Prospects

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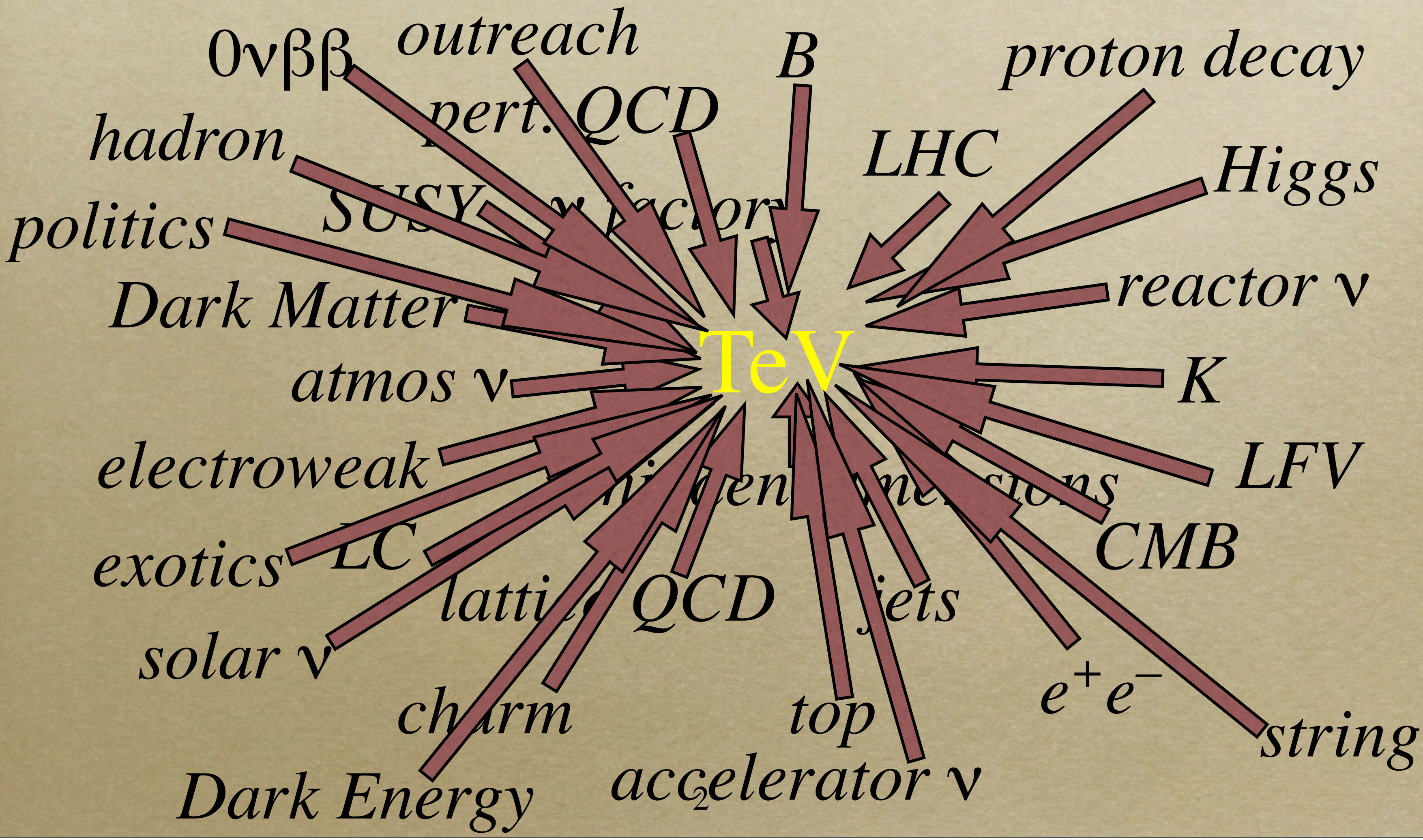
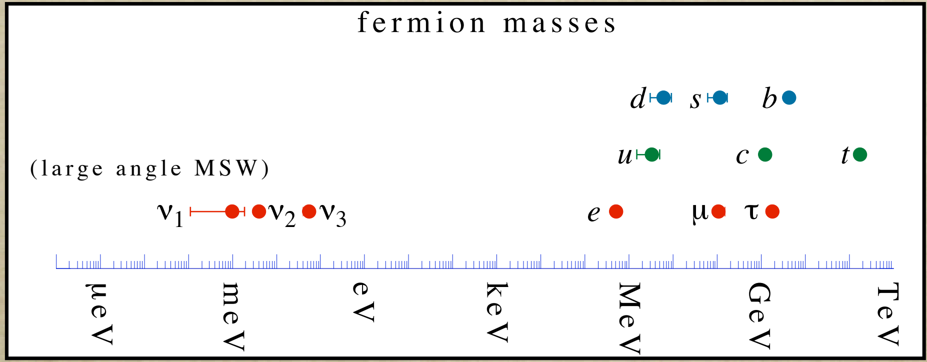
Topical Conference
KEK, Feb 6, 2007

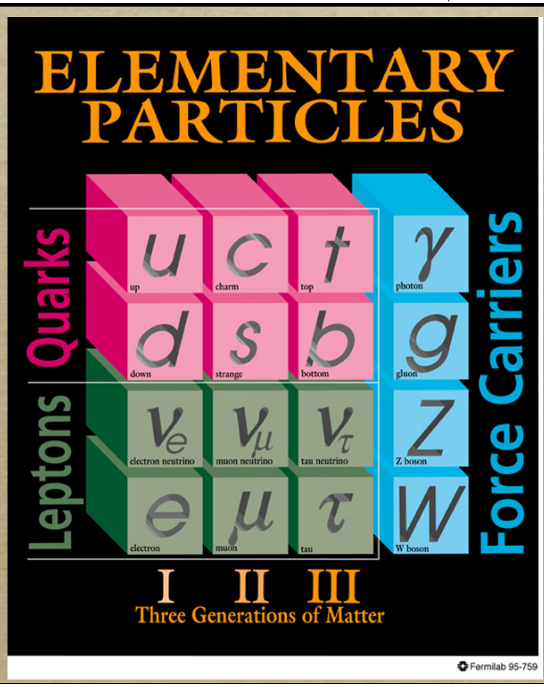
Our Field


0νββ
outreach
B
proton decay
pert. QCD
hadron
LHC
Higgs
SUSY
ν factory
politics
reactor ν
Dark Matter
TeV
atmos ν
K
electroweak
LFV
hidden dimensions
CMB
exotics
LC
lattice QCD
jets
solar ν
e+e−
charm
top
string
accelerator ν
Dark Energy

Big Questions –Horizontal–

- *Why are there three generations?*
- *What physics determines the pattern of masses and mixings?*
- *Why do neutrinos have mass yet so light?*
- *What is the origin of CP violation?*
- *What is the origin of matter anti-matter asymmetry in Universe?*

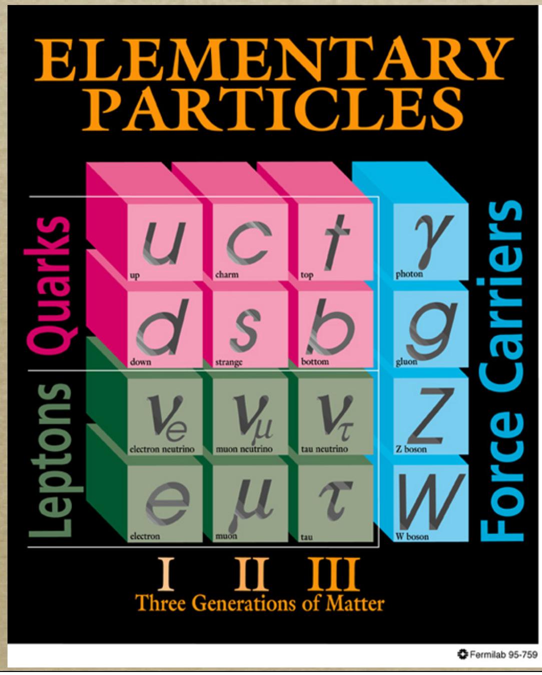




Big Questions
–Vertical–

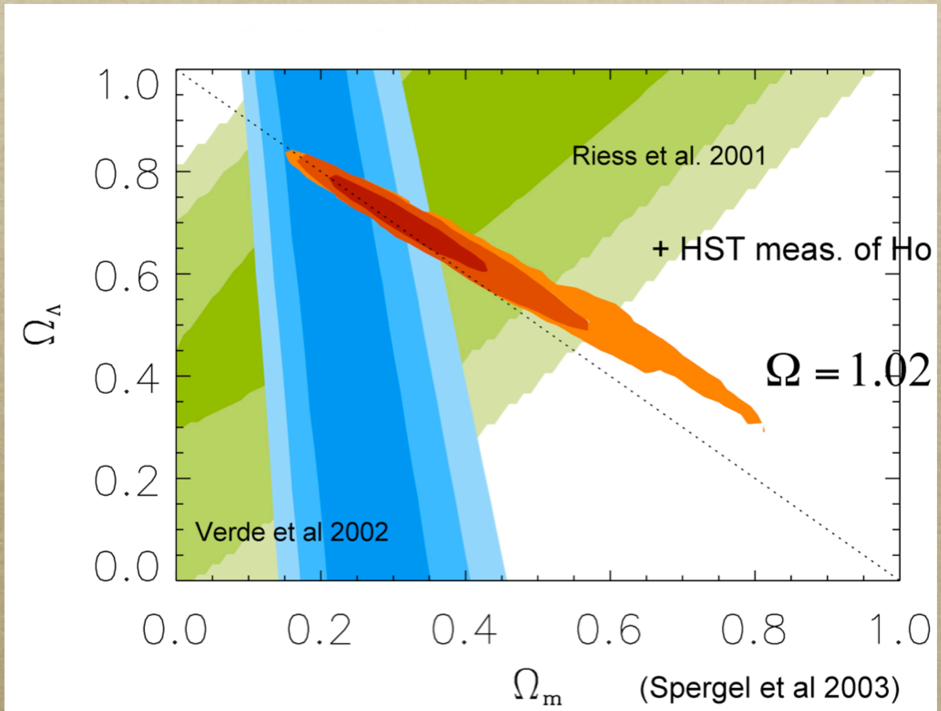
- *Why are there three unrelated gauge forces?*
- *Why is strong interaction strong?*
- *Charge quantization*
- *anomaly cancellation*
- *quantum numbers*
- *Is there a unified description of all forces?*
- *Why is* $m_W \ll M_{Pl}$ *?* *(Hierarchy Problem)*

$$Q(\mathbf{3},\mathbf{2},+\frac{1}{6}),\quad u(\mathbf{3},\mathbf{1},+\frac{2}{3}),\quad d(\mathbf{3},\mathbf{1},-\frac{1}{3}),$$
$$L(\mathbf{1},\mathbf{2},-\frac{1}{2}),\quad e(\mathbf{1},\mathbf{1},-1)$$

