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,***

$$\lambda_J = c_s\sqrt{\frac{\pi}{G\rho}}$$

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.

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

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

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…

$$v_{pec}(r) = -\frac{H_0 r}{3}\frac{\Omega_M^{0.6}}{b}\delta_{gal}(r)$$

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

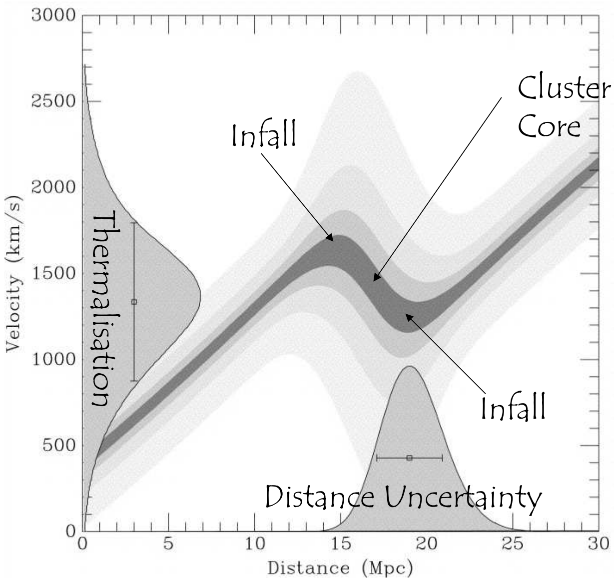
Bias: light vs *mass*

- ***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).**

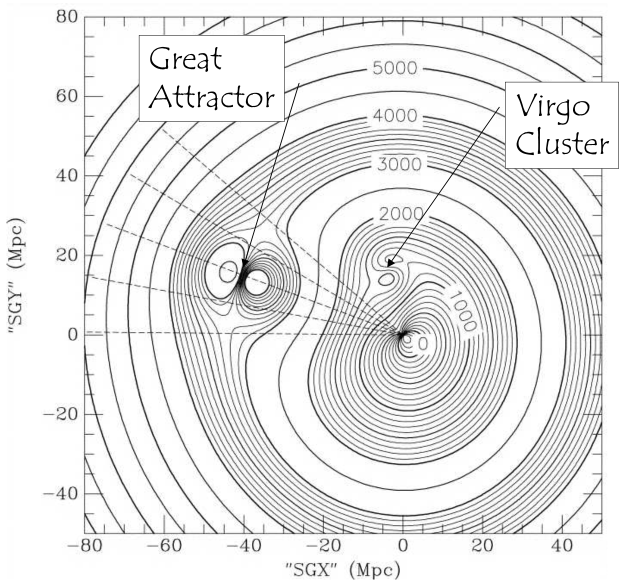
Non-Linear Growth

- ***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



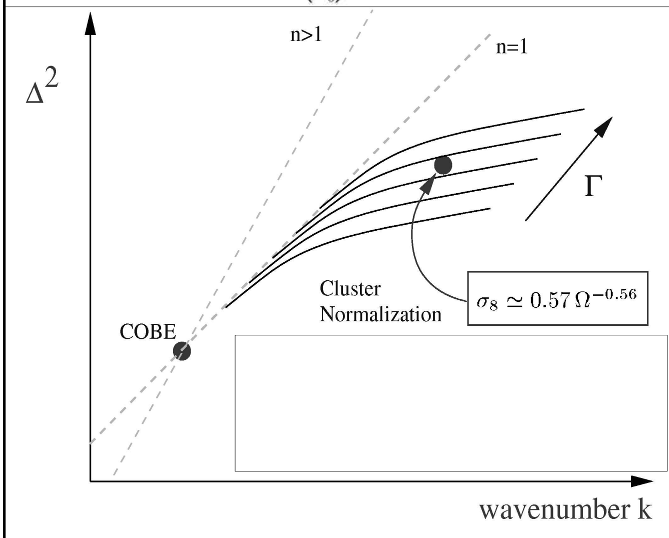
Map of velocities in nearby Universe-SBF



