Our implausible Universe
• The standard model of cosmic structure

- \( \Lambda \text{CDM} \)

- Material content:
  - Cold dark matter (e.g., neutralino; 21%), baryons (4%), dark energy (\( \Lambda \); 75%)

- Initial conditions for formation of structure:
  - Quantum fluctuations during inflation:
    \( |\delta_k|^2 \propto k^n, n \approx 1 \); Gaussian amplitudes

- Growth processes:
  - Gravitational instability

- Parameters:
  \[
  \begin{align*}
  \Omega_{CDM} &= 0.21, \quad \Omega_b = 0.04, \quad \Omega_\Lambda = 0.75, \\
  h &= 0.70, \quad \sigma_8 = 0.8, \ldots
  \end{align*}
  \]
The galaxy distribution evolves from fluctuations seen in CMB by gravitational amplification.

- The galaxy distribution evolves from fluctuations seen in CMB by gravitational amplification.

- Initial conditions:
  - Cold dark matter
  - \( \delta \rho / \rho \sim 10^{-5} \) at \( z=1000 \)
  - \( \delta \rho / \rho \sim 10^6 \) at \( z=0 \)

- Testing the CDM paradigm
$z = 0$  Dark Matter

Springel et al. 05
The halo mass function and the galaxy luminosity function have different shapes. Complicated variation of M/L with halo mass.

Benson, Bower, Frenk, Lacey, Baugh & Cole '03
• **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
  - Star formation and feedback
  - Production & mixing of metals
  - Evolution of stellar populations
  - Dust extinction & emission
  - Black hole formation, AGN feedback
  - Galaxy mergers

**Semi-analytical model**
- Parametrize physics
- Set of coupled differential equations
- Predict galaxy properties (lum, mass, B/T, radius, metallicity etc) and evolution with redshift
z = 0  Dark Matter

- Populating the MS with galaxies

125 Mpc/h

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

- Springel et al. 05
$z = 0$  Galaxy light

Croton et al 06
Dark matter

Galaxies

$10^{14} M_\odot$
• The halo mass function and the galaxy luminosity function have different shapes

• Complicated variation of M/L with halo mass

• Benson, Bower, Frenk, Lacey, Baugh & Cole '03

• Dark halos (const M/L)

• Galaxies
• Deconstructing the galaxy

• Faint end:
  • Photoionization + reheating of cold disk gas by SN

• Bright end:
  • AGN feedback: energy transported by bubbles

• Bower et al 06
The physics of galaxy formation

Galaxy formation is most efficient in $\sim10^{12} M_\odot$ halos


Halo mass-to-light ratios

Halo mass

Log $M/h^{-1} M_\odot$

Long $\tau_{\text{cool}}$ & AGN feedback

Mean

Photoionization & SN feedback

$\Omega_m = 0.30$
$z = 0$  Galaxy light

Croton et al 06
• 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
• Testing the $\Lambda$CDM paradigm with galaxy surveys

• Three tests:

• Origin of fluctuations, nature of DM, cosm.parms (Power spectrum of galaxy distribution)

• Gravitational instability (z-space distortions)

• Hierarchical galaxy formation (non-linear clustering)
• A Cold dark matter universe

• CDM has been ruled out many times in the past:

  • 1984 Large cluster-cluster correlation function (Bahcall)
  • 1986 Great Wall (Geller & Huchra)
  • 1986 High –z qsos (various)
  • 1989 Large-scale streaming motions (7-Samurai)
  • 1990 Extra large-scale power (APM, QDOT)
    • Some of these data were not robust;
  • 1993 LSSM again (Lauer & Postman)
  • Other (APM, QDOT) ruled out $\Omega_m = 1$ standard CDM and replaced it with $\Lambda$CDM
• real

• simulated

• Springel, Frenk & White Nature, April '06
• Real and simulated 2dF galaxy survey

Institute for Computational Cosmology
• The 2dF galaxy power spectrum

• Galaxy power spectrum in redshift space, convolved with survey window, including non-linear effects
• Real and simulated 2dF galaxy survey

