Science From 21 cm Post-EOR Intensity Mapping Surveys

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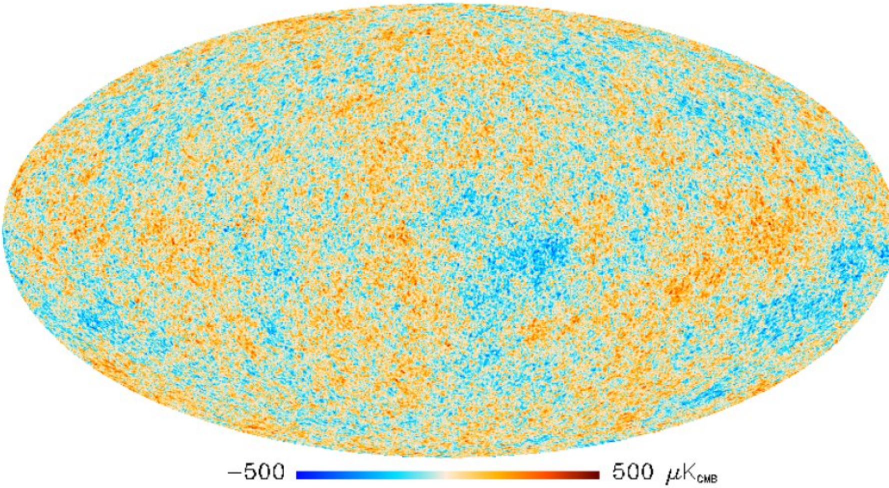
WHAT DO WE ALREADY KNOW ?

Planck ILC Map : Initial Conditions at $z \approx 1100$



Temperature (TT) power spectrum with residuals

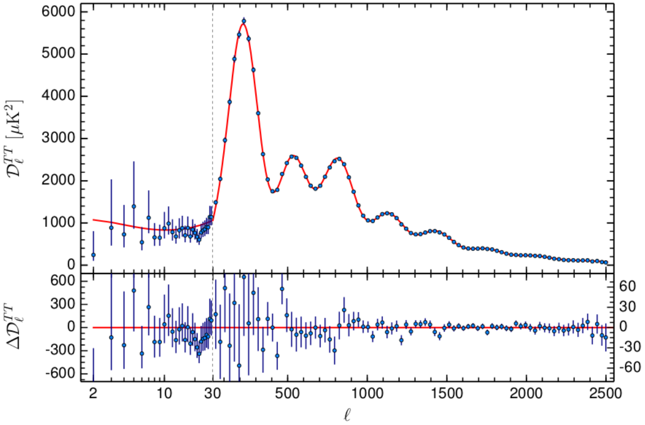
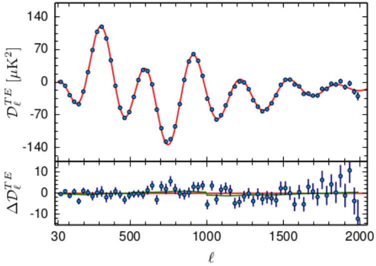
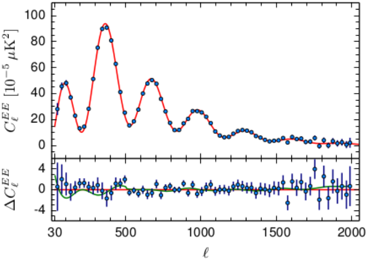


Fig. 1. The *Planck* 2015 temperature power spectrum. At multipoles $\ell \geq 30$ we show the maximum likelihood frequency averaged temperature spectrum computed from the `Plik` cross-half-mission likelihood with foreground and other nuisance parameters determined from the MCMC analysis of the base ΛCDM cosmology. In the multipole range $2 \leq \ell \leq 29$, we plot the power spectrum estimates from the `Commander` component-separation algorithm computed over 94% of the sky. The best-fit base ΛCDM theoretical spectrum fitted to the *Planck* TT+lowP likelihood is plotted in the upper panel. Residuals with respect to this model are shown in the lower panel. The error bars show ±1 σ uncertainties.

