# Evolution of relativistic electron vortices in laser plasmas

Kirill Lezhnin
Princeton University
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In collaboration with **T. Zh. Esirkepov** (KPSI, Japan)

**S.V. Bulanov**, S. Weber, G. Korn, Y. Gu (ELI-Beamlines, Czech Republic)

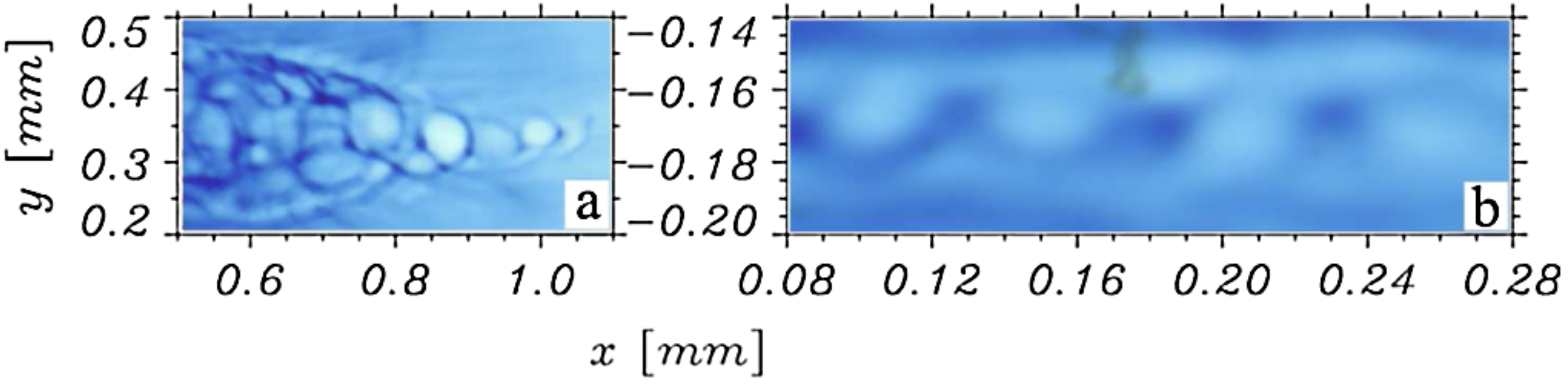
A.R. Kniazev, S.V. Soloviev, F.F. Kamenets, Moscow Institute of Physics and Technology (Russian Federation)

Kansai Photon Science Institute

beamlines

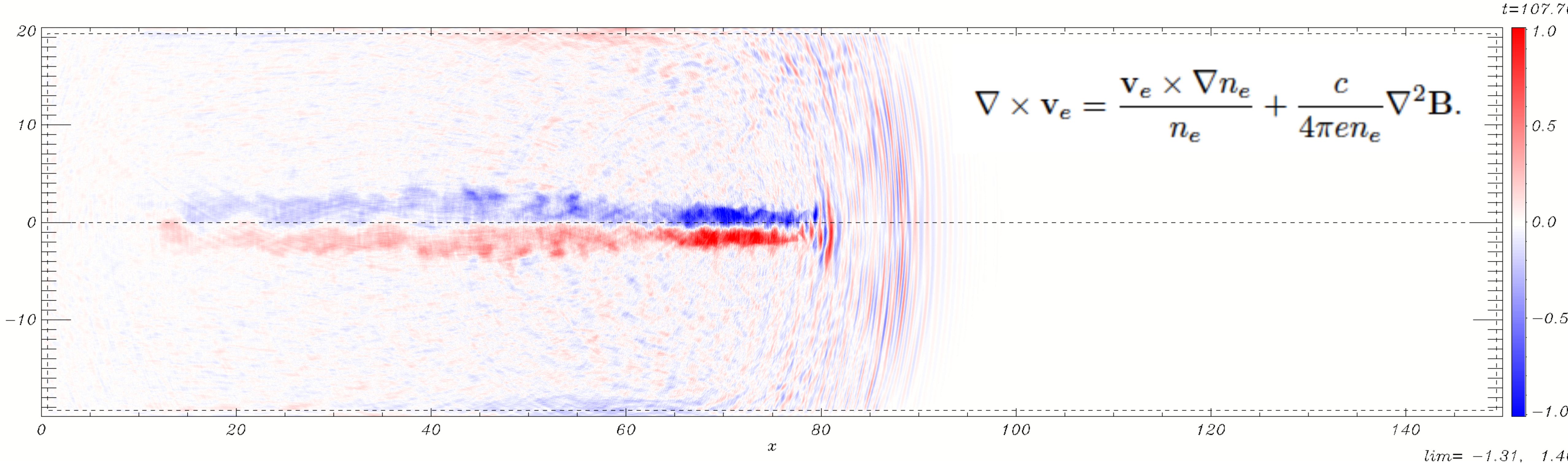
# Motivation

- Electron vortices is what we will see in the target after the laser pulse travelling through it (Romagnani et al., 2010, PRL; Sylla et al., 2012, PRL)




- Electron vortex dynamics is thought to be a final stage of the two-dimensional turbulence (J. Laurie et al., 2014, PRL; B. N. Kuvshinov and T. J. Schep, 2016, Plasm. Phys. Rep.)
- Test of nonlinear models for multiple vortex interactions (e.g., Hasegawa-Mima equation)

