Why neutrinos?

Hitoshi Murayama (Berkeley)

Double Beta Decay and Neutrinos

Osaka, June 12, 2007

Introduction

- Neutrino physics has been full of surprises
- We've learned a lot in the last ~8 years
- We want to learn more. Why?
- *Window to short distance, early universe*
- What exactly *can* we learn from neutrinos?
  - Origin of neutrino mass?
  - Origin of baryon asymmetry?
  - Origin of universe?
- Need data from neutrino oscillations, colliders, $0\nu\beta\beta$, dark matter, cosmology, rare decays

Outline

- Past
- What we now know
- The Big Questions
- Seesaw
- Synergy
- Conclusion

Past

Why Neutrinos?

Interest in Neutrino Mass

- So much activity on neutrino mass already.

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 $\Longleftarrow$

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)

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

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

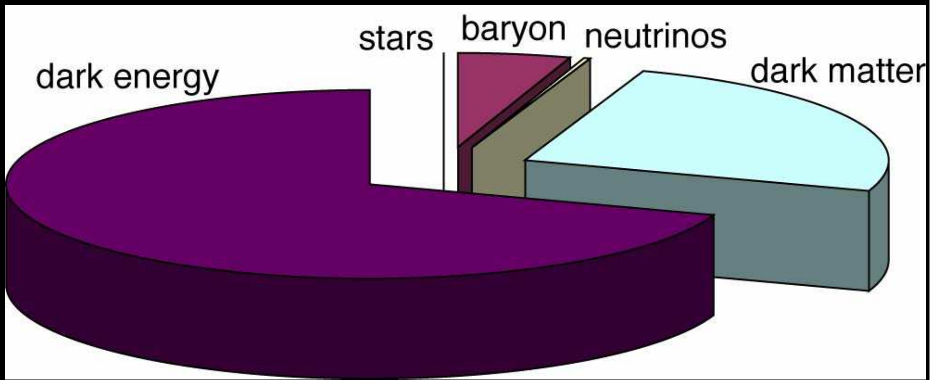
Unique Role of Neutrino Mass

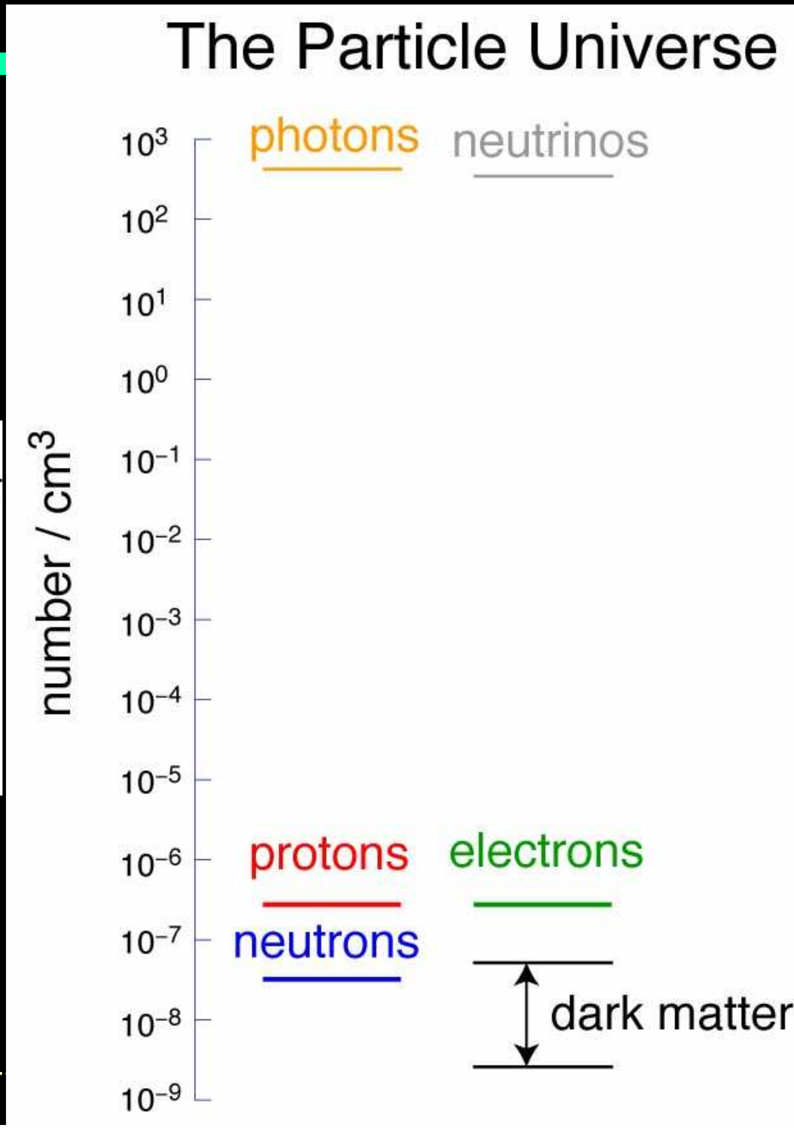
- Lowest order effect of physics at short distances
- Tiny effect $(m_\nu/E_\nu)^2 \sim (0.1\text{eV}/\text{GeV})^2 = 10^{-20}$!
- Interferometry (*i.e.*, Michaelson-Morley)
  - Need coherent source
  - Need interference (*i.e.*, large mixing angles)
  - Need long baseline

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

Ubiquitous Neutrinos



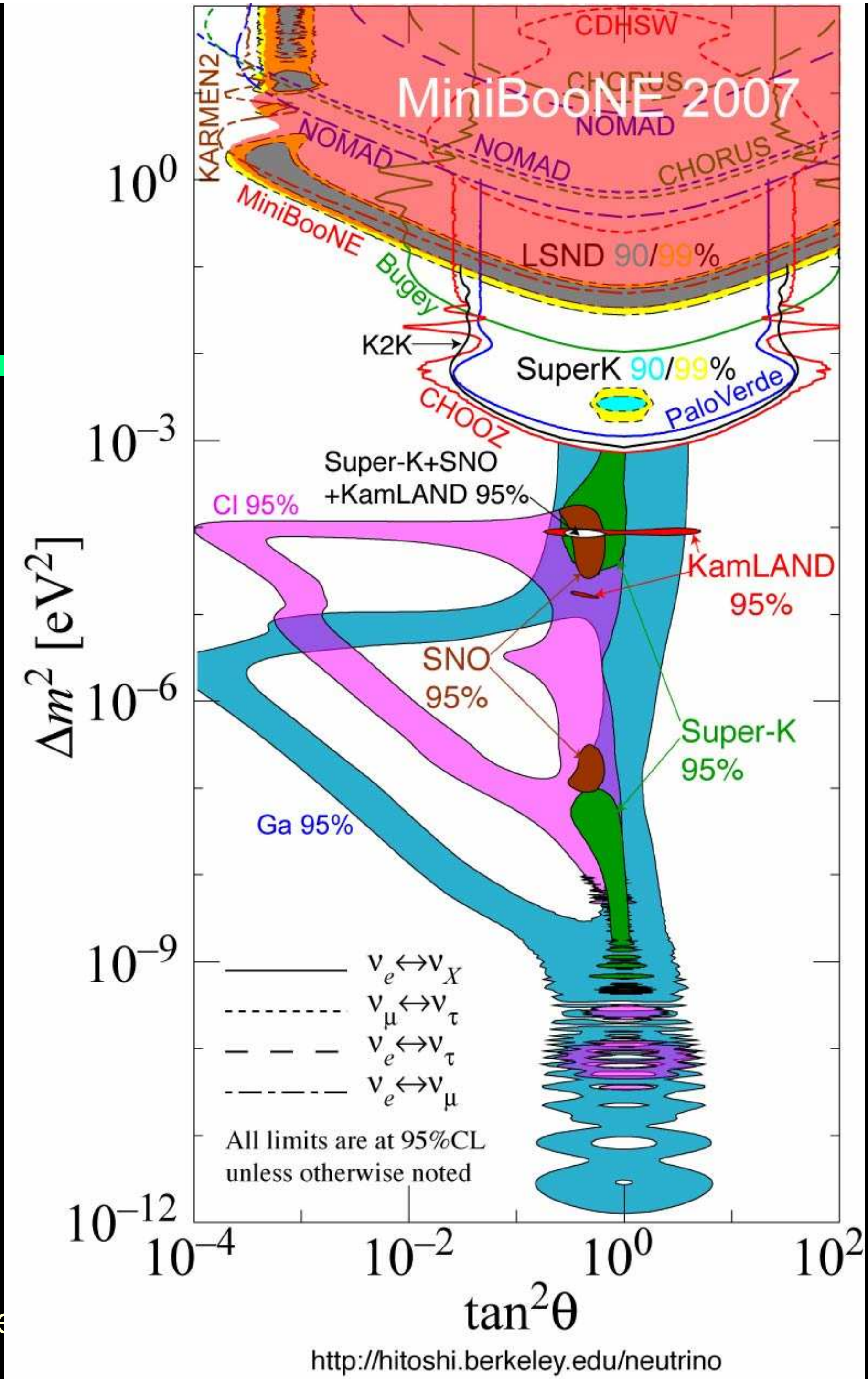


They must have played some important role in the universe!

