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Roadmap to the Future

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Roadmap to the Future

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Questions

- What is the nature of the universe and what is it made of?
- What are matter, energy, space and time?
- How did we get here and where are we going?

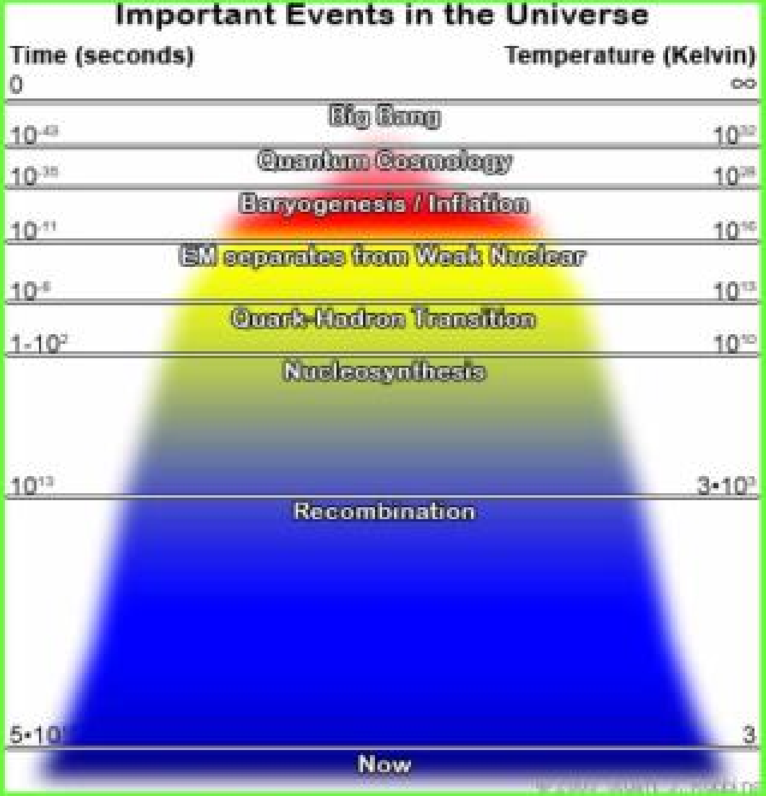
Particle Physics Definition

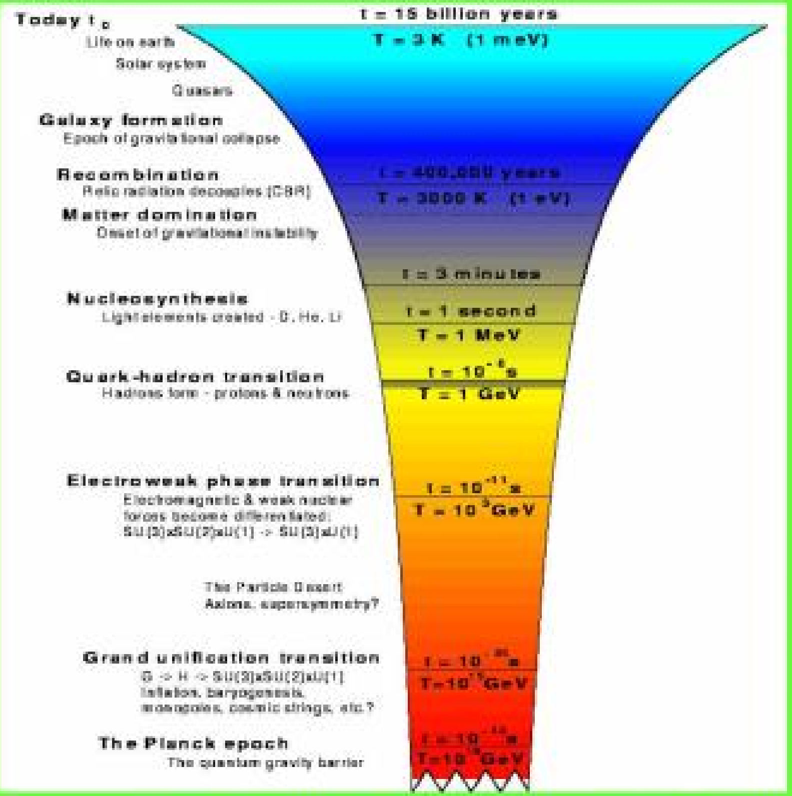
These basic questions about the universe through human history provide a definition of particle physics that reflects the evolving nature of the field in the second half of the 20th century.

The answers to these questions have become increasingly interconnected; they have particularly related fundamental particles to cosmology:

- 3 light neutrinos ⇔BBN
- quarks ⇔ the "hadron wall"

Early-Universe Timeline





More Specific Questions

- A longer and more specific set of sub-questions at a given time characterize the frontier of particle physics.
- Such a set of interrelated questions defines the path ahead, i.e., the scientific roadmap for particle physics.

Old Questions, New Questions

- As precise, narrowly defined, “small” questions are answered, they may contribute to answering “big” questions as well.
- As our understanding has increased and old questions get answered, new ones arise. We sometimes learn to pose questions that we didn’t even know were answerable.
- Part of our progress is understanding at what energy scale a question may be answered.

As We Ended the 20th Century

- For the part of the universe made of quarks and leptons that we find immediately around us, four decades of extraordinary experimental and theoretical ferment have led to a great synthesis in our understanding of these particles and their interactions – the Standard Model
- It is simple, elegant, and predictive through the level of quantum loops.
- The last few years have seen great progress as experiments at accelerators and theoretical work have led to a precise understanding of the way the weak force affects matter and antimatter, a major achievement in itself.

