Quarks to the Cosmos Study

Committee on the Physics of the Universe (CPU)

November 1999: NASA's Dan Goldin asks the National Academy to carry out a study on science at the intersection of physics and astronomy; quickly joined by DOE's S. Peter Rosen and NSF's Robert Eisenstein.

Charge: To COMPLEMENT the Astronomy and Physics Decadal Surveys by

(**phase 1)** Identifying science opportunities at the INTERSECTION (not union) of physics and astronomy; and

(**phase 2)** Recommending a strategy for achieving these opportunities

March 2000: First of 8 CPU meetings (2 at AAS, 1 at APS, 1 at DPF's Snowmass; 2 at O'Hare; 1 at Beckman Center; 2 at NRC Georgetown)

Community Input: 5 Town Meetings; e-mail to DPF, DAP, DNP, TGG of the APS, and AAS; 61 project proposals; 45 invited presenters at CPU meetings

January 2001: Phase 1 Report: The 11 Questions

April 2002: Final Report: 11 Questions and 7 Recommendations

http://www.nas.edu/bpa/projects/cpu

Committee on the Physics of the Universe

- Michael Turner (Chicago), Chair

- Eric Adelberger** (UWash)
- Arthur Bienenstock** (SLAC)
- Roger Blandford (Caltech)
- Sandra Faber* (Santa Cruz)
- Thomas Gaisser (Bartol)
- Fiona Harrison (Caltech)
- John Huchra (Harvard)
- John Mather** (GSFC)
- John Peoples, Jr.** (FNAL)
- Helen Quinn (SLAC)
- R.G.H. Robertson (U Wash)
- Bernard Sadoulet (Berkeley)
- Frank Sciulli (Columbia)
- David N. Spergel* (Princeton)
- Harvey Tananbaum** (CfA)
- J. Anthony Tyson (Lucent)
- Frank Wilczek (MIT)
- Clifford Will (Wash U)
- Bruce Winstein (Chicago)
- Edward Wright** (UCLA)

- Don Shapero, Director
- Joel Parriott, Program Officer
- Michael Maloney, Program Officer

* phase I member only
** phase II member only

Why Now?

Recently, Many of the Most Important Discoveries in Astronomy and in Physics Have Come at their Boundary

•Dark Matter

Something other than ordinary matter holds the Universe together

•The Accelerating Universe

A strange form of energy with repulsive gravity accounts for 2/3rds of the stuff in the Universe and is causing it to speed up

•Evidence for Inflation

The Universe is flat and the fluctuations found in the Cosmic Microwave Background are consistent with inflationary origin.

•Neutrino Mass

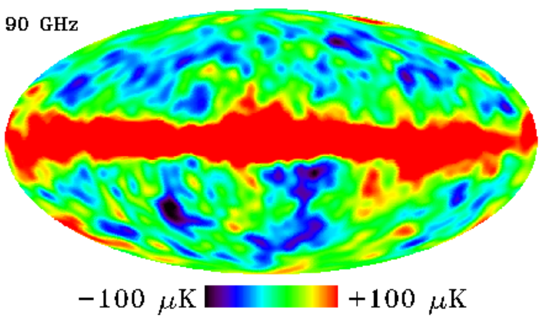
Neutrinos have mass and contribute as much to the mass budget of the Universe as do stars

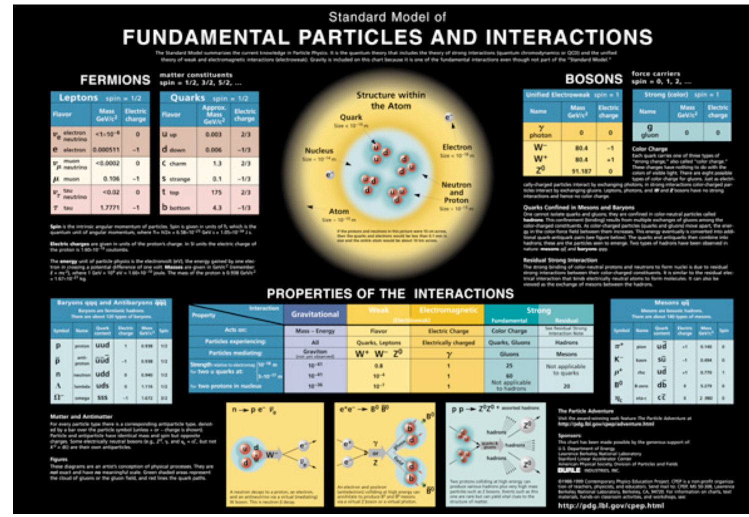
•Extreme Objects in the Universe

Neutron stars, black holes, magnetars and ultra-high energy cosmic-rays are testing "known physics" at new extremes

