Self-Similar Distribution Functions in the Solar Wind

Konstantinos Horaites*
Stanislav Boldyrev*
**University of Wisconsin-Madison*

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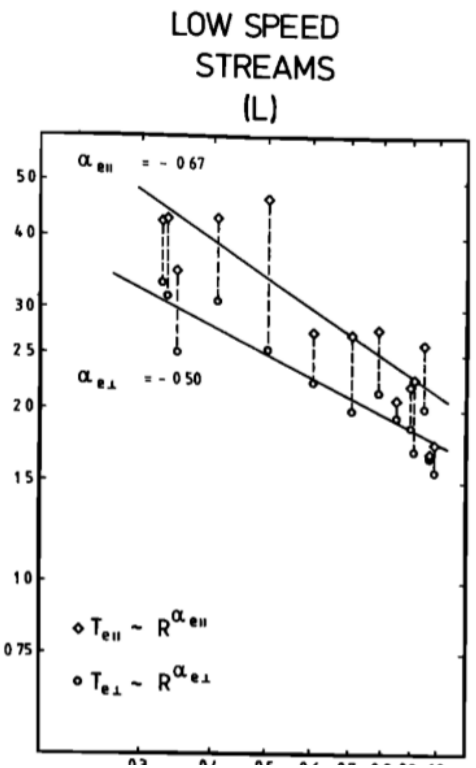
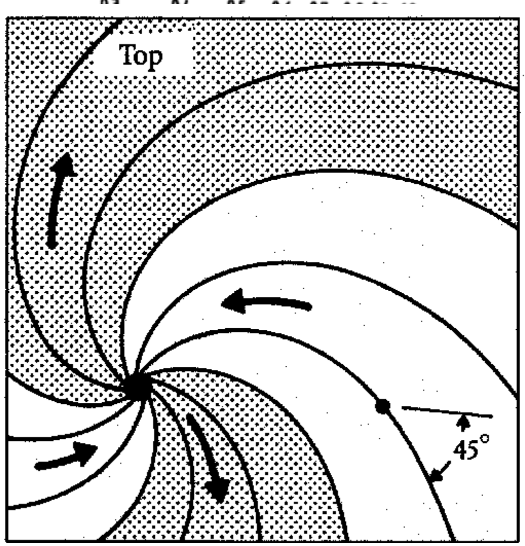
Background: Solar Wind Electrons

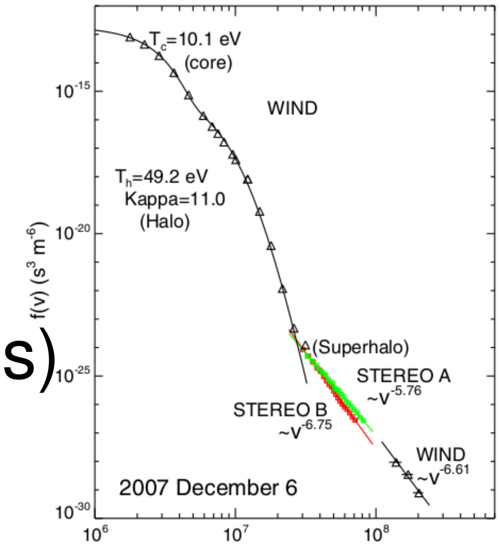


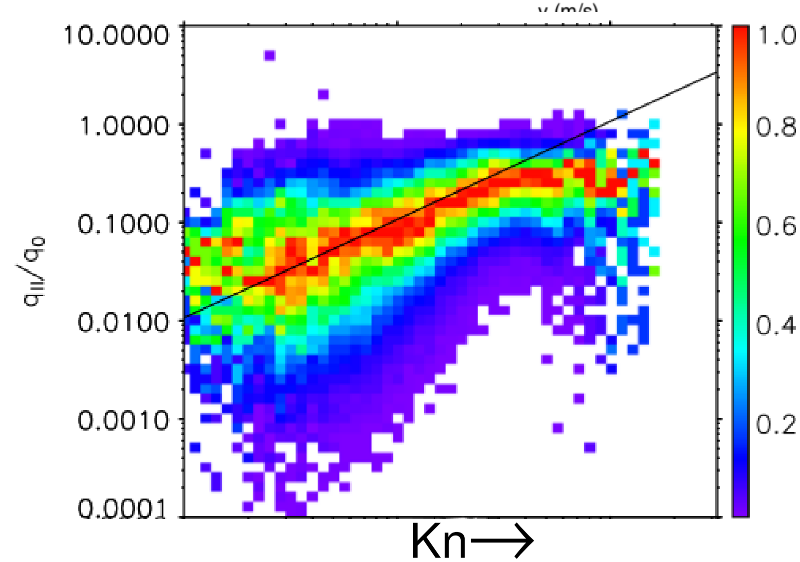
- Power laws:
  $n(r) \sim r^{-2}$
  $T(r) \sim r^{-1/2}$
  $q(r) \sim r^{-3}$
  (Pilipp 1990)



