Stochastic particle acceleration in solar flares

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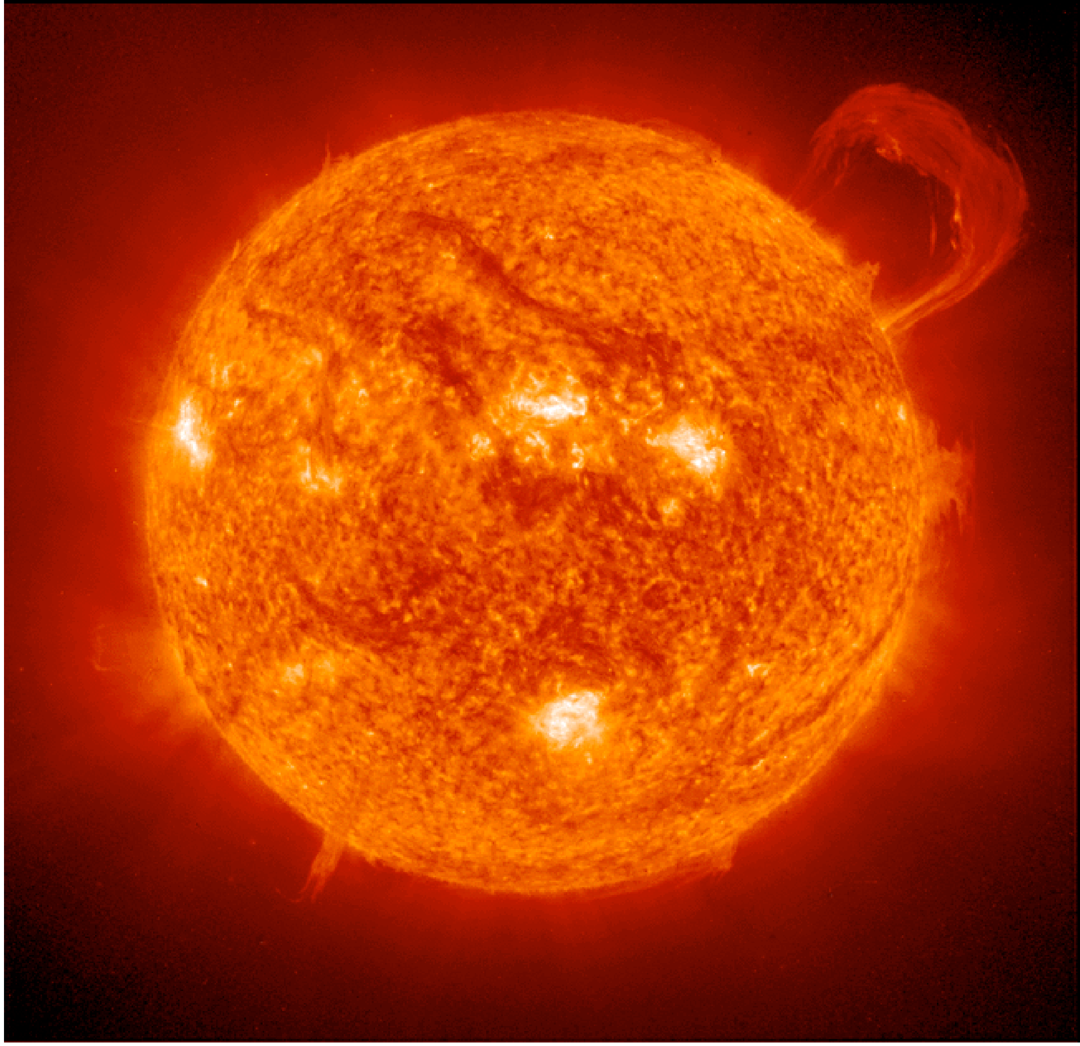
Outline

- Observations
- Overview of stochastic acceleration model
- Plasma waves and turbulence
- Wave-particle interactions
- Application to flares