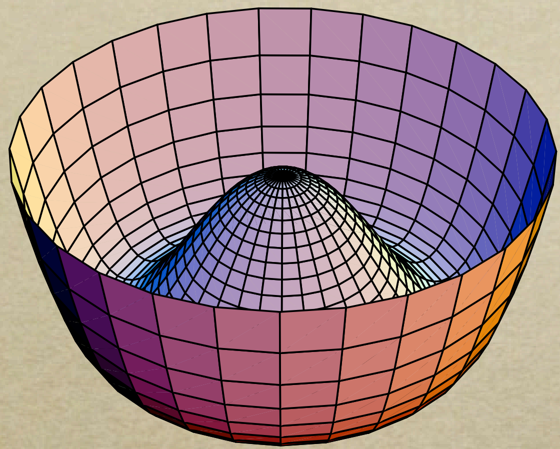


Big Questions –From the Heaven–

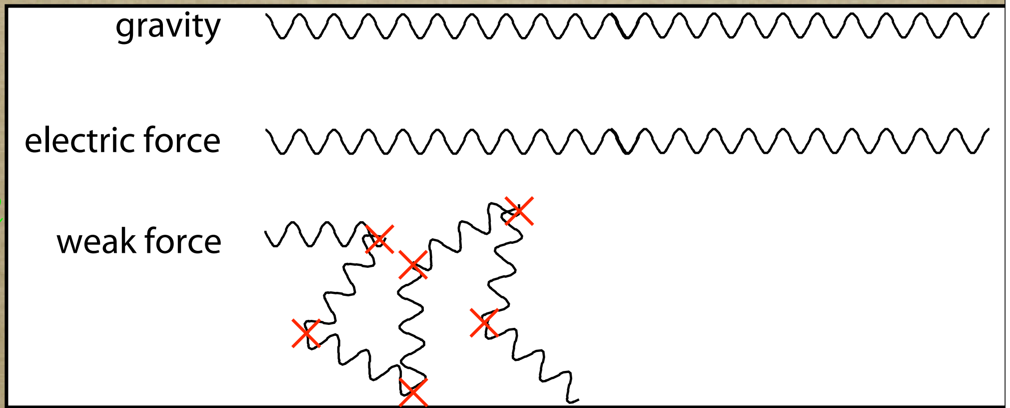
- *What is Dark Matter?*
- *What is Dark Energy?*
- *Why now? (Cosmic coincidence problem)*
- *What was Big Bang?*
- *Why is Universe so big? (flatness problem, horizon problem)*
- *How were galaxies and stars created?*



Big Questions
–From the Hell–



- *What is the Higg boson?*
- *Why does it have negative mass-squared?*
- *Why is there only one scalar particle in the Standard Model?*
- *Is it elementary or composite?*
- *Is it really condensed in our Universe?*



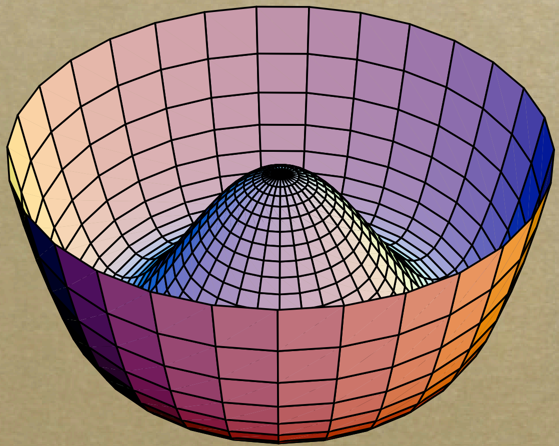
Outlook

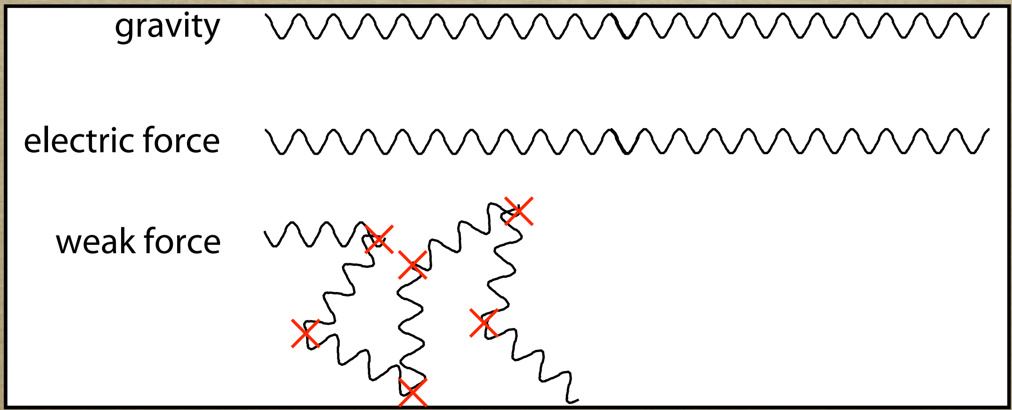
- *We do not have right to expect that any of big questions can be answered*
- *Nonetheless there is a good potential for us to answer some or many of them*
- *How exactly do we do it?*
- *Use supersymmetry as an example, but I expect similar stories with any scenario of TeV-scale physic*

Outline

- *Introduction*
- *Hell*
- *Heaven*
- *Vertical*
- *Horizontal*
  - *Flavor*
  - *Leptogenesis*
- *Conclusion*

Hell

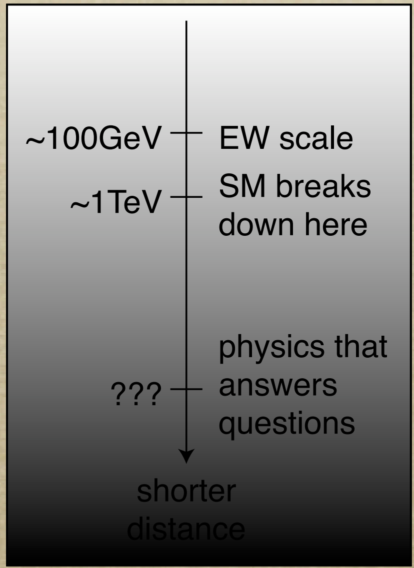




The Main Obstacle

- *We look for physics beyond the Standard Model that answers these big questions*
- *By definition, that is physics at shorter distances*
- *Then the Standard Model must survive down to whatever shorter distance scale*
- *Hierarchy problem is the main obstacle to do so*

⇒ *We can't even get started!*



Once upon a time, there was a hierarchy problem...

- *At the end of 19th century: a "crisis" about electron*
  - *Like charges repel: hard to keep electric charge in a small pack*
  - *Electron is point-like*
  - *At least smaller than* 10^{-17}cm
- *Need a lot of energy to keep it small!*

$$\Delta m_e c^2 \sim \frac{\alpha}{r_e} \sim \text{GeV} \frac{10^{-17}\,\text{cm}}{r_e}$$

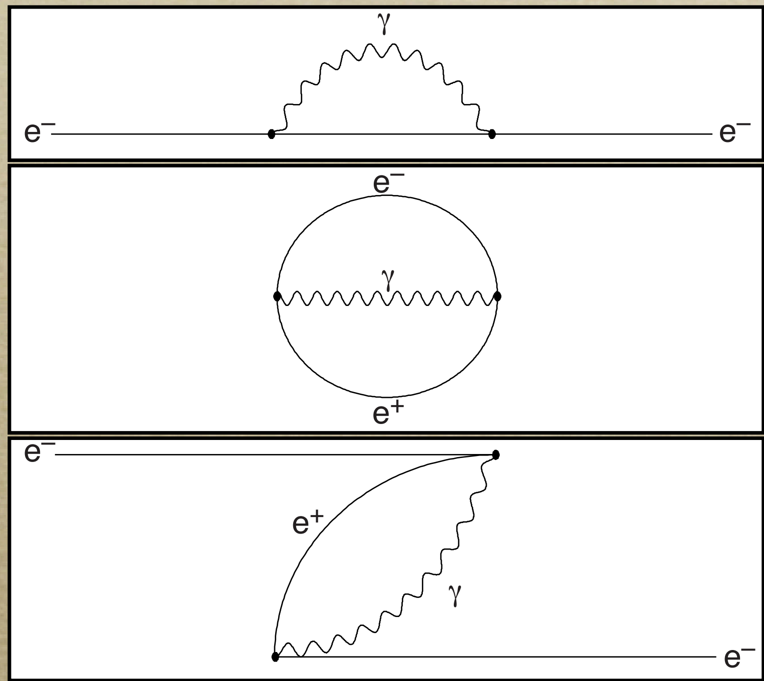
- *Correction* $\Delta m_e c^2 > m_e c^2$ *for* $r_e < 10^{-13}$cm
- *Breakdown of theory of electromagnetism*

$\Rightarrow$ *Can't discuss physics below* 10^{-13}cm

Anti-Matter Comes to Rescue by Doubling of #Particles

- *Electron creates a force to repel itself*
- *Vacuum bubble of matter anti-matter creation/annihilation*
- *Electron annihilates the positron in the bubble*

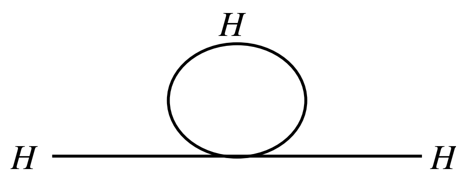
⇒ *only 10% of mass even for Planck-size*



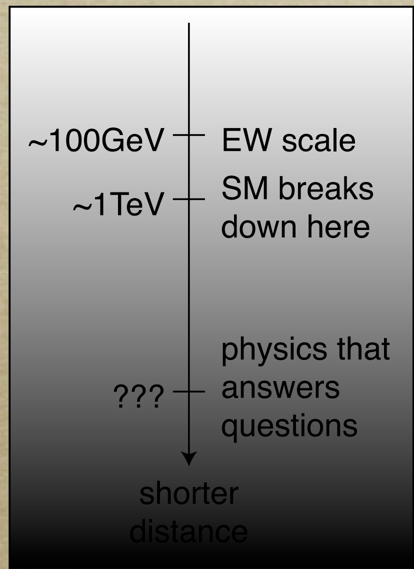
$$\frac{\Delta m_e}{m_e} \sim \frac{\alpha}{4\pi} \log(m_e r_e)$$

Higgs repels itself, too

- *Just like electron repelling itself because of its charge, Higgs boson also repels itself*
- *Requires a lot of energy to contain itself in its point-like size!*
- *Breakdown of theory of weak force*
- *Can't get started!*

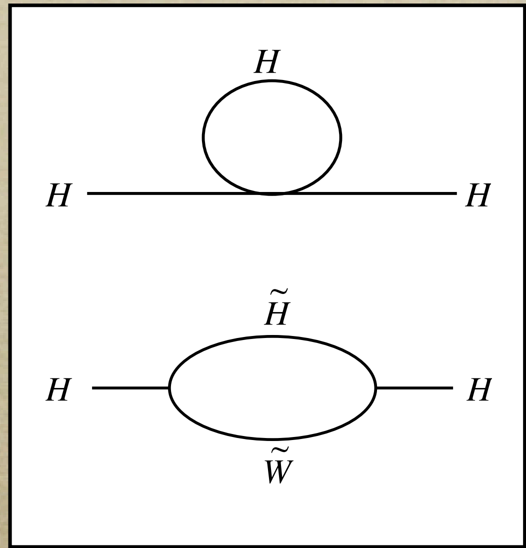


$$\Delta m_H^2 c^4 \sim \left(\frac{\hbar c}{r_H}\right)^2$$



History repeats itself?

