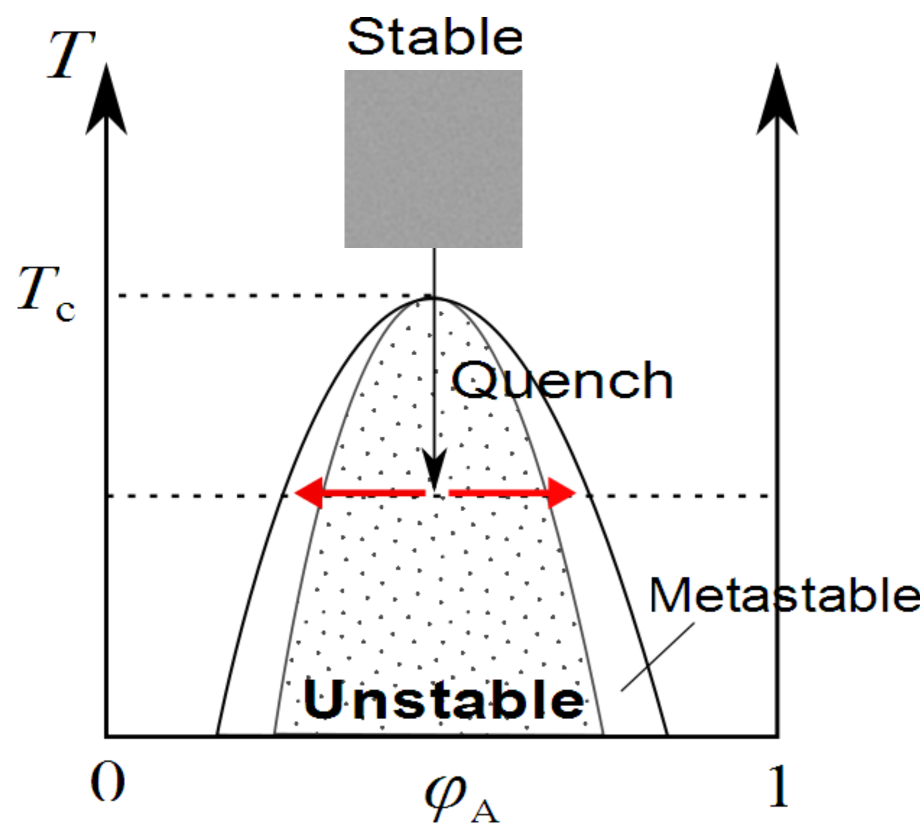
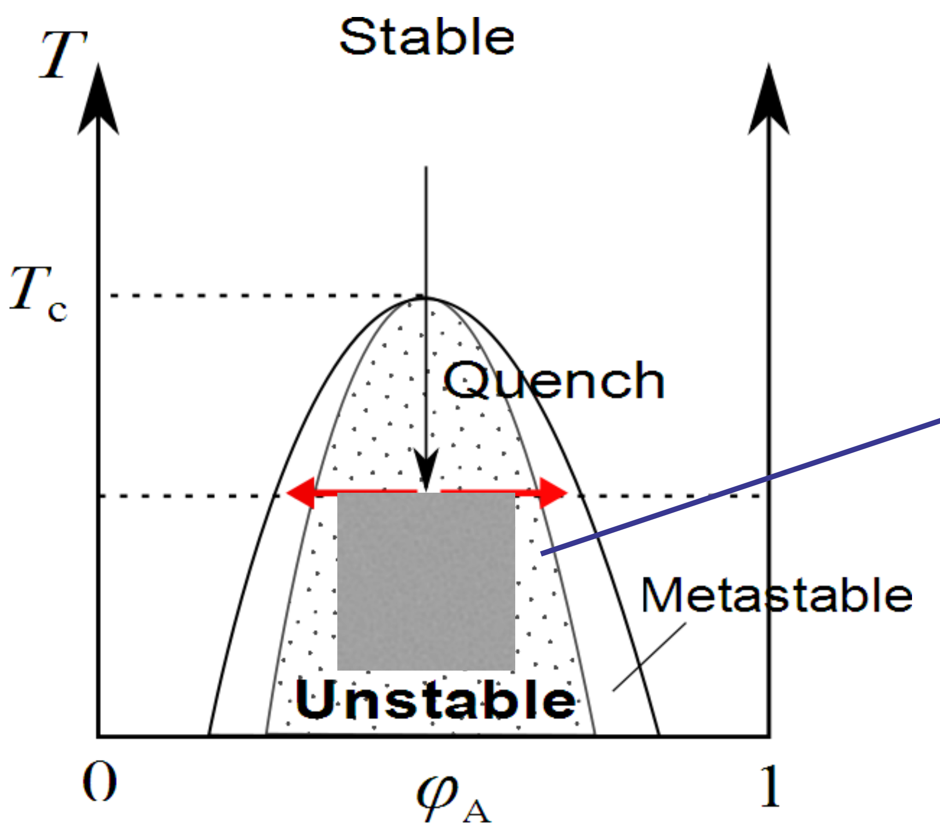
Turbulent effect on self-organized structure formation in phase separation system

