Galaxy Formation

Carlos Frenk
Institute of Computational Cosmology
University of Durham

Goal: understand origin and evolution of cosmic structures

- Review of standard Big Bang model
- Growth of small fluctuations (linear theory)
- Fluctuations in the microwave background radiation
- The formation of galaxies and clusters

Connection to three outstanding problems in 21st Physics:

- The identity of the dark matter
- The nature of the dark energy
- Origin of cosmic structure

Galaxy Formation

Carlos Frenk
Institute of Computational Cosmology
University of Durham

You should be familiar with:

- Basic concepts in Big Bang theory
- The contents of the Universe
- The expansion properties of the Universe

Books:

Cole & Lucchin: Cosmology -- about the right level

Peacock: Galaxy Formation -- advanced

Liddle: Cosmology -- basic background

http://star-www.dur.ac.uk/~csf/homepage/GalForm_lectures

The Big Bang Theory

What it is:

- Theory that the Universe as we know it began 10 – 15 billion years ago
- Initial state was a hot, dense, uniform sea of particles that filled space uniformly and was expanding

What it describes:

- How the universe expands and cools
- How the light chemical elements formed
- How matter congealed to form stars and galaxies

What it does not describe:

- What caused the expansion (*expanding initial state assumed*)
- Where did matter come from (*energy assumed to be there from start*)

Empirical evidence for the Big Bang

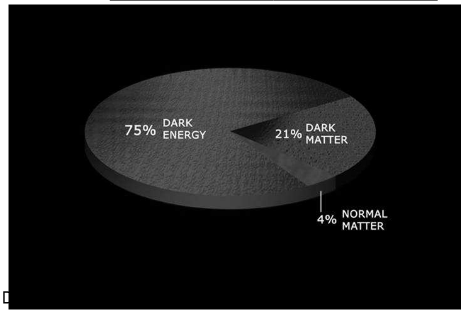
1. The expansion of the universe of galaxies
   - galaxies are receding from us with speed proportional to their distance
   - expansion is the same for all observers
2. The microwave background radiation
   - heat left over from Big Bang explosion
   - comes from everywhere in space (homogeneous and isotropic)
   - it was emitted when the universe was 300000 years old
3. The abundance of the light elements
   - BB theory predicts that 75% of mass is hydrogen, 24% is helium and 1% is the rest
   - These are precisely the abundances observed in distant gas clouds!

(*nb: elements heavier than H and ^{4}He were produced billions of years later inside stars)*

University of Durham

What is the Universe made of?

The content of our universe



University of Durham

What is the universe made of?

$$\Omega = \frac{\text{density}}{\text{critical density}} \qquad \rho = \rho_{mass} + \rho_{rel} + \rho_{vac}$$

critical density = density that makes univ. flat: (Ω = 1 for a flat univ.)

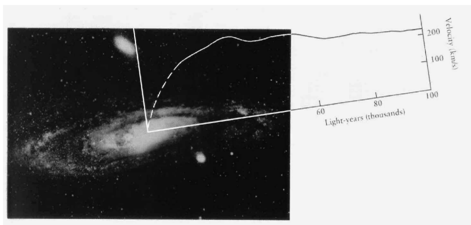
- Radiation (*CMB, T=2.726±0.005* °K) Ω_r = 4.7 x 10^{-5}
- Massless neutrinos Ω_ν = 3 x 10^{-5}
- Massive neutrinos Ω_ν = 6 x 10^{-2} (<m_ν>/ev)
- Baryons Ω_b = 0.037 ± 0.009
  (of which stars) Ω_s = 0.0023 ± 0.0003
- Dark matter (cold dark matter) $\Omega_{dm} \cong$ 0.26
- Dark energy (cosm. const. Λ) $\Omega_\Lambda \cong$ 0.7

$$\longrightarrow \Omega = \Omega_b + \Omega_{dm} + \Omega_\Lambda \cong 1$$

(assuming Hubble parameter h=0.7)