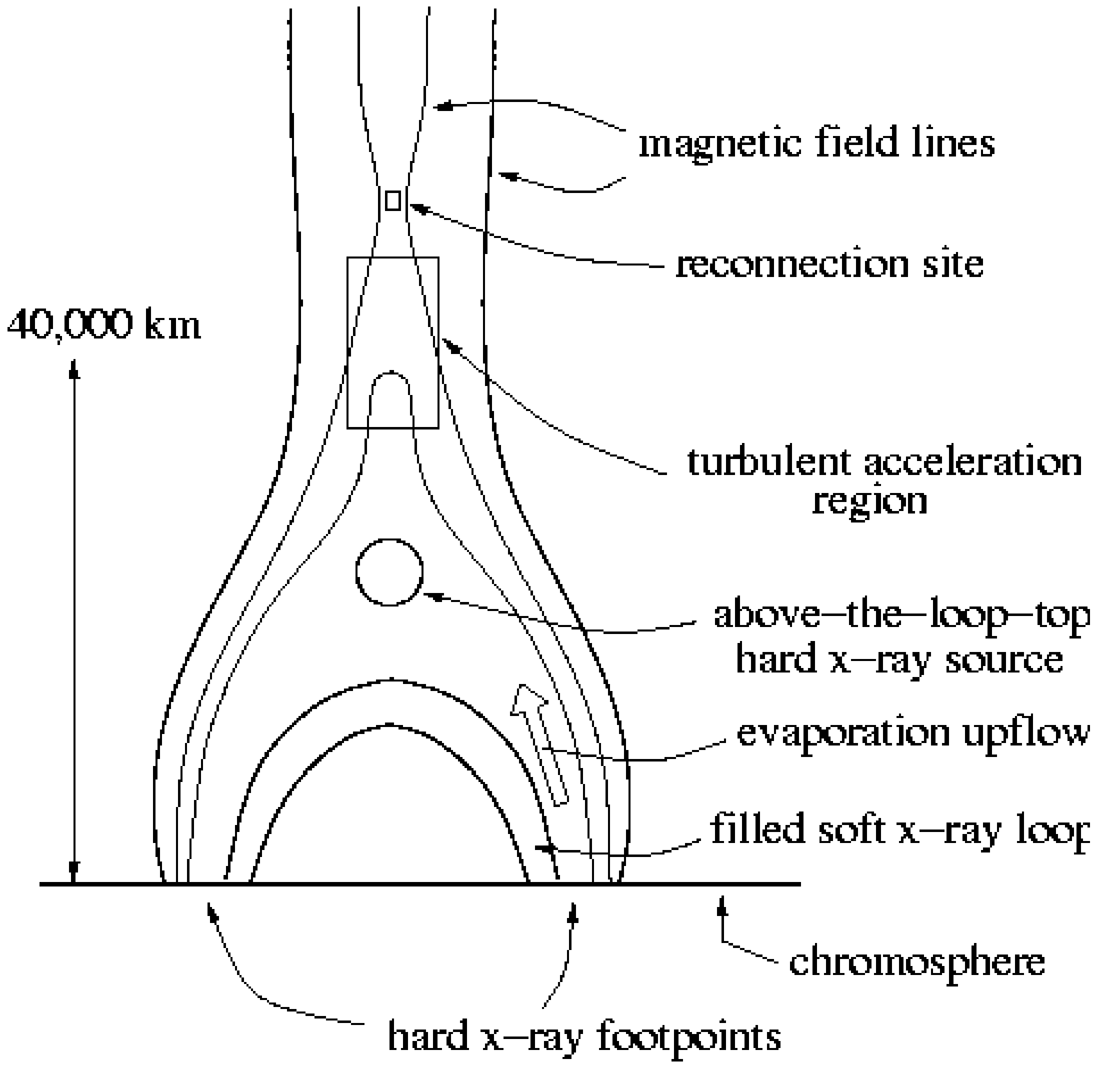
Observations



- 10^{28} - 10^{34} ergs
- 0.5 - 1000 sec
- L of order 10^{9} cm

- X-rays
- Microwaves
- Gamma-rays
- Particles

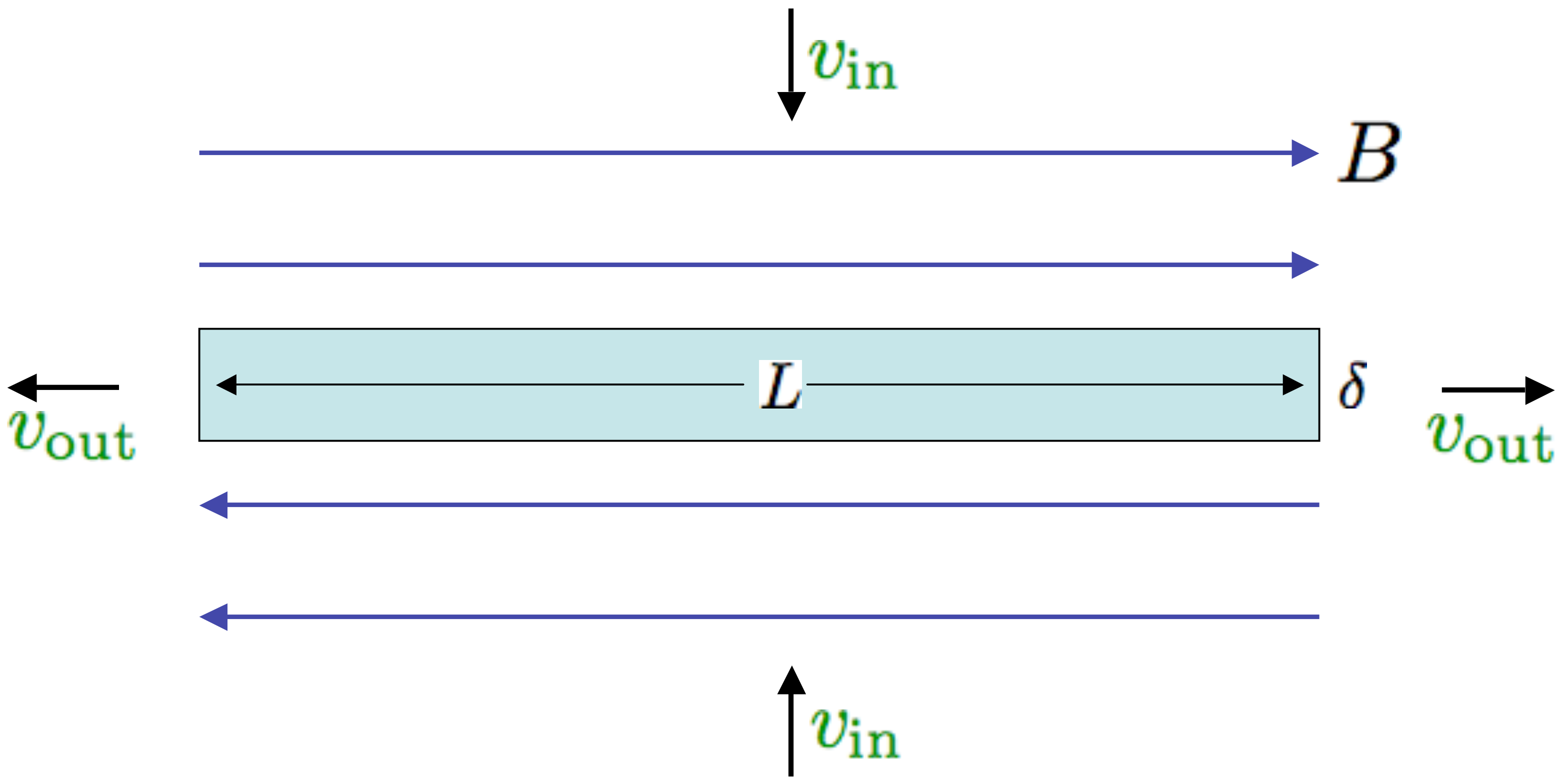
Idealized geometry



Basic idea

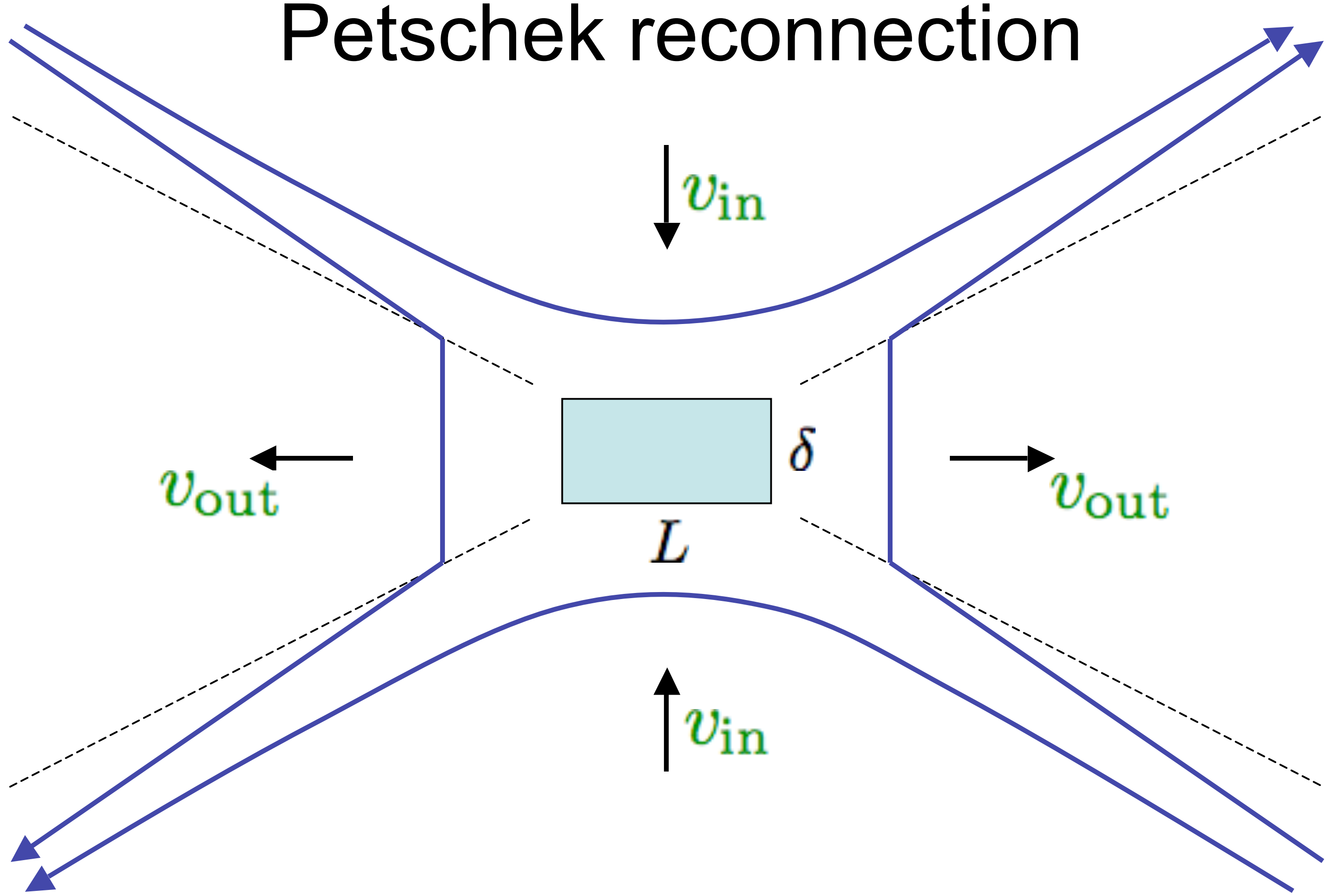
- Trigger
- Reconnection
- Outflow
- Waves/turbulence
- Particle acceleration
- Radiation

Sweet-Parker reconnection



- Magnetic energy dissipated in reconnection layer
- Dissipation involves $E_{||}$
- Too slow to explain flares

Petschek reconnection

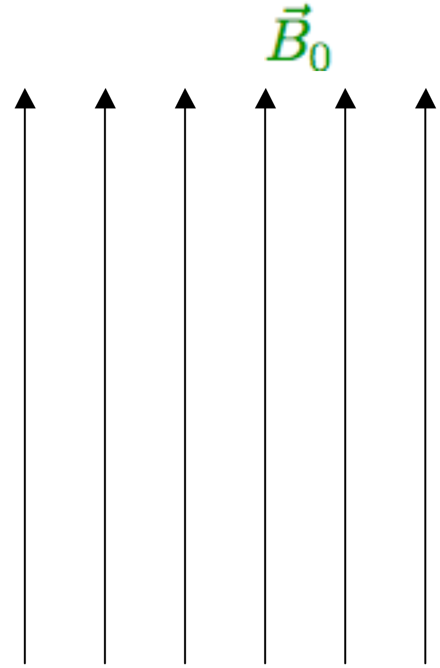


- Fast - more promising for flares.
- Arises with anomalous resistivity and in collisionless reconnection, but not in standard MHD
- **Magnetic energy converted to bulk-flow KE mainly through magnetic tension.**
- Very little magnetic dissipation via $E_{||}$

Energy arguments

- Whatever the physics, most of the magnetic energy is tapped
- Petschek is favored over Sweet-Parker because it is faster
- The acceleration mechanism likely involves the KE generated by magnetic tension
- This argument favors turbulence or shocks over direct E fields

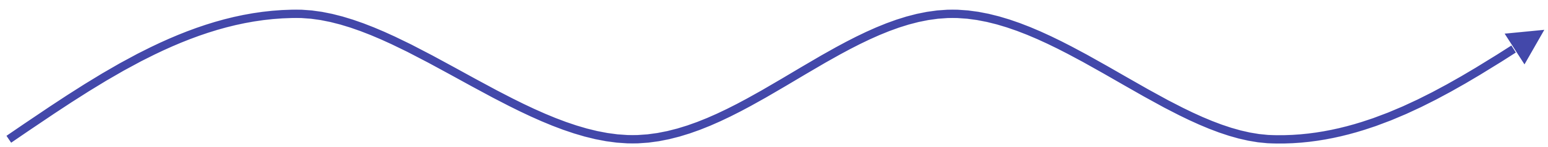
Plasma waves



- $\vec{B} = B_0 \hat{z}$
- $\delta\vec{B},\ \delta\vec{E},\ \delta\vec{v}\ \propto\ e^{i\vec{k}\cdot\vec{r}-i\omega t}$
- Dispersion relation: $\omega = \omega(\vec{k})$

- Alfvén waves $(\omega = k_{\|} v_A,\ \ v_A^2 = B_0^2/4\pi\rho)$
- fast magnetosonic waves ("fast waves" - $\omega = k v_A$)
- ion-cyclotron waves
- whistler waves

Alfven wave



- like a wave on a string
- $\omega = k_{||} v_A$ when $\omega \ll \Omega_i$,
- propagates along magnetic field lines
- $\delta\vec{B} \perp \vec{B}_0$, so to first order, no perturbation to field strength:

