The Next Twenty Years in Particle Physics

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UC Berkeley Physics Colloquium

November 4, 2002

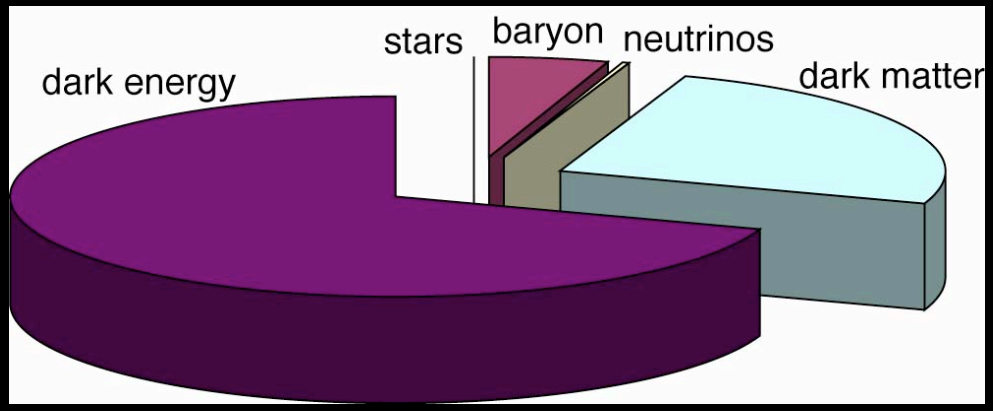
Hubble Deep Field

Hubble Space Telescope • WFPC2

PRC96-01a • ST ScI OPO • January 15, 1995 • R. Williams (ST ScI), NASA

Energy budget of Universe

- Stars and galaxies are only ~0.5%
- Neutrinos are ~0.3–10%
- Rest of ordinary matter (electrons and protons) are ~5%
- Dark Matter ~30%
- Dark Energy ~65%
- Anti-Matter 0%
- Higgs condensate ~10^{62}%??



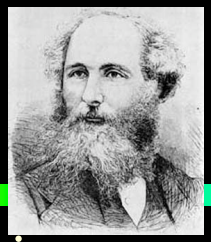
The Cosmic Questions

- What is Dark Matter?
- What is Dark Energy?
- How much is Neutrino component?
- Is Higgs Boson really there?
- Where did Anti-Matter go?

Einstein's Dream

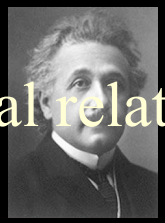
- Is there an underlying simplicity behind vast phenomena in Nature?
- Einstein dreamed to come up with a *unified* description
- But he failed to unify electromagnetism and gravity (GR)

History of Unification

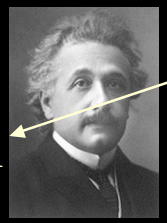


planets apple electric magnetic atoms

gravity mechanics electromagnetiesm Quantum mechanics



Special relativity



GR

-decay -decay -decay

Quantum ElectroDynamics

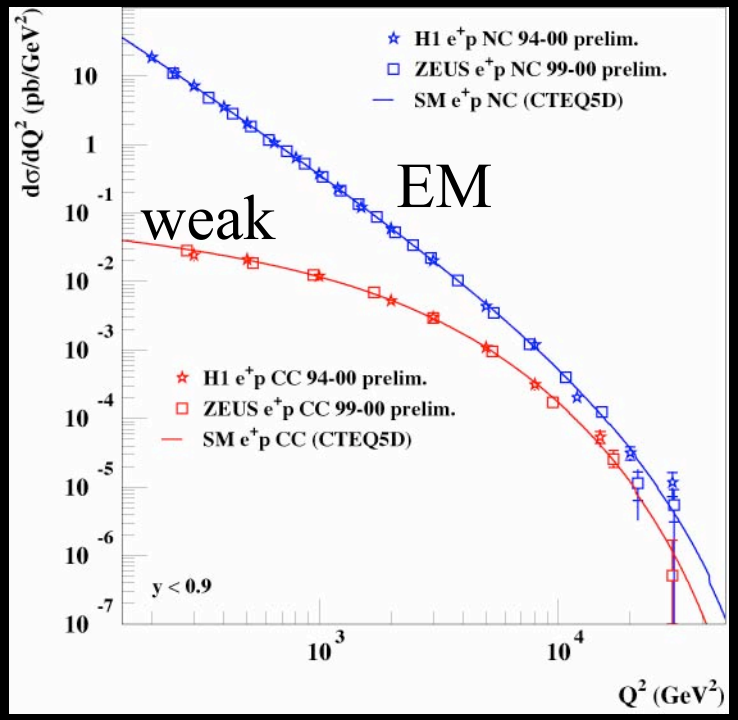
Weak force

Electroweak theory Strong force

String theory? Grand Unification?

We are just about to achieve another layer of unification

- HERA *ep* collider



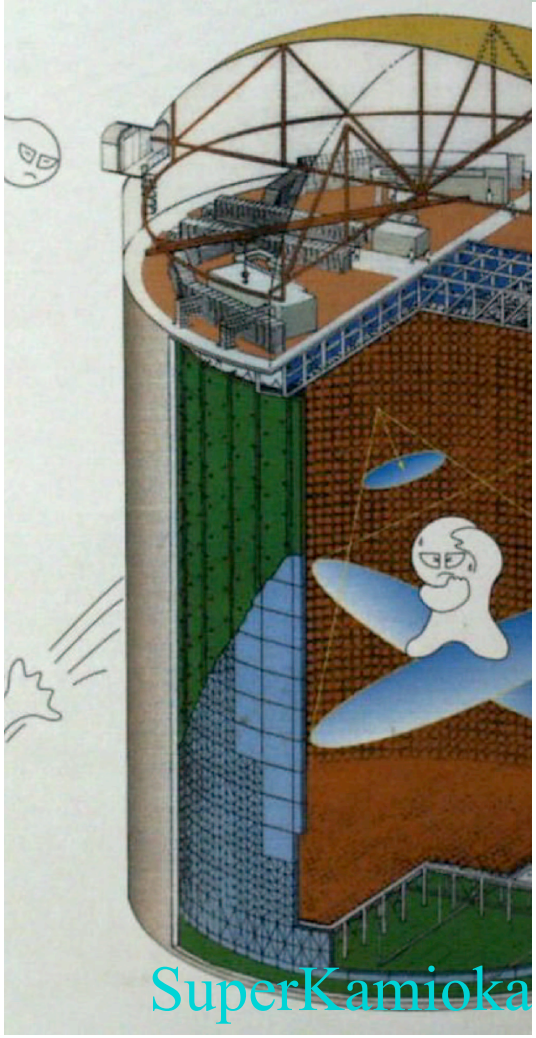
- Unification of electromagnetic and weak forces
  - *electroweak theory*
- Long-term goal since ‘60s
  - *We are getting there!*
- The main missing link:
  - Higgs boson

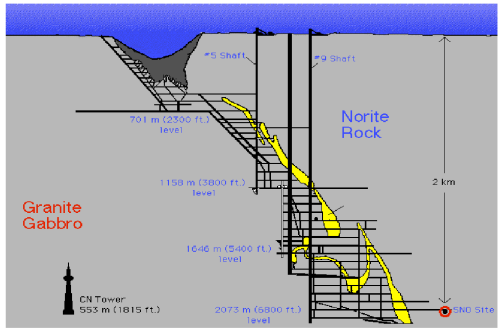
Outline

- Introduction
- Recent Surprises
- Dark Side of Universe
- Condensate in Universe
- Beyond Higgs Condensate
- Anti-Matter
- Conclusions

Recent Surprises

Neutrinos Have Mass





Sudbury Neutrino Observatory

1000 tonnes D_2O

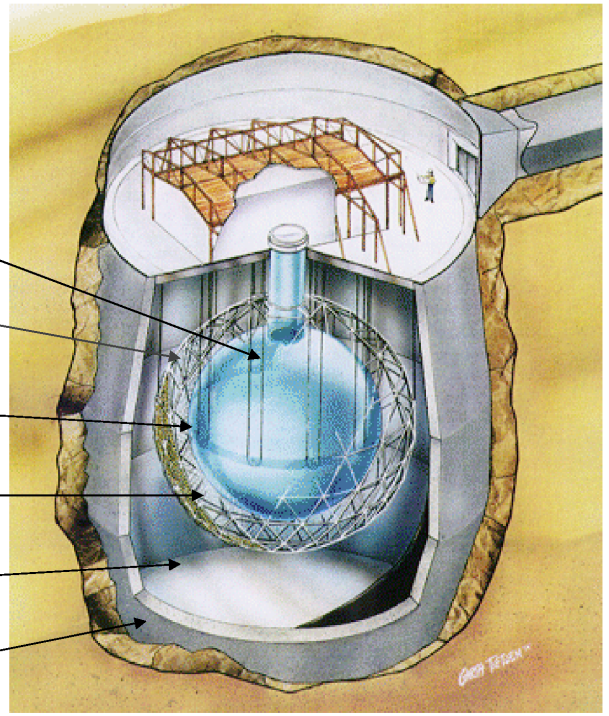
Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

Urylon Liner and Radon Seal

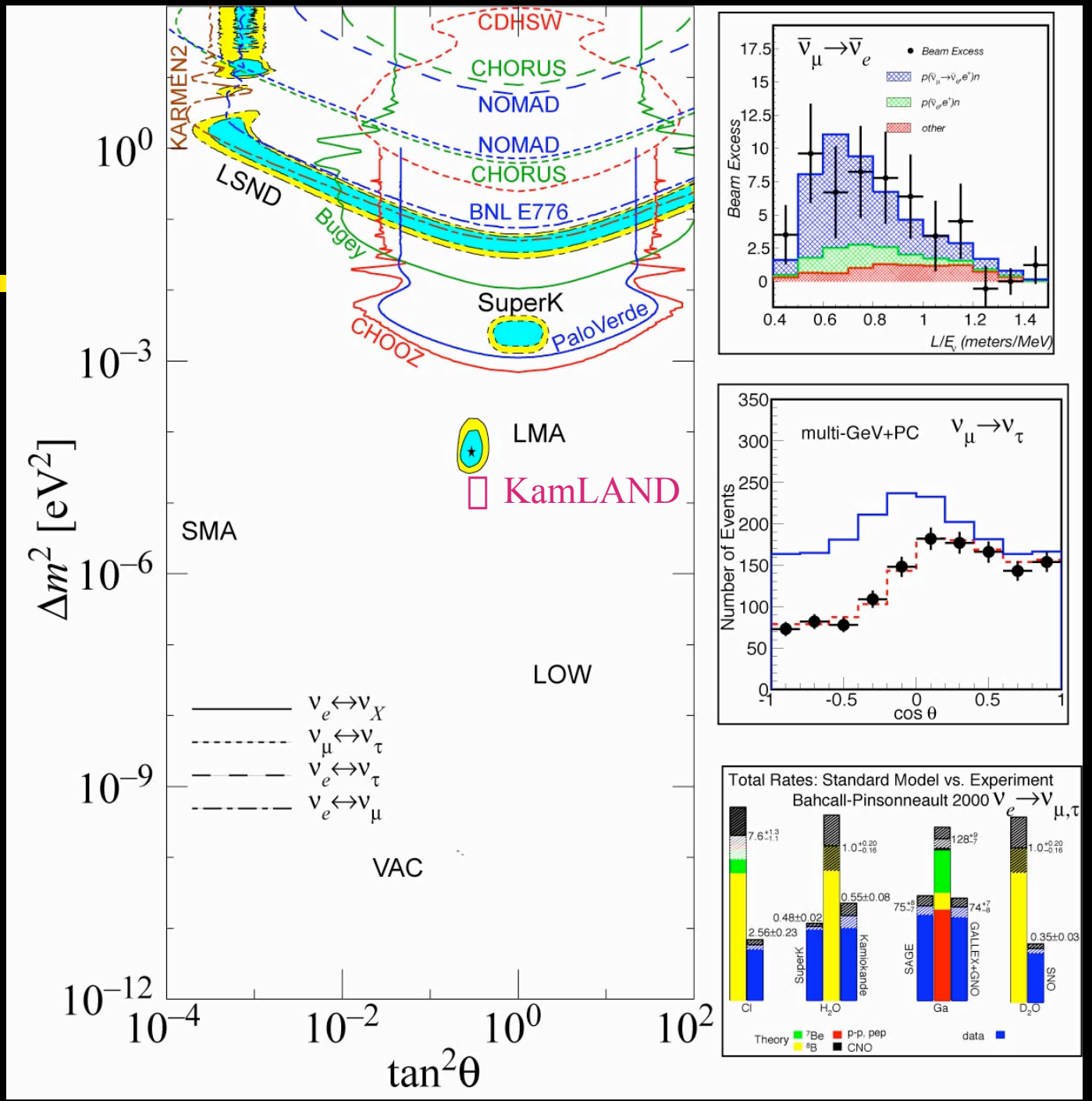


From an Orphan to the Center Stage

- Pauli postulated neutrinos in order to save the energy conservation in nuclear β-decay in 1930
- Finally discovered by Cowan and Reines using a nuclear reactor in 1958
- Massless Neutrinos in the Standard Model ('60s)
- Evidence for neutrino mass from SuperK (1998) and SNO (2002)
- *First evidence that the minimal Standard Model of particle physics is incomplete!*
- 2002 Nobel to pioneers: Davis and Koshiba