Real ↔ Simulated
The 2dF galaxy power spectrum

- From N-body simulation
- Galaxy power spectrum in redshift space, convolved with 2dF window
- $\Lambda$CDM ($\Omega = 0.3$, $\Lambda = 0.7$, $h=0.7$)
- Simulated 2dF
• The 2dF galaxy power spectrum

• Galaxy power spectrum in redshift space, convolved with 2dF window
The final 2dFGRS power spectrum

- 2dFGRS $P(k)$ well fit by $\Lambda$CDM model convolved with window function

- Cole, Percival, Peacock, Baugh, Frenk \& 2dFGRS '05
• The final 2dFGRS power spectrum

• Overall shape and amplitude of 2dFGRS $P(k)$ extremely well fit by $\Lambda$CDM model convolved with window function

• Cole + 2dFGRS ‘05
• The final 2dFGRS power spectrum

• 2dFGRS $P(k)$ well fit by $\Lambda$CDM model convolved with window function

• $\Omega_m h = 0.168$
• $\Omega_b/\Omega_m = 0.17$
• $\sigma_8 = 1.125$

• Cole, Percival, Peacock, Baugh, Frenk + 2dFGRS ‘05
CMB anisotropies and large-scale structure

\[ \Omega_0 = 0.4, \ h = 0.65, \ \Omega_b h^2 = 0.02 \]

CMB

\( \Delta^2_q(k) \) vs. \( k (h/\text{Mpc}) \)
CMB anisotropies and large-scale structure

\( \Omega_0 = 0.4, \ h = 0.65, \ \Omega_b h^2 = 0.02 \)

- CMB
- LSS

CMB and LSS out of phase:
‘velocity overshoot’
LSS amplitude smaller than CMB

- 2dFgrs
- Meiksin et al. 99

Institute for Computational Cosmology
$z = 0$ Galaxy light
Baryon wiggles in the galaxy distribution

Power spectrum from MS divided by a baryon-free ΛCDM spectrum

Galaxy samples matched to plausible large observational surveys at given $z$

Springel et al 2004
• The final 2dFGRS power spectrum

• Baryon oscillations conclusively detected in 2dFGRS!!!

• Suggests that structure grew by gravitational instability in $\Lambda$CDM universe

• Also detected in SDSS LRG sample (Eisenstein et al. 05)

$P(k) / P_{\text{ref}}(\Omega_{\text{baryon}}=0)$

$\Lambda$CDM model

$\Lambda$CDM convolved with window

Cole, Percival, Peacock, Baugh, Frenk + 2dFGRS ‘05
Again, CDM models fit the correlation function adequately well (although peak height is slightly too large; assuming $n_s=1$, $h=0.72$)

- $\Omega_b h^2 = 0.024$,
- $\Omega_m h^2 = 0.133 \pm 0.011$,

$\Rightarrow \frac{\Omega_b}{\Omega_m} = 0.18$

- Eisenstein et al. 05
• Dimensionless power:
  \[ \Delta^2 \text{ (fractional variance in density) per } \ln k \]

\[ \delta(r) \equiv \frac{\delta \rho}{\rho} = \sum_k \delta_k e^{-i k \cdot r} \]

\[ \Delta^2(k) \equiv \frac{d \sigma^2}{d \ln k} \propto k^3 |\delta_k|^2 \]

• Percival et al. MNRAS 327, 1279 (2001)
• The final 2dFGRS power spectrum: parameter estimation

• Shape of $P(K)$ depends on $\Omega h$

• Oscillations depend on $\Omega_b / \Omega_m$

• Amplitude depends on $\sigma_8^{gal}$

• $\Omega h = 0.161 \pm 0.015$

• $\Omega_b / \Omega_m = 0.194 \pm 0.045$

• $\sigma_8^{gal} (L_*) = 0.870 \pm 0.029$

• Cole + 2dFGRS ‘05
Free-stream length: \(80(\Sigma m_\nu / \text{eV})^{-1}\) Mpc