- *Double #particles again ⇒ superpartners*
- *"Vacuum bubbles" of superpartners cancel the energy required to contain Higgs boson in itself*
- *Standard Model made consistent with whatever physics at shorter*



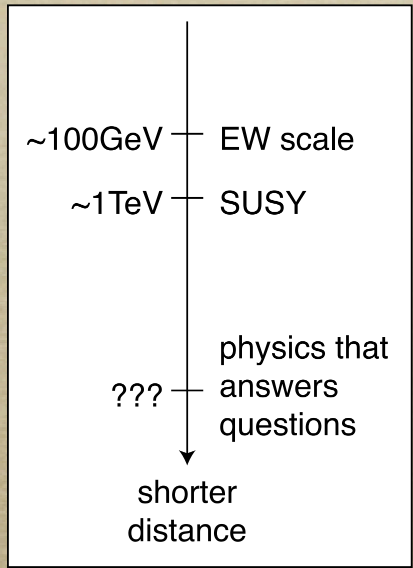
$$\Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H)$$

Opening the door

- *Once the hierarchy problem solved, we can get started to discuss physics at shorter distances.*
- *It opens the door to the next level:*

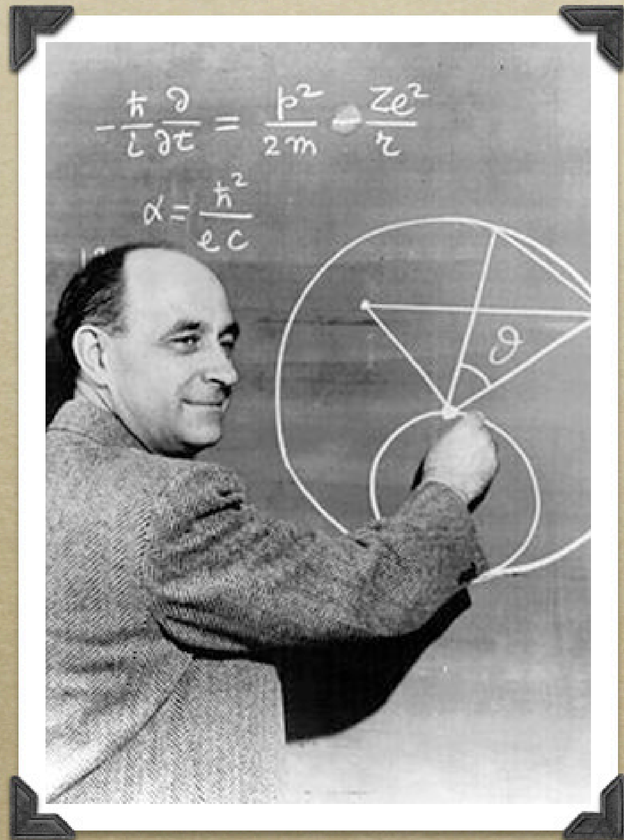
Hope to answer big questions

- *The solution to the hierarchy problem itself, e.g., SUSY, provides additional probe to physics at short distances*



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!*



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

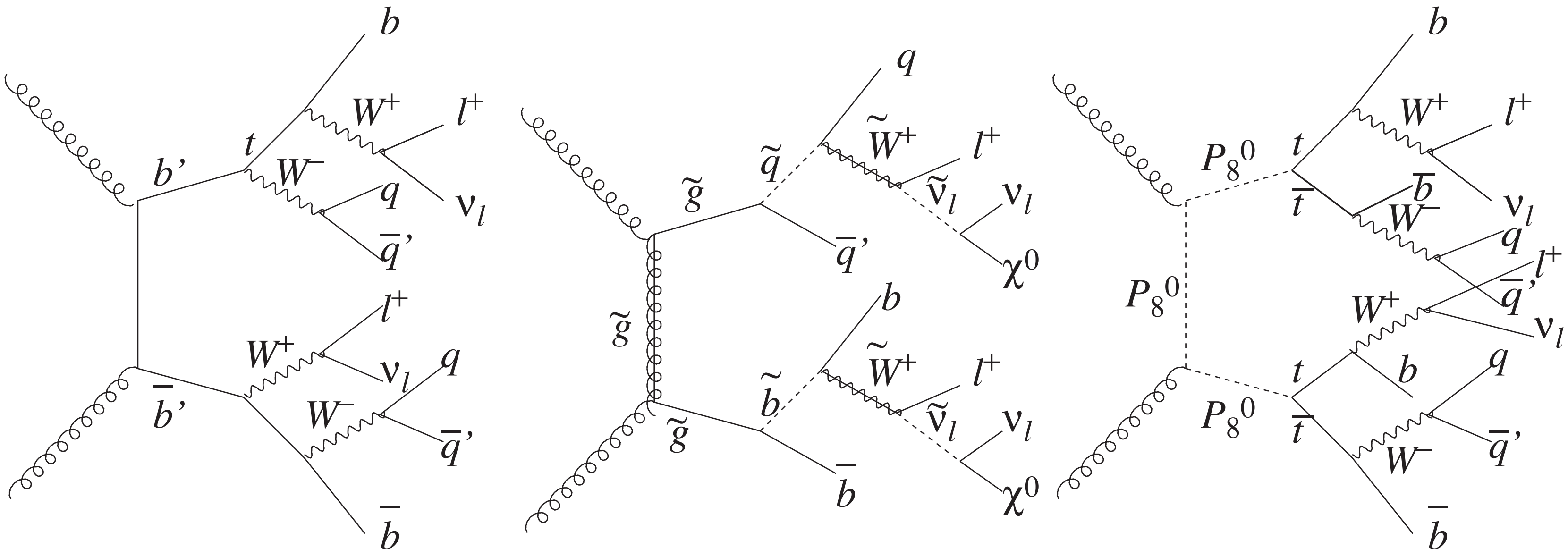
More Directions

- *Higgs boson as a Pseudo-Nambu-Goldstone boson (Little Higgs)*
- *Higgs boson as an extra-dimensional gauge boson (Gauge-Higgs Unification)*
- *No Higgs and $W^{\pm}$ as Kaluza-Klein boson*
- *technicolorful supersymmetry*

bosonic TC
composite Higgs
TC-TC
hypercolor
supercolor
techni-GIM
extended TC
pseudo NGB
NOT YET THOUGHT OF
NOT YET THOUGHT OF
NOT YET THOUGHT OF
NOT YET THOUGHT OF
effective SUSY
SUSY
NMSSM
nMSSM
MSSM +νR
ununified SM
axigluon
sterile ν
6th gen
5th gen
4th gen
lepto quark
heavy Majorana
vector-like family
fractionally charged
milli-charged
monopole
WR
X
Y
S,T,U
shadow matter
mirror symmetry
triplet Higgs
doubly charged Higgs
Type I
Type II
general 2HDSM
spontaneous CP
superweak
Weinberg's 3HD
milli-weak
Majoron
axion
saxion
axino
familon
NGB
worm-hole
Extra dim
quintessence
k-essence
composite W,Z
contact int.
string
hetero tic
matrix
M
IIB
IIA
F
I
N=2
N=4
N=8

New physics looks alike

missing E_T, multiple jets, b-jets, (like-sign) di-leptons



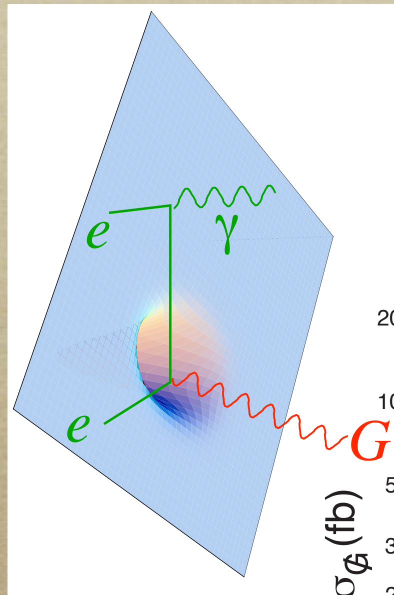
4th generation   *SUSY*   *technicolor*

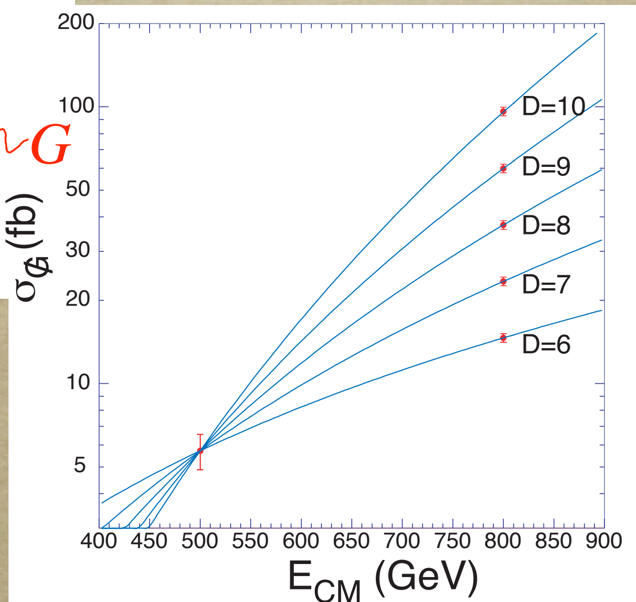
+Universal extra dimension, little Higgs with T-parity

Hidden Dimensions

- *Hidden dimensions*
- *Can emit graviton into the bulk*
- *Events with apparent energy imbalance*

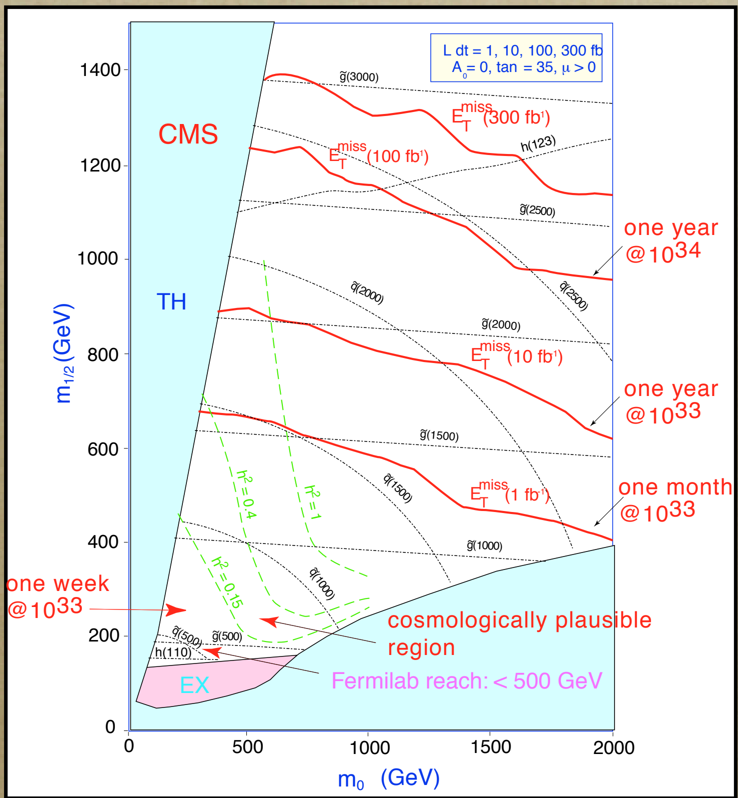
$\Rightarrow$ *How many extra dimensions are there?*