As We Begin the 21st Century

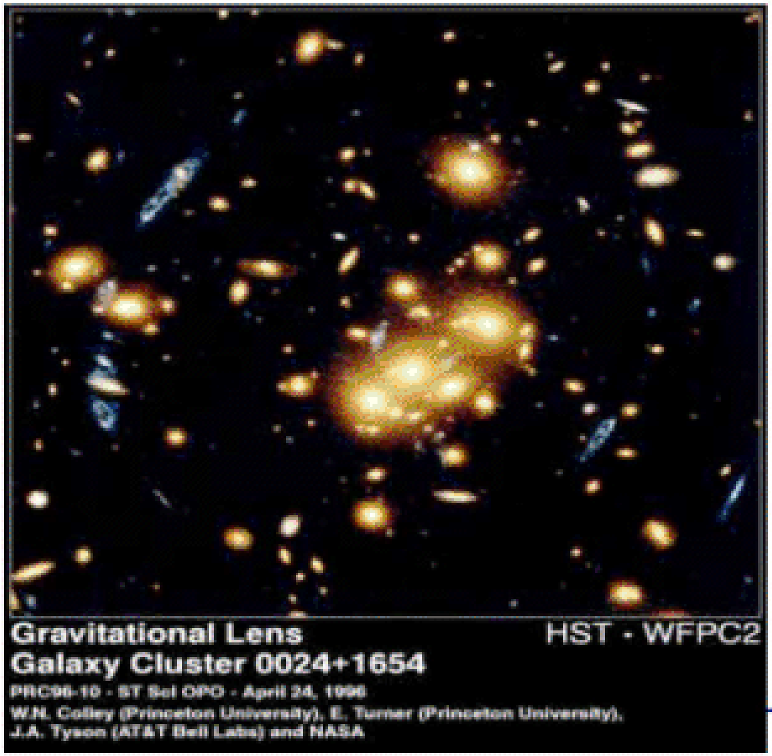
- We thought we knew all the fundamental fields that make up the universe. In fact, our commanding knowledge of "normal" matter has provided the framework against which surprises can be measured.
- Astrophysical observations have shattered the view that we understood the fundamental fields: the bulk of the universe is dark matter and dark energy.

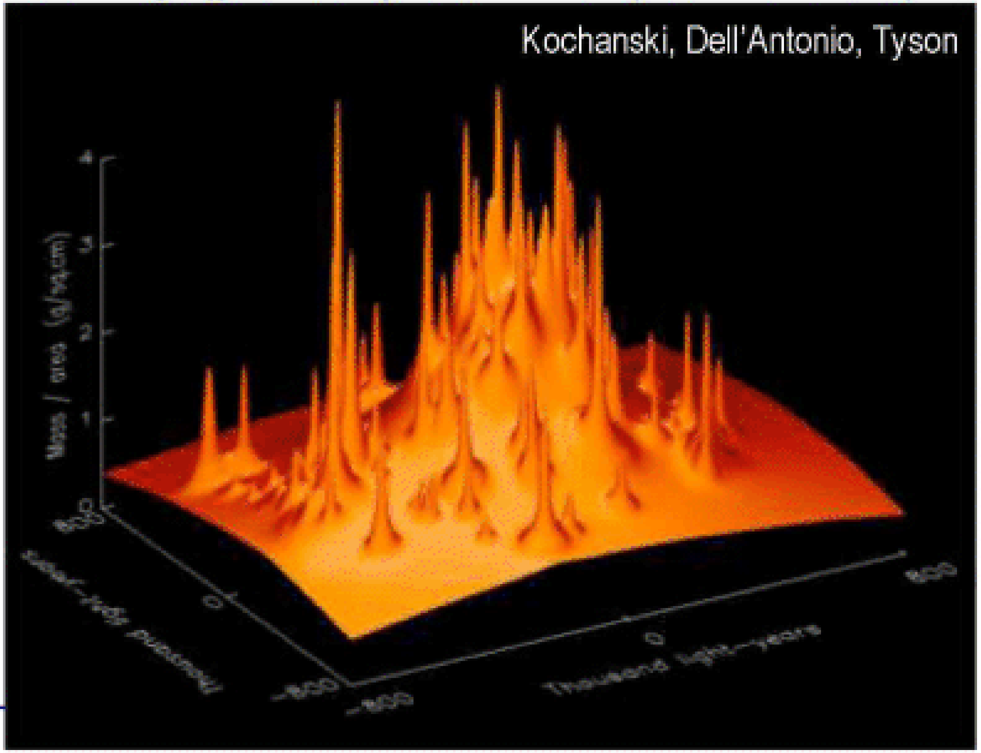
Dark Matter

- The existence of dark matter was established from galactic rotation curves, motion within clusters of galaxies, strong lensing, and weak lensing.
- It is needed in simulations to understand the evolution of large scale structure in the universe, the formation and properties of clusters of galaxies, and, e.g., the formation of black holes within galaxies.

Measurement of Cluster Mass by Strong Lensing (2)

- If the deflection angle is large there are multiple images - strong lensing
- CL0024+1654
  - Foreground galaxy cluster z=0.39 (false yellow = Near Infrared)
  - Background galaxy source z=1.6 (blue, color due to star formation, young galaxy)
    - Einstein Ring ~100 kpc radius @ z=0.39
  - Mass Distribution deconvolved from Hubble Image (galaxies=spikes, DM=hump dominant mass)

