Shock – planar curtain interactions

Strong Secondary baroclinic deposition and emergence of coherent and random vortex projectiles (VPs), and decaying stratified turbulence

VIZLAB

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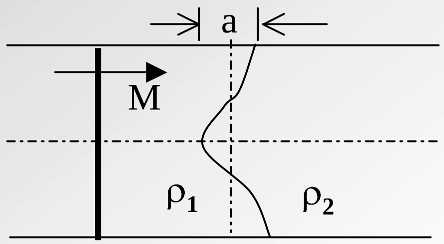
Brief Review

Common geometries for studying accelerated inhomogeneous flows (**aifs**)



Linear, Nonlinear & Vortex: growth rate

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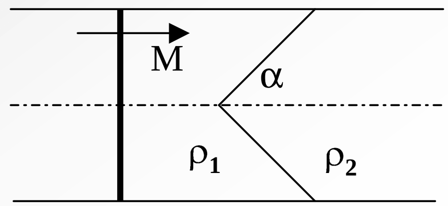
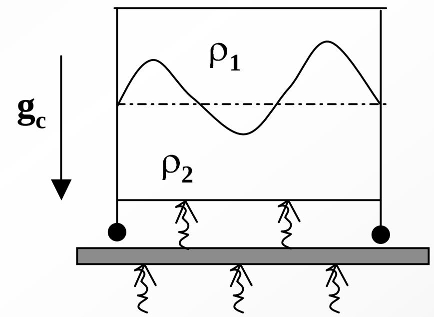
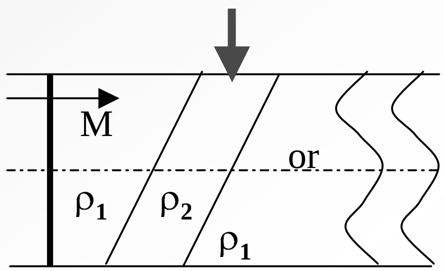


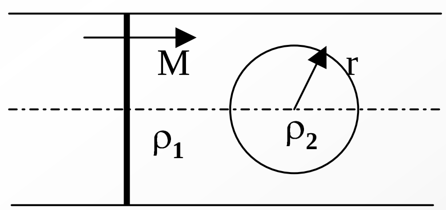
Self-similar Solution; Quantification on: Circulation, baroclinic effects & convergence



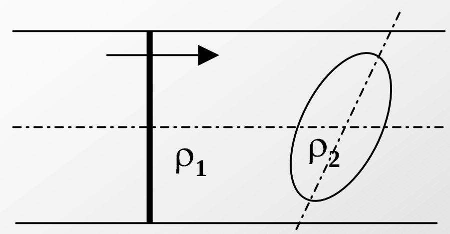
Reaccelerated tank (Jacobs & Niederhaus, 97)



Curtain: inclined or perturbed (Sturtevant, 87; Benjamin et al, 84)



Circular Cylinder or Sphere (axisymmetric or 3D): Vortex separation & vortex projectiles (VPs)



Elliptical cylinder or ellipsoid: Cavity implosion, vortex separation & vortex projectiles (VPs)

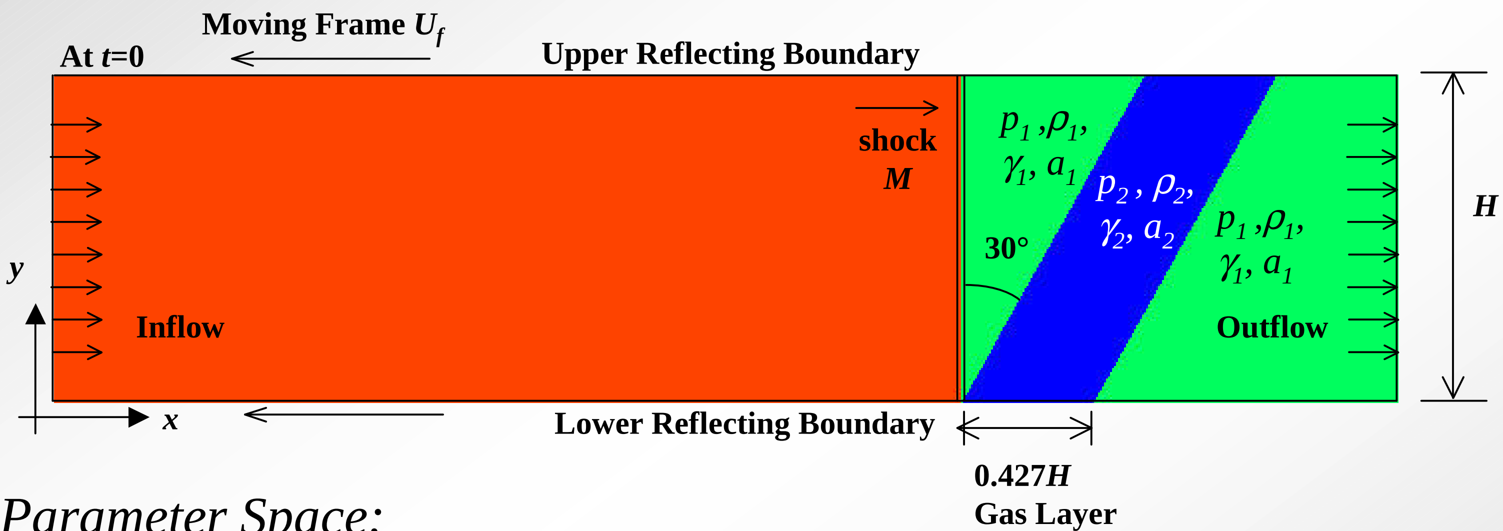
Motivations

Visualize, ***Quantify*** and ***Model*** the vortex dominated physical process, including:

1. Baroclinic vorticity
   - Main baroclinic vorticity deposition by the shock wave: *vortex double layers (VDL*)
   - Secondary baroclinic vorticity deposition by vortex interaction
   - Scaling with regard to Mach number
2. Emergence, evolution and modeling of "*Vortex Projectiles*" (**VP**) or coherent dipolar vortex structures
3. Turbulent mixing and rapid turbulization at high Mach number
4. Study of 3D effects

Computational Domain

1. Schematic (following [Yang, Zabusky & Chern, 1990]):



2. Parameter Space:

- **Density ratio:** $\eta = \rho_2 / \rho_1$ **(Slow/Fast/Slow (0.14)**
- **Mach #: 1.5, 2.0, 5.0**

- **Resolution(2D & 3D):**

  800×160(H)