What we now know

The Data

- Atmospheric
  - $\Delta m_{23}^2 \sim 2.5\times10^{-3}\,eV^2$
  - $\sin^2 2\theta_{23} \sim 1$
- Solar
  - $\Delta m_{12}^2 \sim 3\text{–}12\times10^{-5}\,eV^2$
  - $\sin^2 2\theta_{12} \sim 0.9$
- Reactor
  - $\Delta m_{12}^2 \sim 8\times10^{-5}\,eV^2$
- Accelerator (K2K/MINOS)
- LSND vs Mini-BooNE



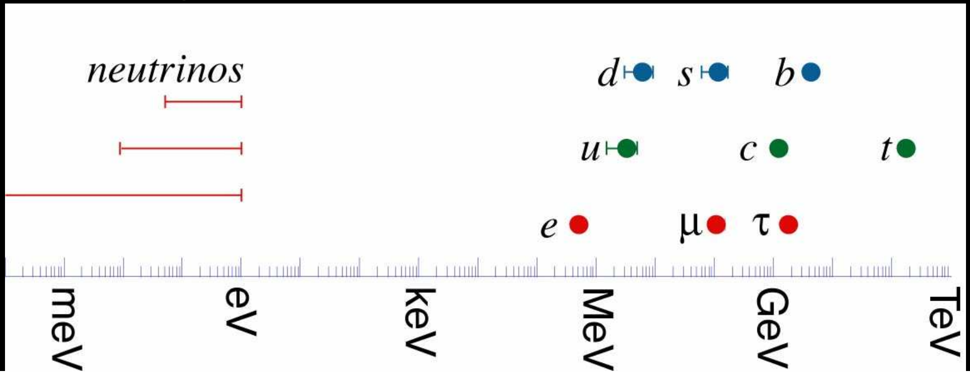
What we learned

- Lepton Flavor is not conserved
- Neutrinos have tiny mass, not very hierarchical
- Neutrinos mix a lot

the first evidence for

incompleteness of Minimal Standard Model

Very different from quarks



Typical Theorists' View ca. 1990

- Solar neutrino solution *must* be small angle MSW solution because it's cute *Wrong!*
- Natural scale for $\Delta m^2_{23} \sim 10\text{–}100\ \mathrm{eV}^2$ because it is cosmologically interesting *Wrong!*
- Angle θ_{23} must be $\sim V_{cb} = 0.04$ *Wrong!*
- Atmospheric neutrino anomaly must go away because it needs a large angle *Wrong!*

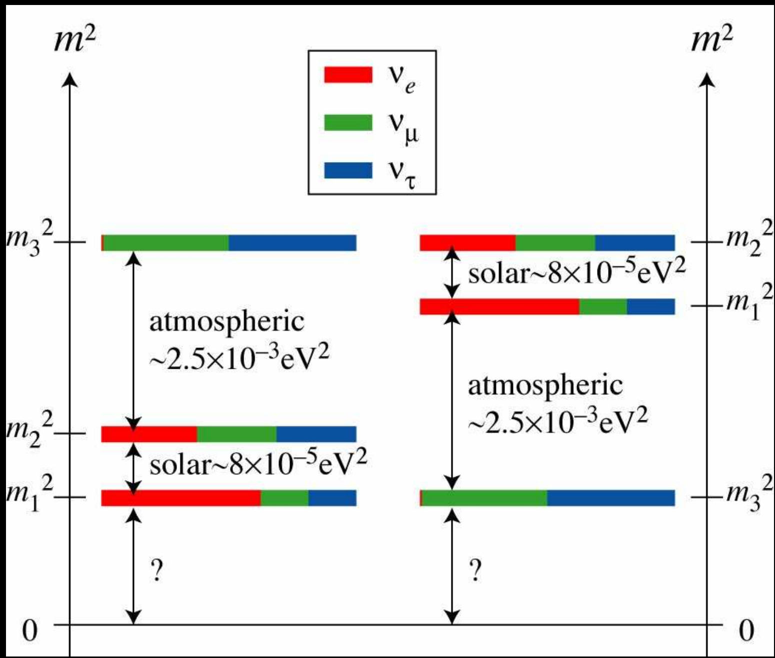
The Big Questions

- What is the origin of neutrino mass?
- Did neutrinos play a role in our existence?
- Did neutrinos play a role in forming galaxies?
- Did neutrinos play a role in birth of the universe?
- Are neutrinos telling us something about unification of matter and/or forces?
- Will neutrinos give us more surprises?

Big questions ≡ tough questions to answer

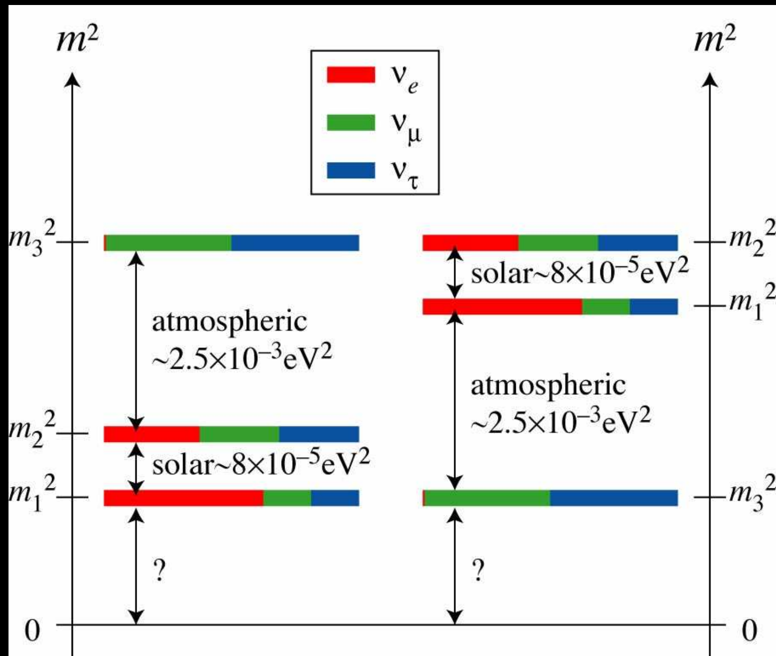
Immediate Questions

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



Immediate Questions

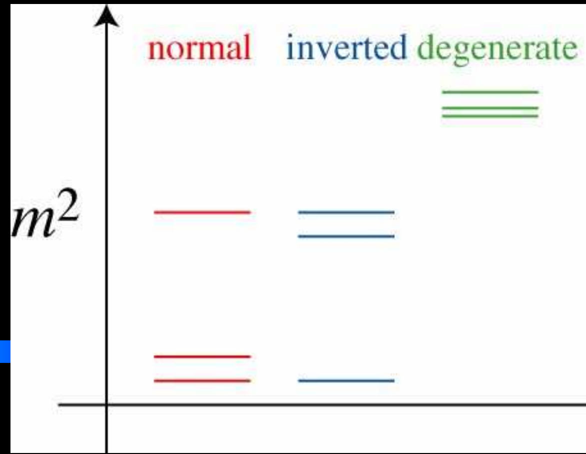
- Dirac or Majorana?
- Absolute mass scale?
- How small is θ_{13}?
- CP Violation?
- Mass hierarchy?
- Is θ_{23} maximal?



Extended Standard Model

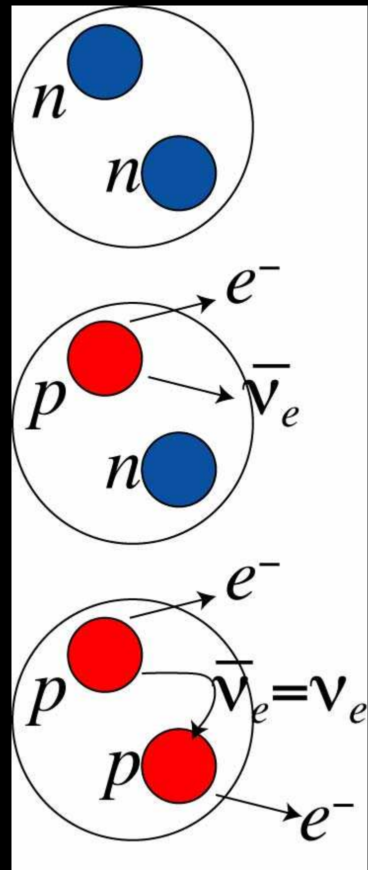
- Massive Neutrinos $\Rightarrow$ Minimal SM incomplete
- How exactly do we extend it?
- Abandon either
  - Minimality: introduce new unobserved light degrees of freedom (right-handed neutrinos)
  - Lepton number: abandon distinction between neutrinos and anti-neutrinos and hence matter and anti-matter
- Dirac or Majorana neutrino
- Without knowing which, we don't know how to extend the Standard Model

