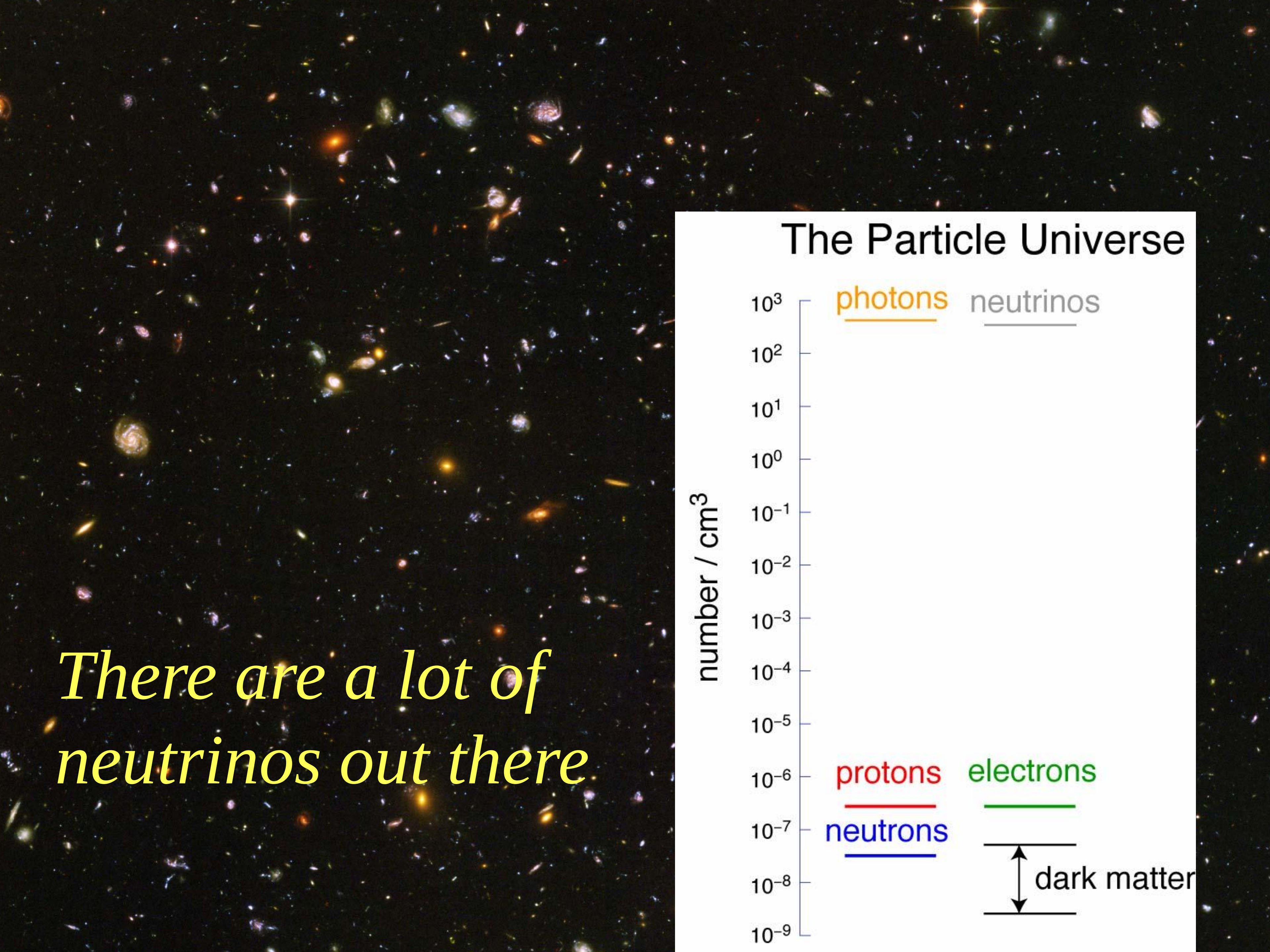
Theory Overview

Hitoshi Murayama (IPMU & Berkeley)

APS/JPS meeting 0νββ seminar

Oct 11, 2009, Waikoloa Hilton



There are a lot of neutrinos out there
The Particle Universe
number / cm3
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
photons
neutrinos
protons
electrons
neutrons
dark matter

Window to Short Distances

- 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)

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

$$\begin{aligned}\mathcal{L}_6 &= QQQL, \bar{L}\sigma^{\mu\nu}W_{\mu\nu}He, \\ &\quad \epsilon_{abc}W_\nu^{a\mu}W_\lambda^{b\nu}W_\mu^{c\lambda}, (H^\dagger D_\mu H)(H^\dagger D^\mu H), \cdots\end{aligned}$$

Unique Role of Neutrino Mass

- Lowest order effect of physics at short distances
- Tiny effect $(m_\nu/E_\nu)^2 \sim (0.1\,\mathrm{eV}/\mathrm{GeV})^2 = 10^{-20}$!
- 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.

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Neutrinos are Left-handed

Helicity of Neutrinos*

M. GOLDHABER, L. GRODZINS, AND A. W. SUNYAR

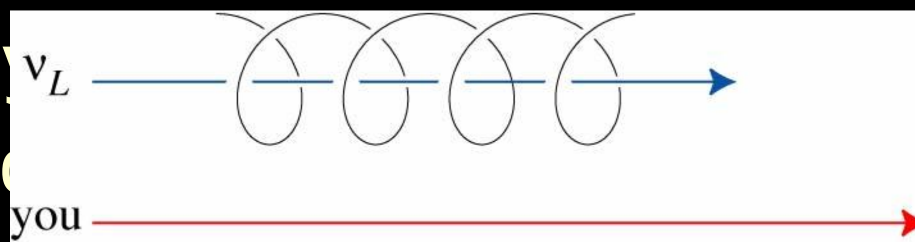
Brookhaven National Laboratory, Upton, New York

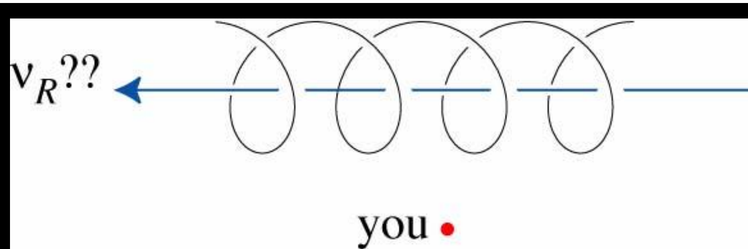
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] $0-$, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

Neutrinos must be Massless

- All neutrinos left-handed ⇒ massless
- If the ... at speed ...



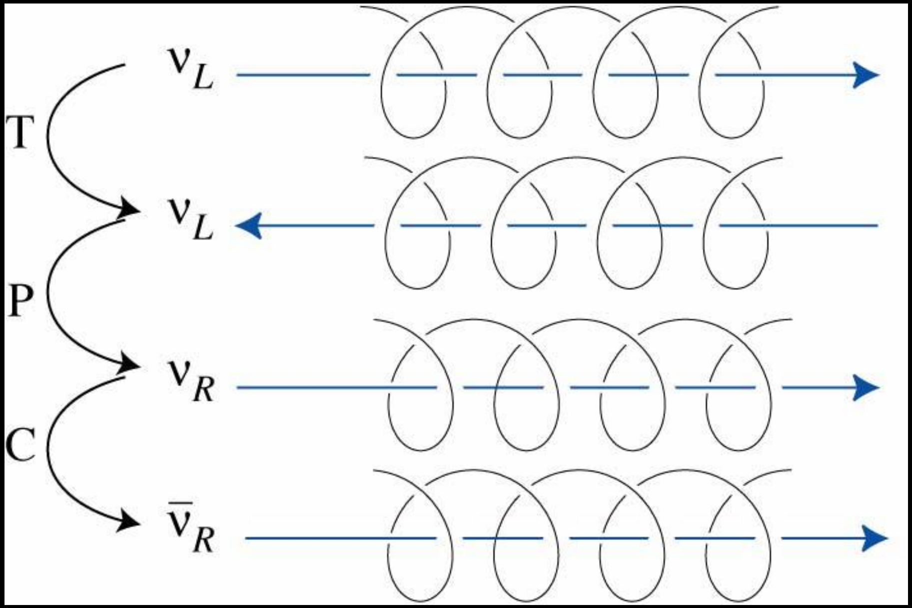


- Now neutrino right-handed??

⇒ contradiction ⇒ can't have a mass

Anti-Neutrinos are Right-handed

- CPT theorem in quantum field theory
  - C: interchange particles & anti-particles
  - P: parity
  - T: time-reversal
- State obtained by CPT from ν_L must exist: $\bar{\nu}_R$



Other Particles?

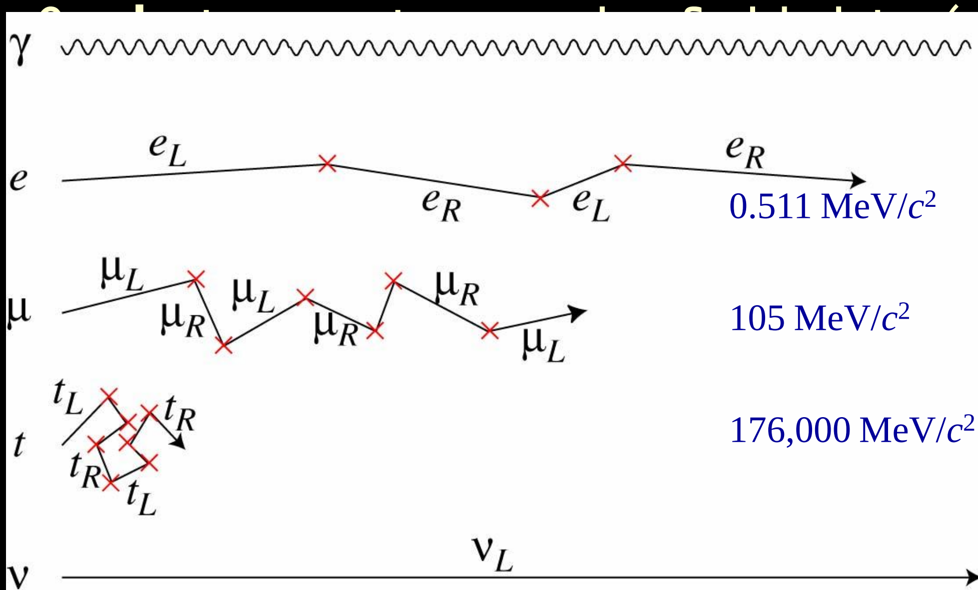
- What about other particles? Electron, muon, up-quark, down-quark, etc
- We say "weak force acts only on left-handed particles" yet they are massive.

Isn't this also a contradiction?

