The large-scale structure of the Universe

Carlos S. Frenk
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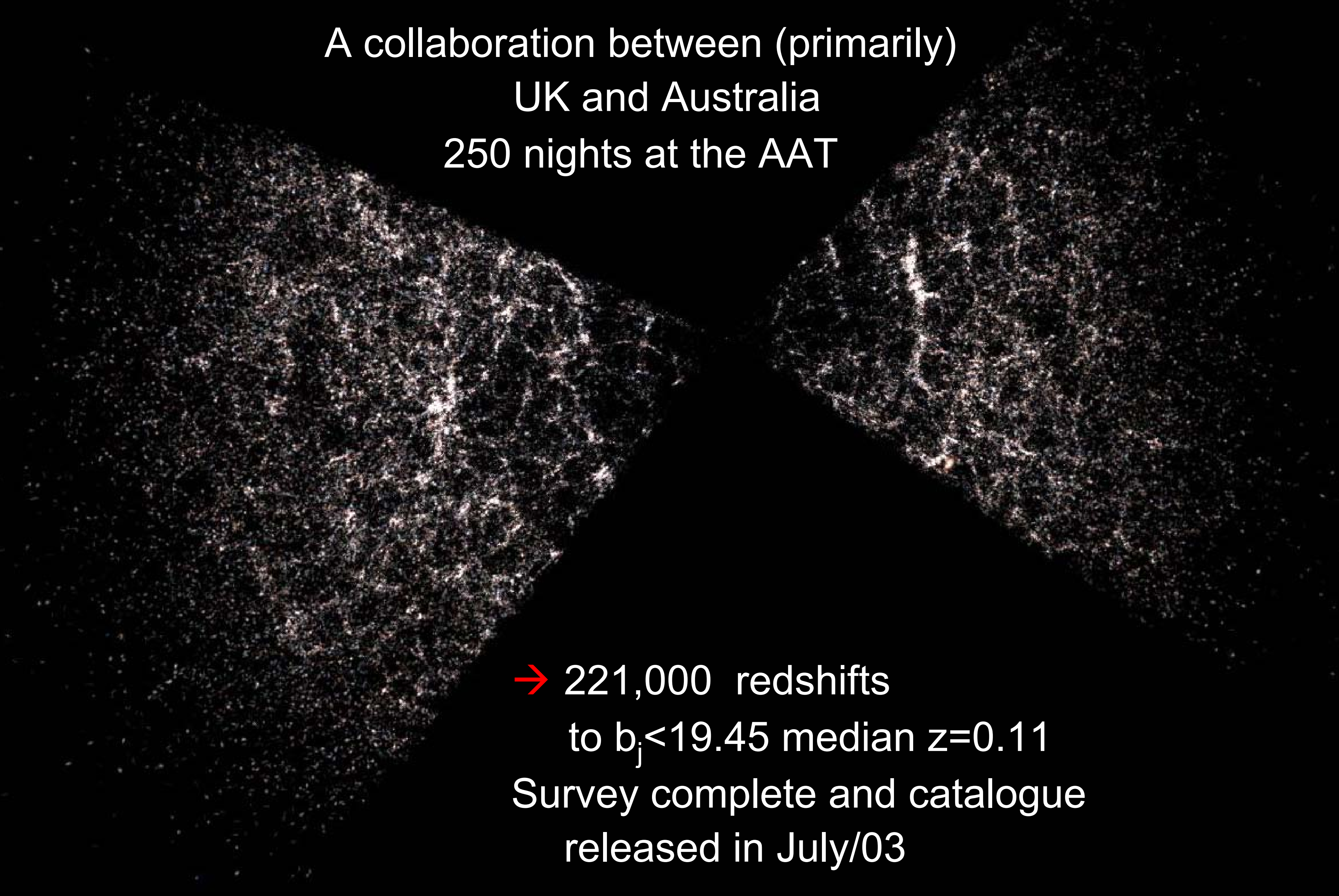
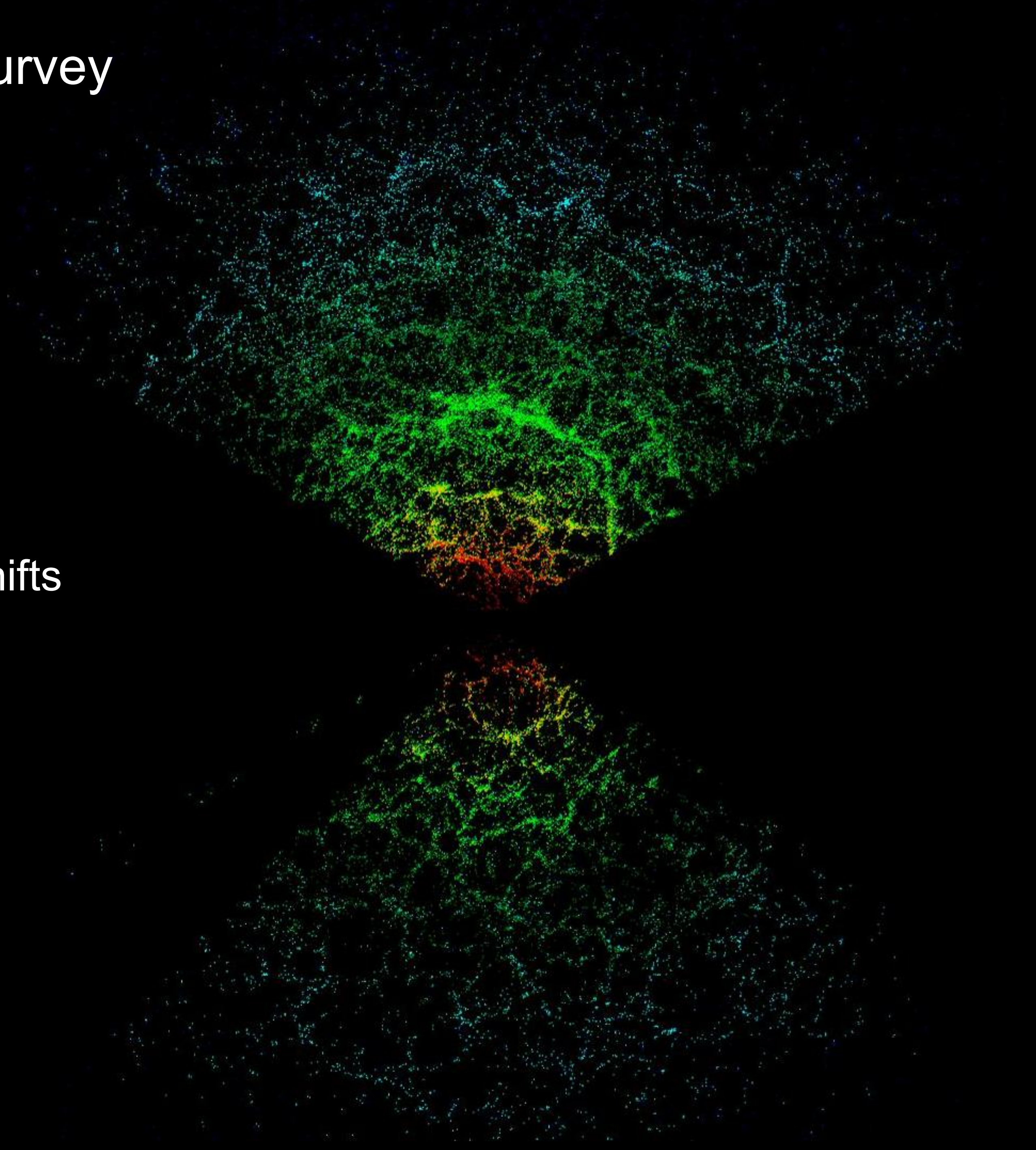
The 2dF Galaxy Redshift Survey

A collaboration between (primarily)
UK and Australia
250 nights at the AAT



→ 221,000 redshifts
to b_j<19.45 median z=0.11
Survey complete and catalogue
released in July/03

Sloan Digital Sky Survey



~500,000 galaxy redshifts

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2dF Galaxy Redshift Survey:
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Institutions

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The 2dF galaxy redshift survey

- → 1997-2003: 250 nights at 4m AAT
- → 221,000 redshifts to b_j<19.45

Use large-scale structure data to test a priori cosmological models

Modelling large-scale structure

Cosmological model

(Ω, Λ, h…); dark matter

Standard model: ΛCDM

Primordial fluctuations

$\delta\rho/\rho(M, t)$

- Material content: Cold dark matter (eg neutralino;21%), baryons (4%), dark energy (Λ; 75%)
- Initial conditions: Quantum fluctuations during inflation: $|\delta_k|^2 \propto k$; Gaussian amplitudes
- Growth processes: Gravitational instability
- Parameters:

$$\Omega_{CDM} = 0.21,\ \Omega_b = 0.04,\ \Omega_\Lambda = 0.75,$$
$$h = 0.70,\ \sigma_8 = 0.9,\ \ldots$$

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Non-baryonic dark matter candidates

Best candidate

Cold dark matter:

- Axion $m_a \sim 10^{-5}$ eV
- Sterile neutrino $m_\nu \sim 100$ MeV
- Neutralino (lightest stable susy particle) $m_X > 100$ GeV

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The cold dark matter cosmogony

The Astrophysical Journal, 263:L1–L5, 1982 December 1

Peebles '82

LARGE-SCALE BACKGROUND TEMPERATURE AND MASS FLUCTUATIONS DUE TO SCALE-INVARIANT PRIMEVAL PERTURBATIONS

P. J. E. Peebles
Joseph Henry Laboratories, Physics Department, Princeton University

The Astrophysical Journal, 292:371–394, 1985 May 15

Davis, Efstathiou, Frenk & White 1985

THE EVOLUTION OF LARGE-SCALE STRUCTURE IN A UNIVERSE DOMINATED BY COLD DARK MATTER

Marc Davis,[1,2] George Efstathiou,[1,3] Carlos S. Frenk,[1,4] and Simon D. M. White[1,5]
Received 1984 August 20; accepted 1984 November 30

The Astrophysical Journal, 304:15–61, 1986 May 1

Bardeen, Bond, Kaiser & Szalay 1986

THE STATISTICS OF PEAKS OF GAUSSIAN RANDOM FIELDS

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Received 1985 July 25; accepted 1985 October 9

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Formation of galaxies and large-scale structure with cold dark matter

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Blumenthal, Faber, Primack & Rees 1984

The cold dark matter cosmogony

The CDM model is an intrinsically implausible model, all the more so when the cosmological constant Λ is required.

Couldn't we have something simpler?

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Non-baryonic dark matter candidates

Type	candidate	mass
hot	neutrino	a few eV
warm	Sterile neutrino	keV-MeV
cold	axion neutralino	10^{-5}eV- >100 GeV

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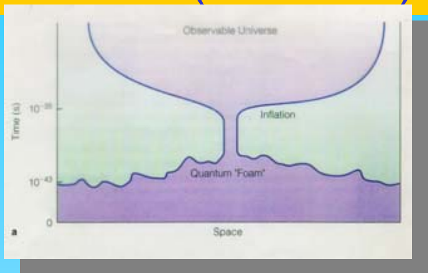
The origin of cosmic structure

Inflation ($t \sim 10^{-35}$ s)



→ **QUANTUM FLUCTUATIONS:**

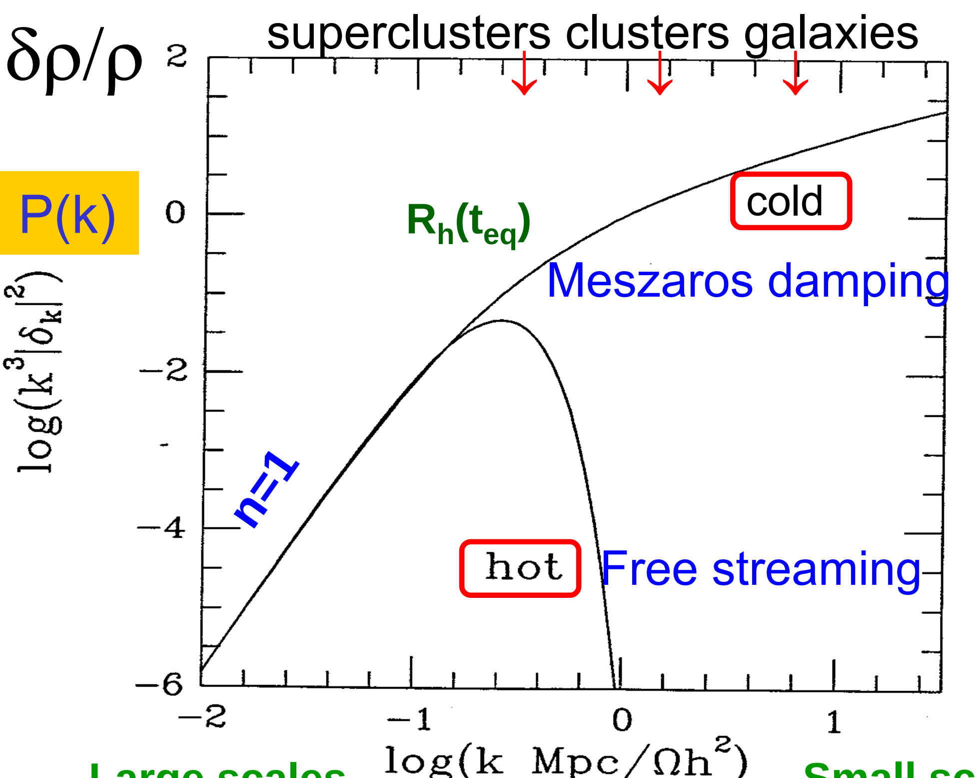
$$\left\{ \begin{array}{l} |\delta_k|^2 \propto k^n \quad n \approx 1 \\ \text{Gaussian amplitudes} \end{array} \right.$$

\+ Damping (nature of dark matter)

→ **FLAT UNIVERSE**

$P(k)=Ak^n\, T^2(k,t)$

→ Transfer function



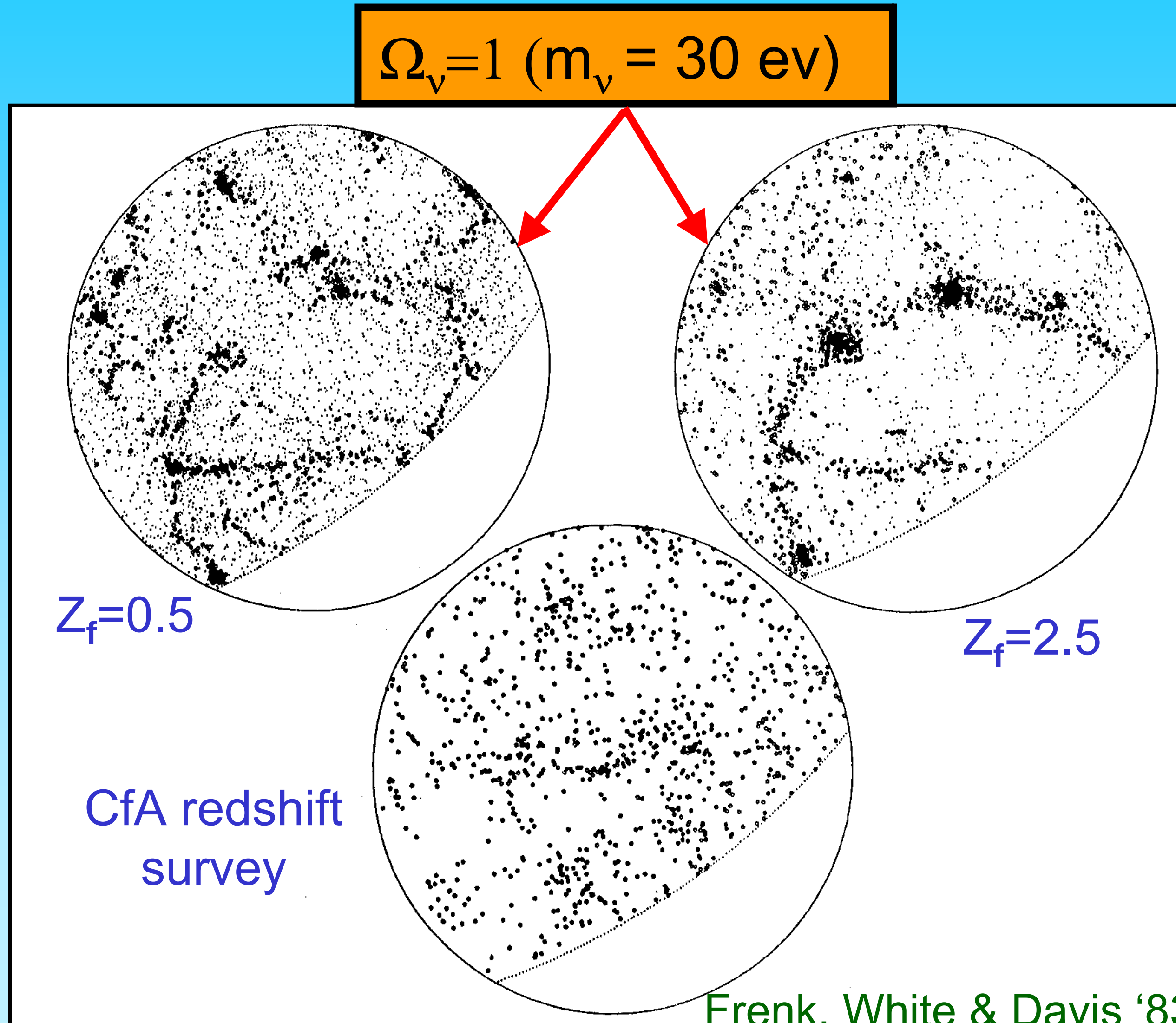
- Hot DM (eg ~30 ev neutrino)
  - Top-down formation
- Cold DM (eg ~neutralino)
  - Bottom-up (hierachical)

Neutrino (hot) dark matter

Free-streaming length so large that superclusters form first and galaxies are too young

⇨

Neutrinos cannot make an appreciable contribution to Ω and $m_\nu << 10$ ev

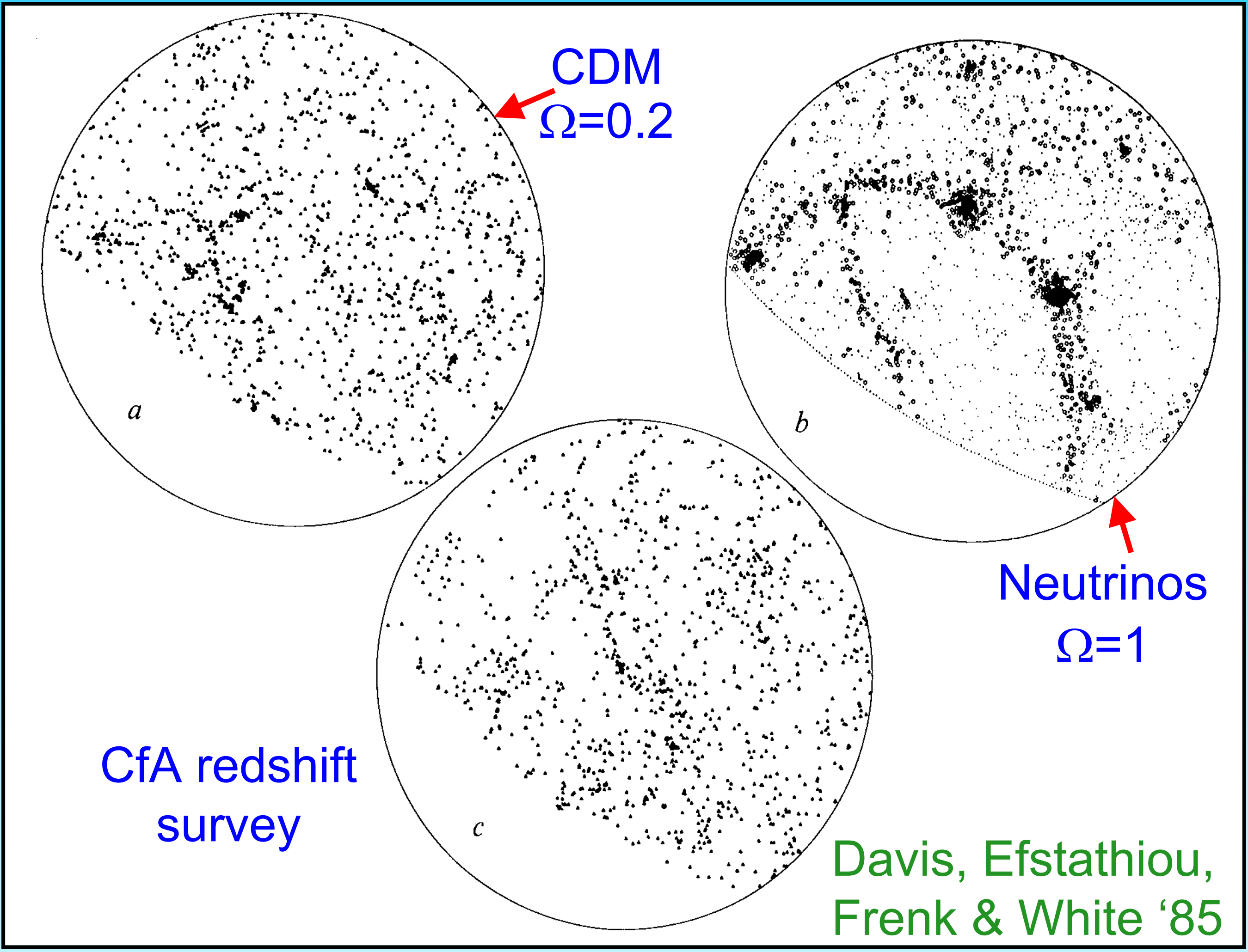


Non-baryonic dark matter cosmologies

Neutrino dark matter produces unrealistic clustering

Early CDM N-body simulations gave promising results

In CDM structure forms hierarchically



Even if it is CDM, couldn't we have something simpler?

i.e. $\Omega_{matter} = 1$

Clusters give direct evidence for $\Omega_{matter} < 1$

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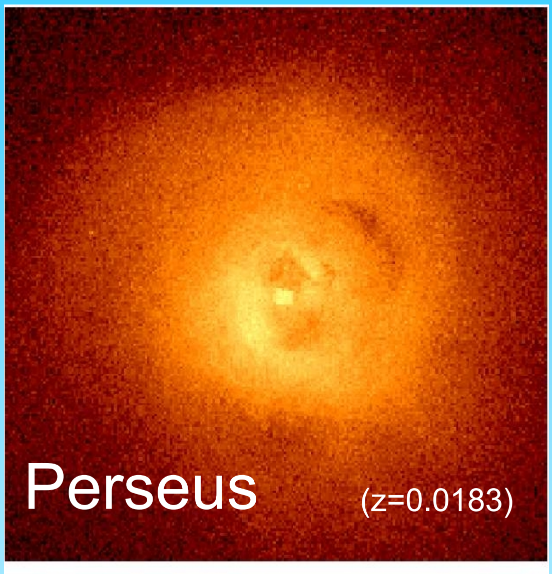
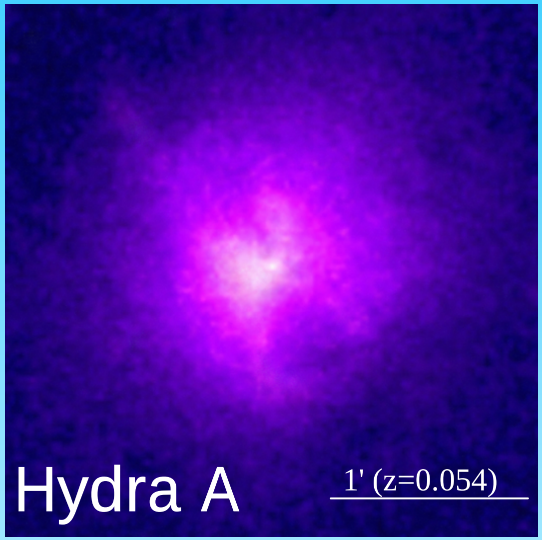
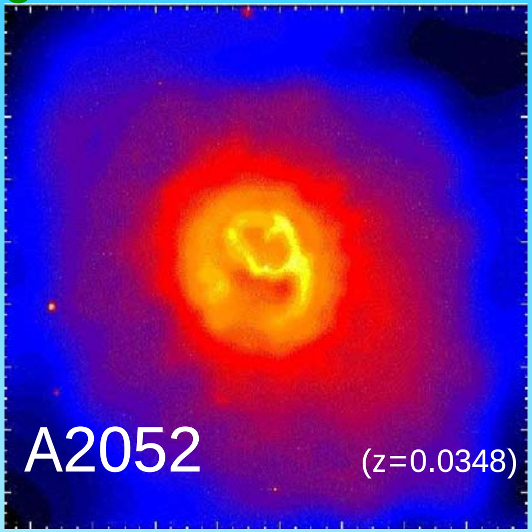
Galaxy clusters

X-ray emission from hot plasma in clusters

Images from David Buote







About 90% of baryons in clusters are in hot gas

X-rays $\Rightarrow$ gas mass

Photometry $\Rightarrow$ stellar mass

Gas in hydrostatic equilibrium so X-rays (or lensing) $\Rightarrow$ total gravitating mass

} $\Rightarrow$ Baryon fraction, f_b

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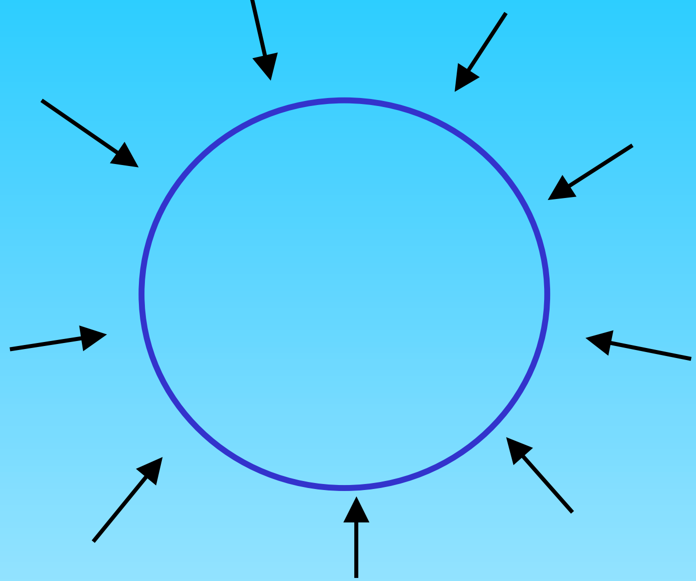
Ω from the baryon fraction in clusters



In clusters matter that has fallen in is still in the cluster ($r_{vir} \sim r_{non\text{-}linear}$)

$\Rightarrow$ baryon fraction in clusters $\approx$ baryon fraction of universe

$$f_{baryon} = \frac{\text{mass in baryons}}{\text{total mass}}$$

$$M_b = M_{gas} + M_{stars}$$

$$f_b = \gamma \frac{\Omega_b}{\Omega}$$

White, Navarro, Evrard & Frenk '93

where $\gamma=1$ if f_b has the universal value

Simulations $\Rightarrow$ $\gamma=0.9$

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Ω from the baryon fraction in clusters

The baryon fraction in clusters, f_b, is related to the universal baryon fraction by:

$$f_b = \frac{M_b}{M_{tot}} = \gamma \frac{\Omega_b}{\Omega_m}$$

White, Navarro, Evrard & Frenk '93

where $\gamma=1$ if f_b has the universal value

simulations → $\gamma = 0.9 \pm 10\%$

X-rays+lensing → $f_b = (0.060h^{-3/2} + 0.009) \pm 10\%$

BBNS, CMB → $\Omega_b h^2 = 0.019 \pm 20\%$

HST → $h = 0.7 \pm 10\%$

→ $$\Omega_m = \frac{\Omega_b \gamma}{f_b} = 0.31 \pm 0.12$$

Allen etal '04

$\Omega < 1$: open or flat universe?

