Looking up at seesaw and GUT scales from TeV

Hitoshi Murayama
(Berkeley/IPMU)

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With Matt Buckley

Also based on works with K. Fujii, T. Tsukamoto, M. Yamaguchi, Y. Okada, Y. Kawamura

The Question

- Neutrino physics has been full of surprises
- We've learned a lot in the last ~8 years
- We want to learn more
- What exactly *can* we learn from neutrinos?
  - Origin of neutrino mass?
  - Origin of baryon asymmetry?
  - Origin of universe?

The Question

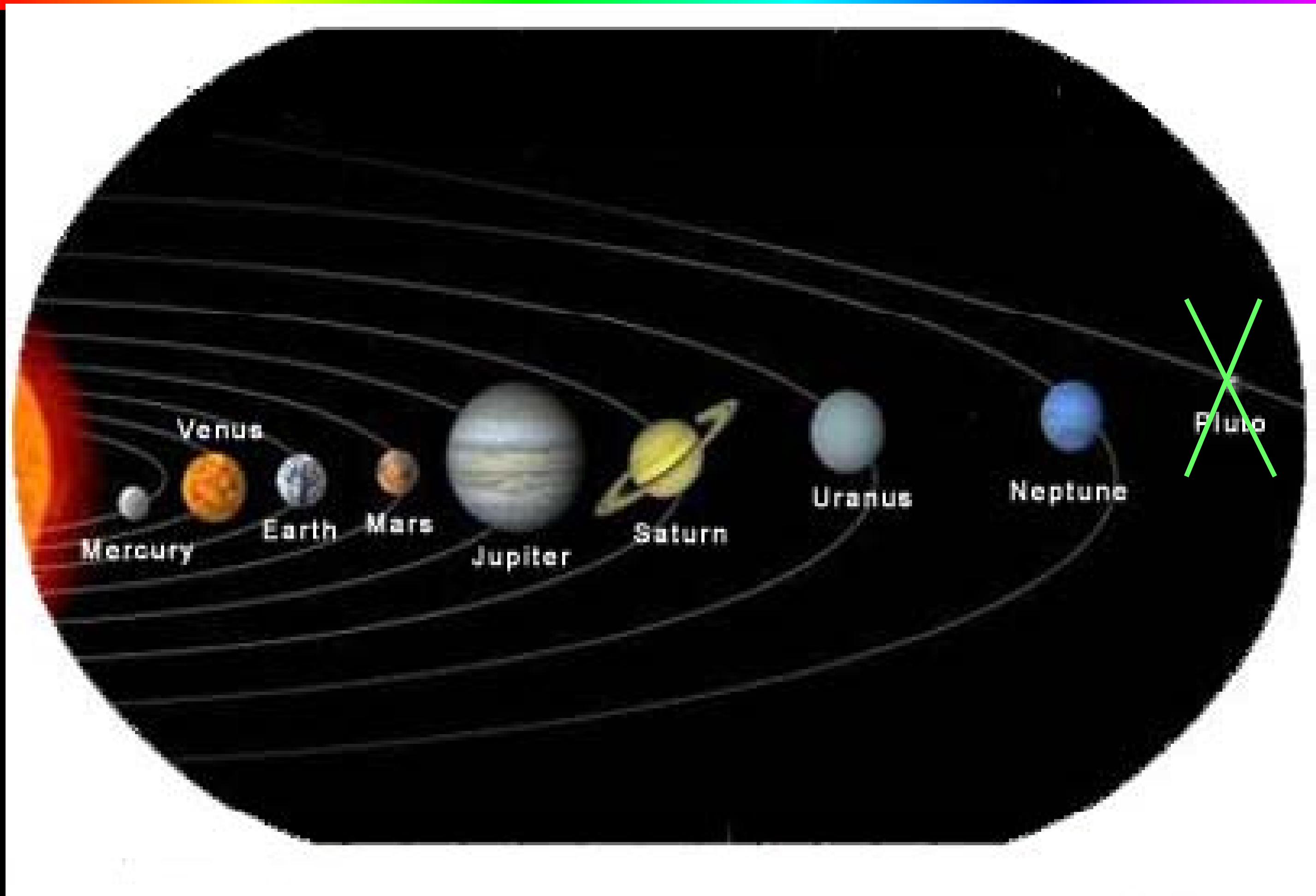
- The seesaw mechanism has been the dominant paradigm for the origin of tiny neutrino mass
- Physics close to the GUT scale
- How do we know if it is true? Is there a way to test it experimentally?
- Short answer: *No*
- However, we can be convinced of it

