

20. S. Dimopoulos, S. Raby, F. Wilczek, *Phys. Rev. D* **24**, 1681 (1981).
21. N. Arkani-Hamed, S. Dimopoulos, G. Dvali, *Phys. Rev. D* **59**, 086004 (1999).
22. S. Cullen, M. Perelstein, *Phys. Rev. Lett.* **83**, 268 (1999).
23. W. D. Goldberger, M. B. Wise, *Phys. Rev. Lett.* **83**, 4922 (1999).
24. S. B. Giddings, S. Kachru, J. Polchinski, available at <http://xxx.lanl.gov/abs/hep-th0105097>.
25. H. Verlinde, *Nucl. Phys. B* **580**, 264 (2000).
26. J. Lykken, L. Randall, *J. High-Energy Phys.* **0006**, 014 (2000).
27. H. Davoudiasl, J. L. Hewett, T. G. Rizzo, *Phys. Rev. Lett.* **84**, 2080 (2000).
28. L. Randall, M. D. Schwartz, *Phys. Rev. Lett.* **88**, 081801 (2002).
29. ———, *J. High-Energy Phys.* **0111**, 003 (2001).
30. M. Tegmark, *Science High-Energy Phys.* (2002). [this issue]
31. L. Randall, R. Sundrum, *Nucl. Phys B* **557**, 79 (1999).
32. A. Pomarol, R. Rattazzi, *J. High-Energy Phys.* **9905**, 013 (1999).
33. Z. Chacko, M. A. Luty, I. Maksymyk, E. Ponton, *J. High-Energy Phys.* **0004**, 001 (2000).
34. E. Katz, Y. Shadmi, Y. Shirman, *J. High-Energy Phys.* **9908**, 015 (1999).
35. J. Jones, D. R. Jones, *Phys. Lett. B* **482**, 167 (2000).
36. Z. Chacko, M. A. Luty, E. Ponton, Y. Shadmi, Y. Shirman, *Phys. Rev. D* **64**, 055009 (2001).
37. N. Arkani-Hamed, D. E. Kaplan, H. Murayama, Y. Nomura, *J. High-Energy Phys.* **0102**, 041 (2001).
38. J. L. Feng, T. Moroi, L. Randall, M. Strassler, S. Su, *Phys. Rev. Lett.* **83**, 1731 (1999).
39. N. Arkani-Hamed, M. Schmaltz, *Phys. Rev. D* **61**, 033005 (2000).
40. N. Arkani-Hamed, S. Dimopoulos, *Phys. Rev. D* **65**, 052003 (2002).
41. N. Arkani-Hamed, A. G. Cohen, H. Georgi, *Phys. Lett. B* **513**, 232 (2001).
42. C. T. Hill, S. Pokorski, J. Wang, *Phys. Rev. D* **64**, 105005 (2001).
43. S. B. Giddings, E. Katz, L. Randall, *J. High-Energy Phys.* **0003**, 023 (2000).
44. S. Hawking, J. Maldacena, A. Strominger, *J. High-Energy Phys.* **0105**, 001 (2001).
45. N. Arkani-Hamed, M. Porrati, L. Randall, *J. High-Energy Phys.* **0108**, 017 (2001).
46. R. Rattazzi, A. Zaffaroni, *J. High-Energy Phys.* **0104**, 021 (2001).
47. M. A. Luty, R. Sundrum, *Phys. Rev. D* **65**, 066004 (2002).
48. ———, available at <http://xxx.lanl.gov/abs/hep-th0111231>.
49. M. Porrati, available at <http://xxx.lanl.gov/abs/hep-th0112166>.
50. A. Karch, L. Randall, *J. High-Energy Phys.* **0106**, 063 (2001).
51. ———, *Phys. Rev. Lett.* **87**, 061601 (2001).

REVIEW

# Measuring Spacetime: From the Big Bang to Black Holes

Max Tegmark

Space is not a boring static stage on which events unfold over time, but a dynamic entity with curvature, fluctuations, and a rich life of its own. Spectacular measurements of the cosmic microwave background, gravitational lensing, type Ia supernovae, large-scale structure, spectra of the Lyman  $\alpha$  forest, stellar dynamics, and x-ray binaries are probing the properties of spacetime over 22 orders of magnitude in scale. Current measurements are consistent with an infinite flat everlasting universe containing about 30% cold dark matter, 65% dark energy, and at least two distinct populations of black holes.

Traditionally, space was merely a three-dimensional (3D) static stage where the cosmic drama played out over time. Einstein's theory of general relativity (1) replaced this concept with 4D spacetime, a dynamic geometric entity with a life of its own, capable of expanding, fluctuating, and even curving into black holes. Now, the focus of research is increasingly shifting from the cosmic actors to the stage itself. Triggered by progress in detector, space, and computer technology, an avalanche of astronomical data is revolutionizing our ability to measure the spacetime we inhabit on scales ranging from the cosmic horizon down to the event horizons of suspected black holes, using photons and astronomical objects as test particles. The goal of this article is to review these measurements and future prospects, focusing on four key issues: (i) the global topology and curvature of space, (ii) the expansion history of spacetime and evidence for dark energy, (iii) the fluctuation history of spacetime and evidence for dark matter, and (iv) strongly curved

spacetime and evidence for black holes. In the process, I will combine constraints from the cosmic microwave background (CMB) (2), gravitational lensing, supernovae Ia, large-scale structure (LSS), the hydrogen Lyman  $\alpha$  forest (Ly $\alpha$ F) (3), stellar dynamics, and x-ray binaries. Although it is fashionable to use cosmological data to measure a small number of free "cosmological parameters," I will argue that improved data allow raising the ambition level beyond this, testing rather than assuming the underlying physics. I will discuss how, with a minimum of assumptions, one can measure key properties of spacetime itself in terms of a few cosmological functions—the expansion history of the universe, the spacetime fluctuation spectrum, and its growth.

Before embarking on a survey of spacetime, a brief review is in order of what it is we want to measure, the basic tools at our disposal (4, 5), and the general picture of how spacetime relates to the structure of the universe. According to general relativity theory (GR), spacetime is what mathematicians call a manifold, characterized by a topology and a metric. The topology gives the global structure (Fig. 1, top), and we can ask: Is space infinite in all directions or multiply connect-

ed, like say a hypersphere or doughnut, so that traveling in a straight line could in principle bring you back home—from the other direction? The metric determines the local shape of spacetime (i.e., the distances and time intervals we measure) and is mathematically specified by a  $4 \times 4$  matrix at each point in spacetime.

