2010 HIPACC Astro-Computing Summer School

Galaxy Simulations Using the N-Body/SPH code GADGET

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Outline

1. ~~Who am I and what am I doing here? My perspective, my science, and where my focus will be this week~~
2. ~~An overview of GADGET projects (+other practical - I hope - information)~~
3. ~~A brief overview of GADGET~~
4. ~~Adding "Astrophysics" to GADGET~~
5. ~~Loose Ends ... data structures, analysis, and visualization (w/ P. Hopkins)~~
6. Odds & Ends, & What's next? (Arepo: the next generation of code)

6. What's Next

6.1 A quick word about visualization/analysis

6.2 Additional components added to Gadget (an extension of Wed.)

6.3 Arepo

6.1 A quick word about visualization/analysis

* triton:/home/hipacc-5/Analysis_public/
* Splash (F90/PGPLOT by D. Price)
  http://users.monash.edu.au/~dprice/splash/index.html
* Gadgetviewer (C/F90 by J. Helly)
  http://star-www.dur.ac.uk/~jch/gadgetviewer/index.html
* IFRIT (C++/VTK by N. Gnedin)
  http://sites.google.com/site/ifrithome/
* TIPSY (by UW/N-body Shop)
  http://www-hpcc.astro.washington.edu/tools/tipsy/tipsy.html
* A set of homegrown IDL routines; a well developed backbone, but a very organic front-end - feel free to email me to access this

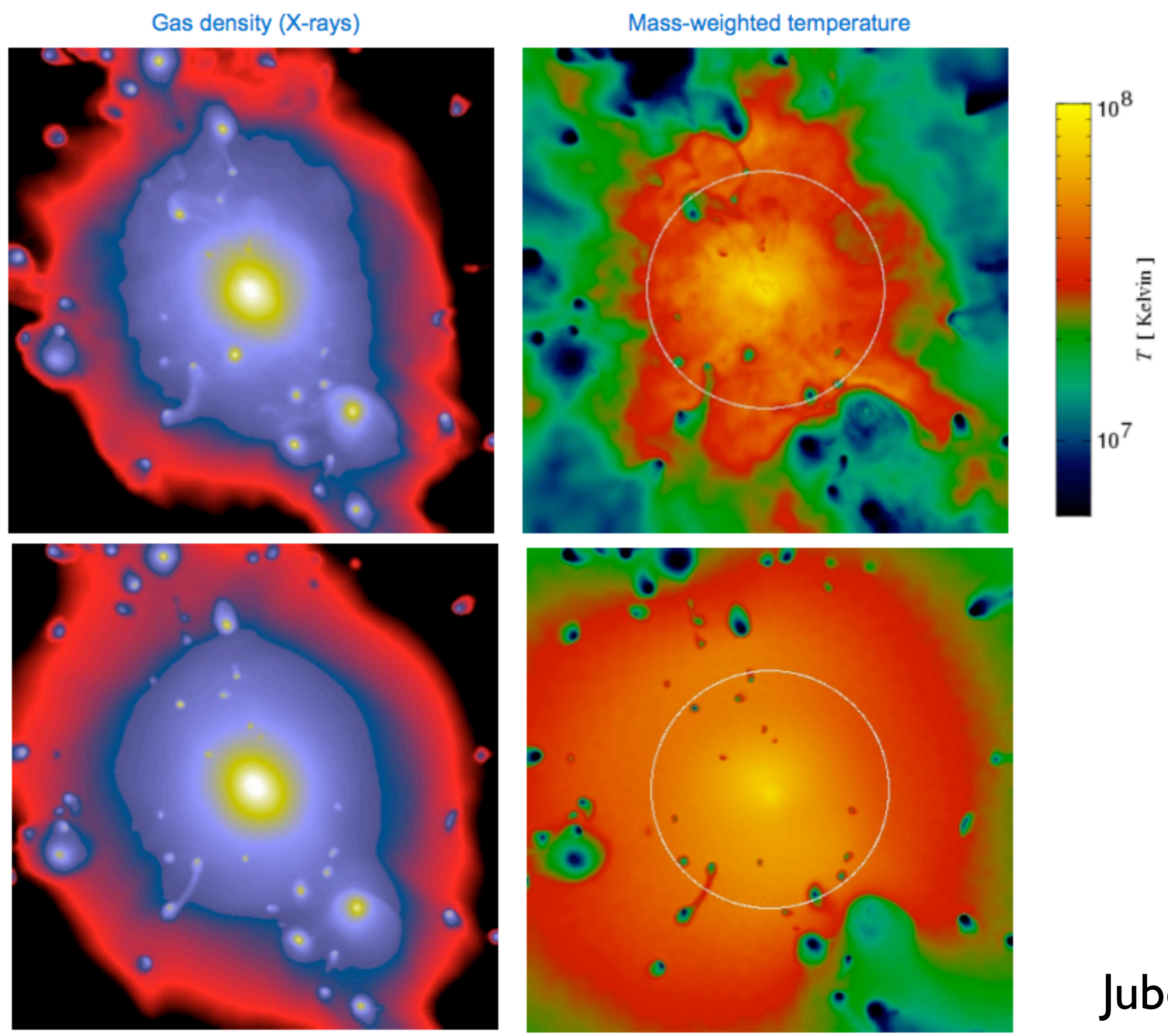
6.2 Additional components added to Gagdet

* Thermal Conduction: $$\frac{\mathrm{d}u_i}{\mathrm{d}t} = \sum_j \frac{m_j}{\rho_i \rho_j} \frac{(\kappa_j + \kappa_i)\,(T_j - T_i)}{|\mathbf{x}_{ij}|^2} \mathbf{x}_{ij} \nabla_i W_{ij}$$

Brookshaw (1985), note requires assumptions about magnetic fields

w/o conduction

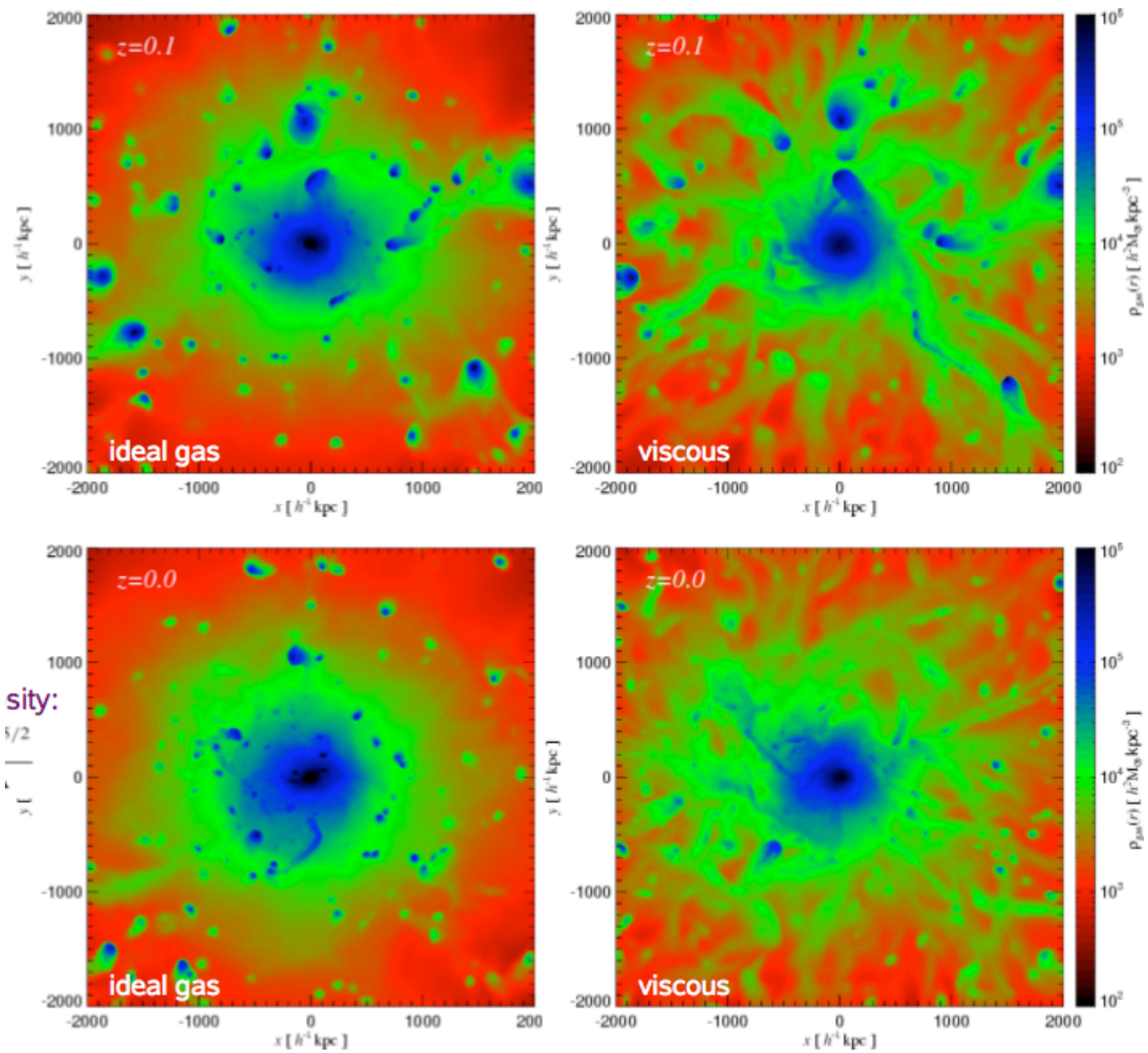
w/ conduction



Jubelgas et al. (2004)

6.2 Additional components added to Gagdet

* Physical Viscosity: Add a term to hydrodynamic equations which includes bulk and shear viscosities which are determined by a stress-energy tensor.



Sijacki & Springel (2006)

6.2 Additional components added to Gagdet

* Radiative Transfer: SPHRAY (Altay et al. 2008) - individual rays integrated in Monte Carlo fashion

  TRAPHIC (Pawlik & Schaye 2008) - radiation propogated in emission cones

  use Optically Thin Variable Eddinton Tensor (OTVET) approximation (Petkova & Springel 2009)

6.2 Additional components added to Gagdet

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* Magnetic fields: see, e.g., Dolag et al. 1999, Dolag & Stasyszyn 2009, Rosswog & Price 2008, Price 2010

* Relativistic Dynamics: see, e.g., Laguna et al. 1993, Monoghan & Price 2001, Rosswog (2009)

6.2 Additional components added to Gagdet

* Other improvements:

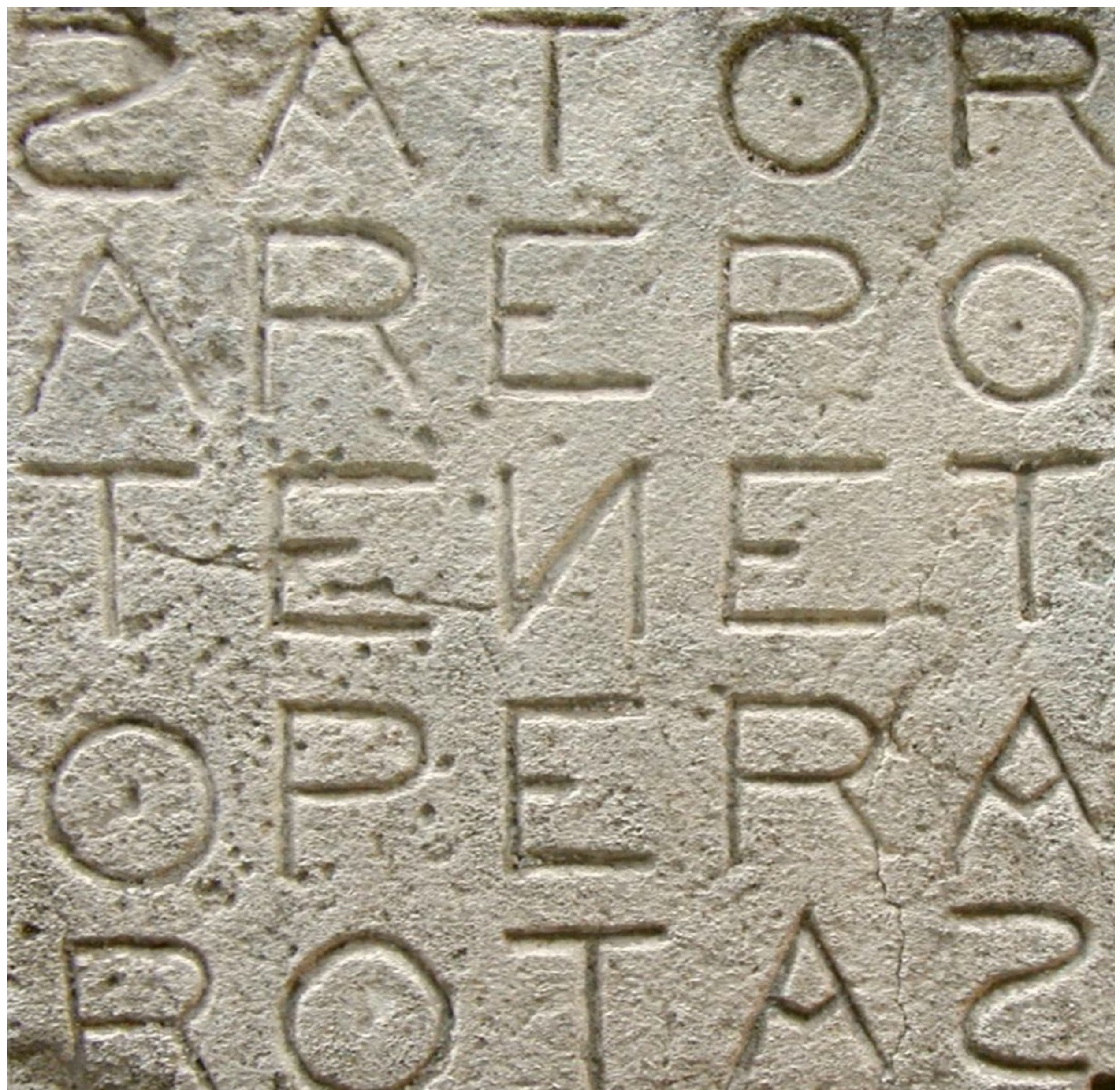
- different Kernels: anisotropic (Shapiro et al. 1996, Owen et al. 1998), energy weighting (Read et al. 2009)

- improved viscosity: vary it with time (e.g., Dolag et al. 2005)

- mixing: including this via artificial heat conduction (Price 2008, Wadsley et al. 2008)

- estimate density by Voronoi volume (Hess & Springel 2009)

Results from: arXiv:0901.4107, by Volker Springel;
(see, also, http://www.mpa-garching.mpg.de/~volker/arepo)



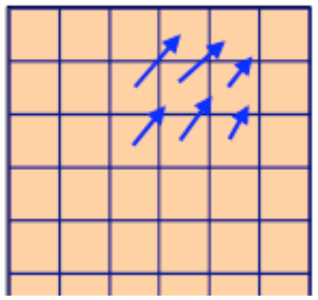
The challenges of modeling galaxy formation and evolution:

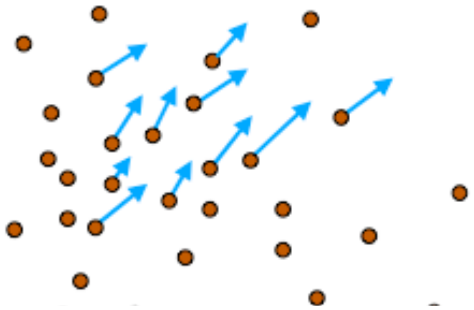
- vast range in spatial, temporal scales
- non-linear dynamics; e.g. shocks
- coupled “fluids:” collisionless, multiphase gas
- complex, well-understood physics: non-linear gravity, radiative processes
- complex, poorly-understood physics: star formation, black hole growth, feedback

$\Rightarrow$ numerical approach essential

Traditional methods for cosmology

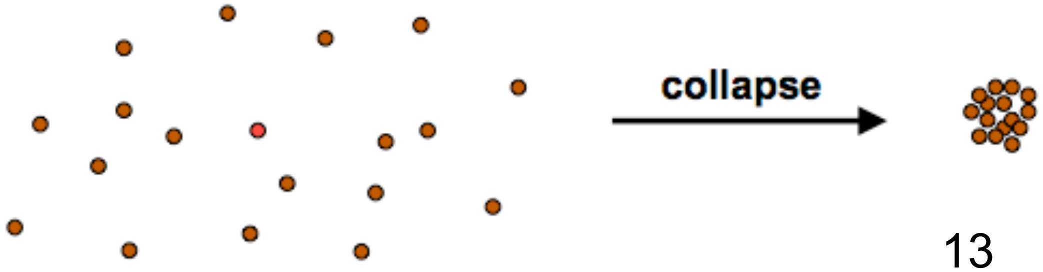
Eulerian	Lagrangian
discretize space	**discretize mass**
representation on a mesh (volume elements)	representation by fluid elements (particles)





numerical viscosity

automatically to the flow



Advantages / disadvantages

SPH

- accurate gravity solvers
- Galilean invariant
- spatially/temporally adaptive
- free surfaces

- artificial viscosity: shocks broadened, source of diffusion
- smoothing can suppress instabilities
- mass resolution limited
- how to handle multiphase media?

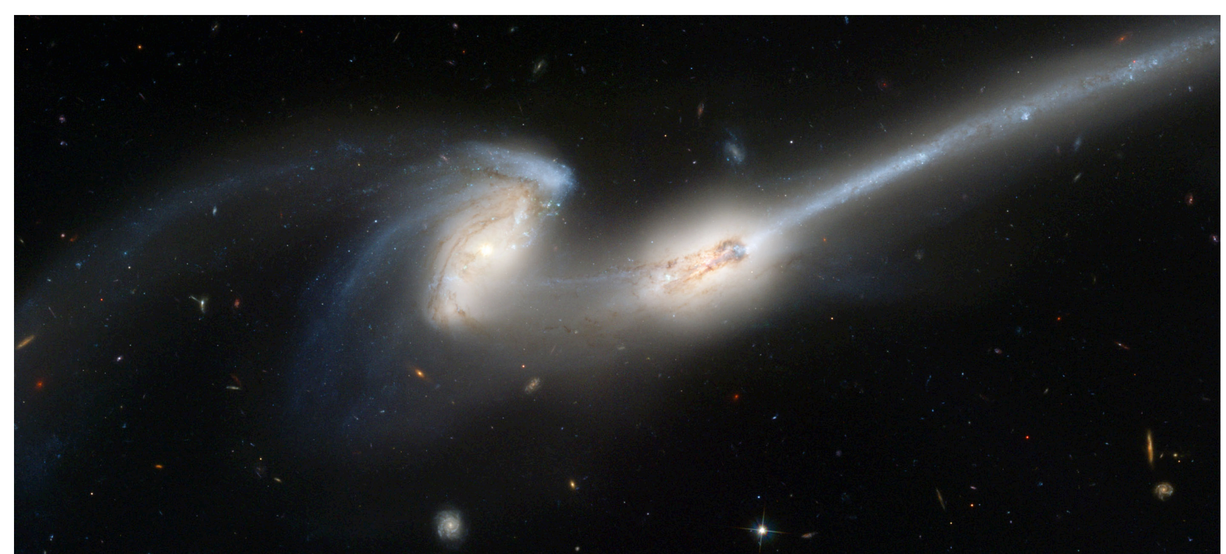
Eulerian

- accurate shock solvers (Godunov)
- good resolution of discontinuities
- explicit mixing
- AMR adaptive, but stationary mesh

- truncation error not Galilean invariant
- complicated refinement criteria
- handling of free surfaces
- gravity of collisionless fluid still done with particles

Motivation for something better

- consistency checks
- instabilities in outflows & inflows
- geometrical flexibility
- going beyond sub-resolution models, e.g., shock-induced star formation in galaxy mergers



