What is the Universe made of? How old is it?

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ABSTRACT

For the past 15 years most astronomers have assumed that 95% of the Universe was in some mysterious form of cold dark matter. They also assumed that the cosmological constant, Ω_Λ, was Einstein's biggest blunder and could be ignored. However, recent measurements of the cosmic microwave background combined with other cosmological observations strongly suggest that 75% of the Universe is made of cosmological constant (vacuum energy), while only 20% is made of non-baryonic cold dark matter. Normal baryonic matter, the stuff most physicists study, makes up about 5% of the Universe. If these results are correct, an unknown 75% of the Universe has been identified. Estimates of the age of the Universe depend upon what it is made of. Thus, our new inventory gives us a new age for the Universe: 13.4 ± 1.6 *Gyr.*

> "The history of cosmology shows us that in every age devout people believe that they have at last discovered the true nature of the Universe."
> (E. Harrison in **Cosmology: The Science of the Universe** 1981)

1 Progress

A few decades ago cosmology was laughed at for being the only science with no data. Cosmology was theory-rich but data-poor. It attracted armchair enthusiasts spouting speculations without data to test them. It was the only science where the errors could be kept in the exponents – where you could set the speed of light $c = 1$, not for dimensionless convenience, but because the observations were so poor that it didn't matter. The night sky was calculated to be as bright as the Sun and the Universe was younger than the Galaxy.

Times have changed. We have entered a new era of precision cosmology. Cosmologists are being flooded with high quality measurements from an army of new instruments [1] . We are observing the Universe at new frequencies, with higher sensitivity, higher spectral resolution and higher spatial resolution. We have so much new data that state-of-the-art computers process and store them with difficulty. Cosmology papers now include error bars – often asymmetric and sometimes even with a distinction made between statistical and systematic error bars. This is progress.

[1] COBE, ISO, IRAS, HIPPARCOS, HST, IUE, BeppoSax, UHURU, ROSAT, Chandra, BATSE, VLA, ATCA, Arecibo, KAO, SOFIA, SCUBA, BIMA, KECK, VLT, CFHT, MMT, UKIRT, AAT, CTIO, FLY's EYE, CSO, JCNT, NTT, KPNO, UKIRT, INT, JKT, WHT, Magellan, GTC, LBT, MAX, Kamiokande, Super Kamiokande, HOMESTAKE, VIRGO, LIGO, Gravity Probe-B, GINGA, ASTRO A,B,C,D, CERN, FERMILAB, STANFORD, DS1, MILAGRO, Gran Sasso, SNO...

The standard hot big bang model describes the evolution of the Universe. It is the dominant paradigm against which all new ideas are tested. It provides a consistent framework into which all the relevant cosmological data seem to fit. Progress has been made in working out the details of this hot big bang model – for it is the details which provide new, unprecedentedly precise answers to questions of mythical importance: What is the Universe made of? How old is the Universe?

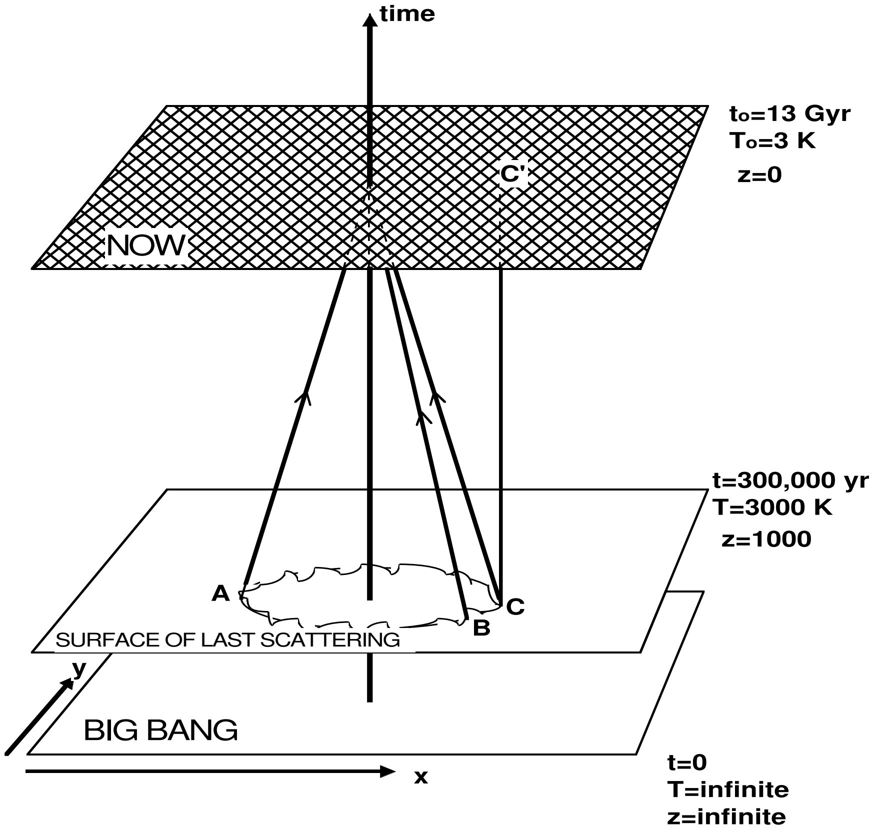

Figure 1. Our view of the Universe

In this spacetime diagram we are at the apex of our past light cone. All the photons we see come to us along the surface of this cone. One spatial dimension has been suppressed. When we look as far away as we can, we see the oldest observable photons – the CMB – coming from the wavy circle in the surface of last scattering (A, B and C are on the circle). The opaque surface of last scattering is the boundary between the current transparent universe and the hotter, denser, opaque, ionized universe. The figure gives the time, temperature and redshift of the big bang, the surface of last scattering and today. This is a comoving diagram, that is, the expansion of the Universe is not shown. We see the object C on the surface of last scattering as it was 13 Gyr ago. Today C has become C', but since the speed of light is not infinite, we cannot see C' now.

