# Turbulent Transport of Energetic Particles in Global Gyrokinetic Particle Simulations

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Supported by US DOE SciDAC Center for Gyrokinetic Simulation of
Energetic Particle Turbulence and Transport (GSEP) in Burning Plasmas

## The Transport and Confinement of Energetic particles is a Crucial Issue

The effect of microscopic turbulence on the energetic particle transport is far from being understood on the basis of the existing theoretical models:

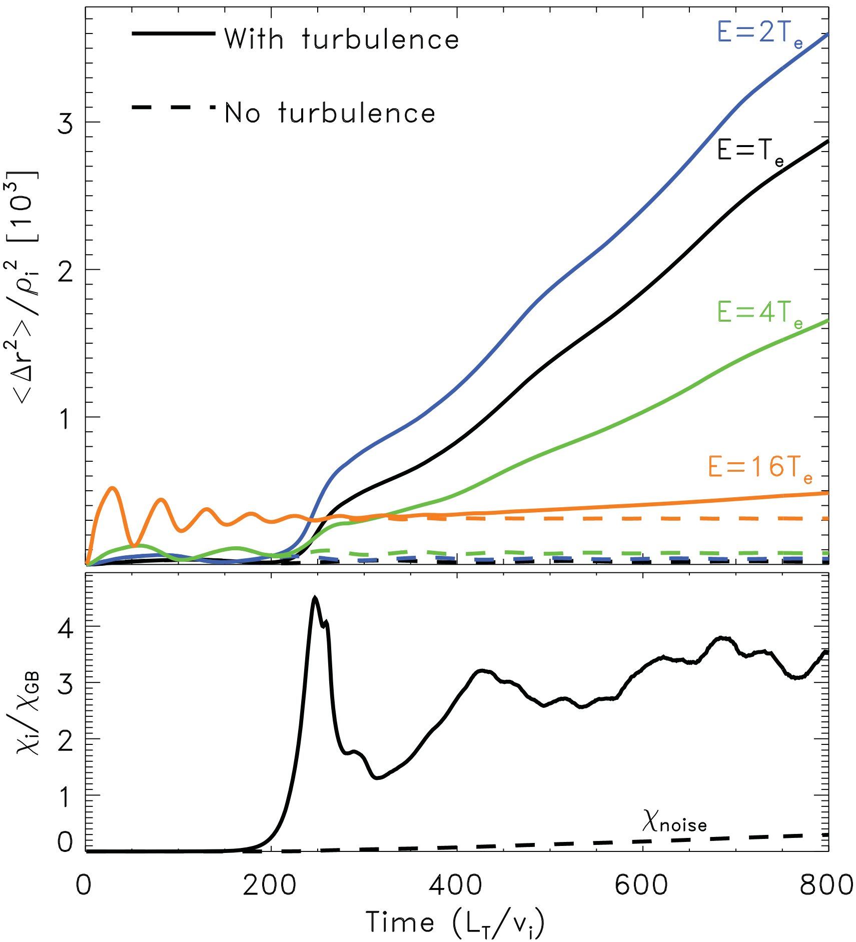
1. Usually it is believed that energetic particles do not interact with microturbulence, and creates a different response to the thermal ions:
   - W. W. Heidbrink and G. J. Sadler, *Nuclear Fusion* **34**, 535 (1994).
   - S. J. Zweben, R. V. Budny, D. S. Darrow, S. S. Medley, R. Nazikian, B. C. Stratton, E. J. Synakowski, G. Taylor, and T. Grp, *Nuclear Fusion* **40**, 91 (2000).
   - H. E. Mynick, *Phys. Rev. Lett.* **43**, 1019 (1979); *Nuclear Fusion* **32**, 518 (1992).
2. Some suggest that microscopic turbulence will significantly affect transport of energetic particles and lead to re-distribution of NBI beam ions:
   - S. Gunter *et al.*, *Nuclear Fusion* **47**, 920 (2007).
   - G. Manfredi, and R.O. Dendy, *Phys. Rev. Lett.* **76**, 4360 (1996); *Phys. Plasmas* **4**, 628 (1997).
   - M. Vlad *et al.*, *Plasma Phys. Controlled Fusion* **47**, 281 (2005); **47**, 1015 (2005).
   - C. Estrada-Mila, J. Candy, and R. E. Waltz, *Phys. Plasmas* 13 (2006).

