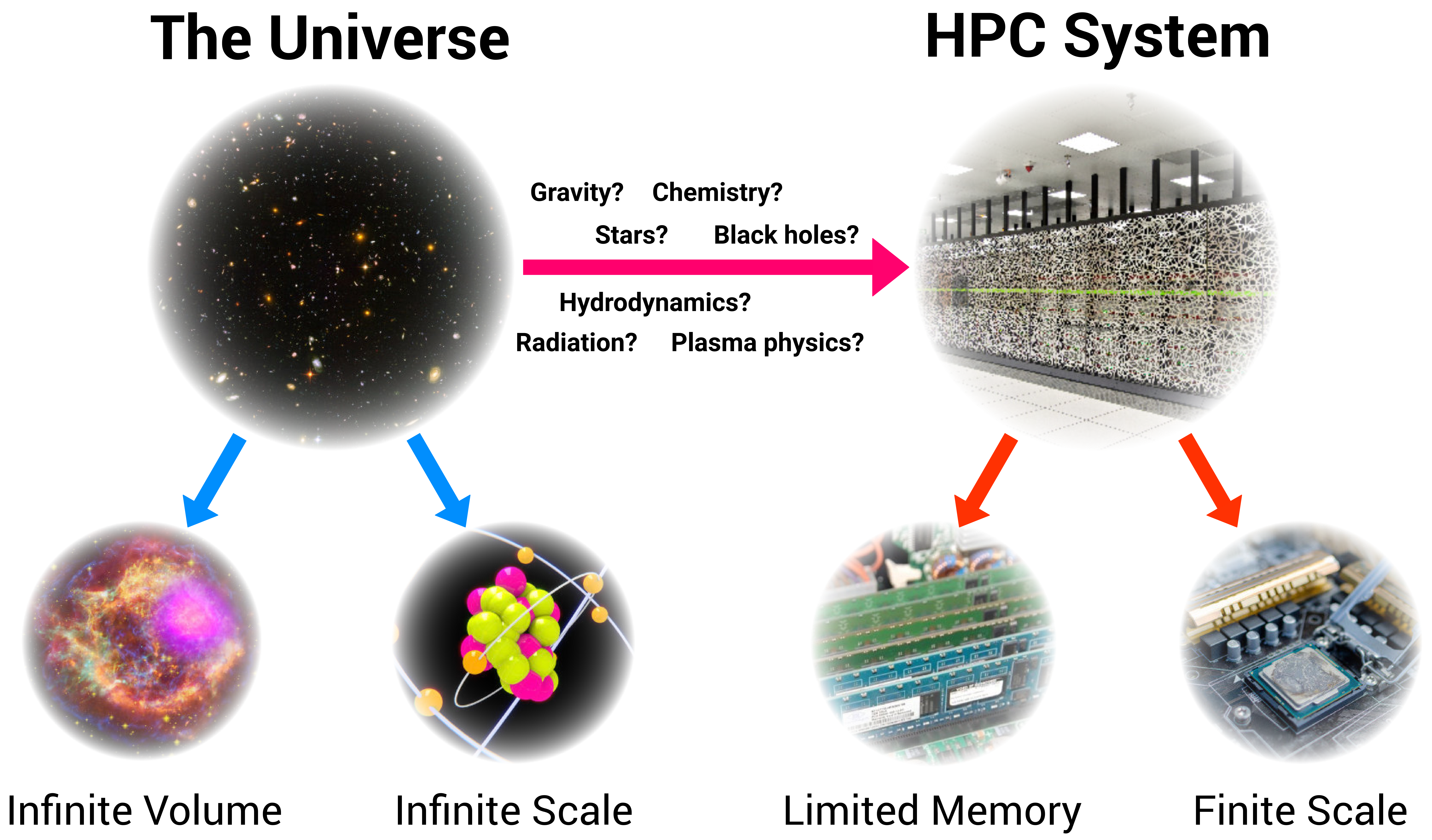
Choosing the best flavour of SPH for astrophysics problems:

More complex may not be better

Josh Borrow

ICC, Durham

With Bert Vandenbroucke (St. Andrews) and Matthieu Schaller (Leiden Observatory)


The Universe
HPC System
Gravity?
Chemistry?
Stars?
Black holes?
Hydrodynamics?
Radiation?
Plasma physics?
Infinite Volume
Infinite Scale
Limited Memory
Finite Scale


