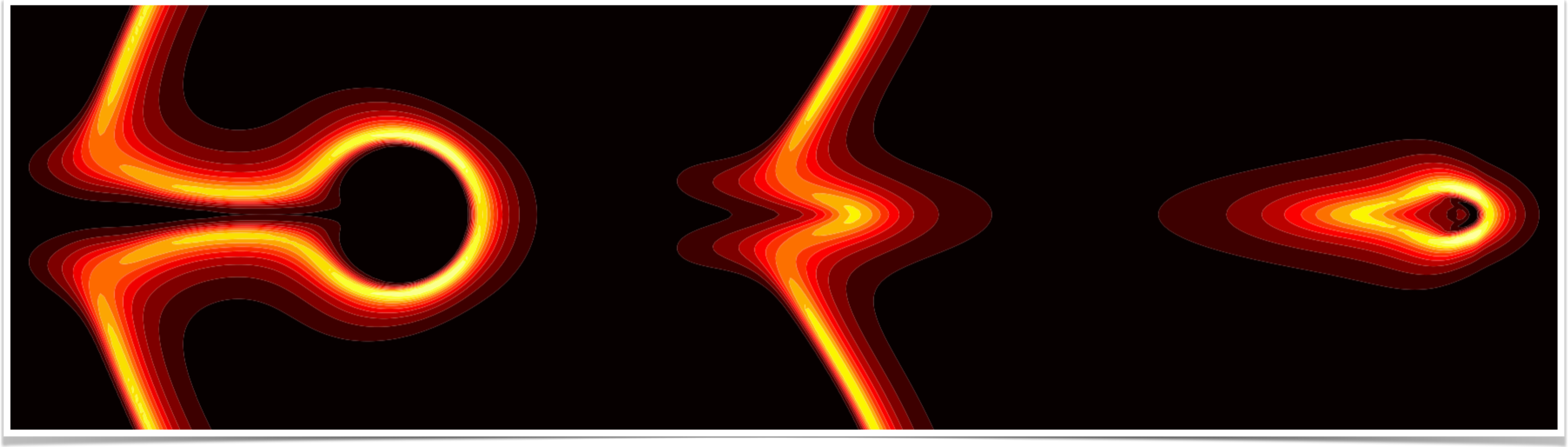


Groupe de travail « Schémas de Boltzmann sur réseau » — 24 février 2021.

LBM – reactive flows

P. Boivin (et al. surtout)

Outline

- Part I : M2P2 & me…
- Part II : LBM : price & prejudices
- Part III : LBM & reactive flows (theory)
- Part IV : Validations (academic & benchmarks)
- Part V: Towards complex configurations
- Part VI : Discussion, perspectives

M2P2

- ~40 EC+C (permanent staff)
- 3 tutelles, 2 sites: Ecole Centrale Marseille & Arbois
- Membre Fédération Fabri de Peiresc (IRPHE, IUSTI, LMA)
- Membre de l'Institut de Mécanique et d'Ingénierie (Idex Marseille)
- 6 équipes de recherches en mécanique et génie des procédés
- TONIC: Thermodynamique, Ondes, Numérique, Instabilités, Combustion.
  7 permanents, 2 émérites.
- Financement industriel ~ 80%.

About me…

Since 2016 : CNRS research fellow
- TONIC team leader
- CR @ M2P2

2014-2016: Post-doctoral studies
- CNES + ANR
- UC3M

2012-2013: Snecma (Vernon)
- Cryogenic engines
- Ignition specialist

2009-2011: PhD - UC3M (Madrid)
- PhD *cum laude*

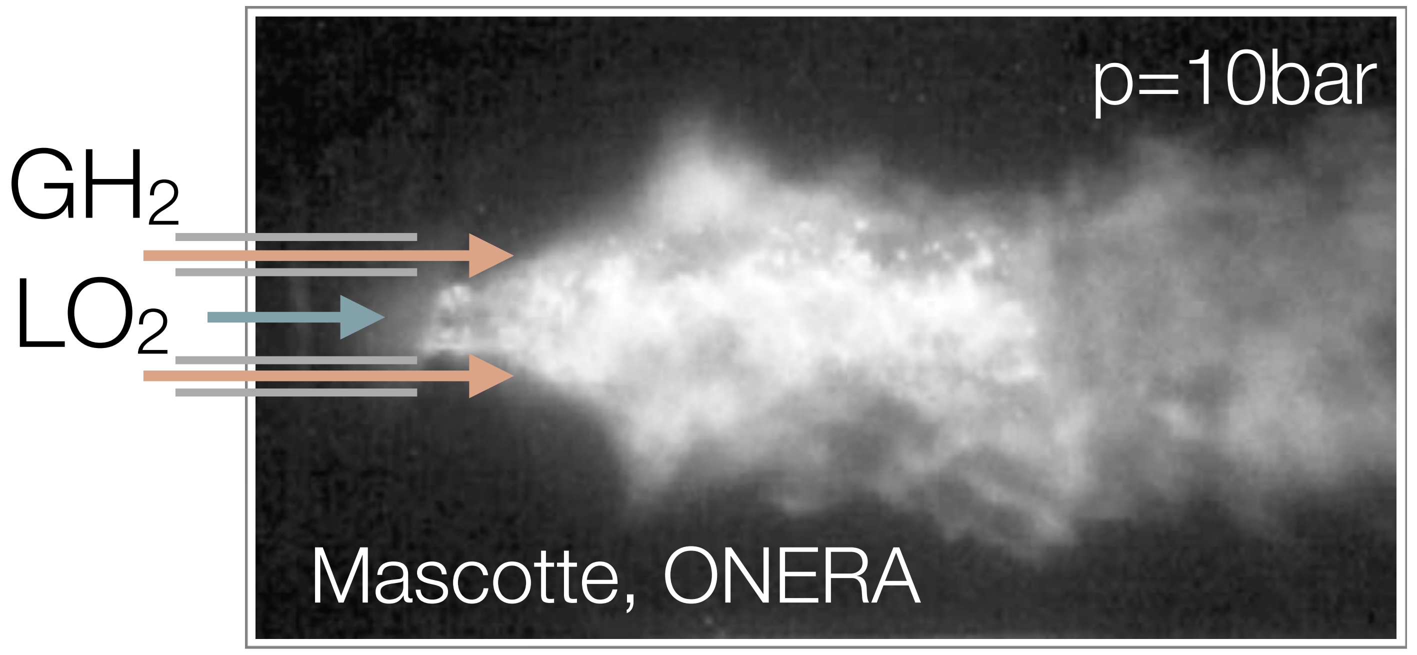
2007-2008: PSA (Vélizy)
- MSc thesis

2006-2007: KTH (Stockholm)
- Double degree

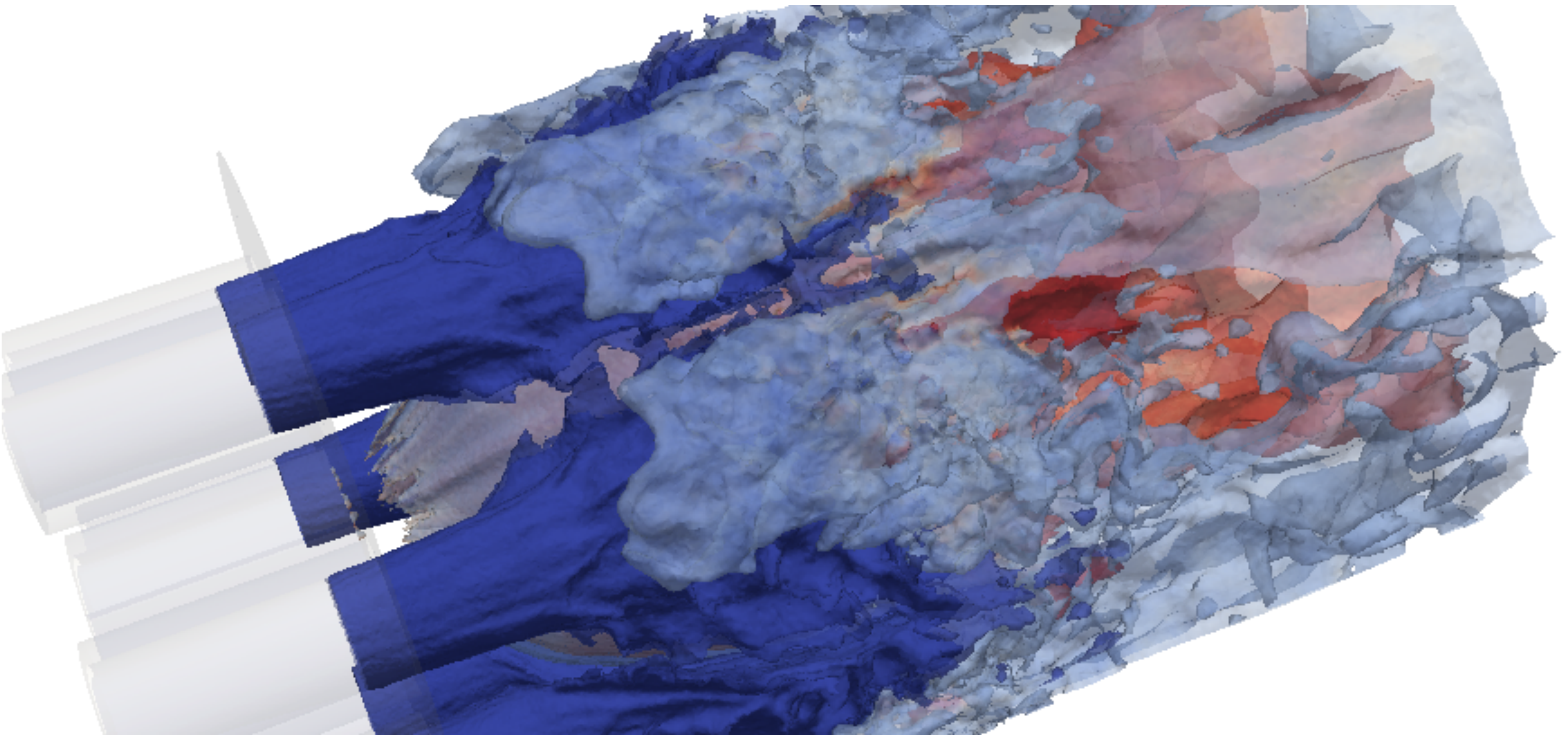
2003-2007: Ecole Polytechnique
- Diplôme d'ingénieur

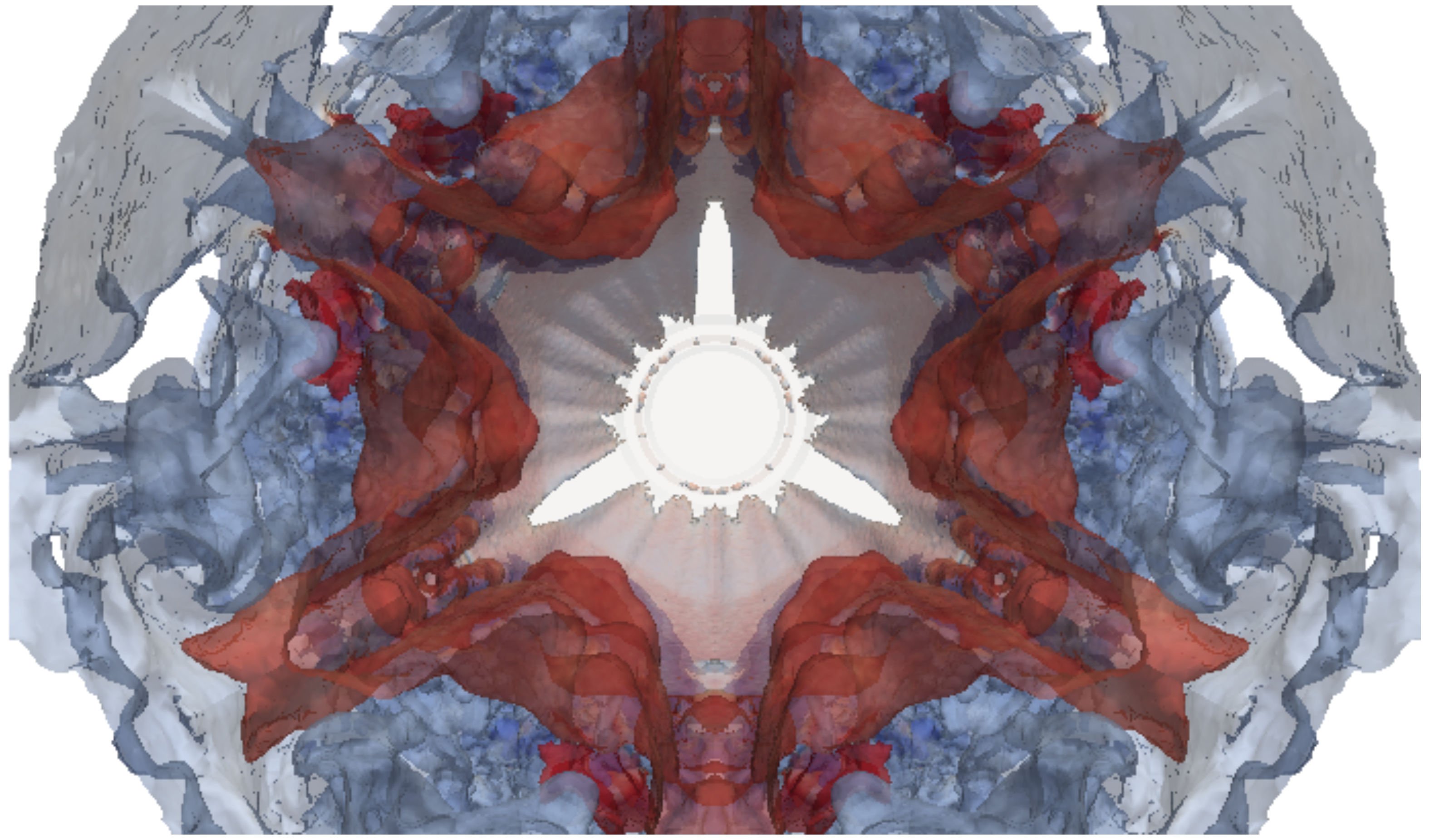
Main research lines

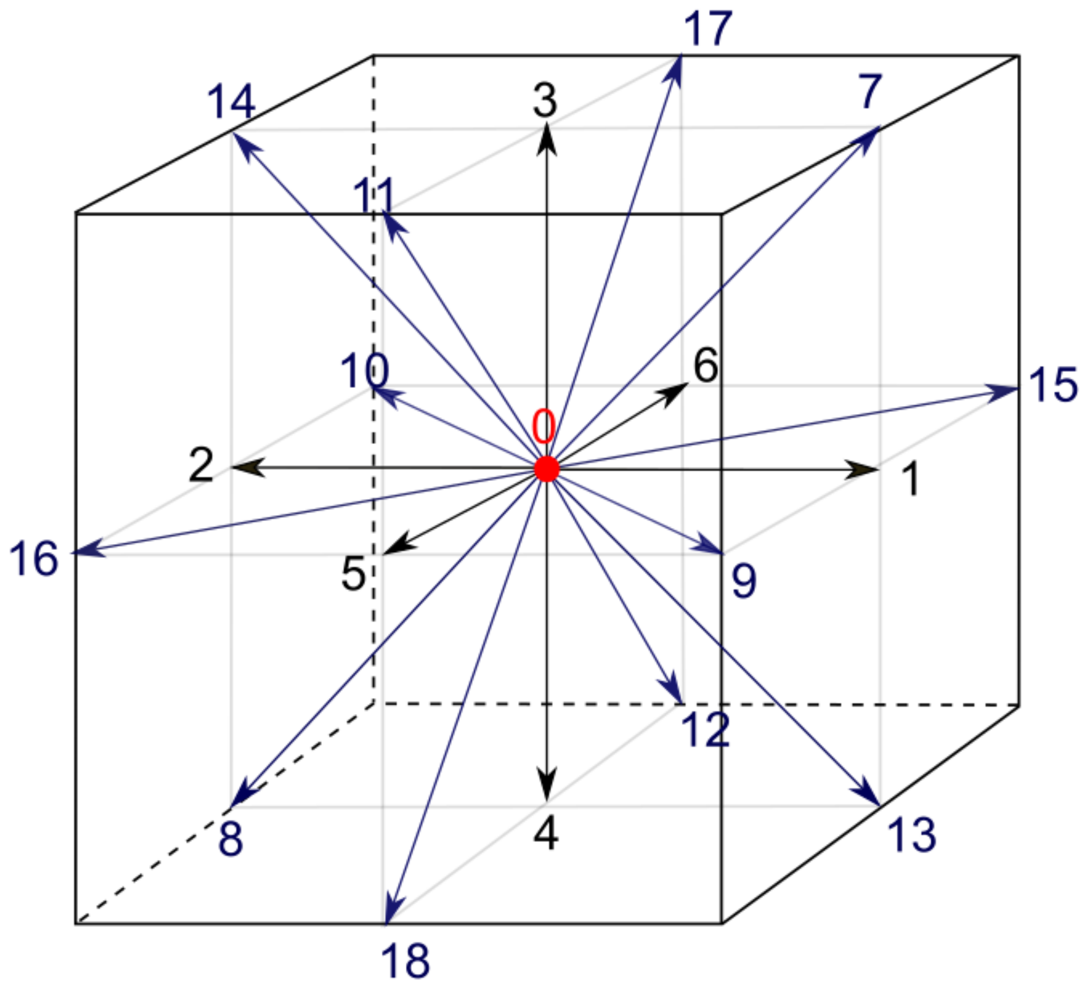
- Difficulty in developing methods able to encompass both multiphase (including a dense part) and reactive flows
    - Multiphase & reactive flows have evolved in separate disciplines
    - Development of thermodynamics & kinetics model simple enough for use in practical applications



Coaxial flame (cryogenic injector)







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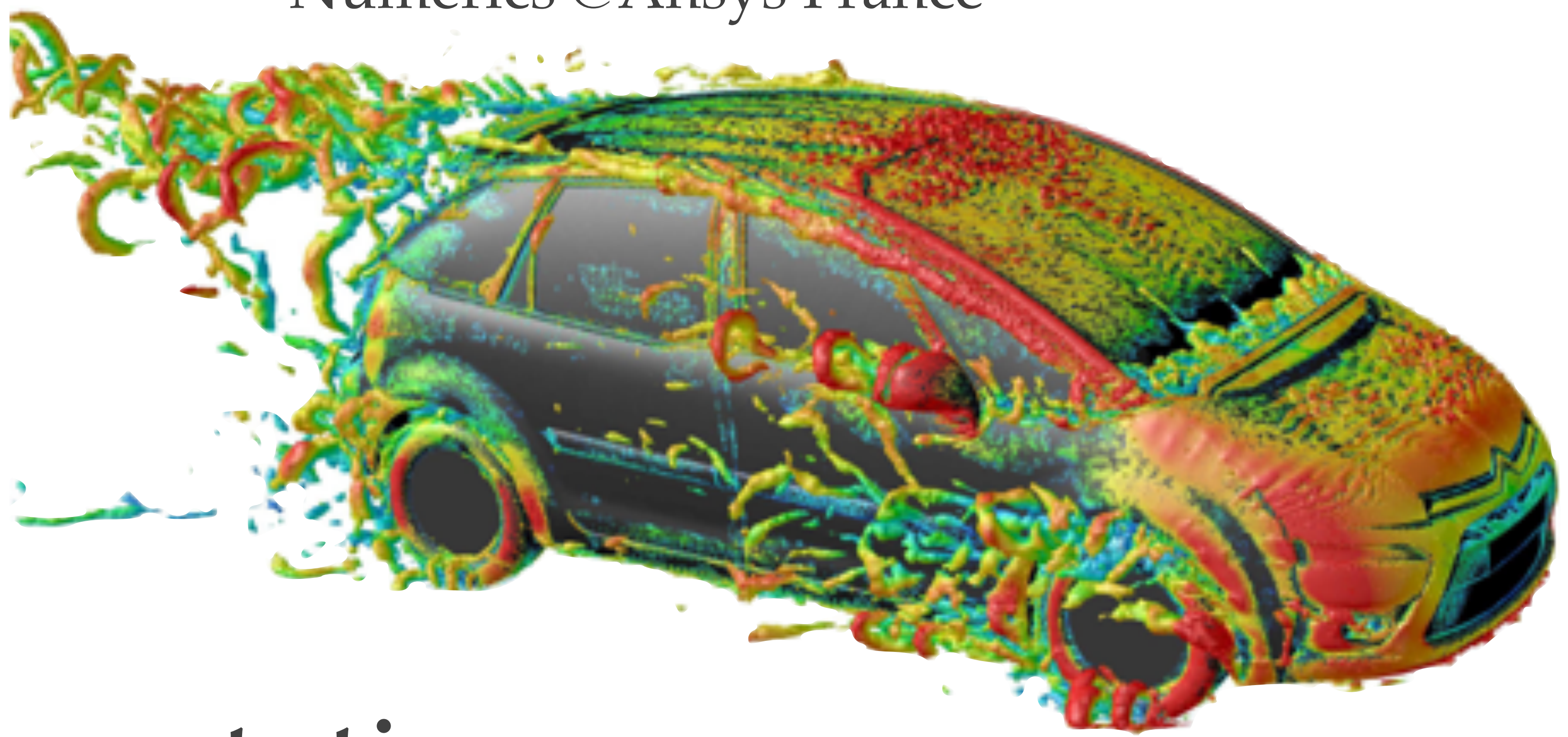
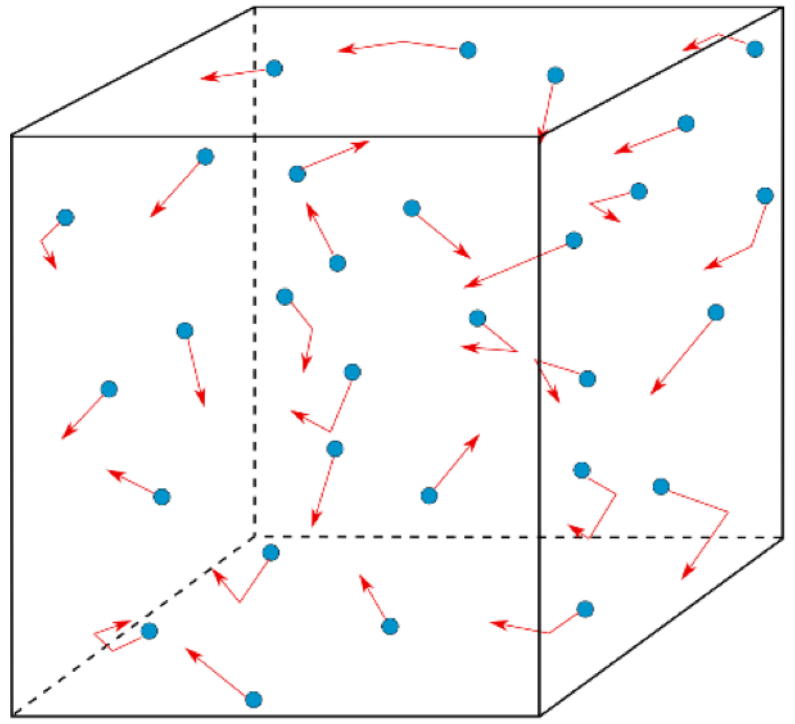
A short & naive history of LBM

Assessment of DES/DDES for external aerodynamics
- Experiments @S2A windtunnel
- Numerics @Ansys France



- Hard to work on real geometries:
  meshing can take up to 3 weeks.
- Coding and scaling NS codes is tedious
- Powerflow came up ~2007 at PSA, doing « free » computations
- Now (2015!) claims to have 85% market share on car aerodynamics
- Expensive > ProLB, French consortium including AMU, Renault, Airbus…
  …. and co-developed at M2P2

LBM - principles



Lattice Boltzmann equation

$$\frac{\partial f}{\partial t} + \xi_\beta \frac{\partial f}{\partial x_\beta} + F_\beta \frac{\partial f}{\partial \xi_\beta} = \Omega(f)$$

$$-\frac{1}{\tau}(f - f^0)$$

BGK

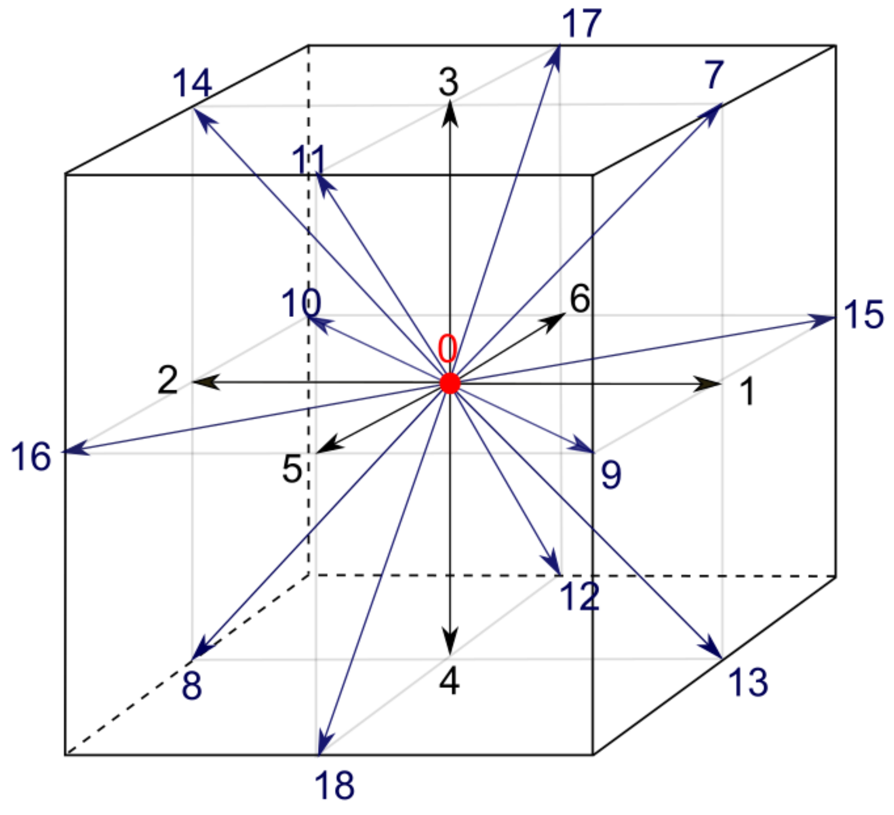
Maxwell-Boltzmann distribution function

$$f^{(0)} = \frac{\rho}{(2\pi c_T^2)^{D/2}} \exp\left(\frac{-(\vec{\xi} - \vec{u})^2}{2c_T^2}\right)$$

Continuum-statistical variables

$$\begin{aligned}
\rho(x,t) &\equiv mn(x,t) = m\int f dv \\
\rho u(x,t) &= m\int f v dv \\
\rho e(x,t) &= \frac{1}{2}m\int f|\underbrace{v-u}_{c}|dv
\end{aligned}$$

LBM - principles

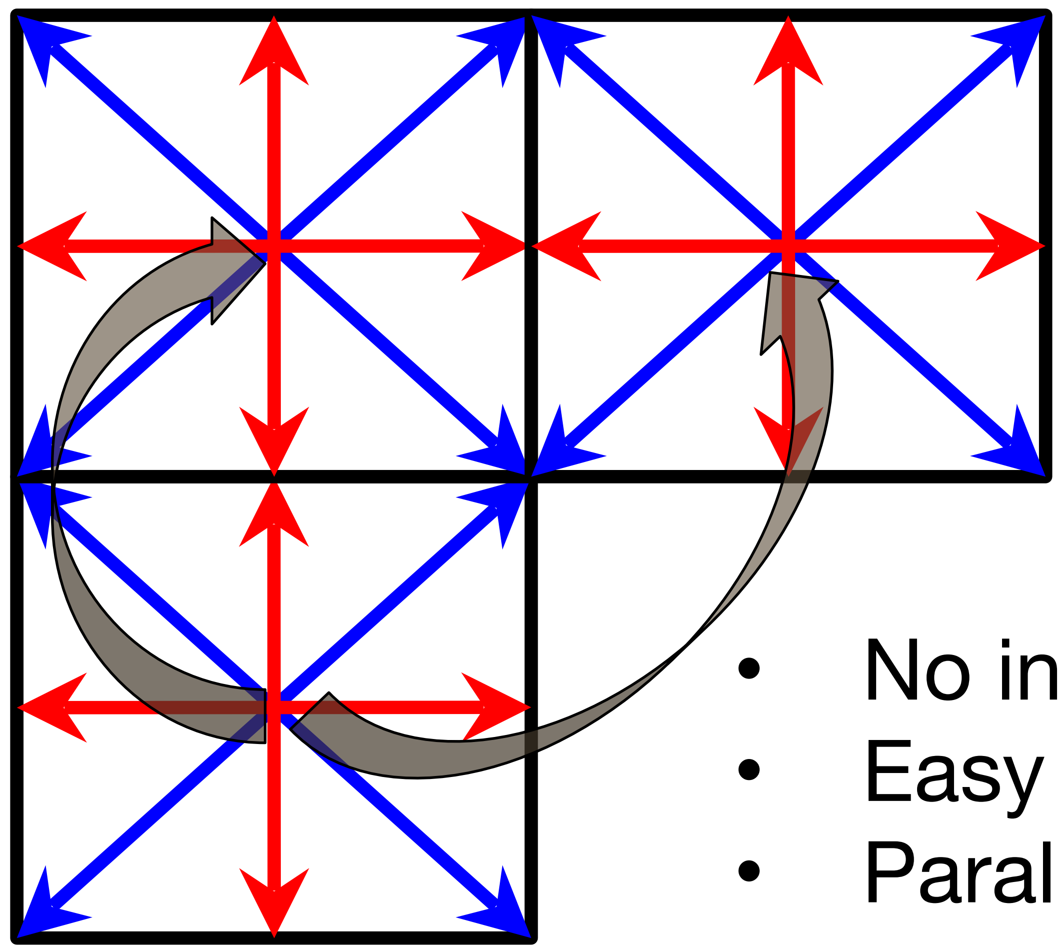


Lattice Boltzmann equation

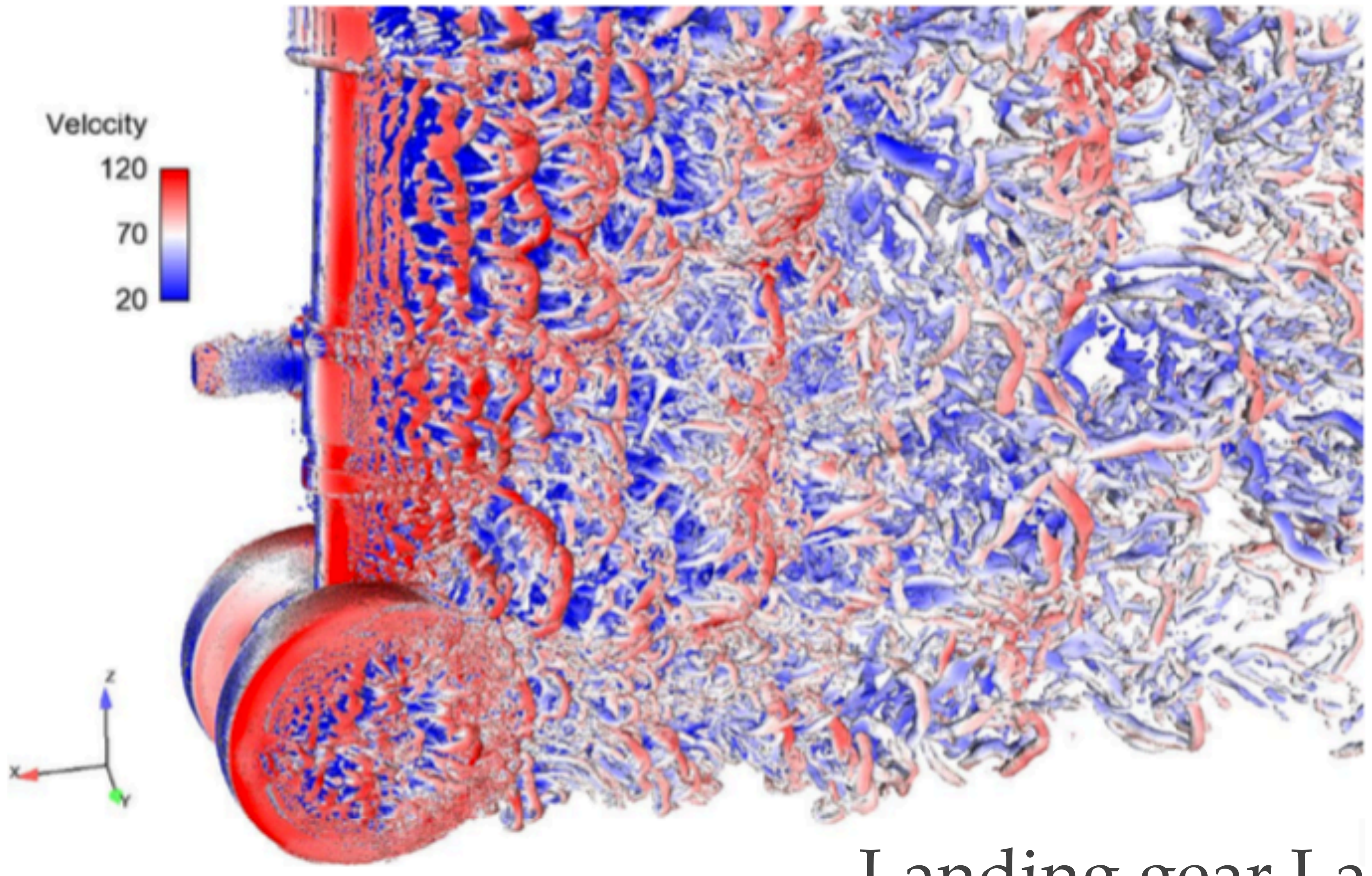
$$\underbrace{\boxed{f_i(\boldsymbol{x}+\boldsymbol{c}\delta t, t+\delta t) - f_i(\boldsymbol{x},t)}}_{\textbf{Streaming}} = \underbrace{\boxed{-\frac{1}{\tau}[f_i(\boldsymbol{x},t) - f_i^{eq}(\boldsymbol{x},t)]}}_{\textbf{Collision}}$$

Maxwell-Boltzmann distribution function

$$f_i^{eq} = \rho w_i \left[1 + \frac{\boldsymbol{c}_i \cdot \boldsymbol{u}}{c_s^2} + \frac{(\boldsymbol{c}_i \cdot \boldsymbol{u})^2}{2c_s^4} - \frac{\boldsymbol{u}^2}{2c_s^2} \right]$$



- No interpolation (in transport)
- Easy to code
- Parallel Computing



Landing gear Lagoon3

But…

$$p = \rho \, . \, c_s^2$$

Classical (athermal) LBM only solves mass & momentum equations…

Some prejudices about LBM for combustion

- LBM is for rarefied gases and the Chapman Enskog expansion is dubious, so why bother ?
- Extending LBM to multicomponent requires many distributions
  > can become stringent in terms of memory usage
- The expensive part of a NS solver is computing combustion related quantities (diffusion / kinetics / …).
- From the last point, one could infer that the same could be obtained with an octree cartesian NS solver.