GR consists of two parts, each providing a tool for measuring the metric. The first part of GR states that, in the absence of nongravitational forces, test particles (objects not heavy enough to have a noticeable effect on the metric) move along geodesics in spacetime, in generalized straight lines, so the observed motions of photons and astronomical objects allow the metric to be reconstructed. I will refer to this as *geometric* measurements of the metric. The second part of GR states that the curvature of spacetime (expressions involving the metric and its first two derivatives) is related to its matter content—in most cosmological situations simply the density and pressure, but sometimes also bulk motions and stress energy. I will refer to such measurements of the metric as *indirect*, because they assume the validity of the Einstein field equations (EFE) of GR.

The current consensus in the cosmological community is that spacetime is extremely smooth, homogeneous, and isotropic (translationally and rotationally invariant) on large ( $\sim 10^{23}$  to  $10^{26}$  m) scales, with small fluctuations that have grown over time to form objects like galaxies and stars on smaller scales. CMB observations (2) have shown that space is almost isotropic on the scale of our cosmic horizon ( $\sim 10^{26}$  m), with the metric fluctuating by only about one part in  $10^5$

Department of Physics, University of Pennsylvania, Philadelphia, PA 19104, USA.

from one direction to another; combining this with the so-called cosmological principle (the assumption that there is nothing special about our vantage point) implies that space is homogeneous as well. 3D maps of the galaxy and quasar distribution give more direct evidence for large-scale homogeneity (6).

The fact that the CMB fluctuations are so small is useful, because it allows the intimidating nonlinear partial differential equations governing spacetime and its matter content to be accurately solved using a perturbation expansion. To zeroth order (ignoring the fluctuations), this fixes the global metric to be of the so-called Friedman-Robertson-Walker (FRW) form, which is completely specified except for a curvature parameter and a free function giving its expansion history. To first order, density perturbations grow due to gravitational instability, and gravitational waves propagate through the FRW background spacetime, all governed by *linear* equations. Only on smaller scales ( $\leq 10^{23}\text{m}$ ) do the fluctuations get large enough that nonlinear dynamics becomes important—in the realm of galaxies, stars, and, perhaps, black holes. The sections below are organized accordingly, discussing spacetime to zeroth, first, and higher order.

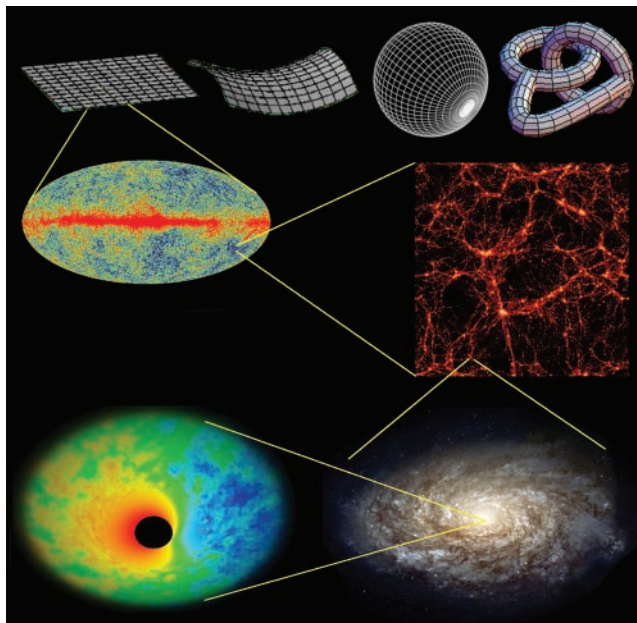
### Overall Shape of Spacetime

*Curvature of space.* The question of whether space is infinite was answered last year with a resounding *maybe*. For an FRW metric, answering this question is equivalent to measuring the curvature of space (Fig. 1), specifically the radius of curvature ( $R$ ).  $R$  is the radius of the hypersphere if space is finite,  $R = \infty$  if space is flat, and  $R$  is an imaginary number ( $R^2 < 0$ ) for saddlelike curvature. Because the three angles of a triangle will add up to  $180^\circ$  in flat space, more if  $R^2 > 0$  (like on a sphere) and less if  $R^2 < 0$  (like on a saddle), cosmologists have measured  $R$  using the largest triangle available: one with us at one corner and the other two corners on the hot opaque surface of ionized hydrogen that delimits the visible universe and emits the CMB, merely 400,000 years after the Big Bang. Photographs of this surface reveal hot and cold spots of a characteristic angular size that can be predicted theoretically. This characteristic spot size [or, more rigorously, the first peak in the CMB power spectrum (7)] subtends about  $0.5^\circ$ , like the Moon, if space is flat. Spherelike curvature would make all angles appear larger, so characteristic spots much larger than the Moon would indicate a finite universe curv-

ing back on itself, whereas smaller spots would indicate infinite space with negative curvature. Recent experiments have observed the first peak and hints of additional smaller scale peaks (2).

The universe may be infinite, because the measured characteristic spot size is so close to  $0.5^\circ$  that we still cannot tell whether space is perfectly flat or very slightly curved either way. The sharpest current limits on  $R$ , obtained by combining all CMB experiments with galaxy clustering data (8, 9) to constrain

plest nontrivial model has flat space and the topology of a 3D torus, where opposing faces of a cube of size  $L \times L \times L$  are identified to be one and the same. Living in such a universe would be indistinguishable from living in a perfectly periodic one. If  $L = 10$  m, you could see the back of your own head 10 m away, and additional copies at 20 m, 30 m, and so on—searches for multiple images of cosmological objects have constrained such models. Also, just as a finite guitar string has a fundamental tone and overtones, linear spacetime fluctuations in such a toroidal universe could have only certain discrete wave numbers. As a result, its CMB power spectrum would differ on large scales, and it was shown that if the universe were such a torus, then  $L$  would have to be at least of the order of the cosmic horizon (11, 12). Indeed, it was shown that all three dimensions of the torus would have to be at least about this large to explain the absence of a type of approximate reflection symmetry in the CMB sky (13). Cosmic topology is now a burgeoning field of study (14), but all available data so far is still consistent with the simplest possible 3D space, the infinite flat Euclidean space that we learned about in high school. The global structure of our 4D spacetime also depends on the beginning and end of time, to which we now turn.



