

*The Next Twenty Years
in Particle Physics*



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HEPAP

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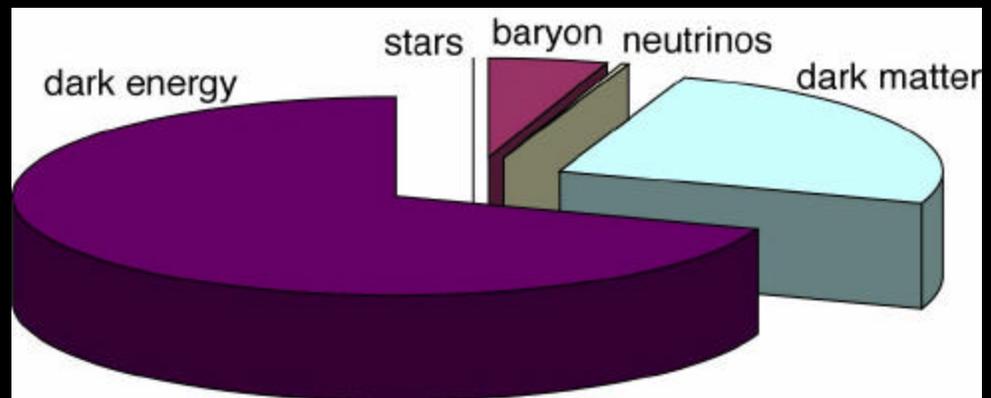
*We are interested in
things we don't see*



Energy budget of Universe



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



The Cosmic Questions



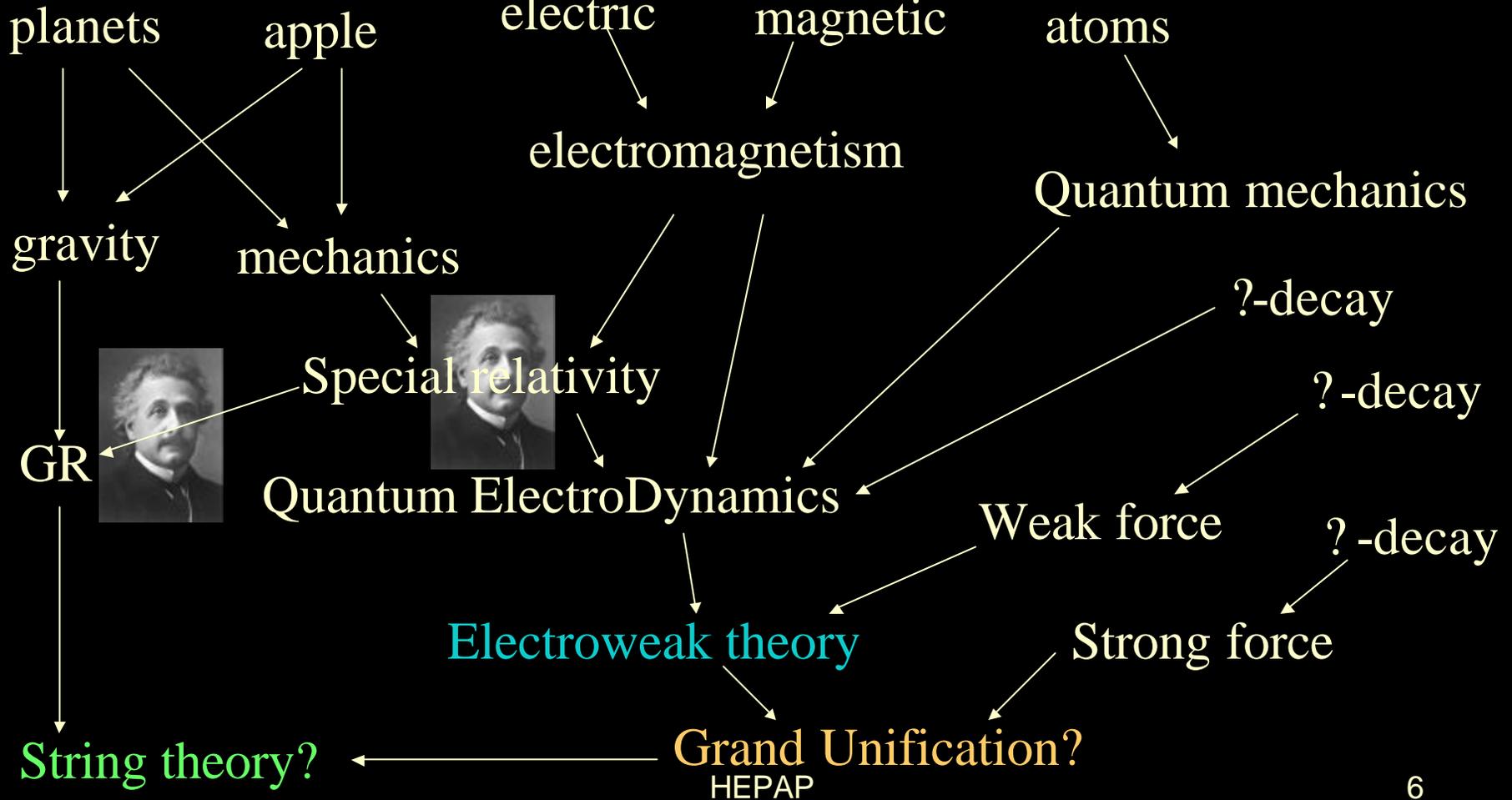
- What is Dark Matter?
- What is Dark Energy?
- How much is Neutrino component?
- Are we really swimming in a Condensate?
- What is the condensate and why is it there?
- Where did Anti-Matter go?

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)

