PDE-BASED METHODS FOR MULTISCALE COMPUTATIONAL FLUID DYNAMICS

FRONT-CAPTURING & FRONT-TRACKING WITH ADAPTIVITY

Raag Ramani

Joint with Steve Shkoller

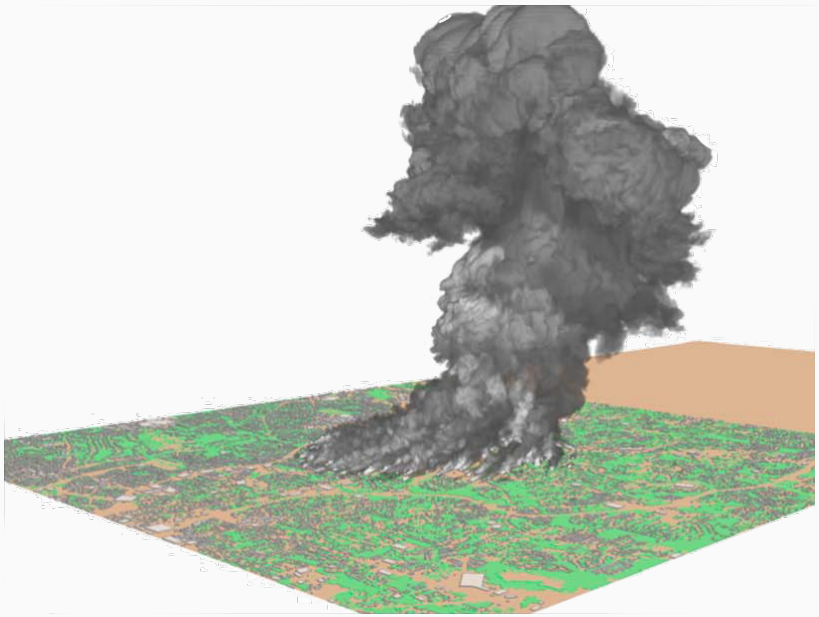
Department of Mathematics, UC Davis

Advanced Modeling & Simulation (AMS) Seminar Series
NASA Ames Research Center, September 14th, 2023

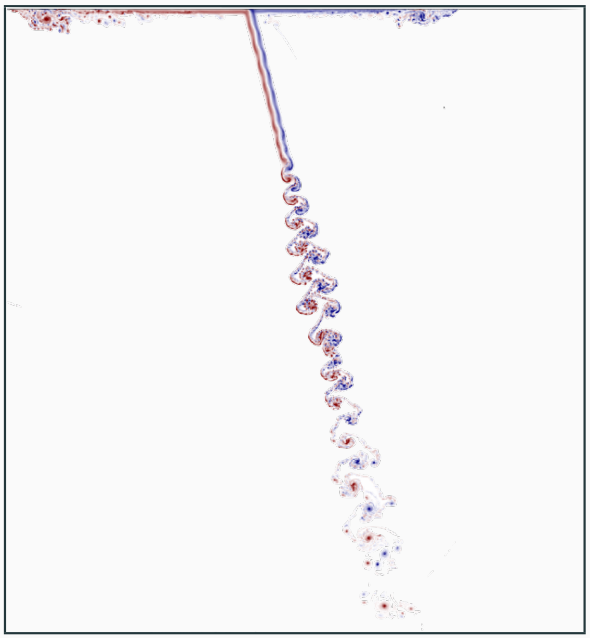
BACKGROUND

APPLICATIONS AT LOS ALAMOS LAB

- Blast waves, turbulence model initialization, mega fires & cloud physics
- Implementation in LANL codes (HIGRAD-FIRETEC, FIESTA, xRAGE)



pyroCb simulation, (Reisner 2021)



Romero et al. (2021)

- Our methods are developed with **rigorous testing** on **test problems**

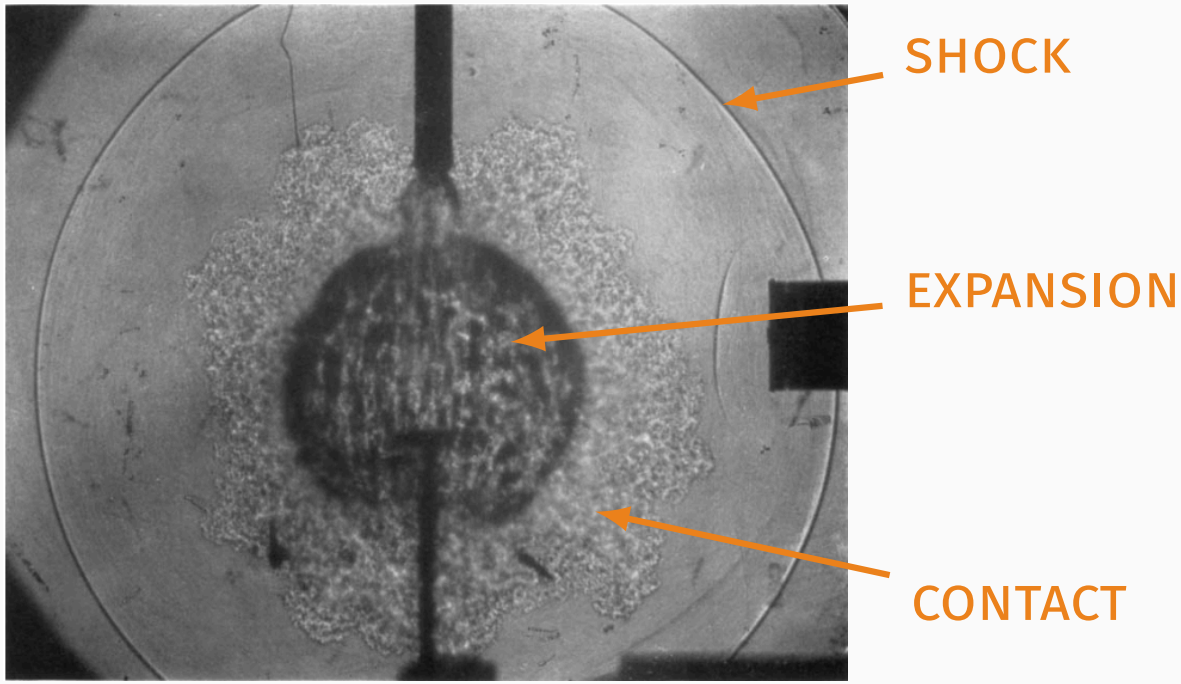
Compressible Euler system (1757)

$$\partial_t \rho + \operatorname{div}(\rho u) = 0 \qquad \text{(mass)}$$
$$\partial_t (\rho u) + \operatorname{div}(\rho u \otimes u + p\mathbb{I}) = 0 \qquad \text{(momentum)}$$
$$\partial_t E + \operatorname{div}(u(E+p)) = 0 \qquad \text{(energy)}$$

- ρ **density**, $u = (u^1, \dots, u^d)$ **velocity**, E **energy**
- p **pressure**

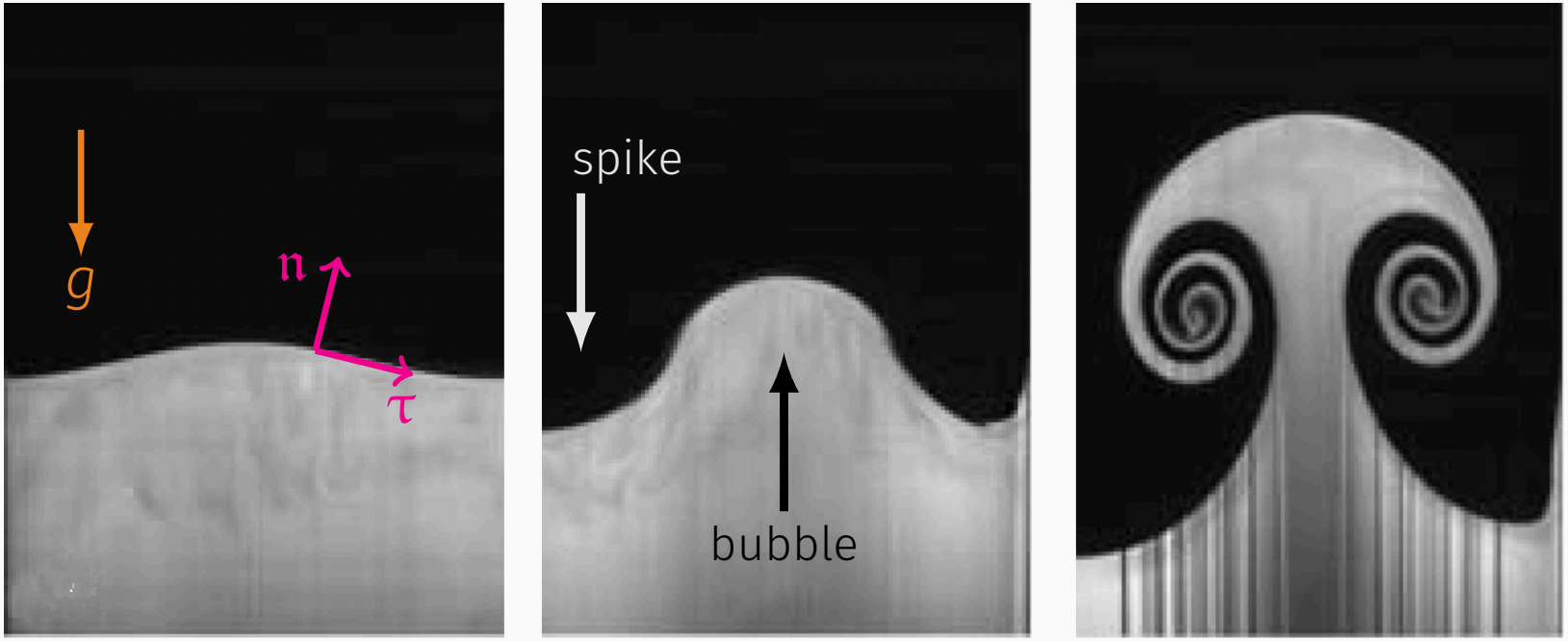
$$E = \frac{1}{2}\rho |u|^2 + \frac{p}{\gamma - 1}, \quad \gamma > 1$$

NONLINEAR WAVES IN GAS DYNAMICS



D.W. Boyer (1960), *An experimental study of the explosion generated by a pressurized sphere*

CLASSICAL FLUID INSTABILITIES



- $\nabla p \cdot \nabla^{\perp} \rho \neq 0 \implies$ vorticity production
- $[u \cdot \tau]_{-}^{+} \neq 0 \implies$ Kelvin-Helmholtz (KH) *roll up*

Waddell et al. (2001), *Experimental study of Rayleigh-Taylor instability: Low Atwood number liquid systems with single-mode initial perturbations*

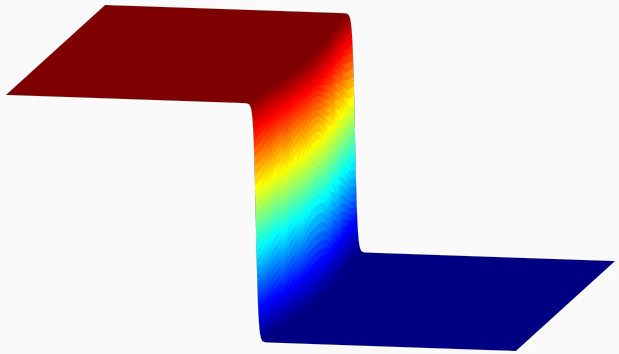
FRONT-CAPTURING & FRONT-TRACKING WITH ADAPTIVITY

LAGRANGIAN

EULERIAN

ALE

FRONT-CAPTURING & FRONT-TRACKING WITH ADAPTIVITY

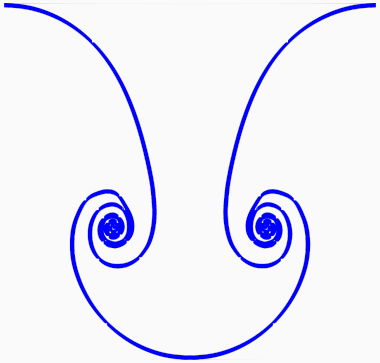


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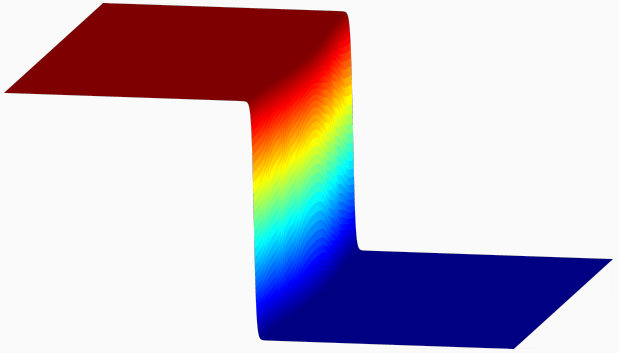
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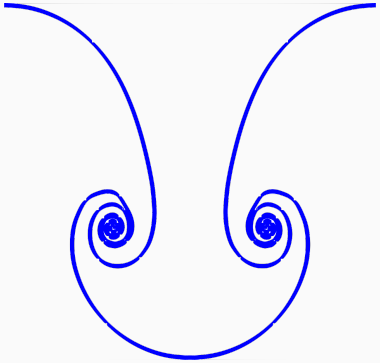
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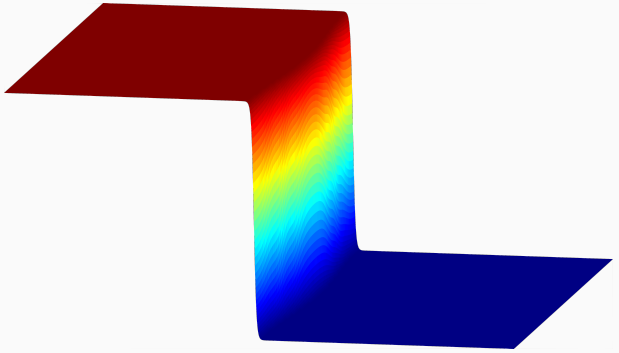