## Simulations on Turbulent Transport of Energetic Particles by Microturbulence

- GTC has been extended with the multi-species capability, which make it possible to simulate the physics including D-T particles, fast ions, helium ash and impurities.
- The effect of FULLY SELF-CONSISTENT microscopic ITG turbulence on the transport of PASSIVE energetic particles is investigated.
- Passive energetic particles, with $17 \times 40$ samples in energy and pitch-angle, are loaded simultaneously with bulk ions.
- Running parameters with and without fluctuations

$$R_0 = 372.8\text{cm}, \quad a = 0.358R_0, \quad a_0 = 0.1a, \quad a1 = 0.9a, \quad q_0 = 0.854,$$
$$q1 = 0.0, \quad q2 = 2.184, \quad R/L_{Ti} = 6.92, \quad R_0/L_{Te} = 6.92, \quad R_0/L_n = 2.22,$$
$$B_0 = 19100.0\text{G}, \quad T_i = T_e = 2500.0\text{eV},$$
$$a_{ep0} = 0.45a, \quad a_{ep1} = 0.55a, \quad T_{ep}/T_i = 0.125, 0.25, 0.5, 1, 2, 3, \ldots, 64.$$

# Time History of Radial Excursion




In linear regime

- Orbit effect dominates
- Bounce time $\tau \simeq \frac{2\pi q R}{(\sqrt{\epsilon} v_E}$

In nonlinear regime

- Equilibrium cases remains in a low level
- Turbulence cases turn into a fast growing slope and show a good linear relation