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Notations from Poinsot & Veynante combustion textbook

Combustion - macroscopic equations

Macroscopic equations

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_\beta}{\partial x_\beta} = 0$$

$$\frac{\partial \rho u_\alpha}{\partial t} + \frac{\partial \rho u_\alpha u_\beta + p\delta_{\alpha\beta} - \mathcal{T}_{\alpha\beta}}{\partial x_\beta} = 0$$

$$\rho\frac{\partial h}{\partial t} + \rho u_\alpha \frac{\partial h}{\partial x_\alpha} = \frac{Dp}{Dt} - \frac{\partial q_\alpha}{\partial x_\alpha} + \mathcal{T}_{\alpha\beta}\frac{\partial u_\alpha}{\partial x_\beta}$$

$$\rho\frac{\partial Y_k}{\partial t} + \rho u_\alpha \frac{\partial Y_k}{\partial x_\alpha} = \frac{\partial}{\partial x_\alpha}(-\rho Y_k V_{k,\alpha}) + \dot{\omega}_k$$

Thermodynamic closure

$$p = \rho \bar{r} T$$

$$\bar{r} = R/\overline{W} \qquad \overline{W} = \frac{1}{\sum_k Y_k/W_k}$$

$$h = \sum_{k=1}^{N} h_k Y_k \ , \ h_k = \int_{T_0}^{T} C_{p,k}(T)dT + \Delta h^0_{f,k}$$

Viscous term

$$\mathcal{T}_{\alpha\beta} = \rho\nu\left(\frac{\partial u_\alpha}{\partial x_\beta} + \frac{\partial u_\beta}{\partial x_\alpha} - \delta_{\alpha\beta}\frac{2}{3}\frac{\partial u_\gamma}{\partial x_\gamma}\right)$$

$$\mu = \mu_0\left(\frac{T}{T_0}\right)^\beta$$

Diffusion terms

$$V_{k,\alpha} = -D_k\frac{\partial X_k}{\partial x_\alpha}\frac{W_k}{\bar{W}} + V^c_\alpha Y_k \qquad D_k = \frac{\mu}{\rho \mathrm{Sc_k}}$$

$$V^c_\alpha = \sum_{k=1}^{N} D_k \frac{\partial X_k}{\partial x_\alpha}\frac{W_k}{\overline{W}} \qquad \lambda = \frac{\mu}{\mathrm{Pr}}\sum_{k=1}^{N} Y_k C_{p,k}$$

$$q_\alpha = -\lambda\frac{\partial T}{\partial x_\alpha} + \rho\sum_{k=1}^{N} h_k Y_k V_{k,\alpha}$$

Fully defined provided

- EOS given (Nasa polynomials)
- Sc_k provided for each species
- Pr provided
- $\mu(T)$ law given
- $\dot{\omega}_k$ given via kinetic scheme

LBM - Multi-physics

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0$$

$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}\boldsymbol{u}) = -\nabla p + \nabla \cdot \left[\rho \nu (\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T)\right]$$

→ **LBM**

+

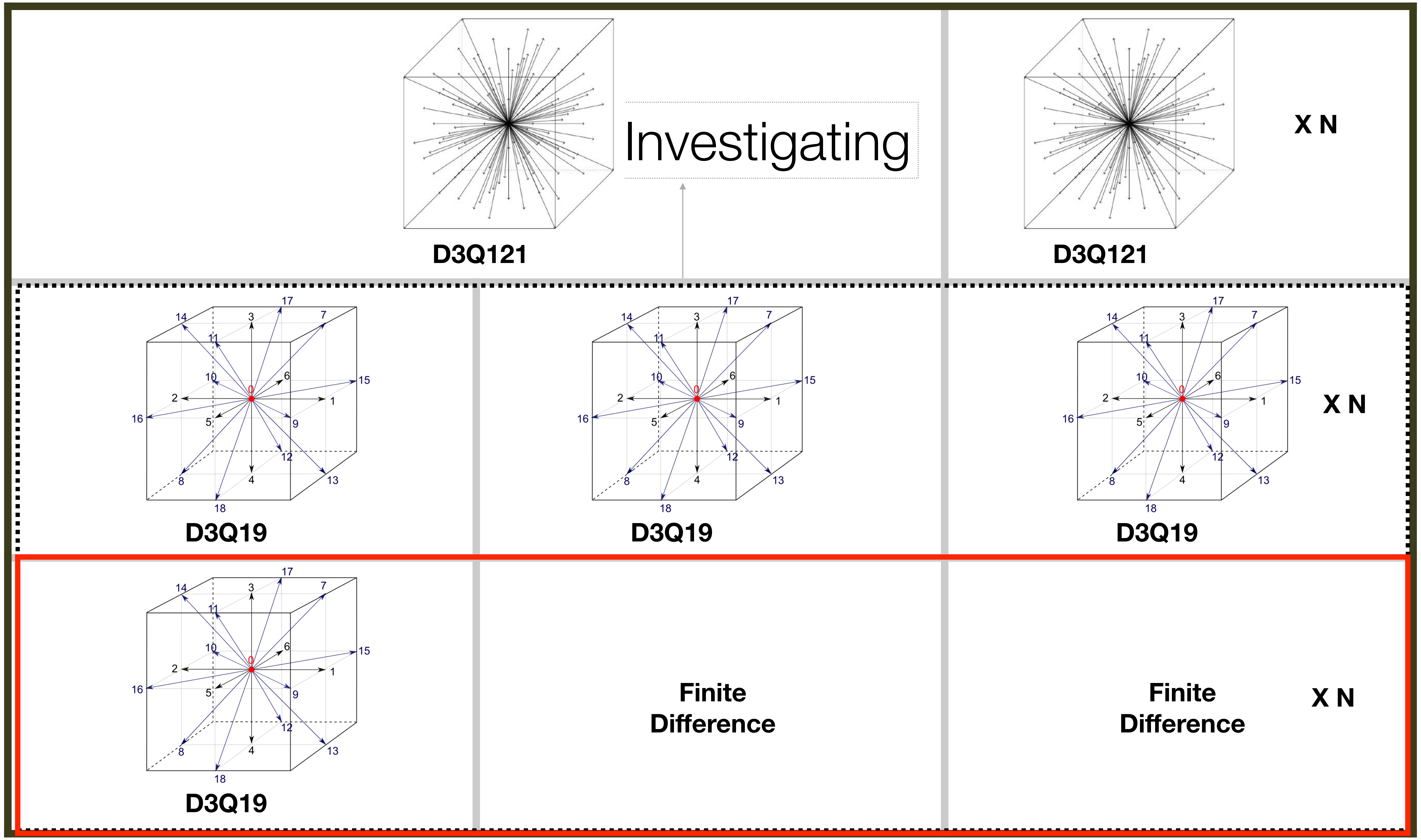
$$\frac{\partial T}{\partial t} + u_\alpha \frac{\partial}{\partial x_\alpha} T = \frac{1}{\rho} \frac{\partial}{\partial x_\alpha} (\rho D_T \frac{\partial T}{\partial x_\alpha}) + \frac{\omega_h}{\rho c_p}$$

+

$$\frac{\partial Y_k}{\partial t} + u_\alpha \frac{\partial}{\partial x_\alpha} Y_k = \frac{1}{\rho} \frac{\partial}{\partial x_\alpha} (\rho D_k \frac{\partial Y_k}{\partial x_\alpha}) + \frac{\omega_k}{\rho}$$

→ **???**

Possible Strategies



Mass/Momentum	Energy	Species
D3Q121	Investigating	D3Q121 X N
D3Q19	D3Q19	D3Q19 X N
D3Q19	Finite Difference	Finite Difference X N

Hybrid LBM (v1: density - based)

- Mass conservation
- Momentum conservation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0$$

$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}\boldsymbol{u}) = -\nabla p + \nabla \cdot \left[\rho \nu (\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T)\right]$$

Chapman-Enskog
or Taylor Expansion

$$f_i(\boldsymbol{x} + \boldsymbol{c}\delta t, t + \delta t) - f_i(\boldsymbol{x}, t) = -\frac{1}{\tau}[f_i(\boldsymbol{x}, t) - f_i^{eq}(\boldsymbol{x}, t)]$$

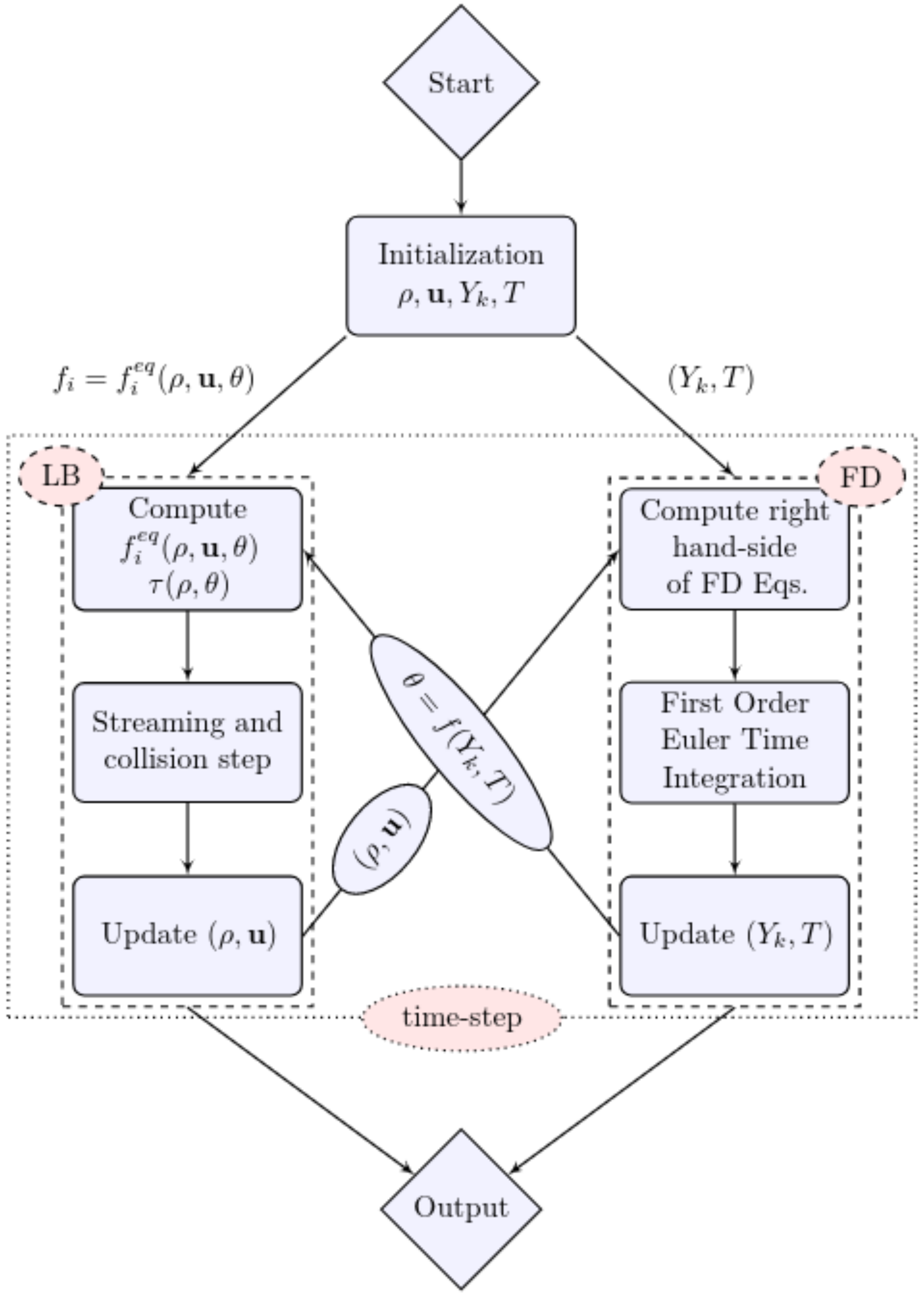
$$f_i^{eq} = \rho w_i \Bigg[1 + \frac{\boldsymbol{c}_i \cdot \boldsymbol{u}}{c_s^2} + \frac{(\boldsymbol{c}_i \cdot \boldsymbol{u})^2}{2c_s^4} - \frac{\boldsymbol{u}^2}{2c_s^2}$$
$$+(\theta - 1)\left(\frac{1}{2}(\frac{\boldsymbol{c}_i^2}{c_s^2} - D) + \frac{\boldsymbol{c}_i \cdot \boldsymbol{u}}{2c_s^2}(\frac{c_i^2}{c_s^2} - D - 2)\right)\Bigg]$$

$$\theta = \frac{\overline{r}T}{c_s^2} = \frac{RT}{c_s^2}\sum_k \frac{Y_k}{W_k} = f(T, Y_k)$$

- Energy conservation
- Species conservation

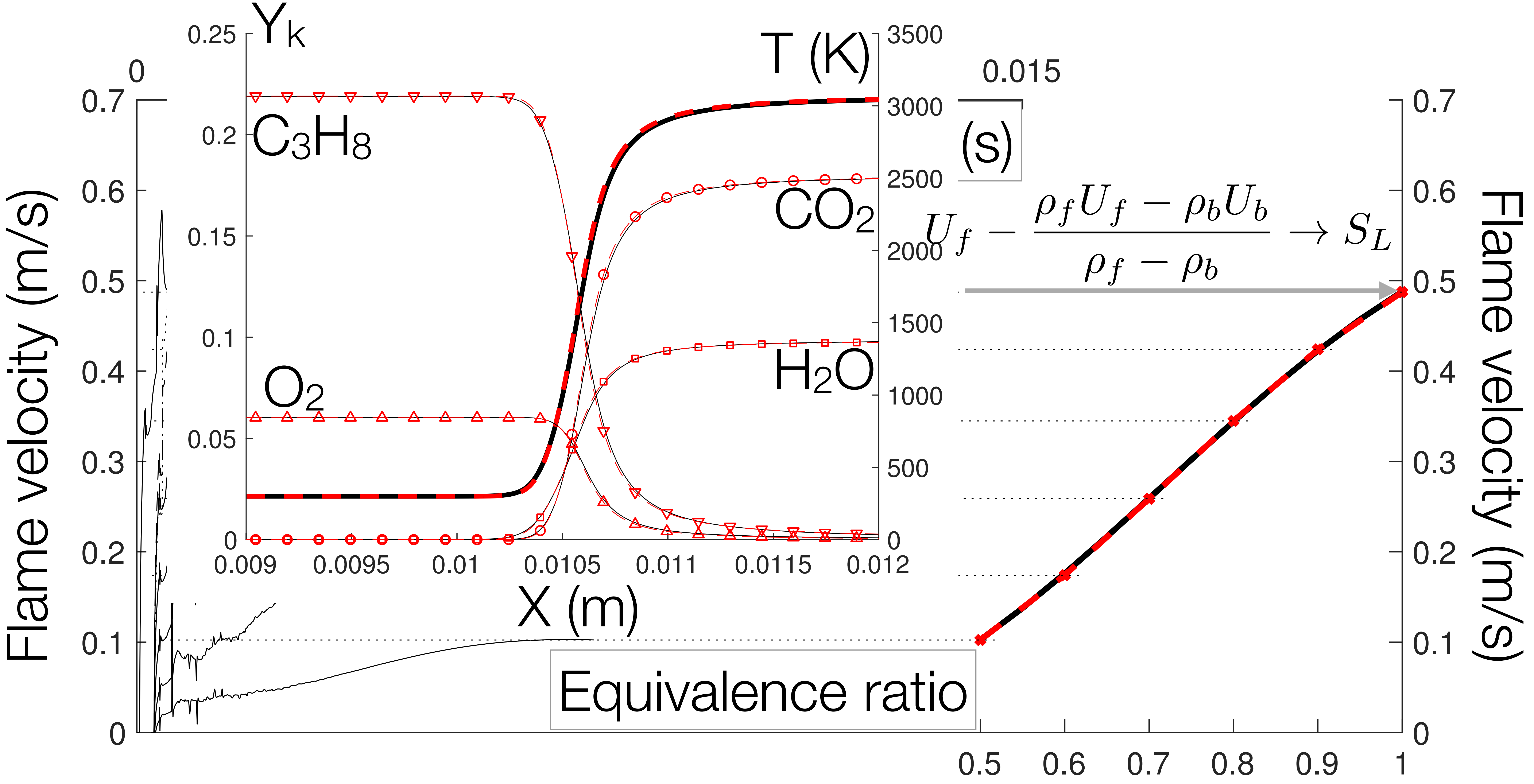
$$\frac{\partial T}{\partial t} + u_\alpha \frac{\partial}{\partial x_\alpha} T = \frac{1}{\rho}\frac{\partial}{\partial x_\alpha}(\rho D_T \frac{\partial T}{\partial x_\alpha}) + \frac{\omega_h}{\rho c_p}$$

$$\frac{\partial Y_k}{\partial t} + u_\alpha \frac{\partial}{\partial x_\alpha} Y_k = \frac{1}{\rho}\frac{\partial}{\partial x_\alpha}(\rho D_k \frac{\partial Y_k}{\partial x_\alpha}) + \frac{\omega_k}{\rho}$$



Successes with v1: premixed flame.

C_3H_8-air - 1s
Lewis transp.
Cp(T)

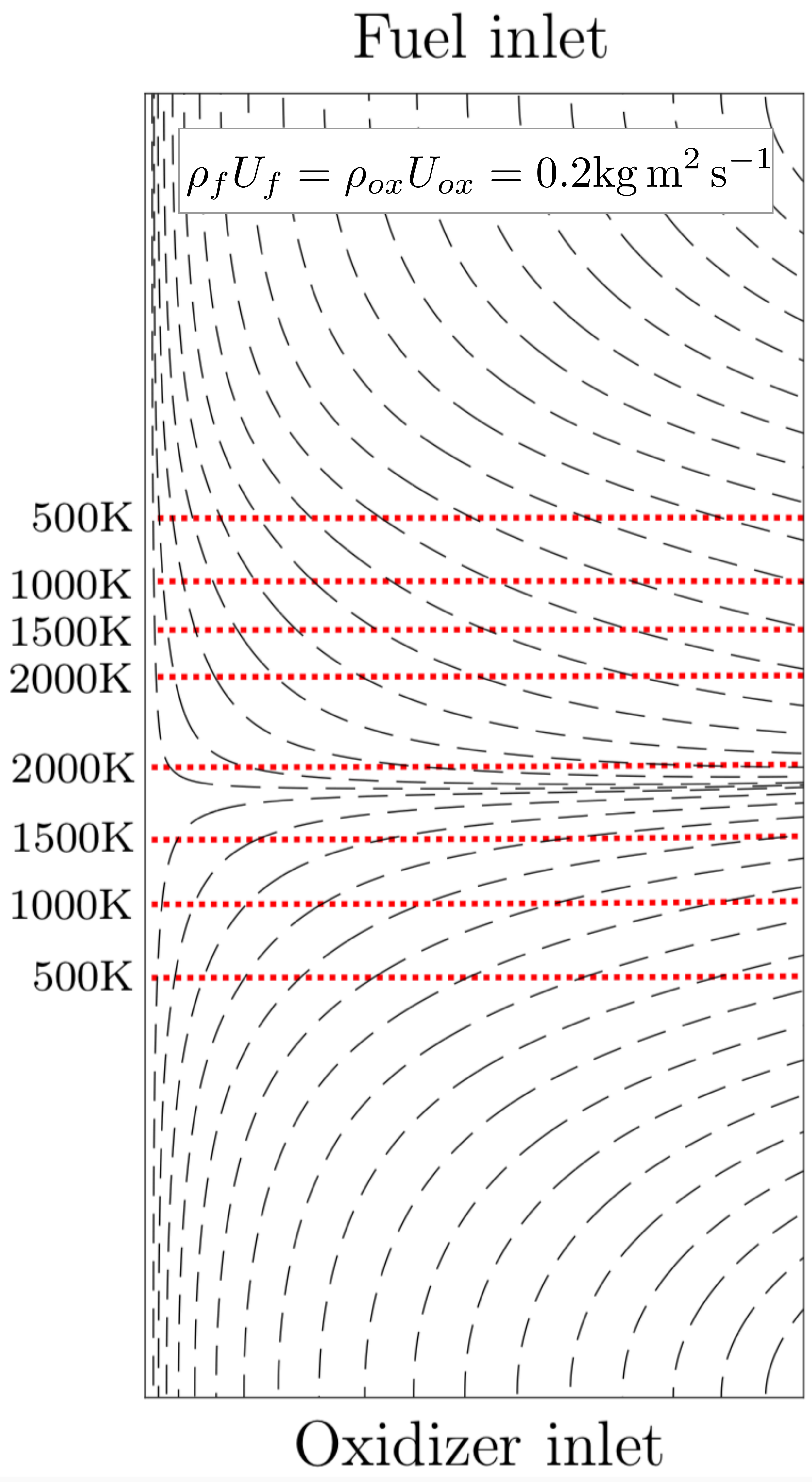


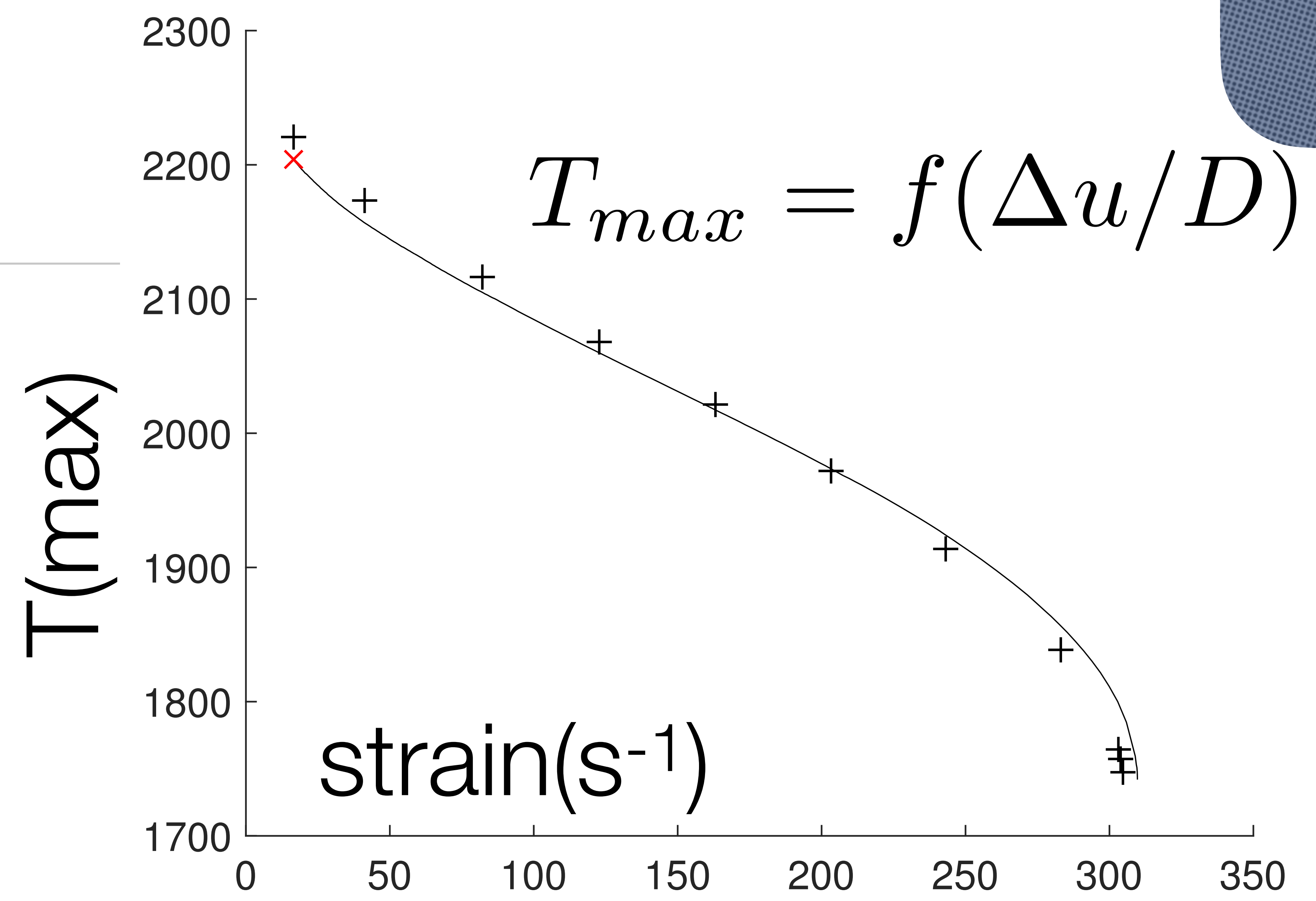
$$U_f - \frac{\rho_f U_f - \rho_b U_b}{\rho_f - \rho_b} \rightarrow S_L$$

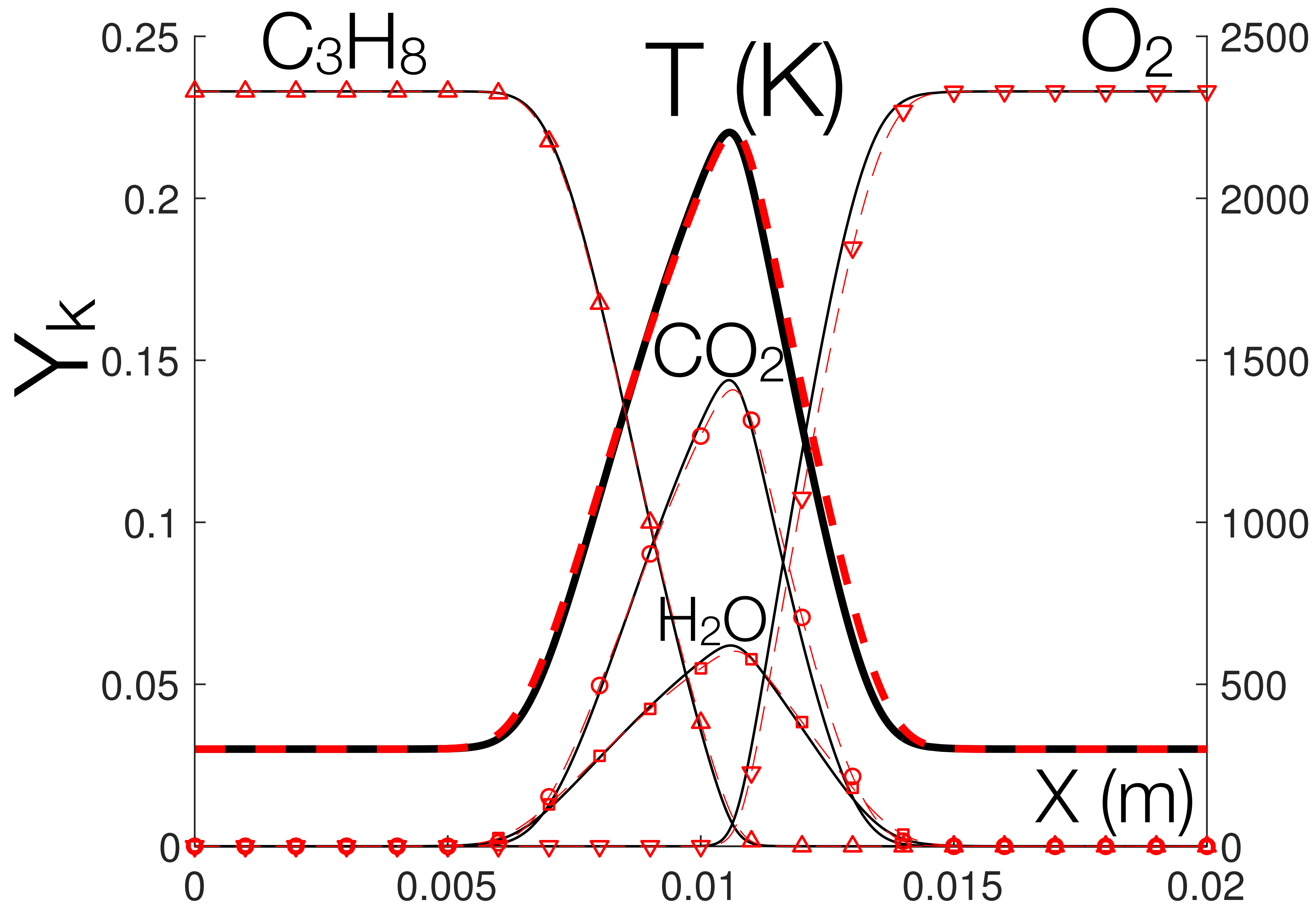
Chemistry: One Step - Propane (S. Chen et al. (2007), AMC)

C_3H_8-air - 1s
Lewis transp.
Cp(T)

Diffusion flame







Going more complex…

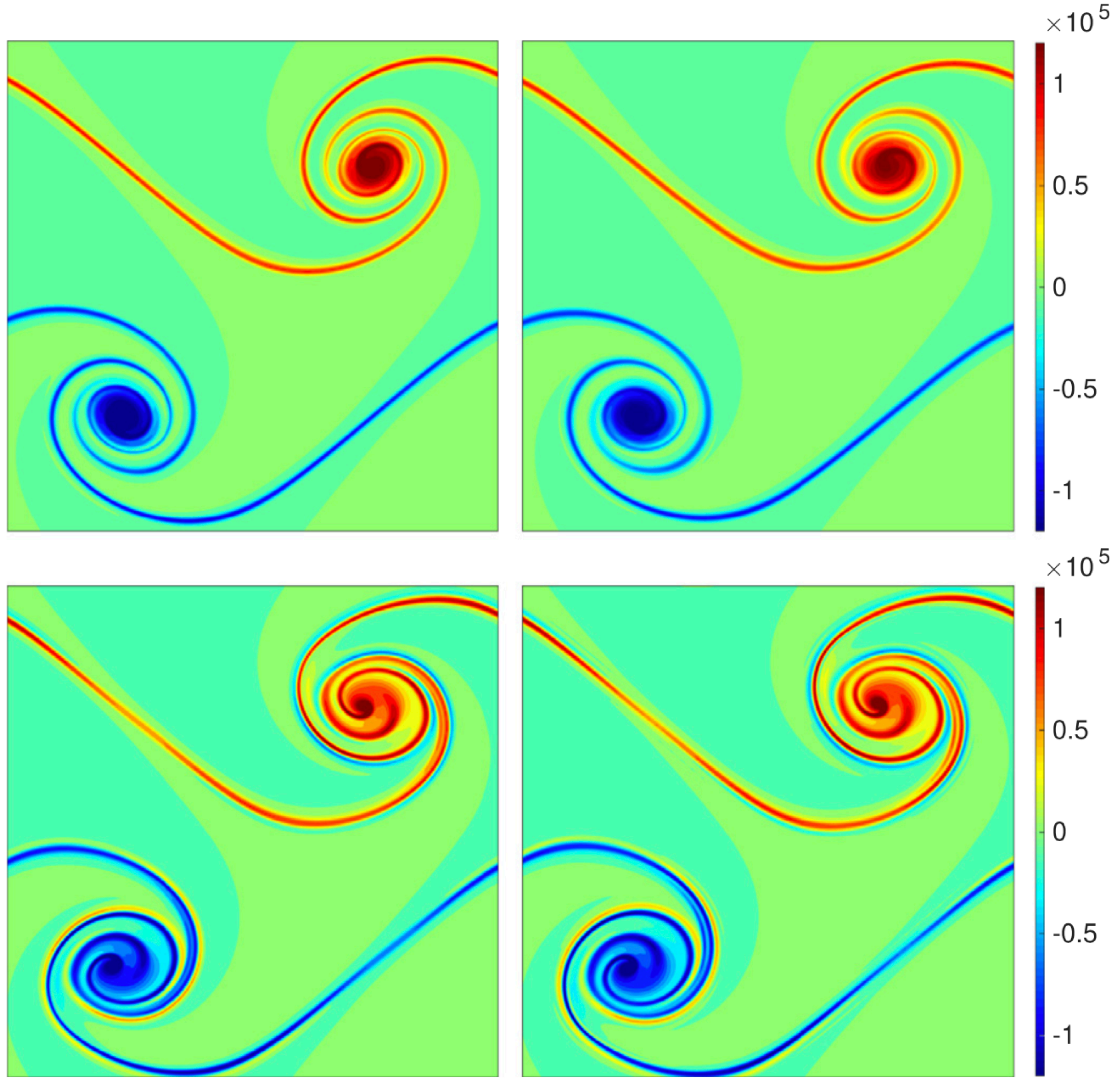
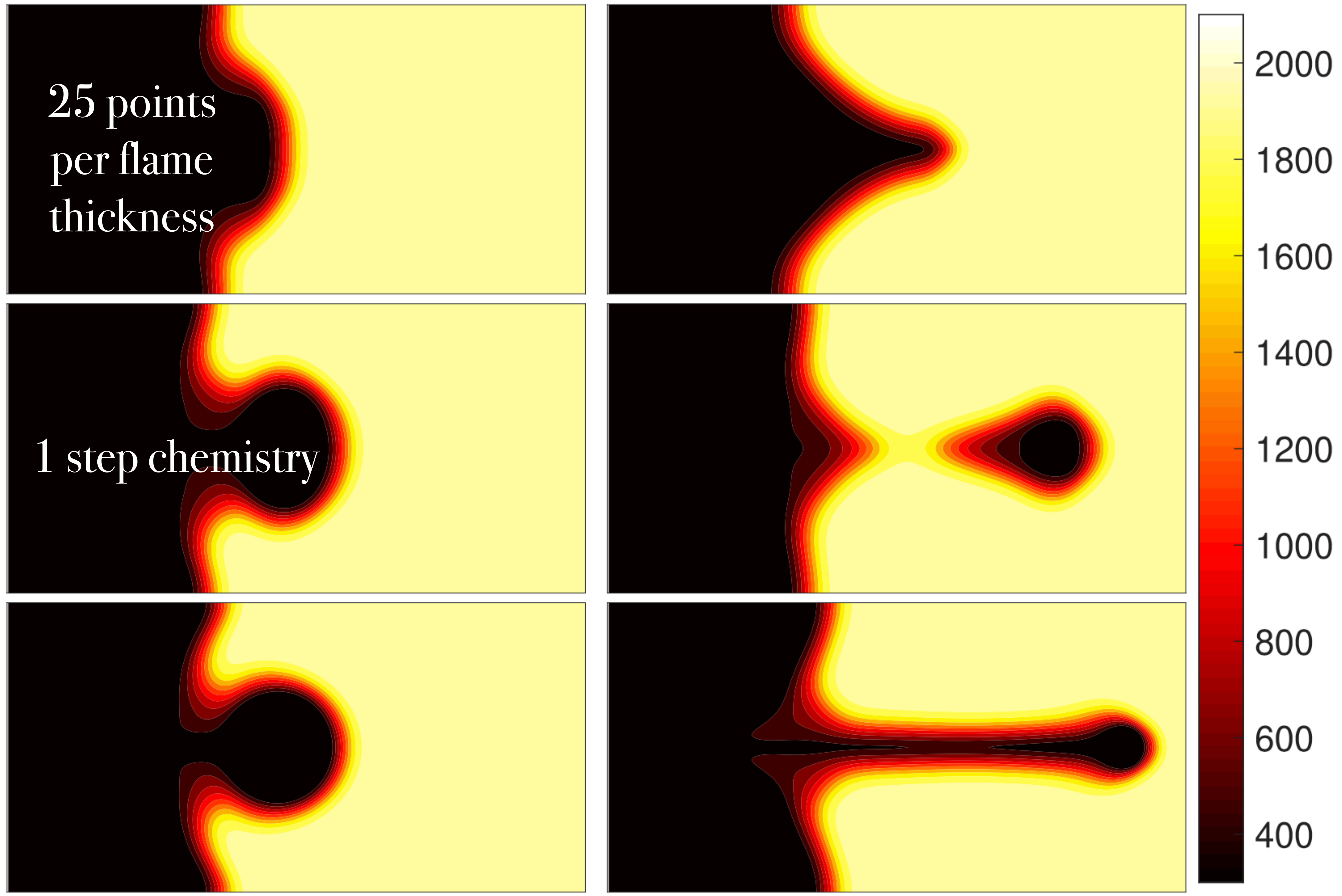


Fig. 6. Doubly periodic shear layer at $Re = 3.10^4$. Vorticity contours (magnitude of the z-component) at $t = t_c$. NTMIX contours (left) compared with the LBM contours (right), for the compressible "cold" flow (top) and the "hot" flow (bottom), e.g. including the chemical source term, on a 1024×1024 grid.

