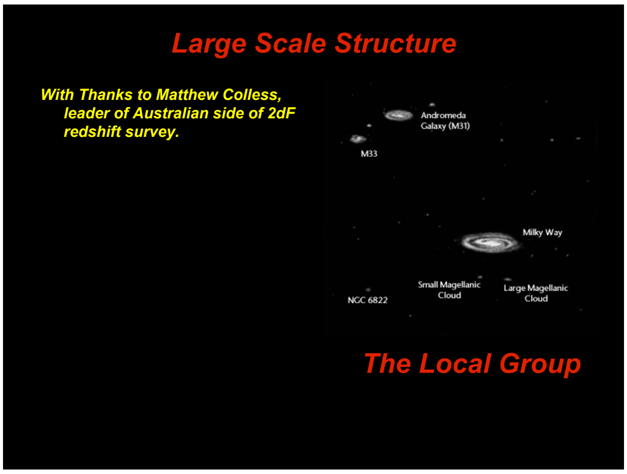
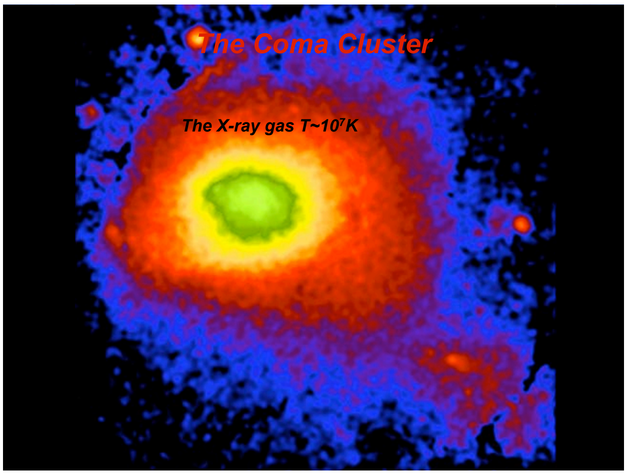
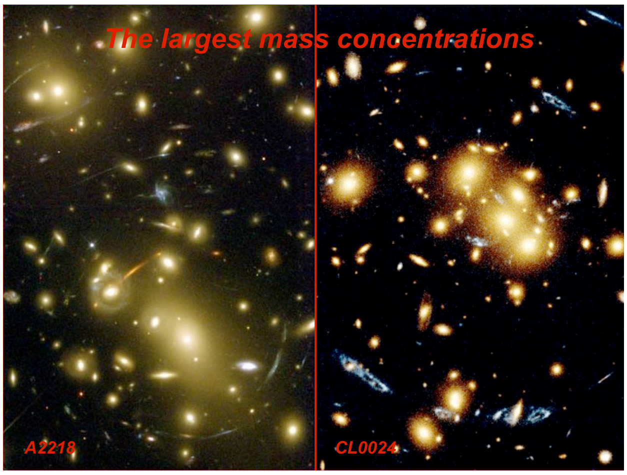


Large Scale Structure
With Thanks to Matthew Colless,
leader of Australian side of 2dF
redshift survey.
Andromeda Galaxy (M31)
M33
Milky Way
Small Magellanic Cloud
Large Magellanic Cloud
NGC 6822
The Local Group

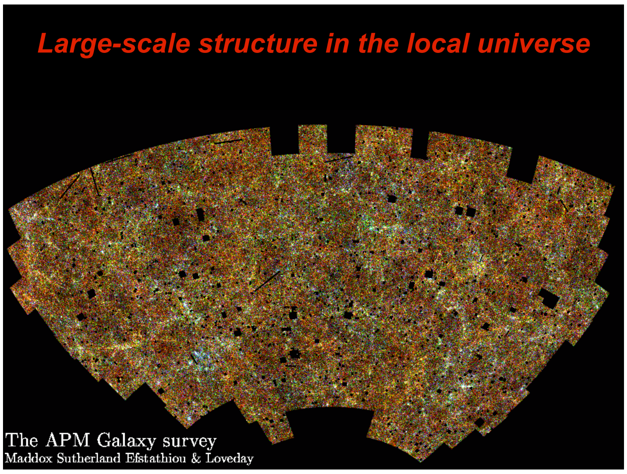
© Anglo-Australian Observatory
The Hydra cluster