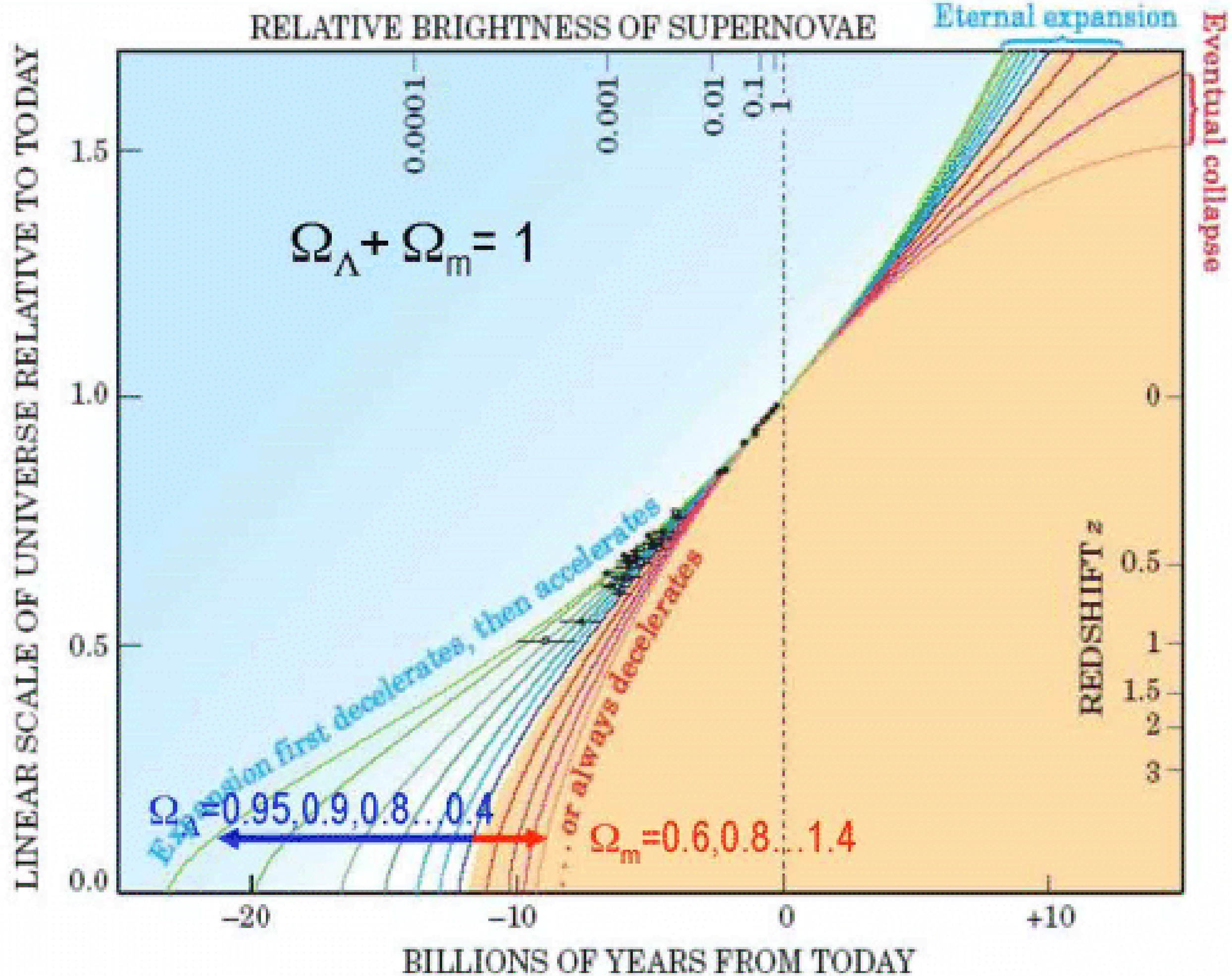




Dark Energy

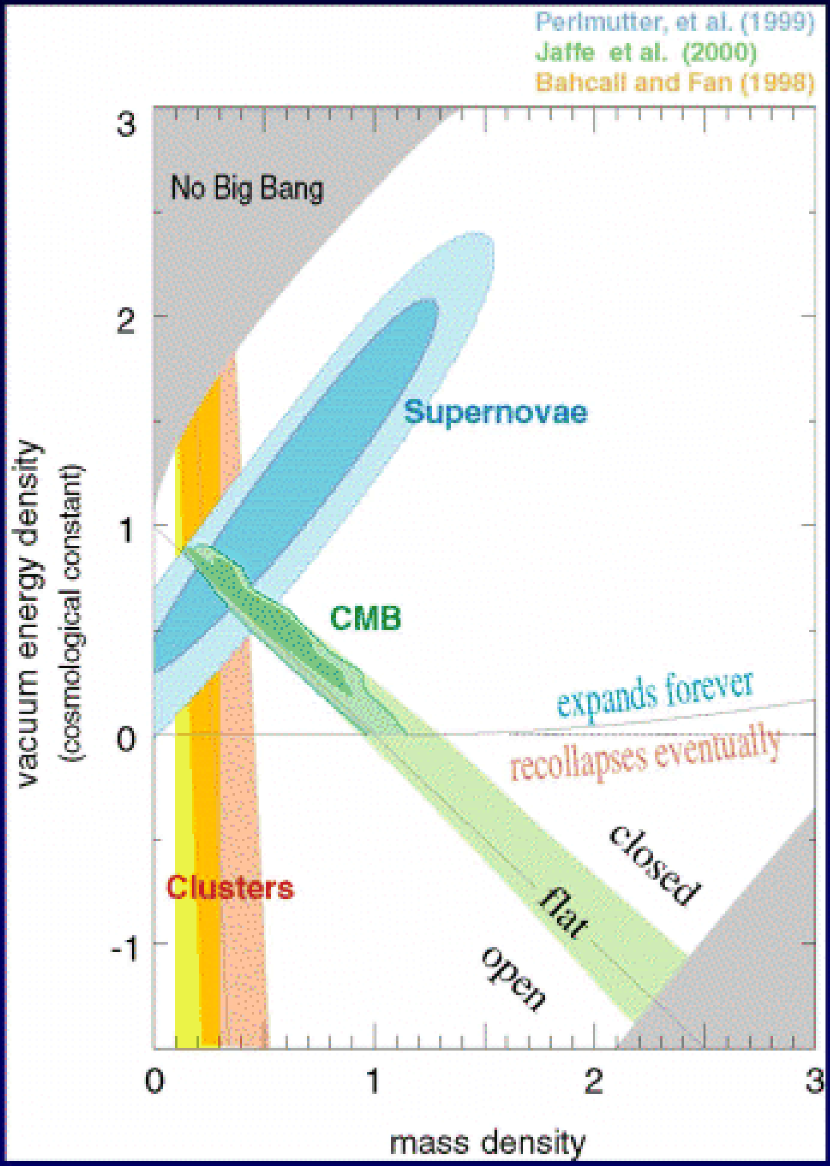
- The presence of dark energy was deduced from measuring the accelerating expansion of the universe using supernovae as standard candles.
- There is also evidence from properties of the CMB and other data.