  200×80×80

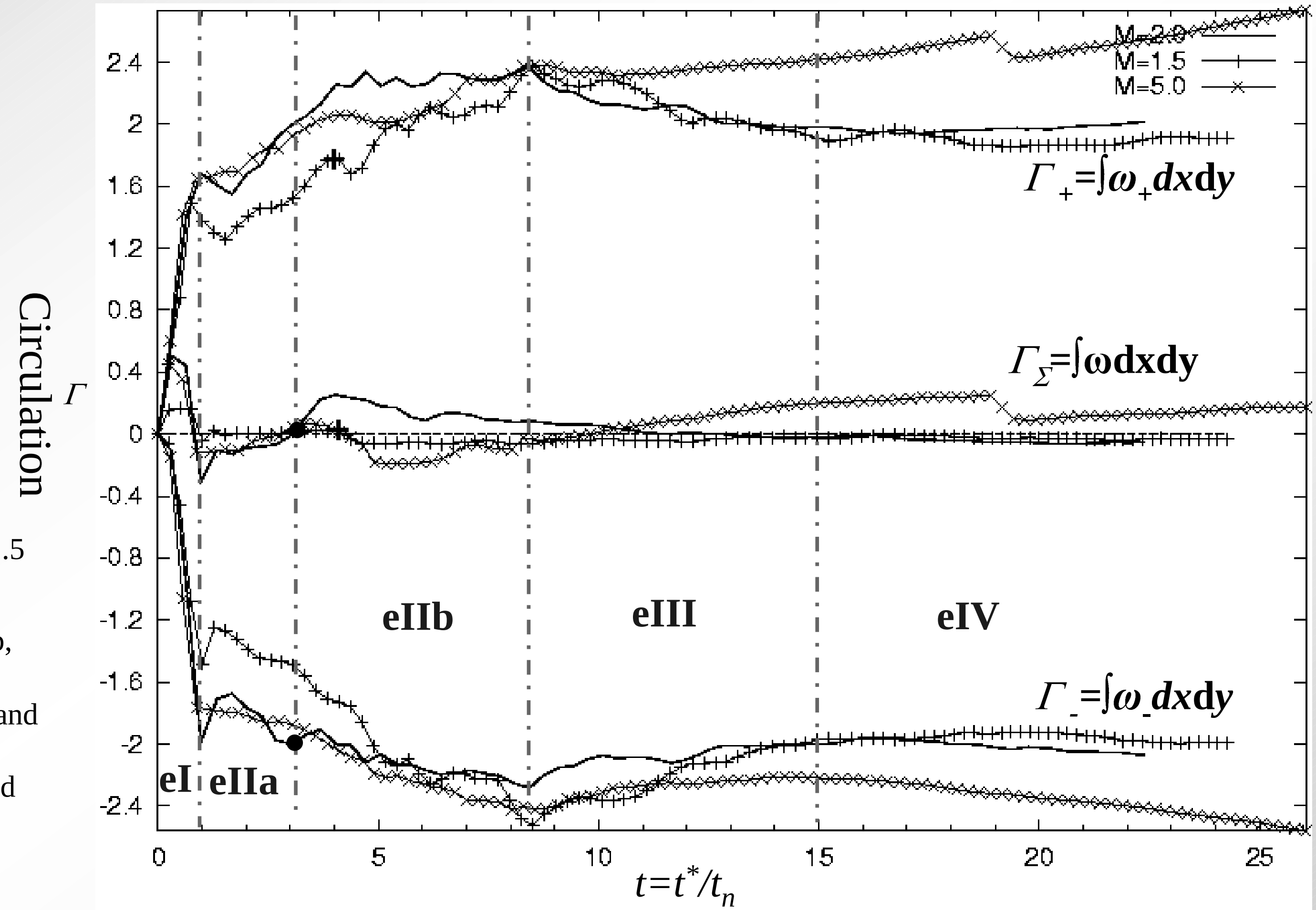
3. Numerical Method:

- Compressible Euler Equation
- Piecewise Parabolic Method [Woodward & Colella, 1984]

Global Quantification I: Evolution of normalized circulation

Normalization factors:

- M=1.5 circulation:
$\max\Gamma_{+|M=2.0}/max\Gamma_{+|M=1.5} \approx 1.4$
- M=5.0 circulation:
$\max\Gamma_{+|M=2.0}/max\Gamma_{+|M=1.5} \approx 0.39$,
- t_n: a plain shock traveling through length of the curtain thickness horizontally without inhomogeneity.



Note

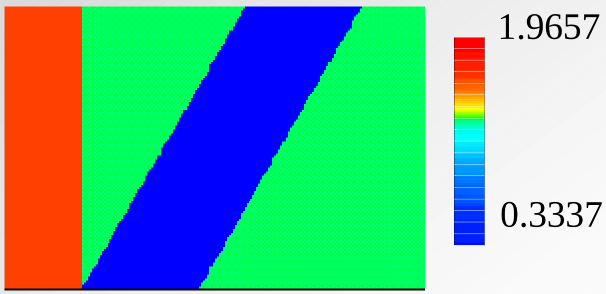
- The time epoch: according to M=2.0 run, good for most of M=1.5 run
- Separation point of eIIa and eIIb, characterized by the time *VP1* hit the upper boundary, • *for M*=2.0 and + *for M*=1.5, are identified via negative circulation for M=2.0 and positively circulation for M=1.5 respectively.

Time Epoch, Feature Phenomena and Physical Processes

Time Epochs	Feature Phenomena		Physical Processes
	Density	Vorticity	
e①	Shock wave passes the curtain: reflection (upstream expansion wave), refraction and transmission.	Opposite sign vortex sheet deposition and approach; Circulation increases with significant rate.	Primary baroclinic effects
e②	Curtain "breakthrough"; Mushroom structure hits the upper boundary; Secondary reflected shock wave hits the deformed curtain	Collision of vortex layers; "Vortex binding" of oppositely signed; Formation of complex VP1; VP1 hits the boundary Circulation increases with lower rate but longer term (total amount almost the 50% as e①)	Secondary baroclinic effect due to mutual acceleration of inhomogeneity and vortex interaction
e③	Complete formation of upstream and downstream bubbles (VP's); Translating dipolar structures; Transition to turbulence	Separation of VPs; Vortex binding with image; Circulation decreasing	Vortex merging; and turbulent mixing
e④	Emergence of dipolar VP's which are well isolated; and intermediate turbulent interval	Approach to nearly stationary configuration of VPs and intermediate turbulent domain; nearly constant circulation	Dissipation and baroclinic re-acceleration

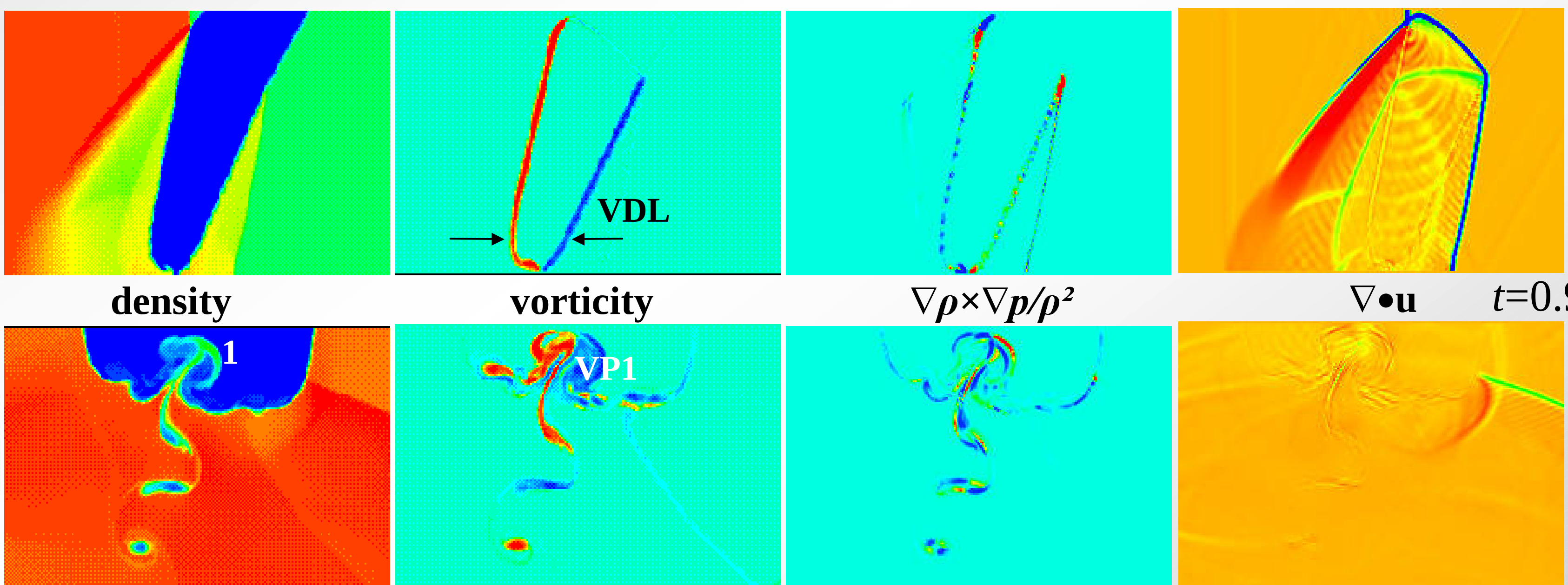
Simulations

Early time snapshots for *M*=1.5:



t=0

- Juxtaposition of density, vorticity, baroclinic term $\nabla\rho\times\nabla p/\rho^2$, and dilatation $\nabla\bullet\mathbf{u}$
- *VDL*, shock wave patterns, breaking through process and dominant *VP1*
- Following our previous work [Yang, Zabusky & Chern, 1990]



