Modern cosmology 3: The Growth of Structure

- **Growth of structure in an expanding universe**
- **The Jeans length**
- **Dark matter**
- **Large scale structure simulations**
  - **effect of cosmological parameters**
- **Large scale structure data**
  - **galaxy surveys**
  - **cosmic microwave background**

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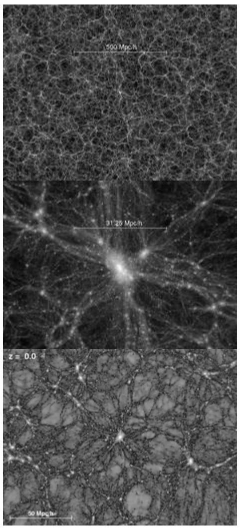
Large scale structure simulations

- **Simple theory only adequate for small changes in density**
- **Need big changes (e.g. $\rho_{univ.} \sim 10^{-27}$ kg m^{-3}, $\rho_{galaxy} \sim 10^{-20}$ kg m^{-3})**
- **Therefore use numerical simulations**
  - **input cosmological parameters**
  - **evolve using general relativity**
  - **may include only dark matter or dark matter + gas**



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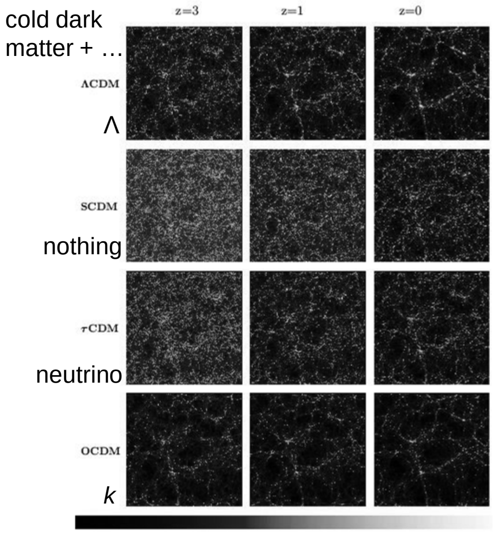
Simulations

- **Information from simulations**
  - **strength of clustering on different scales**
    - compare with galaxy surveys
  - **evolution of clustering**
    - compare with ages of structures such as galaxies and clusters



The VIRGO Collaboration 1996

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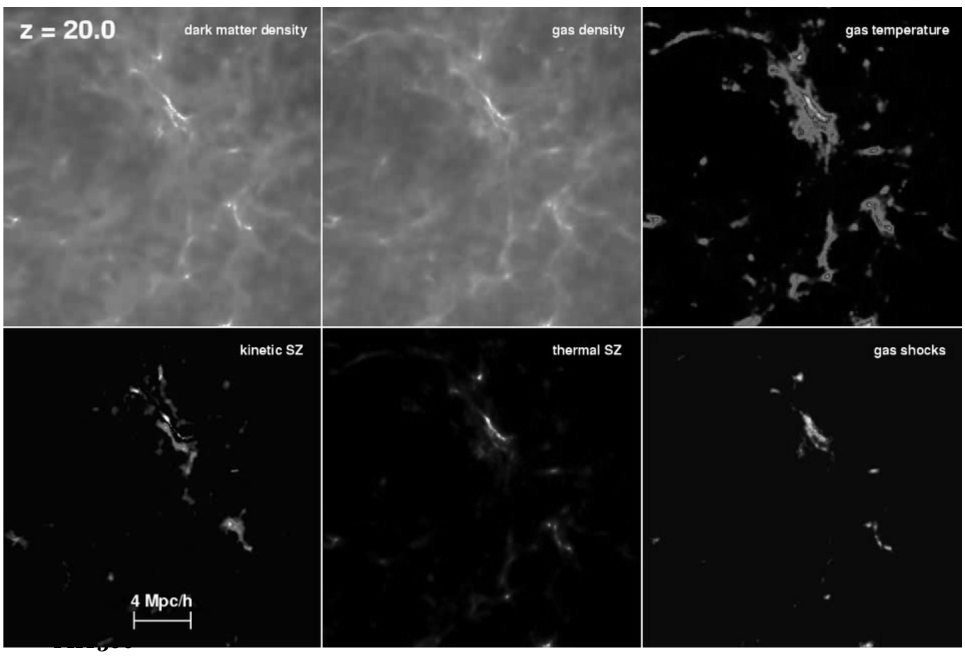
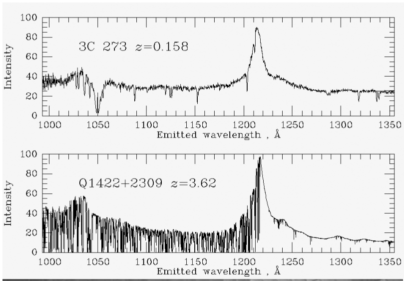
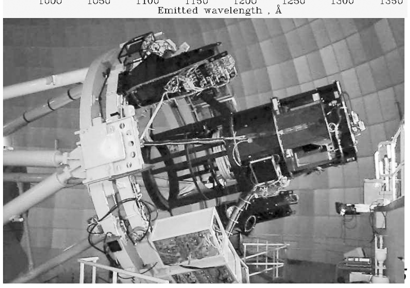