ΛCDM Cosmology Evolution - z vs time



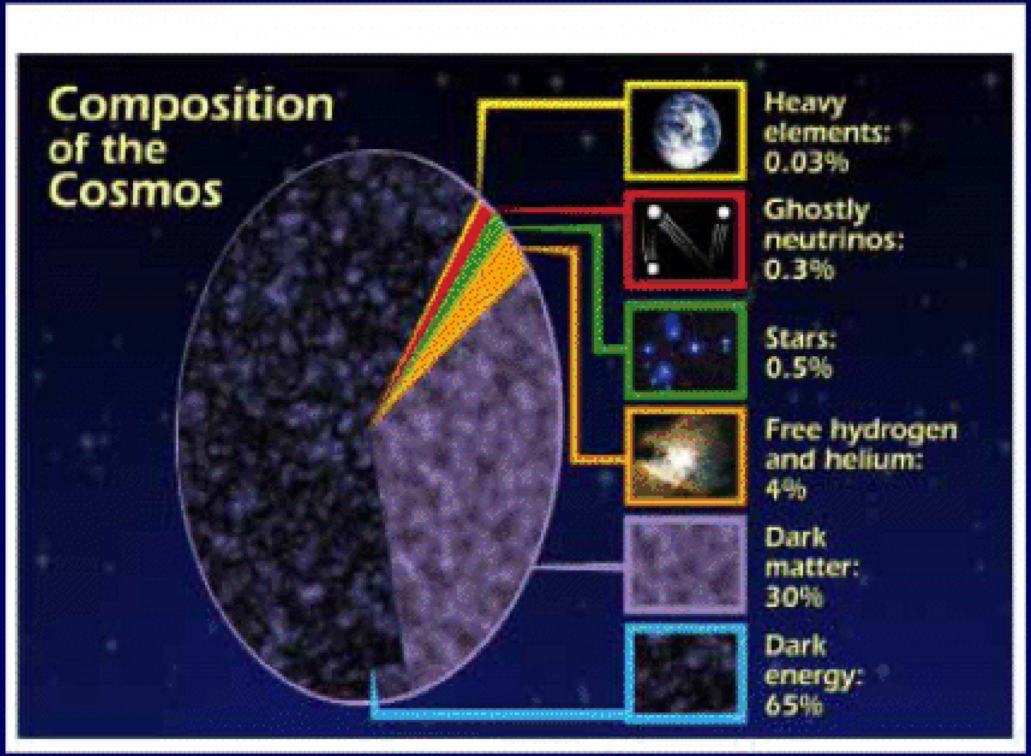
Saul Perlmutter, Physics Today, Apr 2003

Concordance ΛCDM Model



Outstanding questions:

- initial conditions (inflation?)
- nature of the dark matter
- nature of the dark energy



Accelerators and the Cosmos

- We can observe around us the relics of the Big Bang, the ultimate particle physics experiment.
- We can produce at accelerators, under controlled conditions, time/energy-slices of the universe right after the Big Bang – “melting the vacuum” – to reveal the fundamental constituents in that epoch and to allow their detailed study and understanding.
- This is essential to answering the big questions – working forward from the Big Bang, we aim to understand how to match up with what we see today.

“Do the two ends meet?”