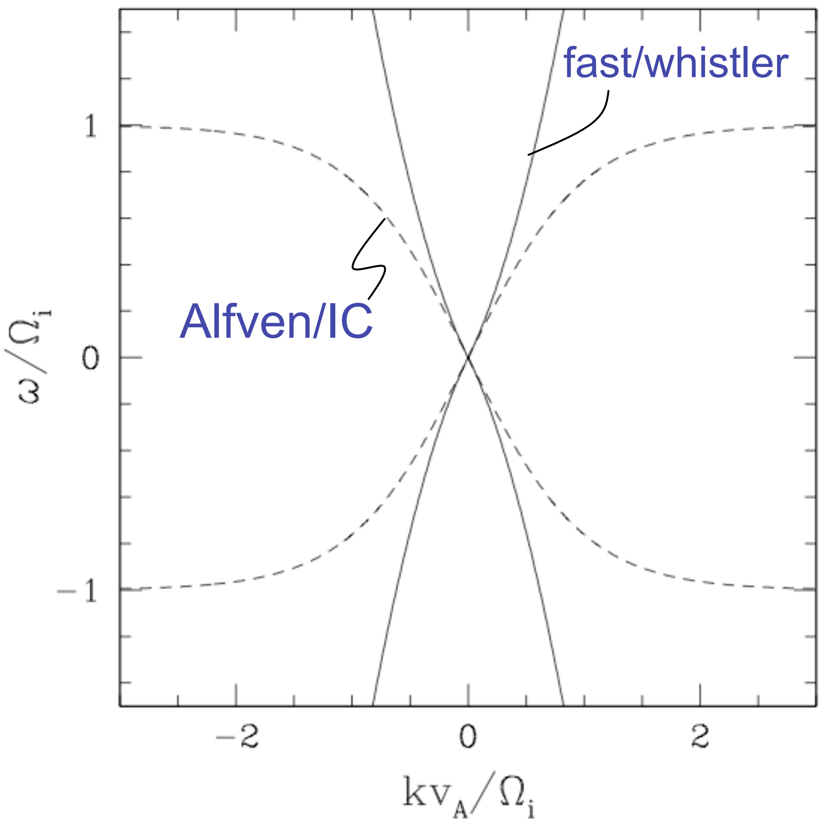
$$|\vec{B}_0 + \delta\vec{B}| = \sqrt{B_0^2 + 2\vec{B}_0 \cdot \delta\vec{B} + (\delta B)^2} = \sqrt{B_0^2 + (\delta B)^2}$$

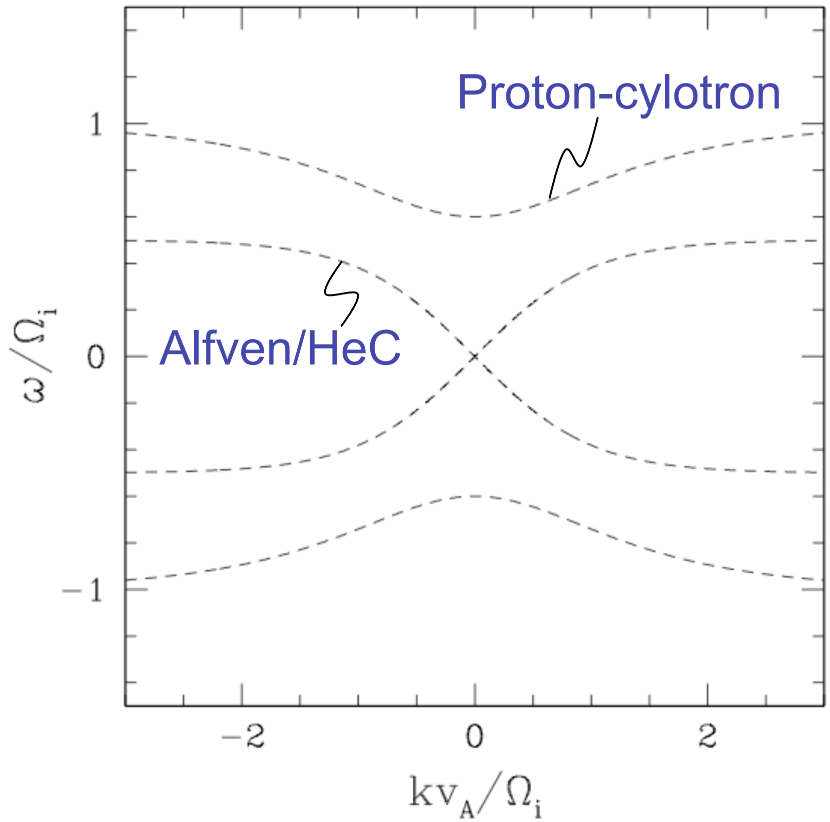
$$= B_0 \sqrt{1 + \frac{(\delta B)^2}{B_0^2}} \simeq B_0 \left[1 + \frac{(\delta B)^2}{2B_0^2}\right]$$

Fast magnetosonic wave
("fast wave")

- $\omega = kv_A$ when $\beta = \dfrac{8\pi p}{B^2} \ll 1$ and $\omega \ll \Omega_i$
- in some ways like a sound wave
- $\delta\vec{B}$ is not $\perp$ to $\vec{B}_0$
- field-strength perturbation is much stronger than for the Alfvén wave

Whistlers and ion-cyclotron waves

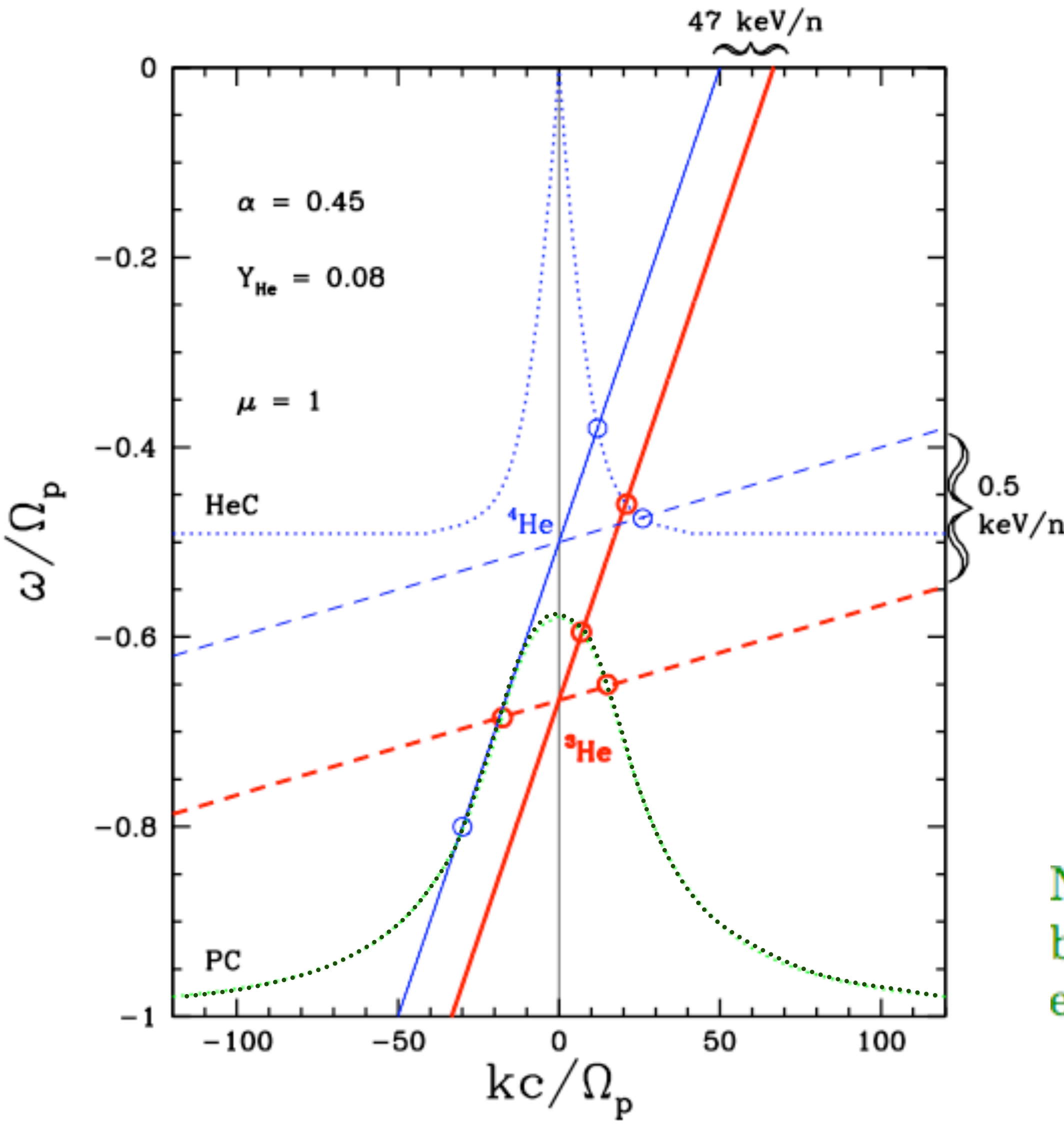




$$\Omega_i = \frac{qB}{mc} = \text{proton cyclotron frequency}$$

- Parallel propagation
- Left panel: proton/electron plasma
- Right panel: protons, alpha particles, and electrons