\((\Omega_m h^2 = \Sigma m_\nu / 93.5 \text{ eV})\)

\(\Sigma m_\nu \sim 1 \text{ eV} \) causes lower power at almost all scales, or a bump at the largest scales

\(\Sigma m_\nu < 1.2 \text{ eV}\)

Sanchez et al ‘06
Cosmological parameters: CMB + 2dF

- The 2dF power spectrum depends on
  - $\Omega_m h$, $\Omega_b/\Omega_m$, $\sigma_8^{\text{gal}}$, $f_\nu$, ...

- The CMB power spectrum depends on
  \[ (\Omega_k, \Omega_\Lambda, \omega_b, \omega_{\text{dm}}, f_\nu, w_{DE}, \tau, n_s, n_t, A_s, r, b) \]

- Combining 2dF and CMB breaks parameter degeneracies
Parameter constraints

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

- CMB only…
- CMB + 2dF…

Sanchez et al ’06
## Results: comparison with WMAP3

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<td>parameter</td>
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Testing the $\Lambda$CDM paradigm with galaxy surveys

Three tests:

- Origin of fluctuations, nature of DM, cosm.parms (Power spectrum of galaxy distribution)
- Gravitational instability (z-space distortions)
- Hierarchical galaxy formation (non-linear clustering)
Testing the $\Lambda$CDM paradigm with galaxy surveys

Three tests:

- Origin of fluctuations, nature of DM, cosm.parms
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  (z-space distortions)

- Hierarchical galaxy formation
  (non-linear clustering)
Evolution of spherical perturbations

\[ \text{Scale factor, } a \]

\[ \text{Time} \]

- **UNPERTURBED E. de S. q(t)**
- **MAX EXPANSION**
- **INFALL**
- **R_{NL}**
- **NON-LINEAR**
- **VIRALISED**

\[ R_{NL} \] separates unmixed, unshocked (primordial) material from mixed, shocked, non-linear material in E-dS. \[ R_{NL} \] corresponds to \( t/\ell \sim 100 \).
Large Scale Flattening Due To Coherent Cluster Infall

\[ V_{\text{obs}} = v_{\text{hubb}} + \delta v \]

\[ \delta v \propto \Omega^{0.6} \frac{\delta \rho/\rho}{b^{-1}} \frac{\delta n/n}{\Omega^{0.6}} \]

“bias” parameter

Kaiser 1987
The signature of hierarchical clustering

- Correlation function
  - $\xi(\sigma, \pi)$

- Parallel to l.o.s

- Perpendicular to l.o.s

APM ($\beta=0.5$) $\xi(\sigma, \pi) = 10, 5, 2, 1, 0.5, 0.2, 0.1, 0, -0.1$

- Fingers of God

- Infall

- Perpendicular to l.o.s
2003: The 2dF Galaxy Redshift Survey

221,000 redshifts
Large Scale Flattening Due To Coherent Cluster Infall measured via Redshift Space Galaxy Clustering

\[ \beta = \Omega^{0.6} / b \]
\[ = 0.43 \pm 0.07 \]


- Demonstration of gravitational instability
• Demonstration of gravitational instability

\[ \beta = \Omega^{0.6}/b \]

\[ = 0.49 \pm 0.09 \]

• \( b \) is "biasing" parameter

• \( b=1.0 \rightarrow \Omega=0.3 \)

Hawkins + 2dFGRS astro-ph/0212375
The case for dark matter

Baryon acoustic oscillations

+ Large–scale infall

Consistent with growth of structure by gravitational instability in CDM universe
• Testing the ΛCDM paradigm with galaxy surveys

• Three tests:
  • Origin of fluctuations, nature of DM, cosm.parms (Power spectrum of galaxy distribution)
  • Gravitational instability (z-space distortions)
  • Hierarchical galaxy formation (non-linear clustering)
Galaxy formation is most efficient in $\sim 10^{12} M_\odot$ halos

• Theoretical prediction

• (semi-analytic)

• Halo mass-to-light ratios


• Can we test this?