The CDM Power Spectrum

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

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

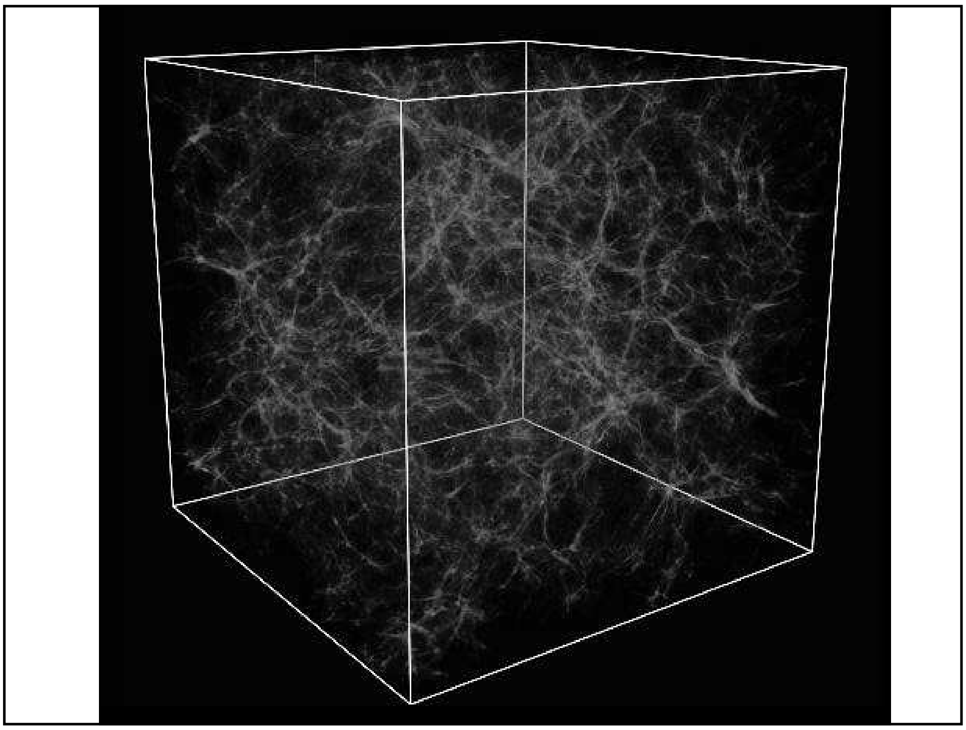


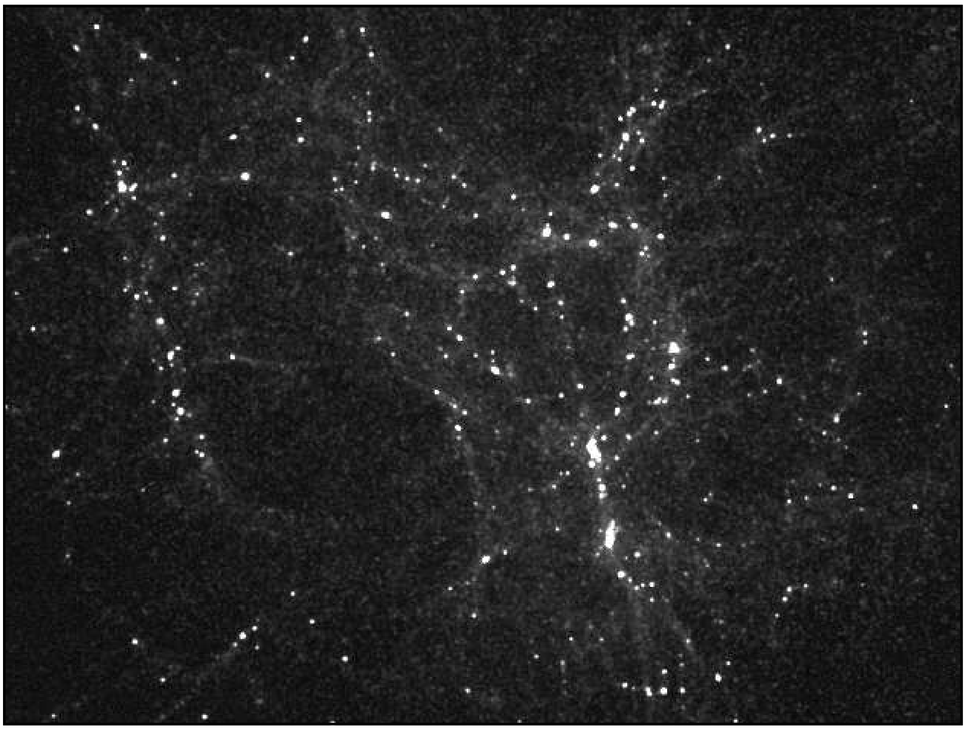
Fluctuations in the density grow as **$\delta(a) = a\, f(\Omega[a])$**

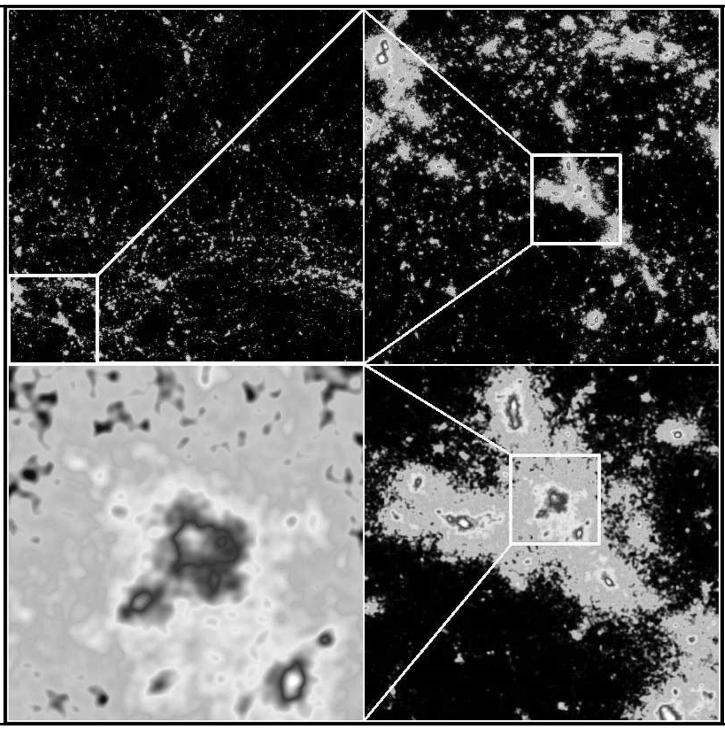
Scale of break in power spectrum relates to baryons suppressing growth of CDM

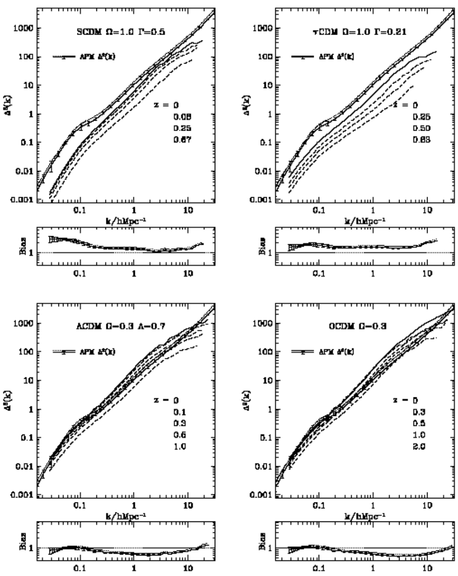
In practice, get shape parameter **$\Gamma \approx \Omega_m h$**