**Fig. 1.** Summary of the spacetime issues discussed in this article. One can use photons and astronomical objects as test particles to measure spacetime over 22 orders of magnitude in scale, ranging from the cosmic horizon [probing the global topology of and curvature of space (top)] down to galaxies [giving evidence for dark matter], galactic nuclei, and binary stellar systems (giving evidence for black holes). The figure illustrates how spacetime ripples at the  $10^{-5}$  level, will be imaged by the cosmic microwave background satellite MAP (38), and has grown from gravitational instability into cosmic LSS (73), galaxies, and, it seems, black holes (74).

other parameters, are  $|R| > 20 h^{-1} \text{Gpc} \approx 10^{27}\text{m}$  ( $1 \text{pc} = \sim 3 \text{light-years}$ ). This is in sharp contrast to the most popular models proposed a few years ago, which had negatively curved space with  $|R| \approx 4 h^{-1} \text{Gpc}$ . In other words, space now seems to be either infinite or much larger than the observable universe, whose radius is about  $9 h^{-1} \text{Gpc}$ . In 1900, Karl Schwarzschild discussed the possibility that space was curved and published a paper with a lower limit  $R > 2500 \text{light-years} \approx 2 \times 10^{19}\text{m}$  (10). A century later, we thus know that the universe is at least another 40 million times larger!

*Topology of space.* Even if space turns out to be negatively curved or perfectly flat, it might be finite. General relativity does not prescribe the global topology, so various possibilities are possible (Fig. 1, top). The sim-

### Spacetime Expansion History

One of the key quantities that cosmologists yearn to measure is the function  $a(t)$ , describing the expansion of the universe over time—if space is curved,  $a$  is simply the magnitude of the radius of curvature,  $a = |R|$ . A mathematically equivalent function more closely related to observations is the Hubble parameter as a function of redshift,  $H(z)$ , giving the cosmic expansion rate and defined by  $H \equiv d \ln a/dt$ ,  $1 + z \equiv a(t_{\text{now}})/a(t)$ .

*What  $\rho(z)$  tells us about dark energy.* Squaring our curve  $H(z)$  gives us the cosmic matter density (Fig. 2).<sup>2</sup> If the EFE of GR are correct, then the mean density of the universe is given by the Friedmann equation

$$\rho(z) = \frac{3H(z)^2}{8\pi G}.$$

Here,  $G$  is Newton's gravitational constant and, if space is curved, the density  $\rho$  is defined to include an optional curvature contribution  $\rho_{\text{curv}} \equiv -3c^2/8\pi GR^2$ , where  $c$  is the speed of light. Conveniently, all standard components of the cosmic matter budget contribute simple straight lines to this plot, be-

cause their densities drop as various power laws as the universe expands. For instance, the densities of both ordinary and cold dark matter particles are inversely proportional to the volume of space, scaling as  $\rho \propto (1+z)^3$ .

The cosmic density  $\rho(z)$  measured from supernovae type Ia and CMB (Fig. 2, yellow band) was higher in the past but rises slower than  $(1+z)^3$  toward higher  $z$ , with a slope that is shallower than 3 at recent times. This is evidence for the existence of dark energy, a substance whose density does not rise rapidly with  $z$ . Adding a cosmological constant contribution  $\rho_\Lambda \approx 4 \times 10^{-26} \text{ kg/m}^3$  (about 2/3 of the current matter budget), whose density is, by definition, constant, provides a good fit to the measurements (Fig. 2). This 1998 discovery (15, 16) stunned the scientific community and triggered a worldwide effort to determine the nature of the dark energy. A model-independent approach involves measuring the curve  $\rho(z)$  more accurately (Fig. 2), to determine whether independent measurements of  $\rho(z)$  agree (so that we can rule out problems with observations) and to determine the time dependence of dark energy density  $\rho_x(z)$ . If it is constant, we may have measured vacuum energy/Einstein's cosmological constant, and, if not, we should learn interesting physics about a new scalar quintessence field, or whatever is responsible. A less ambitious approach that is currently popular is assuming that the equation of state (pressure-to-density ratio)  $w$  of the dark energy is constant (17, 18), which is equivalent to assuming that  $\rho_x(z)$  is a straight line in Fig. 2 with a free amplitude and slope.

What  $\rho(z)$  tells us about our origin and destiny. If we can understand the different components of the cosmic matter budget well enough to extrapolate the curve  $\rho(z)$  (Fig. 2) to the distant past and future, we can use the Friedmann equation to solve for  $a(t)$  and obtain information about the origin and ultimate fate of spacetime.  $a(t) = 0$  in the past or future would correspond to a singular big bang or big crunch, respectively, with infinite density  $\rho(z)$ . As to the past, such extrapolation seems justified at least back to the first seconds after the Big Bang, given the success of big bang nucleo-

synthesis in accounting for the primordial light element abundances (19). Extrapolation back to the very beginning is more speculative. According to the currently most popular scenario, a large and nearly constant value of  $\rho$  at  $t \lesssim 10^{-34}$  s caused exponential expansion  $a(t) \propto e^{Ht}$  during a period known as inflation (20), successfully predicting both negligible spatial curvature and a nearly scale-invariant adiabatic scalar power spectrum (7) with subdominant gravitational waves. A rival ekpyrotic model inspired by string theory and a related eternally oscillating model have attracted recent attention (21–

23). If the density approaches the Planck density ( $10^{97} \text{ kg/m}^3$ ) as  $t \rightarrow 0$ , quantum gravity effects for which we lack a fundamental theory should be important, and a host of speculative scenarios have been put forward for what happened at  $t \sim 10^{-43}$  s. A very incomplete sample includes the Hawking-Hartle no-boundary condition (24), the universe creating itself (25), and so-called pre-Big Bang models (26). Another possibility is that the Planck density was never at-

tained and that there was no beginning, just an eternal fractal mess of replicating inflating bubbles, with our observed spacetime being merely one in an infinite ensemble of regions where inflation has stopped (27, 28). As to the future, the expansion can only stop ( $H = 0$ ) if the effective density  $\rho(z)$  drops to zero. The only two density contributions that can in principle be negative are those of curvature (measured to be negligible) and dark energy (measured to be positive), suggesting that the universe will keep expanding forever. Indeed, if the dark energy density stays constant, we are now entering

another inflationary phase of exponential expansion [ $a(t) \propto e^{Ht}$ ], and in about  $10^{11}$  years, our observable universe will be dark and lonely with almost all extragalactic objects having disappeared across our cosmic horizon (29). However, such conclusions must clearly be considered tentative until the nature of dark energy is understood.