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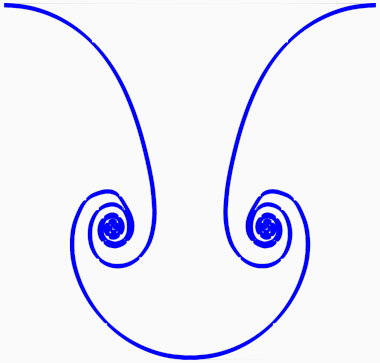
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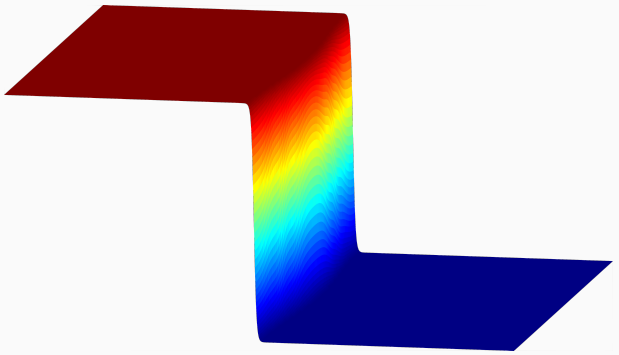
$\psi^{-1}\circ$

$\circ\psi$

ALE

FRONT-CAPTURING & FRONT-TRACKING WITH ADAPTIVITY





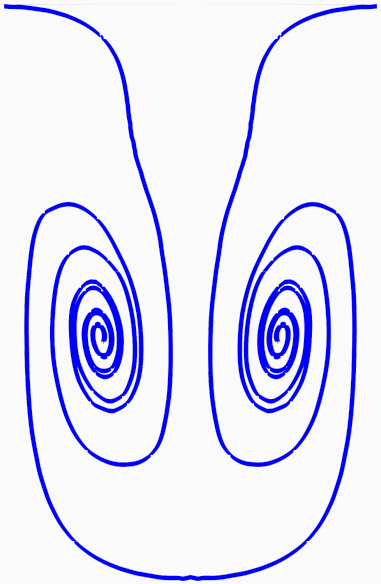
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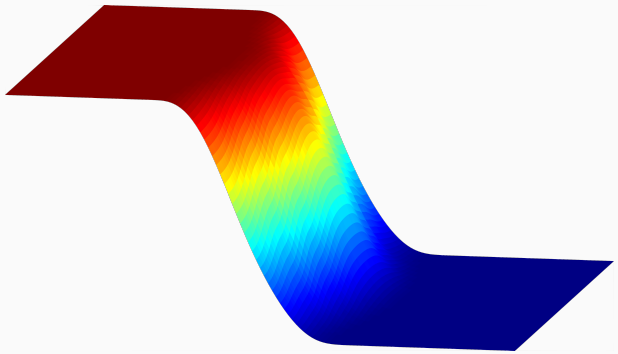
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$\psi^{-1}\circ$

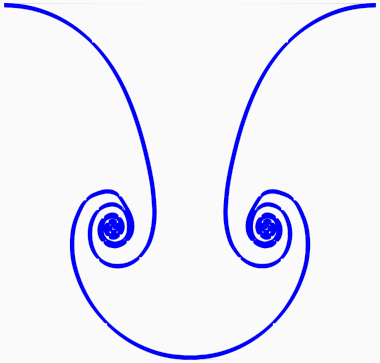
$\circ\psi$

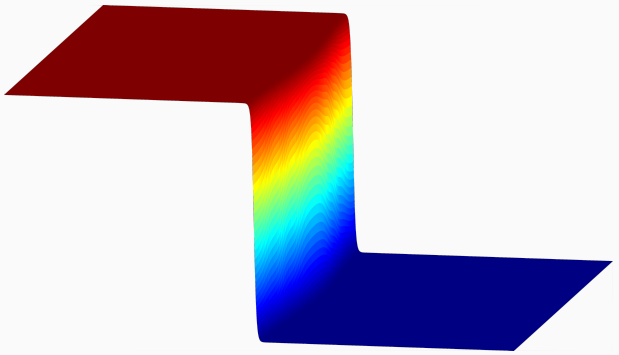
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FRONT-CAPTURING & FRONT-TRACKING WITH ADAPTIVITY





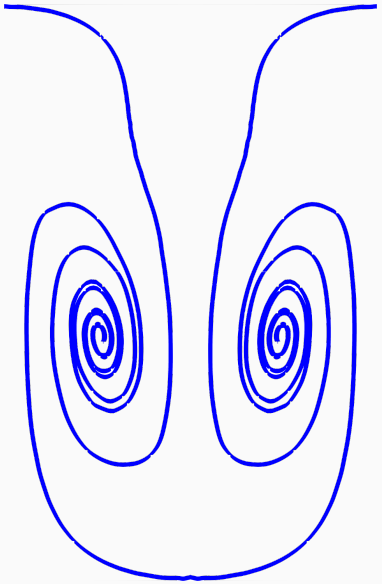
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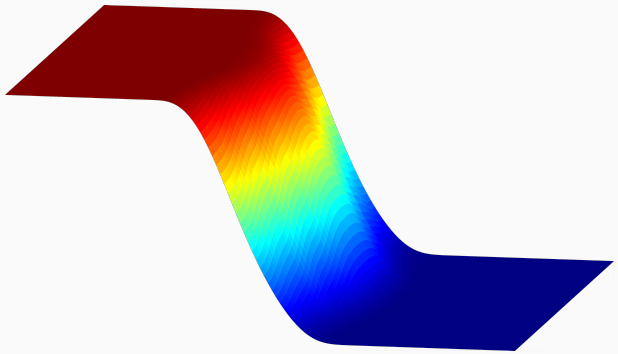
EULERIAN

$\psi^{-1}\circ$

$\circ\psi$

ALE





ALGORITHMIC COMPONENTS

- The C-method: **front-capturing**
  - Space-time smooth representation of front location & geometry
  - Smooth directionally isotropic & anisotropic artificial viscosity
  - Shock reflection stabilization scheme
  - Wavelet-based noise detection & removal

- A multiscale RT-RM model: **front-tracking**
  - Dimensionally-reduced Birkhoff-Rott formulation
  - z-model based on asymptotics in non-locality
  - Multiscale Hodge-type decomposition of the velocity
  - Shock physics coupling

- Smooth Adaptive Meshing: **adaptivity**
  - High-order accurate adaptive-mesh generation
  - Perturbative formulation for dynamic & large zoom-in meshing
  - Reformulation in smooth ALE coordinates

PUBLICATIONS

[1] R. Ramani, J. Reisner, & S. Shkoller
A space-time smooth artificial viscosity method with wavelet noise indicator and shock collision scheme, Part 1: the 1D case
Journal of Computational Physics 387 (2019)

[2] R. Ramani, J. Reisner, & S. Shkoller
A space-time smooth artificial viscosity method with wavelet noise indicator and shock collision scheme, Part 2: the 2D case
Journal of Computational Physics 387 (2019)

[3] R. Ramani & S. Shkoller
A multiscale model for Rayleigh-Taylor and Richtmyer-Meshkov instabilities
Journal of Computational Physics 405:109177 (2020)

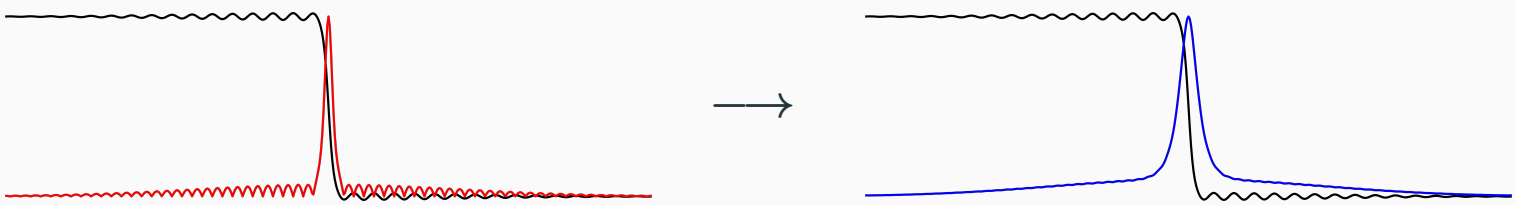
[4] R. Ramani & S. Shkoller
A fast dynamic smooth adaptive meshing scheme with applications to compressible flow
Journal of Computational Physics 490:112280 (2023)

FRONT-CAPTURING

SPACE-TIME SMOOTH REGULARIZATION

- *Classical* artificial viscosity (RICHTMYER 1948) for 1*D* scalar conservation law

$$u_t + f(u)_x = (\beta |u_x| u_x)_x$$



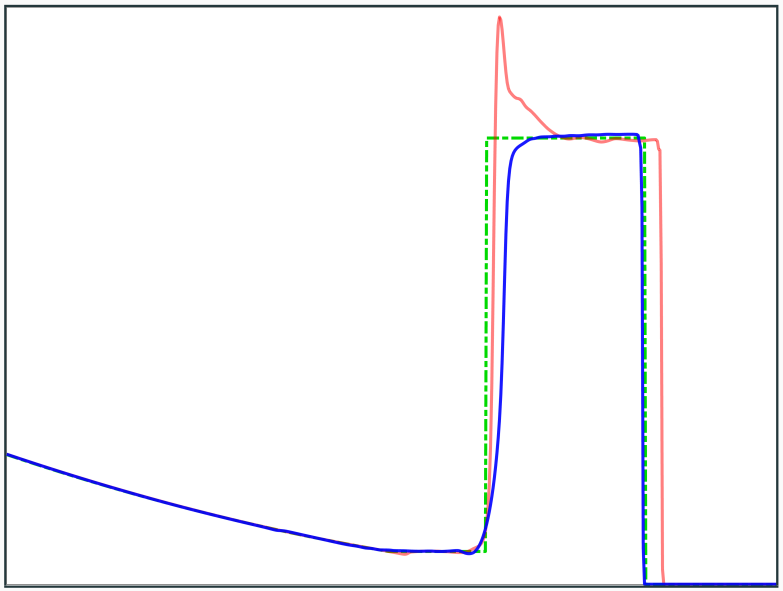
C-method artificial viscosity

$$u_t + f(u)_x = (\beta C u_x)_x$$
$$C(x,t) = \mathcal{L}_{t,x}^{-1}(|u_x|)$$

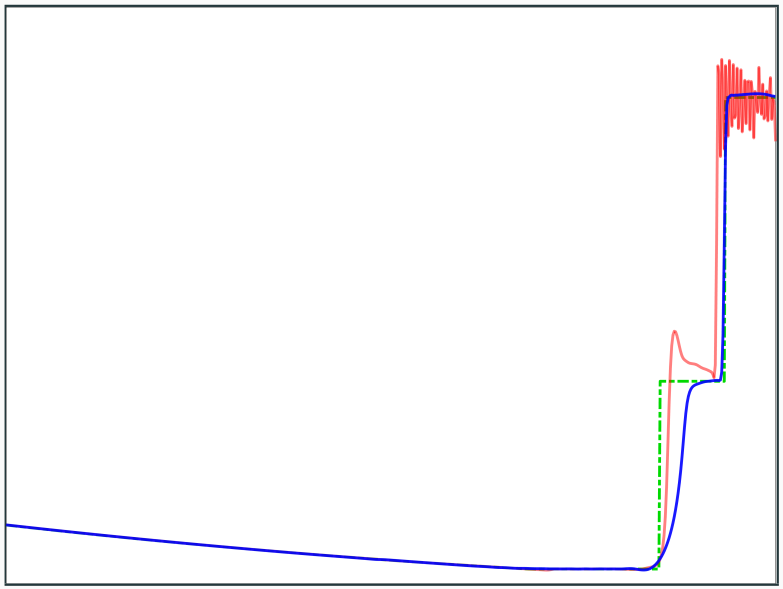
- $\mathcal{L}_{t,x} = \partial_t - \kappa \partial_{xx} + \frac{1}{\varepsilon}\mathbb{I} \implies$ reaction-diffusion equation
- **Theorem**: convergence to entropy solution as $\beta, \Delta x \to 0$ for 1*D* isentropic Euler

LEBLANC TEST WITH SHOCK REFLECTION

- Pressure jump **1 : 1 billion**
- $\Delta x = 0.0125$, CFL $= 0.2$
- WENO vs *C*-method with shock reflection scheme
- L^1 velocity error: 1.7×10^{-2} vs 3.9×10^{-3}



