Pick-up Ion Scattering in the Outer Heliosheath - Implications for IBEX and Voyager 1 Observations

Jacek Niemiec

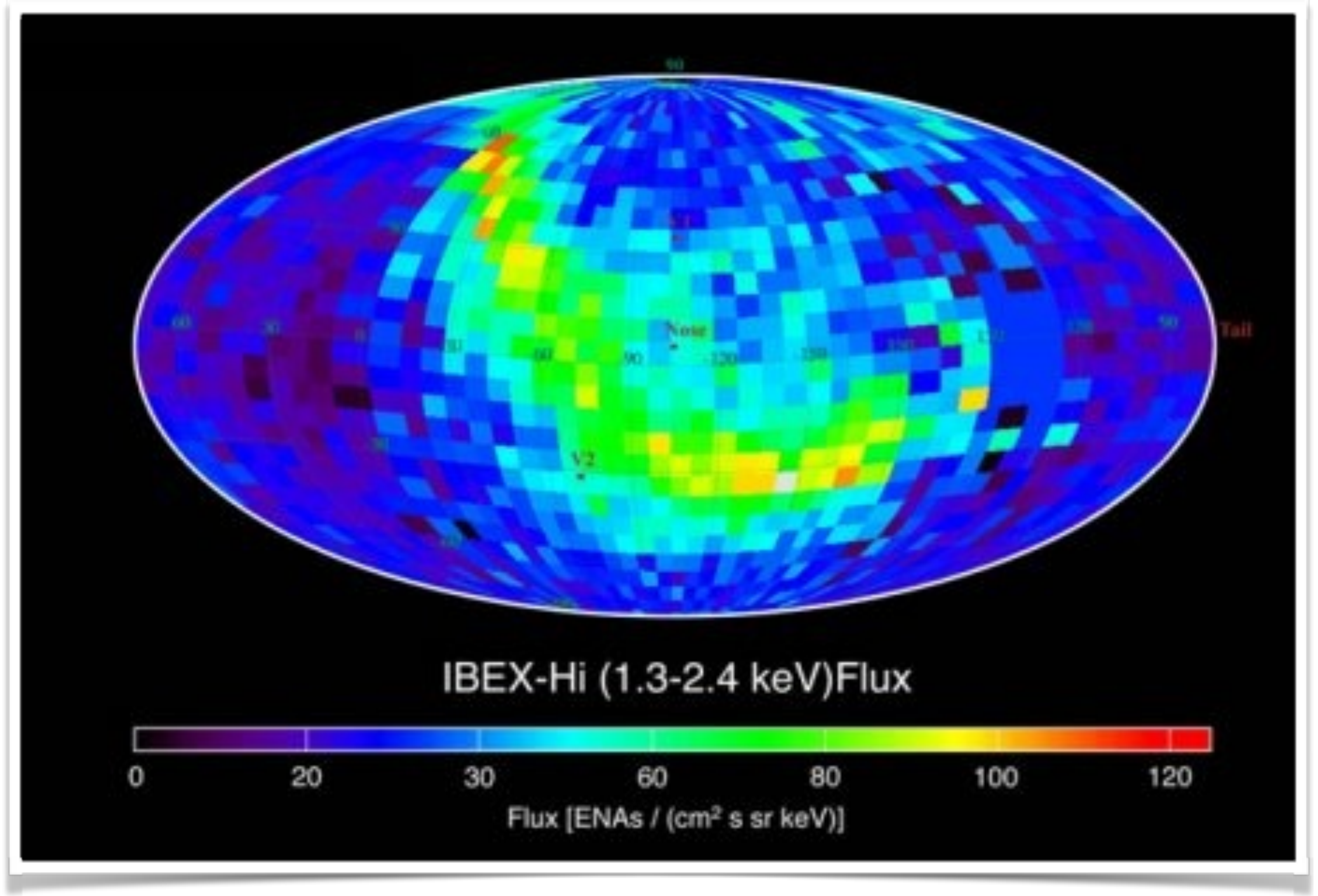
Institute of Nuclear Physics PAS, Kraków, Poland

Vladimir Florinski, Jacob Heerikhuisen

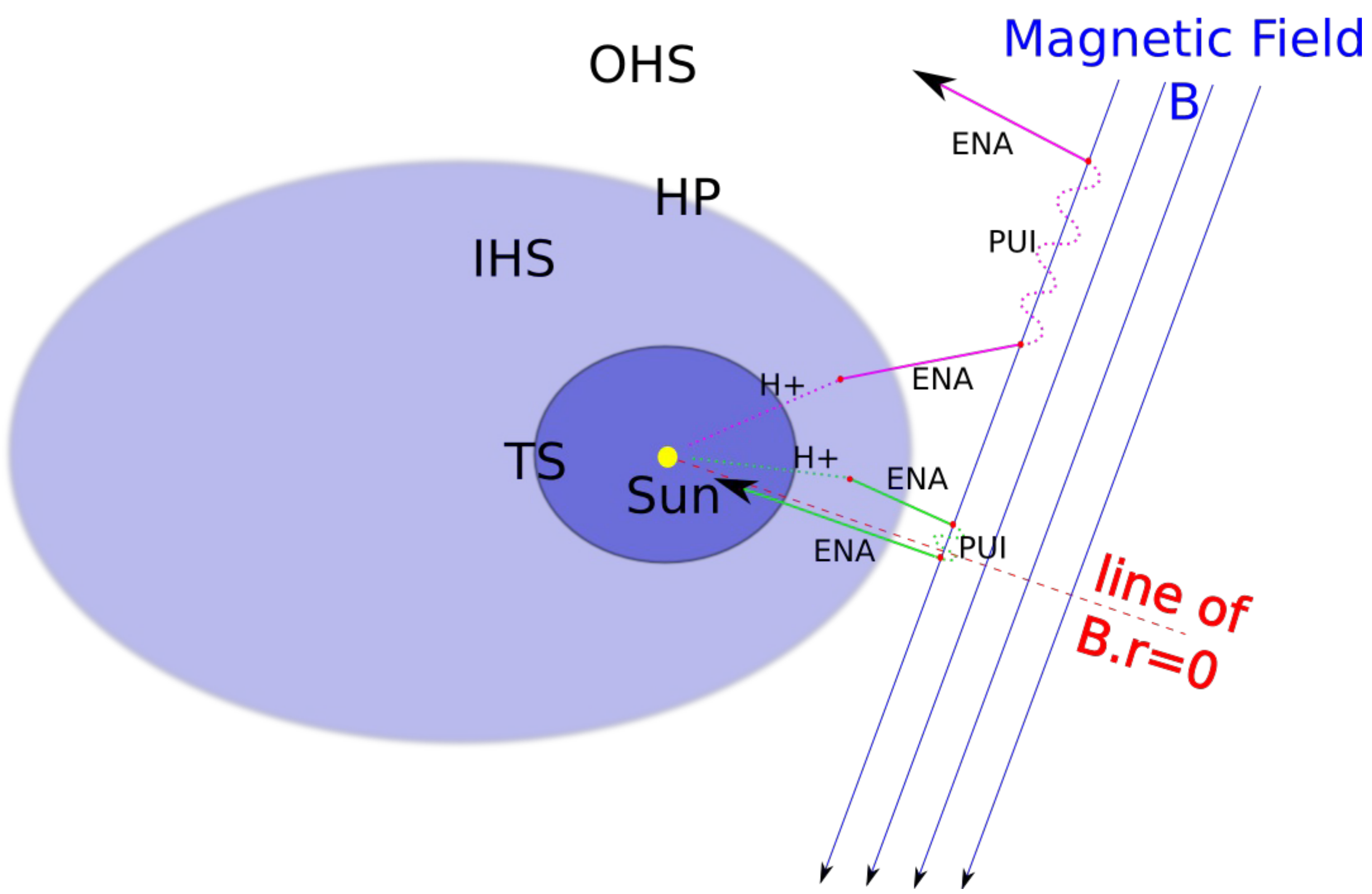
Department of Space Science, University of Alabama in Huntsville, Huntsville, AL, USA

Ken-Ichi Nishikawa

Department of Physics, University of Alabama in Huntsville, Huntsville, AL, USA



Introduction



- Ribbon seen by IBEX is thought to be produced by secondary energetic neutral atoms (ENAs) in the outer heliosheath by a secondary pickup ion ring from solar-wind primary ENAs
- a key feature in this mechanism is wave-particle scattering of PUIs before they charge-exchange to become secondary ENAs; enhanced ENA fluxes are expected from regions with $\mathbf{B}\cdot\mathbf{r}\approx 0$
- recent Voyager 1 observations reveal a very low level of magnetic fluctuations in the region beyond the heliopause
- narrow sharply defined PUI ring distributions are always unstable in linear theory through resonant interactions with RH polarized waves; hybrid simulations showed that m.f. turbulence quickly scatters initial ring toward an isotropic shell

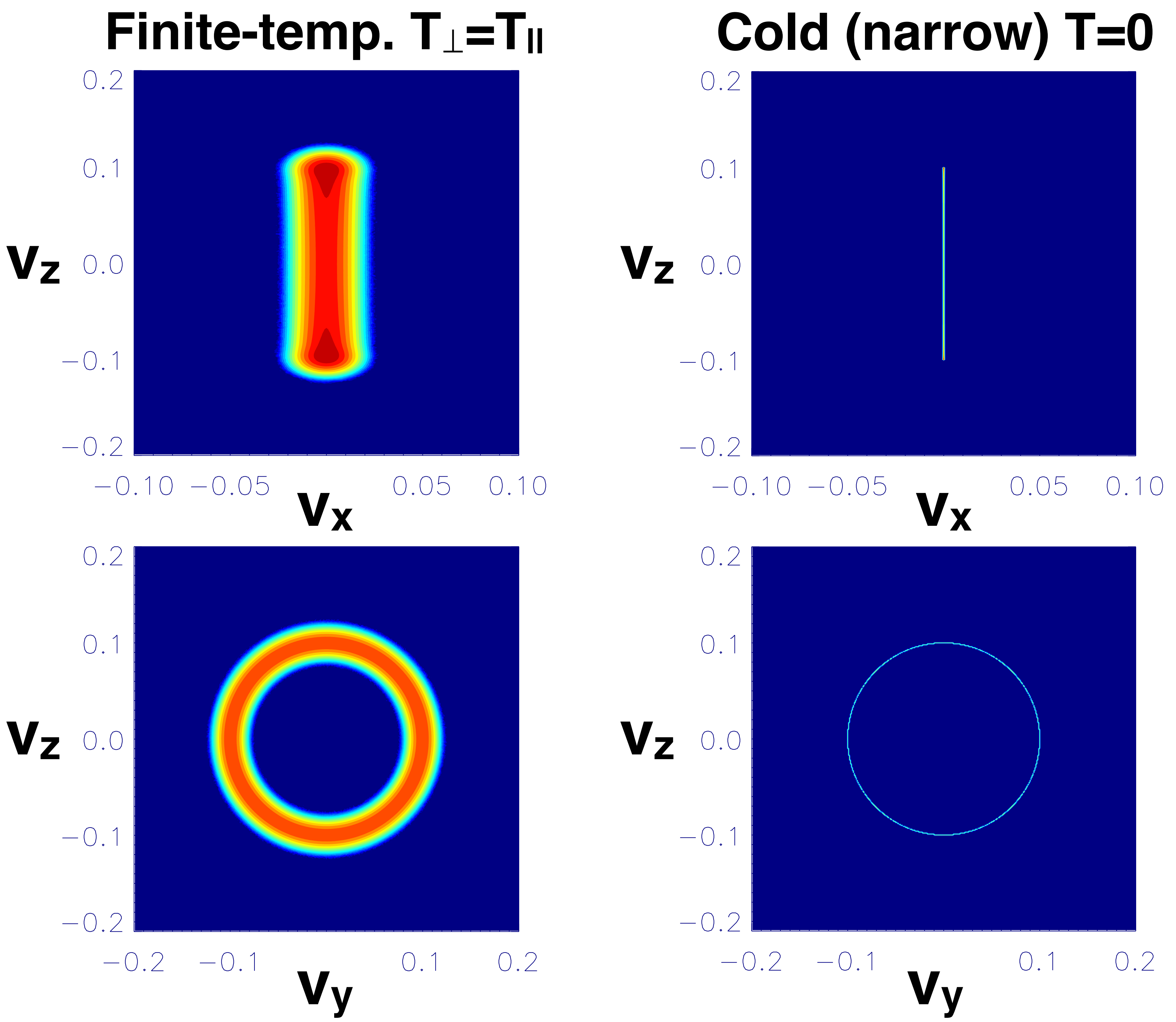
Aim of this work:

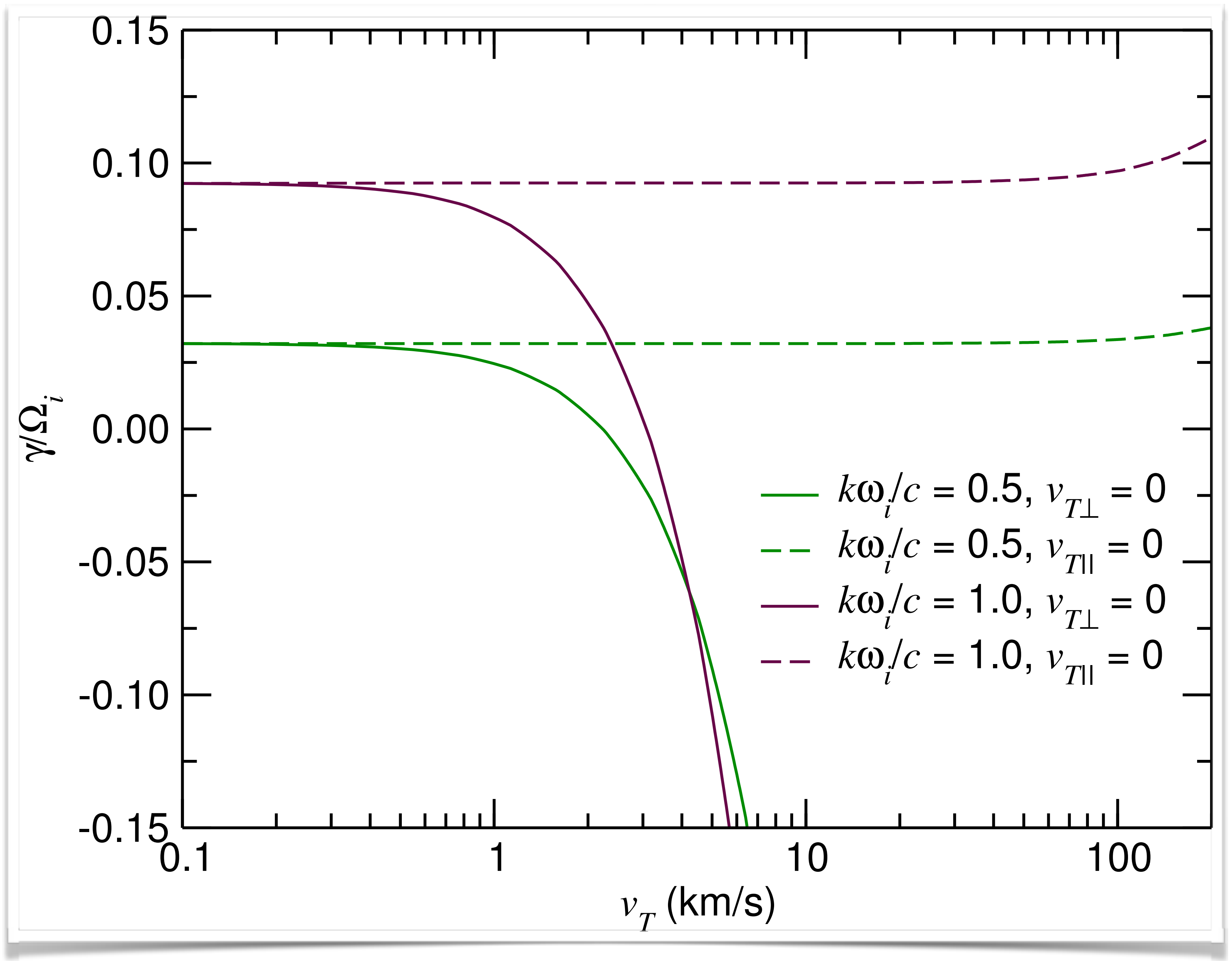
- investigate long-time stability of two different classes of PUI ring distributions using 1D hybrid and 2D PIC simulations
- concentrate on rings with 90^{o} pick-up angle

Initial ring distributions

- warm (**finite-temperature**) toroidal distribution (Summerlin et al. 2014)

$$f(\mathbf{v}) = \frac{1}{\pi^{3/2}\delta v_\perp^2 \delta v_\parallel}\left\{\exp\left(-\frac{v_{\perp,0}^2}{\delta v_\perp^2}\right) + \frac{\sqrt{\pi}v_{\perp,0}}{\delta v_\perp}\mathrm{erfc}\left(-\frac{v_{\perp,0}}{\delta v_\perp}\right)\right\}^{-1} \times \exp\left[-\frac{(v_\perp - v_{\perp,0})^2}{\delta v_\perp^2}\right]\exp\left(-\frac{v_\parallel^2}{\delta v_\parallel^2}\right)$$





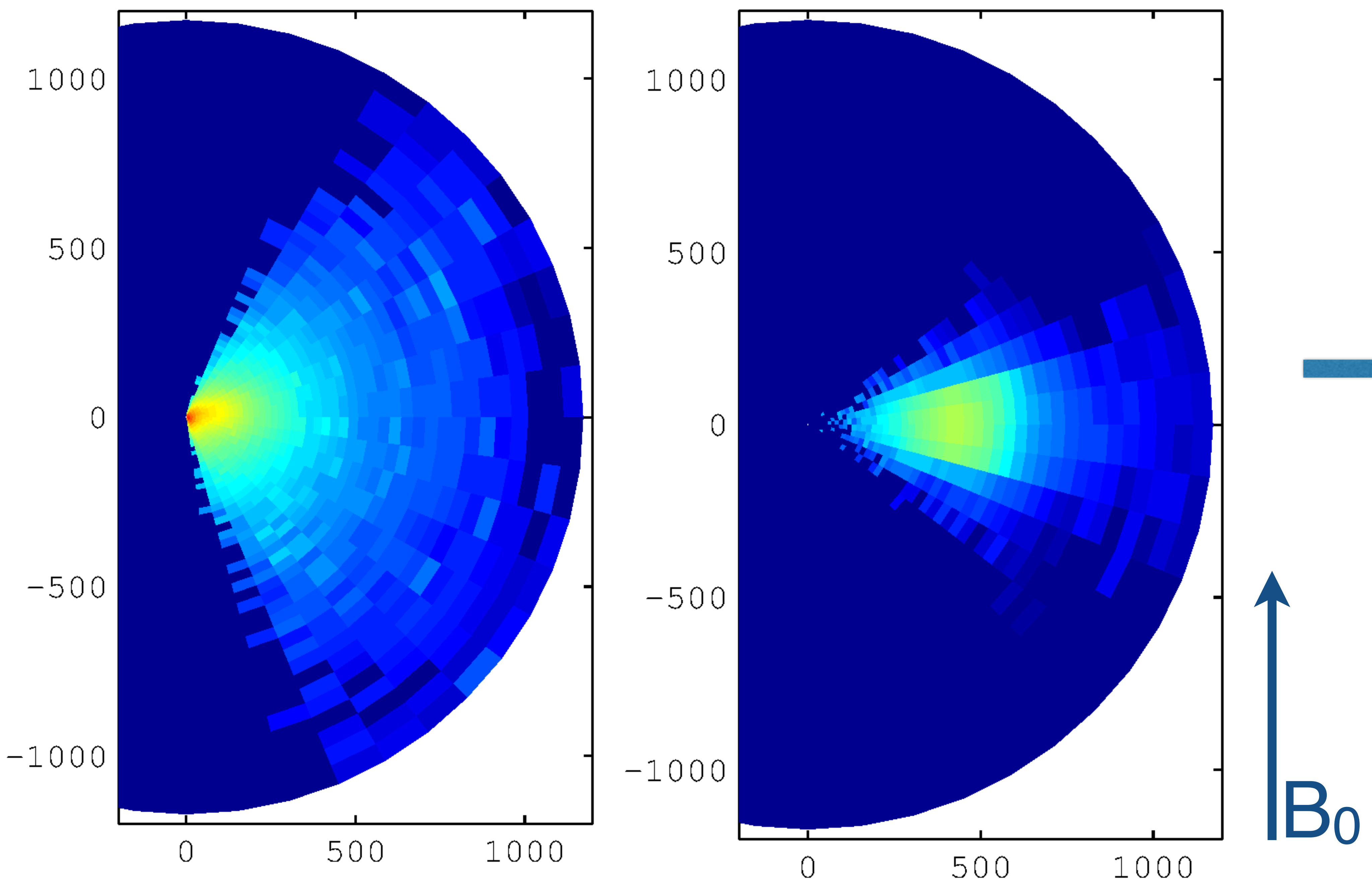
- flat rings spread in perpendicular velocity are always unstable (Florinski et al. 2010)
- parallel broadening leads to stable rings