- Parker Spiral

- Non-thermal electron velocity distribution functions (eVDFs) (Wang 2012)

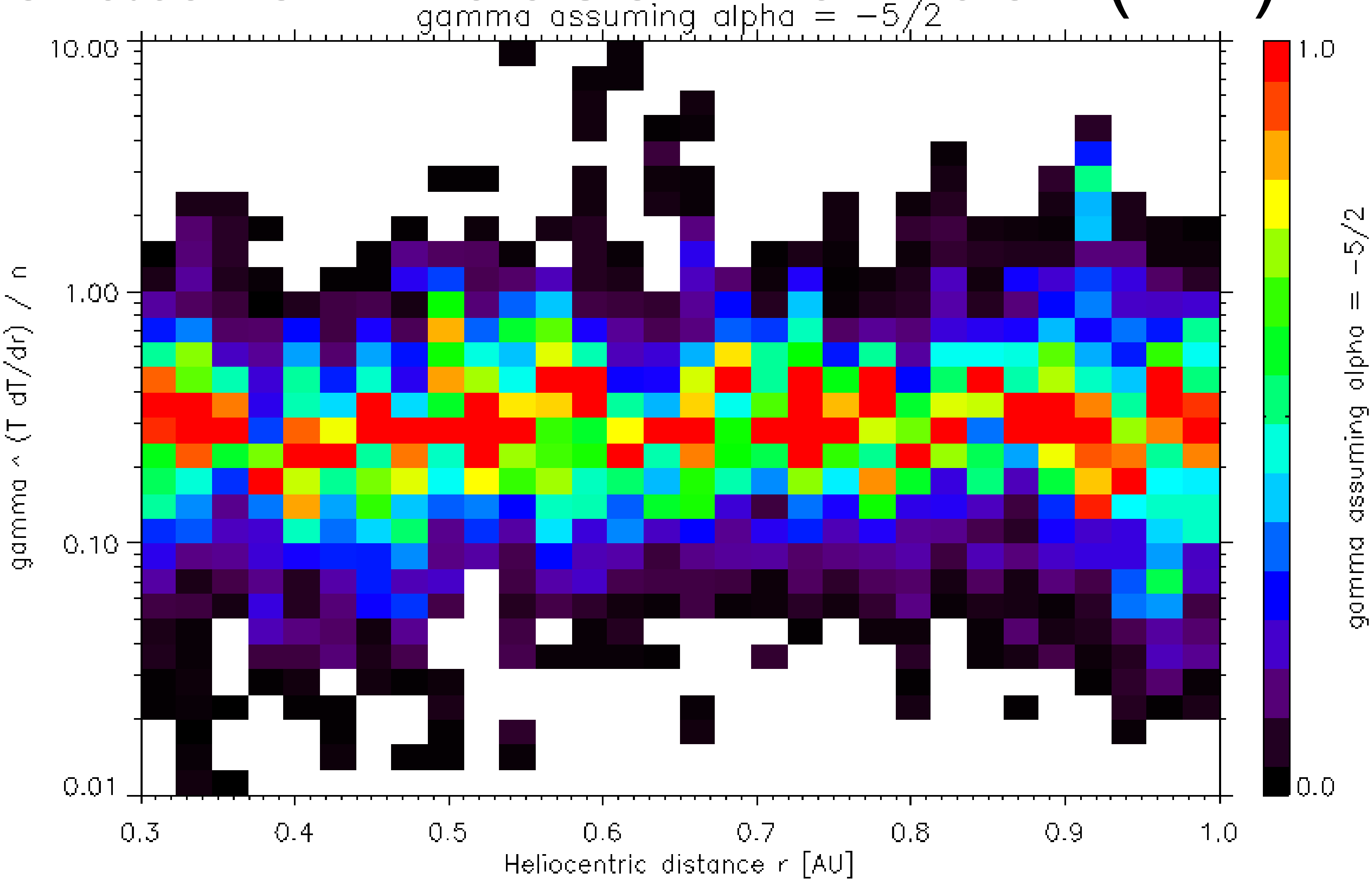




- Spitzer Conductivity → free streaming (Bale 2013)

Temperature Knudsen number (Kn)

Helios Data



$Kn \sim (d\ln T/dr) * L_{mfp}$

Constant on average!

