Formation and evolution of complex soliton structures in the early Universe

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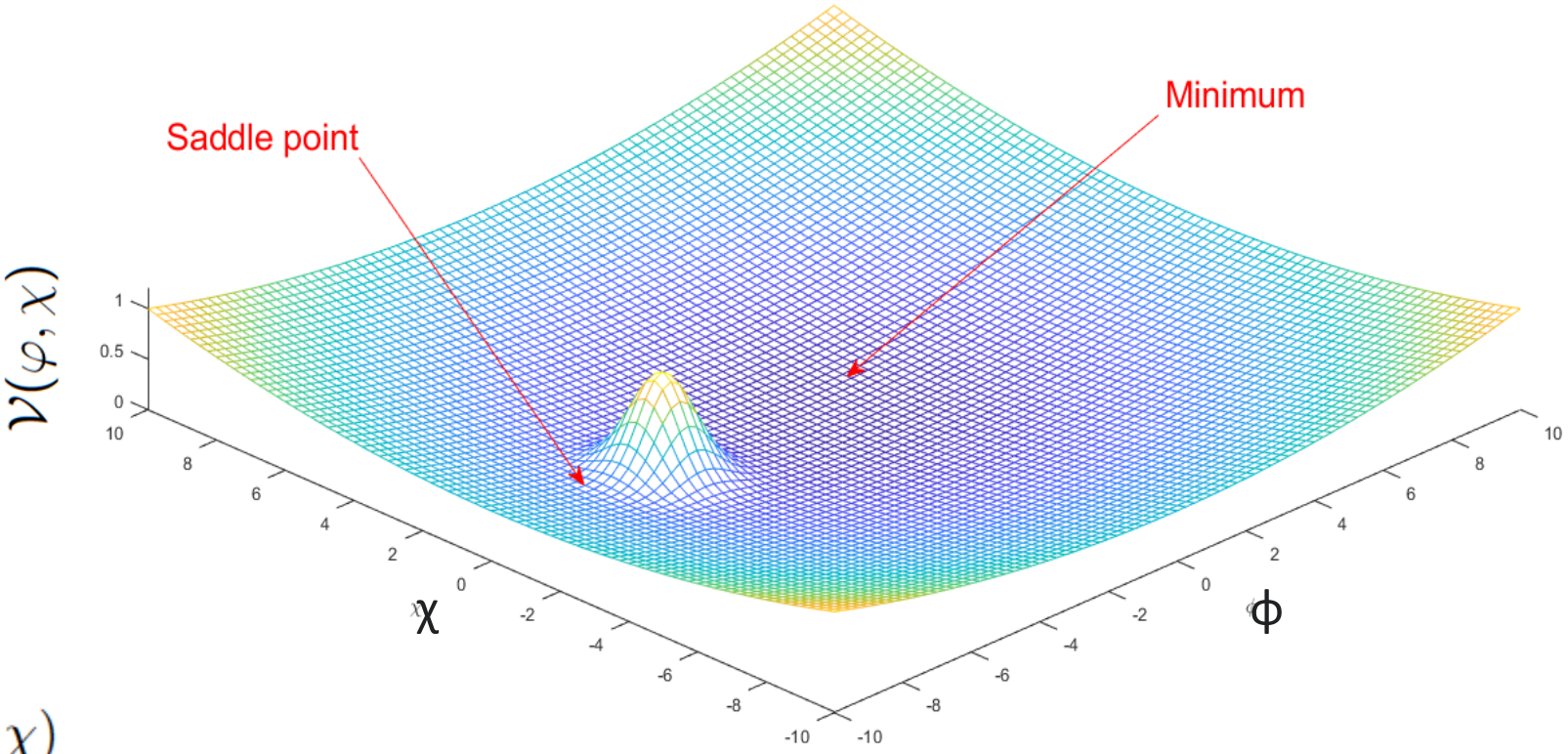
Model

Model potential in the space of fields ϕ and χ. It is worth noting that there is only one vacuum in the model, and there is also a saddle point (indicated by a red arrow)