No, because we are swimming in a

Universe is filled with Higgs

- “Empty” space filled with a BEC: cosmic superconductor
- Particles bump on it, but not photon because it is neutral.
- massive), and particles mix ⇒

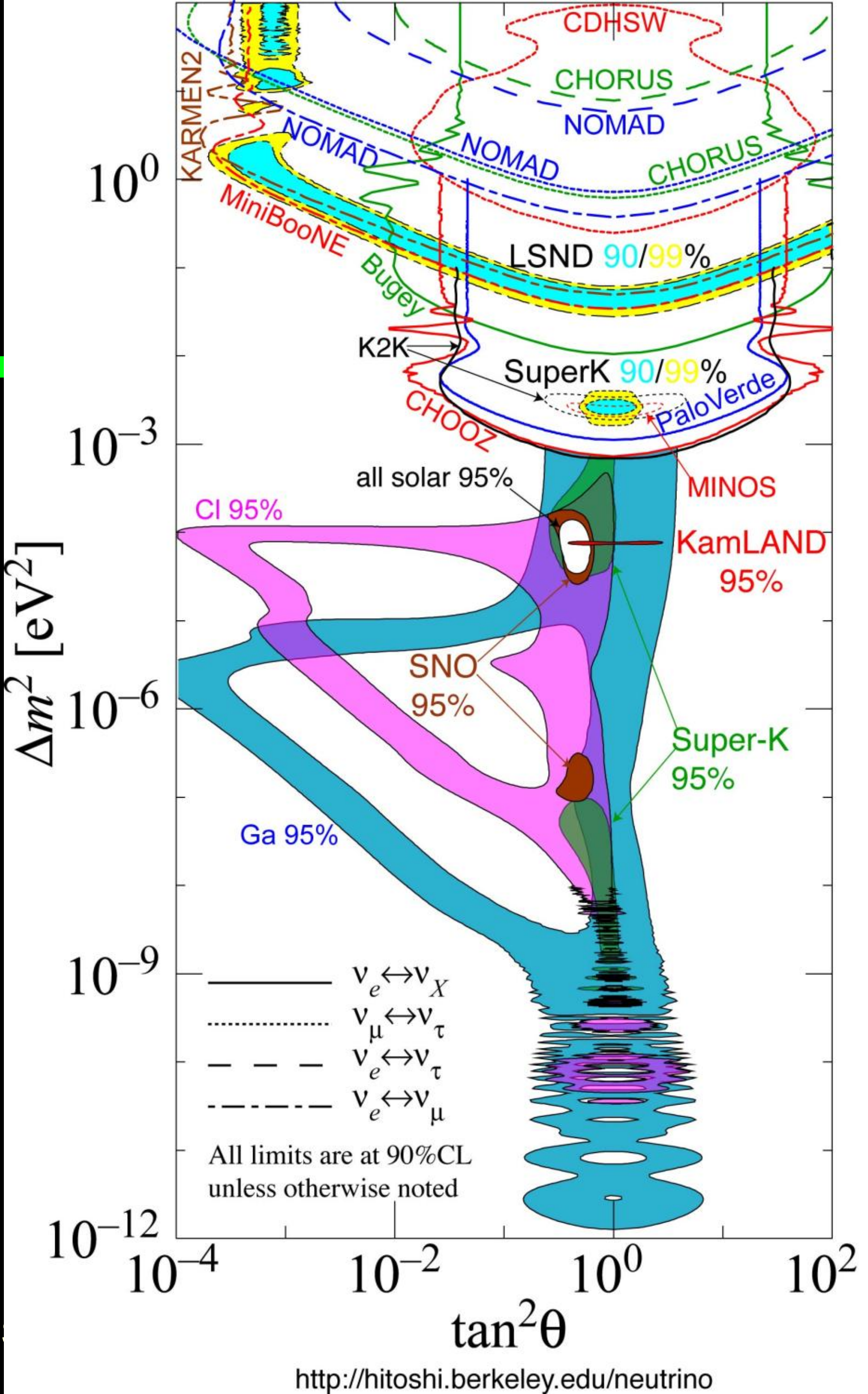


But neutrinos can’t bump because there isn’t a right-handed one ⇒ stays massless

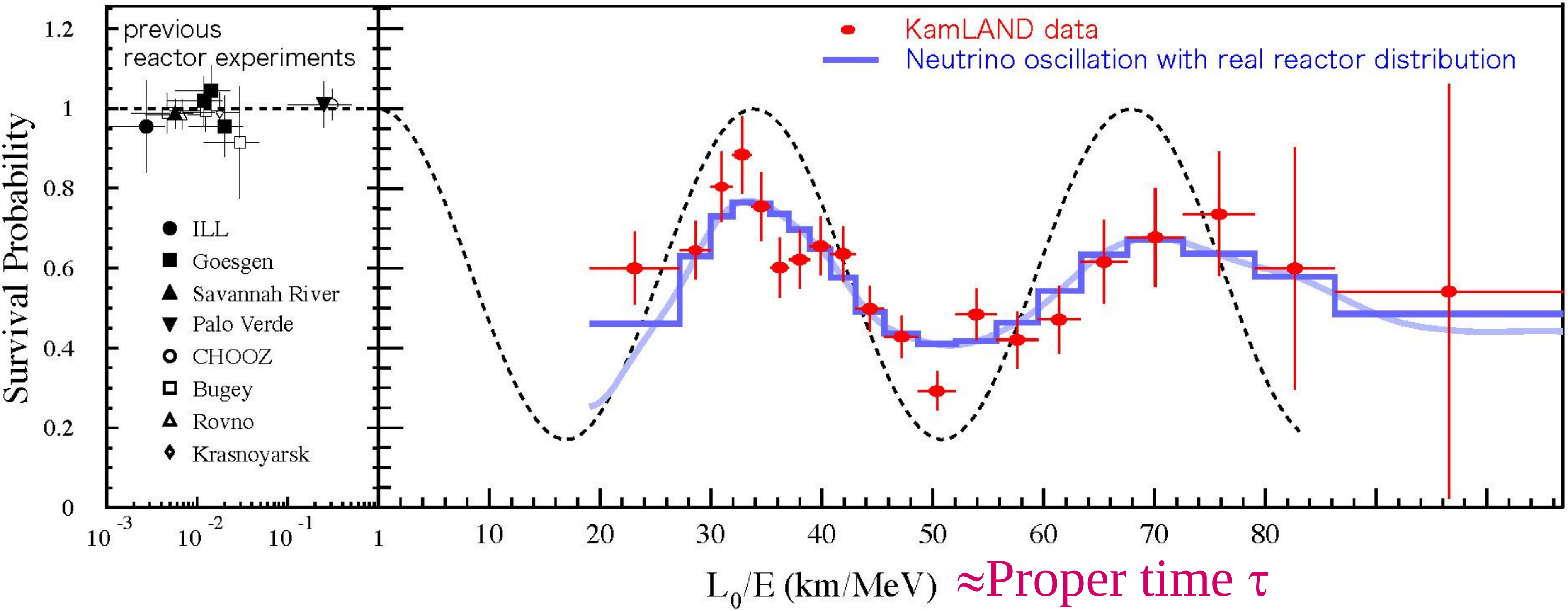
Lot of effort since '60s

Finally convincing evidence for "neutrino oscillation"

Neutrinos have tiny but finite mass



KamLAND '08
neutrinos do oscillate!

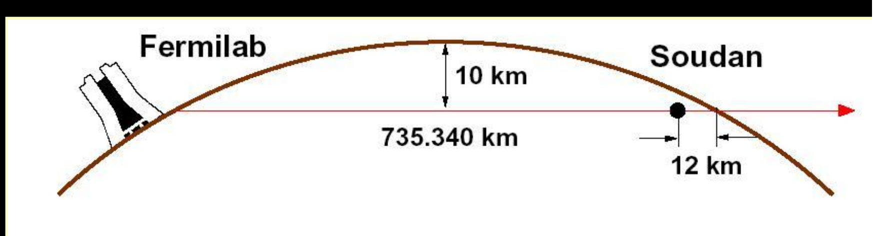


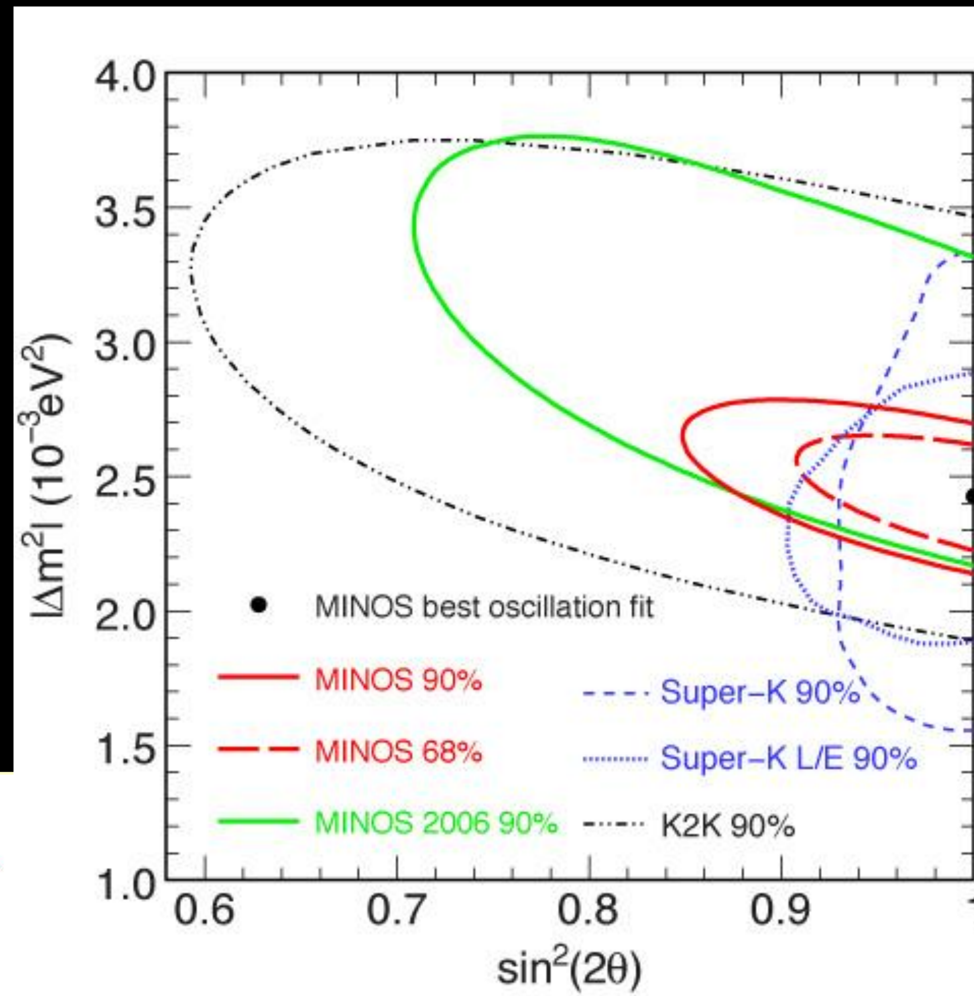
≈Proper time τ

L_0=180 km

MINOS '08

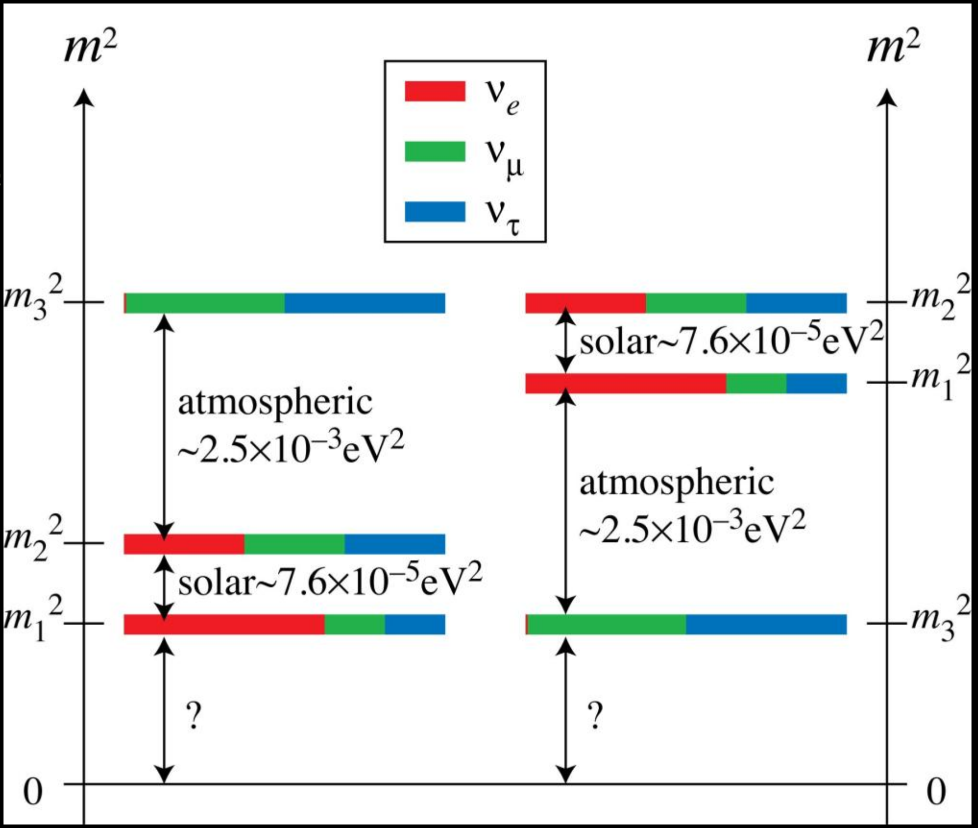
- SuperK atmospheric neutrino result confirmed with m