Initial ring distributions

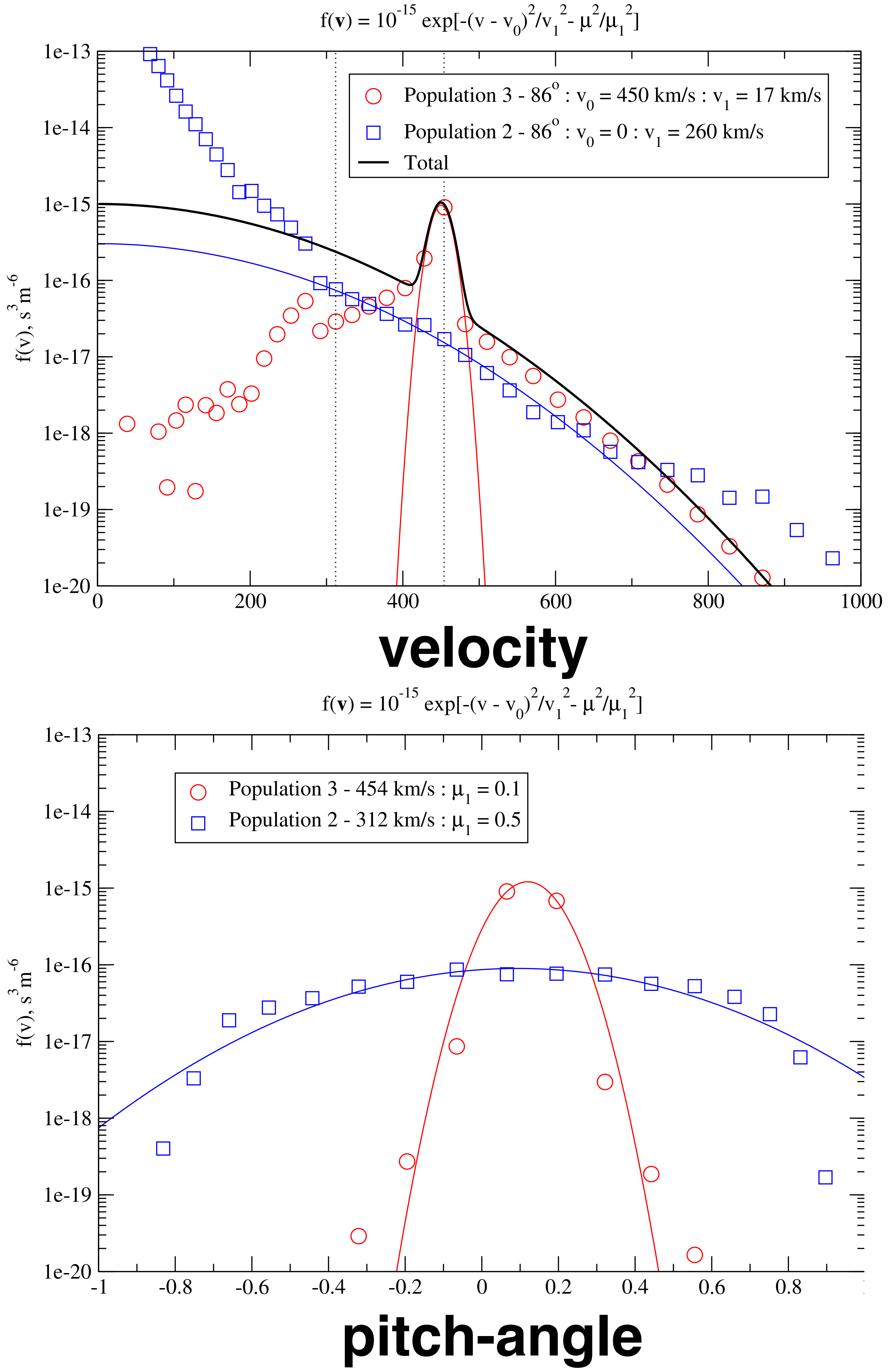
- **realistic** distribution from MHD-MC global heliosphere modeling (Heerikhuisen et al. 2014)

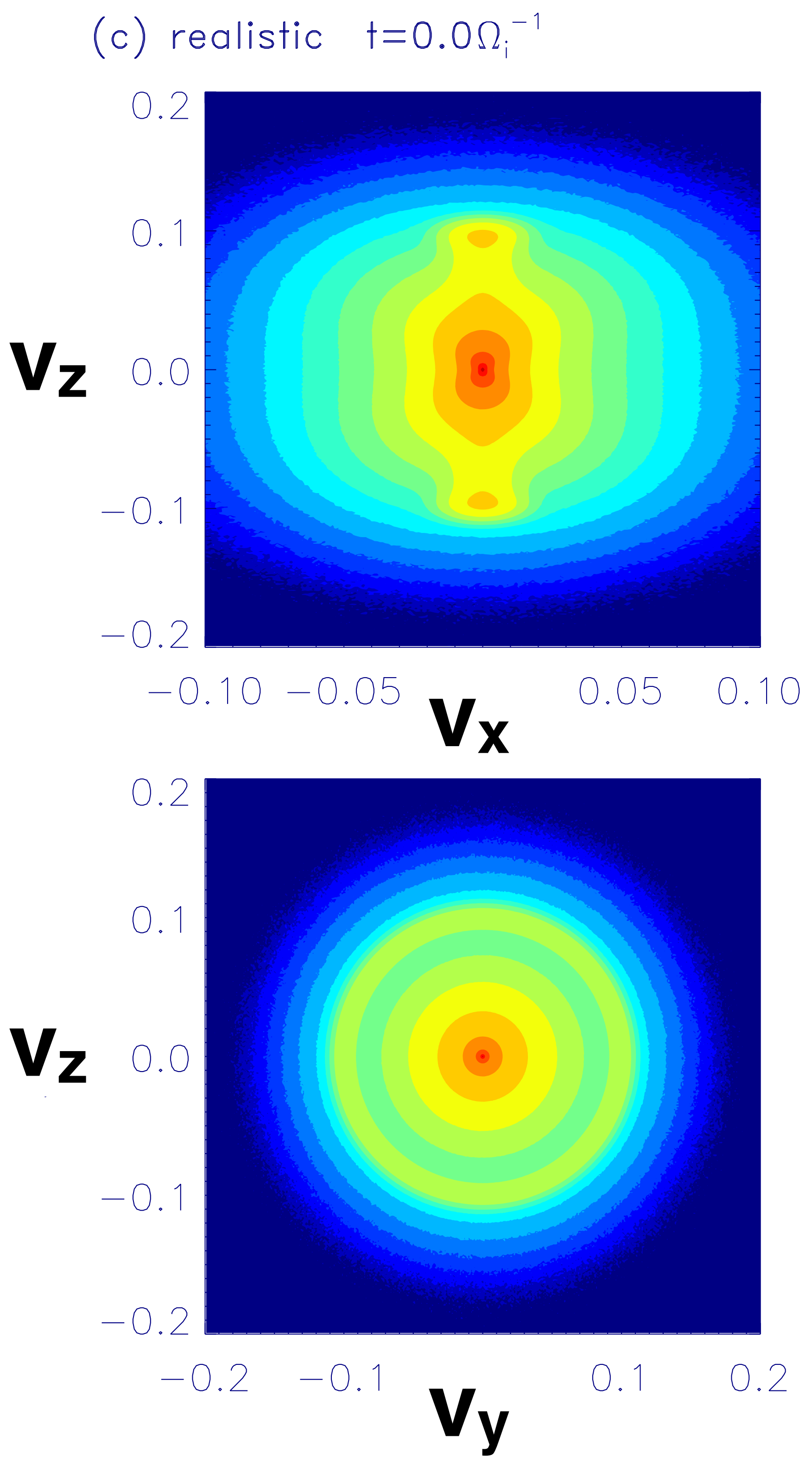
2D slices through raw neutral hydrogen in OHS from MHD-MC model

Inner heliosheath ENAs (Population 2) ***Solar wind ENAs (Population 3)***



Gyroangle-averaged PUI distribution





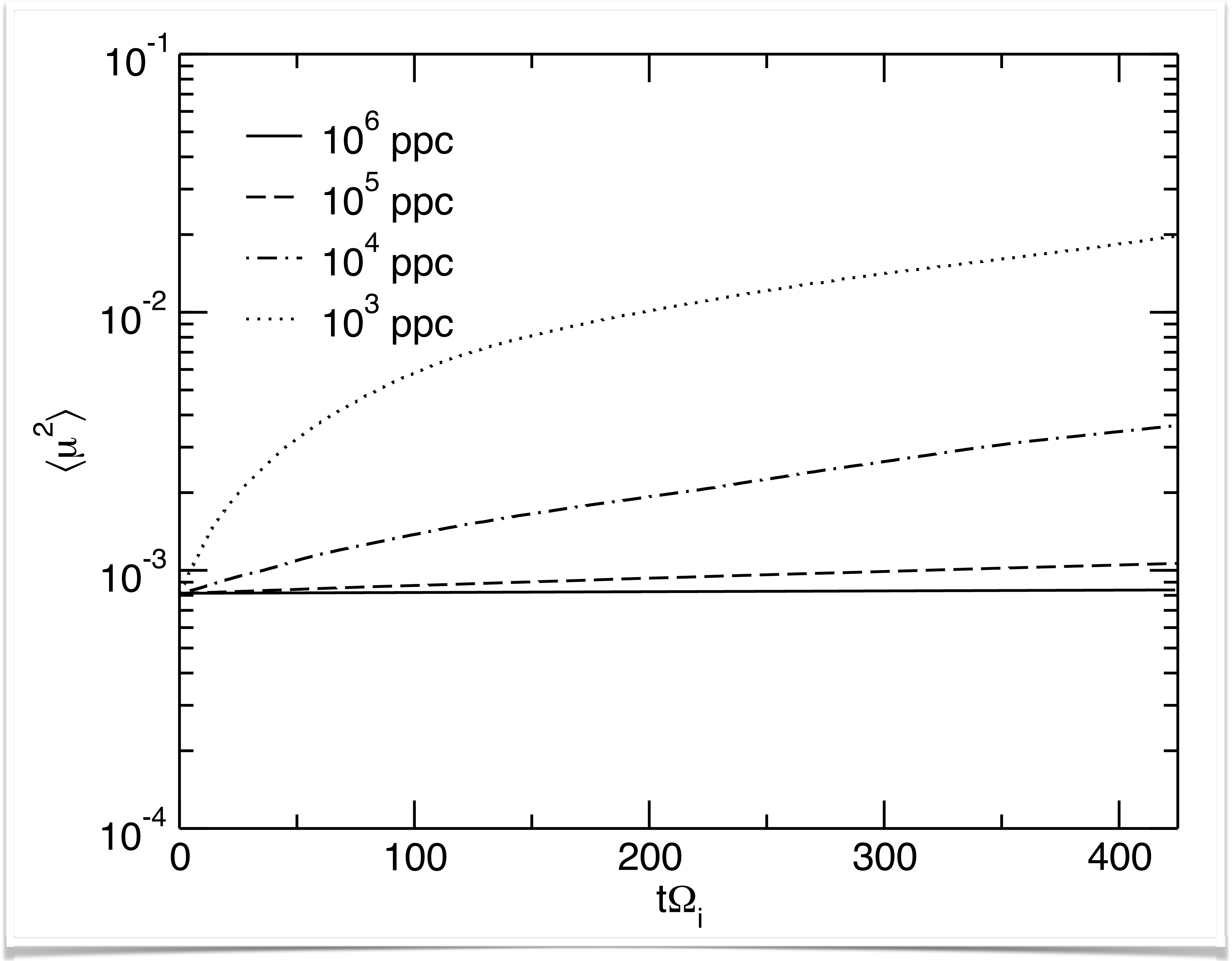
Hybrid simulations of finite-temperature rings

- improvements to the 2010 **1D** code (Florinski et al. 2010): implicit advance for particle and fields, parabolic spline shape function; Δx=0.5 c/ω_i, **N_{ppc}=1000,000**