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







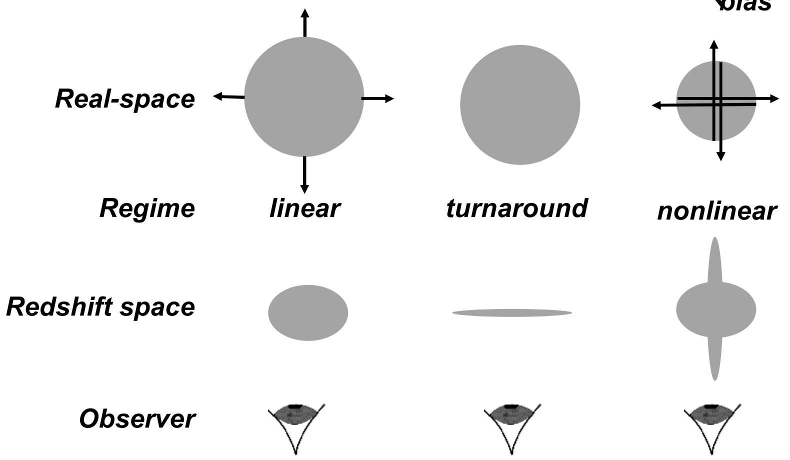


SCDM Ω=1.0 Γ=0.5
APM Δ²(k)
z = 0
0.08
0.25
0.67
Δ²(k)
k/hMpc⁻¹
Bias
νCDM Ω=1.0 Γ=0.21
APM Δ²(k)
z = 0
0.25
0.50
0.83
Δ²(k)
k/hMpc⁻¹
Bias
ΛCDM Ω=0.3 Λ=0.7
APM Δ²(k)
z = 0
0.1
0.3
0.6
1.0
Δ²(k)
k/hMpc⁻¹
Bias
OCDM Ω=0.3
APM Δ²(k)
z = 0
0.3
0.5
1.0
2.0
Δ²(k)
k/hMpc⁻¹
Bias

Redshift-space distortions

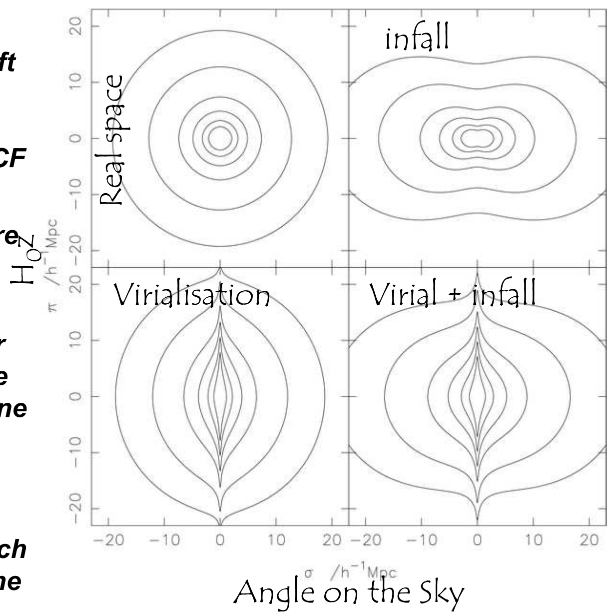
$z_{obs} = z_{true} + v_{pec}/c$ *where* $v_{pec} \propto \Omega^{0.6}\, \delta\rho/\rho = (\Omega^{0.6}/b)\, \delta n/n$

bias



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

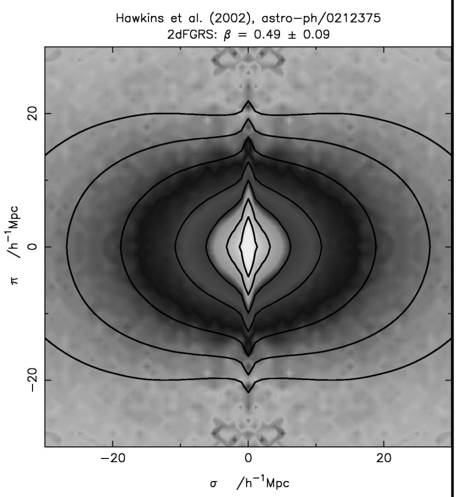
- ***What is the shape of the power spectrum?***
  what is the value of $\Gamma = \Omega h$***?***
- ***Mass and bias:***
  - ***what is the value of*** $\beta \approx \Omega^{0.6}/b$***?***
  - ***can we obtain*** Ω ***and*** b ***independently of each other?***
  - ***what are the relative biases of 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:***
- $\frac{P_2^s(k)}{P_0^s(k)} = \frac{4/3\beta + 4/7\beta^2}{1 + 2/3\beta + 1/5\beta^2}$

