

Discovering the Quantum Universe Report

Hitoshi Murayama

HEPAP meeting, 3 March 2006

Organization

- First half is about the process
- Second half is a presentation of the report itself

The Process

Outline

- Charge
- Membership
- Two versions
- Timeline
- Challenges
- Outreach to our own community
- Dispelling Misconceptions

CHARGE TO THE COMMITTEE

Professor Frederick Gilman
Chair, HEPAP
Carnegie-Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213



Dear Professor Gilman:

We wish to congratulate you on the widely successful *Quantum Universe* report that with clarity and elegance expresses the great discovery opportunities in particle physics today. It has made a positive impact in Washington, DC, in the Nation, and abroad in conveying the drivers of the coming scientific revolution. As funding agencies and advisors of the Nation's research portfolio in this field, our ability to bring clarity and focus to outstanding scientific issues is an important responsibility. You have succeeded well with *Quantum Universe*.

This brings us to the following. The successful outcome of the International Technology Recommendation Panel, in coming to a clear technology recommendation, was a significant step toward a future Linear Collider. We now ask for your help in addressing another important issue in program planning and public communication. We need to explain clearly to the broad non-scientific community the need for a second large particle accelerator in addition to the Large Hadron Collider (LHC). Inevitably, the question arises as to how a less energetic electron accelerator would work in tandem with a higher energy proton machine

in exploring the energy frontier. How would these two accelerators complement one another? What crucial scientific discoveries might not be made without the LC?

To educate us and the public, and to clarify the matter more generally, we would like HEPAP to form a committee to write a document that addresses the following:

- In the context of already known physics, i.e. our current understanding of the electroweak symmetry breaking sector, what are the synergies and complementarities of these two machines? How would an LC be utilized in understanding a Standard Model Higgs, or whatever fulfills its role in the electroweak interaction?
- In the context of physics discoveries beyond the Standard Model (supersymmetry, extra dimensions or other new physics) that are assumed to be made at the Tevatron or early at the LHC, what would be the role of a TeV Linear Collider in making additional and unique contributions to these discoveries, in distinguishing between models, and in establishing connections to cosmological observations?

You may assume that the LHC will be operating over a 15–20 year timeframe with likely upgrades.

We are not asking for any new physics or simulation studies. As you know, there is by now a rather large body of work on this subject. Rather, we are asking for your help in distilling this body of work into a crisp, accessible, and persuasive case. The deliverable should be a short document (10 pages), accessible to knowledgeable non-experts (e.g., members of the EPP2010 Study, OSTP/OMB staff and ourselves). We ask that the report be completed as soon as practical but no later than summer 2005.

Finally, to further educate us as well as giving us an opportunity to refine the charge in conjunction with the committee that you appoint, we would suggest a half-day session at an upcoming HEPAP meeting devoted to this topic.

With best regards,

A handwritten signature in black ink, appearing to read "Robin Staffin".

Robin Staffin
Associate Director
Office of High Energy Physics
Office of Science
U.S. Department of Energy

A handwritten signature in black ink, appearing to read "Michael Turner".

Michael Turner
Assistant Director
Mathematical and Physical Sciences
National Science Foundation

cc: Joseph Dehmer, NSF
Bruce Strauss, DOE SC-20

Charge

- ... what are the synergies and complementarities of these two machines (LHC & ILC)? How would an LC be utilized in understanding a Standard Model Higgs, or whatever fulfills its role in the electroweak interaction?
- In the context of discoveries beyond the Standard Model ... what would be the role of a TeV Linear Collider ... in distinguishing models, and in establishing connections to cosmological observations?

Charge

The way we understood the charge:

- Quantum Universe questions are compelling!
- To address them, why do we need accelerators at all?
- Given the LHC coming online, why do we need the ILC at all?

Who We Are

Jim Siegrist (LBNL), Joe Lykken (Fermilab) co-chairs

Jonathan Bagger (JHU, EPP2010)

Barry Barish (Caltech, GDE)

Neil Calder (SLAC, ILCCG)

Albert de Roeck (CERN, CMS)

Jonathan L. Feng (Irvine, ILC Cosmo WG)

Fred Gilman (CMU, HEPAP)

JoAnne Hewett (SLAC, HEPAP, ALCPGEC)

John Huth (Harvard, ATLAS)

Judy Jackson (Fermilab, ILCCG)

Young-Kee Kim (UC, CDF, HEPAP, ALCPGEC)

Rocky Kolb (Fermilab, DE Task Force)

Konstantin Matchev (Florida, CMS, ILC Cosmo WG)

Hitoshi Murayama (Berkeley, ALCPGEC)

Rainer Weiss (MIT, CMB Task Force)

Two versions

- EPP2010 NRC committee wanted a “White Paper” from HEPAP, providing technical arguments with a deadline of Aug 2, 2005
- This conflicted with the broader aspects of our charge from HEPAP, and requests we heard during our meeting with Washington customers
- Solution: we produced two reports, the first for EPP2010, then a later document for a wider audience
- You have approved the EPP2010 document
- then HEPAP disappeared for a while
- The second report for wider audience is presented here

Timeline (all in 2005!)

25 March: first meeting at LCWS Palo Alto

30 March: first weekly telecon

22 April: meeting in Washington with J. Marburger, M. Turner, R. Staffin, P. Looney, M. Holland, J. Parriott, K. Carroll

23 April: writing begins

19 May: HEPAP

26 May: meeting at Fermilab

15 June: meeting at SLAC

16 June – 8 July: ten writers/editors iterating on a daily basis

24 June: first complete pre-draft sent to R. Staffin and M. Turner

1 July: first draft circulated to some leaders of the community

8 July: new draft report sent to HEPAP, approved on July 12

2 August: unveiling to EPP2010

August – September: continue with phase two document

10 September: final version for broader audience goes to printer

Challenges

- Electroweak symmetry breaking is the heart of the case for accelerators: **hard to explain!**
- When explaining the need for the ILC, can't hurt the importance of the LHC: **need community input**
- Targeted at a very broad audience: **keep it simple**
- Scientifically, we don't know what we will find at the TeV scale and therefore can't guarantee anything specific: **talk about scenarios**

Outreach to our own community

- We have solicited and received feedback on the first draft from **leaders of the LHC**:
Fabiola Gianotti, Albert De Roeck, John Huth, William Trischuk
- We have solicited and received feedback on the first draft from **leaders of the ILC**:
Jim Brau, Harry Weerts, Ritchie Patterson
- This feedback was incorporated into the report
- We were very encouraged by the constructive tone of the feedback

Outreach to our own community

- We kept the community informed about our progress
- JoAnne is a member of the LHC/ILC Study Group
- We participated in the last ALCPG EC phone meeting
- We are coordinating with the ILC Worldwide Study Group
- Judy, Neil, and Jon B. are in the ILC Communications Group
- Joe and Hitoshi briefed the rest of the DPF EC in Tampa

More input

- We incorporated feedback from other sources as well:
 - Lab directors
 - More leaders of the LHC, ILC, and non-collider communities
 - HEPAP (i.e. you)
 - Jack Marburger!

Science First

- The report is organized around the science
- It begins with the 9 great questions from Quantum Universe
- These are mapped into the three basic physics themes that are most relevant for LHC and ILC
 - Mysteries of the Terascale
 - Light on dark matter
 - Einstein's telescope
- Explain their roles in nine discovery scenarios

Dispelling Misconceptions

- There is a misconception that if LHC discovers more and measures more, then there is less motivation for the ILC
- Our report makes it clear that the opposite is true

Dispelling Misconceptions

- There is a misconception that once LHC discovers a Higgs particle, the rest is details
- Our report makes it clear that the discovery of a Higgs particle would raise urgent questions leading to even greater discoveries

Dispelling Misconceptions

- There is a misconception that the only thing colliders do is discover particles
- Our report explains how particles are the tools that we use to resolve mysteries and to discover new laws of nature
- See the p23 sidebar: "Particles tell stories"

The Report

Quantum Universe Questions

Nine key questions define the field of particle physics.