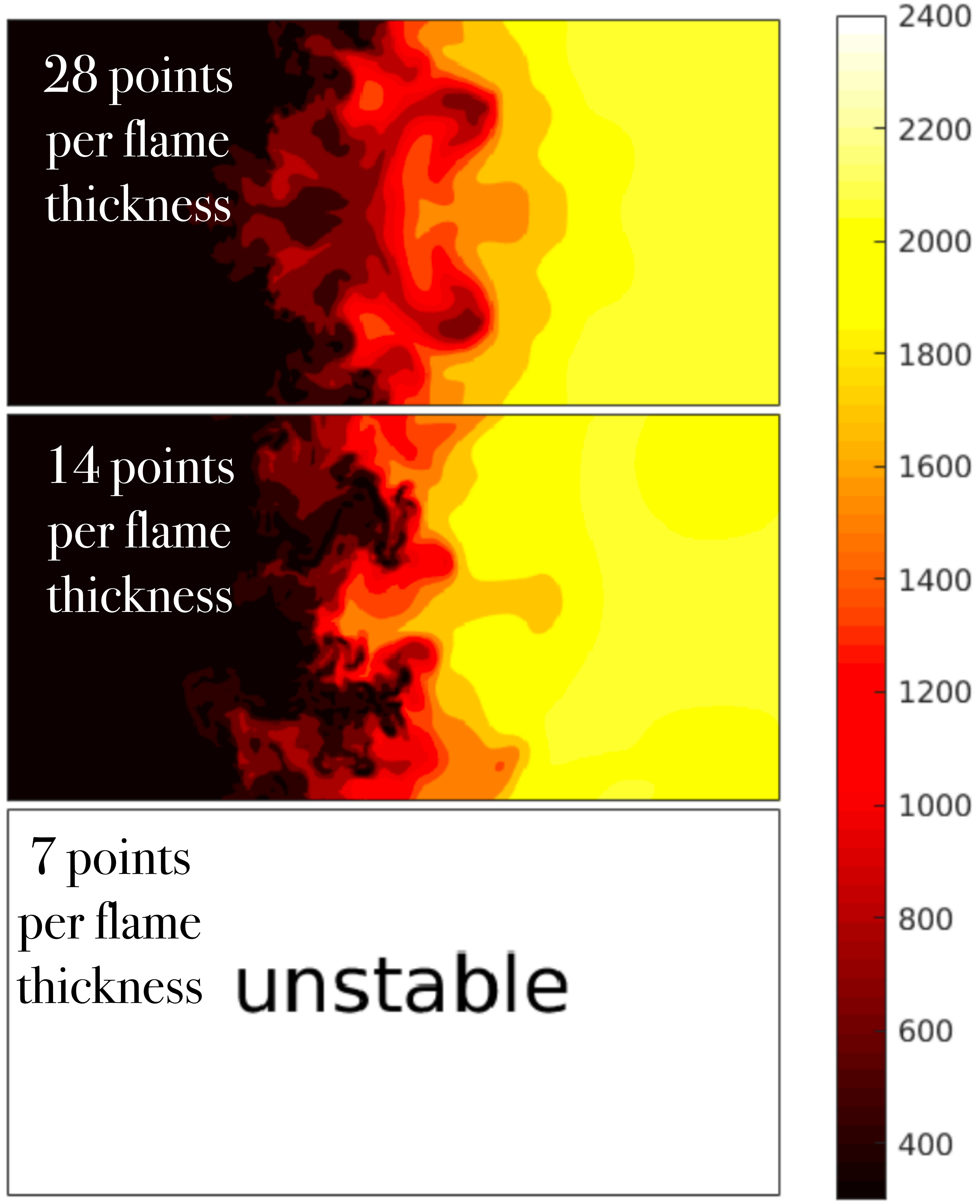


25 points per flame thickness

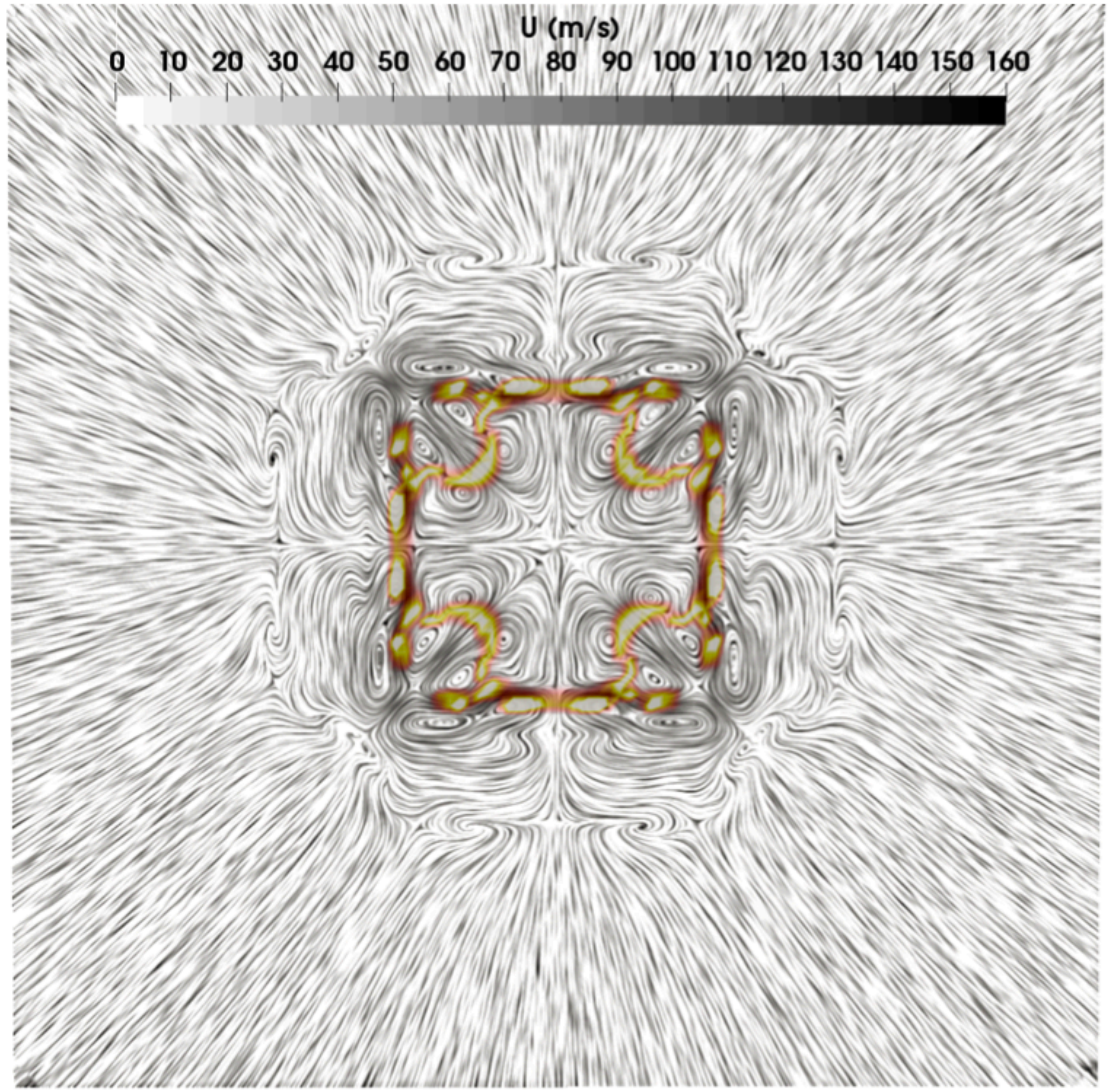
1 step chemistry

Fig. 4. Contours of the temperature in a premixed flame - vortex interaction. From top to bottom: case A at $t = 2.12$ and $t = 2.83$; case B at $t = 1.42$ and $t = 1.80$; case C at $t = 0.90$ $t = 1.09$.

… and quickly reaching limitations …



Vortex/flame (hydrogen, 12 steps)



« Spherical flame »

General idea for model 2.0

- About segregated density/pressure-based methods
  - A classical CFD approach (1980s - now) for "all speed methods"
  - used in FLUENT, STARCCM+, some OpenFoam versions …
- Generic structure
  - Predictor step (starting from (u^n, p^n, T^n, ρ^n))
    - compute intermediary variables $(u*, p*, T*, \rho*)$ solving a (nearly) incompressible problem with a robust (usually implicit) method
    - Segregated = energy equation solved separately from mass+momentum
  - Corrector step
    - Solve an equation for pressure/density correction to recover full compressibility
    - update other variables using the new pressure/density $(u*, p*, T*, \rho*) \to (u^{n+1}, p^{n+1}, T^{n+1}, \rho^{n+1})$

Model 1.0 « density »

- Resolution for f
- $(\theta - 1)$ term in f_{eq}
- 3rd order eq. Distribution
- $$\begin{cases} \sum_i f_i = \rho \\ \sum_i c_{i,\alpha}\, f_i = \rho u_\alpha \\ \sum_i c_{i,\alpha} c_{i,\beta}\, f_i = \rho u_\alpha u_\beta + \rho c_s^2\, \delta_{\alpha\beta} \end{cases}$$
- Collision kernel:
  hybrid regularized ($\sigma \in [0,0.5]$)
- Correction term to account for the lattice defect (stress tensor)

[1] Y. Feng, M. Tayyab, and P. Boivin, "A lattice-boltzmann model for low-mach reactive flows," Combustion and Flame, vol. 196, pp. 249 – 254, 2018.
[2] Y. Feng, P. Boivin, J. Jacob, and P. Sagaut, "Hybrid recursive regularized thermal lattice boltzmann model for high subsonic compressible flows," Journal of Computational Physics, vol. 394, pp. 82 – 99, 2019.

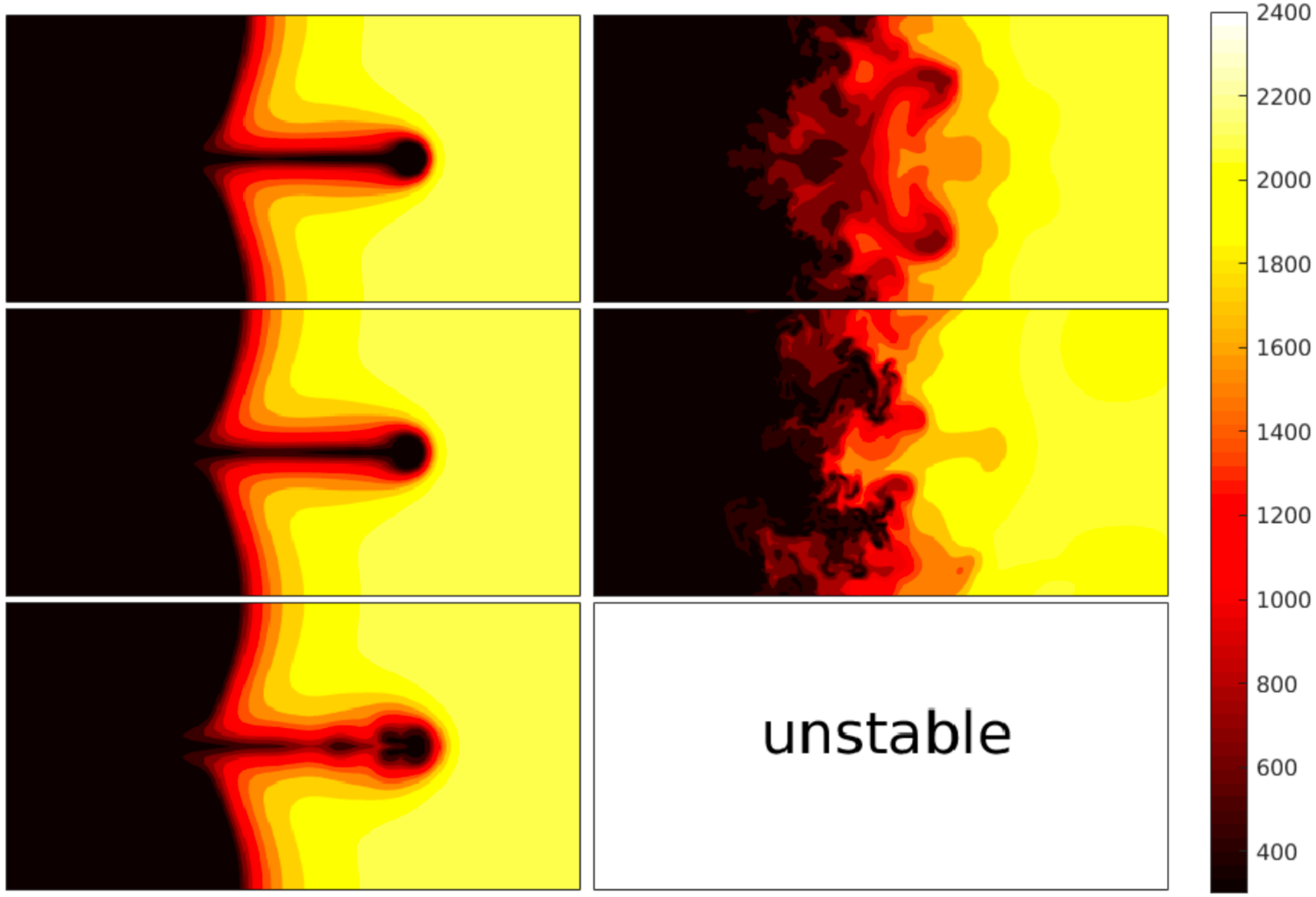
Model 2.0 « pressure »

- Resolution for g
- Athermal formulation for g_{eq} (orders > 0)
- 2^{nd} order is enough…
- $$\begin{cases} \sum_i g_i = \rho\theta \\ \sum_i c_{i,\alpha}\, g_i = \rho u_\alpha \\ \sum_i c_{i,\alpha} c_{i,\beta}\, g_i = \rho u_\alpha u_\beta + \rho\theta c_s^2\, \delta_{\alpha\beta} \end{cases}$$
- Modified macroscopic variable reconstruction
  $$\rho(t+\Delta t, x) = \sum_i \left[g_i^*(t+\Delta t, x) \right] - \rho(t,x)\theta(t,x) + \rho(t,x)$$
- Additional 2^{nd} order correction needed
  $$a_{\alpha\beta}^{\text{cor}} \equiv c_s^2 \delta_{\alpha\beta} \Big[\rho(t+\Delta t, x)(1 - \theta(t+\Delta t, x)) - \rho(t,x)(1 - \theta(t,x)) \Big]$$

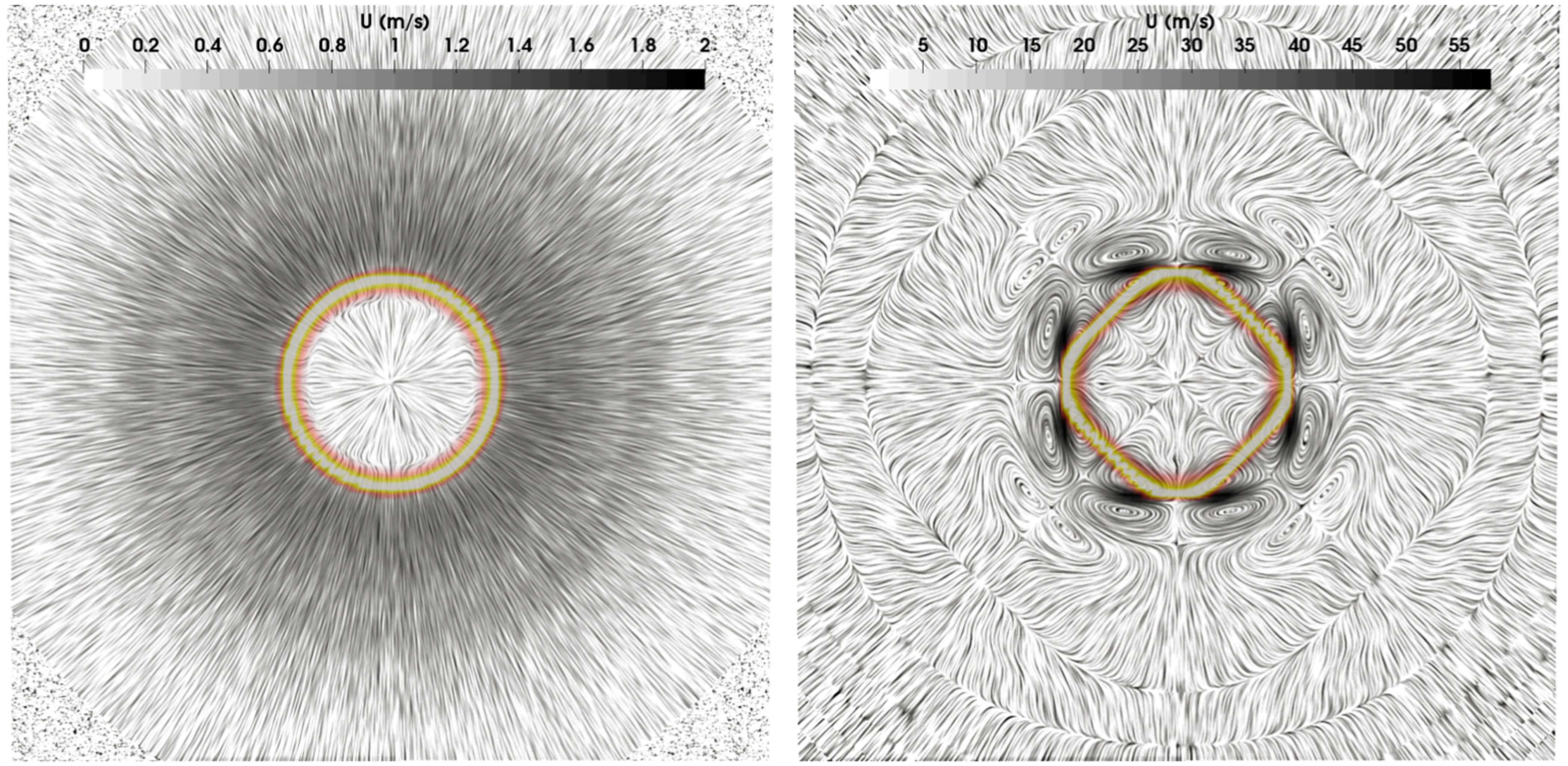
[1] G. Farag, S. Zhao, T. Coratger, P. Boivin, G. Chiavassa, and P. Sagaut, "A pressure-based regularized lattice-boltzmann method for the simulation of compressible flows," Physics of Fluids, vol. 32, no. 6, p. 066106, 2020.

H_2-air - 12s
Lewis transp.
Cp(T)

Pressure-based vs Density-based



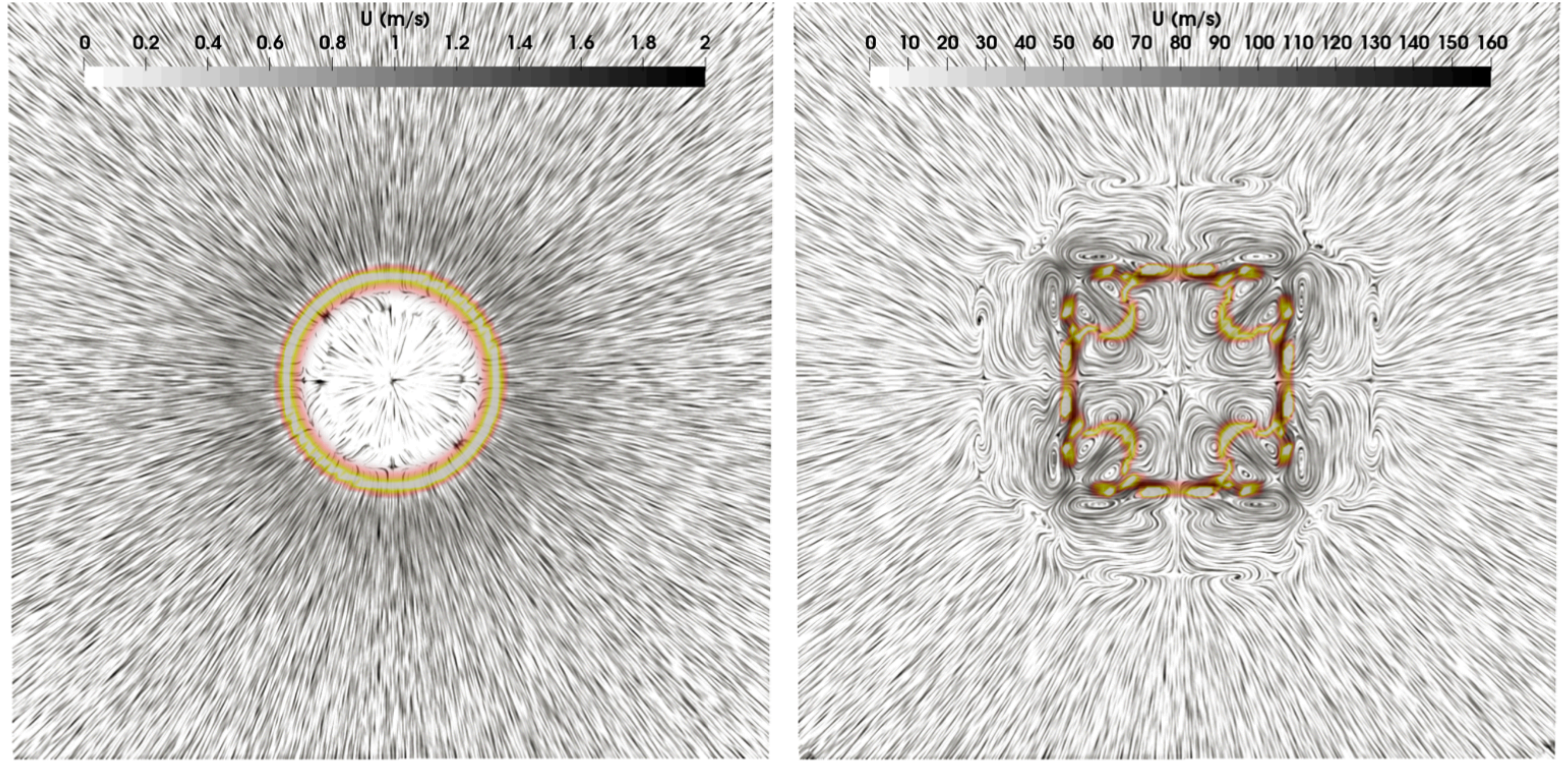
Vortex/flame interaction for 3 for H_2-air flames (28, 14, 7 pts/flame thickness)



Pressure-based

(a) t=2.0×10^{-2}ms

Density-based



(b) t=4.0×10^{-2}ms

References

- Y. Feng, M. Tayyab, and P. Boivin, “A lattice-boltzmann model for low-mach reactive flows,” Combustion and Flame, vol. 196, pp. 249 – 254, 2018. **(v1)**
- Y. Feng, P. Boivin, J. Jacob, and P. Sagaut, “Hybrid recursive regularized thermal lattice boltzmann model for high subsonic compressible flows,” Journal of Computational Physics, vol. 394, pp. 82 – 99, 2019. **(v1)**
- M. Tayyab, S. Zhao, Y. Feng, and P. Boivin, “Hybrid regularized lattice-boltzmann modelling of premixed and non-premixed combustion processes,” Combustion and Flame, vol. 211, pp. 173–184, 2020. **(v1)**
- G. Farag, S. Zhao, T. Coratger, P. Boivin, G. Chiavassa, and P. Sagaut, “A pressure-based regularized lattice-boltzmann method for the simulation of compressible flows,” Physics of Fluids, vol. 32, no. 6, p. 066106, 2020. **(v2)**
- M. Tayyab, B. Radisson, C. Almarcha, B. Denet, and P. Boivin, “Experimental and numerical lattice- boltzmann investigation of the darrieus-landau instability,” Combustion and Flame, vol. 221, pp. 103–109, 2020. **(v2)**
- S. Zhao, G. Farag, P. Boivin, and P. Sagaut, “Toward fully conservative hybrid lattice boltzmann methods for compressible flows,” Physics of Fluids, vol. 32, no. 12, p. 126118, 2020. **(v2)**
- M. Tayyab, S. Zhao, and P. Boivin, “Lattice-boltzmann modelling of a turbulent bluff-body stabilized flame,” Physics of Fluids, 2021. **(v2)**
- G. Farag, S. Zhao, G. Chiavassa, and P. Boivin, “Consistency study of lattice-boltzmann schemes macroscopic limit,” Physics of Fluids, 2021. (Theory)

Remarks

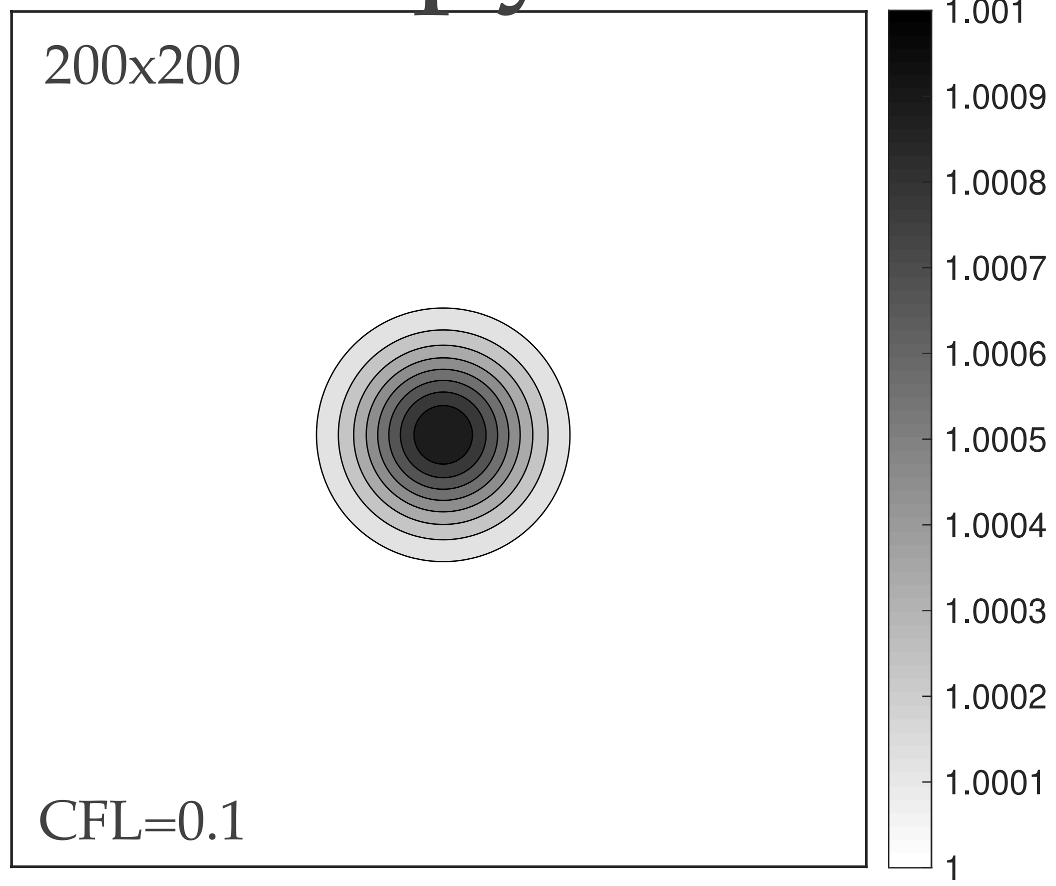
- Mass is (non-trivially) globally conserved as before for closed periodic domains
- A priori compatible with your favorite collision kernel…

And the scalar equations ?