2 The CMB: cosmology's coolest new tool.

The cosmic microwave background (CMB) is the oldest fossil we have ever found. It is a bath of photons coming from every direction. These photons are the afterglow of the big bang. Their long journey toward us has lasted more than 99.99% of the age of the Universe and began when the Universe was one thousand times smaller than it is today. The CMB was emitted by the hot plasma of the Universe long before there were planets, stars or galaxies. The CMB is an isotropic field of electromagnetic radiation – the redshifted relic of the hot big bang.

One of the most recent and most important advances in astronomy has been the discovery of hot and cold spots in the CMB based on data from the COBE satellite (Smoot *et al.* 1992). This discovery has been hailed as "Proof of the Big Bang" and the "Holy Grail of Cosmology" and elicited comments like: "If you're religious it's like looking at the face of God" (George Smoot) and "It's the greatest discovery of the century, if not of all time" (Stephen Hawking). As a graduate student analyzing COBE data at the time, I knew we had discovered something fundamental but its full import didn't sink in until one night after a telephone interview for BBC radio. I asked the interviewer for a copy of the interview, and he told me that would be possible if I sent a request to the *religious affairs* department.

The CMB comes from the surface of last scattering of the Universe. When you look into a fog, you are looking at a surface of last scattering. It is a surface defined by all the molecules of water which scattered a photon into your eye. On a foggy day you can see 100 meters, on really foggy days you can see 10 meters. If the fog is so dense that you cannot see your hand then the surface of last scattering is less than an arm's length away. Similarly, when you look at the surface of the Sun you are seeing photons last scattered by the hot plasma of the photosphere. The early Universe is as hot as the Sun and similarly the early Universe has a photosphere (the surface of last scattering) beyond which (in time and space) we cannot see (Fig. 1). As its name implies, the surface of last scattering is where the CMB photons were scattered for the last time before arriving in our detectors. The 'surface of last screaming' presented in Fig. 2 is a pedagogical analog.

Since the COBE discovery of hot and cold spots in the CMB, anisotropy detections have been reported by more than a dozen groups with various instruments, at various frequencies and in various patches and swathes of the microwave sky. Fig. 3 is a compilation of recent measurements. The COBE measurements (on the left) are at large angular scales while most recent measurements are trying to constrain the angular scale and amplitude of the dominant first peak at $\sim 1/2$ degree (the size of the full Moon). This dominant peak and the smaller amplitude peaks at smaller angular scales are due to acoustic oscillations in the photon-baryon fluid in cold dark matter (CDM) gravitational potential wells. The detailed features of these peaks in the power spectrum are dependent on a large number of cosmological parameters including,

$\mathbf{\Omega_m}$ the density of matter (where $\Omega_m = \Omega_{CDM} + \Omega_b$)

- $\mathbf{\Omega_{CDM}}$ the density of cold dark matter
- $\mathbf{\Omega_b}$ the density of normal baryonic matter

$\mathbf{\Omega_\Lambda}$ the density of vacuum energy (cosmological constant)

$\mathbf{h}$ the Hubble constant (giving the rate of expansion of the Universe)

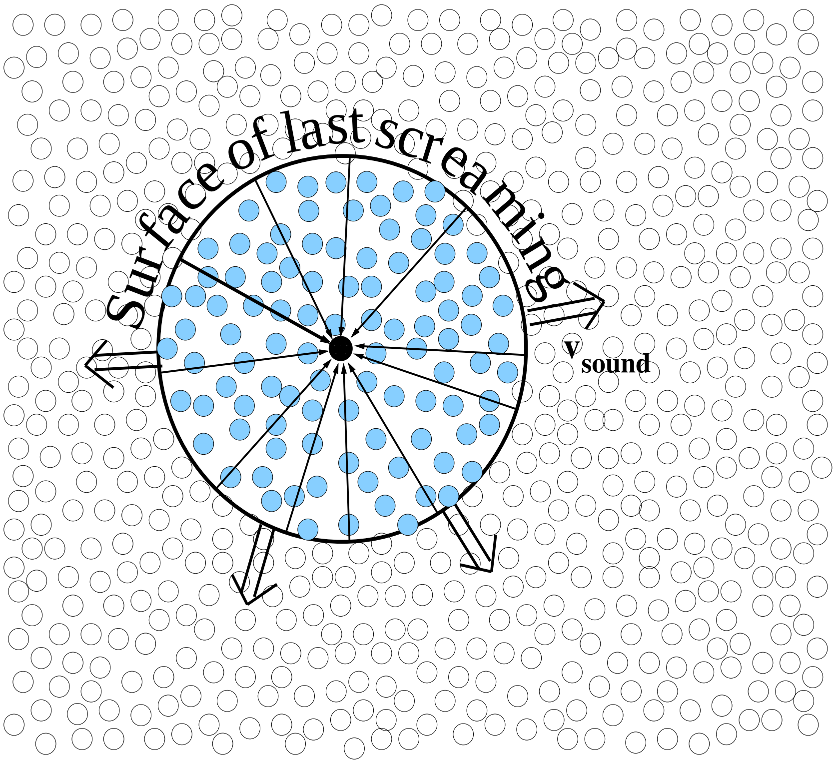

Figure 2. The Surface of Last Screaming.
Consider an infinite field full of people screaming. The circles are their heads. You are screaming too. (Your head is the black dot.) Now suppose everyone stops screaming at the same time. What will you hear? Sound travels at 330 m/s. One second after everyone stops screaming you will be able to hear the screams from a 'surface of last screaming' 330 meters away from you in all directions. After 3 seconds the faint screaming will be coming from 1 km away...etc. No matter how long you wait, faint screaming will always be coming from the surface of last screaming – a surface that is receeding from you at the speed of sound ('v_{sound}'). The same can be said of any observer – each is the center of a surface of last screaming. In particular, observers on your surface of last screaming are currently hearing you scream since you are on their surface of last scattering. The screams from the people closer to you than the surface of last screaming have passed you by – you hear nothing from them (grey heads). When we observe the CMB in every direction we are seeing photons from the surface of last scattering. We are seeing back to a time soon after the big bang when the entire Universe was opaque (screaming). If the Universe were not expanding, the surface of last scattering would be receding at the speed of light. The expansion of the Universe adds an additional recession velocity and makes the surface of last scattering recede at $\sim 3\,c$.

