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GALAXY FORMATION ON A MOVING MESH

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How to reliably simulate galaxies in cosmological environment?

- Formation of galaxies requires proper modeling of:
  - Structure formation
  - Gas infall into galaxies
  - Outflows out of galaxies
  - Interactions of infall/outflows/galaxies with the IGM/CGM
- Complex, nonlinear processes, large dynamical range!
- Successful codes applied to these problems need to:
  - Be adaptive to cover huge dynamical range.
  - Quickly and accurately calculate gravitational interactions.
  - Properly model hydrodynamics: discontinuities, steep gradients, shocks, instabilities, shear flows etc.
- Both SPH and AMR have weaknesses in some of these areas.

Some Strengths & Weaknesses

SPH

- accurate gravity solvers
- Galilean invariant
- spatially/temporally adaptive
- continuous refinement
- flexible geometries

- shocks broadened
- discontinuities not well-resolved
- relatively diffusive (artificial viscosity)
- instabilities suppressed
- limited mass resolution
- mixing suppressed

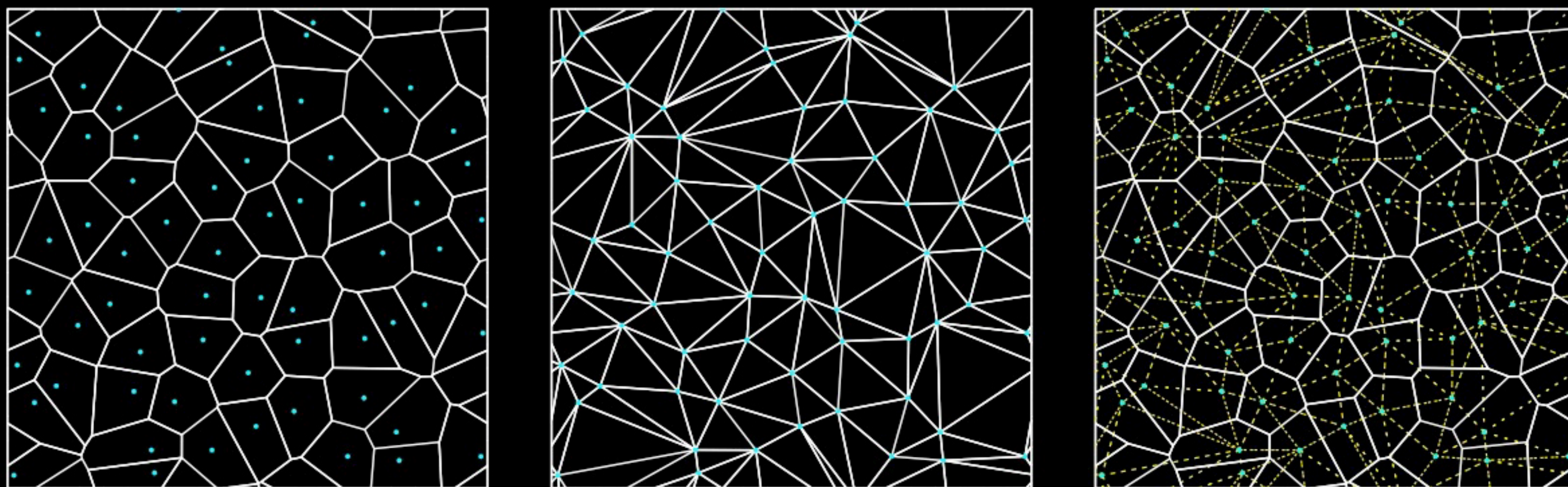
Eulerian-AMR

- accurate shock solvers (Godunov)
- resolution of discontinuities
- relatively less diffusive
- spatially/temporally adaptive
- large dynamic ranges
- mixing

