Part 7

Concluding Remarks

https://doi.org/10.1017/S1743921305002255 Published online by Cambridge University Press

John A. Peacock

https://doi.org/10.1017/S1743921305002255 Published online by Cambridge University Press

Impact of Gravitational Lensing on Cosmology
Proceedings IAU Symposium No. 225, 2004
Mellier, Y. & Meylan, G. eds.

doi:10.1017/S1743921305002255

Gravitational Lensing: Past and Future

J.A. Peacock[1]

[1]Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK. email: jap@roe.ac.uk

Abstract. The subject of gravitational lensing is now a mature discipline, with an automatic place in cosmology. The robust mass measures provided by lensing are one of the key reasons for having confidence in the standard model of structure formation. For the future, things are more challenging: the next set of interesting questions requires the measurement of small effects with non-trivial systematics. The real question will be whether lensing can overcome these problems rapidly enough that it becomes the most precise probe of the cosmological parameters, in particular the equation of state of the vacuum and its evolution.

1. Preamble

This has been a wonderful meeting, full of so many impressive results that an effective summary is impossible. Fortunately, this is not my task; rather, the organisers asked me to be provocative. I will therefore try to give a critical view of the field of lensing and where it is going. In the end, I expect to sound rather like John Cleese in Monty Python's *Life of Brian*, complaining that the Romans never did anything for the Judeans (apart from roads, sanitation, education, public order...).

2. A brief history of lensing

Looking over the history of this subject, it seems that lensing has just come of age. The first large international meeting devoted to the subject was the 1983 Liège meeting, 21 years ago (Swings 1983). It's sobering to think how few of the speakers then are still here to speak today. Certainly, at that time only a few elements of the current subject were in place: mainly the analysis of lensing cross-sections, amplification selection effects, and H_0 from time delays. Since then, there is some evidence for quantization of interest in lensing on roughly decadal intervals: Liège again in 1993 (Surdej *et al.* 1993) and Melbourne in 1995 (Kochanek & Hewitt 1996). By this time, most of the subject matter is recognisable: limits on Λ; weak lensing; cluster arcs; galaxy-galaxy lensing; MACHO searches. The current meeting fits the decadal trend, and allows us to look forward to the IAU's next upsurge of interest in lensing sometime around 2015. Judging by the number of proposed facilities due for completion at or around this date, it should be a vintage period in cosmology.

To start with a warning about the dangers of prediction, it is instructive to look at an observation by Bill Press (1996). In the closing summary of the 1995 Melbourne meeting, he noted that the number of papers per unit time on lensing was rising exponentially, with a doubling time of about four years. The implication of this trend was that lensing would dominate astronomical research by about the year 2008. Of course, I couldn't resist checking this prediction, and the result is shown in figure 1: it looks like lensing researchers have been taking things too easily in the last few years. More charitably, lensing has made the demographic transition from the exponential startup phase, to being a standard part of the wider picture in cosmology.

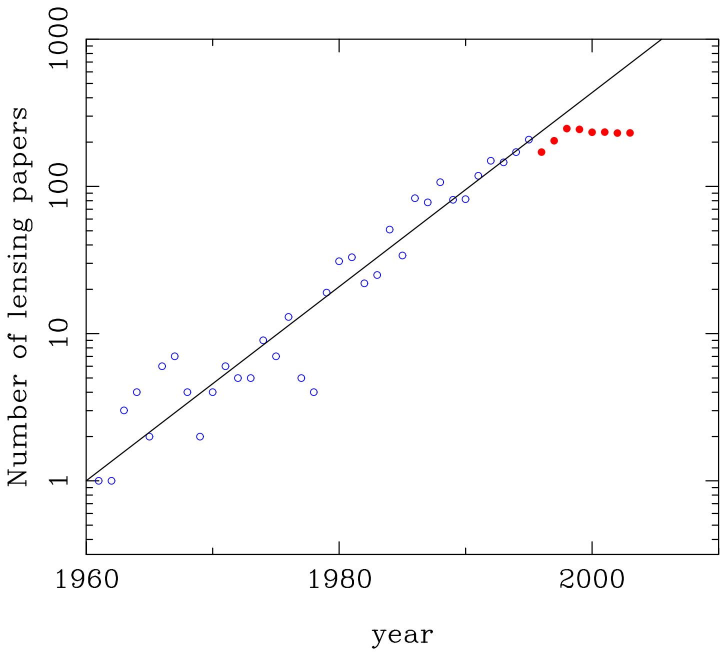

Figure 1. Press's Law (1996) stated that the rate of production of lensing papers was doubling roughly every four years, so that lensing should by now be close to dominating world astronomy. According to the bibliography in Surdej (2004), this is not happening: the subject has reached equilibrium at around 250 papers per year. The lesson is that predictions for the future of this subject should not be taken too seriously.