1 Mpc

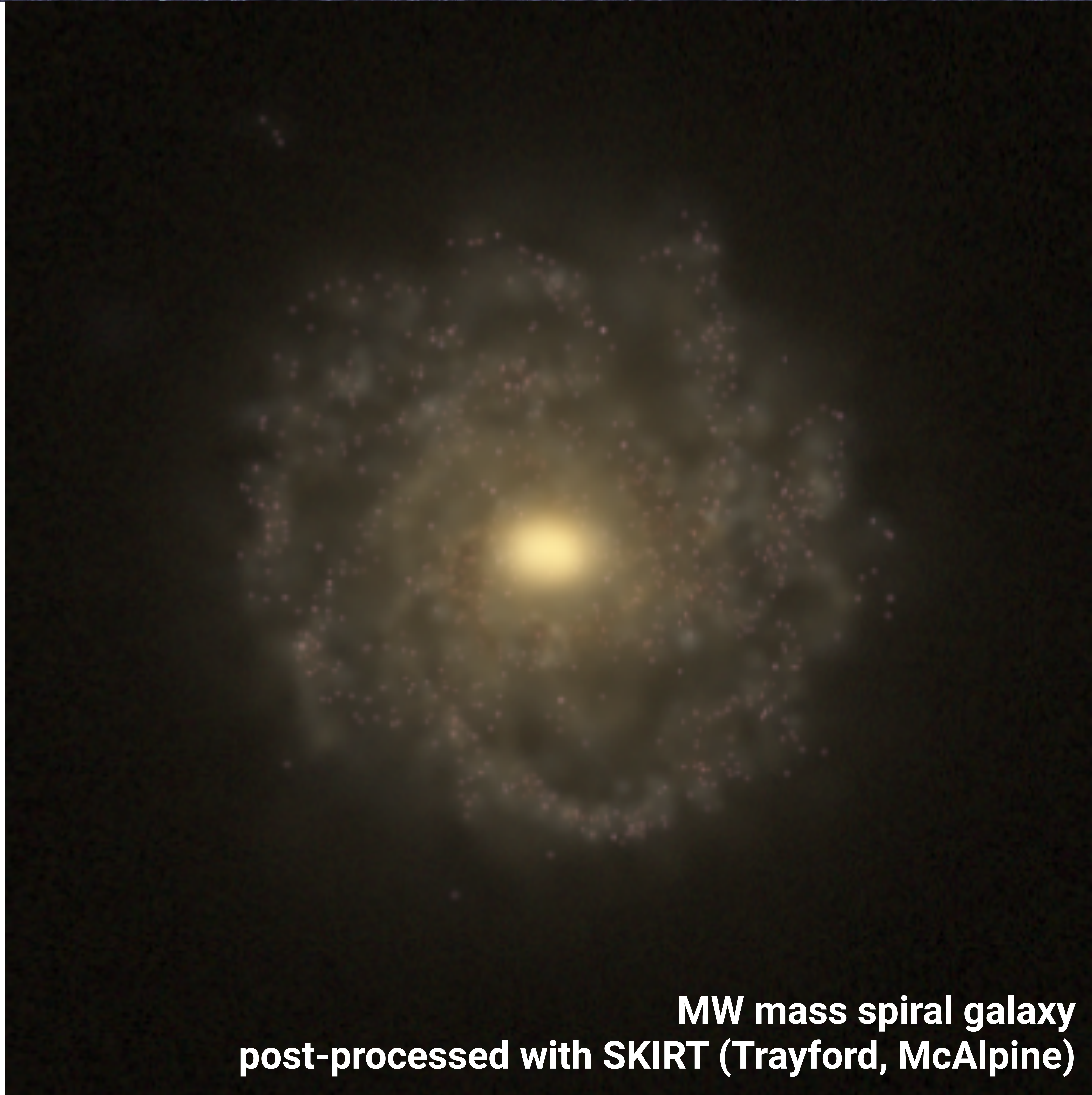

250 kpc


25 kpc


Sheared satellite accretion
Individual feedback event
Spiral structure
25 kpc

What can we actually see?

- Mass resolution $M_g = M_* \approx 10^6 \ \mathrm{M}_\odot$
- Spatial resolution $\ell_g \approx 1 \ \mathrm{kpc}$
- Processes on smaller scales than these included in '**sub-grid**' models
- Galaxies resolved by **100'000** particles, despite there being **100 billion** particles integrated



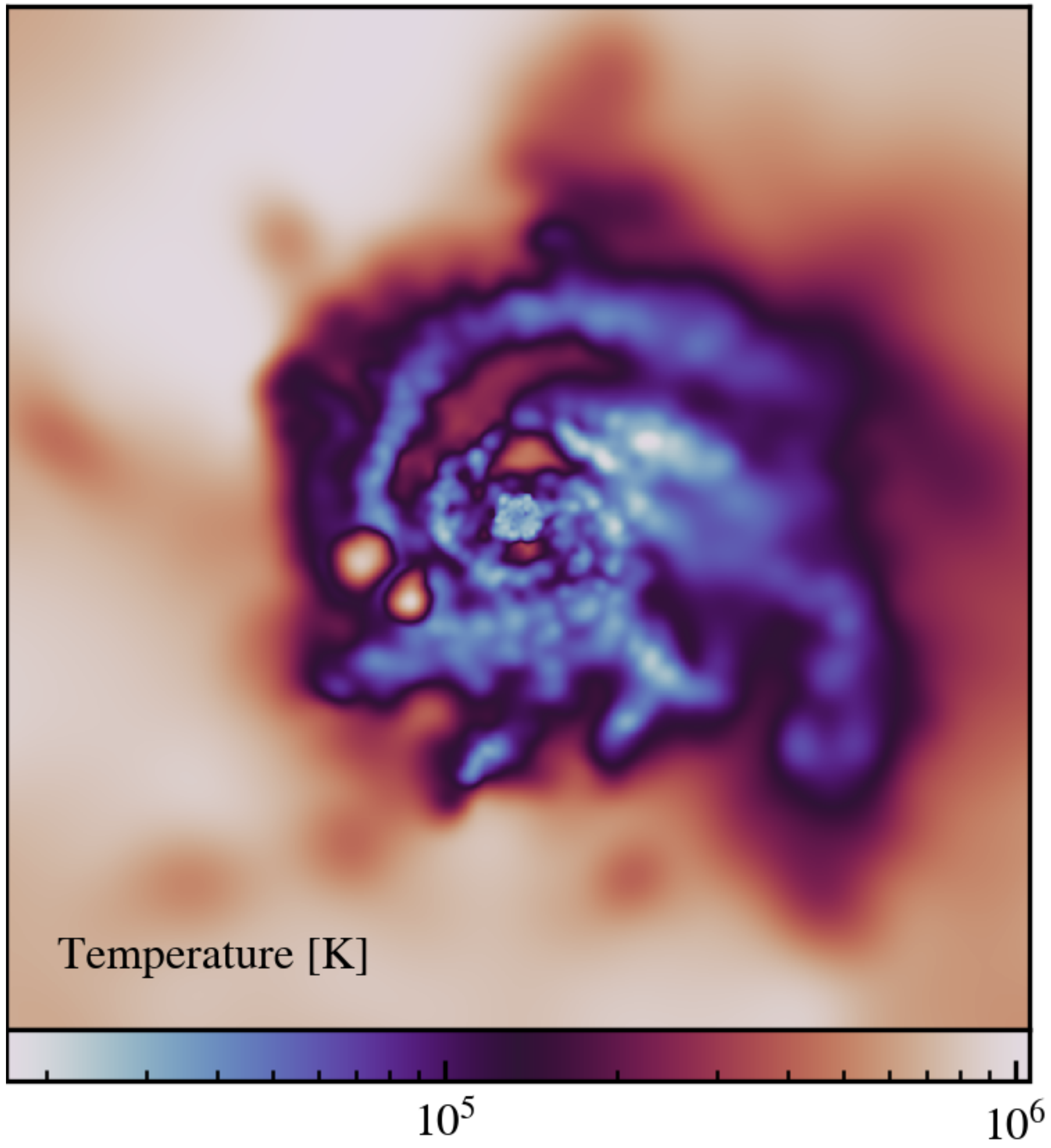
MW mass spiral galaxy
post-processed with SKIRT (Trayford, McAlpine)

What are the challenges?