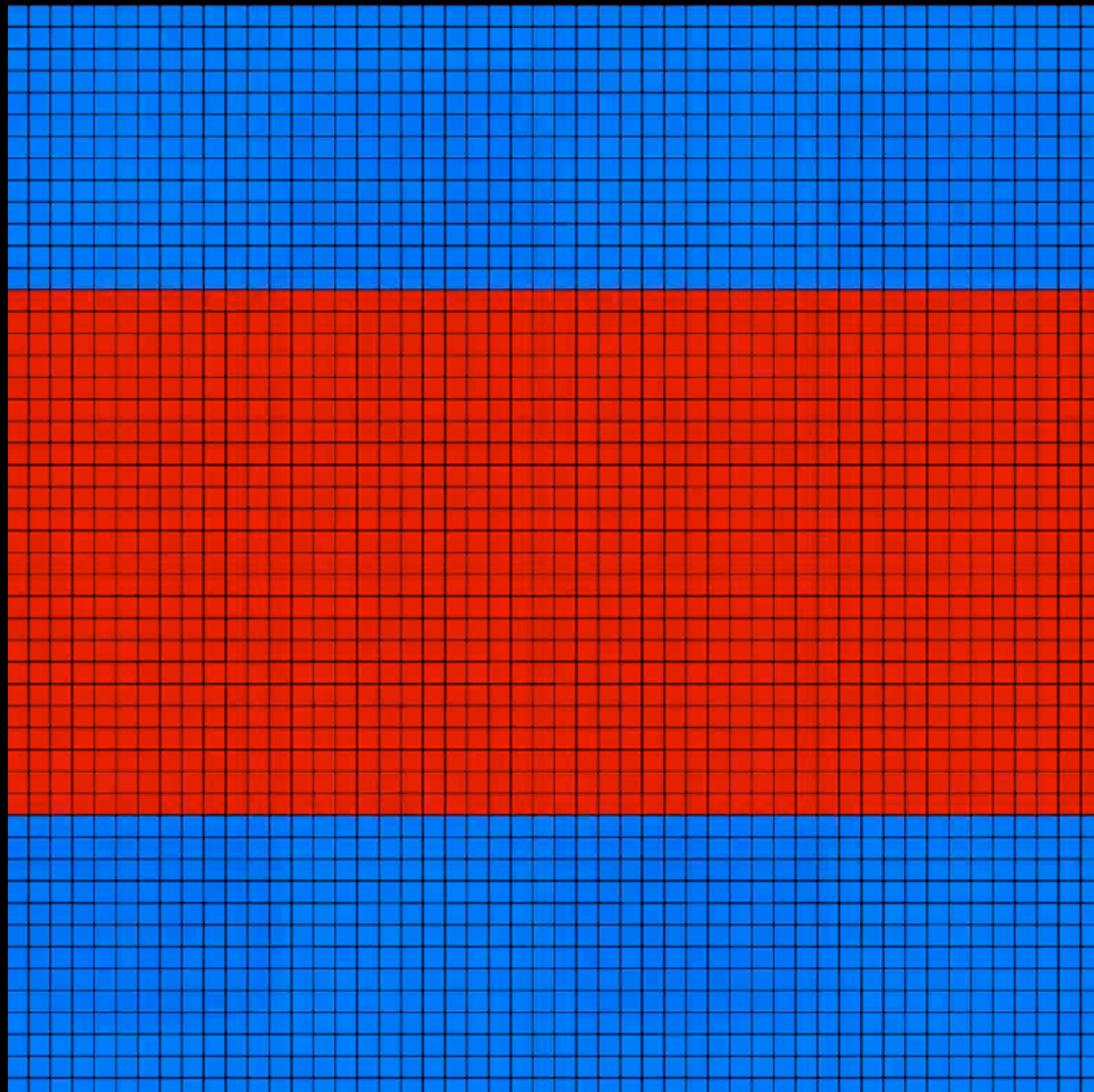
- less accurate gravity solvers
- not Galilean invariant
- discontinuous refinement
- refinement criteria
- less flexible geometries

Mostly complementary attributes

Hybrid approach: moving mesh AREPO (Springel 2010)



- Voronoi tessellation of the computational domain
- Locations, motion of mesh-generating points arbitrary
- AREPO can mimic pure Lagrangian, static mesh & AMR codes
- If mesh-generating points move with fluid velocity: Galilean-Invariant
- Example: Kelvin-Helmholtz instability on 50 x 50 mesh