$$\mathcal{P}(k) = A_S (k/k_0)^{n_S - 1}$$

Polarization TE and EE spectra with residuals





Polarization Power Spectrum Reinforces Six-Parameter Orthodoxy

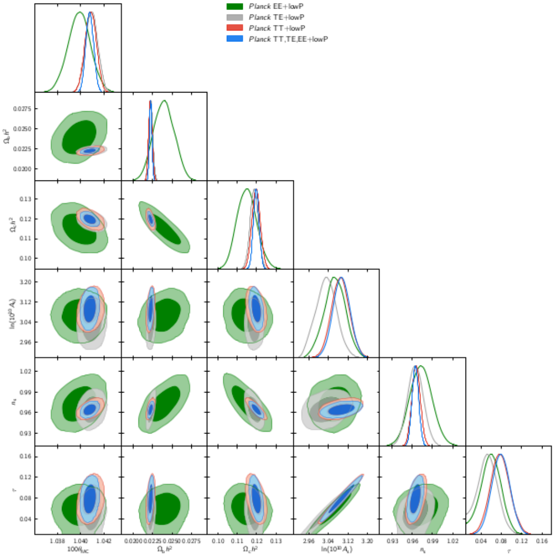


Fig. 6. Comparison of the base ΛCDM model parameter constraints from *Planck* temperature and polarization data.

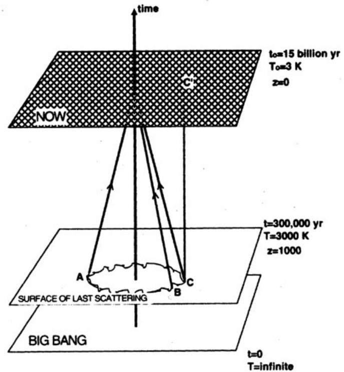
Theory – origin of the CMB anisotropy

Sachs-Wolfe formula

$$\frac{\delta T}{T}(\hat{\mathsf{n}}) = \left[\frac{1}{4}\delta_\gamma + \mathsf{v}_\gamma \cdot \mathsf{n} + \Phi i\right]_i^f + 2\int_i^f d\eta \frac{\partial \Phi'}{\partial \eta}(\eta, \hat{\mathsf{n}}(\eta_0 - \eta))$$

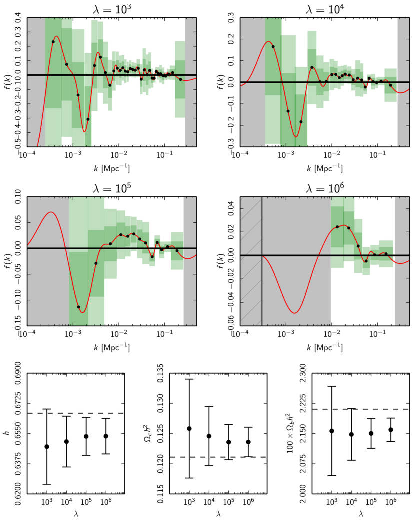
$\Phi \equiv$ Newtonian gravitational potential (dimensionless)

δ_γ and v_γ describe the fractional density contrast and peculiar 3-velocity of of the photon component.



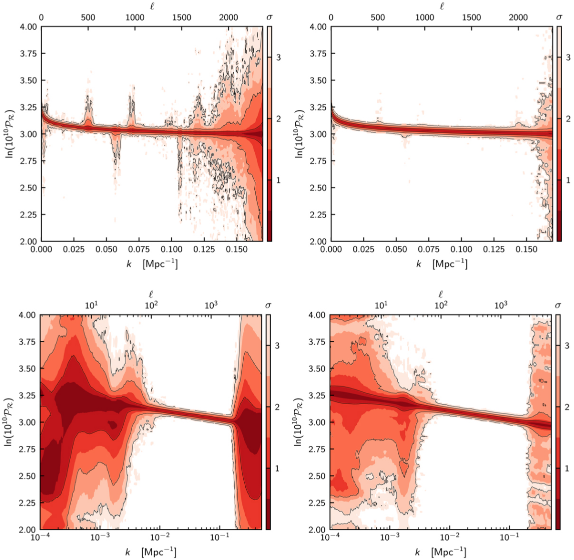
This treatment is somewhat naive in assuming that the surface of last scatter is infinitely thin.
In reality the surface of last scatter has a width that smears the small-scale anisotropies.

