Effects of Trapped Particles on Spectroscopic Measurements of Ion Temperature in NSTX

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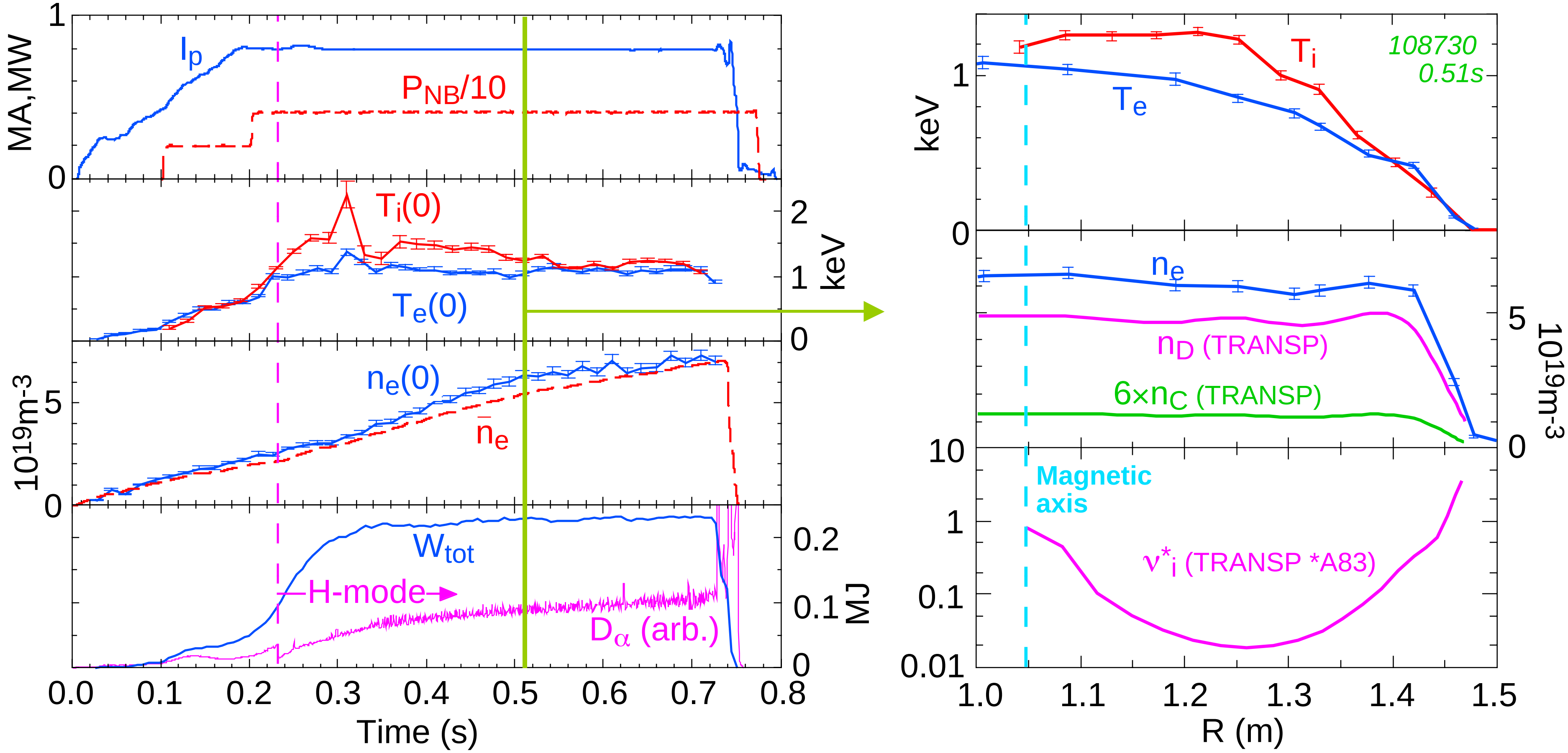
Abstract

The NSTX Charge Exchange Recombination Spectroscopy (CHERS) diagnostic measures the emission from carbon ions on lines of sight essentially in the toroidal direction across the outboard midplane. Except near the edge, it predominantly measures the velocity of the ions parallel to the local field. Fully stripped carbon impurity ions undergo charge-exchange with beam neutrals and emit light within ~1ns, so their apparent velocity distribution is determined by their orbits as C^{6+}. In typical conditions in NSTX, the time for a C^{6+} ion to complete a toroidal transit is of the order of its collision time with the majority deuterons. Trapped ions, and to a lesser, but still significant extent, passing ions have their greatest velocity parallel to the local magnetic field in the region where they are observed, so the line shape can become distorted from a Gaussian when the fraction of trapped particles is large, as is the case in NSTX for the mid regions of the profile, r/a $\approx$ 0.5.

The correction to the temperature obtained by fitting the line to a simple Gaussian ranges from 2% to 10%, depending on the plasma conditions and the region of the line profile over which the fit is performed.

CHERS Measurement of T_i Pivotal to Understanding Confinement in NSTX

$$P_{i,cond} \approx P_{i,NB} - Cn_e^2(T_i - T_e)/T_e^{3/2} - {}^d/_{dt}({}^3/_2 n_i T_i)$$