t=0.9, eI

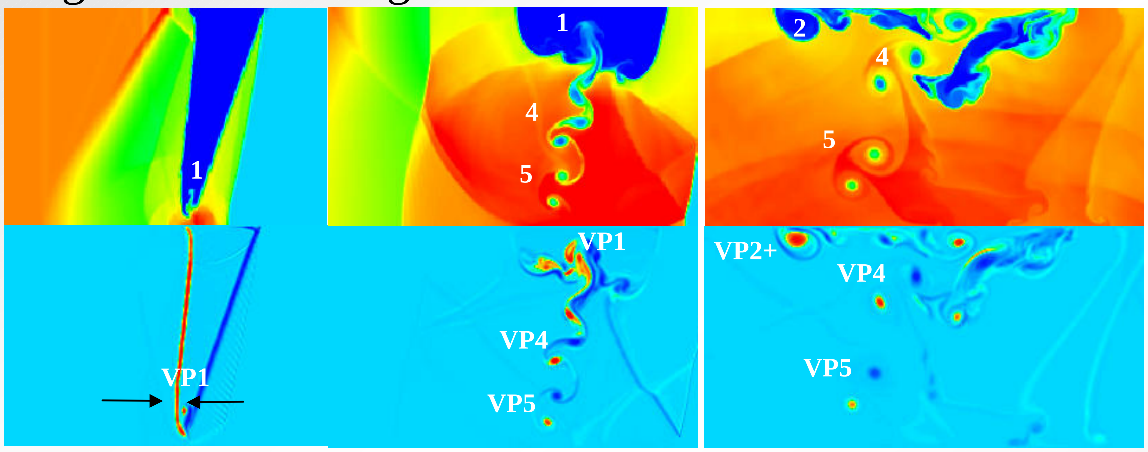
t=3.6, eIIa

Early time snapshots for *M*=2.0

- Similar to M=1.5: VDL, breaking through process, and dominant VP1
- More generic VP configuration

density

vorticity

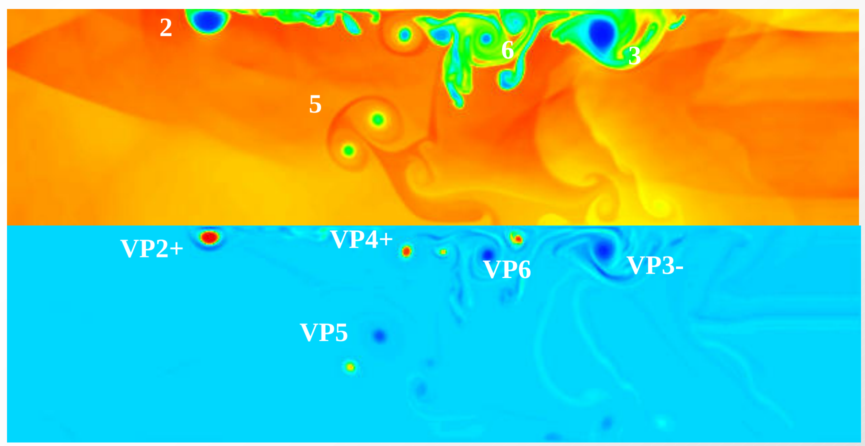


(a) t=0.95, eIIa begins (b) t=2.62, during eIIa (c) t=7.25, during eIIb

density

vorticity

(d) t=12.54, during eIII



(colormap at t=13.91)

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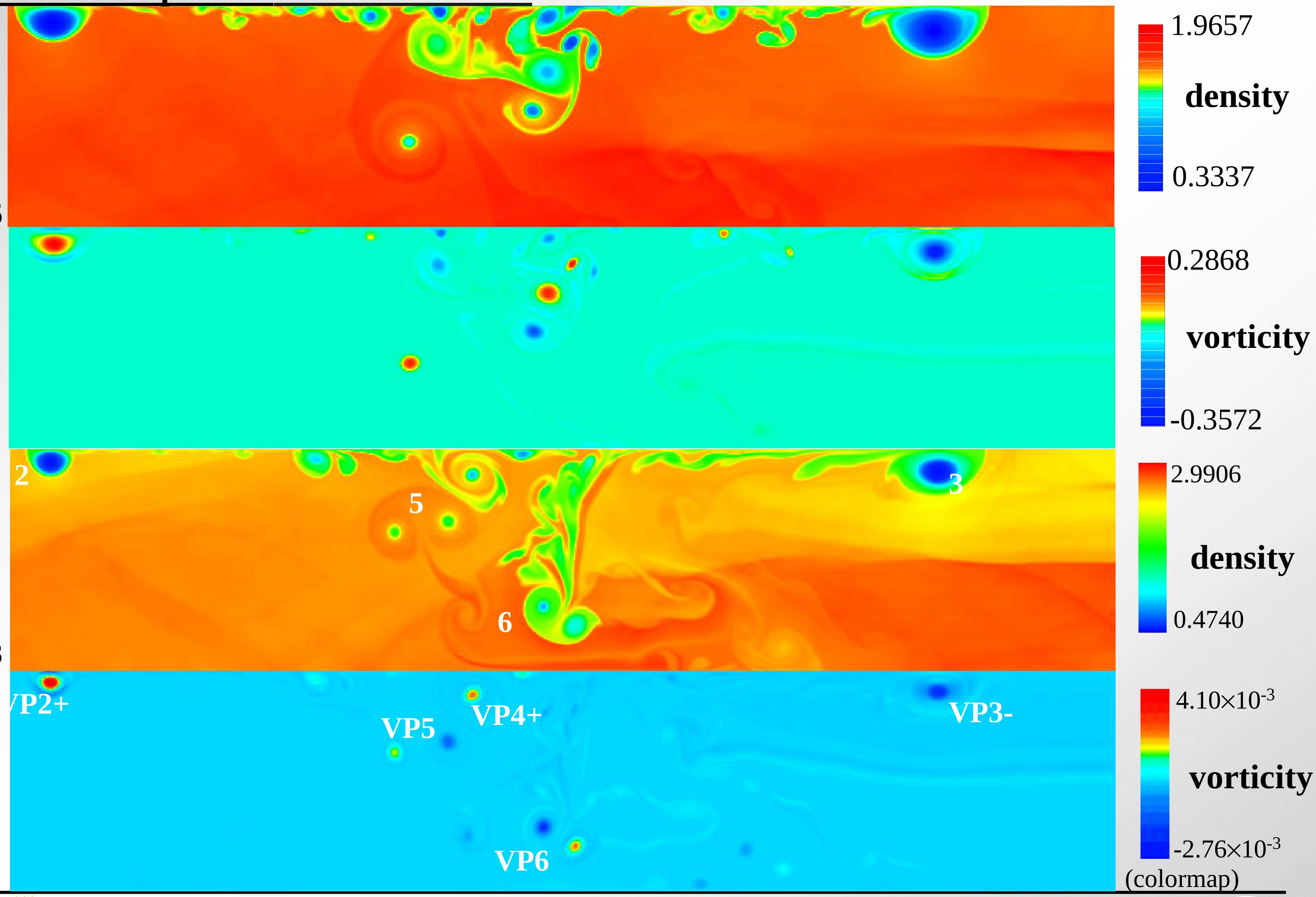
Late time snapshots: *M*=1.5 and *M*=2.0

Simulation Cont.