Hybrid method: moving mesh

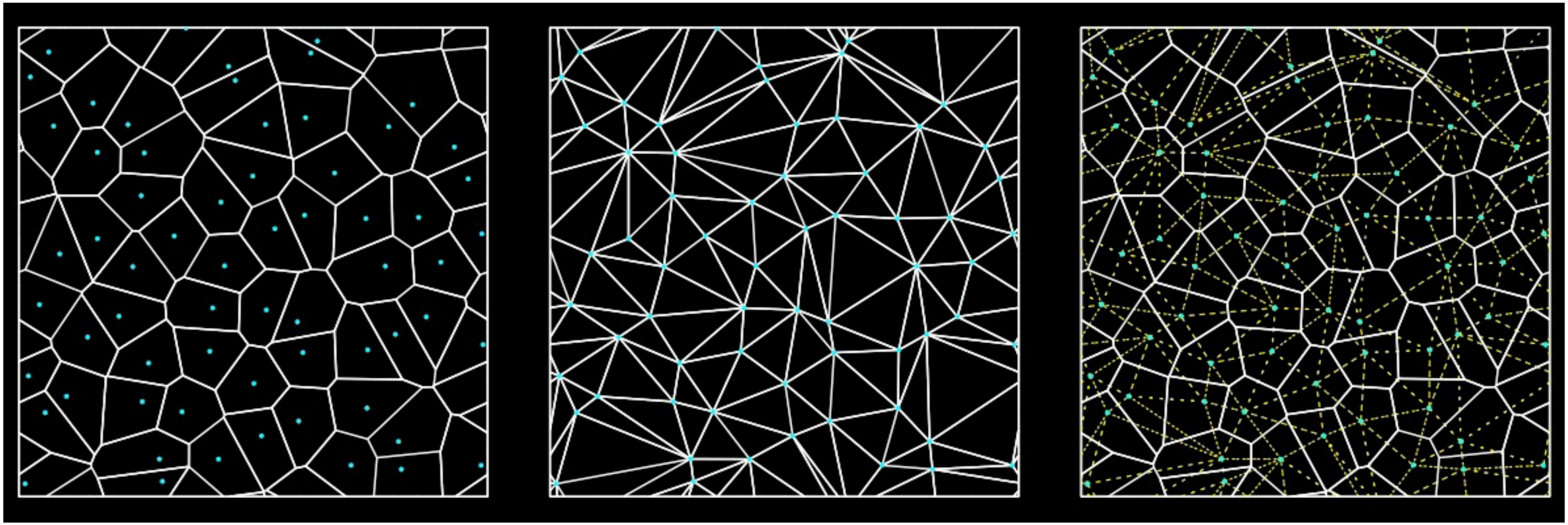
(Earlier, related efforts: Pen, Gnedin, Xu)

Springel (2009): "unstructured" mesh & tree code:

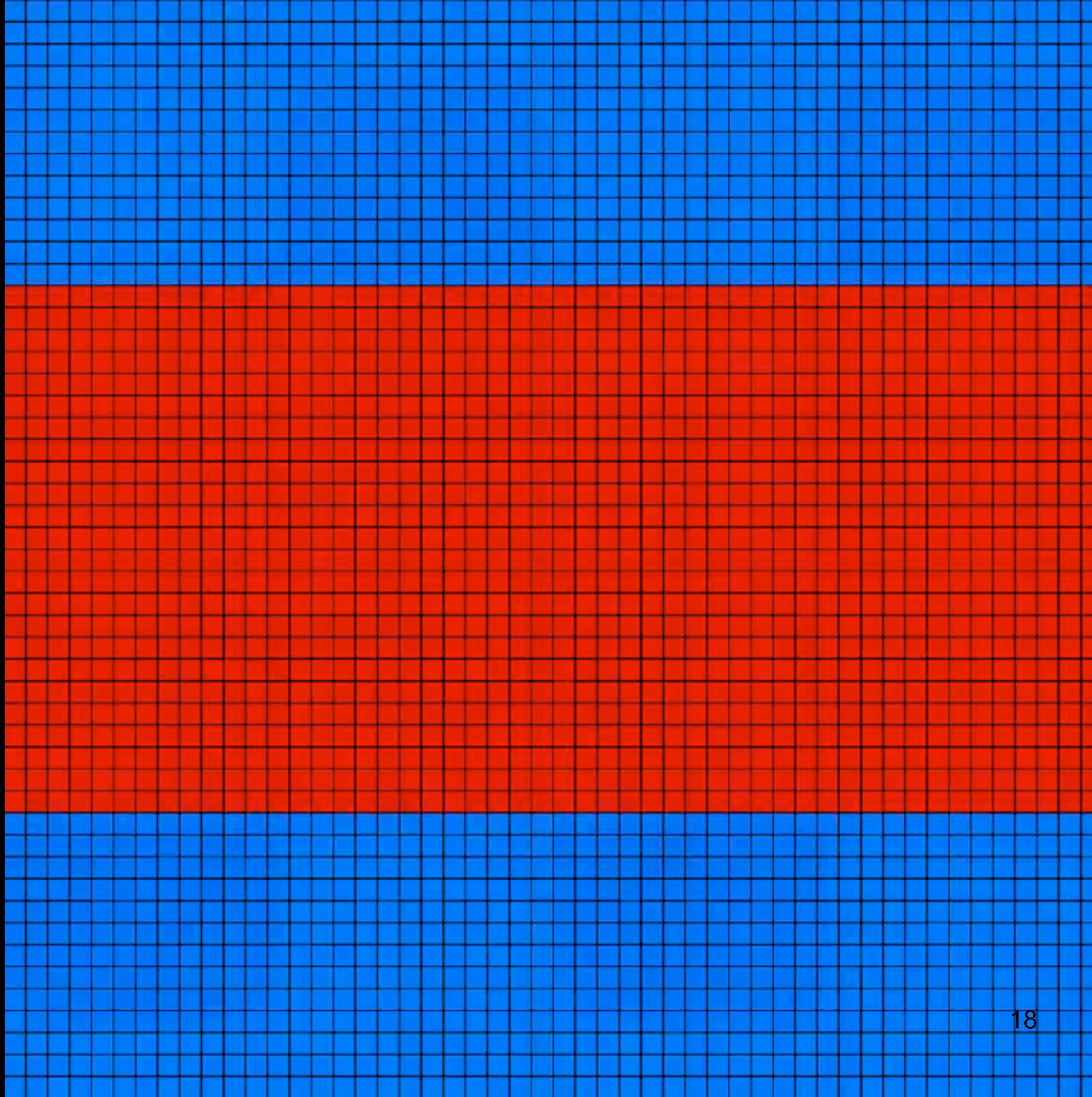
- AREPO (Latin palindrome "Sator Square")
- Voronoi tessellation (used elsewhere, e.g. aerodynamics, plasma physics)
- Mesh generated from tracer particles, avoids problems with twisting and tangling
- peculiar to astrophysics: very large dynamic ranges in spatial, temporal scales; motion driven by gravity, especially dark matter

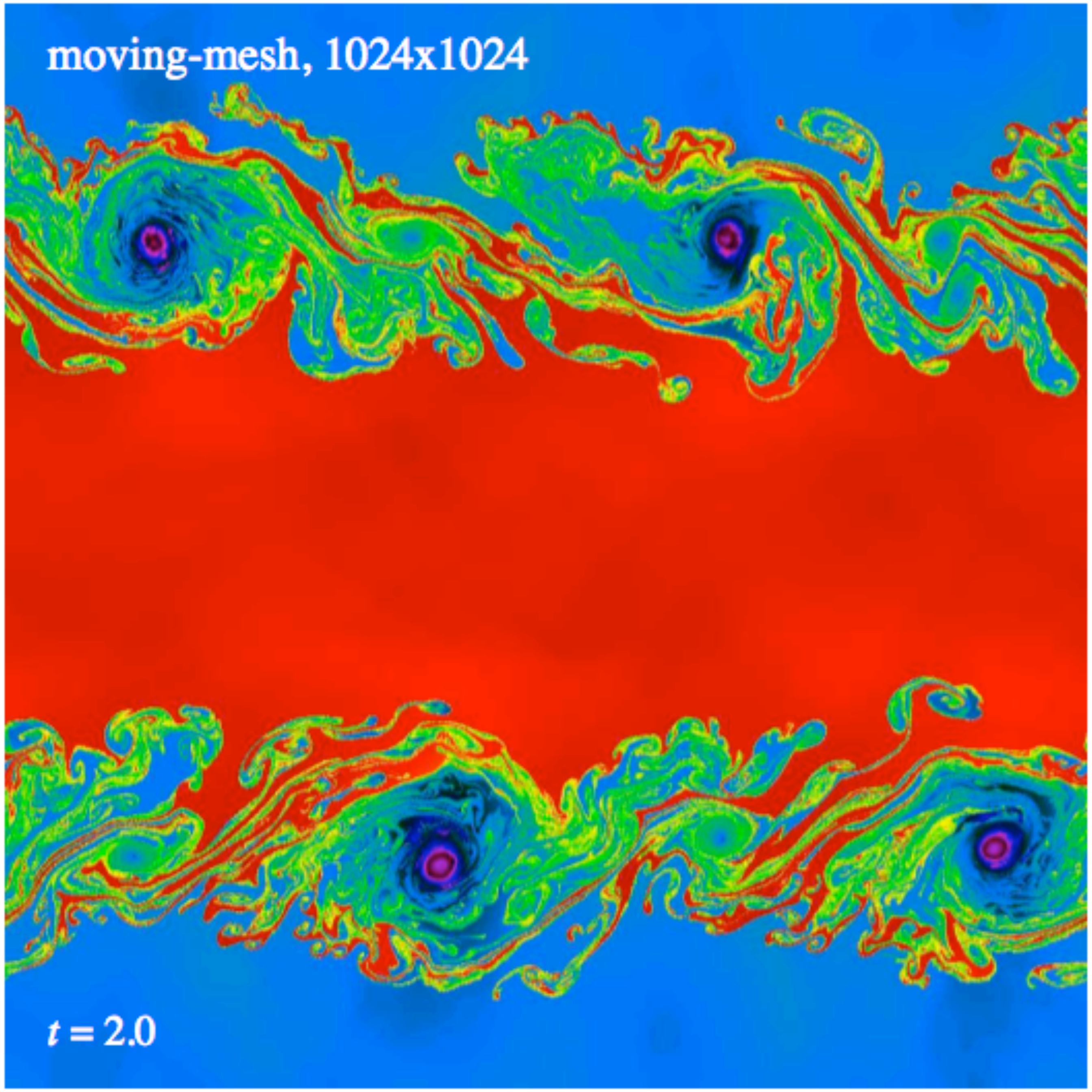
6.3 Arepo

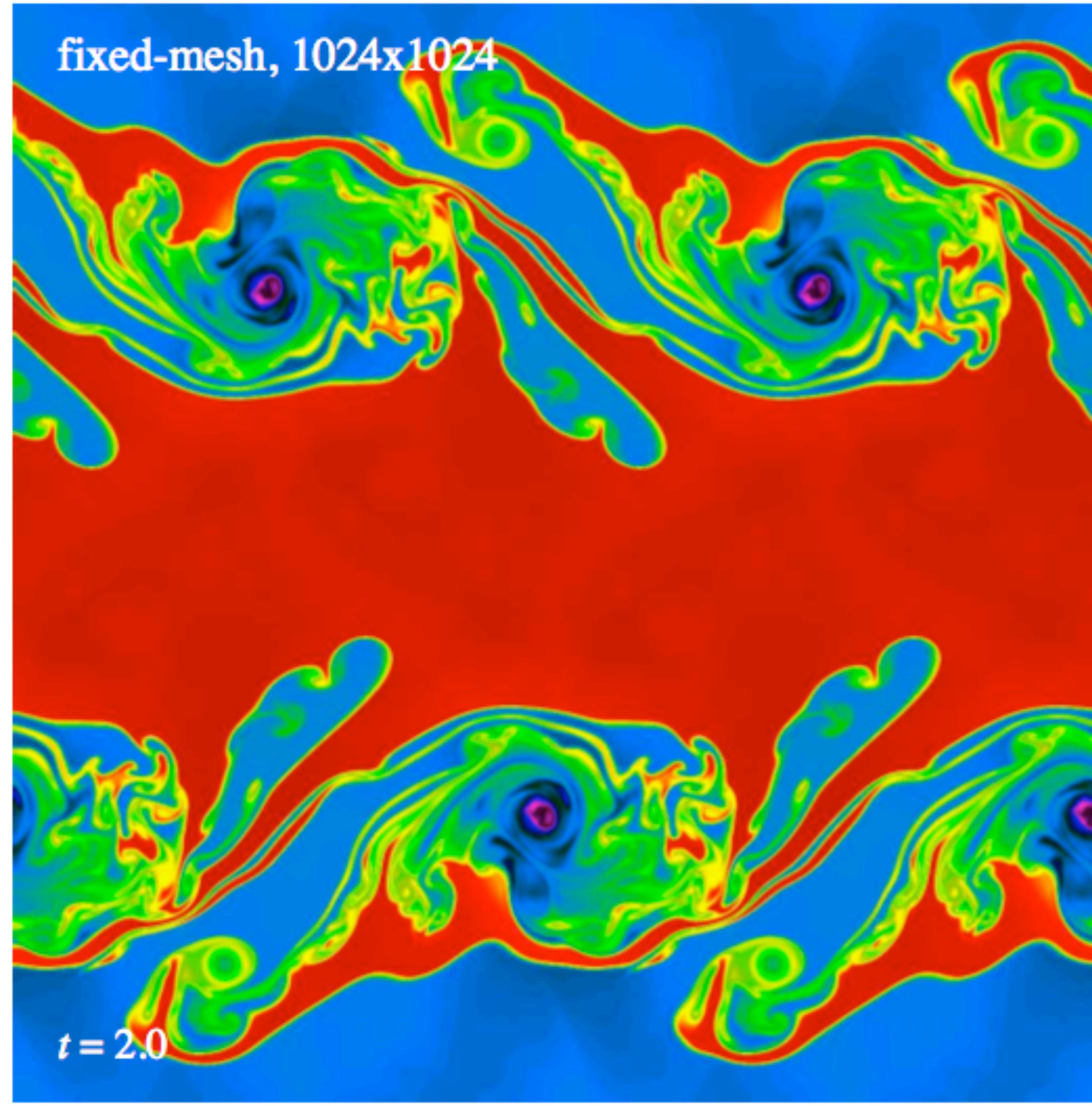
Voronoi mesh   Delaunay triangulation

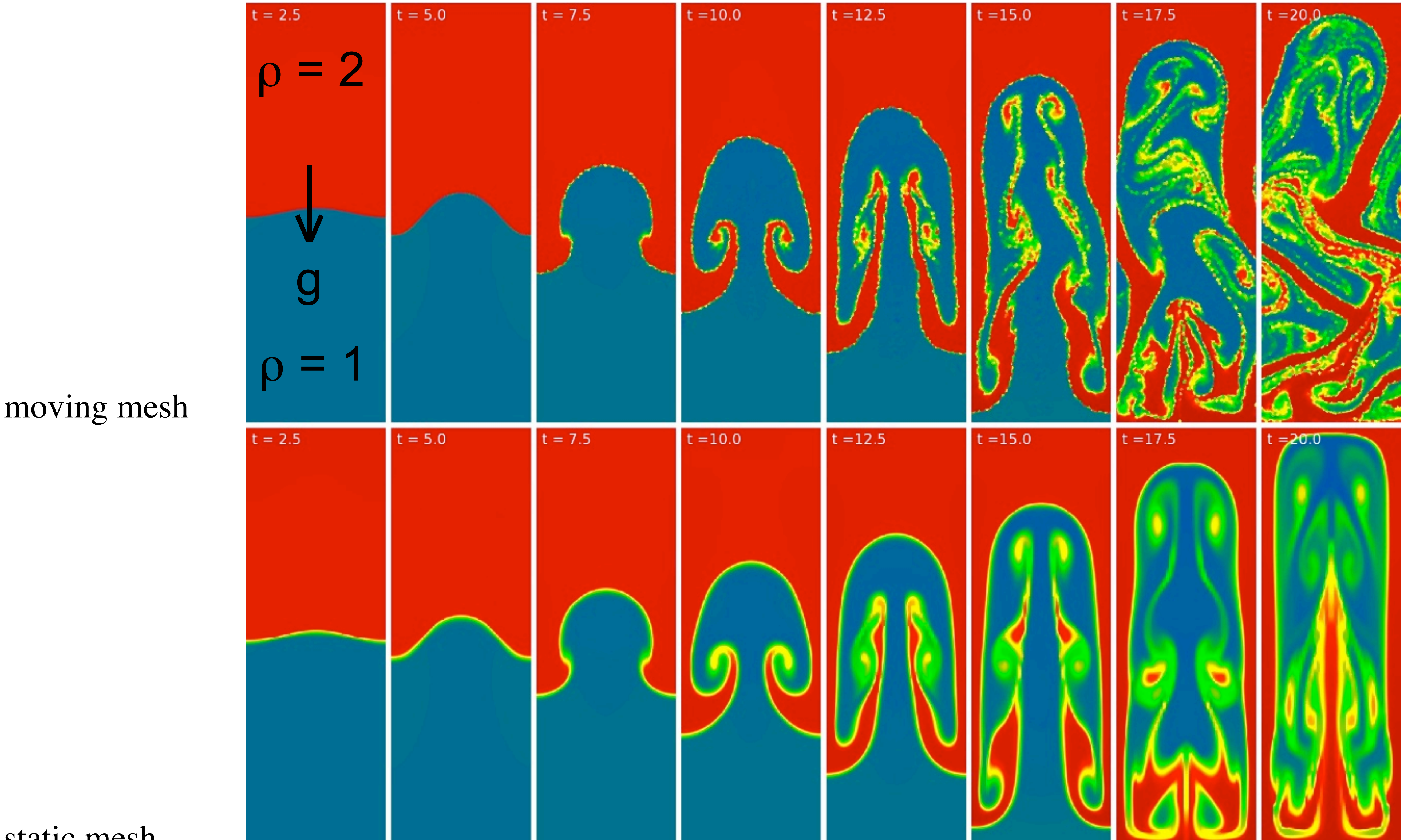


- marker points to generate mesh (Voronoi tessellation)
- locations, motion of mesh-generating points is arbitrary
- AREPO can mimic pure Lagrangian, static mesh & AMR codes
- Galilean-invariant case: mesh-generating points move with local fluid velocity. Example: Kelvin-Helmholtz instability on 50 x 50 mesh.




moving-mesh, 1024x1024
$t = 2.0$

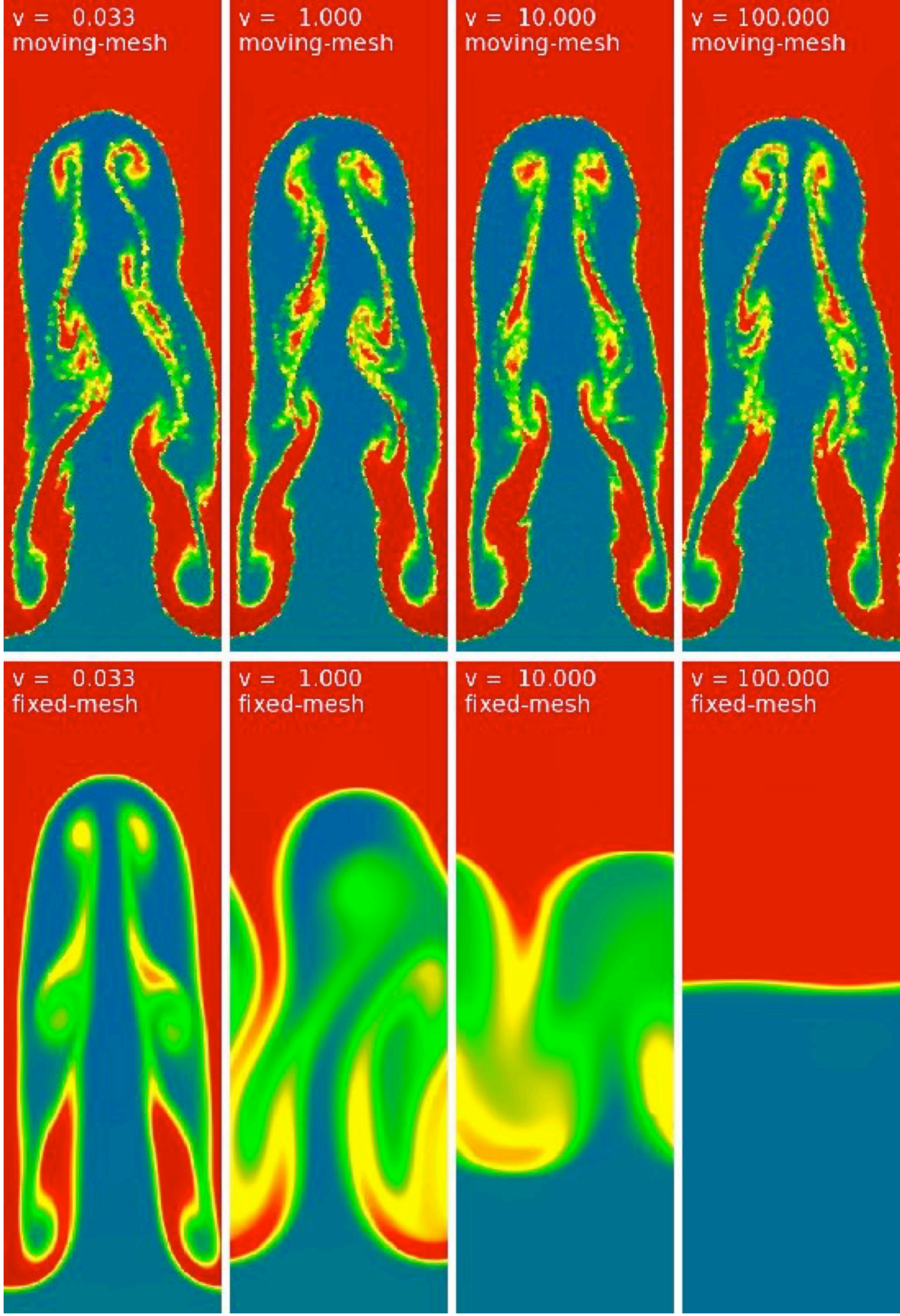

fixed-mesh, 1024x1024
$t = 2.0$



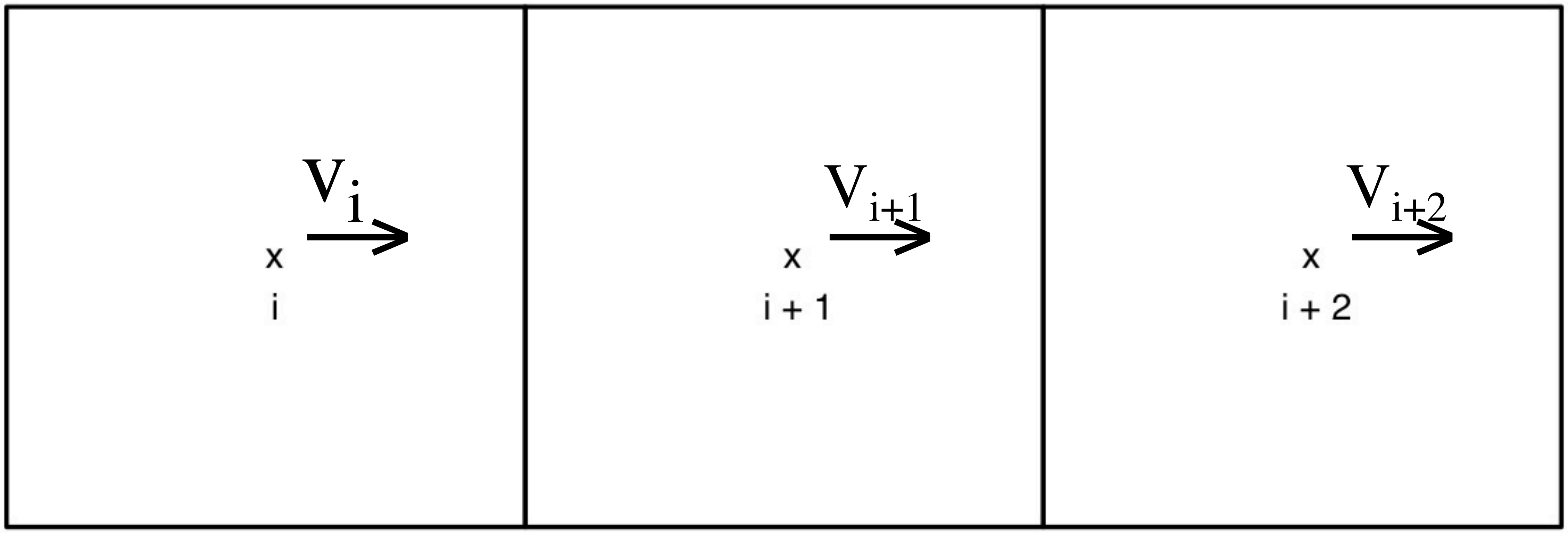
Rayleigh-Taylor instability; 48 x 144 cells

