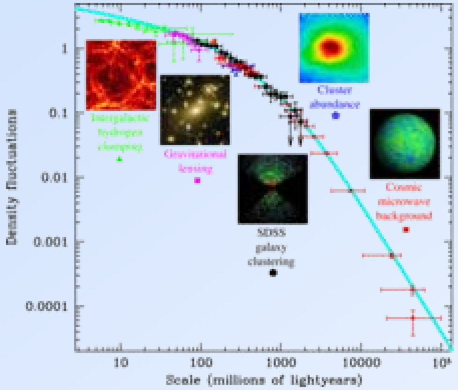
The Clustering of Dark Matter in ΛCDM on Scales Both Large and Small

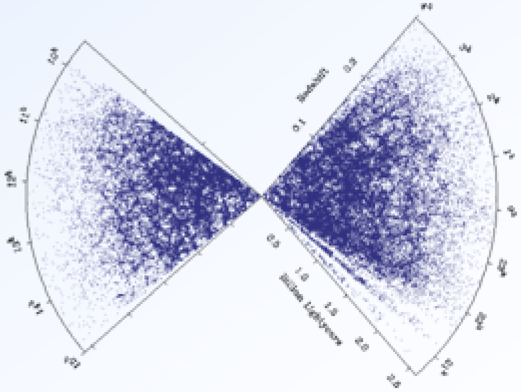
Large Scales

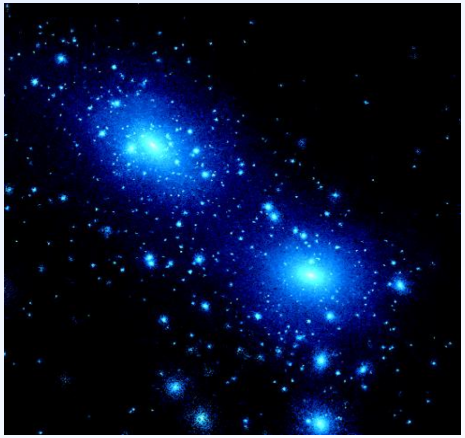


by Chris Orban

May 19, 2008

Galaxy-redshift Survey





Small Scales

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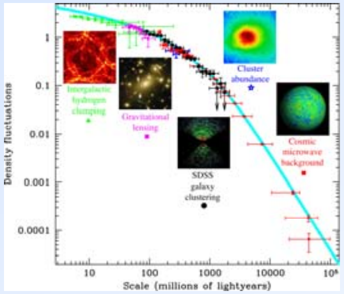
Outline

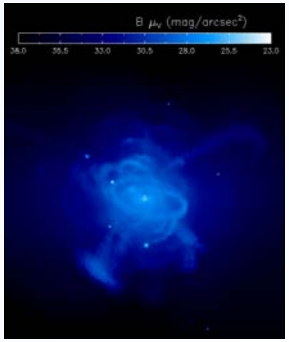
0. Dark Matter Exists!

1. Large-Scale Structure
   - What is P(k)?
   - Theory/Observations



2. N-body Simulations
   - Usefulness, Limitations
   - Self-similarity

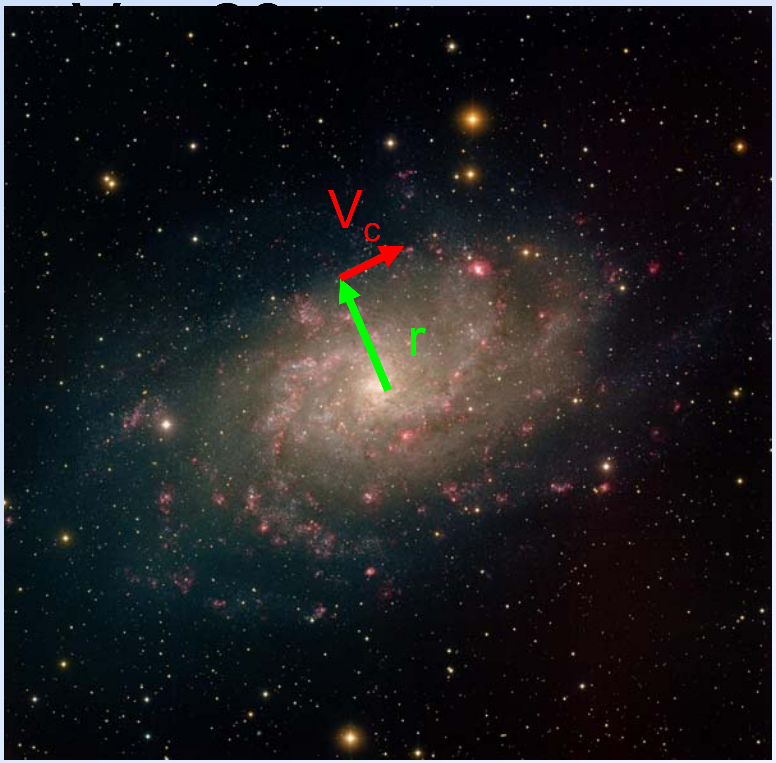
3. Small Scales
   - Local Group
   - Tidal Streams
   - Strong Gravitational Lensing



4. Summary

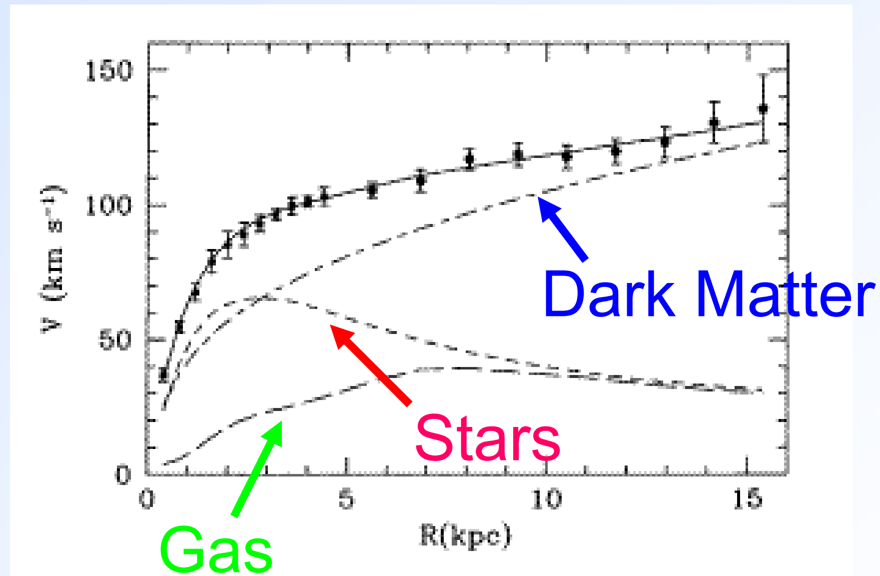
Dark Matter Exists! (Part 1)

M33: A Spiral Galaxy



$$V_c = \sqrt{\frac{2GM_{\rm tot}(<r)}{r}}$$

M33 Rotation Curve



Observationally:

$M_{tot}(<r) \sim r$, at large r

$M_{light}(<r) \sim$ constant, at large r

Dark Matter Exists! (Part 2)

The Coma Cluster

Mass Estimate:

$M_{guess} \sim N_{gal} \times M_{gal} \sim 10^{12}\ M_{sun}$

Right Answer:

$M_{virial} \sim R\ V^2/G \sim 4 \times 10^{14} M_{sun}$

$M_{virial} >> M_{guess}$

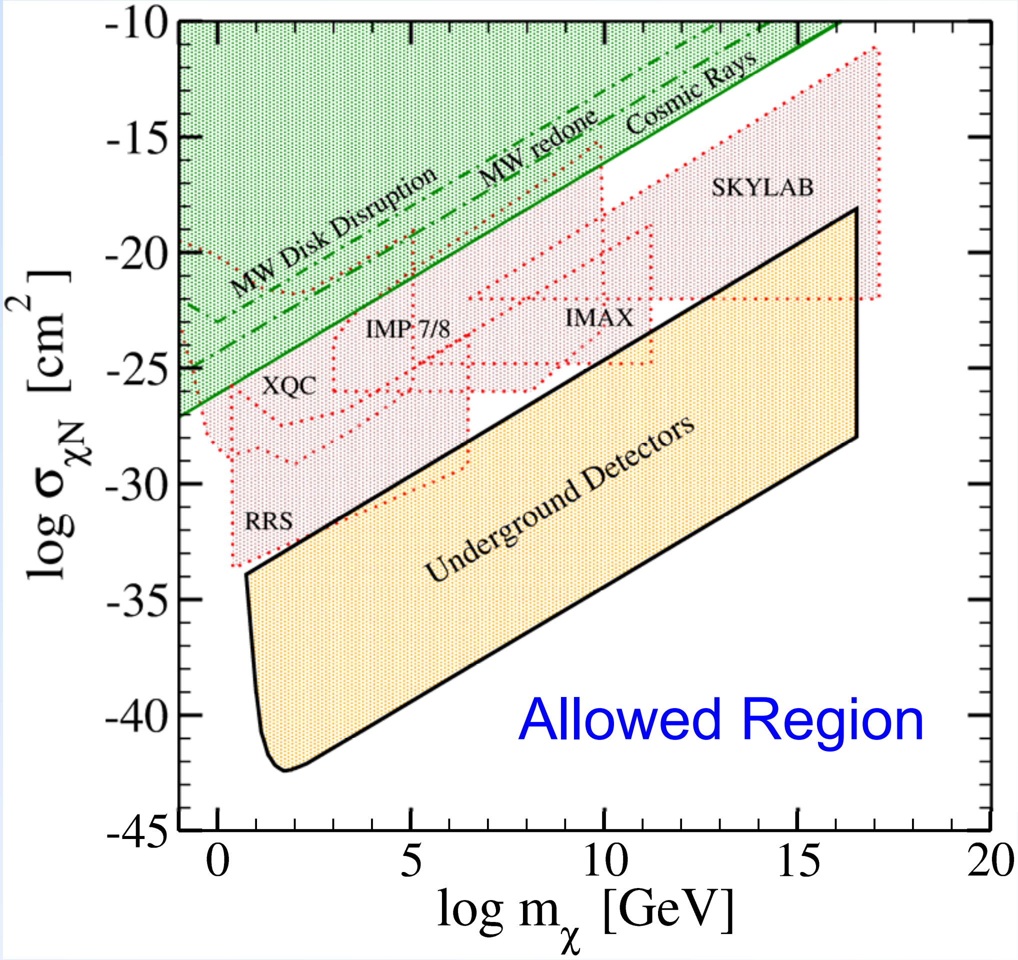
"…dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie*[!!!]*"

- Fritz Zwicky, 1933

Dark Matter Exists! (Part 3)

Constraints on Matter Cross Section

Cross Section

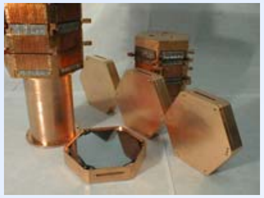


Mass

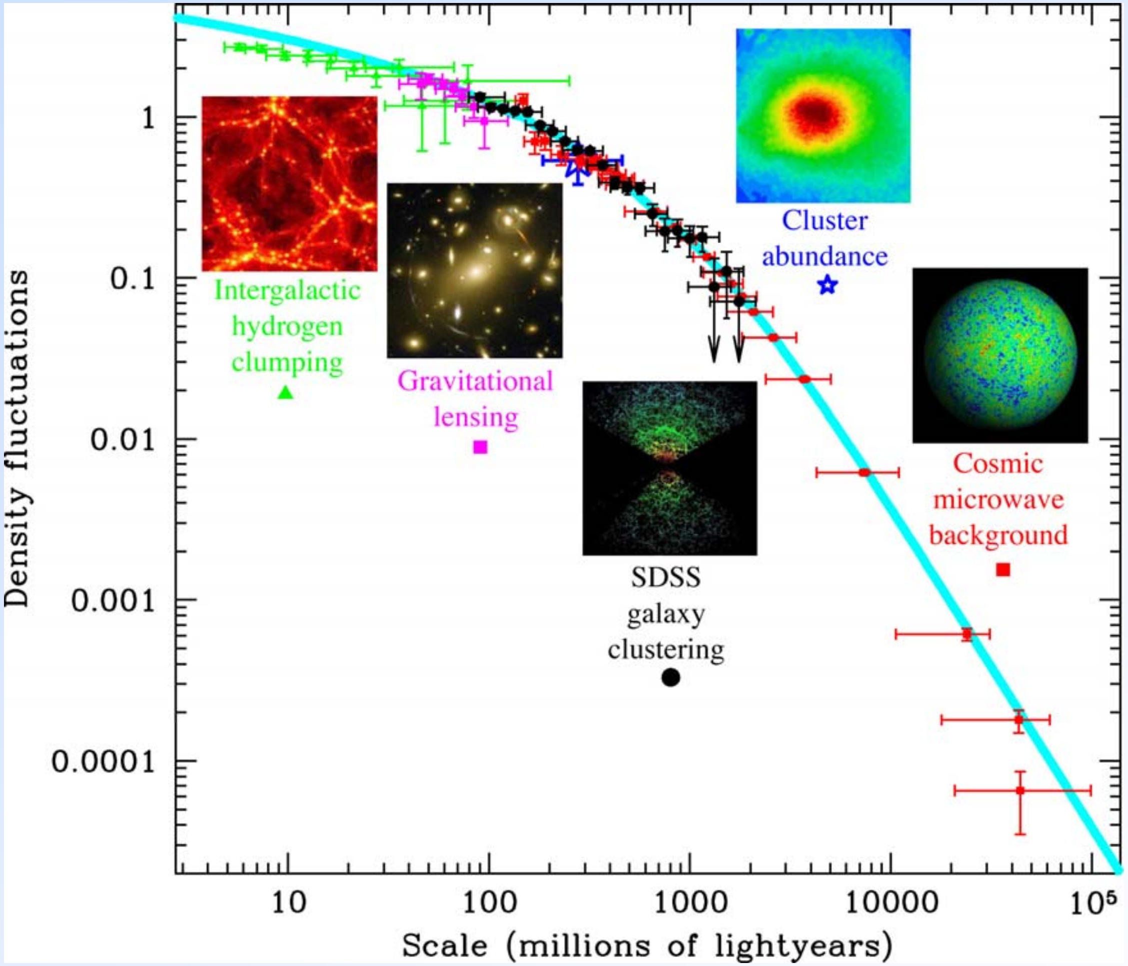
The Bottom Line:

Cross section is small enough to not be important for clustering!

