
Analysis of turbulent premixed **flame-wall interaction**
using simple and detailed chemistry based
Direct Numerical Simulation data

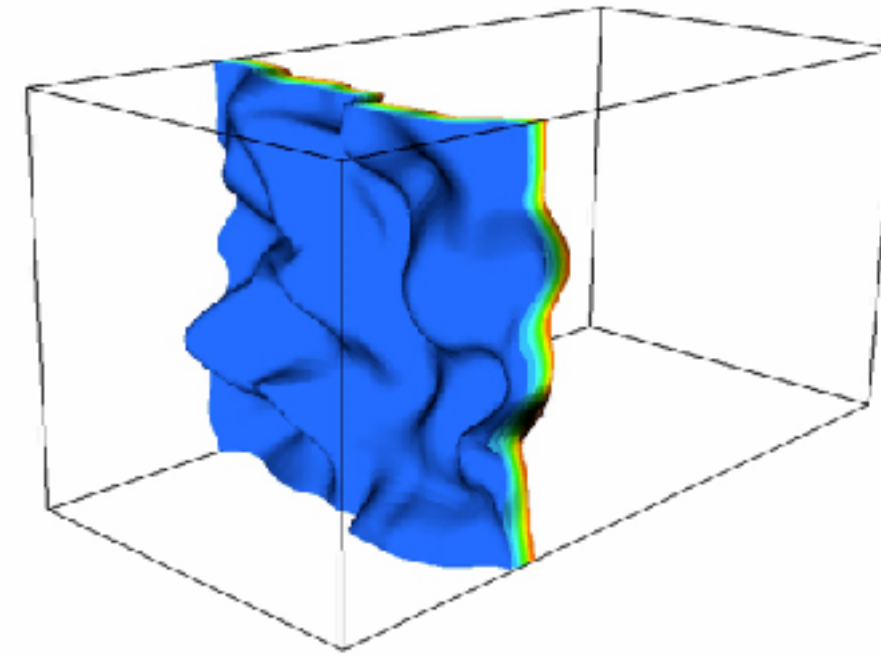
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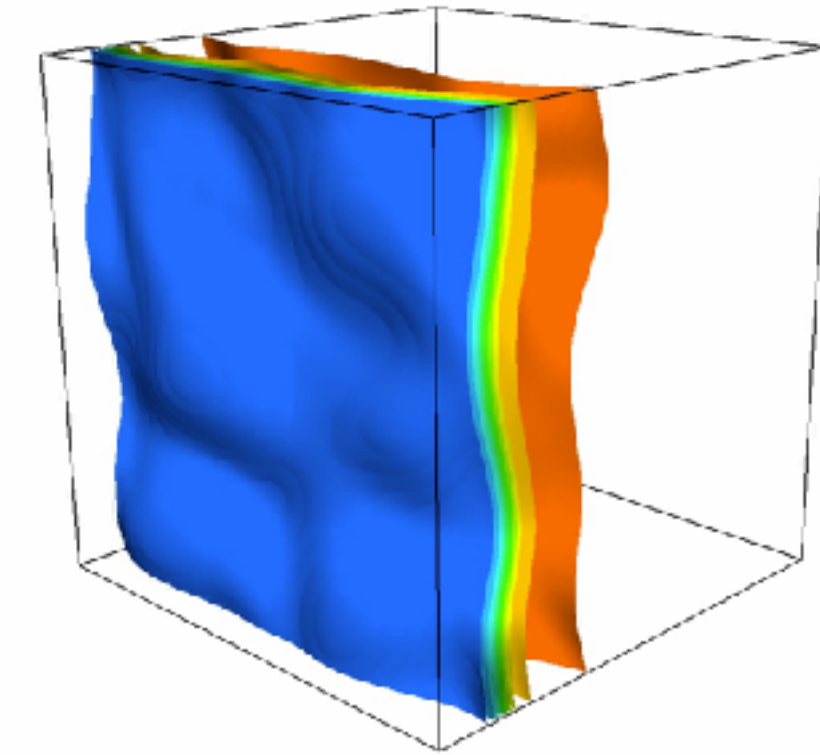
CONTENT



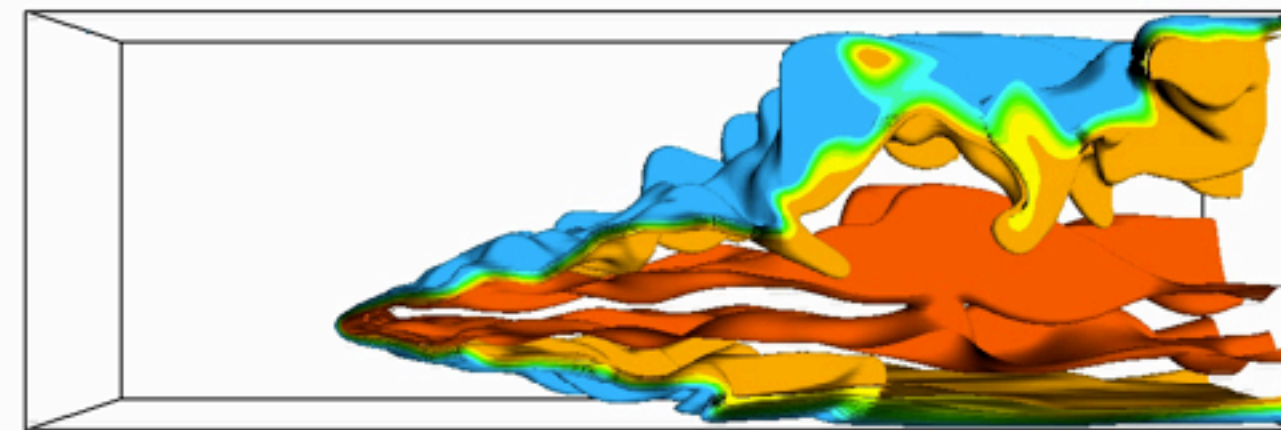
Introduction



Simple chemistry based



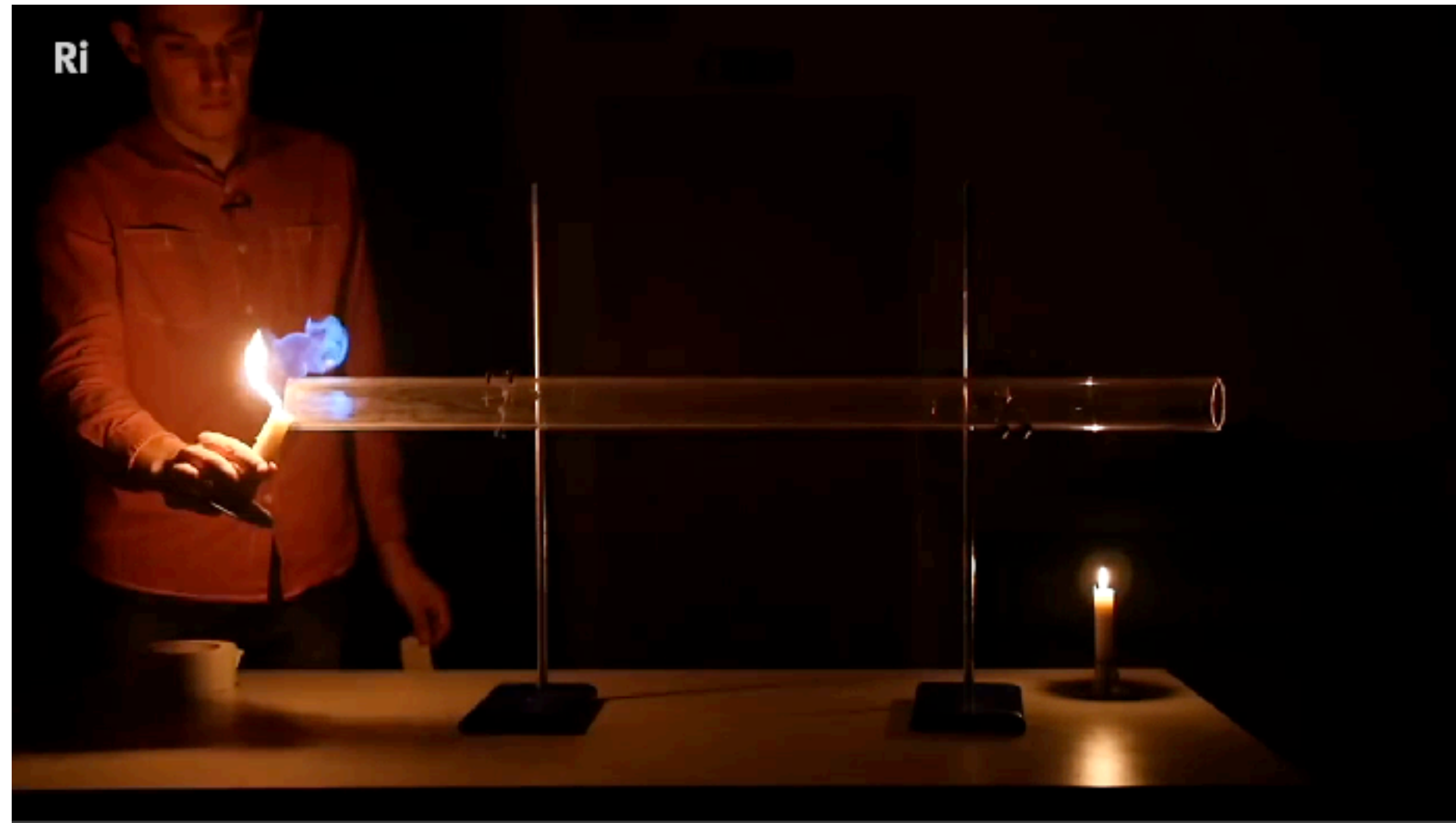
Detailed chemistry based



V-flame side-wall quenching



Conclusions



Sir Humphry Davy



- **Flame Wall Interactions**

1. **Safety technology**

2. **Gas turbine combustion**

3. **Internal Combustion (IC) engines**

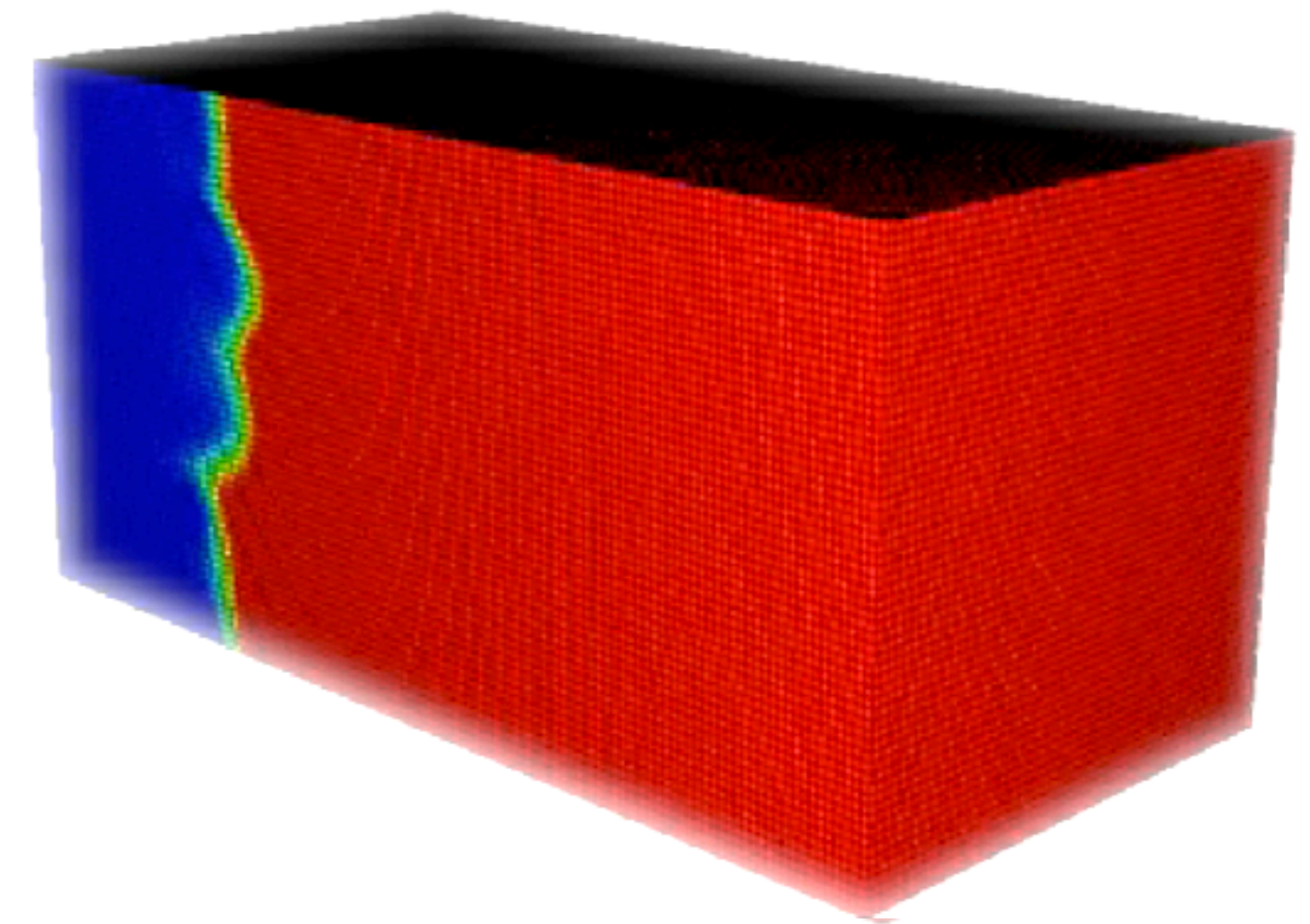
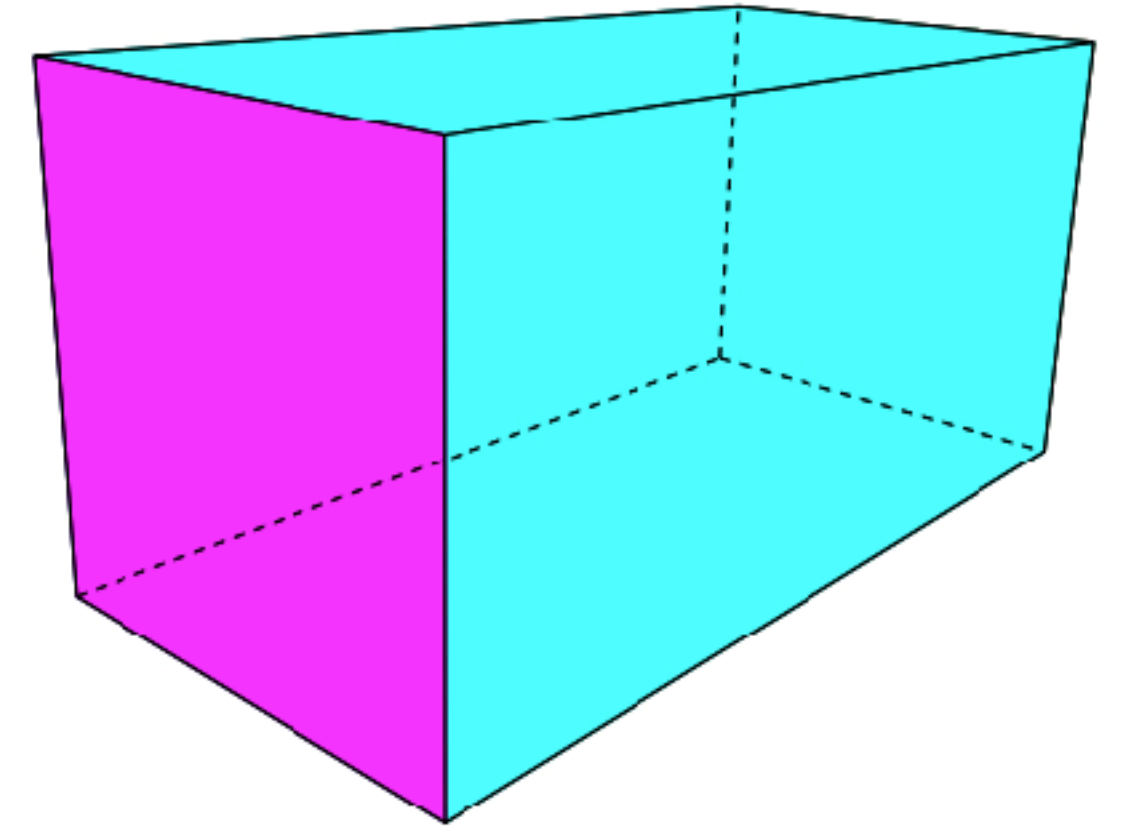
- **Modelling**

1. **Flame Surface Density (FSD)**

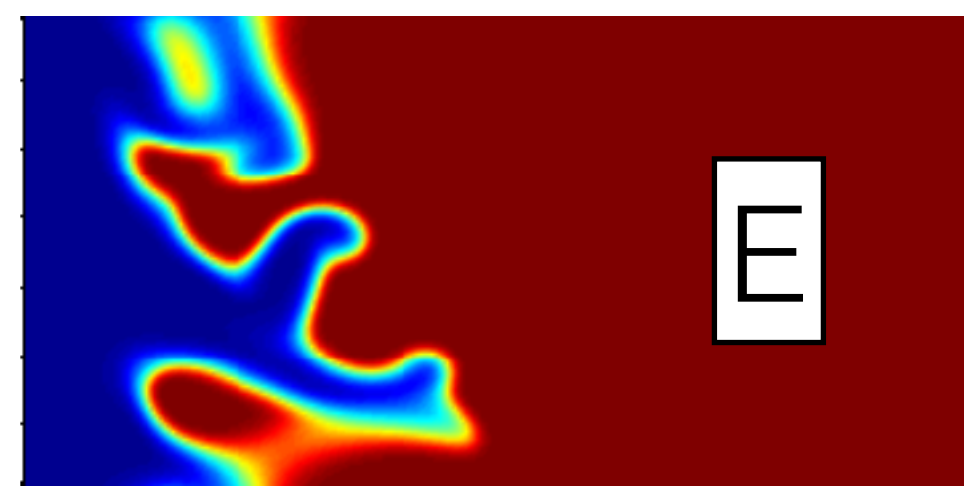
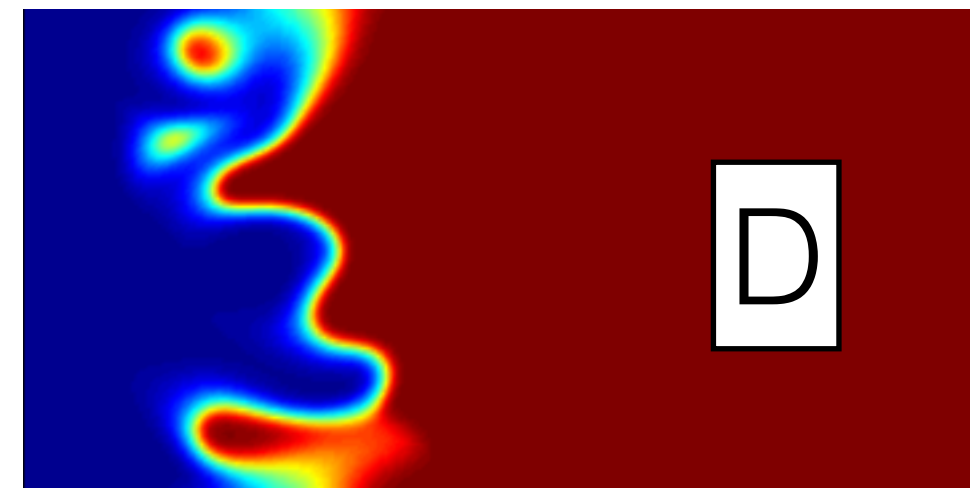
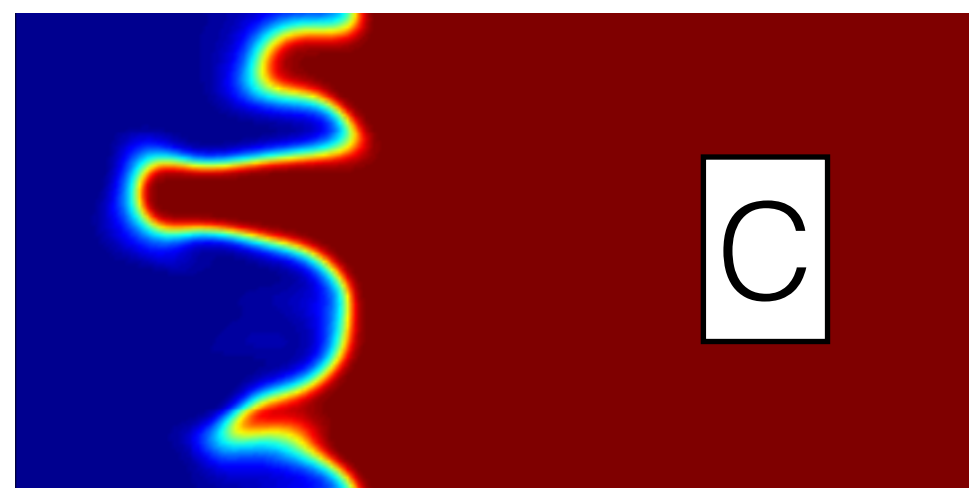
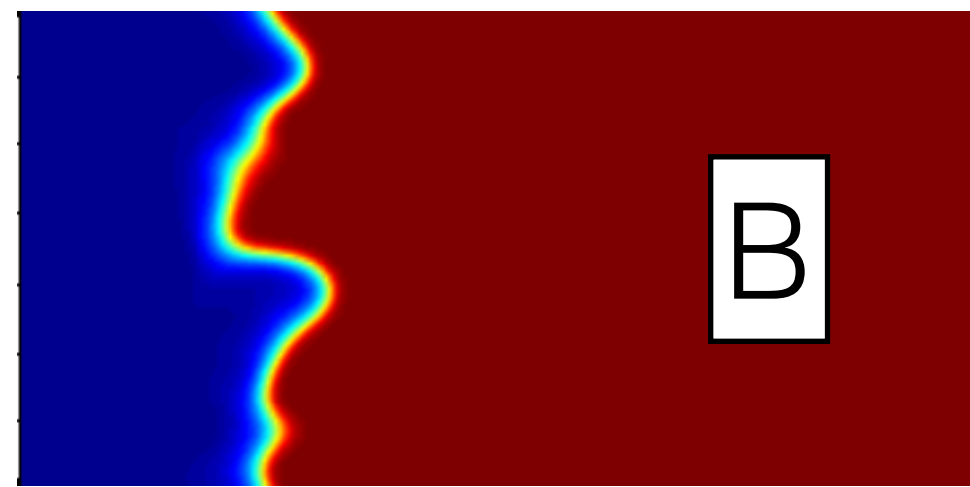
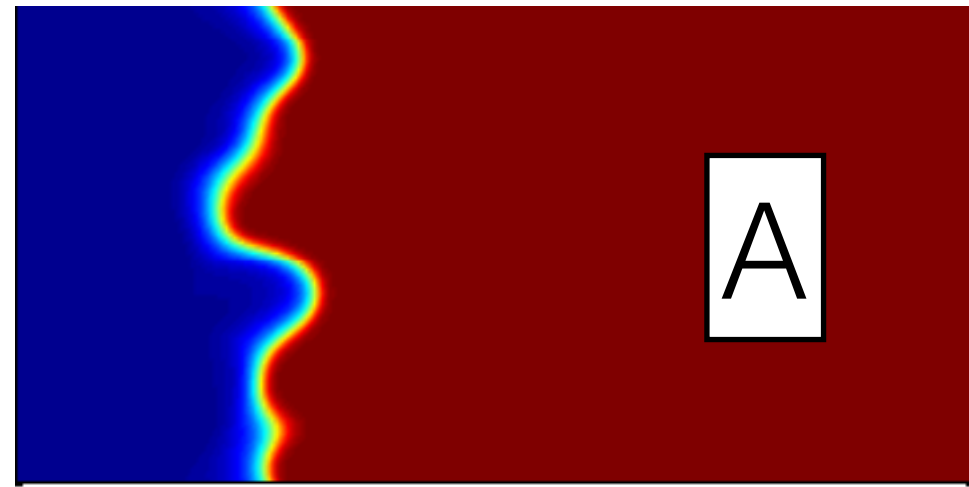
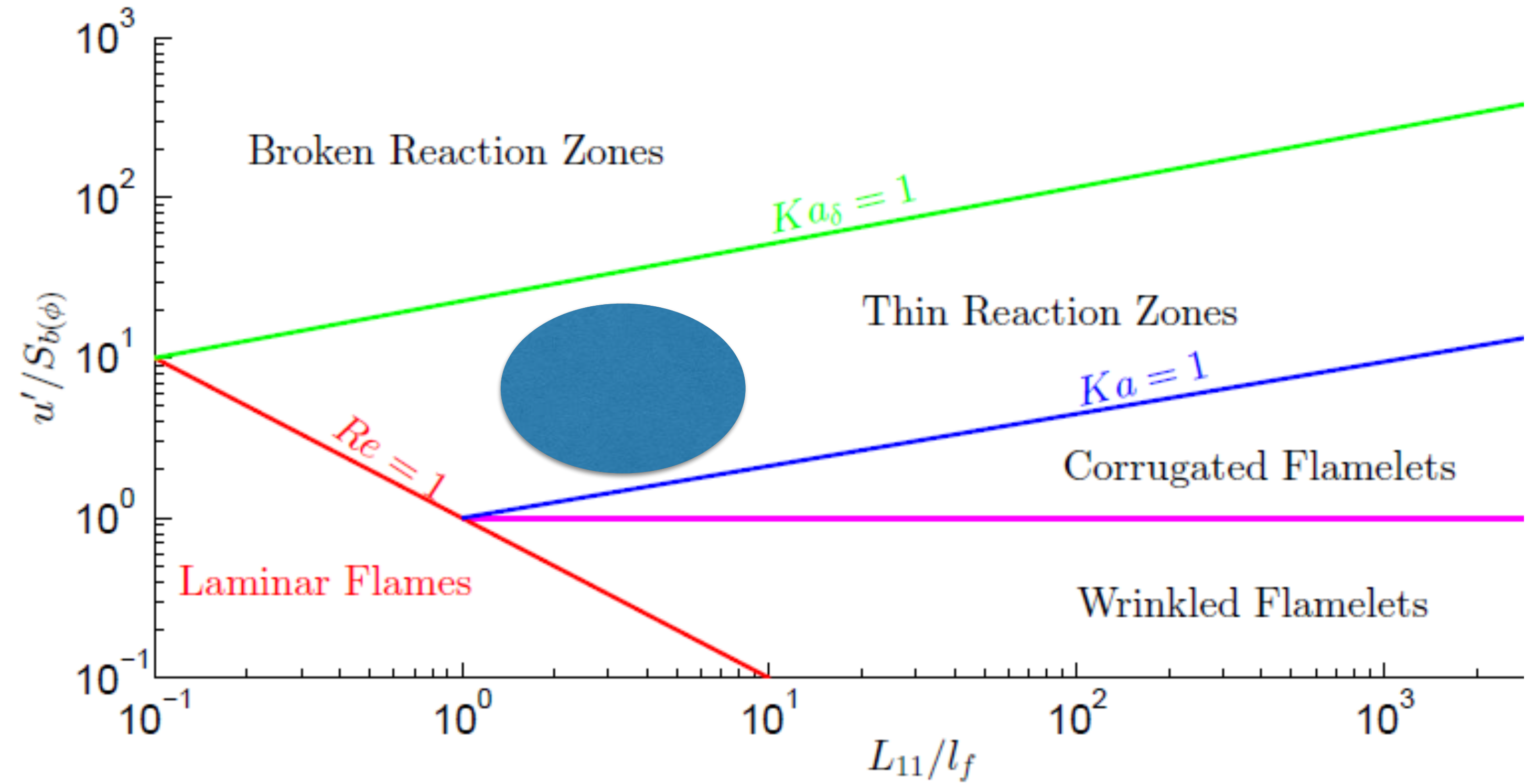
2. **Scalar Dissipation Rate (SDR)**

$$\Sigma_{gen} \quad \tilde{\epsilon}_c \quad \tilde{c}''^2 \quad \overline{\rho u_i'' c''} \quad \tilde{k} \quad \bar{\Omega}$$

