Cours/Lecture Series

1997–1998 ACADEMIC TRAINING PROGRAMME

LECTURE SERIES

SPEAKER : C. FRENK / Durham University, GB
TITLE : The cosmic large-scale structure, dark matter and
the origin of galaxies
TIME : 2, 3, 4, 5 & 6 March, from 11.00 to 12.00hrs
PLACE : Council Chamber

ABSTRACT

In this series of lectures, I will review the main events and processes which are
thought to have led to the build of structure in the Universe. First, I will provide
an overview of some basic ideas such as inflation, Big Bang nucleosynthesis, the
microwave background radiation and gravitational instability. I will then discuss
the evidence for dark matter in the universe and current ideas on the nature and
amount of this dark matter, including their consequences for the values of the
fundamental cosmological parameters. Next, I will review the processes that give
rise to the cosmic large-scale structure, starting with a discussion of the main
fluctuation damping mechanisms at early times and finishing with a description
of the non-linear phases of evolution. I will discuss how these calculations compare
with observations and present the current status of competing cosmological
models. Finally I will summarize the most recent and very exciting developments
in observational and theoretical studies of galaxy formation, including the discovery
of primordial galaxies.
The formation of structure in the Universe

Carlos S. Frenk

University of Durham

- The microwave background radiation
- Gravitational instability
- Dark matter: identity and amount
- Large-scale structure of the universe
- The formation of galaxies
A Brief History of the Universe

Today $t_0$
- Life on Earth
- Solar system forms

Galaxy Formation
- Gravitational collapse

Recombination
- Reionization occurs

Nucleosynthesis

Quark confinement
- Hadrons form & protons

Electroweak Phase Transition
- Electromagnetic & weak nuclear forces differentiate
- $SU(3) \times SU(2) \times U(1) \rightarrow SU(3) \times U(1)$

The particle desert

Grand Unified Phase Transition
- $SU(2) \times U(1)$ to topological defects?
- $G \rightarrow H \rightarrow SU(3) \times SU(2) \times U(1)$

The Planck Epoch
- The quantum gravity wall

Time

$t = 15$ billion years
$T = 3$ K (-270°C)

$t = 100,000$ years
$T = 3000$ K

$t = 1$ minute

$t = 1$ second
$T = 10^{11}$ K

$t = 10^{-6}$ s
$T = 10^{13}$ K

$t = 10^{-11}$ s
$T = 10^{15}$ K

$t = 10^{-35}$ s
$T = 10^{27}$ K

$t = 10^{-43}$ s
$T = 10^{31}$ K
Cosmic microwave Background Spectrum from COBE

Theory and observation agree

\[ T = 2.726 \pm 0.010 \text{ K} \]
\[ (95\% \text{ C.L.)} \]

\[ \frac{\Delta T}{T_{\text{max}}} < 0.03 \text{ \%} \]

\[ |\Delta T| < 2.5 \times 10^{-5} \text{ \text{mK} \, \text{rms}} \]

\[ |\mu T| < 3.3 \times 10^{-4} \text{ \text{mK} \, \text{rms}} \]

J.C. Mather, Presented at International School of Astrophysics D. Chalenge
The Friedmann model

\[ H^2(1 - \Omega - \frac{\Lambda c^2}{3H^2}) = -\frac{k c^2}{a^2} \]

- \( k \) = curvature
- \( H = \dot{a}/a \equiv \text{expansion rate} = 100h \text{ kms}^{-1}\text{Mpc}^{-1} \)

**Best current estimate:** \( h \simeq 0.6 \pm 0.1 \)

- \( \Omega = \rho/\rho_{\text{crit}} \equiv \text{density parameter} \ (\rho_{\text{crit}} \simeq 3 \text{ H atoms per m}^3) \)

**Best current estimate:** \( \Omega \simeq 0.4 \pm 0.1 \)

- \( \Lambda \equiv \text{cosmological constant (Einstein's "Big mistake")} \)