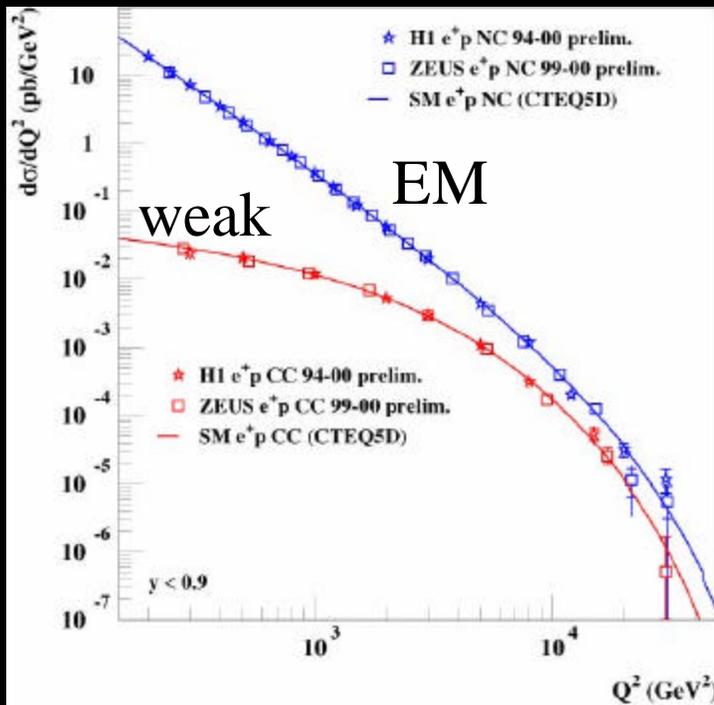


History of Unification



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

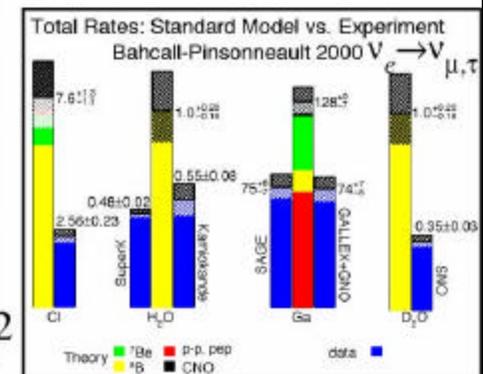
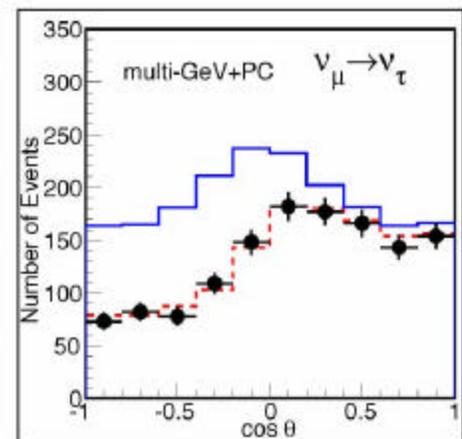
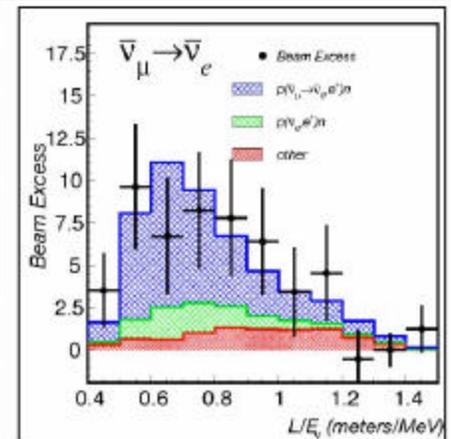
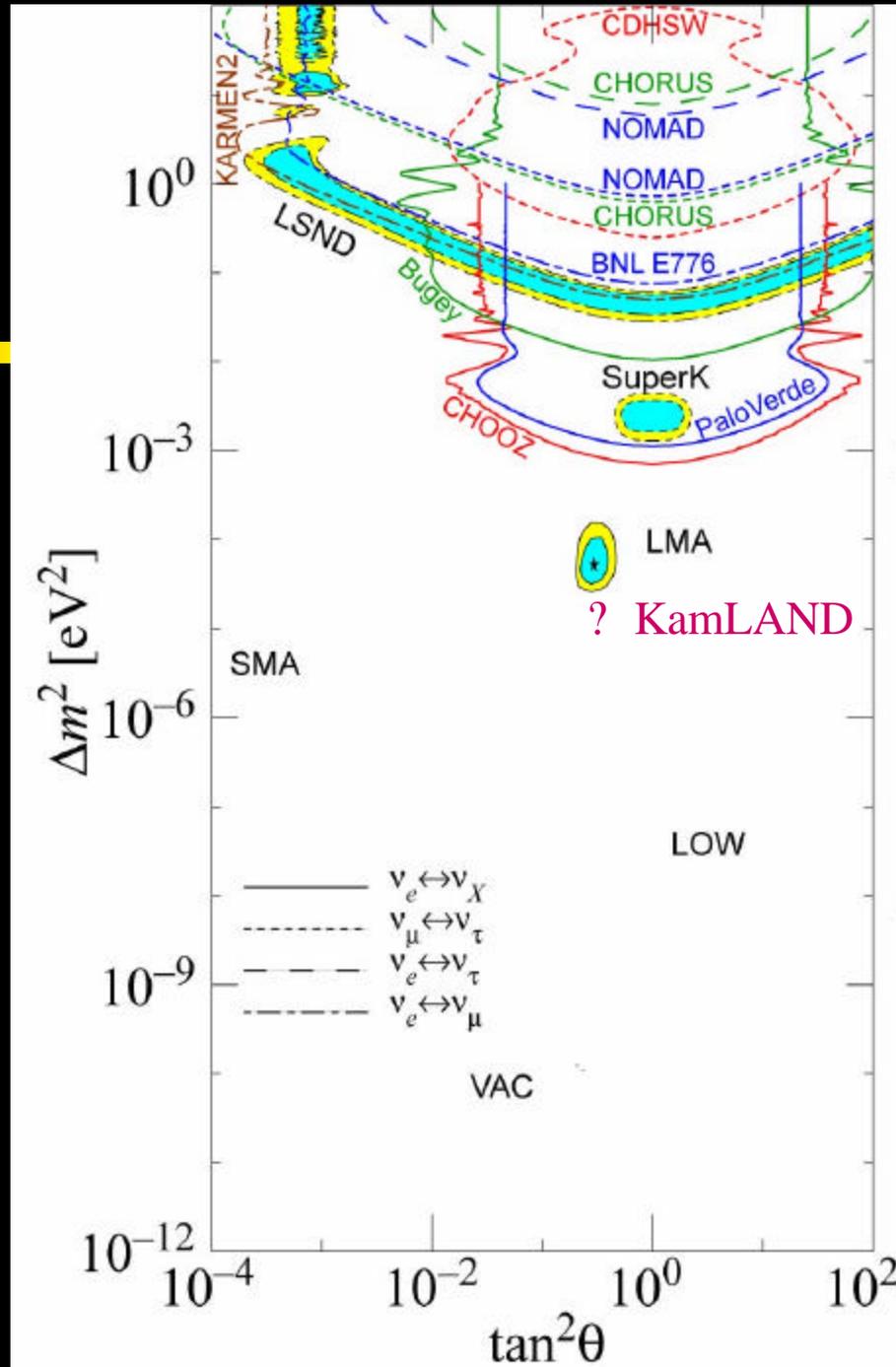
from backstage to center stage

- 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



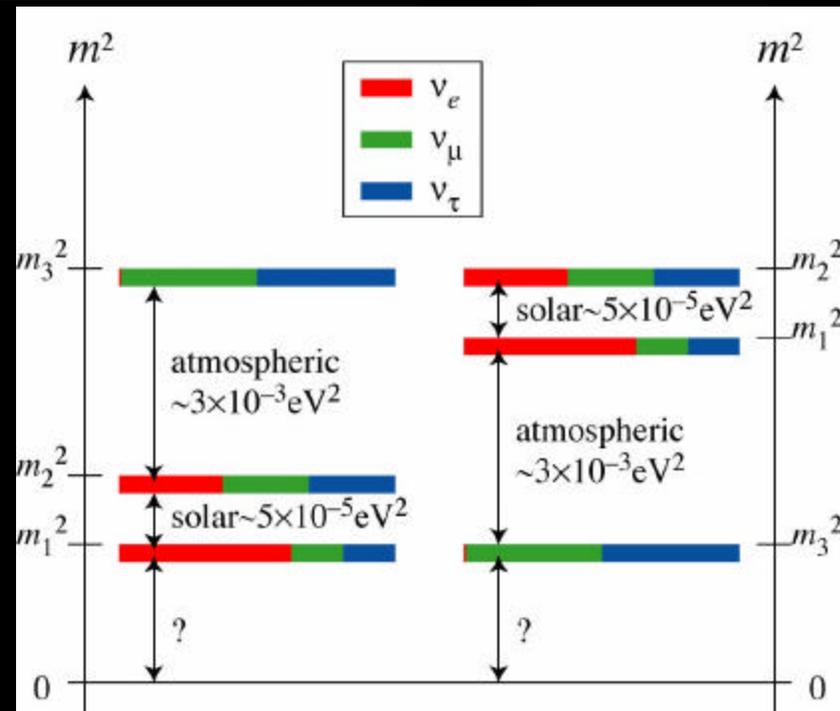
March 2002

April 2002
with SNO



Raised More Questions

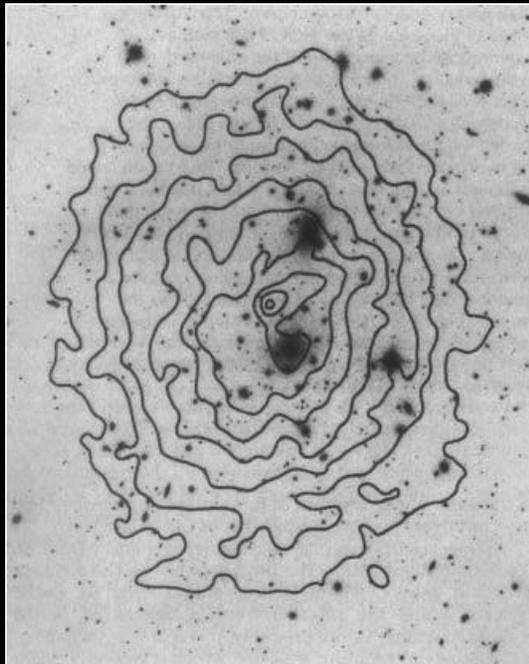
- Why do neutrinos have mass at all?
- Why so small?
- We have seen mass *differences*. What are the masses?
 $? \quad \gamma \sim m_{\gamma} / 15 \text{eV}$
- Do we need a fourth neutrino?
- Are neutrinos and anti-neutrinos the same?