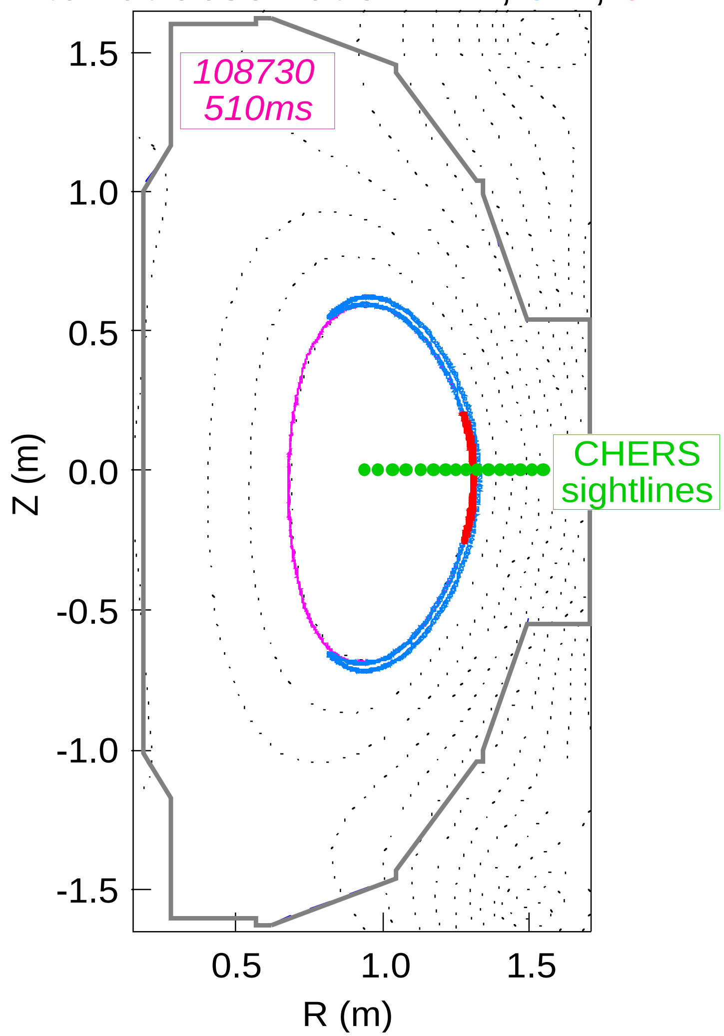
- Most NB power flows to electrons *but*
- $T_i > T_e$ in mid-radius region where n_e is high

Low Aspect Ratio Creates a Unique Situation for Measuring Ion Temperature

- A large fraction of the ions is trapped: ~ $\sqrt{(r/R)}$
  - The main ions are collisionless over most of the profile
  - Impurity ions are more collisional but for C^{6+} ions $t_{orbit} \sim t_{collision}$
- NSTX Toroidal CHERS measures the velocity distribution of carbon ions in the toroidal direction at the outboard midplane
  - C^{6+} ions undergo charge-exchange with beam neutrals and emit light within ~1ns
    - Apparent energy distribution is determined by their orbits as C^{6+}
  - Trapped ions have their greatest velocity parallel to **B** in this region
    - Also true for passing ions, but to a lesser extent
  - For most of profile, CHERS predominantly measures *parallel* velocity
    - The angle of the field lines to the CHERS lines of sight can exceed 45°at the outermost edge at low q_{edge}
- *Could this situation affect the spectra we measure?*

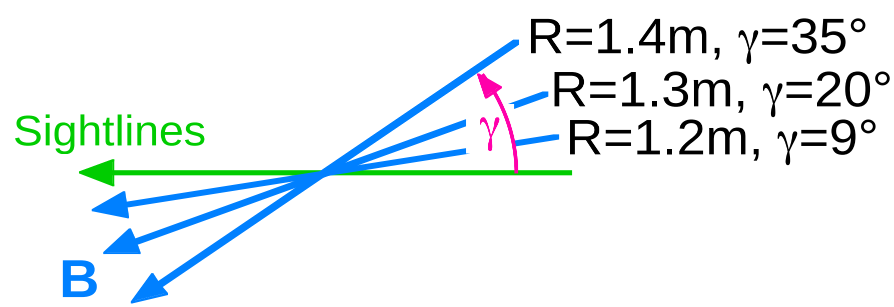
CHERS Observation Geometry in Relation to Orbits of Representative Carbon Ions

C^{6+}, 1.2keV, R_{obs} = 1.3m
Pitch at observation: 27°, 54°, 81°



- Follow ions with ORBIT205 code*
  - direct integration of orbits
  - specify particle conditions at observation point
    - energy, pitch angle, azimuth
  - follow particles backwards in time through one complete orbit
- Magnetic geometry from EFIT

View inwards along a major radius



* J. Felt, C.W. Barnes, R.E. Chrien, *et al.*, Rev. Sci. Instrum. **61**, 3262 (1990)

Carbon Ions Are Relatively Collisionless

- Energy equilibration rate for C^{6+} dominated by collisions with thermal D^+

$$\nu_{E(C/D)} = 1.4\times10^{-7}\, n_D\, Z_D^2\, Z_C^2\, \lambda_{CD}\, \mu_D^{1/2}\, \mu_C^{-1}(1+\mu_D/\mu_C)^{-1/2}\, T_D^{-3/2}$$

(NRL Plasma Formulary, 1994)

  - For $n_D = 4.5 \times 10^{13}\mathrm{cm}^{-3}$, $T_i = 1200\mathrm{eV}$ ($\lambda_{CD} \approx 16$)

$$\tau_{E(C/D)} = 1/\nu_{E(C/D)} \approx 100\mu s$$

  - Timescale for energy transfer to electrons is longer

$$\tau_{E(C/e)} \approx 1 - 5 \text{ ms}$$

  - Heating rate from fast ions independent of C energy

- Velocity of C at 1.2keV ~140km/s

$2\pi R/v_C \sim 40\mu s$ – less than, or comparable to collision time

Heuristic Model for Isotropization of Motion

- Collisions act to restore isotropy on the timescale of velocity diffusion as the particle executes its orbit
- Assume that for particles observed with a particular parallel velocity, the weighted average

