dark matter was completely unknown, it was often ignored. During the 1970s, it became clear that the motion of stars and gas in galaxies—and of satellite galaxies around them—required that this dark matter must greatly outweigh the visible matter in galaxies. The data gathered since then provides very strong evidence that most of the matter in the Universe is invisible.

**DARK MATTER** made of light neutrinos, with masses of a few electron volts (eV) or less, is called “hot dark matter” (HDM) by cosmologists, because those neutrinos would have been moving at nearly the speed of light in the early Universe. (See the tables on the next page for a summary of dark-matter types and associated cosmological models.) For a few years in the late 1970s and early 1980s, hot dark matter looked like the best dark-matter candidate. But HDM models of cosmological structure formation led to a “top-down” formation scenario, in which superclusters of galaxies are the first objects to form after the Big Bang, with galaxies and clusters forming through a subsequent process of fragmentation. Such models were abandoned by the mid-1980s after cosmologists realized that
if galaxies had formed early enough to agree with observations, their distribution would be much more inhomogeneous than is the case. Since 1984, the most successful structure-formation models have been those in which most of the mass in the Universe comes in the form of cold dark matter (CDM)—particles that were moving sluggishly in the early Universe. But the HDM stock rose again a few years later, and for a while in the mid-1990s it appeared that a mixture of mostly CDM with 20–30 percent HDM gave a better fit to the observations than either one or the other. This “cold plus hot dark matter” (CHDM) theory fit data on nearby galaxies and clusters only if the average density of matter in the Universe were at or close to the critical density (Ωₘ =1). But like all such critical-density models, CHDM required that galaxies and clusters must have formed fairly recently, which disagrees with observations. The evidence now increasingly favors ΛCDM models, in which cold dark matter makes up about a third of the critical density, with a cosmological constant Λ or some other form of “dark energy” contributing the remainder. This model also helped resolve the crisis regarding the age of the Universe (see box on next page). The question has now become one of how much room is left for neutrinos in these cosmological models.

To describe the possible role of neutrinos as dark matter, I must now explain how structures such as galaxies formed as the Universe expanded. The expansion itself is described by our modern theory of gravity and spacetime, Einstein’s theory of general relativity. In order for structure to form, there must have been some small fluctuations in the initial density of matter, or else some mechanism had to generate such fluctuations afterward. The only such mechanisms that have been investigated are “cosmic defects” such as cosmic strings, and the pattern of fluctuations produced by such defects is inconsistent with the temperature fluctuations observed in the cosmic microwave background (CMB) radiation. On the other hand, “adiabatic” fluctuations—in which all components of matter and energy fluctuate together—occur naturally in the simplest cosmic inflation models and are in excellent agreement

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### Types of Dark Matter

Ωᵢ represents the fraction of the critical density ρₖ = 10.54 h² keV/cm³ needed to close the Universe, where h is the Hubble constant H₀ divided by 100 km/s/Mpc.

<table>
<thead>
<tr>
<th>Dark Matter Type</th>
<th>Fraction of Critical Density</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baryonic</td>
<td>Ωₜ ~ 0.04</td>
<td>about 10 times the visible matter</td>
</tr>
<tr>
<td>Hot</td>
<td>Ων ~ 0.001–0.1</td>
<td>light neutrinos</td>
</tr>
<tr>
<td>Cold</td>
<td>Ωc ~ 0.3</td>
<td>most of the dark matter in galaxy halos</td>
</tr>
</tbody>
</table>

### Dark Matter and Associated Cosmological Models

Ωₚ represents the fraction of the critical density in all types of matter. Ωₐ is the fraction contributed by some form of “dark energy.”

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Cosmological Model</th>
<th>Flourished</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDM</td>
<td>hot dark matter with Ωₚ = 1</td>
<td>1978–1984</td>
</tr>
<tr>
<td>SCDM</td>
<td>standard cold dark matter with Ωₚ = 1</td>
<td>1982–1992</td>
</tr>
<tr>
<td>CHDM</td>
<td>cold + hot dark matter with Ωc ~ 0.7 and Ων ~ 0.2–0.3</td>
<td>1994–1998</td>
</tr>
<tr>
<td>ΛCDM</td>
<td>cold dark matter Ωc ~ 1/3 and Ωλ ~ 2/3</td>
<td>1996–today</td>
</tr>
</tbody>
</table>
with the latest CMB results announced at the American Physical Society meeting in April 2001.