Galilean invariance

- x-velocity boost, v_x
- equations of motion Galilean invariant
- moving mesh results invariant to v_x
- solution with stationary grid sensitive to v_x
- evolution corrupted for large fluid motion relative to stationary mesh
- similar outcome for AMR
- SPH Galilean invariant

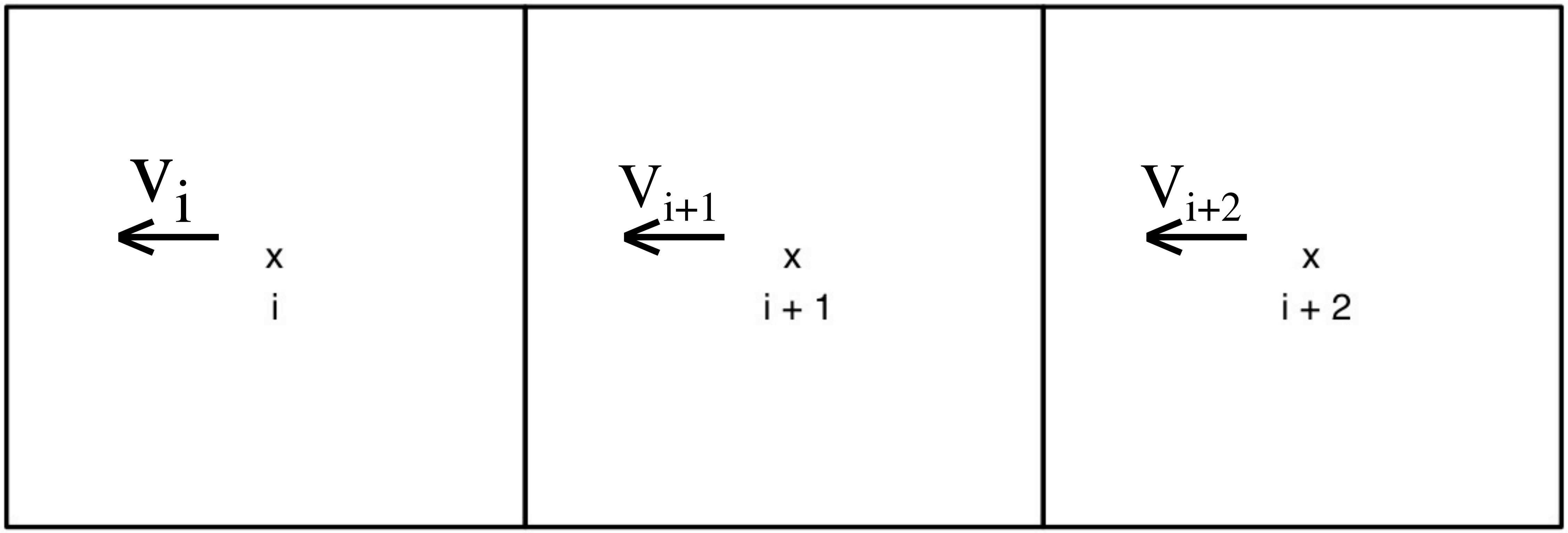


The Challenge of Galilean invariance (on a fixed mesh)



- solve $\partial U / \partial t + \nabla \cdot F = 0$ where U (e.g. ρ) known at cell centers and F (e.g. ρ v) needed at cell edges
- equations Galilean invariant
- but, numerical stability: must weight value in direction of flow more heavily ("upwind differencing")
- e.g. $F_{i+1/2}$ weights ρ_{i+1} (etc.) more than ρ_i

The Challenge of Galilean invariance (on a fixed mesh)



- add velocity boost = - 2 * v_i
- equations Galilean invariant
- now $F_{i+1/2}$ weights ρ_i (etc.) more than ρ_{i+1}
- solution not identical in general
- moving mesh invariant, same forwards and backwards (AREPO)

Advantages / disadvantages

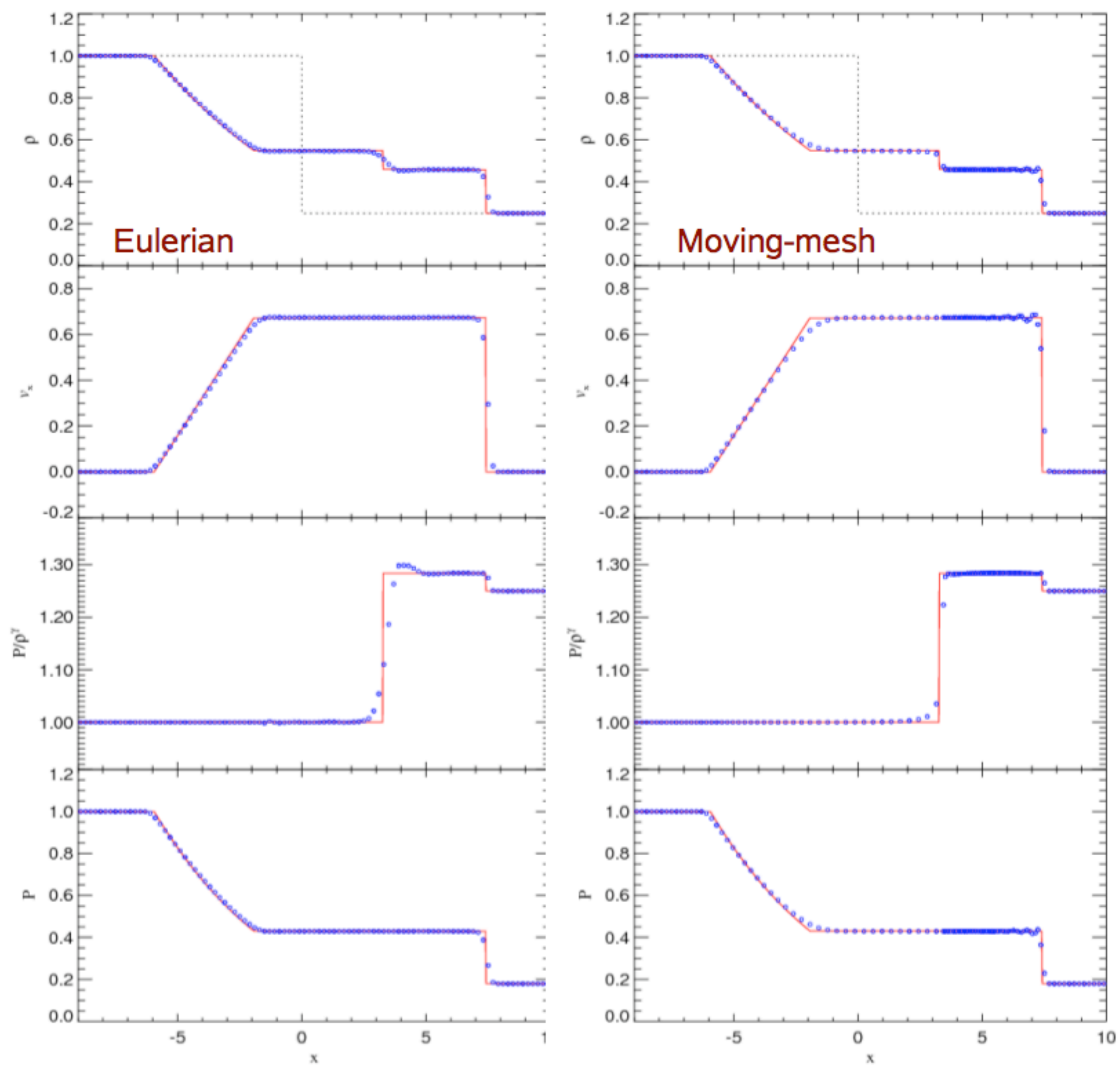
AREPO

- accurate gravity solver (hierarchical tree/PM - same as Gadget)
- Galilean invariant
- spatially / temporally adaptive
- all types of boundary conditions: free & solid surfaces
- accurate shock solvers (Godunov)
- discontinuities well-resolved
- relatively less diffusive (no artificial viscosity)
- no limits on mass resolution
- path to better sub-resolution models (?)

Disadvantages: ?

Test problems

- isothermal shocks
- Evrard collapse
- interacting blast waves
- Kelvin-Helmholtz
- Rayleigh-Taylor
- fluid mixing
- Zeldovich pancake
- Santa Barbara cluster



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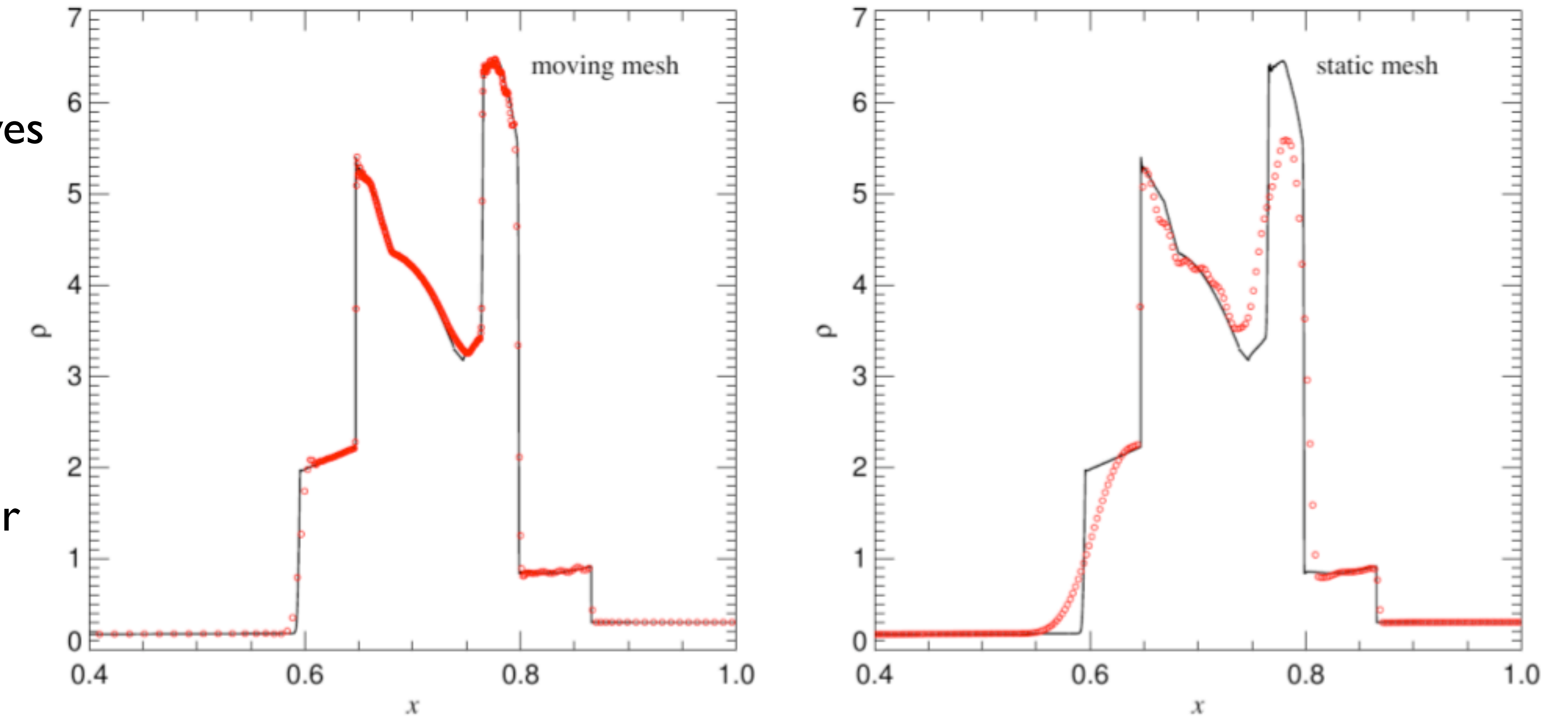

6.3 Arepo

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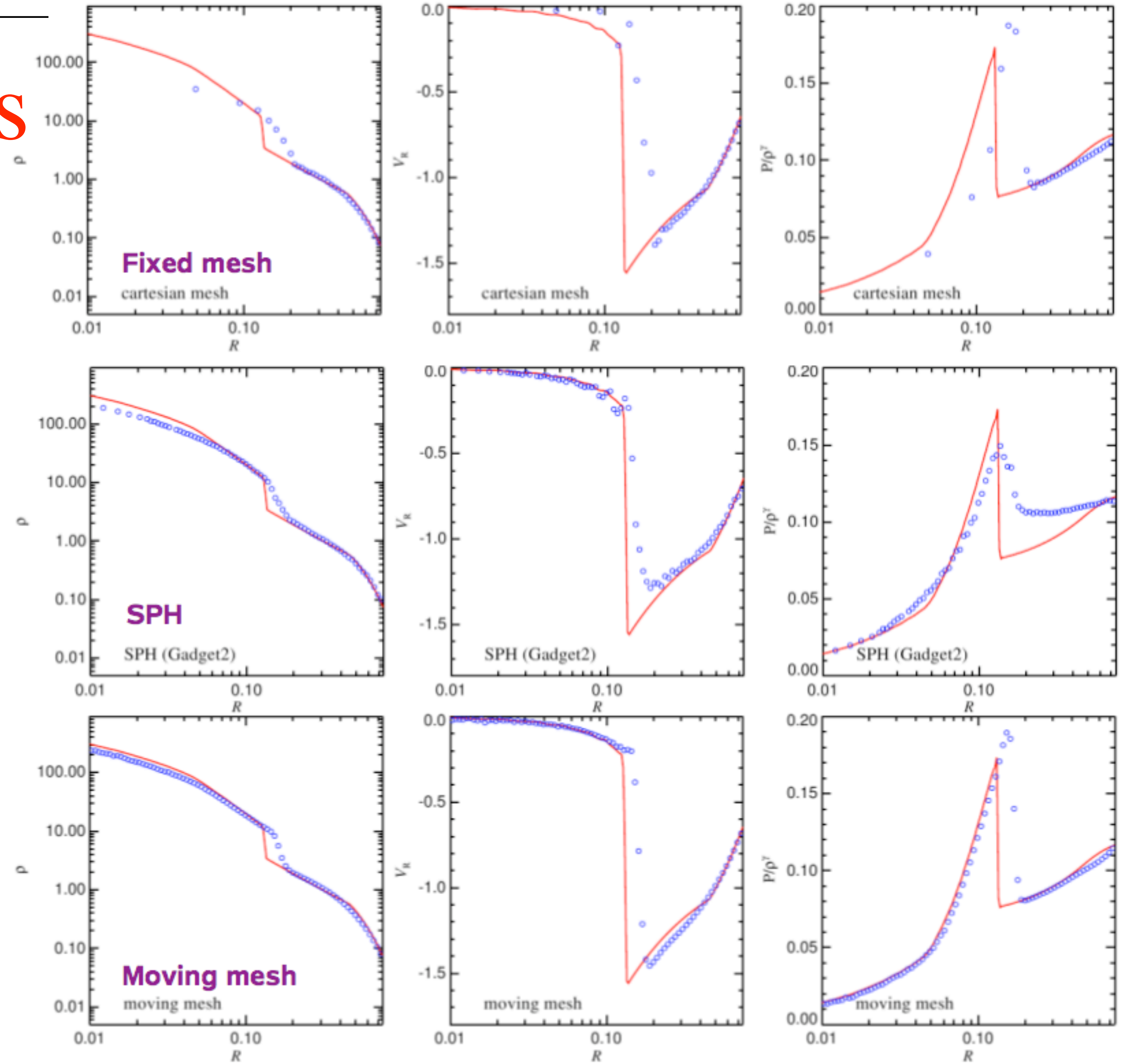

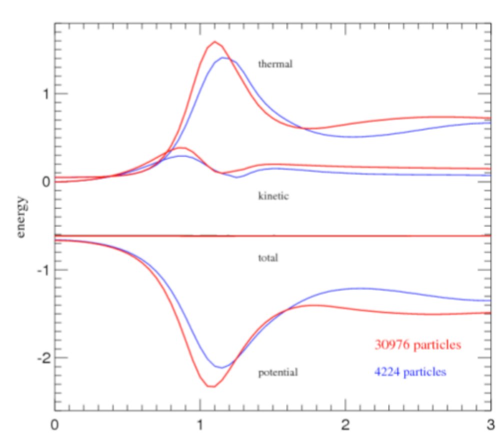

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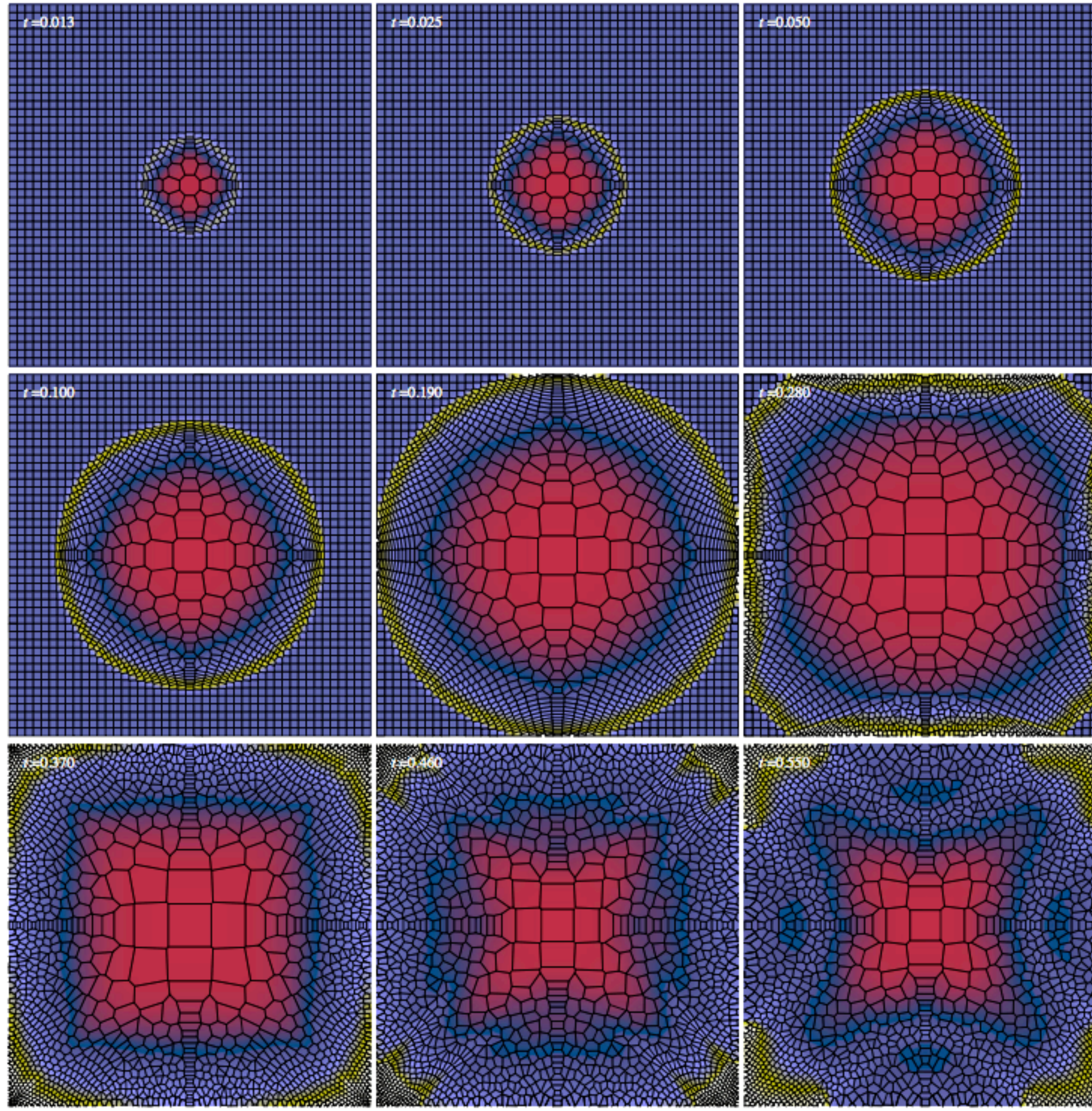