How can it be possible at all?

- We can (hope to) do good measurements on observables at low energies (meV–TeV)
- If we know something about the boundary conditions at high energies, we can say something non-trivial about physics between the two energy scales
- We have to be very lucky to be able to do this

Need the whole planets lined up!

Alignment of the Planets



Outline

- Why Neutrinos?
- The Big Questions
- Seesaw and SUSY-GUT
- Experimental Tests
- Conclusion

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!

Why Beyond the Standard Model

- Standard Model is *sooooo* successful. But none of us are satisfied with the SM. Why?
- Because it leaves so many great questions unanswered

  $\Rightarrow$ Drive to go beyond the Standard Model
- Two ways: $\Leftarrow$
  - Go to high energies
  - Study rare, tiny effects

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)

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

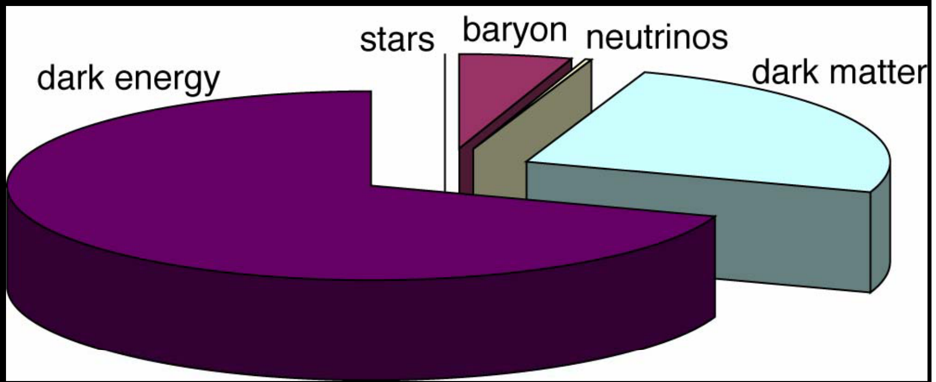
$$\begin{aligned}\mathcal{L}_6 \quad &= \quad QQQL, \bar{L}\sigma^{\mu\nu}W_{\mu\nu}He, \\ &\quad W^\mu_\nu W^\nu_\lambda B^\lambda_\mu, (H^\dagger D_\mu H)(H^\dagger D^\mu H), \cdots\end{aligned}$$