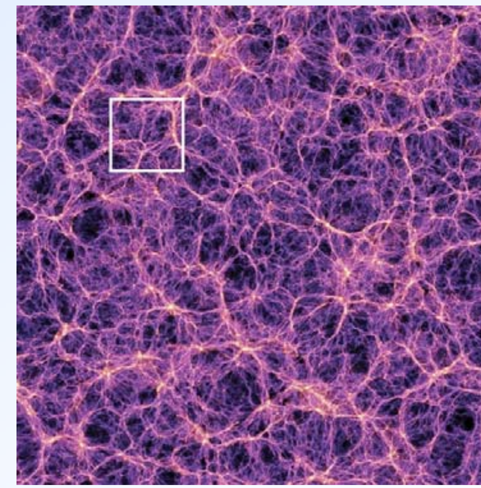
(Mack et al. 2007)



Large-Scale Structure



Dark Matter Density Field



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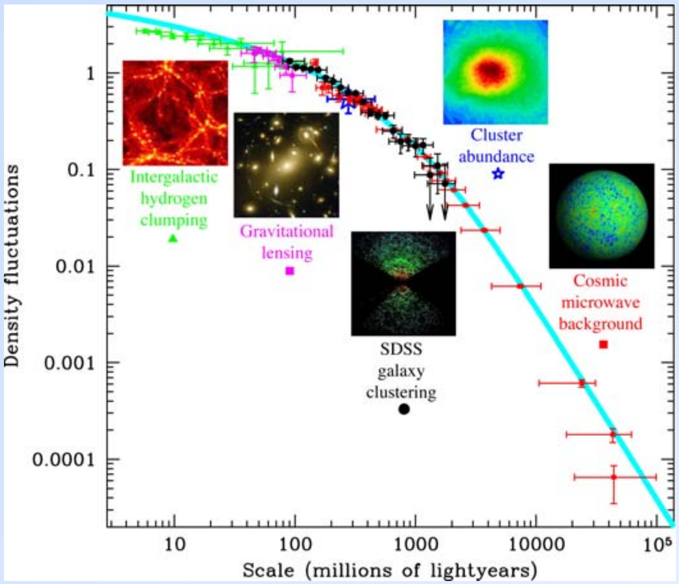
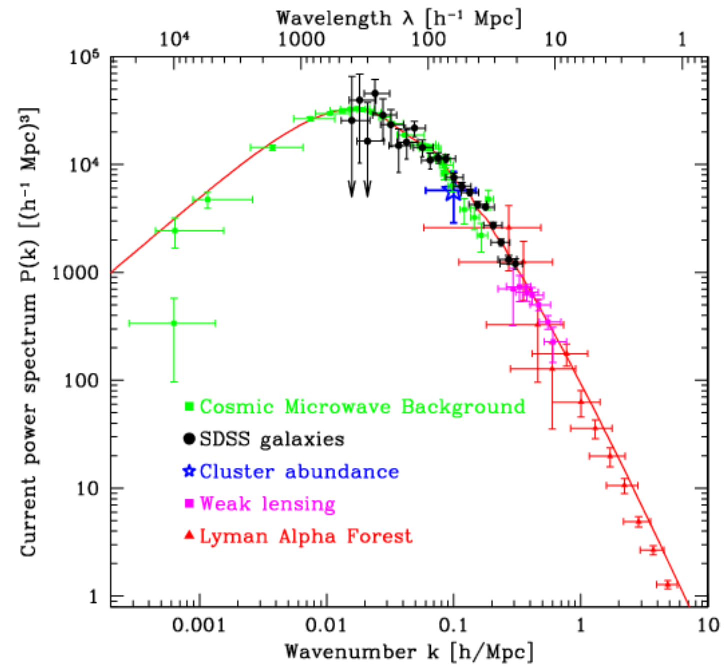
The Power Spectrum: P(k)



$\times \; \frac{2\pi^2}{k^3}$

P(k)



Scale

λ → Wavenumber $k = \frac{2\pi}{\lambda}$

Wavenumber

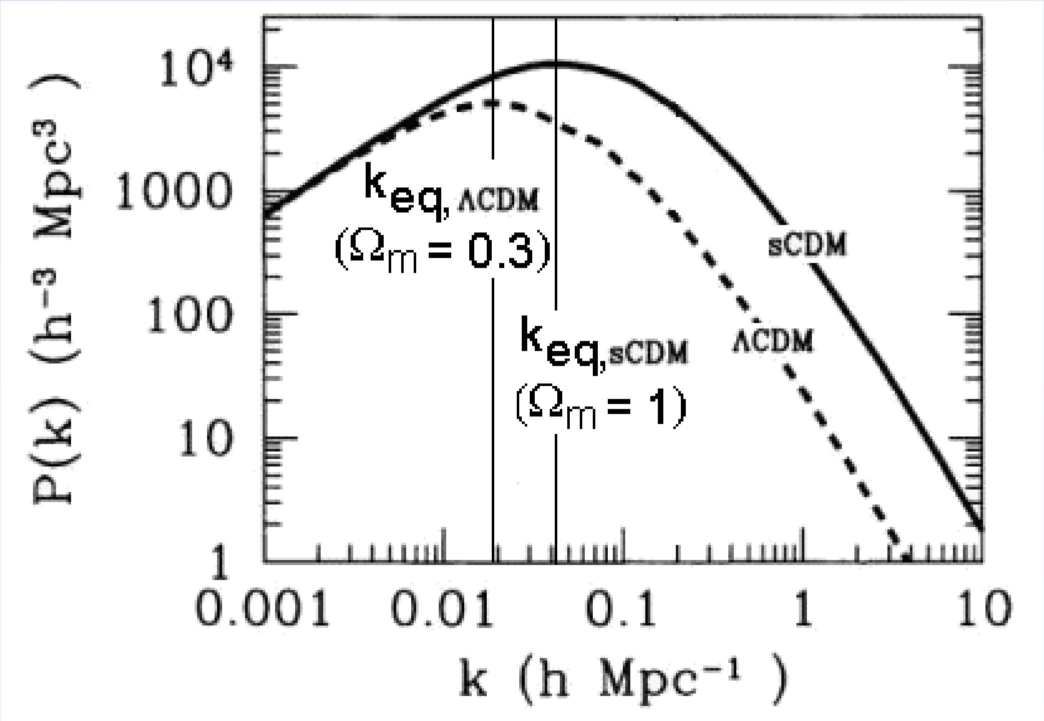
k

Density Contrast

$$\delta(\mathbf{x}) = \frac{\rho(\mathbf{x}) - \rho_{m,avg}}{\rho_{m,avg}}$$

Fourier Transform ⟷ $\delta(\mathbf{k})$ → Power Spectrum $P(\mathbf{k})$

What is P(k) Good for?



Ω_m ; total amount of dark matter in the universe

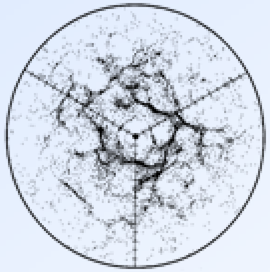
$$H(a) = H_o\,(\Omega_m a^{-3} + \Omega_\Lambda)^{1/2}$$

= expansion rate

$$k_{eq} = \frac{2^{1/2} H_o}{c} \frac{\Omega_m}{\Omega_r^{1/2}}$$

Higher Ω_m ⇨ earlier epoch of equality ⇨ smaller horizon scale at a_{eq} ⇨ smaller modes survive ⇨ higher k_{eq}