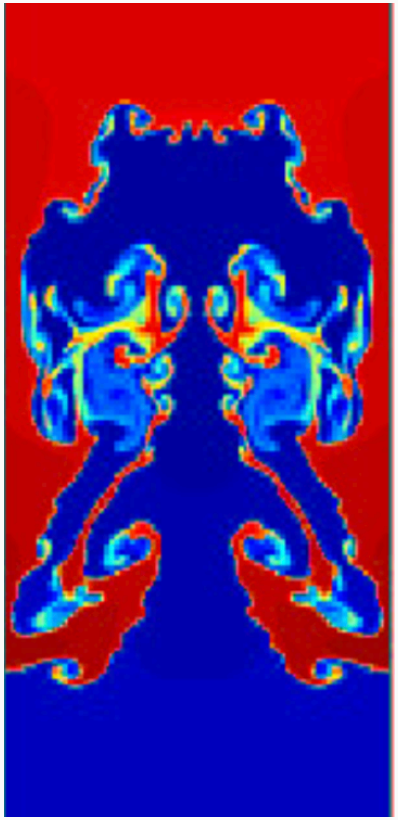
pre-reflection



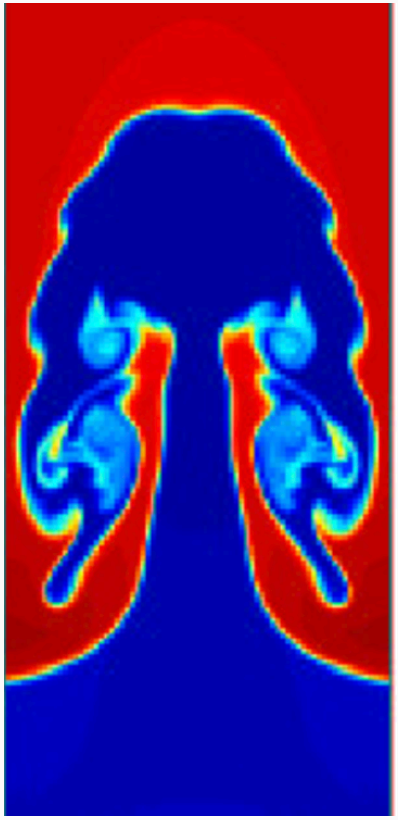
post-reflection

MULTI-D ADVECTION ERRORS

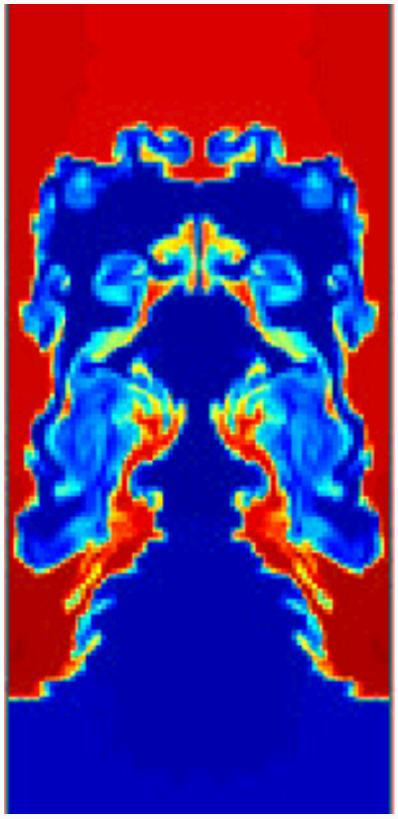
- Single-mode RT instability
- Split advection produces spurious KH structures



PPM



WENO



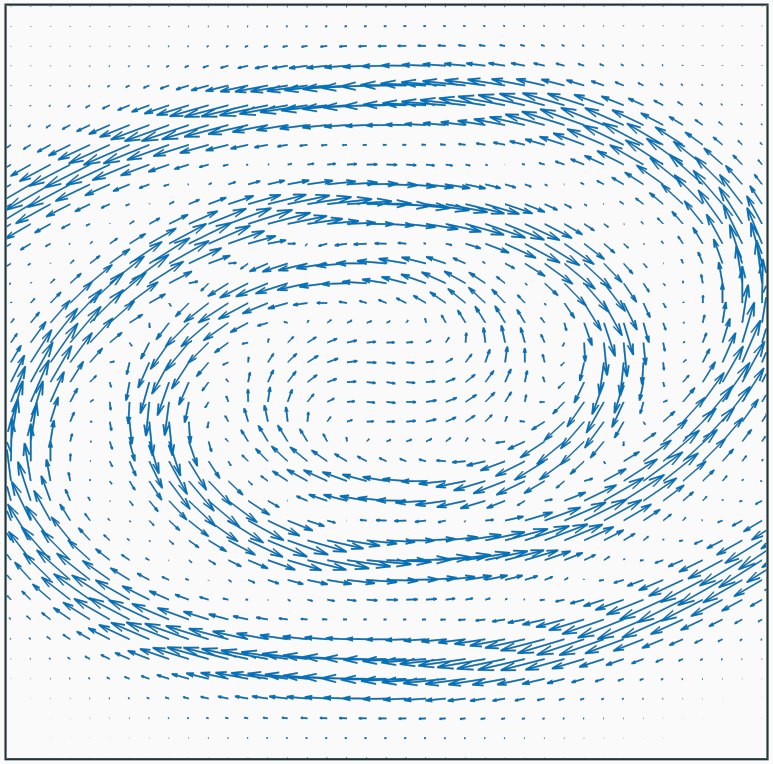
WAFC

R. Liska & B. Wendroff (2003), *Comparison of several difference schemes on 1D and 2D test problems for the Euler equations*

REGULARIZING FRONTS WITH GEOMETRY

$$\text{SHOCK}: \quad [u \cdot \mathfrak{n}]_-^+ \neq 0 \quad \text{and} \quad [u \cdot \tau]_-^+ = 0$$

$$\text{CONTACT}: \quad [u \cdot \mathfrak{n}]_-^+ = 0 \quad \text{and} \quad [u \cdot \tau]_-^+ \neq 0$$



- Smoothed front geometry tracking & directional artificial viscosity

THE C-METHOD IN MULTI-D

- Isotropic diffusion for shocks
- Anisotropic diffusion for contacts

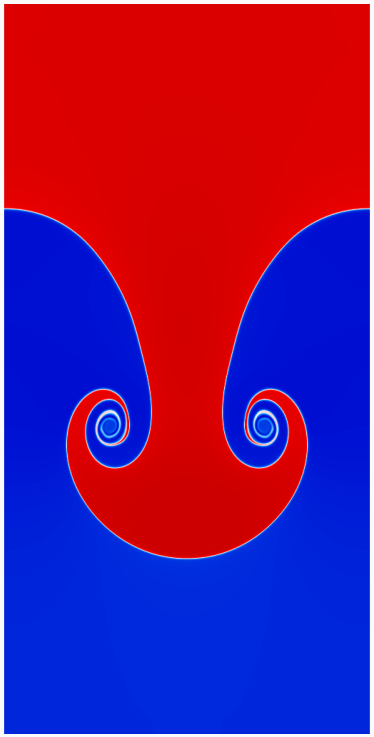
$$\partial_t \rho + \partial_j(\rho u^j) = 0$$
$$\partial_t(\rho u^k) + \partial_j(\rho u^k u^j + p\delta_j^k) = \partial_j(\beta \rho C \partial_j u^k) + \partial_i(\mu \rho \tau^i \tau^j \partial_j u^k)$$
$$\partial_t E + \partial_j(u^j(E+p)) = \partial_j(\sigma \rho C \partial_j(E/\rho))$$

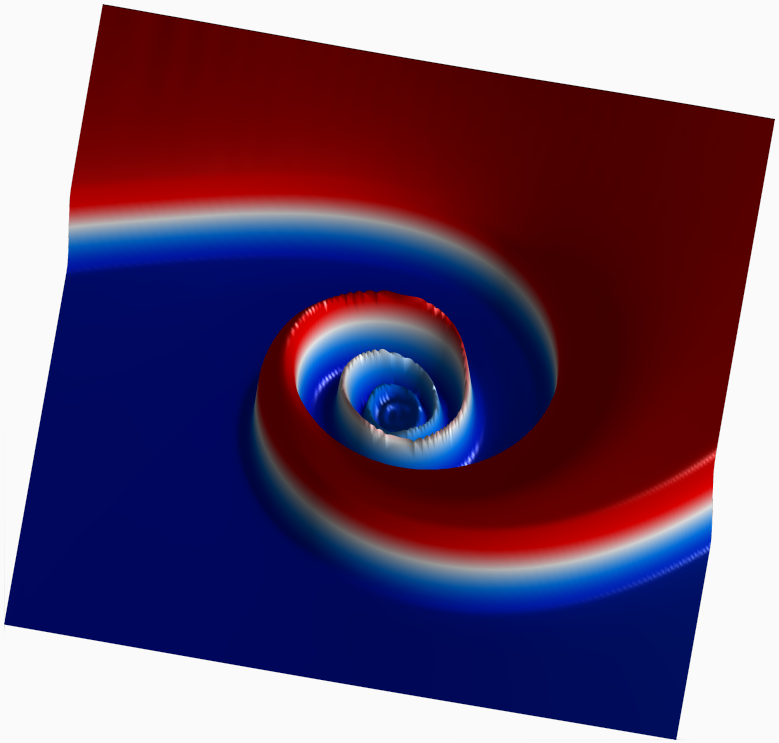
- C-functions are smooth solutions to reaction-diffusion equations
- Track location and geometry of fronts

$$\{C, \tau\} = \mathcal{L}_{t,x}^{-1}\left\{|\nabla u|, \nabla^\perp \rho\right\}$$
$$\mathcal{L}_{t,x} = \partial_t - \mathcal{S}|\Delta x|\kappa\Delta + \frac{\mathcal{S}}{|\Delta x|\varepsilon}\mathbb{I}$$

RT INSTABILITY SIMULATION

- Example from CASTRO 2010 paper
- 512×1024 cells, CFL $= 0.4$
- *C*-method with tangential viscosity

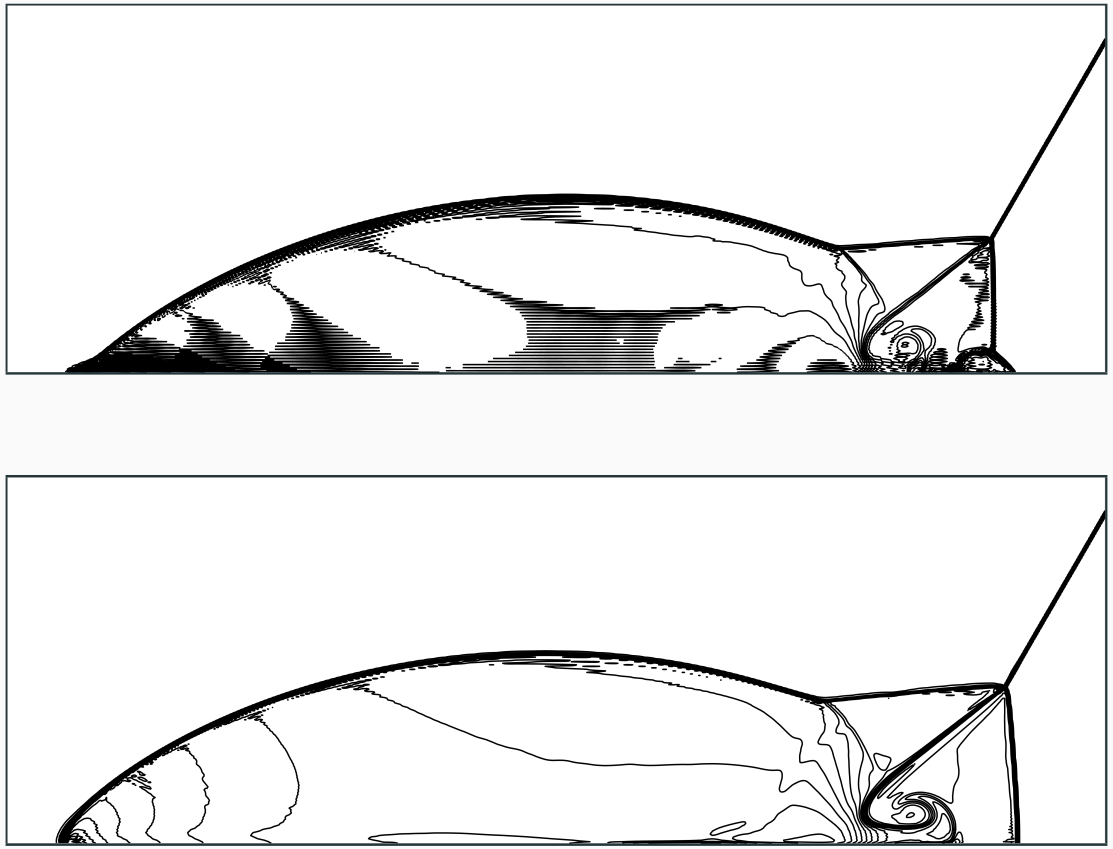




Almgren et al. (2010), *CASTRO: A new compressible astrophysical solver. I. Hydrodynamics and self-gravity*

DOUBLE MACH SHOCK REFLECTION

- 960×240 cells, CFL $= 0.4$
- simplified WENO vs *C*-method



FRONT-TRACKING

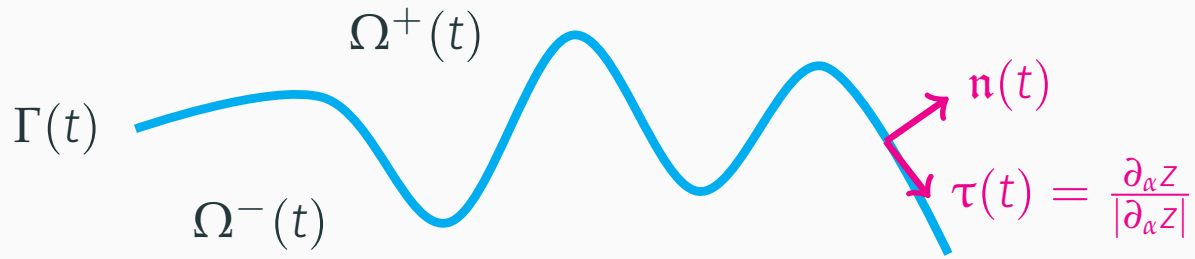
FRONT-TRACKING FOR COMPRESSIBLE FLOWS

- Problem: difficult & expensive to capture fluid instabilities on an Eulerian mesh

