Hybrid-Vlasov simulations of ion velocity distribution functions within Kelvin-Helmholtz vortices

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EGU General Assembly
27.05.2022

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VLASIATOR

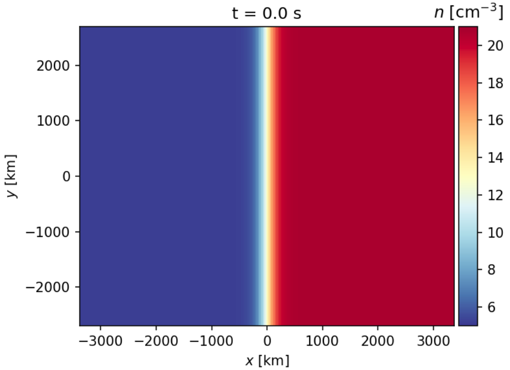
Simulation setup

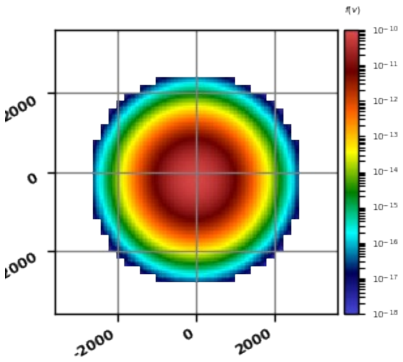
- **Local simulation of the Kelvin-Helmholtz instability (KHI)**
  - 2D-3V hybrid-Vlasov simulation using the Vlasiator model [von Alfthan et al., 2014; Palmroth et al., 2018]
  - Full ion velocity distribution functions (VDFs)
- **Parameters based on spacecraft observations of KHI at Earth's magnetopause** [Eriksson et al. 2016; Sisti et al. 2019]
  - Density/temperature jump set to 4, constant out-of-plane B, shear layer width ~3d_i
- **Hyperbolic tangent velocity/density shear layer, constant pressure**

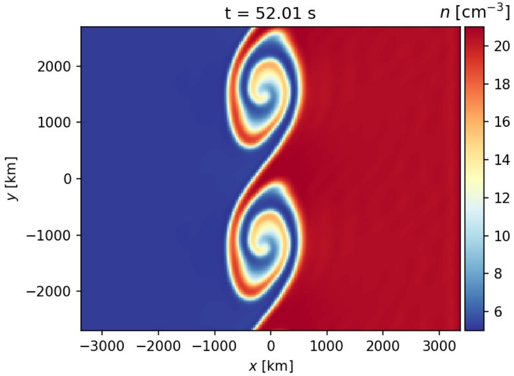
$$n(x)=\frac{1}{2}\left((n_2-n_1)*\tanh(x/L)+n_2+n_1\right)$$

$$v_y(x)=\frac{1}{2}\left((v_{y,2}-v_{y,1})*\tanh(x/L)+v_{y,2}+v_{y,1}\right)$$

$$P_0=n(x)k_B T(x)$$







Velocity space evolution

- **Non-Maxwellianity ϵ_M** [Graham et al., 2021]

$$\boxed{\epsilon_{\mathrm{M}} = \frac{1}{2n}\int |f_{measured}(v) - f_{model}(v)| d^3v \in [0,1]}$$

