Monte Carlo tracers implemented for the adaptive mesh refinement code RAMSES

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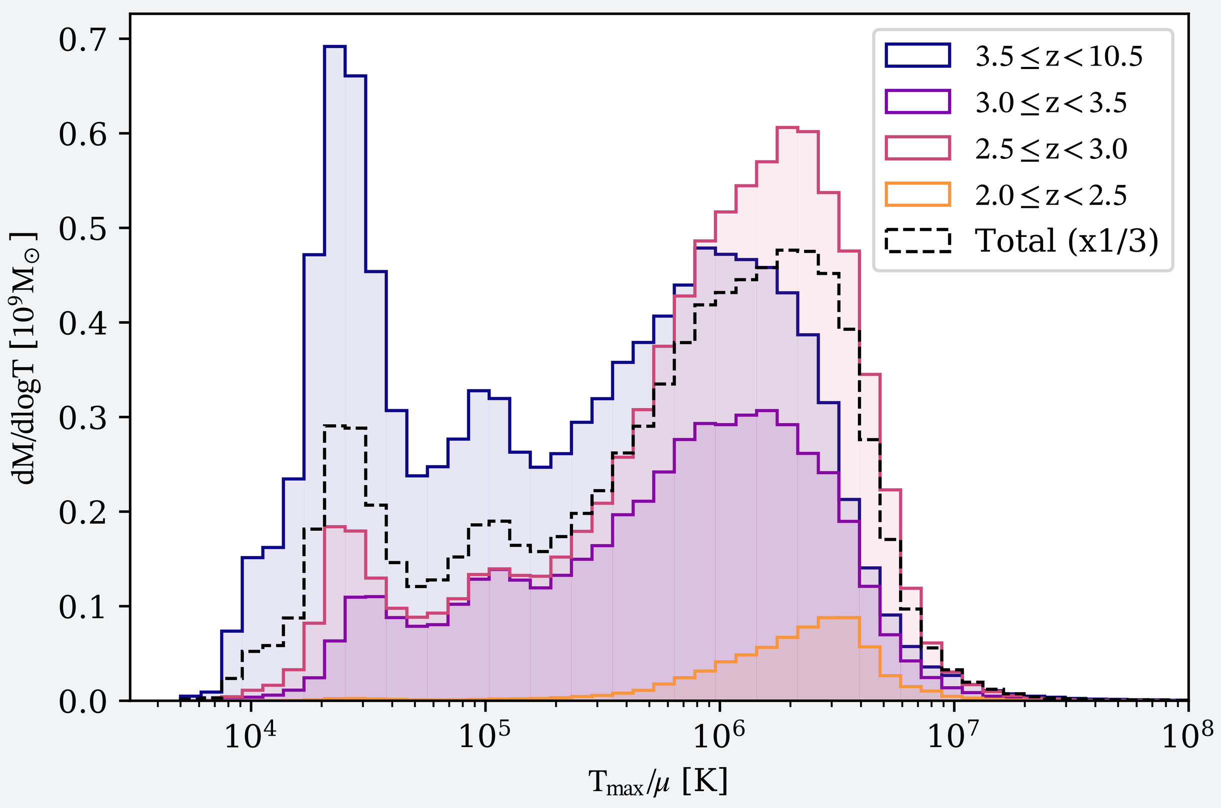
Need for Lagrangian history

Numerical hydrodynamical simulations solving the Euler equations usually use one of two approaches. In **Smooth Particle Hydrodynamics** (SPH, e.g. [1]), the equations are solved in a Lagrangian framework. Other codes use a Eulerian approach and solve the equations on a grid: they are called **Adaptative Mesh Refinement** codes (AMR codes, e.g. [2]). AMR codes have a very flexible approach to tweak the spatial resolution. Yet they fail at providing the **Lagrangian history** of the gas.

To tackle this issue, one need to add tracer particles in the code. The particles should have the same spatial distribution as the gas.

Science Case

When studying the accretion of gas at high redshift $z \lessapprox 2$, [3] found that in SPH simulations, most of the accreted gas has never heated above $T_{\rm max} \sim 10^5\,$K. To study these processes in AMR code, one need reliable tracer particles to follow the evolution of a parcel of gas as it falls onto a galaxy, eventually shock-heats at the virial radius.