Multiple time-stepping

Variable *h*

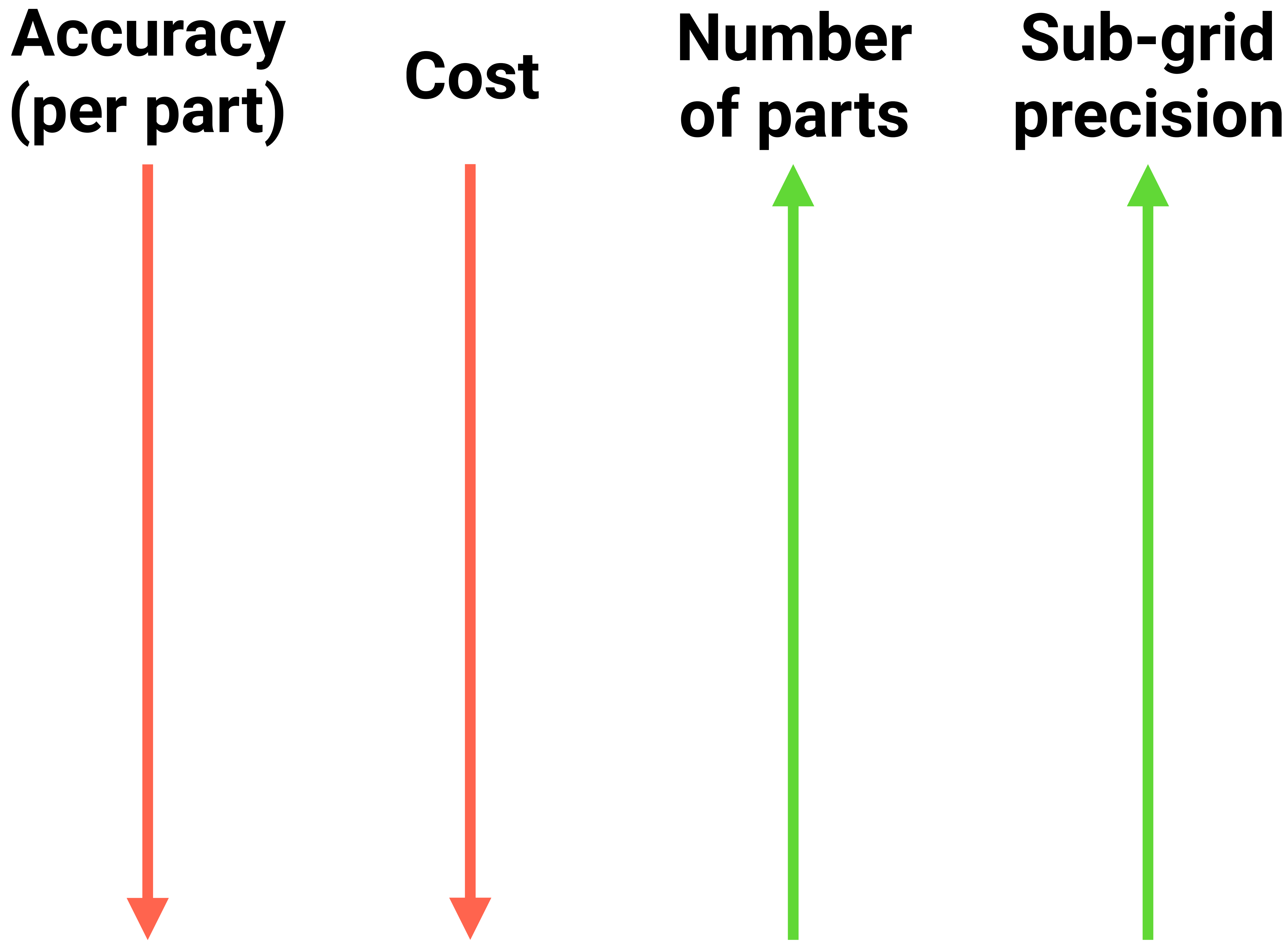
- **Computational**: how do we scale our calculation to tens of thousands of cores?
- **Physical**: how do we model the <u>gas dynamics</u> and sub-grid physics?
- **Astrophysical**: how do we calibrate our model?



Grand design spiral from SWIFT/EAGLE tests

Cosmological hydrodynamics

- **Smoothed Particle Hydrodynamics** (SPH / ANARCHY) - EAGLE, FIRE
- **SPH-Arbitrary Lagrange-Euler** (SPH-ALE / GIZMO) - FIRE-II, SIMBA
- Moving mesh (AREPO) - Illustris, Illustris-TNG



Possible Schemes

"Traditional SPH"

Basic Density-Energy SPH

$$\rho_i = \sum_j m_j W_{ij}$$

$$\left.\frac{dv}{dt}\right|_{\text{sph}} \propto \sum_j \frac{P_i}{\rho_i^2} \nabla W_{ij}$$

Fixed artificial viscosity (Monaghan 1992)

$$\left.\frac{dv}{dt}\right|_{\text{visc}} \propto \alpha \sum_j \nabla W_{ij}$$

SPH-ALE (Finite Mass)

Volume estimate from SPH

$$V_i = \frac{1}{\sum_j W_{ij}}$$

Primitive interface moves with the velocity of the contact discontinuity

Gradient-based slope-limiter

HLLC Riemann Solver

ANARCHY-SPH

Variable artificial viscosity

$$\alpha \sim \dot{\nabla} \cdot \mathbf{v}$$

Artificial diffusion/conduction

$$\alpha_D \sim \nabla^2 u$$

$$\left.\frac{du}{dt}\right|_{\text{diff}} \propto \sum_j \alpha_{D,i}(u_i - u_j)$$

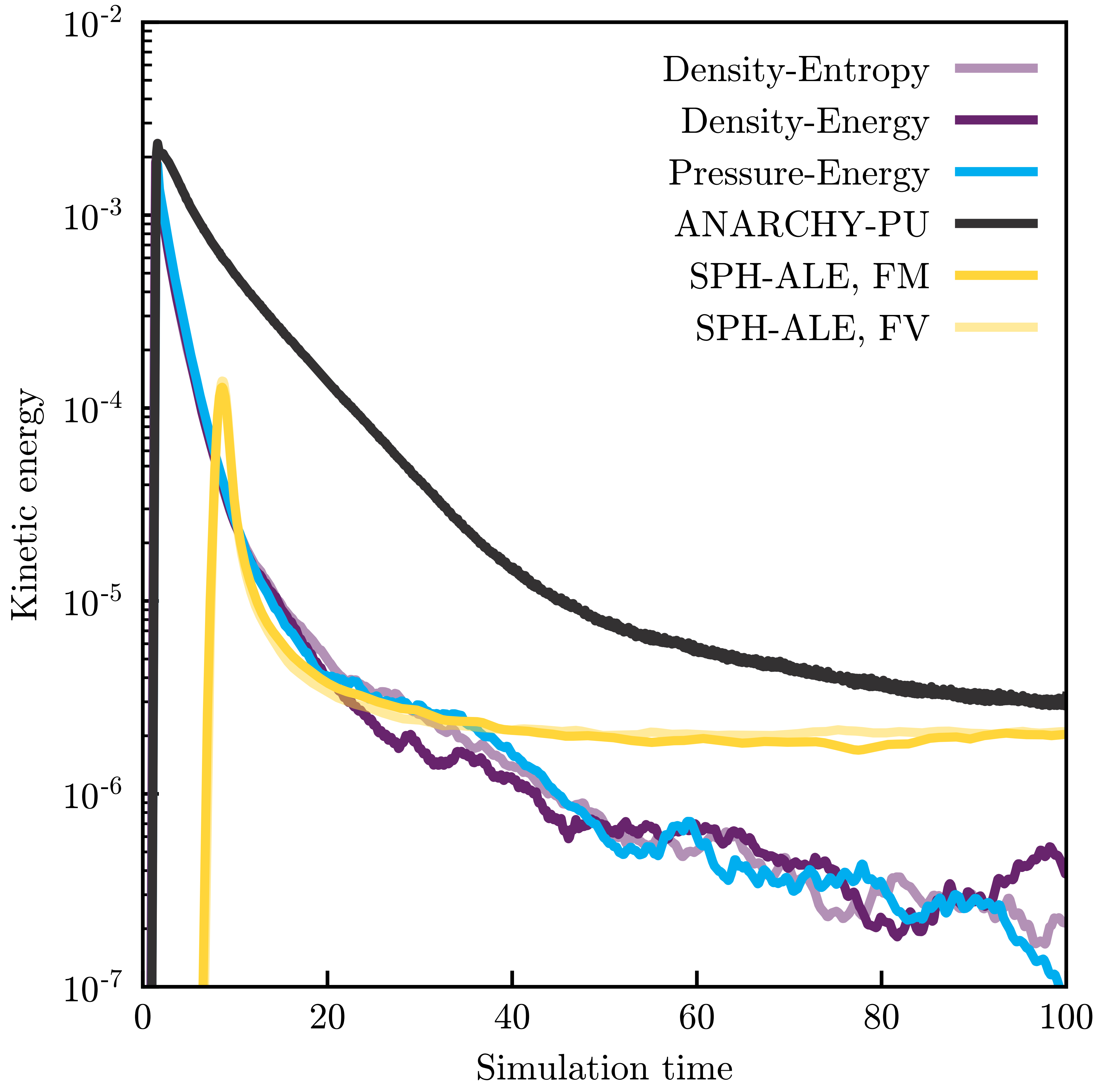
No Riemann solver!