EINSTEIN'S DREAM OF UNIFIED FORCES

1 ARE THERE UNDISCOVERED PRINCIPLES OF NATURE: NEW SYMMETRIES, NEW PHYSICAL LAWS?

THE PARTICLE WORLD

5 WHY ARE THERE SO MANY KINDS OF PARTICLES?

THE BIRTH OF THE UNIVERSE

8 HOW DID THE UNIVERSE COME TO BE?

2 HOW CAN WE SOLVE THE MYSTERY OF DARK ENERGY?

6 WHAT IS DARK MATTER? HOW CAN WE MAKE IT IN THE LABORATORY?

3 ARE THERE EXTRA DIMENSIONS OF SPACE?

7 WHAT ARE NEUTRINOS TELLING US?

4 DO ALL THE FORCES BECOME ONE?

DISCOVERING THE QUANTUM UNIVERSE

THE ROLE OF PARTICLE COLLIDERS

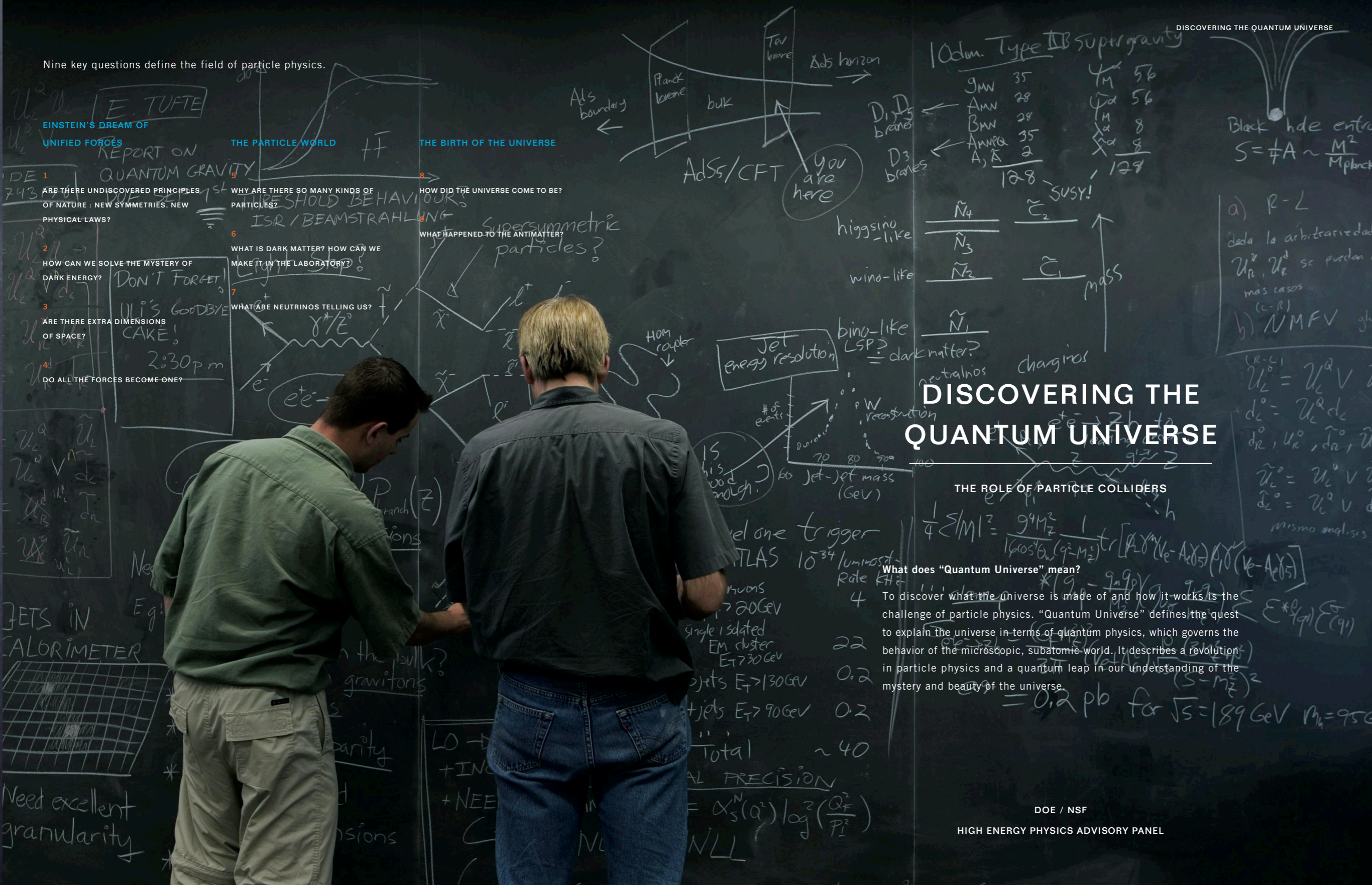
What does "Quantum Universe" mean?

To discover what the universe is made of and how it works is the challenge of particle physics. "Quantum Universe" defines the quest to explain the universe in terms of quantum physics, which governs the behavior of the microscopic, subatomic world. It describes a revolution in particle physics and a quantum leap in our understanding of the mystery and beauty of the universe.

DOE / NSF

HIGH ENERGY PHYSICS ADVISORY PANEL

DISCOVERING THE QUANTUM UNIVERSE



Quantum Universe Questions

Einstein's Dream of Unified Forces

- Are there undiscovered principles of nature: new symmetries, new physical laws?
- How can we solve the mystery of dark energy?
- Are there extra dimensions of space
- Do all the forces become one?

The Particle World

- Why are there so many kinds of particles?
- What is dark matter? How can we make it in the laboratory?
- What are neutrinos telling us?

The Birth of the Universe

- How did the universe come to be?
- What happened to the antimatter?

Who is this?

02

INTRODUCTION

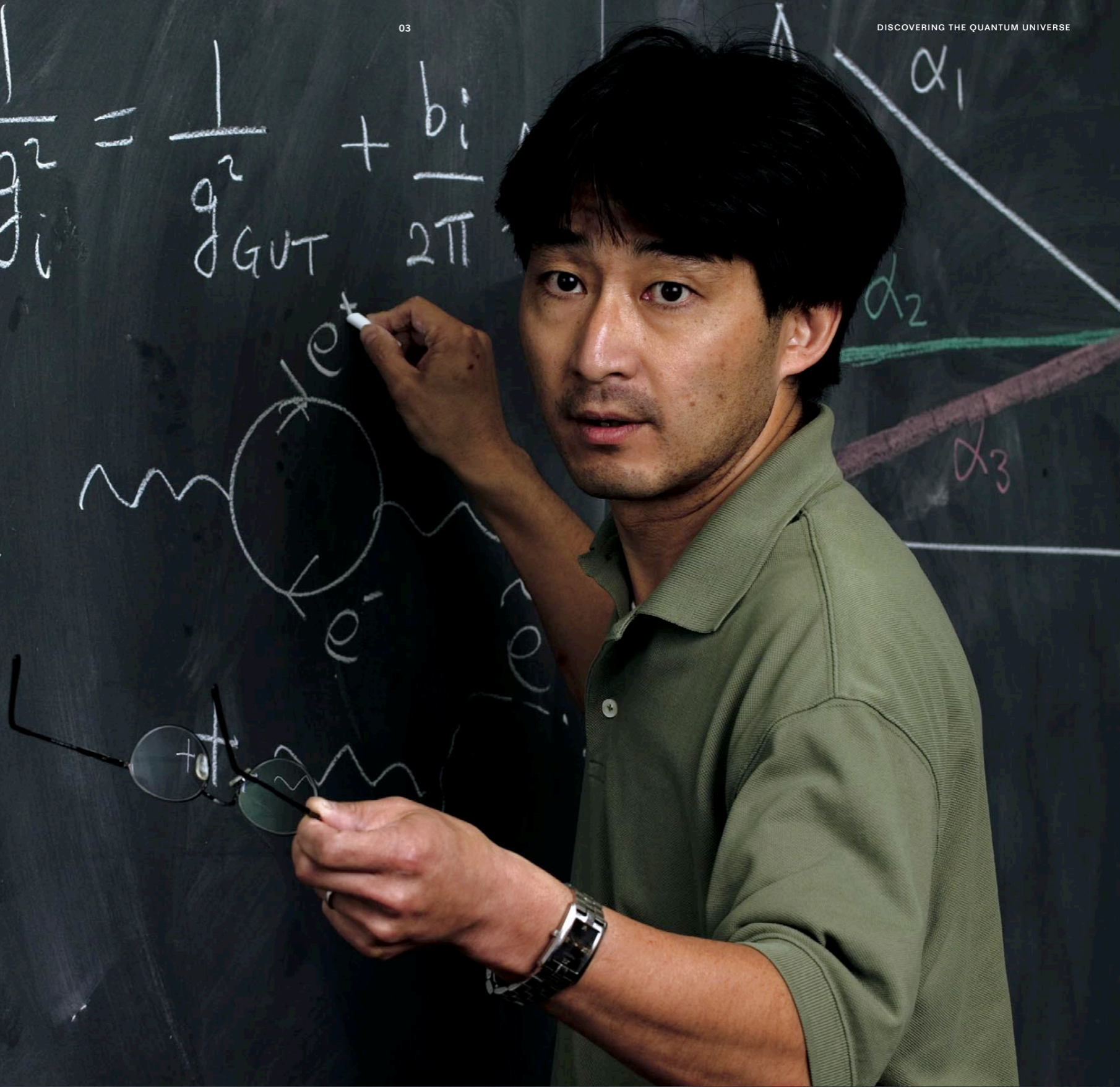
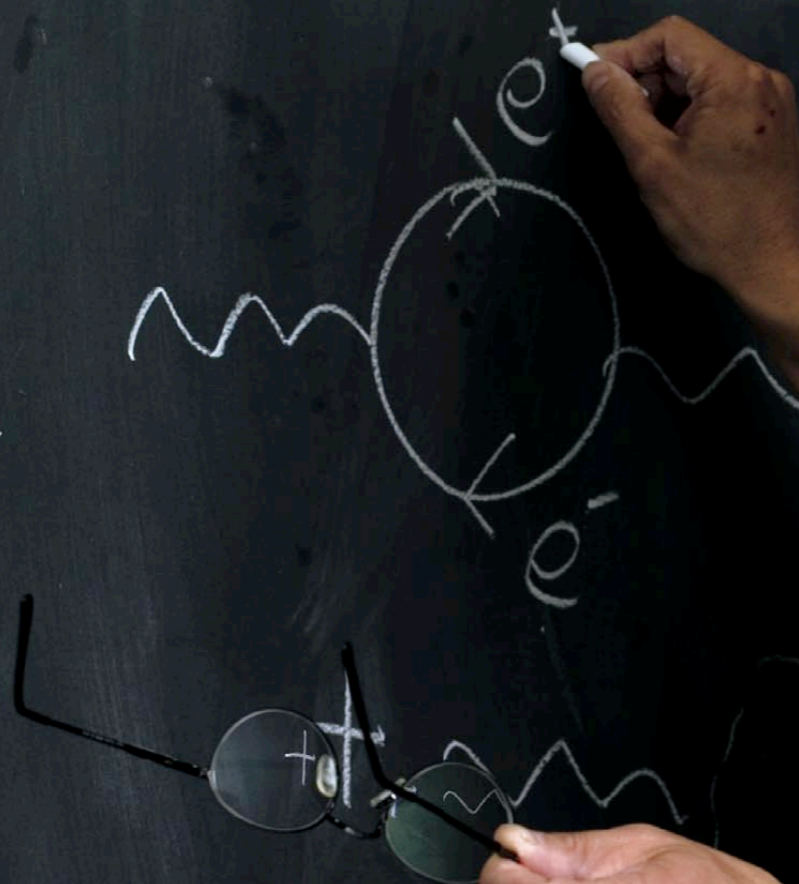
DISCOVERING THE QUANTUM UNIVERSE