FRONT-TRACKING STRATEGY

1. Use a **dimensional-reduction** in the case of incompressible & irrotational flow
2. Develop a reduced-order model using **asymptotics in non-locality**
3. Incorporate compressibility effects via a **multiscale decomposition** of the velocity field

Boundary integral formulation



INTERFACE PARAMETRIZATION : $z(\alpha, t) = (z^1, z^2)$

VORTICITY AMPLITUDE : $\omega(\alpha, t) = [w]^+_- \cdot \partial_\alpha z$

$$\partial_t z(\alpha, t) = \overline{w} \circ z(\alpha, t) = \text{p.v.} \int \mathcal{K}_{\text{BR}}(z(\alpha, t) - z(\beta, t)) \omega(\beta, t) \, \mathrm{d}\beta$$

$$\partial_t \omega(\alpha, t) = -\partial_\alpha \left[A \left| \text{p.v.} \int \mathcal{K}_{\text{BR}}(z(\alpha, t) - z(\beta, t)) \omega(\beta, t) \, \mathrm{d}\beta \right|^2 - \frac{A}{4} \frac{\omega(\alpha, t)^2}{|\partial_\alpha z(\alpha, t)|^2} - 2Agz^2 \right]$$

$$+ 2A \, \partial_t \, \text{p.v.} \int \partial_\alpha z(\alpha, t) \cdot \mathcal{K}_{\text{BR}}(z(\alpha, t) - z(\beta, t)) \omega(\beta, t) \, \mathrm{d}\beta$$

ASYMPTOTIC EXPANSION IN NON-LOCALITY

- BR operator simplifies at small scales (Hou, Lowengrub, & Shelley 1994)
- Taylor expand and identify structure, e.g.,

$$\frac{1}{\pi}\text{p.v.}\int \frac{(z(\alpha)-z(\beta))^\perp}{|z(\alpha)-z(\beta)|^2}\omega(\beta)\,\mathrm{d}\beta \approx \frac{\partial_\alpha z(\alpha)^\perp}{|\partial_\alpha z(\alpha)|^2}\frac{1}{\pi}\text{p.v.}\int \frac{\omega(\beta)}{\alpha-\beta}\,\mathrm{d}\beta = \frac{\partial_\alpha z(\alpha)^\perp}{|\partial_\alpha z(\alpha)|^2}H\omega(\alpha)$$

  where H is the **Hilbert transform**

- Laurent expansion in *non-locality* of $\mathcal{K}_{\text{BR}}$

$$\mathcal{K}_{\text{BR}} = \sum_{j\geq -1}\mathcal{O}_j(\alpha)\beta^j \quad \text{with} \quad \mathcal{O}_{-1}(\alpha) = \frac{\partial_\alpha^\perp z(\alpha)}{|\partial_\alpha z(\alpha)|^2}$$

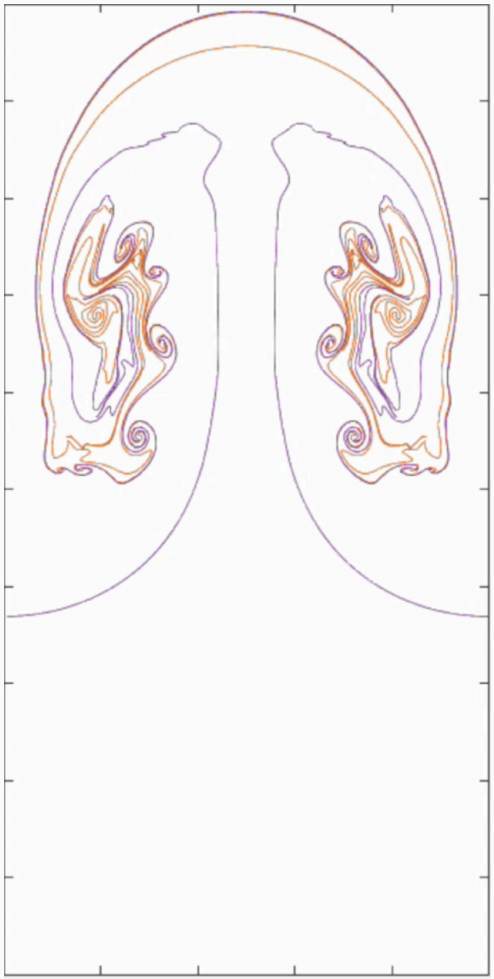
THE HIGH-ORDER Z-MODEL

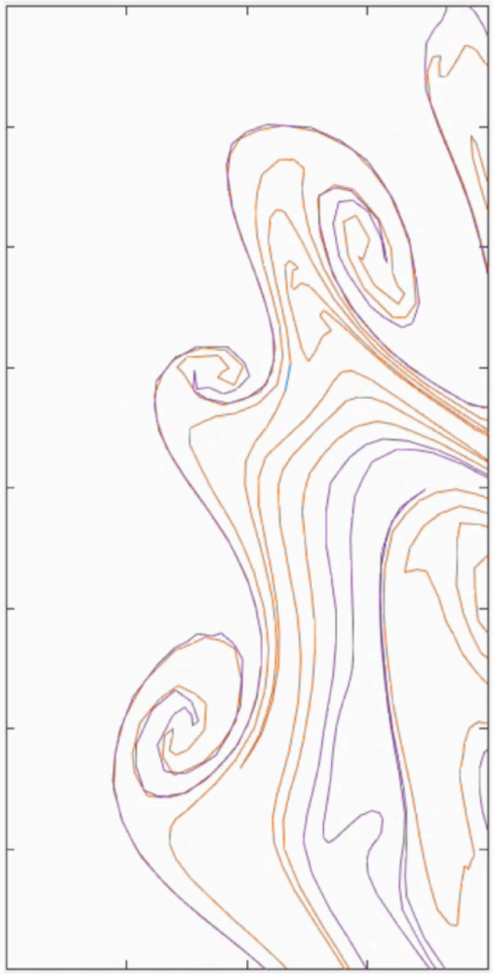
$$\partial_t z(\alpha,t) = \text{p.v.}\int \mathcal{K}_{\text{BR}}(z(\alpha,t)-z(\beta,t))\omega(\beta,t)\,\mathrm{d}\beta$$

$$\partial_t \omega(\alpha,t) = -\partial_\alpha\left[\frac{A}{2}\frac{H(\omega H\omega)}{|\partial_\alpha z(\alpha,t)|^2} - 2Agz^2\right]$$

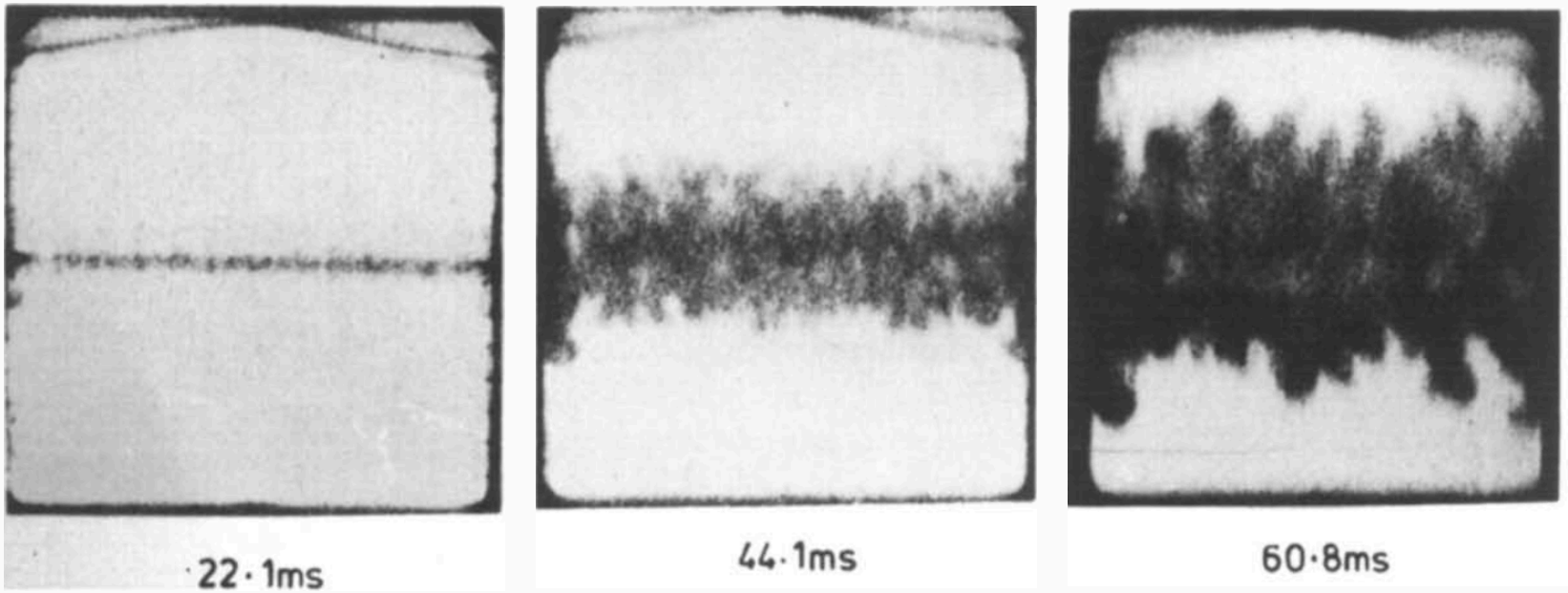
TRANSITION TO TURBULENCE IN RT INSTABILITY

- The z-model efficiently captures small-scales





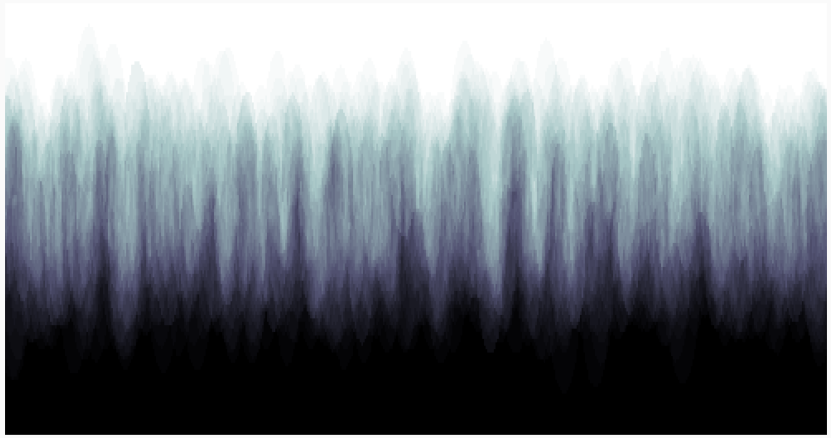
TURBULENT MIXING: THE ROCKET-RIG TEST

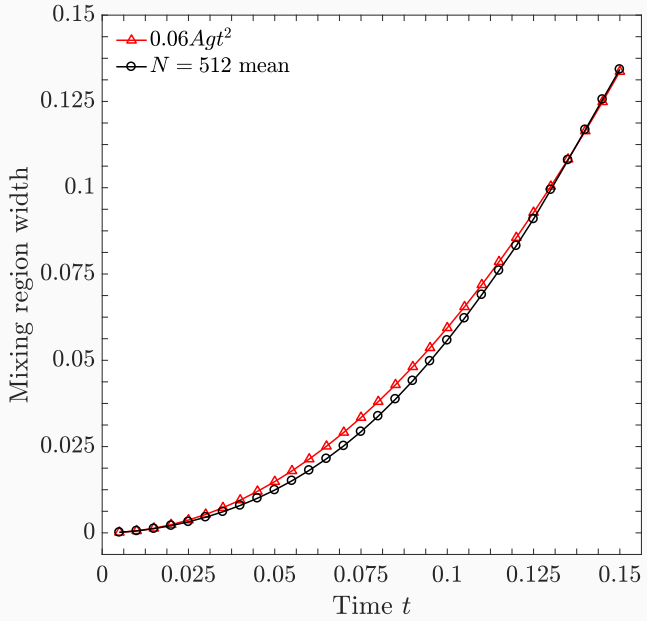


K.I. Read (1984), *Experimental investigation of turbulent mixing by Rayleigh-Taylor instability*

TURBULENT MIXING: THE ROCKET-RIG TEST

- Ensemble averages replicate the effects of **diffusion & mixing**
- z-model predicts correct growth rate of mixing region $\sim \alpha A g t^2$