University of Durham

Galaxy rotation curves

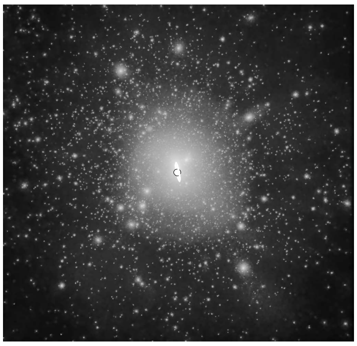


Flat V_c → $M(<r) \propto r$

⇒ **dark halos around galaxy**

University of Durham

Computer simulation of galaxy halo

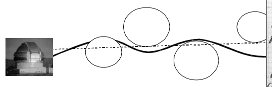


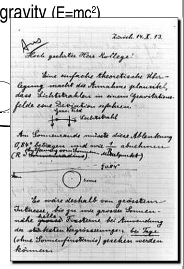
0.5 Mpc/h

University of Durham

Mapping the dark matter

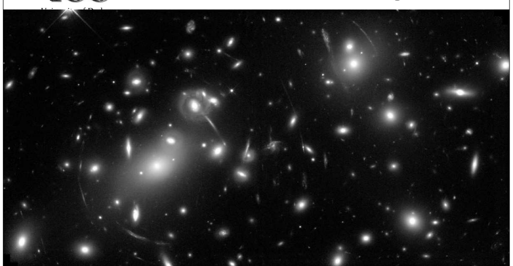
Light rays are deflected by gravity ($E=mc^2$)





Institute for Computational Cosmology

Gravitational lensing



Light from distant galaxies is deflected by dark matter in cluster, distorting the galaxies' images into arcs

Institute for Computational Cosmology

University of Durham

The visible and dark sides of the universe

- There is ~5 times more dark matter than there is ordinary (baryonic) matter

(~90% of the mass of the Universe is dark matter)

⇨

→ Most of the dark matter is NOT ordinary (baryonic) matter

→ **Weakly interacting massive particles (WIMPS)**

Institute for Computational Cosmology

ICC University of Durham

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

ICC University of Durham

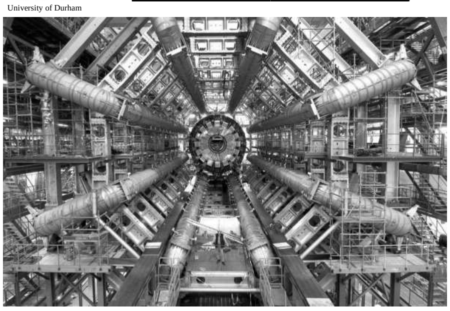
Looking for WIMPS

CERN

Geneva

ICC University of Durham

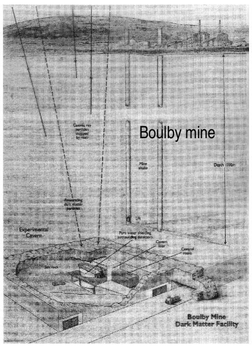
The search for dark matter



ICC University of Durham

Looking for dark matter … down the mine

(where cosmic rays can't penetrate)



Look
dowr

(wh

University of Durham

What is the universe made of?

So, the Universe contains:

- Ordinary matter (Ω_b=0.04)
- Dark matter (Ω_{dm}= 0.21)

Anything else?

Yes! Dark energy

Dark energy is a property of space itself.

It has the opposite effect to gravity

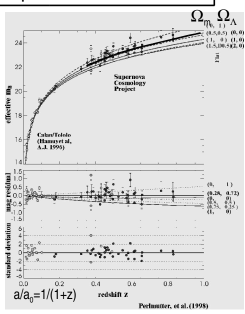
University of Durham

Evidence for Λ from high-z supernovae

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

flux

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



Perlmutter et al '98

University of Durham

Friedmann equations

$$\ddot{a} = -\frac{4 p}{3} G \quad (3w+1) \qquad c^2 a \frac{d}{da} = -3(pc + \ ^2)$$

$$\rho_{tot} = \underbrace{\rho_{mass}}_{a^{-3}} + \underbrace{\rho_{rel}}_{a^{-4}} + \underbrace{\rho_{vac}}_{const?} \qquad \text{where} \qquad p = w \ ^2$$

$$\Rightarrow 3w + 1 < 0 \Rightarrow \ddot{a} > 0 \Rightarrow$$ expansion accelerates

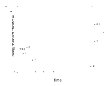
If $\boldsymbol{\rho} = \boldsymbol{\rho}_{vac} = \text{const}$, $\frac{d\boldsymbol{\rho}}{da} = 0 \ \Rightarrow \ \boldsymbol{p} = -\boldsymbol{\rho c}^2 \ \Rightarrow \ \boldsymbol{w} = -1$
cosmological constant