# Vortex formation: evolution of p-polarization laser pules in 2D PIC, Bz

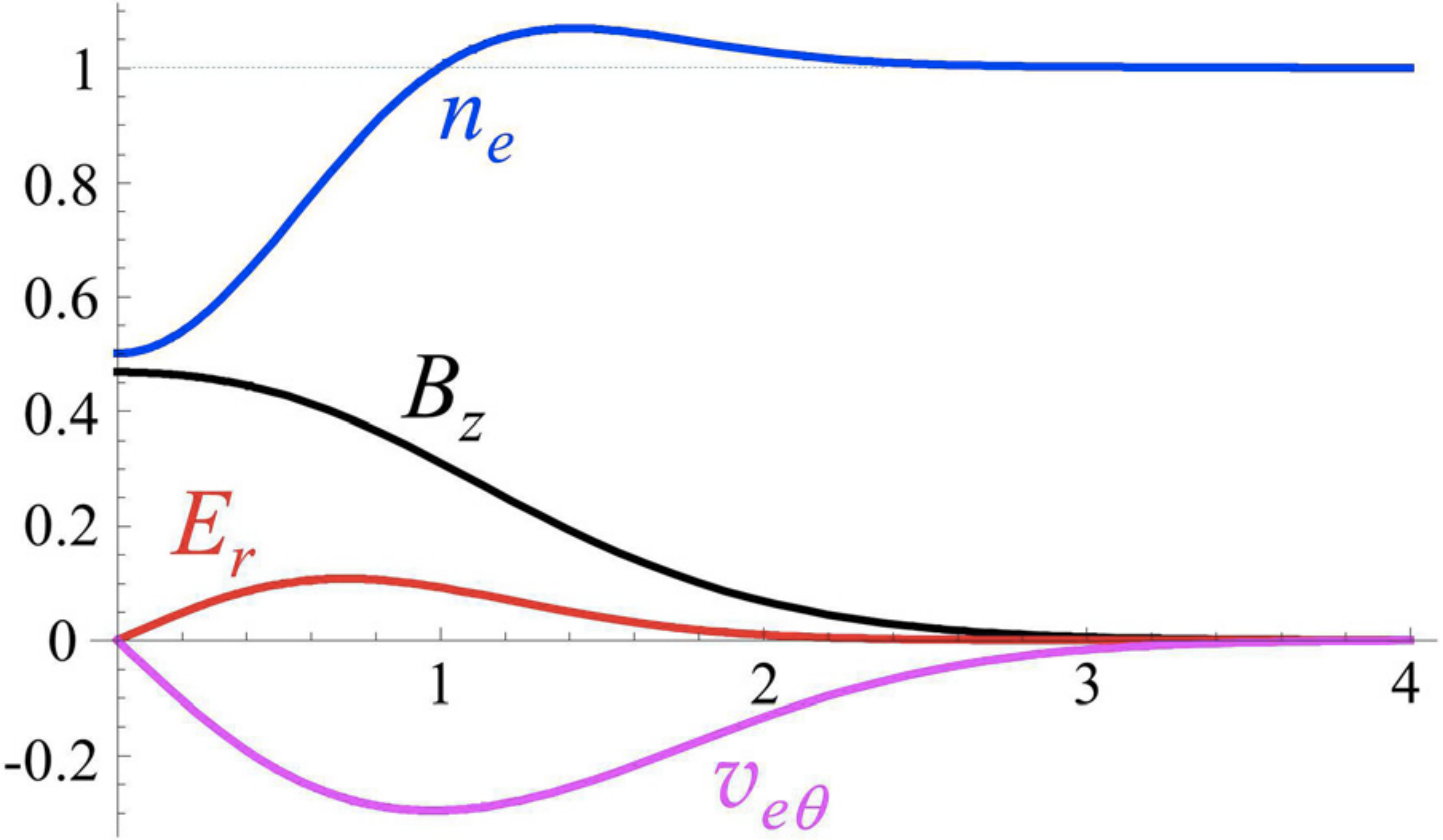



- Two vortex streets are formed behind the laser pulse : Naumova et al., PoP (2001)
- The dipole vortex structure is observed, which is eventually destroyed by the electron current bending
- For 10 petawatt laser pulse, we will observe relativistic electron vortex structures with the super strong magnetic fields (up to Gigagauss! - Askar’yan et al., JETP Lett. (1994))

How do single electron vortices evolve on ion timescales?

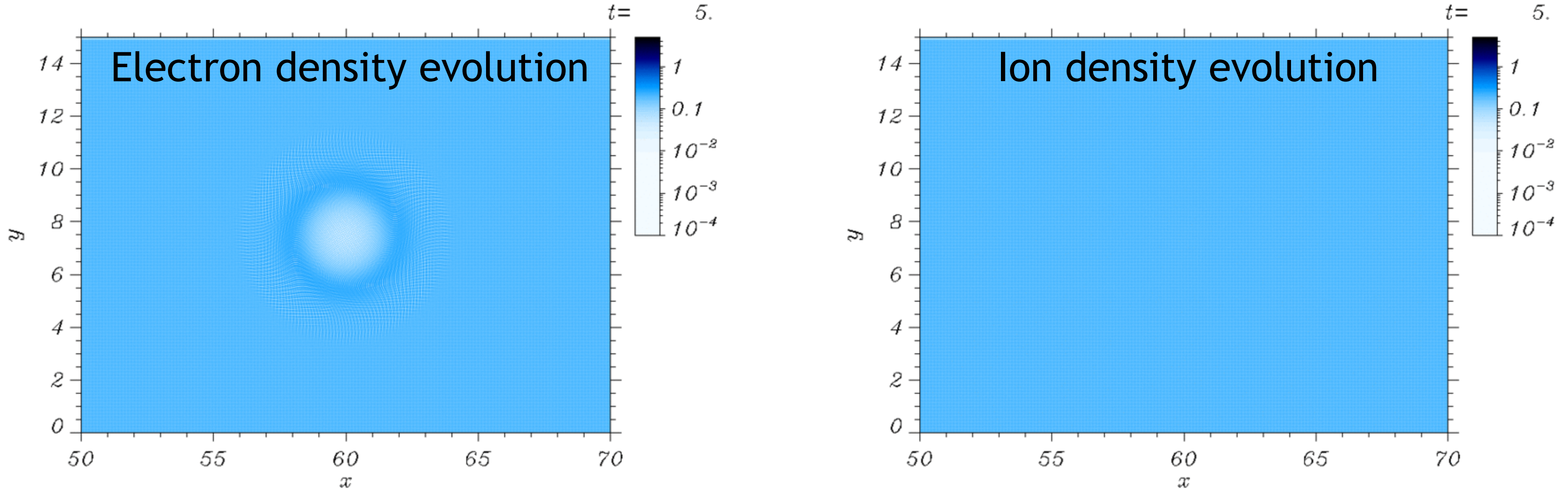
How do binary electron vortices evolve on electron timescales (immobile ions)?

