



Effects of dispersive wave modes on charged particles transport

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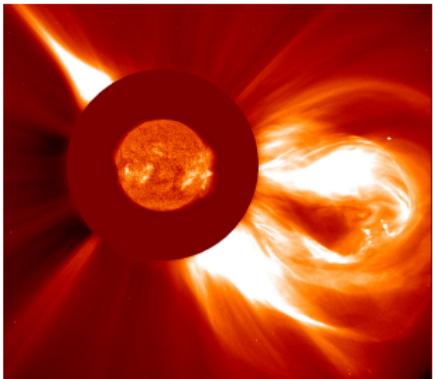
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ICRC 2015 – SH08



Heliosphere and Solar Wind:

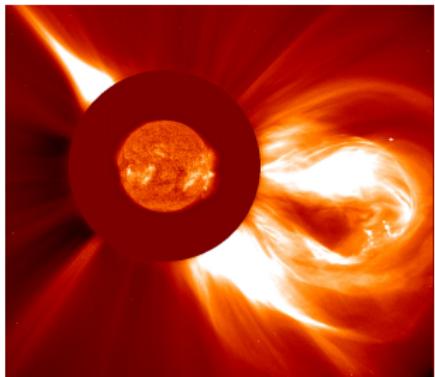
- magnetized, thermal background plasma
- plasma waves, shocks, magnetic inhomogeneities, ...
- particle scattering and acceleration
- ⇒ non-thermal population of energetic particles



Source: Sun-Earth Day 2010, NASA Goddard Space Flight Center

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Transport of Energetic Particles:

- interaction of particles and magnetic fields
- resonant scattering of particles and waves
- acceleration of energetic particles

Theoretical Modeling:

- quasi-linear Vlasov theory with test particle approach
- Fokker-Planck diffusion equation → pitch angle diffusion coefficient
- efficient scattering of particles at resonant pitch angle μ_{res}

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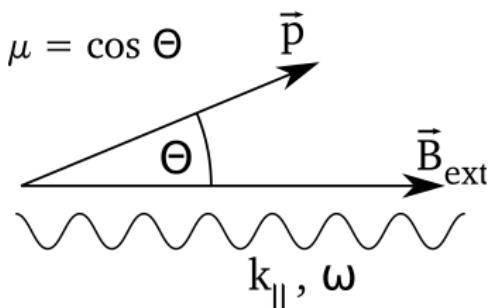
resonance condition:

plasma frame:

$$k_{\parallel} v_s \mu_{\text{res}} + n \Omega_s / \gamma_s - \omega = 0$$

wave frame:

$$k_{\parallel} v_s \mu_{\text{res}} + n \Omega_s / \gamma_s = 0$$



Wave Frame:

$$k_{\parallel} v'_s \mu'_{\text{res}} + n \Omega_s / \gamma'_s = 0$$

- particle speed v'_s
- Lorentz factor γ'_s
- pitch angle cosine μ'

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Wave Propagation

$$|\boldsymbol{k}| = k_{\parallel}, \quad v_{\text{ph}} = \frac{\omega}{k_{\parallel}}, \quad \boldsymbol{v}_{\text{ph}} \parallel \boldsymbol{B}_{\text{ext}}$$

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- $v'_s = \sqrt{v_s^2 - 2 v_s v_{\text{ph}} \mu + v_{\text{ph}}^2}$
- $\gamma'_s = \left(\sqrt{1 - \left(\frac{v'_s}{c} \right)^2} \right)^{-1}$
- $\mu' = \frac{\mu v_s - v_{\text{ph}}}{\sqrt{v_s^2 - 2 v_s v_{\text{ph}} \mu + v_{\text{ph}}^2}}$

Wave Frame:

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Plasma Frame:

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Theoretical Predictions

in the rest frames of the wave or the plasma

standard QLT:

$$\Delta\mu'^{\pm}(\mu', t, \Psi'^{\pm})$$

⇒ wave frame only
(magnetostatic limit)