March 2002

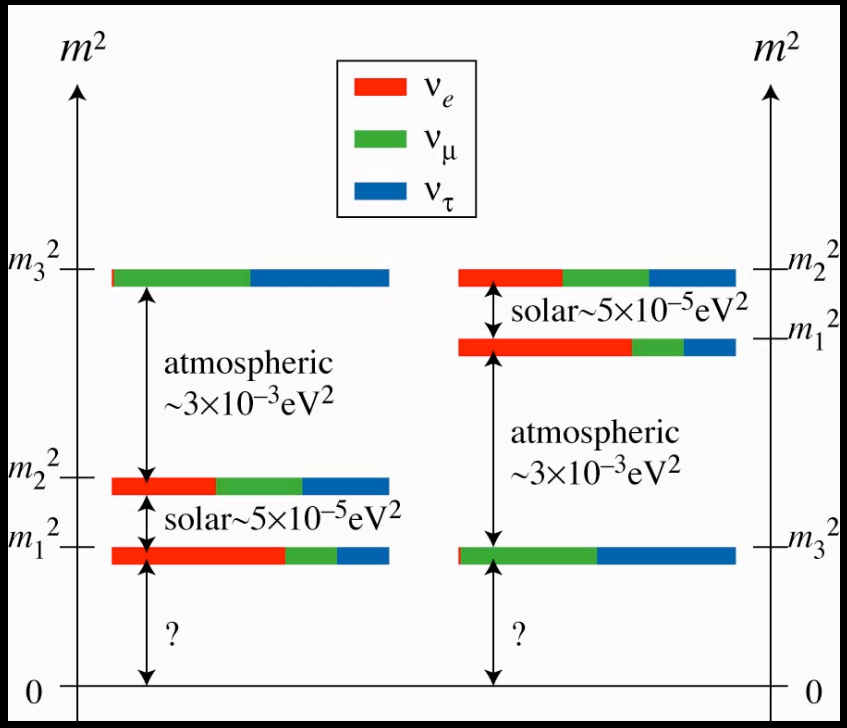
April 2002
with SNO



Raised More Questions

- Why do neutrinos have mass at all?
- Why so small?
- We have seen mass *differences*. What are the masses?

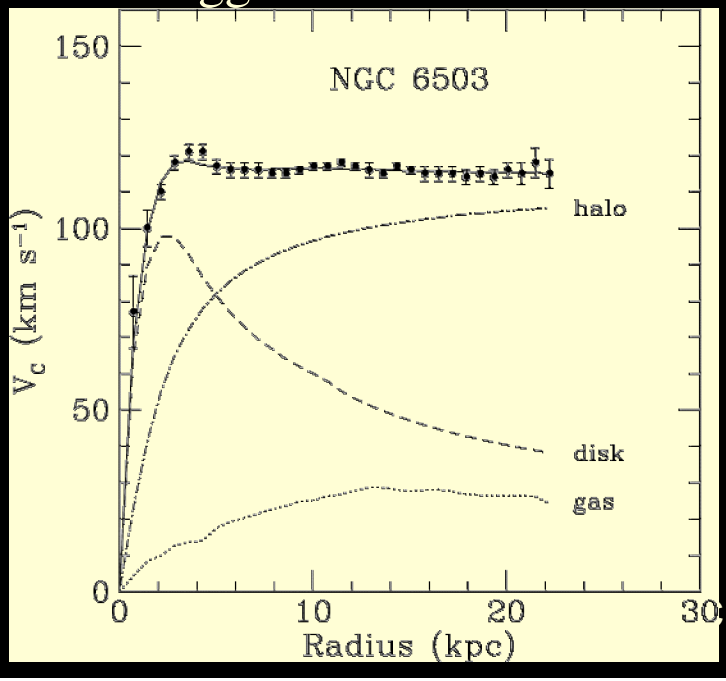
  $\Sigma_\nu \sim m_\nu / 15\text{eV}$
- Do we need a fourth neutrino?
- Are neutrinos and anti-neutrinos the same?



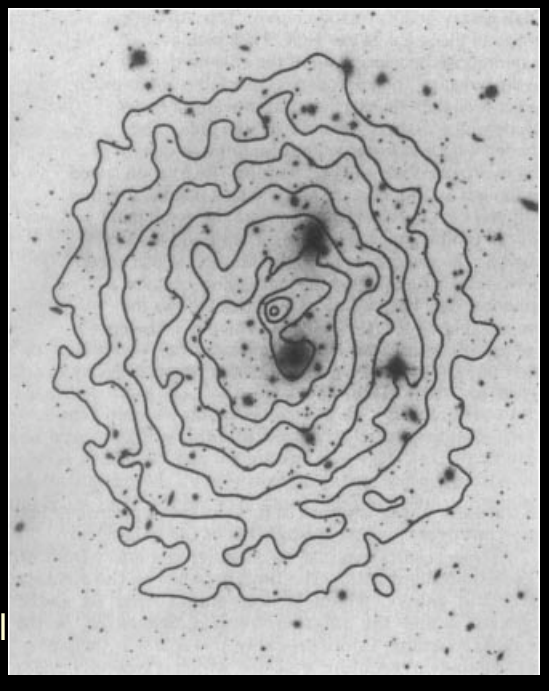
- How do we extend the Standard Model to incorporate massive neutrinos?

Evidence for Dark Matter

- Observe galaxy rotation curve using Doppler shifts in 21 cm line from hyperfine splitting
- Galaxy is held together by mass far bigger than all stars



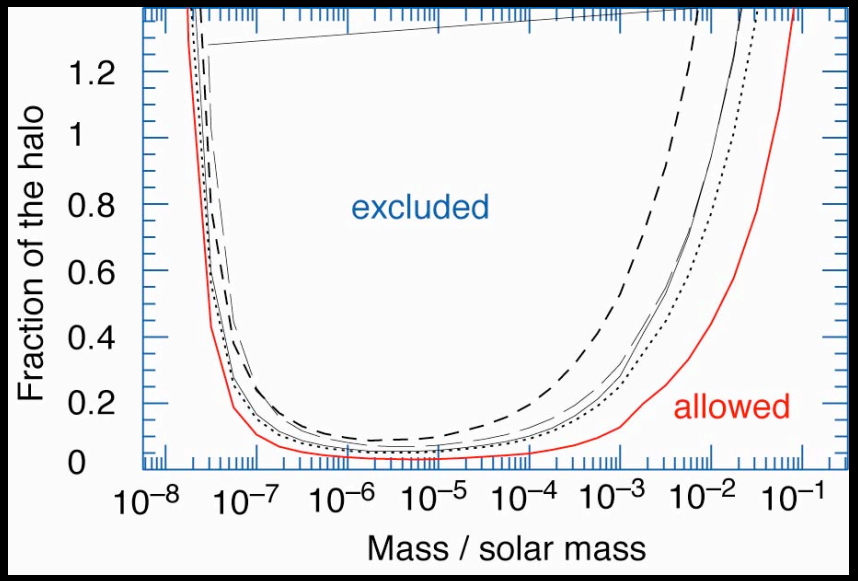
- Galaxies form clusters bound in a gravitational well
- Hydrogen gas in the well get heated, emit *X*-ray
- ~20 times more mass than seen



Giacconi
2002 Nobel
Father of
X-ray astronomy

Particle Dark Matter

- It is not dim small stars (e.g., MACHOs)



- WIMP (Weakly Interacting Massive Particle) strongly favored
- Stable heavy particle produced in early Universe, left-over from near-complete annihilation

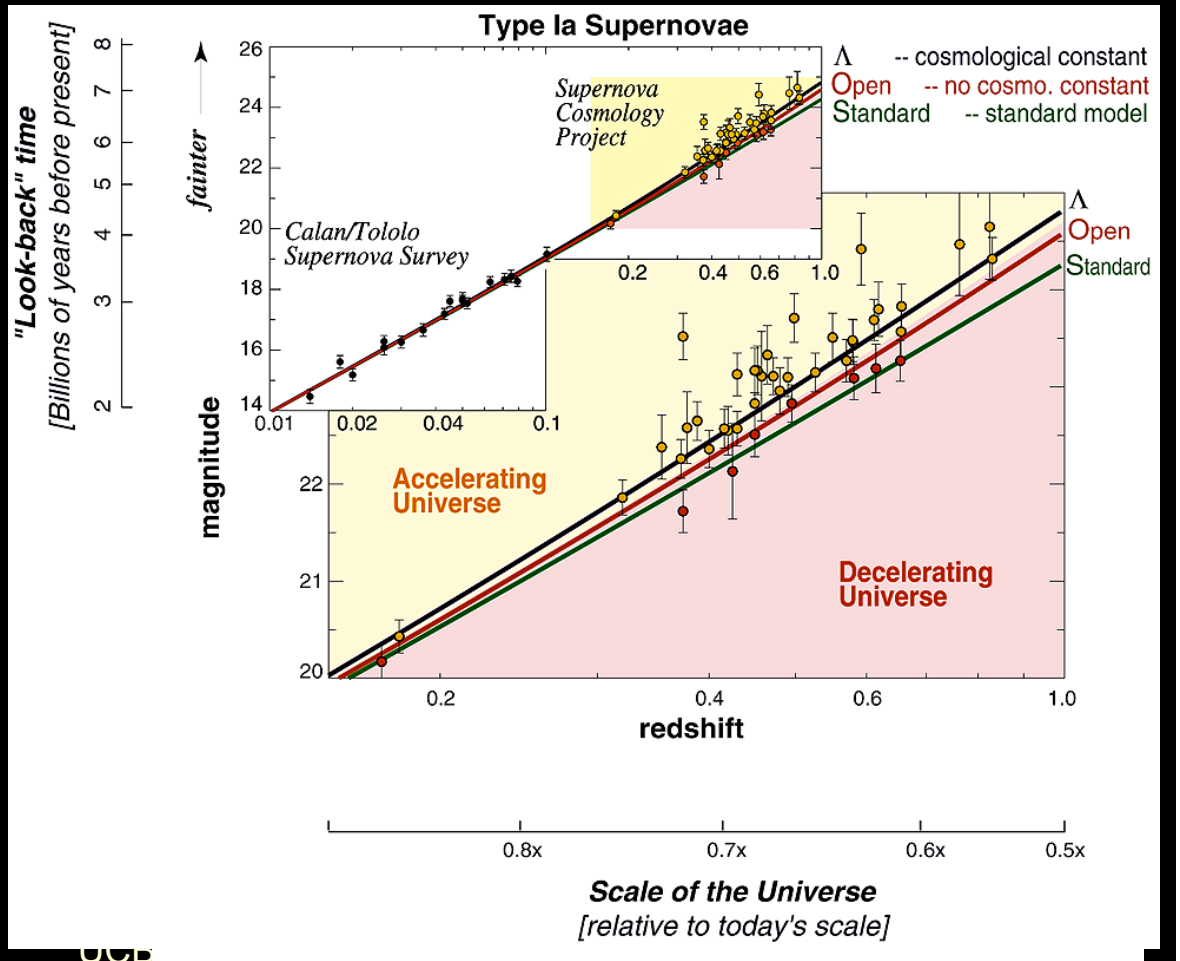
$$\Omega_M = \frac{0.756(n+1)x_f^{n+1}}{g^{1/2}\Omega_{ann}M_{Pl}^{\ 3}} \frac{3s_0}{8\pi H_0^2} \Omega \frac{\Omega^2/(TeV)^2}{\Omega_{ann}}$$

