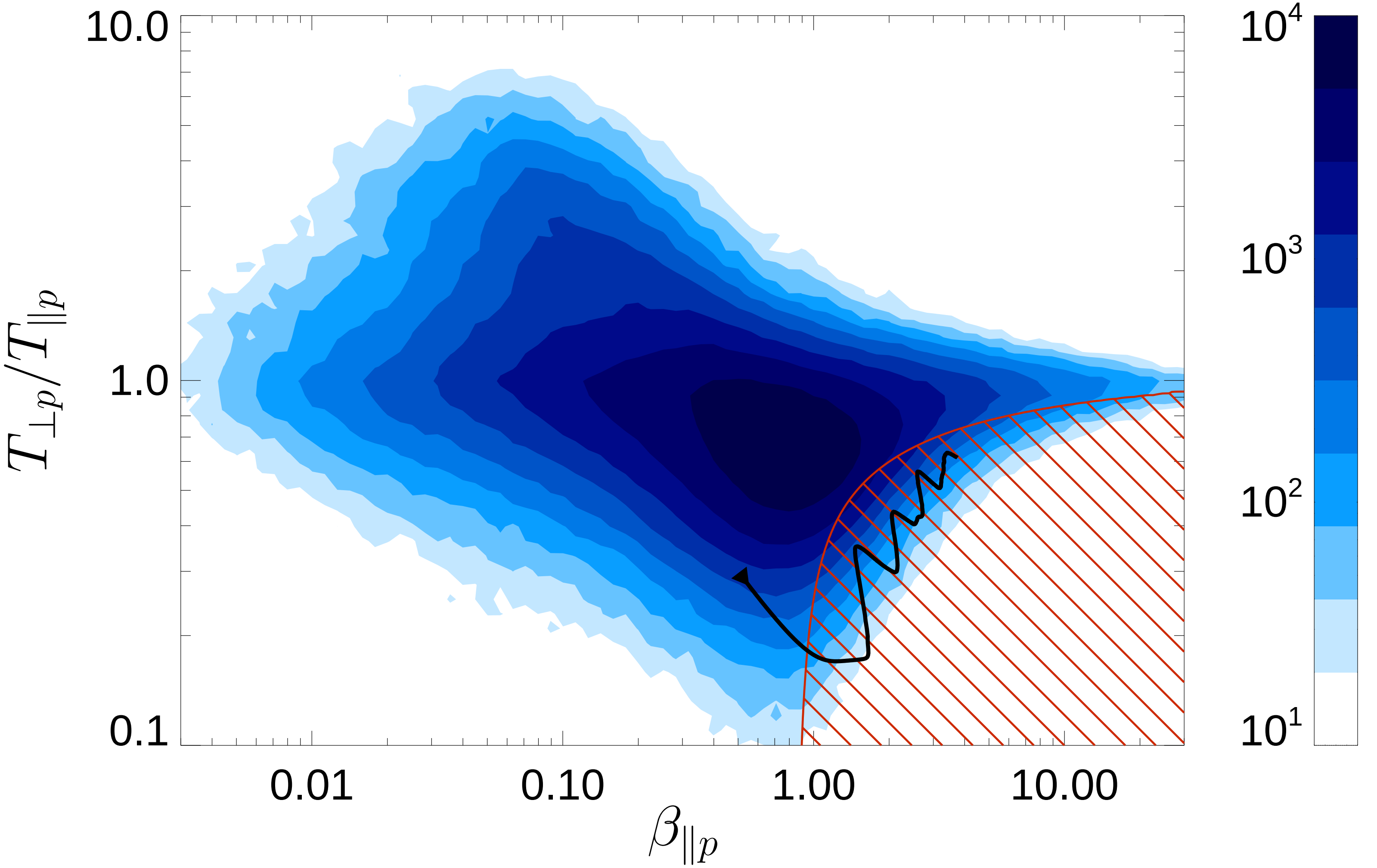
Schematic view – spatial vs temporal:

Spherical expansion Expanding box



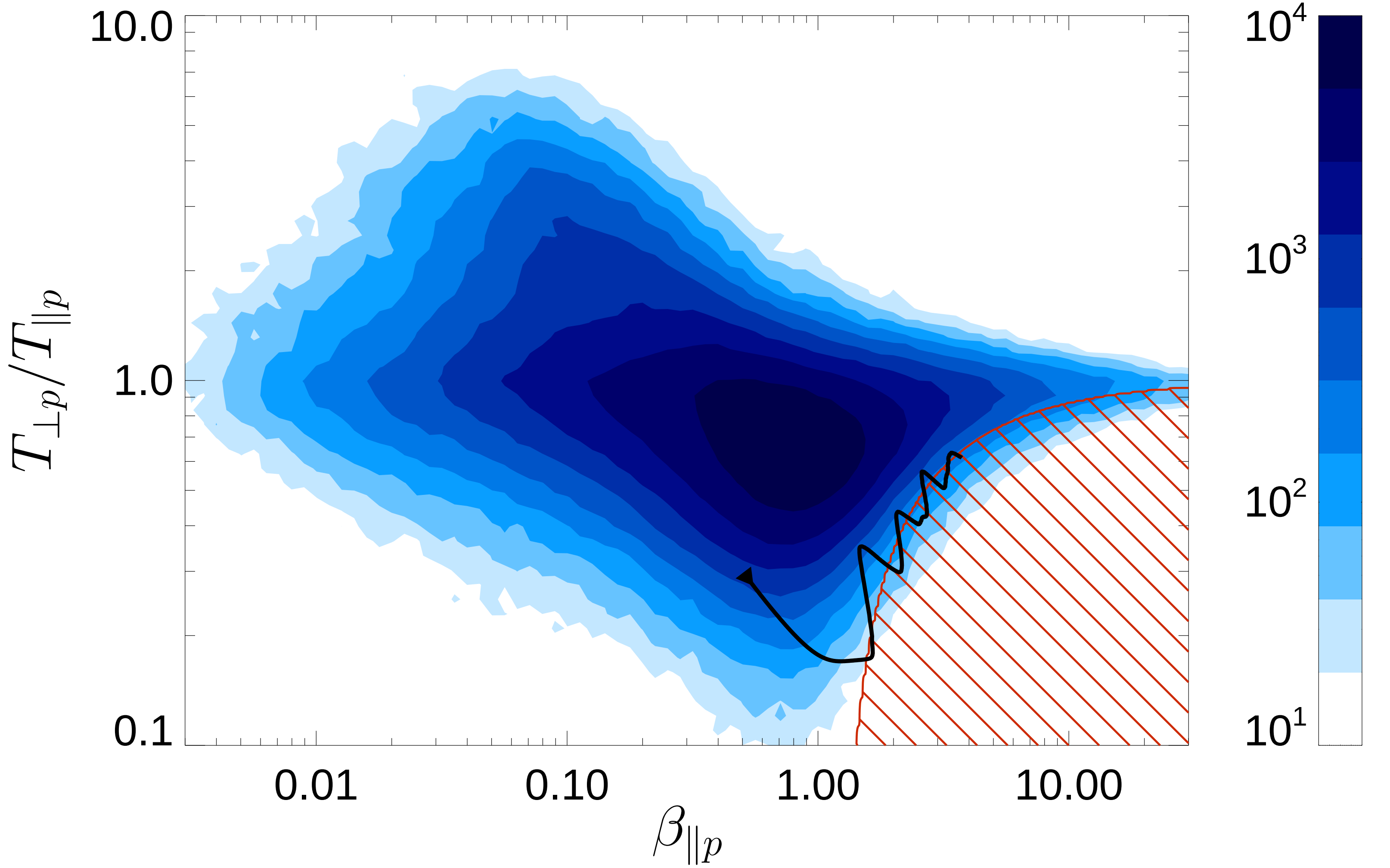
2-D Hybrid Expanding Box Simulation I

Ideal expansion versuss the parallel fire hose (cf., *Matteini et al., 2006*)