If $\rho_{vac} = \rho_{vac}(z,\mathbf{x})$ and $\Rightarrow$ quintessence

Evolution of Cosmic Scale Factor in FRW Model

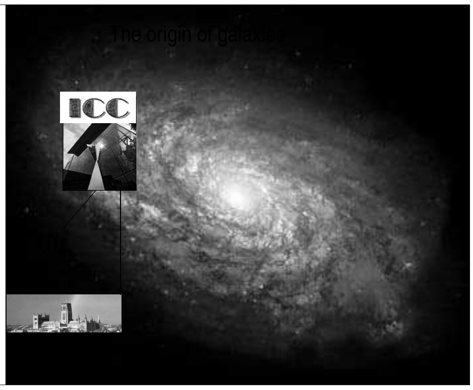
$$\rho = \rho_{mass} + \rho_{rel} + \rho_{vac}$$

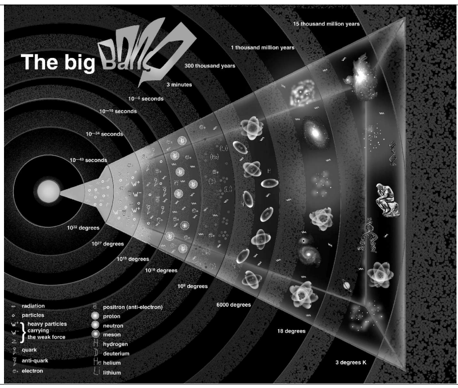
$\rho_{mass} \propto a^{-3}$, $\rho_{rel} \propto a^{-4}$, ρ_{vac} const



Λ>0

Institute for Computational Cosmology



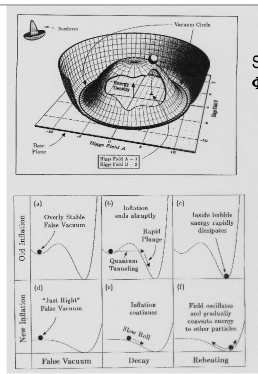


Inflation

Initially, Universe is trapped in false vacuum

Universe decays to true vacuum keeping ρ_v~ const

Universe oscillates converting energy into particles



Scalar field **Φ**

Friedmann equations

ICC University of Durham

$$\dot{a}^2+kc^2=\frac{8p}{3}G \quad ^2$$

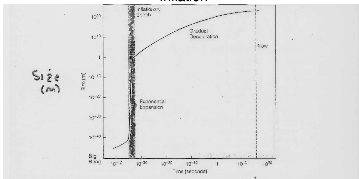
If $k=0$ and $= \ _{vac}=const$ $(w=-1)$

$$\left(\frac{\dot{a}}{a}\right)^2=\frac{8p}{3}G$$

$$\Rightarrow \quad a\mu e^{t/t} \qquad t=\left(\frac{3}{8p}\right)^{1/2}$$

$\Longrightarrow$ Universe expands exponentially

Inflation



INFLATION SOLVES 4 MAJOR COSMOLOGICAL PROBLEMS

1. FLATNESS: $\frac{\Omega_{PL}^{-1}-1}{\Omega_0^{-1}-1}=\frac{T_0}{T_{eq}}\left(\frac{T_{eq}}{T_{PL}}\right)^2 \simeq 10^{-57}$ & $\Omega_0^{-1}-1<100$

SO, AT T_{PL} UNIVERSE FLAT TO 1 PART IN 10^{55} !

2. HORIZON: $R_H(z_{ls}) = 3ct_{ls} \simeq 10^{-1} r_{ls}$

horizon at "last scattering" — radius of "last scattering" surface

BUT $\Delta T/T \simeq 10^{-5}$!

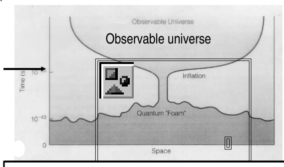
3. MONOPOLE: GUT PRODUCES ~1 MAGNETIC MONOPOLE PER HORIZON VOL. AT $t_{GUT} \Rightarrow \Omega_M \simeq 10^{16}$!

