Krajowy Naukowy
Ośrodek Wiodący

Pick-up Ion Ring Stability in the Outer Heliosheath

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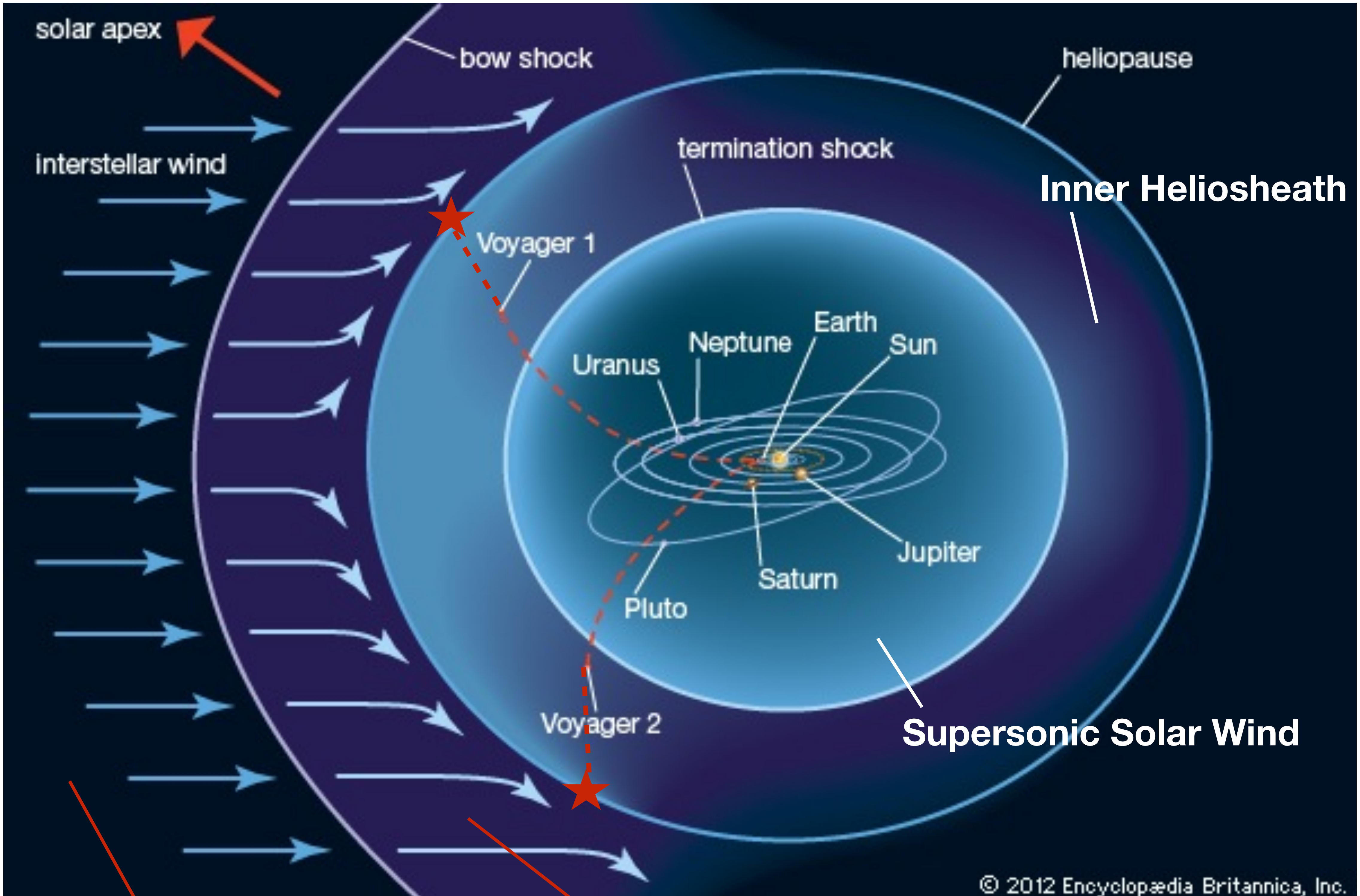
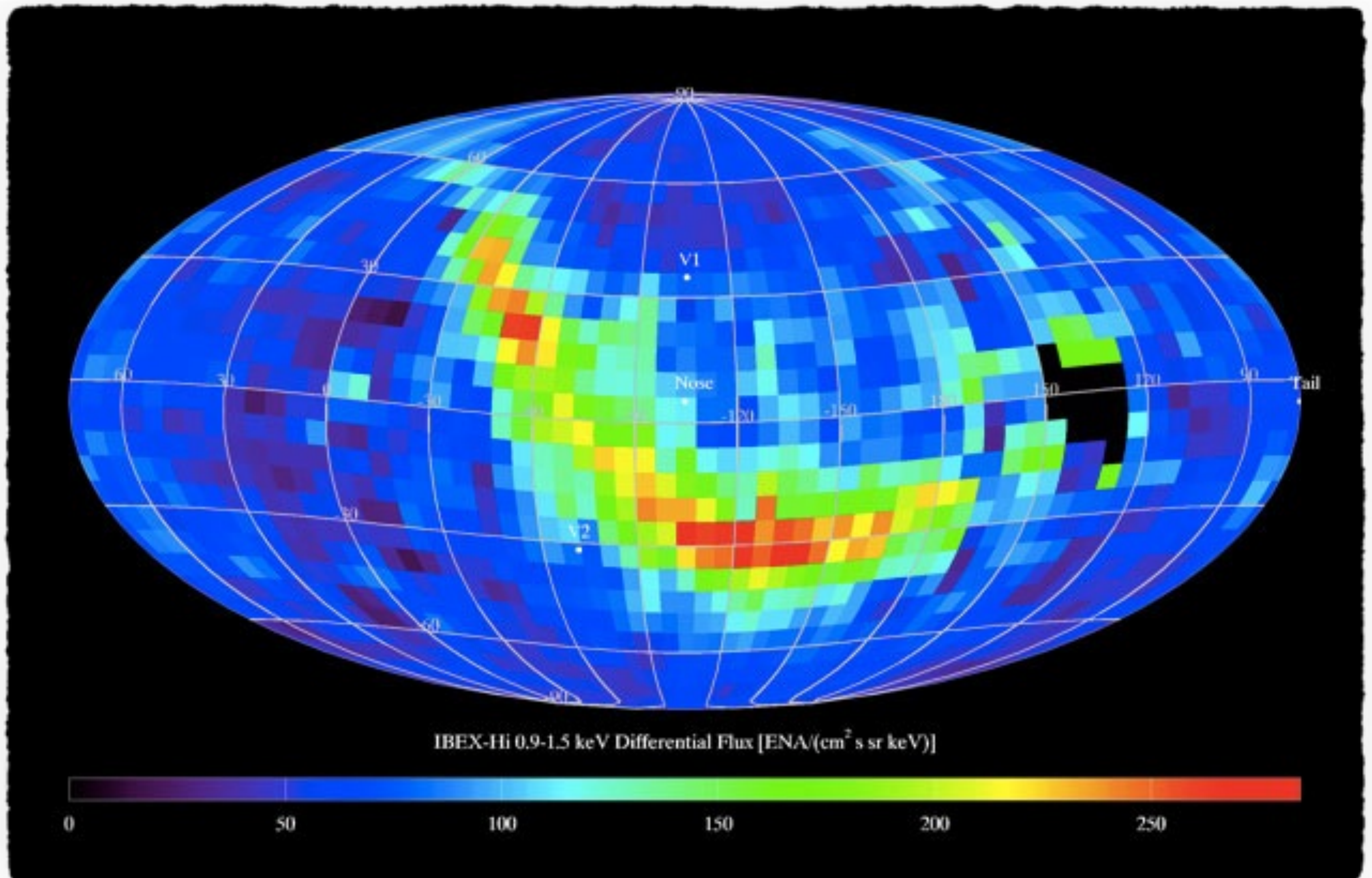
NARODOWE CENTRUM NAUKI

