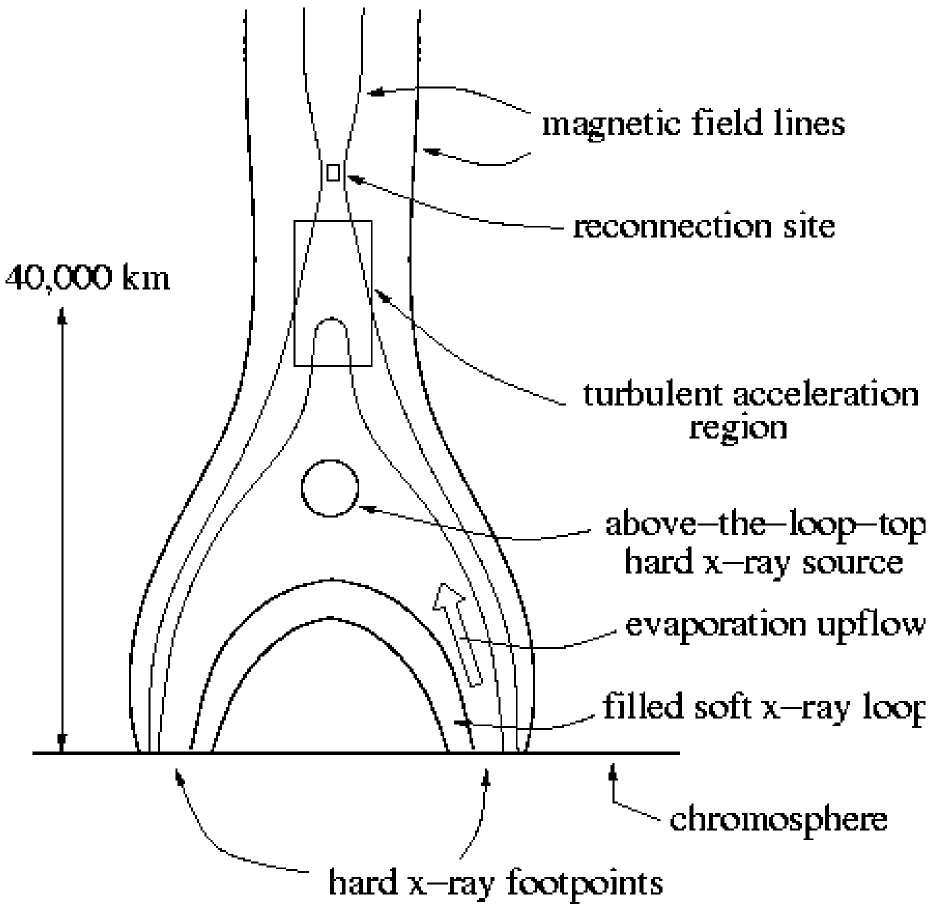
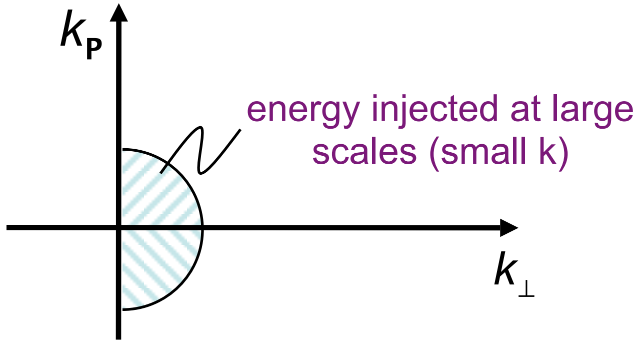
# Particle acceleration by MHD turbulence in solar flares

Ben Chandran
Space Science Center and Department of Physics
University of New Hampshire

# Turbulent particle acceleration models for solar flares
(e.g., Miller et al 1997)




- Reconnection triggers MHD turbulence




- Key questions:
  - what are the properties of this turbulence?
  - is it good at accelerating electrons?
  - is it good at accelerating ions?

# Approach: weak turbulence theory

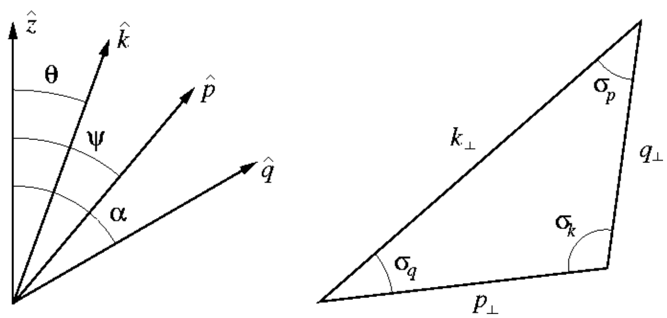
- assume $\beta = 8\pi p/B^2 \ll 1$
- Alfvén waves, $\omega = k_\| v_A$
- Fast magnetosonic waves ("fast waves"), $\omega = k v_A$
- AAA interactions = interactions among 3 Alfvén waves
- FFF interactions = interactions among 3 fast waves
- AFF interactions — 2 fast waves and one Alfvén wave
- AAF interactions — 2 Alfvén waves and one fast wave