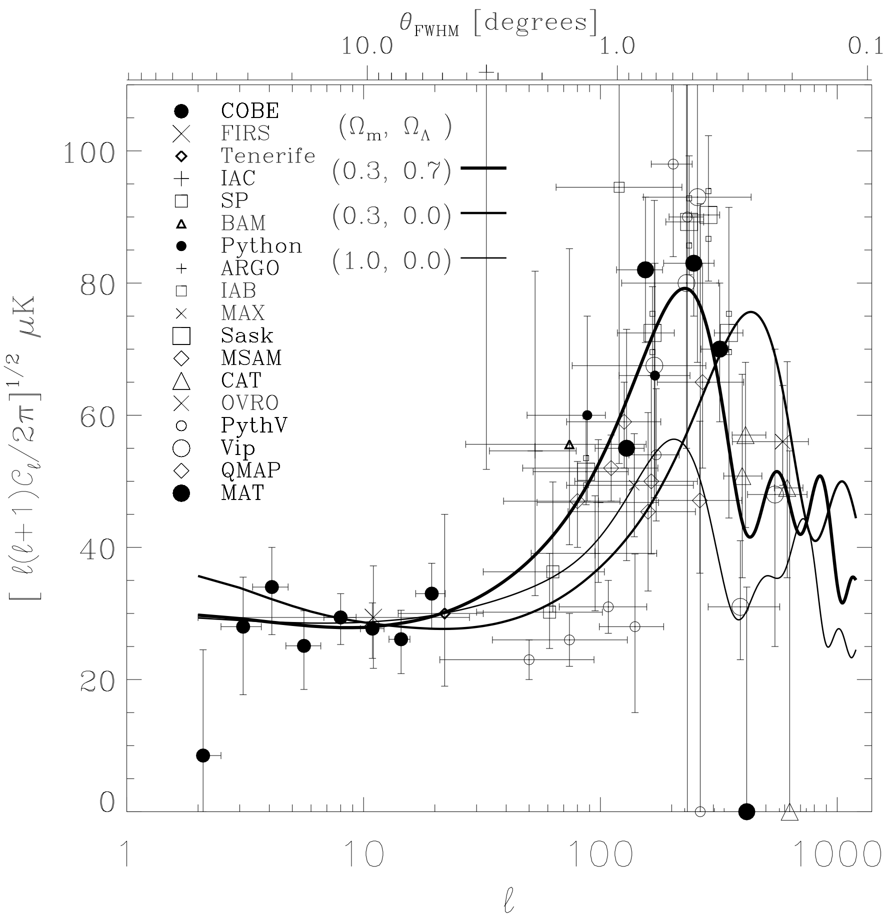

Figure 3. Measurements of the CMB power spectrum.
The amplitudes of the hot and cold spots in the CMB depend on their angular size. Angular size is noted in degrees on the top x axis. The y axis is the rms amplitude of the temperature fluctuations. For example, the fluctuations at 1/2 degree are at 90 μK while the fluctuations at 10 degrees are at 30 μK. This means that at the 1/2 degree angular scale, the hot spots are 3 times hotter and the cool spots are 3 times cooler than at the 10 degree scale. Each CMB experiment is sensitive only to a limited range of angular scale. When the measurements at various angular scales are put together they form the CMB power spectrum. The COBE-DMR points at $\theta_{FWHM} \gtrsim 7^o$ are primordial fluctuations corresponding to scales so big they are 'non-causal', i.e., they have physical sizes larger than the distance light could have travelled between the big bang and their age at the time we see them (300,000 years after the big bang). They are either the initial conditions of the Universe or were laid down during an epoch of inflation $\sim 10^{-35}$ seconds after the big bang. New sets of points are being added every month or so. The three curves represent the three most popular models. χ^2 fits of this data to such model curves yields the constraints in Fig. 5A.

My work over the past few years has been to extract values for these parameters by comparing the most recent measurements of the CMB with parameter-dependent models (Lineweaver & Barbosa 1998, Lineweaver 1998, 1999a). The three curves in Fig. 3 are examples of such models and represent the three most popular candidates for the best fit to reality. They are known as standard-CDM, Open-CDM and ΛCDM: $(\Omega_m, \Omega_\Lambda) = (1.0, 0.0), (0.3, 0.0)$ and $(0.3, 0.7)$ respectively. The principal support for these models comes from theory, tradition and data, respectively. The ΛCDM model fits the position and amplitude of the dominant first peak quite well. The standard-CDM model has a peak amplitude much too low. The open-CDM model has the peak at angular scales too small to fit the data and is strongly excluded by a fuller analysis (see Fig. 5A).

3 What is the Universe made of?

If we know what the Universe is made of, we know how it will behave and how it has behaved – we know its dynamics and shape and destiny – whether it will expand forever or collapse in a big crunch – whether it is spatially finite or infinite – whether it is 10 billion years old or 20. Many of these issues can be reduced to the question: Where does our Universe lie in the $(\Omega_m, \Omega_\Lambda)$ plane? Observational constraints in this plane are then the crucial arbiters. Figure 4 can be used to translate Ω_m and Ω_Λ constraints into the words most commonly used to describe the Universe.

In cosmology we keep track of the components of the Universe by their densities: Ω_m, Ω_{CDM}, Ω_b, Ω_Λ. These are all dimensionless densities expressed in units of the critical density, 10^{-29} g cm^{-3} (9 orders of magnitude emptier than the best laboratory vacuums). If the Universe has the critical density ($\Omega_m = 1$), then its current rate of expansion is analogous to the escape velocity, that is, it will expand forever, asymptotically approaching no expansion as $t \rightarrow \infty$ (just as the velocity of an object with escape velocity asymptotically approaches 0). One can read from Fig. 4 that an $(\Omega_m, \Omega_\Lambda) = (1.0, 0.0)$ universe is flat, decelerating and will expand forever.