The evolution of adiabatic fluctuations into galaxies and clusters is easy to understand if you just think of gravity as the ultimate capitalist principle: the rich always get richer and the poor get poorer. A “rich” region of the Universe is one that has more matter than average. Although the average density of the Universe steadily decreases due to its expansion, those regions that start out with a lower density than average expand a little slower than average and become relatively more dense, while those with lower density expand a little faster and become relatively less dense. When any region has achieved a density about twice the average, it starts expanding and begins to collapse—typically first in one direction, forming a pancake-shaped structure, and then in the other two directions.

I can now explain why the first hot-dark-matter boom occurred about two decades ago. Improving upper limits on CMB anisotropies were ruling out the previously favored cosmological model, which included only ordinary matter. There was also evidence from a Moscow experiment suggesting that the electron neutrino mass was about 20–30 eV, which would have corresponded to a nearly critical-density Universe in which neutrinos would have dominated the total mass (see box on page 56). In such a cosmology, the primordial fluctuations on galaxy scales are erased by “free streaming” of the relativistic neutrinos in the early Universe. One year after the Big Bang, a region about one light year across contained the amount of matter (both ordinary and dark) in a large galaxy like our own Milky Way. But the temperature was then about 100 million degrees, so each particle had a thermal energy far higher than the rest energy of light neutrinos. As they would therefore have been moving at nearly the speed of light, these neutrinos would have rapidly spread out, and any fluctuations in density on the scale of galaxies would soon have been smoothed back to the average density.

The first scales to collapse in such a HDM scenario would therefore correspond to the mass inside the cosmic horizon when the temperature dropped to a few eV and the neutrinos inside it became nonrelativistic. This mass turns out to be about 10,000 times the mass of our galaxy, including its dark halo. Evidence was just then becoming available from the first large-scale galaxy surveys that the largest cosmic structures—superclusters—have masses of approximately this size, which at first glance appeared to be a big success for the HDM scenario.

Superclusters of roughly pancake shape were observed to surround roughly spherical voids (regions where few galaxies are found), in agreement with the first cosmological computer simulations, which were run for the HDM model. In this picture superclusters should have formed first, since any smaller-scale fluctuations in the dominant hot dark matter would have been erased by free streaming. Galaxies then had to form by fragmentation of the superclusters. But it was already becoming clear from observations that galaxies are much older than

IN THE MID-1990S there was a crisis in cosmology, because the age of the old globular-cluster stars in the Milky Way, then estimated to be $t_{GC} = 16.3$ billion years (Gyr), was higher than the expansion age of the Universe, which for $\Omega_m = 1$ is $t_{exp} = 9.2$ Gyr. Here I have assumed that the Hubble parameter has the value $H_0 = H_0/(100 \text{ km/s/Mpc}) = 0.72 \pm 0.07$, the final result from the Hubble Space Telescope project measuring $H_0$.

But when the data from the Hipparcos astrometric satellite became available in 1997, it showed that the distances to the globular clusters had been underestimated, which implied in turn that their ages had been overestimated; now $t_{GC} = 13.3$ Gyr. The age of the Universe is consequently $t_U = t_{GC} + 1 = 14.3$ Gyr.

Several lines of evidence now show that the Universe does not have $\Omega_m = 1$ but rather $\Omega_m + \Omega_\Lambda = 1.0 \pm 0.1$ and $\Omega_m = 0.3 \pm 0.1$. Taken together, these yield $t_{exp} = 13.2$ Gyr, in excellent agreement with the revised globular cluster age. The high-redshift supernova data alone give $t_{SN} = 14.2 \pm 1.7$ Gyr.

Moreover, a new type of age measurement based on radioactive decay of Thorium-232 (half-life 14.1 Gyr) measured in a number of very old stars gives a completely independent age $t_{decay} = 14.3$ Gyr. A similar measurement, based on the first detection in a star of Uranium-238 (half-life 4.47 Gyr), reported this past February, gives $t_{decay} = 12.5 \pm 3$ Gyr. Work in progress should soon improve the precision of these measurements.