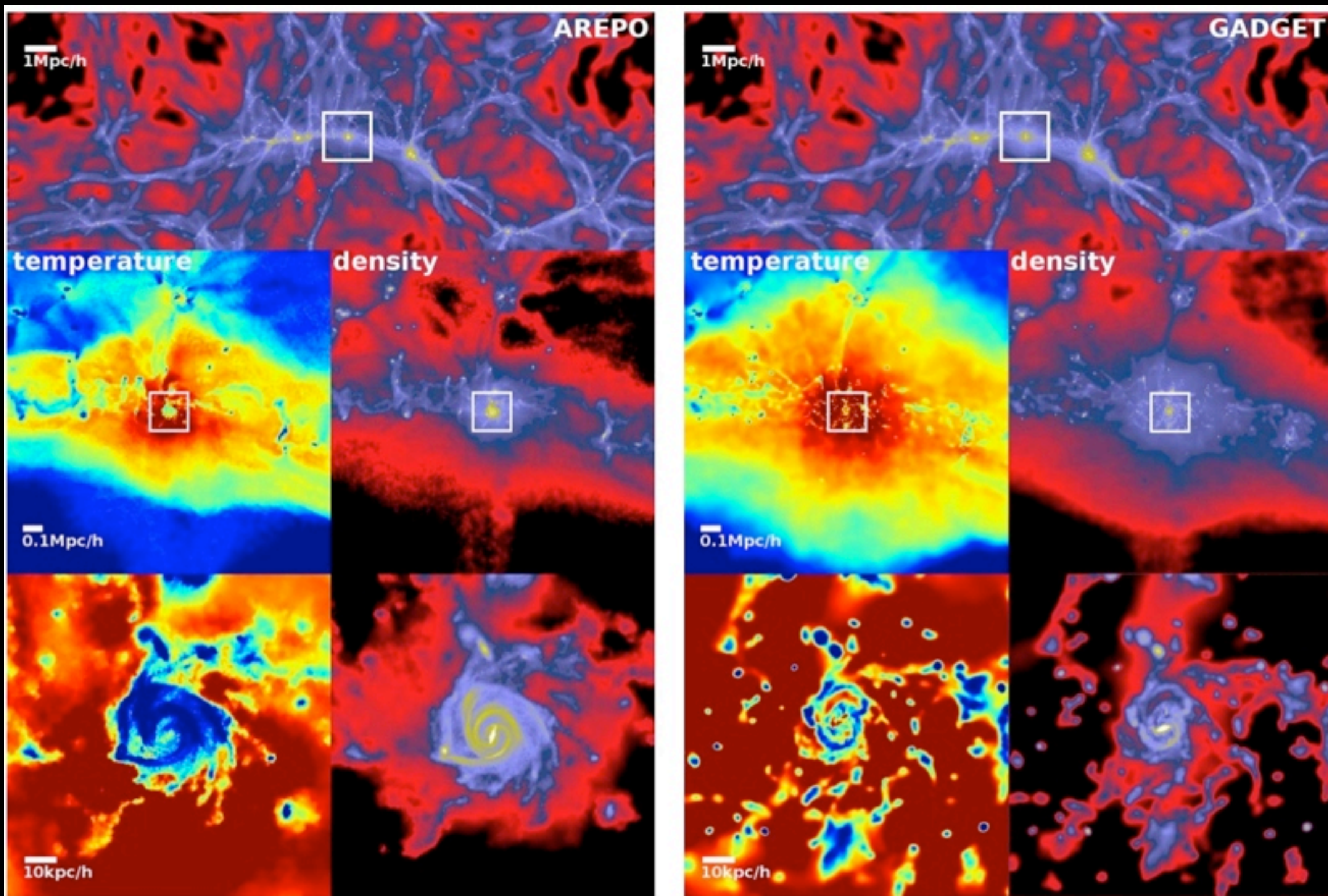
From V. Springel

Cosmological simulations with moving mesh and SPH

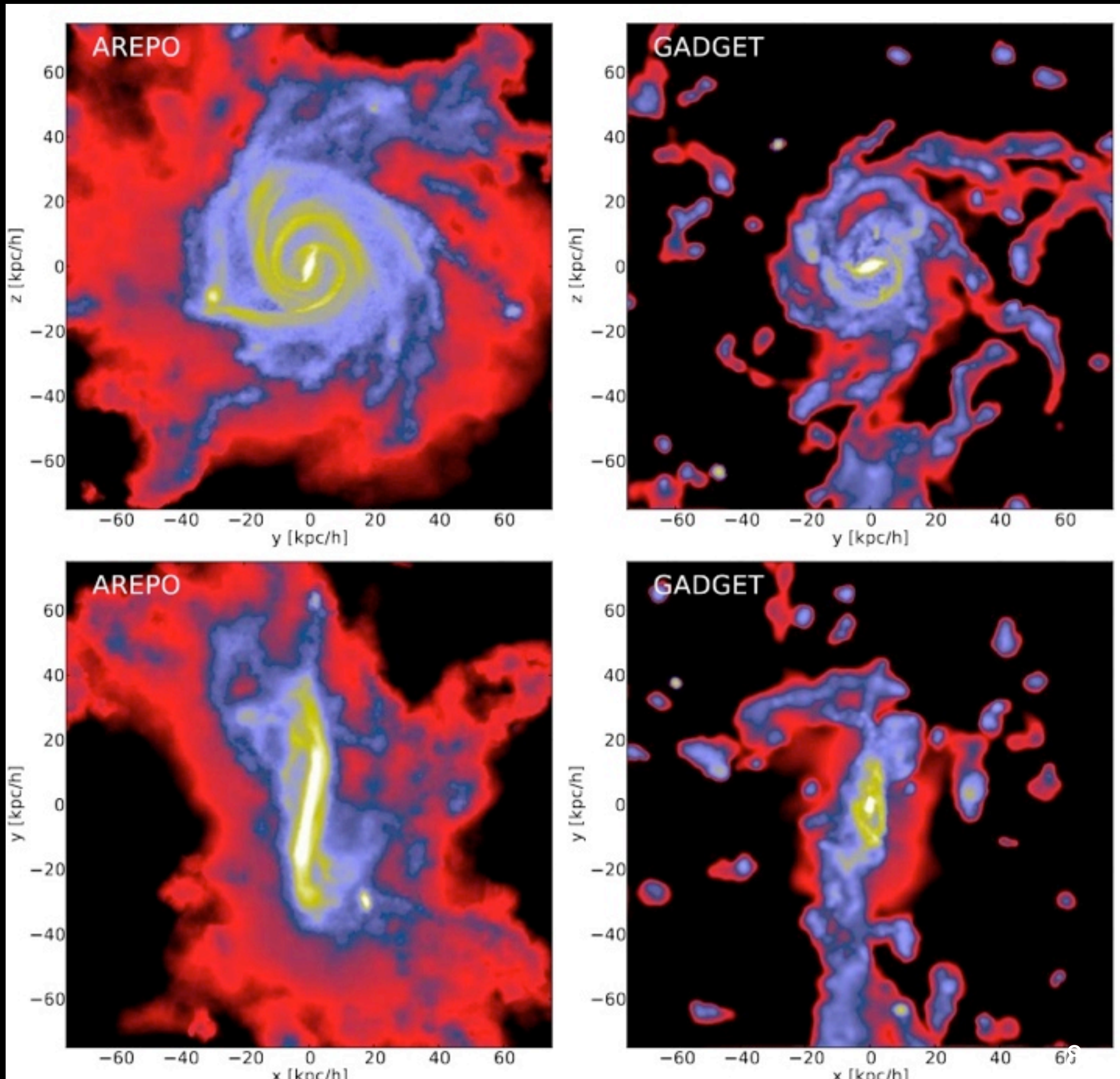
- Moving mesh code AREPO and SPH code GADGET-3.
- Start with the same ICs: 20/h Mpc box realized with 2x128^3, 2x256^3, 2x512^3 particles/cells:
  - ΛCDM cosmology, UV background, primordial cooling curve.
  - Star formation prescription in pressurized medium of Springel & Hernquist (2003), no outflows from galaxies.
  - Standard implementations, no parameter change to make results agree.
- AREPO is built on GADGET frame: uses the same gravity solver.
- AREPO in Lagrangian mode: relatively constant mass in a fluid element, set to be similar to SPH particle mass.
  - We add refinement and de-refinement, that are only occasionally applied to keep the mass in cell even closer to SPH mass over time.