$A_k$ = Alfvén-wave power spectrum
$F_k$ = fast-wave power spectrum

# Wave kinetic equations

$$\frac{\partial A_k}{\partial t} = \frac{\pi}{8v_{\mathrm{A}}}\int d^3p\, d^3q\, \delta(\mathbf{k}-\mathbf{p}-\mathbf{q})\,\{\delta(q_z)8(p_\perp n\bar{l})^2 A_q(A_p-A_k) + \delta(k_z+p_z+q)M_1[M_2F_q(A_p-A_k)+M_3A_p(F_q-A_k)]$$
$$+\,\delta(k_z+p_z-q)M_4[M_5F_q(A_p-A_k)+M_3A_p(F_q-A_k)] + \delta(k_z+p-q)\,M_6[M_7F_q(F_p-A_k)+M_8F_p(F_q-A_k)]\}$$

$$\frac{\partial F_k}{\partial t} = \frac{\pi}{8v_{\mathrm{A}}}\int d^3p\, d^3q\, \delta(\mathbf{k}-\mathbf{p}-\mathbf{q})\,\{9\sin^2\theta[\delta(k-p-q)kqF_p(F_q-F_k) + \delta(k+p-q)(k^2F_pF_q+kpF_qF_k-kqF_pF_k)]$$
$$+\,\delta(k-p_z+q_z)M_9[M_{10}A_q(A_p-F_k)+M_{11}A_p(A_q-F_k)] + \delta(k-p_z-q)M_{12}[M_{13}F_q(A_p-F_k)+M_{14}A_p(F_q-F_k)]$$
$$+\,\delta(k+p_z-q)M_{15}[M_{16}F_q(A_p-F_k)+M_{17}A_p(F_q-F_k)]\,\},$$



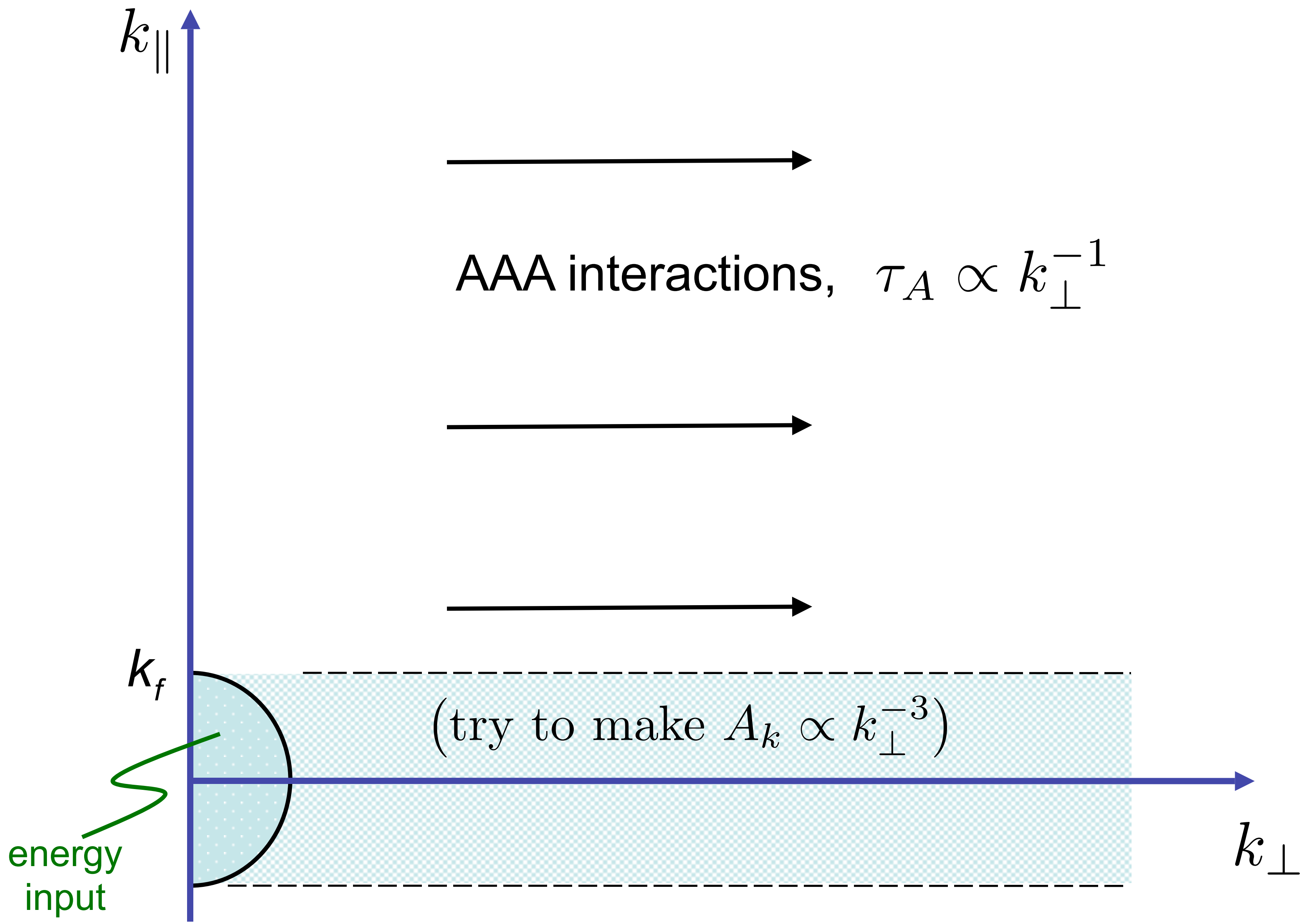

- analytic results for nonlinear time scales
- solve equations numerically

$$M_2 = -p_\perp m-(\cos\alpha+1/2)(k_\perp l+p_\perp m+q_\perp n),$$
$$M_3 = 2k_\perp l+2p_\perp m+q_\perp n,$$