How do you decide on a scheme?

- Selection of **hydrodynamics test problems that are relevant**
- Important to study these at the **relevant resolutions** to your problem (here we mean that to have a number of particles comparable to the number of particles in a Milky-Way galaxy)
- Lots of schemes are shown to converge at high resolution but we are **fundamentally in a low resolution regime**.
- Need to **fix everything else** - neighbour search, gravity, etc. - use **SWIFT**!

Realistic ICs

- Generate **glass files**, instead of using perfect BCC ICs
- In a real simulation, this is the best feasible situation
- We then 'mess around' with particles, **changing** their **internal energies** and **removing/adding particles** as part of our **sub-grid** modelling.



Sedov-Taylor Blastwave

- Very high mach shock; $\mathscr{M} = 1000$
- Created by injection of energy into a handful of particles
- Relevance:
  - Shock handling
  - This is exactly how supernovae are implemented in our sub-grid model

Sedov-Taylor Blastwave

Monaghan 1992, Agertz+ 2007 for deficiencies

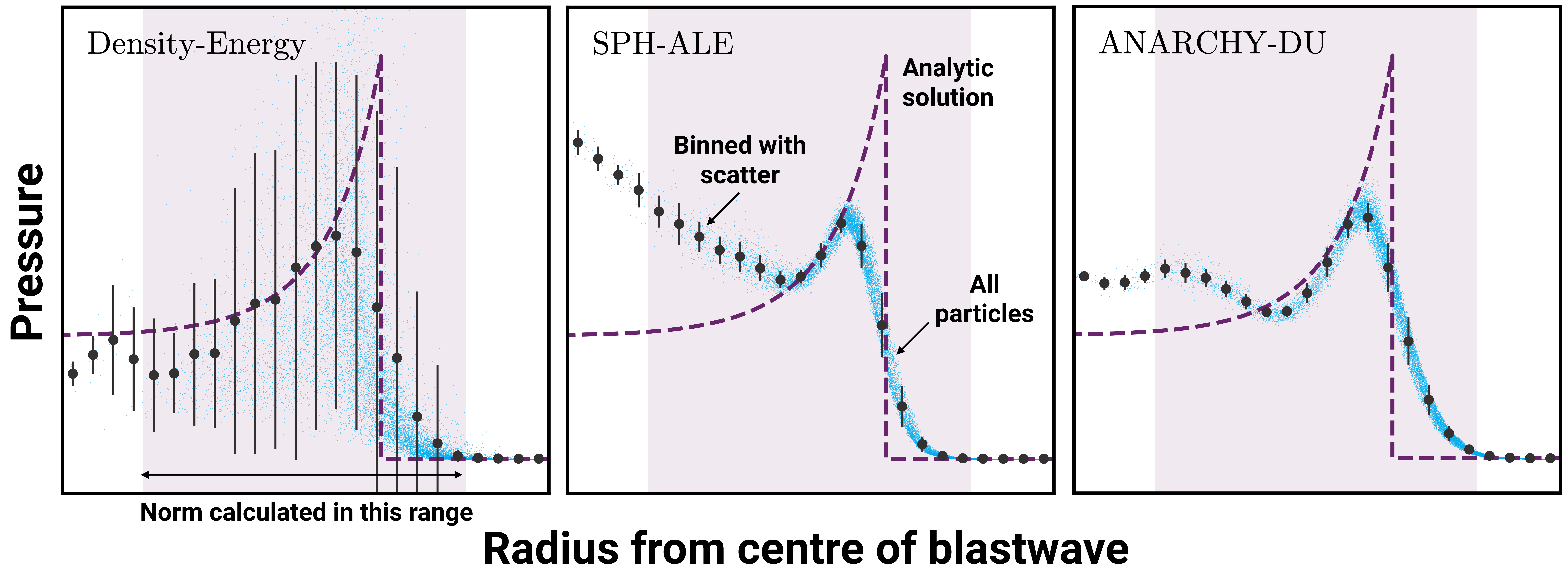
Density-Energy SPH

Moussa+ 1999, Villa+ 2012, Hopkins 2015

SPH-ALE (MFM)