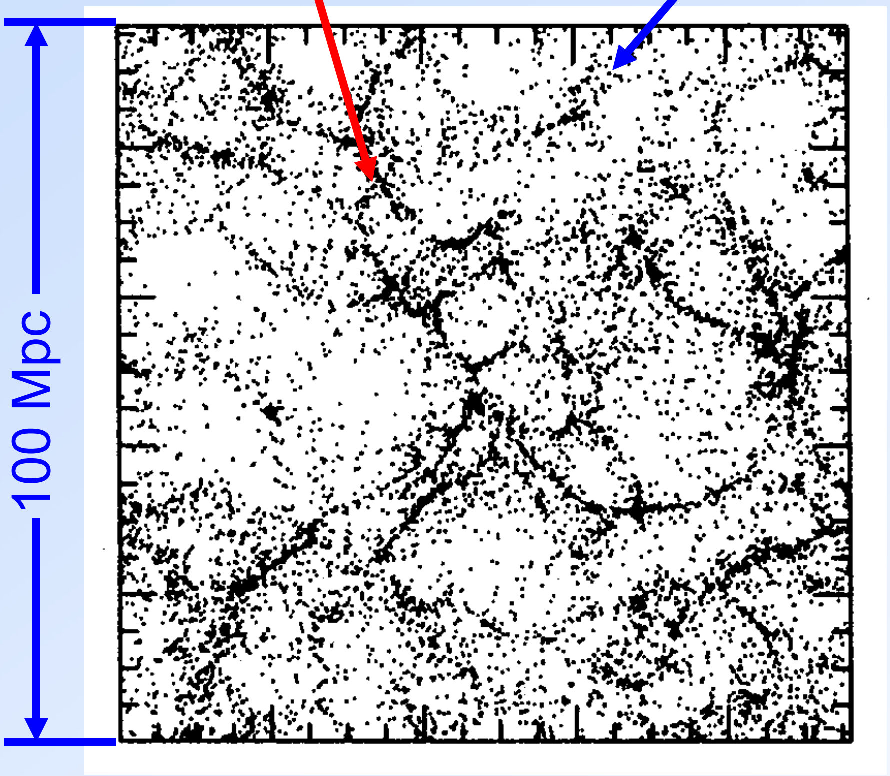
A Tale of Two Universes

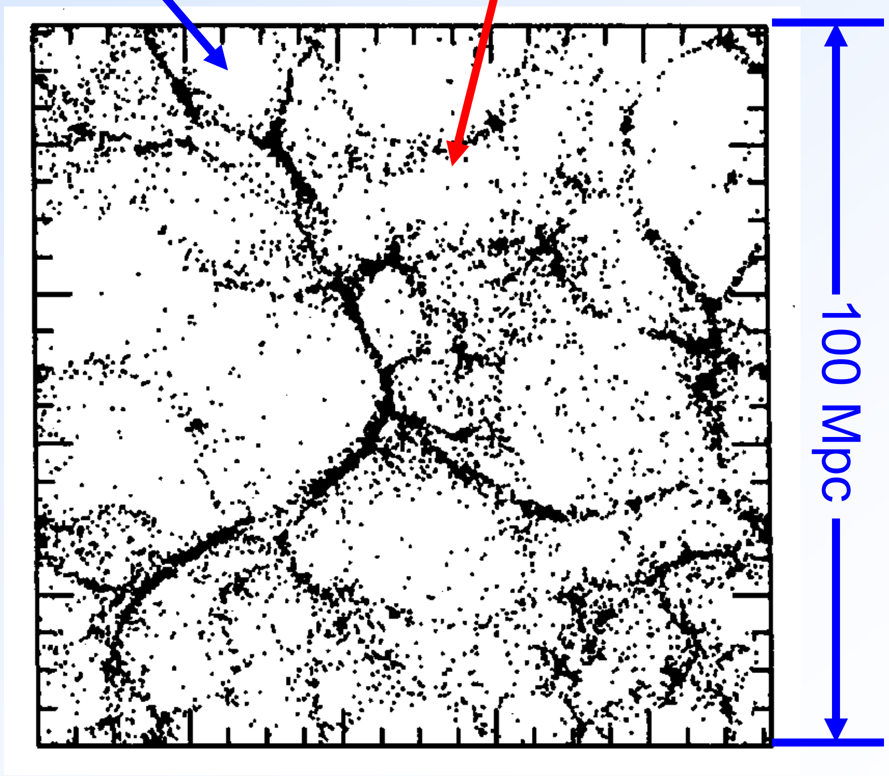


CMB predicts this

Dark Matter

galaxy surveys see this

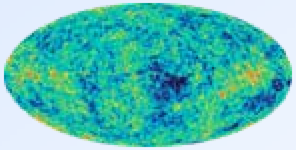




Low σ_8

High σ_8

σ_8 ; total amount of clustering



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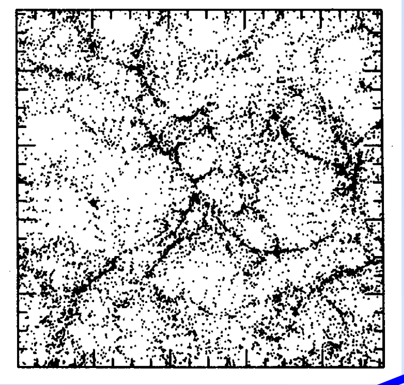
A Galaxy Factory

