Cosmological Simulations
and
their Analyses

S.R. Knollmann

Universidad Autónoma de Madrid
Outline

Introduction

Numerical Cosmology

Analysis/Halo Finding

Summary&Outlook

In collaboration with:

Alexander Knebe (UAM)
Gustavo Yepes (UAM)
Stefan Gottlöber (AIP)
Cosmology
Numerical Cosmology means: *Simulating structure formation in the Universe*
Numerical Cosmology

means: Simulating structure formation in the Universe
The Equations

\[
\frac{d \mathbf{x}}{dt} = \mathbf{v}
\]
\[
\frac{d \mathbf{v}}{dt} = -\nabla \Phi
\]
\[
\Delta \Phi = 4\pi G (\rho_{\text{tot}} - \bar{\rho}_{\text{tot}}) a(t)
\]
\[
\frac{\partial \rho}{\partial t} + \nabla (\rho \mathbf{v}) = 0
\]
\[
\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla (\rho \mathbf{v} \cdot \mathbf{v}) + (p + \frac{B^2}{2\mu}) 1 - \frac{1}{\mu} \mathbf{B} \cdot \mathbf{B} = -\rho \nabla \Phi
\]
\[
\frac{\partial (\rho \mathbf{E})}{\partial t} + \nabla (\mathbf{v} (\rho \mathbf{E} + p + \frac{B^2}{2\mu}) - \frac{1}{\mu} \mathbf{B} (\mathbf{v} \cdot \mathbf{B})) = -\rho \mathbf{v} (\nabla \Phi) + H \frac{B^2}{2\mu}
\]
\[
\frac{\partial \mathbf{B}}{\partial t} + \nabla \times (\mathbf{v} \times \mathbf{B}) = \frac{1}{2} H \mathbf{B}
\]
\[
\nabla \cdot \mathbf{B} = 0
\]

See, e.g. Doumler, 2009, Diploma thesis
The Equations

Monte Carlo integration
Up to $4096^3$ particles achieved

SPH or grid based
SPH: $1024^3$ particles
AMR: 42 refinement levels
Cosmological Simulations

Physical parameters:
- cosmology
- included physics

Technical parameters:
- boxsize $L$
- number of particles $N^3$

Get initial particle distribution.

Simulate.

Analyze.
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Halo Finding

Objective:
- identify bound structures
- treat substructures
Halo Finding

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- identify bound structures
- treat substructures
AHF: The AMIGA halo finder

...is a freely available multi-purpose halo finder

- using an adaptive mesh hierarchy to identify isodensity contours.
- using isolated grids to identify prospective halo centers
- nested grids give substructure naturally
- grow haloes around those centers
Using the AMR hierarchy
Using the AMR hierarchy
Using the AMR hierarchy
Using the AMR hierarchy
Parallelization

Requirement:
handling large amount of data
(DM+SPH+stars: $2 \times 10^{24^3} \sim 94$GB/snapshot)
→ parallel

Two parallelization levels:
- MPI domain decomposition along Hilbert curve + boundary buffer
- OpenMP within the sub-chunks (recent feature)
AHF: Parameters

- Size of Domain Grid

- Refinement Criterion Domain Grid

- Refinement Criterion refined grids
AHF: Parameters

- Size of Domain Grid

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- Refinement Criterion refined grids
Strong scaling (MPI only)

![Graph showing strong scaling for different halo finding algorithms.](image-url)
Weak scaling (MPI only)
Comparison to other halo finders
Comparison to theory: Mass function

![Graph showing comparison to theory: Mass function](Image)
Comparison to theory: Subhalo mass function

\[ N(\Delta M) \text{ vs. } \frac{\text{Mass } [M_{\text{sat}}/M_{\text{host}}]}{10^2} \]

K&K, 2009
Summary:

- freely available simulation codes (Gadget2[-3], RAMSES,...) are very efficient and sophisticated today

- data handling and analysis tools are only slowly catching up

- AHF:
  - freely available MPI(+OpenMP) parallelized halo finder
  - multi-purpose: handles DM+SPH+stars
  - flexible input routines (relatively straight forward to support different file formats)

Outlook/Challenges:

Simulation codes:
- scalability and load-balancing
- more (reliable) physics

Analysis tools:
- more sophistication in halo indentification and substructure treatment
- IO?
- optimizing, optimizing, optimizing...
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