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

Evidence for Dark Matter

- Galaxy and cluster of galaxies are held together by mass far bigger than all stars combined



Giacconi
2002 Nobel
Father of
X-ray astronomy

- It is not dim small stars (e.g., MACHOs)
- WIMPs (Weakly Interacting Massive Particle) strongly favored
- Stable heavy particle produced in early Universe, left-over from near-complete annihilation

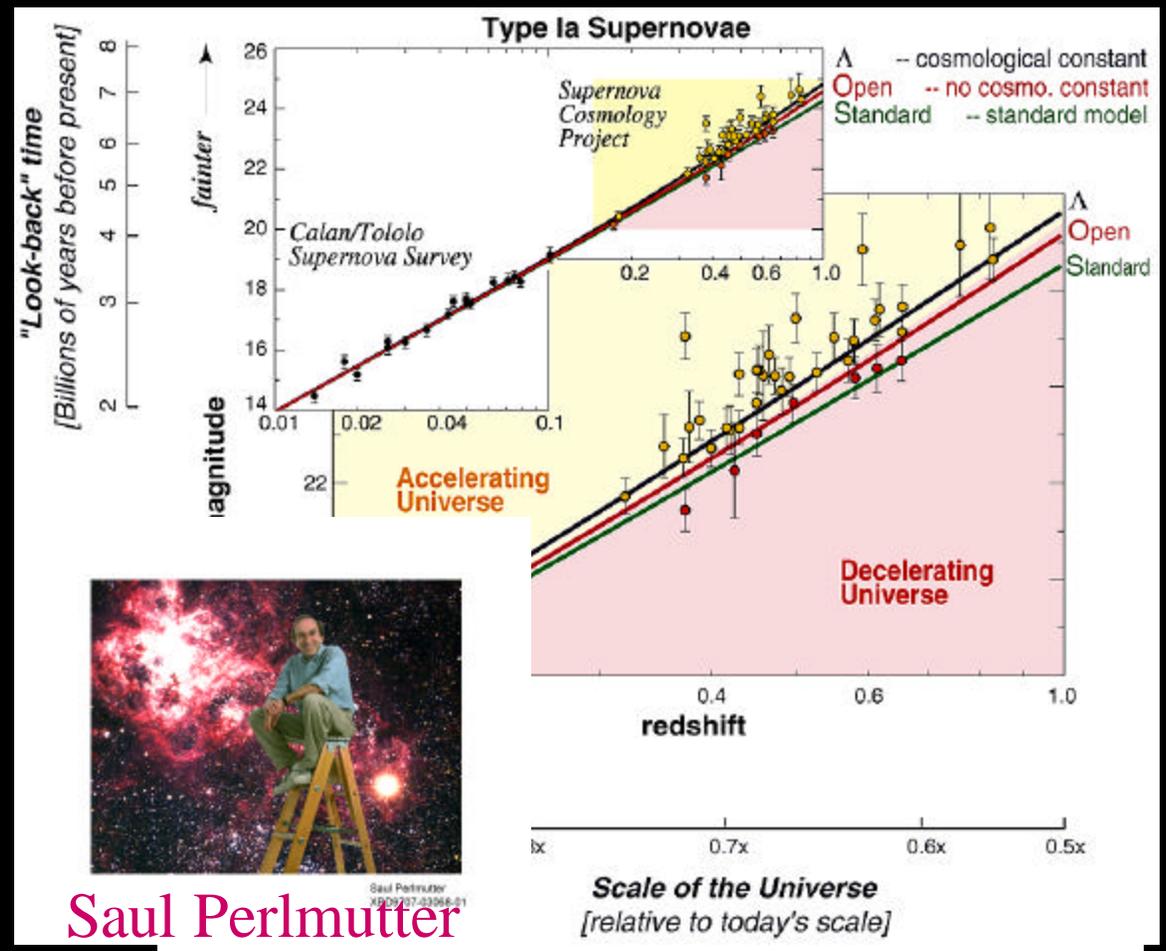
$$M \sim \frac{0.756(n+1)x_f^{n+1}}{g^{1/2} \Omega_{ann} M_{Pl}^3} \frac{3s_0}{8H_0^2} \frac{\Omega_{ann}^2 / (TeV)^2}{\Omega_{ann}}$$

scale

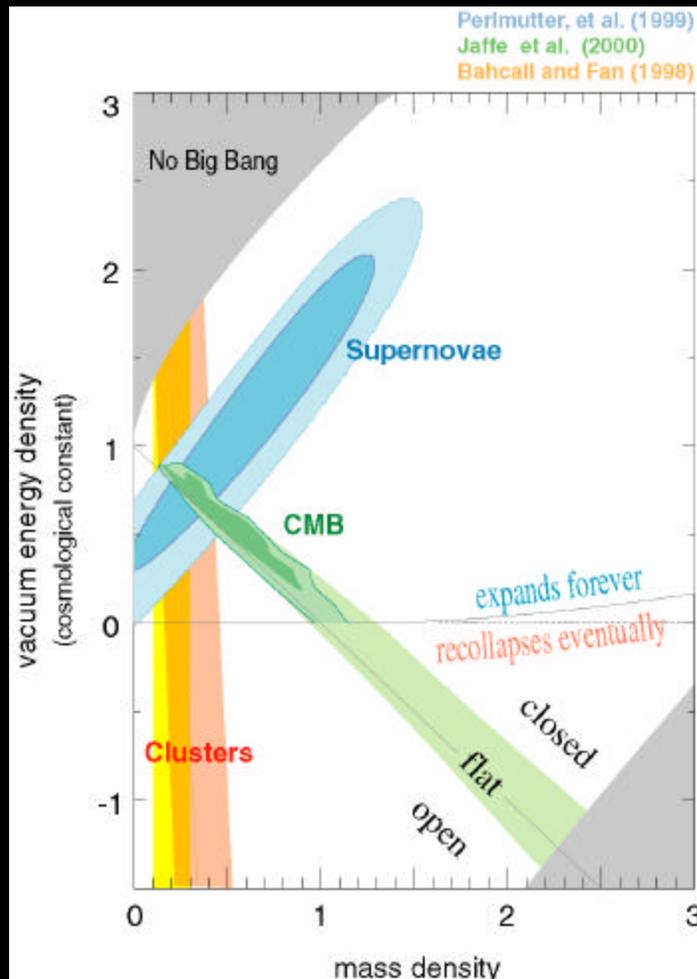
Type-IA Supernovae

- Type-IA Supernovae “standard candles”
 - Apparent brightness ? how far (“time”)
 - Know redshift ? expansion since then
- Expansion of Universe is *accelerating*

2002 Lawrence Award



Accelerating Universe



- Einstein's equation:

$$\frac{\ddot{R}}{R} = -\frac{8\pi}{3} G_N \rho$$

- 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”

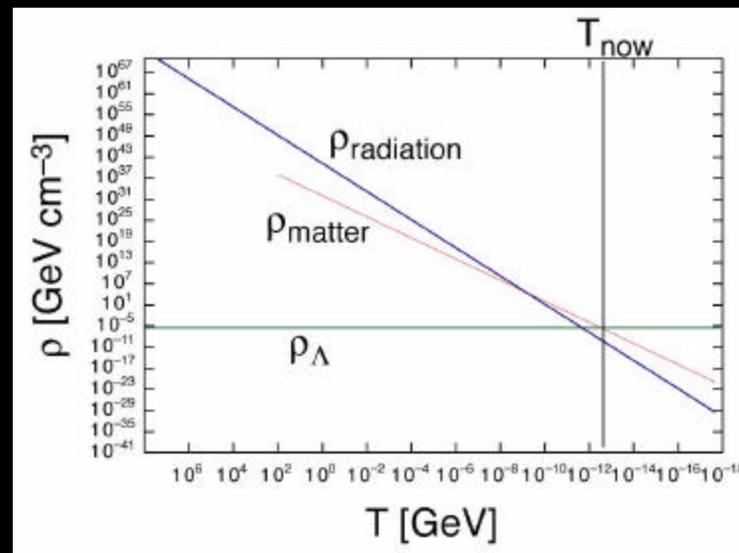
Embarrassment with Dark Energy

- A naive estimate of the cosmological constant in Quantum Field Theory:
 $\rho_{\Lambda} \sim M_{\text{Pl}}^4 = G_N^{-2} \sim 10^{120}$ 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???**

- “Why Now” problem
- If there is a deep reason for $\rho_{\Lambda} \sim ((\text{TeV})^2/M_{\text{Pl}})^4$, coincidence natural



Cosmology and Particle Physics meet at TeV scale



- Dark Matter

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

- Fermi (Higgs) scale

$$v \sim 250 \text{ GeV}$$

- Dark Energy

$$\Omega_\Lambda \sim (2 \text{ meV})^4 \text{ vs } (TeV)^2 / M_{Pl} \sim 0.5 \text{ meV}$$