Structure of the Heliosphere/ISM Boundary



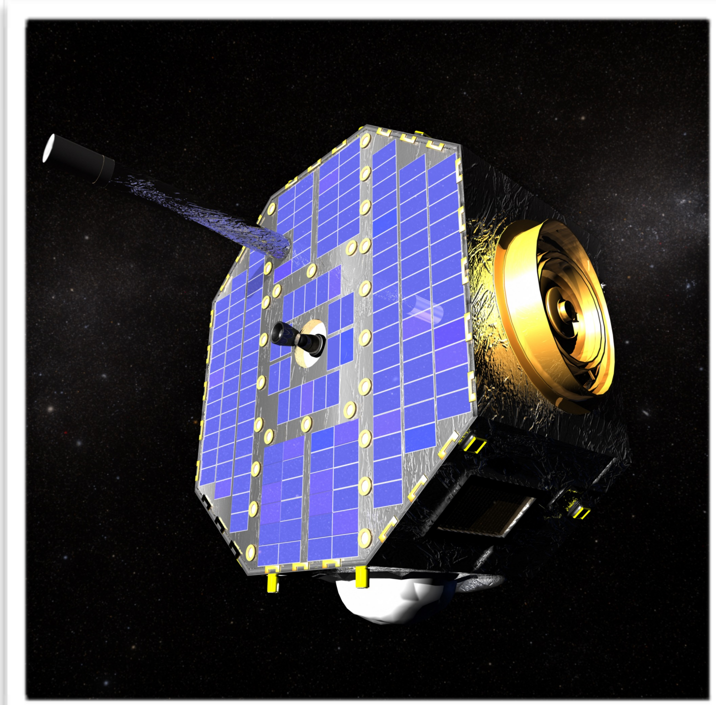
Interstellar Medium (ISM) **Outer Heliosheath (OHS)**

Interstellar Boundary Explorer (IBEX)



IBEX ribbon (NASA)

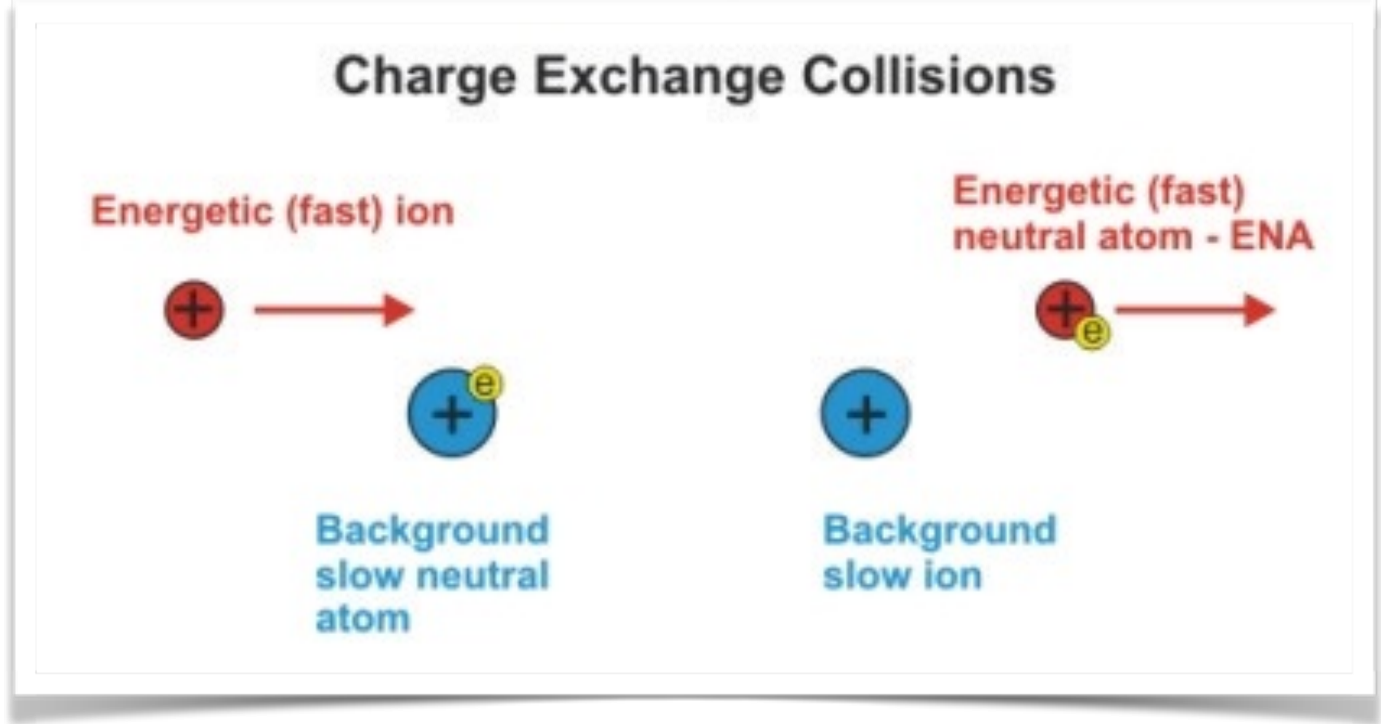
- mapping the boundary between the heliosphere and the true interstellar space by detecting fast moving energetic neutral atoms of hydrogen (ENAs) produced at the heliosheath



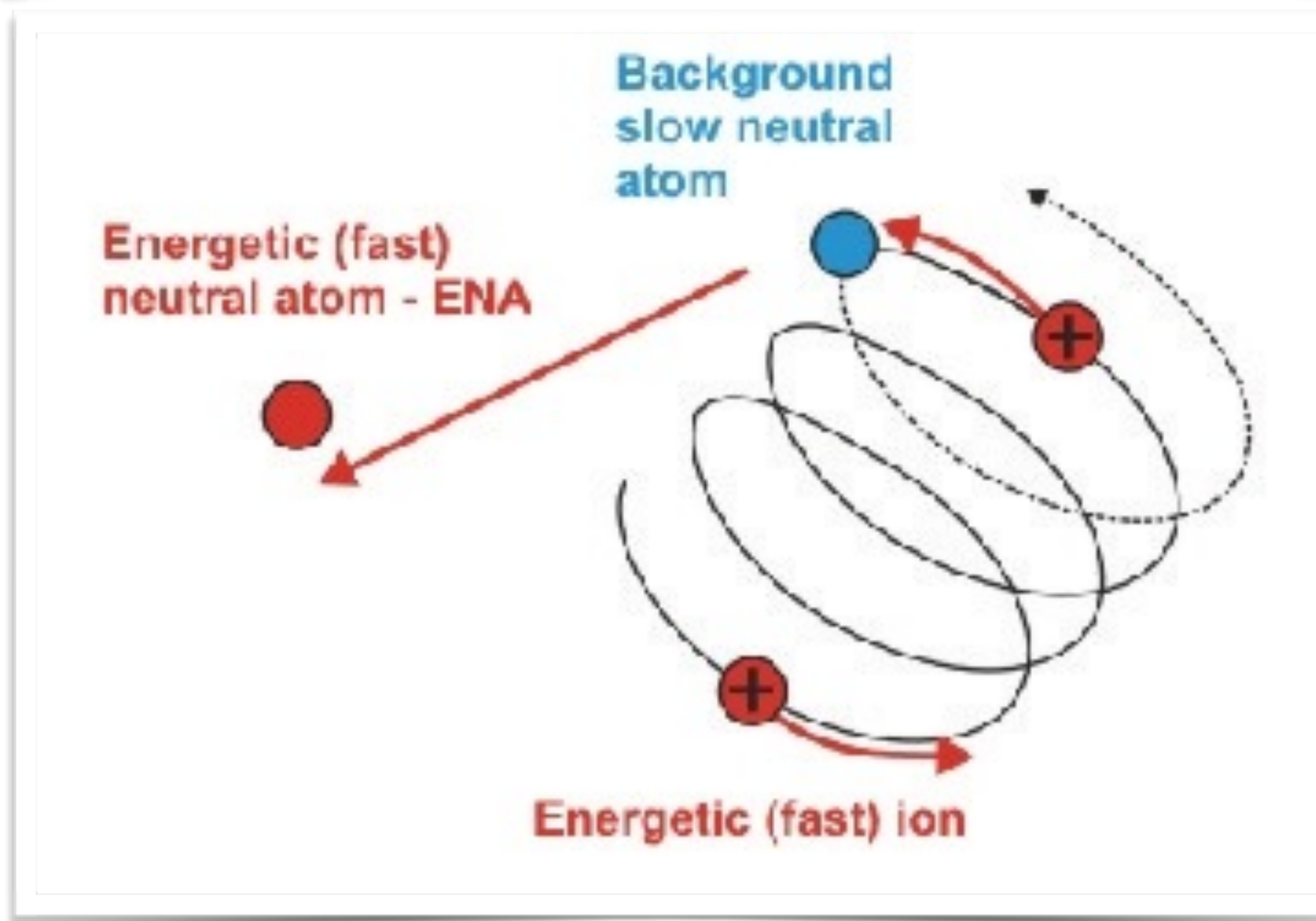
IBEX (NASA)