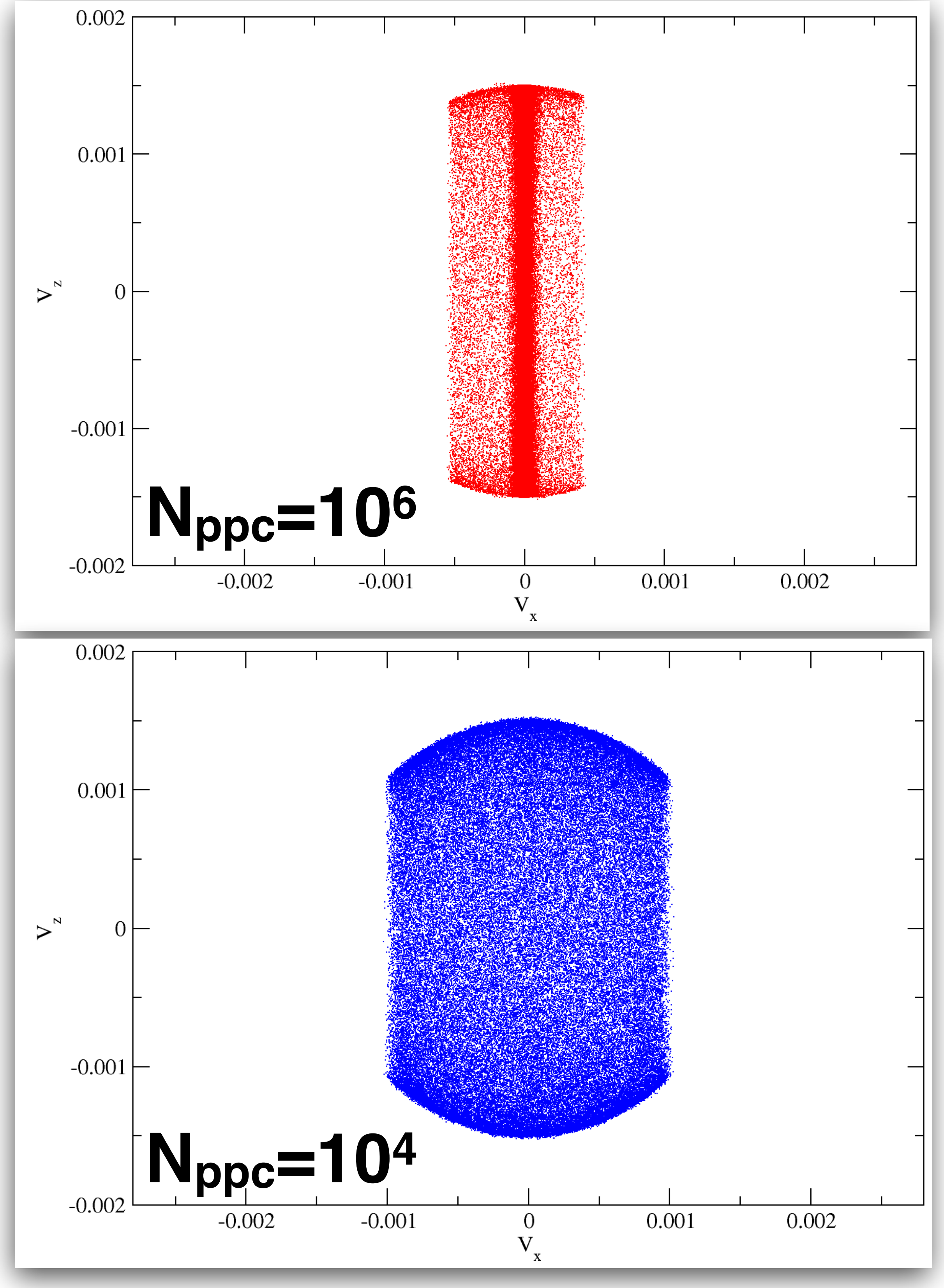
Hybrid simulations of finite-temperature rings

- improvements to the 2010 **1D** code (Florinski et al. 2010): implicit advance for particles and fields, parabolic spline shape function; Δx=0.5 c/ωi, **N_{ppc}=1000,000**

Pitch-angle spread for a stable ring of finite width



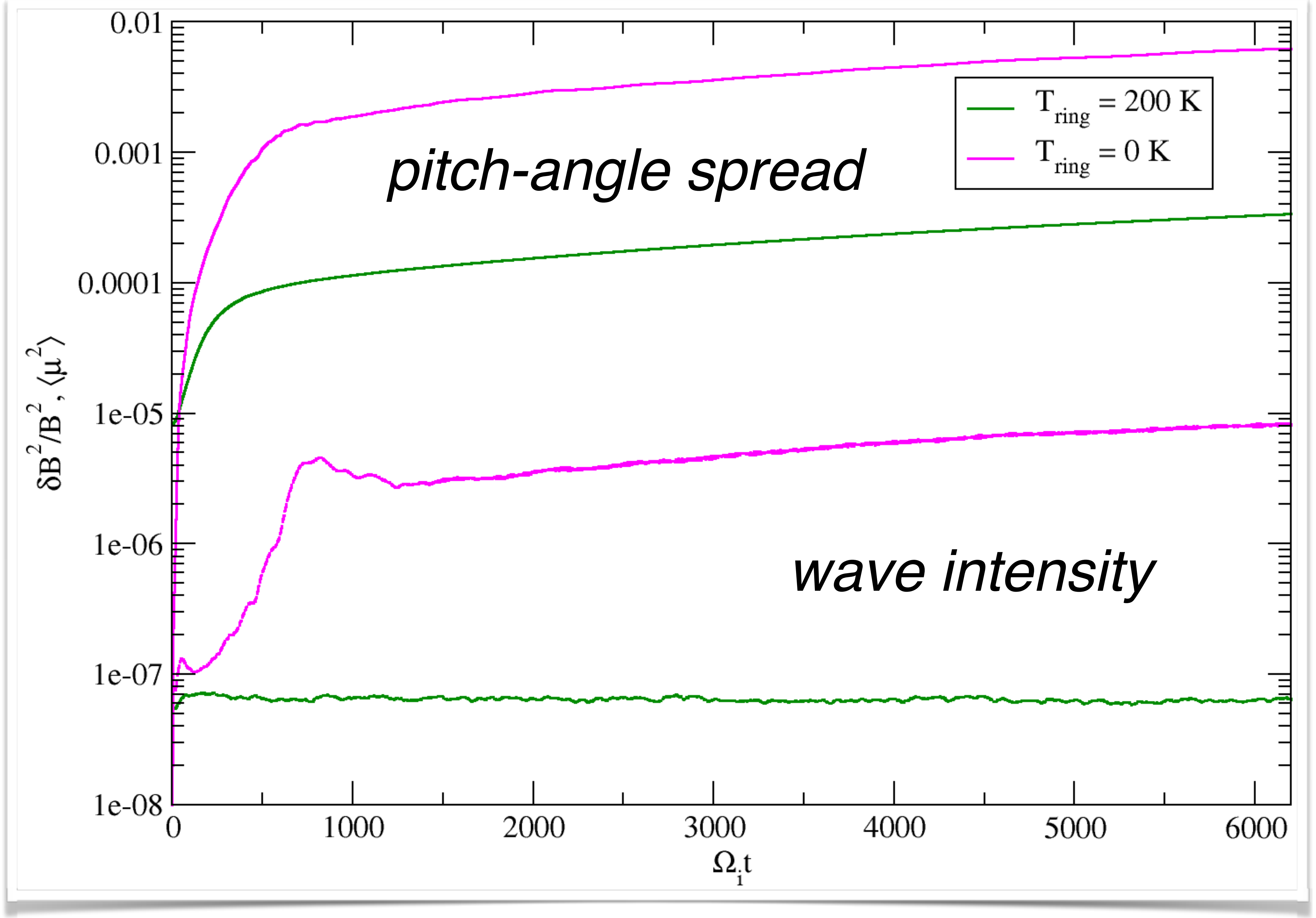
Cold ring after 1000 orbits



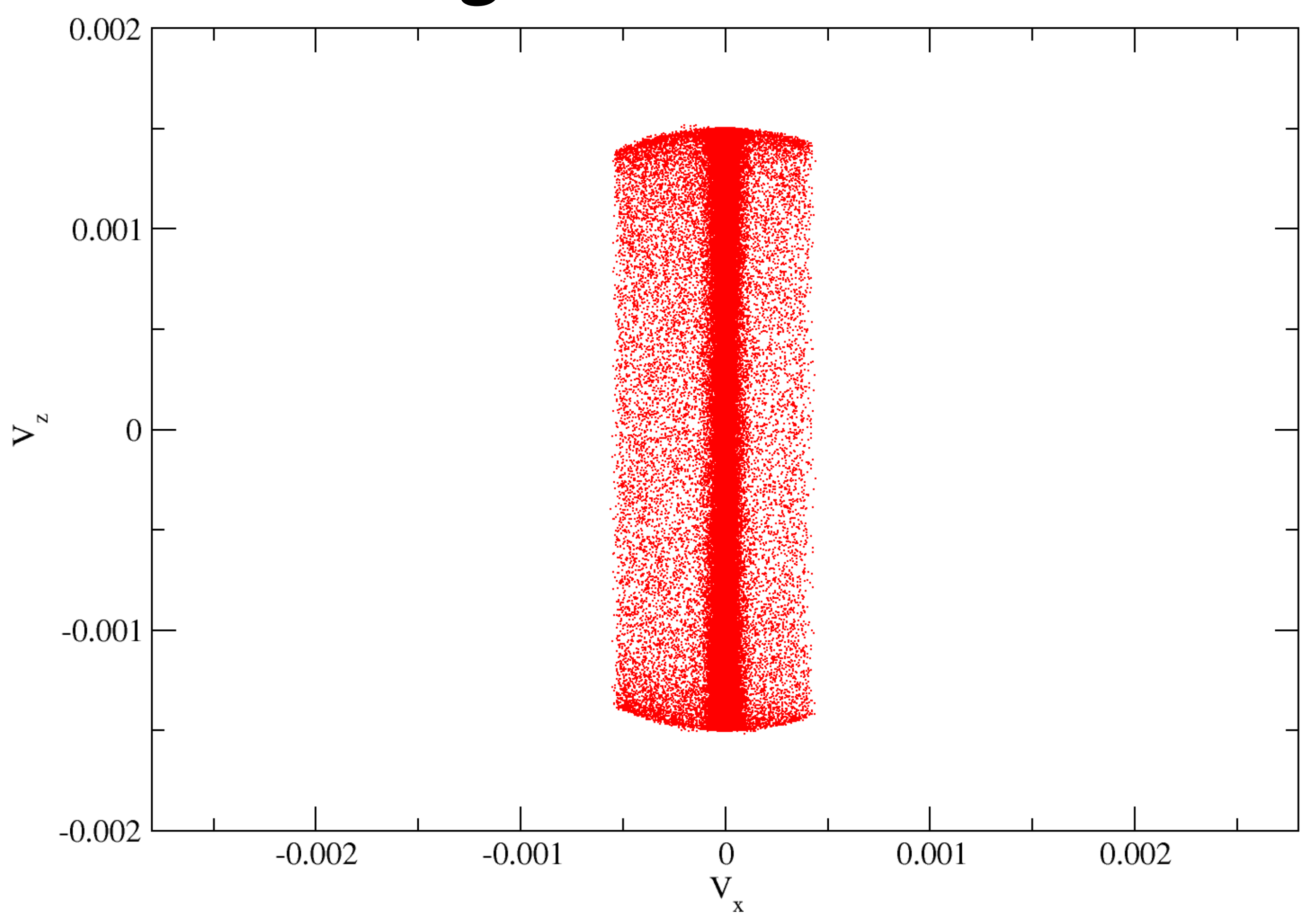
- for low ***N_{ppc}*** scattering is due to statistical noise, not an instability