Gyro-Bohm value

$$\chi_0 = 3.1\chi_{GB}$$

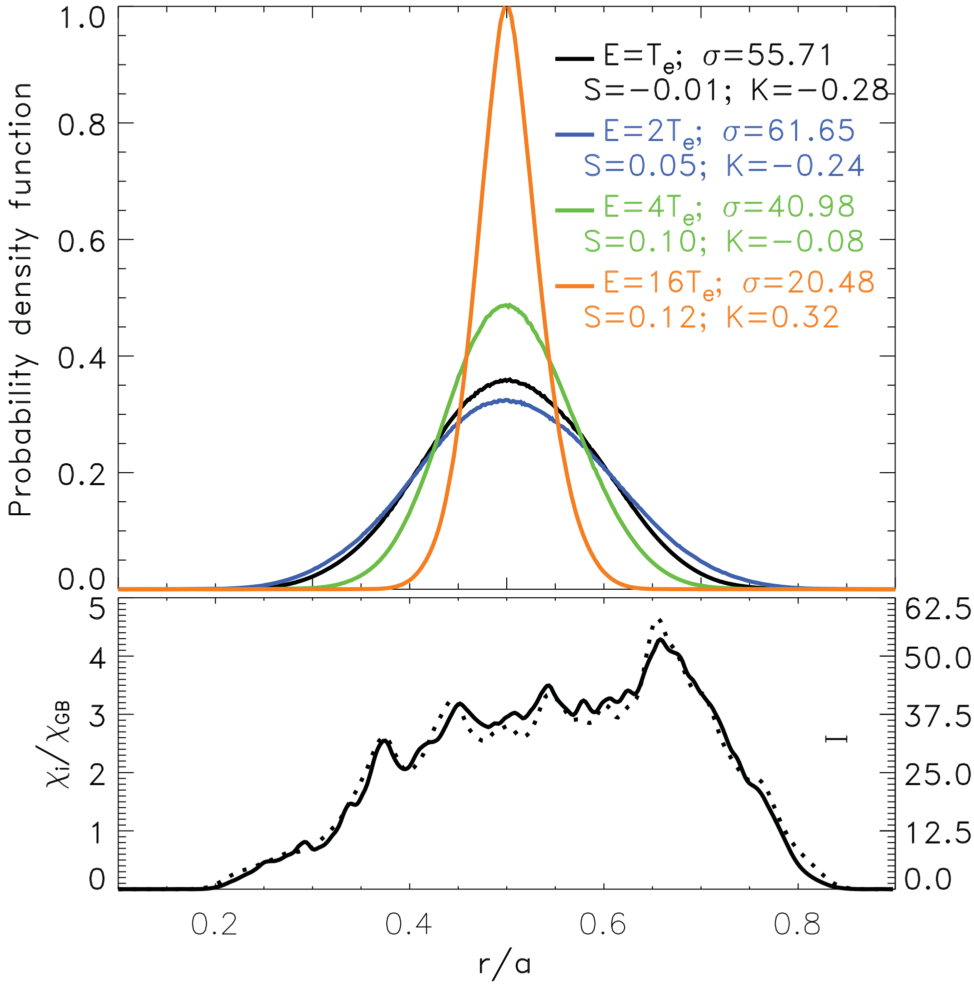
Gyro-Bohm unit

$$\chi_{GB} = \rho^* \chi_B = \frac{\rho}{a}\frac{cT_e}{eB}$$

Noise-driven Flux

$$\chi_{noise} = \chi(t=0)\frac{W_i^2(t)}{W_i^2(0)}$$

# Radial Excursion is Diffusive




Standard deviation

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

Skewness

$$S = \sqrt{n}\frac{\sum_{i=1}^{n}(x_i - \bar{x})^3}{\left(\sum_{i=1}^{n}(x_i - \bar{x})^2\right)^{3/2}}$$

Kurtosis

$$K = \frac{n\sum_{i=1}^{n}(x_i - \bar{x})^4}{\left(\sum_{i=1}^{n}(x_i - \bar{x})^2\right)^2} - 3$$

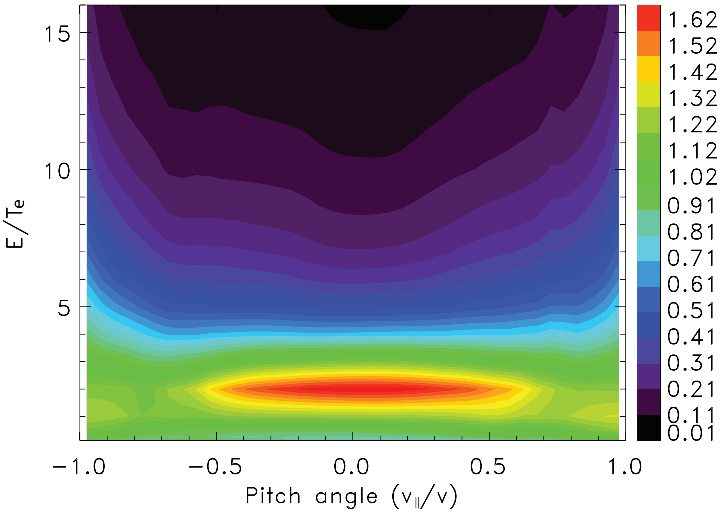
For perfect Gaussian

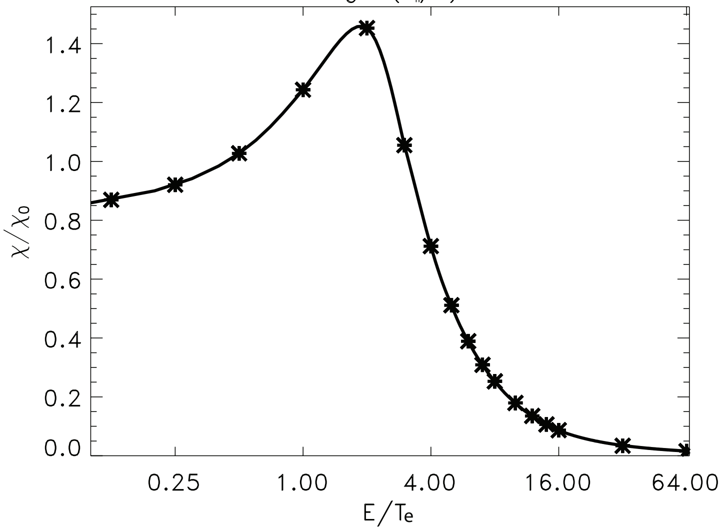
$$S \rightarrow 0; \qquad K \rightarrow 0$$