Right now is a time of radical change in particle physics. Recent experimental evidence demands a revolutionary new vision of the universe. Discoveries are at hand that will stretch the imagination with new forms of matter, new forces of nature, new dimensions of space and time. Breakthroughs will come from the next generation of particle accelerators – the Large Hadron Collider, now under construction in Europe, and the proposed International Linear Collider. Experiments at these accelerators will revolutionize your concept of the universe.

03

DISCOVERING THE QUANTUM UNIVERSE

$$\frac{1}{g_i^2} = \frac{1}{g_{GUT}^2} + \frac{b_i}{2\pi}$$

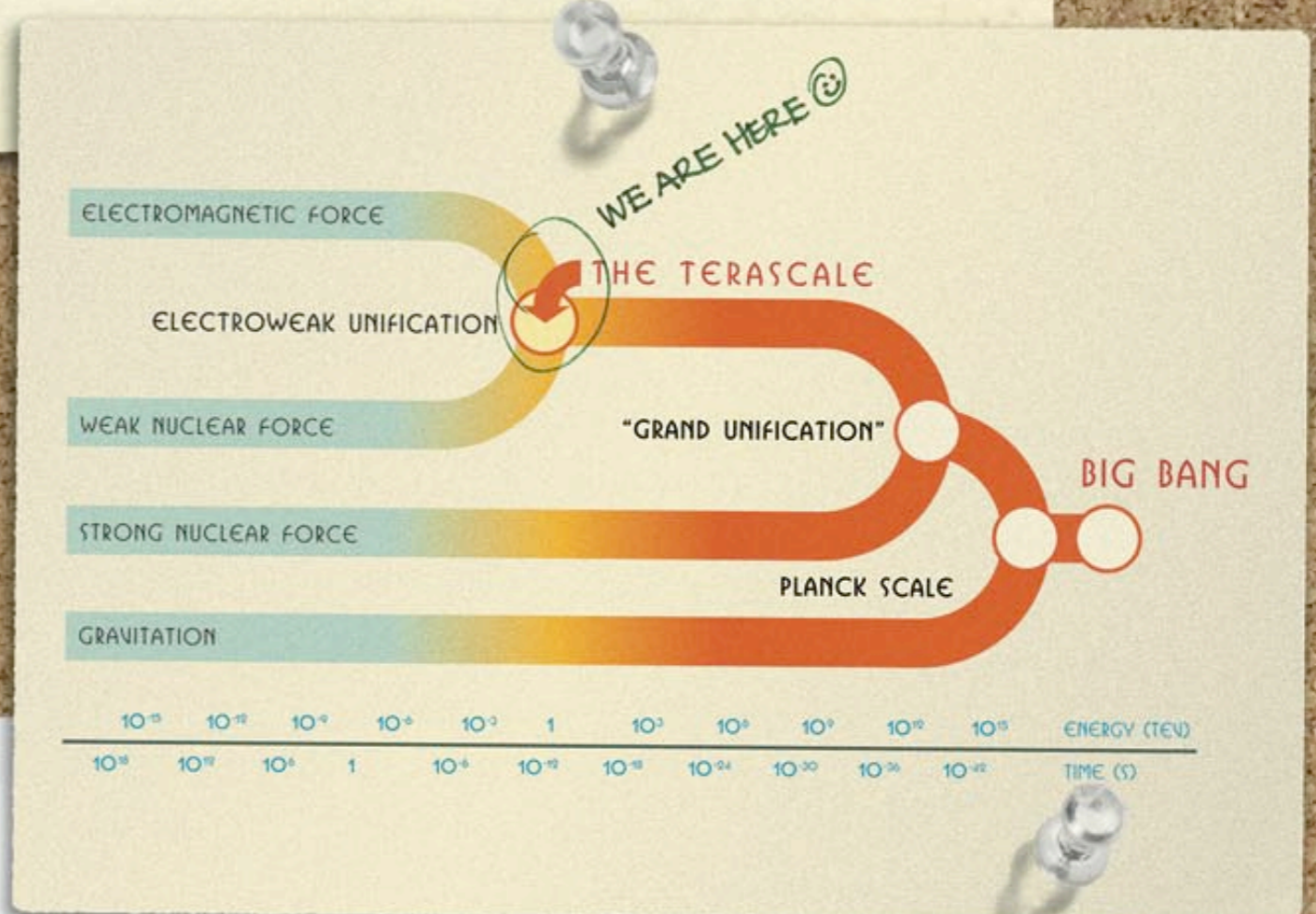


Colliders are Time Machines

06



BACK TO THE BIG BANG: PARTICLE ACCELERATORS ALLOW PHYSICISTS TO LOOK FARTHER AND FARTHER BACK IN TIME, TO REVISIT THE HIGH ENERGIES OF THE EARLY UNIVERSE AFTER THE BIG BANG. DO THE FOUR FORCES WE OBSERVE TODAY CONVERGE TO A SINGLE UNIFIED FORCE AT ULTRAHIGH ENERGY? PARTICLE COLLISIONS MAY PROVIDE THE FIRST EVIDENCE FOR SUCH UNIFICATION OF FORCES.