TWO-PHASE EULER EQUATIONS WITH COMPRESSION & VORTICITY

1. **Dimensional reduction**
2. z-model
3. Compressibility

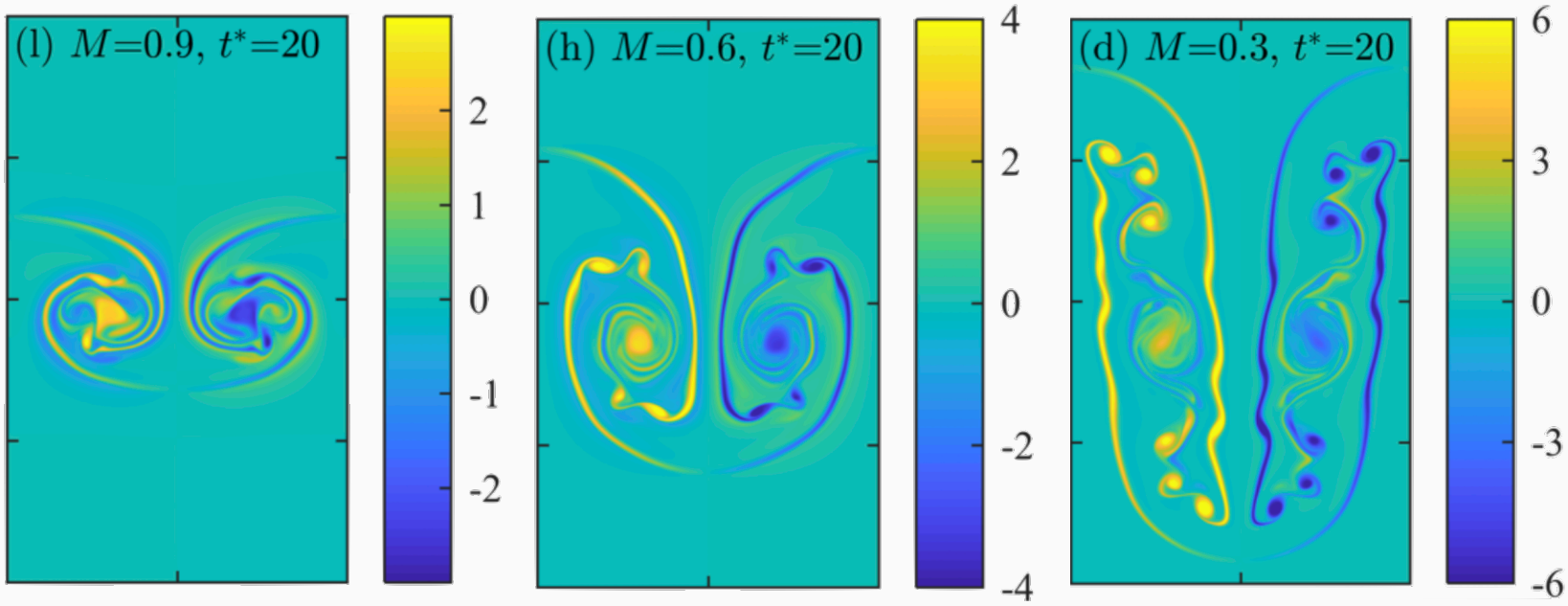


The compressible Euler system as a **two-phase elliptic system of Hodge-type**

$$\begin{aligned} \operatorname{div} u^\pm &= F^\pm && \text{in } \Omega^\pm(t) \\ \operatorname{curl} u^\pm &= \omega^\pm && \text{in } \Omega^\pm(t) \\ [u \cdot \mathfrak{n}]^+_- &= 0 && \text{on } \Gamma(t) \\ [u \cdot \tau]^+_- &= \varpi && \text{on } \Gamma(t) \end{aligned}$$

- $F = -(\partial_t \log \rho + u \cdot \nabla \log \rho)$
- ω is solution to $\partial_t \omega + u \cdot \nabla \omega + \omega \operatorname{div} u = \rho^{-2} \nabla \rho \times \nabla p$

THE EFFECTS OF COMPRESSIBILITY ON RT INSTABILITY



incompressible limit

Wieland et al. (2019), *Effects of isothermal stratification strength on vorticity dynamics for single-mode compressible Rayleigh-Taylor instability*

A MULTISCALE DECOMPOSITION OF THE VELOCITY

- Decompose $u = v + w$

LARGE-SCALE

$$\begin{aligned} \operatorname{div} v^{\pm} &= F^{\pm} && \text{in } \Omega^{\pm}(t) \\ \operatorname{curl} v^{\pm} &= \omega^{\pm} && \text{in } \Omega^{\pm}(t) \\ [v \cdot \mathfrak{n}]^{+}_{-} &= 0 && \text{on } \Gamma(t) \\ [v \cdot \tau]^{+}_{-} &= 0 && \text{on } \Gamma(t) \end{aligned}$$

- Coarse-grid C-method computation

SMALL-SCALE

$$\begin{aligned} \operatorname{div} w^{\pm} &= 0 && \text{in } \Omega^{\pm}(t) \\ \operatorname{curl} w^{\pm} &= 0 && \text{in } \Omega^{\pm}(t) \\ [w \cdot \mathfrak{n}]^{+}_{-} &= 0 && \text{on } \Gamma(t) \\ [w \cdot \tau]^{+}_{-} &= \varpi && \text{on } \Gamma(t) \end{aligned}$$

- Fine-grid z-model computation

A MULTISCALE DECOMPOSITION OF THE VELOCITY

- Decompose $u = v + w$

LARGE-SCALE

$$\begin{aligned} \operatorname{div} v^{\pm} &= F^{\pm} && \text{in } \Omega^{\pm}(t) \\ \operatorname{curl} v^{\pm} &= \omega^{\pm} && \text{in } \Omega^{\pm}(t) \\ [v \cdot \mathfrak{n}]_{-}^{+} &= 0 && \text{on } \Gamma(t) \\ [v \cdot \tau]_{-}^{+} &= 0 && \text{on } \Gamma(t) \end{aligned}$$

- Coarse-grid C-method computation

SMALL-SCALE

$$\begin{aligned} \operatorname{div} w^{\pm} &= 0 && \text{in } \Omega^{\pm}(t) \\ \operatorname{curl} w^{\pm} &= 0 && \text{in } \Omega^{\pm}(t) \\ [w \cdot \mathfrak{n}]_{-}^{+} &= 0 && \text{on } \Gamma(t) \\ [w \cdot \tau]_{-}^{+} &= \varpi && \text{on } \Gamma(t) \end{aligned}$$

- Fine-grid z-model computation

COUPLING

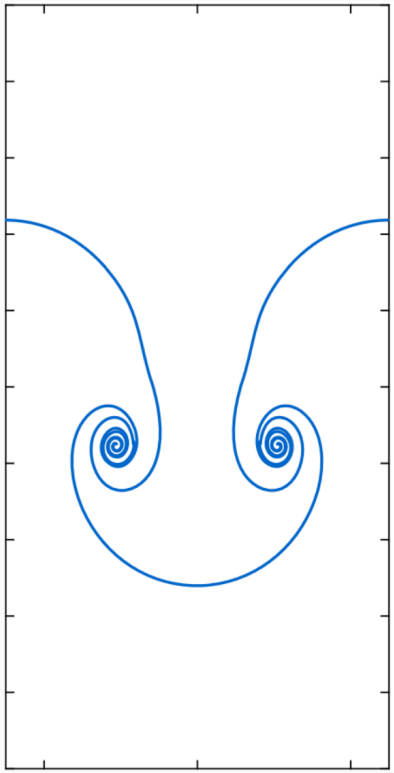
- Coupling terms calculated from Biot-Savart law & interpolation
- Shock physics

BAROCLINIC TORQUE : $[\nabla p/\rho]_{-}^{+} \cdot \partial_{\alpha} z$

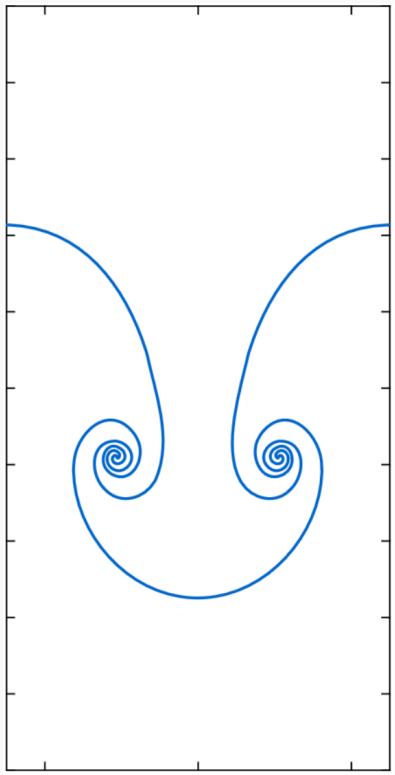
TAYLOR HYPOTHESIS : $\partial_t w + v \cdot \nabla w = 0$

SIMULATION OF COMPRESSIBLE RT INSTABILITY

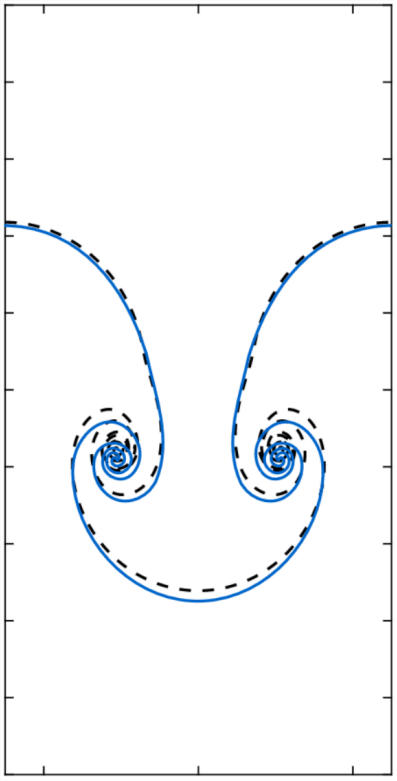
- Multiscale on 32×64 grid with 256 nodes vs *C*-method on 256×512 grid
- Speed-up factor of 48



high-res *C*-method



low-res multiscale

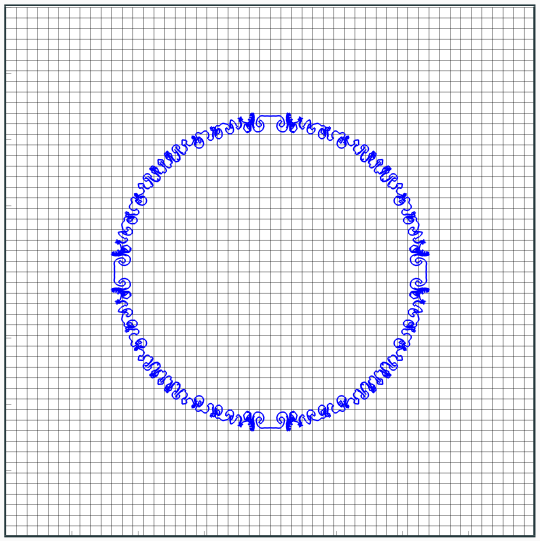


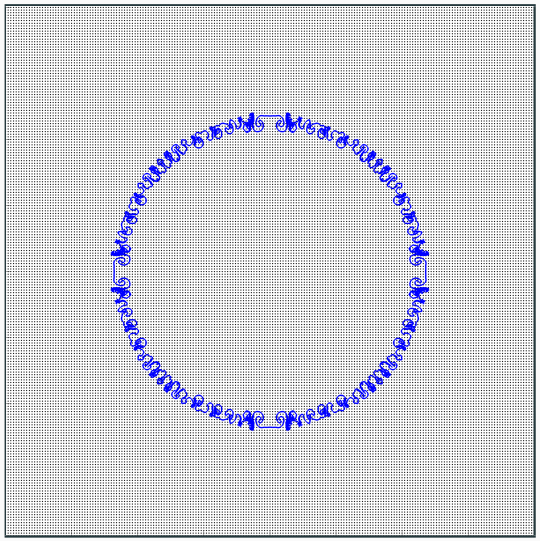
comparison

ADAPTIVITY

MESH ADAPTATION FOR PROPAGATING INTERFACES

- Problem: add mesh resolution around dynamically evolving interfaces
  - Adaptive mesh must “conform” to the geometry of the front





OUR STRATEGY

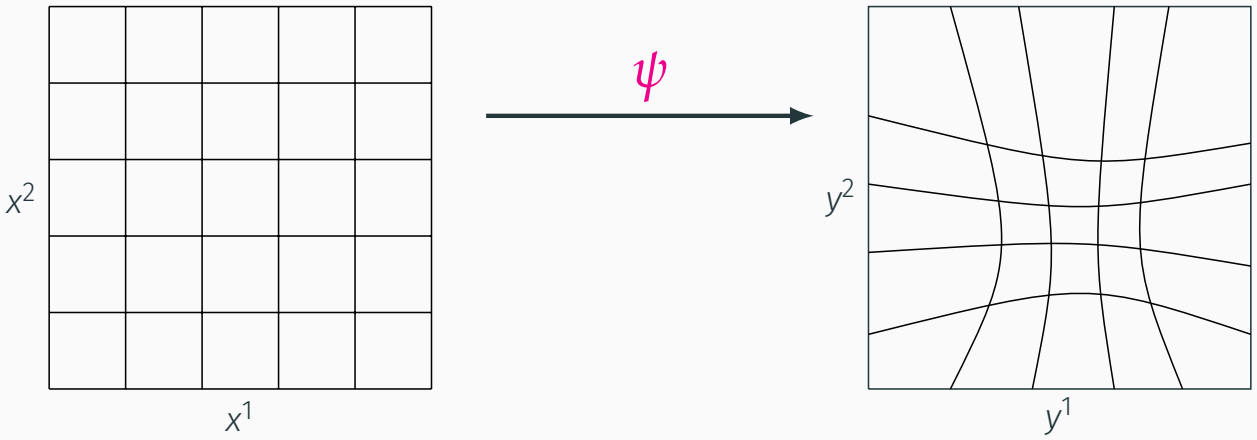
Construct a smooth map that takes a fixed reference mesh to a moving adaptive mesh