How to measure  $\rho(z)$ . In conjunction with the  $R$ , the curve  $H(z)$  can be measured geometrically, using photons as test particles. Objects of known luminosity (called standard candles) or known physical size (called standard yardsticks) at different redshifts can be used to determine  $H(z)$  by comparing their measured brightness or angular size with theoretical predictions, which follow from computing the trajectories of nearly parallel light rays and depend only on  $H(z)$  and the (apparently negligible) curvature of space (30, 31). The best standard candles to date are supernovae of type Ia, and 92 SN Ia (15, 16) were used (31) to measure  $H(z)$  and thereby  $\rho(z)$  (Fig. 2). The best standard yardstick so far is the characteristic CMB spot size, suggesting that space is flat.

$H(z)$  can also be measured indirectly. As discussed below,  $H(z)$  affects the growth of density fluctuations and can therefore be probed by galaxy clustering and other techniques (Fig. 2). Such fluctuation measures have constrained matter to make up no more than about a third of the critical density needed to explain why space is flat. This Enron-like accounting situation provides supernova-independent evidence for dark energy (8, 9, 32).

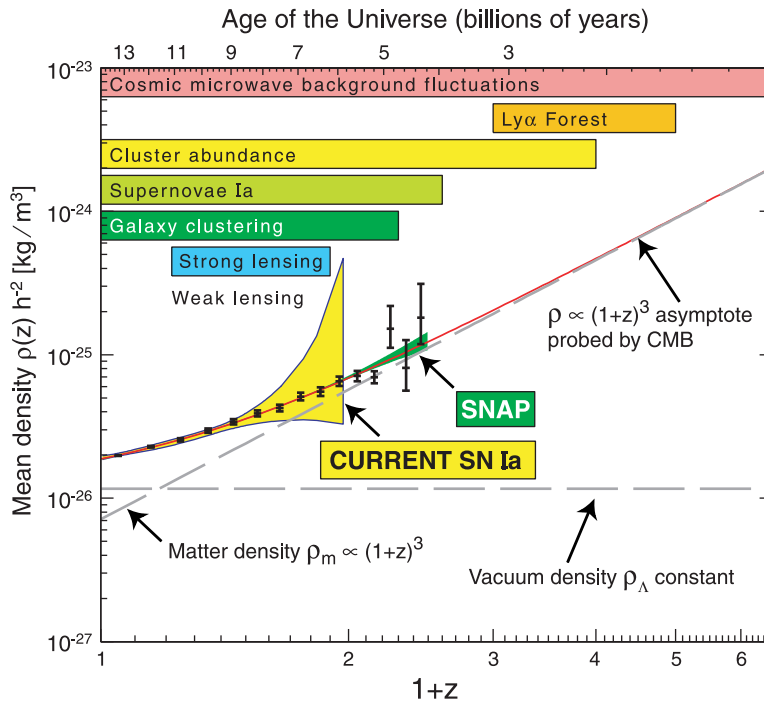


Fig. 2. The solid curve shows the concordance model (8) for the evolution of the cosmic mean density  $\rho(z) \propto H(z)^2$ . This curve uniquely characterizes the spacetime expansion history. The horizontal bars indicate the rough redshift ranges over which the various cosmological probes discussed are expected to constrain this function. Because the redshift scalings of all density contributions except that of dark energy are believed to be straight lines with known slopes in this plot (power laws), combining into a simple quartic polynomial, an estimate of the dark energy density  $\rho_x(z)$  can be readily extracted from this curve. Specifically,  $\rho \propto (1+z)^4$  for the CMB,  $\rho \propto (1+z)^3$  for baryons and cold dark matter,  $\rho \propto (1+z)^2$  for spatial curvature,  $\rho \propto (1+z)^0$  for a cosmological constant, and  $\rho \propto (1+z)^{3(1+w)}$  for dark energy with a constant equation of state  $w$ . Measurement errors are for current SN Ia constraints (yellow band) and a forecast for what the Supernova Anisotropy Probe (SNAP) satellite (75) can do (green band), assuming flat space as favored by the CMB. Error bars are for a nonparametric reconstruction with SNAP.

23). If the density approaches the Planck density ( $10^{97} \text{ kg/m}^3$ ) as  $t \rightarrow 0$ , quantum gravity effects for which we lack a fundamental theory should be important, and a host of speculative scenarios have been put forward for what happened at  $t \sim 10^{-43}$  s. A very incomplete sample includes the Hawking-Hartle no-boundary condition (24), the universe creating itself (25), and so-called pre-Big Bang models (26). Another possibility is that the Planck density was never at-

**Growth of Cosmic Structure**

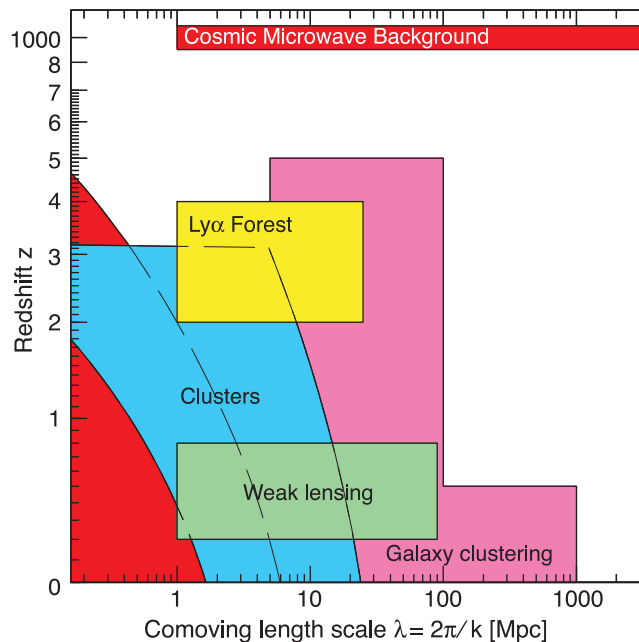
While SN Ia and CMB peak locations have recently revolutionized our knowledge of the metric to zeroth order (curvature, topology, and expansion history), other observations are probing its first-order fluctuations with unprecedented accuracy. These perturbations come in two important types. The first are gravitational waves, hitherto undetected ripples in spacetime that propagate at the speed of light without growing in amplitude. The second are density fluctuations, which can get amplified by gravitational instability (Fig. 1) and are being measured by CMB, gravitational lensing, and the clustering of extragalactic objects, notably galaxies and gas clouds absorbing quasar light (Ly $\alpha$ F) over a range of scales and redshifts (Fig. 3).