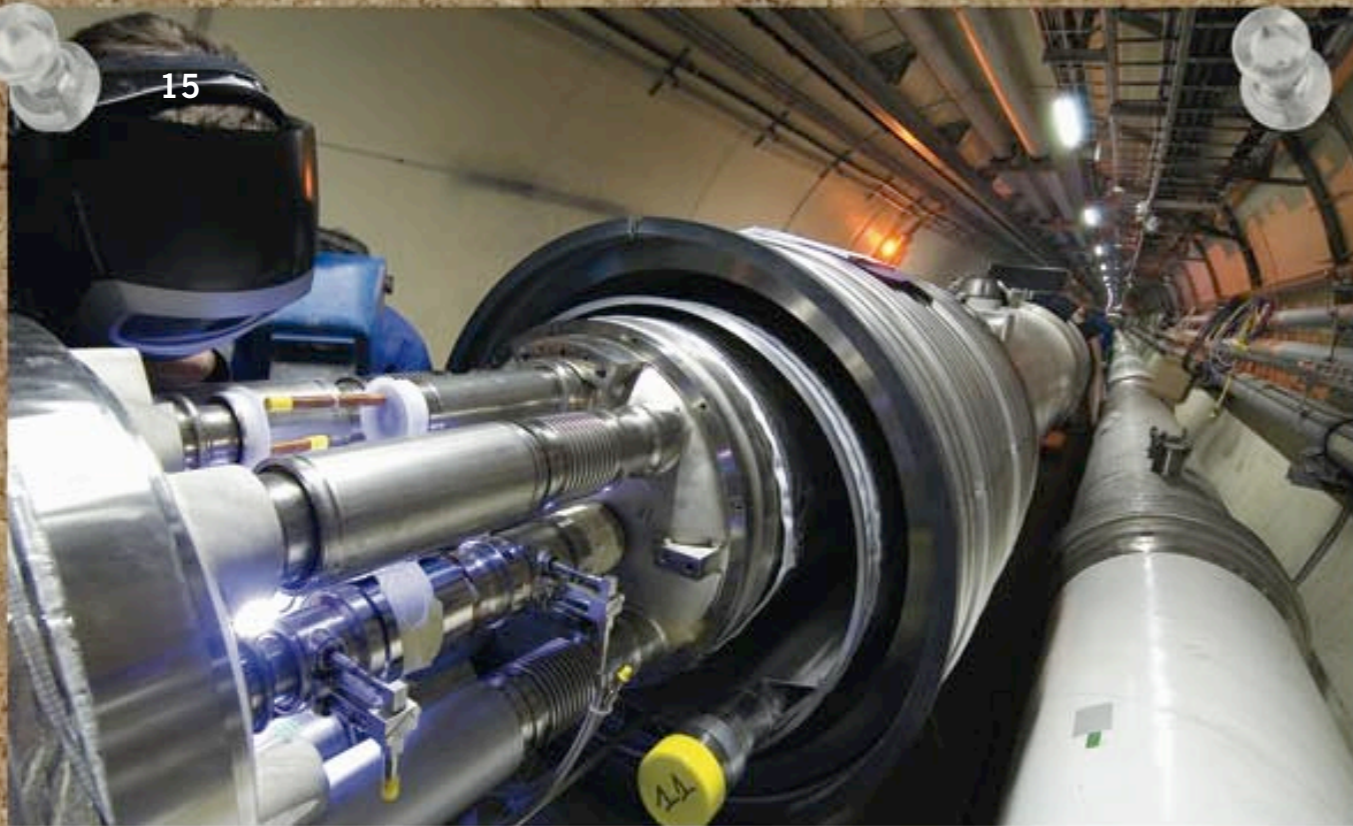


Why Terascale?

“Particle physicists are about to light out for a vast new scientific *terra incognita*. This unexplored country is the Terascale, named for the Teravolts of particle accelerator energy that will open it up for scientific discovery. **Once they've seen the Terascale, physicists believe, the universe will never look the same.**

“About certain features of the Terascale, most physicists expect to find the Higgs boson – or, if not the Higgs, whatever it is that does Higgs's job of giving mass to the particles of matter.

“Less certain, but also distinctly likely, are discoveries of dark matter, extra dimensions of space, “superpartners” for all the familiar particles of matter, parallel universes – and completely unexpected phenomena.”

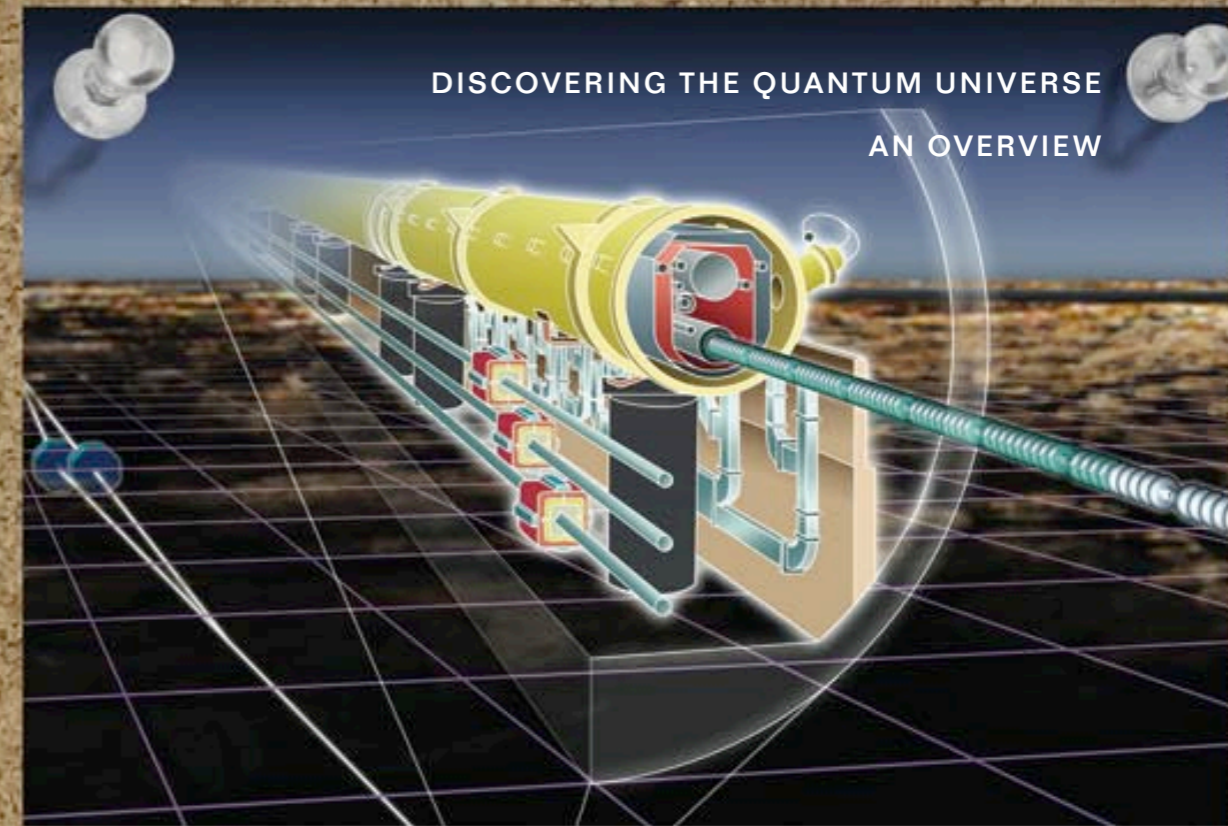


LARGE HADRON COLLIDER

The Large Hadron Collider at CERN, the European Organization for Nuclear Research, will be the biggest and most powerful particle accelerator ever built when it turns on in 2007. It will operate in a circular tunnel 27 km in circumference, between France's Jura mountains and Switzerland's Lake Geneva. Experiments at the LHC will give scientists their first view of the Terascale energy region.

The LHC will accelerate two beams of particles in opposite directions, smashing them together to create showers of new particles via Einstein's famous equation, $E=mc^2$. Colliding beams of protons will generate some 800 million collisions per second.

Superconducting magnets will guide the beams around the



INTERNATIONAL LINEAR COLLIDER

The International Linear Collider is a proposed new accelerator designed to work in concert with the LHC to discover the physics of the Terascale and beyond. The ILC would consist of two linear accelerators, each some 20 kilometers long, aimed at each other, hurling beams of electrons and positrons toward each other at nearly the speed of light.

When electrons and positrons accelerate in a circle, they lose energy. The higher the acceleration energy, the more energy the electrons lose. At very high energies, a circular electron accelerator is no longer an option; too much energy

Three scientific themes at the Terascale

- Mysteries from the Terascale
- Light on Dark Matter
- Einstein's Telescope

Mysteries from the Terascale

“Like an invisible quantum liquid, it (Higgs) fills the vacuum of space, slowing motion and giving mass to matter. Without this Higgs field, all matter would crumble; atoms would fly apart at the speed of light.

“So far, no one has ever seen the Higgs field. The LHC is designed with enough energy to create Higgs particles and launch the process of discovery. To determine how the Higgs really works, though, experimenters must precisely measure the properties of Higgs particles without invoking theoretical assumptions (at the ILC).”

06

EXPLORE THE TERASCALE!

BACK TO THE BIG BANG: PARTICLE ACCELERATORS ALLOW PHYSICISTS TO LOOK FARTHER AND FARTHER BACK IN TIME, TO REVISIT THE HIGH ENERGIES OF THE EARLY UNIVERSE AFTER THE BIG BANG. DO THE FOUR FORCES WE OBSERVE TODAY CONVERGE TO A SINGLE UNIFIED FORCE AT ULTRAHIGH ENERGY? PARTICLE COLLISIONS MAY PROVIDE THE FIRST EVIDENCE FOR SUCH UNIFICATION OF FORCES.

TERASCALE QUANTUM UNIVERSE 35¢ Peter Higgs

WE ARE HERE

THE TERASCALE

“GRAND UNIFICATION”

PLANCK SCALE

BIG BANG

POSTCARDS FROM THE TERASCALE

The sun warms planet Earth, but we live in a universe where the temperature of space is only three degrees above absolute zero. Its energy is so low that we can no longer see what space contained in the inferno of its birth. As the universe cooled from the Big Bang, it passed through a series of phases, each at a lower energy and each with its own set of particles and forces acting according to its own physical laws.

Particle accelerators give us the opportunity to go back and revisit the higher energies of our ancestral universe, to observe phenomena no longer visible in our own era. These high-energy phenomena are important to us, because our universe today still feels their imprint. The order behind what appears arbitrary in our own universe becomes clear at higher energies.