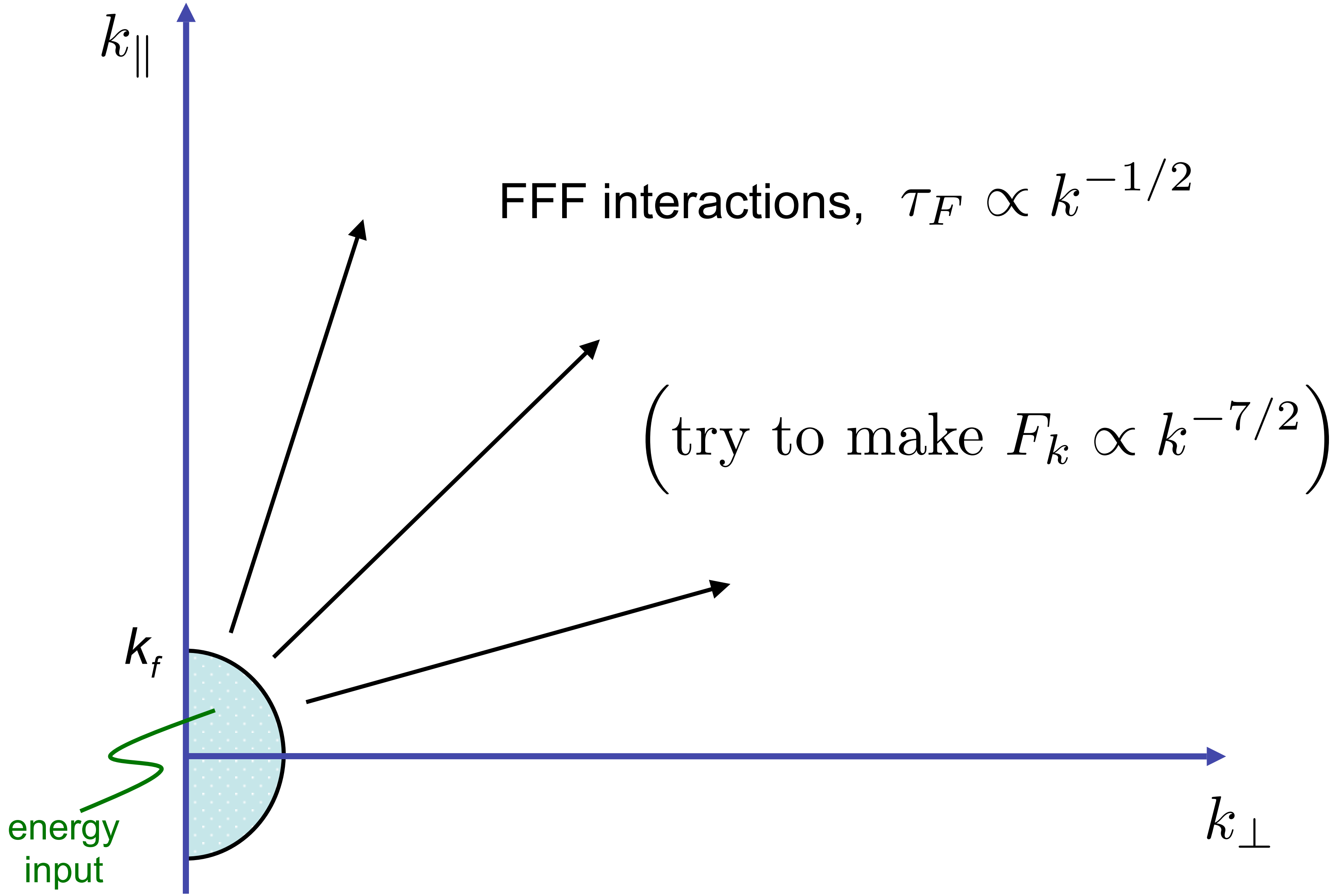
$$M_1 = M_2+M_3,\quad M_4 = M_5+M_3,\quad M_6 = M_7+M_8,$$
$$M_9 = M_{10}+M_{11},\quad M_{12} = M_{13}+M_{14},\quad M_{15} = M_{16}+M_{17},$$

$$l = \cos(\sigma_k)\quad m = \cos(\sigma_p)\quad n = \cos(\sigma_k)$$
$$\bar{l} = \sin(\sigma_k)\quad \bar{m} = \sin(\sigma_p)\quad \bar{n} = \sin(\sigma_k)$$