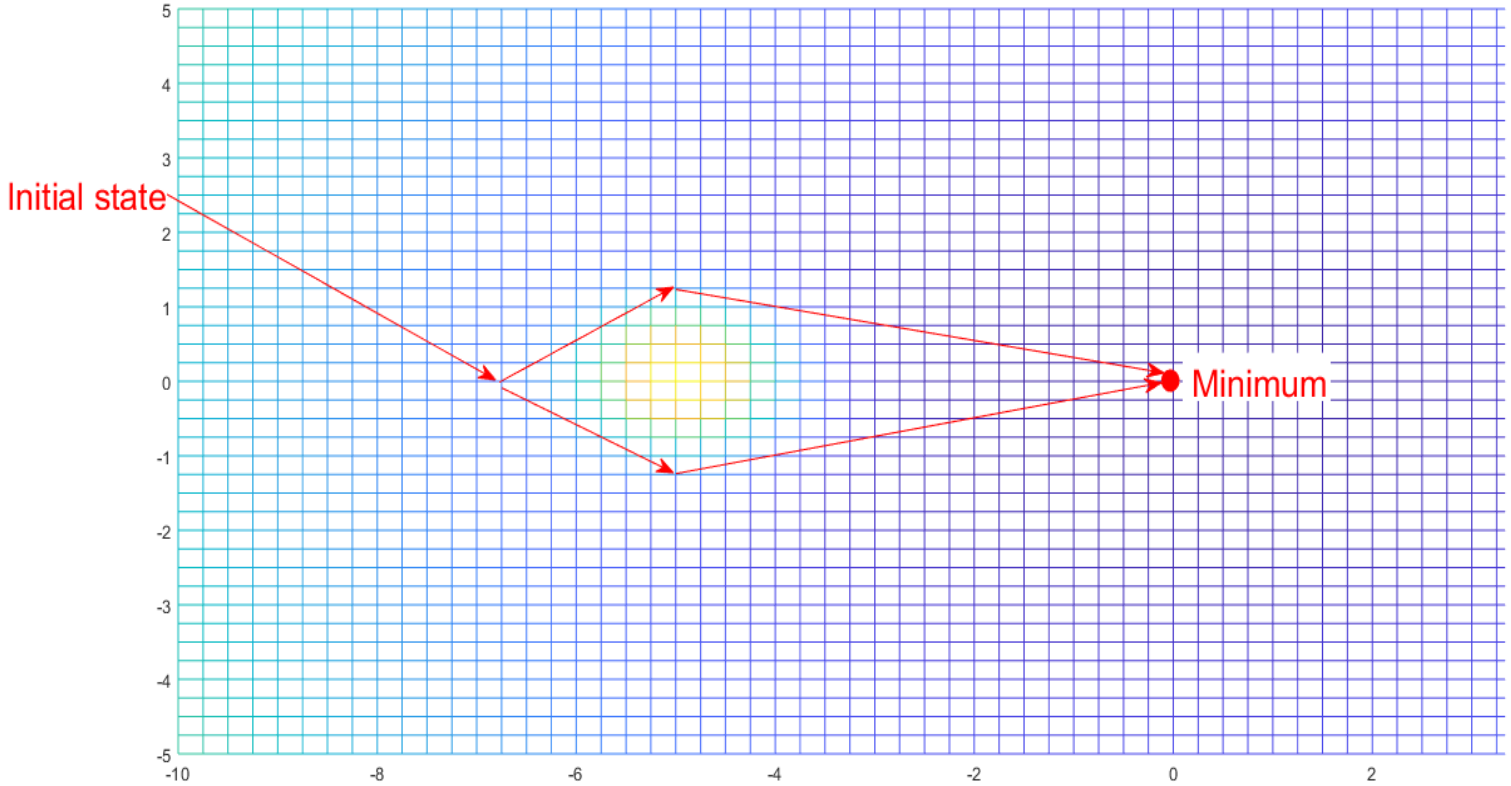
$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 + \frac{1}{2}(\partial\chi)^2 - \mathcal{V}(\phi,\chi)$$

$$\mathcal{V}(\varphi,\chi) = \frac{m^2}{2}(\varphi^2+\chi^2)+\Lambda^4 \exp\left[-\lambda\left((\varphi-\varphi_0)^2+(\chi-\chi_0)^2\right)\right].$$

Model

$$\ddot{\phi} + 3H\dot{\phi} - \frac{\nabla^2\phi}{a^2} = -m^2\phi + \frac{\Lambda^4}{\sigma^2}(\phi - \phi_0)\, e^{-\frac{(\phi-\phi_0)^2+(\chi-\chi_0)^2}{2\sigma^2}}$$

$$\ddot{\chi} + 3H\dot{\chi} - \frac{\nabla^2\phi}{a^2} = -m^2\chi + \frac{\Lambda^4}{\sigma^2}(\chi - \chi_0)\, e^{-\frac{(\phi-\phi_0)^2+(\chi-\chi_0)^2}{2\sigma^2}}$$

