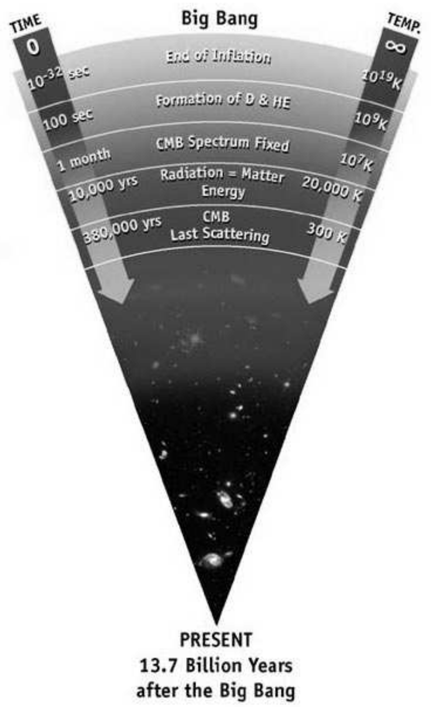
# WMAP CMB Conclusions

- *A flat universe with a scale-invariant spectrum of adiabatic Gaussian fluctuations, with re-ionization, is an acceptable fit to the WMAP data.*
- *The correlations of polarisation and the acoustic peaks imply the initial fluctuations were primarily adiabatic (the primordial ratios of dark matter/photons & baryons/photons do not vary spatially).*
- *The initial fluctuations are consistent with a Gaussian field, as expected from most inflationary models.*

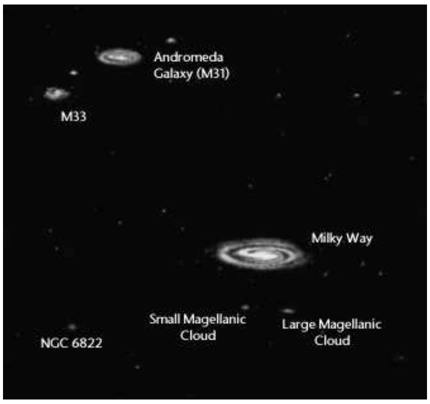
# WMAP's cosmic timeline

- *CMB last scattering surface:*
  $t_{dec}$ = 379 ± 8 *kyr* ($z_{dec}$ = 1089 ± 1)
- *Epoch of re-ionization:*
  $t_r$ = 100 - 400 *Myr (95% c.l.)*