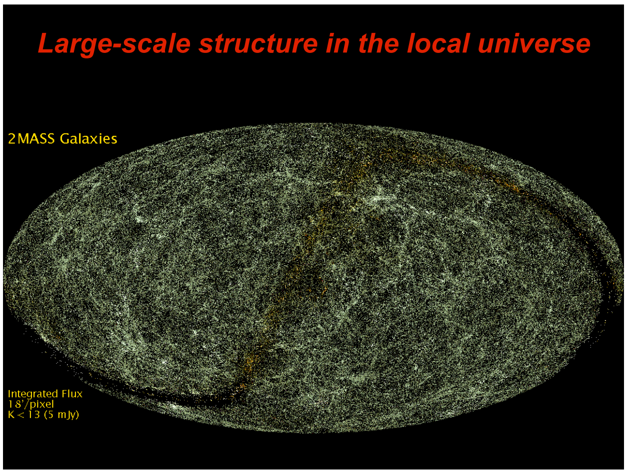
The Coma Cluster
The X-ray gas T~10^7K



The largest mass concentrations
A2218
CL0024

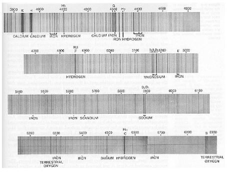


Large-scale structure in the local universe
The APM Galaxy survey
Maddox Sutherland Efstathiou & Loveday



Large-scale structure in the local universe
2MASS Galaxies
Integrated Flux
1 8'/pixel
K < 13 (5 mJy)

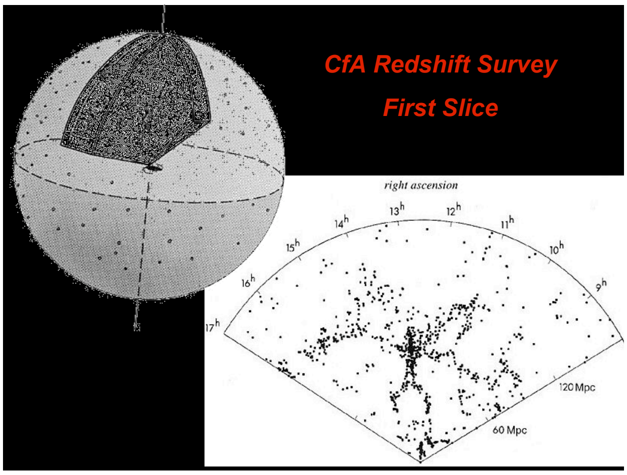
Redshift surveys



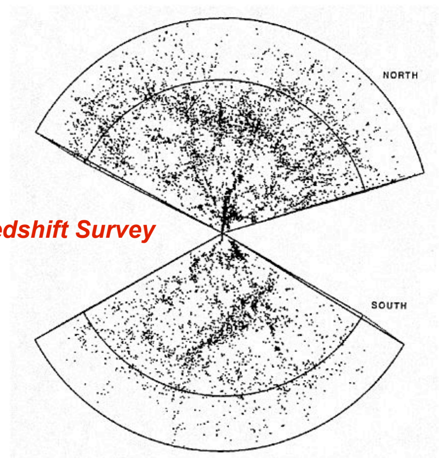
- A z-survey is a systematic mapping of a volume of space by measuring redshifts: $z = \lambda_1/\lambda_0 - 1 = a\text{-}1$
- Redshifts as distance coordinates…
  $H_0 D_L = c(z+(1-q_0)z^2/2+\ldots)$
  …this is the viewpoint in low-z surveys of spatial structure.
- For low-z surveys of structure, the Hubble law applies:
  $cz = H_0 d$ (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

- Three (partial) views of redshift:
  - z measures the distance needed to map 3D positions
  - z measures the look-back time needed to map histories
  - $cz\text{-}H_0 d$ measures the peculiar velocity needed to map mass
- Three main uses of z-surveys:
  - 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