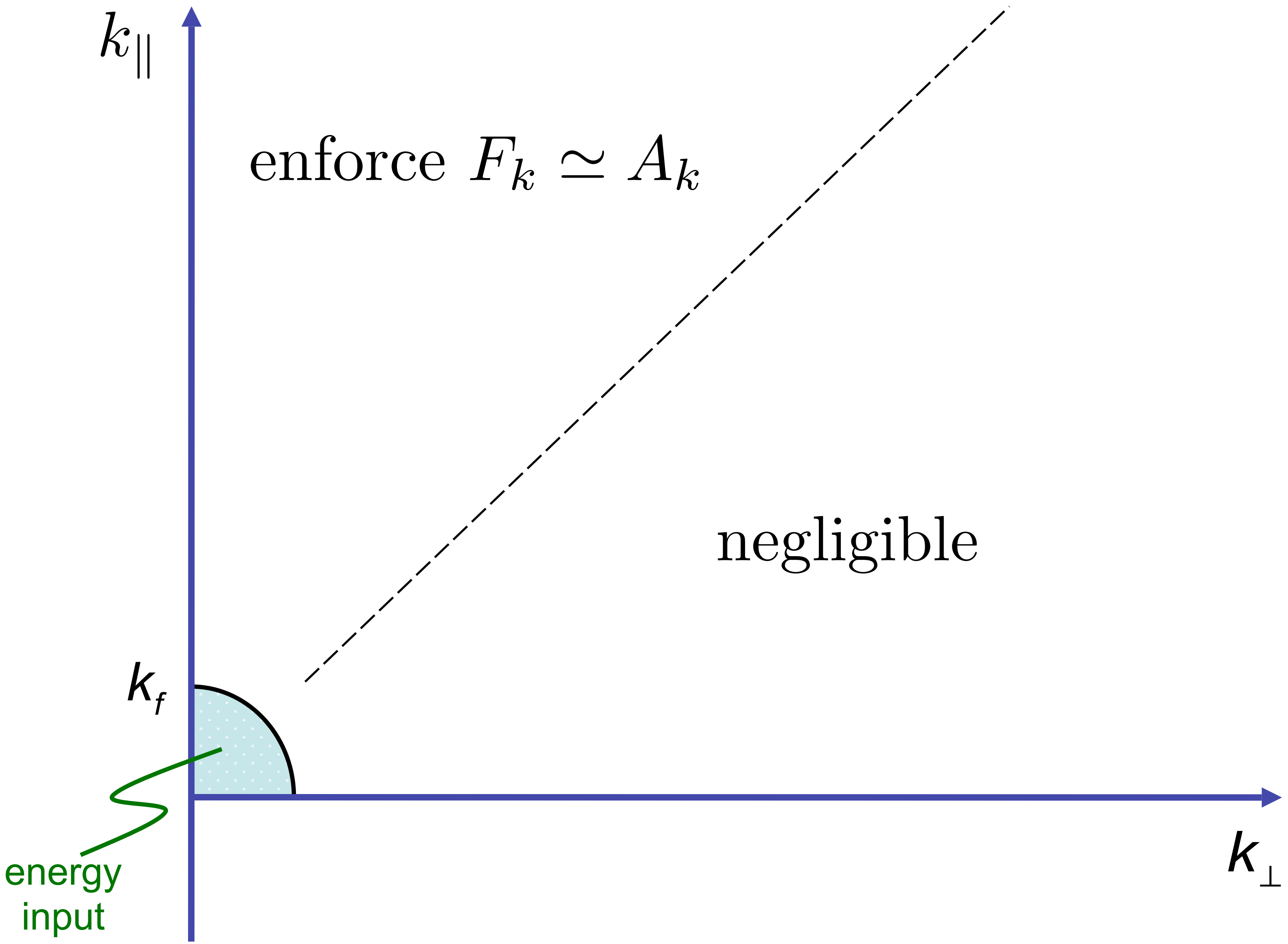
# Energy cascade mechanisms. I.