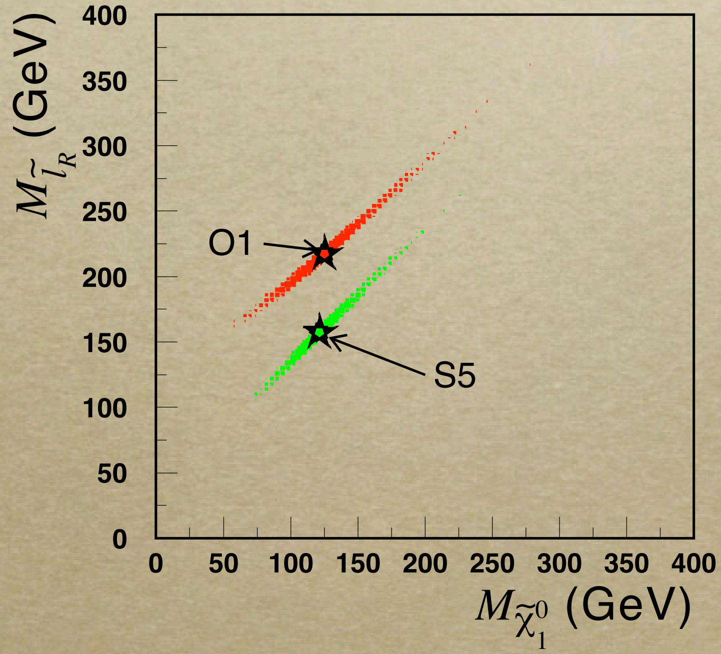


Supersymmetry

Tevatron/LHC will discover supersymmetry



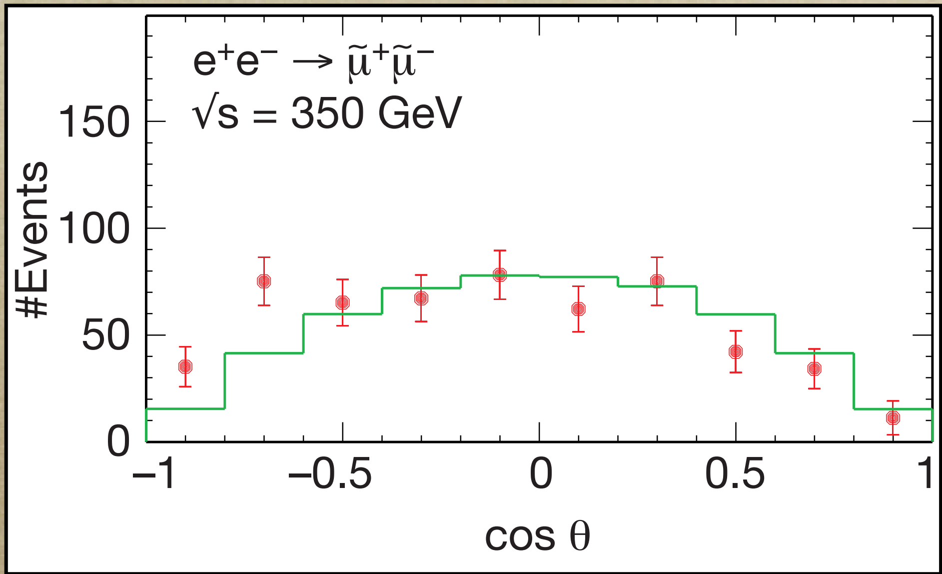
Can do many measurements at LHC



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?



Growing Uneasiness

- *If there are indeed new physics ≤TeV that makes EW scale "natural"*
- *Then why didn't it show any imprints in*
  - *EW precision observables?*
  - *FCNC (K^0-$\bar{K}^0$, $B_d \to \phi K_S$, B_s-$\bar{B}_s$)?*
  - *CP violation (EDMs)?*
- *Maybe no new physics ≤TeV?*

Anthropic reason?

- *Electroweak scale is what it is because that is the only kind of universe that admits life and hence we can observe*
- *After all, cosmological constant is "clearly" not natural*
- *There may be nothing else to be seen at the LHC other than the Higgs boson*
- *See, however, "A Universe Without Weak Interactions" (Harnik, Kribs, Perez)*

uneasiness in cosmology

- *Before 1992, upper limit on CMB anisotropy kept getting better and better*
- *Before 1998, the universe appeared younger than oldest stars*
- *cosmologists got antsy*
- *“crisis in standard cosmology”*
- *it turned out a little “fine-tuned” with a surprise*
  - *low quadrupole*
  - *dark energy*

“B

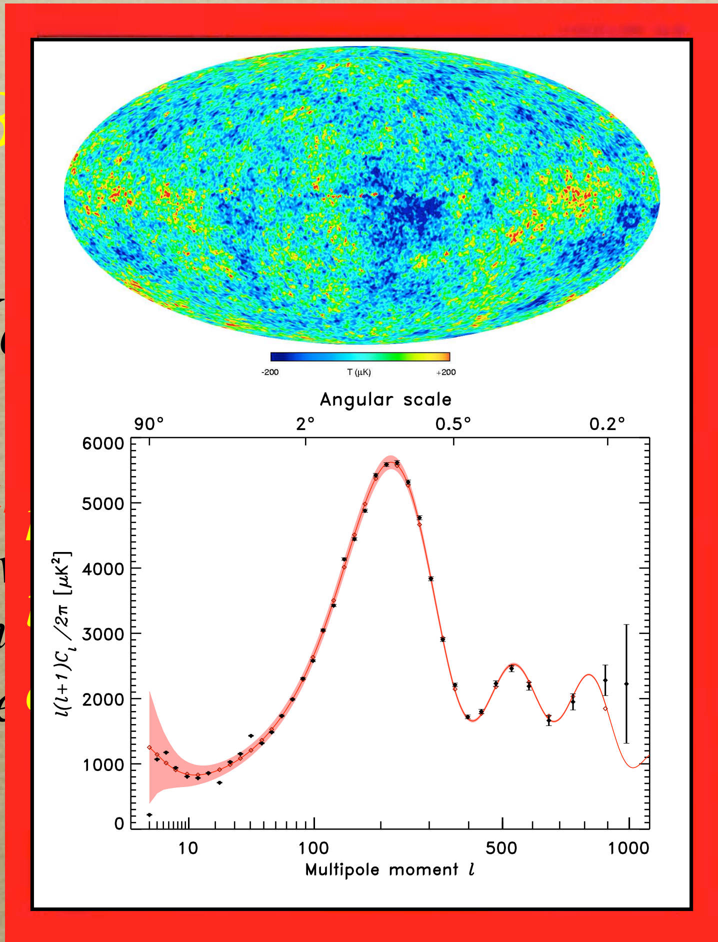
N

“Ba ot”

A ne e

the h

Time



Very Simple Model

- *SUSY SM*
- *SUSY QCD*
- *Both with massive vector-like fields*
- *SUSY breaking with naturally small FCNC via gauge mediation*
- *No need to get antsy*

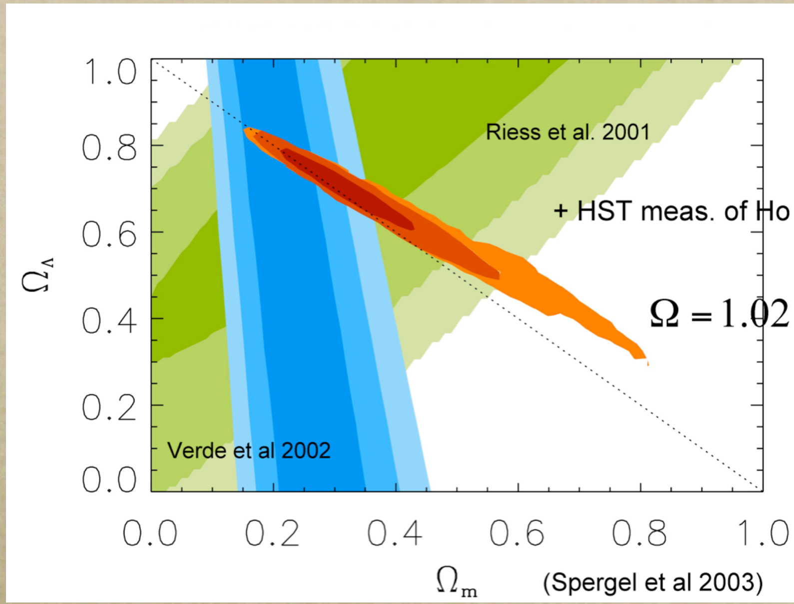
$$\frac{1}{M_{Pl}}\bar{Q}Q\bar{F}F$$

SUSY QCD: $m\bar{Q}Q$

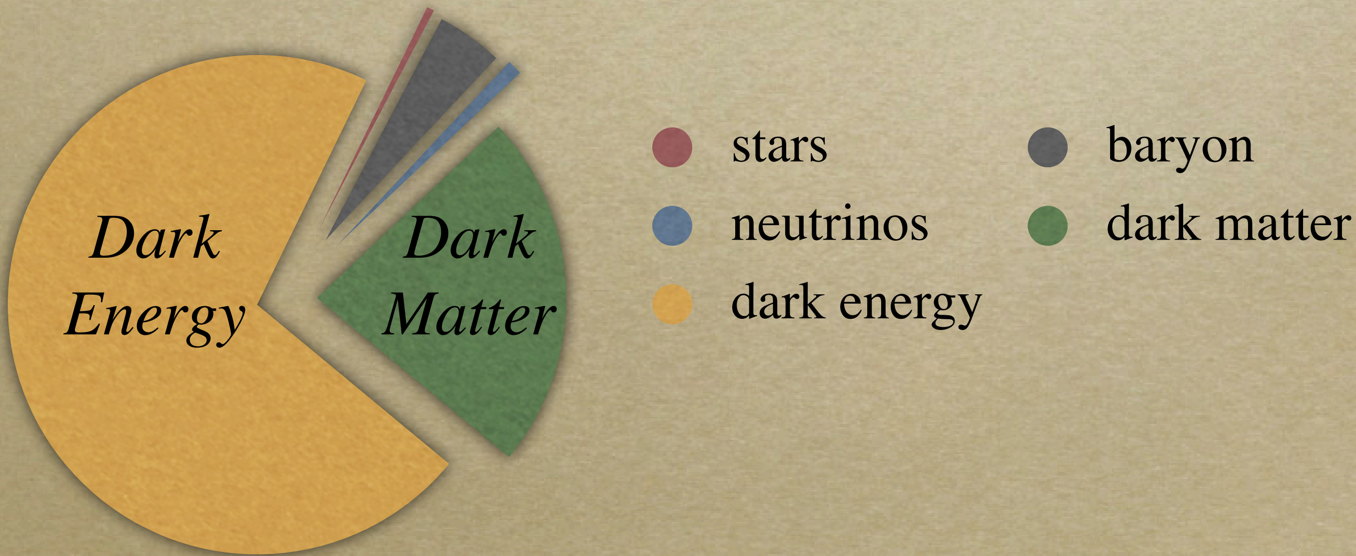
$M\bar{F}F$: SUSY SM

Anti-Anthropic!

