Parallel cooling of protons in the solar wind

Petr Hellinger,[1] Pavel M. Trávníček,[1,2] Štěpán Štverák,[1]
Lorenzo Matteini,[3] and Marco Velli[3,4]

[1]Astronomical Inst. & Inst. of Atmospheric Physics, AS CR, Prague, Czech Republic
[2]SSL, University of Berkeley, USA
[3]Dipartimento di Fisica e Astronomia, Università degli Studi di Firenze, Italy
[4]JPL, Pasadena, USA

Turbulent Cascade in the Solar Wind, Paris/Meudon
September 18, 2012

SHOCK. SOLAR AND HELIOSPHERIC COLLISIONLESS KINETICS
SEVENTH FRAMEWORK PROGRAMME

Introduction

Proton energetics in the solar wind

- non adiabatic evolution, T decreases slower than $R^{-4/3}$
- heating rates usually estimated assuming isotropic approximation

Protons

- collisionless/weakly collisional
- temperature anisotropies $T_{\|} \neq T_{\perp}$
- non CGL evolution

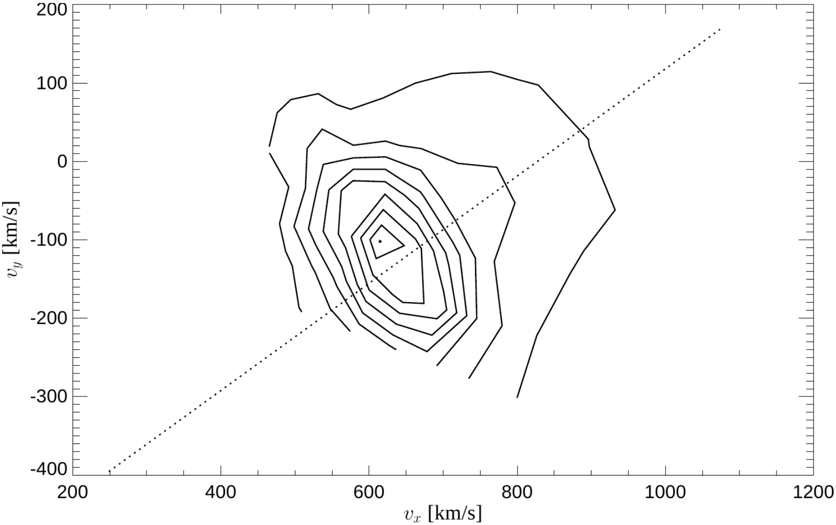
$$T_{\perp} \text{ decreases slower than } B$$

$$T_{\|} \text{ often decreases faster than } \frac{n^2}{B^2}$$

Quantification of $\|$ and $\perp$ heating/cooling rates using Helios data.

Helios 2 proton velocity distribution function

In situ proton data at 0.3 AU: anisotropic core & beam



Heating and cooling rates

Isotropic approximation:

$$Q = nk_\mathrm{B}\boldsymbol{u}\cdot\boldsymbol{\nabla}T + \frac{2}{3}nk_\mathrm{B}T\boldsymbol{\nabla}\cdot\boldsymbol{u}$$

For $T = T_0(R/R_0)^\xi$:

$$Q = \left(\frac{4}{3}+\xi\right)\frac{nk_\mathrm{B}Tv_{sw}}{R} = \left(\frac{4}{3}+\xi\right)Q_E$$

.

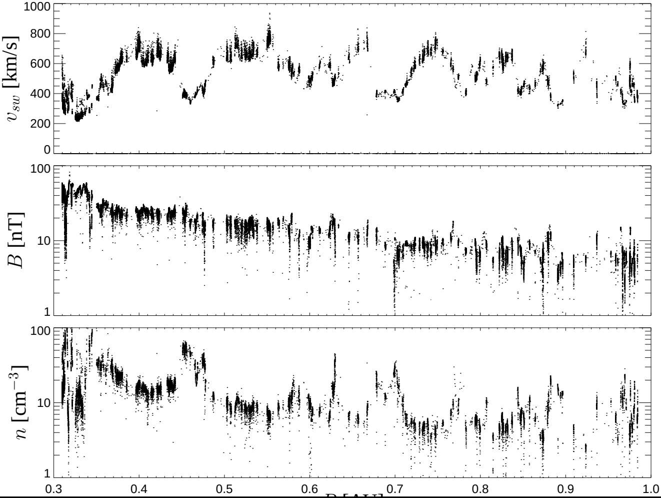
Anisotropic approximation:

$$Q_\| = nk_\mathrm{B}\left(\boldsymbol{v}_{sw}\cdot\boldsymbol{\nabla}T_\| + 2T_\|\boldsymbol{\nabla}_\|\cdot\boldsymbol{v}_{sw}\right)$$
$$Q_\perp = nk_\mathrm{B}\left(\boldsymbol{v}_{sw}\cdot\boldsymbol{\nabla}T_\perp + T_\perp\boldsymbol{\nabla}_\perp\cdot\boldsymbol{v}_{sw}\right)$$

where $\boldsymbol{\nabla}_\| = \boldsymbol{b}(\boldsymbol{b}\cdot\boldsymbol{\nabla})$, $\boldsymbol{\nabla}_\perp = \boldsymbol{\nabla} - \boldsymbol{\nabla}_\|$ and $\boldsymbol{b} = \boldsymbol{B}_0/|\boldsymbol{B}_0|$.
Mean heating rate $Q = (2Q_\perp + Q_\|)/3$.

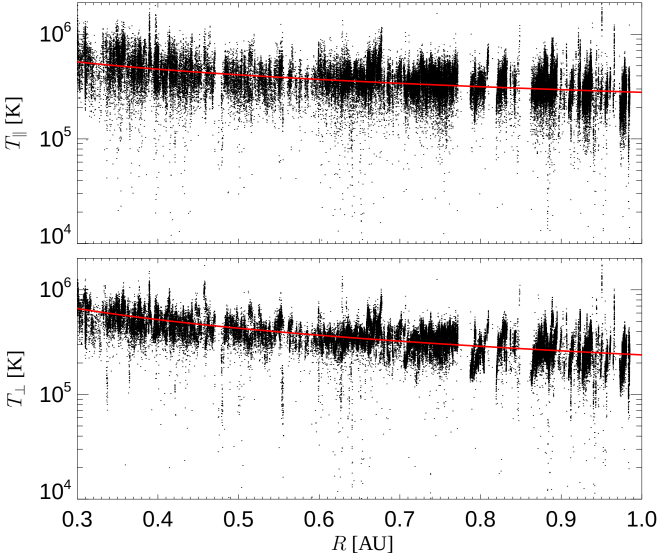
Typical radial profile (Helios 1)

v_{sw}, B, and n as a function of R (a part of the trajectory).