$\Omega_{matter} < 1 \Rightarrow$

- Open universe
- Cosmological constant to give $\Omega_{tot}=1$

White et al 1993

(Some) evidence for dark energy

Evidence for Λ from high-z supernovae

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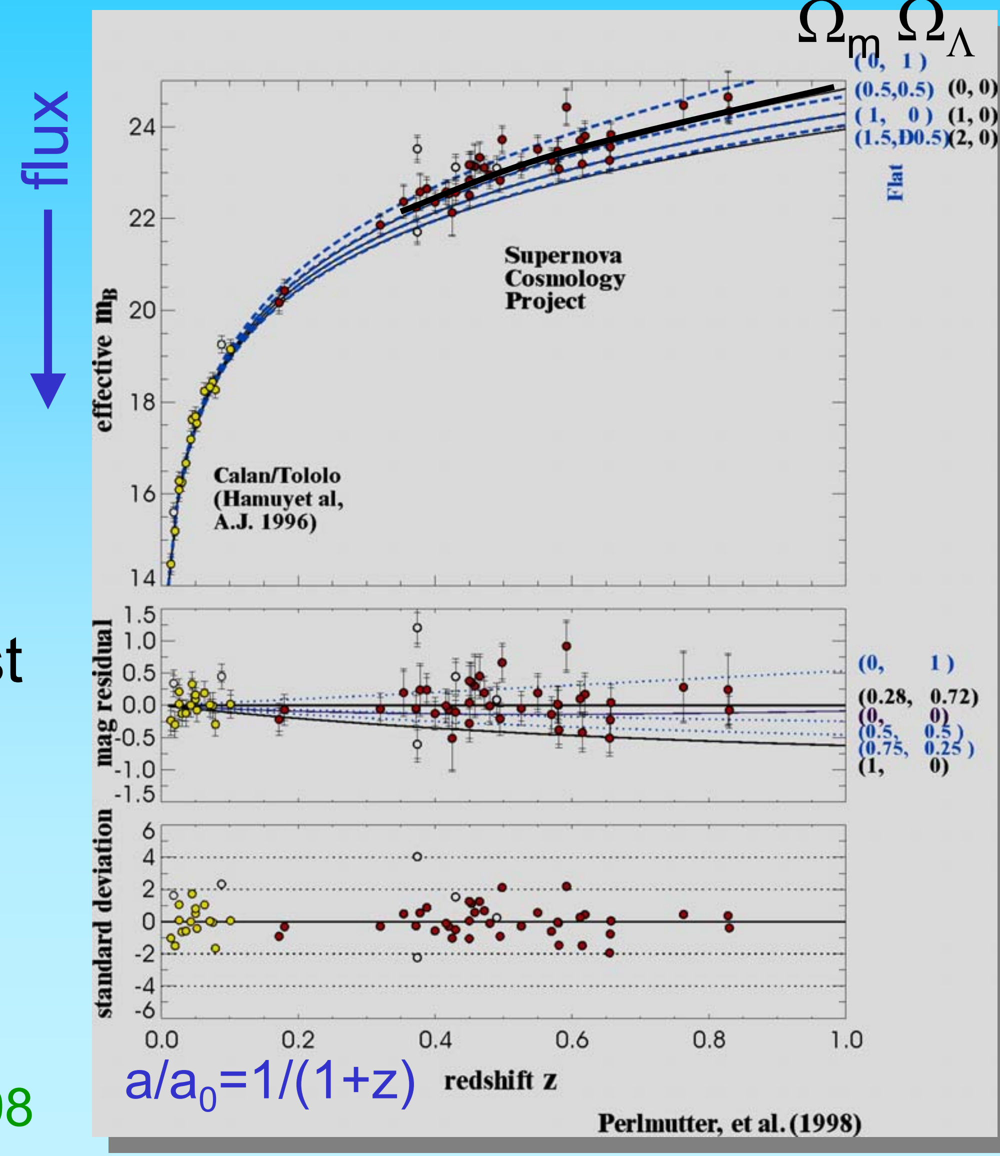
SN type Ia (standard candles) at z~0.5 are fainter than expected even if the Universe were empty



The cosmic expansion must have been accelerating since the light was emitted

Perlmutter et al '98

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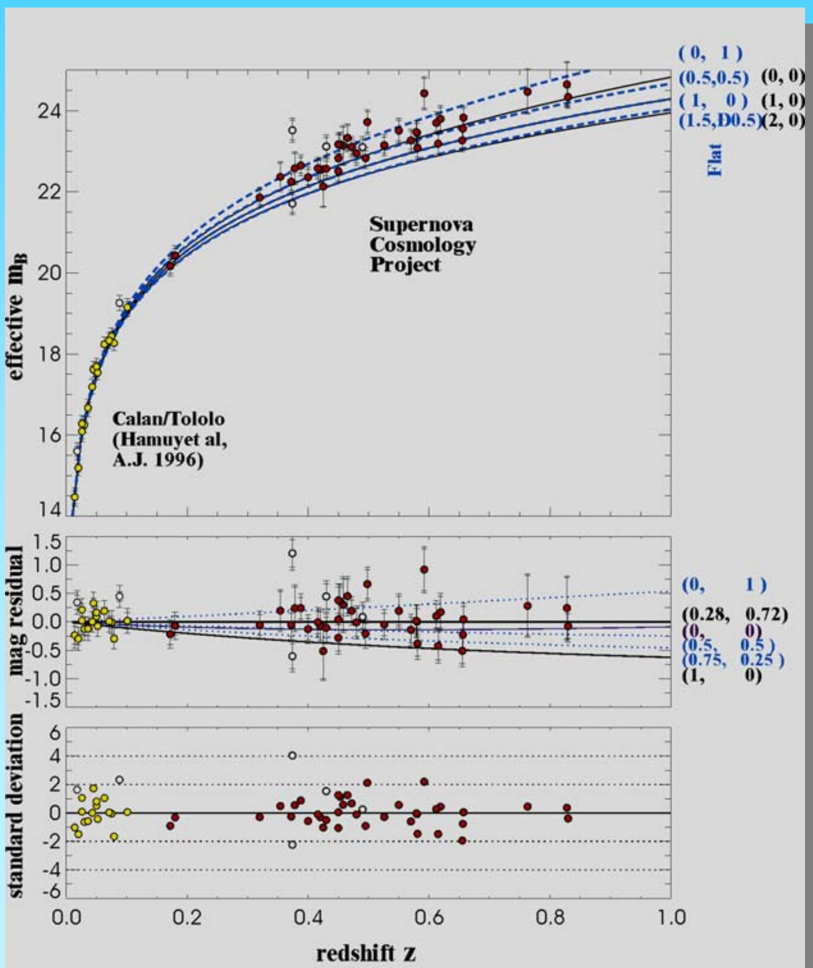
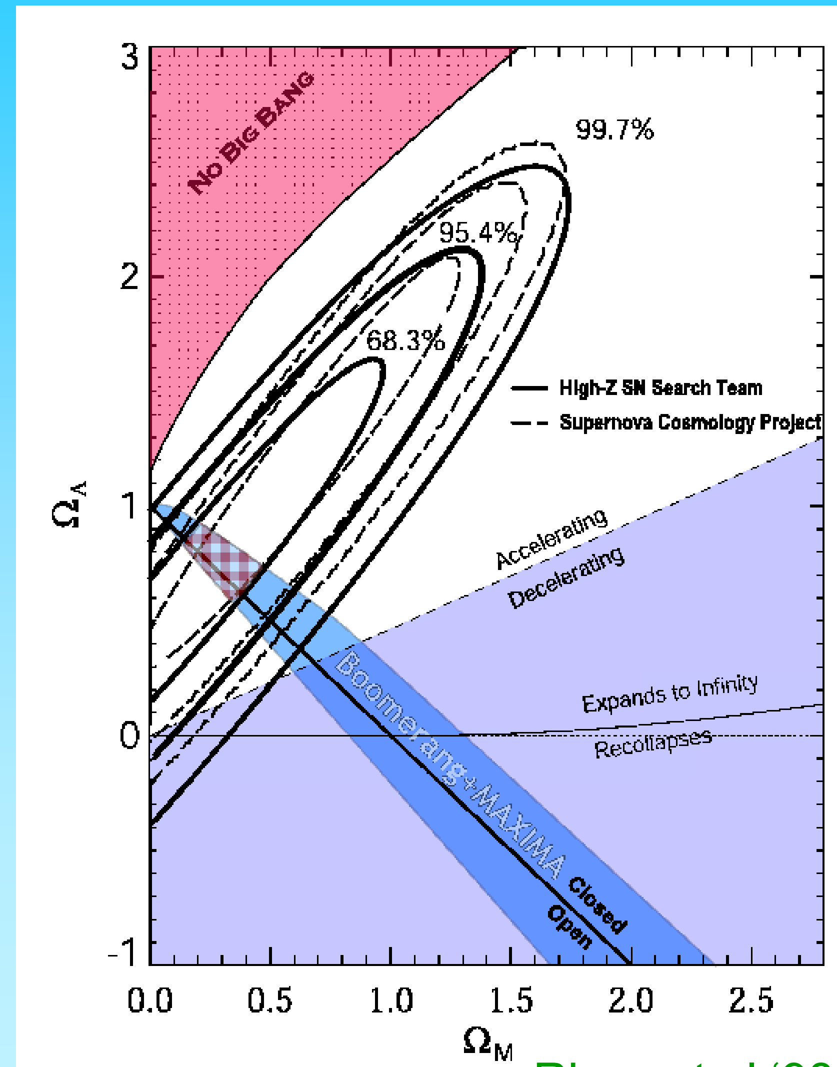
Evidence for Λ from high-z supernovae

Distant SN are fainter than expected if expansion were decelerating

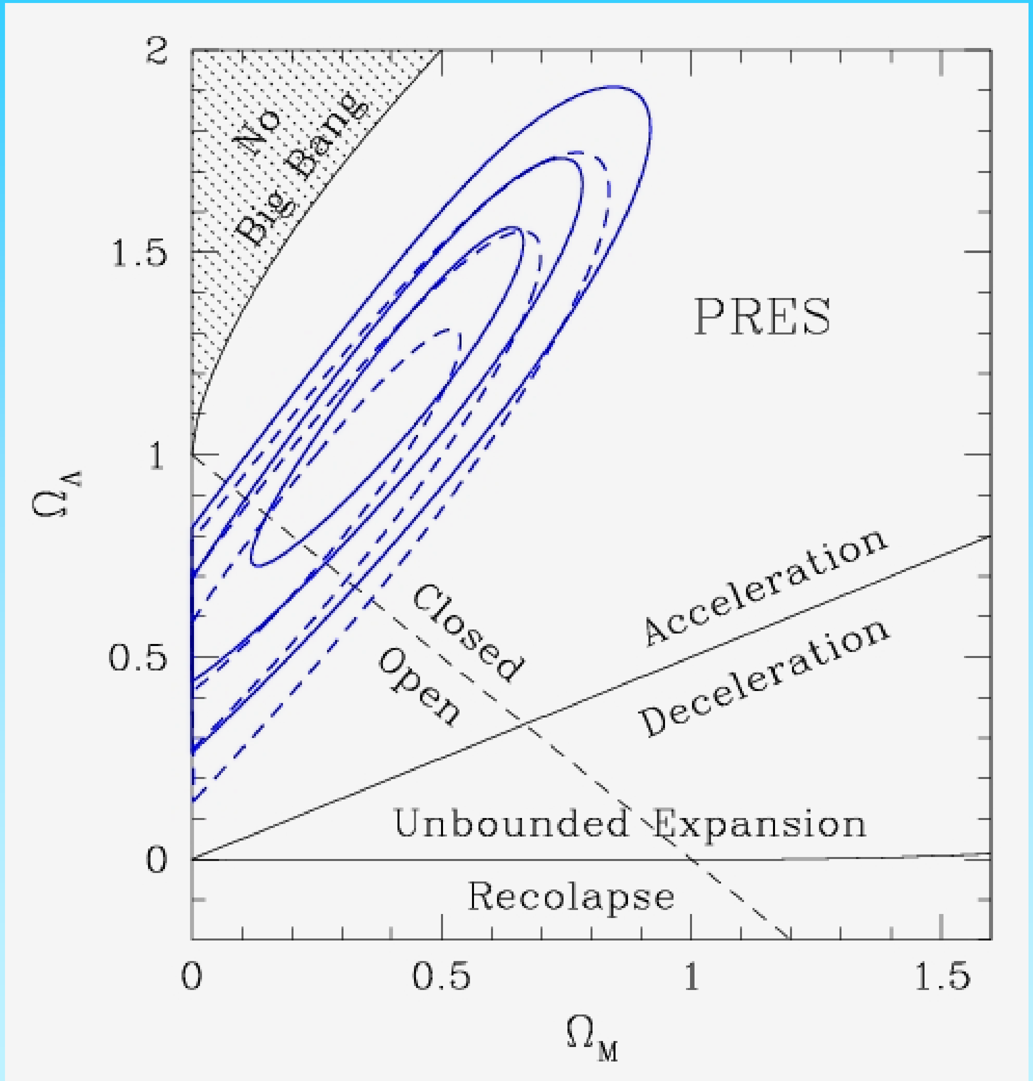


Perlmutter, et al.(1998)



Riess et al '98

Evidence for Λ from high-z supernovae



Latest data rules out $\Omega_\Lambda = 0$.

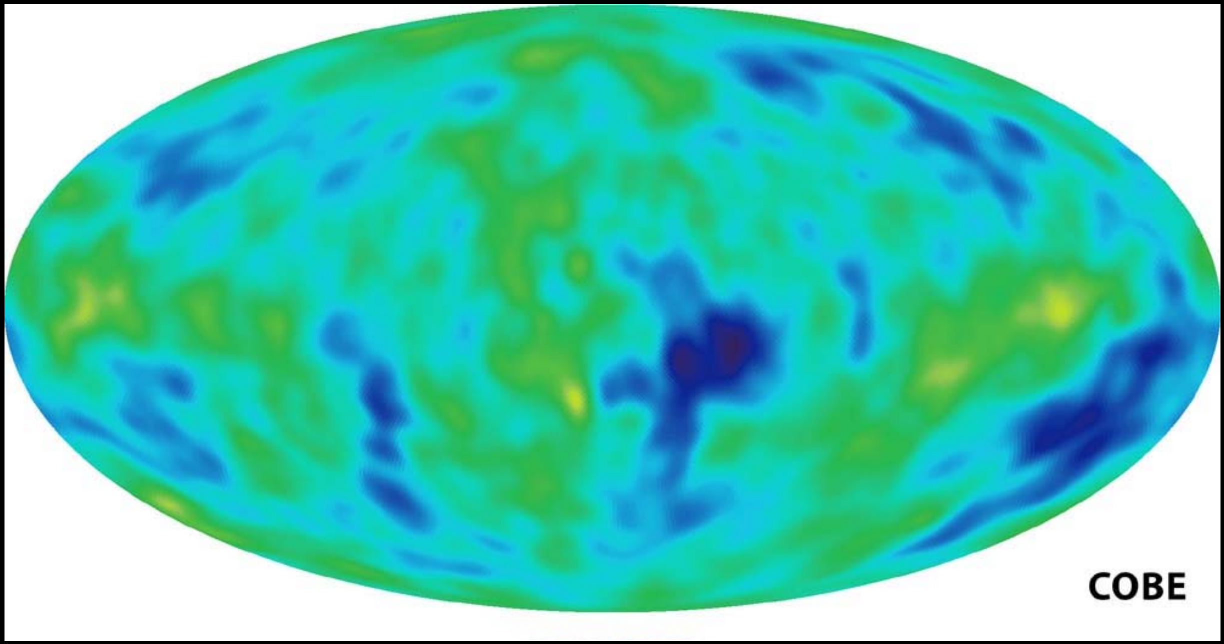
Main concerns:

- Physics of SNIa not understood
- Systematic errors?

Clocchiatti et al '06

The CMB

1992



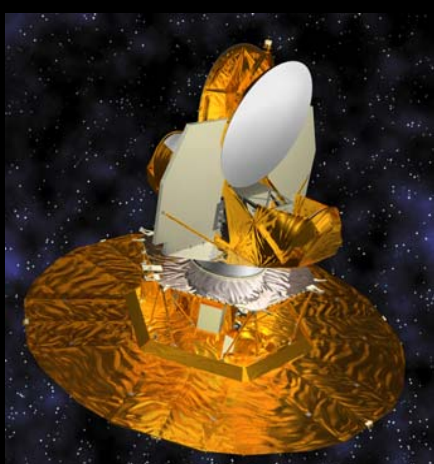
The cosmic microwave background radiation (CMB) provides a window to the universe at t~3x10^5 yrs

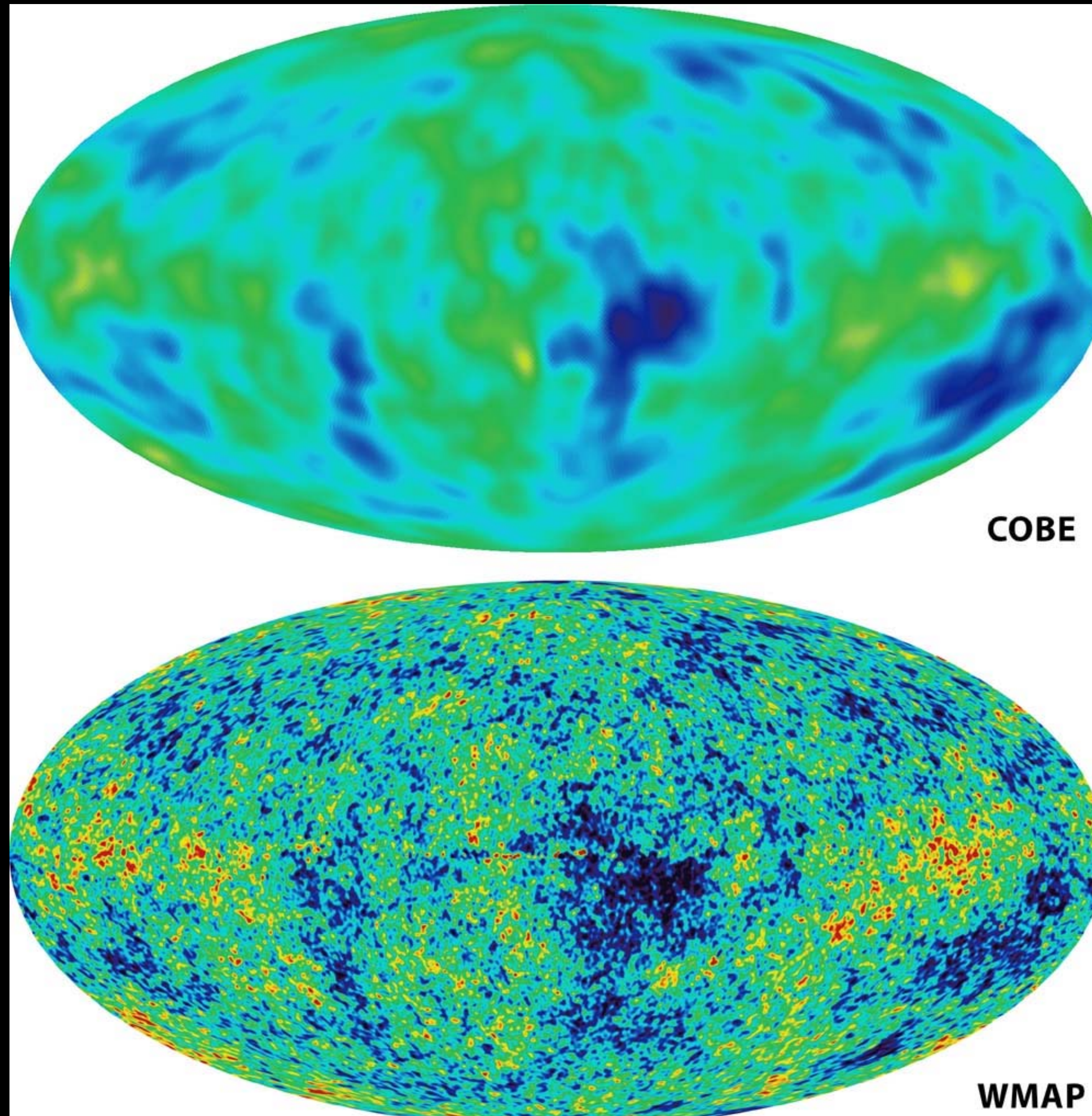
In 1992 COBE discovered temperature fluctuations ($\Delta T/T \sim 10^{-5}$) consistent with inflation predictions

The CMB

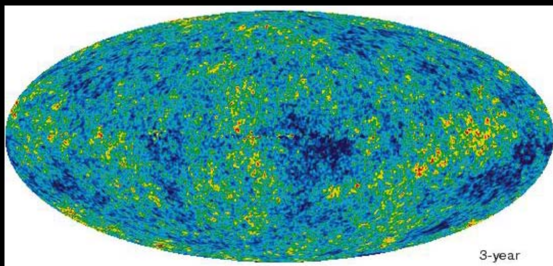
1992

2003





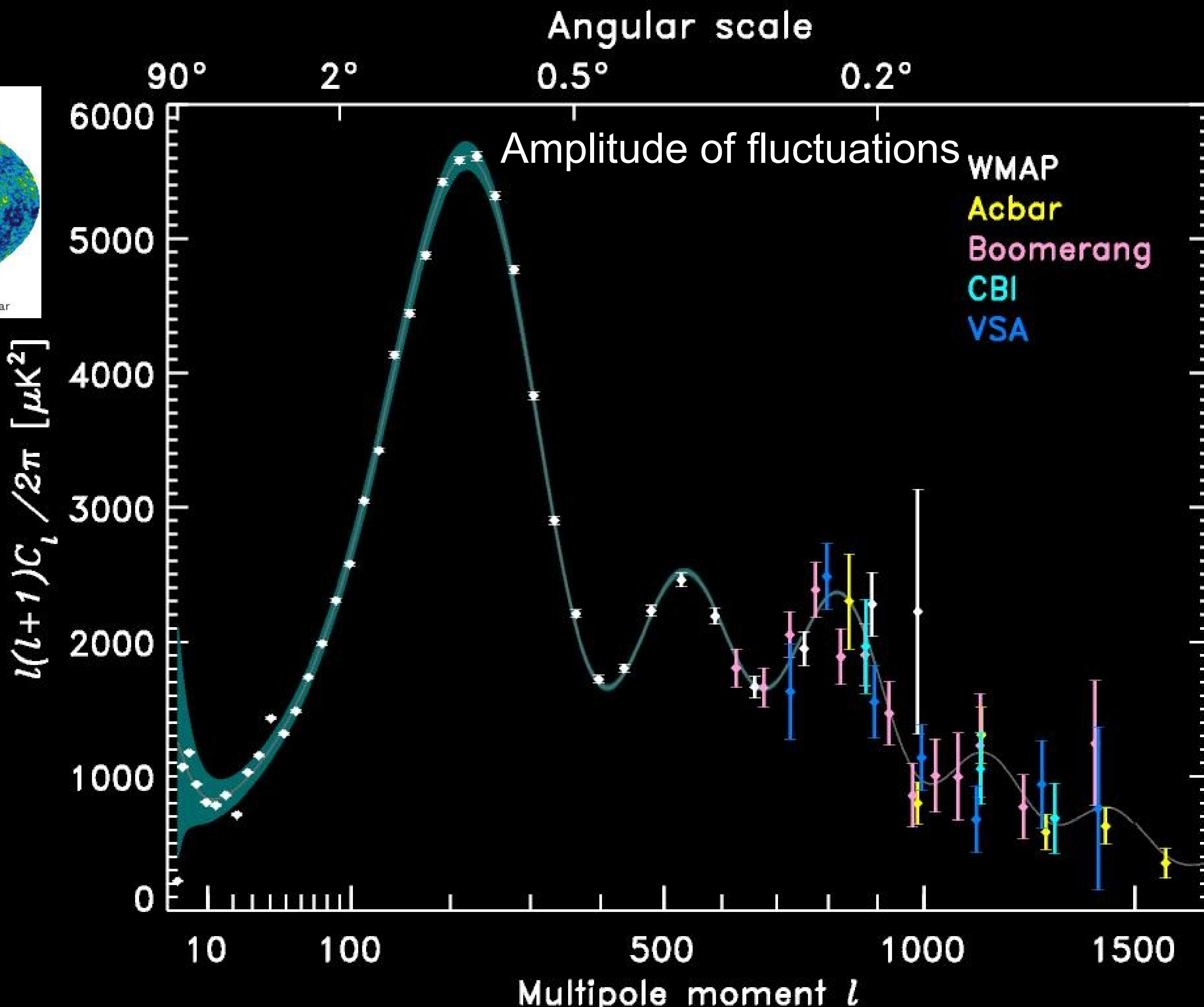
WMAP temp anisotropies in CMB



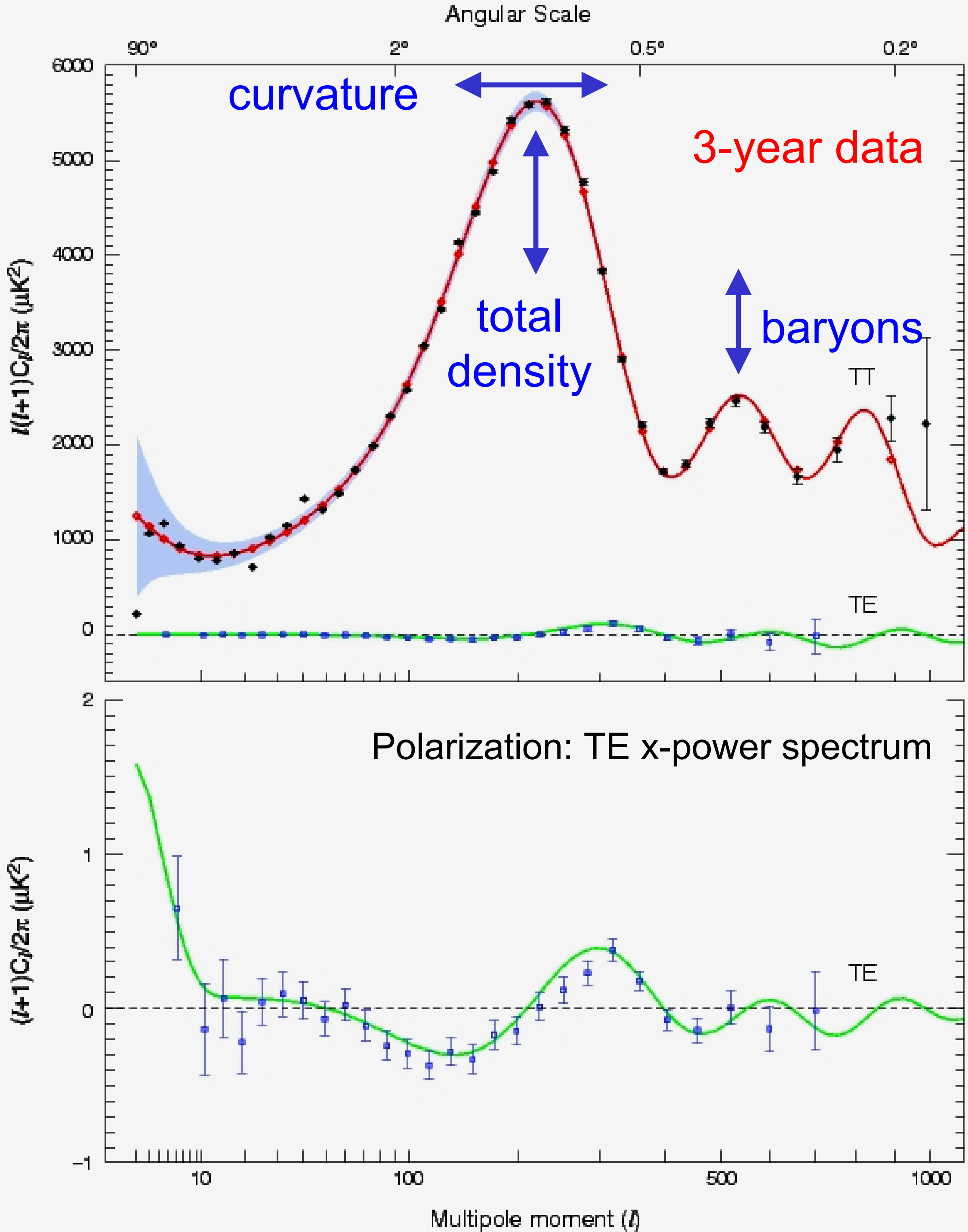
The amplitude of the CMB ripples is exactly as predicted by inflationary cold dark matter theory

The position of the first peak

➔ FLAT UNIVERSE

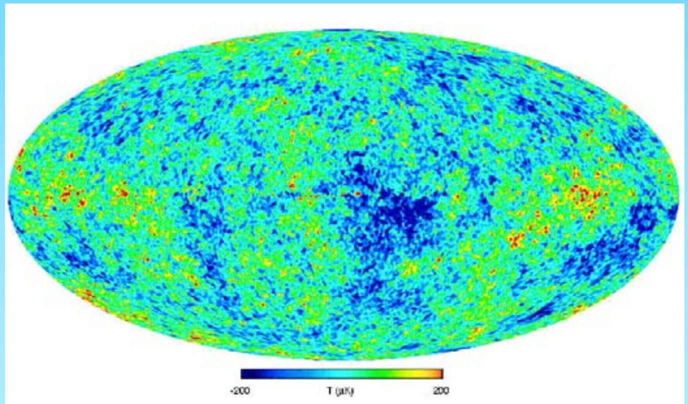


Hinshaw etal '06



The Emergence of the Cosmic Initial Conditions

> 10^5 independent ~ 5σ measurements of T are fit by *a priori* model: ΛCDM



T-P x-corr → Adiabatic fluctns

Testing the CDM paradigm

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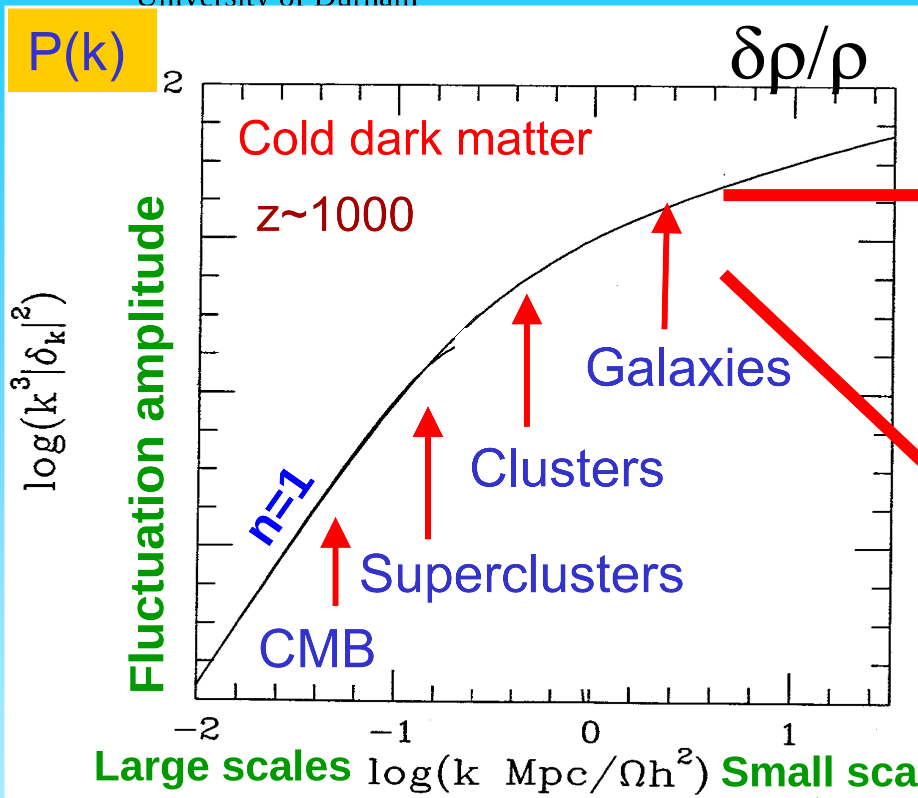
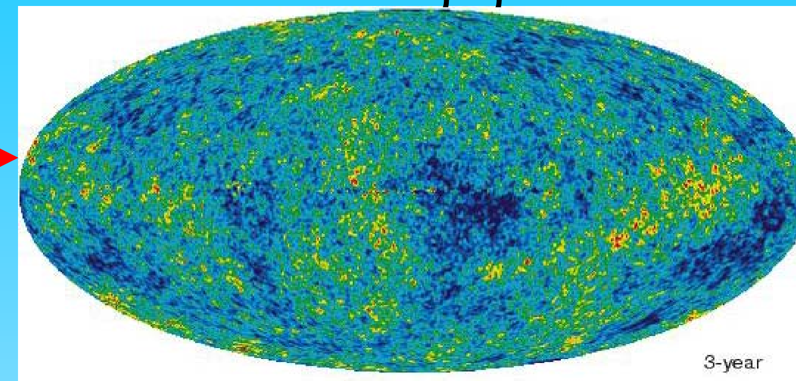
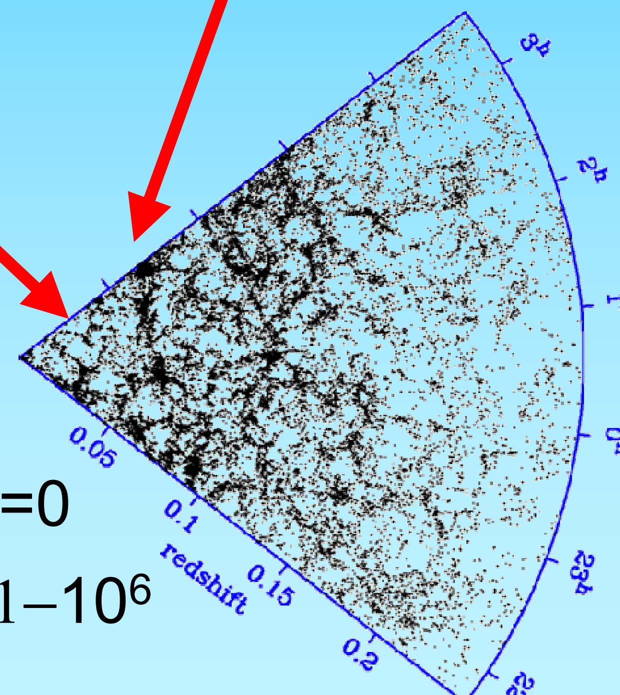