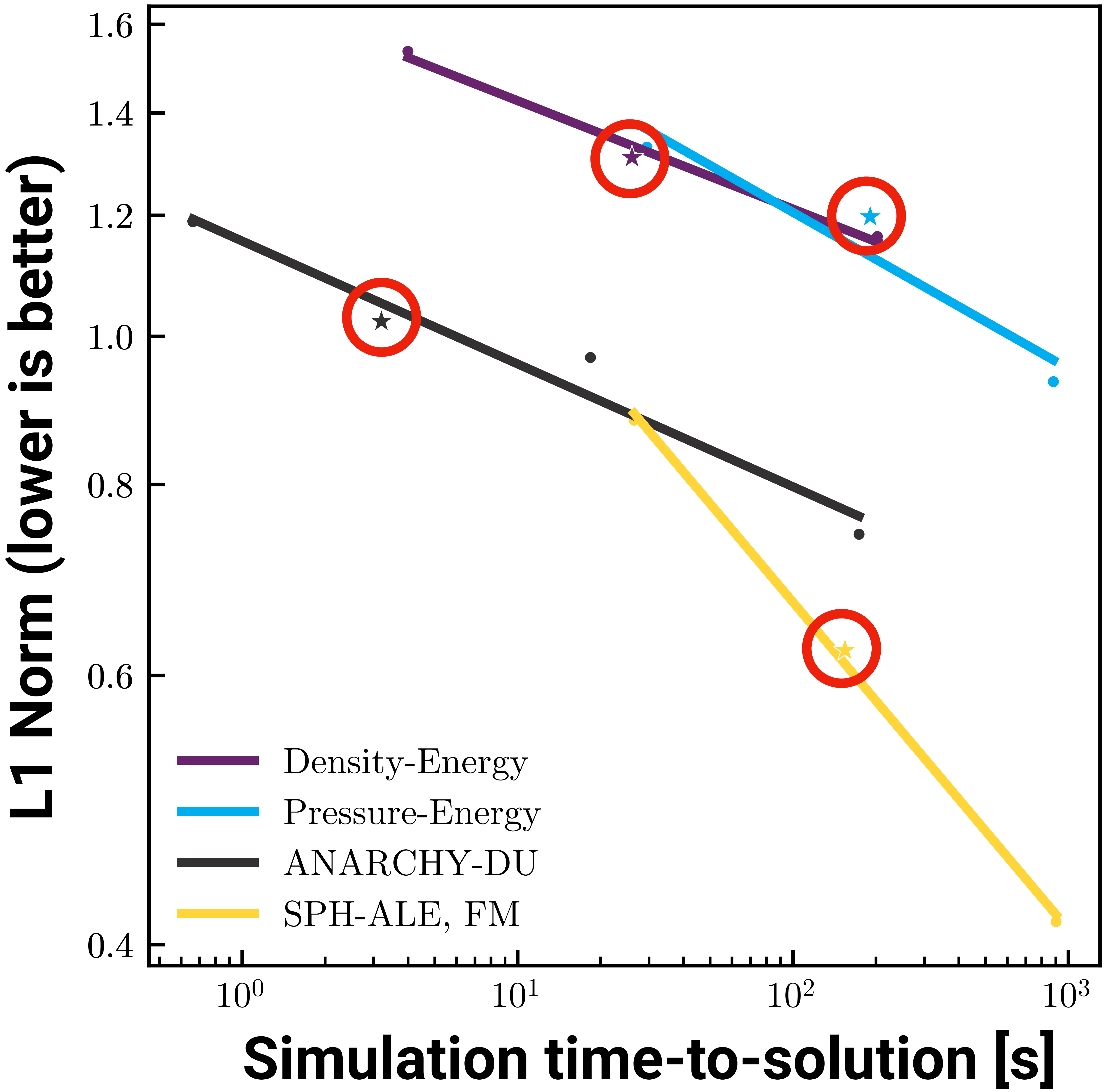
Agertz+ 2007, Price+ 2008, Hopkins 2013, Price+ 2018

ANARCHY SPH



Sedov-Taylor Blastwave

- **SPH-ALE** gives a **lower** L1 **norm** in this regime
- We see from the previous images, though, **that this doesn't necessarily mean a 'better' answer**
- Note how **traditional SPH** gives a **longer time-to-solution** on this problem; it takes **more steps**