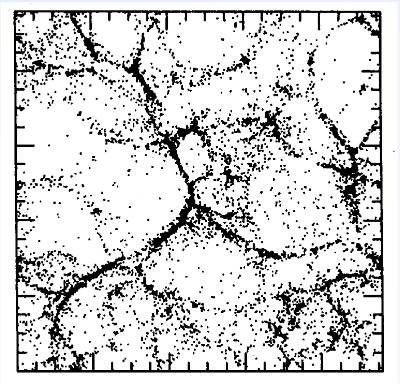
Dark Matter

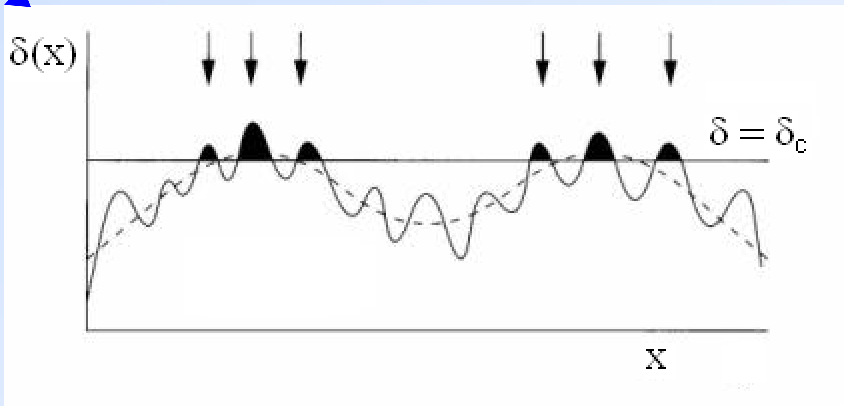


Halo Formation

Galaxy Formation

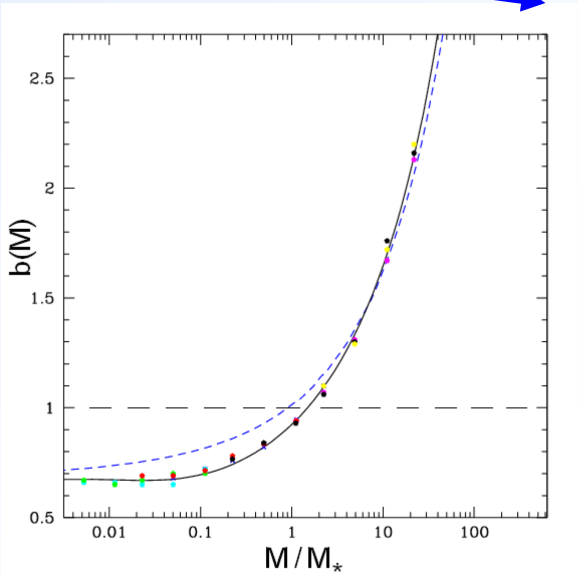
Galaxy Field





Collapse Theory

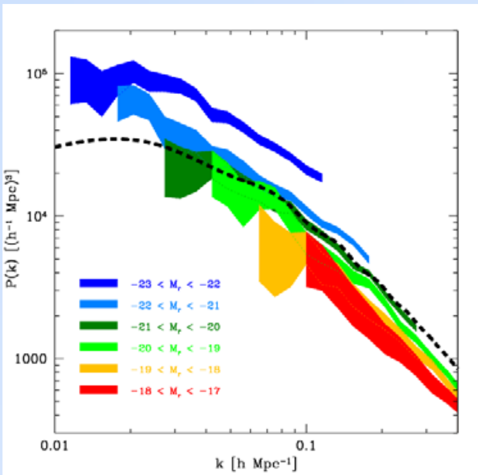
N-body Simulations

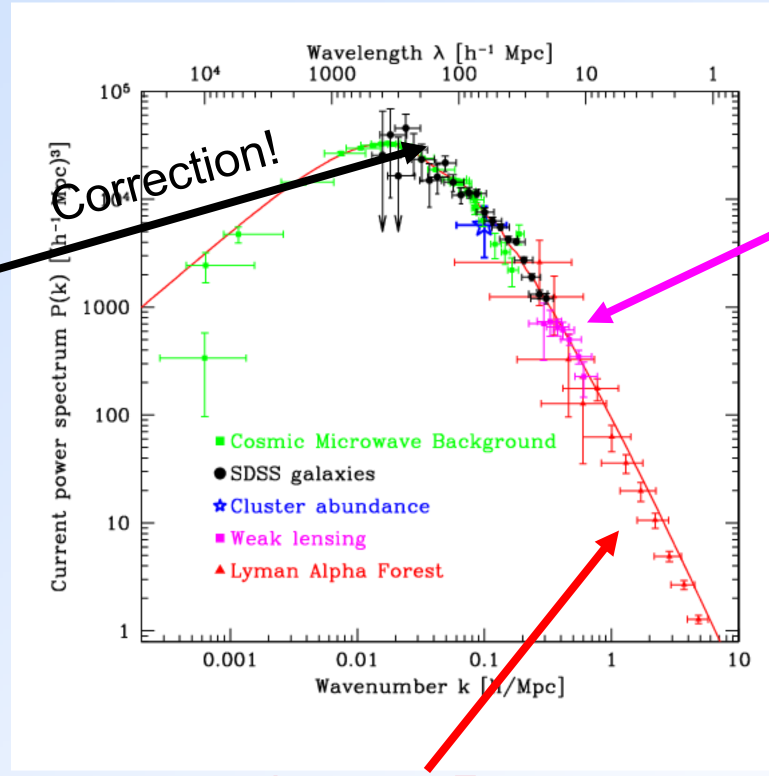


$$\delta_h(x) = b(M)\ \delta(x)$$

Observations

Biased Galaxy-Galaxy Power Spectrum

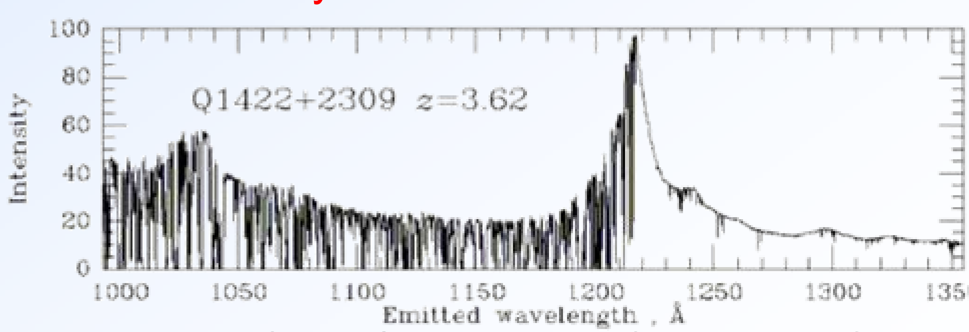




Correction!

Weak Gravitational Lensing

Lyman-α Forest



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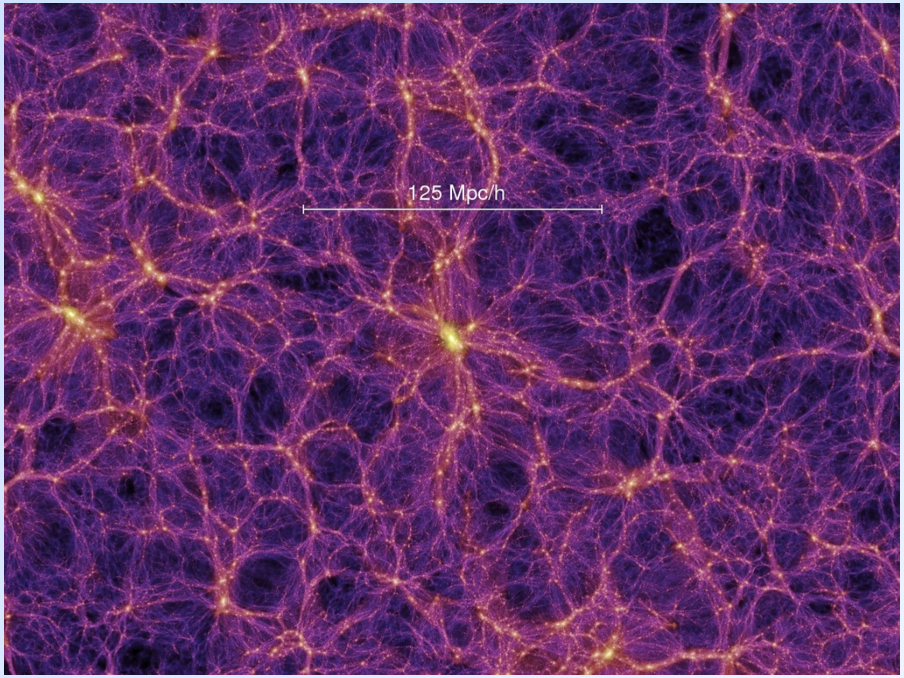
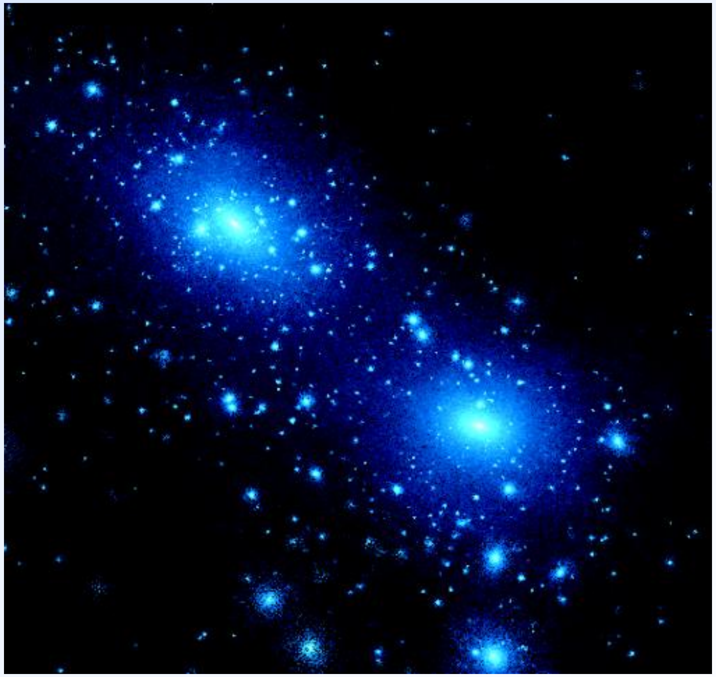
N-body Simulations

