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Structure growth in the dark universe

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Visualizing Darkness

• Uniformity, filamentarity, hierarchy – it all depends on scale

• ...and the smooth shall be made rough with the passing of time

• ...and the dark brings forth light – through shocks

• ...while around us the Milky Way hums with unseen activity

Scale invariance of *A***CDM halos?**

A rich galaxy cluster halo Springel et al 2001

A 'Milky Way' halo Power et al 2002











Gao et al 2005

A massive cluster at z=0

Simulating the growth of a cluster from z=100 to z=0

0.00

Gao et al 2005



...and its largest progenitor at z=49

Simulating the growth of a cluster from z=100 to z=0

Gao et al 2005

Large-scale structure at z=49 does NOT look like that at z=0



"Milky Way" halo z = 1.5 $N_{200} = 3 \times 10^{6}$ "Milky Way" halo z = 1.5 $N_{200} = 94 \times 10^{6}$ "Milky Way" halo z = 1.5 N₂₀₀ = 750 x 10⁶

How well do density profiles converge?

Virgo Consortium 2007



How well do density profiles converge?

Virgo Consortium 2007



How well does substructure converge?

Virgo Consortium 2007



Mean density profiles of dark halos



- Smooth since many halos are averaged together 2491565 at 6 x $10^{10}M_{\odot}$ 67400 at 3.5 x $10^{12}M_{\odot}$ 650 at 2.4 x $10^{14}M_{\odot}$
- Fit by an NFW or Einasto profile on small scales
- Fit by a biased *linear* 2-point correlation function on large scales
- A <u>sharp</u> transition

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- Directly observable through galaxy-galaxy grav. lensing



z = 0 Galaxy Light



Mean DM profiles around galaxies



- Smooth since many galaxies are averaged together $600710 \text{ at } M_r = -20.5$ $15984 \text{ at } M_r = -22.5$ $617 \text{ at } M_r = -23.5$
- <u>Central</u> galaxy profiles are well fit by halo profile model for the mean halo mass
- Central galaxy lenses can be identified in lensing surveys
- Features in profile at large radius provide a <u>strong</u> test of the ΛCDM cosmology

Mean DM profiles around galaxies



- Smooth since many galaxies are averaged together 3283080 at $M_r = -17.5$ 833588 at $M_r = -20.5$ 647 at $M_r = -23.5$
- Profiles for *all* galaxies are more complex than for central galaxies

Mean DM profiles around galaxies

Hayashi & White 2007



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- Profiles for *all* galaxies are more complex than for central galaxies
- ...but the tangential shear profiles still show features
- Test of *how* galaxies populate halos as well as of DM model





Hilbert et al 2007

0.3

-0

_-0.1

 $z_{source} = 15$ $\theta_{res} = 30''$ 21 cm noise





....in conclusion

- Simulations now make precise predictions for the properties of nonlinear DM structures, both statistical and individual
- The statistical properties are directly observable from the mean tangential gravitational shear around galaxies
- Features are predicted in such galaxy-galaxy lensing which test the Λ CDM cosmology, allow estimates of its parameters and show how galaxies populate dark halos
- Lensing of high redshift 21cm emission from the *pre*galactic medium would allow the distribution of mass to be *imaged*