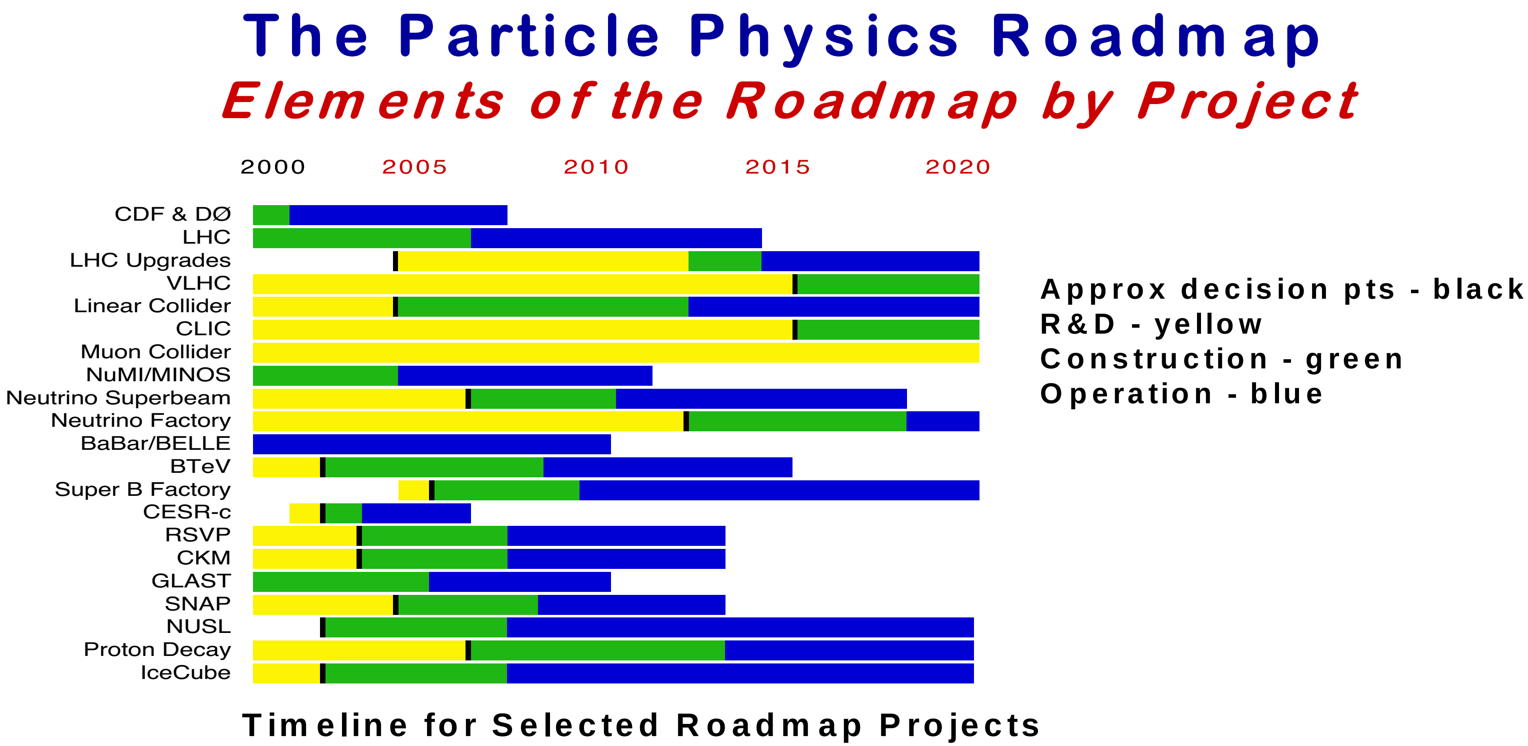
21st Century Particle Physics

- Our present model of the Universe must be incorporated into a deeper theory that can explain these new phenomena. New physics is necessary.
- We know the tools that will provide us with the information we need to begin to take the next steps. In combination, the data from particle accelerators, cosmological observations, and underground experiments place us now in the early stages of a new era of discovery.

The Particle Physics Roadmap

- The set of current and future experiments directed at our set of questions can be viewed in terms of a roadmap.
- A U.S. particle physics roadmap of projects and their timeline was set forth by the Long-Range Planning Subpanel of HEPAP in 2002. These projects will be done in the context of particle physics across the globe.

Particle Physics Roadmap from the Long-Range Planning Subpanel

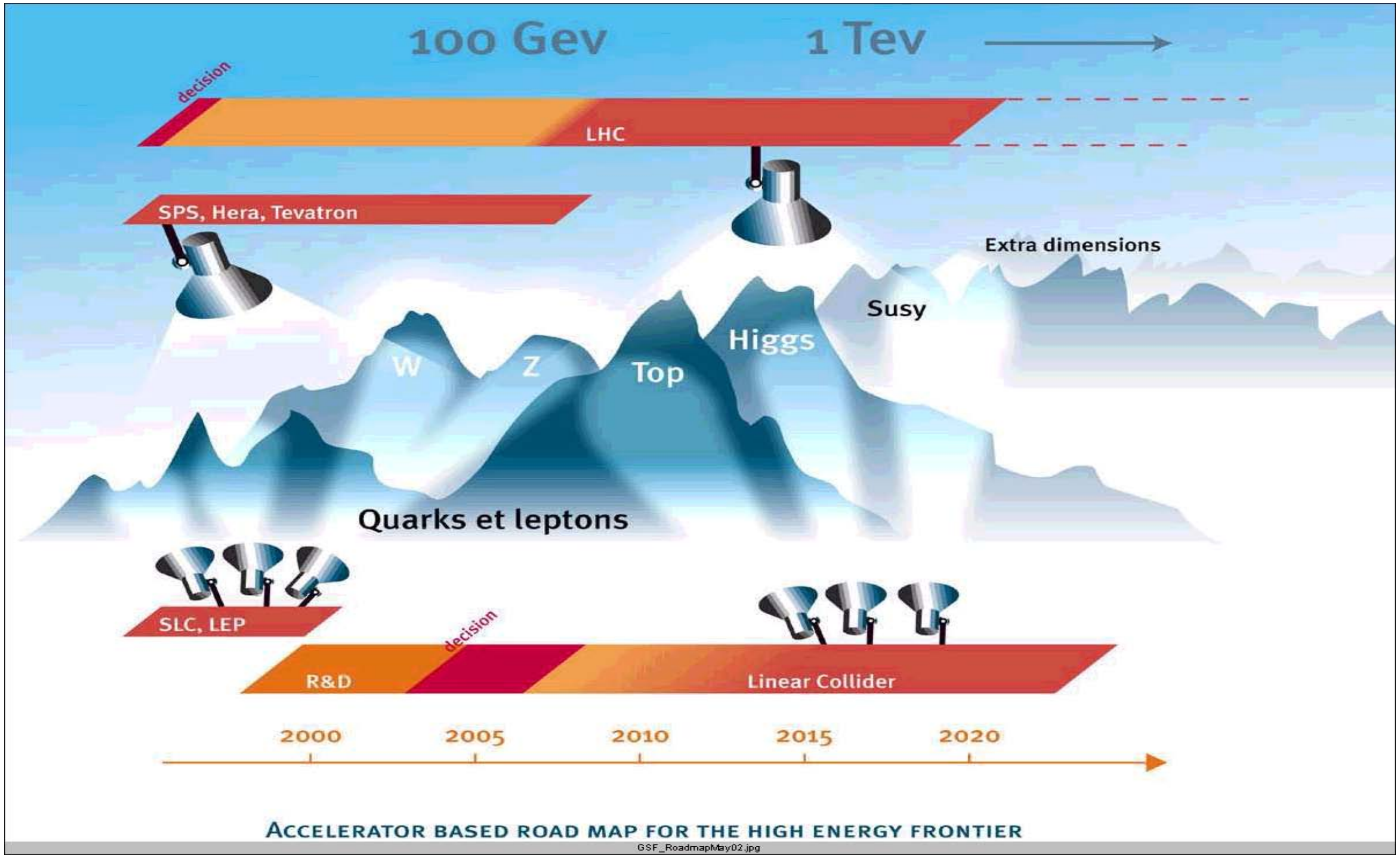


Not all projects illustrated on the roadmap can be pursued. Some will have to be sacrificed because of limited manpower and resources in the field.