Large scale structure data

- **Galaxy surveys**
  - **pencil beam**
    - e.g. Lyman α lines in quasar spectrum
  - **slice of sky**
    - e.g. 2dF galaxy redshift survey
  - **whole sky (or large piece thereof)**
    - e.g. Sloan Digital Sky Survey





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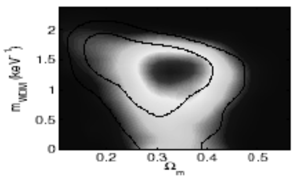
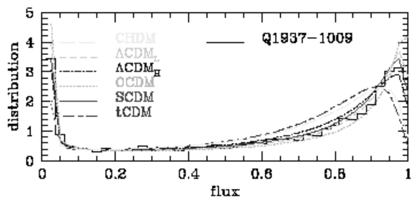
Lyman α forest

- **Study distribution of neutral hydrogen along particular lines of sight**
  - **potential information on clustering, metallicity, ionisation level, etc., at redshifts up to 6 or more**
  - **but systematic errors are difficult to control**



Matteo Viel, 2004



Meiksin, Bryan, Machacek, *MNRAS* **327** (2001) 296

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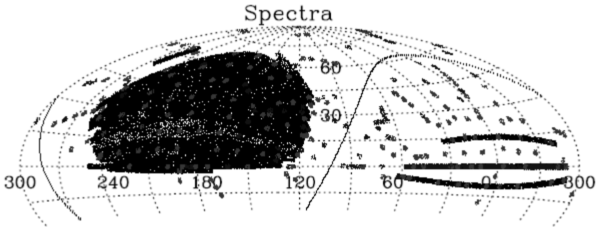
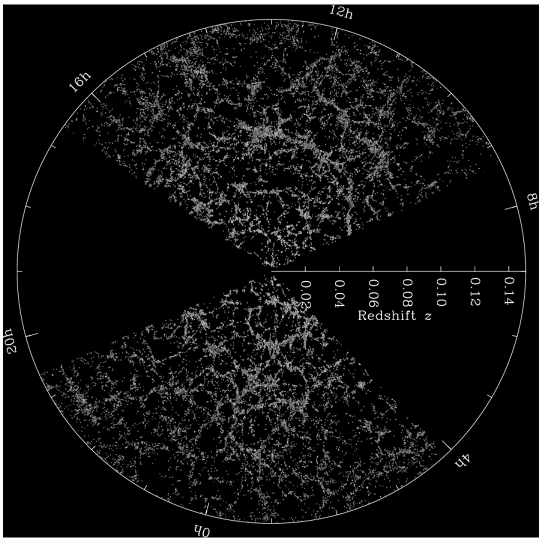
Sloan Digital Sky Survey

- Dedicated 2.5-m telescope equipped with 120 megapixel camera and two multi-object spectrographs
- Imaged 8400 square degrees of sky
  - spectra of 930000 galaxies, 120000 quasars, 225000 stars



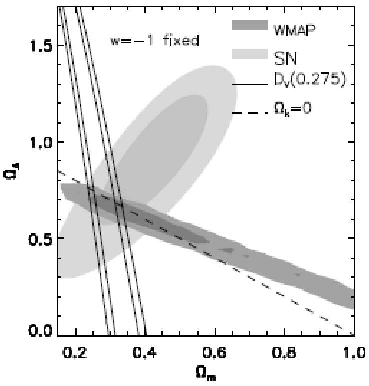
SDSS Galaxy Map

- Slice of SDSS survey around celestial equator
  - $-1.25° < \delta < +1.25°$
- Galaxies colour coded by stellar population
  - red = old