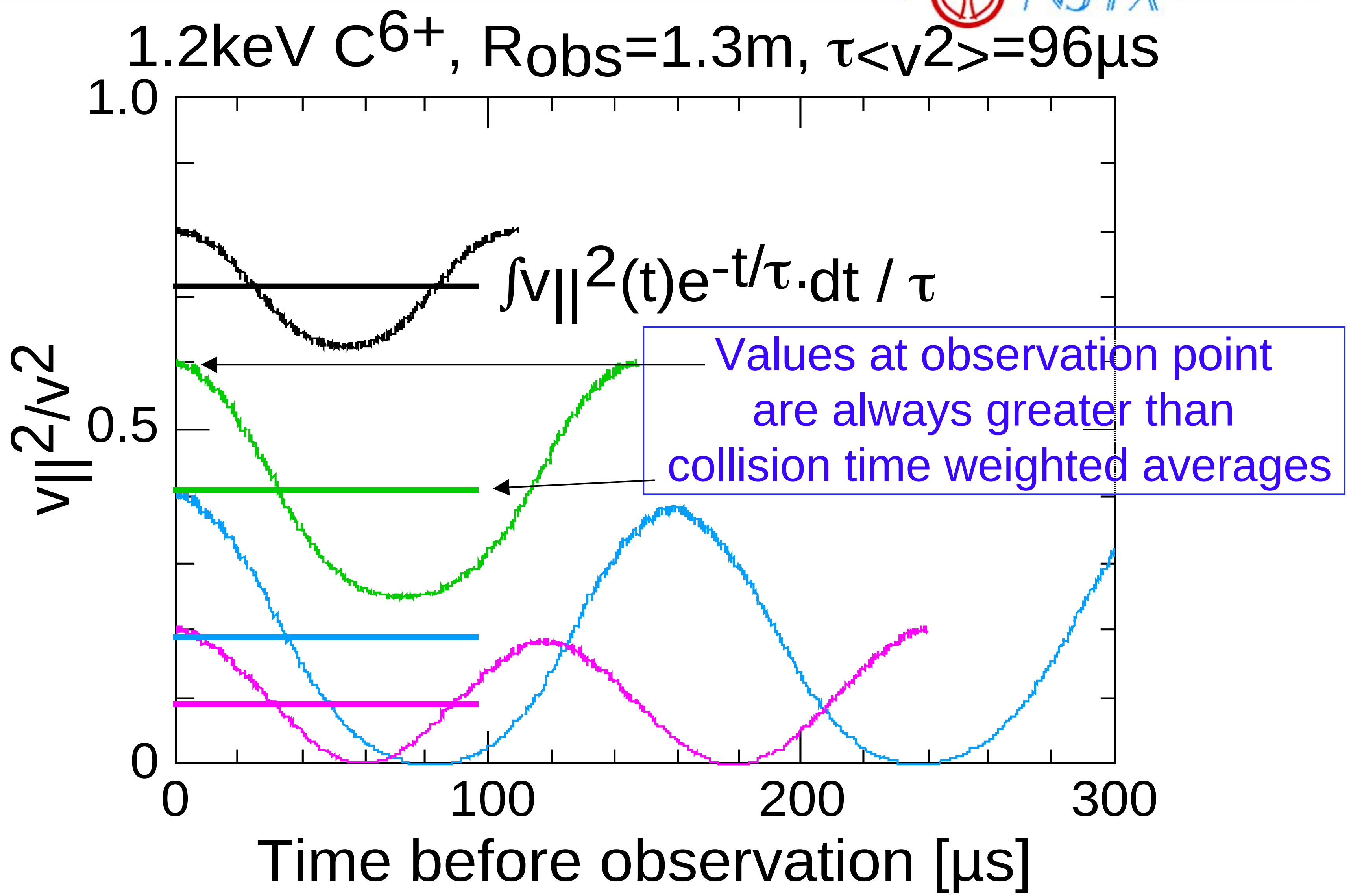
$$\left\langle v_{||}^2 \right\rangle = \int_0^\infty v_{||}^2(t') \cdot \exp(-t' / \tau_{\langle v_{||}^2 \rangle}) \cdot dt' / \tau_{\langle v_{||}^2 \rangle}$$

where $v_{||}(t')$ is the instantaneous parallel velocity on the particle orbit at time t' before the time of observation, is part of an isotropic Maxwellian distribution

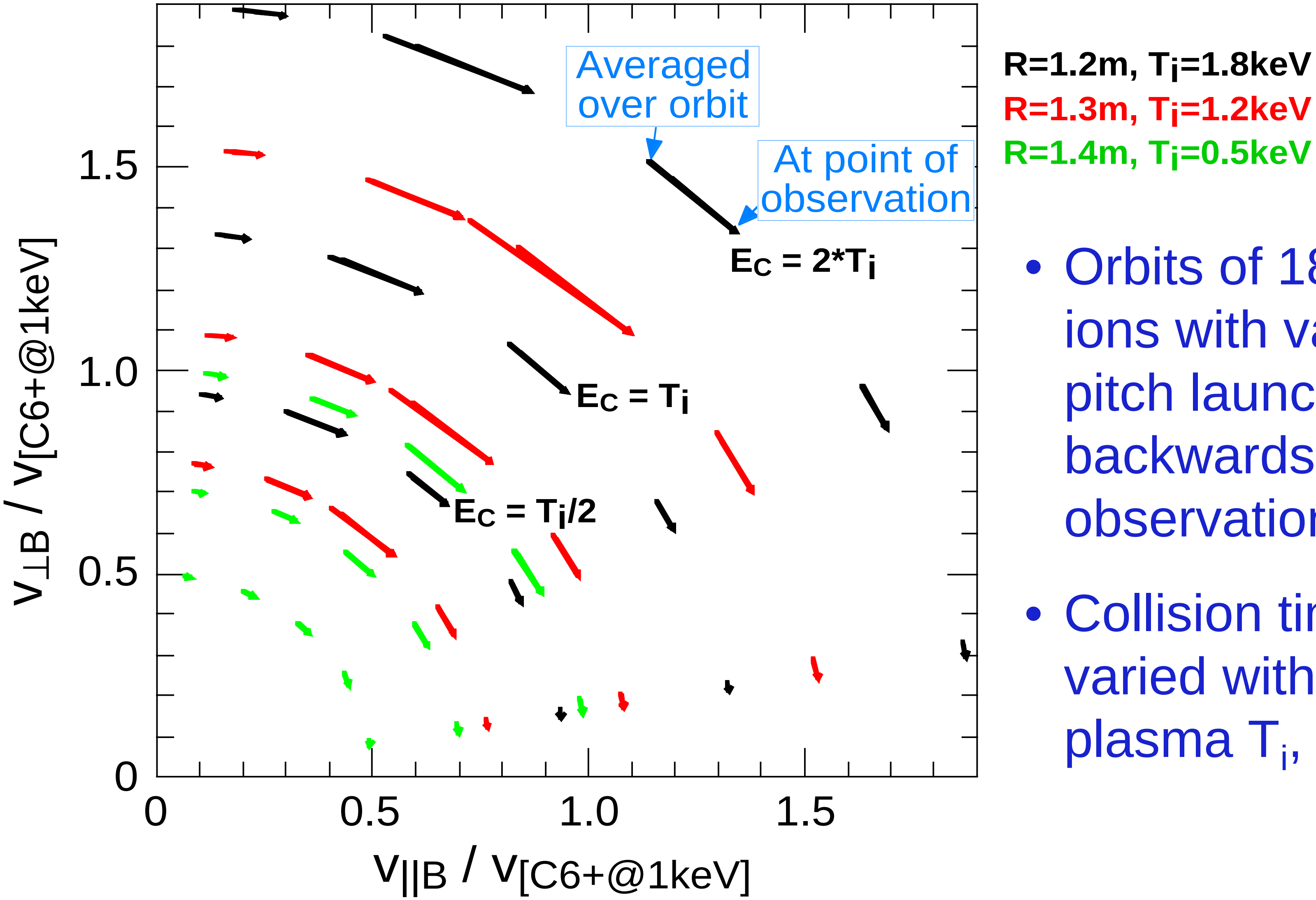
  – *i.e.* a particle loses the memory of what has happened in its orbit more than a collision time before it is observed