Press also defined a series of future challenges for lensing. We don't need to consider the whole list, but the top 'not whether, but when' items are instructive. These were (1) measure H_0 to 2 figures; (2) show that $\Lambda < 0.5$; (3) measure Ω to one figure; (4) map the MW bar with microlensing. The latter two are coming along well, but item (2) is false, and there must be major doubt whether item (1) will ever be achieved through lensing (see later). Having poured a little scorn on Press, I am now nicely positioned to make some predictions (doubtless wildly misguided) of my own, so that whoever gives the closing talk in 2015 will have plenty of ammunition.

3. The future of cosmology

3.1. *Goals*

Looking ahead a decade or so, we can afford to set ambitious targets. Therefore, with our present knowledge, what questions would need to be answered in order to claim that cosmology was solved? (the 'known unknowns', in Rumsfeld–speak). One can divide these into two lists. There is fundamental physics:

(1) Can we prove inflation happened?
(2) What is the dark matter?
(3) What is the vacuum energy?
(4) How did baryogenesis happen?
(5) Do fundamental constants vary?
(6) Are there extra dimensions?

https://doi.org/10.1017/S1743921305002255 Published online by Cambridge University Press

We also have 'gastrophysical' targets:

(1) Measure the galaxy merger history
(2) Understand the relation of this to star formation
(3) Understand how feedback regulates star formation
(4) Measure the ionization and metal history of the IGM

3.2. *Potential contribution of lensing*

Lensing is likely to contribute to these goals to varying degrees. At the simplest level, the importance of straightforward gravity telescopes is certain to continue. As we reach diminishing returns on new instrumentation and growth in telescope aperture, there will be a growing attraction in targeting special amplified objects similar to cB58 (e.g. Teplitz *et al.* 2004). Indeed, these studies may tell as as much about the gastrophysical questions as all the studies of non-lensed objects put together.

On the fundamental-physics side, the greatest expected impact of lensing is likely to be in the areas of inflation and vacuum energy. Sticking to my brief, I will take a critical view of these topics.

4. Scepticism

4.1. *Inflation*

Testing whether inflation is the correct theory of initial conditions is really the outstanding aim of cosmology. In recent years, there have been some egregious attempts to move the goalposts, so that inflation becomes true by definition provided the CMB sky contains super-horizon perturbations. This must be resisted: a proof of inflation requires evidence that there was a period of nearly de Sitter expansion driven by vacuum energy. The only characteristic relics of this era that have been suggested are the tilt of the scalar spectrum and the existence of gravity waves.

Tilt alone is an interesting signature. If $n \neq 1$, would that prove inflation? Prior to inflation being suggested, it was common to consider the scale-invariant $n = 1$ to be generic (no preferred scale in the metric). But this is not right: the pre-inflationary view of the origin of inhomogeneities was a vague hope that it was all connected in some way with quantum gravity, so the Planck scale should enter. In the spirit of many field-theory calculations that show log divergences, it might not be surprising for the scale-dependence of the horizon-scale amplitude to look like

$$\delta_{\rm H}(L) = \epsilon \ln(L/L_{\rm Planck}). \tag{1}$$

The present-day horizon at the Planck time had a size $\sim 10^{-5}$ m, which requires $\epsilon \sim 10^{-7}$ and suggests a tilt of $n - 1 = 2/\ln(L/L_{\rm Planck}) \simeq 0.03$.

Therefore, measuring a small tilt would not really allow us to state with much confidence that we have detected a scalar-field potential and shown it to be flat. The more generic signature of the de Sitter phase is that fluctuations in all fields are excited, so that there is a tensor contribution to the CMB:

$$C_\ell^{\rm tensor} \propto H^2_{\rm inflation} \propto E^4_{\rm inflation} \tag{2}$$

We really need to see both tilt and this signature to be at all convinced. As an aside, note the depressing fact that improving limits on r (the tensor–to–scalar power ratio) by a factor of 10^4 only improves knowledge of $E_{\rm inflation}$ by one power of 10. In practice, $E_{\rm inflation}$ will need to be not far below current limits if we are to have a chance of seeing anything.