All the recent measurements of the age of the Universe are therefore in excellent agreement. It is reassuring that three completely different cosmological clocks—stellar evolution, expansion of the Universe, and radioactive decay—agree so well.
predicted (to within a normalization uncertainty factor of about 2) the magnitude of the CMB temperature fluctuations, which were discovered in 1992 using the COBE satellite. But the simplest CDM model, standard CDM (or SCDM) with the matter density equal to the critical value ($\Omega_m = 1$), had already begun to run into trouble.

Cosmological theories predict statistical properties of the Universe—for example, the size of density fluctuations on various scales, described mathematically by a power spectrum. Sound or other fluctuation phenomena can be described in the same way—for example, low frequencies might be loud, corresponding to relatively high power at long wavelengths. Put simply, SCDM had difficulty fitting the full spectrum of density fluctuations at both short and long wavelengths—or at small and large scales. With a given amount

HOT MATTER FELL into decline.

I HELPED TO DEVELOP the cold dark matter model in 1982–1984 just as the problems with the hot dark matter model were becoming clear. Proto-galaxies form first in a CDM cosmology, and galaxies and larger-scale objects form by aggregation of these smaller lumps—although the cross-talk between smaller and larger scales in the CDM theory naturally leads to galaxies forming earlier in clusters than in lower-density regions. In this and other respects, CDM models appeared to fit observations much better than HDM. The first great triumph of cold dark matter was that it successfully

predicted (to within a normalization uncertainty factor of about 2) the magnitude of the CMB temperature fluctuations, which were discovered in 1992 using the COBE satellite. But the simplest CDM model, standard CDM (or SCDM) with the matter density equal to the critical value ($\Omega_m = 1$), had already begun to run into trouble.

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of fluctuation power on the large scales probed by COBE (billions of light years), that is, SCDM has a little too much power on small scales relevant to galaxies and clusters (millions of light years and less). It produces too many of them. But the fact that the SCDM theory could work fairly well across such a wide range of size scales suggested that it had a kernel of truth. Cosmologists began to examine whether some variant of SCDM might work better.

Although these COBE results did not come in until 1992, I became worried that SCDM was in trouble when the large-scale flows of galaxies were first observed by my UC Santa Cruz colleague Sandra Faber and her “Seven Samurai” group of collaborators. Earlier studies had established that the local group of galaxies (including the Milky Way and the “nearby” Andromeda galaxy) is speeding at a velocity of about 600 kilometers per second with respect to the CMB reference frame. But the Seven Samurai and others found that bulk motions of other galaxies often had similar high velocities across regions several tens of millions of light years wide. It soon became clear that this result was inconsistent with the expectations of the “biased” SCDM model that seemed to fit the properties of galaxies on smaller scales.

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In the late 1980s Jon Holtzman, then Faber’s graduate student, did a theoretical dissertation with me in which he calculated detailed expectations for 96 variants of cold dark matter on smaller scales. In the early 1990s, when cold dark matter was still a new idea, but their detailed consequences were not worked out until the problems with SCDM began to surface.

**EVEN IF MOST** of the dark matter is cold, a little hot dark matter can still have dramatic effects on the small scales relevant to the formation and distribution of galaxies. In the early Universe, the free streaming of fast-moving neutrinos would have washed out any spatial inhomogeneities on the scales that later became galaxies, just as in the HDM scenario. Consequently, CDM fluctuations did not grow as fast on these scales, and at the relatively late times when galaxies formed there was less fluctuation power on small scales in CHDM and ΛCDM models. The main problem with $\Omega_m = 1$ cosmologies containing only cold dark matter plus a small admixture of ordinary baryonic matter is that the galaxy-scale inhomogeneities are too big compared to those on larger scales. Adding a little hot dark matter appeared to be just what was needed to solve this problem.

