Theoretical Summary

Hitoshi Murayama (Berkeley)

B-L Workshop @ LBNL

Sep 22, 2007

Outline

- Why We Expect *B* & *L* Violation
- History of Conservaton Laws
- What I've Learned Here
  - Summary of Conclusions
- How do we make real progress?
- Conclusion of Summary

Why We Expect B & L Violation

Why look for B & L Violation?

Why am I interested in this?

Window to (way) high energy scales beyond the Standard Model!

- Two ways:
  - Go to high energies
  - Study rare, tiny effects ⇐

Historical Perspective

- ~1900 accelerators of ~eV scale
- E&M and strong interactions conserve numbers (*i.e. #p, #n*)
- Violation of this conservation law discovered in rare process (*i.e.* β-decay)
- Probed ~100 GeV
- Incredible reach by 10^{11}!
- Violation of conservation laws: powerful probe to *very* high energies, short distances, early universe

Historical Perspective

- ~2000 accelerators of ~TeV scale
- E&W and strong interactions conserve numbers (*i.e. #B, #L*)
- Violation of this conservation law looked for in rare process (*i.e. p*-decay, $0\nu\beta\beta$)
- Probes ~10^{15} GeV
- Incredible reach by 10^{12}!
- Violation of conservation laws: powerful probe to *very* high energies, short distances, early universe

Standard Model Has Fallen!

- There are now experimental proofs that the standard model is incomplete since 1998
  - Neutrino mass
  - Dark energy
  - Non-baryonic dark matter
  - Acausal scale-invariant density fluctuation
  - Baryon asymmetry *after* inflation
- Naively, they suggest physics >> TeV
- Physics beyond the SM no longer academic!

Rare Effects from High-Energies

- Effects of physics beyond the SM as effective operators

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

- Can be classified systematically (Weinberg)

$$\mathcal{L}_5 = (\bar{L}H)(\bar{L}H) \to \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

$$\mathcal{L}_6 = QQQL, \bar{L}\sigma^{\mu\nu}W_{\mu\nu}He,$$
$$W^\mu_\nu W^\nu_\lambda B^\lambda_\mu, (H^\dagger D_\mu H)(H^\dagger D^\mu H), \cdots$$

Unique Role of Neutrino Mass

- Lowest order effect of physics at short distances
- Tiny effect $(m_\nu/E_\nu)^2 \sim (0.1\text{eV/GeV})^2 = 10^{-20}$!
- Inteferometry (*i.e.*, Michaelson-Morley)
  - Need coherent source
  - Need interference (*i.e.*, large mixing angles)
  - Need long baseline

Nature was kind to provide all of them!

- "neutrino interferometry" (a.k.a. neutrino oscillation) a unique tool to study physics at very high scales
- Not entirely surprising (in *retrospect*) that neutrino mass was the first evidence for physics beyond standard model

History of Conservation Laws

Problem with Anti-Matter

- Anderson discovered positron e^+, anti-matter of electron in 1932
- A very naïve question:

  Why doesn't proton decay $p \rightarrow e^+ \gamma$?
- Stückelberg (1939) made up a new conservation law:

  Baryon number must be conserved

  (later also by Wigner, 1949)

Lepton Family Number

- Similarly ad-hoc conservation law
- Neddermeyer-Anderson discovered muon in 1937
- A very naïve question:

  Why doesn't muon decay $\mu^- \rightarrow e^- \gamma$?
- Inoue-Sakata made up a new conservation law:

  Lepton Family number must be conserved
- Neutrino oscillations (SuperK, SNO, KamLAND) have disproven lepton family number conservation!

Sacred and secular laws

- Sacred conservation laws:

  consequences of fundamental principles such as gauge invariance, Lorentz invariance, unitarity

  e.g., electric charge, CPT, energy-momentum

- Secular conservation laws:

  Happen to be approximately true, but ultimately violated

  e.g., parity, CP, lepton family

Fate of Secular Conservation Laws

• Parity	Fallen 1956
• Charge Conjugation	Fallen 1956
• CP	Fallen 1964
• T	Fallen 1999
• Lepton Family	Fallen 1998 (μ), 2002 (e)
• Lepton Number	Still viable ($0\nu\beta\beta$?)
• Baryon Number	Still viable

Maurice Goldhaber's View (1977)

- "Why did these three learned gentlemen, Weyl, Stückelberg, and Wigner, feel so sure that baryons are conserved? Well, you might say that it's very simple: they felt it in their bones. Had their bones been irradiated by the decays of nucleons, they would have noticed effects considerably exceeding "permissible radiological limits" if the nucleon lifetime were $<10^{16}$ years and if at least 10% of the nucleon rest mass were to appear as radiation absorbable in the body. That is a fairly sensitive measurement, but one can do much better by a deliberate experiment."