- Scalar equations are solved on the same grid.
- Explicit time-stepping is used (same time-step as LB time-step) - yet, the method is 2nd order in time
- Finite volume methods to compute all RHS terms
  - Second-order isotropic operator = non-conservative form (OK for Ma<0,3)
  - Or MUSCL = non-conservative form (necessary for higher speeds)
  - Or (new) flux reconstruction from LB mass fluxes = conservative form
  - Coupling is paramount…
- Any number of explicit advection/diffusion equation can be included (energy / mass fraction / liquid / spray/…)

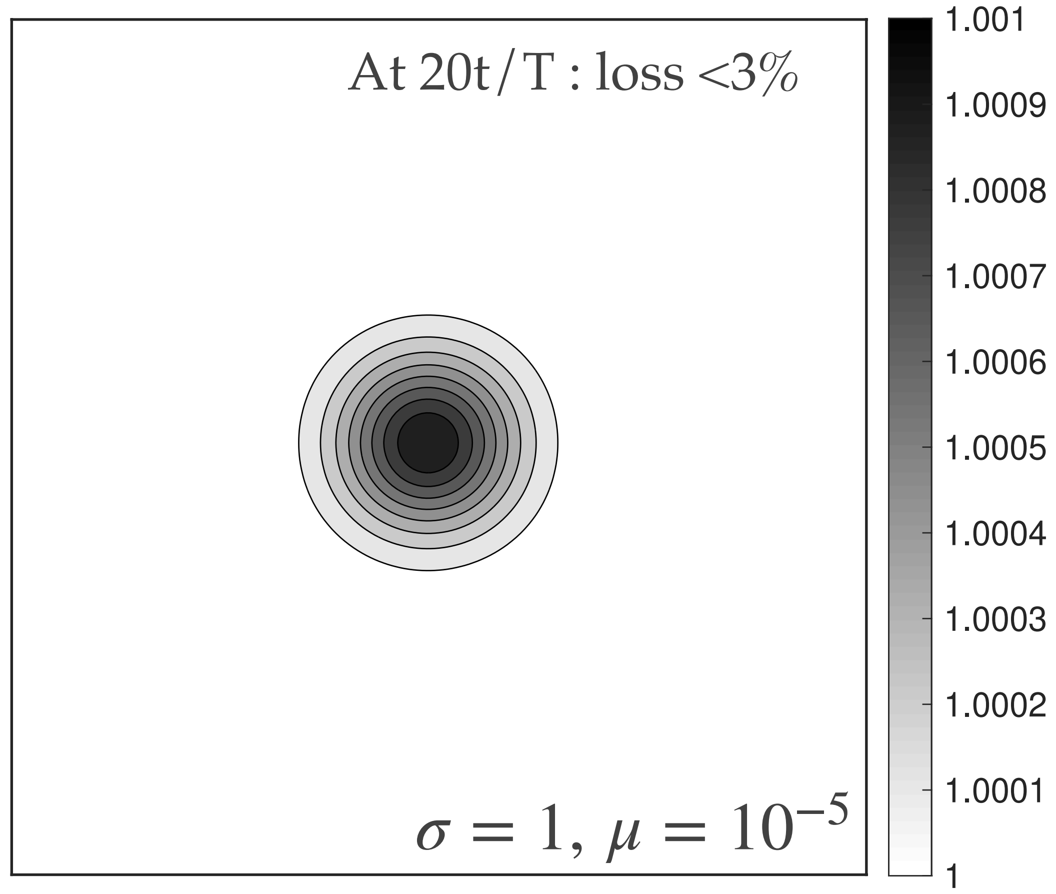
Compressible core

Entropy mode


200x200

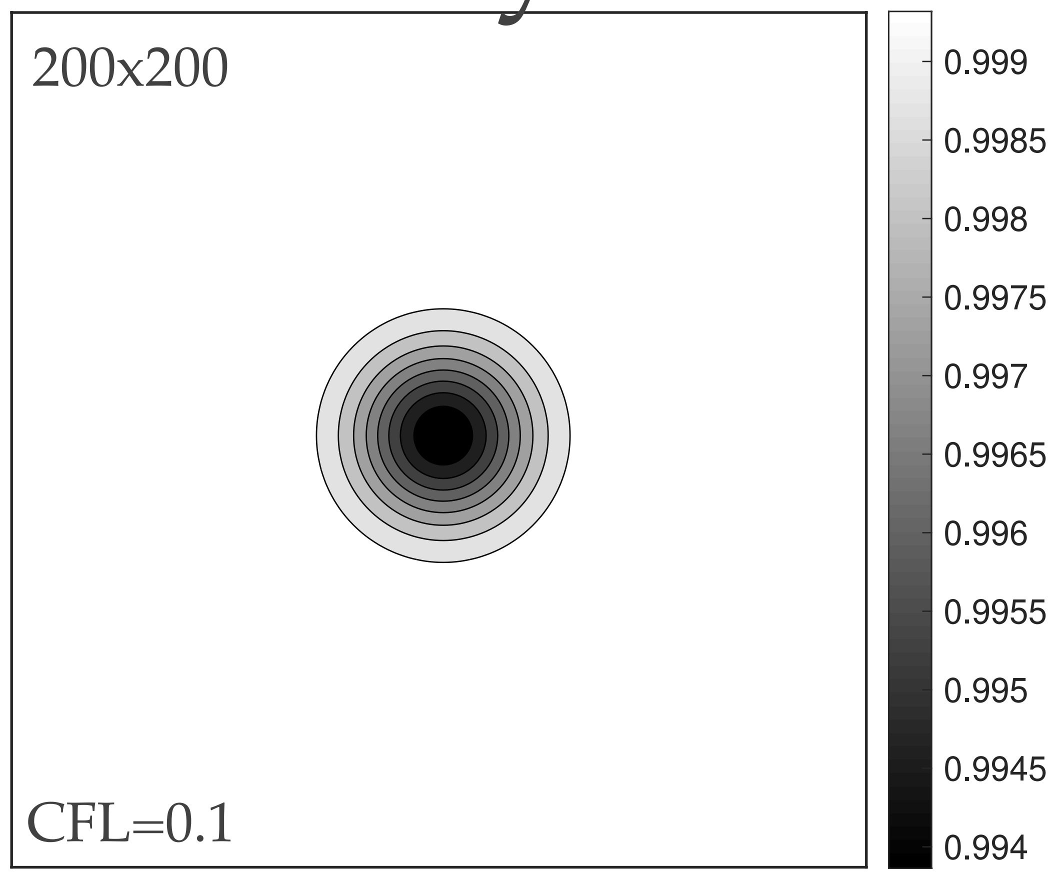
CFL=0.1

MUSCL-Hancock


At 20t/T : loss <3%

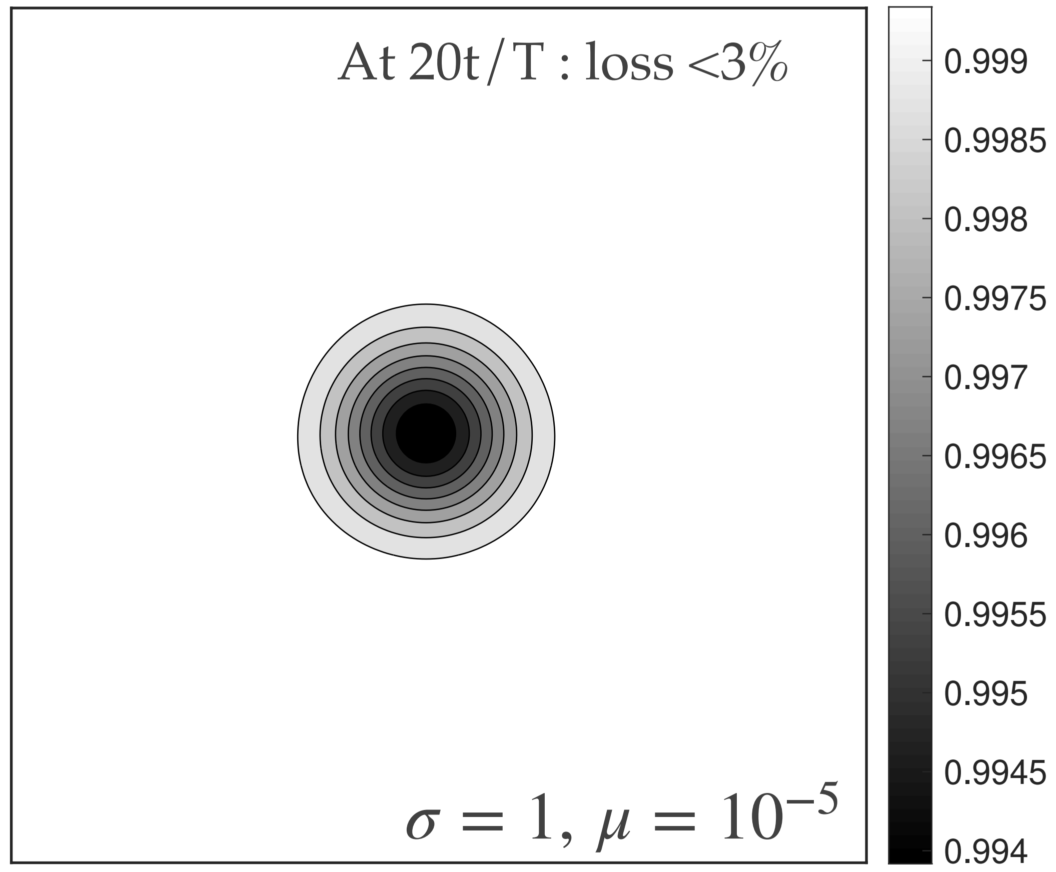
$\sigma = 1, \mu = 10^{-5}$

Vorticity mode


200x200

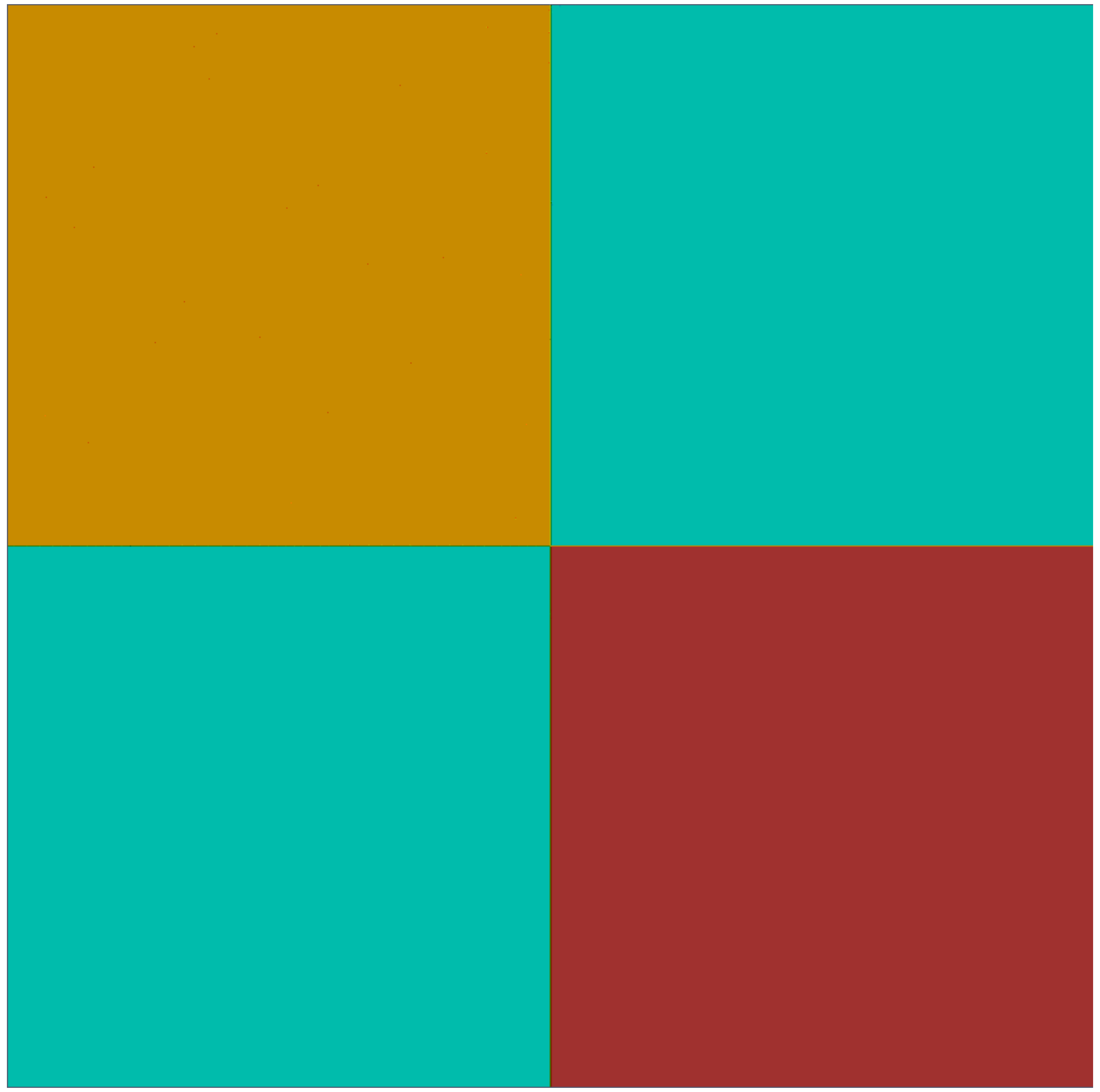
CFL=0.1

MUSCL-Hancock

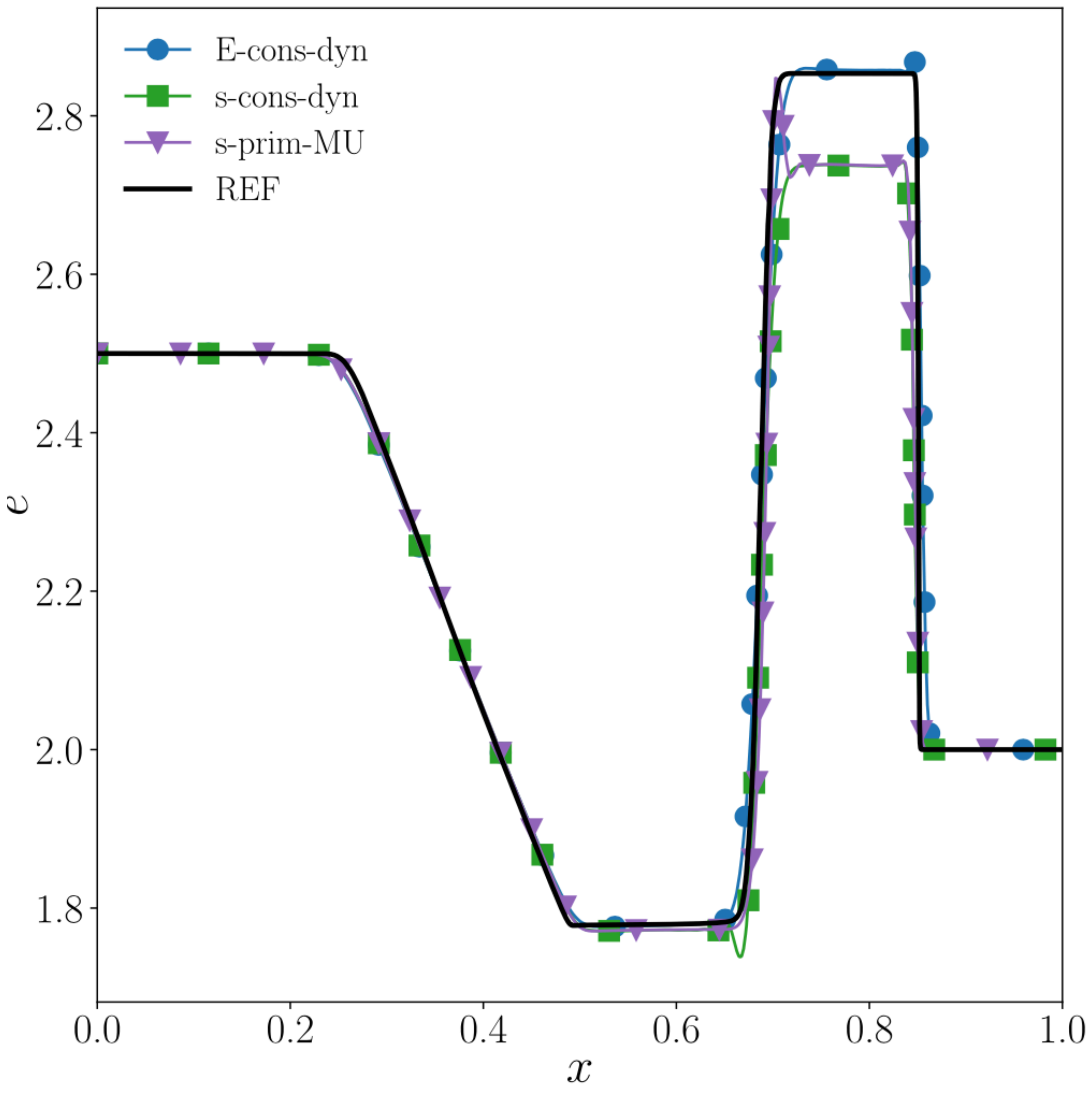

At 20t/T : loss <3%

$\sigma = 1, \mu = 10^{-5}$

$\underline{Ma = 1.5}$

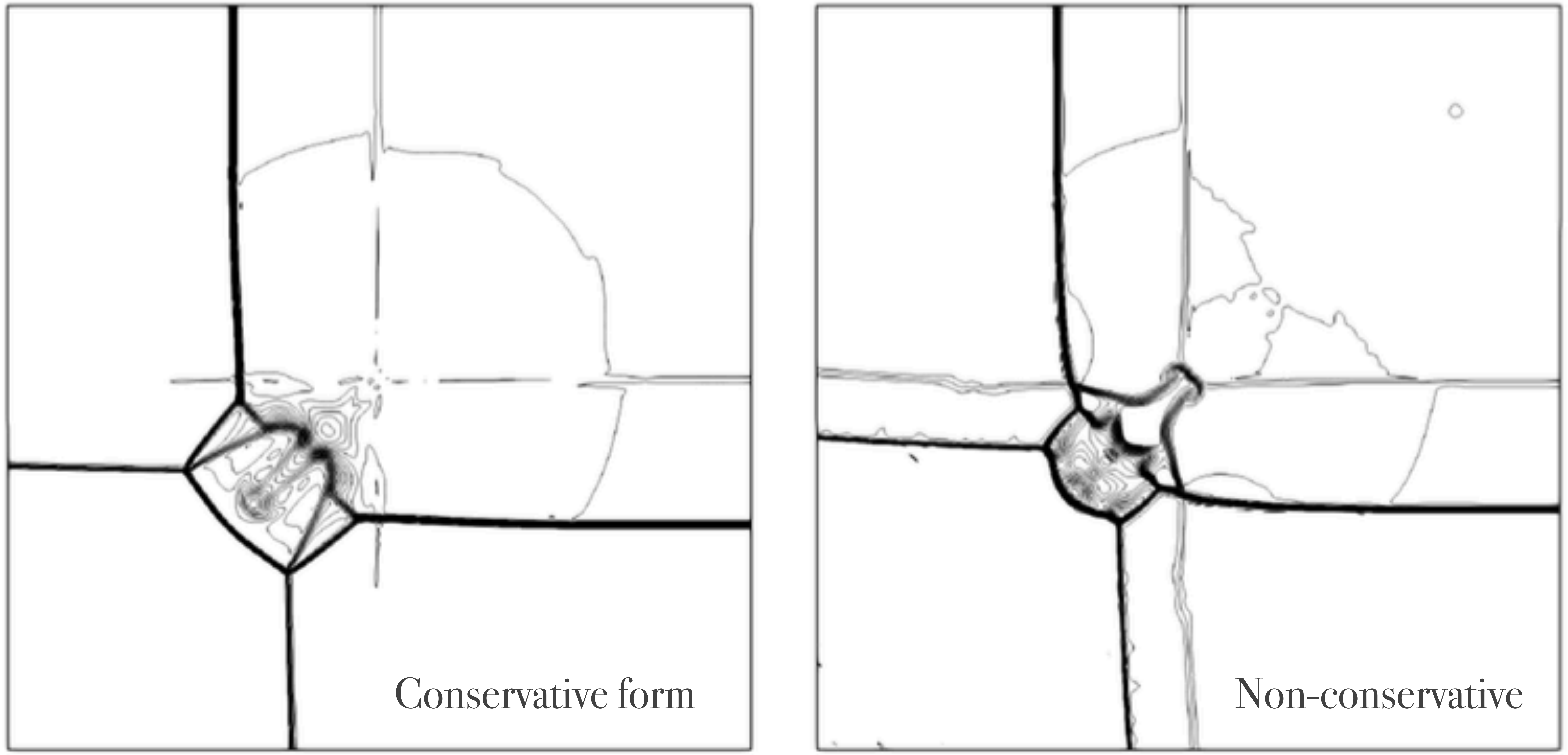

Entropy equation (MUSCL)

Conserving Scalars…



- For any advection equation $\dfrac{\partial \rho\phi}{\partial t} + \nabla \rho u \phi = 0,$
  - (= mass conservation + non-conservative scalar eq)
  - $\nabla^C \cdot (\rho \boldsymbol{u} \phi) \equiv \dfrac{1}{\Delta t} \sum_i \left[f_i^{\mathrm{col}} \dfrac{\phi^+ + \phi}{2} - f_i^{\mathrm{col}-} \dfrac{\phi + \phi^-}{2} \right]$
  - ~ Match the LBM mass flux computation to compute scalar eqs.
  - => numerically conserve $\rho\phi$ and $\rho\phi^2$
  - And respect the Hugoniot jump conditions !
  - *S. Zhao, G. Farag, P. Boivin, and P. Sagaut, "Toward fully conservative hybrid lattice boltzmann methods for compressible flows," Physics of Fluids, vol. 32, no. 12, p. 126118, 2020.*

Conserving Scalars…



2D Riemann problem. Conservative form is mandatory to properly capture Hugoniot jumps…

Outline

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H_2-air - 12s
Lewis transp.
Cp(T)

Validation

$$1: H + O_2 \rightleftharpoons OH + O$$
$$2: H_2 + O \rightleftharpoons OH + H$$
$$3: H_2 + OH \rightleftharpoons H_2O + H$$
$$4: H + O_2 + M \rightarrow HO_2 + M$$
$$5: HO_2 + H \rightarrow 2\ OH$$
$$6: HO_2 + H \rightleftharpoons H_2 + O_2$$
$$7: HO_2 + OH \rightarrow H_2O + O_2$$
$$8: H + OH + M \rightleftharpoons H_2O + M$$
$$9: 2\ H + M \rightleftharpoons H_2 + M$$
$$10: 2\ HO_2 \rightarrow H_2O_2 + O_2$$
$$11: HO_2 + H_2 \rightarrow H_2O_2 + H$$
$$12: H_2O_2 + M \rightarrow 2\ OH + M$$

12-Step

$$Pr: 0.75 \qquad Sc_O: 0.53$$
$$Sc_{H_2}: 0.21 \qquad Sc_{H_2O}: 0.60$$
$$Sc_H: 0.14 \qquad Sc_{HO_2}: 0.80$$
$$Sc_{O_2}: 0.80 \qquad Sc_{H2O_2}: 0.82$$
$$Sc_{OH}: 0.53 \qquad Sc_{N_2}: 1.00$$

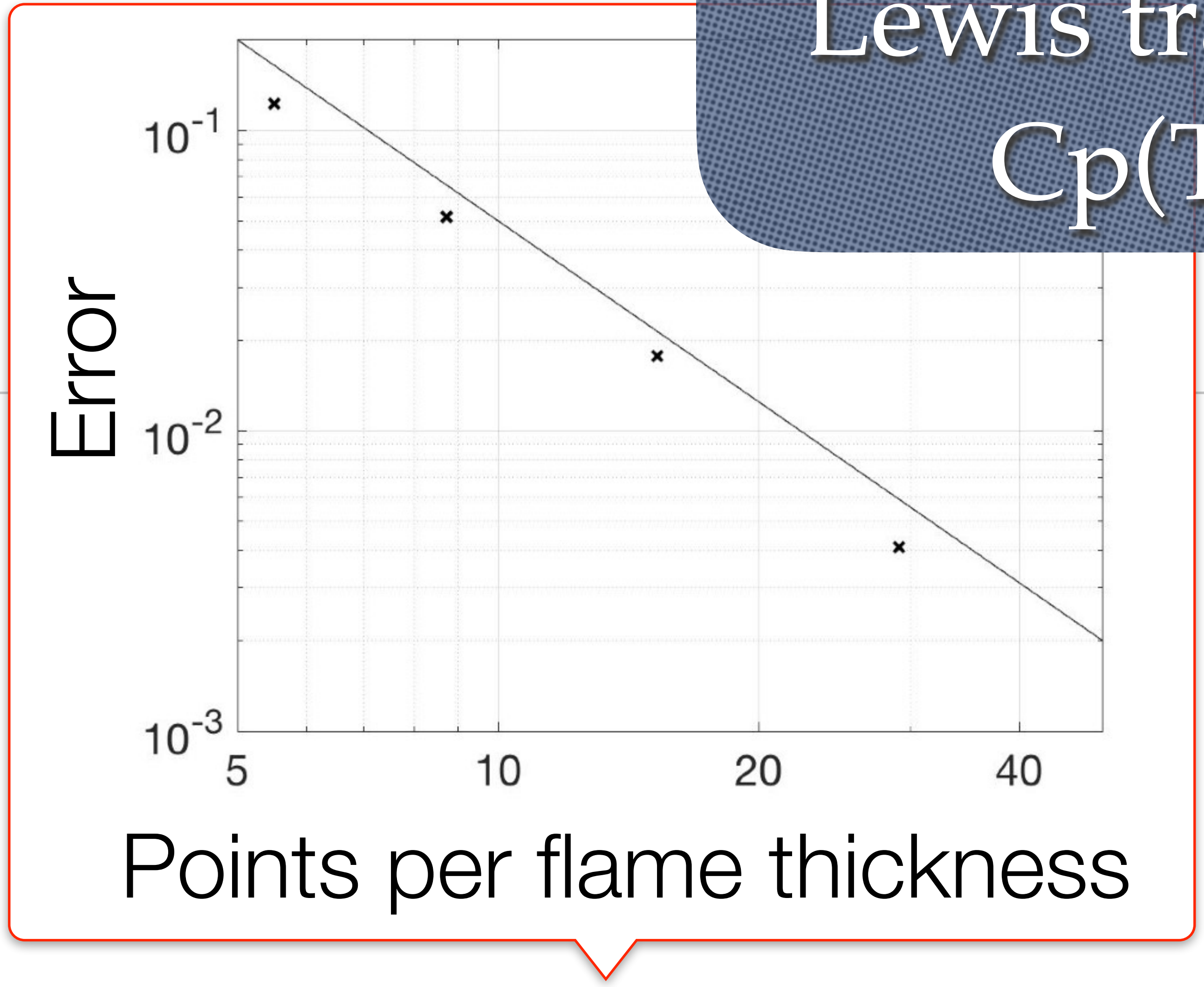
Heat and Diffusion

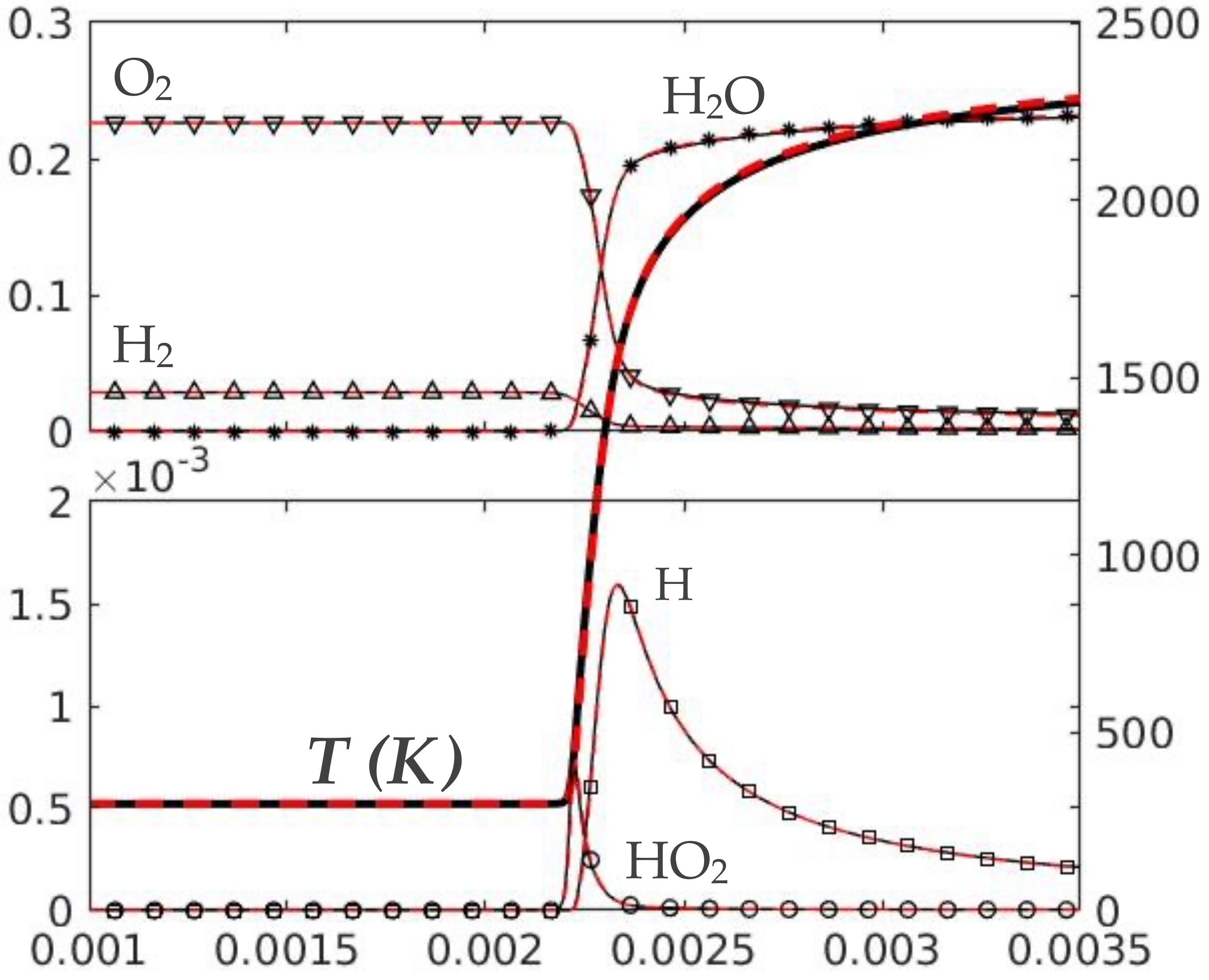
$$C_p(T) = R(a_1 + a_2T + a_3T^2 + a_4T^3 + a_5T^4)$$

Variable Heat Capacity

$$\mu = \mu_0 \left(\frac{T}{T_0}\right)^\beta$$

Viscosity's Power Law



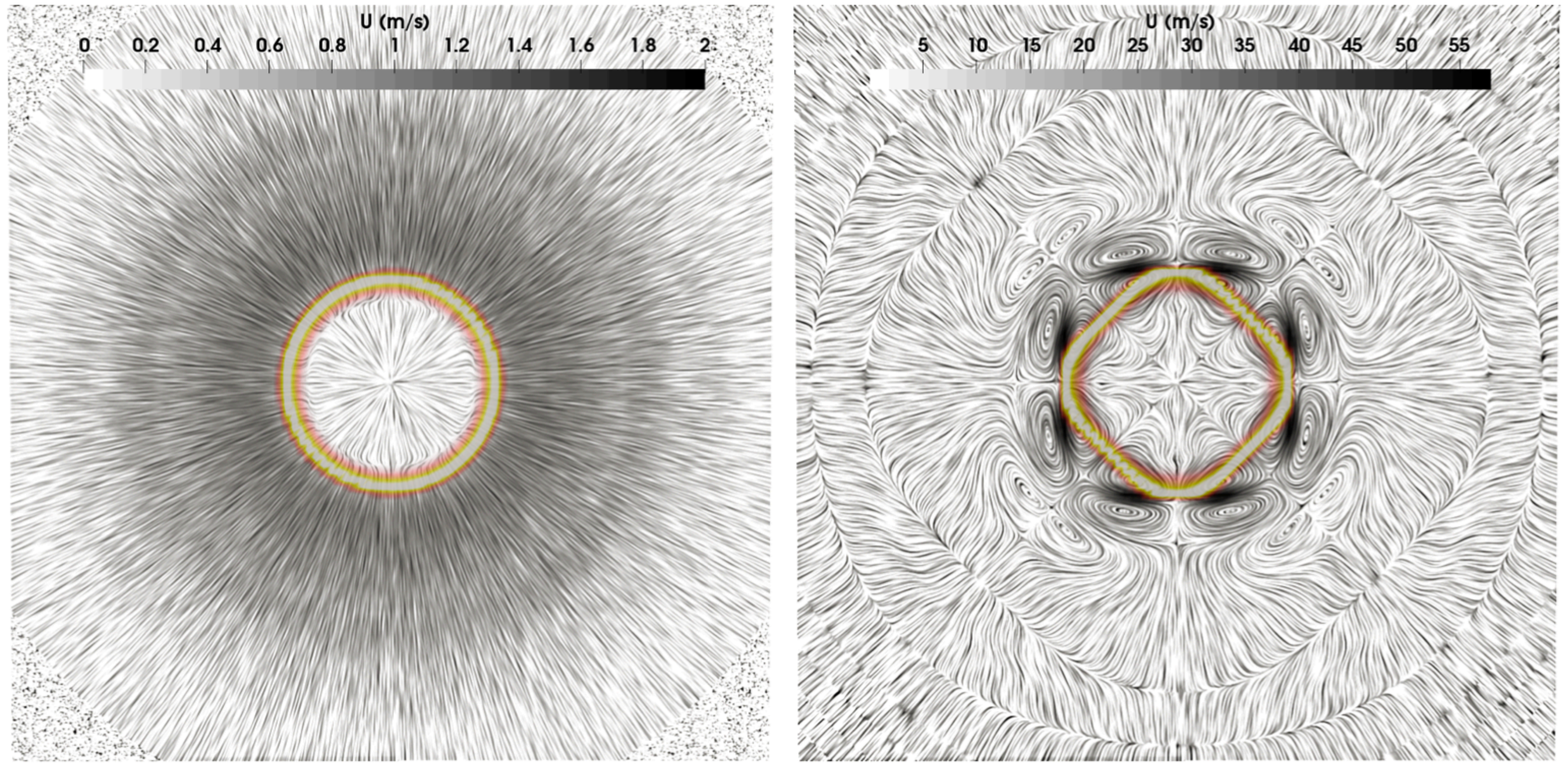


Stoichiometric H_2-air premixed flame.
Ref: Cantera.