- TeV=10^{12}eV the correct energy scale

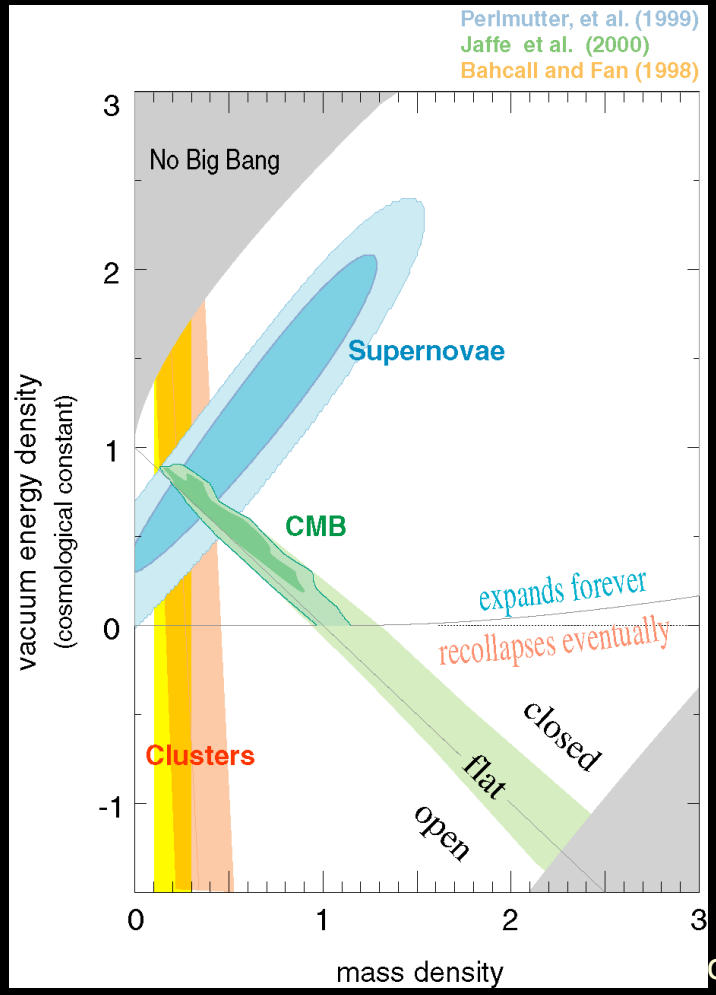
Type-IA Supernovae

- Type-IA Supernovae "standard candles"
- Brightness not quite standard, but correlated with the duration of the brightness curve
- Apparent brightness
  - ⇒ how far ("time")
- Know redshift
  - ⇒ expansion since then

Expansion of Universe is *accelerating*



Accelerating Universe



- Einstein's equation:

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3} G_N \rho$$

- If the energy dilutes as Universe expands, it must slow down
- Need something that gains in energy as Universe stretches

  i.e, negative pressure
- The cosmological constant Λ has the equation of state $w=p/\rho=-1$
- Generically called "Dark Energy"

Embarrassment with Dark Energy

- A naïve estimate of the cosmological constant in Quantum Field Theory:

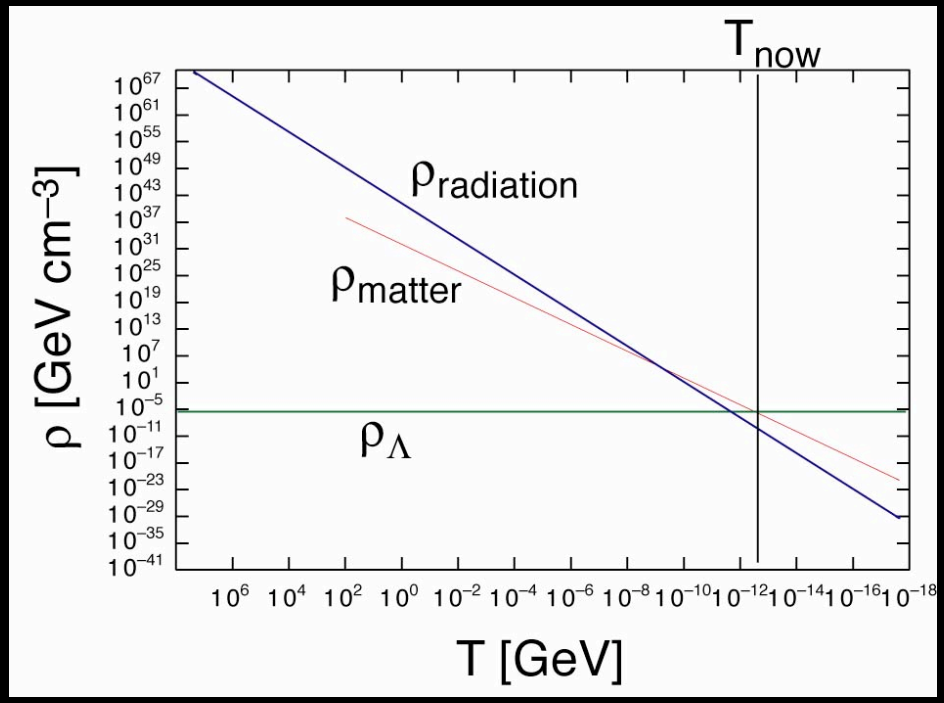
  $\Lambda \sim M_{\rm Pl}^4 = G_N^{-2} \sim 10^{120}$ times observation

The worst prediction in theoretical physics!

- People had argued that there must be some mechanism to set it zero
- But now it seems finite???

Cosmic Coincidence Problem

- Why do *we* see matter and cosmological constant almost equal in amount?
- "Why Now" problem
- Actually a triple coincidence problem including the radiation
- If there is a deep reason for $\rho_\Lambda \sim ((\mathrm{TeV})^2/M_{\mathrm{Pl}})^4$, coincidence natural



Arkani-Hamed, Hall, Kolda, HM

Cosmology and Particle Physics meet at TeV scale

- Dark Matter

$$\Omega_M = \frac{0.756(n+1)x_f^{n+1}}{g^{1/2}\sigma_{ann}M_{Pl}{}^3}\frac{3s_0}{8\pi H_0^2}\rho\frac{\sigma^2/(TeV)^2}{\sigma_{ann}}$$

- Fermi (Higgs) scale

  v~250GeV

- Dark Energy

  ρ_Λ~(2meV)^4 *vs* (TeV)^2/$M_{\rm Pl}$~0.5meV

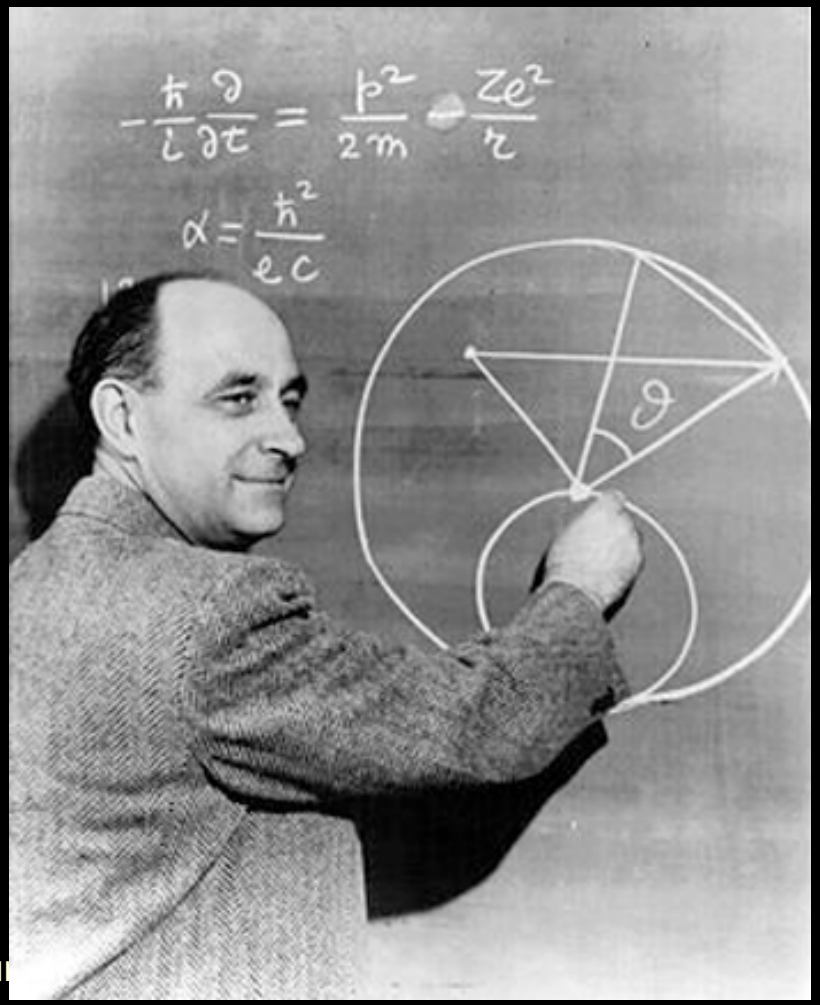
- Neutrino

  $(\Delta m^2_{\rm LMA})^{1/2}$~7meV *vs* (TeV)^2/$M_{\rm Pl}$~0.5meV

TeV-scale physics likely to be rich

Fermi's dream era

- Fermi formulated the first theory of the weak force (1933)
- The required energy scale to study the problem known since then: ~TeV
- We are finally getting there!



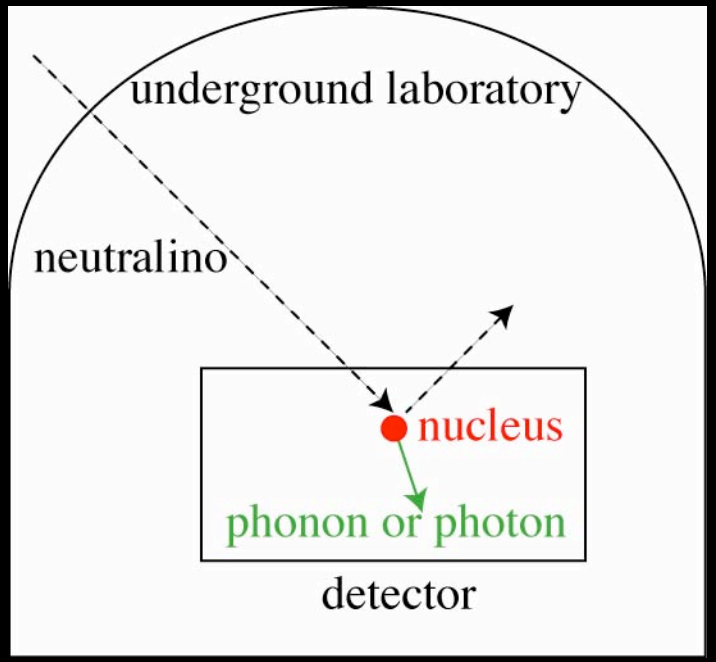
Where we are

- Decades-long problems are being resolved
  - CP violation, T violation, Dark Matter
- New surprises
  - Neutrino mass, Dark Energy
- There are many reasons to believe that this decade will be particularly exciting
- *We plan for a further program to bring the science to the next level*