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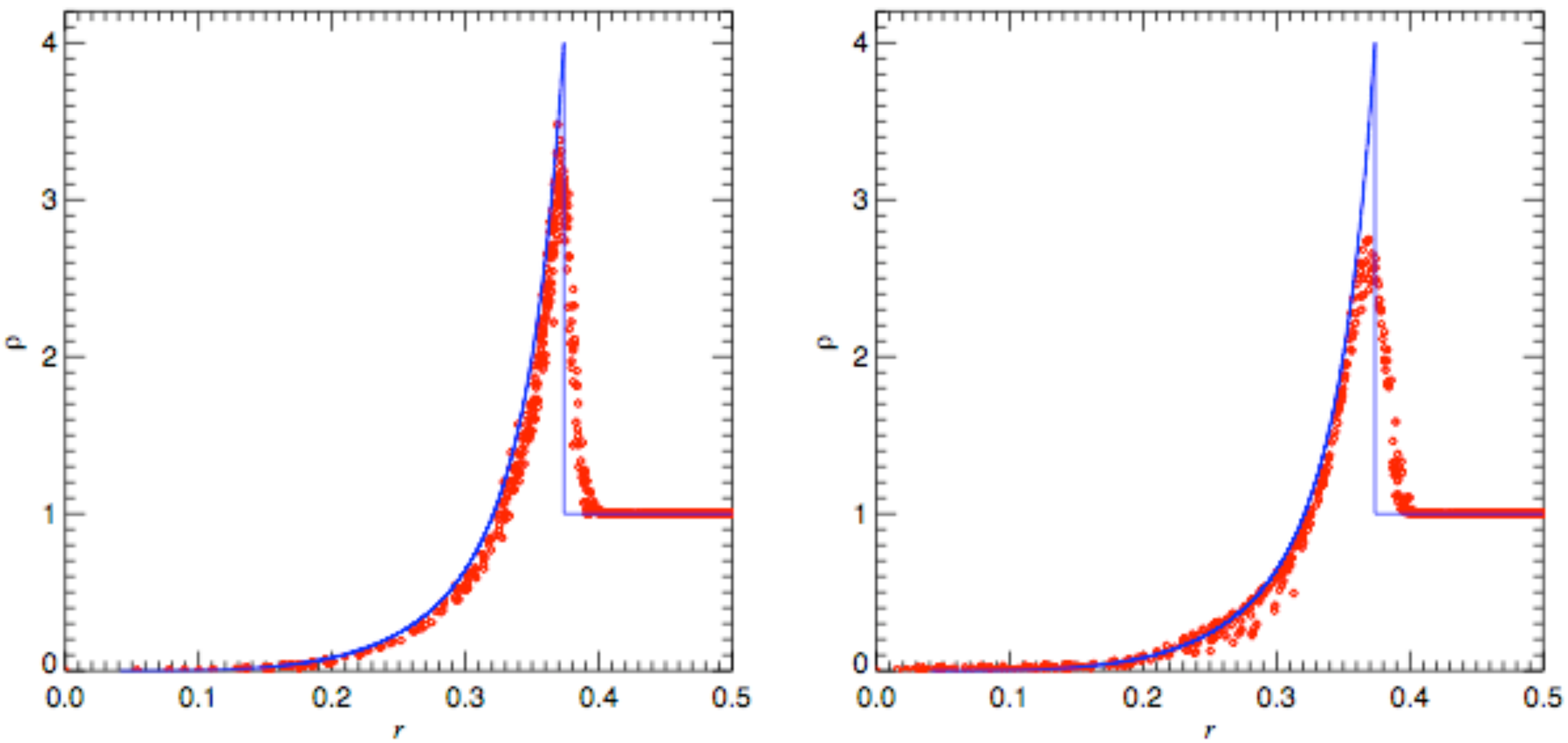

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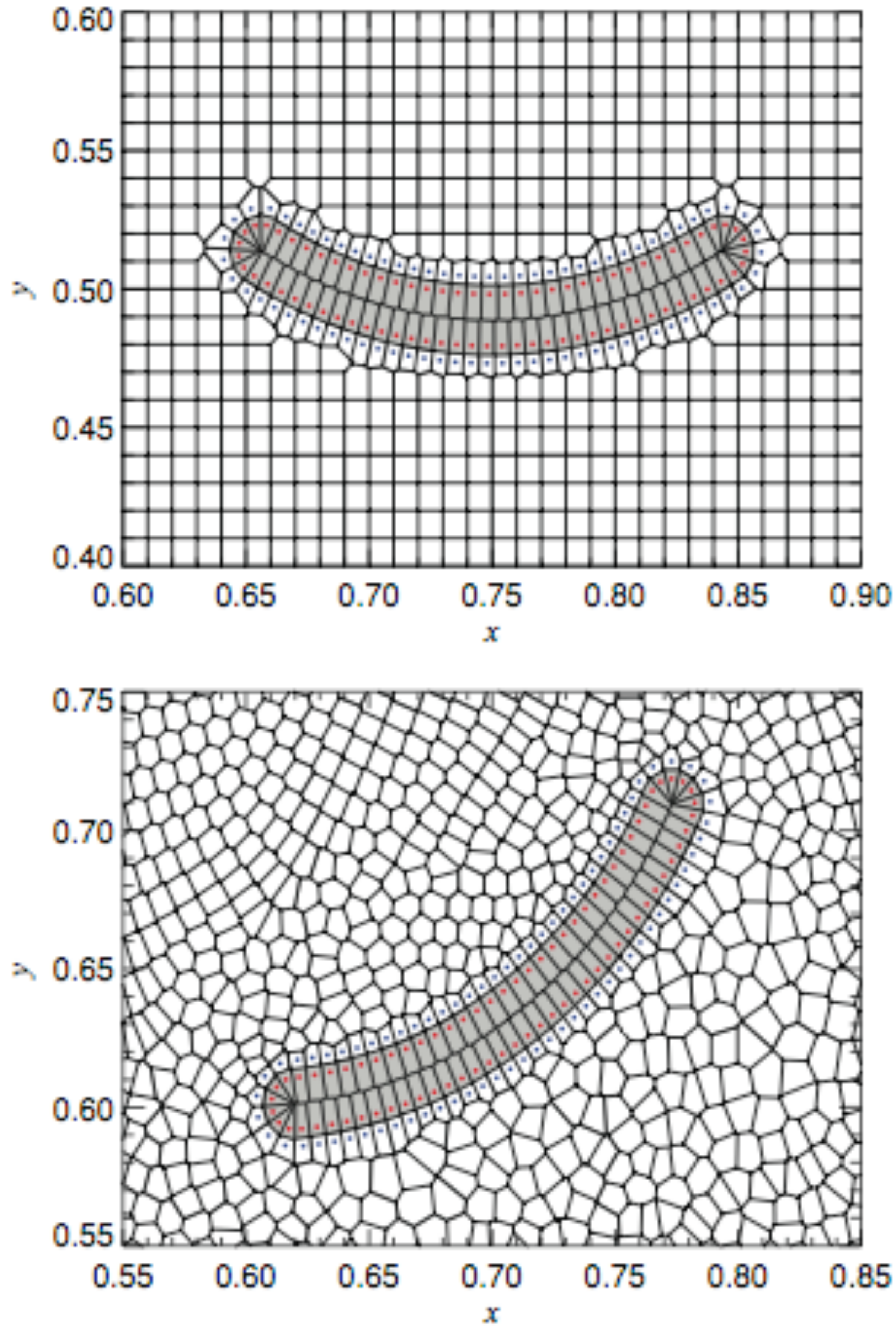
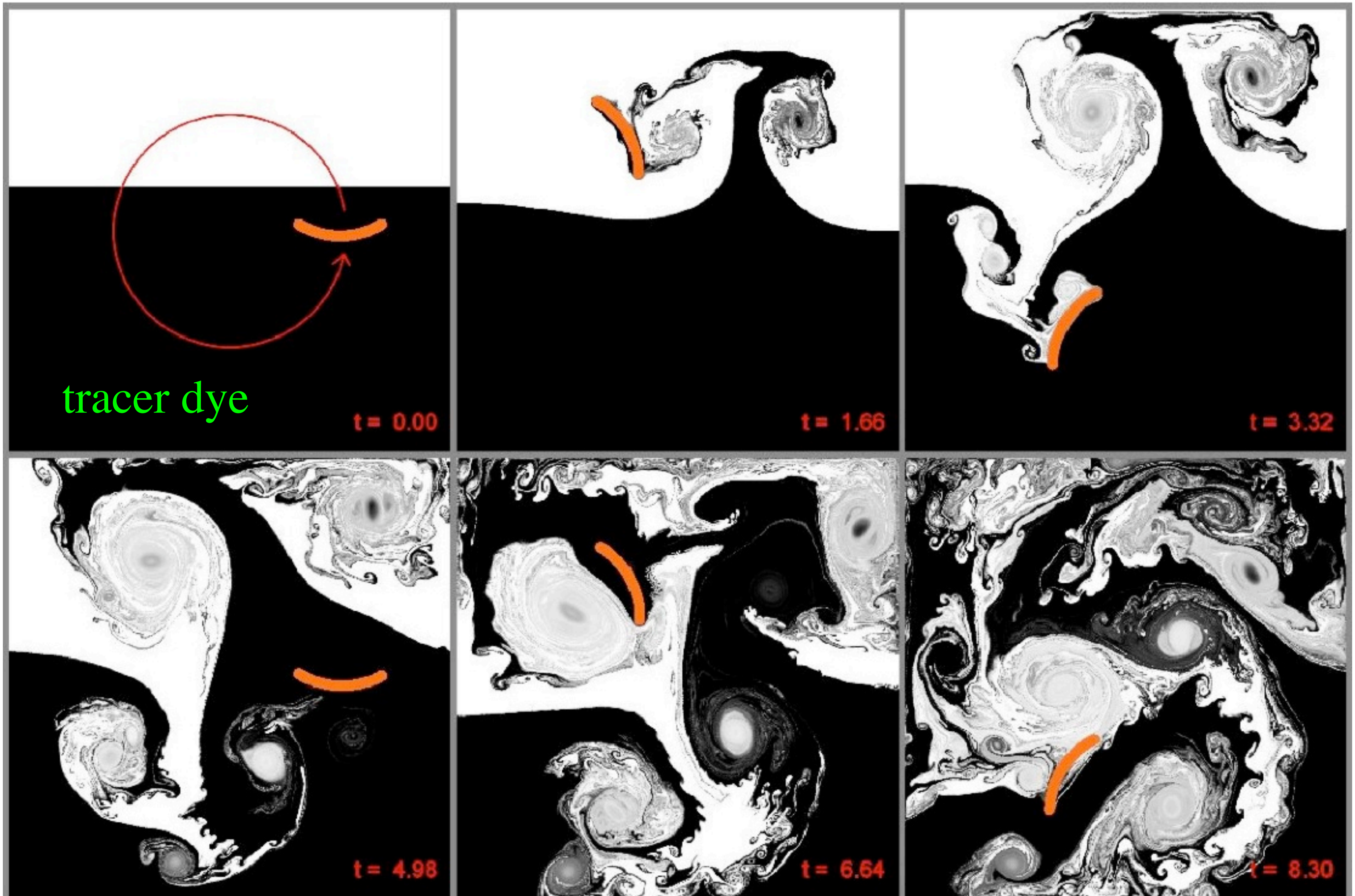
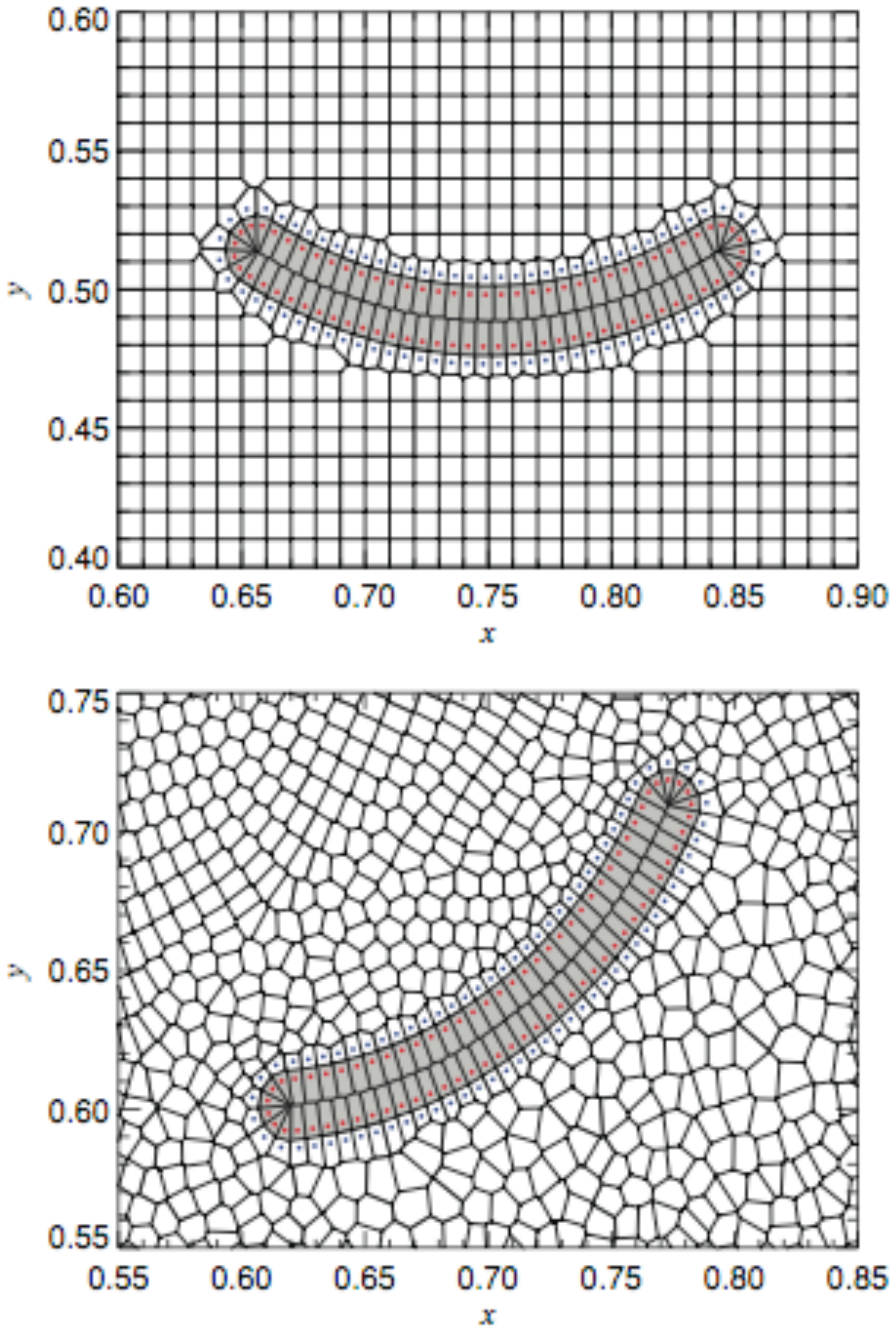


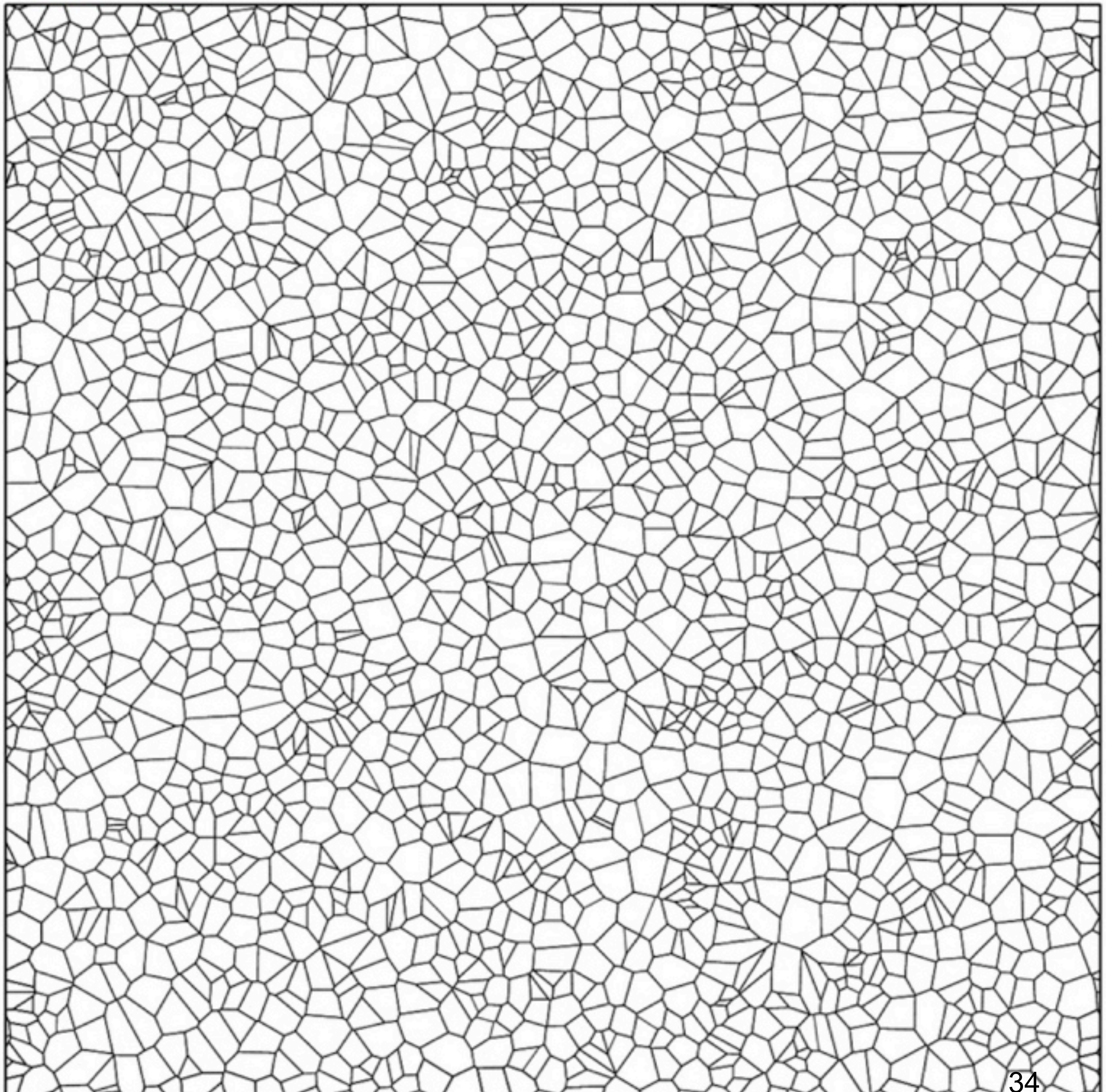
Fluid mixing; 768 x 768 cells, reflecting boundaries