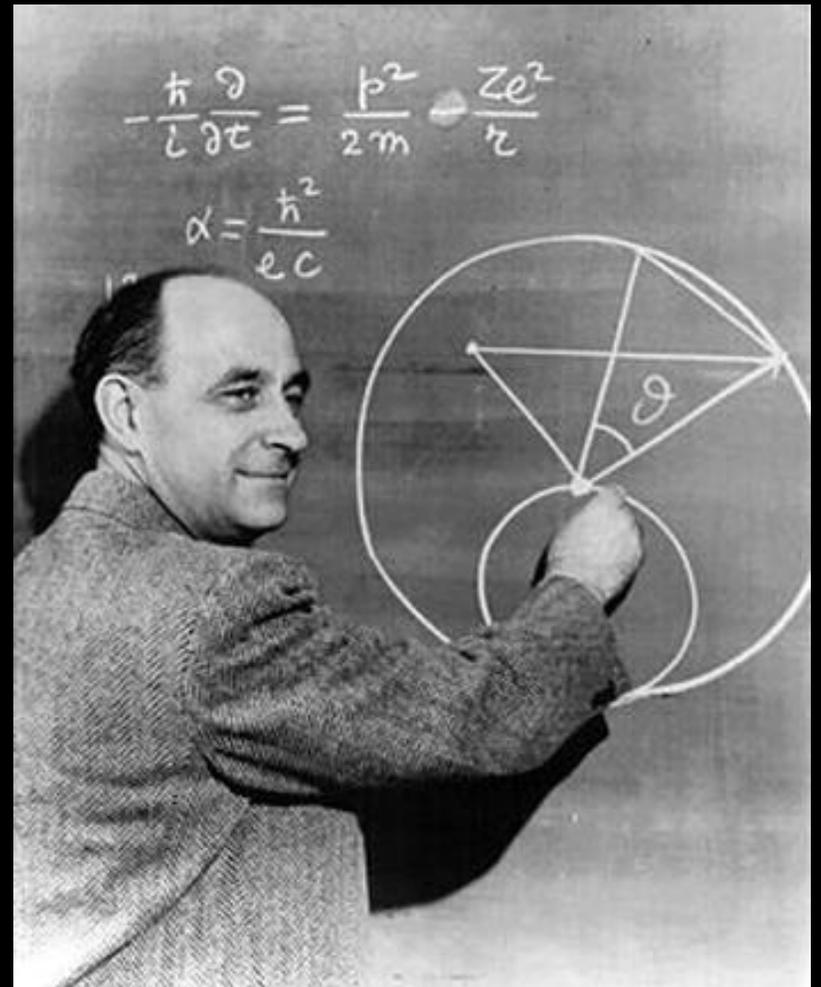
- Neutrino

$$(\Delta m_{LMA}^2)^{1/2} \sim 7 \text{ meV vs } (TeV)^2 / M_{Pl} \sim 0.5 \text{ meV}$$

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: $\sim\text{TeV}$
- **We are finally getting there!**

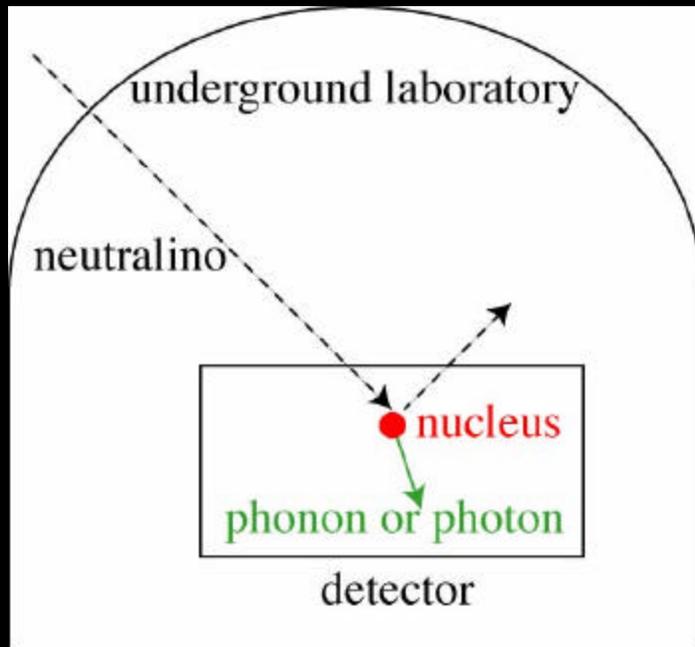


Dark Side of Universe

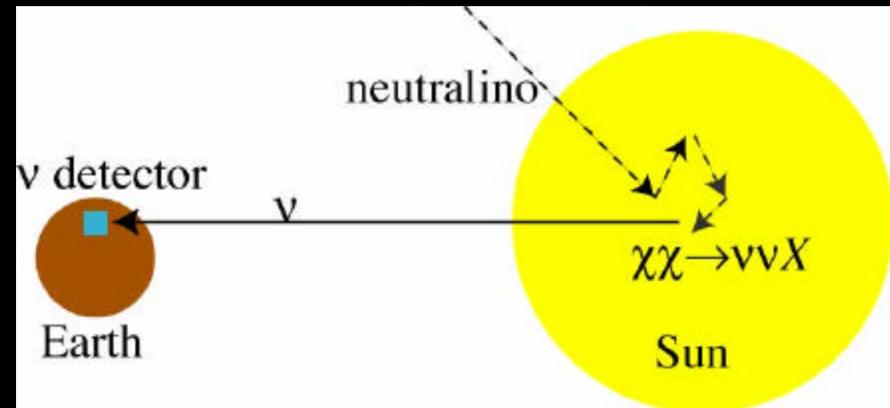


Detection of Dark Matter

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



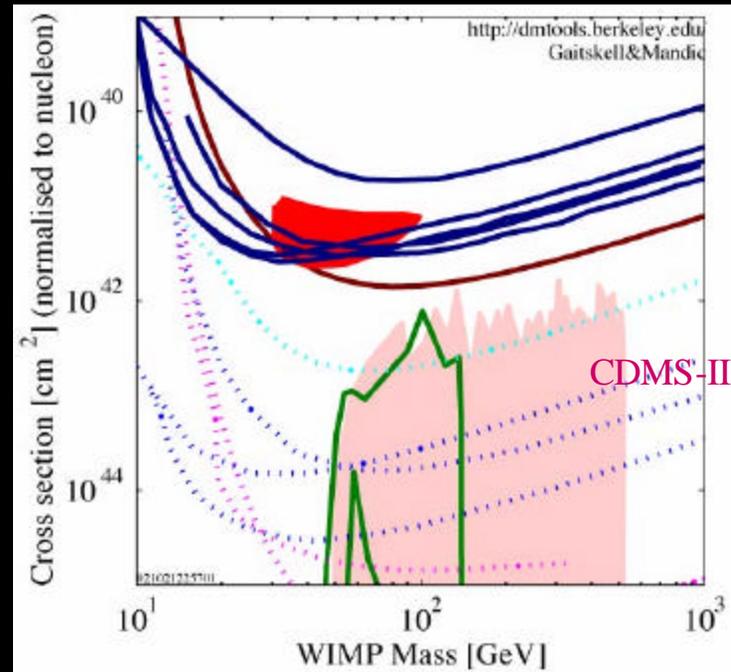
- Indirect detection
- SuperK, AMANDA, ICECUBE, Antares, etc



complementary techniques are getting into the interesting region of parameter space

Particle Dark Matter

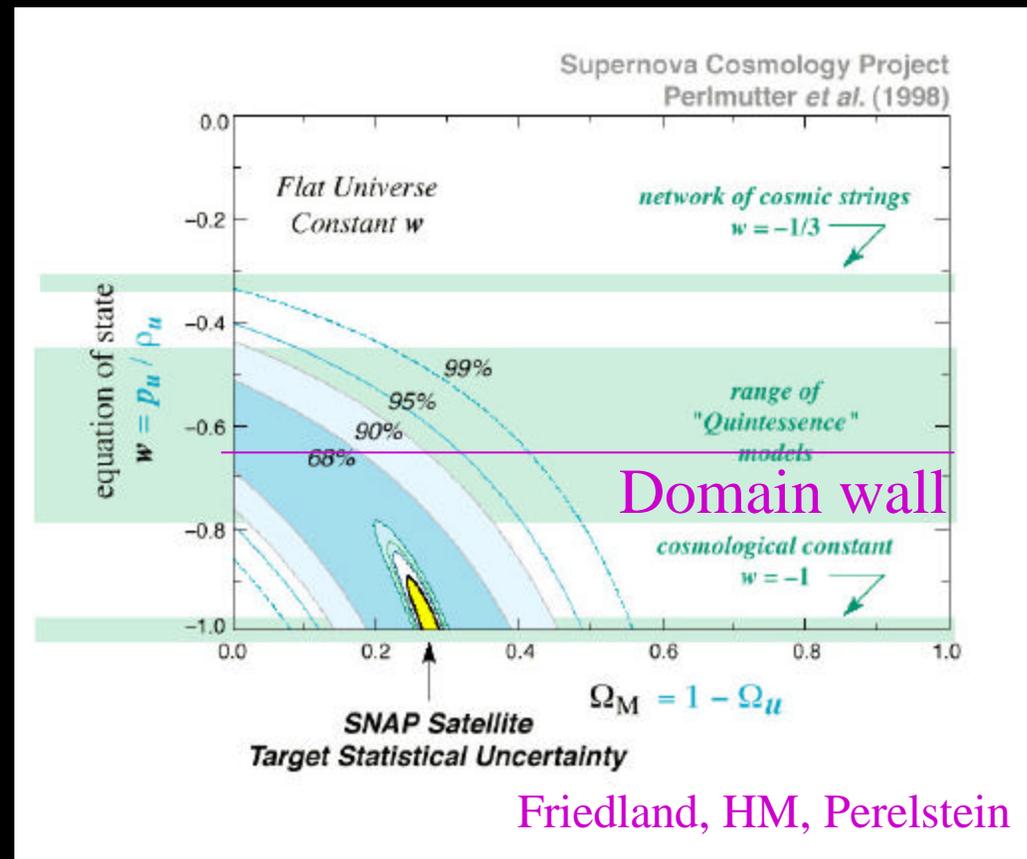
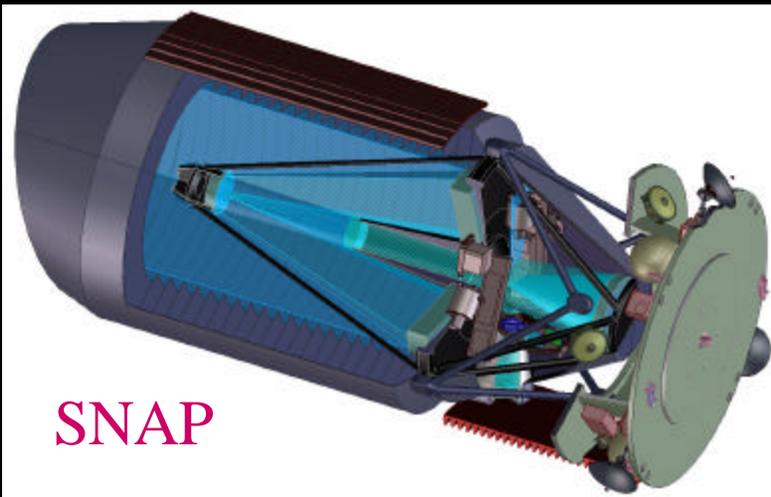
- Stable, TeV-scale particle, electrically neutral, only weakly interacting
- No such candidate in the Standard Model
- Lightest Supersymmetric Particle (LSP): superpartner of a gauge boson in most models
- LSP a perfect candidate for WIMP