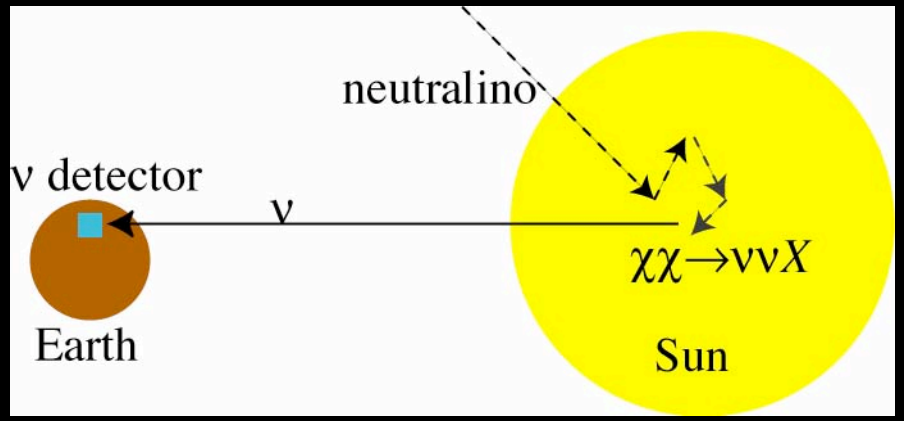
Dark Side of Universe

Detection of Dark Matter

- Direct detection
- CDMS-II, Edelweiss, DAMA, GENIUS, etc



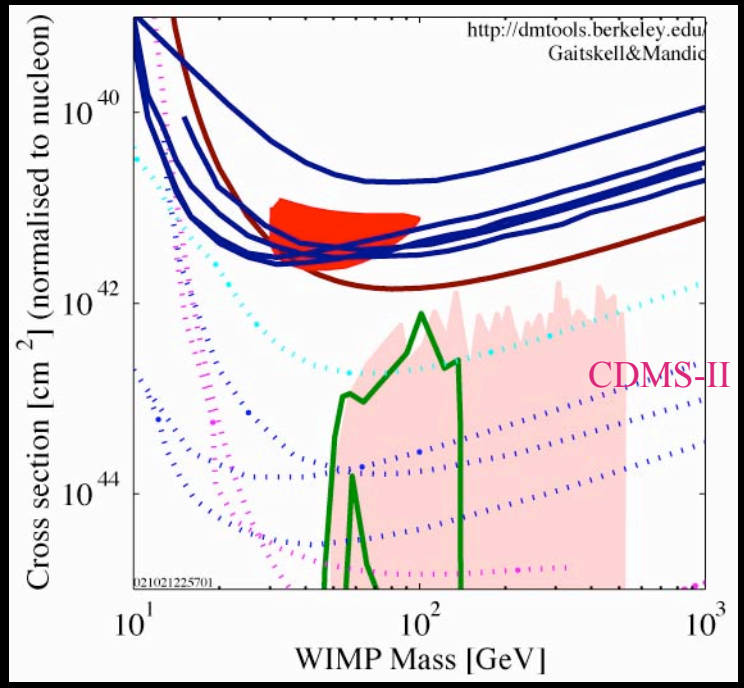
- Indirect detection
- SuperK, AMANDA, ICECUBE, Antares, etc



complementary techniques are getting into the interesting region of parameter space

Particle Dark Matter

- Stable, TeV-scale particle, electrically neutral, only weakly interacting
- No such candidate in the Standard Model
- Lightest Supersymmetric Particle (LSP): superpartner of a gauge boson in most models
- LSP a perfect candidate for WIMP

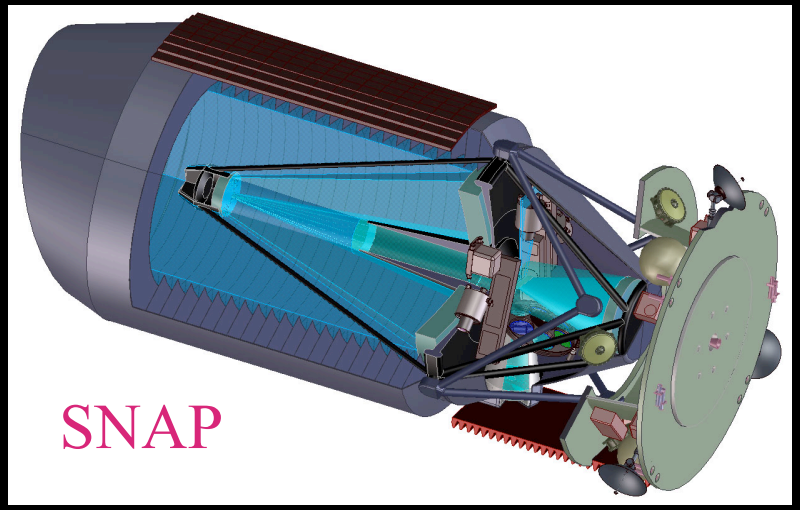


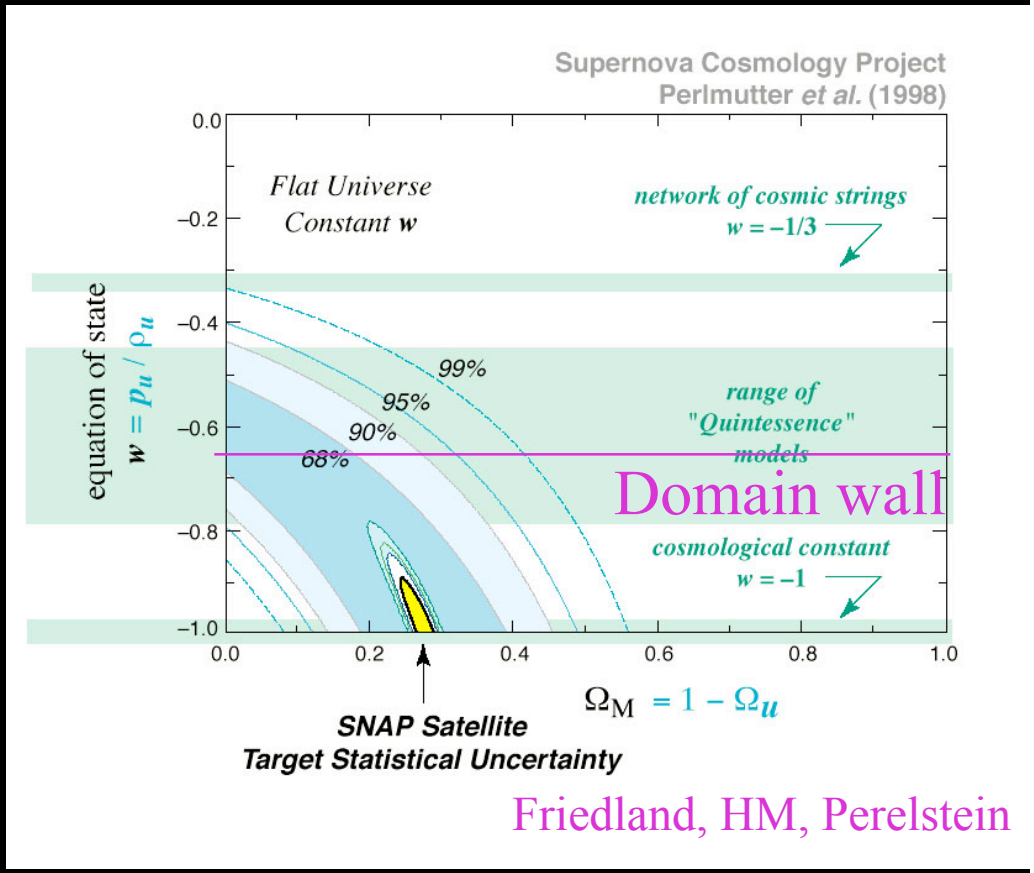
Detect Dark Matter to see *it is there*.

Produce Dark Matter in accelerator experiments to see *what it is*.

What is the Dark Energy?

- We have to measure *w*
- For example with a dedicated satellite experiment



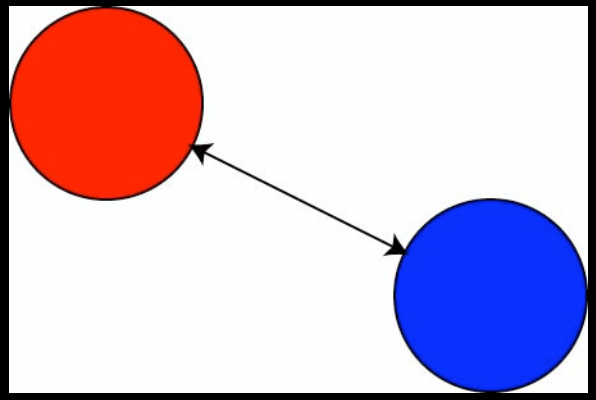


Friedland, HM, Perelstein

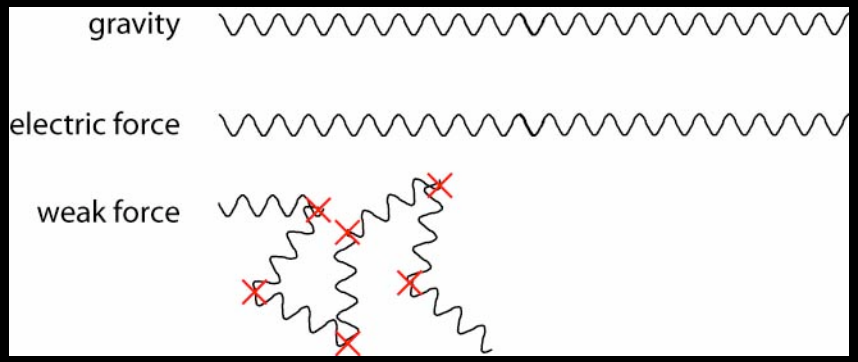
Condensate in Universe

Mystery of the "weak force"

- Gravity pulls two massive bodies (*long-ranged*)
- Electric force repels two like charges (*long-ranged*)
- "Weak force" pulls protons and electrons (*short-ranged*) acts only over 10^{-16} cm [need it for the Sun to burn!]



Something is in the Universe



- There is something filling our Universe
- It doesn't disturb gravity or electric force
- It does disturb weak force and make it short-ranged
- What is it??

Like a superconductor

- In a superconductor, magnetic field gets repelled (Meißner effect), and penetrates only over the "penetration length"

  ⇒ Magnetic field is short-ranged!

Imagine a physicist living in a superconductor

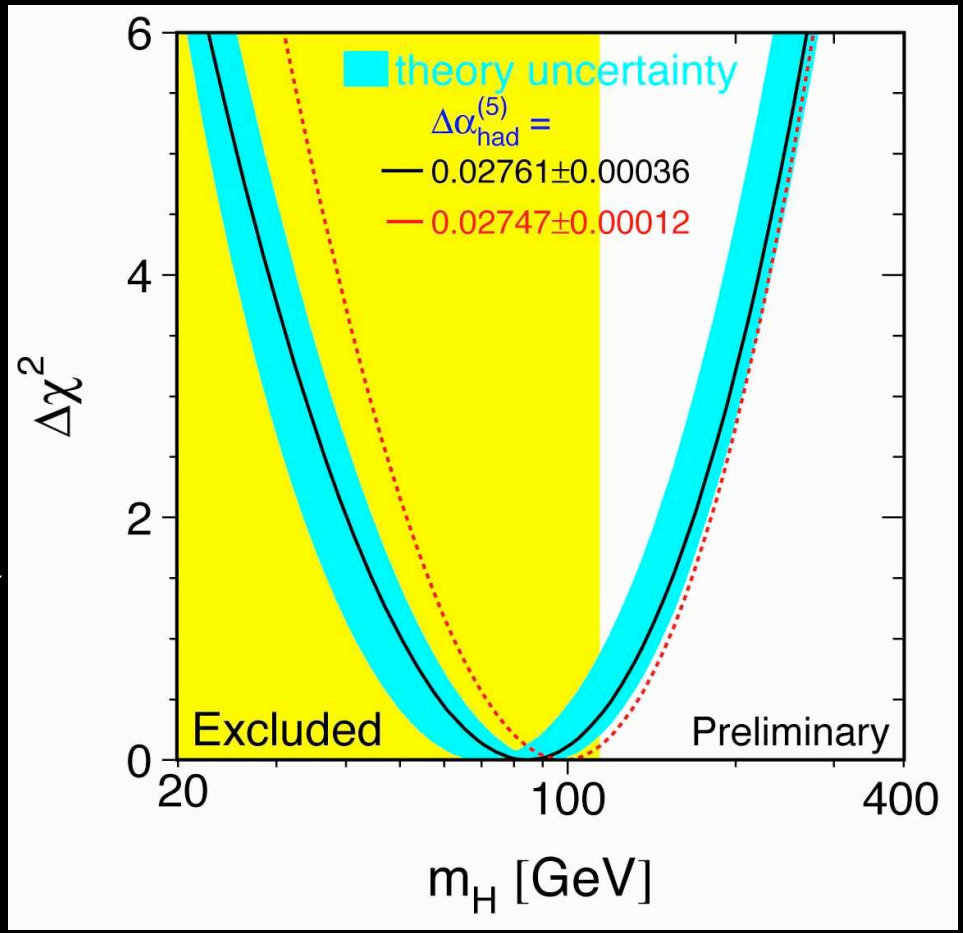
- She finally figured:
  - magnetic field must be long-ranged
  - there must be a mysterious charge-two condensate in her "Universe"
  - But doesn't know what the condensate is, nor why it condenses
  - Doesn't have enough energy (gap) to break up Cooper pairs

That's the stage where we are!