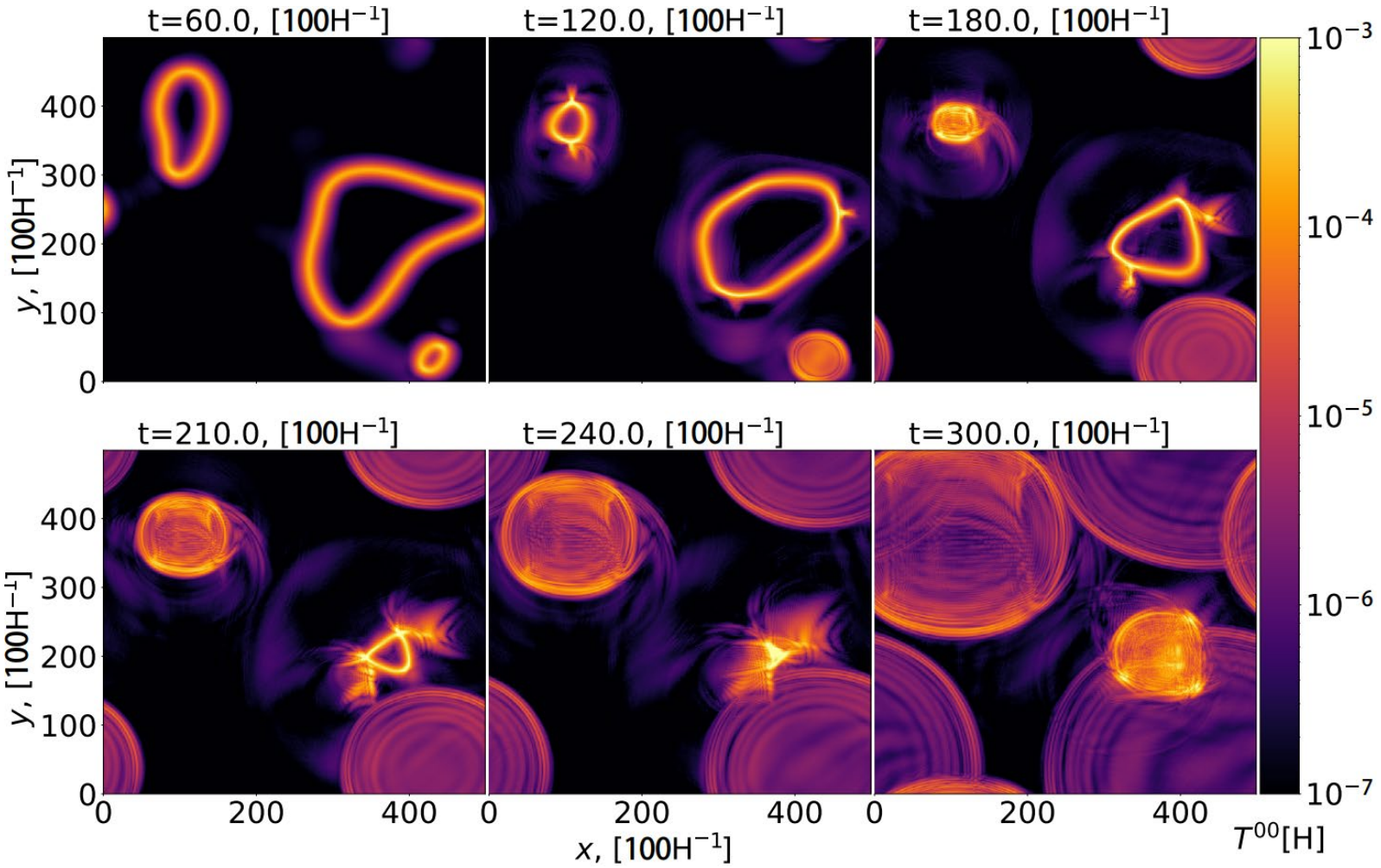


Model potential in the space of fields ϕ and χ (top view).

In the figure, red arrows indicate the initial values of the fields and the path of the fields rolling down to the minimum required for the formation of a domain wall.

For a domain wall to form, rolling must occur simultaneously on both sides of the local maximum.

Bubble Collapse

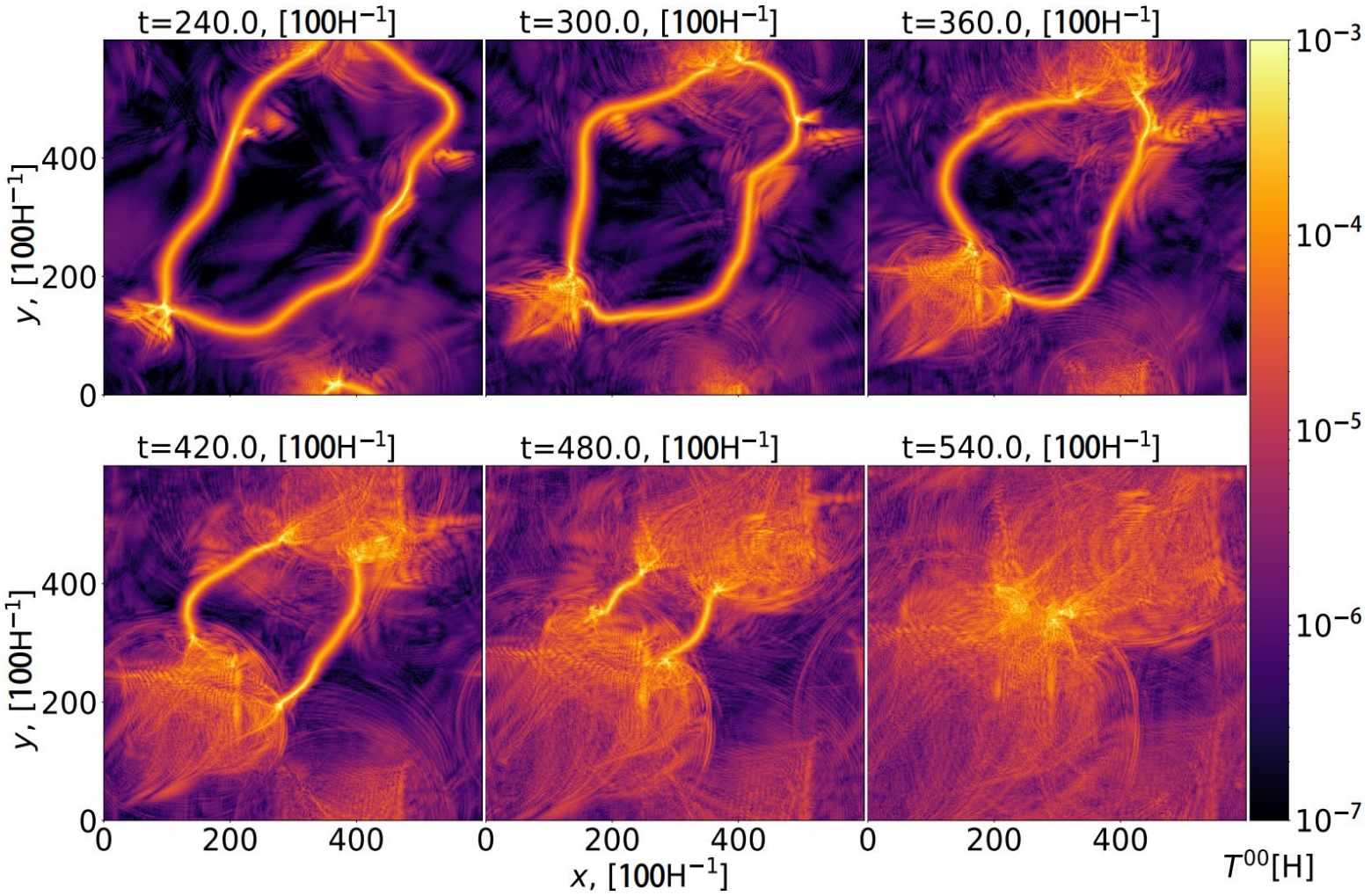


Two-dimensional distribution of field energy density in physical space.

The figure shows the evolution of vacuum bubbles in the model.

In this work, all 2D figures are 2D slices within a 3D simulation.