And there was even a hint from an accelerator experiment that neutrino mass might lie in the relevant range. The experiment was the Liquid Scintillator Neutrino Detector (LSND) experiment at Los Alamos National Laboratory (see photograph on page 38), which recorded a number of events that appear to be $\nu_\mu \rightarrow \nu_e$ oscillations. Comparison of the LSND data with results from other neutrino experiments allows two discrete values of $\Delta m^2_{\nu_e}$ (see box, next page) around 10.5 and 5.5 eV$^2$, or a range of values between 0.2 and 2 eV$^2$. If true, this means that at least one neutrino has a mass greater than 0.5 eV, which would imply that the contribution of hot dark matter to the cosmological density is much greater than that of all the visible stars. Such an important conclusion requires independent confirmation. The KARlsruhe Rutherford Medium Energy Neutrino (KARMEN) experiment results exclude a significant portion (but not all) of the LSND parameter space, and the numbers quoted above take into account the current KARMEN limits. The Booster Neutrino Experiment (BooNE) at Fermilab (see article by Paul Nienaber, this issue) should attain greater sensitivity and help to resolve this issue.

By 1995 simulation techniques and supercomputer technology had advanced to the point where it
Neutrino Mass and Cosmological Density

THE ATMOSPHERIC-NEUTRINO DATA from the Super-Kamiokande underground neutrino detector in Japan provide strong evidence of muon to tau neutrino oscillations, and therefore that these neutrinos have nonzero mass (see the article by John Learned in the Winter 1999 Beam Line, Vol. 29, No. 3). This result is now being confirmed by results from the K2K experiment, in which a muon neutrino beam from the KEK accelerator is directed toward Super-Kamiokande and the number of muon neutrinos detected is about as expected from the atmospheric-neutrino data (see article by Jeffrey Wilkes and Koichiro Nishikawa, this issue).

But oscillation experiments cannot measure neutrino masses directly, only the squared mass difference \( \Delta m^2 = |m^2_i - m^2_j| \) between the oscillating species. The Super-Kamiokande atmospheric neutrino data imply that \( 1.7 \times 10^{-4} < \Delta m^2_{\nu_{\mu} \nu_{\tau}} < 4 \times 10^{-3} \text{ eV}^2 \) (90 percent confidence), with a central value \( \Delta m^2_{\nu_{\mu} \nu_{\tau}} = 2.5 \times 10^{-3} \text{ eV}^2 \). If the neutrinos have a hierarchical mass pattern \( m_{\nu_e} \ll m_{\nu_\mu} \ll m_{\nu_\tau} \), like the quarks and charged leptons, then this implies that \( \Delta m^2_{\nu_{\mu} \nu_{\tau}} \equiv m^2_{\nu_\tau} \), so \( m_{\nu_\tau} \sim 0.05 \text{ eV} \).

These data then imply a lower limit on the HDM (or light neutrino) contribution to the cosmological matter density of \( \Omega_\nu > 0.001 \) —almost as much as that of all the stars in the disks of galaxies. There is a connection between neutrino mass and the corresponding contribution to the cosmological density, because the thermodynamics of the early Universe specifies the abundance of neutrinos to be about 112 per cubic centimeter for each of the three species (including both neutrinos and antineutrinos). It follows that the density \( \Omega_\nu \) contributed by neutrinos is \( \Omega_\nu = m(\nu)/(93 \text{ } h^2 \text{ eV}) \), where \( m(\nu) \) is the sum of the masses of all three neutrinos. Since \( h^2 \sim 0.5 \), \( m_{\nu_\tau} \sim 0.05 \text{ eV} \) corresponds to \( \Omega_\nu \sim 10^{-3} \).