3.1 Much Ado About Nothing

One of the most surprising recent advances in cosmology is that 75% of the Universe seems to be made out of nothing, i.e., the energy of the vacuum. I have assembled much of the observational evidence for this in Fig. 5. Recent CMB anisotropy measurements favour the elongated triangle in panel A of Fig. 5. This plot shows that if $\Omega_\Lambda = 0$ then $\Omega_m \sim 0.3$ is more than $\sim 4\sigma$ from the best fit and $\Omega_m \sim 0.1$ is more than $\sim 7\sigma$ away. The confidence levels in this diagram are very rough but the message is clear: if $\Omega_\Lambda = 0$, then low Ω_m models are strongly excluded by the CMB data. No other data set can exclude this region with such high confidence. The combination of CMB and supernovae constraints (Fig.5B) provides strong evidence that $\Omega_\Lambda > 0$. If any $\Omega_\Lambda = 0$ model can squeak by the new supernovae constraints it is the very low Ω_m models. However these models are the ones most strongly excluded by the CMB data. The constraints shown in panels C, D and E support this result. Separately these data sets cannot determine unambiguously what the destiny of the Universe will be. However, together they form a powerful interlocking network of constraints yielding the most precise estimates of Ω_m and Ω_Λ. The result is strong evidence and the best evidence to date that the Universe will expand forever, dominated by a 75% contribution from the vacuum.

I believe this result is robust because of a series of conservative choices made in the analysis and because it arises when the data sets are combined individually (as in panels B,C,D and E) or combined together (as in F). Systematic errors may compromise one or the other of the observations but are less likely to bias all of the observations in the same way.

The ΛCDM region of the $(\Omega_m, \Omega_\Lambda)$ plane fits the CMB, supernovae and other data sets and should be viewed as the new standard model of cosmology. Standard CDM with $\Omega_m = 1$ and $\Omega_\Lambda = 0$ is a simpler model, but circular planetary orbits are also simpler than ellipses. The results presented in Fig. 5F (Lineweaver 1999a) quantify the main components of the new standard ΛCDM model. They are depicted in Fig. 6 and are as follows:

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- **75% Vacuum energy, cosmological constant, Ω_Λ**

  The vacuum of modern physics is not empty. It is seething with virtual particles coming in and out of existence. All this seething produces a vacuum energy (the zero point energy of quantum field theory) which has a negative pressure. Unlike normal mass which slows down the expansion of the Universe, vacuum energy speeds up the expansion. It's a bit like discovering compressed springs everywhere in the vacuum of space. These springs make the Universe expand. This mysterious stuff does not clump. It is the Lorentz invariant structure of the vacuum and its existence is probably most directly established by the Casimir effect and the Lamb shift. $\Omega_\Lambda = 0.65 \pm 0.13$ corresponding to $74 \pm 4\%$ of the Universe.

- **20% Cold Dark Matter (CDM)**

  Non-baryonic and non-relativistic, CDM density fluctuations collapse gravitationally. It clumps. Corresponding CDM potential wells (and hills) produce the hot and cold spots in the CMB and are the principle seeds for the formation of the large scale structure we see around us today (galaxies, great walls, voids etc). This non-baryonic stuff has never been detected directly. $\Omega_{CDM} = 0.19 \pm 0.09$ corresponding to $21 \pm 7\%$ of the Universe. Leading candidates for it are axions or neutralinos (see Turner 1999).

- **5% Normal baryonic matter**

  This is the normal stuff that stars and ourselves are made of. We breathe it, eat it and physicists study it. $\Omega_b = 0.04 \pm 0.02$, corresponding to $5 \pm 2\%$ of the Universe. This value comes from big bang nucleosynthesis calculations and deuterium measurements in quasar spectra. In terms of elemental composition this normal baryonic matter is 75% hydrogen, 23% helium, and 2% all other elements. In terms of phase (see Fukugita *et al.* 1998, Cen & Ostriker 1998), it is 80% diffuse hot ionized gas, 17% stars and 3% neutral gas and dust.

The total density of the Universe is $\Omega_{total} = \Omega_m + \Omega_\Lambda = 0.88^{+0.07}_{-0.10}$ (Fig. 5F). The percentages listed above are based on $\Omega_{total} = 0.88$ (not $\Omega_{total} = 1$, most versions of inflation have $\Omega_{total} = 1$). The density from photons (from the CMB and from stars) is negligible: 0.006% of the Universe. I have left out one ingredient of the universe because we don't know whether it is important or not – neutrinos. We know their number density fairly accurately. It's