Formation of holes in the walls

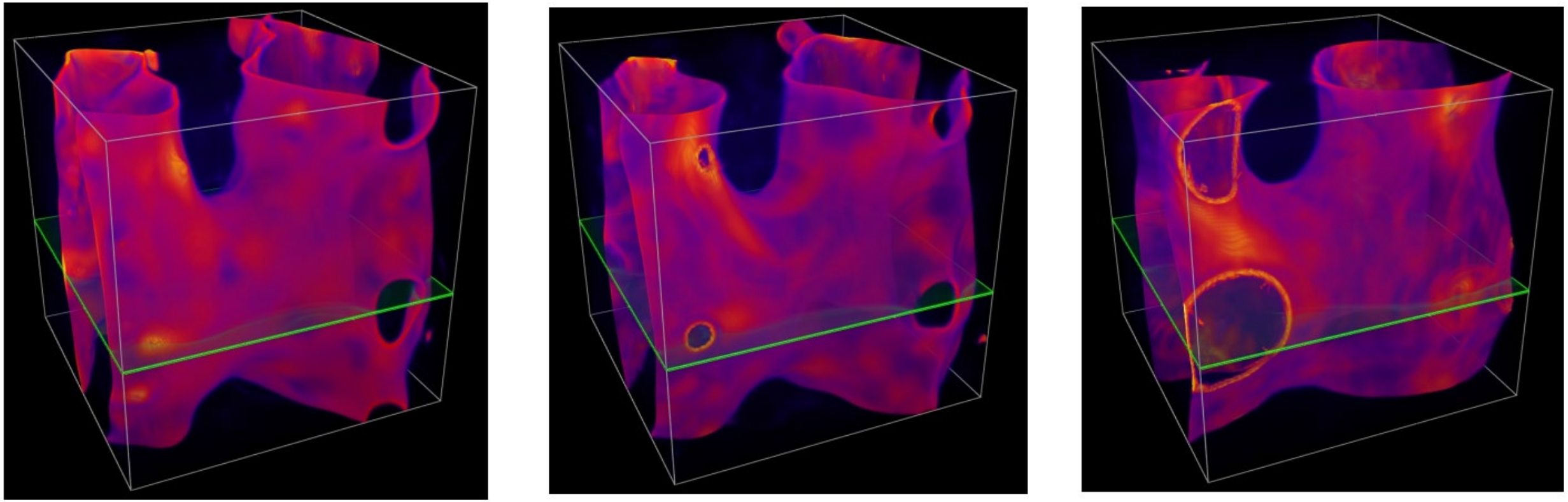


The figure shows the formation of holes (bounded by strings) in vacuum bubbles.

In the first and second pictures in the top row you can see the formation of two holes in the vacuum bubbles.

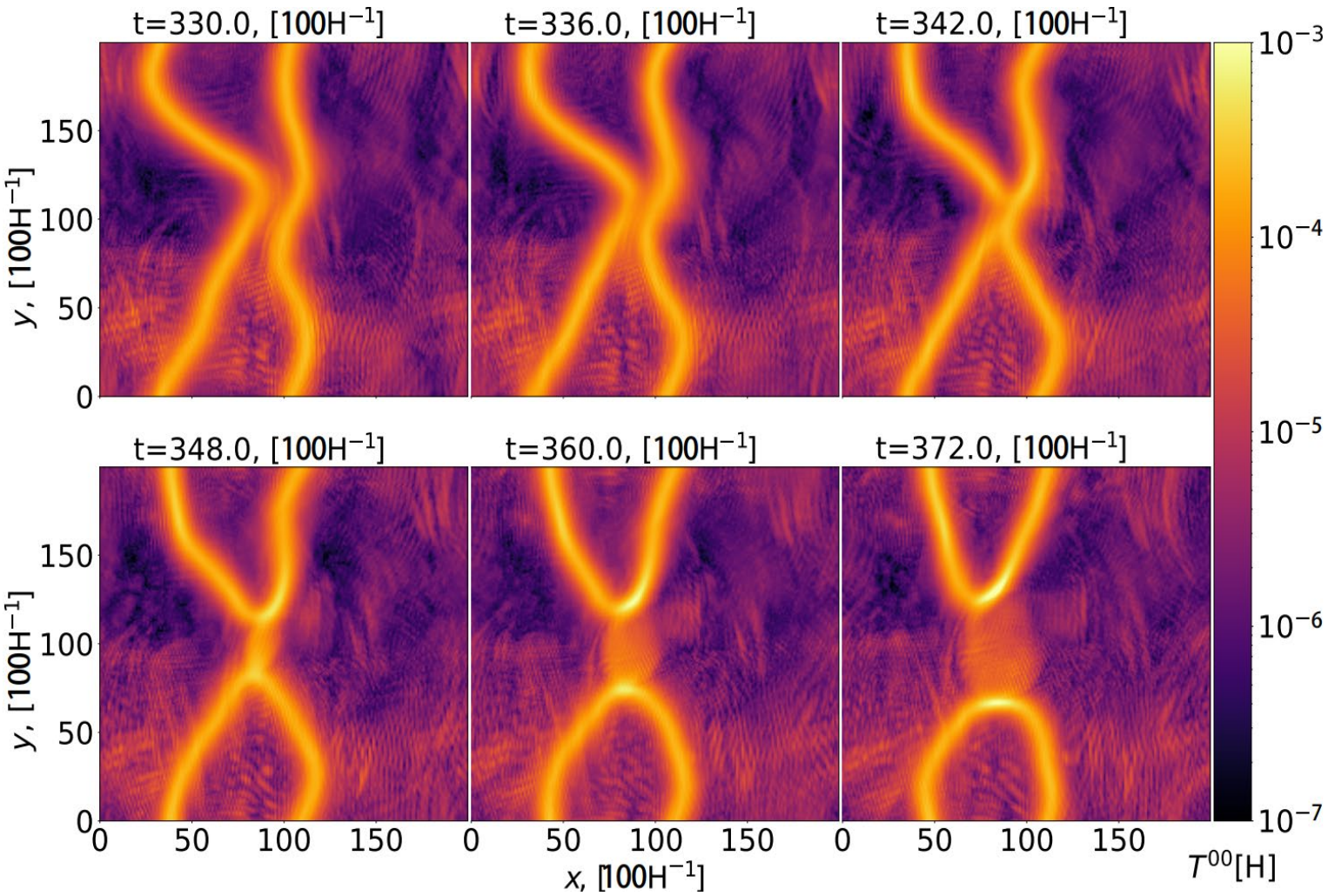
After the formation of holes, bubbles tend to collapse, the mechanism of which is different from the collapse of pure bubbles.