$0\nu\beta\beta$



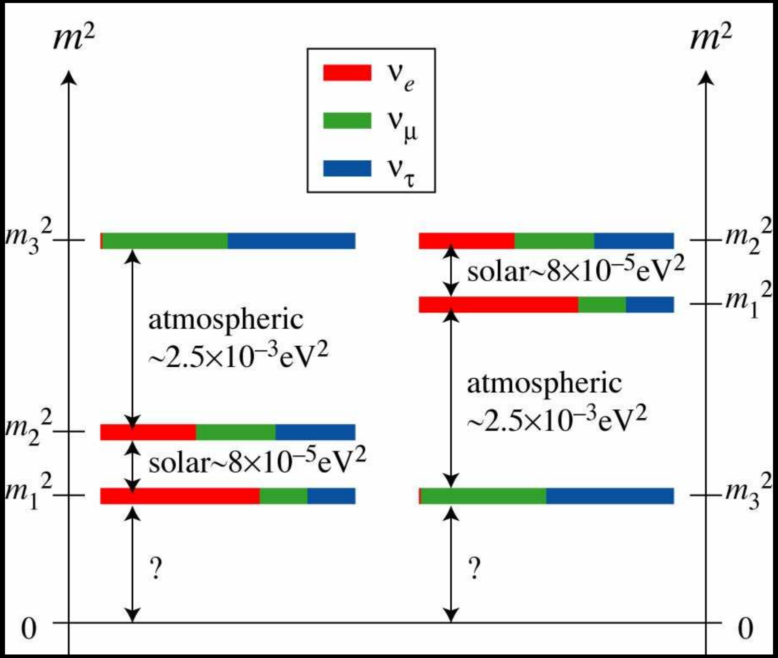
- The only known practical approach to discriminate Majorana vs Dirac neutrinos

  $0\nu\beta\beta$: $nn \rightarrow ppe^-e^-$ with no neutrinos
- Matrix element ∝ $\langle m_{\nu e}\rangle = \Sigma_i m_{\nu i} U_{ei}^2$
- Current limit $|\langle m_{\nu e}\rangle| \lesssim$ about 1eV
- $m_3 \sim (\Delta m^2_{23})^{1/2} \approx 0.05$eV looks a promising goal
- Good chance to discover it for degenerate and inverted spectra $\langle m_{\nu e}\rangle > 0.01$eV
- Not clear if we can see it for the normal spectrum, need ~0.001 eV sensitivity
- Majorana, CANDLES, Cuore, GERDA, MOON, EXO, XMASS, SuperNEMO, COBRA, …



Immediate Questions

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



Now that LMA is confirmed...

$\Delta m_{12}{}^2$, s_{12} came out as large it could be (LMA)

- Dream case for neutrino oscillation physics!

$\Delta m^2{}_{\text{solar}}$ within reach of long-baseline expts

- Even CP violation may be probed
  - neutrino superbeam
  - muon-storage ring neutrino factory

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

- What it would take to see it depends on θ_{13}!

θ_{13}

- Two approaches
- Reactor anti-neutrino experiments
  - Disappearance of anti-ν_e
  - measures purely $\sin^2 2\theta_{13}$
  - Double-CHOOZ, Daya Bay, RENO, ANGRA, …
- Long-baseline accelerator experiments
  - Appearance of ν_e from ν_μ
  - Combination of θ_{13}, matter effect, CP phase
  - MINOS, T2K, NOνA, T2KK, …

The Big Questions

- What is the origin of neutrino mass?
- Did neutrinos play a role in our existence?
- Did neutrinos play a role in forming galaxies?
- Did neutrinos play a role in birth of the universe?
- Are neutrinos telling us something about unification of matter and/or forces?
- Will neutrinos give us more surprises?

Big questions ≡ tough questions to answer

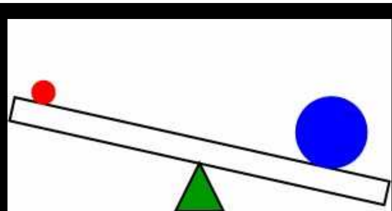
Seesaw

Seesaw Mechanism

- Why is neutrino mass so small?
- Need right-handed neutrinos to generate neutrino mass , but ν_R SM neutral

$$\begin{pmatrix} \nu_L & \nu_R \end{pmatrix} \begin{pmatrix} & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

$$m_\nu = \frac{m_D^2}{M} << m_D$$



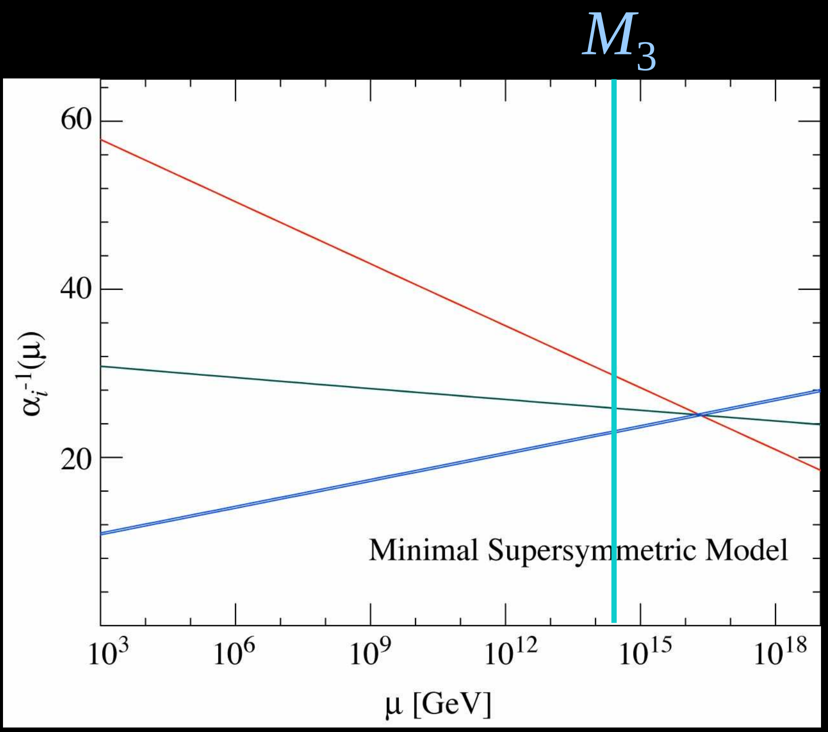
To obtain $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim m_t$, $M_3 \sim 10^{14}$GeV

Grand Unification

- electromagnetic, weak, and strong forces have very different strengths
- But their strengths become the same at ~2×10^{16} GeV if supersymmetry
- To obtain

$m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim m_t$

$\Rightarrow M_3 \sim 10^{14}$ GeV!



Matter and Anti-Matter Early Universe

1,000,000,001

Matter

1,000,000,000

Anti-matter

Matter and Anti-Matter Current Universe

ůs

1

Matter Anti-matter

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

    $\Rightarrow \Gamma(\Delta B{>}0) > \Gamma(\Delta B{<}0)$
- It looks like neutrinos have no role in this…

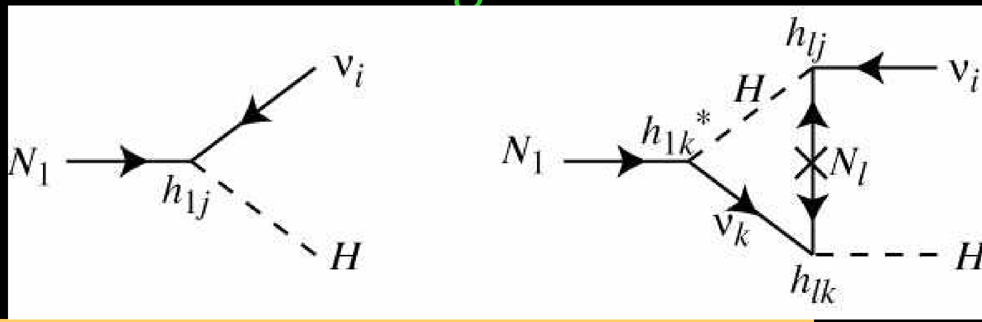
Electroweak Anomaly

- 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-dingly

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

Leptogenesis

- You generate *Lepton Asymmetry* first. (Fukugita, Yanagida)
- Generate L from the direct CP violation in right-handed neutrino decay



$$\Gamma(N_1 \to \nu_i H) - \Gamma(N_1 \to \bar{\nu}_i H) \propto \mathrm{Im}(h_{1j} h_{1k} h_{lk}^* h_{lj}^*)$$

- L gets converted to B via EW anomaly
  $\Rightarrow$ More matter than anti-matter
  $\Rightarrow$ *We have survived "The Great Annihilation"*
- Despite detailed information on neutrino masses, it still works (*e.g.*, Bari, Buchmüller, Plümacher)