.. but some of this science falling through the cracks (e.g., solar neutrinos)

These Discoveries, the Success of the Standard Models of Particle Physics and the Hot Big Bang Model, an Explosion of Technology and Powerful Ideas

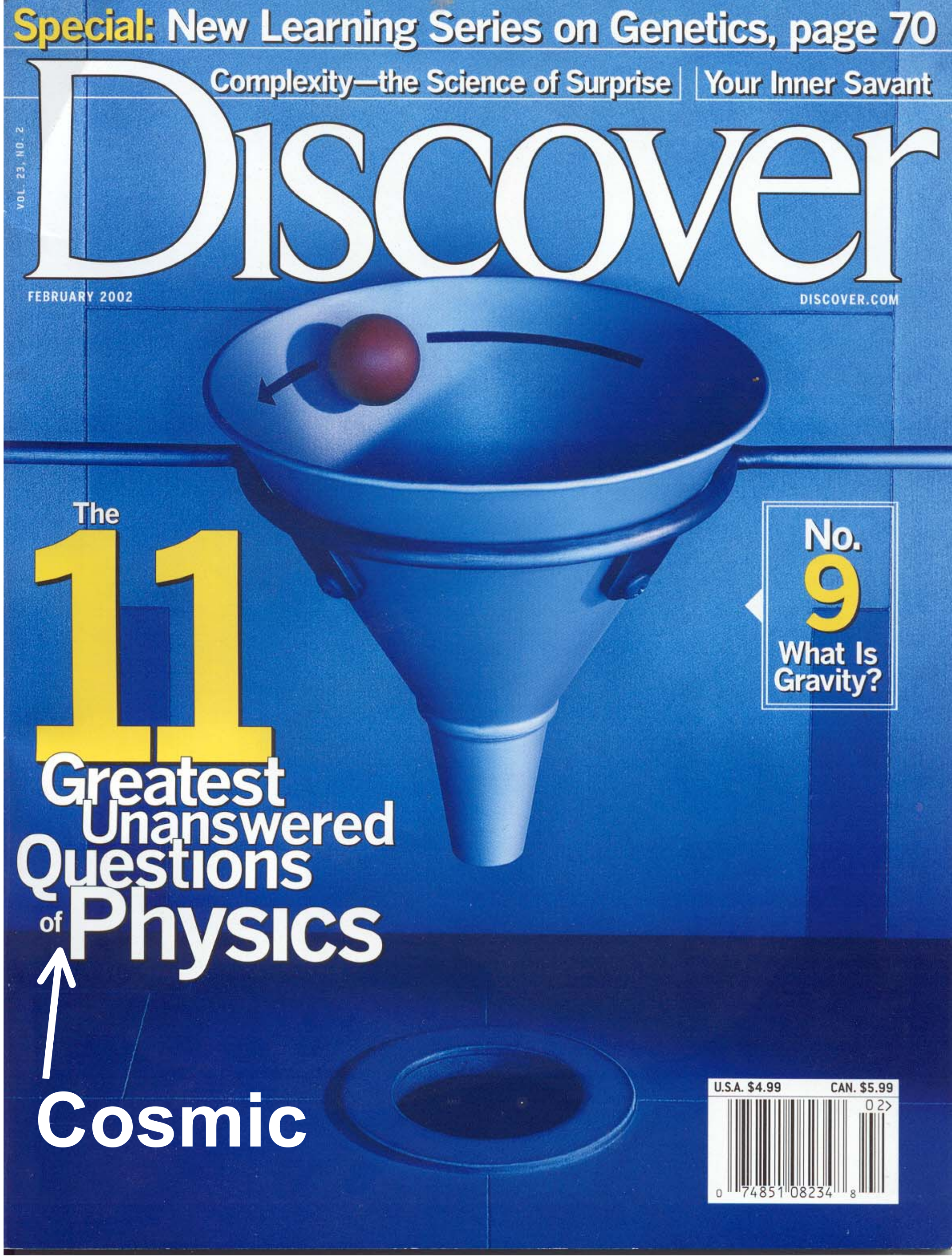




200 million pixel SDSS CCD

Have Created a Special Opportunity to Significantly Advance Our Understanding of the Universe, the Laws that Govern it, and Possibly Our Place With In It

The answers to these questions strain the limits of human ingenuity, but the questions themselves are crystalline in their clarity and simplicity.



CONNECTING QUARKS WITH THE COSMOS:
11 SCIENTIFIC CHALLENGES FOR THE NEW CENTURY

WHAT IS THE DARK MATTER?

Astronomers have shown that the objects in the universe from galaxies a million times smaller than ours to the largest clusters of galaxies are held together by a form of matter that is not what we are made of and that gives off no light. This matter probably consists of one or more as-yet-undiscovered elementary particles, and aggregations of it produce the gravitational pull leading to the formation of galaxies and large-scale structures in the universe. At the same time these particles may be streaming through our Earth-bound laboratories.

WHAT IS THE NATURE OF THE DARK ENERGY?

Recent measurements indicate that the expansion of the universe is speeding up rather than slowing down. This conclusion goes against the fundamental idea that gravity is always attractive. This discovery calls for the presence of a form of energy, dubbed "dark energy," whose gravity is repulsive and whose nature determines the destiny of our Universe.

HOW DID THE UNIVERSE BEGIN?

There is evidence that during its earliest moments the universe underwent a tremendous burst of additional expansion, known as inflation, so that the largest objects in the universe had their origins in subatomic quantum fuzz. The underlying physical cause of this inflation is a mystery.

DID EINSTEIN HAVE THE LAST WORD ON GRAVITY?