Hybrid simulations of finite-temperature rings

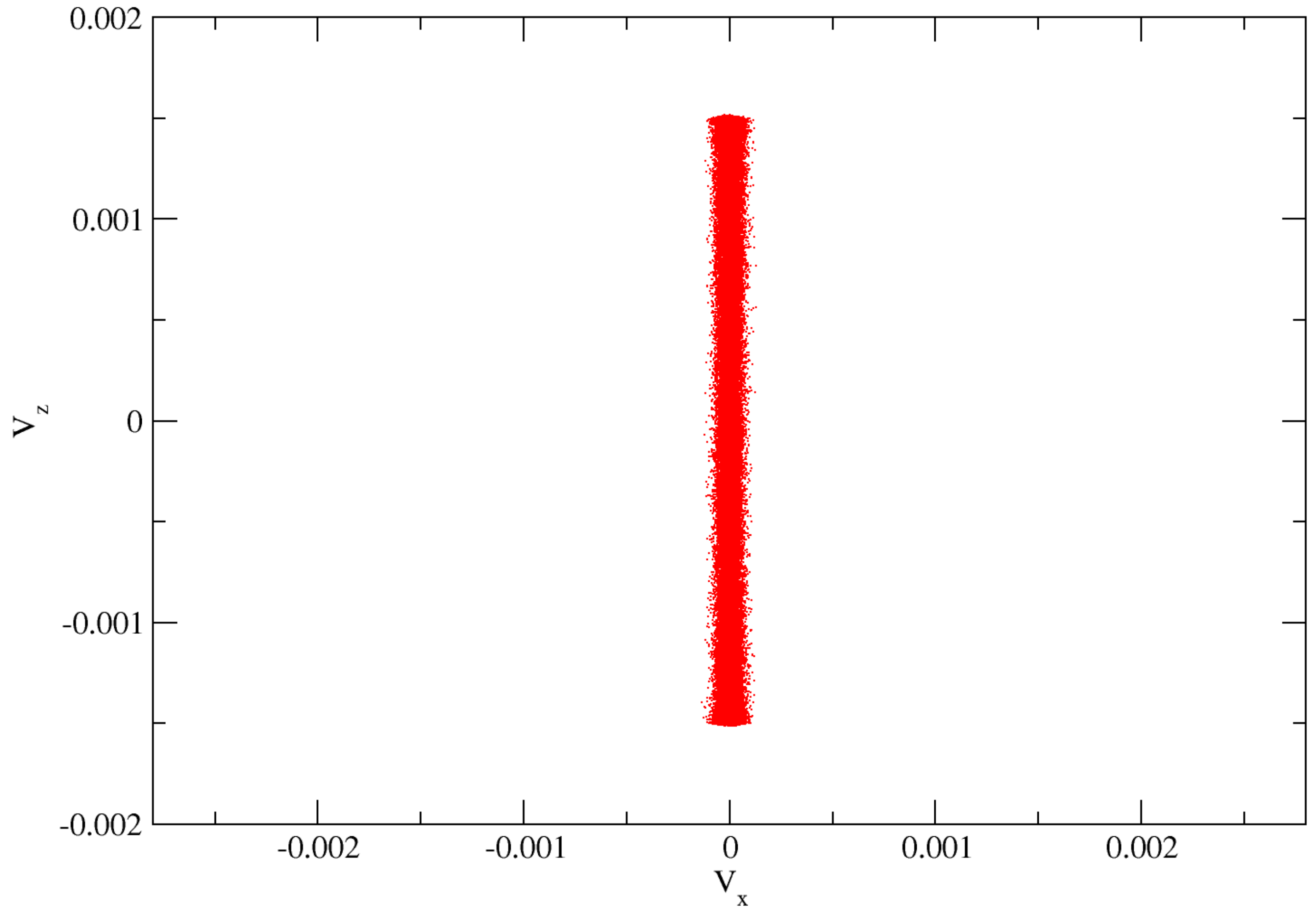
- N_{ppc}=1000,000



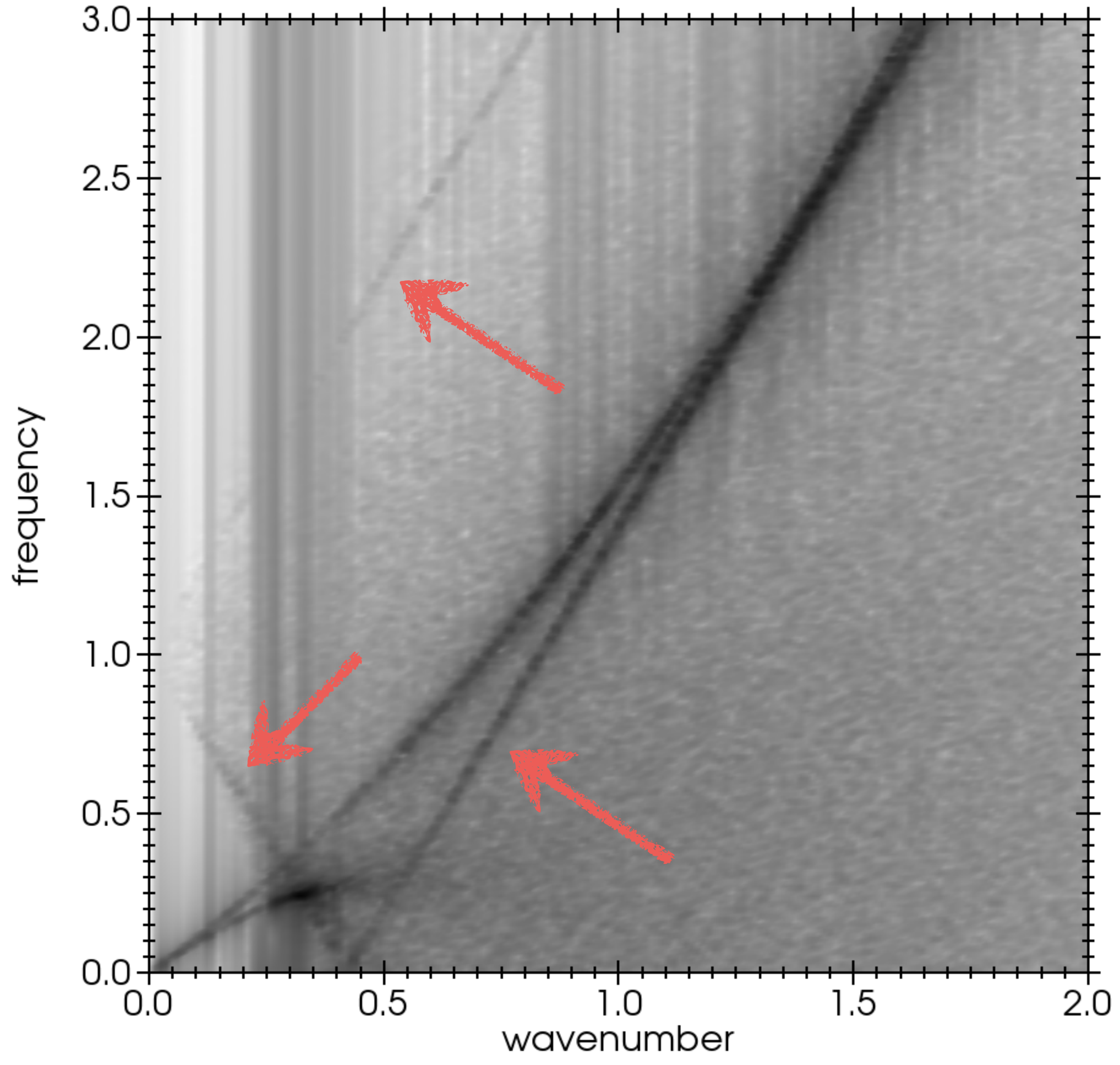
Cold ring after 1000 orbits



T=200 K ring after 1000 orbits



Fourier spectra (600-1200/Ω_i)



- resonance relations for ions ($\pm\Omega_i$) at the edges of the broadened ring

2D Particle-In-Cell simulations

- realistic parameters not computationally feasible for 2D PIC simulations
- approximate model assumes the scaling for frequencies in the OHS plasma:

$$\omega_{\mathrm{pe}} \gg \omega_{\mathrm{pi}} \gg \Omega_e \gg \Omega_i$$

- for ion-to-electron mass ratio $m_i/m_e=50$* we choose: $\omega_{\mathrm{pe}}/\Omega_e = 20,\ \omega_{\mathrm{pi}}/\Omega_i \simeq 141.42,\ \omega_{\mathrm{pi}}/\Omega_e \simeq 2.83$

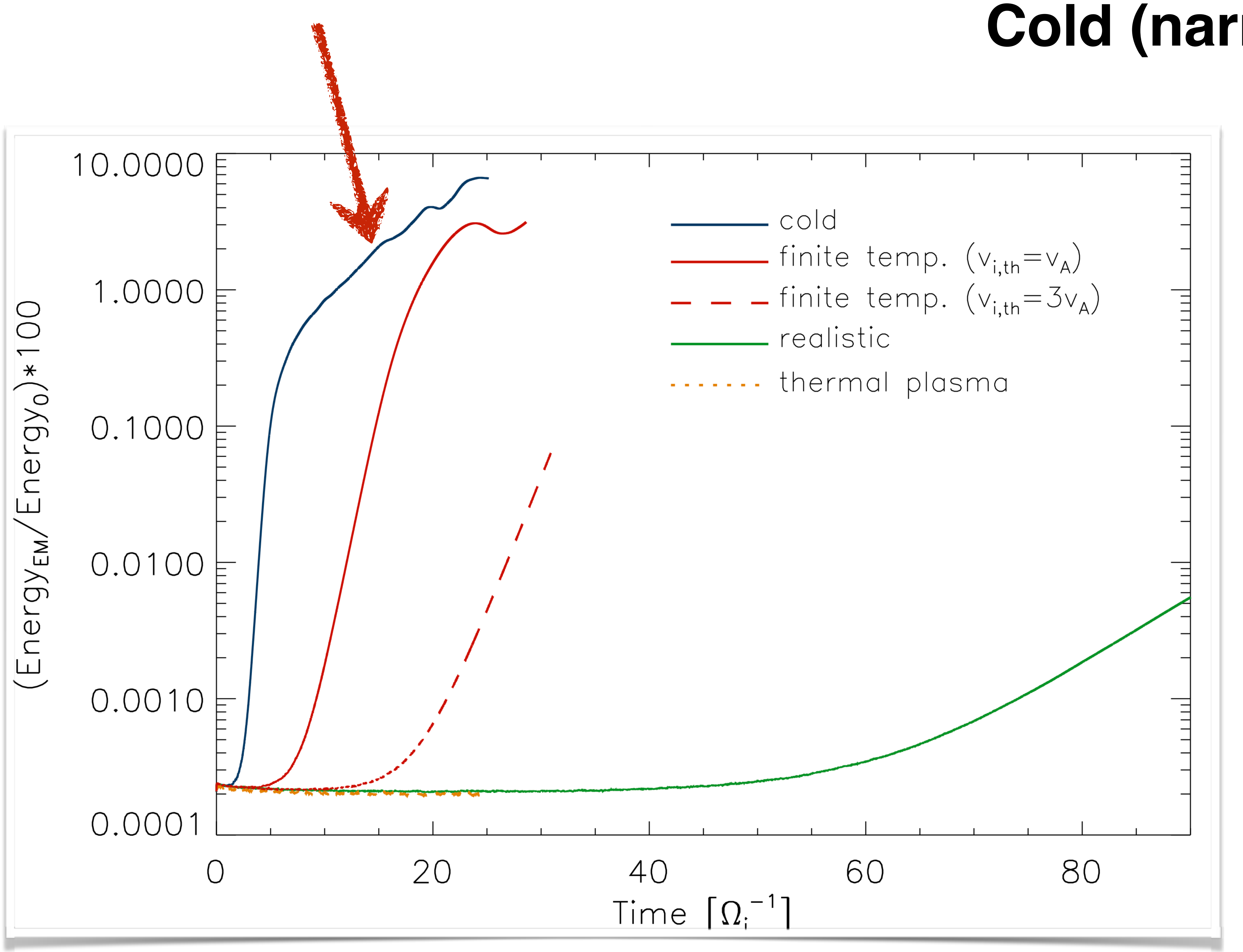
- other parameters:
  - plasma beta: $\beta = v_{i,\mathrm{th}}^2/v_{\mathrm{A}}^2 = 1$
  - solar wind speed: $v_{\mathrm{SW}} = 0.1c \simeq 14\, v_{\mathrm{A}}$
  - ion ring-beam to background density ratio: $N_{\mathrm{ring}}/N_i = 0.025$
  - N_{ppc} = 2500