With Lagrangian information we recover their result: the accretion is mostly bimodal with anisotropic, cold neutral gas at $T_{\rm max} \sim 2\times10^4\,$K and diffuse, shock-heated gas at $T_{\rm max} \sim 10^6\,$K. The advantage of AMR codes is that they can trigger super-Lagrangian refinement, with, e.g., refinement criteria based on shock structure of the gas, vorticity of the flow, etc., with tracer particles still providing the Lagrangian history! This can be used to e.g. resolve the turbulence in cosmic filaments and track how their structure evolve as they fall onto galaxies.

Bibliography

[1] V. Springel, "The cosmological simulation code GADGET-2", en, (2005).

[2] R. Teyssier, "Cosmological hydrodynamics with adaptive mesh refinement. A new high resolution code called RAMSES", (2002).

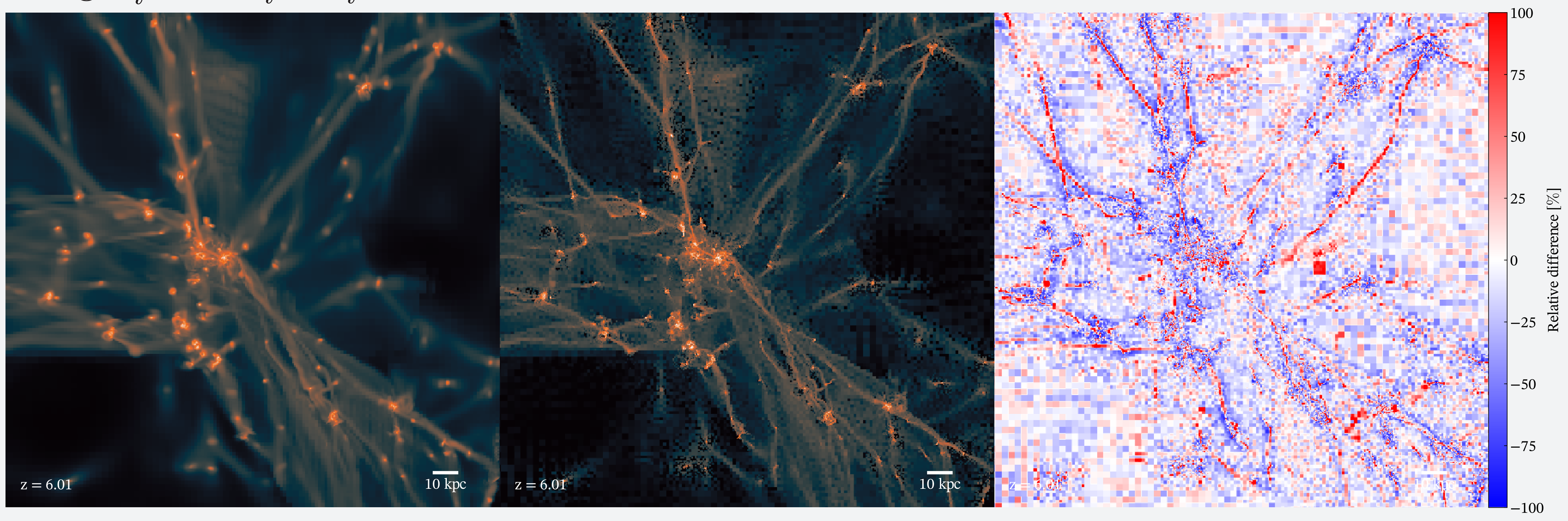
[3] D. Kereš, N. Katz, et al., "How do galaxies get their gas?", (2005).

[4] D. J. Price and G. Laibe, "Two phase mixtures in SPH - A new approach", arXiv:1505.00973 (2015).

[5] S. Genel, M. Vogelsberger, et al., "Following the flow: tracer particles in astrophysical fluid simulations", (2013).