Wiggles in the primordial power spectrum ? (I)



Planck 2018 Results

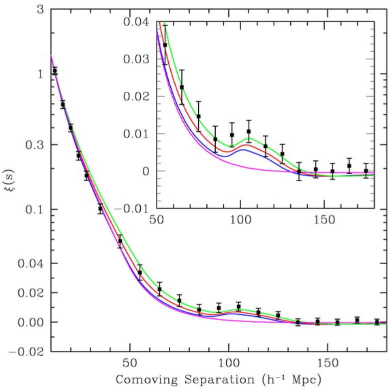
Wiggles in the primordial power spectrum ? (II)



Planck 2018 Results – Another point of view

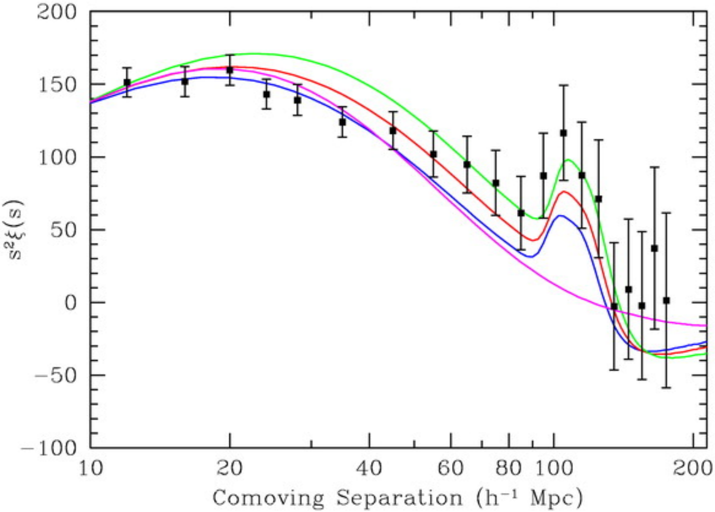
Seeing the Acoustic Oscillations in the Matter Power Spectrum

Baryon Acoustic Oscillations



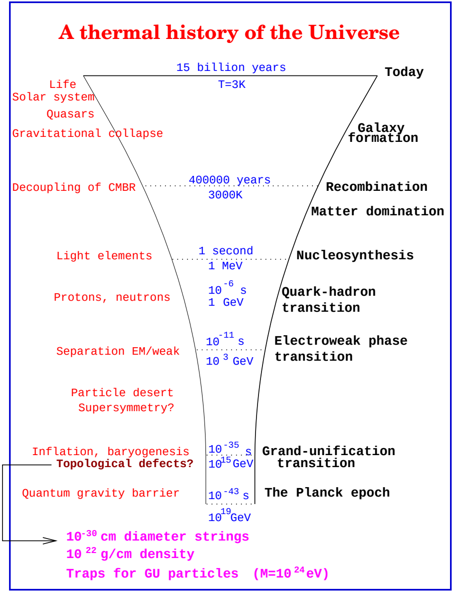
Eisenstein et al. (2005) First Detection with SDSS LRG with spectroscopic followup.

Same but multiplied by s^2



WHAT DON'T KNOW

Cosmic History in Perspective



A thermal history of the Universe

15 billion years — T=3K — **Today**

Life
Solar system
Quasars
Gravitational collapse

Galaxy formation

Decoupling of CMBR — 400000 years, 3000K — **Recombination**

Matter domination

Light elements — 1 second, 1 MeV — **Nucleosynthesis**

Protons, neutrons — 10^{-6} s, 1 GeV — **Quark-hadron transition**

Separation EM/weak — 10^{-11} s, 10^{3} GeV — **Electroweak phase transition**

Particle desert
Supersymmetry?