Plane-wave perturbations of different wave number evolve independently by linearity and are so far consistent with having uncorrelated Gaussian-distributed amplitudes, as predicted by most inflation models (20). The first-order density perturbations are therefore characterized by a single function  $P(k, z)$ , the *power spectrum* (7), which gives the variance of the fluctuations as a function of  $z$  and wave number  $k$ .  $P(k, z)$  depends on and can therefore teach us about three things—the cosmic matter budget, the seed fluctuations created in the early universe, and Galaxy formation. A challenge is to robustly disentangle the three. We are not there yet, but new data is making this increasingly feasible because each of the probes (Fig. 3) involves different physics and is affected by the three in different ways.

Given the profusion of recent measurements of  $H(z)$  and  $P(k, z)$ , it is striking that there is a fairly simple model that currently seems to fit everything (Figs. 2 and 4). In this so-called concordance model (8, 9, 32, 33), the cosmic matter budget consists of about 5% ordinary matter (baryons), 30% cold dark matter, 0.1% hot dark matter (neutrinos), and 65% dark energy based on CMB and LSS observations, in good agreement with Ly $\alpha$ F (34), lensing (35, 36), and SN Ia (15, 16). The seed fluctuations created in the early universe are consistent with the inflation prediction of a simple power law  $P(k, z) \propto k^n$  early on, with  $n = 0.9 \pm 0.1$  (8, 9). Galaxy

formation appears to have heated and reionized the universe not too long before  $z = 6$ , based on the Ly $\alpha$ F (37).

Although inferences about things like the expansion history, matter budget, and early universe involve many assumptions (about



**Fig. 3.** Shaded regions show ranges of scale and redshift over which various observations are likely to measure spacetime fluctuations over the next few years. The lower left region, delimited by the dashed line, is the nonlinear regime where rms density fluctuations exceed unity in the concordance model (8).

the nature of dark energy, dark matter, gravity, galaxy formation, and so on), the avalanche of new cosmology data allows us to raise the ambition level and test these assumptions about the underlying physics. Given the matter budget and the expansion history  $H(z)$ , theory predicts the complete time evolution of linear clustering, so measuring its redshift dependence (Fig. 3) offers redundancy and powerful cross-checks.

Many power spectrum probes are improving rapidly (Fig. 3). Gravitational lensing uses photons from distant galaxies as test particles to measure the metric fluctuations caused by intervening matter, as manifested by distorted images of distant objects, and first measured  $P(k, z)$  in 2000. 3D mapping of the universe with galaxy redshift surveys offers another window on the cosmic matter distribution, through its gravitational effects on galaxy clustering. This field is currently being transformed by the 2-degree Field (2dF) survey and the Sloan Digital Sky Survey, and complementary surveys will map high redshifts and the evolution of clustering. The abundance of galaxy clusters at different epochs, as probed by optical, x-ray, CMB, or gravitational lensing surveys, is a sensitive probe

of  $P(k, z)$  on smaller scales; and the Ly $\alpha$ F offers a new and exciting probe of matter clustering on still smaller scales when the universe was merely 10 to 20% of its present age. CMB experiments probe  $P(k, z)$  through a variety of effects as far back as to  $z > 10^3$ , with exciting new fronts being increased sensitivity (38), increased angular resolution, and CMB polarization (still undetected).

These complementary probes can be combined to break each others' degeneracies and independently measure the matter budget, the primordial power spectrum, and galaxy formation details (39). The power spectra measured by CMB, LSS, lensing, and Ly $\alpha$ F are the product of the three terms: (i) the primordial power spectrum, (ii) a so-called transfer function quantifying the subsequent fluctuation growth, and (iii) for LSS and Ly $\alpha$ F only, a so-called bias factor accounting for the fact that the measured galaxies and gas clouds may cluster differently than the underlying matter.

Galaxy bias has now been measured from data and found to be of order unity for typical 2dF galaxies (33, 40), and Ly $\alpha$ F bias may be computable with hydrodynamics simulations (34). Although CMB, LSS, lensing, and Ly $\alpha$ F each comes with caveats of its own, their substantial overlap (Fig. 3) should allow disagreements between data sets to be distinguished from disagreements between data and theory. The transfer function can be disentangled from the primordial power because it depends on the matter budget and, conveniently, in rather opposite ways for CMB than for lower  $z$   $P(k)$  measurements (LSS, lensing, and Ly $\alpha$ F). For instance, increasing the cold dark matter density ( $h^2\Omega_c$ ) shifts the galaxy power spectrum up to the right and the CMB peaks down to the left if the primordial spectrum is held fixed. Adding more baryons boosts the odd-numbered CMB peaks but suppresses the galaxy power spectrum rightward of its peak and also makes it wigglier. Increasing the dark matter percentage that is hot (neutrinos) suppresses small-scale galaxy power while leaving the CMB almost unchanged. This means that combining CMB with other data allows unambiguous determination of the matter budget, and the primordial power spectrum can then be inferred. Combining CMB temperature and polarization measurements also helps in this regard, because the characteristic wiggles imprinted by the baryons and dark matter are out of phase for the two, whereas wiggles due to the primordial spectrum would of course line up for the two (41).

Although the best is still to come in this area, the basic conclusion that the universe is awash in nonbaryonic dark matter is already supported independently by CMB, Ly $\alpha$ F, galaxy surveys, cluster counting, and lensing.

The agreement on the baryon density between fluctuation studies (CMB + galaxy surveys) and nucleosynthesis and on the dark energy density between fluctuation studies and SN Ia are both indications that spacetime fluctuation measurements are on the right track and will live up to their promise in this decade of precision cosmology.

### Nonlinear Clustering and Black Holes

On small scales, the linear perturbation expansion eventually breaks down as density fluctuations grow to be of order unity, collapsing to form a variety of interesting astrophysical objects. Although the theoretical predictions are more difficult in this regime, the metric can still be accurately measured using photons and astrophysical objects as test particles. The gravitational potential well is probed by strong gravitational lensing of photons through its distorting effect on background objects (41) and also by the motions of massive objects like galaxies, stars, or gas clouds. The orbital parameters in a binary system reveal the masses of the two objects, just as we once weighed the Sun by exploiting Earth's orbit around it. In more complicated systems, the central mass distribution can be inferred statistically from velocity dispersions observed in the vicinity. Below, I review how these basic tools have revealed surprises on three different scales: dark matter in galaxies and clusters ( $\sim 10^{20}$  to  $10^{23}$  m), supermassive black holes in galactic bulges ( $\sim 10^{10}$  to  $10^{13}$  m), and stellar-mass black holes ( $\sim 10^4$  to  $10^5$  m). Recent black hole reviews include (43–45).