Formation of holes in the walls



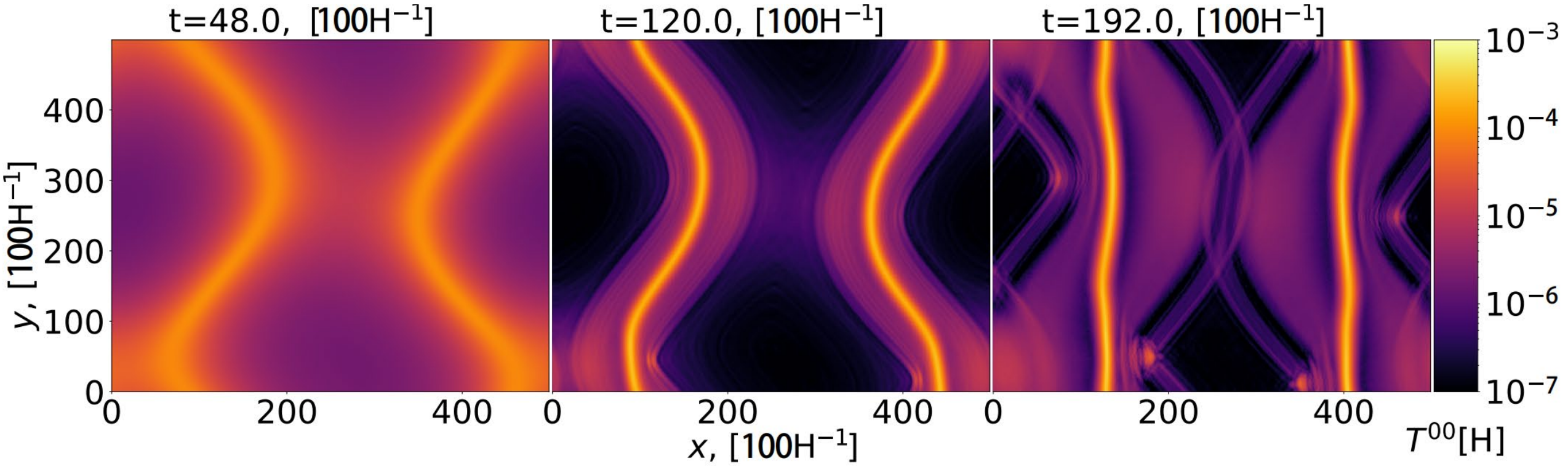
The figures show the formation of holes in a vacuum bubble (the formation occurs in the second picture) in a three-dimensional picture.

Interconnection



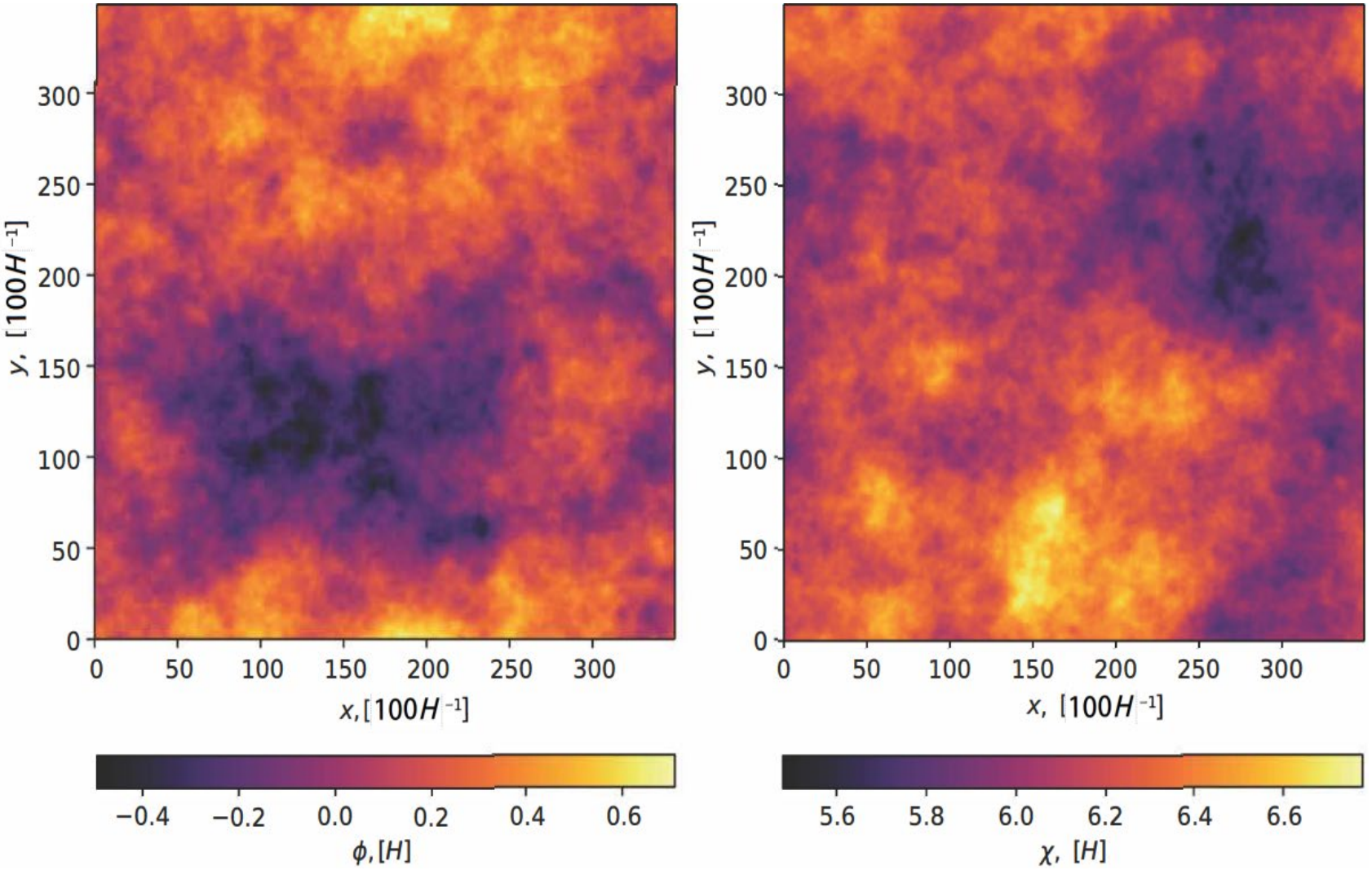
The figure shows the effect of Interconnection. In this case, two vacuum bubbles collide as a result of their evolution and eventually merge into one (the boundary conditions are cyclic).