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



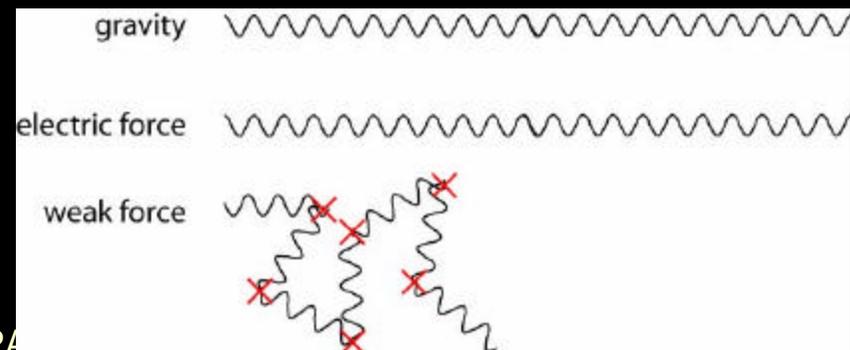
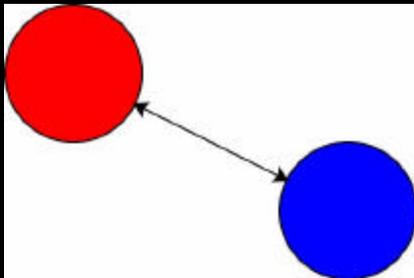
Condensate in Universe



Mystery of the “weak force”

Something is stuffed in Universe

- 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!]
- 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!

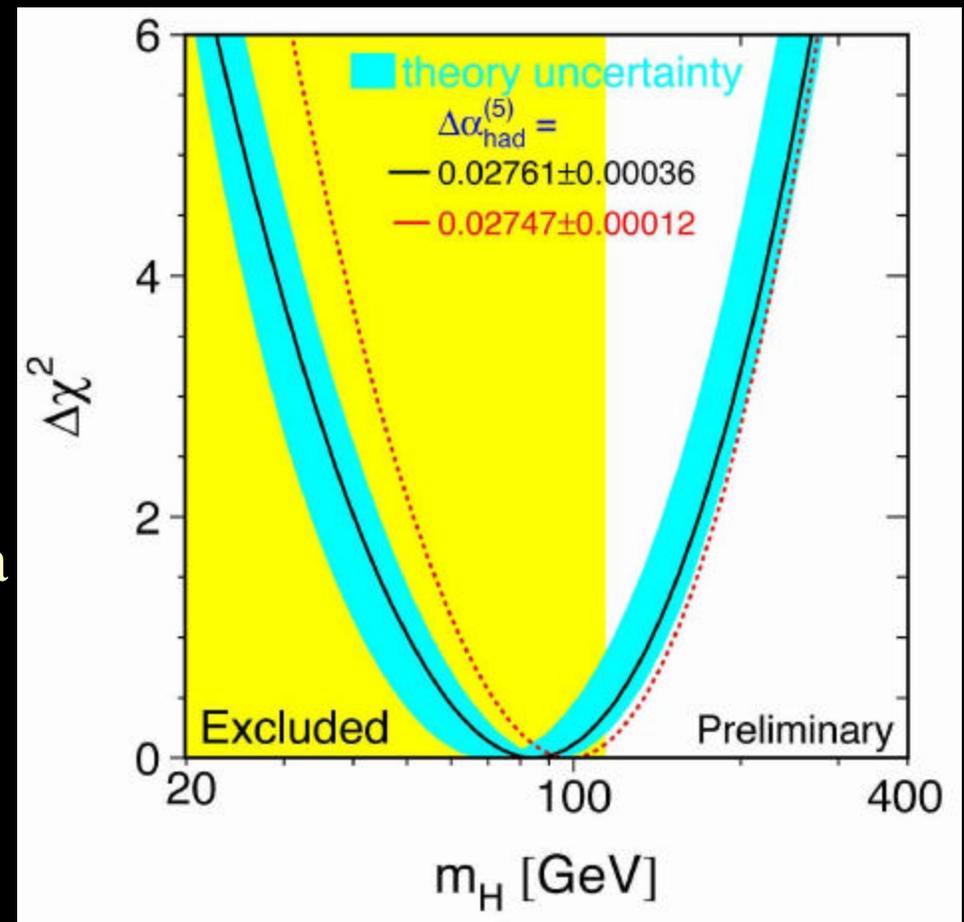
Imagine a physicist living in a superconductor

- She finally figured:
 - magnetic field must be long-ranged
 - there must be a mysterious charge-two condensate in her “Universe”
 - Condensate is the “mother of masses”
 - 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”

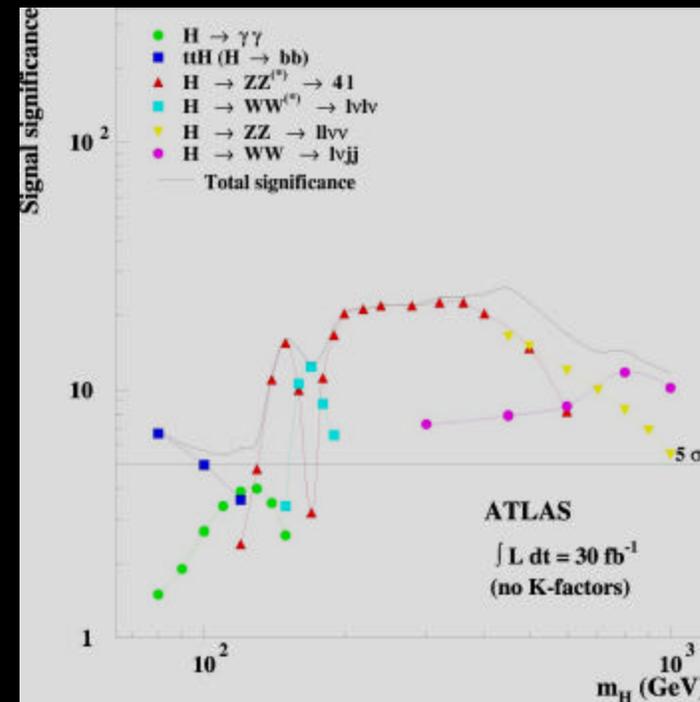
- Higgs boson
= gap excitation
- Current data combined with the Standard Model theory predict
 $m_H < 196 \text{ GeV}$ (95% CL)
- Tevatron at Fermilab has a chance to discover or exclude the SM Higgs boson by 2008



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

- proton-proton collider
14TeV energy
- Under construction at
CERN, Geneva, mostly
European
- Contributions from US,
Japan, Canada
- Turn on in ~2007
- LHC would discover
Standard Model Higgs
boson of any mass within
3 years!