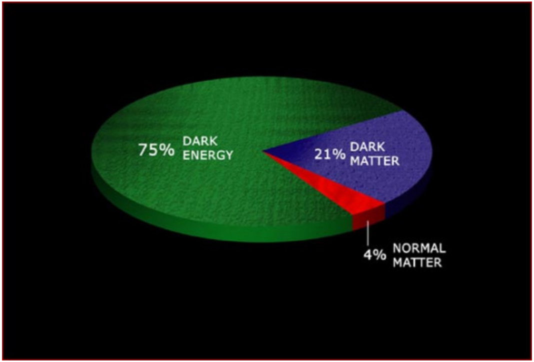
Inflation, baryogenesis — 10^{-35} s, 10^{15} GeV — **Grand-unification transition**

Topological defects?

Quantum gravity barrier — 10^{-43} s, 10^{19}GeV — **The Planck epoch**

10^{-30} cm diameter strings
10^{22} g/cm density
Traps for GU particles (M=10^{24}eV)

Breakdown of the Present Mean Energy Density of the Universe



Empirical Ansatz

$$w(a) = \frac{p(a)}{\rho(a)} = w_0 + (1-a)w_a$$

$w = -1$ or something else

Angular Diameter Distance and All That

$$a = (1+z)^{-1}, \qquad a_0 = 1 \qquad ds^2 = a^2(\eta)[-d\eta^2 + dx^2]$$

$$\begin{aligned} D_S(a) &= \Delta\eta(a) \\ &= \int_a^1 \frac{da}{a'} = \int_a^1 \frac{da}{a^2}\frac{a^2}{a'} = \int_a^1 \frac{da}{a^2}\frac{1}{H(a)} = H_0^{-1}\int_a^1 \frac{da}{a^2}\frac{H(a=1)}{H(a)} \\ &= H_0^{-1}\int_a^1 \frac{da}{a^2}\left(\Omega_\Lambda a^0 + \Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_w a^{-3(1+w)} + \dots\right)^{1/2} \end{aligned}$$

This is physical distance is co-moving coordinates today.
Let ℓ_{phys} be the transverse distance of an object at redshift $z = a^{-1} - 1$. The angle in subtended in the sky is given by

$$\Delta\theta = \frac{a^{-1}\ell_{phys}}{D_S(a)} = \frac{\ell_{phys}}{D_A(a)}$$

so that the **angular diameter distance** is defined as

$$D_A(a) = a\ D_S(a).$$

Claim : We can recover the expansion history of the universe from the run of $\theta(a)$ for a so-called "standard ruler."

Intensity Mapping : Advantages

Basic Idea :

- In the radio redshifts come for free. In the optical redshifts are extremely costly to acquire, especially spectroscopic reshifts.
- BAO needs large volumes because the BAO scale is very large, and good statistics because the correlations are small.
- Intensity Mapping acquires power spectrum directly using a coarse resolution. No need to catalogue individual objects.
- Data cube is 3d : 2d angle + frequency

The Forecasts (Bull et al. (2018)

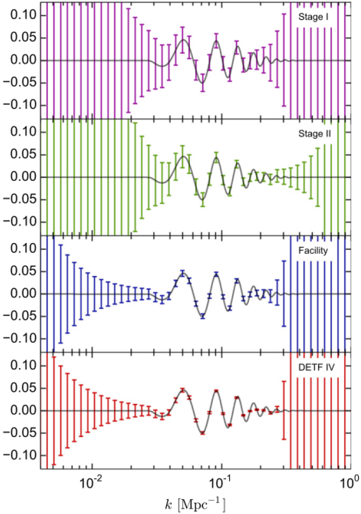


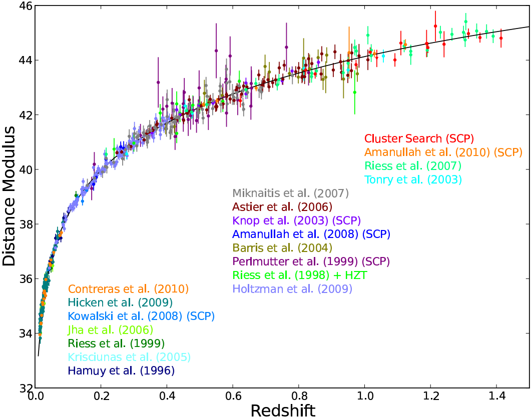
Figure 5. Forecast constraints on the BAO wiggles, combined over the whole redshift range for each of the reference surveys.