Fourth Workshop on GUT (1983)

- "Results are presented from the first 80 days of the IMB detector… Limits are set at the 90% CL for the lifetime/branching ratio τ/B for $p \rightarrow e^+ \pi^0$ at 6.5×10^{31} years…"
- "That bound appears to rule out minimal SU(5) with a great desert" (Marciano)

Weinberg's view (1980)

- "One is tempted to conclude that the only fundamental conservation laws left in physics are the gauge symmetries: Lorentz invariance and SU(3)×SU(2)×U(1). But then what about baryon and lepton conservation? They appear to be exact and unbroken, but they are surely not exact unbroken gauge symmetries, because we do not see the effects of a long-range vector field coupled to baryon or lepton number. The peculiar position of baryon and lepton conservation in today's physics suggests that baryon and lepton conservation may go the way of the other non-gauge symmetries, and turn out to be only approximate consequences of the gauge symmetries and renormalizability."

Baryon Number as an Accidental Symmetry

- In the Standard Model, the proton is absolutely stable
- *B* is an "accidental" symmetry, *i.e.*, there is no renormalizable interaction you can write down that violates *B* with the minimal particle content
- But once beyond the Standard Model, there is no reason for *B* to be conserved.
- Grand Unified Theories prime example of well-motivated theories that lead to proton decay
- But doesn't have to be GUTs

Baryon Number is Probably Violated

- Universe is made of baryons, no anti-baryons
  - There must have been a process in early Universe that created this asymmetry via baryon number violation
  - Such baryon number violation may (but not necessarily) lead to proton decay
- Old philosophy (*e.g.*, Yang-Mills): all conserved quantities must be local gauge charges
- Quantum gravity (virtual blackholes, wormholes) violate global (non-gauge) charges

B is Violated

- Actually, SM violates *B* (but not *B*–*L*).
  - In Early Universe (*T* > 200GeV), *W/Z* are massless and fluctuate in *W/Z plasma*
  - Energy levels for left-handed quarks/leptons fluctuate correspondingly

$\Delta L = \Delta Q = \Delta Q = \Delta Q = \Delta B = N_g$

Crucial ingredient of leptogenesis, EW baryogenesis

But Anomaly is Small

- At zero temperature, the anomaly process occurs only via tunneling $\Delta B=\Delta L=N_g$
- 't Hooft (1976) estimated its effect on two-generation case $\Delta B=\Delta L=2$

$$\tau(d\to e^+\nu_\mu)\sim 10^{120}\ \text{years}$$

- Three-generation case gives $\Delta B=\Delta L=3$

$$\tau(^3He\to e^+\mu^+\bar{\nu}_\tau)\sim 10^{150}\ \text{years}$$

Need motivated model of *B* violation $\Rightarrow$ *e.g.*, GUT

(Note any new particles potential source of *B* viol.)

What I've Learned Here

Summary of Conclusions

Overviews

- Wolfenstein: “In conclusion, the search for baryon and lepton number non-conservation represents an important probe of physics beyond the standard model and particularly new physics at a very high mass scale.”
- Dolgov: “Half a century ago: we exist, so baryons are conserved.

  Now: we exist, so baryons are not forever.”
- Mohapatra: $\Delta L=2$ m_ν & *q–l* unification may imply $\Delta B=2$ diquark Higgs + SUSY allows *n*-*n*bar oscillation to probe energy scale up to 10^{12} GeV!

GUT models

- Dutta: minimal SO(10)
  - U_{e3}=0.05–0.12
  - Cancellation in $p \to \bar{\nu} K^0$, viable
- Raby: orbifold GUT from heterotic string
  - $p \to \bar{\nu} K^0$ tends to be too large!
- Fukuyama: difficulties with 4D SO(10) GUT, intermediate scales, proton decay, etc. orbifold GUT may be better

proton decay

- Pati: $\tau(p\to e^+\pi^0)=10^{35\pm1}$ years
  $\tau(p\to\bar{\nu}K^0)=10^{33-34}$ years
- Nath: minimal SU(5) dead because $\bar{p}\to\nu K^0$
  various suppression mechanisms
  more precise calculations needed
- Wiesenfeldt: non-SUSY trinification gives $p\to\bar{\nu}K^0$ without $p\to e^+\pi^0$
- Hope for ~Mt experiments!

n-nbar oscillation

Because! Why not?