Okano laboratory

Phase separation: spinodal decomposition

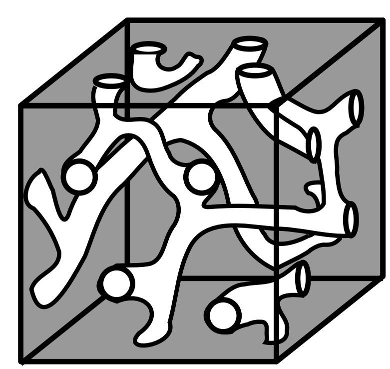


Phase separation: spinodal decomposition



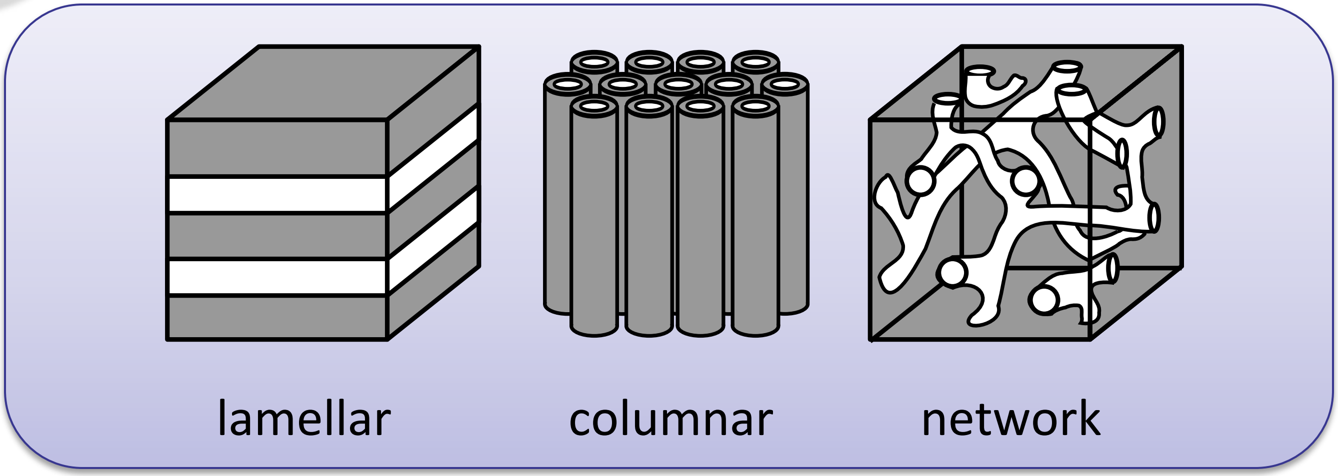
Multicomponent mixture
phase separates by thermodynamic instability
forming network structure.

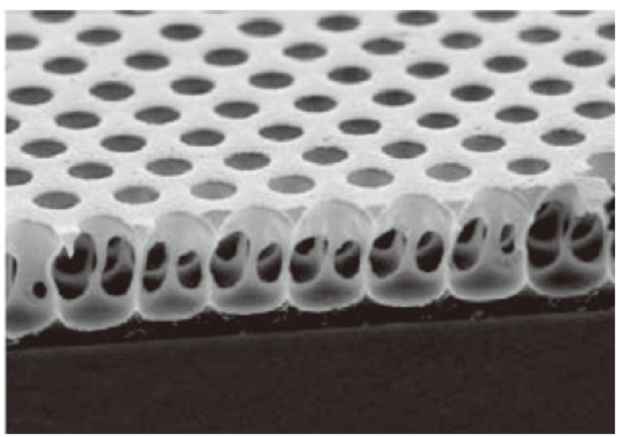
Network structure



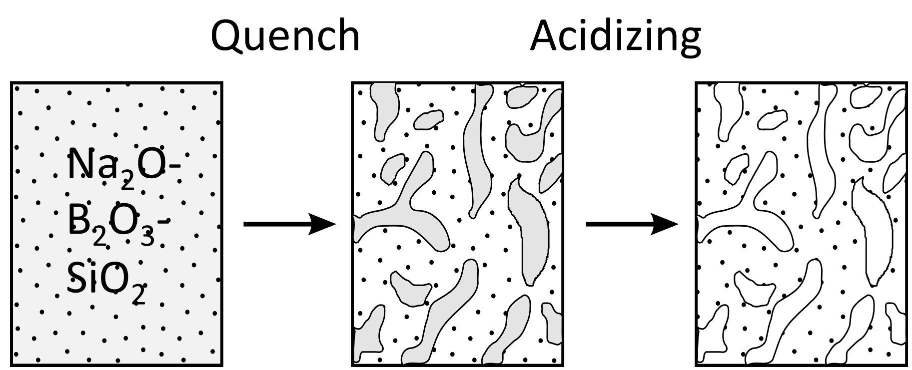
Self-organization structure

Self-organization structure





Honeycomb film (下村ら 特開 2002-335949, Fuji Film)



Processing of porous glass

What/How does the flow field (turbulent flow) affect a self-organization structure?