Intensity Mapping : Challenges

- The foregrounds are huge, but believed to be smooth. Galactic synchrotron emission is a combination of magentic fields + cosmic ray energy spectrum. Theory well understood. Formulas for emission frequency spetrum include broad smoothing kernels.
- Antenna chromaticity and antenna modelling. Antennas are electrically large. Antenna pattern changes as a function of frequency, and this can introduce artefacts. Antenna modelling software was developed for other purposes : (1) communication, (2) radar etc. to meet other less stringent requirements.
- Far sidelobes and the ground
- Radio frequency interference
- Calibration
- Untested : Signal detected in cross-correlation so far, but forecasts (eg Bull et al.) have not yet been realized in practice.
- Advantages : Comparatively inexpensive. Different systematic errors.

Preview : Devin Crichton HIRAX talk later this week

The Competition : Type Ia Supernovae



The Problem : Systematic Errors and Evolution

Errors do not go down as $1/\sqrt{N}$

Alcock-Paczynski Test (1979)

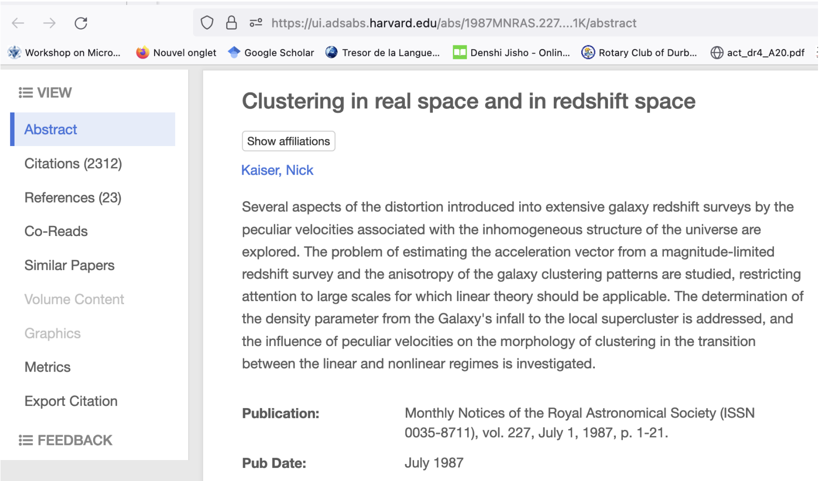
Basic Idea Suppose we have a set of large standard spheres (or objects that on the average are spherical) at various redshifts. From $\Delta\theta/\Delta z$ we may obtain an additional independent constraint on the cosmological model.

We are sensitive to $H(a)$

Caveat : The analysis seems to ignore the "pancakes of God", discussed in the next section, from Kaiser (1987).

Redshift Distortion - Pancakes of God versus Fingers on God

$$\delta_{HI}(\mathsf{k}_{\mathrm{app}}) = \left(b_{HI} + f\mu^2\right) \exp\left(-\mu^2 k^2 \sigma_{NL}^2\right) \delta_{prim}(\mathsf{k})$$



Clustering in real space and in redshift space

Kaiser, Nick

Several aspects of the distortion introduced into extensive galaxy redshift surveys by the peculiar velocities associated with the inhomogeneous structure of the universe are explored. The problem of estimating the acceleration vector from a magnitude-limited redshift survey and the anisotropy of the galaxy clustering patterns are studied, restricting attention to large scales for which linear theory should be applicable. The determination of the density parameter from the Galaxy's infall to the local supercluster is addressed, and the influence of peculiar velocities on the morphology of clustering in the transition between the linear and nonlinear regimes is investigated.

