Project EXAMAG

Universität Heidelberg | Heidelberg Institute for Theoretical Studies HITS | Julius-Maximilians-Universität Würzburg

Exascale Simulations of the Evolution of the Universe including Magnetic Fields

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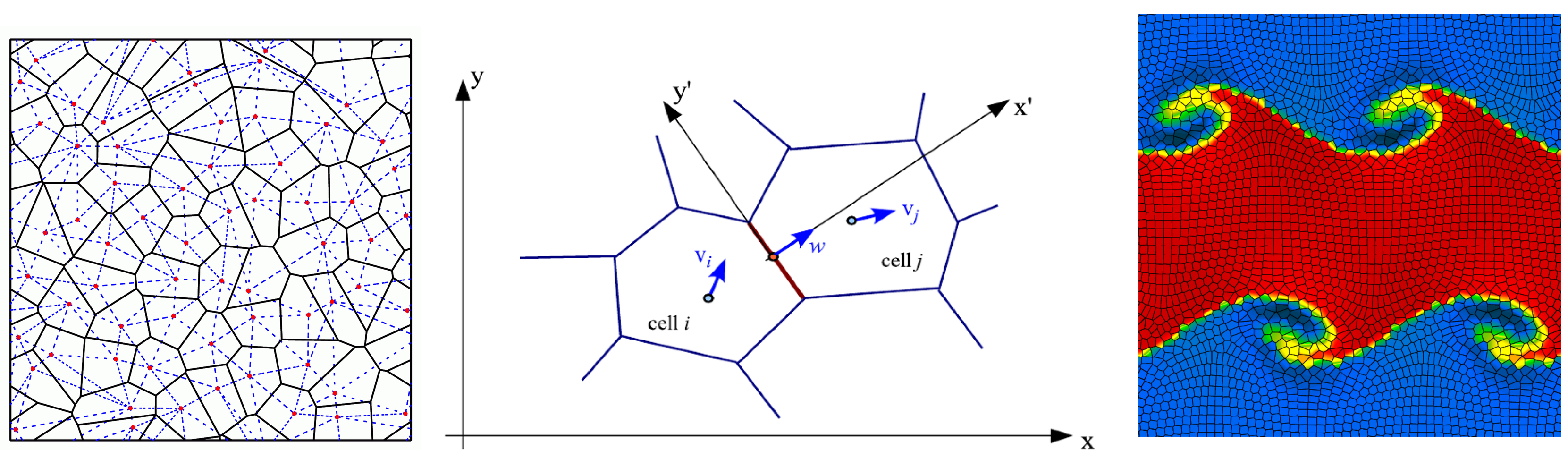
Key Science Drivers

- Can galaxies form successfully from ΛCDM cosmological initial conditions?
- What role do magnetic fields and anisotropic thermal conduction play in cosmic structure formation?
- How do we arrive at highly accurate and extremely scalable hydrodynamical algorithms for astrophysical fluid dynamics?
- Do novel discretization schemes for astrophysical hydrodynamics offer significant cost/accuracy advantages?

Cosmology relies on the exploitation of HPC techniques on the largest supercomputers

The AREPO code – an innovative technique



Finite-volume hydrodynamics on a fully adaptive and dynamically moving Voronoi mesh, yielding quasi-Lagrangian behavior. The code is coupled to a powerful TreePM solver for self-gravity and the additional treatment of a collisionless fluid (dark matter).