Previous studies

Theory & experiment

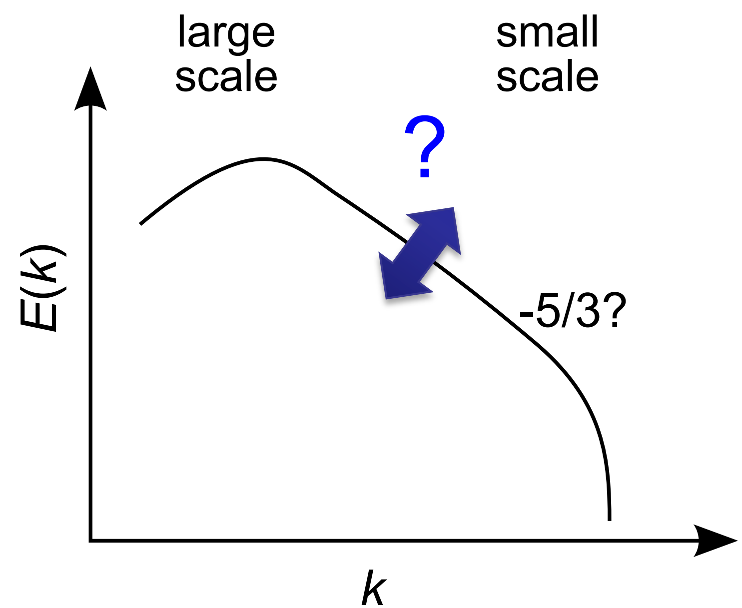
Author	Year	Remark
Ruiz & Nelson	1981	Energy cascade
Aronovitz & Nelson	1984	Energy cascade, quench
Pine et al.	1984	Light scattering exp.
Tanaka	~ Present	Temp. quench, visoelastic

Numerical simulation

Author	Year	Dimension	Method
Berti *et al.*	2005	2D	Spectral
Kendon *et al.*	1999,2000,2001	3D	LBM
Perlekar *et al.*	2013	3D	LBM

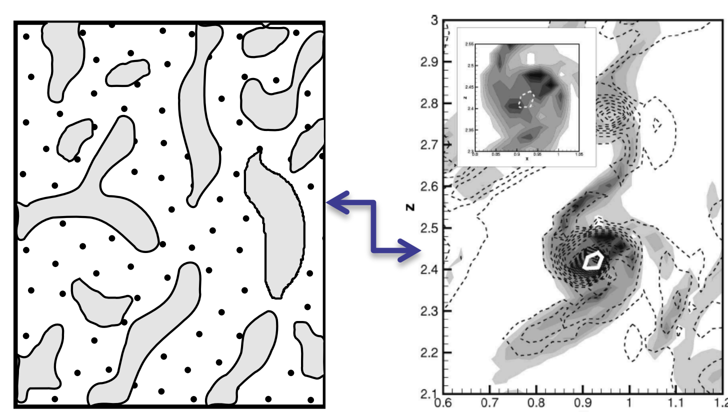
Objective

- Relation between turbulent suppression by phase separation and energy cascade
- Analogy between self-organized structure by spinodal decomposition and coherent eddy structures in turbulence



Method:

•Three-dimensional simulation for homogeneous isotropic turbulence with phase separation



Horiuti & Takagi, PoF, 2005

Simplified model (Diffusion type)

- Order parameter (phase field):

$$\psi(\mathbf{r},t) \equiv \left[\rho_A(\mathbf{r},t) - \rho_B(\mathbf{r},t)\right] / \rho_0$$

- Diffusion equation:

$$\frac{\partial \psi}{\partial t} + (\mathbf{v} \cdot \nabla)\psi = D\nabla^2\psi$$

- Navier-Stokes equation:

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\frac{1}{\rho_0}\nabla p' - \alpha \nabla \psi^2 \nabla \psi + \nu \nabla^2 \mathbf{v} + \cancel{\mathbf{f}}$$

f = 0: Decaying flow

See abstract

Numerical model (phase separation under flow)

- Navier-Stokes equation

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{1}{\rho_0}\nabla p' - \xi^2\nabla^2\psi\nabla\psi + \nu\nabla^2\mathbf{v} + \mathbf{f}$$

- Continuity equation

$$\nabla\cdot\mathbf{v} = 0$$

$$\mathbf{f} = \begin{cases} Q\mathbf{v} & \text{Linear forcing} \\ 0 & \text{Decaying flow} \end{cases}$$

- Cahn-Hilliard equation

$$\frac{\partial \psi}{\partial t} + (\mathbf{v}\cdot\nabla)\psi = \Gamma\nabla^2\mu$$

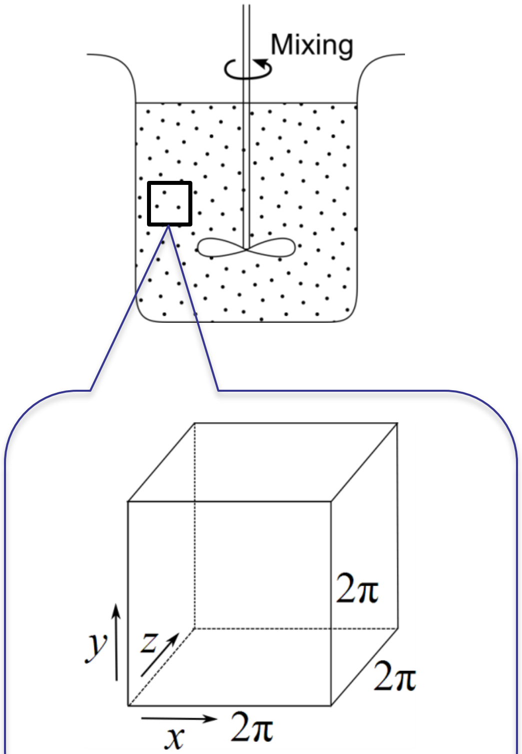
$$\mu = -\psi + \psi^3 - \xi^2\nabla^2\psi$$