Results on different scales

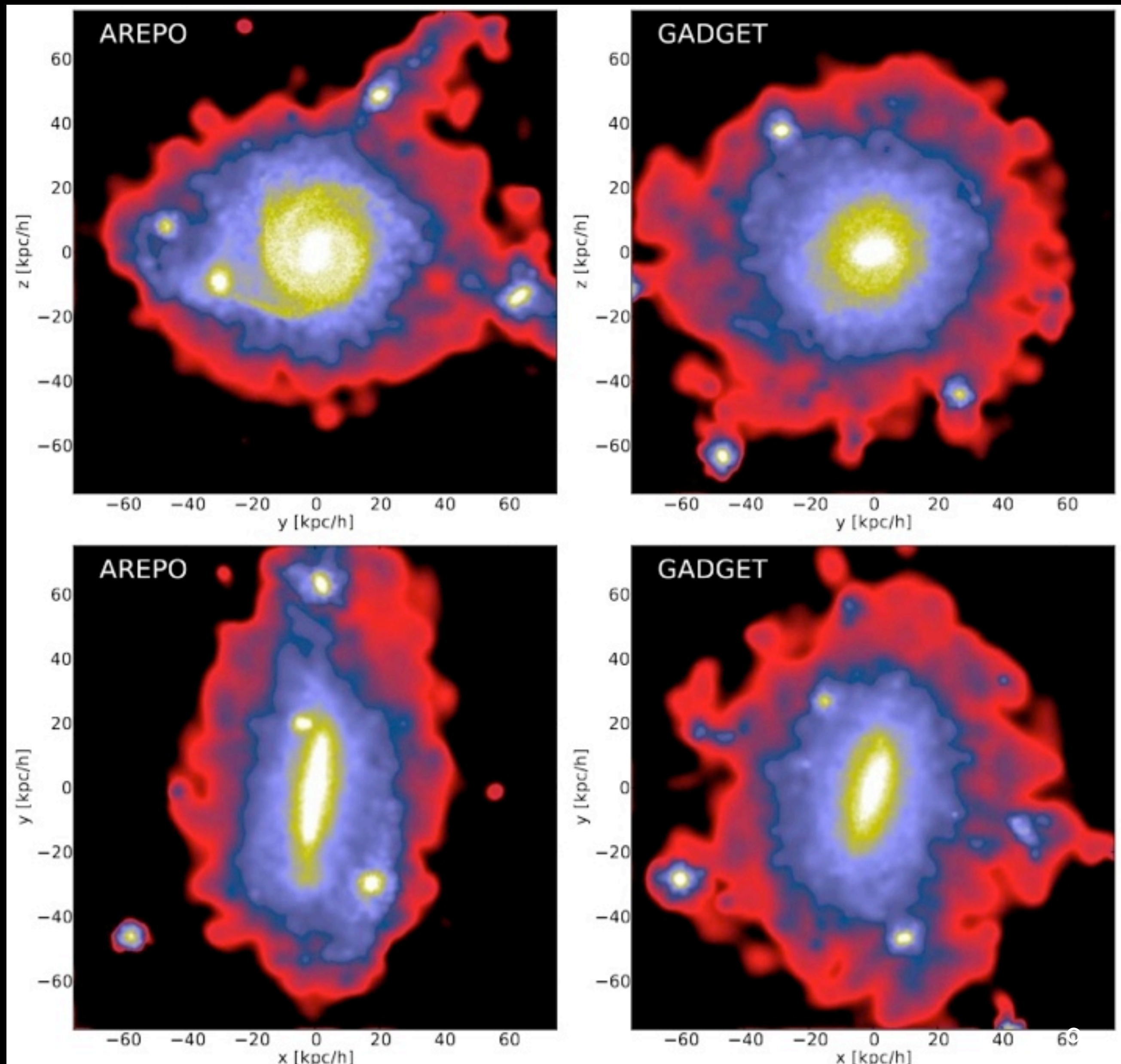
- *AREPO runtimes are only ~1.2-1.5 times slower than GADGET*



Extended disks, without ejective feedback...