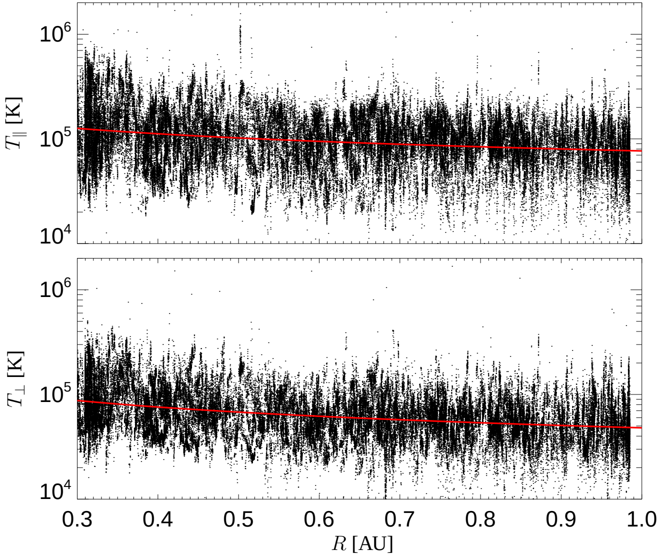


Temperatures (Helios 1 & 2), $v_{sw} > 600$ km/s

Radial profiles of $T_{\|}$ and $T_{\perp}$



Radial profiles of $T_{\|}$ and $T_{\perp}$



Fitted results

Fast SW	**Slow SW**
$v_{sw} > 600$ km/s	$v_{sw} < 400$ km/s
$B \simeq 5.8\,(R/\mathrm{AU})^{-1.6}$ nT	$B \simeq 5.5\,(R/\mathrm{AU})^{-1.5}$ nT
$n \simeq 2.8\,(R/\mathrm{AU})^{-1.8}$ cm^{-3}	$n \simeq 7.8\,(R/\mathrm{AU})^{-2.1}$ cm^{-3}
$T_\parallel \simeq 2.7 \cdot 10^5 (R/\mathrm{AU})^{-0.54}$ K	$T_\parallel \simeq 7.7 \cdot 10^4 (R/\mathrm{AU})^{-0.41}$ K
$T_\perp \simeq 2.4 \cdot 10^5 (R/\mathrm{AU})^{-0.83}$ K	$T_\perp \simeq 4.8 \cdot 10^4 (R/\mathrm{AU})^{-0.50}$ K

NB: Proton density decreases slower than R^{-2} in fast streams and faster than R^{-2} in slow streams.

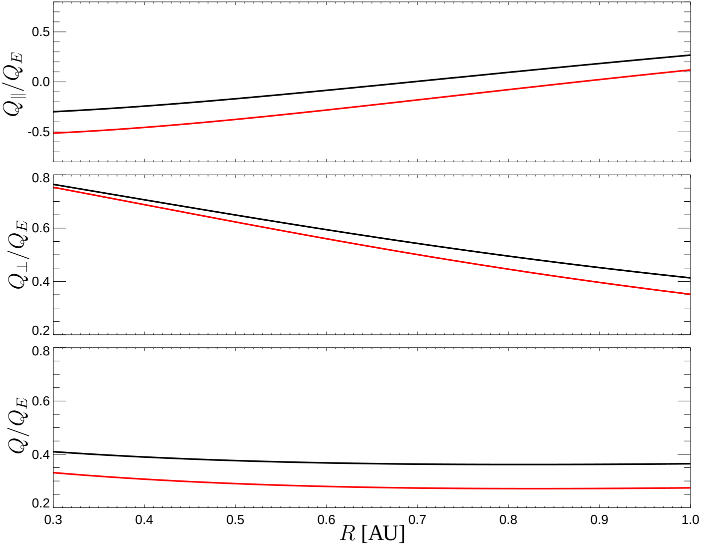
Two cases for slow and fast winds:

- constant solar wind velocity
- decelerating/accelerating solar wind

+ Parker spiral magnetic field.

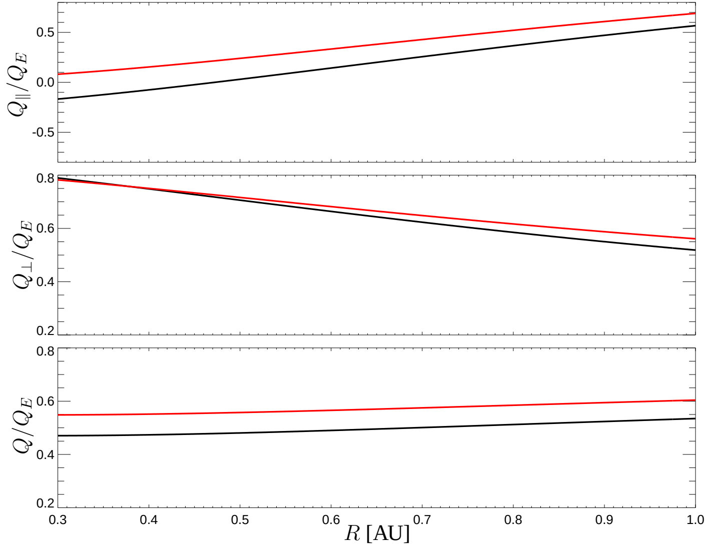
Heating rates $v_{sw} > 600$ km/s

constant v_{sw} vs decelerating wind



Heating rates $v_{sw} < 400$ km/s

constant v_{sw} vs accelerating wind



Total heating rates

Fast SW

- constant v_{sw}

$$Q \simeq 2.4 \cdot 10^{-17} (R/\mathrm{AU})^{-3.8}\ \mathrm{W/m^3}$$
$$\epsilon \simeq 7.9 \cdot 10^{3} (R/\mathrm{AU})^{-1.8}\ \mathrm{W/kg}$$