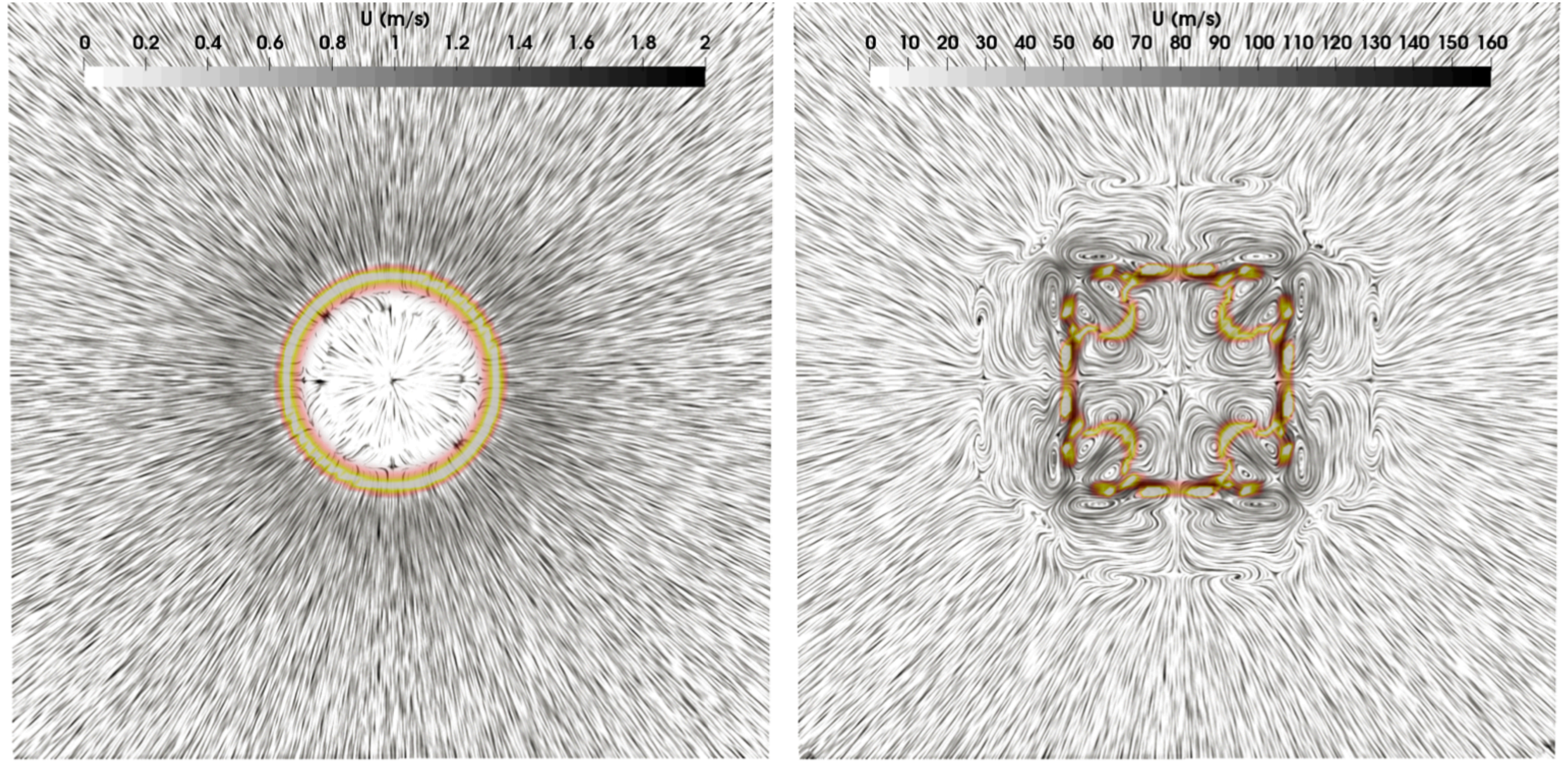
C_3H_8-air - 1s
Lewis transp.
Cp(T)

Spherical premixed flame

- Isotropy & stability test
- ~3 pts in flame thickness
- Excellent isotropy



Pressure-based (a) t=2.0×10^{-2}ms Density-based

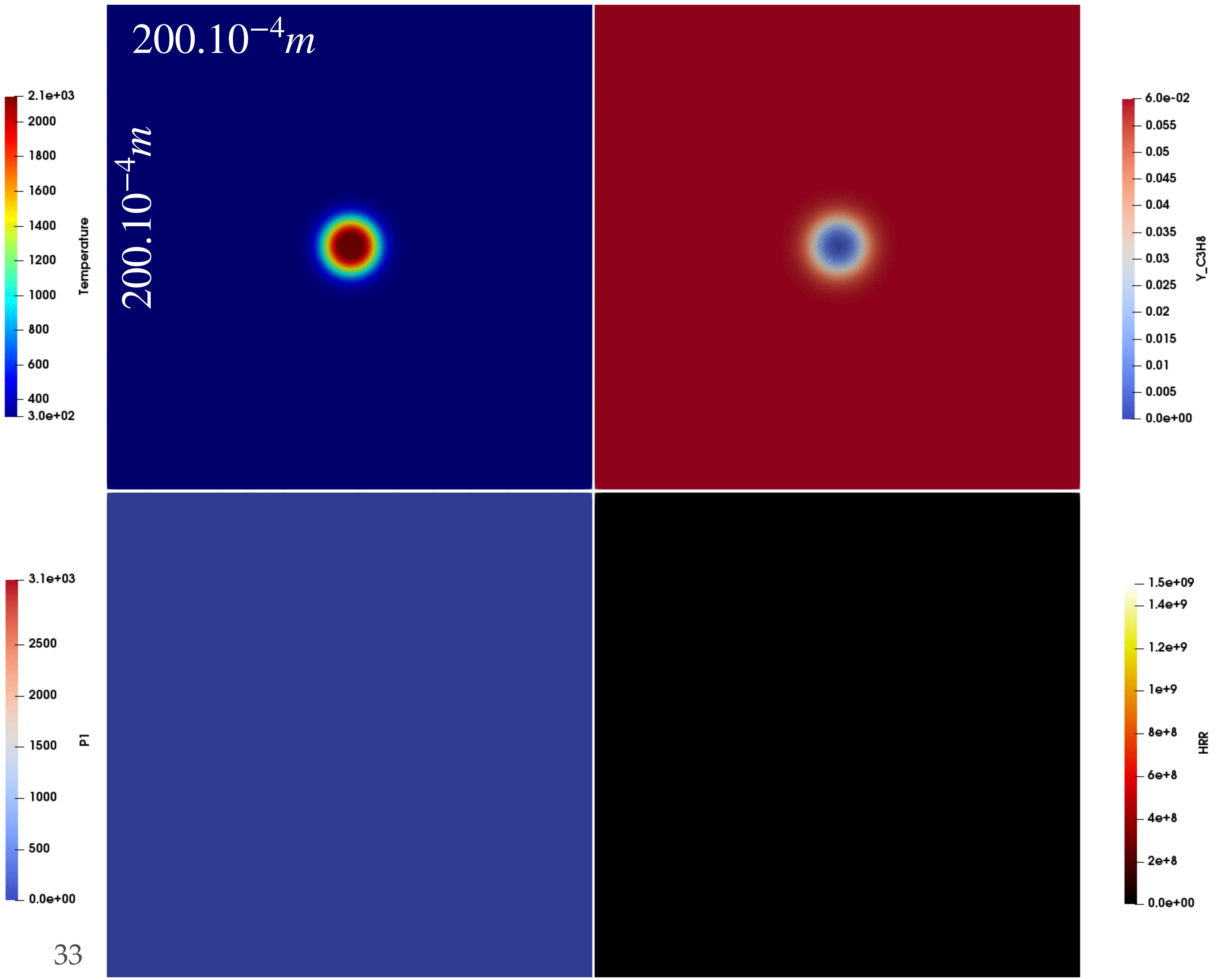


(b) t=4.0×10^{-2}ms

C_3H_8-air - 1s
Lewis transp.
Cp(T)

Spherical premixed flame

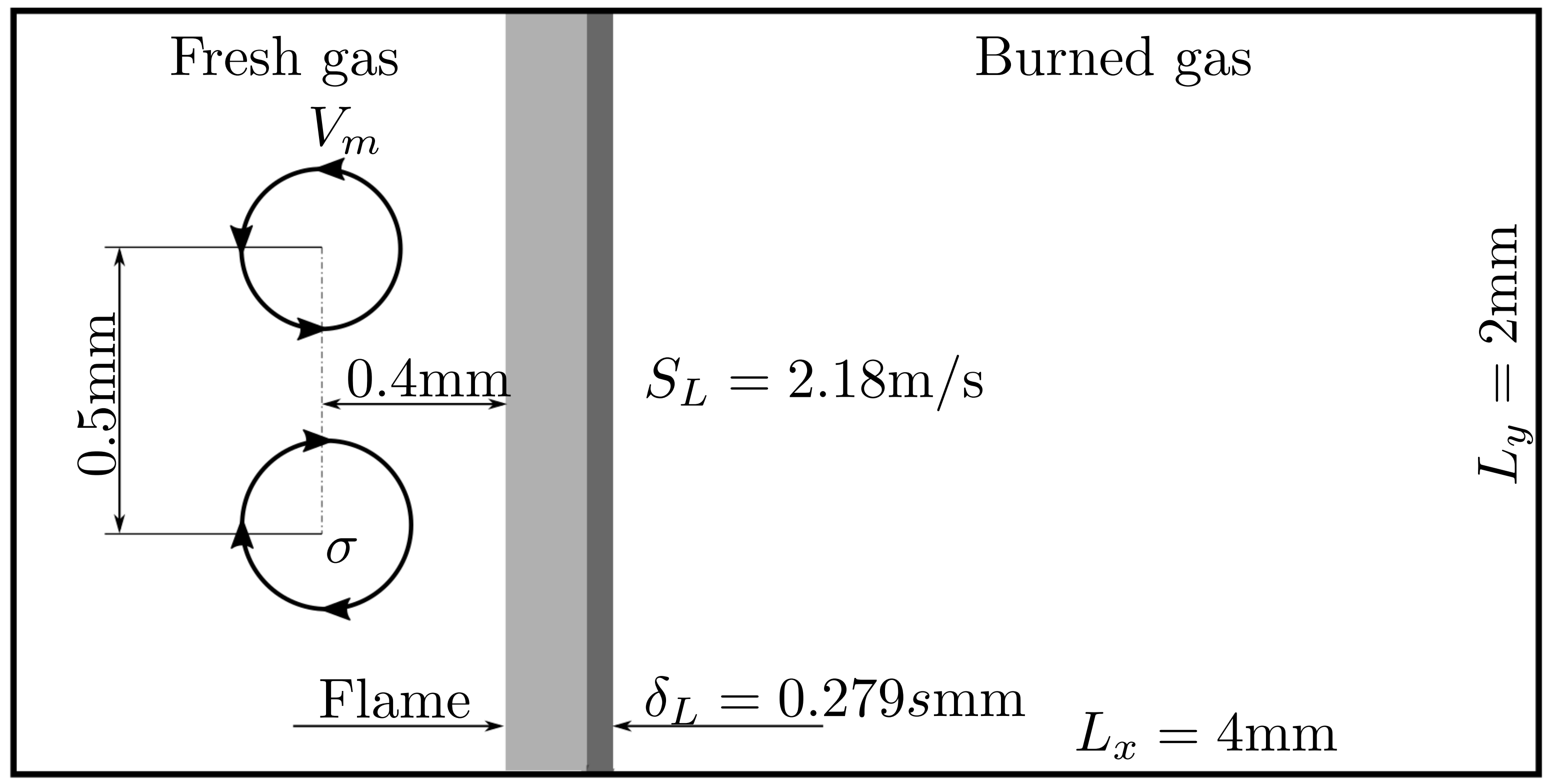
- Isotropy & stability test
- ~3 pts in flame thickness
- Excellent isotropy
- Non-reflecting outlets OK



Vortex-Flame interaction

H_2-air - 12s
Lewis transp.
Cp(T)

Grid : 400x200

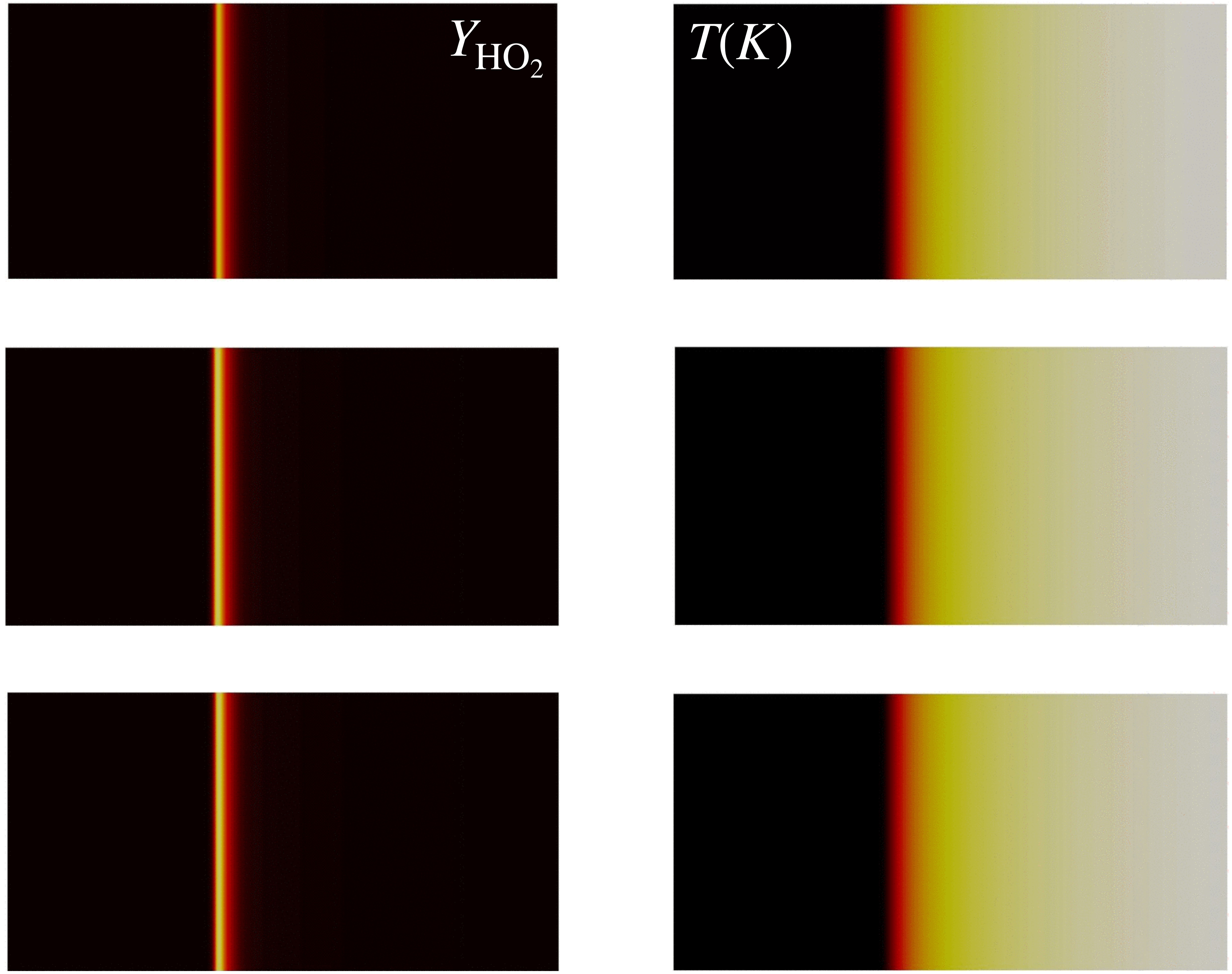


	V_m/s_L	σ/δ_L	Ka
Case A	2.24	1.18	1.89
Case B	16.18	0.93	17.39
Case C	32.68	0.92	35.52

Case A: weak

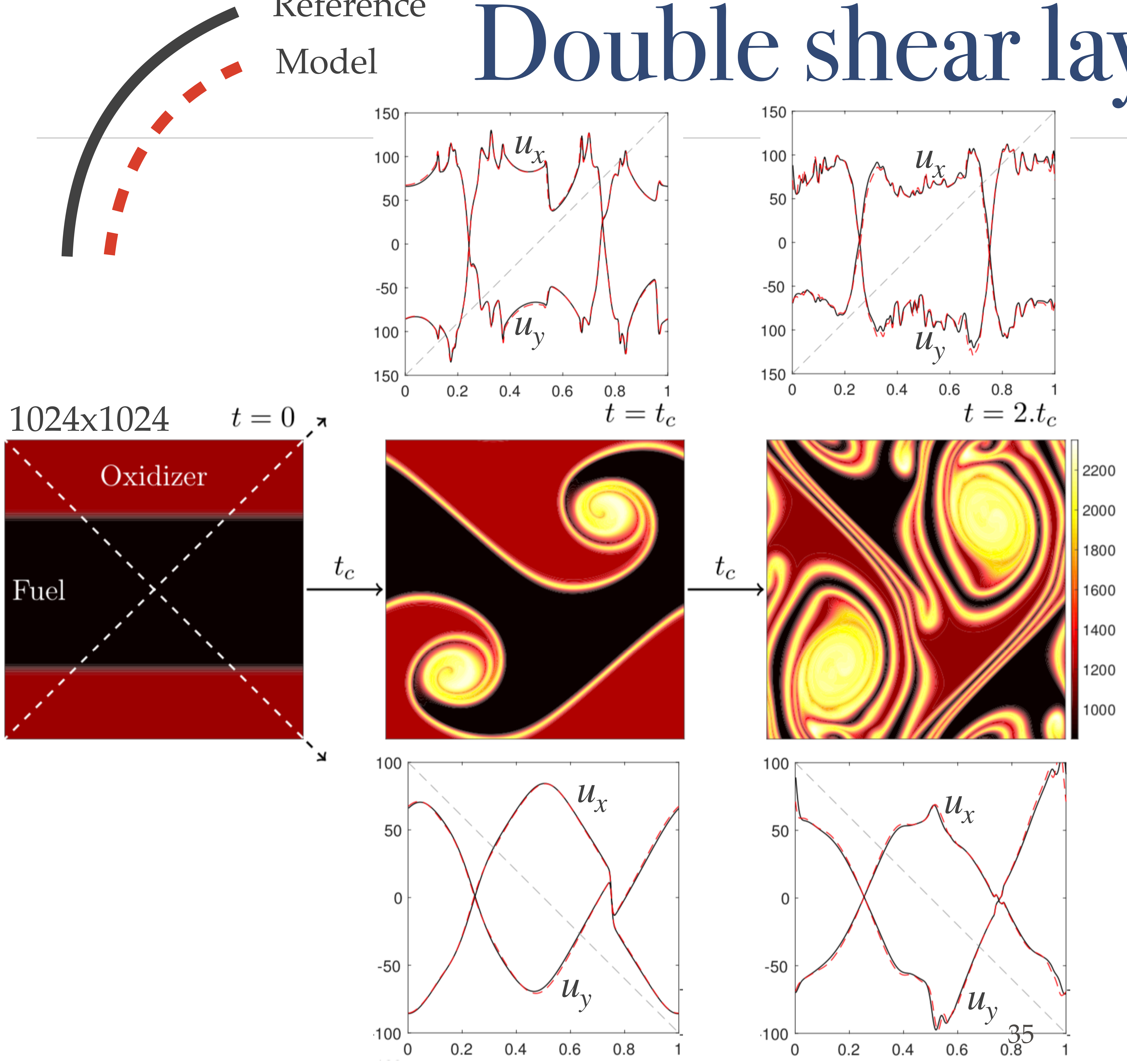
Case B: Moderate

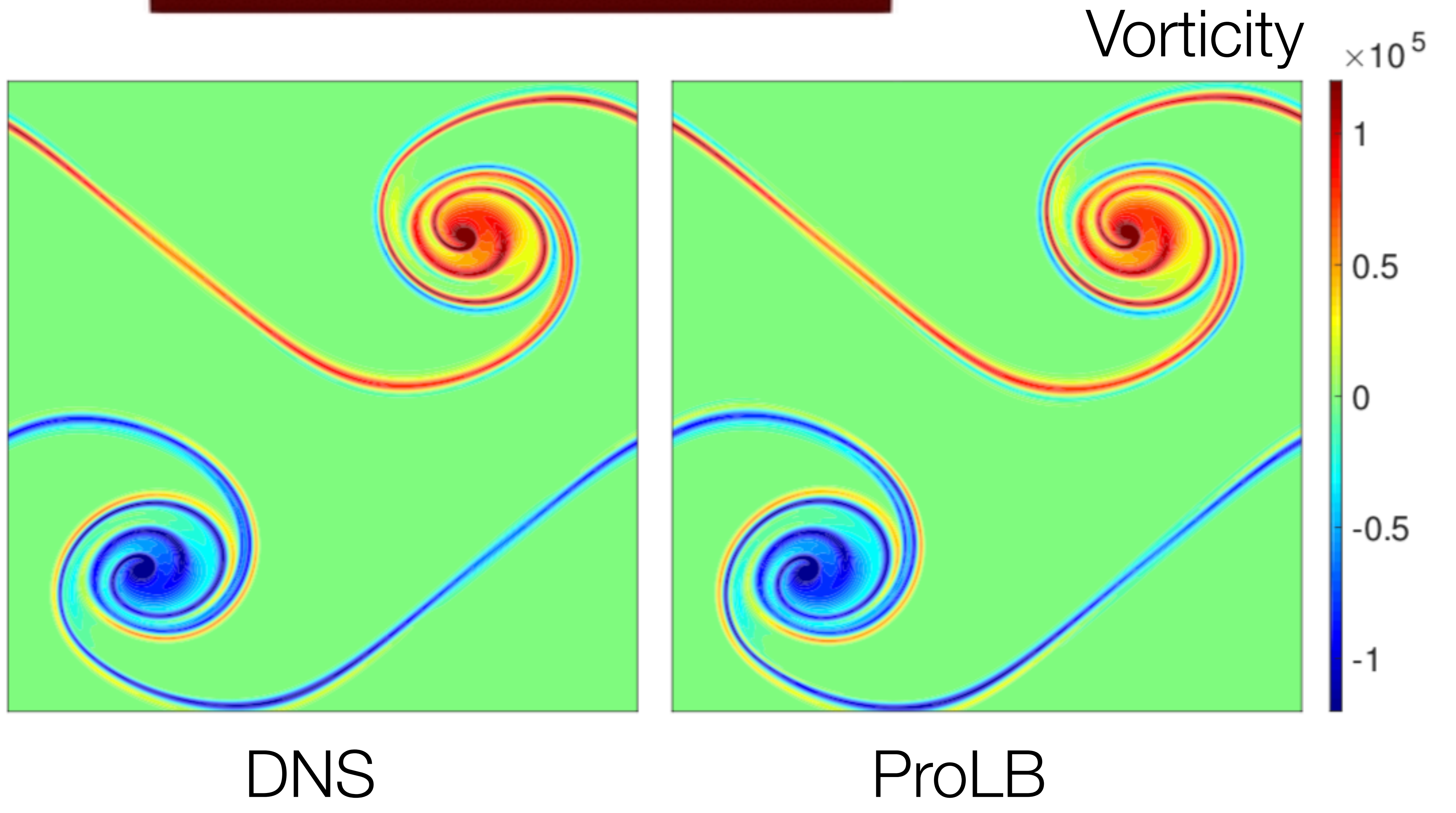
Case C: Strong



Double shear layer

H_2-air - 12s
Lewis transp.
Cp(T)





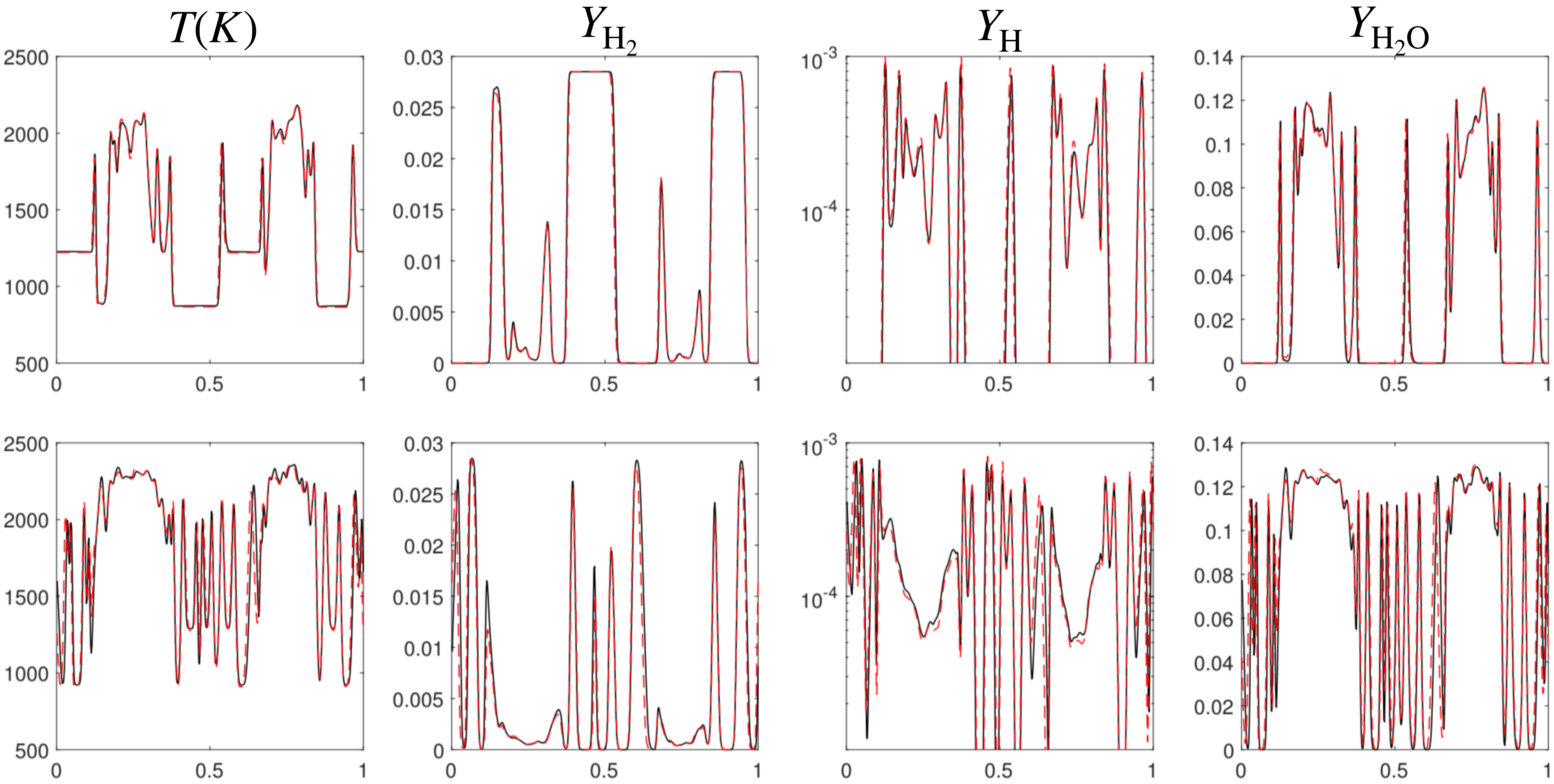
H_2-air - 12s
Lewis transp.
Cp(T)

Reference
Model

Double shear layer

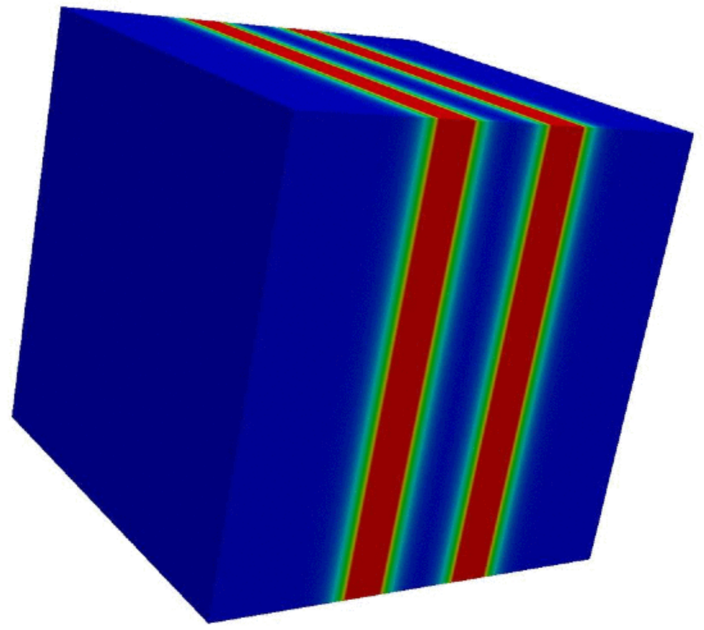
$t = t_c$

$t = 2t_c$



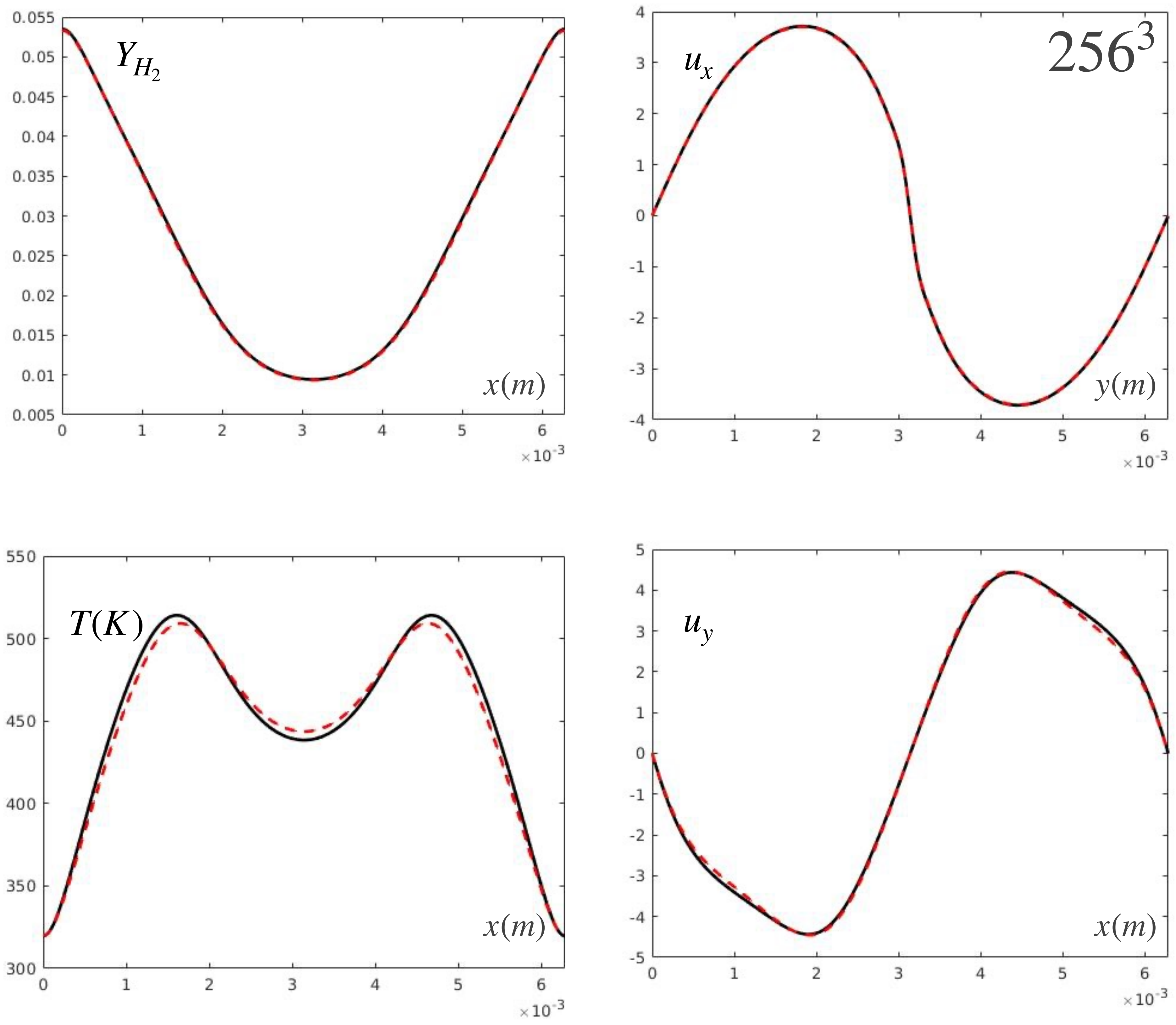
Reference
Model

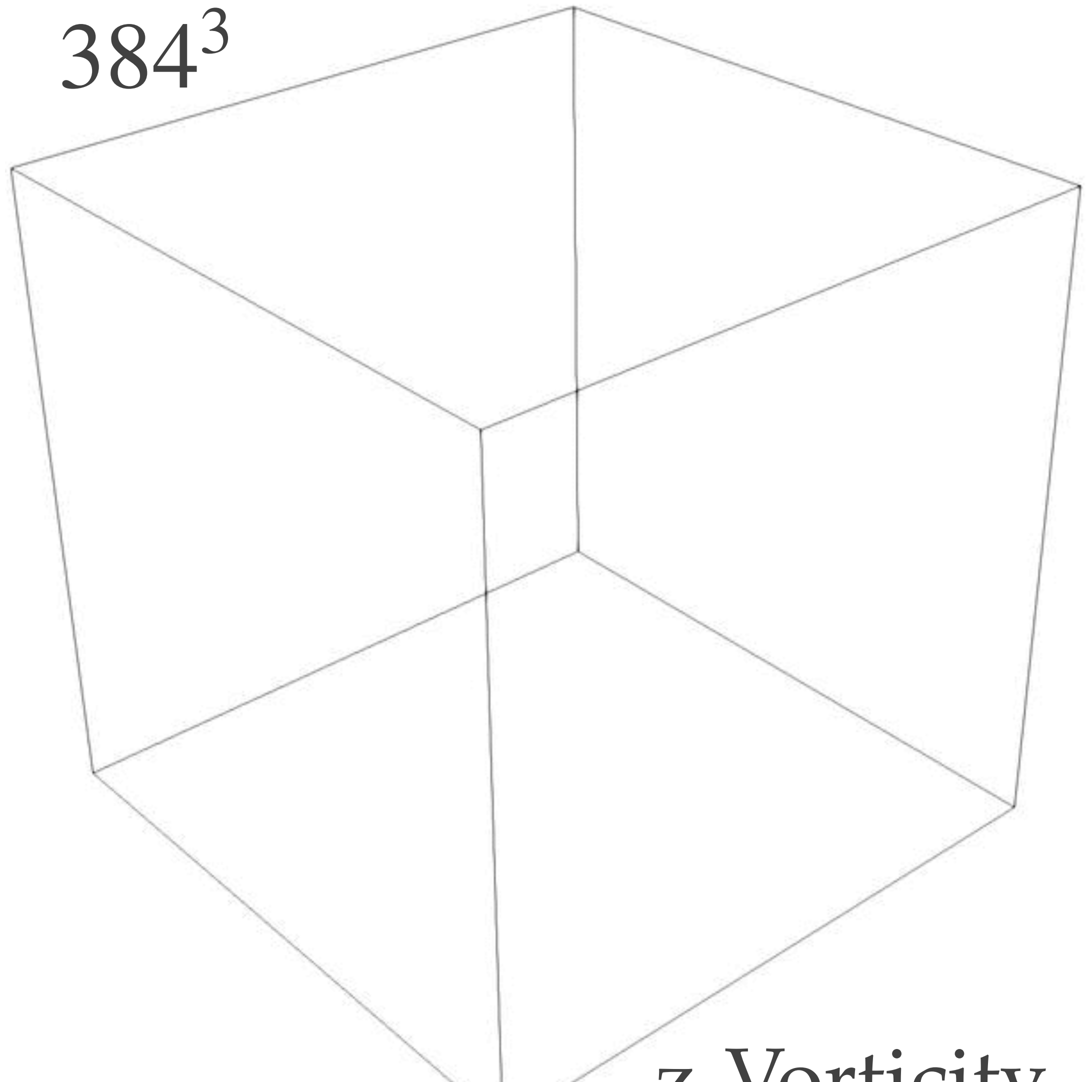
3D Taylor-Green Vortex

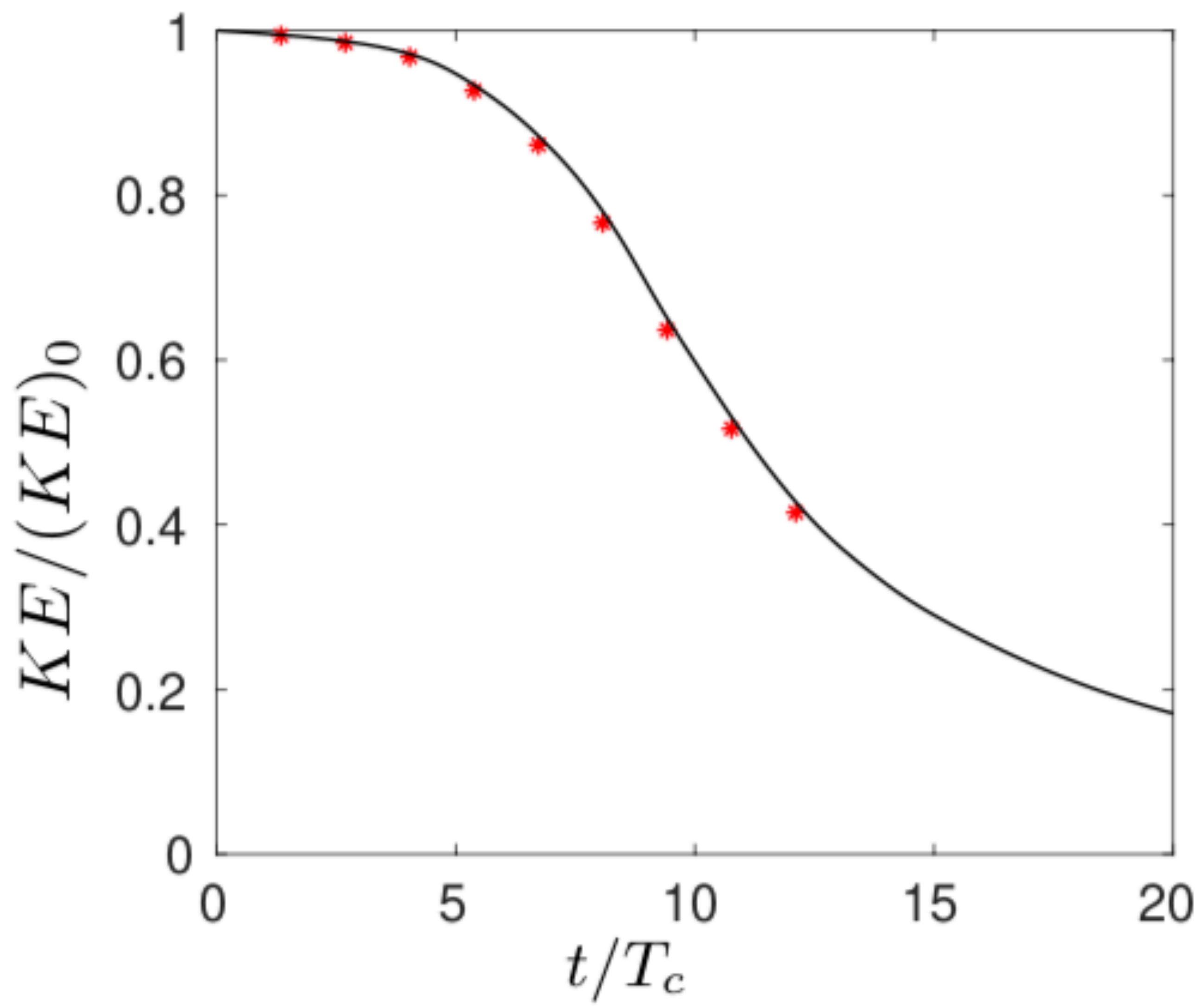


- Benchmark DNS for reactive flow
  - Grids: 256^3, 384^3, 512^3 (mesocentre)
  - ~10 codes participated (ICNC 2019)