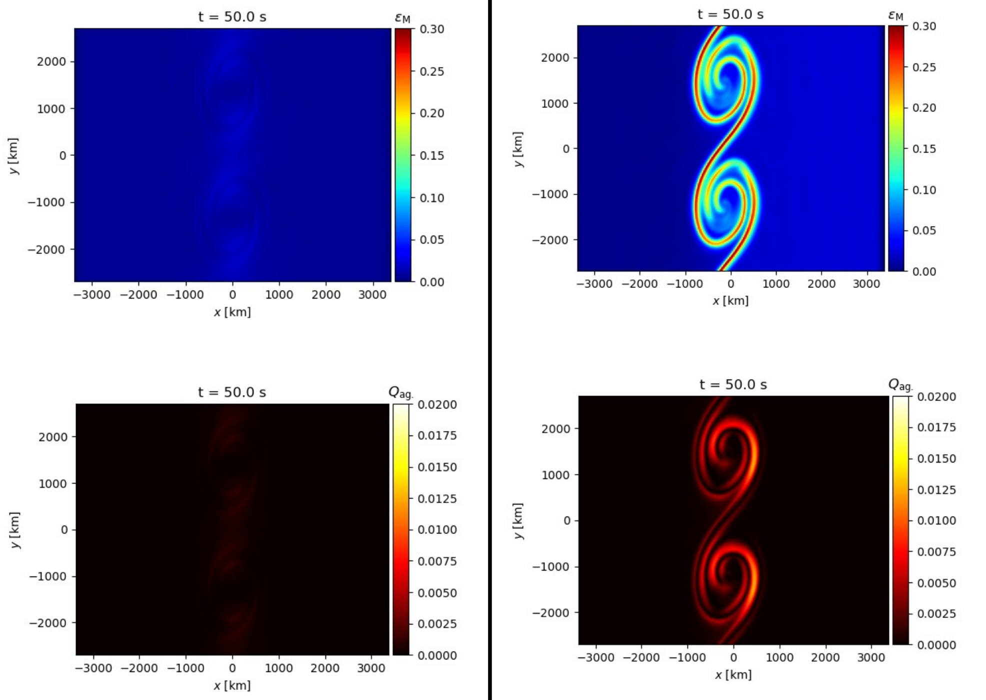
- **Agyrotropy Q_{ag}** [Swisdak et al., 2016]

$$\boxed{Q_{\mathrm{ag}} = \frac{P_{12}^2 + P_{13}^2 + P_{23}^2}{P_\perp^2 + 2P_\perp P_\parallel} \in [0,1]}$$

- **For KHI with non-uniform density/temperature, velocity space evolves as the instability progresses**