Black holes are ubiquitous in the universe, and their intense gravity can be explored. The effects of strong gravity in the early universe have observable consequences. Einstein's theory should work as well in these situations as it does in the solar system. A complete theory of gravity should incorporate quantum effects —Einstein's theory of gravity does not—or explain why they are not relevant.

WHAT ARE THE MASSES OF THE NEUTRINOS, AND HOW HAVE THEY SHAPED THE EVOLUTION OF THE UNIVERSE?

Cosmology tells us that neutrinos must be abundantly present in the universe today. Physicists have found evidence that they have a small mass, which implies that cosmic neutrinos account for as much mass as dostars. The pattern of neutrino masses can reveal much about how the Nature's forces are unified and how the elements in the periodic table were made.

HOW DO COSMIC ACCELERATORS WORK AND WHAT ARE THEY ACCELERATING?

Physicists have detected an amazing variety of energetic phenomena in the universe, including beams of particles of unexpectedly high energy but of unknown origin. In laboratory accelerators, we can produce beams of energetic particles, but the energy of these cosmic beams far exceeds any energies produced on Earth.

ARE PROTONS UNSTABLE?

The matter of which we are made is the tiny residue of the annihilation of matter and antimatter that emerged from the earliest universe in not-quite-equal amounts. The existence of this tiny imbalance may be tied to a hypothesized instability of protons, the simplest form of matter, and to a slight preference for the formation of matter over antimatter built into the laws of physics.

ARE THERE NEW STATES OF MATTER AT EXCEEDINGLY HIGH DENSITY AND TEMPERATURE?

The theory of how protons and neutrons form the atomic nuclei of the chemical elements is well developed. At higher densities, neutrons and protons may "dissolve" into an undifferentiated "soup" of quarks and gluons, which can be probed in heavy-ion accelerators. Still higher densities and temperature occur and can be probed in neutron stars and the early universe.

ARE THERE ADDITIONAL SPACETIME DIMENSIONS?