Publication:	Monthly Notices of the Royal Astronomical Society (ISSN 0035-8711), vol. 227, July 1, 1987, p. 1-21.
Pub Date:	July 1987

From e.g. Peebles (1980) Large-Scale Structure of the Universe

$$\delta \equiv \text{(density contrast)}$$

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G\rho_0\delta = 0$$

$$\ddot{\delta} + 2H\dot{\delta} - \frac{3}{2}H\Omega_m\delta = 0$$

$$\delta(\mathrm{x}, t) = A_g(\mathrm{x})D_g(t) + A_d(\mathrm{x})D_d(t) \approx A_g(\mathrm{x})D_g(t)$$

For $\Omega_m = 1,\ D_g \sim t^{2/3} \sim a$ and $D_d \sim t^{-1} \sim a^{-3/2}$.

$$f = \frac{d\ \ln D_g}{d\ \ln a}$$

For a general cosmology we can use a fitting function (Lahav) :

$$f(\Omega_0, \Omega_\Lambda) = {\Omega_0}^{0.6} + \frac{\Omega_\Lambda}{70}\left(1 + \frac{\Omega_0}{2}\right)$$

$$\nabla \cdot \mathrm{v} = -\dot{\delta} = -fH\delta$$

We can thus “weigh” the universe

$$f(\Omega) = \frac{H^{-1}(\nabla \cdot \mathrm{v})}{\delta}$$

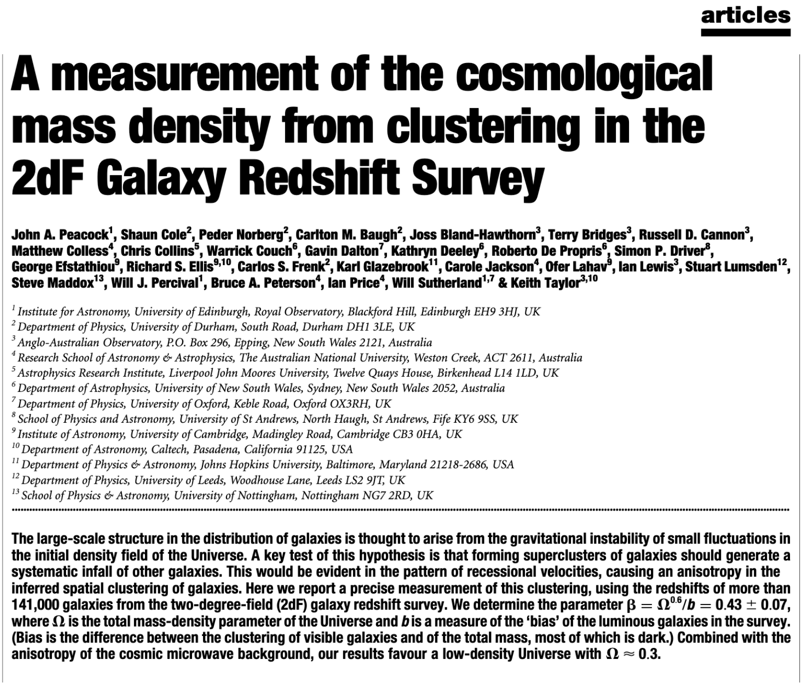
Pre-Kaiser received wisdom (from very famous people) :

> *"A study of these questions can be made using the RSA itself with its nearly complete velocity coverage because the three-dimensional distribution of its member galaxies can be found. The assumption that velocities measure radial distance is a good first approximation since, as just mentioned, the mean random motion about the Hubble flow is so small (de Vaucouleurs 1958 ; Sandage 1972, 1975 ; Sandage and Tammann 1975), and clearly there are no large systematic perturbations (Tammann, Sandage, and Yahil 1980)."*