**Best current limit:** \( \frac{\Lambda c^2}{3H^2} < 0.8 \)

Inflation \( \rightarrow k = 0 \quad \rightarrow \Omega + \frac{\Lambda c^2}{3H^2} = 1 \)
EVOLUTION OF SPHERICAL PERTURBATIONS

Today

Unperturbed E- and q - 4/3

Max expansion R_LUM

Infall

R_{NL}

Non-linear

Virialised

Scale factor, a

Time

- R_{NL} separates unmixed, unshocked (primordial) material from mixed, shocked, non-linear material
- In E-d.s., R_{NL} corresponds to S_g/\delta ~ 100
A NASA spacecraft has detected echoes of the galaxies' birth fourteen thousand million years ago. The discovery about the formation of the stars after the Big Bang has been hailed by excited scientists as the Holy Grail of cosmology. Susan Watts and Tom Wilkie report

How the universe began
Cosmic Inflation

For Eqn of state $P = -\frac{\dot{s}_V}{a^2}$ with $s_V = \text{const}$, e.g. if Universe trapped in false vacuum.

Friedmann Eqn:
\[
\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G (s + s_V) - \frac{k a^2}{a^2} = \frac{4\pi}{3} \dot{s}_V
\]

\[z = \left(\frac{3}{8\pi G s_V}\right)^{1/2}\]

\[s_V = s_Q = \frac{1}{2} \dot{Q}^2 + V(Q, T)\]

\[
\text{Inflation solves 4 major cosmological problems:}
\]

1. Flatness:
\[
\frac{\Omega_{\text{planck}} - 1}{\Omega_{\text{obs}} - 1} = \frac{T_{\text{obs}}}{T_{\text{planck}}} \left(\frac{T_{\text{obs}}}{T_{\text{planck}}}ight)^2 \approx 10^{-52} \quad \Omega_{\text{planck}} - 1 < 100
\]

So, at $T_{\text{planck}}$ universe flat to 1 part in $10^{55}$!

2. Horizon:
\[
\Omega_{\text{H}} (2_{\text{as}}) = 3c^2 t_{\text{as}} \approx 10^8 \text{ } \text{m}_{\text{as}}
\]

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

but $\Delta T/T \approx 10^{-5}$!

3. Monopole: CMB produces $\approx 1$ magnetic monopole per horizon vol. at $t_{\text{CMB}} \Rightarrow \Omega_m = 10^{-6}$!

4. Structure: Generation of $\delta / \theta$?
Figure 3. Schematic space-time diagram showing how inflation circumvents the Horizon Problem (see text).
Old Inflation

(a) Overly Stable False Vacuum
(b) Inflation ends abruptly

Quantum Tunneling
Rapid Plunge

(c) Inside bubble energy rapidly dissipates

New Inflation

(d) "Just Right" False Vacuum
(e) Inflation continues

Slow Roll

(f) Field oscillates and gradually converts energy to other particles

False Vacuum
Decay
Reheating
CONVENTIONAL INFLATION:

CHAOTIC INFLATION:

STANDARD INFLATION PREDICTS:

1. FLAT GEOMETRY: \( \mathcal{R} + \frac{\Delta}{3H^2} = 1 \)

2. \( (\delta s/s)^2 \sim k^2 |\delta k|^2 \) \( \left\{ \begin{array}{ll} |\delta k|^2 \propto k^n & n = 1 \\ \text{Gaussian (random phases)} & \end{array} \right. \)
INFLATION FOR BEGINNERS

Scalar field $\Phi$:

$$ S_{\Phi} = \frac{1}{2} \dot{\Phi}^2 + V(\Phi; T) $$

$$ p_\Phi = \frac{1}{2} \dot{\Phi}^2 - V(\Phi; T) $$

$$ \Rightarrow \ddot{\Phi} + \frac{3a}{a} \dot{\Phi} + \frac{3V(\Phi; T)}{2a} = 0 $$