$Kn \rightarrow 0$: highly collisional

$Kn \sim 1$ weakly collisional

Self-Similar eVDFs (Krasheninnikov 1988)

$$\frac{\partial F}{\partial t} = A\xi^{1/2}\Big[-\gamma\mu\Big(\alpha F + \xi\frac{\partial F}{\partial \xi}\Big)$$

$$+ \delta\Big(\mu\frac{\partial F}{\partial \xi} + \frac{(1-\mu^2)}{2\xi}\frac{\partial F}{\partial \mu}\Big)$$

$$+ \frac{1}{\xi}\Big(\frac{\partial F}{\partial \xi} + \frac{\partial^2 F}{\partial \xi^2}\Big)$$

$$+ \frac{1}{2\xi^2}\frac{\partial}{\partial \mu}(1-\mu^2)\frac{\partial F}{\partial \mu}\Big]$$

Advection

E Field

e-e energy exchange

pitch angle scattering

If the Knudsen number (~gamma) = constant, then the kinetic equation can be written in a **spatially independent** form!

Account for magnetic field geometry!

$$\frac{\partial f_0}{\partial t} + (\boldsymbol{U_d} + v_\parallel \boldsymbol{b}) \cdot \boldsymbol{\nabla} f_0 - \left(\boldsymbol{b} \cdot \frac{D\boldsymbol{U_d}}{Dt} - \boxed{\mu B \boldsymbol{\nabla} \cdot \boldsymbol{b}} - \frac{e}{m} E_\parallel \right) \frac{\partial f_0}{\partial v_\parallel} = 0$$

Diverging magnetic field direction leads to collimation

Extend theory by starting from drift kinetic equation, which accounts for a spatially varying magnetic field

Applicable to solar wind? **YES**

- Non-thermal eVDFs ✓

- Power laws: $n(r) \sim r^{-2}$ ✓

  $T(r) \sim r^{-1/2}$

  $Kn \sim (T\, dT/dr)/n$

  → $Kn = \text{constant!}$

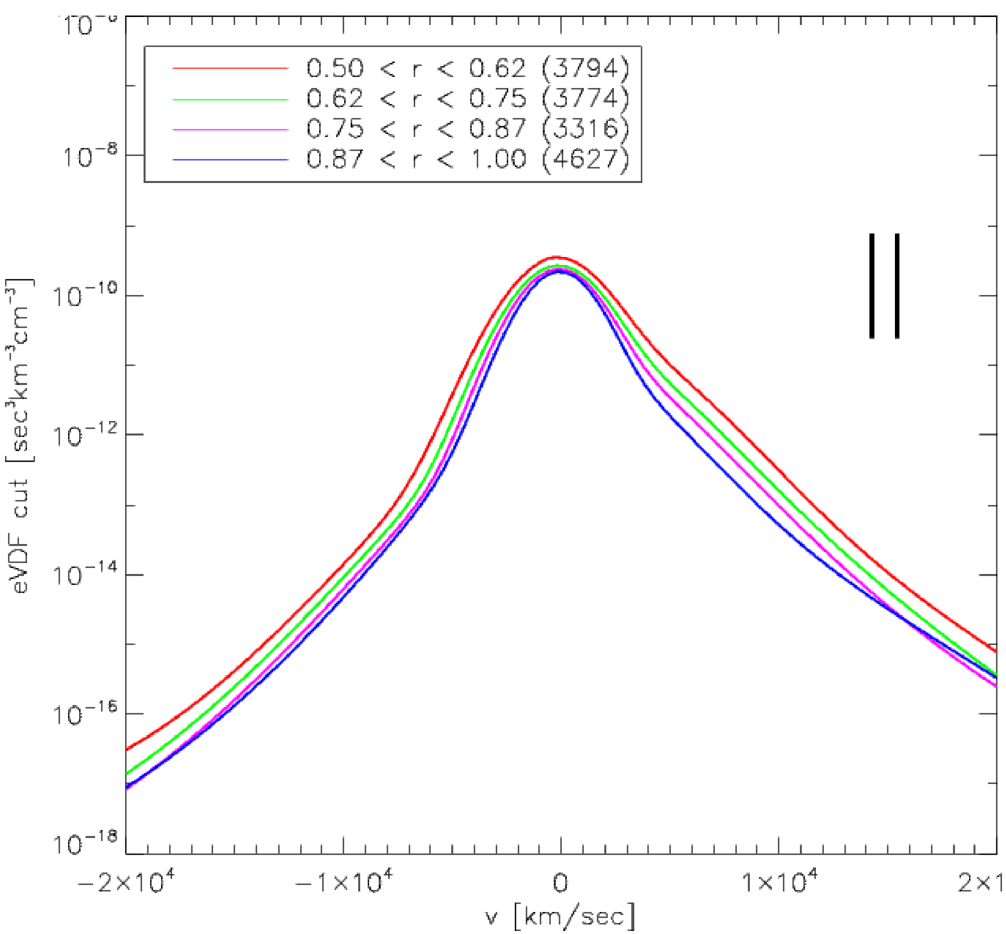
  Predicts $q(r) \sim r^{-11/4}$ (nearly r^{-3}) ✓