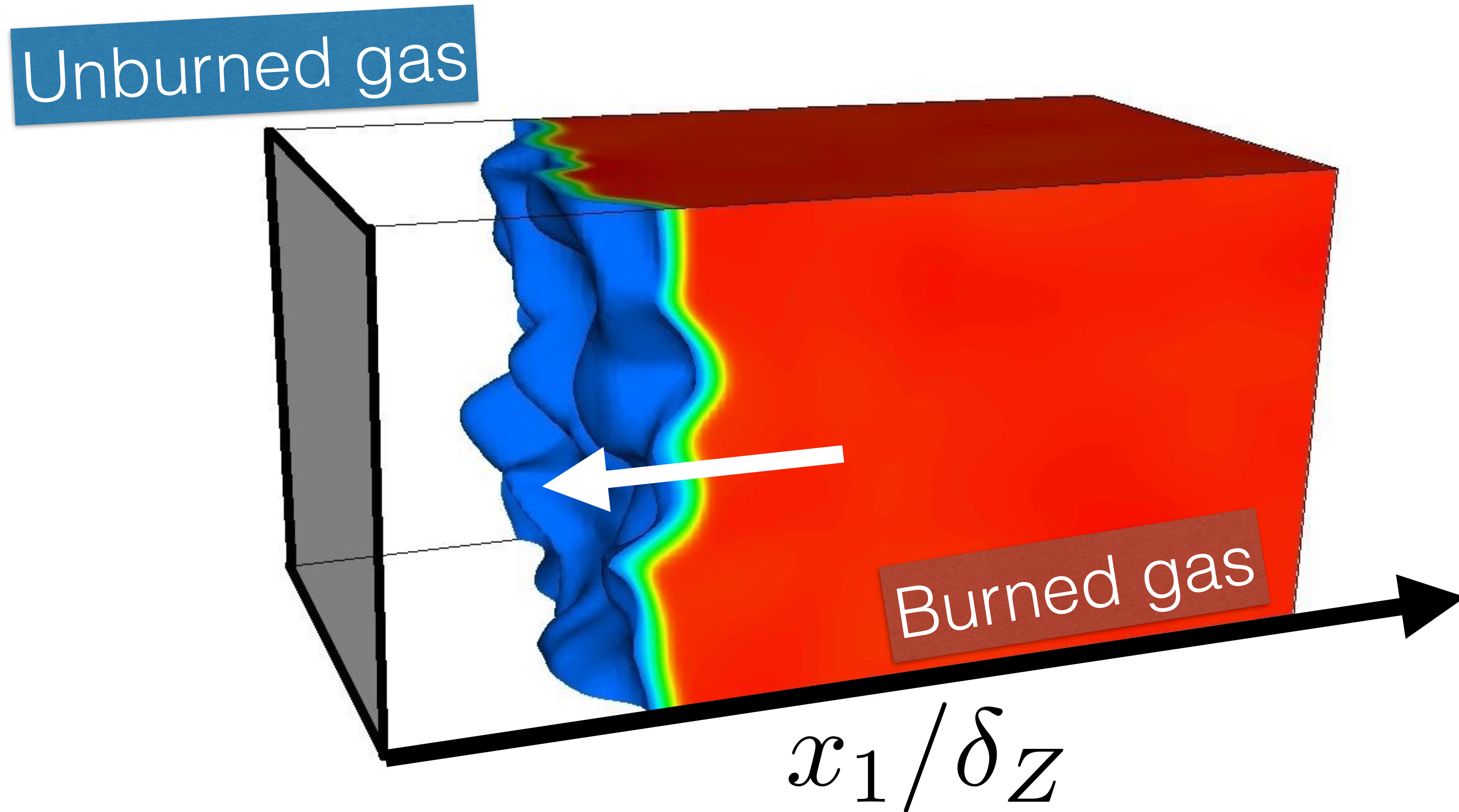
- Compressible 3D DNS **SENGA** [1]
- Cartesian grid: $7056\delta_z \times 350\delta_z \times 236.2\delta_z$
- **No-slip isothermal wall** with temperature $T_w=T_0$,
Zero mass flux is enforced in the wall normal direction
- **Periodic** in transverse directions
- **Partial non-reflecting outlet** specified by Navier-Stokes characteristic boundary condition (NSCBC) technique.
- Initialised: Unstrained steady planar laminar flame +
Initially homogenous isotropic field of turbulent velocity



Case	A	B	C	D	E
u' / S_L	5.0	6.25	7.5	9.0	11.25
L_{11} / δ_{th}	1.67	1.44	2.5	4.31	3.75
Da	0.33	0.23	0.33	0.48	0.33
Ka	8.65	13.0	13.0	13.0	19.5



(Peters, N. 2000)

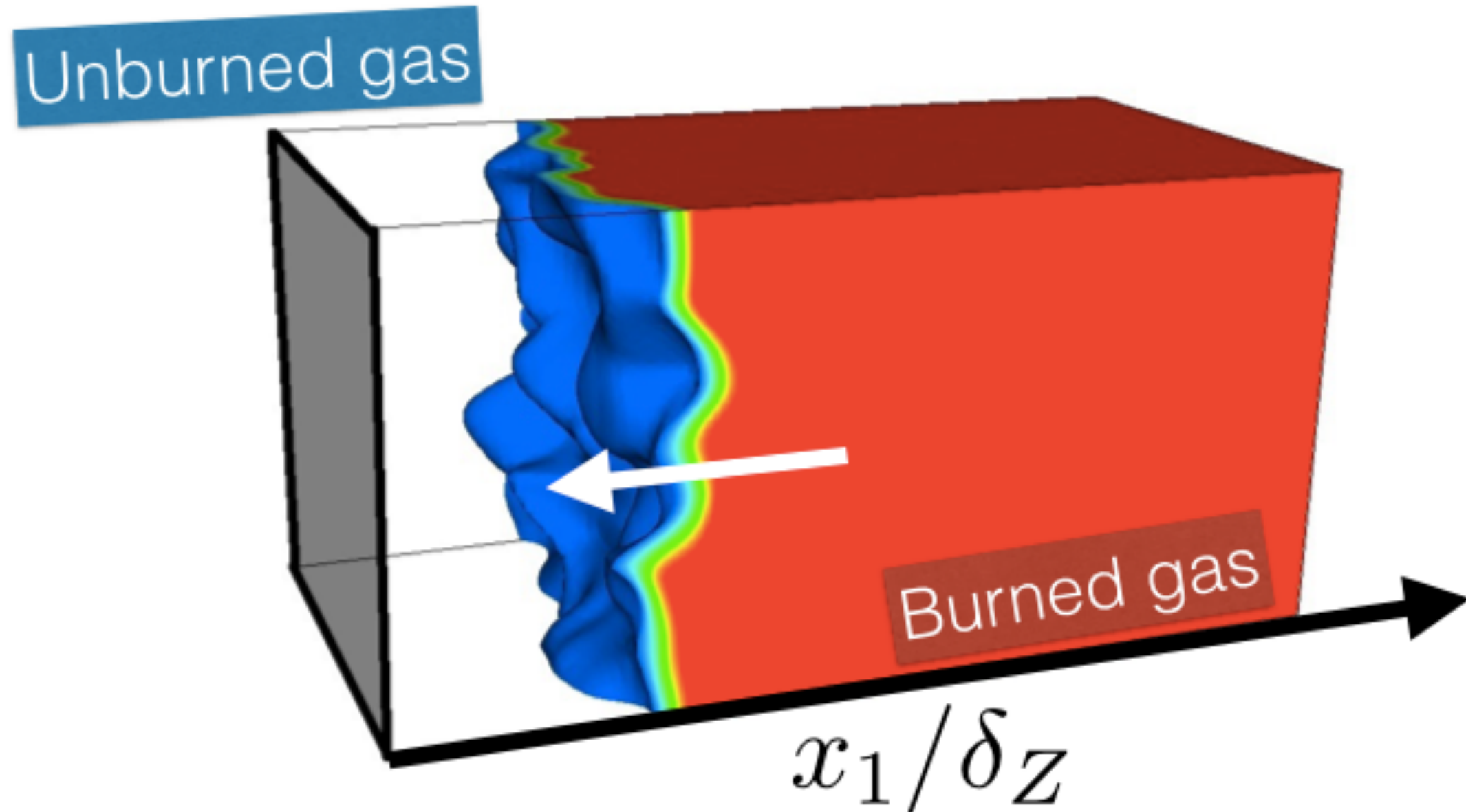


Peclet number:

$$Pe = X / \delta_Z$$

Non-dimensional wall heat flux:

$$\Phi = \frac{|q_w|}{\rho_0 S_L C_P (T_{ad} - T_0)}$$



Peclet number:

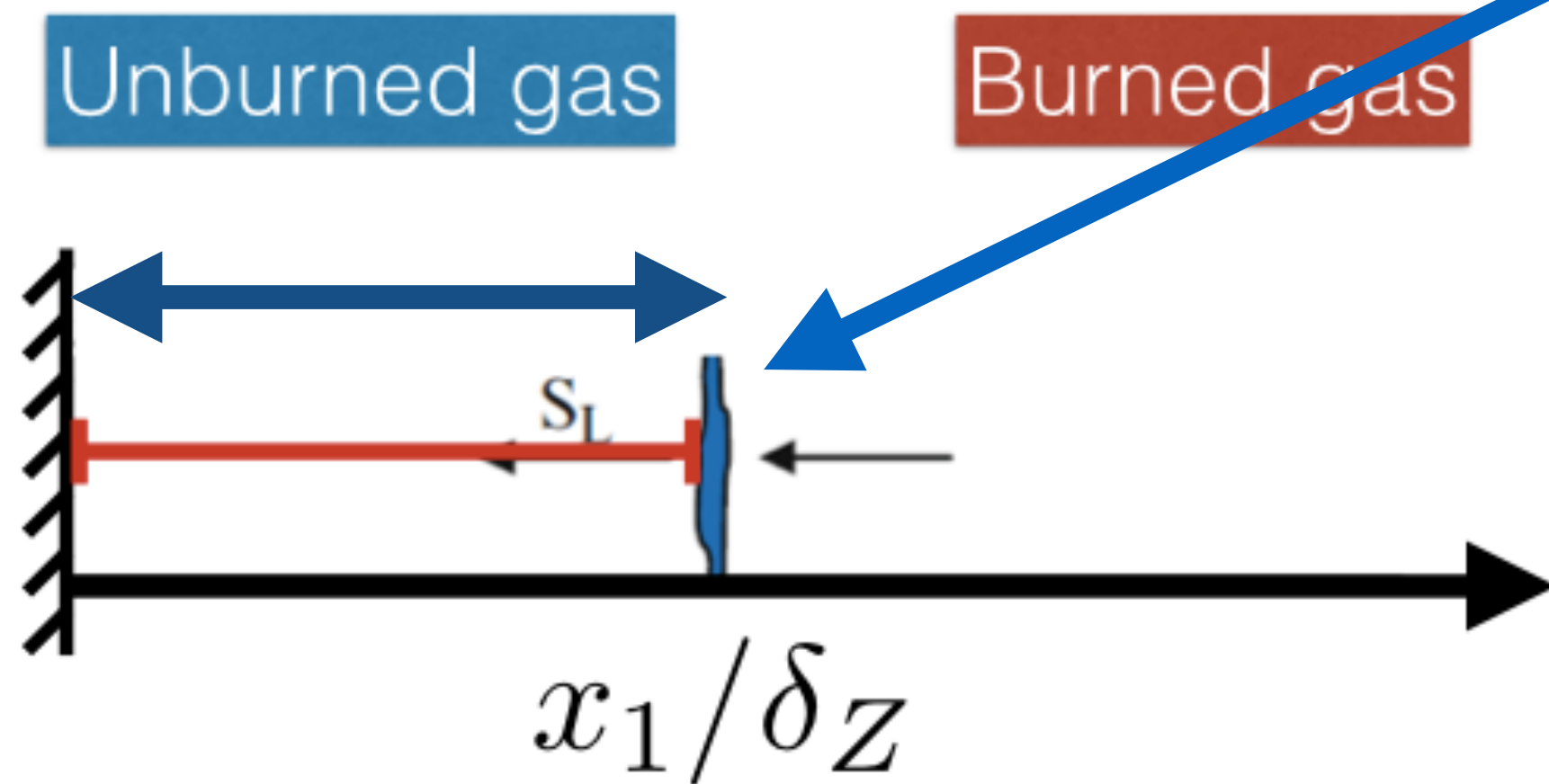
$$Pe = X/\delta_z$$

Iso-surface

$$T = 0.9$$

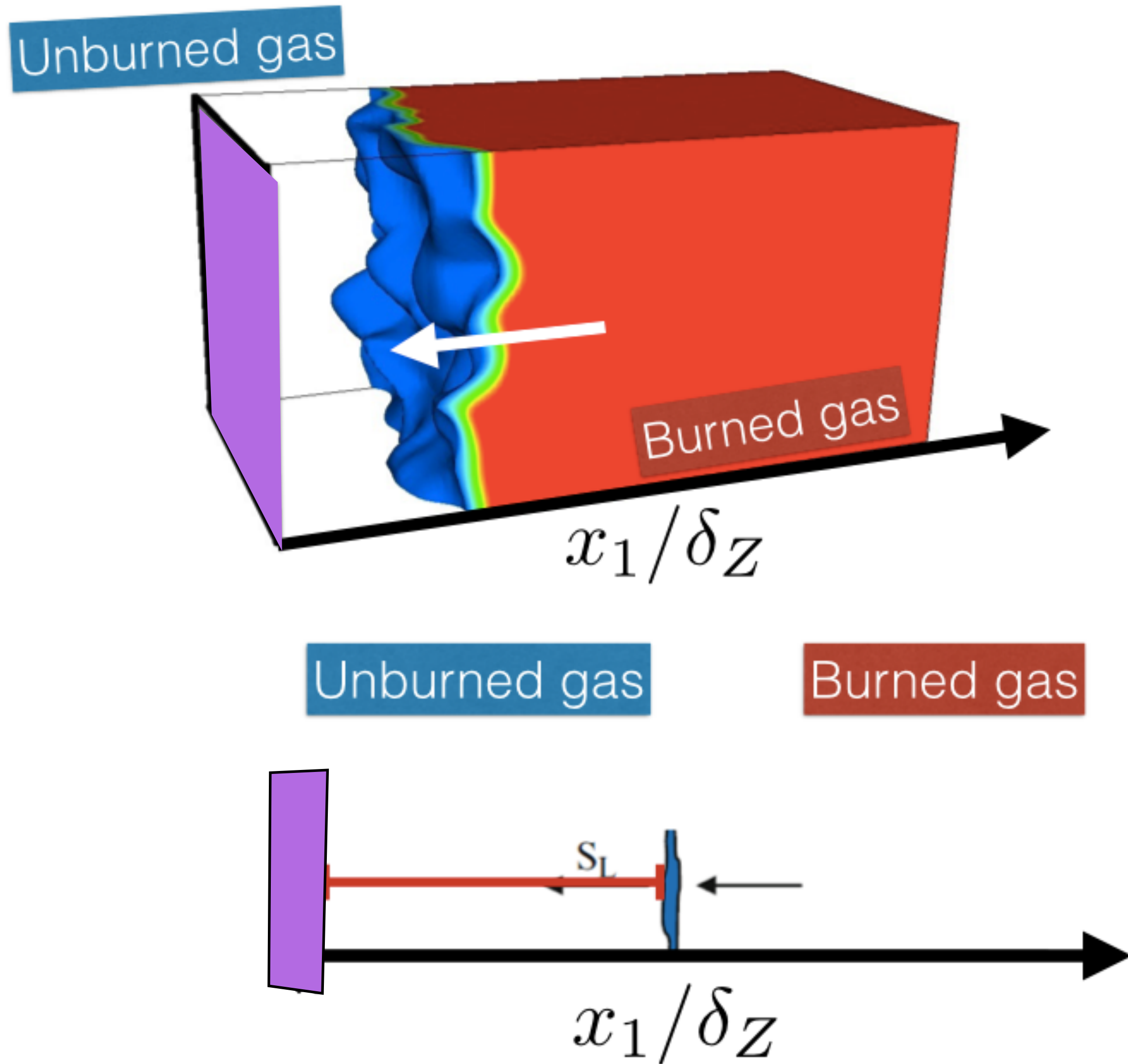
Non-dimensional wall heat flux:

$$\Phi = \frac{|q_w|}{\rho_0 S_L C_P (T_{ad} - T_0)}$$



Non-dimensional temperature

$$T = \frac{\hat{T} - T_0}{T_{ad} - T_0}$$



Peclet number:

$$Pe = X/\delta_Z$$

Non-dimensional wall heat flux:

$$\Phi = \frac{|q_w|}{\rho_0 S_L C_P (T_{ad} - T_0)}$$

Wall heat flux

$$q_w = -\lambda \left(\frac{\partial \hat{T}}{\partial x_1} \right)_w$$

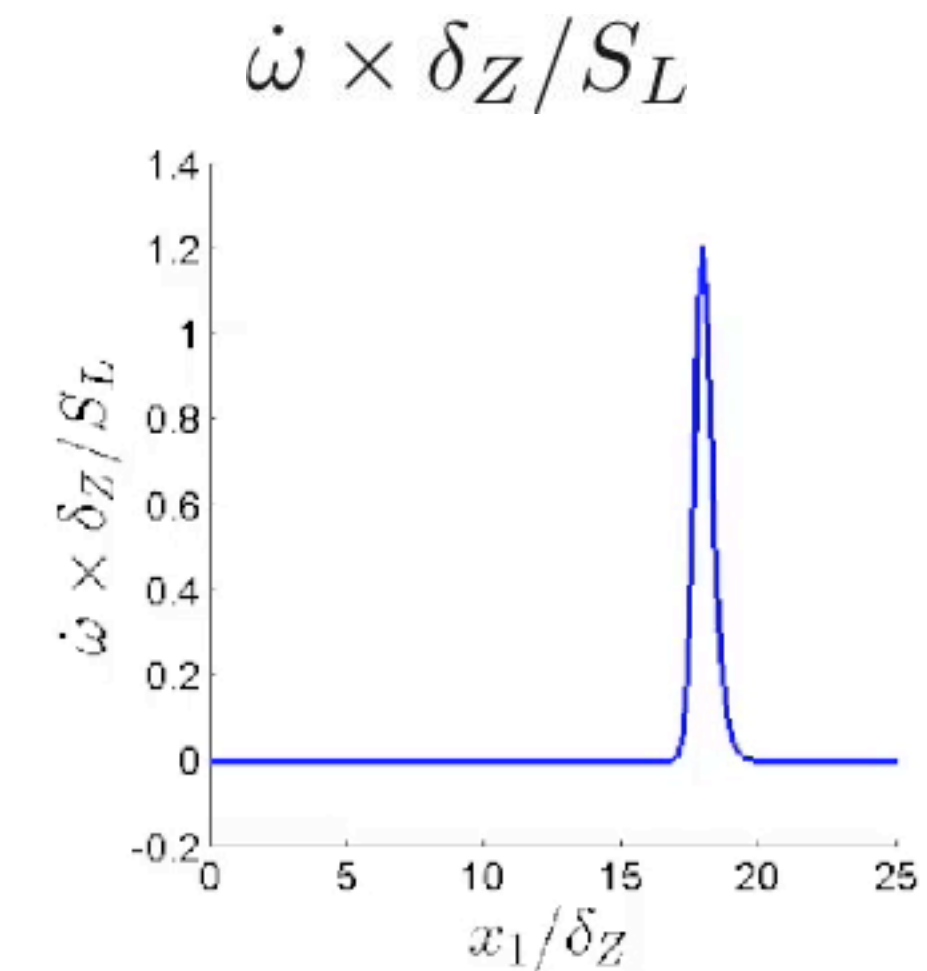
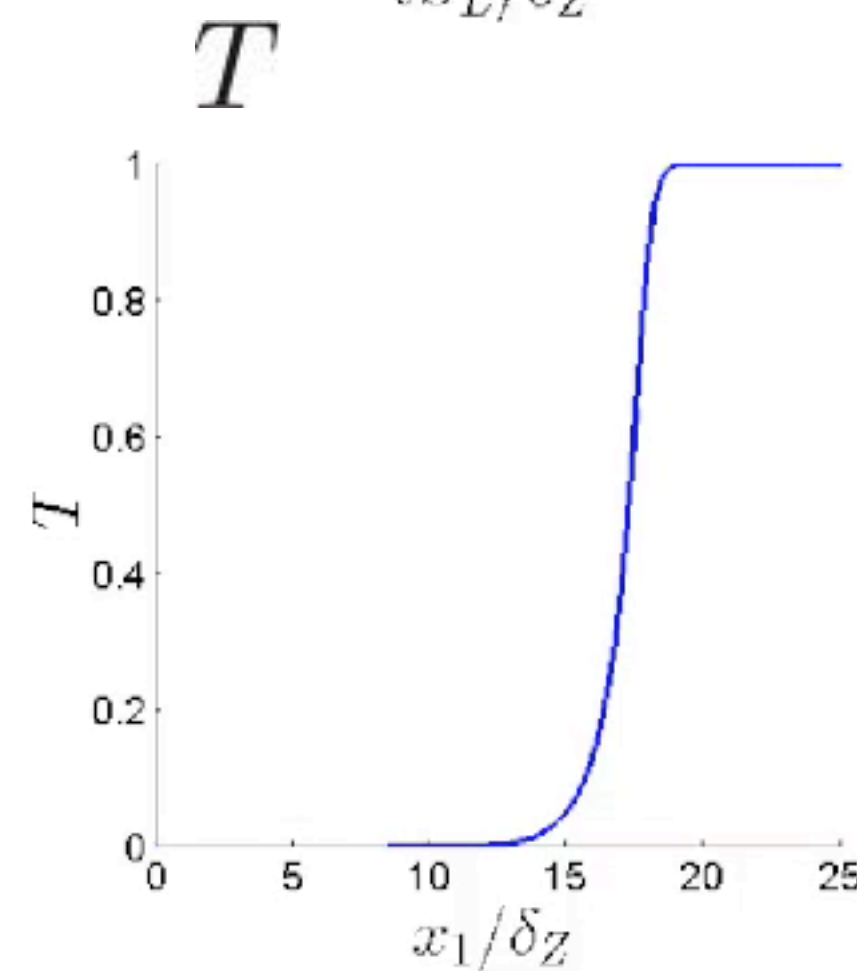
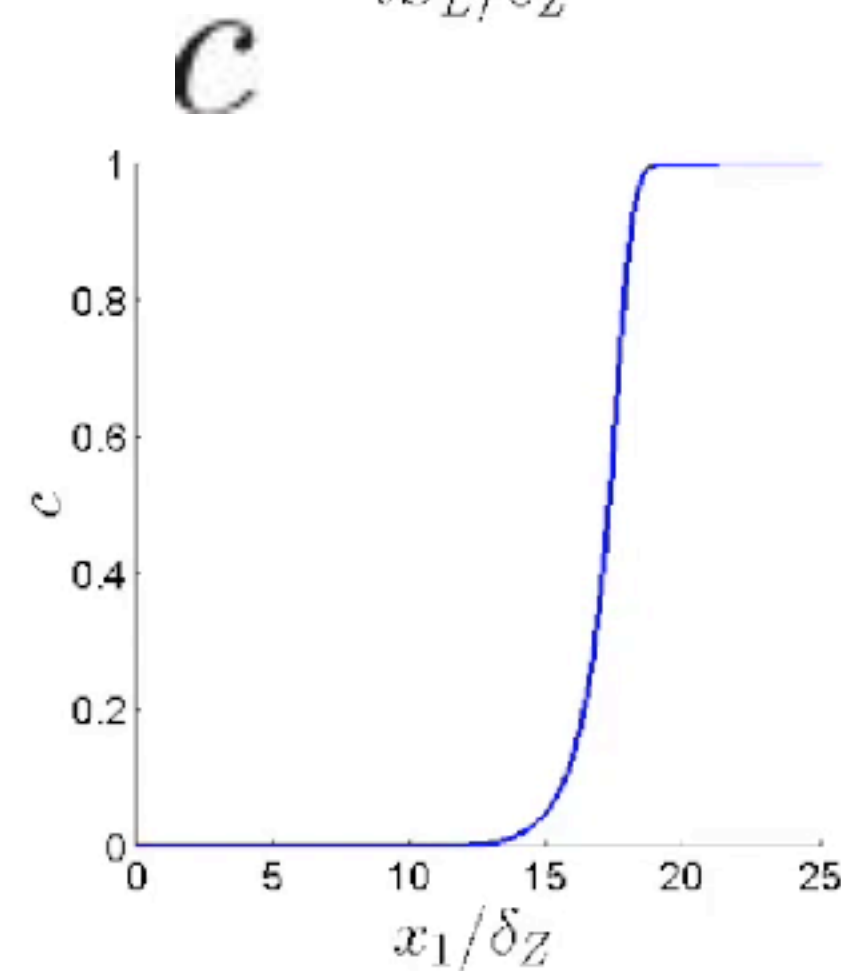
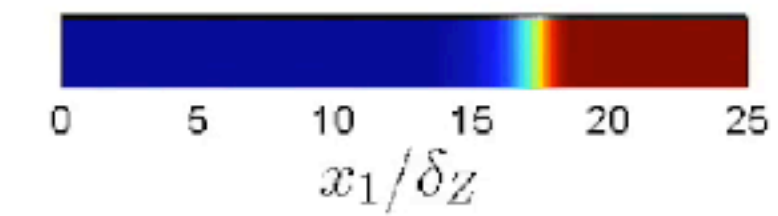
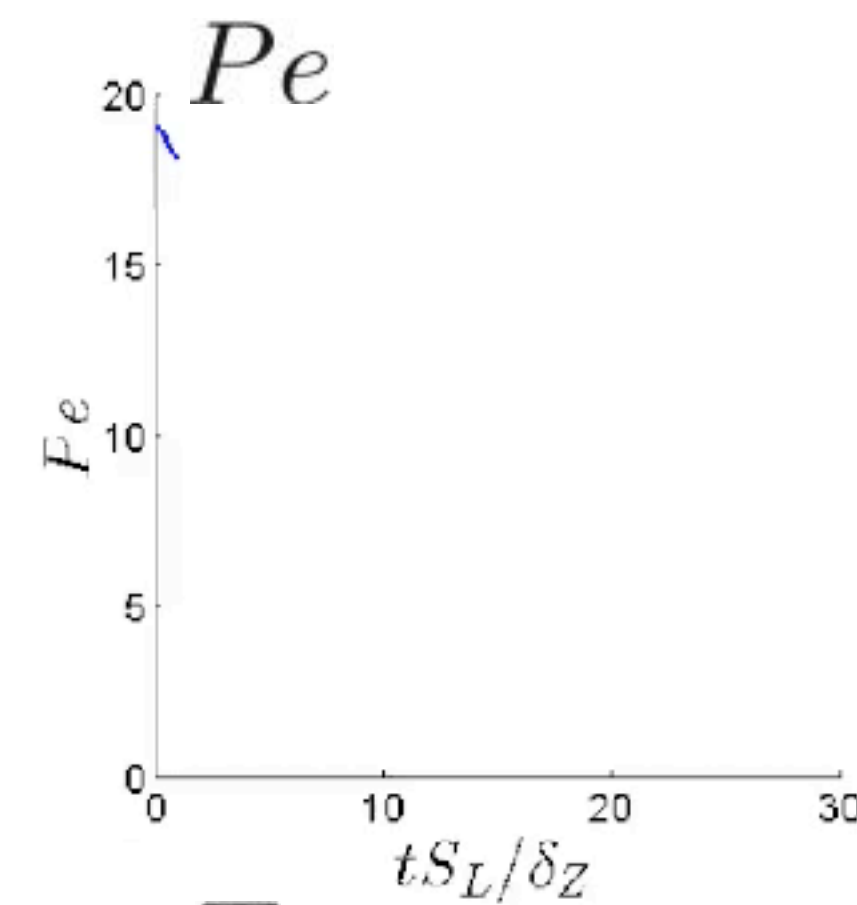
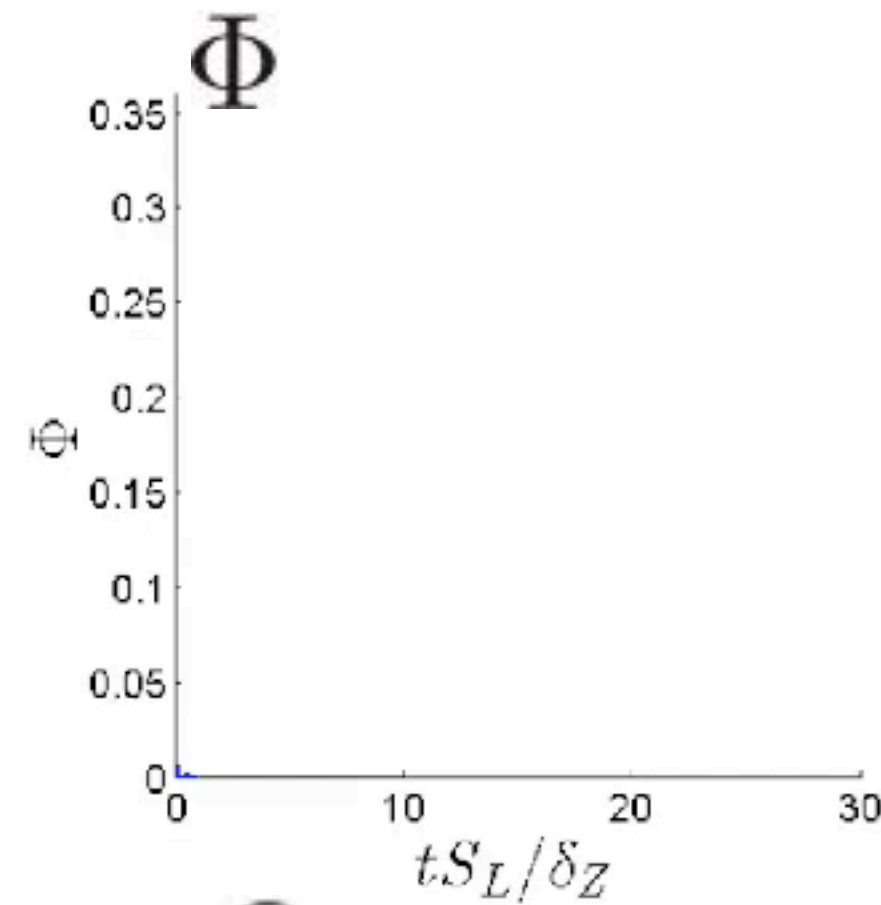