HM, Nomura


1.0
0.8
0.6
0.4
0.2
0.0
Ω_Λ
Riess et al. 2001
+ HST meas. of Ho
$\Omega = 1.02$
Verde et al 2002
0.0 0.2 0.4 0.6 0.8 1.0
Ω_m
(Spergel et al 2003)

Heaven


Dark Energy
Dark Matter
stars
neutrinos
dark energy
baryon
dark matter

Cosmic Microwave Background

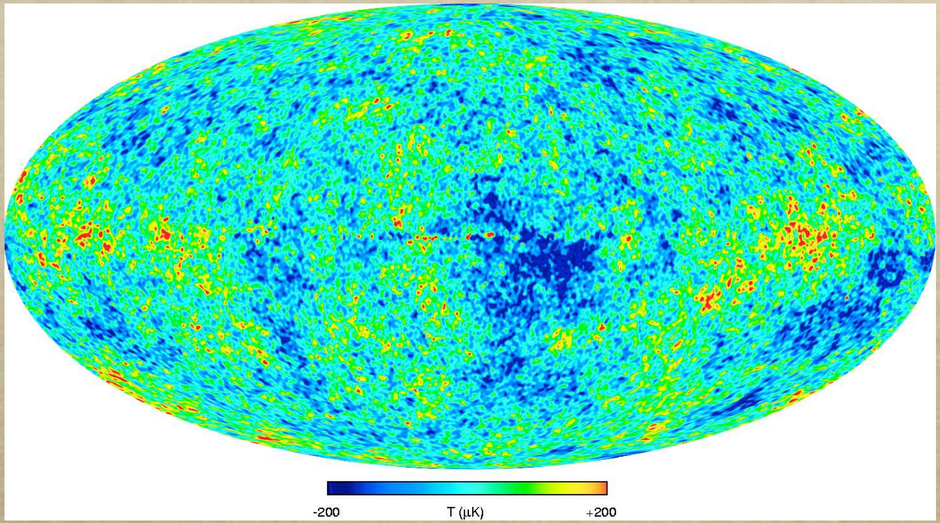
- *WMAP (ΛCDM)*

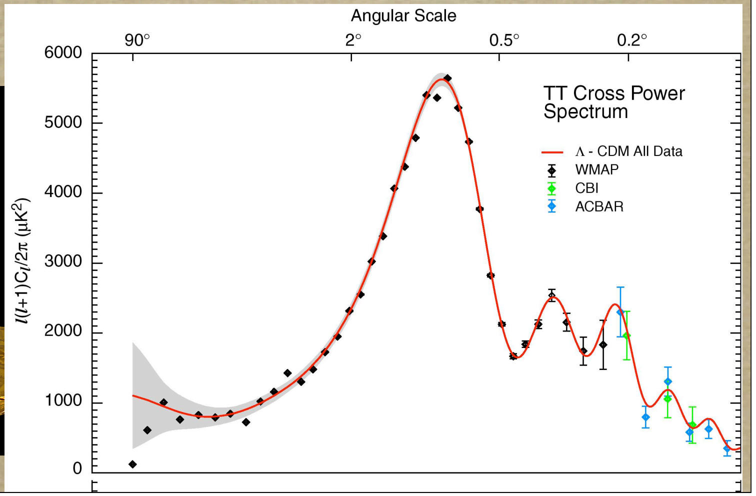
  $h = 0.73 \pm 0.03$

  $\Omega_M h^2 = 0.127^{+0.007}_{-0.013}$

  $\Omega_b h^2 = 0.0223^{+0.0007}_{-0.0009}$

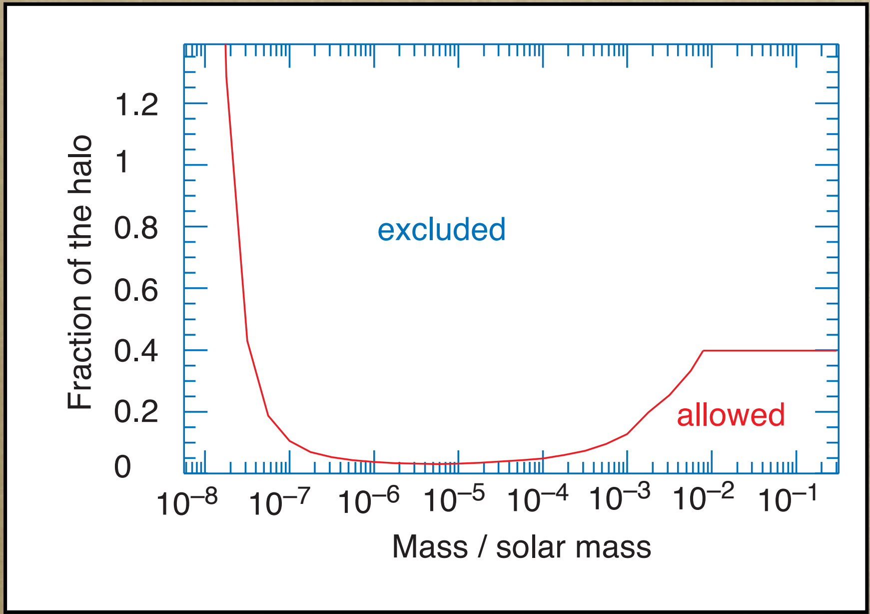
- *Yet another big step in precision cosmology*
- *>8σ signal for non-baryonic dark matter*





Particle Dark Matter

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



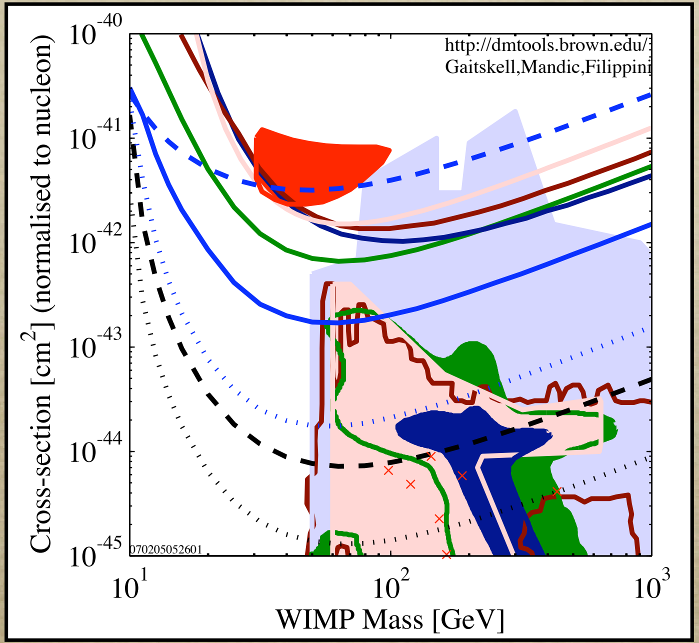
- *WIMP (Weakly Interacting Massive Particle) strongly favored*
- *Stable heavy particle produced in early Universe, left-over from near-complete annihilation*

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

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

Particle Dark Matter

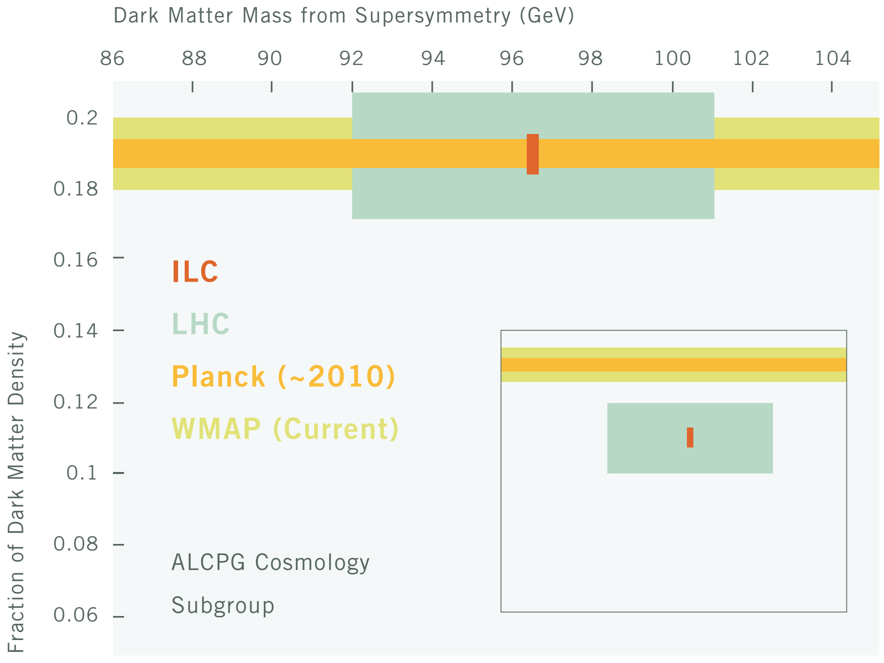
- *Stable, TeV-scale particle, electrically neutral, very weakly interacting*
- *No such candidate in the Standard Model*
- *Many models of stabilizing Higgs provide candidates*
- *LSP in SUSY, LKP in UED, LTP in little Higgs, ...*



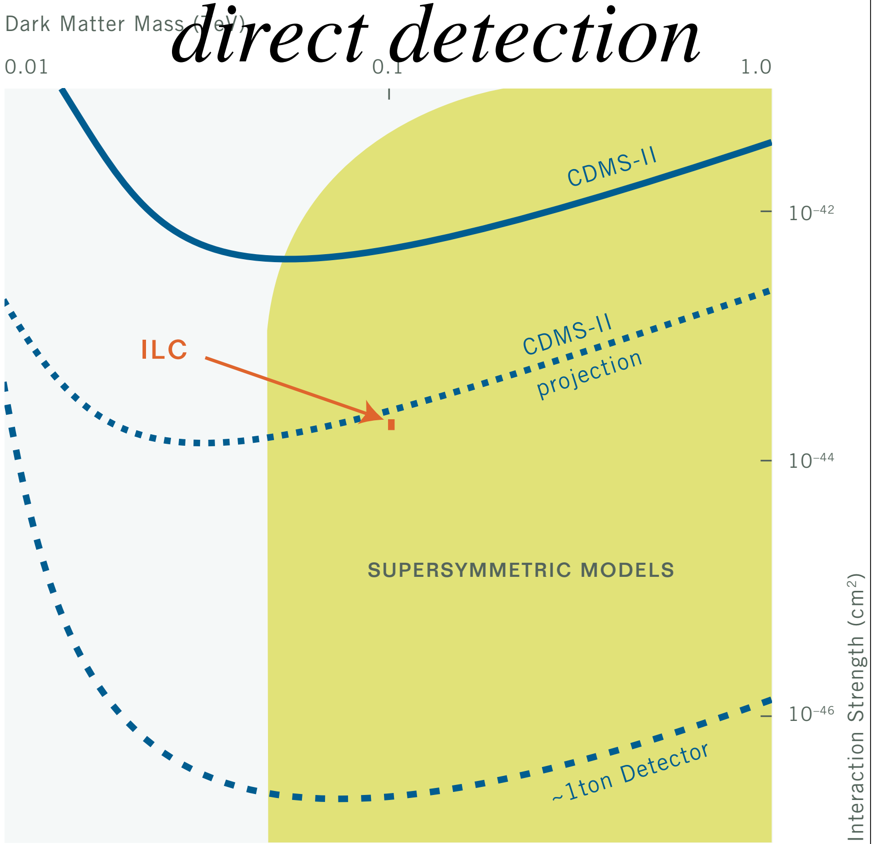
- *Detect Dark Matter to see it is there.*
- *Produce Dark Matter in accelerator experiments to see what it is.*