M = 1.5
t =23.76
eIV

M = 2.0
t =21.88
eIV



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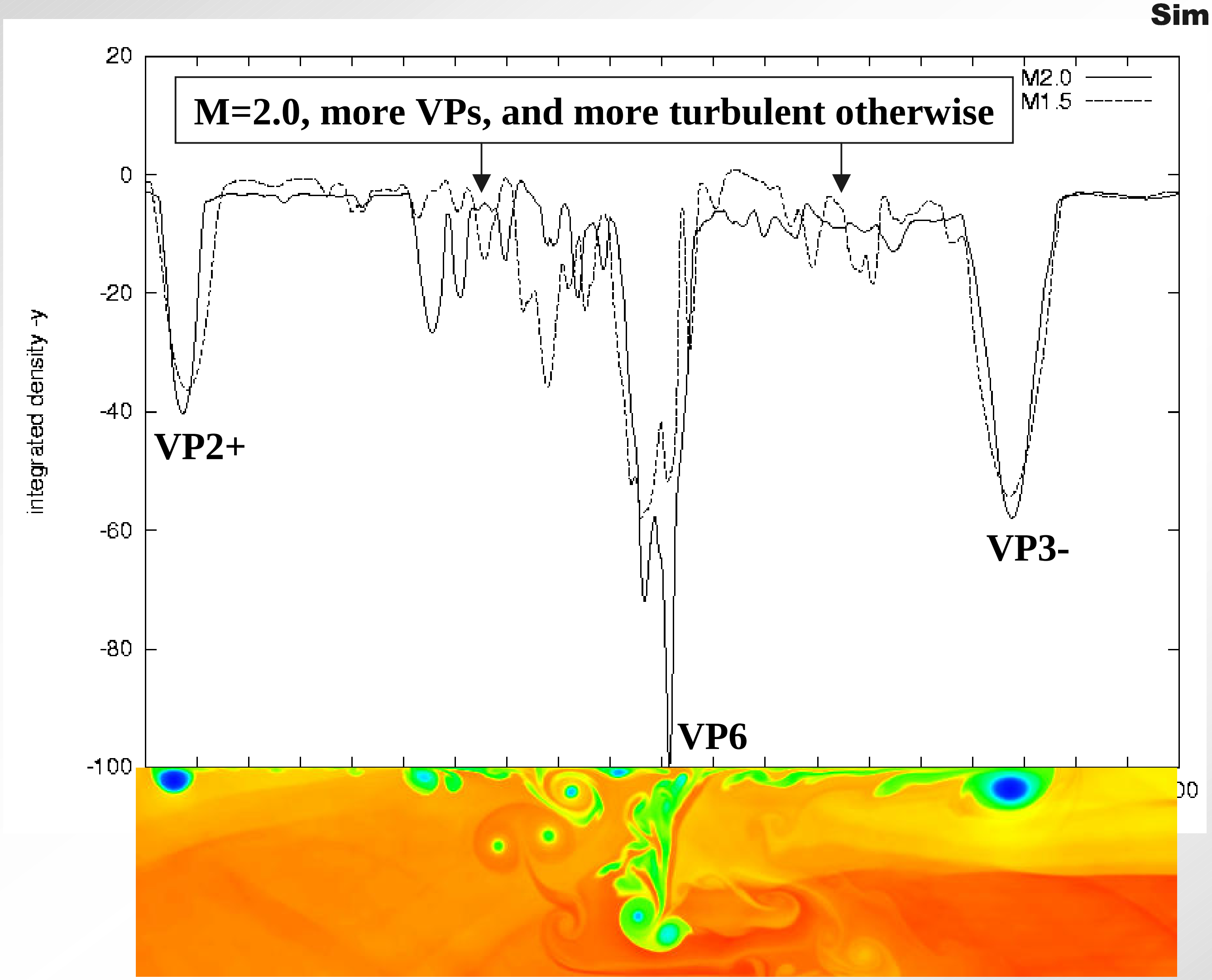
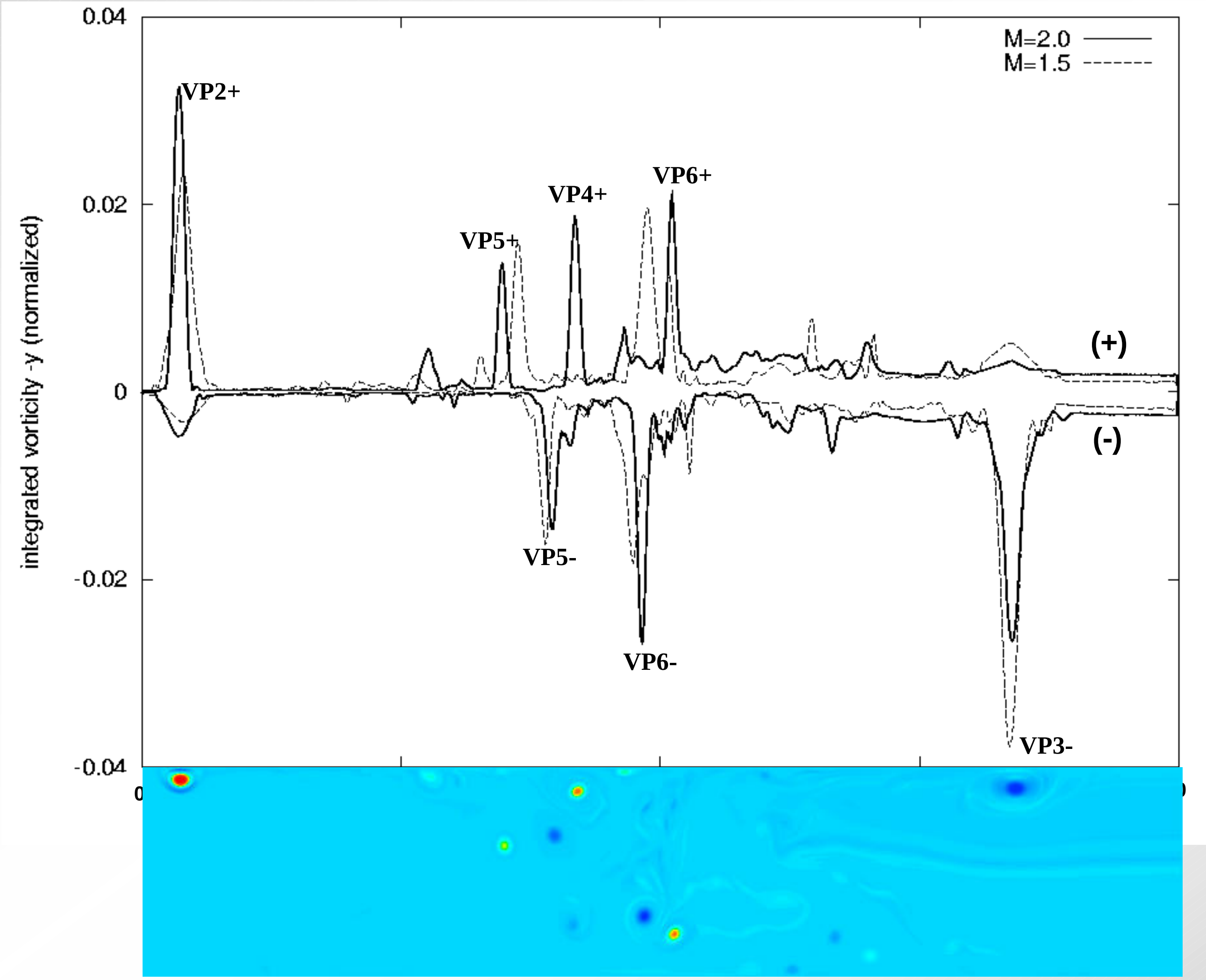
Simulation Cont.



Y-integrated density (filtered the ambient density)

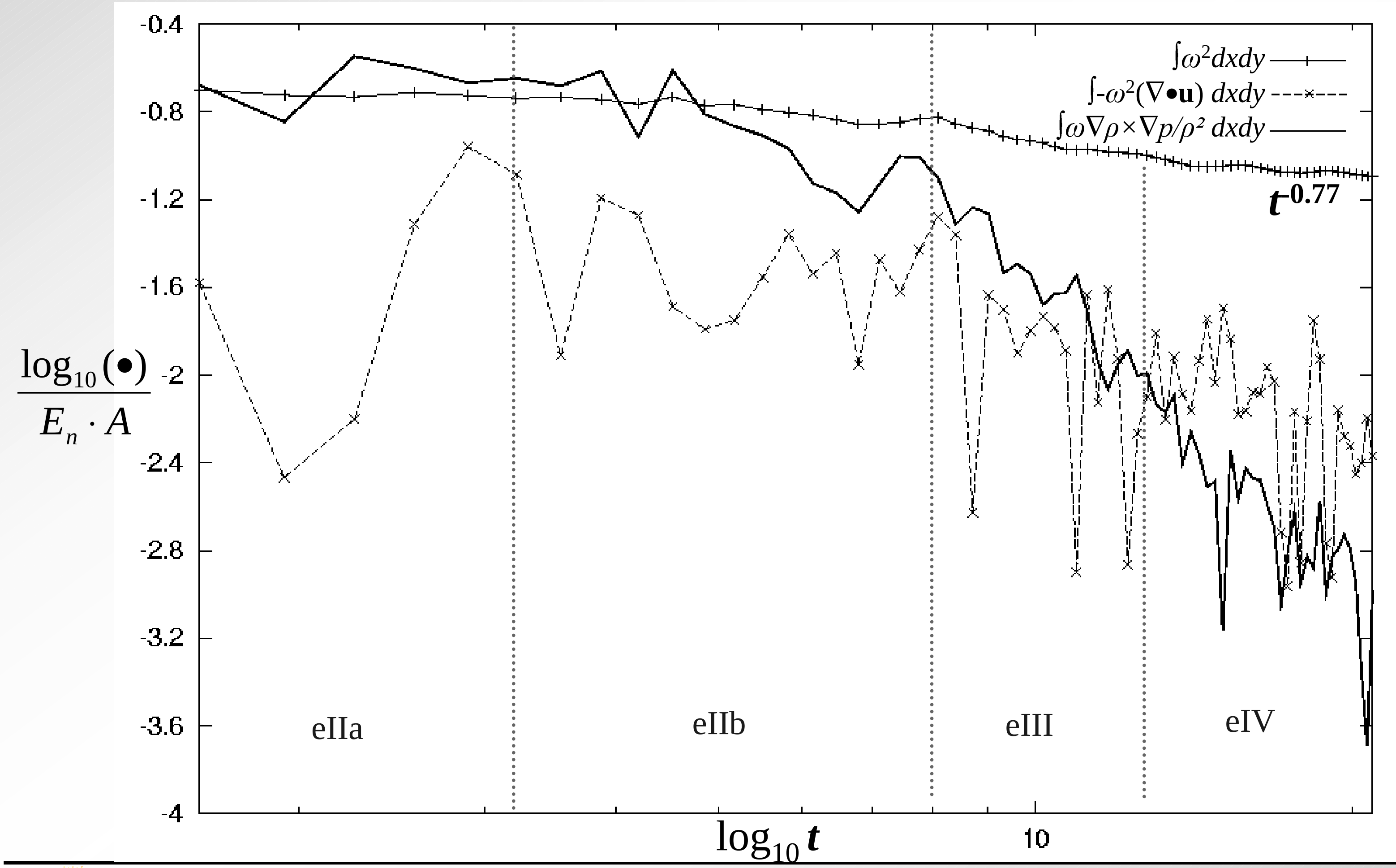
Simulation Cont.