1D laminar flame

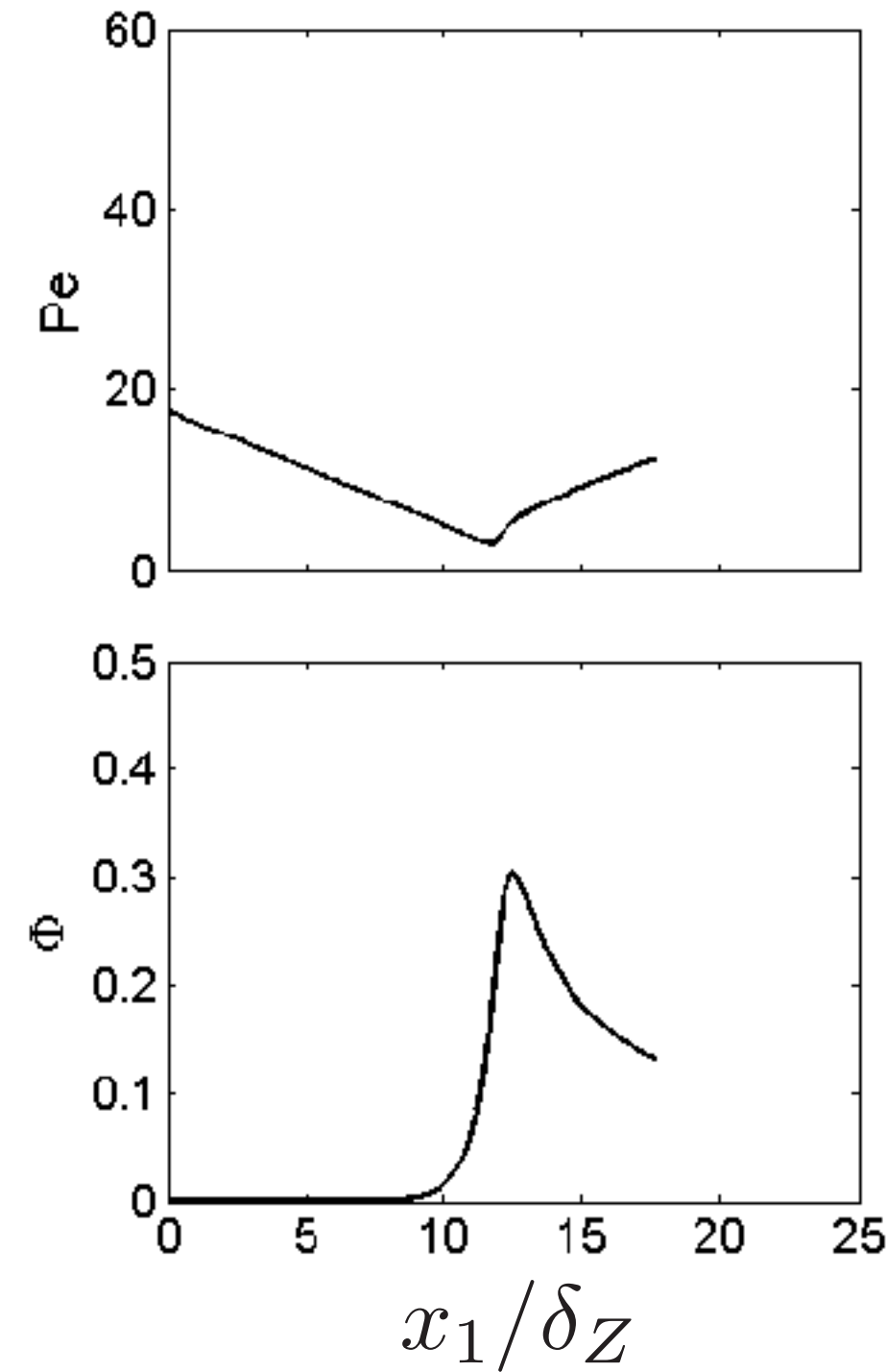
$$Pe_{min} = 2.83$$

$$\Phi_{max} = 0.34$$

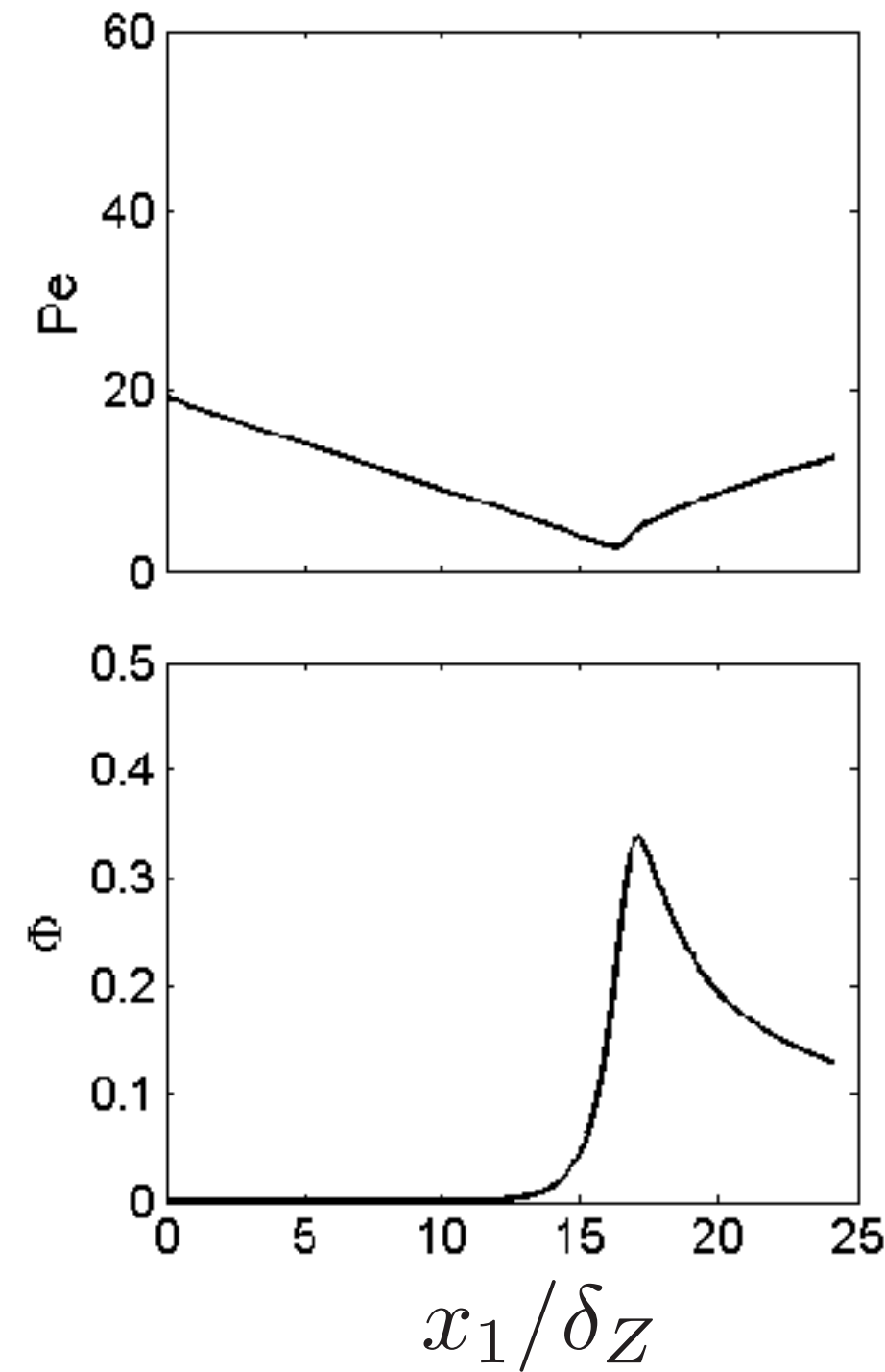
(Poinsot *et al.* 1993; Huang *et al.* 1986; Jarosinsky, 1986; Vosen *et al.* 1984.)



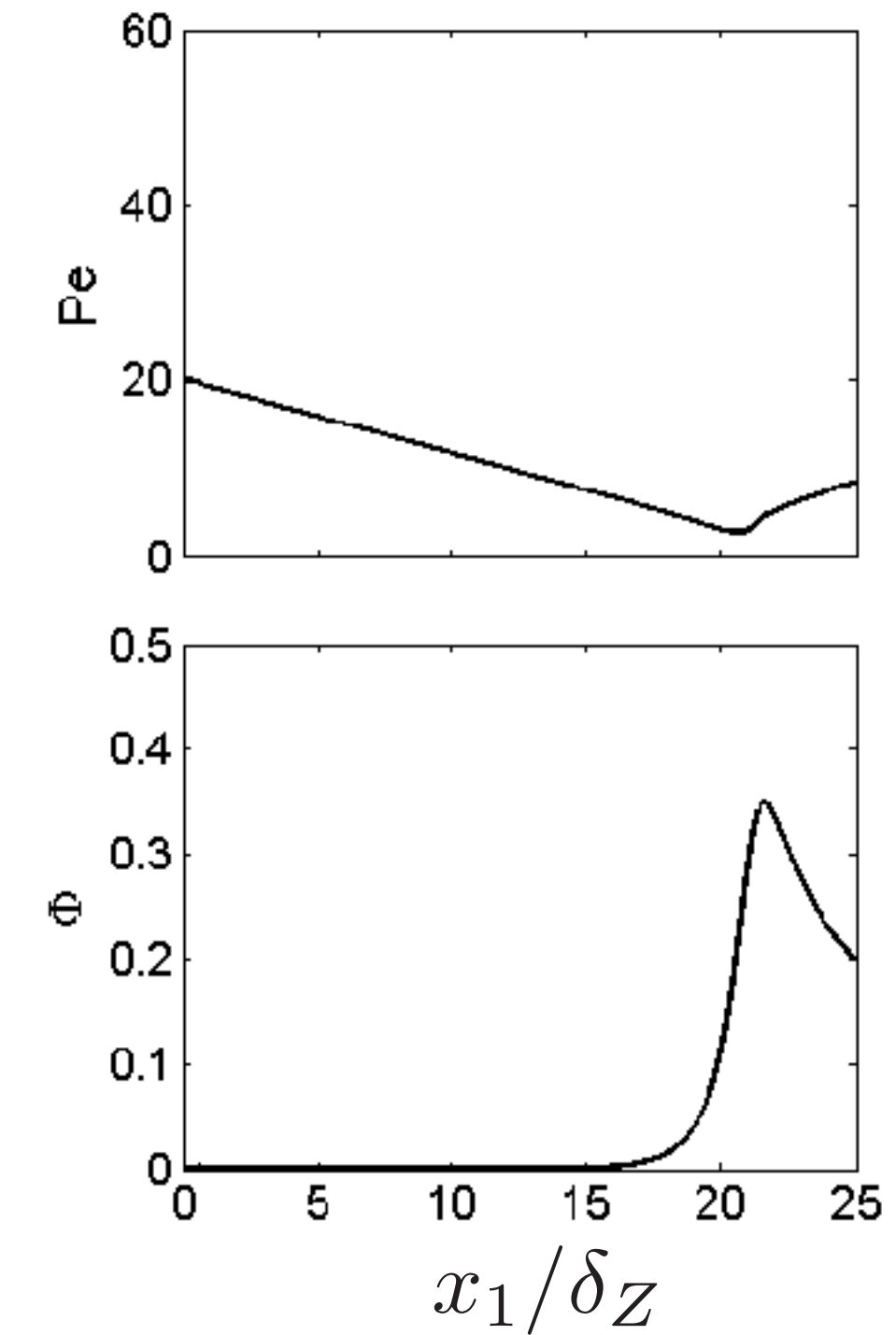
$Le = 0.8$



$Le = 1.0$



$Le = 1.2$

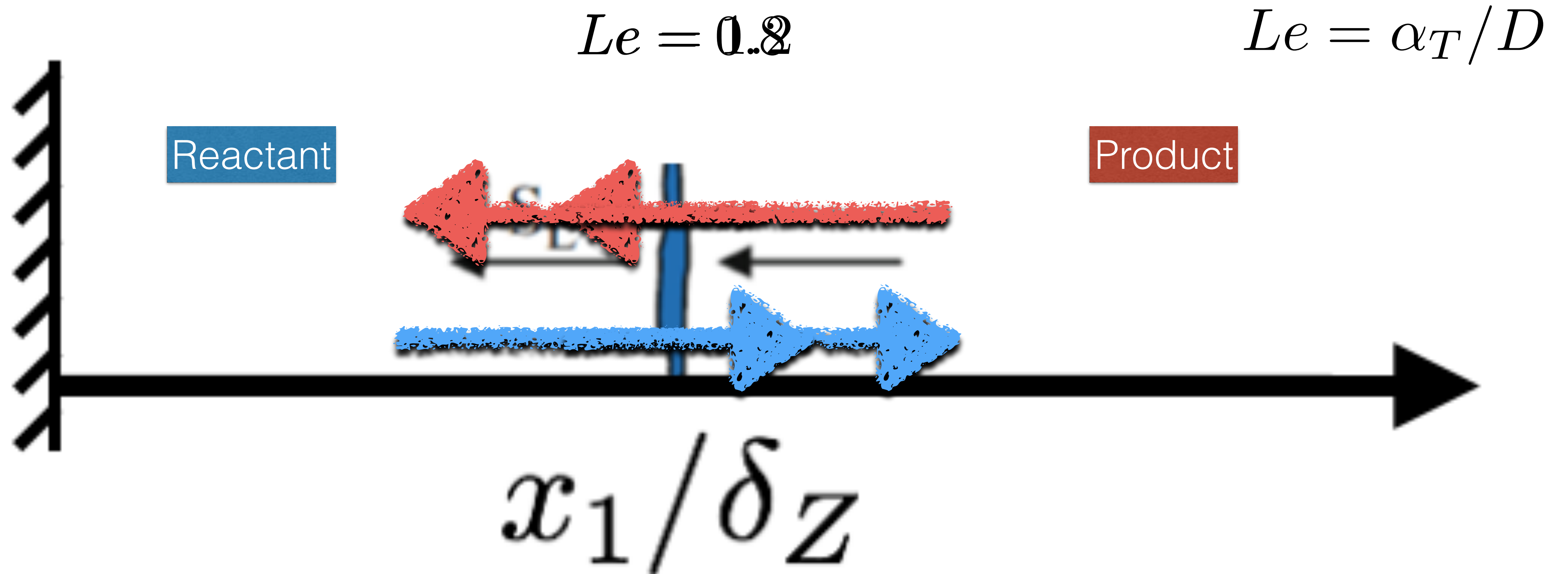


Laminar $Pe_{min} = 3.09$
 $\Phi_{max} = 0.30$

$Pe_{min} = 2.83$
 $\Phi_{max} = 0.34$

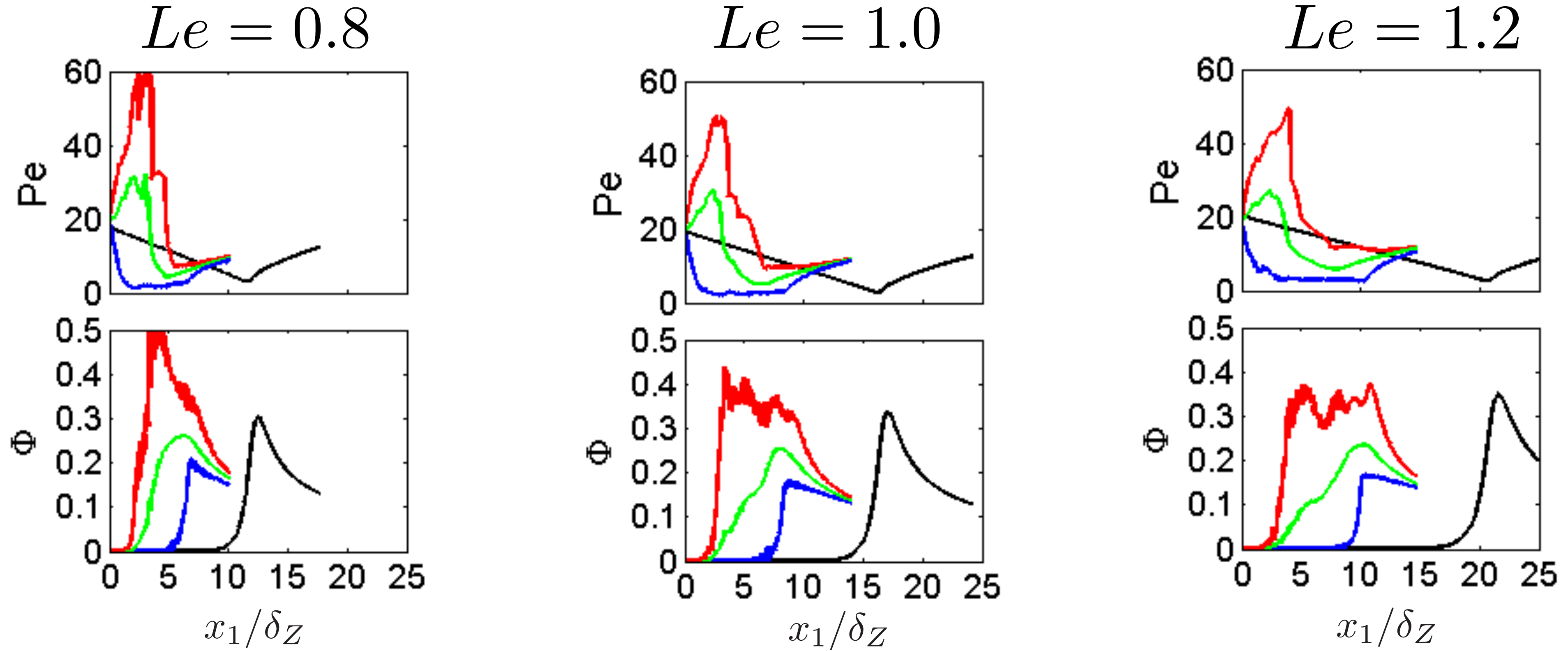
$Pe_{min} = 2.75$
 $\Phi_{max} = 0.35$

— laminar; — max; — mean; — minimum



Laminar	$Pe_{min} = 3.09$	$Pe_{min} = 2.83$	$Pe_{min} = 2.75$
	$\Phi_{max} = 0.30$	$\Phi_{max} = 0.34$	$\Phi_{max} = 0.35$

— laminar; — max; — mean; — minimum



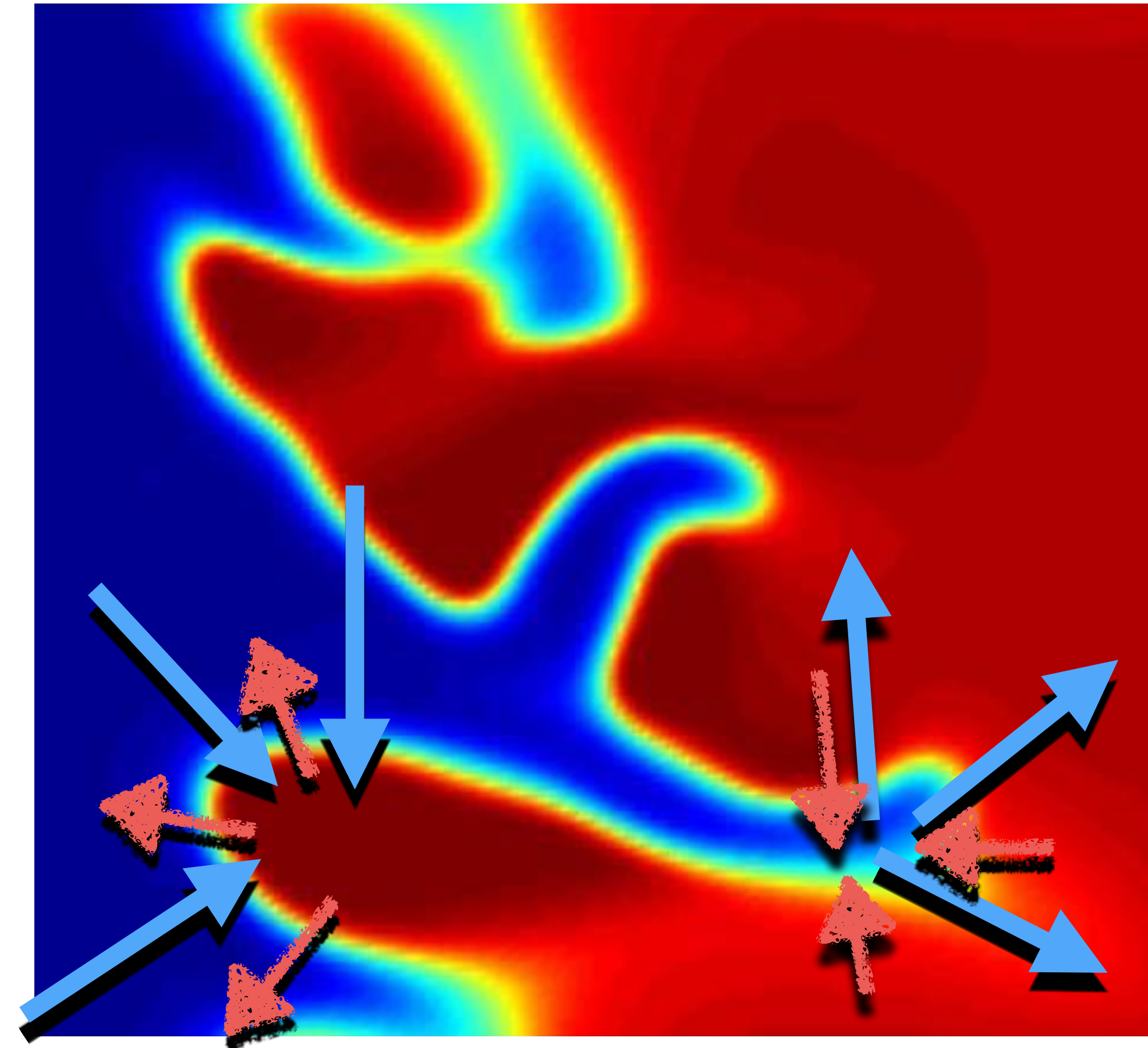
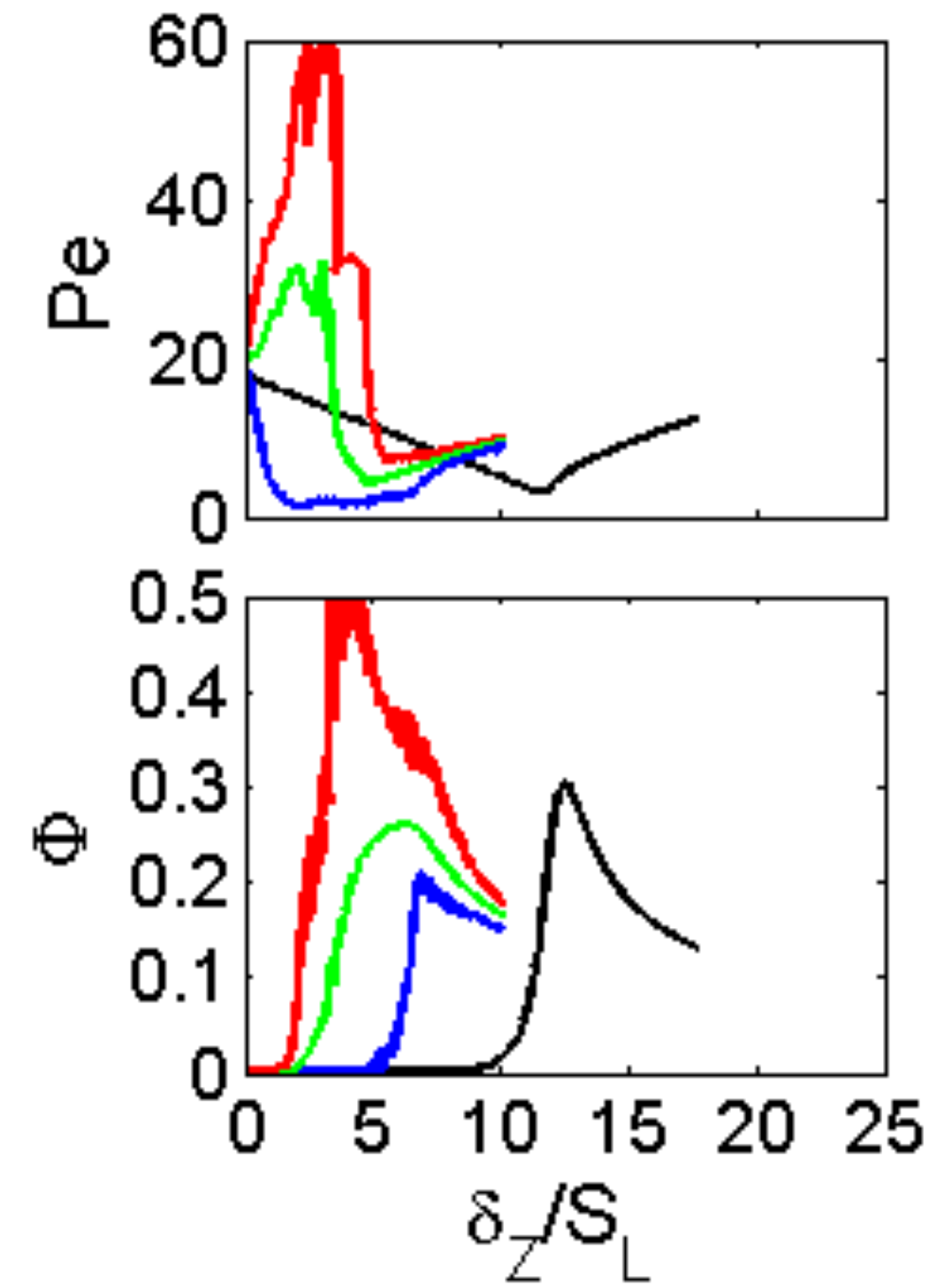
Laminar	$Pe_{min} = 3.09$	$Pe_{min} = 2.83$	$Pe_{min} = 2.75$
	$\Phi_{max} = 0.30$	$\Phi_{max} = 0.34$	$\Phi_{max} = 0.35$

— laminar; — max; — mean; — minimum

Temperature Contour



Le = 0.8



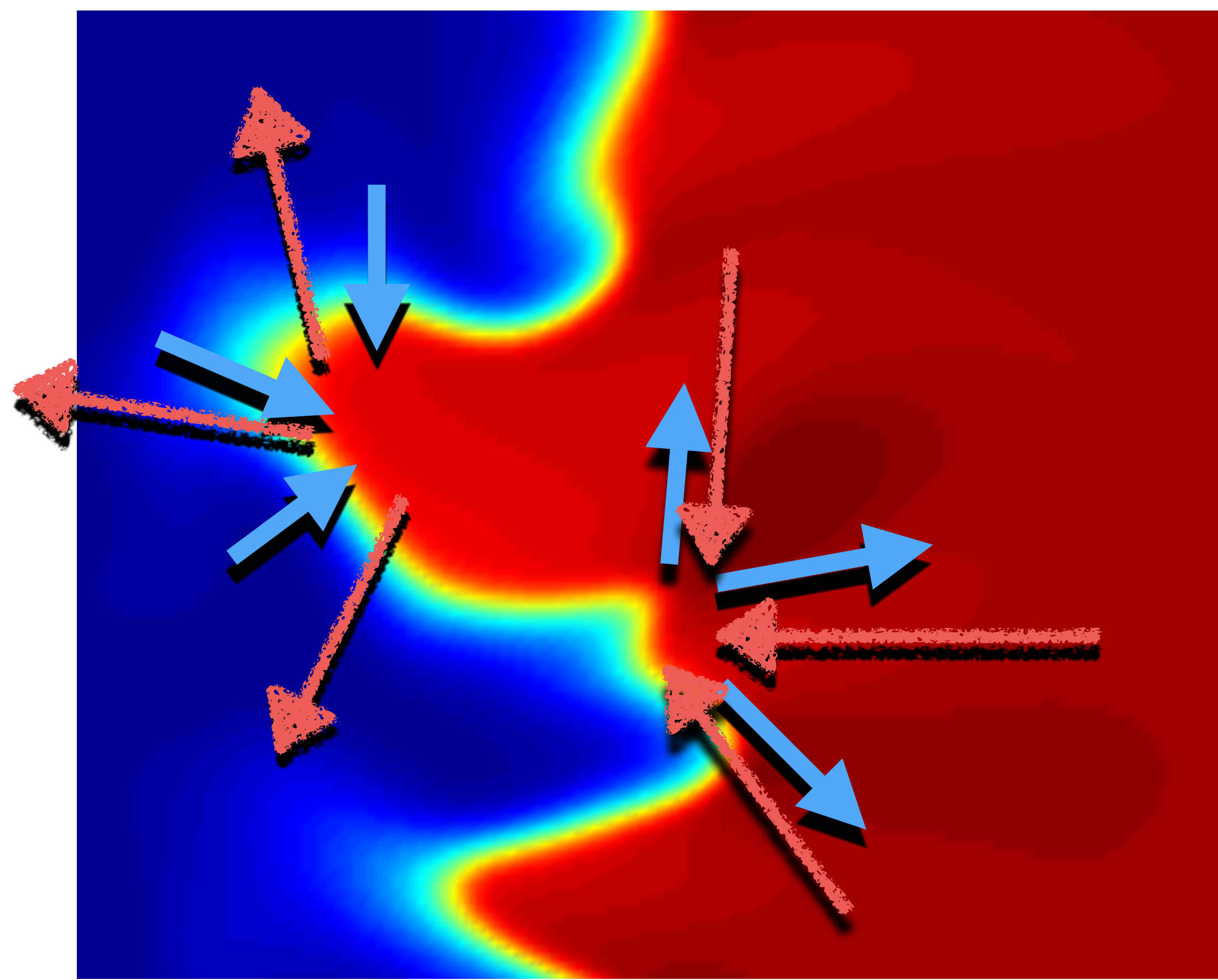
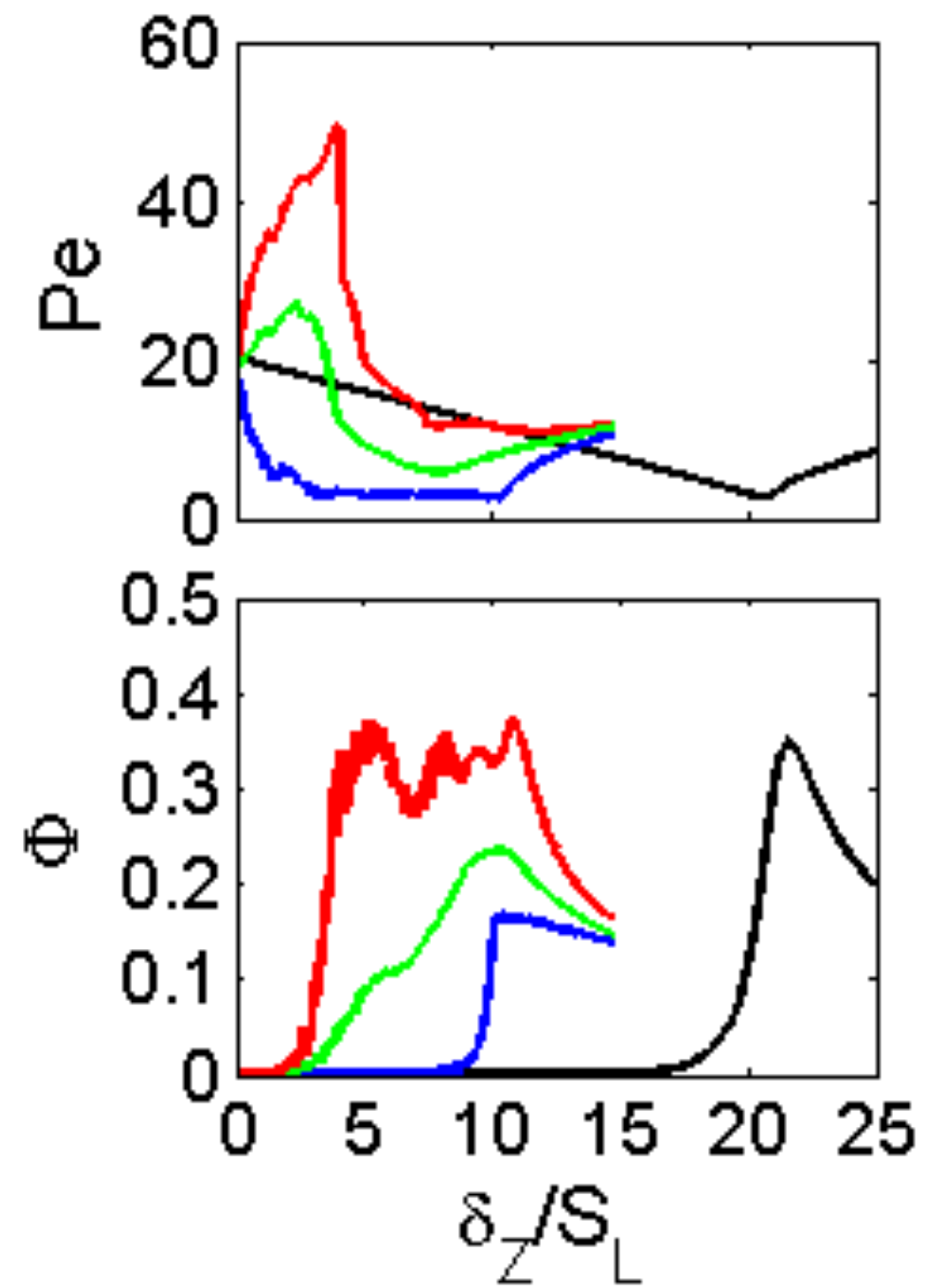
$$Le = \frac{\alpha_T}{D}$$