4. STRUCTURE: GENERATION OF $\delta\rho/\rho$?

Cosmic Inflation

ICC University of Durham

t=10^{-35} s



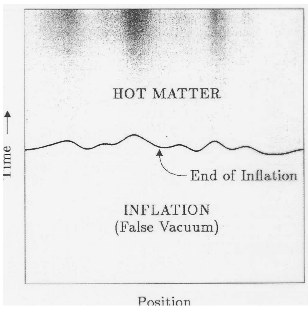
Inflation theory predicts:

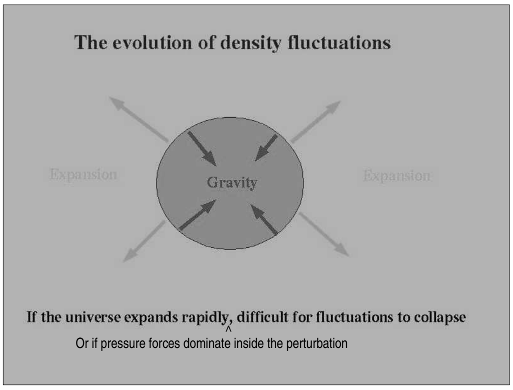
2. Flat geometry (Ω =1) √
   (eternal expansion)
4. Small ripples in mass distribution

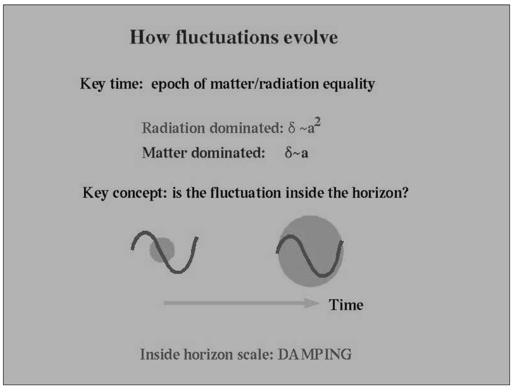
Generation of primordial fluctuations

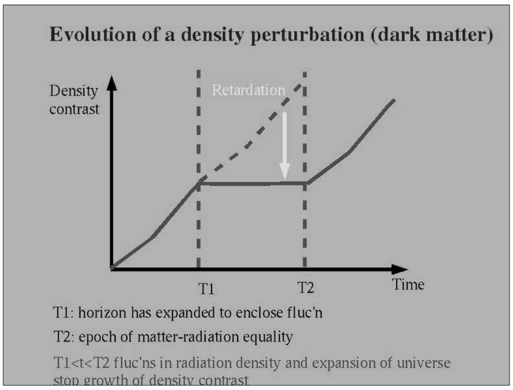
ICC University of Durham

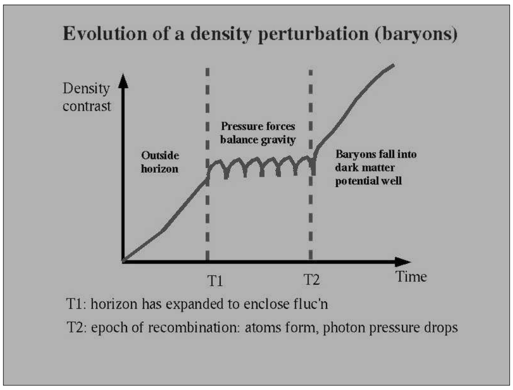
Quantum fluctuations are blown up to macroscopic scales during inflation




The evolution of density fluctuations
Expansion
Gravity
Expansion
If the universe expands rapidly, difficult for fluctuations to collapse
Or if pressure forces dominate inside the perturbation


How fluctuations evolve
Key time: epoch of matter/radiation equality
Radiation dominated: $\delta \sim a^2$
Matter dominated: $\delta \sim a$
Key concept: is the fluctuation inside the horizon?
Time
Inside horizon scale: DAMPING


Evolution of a density perturbation (dark matter)
Density
contrast
Retardation
T1
T2
Time
T1: horizon has expanded to enclose fluc'n
T2: epoch of matter-radiation equality
T1<t<T2 fluc'ns in radiation density and expansion of universe
stop growth of density contrast


Evolution of a density perturbation (baryons)
Density
contrast
Pressure forces
balance gravity
Outside
horizon
Baryons fall into
dark matter
potential well
T1
T2
Time
T1: horizon has expanded to enclose fluc'n
T2: epoch of recombination: atoms form, photon pressure drops

EVOLUTION OF AN ADIABATIC PERTURBATION IN A CDM UNIVERSE

$M = 10^{15}\ M_\odot$ $\Omega = 1$ $h = 0.5$

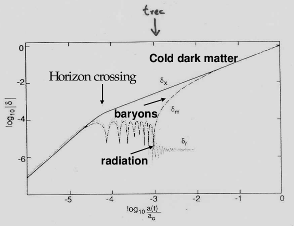
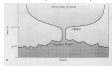