"Slow-roll" approx: $\ddot{\Phi} \ll V(\Phi; T); \dot{\Phi} \approx 0$

$$ \Rightarrow \ddot{\Phi} = -\frac{1}{3H} V' $$

Friedmann's eqn: \( \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G S_{\Phi} = \frac{8\pi}{3} G V(\Phi; T) \approx \text{const} $$

$$ \Rightarrow \quad a \propto e^{\frac{t}{H}} \quad \mathcal{H} \approx \left(\frac{3}{8\pi G V(\Phi; T)}\right)^{1/2} $$

Quantum fluctuations in $\Phi$:

$$ S_{\Phi} \sim \frac{H}{2\pi} \quad \text{(Hawking temp)} $$

At horizon crossing:

$$ S_H \approx \frac{\Delta t}{t_H} \approx H \Delta t = H \frac{S_{\Phi}}{\dot{\Phi}} = \frac{3H^3 V'}{2\pi} = \left(\frac{128\pi G^3}{3}\right)^{1/2} V^{3/2} V' \approx \text{const} $$

$$ \Rightarrow "\text{CONSTANT CURVATURE" FLUCTUATIONS} $$

At any given time: \( S = S_b [1 + \int S_b e^{i\Phi \cdot x} d^3k] \)

with $|S_b|^2 \propto h^\Lambda$. Then const. curvature $\Rightarrow \Lambda = 1$

$$ S(\text{curvat}) = S_{\Phi} \times \frac{G S_H}{\Lambda} \propto \frac{h^{n+3}}{\Lambda^2} \propto h^{n+3} \propto h^{\frac{n+3}{2}} $$

$$ S_{\Phi} / \Lambda \propto h^{n+3}$$
INFLATION AND COBE

STANDARD INFLATION PREDICTS:

ADIABATIC PERTURBATIONS WITH: \( \left( \frac{\delta T}{T} \right)^2 \sim k^3 |\delta_k|^2 \)

\[ |\delta_k|^2 \propto k^n \quad n=1 \]

AND GAUSSIAN DISTR. OF AMPLITUDES

![Graph showing COBE 4-yr data with a line indicating the prediction of inflation.](image-url)
Cosmology and Particle Physics

**Fluctuation Generator**
- *inflation*

**Cosmological Model**
\[ \frac{\Delta \rho}{\rho_0} + \Omega = 1 \]

**Primordial Fluctuations**
- Gaussian \(|\delta|^2 \sim k\)

**Nature of Dark Matter**
- \(\nu\) (hot), SUSY, Axion (cold)

**Damping**

**Linear Evolution of Fluctuations**
\[ \delta_k(t) = T(k,t)\delta_k \]

**Numerical Simulations**

**Observational Data**

**Non-linear Distribution of Galaxies**

**Test of Theory**
BIG BANG NUCLEOSYNTHESIS

allowed by observations

Abundance Relative to Hydrogen

$^{4}\text{He}$
$^{3}\text{He}$
$^{7}\text{Li}$

Density of Ordinary Matter (Baryons) (g/cc)

$\Omega_{b} \equiv \frac{\Phi_{baryon}}{\Phi_{total}}$

$h = \frac{H_0}{100 \text{ km s}^{-1} \text{Mpc}^{-1}}$

$^{2}\text{He} + ^{3}\text{He}, ^{6}\text{Li}, ^{7}\text{He} \rightarrow \Omega_{b} h^2 = 0.015 \pm 0.003$ COPI ET AL'95

'PRIMORDIAL' DEUTERIUM

$\Omega_{b} h^2 = 0.007 \pm 0.002$ RUGERS & HOGAN '96

$\Omega_{b} h^2 = 0.023 \pm 0.003$ TYTLER ET AL'96

$0.005 < \Omega_{b} h^2 < 0.026$ (~90% confidence)
PRIMORDIAL DEUTERIUM ??