# Single electron vortex - simple stationary model

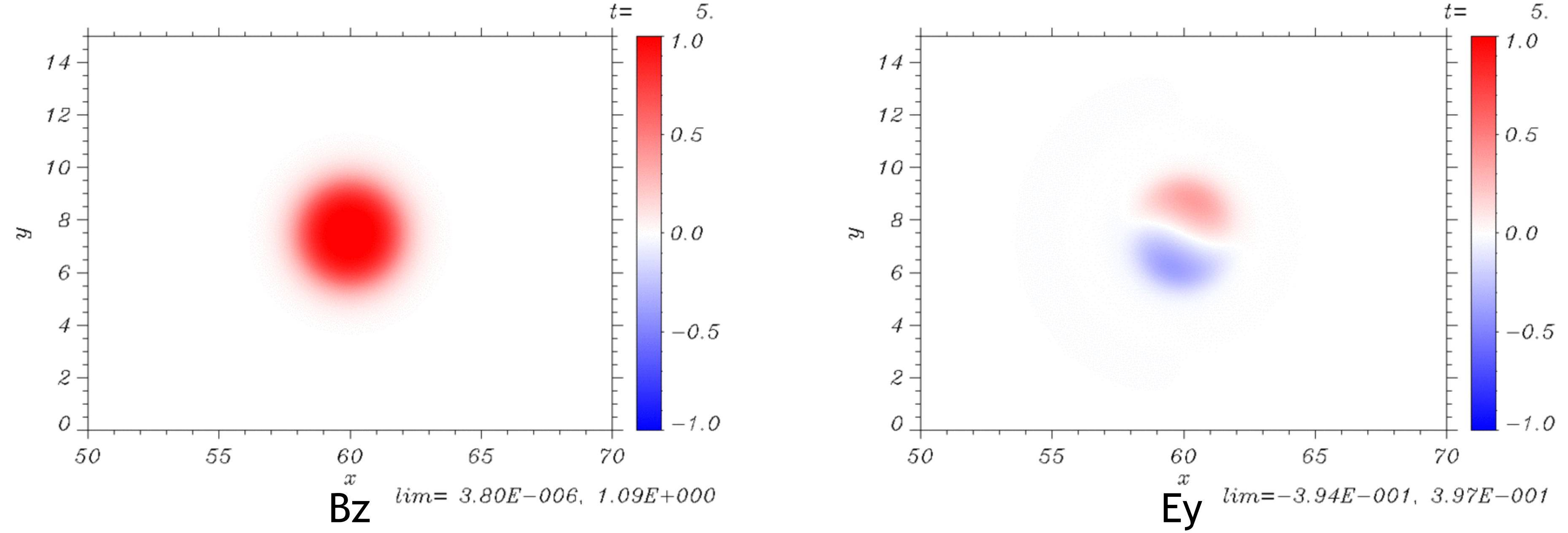


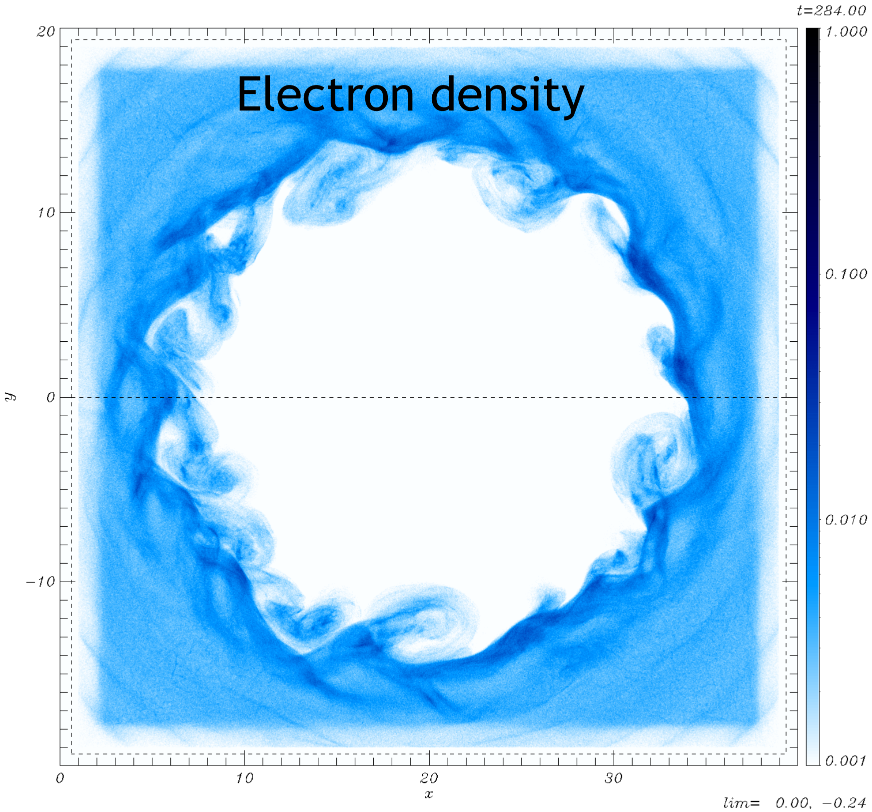

Two-dimensional, axisymmetric, immobile ions, non-relativistic …

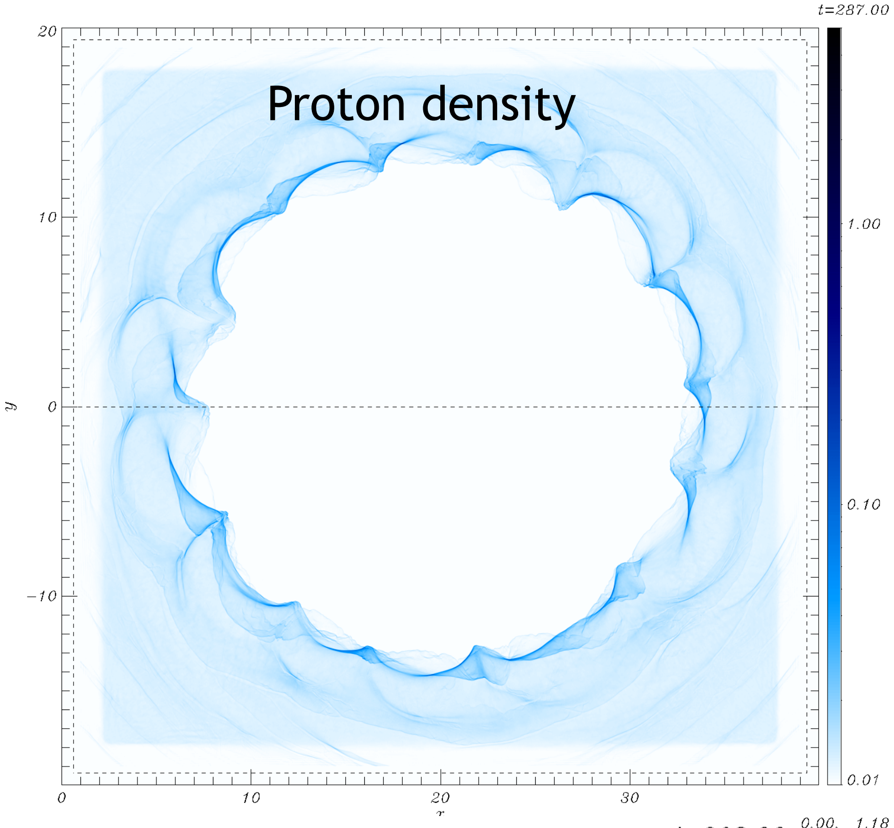
# Single electron vortex evolution on ion timescale

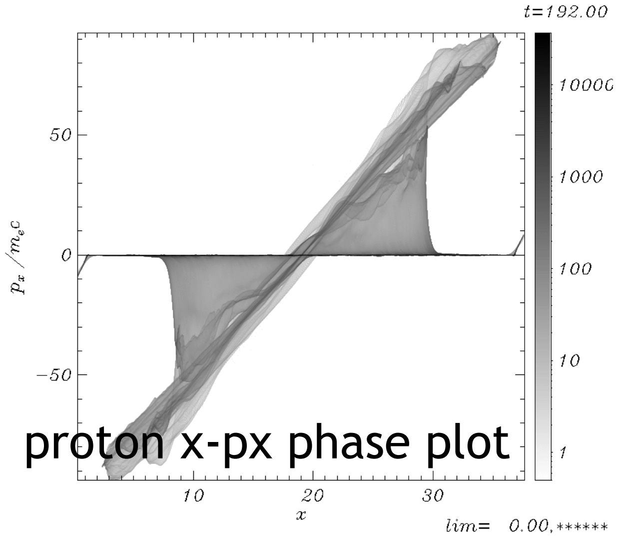


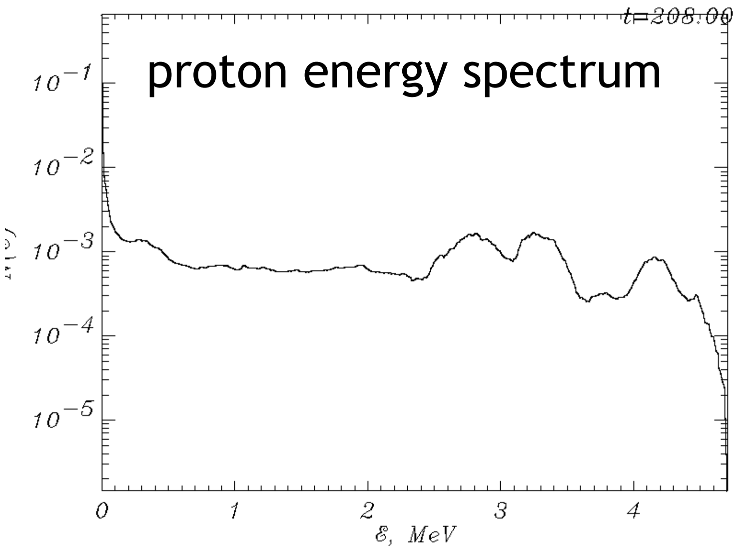

Dimensionless amplitude *a*=1 (Bmax), the plasma density corresponds
to omega_*pe* /omega=0.2 and the vortex width is 1.5 lambda.




Electron density
t=284.00
1.000
0.100
0.010
0.001
20
10
0
−10
y
0
10
20
30
x
lim= 0.00, −0.24