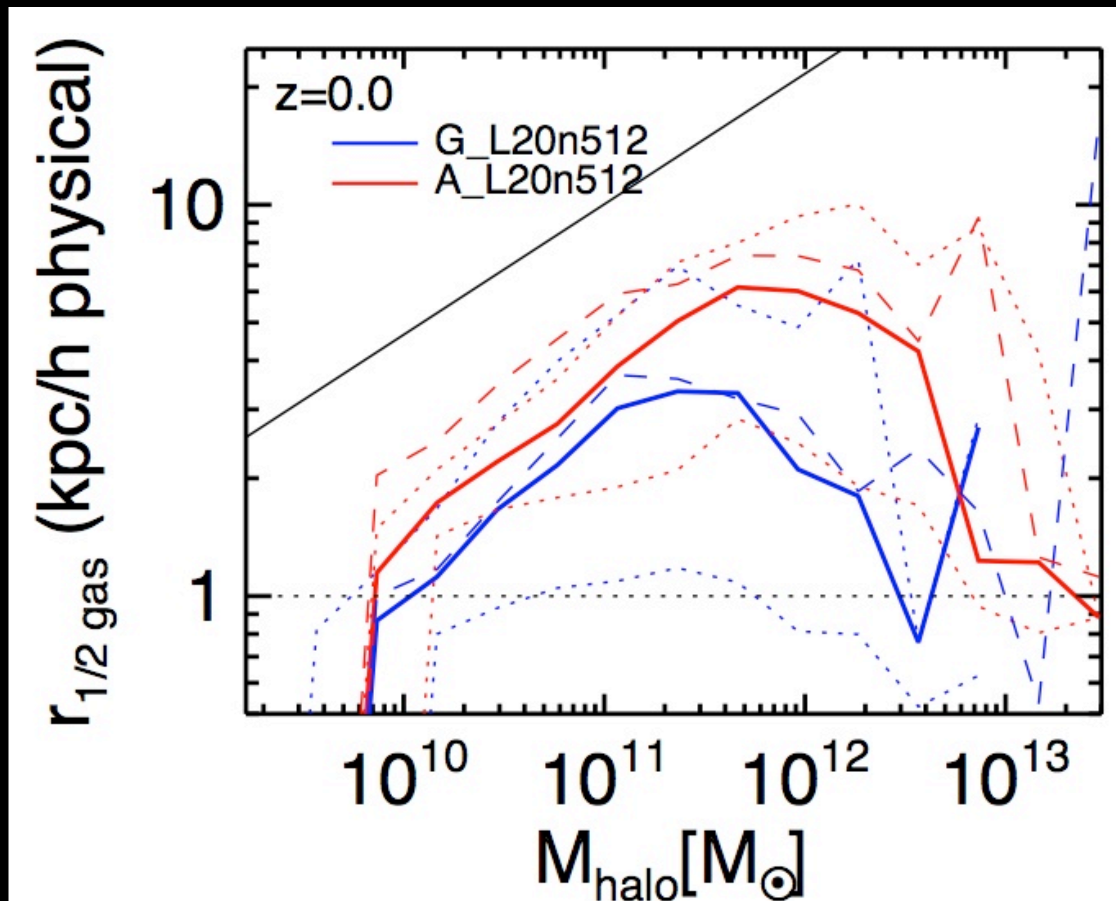


Stellar disks are also more extended



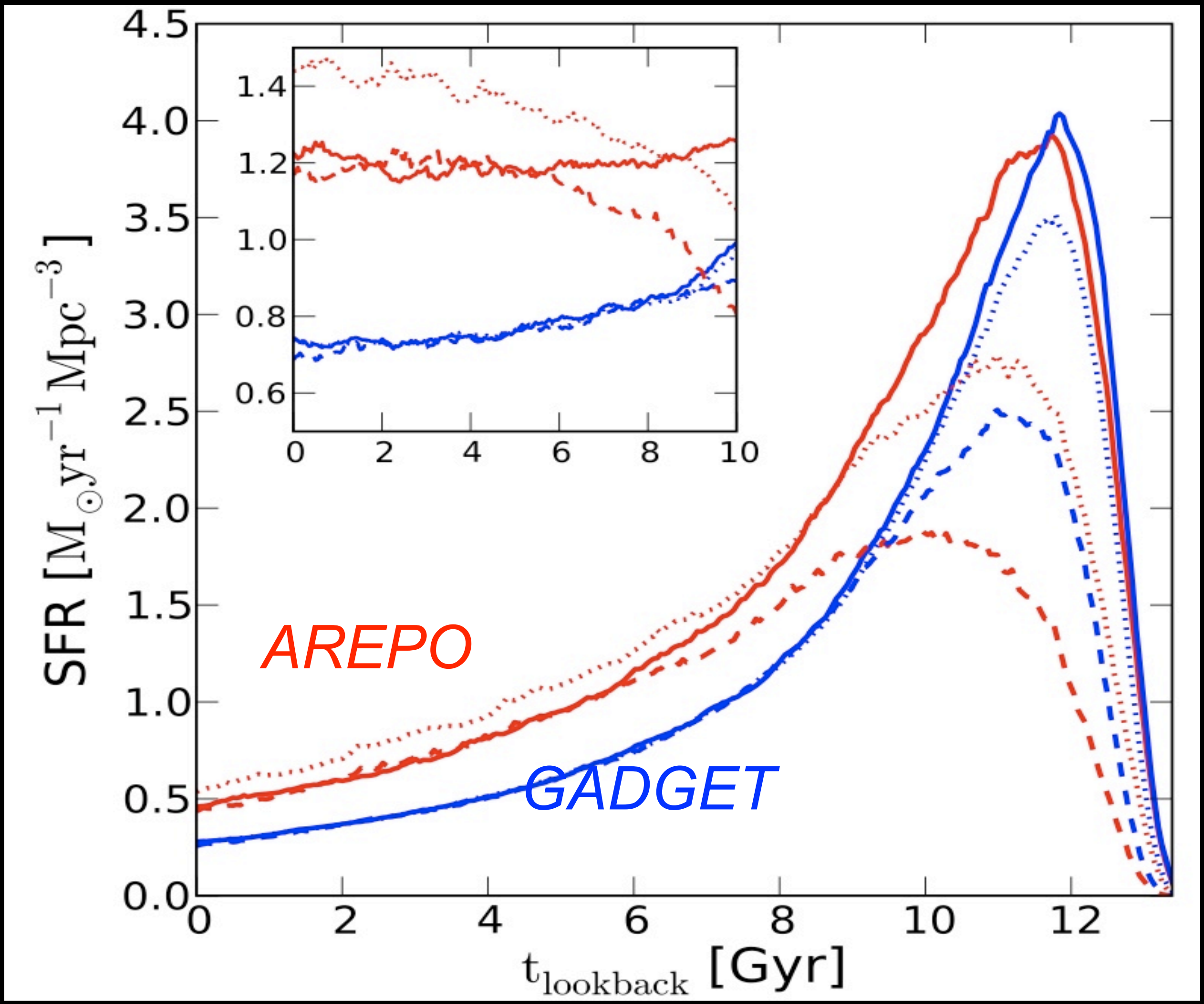
Radii of cold galactic gas

Gaseous disks of galaxies are systematically more extended in AREPO.