— laminar; — max; — mean; — minimum

Temperature Contour

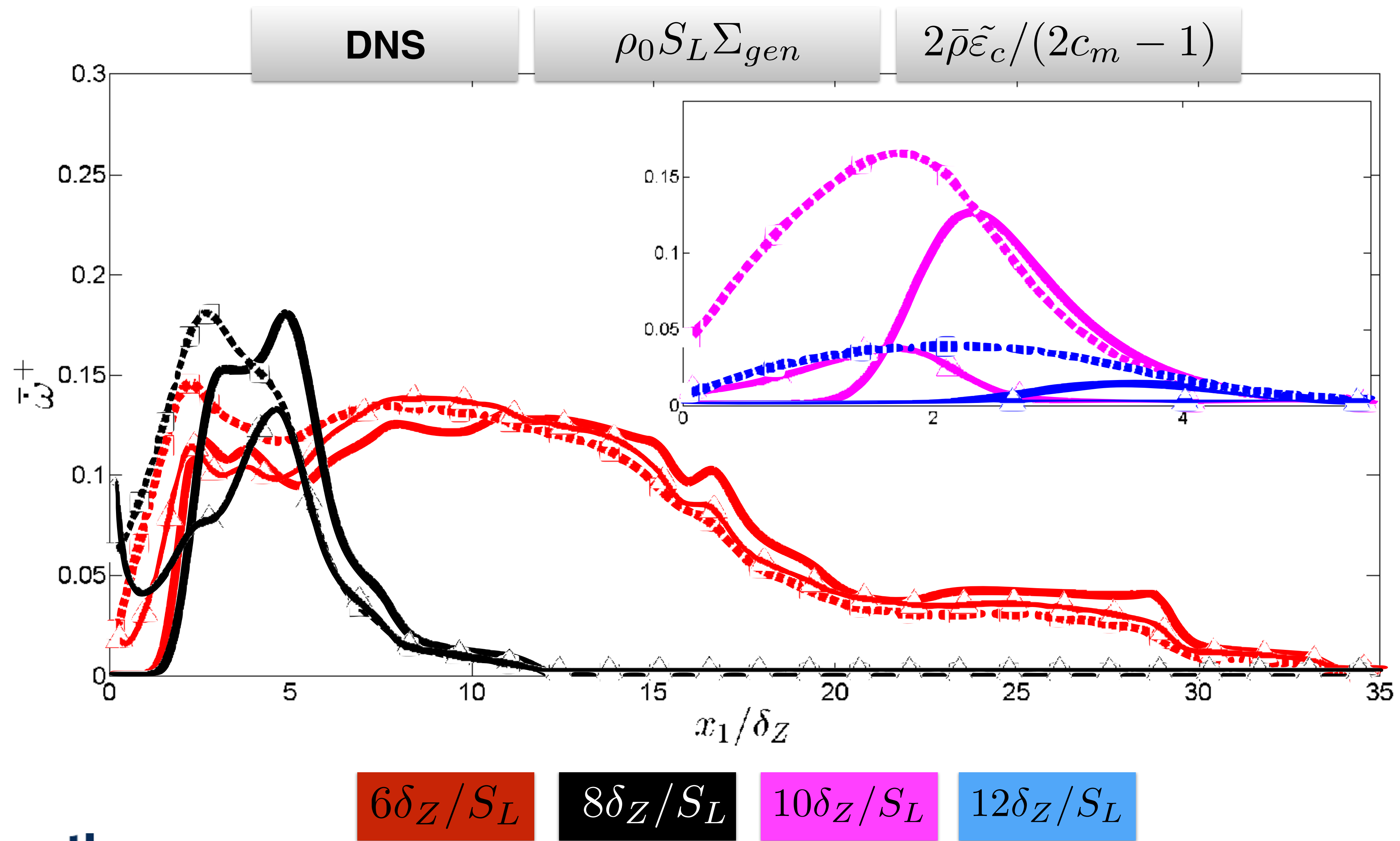


Le = 1.2



$$Le = \frac{\alpha T}{D}$$

— laminar; — max; — mean; — minimum



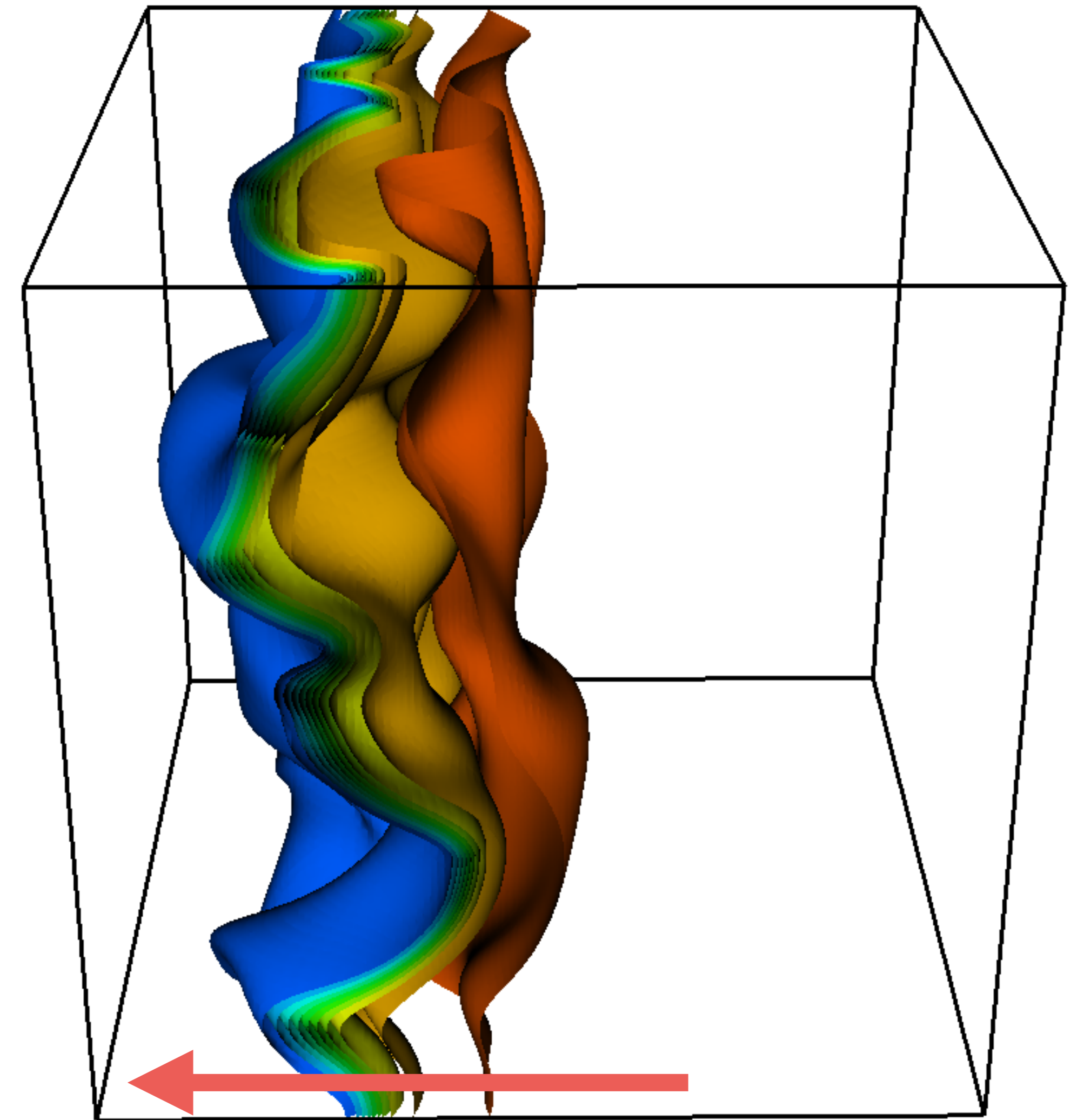
New model of mean reaction rate:

$$\bar{\omega} = \frac{2\bar{\rho}\tilde{\varepsilon}_c}{2c_m - 1} A e^{(\tilde{c} - \tilde{T})} + B\rho_0 S_L \sqrt{\frac{\tilde{\varepsilon}_c}{\tilde{D}}} e^{-0.5\left(\frac{x_1}{\delta_Z} - \Pi\right)^2}$$

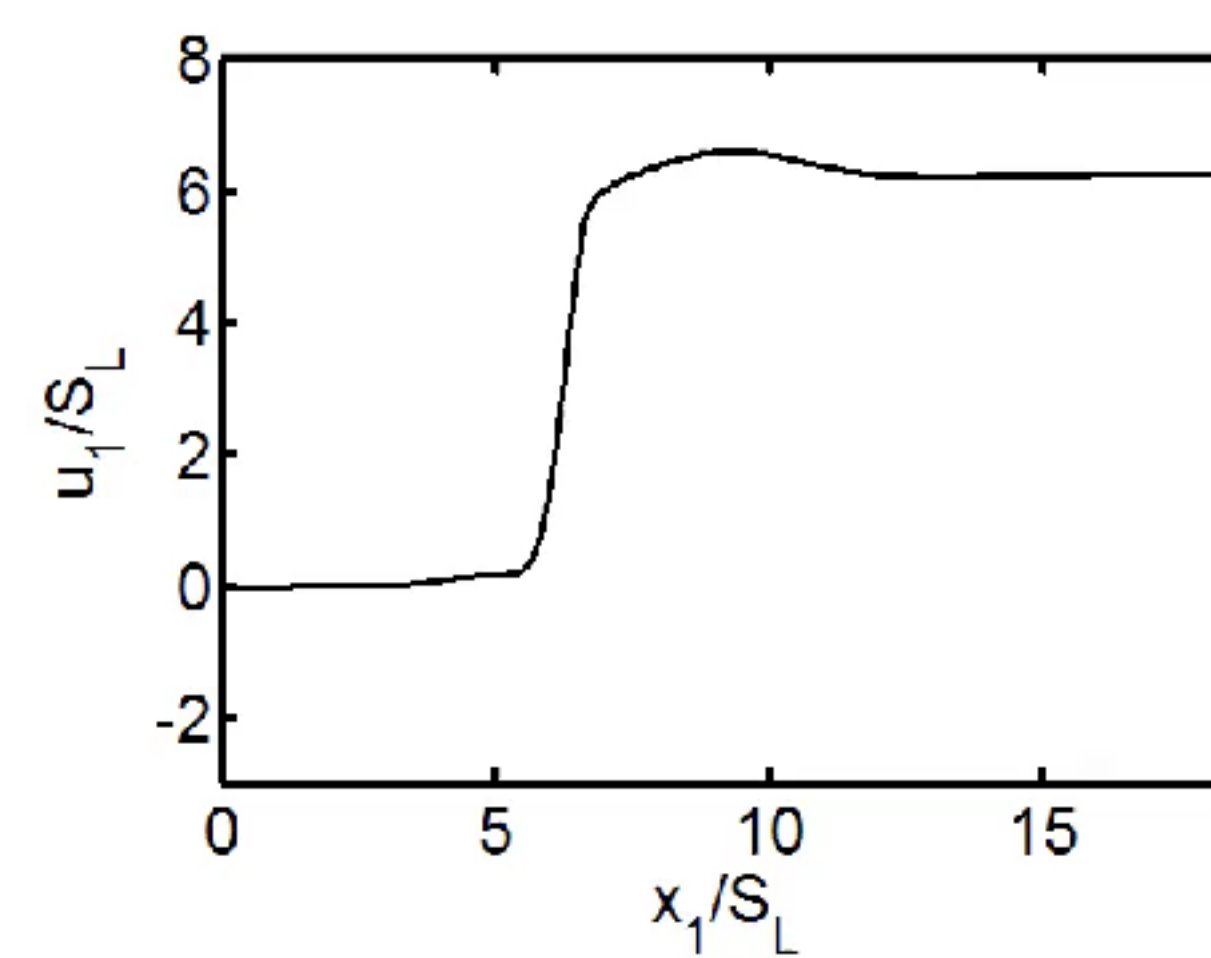
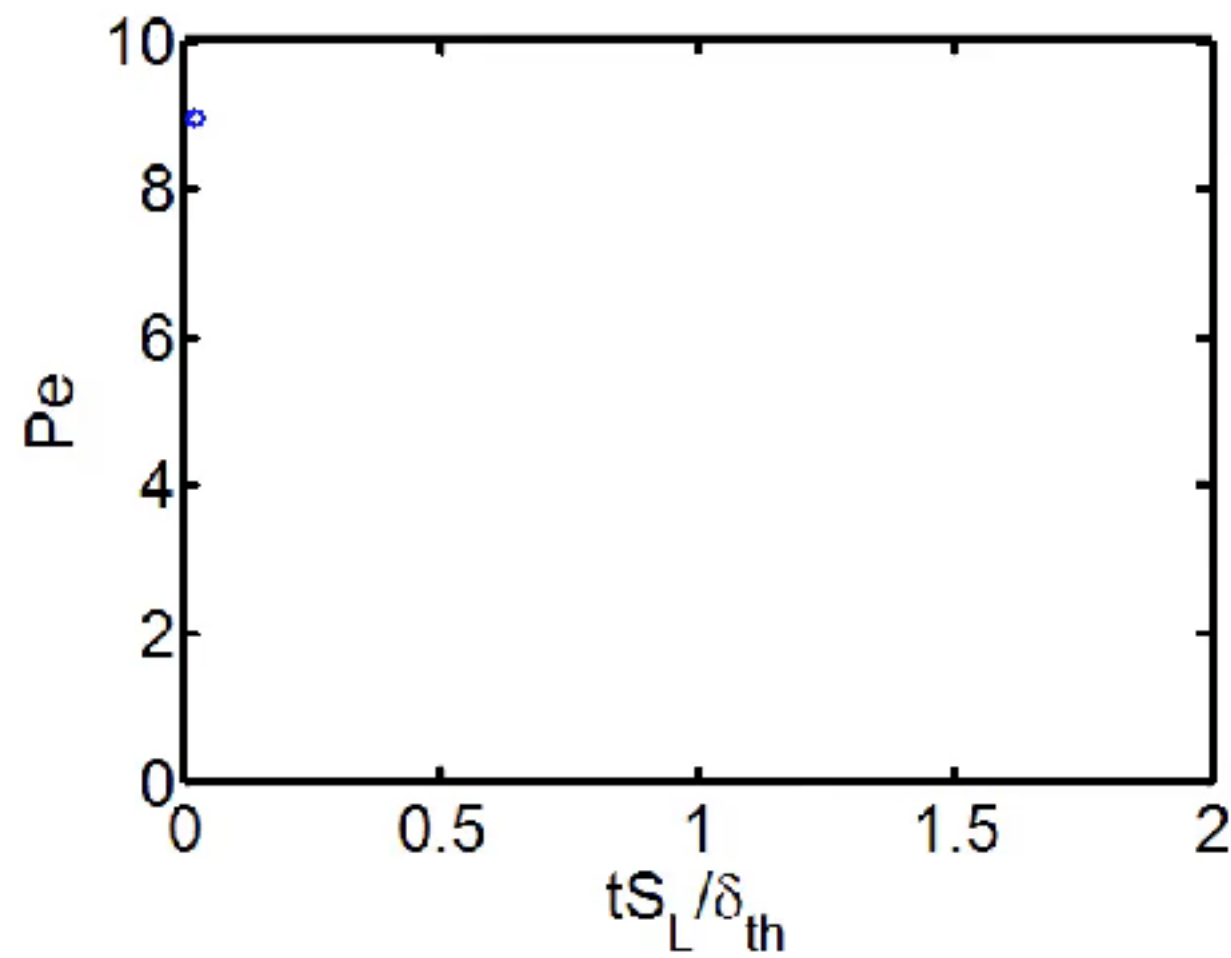
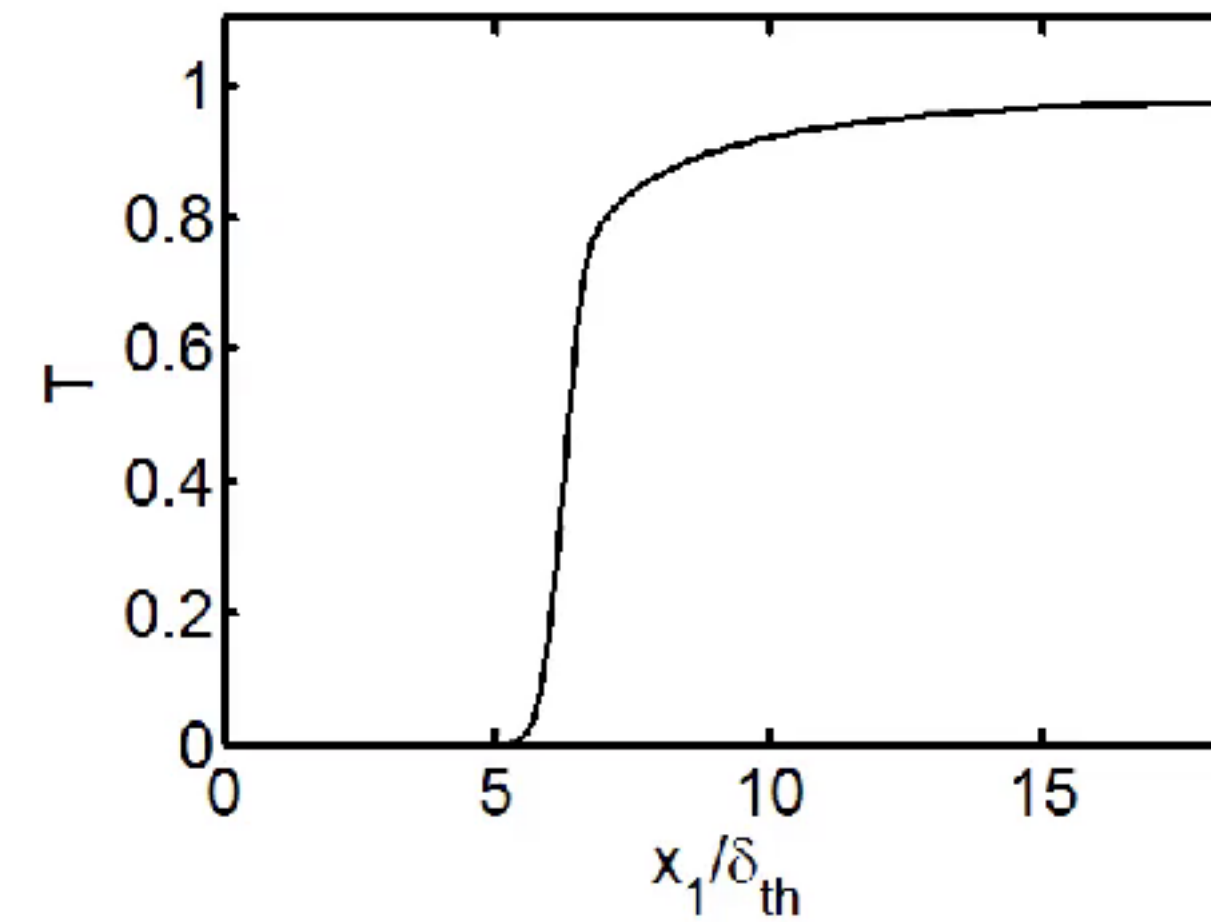
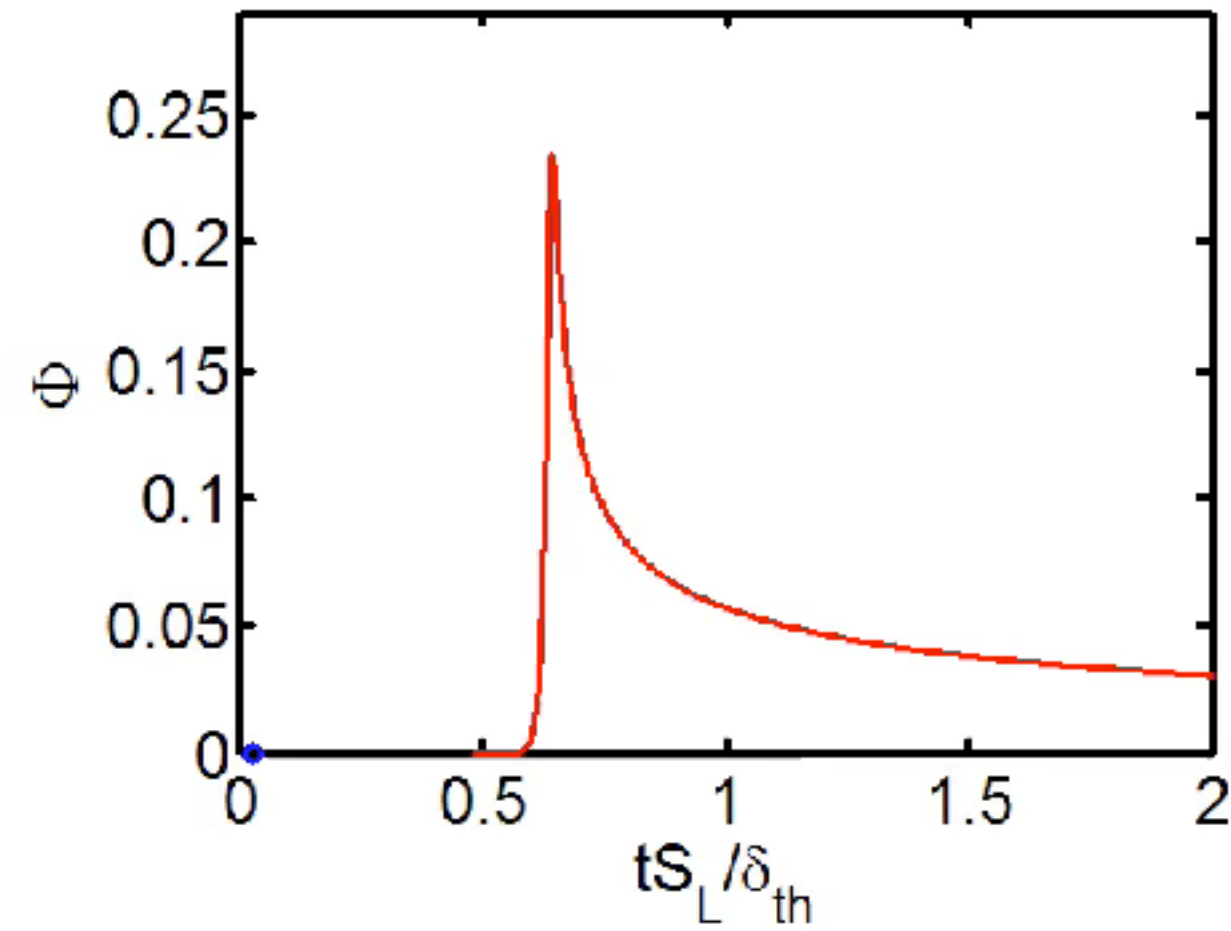
$$2\bar{\rho}\tilde{\varepsilon}_c / (2c_m - 1)$$