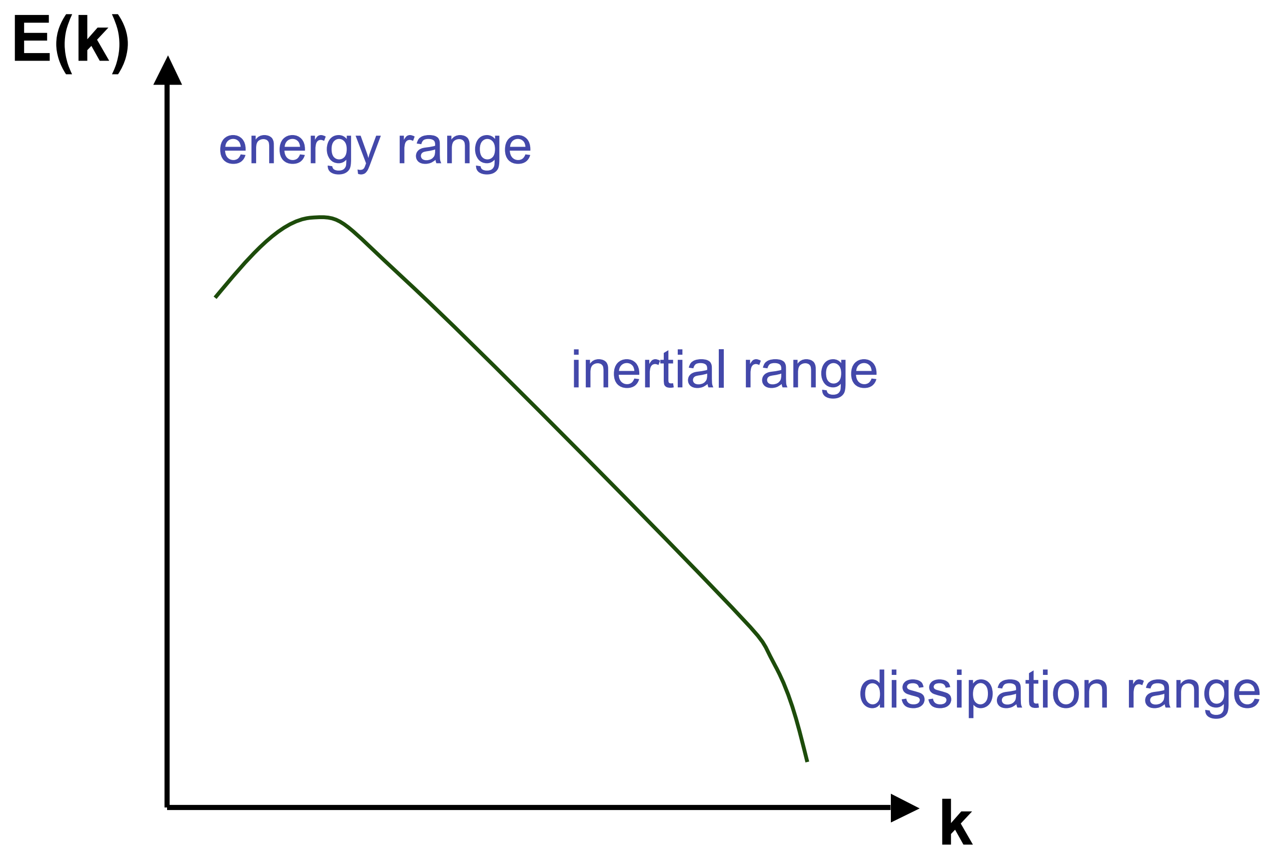
Ion-cyclotron waves



(Liu, Petrosian, & Mason 2004)

Note: as $\omega \rightarrow \Omega$, the IC waves become left-hand circularly polarized, even for oblique propagation

Turbulence and energy cascade



(log-log plot --- power-law inertial-range spectrum)

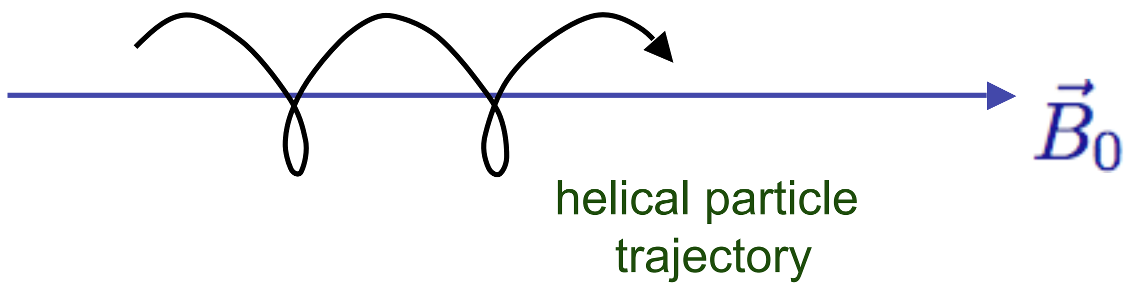
Wave-particle interactions

- Cause diffusion in momentum space
- This talk: focus on small-amplitude waves

Topics

- Resonance condition
- “energy-conservation” reference frame
- Transit-time damping/Landau resonance
- Cyclotron resonance

Resonance condition



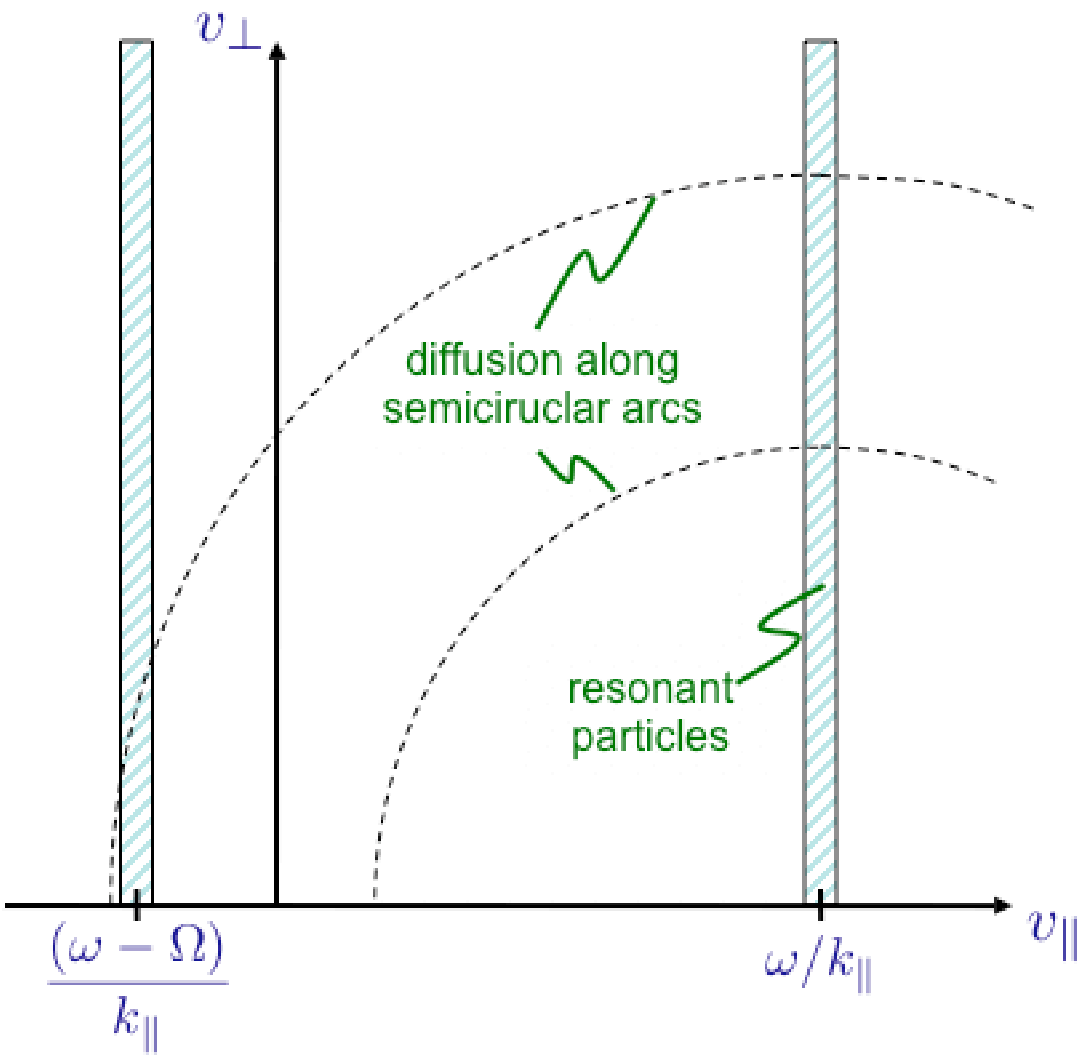
- Consider $\delta\vec{E} = \delta\vec{E}_0 \cos(\vec{k}\cdot\vec{x} - \omega t)$
- Let $\vec{x} = \vec{x}' + v_{||}\hat{b}t$, where $\hat{b} = \vec{B}_0/B_0$
- Primed frame moves with particle guiding center
- Consider $\delta\vec{E} = \delta\vec{E}_0 \cos[\vec{k}\cdot\vec{x}' - (\omega - k_{||}v_{||})t]$, where $k_{||} = \vec{k}\cdot\hat{b}$
- $\omega - k_{||}v_{||}$ = Doppler-shifted frequency in guiding center frame
- Wave-particle resonance when $\omega - k_{||}v_{||} = n\Omega$

Energy conservation frame

- Conisder a frame moving at $\vec{u} = \hat{b}\omega/k_\parallel$ with respect to the plasma
- the wave frequency in this frame is $\omega - k_\parallel u = 0$
- fluctuations are static: $\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t} = 0.$
- $\longrightarrow \vec{E} = -\nabla\Phi$
- Energy gain $= \Delta\mathcal{E} = q\Delta\Phi \longrightarrow$ energy gain can not accumulate over time
- Energy effectively conserved in this frame, but particle direction can change (pitch-angle scattering).

