Self-Similarity of the Electron Strahl: Wind Data

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Abstract

The solar wind strahl is a narrow, field-aligned population of high-energy electrons that originate in the solar corona. The beam-like shape of the strahl in velocity space is believed to come from the competition of two physical processes: the mirror force tends to narrow this population, while Coulomb collisions wave-particle interactions tend to broaden it. Using data from the Wind satellites's SWE strahl detector, we investigate the detailed shape of the strahl and compare with predictions from a kinetic "self-similar" model.

Background

As shown in [1], electron heat conduction in the solar wind is well described by the predictions of a proposed "self-similar" kinetic theory. This theory applies when the temperature Knudsen number $\gamma(x) \sim \frac{T(dT/dx)}{n}$ is nearly constant distance with distance x along the flux tube (this condition was observed to hold 0.3-1 AU). From this point of view γ, which characterizes the importance of Coulomb collisions, is the central parameter that determines the shape of the distribution function $f(x, \mathbf{V})$. The self-similar kinetic equation is the drift-kinetic equation written under a change of variables (see "Definitions" below), under the assumption $\gamma(x) =$const. In the high energy ($\xi >> 1$), field-aligned ($\mu \approx 1$) regime, the kinetic equation can be written as:

$$\alpha\mu F + \mu\xi\frac{\partial F}{\partial \xi} + (2-\alpha')(1-\mu)\frac{\partial F}{\partial \mu} = \frac{\beta}{\gamma\xi^2}\frac{\partial}{\partial\mu}(1-\mu)\frac{\partial F}{\partial \mu}. \qquad (1)$$

Where we used the definitions:

$$f \equiv \frac{NF(\mu,\xi)}{T(x)^\alpha} = \frac{nF}{v_{th}^3}, \gamma \equiv -\frac{T^2(d\ln T/dx)}{2\pi e^4 \Lambda n}$$
$$\mu \equiv \mathbf{v}\cdot\mathbf{B}/(|v||B|) = \cos\theta, \xi \equiv \left(\frac{v}{v_{th}}\right)^2 \qquad (2)$$
$$\beta \equiv (1+Z_{eff})/2, \alpha' \equiv 2-(\alpha+1/2)\alpha_B$$
$$n \propto x^{\alpha_n}, T \propto x^{\alpha_T}, B \propto x^{\alpha_B}$$

Asymptotic Solution

The theory predicts the shape of the "strahl" distribution. Equation 1 has approximate solutions for the distribution $F(\mu, \xi)$ of the form:

$$F(\mu,\xi) \sim C\xi^{\alpha'-\alpha}\exp\left\{\Omega\gamma'\xi^2(1-\mu)\right\} \qquad (3)$$

Where we introduced $\Omega \equiv -\alpha'\alpha_T/\beta$, $\gamma' \equiv \gamma/\alpha_T$. An approximate expression for the full width at half maximum, θ_{FWHM}, of the distribution reads:

$$\theta_{FWHM} \approx \frac{2}{\xi}\sqrt{\frac{2\ln(1/2)}{\gamma'\Omega}}. \qquad (4)$$

Data—SWE Strahl Detector

Our data comes from the Wind satellite's SWE strahl detector [2], which was an electrostatic analyzer devoted solely to observing the strahl.