In trying to extend Einstein's theory and to understand the quantum nature of gravity, particle physicists have posited the existence of spacetime dimensions beyond those that we know. Their existence could have implications for the birth and evolution of the universe, could affect the interactions of the fundamental particles, and could alter the force of gravity at short distances.

HOW WERE THE ELEMENTS FROM IRON TO URANIUM MADE?

Scientists' understanding of the production of elements up to iron in stars and supernovae is fairly complete. The precise origin of the heavier elements from iron to uranium remains a mystery.

IS A NEW THEORY OF MATTER AND LIGHT NEEDED AT THE HIGHEST ENERGIES?

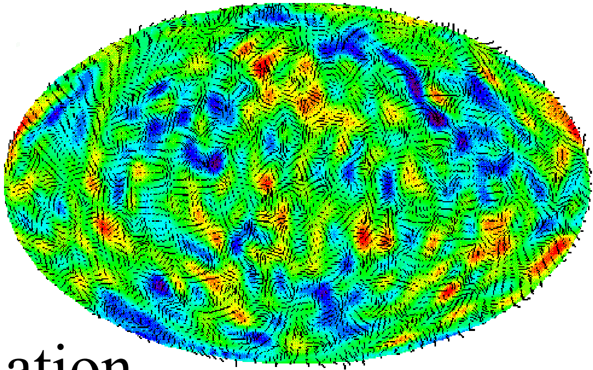
Matter and radiation in the laboratory appear to be extraordinarily well described by the laws of quantum mechanics, electromagnetism and their unification as quantum electrodynamics. The universe presents us with places and objects, such as neutron stars and the sources of gamma ray bursts, where the energies are far more extreme than anything we can reproduce on Earth in order to test these basic theories.

REALIZING THE OPPORTUNITIES

These 11 Questions Cut Across the Traditional Boundaries Of Physics and Astronomy and Illustrate the Vitality of Both Fields

Answering these Questions Will Require Astronomers and Physicists Working Together and the Harnessing and Coordinating of the Unique Capabilities of DOE, NASA and NSF

The Seven Recommendations of the CPU

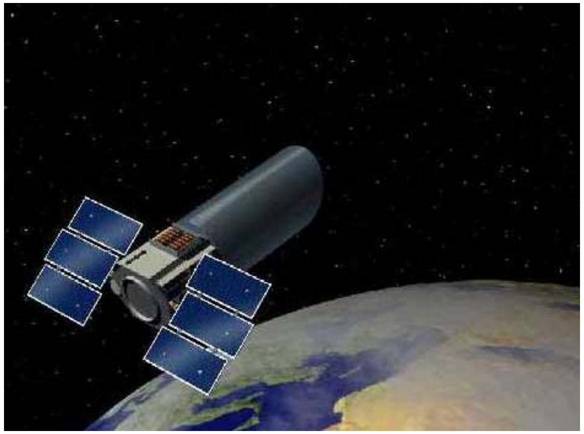


THREE NEW INITIATIVES

Cosmic Microwave Polarization Experiment

measure the gravity-wave signature of inflation
and determine when inflation took place

NASA, NSF & DOE



(e.g., SNAP)

Wide-Field Telescope in Space

use supernovae to probe the expansion
history to get at the nature of dark energy

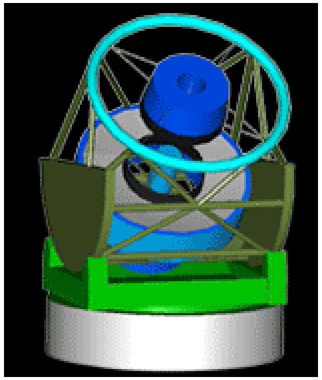
NASA & DOE

Deep (> 4000 mwe) Underground Laboratory

determine neutrino masses and mixings
measure the lifetime of the proton
detect dark matter in our halo

NSF & DOE

Support of 3 Projects Identified by Astronomy Decadal Survey On Their Basis of Their Ability to Address Our 11 Questions



LSST (Large Synoptic Survey Telescope)