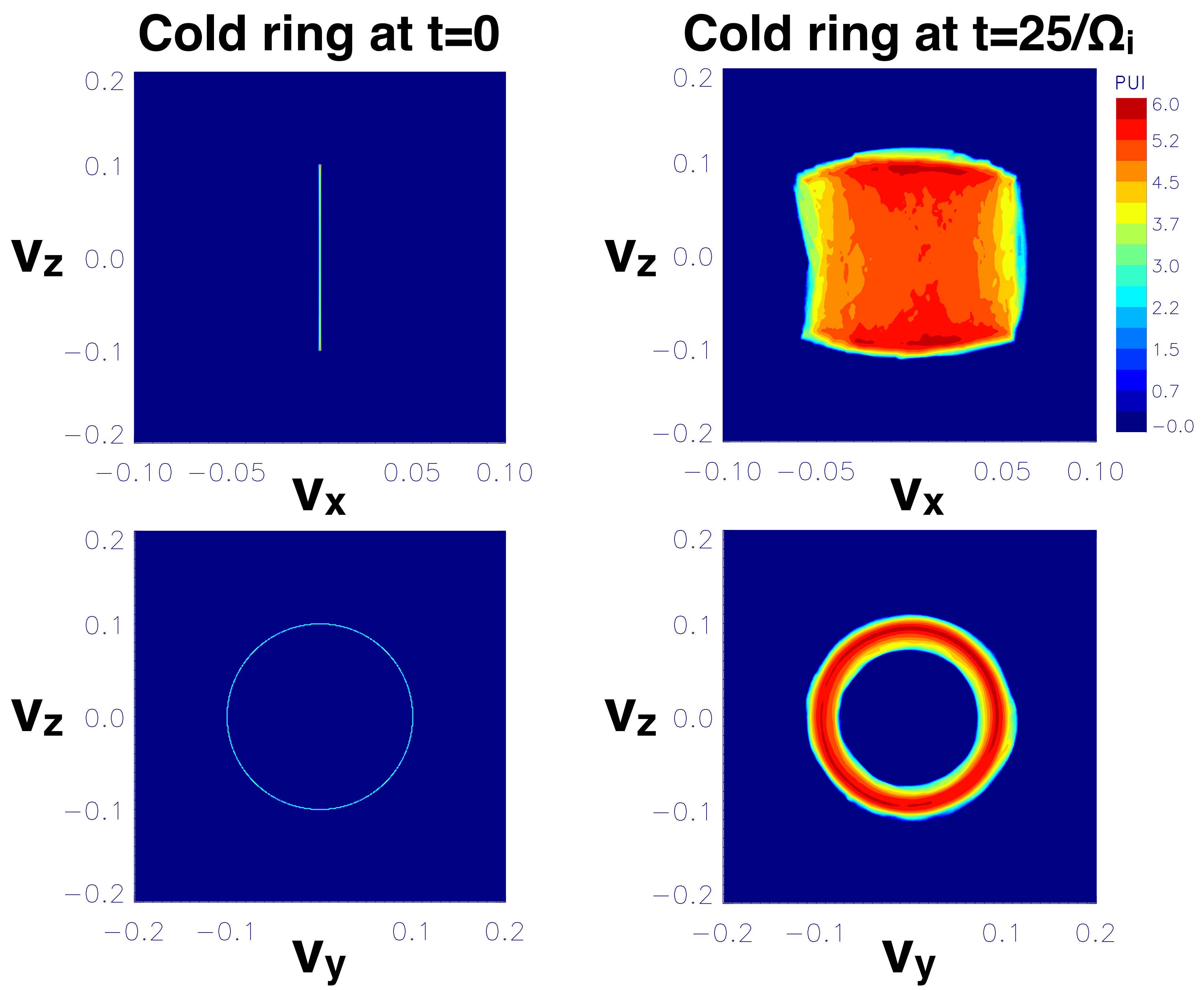
- results converge for N_{ppc} above 250

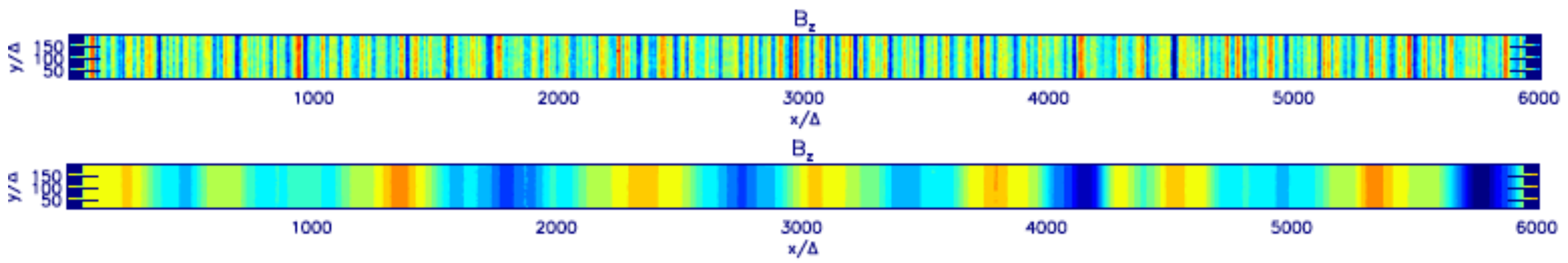
*for real mass ratio m_i/m_e=1836 and $\omega_{\mathrm{pi}}/\Omega_i = c/v_{\mathrm{A}} = 1.74 \times 10^4$
these scalings are numerically: $\omega_{\mathrm{pe}}/\Omega_e \simeq 406,\ \omega_{\mathrm{pi}}/\Omega_e \simeq 9.48$