For example, many theories predict that at the extreme energy just after the Big Bang, all of nature’s forces were combined in one single unified force, splitting as the universe cooled into the four forces that we know today. Reconnecting to the early universe

Since the early cyclotrons of the 1950s, particle accelerators have served as the passports to higher and higher energies. The entire standard model of the structure of matter, with its fundamental particles and forces, has emerged from the increasing energies of particle collisions. Each generation of accelerators has built on the discoveries of previous generations to venture deeper into the history of the universe. Now, a new generation of accelerators with the highest energies yet will open up for exploration a region of energy – the Terascale – that has ten thousand trillion times the energy of space today. Postcards from the Terascale will answer basic questions about the universe.

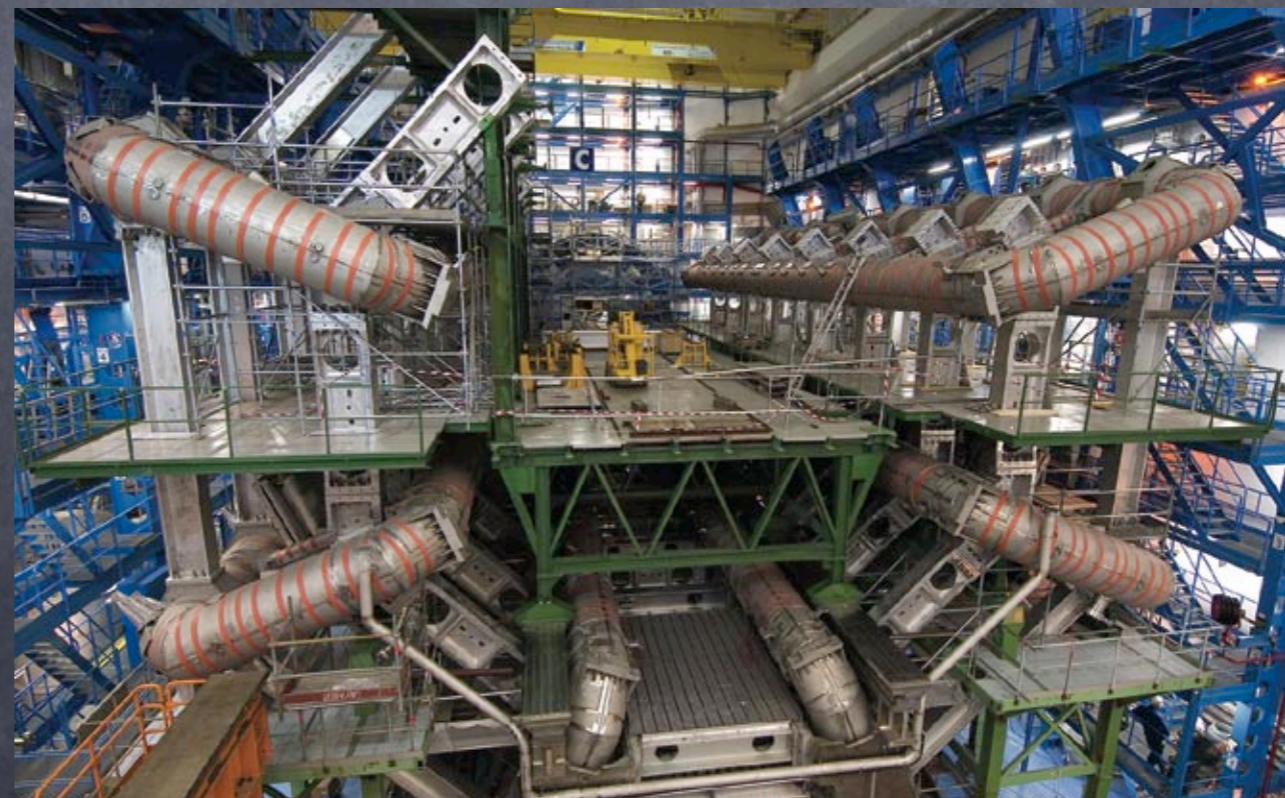
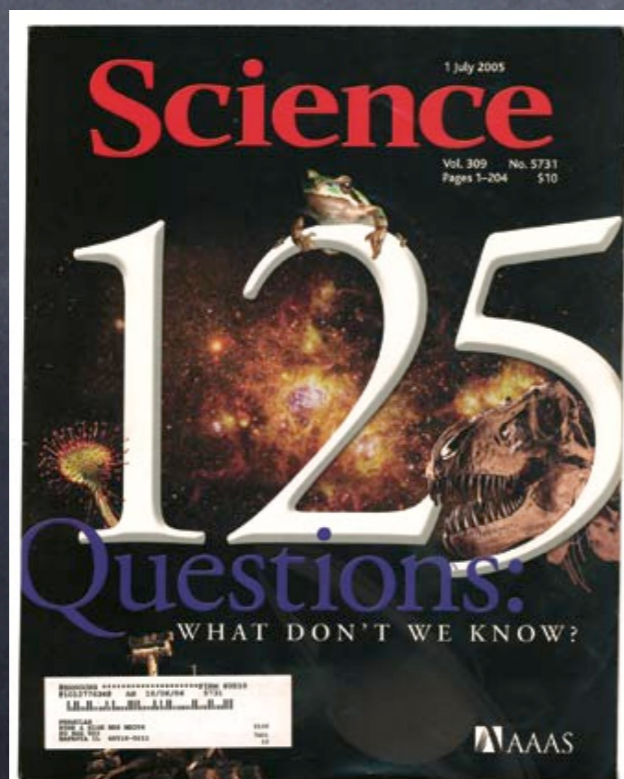
Moreover, the Terascale is not the end of the story. Discoveries there may reveal phenomena occurring at energies so high that no particle accelerator will ever achieve them directly. Such postcards from the Planck scale once seemed an unreachable fantasy. Forwarded from an address in the Terascale, they may one day arrive.

Mysteries from the Terascale

“A Higgs discovery, however, will raise a perplexing new question: Why does the Higgs have a mass at the Terascale?”

“supersymmetry, extra dimensions and new particle interactions. Which, if any, of the theories is correct?”

“The LHC will have enough energy to survey the Terascale landscape. Then a linear collider could zoom in to distinguish one theory from another.”



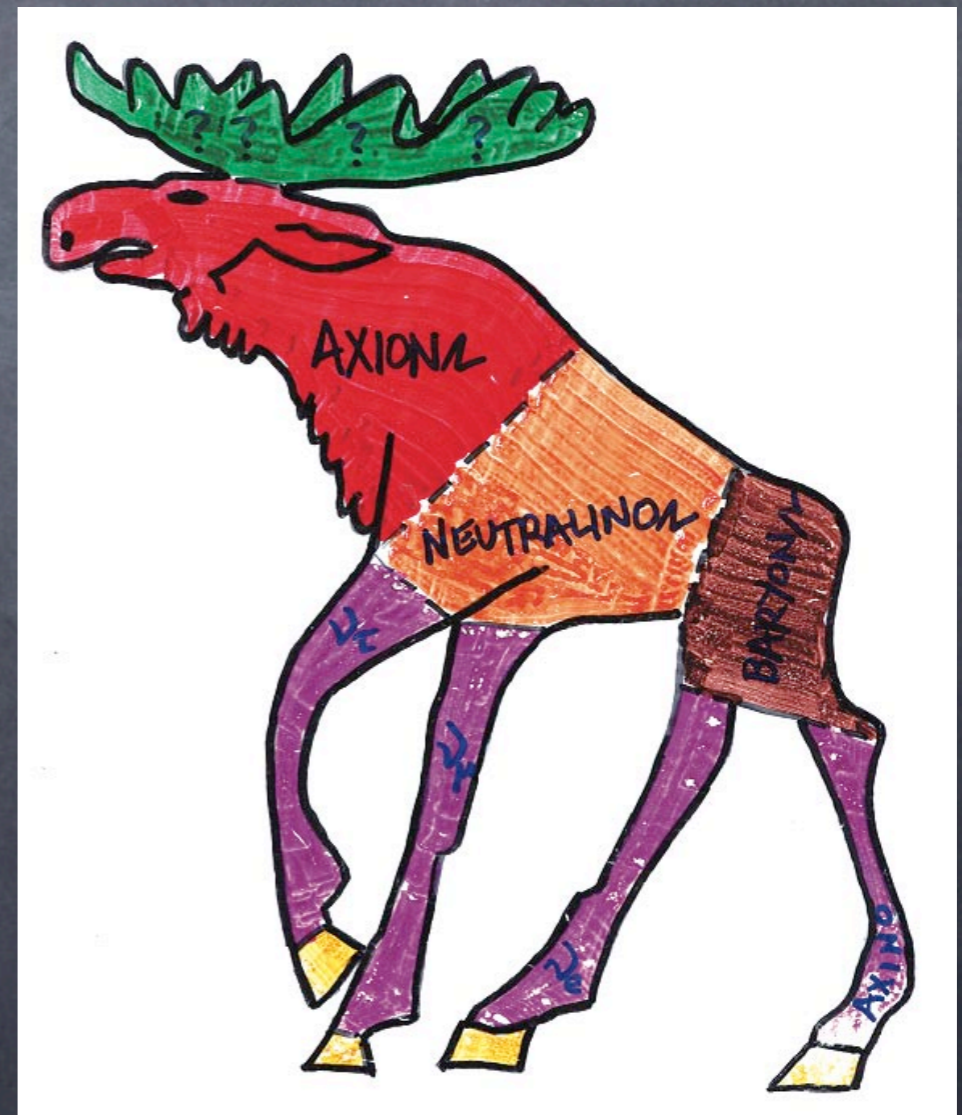
Light on Dark Matter

“What is this dark matter that binds the galaxies and keeps the universe from flying apart? Although dark matter is not made of the same stuff as the rest of the world, physicists have clues to its identity.