*Dark matter in galaxies and clusters.* As noted by Zwicky in 1933 (46), the amount of mass in galaxies and galaxy clusters inferred from rotation curves or velocity dispersions exceeds the mass of luminous matter by a large factor. Precision measurements with a variety of techniques have confirmed this finding, providing evidence that both galaxies and clusters are accompanied by roughly spherical halos of cold dark matter. This dark matter evidence is independent of that from linear perturbation theory described above, yet produces roughly consistent estimates of the total cosmic dark matter density (47, 48).

New measurements such as mapping tidal streamers, stripy remnants of galaxies cannibalized by the Milky Way in the past, may allow 3D reconstruction of our own dark matter halo, and early results suggest that it may be elliptical rather than perfectly spherical (49). Measurements of the shape and substructure of dark matter halos can probe the detailed nature of the dark matter. Indeed, computer simulations with cold dark matter composed of weakly interacting particles appear to predict overly dense cores in the centers of galaxies and clusters and that there should be about  $10^3$  discrete dark matter ha-

los in our Galactic neighborhood (the Local Group), in contrast to the less than  $10^2$  galaxies actually observed. These halo profile and substructure problems have triggered talk of a cold dark matter crisis and much recent interest in self-interacting dark matter (50), warm dark matter (51), and other more complicated dark matter models that suppress cores and substructure. It is not obvious that there really is a crisis, because baryonic feedback properties may be able to reconcile vanilla cold dark matter with observations and substantial halo substructure has recently been detected with gravitational lensing (52), but this active research area should teach us more about dark matter properties, whatever they turn out to be.

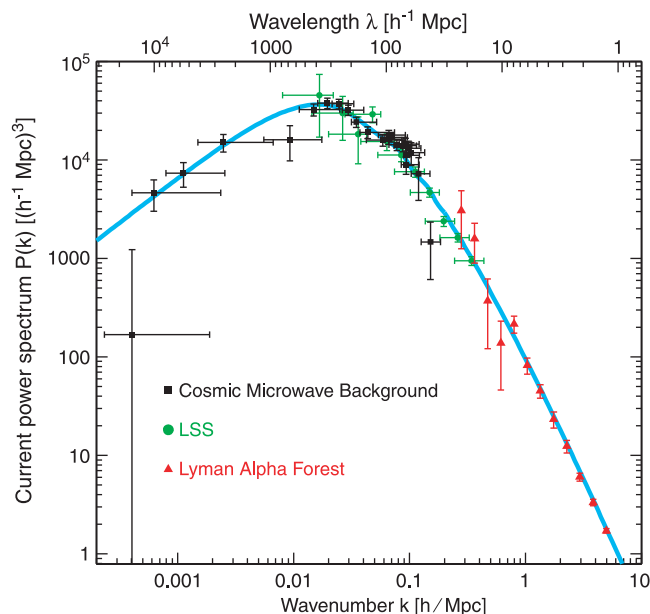
*Supermassive black holes.* Karl Schwarzschild was allegedly so distressed by his 1916 solution to the EFE that he hoped that such sinister objects, later christened black holes by Wheeler, did not exist in the real

own Galaxy, giving a mass around  $3 \times 10^6$  solar masses (53). Here, even individual stellar orbits have been measured and shown to revolve around a single point (53) that coincides with a strong source of radio and x-ray emission.

In many cases, gas disks have been found orbiting the unknown object. For instance, H $\alpha$  emission from such a disk in the galaxy M87 has revealed a record mass of  $3.2 \times 10^9 M_\odot$  in a region merely 10 light years across, and 1.3 cm water maser emission from a disk in the galaxy NGC4258 has revealed  $3.6 \times 10^7 M_\odot$  in a region merely 0.42 light-years across ( $1 \text{ light-year} \approx 10^{16} \text{ m}$ ). This is too compact to be a stable star cluster, so the only alternatives to the black hole explanation involve new physics—like a “fermion ball” made of postulated new particles (54).

Although impressive, these spacetime measurements were still at  $>10^4$  Schwarzschild radii, and so probe no strong GR effects and give only indirect black hole evidence. X-ray spectroscopy provides another powerful probe, because x-rays can be produced closer to the event horizon, less than a light hour from the central engine where the material is hotter and the detailed shape of spacetime can imprint interesting signatures on the emitted radiation. For instance, a strong emission line from the K $\alpha$  fluorescent transition of highly (photo-)ionized iron atoms has been observed (55) to have spectacular properties. Doppler shifts indicate a gas disk rotating with velocities up to 10% of the speed of light, and extremely broadened and asymmetric line profiles are best fit when including both Doppler and gravitational redshifts at 3 to 10 Schwarzschild radii.

In addition to all this geometric evidence for supermassive black holes, further support comes from the processes by which they eat and grow. Infalling gas is predicted to form a hot accretion disk around the hole that can radiate away as much as 10% of its rest energy. It was this idea that led to the suggestions of supermassive black holes in the early 1960s, prompted by the discovery of quasars. About 50% of all galaxies are now known to have active galac-



**Fig. 4.** Measurements of the current ( $z = 0$ ) power spectrum of density fluctuations. Points labeled LSS are from a recent analysis (76) of the 3D distribution of 2dF galaxies (6), which appear to trace the underlying matter distribution without bias on these large scales (33, 40). The CMB measurements combine the information from all experiments to date as in (8) and have been mapped into  $k$ -space assuming the concordance model parameters of (8). The Ly $\alpha$ F points were measured at  $z \approx 2.7$  by (34), and have been transformed to  $z = 0$  using the same concordance parameters and have been rescaled with a bias factor of 1.5.

universe. The irony is that monstrous black holes are nowadays considered the *least* exotic explanation for the phenomena found in the centers of most, if not all, massive galaxies.

The spatial and velocity distribution of stars have unambiguously revealed compact objects weighing  $10^6$  to  $10^{10}$  solar masses at the centers of more than a dozen galaxies. The most accurate measurements are for our

tic nuclei (AGN) at least at some low level—any black holes in the other half are presumed to have quieted down after consuming the gas in their vicinity. AGNs can produce luminosities exceeding that of  $10^{12}$  suns in a region less than a light-year across, and no other mechanism is known for converting matter into radiation with the high efficiency required. In some cases, emission has been localized to a region  $\leq$  a light-hour across (smaller than our solar system) by changing intensity in less than an hour.