International Particle Physics Roadmap

- In the last few years the Consultative Group on High Energy Physics of the OECD Global Science Forum also developed a roadmap for high-energy focused on the future of high-energy accelerators.
- It combines projects, their timeline, and their physics goals into one roadmap graphic.

High-Energy Frontier Roadmap
GSF Consultative Group on HEP



The U.S. Particle Physics Roadmap - A Work in Progress

- The roadmap needs to be updated as science changes, new experiments are proposed, and decisions are made.
- A Particle Physics Project Prioritization Panel (P5) was formed to update the roadmap and make recommendations on mid-sized particle physics projects.
- P5 made its first report to HEPAP in September 2003, assigning priorities to three projects and updating the U. S. roadmap.

The U.S. Particle Physics Roadmap - A Work in Progress (con’t)

- In parallel with the planning for particle physics, the DOE Office of Science Twenty-Year Facilities Plan of September 2003 included five of the HEP facilities recommended by HEPAP: JDEM (SNAP), BTeV, Linear Collider, Double-Beta Decay Detector, and a Neutrino Super Beam.
- In the following, we examine briefly the projects within the broad areas of the U.S. roadmap. We note the changes due to recent developments.

Particle Physics Roadmap Assault on the TeV Scale

- The weak and electromagnetic interactions unify at the TeV scale of energies – How does this work? Assuming just the presently known particles and interactions yields predictions that contradict basic principles and must be wrong.
- We are entering unexplored territory where there must be something fundamentally new: Higgs bosons, supersymmetry, extra dimensions, …
- So far, we have been quite unlucky in finding something new from the TeV scale – no Higgs, no SUSY, no FCNC and CP-violation beyond the SM, … Is this just bad luck?

Particle Physics Roadmap Assault on the TeV Scale (2)

- The TeV scale is also the energy scale where we expect to find dark matter particles.
- To understand dark matter, we must create it in the laboratory and see if colliders meet cosmology – we would want to explore the TeV scale at colliders for this reason alone.

Thermal Relics I

- Thermal equilibrium in the early-enough universe
- Interaction rate becomes smaller than expansion rate – freeze-out
- Calculation of the relic density is straightforward – Boltzmann equation

$$\frac{dn}{dt}+3Hn=-\langle\sigma v\rangle(n^2-n_{eq}^2)$$

- Relativistic particles in equilibrium have n ~ T^3 - same as out of equilibrium
  - relic density insensitive to details of freeze-out
- Non-relativistic particles are Boltzmann-suppressed
  - equilibrium density falls exponentially with temperature
- Large annihilation rates – small relic density, etc. $\rho\propto\frac{1}{\sigma}$
- What is the scaling for relic density vs. cross-section?
  - relativistic freeze-out

$$\Omega h^2\approx\frac{m}{100\ \mathrm{eV}}\frac{10}{g^*}$$

  - non-relativistic freeze-out

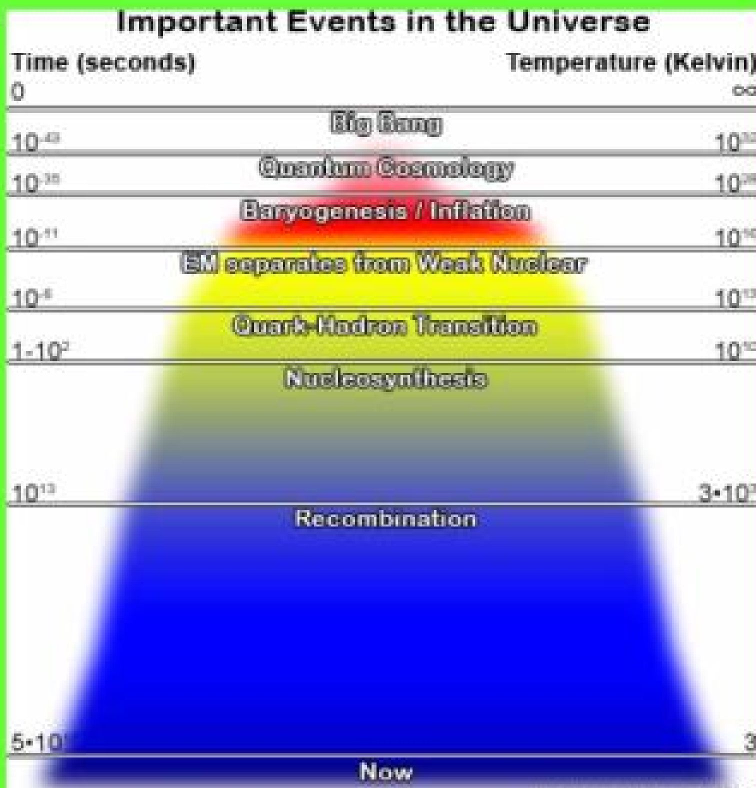
$$\Omega h^2\sim\left(\frac{m}{\mathrm{TeV}}\right)^2$$