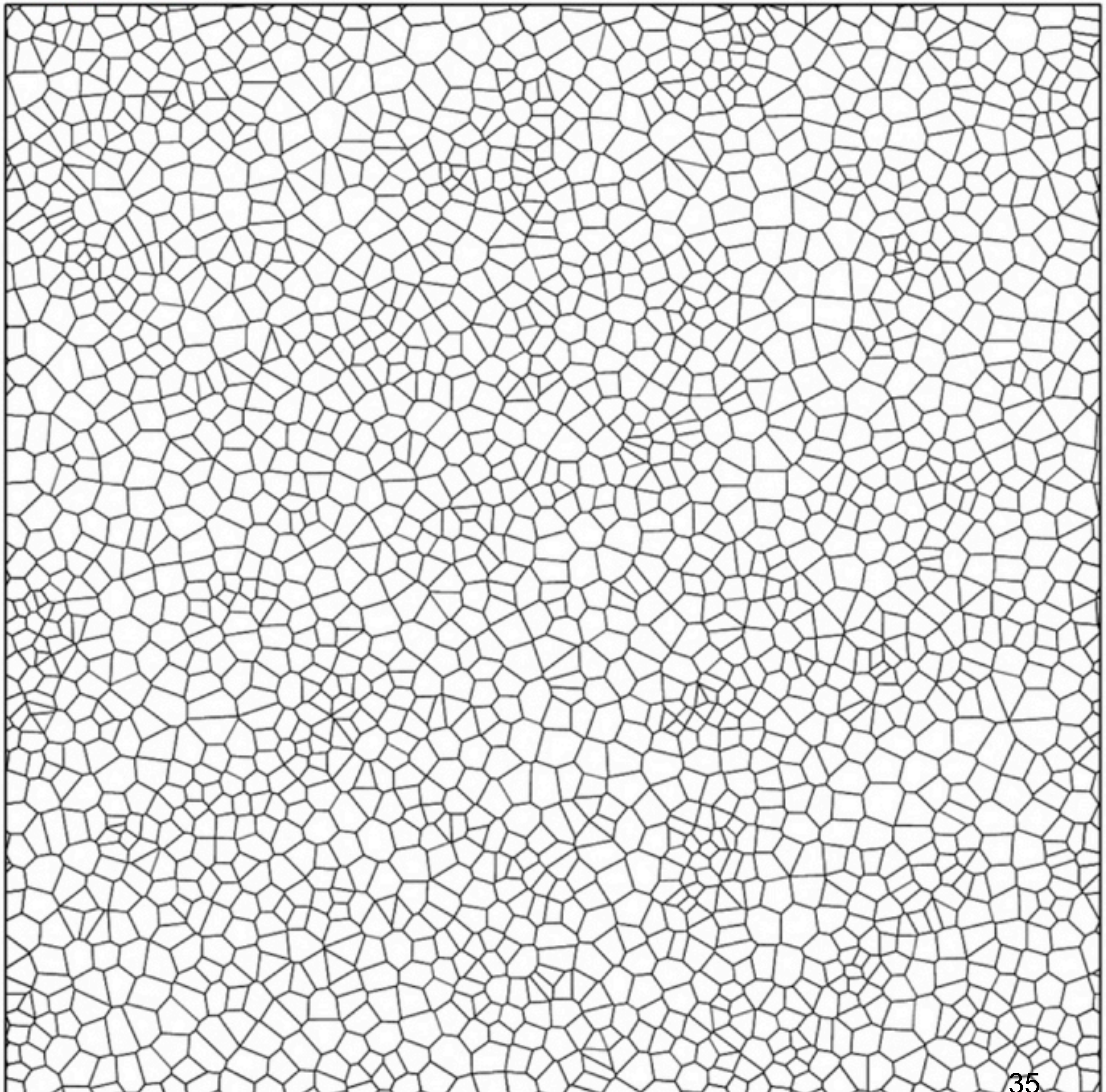
Cell Regularization

- easier to optimize resources
- similar timesteps
- odd cell shapes are harder to deal with (less accurate and change more in time)