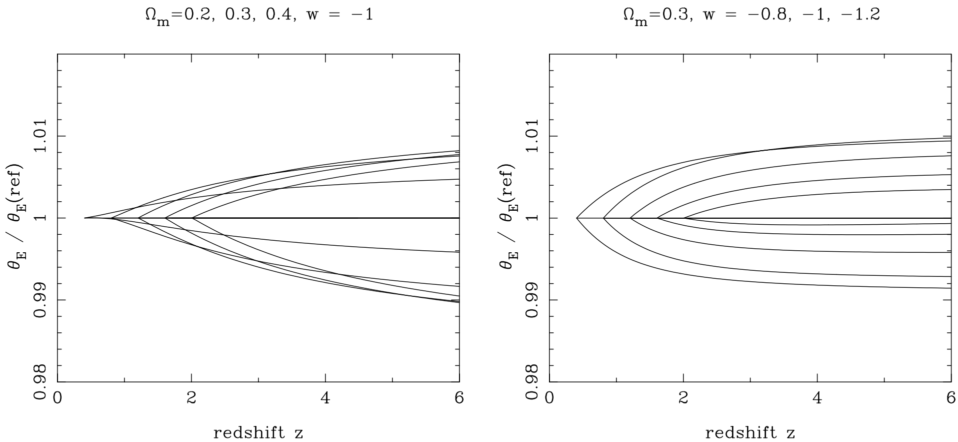

Figure 2. Interesting variations of cosmological parameters yield rather small changes in lensing properties. These plots show the Einstein-ring radius for a lens at redshifts between 0.5 & 2, as a function of source redshift. The vertical normalization is free, corresponding to the unknown lens mass. Changes of the cosmological parameters at an interesting level require measurements of lensing distortion as a function of redshift with much better than 1% precision.

4.2. *The vacuum*

Let us now turn to the equation of state of the vacuum. I have not yet uttered the appalling term 'dark energy'; this is because we surely have to find a better name for the stuff that is neither radiation nor baryons nor dark matter. We need a title that clearly distinguishes it from these, whereas 'dark energy' and 'dark matter' are virtually identical in meaning. The two things we know are that it is close to homogeneous and endowed with negative pressure; 'dark tension' would be a sensible possibility, but I plan to stick with 'vacuum energy'. I don't see that this term need imply a simple cosmological constant.

A measurement of $w \equiv P/\rho c^2$ and its evolution is one of the key future goals for cosmology. Lensing has a good chance of taking the lead in this purely geometrical aim. However, it should be remembered that we will be relying on $\sqrt{n}$ to detect rather small effects – cf. figure 2. This shows how the Einstein-ring radius for a lens varies with redshift for different cosmological parameters, relative to a standard model with $\Omega_m = 0.3$, $w = -1$. The size of the ring changes by $< 1\%$ for interesting variations in these parameters. Moreover, the effects of changing Ω_m and w are clearly degenerate to some extent. A measurement of w to interesting accuracy (5% or better, say) apparently requires both control of systematics in image positions at the 10^{-3} level and a knowledge of Ω_m to an error of $\lesssim 0.01$. This will be challenging, but in principle large surveys with photometric redshifts will mean that there is no S/N barrier to detecting the effect. This has led to considerable discussion of 'lensing tomography' as a future goal (e.g. Jain & Taylor 2003; Hu & Jain 2004).

A more direct signature of $w \neq 1$ is that it affects the growth rate of structure, manifesting itself as a mismatch between the value of σ_8 extrapolated from the CMB assuming $w = -1$ and the (nearly) local value deduced from weak lensing (see e.g. figure 10 of Refregier 2003). There are two problems with this: the precision of σ_8 from the CMB is only moderate while the optical depth to last scattering remains poorly known; the precision of the weak-lensing power spectrum is highest on small scales, where nonlinear effects need to be modelled accurately. The exact nonlinear evolution of the matter power spectrum is probably now known to sufficient accuracy (e.g. Smith *et al.* 2003), but this

https://doi.org/10.1017/S1743921305002255 Published online by Cambridge University Press