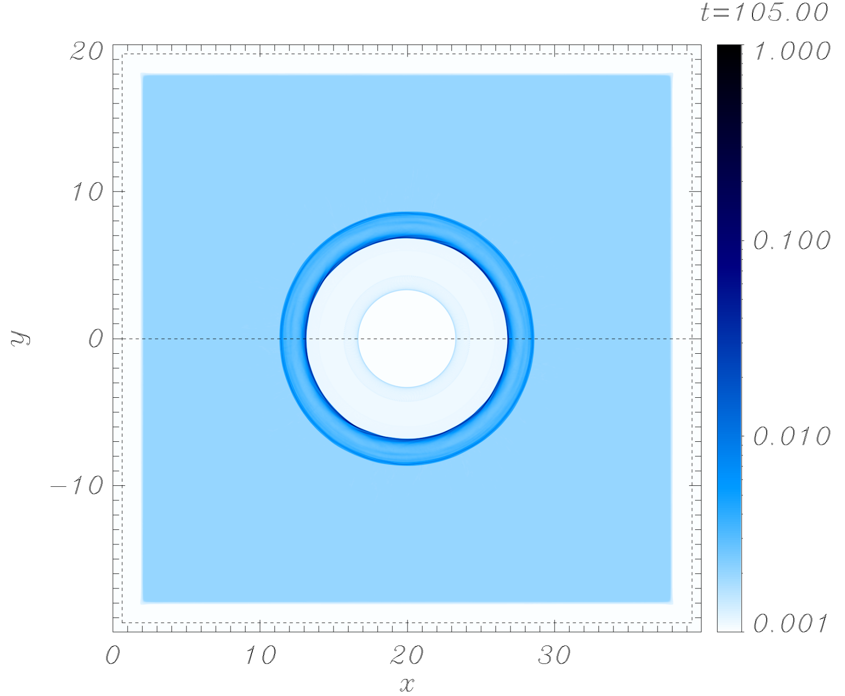

Proton density
t=287.00
1.00
0.10
0.01
20
10
0
−10
y
0
10
20
30
0.00, 1.18

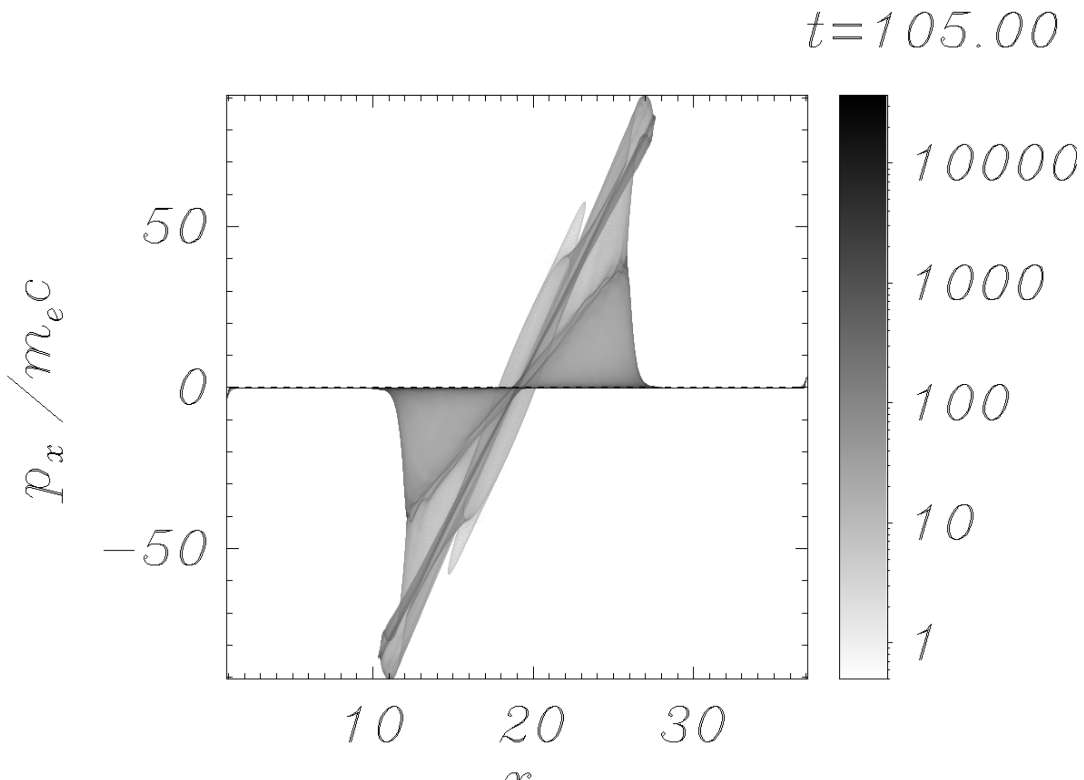

proton x-px phase plot
t=192.00
10000
1000
100
10
1
50
0
−50
$p_x/m_ec$
10
20
30
x
lim= 0.00,******

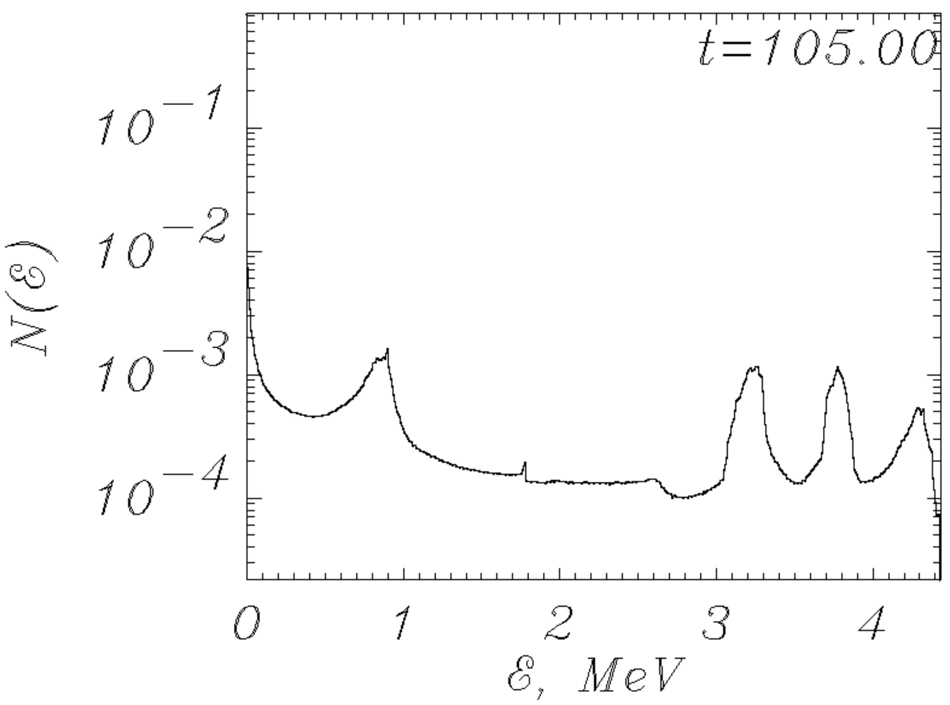

proton energy spectrum
t=208.00
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
0
1
2
3
4
ℰ, MeV

# Notable effects

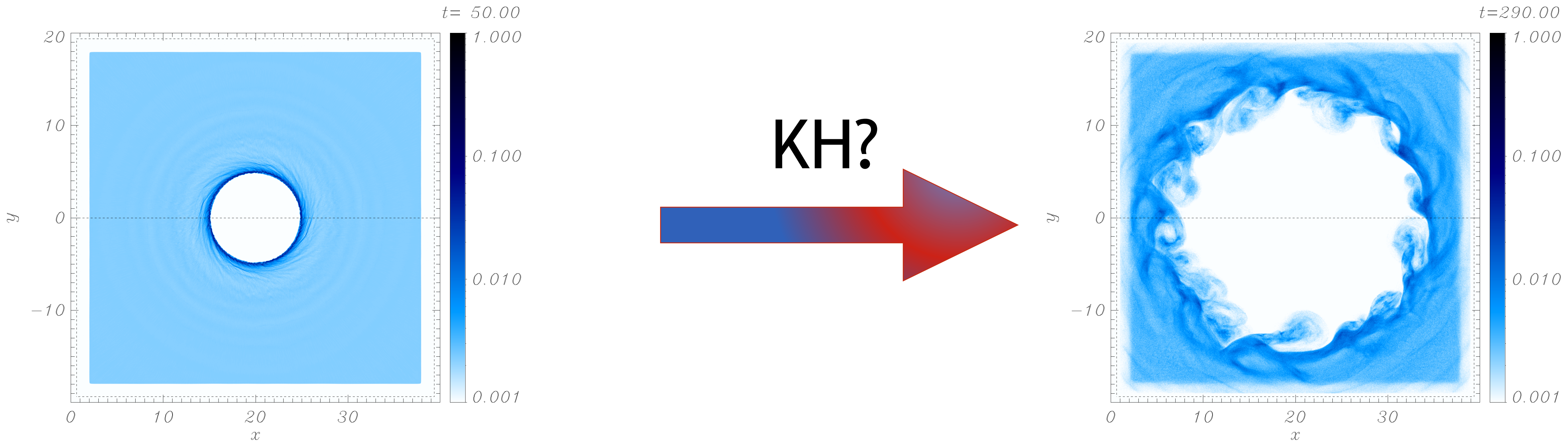
- Multishell motion of fast protons due to boundary multistream instability (Buneman? Similar to S.V. Bulanov et al., 2012, PoP)