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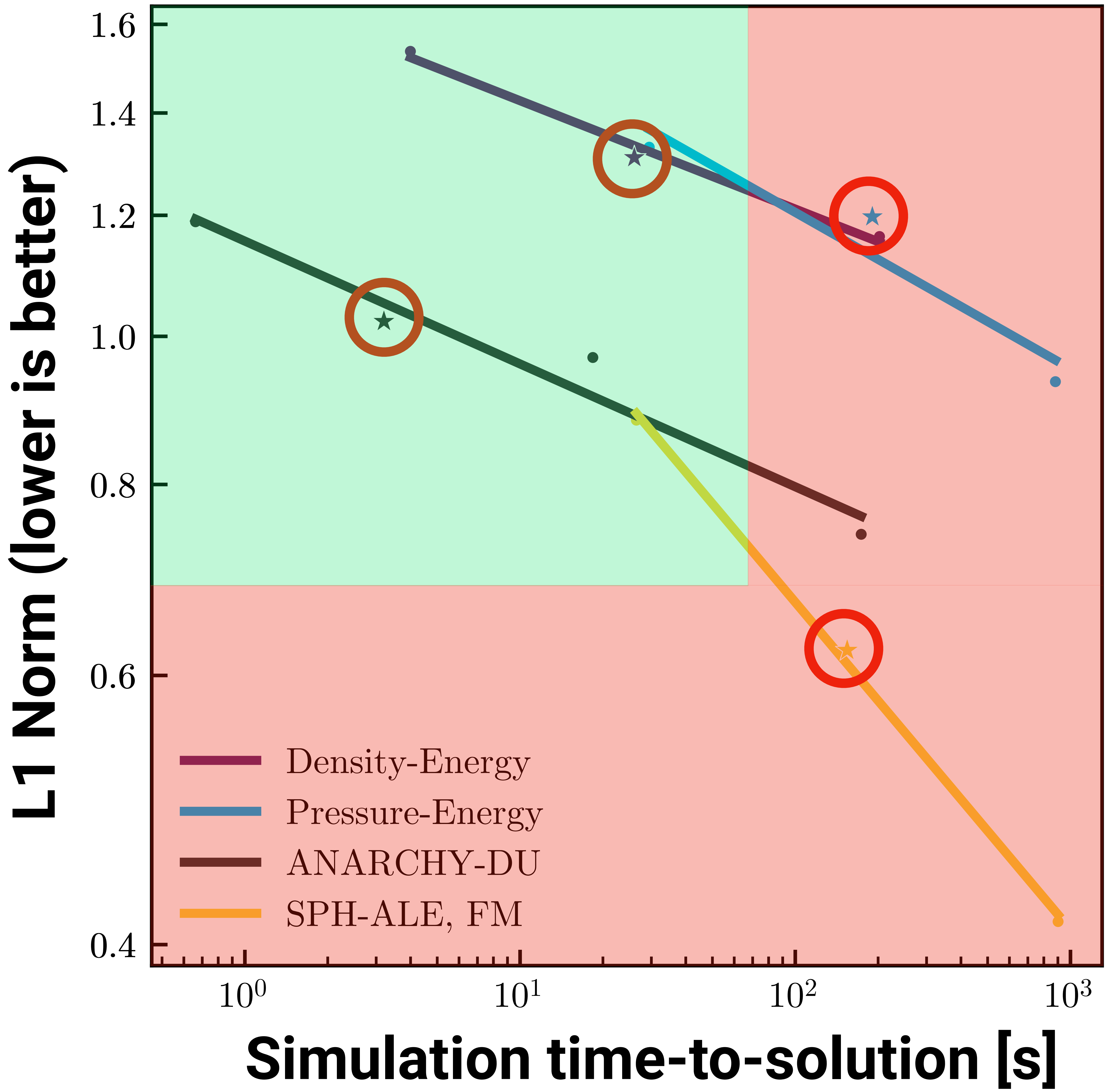
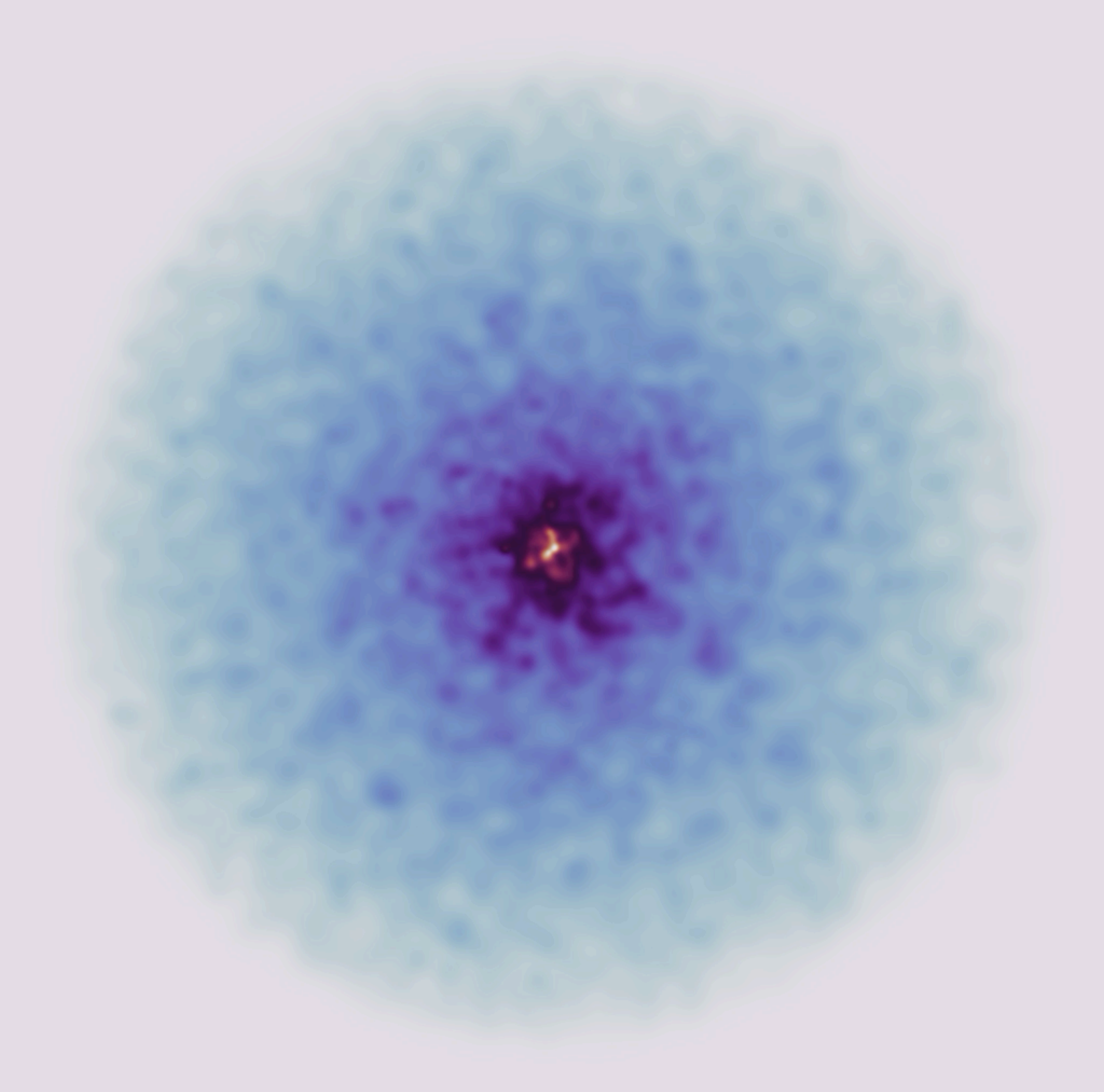


Evrard Collapse

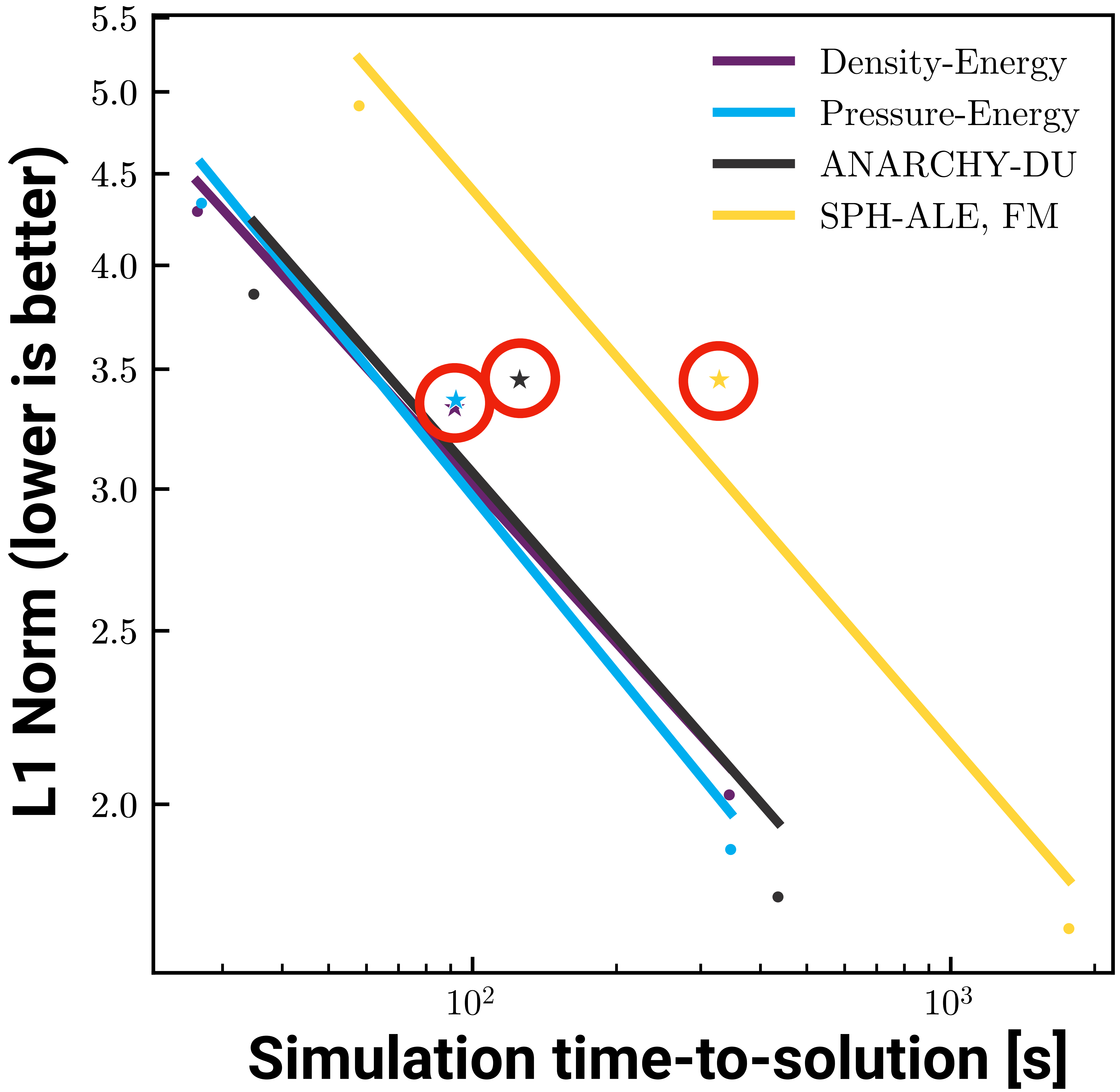
- **Self-gravitating** sphere of gas
- Shock that **propagates outwards**
- Eventually settles into an equilibrium state
- Relevance:
  - Shock handling
  - Coupling to gravity