- Measure mass, some ratio
of couplings



Questions to be answered

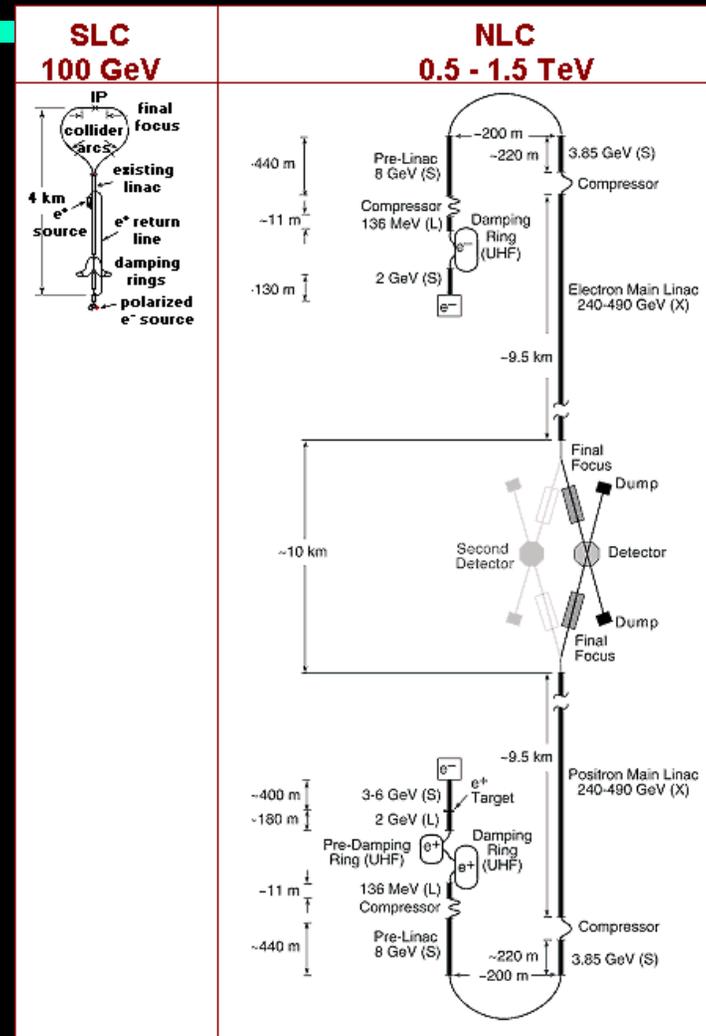


- Is the particle discovered really *the* Higgs boson?
 - Is it really responsible for particle masses?
 - Does this have the right quantum number 0^+ ?
 - Is it condensed in the Universe?
- Prove it is *the* “Mother of Masses”
 - Spin/Parity
 - Couplings
 - *Condensate*
 - Branching Ratios

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 $>10\text{km}$
- Focus beam down to a few nanometers and make them collide

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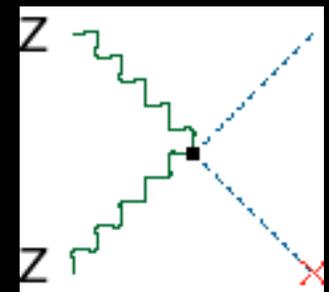
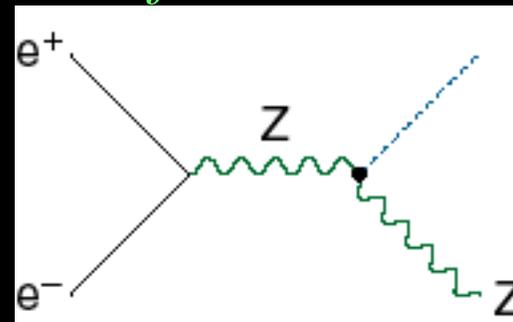
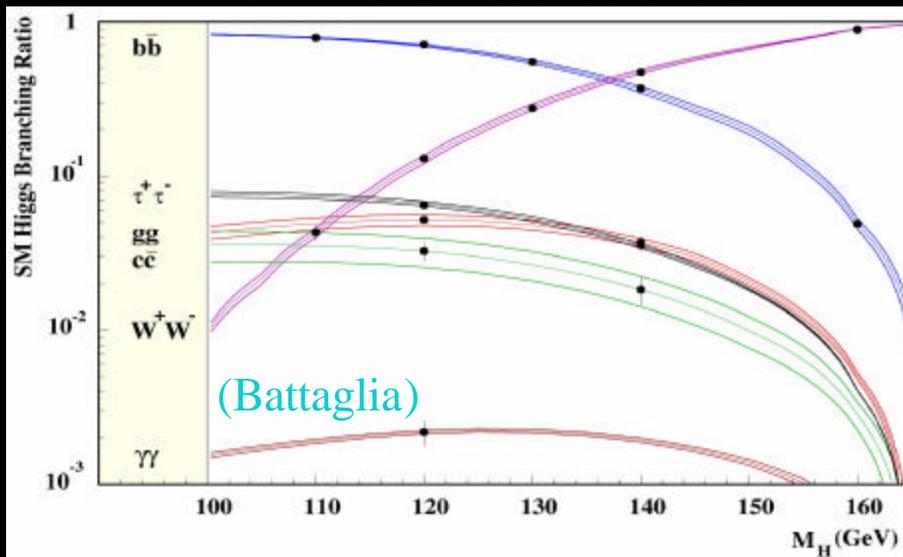
Prove its coupling ? mass

Prove it is condensed in Universe



- Branching Fractions test the relation coupling ? mass
- ? proves that Higgs Boson is the “Mother of Mass”

- Prove the ZZH vertex
- Need a condensate to get ZZH vertex
- ? proves it is *condensed* in Universe
- ? proves *electroweak unification*



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 $\sim \text{TeV} \ll M_{Pl}$
- Explanation most likely to be at $\sim \text{TeV}$ 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)**

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

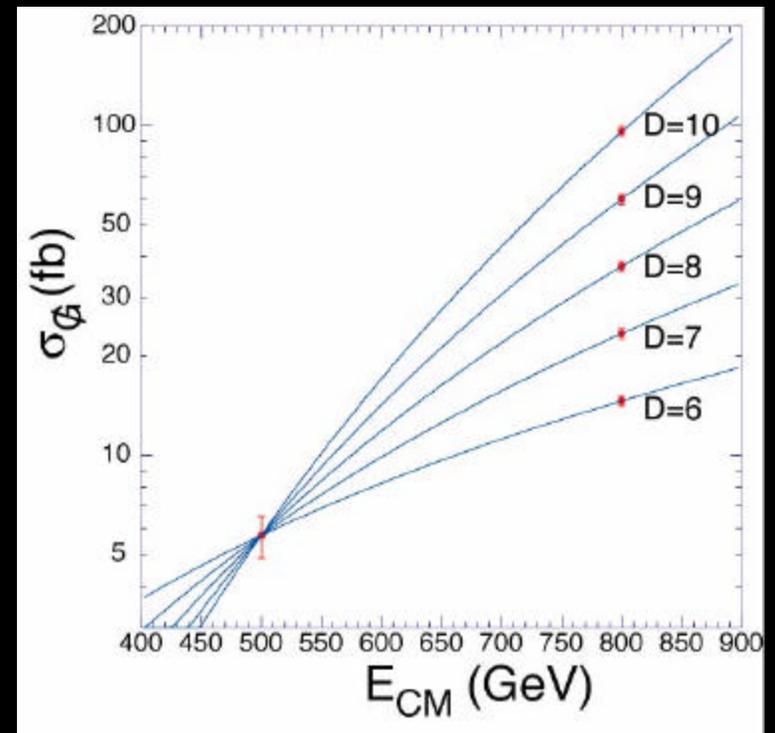
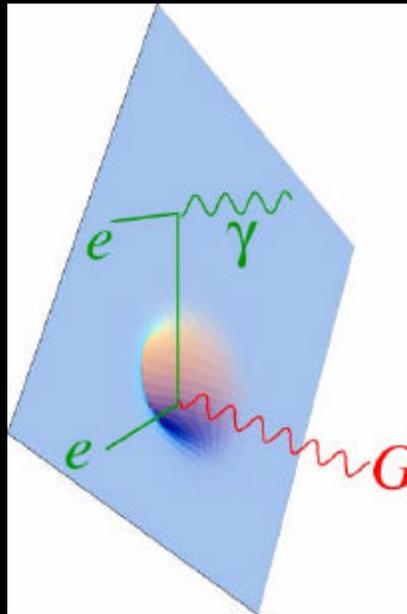


- As an example, supersymmetry
- “New York Times” level confidence
“The other half of the world discovered”
still a long way to
- “Halliday-Resnick” level confidence
“We have learned that all particles we observe have unique partners of different spin and statistics, called superpartners, that make our theory of elementary particles valid to small distances.”