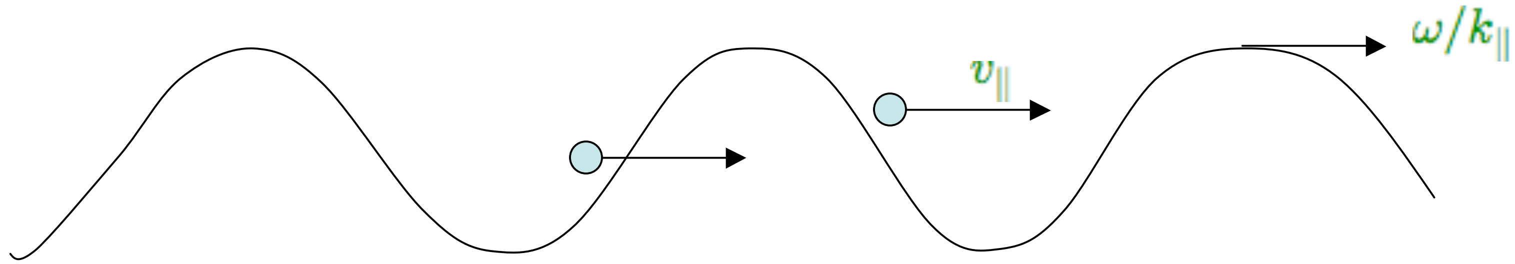
Resonant wave-particle interactions

- wave-particle resonance condition: $\boxed{\omega - k_{\|} v_{\|} = n\Omega}$



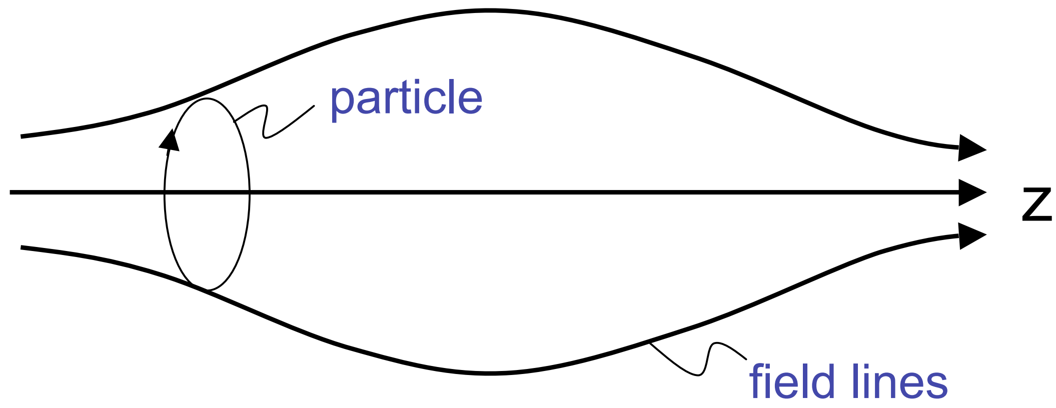
- particle energy is conserved in frame moving at speed $\omega/k_{\|}$ along $\boldsymbol{B}_0$
- n=0 (Landau) resonance results in only parallel heating

Landau resonance



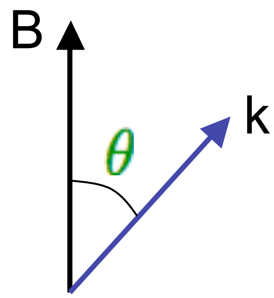
- $n = 0 \quad \longrightarrow \quad \omega - k_{||} v_{||} = 0 \quad \longrightarrow \quad v_{||} = \omega / k_{||}.$
- requires that the wave exert a parallel force on the particle
- for MHD waves, there is no $E_{||}$
- parallel force can only arise from the magnetic perturbation

"mu grad-B" force



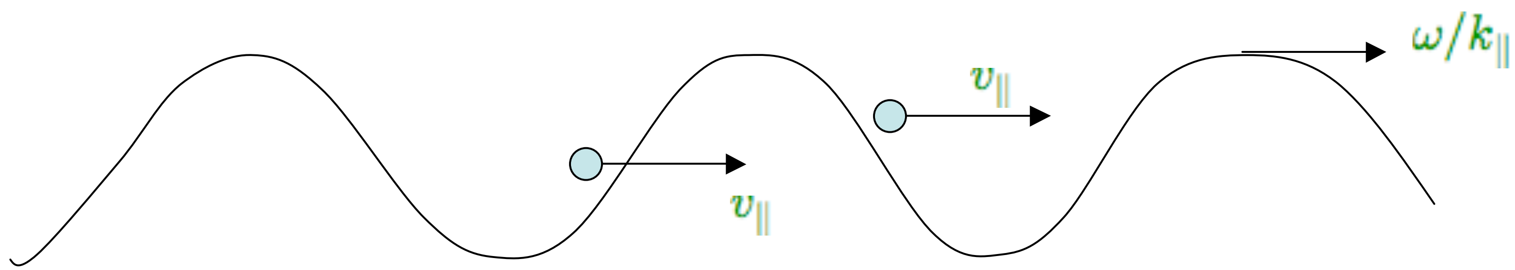
- $\vec{F} = \frac{q\vec{v} \times \vec{B}}{c}$
- gyroradius: $\rho = v_\theta / \Omega$
- qualitatively: $F_z = -q v_\theta B_r / c \propto v_\theta^2 \nabla B$
- quantitatively: $F_z = -\mu \nabla |\vec{B}|$, where $\mu = m v_\theta^2 / 2B$.
- Alfven wave has no $\delta |B|$ to first order in wave amplitude, so does not exert a parallel force
- Fast wave does.
- resonant parallel acceleration by $\delta |\vec{B}|$ called "transit-time damping" (TTD)

Transit-time damping by fast waves



- Resonant particles have $v_{\|} = \dfrac{\omega}{k_{\|}} = \dfrac{k v_A}{k_{\|}} = \dfrac{v_A}{\cos\theta}$
- Thermal ions have $v_{\|} \ll v_A$ and don't undergo TTD
- Thermal electrons have $v_{\|} \sim v_A$ and do undergo TTD
- If there is a continuous range of θ, electrons can be accelerated up to relativistic energies

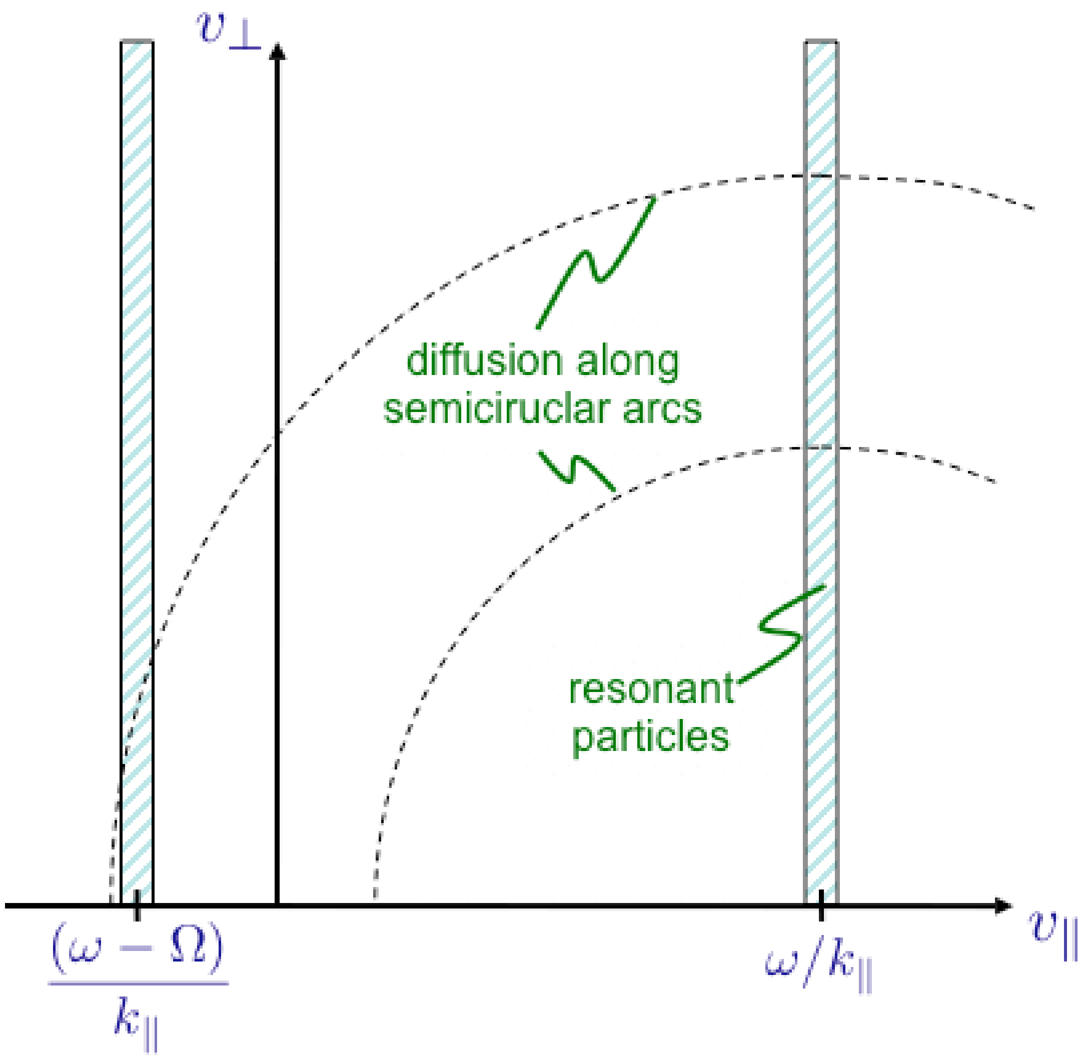
Diffusion in $v_{||}$



- In frame moving at $\vec{u} = \hat{b}\omega/k_{||}$, the wave is stationary,
- If the particle is moving slowly in this frame ($v_{||} \simeq \omega/k_{||}$), it is strongly affected by the wave
- the particle either gains or loses energy.
- the particle then resonates with a different wave
- $\longrightarrow$ diffusing in momentum space