MATHEMATICAL FORMULATION OF SMOOTH ADAPTIVE MESHING

- Construct $\psi : \Omega_{\text{ref}} \to \Omega$ with *prescribed Jacobian determinant*

$$\begin{aligned} \det \nabla \psi(x) &= \mathsf{G} \circ \psi(x) && \text{in } \Omega_{\text{ref}} \\ \psi(x) \cdot n &= x \cdot n && \text{on } \partial\Omega_{\text{ref}} \end{aligned}$$

$\mathsf{G}(y)$ *target Jacobian function* and adaptive mesh $\mathcal{T} = \psi(\mathcal{T}_{\text{ref}})$



$\mathcal{T}_{\text{ref}} \subset \Omega_{\text{ref}}$ $\qquad$ $\mathcal{T} \subset \Omega$

NONLINEAR MONGE-AMPÈRE EQUATION

- Construct $\psi : \Omega_{\text{ref}} \to \Omega$ with *prescribed Jacobian determinant*

$$\begin{aligned} \det \nabla \psi(x) &= \mathrm{G} \circ \psi(x) && \text{in } \Omega_{\text{ref}} \\ \psi(x) \cdot n &= x \cdot n && \text{on } \partial\Omega_{\text{ref}} \end{aligned}$$

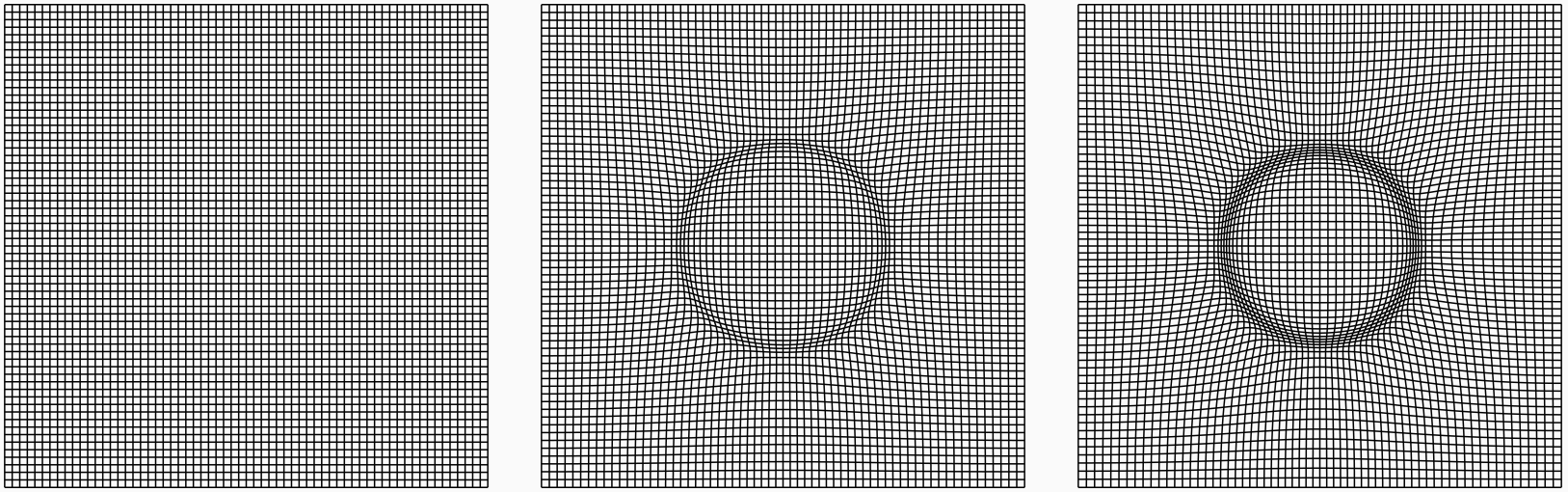
  $\mathrm{G}(y)$ *target Jacobian function* and adaptive mesh $\mathcal{T} = \psi(\mathcal{T}_{\text{ref}})$

- Nonlinear nonlocal elliptic **Monge-Ampère equation**
- *Ill-posed* in multi-*D*; solutions are **not unique**
- Variational methods: expensive
  - Newton-Krylov solver of Chacon, Delzanno, & Finn (2011)
  - Highly non-trivial in general geometries

Chacon, Delzanno, & Finn (2011), *Robust, multidimensional mesh-motion based on Monge–Kantorovich equidistribution*

FLOWING IN PSEUDO-TIME

- A new version of the deformation method of Dacorogna & Moser (1990)



$\tau = 0$ $\tau = 0.5$ $\tau = 1$

THE BASIC SAM ALGORITHM

- **Step 1:** linear Poisson solve

$$\begin{aligned} \Delta\Phi(x) &= F(x) - 1 \quad && \text{in } \Omega_{\text{ref}} \\ \nabla\Phi(x) \cdot n &= 0 && \text{on } \partial\Omega_{\text{ref}} \end{aligned}$$

  with $F = 1/G$, where G is the target function

- **Step 2:** Let $\overline{w}(x) = \nabla\Phi(x)$ and define

$$w(x, \tau) = \frac{\overline{w}(x)}{\tau + (1 - \tau)F(x)}$$

  τ is pseudo-time

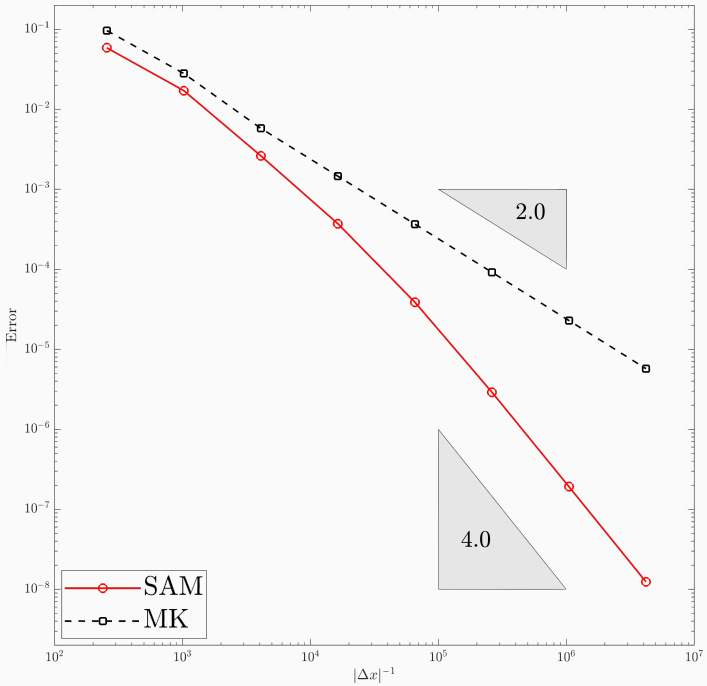
- **Step 3:** linear transport equation for $\eta(x, \tau)$

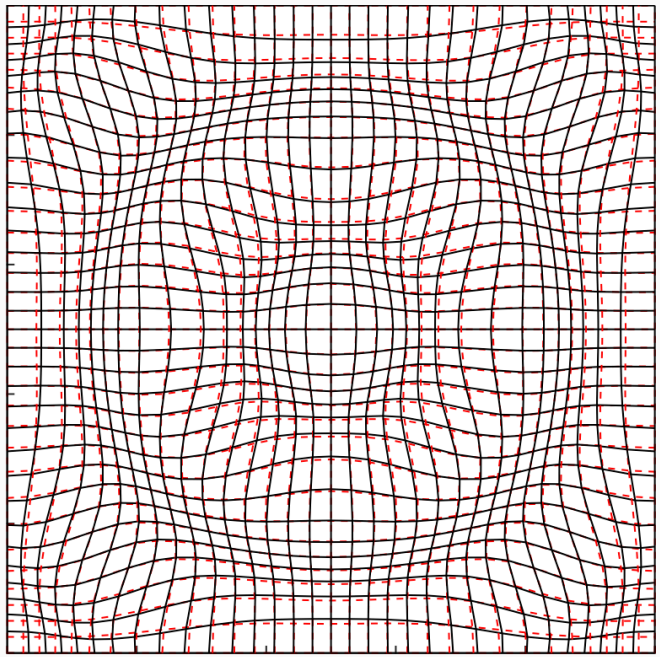
$$\begin{aligned} \partial_\tau \eta + w \cdot \nabla\eta &= 0 \quad && 0 < \tau \leq 1 \\ \eta(x, 0) &= x\,, && \tau = 0 \end{aligned}$$

- **Step 4:** Define $\psi(x) = \eta(x, 1)$

BENCHMARKING THE BASIC SAM ALGORITHM

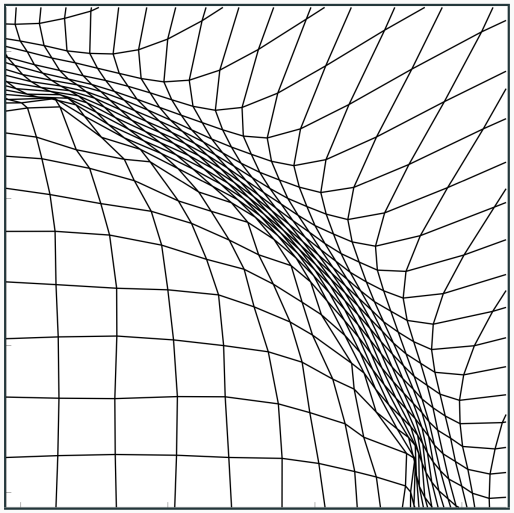
- $>$ 200 times faster than Newton-Krylov scheme
- No parameters to tune

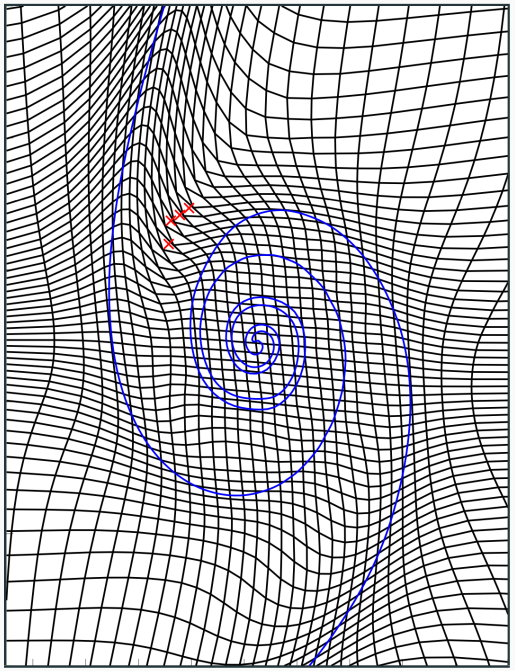


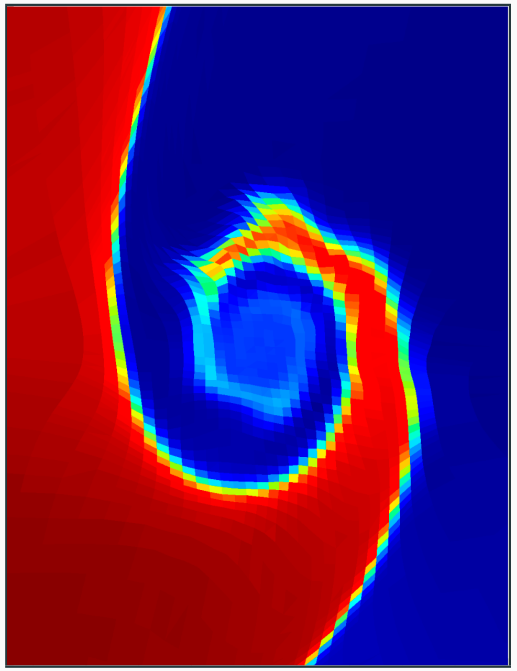


TIME-DEPENDENT & LARGE ZOOM-IN MESHING

- Calculating ψ_k at each time-step t_k is expensive
- Meshing with large zoom-in factors creates non-convex cells