# Secondary vortex formation at the primary vortex boundary

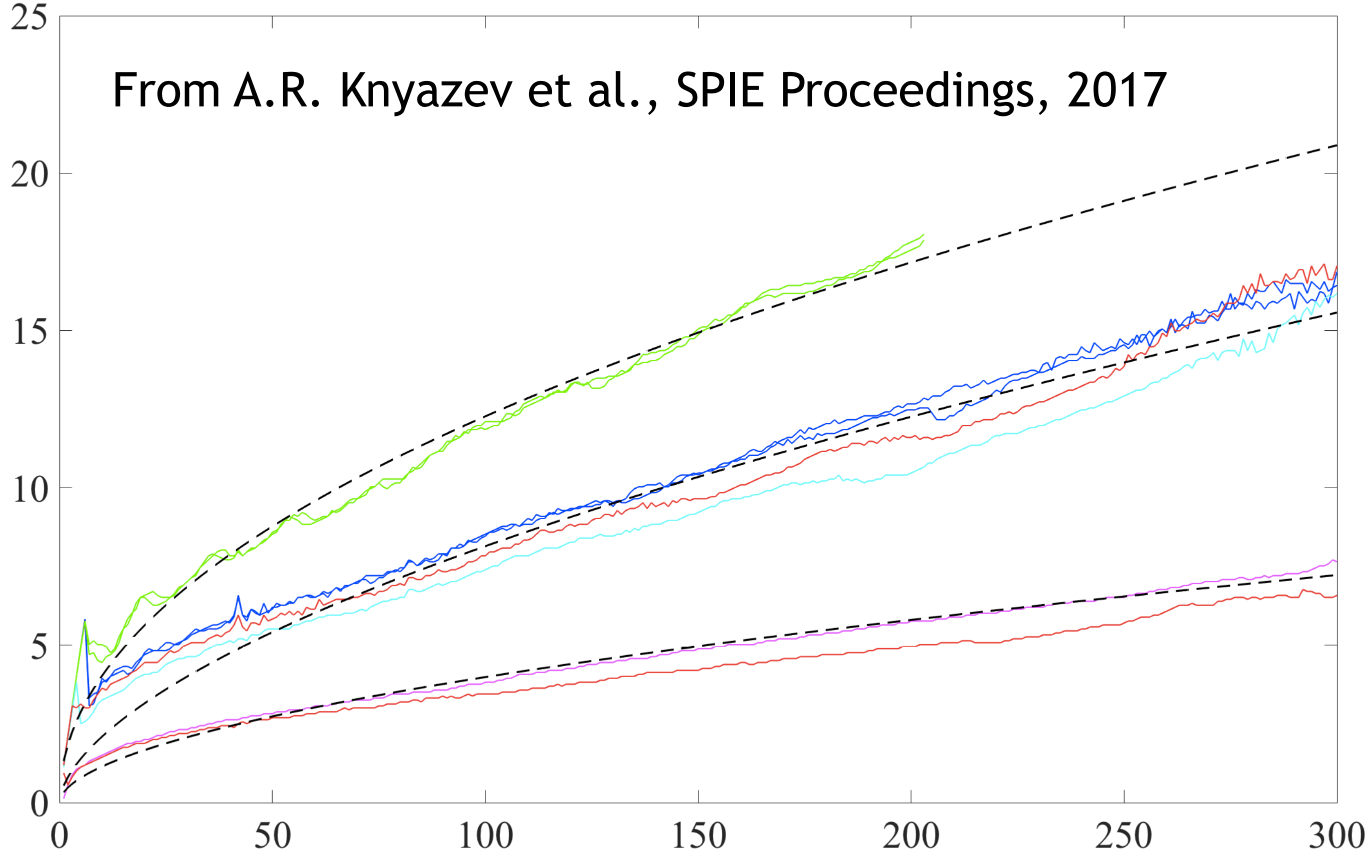



Linear growth rates ~ k*Ve ~ 10 time units - agrees with simulation results

Looks analogous to:

C. Shkula et al., PoP, 2016; L. Ricketson & A. Cerfon, PP&CF, 2016

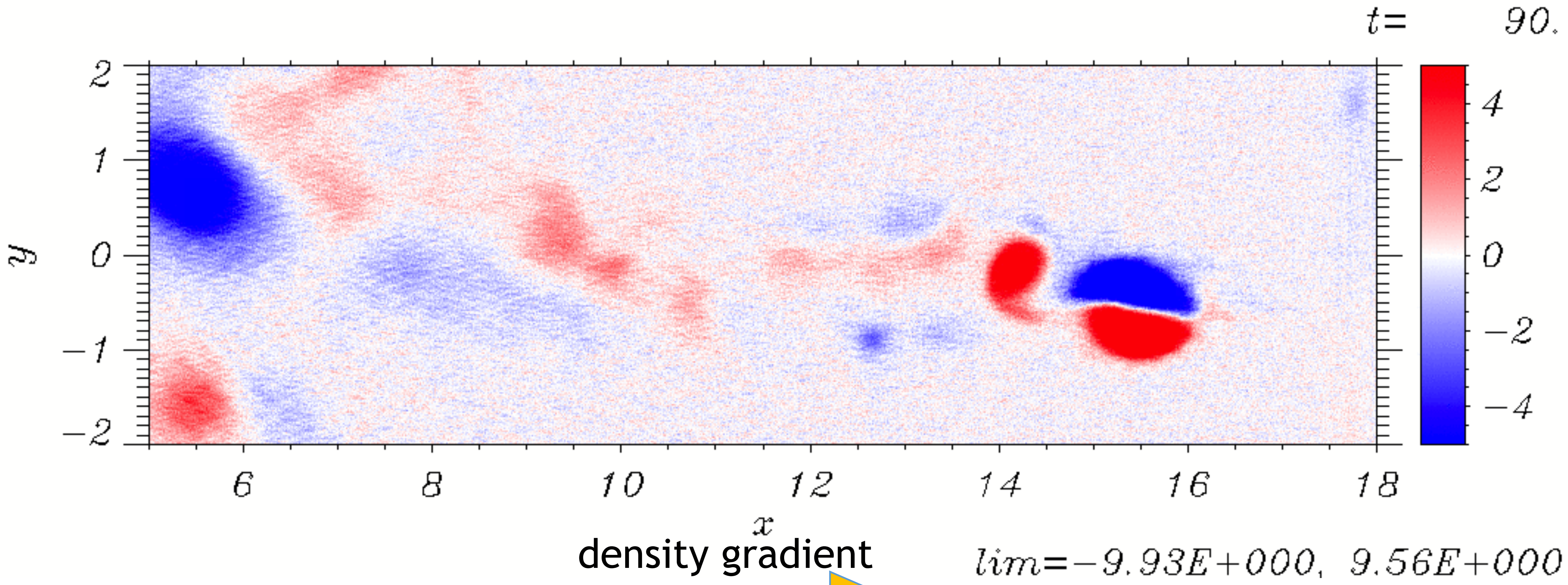
# Growth of electron vortex radius




$$\frac{\mathrm{d}}{\mathrm{d}t}\left(M\frac{\mathrm{d}R}{\mathrm{d}t}\right) = 2\pi R\frac{B^2}{8\pi}, \qquad R \sim t^{1/2},\ \dot{R} \sim t^{-1/2},\ \text{and}\ \dot{B} \sim t^{-1/2}$$

Evolution of vortex radius with time for various initial parameters of the vortex; the power law fits R ~ t^k gives us k which falls down into 0.4-0.6 range, which is a good agreement with R~t^0.5 as for snowplow model

# Formation of dipole electron vortices after the petawatt laser pulse damping in density gradient




density gradient

Immobile ions

# Evolution of binary electron vortices in Hasegawa-Mima model

Point-vortex approach

$$\frac{\partial}{\partial t}(\psi - \Delta\psi) + \{\psi, \psi - \Delta\psi\} - v_0 \frac{\partial \psi}{\partial y} = 0.$$

