Numerical Simulations in Cosmology

Anatoly Klypin
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Presented by:
Amruta Deshpande
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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 ~ 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 = $2\pi/L$**

Techniques

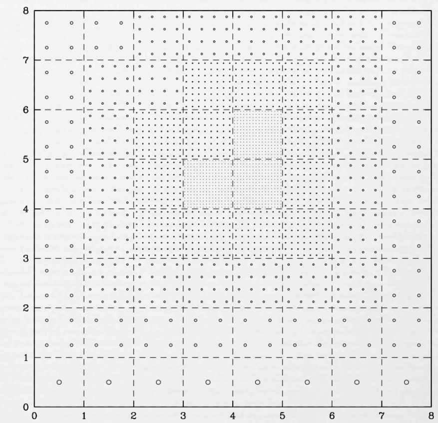
PP	Particle-Particle
PM	Particle-Mesh
P^3M	Particle-Particle/Particle-Mesh
TREE	(not an acronym)
ART	Adaptive Refinement Tree

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)

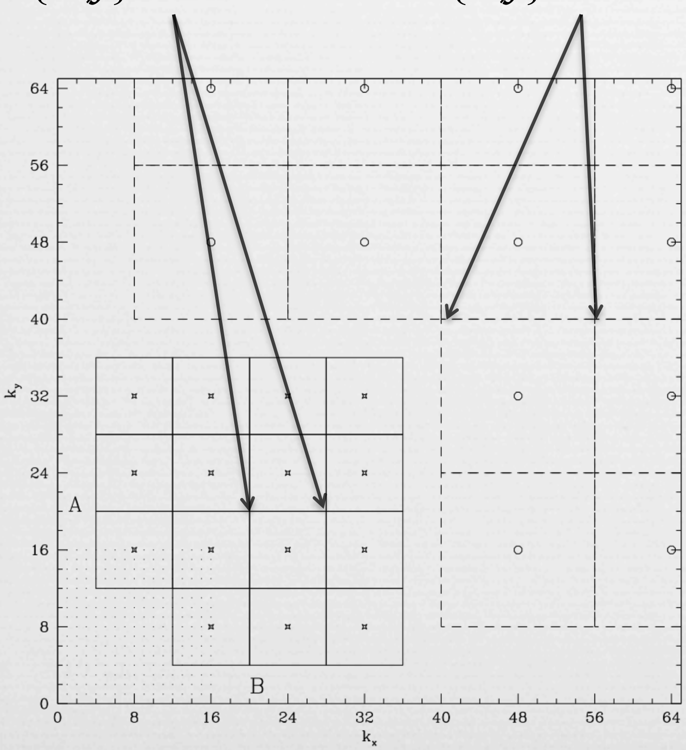
Refinement

REAL SPACE

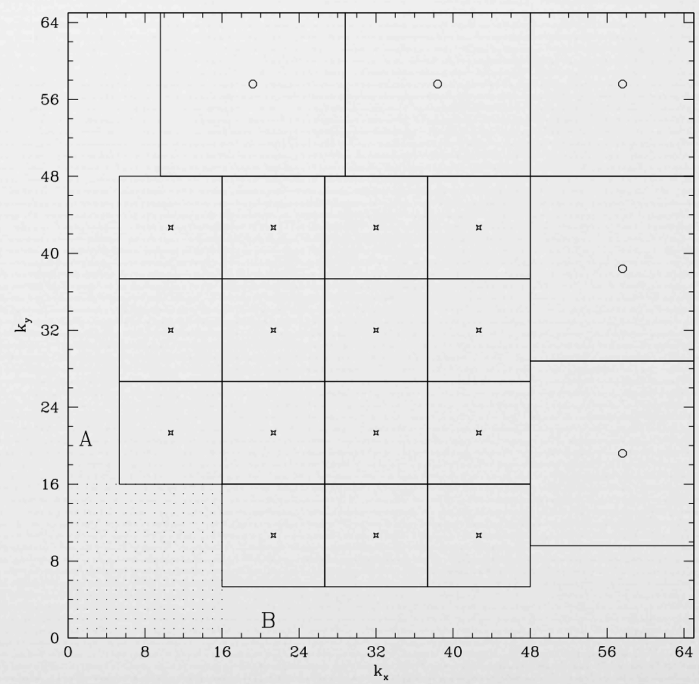


PHASE SPACE

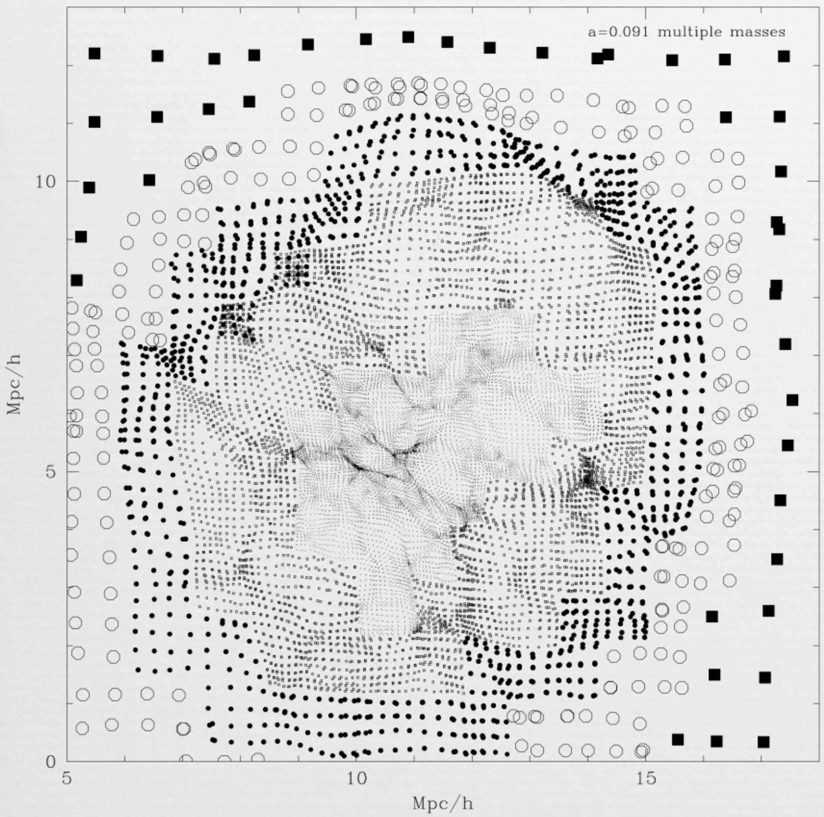
$\{i`,j\} * 2\pi/L`$ $\{i\ ,j\} * 2\pi/L$

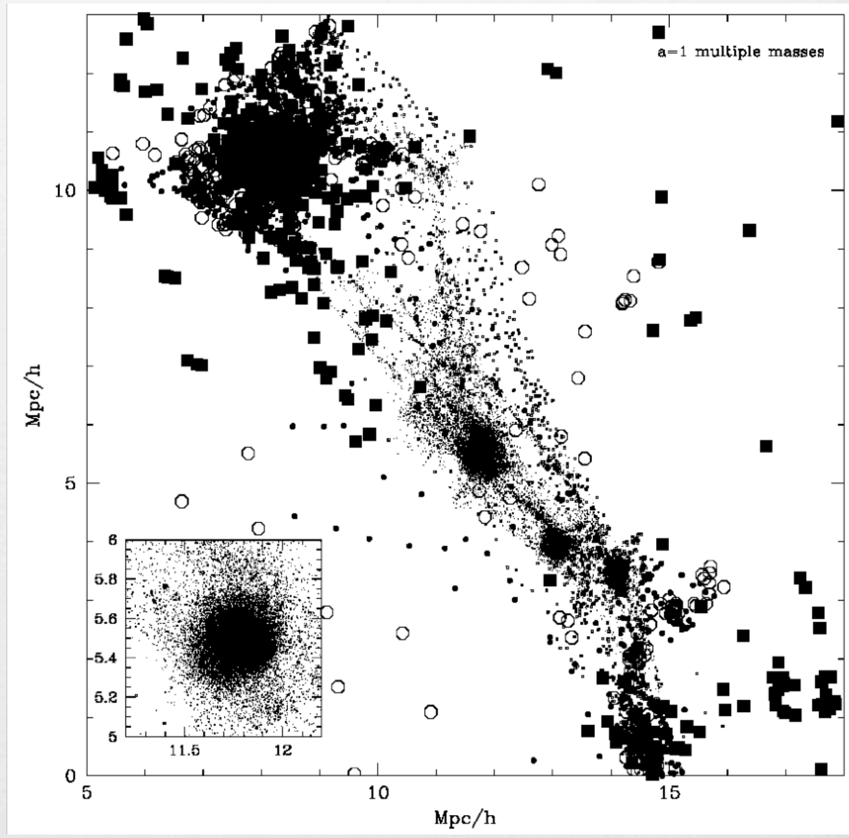


L : L` : L`` = 1 : (3/32) : (5/96)