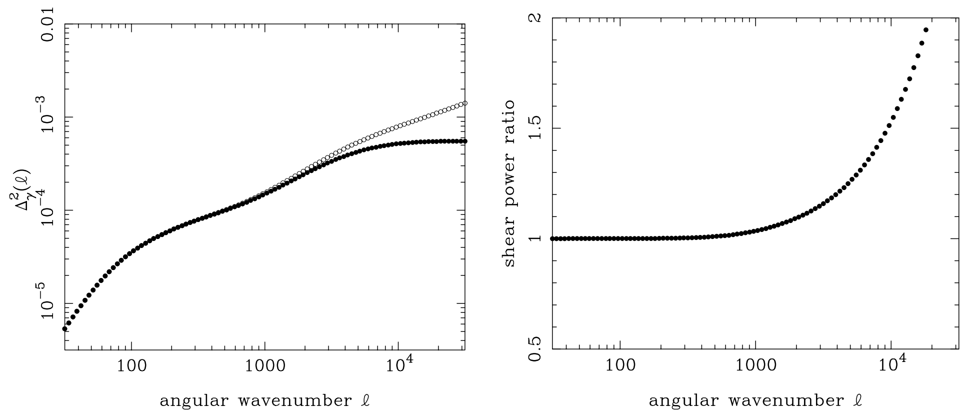

Figure 3. A computation of the weak-lensing power spectrum in the halo model for sources at $z = 2$, indicating the effect of a simple assumption for the redistribution of baryons. The solid points show the case of assumed isothermal haloes, with $\rho \propto 1/r^2$. The open circles correspond to the 20% baryon fraction being given the slightly steeper form $\rho \propto 1/r^{2.5}$, with corresponding adiabatic compression of the dark matter. The second panel shows the fractional change in power. Such effects are of order the shifts expected from interesting changes in cosmological parameters.

is not enough. Plausible changes of the baryon distribution within dark-matter haloes have a significant effect, as shown in figure 3. See White (2004) or Zhan & Knox (2004) for similar calculations. It will not be easy to be certain that these effects are modelled robustly enough to permit the extraction of the information about w.

In any case,

$$w = -1. \tag{3}$$

I state this as a strong prejudice, in the hope that by making it a prediction, it will turn out to be wrong. Certainly, we should take every opportunity to measure the observed value. Nevertheless, it should be remembered that the theoretical grounds for expecting deviations from $w = -1$ are less sound than e.g. the inflationary motivation for $|n-1| \sim 0.01$. The reason for being sceptical about deviations from $w = -1$ is anthropic: we as observers ask why we are living just when the vacuum is starting to become important, and the answer to a question involving observers must also involve observers: i.e. the selection effect that large values of Λ suppress galaxy formation. The only attractive alternative is to appeal to what might be called 'single-universe' anthropic reasoning, in which structure formation requires that we live not too long after matter-radiation equality. If only a dynamical Λ could be switched on by this change in equation of state, the vacuum coincidence problem would be solved. This seems hard to achieve, for two reasons.

The usual approach is the 'quintessence' programme in which the vacuum energy is a rolling scalar field (Ratra & Peebles 1988). However, changing the rolling behaviour around matter-radiation equality requires fine tuning of the potential shape (Liddle & Scherrer 1999). Worse, all such potentials are chosen so that they fall asymptotically to zero, even though a fundamental solution to this 'cosmological constant problem' has never been found. It is therefore much more reasonable to consider what might be dubbed 'anthropic quintessence': a potential that crosses zero, and which which can be adequately approximated by a linear term $V = A\phi$. In an ensemble of universes with random values of ϕ, this generates a range of effective values for Λ. Once the ensemble is weighted by galaxy density, this disfavours extreme values of V – but there is no prejudice in favour

https://doi.org/10.1017/S1743921305002255 Published online by Cambridge University Press