Y-integrated vorticity

Global Quantification II: Integrated enstrophy evolution equation

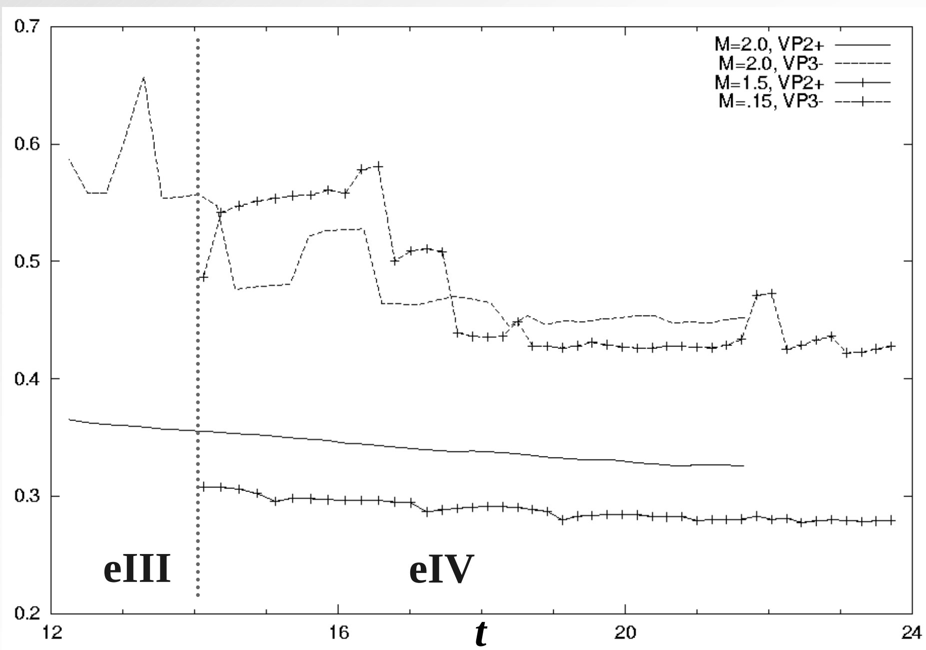
- Emphasizes larger magnitude vortex domains;
- Normalization factor E_n: enstrophy at the end of eI.



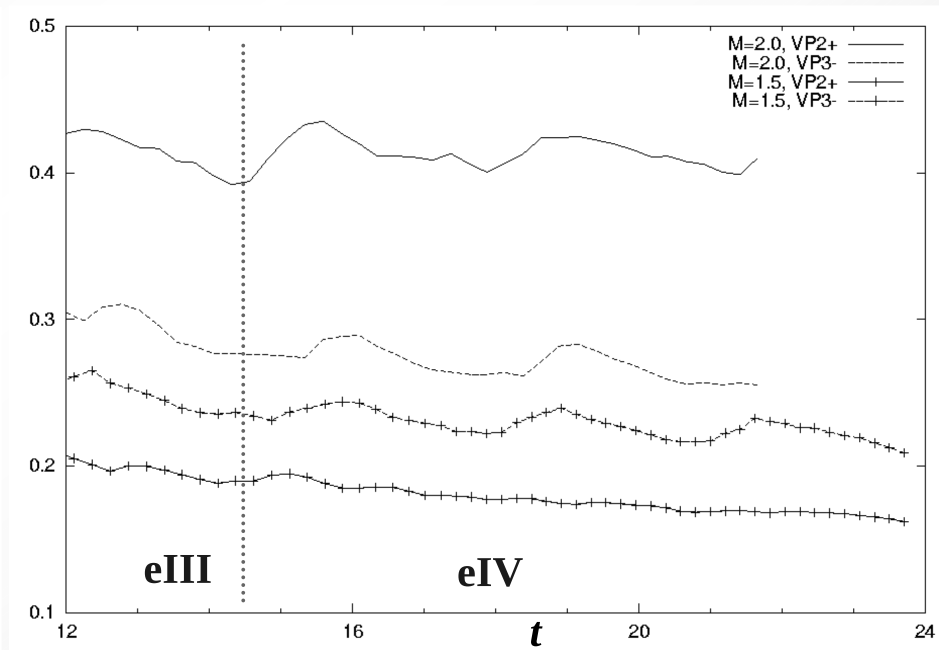
Local Structures' Quantification

Quantification of vortex projectiles

- VP2+ for upstream and VP3- for downstream, respectively
- M=1.5 and M=2.0 (| Γ_{VP2+} |+|Γ_{+VP3-}|+Γ_{affi}|=30%(|Γ_{-}|+| Γ_{+}|)
- Extraction threshold: 4% of the extremum of vorticity