- delerating SW

$$Q \simeq 1.7 \cdot 10^{-17} (R/\mathrm{AU})^{-3.9}\ \mathrm{W/m^3}$$
$$\epsilon \simeq 5.1 \cdot 10^{3} (R/\mathrm{AU})^{-2.0}\ \mathrm{W/kg}$$

Slow SW

- constant v_{sw}

$$Q \simeq 1.2 \cdot 10^{-17} (R/\mathrm{AU})^{-3.3}\ \mathrm{W/m^3}$$
$$\epsilon \simeq 1.3 \cdot 10^{3} (R/\mathrm{AU})^{-1.3}\ \mathrm{W/kg}$$

- accelerating SW

$$Q \simeq 1.3 \cdot 10^{-17} (R/\mathrm{AU})^{-3.4}\ \mathrm{W/m^3}$$
$$\epsilon \simeq 1.5 \cdot 10^{3} (R/\mathrm{AU})^{-1.2}\ \mathrm{W/kg}$$

where $\epsilon = 3/2\ Q/(m_p n)$ is the heating rate per unit mass.

Turbulent heating rates

Kolgomoror-Yaglom law

$$\boldsymbol{\nabla} \cdot \langle \delta z^{\mp} |\delta z^{\pm}|^2 \rangle = -4\epsilon_t^{\pm}$$

MacBride et al. (2008) at 1 AU

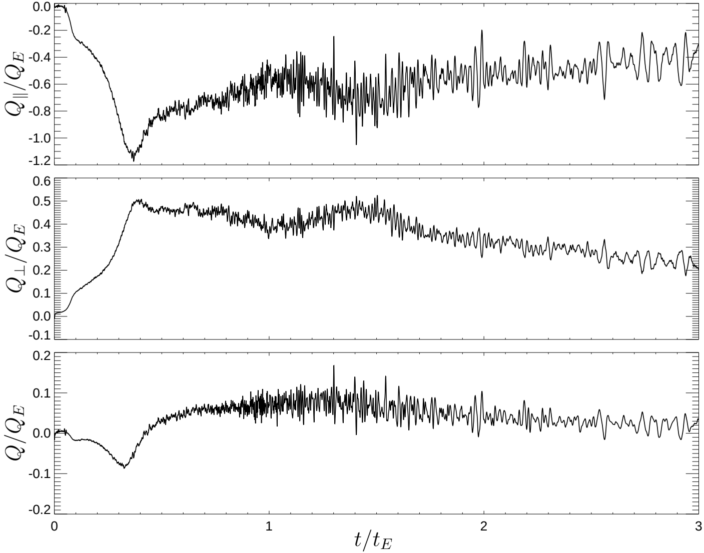
- $\epsilon_t \sim 2 \cdot 10^3$ W/kg in the slow solar wind and
- $\epsilon_{t\perp} \sim 10^4$ W/kg in the fast solar wind.