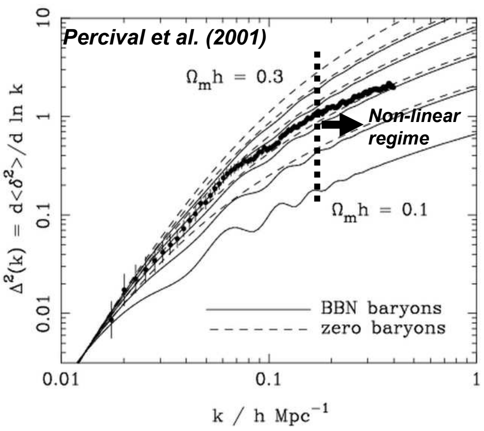
$$(\Omega_M)^{.6} = b * 0.49$$

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



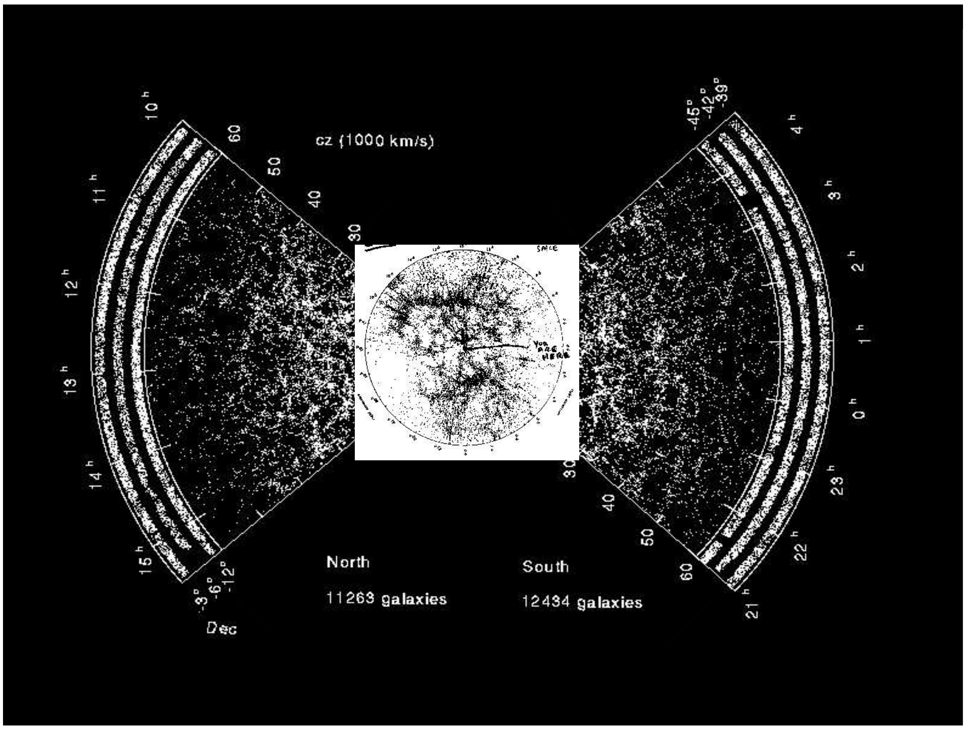
Large scales - P(k)

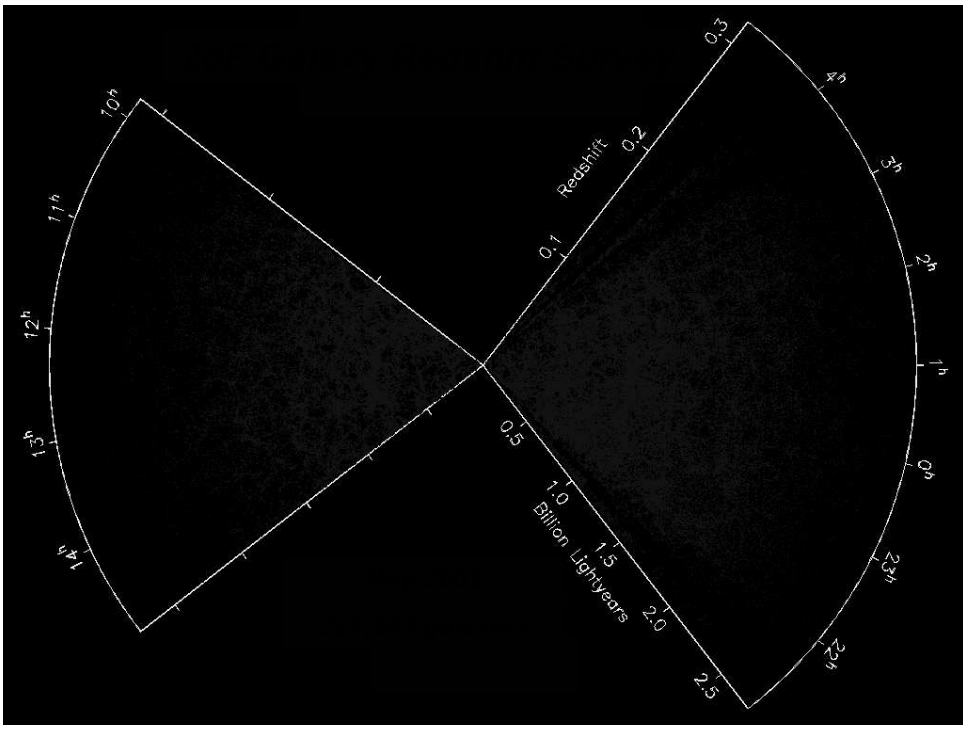
- P(k) *is preferred to* $\xi(r)$ *on large scales: it is more robust to compute, the covariance between scales is simpler, and the error analysis is easier.*
- *Fits to* P(k) *give* $\Gamma \approx 0.2$*, implying* $\Omega \approx 0.3$ *if* $h \approx 0.7$*, but the turnover in* P(k) *around* 200 h^{-1}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



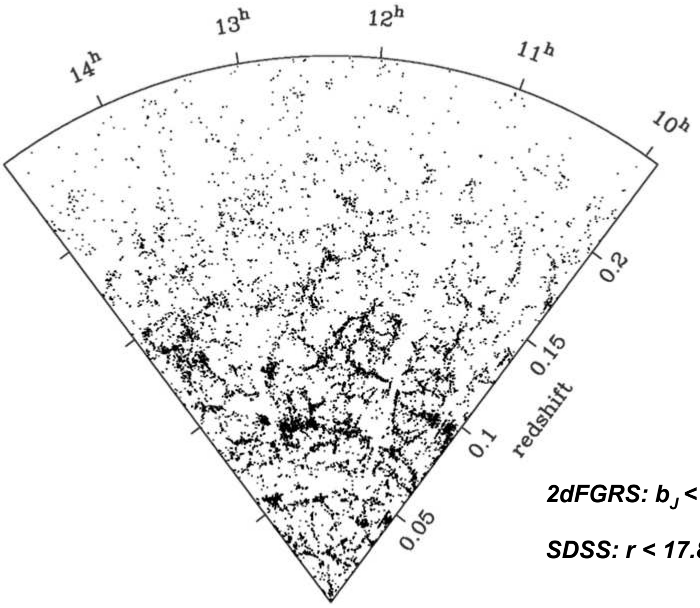
Major new Large Scale Structure Surveys

- *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)


cz (1000 km/s)
North
11263 galaxies
South
12434 galaxies
Dec
-3°
-6°
-12°
-45°
-42°
-39°
10 h
11 h
12 h
13 h
14 h
15 h
4 h
3 h
2 h
1 h
0 h
23 h
22 h
21 h
30
40
50
60