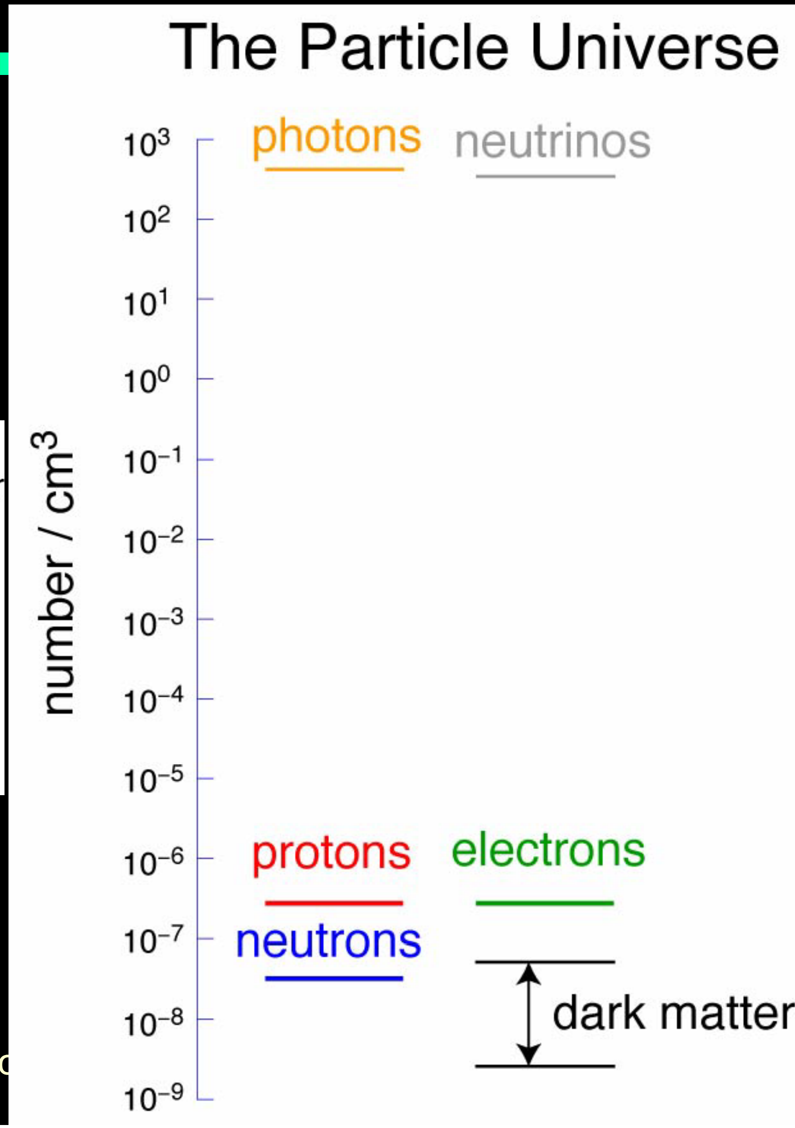
Unique Role of Neutrino Mass

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

Ubiquitous Neutrinos





They must have played some important role in the universe!