Energetic Neutral Atoms

- an energetic solar wind ion (proton) 'steals' charge from a slow moving neutral atom originating, e.g., from iterstellar space to become an Energetic Neutral Atom (ENA)



- the ENA leaves the charge exchange region in a straight line with the velocity of the original plasma ion



wikipedia.org

IBEX ribbon - plausible explanation

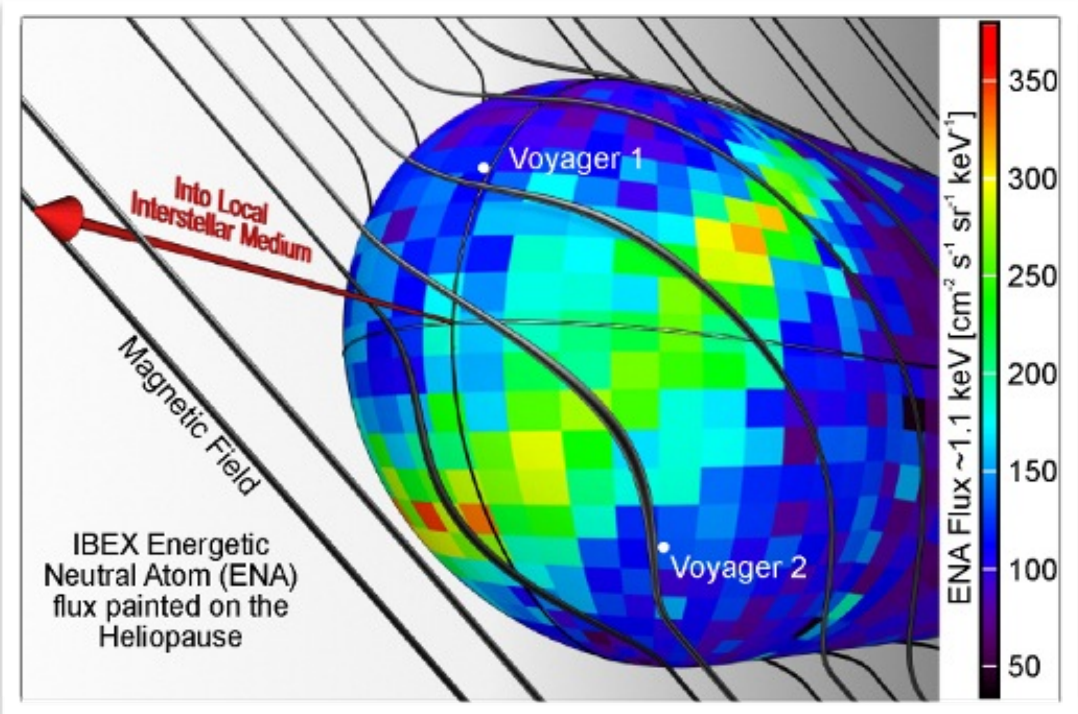
- intergalactic magnetic field shapes the heliosphere as it drapes over it; the ribbon appears to trace the area where the magnetic field is most parallel to the surface of the heliopause, i.e., perpendicular to solar wind particles' velocity

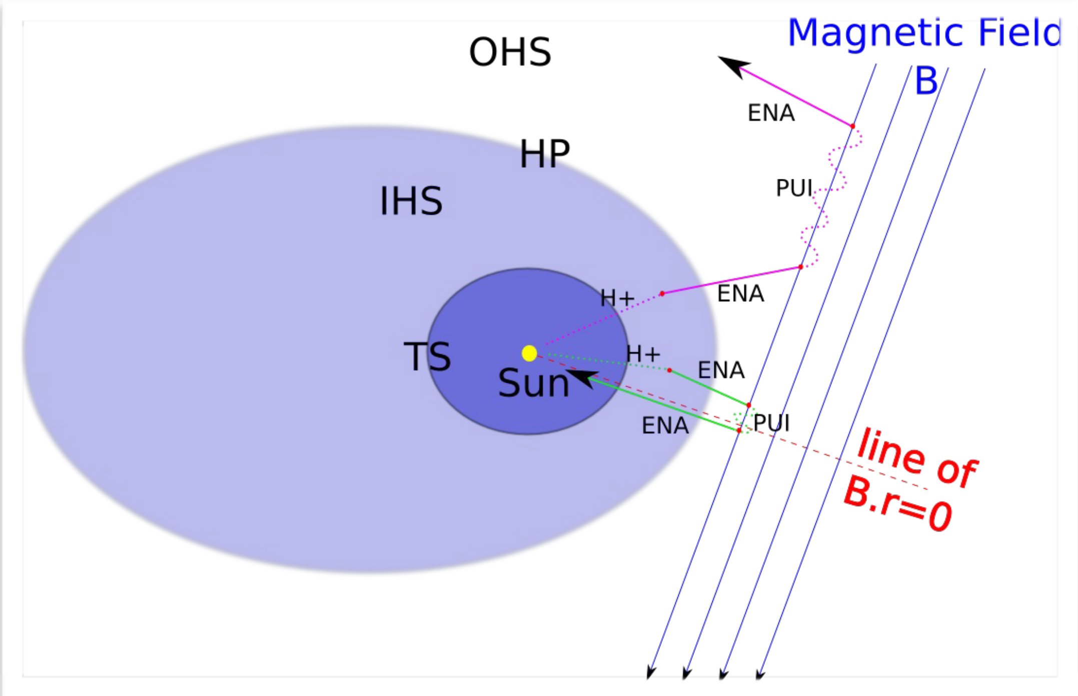
Scenario:

- IBEX ribbon formed by so-called „secondary" ENAs:
  - primary ENAs are born from charge exchange between solar wind protons and ISM neutrals in the heliosphere and propagate away from the Sun
  - primary ENA charge-exchange in the OHS to become the Pick-up Ions (PUIs); due to magnetic field orientation PUIs form a ring distribution in the velocity space
  - PUI charge-exchange again to produce secondary ENAs that have trajectories leading to back to the heliosphere (can be seen by IBEX)

Essential condition:

- PUI ring distribution must not scatter considerably before PUIs become secondary ENAs - PUI distribution must remain stable for several years





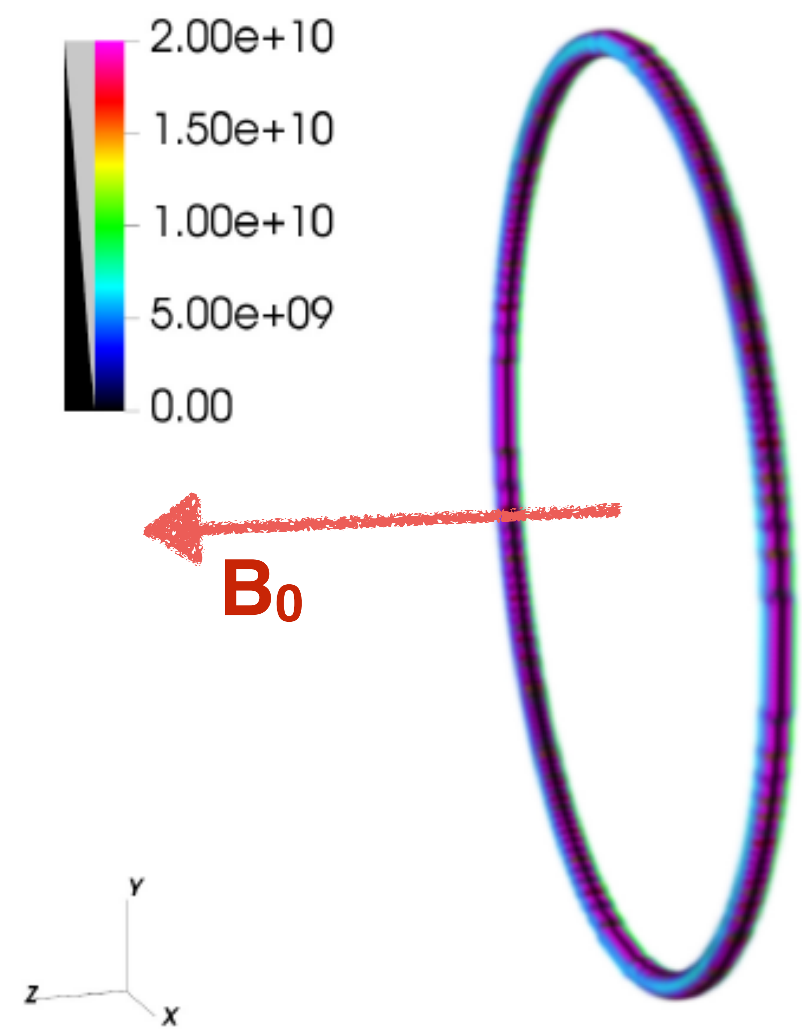
Pick-up Ion Ring Stability in the OHS

Question:

- under what conditions PUI rings remain long-time stable in the OHS?