- Gabadadze: virtual “baby brane” or blackholes can suck in baryon number, potentially observable
- Shrock: extra *D* models with localized fermions suppress proton decay but can lead to observable *n-n*bar oscillation
- Babu: post-sphaleron baryogenesis model motivates $\tau_{n\text{-}nbar} \sim 10^{9-11}$ sec
- Dolgov: low-scale gravity + *R*-parity violation can do baryogenesis, $\tau_{n\text{-}nbar} \sim 10^{9}$ sec
- Vertical experiments ~×1000 improvement!?

Mirror World

- Dolgov: neutron to mirror neutron oscillation, no matter instability but neutron disappearance
- Kerbikov: important to deal with wave packets properly
- Schmidt: possibility of reappearance experiment

leptogenesis

- Petcov: CP violation in LBL oscillation may be the same phase for leptogenesis
- Di Bari: Yet lower bound $M_1 > 10^9$GeV robust for hierarchical spectrum. Fully quantum kinetic treatment needed.

$0\nu\beta\beta$

- Kayser: “Absent L-nonconserving interactions from beyond the Standard Model, $0\nu\beta\beta$ requires Majorana neutrino mass”
- Petcov: “Determining the nature - Dirac or Majorana, of massive neutrinos is of fundamental importance for understanding the origin of neutrino masses.”
- Hirsch: many new physics possibilities for $0\nu\beta\beta$, not easy to tell them apart
- Very active area in experiment

Sterile Neutrinos

- Hung: mirror world restores parity. EW-scale ν_R, L violation at colliders
- Kusenko: may help with baryogenesis, pulsar kicks, warm or cold dark matter
- Lavender: old beam dump experiment suggests ν_a- ν_s oscillation, tension with Bugey. CPT violation?
- Walsh: 3 ν_s with $U(1)_{B-L}$ matter effect can fit LSND & Mini-BooNE

Lepton Flavor Violation

- Tobe: Probe to TeV-scale physics (SUSY, Little Higgs, etc), even to the origin of neutrino mass
- Bambi: low-scale gravity *dangerous* $\tau_p \sim M_*^4/m_p^5$! Classical BH conjecture may help suppress it, other consequences on LFV, *n*-*n*bar etc
- Impressive experimental search efforts at Babar, Belle, NA-48, MEG, future μ-*e* conversion, …

Colliders

- Dawson: LHC coming! Together with Tevatron, ILC,

  "Discoveries coming soon"
- Savinov: impressive array of search programs in place
- Okada: Di-quarks in Pati-Salam models interesting at the LHC

Fascinating!