Higgs Boson is Most Likely "Just Around the Corner"

- Higgs boson
  = gap excitation
- Current data combined with the Standard Model theory predict

  m_H<196GeV (95%CL)
- Tevatron at Fermilab has a chance to discover or exclude the SM Higgs boson by 2008

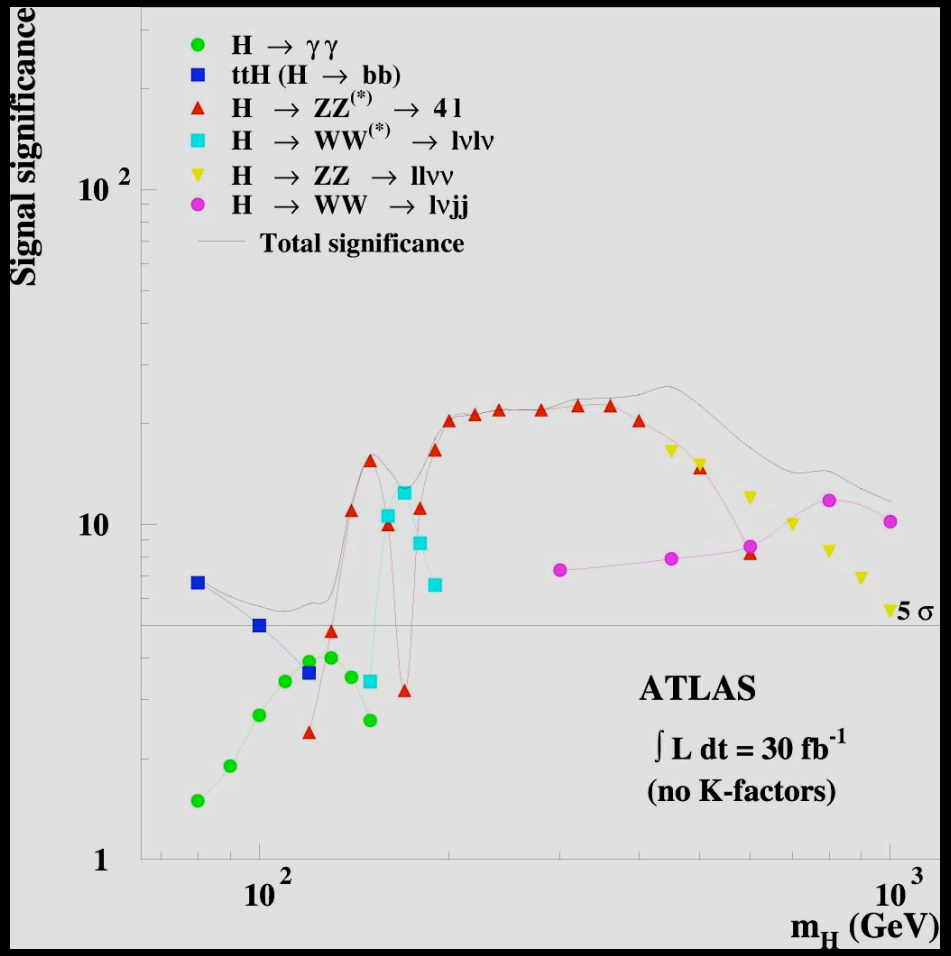


Large Hadron Collider (LHC): Exploring the TeV-scale

- proton-proton collider
- 14TeV energy
  (*cf.* 2TeV @ Fermilab)
- Under construction at CERN, Geneva
- Mostly European
- Contributions from US, Japan, Canada
- Turn on in ~2007

Higgs Boson at LHC

- LHC would discover Standard Model Higgs boson of any mass within 3 years!
- Measure mass, some ratio of couplings

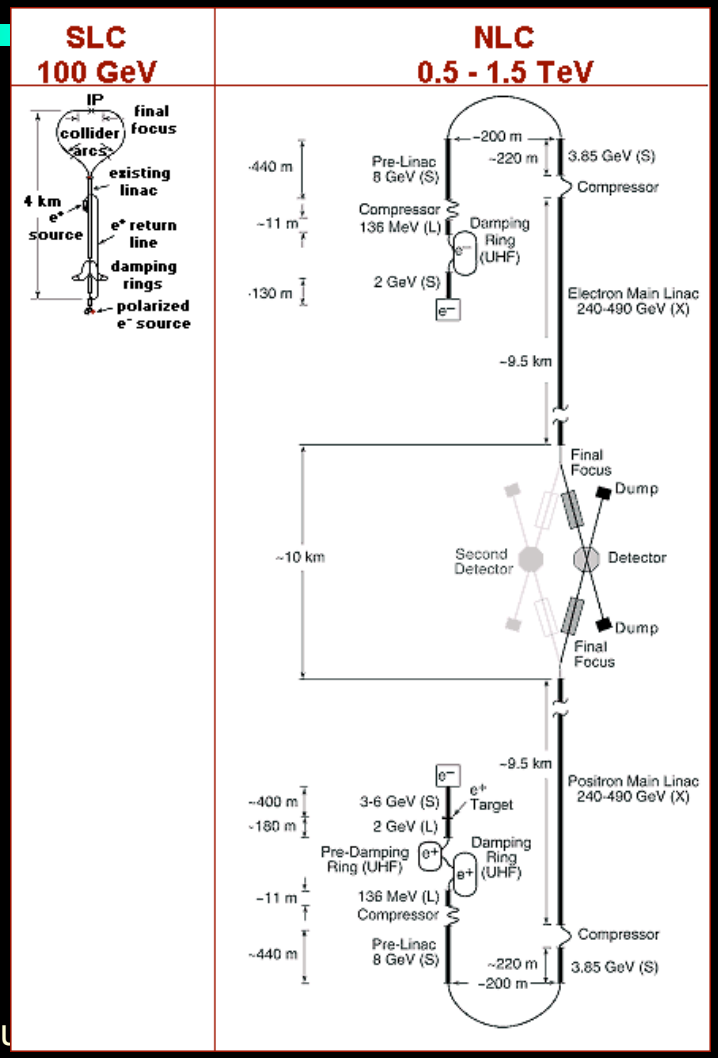


Questions to be answered

- Is the particle discovered really *the* Higgs boson?
  - Is it really responsible for particle masses?
  - Does this have the right quantum number 0^+?
  - Is it condensed in the Universe?
- Prove it is *the* "Origin of Mass"
  - Spin/Parity
  - Couplings
  - *Vacuum expectation value*
  - Branching Ratios

Linear Collider

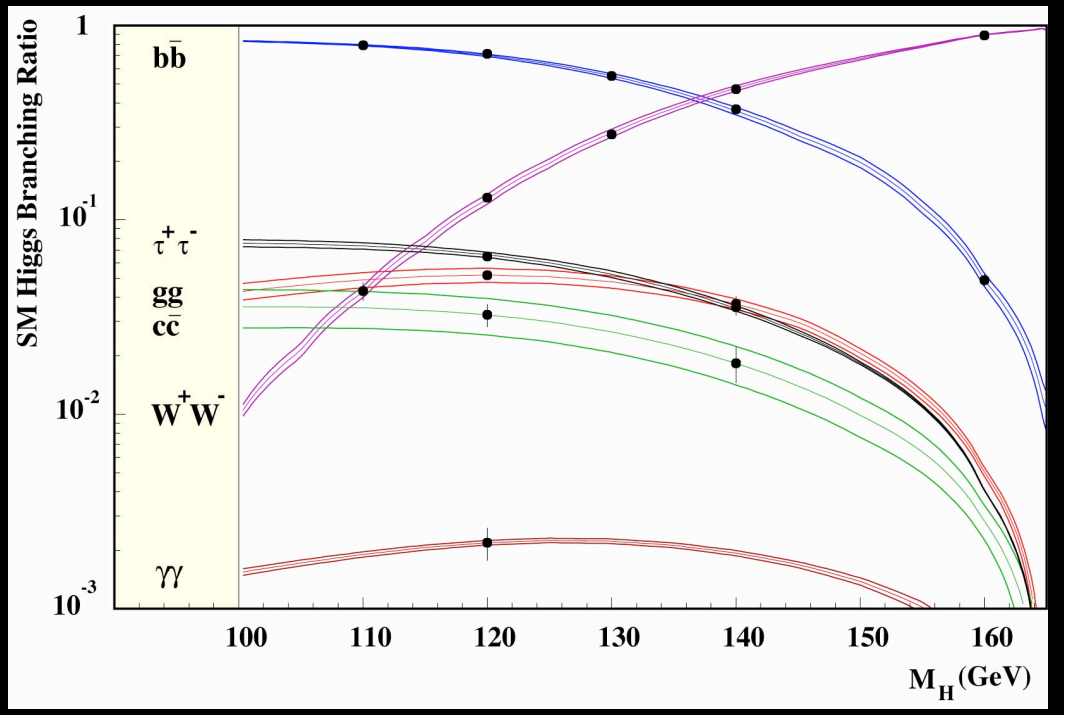
- Electron-positron collider
- e^-, e^+ point-like with no structure
- Well-understood environment
- Linear instead of ring to avoid synchrotron loss
- Super-high-tech machine
- Accelerate the beam over >10km
- Focus beam down to a few nanometers and make them collide



Prove its coupling mass

- Branching Fractions test the relation coupling mass

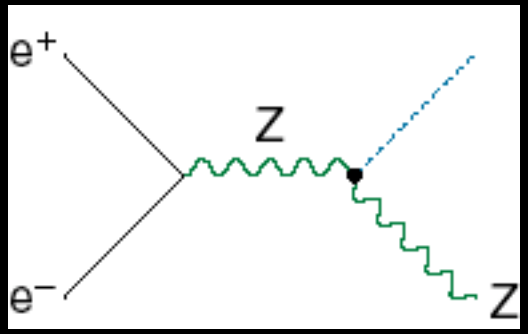
 proves that Higgs Boson is the “Origin of Mass”



(Battaglia)

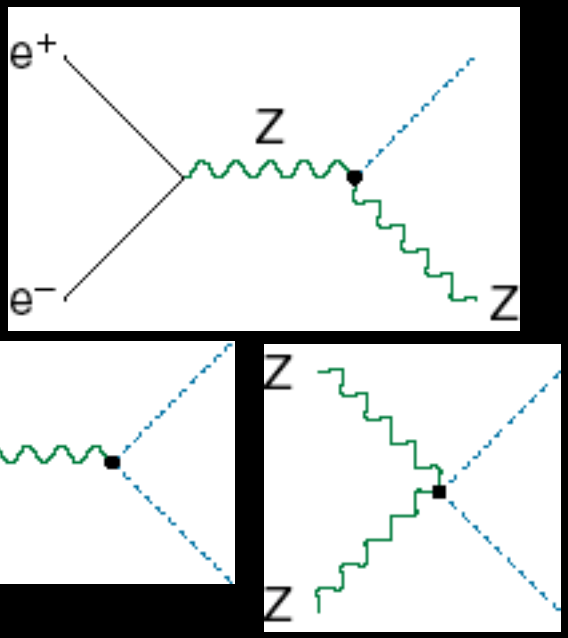
Prove it is condensed

- *ZH* final state
- Prove the *ZZH* vertex



Prove it is condensed

- *ZH* final state
- Prove the *ZZH* vertex
- We know *Z*:gauge boson, *H*: scalar boson
  ⇒ only two vertices