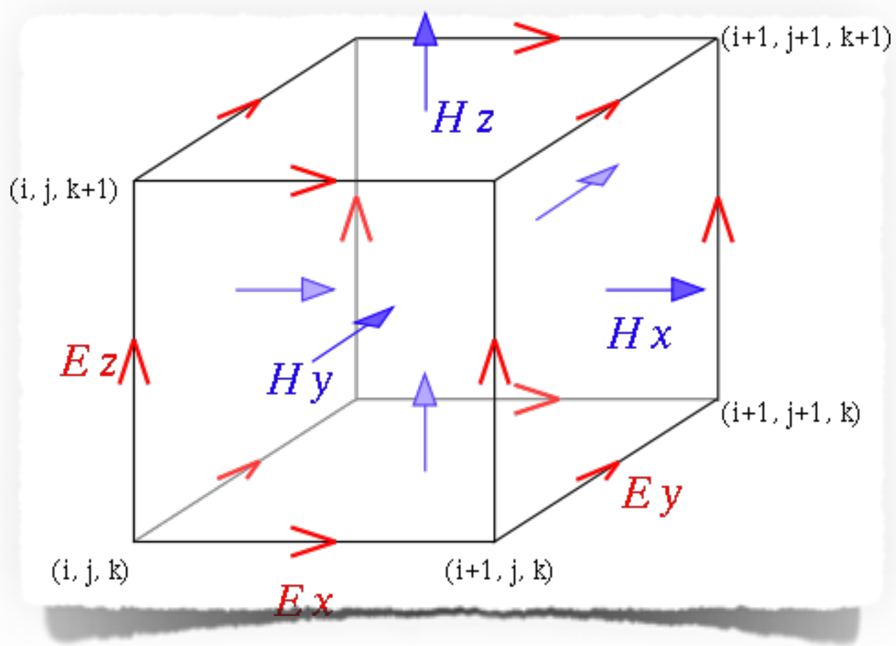
Methods:

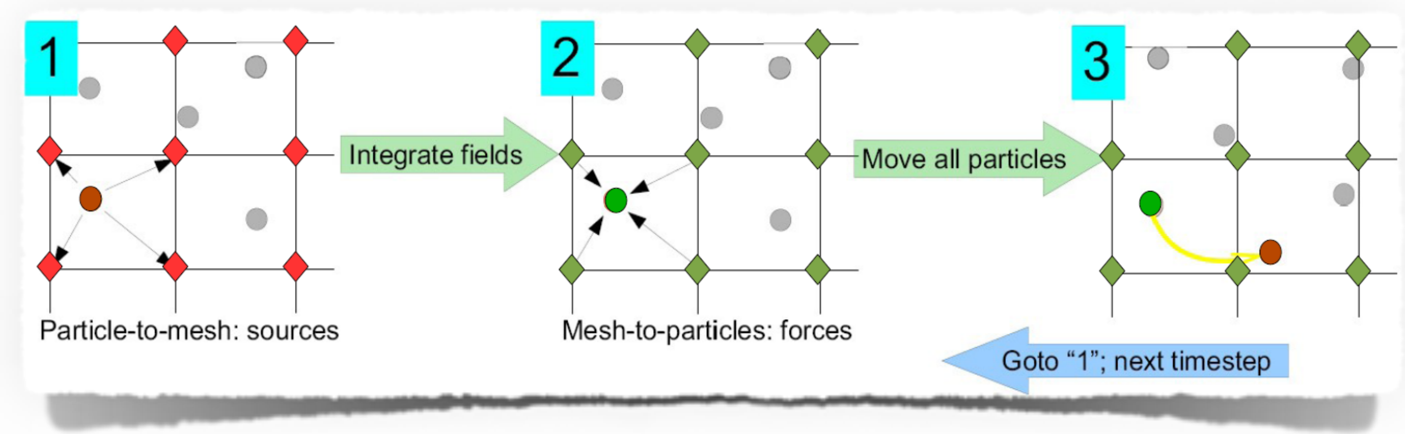
- linear analysis
- hybrid Particle-In-Cell simulations
- full Particle-In-Cell simulations



Method of Particle-In-Cell Simulations

- Particle-In-Cell simulations - an *ab-initio* model of collisionless plasma:
  - integration of Maxwell's equations on a numerical grid
  - integration of relativistic particle equations of motion in collective self-consistent EM fields





- Full PIC simulations: dynamics of both electrons and ions resolved
- Hybrid PIC simulations: only ion dynamics resolved, electrons modeled as a fluid (as in MHD)

Hybrid and full PIC simulations

Hybrid PIC simulations (1D)

- realistic physical parameters, e.g., ring-to-ambient density ratio of 10^{-4}
- grid size: 1024 cells with size 0.5 λ_{si}
- simulation time: 1000 ion orbits (61 h in the OHS) eqv. to 100,000π time steps ($\Delta t=0.02\Omega^{-1}$)
- particle statistics: N_{ppc}=1000,000
- 1h with a 1000 CPU-core simulations (1D)

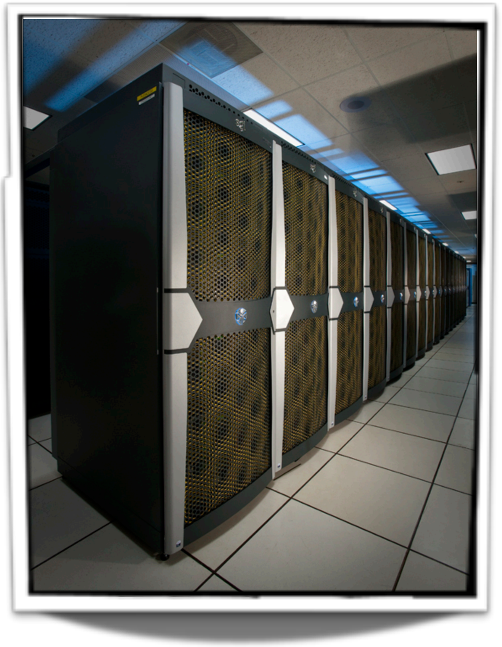
Full PIC simulations with physical m_i/m_e=1826 (1D)

- need to resolve sqrt(m_i) smaller spatial and temporal scales than hybrid PIC
- grid size: 44,000 cells
- simulation time: 75 billion time steps ($\Delta t=0.0625\omega_{pe}^{-1}$)

Our full PIC simulations (2D3V)