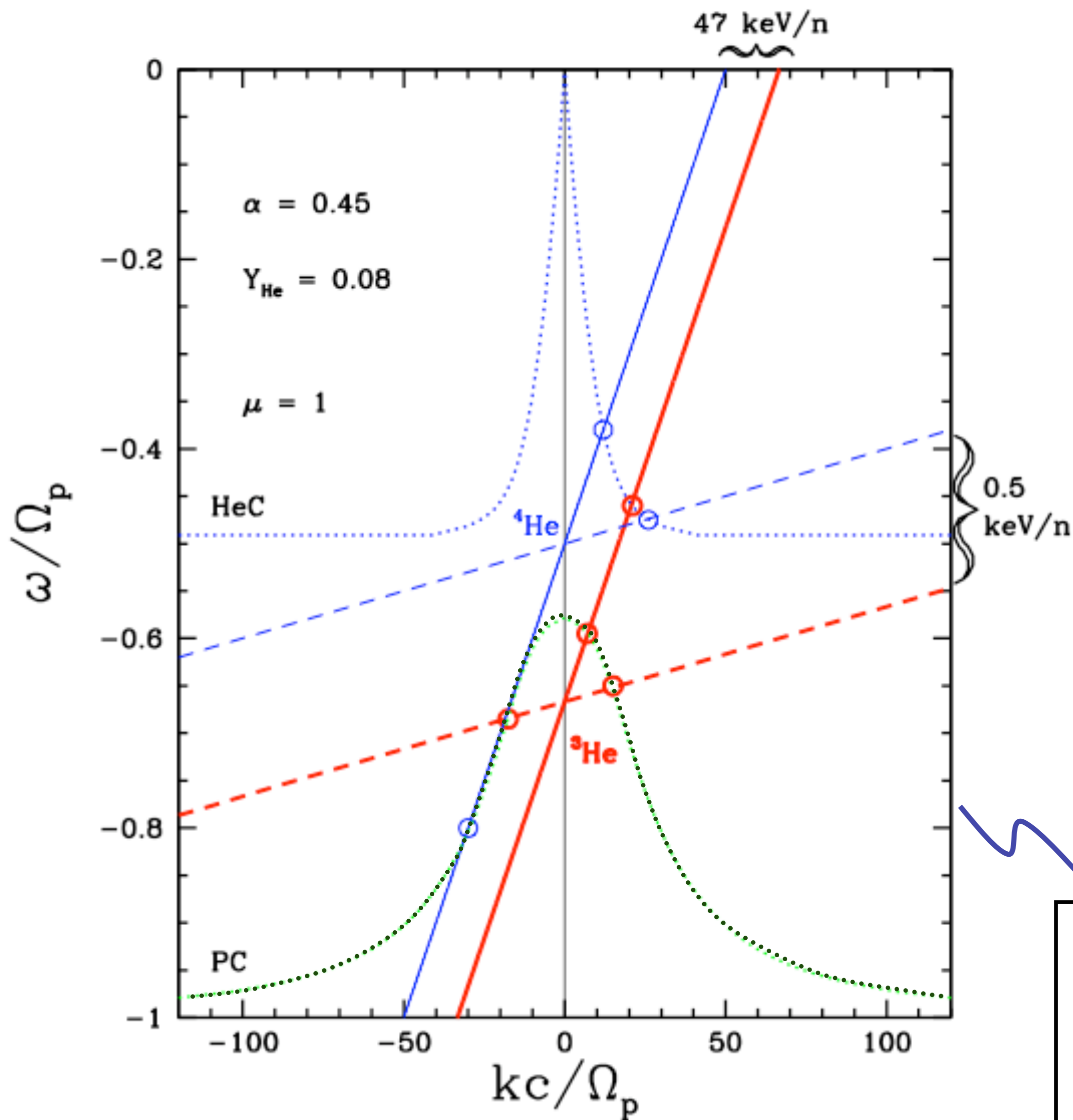
Resonant wave-particle interactions

- wave-particle resonance condition: $\boxed{\omega - k_{\|} v_{\|} = n\Omega}$



- particle energy is conserved in frame moving at speed $\omega / k_{\|}$ along $\boldsymbol{B}_0$
- n=0 (Landau) resonance results in only parallel heating

Ion heating via the cyclotron resonance

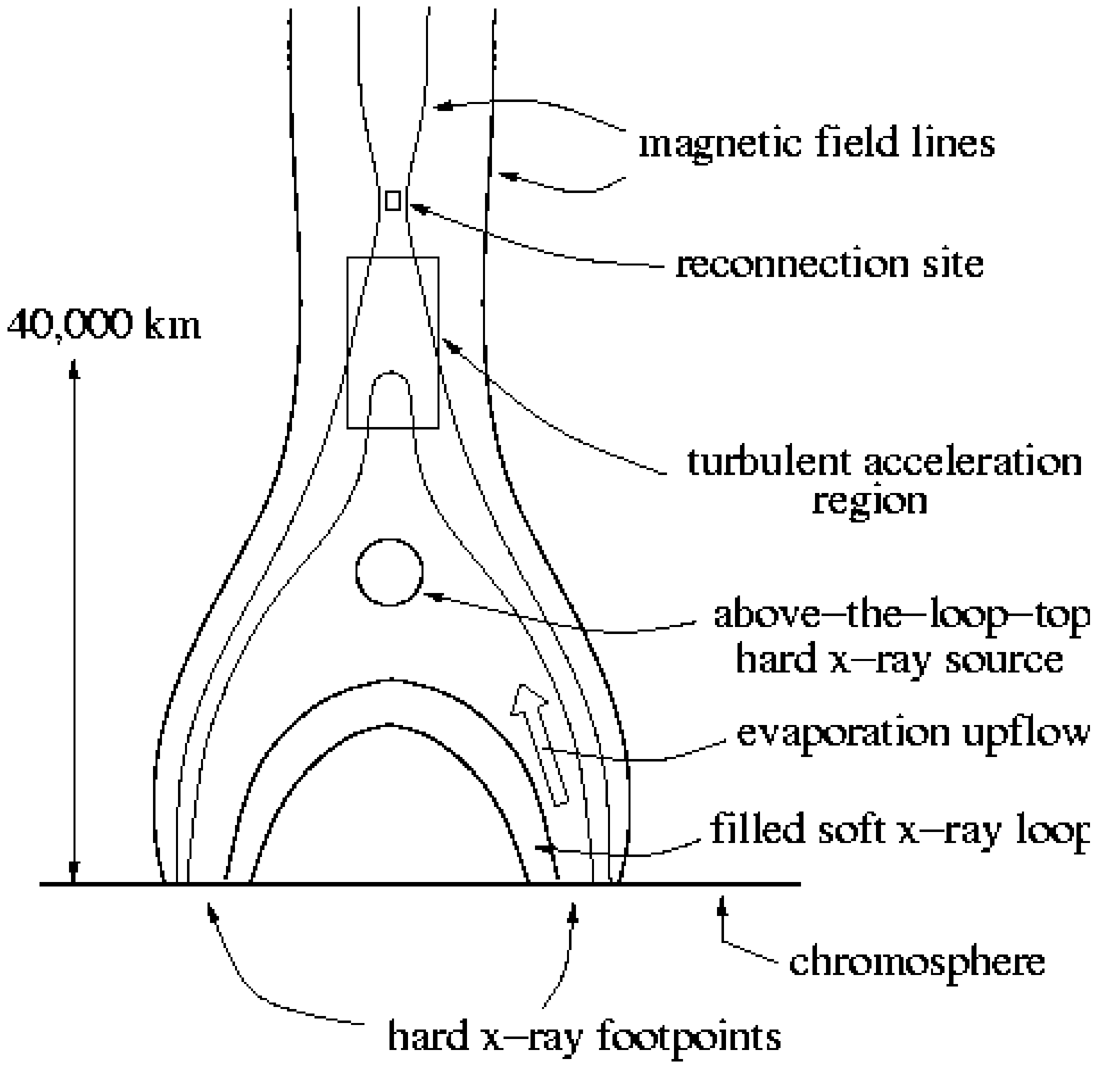


(Liu, Petrosian, & Mason 2004)

- $\omega = n\Omega + k_{\parallel} v_{\parallel}$
- requires a component of left-hand circular polarization
- works for PC and HeC waves
- Does not work for fast/whistler at parallel propagation
- Can work for oblique fast waves

- straight lines give $\omega = -\Omega + k_{\parallel} v_{\parallel}$ for different values of $v_{\parallel}$
- dotted lines give the dispersion relations

Application to flares



- Trigger
- Reconnection
- Outflow
- Waves/turbulence
- Particle acceleration
- Radiation