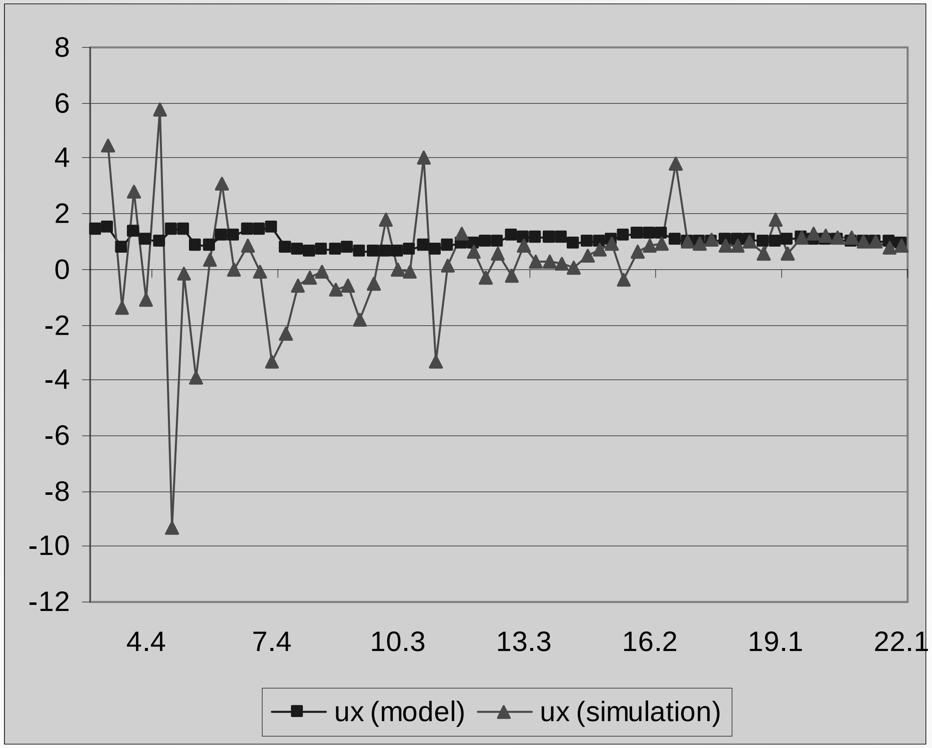
(a) Evolution of local circulation



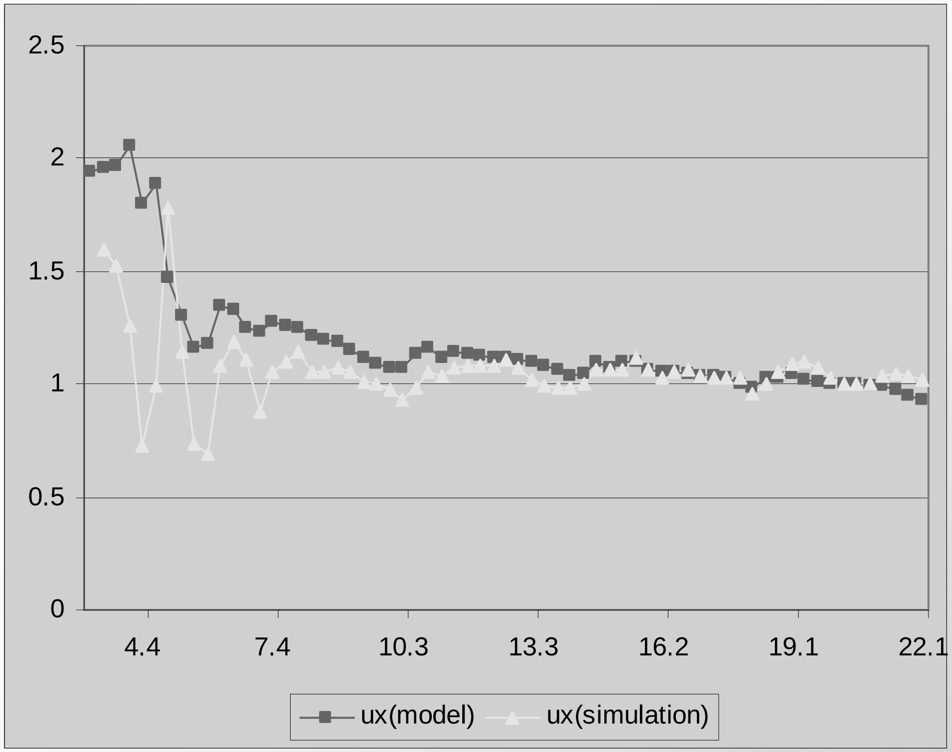
(b) Evolution of local vorticity maxima

Point vortex modeling (M=2.0)