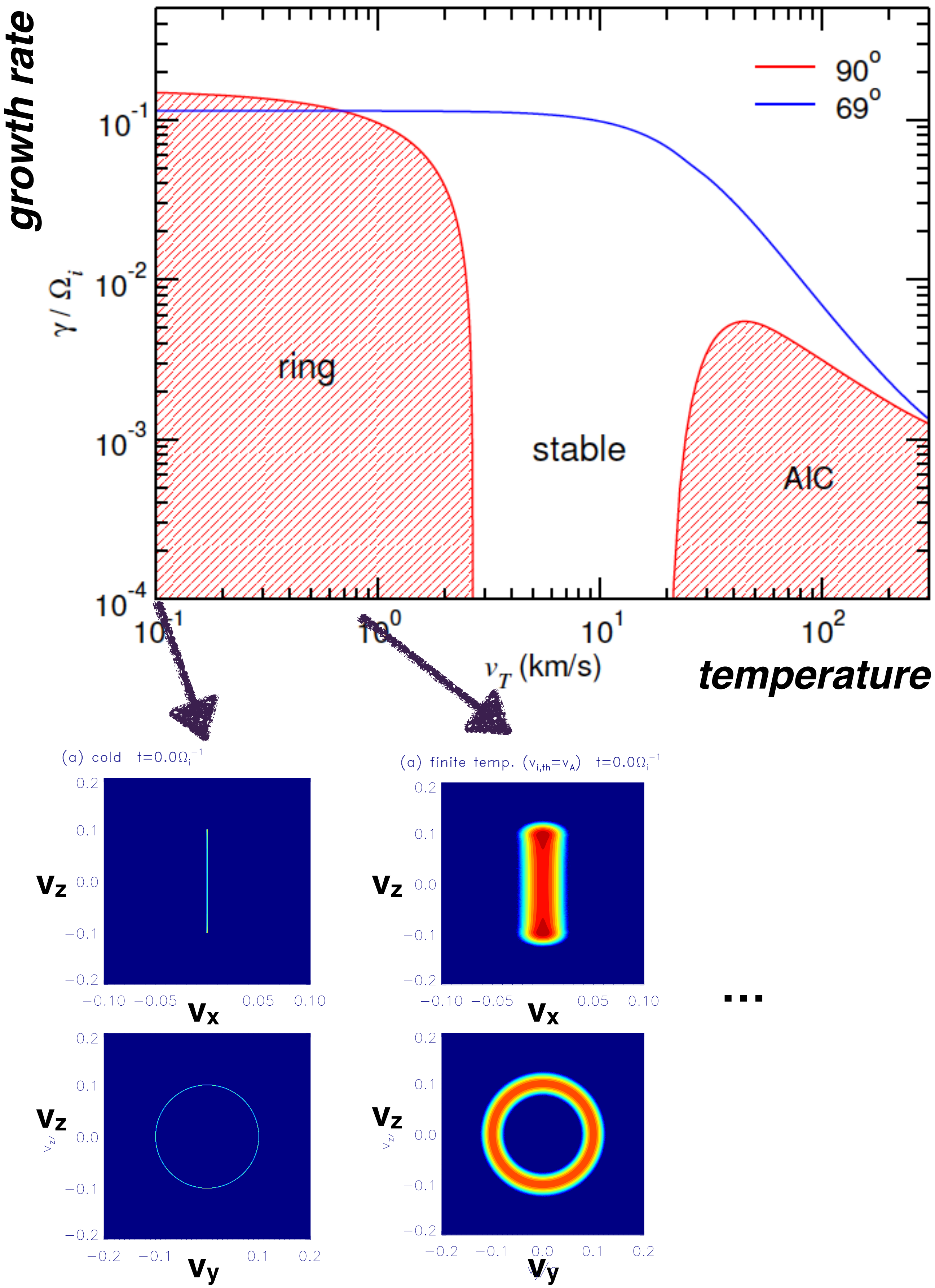
- scaled physical parameters, e.g., ring-to-ambient density ratio 2.5×10^{-2}, m_i/m_e=50
- grid size: 6000x192 cells
- simulation time: up to 2,5 million time steps (10 CPU-days with N_{proc}=4800)
- particle statistics: N_{ppc}=2500
  (up to 25,000; typical in shock physics N_{ppc}=10)

Pleiades (NASA)



- Pleiades (NASA, SGI ICE X, 211,872-core, Haswell, Ivy Bridge,…, 4.09 PFlop/s)

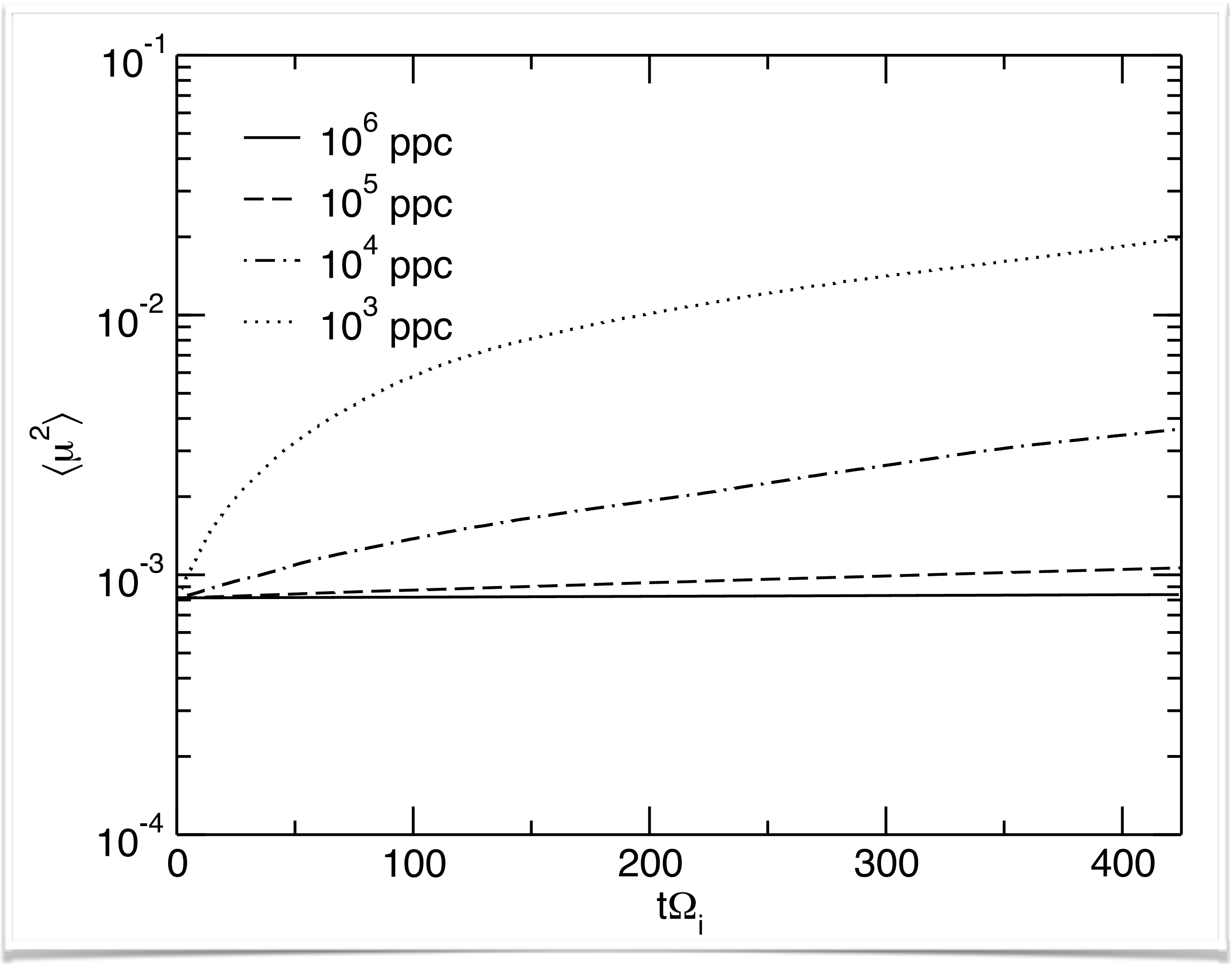
Linear analysis



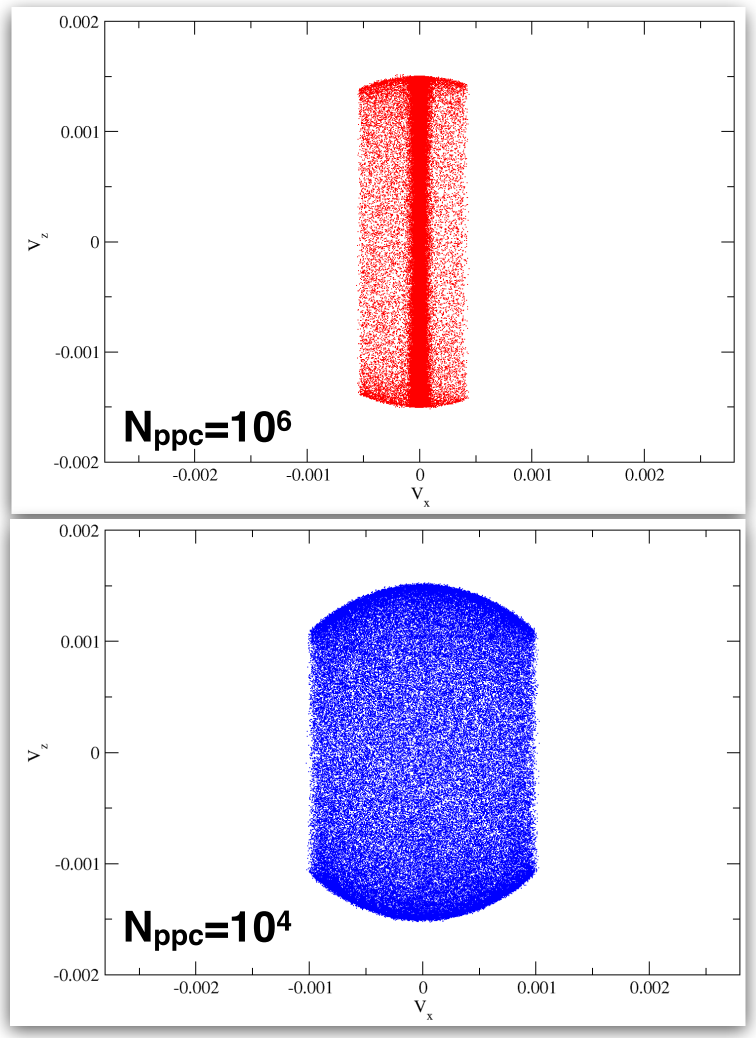
- parallel broadening leads to stable rings but second instability (Alfven Ion Cyclotron) appears for even broader rings
- AIC instability, albeit slowly growing, cannot be stabilized by temperature effects