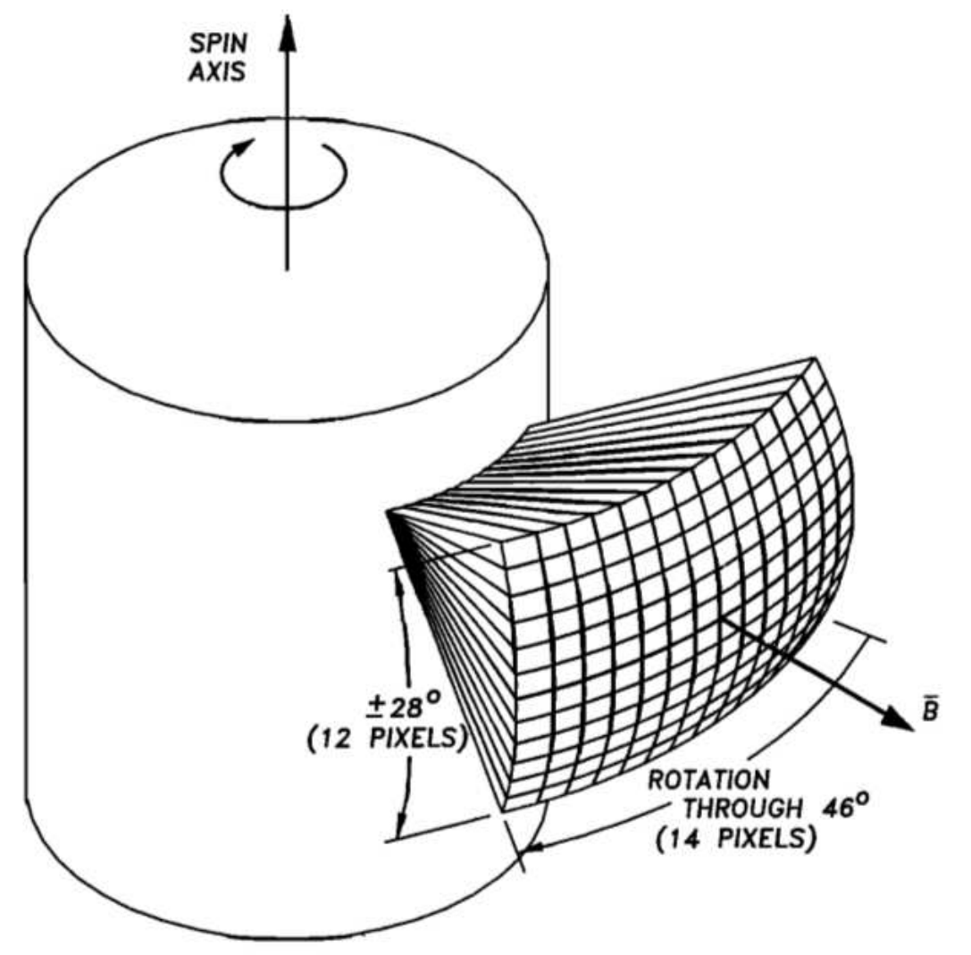

Figure: The SWE strahl detector measured electron counts in a 14x12 angular grid centered on the $\mathbf{B}$ field, as above (from [2])