- Since orbits are periodic, integral is straightforward to evaluate

Parallel Velocity Varies Significantly Within Collision Time, Even for Passing Orbits

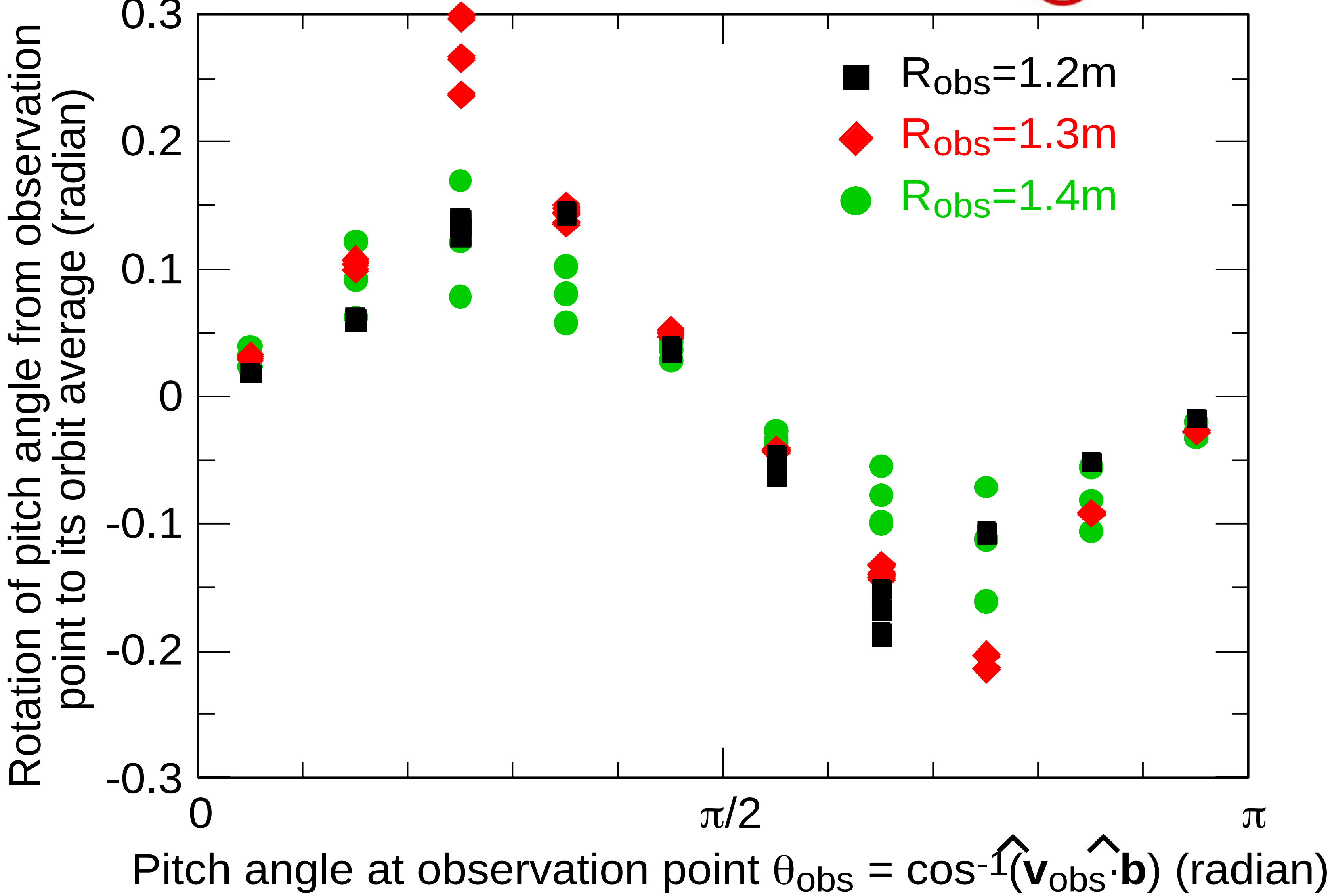


Variation of |B| Along Orbit Rotates Velocity Distribution Towards B at Observation Point