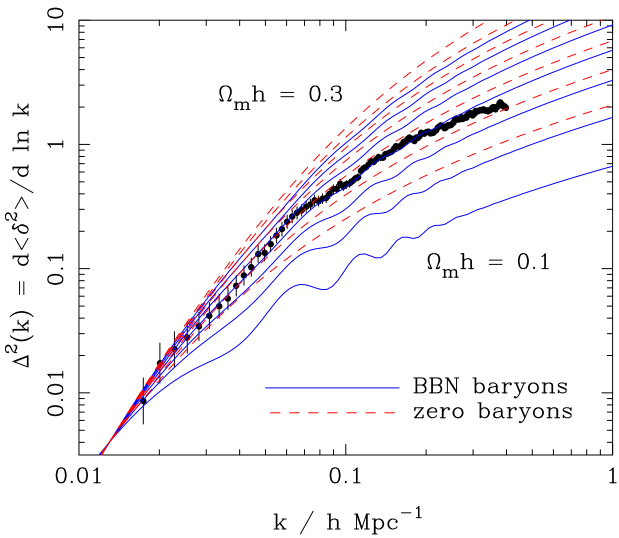

Figure 4. The 2dFGRS redshift-space dimensionless power spectrum, $\Delta^2(k)$. The solid points with error bars show the power estimate. The window function correlates the results at different k values, and also distorts the large-scale shape of the power spectrum. An approximate correction for the latter effect has been applied. The solid and dashed lines show various CDM models, all assuming $n = 1$. For the case with non-negligible baryon content, a big-bang nucleosynthesis value of $\Omega_b h^2 = 0.02$ is assumed, together with $h = 0.7$. Model fitting is generally performed only at $k < 0.15\, h\,\mathrm{Mpc}^{-1}$ in order to avoid the complications of nonlinearities and redshift-space distortions.

of being so extremely close to $\phi = 0$ that V will be evolving at a significant rate (as the field becomes close to changing sign and sending us on the way to a future big crunch). The expectation is therefore that we are in the regime where w is indistinguishable from -1 (Garriga & Vilenkin 2000). This conclusion should stimulate the many people who display an (inexplicable) aversion to anthropic reasoning: by proving that $w \neq -1$, one could effectively show that this is not the correct route to understanding the vacuum energy.

5. The competition

So far, I have not been concerned about whether lensing will be the first or best way of achieving these goals, but this has to be considered. To date, large-scale aspects of lensing have arguably done no more than detect something consistent with predictions. For example, the data on weak shear allow us to reject the $\Omega_m = 1$ CDM model – only about a decade after it was first ruled out. Although alternative confirmation of important facts is always welcome, the real challenge for lensing is to get ahead of the game and be the leading technique.

5.1. *Large-scale structure*

The current best cosmological knowledge comes from the use of large-scale structure and the CMB as a probe, so it is worth giving a brief summary of where this stands, and where the limits are likely to be in a few years. On the LSS side, we now know the 3D distribution of over 500,000 galaxies between the 2dF Galaxy Redshift Survey (2dFGRS; Colless *et al.* 2001, 2003) and the SDSS (Abazajian *et al.* 2004).

https://doi.org/10.1017/S1743921305002255 Published online by Cambridge University Press

The results of direct estimation of the 3D power spectrum from the 2dFGRS are shown in figure 4 (Percival *et al.* 2001). Note that cosmological constraints from the SDSS power spectrum are not yet as precise (Tegmark *et al.* 2004; Pope *et al.* 2004). The fundamental assumption is that, on large scales, linear biasing applies, so that the nonlinear galaxy power spectrum in redshift space has a shape identical to that of linear theory in real space. This assumption is valid for $k < 0.15\,h\,\mathrm{Mpc}^{-1}$; the detailed justification comes from analyzing realistic mock data derived from N-body simulations (Cole *et al.* 1998). The free parameters in fitting CDM models are thus the primordial spectral index, n, the Hubble parameter, h, the total matter density, Ω_m, and the baryon fraction, Ω_b/Ω_m. Note that the vacuum energy does not affect the constraints. Initially, we show results assuming $n = 1$; this assumption is relaxed later. Cole *et al.* (in preparation) give a final analysis, which supersedes that of Percival *et al.* (2001). The preferred solution is

$$\Omega_m h = 0.17 \pm 0.02; \qquad \Omega_b/\Omega_m = 0.19 \pm 0.05 \tag{4}$$

(provisional values). The density is certainly lower than in 2001, and this is almost entirely a result of cosmic variance, reflecting the signal from the newly-included areas.

5.2. *Combination with the CMB and parameter degeneracies*

In order to measure the full set of parameters, it is necessary to combine with the information in the CMB. This has its own degeneracies, which are only properly lifted in a joint analysis of this sort (see e.g. Efstathiou *et al.* 2002). The CMB data alone contain both 'geometrical' and 'tensor' degeneracies. In the former case, one can evade the commonly-stated CMB conclusion that the universe is flat, by adjusting both Λ and h to extreme values (e.g. Efstathiou & Bond 1999). If we take a family of models with fixed initial perturbation spectra, fixed physical densities $\omega_m \equiv \Omega_m h^2$, $\omega_b \equiv \Omega_b h^2$, and vary both Ω_v and the curvature to keep a fixed value of the angular size distance to last scattering, then the resulting CMB power spectra are identical (except for the Integrated Sachs-Wolfe effect at very low multipoles, and second-order effects at high ℓ). This degeneracy occurs because the physical densities control the structure of the perturbations in physical Mpc at last scattering, while curvature, Ω_v and Ω_m govern the proportionality between length at last scattering and observed angle. In order to break the degeneracy, additional information is needed. This could be in the form of external data on the Hubble constant, but the most elegant approach is to add the 2dFGRS data, so that conclusions are based only on the shapes of power spectra. Efstathiou *et al.* (2002) show that doing this yields a total density ($|\Omega - 1| < 0.05$) at 95% confidence. We can therefore be confident that the universe is very nearly flat; hereafter it will be assumed that this is exactly true.