Origin of Universe

- Maybe an *even bigger* role: inflation
- Need a spinless field that
  - slowly rolls down the potential
  - oscillates around it minimum
  - decays to produce a thermal bath
- *The superpartner of right-handed neutrino fits the bill*
- When it decays, it produces the lepton asymmetry at the same time (HM, Suzuki, Yanagida, Yokoyama)
- Decay products: supersymmetry and hence dark matter

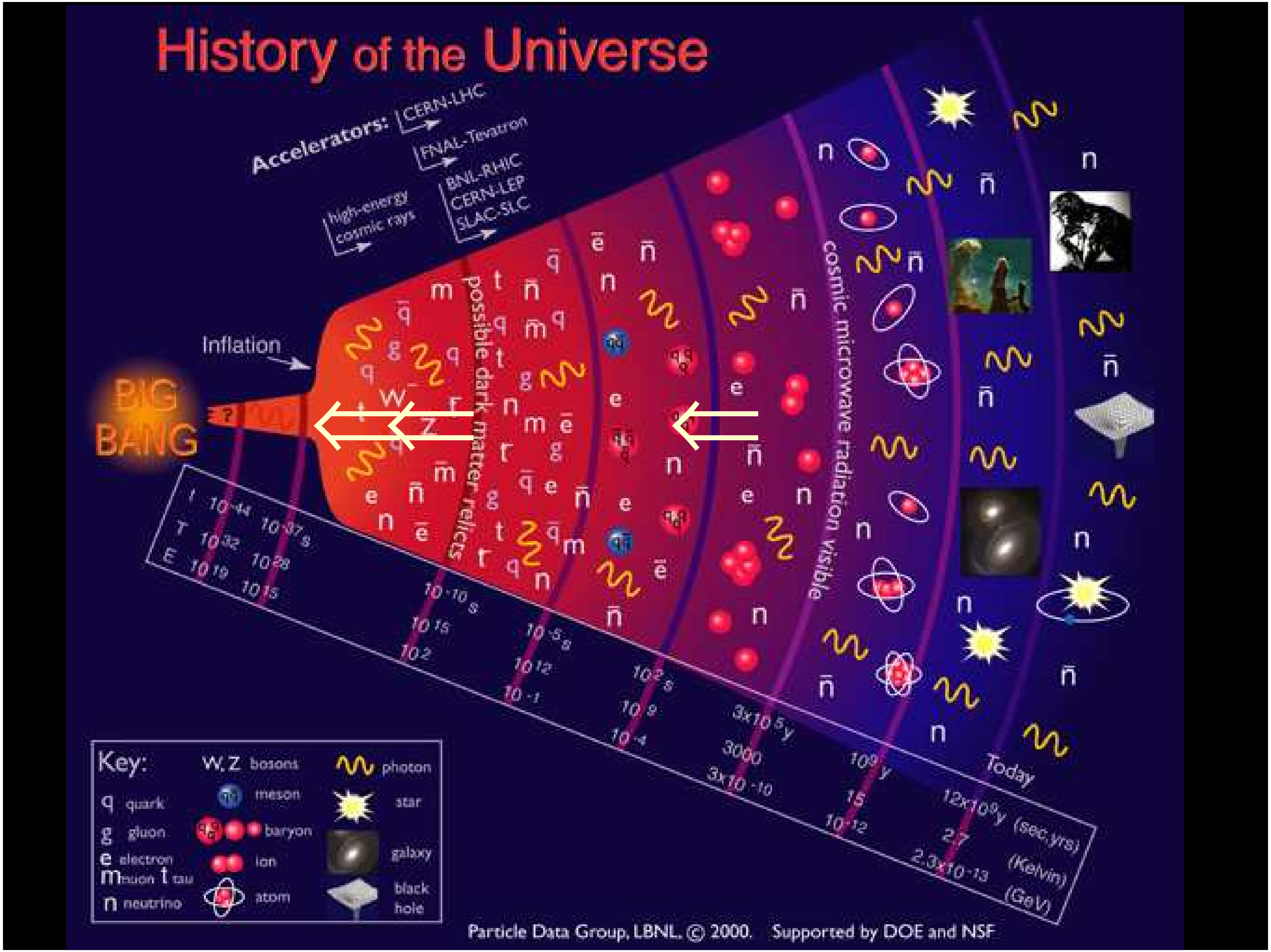
Neutrino is mother of the Universe?

V

size of the universe

$\tilde{\nu}_R$

t


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 relics
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (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

Synergy

Can we prove it experimentally?

- Short answer: no. We can't access physics at $>10^{10}$ GeV with accelerators directly
- But: we will probably believe it if the following scenario happens

Archeological evidences

A scenario to "establish" seesaw

- We find CP violation in neutrino oscillation
  - At least proves that CP is violated in the lepton sector
- U_{e3} is not too small
  - At least makes it plausible that CP asymmetry in right-handed neutrino decay is not unnaturally suppressed
- But this is not enough

A scenario to "establish" seesaw

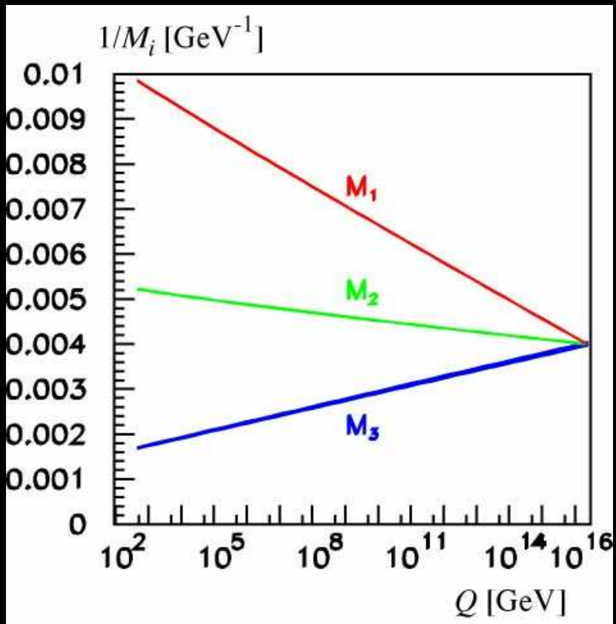
- LHC finds SUSY, ILC establishes SUSY
- no more particles beyond the MSSM at TeV scale
- Gaugino masses unify (two more coincidences)
- Scalar masses unify for 1st, 2nd generations (two for 10, one for 5*, times two)

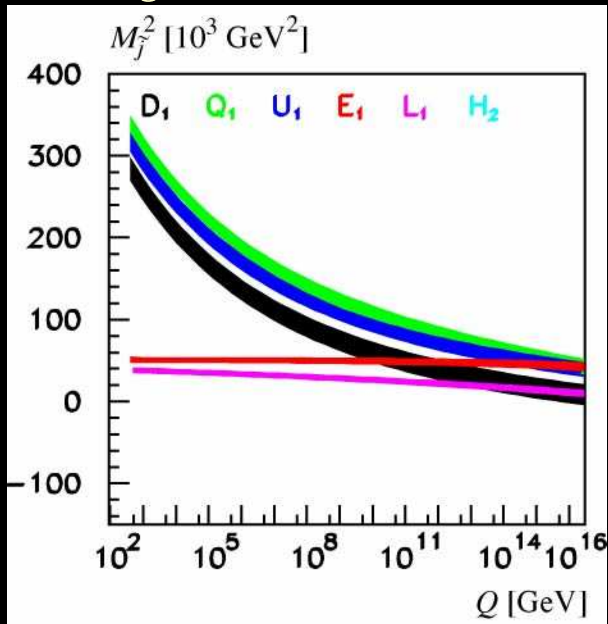
$\Rightarrow$ strong hint that there are no additional particles beyond the MSSM below M_{GUT} except for gauge singlets.