Modeled translational velocity: $u_x = \dfrac{\Gamma}{2\pi d}$



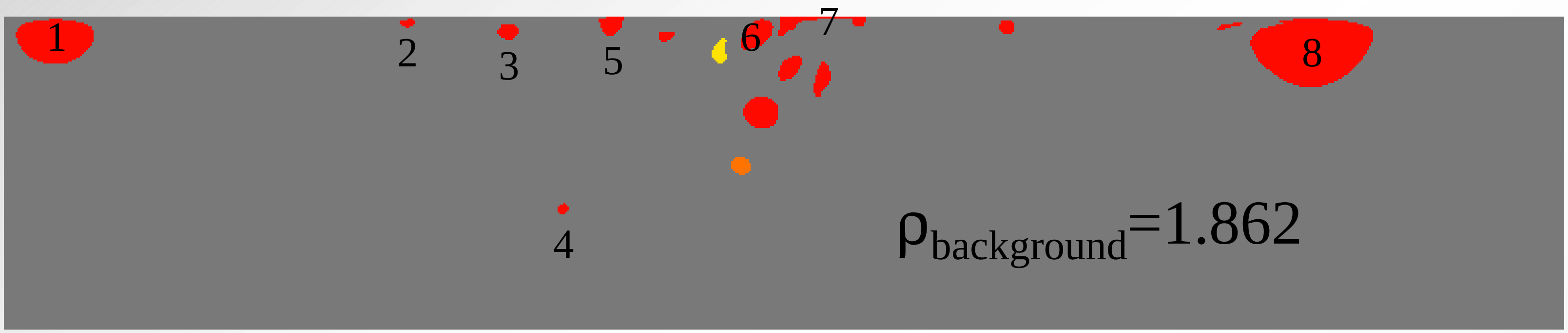
Downstream VP3-



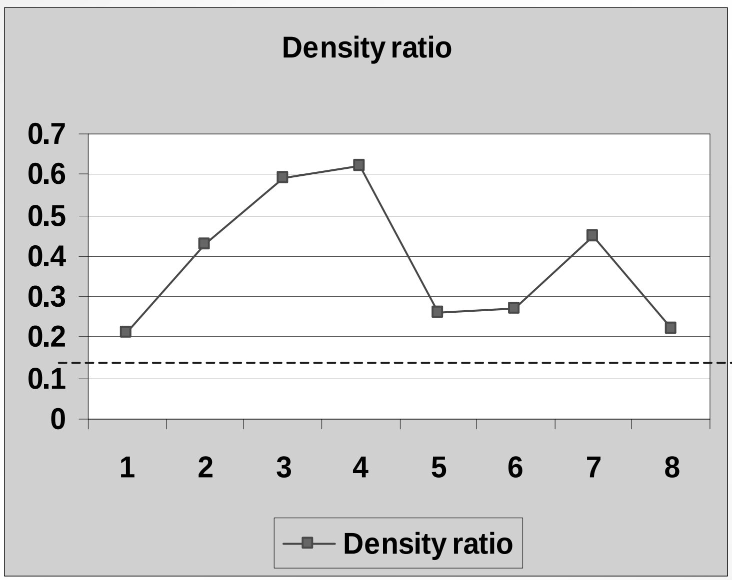
Upstream VP2+

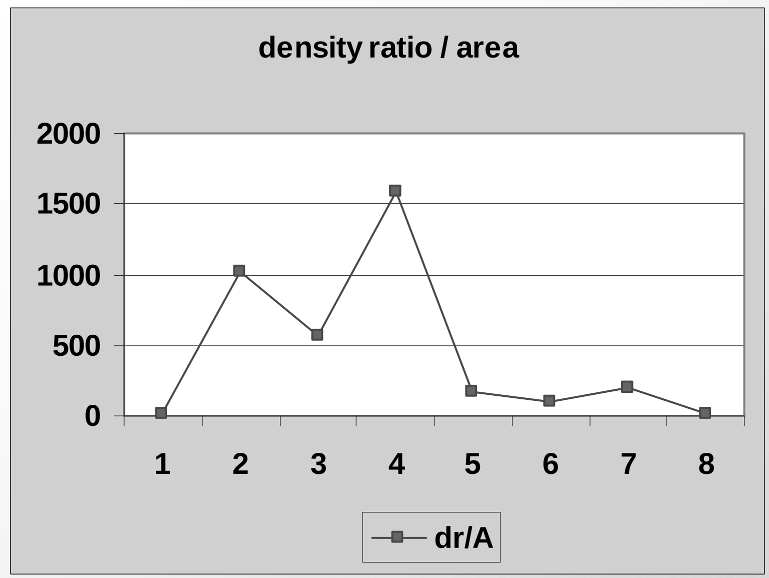
Turbulent mixing

Density distribution

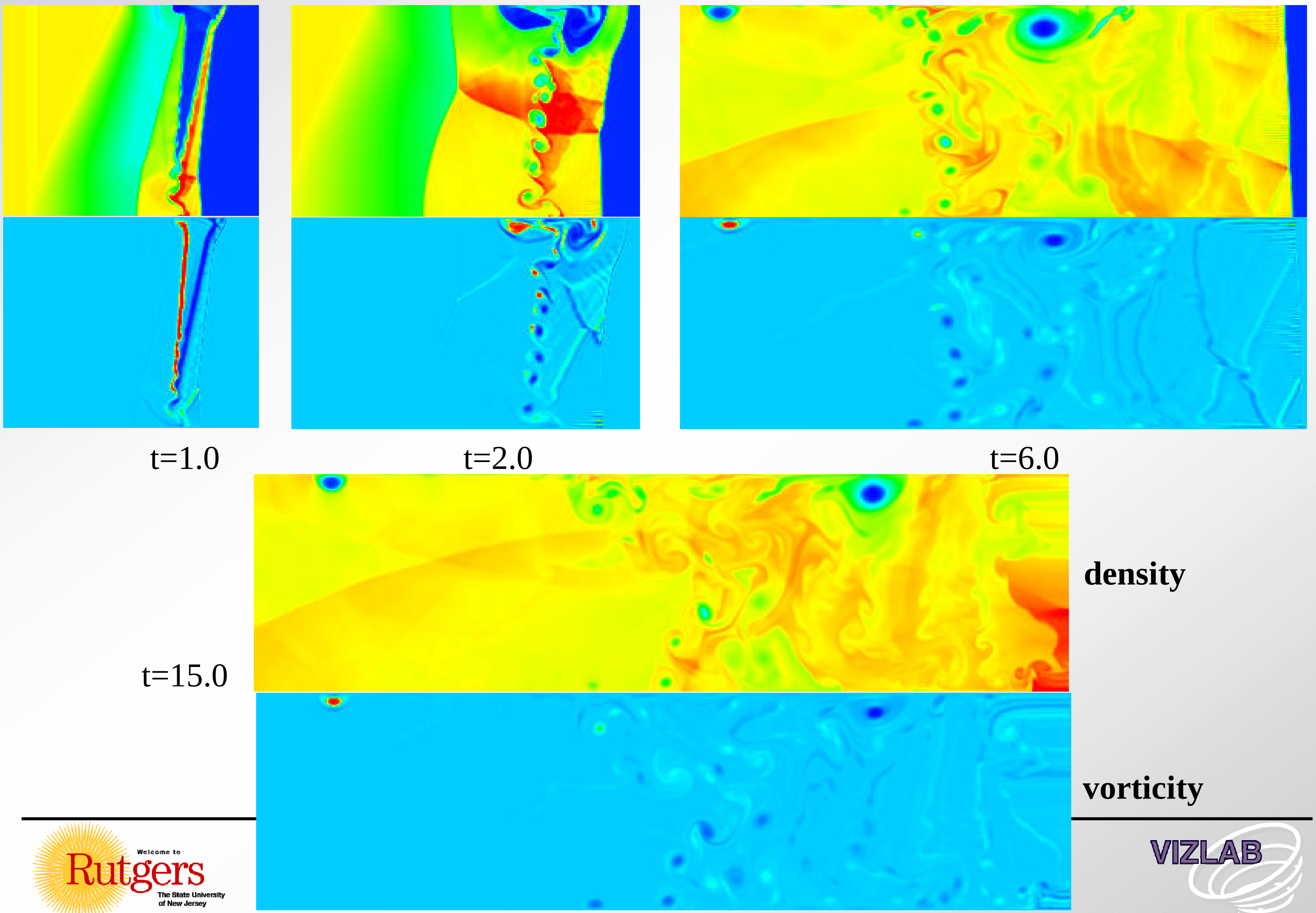


- Initial Density Ratio: 0.14





Rapid Turbulization at High Mach number (*M*=5.0)



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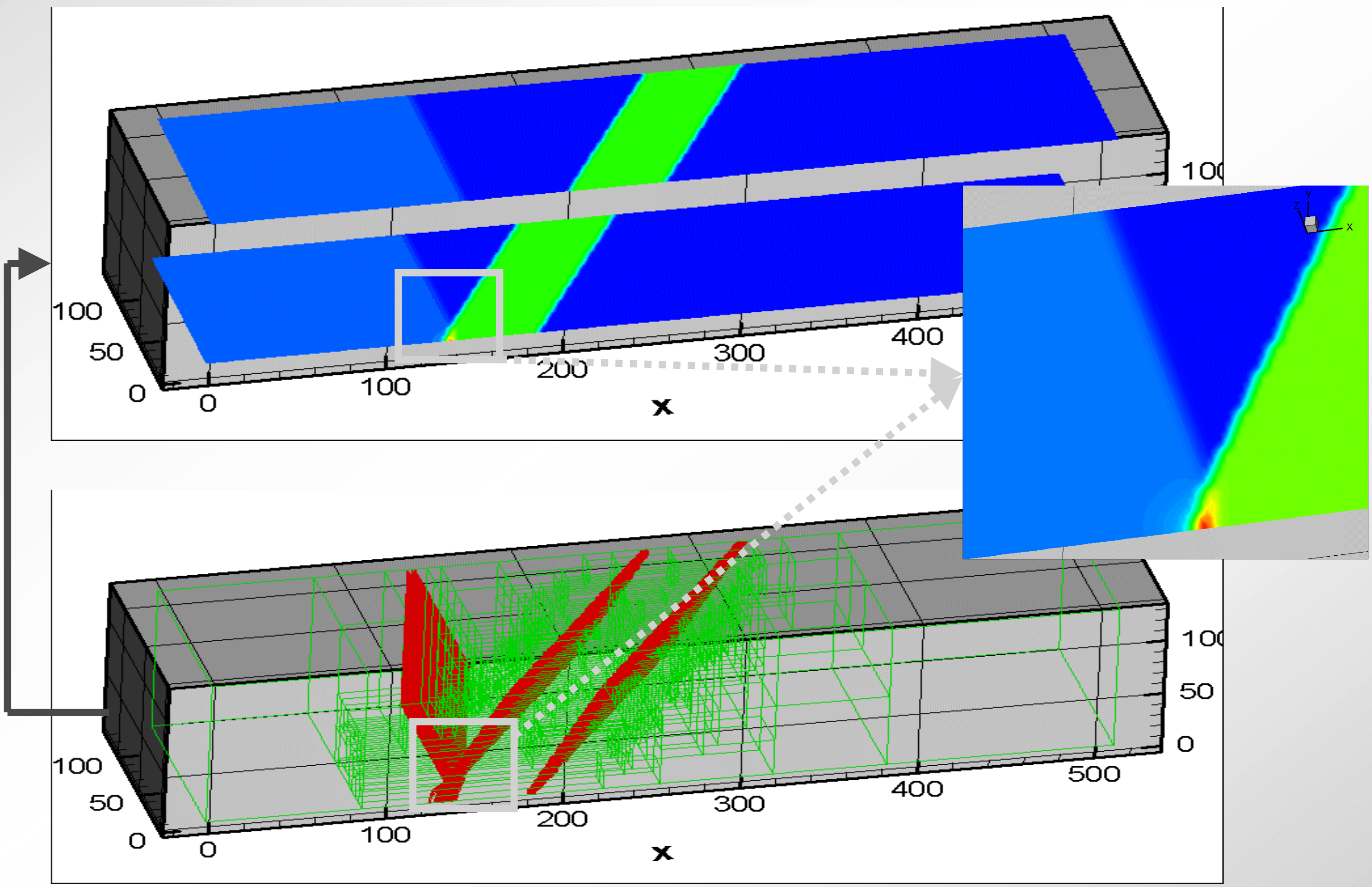
3D Curtain study

Main approaches: Simulation with adaptive mesh; quantification via data projection;