Songaila et al 1993 Nature

ABSORBING "PRIMORDIAL CLOUD" AT z = 3.32.

11 Nov 1993, Keck + HIRES, Songaila et al., Nature

$\gamma = 0.014 \pm 0.013$ (v = 16.9), 4.0 hr, \( \lambda \lambda = 3500-5500 \AA \), \( R = 30,000 \), 14 A INTERNAL SHOWN

$\tilde{z}_{\text{em}} = 3.38$, $\tilde{z}_{\text{abs}} = \frac{1.813}{3.5200} \text{ "Cloud Cloud"}$

"Primordial Cloud"

\[
\frac{C_{\text{S}}}{H} < \frac{1}{10} \% ,
\]

likely \( < 10^{-15} \% \)

\[ \Delta V_{\text{D/H}} = \frac{c \Delta m}{2 m_p} = 82 \text{ km/sec} \]

"PRIMORDIAL" DEUTERIUM \( \rightarrow \) \( \bar{\Sigma}_b h^2 = 0.006 \pm 0.001 \) HOGAN et al

c.f. \( \bar{\Sigma}_b h^2 = 0.003 \) VISIBLE

\( ^2\text{He} + ^3\text{He}, \ ^3\text{Li}, \ ^4\text{He} \) \( \rightarrow \) \( \bar{\Sigma}_b h^2 = 0.024 \pm 0.006 \) TYTLER et al

\( \bar{\Sigma}_b h^2 = 0.015 \pm 0.003 \) COPI ETAL '95
Is $\Omega = 1$?

"This is the part I always hate."

© 1980 Sidney Harris
American Scientist Magazine

"This is the part I always hate"
THE MEAN DENSITY OF THE UNIVERSE

GALAXY DYNAMICS, CLUSTER BARYON FRACTION, CLUSTER EVOLUTION

\[ \Omega_0 > 0.3 \]

BARYON FRACTION IN CLUSTERS \[ \Rightarrow \Omega = 0.45 \pm 0.10 \]

EVOLUTION OF CLUSTER ABUNDANCE \[ \Rightarrow \Omega = 0.55 \pm 0.15 \]

GALAXY PECULIAR VELOCITIES \[ \Rightarrow \Omega = (0.55 \pm 0.2)_{\sigma}^{14}\]
Clues to the Identity of the Dark Matter

\( \Omega_B > \Omega_{\text{lum}} \implies \geq 50\% \text{ of baryons are dark} \)

\( \Omega_c > \Omega_B \implies \text{most dark matter is non-baryonic} \)

\( H_0 / 100 \text{ km s}^{-1} \text{ Mpc}^{-1} \)

\( \Omega_{\text{Baryons}} \)

\( \Omega_{\text{Luminous}} \)

\( \Omega_{\text{Total}} \)

(Dynamics, cluster baryon fraction, ...)

Baryons (BBN, hot gas)

Luminous (stars, hot gas)

Turner '97
### Non-baryonic dark matter candidates

<table>
<thead>
<tr>
<th>Candidate</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axions</td>
<td>$10^{-5}\text{ ev}$</td>
</tr>
<tr>
<td>Neutrinos</td>
<td>30 ev</td>
</tr>
<tr>
<td>Neutralinos (SUSSY)</td>
<td>$&gt;20\text{ Gev}$</td>
</tr>
<tr>
<td>Primordial black holes</td>
<td>$&gt;10^{15}\text{ g}$</td>
</tr>
</tbody>
</table>
Baryonic dark matter candidates

<table>
<thead>
<tr>
<th>Candidate</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>snowballs</td>
<td>$1 - 10^3 \text{ g}$</td>
</tr>
<tr>
<td>Jupiters (brown dwarfs)</td>
<td>$&lt; 0.1M_\odot$</td>
</tr>
<tr>
<td>black hole remnants</td>
<td>$10 - 10^5M_\odot$</td>
</tr>
</tbody>
</table>
Astronomical Evidence for Dark Matter

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Evidence for dark matter in:

- Galaxies
- Cluster of galaxies
- Large scales

Key issues:

- **Amount** of dark matter

Quantified by mean cosmic density:

\[
\Omega_0 = \frac{\bar{\rho}}{\rho_{\text{crit}}} \quad \rho_{\text{crit}} = \frac{3 H_0^2}{8\pi G}
\]

where $H_0$ (Hubble's constant) measures the universal expansion rate.