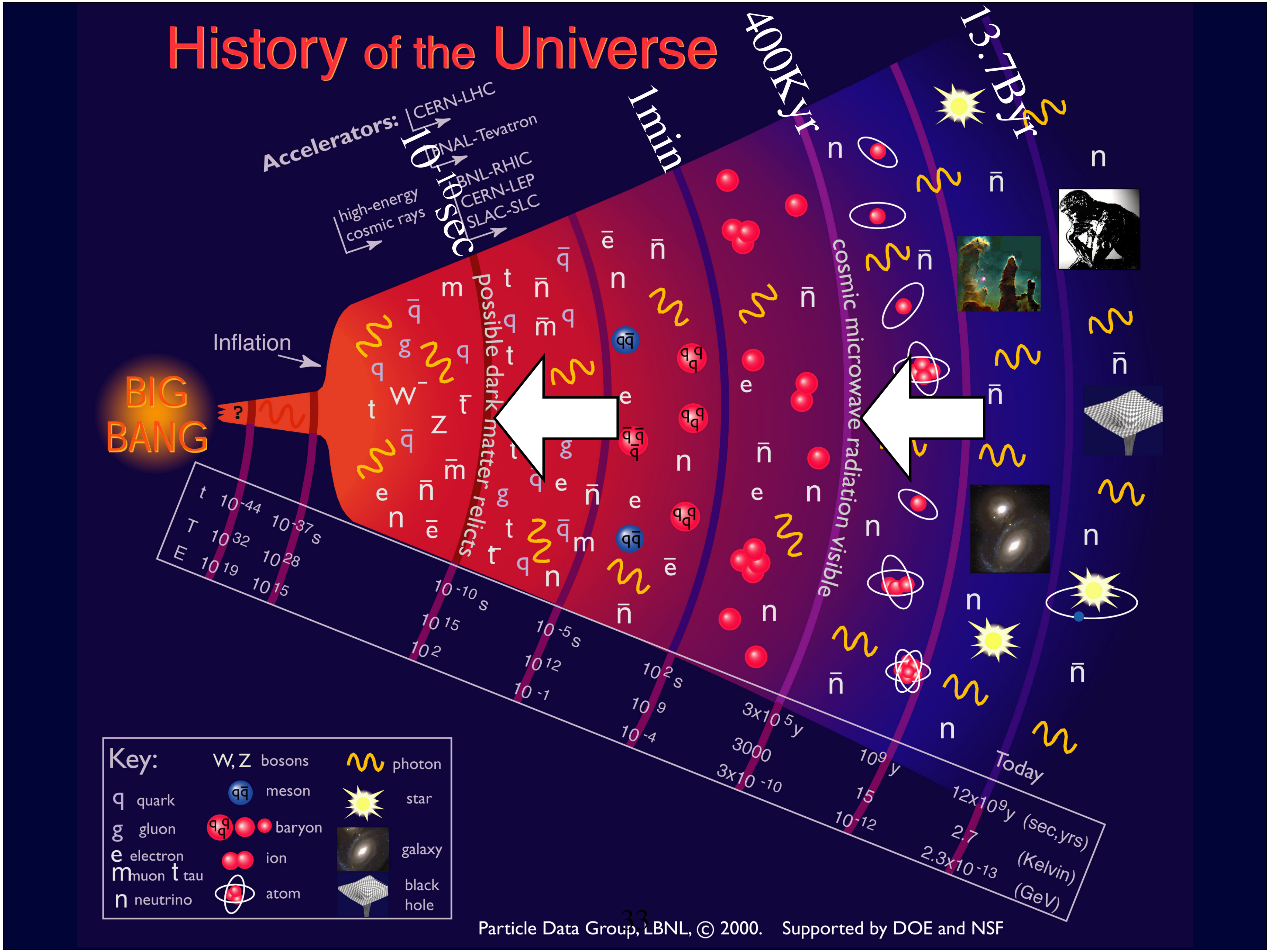
Dark Matter Concordance

abundance



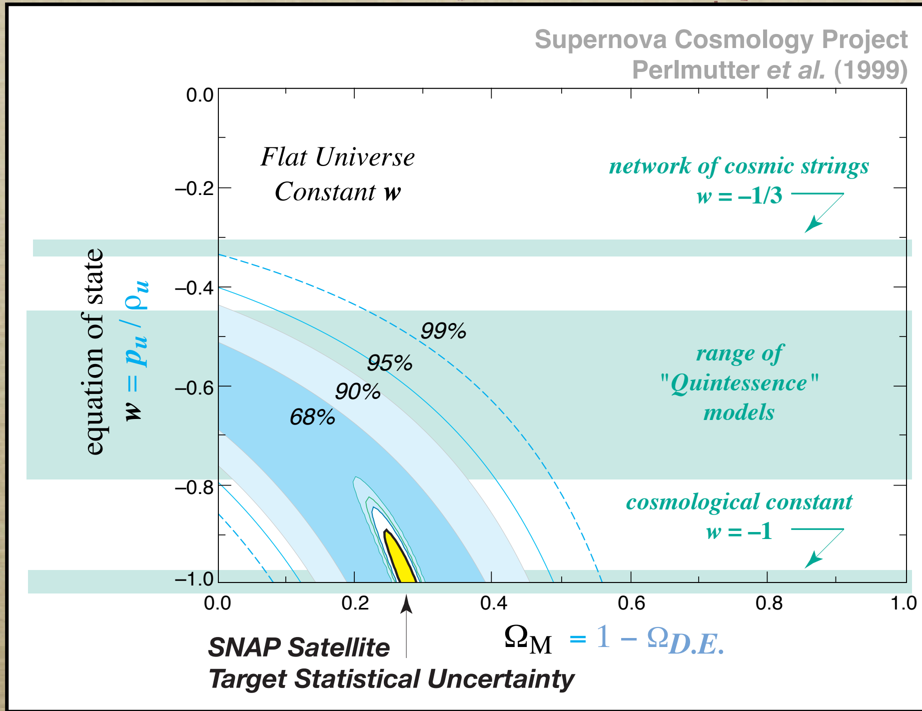
direct detection

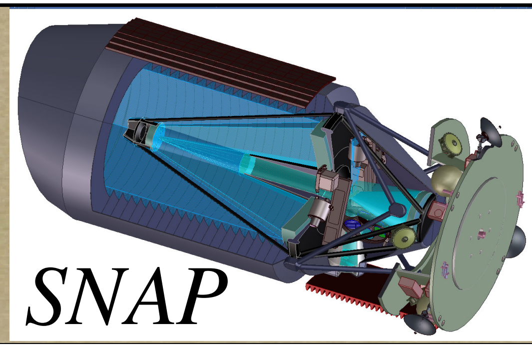



History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
10⁻¹⁰sec
1min
400Kyr
13.7Byr
possible dark matter relics
cosmic microwave radiation visible
t 10⁻⁴⁴ 10⁻³⁷s
T 10³² 10²⁸
E 10¹⁹ 10¹⁵
10⁻¹⁰ s
10¹⁵
10²
10⁻⁵ s
10¹²
10⁻¹
10² s
10⁹
10⁻⁴
3x10⁵ y
3000
3x10⁻¹⁰
10⁹ y
15
10⁻¹²
Today
12x10⁹y (sec,yrs)
2.7 (Kelvin)
2.3x10⁻¹³ (GeV)
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
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Dark Energy

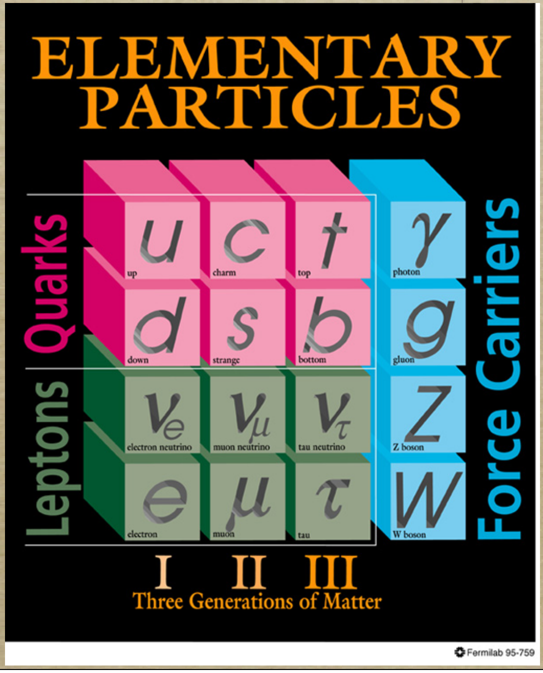
- *"Why Now" problem*
- *Actually a triple coincidence problem including the radiation*
- *If there is a deep reason for* $\rho_\Lambda \sim ((\text{TeV})^2/M_{Pl})^4$, *coincidence natural*
- *Indeed,* $\rho_\Lambda \sim (2\text{meV})^4$ *vs* $(\text{TeV})^2/M_{Pl} \sim 0.5\text{meV}$





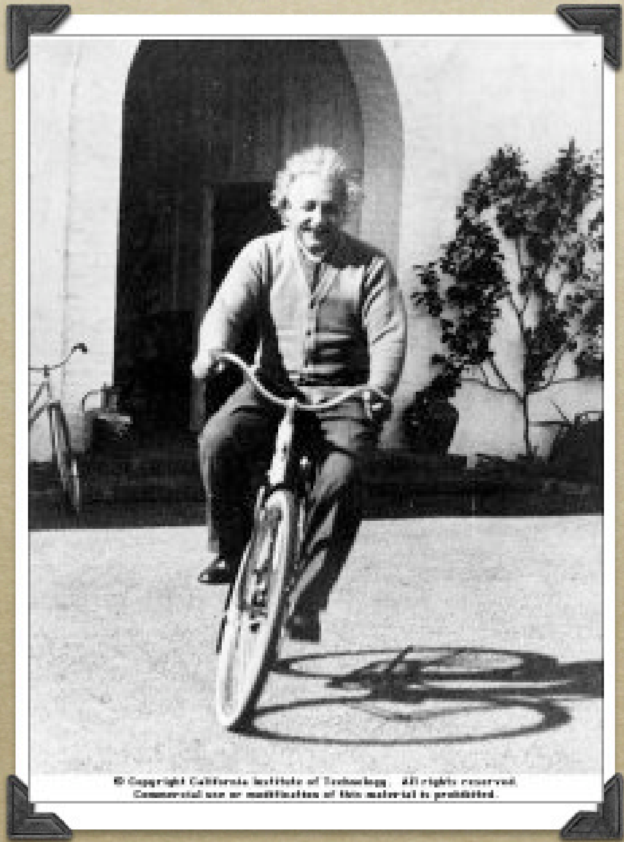
Vertical

$$Q(\mathbf{3},\mathbf{2},+\frac{1}{6}),\quad u(\mathbf{3},\mathbf{1},+\frac{2}{3}),\quad d(\mathbf{3},\mathbf{1},-\frac{1}{3}),$$
$$L(\mathbf{1},\mathbf{2},-\frac{1}{2}),\quad e(\mathbf{1},\mathbf{1},-1)$$