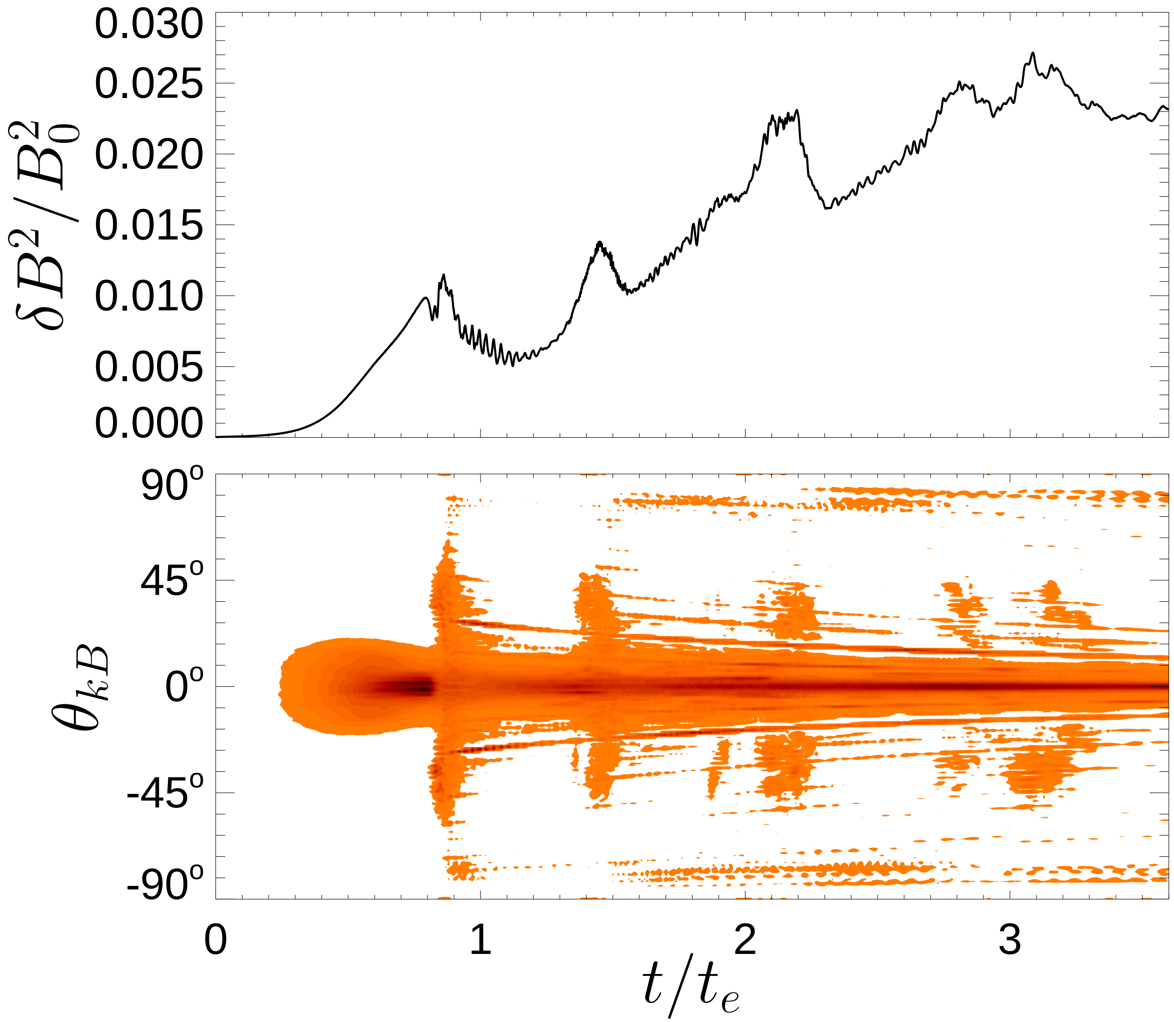
2-D Hybrid Expanding Box Simulation II

Ideal expansion versus the oblique fire hose (*Hellinger and Travnicek, 2008*)



2-D Hybrid Expanding Box Simulation III

Evolution of wave energy



Summary

Proton temperature anisotropy in the solar wind

- constrained by both fire hose instabilities.
- oblique fire hose sets the final frontier for the anisotropy

Simulation results explain the apparent discrepancy between the linear prediction and WIND/SWE observations.