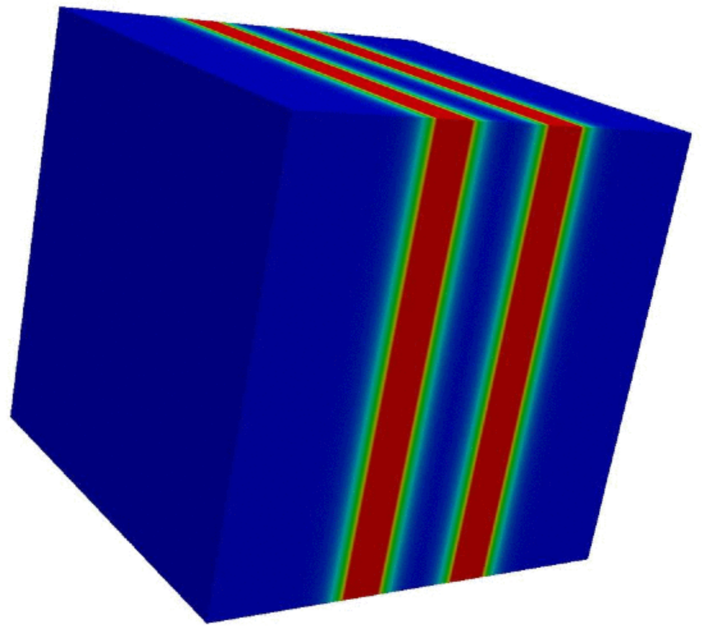
« Cold case »



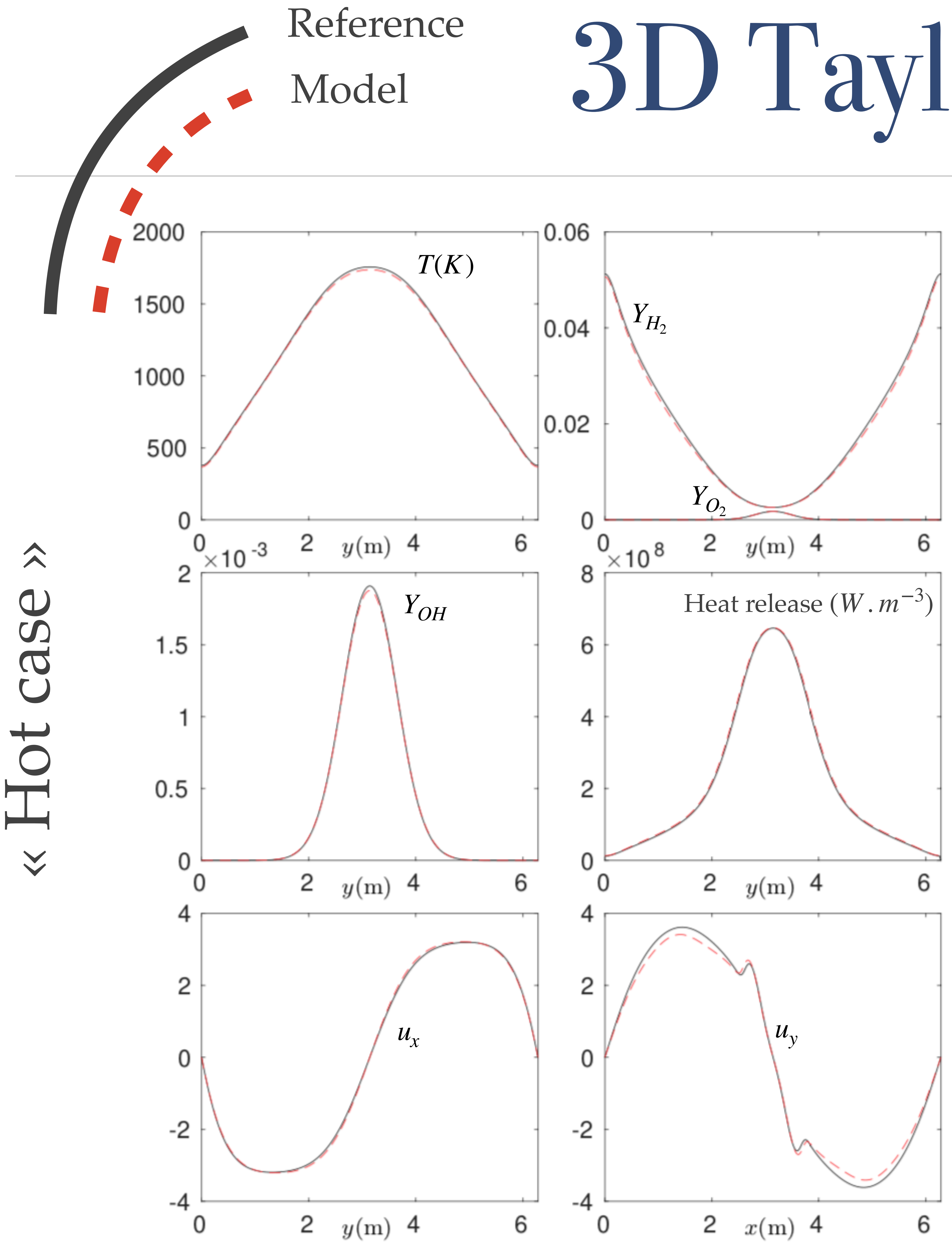




3D Taylor-Green Vortex



« Hot case »



- Benchmark DNS for reactive flow
  - Grids: 256^3, 384^3, 512^3 (mesocentre)
  - ~10 codes participated (ICNC 2019)
- Comparisons are very good
- LBM is very (very) fast!

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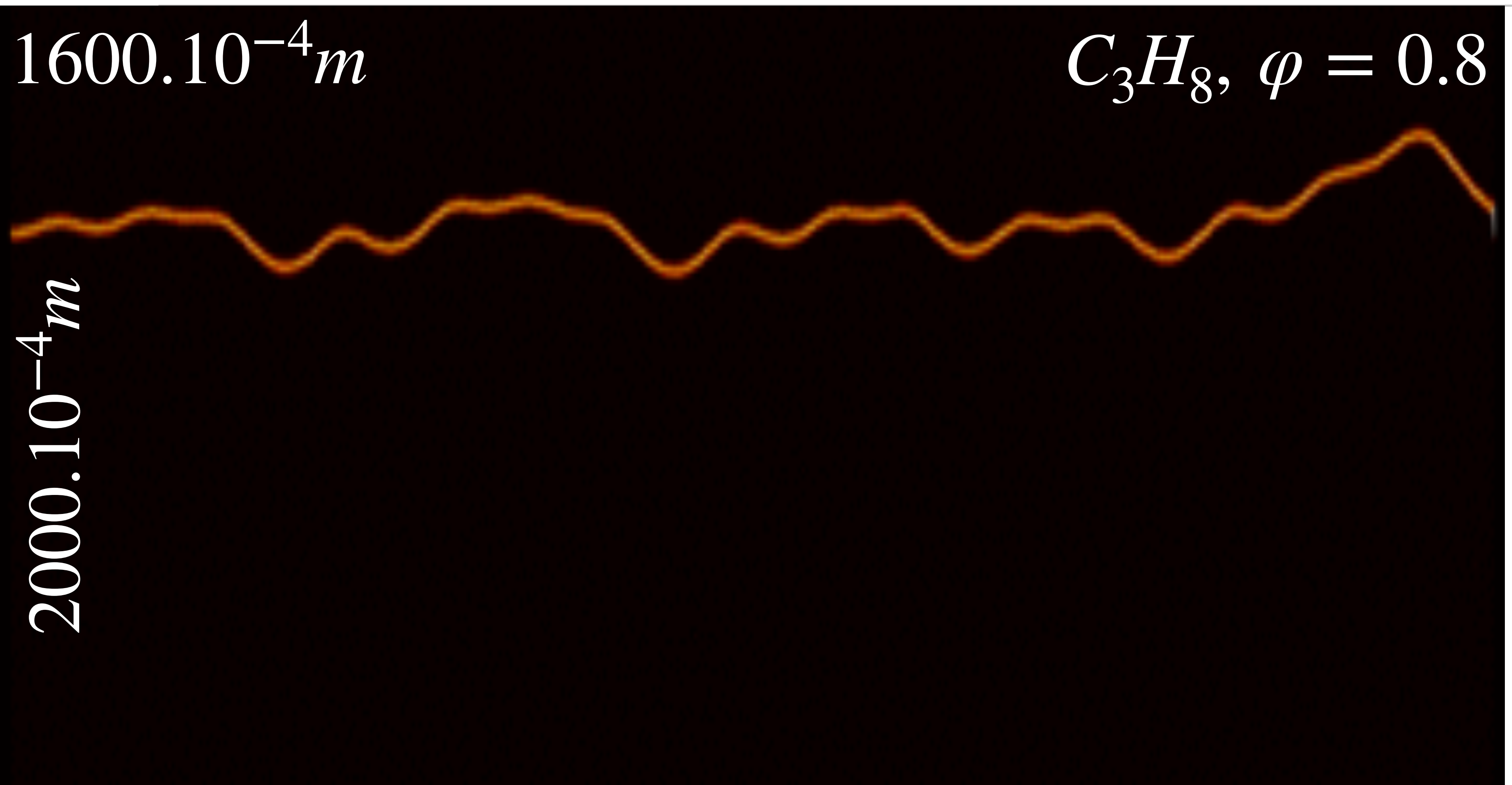
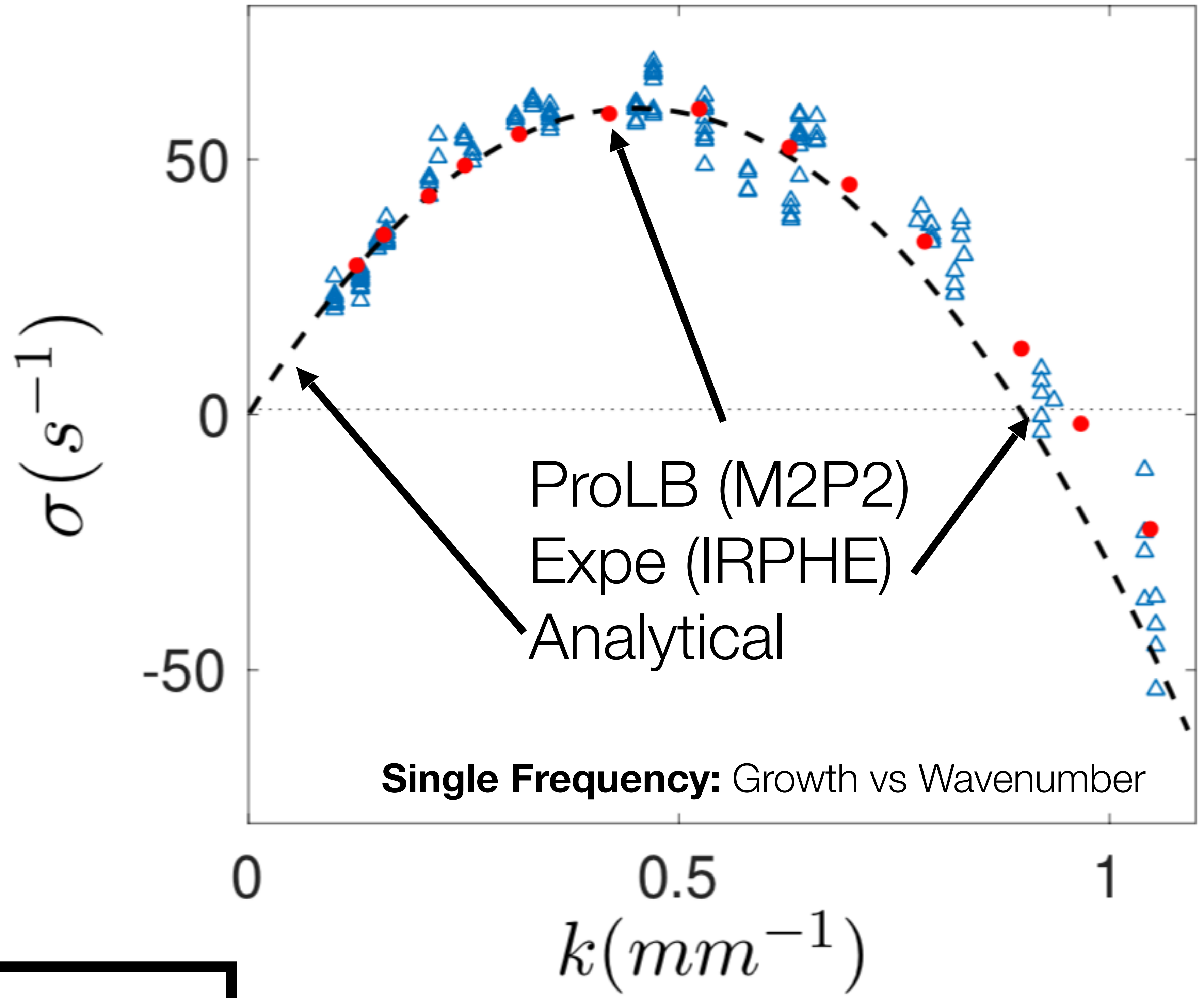
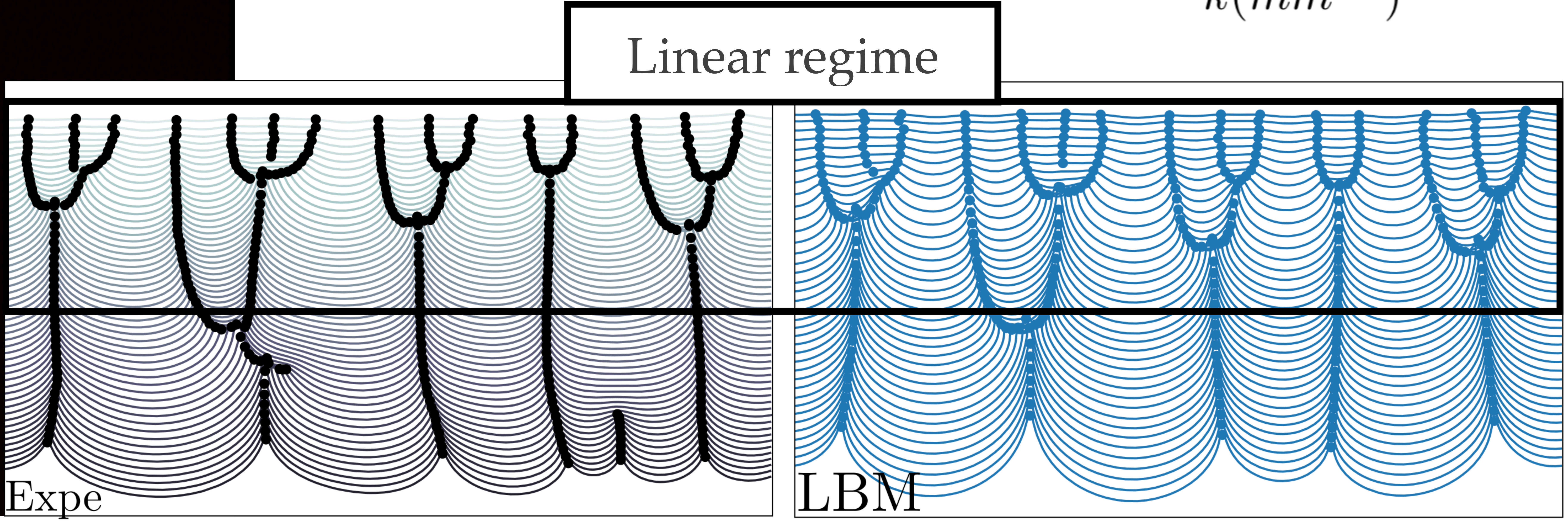
Combustion instabilities





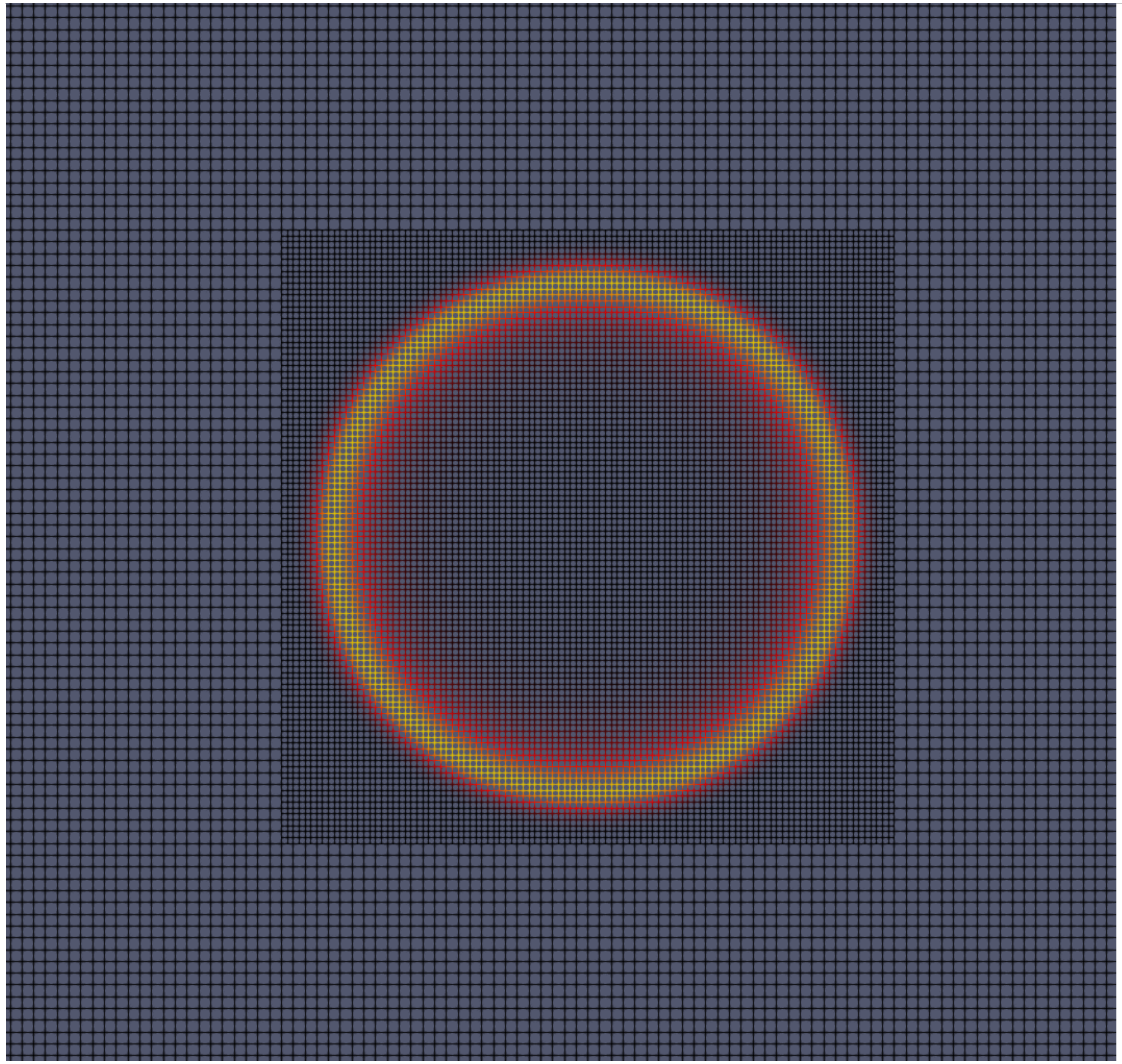
Thermo-diffusive instabilities (propane/air)

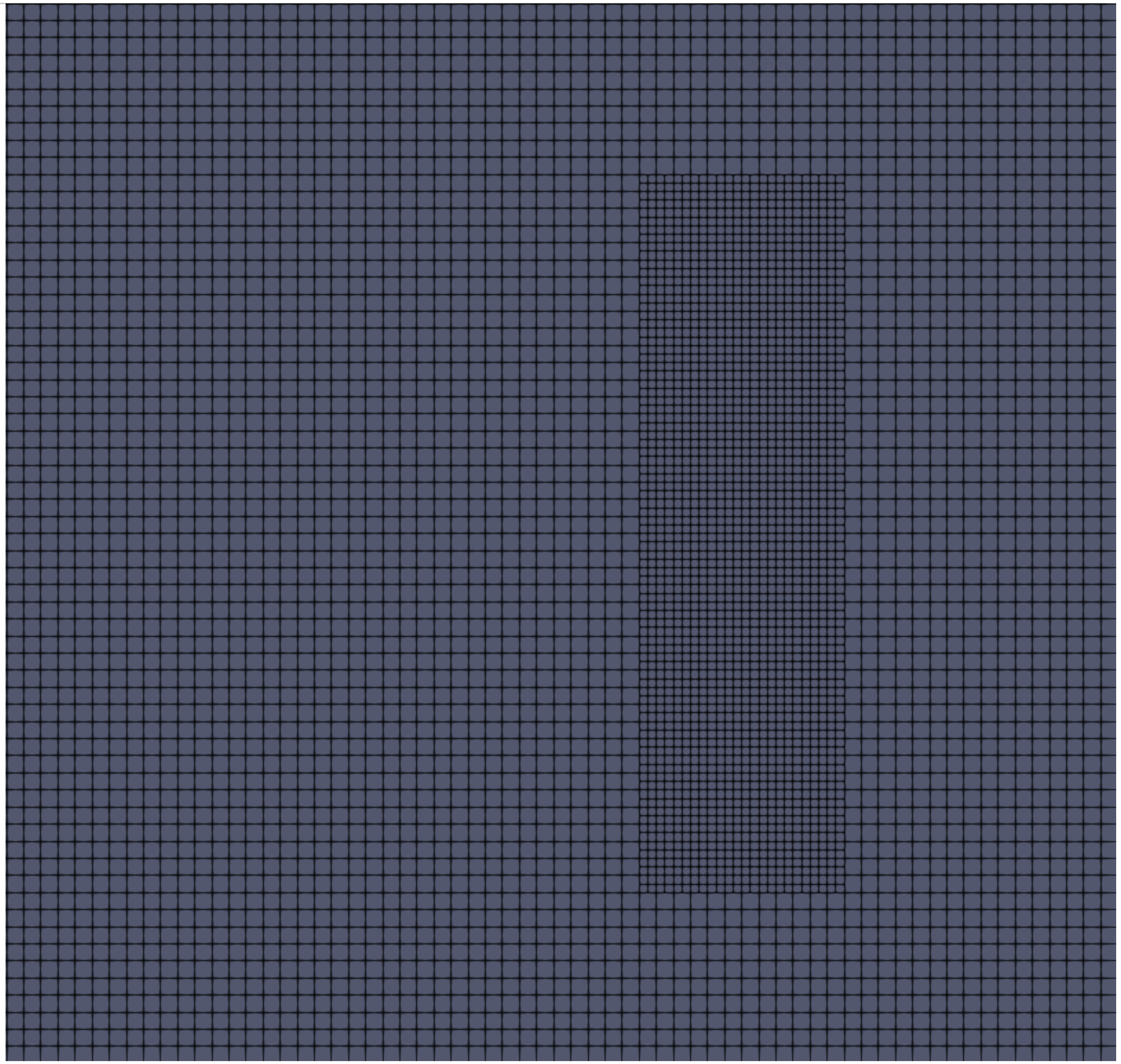
- Hele-Shaw cell



[1] M. Tayyab, B. Radisson, C. Almarcha, B. Denet, and P. Boivin, "Experimental and numerical lattice-boltzmann investigation of the Darrieus-Landau instability," Combustion and Flame, 2020.

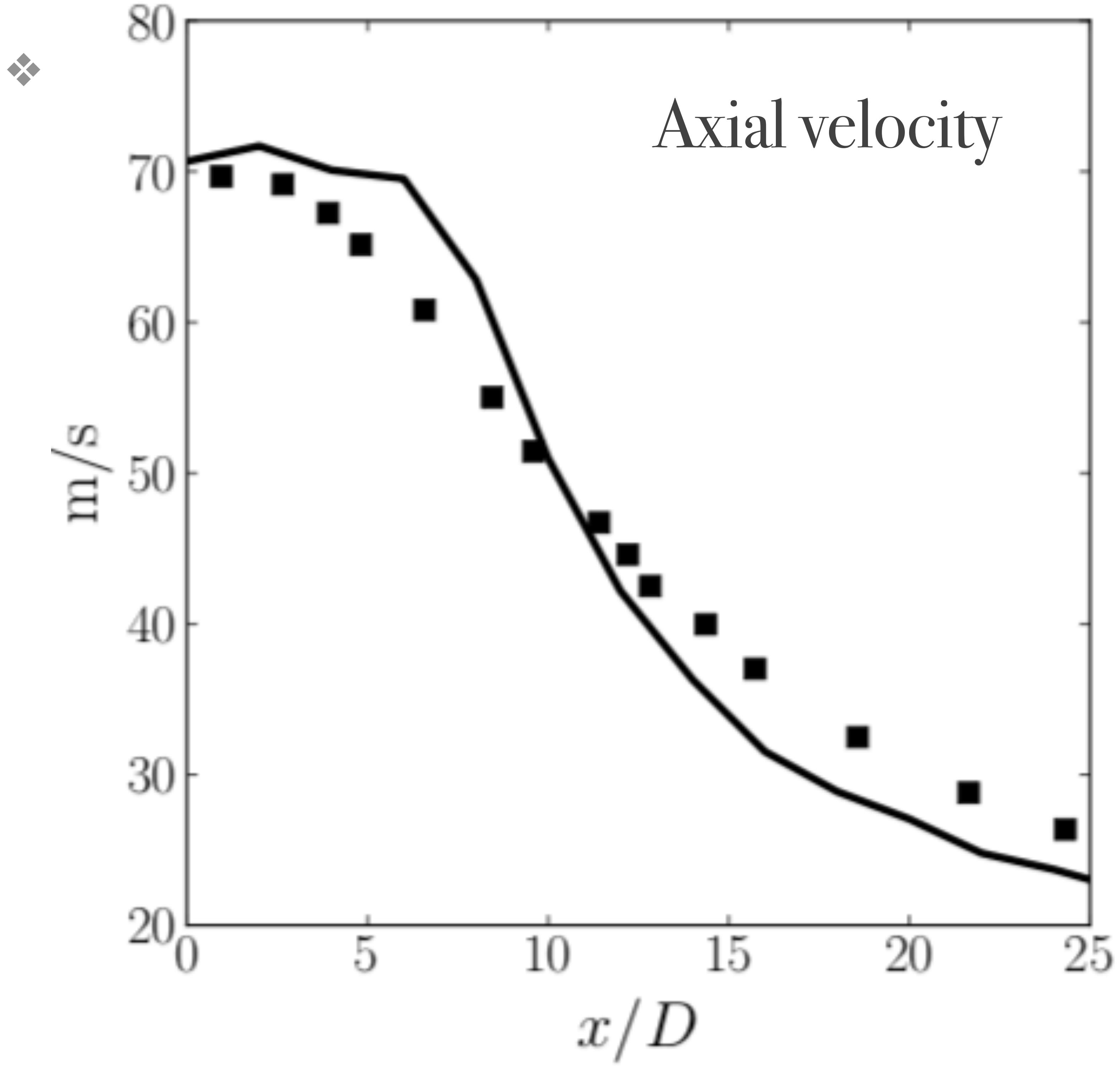
Mesh transitions

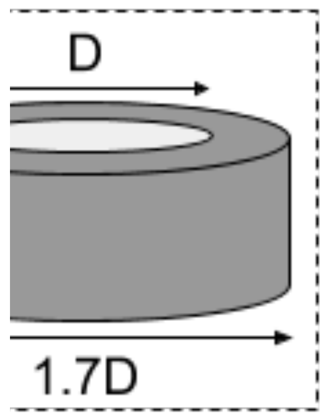


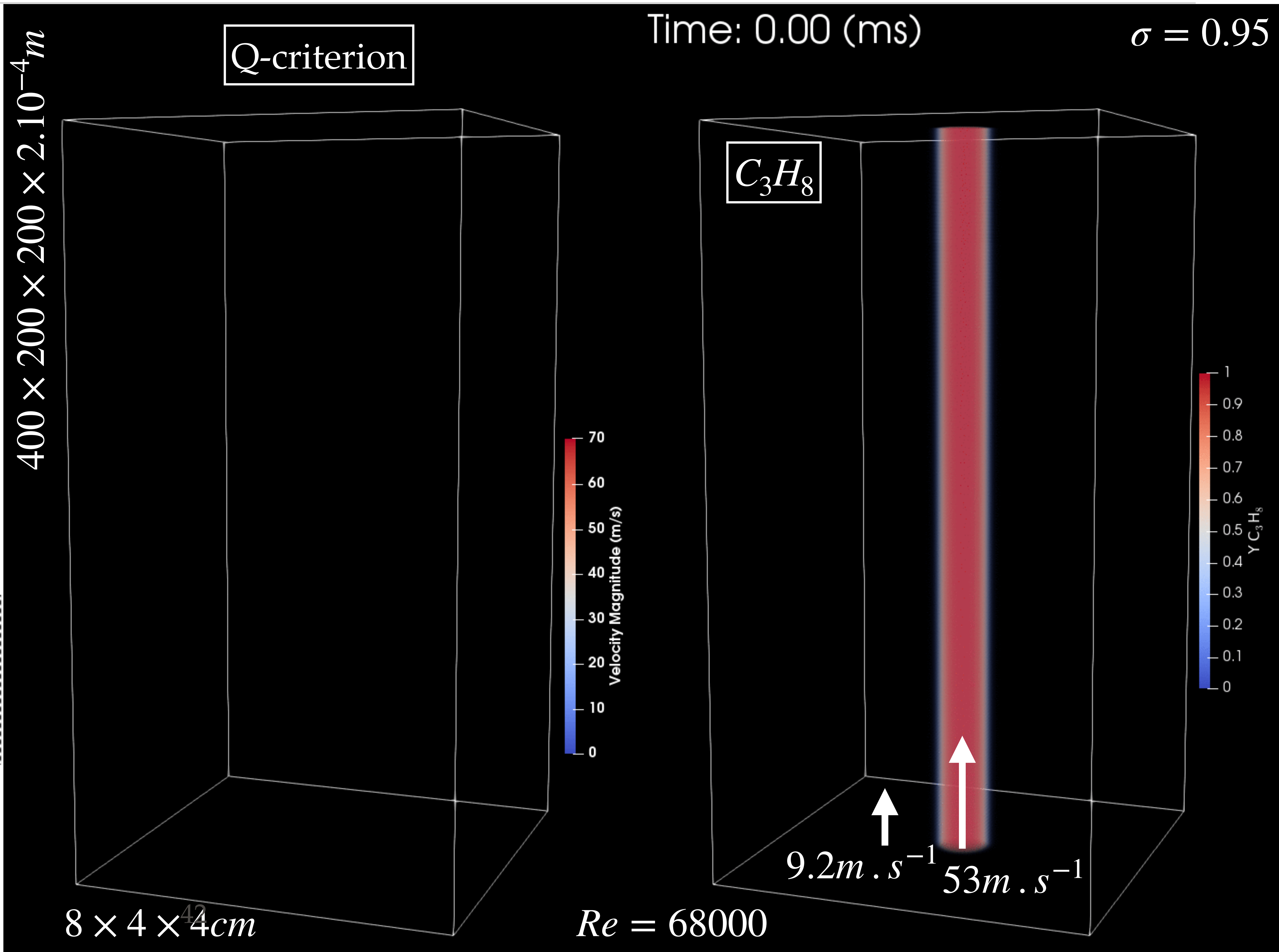


3D turbulent jet

- Propane non-premixed jet flow (variable density) - Sandia
- 300x200x200 + refinement