Electron acceleration by TTD and fast waves

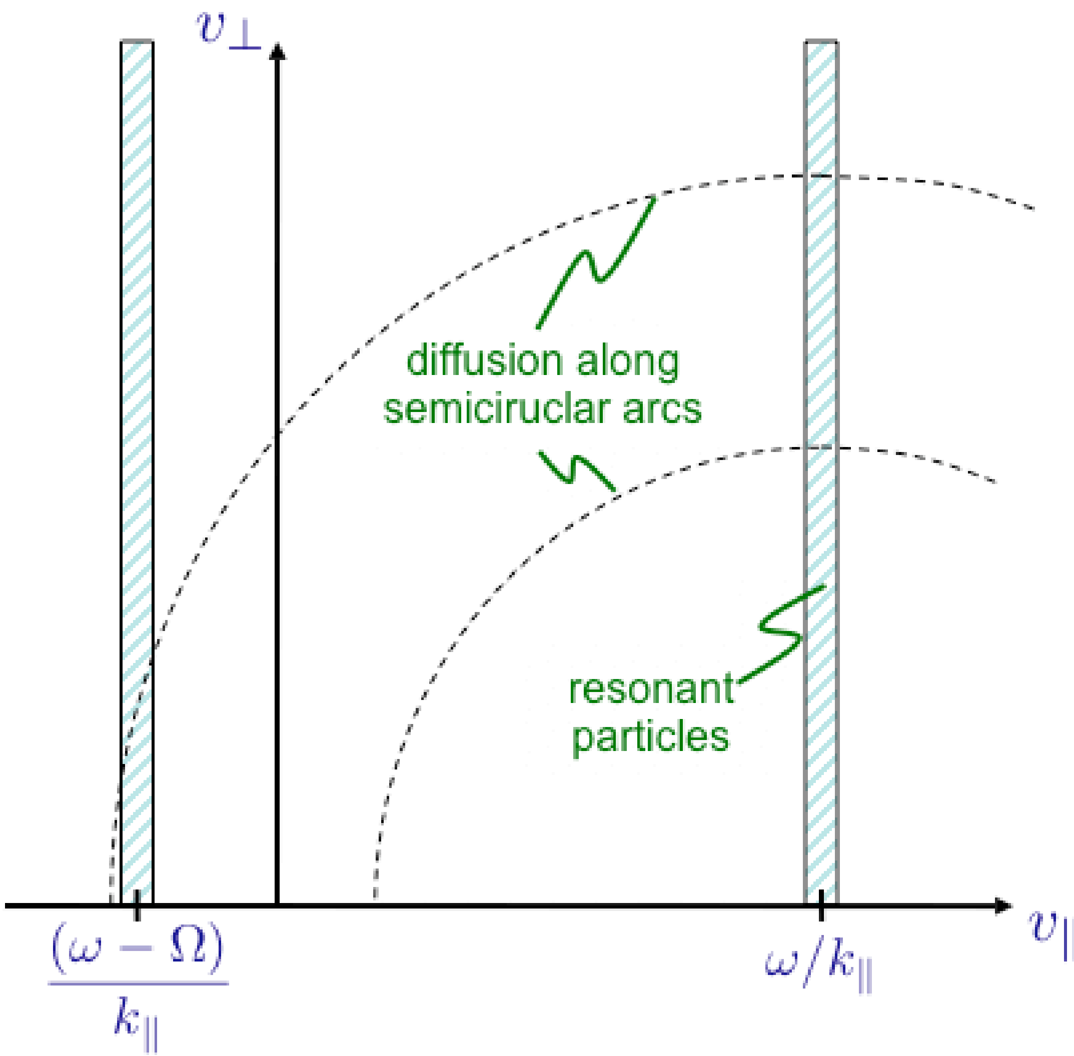
- Can energize electrons to 100 keV in <1 sec for modest overall turbulent energies (in contrast to, e.g., whistlers.) (Miller, LaRosa, & Moore 1996, Miller et al 1997.)

- Energy spectrum of particles depends on particle escape from acceleration region, and Coulomb losses at lower energies. Not clear how well the spectra agree with observations.

- Main open questions:
  - Nature of turbulence
  - Energy spectrum of particles

Ion heating in flares

• wave-particle resonance condition: $\boxed{\omega - k_{\|} v_{\|} = n\Omega}$



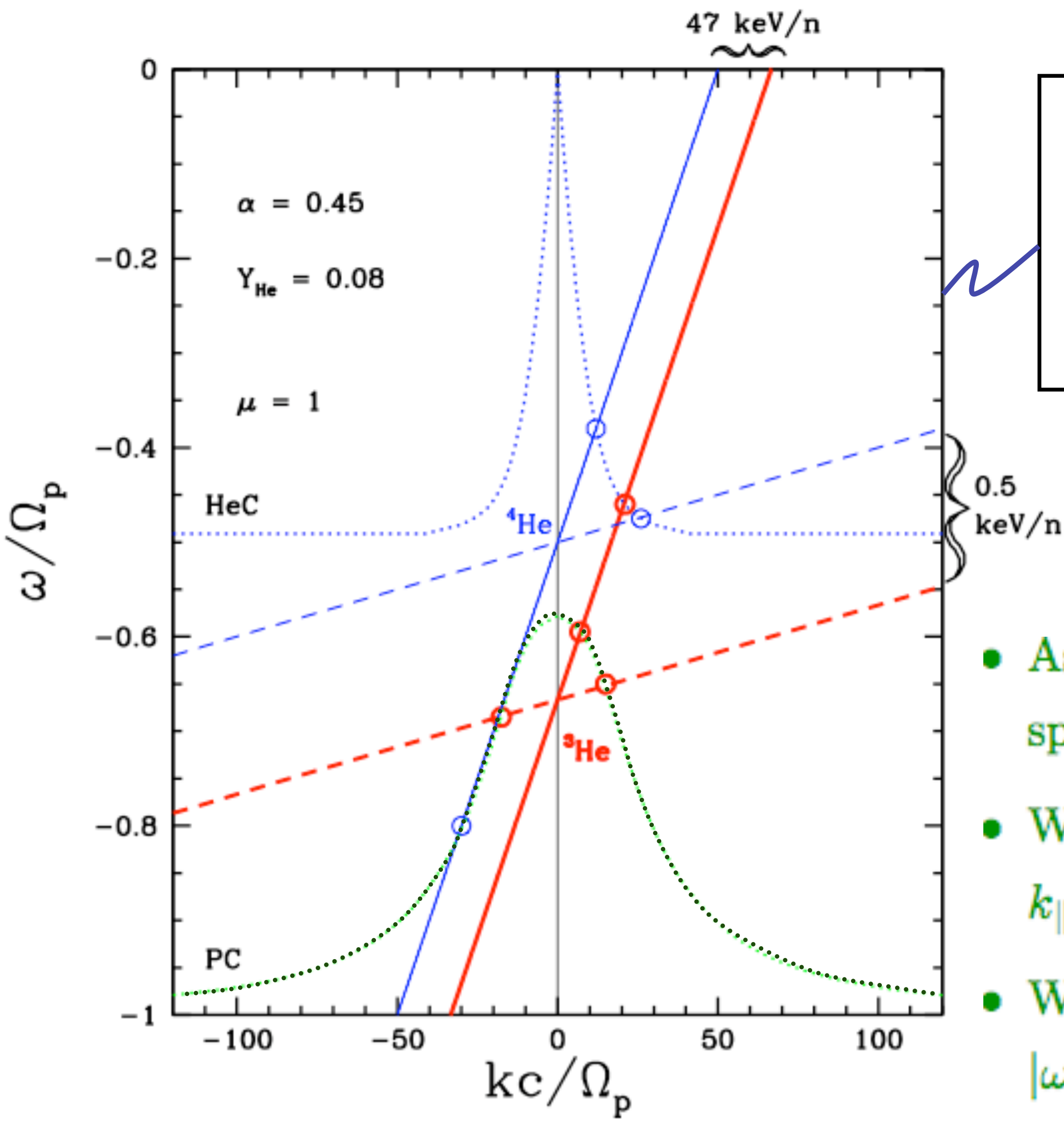
• Acceleration of thermal ions by ion cyclotron waves.
(e.g., Eichler 1979, Miler & Roberts 1995)

• Later acceleration of ions from TTD by fast
(e.g., Emslie, Miller, & Brown 2004).