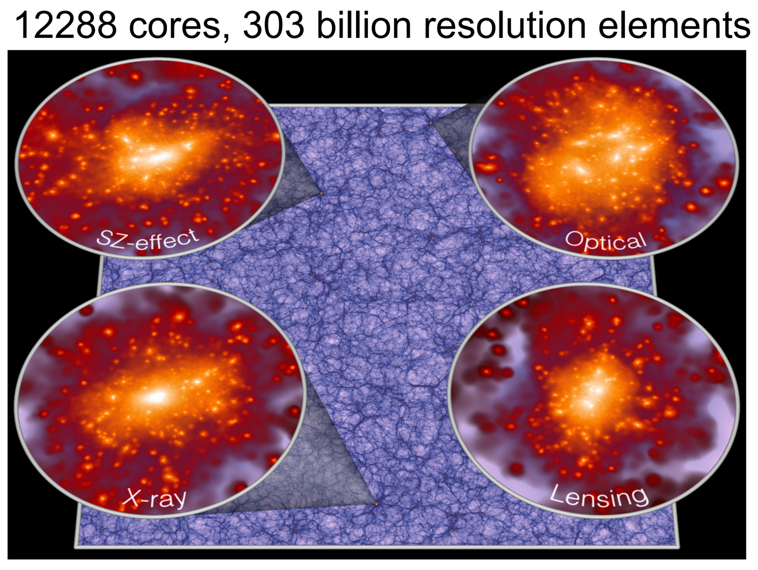
Advantages of this approach

- Very low numerical viscosity, greatly reduced advection errors
- Provides a crucial improvement over the SPH technique
- High accuracy for shocks, fluid instabilities and turbulence
- Full adaptivity and manifest Galilean invariance
- Makes larger timesteps possible in supersonic flows

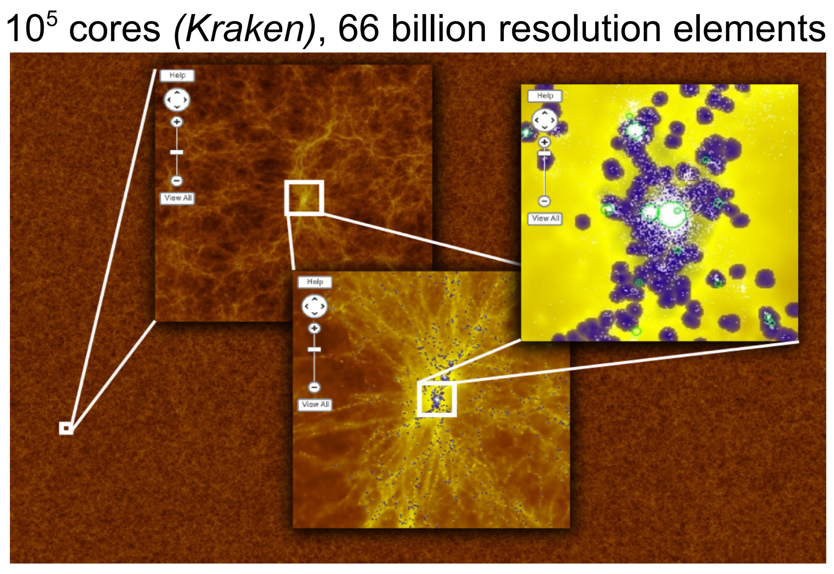
Current code status and previous work in this field

The GADGET code of the PI has been used for the worldwide largest calculations in cosmology, and is presently the most widely used code in the field

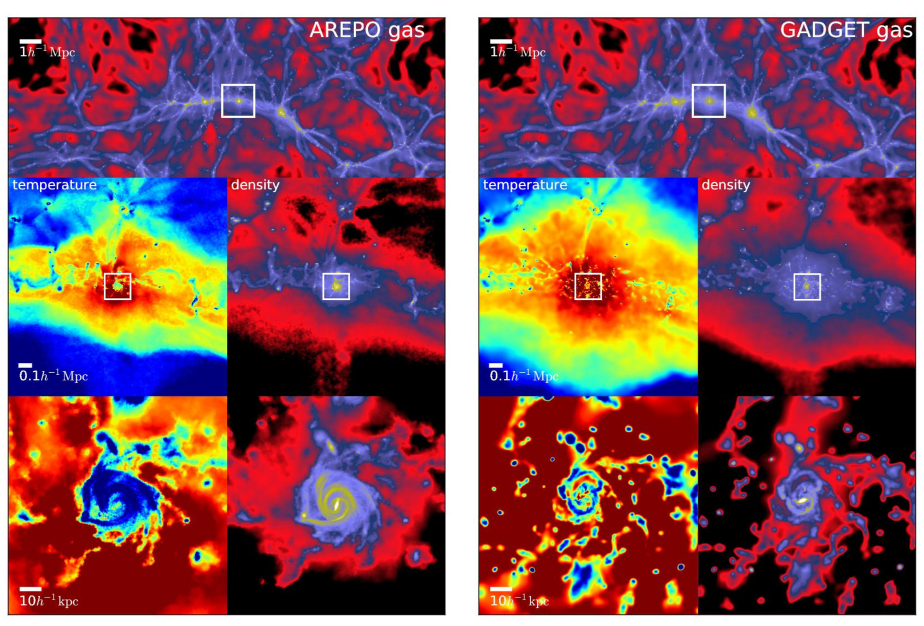
***Millennium XXL* Simulation**
12288 cores, 303 billion resolution elements