Radiation emission



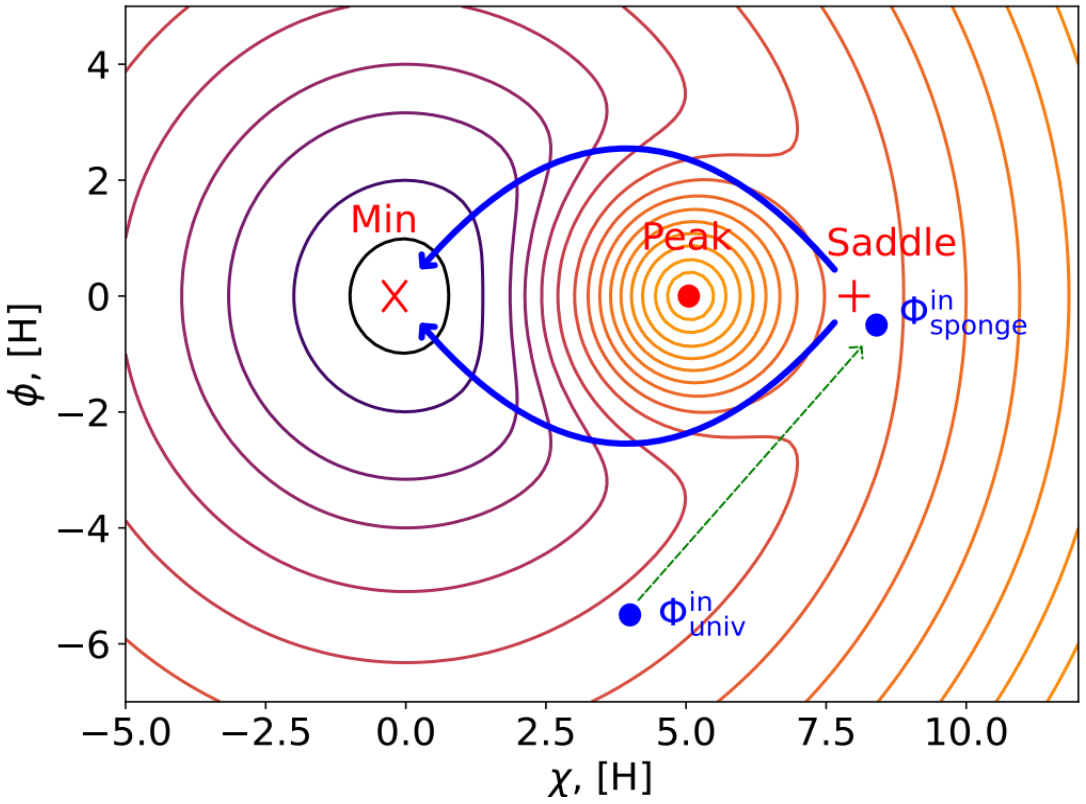
The figure shows the effect of particle radiation. Domain walls tend to get rid of curvature by emitting particles of a scalar field.