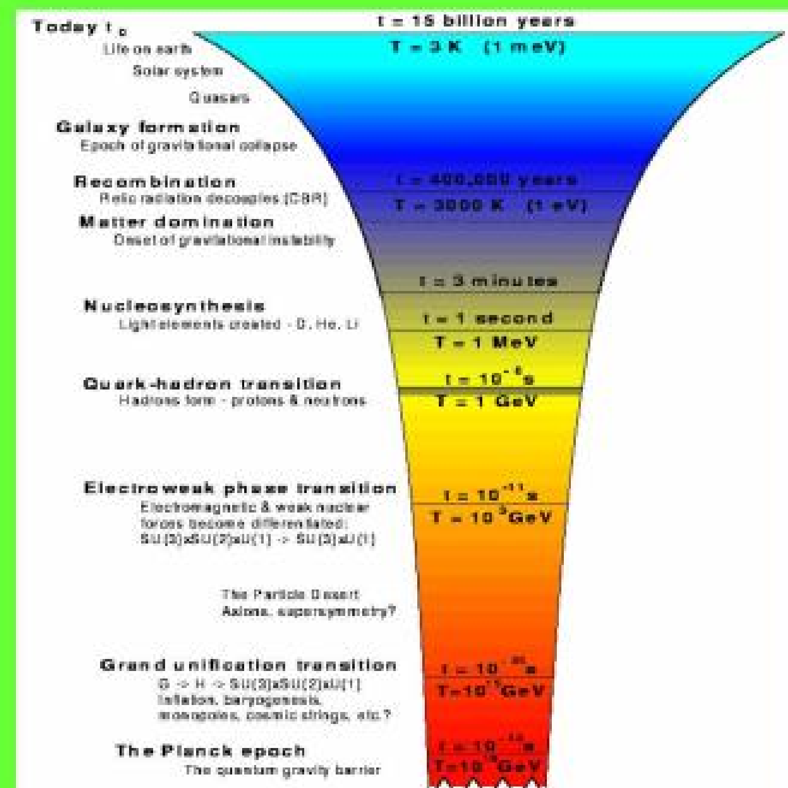
- Weak Interaction Scale!

Particle Physics Roadmap Assault on the TeV Scale (3)

- We want to understand the electroweak phase transition and see what lies beyond it; this is also the next giant step back towards the big bang.
- Can we then see all the way to the GUT scale?

Early-Universe Timeline





Thomas J. Weiler, Vanderbilt University & CERN

Particle Physics Roadmap Assault on the TeV Scale (4)

- We need both blunt instruments and fine tools to discover and examine what we find at the TeV scale and understand how it all fits together.
- On the U.S. roadmap that involves operating the Tevatron, carrying out the US-LHC program, doing R&D for possible future hadron and muon colliders, and moving toward construction of a Linear Collider as an international project.

Linear Collider Developments

- After the worldwide consensus in 2001-2002 on the next large machine, linear collider steering committees were formed in each the three regions, followed by the ILCSC.
- Strong regional R&D has continued to pass the remaining high level milestones.
- The Linear Collider has first priority in the second trimester of the DOE SC 20-Year Facilities Plan.
- The 2003 Report of the GSF Consultative Group on High Energy Physics was endorsed by the OECD Science Ministers.

Statement of the Science Ministers January 2004

High-energy physics

18. Ministers acknowledged the importance of ensuring the long-term vitality of high-energy physics. They noted the worldwide consensus of the scientific community, which has chosen an electron-positron linear collider as the next accelerator-based facility to complement and expand on the discoveries that are likely to emerge from the Large Hadron Collider currently being built at CERN. They agreed that the planning and implementation of such a large, multi-year project should be carried out on a global basis, and should involve consultations among not just scientists, but also representatives of science funding agencies from interested countries. Accordingly, Ministers endorsed the statement prepared by the OECD Global Science Forum Consultative Group on High-Energy Physics (Annex 2).

Linear Collider Developments (2)

- An International Technology Recommendation Panel has been established by ICFA to choose between warm and cold technologies soon.
- ICFA aims to establish an international design effort after the technology choice.
- Meanwhile, linear collider technology is being used to build x-ray laser projects at DESY and at SLAC (LCLS is in the FY05 budget proposal)

Particle Physics Roadmap
Quark Flavor Physics

- Why are there six quarks? Why do they occur in three generations? What happened to the antimatter? Where will new physics show up?
- We have made great progress in understanding precisely how the quarks and antiquarks respond to the weak interaction.
- The establishment of the CKM paradigm is a triumph of a combination of theory, experiment, and accelerators at their best .

Particle Physics Roadmap
Quark Flavor Physics (2)