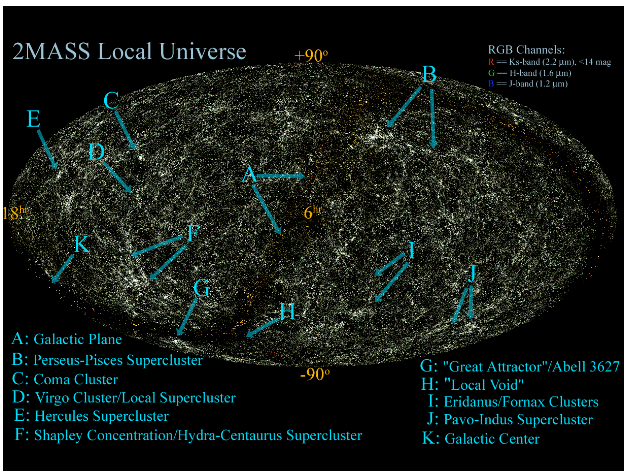


CfA Redshift Survey



Cosmography

- The main features of the local galaxy distribution include:
  - Local Group: Milky Way, Andromeda and retinue.
  - Virgo cluster: nearest significant galaxy cluster, LG→Virgo.
  - Local Supercluster (LSC): flattened distribution of galaxies cz<3000 km/s; defines supergalactic plane (X,Y,Z).
  - 'Great Attractor': LG/Virgo→GA, lies at one end of the LSC, (X,Y,Z)=(-3400,1500,±2000).
  - Perseus-Pisces supercluster: (X,Y,Z)=(+4500, ±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.

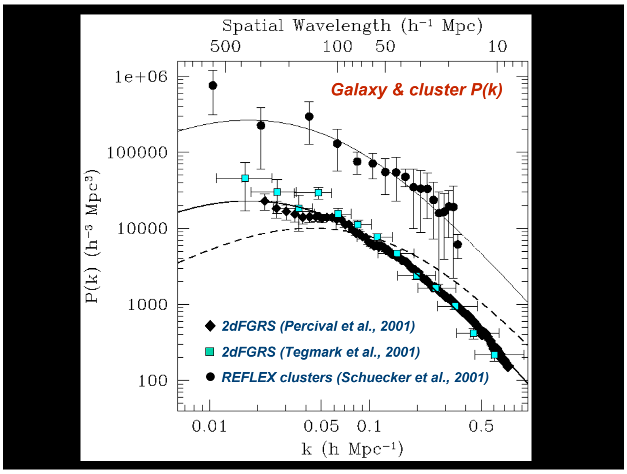


Evolution of Structure

- 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.

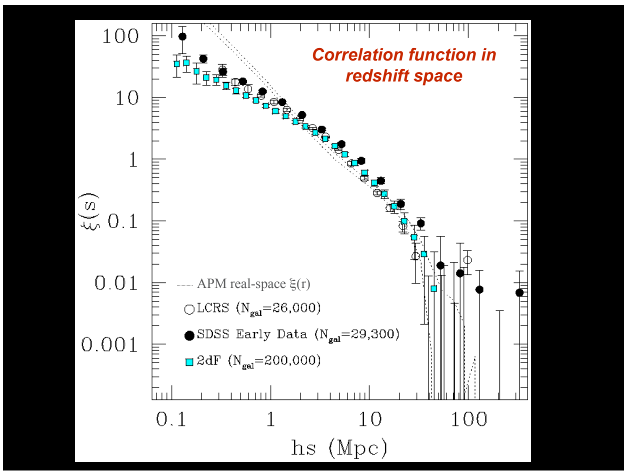
The power spectrum

- It is helpful to express the density distribution $\delta(r)$ in the Fourier domain:
  $\delta(\boldsymbol{k}) = V^{-1}\int \delta(\boldsymbol{r})\, e^{i\boldsymbol{k}\cdot\boldsymbol{r}}\, d^3r$
- 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:
  $\xi(r) = \langle\delta(\boldsymbol{x})\delta(\boldsymbol{x}+\boldsymbol{r})\rangle$
- The CF and the PS are a Fourier transform pair:
  $\xi(r) = V/(2\pi)^3 \int |\delta_k|^2 \exp(-i\boldsymbol{k}\cdot\boldsymbol{r})\, d^3k$
  $= (2\pi^2)^{-1} \int P(k)[(\sin kr)/kr]\, k^2\, dk$
  - Because P(k) and $\xi(r)$ are a Fourier pair, they contain precisely the same information about the density field.
- When applied to galaxies rather than the density field, $\xi(r)$ 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 $\xi(r)$ 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 random phases 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 $\langle\rho\rangle$ and P(k) provide a complete statistical 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) ∝ 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) ∝ 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.***

Growth of perturbations

- ***What does it take for an object to Collapse in the Universe.***
- ***We can estimate this by looking at the Gravitational Binding Energy of a spherical ball and comparing it to the thermal energy of the ball. When gravity dominates, the object can collapse. Scale where this happens is called the Jean's Length***

$$\frac{GM^2}{R} \approx \frac{M}{m}kT \qquad E_{par} \approx kT \qquad \mathrm{N_{par}} = \frac{M}{m}$$
$$\frac{GM}{R} \approx \frac{kT}{m}$$
$$\frac{G(\frac{4}{3}\pi\rho R^3)}{R} \approx \frac{kT}{m}$$
$$R \approx \sqrt{\frac{kT}{mG\rho}} \equiv \lambda_J = c_s\sqrt{\frac{1}{G\rho}}$$