Initial conditions : ΛCDM

$z=1000 \quad \delta\rho/\rho \sim 10^{-5}$





$z=0$

$\delta\rho/\rho \sim 1\text{–}10^6$

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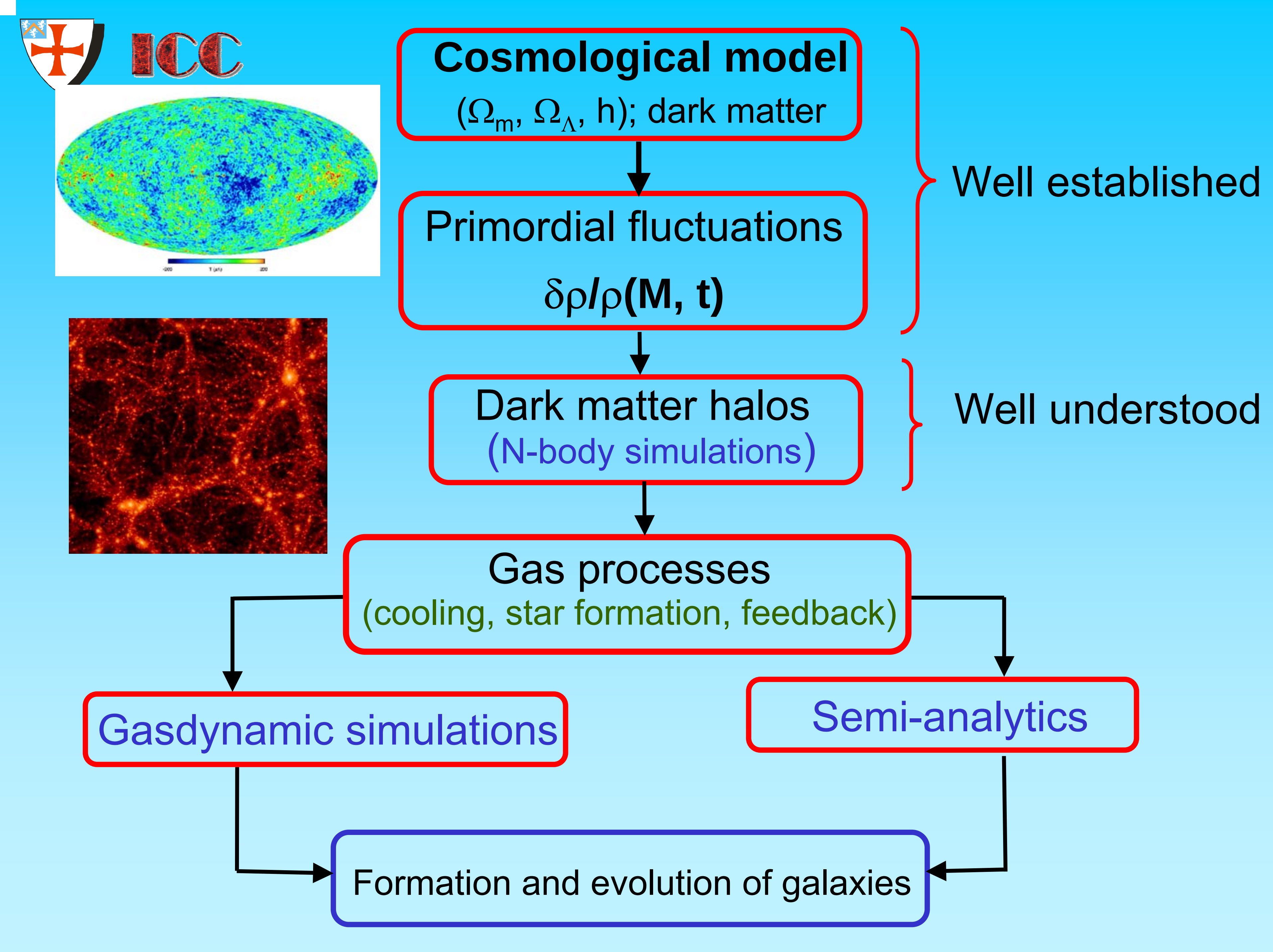
ICC
Cosmological model
(Ω_m, Ω_Λ, h); dark matter
Primordial fluctuations
$\delta\rho/\rho$(M, t)
Well established
Dark matter halos
(N-body simulations)
Well understood
Gas processes
(cooling, star formation, feedback)
Gasdynamic simulations
Semi-analytics
Formation and evolution of galaxies

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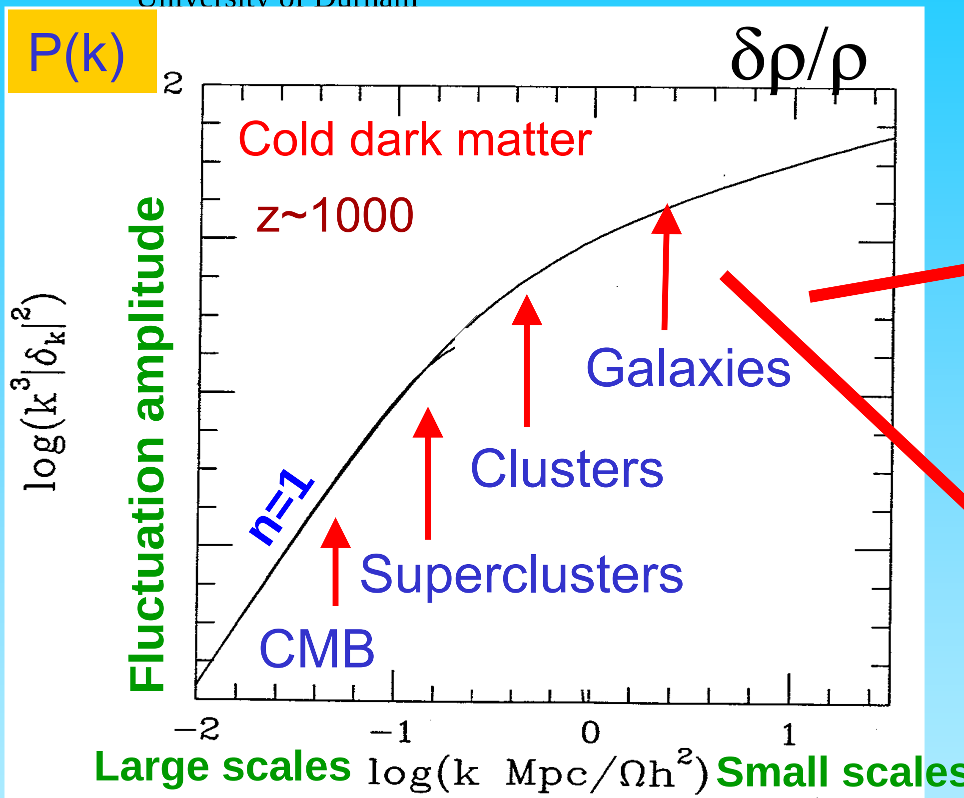
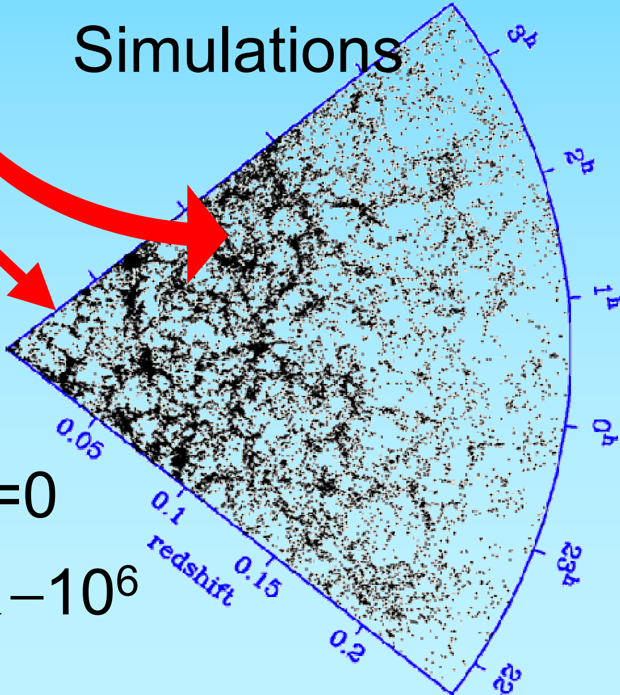
Testing the CDM paradigm



"Cosmology machine"

Simulations



Initial conditions : ΛCDM

Basic physics simple: structure grows primarily by gravity

→ N-body simulations

z=0

$\delta\rho/\rho \sim 1 - 10^6$

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Moore's Law for Cosmological N-body Simulations

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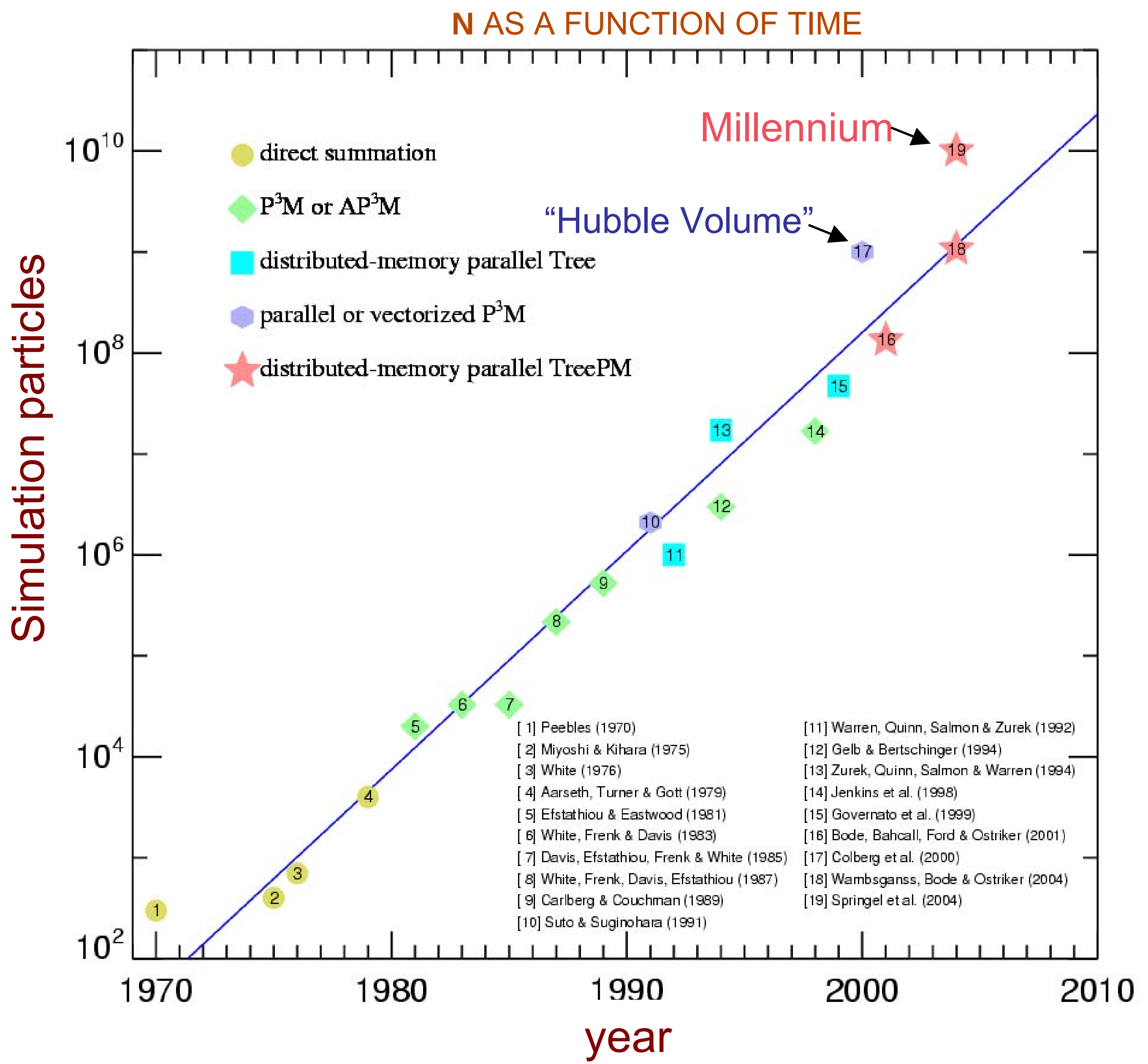
- Computers double their speed every 18 months
- A naive N-body force calculation needs N^2 op's
- Simulations double their size every 16.5 months
- $N = 10^{10}$ should have been reached in 2008
- ..but was reached in 2004



ICC
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Virgo consortium for supercomputer simulations

Core members and associates

- Carlos Frenk – ICC, Durham (P.I.)
- Adrian Jenkins – ICC, Durham
- Tom Theuns – ICC, Durham
- Gao Laing – ICC, Durham
- Simon White – Max Plank Institut für Astrophysik (co-P.I.)
- Volker Springel – Max Plank Institut für Astrophysik
- Frazer Pearce – Nottingham
- Naoki Yoshida – Tokyo
- Peter Thomas – Sussex
- Hugh Couchman – McMaster
- John Peacock – Edinburgh
- George Efstathiou – Cambridge
- Joerg Colberg – Pittsburgh
- Scott Kay – Oxford
- Rob Thacker – McGill
- Julio Navarro – Victoria
- Gus Evrard – Michigan
- Joop Schaye – Leiden

Virgo junior associates

Around 20 Phd students+postdocs

Simulation data available at:

http://www.mpa-garching.mpg.de/Virgo

Pictures and movies available at:

www.durham.ac.uk/virgo

Institute for Computational Cosmology

dalla Vechia,
Jenkins & Frenk

150 Mpc/h

Comoving
coordinates

ICC
University of Durham

The Millennium simulation

UK, Germany, Canada, US collaboration

Simulation data available at:

http://www.mpa-garching.mpg.de/Virgo

Pictures and movies available at:

www.durham.ac.uk/virgo

Nature, June/05

Cosmological N-body simulation

- 10 billion particles
- 500 h^{-1} Mpc box
- $m_p = 8\times10^8\, h^{-1}\, M_o$
- $\Omega =1$; $\Omega_m=0.25$; $\Omega_b=0.045$; $h=0.73$; $n=1$; $\sigma_8=0.9$
- 20×10^6 gals brighter than LMC

Carried out at Garching using L-Gadget by V. Springel

(27 Tbytes of data)

The Millennium simulation

QuickTime™ and a
3ivx D4 4.5.1 decompressor
are needed to see this picture.

Springel et al Nature June/05

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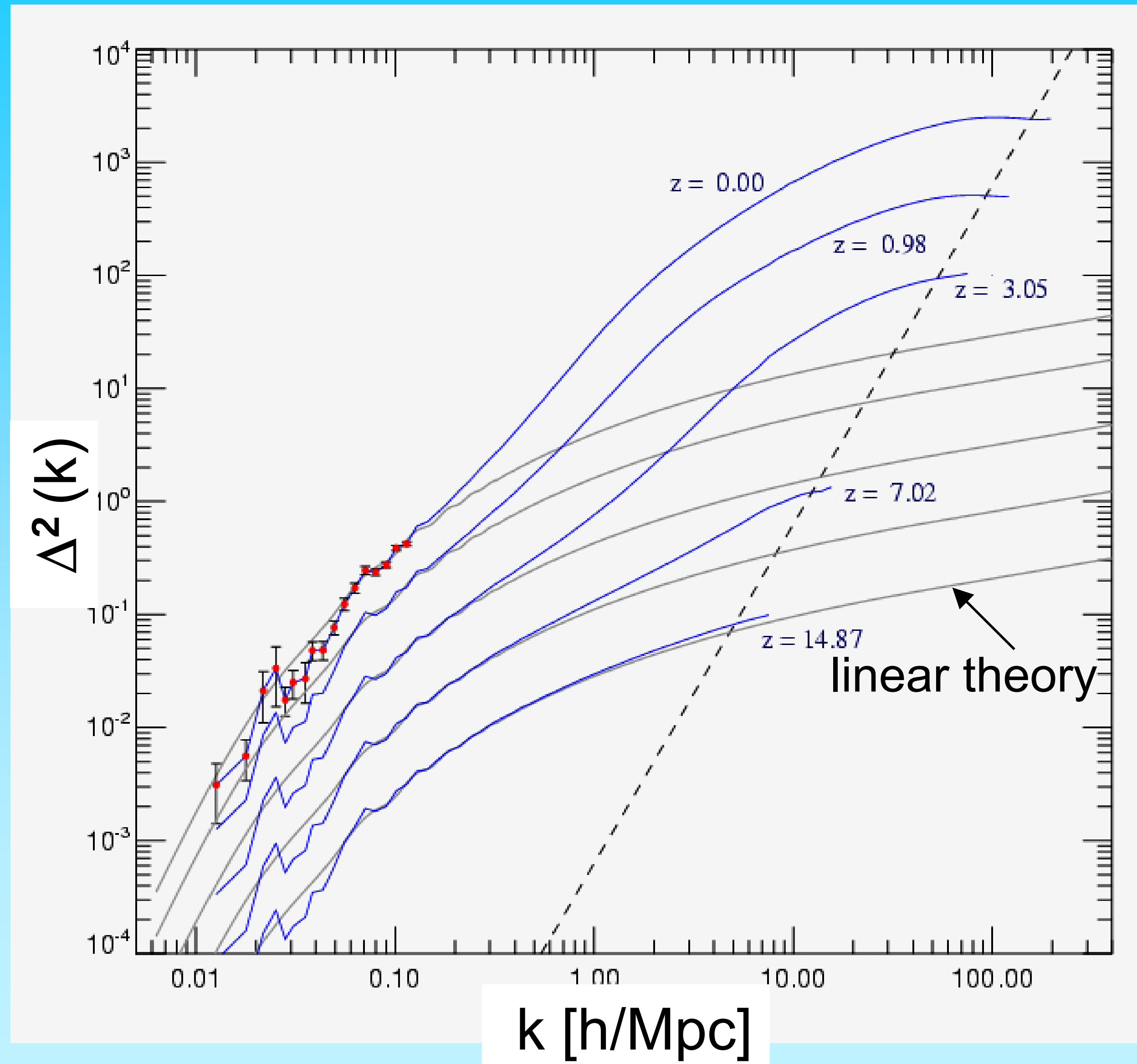
The mass power spectrum

The non-linear mass power spectrum is accurately determined by the Millennium simulation over large range of scales



Halo Mass Functions in Mil Sim

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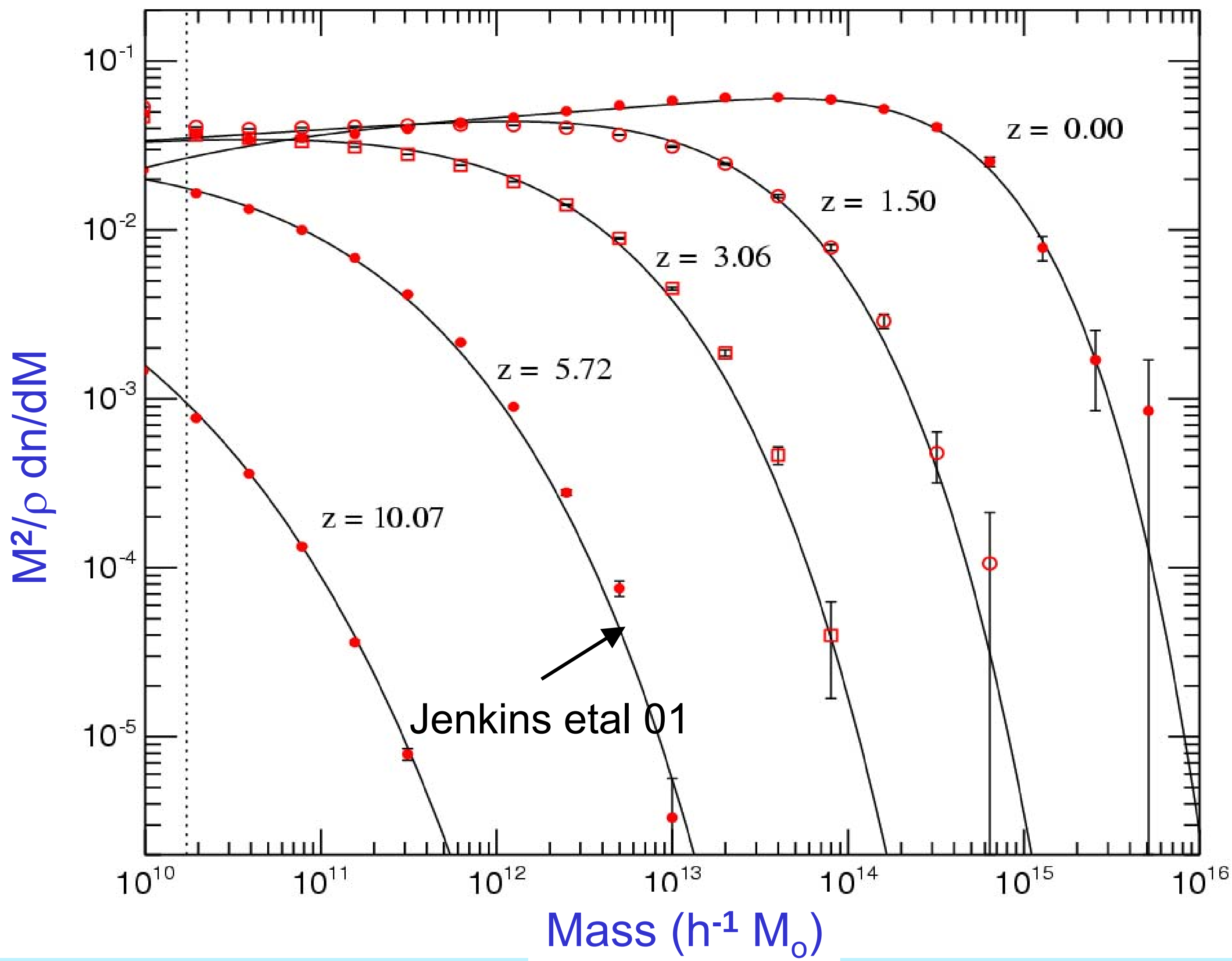
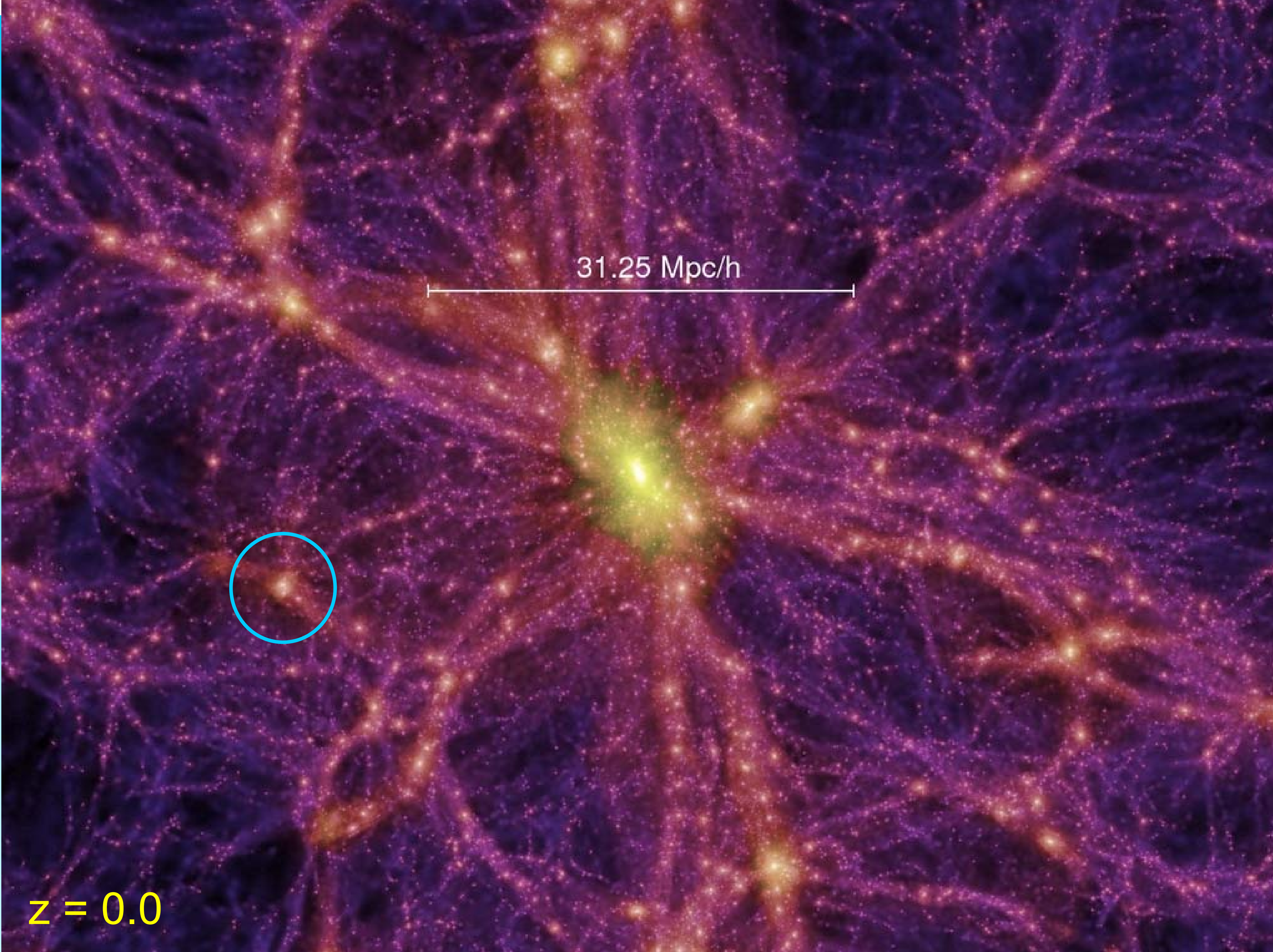
Solid curves are the empirical fitting formula from Jenkins et al 2001 with no parameters adjusted

At z = 0 half of all mass is in lumps of $M > 2.10^{10} M_O$



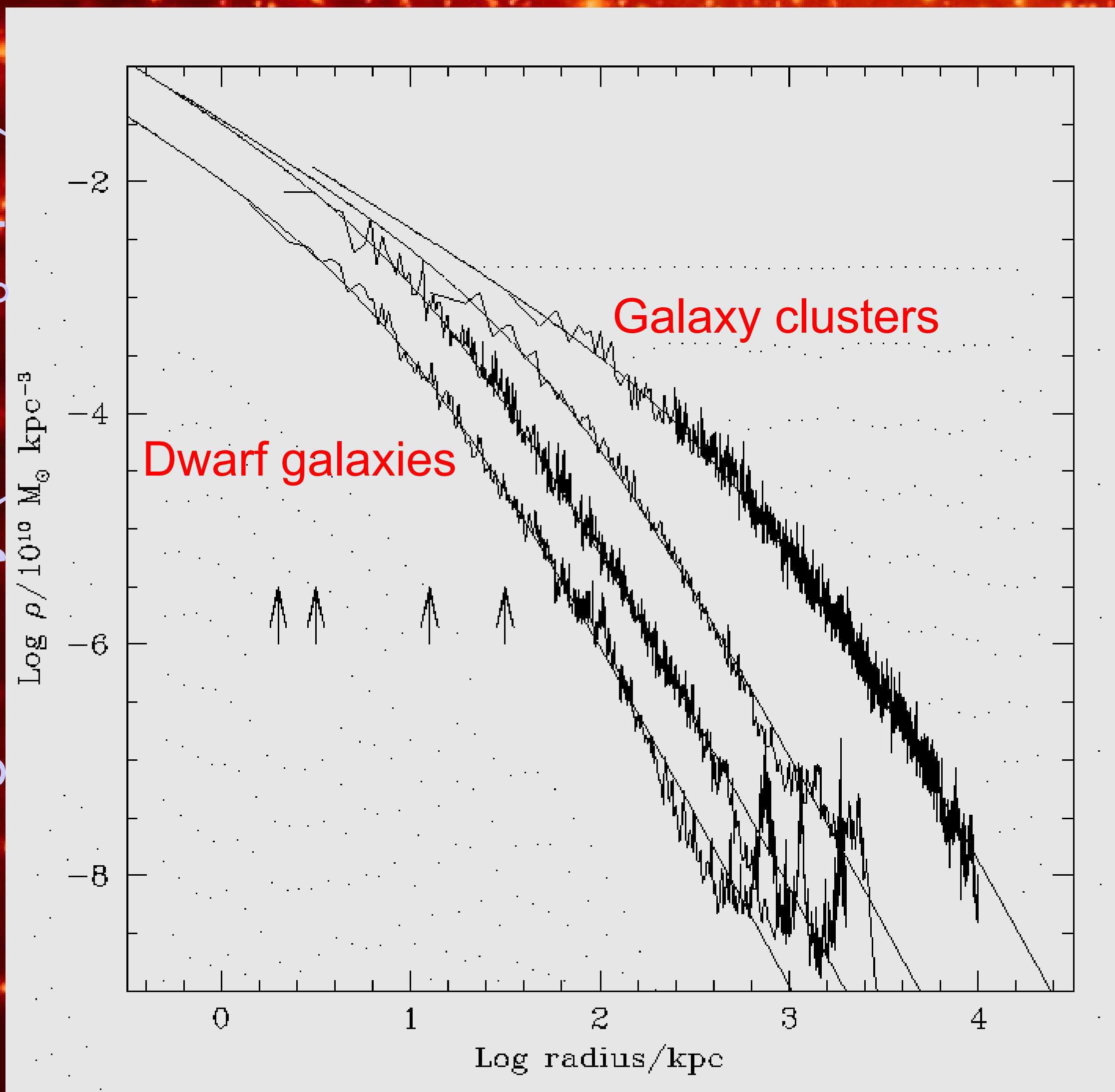
Springel et al 2005


31.25 Mpc/h
z = 0.0

1 Mpc

Jenkins & Frenk 2004

The Density Profile of Cold Dark Matter Halos



Halo density profiles are independent of halo mass & cosmological parameters

There is no obvious density plateau or `core' near the centre.