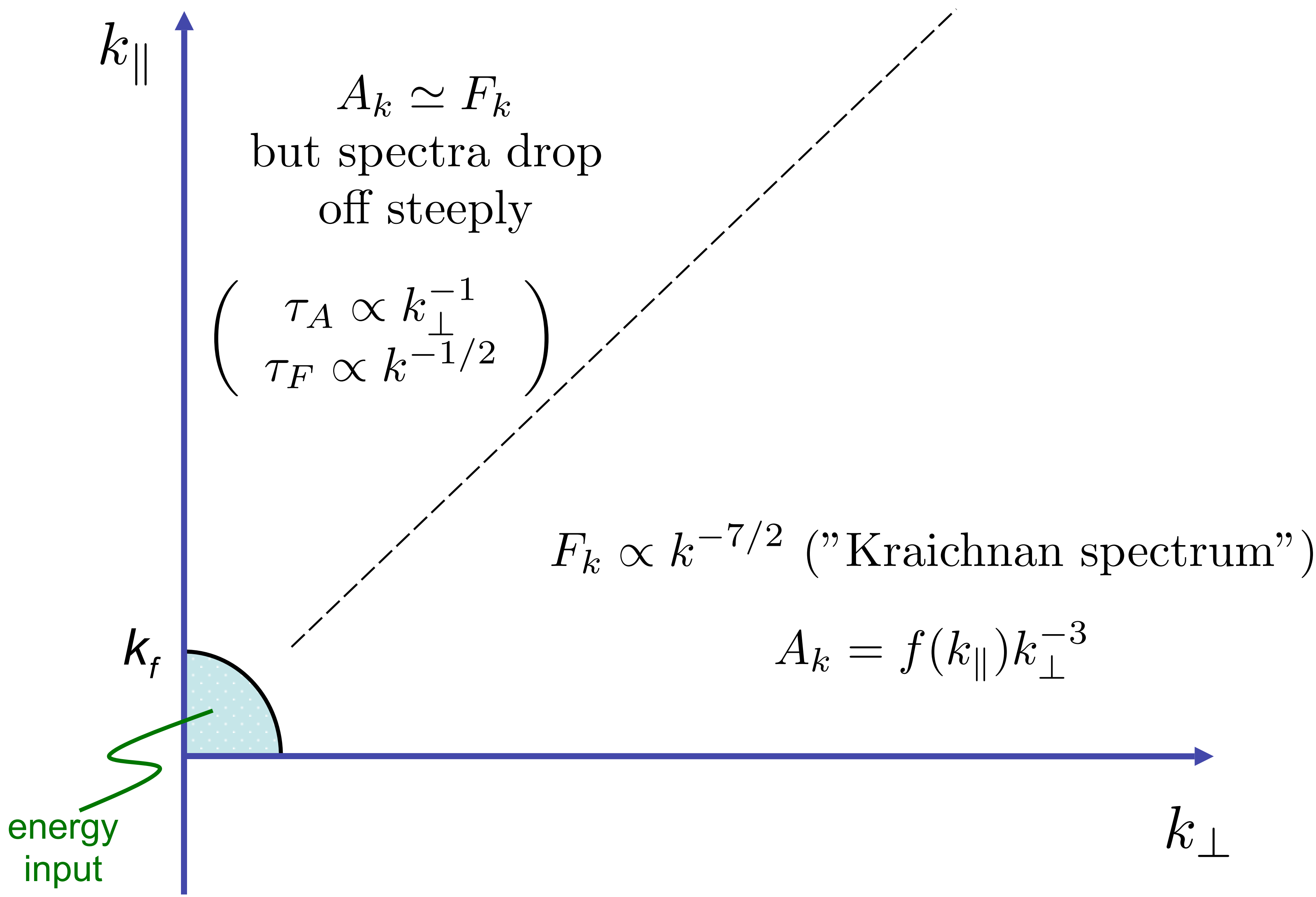
# Energy cascade mechanisms. II.