2 vertical slices



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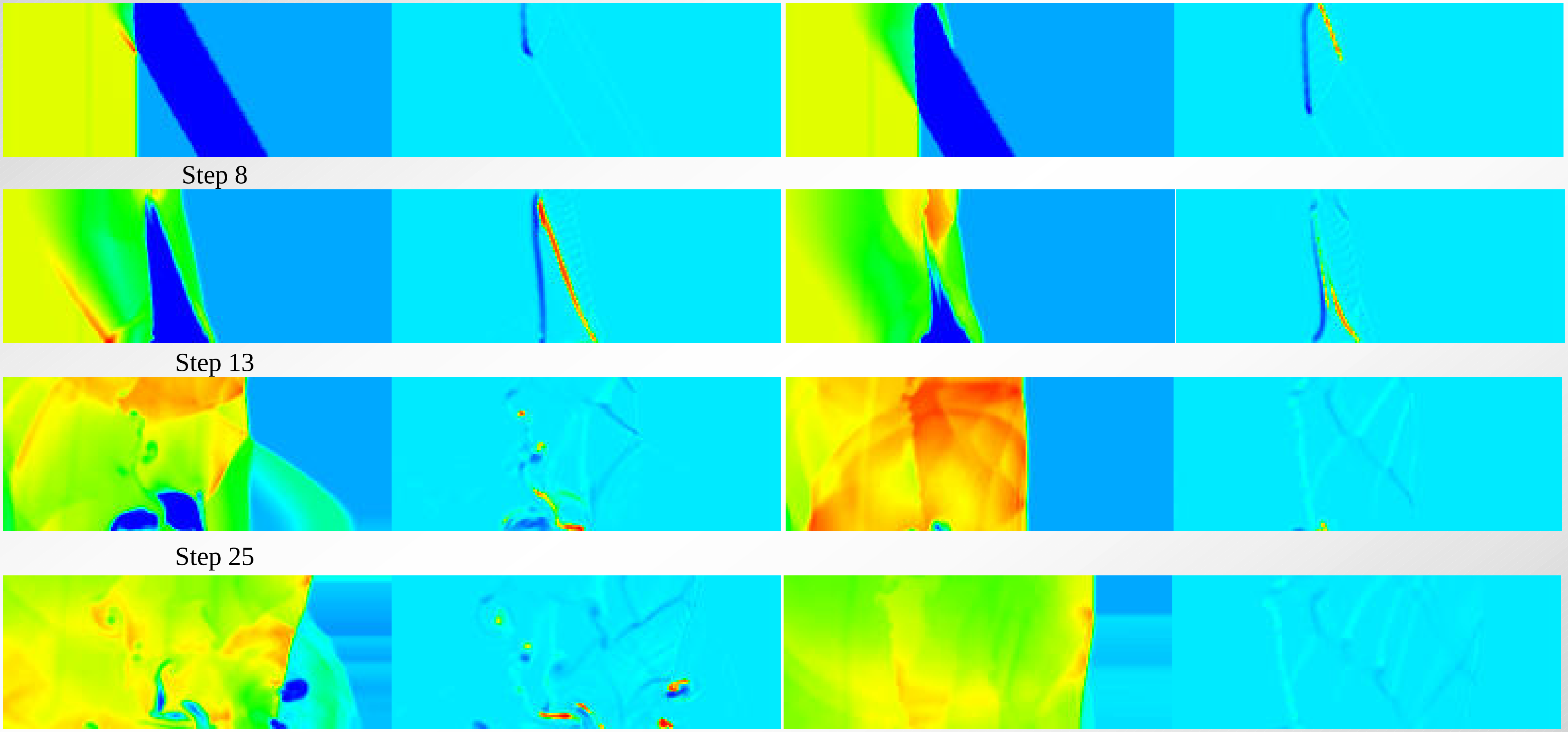
Data Projection: quasi-2D (Resolution: 200*80*80)

3D curtain cont.

Slice 1 (j=72) Slice 2 (j=40)



Step 8

Step 13

Step 25

Step 35

3.48 0.5

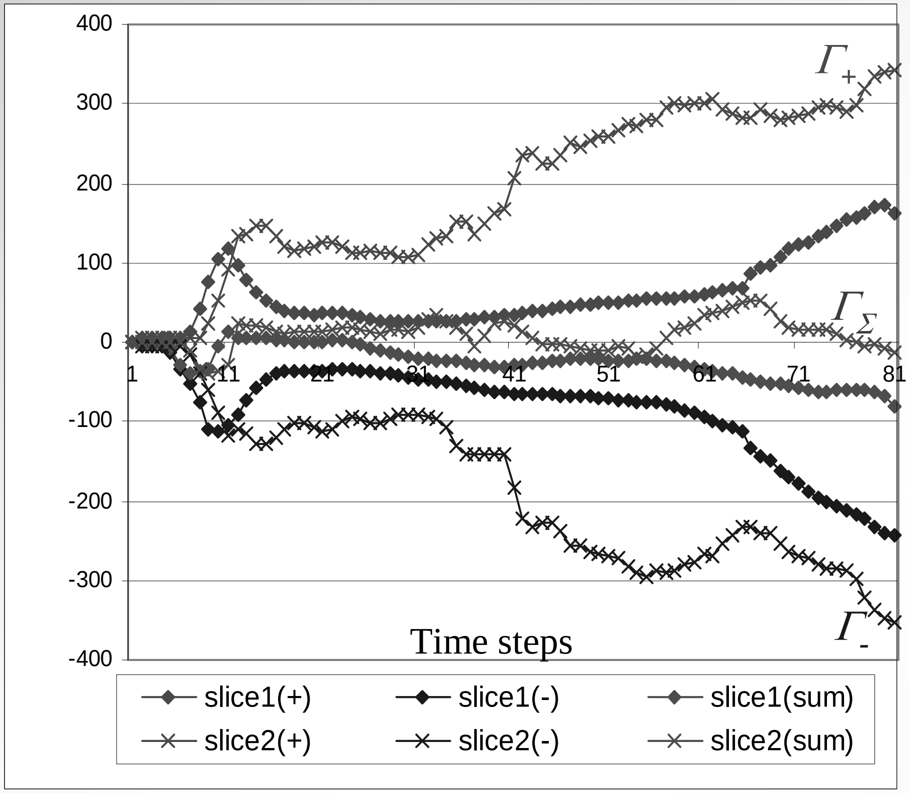
Density colormap

1.07 -1.07

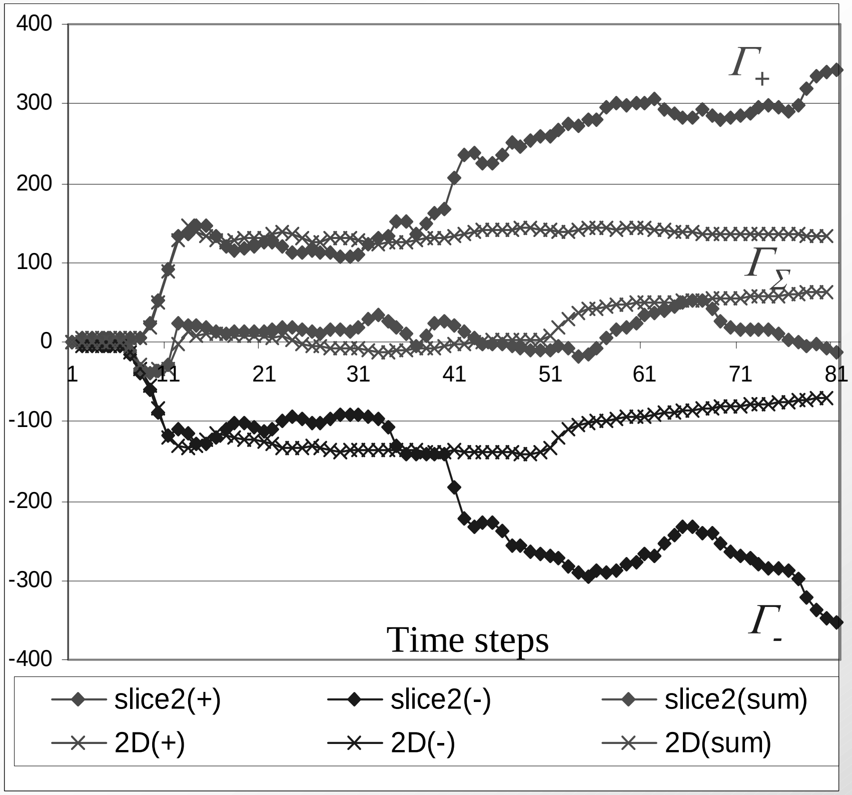
Vorticity colormap

3D curtain cont.

3D effects: juxtaposition of quasi-2D and 2D global circulation



2 of the 3D slices slice1 (y=8), slice2 (y=40)



3D center slice (y=40) and 2D

Note:

1). Resolution: 200*80*80; 2). Early time, the curtain behaves similar to 2D – No obvious 3D effects;
3). The slice near the boundary influenced by 3D early; 4). 3D effects become important and dominant when vortex structures localized

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Summary & Future Directions

- Simulations of s/f/s curtain with M=1.5 to 5.0;
- Vortex double layers and large baroclinic circulation evolution;
- Visiometrics of vortex “layer” collisions and binding; Strong secondary baroclinic deposition,;
- Vortex projectiles emergence: quantitative study and modeling;
- Preliminary study of stratified turbulence domain;
- Preliminary adaptive mesh simulation of 3D planar curtain evolution; quantification via juxtaposition of slices.