Taking into account the expansion

$$\frac{\partial \langle |\delta z^{\pm}|^2 \rangle}{\partial t} + \boldsymbol{\nabla} \cdot \langle \delta z^{\mp} |\delta z^{\pm}|^2 \rangle = -4\epsilon_t^{\pm} + \left(\frac{\partial \langle |\delta z^{\pm}|^2 \rangle}{\partial t} \right)_{WKB}$$

Hybrid Expanding Box Simulations

Heating/cooling rates



Summary

Fast solar wind

- comparable $\perp$ heating & $||$ cooling close to the Sun
- comparable $||$ and $\perp$ heating at 1 AU

Slow solar wind

- weak $||$ heating/cooling close to the Sun
- comparable $||$ and $\perp$ heating at 1 AU

Slow vs fast solar wind

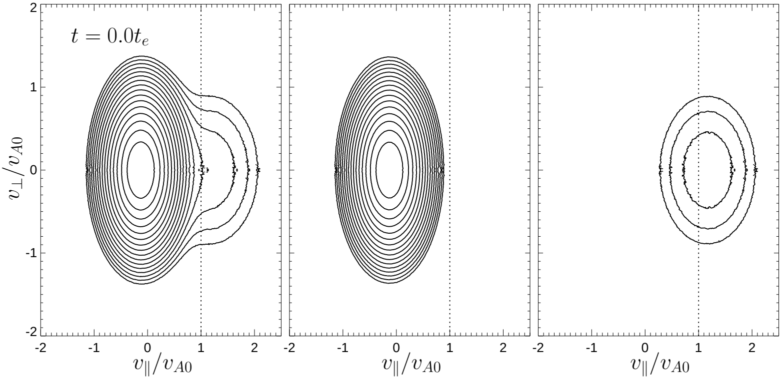
- comparable total heating rates (per unit volume)
- interaction between slow and fast streams

Parallel cooling

- possible related to the beam-core proton VDF
- numerical simulations exhibit comparable parallel cooling rates due to kinetic instabilities driven by the beam-core system