Furthermore, magnetic phenomena in accretion discs can radiate beams of energetic particles, and such jets have been observed to up to  $10^6$  light-years long, perpendicular to the disk as predicted. This requires motions near the speed of light as well as a stable preferred axis over long ( $\gg 10^6$  years) time-scales, as naturally predicted for black holes (44, 56).

*Stellar-mass black holes.* Numerous stars have been found to orbit a binary companion weighing too much to be a white dwarf or a neutron star ( $\geq M_{\odot}$ ), and being too faint to be a normal star. For example, after a transient outburst of soft x-rays in 1989, all orbital parameters of the binary system V404 Cygni were measured, and the black hole candidate was found to weigh  $12 \pm 2 M_{\odot}$  (57). Just as for supermassive black holes, x-ray variability has placed upper limits on the size of such objects that rule out all conventional black hole alternatives.

To counter such indirect arguments for black holes, unconventional compact objects such as “strange stars” and “Q-stars” have been proposed (58, 59). However, the accretion disk model for soft x-ray transients such as V404 Cygni might require the object to have an event horizon that gas can disappear through—a hard surface could cause radiation to come back out. Indeed, the similarities between galactic and stellar accretion disk and jet observations are so striking that a single unified explanation seems natural, and black holes provide one.

There is thus evidence for existence of black holes in two separate mass ranges, each making up perhaps  $10^{-6}$  or  $10^{-5}$  of all mass in the universe. Still smaller classes of black holes have been speculated about without direct supporting evidence, both microscopic ones created in the early universe perhaps making up the dark matter (60) and transient ones constituting “spacetime foam” on the Planck scale.

*Black hole prospects and gravitational waves.* Observations we can look forward to making include galactic center flashes as individual stars get devoured, multiwavelength accretion disk observations as evidence of black hole rotation, and, in particular, detection of gravitational waves (61).

These tiny ripples in spacetime should be produced whenever masses are accelerated, and binary pulsars have been measured to lose energy at precisely the rate gravitational wave emission predicts. They should thus be copiously produced in inspiraling mergers involving black holes, both stellar-mass ones [measurable by ground-based detectors such as the Laser Interferometer Gravitational wave Observatory (LIGO)] and supermassive ones [measurable by space-based detectors such as the Laser Interferometer Space Antenna (LISA)] (61). At still longer wavelengths, the hunt for gravitational waves goes on, using pulsar timing and microwave background polarization that can constrain cosmological inflation.

### Outlook

I have surveyed recent measurements of spacetime over a factor of  $10^{22}$  in scale, ranging from the cosmic horizon down to the event horizon of black holes. On the largest scales, evidence supports a flat infinite space and eternal future time. The growth of spacetime fluctuations has suggested that about 30% of the cosmic matter budget is made up of (mostly cold) dark matter, about 5% ordinary matter, and the remainder dark energy. There is further evidence for the same dark matter in the halos of galaxies and clusters. Finally, spacetime seems to be full of black holes, both supermassive ones in the centers of most galaxies and stellar mass ones wherever high mass stars have died.

The devil’s advocate position requires that we clarify the assumptions underlying these conclusions. The geometric test particle observations have measured the spacetime metric, but all inferences about dark energy, dark matter, and the inner parts of black holes assume that the Einstein Field Equations (EFE) of GR are valid. Attempts have been made to explain away all three by modifying the EFE. So-called scalar-tensor gravity has been found capable of giving accelerated cosmic expansion without dark energy (62). Although not an ab initio theory, the approach known as modified Newtonian dynamics (MOND) attempts to explain galaxy rotation curves without dark matter (63). It is not inconceivable that the EFE can be modified to avoid black hole singularities (64).

So, could dark energy, dark matter, and black holes be merely a modern form of epicycles, which just like those of Ptolemy can be eliminated by modifying the laws of gravity (31, 65–67)? The way to answer this question is to test the EFE observationally, by embedding them in a larger class of equations and quantifying the observational constraints. So far, the true theory of gravity has been shown to be extremely close to GR in the

regime probed by solar system dynamics and binary pulsars (4, 5), and the MOND loophole has been at least partially closed (68–70). However, this does *not* imply that the true theory of gravity must be indistinguishable from GR in all contexts, in particular for very compact objects (61) or for cosmology (4, 5), so testing gravity remains a fruitful area of research. Such tests continue even in the laboratory (71), testing the gravitational inverse square law down to millimeter scales to probe possible extra dimensions (72).

In conclusion, the coming decade will be exciting. An avalanche of astrophysical observations are measuring spacetime with unprecedented accuracy, allowing us to test whether it obeys the EFE and, consequently, whether dark energy, dark matter, and black holes are for real.

### References and Notes

1. E. Einstein, *Relativity: The Special and the General Theory* (Random House, New York, 1920).
2. The CMB is the oldest light around, emanating from the hot opaque hydrogen plasma that filled the universe during its first 400,000 years. An up-to-date review is available from M. White and J. Cohn, <http://arxiv.org/abs/astro-ph/0203120> (2002).
3. The Ly $\alpha$ F is the plethora of absorption lines in the spectra of distant quasars caused by neutral hydrogen in overdense intergalactic gas along the line of sight. It allows us to map the cosmic gas distribution out to great distances.
4. C. M. Will, *Theory & Experiment in Gravitational Physics* (Cambridge Univ. Press, Cambridge, 1993).
5. C. M. Will, <http://arxiv.org/abs/gr-qc/9811036> (1998).
6. M. Colless *et al.*, *Mon. Not. R. Astron. Soc.* **328**, 1039 (2001).
7. The CMB power spectrum is the level of temperature fluctuations as a function of angular scale, defined as the variance of the spherical harmonic coefficients of a sky map. A matter power spectrum is the level of 3D density fluctuations as a function of spatial scale, defined as the variance of the Fourier coefficients of the density field.
8. X. Wang, M. Tegmark, M. Zaldarriaga, in press.
9. G. Efstathiou *et al.*, <http://arxiv.org/abs/astro-ph/0109152> (2001).
10. K. Schwarzschild, *Vier. d. Astr. Ges.* **35**, 337 (1900).
11. D. Stevens, D. Scott, J. Silk, *Phys. Rev. Lett.* **71**, 20 (1993).
12. A. de Oliveira-Costa, G. F. Smoot, *Astrophys. J.* **448**, 477 (1995).
13. ———, A. A. Starobinski, *Astrophys. J.* **468**, 457 (1996).
14. J. Levin, <http://arxiv.org/abs/gr-qc/0108043> (2001).
15. S. Perlmutter *et al.*, *Nature* **391**, 51 (1998).
16. A. G. Riess *et al.*, *Astron. J.* **116**, 1009 (1998).
17. I. Maor, R. Brustein, P. Steinhardt, <http://arxiv.org/abs/astro-ph/0007297> (2000).
18. D. Huterer, M. S. Turner, <http://arxiv.org/abs/astro-ph/0012510> (2000).
19. S. M. Carroll, M. Kaplinghat, *Phys. Rev. D* **65**, 063507 (2002).
20. A. R. Liddle, D. H. Lyth, *Cosmological Inflation and Large-Scale Structure* (Cambridge Univ. Press, Cambridge, 2000).
21. J. Khoury *et al.*, *Phys. Rev. D* **64**, 123522 (2001).
22. R. Kallosh, L. Kofman, A. D. Linde, *Phys. Rev. D* **64**, 123523 (2001).
23. P. J. Steinhardt, N. Turok, *Science* **296**, 1436 (2002).
24. J. B. Hartle, S. W. Hawking, *Phys. Rev. D* **28**, 2960 (1983).
25. R. J. Gott, L. X. Li, *Phys. Rev. D* **58**, 023501 (1998).
26. G. Veneziano, <http://arxiv.org/abs/hep-th/0002094> (2000).

