Numerical Simulations in Cosmology

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May, 200

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October 8, 2009
In The Beginning

- N-body simulations (~100s particles) – to study Cluster formation
  - Cold collapse produces too steep a density profile (Peebles 1970)
  - Distributing mass unequally to galaxies => unobserved mass segregation. EVIDENCE for DM, & its location. (White 1976)
  - Could not get substructure to survive (due to POOR resolution)
- Today’s codes existed, but were impractical to implement due to poor computing power
How To Simulate?

- Pick size of universe to model ($L \sim \text{Mpc}$)
- Pick number of particles you CAN calculate for
- Usually set up a mesh (grid) in phase space, and track particles via evolution of phase space
  - Mesh cell size $= \frac{2\pi}{L}$
Techniques

- **PP**  
  Particle-Particle

- **PM**  
  Particle-Mesh

- **P³M**  
  Particle-Particle/Particle-Mesh

- **TREE**  
  (not an acronym)

- **ART**  
  Adaptive Refinement Tree
Techniques …

- PP – Standard, N-body, $N^2$ calculation of force between all particles.

- PM – tracks density and potential at each cell of a grid (mesh).
  - Fastest method
  - Applies to large number of particles
  - Has some sophisticated versions

- $P^3M$ – Adds small PP calculation for small scales
  - Limited by PP part (# calculations & small range forces)
Refinement

PHASE SPACE

\{i', j\} * 2\pi / L' \quad \{i, j\} * 2\pi / L

\[ L : L' : L'' = 1 : (3/32) : (5/96) \]
Refined Real Space
A Refined Technique

- TREE – Resolve local particles, but not distant ones. Flexible, Expensive, but variants are powerful

- ART – Adaptive Refinement Tree
  - Chooses whether to refine a cell, based on cell-overdensity
Resolution & Performance
Knebe et al 1999

For better resolution, expect higher contribution to $\xi(r)$ at small scales

$$N_{\text{steps}}/\text{dyn. range} \geq 1$$
$$N_{\text{steps}}/\text{dyn. range} \sim 2 \text{ for good performance}$$

<table>
<thead>
<tr>
<th>simulation</th>
<th>softening $(h^{-1}\text{kpc})$</th>
<th>dyn. range</th>
<th>steps</th>
<th>$N_{\text{steps}}/\text{dyn. range}$</th>
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Identifying Halos, Issues

- Large galaxy, small satellite
  - These halos essentially overlap
  - Look at density profiles and rotational velocity (?)

- Tidal Stripping
  - Mergers can strip a halo of 90% of mass
  - How to classify the remnant?
Identifying Halos, Techniques

- Friends of Friends (FOF)
  - bd/2

- DENMAX
  - Find a maximum in density, and look around at particles

- Based on overdensity
  - Find radius where overdensity is 200
Today’s best techniques are modifications of 3 codes (PP, PM, TREE). They are possible because of better computers.

Best resolution doesn’t always yield best results. Need to have sufficient time steps to cover the full dynamic range.

Identifying halos numerically is also not trivial.