Prove it is condensed

- *ZH* final state
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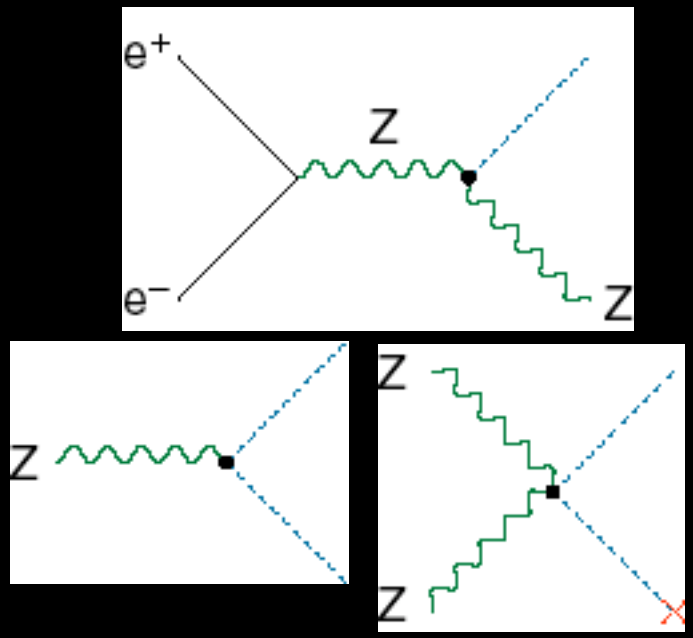
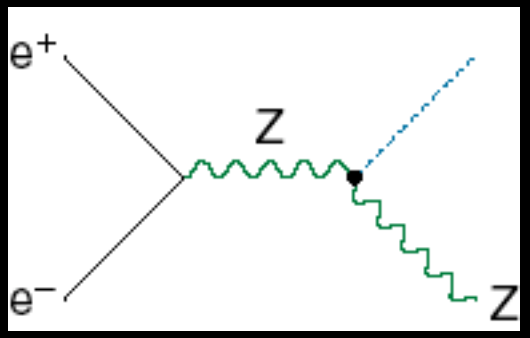
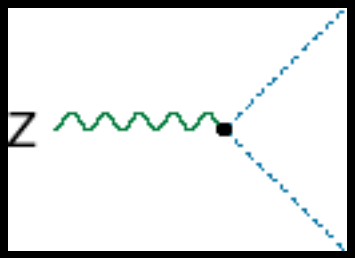


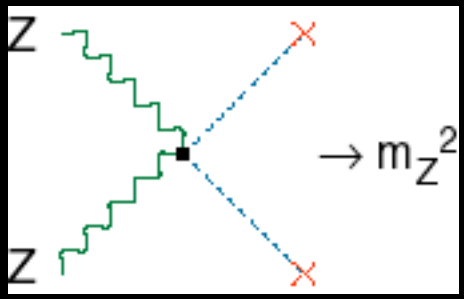
Prove it is condensed

- *ZH* final state
- Prove the *ZZH* vertex
- We know *Z*:gauge boson, *H*: scalar boson
  ⇒ only two vertices
- Need a condensate to get *ZZH* vertex

⇒ proves it is *condensed* in Universe







HM, LBNL-38891

Beyond Higgs Condensate

Post-Higgs Problem

- We see "what" is condensed
- But we still don't know "why"
- Two problems:
  - Why anything is condensed at all
  - Why is the scale of condensation ~TeV<<M_{Pl}
- Explanation most likely to be at ~TeV scale because this is the relevant energy scale

Three Directions

- History repeats itself
  - Crisis with electron solved by anti-matter
  - Double #particles again supersymmetry
- Learn from Cooper pairs
  - Cooper pairs composite made of two electrons
  - Higgs boson may be fermion-pair composite

    technicolor
- Physics as we know it *ends* at TeV
  - Ultimate scale of physics: quantum gravity
  - May have quantum gravity at TeV

    hidden dimensions (0.01cm to 10^{-17} cm)


NOT YET THOUGHT OF
TC-TC
composite Higgs
hypercolor
supercolor
technicolor
extended TC
pseudo NGB
NOT YET THOUGHT OF
NOT YET THOUGHT OF
6th gen
5th gen
4th gen
S.T.U
vector-like family
lepto quark
sterile ν
heavy Majorana ν
fractionally charged
milli-charged
mono-pole
X Y
shadow matter
mirror symmetry
NOT YET THOUGHT OF
triplet Higgs
double charged Higgs
Type I
Type II
general 2HDSM
spontaneous CP
superweak
milli-weak
Weinberg's 3HD
Majoron
axion
familon
NGB
quintessence
K-essence
composite W, Z
contact int.
Extra dim
N=2
N=4
N=8
IIB
IIA
F
I

Task

- Find physics responsible for condensation
- We can eliminate many possibilities at LHC
- But new interpretations necessarily emerge
- Race will be on:
  - theorists coming up with new interpretations
  - experimentalists excluding new interpretations
    - A *loooong* process of elimination
- Crucial information is in *details*
- Elucidate what that physics is
  - Reconstruct the Lagrangian from measurements

Absolute confidence is crucial for a major discovery

- As an example, supersymmetry
- "New York Times" level confidence

  "*The other half of the world discovered*"

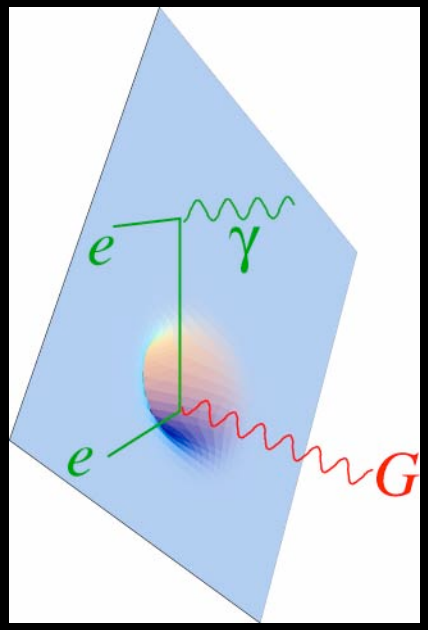
  still a long way to
- "Halliday-Resnick" level confidence

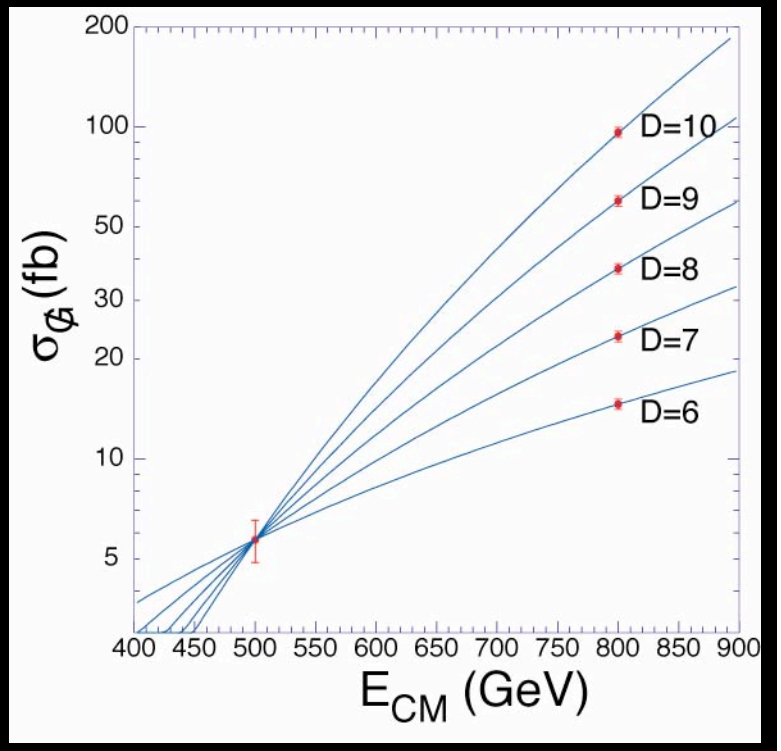
  "*We have learned that all particles we observe have unique partners of different spin and statistics, called superpartners, that make our theory of elementary particles valid to small distances.*"

Hidden Dimensions

Hidden dimensions

- Can emit graviton into the bulk
- Events with apparent energy imbalance
- How many extra dimensions are there?

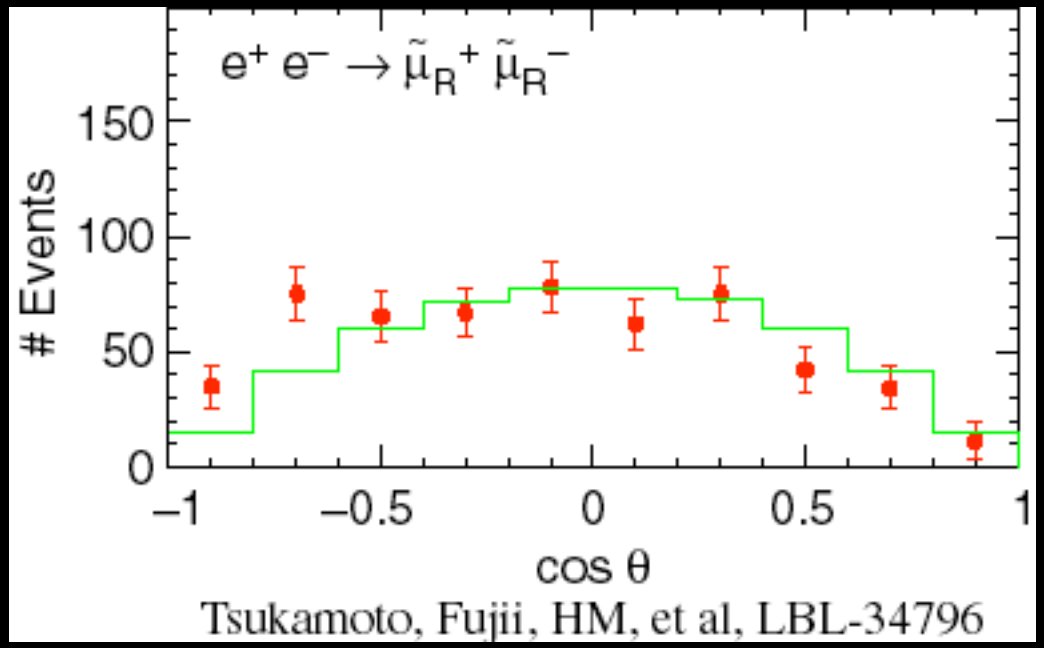




Prove Superpartners have different spin

- Discovery at Tevatron Run II and/or LHC
- Test they are really superpartners
  - Spins differ by 1/2
  - Same SU(3)□SU(2)□U(1) quantum numbers
  - Supersymmetric couplings

Spin 0?