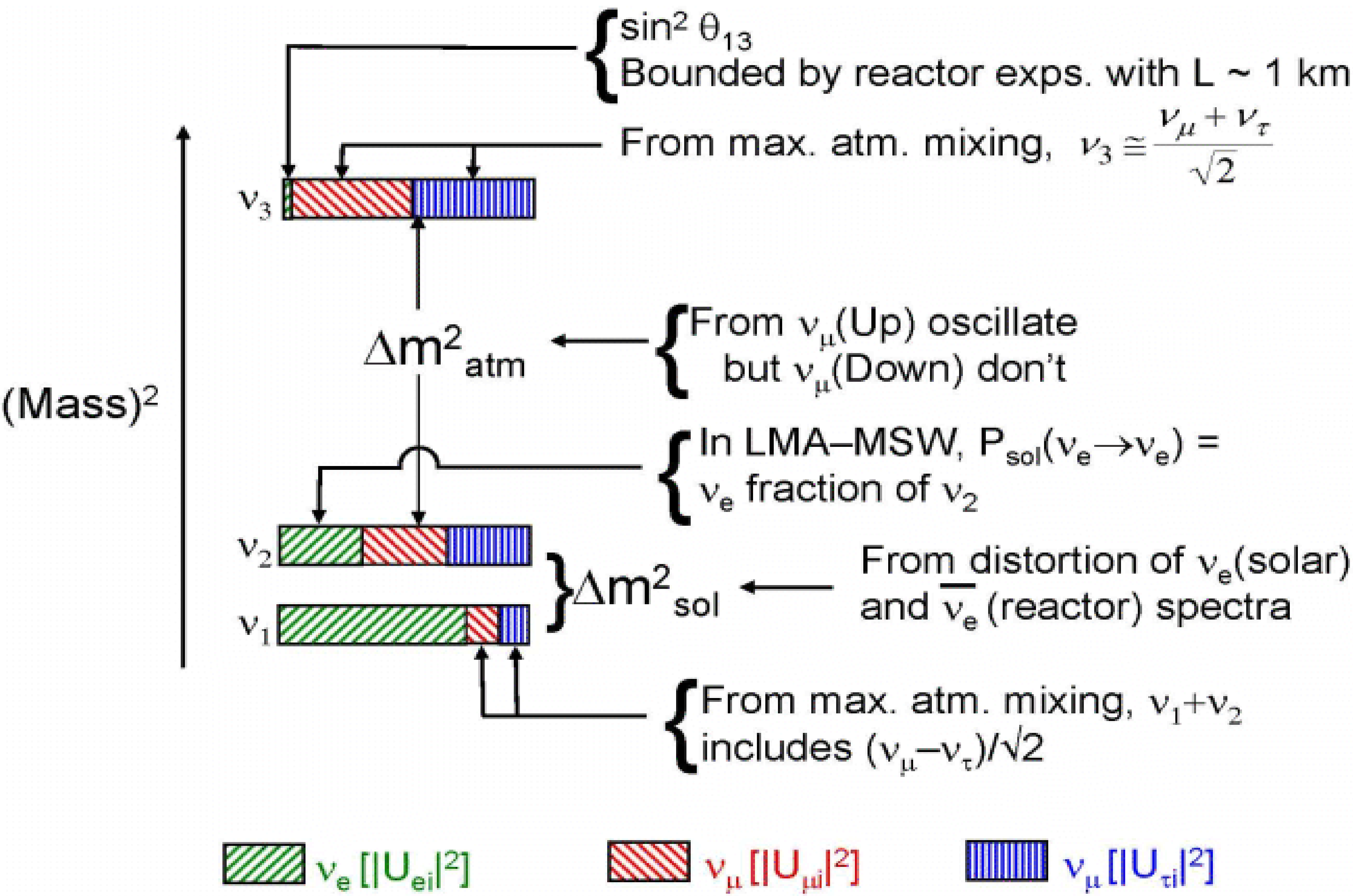
- There is still much to do. There are hints of new physics effects. We will want to know the footprint of TeV-scale physics on quarks and antiquarks, both for its own sake and as a diagnostic of new physics.
- We ultimately want to measure CP violation in the laboratory and match it to the CP violation needed to explain why our present universe is made out of matter and not antimatter.

Particle Physics Roadmap
Quark Flavor Physics (3)

- We need experiments at both electron-positron colliders and hadron machines.
- On the U.S. roadmap that involves operating BaBar, CESR-c, CDF/D0; building K0PI0 and BTeV (recommended by P5 and in the FY05 budget proposal). Discussion continues as well on a Super B-Factory.

Particle Physics Roadmap
Lepton Flavor Physics

- Are there more than three neutrinos? At what level does charged-lepton flavor violation show up? Is the neutrino its own antiparticle with a mass connected to physics at the GUT scale? Is there CP violation in the neutrino sector? Could it explain a universe made of matter?
- A major part of the medium-term world program aims to pin down the parameters describing neutrino oscillations and understand if there are CP violating effects. (What is ❑$_{13}$ and ♎?)



sin² θ13
Bounded by reactor exps. with L ~ 1 km
From max. atm. mixing, $\nu_3 \cong \frac{\nu_\mu + \nu_\tau}{\sqrt{2}}$
ν_3
Δm^2_{atm}
From ν_μ(Up) oscillate
but ν_μ(Down) don't
(Mass)²
In LMA–MSW, $P_{sol}(\nu_e \to \nu_e)$ =
ν_e fraction of ν_2
ν_2
ν_1
Δm^2_{sol}
From distortion of ν_e(solar)
and $\bar{\nu}_e$ (reactor) spectra
From max. atm. mixing, $\nu_1 + \nu_2$
includes $(\nu_\mu - \nu_\tau)/\sqrt{2}$
$\nu_e\ [|U_{ei}|^2]$
$\nu_\mu\ [|U_{\mu i}|^2]$
$\nu_\mu\ [|U_{\tau i}|^2]$

Particle Physics Roadmap Lepton Flavor Physics (2)

- On the US roadmap, that now involves running MiniBooNE; building NuMI/MINOS and MECO.
- In planning the future US roadmap, the APS Neutrino Physics Study will play an important role in laying out the physics opportunities and developing the roadmap of possible experiments both here and abroad. The report is expected soon, so that we can begin filling in the neutrino physics part of the US roadmap.

Particle Physics Roadmap
Lepton Flavor Physics (3)

- In the near- to medium-term, possible projects are the Off-Axis and reactor experiments to determine oscillation parameters and a Double-Beta Decay Detector.
- Longer term projects are a Neutrino Super Beam, a NUSL with possible neutrino and proton decay experiments, and a Neutrino Factory.

Particle Physics Roadmap
Cosmic Connections

- What is the dark matter and dark energy? What is the precise connection of dark matter to physics at the TeV scale? Could the dark energy be related to the scalar sector we expect to explore at the TeV scale? Does the dark energy density vary with time? What does the high-energy universe tell us about astrophysics and about particle physics?
- We are at a very early stage in our understanding of dark energy. First and foremost we need much better data.

Particle Physics Roadmap Cosmic Connections (2)

- On the US roadmap, CDMS and accelerators at the TeV scale are searching for dark matter. JDEM is planned as a joint DOE/NASA probe of dark energy, in addition to ground based observations.
- Auger is measuring the high-energy universe in cosmic rays; GLAST and Ice Cube are under construction.

Conclusions

- The particle physics roadmap is proving to be useful in planning the U.S. program; several decisions have already been taken and others will be coming up in the next few years.
- Particle physics has entered an era that should see major discoveries from experiments in space, underground, and at accelerators. Colliders will push into a region of energies that holds the answers to some of the most basic questions of particle physics, answers that are connected the universe that existed very soon after the Big Bang to the universe we live in today.