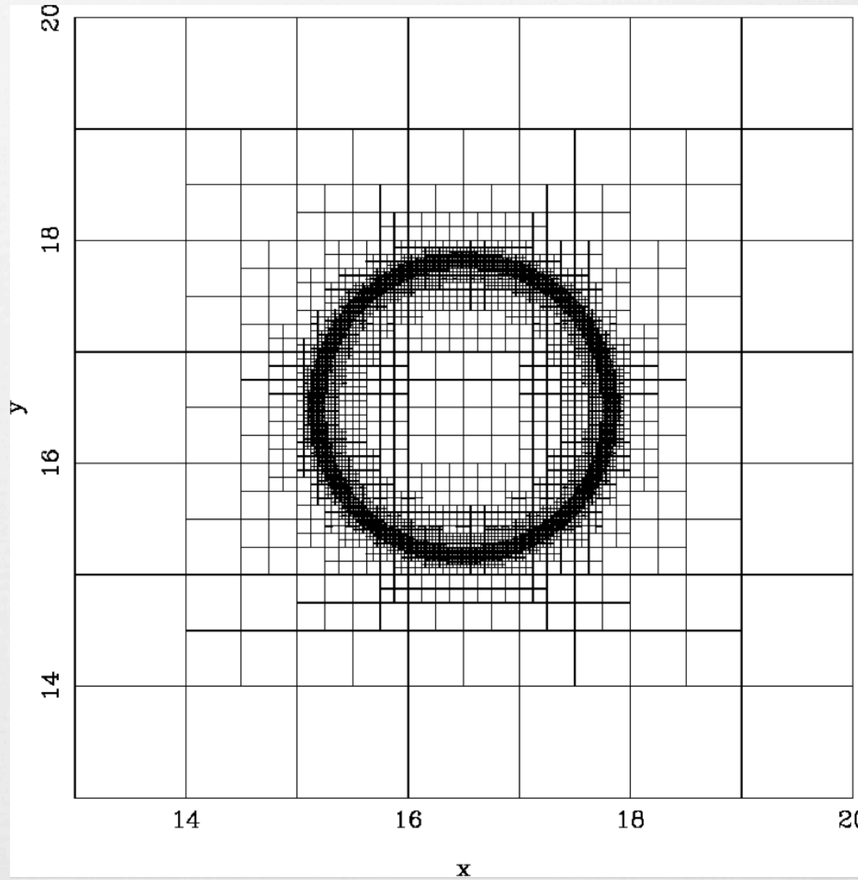
Refined Real Space





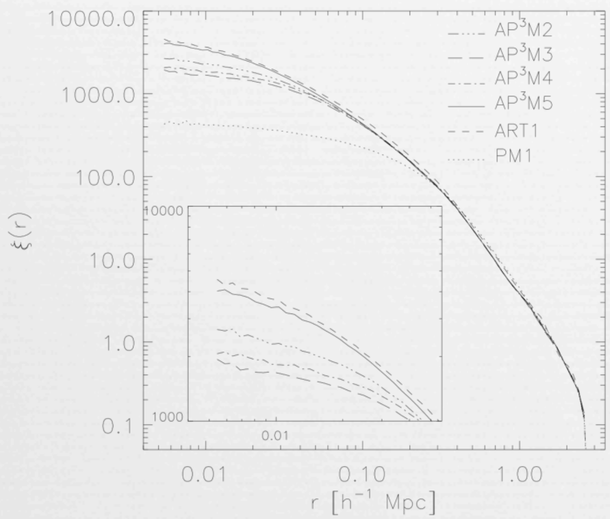
A Refined Technique

- 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 ξ(*r*) at small scales

N_{steps}/dyn.range at least ≥ 1
N_{steps}/dyn.range ~ 2 for good performance

simulation	softening (h^{-1}kpc)	dyn. range	steps (min-max)	N_{steps}/dyn.range
AP^3M_1	3.5	4267	8000	1.87
AP^3M_2	2.3	6400	6000	0.94
AP^3M_3	1.8	8544	6000	0.70
AP^3M_4	3.5	4267	2000	0.47
AP^3M_5	7.0	2133	8000	3.75
ART_1	3.7	4096	660-21120	2.58
ART_2	3.7	4096	330-10560	5.16

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

Summary

- 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