For flat models, there is a closely related degeneracy concerned with the location of the acoustic peaks. The angular scale of these peaks depends on the ratio between the horizon size at last scattering and the present-day horizon size for flat models. As discussed by Percival *et al.* (2002), this has a nontrivial scaling with parameter values owing to the importance of relativistic particles at the time of last scattering. The result can be deduced analytically, but a convenient approximation for the scaling is

$$\theta_{\rm H} \propto (\Omega_m h^{3.4})^{0.14}\, \Omega_{\rm tot}^{1.4} \tag{5}$$

(see also Hu *et al.* 2001).

However, information about the peak heights does alter this degeneracy slightly; the relative peak heights are preserved at constant Ω_m, hence the actual likelihood ridge is a compromise between constant peak location (constant $\Omega_m h^{3.4}$) and constant relative heights (constant $\Omega_m h^2$); the peak locations have more weight in this compromise, leading to a likelihood ridge along approximately $\Omega_m h^{3.0} \simeq$ const. It is now clear how LSS data combine with the CMB: $\Omega_m h^3$ is measured to very high accuracy already, and the first-year WMAP results yield $\Omega_m h^3 = 0.097$ (Spergel *et al.* 2003). The dominant error in Ω_m and h depends on what one chooses to add to this figure. The best approach given current knowledge is probably to combine the WMAP $\Omega_m h^3 = 0.097$ with the updated 2dFGRS $\Omega_m h = 0.17 \pm 0.02$: this yields

$$\Omega_m = 0.23 \pm 15\%; \qquad h = 0.75 \pm 5\%. \tag{6}$$

The next most critical question for the CMB is whether the temperature fluctuations are scalar-mode only, or whether there could be a significant tensor signal. The tensor modes lack acoustic peaks, so they reduce the relative amplitude of the main peak at $\ell = 220$. A model with a large tensor component can however be made to resemble a zero-tensor model by applying a large blue tilt ($n > 1$) and a high baryon content. Efstathiou *et al.* (2002) show that adding the 2dFGRS data weakens this degeneracy, but does not completely remove it. For this reason, the best limits that can currently be set only say that tensors must be sub-dominant.

Using WMAP, 2dFGRS, plus smaller-scale CMB data, Spergel *et al.* (2003) infer (for a flat model)

$$n = 0.97 \pm 0.02; \qquad r < 0.5, \tag{7}$$

where r is the tensor-to-scalar ratio (approximately the ratio of the CMB C_ℓ spectra at $\ell = 10$ but more rigorously defined as the ratio of spatial power spectra).

5.3. *Spectrum normalization and bias*

The value of σ_8 for the dark matter can be deduced from the CMB fits. The year-1 WMAP value for their best-fitting model is

$$\sigma_8 \exp(-\tau) = 0.71; \tag{8}$$

no error is quoted on this figure (Spergel *et al.* 2003). The unsatisfactory feature is the degeneracy with the optical depth to last scattering. For reionization at $z = 8$, we would have $\tau \simeq 0.05$; it is not expected theoretically that τ can be hugely larger, and popular models would place reionization between $z = 10$ and $z = 15$, or $\tau \simeq 0.1$ (e.g. Loeb & Barkana 2001). One of the many impressive aspects of the WMAP results is that they are able to infer $\tau = 0.17 \pm 0.04$ from large-scale polarization. Taken at face value, $\tau = 0.17$ would argue for reionization at $z = 20$, but the error means that more conventional figures are far from being ruled out. Taking all this together, it seems reasonable to assume that the true value of σ_8 is between 0.8 and 0.9. This implies that L^* galaxies are very nearly exactly unbiased (Lahav *et al.* 2002). Since there are substantial variations in the clustering amplitude with galaxy type, this outcome must be something of a coincidence.