# AAF and AFF interactions

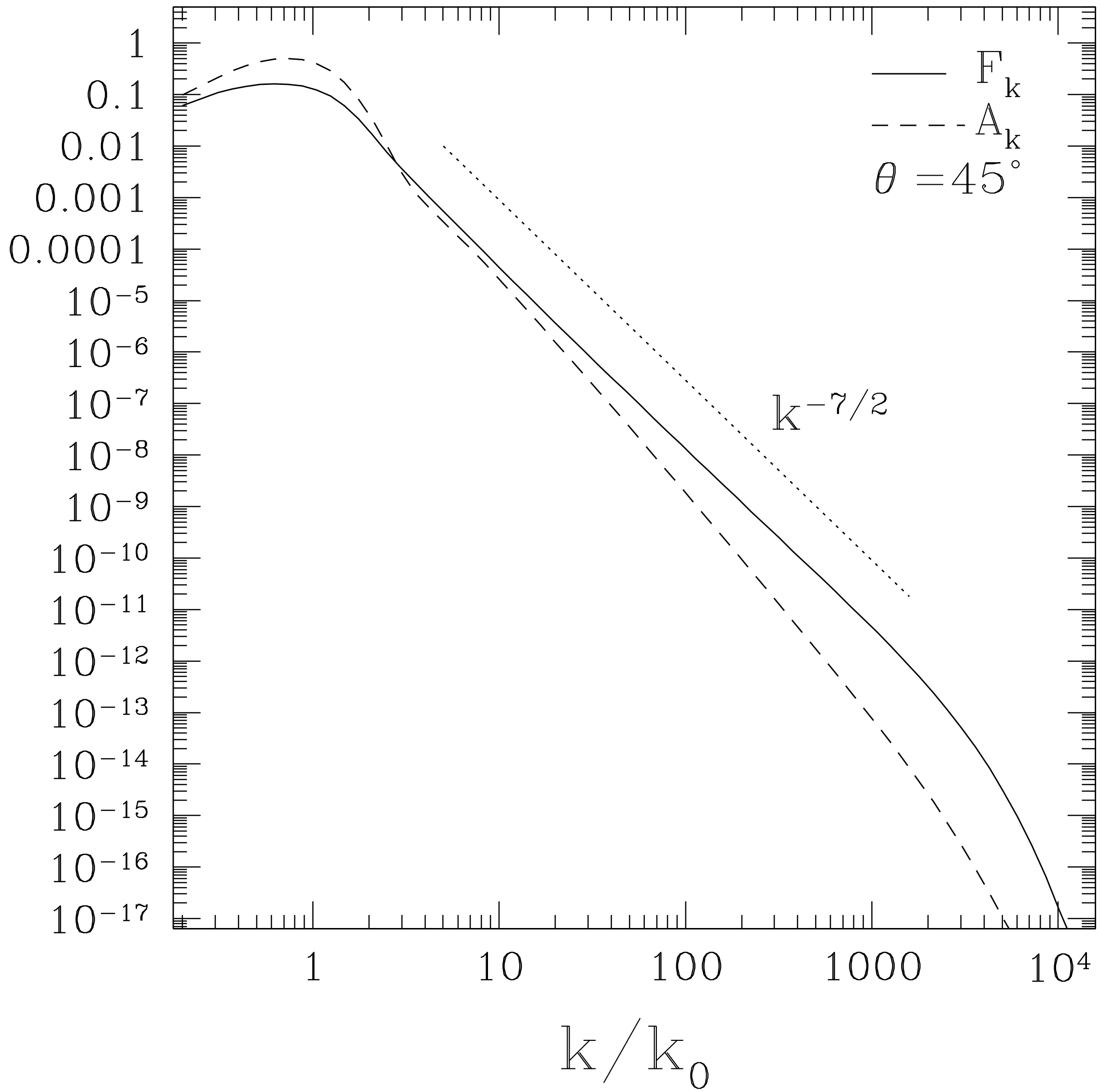


# Structure of solution



# Numerical solutions to wave kinetic equations

(Chandran, Phys. Rev. Lett., 2005)



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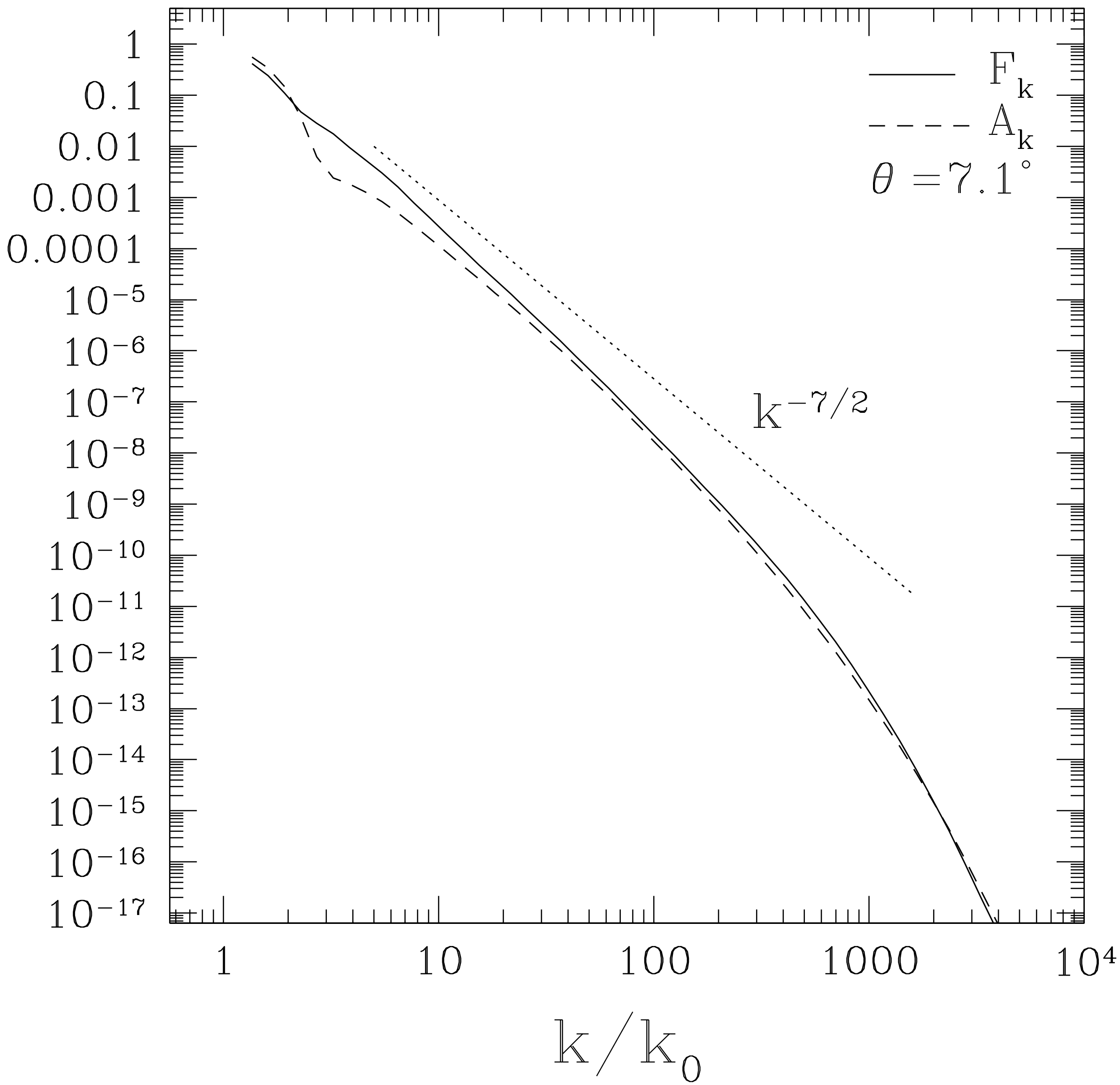