SFR-history

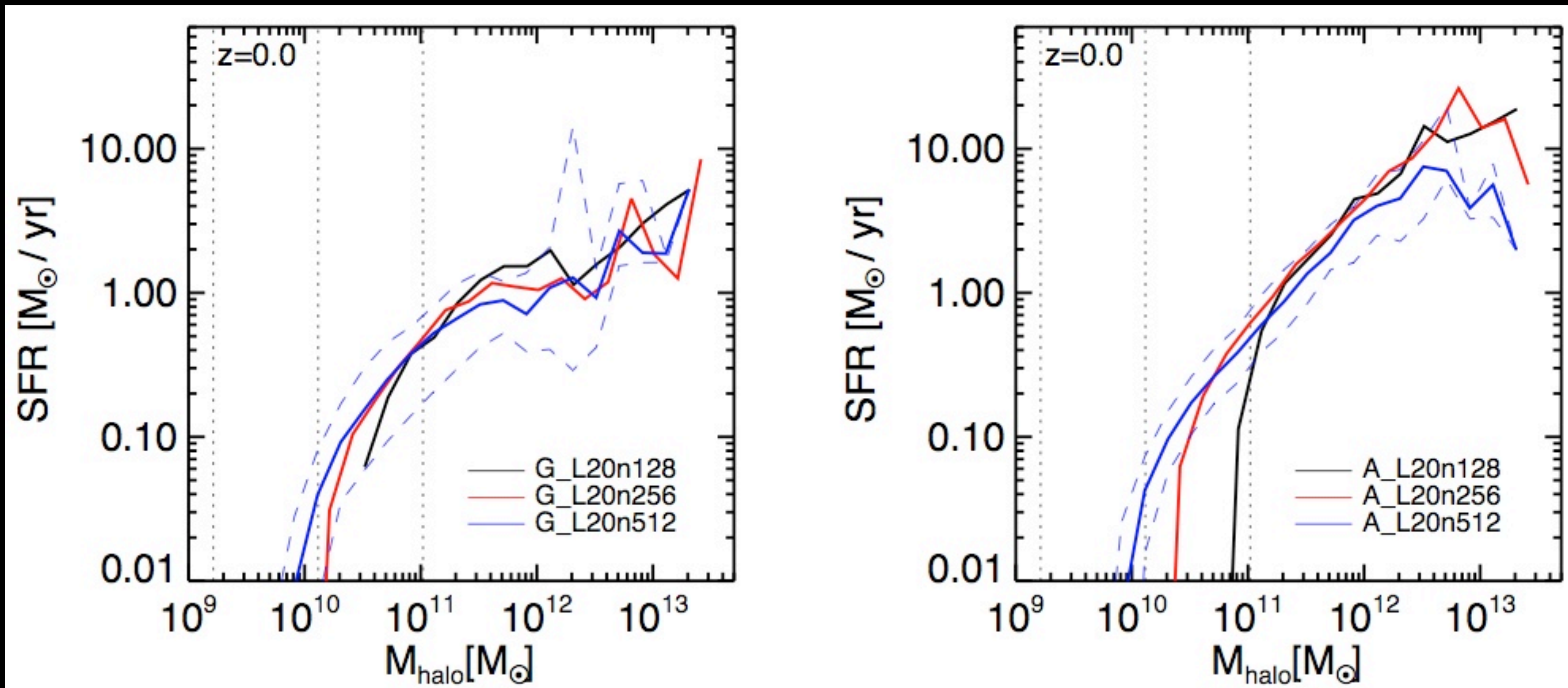
After z~3, AREPO runs have higher SFR density.