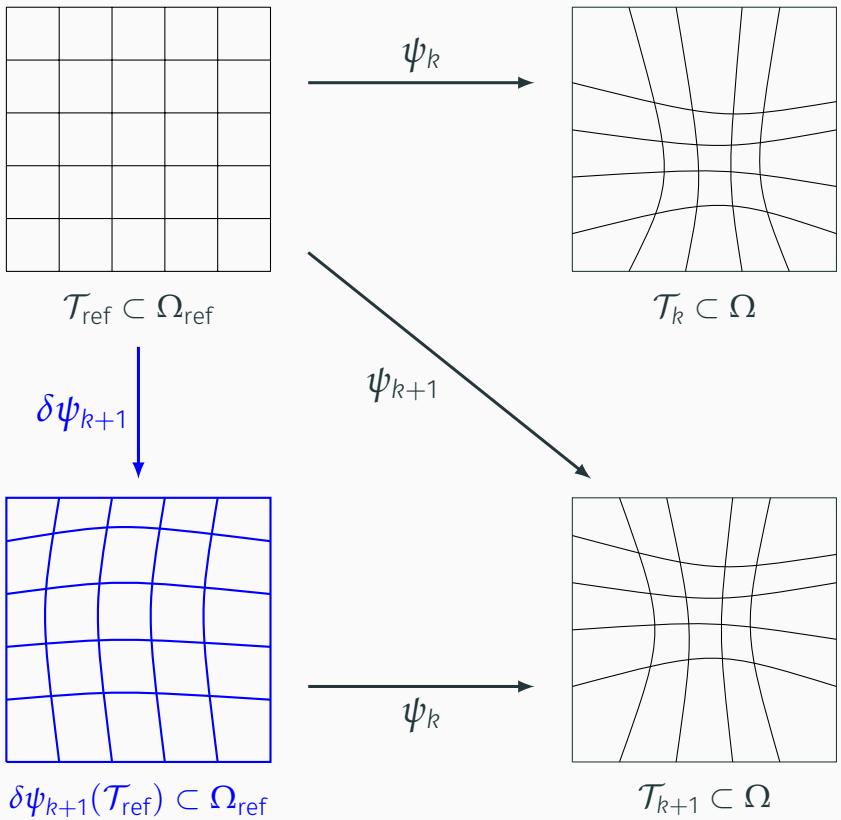


A PERTURBATIVE REFORMULATION

- Construct ψ via sequence of near-identity deformations of $\mathcal{T}_{\text{ref}}$

$$\psi_{k+1}(x) = \psi_k \circ \delta\psi_{k+1}(x)$$

$$\delta\psi_{k+1} \approx \text{id}$$



THE PERTURBATION FORMULATION

- Perturbation map $\delta\psi_{k+1} : \Omega_{\text{ref}} \to \Omega_{\text{ref}}$ satisfies

$$\begin{aligned} \det \nabla \delta\psi_{k+1}(x) &= P_{k+1} \circ \delta\psi_{k+1}(x) && \text{in } \Omega_{\text{ref}} \\ \delta\psi_{k+1}(x) \cdot n &= x \cdot n && \text{on } \partial\Omega_{\text{ref}} \end{aligned}$$

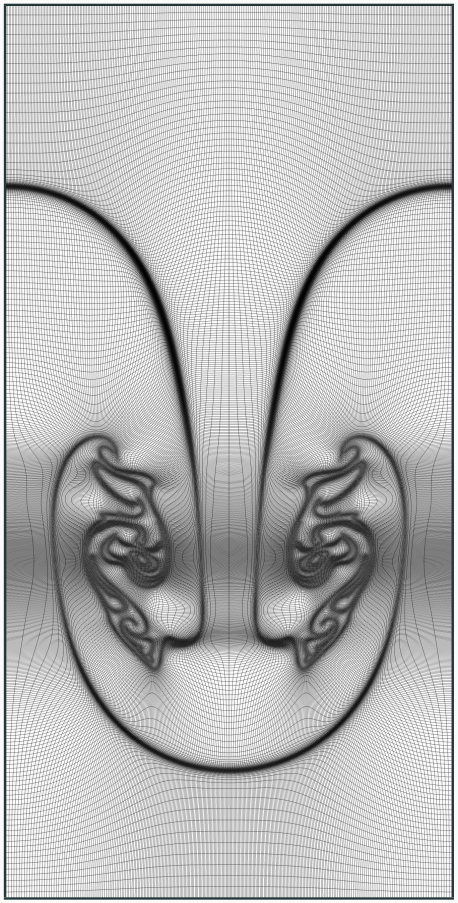
$P_{k+1}(x) = \left(\frac{G_{k+1}}{G_k}\right) \circ \psi_k(x)$ *perturbation target function*

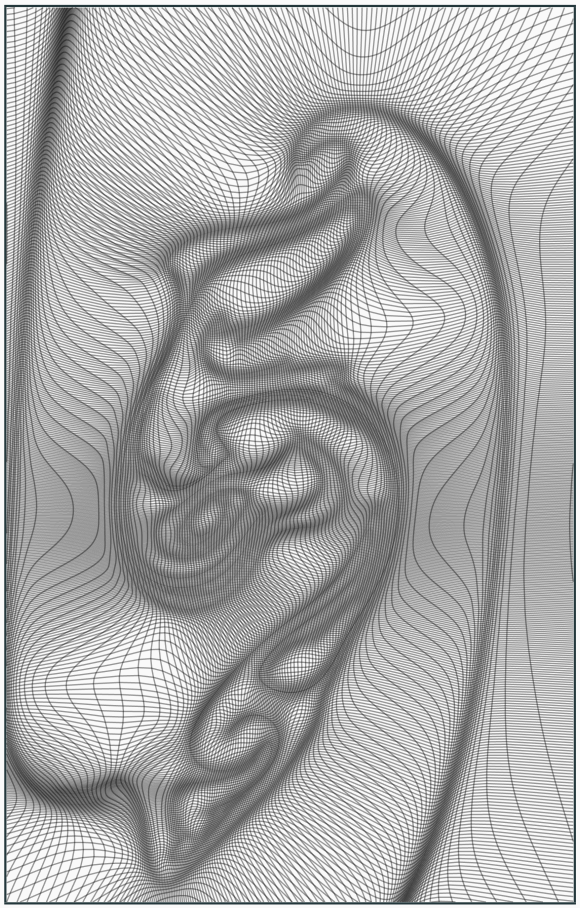
- Discretization of $\delta\psi$ always on $\mathcal{T}_{\text{ref}}$
- Recursive code structure
- For hyperbolic systems $||1 - 1/P(\cdot, t)||_{L^\infty} = \mathcal{O}(\Delta t) = \mathcal{O}(N^{-1/d})$

  $\Longrightarrow$ optimal complexity

SMOOTH ADAPTIVE MESHING EXAMPLE

- RT interface obtained from $2D$ simulation
- 256×512 rectangular mesh





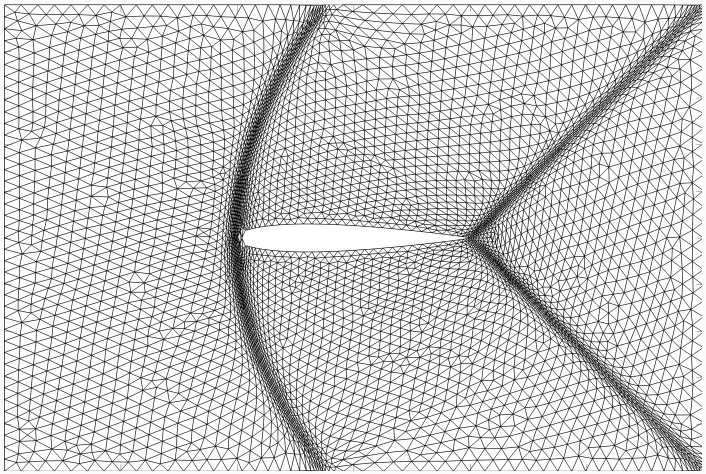
SMOOTH ADAPTIVE MESHING EXAMPLE

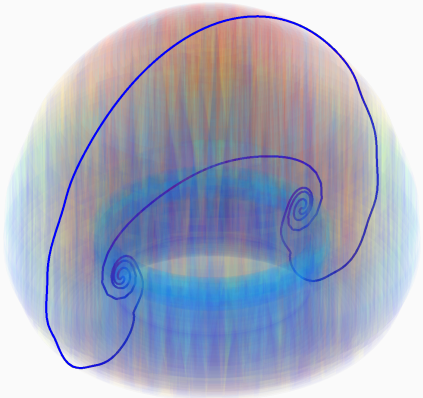
- Rising bubble surface obtained from $3D$ axisymmetric simulation
- $128 \times 64 \times 256$ cylindrical mesh

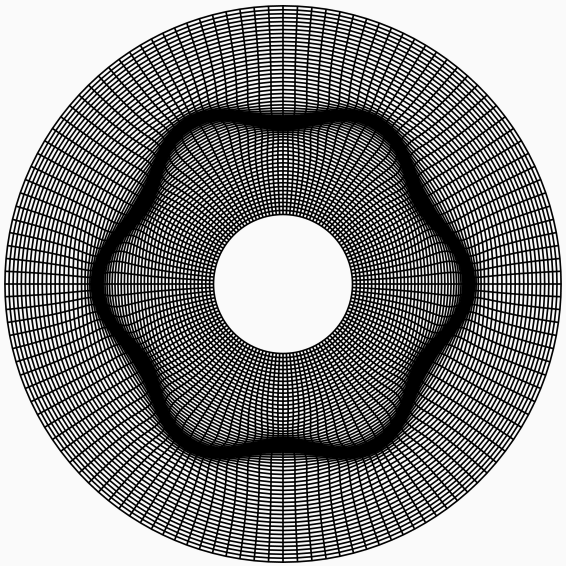


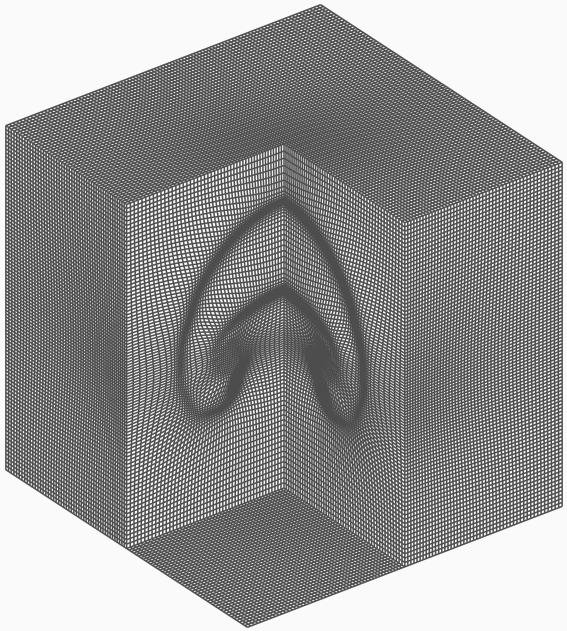


MESH GENERATION IN GENERAL GEOMETRIES

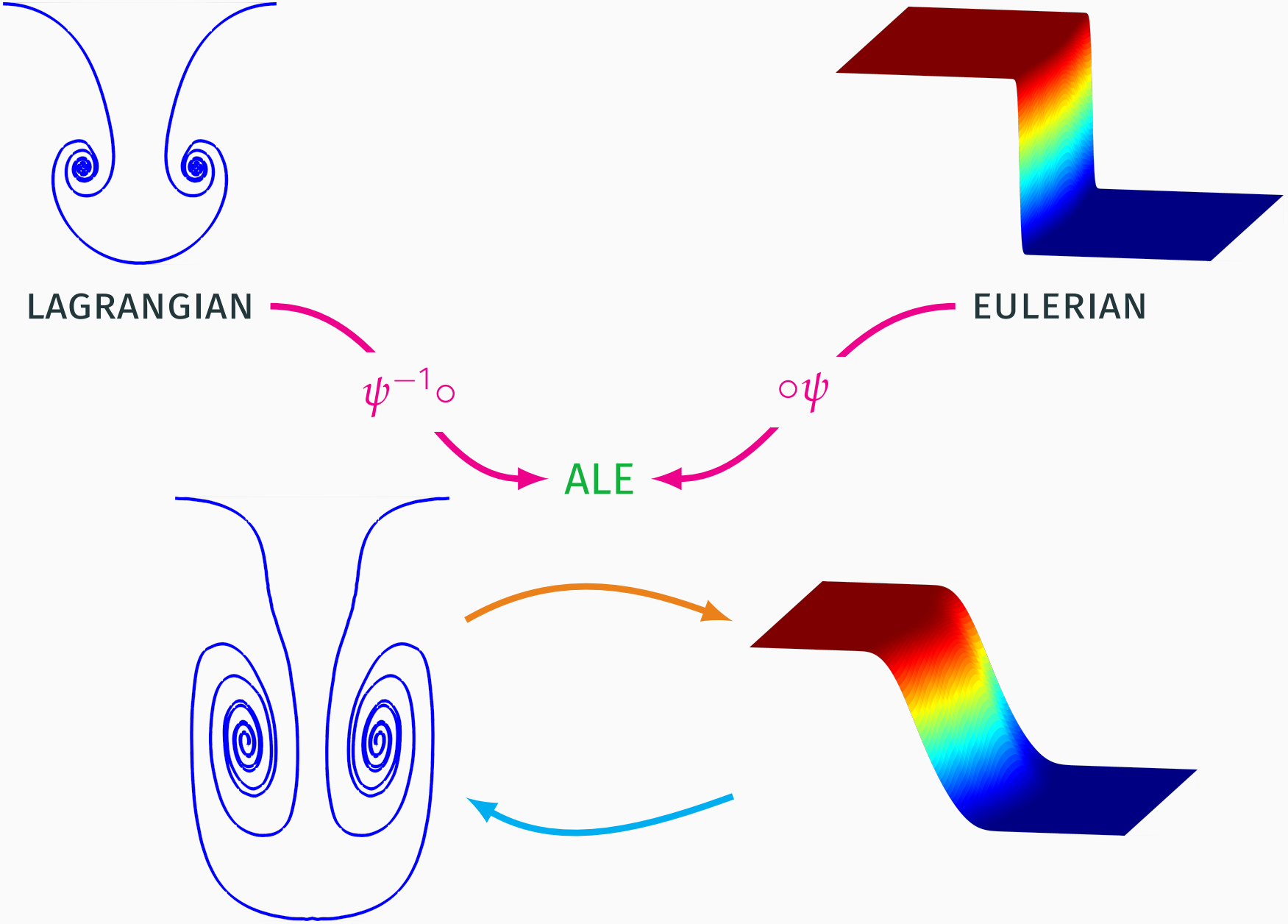








FRONT-CAPTURING & TRACKING WITH ADAPTIVITY



ARBITRARY LAGRANGIAN-EULERIAN DYNAMICS

$$\partial_t \rho + \partial_j(\rho u^j) = 0 \quad \longrightarrow \quad \partial_t(\mathcal{J}\tilde{\rho}) + \partial_j(\mathcal{J}\tilde{\rho} v^j) = 0$$

$$\partial_t z = u \circ z \quad \longrightarrow \quad \partial_t \tilde{z} = v \circ \tilde{z}$$