Evrard Collapse

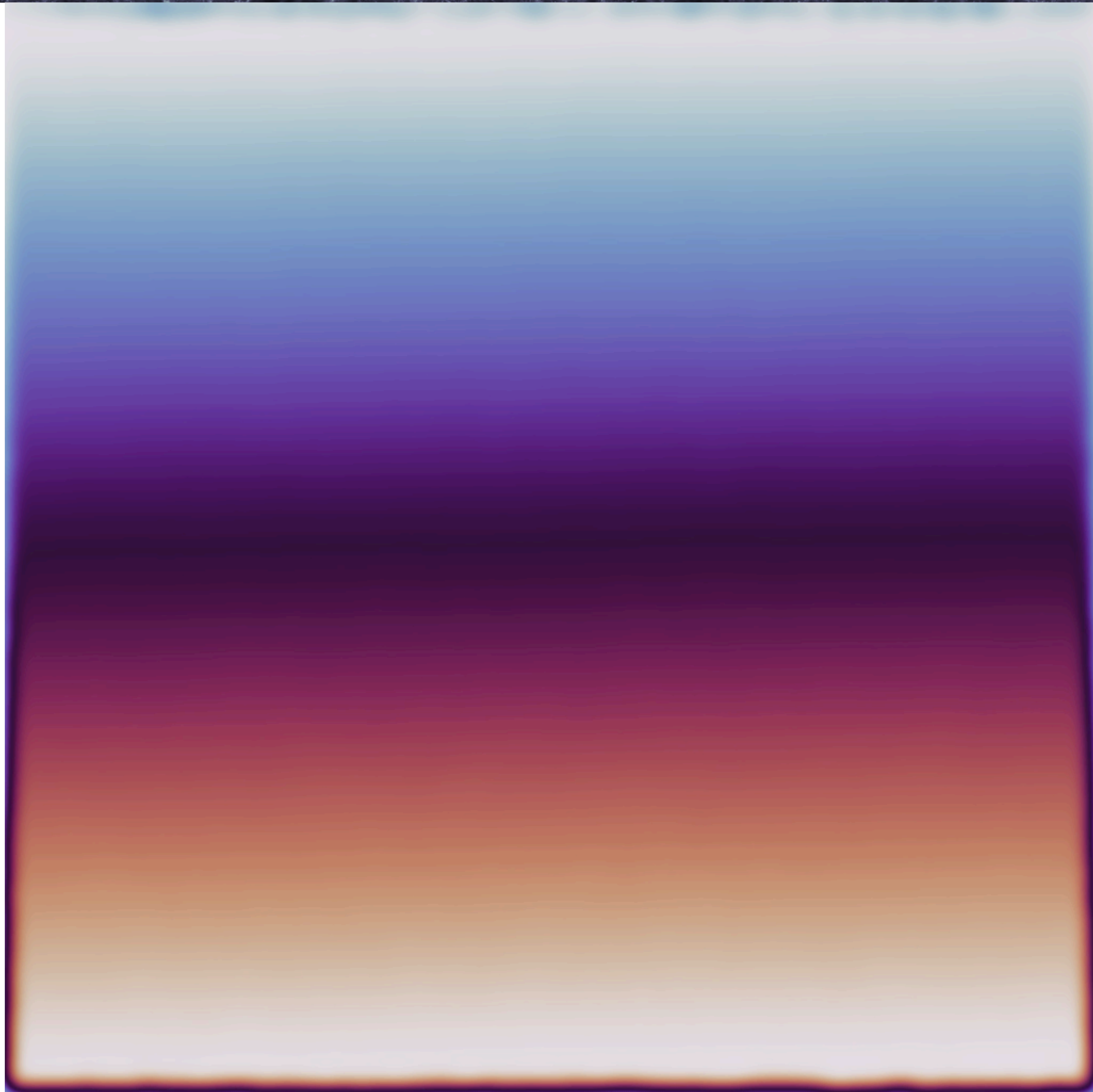
Evrard Collapse

- All schemes give **approximately the same result** here
- Leads to **very similar norms** and convergence
- For the **same cost** as GIZMO, we can integrate **8x more particles** with SPH



Gresho Vortex

- Twirling vortex of gas
- Constant density everywhere
- Relevance:
  - Conservation of angular momentum
  - Numerical stability