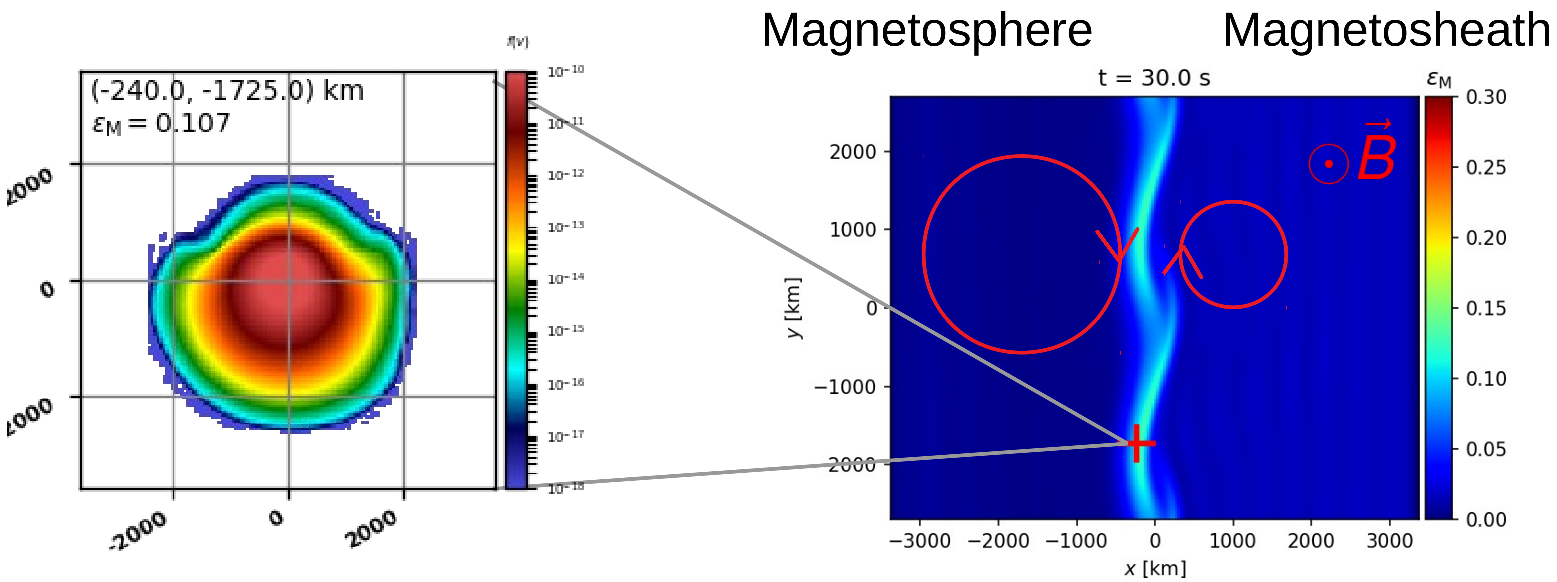
Constant density/temperature

Density/temperature jump=4



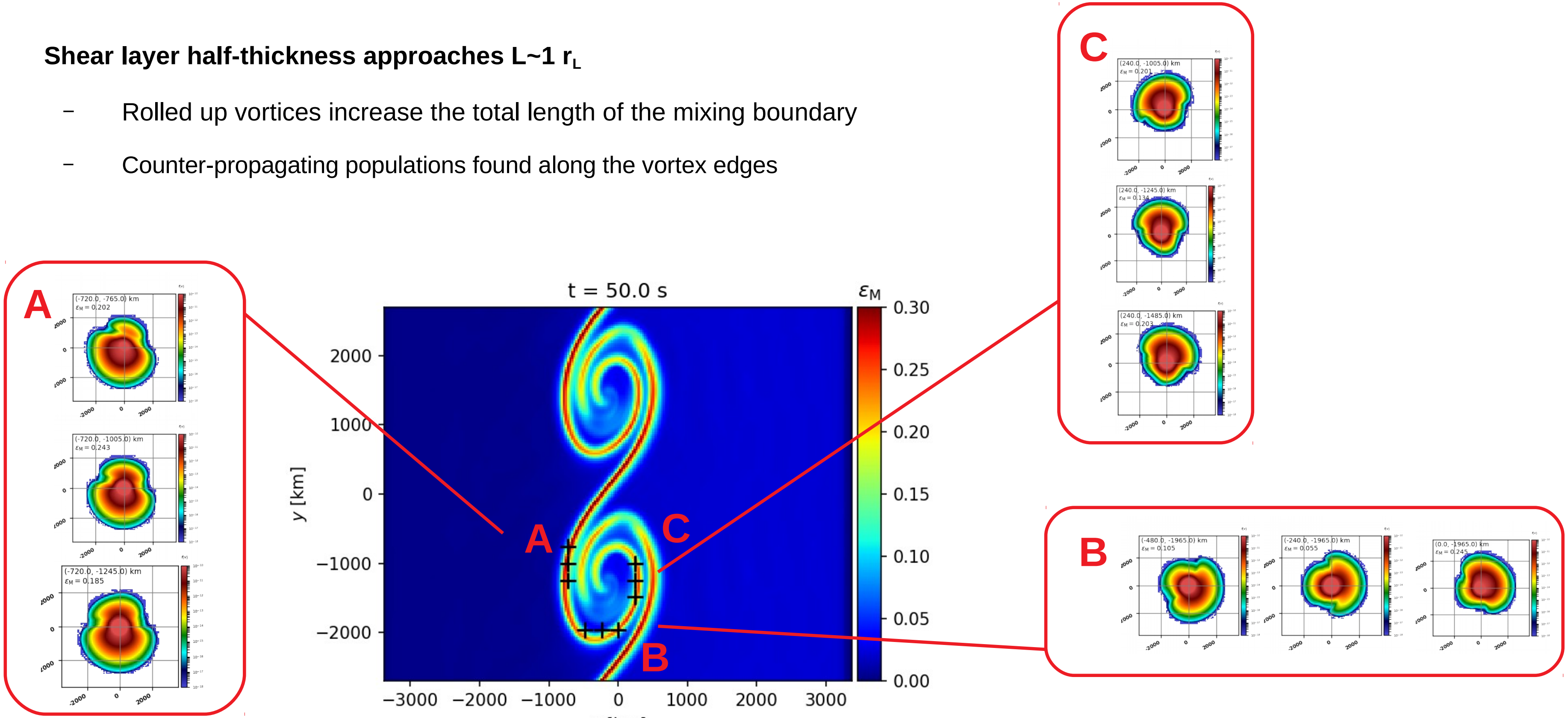
Linear phase

- **Initial shear layer half-thickness $L \sim 2r_L$**
  - Particle mixing at the shear boundary
  - Counter-propagating populations due to particle gyromotion