Fluctuating potential

$$I = (e\delta\phi/\rho^* T_e)^2$$

# Phase-space Structure of Radial Diffusivity




Diffusivity is calculated based on random walk model

$$\chi = \frac{3D}{2}, \qquad D = \frac{< \Delta x^2 >}{2\tau}$$

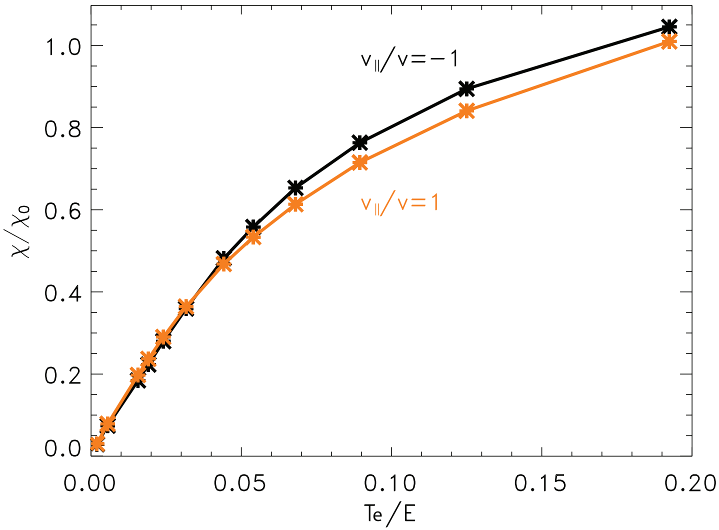
High energy transport is ignorable:

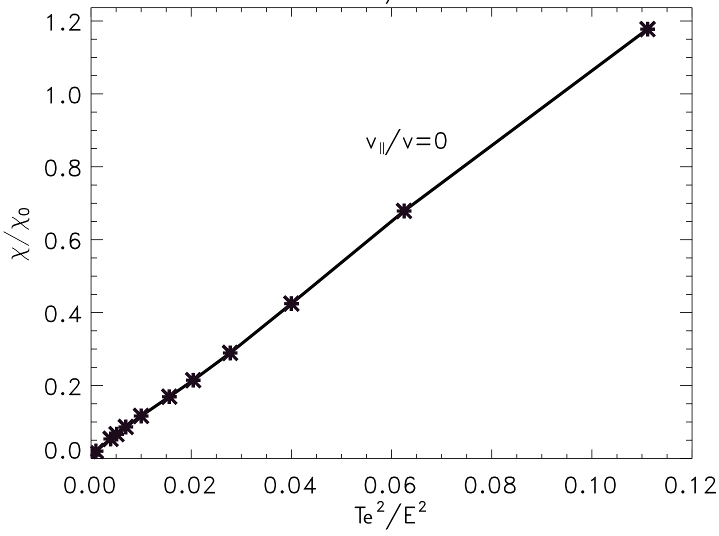
- Diffusivity decays drastically for high energy particles
- Diffusivity of $E/T_e = 16$ only $1/10$ of maximum value
- Maximum diffusivity is contributed by deeply trapped low energy resonance particles, $E/T_e \sim 2$

$$\mathcal{R} \equiv \omega - \bar{\omega}_d \propto 1 - (L_n/R)E/T_e$$

- For nonresonance particles, diffusivity of the passing particles usually larger than that of trapped particles