Growth of linear perturbations

- ***The (non-relativistic) equations governing fluid motion under gravity can be linearized to give the following equation governing the growth of linear density perturbations:***
  $$\ddot{\delta} + \frac{\dot{a}}{a}\dot{\delta} = \delta\left(4\pi G\rho_0 - \frac{c_s{}^2 k^2}{a^2}\right)$$
- ***This has growing solutions for on large scales (small k) and oscillating solutions for for small scales (large k); the cross-over scale between the two is the Jeans length,***
  $$\lambda_J = c_s\sqrt{\frac{1}{G\rho}}$$
  where **c_s** ***is the sound speed,*** **$c_s^2=\partial p/\partial\rho$.**
- ***For*** **$\lambda<\lambda_J$*****, sound waves cross an object on the same time-scale as the gravitational collapse, so pressure can counter gravity.***
- ***In an expanding universe,*** **λ_J** ***varies with time; perturbations on some scales swap between growing and oscillating solutions.***

Peculiar Velocity and Linear Growth

Peebles, (1976) demonstrated in the linear regime (i.e. acceleration Due to a mass concentration is constant – unaffected by the growth of the mass concentration) the following relationship holds.

$$\frac{v_{pec}(r)}{H_0 r} = -\frac{1}{3}\Omega_M^{0.6}\delta(r) \qquad \mathrm{BIAS}: \delta_{gal}(r) = b\delta(r)$$
$$\frac{v_{pec}(r)}{H_0 r} = -\frac{1}{3}\frac{\Omega_M^{0.6}}{b}\delta_{gal}(r)$$

So…We think Ω_M=0.3,
between us and the Virgo Cluster the density of galaxies we see over the background is a factor of 2 in that sphere,
H_0 =70 km/s
Distance to Virgo cluster is 16 Mpc…

$$v_{pec}(r) = -\frac{H_0 r}{3}\frac{\Omega_M^{0.6}}{b}\delta_{gal}(r)$$
$$v_{pec}(r) = -\frac{70*16}{3}\frac{0.3^{0.6}}{b}2 = 362\mathrm{km/s}$$

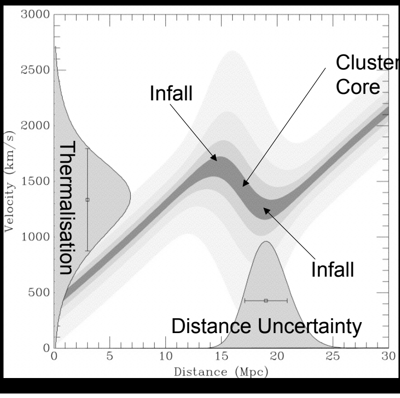
Bias: light vs *mass*

- ***Gravitational instability theory applies to the*** **mass distribution** ***but we observe the*** **galaxy** ***distribution - are these 1-to-1?***
- ***A bias factor*** **b** ***parameterises our ignorance:*** **$\delta_g = b\delta_M$** ***,***
  i.e. fractional variations in the galaxy density are proportional to fractional variations in the mass density (with ratio b).
  - ***What might produce a bias? Do galaxies form only at the peaks of the mass field, due to a star-formation threshold?***
  - ***Variation of bias with scale. This is plausible at small scales (many potential mechanisms), but not at large scales.***
  - ***Observed variation with galaxy type. The ratio E:Sp is 10:1 in clusters (δ_g>>1) but 1:10 in field (δ_g≤1).***

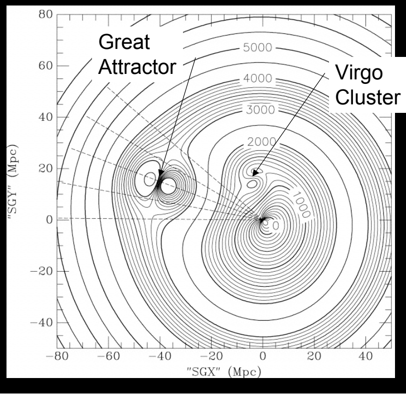
Non-Linear Growth

- ***Eventually structures grow and this causes their Mass to increase, and the linear regime to breakdown***
- ***Galaxies start to interact with each other and thermalise (Called Virialisation)***

