Analysing Cosmological N-body simulations

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Overview

- Visualising the large-scale structure
- Powerspectra
- Halo finders
- Subhalo finders

Every DM particle in a 256³ box is one pixel









Idea: Visualise projection of smoothed density field

- Adaptive smoothing: compute radius hsml of sphere with N_{ngb} (e.g. 32) neighbours.
 Efficiently possible with bisection algorithm and neighbour search via tree.
- Project on Cartesian mesh as sphere with radius html
- Visualise 2D smoothed density field



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- Additional trick: Weight the particle mass with its local density computed from hsml
- Use 2D colormap with local velocity dispersion (see Millennium image)



Powerspectra

Fourier modes of density contrast (FFT of binned density field):

$$\delta_{\mathbf{k}} = \frac{1}{M} \sum_{i} m_{i} \exp(i \, \mathbf{k} \cdot \mathbf{x}_{i}),$$

Power spectrum is the mean expected power per mode (1D average):

$$\hat{P}(k) = \left< |\delta_k|^2 \right>$$

Dimensionless form:

$$\Delta^2(k) = 4\pi k^3 P(k)/(2\pi)^3$$

Computation in large parts similar to PM gravity, smallest k= $2\pi/L$, largest k= $2\pi N_{grid}/L$ -> limited dynamic range

Single powerspectrum (Ngrid=4096)

Limited dynamic range, larger N in practice not possible



Folded powerspectra (Ngrid=4096)

Fold coordinates in box on smaller box, moves power spectrum to smaller scales



Powerspectra of cosmological simulation with L=300Mpc and N=2500³



The effect of baryonic physics on the matter powerspectrum



Friends of Fields Halo finder

Idea: group all particles together that can be connected by line fixed length

$$|\mathbf{x}_i - \mathbf{x}_j| \le b\Delta x = bL/\sqrt[3]{N}$$

 $b \approx 0.2$



Fast, arbitrary halo shapes, but no subhalos, can have linking bridges

Subhalo finder (SUBFIND)

- Estimate local DM density field
- Find local overdense regions with topological method
- Subject each substructure to a gravitational unbinding procedure



Gravitational unbinding

 $\frac{d\phi}{dr} = \frac{GM\left(< r\right)}{r^2}$

Idea: Use velocity information to remove unbound particles from halos

Force in spherical symmetry:

Integrate for potential:

$$\phi(r) = G \int_0^r \frac{M(\langle r')}{r'^2} dr' + \phi(0) \qquad \phi(\infty) = 0$$

Order particles with respect to distance from center:

$$\int_{0}^{r} \frac{M\left(\langle r'\right)}{r'^{2}} dr' = \int_{0}^{r_{1}} \frac{M\left(\langle r\right)}{r^{2}} dr + \int_{r_{1}}^{r_{2}} \frac{M\left(\langle r\right)}{r^{2}} dr + \dots + \int_{N-1}^{N} \frac{M\left(\langle r\right)}{r^{2}} dr$$

Remove unbound particles, i.e. with

$$v_i > v_{\rm esc}(r_i) = \sqrt{2 \left| \phi(r_i) \right|}$$

Repeat until no particles are removed anymore (center of mass velocity changes) Start with halos in leaves of the tree, then walk up the hierarchy

Hierarchy of substructure candidates

- Need to unbind the leaves of the tree first
- Once they are done, erase them from the tree and do the next generation of leaves
- Repeat until you're done



Other halo finders

30	1974	SO	Press & Schechter
	1985	FOF	Davis et al.
	1992	DENMAX	Gelb & Bertschinger
	(1994	SO	Lacey & Cole)
	1995	adaptive FOF	van Kampen et al.
	1996	IsoDen	Pfitzner & Salmon
	1997	BDM	Klypin & Holtzman
	1998	HOP	Eisenstein & Hut
	1999	hierarchical FOF	Gottloeber et al.
25	2001	SKID	Stadel
	2001	enhanced BDM	Bullock et al.
	2001	SUBFIND	Springel
20	2004	MHF	Gill, Knebe & Gibson
	2004	AdaptaHOP	Aubert, Pichon & Colombi
	2005	improved DENMAX	Weller et al.
	2005	VOBOZ	Neyrinck et al.
15	2006	PSB	Kim & Park
	2006	6DFOF	Diemand et al.
	2007	subhalo finder	Shaw et al.
	2007	Ntropy-fofsv	Gardner, Connolly & McBride
	2009	HSF	Maciejewski et al.
	2009	LANL finder	Habib et al.
	2009	AHF	Knollmann & Knebe
	2010	pHOP	Skory et al.
10	2010 2010 2010 2010	ASOHF pSO pFOF ORIGAMI	Planelles & Quilis Sutter & Ricker Rasera et al.
5	2010 2010 2010	HOT Rockstar	Ascasibar Behroozi
			ZZZ

1980-1990

1990-2000

2000-2010

1970-1980

Knebe et al. 2011: The Halo-Finder Comparison Project

Merger trees