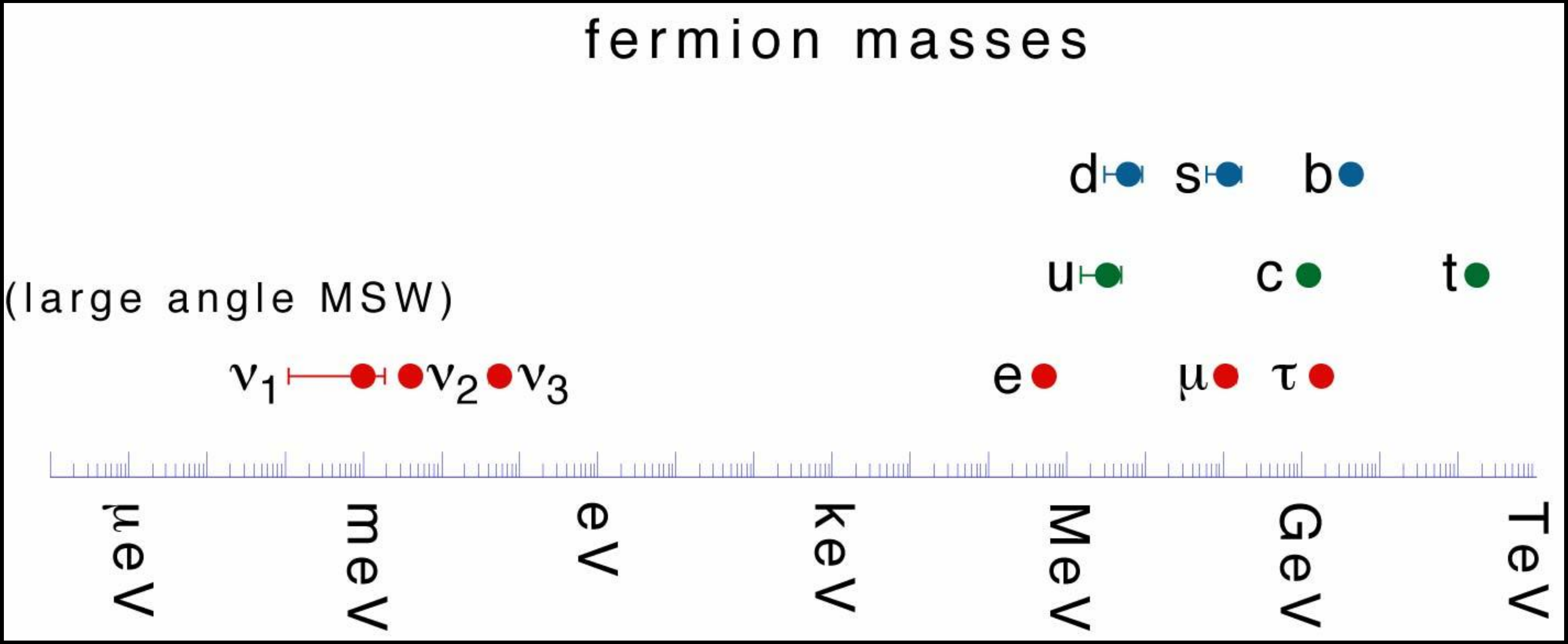


Raised More Questions

- Dirac or Majorana?
- Absolute mass scale
- How small is θ_{13}?
- CP Violation?
- Mass hierarchy?
- Is θ_{23} maximal?



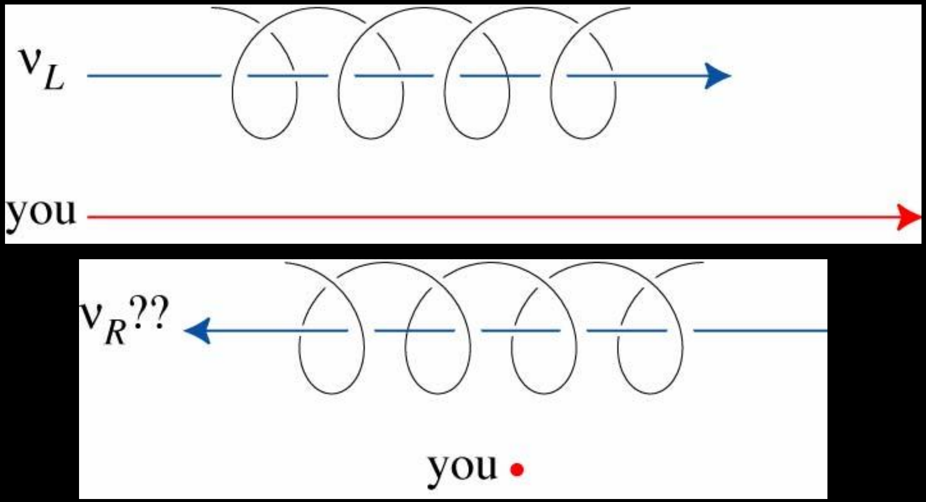
Mass Spectrum



What do we do now?

Neutrinos have mass

- They have mass. Can't go at speed of light.

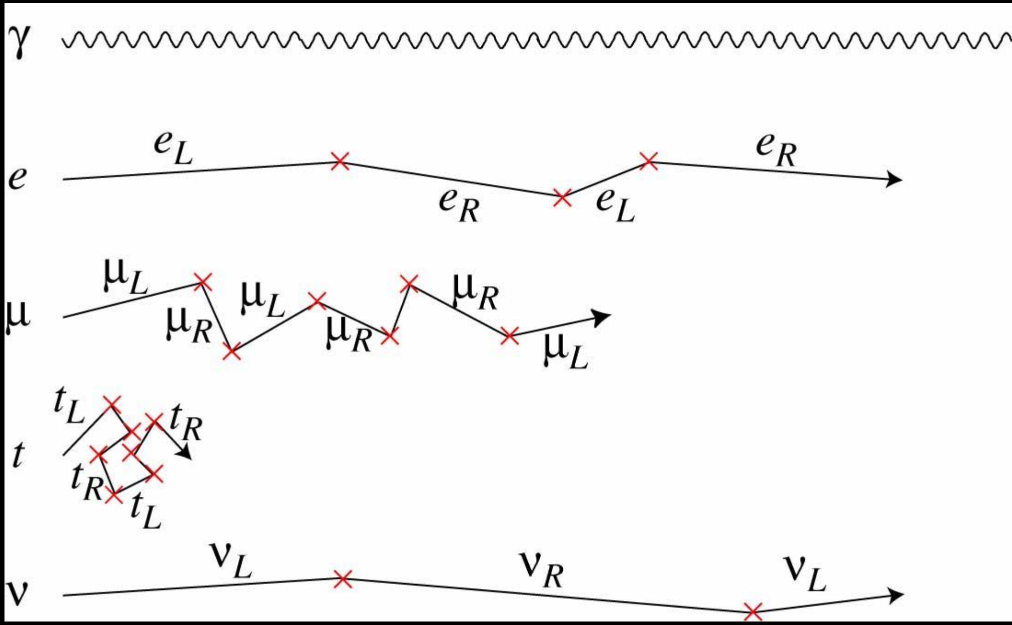


- What is this right-handed particle?
  - New particle: right-handed neutrino (Dirac)
  - Old anti-particle: right-handed anti-neutrino (Majorana)

Two ways to go

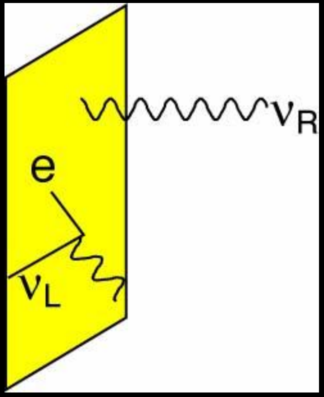
(1) Dirac Neutrinos:

- There are new particles, right-handed neutrinos, after all
- Why haven't we seen them?
- Right-handed neutrino must be *very very weakly coupled*
- Why?



Extra Dimension

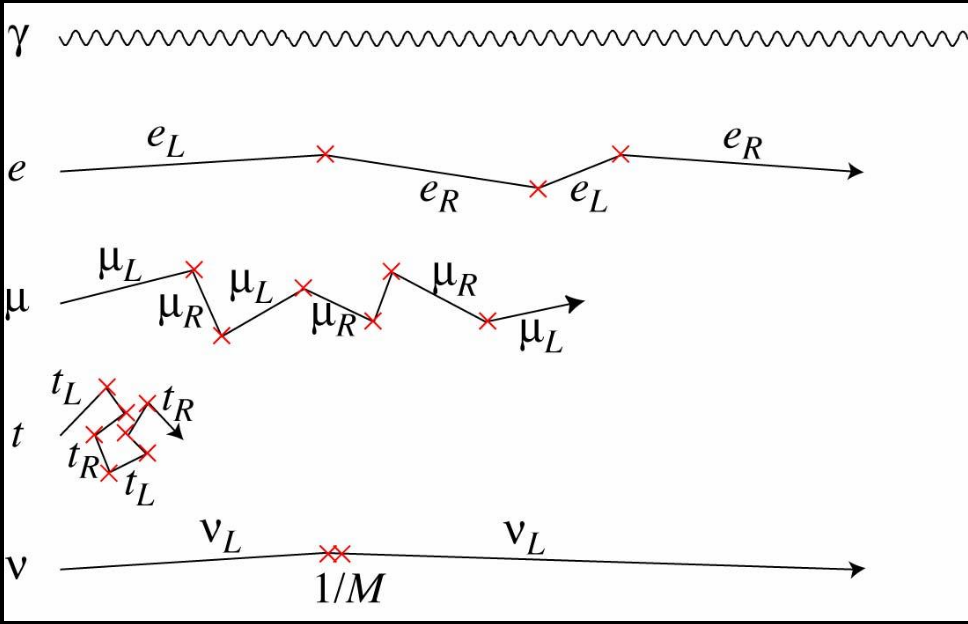
- All charged particles are on a 3-brane
- Right-handed neutrinos SM gauge singlet
  $\Rightarrow$ Can propagate in the "bulk"
- Makes neutrino mass small
- Or SUSY breaking
- Or late-time phase transition



Two ways to go

(2) Majorana Neutrinos:

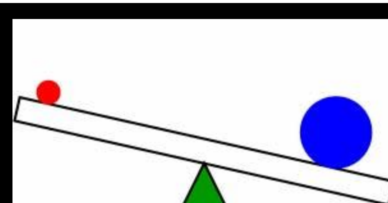
- There are no new light particles
- What if I pass a neutrino and look back?
- Must be right-handed *anti*-neutrinos
- No fundamental distinction between neutrinos



Seesaw Mechanism

- Why is neutrino mass so small?
- Need right-handed neutrinos to generate neutrino mass

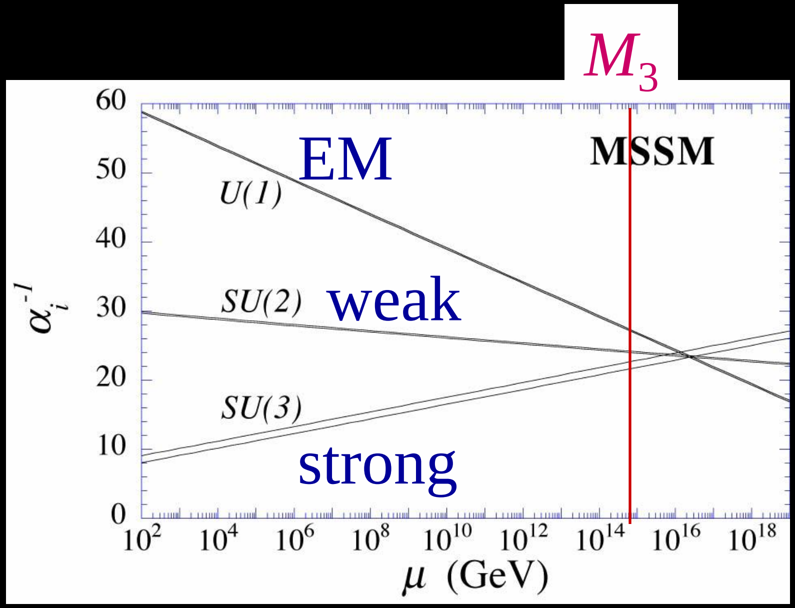
but ν_R SM neutral



To obtain $m_3 \sim (\Delta m^2{}_{\mathrm{atm}})^{1/2}$, $m_D \sim m_t$, $M_3 \sim 10^{15}$GeV (GUT!)

Grand Unification

- electromagnetic, weak, and strong forces have very different strengths
- But their strengths become *the same* at 10^{16} GeV if supersymmetry
- To obtain $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim m_t$
  $\Rightarrow M_3 \sim 10^{15}$GeV!