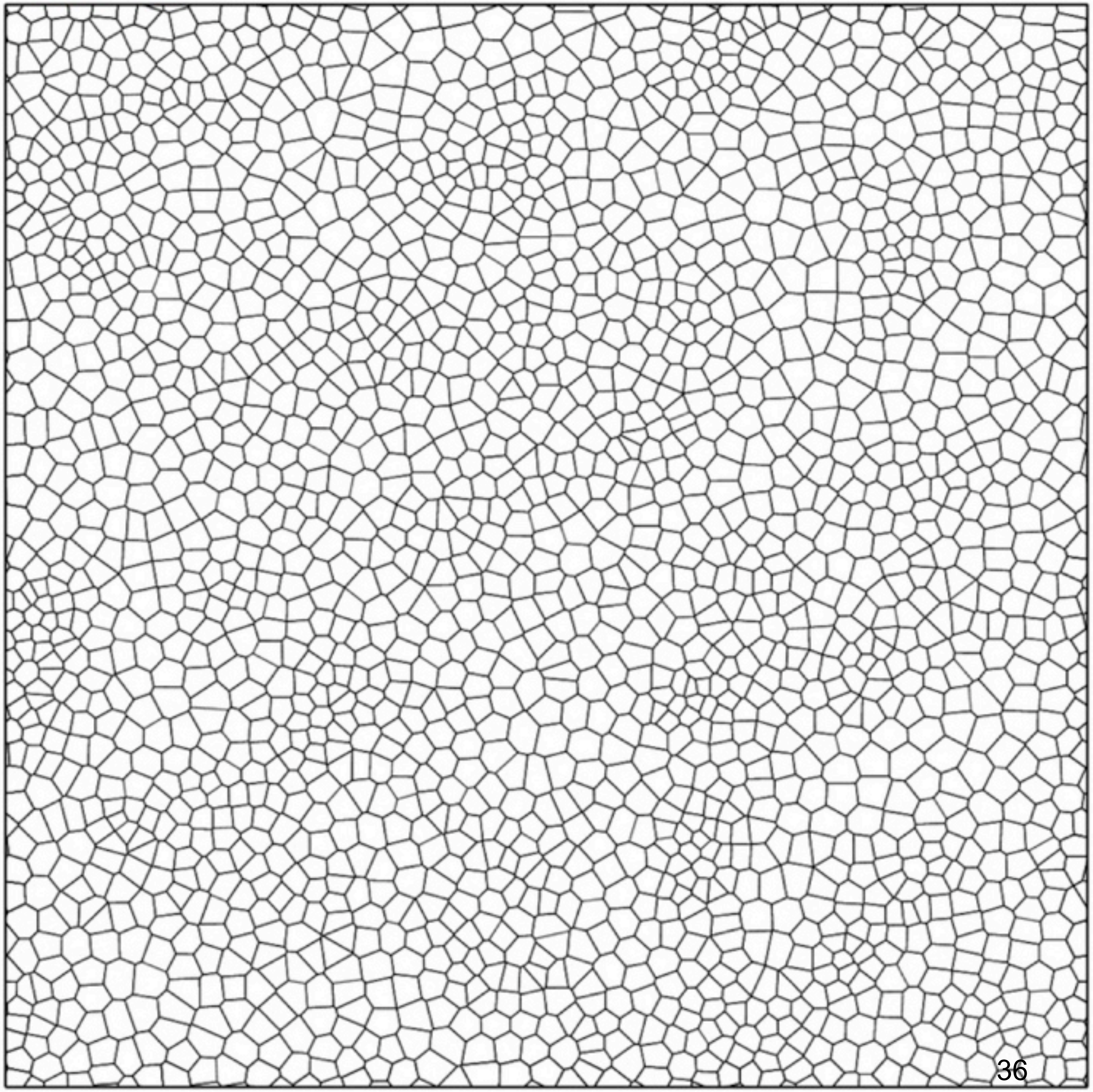



Step 0

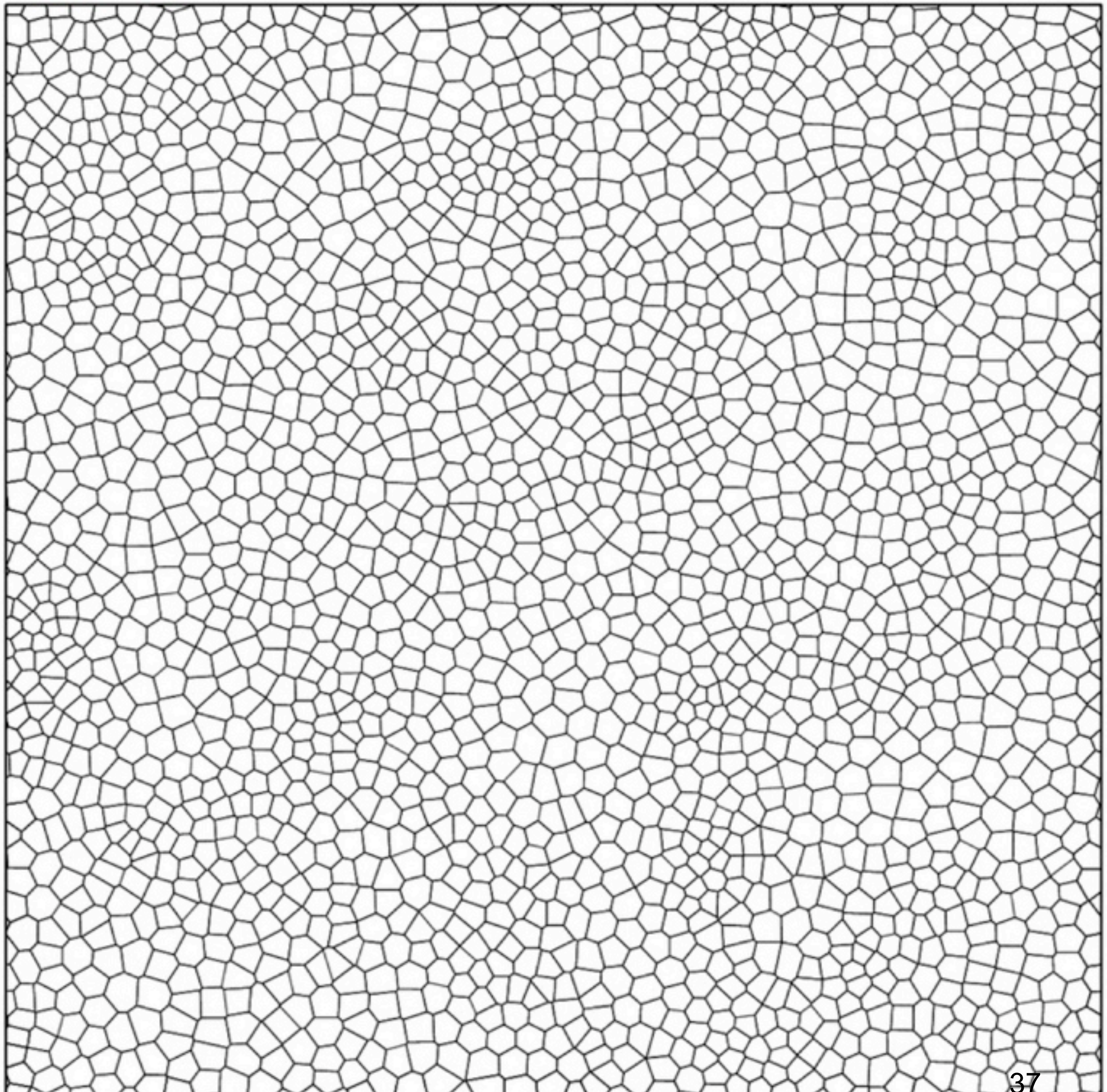
Step 1



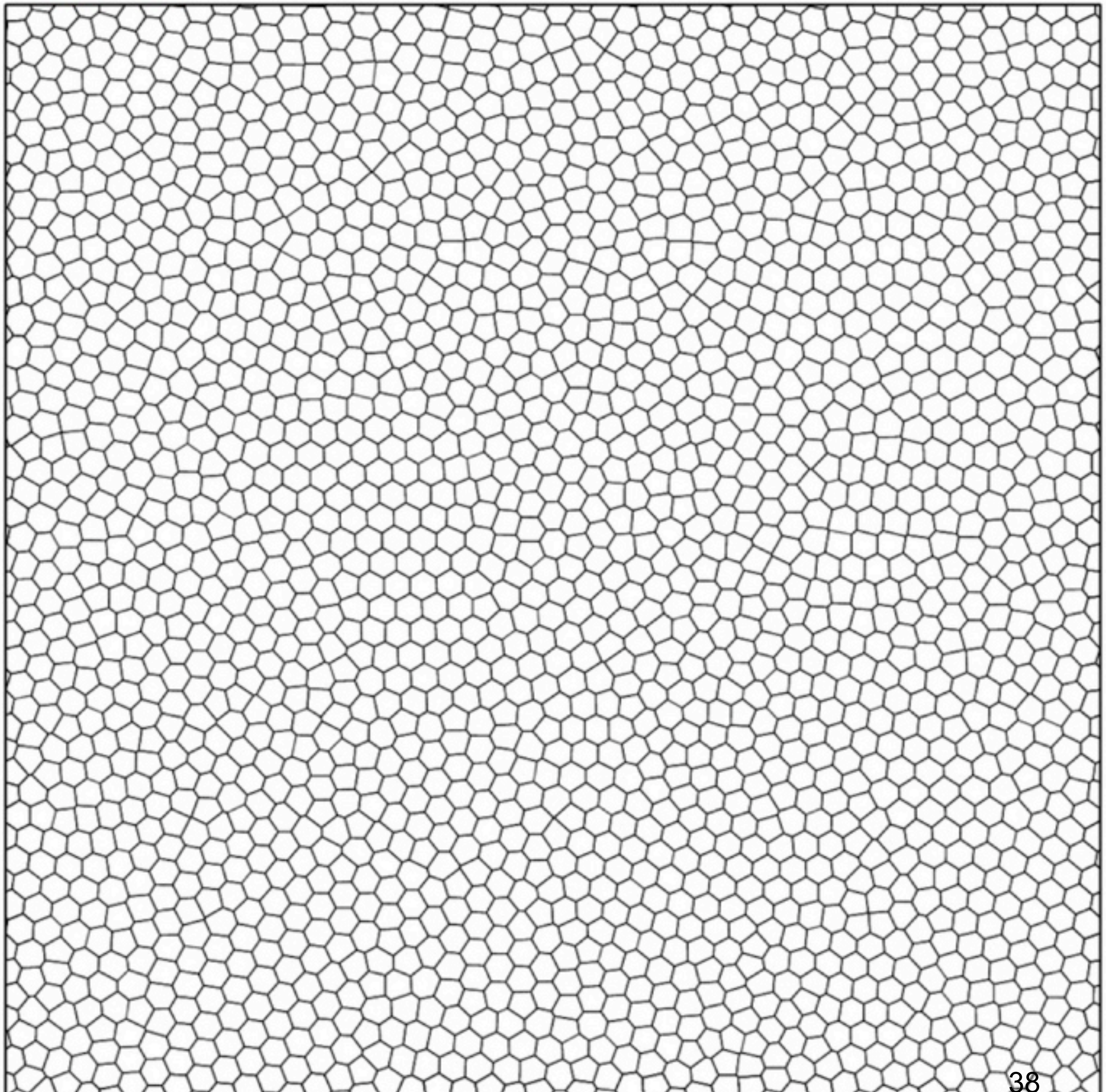
Step 2



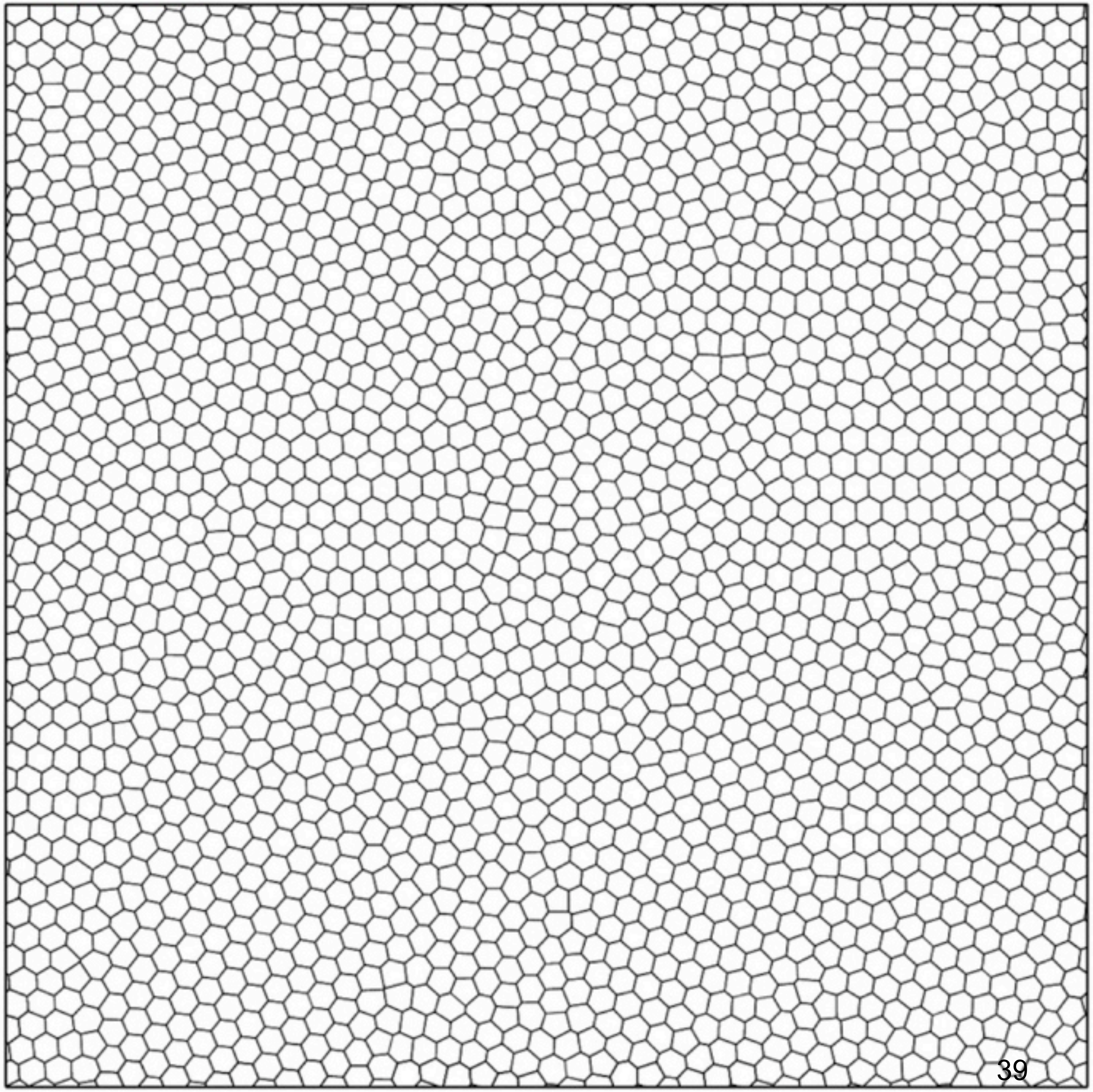
Step 3



Step 100



Step 1000



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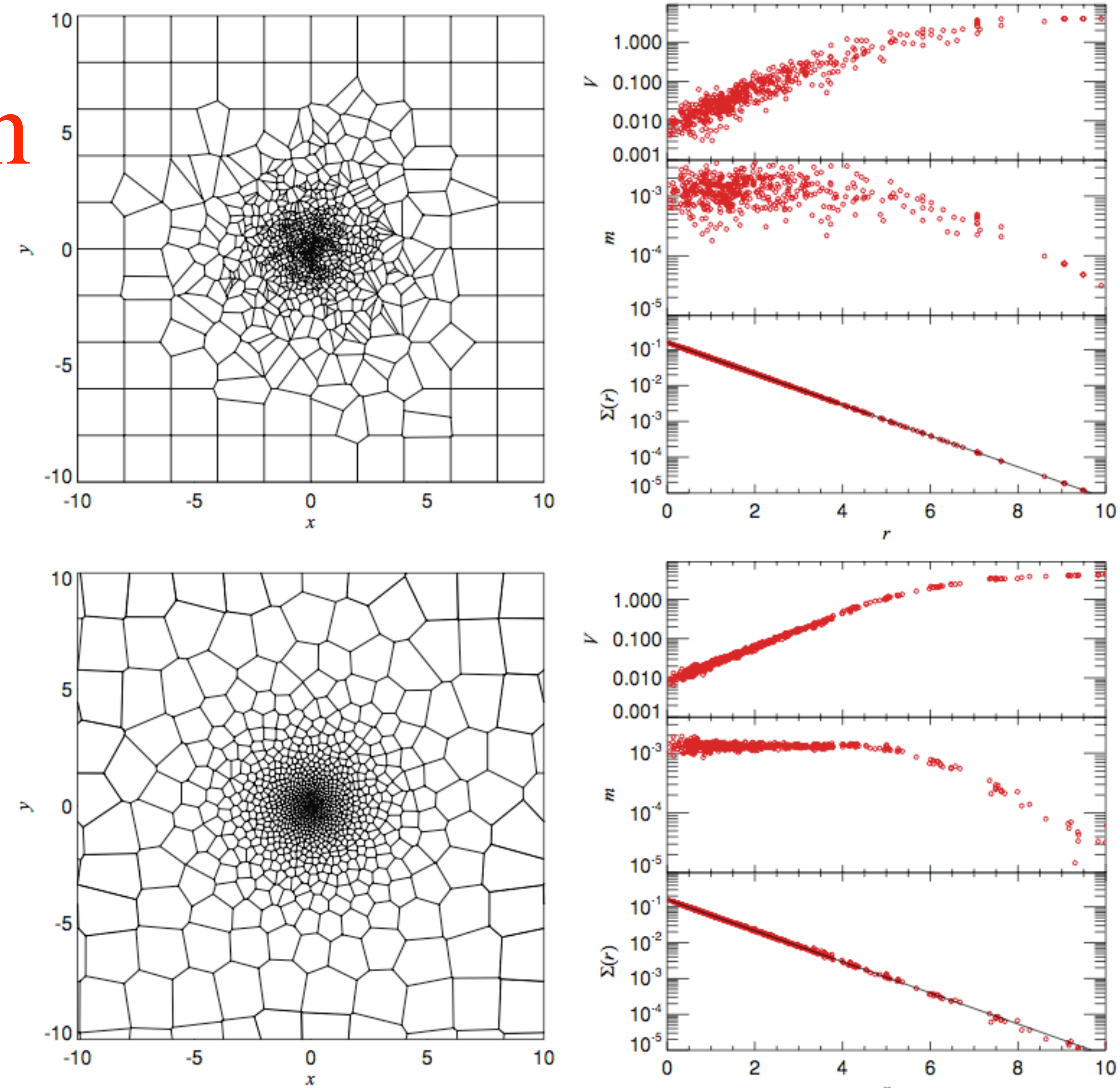
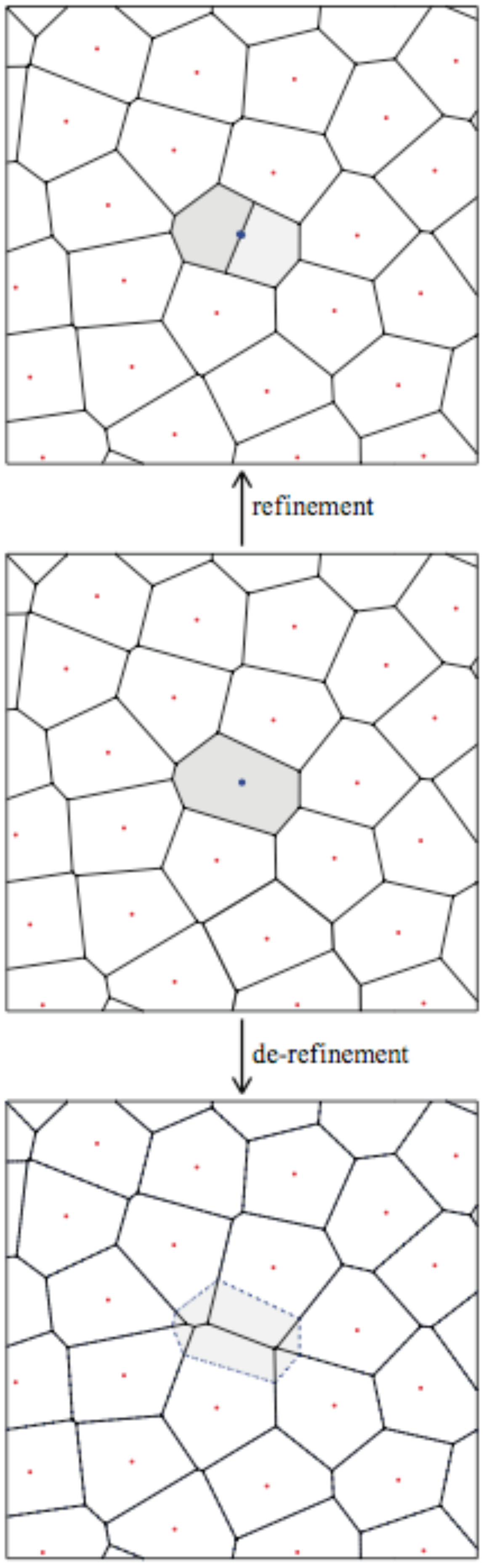


6.3 Arepo

Cell Refinement

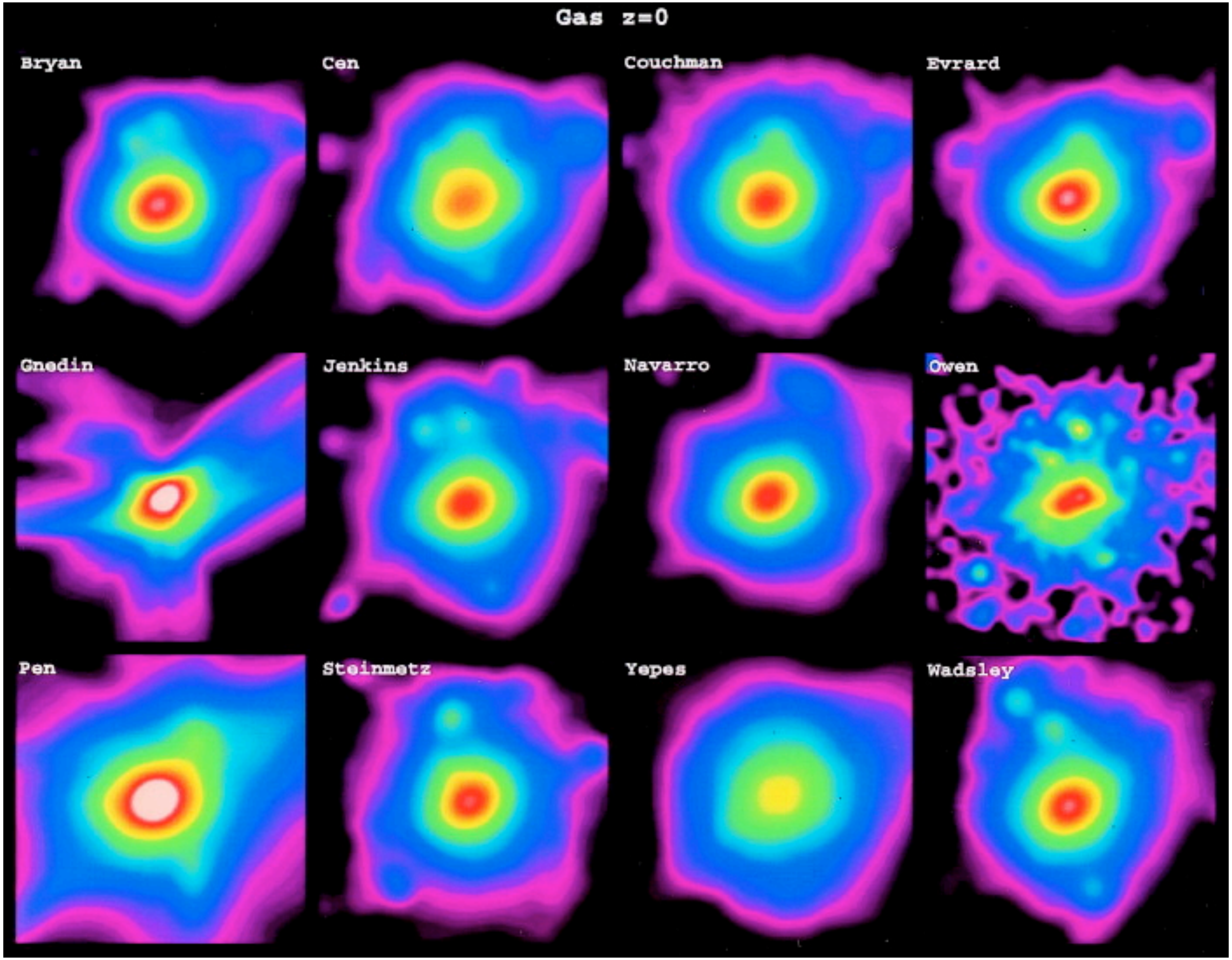
- Cells can be added or removed dynamically
- Cells can be determined to have constant mass, or constant volume
- NOTE: cells can also be fixed in space = AMR



Different hydrodynamical simulation codes are broadly in agreement, but show substantial scatter and differences in detail

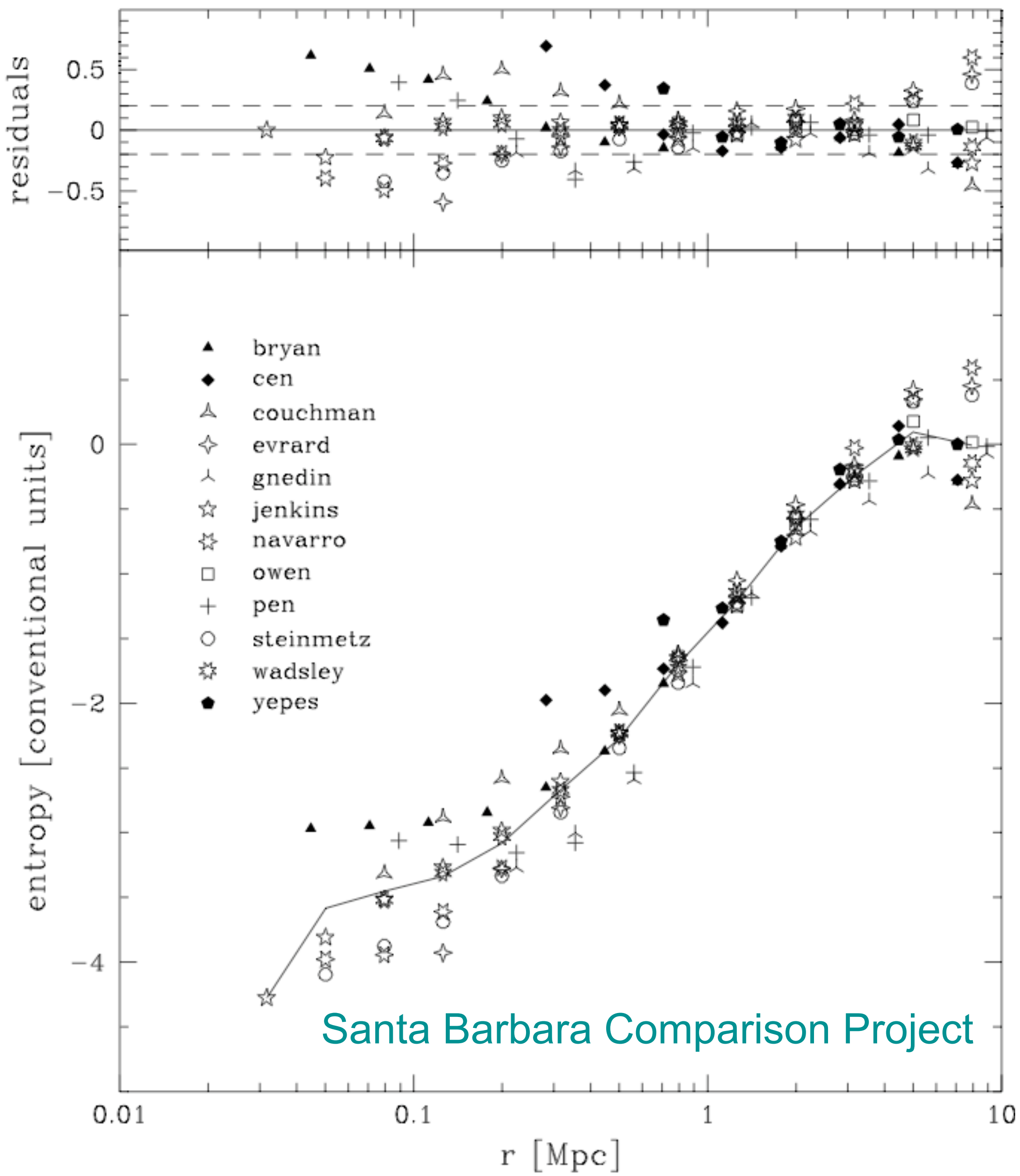
THE SANTA BARBARA CLUSTER COMPARISON PROJECT

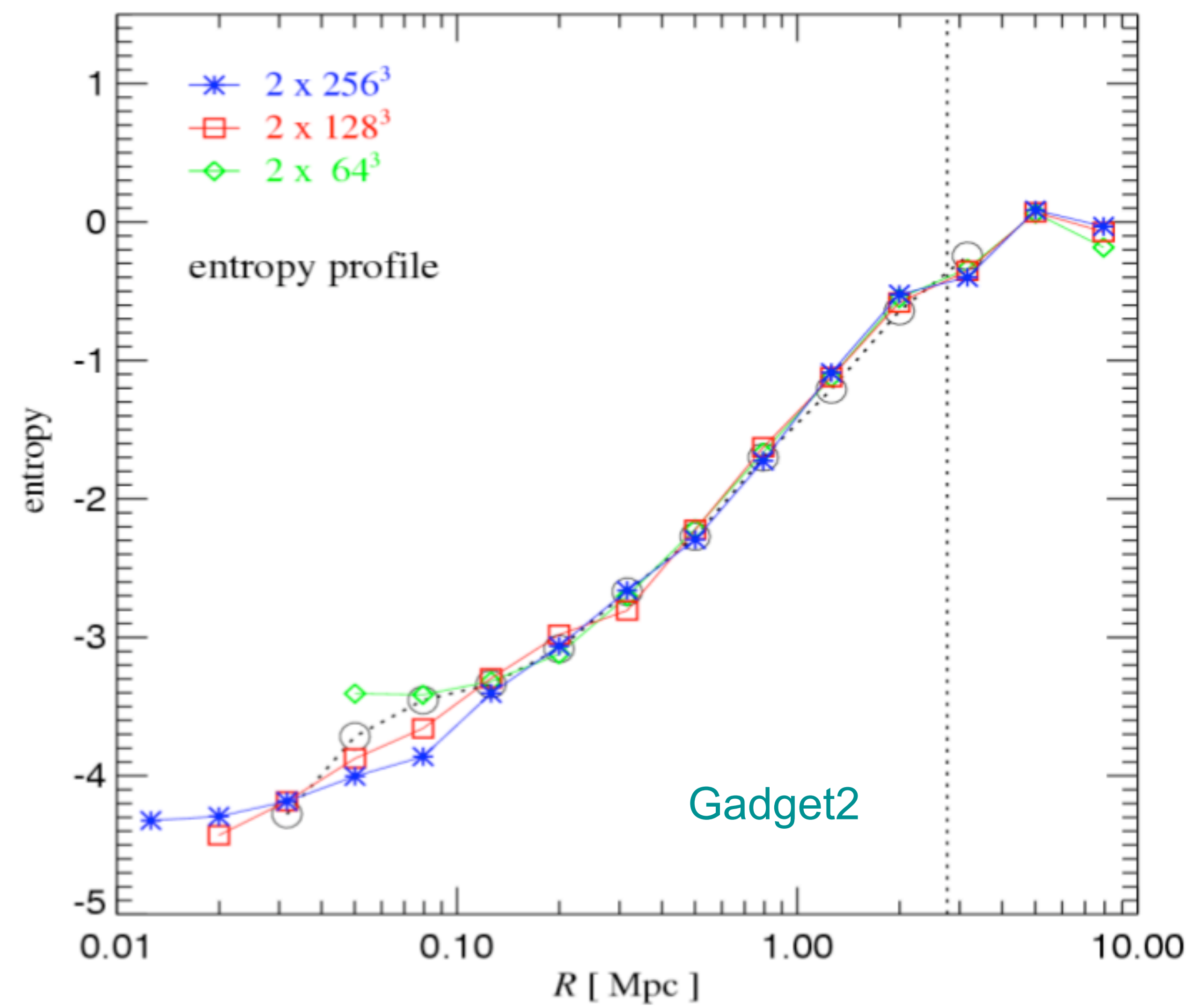
Frenk, White & 23 co-authors (1999)



Mesh codes appear to produce higher entropy in the cores of clusters

RADIAL ENTROPY PROFILE

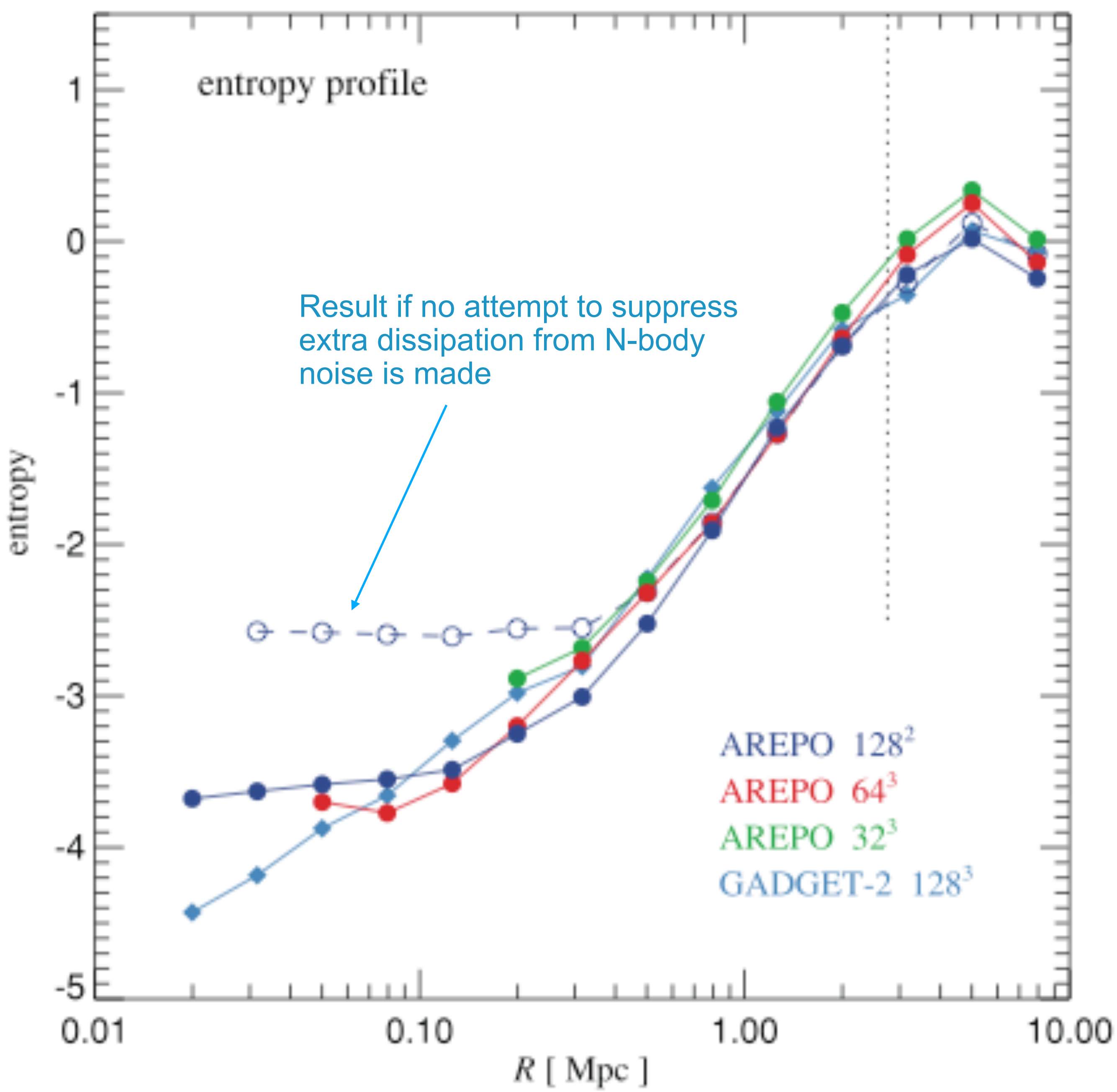


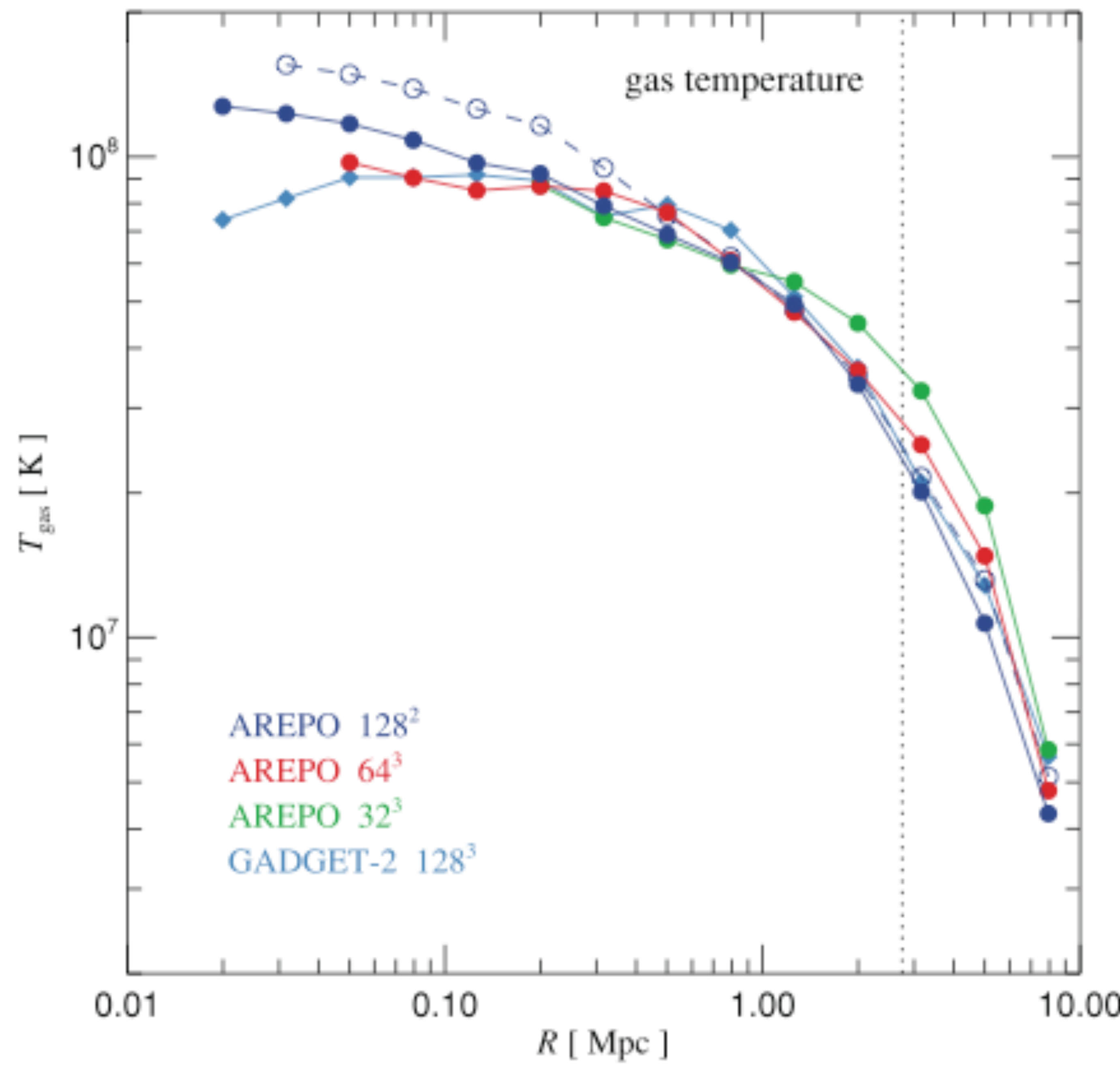


Ascasibar, Yepes, Müller & Gottlöber (2003):
claim that more accurate SPH simulations based on entropy-formulation tend to give higher entropy in the core