Figure 13.3 Evolution of perturbations on a scale $M \simeq 10^{15}\ M_\odot$ for the cold component δ_X, baryonic component δ_m and photons δ_r in a model dominated by CDM ($\Omega = 1$, $h = 0.5$)

ICC University of Durham

The origin of cosmic structure

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

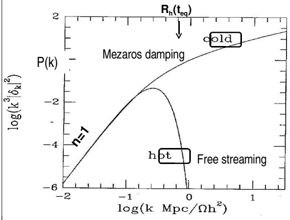


QUANTUM FLUCTUATIONS:

\+ Damping (nature of dark matter)

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

→ Transfer function

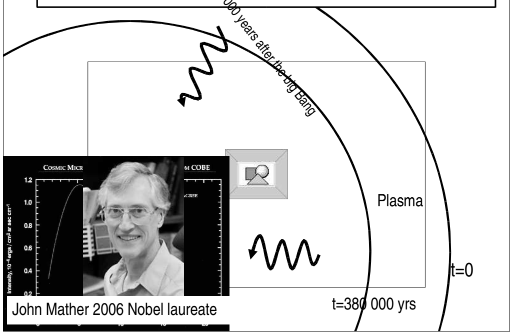


- Hot DM (eg ~30 ev neutrino)
  - Top-down formation
- Cold DM (eg ~neutralino)
  - Bottom-up (hierachical)

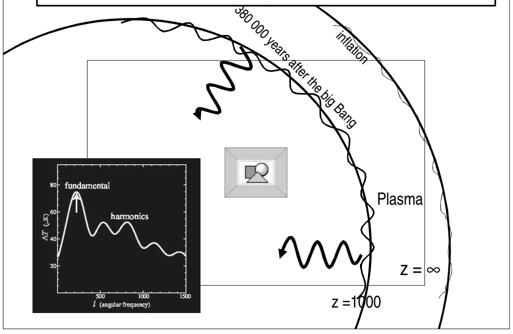
ICC University of Durham

The microwave background radiation

The microwave background radiation

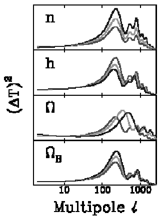


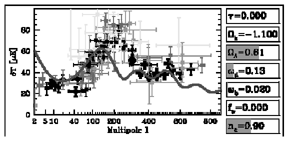
The microwave background radiation



ICC
University of Durham

Dependence of $\Delta T/T$ on cosmological params



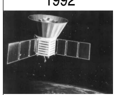


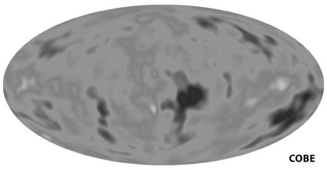
Max Tegmark

ICC
University of Durham

The CMB

1992





COBE

The cosmic microwave background radiation (CMB) provides a window to the universe at $t\sim3\text{x}10^5$ yrs

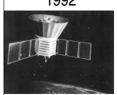
In 1992 COBE discovered temperature fluctuations ($\Delta T/T\sim10^{-5}$) consistent with inflation predictions