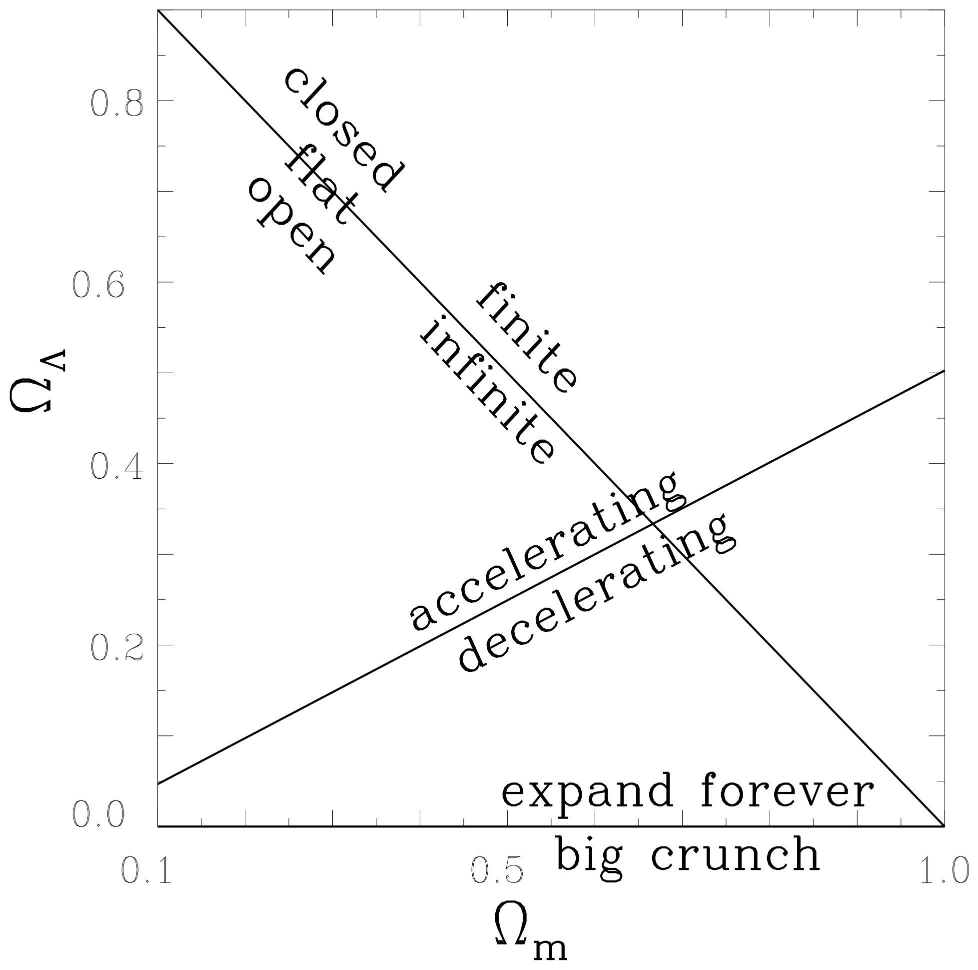

Figure 4. Describing the Universe.

The language used to describe the Universe, e.g. 'infinite/finite', 'open/flat/closed', 'accelerating/decelerating' and 'a universe which will expand forever/end in a big crunch', can be confusing. However the boundaries between these various types of universe can be simply represented in the $(\Omega_m, \Omega_\Lambda)$ plane. For example, spatially open universes (3-D analog of the surface of a saddle, negative curvature) are in the lower left while spatially closed universes (3-D analog of the surface of a sphere, positive curvature) are in the upper right. Flat Euclidean universes are on the diagonal line between them. Flat and open models are spatially infinite; closed models are finite. Notice that one can have finite universes which expand forever and can be either accelerating or decelerating. One can also have infinite universes which collapse into a big crunch (if $\Omega_\Lambda < 0$). A detail that is slightly ambiguous: if $\Omega_\Lambda = 0$ then $\Omega_m \leq 1$ universes expand forever while $\Omega_m > 1$ universes crunch. Observational constraints in this $(\Omega_m, \Omega_\Lambda)$ plane are given in Fig. 5; they favour accelerating, slightly open, but nearly flat universes with $\Omega_m \approx 0.3$ and $\Omega_\Lambda \approx 0.7$.