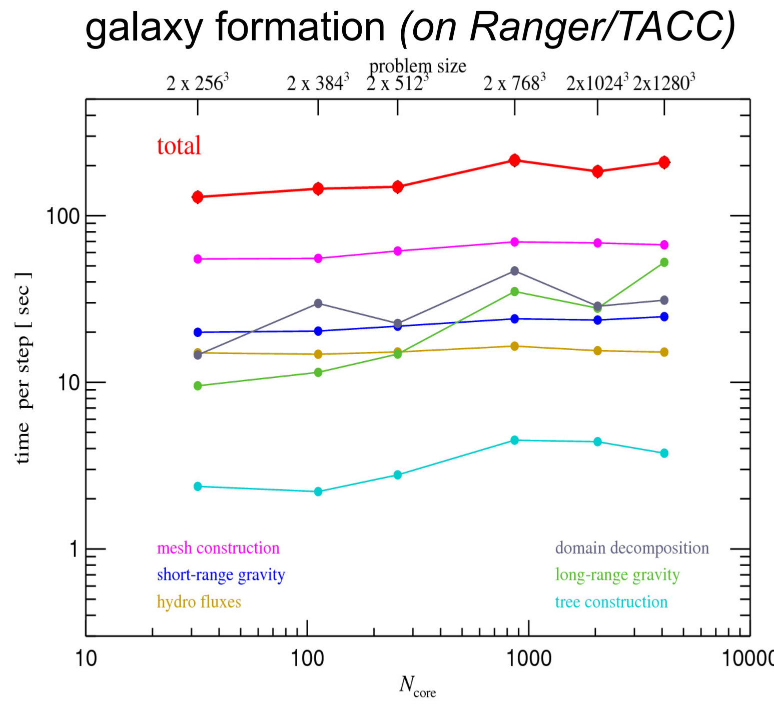
***MassiveBlack* Simulation**
10^5 cores *(Kraken)*, 66 billion resolution elements



Cosmological applications of AREPO demonstrate its large accuracy gain with respect to the traditional SPH technique



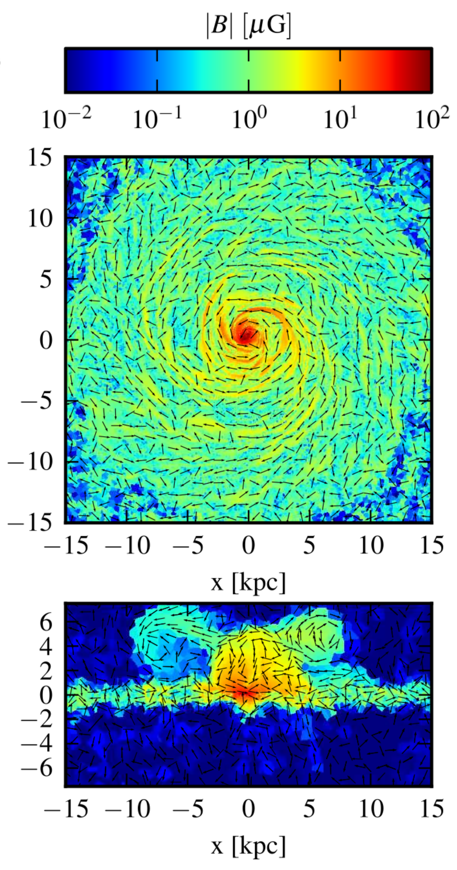
Scalability of the current MPI-only version of AREPO for simulations of galaxy formation *(on Ranger/TACC)*