Neutrino mass may be probing unification:

Einstein's dream

Anti-matter is dangerous

Matter and Anti-Matter Early Universe

Matter	Anti-matter
1,000,000,002	1,000,000,000

Matter and Anti-Matter Current Universe

us

2

Matter

Anti-matter

The Great Annihilation

Matter and Anti-Matter Beginning of Universe

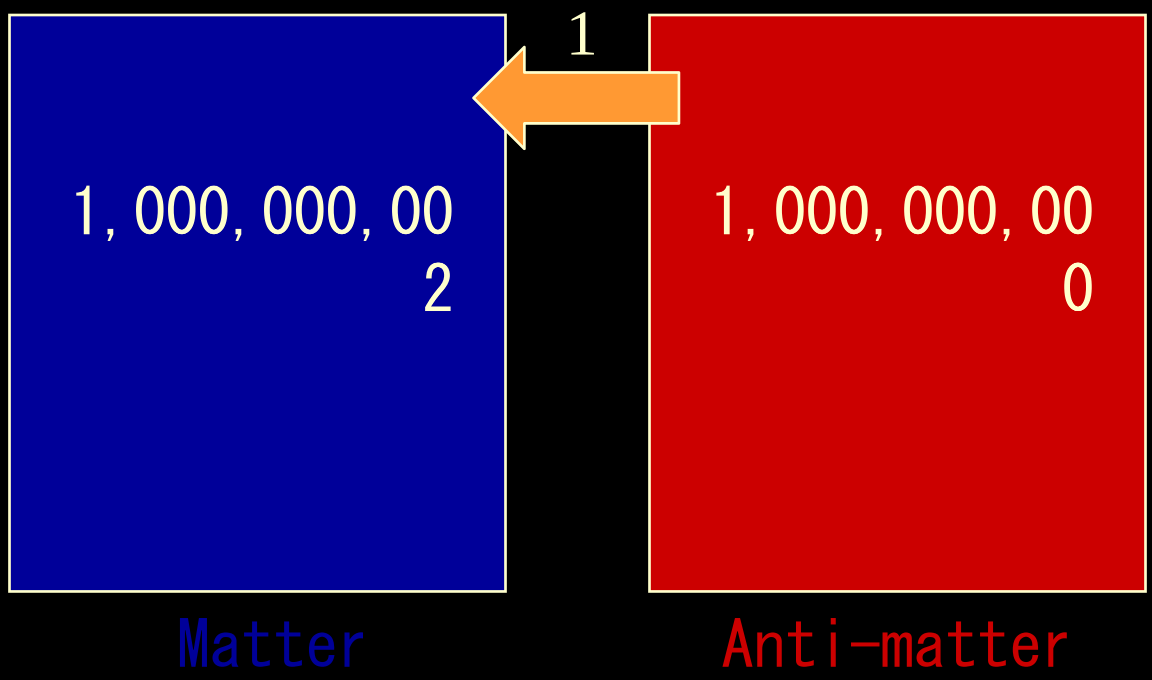
1,000,000,001

Matter

1,000,000,001

Anti-matter

Matter and Anti-Matter Early Universe



Matter and Anti-Matter Current Universe

us

2

Matter Anti-matter

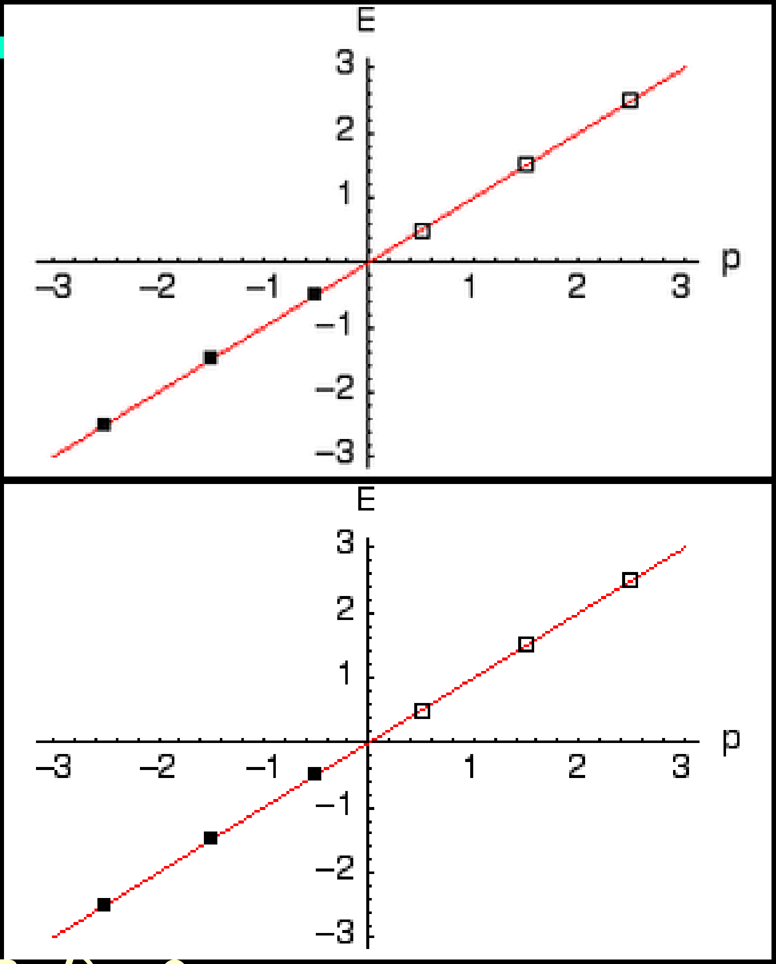
The Great Annihilation

Baryogenesis

- What created this tiny excess matter?
- Need to turn a bit of anti-matter into matter
- *Necessary* conditions for baryogenesis (Sakharov):
  - Baryon number non-conservation
  - CP violation
    (subtle difference between matter and anti-matter)
  - Non-equilibrium
    $\Rightarrow \Gamma(\Delta B>0) > \Gamma(\Delta B<0)$
- It looks like neutrinos have no role in this…

Electroweak Anomaly

- Actually, SM converts *L* (ν) to *B* (quarks).
  - In Early Universe (T > 200GeV), W is massless and fluctuate in W *plasma*
  - Energy levels for left-handed quarks/leptons fluctuate correspon-



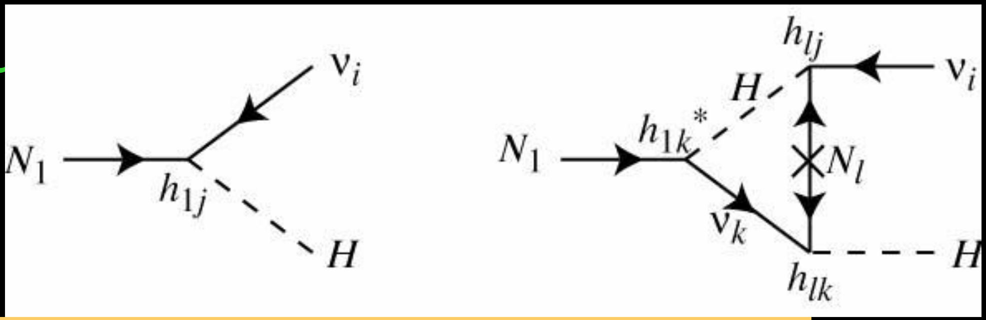
$$\Delta L = \Delta Q + \Delta Q + \Delta Q = \Delta B = 1 \Rightarrow \Delta(B-L) = 0$$

More precisely

- What I showed on the previous slide is a toy model of 1+1-D U(1) gauge theory
- Think of 1D space as S^1, while U(1)=S^1
- non-trivial topology π_1(U(1))=Z, vacuum has winding #
- In 3+1-D SU(2) gauge theory, think of 3D space as S^3, while SU(2)=S^3
- non-trivial topology π_3(SU(2))=Z, vacuum has winding #
- In either case, anomaly violates particle number
- Atiyah-Patodi-Singer index theorem relates

Leptogenesis

- You generate *Lepton Asymmetry* first.
- Generate *L* from the direct CP violation in right-handed neu
- Like ε'/ε

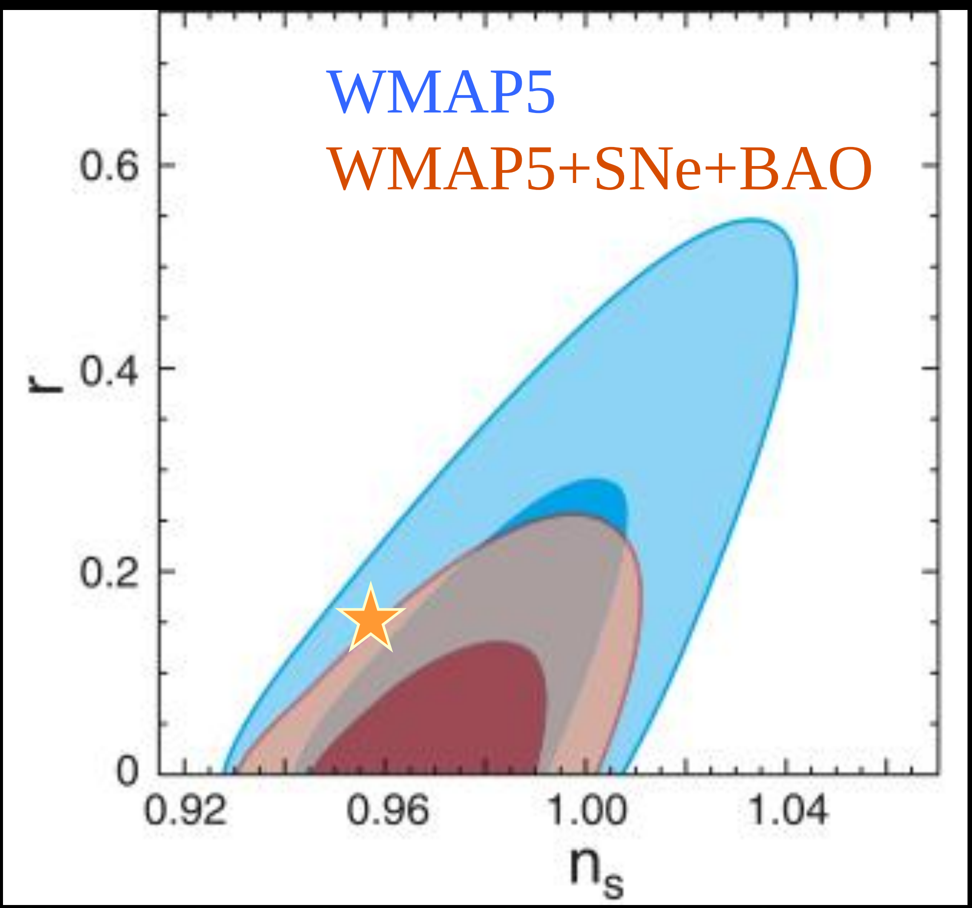


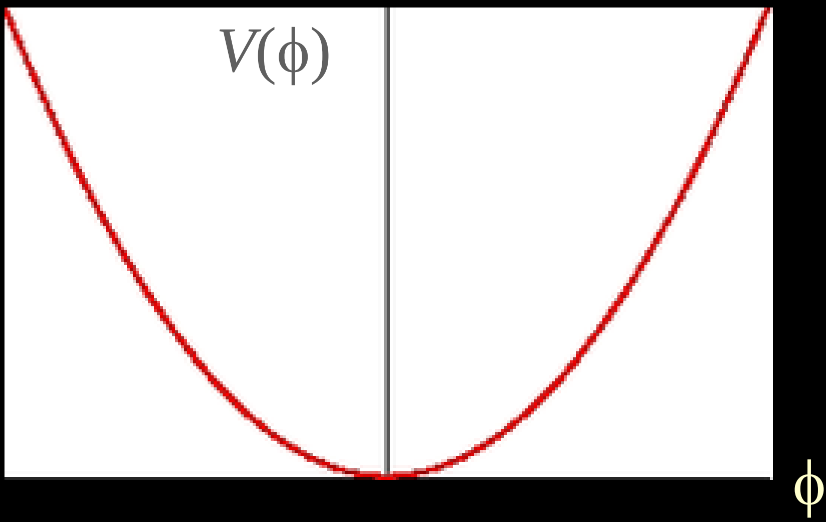
- *L* gets converted to *B* via EW anomaly

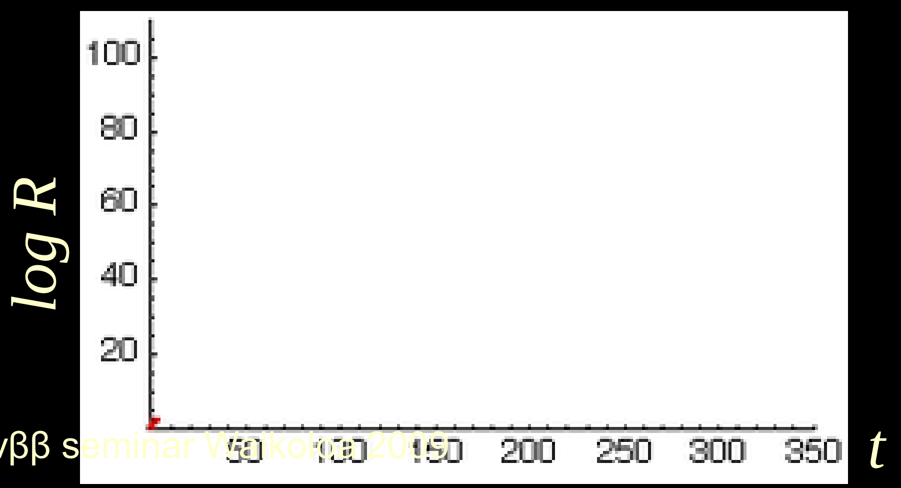
$\Rightarrow$ More matter than anti-matter

$\Rightarrow$ *We have survived "The Great Annihilation"*

Origin of Universe







Neutrino is mother of the Universe?