This is however a lower limit, since in the alternative case where the oscillating neutrino species have nearly equal masses, the values of the individual masses could be much larger. The only other laboratory approaches to measuring neutrino masses are attempts to detect neutrinoless double beta decay, which are sensitive to a possible Majorana component of the electron neutrino mass, and measurements of the endpoint of the tritium beta-decay spectrum. The latter gives an upper limit on the electron neutrino mass, currently taken to be 3 eV. Because of the small values of both squared-mass differences, this tritium limit becomes an upper limit on all three neutrino masses, corresponding to \( m(\nu) < 9 \text{ eV} \). A bit surprisingly, cosmology already provides a stronger constraint on neutrino mass than laboratory measurements, based on the effects of neutrinos on large-scale structure formation.

was possible to do reasonably high-resolution cosmological-scale simulations including the random velocities of a hot dark matter component. The results at first appeared very favorable to CHDM. Indeed, as late as 1998 a CHDM model (with Hubble parameter \( h = 0.5 \), mass density \( \Omega_m = 1 \), and neutrino density \( \Omega_\nu = 0.2 \)) was found to be the best fit of any cosmological mode to the galaxy distribution in the nearby Universe. But cosmological data was steadily improving, and even by 1998 it had become clear that \( h = 0.5 \) and \( \Omega_m = 1 \) were increasingly inconsistent with several observations, and that \( h \sim 0.7 \) and \( \Omega_m \sim 1/3 \) worked much better. For example, CHDM predicts that galaxies and clusters formed relatively recently, but around 1998 increasing numbers of galaxies were discovered to have formed in the first few billion years after the Big Bang. And the fraction of baryons found in clusters, together with the reasonable assumption that this fraction is representative of the Universe as a whole, again gives \( \Omega_m \sim 1/3 \). That there is a large cosmological constant (or some other form of dark energy) yielding \( \Omega_\Lambda \sim 2/3 \) then follows from any two of the following three results: (1) \( \Omega_m \sim 0.3 \), (2) CMB anisotropy data implying that \( \Omega_m + \Omega_\Lambda = 1 \), and (3) high-redshift supernova data implying that \( \Omega_\Lambda - \Omega_m \sim 0.4 \).

The abundance of galaxies and clusters in the early Universe agrees well with the predictions of the \( \Lambda \)CDM model. However, the highest-resolution simulations of this model that were possible in the mid-1990s gave a dark matter spectrum that had more power on scales of a few million light years than did the
observed galaxy power spectrum, although the simulations and data agreed on larger scales. This result was inconsistent with the expectations that galaxies would be (if anything) more clustered than the dark matter on small scales, not less. When it became possible to do even higher-resolution simulations that allowed the identification of the dark matter halos of individual galaxies, however, their power spectrum turned out to be in excellent agreement with observations. The galaxies were less clustered than dark matter because galaxies had merged or were destroyed in very dense regions due to interactions with each other and with the cluster center. This explanation turned a troubling discrepancy into a triumph for $\Lambda$CDM.

Thus $\Lambda$CDM is the favorite theory today. But we know from the Super-Kamiokande evidence for atmospheric neutrino oscillations that there is enough neutrino mass to correspond to some hot dark matter, at least $\Omega_\nu \sim 10^{-3}$ (see box on opposite page) about one-fourth as much as the visible stars. So the remaining question regarding neutrinos in cosmology is how much room remains for a little hot dark matter in $\Lambda$CDM cosmologies. There could be perhaps 10 times the lower limit just quoted, but probably not 100 times. The reason there is any upper limit at all from cosmology is because the free streaming of neutrinos in the early Universe must have slowed the growth of the remaining CDM fluctuations on small scales. Thus to have the galaxy structures we see today, there must be much more cold than hot dark matter. For the observationally favored range $0.2 \leq \Omega_m \leq 0.5$, the limit on the sum of the neutrino masses is $m(\nu) < 24 (\Omega_m/0.17 - 1) \text{ eV}$. Thus for $\Omega_m < 0.5$, the sum of all three neutrino masses is less than 5 eV. This limit on the sum of the neutrino masses is much stronger than the best current laboratory limit.

Astronomical observations that may soon lead to stronger upper limits on $m(\nu)$—or perhaps even a detection of neutrino mass—include data on the distribution of low-density clouds of hydrogen (the so-called “Lyman-alpha forest”) in the early Universe, large-scale weak gravitational lensing data, and improved measurements of the fluctuations in the CMB radiation temperature at small angles. These data are sensitive to the presence of free-streaming neutrinos in the early Universe, which can lead to fewer galaxies on small scales, depending on the values of the neutrino masses.