- **Identity** of the dark matter.

  - clues to identity
    - Big Bang Nucleosynthesis
    - distribution in galaxy and cluster halos
Dark matter in galaxies

- Disk dynamics
- Rotation curves (spiral galaxies)
- Dynamics of satellites
- Direct detection (MACHOS)
- X-ray emitting gaseous coronae (elliptical galaxies)
- Gravitational lensing

Dark matter in clusters

- Virial analyses
- X-ray emitting intracluster plasma
- Gravitational lensing
- Baryon catastrophe

Dark matter on large scales

- Peculiar velocity fields
- Gravitational lensing
Dark matter dominates gravitational potential beyond optical radius
DARK MATTER HALOS AROUND SPIRAL GALAXIES

Figure 10. Properties of the spiral galaxy, NGC 3198.

\[ M_{\text{dark}} \geq M_{\text{vis}} \]

\( \text{optical H} \text{I} \)
15 Satellites around 69 primaries similar to MW

$log r_p < 500 \text{kpc}, \Delta V < 1000 \text{ km/s}, \Delta m > 2.2$

$(r) = 2 \times 1.48 \times \left[ \frac{(\Delta V)_{\text{mod}}}{c} \right]^2 / \sigma = (8 \pm 1) \times 10^{-8}$ No at $r_p = 250 \text{kpc}$

fall models $\Rightarrow \Sigma > 0.15$ ($90\%$ cont.)

[cf. BBNS: $\Sigma < 0.10$ for $h > 0.5$]
BEWARE OF THE **MAC HOS**

Non-baryonic dark matter
MICROLENSING

Characteristic length scale: \[ r_E = \sqrt{\frac{4GM_D (1-x)}{c^2}} \]

- \( m \) = lens mass, \( D \) = source distance
- \( x = D_{0\odot}/D \)

For star in LMC & MACHO in halo: \( D = 50 \text{kpc}, D_{0\odot} = 10 \text{kpc} \)

\[ r_E = 10^9 \text{ km} \sqrt{\frac{m}{M_\odot}} \]

Define \( u = \frac{D}{r_E} \Rightarrow \) Amplification \( A = \frac{u^2 + 2}{u^2} \sim \frac{1}{u} \) (tucc)

Since MACHO is moving ampl. lasts: \[ \tau = \frac{2r_E}{u_A} \sim 10^3 \sqrt{\frac{m}{M_\odot}} \text{ days} \]

Optical depth: \[ \tau = \frac{4\pi G}{c^2} \int_0^D \left( \frac{\rho(l)}{D} \right) dl \approx 5 \times 10^{-2} \text{ for LMC} \]

Events for various \( u_{\min} \); mass density of lenses

- 4x amplification is achromatic
- 2x
The footprint of dark matter?
Fig. 3.—The lightcurves for the 12 candidates (10 stars) in § 3.2. For each object, the upper and lower panels show blue and red passbands. Flux is in linear units with 1σ estimated errors, normalized to the fitted unlensed brightness. For clarity, the points shown are averages in time bins roughly matched to the event timescales, as indicated on each panel. For events 1a, 6 and 8, the wavy lines indicate that different templates were used before and after day 330; thus a separate baseline normalization has been used for each portion; see § 2.
MACHO PROJECT

\[ \tau = \frac{2 \pi r_E}{M \nu} \]

\[ r_E = \int_0^{4 \pi} d\theta \left[ \frac{1}{c^2} \right] \frac{1}{0 \times (1-x)} \]

\[ z = \frac{4 \pi c^2}{c^2} \int_0^{\infty} \frac{s(\nu) L(0-L) dL}{D_0} \]

\[ \tau \text{ is duration} \]

\[ m \text{ is lens mass} \]

\[ 0 \text{ is optical depth} \]

\[ m \text{ is number} \]