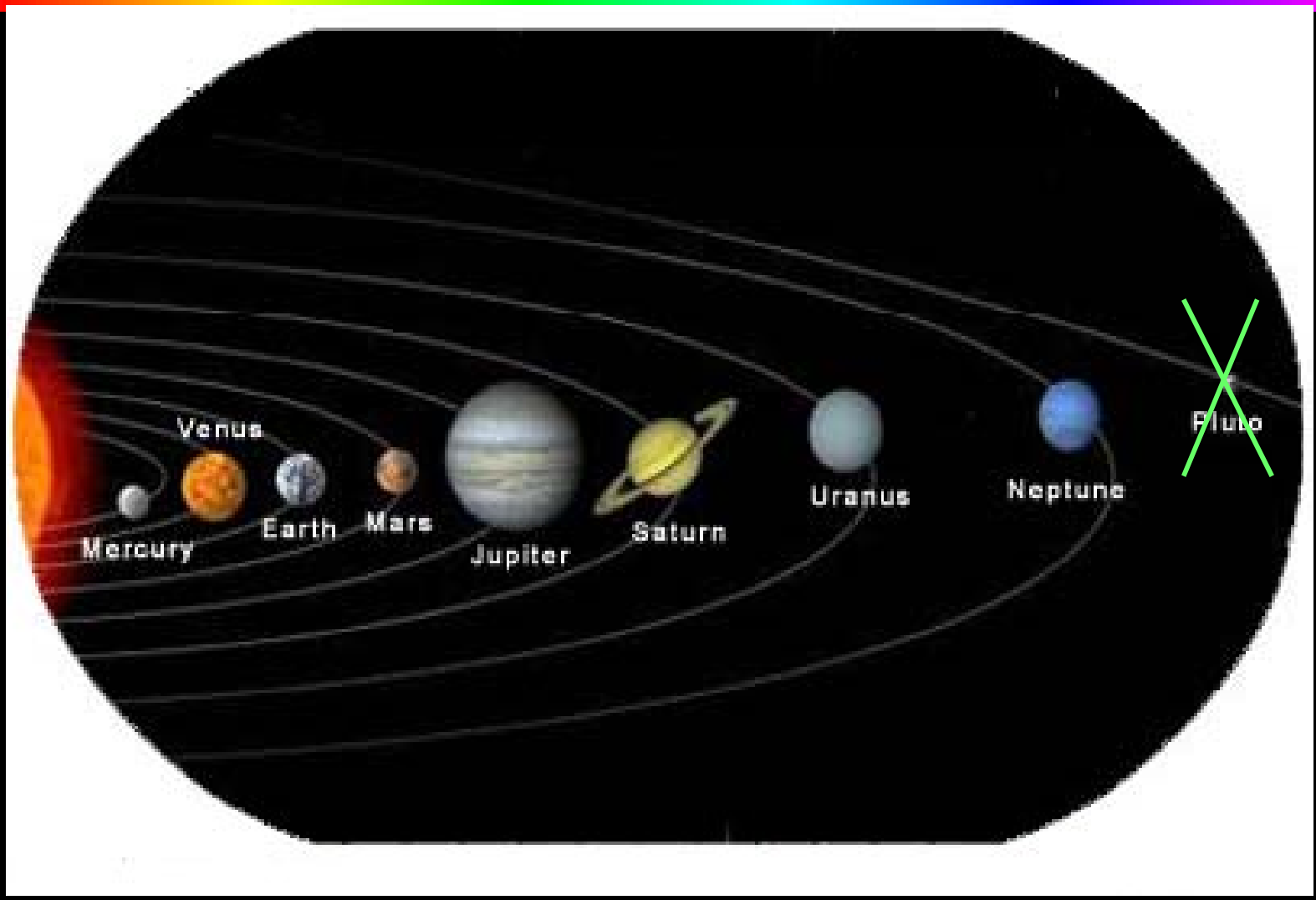
- Yoshimura: metastable atomic levels may decay via ν–νbar emission, tag it with laser-activated emission. May distinguish Dirac vs Majorana, normal vs inverted. Possibly "detect" relic neutrinos by observing Pauli blocking effects.

How do we make real progress?

Neutrino Theory Highlights requires many many approaches

- Case study: can we prove seesaw mechanism? Leptogenesis?
  - Nature needs to be kind to us
  - We also need to be patient
- Need many *many different approaches* to come together
- Electroweak theory required cosmic rays, radioactive decays, fixed target expts, colliders, and *a lot of thinking*!