$$\Sigma_{gen} \sim \sqrt{\tilde{\varepsilon}_c / \tilde{D}}$$

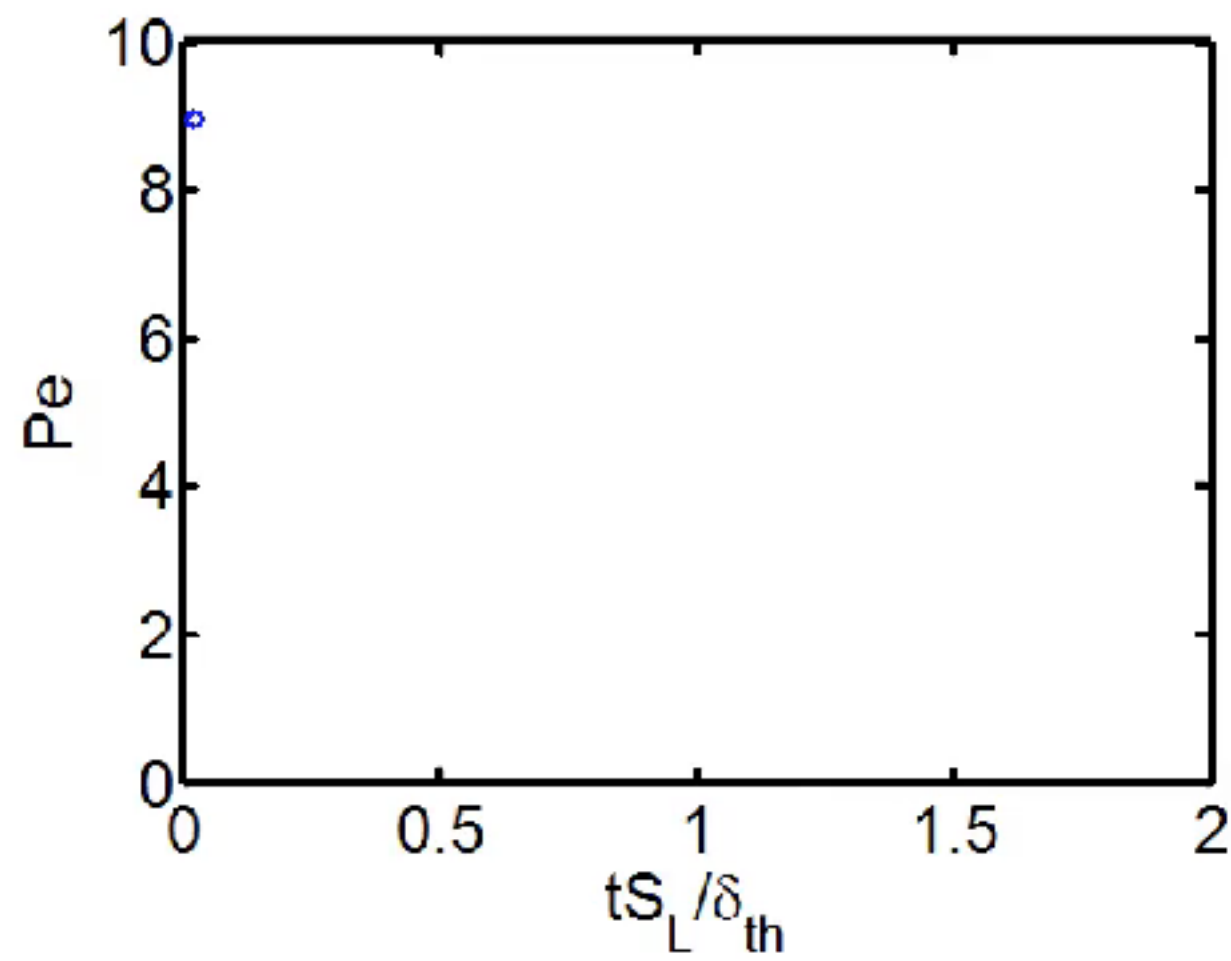
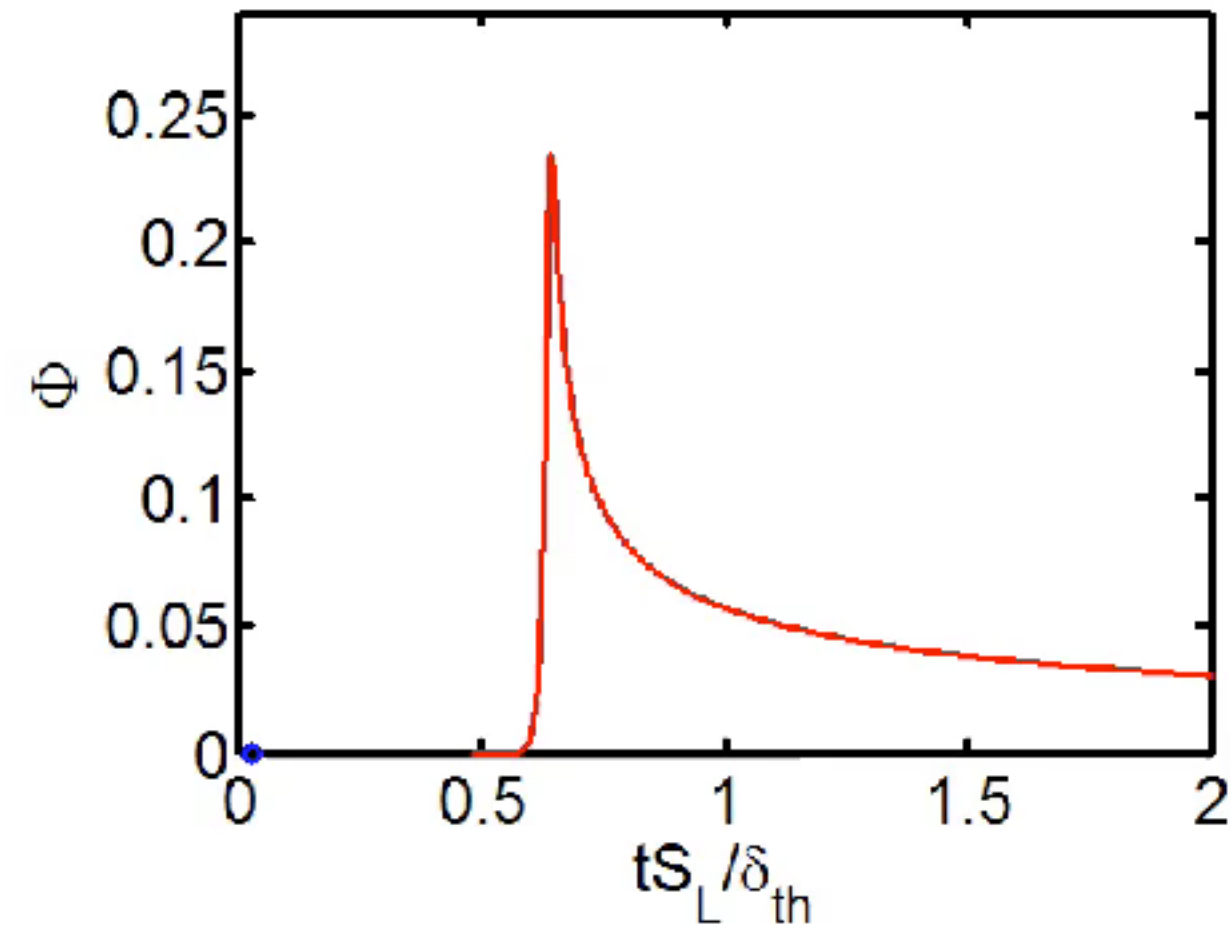
- Compressible code SENGGA2 [1]
- Methane Air mixture
- 16 species with 35 reactions [2]
- Mixture averaged transport
- Simulation domain:
 $7.65\text{mm} \times 7.65\text{mm} \times 7.65\text{mm}$
- Cartesian grid:
 $256 \times 256 \times 256$
- More than 4,100
- More than **65,000** KAu per case



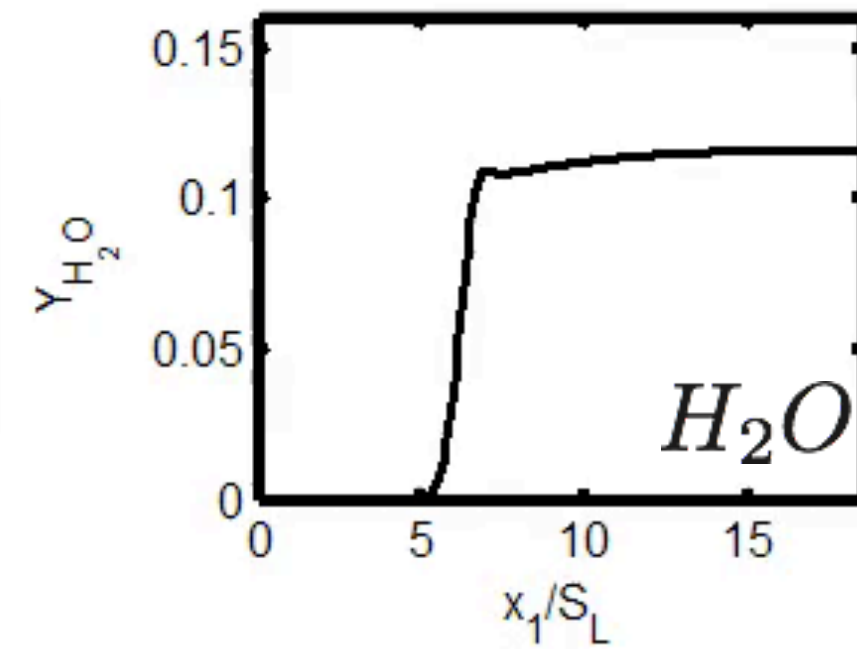
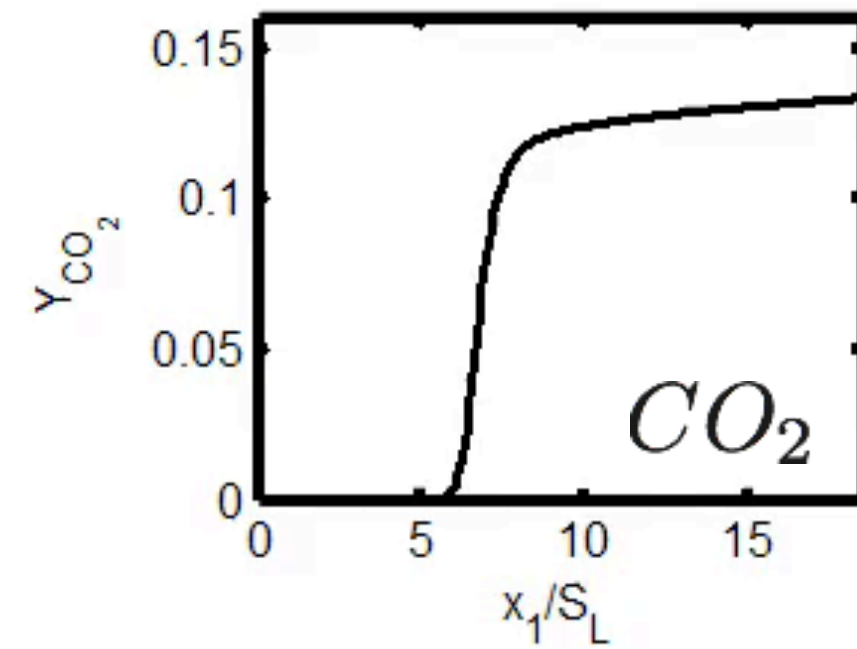
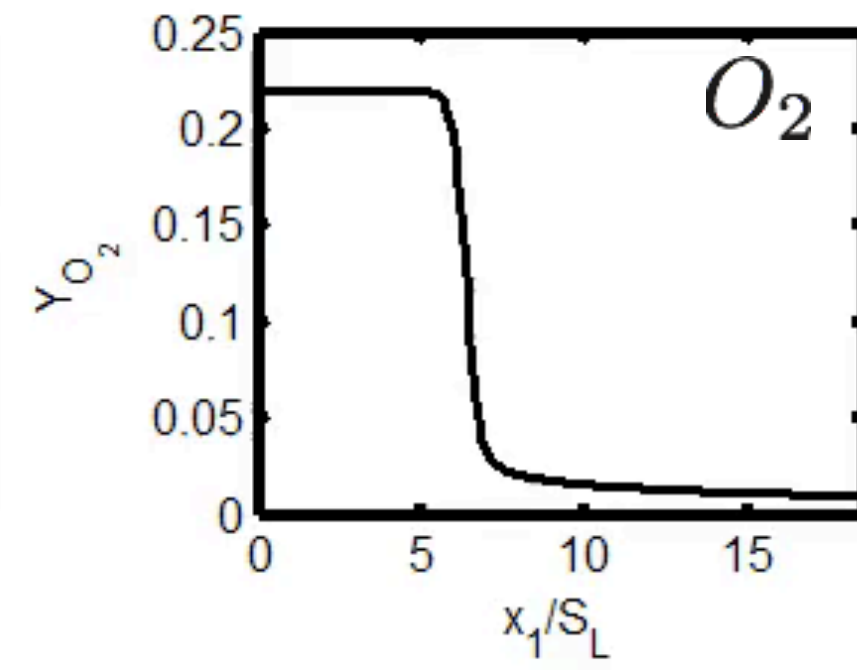
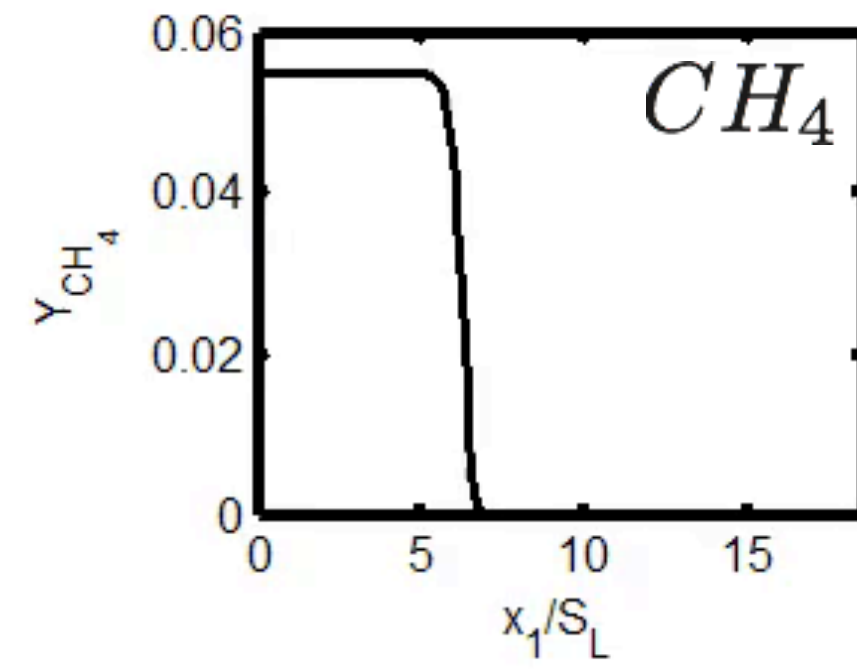
1D laminar flame $Pe_{min} = 2.2$ $\Phi_{max} = 0.24$



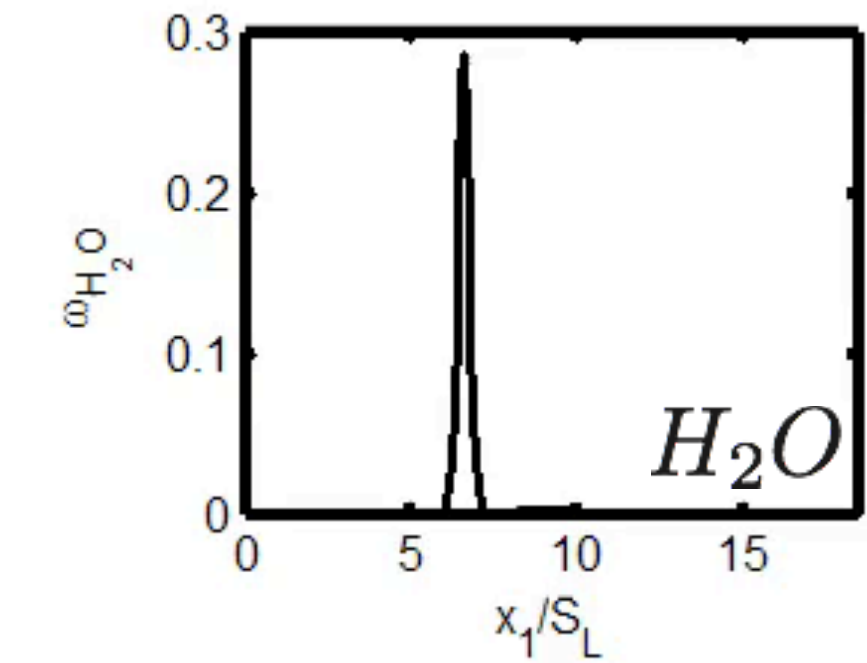
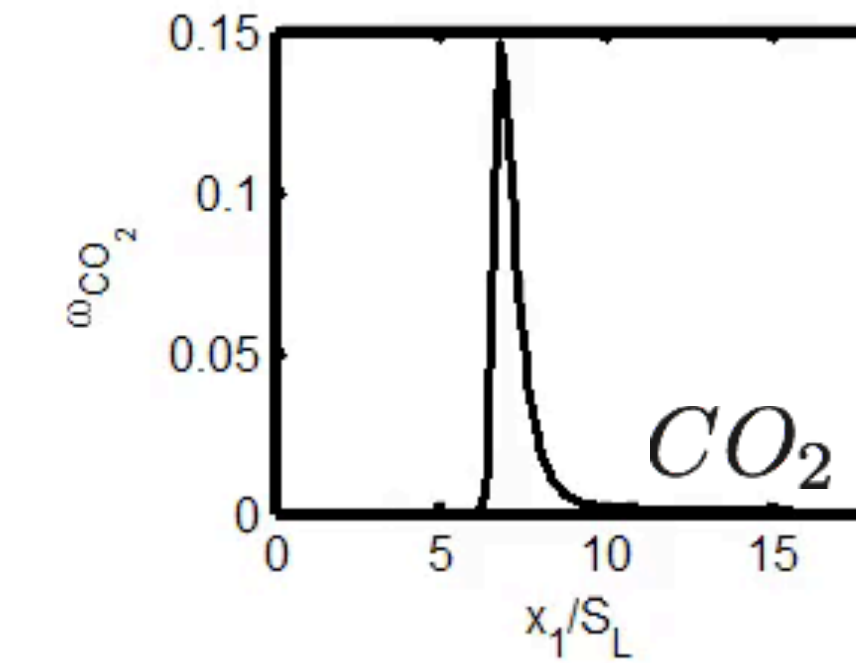
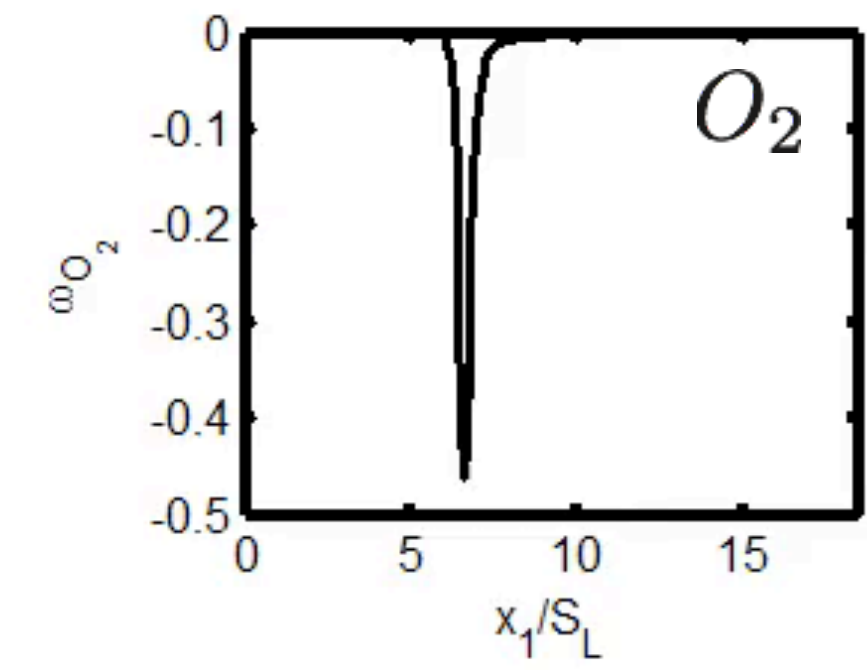
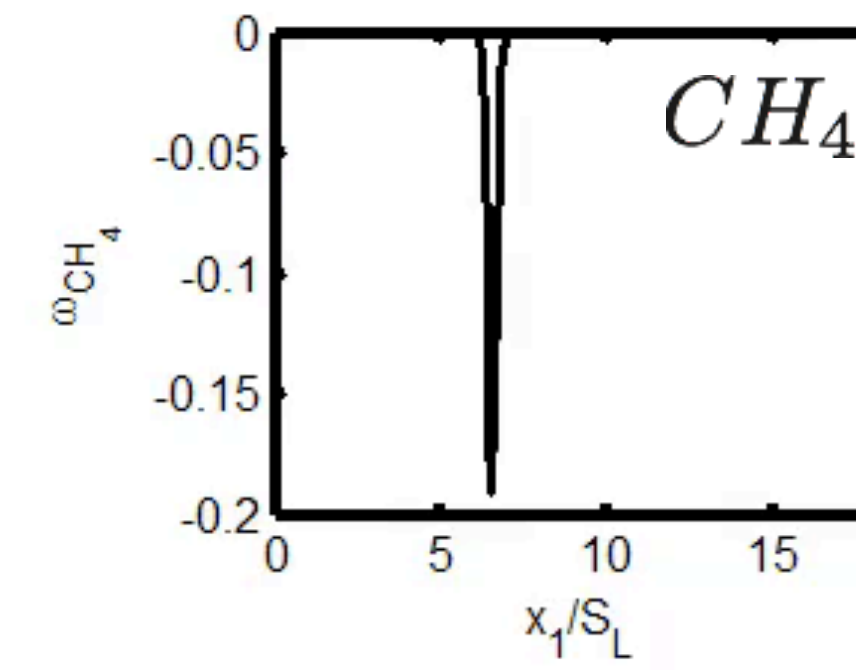
1D laminar flame



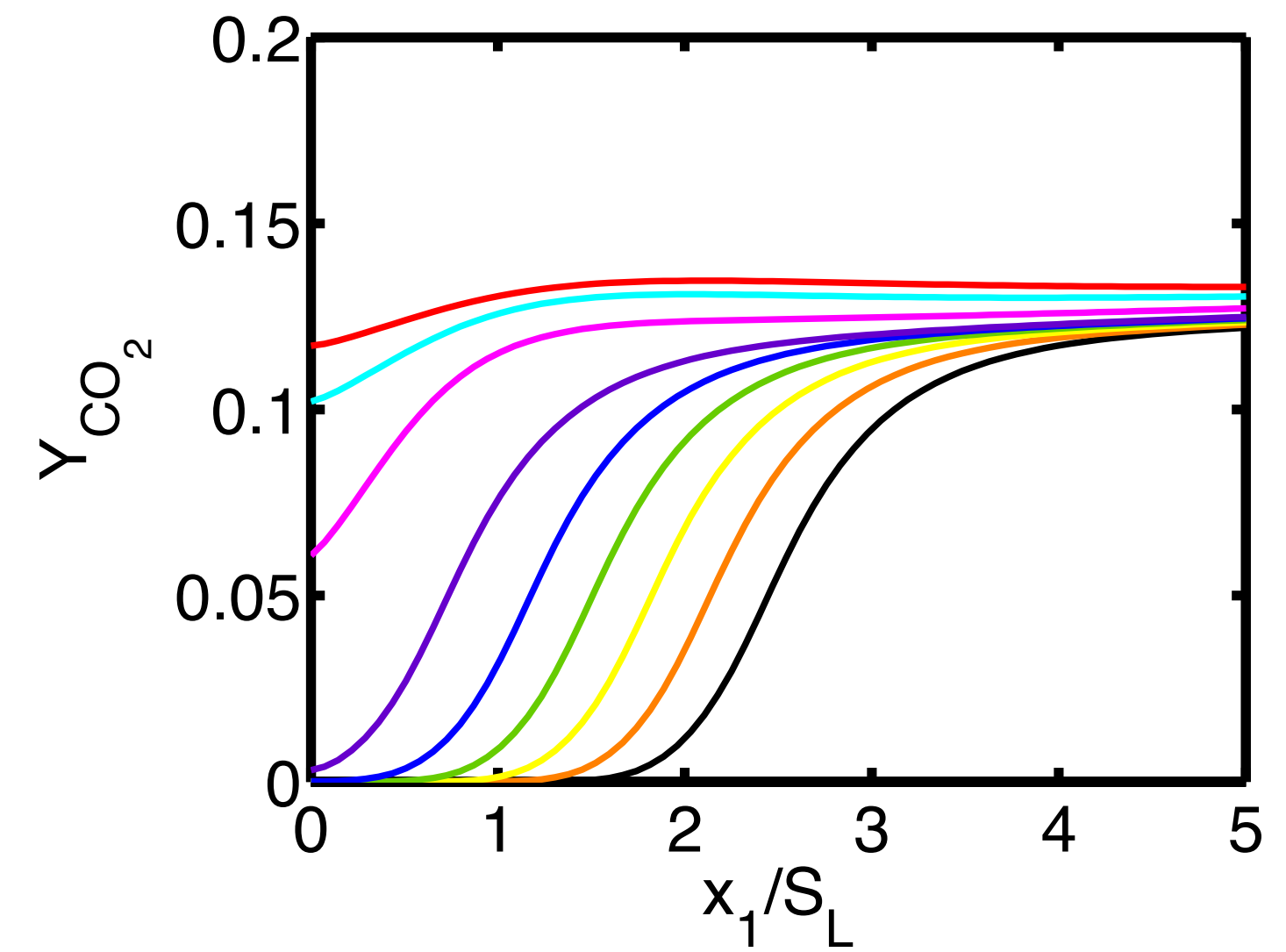
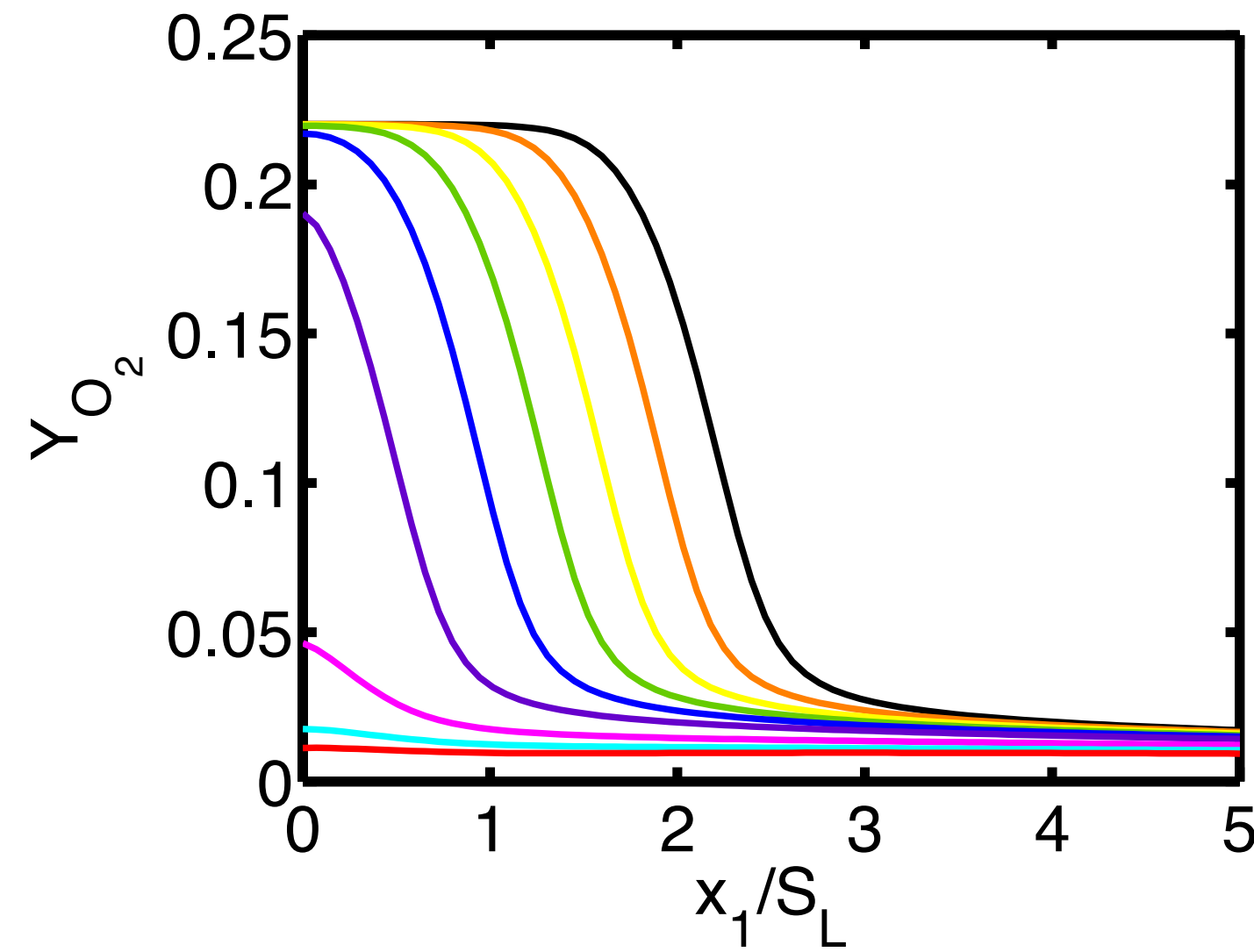
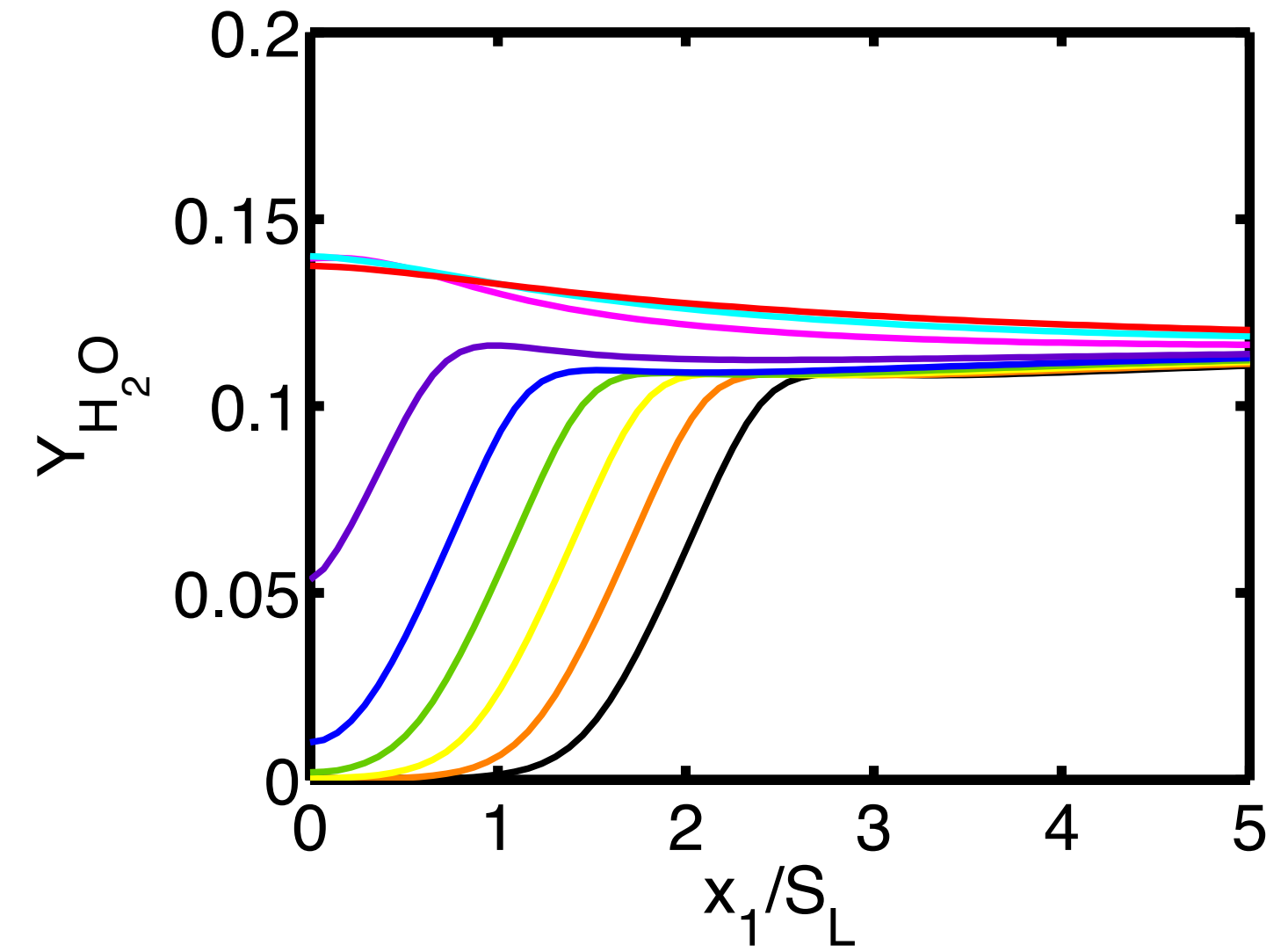
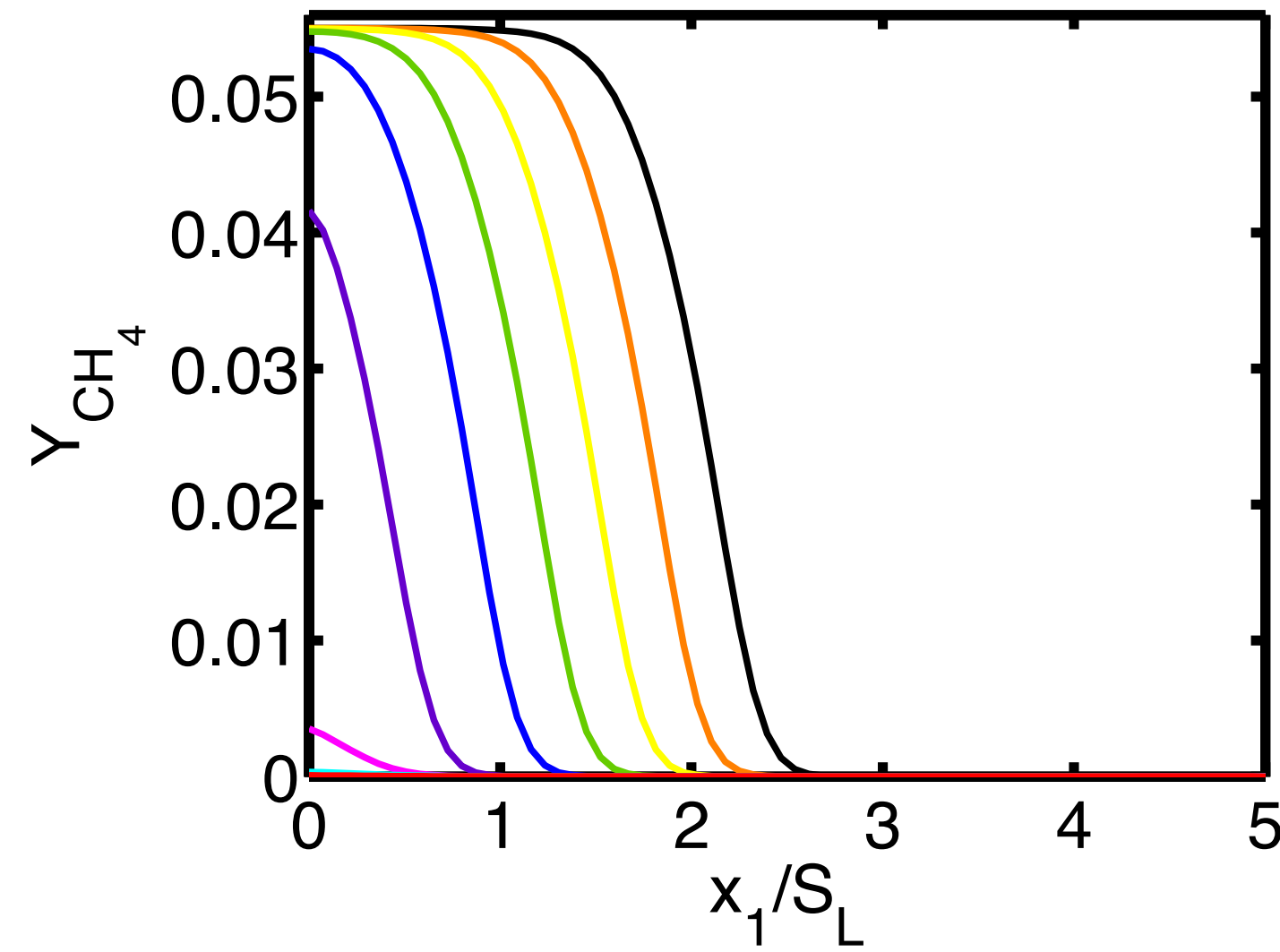
Mass fraction