Large Scales



Small Scales



Useful for: More precise understanding of halo formation

$P(k)$ for $k > k_{nl} = 0.2$ h Mpc^{-1}

Small scale dark matter dynamics

Limitations: Finite box size

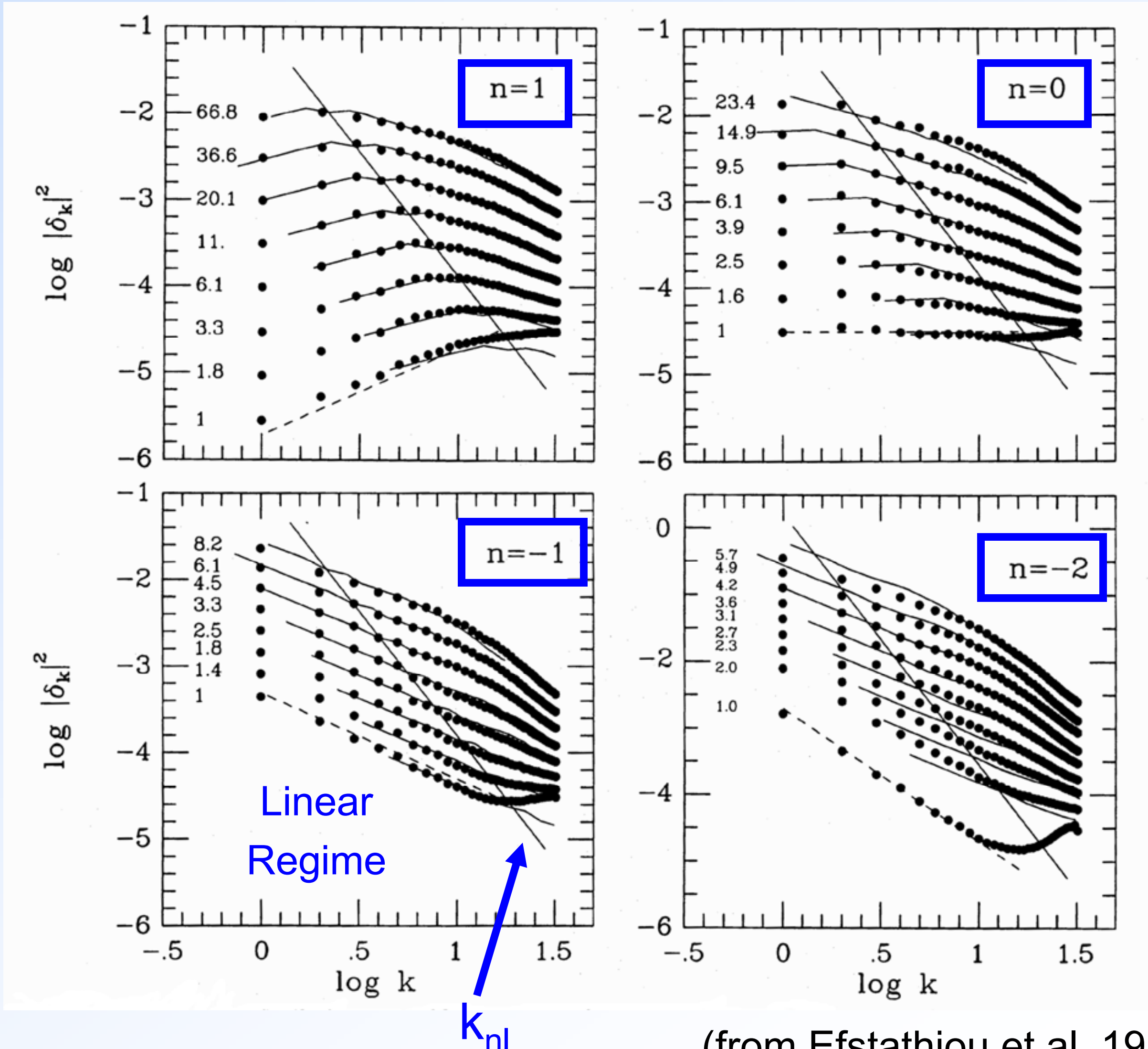
Finite number of particles

Self-Similarity

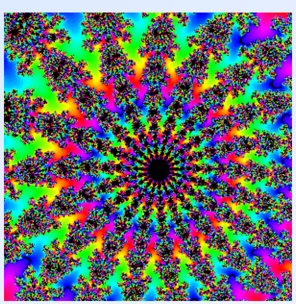
Initial Conditions:

$P(k) = A\,k^n,\ \Omega_m = 1$

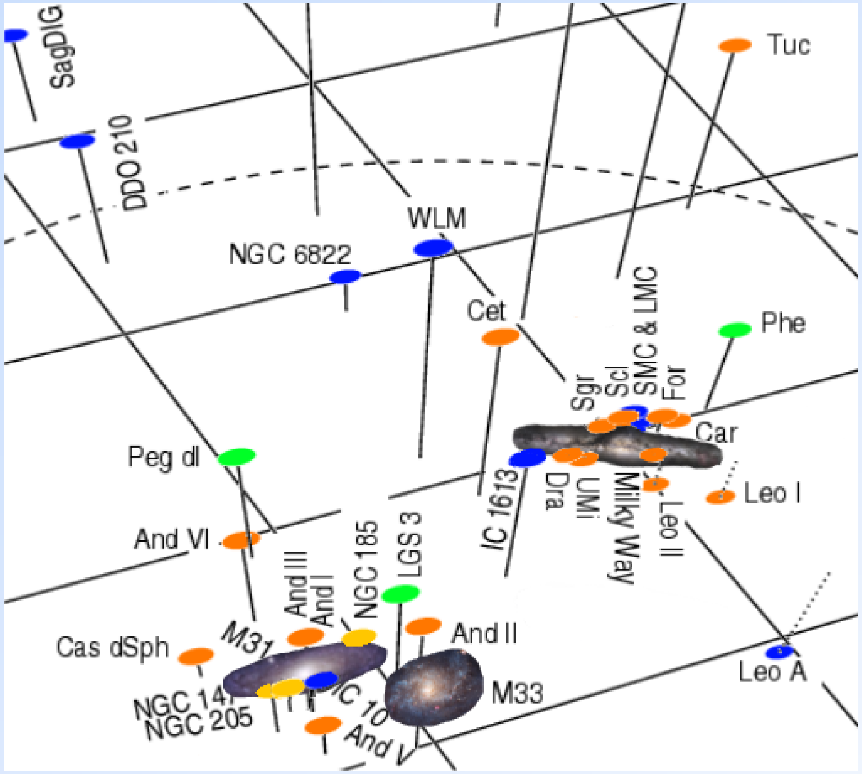
Well-understood time-scaling



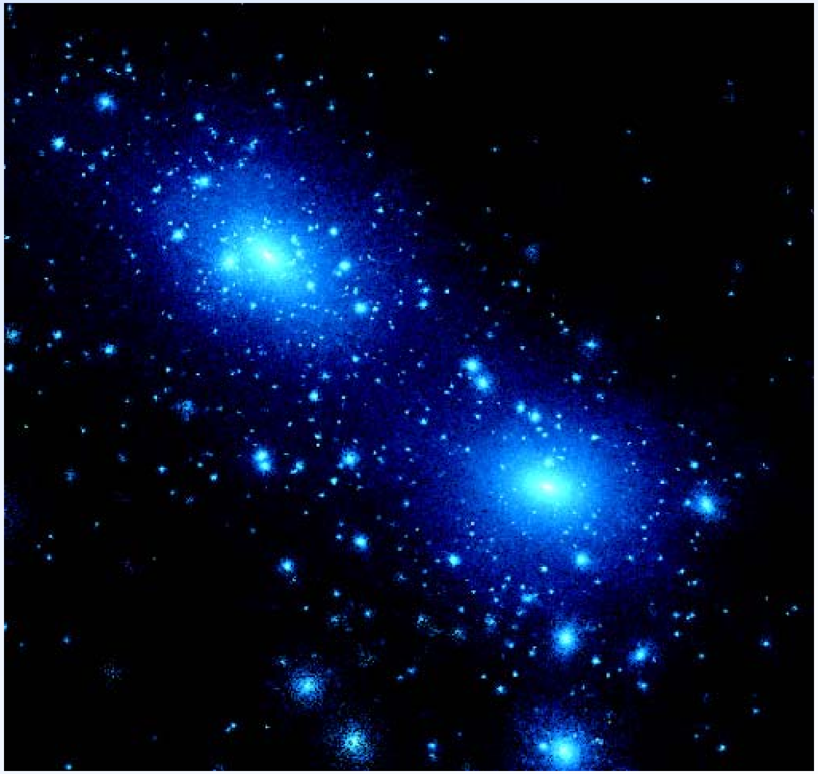
(from Efstathiou et al. 1988)