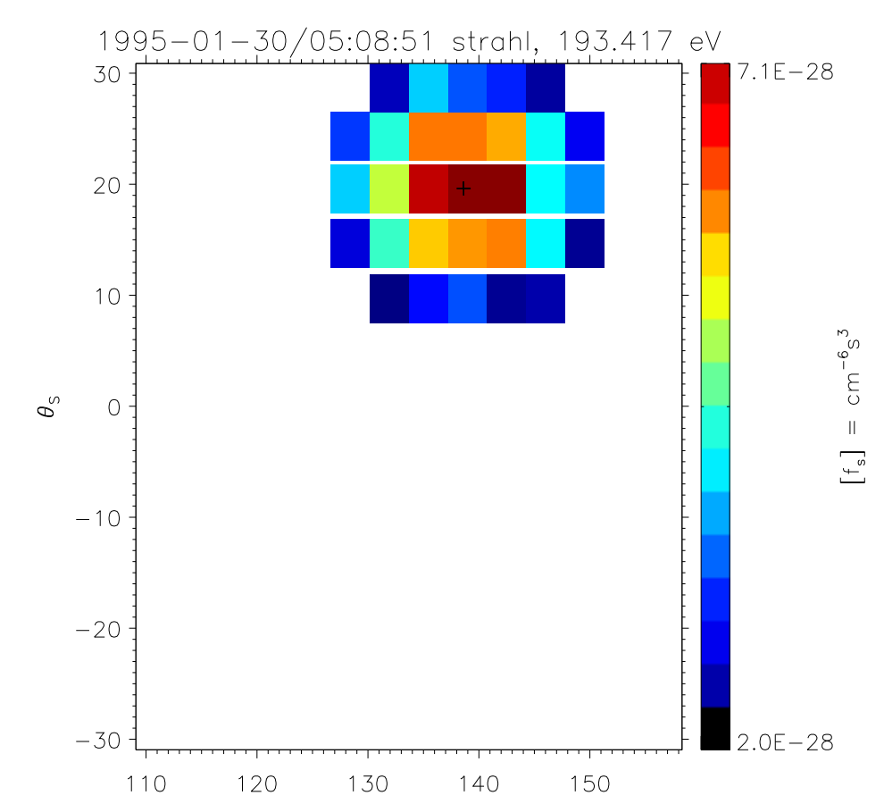

Figure: Example of an angular distribution measured by the SWE strahl detector. The strahl (shown) is isolated from the background with a cleaning procedure