Parameters
ν = 2.5 x 10^{-3} (ν/Γ = 0.1)
Q = 0.25 (Re_λ ~ 75)
ξ = 1.0 x 10^{-3}
ρ_0 = 1

Numerical conditions

Analysis model	Homogeneous isotropic turbulence
Mixture	Binary mixture
Initial concentration	50%-50%
Domain size	$2\pi \times 2\pi \times 2\pi$
Boundary condition	Periodic on all the sides.
Grid points	256^3
Time increment	$\Delta t = 4.0 \times 10^{-3}$
Initial condition of ψ	white noise

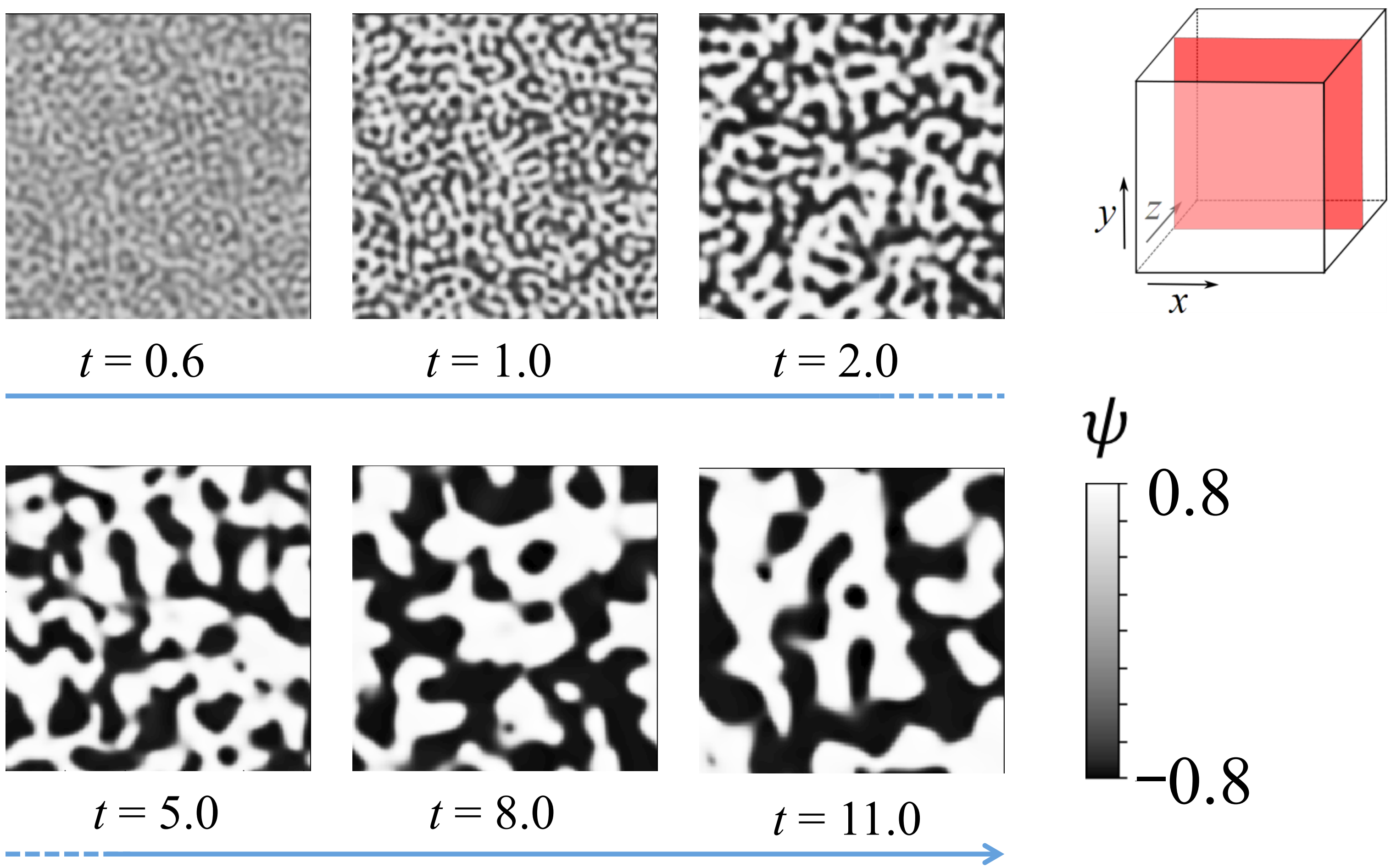
Runs	Velocity forcing	Phase separation
1	OFF (Stationary)	ON
2	Turbulence	OFF (Single component)
3	Turbulence	ON