# Transport scaling of Radial Diffusivity

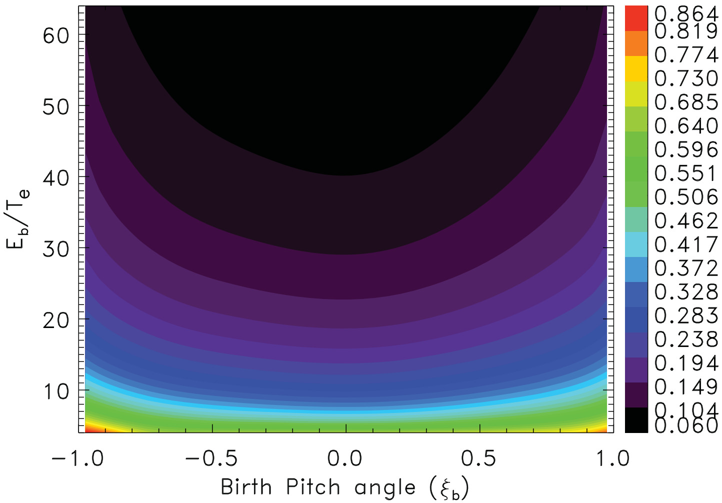


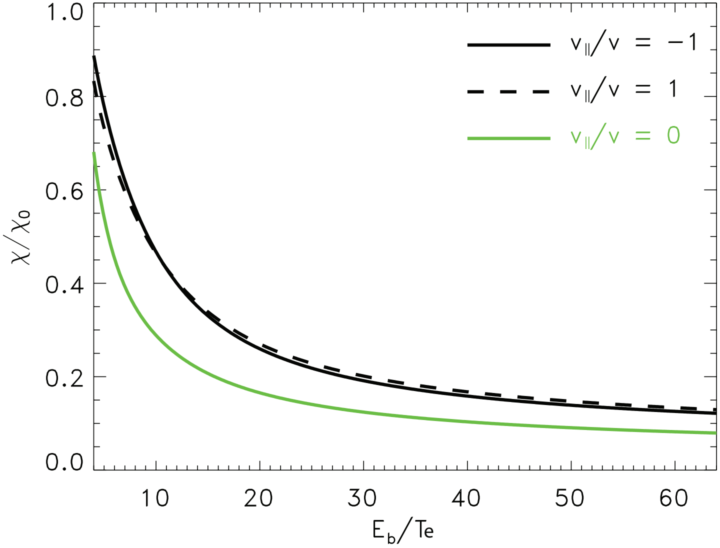




Transport scaling is different for trapped and passing high-energy particles:

- For passing particles, diffusivity inversely proportions to energy $\chi \propto E^{-1}$
- For trapped particles, diffusivity inversely proportions to energy square $\chi \propto E^{-2}$

# Radial Diffusivity of Slowing-down Distribution




Phase-space structure of radial diffusivity can be used to calculate diffusivity of any distribution:

$$\chi(E_b,\xi_b) = \overline{f(E,\xi)\chi(E,\xi)}/\overline{f(E,\xi)},$$

where $\overline{g(E,\xi)} = \int_{E_{min}}^{E_b} \sqrt{2E}dE \int_{-1}^{1} d\xi g(E,\xi)$

- For a Maxwellian: $\chi = 1.225\chi_0$
- For NBI, diffusivity is
  - dominated by the lower energy particles with $E_b < 10T_e$,
  - decays very fast when $E_b < 20T_e$,
  - gradually approaches to a low level, around $10\% - 15\%$ of the maximum value,
  - dominated by passing particles.

Slowing-down distribution

$$f_b(E,\xi) = \frac{S_0\tau_s H(E_b - E)}{E_c^{3/2} + E^{3/2}} \sum_{l=0}^{\infty} C_l(E) P_l(\xi_b) P_l(\xi),$$

$$C_l(E) = \frac{2l+1}{4\sqrt{2}\pi} \left[ \frac{E^{3/2}}{E_b^{3/2}} \frac{E_b^{3/2} + E_c^{3/2}}{E^{3/2} + E_c^{3/2}} \right]^{l(l+1)\mathcal{Z}_2/6}.$$

where$\mathcal{S} = \frac{S_0}{2\pi\sqrt{2E}}\delta(E - E_b)\delta(\xi - \xi_b)$ and $\xi = v_\shortparallel/v$.

# Summary

- Multi-species capability has been added to GTC to investigate the effect of microscopic ion-temperature-gradient (ITG) turbulence on energetic particles transport using the large scale gyrokinetic particle simulations.
- We find that the diffusivity decays drastically for high energy particle due to the averaging effects of the large gyroradius and banana width, and the fast decorrelation of the energetic particles with the waves. Diffusivity of energetic particles with energy higher than $16T_e$ can be neglected.
- The NBI beam ions' diffusivity has been calculated from GTC simulations of the ITG turbulence using a slowing-down distribution. It shows that the NBI beam ion diffusivity decreases rapidly for $E_b/T_e < 20$ and more gradually for $E_b/T_e > 20$ to a very low level.
- Transport of trapped particles and passing particles obey different scaling.
- The probability distribution function (PDF) for the radial spread $\Delta r(t)$ is found to be very close to a Gaussian distribution after some eddy turnover time, which indicates a diffusive process.