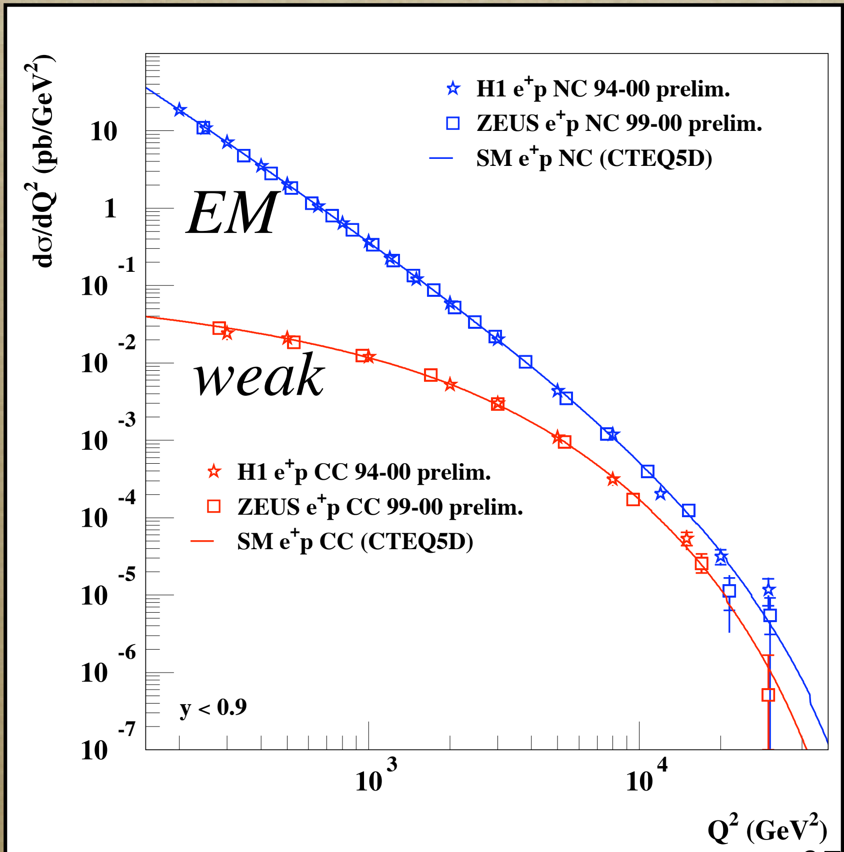
Einstein's Dream

- *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)*



We are just about to achieve another layer of unification

HERA ep collider



- *Unification of electromagnetic and weak forces*

$\Rightarrow$ *electroweak theory*

- *Long-term goal since '60s*
- *We are getting there!*
- *The main missing link: Higgs boson*

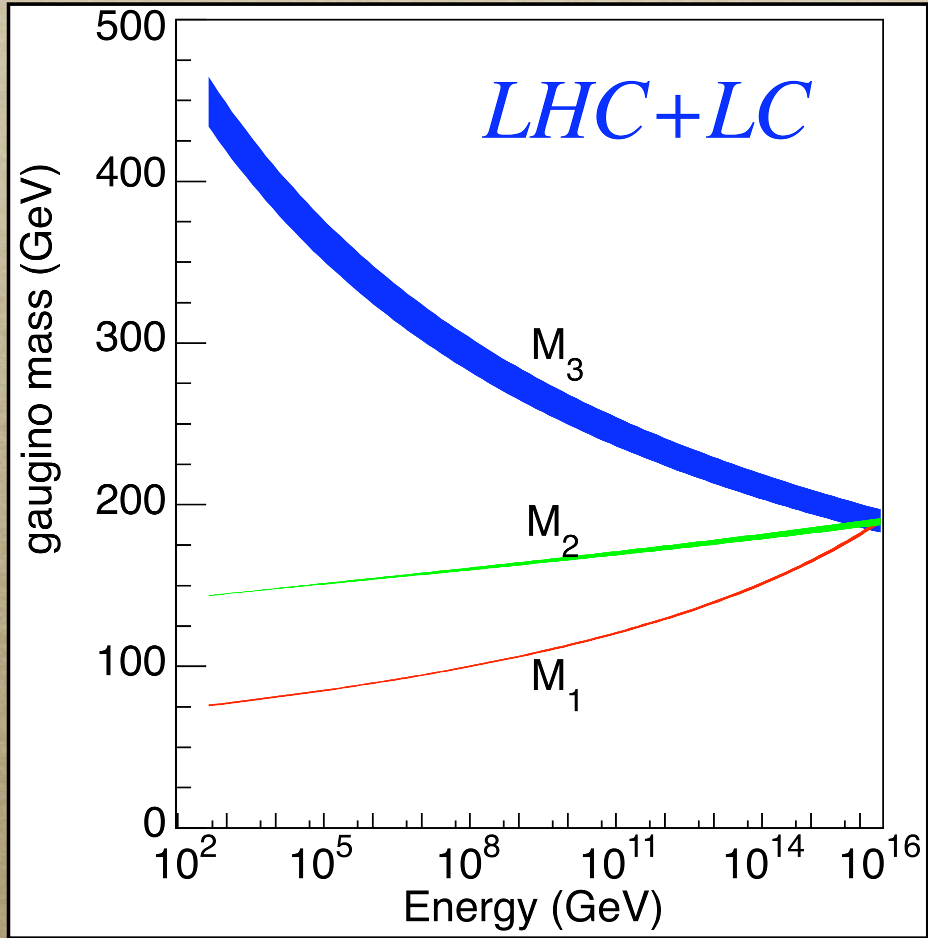
Superpartners as probe

- *Most exciting thing about superpartners beyond existence:*

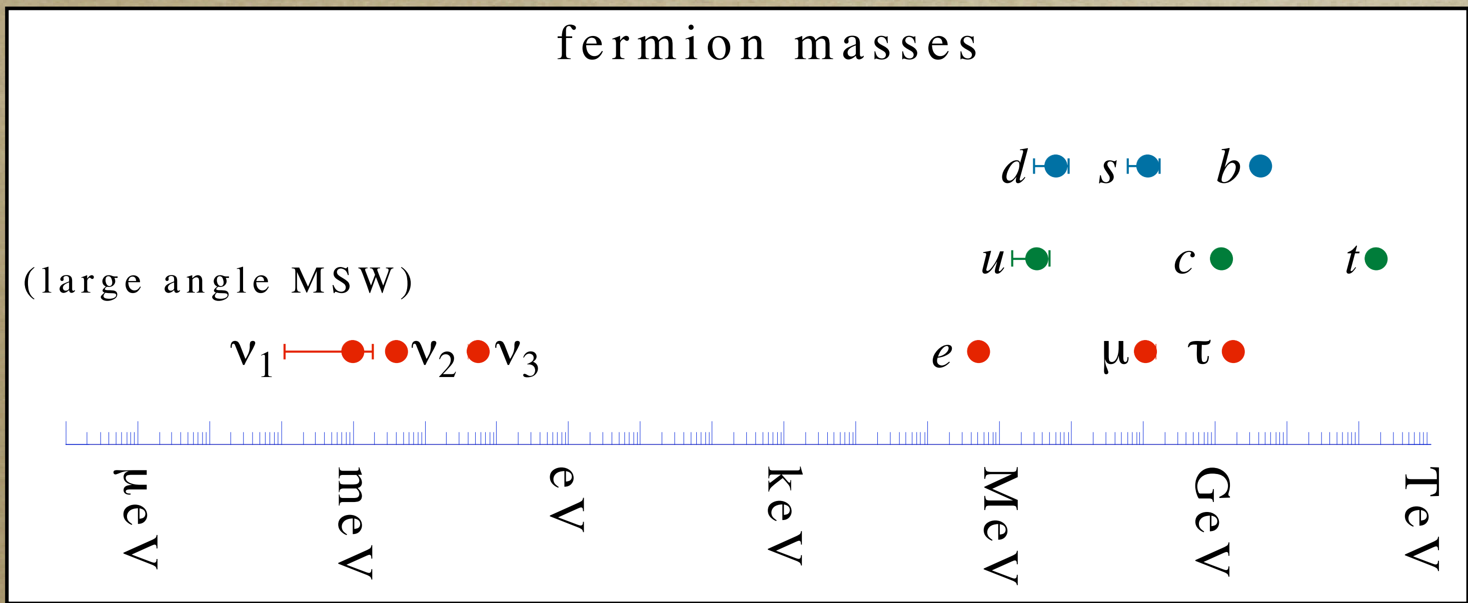
They carry information of small-distance physics to something we can measure

"Are forces unified?"

Need to see proton decay!



Horizontal



fermion masses
d
s
b
u
c
t
(large angle MSW)
ν_1
ν_2
ν_3
e
μ
τ
μeV
meV
eV
keV
MeV
GeV
TeV

Question of Flavor

- *What distinguishes different generations?*
  - *Same gauge quantum numbers, yet different*
- *Hierarchy with small mixings:*

  ⇒ *Need some ordered structure*

- *Probably a hidden flavor quantum number*

  ⇒ *Need flavor symmetry*

  - *Flavor symmetry must allow top Yukawa*
  - *Other Yukawas forbidden*

Broken Flavor Symmetry

- *Flavor symmetry broken by a VEV* 〈ε〉 ~0.02
- SU(5)-*like:*
  - 10(Q, u_R, e_R) (+2, +1, 0)
  - 5*(L, d_R) (+1, +1, +1)

$$M_u \sim \begin{pmatrix} \varepsilon^4 & \varepsilon^3 & \varepsilon^2 \\ \varepsilon^3 & \varepsilon^2 & \varepsilon \\ \varepsilon^2 & \varepsilon & 1 \end{pmatrix}, M_d \sim \begin{pmatrix} \varepsilon^3 & \varepsilon^3 & \varepsilon^3 \\ \varepsilon^2 & \varepsilon^2 & \varepsilon^2 \\ \varepsilon & \varepsilon & \varepsilon \end{pmatrix}, M_l \sim \begin{pmatrix} \varepsilon^3 & \varepsilon^2 & \varepsilon \\ \varepsilon^2 & \varepsilon^2 & \varepsilon \\ \varepsilon^3 & \varepsilon^2 & \varepsilon \end{pmatrix}$$

  - $m_u : m_c : m_t \sim m_d^2 : m_s^2 : m_b^2 \sim m_e^2 : m_\mu^2 : m_\tau^2 \sim \varepsilon^4 : \varepsilon^2 : 1$

New Data from Neutrinos

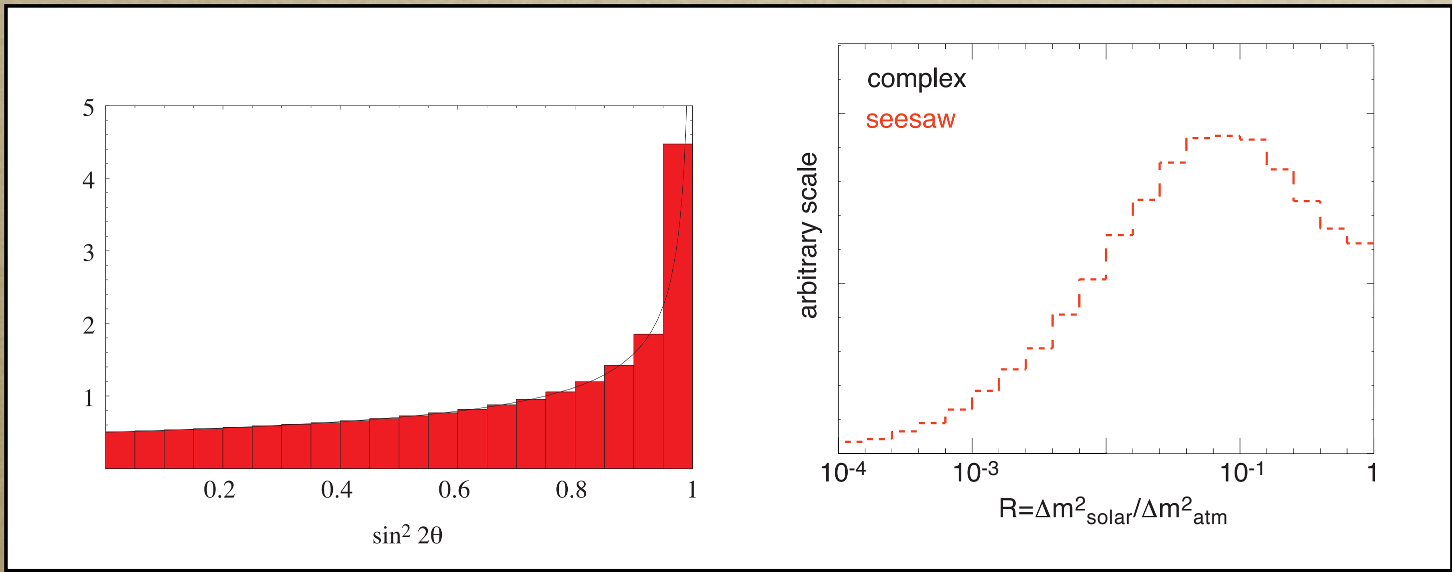
- *Neutrinos are already providing significant new information about flavor symmetries*
- *Given LMA, all mixings except U_{e3} large*

$$\begin{pmatrix} e & \mu & \tau \end{pmatrix} \begin{pmatrix} big & big & small \\ big & big & big \\ big & big & big \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \qquad \frac{\Delta m^2_{solar}}{\Delta m^2_{atm}} \sim 0.01 - 0.2$$

  - *Two mass splittings not very different*
  - *Atmospheric mixing maximal*
- *Any new symmetry or structure behind it?*

Is There A Structure In Neutrino Masses & Mixings?