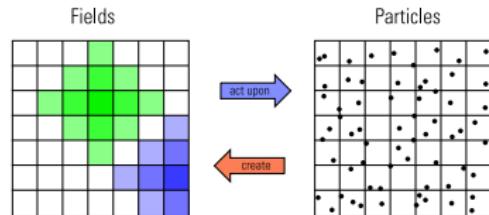
QLT + transformations:

$$\Delta\mu^{\pm}(\mu, t, \Psi^{\pm})$$

⇒ plasma frame

Particle-in-Cell (PiC) method:

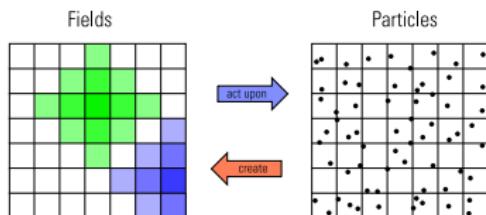
- self-consistent, kinetic simulation
- high spatial and temporal resolution
- computationally expensive
- artificial mass ratio m_p/m_e



Numerical Approach

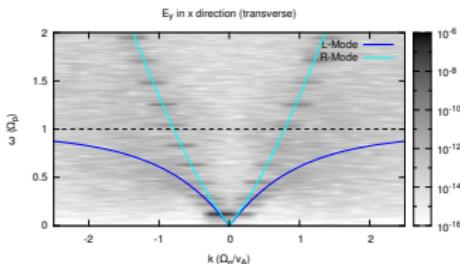
Particle-in-Cell (PiC) method:

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- computationally expensive
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Simulation Setup:

- magnetized, thermal background plasma
 - mono-energetic test particle population of species s (e^- , p)
 - amplified low frequency wave ($\omega < \Omega_s$)
- ⇒ choose specific set of parameters according to resonance condition



Scattering Processes:

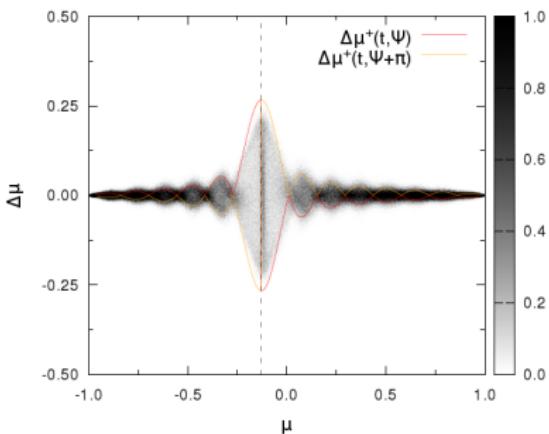
- particle changes its direction
- $\Delta\mu = \mu(t_1) - \mu(t_0)$ as measure of scattering efficiency
- resonance: peak in $\Delta\mu(\bar{\mu})$ (with $\bar{\mu} = \frac{\mu(t_1) + \mu(t_0)}{2}$)

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Example Simulation 1:

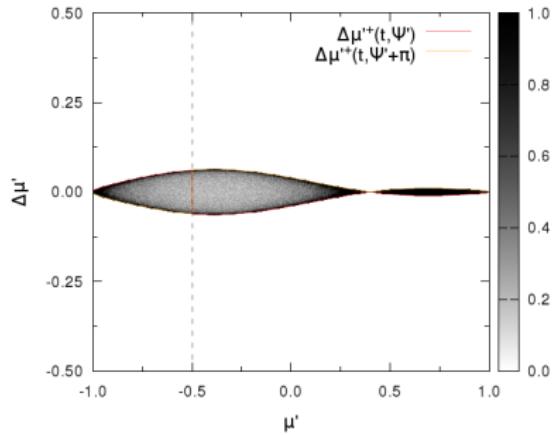
- amplified Whistler wave
- natural mass ratio
- electron scattering
($E_{\text{kin}} \sim 100 \text{ keV}$)