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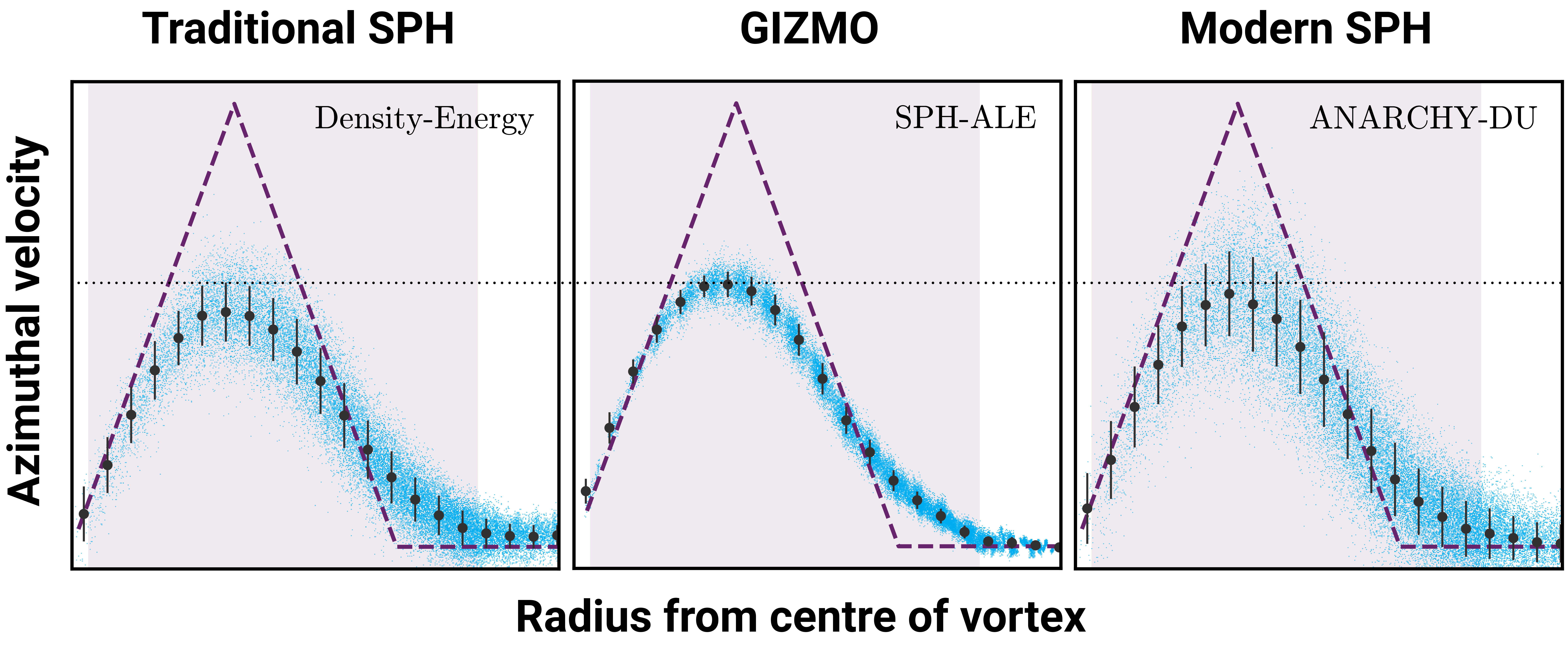
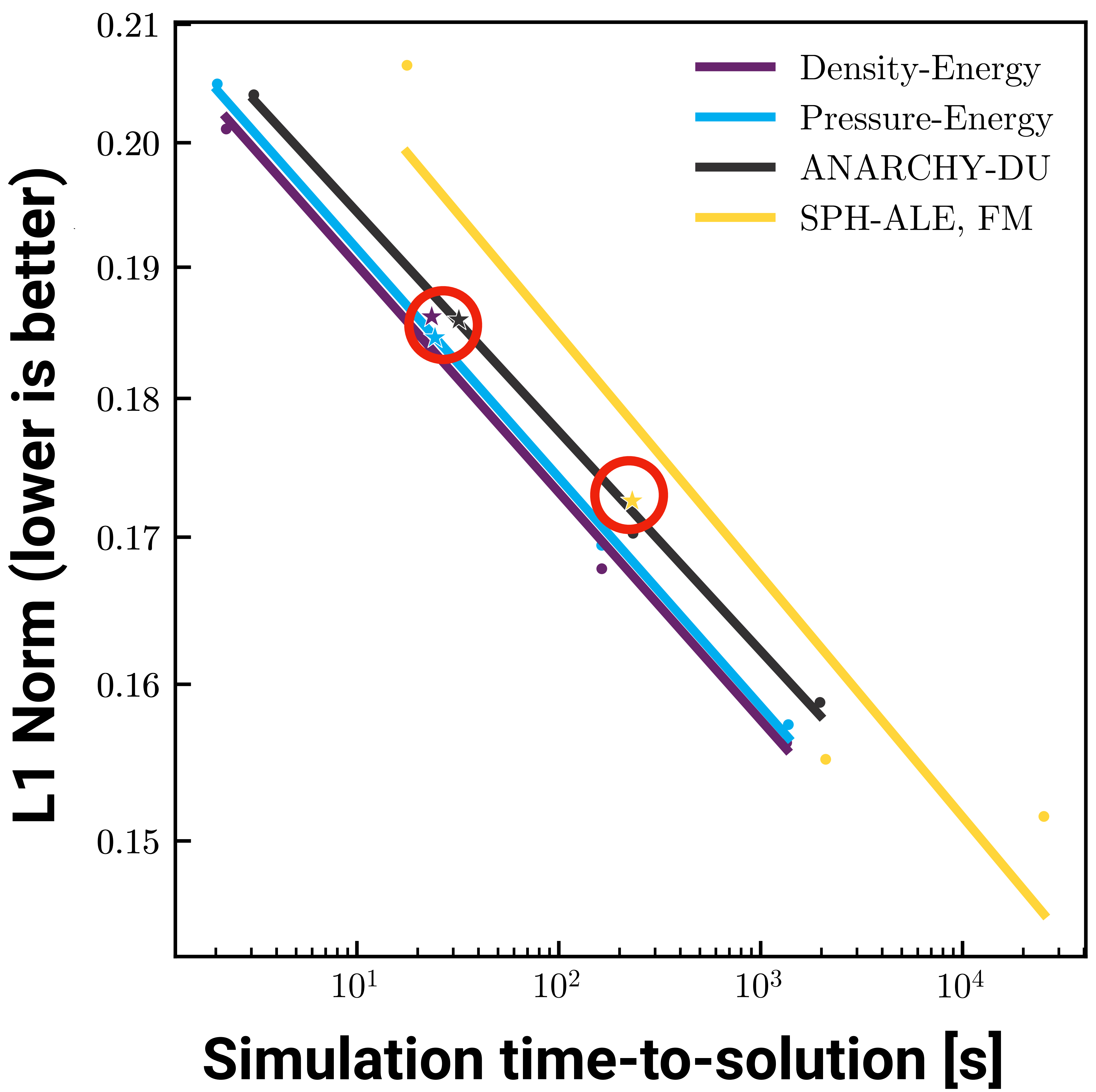


Gresho Vortex

- GIZMO performs extremely well here, but at **8x the cost** again!
- SPH is **never as stable** as GIZMO at late times; the vortex always collapses
- Realistic simulations are nowhere near this idealised case.



Mini-Summary

- The major gains in the past ~12 years for **SPH** have allowed it to **perform similarly to SPH-ALE** at the **resolutions we run at**.
- This makes it a **great choice** for large-scale simulations like **EAGLE**
- What are these advancements?
  - Artificial viscosity (shock handling)
  - Numerical diffusion/conduction (energy transport)


Traditional SPH
Modern SPH


Traditional SPH
Modern SPH


Traditional SPH
Modern SPH

Conclusions

- 'Modern' SPH is still a useful alternative to SPH-ALE
- Our ANARCHY scheme **prevents excess diffusion** in the very **low resolution**, high mach number flows that we simulate
- Choosing the scheme to use is non-trivial and is very problem-dependent: **more complex may not be better**!
- SWIFT is publicly available and ready for general use

@JBorrow
joshua.borrow@durham.ac.uk