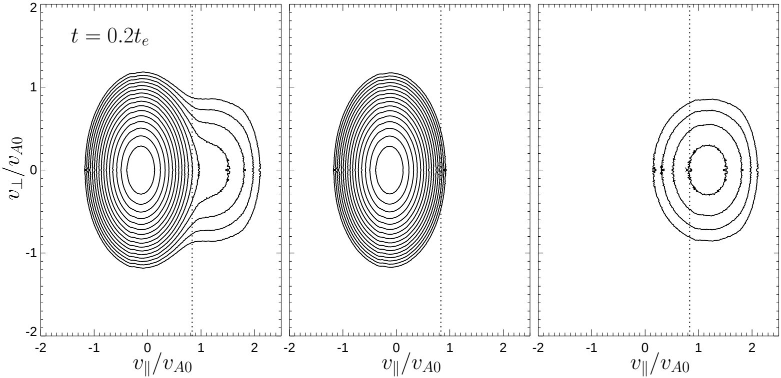
Hybrid Expanding Box Simulation

Evolution of VDF



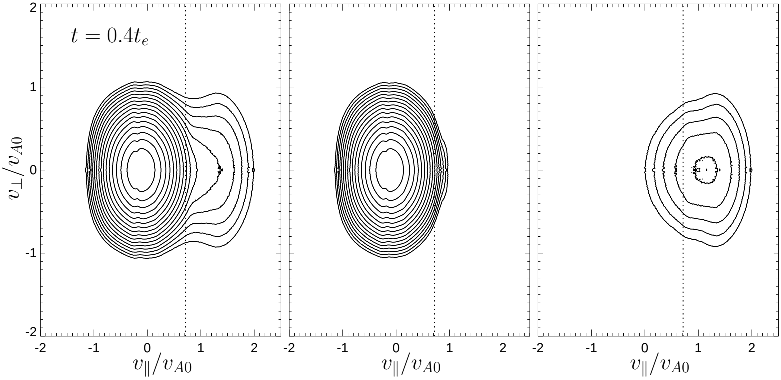
Hybrid Expanding Box Simulation

Evolution of VDF



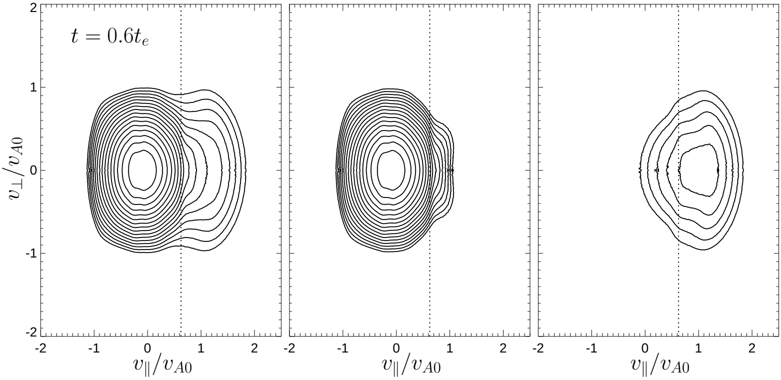
Hybrid Expanding Box Simulation

Evolution of VDF

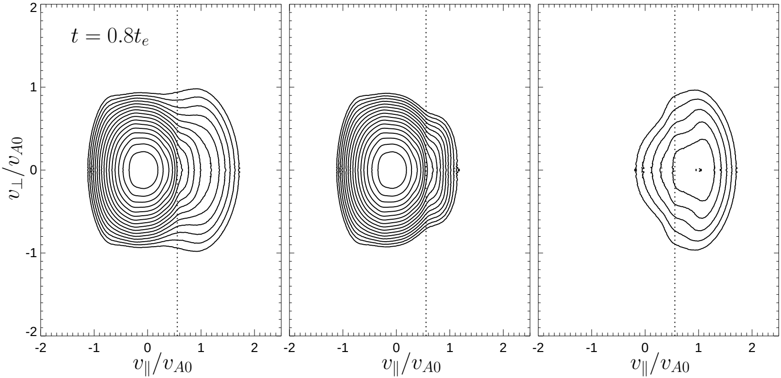


Hybrid Expanding Box Simulation

Evolution of VDF

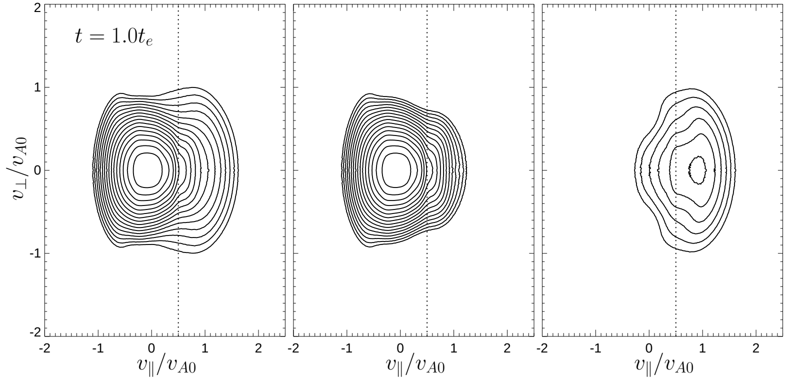