Resonant Scattering

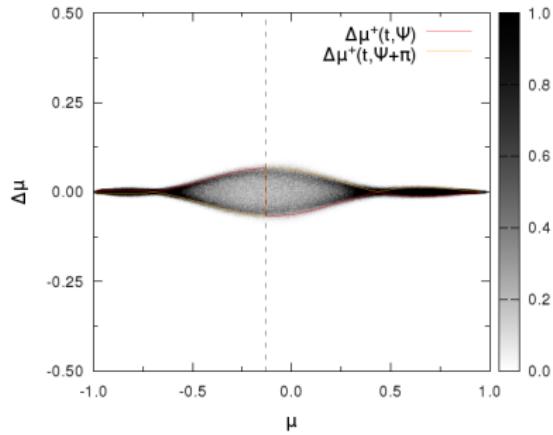
Wave Frame:

("magnetostatic" test particle simulation)



Plasma Frame:

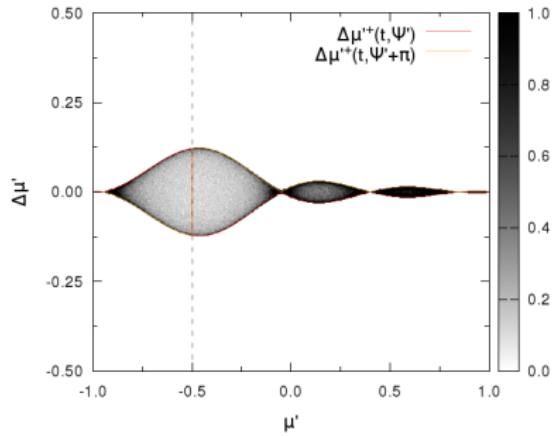
(full PiC simulation, 2d3v)



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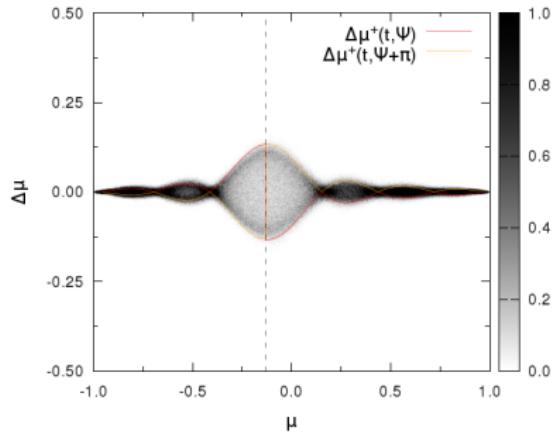
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Plasma Frame:

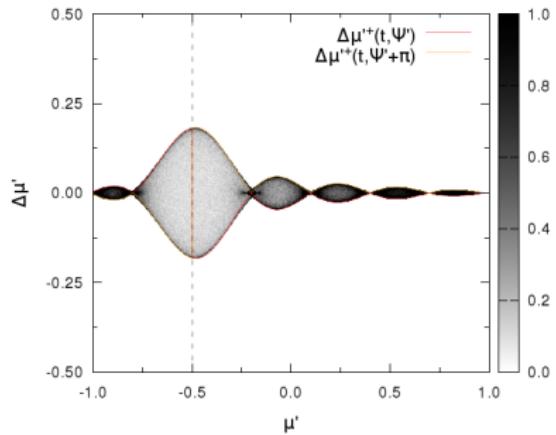
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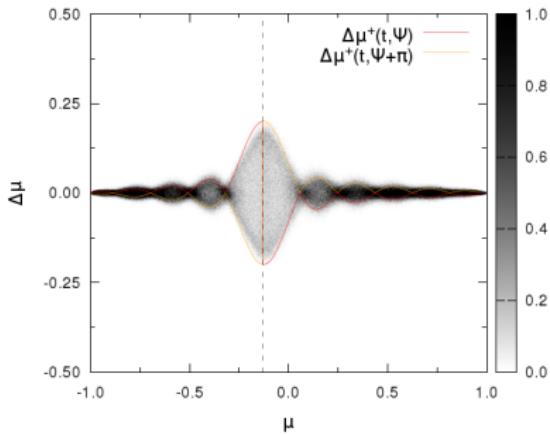
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Plasma Frame:

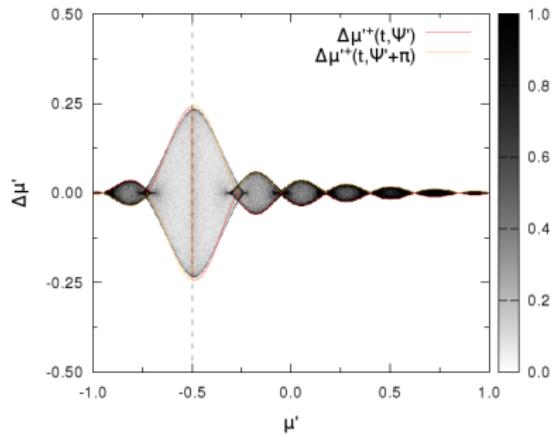
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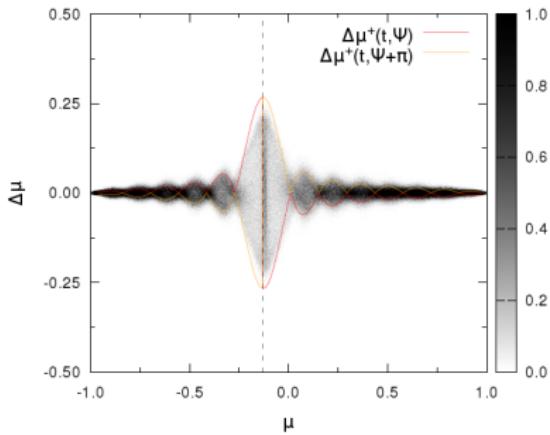
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Plasma Frame:

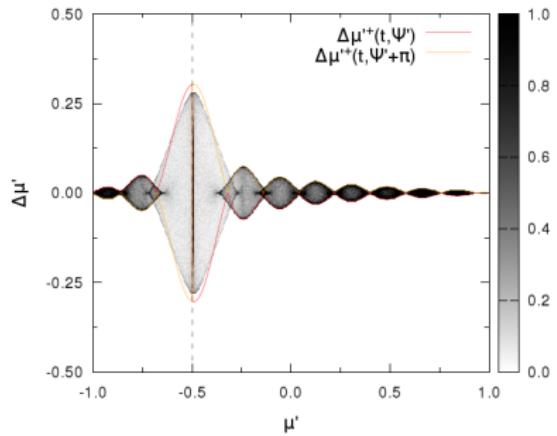
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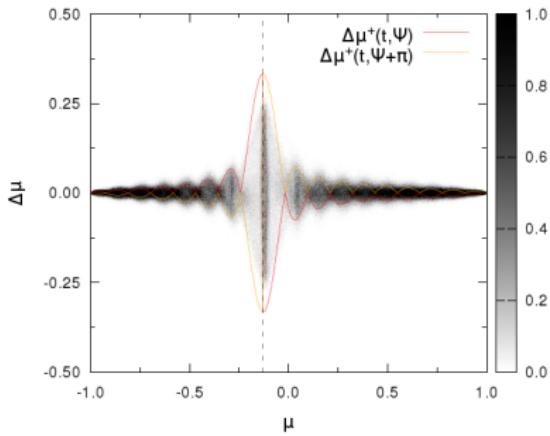
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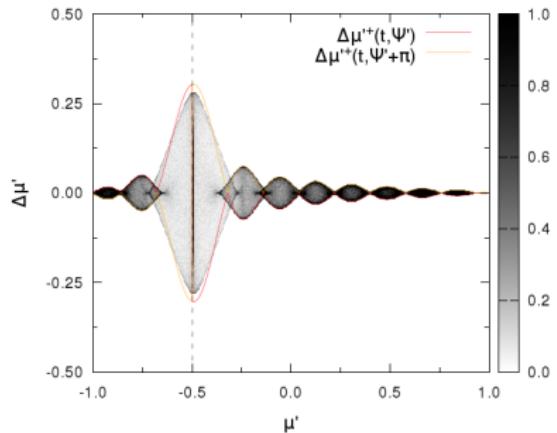
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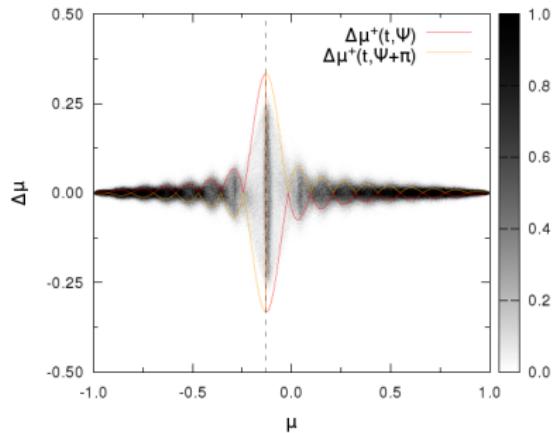
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Plasma Frame:

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⇒ transformation of v'_s , μ' and $\Delta\mu'$ works as expected

Example Simulation 2:

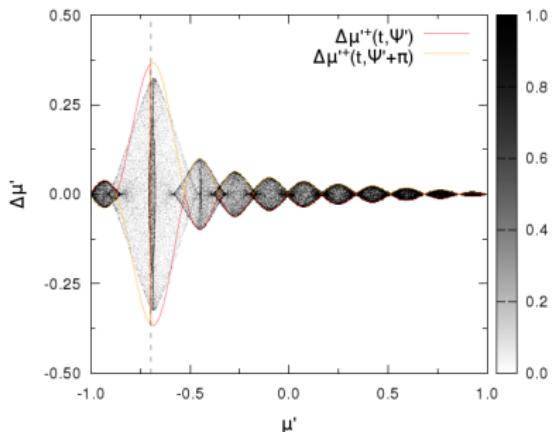
- amplified Whistler wave
- mass ratio: $m_p/m_e = 10$
- electron scattering ($E_{\text{kin}} \sim 250 \text{ keV}$)

Resonant Scattering

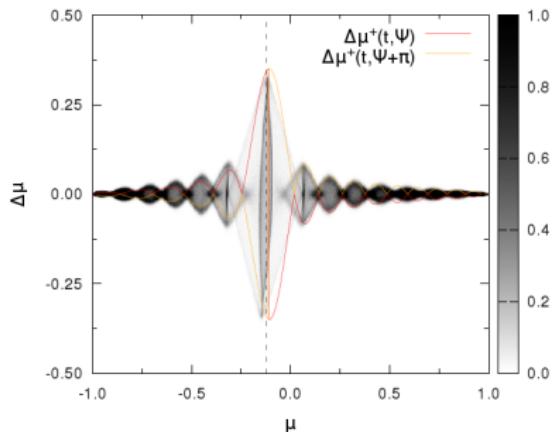
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Wave Frame:



Plasma Frame:



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- QLT works for both protons and electrons
- predictions valid for reference frame of the wave / magnetostatic limit
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Simulations:

- resonant scattering of electrons and (dispersive) waves possible in PiC
- electrons interact with right- and left-handed waves (not shown here)
- results match theoretical expectations – most of the time

Next Steps:

- parameter studies / planning of simulation setup
 - ⇒ realistic solar wind parameters?
- multi-wave-interaction
 - ⇒ (kinetic) turbulence in PiC?

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Long Term Goal:

- particle scattering in turbulent electromagnetic fields
 - ⇒ transport characteristics of fast electrons?