27. A. D. Linde, *Particle Physics and Inflationary Cosmology* (Harwood, Chur, Switzerland, 1990).
28. A. Vilenkin, *Phys. Rev. Lett.* **74**, 846 (1995).
29. A. Loeb, *Phys. Rev. D* **65**, 047301 (2002).
30. Y. Wang, P. M. Garnavich, <http://arxiv.org/abs/astro-ph/0101040> (2001).
31. M. Tegmark, <http://arxiv.org/abs/astro-ph/0101354> (2001).
32. N. Bahcall *et al.*, *Science* **284**, 1481 (1999).
33. O. Lahav *et al.*, <http://arxiv.org/abs/astro-ph/0112162> (2001).
34. R. A. C. Croft *et al.*, <http://arxiv.org/abs/astro-ph/0012324> (2000).
35. M. Bartelmann, P. Schneider, *Phys. Rep.* **340**, 291 (2001).
36. L. Van Waerbeke *et al.*, <http://arxiv.org/abs/astro-ph/0101511> (2001).
37. N. Y. Gnedin, <http://arxiv.org/abs/astro-ph/0110290> (2001).
38. See <http://map.gsfc.nasa.gov>.
39. D. J. Eisenstein, W. Hu, M. Tegmark, *Astrophys. J.* **518**, 2 (1999).
40. L. Verde *et al.*, <http://arxiv.org/abs/astro-ph/0112161> (2001).
41. M. Tegmark, M. Zaldarriaga, in preparation.
42. J. Wambsganss, <http://arxiv.org/abs/astro-ph/0012423> (2000).
43. A. Celotti, J. C. Miller, D. W. Sciama, *Class. Quant. Grav.* **16**, A3 (2000).
44. A. Marconi, <http://arxiv.org/abs/astro-ph/0201504> (2002).
45. J. Frank, King A, D. Raine, *Accretion Power in Astrophysics* (Cambridge Univ. Press, Cambridge, ed. 3, 2002).
46. F. Zwicky, *Helv. Phys. Acta* **6**, 110 (1933).
47. H. Hoekstra *et al.*, *Astrophys. J. Lett.* **548**, L5 (2001).
48. N. Bahcall *et al.*, *Astrophys. J.* **541**, 1 (2000).
49. H. J. Newberg, <http://arxiv.org/abs/astro-ph/0111095> (2001).
50. D. N. Spergel, P. J. Steinhardt, *Phys. Rev. Lett.* **84**, 3760 (2000).
51. P. Bode, J. P. Ostriker, N. Turok, <http://arxiv.org/abs/astro-ph/0010389> (2000).
52. N. Dalal, C. S. Kochanek, <http://arxiv.org/abs/astro-ph/0111456> (2002).
53. A. Eckhardt *et al.*, <http://arxiv.org/abs/astro-ph/astro-ph/0201031> (2002).
54. F. Munyaneza, R. D. Viollier, <http://arxiv.org/abs/astro-ph/0103466> (2001).
55. K. Nandra, <http://arxiv.org/abs/astro-ph/0007356> (2000).
56. R. D. Blandford, R. L. Znajek, *Mon. Not. R. Astron. Soc.* **179**, 433 (1977).
57. T. Shabhz *et al.*, *Mon. Not. R. Astron. Soc.* **271**, L10 (1994).
58. E. Witten, *Phys. Rev. D* **30**, 272 (1984).
59. S. Bahcall, *Astrophys. J.* **362**, 251 (1990).
60. B. Carr, in *The Renaissance of GR and Cosmology*, G. F. R. Ellis *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 1993), p. 277.
61. S. A. Hughes *et al.*, <http://arxiv.org/abs/astro-ph/0110349> (2001).
62. B. Boisseau *et al.*, *Phys. Rev. Lett.* **85**, 2236 (2000).
63. M. Milgrom, *Astrophys. J.* **270**, 365 (1983).
64. P. O. Mazur, E. Mottol, <http://arxiv.org/abs/astro-ph/0103466> (2001).
65. S. S. McGaugh, *Astrophys. J. Lett.* **541**, L33 (2000).
66. P. J. E. Peebles, <http://arxiv.org/abs/astro-ph/9910234> (1999).
67. J. A. Sellwood, A. Kosowsky, <http://arxiv.org/abs/astro-ph/0009074> (2000).
68. L. M. Griffiths, A. Melchiorri, J. Silk, *Astrophys. J.* **553**, L5 (2001).
69. M. White, D. Scott, E. Pierpaoli, <http://arxiv.org/abs/astro-ph/0004385> (2000).
70. M. White, C. S. Kochanek, *Astrophys. J.* **560**, 539 (2001).
71. C. D. Hoyle *et al.*, *Phys. Rev. Lett.* **86**, 1418 (2001).
72. L. Randall, *Science* **296**, 1422 (2002).
73. See [www.mpa-garching.mpg.de/Virgo/](http://www.mpa-garching.mpg.de/Virgo/).
74. B. C. Bromberg, W. A. Miller, V. I. Pariev, *Nature* **391**, 54 (1998).
75. See <http://snap.lbl.gov>.
76. M. Tegmark, A. J. S. Hamilton, H. Y. Xu, <http://arxiv.org/abs/astro-ph/0111575> (2001).
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