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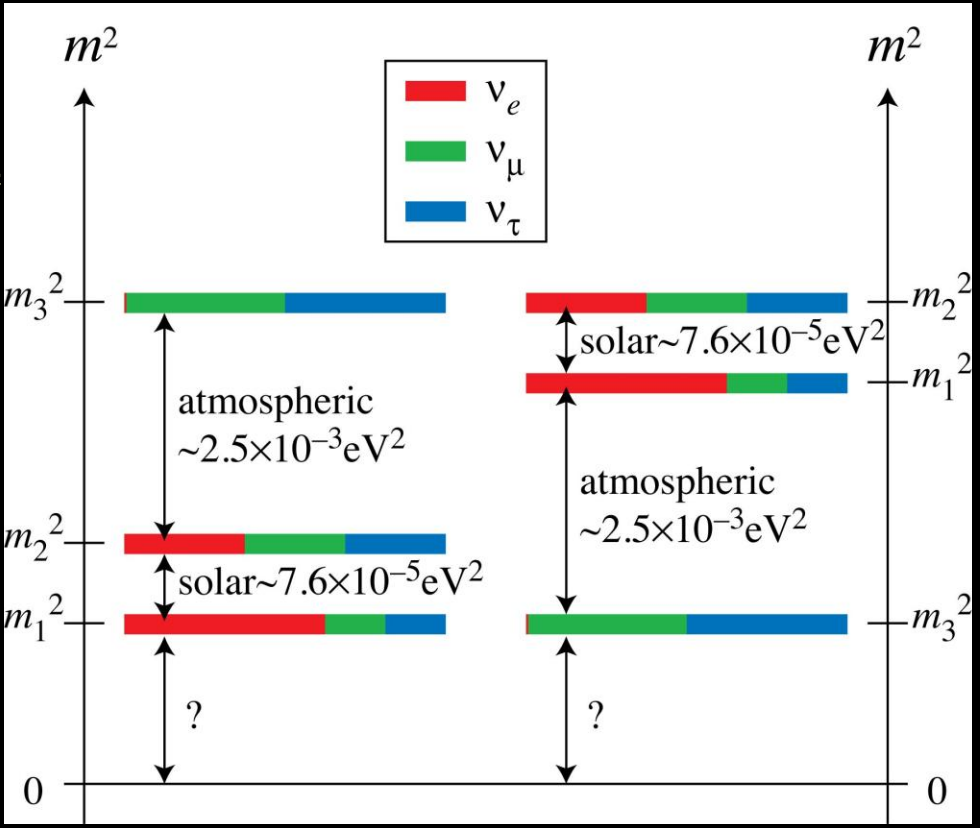

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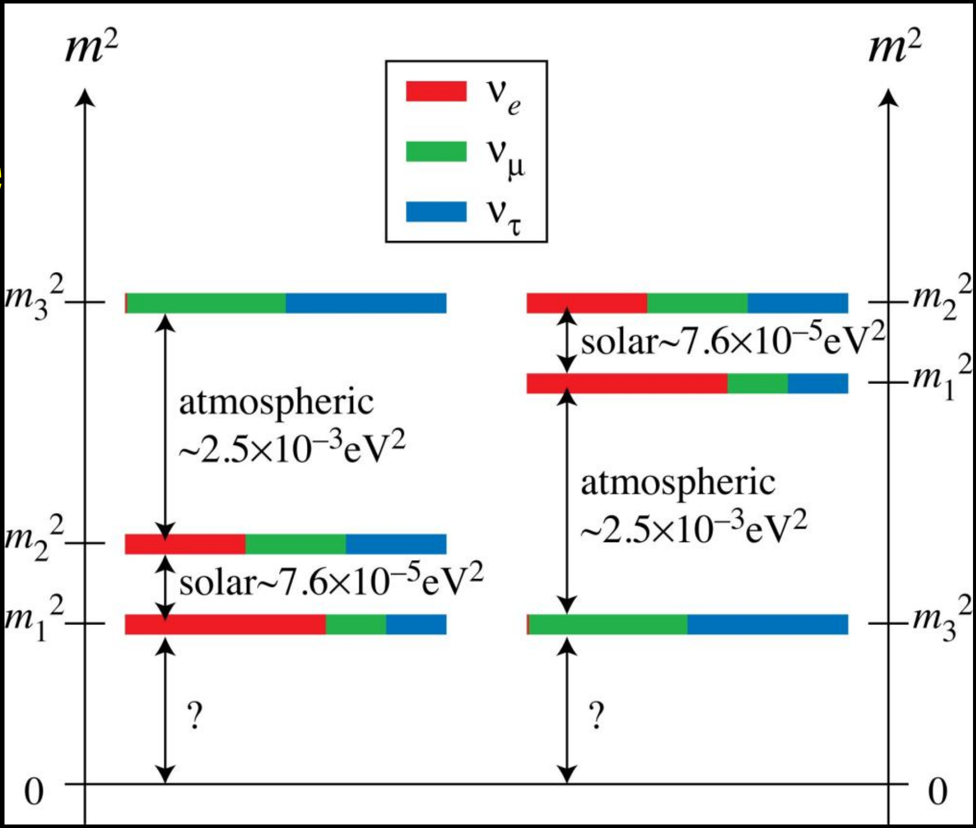
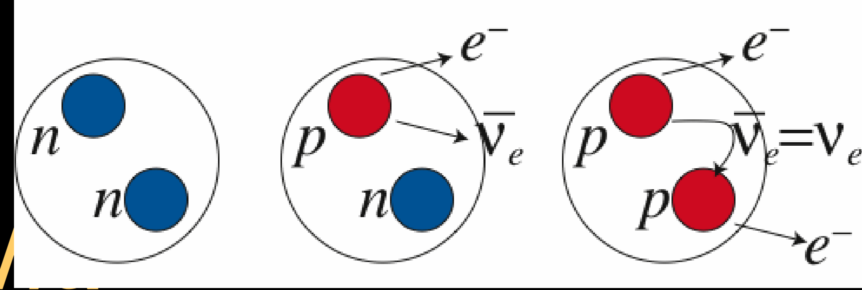
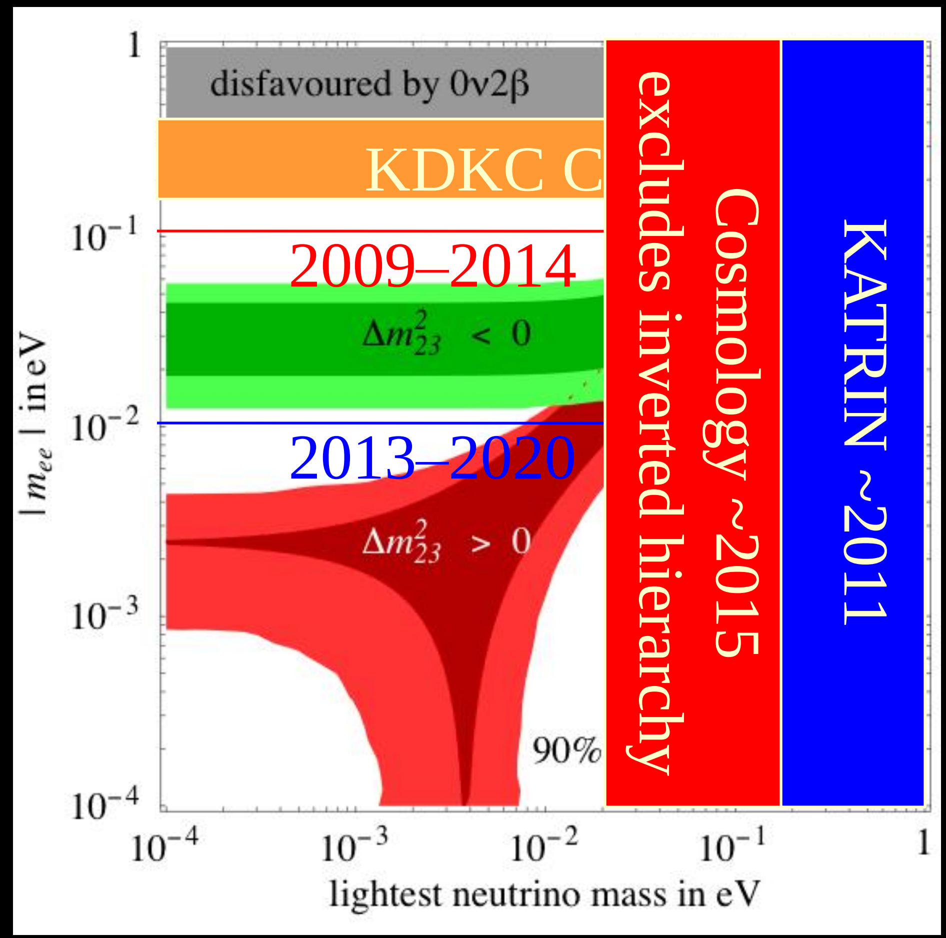


Dirac vs Majora

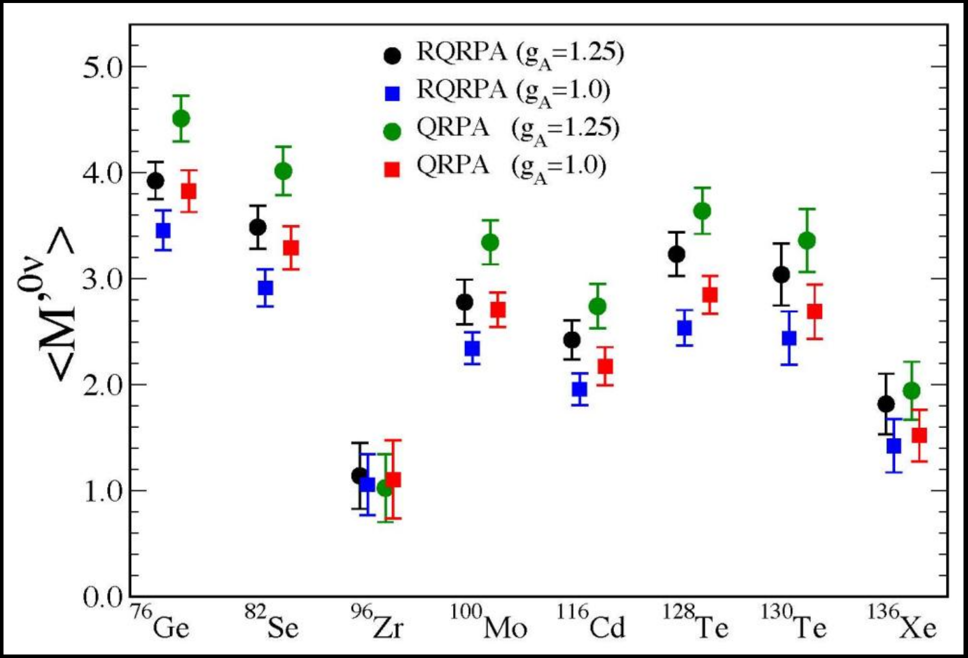


- Many neutrinoless double beta decay experiments aiming at below 0.1eV
- *Turn anti-matter into matter!*
- Thanks to SNO, θ_{12} not maximal, *lower limit* when inverted



Nuclear matrix elements

- $2\nu\beta\beta$ and $0\nu\beta\beta$ matrix elements are *different*!
- Difficult to obtain model-independent constraints
- Need to be calculated in models
- Systematic errors difficult to calibrate
- QRPA models getting



Rodin, Faessler, Šimkovic, Vogel
Nucl. Phys. A766, 107 (2006) erratum

Need multiple nuclear isotopes for believable limits!