Small Scales



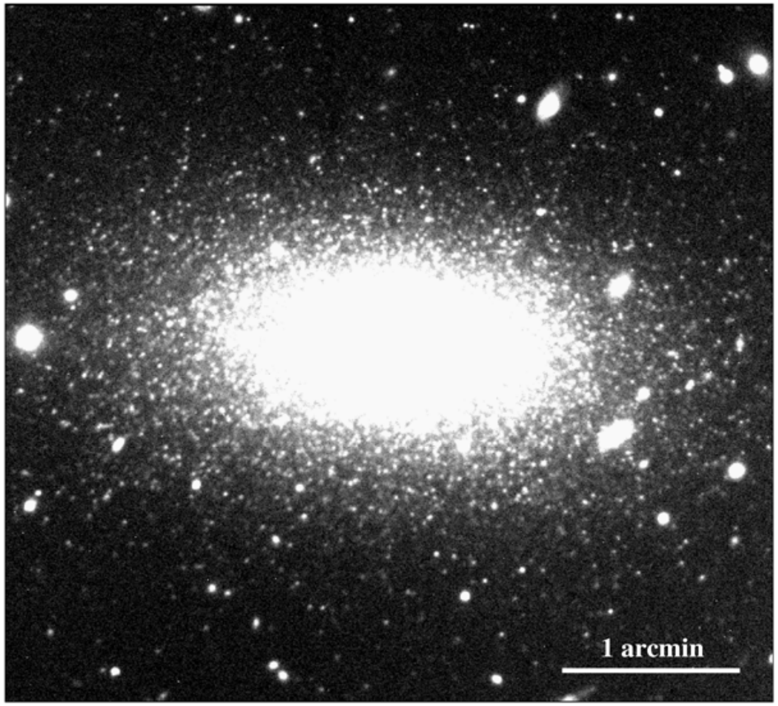
Map of Galaxies in the Local Group



N-body Simulation

(Kravtsov, Gnedin & Kylpin 2004)

Missing!



Reward: Ph.D. Thesis

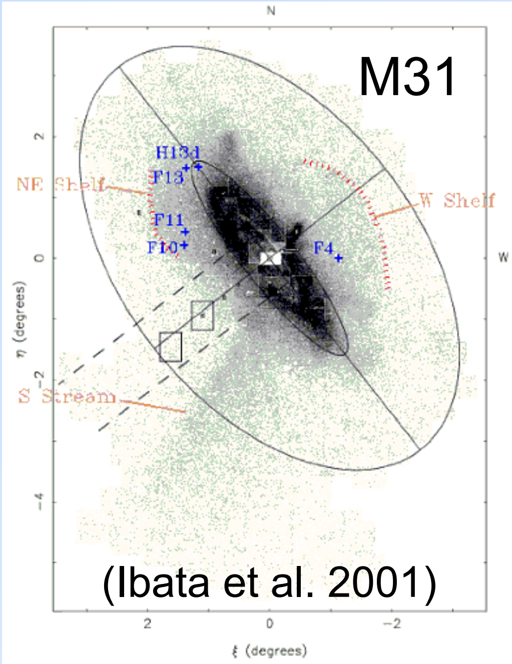
Last Seen: N-body Simulations

Options:

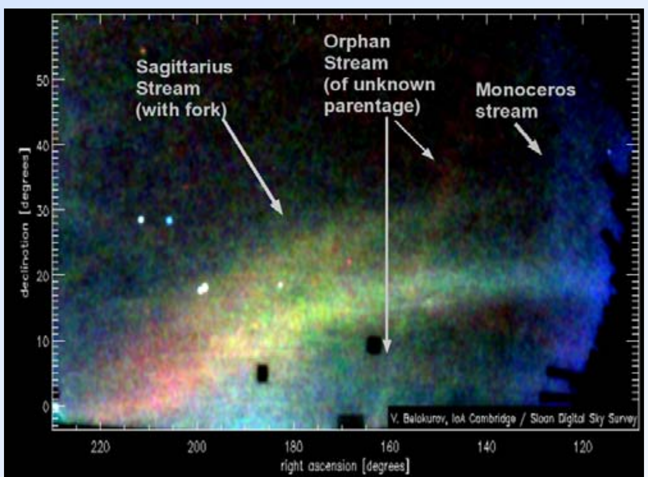
- Keep Looking?
  - Not likely to find enough…
- Maybe they're not there?
  - e.g. Zentner & Bullock 2003, Kamionkowski & Liddle 2000
- Maybe they're just dark?
  - e.g. Kravtsov, Gnedin & Klypin 2004, Madau & Diemand 2008, Thoul & Weinberg 1996, Orban et al. 2008

Tidal Streams

Observations

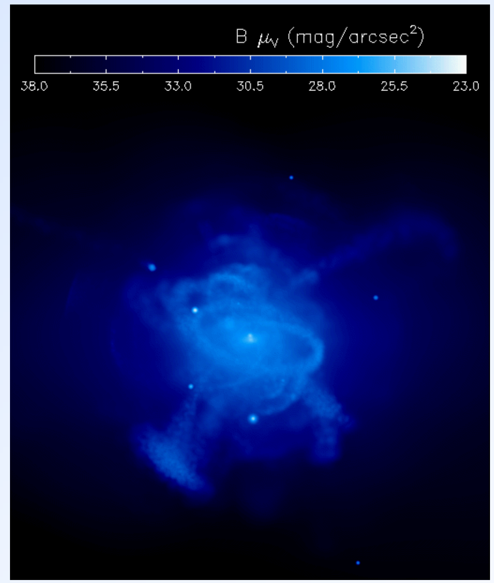


(Ibata et al. 2001)



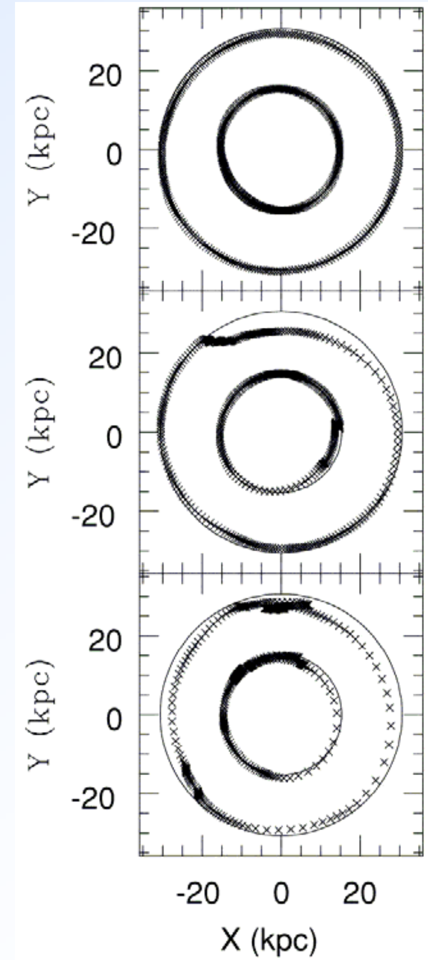
(Martinez-Delgado et al. 2003)