Virgo Cluster as Measured with Surface Brightness Fluctuations

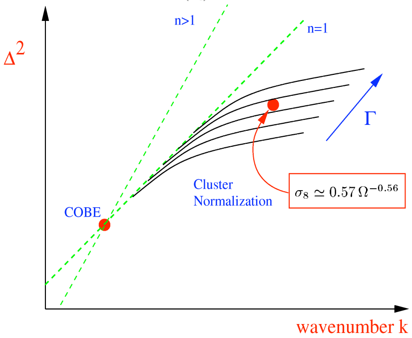


Map of velocities in nearby Universe-SBF



$$\Gamma_{\rm eff}(k) = \Omega_0 h \left[\alpha_\Gamma + \frac{1-\alpha_\Gamma}{1+(0.43ks)^4} \right], \qquad (30)$$

$$\alpha_\Gamma = 1 - 0.328 \ln(431\Omega_0 h^2)\frac{\Omega_b}{\Omega_0} + 0.38 \ln(22.3\Omega_0 h^2)\left(\frac{\Omega_b}{\Omega_0}\right)^2 . \qquad (31)$$



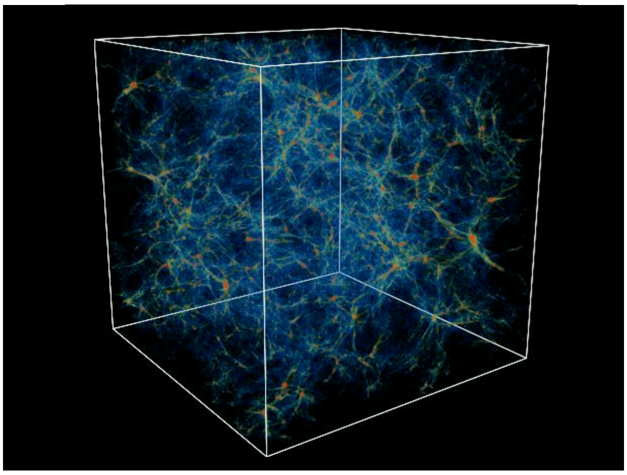
The CDM Power Spectrum

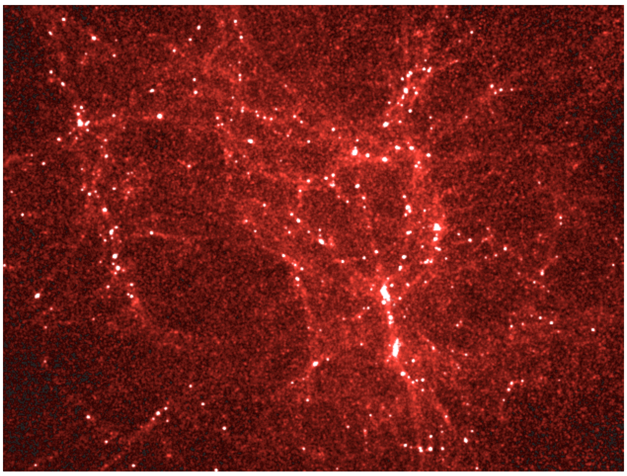
Fluctuations in the density grow as δ(a) = a f(Ω[a])

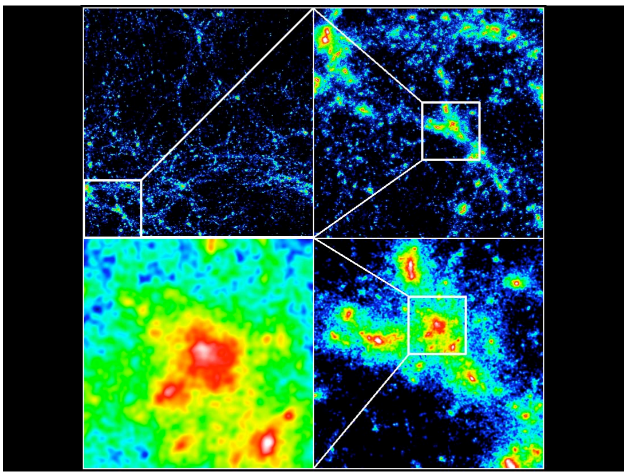
Scale of break in power spectrum relates to baryons suppressing growth of CDM