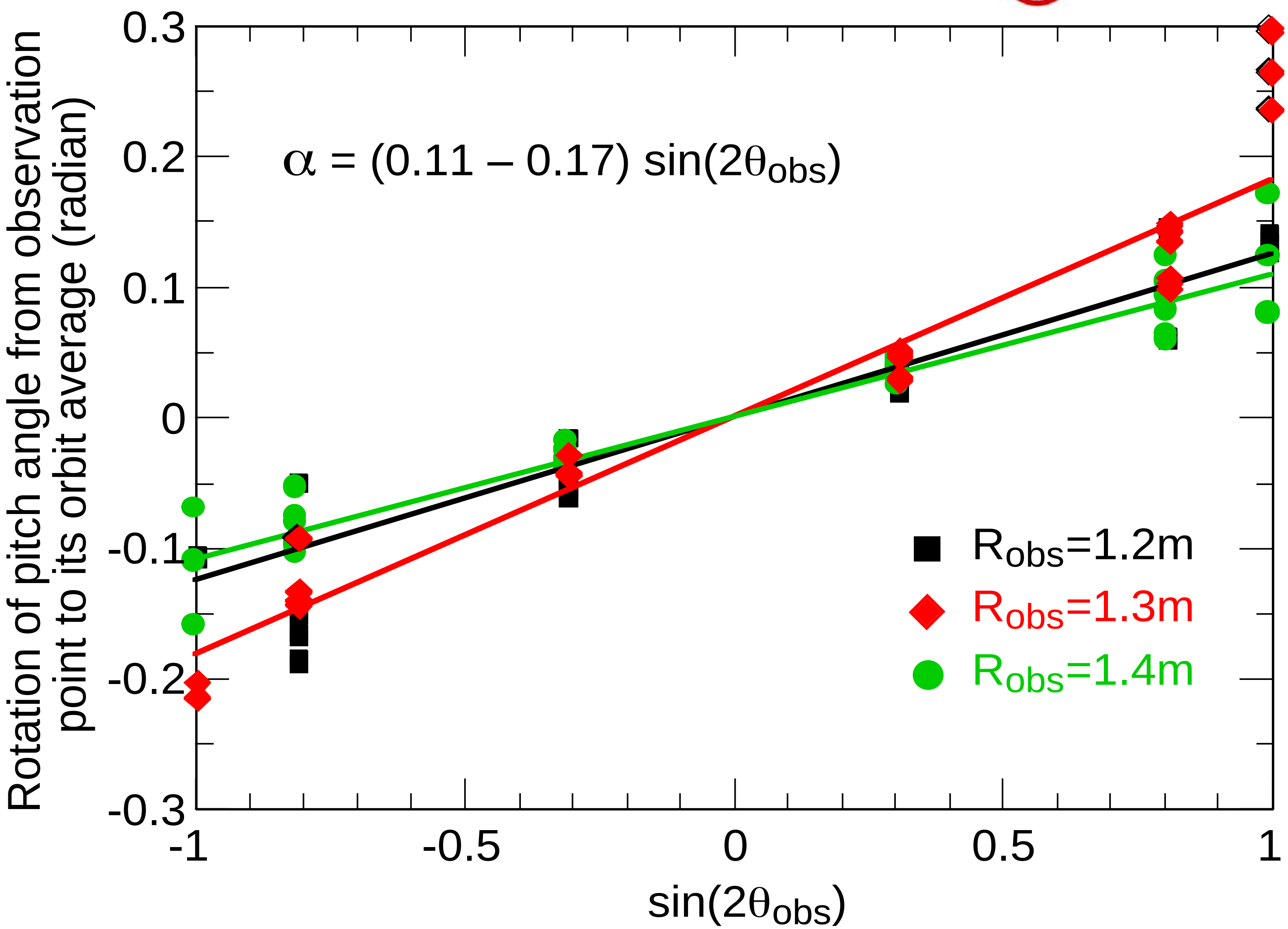


- Orbits of 180 C^{6+} ions with varying pitch launched backwards from observation point
- Collision time varied with local plasma T_i, n_i

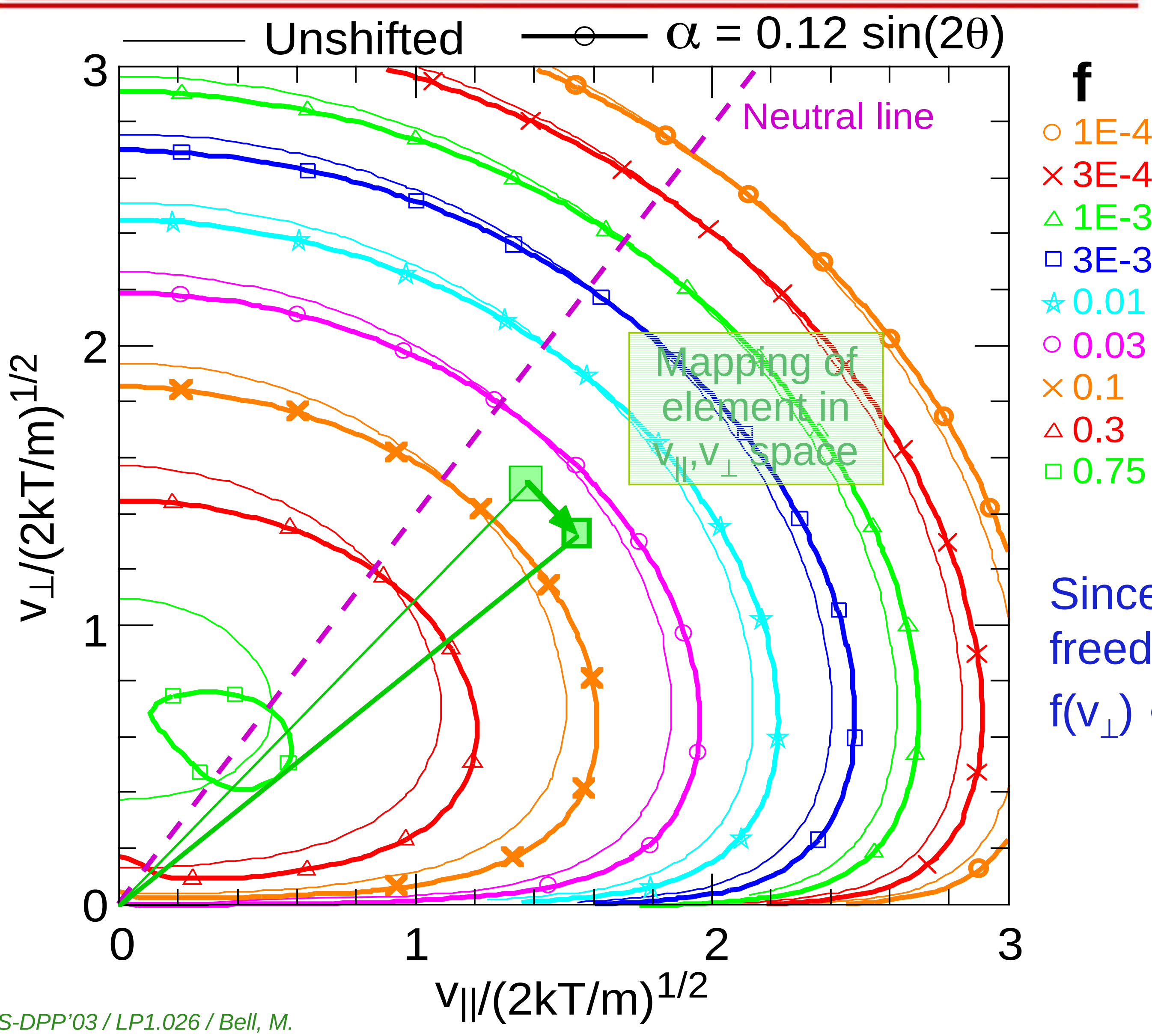
Rotation of Volume Element in Velocity Space Largest at Trapped/Passing Boundary