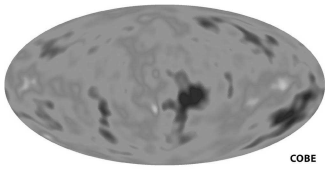
---

ICC
University of Durham

The CMB

1992

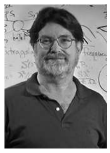


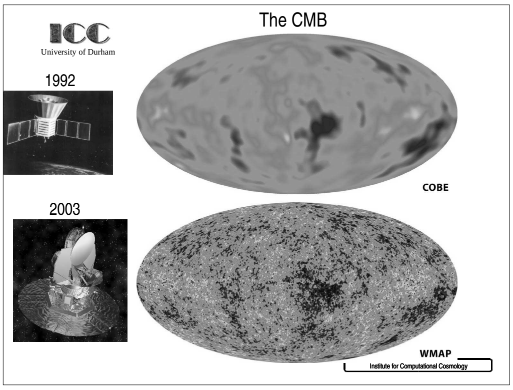


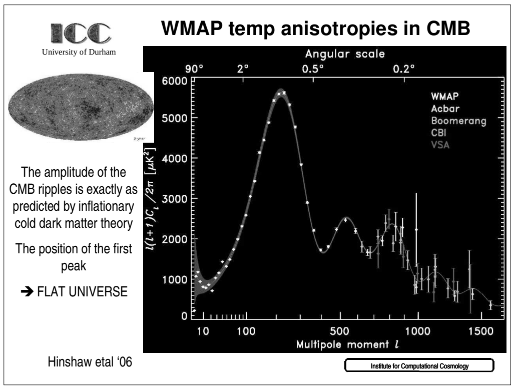
COBE

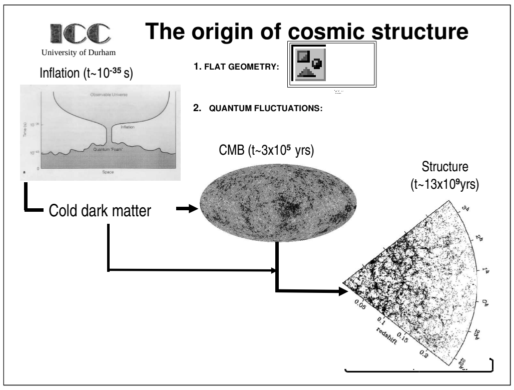
George Smoot - Nobel Prize 2006

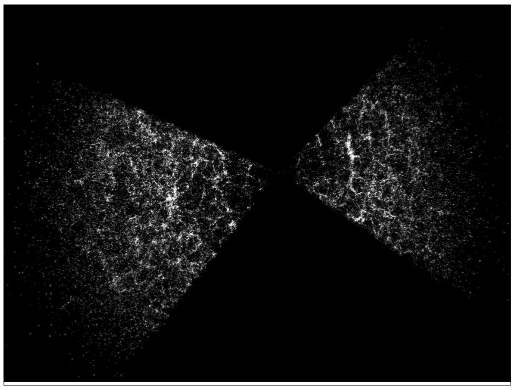
KUNGL.
VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES




ICC
University of Durham
The CMB
1992
COBE
2003
WMAP
Institute for Computational Cosmology


ICC
University of Durham
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
Angular scale
90°
2°
0.5°
0.2°
WMAP
Acbar
Boomerang
CBI
VSA
Multipole moment l
Institute for Computational Cosmology


ICC
University of Durham
The origin of cosmic structure
Inflation (t~10^-35 s)
1. FLAT GEOMETRY:
2. QUANTUM FLUCTUATIONS:
CMB (t~3x10^5 yrs)
Structure
(t~13x10^9yrs)
Cold dark matter
redshift



University of Durham

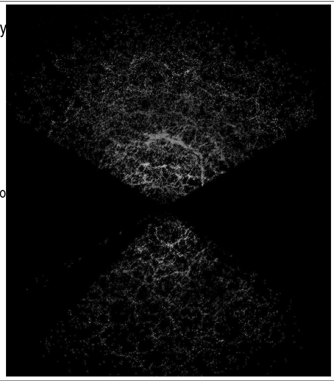
The 2dF galaxy redshift survey

QuickTime® and a
Cinepak decompressor
are needed to see this picture.

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

Institute for Computational Cosmology

Sloan Digital Sky Survey

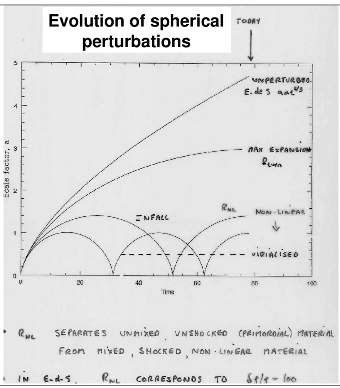


~300,000 galaxy redshifts so

500,000 eventually

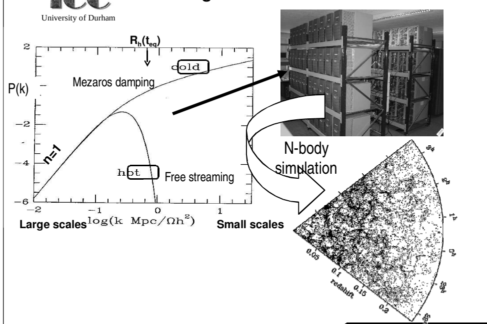
University of Durham

Evolution of spherical perturbations



University of Durham

Calculating the evolution of cosmic structure



Institute for Computational Cosmology

ICC
University of Durham

Non-baryonic dark matter candidates

Candidate	Mass
Axions	10^{-5} eV
Neutrinos	30 eV
Neutralinos (SUSY)	>20 GeV
Primordial black holes	$>10^{15}$ g