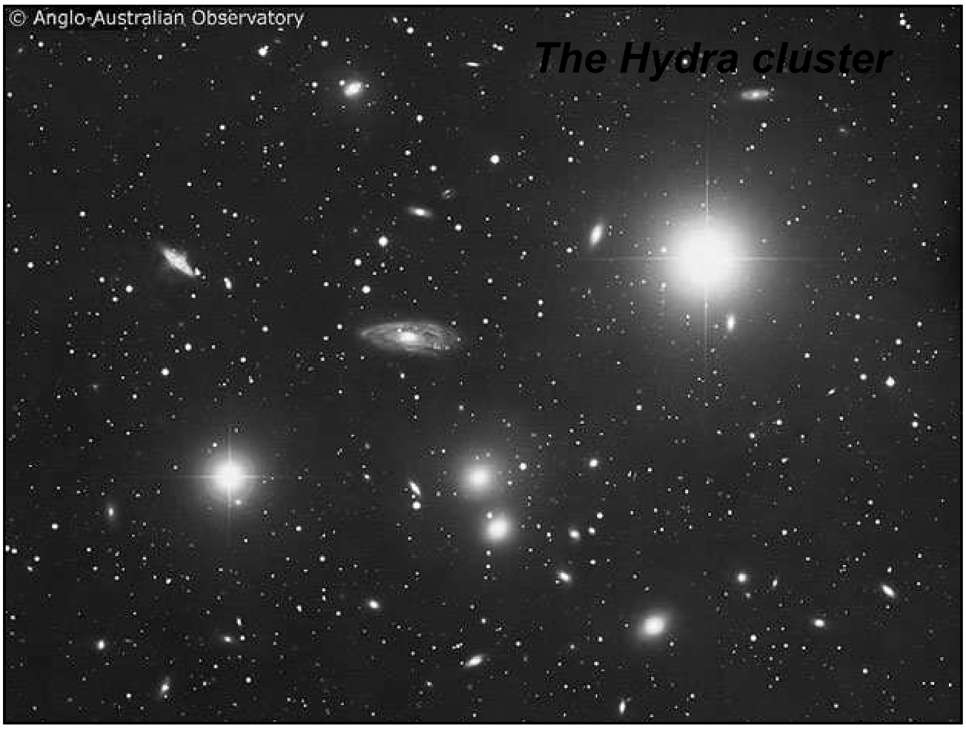


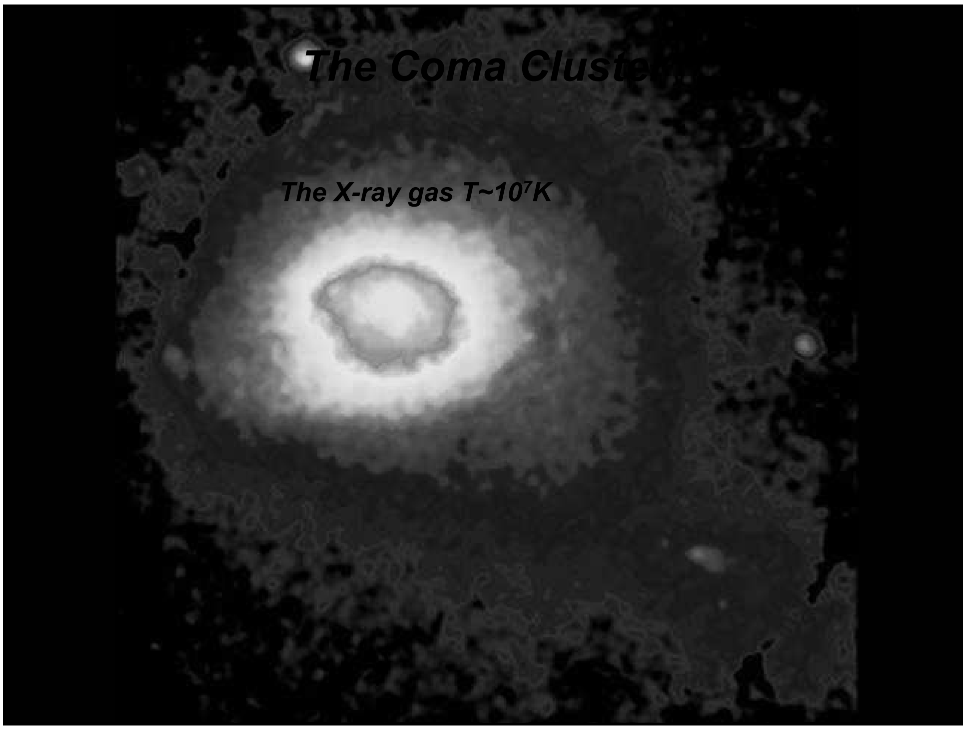
# Large Scale Structure

***With Thanks to Matthew Colless, leader of Australian side of 2dF redshift survey.