The question of this spectrum normalization is the place where lensing is currently most competitive. Published estimates for σ_8 range from approximately to 0.7 to 1.1. The lower values appear to be inconsistent with WMAP (since presumably $\tau > 0$). One problem with this comparison is the dependence on Ω_m. The weak-lensing studies measure something close to $\sigma_8 \Omega_m^{0.6}$, so it is important to scale to the same density. Empirically, the scaling of the σ_8 from WMAP plus smaller-scale data goes approximately as $\Omega_m^{0.4}$ (best-fitting all other parameters). Since Ω_m is known only to 15% precision, the CMB+LSS value of σ_8 should be expressed approximately as

$$\sigma_8(\mathrm{CMB}) = 0.74(\Omega_m/0.3)^{+0.4} \exp(\tau) \pm 7\%. \tag{9}$$

https://doi.org/10.1017/S1743921305002255 Published online by Cambridge University Press

Comparing with a consensus value of

$$\sigma_8(\text{lens}) = 0.83(\Omega_m/0.3)^{-0.6} \pm 5\% \tag{10}$$

(e.g. Refregier 2003), there are a number of choices. If lens values of σ_8 settle towards the lower values, but τ stays high, this would argue for lower densities. If we want to keep the density at 0.3, then either τ should fall or the higher values of σ_8 from lensing must be right (although systematic errors surely go the other way). It will be interesting to see how this develops.

5.4. *The equation of state of the vacuum*

So far, we have assumed that the vacuum energy is exactly a classical Λ, or at any rate indistinguishable from one. If $w \equiv p_v/\rho_v \neq -1$, then it is relatively easy to see how the above conclusions change. We have seen above how the location of the acoustic angular scale depends on $\Omega_m h^{3.4}$; this angle is proportional to the ratio between the horizon size at last scattering and the present horizon, but only the latter depends on w:

$$D_{\rm H}(z=0) = \frac{2c}{H_0}\Omega_m^{-\alpha}; \qquad \alpha = \frac{-2w}{1-3.8w} \tag{11}$$

(Percival *et al.* 2002). For a flat model, we therefore have approximately

$$\theta_{\rm H} \propto (\Omega_m h^{3.4})^{0.14}\, \Omega_m^{0.09(1+w)} \tag{12}$$

If the location of the main CMB acoustic peak is known exactly, this defines a locus on (w, Ω_m) space that is required for a given value of h. If $\Omega_m h$ were to be determined exactly from LSS, this would give a measure of $h^{1-0.27(1+w)}$, which suggests that in the ideal case we would know w to a precision about 3 times worse than our external knowledge of h.

In practice, one does a little better than this even though the knowledge of $\Omega_m h$ is imperfect. This is because the latest CMB data break the $\Omega_m h^{3.4}$ degeneracy to some extent, so there is information on h beyond the HST key project $h = 0.72 \pm 10\%$ (Freedman *et al.* 2001). As a result, WMAP year 1 plus 2dFGRS yields $w < -0.5$ at 95% confidence independent of the HST. Results of similar precision come from the SNe Hubble diagram plus either CMB or LSS (Tonry *et al.* 2003; Knop *et al.* 2003). Adding everything together, Spergel *et al.* (2003) obtain

$$w = -0.98 \pm 0.12 \tag{13}$$

The vacuum energy is indeed looking rather similar to Λ. Alternative experiments for measuring w from lensing will need to deliver a target precision of 5% or better in order to yield a significant advance.

5.5. *Outlook*

Finally, the above constraints may be expected to improve. Even with data that are almost 'in the can' (e.g. WMAP 4-year results), significant improvements can be expected. Many authors have peered into this crystal ball, and the predictions of Bond *et al.* (2004) are representative. WMAP 4-year data should improve most current uncertainties by about a factor of 2, with a further factor 2 to 3 from even one year of Planck data. If betting on the flawless operation of Planck seems too great an extrapolation at present, there will certainly be great improvements in ground-based small-scale data. Therefore, even a rather conservative outlook leads to an expected improvement of a factor 3 in 5 years' time: knowledge of h to 2%, Ω_m to 5% and w to 4%. A lensing optimist might expect to match these figures, but at present it is rather hard to see where the next step (e.g. w to $< 1\%$ could come from).

6. Ending

If Zwicky had witnessed this sceptical talk, he would no doubt have erupted in rage and complained that the modern generation were impossible to please. It should not be forgotten what a tremendous tool gravitational lensing has become, and how important its robust mass estimates have been in establishing the existence of dark matter. Complex lensing systems such as A1689 are astonishing in their beauty – and I am sure no-one will object if I nominate Keren Sharon's talk on the A1689 ACS data as winning the 'best picture' award for this meeting.