The high entropy found in previous mesh-based calculations of the Santa-Barbara cluster was in part caused by dissipation from noise in the N-body gravitational field

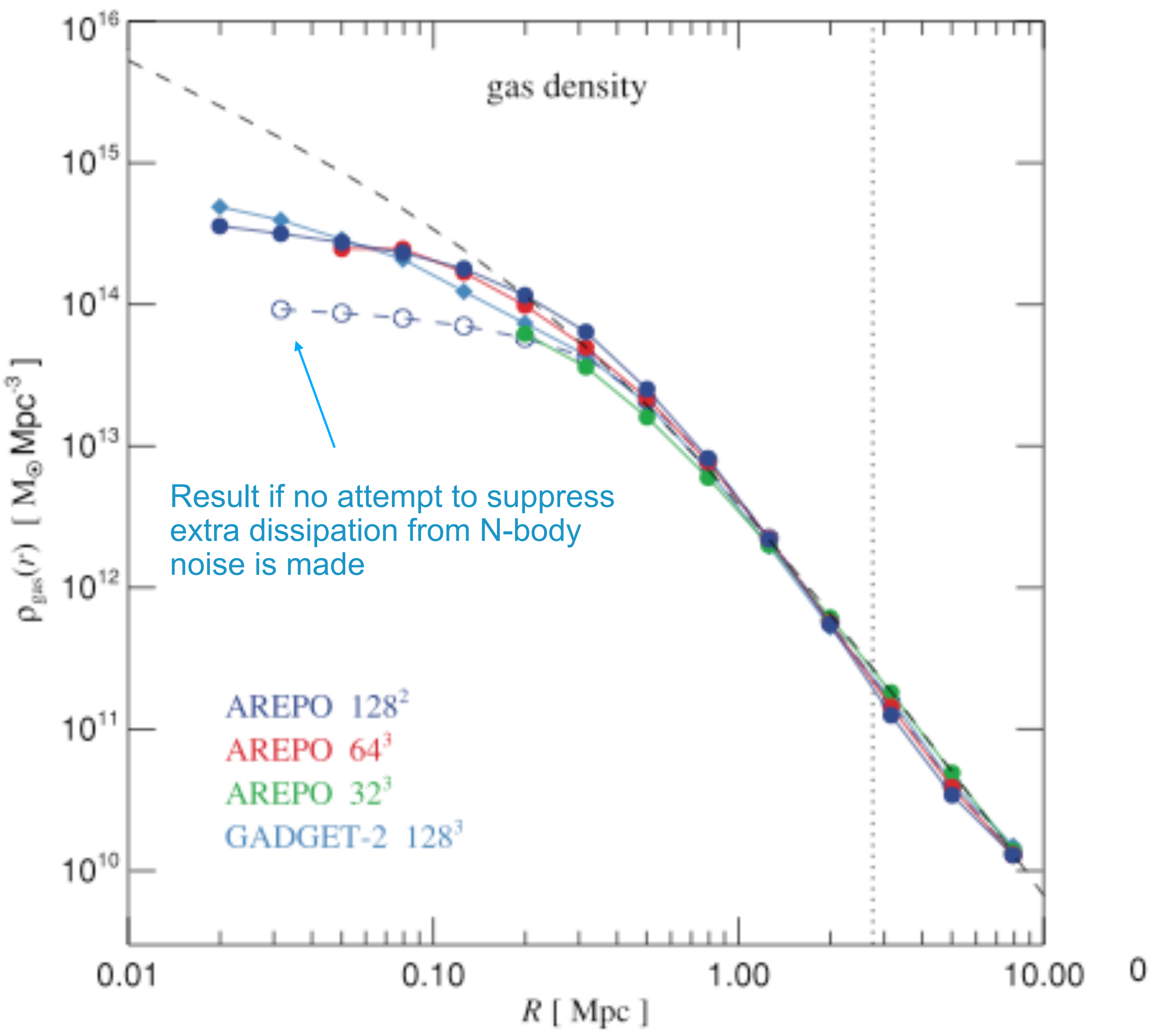
THERMODYNAMIC PROFILES OF THE SB-CLUSTER CALCULATED WITH SPH AND AREPO

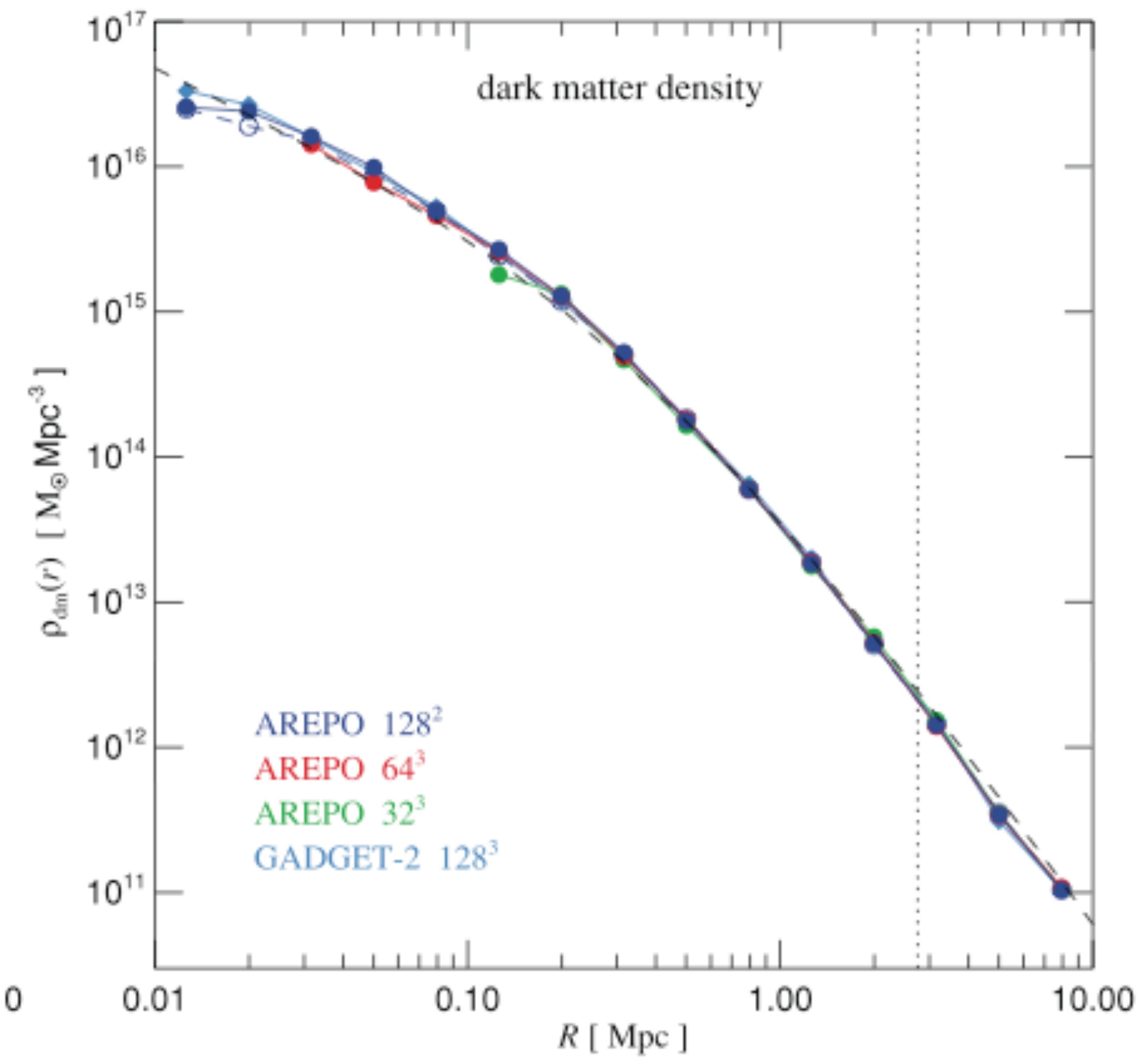




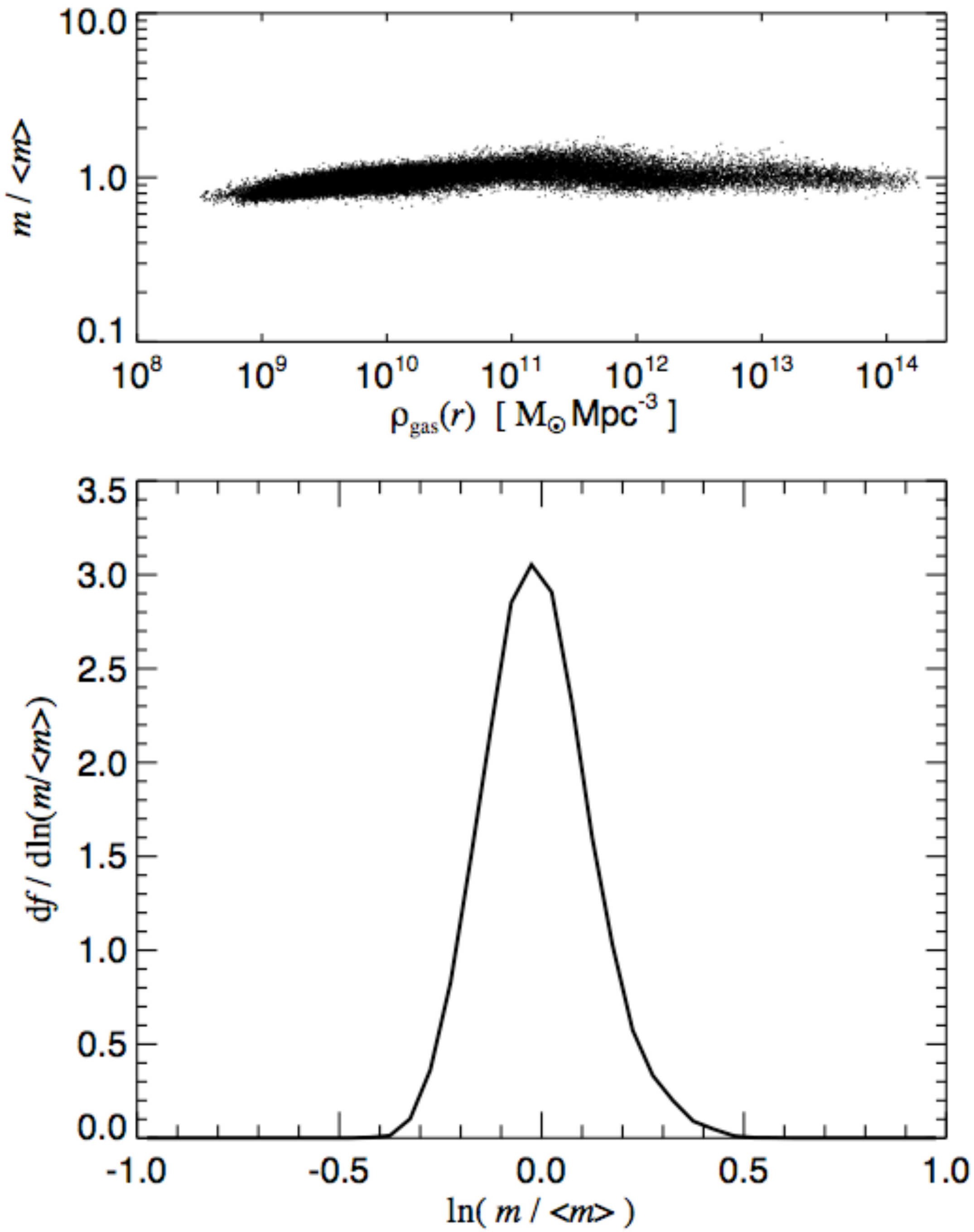
The spherically averaged dark matter and gas density profiles between the moving-mesh code and GADGET agree well

DENSITY PROFILES OF THE SB-CLUSTER CALCULATED WITH SPH AND AREPO

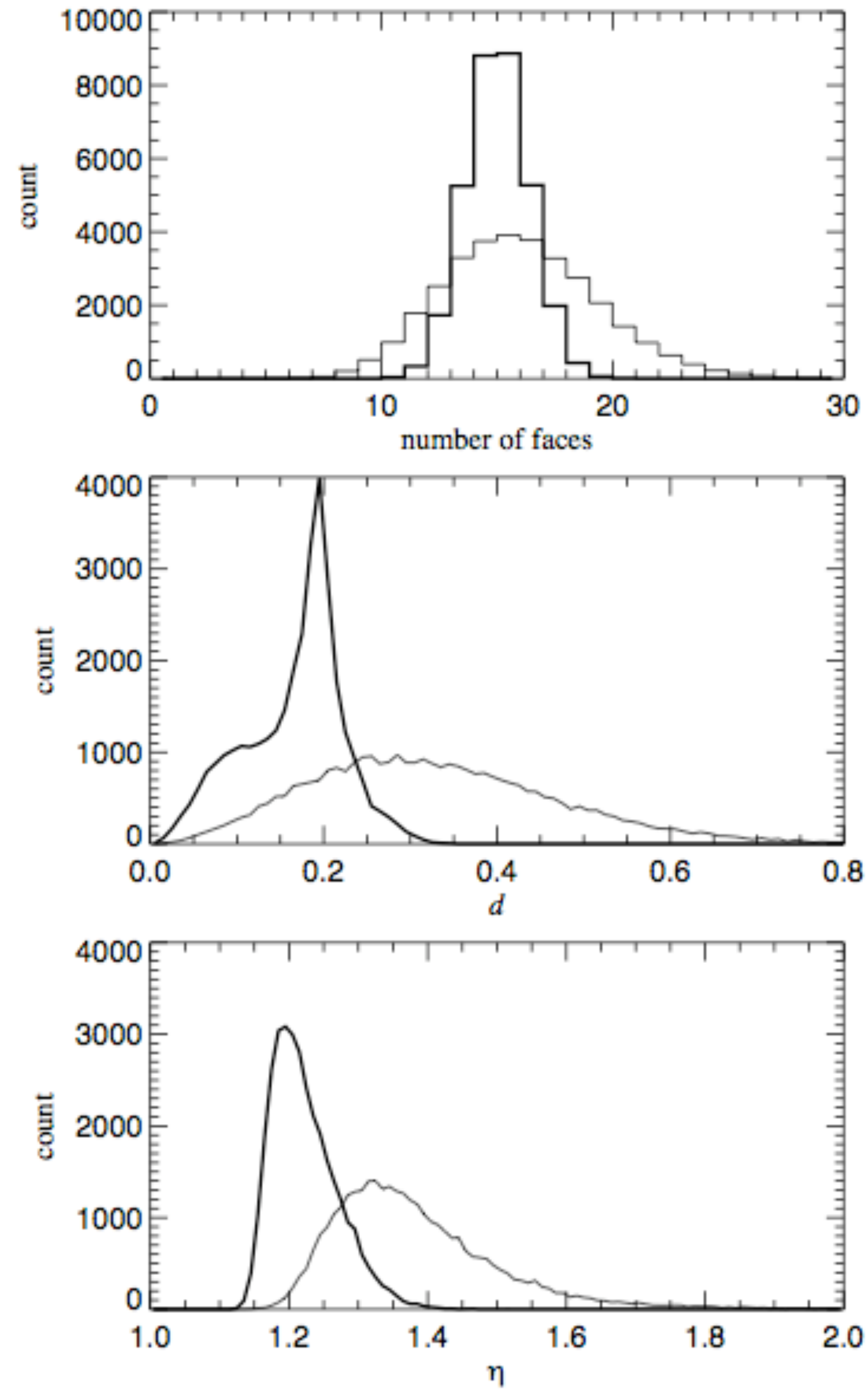




6.3 Arepo



10.0
1.0
0.1
m / $<m>$
10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14}
$\rho_{gas}(r)$ [$M_\odot$ Mpc^{-3}]
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
df / dln(m/$<m>$)
-1.0 -0.5 0.0 0.5 1.0
ln(m / $<m>$)