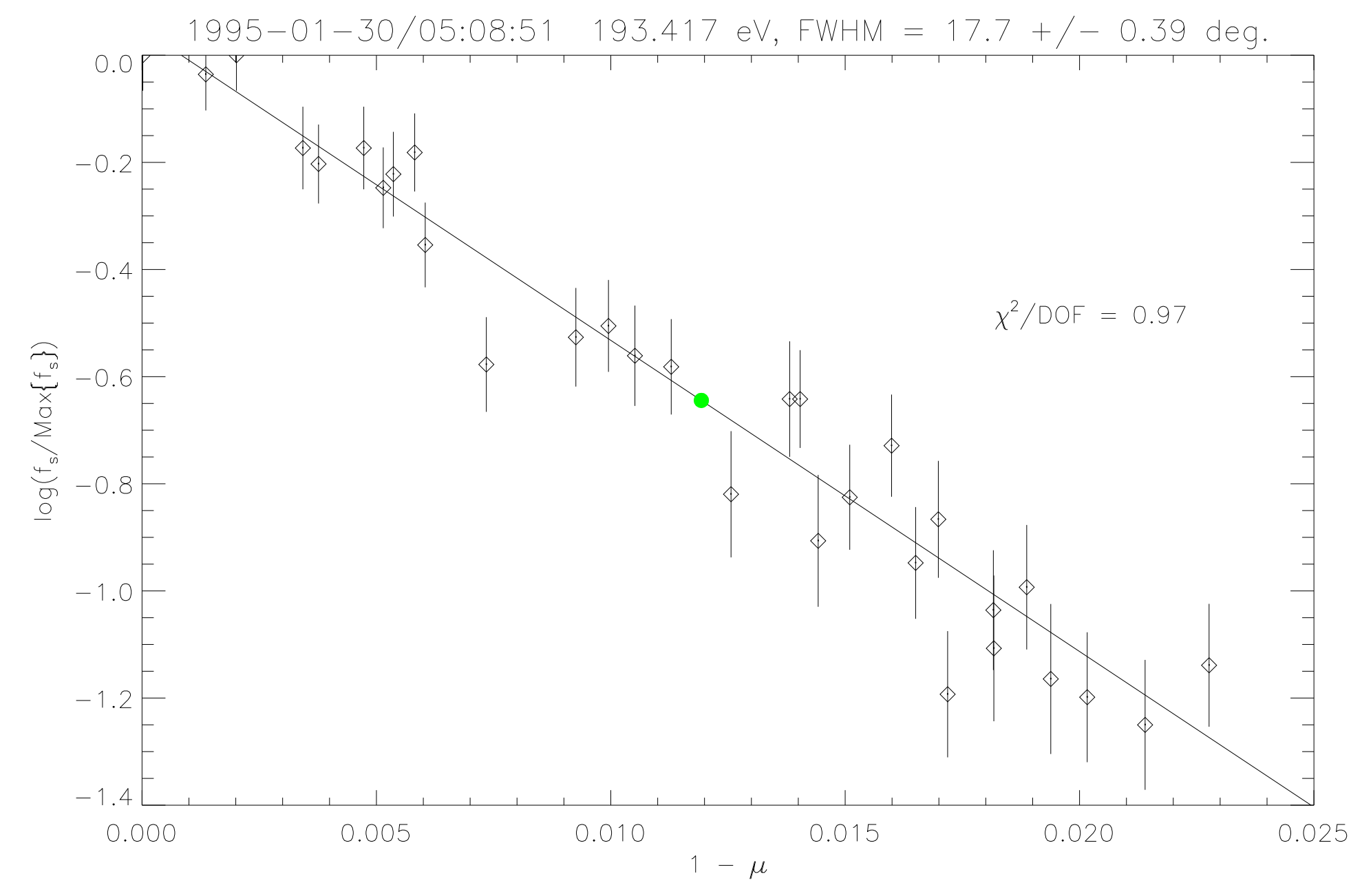

Figure: The full width at half-maximum, θ_{FWHM}, of the strahl (green) at constant energy is found by fitting the data in the vicinity of the strahl peak to the function $y = mx$, where $x = (1-\mu)$ and $y = \ln(F/F_{peak})$.

Results

Our linear fitting procedure for the slope m is equivalent to measuring the quantity Ω for each pitch angle distribution (PAD). Explicitly, $\Omega = m/(\gamma'\xi^2)$. We set $\Omega = -0.41$, which is the average value inferred from our measurements, to calculate an "Expected θ_{FWHM}" for each PAD. We then compare with the "Measured θ_{FWHM}" calculated from the fitting procedure.