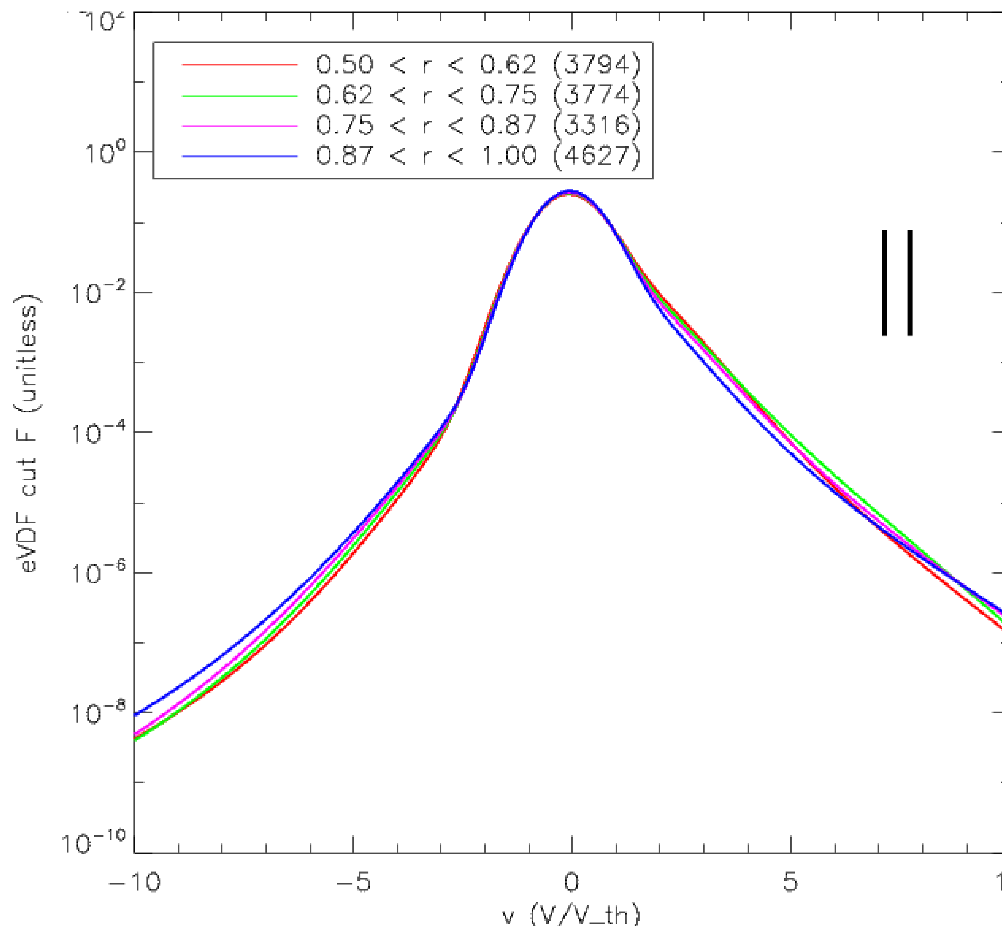
- Spitzer Conductivity $\rightarrow$ free streaming ✓