Gaugino and scalars

- 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



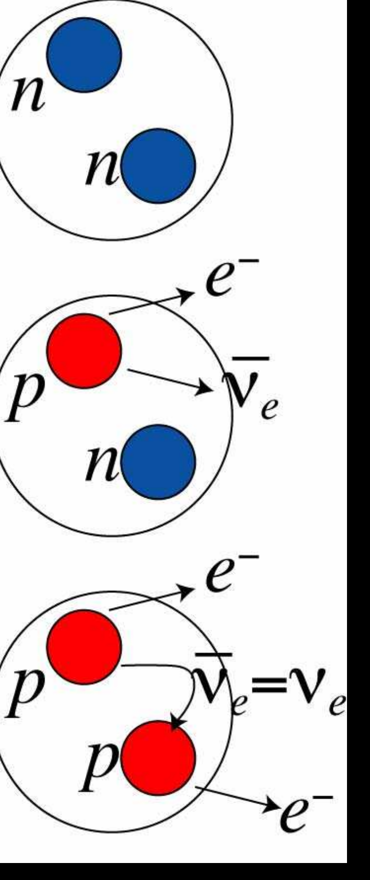


A scenario to "establish" seesaw

- Next generation experiments discover neutrinoless double beta decay
- Say, $\langle m_\nu \rangle_{ee}$~0.1eV
- There must be new physics below Λ~10^{14}GeV that generates the Majorana neutrino mass

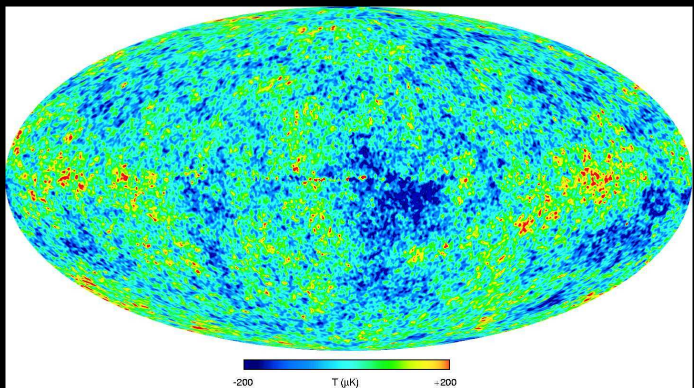
$$\mathcal{L}_5 = (LH)(LH) \to \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

- But it can also happen with R-parity violating SUSY

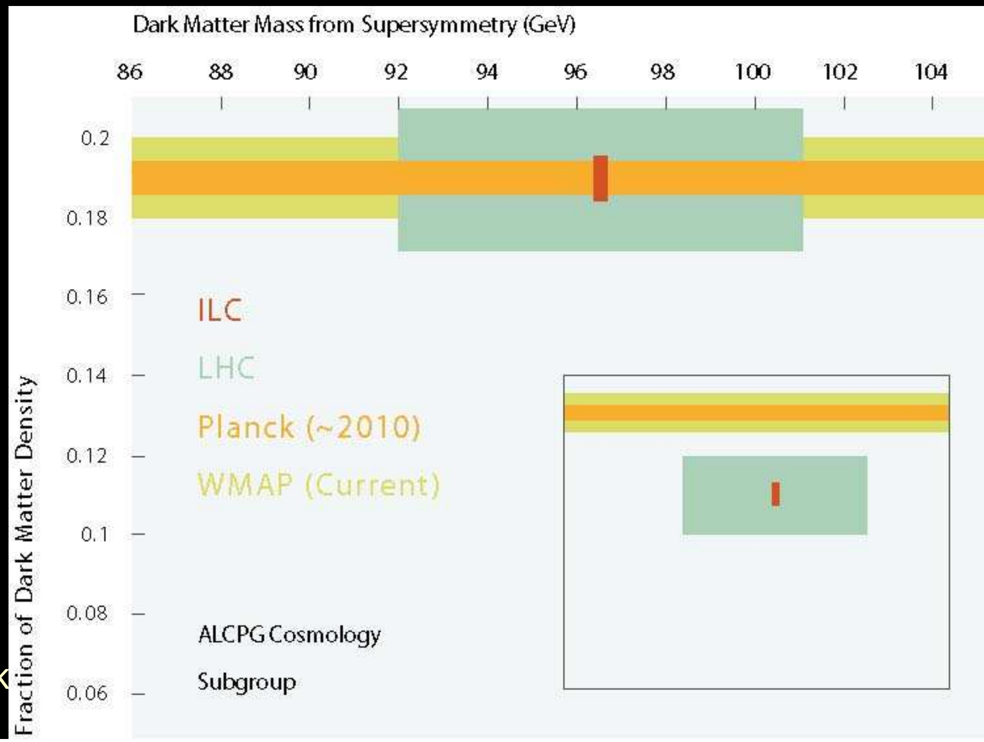


A scenario to "establish" seesaw

- It leaves the possibility for *R*-parity violation
- Consistency between cosmology, dark matter detection, and LHC/ILC will remove the concern



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

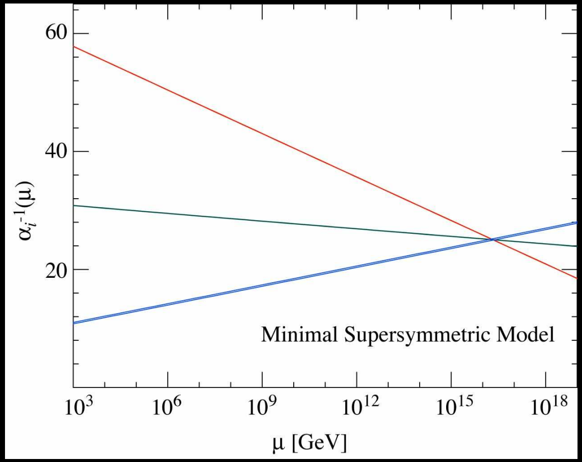


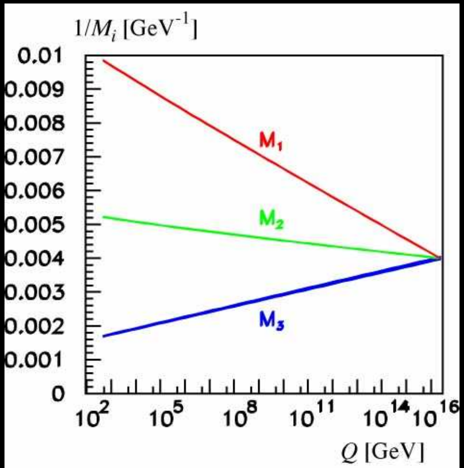
Need "New Physics" $\Lambda<10^{14}$GeV

- Now that there must be D=5 operator at Λ<a few $\times 10^{14}$GeV < M_{GUT}, we need new particles below M_{GUT}

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

- Given gauge coupling and gaugino mass unification, they have to come in complete $SU(5)$ multiplets