Measured: \( 34 \leq \tau/\text{days} \leq 145 \)

\[ z = 2.9^{+1.4}_{-0.9} \times 10^3 \]

Halo model \( \Rightarrow \)

\[ m, \nu, (\nu), n(\nu) \]

![Graph of Halo Fraction](image)

SOUTHERLAND '97

MACHO MASS IN MACHOS:

\[ M(\lesssim 50 \text{kpc}) = 2.0^{+1.2}_{-0.9} \times 10^{11} \text{ M}_\odot \]

\[ M = 0.5_{-0.2}^{+0.3} \text{ M}_\odot \]

\[ \frac{M}{\text{halo}} \]

ACK OF \( t < 20 \text{ days} \) EVENTS:

\[ 10^{-6} < \frac{m}{M_\odot} < 0.02 \text{ contribute less than 20\% of halo} \]

MACHO PROJECT & EROS GIVE CONSISTENT RESULTS.
Weighing the dark matter in galaxy clusters

1. Virial Theorem

For a cluster in equilibrium:

\[ M_v = \frac{3}{G} \sigma_{i.o.s.}^2 r_v \]

\[ \sigma_{i.o.s.}^2 = (\sum_i w_i)^{-1} \sum_i w_i (\Delta v_i)^2; \quad r_v = \frac{\pi}{2} R_H; \quad R_H^{-1} = (\sum_i w_i)^2 \sum_{i \neq j} \frac{w_i w_j}{|r_i - r_j|} \]

virial radius

2. X-ray emitting gas

For spherically symmetric plasma in hydrostatic equilibrium (i.e. supported only by thermal pressure):

\[ M(r) = -\frac{K T(r)}{G \mu m_p} r \left[ \frac{d \log \rho(r)}{d \log r} + \frac{d \log T'(r)}{d \log r} \right] \]

\( \rho(r) \) inferred from \( S_X(\theta) \) and \( T(r) \).

3. Gravitational lensing

Distortion of background galaxy images determined by projected mass distribution.

\[ \alpha(\theta) = \nabla \Phi_{2D}; \quad \nabla^2 \Phi_{2D} = \frac{2S}{S_{crit}}; \quad S_{crit} = \frac{c^2}{4\pi G D_{os} D_{ol} D_{ls}} \]

\[ \frac{S - \tilde{S}}{S_{crit}}(\theta) = -\frac{1}{n} \sum_g W(\theta_g - \tilde{\theta}) \chi_i(\theta_g - \bar{\theta}) e_i(\theta_g) \]

weighting fn.

ellipticity of image

distortion

of point mass

mass surface density

2D potential

deflection angle
PROJECTIONS EECTS IN GALAXY CLUSTERS

CON N-BODY SIMULATIONS

VAN HAARLEN, FRANK & WHITE

TRUE

ES. DISPERSION

MEASURED VELOCITY DISPERSION
GAS TEMPERATURE PROFILES IN GAL. CLUSTERS

Need spatially resolved X-ray spectroscopy
ROSAT → groups & poor clusters (T ≤ 2.5 keV)
ASCA → rich clusters

Lowenstein & Mushotzky 1997

Cooling flow clusters Allen et al 1997
MASS ESTIMATES OF X-RAY CLUSTERS

eurard, Netzer & Navarro 97

\[ M(r) = \frac{\frac{r T(r)}{G \rho(r)}}{G \mu} \left( \frac{d \log S(r)}{d \log r} + \frac{d \log T(r)}{d \log r} \right) \]