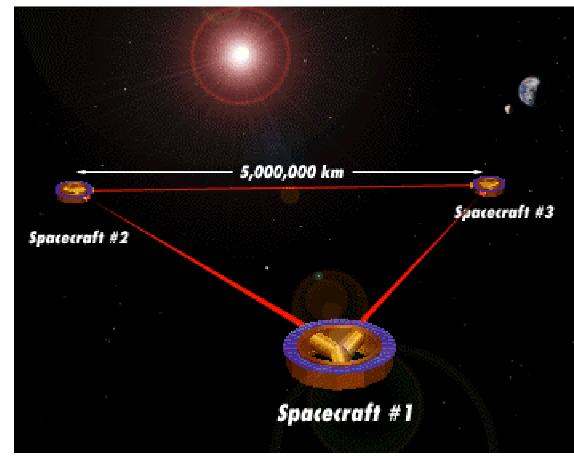
probe dark energy by weak gravitational lensing

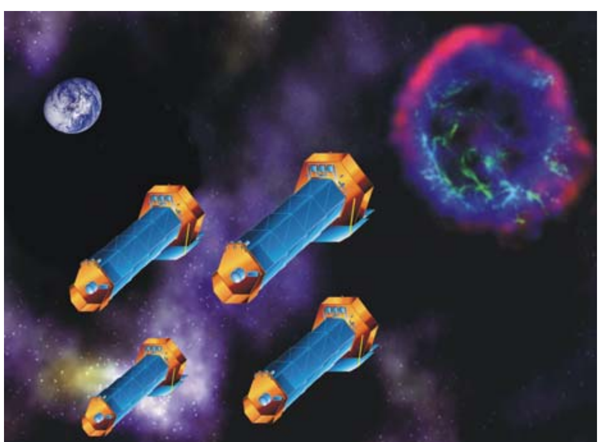
NSF

LISA (Laser Interferometer Space Antenna)

test GR by detecting gravity waves
from colliding massive black holes

NASA & ESA





Con-X (Constellation X)

probe the event horizon of black holes
by Iron-line reverberation

NASA

Significant Opportunities for International Collaboration

With our house in order and priorities set, we are ready for international collaboration

Likely possibilities include Wide-field Telescope in Space, LISA, Underground Laboratory, CMB Polarization

Interagency Initiative

Realize the scientific opportunities at the intersection of physics and astronomy. The Committee recommends establishment of an Interagency Initiative on the Physics of the Universe, with the participation of DOE, NASA and NSF. This initiative should provide structures for joint planning and mechanisms for joint implementation of cross-agency projects.

The scientific opportunities we have identified cut across the disciplines of physics and astronomy as well as the boundaries of DOE, NASA and NSF. No agency has ownership of the science. The unique capabilities of all three as well as cooperation and coordination between the three will be required to realize these special opportunities.

All three agencies are needed and must work together to realize the great opportunity before us

Balance Between Big and Small

In addition, the Committee believes that it is essential that an Interagency Initiative on the Physics of the Universe maintain a balanced approach that provides opportunities for investigator initiated experiments, detector R & D, theoretical work and computational efforts, that address our scientific questions, but that do not necessarily fit within major program themes and their related large projects. Our understanding of the physics of the universe is often advanced by major projects, such as space observatories, large particle-physics laboratories, or major ground-based observation efforts. Indeed, most of our recommendations involve large projects. However, the physics of the universe is also interdisciplinary in character, and significant advances can emerge from work carried out at the interfaces between fields. Often this work involves small-scale efforts, such as table-top experiments and detector development, or computational science and theory. Unlike many major projects, some small-scale efforts are able to respond on a short time scale to address specific but important scientific questions.

Importance of the Existing Programs in Astronomy and Physics

Such an initiative can realize many of the special scientific opportunities that this report has described, but not within the budgets of the three agencies as they stand. The answer is not simply to trim the existing programs to make room for these new initiatives. Many of the existing programs in astronomy and in physics are also critical to answering our questions, as outlined in Section 6.1. Others address exciting and timely questions within physics and astronomy. New funds will be needed to realize the grand opportunities before us.

The existing program includes accelerators (Tevatron, RHIC, B-factory, LHC), Telescopes (ALMA, Gemini, GLAST, Chandra), and other projects (LIGO, RIA, …) which will enable critical science in physics and astronomy as well as at their interface

High-Energy-Density Physics: Probing Extreme Conditions in the Laboratory

Discern the physical principles that govern extreme astrophysical environments through the laboratory study of high-energy-density physics. The Committee recommends that the agencies cooperate in bringing together the different scientific communities that can foster this rapidly developing field.