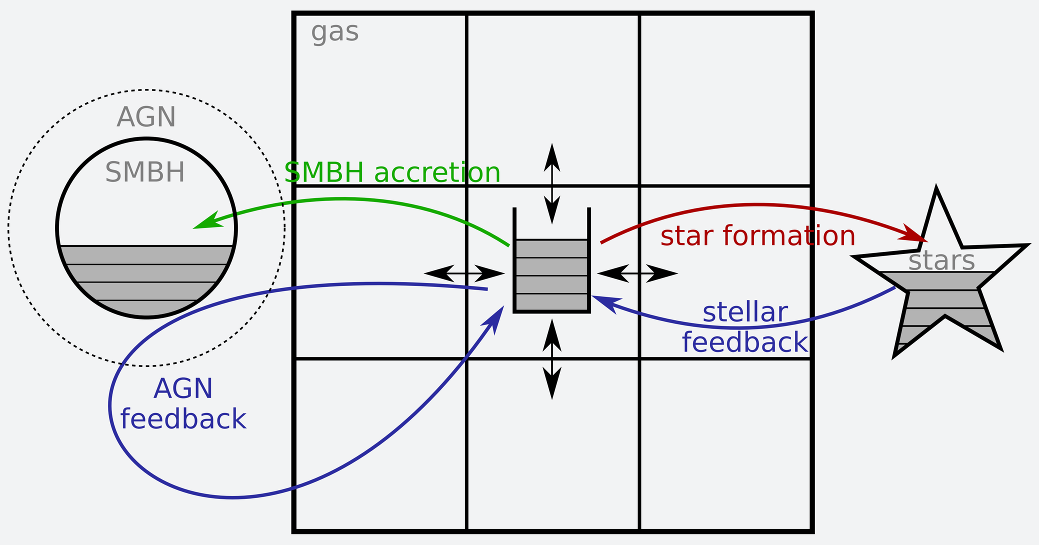
Velocity Tracers

The particles are moved based on the *interpolated local velocity* v_i. The position is updated using $x_i^{t+1} = x_i^t + v_i^t \Delta t$.



Problem: the velocity-advected tracers have a distribution that is **overdense in convergent regions** (filaments, nodes) and underdense in diverging regions (voids), see e.g. [4]. This is due to the divergent term not being taken into account ($\rho\nabla\cdot v$).

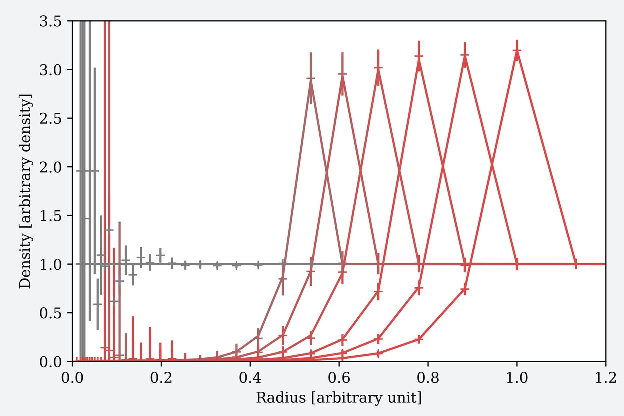
Monte Carlo Tracers – principle



The particles are moved stochastically so that the **tracer flux** equals the **gas flux** (see [5]). For a particle in cell i, the proba of jumping in cell j if the mass transfer is $\Delta M_{i\to j}$ reads

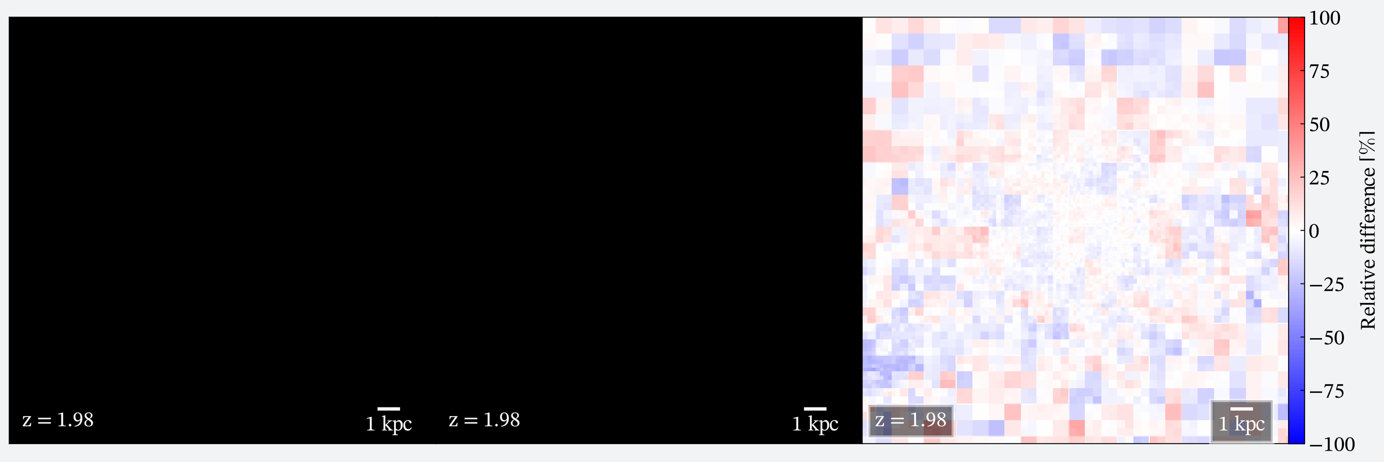
$$p_{i\to j} \equiv \frac{\Delta M_{i\to j}}{M_i}. \quad (1)$$