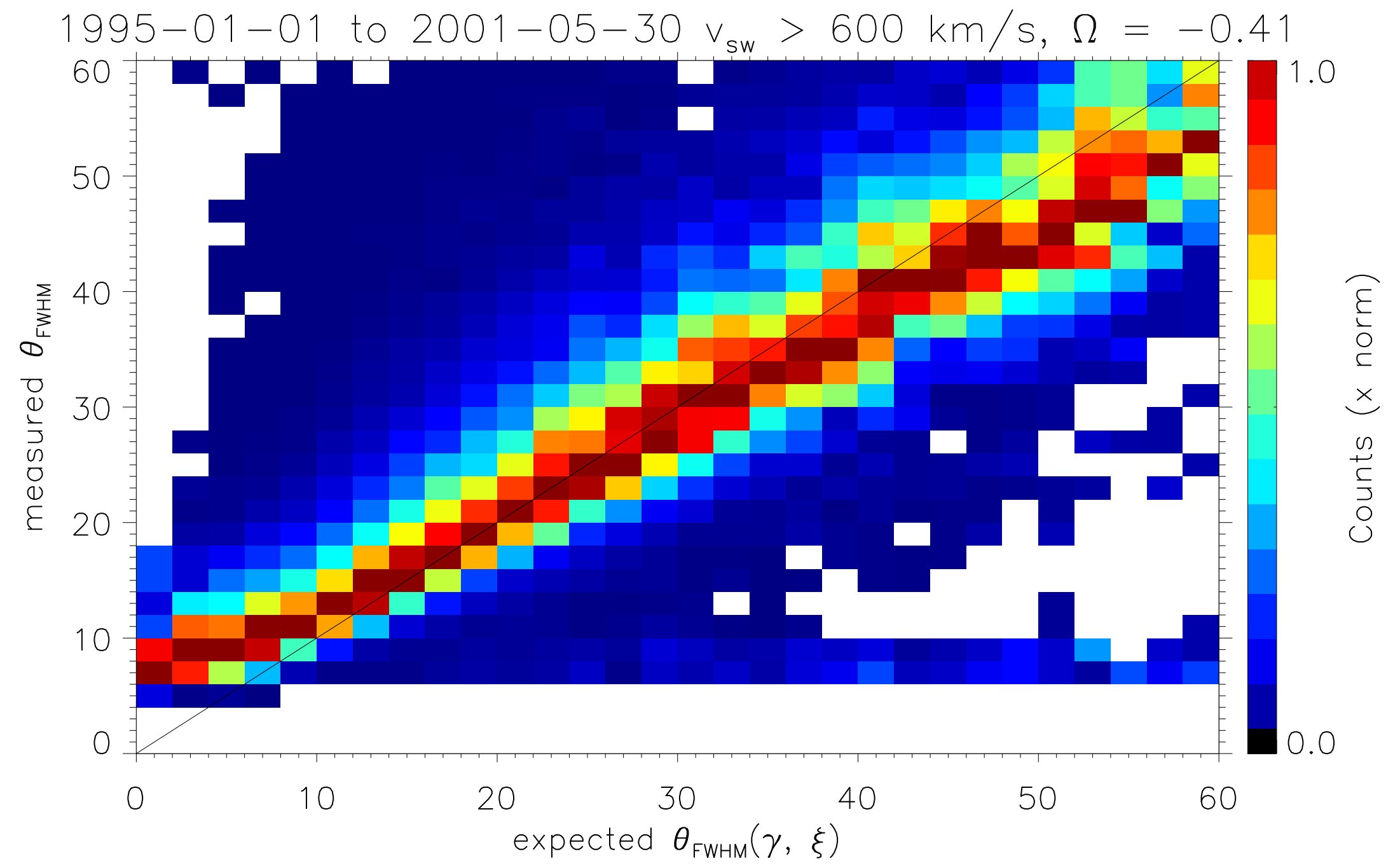

Figure: Expected strahl widths (FWHM, in degrees) from equation 3, plotted versus measured widths. The parameter Ω determines the slope of the data above. Setting $\Omega = -0.41$ shows very good agreement between our model and the data.

Along the B-field direction $\mu = 1$, our model predicts the strahl will vary as a power law with energy. That is, $F(\mu = 1) \propto \xi^{\alpha'-\alpha}$. We fit the peak F vs. ξ, to infer the scaling coefficient $\alpha' - \alpha$. There is a "knee" in our graph, that is likely due to the strahl becoming so narrow at high energies that the detector cannot resolve the angular width.