2D Particle-In-Cell simulations

Cold (narrow) ring



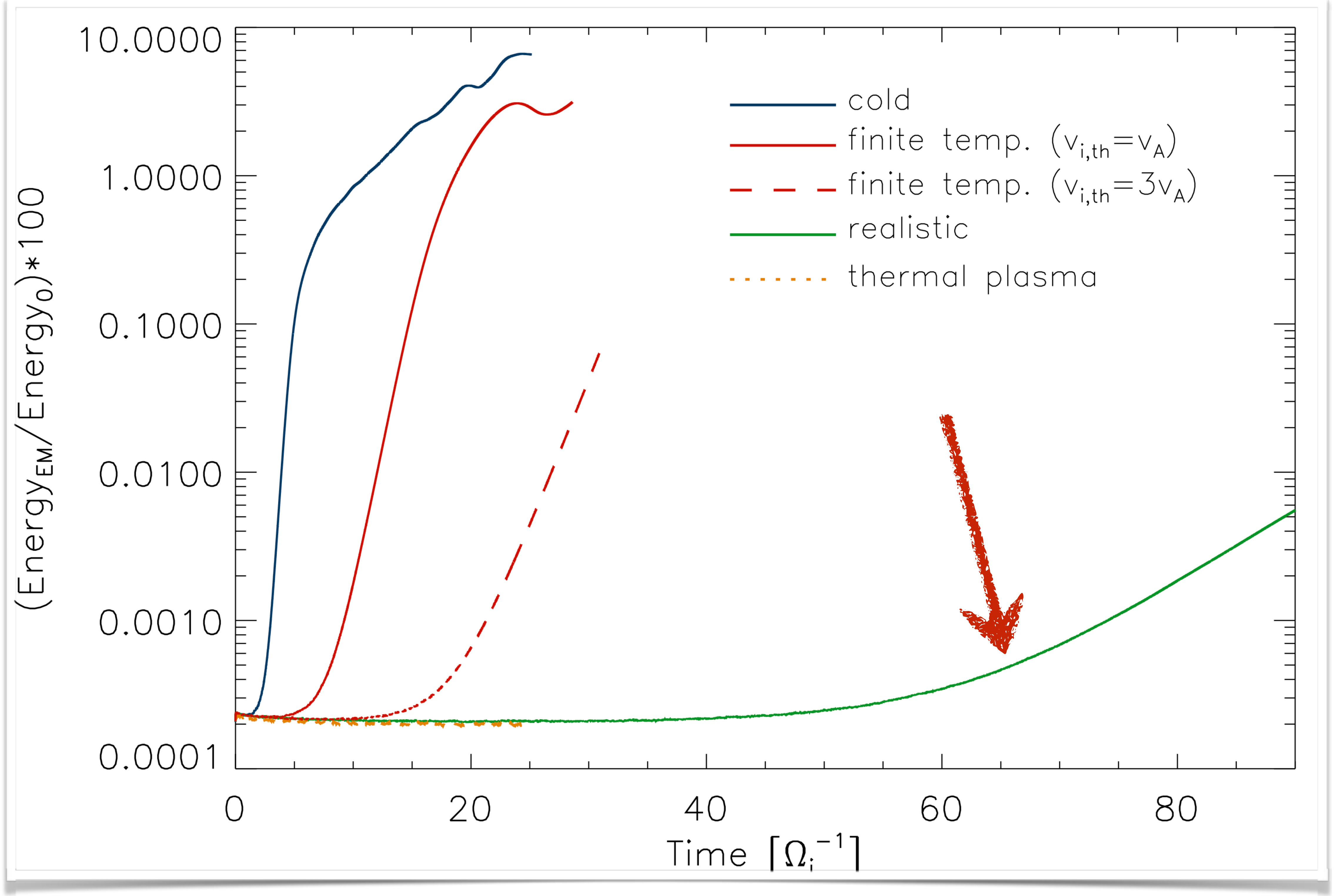


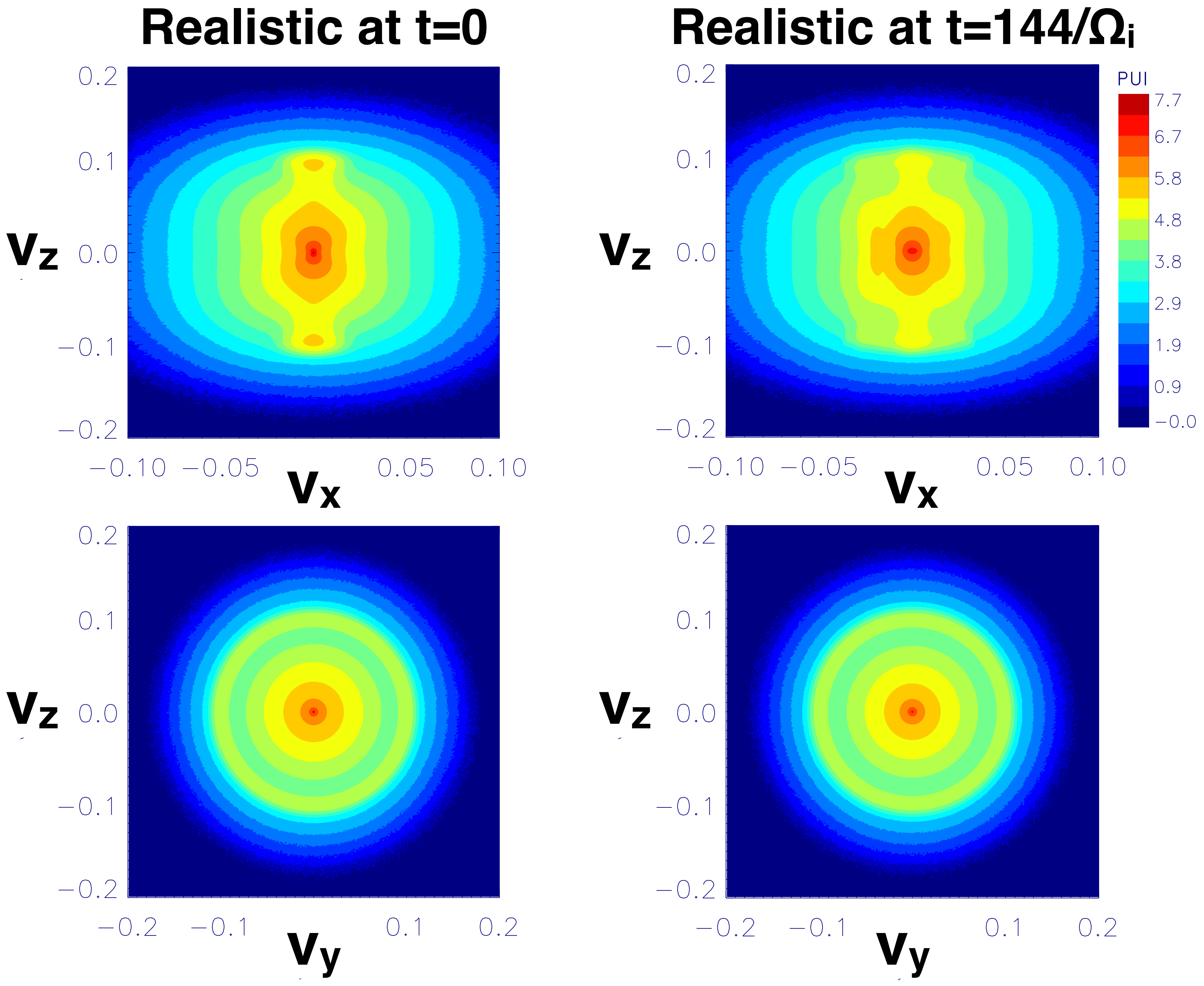


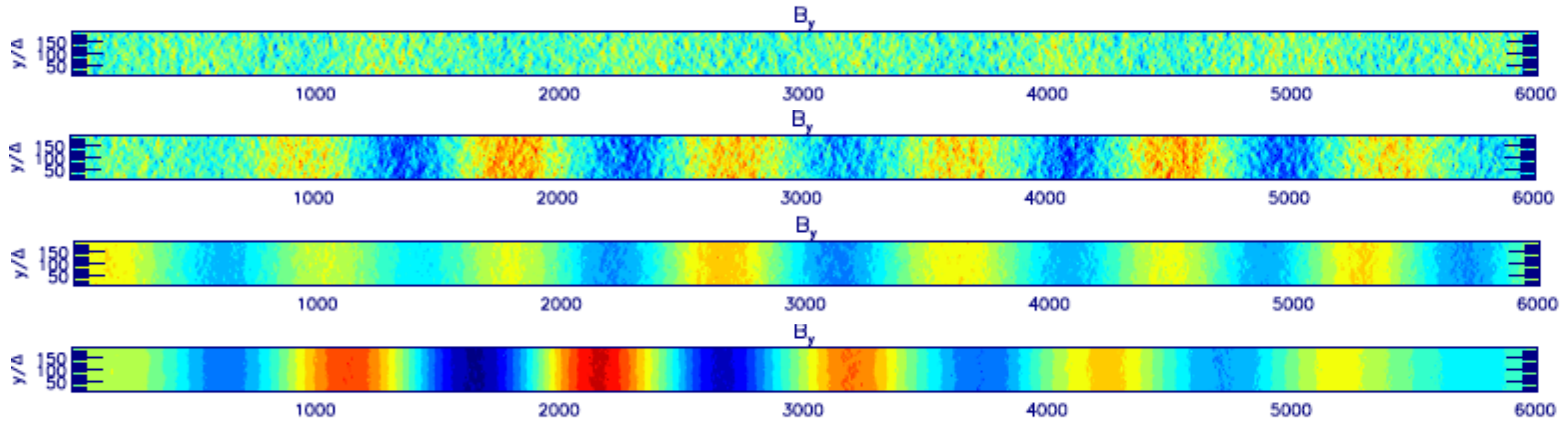
Bz at t=3.75/Ω_i (top) and t=25/Ω_i (bottom)

2D Particle-In-Cell simulations

Realistic ENA distribution





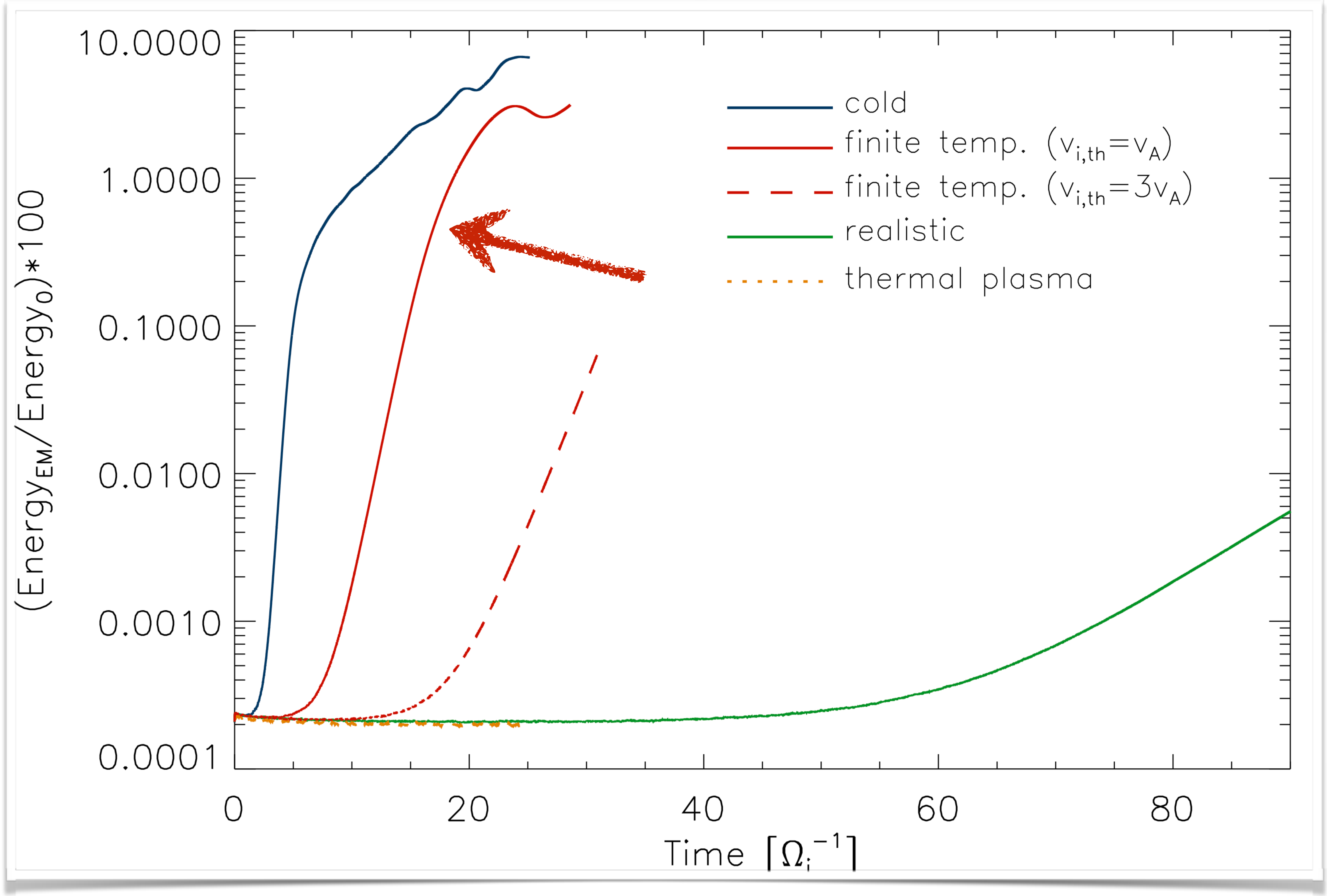


By at $t\Omega_i$ = 31.25, 62.6, 100.0, 143.75 (from top to bottom)

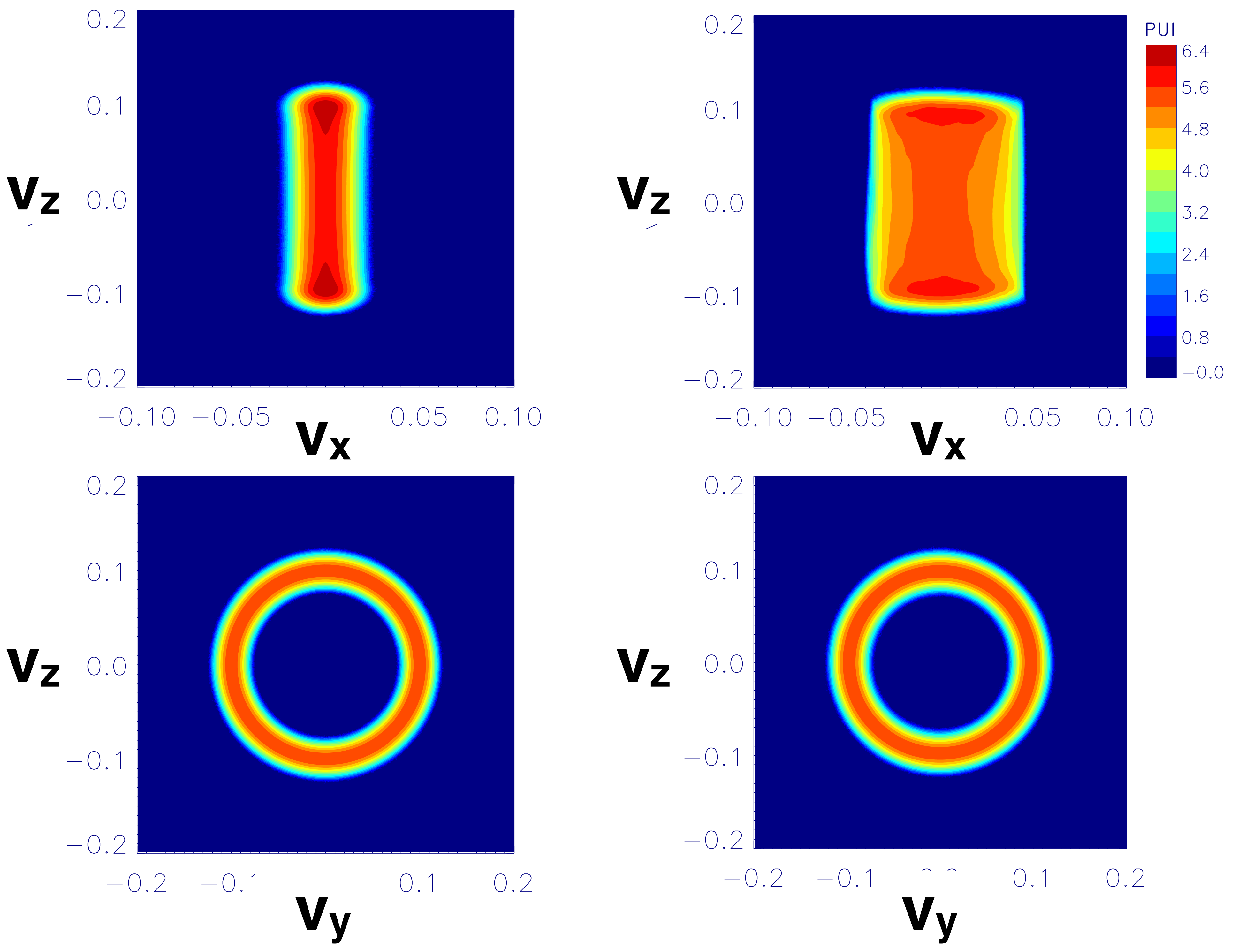
- modes strongly damped up to ~$50/\Omega_i$
- growth rate about 40 times slower than for the cold ring
- PUI distribution at near-saturation at to ~$150/\Omega_i$ only weakly scattered
- simple scaling suggests that this distribution should be stable for at least 10 days