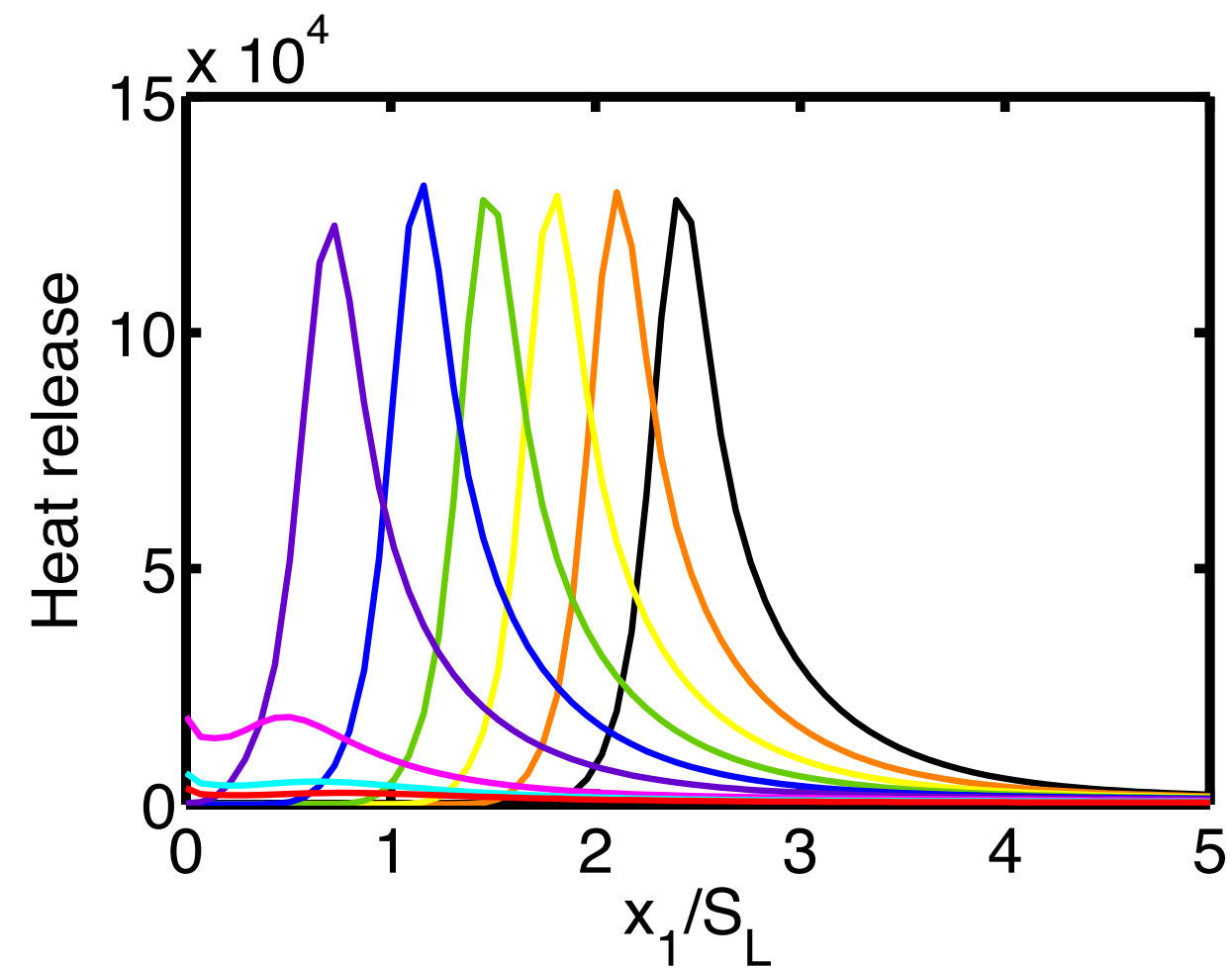
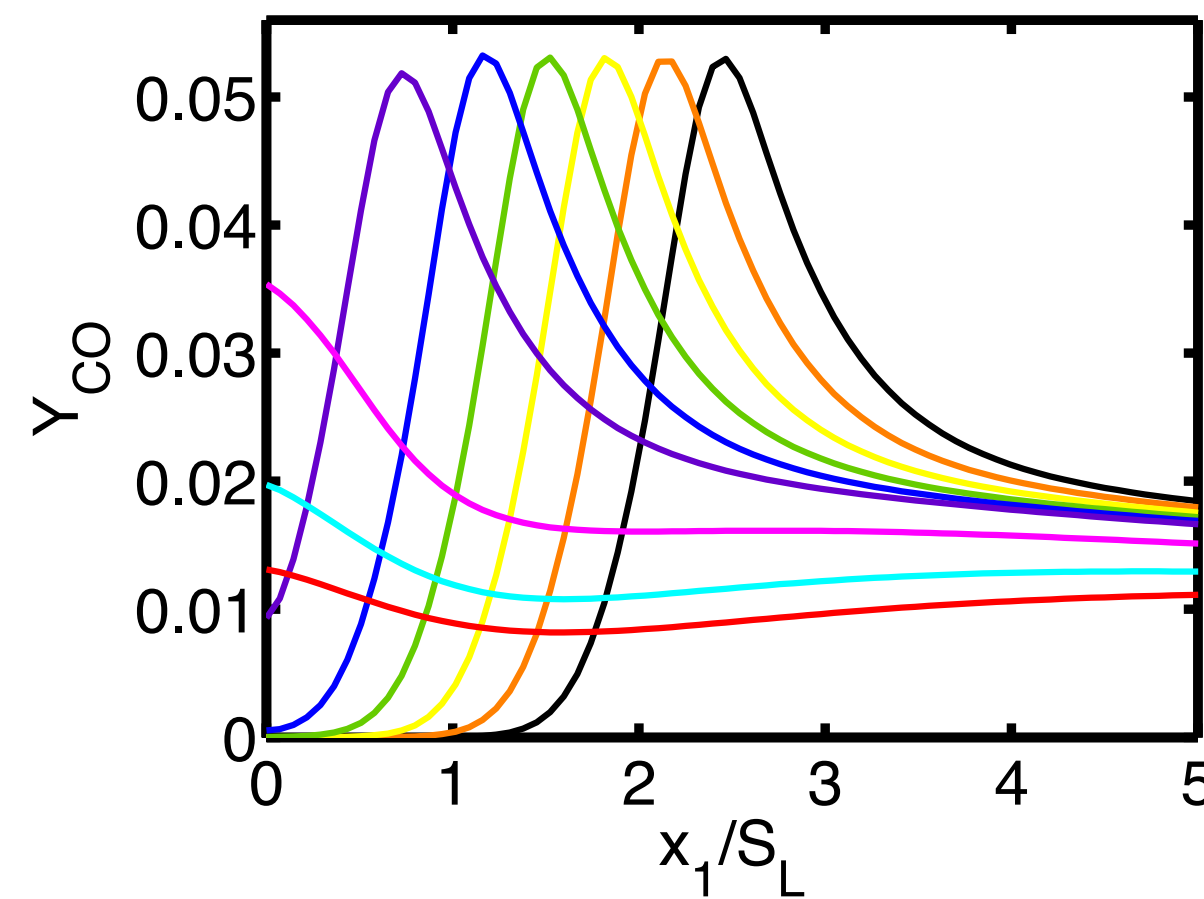
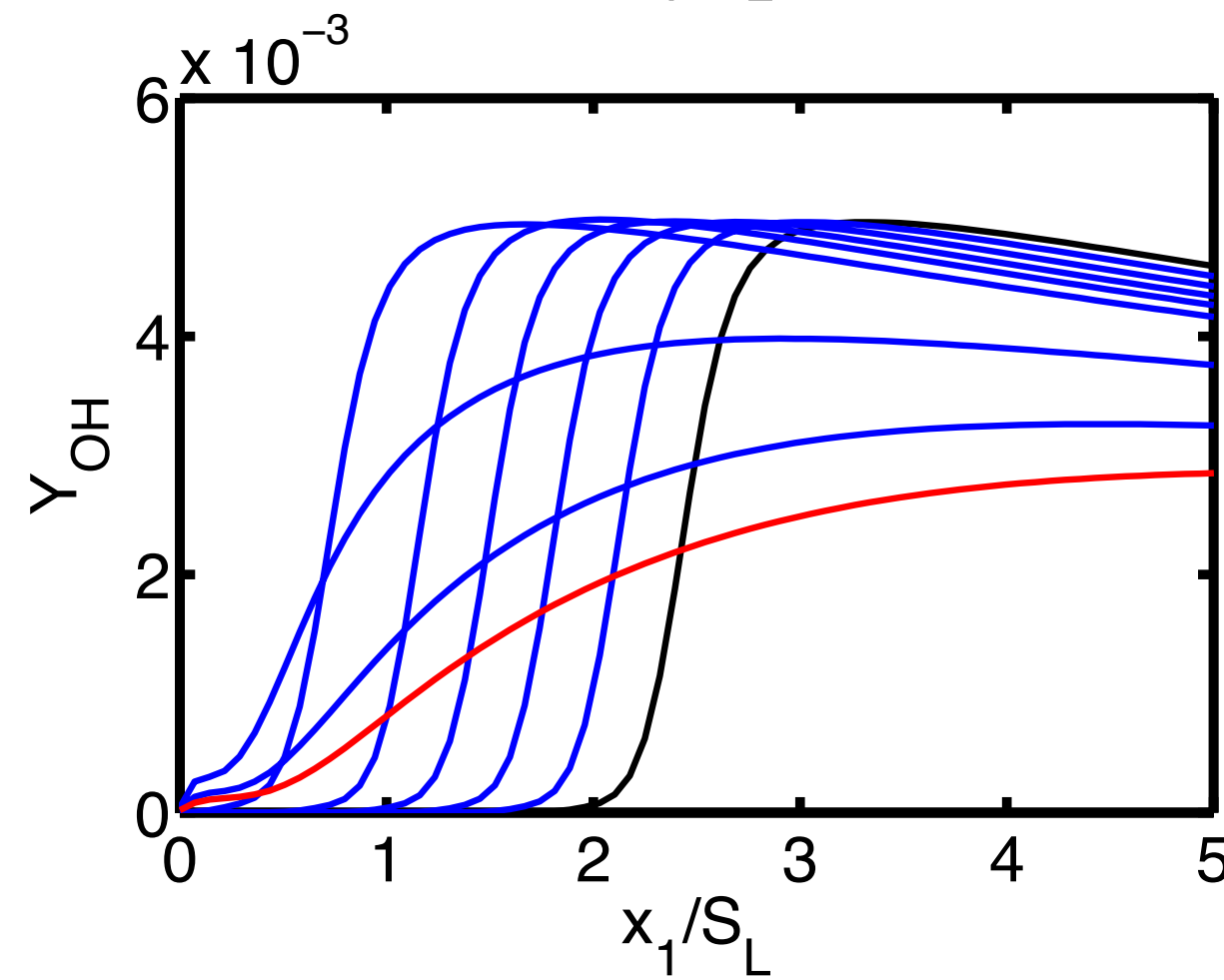
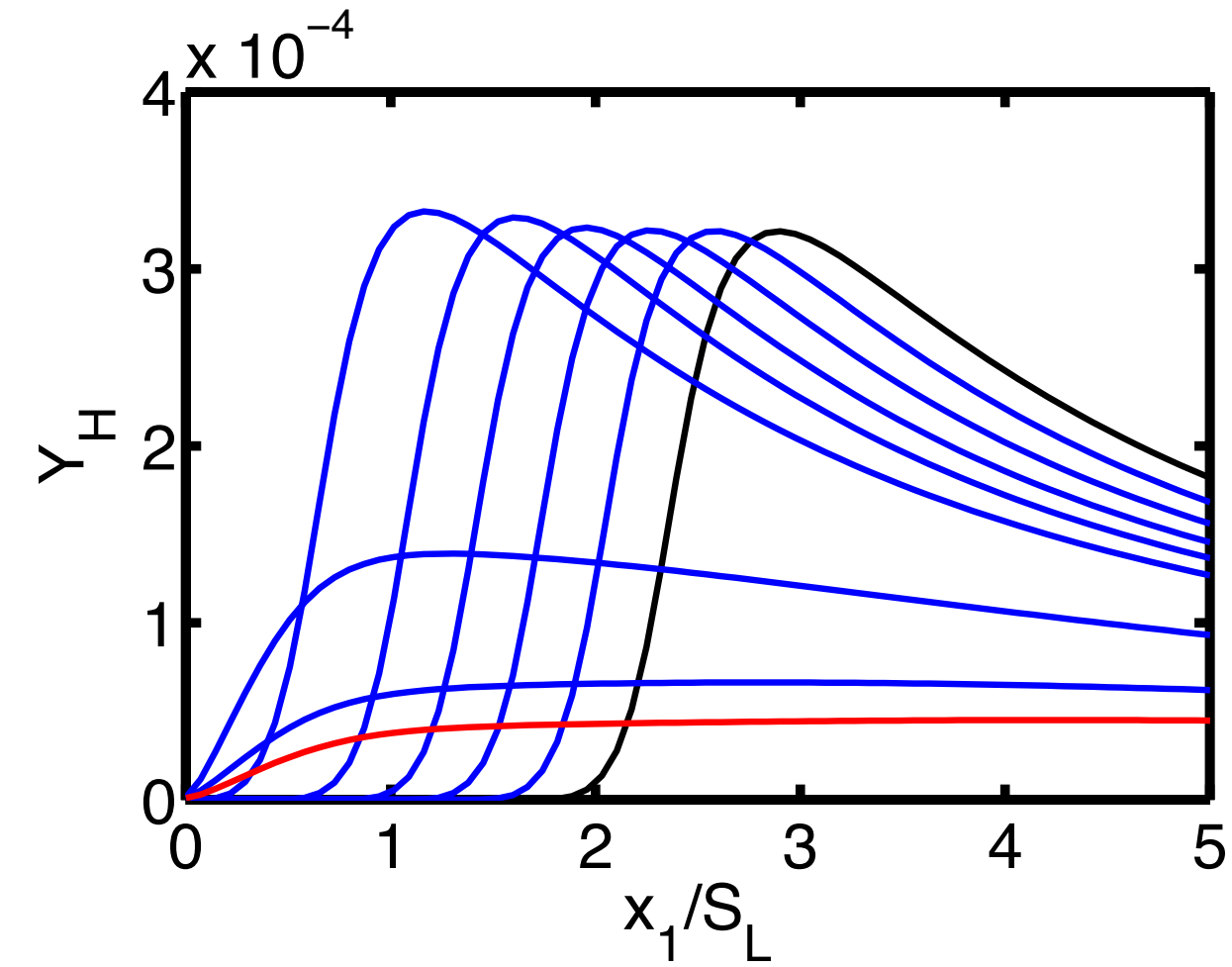
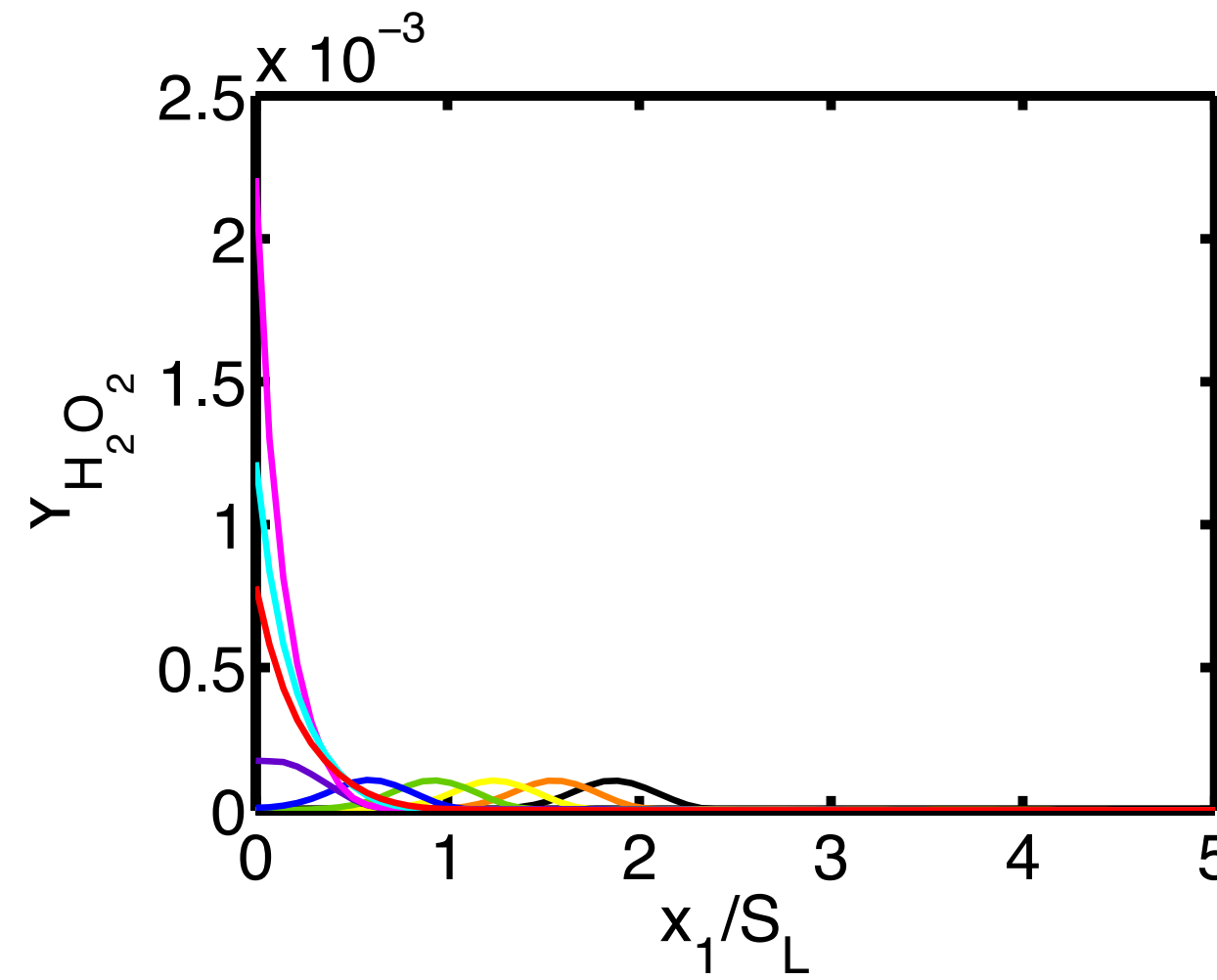
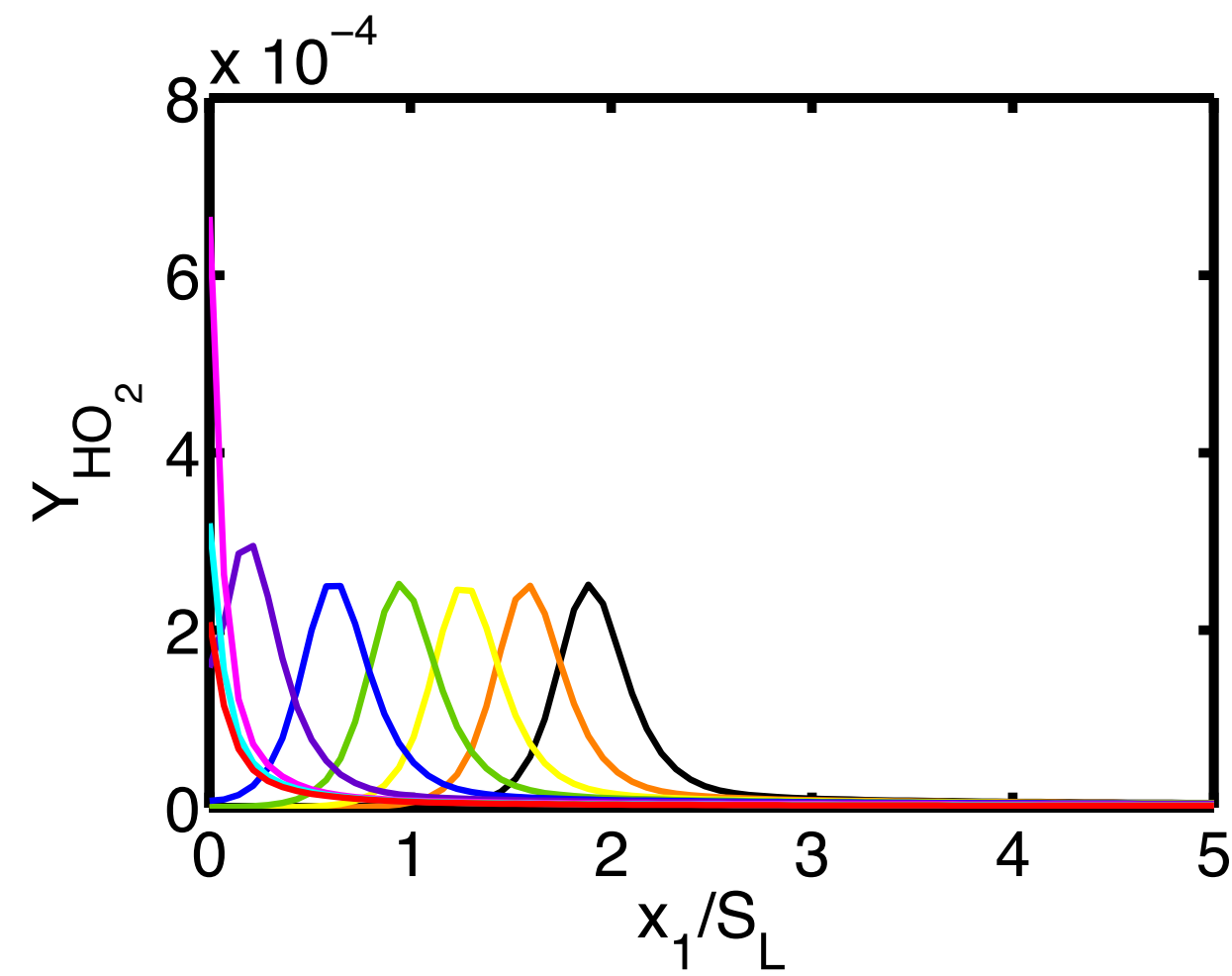
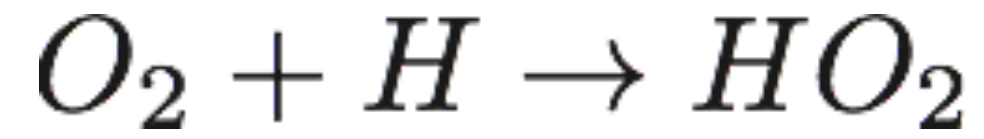
Reaction rate