Importance of particle statistics - hybrid PIC simulations of finite-temperature rings

Pitch-angle spread for a stable ring of finite width

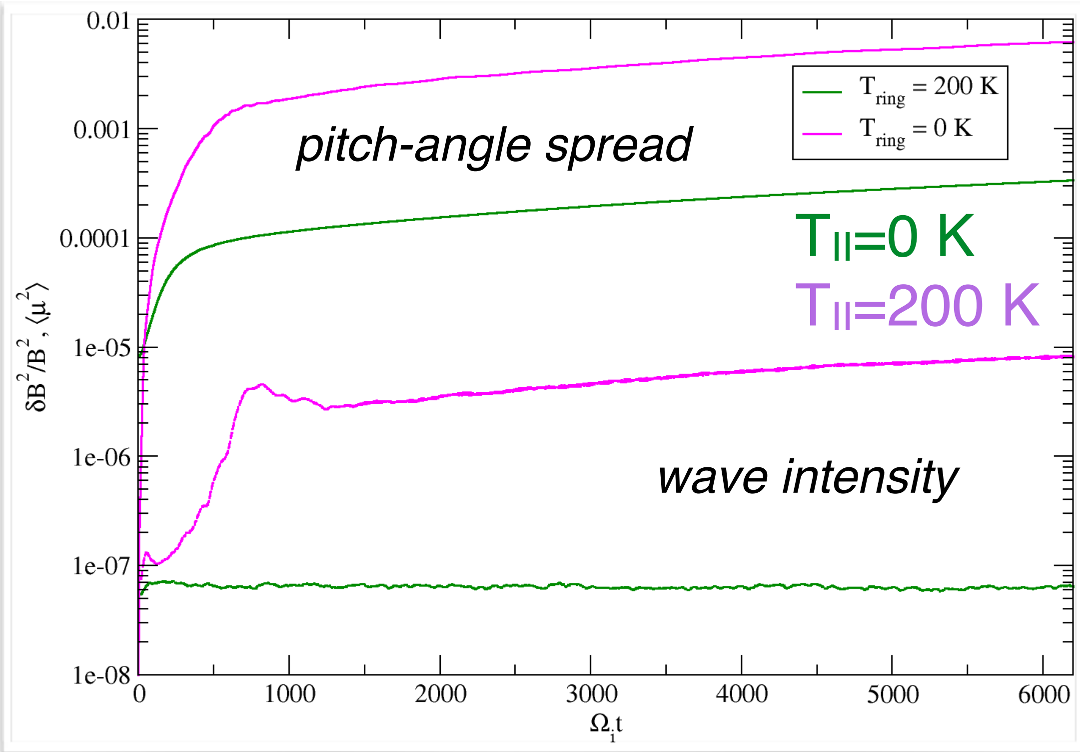


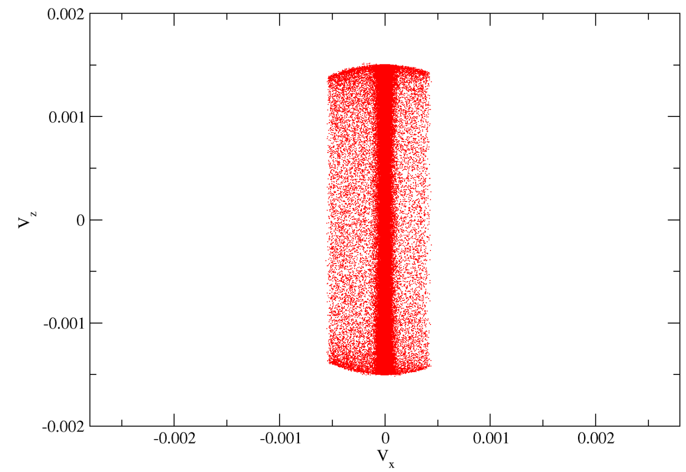
Cold ring after 1000 orbits

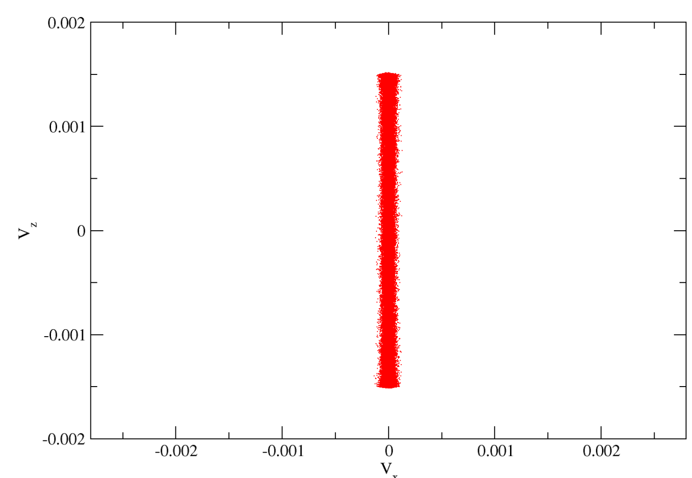


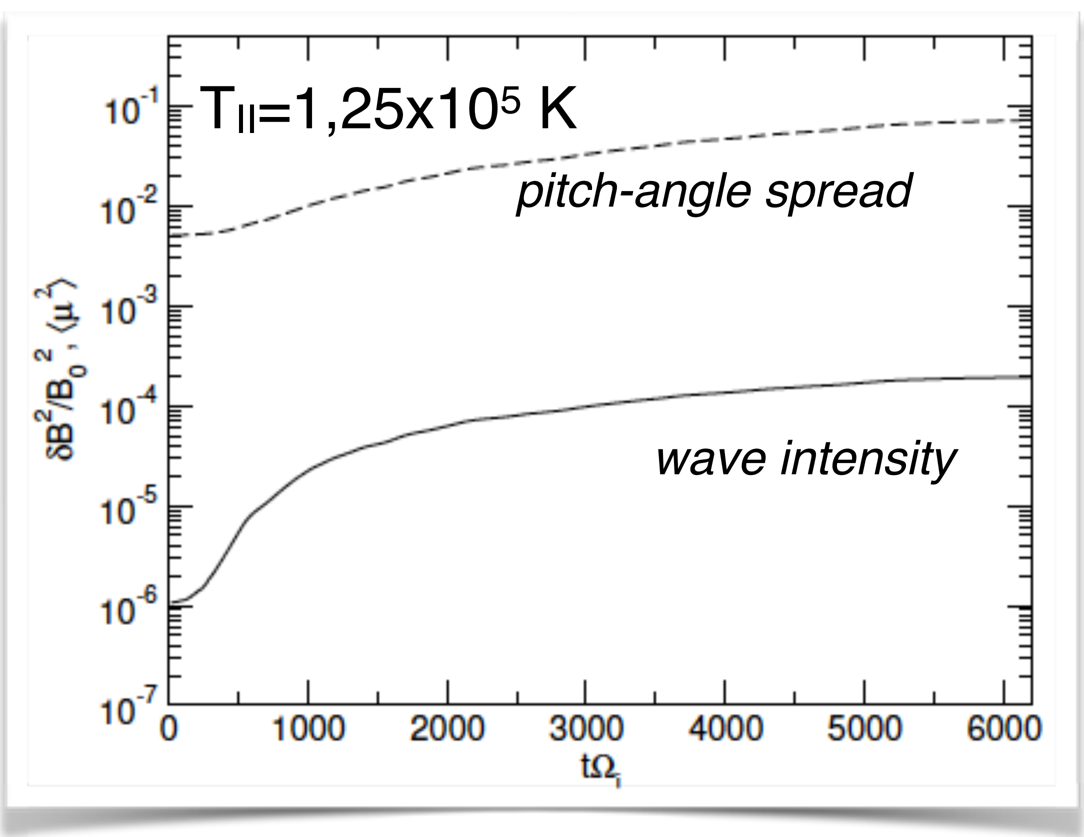
- for low $\boldsymbol{N_{ppc}}$ scattering is due to statistical noise, not an instability