Proportional to density gradient

$$\dot{x}_1 = -\frac{1}{2\pi}\Gamma_2(t) K_1(|\mathbf{r}_1 - \mathbf{r}_2|)\frac{y_1 - y_2}{|\mathbf{r}_1 - \mathbf{r}_2|},$$
$$\dot{y}_1 = \frac{1}{2\pi}\Gamma_2(t) K_1(|\mathbf{r}_1 - \mathbf{r}_2|)\frac{x_1 - x_2}{|\mathbf{r}_1 - \mathbf{r}_2|},$$

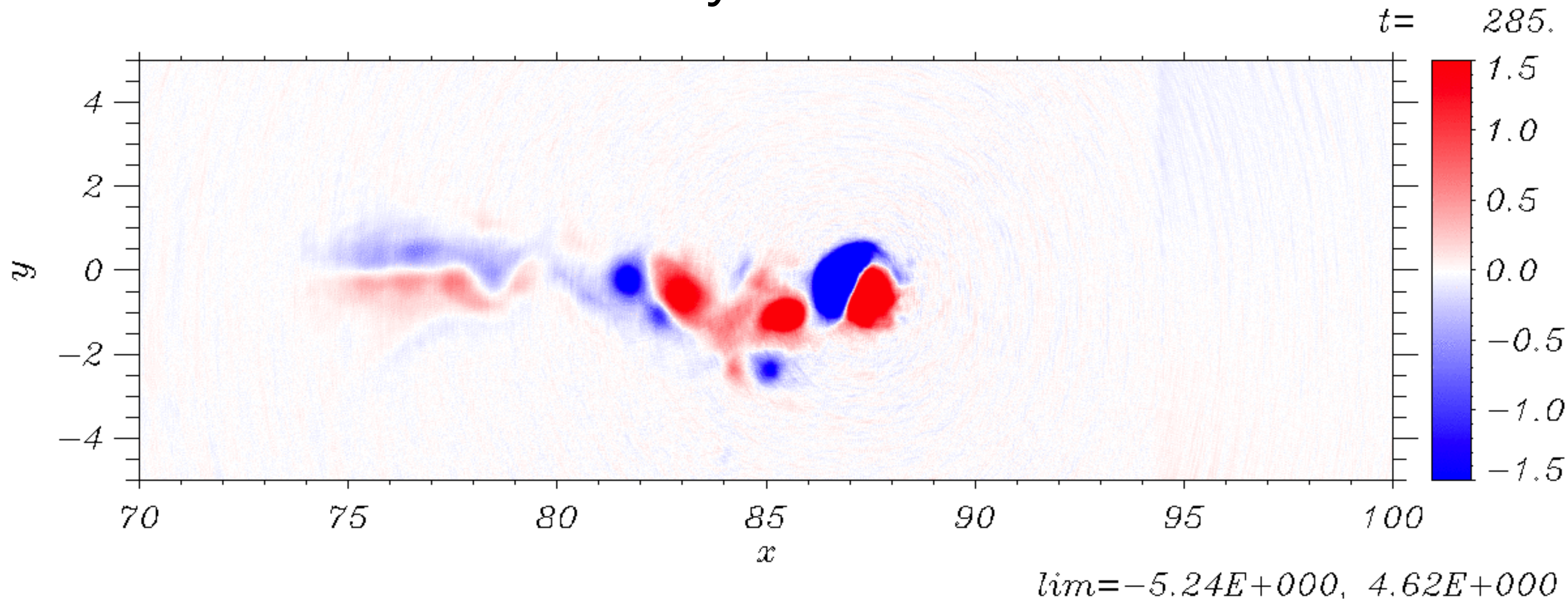
Solution contains various sophisticated trajectories