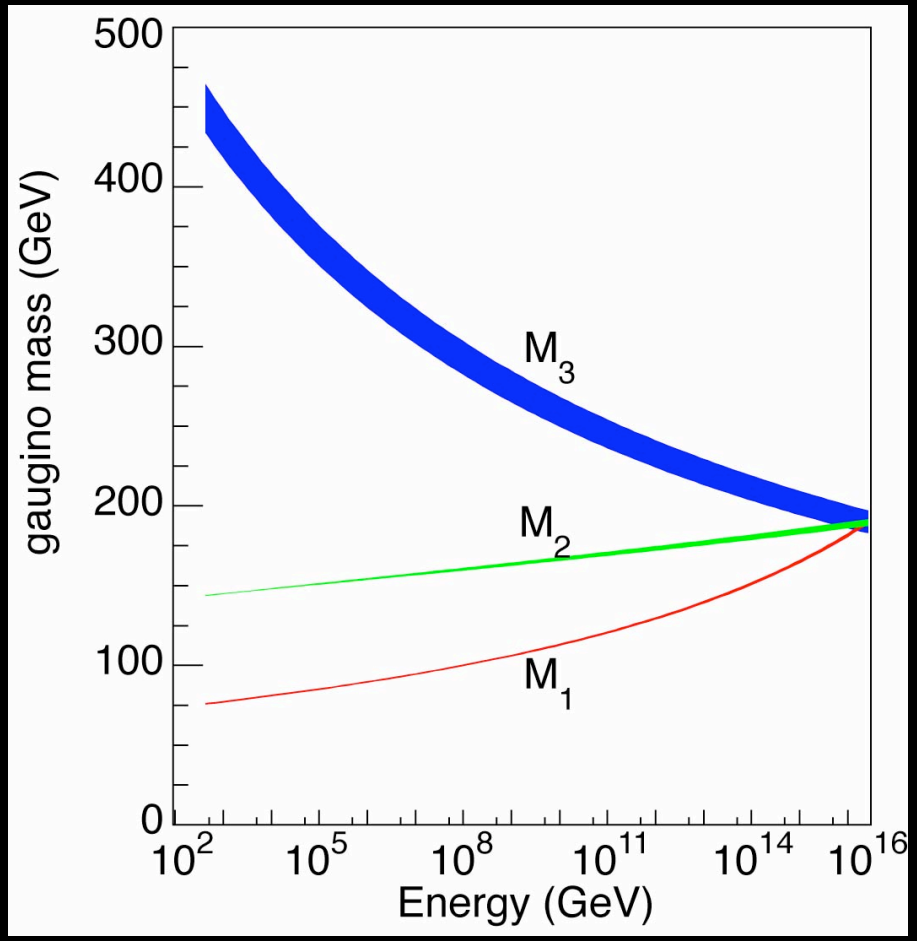


Superpartners as probe

- Most exciting thing about superpartners beyond existence:

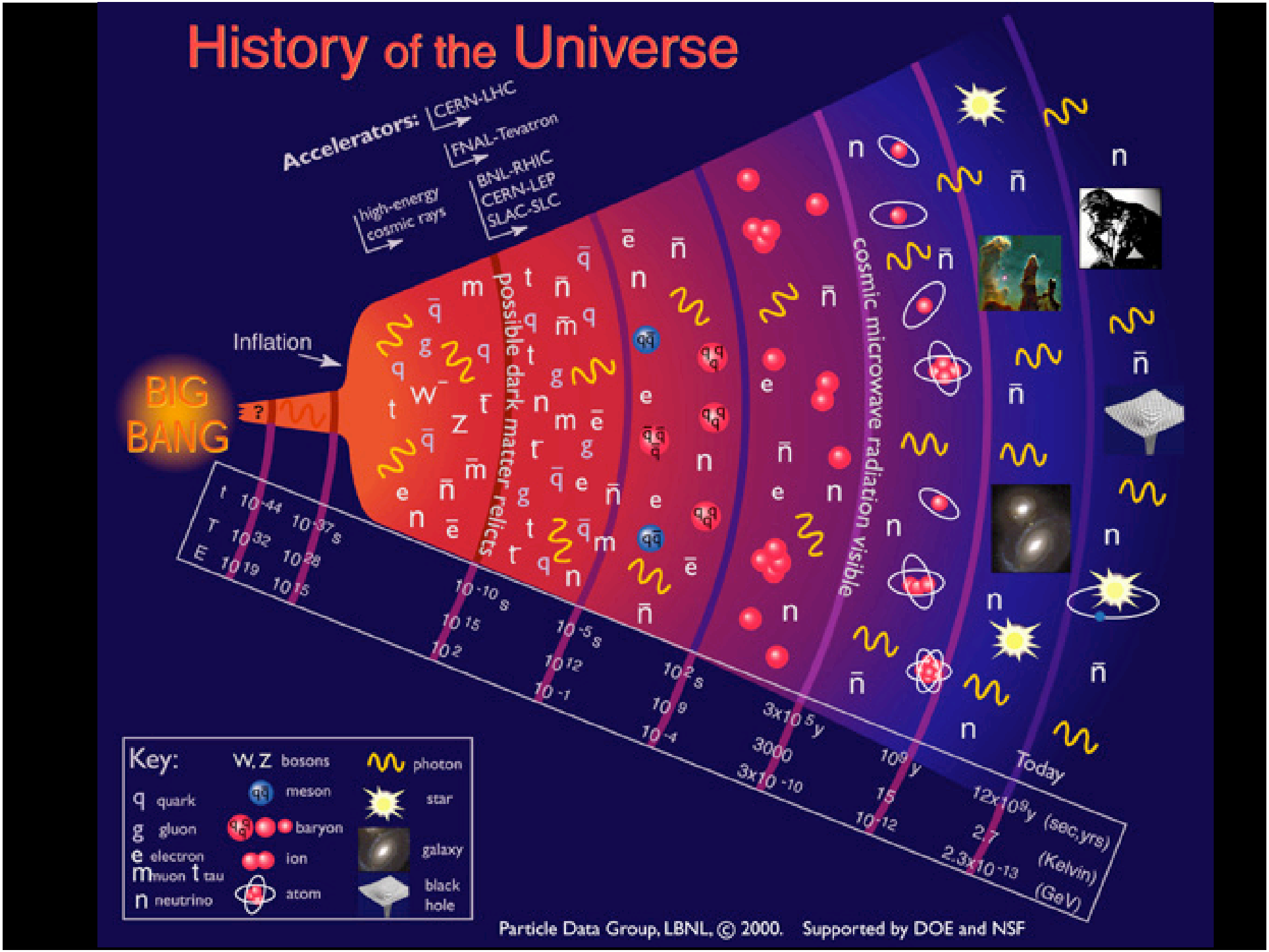
  They carry information of small-distance physics to something we can measure

  "Are forces unified?"



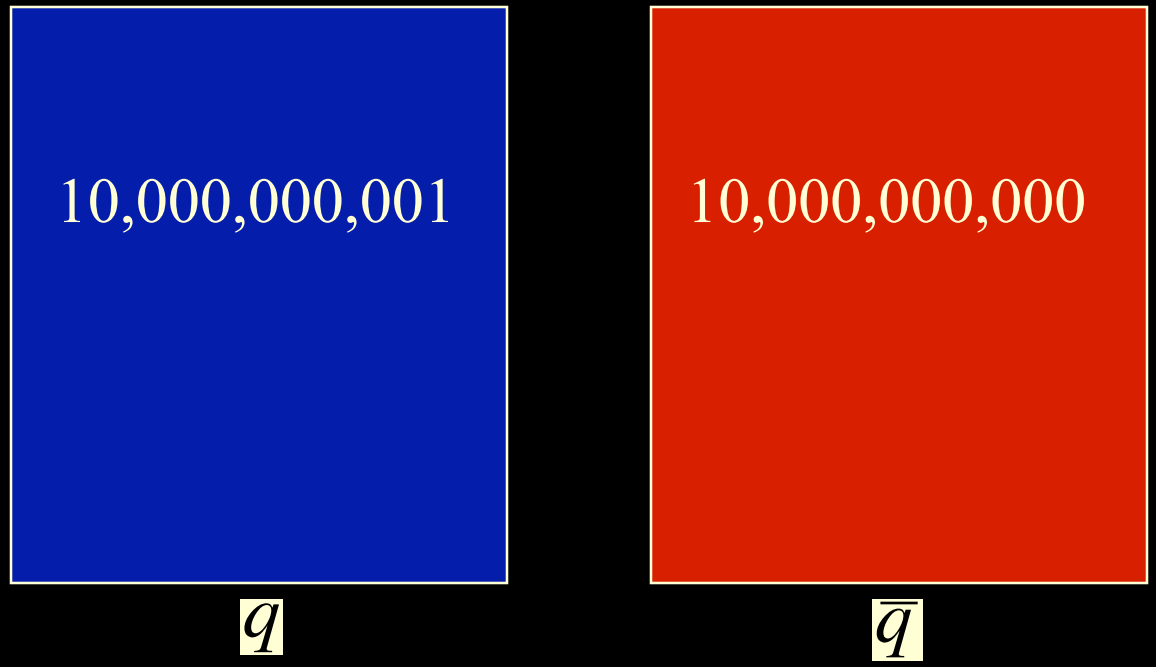
Dark Matter: The Missing Link?

- Dark Matter likely to be TeV-scale electrically neutral weakly interacting particle (*e.g.*, LSP, Lightest KK)
- Accessible at accelerators (LHC & LC)
- Precision measurement at LC of its mass, couplings in order to calculate its cosmic abundance
- If it agrees with cosmological observations, we understand Universe back to 10^{-12} sec after the Big Bang


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
Key:
q quark
g gluon
e electron
m muon
t tau
n neutrino
W,Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
(sec,yrs)
(Kelvin)
(GeV)
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Anti-Matter

Baryon Asymmetry Early Universe



Baryon Asymmetry Current Universe

$u\mathring{s}$

1

q $\bar{q}$

The Great Annihilation

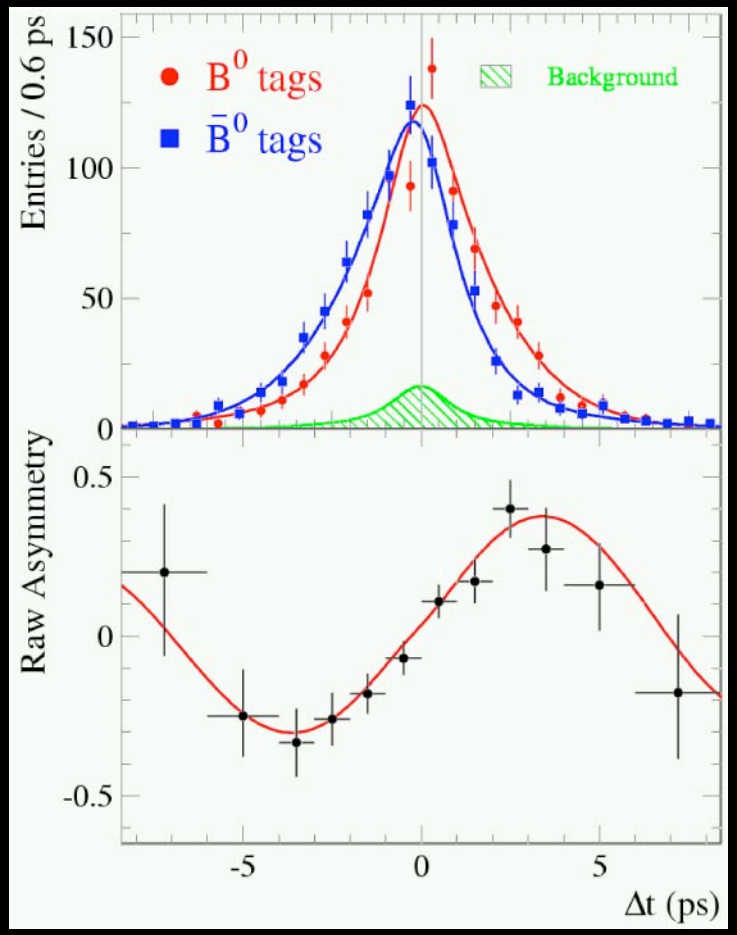
Baryogenesis

- What created this tiny excess matter?
- *Necessary* conditions for baryogenesis (Sakharov):
  - Baryon number non-conservation
  - CP violation
    (subtle difference between matter and anti-matter)
  - Non-equilibrium
    $\Gamma(\Delta B>0) > \Gamma(\Delta B<0)$
- Possible new consequences in
  - Proton decay
  - CP violation

CP Violation

- Is anti-matter the exact mirror of matter?
- 1964 discovery of CP violation in neutral kaon system:

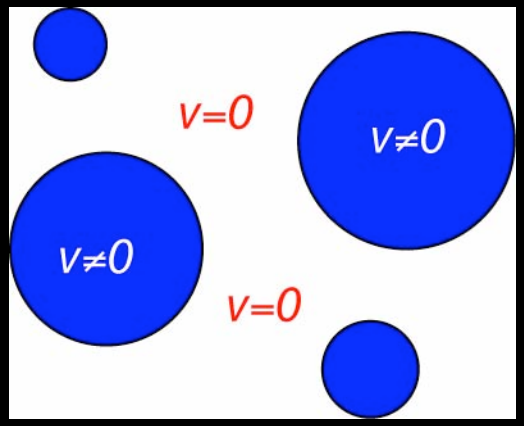
  matter and anti-matter mix but *not* with 50:50 mixture at 0.1%
- But only one system, hard to tell what is going on.
- 2001 Found kaon and anti-kaon decay differently at 10^{-6} level
- 2002 Found CP violation also in *B*-meson system
- But no CP violation observed so far is large enough to explain the absence of anti-matter