Redshift
0.1
0.2
0.3
Billion Lightyears
0.5
1.0
1.5
2.0
2.5
10h
11h
12h
13h
14h
4h
3h
2h
1h
0h
23h
22h

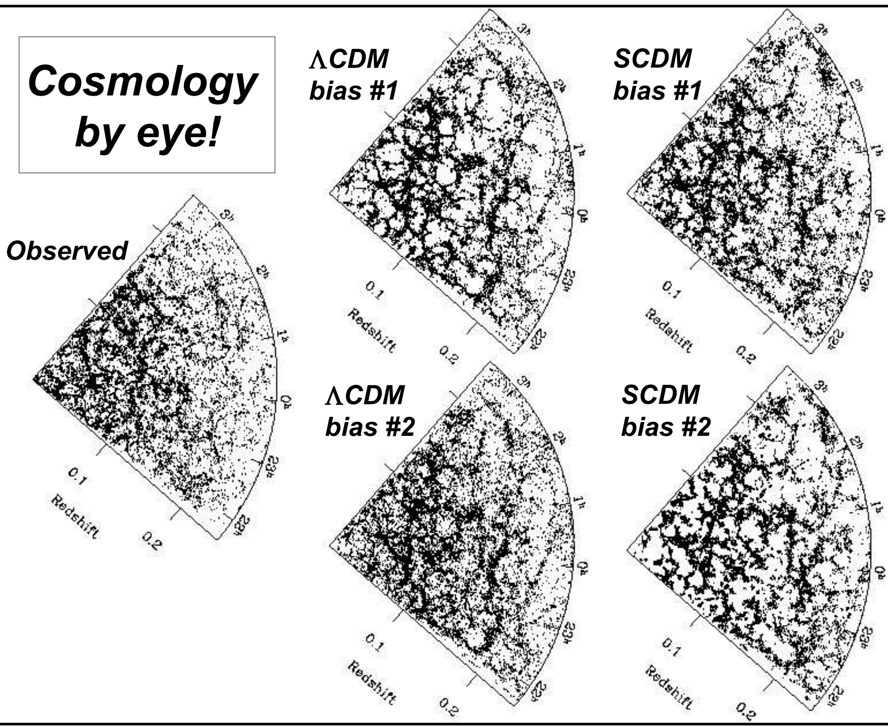
Fine detail: 2-deg NGP slices (1-deg steps)



2dFGRS: $b_J < 19.45$

SDSS: $r < 17.8$

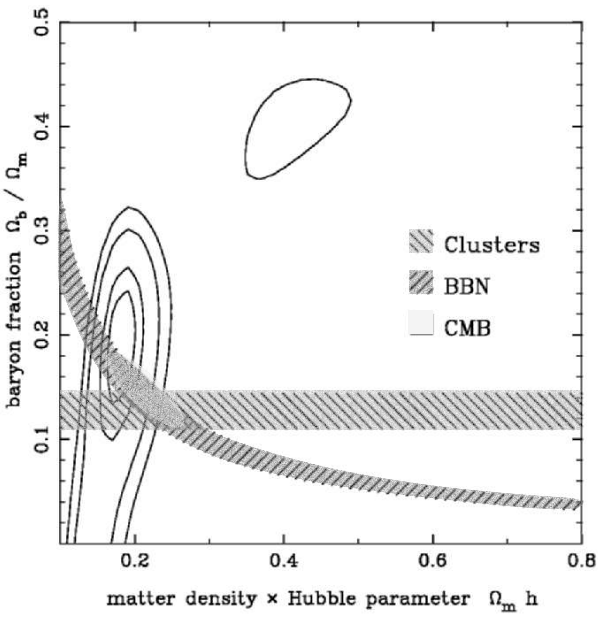
Cosmology by eye!



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:

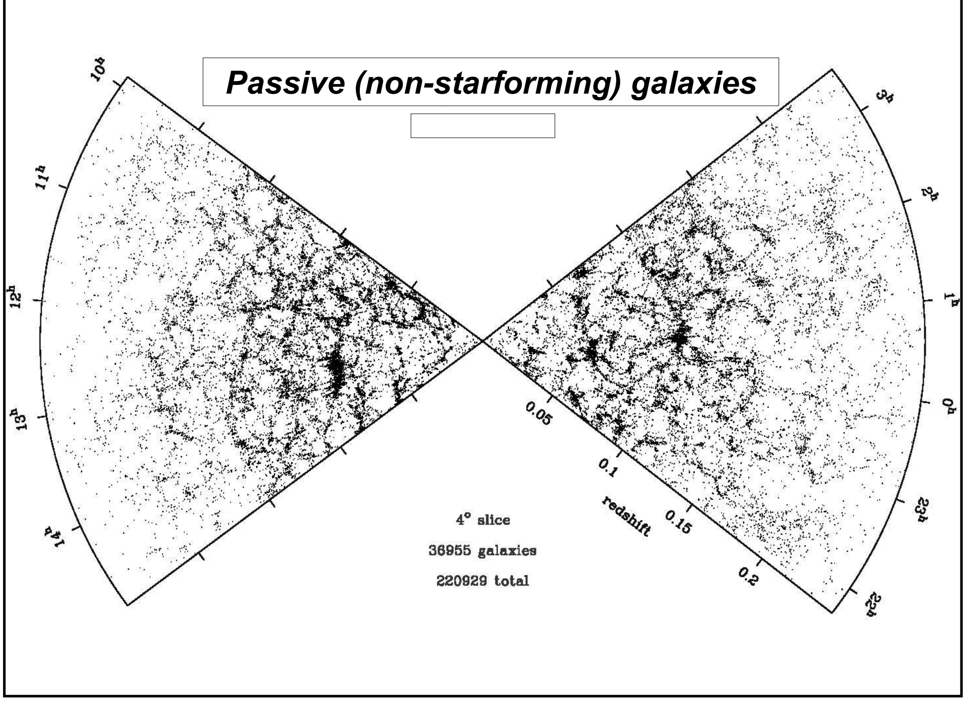
$\Gamma = \Omega_m h = 0.20 \pm 0.03$

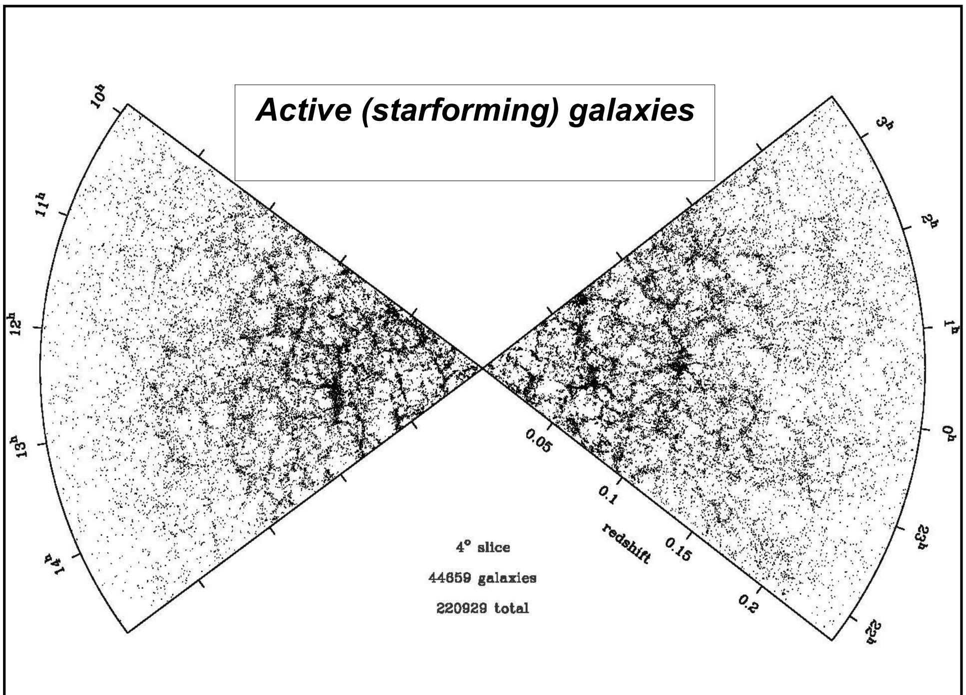
Baryon fraction =
$\Omega_b/\Omega_m = 0.15 \pm 0.07$

If require n=1:

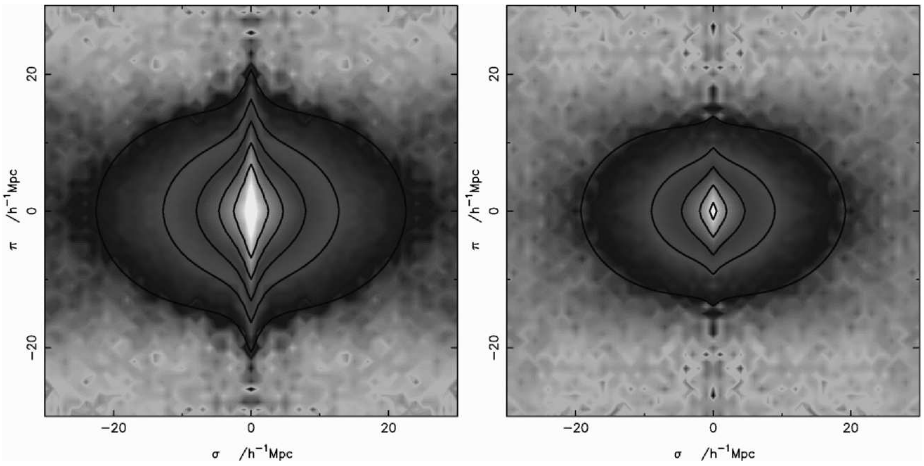
$\Gamma = \Omega_m h = 0.18 \pm 0.02$

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


Passive (non-starforming) galaxies
4° slice
36955 galaxies
220929 total
redshift
0.05
0.1
0.15
0.2


Active (starforming) galaxies
4° slice
44659 galaxies
220929 total
redshift
0.05
0.1
0.15
0.2