Evolution of VDF

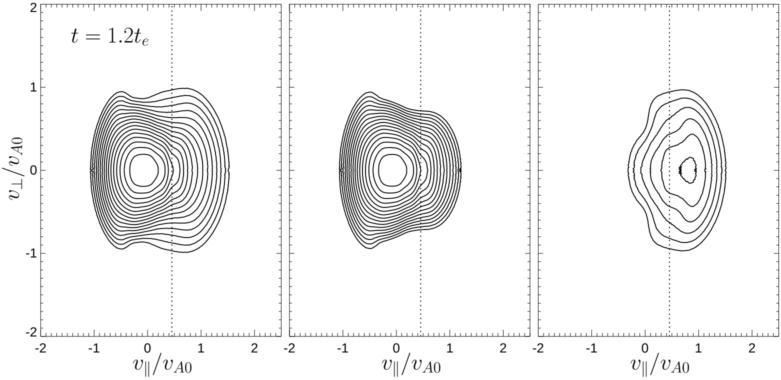


Hybrid Expanding Box Simulation

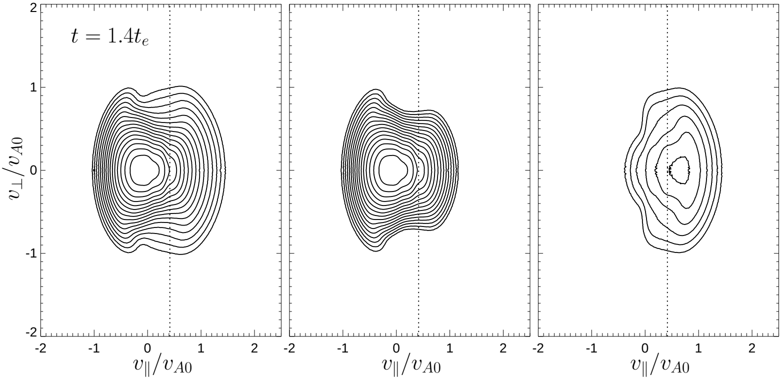
Evolution of VDF



Evolution of VDF

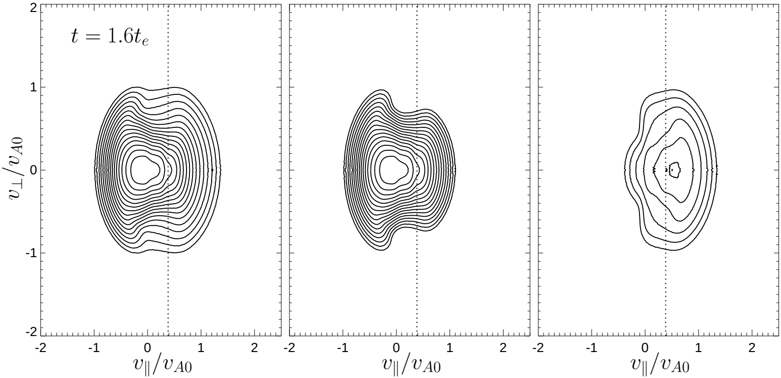


Evolution of VDF



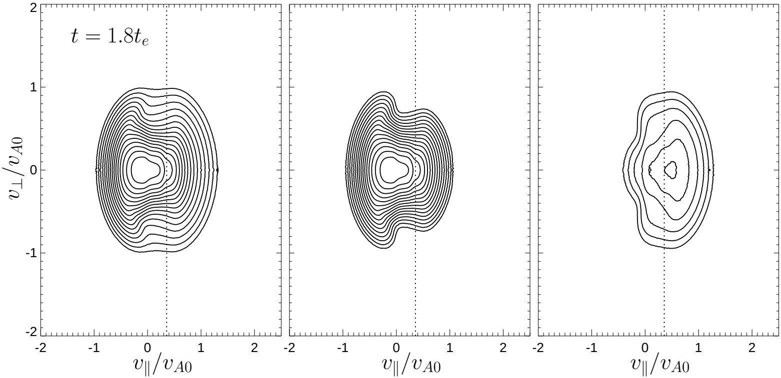
Hybrid Expanding Box Simulation

Evolution of VDF

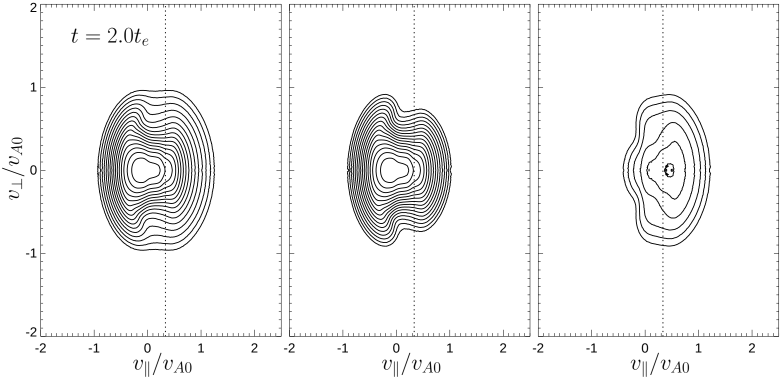


Hybrid Expanding Box Simulation