(Navarro, Frenk & White '97)

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

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Modelling galaxy formation

- **Aim:** follow history of galaxy formation ***ab initio***, i.e starting from a cosmological model for structure formation so as to predict observables
- **Main Physical processes:**
  - Assembly of dark matter halos
  - Shock-heating and radiative cooling of gas within halos

Sub-grid physics

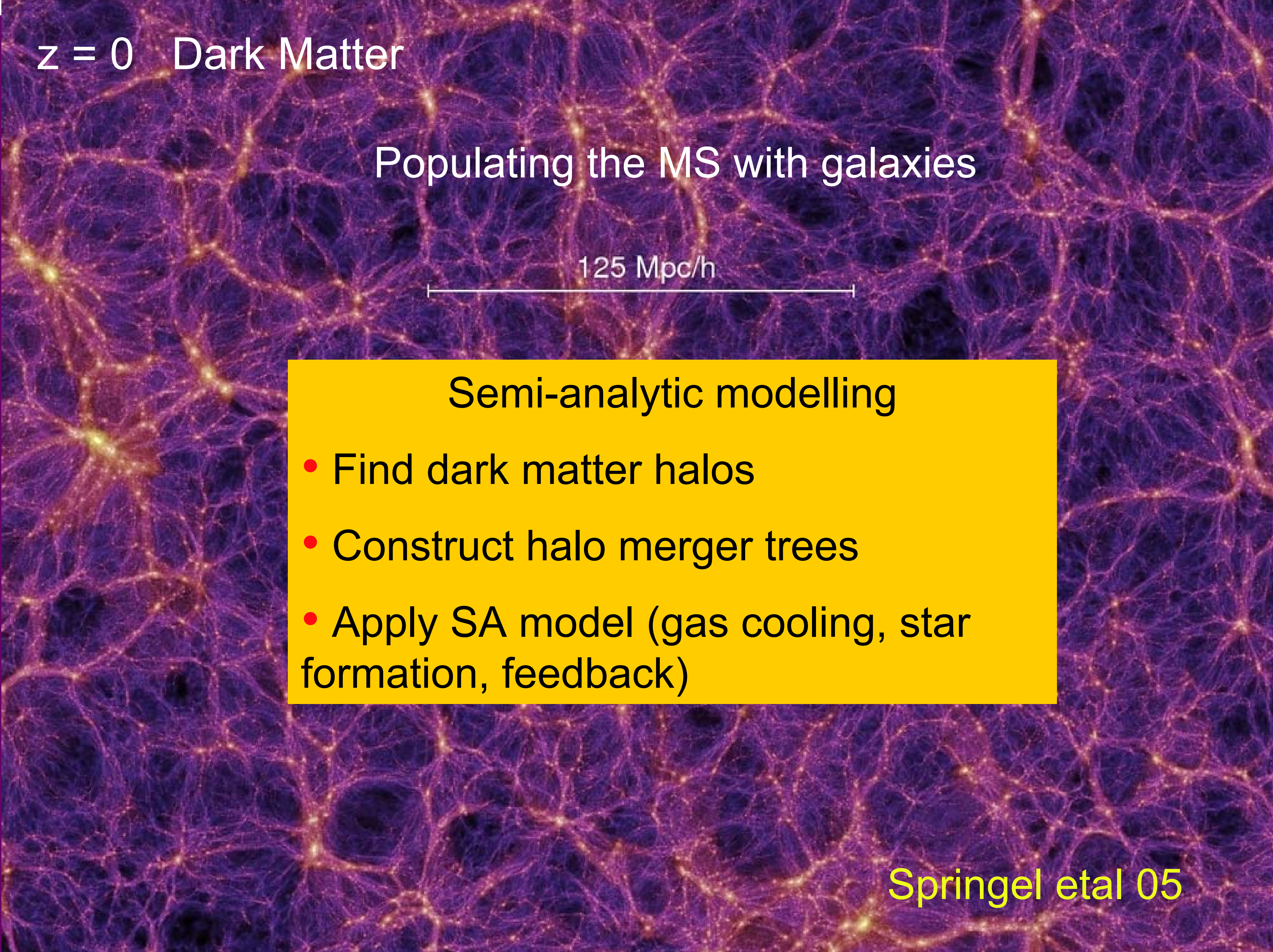
  - Star formation and feedback
  - Production & mixing of metals
  - Evolution of stellar populations
  - Dust obscuration
  - Black hole format'n, AGN feedback
  - Galaxy mergers

Phenomenological models

In semi-analytics and simulations

z = 0 Dark Matter

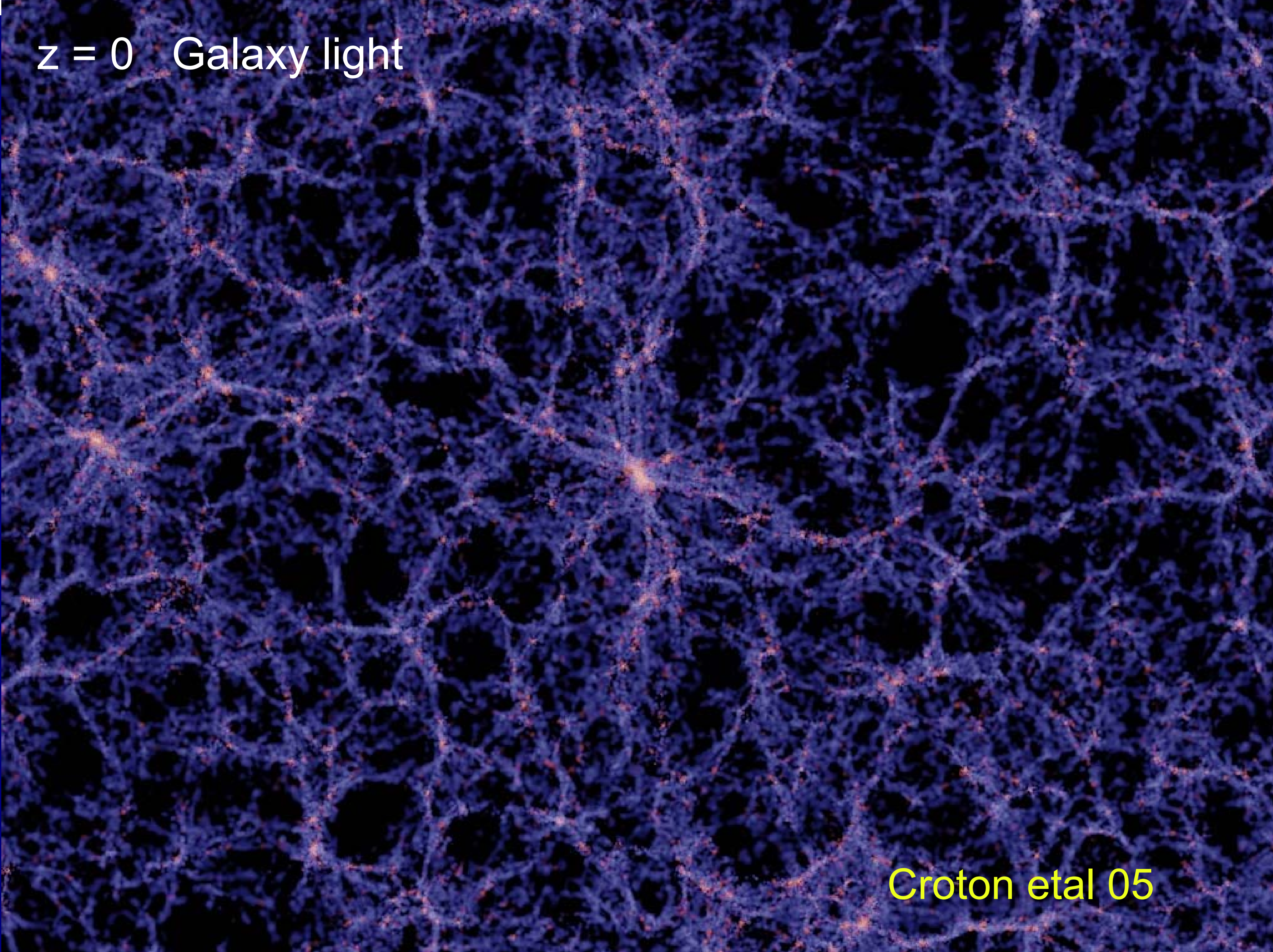
Populating the MS with galaxies



Semi-analytic modelling

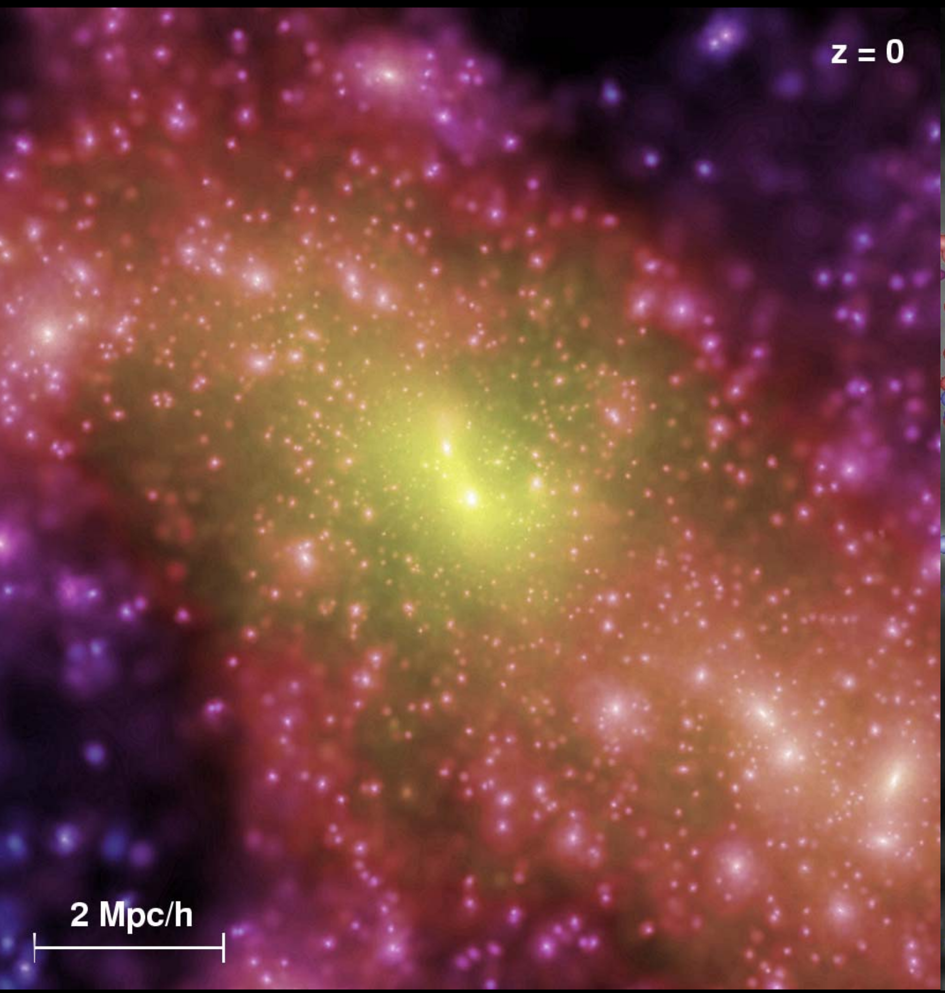
- Find dark matter halos
- Construct halo merger trees
- Apply SA model (gas cooling, star formation, feedback)

Springel etal 05

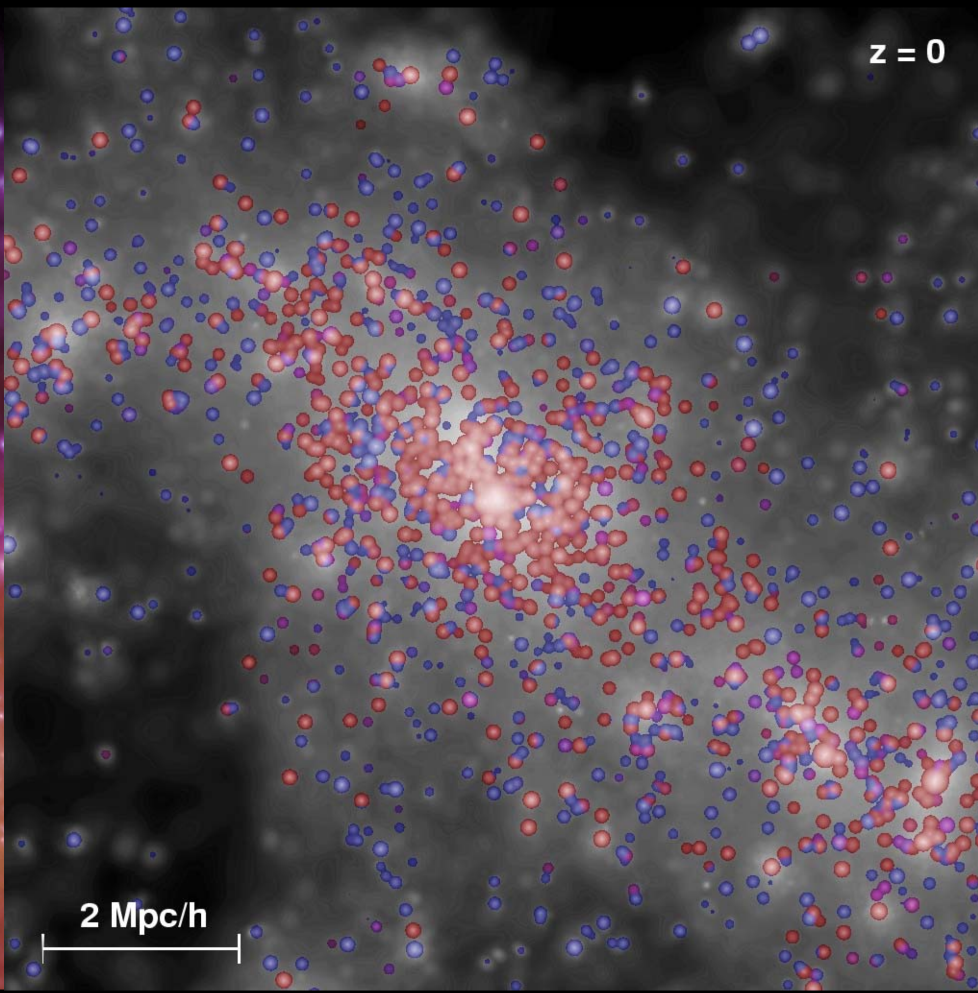

z = 0 Galaxy light
Croton etal 05

$10^{14}M_o$

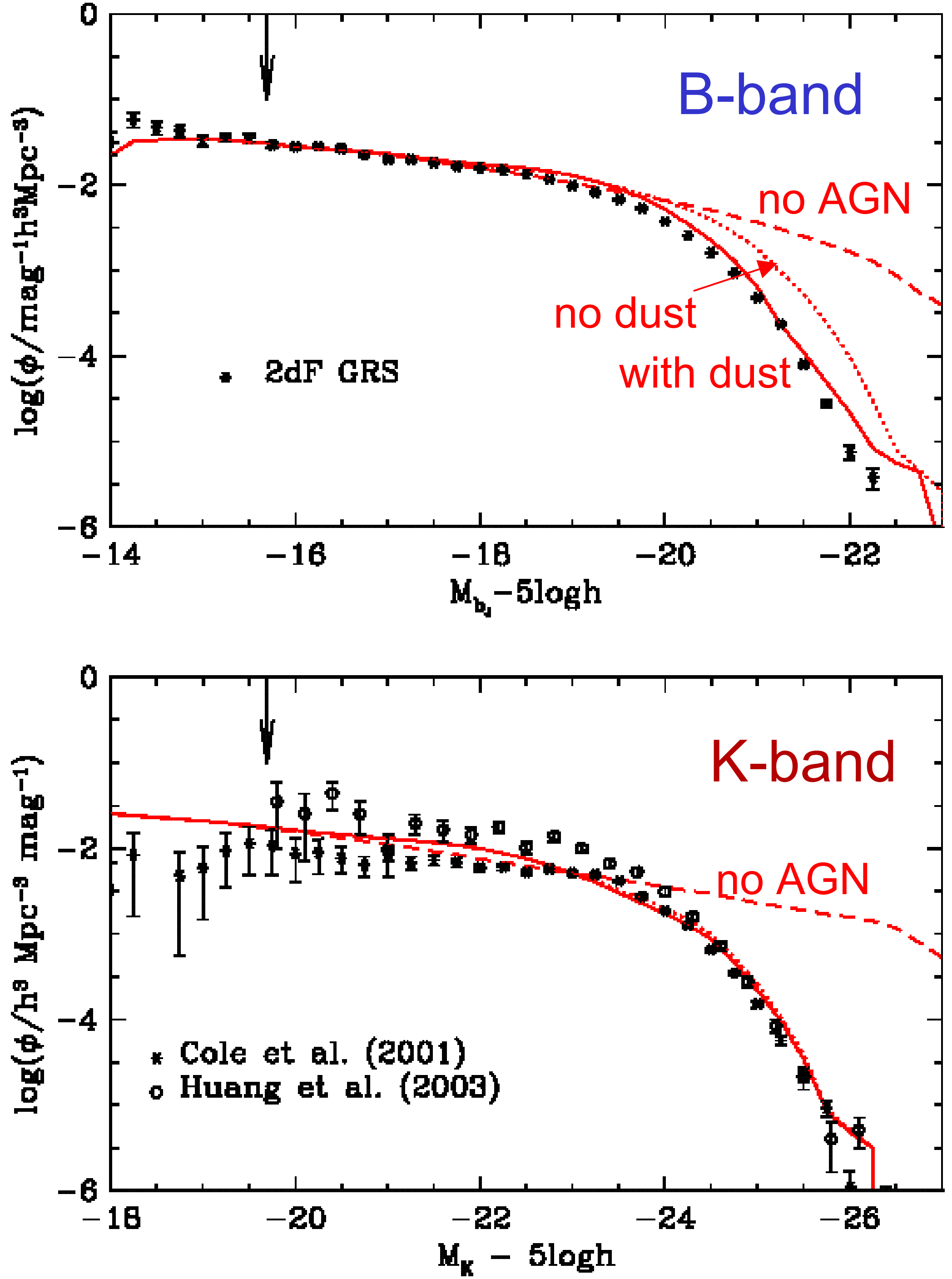
Dark matter



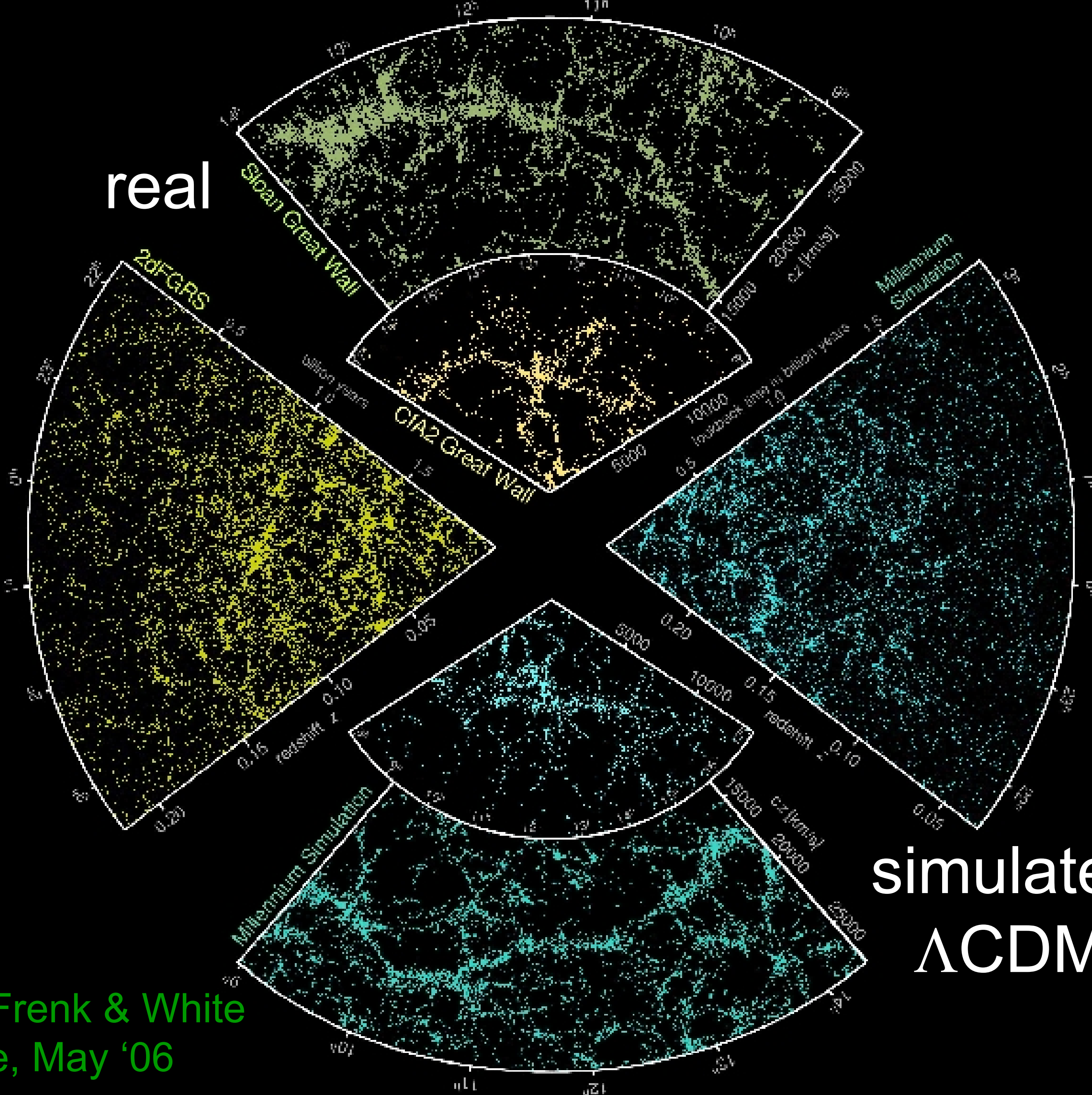
Galaxies



Effect of AGN feedback on lum fn



Bower, Benson, Malbon, Frenk, Baugh, Cole & Lacey 06 real



simulated
ΛCDM

Springel, Frenk & White
Nature, May '06

Real and simulated 2dF galaxy survey

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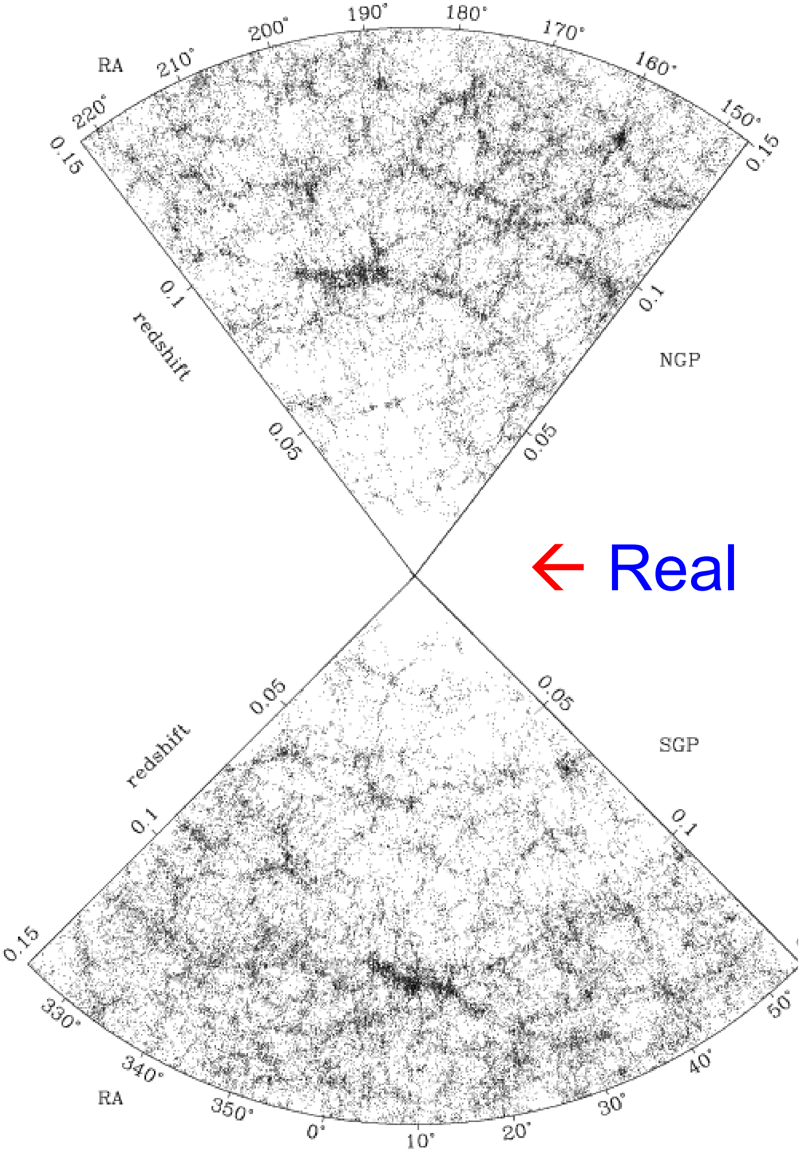
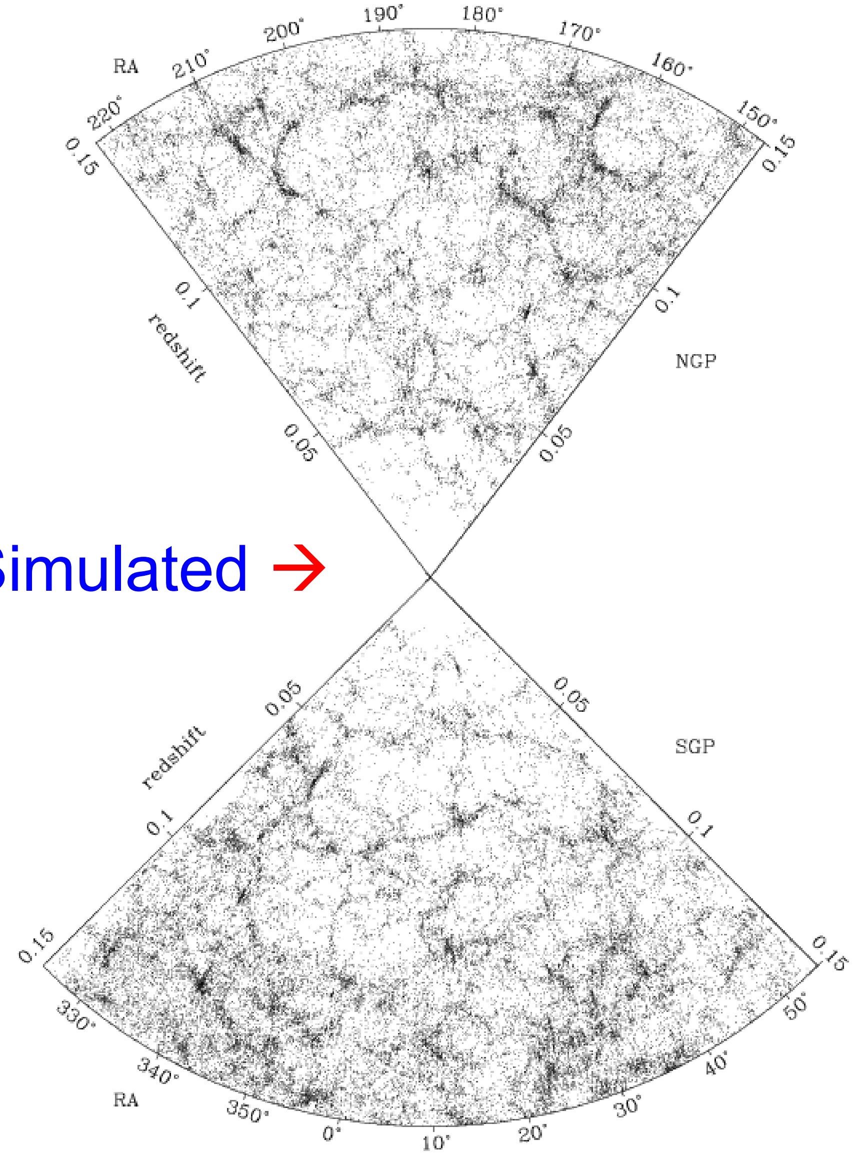


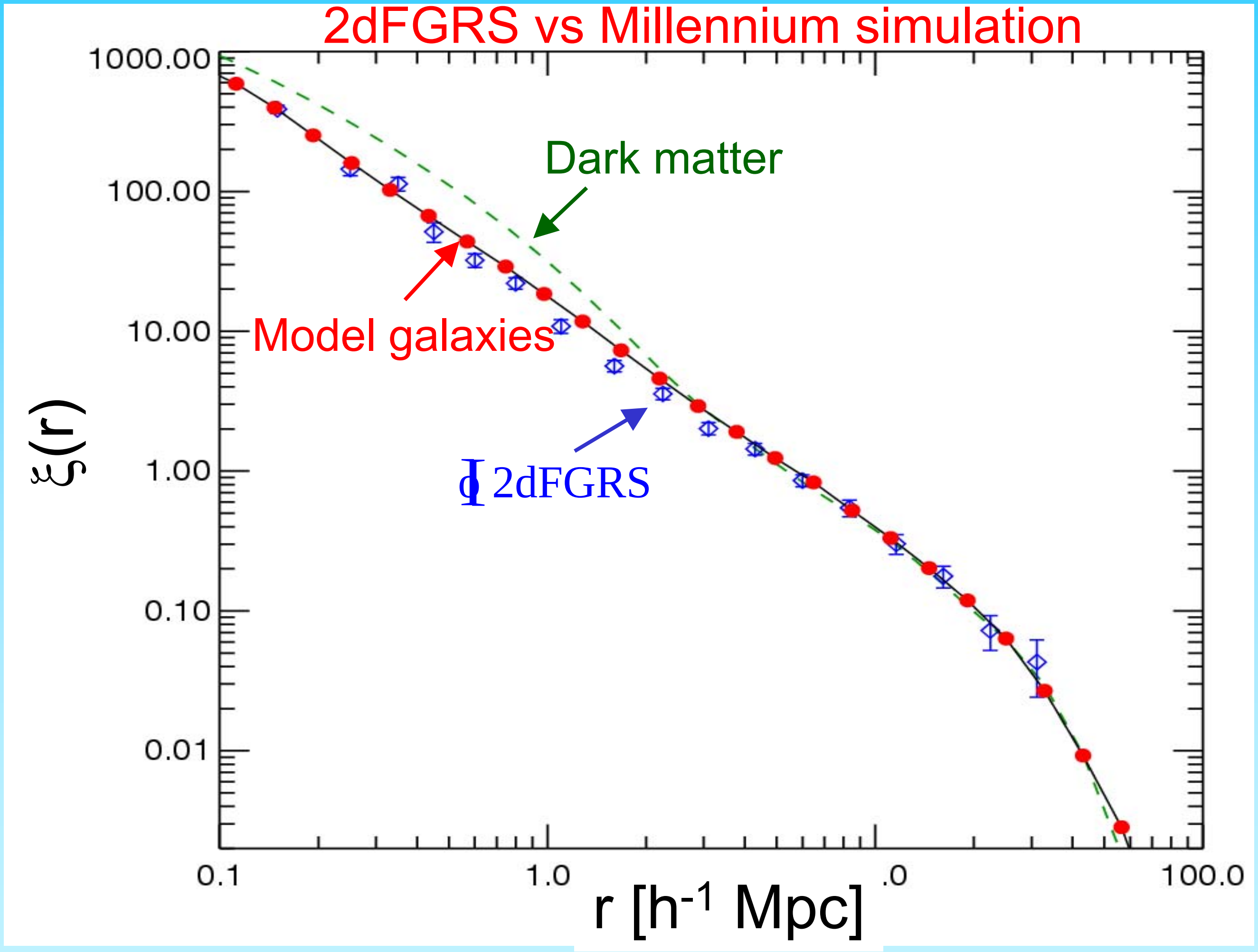
← Real

Simulated →



Galaxy autocorrelation function

- The galaxy 2-point correlation function in the MS agrees well with 2dFGRS
- Galaxies are less clustered than DM on small scales