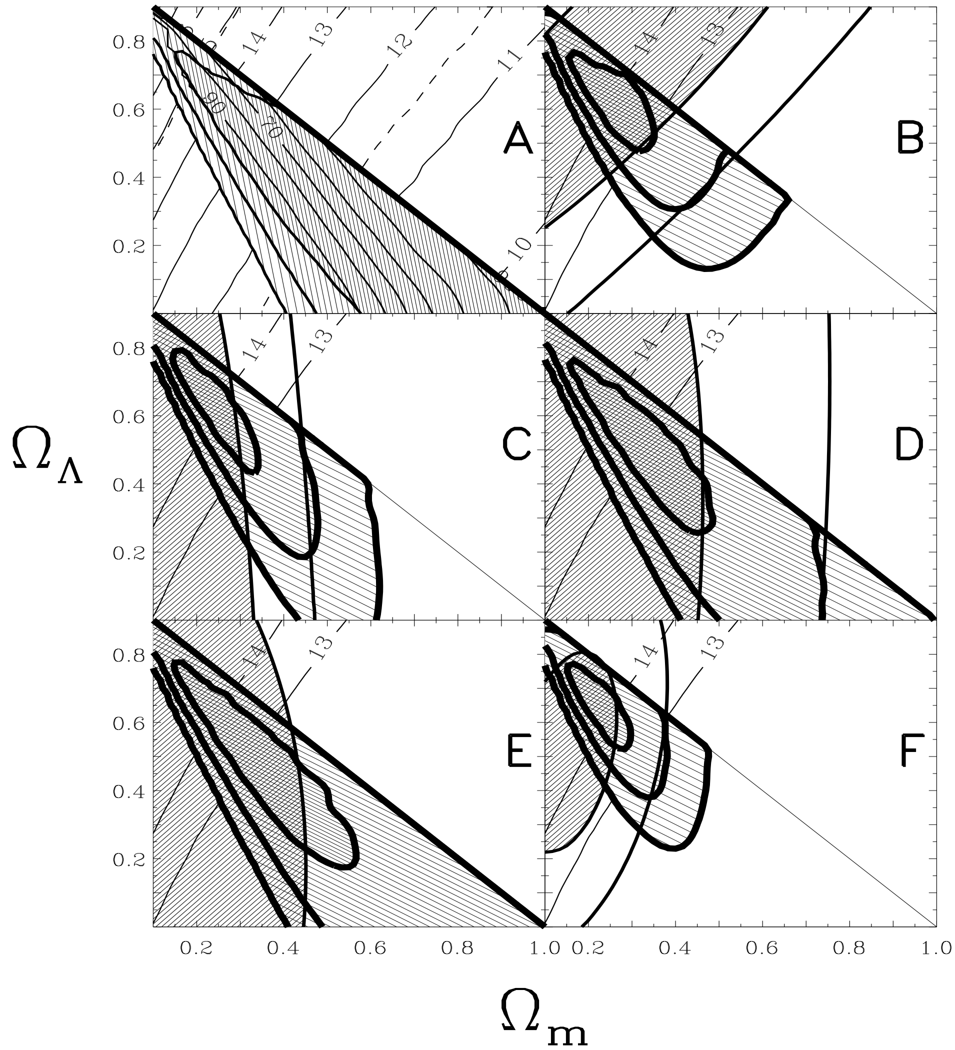

Figure 5. Observational constraints in the $(\Omega_m, \Omega_\Lambda)$ plane.
These 6 panels show the regions of the $(\Omega_\Lambda, \Omega_m)$ plane preferred by the data. The CMB constraint is in the top left panel (A). Other constraints are from type Ia supernovae (B), galaxy cluster mass-to-light ratios (C), galaxy cluster evolution (D) and double lobed radio sources (E) and all combined (F). The thickest contours in each panel are from combining each constraint with the CMB constraint from A. The combined constraints (F) yield $\Omega_\Lambda = 0.65 \pm 0.13$ and $\Omega_m = 0.23 \pm 0.08$ and thus $\Omega_{total} = 0.88^{+0.07}_{-0.10}$. ΛCDM models in the upper left are consistent with all the data sets. The CMB excludes the lower left region of the $(\Omega_m, \Omega_\Lambda)$ plane while each of the other constraints excludes the lower right. In A, the contours labeled '10' through '14' (Gyr) are the iso-age contours for a Hubble constant $h = 0.68$; the 13 and 14 Gyr contours are repeated in all panels. The contours within the CMB 68% CL are the best-fitting H values. See Lineweaver (1998,1999a) for details.

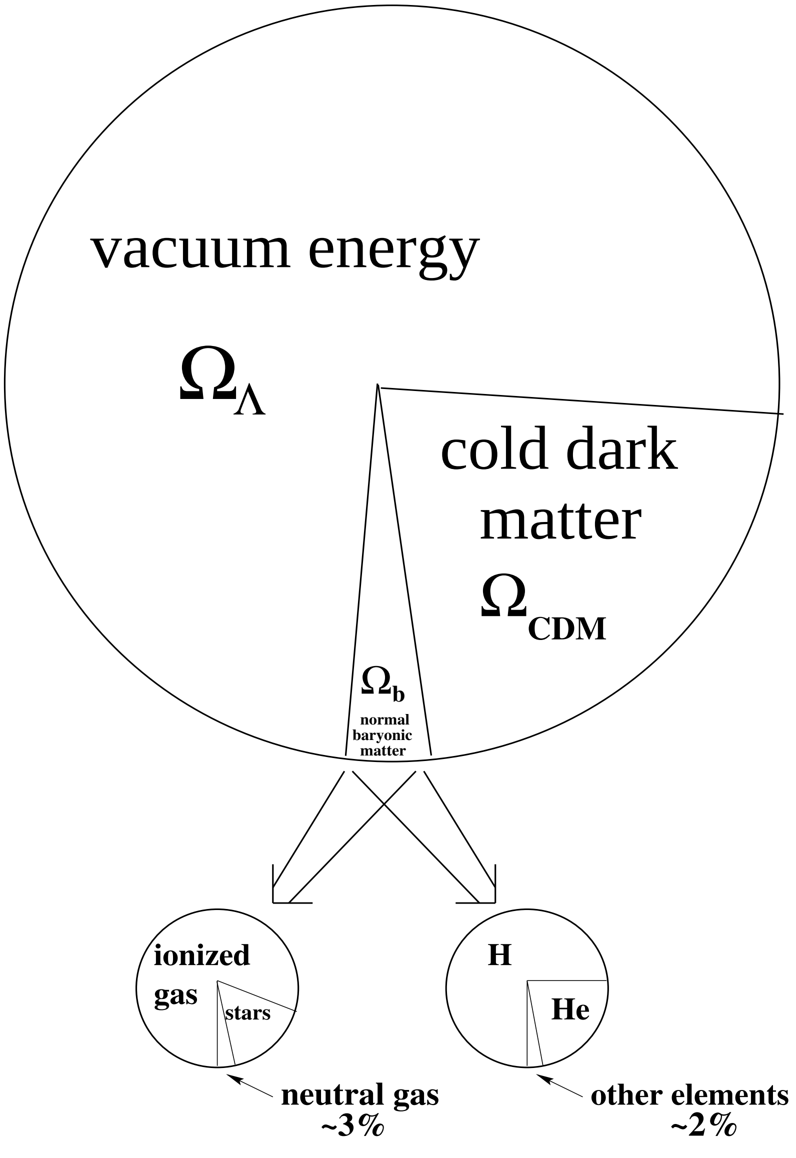

Figure 6. What is the Universe made of?
$\Omega_\Lambda(75\%)$ is now controlling the dynamics of the Universe, causing the Universe to accelerate. $\Omega_{CDM}(20\%)$ acts in the opposite sense, trying to decelerate the Universe (slow down the rate of expansion) but it can't compete with Ω_Λ (see Fig. 8). $\Omega_b(5\%)$ is a pawn, pushed and pulled around by the gravitational potentials due to spatial variations in the density of CDM. Most physicists study the 5% of the Universe made up of normal baryonic matter. Taking a closer look at the baryonic matter, 98% of it is either hydrogen or helium and 80% of it is in difficult to detect ionized gas. See the Table of Contents of the Universe (p. 7) for details.

the uncertainty in their mass which is responsible for our ignorance. Much effort is being put into measuring the mass(es) of neutrinos. Potentially they could contribute more than all the baryons and probably as much as all the stars. A good guess might be $\Omega_\nu = 0.05^{+0.10}_{-0.047}$ where the upper limit comes from the tendency of relativisitc particles to escape from small scale structures, i.e., if neutrinos formed more than 15% of the Universe, we could see much less small scale structure. The lower limit comes from the recent Super Kamiokande detection of a small but positive mass difference between two neutrino species (Fukuda *et al.* 1998). They could be negligible at 0.3% of the Universe or they could be $\sim 15\%$ of the Universe (Turner 1999). A $\sim 10\%$ contribution would make $\Omega_{total} \sim 1$ as preferred by inflation and would reduce the contribution of Ω_Λ from 75% to 65%.

The values quoted above for the composition of the Universe are not universally accepted. A vocal minority of Λ-phobic cosmologists and particle theorists believe that any $\Omega_\Lambda > 0$ result has got to be wrong. Their reasoning goes something like this. Theory predicts that $\Omega_\Lambda \gtrsim 10^{52}$. Since it is obviously not this value, Ω_Λ must be zero based on supersymmetric cancellation of the contributions to the vacuum energy from bosons and fermions. See Cohn (1998, Section II) for a more judicious discussion.