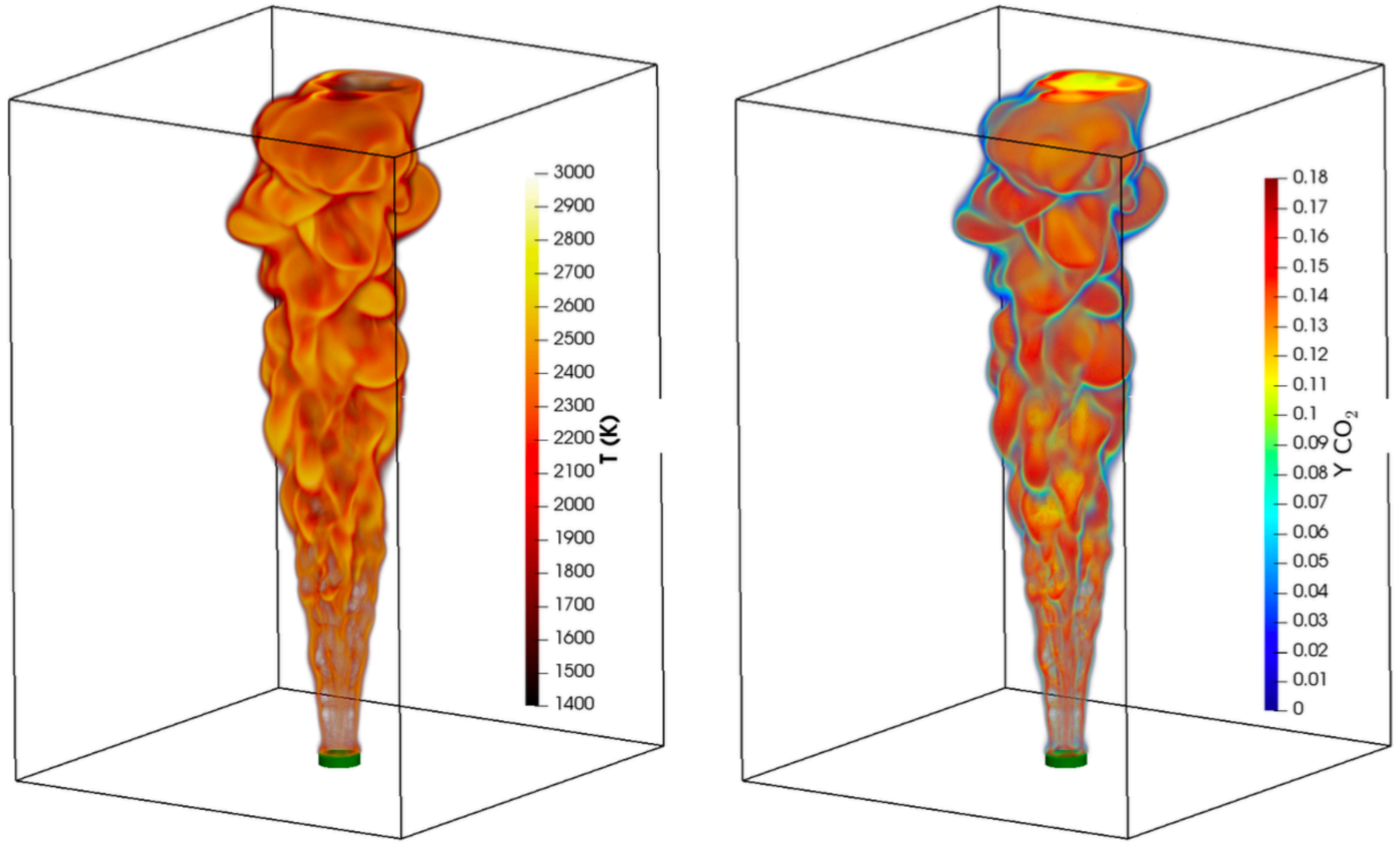




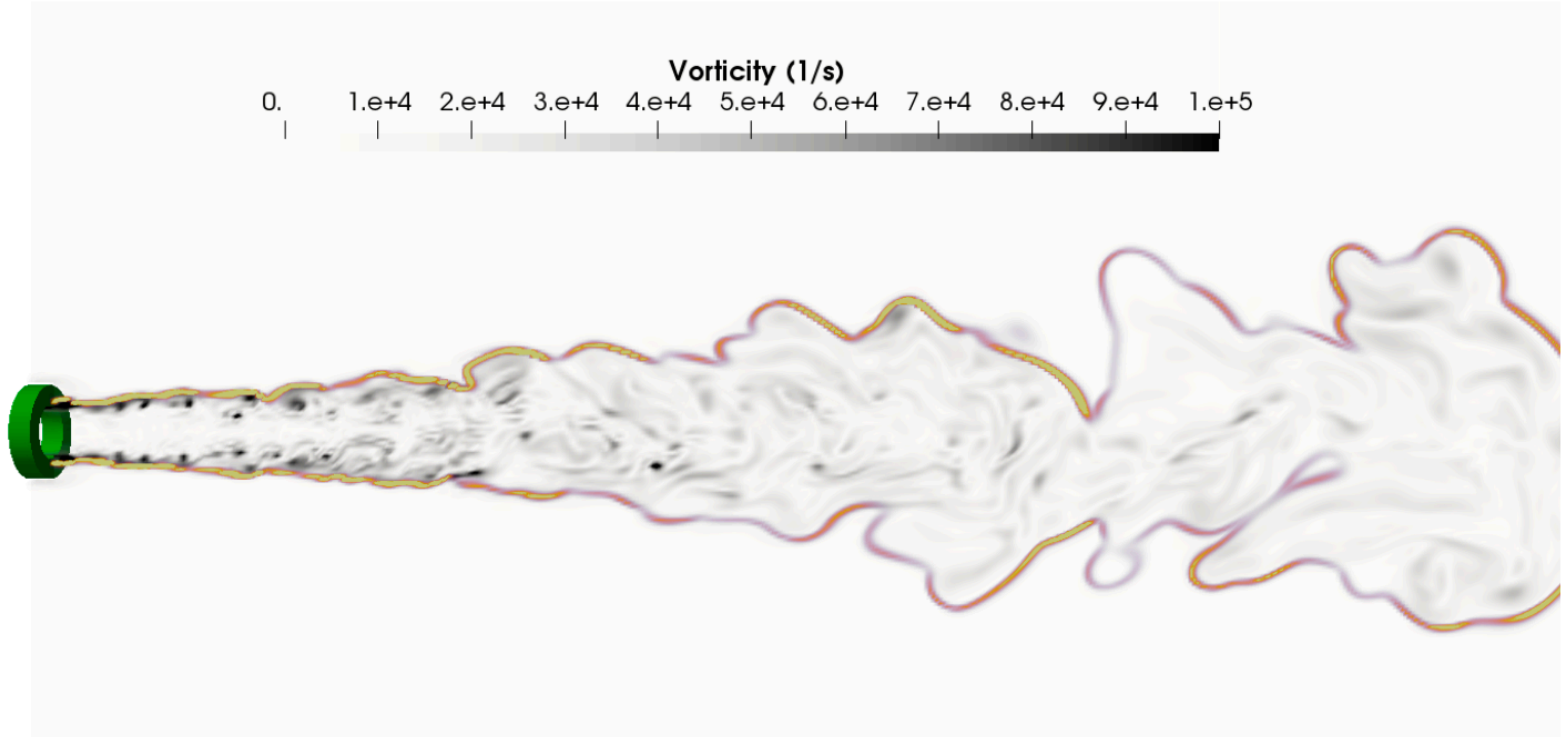


3D turbulent jet

- Propane non-premixed jet flow (variable density) - Sandia
- 300x200x200 + refinement
- The same, reactive
  - No subgrid model (flow)
  - no subgrid model (combustion)
  - = Highly robust !
- Future work - rerun on an experimental jet using a turbulent combustion model

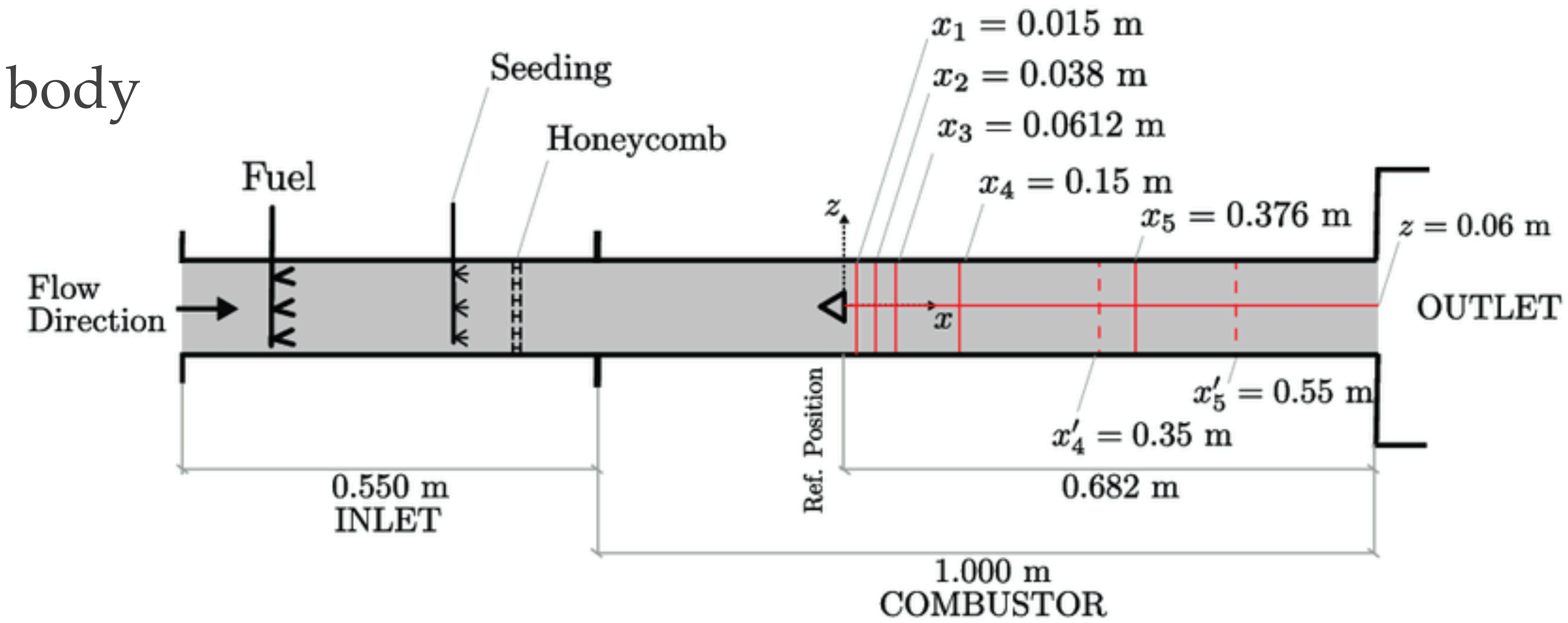


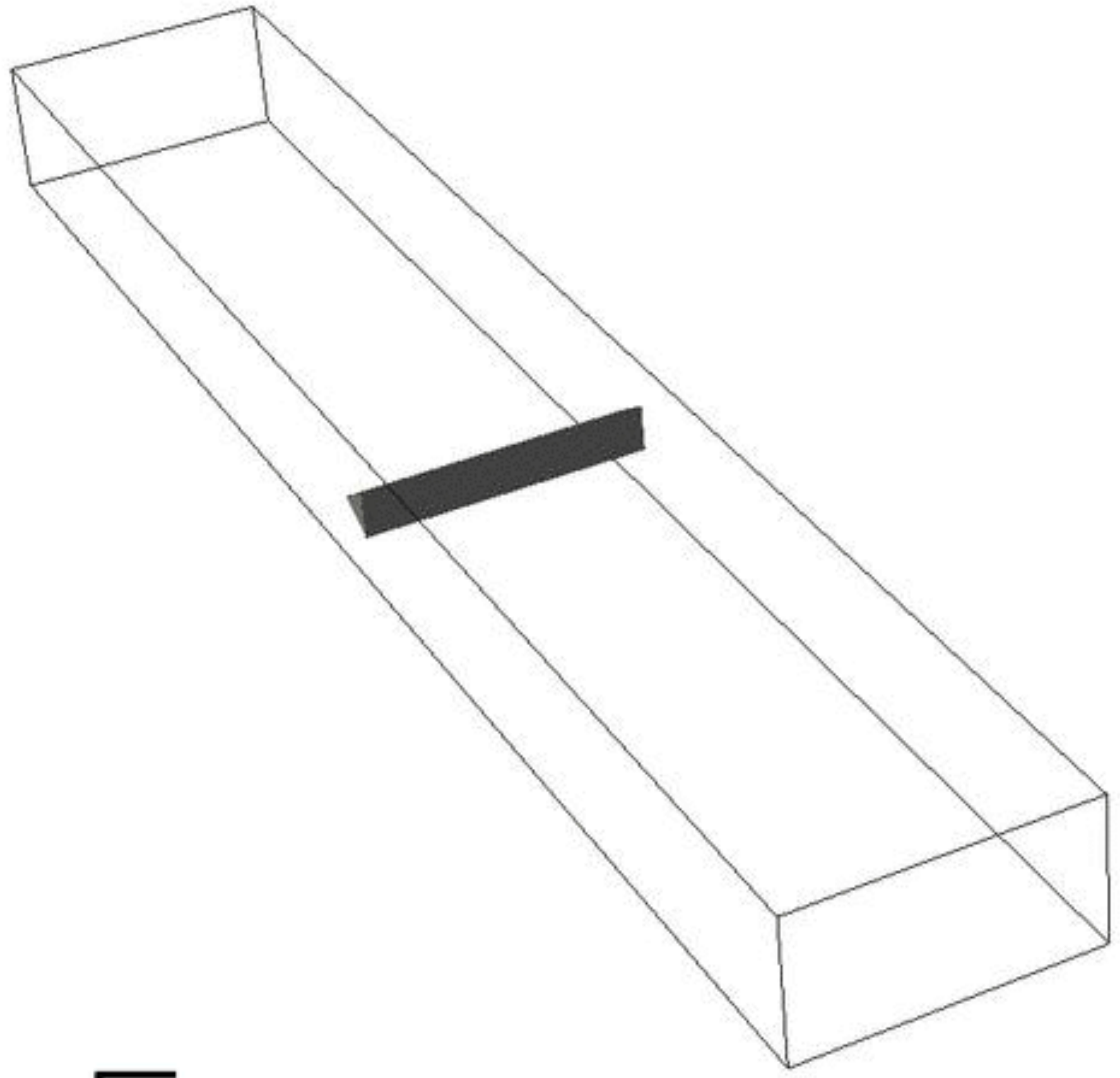
(a) Temperature (b) Y_{CO_2}



Volvo Burner

- Common to validate premixed turbulent combustion model
- Flame stabilized behind bluff body
- Numerical set-up
  - Min grid size: 2mm, 1mm
  - 2 step propane chemistry
  - TFLES model (Rochette C&F 2020)