Cubic domain

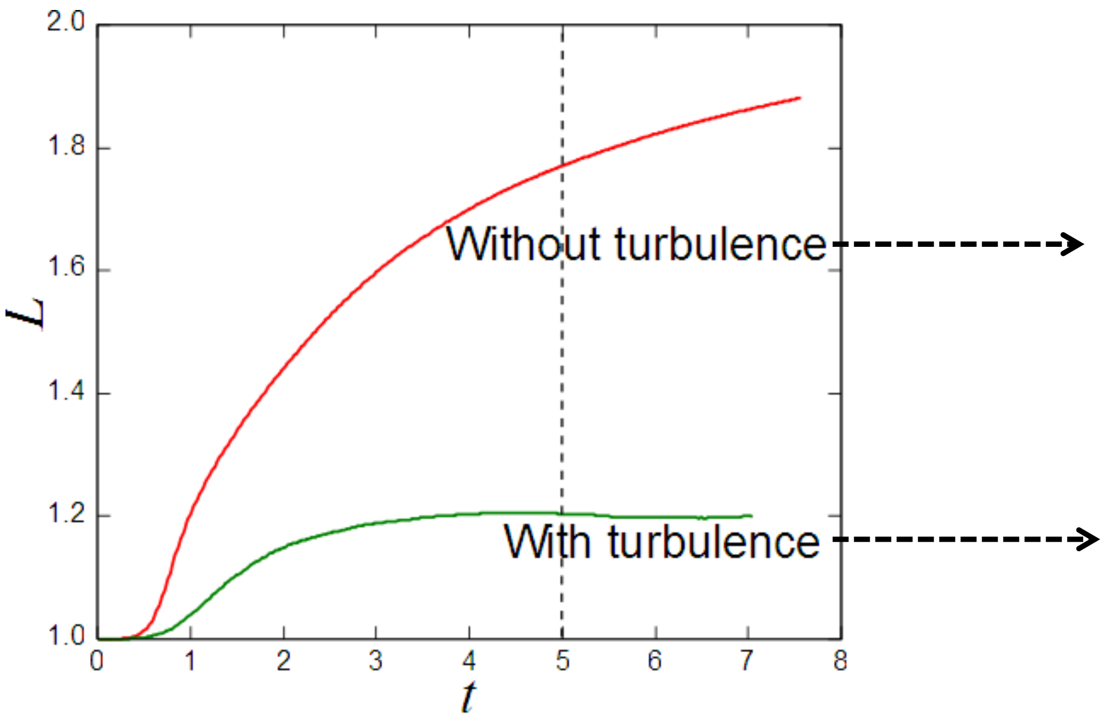
Phase separation without flow field

Order parameter distribution on a x-y plane



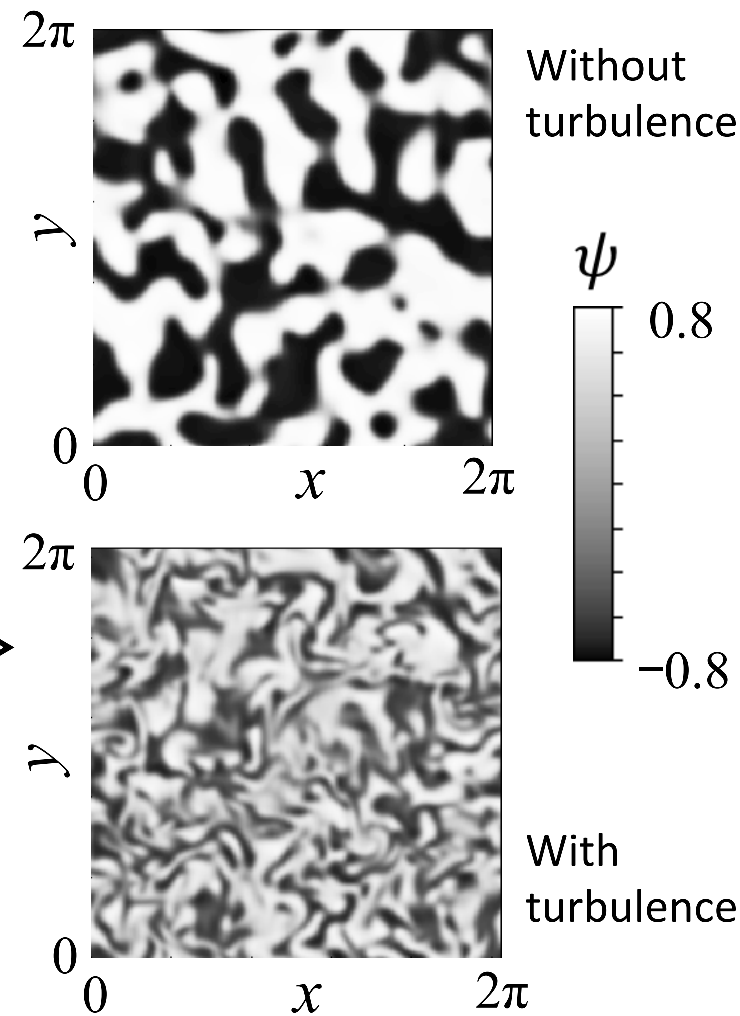
Turbulent effect on phase separation

Coarsening length L $\quad L(t) = \frac{1}{\langle (1-\psi^2) \rangle}$



Phase separation was suppressed in presence of turbulence.