***




***The Local Group***




The X-ray gas T~10$^7$K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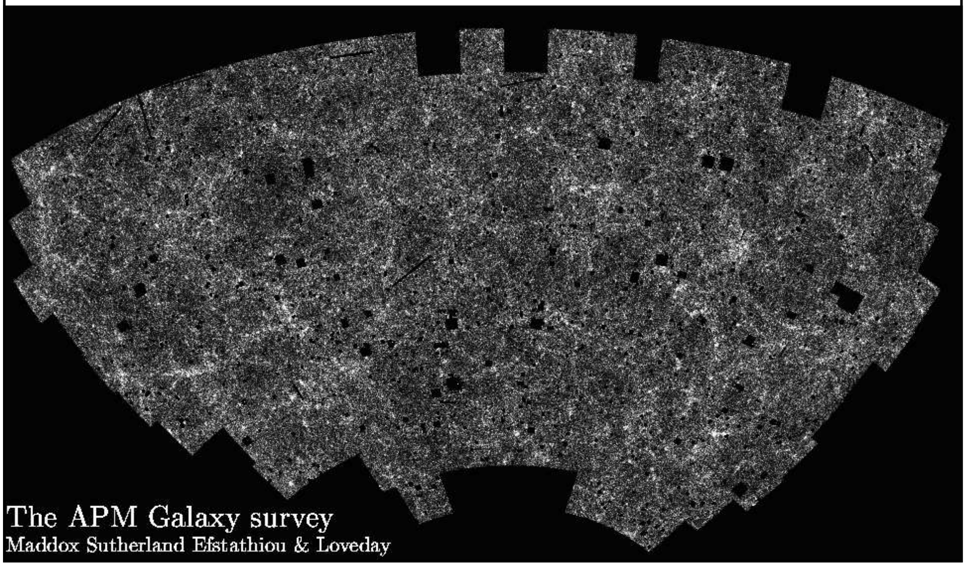
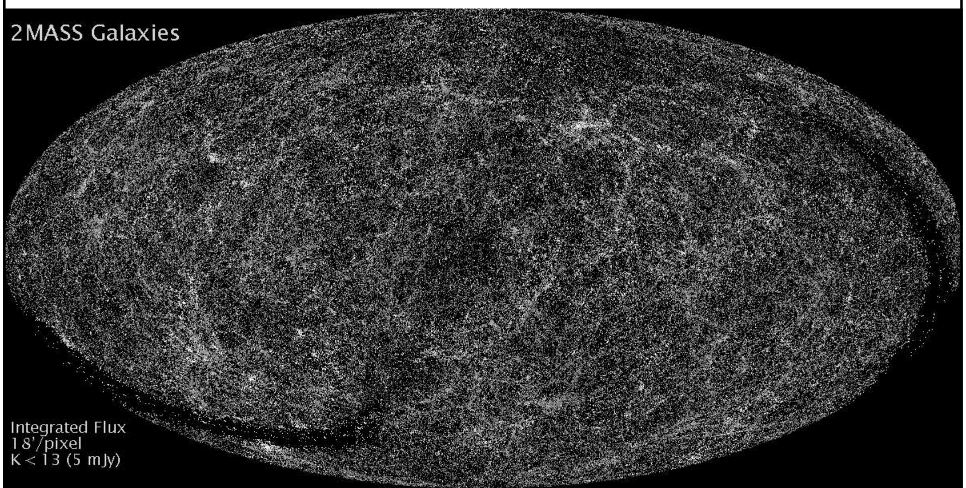
## *Large-scale structure in the local universe*