Cold DM

Hot DM

Cold DM

Cold DM

ICC
University of Durham

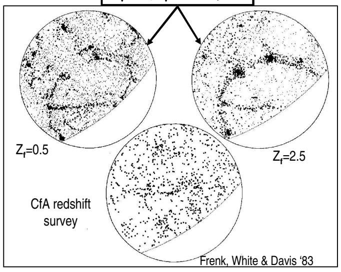
Neutrino (hot) dark matter

Ω_ν=1 (m_ν = 30 ev)

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

⇨

Neutrinos cannot make an appreciable contribution to Ω and m_ν<< 30 ev



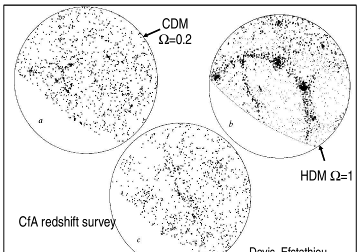
Frenk, White & Davis '83

ICC
University of Durham

Cold dark matter

In CDM structure forms hierarchically

Early CDM N-body simulations gave promising results



Davis, Efstathiou, Frenk & White '85

ICC
University of Durham

dalla Vechia, Jenkins & Frenk

QuickTime® and a YUV420 codec decompressor are needed to see this picture.

150 Mpc/h

Comoving coordinates

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

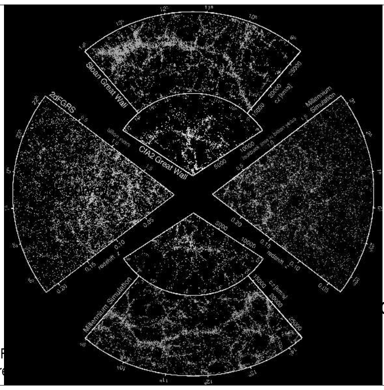
Helly & Frenk 06

1 Mpc

The Millennium simulation

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

Springel et al Nature June/05

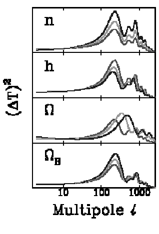


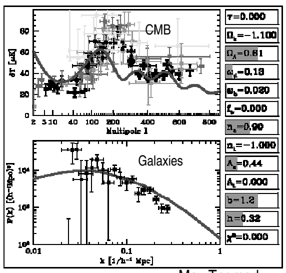
d

Springel, F
Nature

Dependence of $\Delta T/T$ on cosmological params

University of Durham





Max Tegmark

Institute for Computational Cosmology

Old Universe – *New* Numbers

$\Omega_{tot} = 1.02^{+0.02}_{-0.02}$	$n_s = 0.93^{+0.03}_{-0.03}$
$w < -0.78$ (95% CL)	$dn_s/d\ln k = -0.031^{+0.016}_{-0.018}$
$\Omega_\Lambda = 0.73^{+0.04}_{-0.04}$	$r < 0.71$ (95% CL)
$\Omega_b h^2 = 0.0224^{+0.0009}_{-0.0009}$	$z_{dec} = 1089^{+1}_{-1}$
$\Omega_b = 0.044^{+0.004}_{-0.004}$	$\Delta z_{dec} = 195^{+2}_{-2}$
$n_b = 2.5 \times 10^{-7}{}^{+0.1\times10^{-7}}_{-0.1\times10^{-7}}$ cm^{-3}	$h = 0.71^{+0.04}_{-0.03}$
$\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$	$t_0 = 13.7^{+0.2}_{-0.2}$ Gyr
$\Omega_m = 0.27^{+0.04}_{-0.04}$	$t_{dec} = 379^{+8}_{-7}$ kyr
$\Omega_\nu h^2 < 0.0076$ (95%CL)	$t_r = 180^{+220}_{-80}$ Myr (95% CL)
$m_\nu < 0.23$ eV (95% CL)	$\Delta t_{dec} = 118^{+3}_{-2}$ kyr
$T_{cmb} = 2.725^{+0.002}_{-0.002}$ K	$z_{eq} = 3233^{+194}_{-210}$
$n_\gamma = 410.4^{+0.9}_{-0.9}$ cm^{-3}	$\tau = 0.17^{+0.04}_{-0.04}$
$\eta = 6.1 \times 10^{-10}{}^{+0.3\times10^{-10}}_{-0.2\times10^{-10}}$	$z_r = 20^{+10}_{-9}$ (95% CL)
$\Omega_b \Omega_m^{-1} = 0.17^{+0.01}_{-0.01}$	$\theta_A = 0°.598^{+0.002}_{-0.002}$
$\sigma_8 = 0.84^{+0.04}_{-0.04}$ Mpc	$d_A = 14.0^{+0.2}_{-0.3}$ Gpc
$\sigma_8 \Omega_m^{0.5} = 0.44^{+0.04}_{-0.05}$	$l_A = 301^{+1}_{-1}$
$A = 0.833^{+0.086}_{-0.083}$	$r_s = 147^{+2}_{-2}$ Mpc