Redshift-space distortions and galaxy type

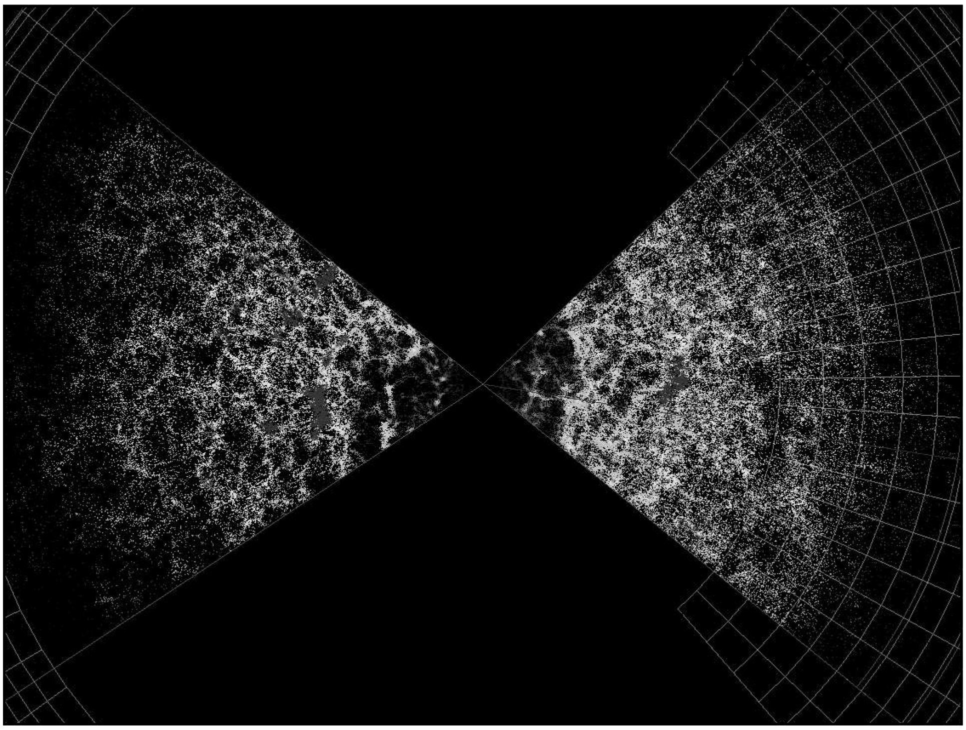


Passive:

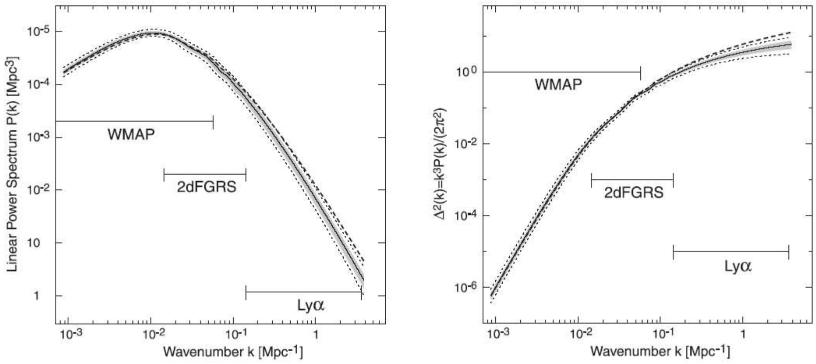
$\beta = \Omega^{0.6}/b = 0.46 \pm 0.13$

Active:

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

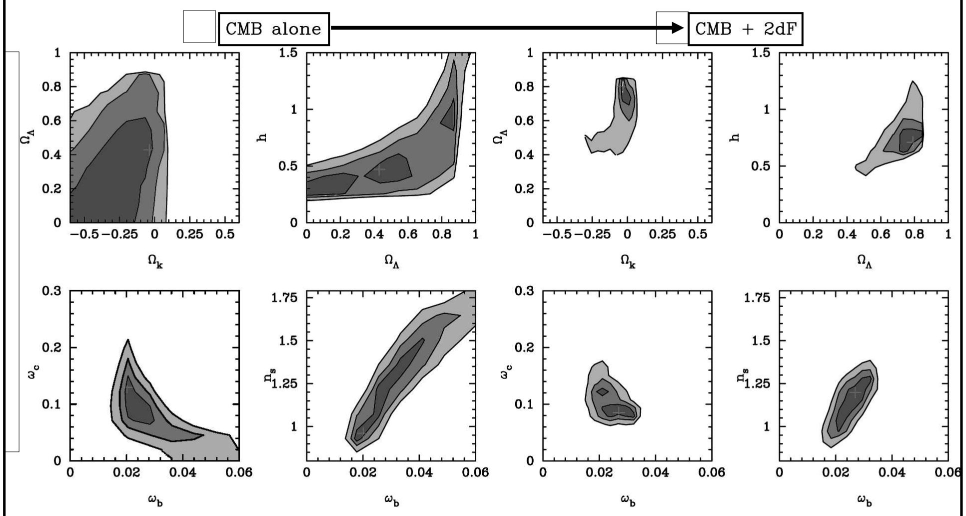


The Power Spectrum from all sources



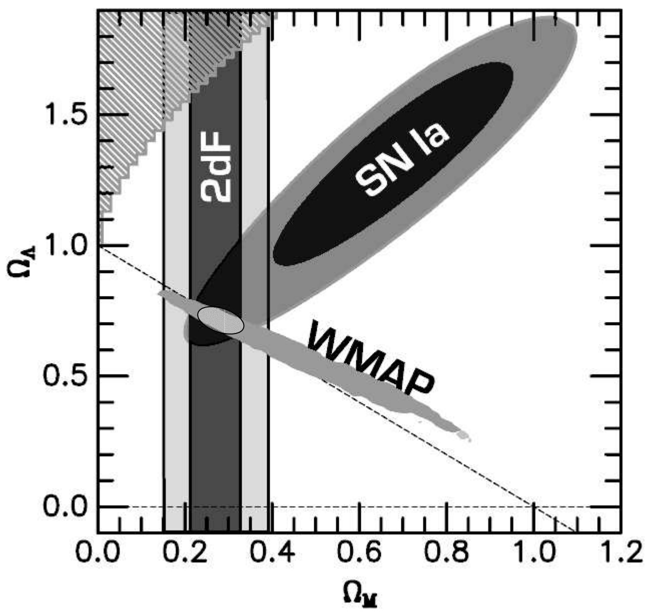
Spergel et al. 2003

Cosmology from 2dFGRS + CMB



The Cosmic Timeline

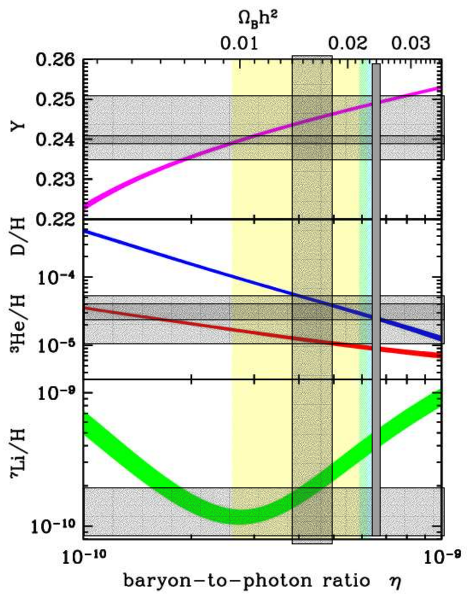
- ***CMB last scattering surface: (WMAP)***
  t_{dec} = 379 ± 8 *kyr*
  (z_{dec} = 1089 ± 1*)*
- ***Epoch of re-ionization?: WMAP and QSOs seem to disagree –***
  t_r = 100 - 1000 *Myr*
- ***Age of the universe today: SN +WMAP agree very well***
  t_0 = 13.7 ± 0.2 *Gyr*
- ***Hubble constant: (CMB+2dF, or Cepheids + SN Ia)***
  H_0 = 71 ± 4 km/s/Mpc



The ‘Concordance model’

(WMAP + 2dFGRS + SN Ia + HST KP)

Description	Symbol	Value	+ uncertainty	− uncertainty
Total density	Ω_{tot}	1.02	0.02	0.02
Equation of state of quintessence	w	< -0.78	95% CL	—
Dark energy density	Ω_Λ	0.73	0.04	0.04
Baryon density	$\Omega_b h^2$	0.0224	0.0009	0.0009
Baryon density	Ω_b	0.044	0.004	0.004
Baryon density (cm^{-3})	n_b	2.5×10^{-7}	0.1×10^{-7}	0.1×10^{-7}
Matter density	$\Omega_m h^2$	0.135	0.008	0.009
Matter density	Ω_m	0.27	0.04	0.04
Light neutrino density	$\Omega_\nu h^2$	< 0.0076	95% CL	—
CMB temperature (K)[a]	T_{cmb}	2.725	0.002	0.002
CMB photon density (cm^{-3})[b]	n_γ	410.4	0.9	0.9
Baryon-to-photon ratio	η	6.1×10^{-10}	0.3×10^{-10}	0.2×10^{-10}
Baryon-to-matter ratio	$\Omega_b \Omega_m^{-1}$	0.17	0.01	0.01
Fluctuation amplitude in $8h^{-1}$ Mpc spheres	σ_8	0.84	0.04	0.04
Low-z cluster abundance scaling	$\sigma_8 \Omega_m^{0.5}$	0.44	0.04	0.05
Power spectrum normalization (at $k_0 = 0.05$ Mpc^{-1})[c]	A	0.833	0.086	0.083
Scalar spectral index (at $k_0 = 0.05$ Mpc^{-1})[c]	n_s	0.93	0.03	0.03
Running index slope (at $k_0 = 0.05$ Mpc^{-1})[c]	$dn_s/d\ln k$	−0.031	0.016	0.018
Tensor-to-scalar ratio (at $k_0 = 0.002$ Mpc^{-1})	r	< 0.71	95% CL	—
Redshift of decoupling	z_{dec}	1089	1	1
Thickness of decoupling (FWHM)	Δz_{dec}	195	2	2
Hubble constant	h	0.71	0.04	0.03
Age of universe (Gyr)	t_0	13.7	0.2	0.2
Age at decoupling (kyr)	t_{dec}	379	8	7
Age at reionization (Myr, 95% CL))	t_r	180	220	80
Decoupling time interval (kyr)	Δt_{dec}	118	3	2
Redshift of matter-energy equality	z_{eq}	3233	194	210
Reionization optical depth	τ	0.17	0.04	0.04
Redshift of reionization (95% CL)	z_r	20	10	9
Sound horizon at decoupling (°)	θ_A	0.598	0.002	0.002
Angular diameter distance to decoupling (Gpc)	d_A	14.0	0.2	0.3
Acoustic scale[d]	ℓ_A	301	1	1
Sound horizon at decoupling (Mpc)[d]	r_s	147	2	2

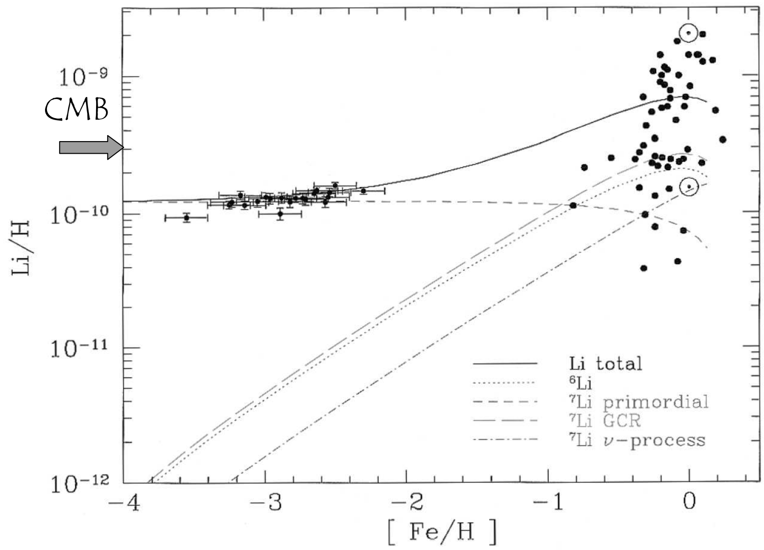


OK

OK

Yuk!

Lithium does evolve slowly due to SN? Or other sources..



Choose stars without convective envelopes…Measure…