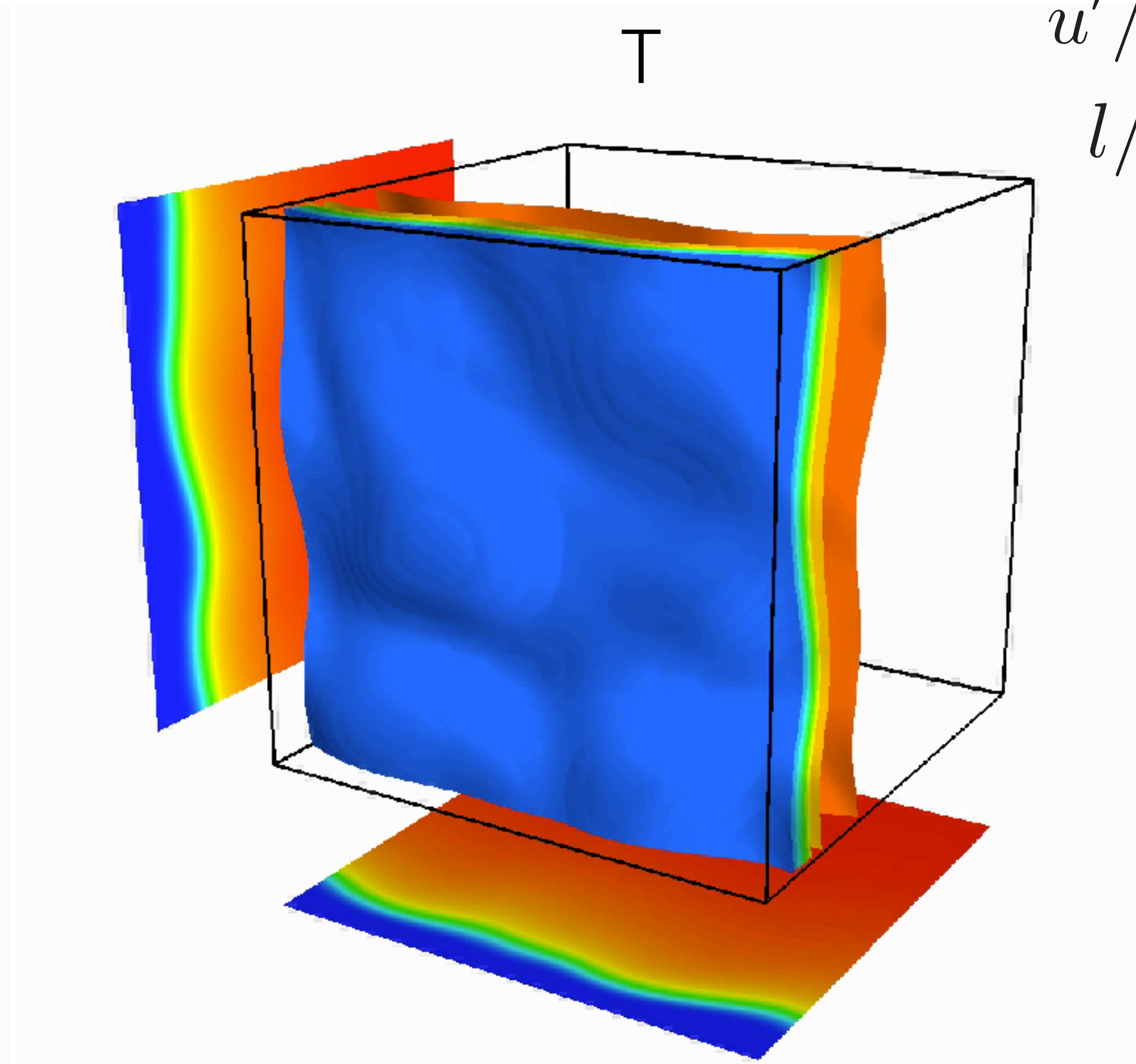
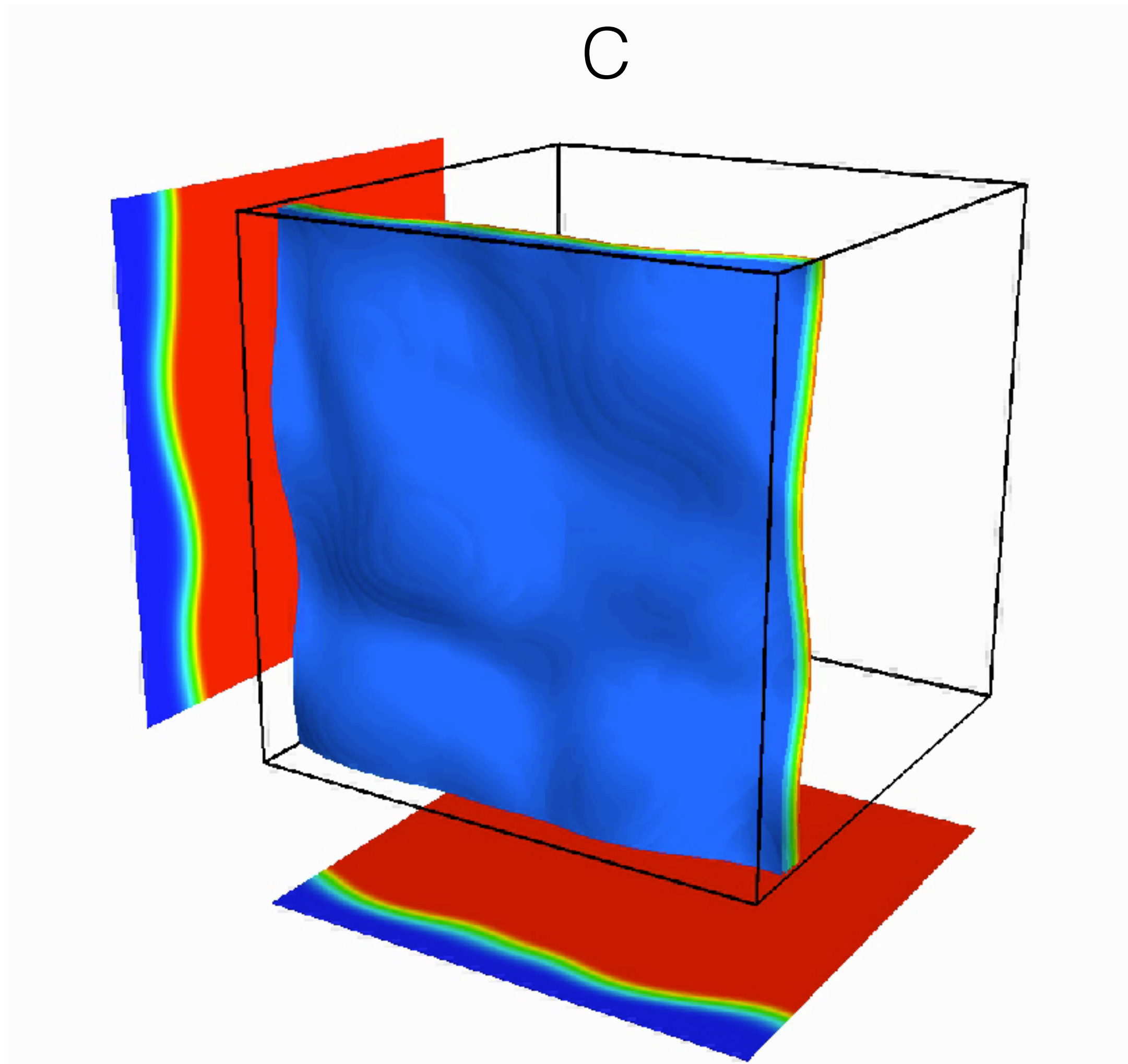


1D laminar flame



1D laminar flame





$$u' / S_L = 5.0$$

$$l / \delta_{th} = 1.67$$

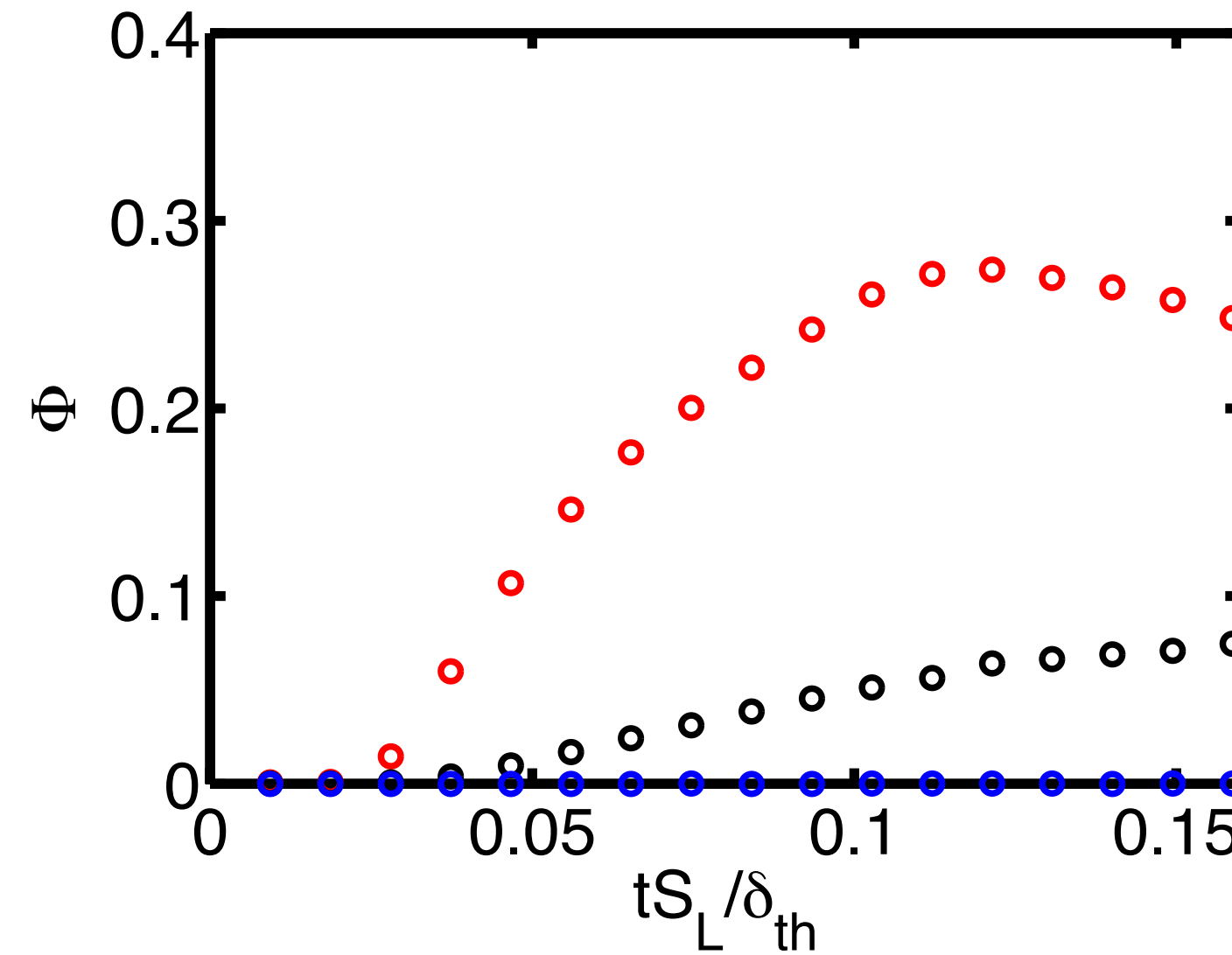
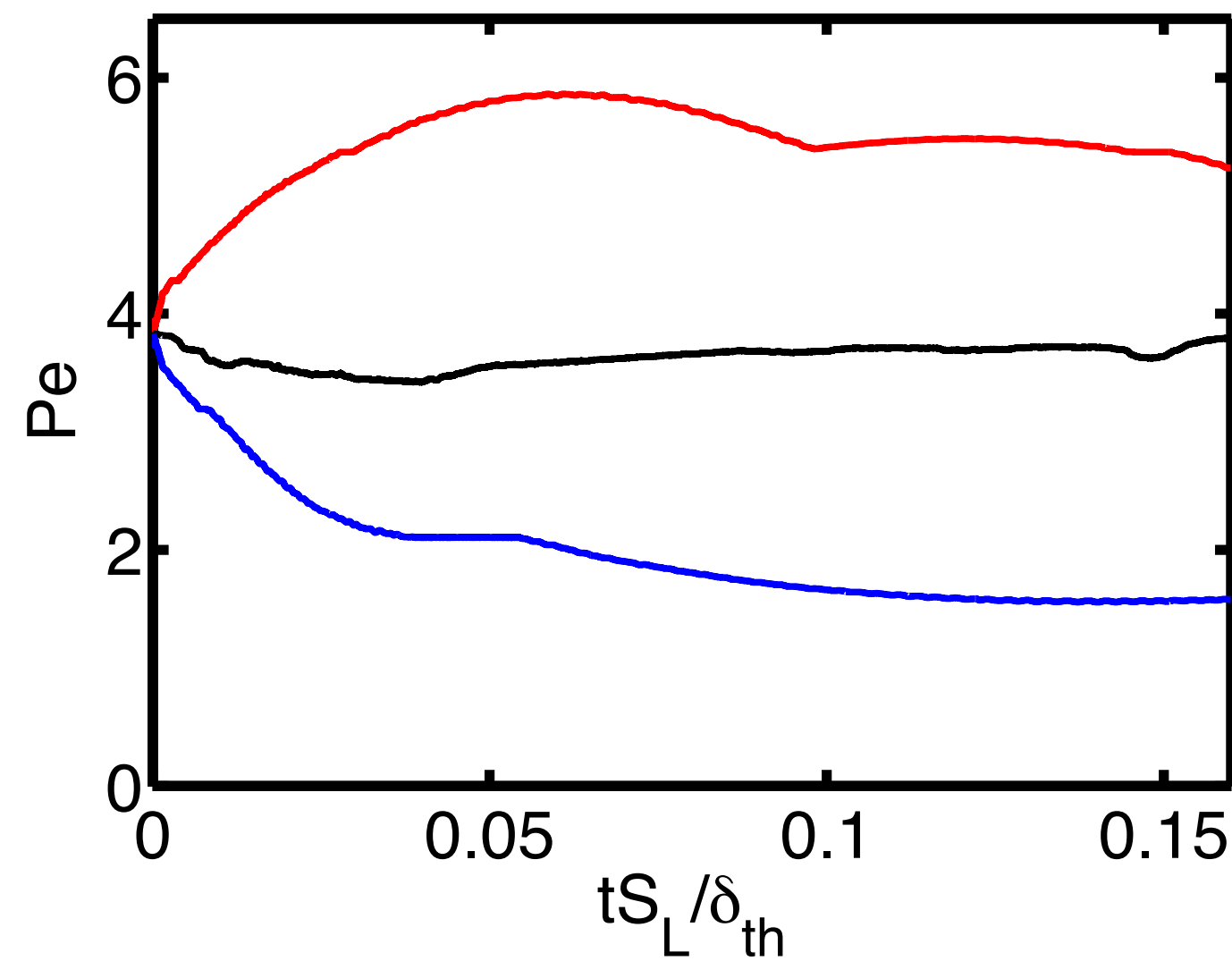
Laminar flame

$$Pe_{min} = 2.2 \quad \Phi_{max} = 0.24$$

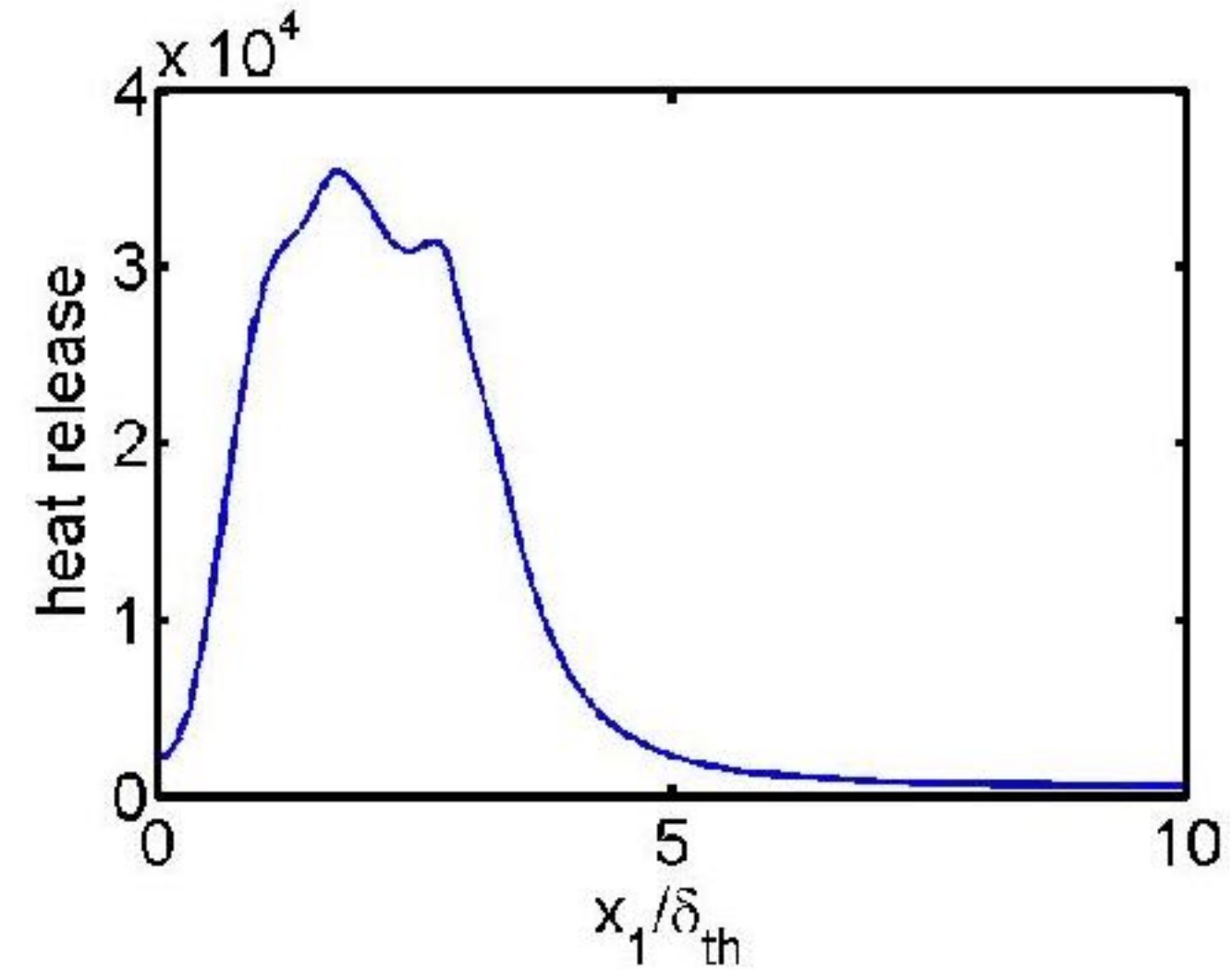
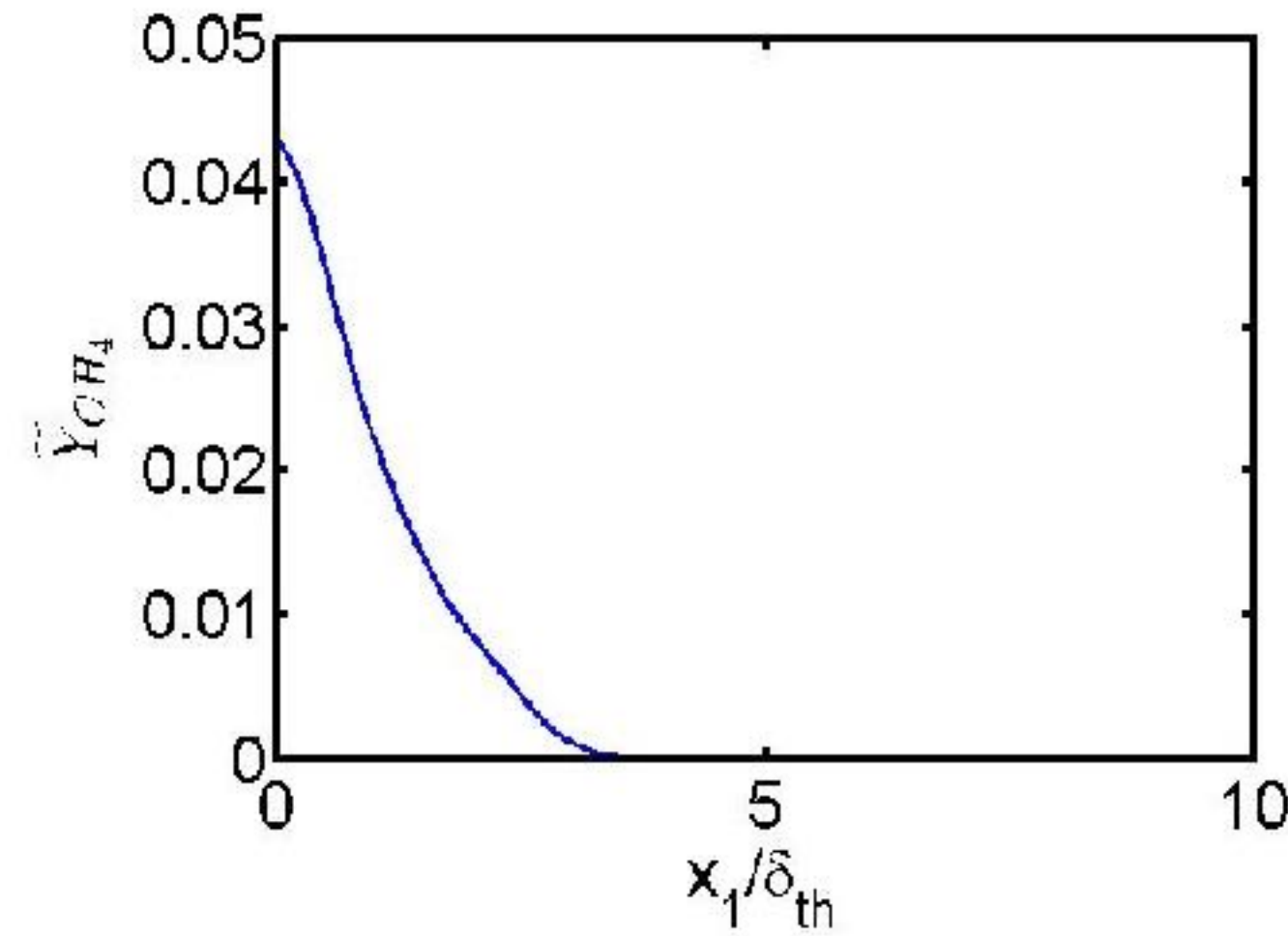
Turbulent flame

$$Pe_{min} = 1.6 \quad \Phi_{max} = 0.27$$

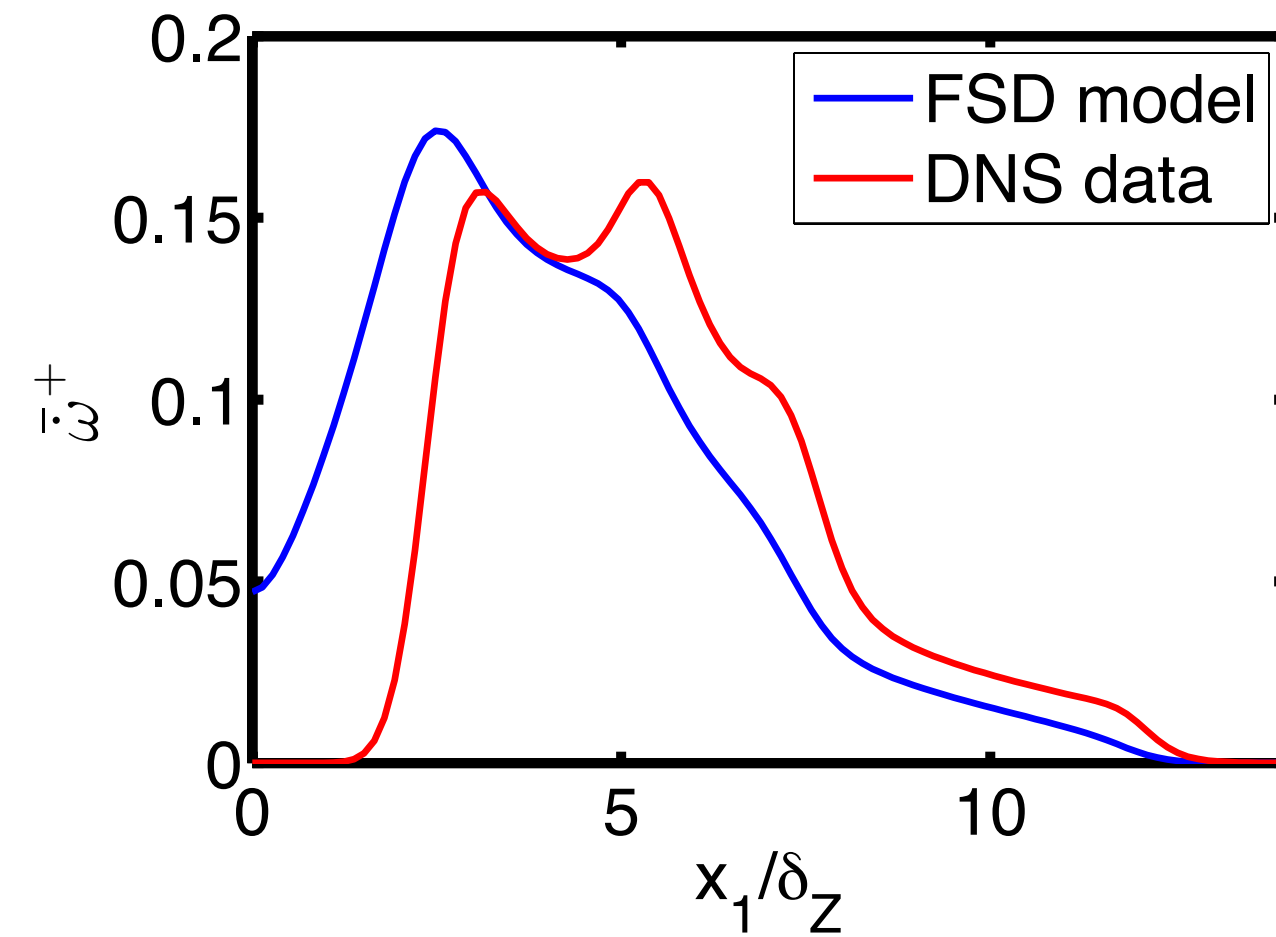
$$Pe_{min} = (Pe_{min})_L [\text{erf}(8Le - 6.0) + 1]/2$$