Springel et al 2005

The final 2dFGRS power spectrum

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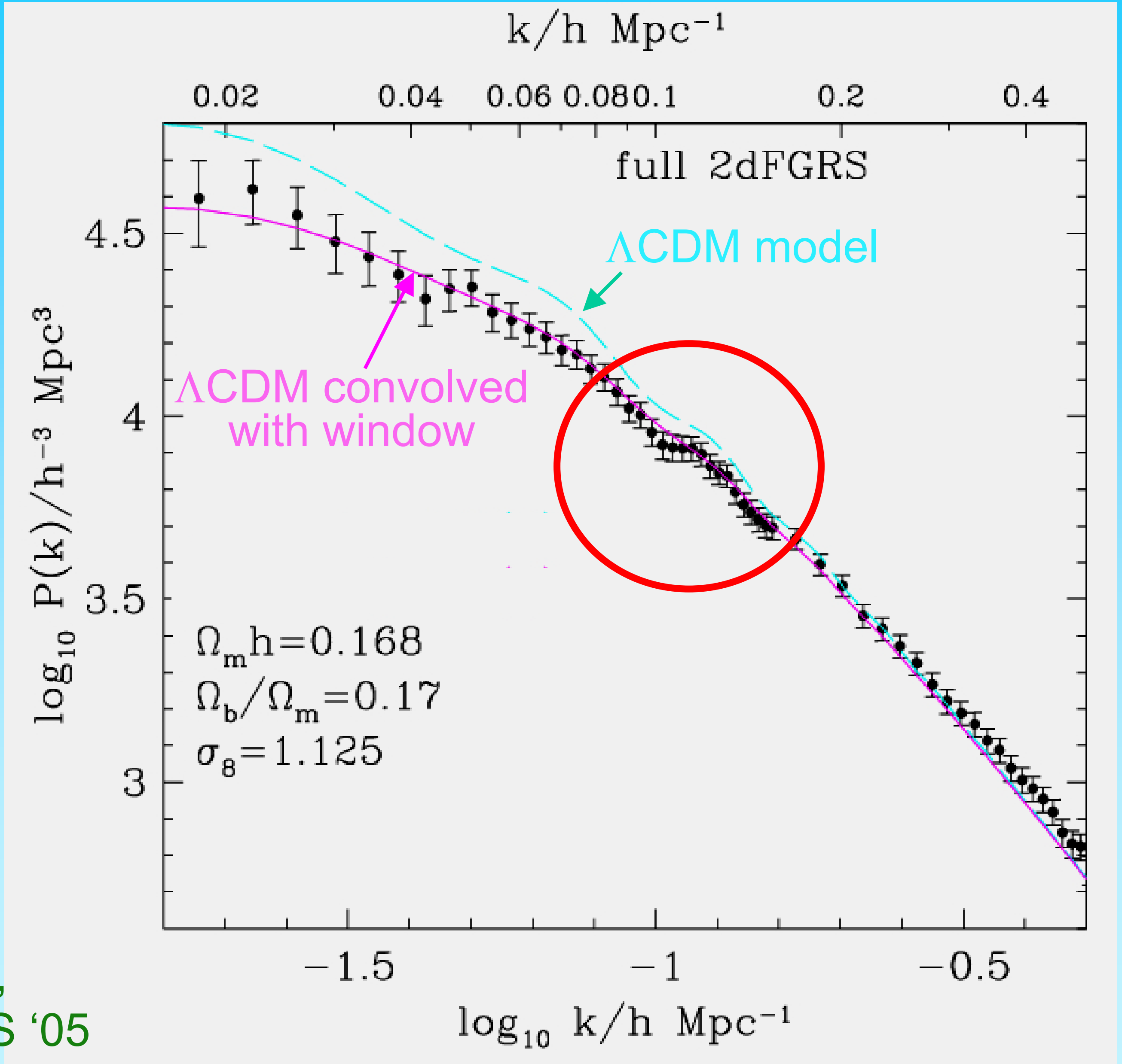
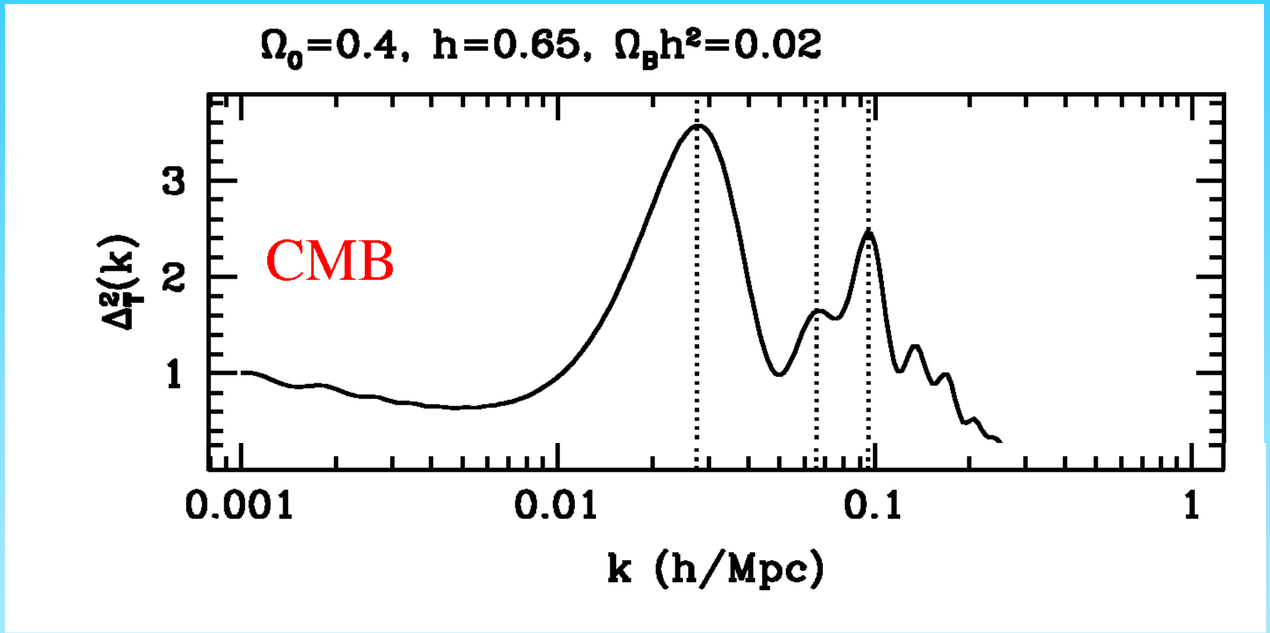
2dFGRS P(k) well fit by ΛCDM model convolved with window function



Cole, Percival, Peacock, Baugh, Frenk + 2dFGRS ‘05

CMB anisotropies and large-scale structure



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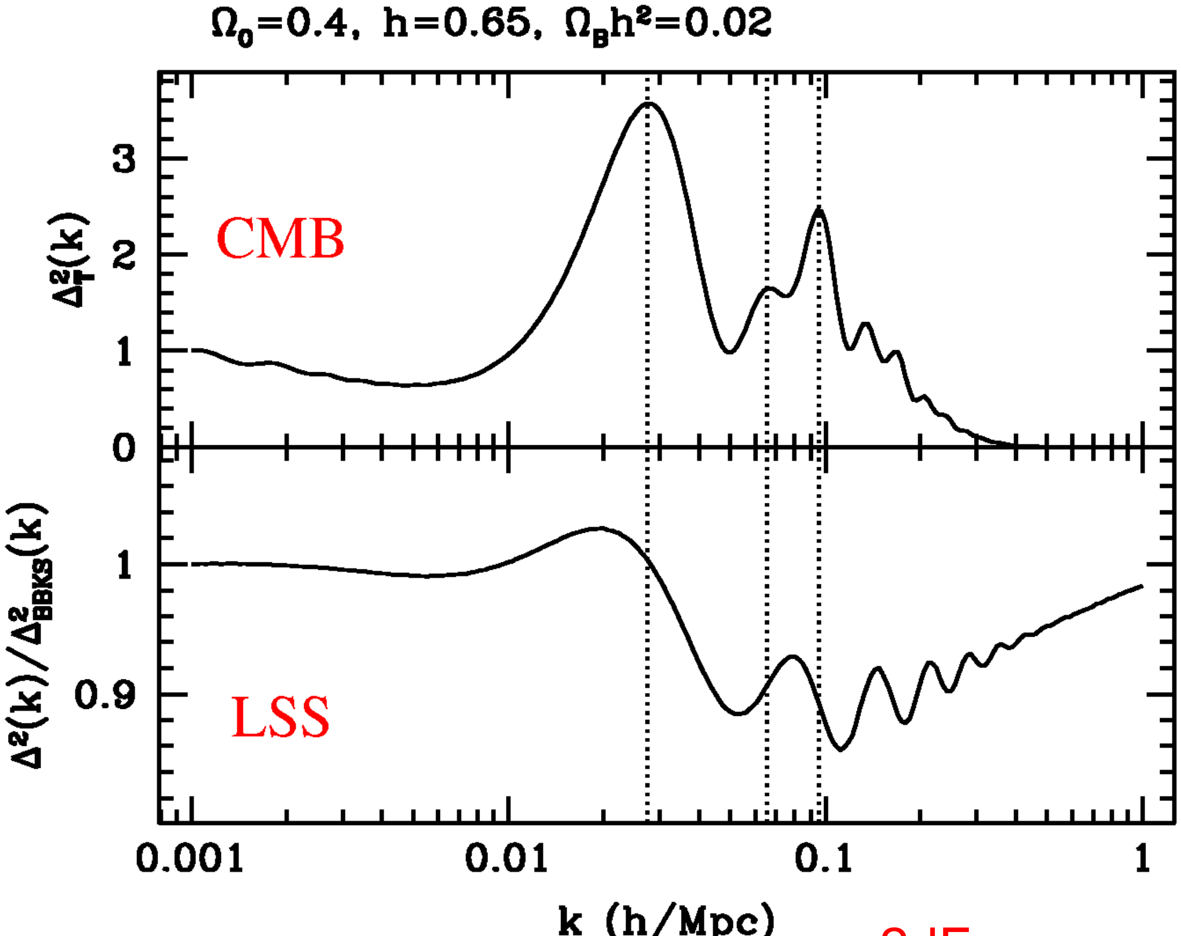
CMB anistropies and large-scale structure



2dFgrs

CMB and LSS out of phase:

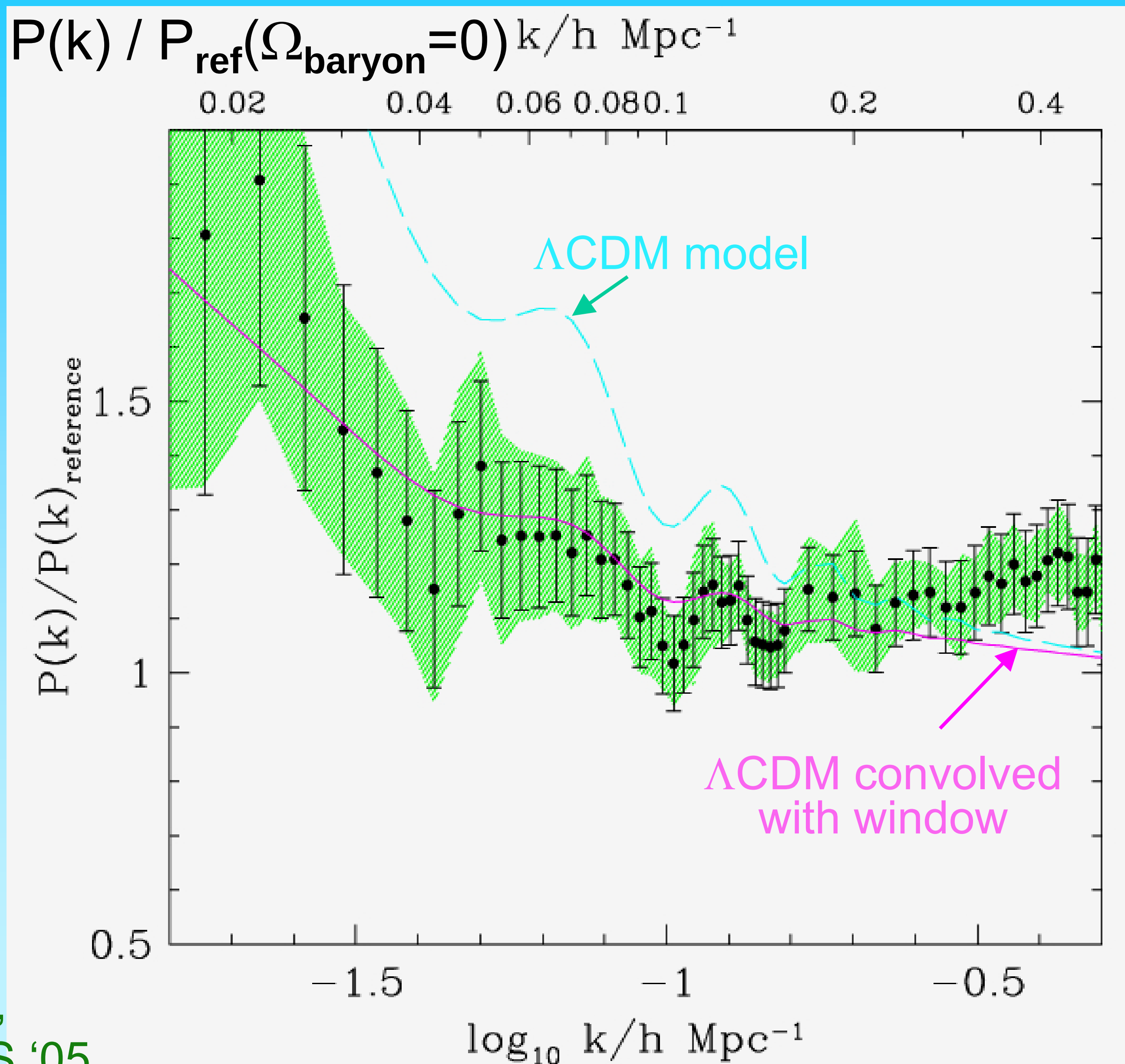
'velocity overshoot'

LSS amplitude smaller than CMB

Meiksin etal 99

University of Durham

The final 2dFGRS power spectrum



Baryon oscillations conclusively detected in 2dFGRS!!!

Demonstrates that structure grew by gravitational instability in ΛCDM universe

Also detected in SDSS LRG sample (Eisenstein etal 05)

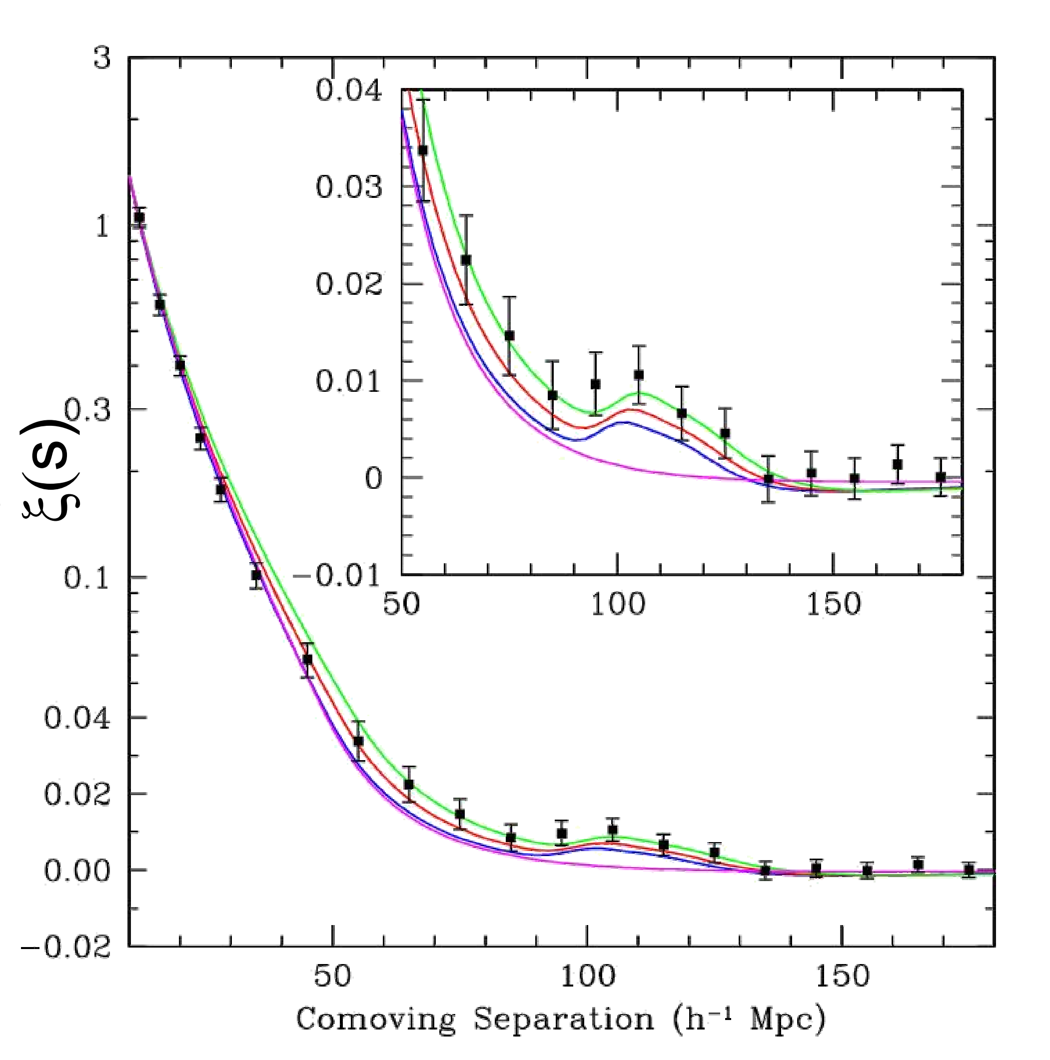
Cole, Percival, Peacock, Baugh, Frenk + 2dFGRS ‘05

SDSS LRG correlation function

University of Durham

Again, CDM models fit the correlation function adequately well (although peak height is slightly too large; assuming n_s=1, h=0.72)

$\Omega_b h^2$ =0.024,
$\Omega_m h^2$ =0.133±0.011,
$\Rightarrow \Omega_b/\Omega_m$= 0.18



Eisenstein et al. 05

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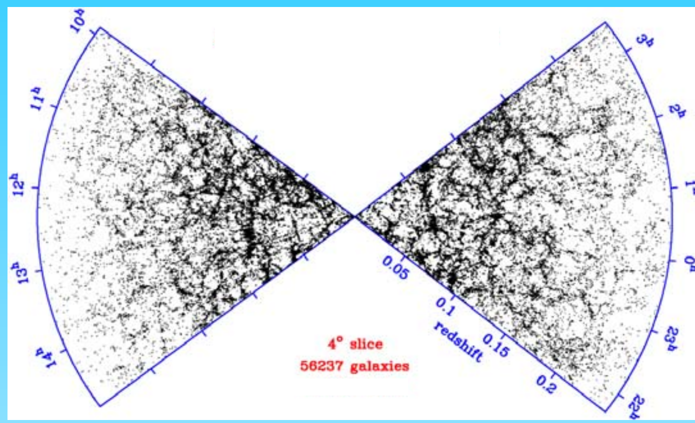
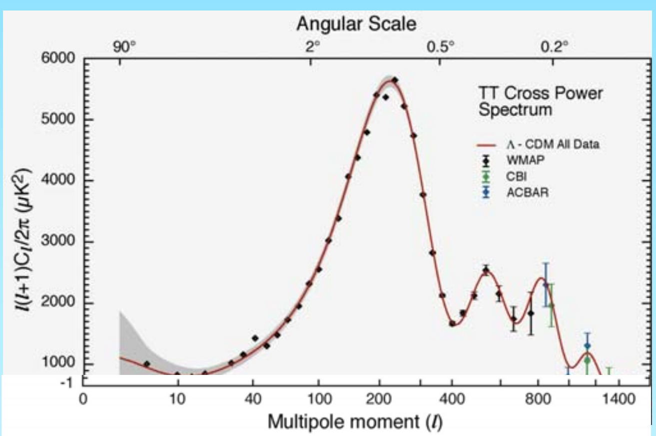
Cosmological parameters: CMB + 2dF



The 2dF power spectrum depends on

$$\Omega_{\mathbf{m}}h,\ \Omega_b/\Omega_{\mathbf{m}},\ \sigma_{\mathbf{8}}^{\mathbf{gal}},\ f_\nu,\ \ldots$$



The CMB power spectrum depends on

$$(\Omega_k, \Omega_\Lambda, \omega_{\mathrm{b}}, \omega_{\mathrm{dm}}, f_\nu, w_{DE}, \tau, n_s, n_t, A_s, r, b)$$

Combining 2dF and CMB breaks parameter degeneracies

See talk by Ariel Sanchez

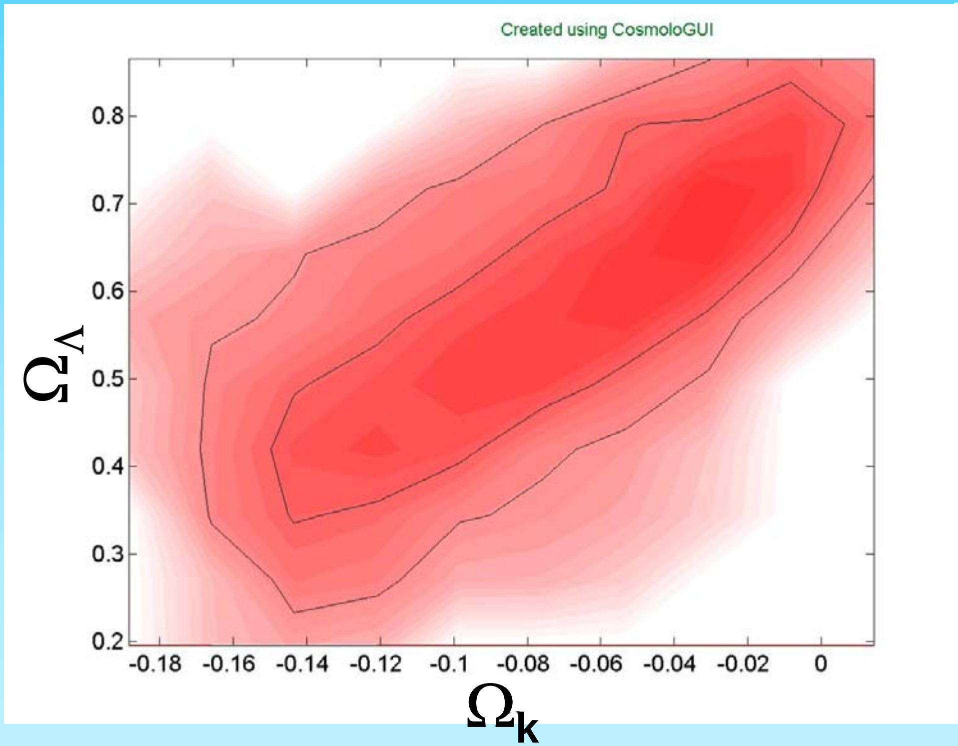
Institute for Computational Cosmology

University of Durham

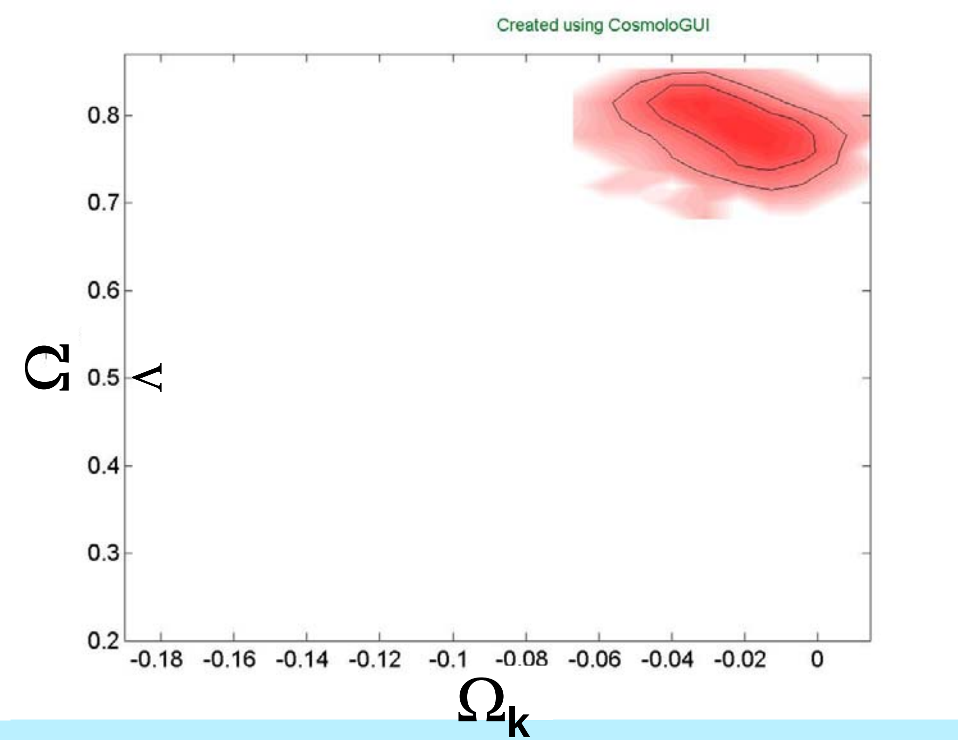
Parameter constraints

$$\mathbf{P} \equiv (\Omega_k, \Omega_\Lambda, \omega_b, \omega_{dm}, \tau, n_s, A_s)$$

CMB only…



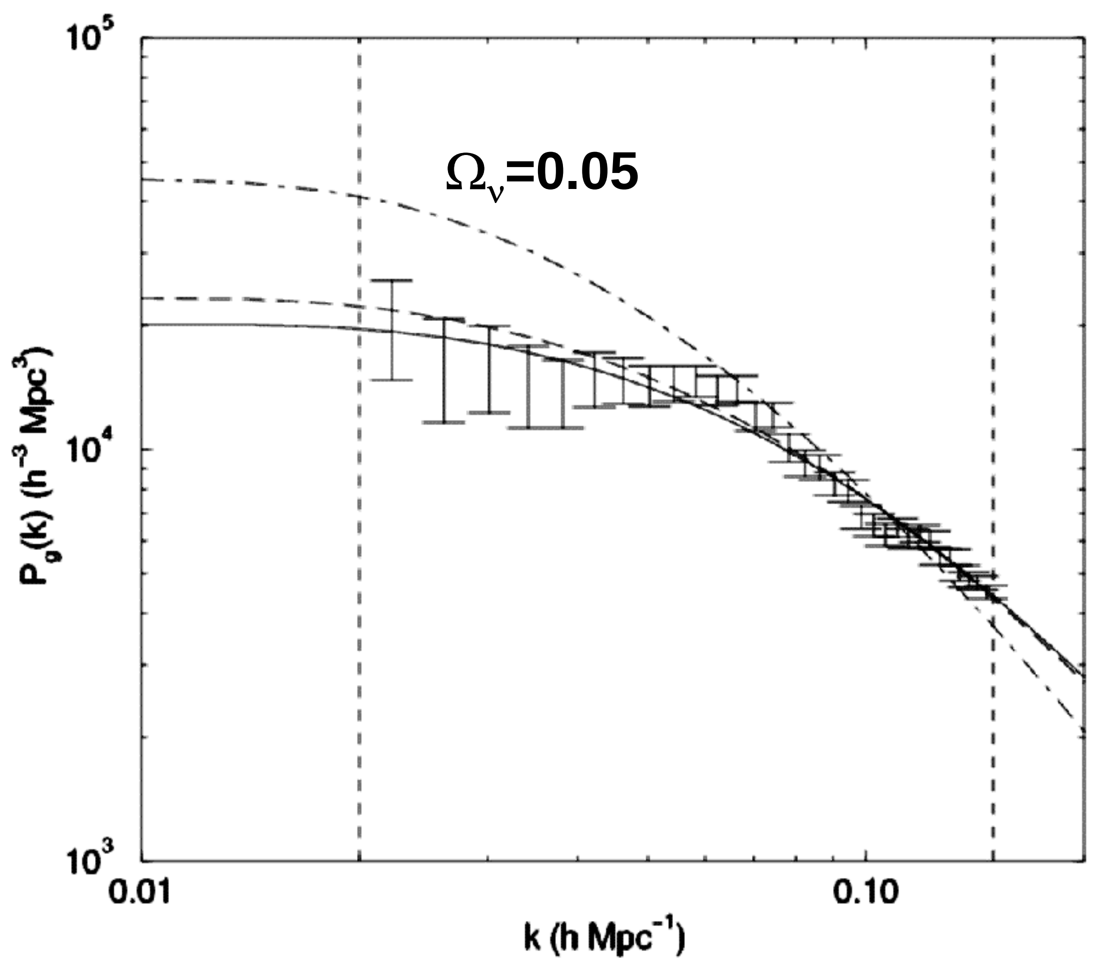
CMB + 2dF…



Sanchez et al ‘06

University of Durham

Effect of neutrinos



Free-stream length: $80(\Sigma\, m_\nu /eV)^{-1}$ Mpc

($\Omega_m h^2 = \Sigma m_\nu$ / 93.5 eV)

$\Sigma m_\nu \sim 1$ eV causes lower power at almost all scales, or a bump at the largest scales

2dFGRS

→ $\Sigma m_\nu < 1.2$ ev

Sanchez et al '06

The cosmic power spectrum: from the CMB to the 2dFGRS

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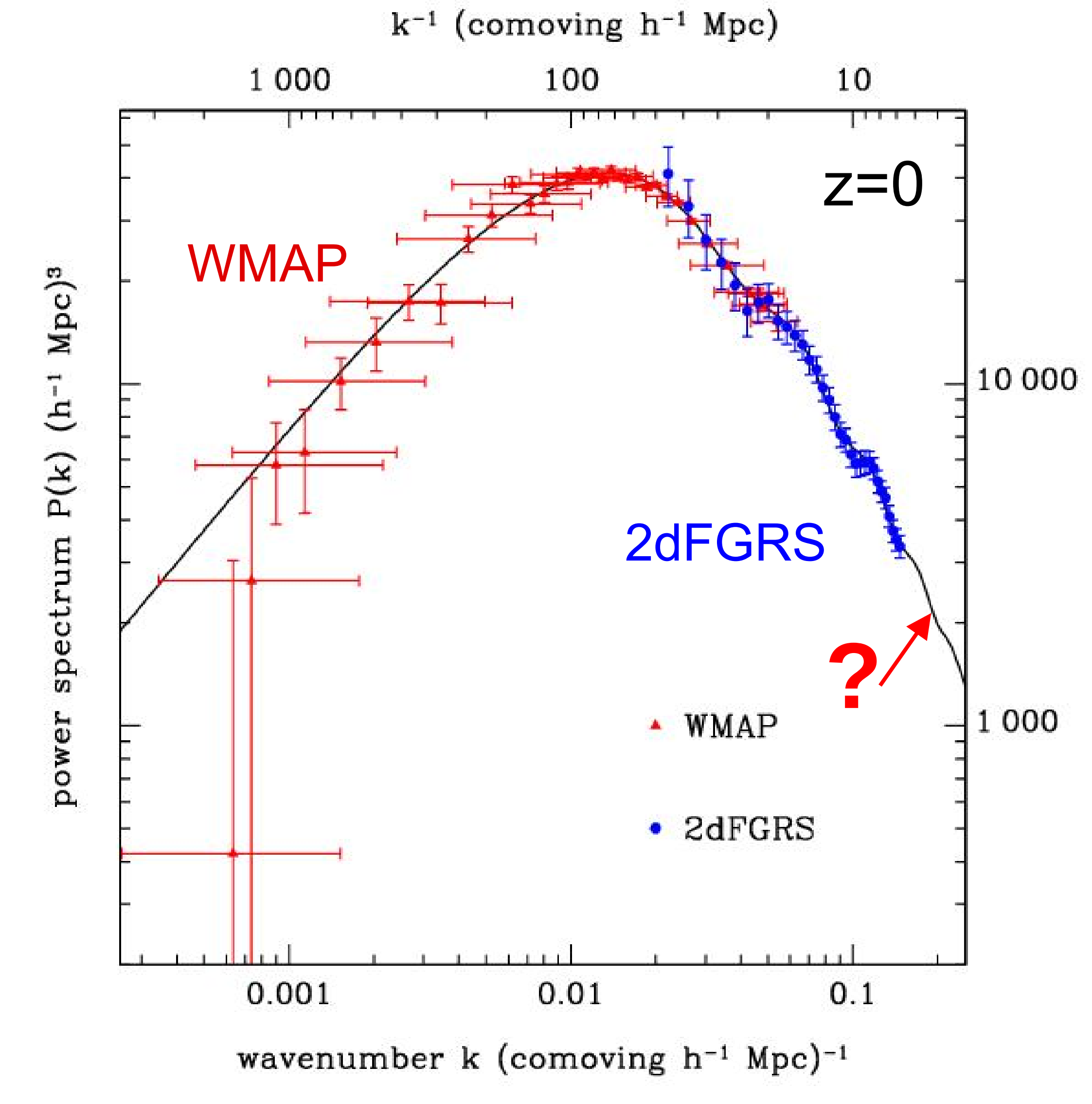
CMB:

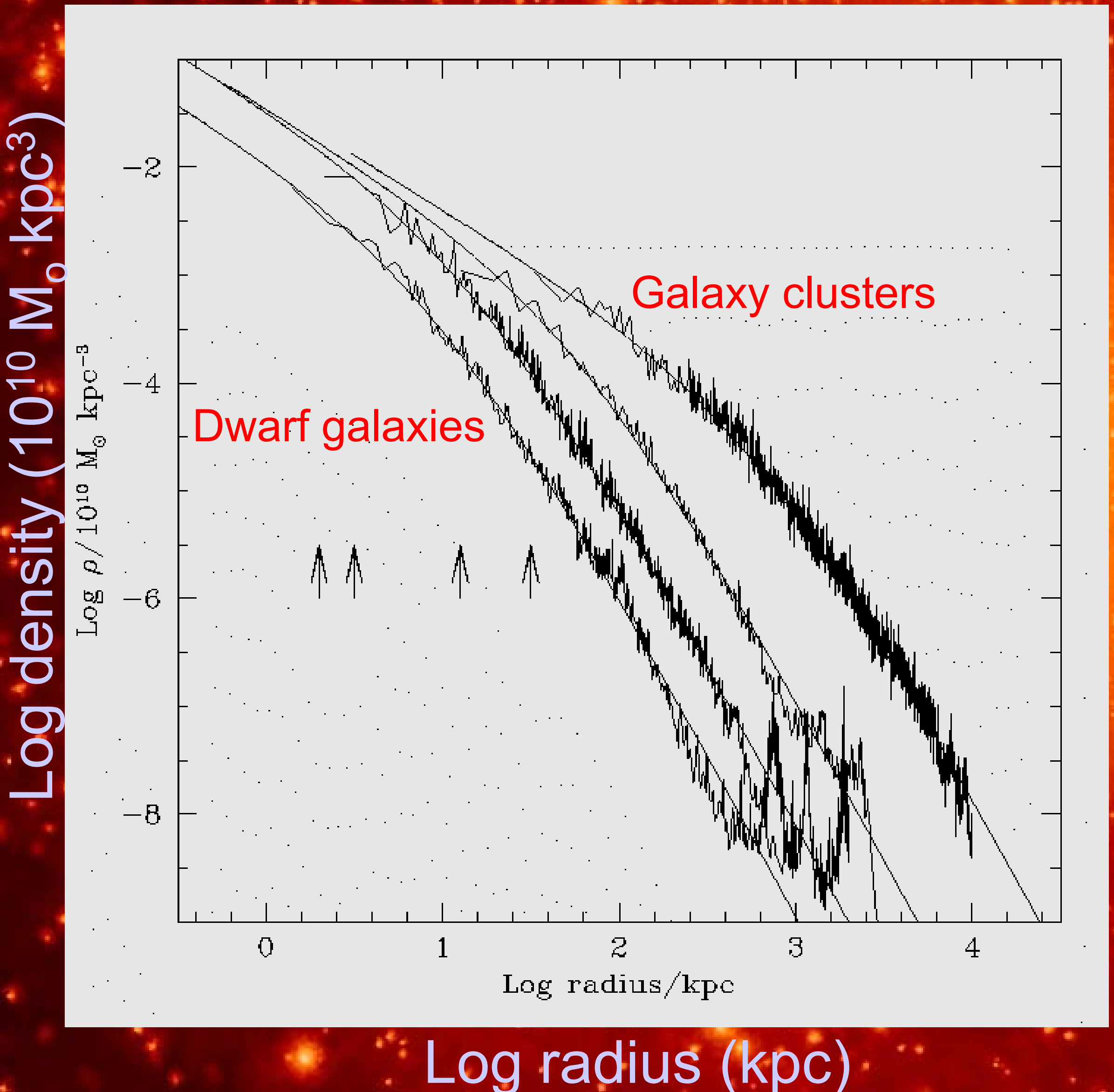
- Convert angular separation to distance (and k) assuming flat geometry
- Extrapolate to z=0 using linear theory

⇒ ΛCDM provides an excellent description of mass power spectrum from 10-1000 Mpc



Sanchez et al 06

The Density Profile of Cold Dark Matter Halos



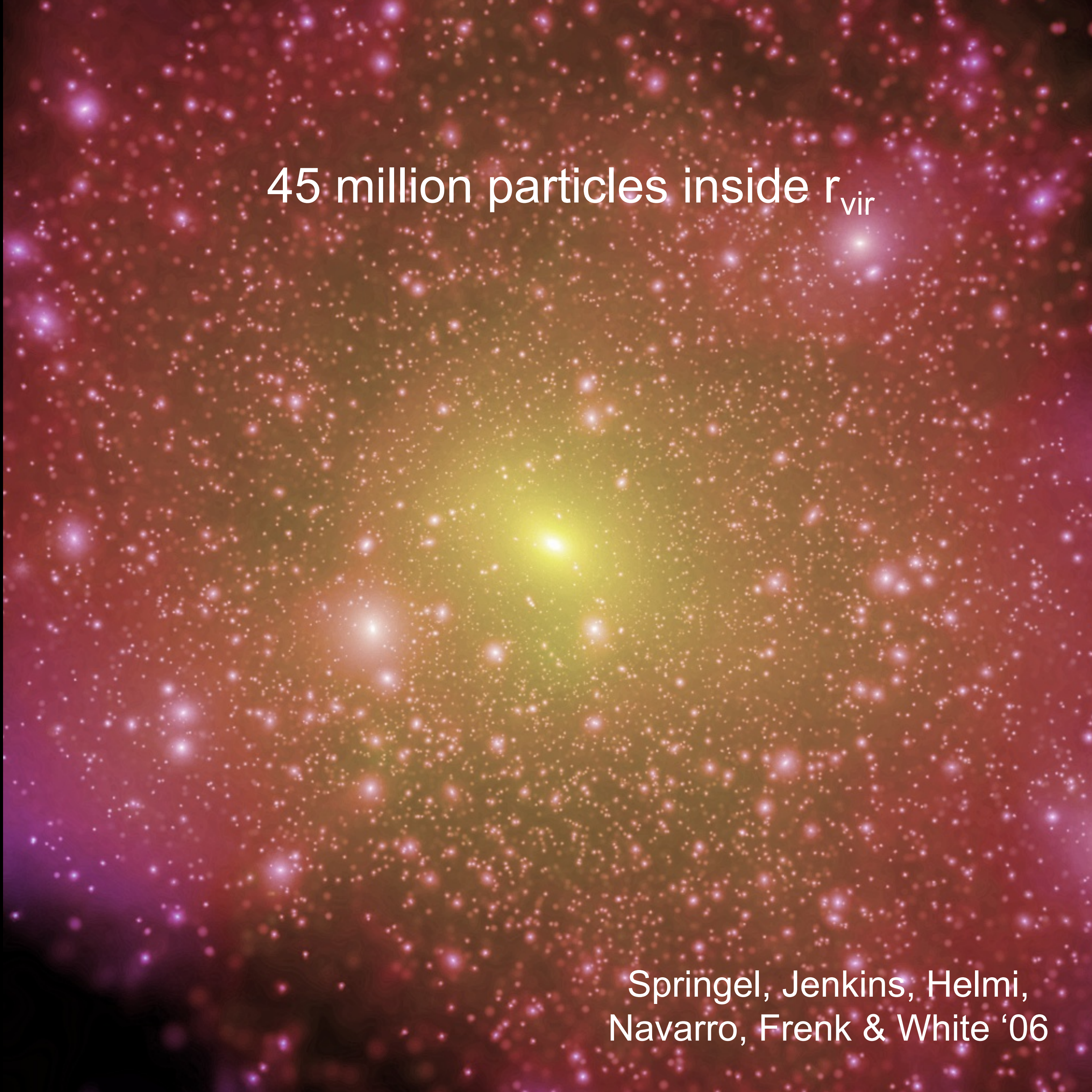
Halo density profiles are independent of halo mass & cosmological parameters

There is no obvious density plateau or `core' near the centre.

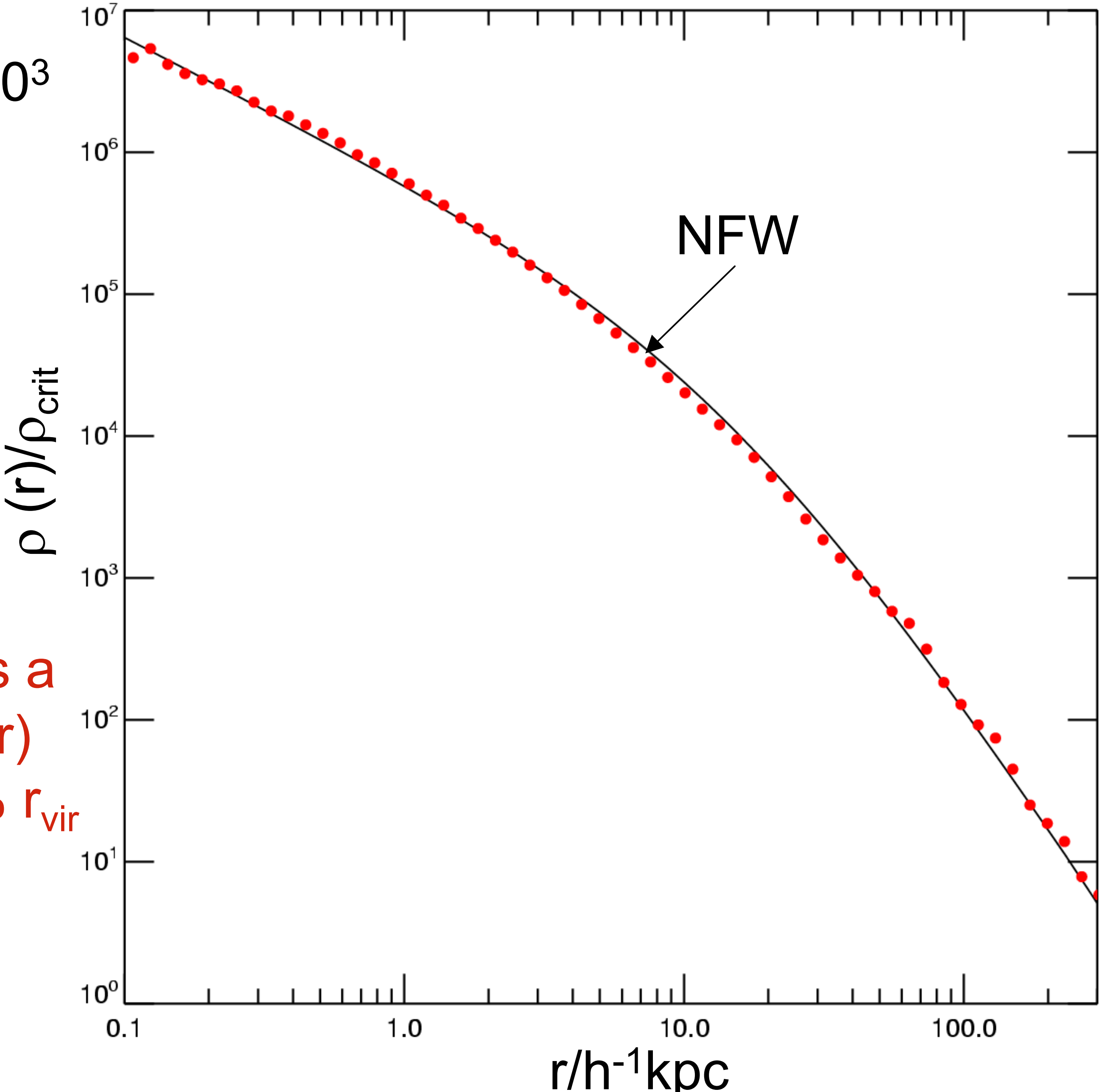
(Navarro, Frenk & White '97)

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

$N=800^3$


45 million particles inside r_{vir}
Springel, Jenkins, Helmi,
Navarro, Frenk & White '06

$N=800^3$



NFW profile is a good fit to $\rho(r)$ down to ~0.1% r_{vir}

Springel, Jenkins, Helmi, Navarro, Frenk & White '06

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A Cold dark matter universe

N-body simulations show that cold dark matter halos (from galaxies to clusters) have:

- “Cuspy” density profiles
- Large number of self-bound substructures (10% of mass)

This has led to two well-publicized “problems”:

- The “halo core” problem
- The “satellite” problem

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Explanations for the core/satellite "crises"

- The dark matter is warm
- The dark matter has a finite self-scattering cross-section
- The primordial density power spectrum has a break (or running spectral index)
- There is no dark matter -- gravity needs modifying
- Astrophysics: baryon effects, black holes, bars
- The comparison of models and data is incorrect

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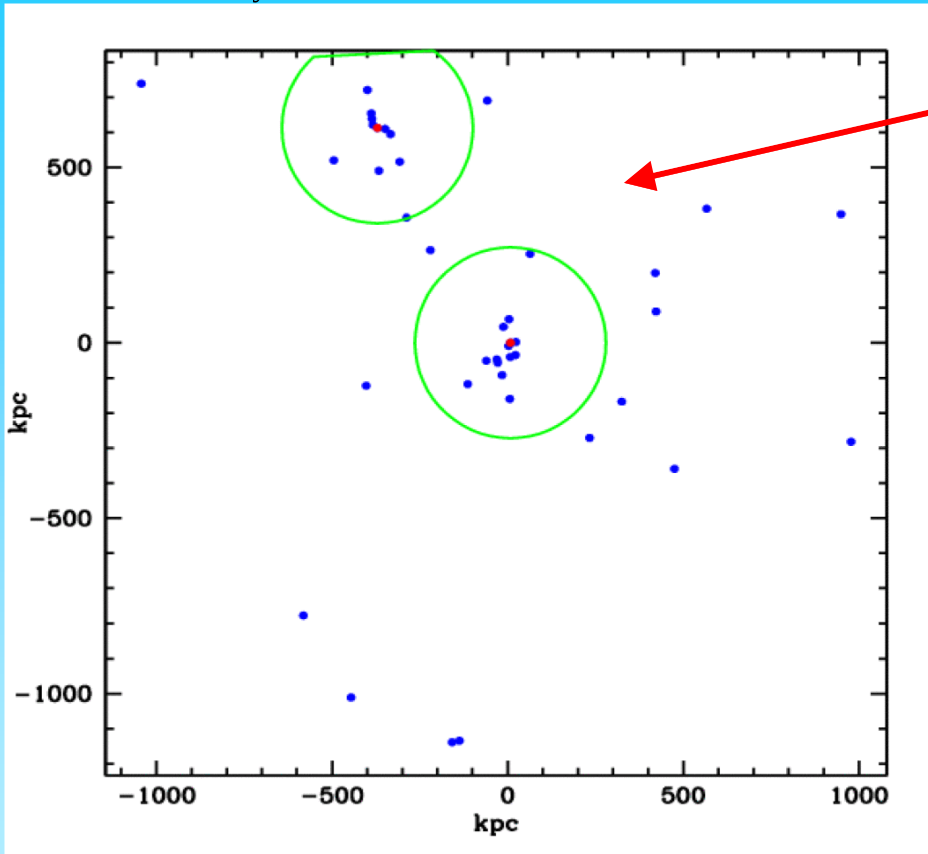
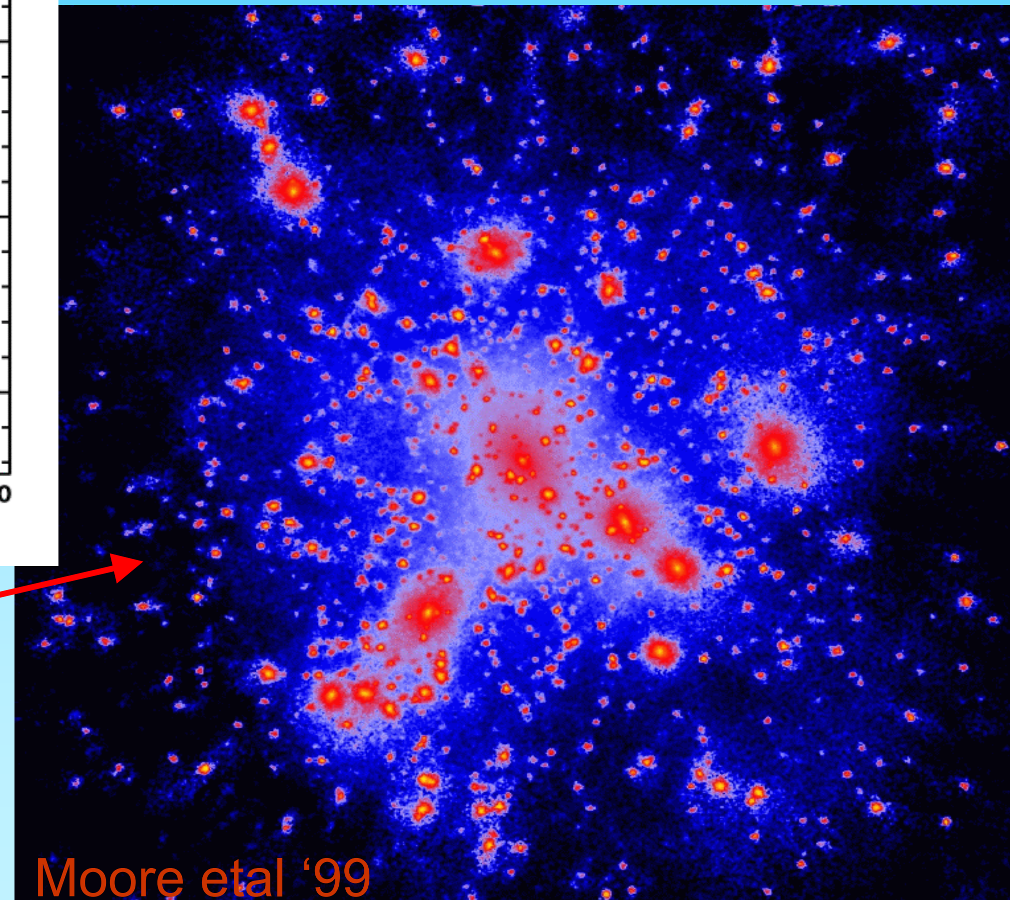
The satellites of the Local Group

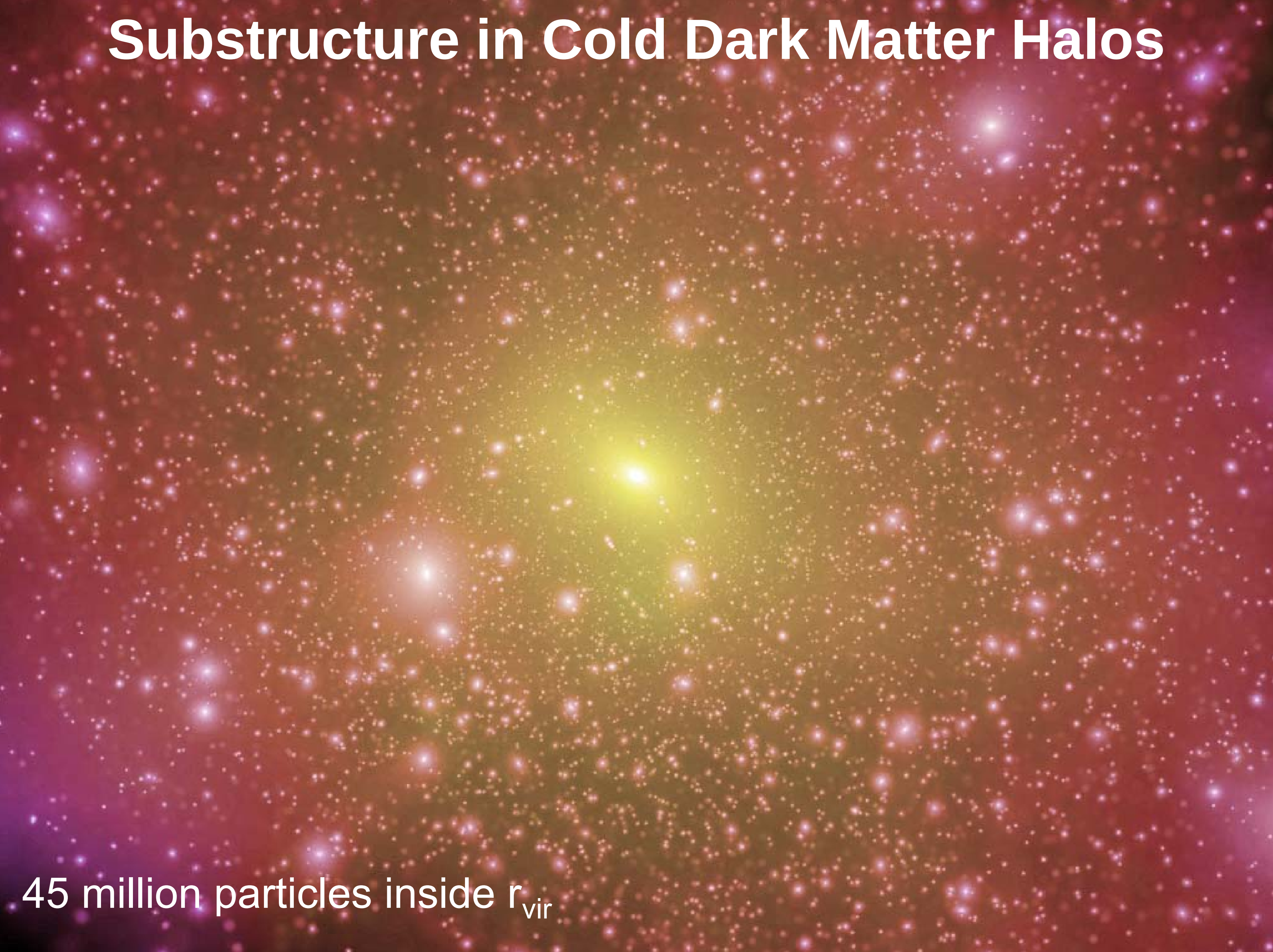


The Local Group contains only about 25 bright satellites



N-body simulations produce 1000s of small subhalos

Substructure in Cold Dark Matter Halos



45 million particles inside r_{vir}

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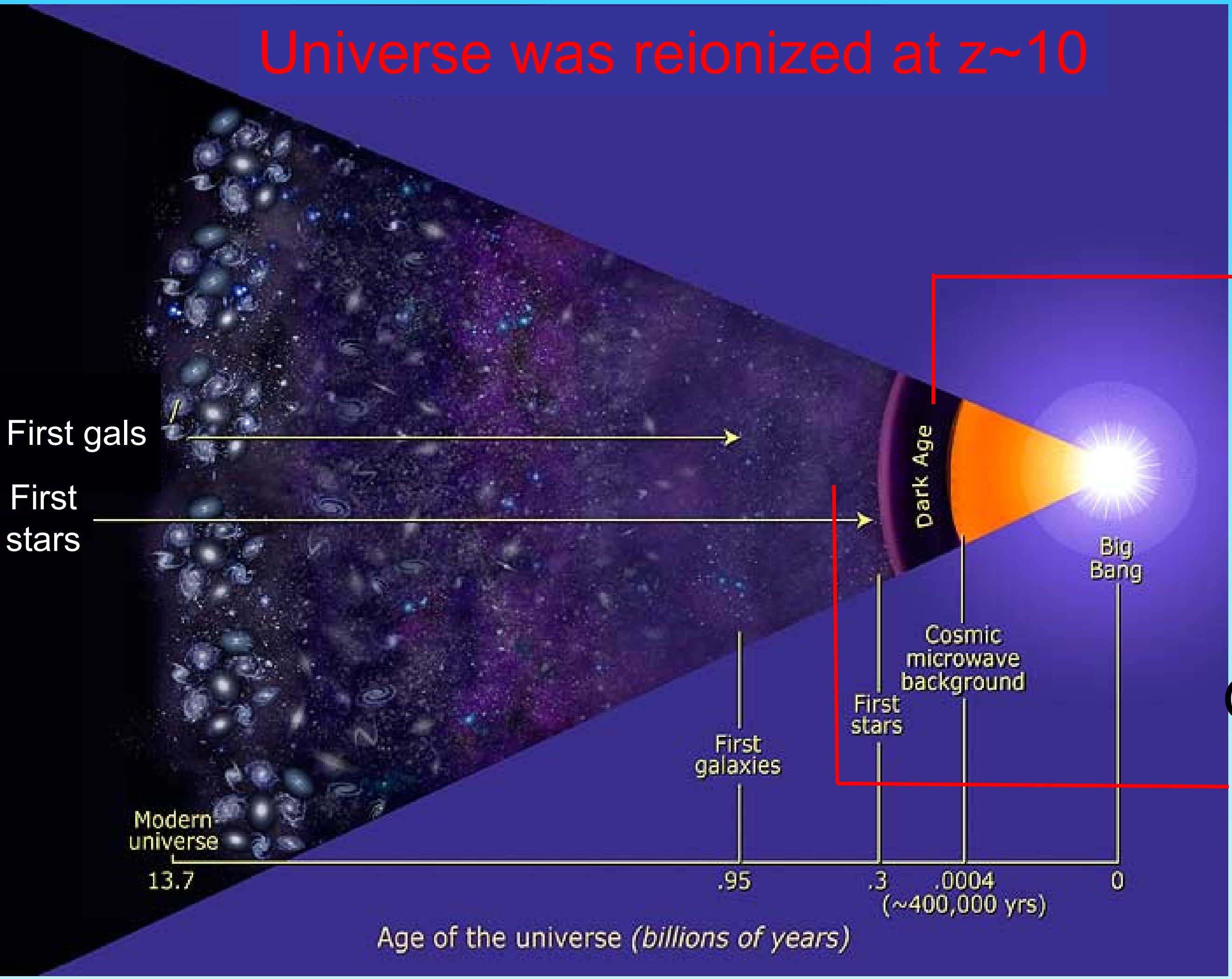
Feedback in galaxy formation



Effects of reionization

Gas is neutral → cools in small halos

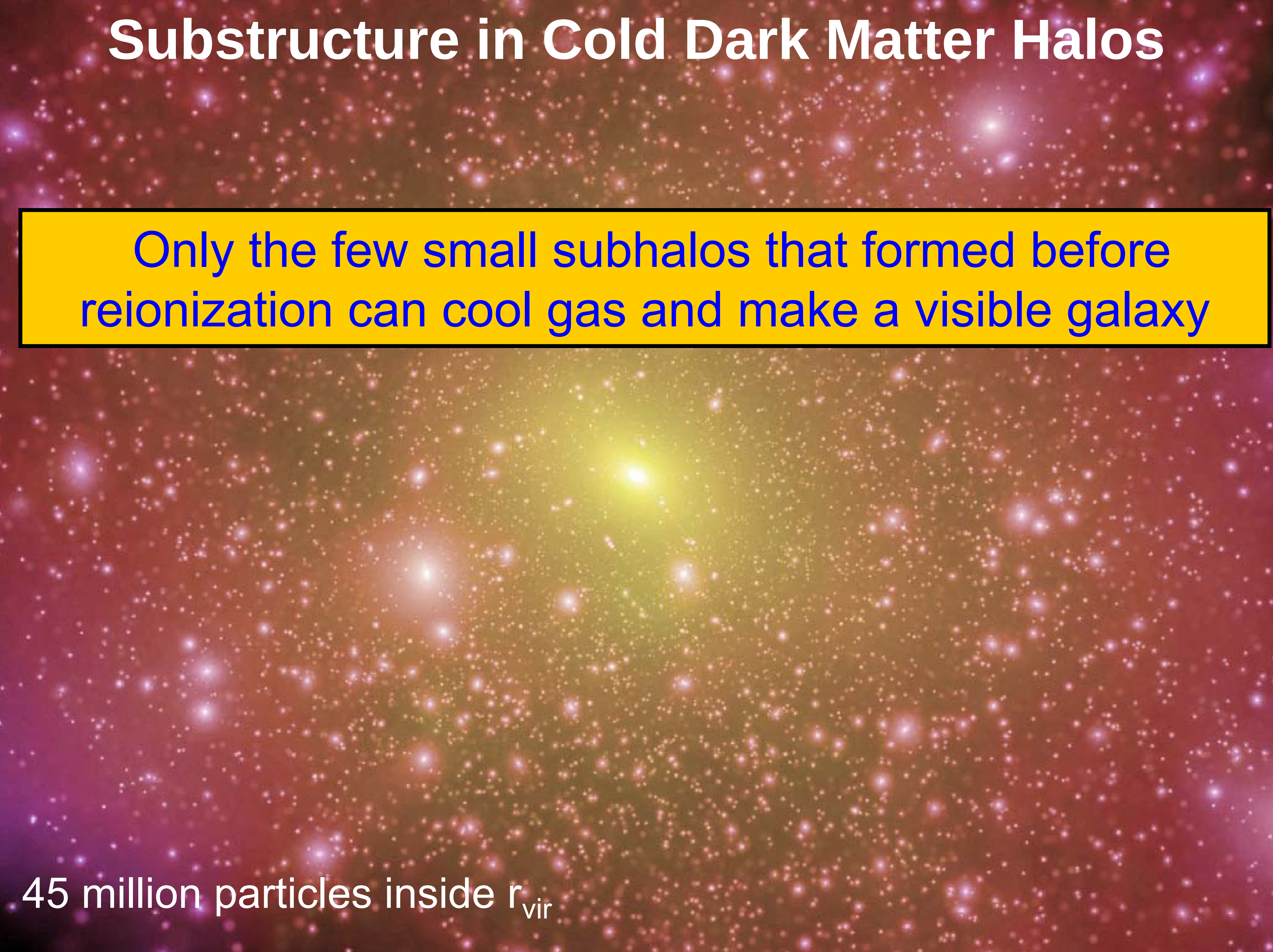
H is reionized at z~(10-6)

Gas heated ~10^4K → cannot cool in halos with V<40 km/s

From STSci picture gallery

Substructure in Cold Dark Matter Halos

Only the few small subhalos that formed before reionization can cool gas and make a visible galaxy