4 How old is the Universe?

In the big bang model, the age of the Universe, t_o, is a function of three parameters: h, Ω_m and Ω_Λ. The dimensionless Hubble's constant, h, tells us how fast the Universe is expanding. The matter density Ω_m slows the expansion while the vacuum energy Ω_Λ speeds up the expansion. Until recently, large uncertainties in the measurements of h, Ω_m and Ω_Λ made efforts to determine $t_o(h, \Omega_m, \Omega_\Lambda)$ unreliable. Theoretical preferences were, and still are, often used to remedy these observational uncertainties. One assumed the standard model ($\Omega_m = 1$, $\Omega_\Lambda = 0$), dating the age of the Universe to $t_o = 6.52/h$ billion years old. However for large, or even moderate h estimates ($\gtrsim 0.65$) these simplifying assumptions resulted in an age crisis in which the universe was younger than our Galaxy ($t_o \approx 10$ Gyr $< t_{Gal} \approx 12$ Gyr).

With a new inventory of the Universe described in the previous section and a new more precise value for the Hubble constant (e.g. Mould *et al.* 2000), a new more precise age for the Universe can be calculated. This was the focus of an article I recently published in Science entitled "A Younger Age for the Universe". The result I obtained was more than a billion years younger than other recent results (see Fig. 7).

5 What could be wrong?

Doubts about some of the observation used here are discussed in Dekel *et al.* (1998). The contribution of neutrinos (or another form of hot dark matter) to Ω_m remains a wild card. It is possible that supernovae are not as uniformly bright as we believe. It is possible that the well-motivated assumptions used in the CMB analysis (gaussian adiabatic fluctuations, structure formation through gravitational instability) are mistaken. A mild conspiracy of unknown systematic errors could substantially change the constraints in Fig. 5F.

There has been some speculation recently that the evidence for Ω_Λ is really evidence for some

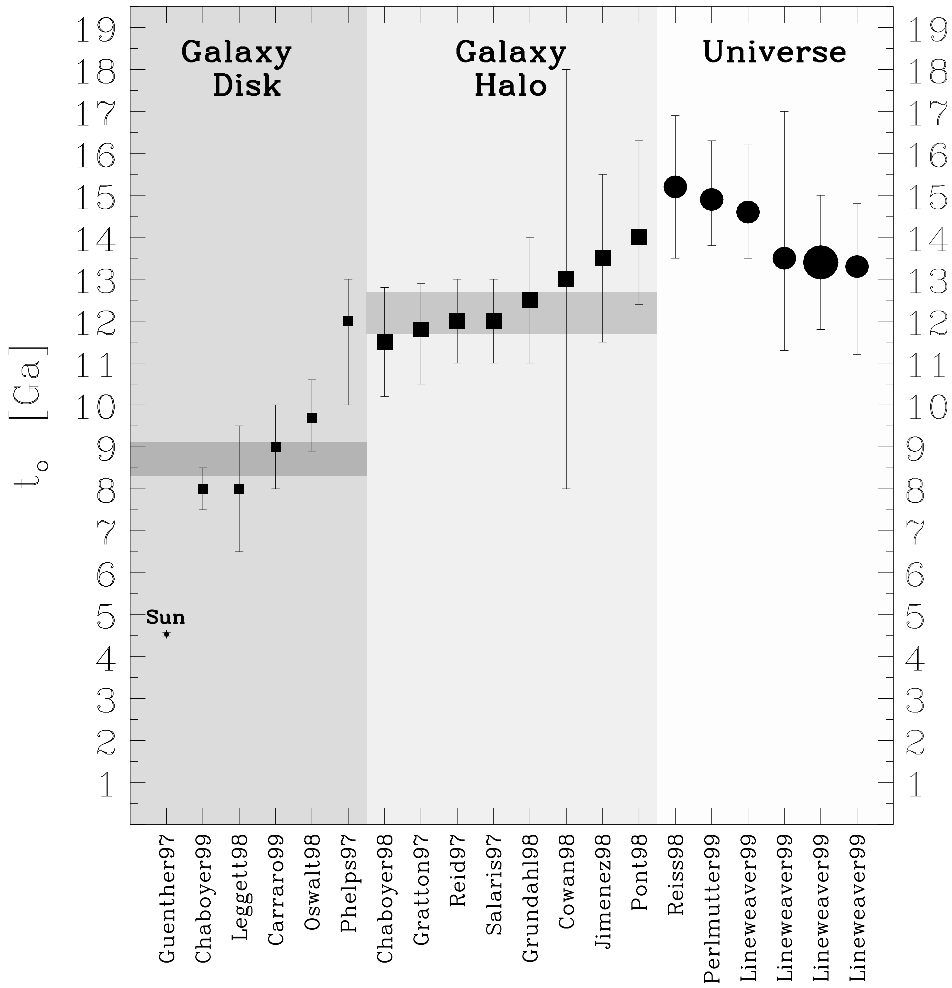

Figure 7. How old is the Universe?

A compilation of recent age estimates for the Universe and for the oldest objects in our Galaxy. Estimates of the age of the Universe are based on estimates of Ω_m, Ω_Λ and h. Galactic age estimates are direct in the sense that they do not depend on cosmology. Averages of the estimates of the age of the Galactic halo and Galactic disk are shaded grey. The absence of any single age estimate more than $\sim 2\sigma$ from the average adds plausibility to the possibly overdemocratic procedure of computing the variance-weighted averages. The age of the Sun is accurately known and is included for reference. The largest dot at 13.4 ± 1.6 Ga (billion years) is the main result of the Lineweaver (1999a) paper. This age range is shaded grey on the x-axis of the Fig. 8. Comfortingly, the Universe is older than the objects in it. This has not always been the case in cosmology and its absence has been a leading cause of cosmology bashing.

form of stranger dark energy (dubbed 'quintessence') that we have been incorrectly interpreting as Ω_Λ. Several workers have tested this idea. The evidence so far indicates that the cosmological constant interpretation fits the data as well as or better than an explanation based on more mysterious dark energy (Perlmutter *et al.* 1999a, Garnavich *et al.* 1998, Perlmutter *et al.* 1999b).