Unique laboratory facilities such as high-power lasers, high-energy accelerators, and plasma confinement devices can be used to explore physics in extreme environments as well as to simulate conditions needed to understand some of the most interesting objects in the Universe, including gamma-ray bursts. The field of high-energy-density physics is in its infancy, and to fulfill its potential, it must draw in expertise from astrophysics, laser physics, magnetic confinement and particle beam research, numerical simulation and atomic physics.

NB: Specific recommendations to come from the NRC Committee on High-Energy-Density Plasma Physics (CHEDPP/Davidson Committee)

Nature's Highest Energy Particles

Determine the origin of the highest energy gamma rays, neutrinos and cosmic rays. The Committee supports the broad approach already in place, and recommends that the US ensure the timely completion and operation of the Southern Auger array.

The highest-energy particles accessible to us are produced by natural accelerators throughout the Universe and arrive on Earth as high-energy gamma rays, neutrinos and cosmic rays. A full understanding of how these particles are produced and accelerated could shed light on the unification of Nature's forces. The Southern Auger array in Argentina is crucial to solving the mystery of the highest energy cosmic rays.

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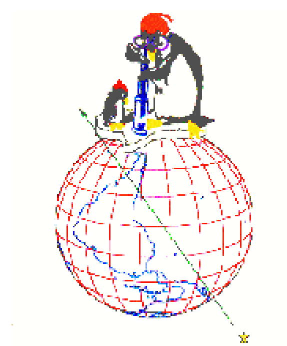

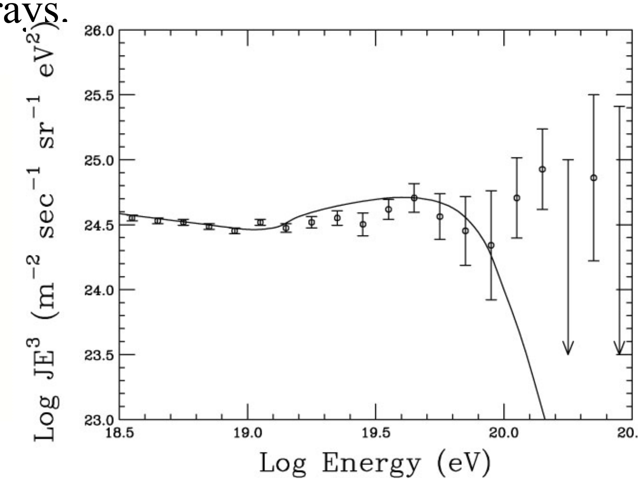

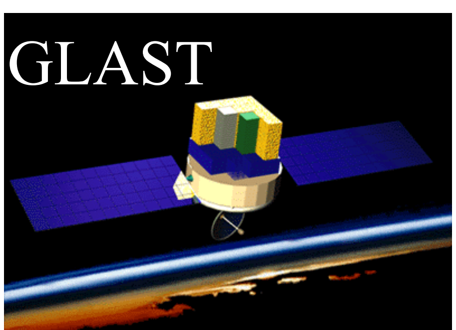

CRs beyond the GZK cutoff? What are they? How are they accelerated?

Physics and Astronomy are Inextricably Tied Together in Both the Asking and the Answering of these 11 Questions

It Will Take Physicists and Astronomers Using Telescopes, Accelerators, and Spacecraft to Answer Them

We Have a Special Opportunity to Advance Our Understanding of the Universe, the Laws That Govern It and Even Our Place Within

These Recommendations Provide a Strategy for Realizing This Opportunity

Getting the Word Out

Briefings with Weiler (NASA), Rosen (DOE), OMB, OSTP (with Marburger), House & Senate Science Committee staff, Senate Appropriation & Energy Committee staff

Official roll out at APS/AAS Head Meeting in Albuquerque followed by Press Conference with APS President-elect Helen Quinn and Roger Blandford

The 7 Recommendations of the CPU
word for word

Measure the polarization of the cosmic microwave background with the goal of detecting the signature of inflation. The Committee recommends that NASA, NSF and DOE undertake research and development to bring the needed experiments to fruition.