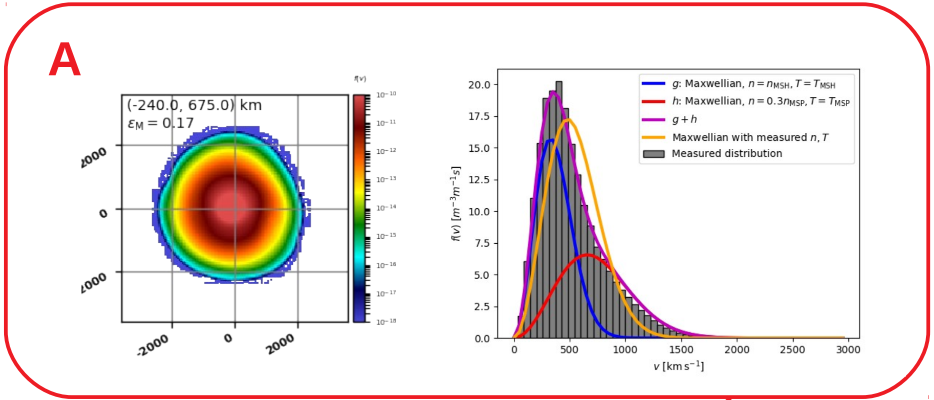
Vortex roll-up

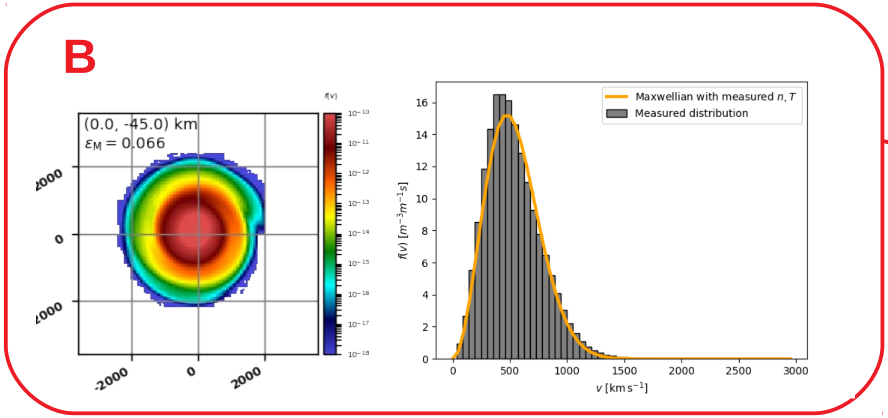
- **Shear layer half-thickness approaches $L \sim 1\ r_L$**
  - Rolled up vortices increase the total length of the mixing boundary
  - Counter-propagating populations found along the vortex edges

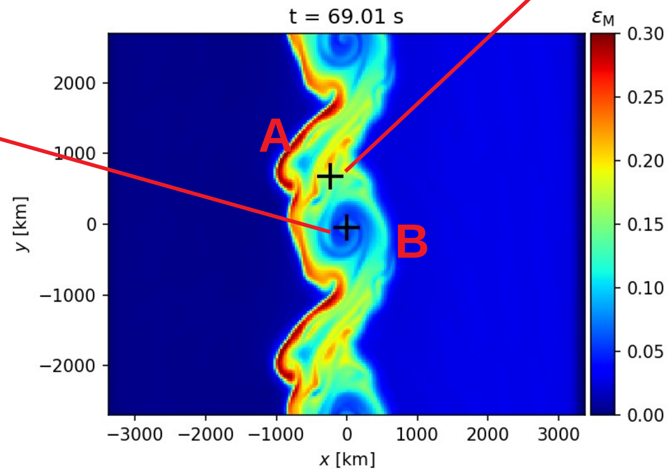


Vortex saturation

- **A thick layer of isotropic plasma is formed**
  - **(A)** Non-Maxwellian superposition of magnetosphere/magnetosheath populations around vortex centers
  - **(B)** Maxwellian plasma at vortex centers







Summary

- **Linear phase**:
  - Particle mixing at shear boundary
  - Low agyrotropy, low non-Maxwellianity
- **Vortex roll-up**:
  - Enhanced particle mixing due to extended shear layer
  - Enhanced agyrotropy, enhanced non-Maxwellianity
- **Vortex saturation**:
  - A layer of isotropic plasma forms
  - Low agyrotropy, enhanced non-Maxwellianity