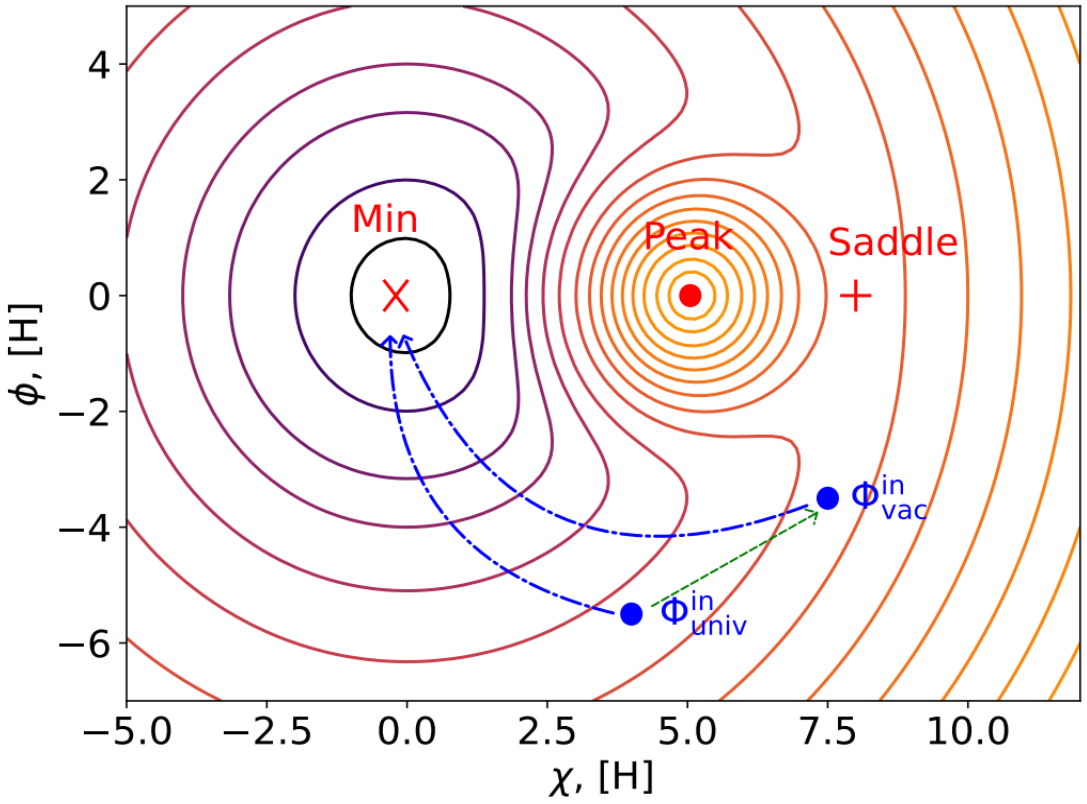
Inflationary initial conditions



Distribution in physical space of field ϕ (left) and field χ (right)