The hot dark matter saga thus illustrates once again the fruitful marriage between particle physics and cosmology. While neutrino-oscillation experiments can tell us only about differences between the squared masses of the neutrinos, the structure of the Universe can give us information about the neutrino masses themselves. In an earlier example of this connection, cosmological arguments based on Big Bang nucleosynthesis of light elements put a strict limit on the possible number of light neutrino species; this limit was eventually borne out by high-energy physics experiments on Z bosons at CERN and SLAC. The detailed studies of cosmological structures now going on or about to begin may eventually reveal something about neutrino mass itself.

For Further Reading

For a more technical article on the present subject with extensive references, see “Hot Dark Matter in Cosmology,” by Joel R. Primack and Michael A. K. Gross, in Current Aspects of Neutrino Physics, D. O. Caldwell, Ed. (Berlin: Springer, 2001); also available on the Internet as astro-ph/0007165 and interactively as nedwww.ipac.caltech.edu/level5/Primack4/frames.html
PAUL NIENABER has the great good fortune to be part of two extraordinary neutrino groups at Fermilab. He joined the NuTeV collaboration in 1992 and is now working on data analysis from that experiment; in addition, he became a member of the BooNE collaboration in 2000 and is participating in construction and testing of its detector.

The photograph above shows Paul inside the BooNE tank, surrounded by the photomultiplier tubes he helped install. He is a Jesuit priest, a Guest Scientist at Fermilab, and a member of the physics faculty at the College of the Holy Cross in Worcester, Massachusetts, where he thoroughly enjoys infecting college students’ minds with the manifold pleasures of doing physics. This is his first article for the Beam Line.

JOSHUA KLEIN received his Ph.D. from Princeton University in 1994. He then moved to the University of Pennsylvania where he has worked on building and making measurements with the Sudbury Neutrino Observatory. He is currently Research Assistant Professor of Physics at Pennsylvania.

SNO is in many ways the quintessential particle astrophysics experiment featuring the Sun as a neutrino laboratory and neutrinos as solar probes. Klein’s interest in SNO encompasses both of these features, including an interest in neutrinos themselves as the Standard Model’s most enigmatic particle.

MICHAEL RIORDAN is Assistant to the Director at the Stanford Linear Accelerator Center, Lecturer in the History and Philosophy of Science Program at Stanford, and Adjunct Professor of Physics at the University of California, Santa Cruz. A Contributing Editor of the Beam Line, he is author of The Hunting of the Quark, and coauthor of The Shadows of Creation: Dark Matter and the Structure of the Universe and Crystal Fire: The Birth of the Information Age. He leads a group of historians and physicists researching and writing the history of the Superconducting Super Collider. In 1999 he received a Guggenheim Fellowship to pursue research on this subject at the Smithsonian Institution in Washington, DC. While there, he also got married again.

CONTRIBUTORS

PAUL NIENABER has the great good fortune to be part of two extraordinary neutrino groups at Fermilab. He joined the NuTeV collaboration in 1992 and is now working on data analysis from that experiment; in addition, he became a member of the BooNE collaboration in 2000 and is participating in construction and testing of its detector.

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BORIS KAYSER is a theoretical physicist who has been particularly interested in the physics of massive neutrinos and the asymmetry between matter and antimatter. He also enjoys brachiating around in quantum mechanics. An author of well over 100 scientific papers, he is also co-author of a popular slender book on neutrino physics and a frequent, enthusiastic speaker on particle physics topics.

For nearly three decades, Kayser served as Program Director for Theoretical Physics at the National Science Foundation, in which capacity he was instrumental in establishing the Institute for Theoretical Physics at the University of California, Santa Barbara. He has now joined Fermilab as a Distinguished Scientist and looks forward to spending full time on his first love—physics research.

Kayser enjoys nature, and he is one of the primates in the photo above.

KOICHIRO NISHIKAWA is Professor of Physics at Kyoto University. He received his Ph.D. in 1980 from Northwestern University, where his thesis research involved di-muon production using the high energy neutrino beam at Fermilab. As a postdoc at the University of Chicago, he was subsequently involved in an experiment on CP violation in the neutral kaon system.