- *Monte Carlo random complex* 3×3 *matrices with seesaw mechanism*



Apparently no particular structure in neutrino mass matrix needed! Anarchy

Different Flavor Symmetries

Altarelli-Feruglio-Masina hep-ph/0210342

Model	parameters	d_{23}	$\Delta m^2_{12}/\lvert\Delta m^2_{23}\rvert$	U_{e3}	$\tan^2\theta_{12}$	$\tan^2\theta_{23}$
A	$b=0$	O(1)	O(1)	O(1)	O(1)	O(1)
SA	$b=1$	O(1)	$O(d_{23}^2)$	$O(\lambda)$	$O(\lambda^2/d_{23}^2)$	O(1)
~~H_{II}~~	~~$a=1,\ b=2$~~	~~$O(\lambda^2)$~~	~~$O(\lambda^4)$~~	~~$O(\lambda^2)$~~	~~O(1)~~	~~O(1)~~
~~H_I~~	~~$a=1,\ b=2$~~	~~0~~	~~$O(\lambda^6)$~~	~~$O(\lambda^2)$~~	~~O(1)~~	~~O(1)~~
IH		$O(\lambda^4)$	$O(\lambda^2)$	$O(\lambda^2)$	$1+O(\lambda^2)$	O(1)

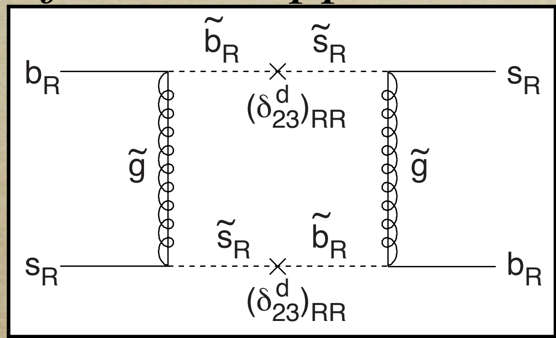
$\theta_{13}\approx O(1)$? $O(\lambda)$?(λ^2)?

$\sin^2 2\theta_{23}=1.00\pm0.01$? $\Rightarrow$ new symmetry

Program:More flavor parameters

- *Squarks, sleptons also come with mass matrices*
- *Off-diagonal elements violate flavor: suppressed by flavor symmetries*

$$M^2_{\tilde{Q}} \sim M^2_{\tilde{L}} \sim \begin{pmatrix} 1 & \varepsilon & \varepsilon^2 \\ \varepsilon & 1 & \varepsilon \\ \varepsilon^2 & \varepsilon & 1 \end{pmatrix}$$



- *Look for flavor violation due to SUSY loops*
- *Then look for patterns to identify symmetries*

  $\Rightarrow$ *Repeat Gell-Mann–Okubo!*

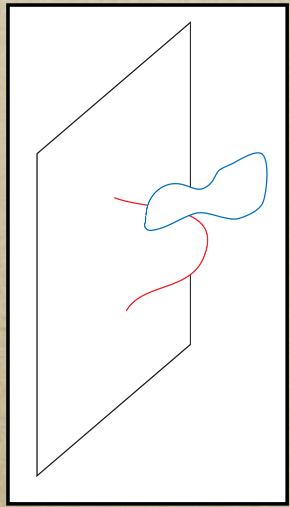
- *Need to know SUSY masses or TeV-scale physics*

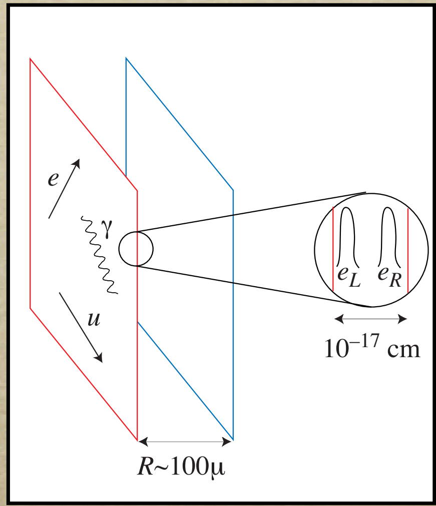
To Figure It Out…

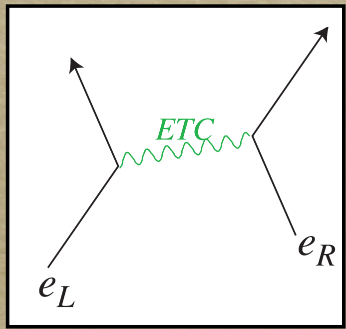
- *Models differ in flavor quantum number assignments*
- *Need data on* θ_{13}, *matter effect, CP violation, B/K-physics, Lepton Flavor Violation, EWSB, proton decay*
- *Archaeology*
- *We will learn insight on origin of flavor by studying as many fossils as possible*
  - *cf. CMBR in cosmology*

Dynamics behind flavor symmetry?

- *Once flavor symmetry structure identified (e.g., Gell-Man–Okubo), what is dynamics? (e.g., QCD)*
- *Supersymmetry:*
  – *Anomalous* U(1) *gauge symmetry with Green-Schwarz mechanism*
- *Large Extra Dimensions:*
  – *Fat brane with physically separated left- and right-handed particles*
- *Technicolor:*
  – *New broken gauge symmetries at* 100TeV *scale*

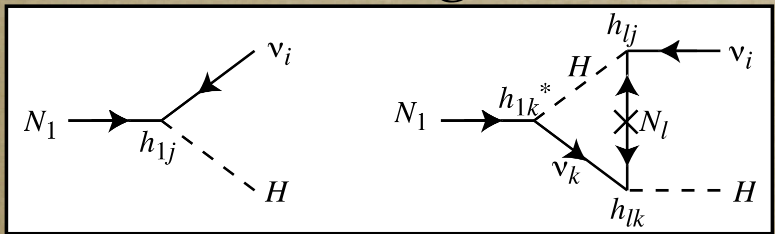






Leptogenesis

- *You generate Lepton Asymmetry first.*
- *L gets converted to B via EW anomaly*
  - *generate L from the direct CP violation in right-handed neutrino decay*



$$\varepsilon = \frac{\Gamma(N_1 \to \nu_i H) - \Gamma(N_1 \to \bar{\nu}_i H)}{\Gamma(N_1 \to \nu_i H) + \Gamma(N_1 \to \bar{\nu}_i H)} \sim \frac{1}{8\pi} \frac{\mathrm{Im}(h_{13} h_{13} h_{33}^* h_{33}^*)}{|h_{13}|^2} \frac{M_1}{M_3}$$

  - *Two generations enough for CP violation because of Majorana nature (choose 1 & 3)*
  - *It is non-trivial that it still works!*

Can we prove it experimentally?

- *Unfortunately, no: it is difficult to reconstruct relevant CP-violating phases from neutrino data*
- *But: we will probably believe it if*
  - 0νββ *found*
  - *CP violation found in neutrino oscillation*

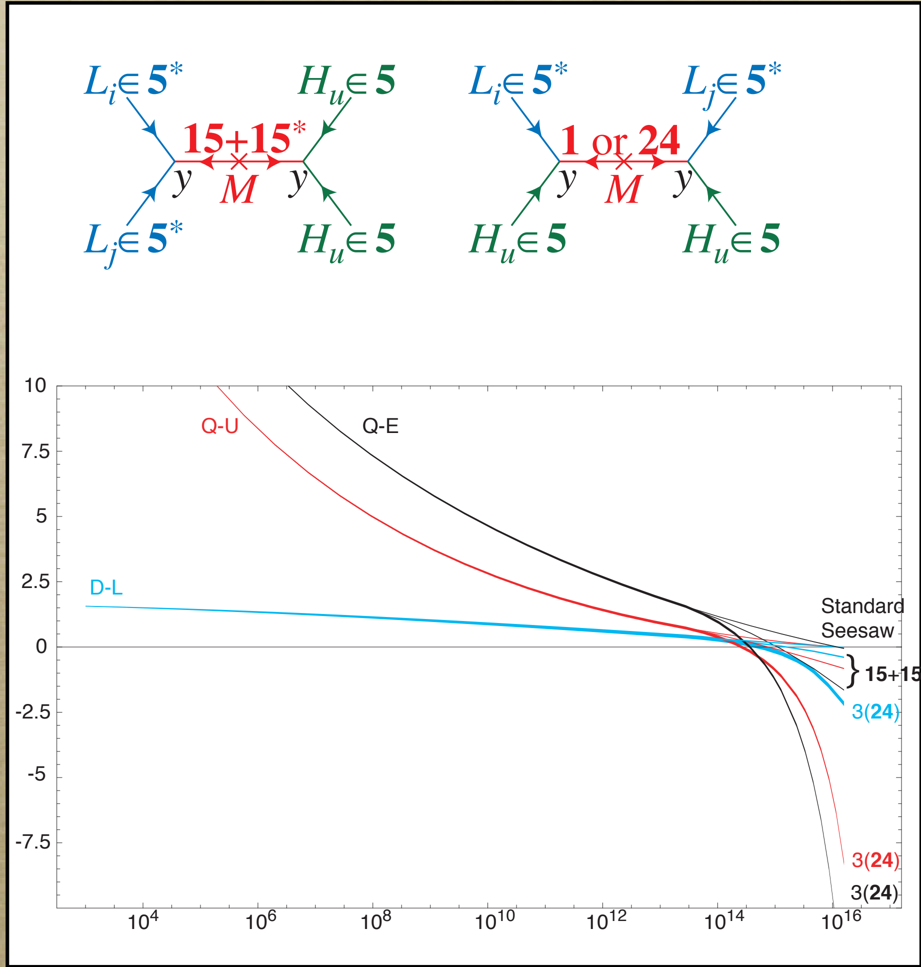
$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23}$$
$$\sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

  - *EW baryogenesis ruled out*
  - *Archeological evidences e.g,* $B_d \to \phi K_s$

Can prove seesaw

- *Majorana neutrino established (0νββ)*
- *gaugino/scalar unification seen*
- *only three possible particle content below M_{GUT}*
- *3×24, 15+15*, 3×1*
- *only 3×1 (seesaw) preserve scalar unification*

Buckley, HM



Bottomline: Synergy

- *Big questions = ambitious questions*
- *Need to clear the cloud of TeV-scale physics to obtain clear views*
- *Many different approaches will converge to reveal the big picture*
- *Hard, ambitious, but conceivable*
- *Expect similar story with ANY scenario of TeV-scale physics*