Rotation of Volume Element in Velocity Space Can Be Approximated Analytically



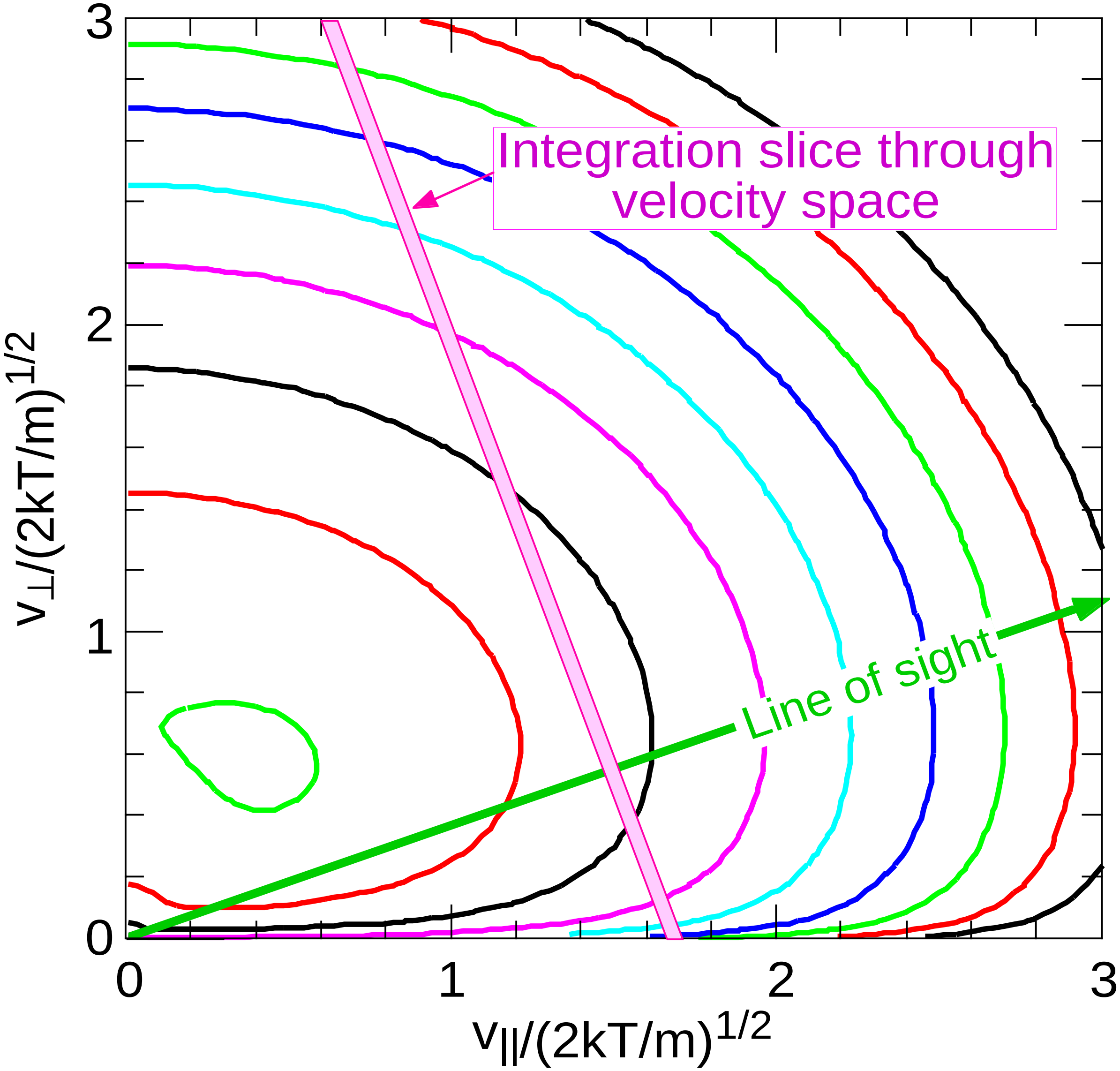
Orbit-Averaged Isotropic Distribution Distorted by Velocity Rotation



Since $v_\perp$ has 2 degrees of freedom, Maxwellian

$f(v_\perp) \propto v_\perp \exp(-mv_\perp^2/2kT)$

Integrate Through Velocity Space to Obtain Apparent Line-of-Sight Velocity Distribution



