Dark matter halos in numerical simulations

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Dark Side II, 2008
Overview

• What is a dark matter halo?
• Why simulate dark matter?  Link $P(k)$ (@ high redshift) to:
  • Halo numbers (how many?)
  • Halo distribution (where?)
  • Halo internal structure
• Problems
  • Simulation difficulties
  • CDM difficulties
• Conclusions
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What are dark matter halos?

- Bound, collapsed, virialized, ellipsoids
- Hosts to galaxies, groups, and clusters
- Rotation curves, lensing, x-rays → Dark matter
- Overdensity $\Delta \sim 200$
Simulation Techniques

Cosmological parameters: $(\Omega=0.25, \Lambda=0.75, \sigma_8=0.9, H_0=73, n_s=1)$

$\sigma_8$: amplitude of power spectrum, (rms mass fluctuation of 8 Mpc/h spheres)

High-z (linear) gaussian random realization

Hi-z SNe, 2df, etc.

Evolve particles (gravity)
L-GADGET2 (PM-tree code V. Springel)
GASOLINE (Stadel, Wadsley, Quinn)
$z=3$
What is a halo?

friends-of-friends

\( \sim \) iso-density

link length \( \sim 0.2 \) lmean

\( \sim \) "universal" halo

mass function

\( f(\sigma_{\text{mass}}(m)) \) (Jenkins et al. 2001)
What is a halo?

$c=8.1 \text{ Mfof}/\text{Mso}=1.8$
What is a halo?

c=1.4 M_{fof}/M_{so}=1.37
What is a halo?

c=9.0  Mfof/Mso=1.15
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why simulate halos?

Cosmological probe:

**numbers:** e.g. halo numbers vs. cluster numbers

**clustering:** halo bias relates observable galaxies to underlying mass distribution ($p(k)$)

**internal structure:** satellite numbers, density profiles

Astrophysics: e.g. galaxy formation
Halos: Press & Schechter approach

- $P(k)$, initial gaussian random field of linear fluctuations
  - Spherical fluctuations grow (linear, $\Delta \rho/\rho$) until critical overdensity, $\delta_c=1.686$
    - enclosed mass collapses
    - halo forms

- $P(k) \rightarrow \sigma^2(M)$ (cosmology dependent)

$\Delta \rho/\rho$

$\delta_c$

$n(m,z)$

statistics (universality)

clustering
Solid: Sheth & Tormen fit/“prediction”: ellipsoidal collapse

Halo selection:
1-friends-of-friends
links together particles separated by < `1.1.'
1.1.=0.2 mean part. sep.

Reed et al 2003
The dark ages...

ionized, $z > 1100$ (CMB)

neutral $\rightarrow$ 21cm

reionized, $z \approx 6$

L. Hernquist
star formation in metal free gas

\[ T_{\text{vir}} > 10^4 \text{K}: \]
- Mhalo ≥ \( \sim 10^8 \) M\(_{\text{Sun}}\)
- Atomic cooling
  - Efficient
  - lots of stars?
  - 1\textsuperscript{st} galaxies?

\[ T_{\text{vir}} > 2000 \text{K}: \]
- Mhalo ≥ \( \sim 10^{5.5} \) M\(_{\text{Sun}}\)
- \( \text{H} + \text{e}^- \rightarrow \text{H}^- + \hbar\nu \)
- \( \text{H}^- + \text{H} \rightarrow \text{H}_2 + \text{e}^- \)
- \( \text{H}_2 \) line cooling
  - Inefficient

\[ \sim 10 - 1000 \text{M}_{\text{Sun}}? \]
high z (reionizing era) halos

-z >~ 8 galaxy luminosity functions
-JWST (or sooner) to measure z >~ 6 clustering
  --galaxies form within halos

galaxies + clustering at high redshift
  --sensitive to cosmology (e.g. $\sigma_8$, D.M. type)
  --sensitive to galaxy formation physics (e.g. SNe)
  \(\rightarrow\) probe cosmology and galaxy form. physics
  & robust test of analytics
$z=10$
**$1^{\text{st}}$ stars**
H$_2$-cooled halos

**$1^{\text{st}}$ galaxies**
atomic-cooled halos

comoving abundance

friends-of-friends halos: linking length = 0.2lmean

Reed et al 2007
Is \( f(\sigma) \) redshift invariant?
Is $f(\sigma)$ redshift invariant? “almost”

\[ n_{\text{eff}} \equiv \text{slope of } P(k) \text{ at scale of halo} \]

\[ P(k) \propto k^{n_{\text{eff}}} \]

\[ f_{\text{sim}}/f(\sigma) \]

\[ f_{\text{sim}}/f(\sigma,n_{\text{eff}}) \text{ (z dependent)} \]

Reed et al. 2007
Problem: Starting redshift

Random realization of \( \Lambda \text{CDM} \) density fluctuation spectrum.