N-BODY / HYDRODYNAMICS SIMULATIONS IN CDM

"\( \beta \)-Model"

\[ S_{\text{gas}} = S_0 \left( 1 + \left( \frac{r}{r_c} \right)^2 \right)^{-3D} \]

mean = 1.02
s.d. = 0.28
\[ \frac{\hat{M}}{M_{\text{true}}} = 1.02 \pm 0.29 \]

ESTIMATED MASS / TRUE MASS

'Scaling-law' method

\[ I_8 = \text{const} \, T_x^{3/2} \]

mean = 1.00
s.d. = 0.15
\[ \frac{\hat{M}}{M_{\text{true}}} = 1.00 \pm 0.15 \]
GRAVITATIONAL LENSING $\rightarrow$ RECONSTRUCT DARK MATTER DISTRIBUTION

SIMULATED CLUSTER

ACTUAL MASS DISTRIBUTION

RECONSTRUCTED MASS DISTRIBUTION
Gravitational Lensing by Clusters

Map Dark Matter Distribution in Cluster

Reconstructed Dark Matter Map

Observed Light Distribution
Fig. 8.—Mass map derived using Eqn. 8 with smoothing scale $s = 43''$. A total of 2735 galaxies with $23.0 \leq B_J \leq 25.0$ are used in this reconstruction. The contours are spaced in 1σ intervals. The peak of the mass distribution is consistent with the position of the central dominant galaxy. North is up and East is to the left. The field is 14' on a side.
A2390

Mass from X-rays

Mass from lensing

BOHRINGER ET AL. 1997
Cluster Mass Estimates

David Jones & Forman 1995

Mass (Virial Theorem) vs. Mass (Optical)

Mass (X-Ray) vs. Mass (X-Ray)

Mass (Weak Lensing) vs. Mass (X-Ray) / Const

Small 1997
M/L FOR CLUSTERS & THE VALUE OF $\Omega$

$M_{\text{cluster}}$ MEASURED FROM GAL. DYNAMICS (UIRAL THEO.)
AND/OR X-RAY GAS DATA (HYDR. EQ.)
AND/OR GRAVITATIONAL LENSING

$L_{\text{cluster}}$ MEASURED FROM PHOTOMETRY (AND ASSUME L/F)

\[
\left( \frac{M}{L} \right)_{\text{cluster}} = B^{-1} \left( \frac{M}{L} \right)_{\text{universe}} = B^{-1} \left( \frac{\rho}{\rho} \right)_{\text{universe}} = B^{-1} \left( \frac{3.0 \text{H}_2/80 \text{eV}}{1.2 \times 10^5 \text{H}_20} \right)
\]

$\rightarrow \frac{\Omega}{B}$ (INDEPENDENT OF $H=100 h \text{ km s}^{-1} \text{Mpc}^{-1}$)

$B = 1$ IF GALS IN CLUSTERS ARE FAIR TRACERS OF MASS

$B > 1$ IF GALS MORE STRONGLY CLUSTERED THAN MASS.

(And inferred
$\Omega$ larger)
M/L for Clusters and the Value of $\Omega$

$\mathbf{M/L\ from\ virial\ thm}$
(Carlberg et al. 1997)

$\mathbf{M/L\ from\ X-ray\ data}$
(David et al. 1995)

**CNOC Cluster Survey:**
16 clusters $0.12 < z < 0.55$
2600 Vels

**In R-Band**

Mean of 16 clusters:
$\langle \frac{M}{L} \rangle_{Cl} = 214 \pm 56 \, h \left( \frac{M}{L} \right)_0$

Field Survey:
$\langle \frac{M}{L} \rangle_{Universe} = 1136 \pm 138 \, 50h \left( \frac{M}{L} \right)_0$

$\Rightarrow \quad \Omega = (0.19 \pm 0.06) \times \frac{B_{Cl}}{B}$

$B_{Cl} = 1$ if gals trace mass

$\ldots$ if gals more clustered than mass

[Carlberg et al. 1997]