Integration is straight-forward along $v_{||}$ or $v_{\perp}$

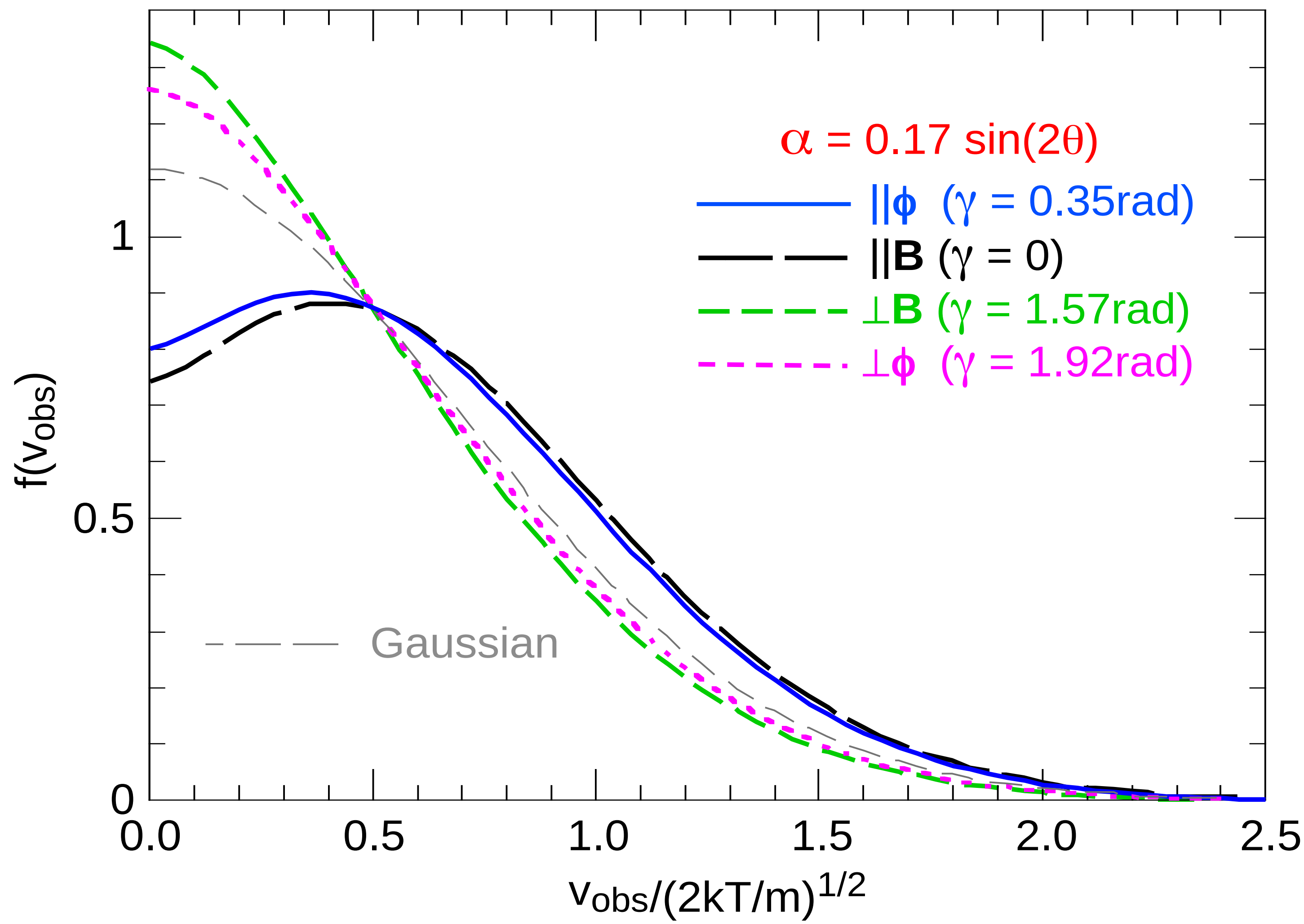
Unfold to 3D for an arbitrary line of sight

Check mapping by calculating moments:

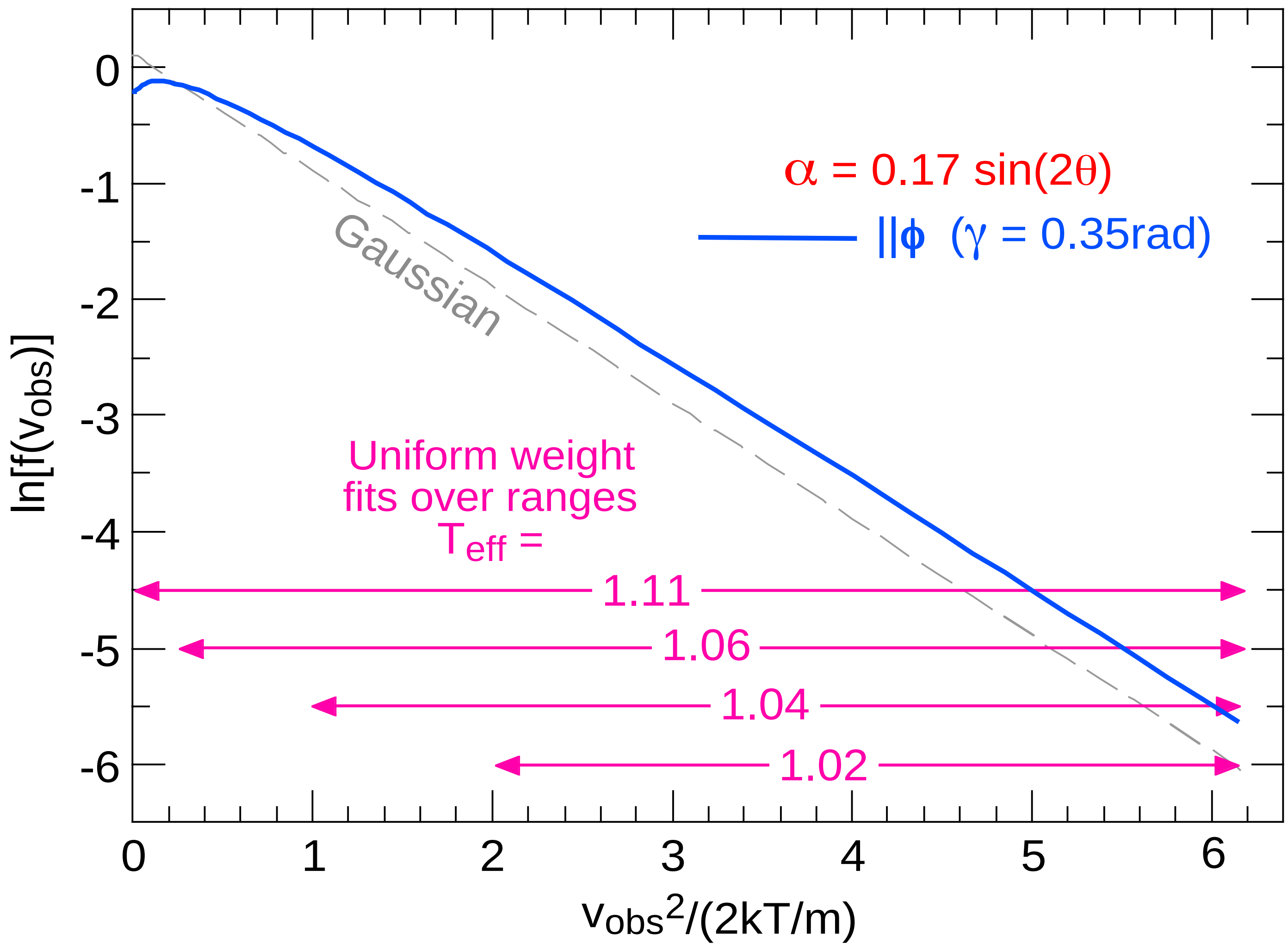
$\int f(v_{||},v_{\perp})dv_{||}dv_{\perp} = 1$