“cosmological calculations suggest that they would have Terascale masses, in the energy region of the LHC and the ILC.

“the LHC may identify a dark matter candidate in particle collisions. A linear collider could then zero in to determine its mass and interaction strength – to take its fingerprints and make a positive identification.”

Dark, *adj.* 1a. Lacking or having very little light. b. Lacking brightness...8. Difficult to understand; obscure. 9. Concealed or secret; mysterious.

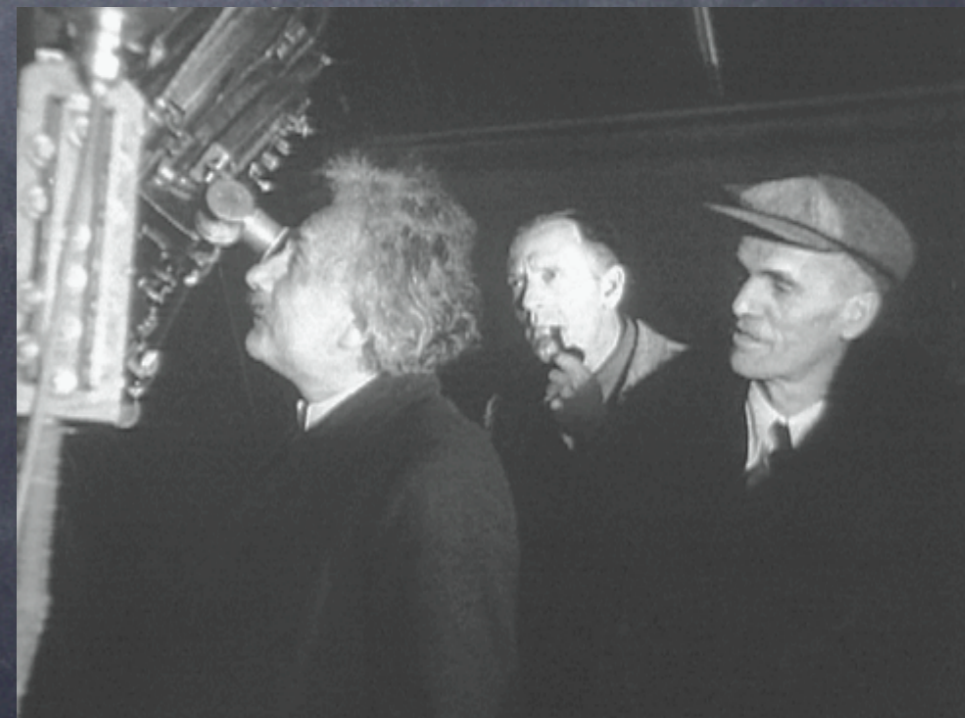


Einstein's Telescope

"The precision of its electron-positron collisions would give a linear collider the potential to act as a telescope to see into energies far beyond those that any particle accelerator could ever directly achieve.

"For now, though, the telescopic view to the beyond is obscured by lack of knowledge of Terascale physics. Data from the LHC and the ILC would part the clouds of physicists' ignorance of the Terascale and allow a linear collider to act as a telescope to the unknown.

"Physicists could use a linear collider to focus on the point where both forces and masses may unify, linked by supersymmetry into one theory that encompasses the laws of the large and the laws of the small."



LHC and ILC

If LHC discovers:	What ILC could do:
Higgs	discover why it exists, who its cousins are, effects of extraD, new source of matter anti-matter asymmetry
superpartner	detect symmetry of supersymmetry, reveal nature of dark matter, discover force unification and matter
extra dimensions	discover the number and shape, what particles travel there, their locations within them
missing energy	discovery its identity as dark matter, determine its fraction of dark matter
heavy "stable" charged particle	discover what they decay into, identify the "super-WIMPs" as dark matter
new force	discovery its origin, connect the force to the unification of quarks and neutrinos, Higgs, or extra
supersymmetry from supergravity	discover the telltale effects from the vibrations of superstrings

Discovery Scenarios

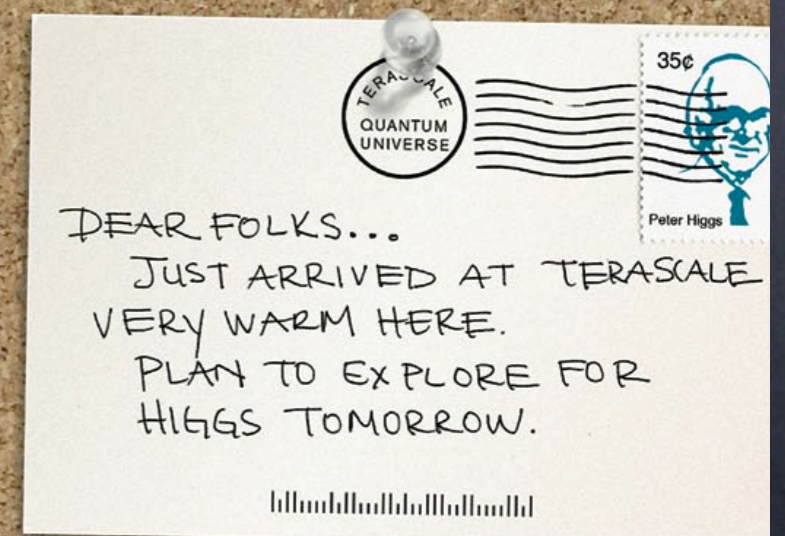
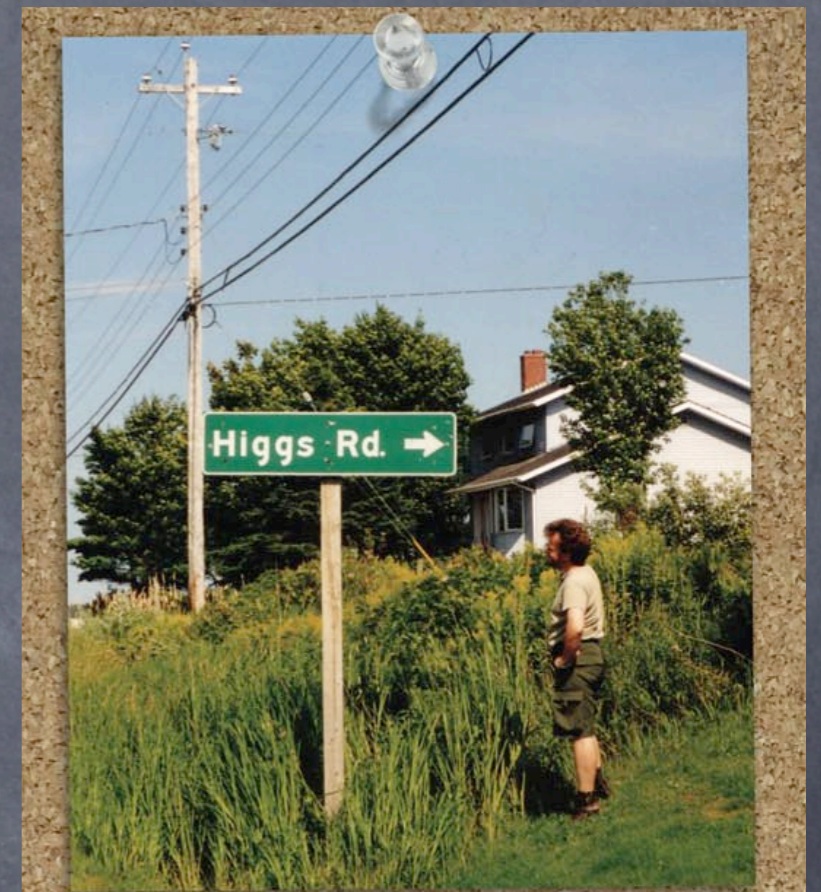
- The Higgs is Different
- A Shortage of Antimatter
- Mapping the Dark Universe
- Exploring Extra Dimensions
- Dark Matter in the Laboratory
- Supersymmetry
- Matter Unification
- Unknown Forces
- Concerto for Strings

The Higgs is Different

“Discovery of a Higgs particle at the LHC would present mysteries of its own that would be even more challenging to solve than detecting the Higgs particle. Higgs is neither matter nor force; the Higgs is just different.

“Physicists suspect the existence of many Higgs-like particles: Why, after all, should the Higgs be the only one of its kind? They predict that new particles related to the Higgs play essential roles in cosmology, giving the universe the shape it has today.