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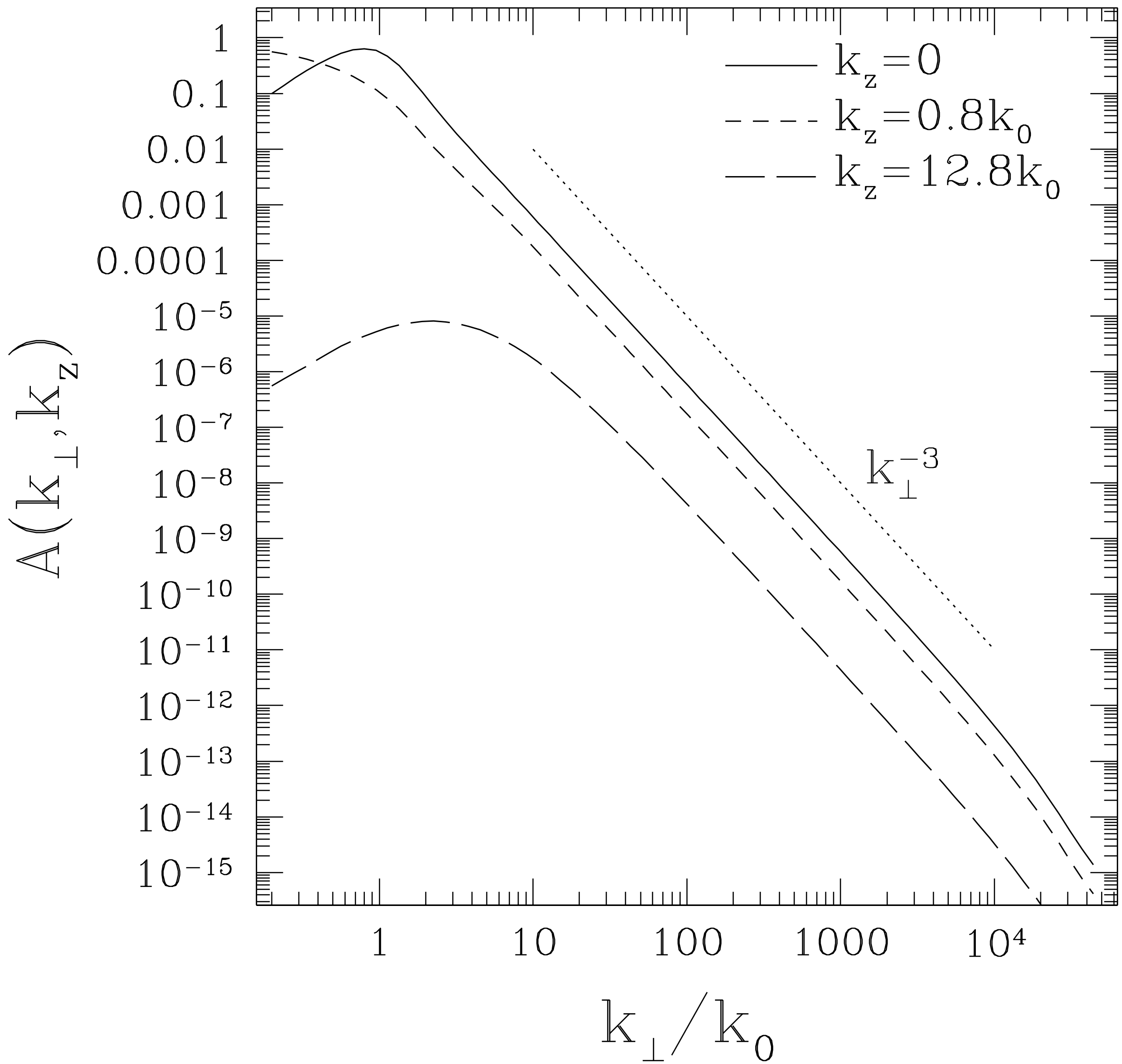
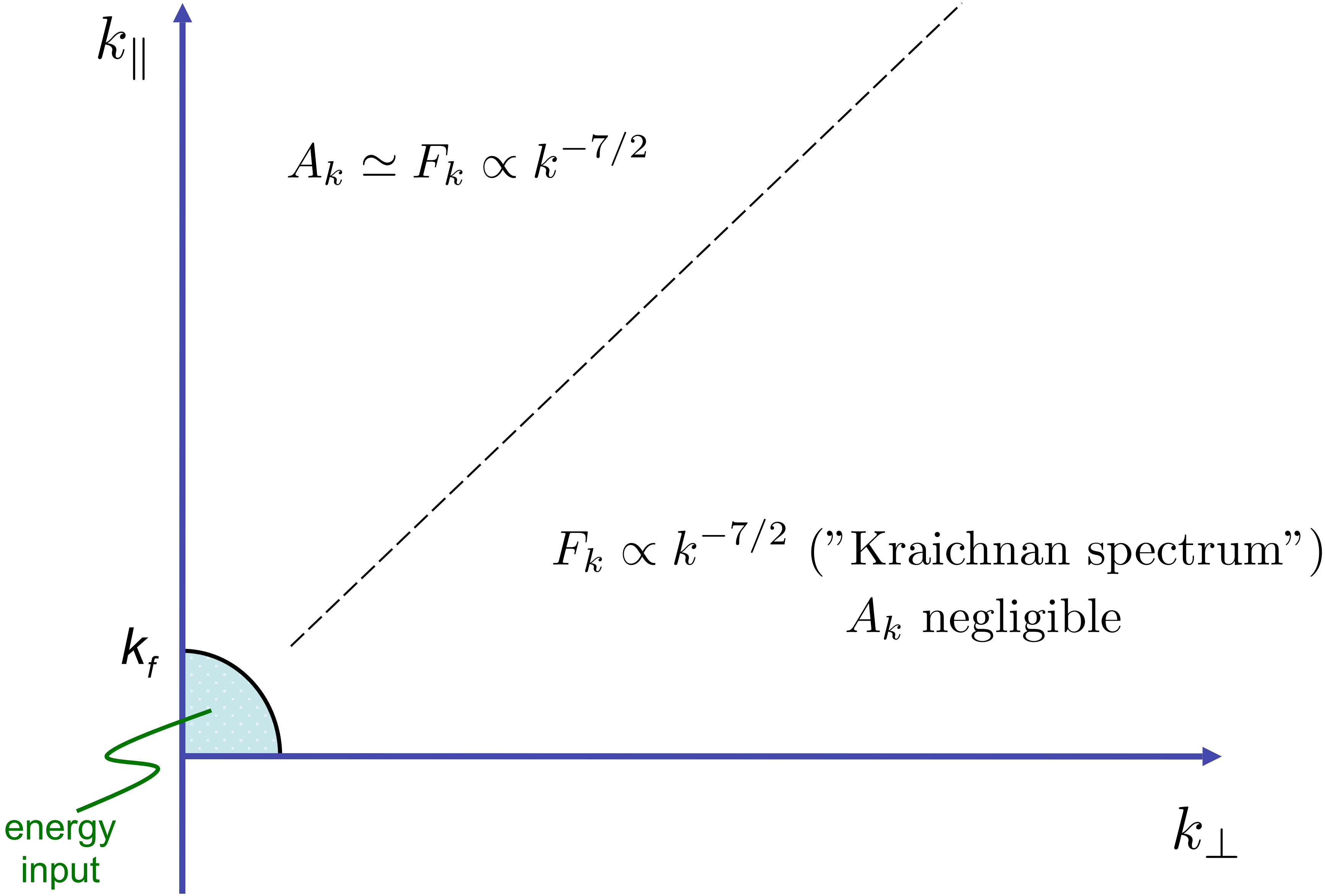
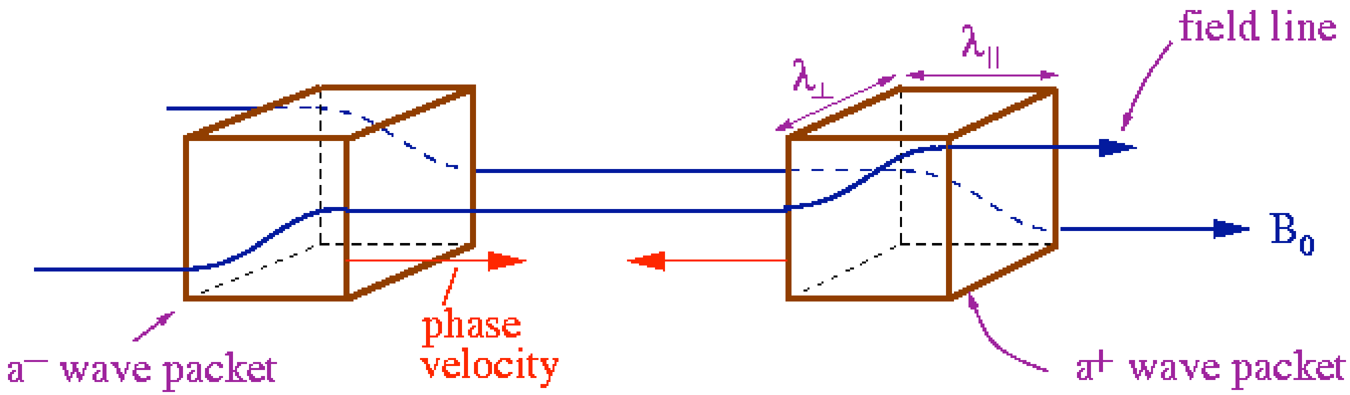


# Structure of solution without counter-propagating waves



BEFORE COLLISION:




DURING COLLISION: each wave packet follows the field lines of the other wave packet (Ng & Bhattacharjee 1996, Maron & Goldreich 2001)

AFTER COLLISION: wave packets pass through each other and are sheared