- Linearly extrapolate to \( z_{\text{start}} \) \( \left( \delta \propto (1+z)^{-1} \right) \)

- High \( z_{\text{start}} \): avoid non-linear structures

- Map particle positions to density field – Zeldovich approx.

\[
\vec{x} = \vec{q} - D(t) \vec{S}(\vec{q})
\]

- Evolve with gravity, gas physics
$z=10$

- $z_{\text{start}} = 299$
- $z_{\text{start}} = 119$
- $\Delta_{\text{force acc.}} = 0.001$
- $r_{\text{soft}} = \frac{1_{\text{mean}}}{40}$
- $\Delta_t = 0.005$
- $z_{\text{start}} = 599$

Reed et al 2007
$z=20$

Reed et al. 2007

$z_{\text{start}} = 299$

$z_{\text{start}} = 119$

$\Delta_{\text{force acc.}} = 0.001$

$r_{\text{soft}} = l_{\text{mean}} / 40$

$\Delta_t = 0.005$

$z_{\text{start}} = 599$
$z=30$

$z_{\text{start}} = 299$

$z_{\text{start}} = 119$

$\Delta_{\text{force acc.}} = 0.001$

$r_{\text{soft}} = \frac{r_{\text{mean}}}{40}$

$\Delta_t = 0.005$

$z_{\text{start}} = 599$

Reed et al 2007
cosmological probe at high $z$?
Problem: finite box size

\[ n_{\text{eff}} \rightarrow 1 \]

\[ n_{\text{eff}} \rightarrow -3 \]
Want micro-halo mass function......

Earth-mass halo (Diemand, Moore & Stadel 2005) – tiny region. high redshift.

No “global” mass function
highly clustered, “biased”

\[ \xi(r) = \frac{N_{\text{pair}}}{N_{\text{pair\_random}}} - 1 \]

weakly clustered

\[ \text{bias}(r) = \left( \frac{\xi_{\text{halos}}(r)}{\xi_{\text{mass}}(r)} \right)^{1/2} \]
- halo bias
- auto-correlation function of “galaxy” halos

$$\xi(r) = \frac{N_{\text{pair}}}{N_{\text{pair\_random}}} - 1$$

$$b = \left( \frac{\xi_{\text{halos}}}{\xi_{\text{mass}}} \right)^{1/2}$$

Reed et al 2008
Scale-dependence of halo bias

Small scales strongly biased “non-universal” vs lo-z sims

Sheth, Mo & Tormen large scale prediction ($b_{SMT}$)

Redd et al 2008
Sheth, Mo & Tormen large scale prediction ($b_{SMT}$)

Small scales strongly biased “non-universal” vs lo-z sims

$b(r) = f(\sigma_{\text{mass}}(r))$

$b(m, r, z) = b_{SMT}(m, z)[1 + 0.03b_{SMT}(m, z)^3 \sigma(r, z)^2]$
Why is the scale dependence of halo bias so steep during the dark ages?
“universal” mass variable, $\nu$,

$$\text{MW} = \text{predictions of Mo & White (1996)}$$

$$\text{SMT} = \text{Sheth, Mo & Tormen (2001)}$$

Millennium run data from Gao et al. (2005).
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  • *Simulation difficulties*
  • *CDM difficulties*

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Motivations for studying halo structure

- Probe fluctuation spectrum & dark matter type
- Observational comparisons
  - Subhalos- satellites, lensing, D.M. Annihilation (e.g. Koushiappas)
  - Density profiles-- rotation curvies, lensing, X-ray
  - $r^{-1}$ or $r^{-1.5}$ cusp?
  - asymptotic central slope down to what radius?

● Universal? How does profile shape or subhalo distribution depend on mass, redshift?
● Baryons ignored
Density profile convergence tests

\[ R_{\min} \approx Np^{-1/3} \]

Moore et al 1998

\[ Np = \# \text{ particles within virial radius} \]

Power et al.

FM

L_{\text{mean}/2}
Not “universal”

Asymptotic Cusps?

Logarithmic profile slope:

Sims best fit:

NFW

Moore
Physical (non-comoving) slope:

no evolution

\[ \rho'(r/r_{\text{vir}}(z=0)) \]

instead of

\[ \rho'(r/r_{\text{vir}}(z)) \]

Hi-z: \( r_{\text{vir}} \) small

Halo cusp is frozen in at high \( z \).

Low \( z \) merging halos don’t affect cusp.