“Experiments at a linear collider would zoom in on the Higgs to discover these innermost secrets.”

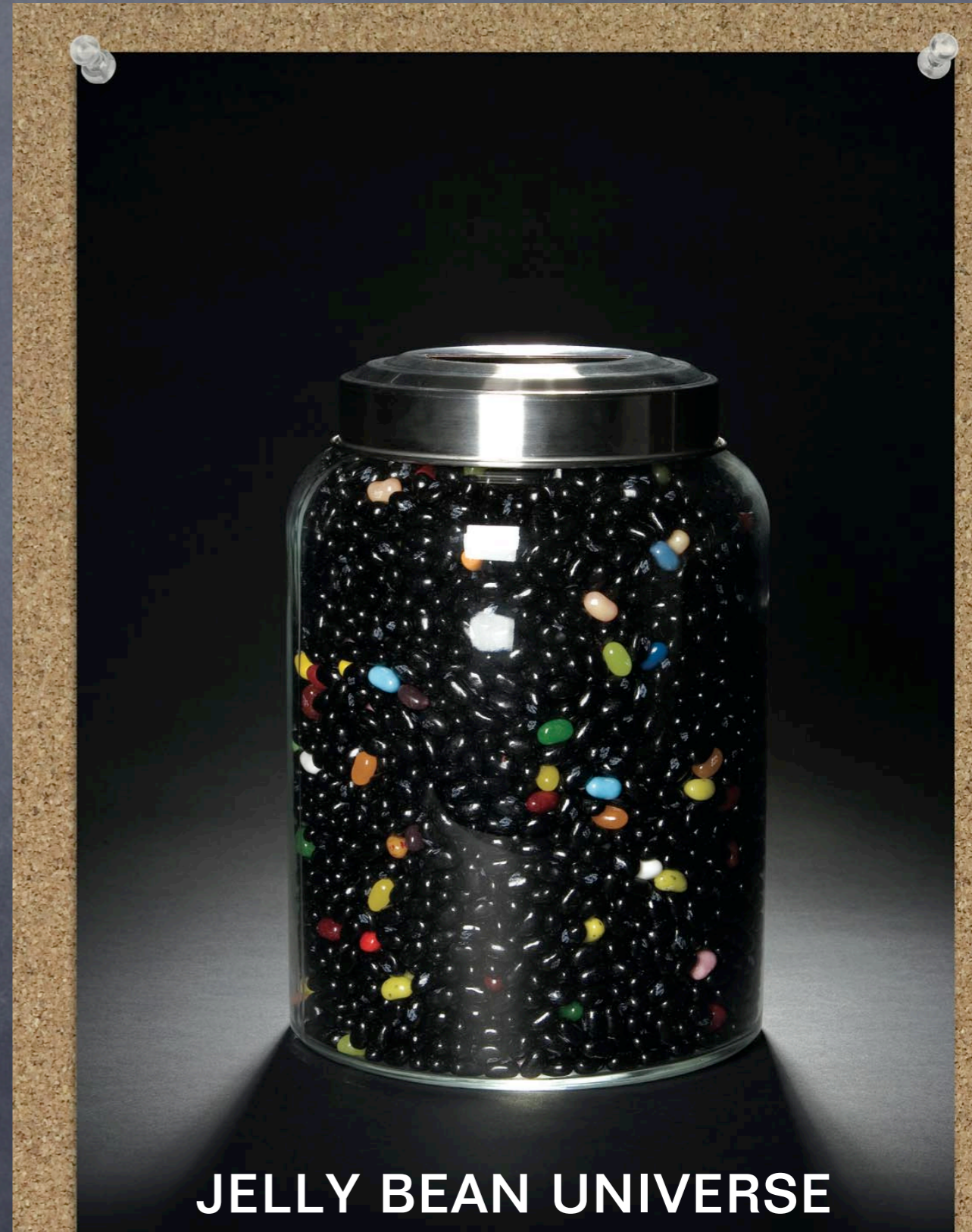


Dark Matter in the Laboratory

“Four percent of the universe is familiar matter; 23 percent is dark matter, and the rest is dark energy. Its identity is a complete mystery.

“Astrophysical evidence suggests that dark matter particles will show up at the Terascale.

“Physicists working at the LHC are likely to find the first evidence for Terascale dark matter. But is it really dark matter? Is it all of the dark matter? Why is it there? A linear collider would be essential for answering these questions, making precise measurements of the dark matter particles and their interactions with other particles. Linear collider experiments could establish both the what and the why for this chapter of the dark matter story.”



JELLY BEAN UNIVERSE

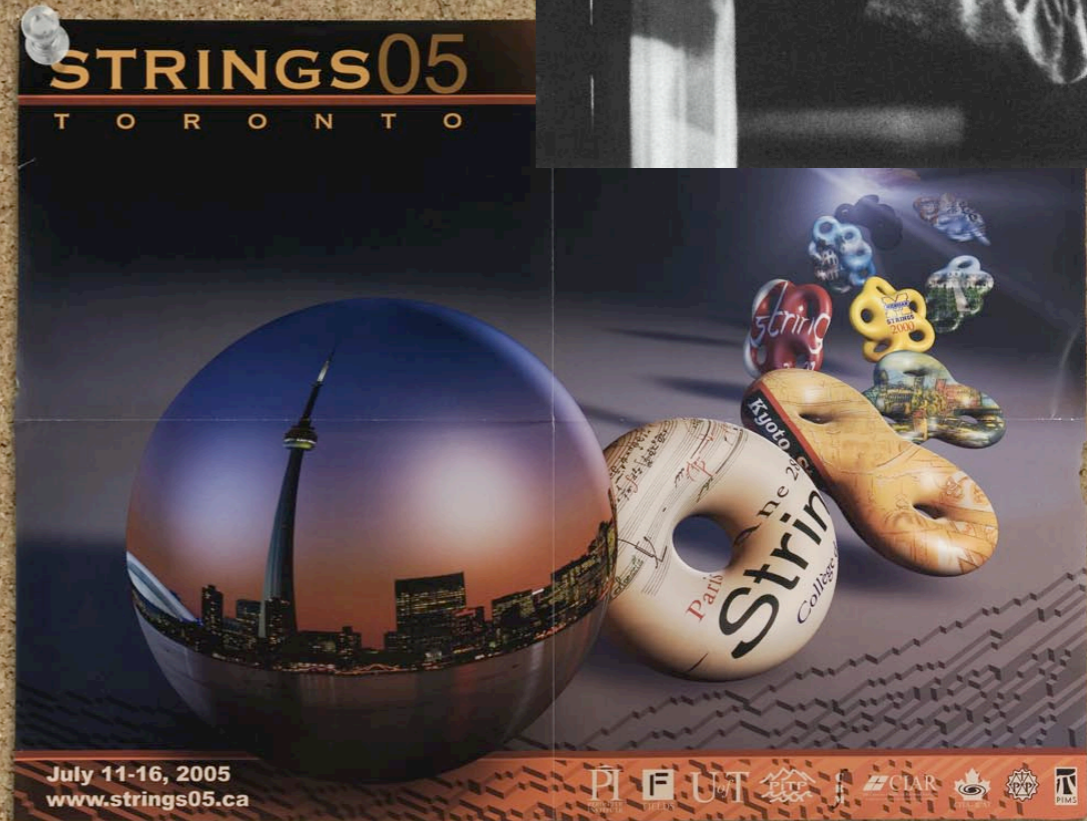
Concerto for Strings

“String theory is the most promising candidate to unify the laws of the large and the small. If supersymmetry is discovered at the LHC and ILC, physicists will be able to test string-motivated predictions for the properties of superpartner particles.

“Here linear collider precision is essential, since the string effects appear as small differences in the extrapolated values of the superpartner parameters. A combined analysis of simulated LHC and ILC data shows that it may be possible to match the fundamental parameters of the underlying string vibrations. While not a direct discovery of strings per se, such an achievement would truly be the realization of Einstein’s boldest aspirations.”