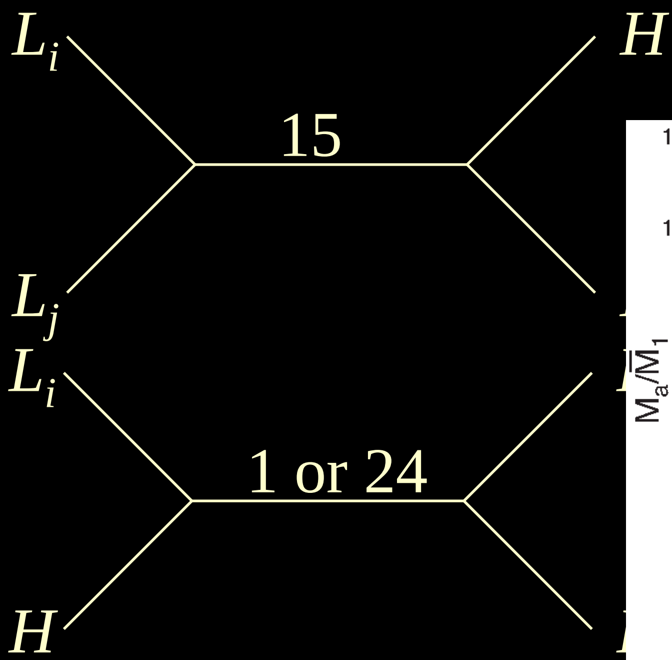


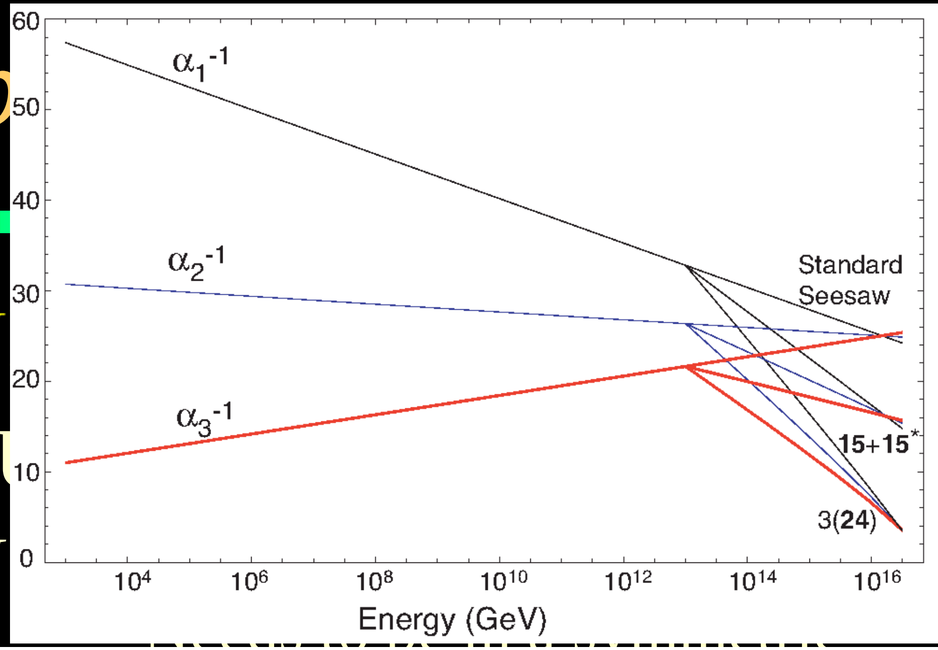


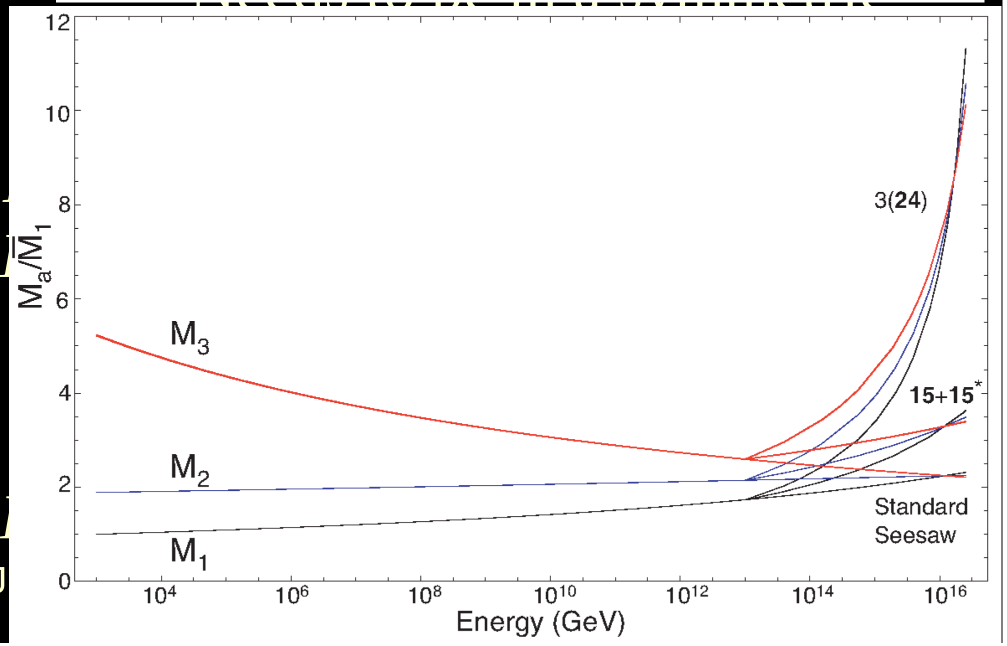
Possib

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

- L is in 5^*, H in 5 of SU







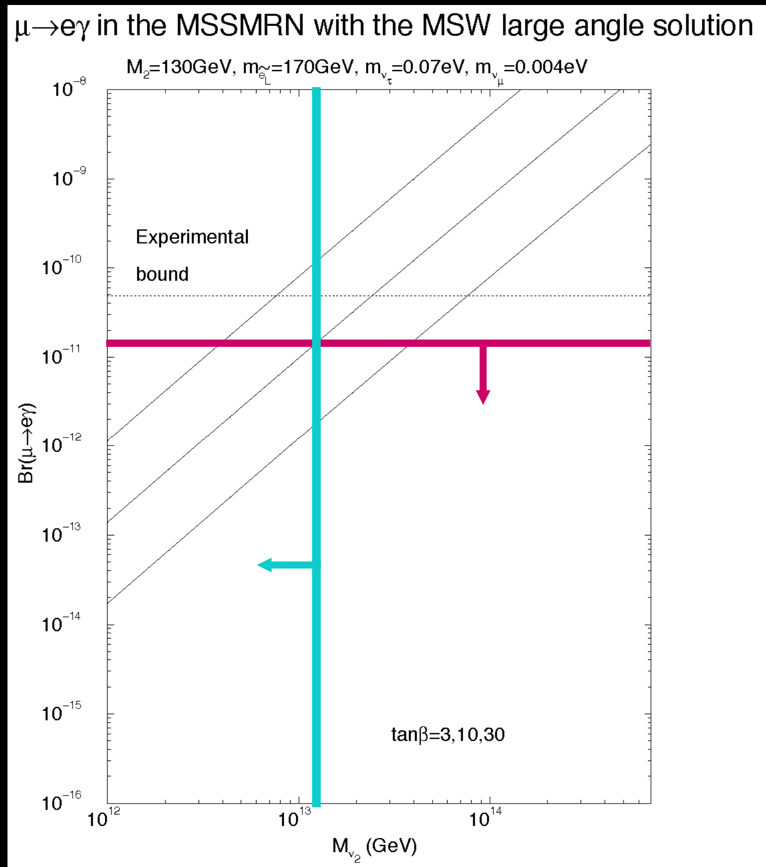
Scalar masses tell them apart

$\Lambda = 10^{13}$GeV	Standard seesaw	Modified Type-I	Type-II
New particles	3×1	3×24	15+15*
$(m_Q^2 - m_U^2)/M_1^2$	1.90	4.68	2.29
$(m_Q^2 - m_E^2)/M_1^2$	21.30	29.52	22.60
$(m_D^2 - m_L^2)/M_1^2$	17.48	20.15	18.02

Matt Buckley, HM

What about Yukawa couplings?

- Yukawa couplings can in principle also modify the running of scalar masses
- We may well have an empirical upper limit on *M* by the lack of lepton-flavor violation
- Justifies the analysis!



Hisano&Nomura, hep-ph/9810479

If this works out

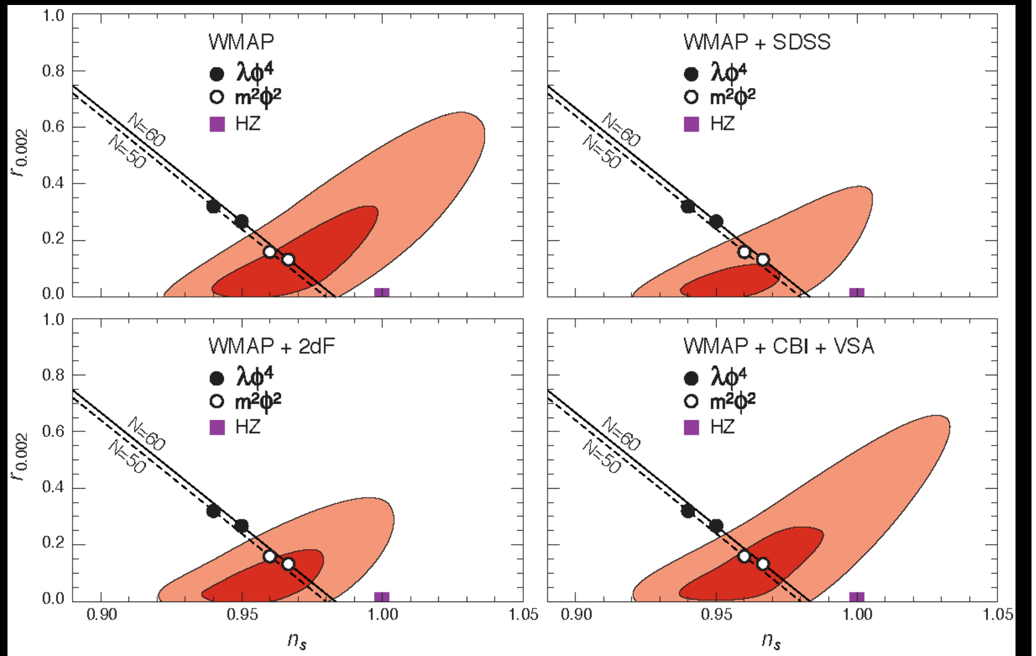
- Evidence for SU(5)-like unification hard to ignore
- Only three possible origins of Majorana neutrino mass < 10^{14} GeV consistent with gauge coupling and gaugino unification
- Only one consistent with scalar mass unification
- Could well “establish” the standard seesaw mechanism this way
- Need collider, dark matter, $0\nu\beta\beta$, cosmology, LFV, proton decay

Leptogenesis?

- No new gauge non-singlets below M_{GUT}
- 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
- Ultimate: measure asymmetry in background ν's

Origin of the Universe

- Right-handed scalar neutrino: $V=m^2\phi^2$
- n_s~0.96
- r~0.16
- Need m~10^{13}GeV
- Consistent with WMAP+LSS
- Verification possible in the near future



Conclusions

- *Revolutions in neutrino physics*
- Neutrino mass probes very high-energy physics
- But how do we know?
- By collection of experiments: collider, dark matter, $0\nu\beta\beta$, cosmology, LFV, proton decay
- We could well find convincing enough experimental evidence for seesaw mechanism
- May even learn something about our existence, the birth of the universe itself

The Iνvisibles


DISNEY PRESENTS A PIXAR FILM
THE IνCREDIBLES
NOW PLAYING
© Disney Enterprises, Inc./Pixar Animation Studios. All Rights Reserved.