Hidden Dimensions

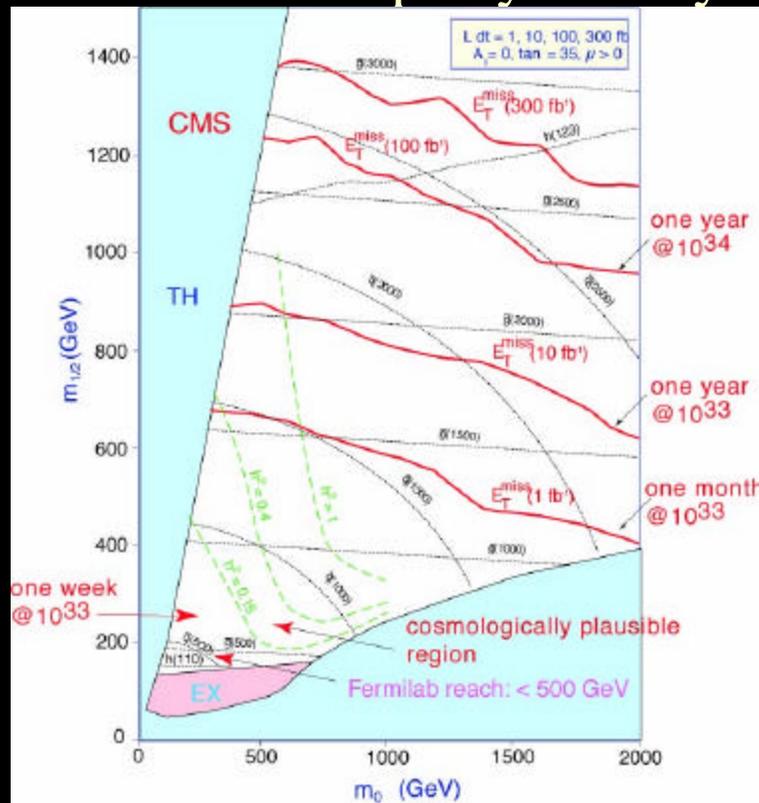
Hidden dimensions

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

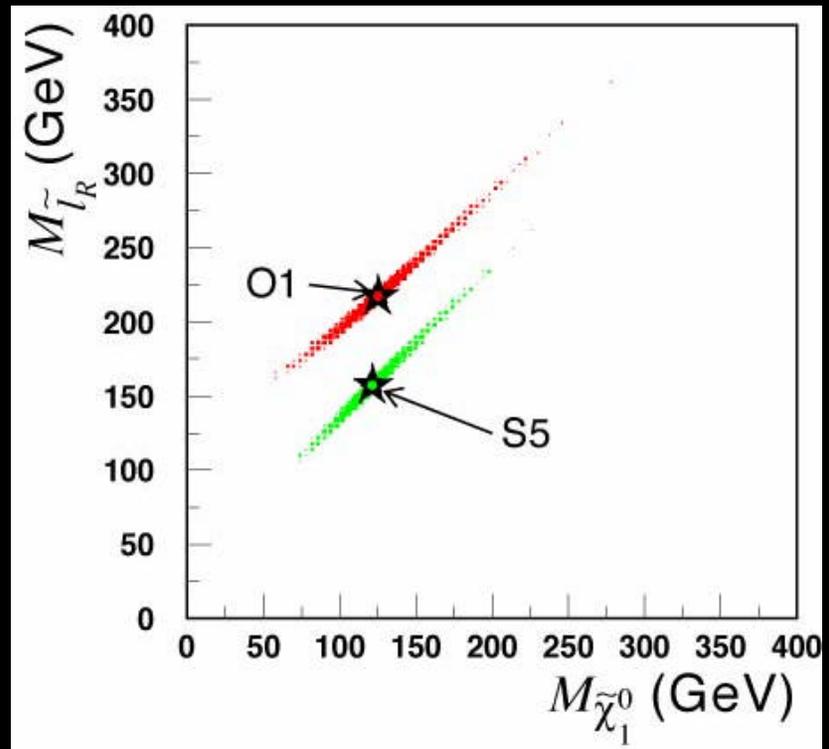


Supersymmetry

- Tevatron/LHC will discover supersymmetry



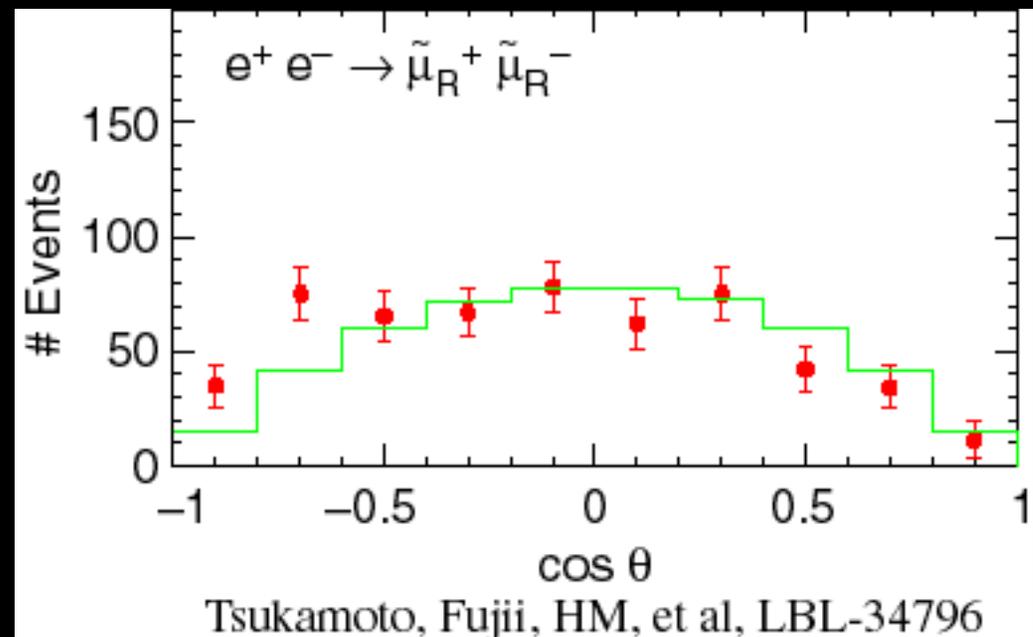
- Can do many measurements at LHC



Prove Superpartners have different spin

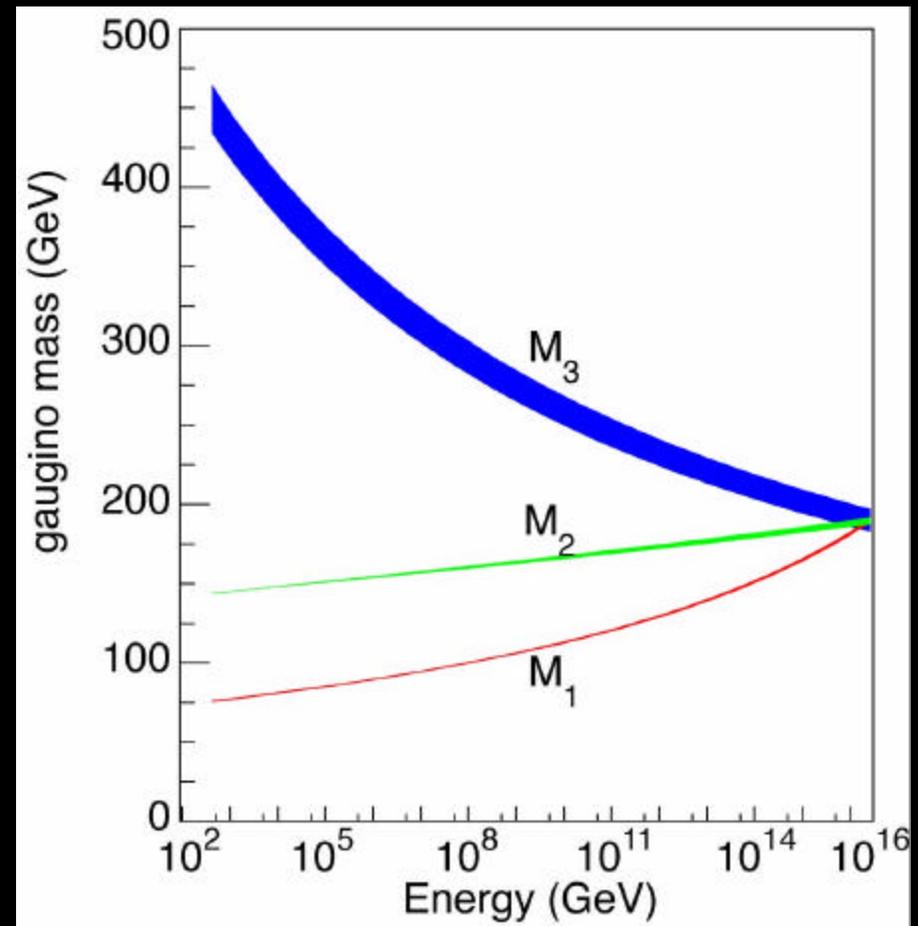
- Test they are really superpartners
 - Spins differ by 1/2
 - Same SU(3)? SU(2)? U(1) quantum numbers
 - Supersymmetric couplings

Spin 0?

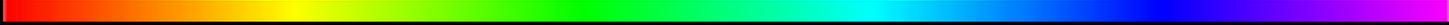


Superpartners as probe

- Most exciting thing about superpartners beyond existence:
They carry information of small-distance physics to something we can measure
“Are forces unified?”