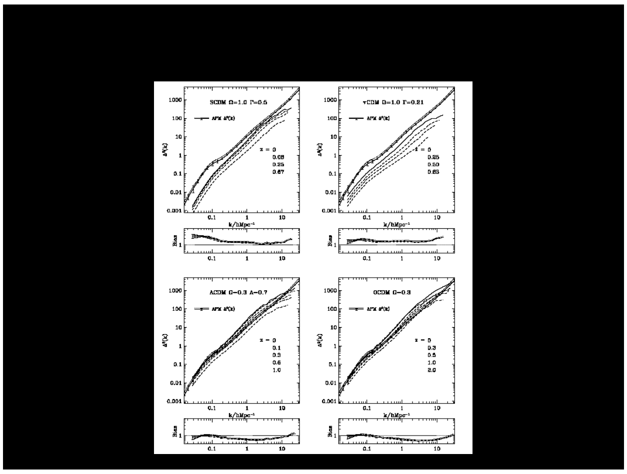
In practice, get shape parameter **$\Gamma \approx \Omega_m h$**

Γ is a shorthand way of fitting the actual power spectra coming out of Nbody models



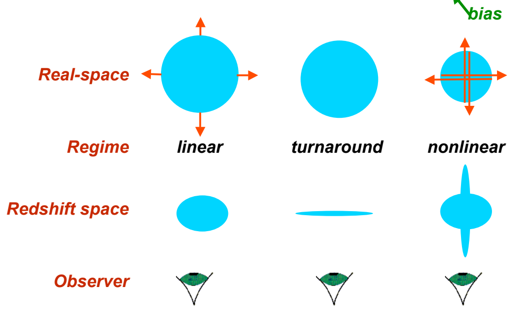






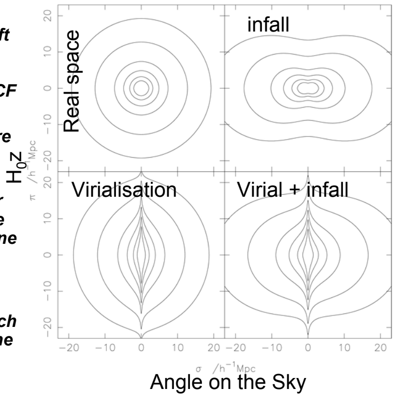
Redshift-space distortions

$z_{obs} = z_{true} + v_{pec}/c$ where $v_{pec} \propto \Omega^{0.6}\, \delta\rho/\rho = (\Omega^{0.6}/b)\, \delta n/n$



Redshift-space distortions

- *Because of peculiar velocities, the redshift space Correlation Function is distorted w.r.t. the real-space CF*
- *In real space the contours of the CF are circular.*
- *Coherent infall on large scales (in linear regime) squashes the contours along the line of sight.*
- *Rapid motions in collapsed structures on small scales stretch the contours along the line of sight.*



Some Relevant questions in Large Scale Structure

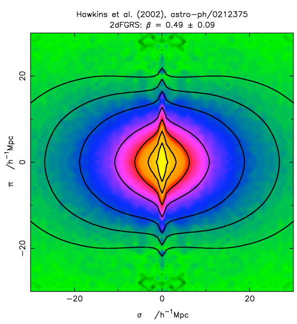
- *What is the shape of the power spectrum?*
  what is the value of $\Gamma = \Omega h$*?*
- *Mass and bias:*
  - *what is the value of* $\beta \approx \Omega^{0.6}/b$*?*
  - *can we obtain* Ω *and b independently of each other?*
  - *what are the relative biases of different galaxy populations?*
- *Can we check the gravitational instability paradigm?*
- *Were the initial density fluctuations random-phase (Gaussian)?*

Measuring β from P(k)

- *z-space distortions produce 'Fingers of God' on small scales and compression along the line of sight on large scales.*
- *Or can measure the degree of distortion of* ξ_s *in* σ-π *plane from ratio of quadrupole to monopole:*
- $P_2^s(k) = 4/3\beta + 4/7\beta^2$
  $P_0^s(k) \quad 1 + 2/3\beta + 1/5\beta^2$

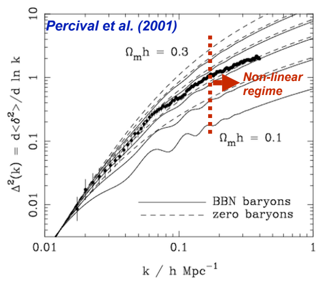
$$(\Omega_M)^6 = b * 0.49$$

$$\Omega_M = .30 * b^{5/3}$$



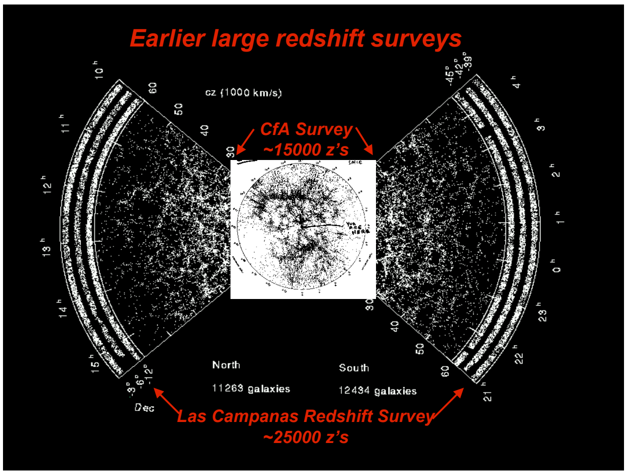
Large scales - P(k)