***Going deeper, $2x10^6$ optical galaxies over 4000 sq. deg.***

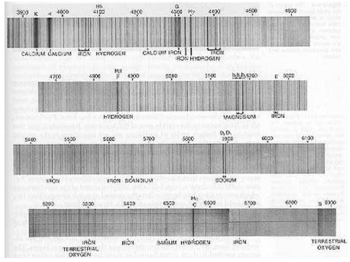



## *Large-scale structure in the local universe*

***The $10^6$ near-infrared brightest galaxies on the sky***



## *Redshift surveys*



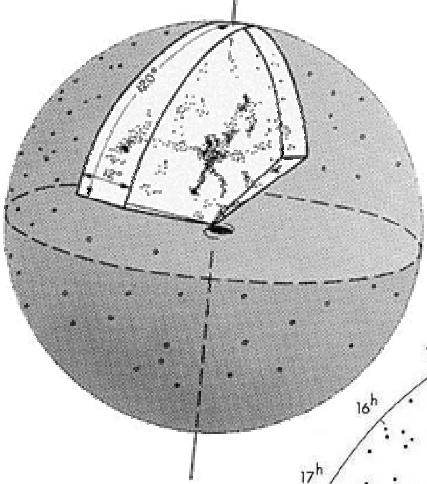
- ***A z-survey is a systematic mapping of a volume of space by measuring redshifts:*** $z = \lambda_1/\lambda_0 - 1 = a-1$
- ***Redshifts as distance coordinates…***
  $H_0D_L = c(z+(1-q_0)z^2/2+…)$
  ***…this is the viewpoint in low-z surveys of spatial structure.***
- ***For low-z surveys of structure, the Hubble law applies:***
  $cz = H_0d$ (for $z<<1$)
- ***For pure Hubble flow, redshift distance = true distance, i.e. s=r, where s and r are conveniently measured in km/s.***
- ***But galaxies also have 'peculiar motions' due to the gravitational attraction of the surrounding mass field, so the full relation between z-space and real-space coordinates is :***
  $s = r + v_p \cdot r/r = r + v_p$ (for $s<<c$)

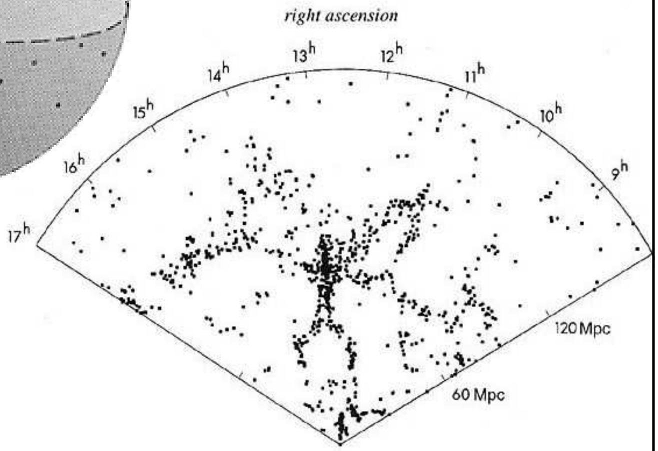
## *Uses of z-surveys*

- ***<u>Three (partial) views of redshift</u>:***
  - ***z measures the distance needed to map 3D positions***
  - ***z measures the look-back time needed to map histories***
  - ***$cz-H_0d$ measures the peculiar velocity needed to map mass***
- ***<u>Three main uses of z-surveys</u>:***
  - ***to map the large-scale structures, in order to…***
    - ***do cosmography and chart the structures in the universe***
    - ***test growth of structure through gravitational instability***
    - ***determine the nature and density of the dark matter***
  - ***to map the large-velocity field, in order to***
    - ***`see' the mass field through its gravitational effects***
  - ***to probe the history of galaxy formation, in order to…***
    - ***characterise the galaxy population at each epoch***
    - ***determine the physical mechanisms by which the population evolves***