For the future, this importance will only increase. Lensing of the CMB will need to be accounted for routinely in future analyses, and lensing-induced B modes will be one of the first targets for the new generation of polarization experiments. Ultimately, these effects may limit the detection of intrinsic B modes, so they will need to be understood in detail.

In the case of lensing in the optical, I have argued that the subject faces a challenge: so far, it has not measured $P(k)$ or H_0 as accurately as can be achieved by other means. Judging by Paul Schechter's talk, even the experts may agree that much further progress on H_0 will be hard. The large-scale weak-lensing programme may yet succeed in taking the lead in measuring cosmological parameters, but this will depend on measuring small effects, where the theory is not as clean as one would like.

The ultimate in scepticism, however, is to wonder whether cosmology may be chasing after nonexistent goals. It is certainly conceivable that relic gravity waves and deviations from $w = -1$ are unmeasurably small, and it is not clear how the subject would progress from such an impasse. But this is too negative: our view of the universe has changed too much in recent years to bet that there are no big surprises left. Lensing may well be the way to find them.

References

Abazajian K. *et al.*, 2004, AJ, 128, 502
Bond J.R., Contaldi C.R., Lewis A.M., Pogosyan D., 2004, astro-ph/0406195
Cole S., Hatton S., Weinberg D.H., Frenk C.S., 1998, MNRAS, 300, 945
Colless M. *et al.*, 2001, MNRAS, 328, 1039
Colless M. *et al.*, 2003, astro-ph/0306581
Efstathiou G., Bond J.R., 1999, MNRAS, 304, 75
Efstathiou G. *et al.*, 2002, MNRAS, 330, L29
Freedman W.L. *et al.*, 2001, ApJ, 553, 47
Garriga J., Vilenkin A., 2000, Phys. Rev. D, 61, 083502
Hu W. *et al.* 2001, ApJ, 549, 669
Hu W., Jain B., 2004, Phys. Rev. D, 70, 043009
Jain B., Taylor A.N., 2003, Phys. Rev. Lett., 91, 141302
Knop R.A. *et al.*, 2003, ApJ, 598, 102
Kochanek C.S., Hewitt J.N., 1996, proc. IAU Symposium no. 173, *Gravitational lensing* (Kluwer)
Lahav O. *et al.*, 2002, MNRAS, 333, 961
Liddle A.R., Scherrer R.J., 1999, 1999, Phys. Rev. D, 59, 023509
Loeb A., Barkana R., 2001, ARAA, 39, 19
Percival W.J. *et al.*, 2001, MNRAS, 327, 1297
Percival W.J. *et al.*, 2002, MNRAS, 337, 1068
Pope A.C. *et al.*, 2004, ApJ, 607, 655

https://doi.org/10.1017/S1743921305002255 Published online by Cambridge University Press

Press W.H., 1996, in proc. IAU Symposium no. 173, *Gravitational lensing*, eds Kochanek C.S. & Hewitt J.N., p407 (Kluwer)
Ratra B., Peebles P.J.E., 1988, Phs. Rev. D, 37, 3406
Refregier A., 2003, ARAA, 41, 645
Smith R.E. *et al.*, 2003, MNRAS, 341, 1311
Spergel D.N. *et al.*, 2003, astro-ph/0302209
Swings J.-P., 1983, proc. Liège Astrophysical Symposium no. 24, *Quasars and gravitational lenses* (Univ. Liège)
Surdej A., 2004. The Liège online lensing bibliography: `http://vela.astro.ulg.ac.be/themes/extragal/`
Surdej J., Fraipont-Caro D., Gosset E., Refsdal S., Remy M., 1993, proc. Liège Astrophysical Symposium no. 31, *Gravitational lenses in the universe* (Univ. Liège)
Tegmark M. *et al.*, 2004, ApJ, 606, 702
Teplitz H., Malkan M.A., McLean I.S., 2004, astro-ph/0402519
Tonry J.L. *et al.*, 2003, ApJ, 594, 1
White M., 2004, astro-ph/0405593
Zhan H., Knox L., 2004, astro-ph/0409198

https://doi.org/10.1017/S1743921305002255 Published online by Cambridge University Press

Paul Schechter, Danielle Alloin, Georges Meylan

Sjur Refsdal

https://doi.org/10.1017/S1743921305002255 Published online by Cambridge University Press

Alexander Eigenbrod, Christel Vuissoz

https://doi.org/10.1017/S1743921305002255 Published online by Cambridge University Press