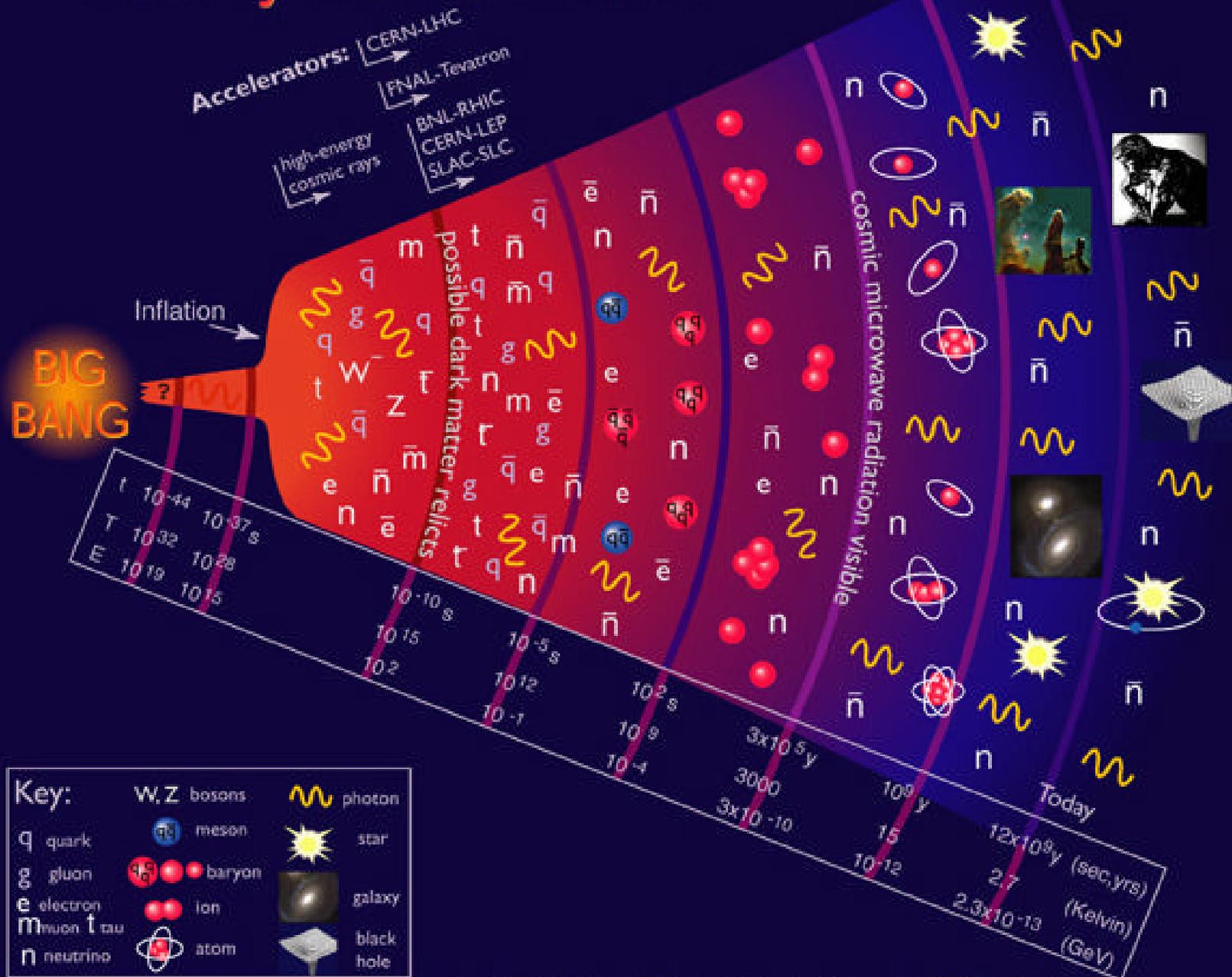


Dark Matter: The Missing Link?



- 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



Anti-Matter



Baryon Asymmetry Early Universe



10,000,000,001

q

10,000,000,000

\bar{q}

Baryon Asymmetry Current Universe



$\overset{\circ}{u}s$

1

q

\bar{q}

The Great Annihilation

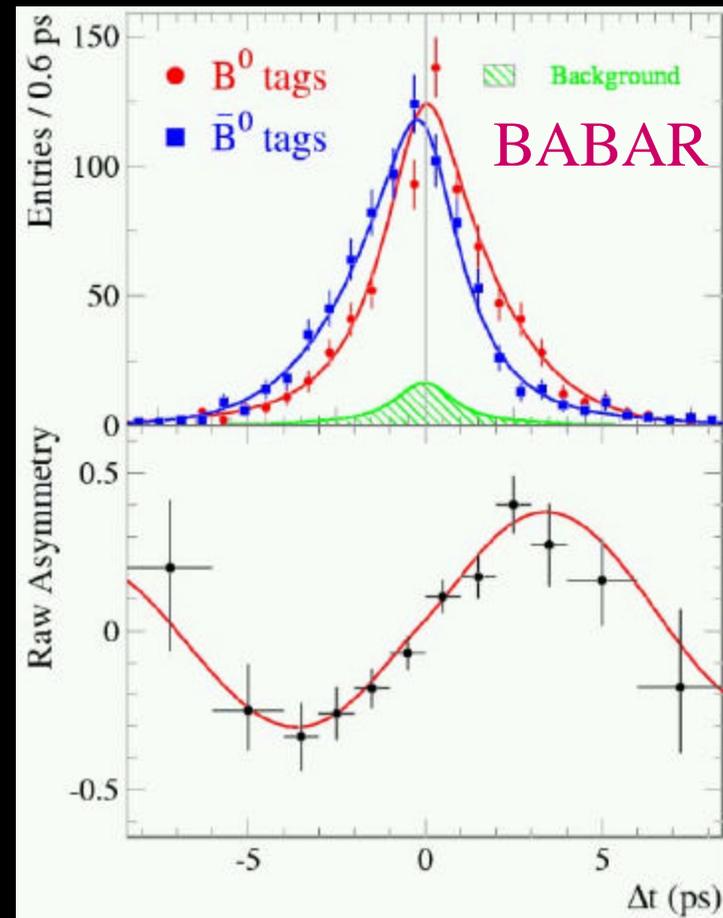
Baryogenesis



- 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
 $\Gamma(B > 0) > \Gamma(B < 0)$
- Possible new consequences in
 - Proton decay
 - CP violation

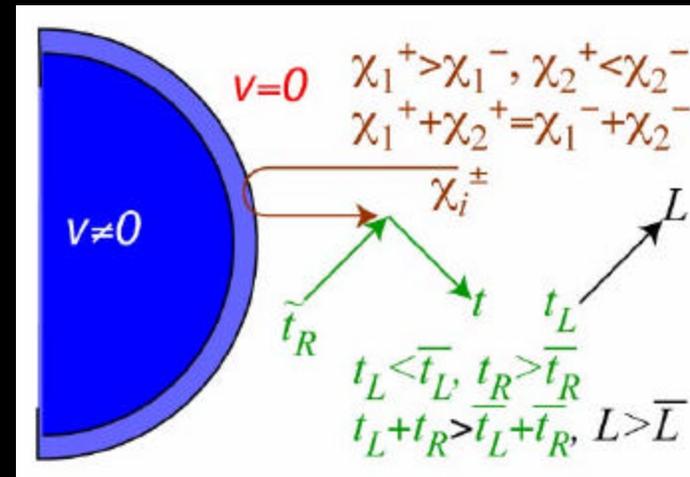
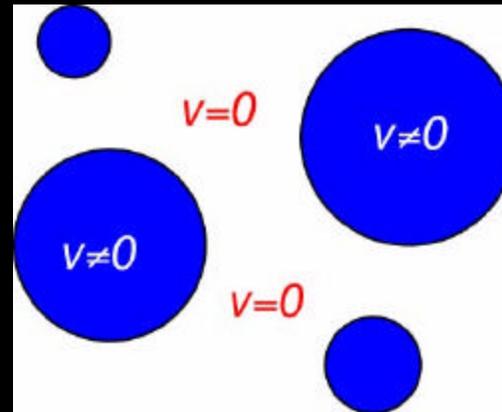
CP Violation

- 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



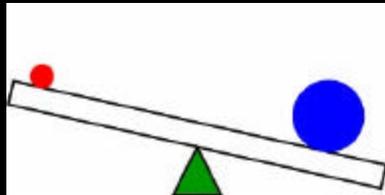
Electroweak Baryogenesis

- 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



Leptogenesis

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

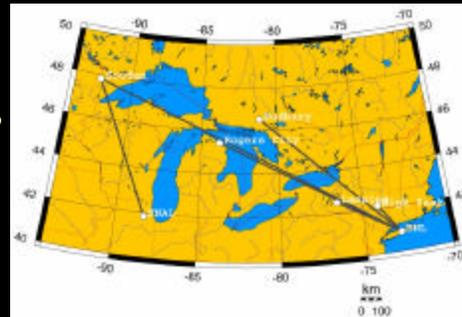


- The decay of the heavy particle may create imbalance between matter and anti-matter if there is CP violation in neutrinos

- CP-violation may be observed in neutrino oscillation

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

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



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 live in this age!