The satellites of the Local Group

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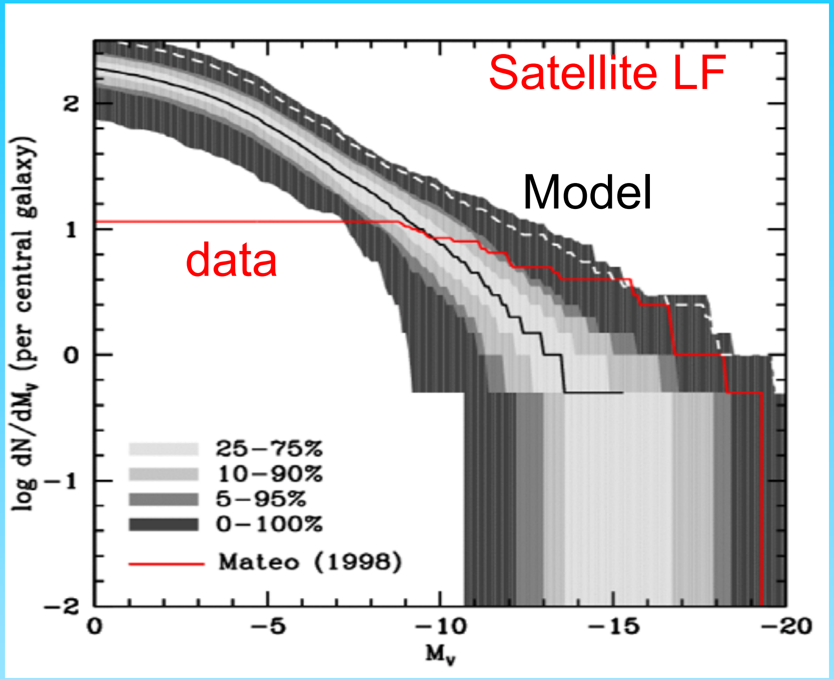
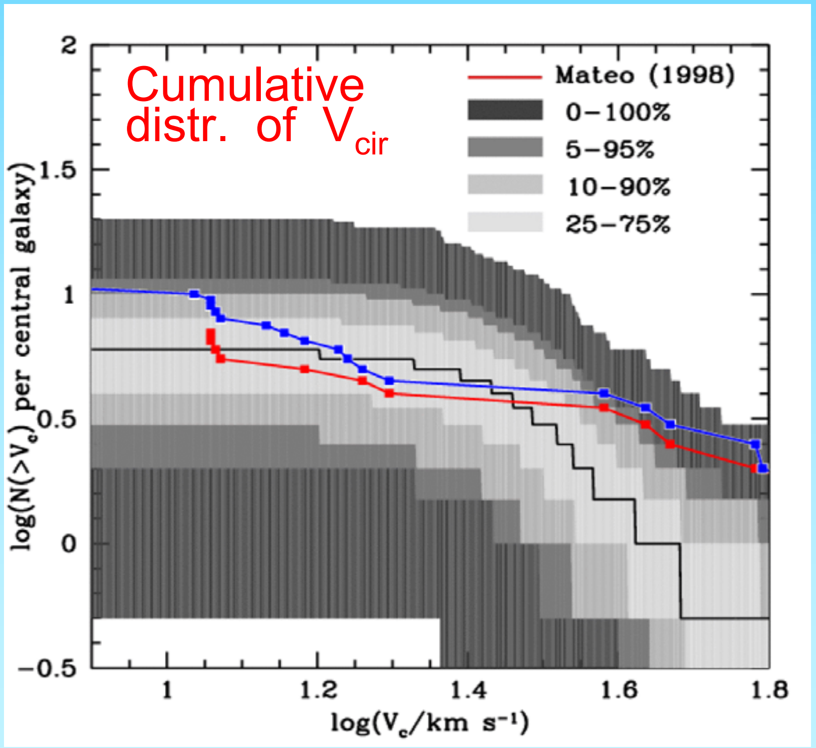
LF of satellites within the virial radii of MW and M31

Photoionization inhibits the formation of satellites





- Median model gives correct abundance of satellites brighter than M_V=-9 and V_{cir} > 12 km/s
- Model predicts many, as yet undiscovered, faint satellites

Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman etal '93, Bullock etal '01)

Simulations of disc galaxy formation

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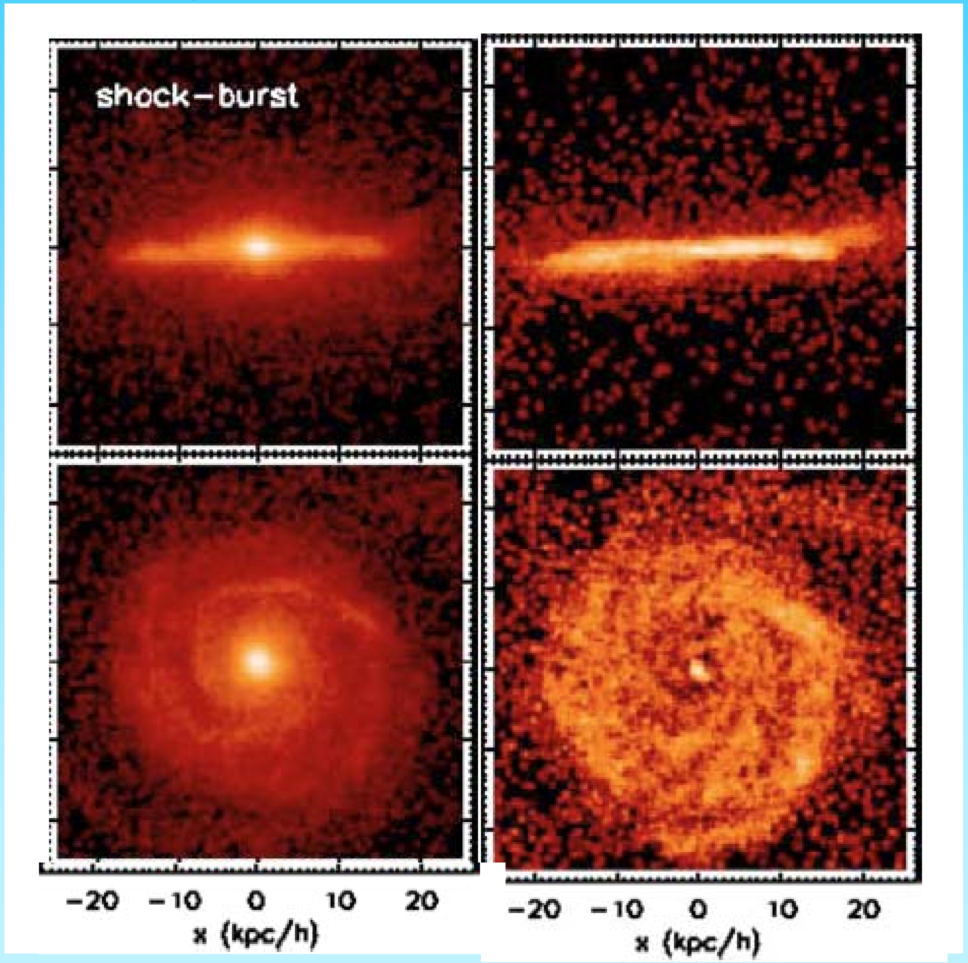
ΛCDM initial conditions

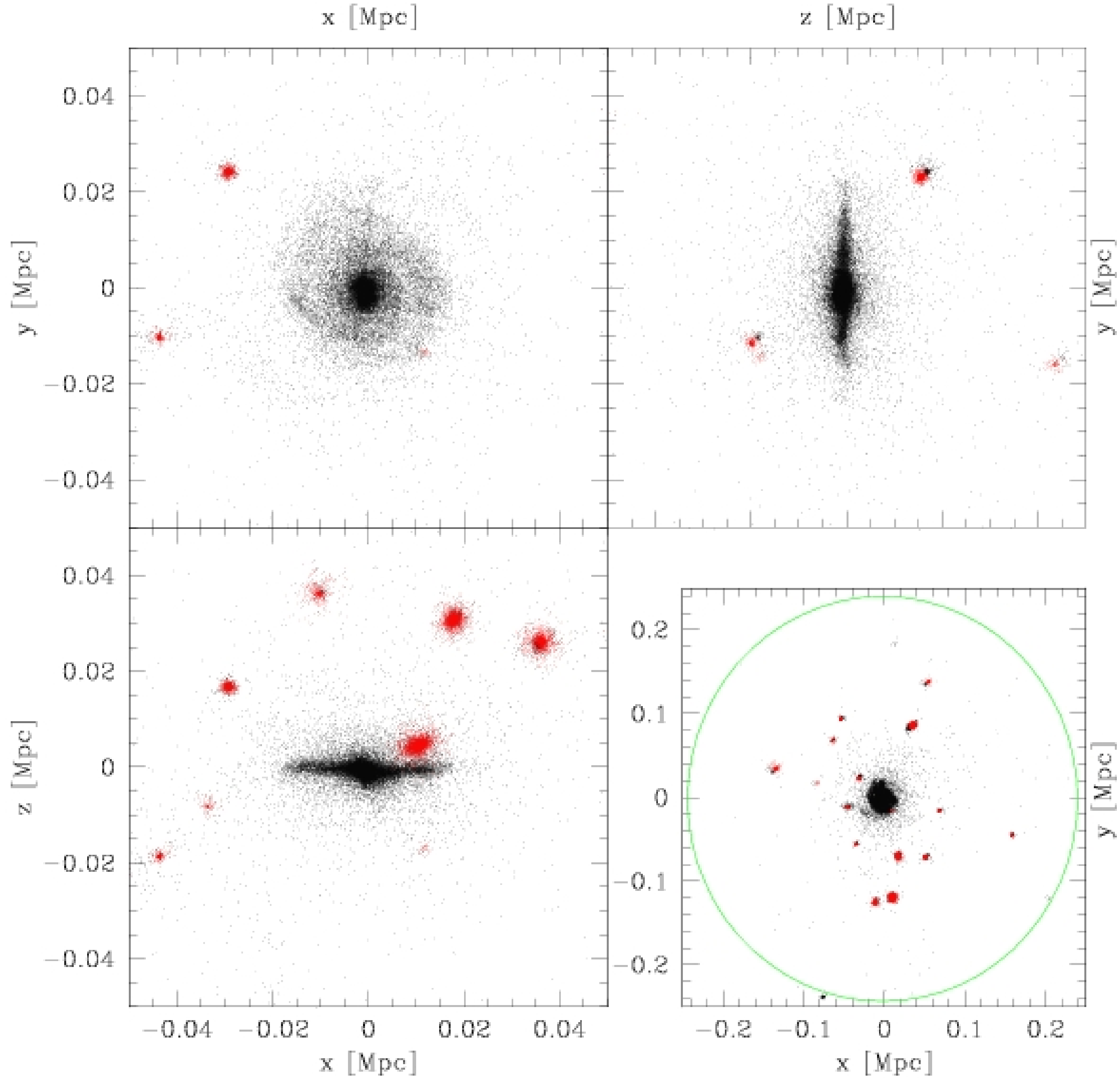
gas stars



Smooth Particle
Hydrodynamics
(SPH)

Okamoto, Jenkins, Eke, & Frenk '05

University of Durham



The luminosity function of Local Group satellites

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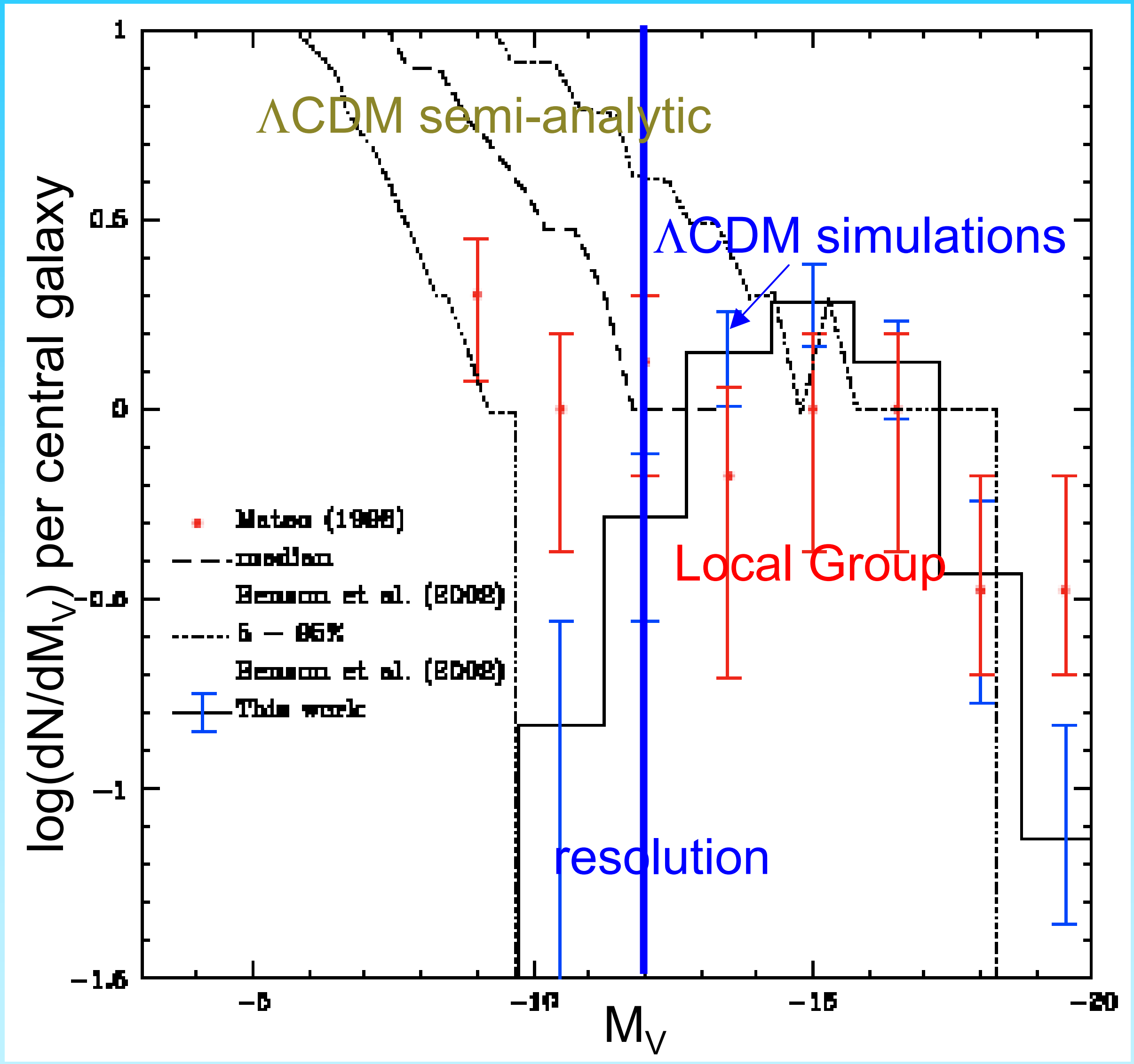
"Satellite problem" is a … non-problem



Libeskind, Frenk, Cole, Okamoto & Jenkins 06

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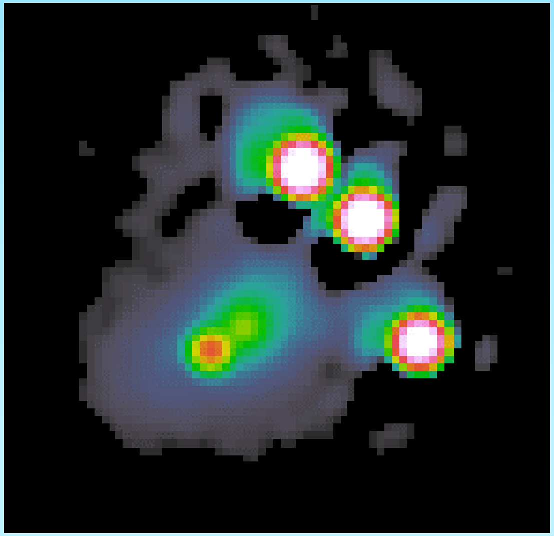
Substructure in CDM halos

Halos have large number of self-bound substructures containing ~10% of the masss and with $d N / d M \sim M^{-1.8}$

→ Substructures may be observable
- Gravitational lensing effects
- γ -ray annihilation emission



Anomalous flux ratios in multiply-imaged quasars ⇒ Substructure

Dalal & Kochanek ‘02, Metcalfe & Zhao ‘02

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γ-rays from the annihilation of DM particles

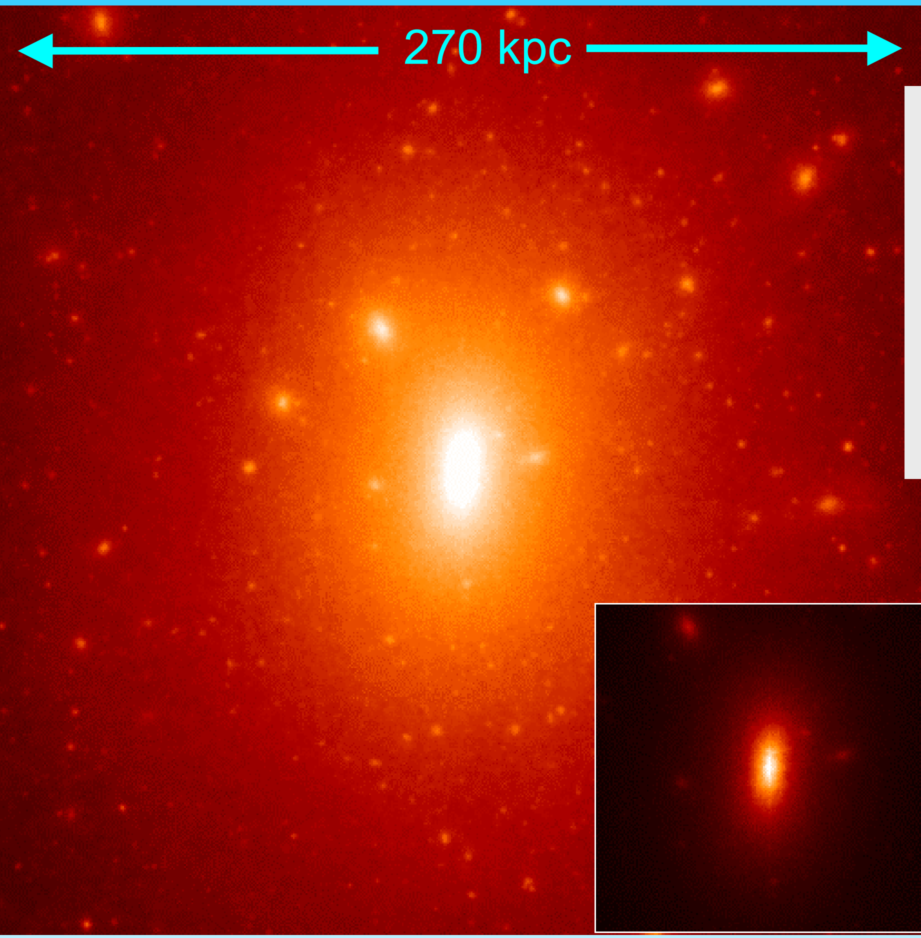
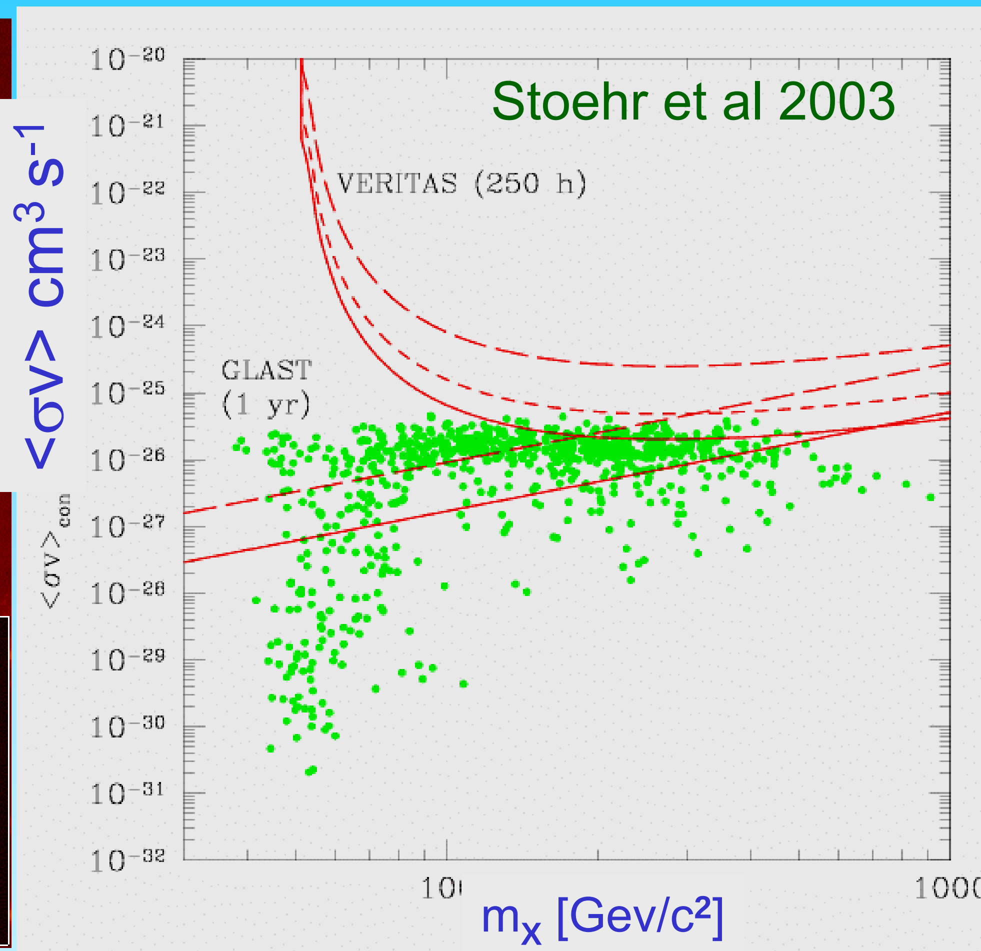
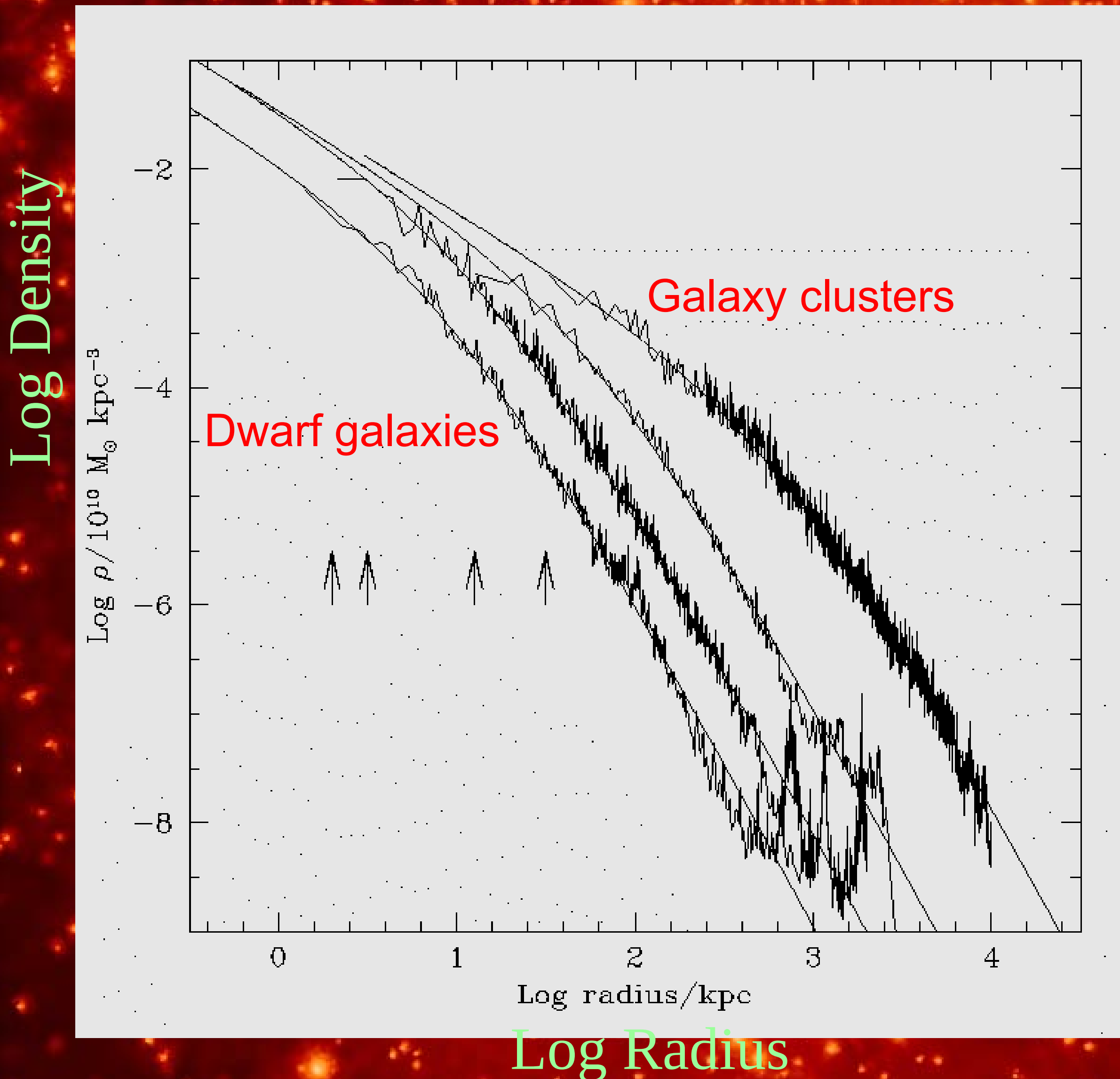


Image of a 'Milky Way' halo in annihilation radiation



Detection limits for minimal supersymmetric DM models

The Density Profile of Cold Dark Matter Halos



Halo density profiles are independent of halo mass & cosmological parameters

There is no obvious density plateau or `core' near the centre.

(Navarro, Frenk & White '97)

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

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The density profile of galaxy cluster dark halos

Do real dark halos have the profiles found in the simulations?

Profiles can be probed by:

- Galaxy rotation curves → messy { Galaxy changes $\rho(r)$; Halos are triaxial }

- Gravitational lensing and/or X-ray emission in clusters

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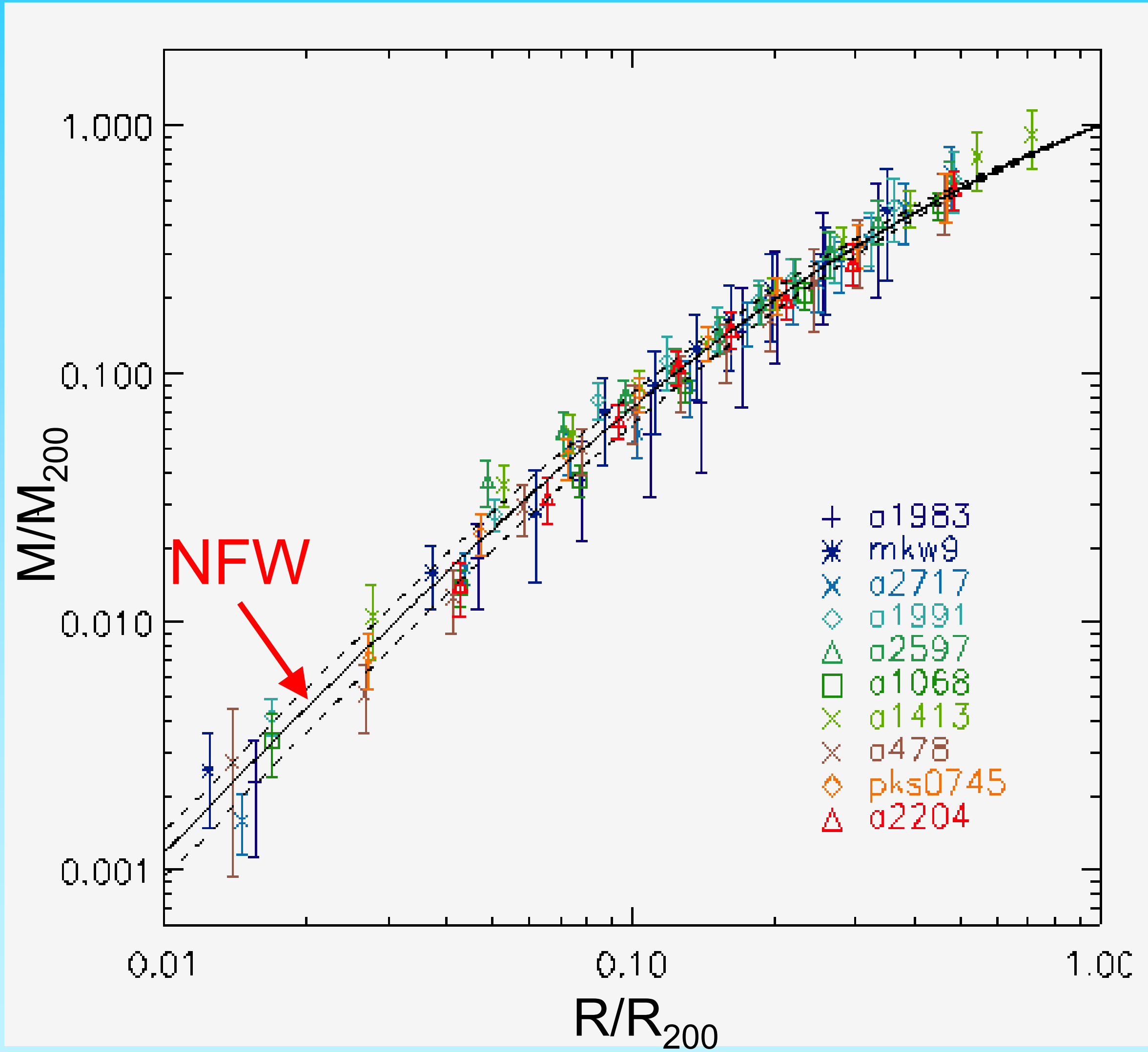
The central density profile of galaxy cluster dark halos

X-ray data



Mass profile of galaxy clusters, from X-ray data & assumption of hydrostatic equilibrium