Nishikawa returned to Japan—to the Institute for Nuclear Study of the University of Tokyo—and joined the Super-Kamiokande experiment. He moved to Kyoto University in 1999. He serves as the spokesman for the K2K long-baseline neutrino experiment.

JEFFREY WILKES is Kenneth K. Young Memorial Professor of Physics at the University of Washington in Seattle. His thesis research at the University of Wisconsin involved the last of many cosmic-ray experiments conducted at Echo Lake, Colorado. As a postdoc at the University of Washington, he learned the nuclear emulsion trade as Jere Lord’s apprentice and has been there ever since.

After an interlude with the quixotic and habit-forming enterprise called DUMAND, he joined Super-Kamiokande, where he is convener of an analysis group. He is US co-spokesman for the K2K long-baseline neutrino experiment, to which his main contribution seems to be the care and feeding of a wildly fluctuating shift schedule. Most recently, he has been developing WALTA, a school-network cosmic-ray detector project in Seattle.
JOEL PRIMACK is Professor of Physics at the University of California, Santa Cruz. He has been working at the interface between particle physics and cosmology since the early 1980s, when he and several colleagues conceived the idea of cold dark matter, which has since become the “standard model” of cosmological structure formation. He is currently doing research in Germany under an award from the Humboldt Foundation.

Primack has also worked extensively on science and public policy issues. He helped initiate the Congressional Fellowship program sponsored by the American Association for the Advancement of Science, as well as the American Physical Society’s Forum on Physics and Society.

A Brief Neutrino Bibliography

Nickolas Solomey, *The Elusive Neutrino* (Scientific American Library, New York, 1997)
Jan 7 - Mar 15 Joint Universities Accelerator School: Courses in the Fundamentals of the Physics, Technologies, and Applications of Particle Accelerators (JUAS 2002), Archamps, France, (J. Delteil, ESI/JUAS, Centre Universitaire de Formation et de Recherche, F-74166 Archamps, France or juas@esi.cur-archamps.fr or http://www.esi.cur-archamps.fr)

Jan 14 - 25 US Particle Accelerator School, Long Beach, CA (uspas@fnal.gov or http://www.indiana.edu/~uspas/programs/ucla.html)

Feb 4 - 8 9th International Workshop on Linear Colliders, Menlo Park, CA (Robbin Nixon, SLAC, MS 66, Box 4349, Stanford, CA 94309 or lc02@slac.stanford.edu)


Mar 7 - 9 IUPAP International Conference on Women in Physics, Paris, France (Dr. Judy Franz, American Physical Society, One Physics Ellipse, College Park, MD 20740 or http://www.if.ufrgs.br/~barbosa/conference.html)

Mar 18 - 22 Annual Meeting of the APS, Indianapolis, IN (American Physical Society, One Physics Ellipse, College Park, MD 20740 or http://www.aps.org/meet/MAR02/)

Apr 20 - 23 Meeting of the APS and the High-Energy Astrophysics Division (HEAD) of the American Astronomical Society, Albuquerque, NM (American Physical Society, One Physics Ellipse, College Park, MD 20740 (http://www.aps.org/meet/APR02/)

May 8 - 17 CERN Accelerator School: Superconductivity and Cryogenics for Accelerators and Detectors, Erice, Sicily (CERN Accelerator School, AC Division, 1211 Geneva 23, Switzerland or suzanne.von.warburg@cern.ch)

May 24 - 28 DPF 2002: Meeting of the Division of Particles and Fields of the American Physical Society, Williamsburg, VA (Marc Sher, Physics Department, College of William and Mary, Williamsburg, VA 23187 or sher@physics.wm.edu or http://www.dpf2002.org)

May 25 - 30 20th International Conference on Neutrino Physics and Astrophysics (Neutrino 2002), Munich, Germany (NEUTRINO 2002 Secretariat, Technische Universitat Munchen, Physik Department E15, D-85747 Garching, Germany or neutrino2002@ph.tum.de or http://neutrino2002.ph.tum.de/)

Jun 20 - 22 Physics in Collisions, Stanford, CA (Maura Chatwell, MS 81, 2575 Sand Hill Road, Menlo Park, CA 94025 or maura@slac.stanford.edu)