- Geometric quantities

$$a = \mathcal{J}\,[\nabla \psi]^{-1}$$
COFACTOR MATRIX

$$\psi_t \equiv \partial_t \psi$$
MESH VELOCITY

$$v^j = \tfrac{1}{\mathcal{J}} a^j_i (u^i - \psi^i_t)$$
ALE TRANSPORT VELOCITY

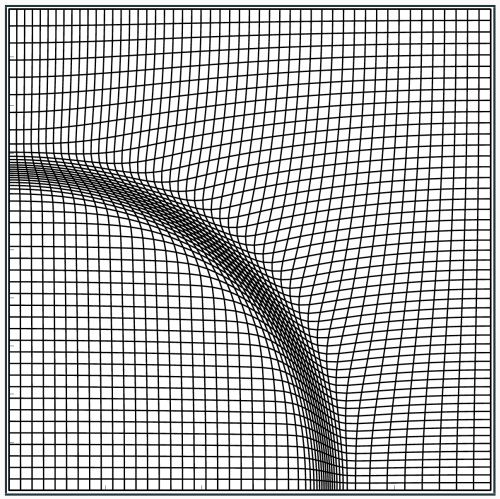
- Geometric identities

$$\partial_t \mathcal{J} = \partial_j(a^j_i \psi^i_t)$$
GEOMETRIC CONSERVATION LAW

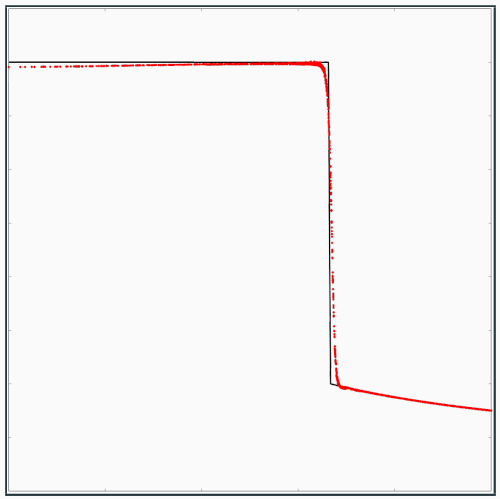
$$\partial_j(a^j_i) = 0, \text{for } i = 1, 2$$
PIOLA IDENTITY

NOH INFINITE STRENGTH SHOCK

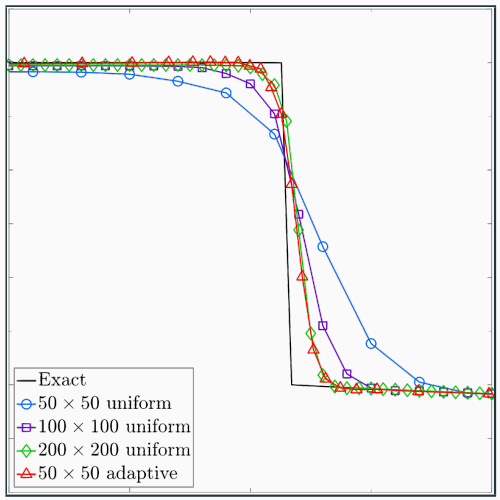
- 50×50 ALE solution with C-method
- Speed-up factor of 6



SAM mesh



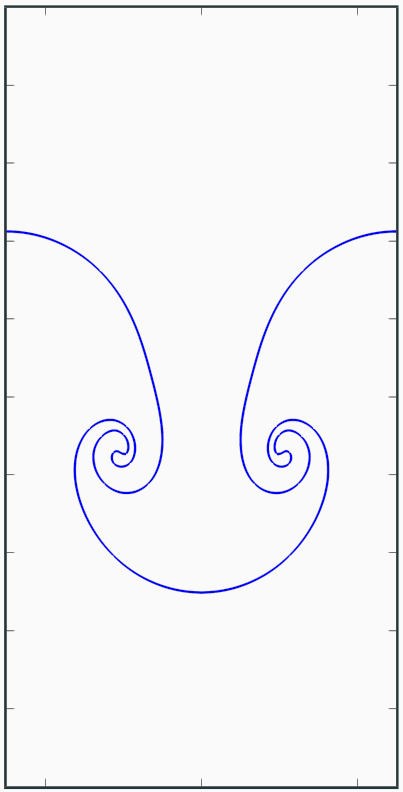
ρ scatter plot



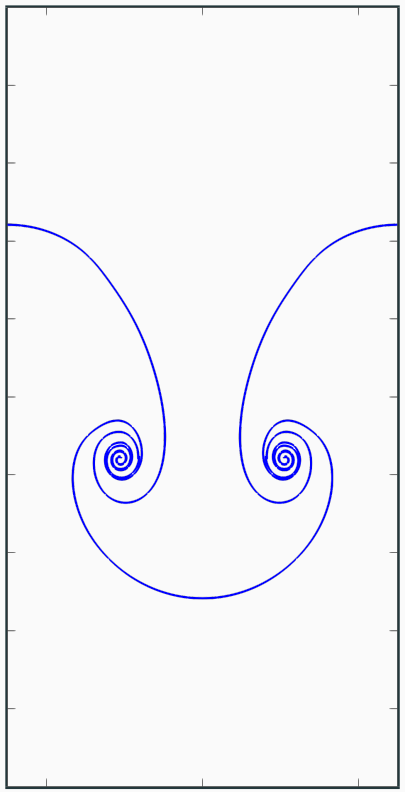
uniform vs. adaptive

RT INSTABILITY

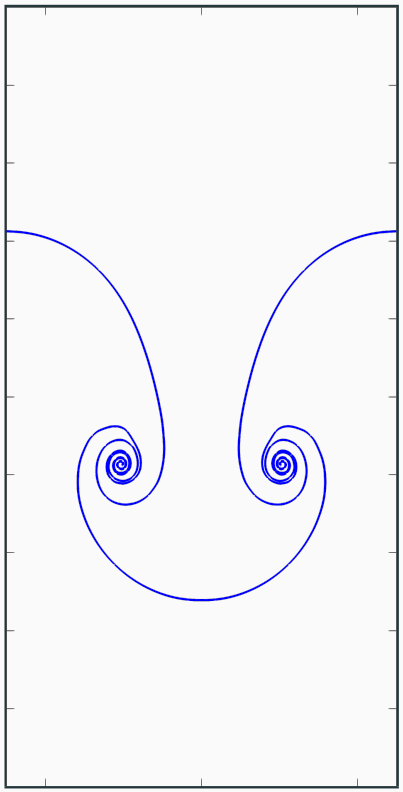
- 64×128 adaptive simulation
- C-method tangential viscosity & simplified front-tracking
- Speed-up factor of 10



64×128 uniform



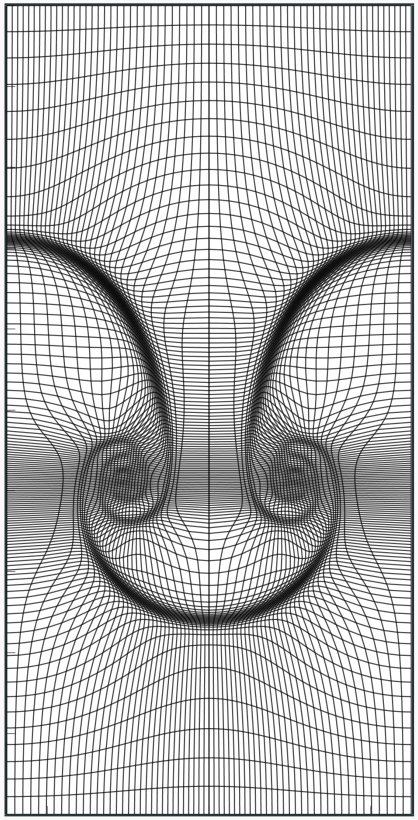
256×512 uniform

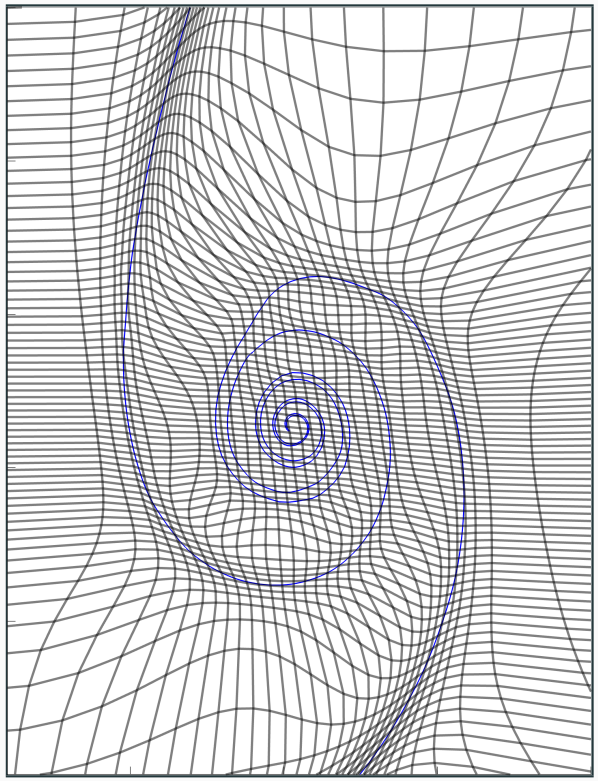


64×128 adaptive

RT INSTABILITY

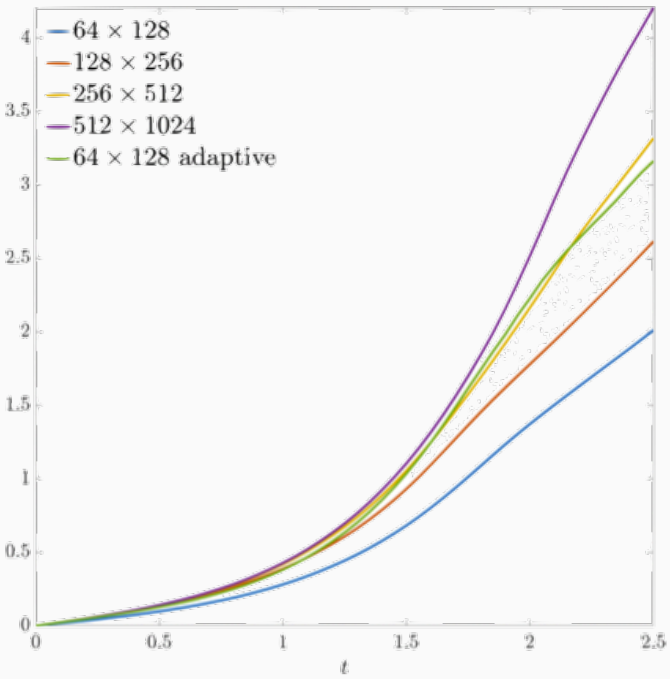
- Adaptive mesh & zoom-in



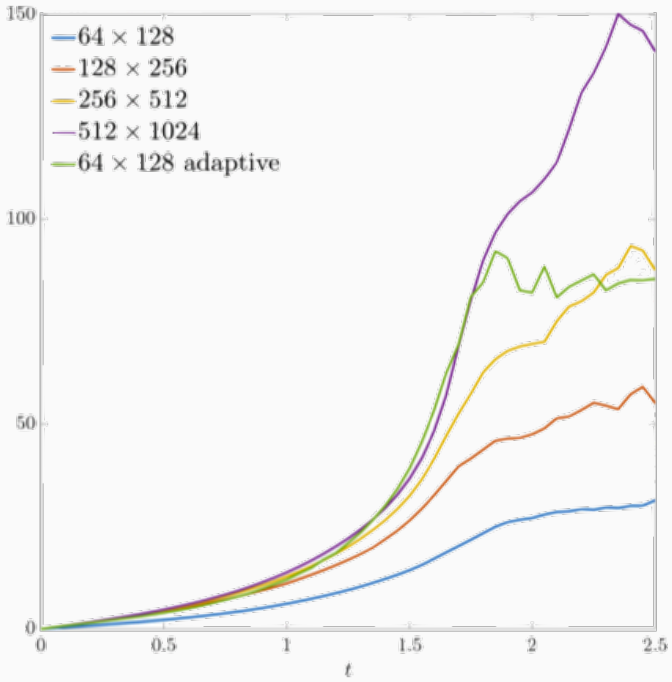


RT INSTABILITY

- Comparison of growth of vorticity



(a) $\|\omega(\cdot,t)\|_{L^2}$ vs t



(b) $\|\omega(\cdot,t)\|_{L^\infty}$ vs t

SUMMARY

SUMMARY

- A new numerical framework for front-capturing & front-tracking with adaptivity for multi-D fluid flows
- Methodology is founded upon **PDE-based techniques**
  - *C*-method artificial viscosity
  - Multiscale RT-RM model
  - Smooth Adaptive Meshing
- Results from challenging test problems demonstrate the efficacy of the methodology
  - LeBlanc, double Mach, rocket rig, Noh, RT instability

THANK YOU FOR YOUR ATTENTION!

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