1D hybrid PIC simulations of finite-temperature rings









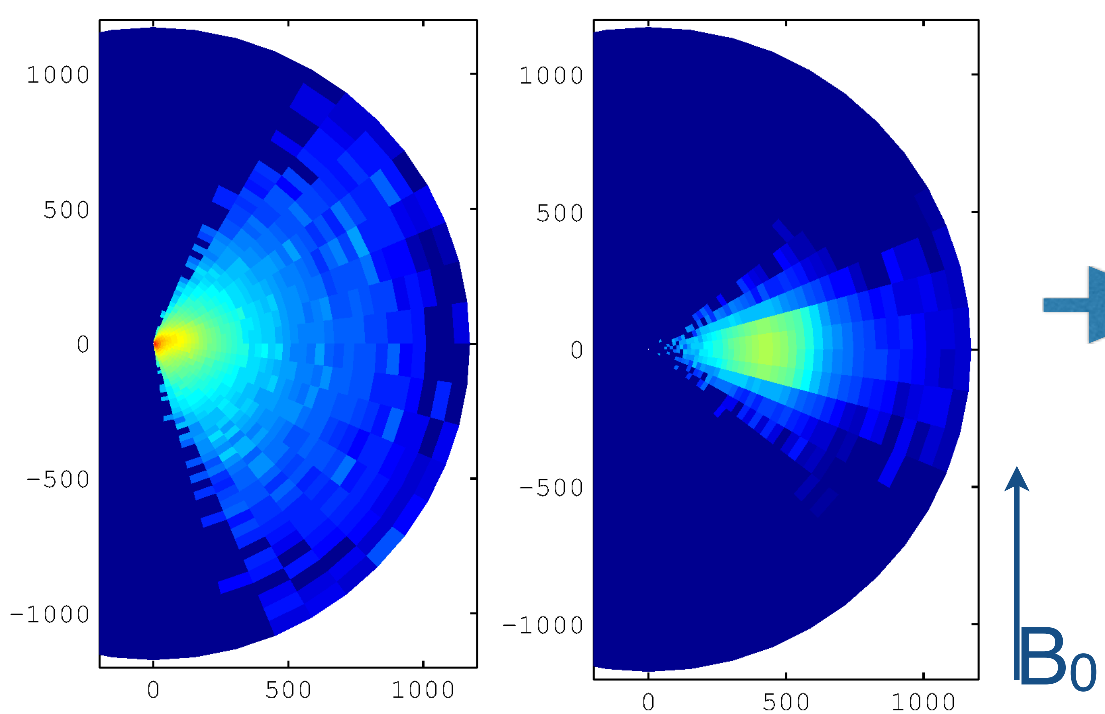
- low temperature (cold) rings take several years to scatter onto an isotropic shell ($\langle\mu^2\rangle=1/3$), allowing ample time for charge exchange that produces a ribbon
- initially broad rings unstable and scatter toward isotropy on much shorter time scales
- what is the actual width of PUI distribution in the OHS?

Realistic initial ring distributions

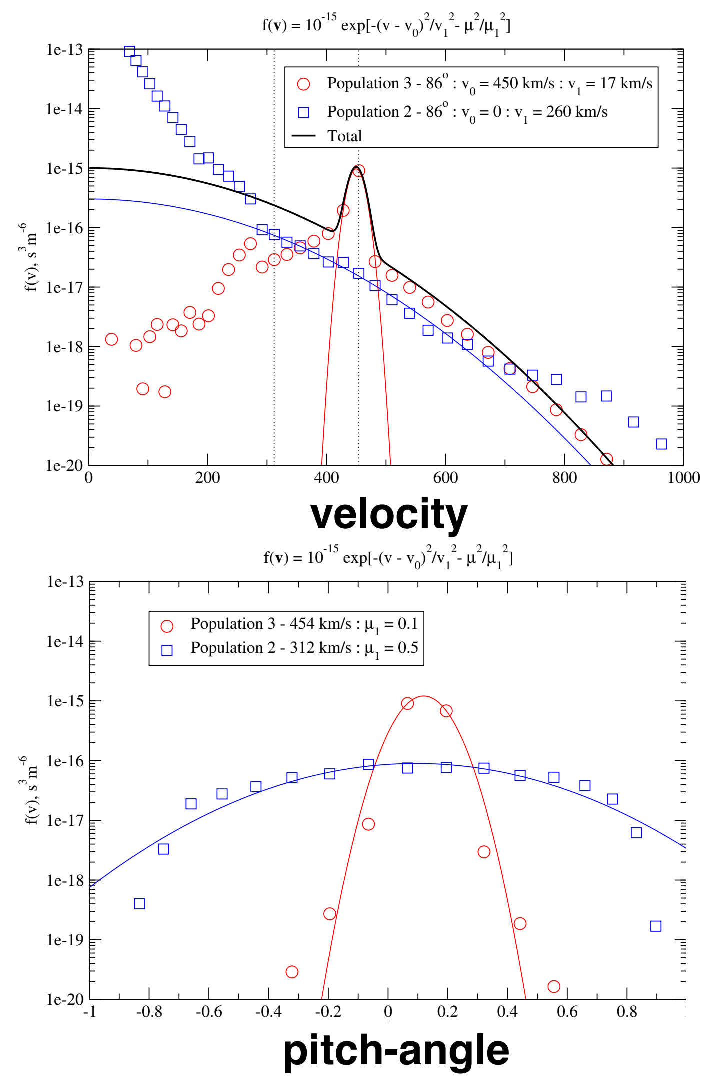
- **realistic** distribution from MHD-MC global heliosphere modeling of atomic hydrogen (Heerikhuisen et al. 2014)

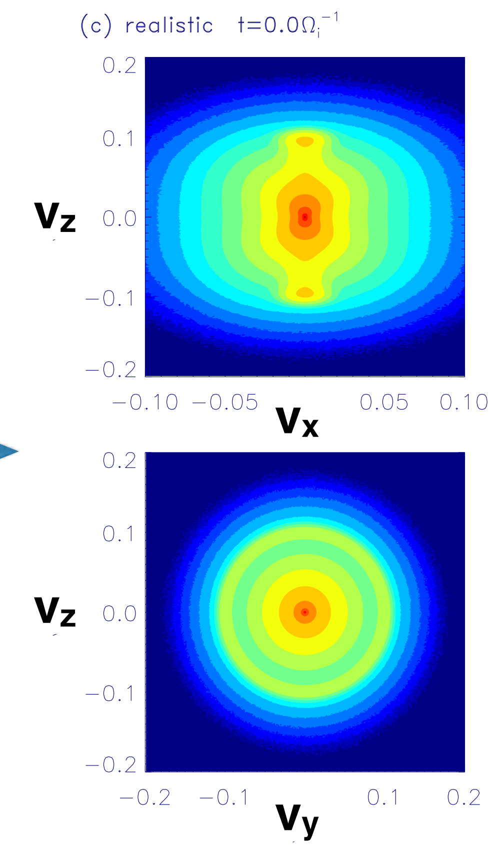
2D slices through raw neutral hydrogen in OHS from MHD-MC model