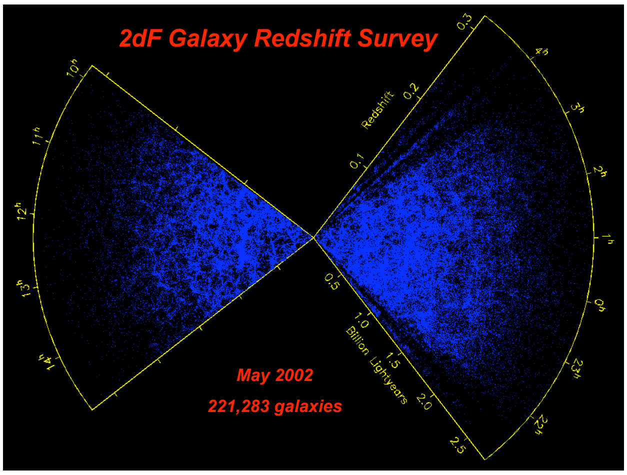
- P(k) *is preferred to* ξ(r) *on large scales: it is more robust to compute, the covariance between scales is simpler, and the error analysis is easier.*
- *Fits to* P(k) *give* $\Gamma \approx 0.2$, *implying* $\Omega \approx 0.3$ *if* $h \approx 0.7$, *but the turnover in* P(k) *around* $200\, h^{-1}$ Mpc *(the horizon scale at matter-radiation equality) is not well determined.*



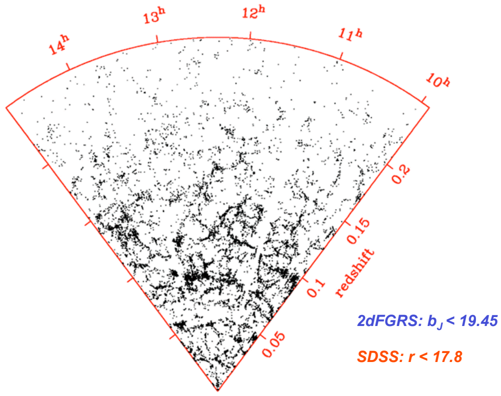
Major new Large Scale Structure Surveys

- *Massive surveys at low z* (10^5-10^6 *galaxies* $\langle z \rangle \approx 0.1$):
  - *2dF Galaxy Redshift Survey and Sloan Digital Sky Survey*
  - *high-precision Cosmology: measure* P(k) *on large scales and* β *from z-space distortions to give* Ω_M *and* b.
  - *low-z galaxy population:* Φ *and* ξ *as joint functions of* luminosity, *type, local density and star-formation rate*
- *Massive surveys at high redshift* ($\langle z \rangle \approx 0.5$-$1.0$ *or higher*):
  - *VIMOS and DEIMOS surveys (and others)*
    - *evolution of the galaxy population*
    - *evolution of the large-scale structure*
- *Mass and motions survey (6dF Galaxy Survey):*
  - *NIR-selected z-survey of local universe, together with...*
  - *measurements of* σ *for 15000 E/S0 galaxies...*
    - $\Rightarrow$ *masses and distances from Fundamental Plane*
    - $\Rightarrow$ *density/velocity field to* 15000 km/s (150 h^{-1} Mpc)

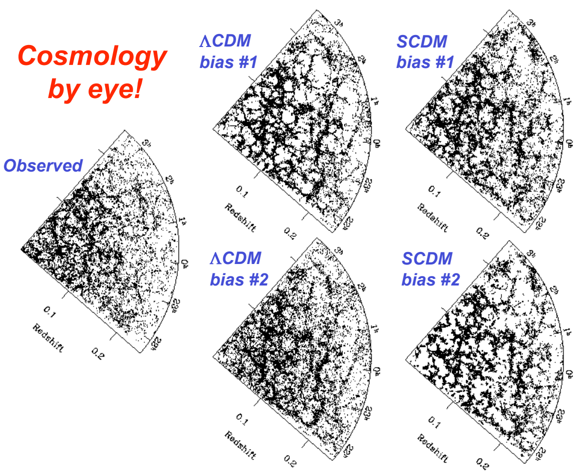




Fine detail: 2-deg NGP slices (1-deg steps)