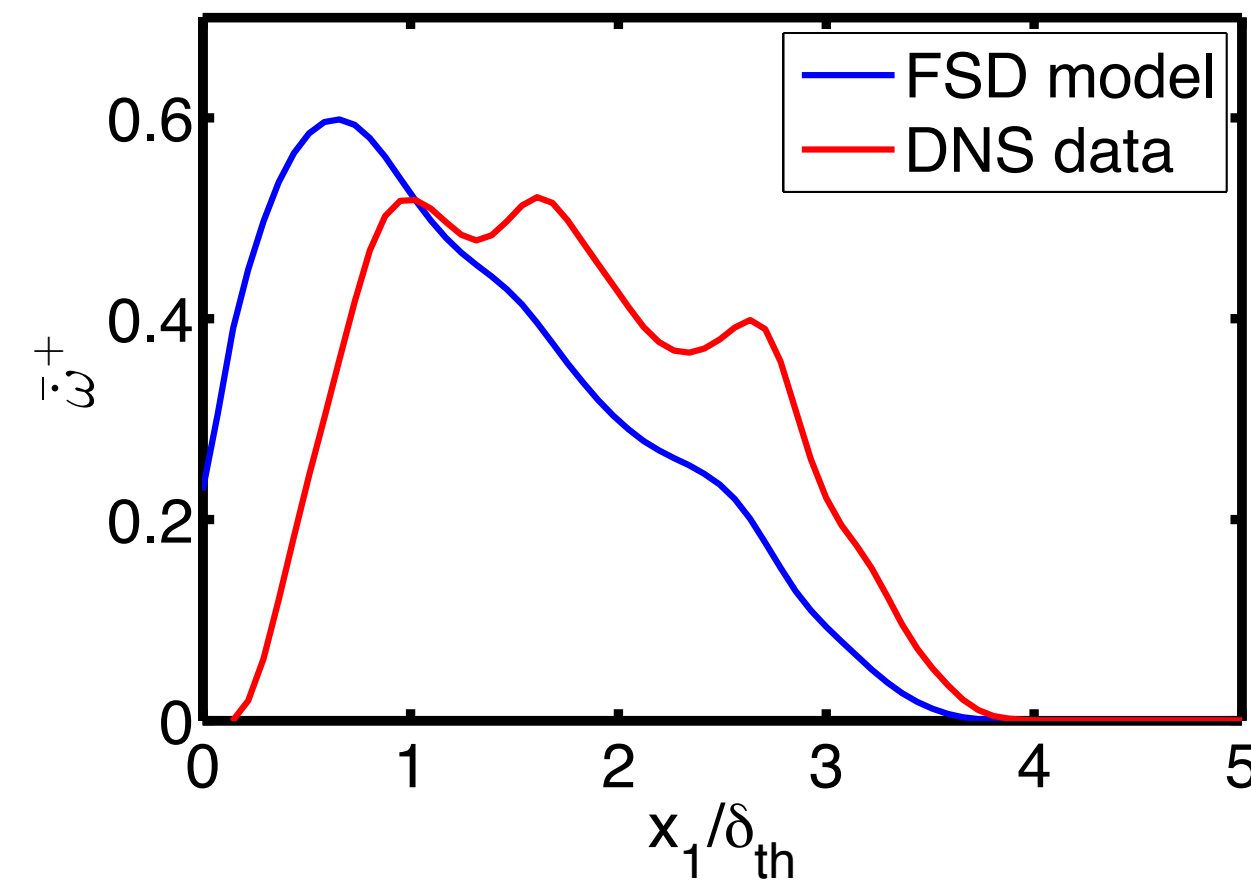
$$t = 0.14\delta_{th}/S_L$$



Simplified chemistry



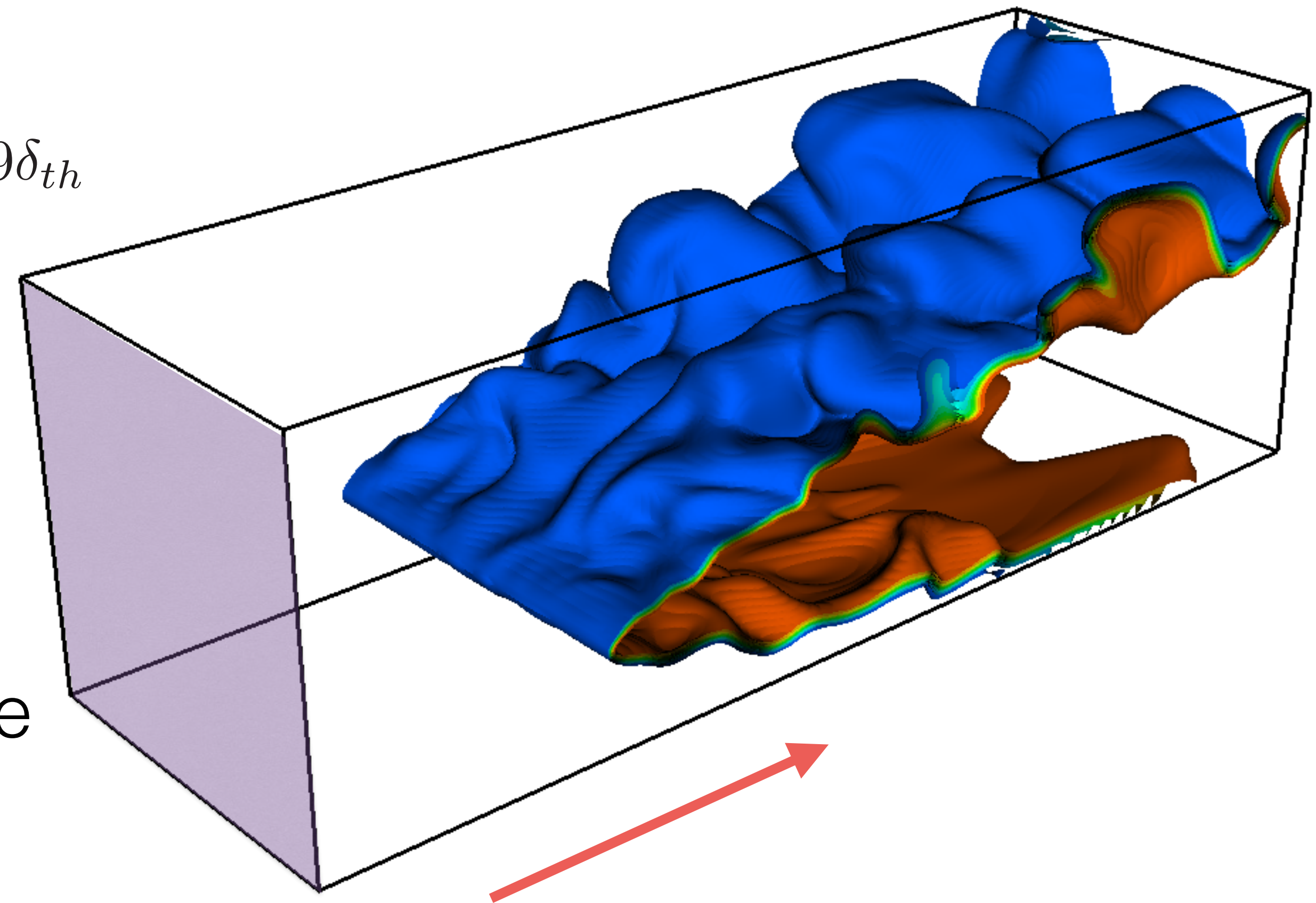
Detailed chemistry



$$\bar{\dot{\omega}} = \rho_0 S_L \Sigma_{gen}$$

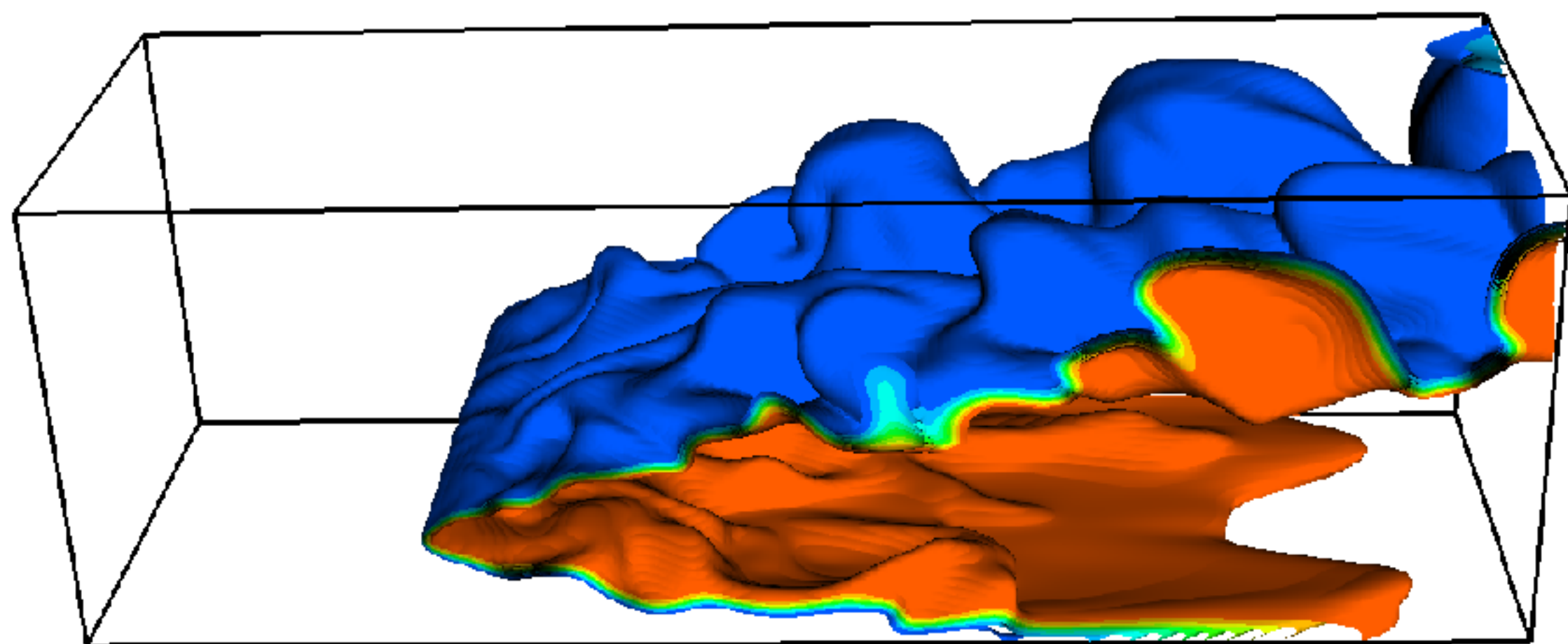
$$\Sigma_{gen} = \overline{|\nabla c|}$$

- Compressible code SENGGA [1]
- Methane Air mixture at an equivalence ratio of $\phi = 1.0$
- Simplified chemistry
- Simulation domain: $83.7\delta_{th} \times 27.9\delta_{th} \times 27.9\delta_{th}$
- Cartesian grid: $900 \times 300 \times 300$
- Improved NSCBC [2]
- Flame holder
- More than 200 cores
- More than **2,500** KAu per turbulent case

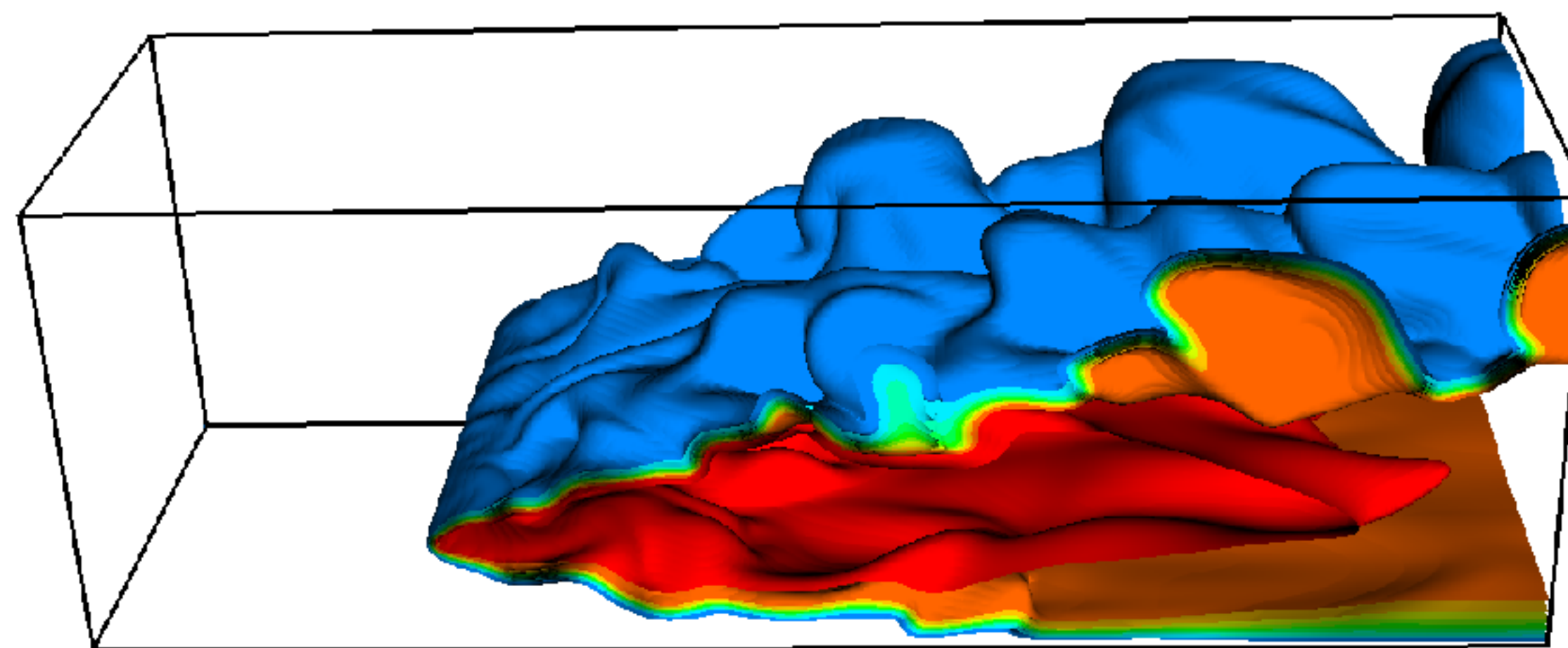


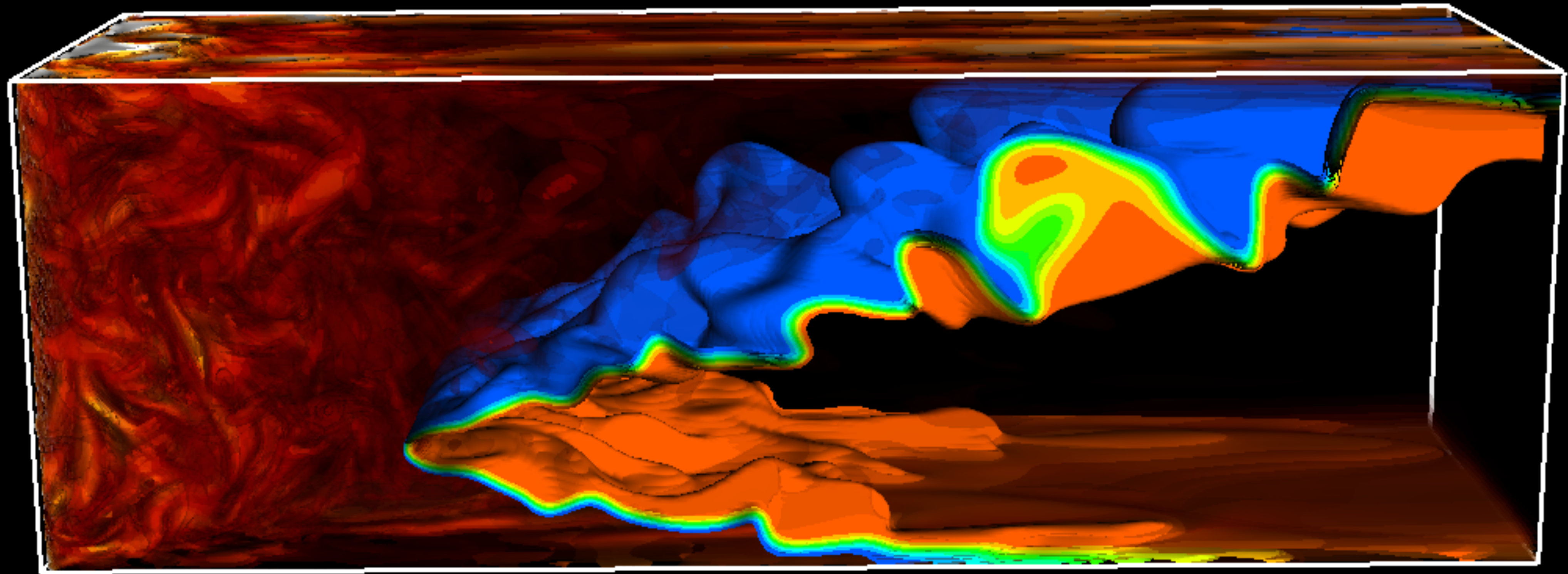


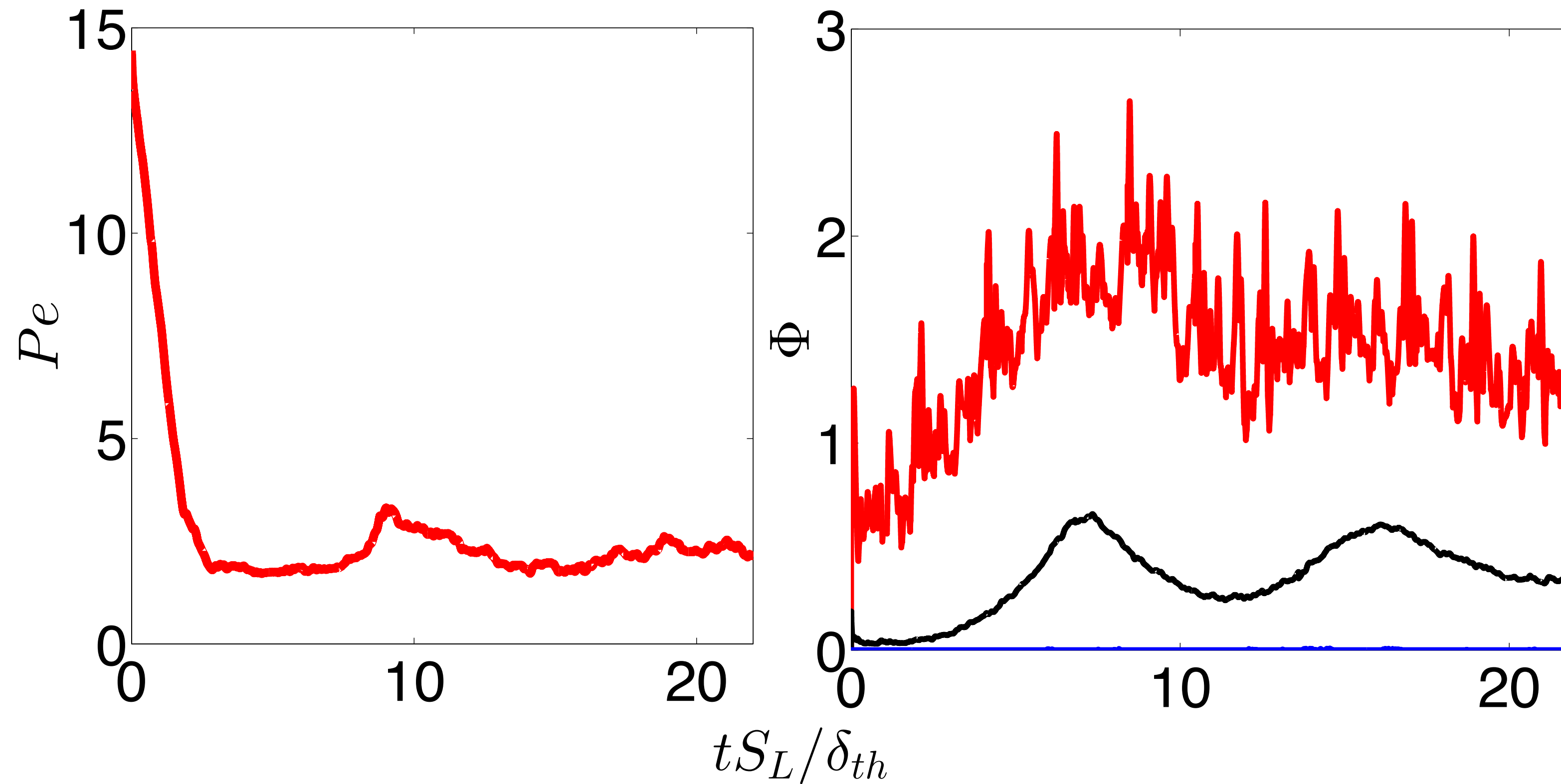
C



T







Laminar

$$\Phi_{mean} = 0.36$$

$$Pe_{min} = 3.1$$

Turbulence

$$\Phi_{mean} = 0.6$$

$$Pe_{min} = 1.7$$

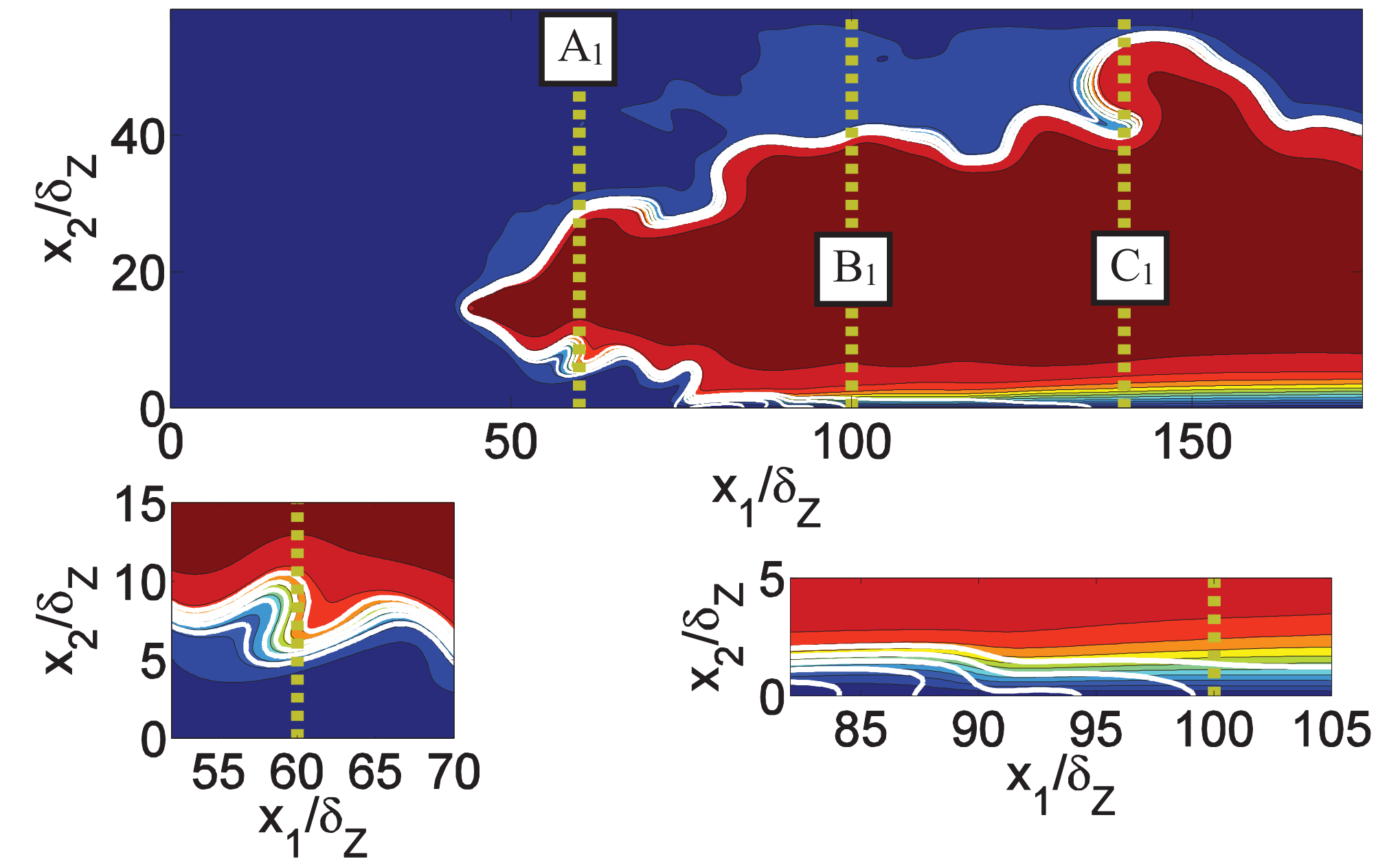
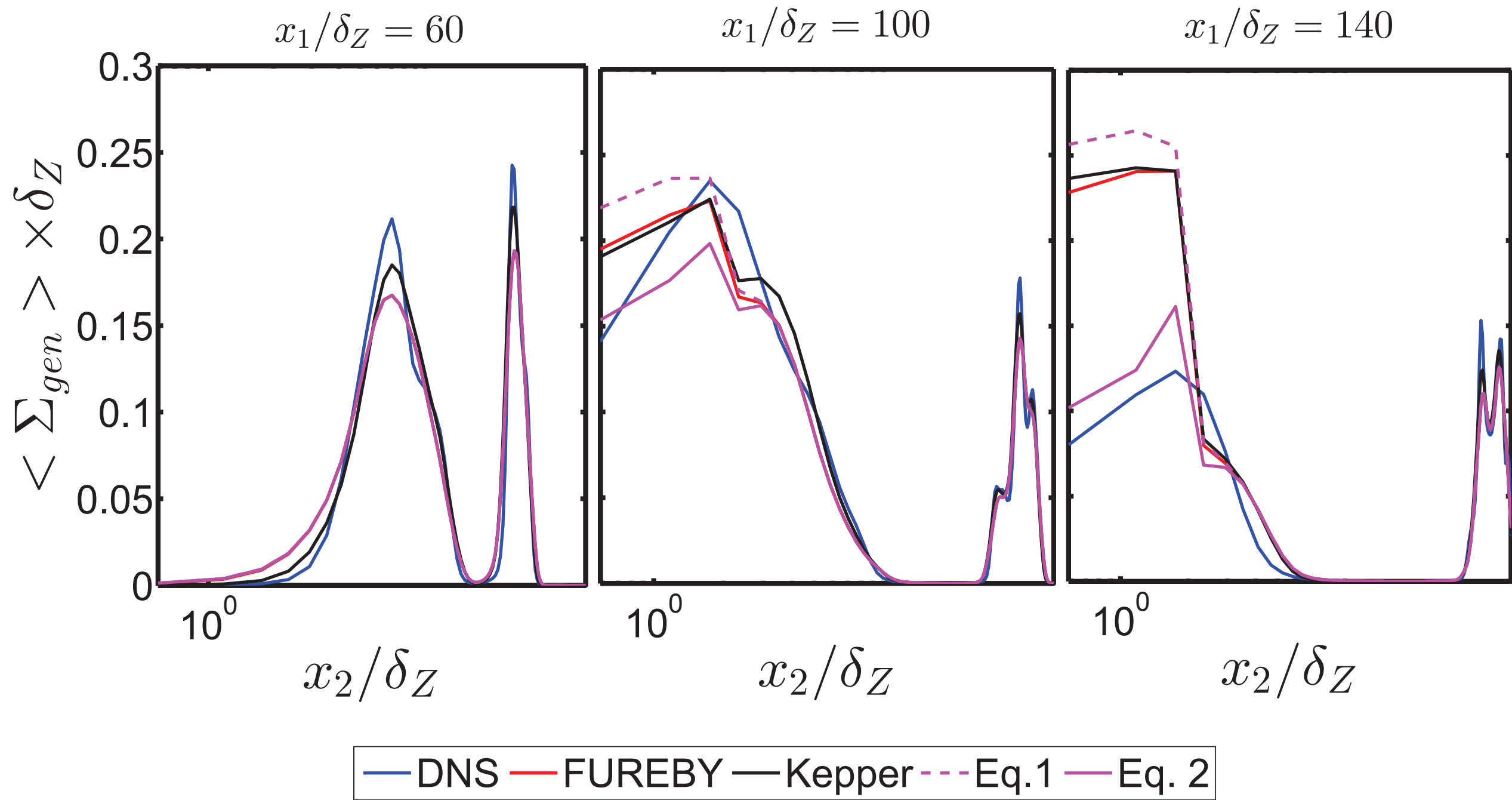
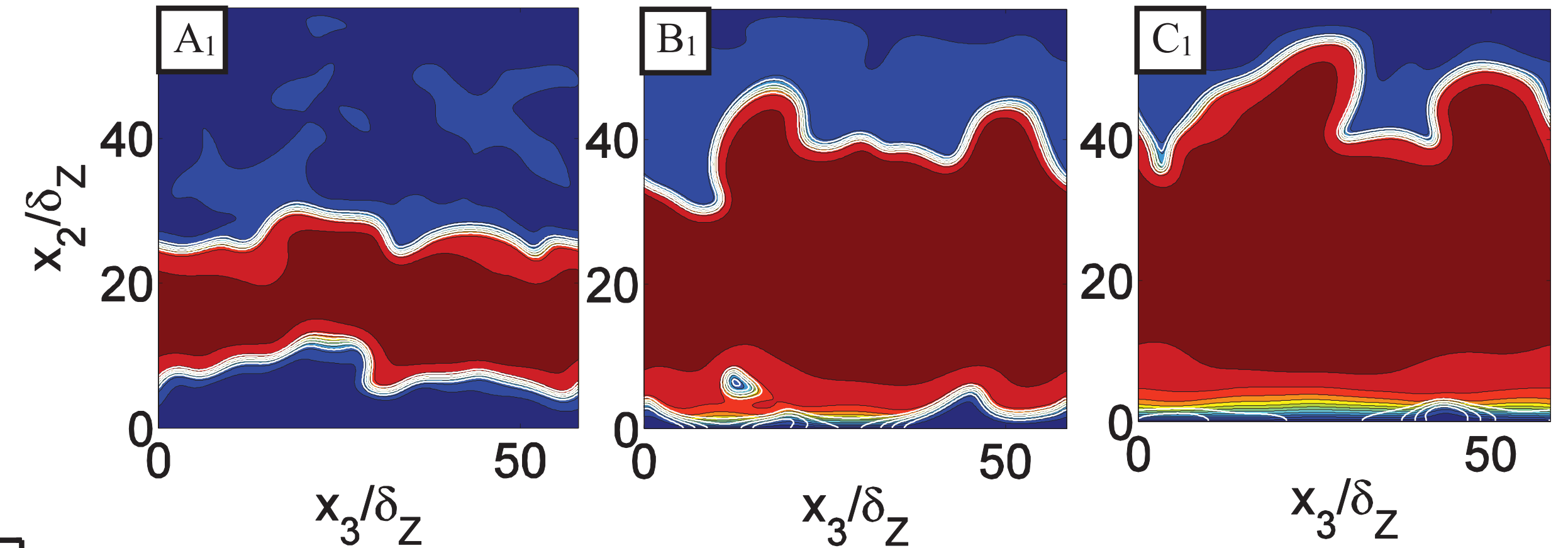
$$\Sigma_{gen} = \exp[-0.25E_1G_x(1 - fb)](1 + \Gamma \cdot u'_\Delta/S_L)^{D-2}|\nabla\bar{c}|$$

$$G_x = 3.0(\bar{c} - \bar{T})^{0.4}\exp\left[-0.5\left(\frac{x_1/\delta_Z - Pe_{min}}{1.2}\right)^4\right]$$

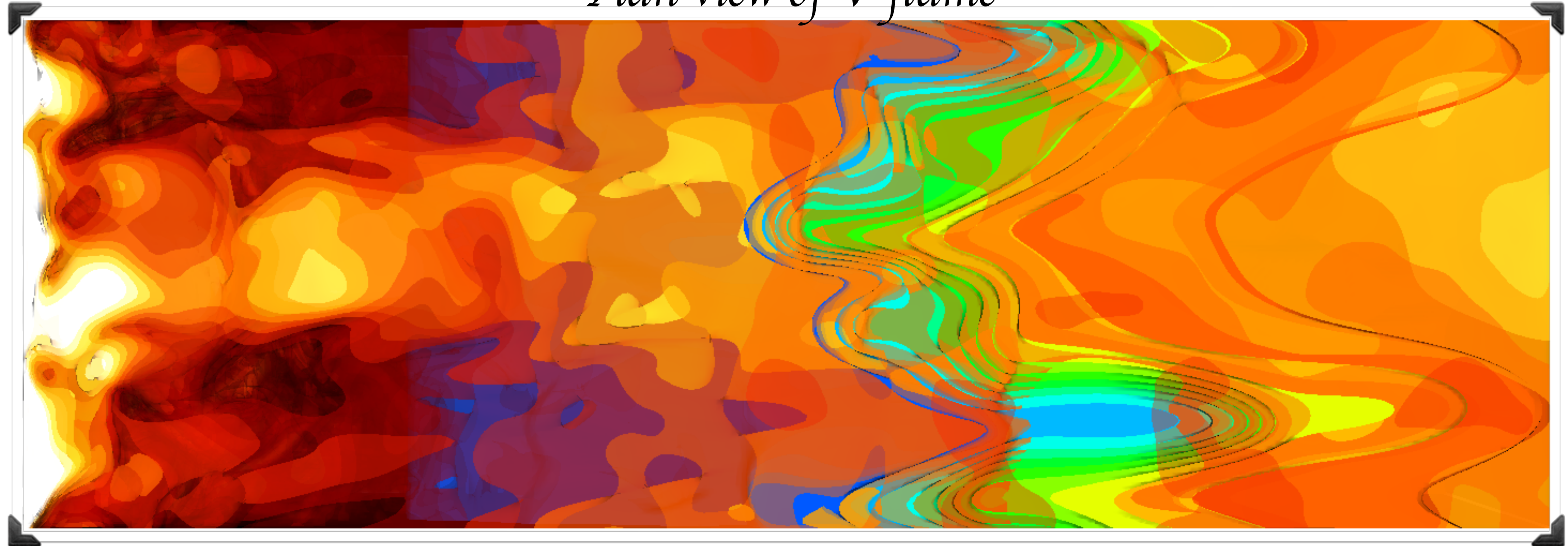
$$E_1 = 0.5[\text{erf}(x_1/\delta_Z - Pe_{min}) - 1]$$

$$\Sigma_{gen} = \exp[B_W E_1 G_x (1 - fb)](1 + \Gamma \cdot u'_\Delta/S_L)^{D-2}|\nabla\bar{c}|$$

$$B_W = 4.22(1 - \cos\alpha)^{0.1}(\bar{c}_W - T_W) - 0.25$$



Plan view of V-flame



- **Maximum Strouhal number is 0.15** with the reference velocity U_{ref} and the characteristic length L_{ref} is the distance between the two side walls.

Thank you for your time!