Area 1 – achieving exascale scalability

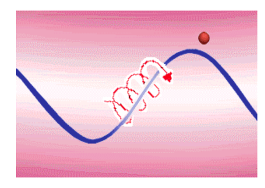
- Need multi-treading in all parts of the code
- Preparation for many-core architectures
- Develop alternative mesh-construction algorithm
- Implement GPU support for gravity and mesh calculation
- Prepare for MPI-3 and fault-tolerant/redundant calculations
- Improve ability to do on-the-fly data reduction and postprocessing

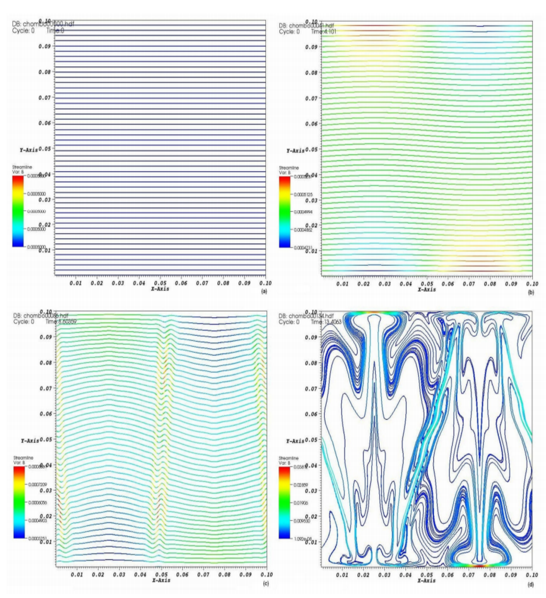
Area 2 – improving magnetic field solvers



- Magnetic fields are crucial for the regulation of star formation and accretion, and for the intracluster medium
- The div B = 0 constraint is difficult to guarantee numerically
- New numerical solvers that are robust on unstructured moving grids need to be developed and implemented
- New positivity preserving schemes for fluid dynamics desirable for improved robustness

Area 3 – anisotropic thermal conduction

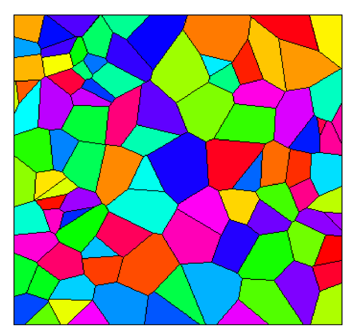




Li, Frank & Blackman, 2012, ApJ, 748, 24

- Magnetic fields channel heat transport through electrons along field lines
- The magnetothermal (MTI) and heat-flux driven buoyancy instability (HBI) induce cluster turbulence
- Cosmological simulations combining magnetohydrodynamics and anisotropic thermal conduction largely unexplored
- Crucial impact on IGM and ISM is expected

Area 4 – discontinuous Galerkin (DG) solvers



- Stable and locally conservative
- Can deliver high-order accuracy
- Can easily handle complex geometries
- Highly parallelizable for hyperbolic problems

Great potential for applications in astrophysics, yielding more accurate solutions at lower computational cost

Work plan

Postdoc (Heidelberg):
Will lead the scaling work on the code

PhD Student (Heidelberg)
Carries out state-of-the art application studies of magnetic fields in cosmology

Postdoc + PhD (Würzburg):
Develop discontinuous Galerkin solver in the AREPO code framework and improve the magnetic field discretization

Postdoc + PhD (Würzburg)
Develop treatment of anisotropic conduction and study its physics applications

Longer-term perspective

- Public release of the AREPO code (like GADGET)
- Include radiative transport
- Investigate applications outside astrophysics

SPPEXA — DFG Priority Program 1648