Amos Yahil, Allan Sandage, and G.A. Tammann, THE VELOCITY FIELD OF BRIGHT NEARBY GALAXIES. HI. THE DISTRIBUTION IN SPACE OF GALAXIES WITHIN 80 MEGAPARSECS : THE NORTH GALACTIC DENSITY ANOMALY Astrophysical Journal 242 (1980) 448

Conclusion :

$$q_0 = -\frac{\ddot{a}a}{\dot{a}^2} \ll 0.5$$



A measurement of the cosmological mass density from clustering in the 2dF Galaxy Redshift Survey

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The large-scale structure in the distribution of galaxies is thought to arise from the gravitational instability of small fluctuations in the initial density field of the Universe. A key test of this hypothesis is that forming superclusters of galaxies should generate a systematic infall of other galaxies. This would be evident in the pattern of recessional velocities, causing an anisotropy in the inferred spatial clustering of galaxies. Here we report a precise measurement of this clustering, using the redshifts of more than 141,000 galaxies from the two-degree-field (2dF) galaxy redshift survey. We determine the parameter $\beta = \Omega^{0.6}/b = 0.43 \pm 0.07$, where Ω is the total mass-density parameter of the Universe and b is a measure of the 'bias' of the luminous galaxies in the survey. (Bias is the difference between the clustering of visible galaxies and of the total mass, most of which is dark.) Combined with the anisotropy of the cosmic microwave background, our results favour a low-density Universe with $\Omega \approx 0.3$.

Redshift Distortion as Seen by 2dF

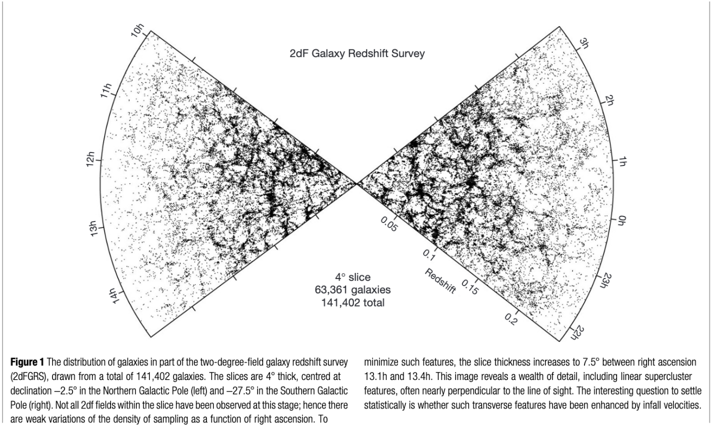


Figure 1 The distribution of galaxies in part of the two-degree-field galaxy redshift survey (2dFGRS), drawn from a total of 141,402 galaxies. The slices are 4° thick, centred at declination –2.5° in the Northern Galactic Pole (left) and –27.5° in the Southern Galactic Pole (right). Not all 2df fields within the slice have been observed at this stage; hence there are weak variations of the density of sampling as a function of right ascension. To minimize such features, the slice thickness increases to 7.5° between right ascension 13.1h and 13.4h. This image reveals a wealth of detail, including linear supercluster features, often nearly perpendicular to the line of sight. The interesting question to settle statistically is whether such transverse features have been enhanced by infall velocities.