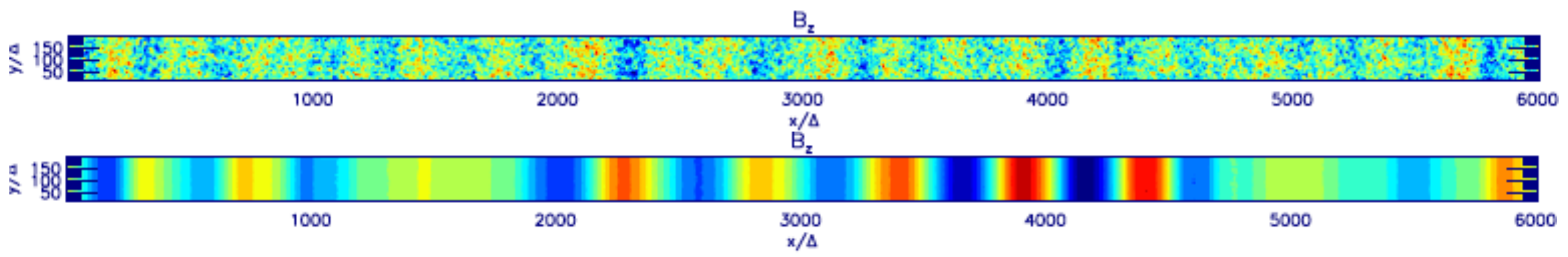
2D Particle-In-Cell simulations

Finite-temperature distribution with $\delta v_{||} = \delta v_{\perp} = v_{i,th}$



Finite-temp $v_{i,th}$ at t=0 **Finite-temp $v_{i,th}$ at t=25/Ω_i**

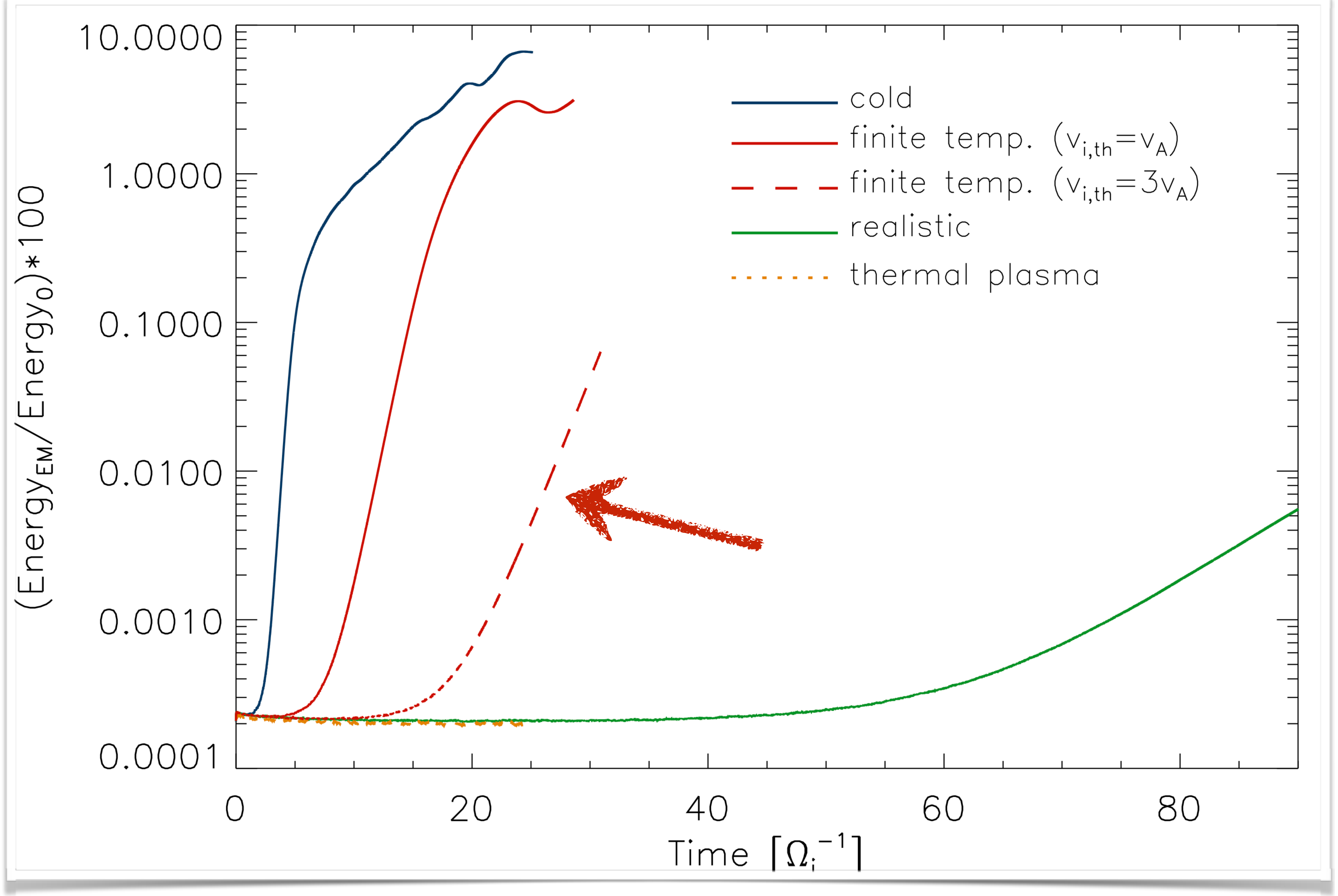




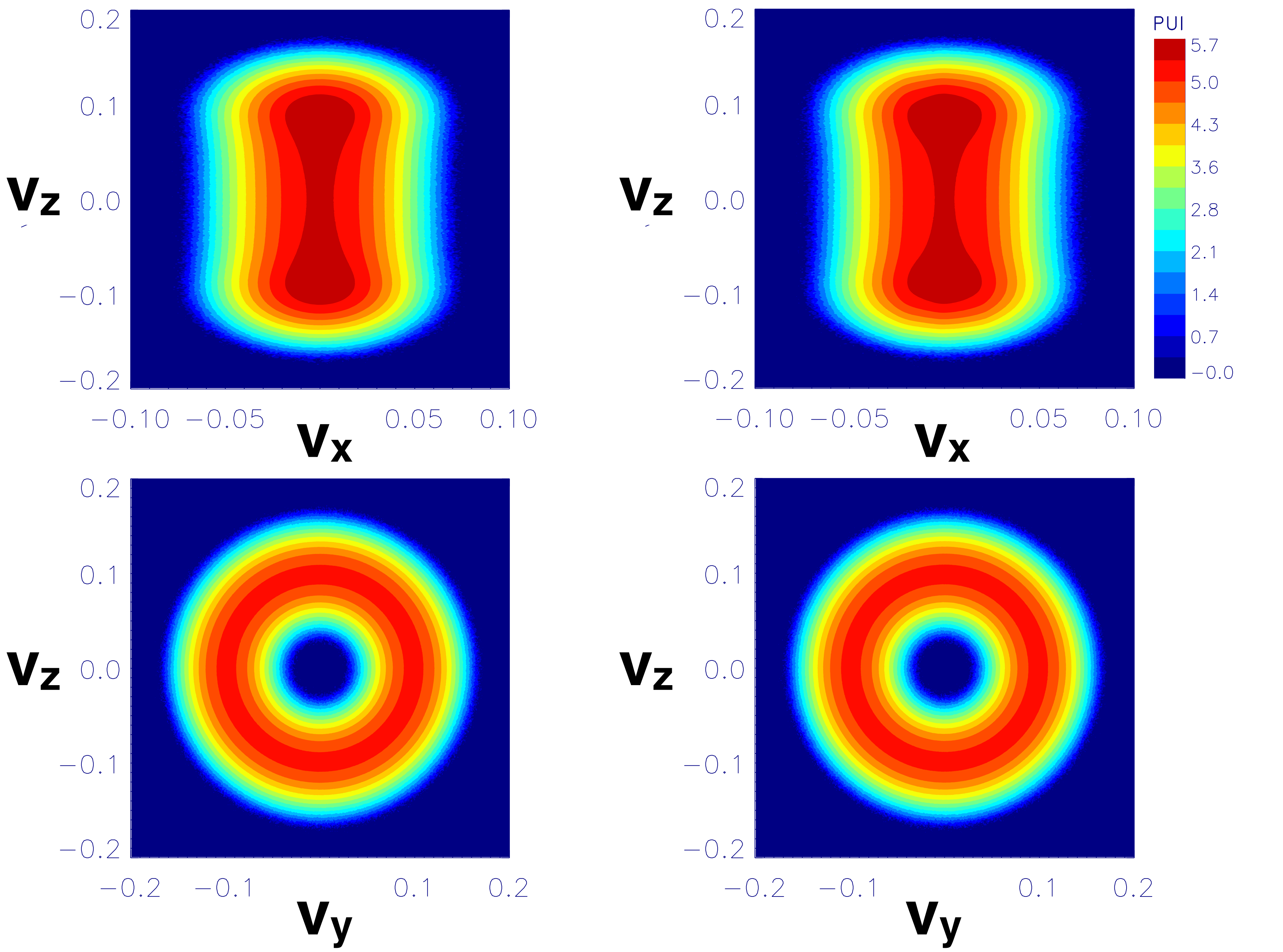
Bz at t=6.25/Ω_i (top) and t=25/Ω_i (bottom)

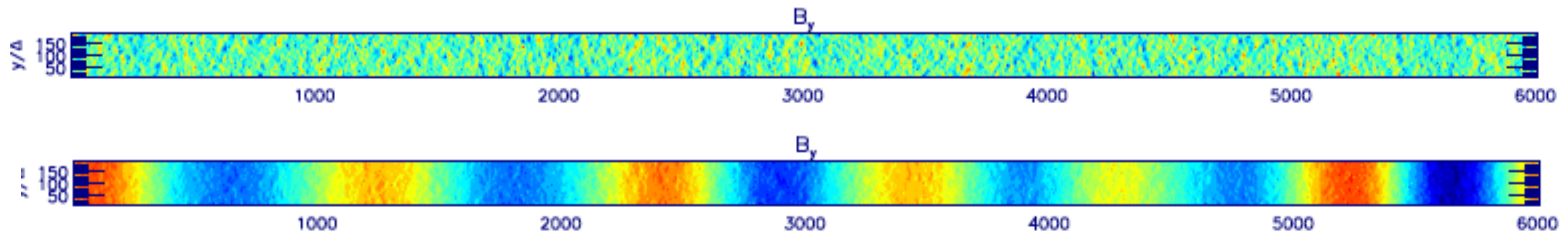
2D Particle-In-Cell simulations

Finite-temperature distribution with $\delta v_{||}=\delta v_{\perp}=3v_{i,th}$



Finite-temp $3v_{i,th}$ at t=0 **Finite-temp $3v_{i,th}$ at t=$31/\Omega_i$**





By at t=$6.25/\Omega_i$ (top) and t=$25/\Omega_i$ (bottom)

Summary

- the stability of two different classes of pick-up ion ring distributions that serve as parent ions of the ribbon ENA has been investigated with 1D hybrid and 2D (scaled) Particle-In-Cell simulations
- PIC modeling shows that realistic broadened ring+halo distribution derived from simulations of neutral atoms in the heliosphere is the most stable, exhibiting no scattering for at least 10 days
- hybrid simulations show that warm toroidal distributions broadened in velocity parallel to the mean magnetic field can be stable over 1000 orbits
- hybrid modeling also suggests that even cold narrow rings can be stabilized in the nonlinear stage once cold PUI loose resonance with the waves generated by the edges of the initially broadened ring
- such distributions may thus remain stable long enough for charge-exchange to take place and generate ENAs that would be detected by IBEX
- in such case the absence of magnetic fluctuations at Voyager 1 is naturally explained