• Efficiency of galaxy formation

• Long $\tau_{\text{cool}}$ & AGN feedback

• Mean

• Photoionization & SN feedback

• $\Omega_m = 0.30$

• Halo mass

$\log M/h^{-1} M_\odot$
• Groups in 2dFGRS

• 28,213 groups with $n_{gal} \geq 2$
  • (53% of gals)

• 6,773 groups with $n_{gal} \geq 4$
  • $n_{gal} \geq 4$:
    • Median $z$ 0.11
    • Median vel disp 266 km/s

• Eke, Frenk, Cole, Baugh + 2dFGRS 2003
• 2dFGRS groups and galaxy formation

• The mass-to-light ratio and the efficiency of galaxy formation
• $N_{\text{min}} = 2$, $z_{\text{max}} = 0.07$

• Factor of 4 decrease in M/L from rich clusters to poor groups

• Eke et al. '04

• Halo mass-to-light ratios

![Graph showing the relationship between group luminosity and group M/L ratio. The x-axis represents the logarithm of the ratio of luminosity to some base, and the y-axis represents the group M/L ratio. The graph includes data points and error bars, with a model line and a mean line at $\Omega_m = 0.30$. The graph also indicates a decrease in M/L factor of 4 from rich clusters to poor groups.]
• Halo mass-to-light ratios

• $N_{\text{min}} = 2, \ z_{\text{max}} = 0.07$

• Factor of 4 decrease in M/L from rich clusters to poor groups

• Minimum in M/L detected!

• Eke, Frenk, Baugh & Cole '06

• $\Omega_m = 0.30$

• $\Omega_{\Lambda} = 0.70$

• Set $n_{2\text{PIGG}}(>L) = n_{\Lambda\text{CDM}}(>M)$

• $2d$FGRS groups

• SN & photoi feedback

• $\Lambda$CDM model

• Long $\tau_{\text{cool}}$ & AGN feedback
• Large-scale structure for the new generation

The use of baryon acoustic oscillations to constrain dark energy
Baryon oscillations in the power spectrum

- Comoving sound horizon at $t_{\text{rec}}$
- $(\text{depends mostly on } \Omega_m h^2 \text{ and weakly on } \Omega_b h^2)$
- “wavenumber” of acoustic oscillations: $k_A = 2\pi/s$

Comoving distance/redshift:

$$\frac{dx}{d\tilde{z}} = \frac{c}{H_0 \Omega_m^{1/2}} \frac{1}{\sqrt{(1 + \tilde{z})^3 + (\Omega_m^{-1} - 1)(1 + \tilde{z})^3(1 + w)}}$$

- (depends on $\Omega_m h^2$ and $w$)
- Apparent size of standard ruler depends on cosmology

- $\Rightarrow$ dark energy eqn of state $w$

(e.g. Eisenstein & HU 1998; Blake & Glazebrook 2003, 2005; Seo & Eisenstein 2003; 2005......)
How well do we need to measure the BAO scale?

- Error in BAO scale translates to bigger error in dark energy $w$
- Size of shift depends on which other parameters are held fixed
- For fixed $w$ require distance scale to 0.2% to get 1% in $w$
- Demands accurate knowledge of systematics

• Angulo et al. 2008
• N-body simulations of large cosmological volumes

• BASICC

• $L = 1340/h$ Mpc

• $N = 3,036,027,392$

• 20 times the Millennium volume

Angulo, Baugh, Frenk & Lacey ‘07
• Non-linear evolution of matter fluctuations

- BASICC simulation
- dark matter real space

- $P(k)$ divided
- by linear theory $P(k)$,
- scaling out growth factor

• Angulo, Baugh, Frenk & Lacey '07
Non-linear evolution of matter fluctuations

$\log(P(k)/P_{\text{linear}}(k))$

at $z=1$

Angulo, Baugh, Frenk & Lacey ‘07
Redshift space distortions

- Peculiar motions distort
- Clustering pattern
- Coherent bulk flows
- Boost large scale power (Kaiser 1987)

Kaiser (1987) related the spherically averaged power spectrum measured in redshift ($P_s$) and that in real space ($P$):

$$P_s(k) = \left(1 + \frac{2}{5} \beta + \frac{1}{5} \beta^2\right) P(k).$$

where $\beta(\Omega_m) = \frac{d \log \delta}{d \log a} \simeq \Omega_m^{0.6}/b$ and $b$ is the bias factor.