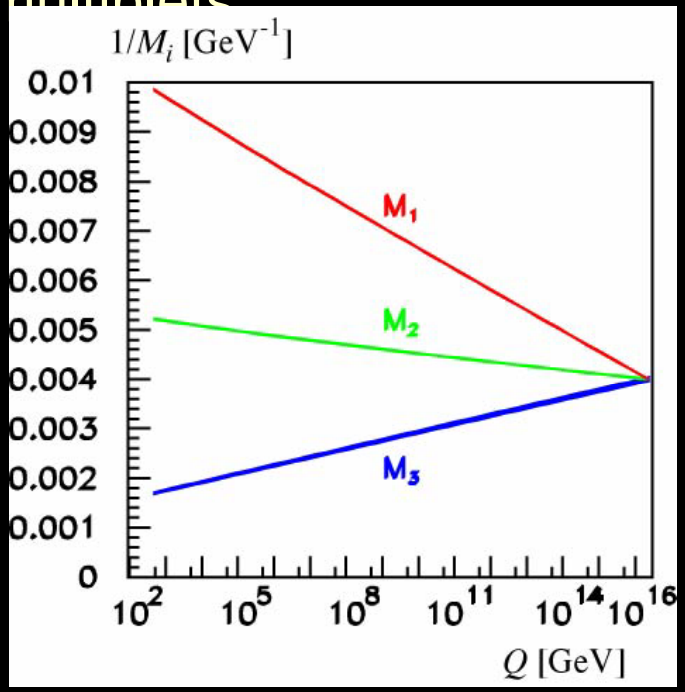
Alignment of the Planets

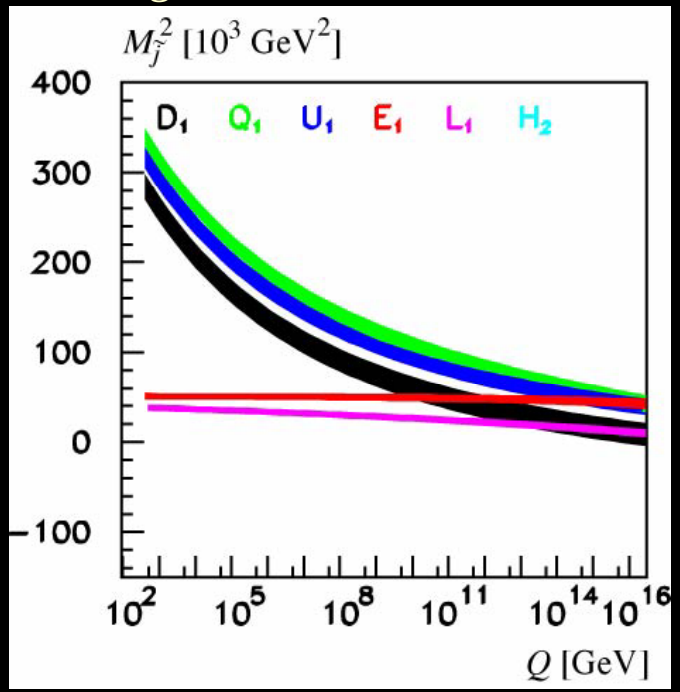


A scenario to "establish" seesaw

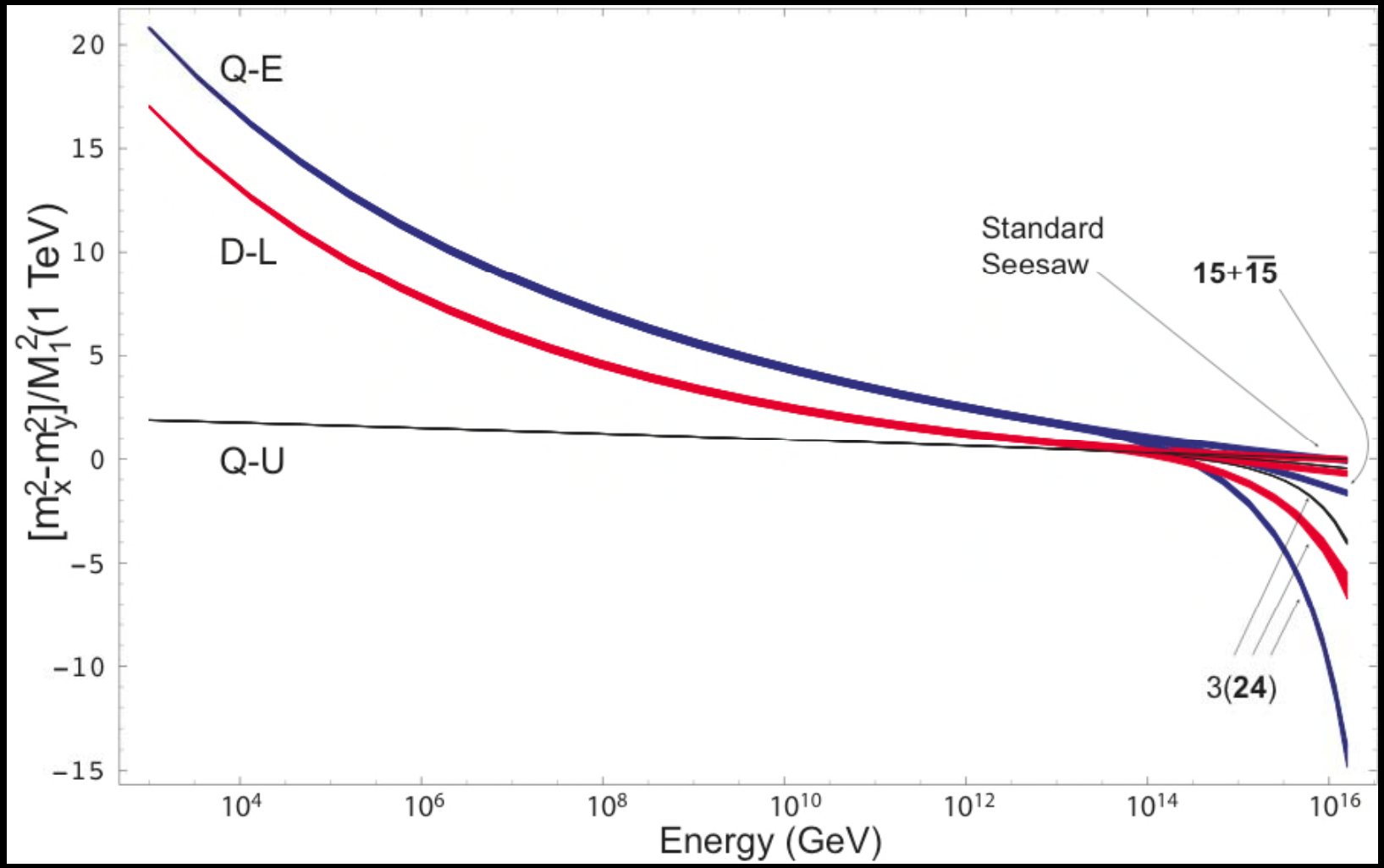
- Gaugino masses test unification itself independent of intermediate scales and extra complete SU(5) multiplets
- Scalar masses test beta functions at all scales, depend on the particle content