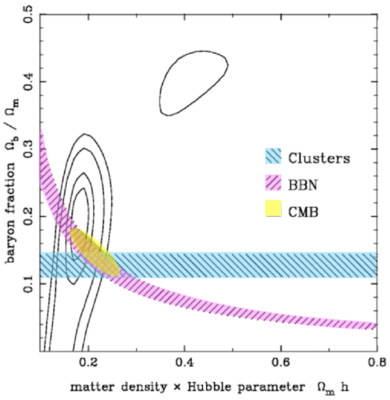
Cosmology by eye!



2dFGRS: LSS + Cosmology Highlights

- *The most precise determination of the large-scale structure of the galaxy distribution on scales up to* 600 h^{-1} Mpc.
- *Unambiguous detection of coherent collapse on large scales, confirming structures grow via gravitational instability.*
- *Measurements of* Ω_M *(mean mass density) from the power spectrum and redshift-space distortions:* $\Omega = 0.27 \pm 0.04$
- *First measurement of galaxy bias parameter:* $b = 1.00 \pm 0.09$
- *An new upper limit on the neutrino fraction,* $\Omega_\nu/\Omega < 0.13$*, and a limit on the mass of all neutrino species,* $m_\nu < 1.8$ eV.

Confidence Limits on Γ and Ω_b/Ω_m



If no constraint on n:

$\Gamma = \Omega_m h = 0.20 \pm 0.03$

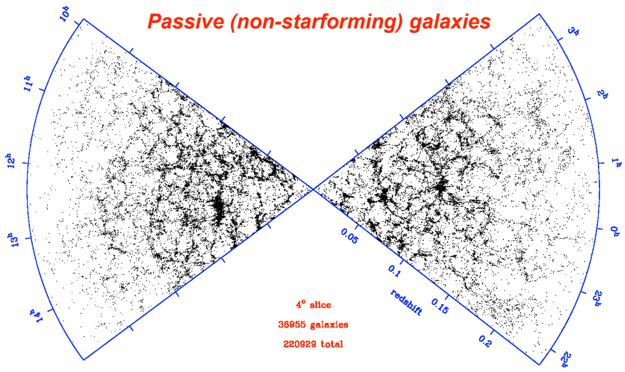
Baryon fraction = $\Omega_b/\Omega_m = 0.15 \pm 0.07$

If require n=1:

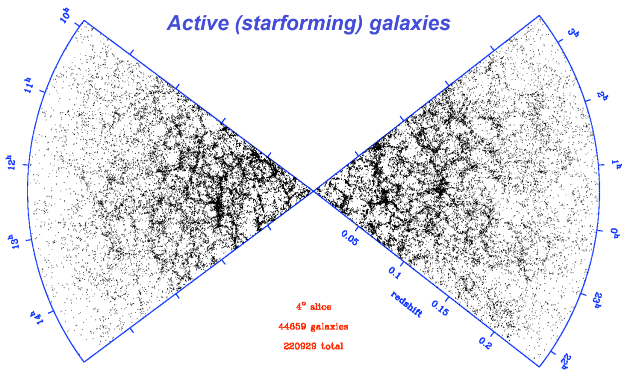
$\Gamma = \Omega_m h = 0.18 \pm 0.02$

Baryon fraction = $\Omega_b/\Omega_m = 0.17 \pm 0.06$

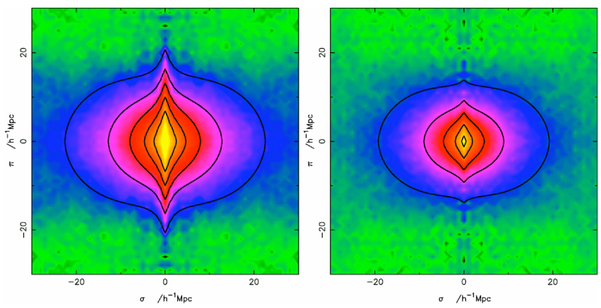
Passive (non-starforming) galaxies



Active (starforming) galaxies



Redshift-space distortions and galaxy type



Passive:

$\beta = \Omega^{0.6}/b = 0.46 \pm 0.13$

Active:

$\beta = \Omega^{0.6}/b = 0.54 \pm 0.15$