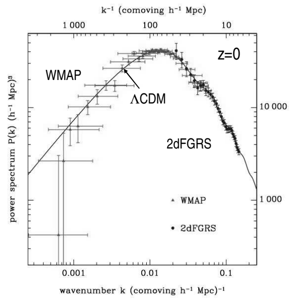
ICC University of Durham

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

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

CMB:

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

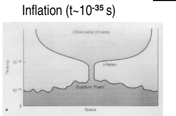


Sanchez et al 06

ICC University of Durham

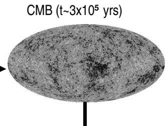
Conclusions
The origin of cosmic structure

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

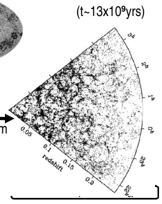


1. FLAT geometry:
2. Small (quantum) ripples

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



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



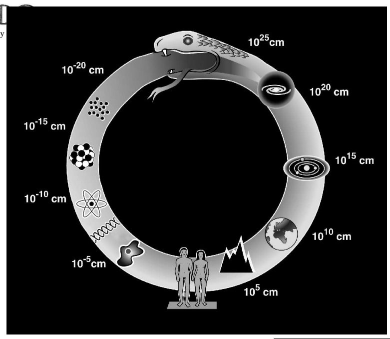
Cold dark matter

Ripples seen as hot & cold spots in cosmic radiation

Galaxies form

- Recent measurements of fluctuations in the temperature of the microwave background confirm this paradigm.

ICC University of Durham



Institute for Computational Cosmology

Open questions

- What is the dark matter?
- What is the dark energy?
- What happened in the first 10^{-35}s after the Big Bang?
- How, in detail, did stars and galaxies form?
- How much farther will the simulations go?

Open questions

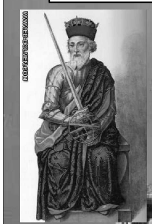
Tools:

- Satellites to study the CMB & distant galaxies
- Large telescopes
- Direct dark matter searches
- Particle accelerators (CERN)
- Supercomputer simulations

Ideas:

- Theoretical physics & mathematics

Our implausible Universe



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

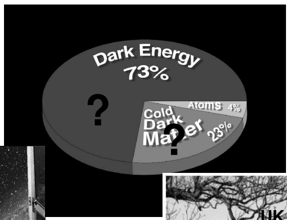
The paradigm of structure formation ΛCDM

- Material content: Cold dark matter, baryons, Λ
- Initial conditions: From quantum fluctuations during inflation: $|\delta_k|^2$ k; Gaussian ampl.
- Growth processes: Gravitational instability; gas (cooling, star formation, etc)
- Parameters: $\Omega_{CDM}=0.26,\ \Omega_b=0.04,\ h=0.70,$ $/3H_0^2=0.7,$ $_8=0.9$

⟹ Galaxies form hierarchically

ICC
University of Durham

Conclusions: open questions



ICC
University of Durham

The future of cosmology

Open questions:

➔ Detection (or manufacture) dark matter
➔ The origin of the dark energy ?
➔ The astrophysics of galaxy formation ?

- Direct searches for CDM (Boulby, CDMS, G Sasso)
- Constraints on w (high-z SN, lensing, high-z clustering)
- Surveys of galaxies at high-z (VLT, SIRTF, ALMA, NGST)
- Supercomputers simulations
- New ideas on w