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taking part in a revolution



DISCOVERING THE QUANTUM UNIVERSE

CONCLUSION

DISCOVERING THE QUANTUM UNIVERSE

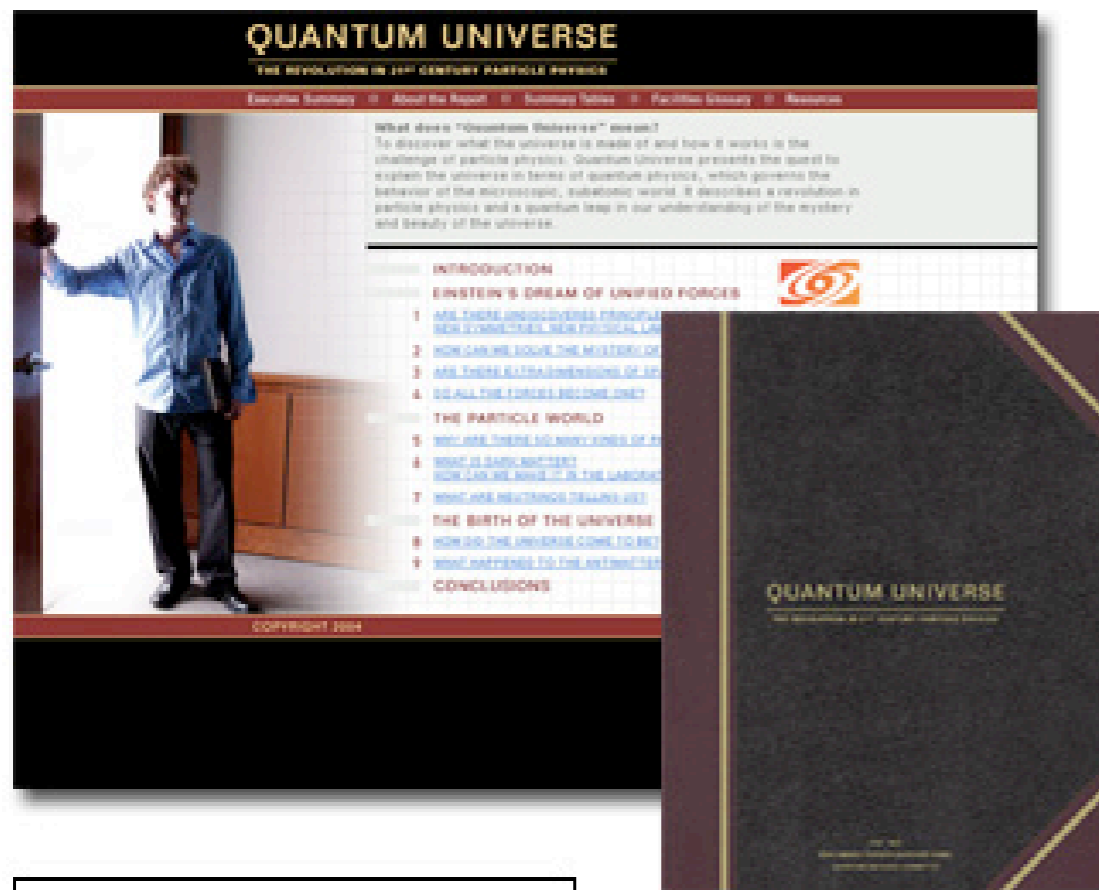
In graduate school at the University of Rochester, I decided to study particle physics, because to me it seemed the most exciting field I could imagine, and the most rewarding way to spend my life. But back then I never realized just how exciting it would be. In the past decade, we have understood that the beautiful and orderly universe we thought we knew so well, with its quarks and leptons and fundamental forces, is only a tiny fraction of what's out there. Ninety-five percent of the universe is a complete mystery: dark matter and dark energy. That's paradise for a particle physicist: a universe of unknown particles and forces to discover. I tell my students they are taking part in a revolution, not just in particle physics but in the way human beings see the universe. Every day brings us closer to the most amazing discoveries. That's what keeps me working late at night.

Young-Kee Kim
Physicist, University of Chicago

Ready for distribution

QUANTUM UNIVERSE

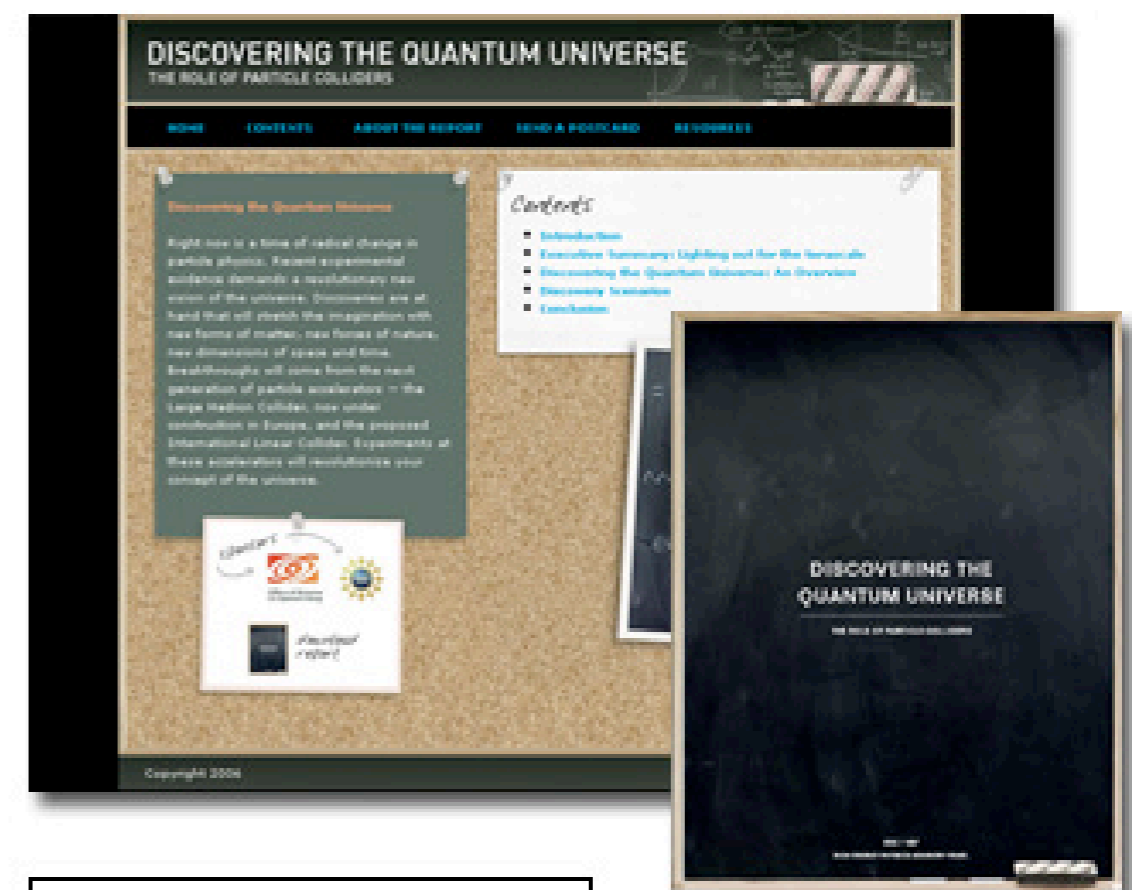
THE REVOLUTION IN 21ST CENTURY PARTICLE PHYSICS



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DISCOVERING THE QUANTUM UNIVERSE

THE ROLE OF PARTICLE COLLIDERS



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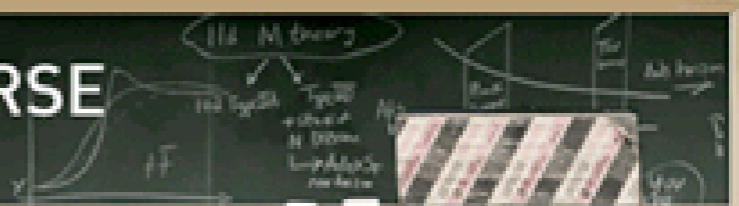
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New Tab Discovering the Quantum Universe

DISCOVERING THE QUANTUM UNIVERSE

THE ROLE OF PARTICLE COLLIDERS



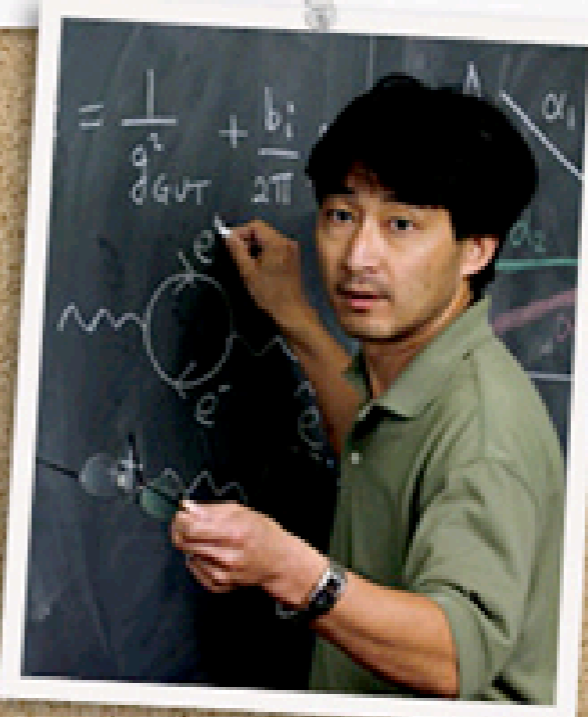
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Discovering the Quantum Universe

Right now is a time of radical change in particle physics. Recent experimental evidence demands a revolutionary new vision of the universe. Discoveries are at hand that will stretch the imagination with new forms of matter, new forces of nature, new dimensions of space and time. Breakthroughs will come from the next generation of particle accelerators – the Large Hadron Collider, now under construction in Europe, and the proposed International Linear Collider. Experiments at these accelerators will revolutionize your concept of the universe.

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