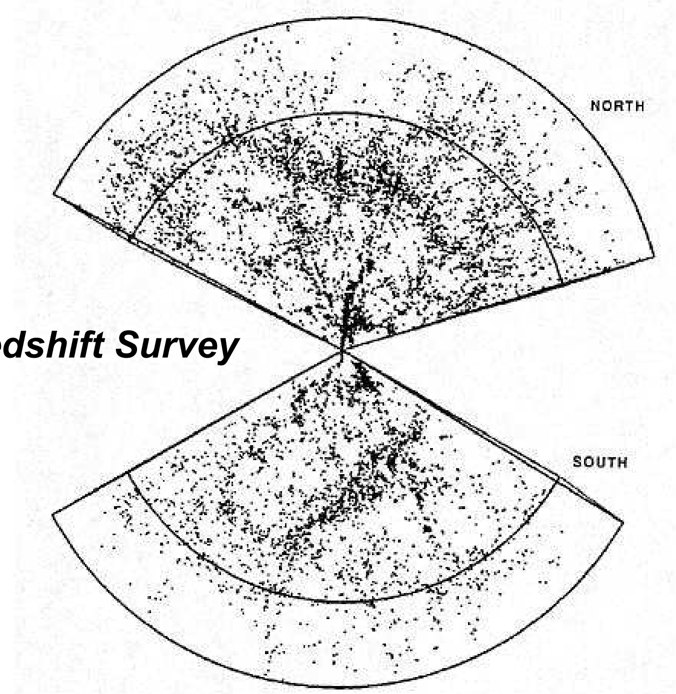
## *CfA Redshift Survey*

## *First Slice*



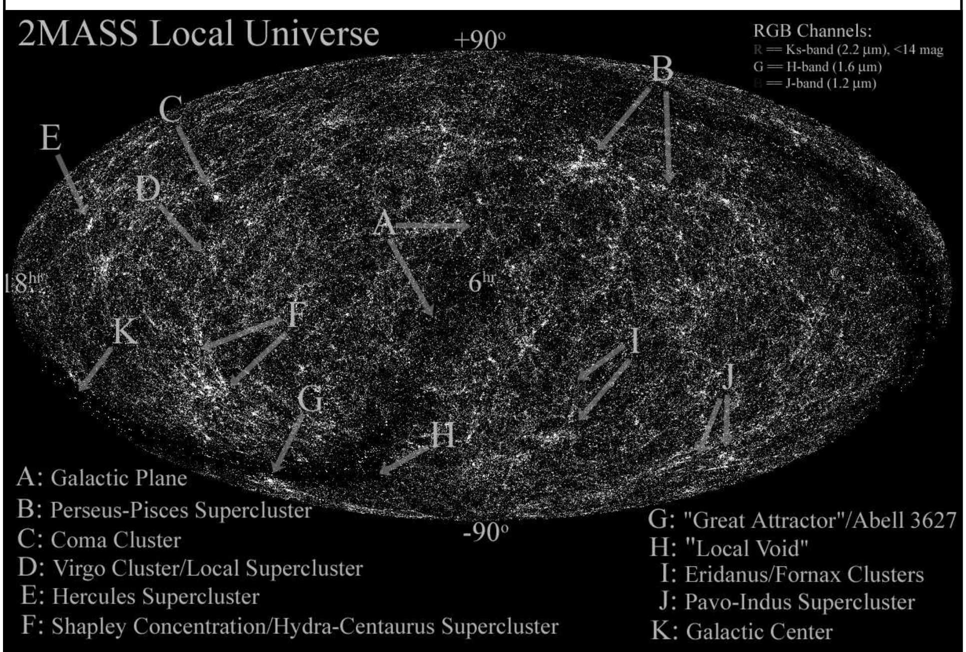




## *CfA Redshift Survey*



# *Cosmography*

- ***The main features of the local galaxy distribution include:***
  - *Local Group: Milky Way, Andromeda and retinue.*
  - *Virgo cluster: nearest significant galaxy cluster, LG$\rightarrow$Virgo.*
  - *Local Supercluster (LSC): flattened distribution of galaxies* **cz<3000 km/s***; defines supergalactic plane* **(X,Y,Z).**
  - *'Great Attractor': LG/Virgo$\rightarrow$GA, lies at one end of the LSC,* **(X,Y,Z)=(-3400,1500,$\pm$2000).**
  - *Perseus-Pisces supercluster:* **(X,Y,Z)=(+4500, $\pm$2000,–2000),** *lies at the other end of the LSC.*
  - *Coma cluster: nearest very rich cluster,* **(X,Y,Z)=***(0,+7000,0); a major node in the 'Great Wall' filament.*
  - *Shapley supercluster: most massive supercluster within z<0.1, at a distance of 14,000 km/s behind the GA.*
  - *Voids: the Local Void, Sculptor Void, and others lie between these mass concentrations.*
- ***Yet larger structures are seen at lower contrast to* >100 $h^{-1}$ Mpc.**