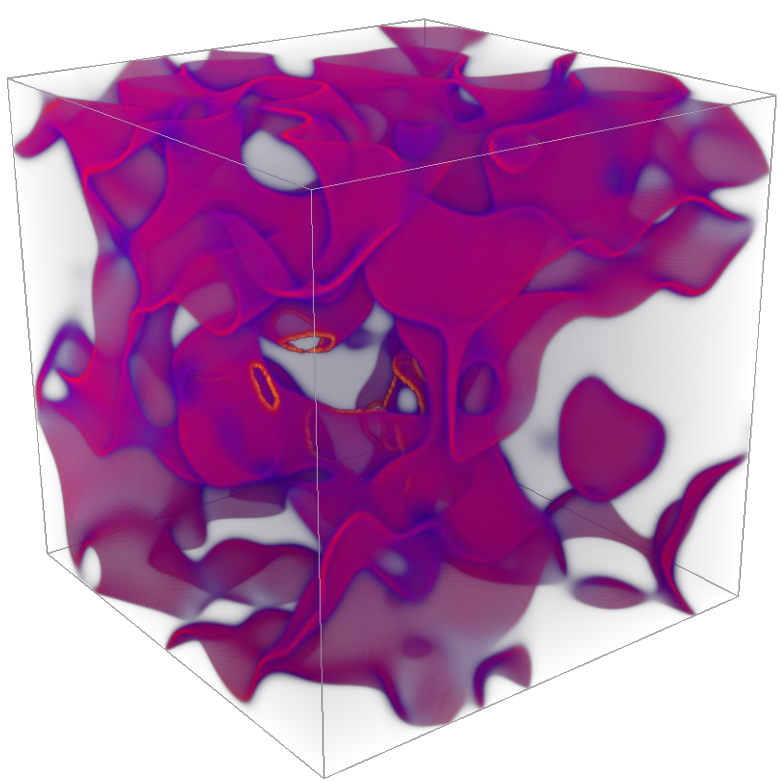
Foam formation mechanism

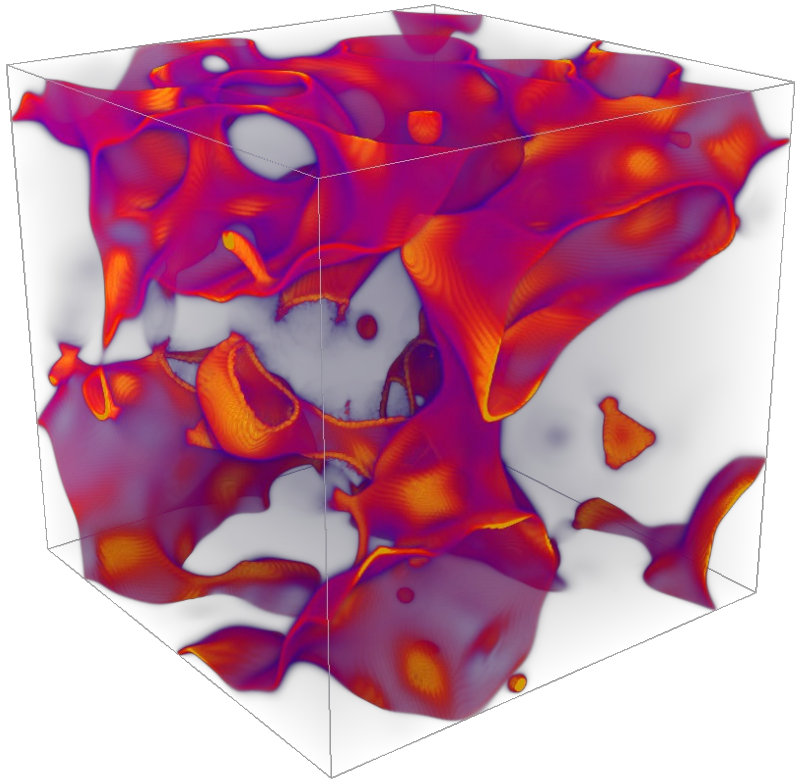


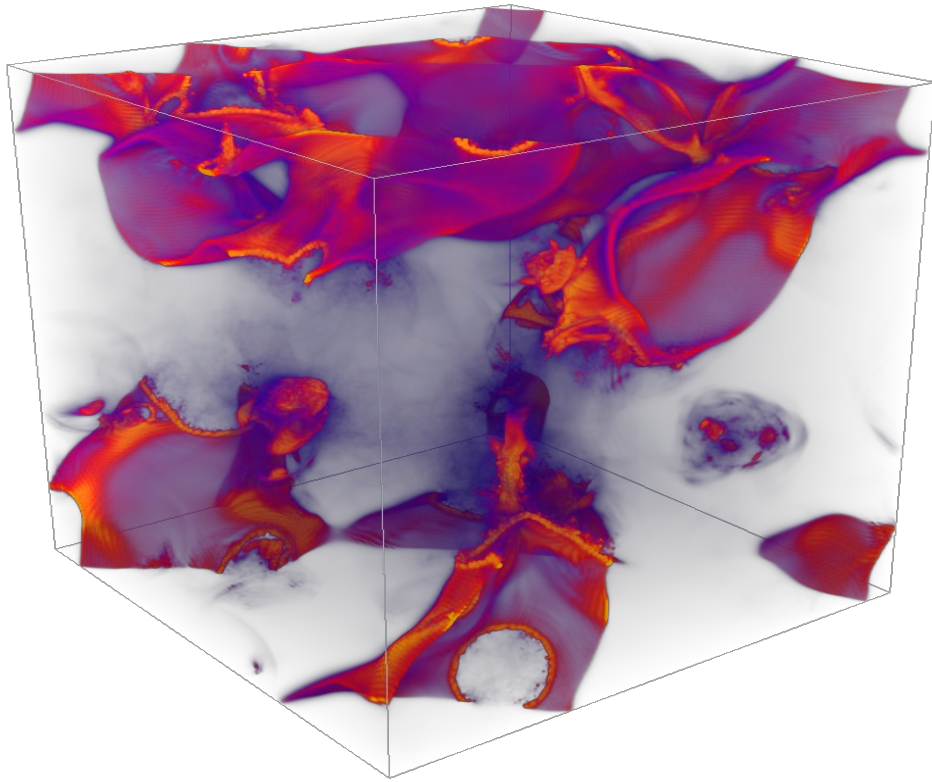


Soliton foam

Three-dimensional distribution of energy density of the field configuration in space.

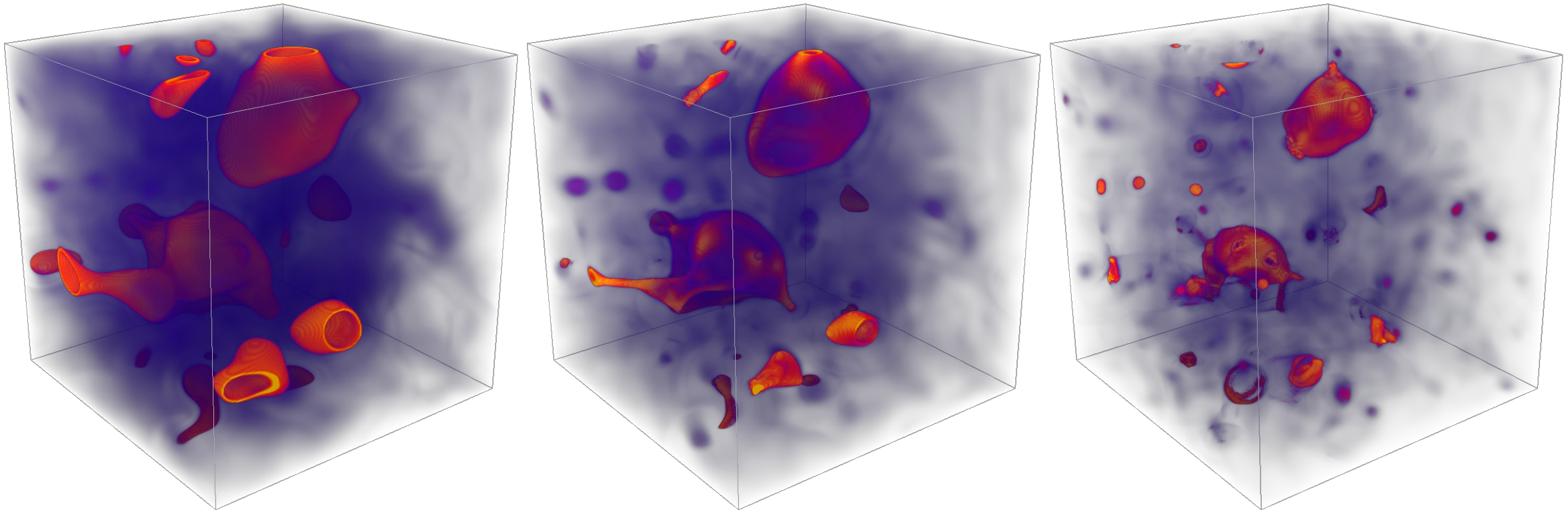






Soliton foam

Three-dimensional energy density distribution field configuration in space for the case where vacuum bubbles are mainly produced.



Conclusion

- A field model with a soliton formation mechanism based on the dynamic evolution of scalar fields is considered.
- The mechanism of soliton formation in the model does not require phase transitions, and therefore may be rare enough in the Universe so as not to contradict observational data.
- Solitons in the model with initial conditions obtained at the inflation stage are formed immediately in clusters along with a halo of particles of the scalar field.