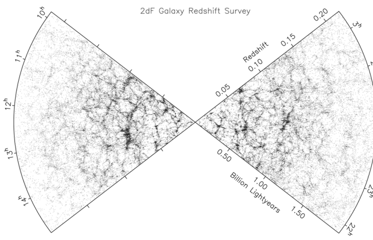


Results

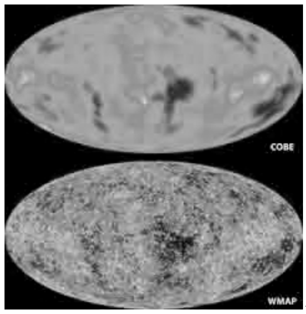
- **Sensitive to $\Omega_m H_0$, which is a different combination from nucleosynthesis**
- **Analysis is similar to CMB (see later), but expected shape differs**
- **Best results obtained by combining redshift surveys with WMAP**



Analysis of survey data



- **Survey data typically produce "maps"**
- **How do we analyse these?**
  - **they have finite resolution**
  - **they may not cover the whole sky**
  - **we probably don't care about the actual locations of 'hot' and 'cold' spots**
    - we want to look at strength of variation and characteristic size



The power spectrum

- **Consider CMB data, i.e. map of temperature fluctuations δT across sky**
  - **expand in spherical harmonics:** $\frac{\delta T}{T}(\theta,\phi)=\sum_{l=0}^{\infty}\sum_{m=-l}^{l}a_{lm}Y_{lm}(\theta,\phi)$
  - **consider correlation between pairs of points separated by angle θ:**

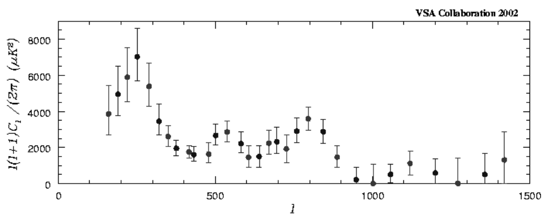
$$C(\theta)=\left\langle \frac{\delta T}{T}(\hat{\mathbf{n}})\frac{\delta T}{T}(\hat{\mathbf{n}}')\right\rangle_{\hat{\mathbf{n}}\cdot\hat{\mathbf{n}}'=\cos\theta}$$

  - **by applying the spherical harmonic expansion this can be expressed as a sum of Legendre polynomials:**

$$C(\theta)=\frac{1}{4\pi}\sum_{l=0}^{\infty}(2l+1)C_l P_l(\cos\theta)$$

The power spectrum

- **Parameter describing characteristics of map is the coefficient C_l**
  - **customary to plot** $\Delta_T \equiv \sqrt{\frac{l(l+1)}{2\pi}C_l}\langle T\rangle$ **vs** l
  - **this is the contribution per logarithmic interval in l to the total temperature fluctuation δT**
  - **the multipole number l gives the angular scale: θ ~ 180°/l**



The power spectrum

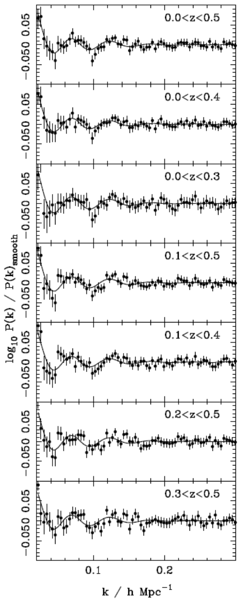
- **3D galaxy surveys are analysed in a similar way**
  - **expand as Fourier series**

    $$\delta(\mathbf{r}) = \frac{V}{(2\pi)^3}\int \delta_{\mathbf{k}} e^{-i\mathbf{k}\cdot\mathbf{r}}\, \mathrm{d}^3\mathbf{k}$$

    where each Fourier component $\delta_{\mathbf{k}}$ is a complex number
  - **construct power spectrum using mean square amplitude**

    $$P(k) = \left\langle \left|\delta_{\mathbf{k}}\right|^2 \right\rangle$$

Will Percival et al., *MNRAS* **401** (2010) 2148



Conclusion

- **Large scale structure is very sensitive to cosmological parameters**
  - **cold vs hot dark matter, Λ, etc.**
- **2D or 3D maps can be analysed by expanding as spherical harmonics or Fourier series**
- **Most significant contributors: galaxy surveys (especially SDSS) and CMB**