Raised More Questions

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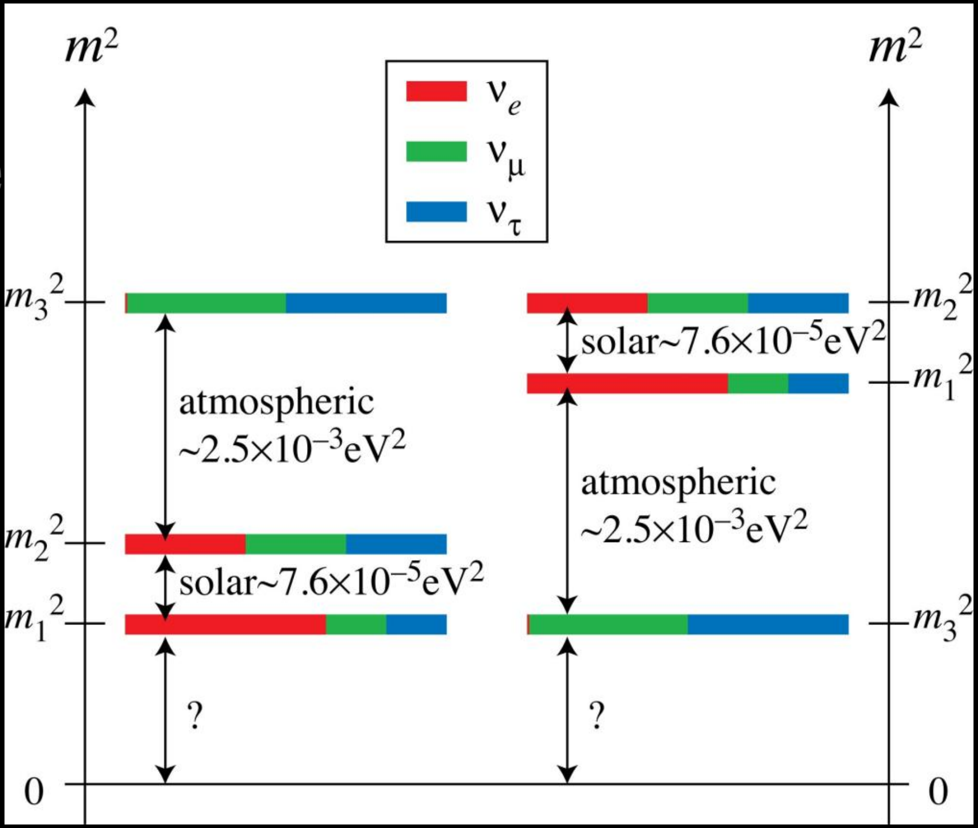
$\Rightarrow$1%@T2K, NOνA



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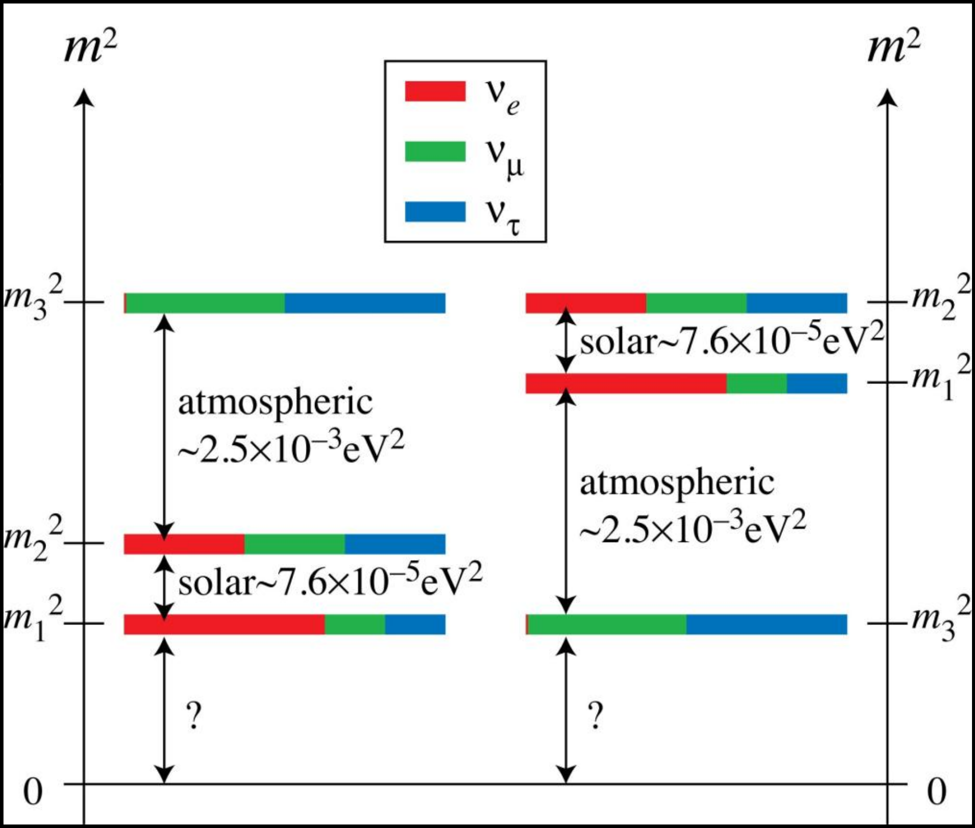
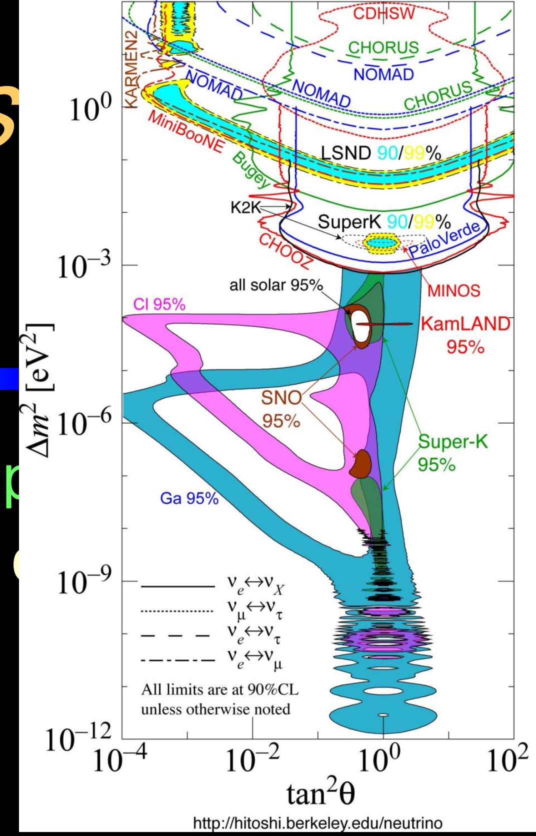
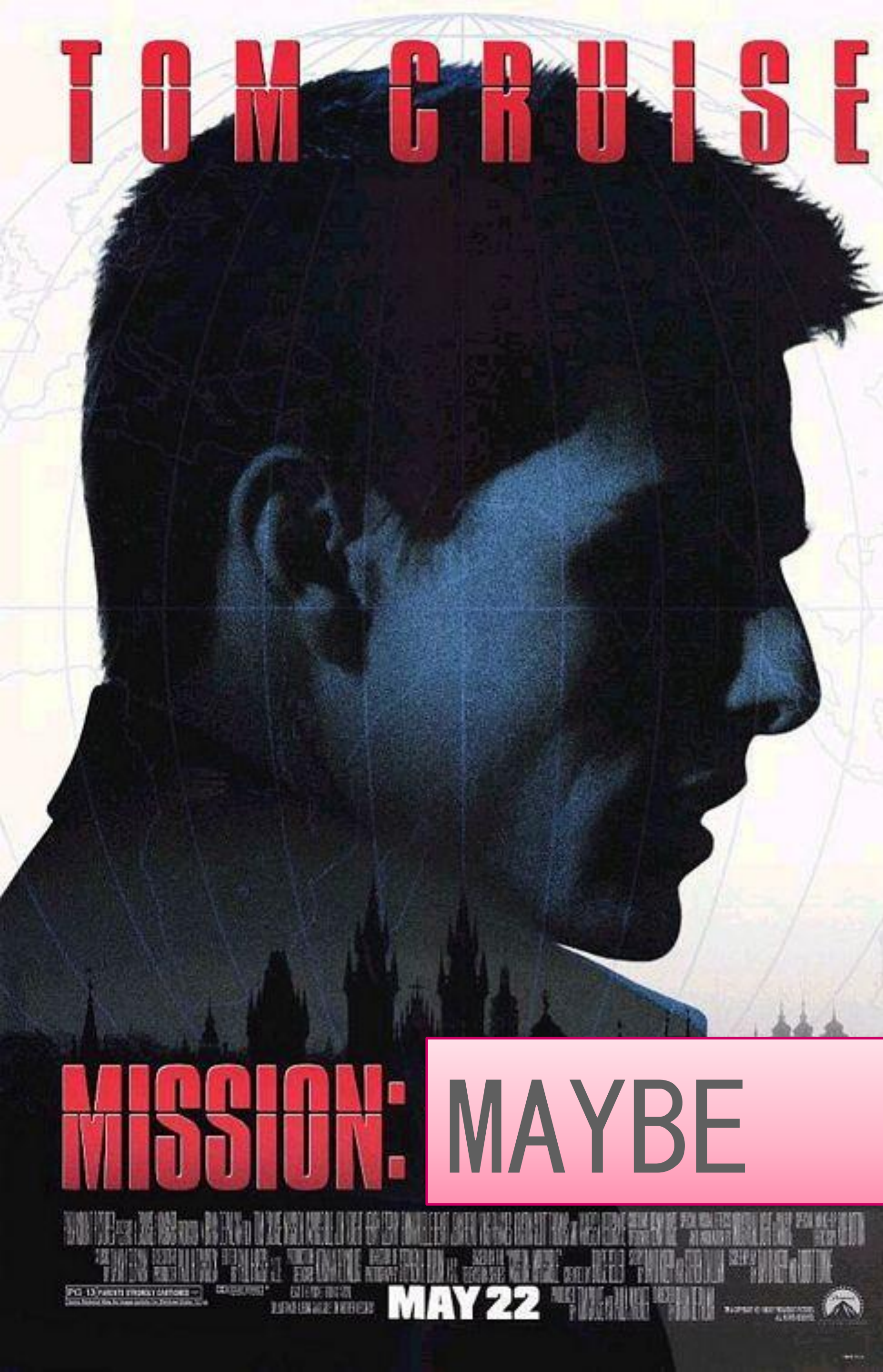


Now that LMA is established...



- Dream case for neutrino oscillation p
- Δm^2_{solar} within reach of terrestrial e
- Even CP violation may be probed by
  - neutrino superbeam
  - muon-storage ring neutrino factory
  - beta beam
- Possible only if
  - Δm_{23}^2, s_{23} large (near maximal)
  - Δm_{12}^2, s_{12} also large (LMA)
  - θ_{13} large enough: *it decides the future!*
  - *Reactor and long-baseline experiments*

Can we prove seesaw?