Reed et al 2005

\[ r/r_{\text{vir,0}} \]

\[ r_{\text{vir}} \text{ at } z=0 \]
Subhalos:
Too few satellites?---
overmerging

$c=9.0 \quad M_{\text{fof}}/M_{\text{so}}=1.15$
Resolution Issues:

2-body relaxation

\[ \rho(r): R_{\text{min}} \approx Np^{-1/3} \]
Subhalo convergence tests:

Minimum "complete" $V_{\text{cmax}}$

Small halos too easily destroyed

Reed et al. 2005

$N_p > 32$

$7 \times 10^6$

$10^6$

$10^5$
Cluster “satellite” numbers vs. simulations

Desai et al. 2004
CDM crisis
“missing” local group satellite galaxies

Simulated Halos

dwarf
Group

MW
Cluster

MW
Cluster

Real Halos

Gravitational Lens
Galaxy Cluster 0024+1654

M83 © Anglo-Australian Observatory
Photograph by David Malin
Moore et al 1999

Graph showing the cumulative number of halos versus the ratio of the escape velocity ($v_e$) to the global velocity ($V_{\text{global}}$). The graph compares simulated cluster data with simulated galaxy data and includes data points for Virgo cluster and individual galaxies such as dSph's, Fornax, Sagittarius, SMC, and LMC.
Hayashi et al. 2003 works well if subhalos not cuspy.
Solutions to missing satellite problem

- Warm dark matter
- Supernovae
- Reionization/ UV background
- We see only inner parts of large satellites
- We only see most massive satellites
- We only see oldest satellites
- Decaying dark matter
- Faulty intelligence
Cosmological Simulations
some problems

• Simulation:

   An imitation; a sham.

   Assumption of a false appearance.

   (American Heritage Dictionary)

Kolb & Turner(?)

Cosmological Simulations

some problems

Answers.com:

**Simulation:**

1. *Something false or empty that is purported to be genuine; a spurious imitation.*
2. *The quality of deceitfulness; empty pretense.*
3. *One who assumes a false character; an impostor: “He a man! Hell! He was a hollow sham!” (Joseph Conrad).*
4. *A decorative cover made to simulate an article of household linen and Used over or in place of it: A pillow sham*
Another CDM crisis
Flat cores in LSBs
(low surface brightness galaxies)

Observed “cores” vs CDM simulation cusps
Disk placed in triaxial halo: $V_c \neq (GM/R)^{1/2}$

Hayashi et al. 2004
Rotation curve problem solved(?)

Hayashi et al. 2004

- UGC 5750 (B02) ($\gamma=5.0$)
- disk ($\gamma=4.8$)
- NFW
When to trust simulations?

- **Convergence tests:**
  - Particle number, **starting redshift**, force resolution, timestep, boxsize
  - Gravity only simulations OK
  - Simple, adiabatic hydrodynamics, OK?

- **Simulations break when:**
  - Galaxies, star formation, feedback, other “unresolved” physics
  - Resolution issues not tested/understood
“successes” - simulating nonlinear problems

- Cuspy profile – but assumes dark matter only universe
  - Not predicted

- “painting” galaxies onto halos for observational comp.
  - semi-analytics (e.g. starburst during halo merger)
  - HOD (Halo Occupation Distribution)
    - Prob. Ngal within Mhalo, to match galaxy correlation function

- Basis for “precision” cosmology:
  - Cluster mass function
  - p(k) for weak lensing
$\log \Phi$

$[\text{GeV}^2 \text{ cm}^{-6} \text{ kpc sr}^{-1}]$
\[ R_{\text{min}} \sim N_p^{-1/3} \]

10^6 vs. 10^9 particles.

10 x better (spatial) res. for 10^6 x more work.

Diemand et al. 2008
All subhalos

$r<100\text{kpc}$

$r<50\text{kpc}$

Diemand et al. 2008
Big Simulations

• Now: >billion particles in a halo
  – “Via Lactea 2” (Stadel, Madau, Kuhlen et al.)
  – “billionennium” (Springel, Navarro et al)

• To model Milky Way halo, including micro-(sub)halos
  – get D.M. Annihilation signal (e.g. Koushiappas)
  – Earth mass: need \( \sim 10^{-8} \) Msun particle ------- \( \sim 10^{20} \) particles
  – \( 10^{11} \) times more particles ------- \( \sim 2060 \)?
Conclusions

• Simulation successes:
  – Halo numbers
  – Halo distribution, clustering
  – Halo structure

• Problems
  • Simulations difficult to interpret
  • “trust” D.M.-only, w/convergence tests
  • Always need bigger sim., smaller scales
  • CDM lives, so far

• Precision cosmology still needs simulations (e.g. evolution of cluster mass function, matter power spectrum)