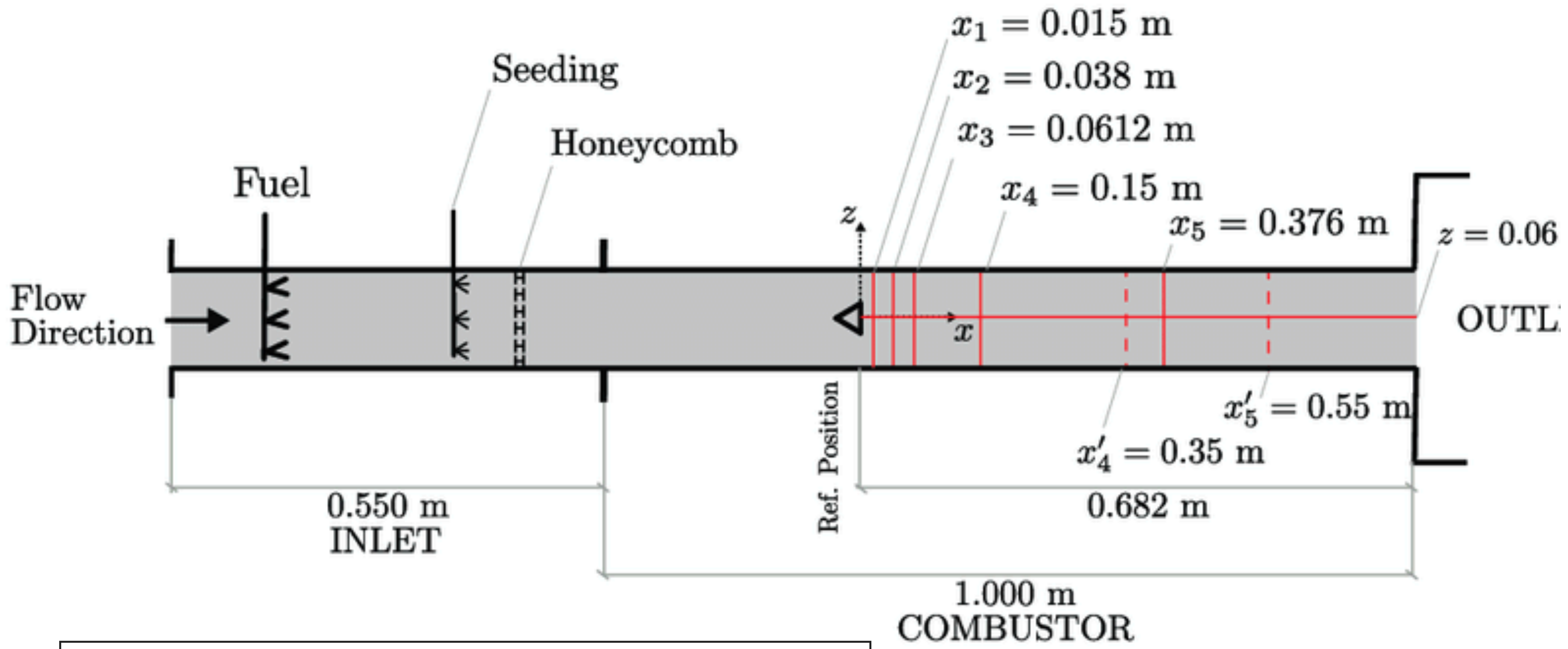
Progress variable

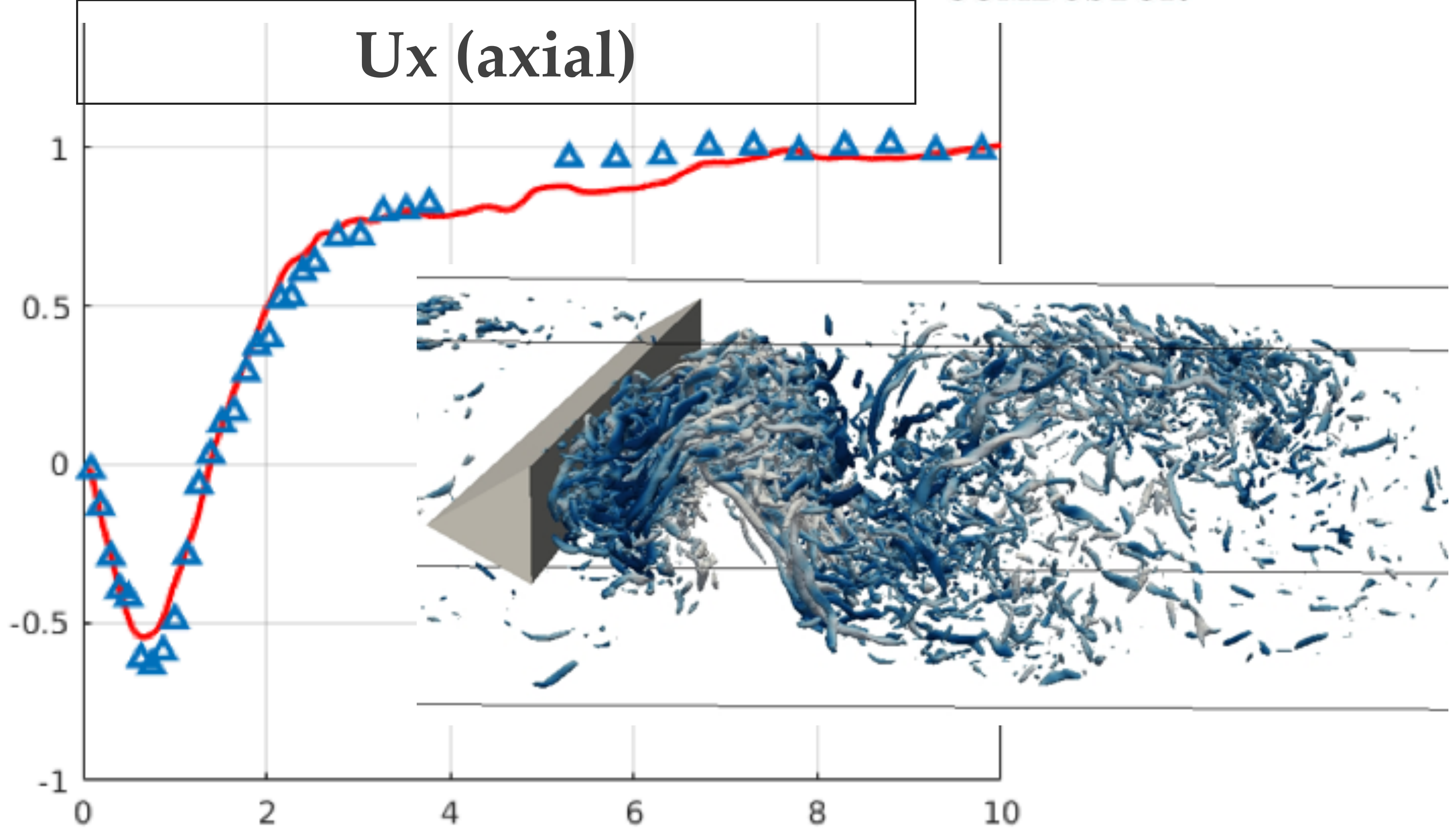
Velocity field

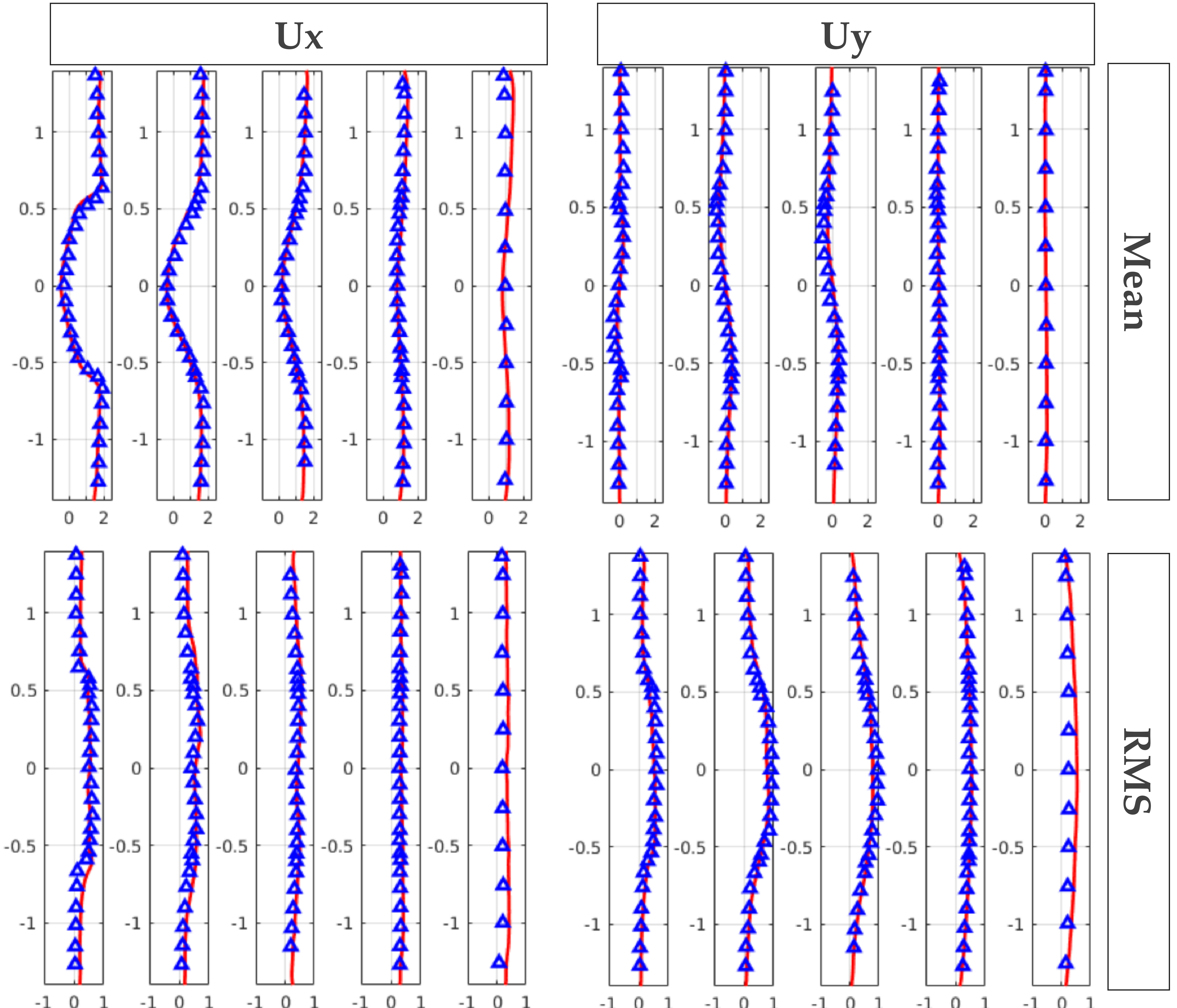
Cold case

Volvo burner

- Premixed propane-air

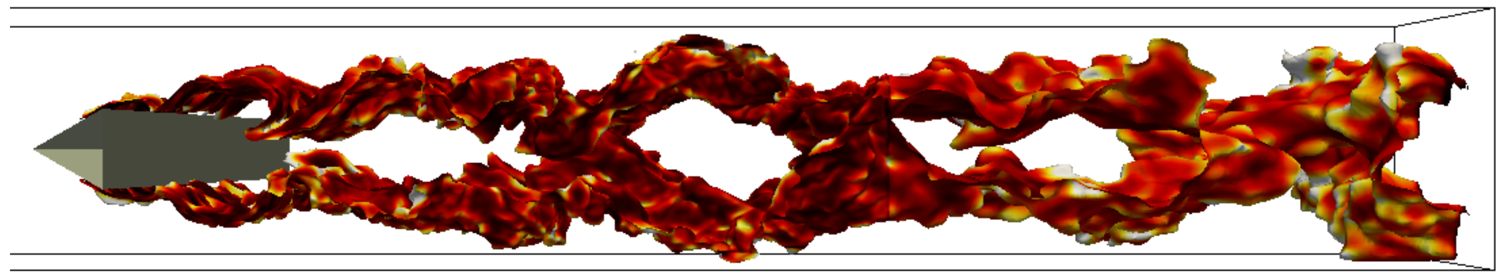




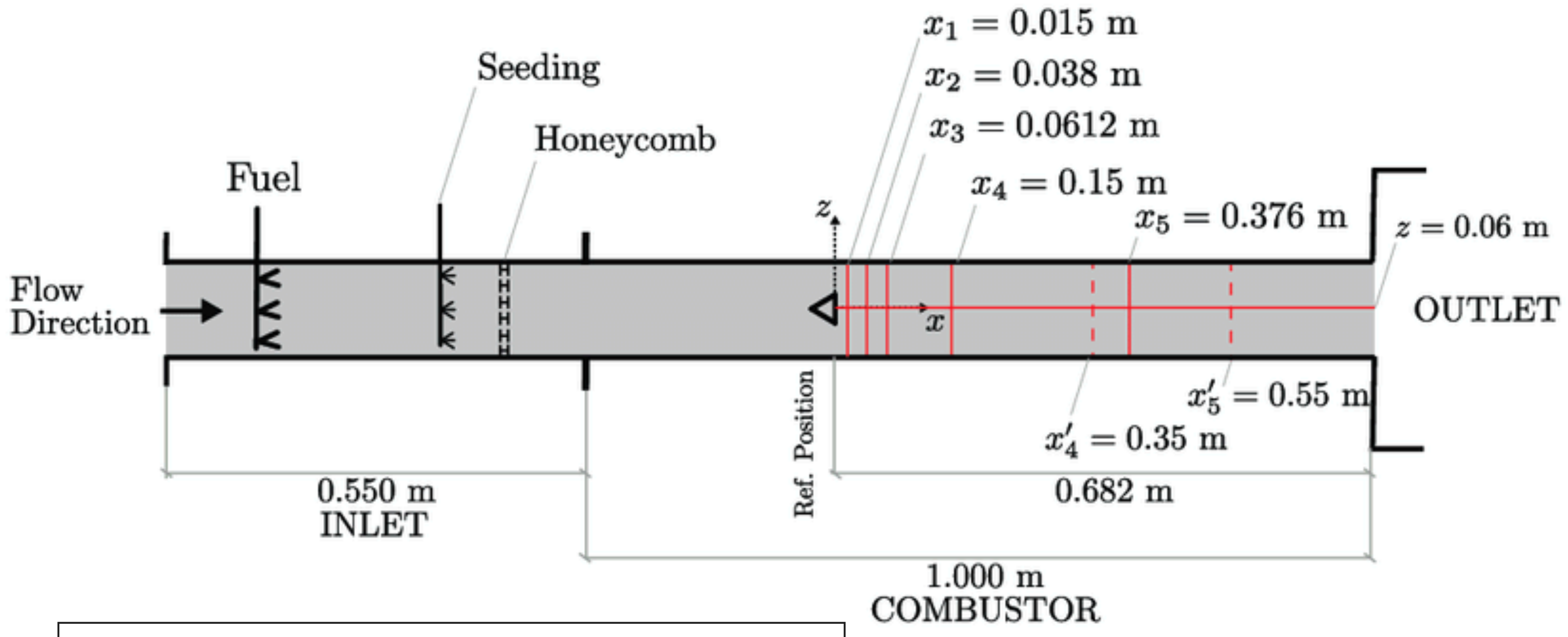


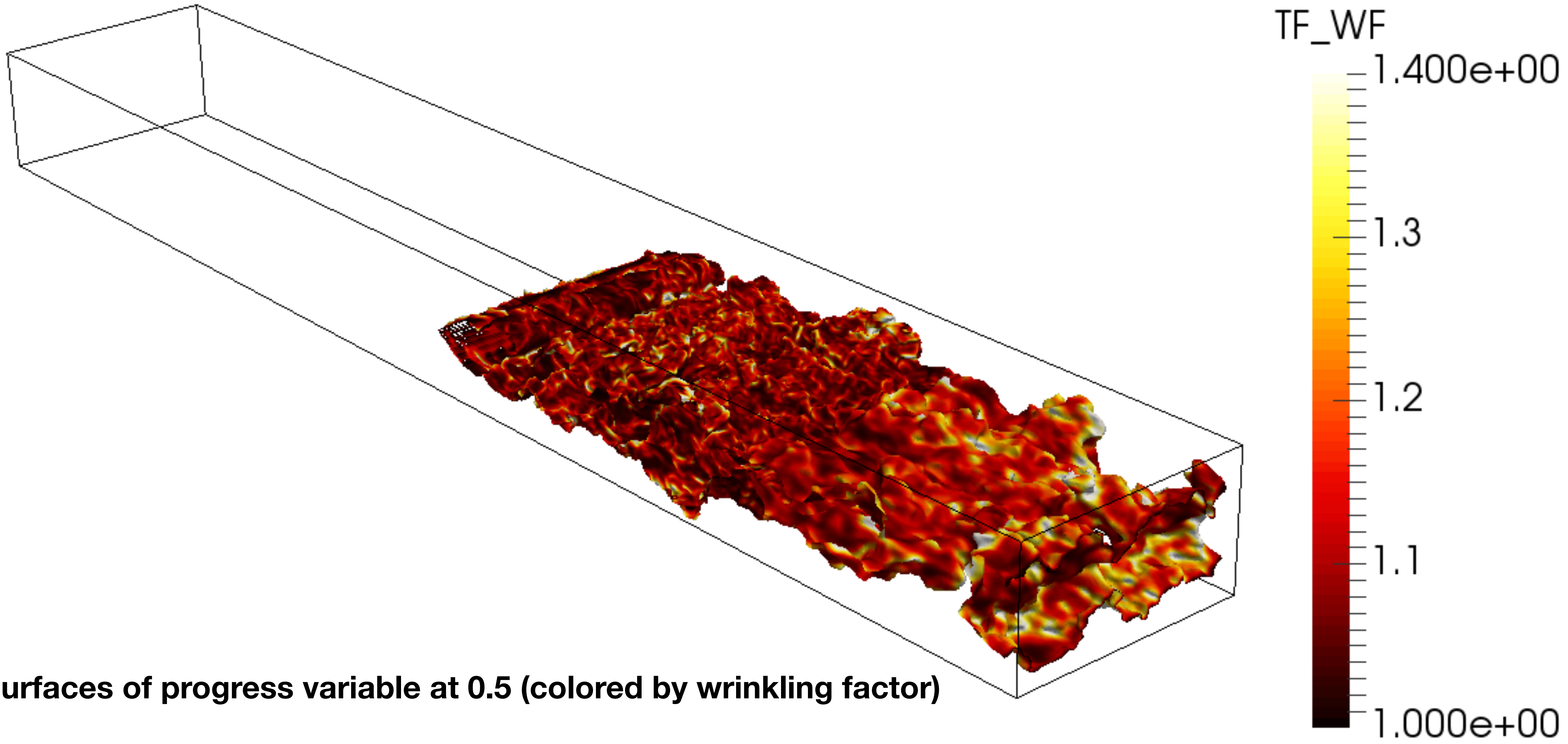
Hot case

Volvo burner

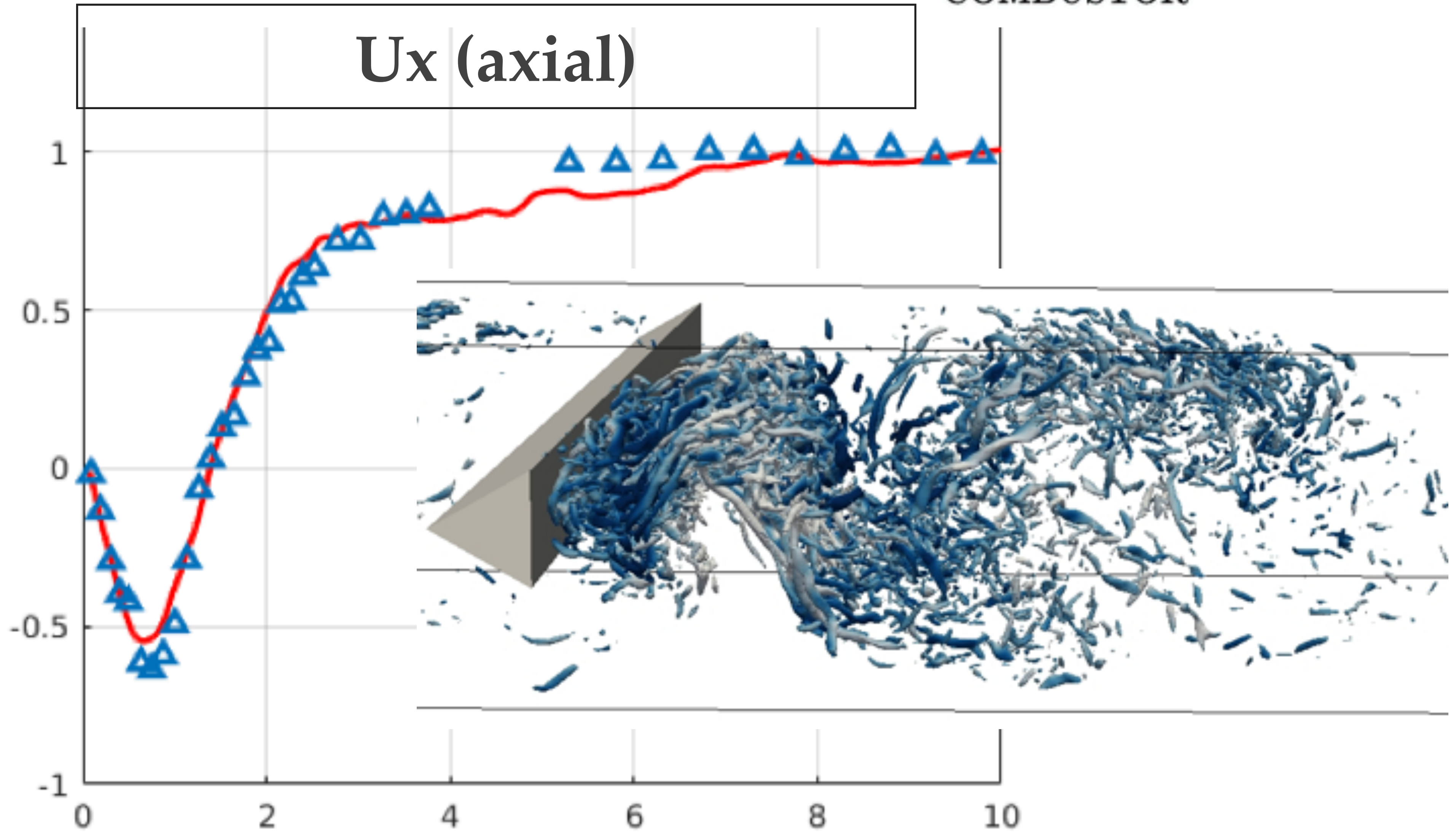


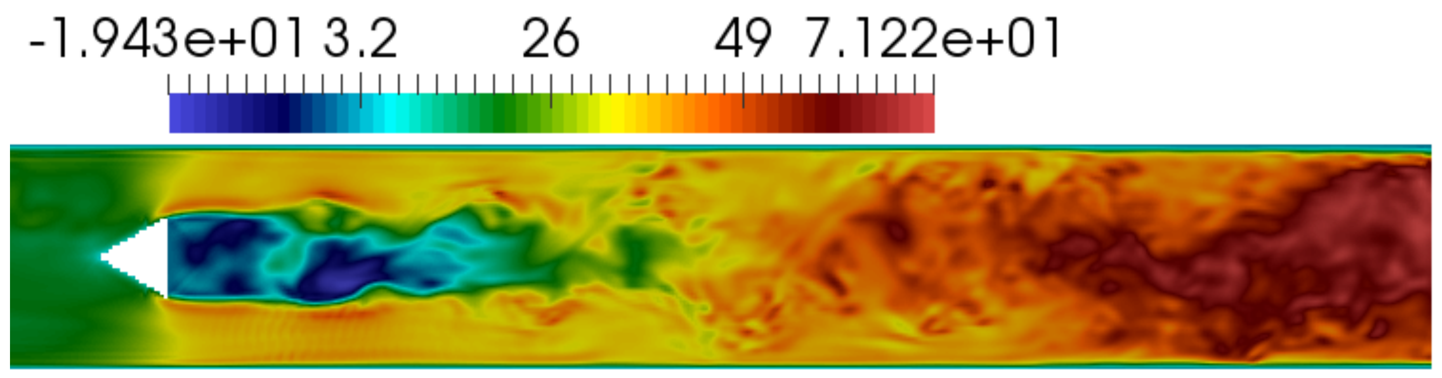
- Premixed propane-air



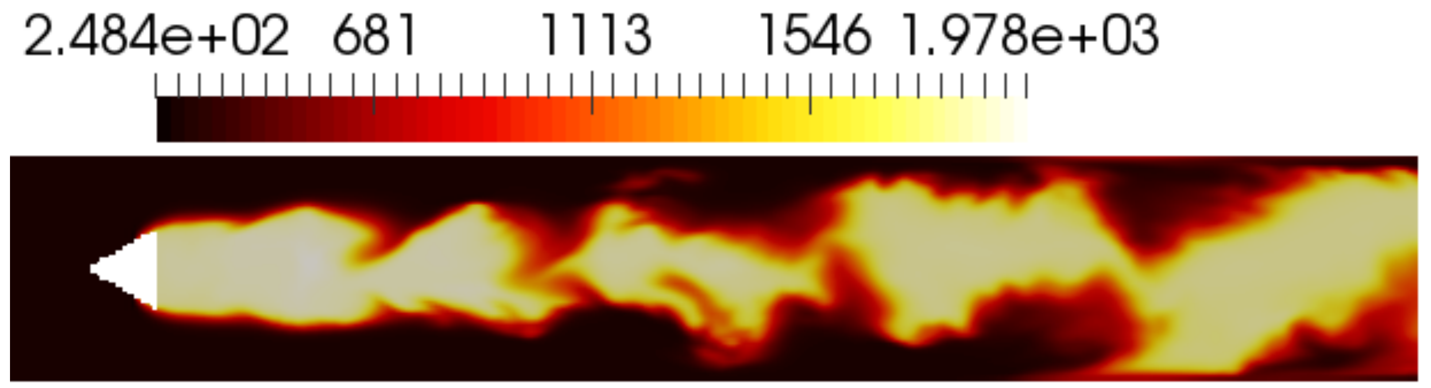


Iso-surfaces of progress variable at 0.5 (colored by wrinkling factor)

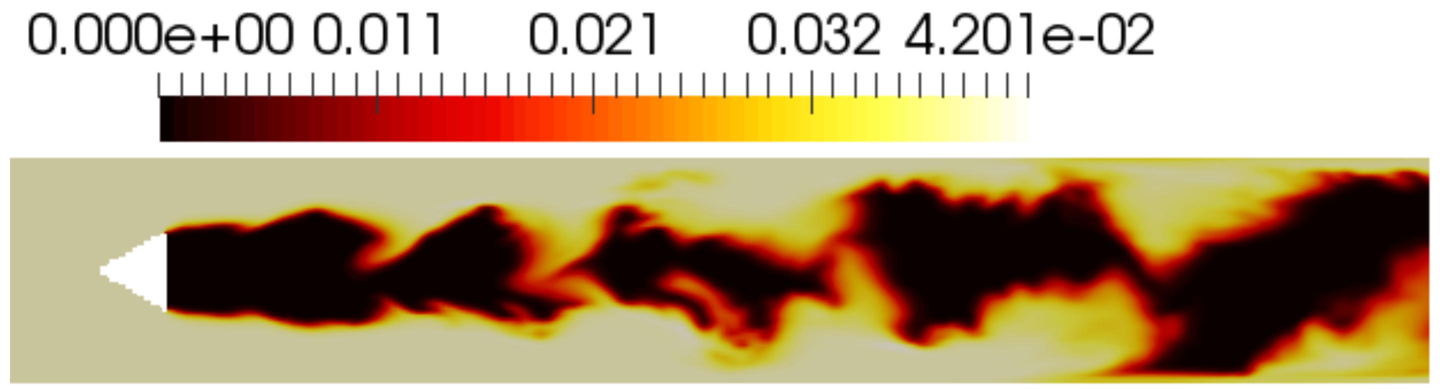




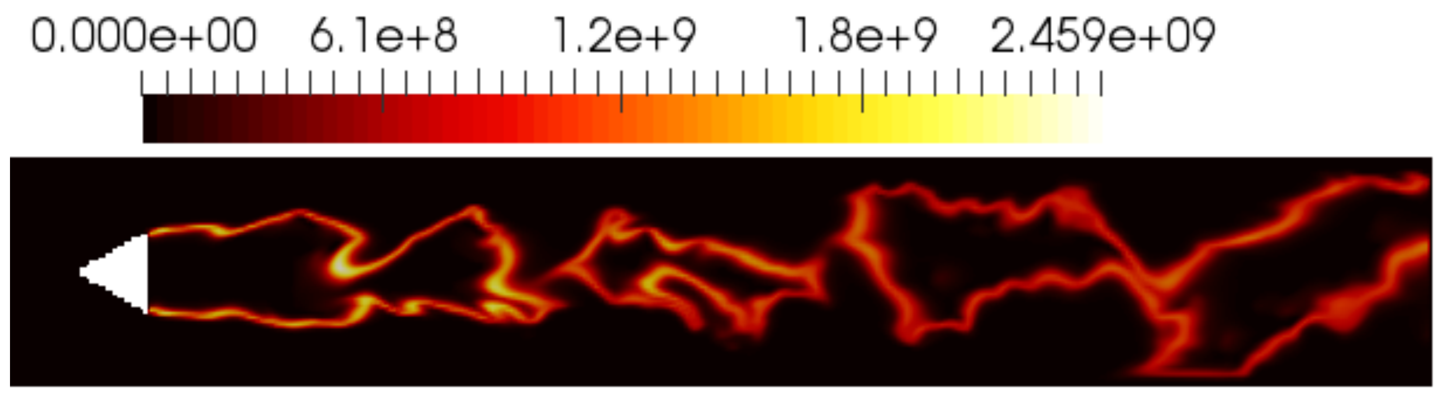
Axial Velocity



Temperature



C_3H_8

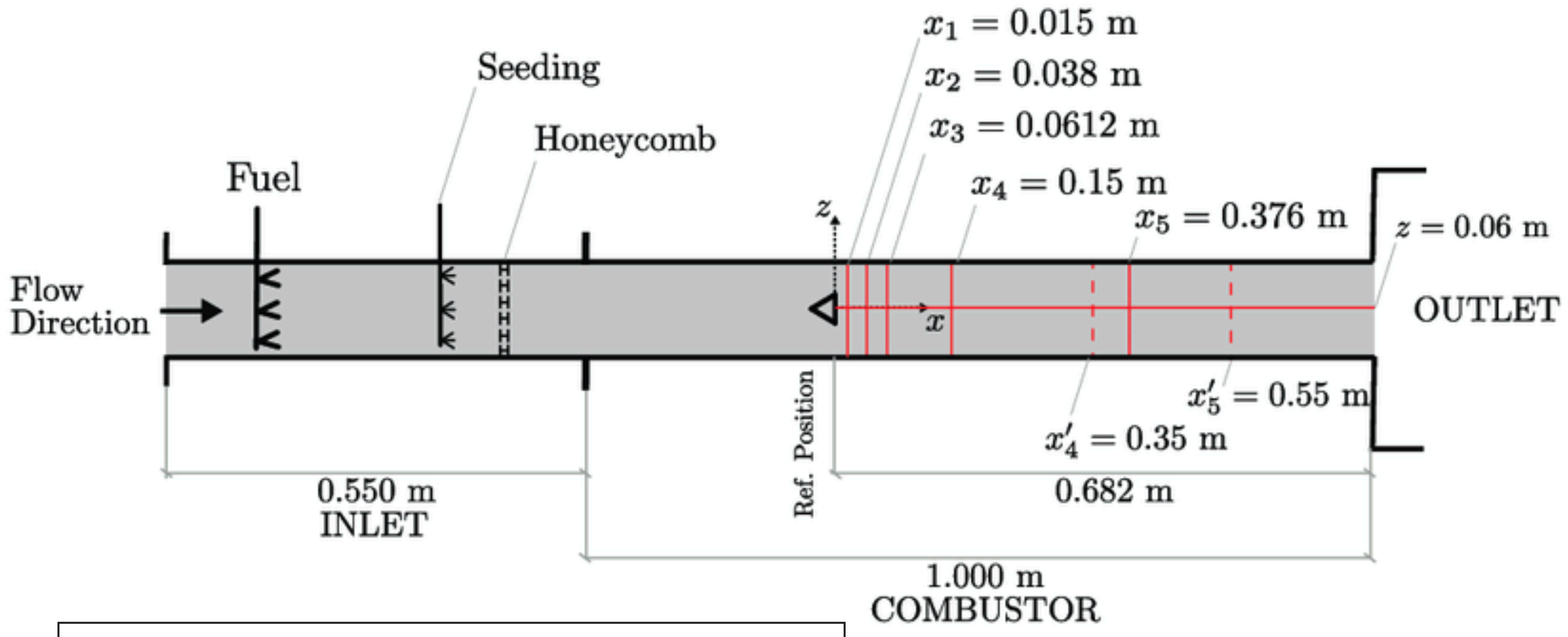


Heat Release Rate

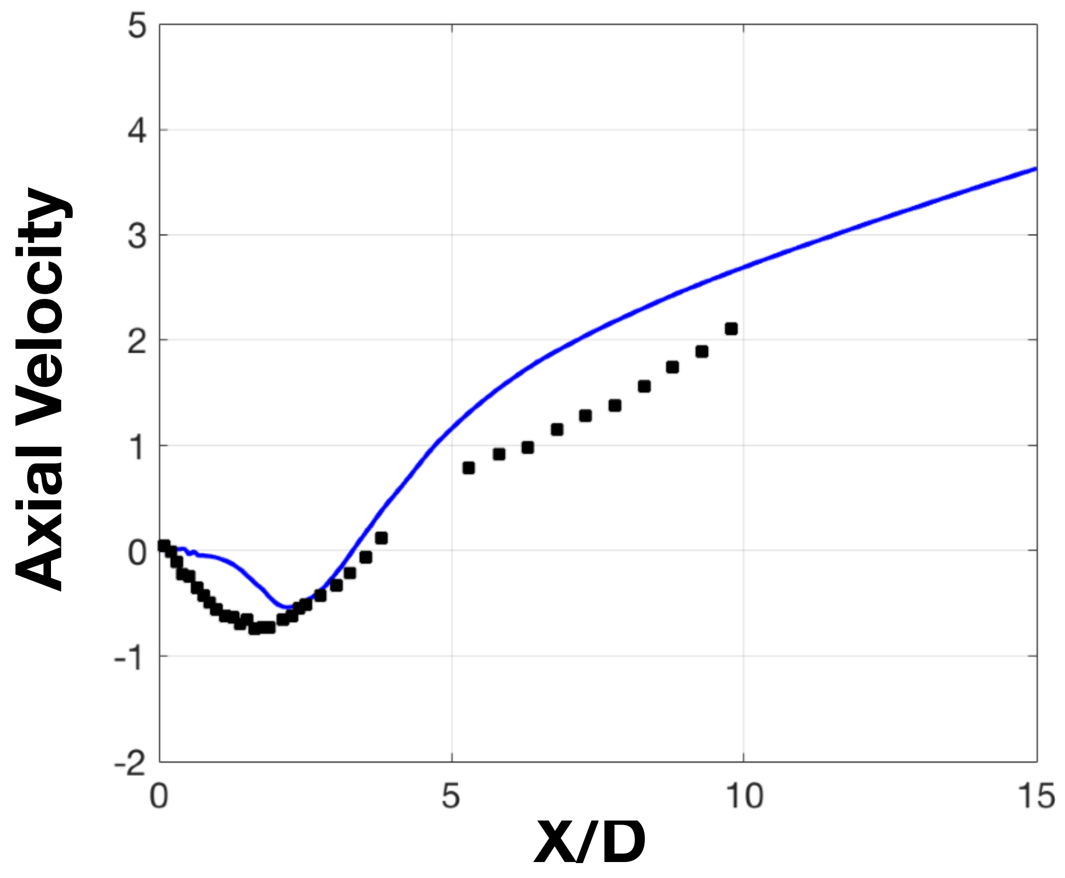
Hot case

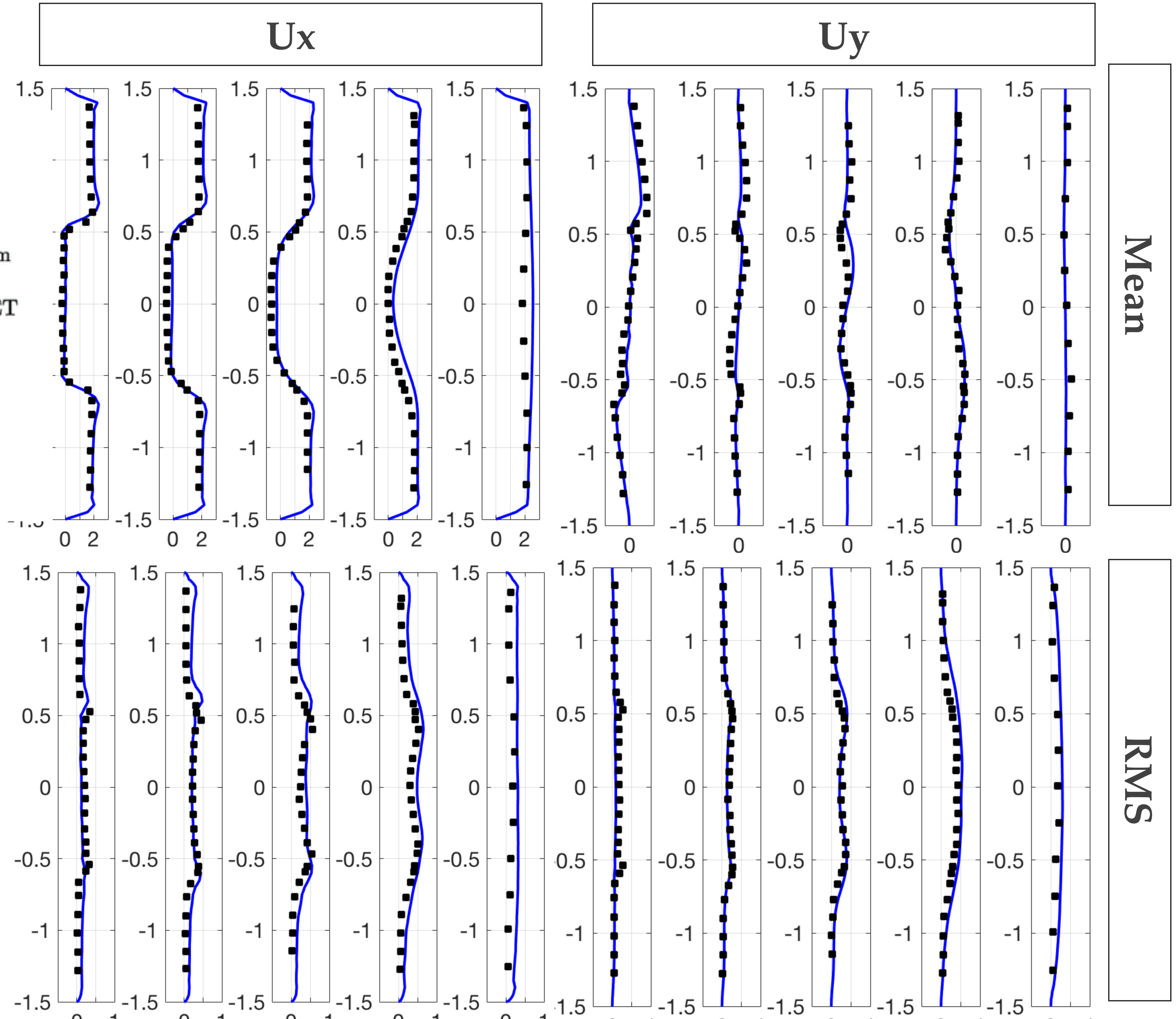
Volvo burner

- Premixed propane-air



Ux (axial)

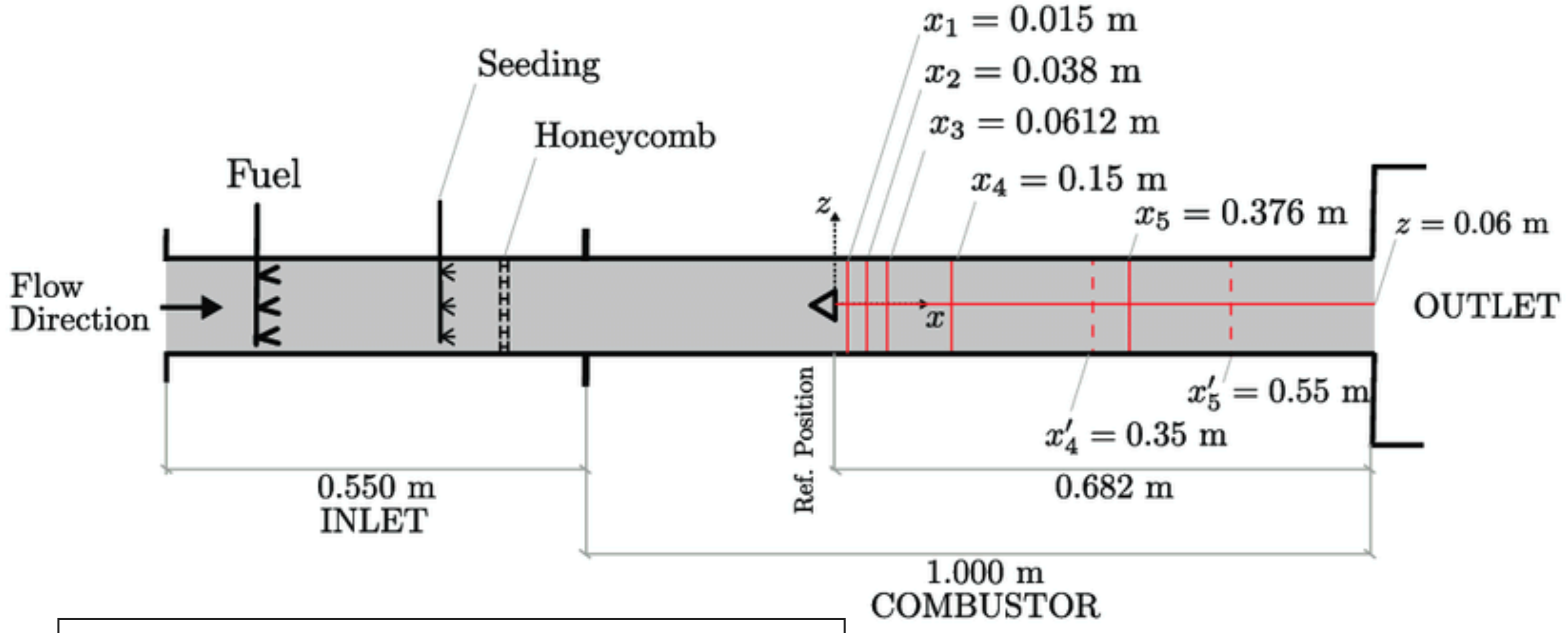




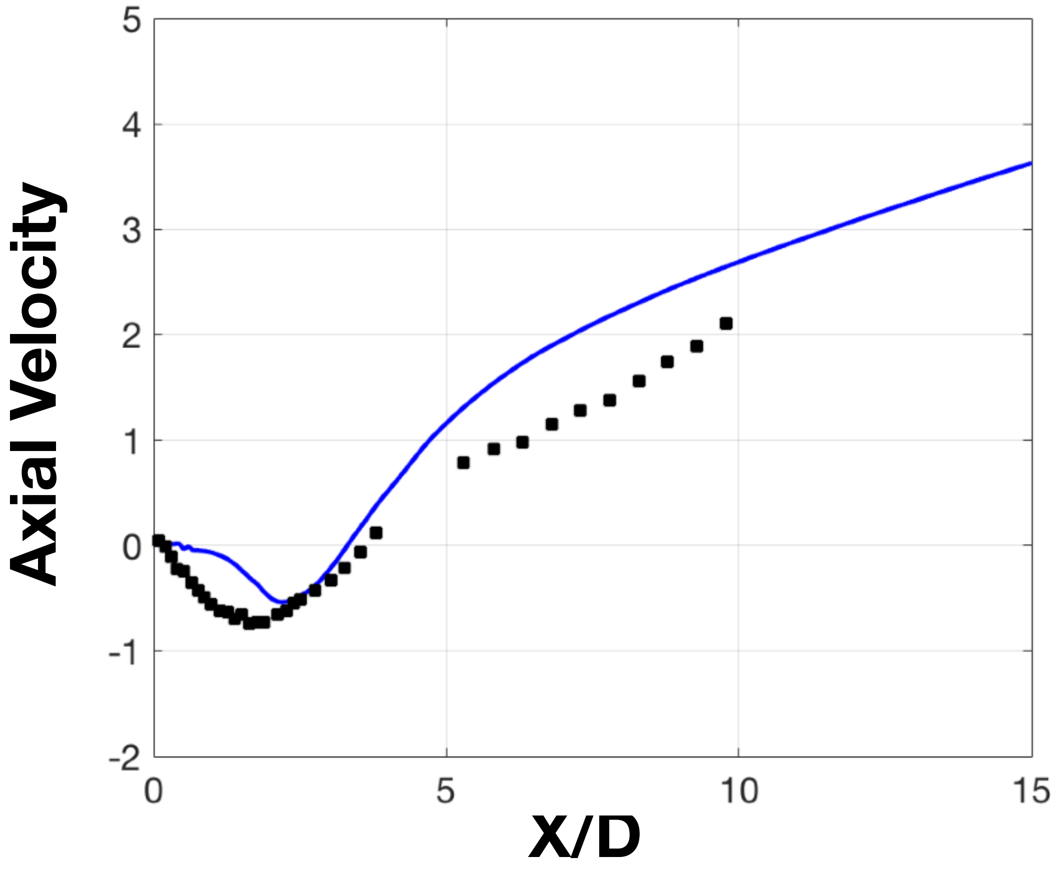
Hot case

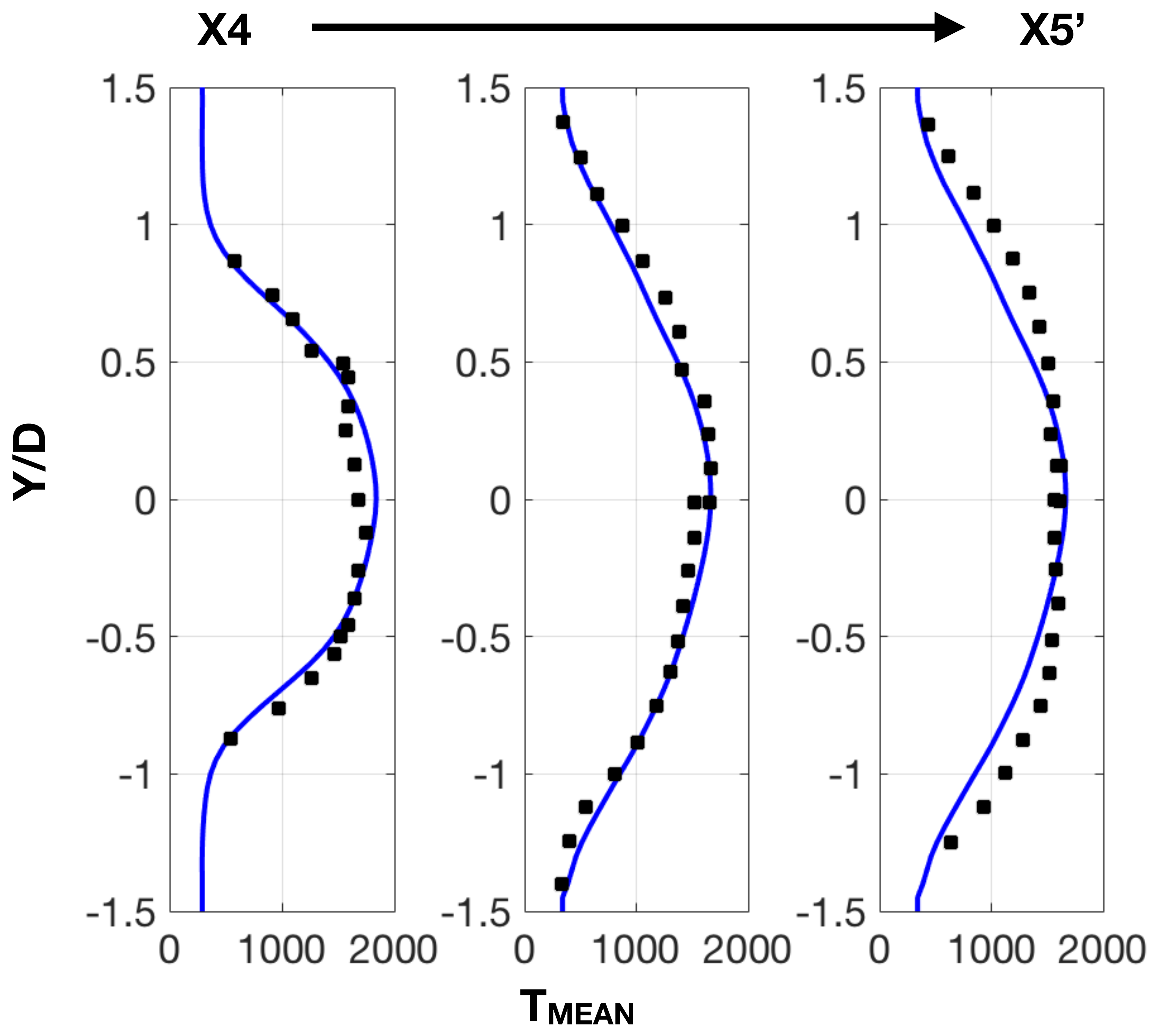
Volvo burner

- Premixed propane-air



Ux (axial)





Cost: 1000 cpu.h per flow-through-time (5.5M points)

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Conclusions

- A Hybrid LB model suitable for combustion application
- Acoustic solver for less the cost of a LMNA code (on uniform grid)
- Local time-stepping (multi-level grid) => **even cheaper**
- Keeps the low-dissipative LB features (aeroacoustics)

Merci à…

- Muhammad Tayyab (PhD 2017-2020 - LBM combustion)
- Song Zhao (Post-Doc CNES 2018-2020, now IR - LBM combustion)
- Gabriel Farag (PhD 2018-2021 - LBM compressible)
- Thomas Coratger (PhD 2019-2022 - LBM compressible, chaire ALBUMS)
- Camille Sarotte (Post-Doc 2019-2020 - LBM compressible, chaire ALBUMS)
- Mostafa Taha (PhD 2019-2022 - LBM fire/plumes)
- Karthik Guruprasad (PhD 2020-2023 - LBM combustion)
- Yongliang Feng
- Jérome Jacob (IR, ProLB, M2P2)
- Pierre Sagaut (PR, ProLB, M2P2)
- Et pour les discussions et l'aide: les collègues du Cerfacs, de l'Irphe, du Coria
- Ceux que j'oublie…

… Questions ?