(a) Wobbling

(b) Tumbling

D.D. Hobson, 1994, Phys. Fluids

# Evolution of binary electron vortices




density gradient

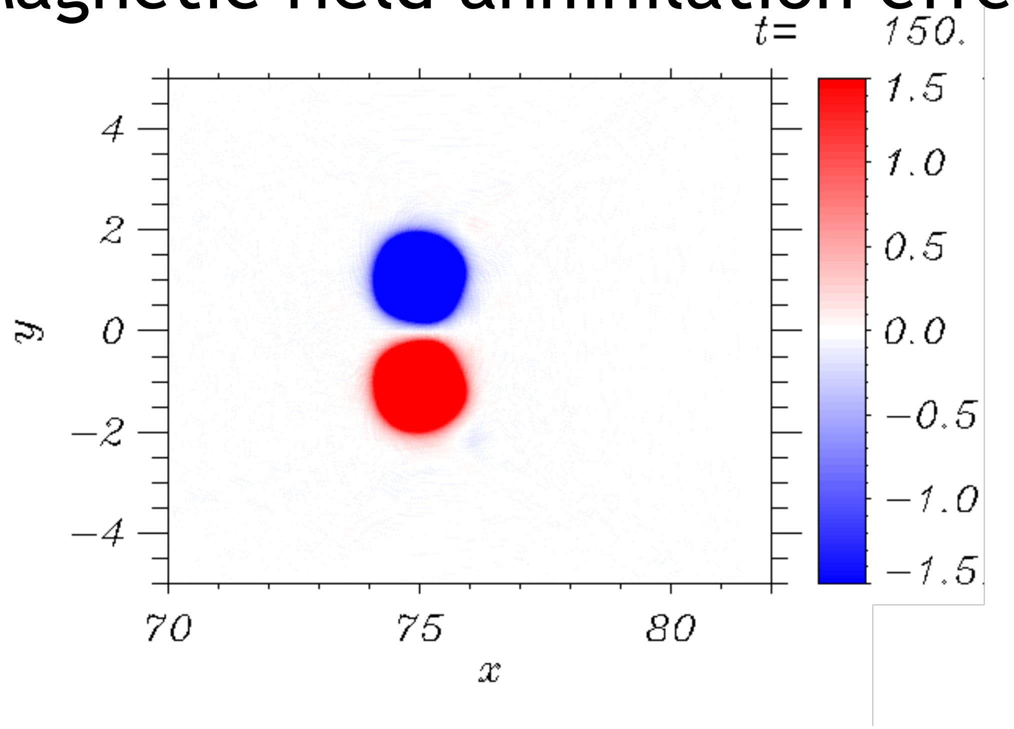
Immobile ions

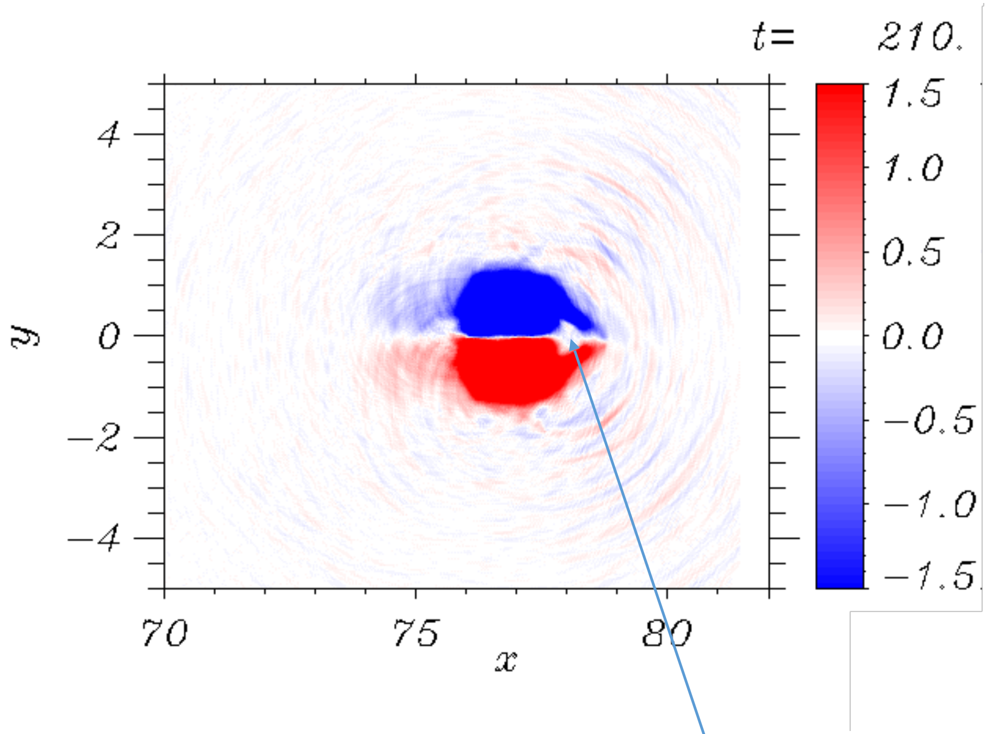
# Evolution of binary electron vortices

- **First stage**: motion of vortices perpendicular to the density gradient due to the finite radius effects - conservation of Ertel's invariant (vorticity/electron density)
- **Second stage**: motion of dipole vortex - can be described by HM equation
- **Third stage**: includes 1)magnetic field annihilation effect leading to EM wave radiation and electron acceleration; 2)secondary vortex formation due to the boundary fragmentation (similar to the one observed in single vortex case)
- **Final stage**: multiple solitary vortices which are a few electron skin depth far away from each other

# Notable effects

- Magnetic field annihilation effect



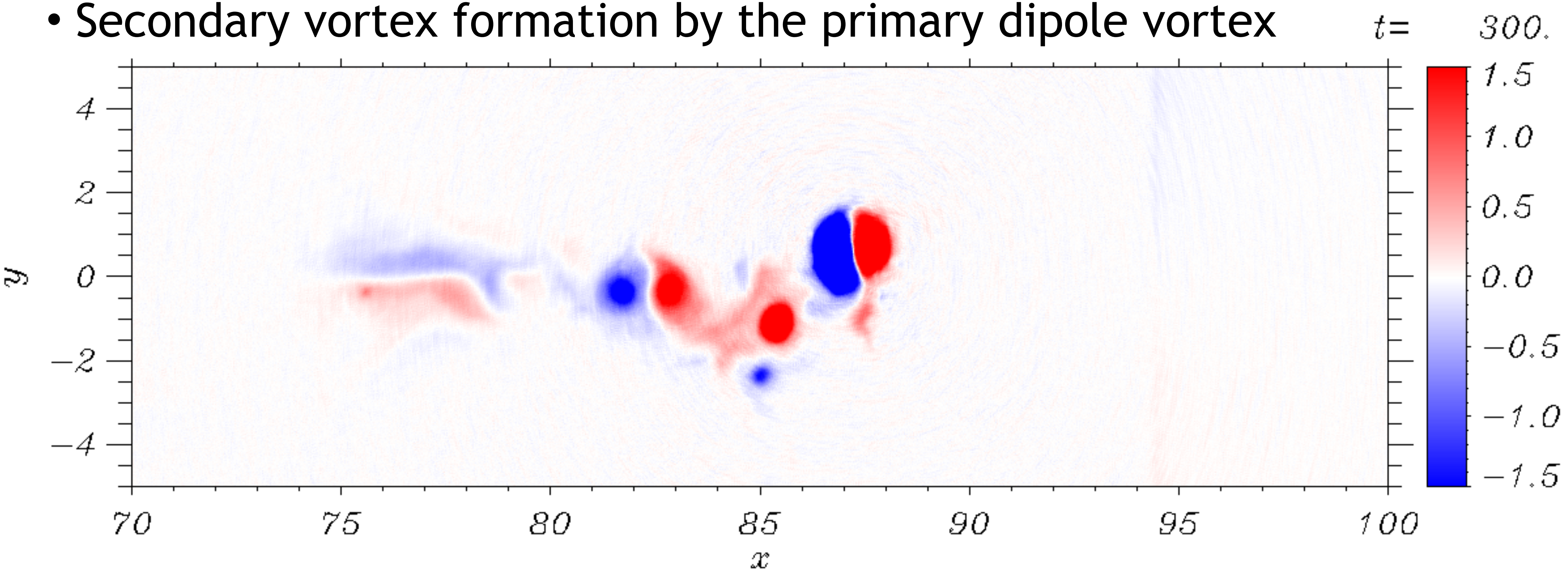




The rapid electron acceleration: up to 30 MeV electrons are seen at this spot, ~6 time energy increase

Analogous effect was observed in different simulations setup with the usage of two petawatt laser pulses, see Y. Gu et al., 2016 PRE

# Notable effects

- Secondary vortex formation by the primary dipole vortex

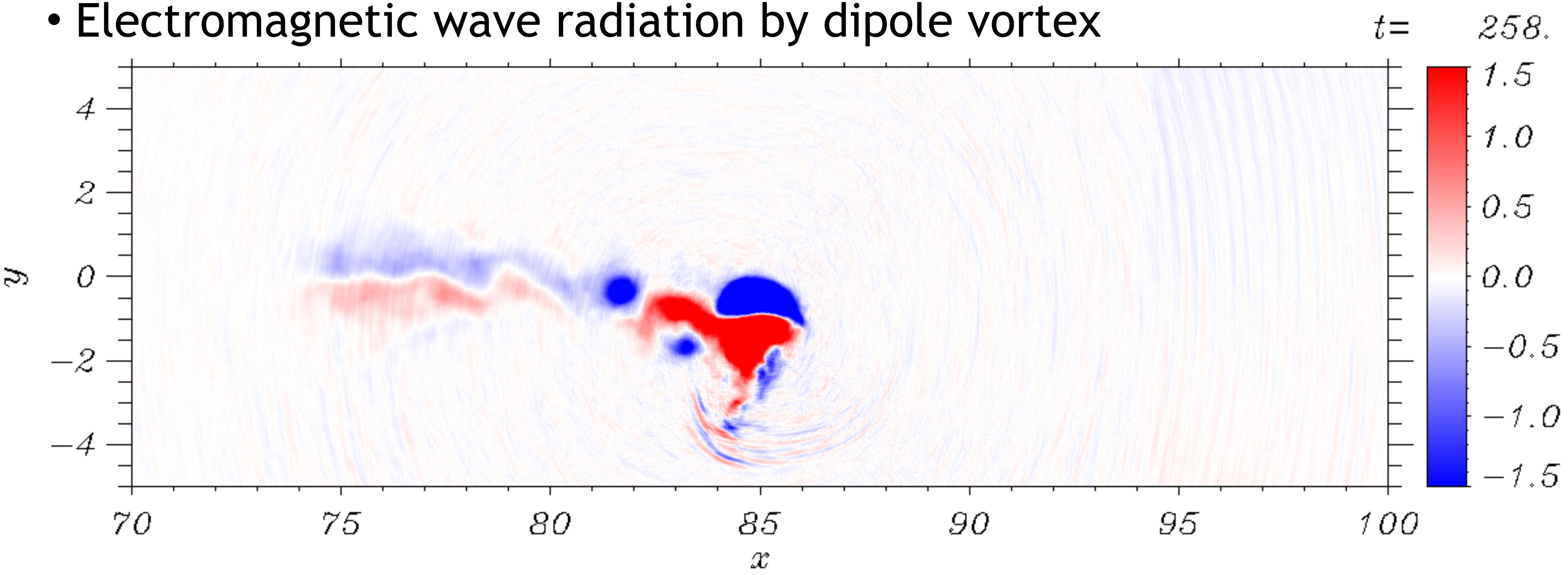



Von Karman-like streets of secondary vortices can be formed during the propagation of a dipole vortex structure. Non-regular due to bending instability (S.V. Bulanov et al., 1996, PRL)

Similar effect was observed in other works (Naumova et al., 2001, PoP; Nakamura & Mima, 2008, PRL)