# Evolution of Structure

- *The goal is to derive the evolution of the mass density field, represented by the dimensionless density perturbation:*

  $$\delta(x) = \rho(x)/\langle\rho\rangle - 1$$

- *The framework is the growth of structures from 'initial' density fluctuations by gravitational instability.*
- *Up to the decoupling of matter and radiation, the evolution of the density perturbations is complex and depends on the interactions of the matter and radiation fields - 'CMB physics'*
- *After decoupling, the linear growth of fluctuations is simple and depends only on the cosmology and the fluctuations in the density at the surface of last scattering - 'large-scale structure in the linear regime'.*
- *As the density perturbations grow the evolution becomes non-linear and complex structures like galaxies and clusters form - 'non-linear structure formation'. In this regime additional complications emerge, like gas dynamics and star formation.*

# The power spectrum

- *It is helpful to express the density distribution* $\delta(r)$ *in the Fourier domain:*

  $$\delta(\mathbf{k}) = V^{-1}\int \delta(\mathbf{r})\, e^{i\mathbf{k}\cdot\mathbf{r}}\, d^3r$$

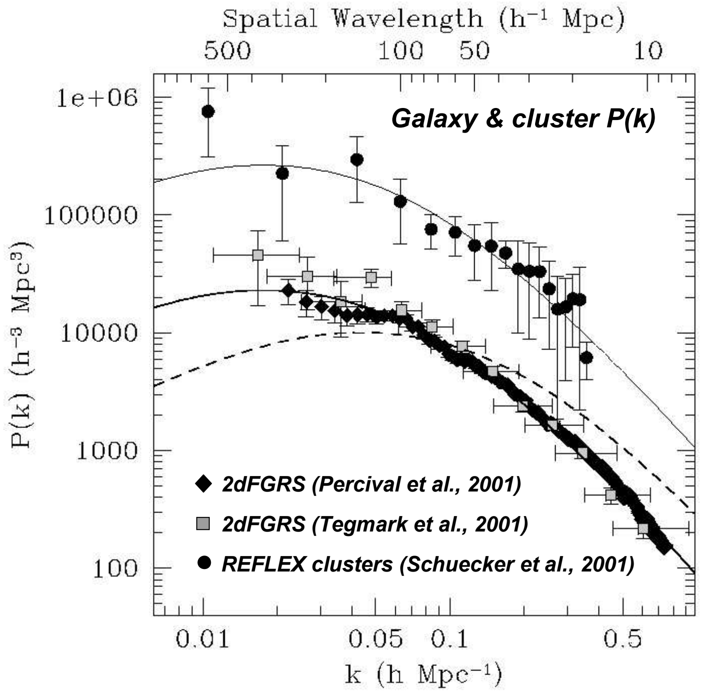
- *The power spectrum (PS) is the mean squared amplitude of each Fourier mode:*

  $$P(k) = \langle|\delta(k)|^2\rangle$$

  - *Note* P(k) *not* P(**k**) *because of the (assumed) isotropy of the distribution (i.e. scales matter but directions don't).*
  - P(k) *gives the power in fluctuations with a scale* $r=2\pi/k$*, so that* $k = (1.0, 0.1, 0.01)\ \mathrm{Mpc}^{-1}$ *correspond to* $r \approx (6, 60, 600)$ Mpc.
- *The PS can be written in dimensionless form as the variance per unit* ln k*:*

  $$\Delta^2(k) = d\langle|\delta(k)|^2\rangle/d\ln k = (V/2\pi)^3\, 4\pi k^3\, P(k)$$

  - *e.g.* $\Delta^2(k) = 1$ *means the modes in the logarithmic bin around wavenumber k have rms density fluctuations of order unity.*