Order parameter distribution on a x-y plane at $t = 5.0$



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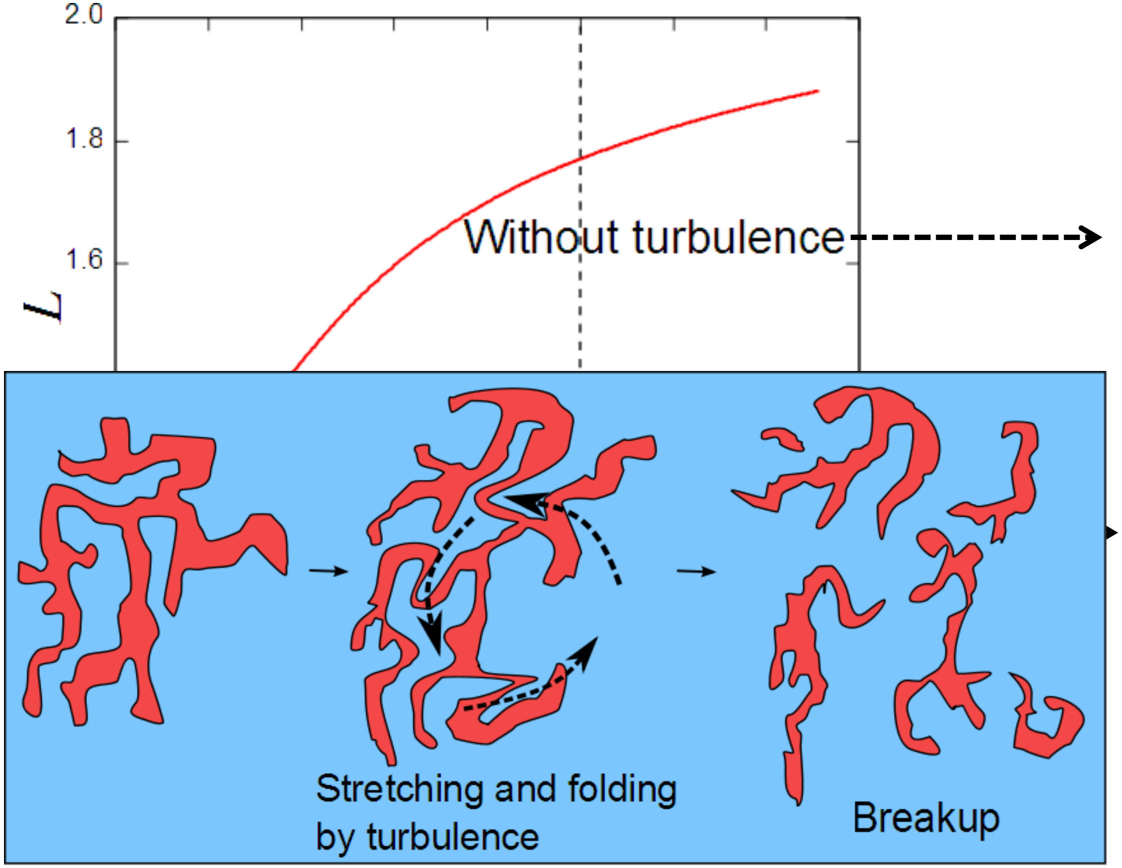

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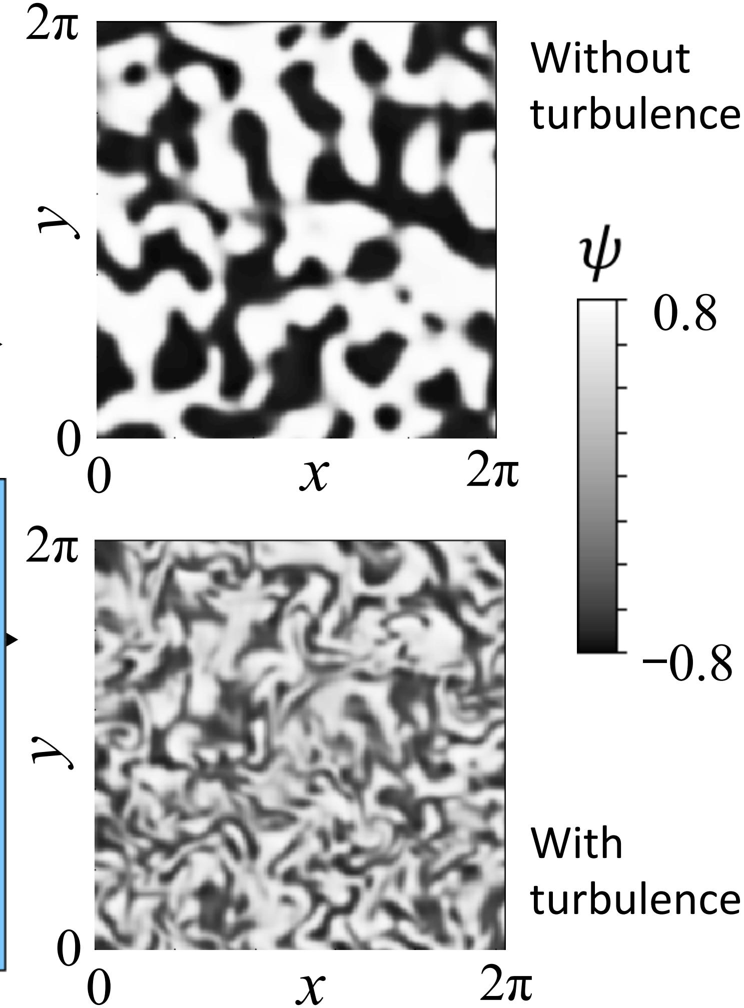
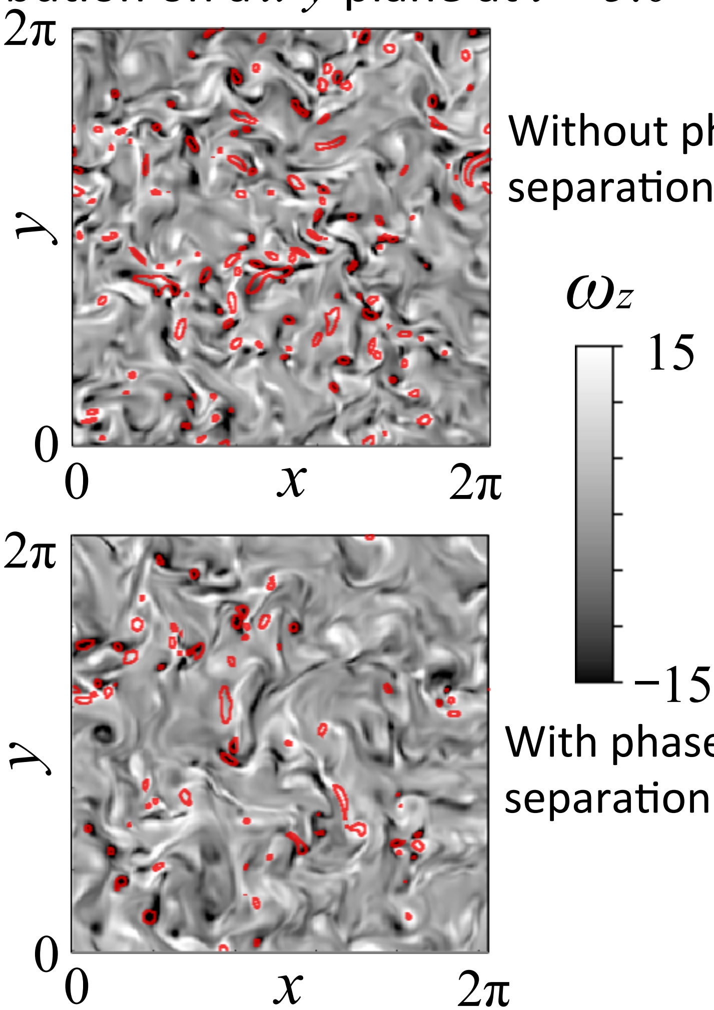


