Galaxy Formation and Evolution through simulations and SAMs

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8 June 2011

Outline

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Cosmological Introduction

Let's gain some perspective

- Theoretical framework: the ΛCDM model
- Flat geometry
- $\Lambda \rightarrow$ Accounts for accelerating expansion
- CDM $\rightarrow$ Accounts for gravitational evolution
- Bottom-up hierarchical scenario
- Collision and accretion process $\rightarrow$ halos from small to large

Simulations and SAMs

Two approaches: Simulations and Semi-analytic models

SA Models Physical assumptions, good resolution and dynamic range

- Good to understand underlying processes driving evolution
- Computationally unexpensive (compared to simulations)

Simulations Direct numerical integration, light wick and step aside

- Gravitational component very accurate
- Lack resolution
- Computationally **horrible**

Outline

Semi-analytic models I

Main features

- Made of recipes based on physical models of reality
- Fine-tuning iterative process → Test assumptions to see which best fits observables
- Pre-calculate a merger tree
  - Using a formalism (EPS, ST)
  - Using simulations (latest tendency)
- Run model into merger tree

Recipe

Cosmology $h, \Omega_\Lambda, \Omega_m, \Omega_k$, etc. WMAP $\rightarrow$ great time saver

Dark haloes How to describe clustering of dark matter? Press-Schechter, N-body?

Gas cooling Decrease of internal energy of gas due to radiative processes. Also, conservation of angular momentum to form disc, etc.

Star formation Population-III stars, Star formation efficiency, IMF...

Feedback Energy and matter feedback from SNs and AGNs. Heating, winds IGM chemical enrichment...

SAMs pros and cons I

Cool!

- Good at reproducing statistical observed properties
- Large dynamic range of scales
- Effectively no resolution limit
- Not very resource-consuming

SAMs pros and cons II

Not so cool

- Assumptions and simplifications in treatment of gas to obtain simple analytic solutions to complex hydrodynamical processes
- Arguably, too many free parameters
- Compensate inadequately modeled process by tuning competing one $\rightarrow$ wrong physics!
- Does not provide info on actual spatial distribution

Cosmological SAM works I

AMIGA Fully analytic, focused on cosmological evolution of IGM at high redshifts

Santa Cruz By Primack and Somerville

- Uses Monte-Carlo to build the merger tree (EPS)
- Cosmology fitted COBE data, probably updated by now
- Article with detailed description of recipes

Cosmological SAM works II

GALFORM Durham group

- Monte-Carlo, again
- Good with density profiles of DM haloes and gas

Galacticus By A. Benson (Caltech)

- Free, open source
- Very modular
- Provides parameter sets with versioning, ongoing search
- Youtube Channel, Facebook page, very academic!

Outline

N-Body Simulations

Simulations of particles under influence of physical forces

Force routine Computes forces acting on each particle

Integrator Solves equations of motion to determine positions, velocities...

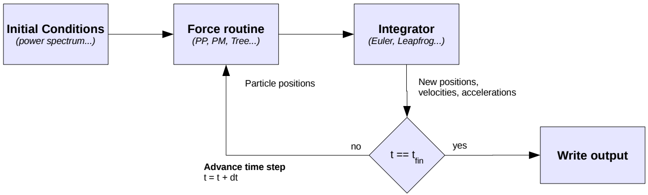

Figure: Flow chart for an N-body code

Force calculators

PP Particle-Particle, direct method, $O(n^2)$

PM Particle-Mesh, particles interact with mesh $O(n + n_g log(n_g))$

Tree Space divided incrementally depending on density $O(nlog(n))$

P^3M Hybrid method, PM for larg-scales and PP for small-scales

Integrators

Euler 1st order, calculate all values at each time step

Leapfrog 2d order, calculate velocities and positions interleaved in time steps

Symplectic Based on canonical transformations

Runge Kutta Iterative approach

SPH

Smoothed-Particle Hydrodynamics

Used to simulate fluid flows, such as gas

- Fluid divided into discrete elements, referred to as particles, from which continuous properties are derived
- Particles have a *smoothing length*, h, over which physical properties are smoothed by a kernel function, W
- Contribution of particle to a property weighted according to distance and density

$$F(r_i) = \sum_{j=1}^{n} F_j \frac{m_j}{\rho_j} W(|r_{ij}|, h_i)$$

W: Gaussian function, cubic spline, etc.

Simulations pros and cons I

Cool!

- Few guessing, based on elemental physical principles
- Due to previous point, more reliable
- Accurate description of evolution in highly non-linear regime
- Fluid dynamics treated more realistically through SPH
- They are nice to watch!

Simulations pros and cons II

Not so cool

- Discrete model to represent rather continuous world (time step, particles, etc.)
- Resolution $\longrightarrow$ Difficult to model large volumes
- Sub resolution? Recipes = Free parameters to adjust
- Dynamic range limitations
- Computationally expensive in terms of memory and CPU time

Cosmological simulations

Virgo Consortium Founded in 1994, formed by scientists in the UK, Germany, Netherlands, Canada, USA and Japan.

GADGET-2 Free, open source code. Tree+SPH. Starting point of many sims

Millenium 10 billion particles, cube of 2 billion light-years per side, based on GADGET-2

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Conclusions

- Presented two methods to study galaxy formation and evolution
- Both approaches display pros and cons
- Models lack understanding of physics to better adjust parameters
- Simulations lack computer power and must go into sub-resolution
- SIMs and SAMs should be complementary!

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