Motions of particles inside
- Virialised structures
- Damp power at high $k$
• Redshift space distortions

• Peculiar motions distort
  • clustering pattern

• Boost in power on large scales due to coherent flows

• Damping at higher $k$
  • affects DM but not the halos
Galaxy bias in redshift space

- Galaxy P(k) cannot be reproduced by multiplying mass P(k) by constant factor in redshift space.
- In z-space, galaxies have a scale-dependent bias out to k~0.1
Comparison of different selections, e.g. colour, emission line strength.

- Angulo et al. '07

Galaxy bias in redshift space

\[ \frac{P_s(k,z)}{P_r} / b^2 \]

Real Space

- \( R-I < 0.321, b = 1.28 \)
- \( R-I > 0.321, b = 1.42 \)
- \( EW(OII) < 2.520, b = 1.39 \)
- \( EW(OII) > 2.520, b = 1.29 \)

Redshift Space

- \( n = 5.0e-04, b = 1.34 \)
- \( n = 2.5e-04, b = 1.34 \)
- \( 5.0e-04 \cdot R_I.I, b = 1.03 \)
- \( 5.0e-04.RI.gt, b = 1.33 \)
- \( 5.0e-04.ewol.lt, b = 1.32 \)
- \( 5.0e-04.ewoll.gt, b = 1.04 \)
• Projected BAO data for planned surveys at $z=1$

• Projections based on mock catalogues made from large N-body simulation plus semi-analytic galaxy formation model
Headline forecasts for $w$

<table>
<thead>
<tr>
<th>Survey</th>
<th>Error in $w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WiggleZ</td>
<td>9.5%</td>
</tr>
<tr>
<td>WFMOS</td>
<td>4.0%</td>
</tr>
<tr>
<td>Pan-STARRS</td>
<td></td>
</tr>
<tr>
<td>0.03 photo-z</td>
<td>1.6%</td>
</tr>
<tr>
<td>0.06 photo-z</td>
<td>2.2%</td>
</tr>
</tbody>
</table>

Angulo et al 07

Survey performance for constant $w$
The origin of cosmic structure

1. FLAT GEOMETRY:
\[ \Omega_b + \Omega_m + \Omega_k = 1 \]

2. QUANTUM FLUCTUATIONS:
   - adiabatic
   \[ |\delta_k|^2 \propto k^n \quad n = 1 \]
   Gaussian amplitudes

• Inflation
  (t~10^{-35} s)

• CMB (t~3x10^5 yrs)

• Structure
  (t~13x10^9 yrs)

• Dark matter
Conclusions: the $\Lambda$CDM model

$\Lambda$CDM is an intrinsically implausible model that requires:

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

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

- Existence of dark energy supported by WMAP+LSS

Basic cosmological params determined by WMAP+LSS+SN+…
Current limits $w<-0.9$ ($p= wpc^2$)
• The cosmic power spectrum: from the CMB to the 2dFGRS

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

• $\Lambda$CDM provides an excellent description of mass power spectrum from 10-1000 Mpc

• Sanchez et al 06
Open questions

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

• What is it?
  – Nothing is known! → theory
    • Is it:
      – constant in time ($\Lambda$) or varying (quintessence)?
      – Is it a reflection of non_Einsteinian gravity

• Fluctuation growth rate and geometry depend on $w(z)$
  – effects are small but perhaps measurable
Dark energy?

Help!