Suppression of vortex formation by phase separation

Vorticity (z-component) distribution on a x-y plane at $t = 5.0$



Without phase separation effect

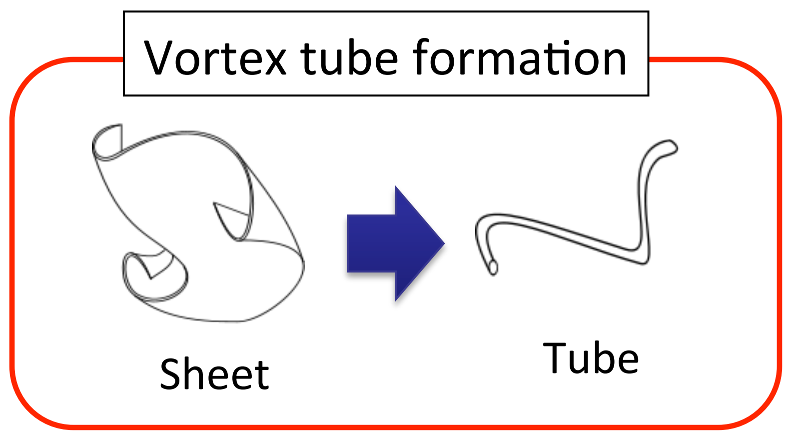
With phase separation effect

Vortex tube structure (red line contour of Q = 100): second invariant of velocity gradient tensor