High precision needed

$\Lambda = 10^{14}$GeV	Standard seesaw	Modified Type-I	Type-II
New particles	3×1	3×24	15+15*
$(m_Q^2 - m_U^2)/M_1^2$	1.90	2.41	2.04
$(m_Q^2 - m_E^2)/M_1^2$	21.30	22.58	21.70
$(m_D^2 - m_L^2)/M_1^2$	17.48	17.77	17.62

Matt Buckley, HM

Can we do this?

- CMS: in some cases, squark masses can be measured as Δm ~3 GeV, if LSP mass provided by ILC, with jet energy scale suspect. No distinction between u_R and d_R (Chiorboli)
- ILC measures gaugino mass and slepton mass at permille levels: negligible errors (HM)
- squark mass from kinematic endpoints in jet energies: Δm~a few GeV (Feng-Finnell)
- Can also measure squark mass from the threshold: Δm~2-4 GeV (Blair)
- 1% measurement of m^2 Not inconceivable

Threshold scan @ ILC

Sparticle	True Mass	True Width	Fit Mass Error	Fit Width Error	Fit Mass Error (Width Fixed)
$\tilde{\mu}_R$	143	0.20	0.18	0.06	0.15
$\tilde{\mu}_L$	202	0.25	0.30	0.11	0.26
$\tilde{u}_R$	520	25	11	14	2.7
$\tilde{u}_L$	537	30	5.3	9.0	1.9
$\tilde{d}_R$	520	25	24	30	5.8
$\tilde{d}_L$	543	30	8.0	12	2.7
χ_1^+	175	0.002	0.17	0.003	0.09
χ_2^+	364	1.9	0.44	0.24	0.23

100 fb^{-1}

Grahame Blair

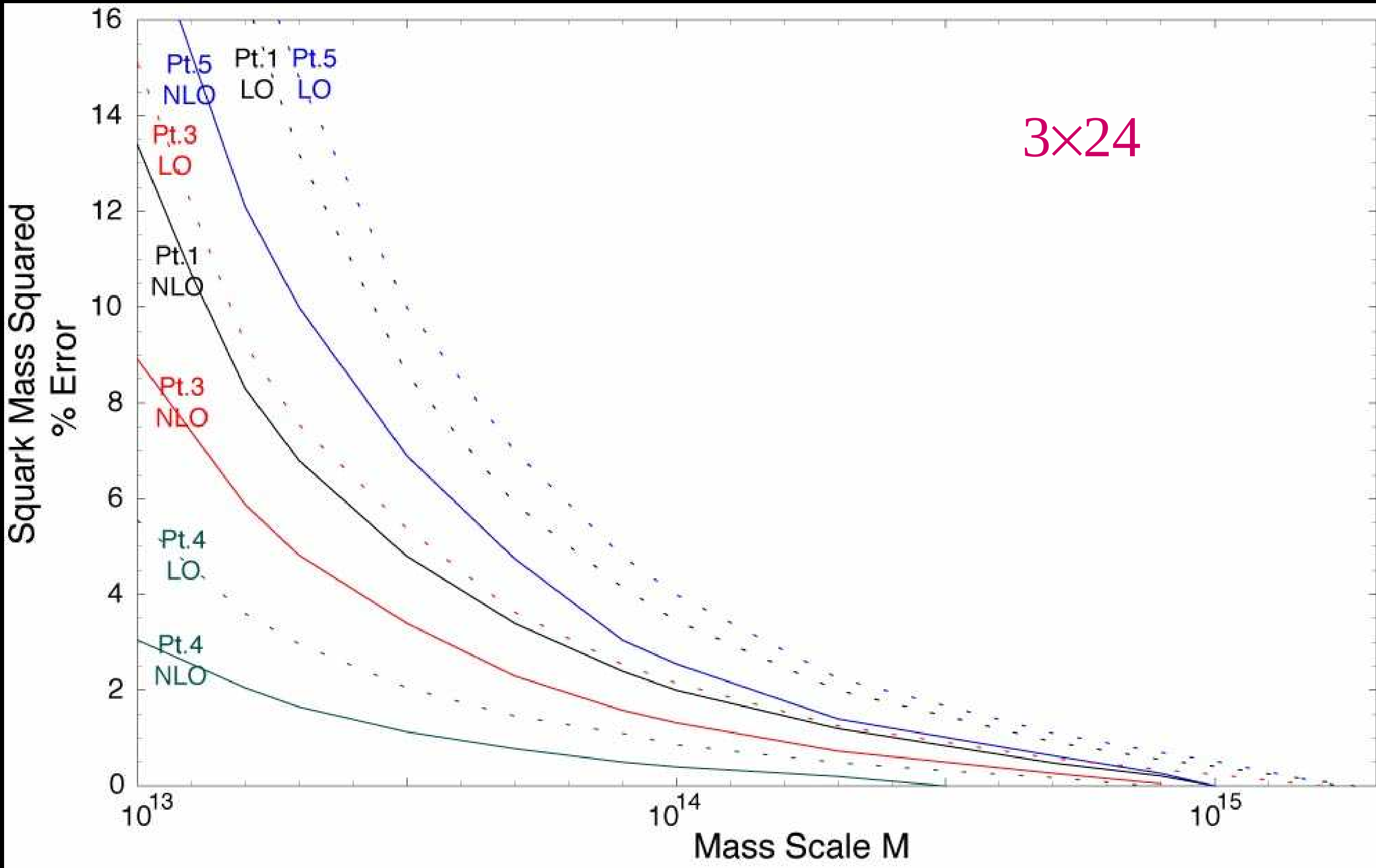
Comments

- Threshold behavior for squark-pair production has not been calculated with QCD effects (à la ttbar threshold)
- Mass differences presumably better measured
  - Jet energy scale uncertainties cancel
  - Difference in end points
  - But flavor tagging a challenge

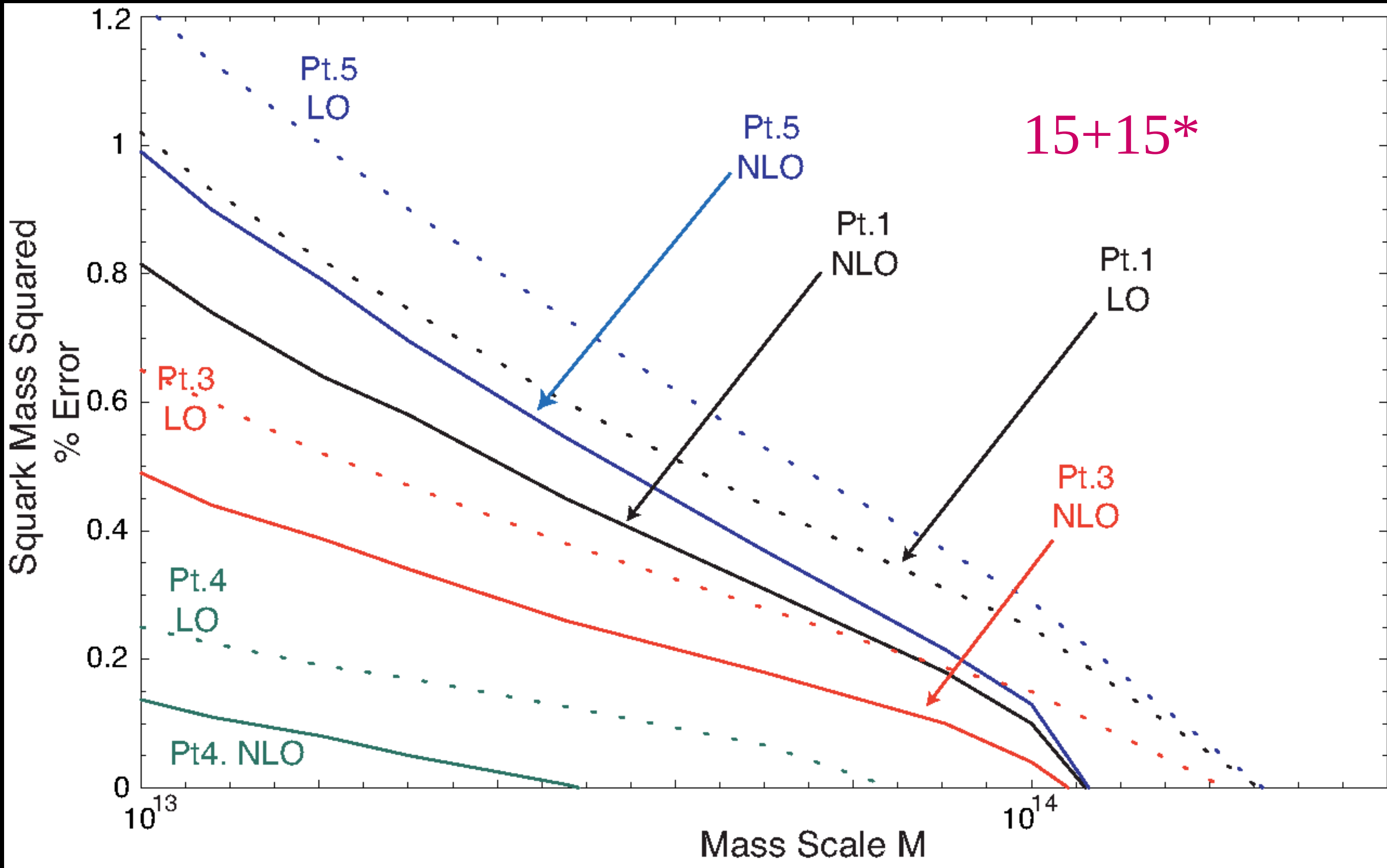
Scalar Mass Unification

- Because the scalar masses also appear to unify, their running constrain gauge non-singlet particle content below the GUT scale
- Need to see the level of mismatch generated by 3×24 (modified Type I), $15+15^*$ (Type II), compared to 3×1 (Standard seesaw) that does not modify the scalar mass unification