Theory



(Bullock & Johnston 2005)

(Johnston et al. 2002)



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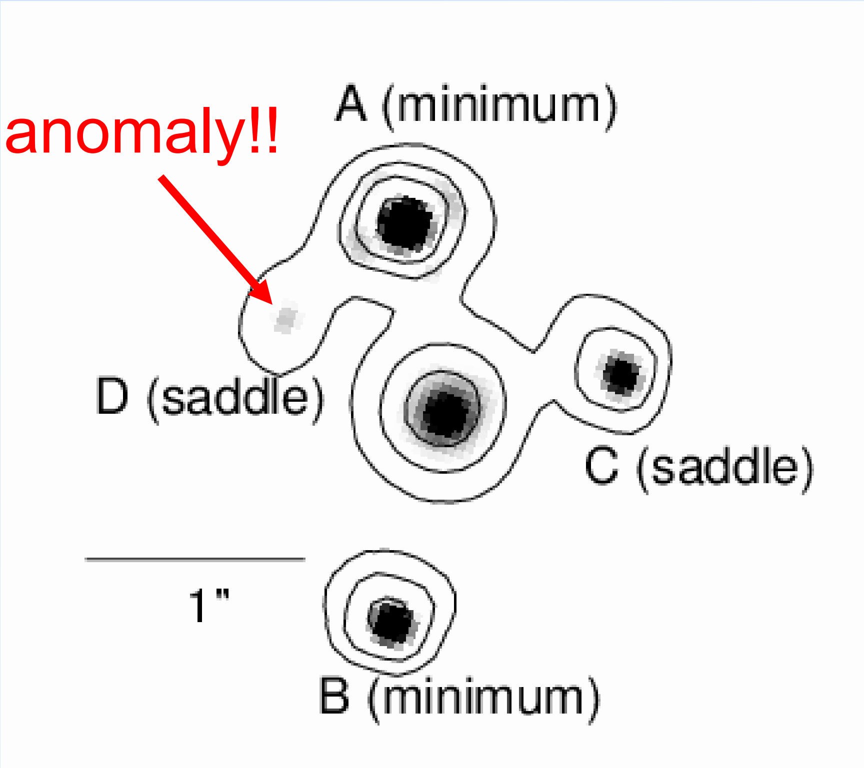
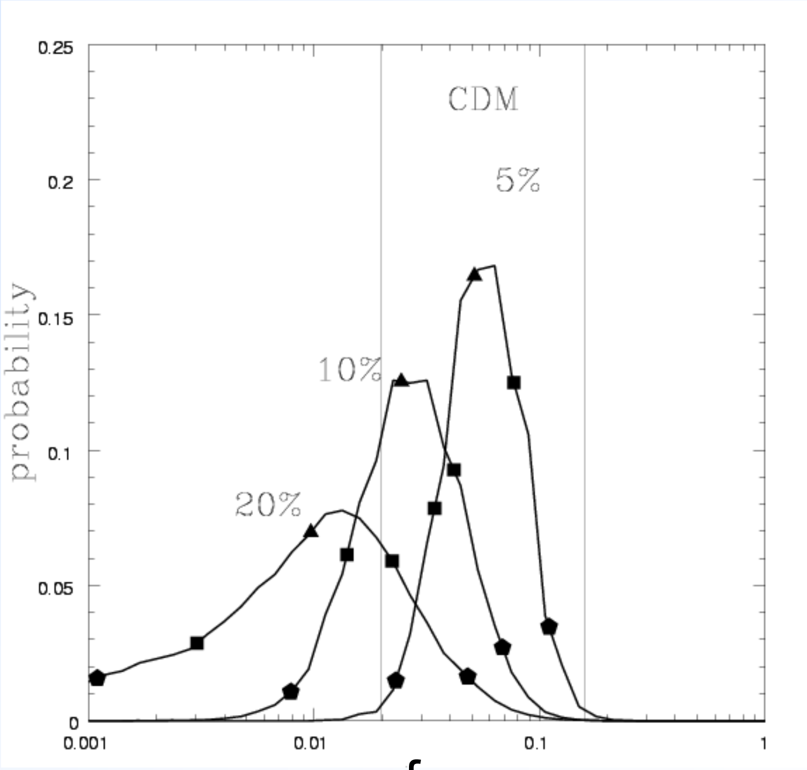
Strong Gravitational Lensing

Four-image Quasar Lens System



(Inada et al. 2003)

Substructure Likelihood



f_{sat}

(Dalal & Kochanek 2002)

f_{sat} = fraction of mass in substructure

Summary

- The existence of dark matter is indisputable (e.g. galaxy rotation curves, virial relation arguments)
- Perturbation theory and N-body simulations make definite predictions for the clustering of dark matter; also give better understanding of halo formation and bias
- Observationally, we have a very good idea of how the dark matter clusters on cosmological scales
- On the scale of the Local Group the clustering of dark matter is harder to asses observationally; strong gravitational lensing may have detected dark matter substructure

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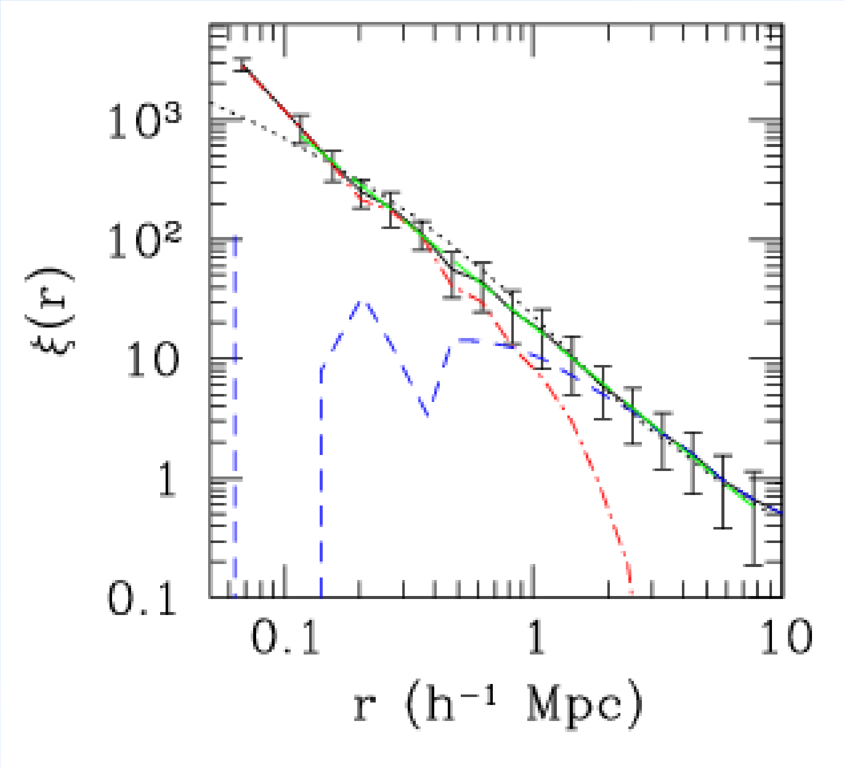
Not the Only Game in Town

Two-Point Correlation Function



Correlation Function		Power Spectrum
$\xi(r)$	⟷ Fourier Transform	$P(k)$

$\xi(r)$ = (increased) likelihood that at a patch of dark matter there will be another patch distance, r, away

More formally:

$$\xi(r) = \langle \delta(x)\delta(x+r) \rangle$$

Statistical Ensemble