$\int {}^{1}/_{2}mv^{2}f(v_{||},v_{\perp})dv_{||}dv_{\perp} = {}^{3}/_{2}kT$

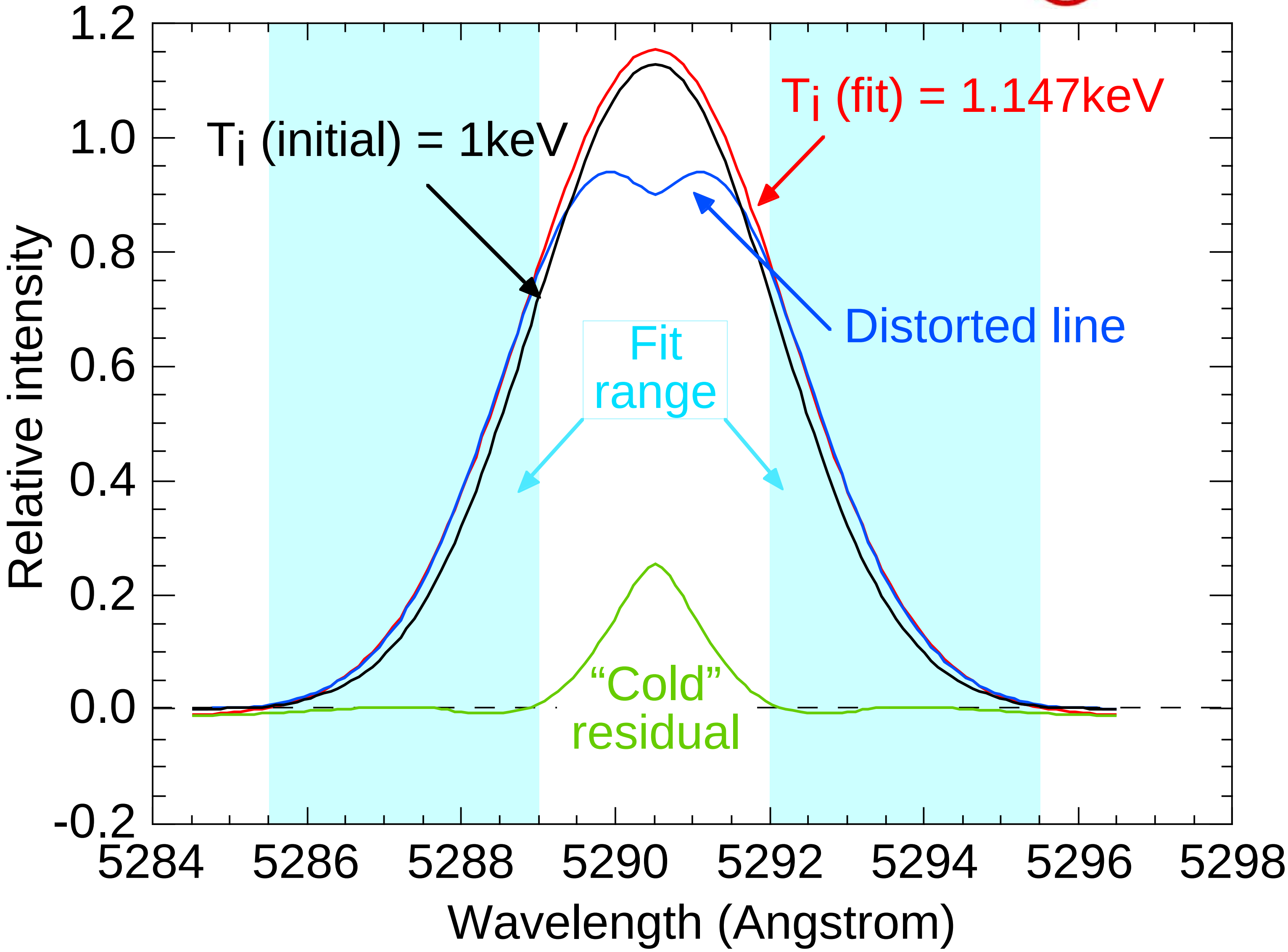
Observed Velocity Distribution is Broader or Narrower Depending on Viewing Angle



Apparent Temperature Depends on Range of Fit



Line Distortion Resembles an Additional Cold Component in Spectrum



Discussion

- This model suggests that the line shape measured by NSTX toroidal CHERS will be broader than the simple Gaussian characterizing "average" carbon temperature
  - Effect most pronounced in mid-radius region
    - Large fraction of trapped particles and low collisionality
  - Depending on fit limits, can overestimate T_i by 2 – 10 %
  - Approaches underlying Gaussian in wings: $v^2/(2kT/m) >> 1$
  - Line appears to have a cold component *subtracted* from it
- *Poloidal* CHERS at the outboard midplane would see an *added* cold component

- Analysis of CHERS data already involves removing a cold component due to intrinsic carbon light from nearer edge
  - edge emission measured by separate background array but effective amplitude difficult to determine absolutely due to possible reflections
  - separation helped by rotational shift of CHERS line *but*
  - intrinsic distortion of CHERS line shape underneath the cold edge component may not be apparent

Conclusion

- Model presented suggests an intriguing possibility *but*
- It is very approximate
  - It has been argued on the basis of kinetic theory that there can be no variation of the temperature anisotropy on a flux surface
- To calculate the orbit effects properly we should apply the drift-kinetic equation to the ions, *both bulk and impurity*
- Model will be tested when poloidal CHERS is deployed
  - Measure differences between $T_{i,tor}$ and $T_{i,pol}$ profiles