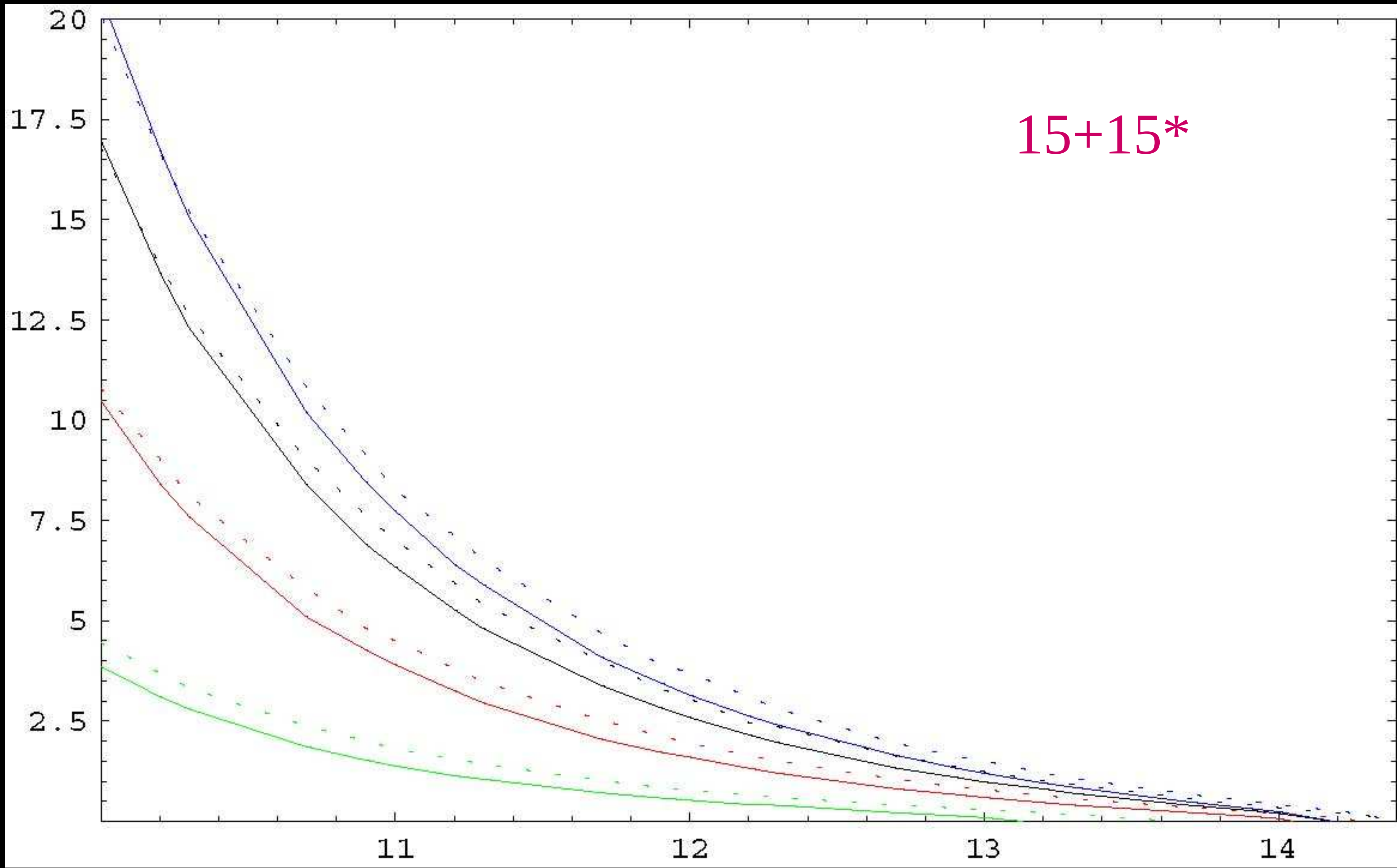
Needed accuracy (3σ)



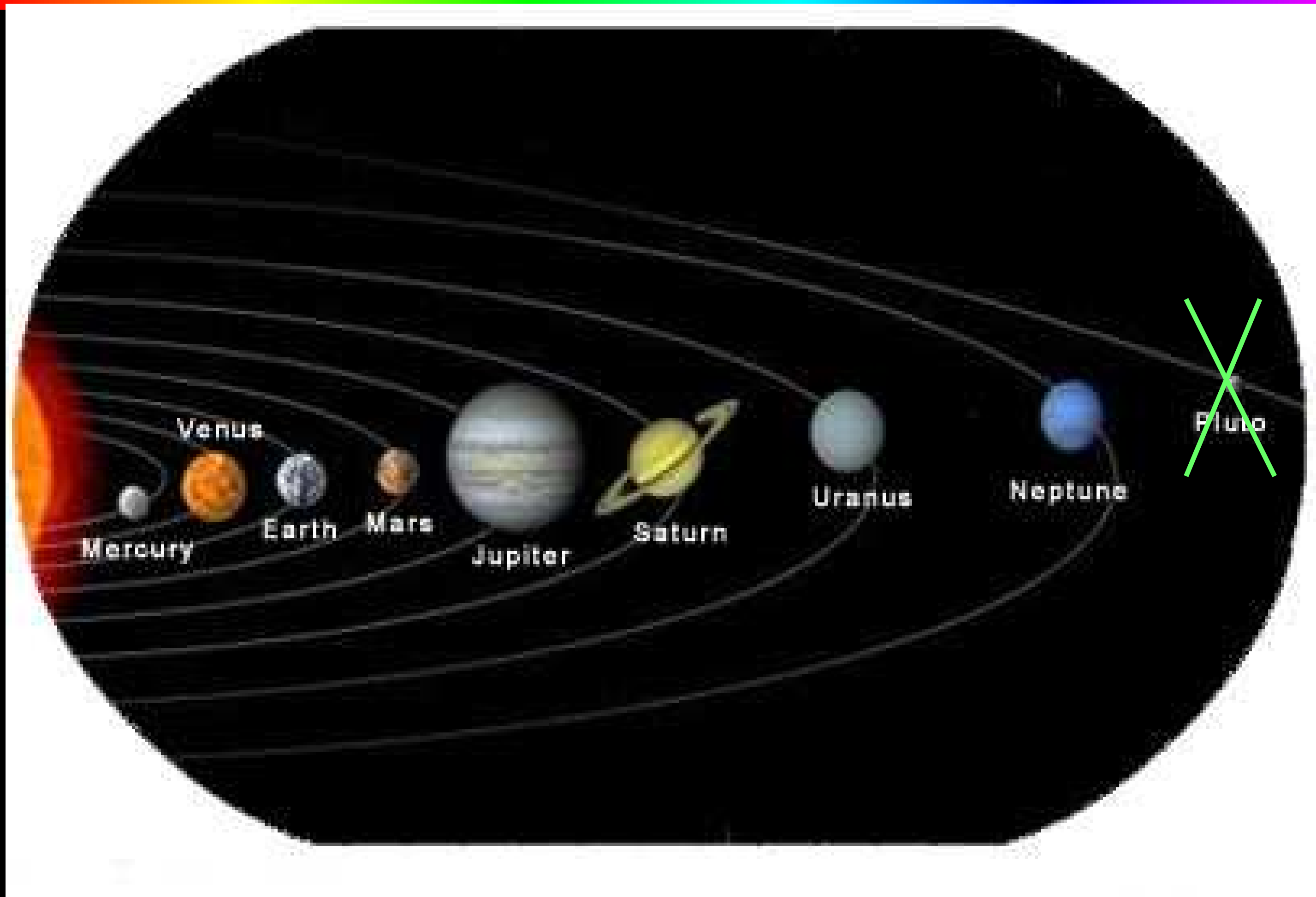
Needed accuracy (3σ)



Needed accuracy (3σ)



Alignment of the Planets



The Question

- The seesaw mechanism has been the dominant paradigm for the origin of tiny neutrino mass
- Physics close to the GUT scale
- How do we know if it is true? Is there a way to test it experimentally?
- Short answer: *No*
- However, we can be convinced of it

Neutrinos do oscillate!