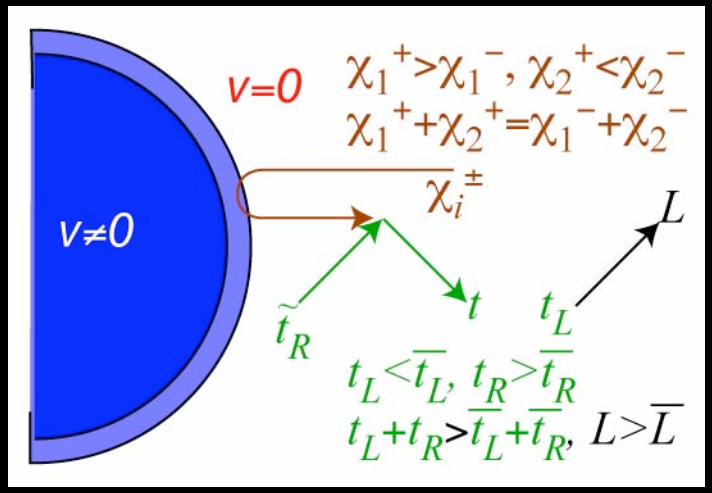


Electroweak Baryogenesis

- Supersymmetric Standard Model
- First order phase transition when Higgs condenses
- Bubbles form and expand, eventually fill up Universe
- Particles get reflected by expanding bubble walls
- Different reflection probability for matter and anti-matter
- Excess matter in the end
- Consequences on properties of *B*-mesons
- Testable at Tevatron and future improvements in *B* physics

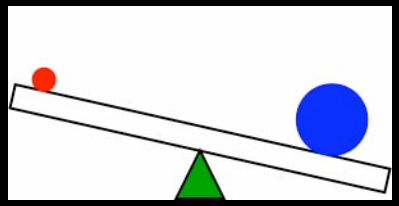
(HM, Pierce)





Leptogenesis

- Why are neutrinos so light?
- Most ideas use a heavy particle to suppress the neutrino mass $m_{\square} \sim m_q^2/M$ (seesaw mechanism)



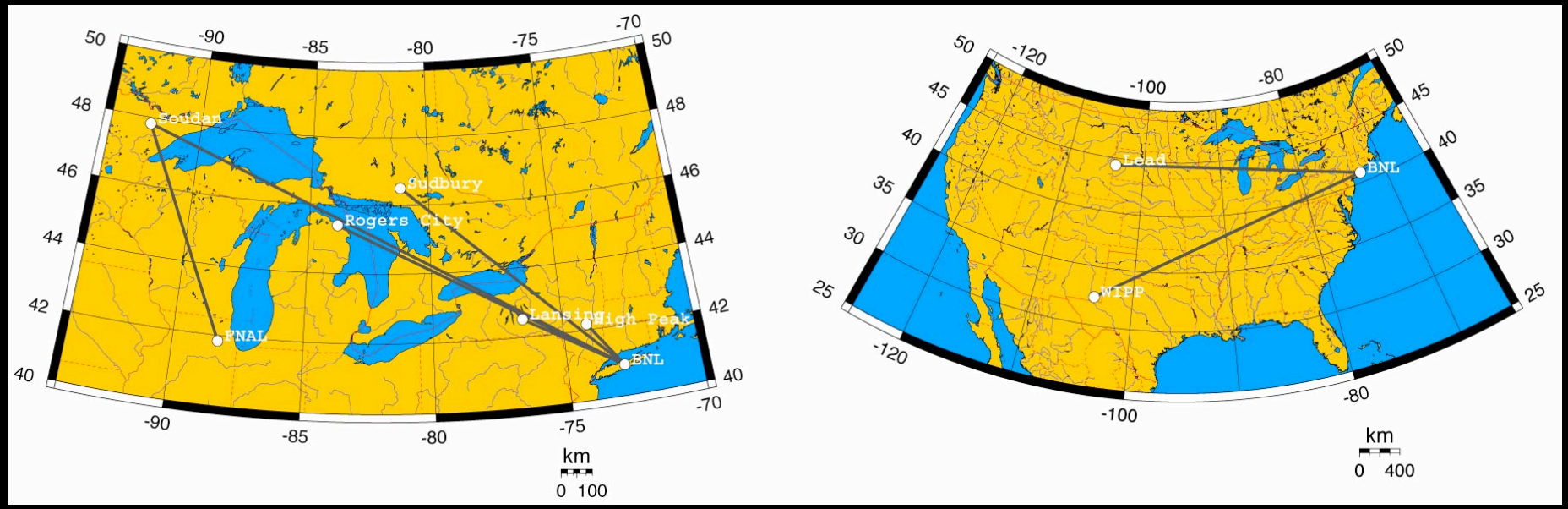
- The decay of the heavy particle may create imbalance between matter and anti-matter if there is CP violation in neutrinos

- CP-violation may be observed in neutrino oscillation

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

- Plans to shoot neutrino beams over thousands of kilometers to see this

Very Long Baseline Experiment

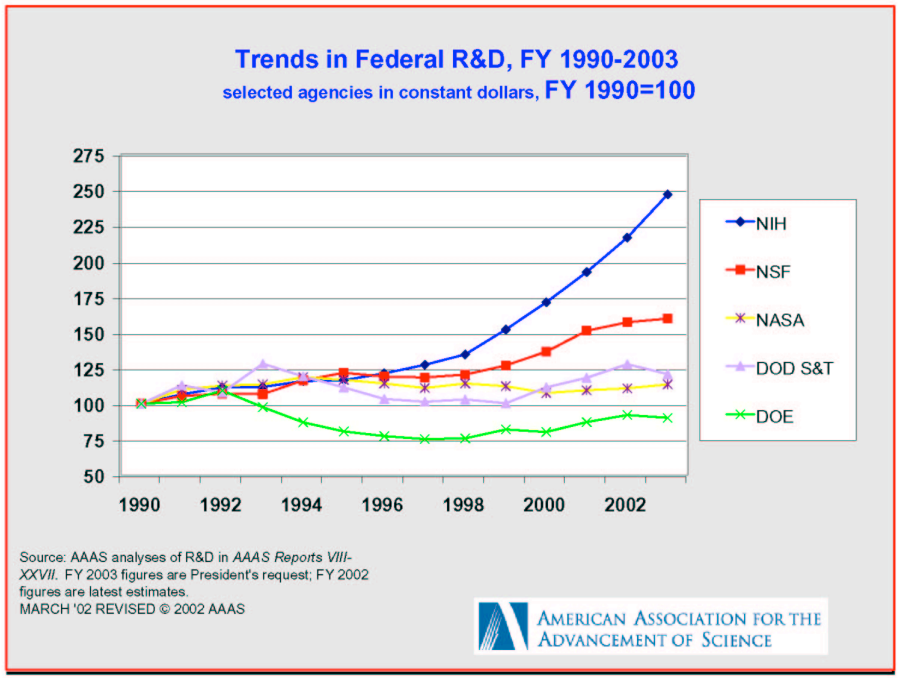


It's of course completely safe!

But aren't these all expensive?

US Budget in Basic Research

- US budget in physical sciences declined over many years
- Need boost to the entire physical sciences

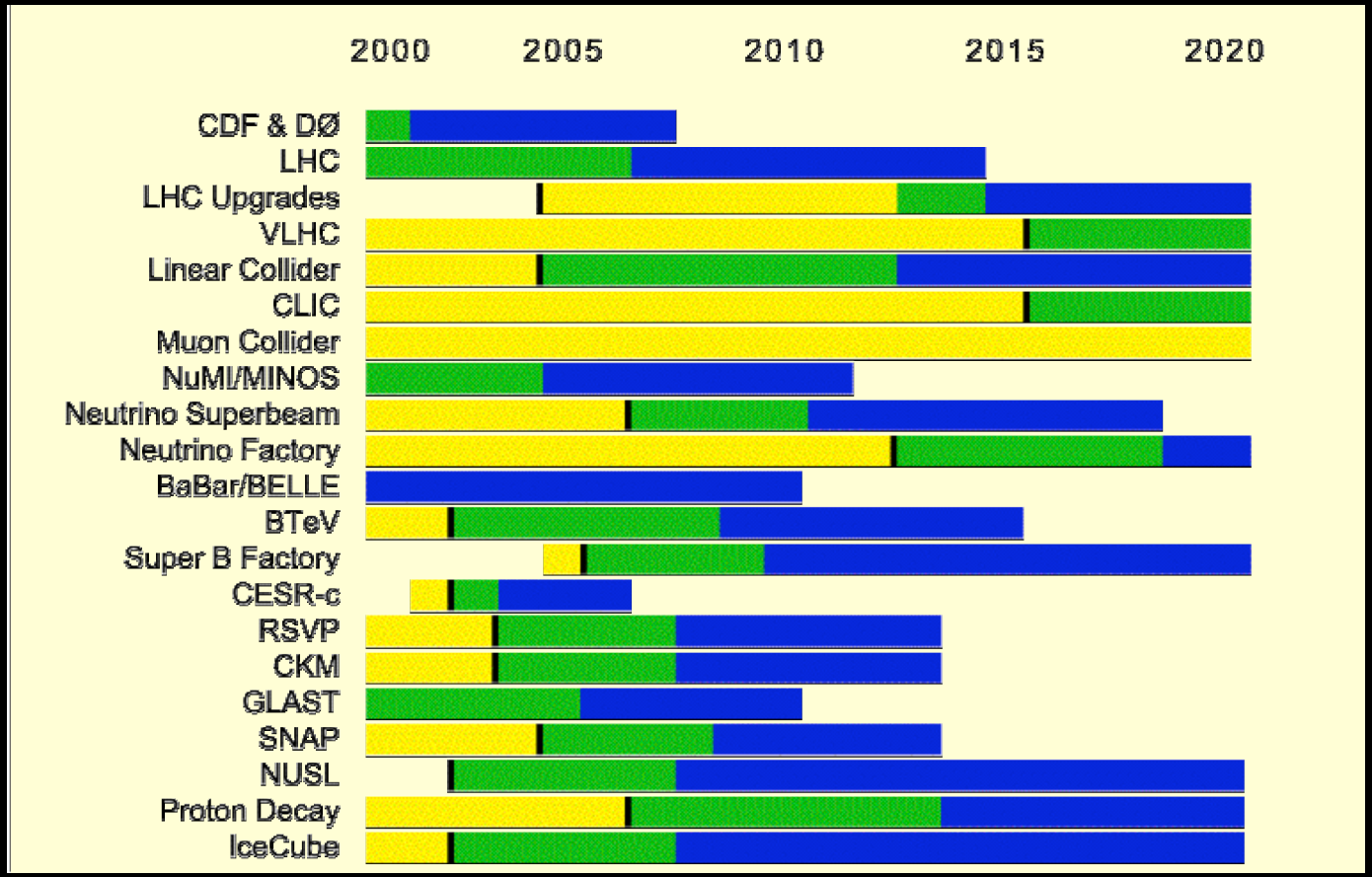


Time for True Internationalism

- The goal in particle physics common throughout the globe
- We have been sharing facilities all along
- Putting together world-wide resources will move us ahead
- Possible thanks to world-wide agreement:

  ECFA, ACFA, HEPAP, all put a LC as the next major step beyond the LHC
- We can realize this ambitious program including LC in the US with ~30% boost in particle physics budget if foreign contribution of ~1/3

Many Interesting Proposals…



Choices need to be made.

Setting Priorities

- HEPAP subpanel
  - Largest projects, decision every ~5years
- P5 (Particle Physics Projects Prioritization Panel)
  - Medium-size projects, on-going
- Laboratory PAC (Physics Advisory Committee)
  - Projects at a given laboratory
- Sometimes tough decision is necessary to keep projects in line with funding with sound scientific priorities

Conclusion

- Many cosmic questions accessible
  - Dark Matter, Dark Energy, Higgs Condensate, Anti-Matter
- The current program well positioned
  - Tevatron, *B*-factory, neutrino experiments, etc
- Physics at TeV scale likely to be rich
- LHC the next major breakthrough at TeV-scale
- To fully understand it, we will likely need *a lot* of detailed information
- LC will study new particles one by one
  reconstruct the underlying Lagrangian
- Then we can move on further with an absolute confidence

I feel lucky to be in this age.