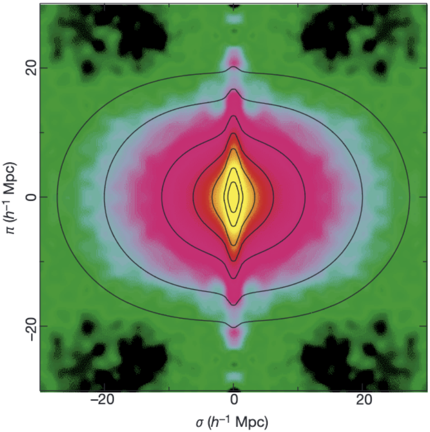
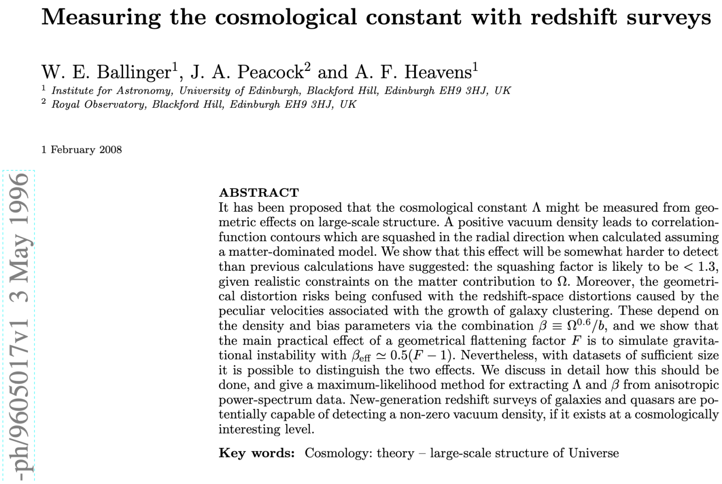


Figure 2 The redshift-space correlation function for the 2dFGRS, $\xi(\sigma,\pi)$, plotted as a function of transverse (σ) and radial (π) pair separation. The function was estimated by counting pairs in boxes of side 0.2 h^{-1} Mpc, and then smoothing with a gaussian of r.m.s. width 0.5 h^{-1} Mpc. To illustrate deviations from circular symmetry, the data from the first quadrant are repeated with reflection in both axes. This plot clearly displays redshift distortions, with finger-of-God elongations at small scales and the coherent Kaiser flattening at large radii. The overplotted contours show model predictions with flattening parameter $\beta \equiv \Omega^{0.6}/b = 0.4$ and a pairwise dispersion of $\sigma_p = 400\,\mathrm{km\,s^{-1}}$. Contours are plotted at $\xi = 10, 5, 2, 1, 0.5, 0.2$ and 0.1.

The model predictions assume that the redshift-space power spectrum (P_s) may be expressed as a product of the linear Kaiser distortion and a radial convolution[37]: $P_s(\mathbf{k}) = P_r(k)(1+\beta\mu^2)^2(1+k^2\sigma_p^2\mu^2/2H_0^2)^{-1}$, where $\mu = \hat{\mathbf{k}}\cdot\hat{\mathbf{r}}$, and σ_p is the r.m.s. pairwise dispersion of the random component of the galaxy velocity field. This model gives

Implementation not so simple, but redshift distortion here to stay



Measuring the cosmological constant with redshift surveys

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1 February 2008

ABSTRACT
It has been proposed that the cosmological constant Λ might be measured from geometric effects on large-scale structure. A positive vacuum density leads to correlation-function contours which are squashed in the radial direction when calculated assuming a matter-dominated model. We show that this effect will be somewhat harder to detect than previous calculations have suggested: the squashing factor is likely to be < 1.3, given realistic constraints on the matter contribution to Ω. Moreover, the geometrical distortion risks being confused with the redshift-space distortions caused by the peculiar velocities associated with the growth of galaxy clustering. These depend on the density and bias parameters via the combination $\beta \equiv \Omega^{0.6}/b$, and we show that the main practical effect of a geometrical flattening factor F is to simulate gravitational instability with $\beta_{\rm eff} \simeq 0.5(F-1)$. Nevertheless, with datasets of sufficient size it is possible to distinguish the two effects. We discuss in detail how this should be done, and give a maximum-likelihood method for extracting Λ and β from anisotropic power-spectrum data. New-generation redshift surveys of galaxies and quasars are potentially capable of detecting a non-zero vacuum density, if it exists at a cosmologically interesting level.

Key words: Cosmology: theory – large-scale structure of Universe

Summary

- Intensity Mapping is a low-cost alternative to conventional galaxy surveys, with independent systematic errors, and is well worth pursuing
- The lack of direct link between redshift and radial distance is both a curse and a blessing. There is more to explore than simply the BAO scale. In principle, there are a number of cross-checks and redundancies in the data.
- It will be exciting to see to what extent the full dream of learning about the dark energy through intensity mapping will be realized.