10000
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6000
4000
2000
0
count
0 10 20 30
number of faces
4000
3000
2000
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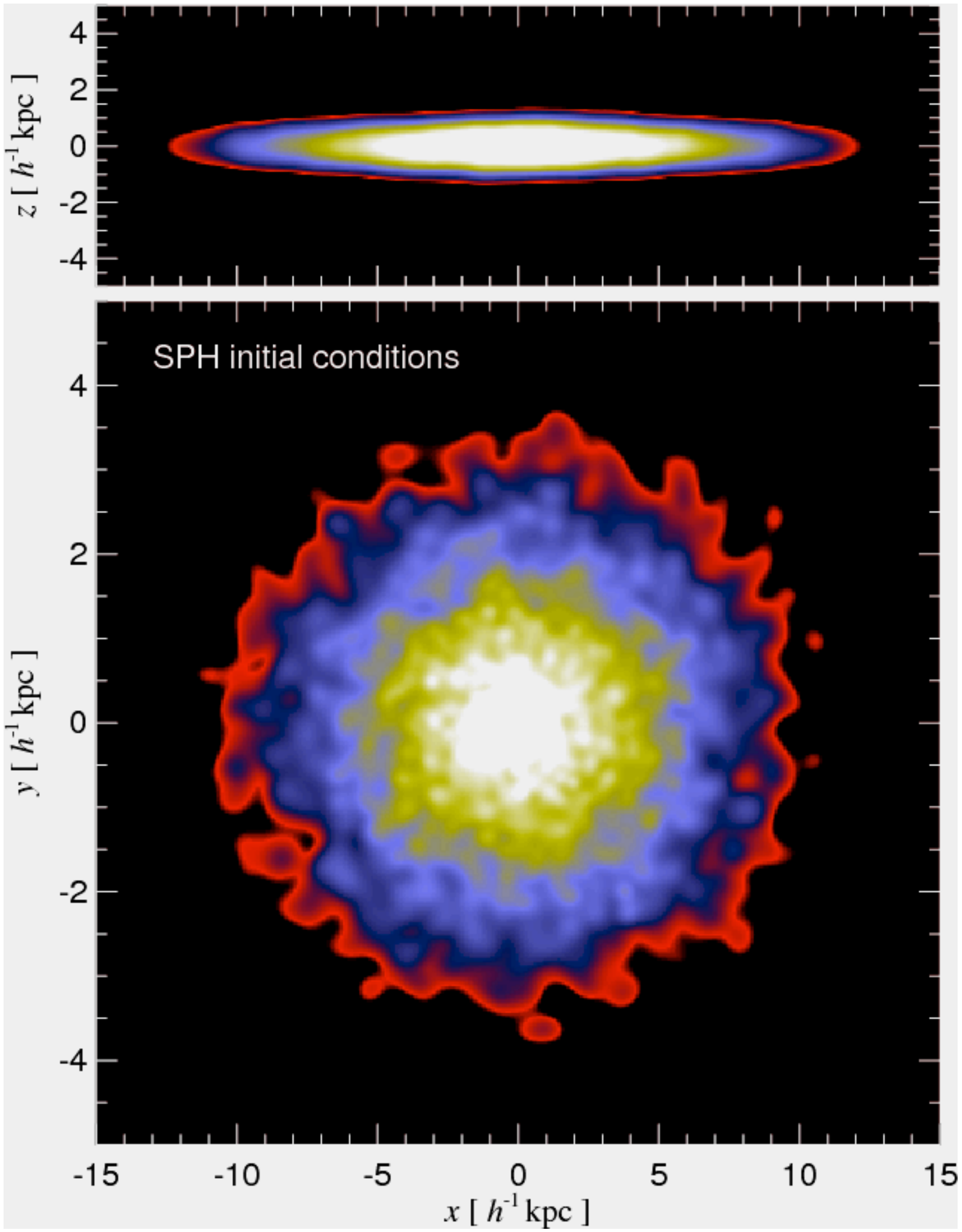
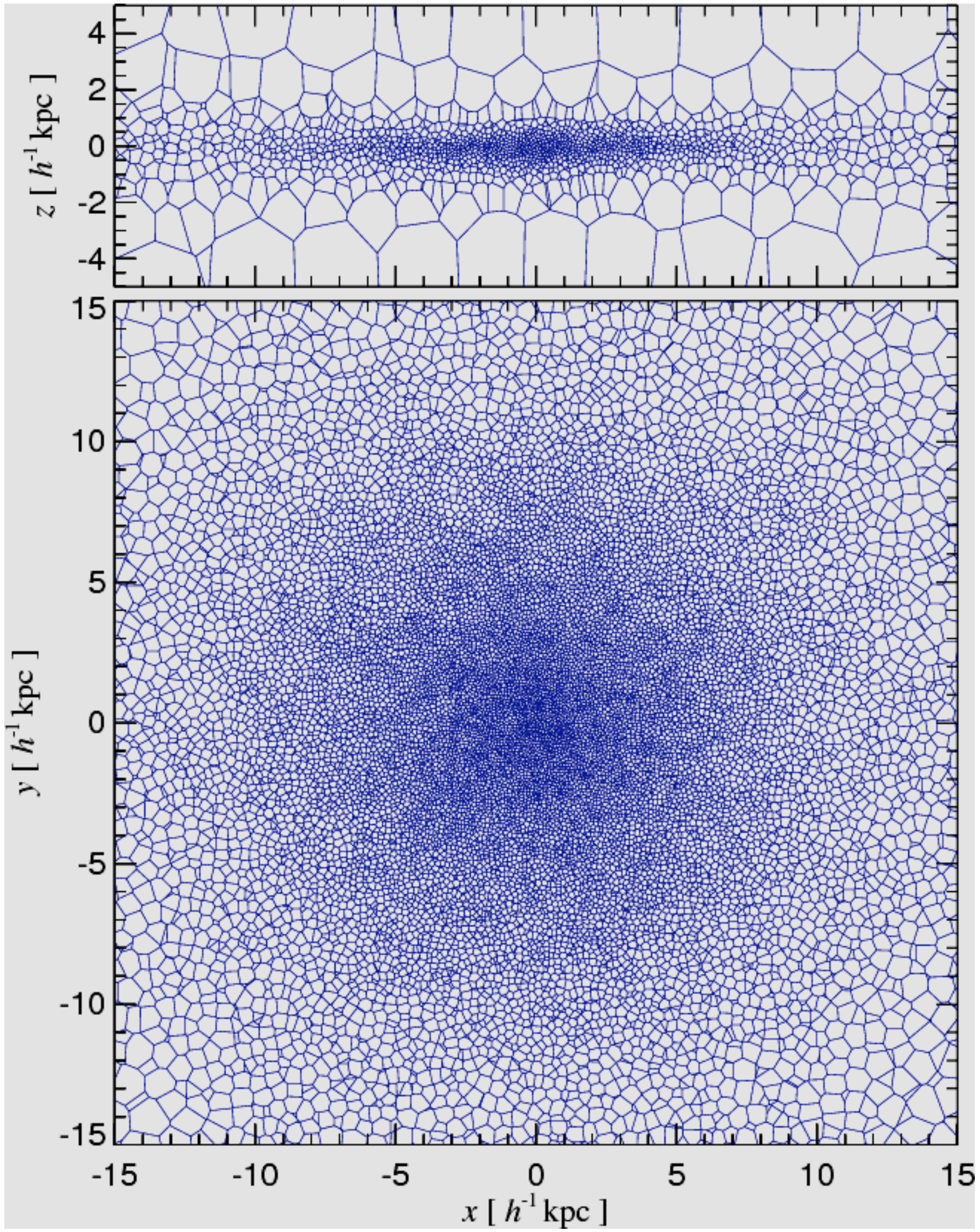
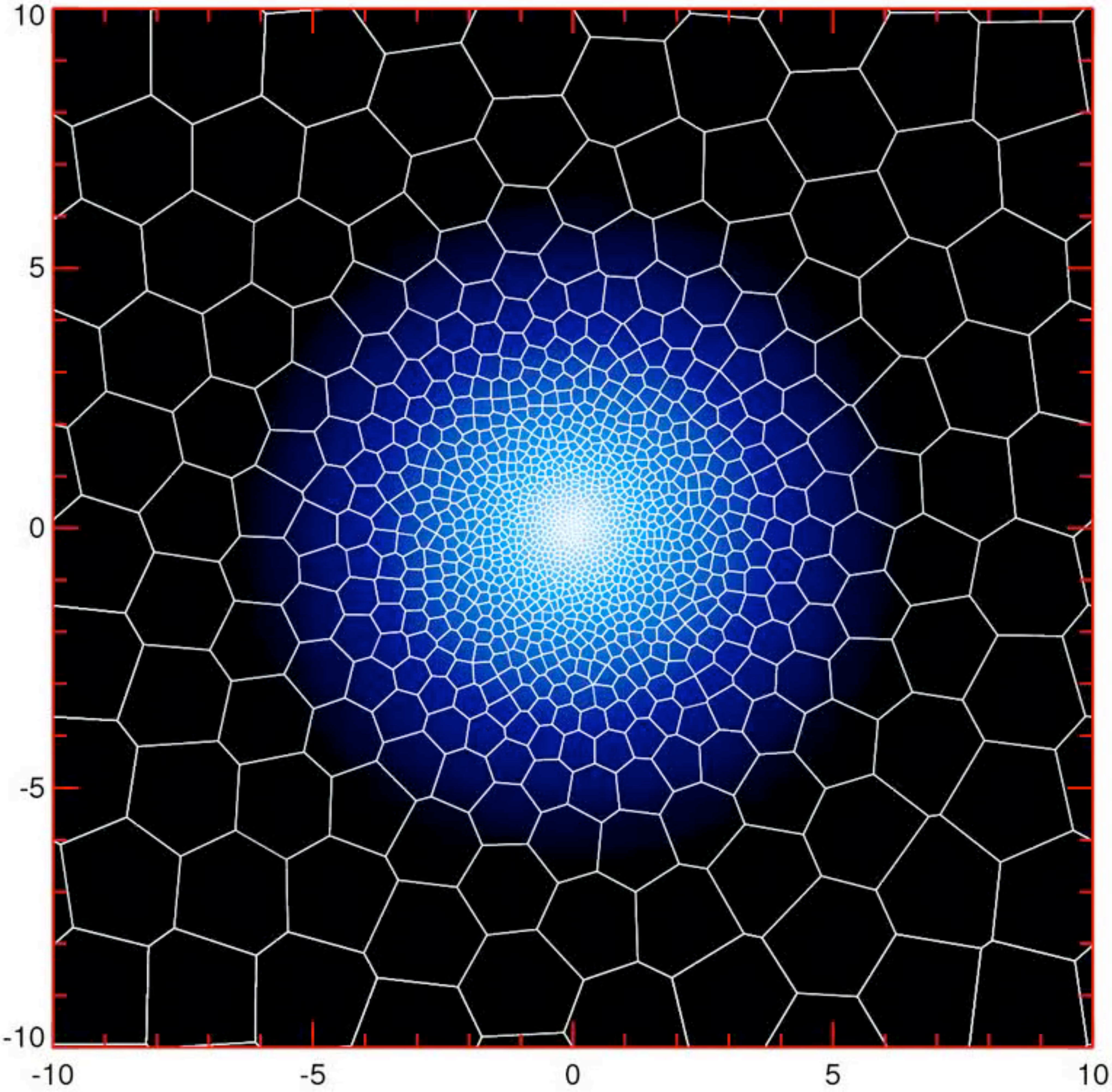
0
count
0.0 0.2 0.4 0.6 0.8
d
4000
3000
2000
1000
0
count
1.0 1.2 1.4 1.6 1.8 2.0
η

Galaxy interactions: In moving-mesh calculations, “empty space” must be (at least coarsely) covered with cells, unlike in SPH

Existing SPH initial conditions can be translated automatically to initial conditions for AREPO







10
5
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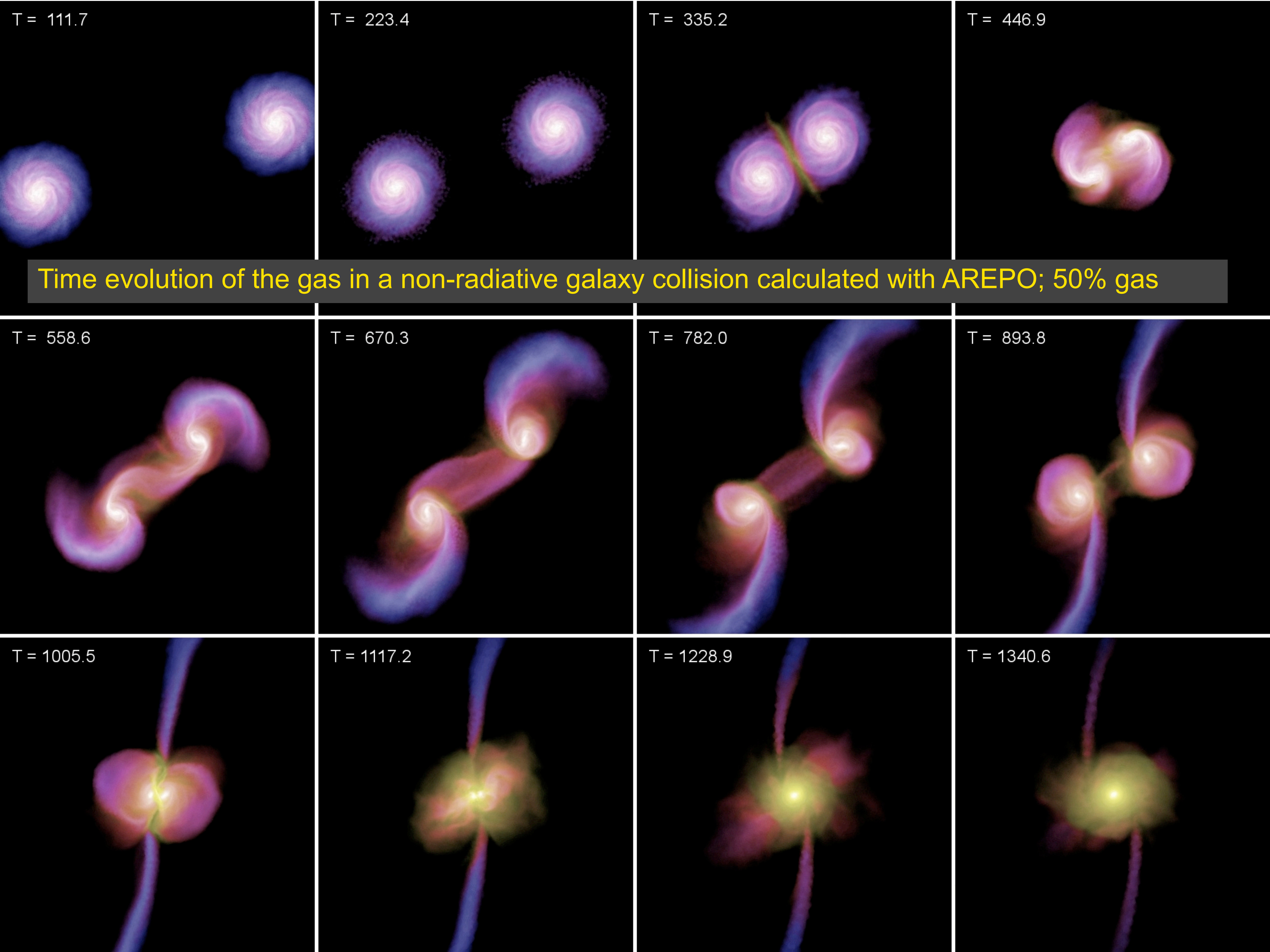
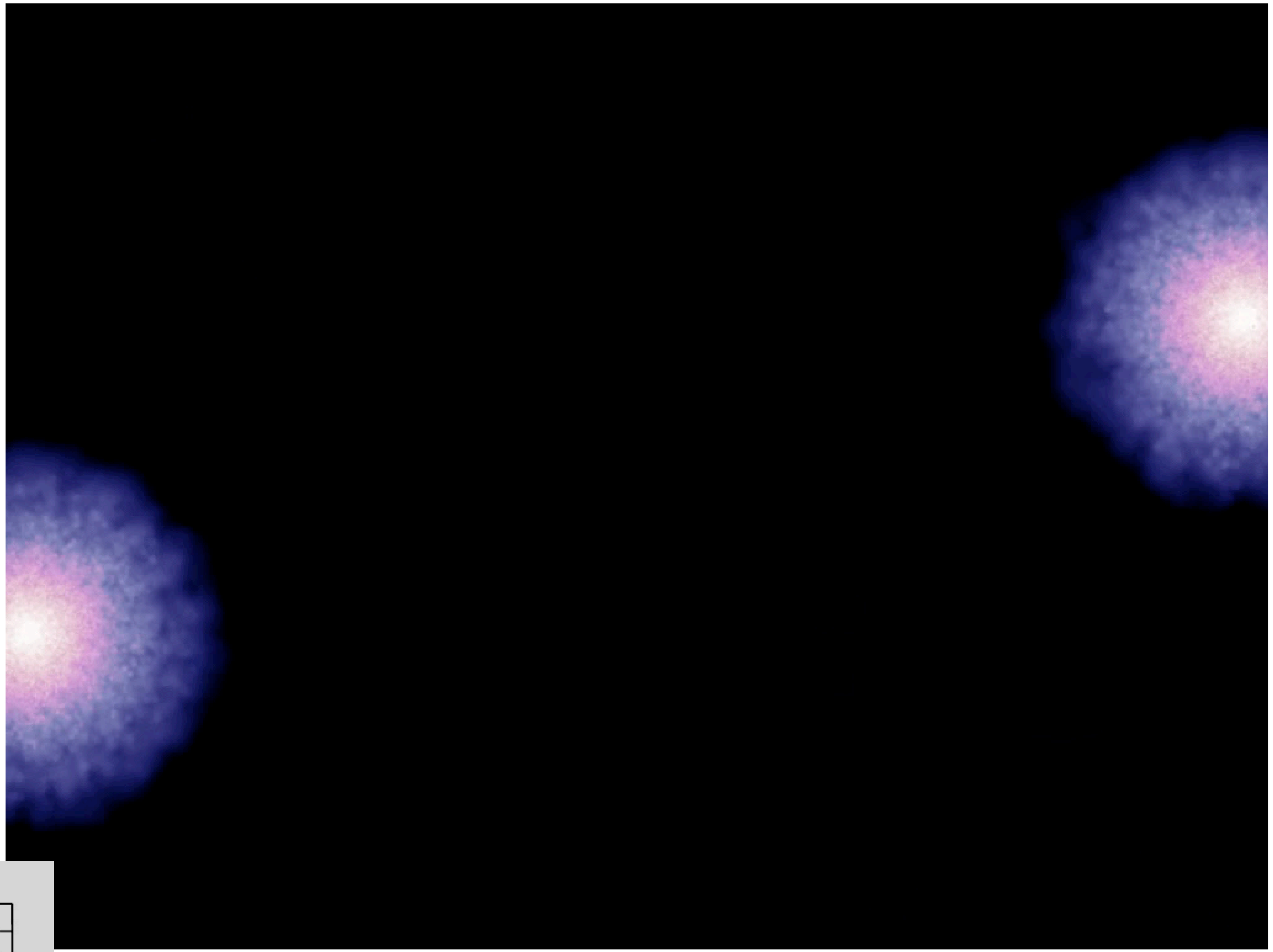
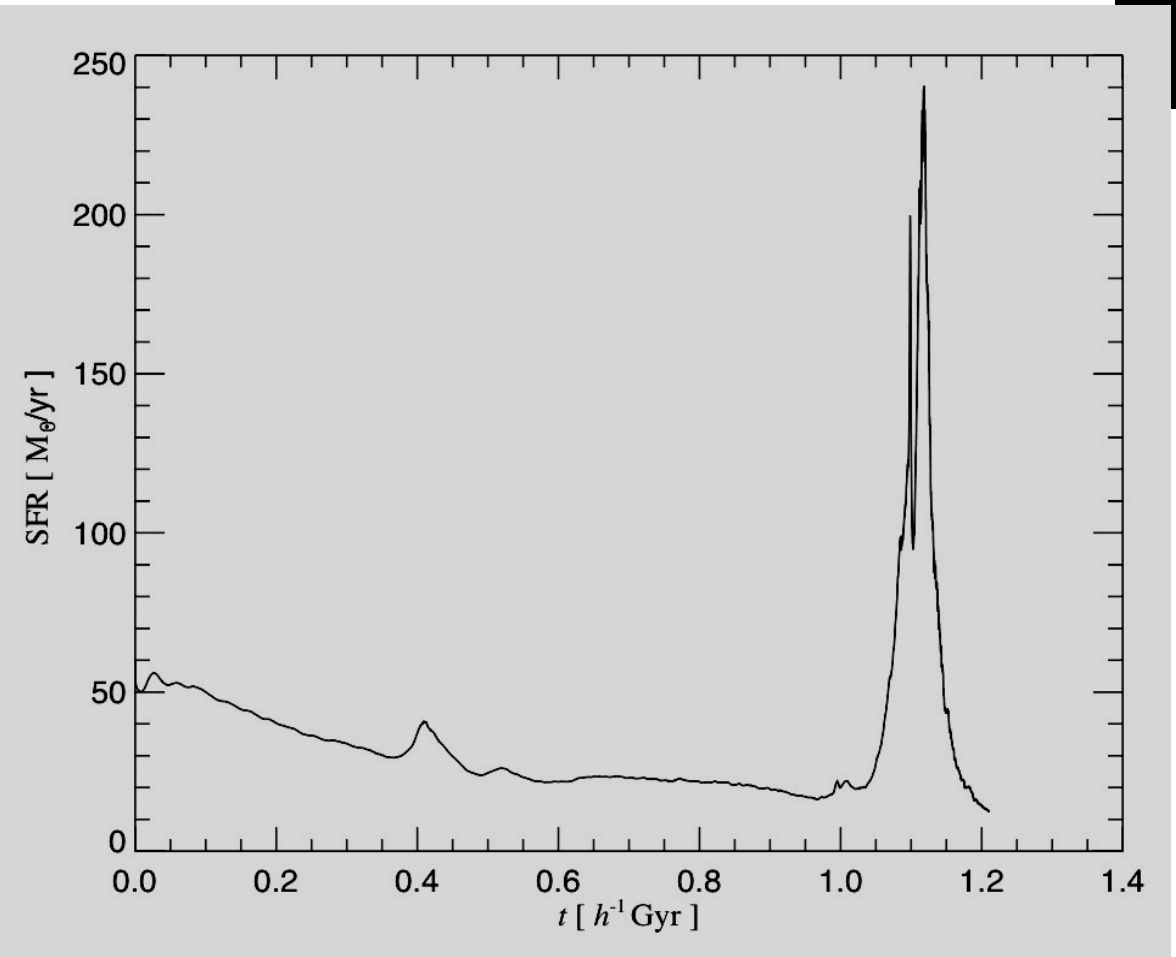
-10
-10
-5
0
5
10



Time evolution of the gas in a non-radiative galaxy collision calculated with AREPO; 50% gas

Runs with star formation, BH growth in progress.





Preliminary result with star formation, no BHs.

Potential applications

- cosmological disk formation
- outflows & inflows
- ram pressure stripping
- shock-induced star formation
- Including radiative transfer
- galaxy mergers:
  - simulation library / archive
  - more physical sub-resolution models