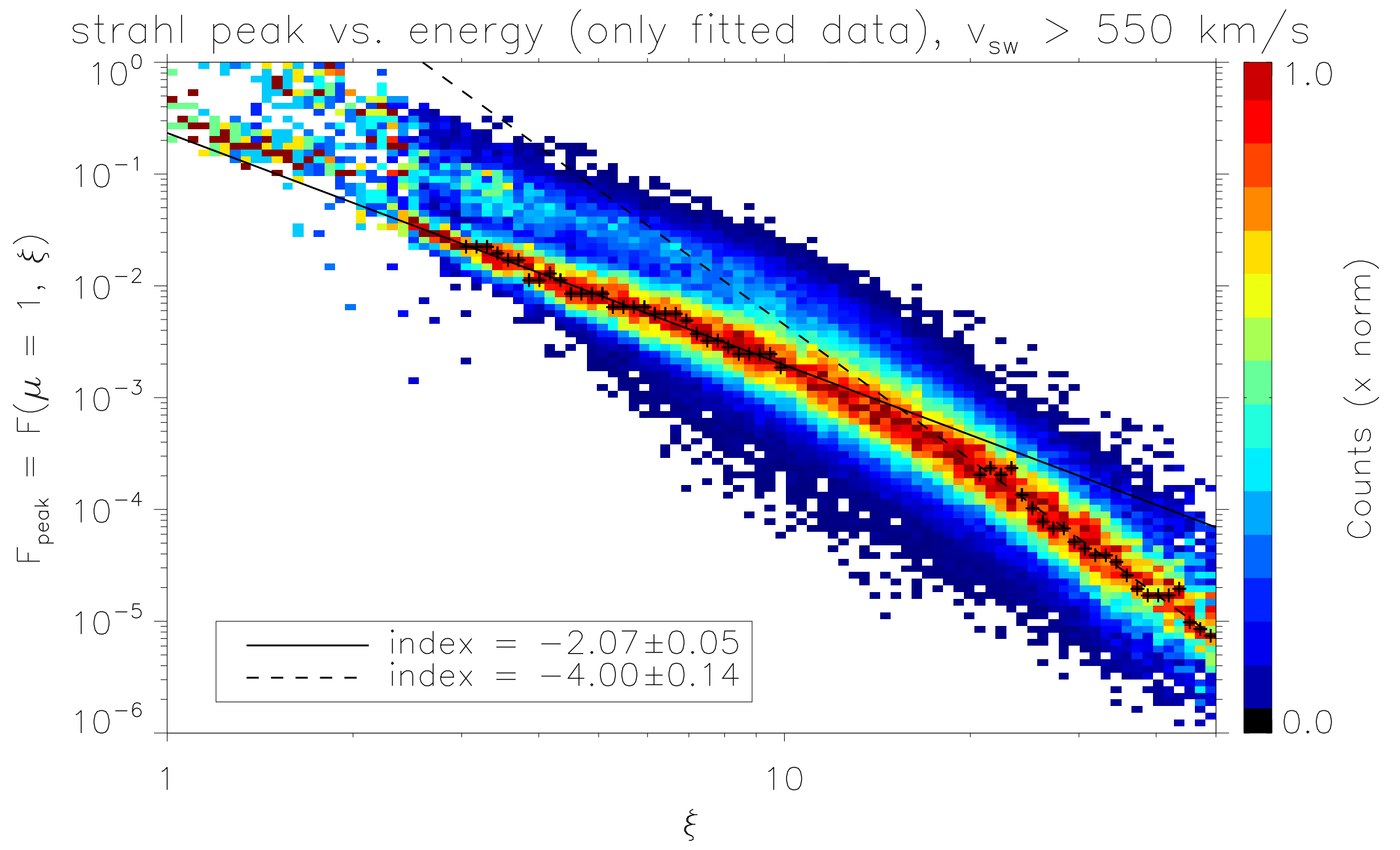

Figure: Along the magnetic field direction, the distribution function is a power law: $F \propto \xi^{\alpha'-\alpha}$. The power law exhibits a break around $\xi \approx 20$, as expected when the strahl becomes too narrow to be resolved.

Diffusion Coefficient

Consider an ideal model of the solar wind in the inner heliosphere, with radial field lines: $\alpha_n = -2$, $\alpha_T = -1/2$, $\alpha_B = -2$. This corresponds with $\alpha' = -2$. If we set $\Omega = -2/5$, as indicated by our measurements, then we conclude $\beta = \alpha'\alpha_T/\Omega = 5/2$. However, for a hydrogen-dominated plasma, $Z_{eff} \approx 1$ and $\beta \approx 1$. A more realistic set of α_n, α_T, α_B does not fix the problem: the β inferred from measurements of Ω is too large by a factor $\sim 2-5$.

This implies a source of anomalous diffusion, beyond Coulomb collisions, that leads to broadening of the strahl population.

Conclusions

- The asymptotic solution (3) correctly predicts the shape of the strahl distribution. Our model has one free parameter, Ω, that can be measured by least-squares fitting.
- The measured Ω is lower than expected, i.e. the strahl is too broad. An additional source of broadening, that mimics Coulomb collisions, may be required to explain the data.
- Our data was taken at 1 AU. The field lines are not purely radial here (and B) so measurements of the strahl in the inner heliosphere would provide a better test of our model.

References

[1] K. Horaites *et al.*, Self-similar theory of thermal conduction and application to the solar wind. *Phys. Rev. Lett.*, 114:245003, Jun 2015.

[2] K. W. Ogilvie *et al.*, SWE, A Comprehensive Plasma Instrument for the Wind Spacecraft. *Space Science Rev.*, 71:55–77, February 1995.

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