Kawamura, HM, Yamaguchi





singlets between TeV and M_{GUT}



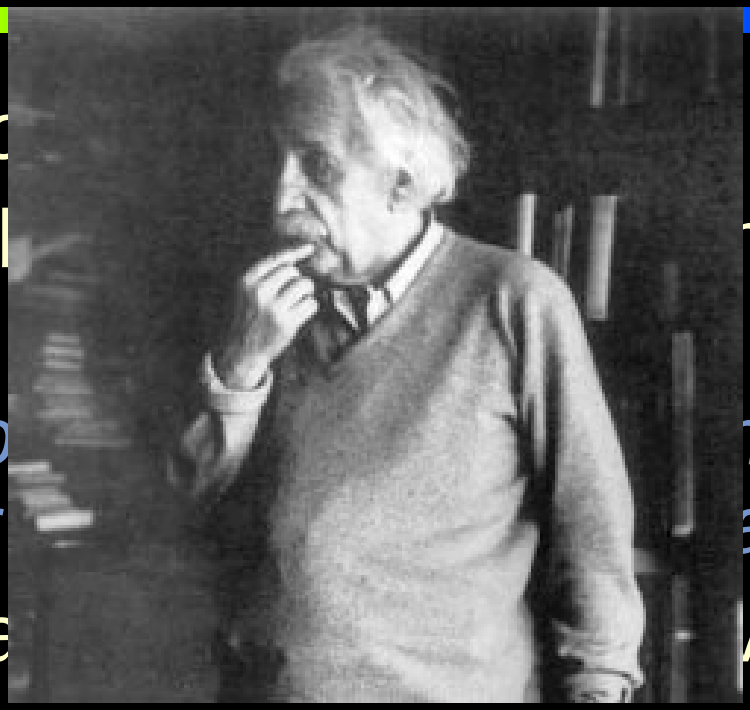
Plausible scenario

- No gauge non-singlets between TeV and M_{GUT}
- $0\nu\beta\beta$ found
- Dark matter concordance between collider, cosmology, direct detection$\Rightarrow$ not R_p violation
- Must be due to gauge-singlets: *seesaw!*

- $\not{CP}$ in ν-oscillation found
- Lepton flavor violation limits ($\mu\to e\gamma$, $\mu\to e$ conversion, $\tau\to\mu\gamma$ etc) improve, or discovered
- Tevatron and EDM (*e* and *n*) exclude Electroweak Baryogenesis
- CMB *B*-mode polarization gives tensor mode

If this happens, we will be led to believe seesaw+leptogenesis (Buckley, HM)

Conclusions



- *Standard Mo*
- There must l ne standard model
- *The most po nergy physics is to look for ation laws*
- But no one a veal what is going on
- By collection of experiments: underground, sky, accelerators, and *a lot of thinking*

I feel lucky to be in this exciting era!

The Iνvisibles


Disney presents a PIXAR film
THE INCREDIBLES
NOW PLAYING
© Disney Enterprises, Inc./Pixar Animation Studios. All Rights Reserved.