Sedov Test



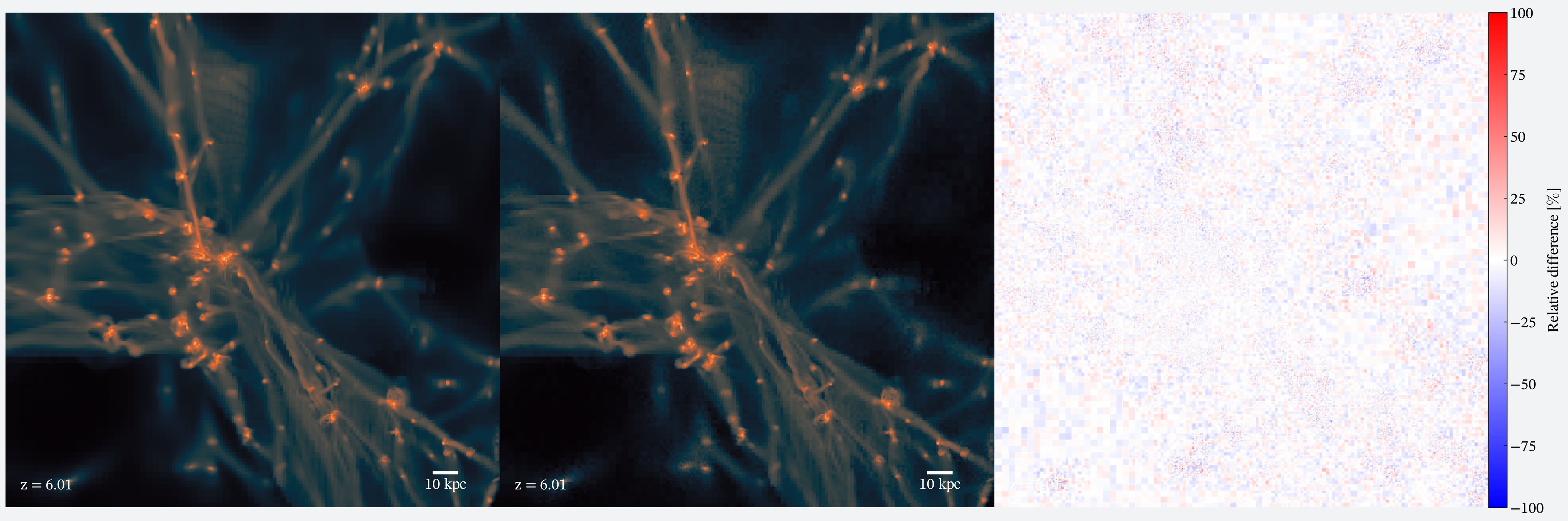
3D Sedov blast. Solid: gas radial profile at different times. Symbols: tracer density profile with errobars at $\pm10\sigma$.

Stars



Star formation: gas tracers are attached onto stars at star formation using $p_{i\star} = M_\star/M_i$.
Supernova feedback: star tracers are released with probability $p_{\star i} = \eta$. Tracers are released in the up-to-48 neighboring cells.

Monte Carlo Tracers – results



The gas tracer distribution (center) matches the gas distribution (left) at percent level, regardless of the geometry of the flow (right, same scale as for the velocity tracers). The distribution of the number of tracers per cell is given by a Poisson law

$$p(N_{\rm tracer} = k) \sim \text{Poisson}\left(\lambda = M_{\rm cell}/m_{\rm tracer}\right) \equiv e^{-\lambda}\frac{\lambda^k}{k!}. \quad (2)$$

The distribution of number of tracers per star is well approximated by a Poisson law with parameter $\lambda = M_\star/m_{\rm tracer}$.

The tracer particles are correctly interfaced with gas, star formation, SN feedback and AGN feedback.