# Notable effects

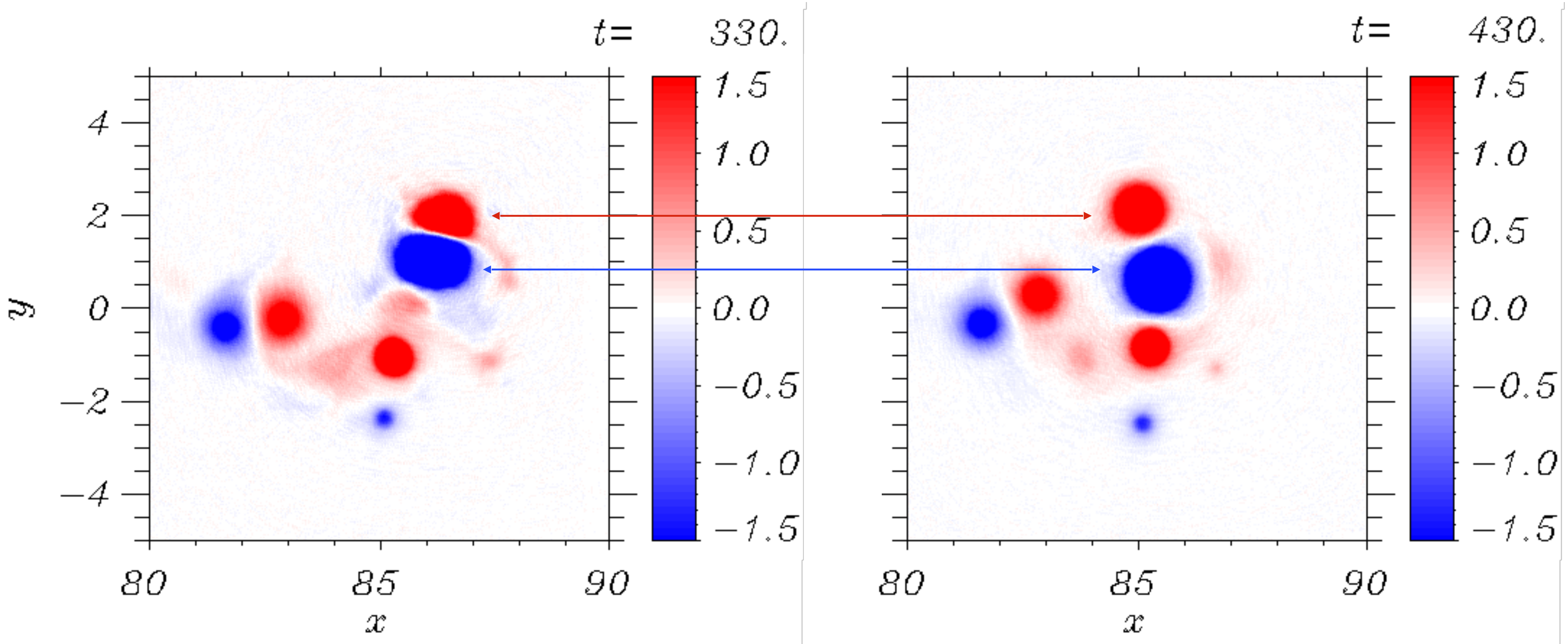
- Electromagnetic wave radiation by dipole vortex




Electromagnetic wave radiation as one of the consequences of the magnetic field annihilation

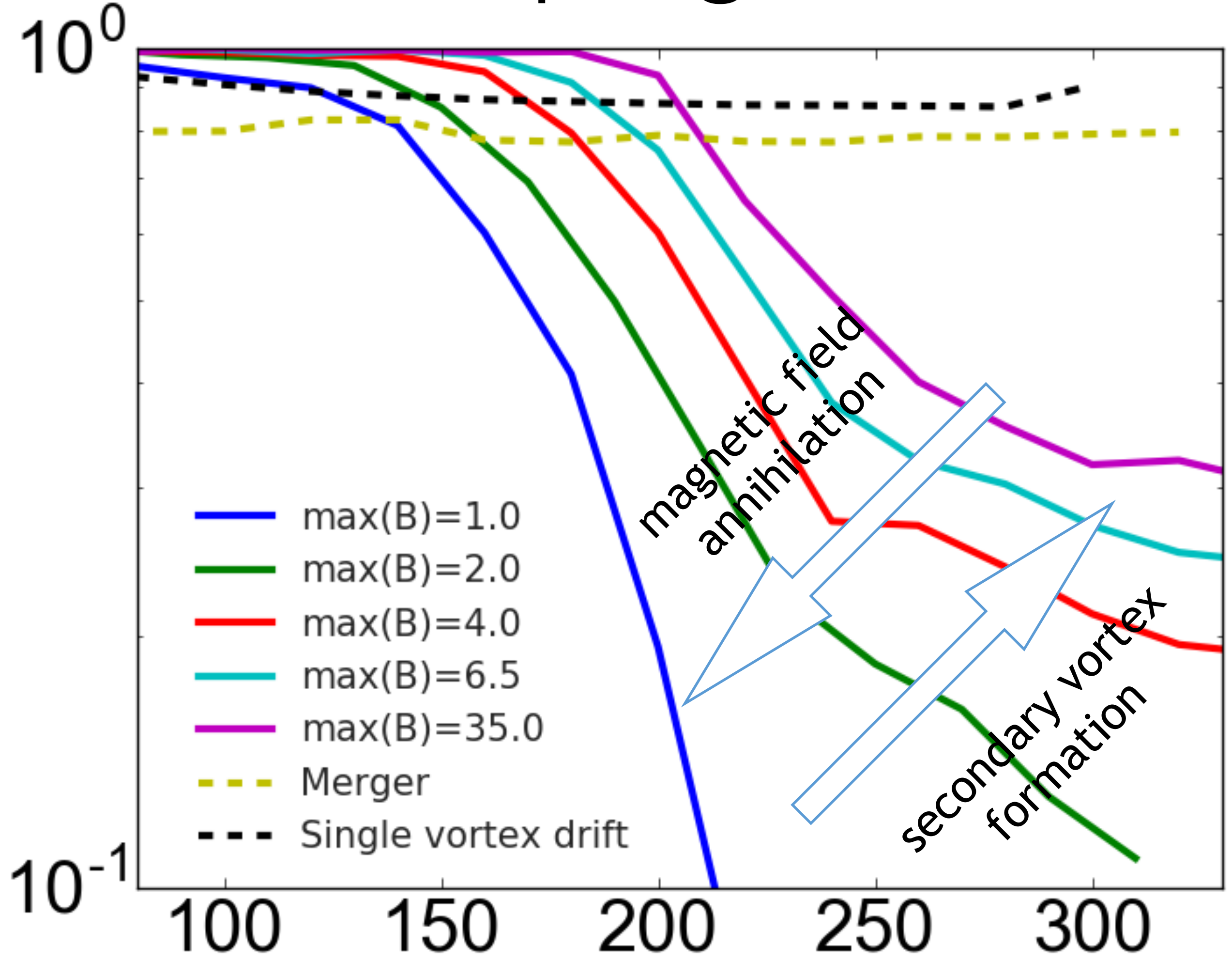
# Notable effects

- Background density gradient may break binary vortex into single vortices




Finite radius electron vortices drift perpendicular to the density gradient to the conservation of the Ertel's invariant (vorticity/density). This drift may decouple electron vortices

# Binary vortex damping




* 3.3 fs

Evolution of magnetic energy in the binary vortex over time: all the processes mentioned above contribute to the vortex damping; for larger plasma densities the secondary vortex formation is more pronounced

# Summary

- Anisotropy in ion acceleration + shell-like structure of proton movement
- Bending of the vortex outer boundary
- Damping of binary electron vortex structures due to the magnetic field annihilation and secondary vortices formation
- As a result of damping, fast electrons, secondary vortices, and plasma waves are formed

K. V. Lezhnin et al., PoP (2016b); arXiv 1606.05914
K. V. Lezhnin et al., Proceedings of SPIE (2017)
A. R. Knyazev et al., Proceedings of SPIE (2017)

K. V. Lezhnin et al., “Relativistic electron vortex damping in collisionless plasmas”, *in preparation*