• Can provide acceleration time scale for modest turbulent energies

• Open questions:
nature of turbulence
particle spectra

Preferential ^{3}He acceleration

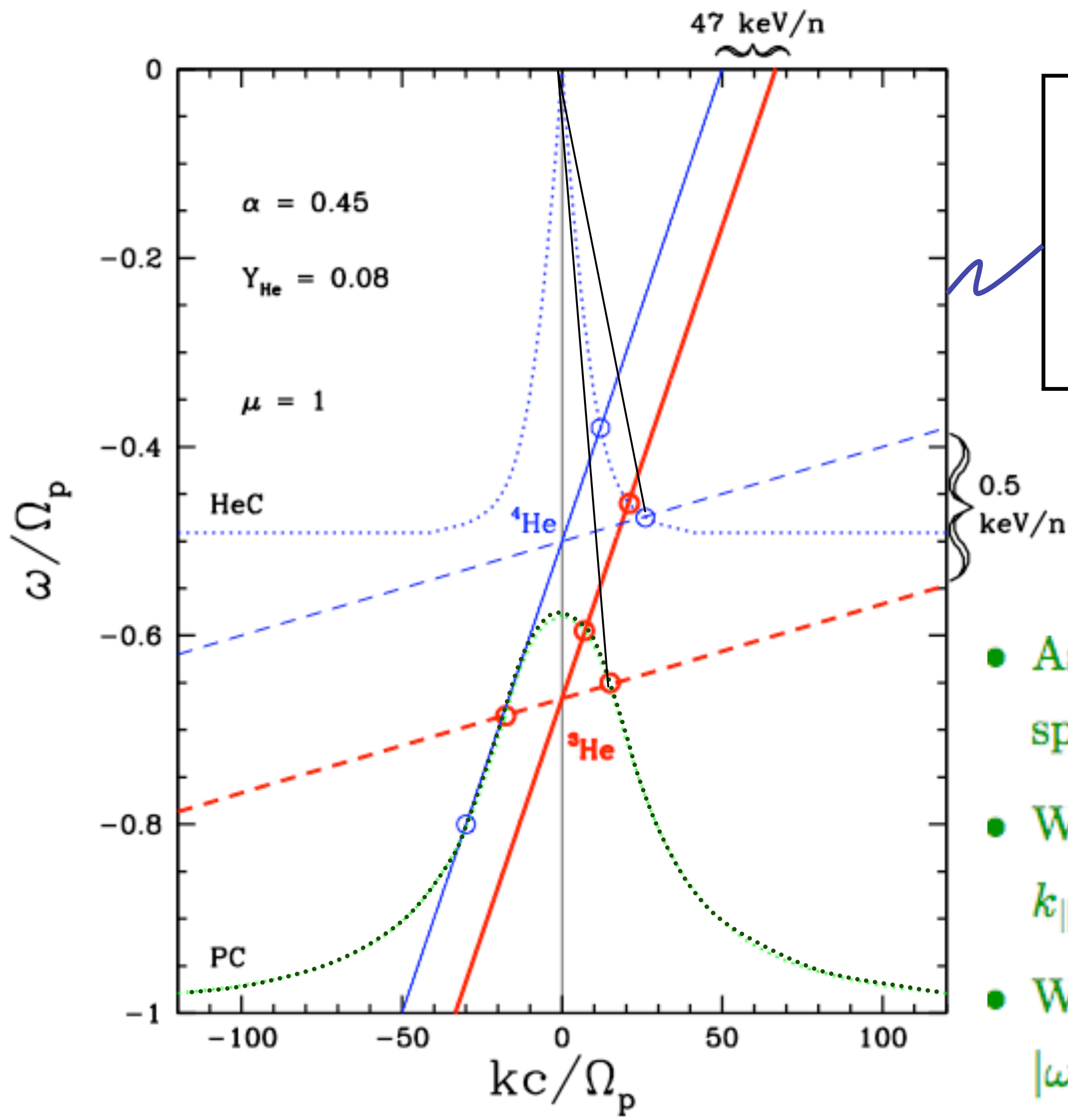


(Liu, Petrosian, & Mason 2004)

- straight lines give $\omega = -\Omega + k_{\|} v_{\|}$ for different values of $v_{\|}$
- dotted lines give the dispersion relations

- Assume magnetic field has same power spectrum for each type of wave
- Waves resonating with ^{3}He have smaller $k_{\|}$ than waves resonating with ^{4}He
- Waves resonating with ^{3}He have larger $|\omega/k_{\|}|$ than waves resonating with ^{4}He

Preferential ^{3}He acceleration



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Why is phase velocity important?

$$\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t} \longrightarrow i\vec{k} \times \delta\vec{E} = \frac{i\omega}{c}\delta\vec{B}$$

Let $\vec{k} = k_{||}\hat{b} \longrightarrow \delta\vec{B} \perp \hat{b}$

for the waves we're considering, $\vec{k} \parallel \hat{b} \longrightarrow \delta\vec{E} \perp \hat{b}$

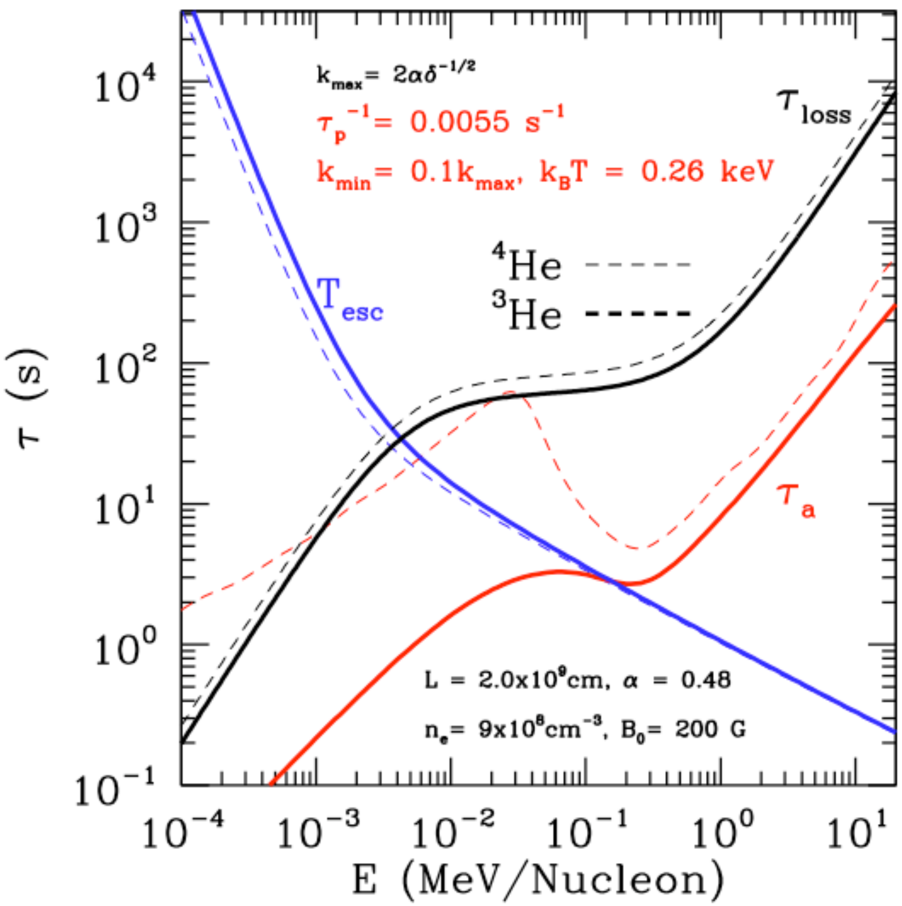
$$|k_{||}\delta E| = \left|\frac{\omega}{c}\delta B\right|$$

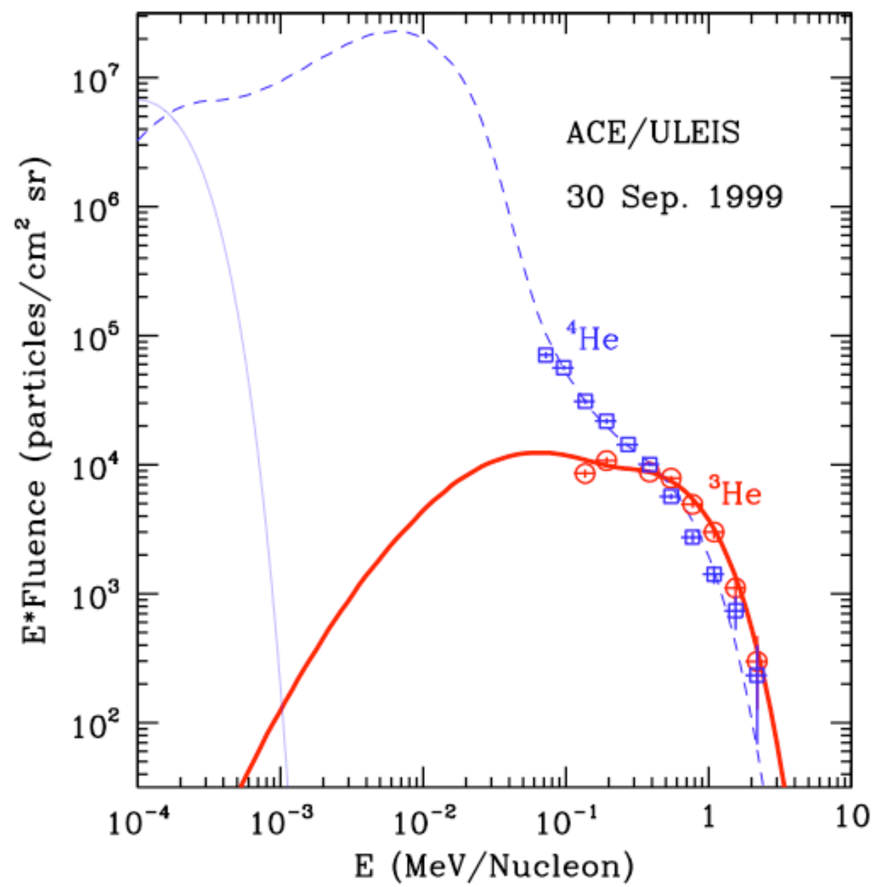
$$|\delta E| = \left(\frac{\omega}{k_{||}c}\right)|\delta B|$$

Now, $\vec{v} \cdot \vec{F} = \vec{v} \cdot q\left(\vec{E} + \frac{\vec{v} \times \vec{B}}{c}\right) = \vec{v} \cdot \vec{E}.$

It's δE, not δB, that accelerates the particle

Time scales for ^{3}He and ^{4}He acceleration





(Liu, Petrosian, & Mason 2004)

Attractive features of SA model for impulsive flares

- Strong arguments (and growing evidence from numerical simulations) that turbulence exists in flares
- Can explain short acceleration time for modest turbulent energy
- Can accelerate both ions and electrons out of thermal pool and up to high energies
- Can explain large ^{3}He enhancement
- But: more work needed to understand the turbulence and particle energy spectra

Summary

- Alfven waves, fast waves, cyclotron waves, whistler waves
- Wave-particle resonance condition
- Energy-conservation frame
- TTD by fast waves - good for accelerating electrons and energetic ions
- Cyclotron resonance - good for accelerating thermal ions
- Stochastic acceleration can in principle explain the enhancement of ^{3}He in impulsive flares