TOM CRUISE
MISSION:
MAY 22

MAYBE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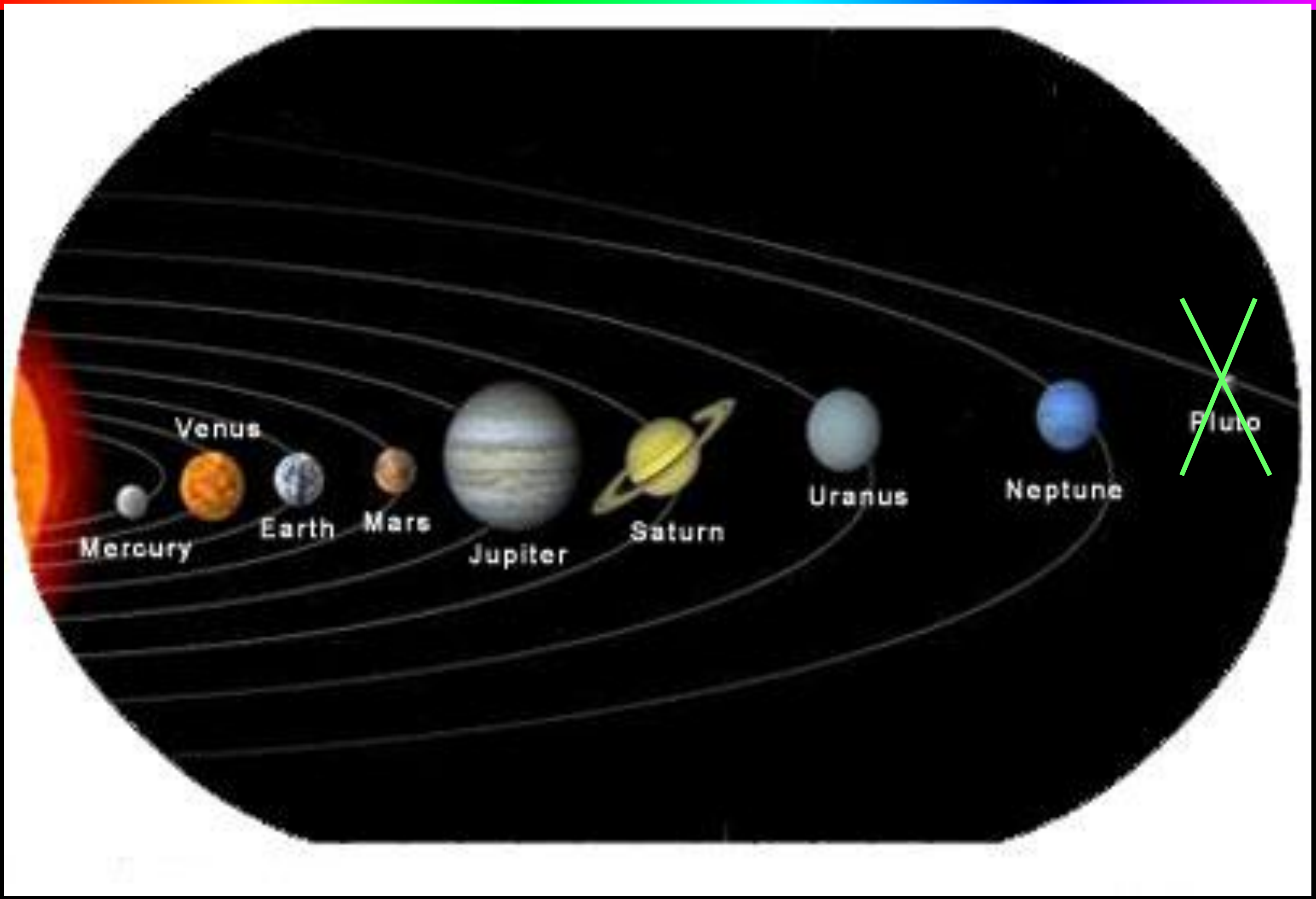
THE MISSION BEGINS MAY 5

Alignment of the Planets



A scenario to "establish" seesaw

- $0\nu\beta\beta$ discovered: neutrinos are Majorana
  - Need "new physics" below ~10^{14}GeV
- LHC finds SUSY, ILC establishes SUSY
- Gaugino masses unify (two more coincidences)
- Scalar masses unify for 1st, 2nd generations (two for 10, one for 5*, times two)

$\Rightarrow$ strong hint that there are no additional particles beyond the MSSM below M_{GUT} except for gauge singlets.

Buckley & HM, 2006 and in preparation

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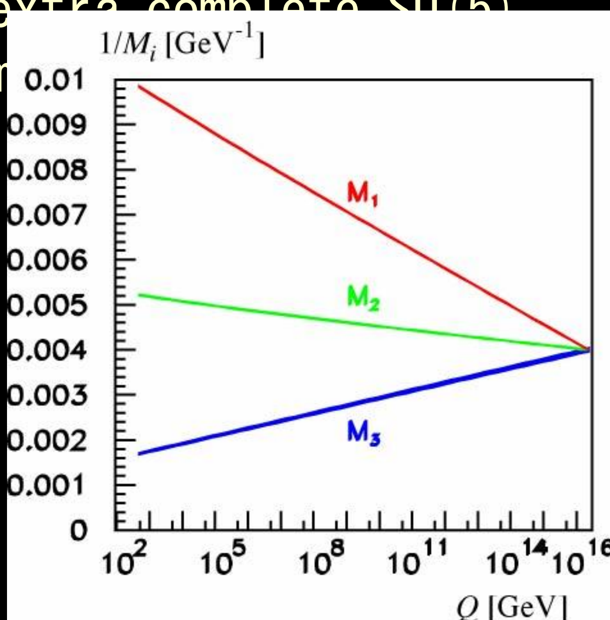
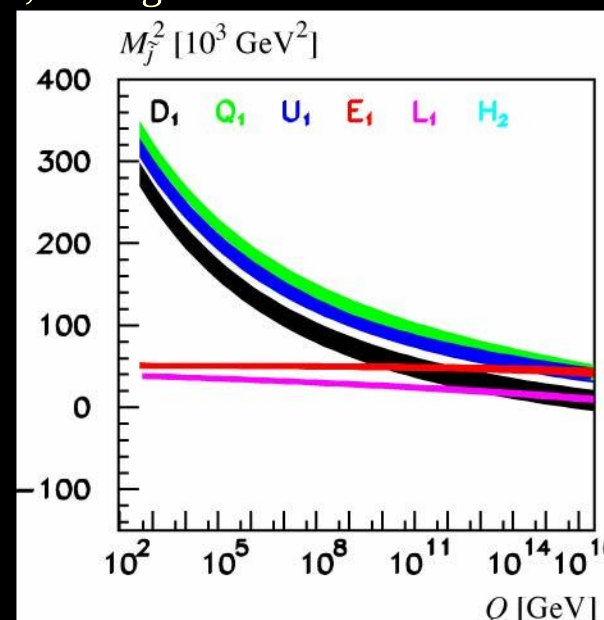
Gaugino and scalars