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

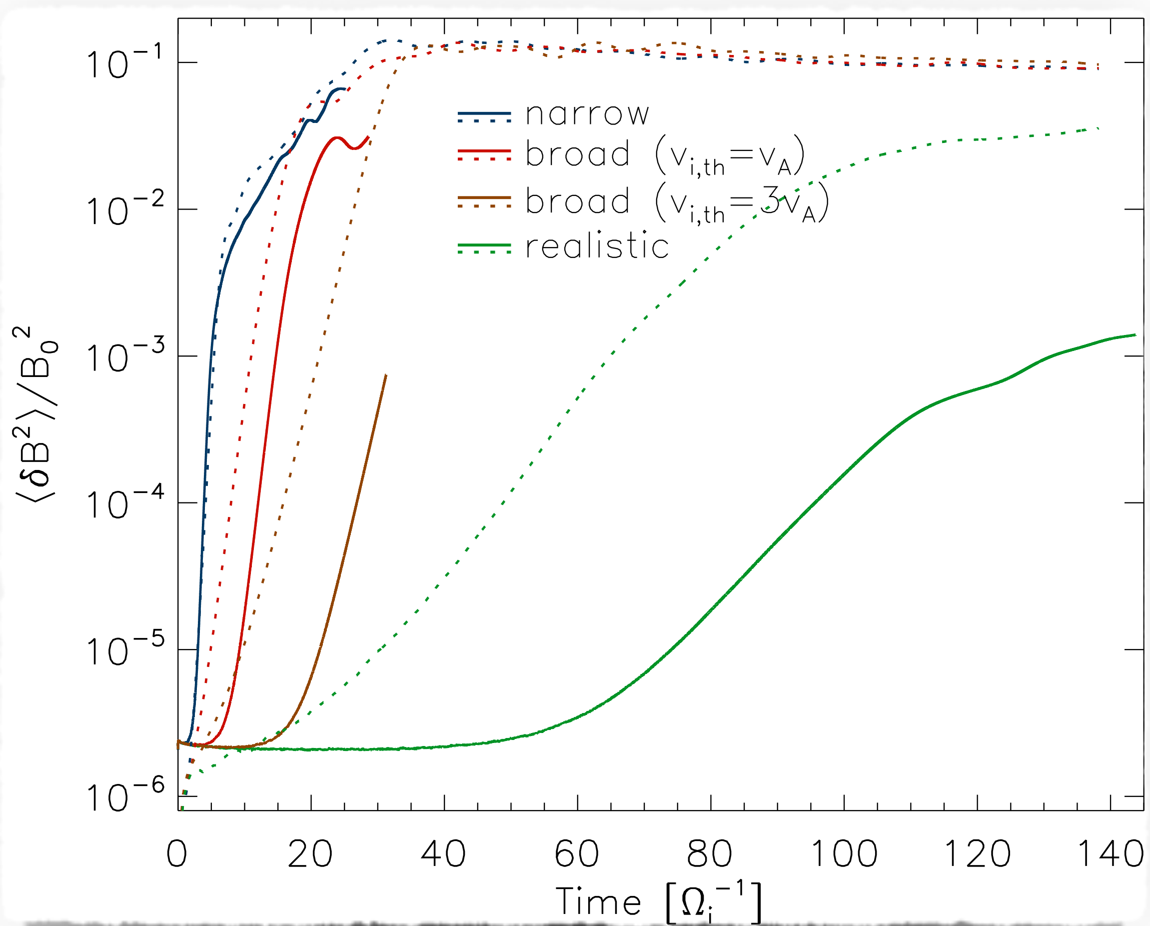


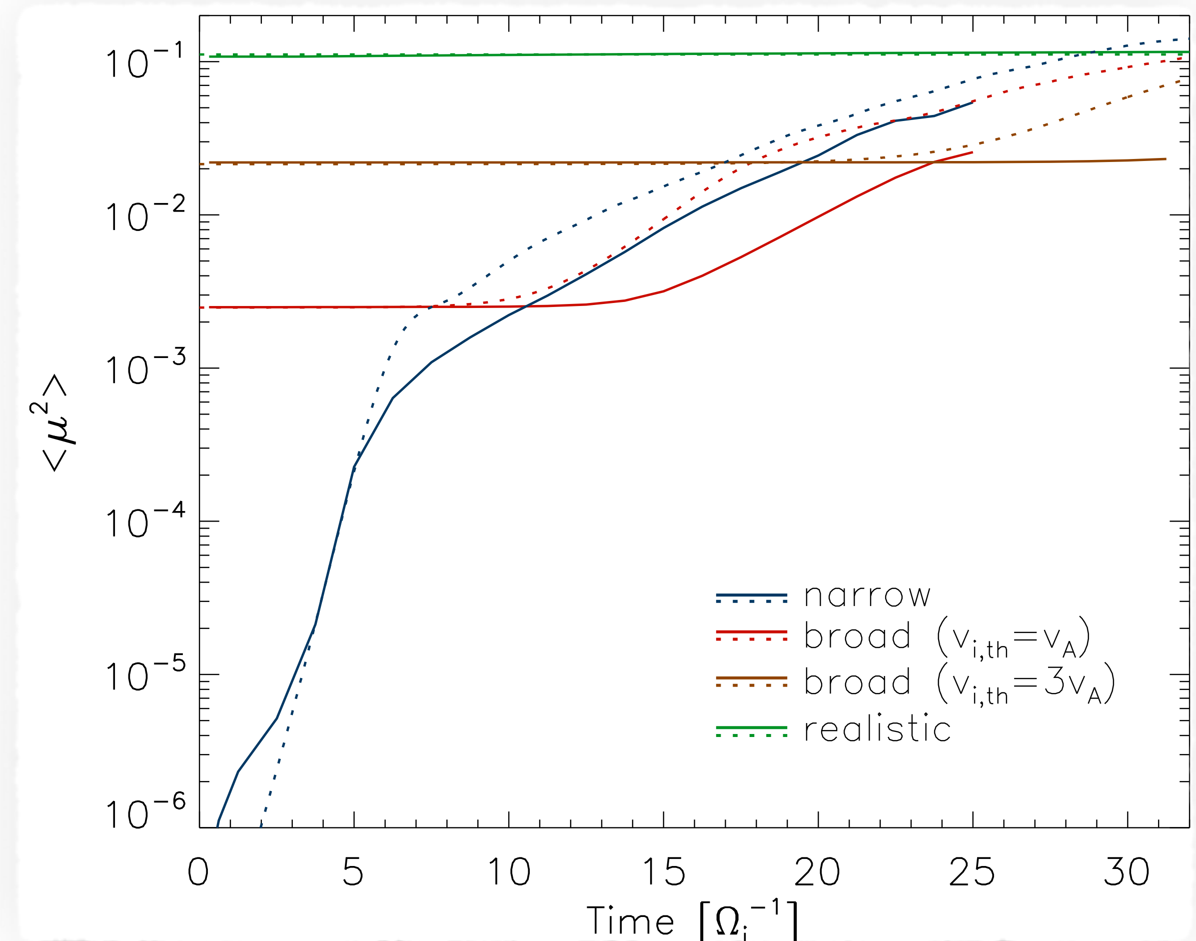
Gyroangle-averaged PUI distribution



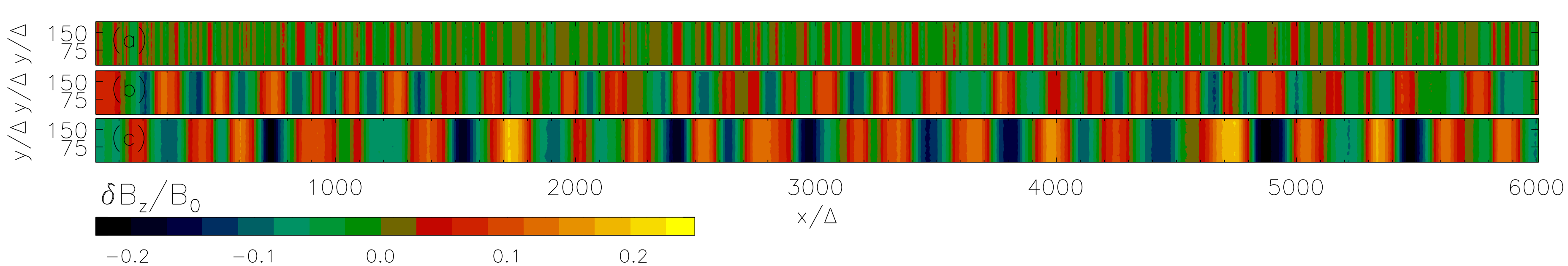


2D full PIC simulations





- good agreement between full PIC and hybrid PIC simulations for the same parameters
- all rings unstable, although the growth rate decreases for broader rings
- scaling to 1D hybrid results with physical parameters suggests that realistic distributions can be stable for about 21 days



Conclusions

- PUI distributions in the outer heliosheath can be stable and produce the IBEX ribbon unless parallel ring temperatures fall in the AIC unstable region
- this may be the case for realistic PUI distributions derived from primary ENAs
- careful and detailed studies of these distributions needed to see whether it is possible to prevent significant growth of the PUI instability

Results of full PIC simulations show that:

- electron dynamics is unimportant for the problem of the PUI rings stability
- the system is essentially one-dimensional and 1D hybrid kinetic modeling can accurately model the relevant physics

Dziękuję za uwagę

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