$$Q = \frac{1}{2}(|\Omega|^2 - |S|^2)$$

Ω_{ij} : Vorticity tensor

S_{ij} : Strain rate tensor



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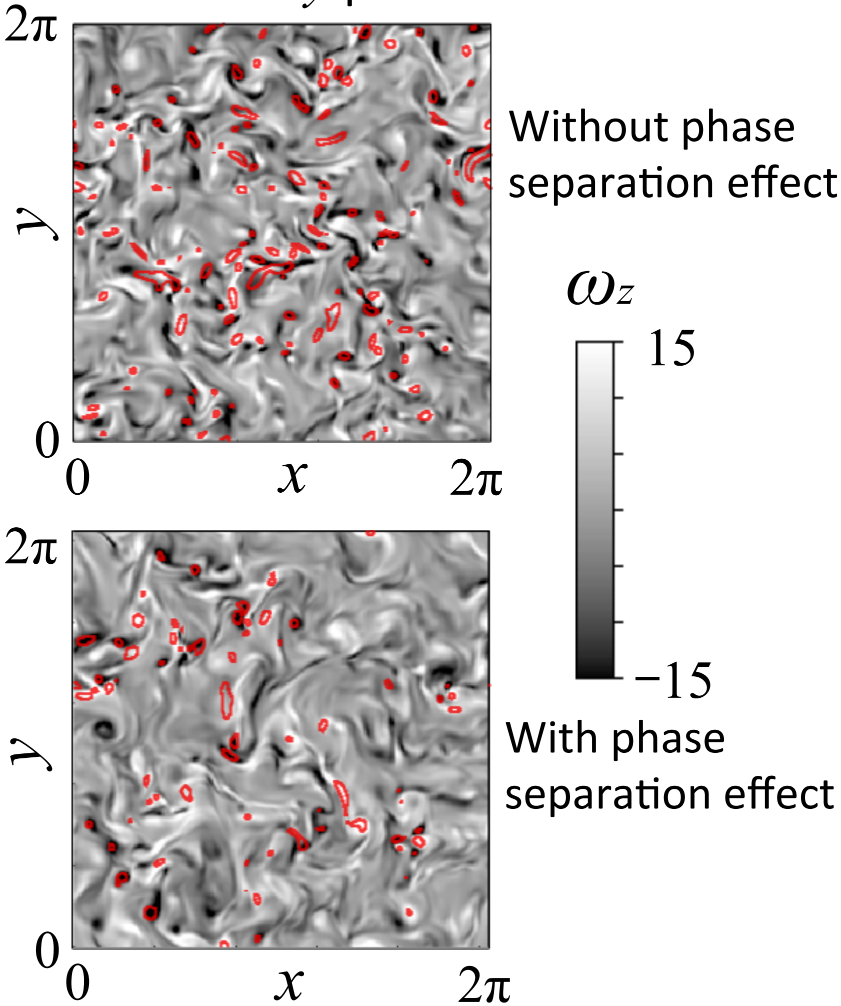
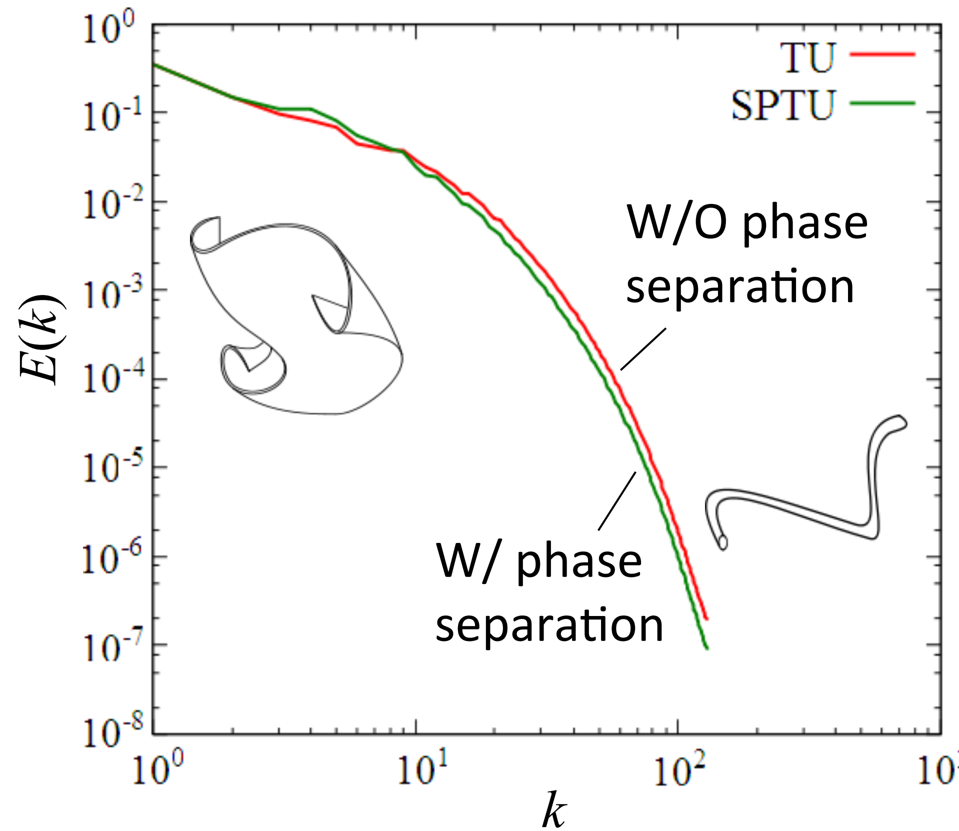


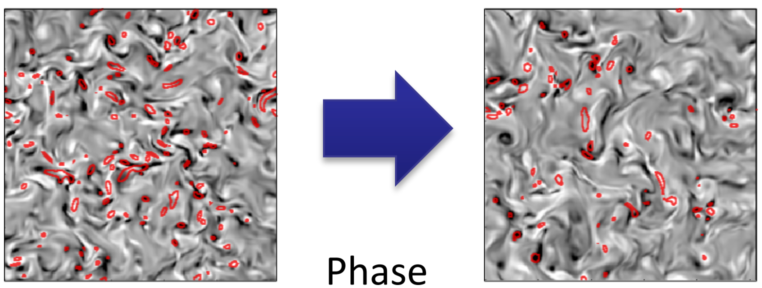
Energy spectrum at $t = 5.0$



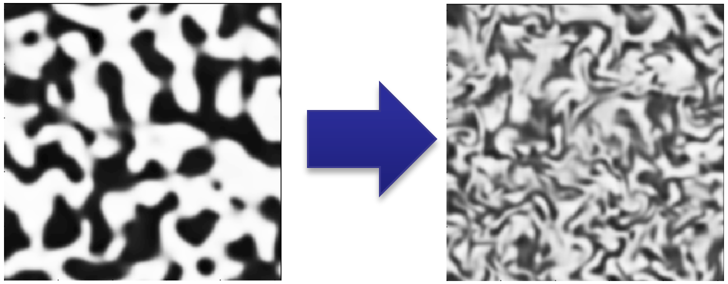
Energy in wide range of wave number decreased with phase separation.

Conclusions

- Turbulent vortex structure was more coarse in phase-separating mixture.
- Phase separation was suppressed and formed elongated structure in the presence of turbulence.



Phase separation



Turbulence

Self-organization structure can be selectively formed by turbulent field.