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

Kawamura, HM, Yamaguchi



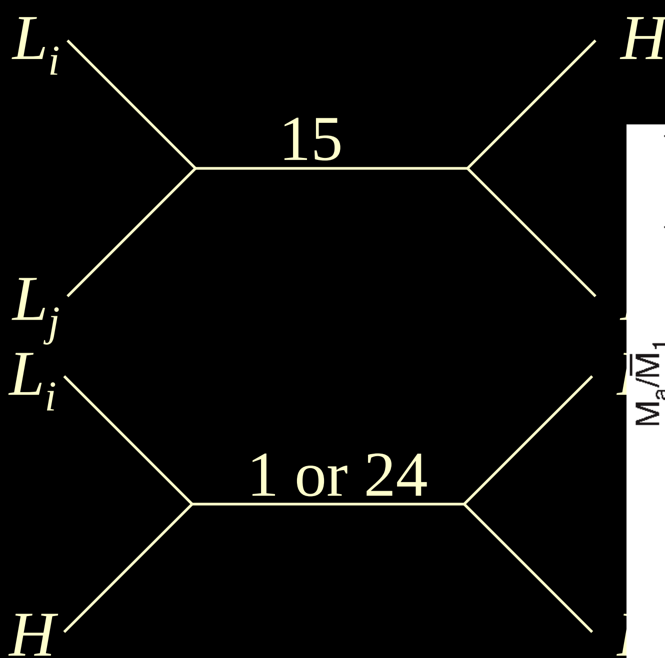


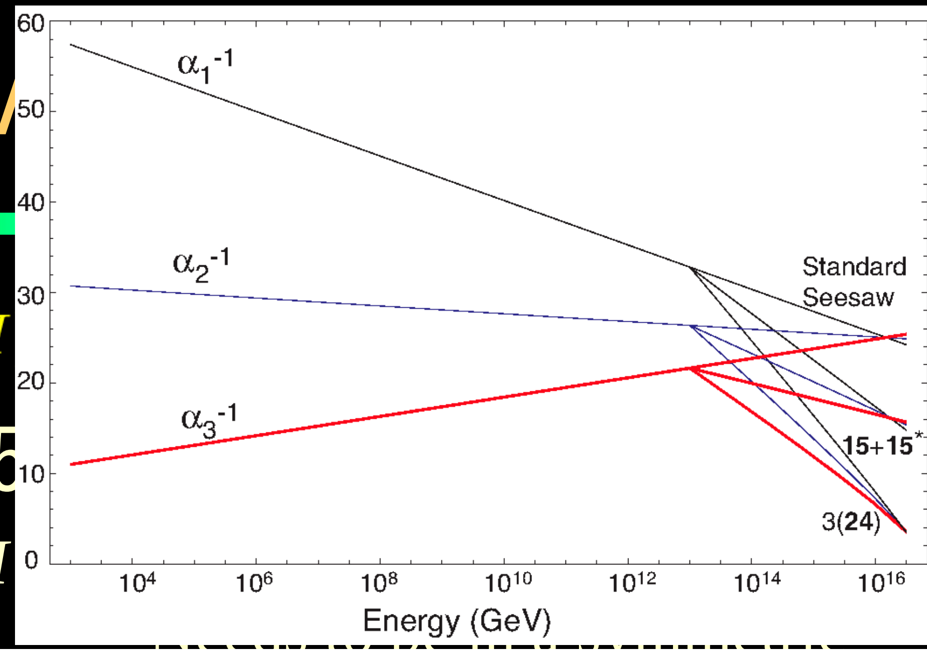
Zerwas and co

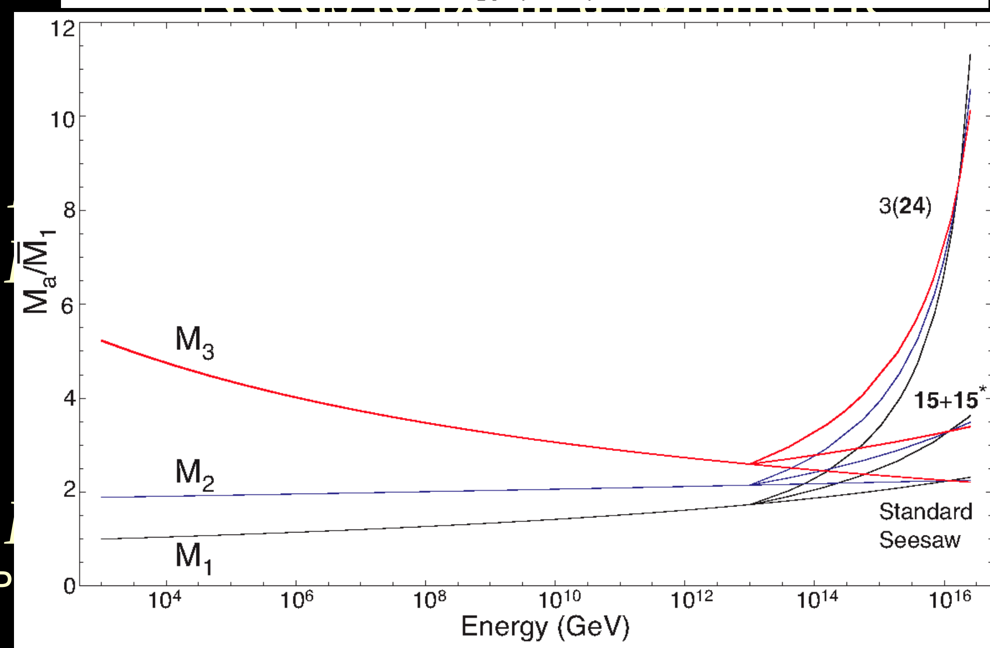
Possib

$$\mathcal{L}_5 = (LH)(LH) \to \frac{1}{\Lambda}(L\langle H$$

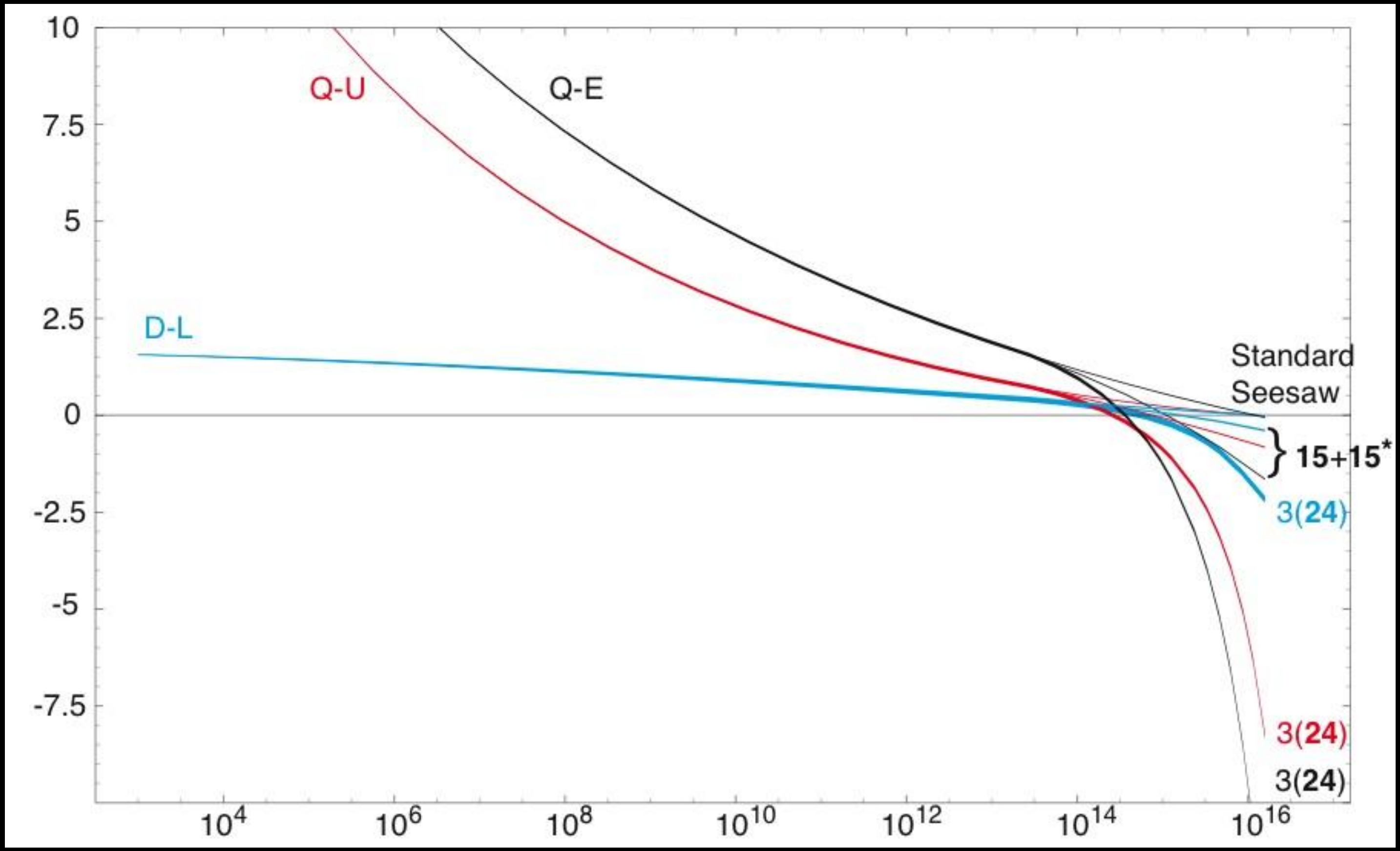
- L is in 5*, H in 5







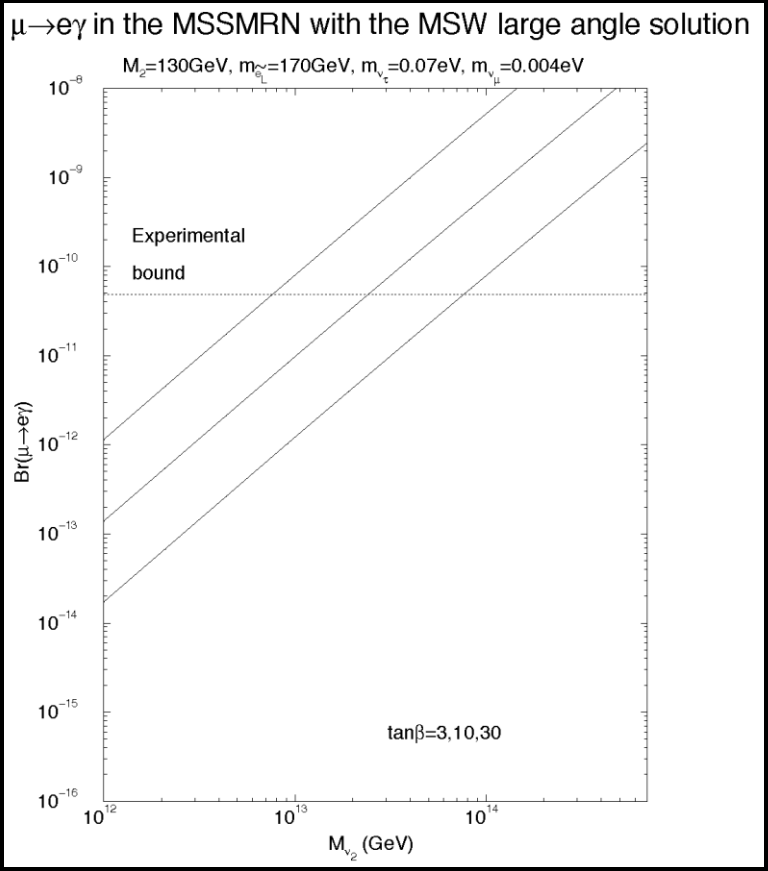
Scalar Masses



Hitoshi Murayama, APS/JPS 0νββ seminar Waikoloa 2009

What about Yukawa couplings?

- Yukawa couplings can in principle also modify the running of scalar masses
- We may well have an empirical evidence against large neutrino Yukawa coupling and large *M* by the lack of lepton-



Hisano&Nomura, hep-ph/9810479

Leptogenesis?

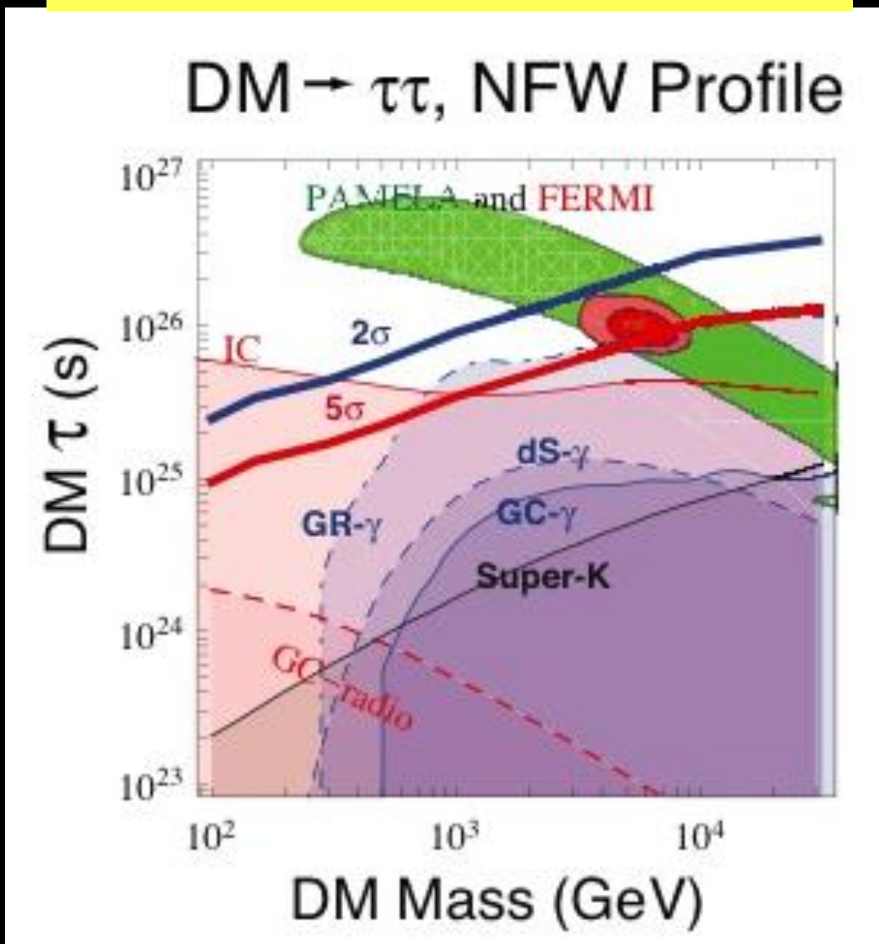
- Only gauge neutrals below M_{GUT} beyond MSSM
- Either
  - Baryogenesis due to particles we know at TeV scale, *i.e.*, electroweak baryogenesis
  - Baryogenesis due to gauge-singlets well above TeV, *i.e.*, leptogenesis by ν_R
- The former can be excluded by colliders & EDM
- The latter gets support from Dark Matter concordance, *B*-mode CMB fluctuation that point to "normal" cosmology after inflation

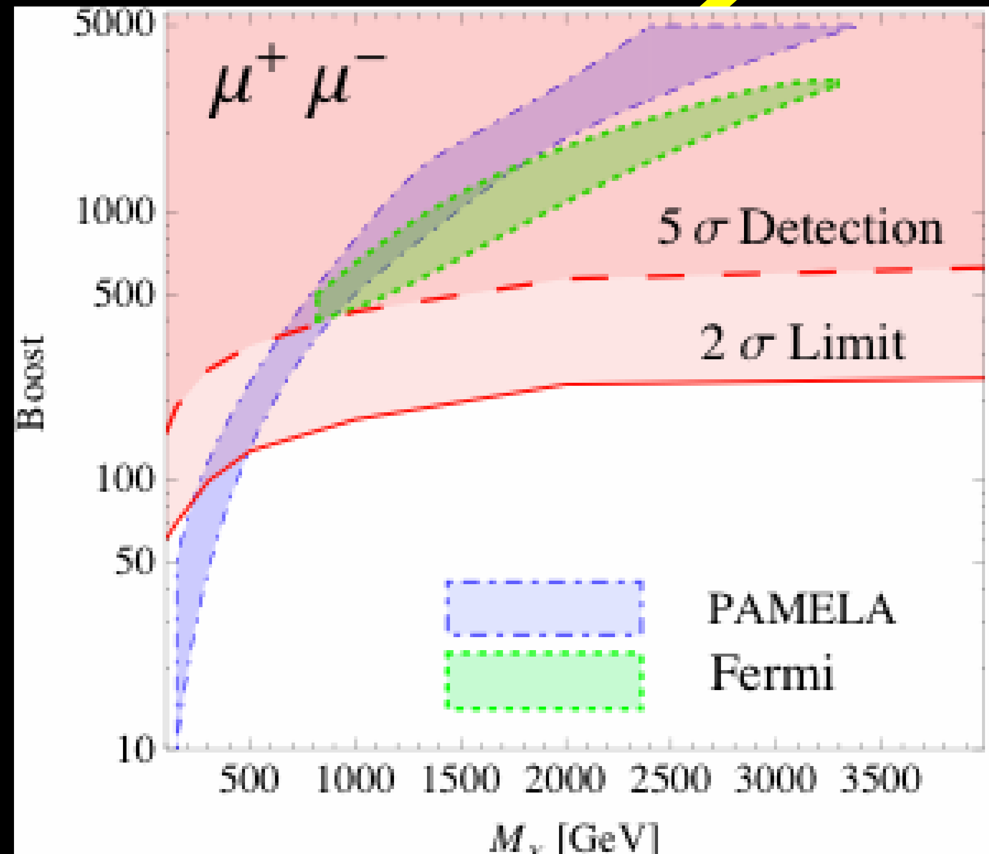
Indirect Dark Matter Detection

Dark Matter Heavy?

Galactic Center

Superimposed on plots by
Meade, Papucci, Strumia, Volansky





Spolyar, Buckley, Freese, Hooper, HM

for direct

Conclusions

- Neutrino oscillation firmly established
- Yet many more important questions remain
- $0\nu\beta\beta$ the only practical way to decide Dirac vs Majorana
- connections to big questions about the universe
  - Did neutrinos affect structure formation?
  - Why do we exist?
  - Why does the Universe exist?
- *Challenge to test the origin of neutrino mass*
  - SUSY-GUT allows test for seesaw
- Neutrinos probe dark matter