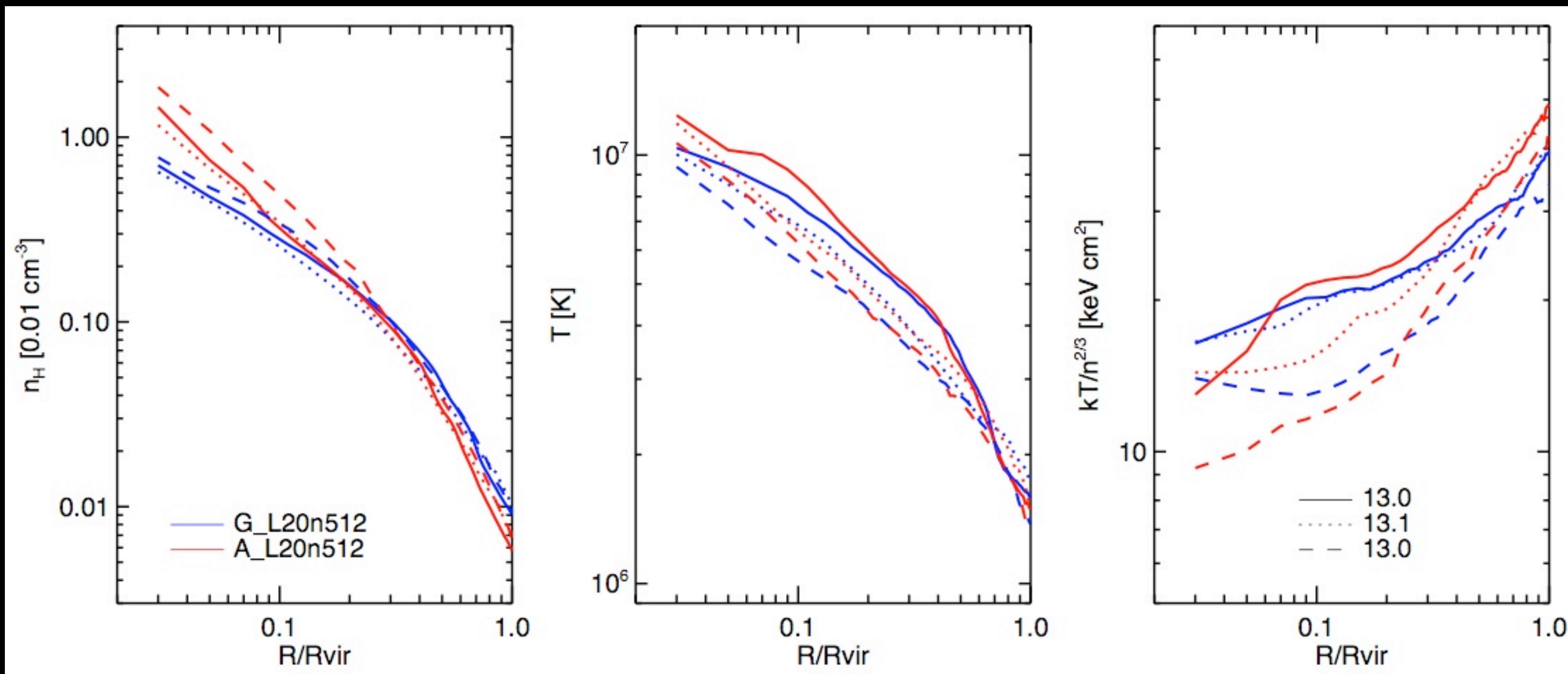
Higher SFRs in massive halos -> efficient hot gas cooling in AREPO

-Late time difference in global star formation is caused by massive halos

GADGET *AREPO*



Massive halos in AREPO have higher central densities and lower central entropies



z=0

What causes the differences?

- Sizes and efficient gas cooling in massive galaxies are likely connected.
- AREPO:
  - Extended, das rich disks are easily stripped in hot halos.
  - Stripped material will not loose angular momentum via dynamical friction like the rest of the infalling substructure (e.g. Maller&Dekel 2002)
  - It is efficiently mixed with hot gas, enabling more efficient cooling of hot halo.
- GADGET:
  - Harder to strip compact disks with lower gas fractions.
  - Clumps of gas form via cooling instability and from the stripped material.
  - These clumps survive too long owing to inability of SPH to properly capture hydro-instabilities (Agertz et al. 2007).
  - Clumps can heat the surrounding gas and loose angular momentum during the infall.
  - This process can lower cooling efficiency of the hot gas and cause transfer of angular momentum to the hot gas.
- Large differences in energy dissipation of sub-sonic turbulence in the halo infall region and differences in shock capturing create stronger heating of gas at intermediate radii in GADGET.

CONCLUSIONS

- AREPO is a very efficient code, suitable for cosmological simulations of galaxy formation.
- Gas in centers of hot halos in AREPO cools more efficiently than in the SPH code GADGET.
- Specific angular momentum of galactic gas is higher and more aligned in AREPO -> more extended, regular, gaseous disks.
- AREPO will likely improve our understanding of important aspects of galaxy and IGM evolution (e.g. disk formation, halo absorbers, hot mode accretion and more).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Transition from cold to hot halos