- Parker Spiral ✓

Also Verify Self-Similarity Directly

(Averaged Helios 1 eVDFs: 0.5-1 AU)



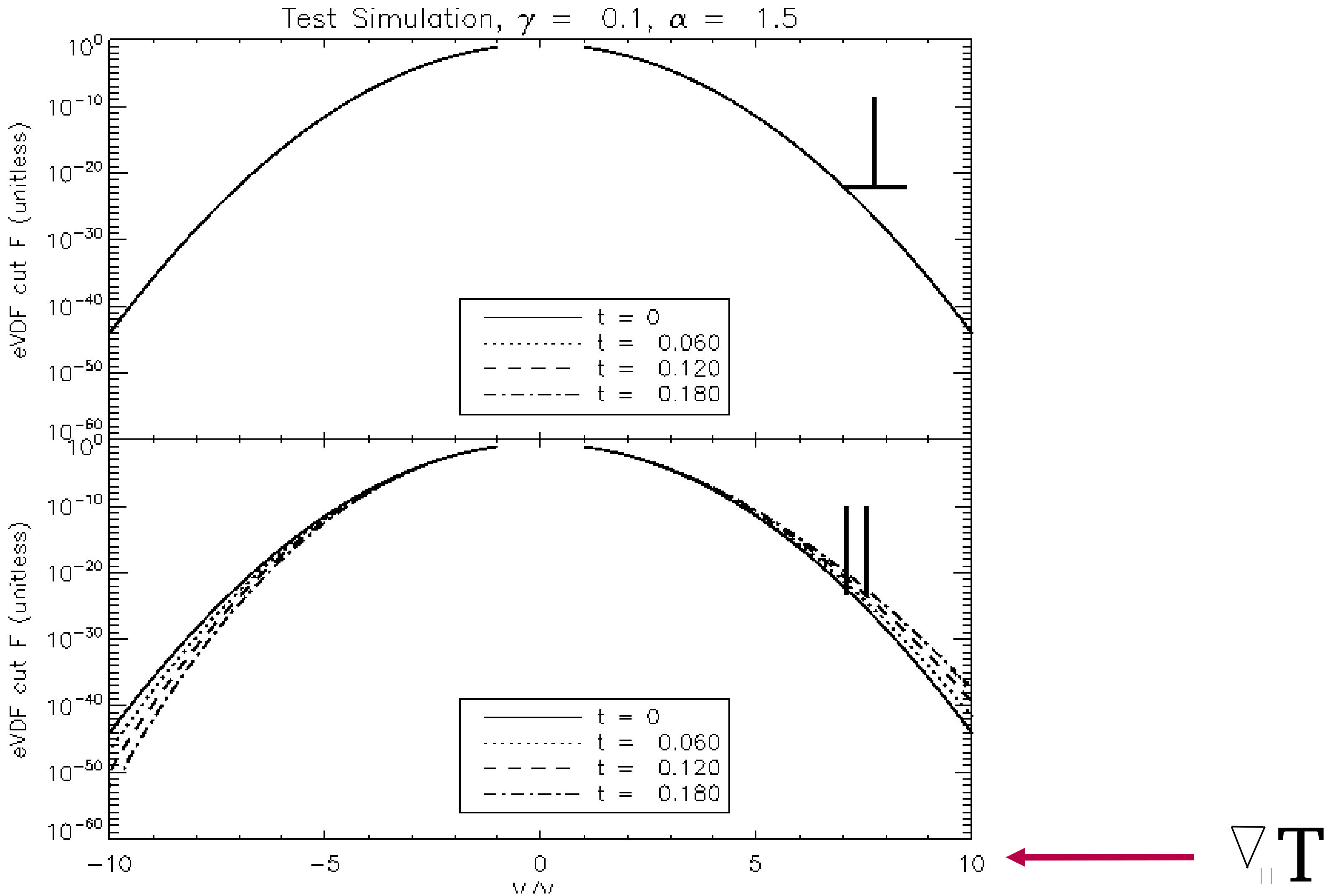


$f(x, v)$

Normalize

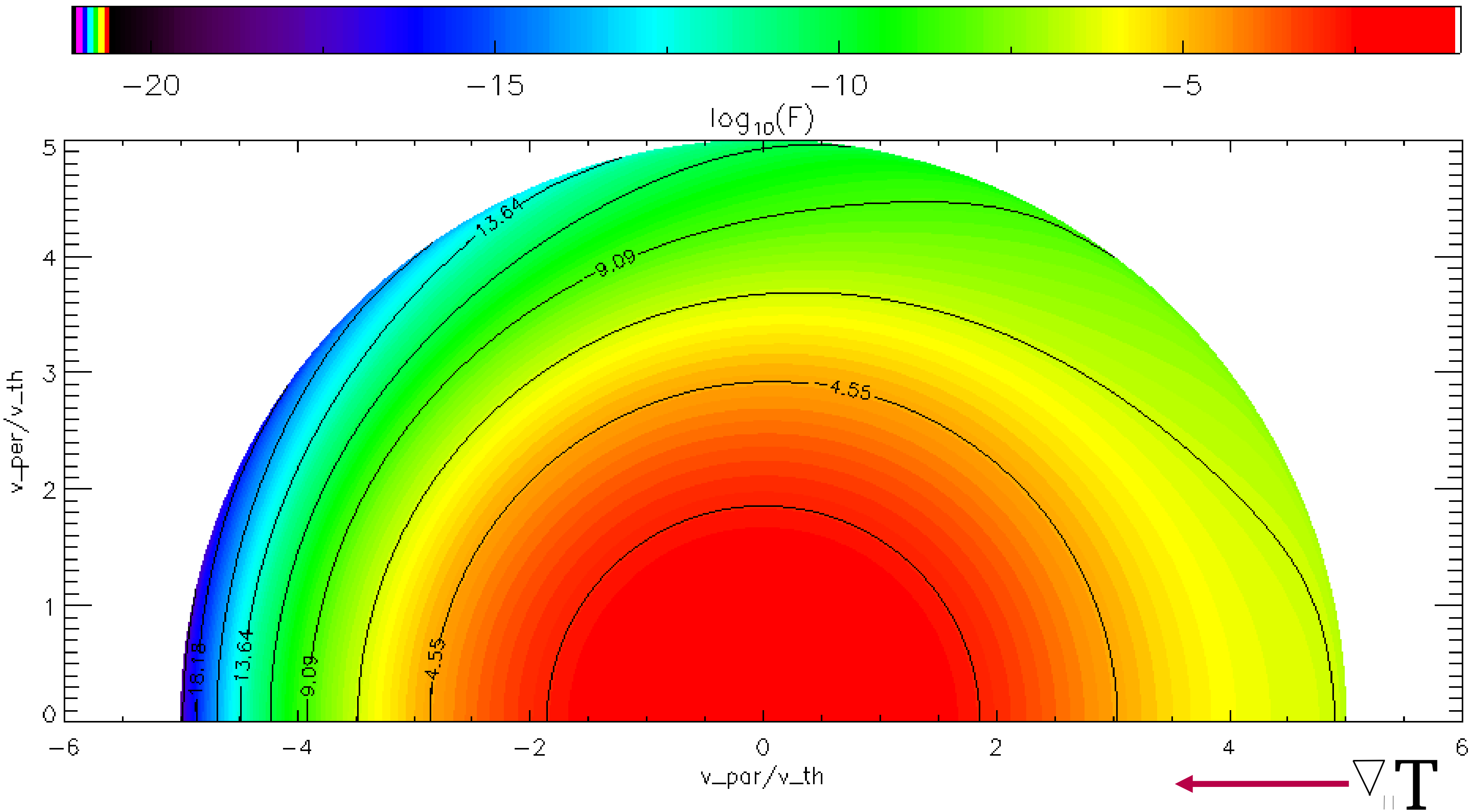
$F(x, v/v_{th}) \sim F_0(v/v_{th})$

Simulations



Test case with no magnetic field. Heat flux (from skewness of distribution) develops in time

Simulations



gamma (Kn) = 0.004

Heat flux and (slight) collimation

Conclusions

Knudsen number in solar wind is constant as a function of radial distance

Theory of self-similar kinetic equation is consistent with measured properties of solar wind. Measured eVDF profiles indicate self-similarity

Hope to explain solar wind eVDFs with simulations