Evolution of VDF

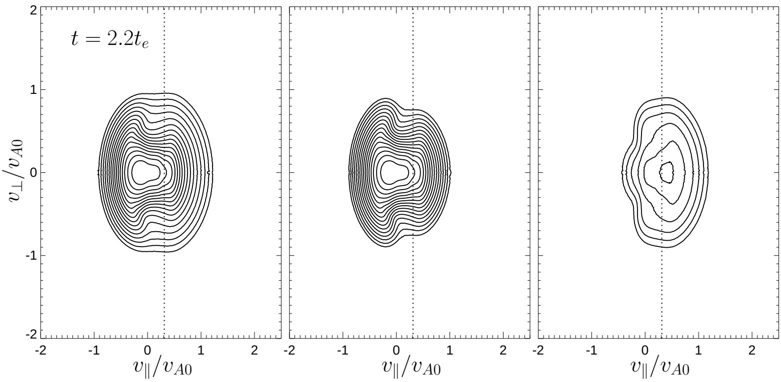


Evolution of VDF



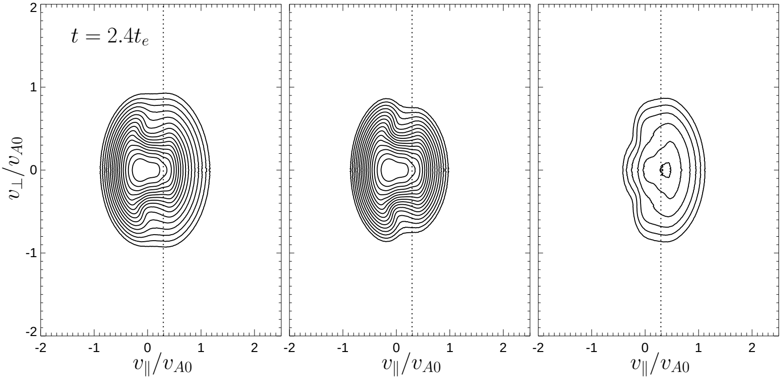
Hybrid Expanding Box Simulation

Evolution of VDF

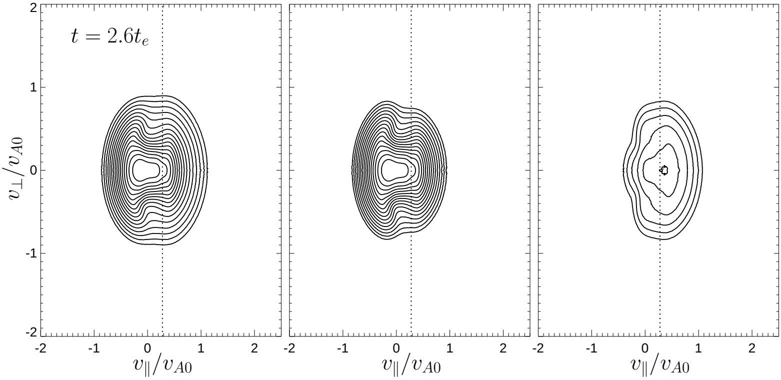


Hybrid Expanding Box Simulation

Evolution of VDF

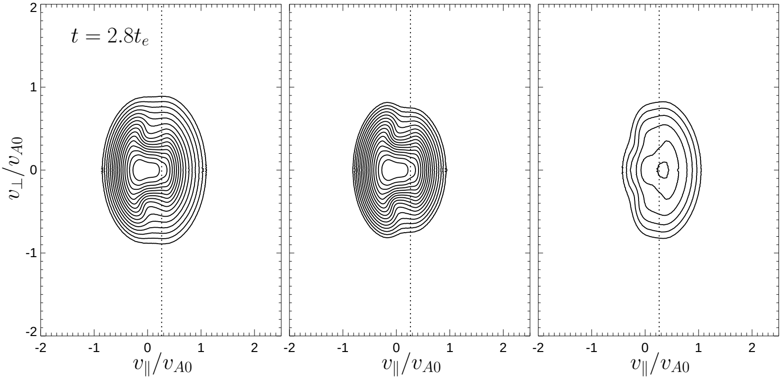


Evolution of VDF



Hybrid Expanding Box Simulation

Evolution of VDF



Evolution of VDF