Cosmic inflation holds that all the structures we see in the Universe today - galaxies, clusters of galaxies, voids and the great walls of galaxies - originated from subatomic fluctuations that were stretched to astrophysical size during a tremendous spurt of expansion (inflation). Quantum fluctuations in the fabric of spacetime itself lead to a cosmic sea of gravitational waves which can be detected by their polarization signature in the cosmic microwave background radiation.

Determine the properties of the dark energy. The Committee supports the Large Synoptic Survey Telescope (LSST) project, which has significant promise for shedding light on the dark energy. The Committee further recommends that NASA and DOE work together to construct a wide-field telescope in space to determine the expansion history of the Universe and fully probe the nature of the dark energy.

The discovery that the expansion of the Universe is speeding up and not slowing down has revealed the presence of a mysterious new energy form that accounts for 2/3 of all the matter and energy in the Universe. Because of its diffuse nature, it can only be probed through its effect on the expansion of the Universe. The NRC's most recent Astronomy Decadal Survey has recommended building an LSST to study transient phenomena in the Universe; it will also have significant ability to probe dark energy. To fully characterize the expansion history and probe the dark energy will require a wide-field telescope in space (such as SNAP).

Determine the neutrino masses, the constituents of the dark matter and the lifetime of the proton. The Committee recommends that DOE and NSF work together to plan for and to fund a new generation of experiments to achieve these goals. We further recommend that an underground laboratory with sufficient infrastructure and depth be built to house and operate the needed experiments.

Neutrino mass, new stable forms of matter, and the instability of the proton are all predictions of theories that unify the forces of Nature. Fully addressing all three issues requires a laboratory that is well shielded from the cosmic-ray particles that constantly bombard the surface of Earth.

Use space to probe the basic laws of physics. The Committee supports the Constellation-X and LISA missions, which have high promise for studying black holes and for testing Einstein's theory in new regimes. The Committee further recommends that the agencies proceed with an advanced technology program to develop instruments capable of detecting gravitational waves from the early Universe.

The Universe provides a laboratory for exploring the laws of physics in regimes that are beyond the reach of terrestrial laboratories. The NRC's most recent Astronomy Decadal Survey has recommended the Constellation-X and LISA missions on the basis of their great potential for astronomical discovery. These missions also have unique capabilities for testing Einstein's theory in regimes where gravity is very strong, near the event horizons of black holes and near the surfaces of neutron stars. For this reason, the CPU adds its support to the Decadal Survey's previous recommendations.

Determine the origin of the highest energy gamma rays, neutrinos and cosmic rays. The Committee supports the broad approach already in place, and recommends that the US ensure the timely completion and operation of the Southern Auger array.

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HOUSE SCIENCE (3 PM, April 18)

Sharon Hayes - Staff Director, Research Subcommittee
Jim Wilson - Minority Staff Director,. Research Subcommittee
Ed Fedderman - Majority Staff, Space and Aeronuatics Subcommittee
Chris Shank - Majority Staff, Space and Aeronautics Subommittee
David Goldston (brief appearance) - Committee Staff Director
Dan Morgan - Congressional Research Service

SENATE COMMERCE, Subcommittee on Science, Technology and Space (4 PM, April 18)

Jean Eisen - Senior Staff Member, Majority
Ken LaSala - Staff Member, Minority
Floyd DesChamps - Senior Staff Member, Minority

SENATE ENERGY COMMITTEE (10:30 AM, April 19)

Jon Epstein - Sen. Bingaman and Committee R&D activities
Jon Kotek - Sen. Bingaman and Committee R&D activities
Pete Lyons - Sen. Domenici, energy and R&D activities

(Sen. Bingaman is chair of the Energy Committee and Sen. Domenici is on the Committee and is ranking minority of the Energy and Water Development Appropriations Subcommittee)

SENATE VA, HUD, AND INDEPENDENT AGENCIES APPROPRIATIONS SUBCOMMITTEE

Joel Widder - Staffmember, Majority (NSF, NASA)