Excellent agreement with CDM halo predictions

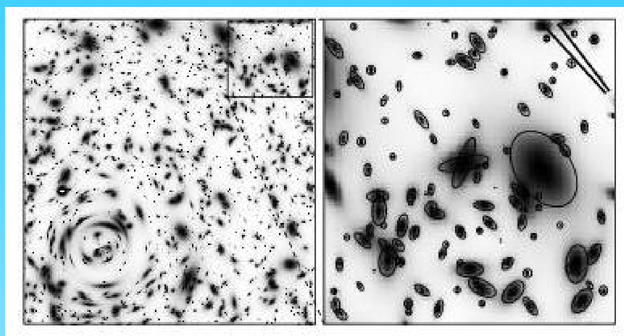
Pointecouteau et al ‘05

Institute for Computational Cosmology

The central density profile of galaxy cluster dark halos

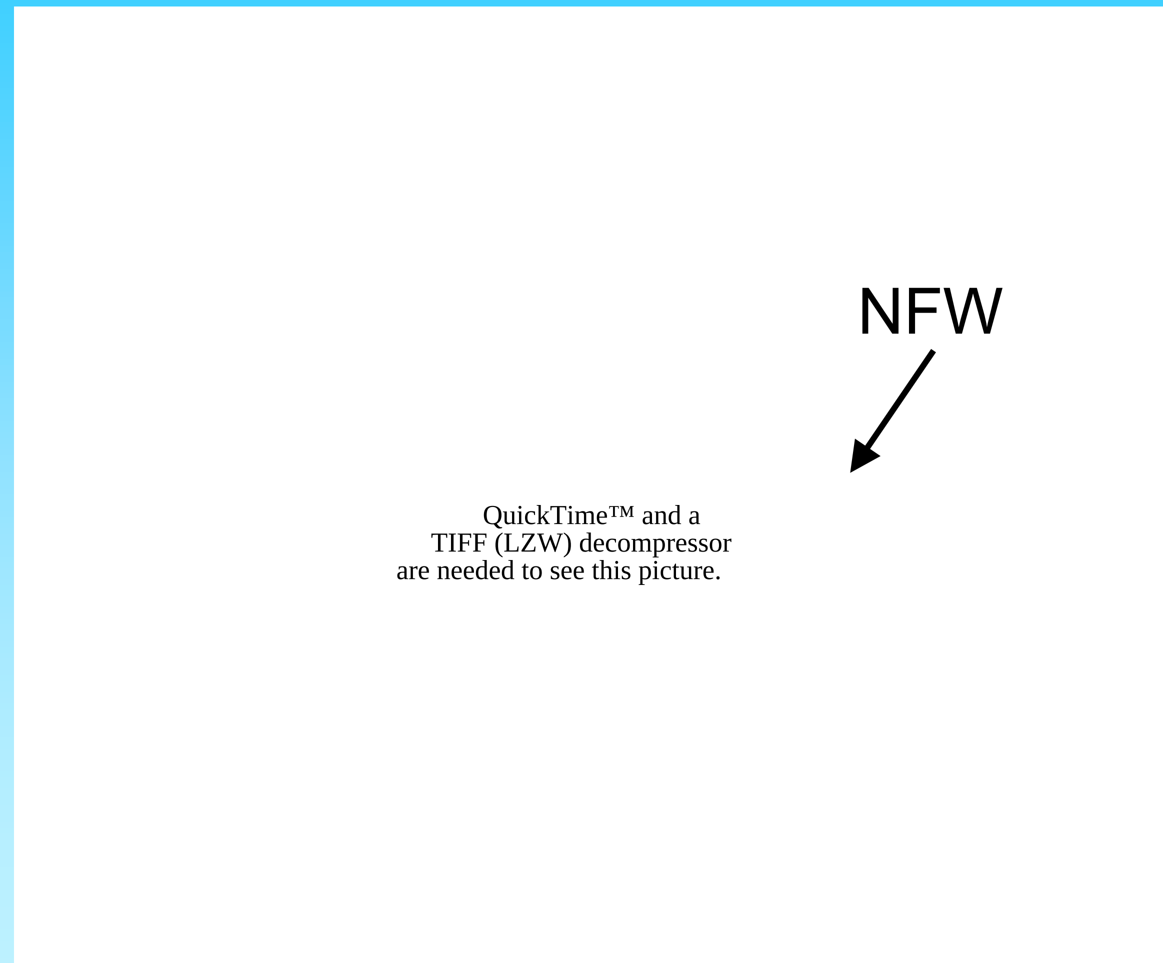
University of Durham

Lensing data



Mass distribution inferred from weak & strong lensing

Excellent agreement with CDM halo predictions



Abell cluster 1689 - Oguri et al 05

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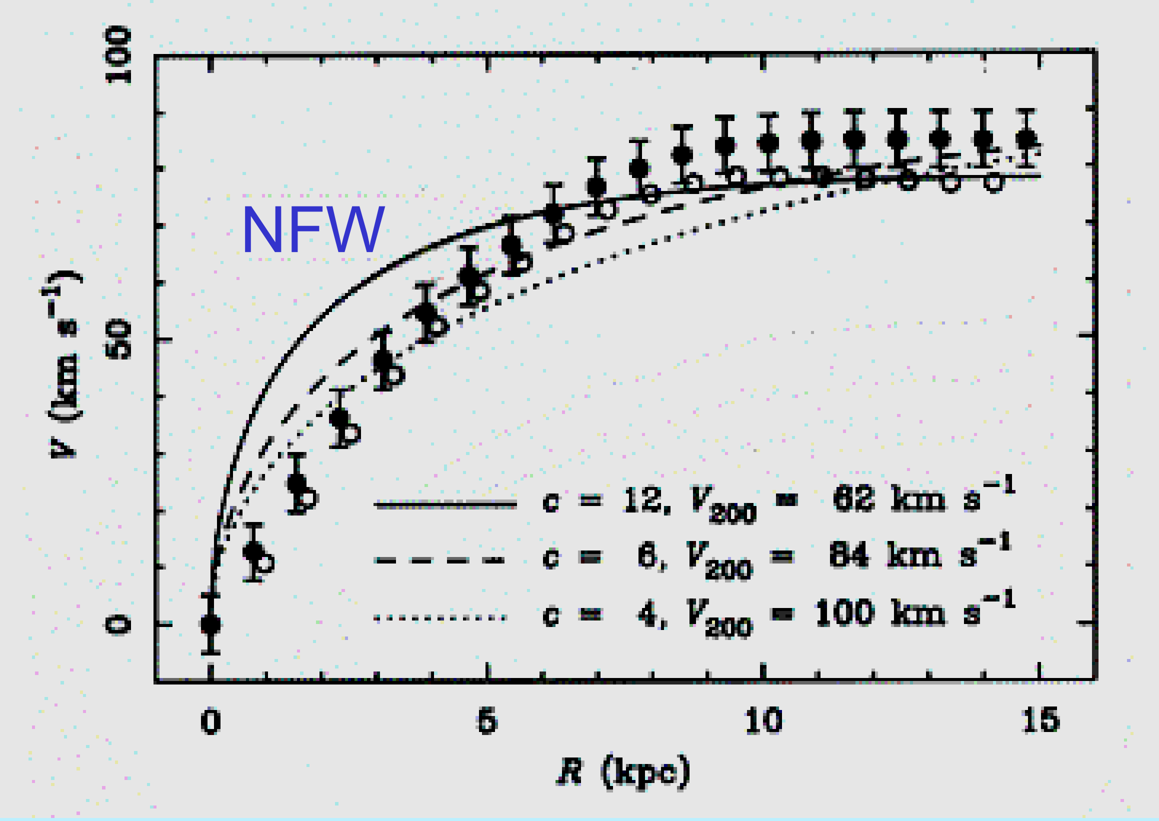
Rotation curves of LSBs and CDM halos

Some rotation curves of LSB and dwarf galaxies seem to disagree with NFW profiles



McGaugh & de Block 1998

see also Moore 1994; Flores & Primack 1994

Scaled LSB rotation curves: a representative sample

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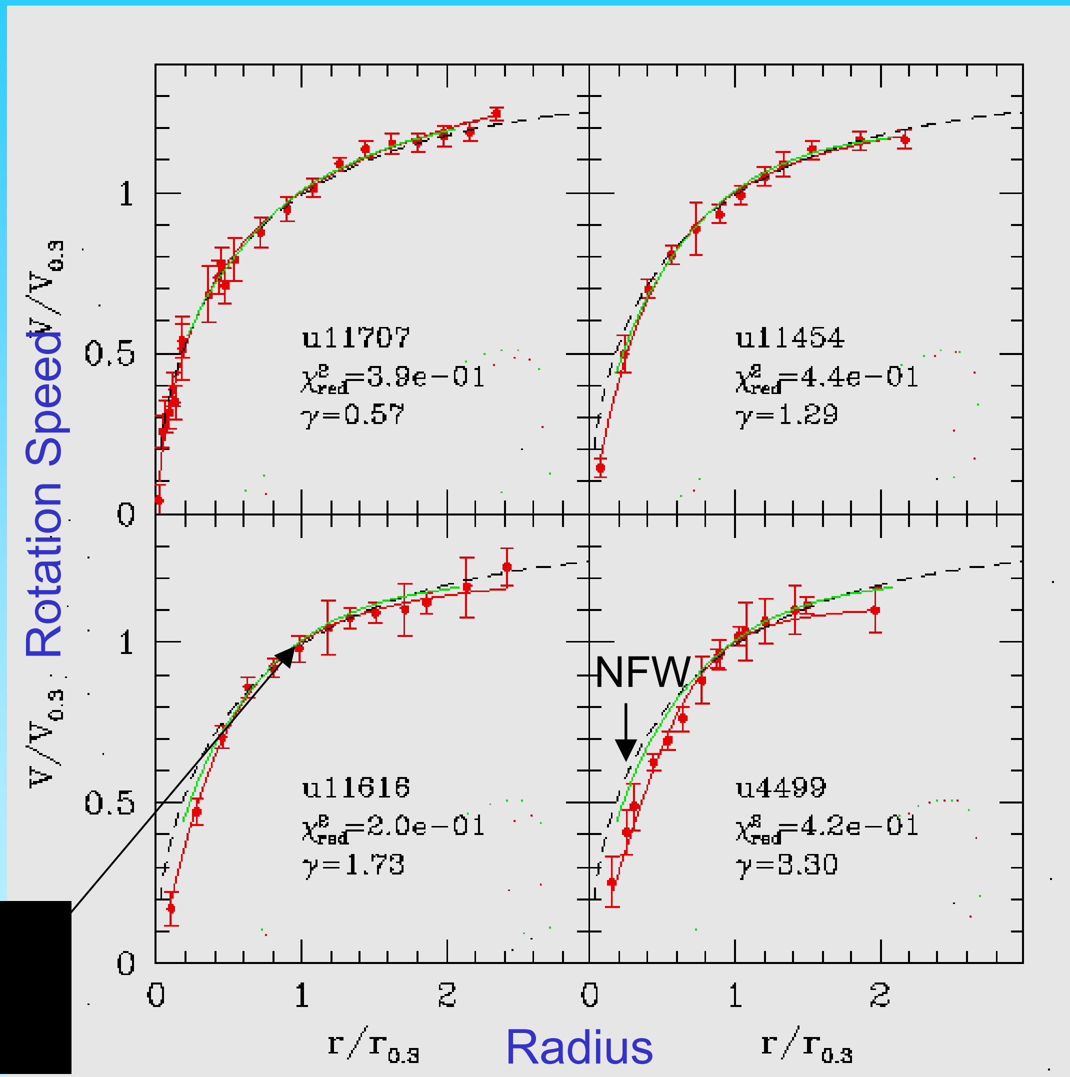
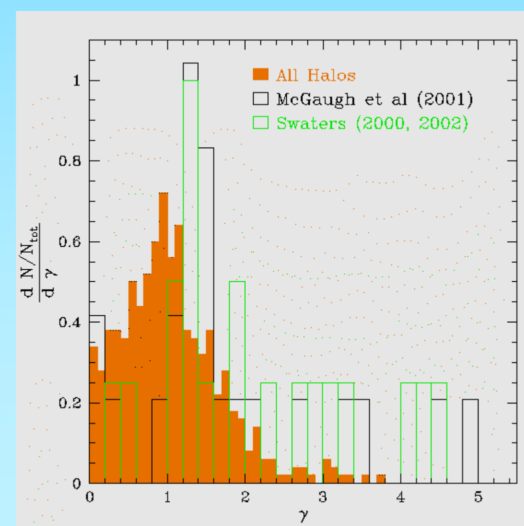


- Two thirds of the galaxies have 0.5<γ<2 (these are reasonably well fitted by CDM halos)
- The rest have γ>2 (not fitted by CDM halos)

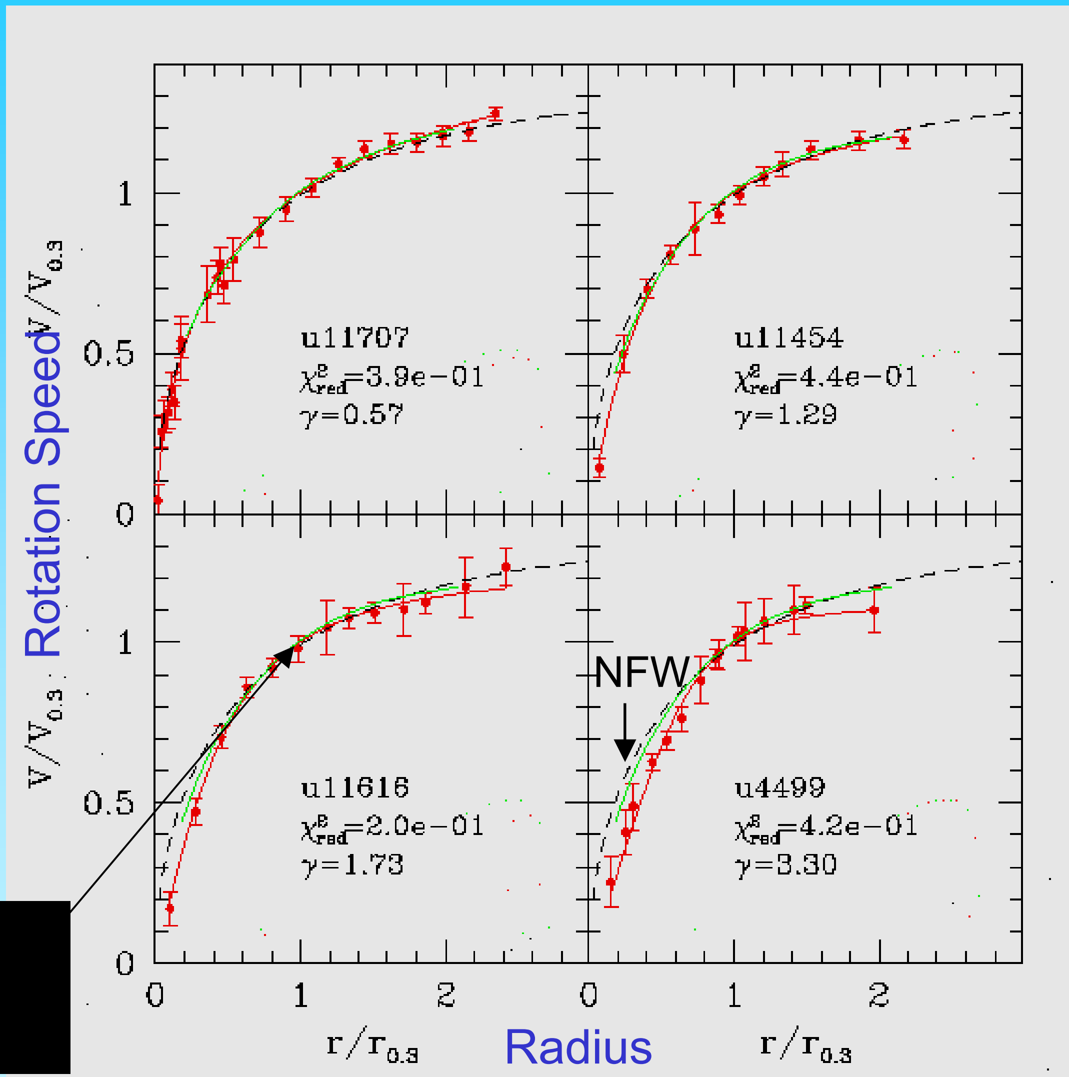


Data from McGaugh & de Block '98 sample

Hayashi et al 2003

University of Durham

Scaled LSB rotation curves: a representative sample



- Two thirds of the galaxies have 0.5<γ<2 (these are reasonably well fitted by CDM halos)
- The rest have γ>2 (not fitted by CDM halos)

NFW :
for spherical halo

$$V_c = \sqrt{\frac{GM(<r)}{r}}$$

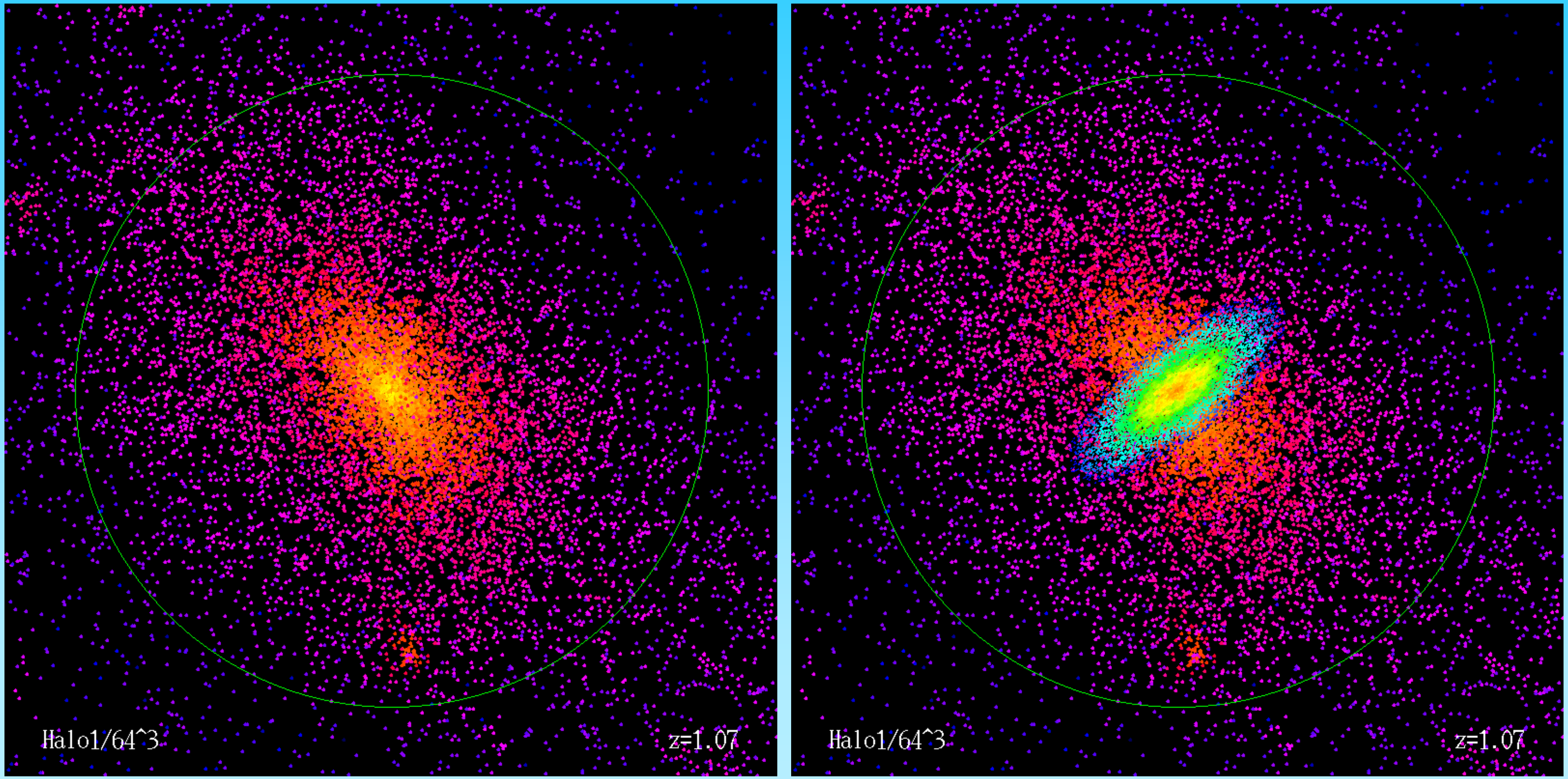
Obs:
Radial velocity
→ rotation speed

Data from McGaugh & de Block '98 sample

Hayashi et al 2003

University of Durham

Disks in realistic dark matter halos



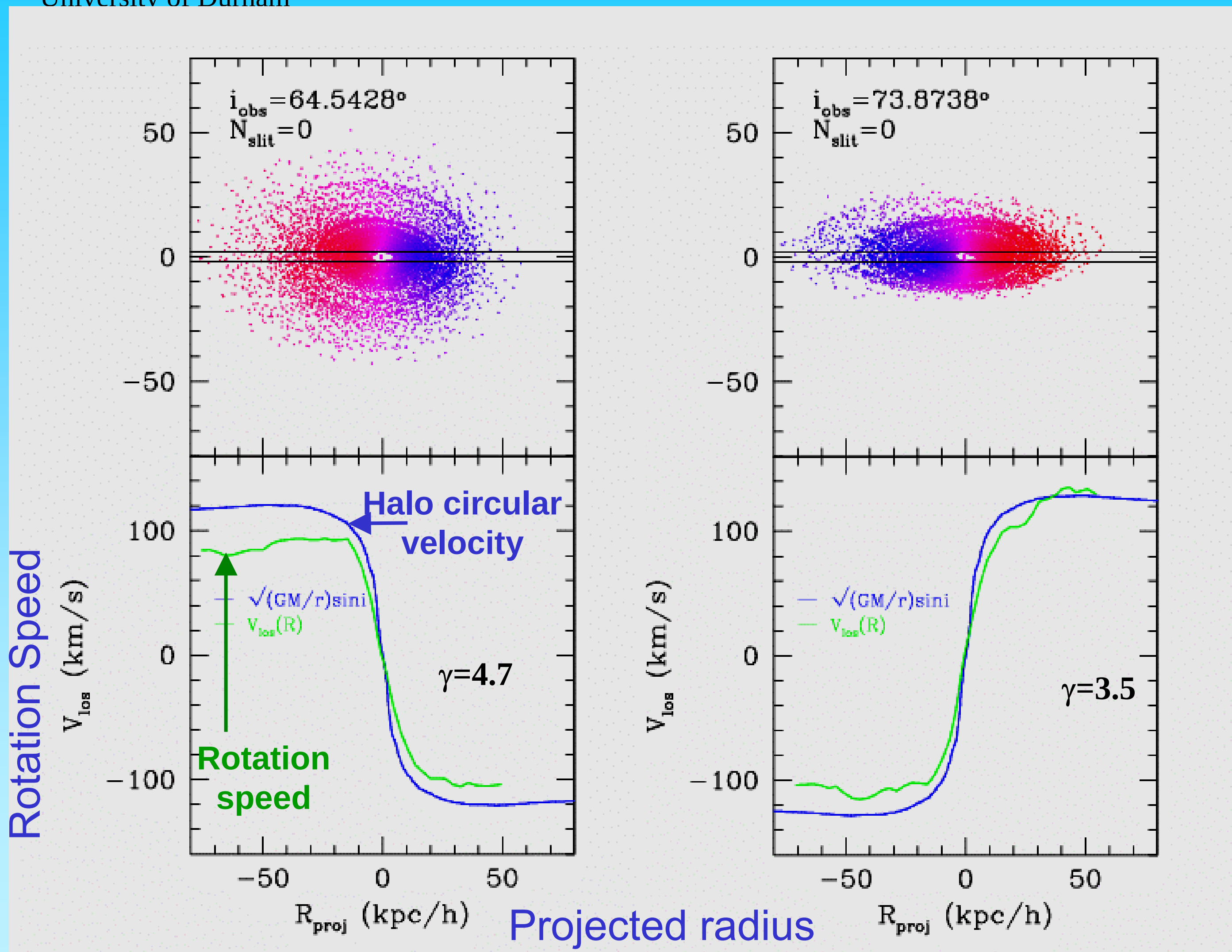
Massless isothermal gaseous disk in the DM halo potential tracks the closed orbits within this non-spherical potential

Hayashi, Navarro, Frenk, White, Jenkins, Power ‘03

Institute for Computational Cosmology

ICC
University of Durham

Disks in realistic dark matter halos



Inferred rotation speeds may differ significantly from actual circular velocity.

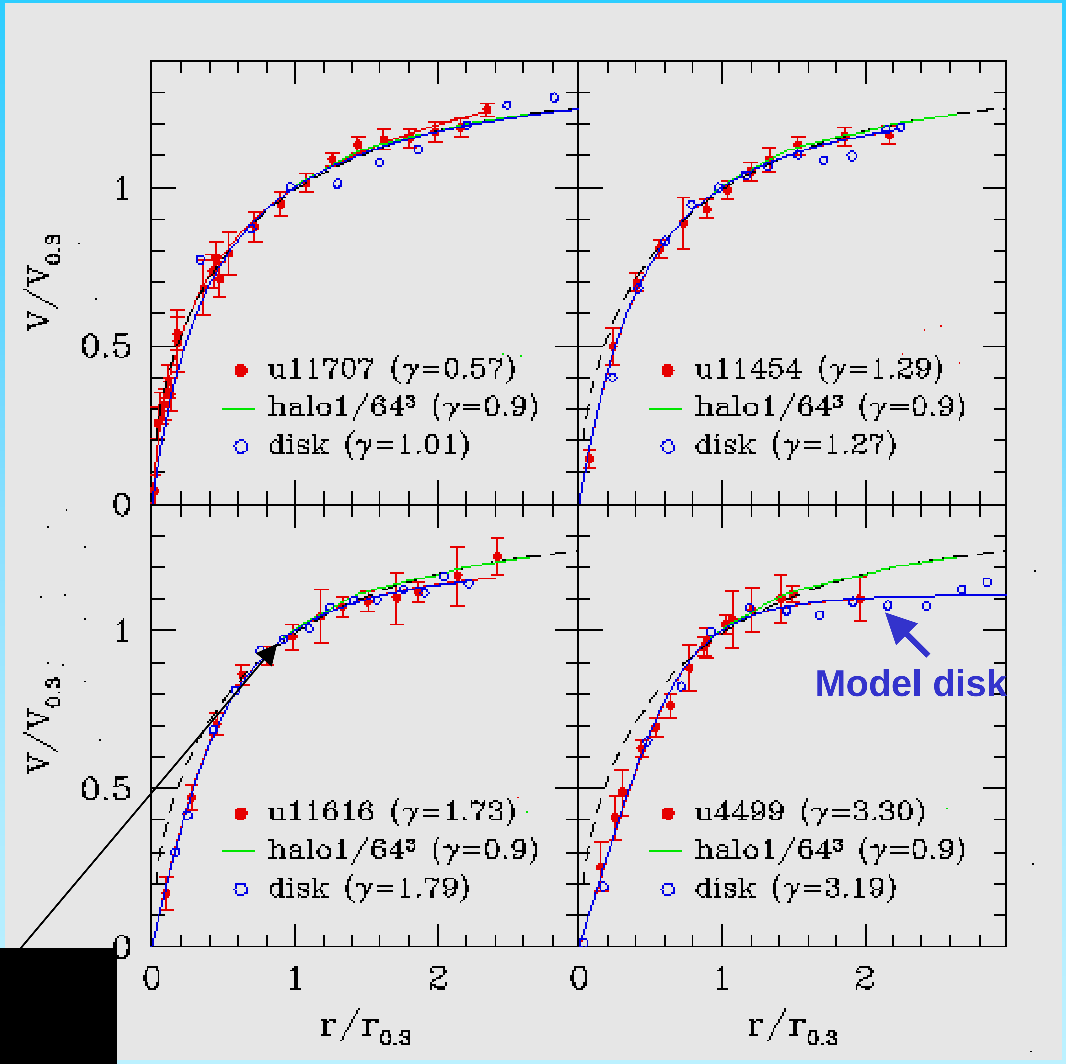
Inclination: 50 degrees 67 degrees

Hayashi et al 2003

Hayashi et al 2003

Scaled Rotation Curves: disk in CDM halo vs LSBs

Scaled Rotation Speed



Scaled radius

All LSB rotation curve shapes may be accounted for by various projections of a disk in a single triaxial CDM halo

Hayashi et al 2003

Cuspy profiles?

Conclusions from galaxy rotation curves:

Problem is complicated:

– Halos are triaxial, not spherical

– Effect of baryons on density profile not understood

$\Rightarrow$ Data could be consistent with cusps

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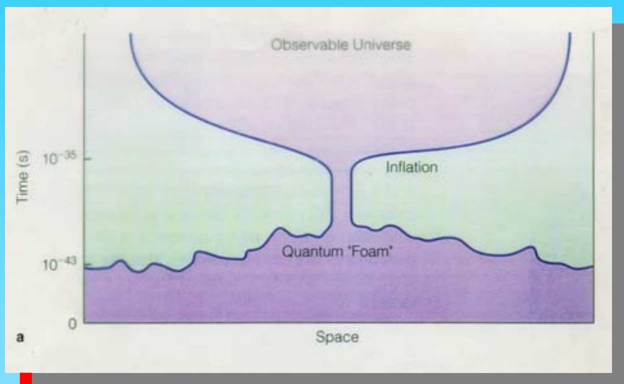
The origin of cosmic structure

Inflation ($t \sim 10^{-35}$ s)

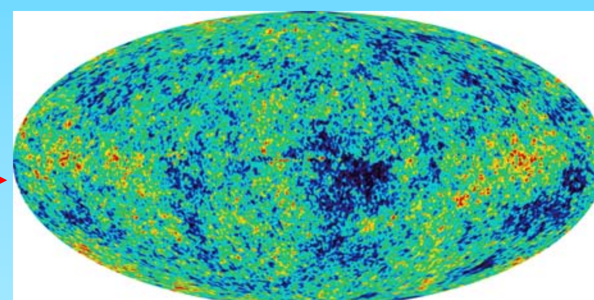


1. FLAT GEOMETRY: $\Omega + \dfrac{\Lambda}{3H^2} = 1$

2. QUANTUM FLUCTUATIONS: adiabatic

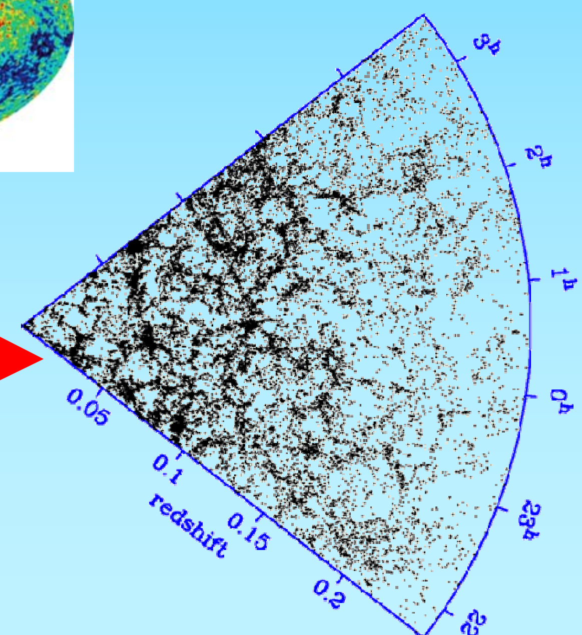
$\left\{ \begin{array}{l} |\delta_k|^2 \alpha\, k^n \quad n = 1 \\ \text{Gaussian amplitudes} \end{array} \right.$

CMB ($t \sim 3\times10^5$ yrs)



Dark matter

Structure ($t \sim 13\times10^9$ yrs)



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Conclusions: the ΛCDM model

➔ ΛCDM is an intrinsically implausible model that requires:

- An early epoch of inflation
- Quantum fluctuations in the early universe
- Non-baryonic dark matter
- Dark energy

➔ Yet, it agrees with staggering amount of data, from CMB to gals

➔ Existence of dark energy supported by WMAP+2dFGRS

➔ Most cosmological params determined by WMAP+2dFGRS
Current limits $w<-0.8$ ($p= w\rho c^2$)

➔ No "satellite problem;" no convincing evidence against cusps

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Open questions

Dark matter

- What is it?
  - If SUSY particle, will LHC make it?
  - Will direct searches find it?
- Is ΛCDM really right on large scales?
  - Map DM directly → gravitational lensing
  - Measure PS growth → galaxy surveys at high z
  - Do galaxies trace mass ? → galaxy formation theory
- Is ΛCDM right on small scales?
  - Detect dark substructures → gravitational lensing
  - Sort out rotation curve mess → simulations, observations
  - Further study of cluster halo structure → X-rays, lensing

Open questions

Dark energy

- What is it?
  - Nothing is known! → theory
- Is it:
  - constant in time (Λ) or varying (quintessence)?
- Fluctuation growth rate and geometry depend on w(z)
  - effects are small but measurable
  - baryon wiggles in clusters are a promising diagnostic

Our implausible Universe

If the Lord Almighty had consulted me before embarking upon creation, I would have recommended something simpler

Alfonso X, the Learned