6 The Future

As the quality and quantity of cosmological data improve, the questions: What is the Universe made of? How old is the Universe? will get increasingly precise answers from an ever-tightening network of constraints. An army of instruments is coming on line. Better CMB detectors are being built; long duration balloons will fly; sensitive new high resolution interferometers will soon be on line and we all have high expectations for the two CMB satellites MAP and Planck. In the near future, new CMB measurements will reduce the error bars in Fig. 5 by a factor of ~ 5 and/or... if some inconsistency is found, force us to change our basic understanding of the Universe. Maybe inflation is wrong, maybe CDM doesn't exist or we live in an eternally inflating multiverse.

The biggest prize of all may be something unexpected. We know that our model of the Universe is incomplete at the largest scales and that it breaks down as we get closer and closer to the big bang. It seems very probable that our model is wrong in some unexpectedly fundamental way. It may contain some crucial conceptual blunder (as has happened so many times in the past). Some unexpected quirk in the data may point us in a new direction and revolutionize our view of the Universe on the largest scales. Surely this is the golden age of cosmology.

What does this all mean for the physicists in the street? We should devote more effort to studying nothing – the vacuum. We should improve on measurements of the Casimir effect. Maybe one of us will invent a heat engine based not on a phase transition of water but on a phase transition of the vacuum. In the past, on the few occasions where general relativity and quantum theory intersected (Ω_Λ is a quantum term in a classical equation) exciting new things have emerged: Hawking radiation, entropy calcuations of black holes and maybe soon a theoretical calculation of Ω_Λ which will lead to a plausible theory of quantum gravity.

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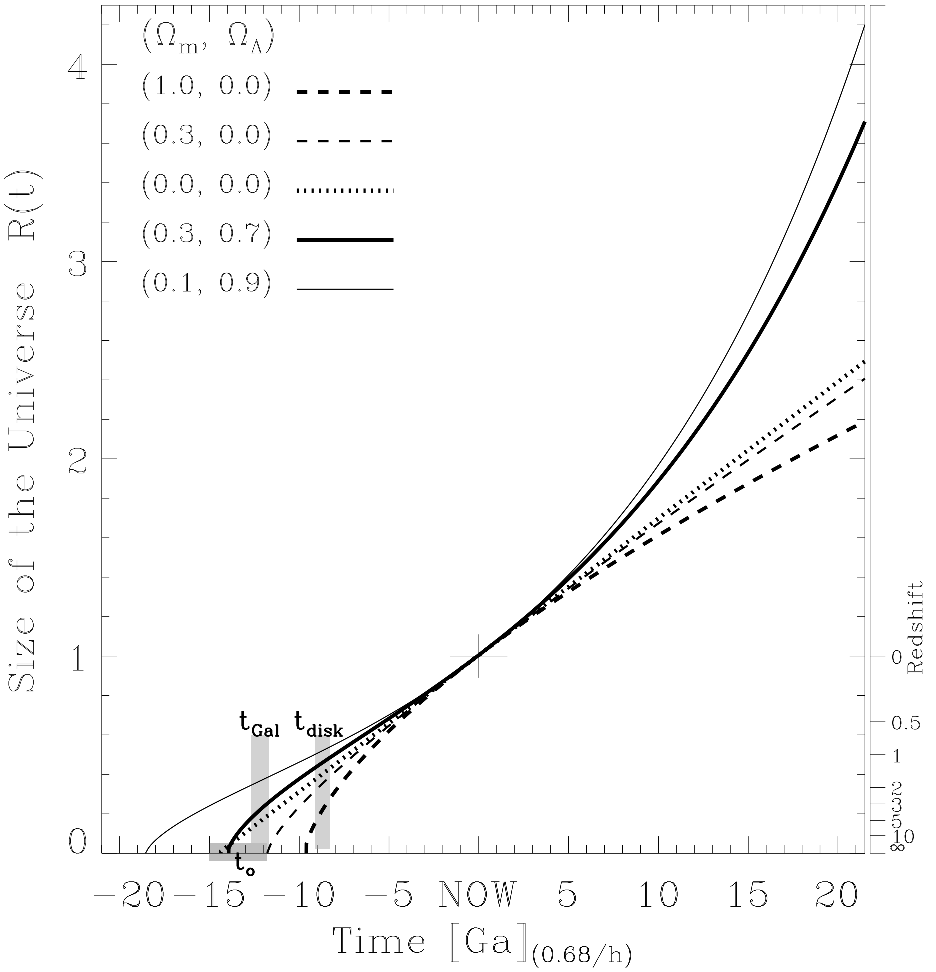

Figure 8. Destiny of the Universe.
The size of the Universe, in units of its current size, as a function of time. The age of the five models can be read from the x axis as the time between 'NOW' and the intersection of the model with the x axis. The main age result from Lineweaver 1999a, $t_o = 13.4 \pm 1.6$ Gyr, is labeled t_o and is shaded grey on the x axis. Models containing Ω_Λ curve upwards ($\ddot{R} > 0$) and are currently accelerating. The empty universe has $\ddot{R} = 0$ (dotted line) and is 'coasting'. The expansion of matter dominated universes is slowing down ($\ddot{R} < 0$). The $(\Omega_\Lambda, \Omega_m) = (0.3, 0.7)$ model is favoured by the data. Over the past few billion years and on into the future, the rate of expansion of this model increases. This acceleration means that we are in a period of slow inflation.

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7 Bio

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Charles Lineweaver is a Vice Chancellor's Research Fellow at the University of New South Wales. He studied undergraduate physics at Ludwig Maximillian Universität, Germany and at Kyoto University, Japan. He obtained his PhD in Physics from the University of California at Berkeley. After a postdoctoral fellowship at Strasbourg, France he came to UNSW in 1997. He also has an undergraduate degree in history and a masters degree in English. He has lived or travelled in 58 countries, speaks four languages and has played semi-professional soccer. He is co-convener with John Webb of a popular new UNSW course on bioastronomy: "Are We Alone?".