# *The correlation function*

- ***The autocorrelation function of the density field (often just called 'the correlation function', CF) is:***

  $$\xi(r) = \langle\delta(x)\delta(x+r)\rangle$$

- ***The CF and the PS are a Fourier transform pair:***

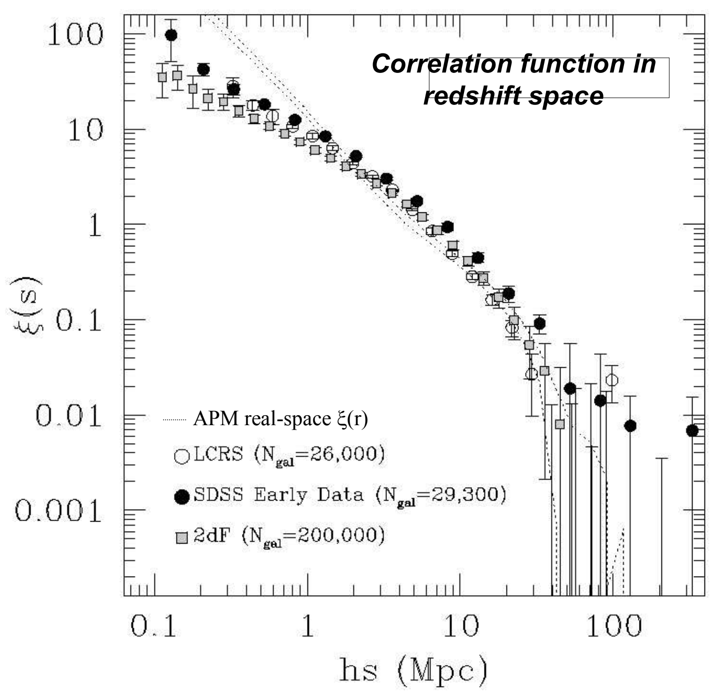
  $$\xi(r) = V/(2\pi)^3 \int|\delta_k|^2 \exp(-ik\cdot r)\, d^3k$$
  $$= (2\pi^2)^{-1} \int P(k)[(\sin kr)/kr]\, k^2\, dk$$

  – ***Because*** P(k) ***and*** ξ(r) ***are a Fourier pair, they contain precisely the same information about the density field.***

- ***When applied to galaxies rather than the density field,*** ξ(r) ***is often referred to as the 'two-point correlation function', as it gives the excess probability (over the mean) of finding two galaxies in volumes*** dV ***separated by*** r:

  $$dP = \rho_0^2[1 + \xi(r)]\, d^2V$$

  – ***By isotropy, only separation*** r ***matters, and not the vector r.***
  – ***Can thus think of*** ξ(r) ***as the mean over-density of galaxies at distance*** r ***from a random galaxy.***




## *Gaussian fields*

- ***A Gaussian density field has the property that the joint probability distribution of the density at any number of points is a multivariate Gaussian.***
- ***Superposing many Fourier density modes with <u>random phases</u> results, by the central limit theorem, in a Gaussian density field.***
- ***A Gaussian field is fully characterized by its mean and variance (as a function of scale).***
- ***Hence <ρ> and P(k) provide a complete <u>statistical</u> description of the density field if it is Gaussian.***
- ***Most simple inflationary cosmological models predict that Fourier density modes with different wavenumbers are independent (i.e. have random phases), and hence that the initial density field will be Gaussian.***
- ***Linear amplification of a Gaussian field leaves it Gaussian, so the large-scale galaxy distribution should be Gaussian.***

## *The initial power spectrum*

- ***Unless some physical process imposes a scale, the initial PS should be scale-free, i.e. a power-law,*** $P(k) \propto k^n$ .
- ***The index n determines the balance between large- and small-scale power, with rms fluctuations on a mass scale*** M ***given by:***

  $$\delta_{rms} \propto M^{-(n+3)/6}$$

- ***The 'natural' initial power spectrum is the power-law with n=1 (called the Zel'dovich, or Harrison-Zel'dovich, spectrum).***
- ***The*** $P(k) \propto k^1$ ***spectrum is referred to as the scale-invariant spectrum, since it gives variations in the gravitational potential that are the same on all scales.***
- ***Since potential governs the curvature, this means that space-time has the same amount of curvature variation on all scales (i.e. the metric is a fractal).***
- ***In fact, inflationary models predict that the initial PS of the density fluctuations will be approximately scale-invariant.***