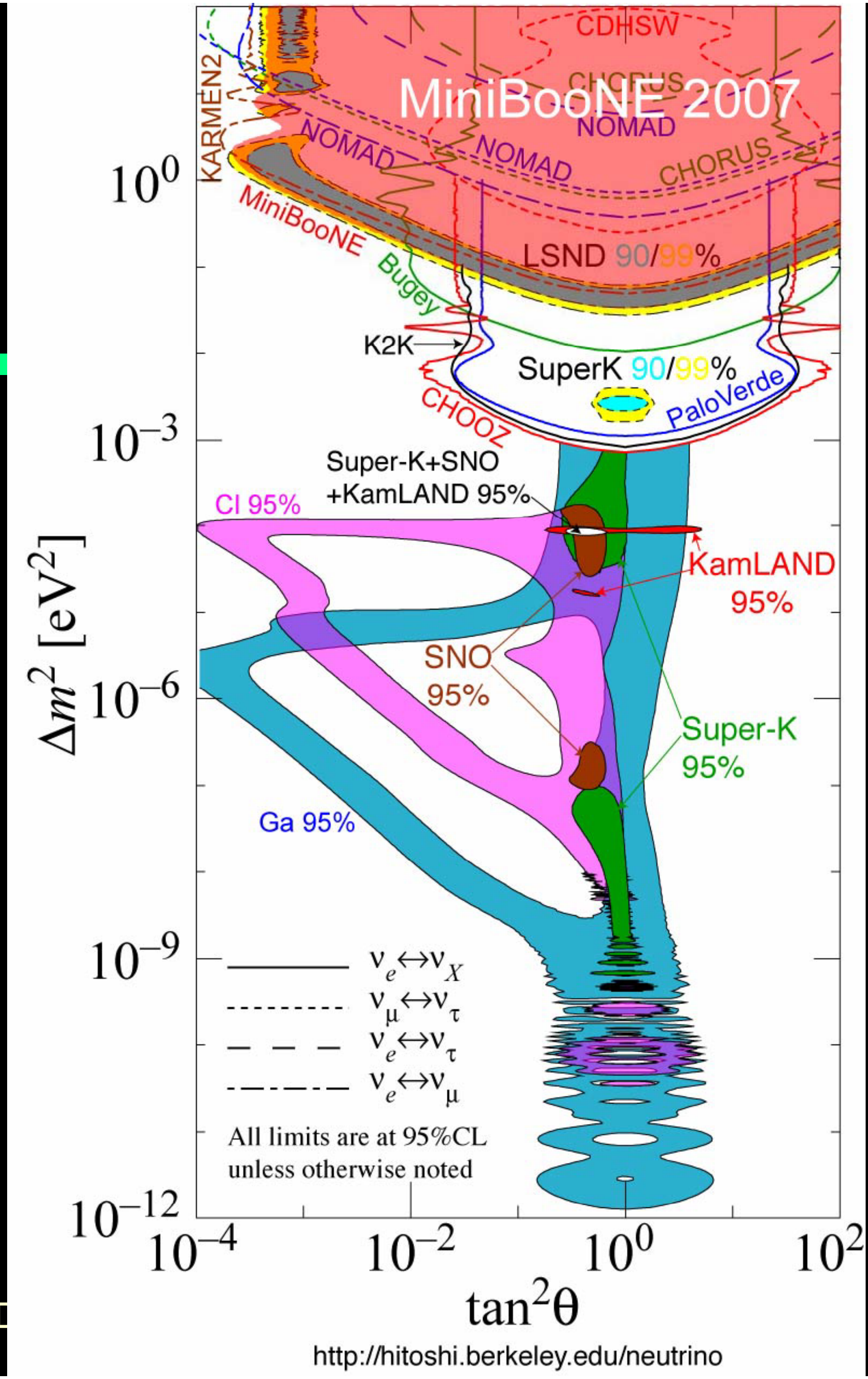
The Data

de Gouvêa's classification:

- "Indisputable"
  - Atmospheric
  - Solar
  - Reactor
- "strong"
  - Accelerator (K2K)

And we shouldn't forget:

- "unconfirmed"
  - Accelerator (LSND)



Historic Era in Neutrino Physics

We learned:

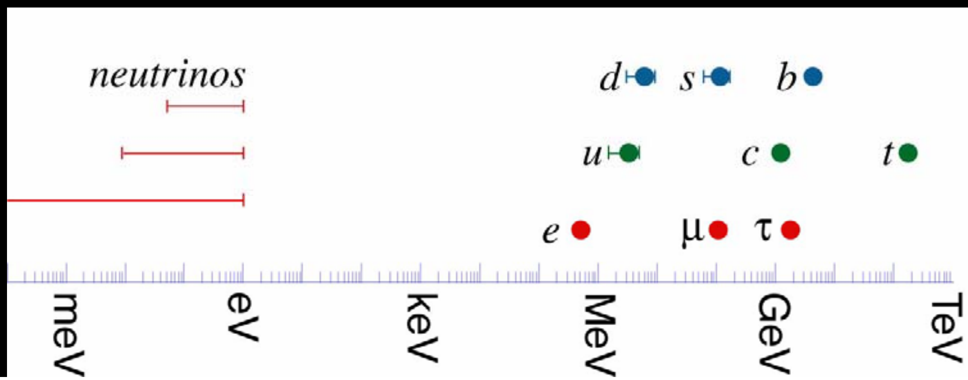
- Atmospheric ν_μs are lost. P=4.2 10^{-26} (SK) (1998)
- converted most likely to ν_τ (2000)
- Solar ν_e is converted to either ν_μ or ν_τ (SNO) (2002)
- Only the LMA solution left for solar neutrinos (Homestake+Gallium+SK+SNO) (2002)
- Reactor anti-ν_e disappear (2002) and reappear (KamLAND) (2004)

What we learned

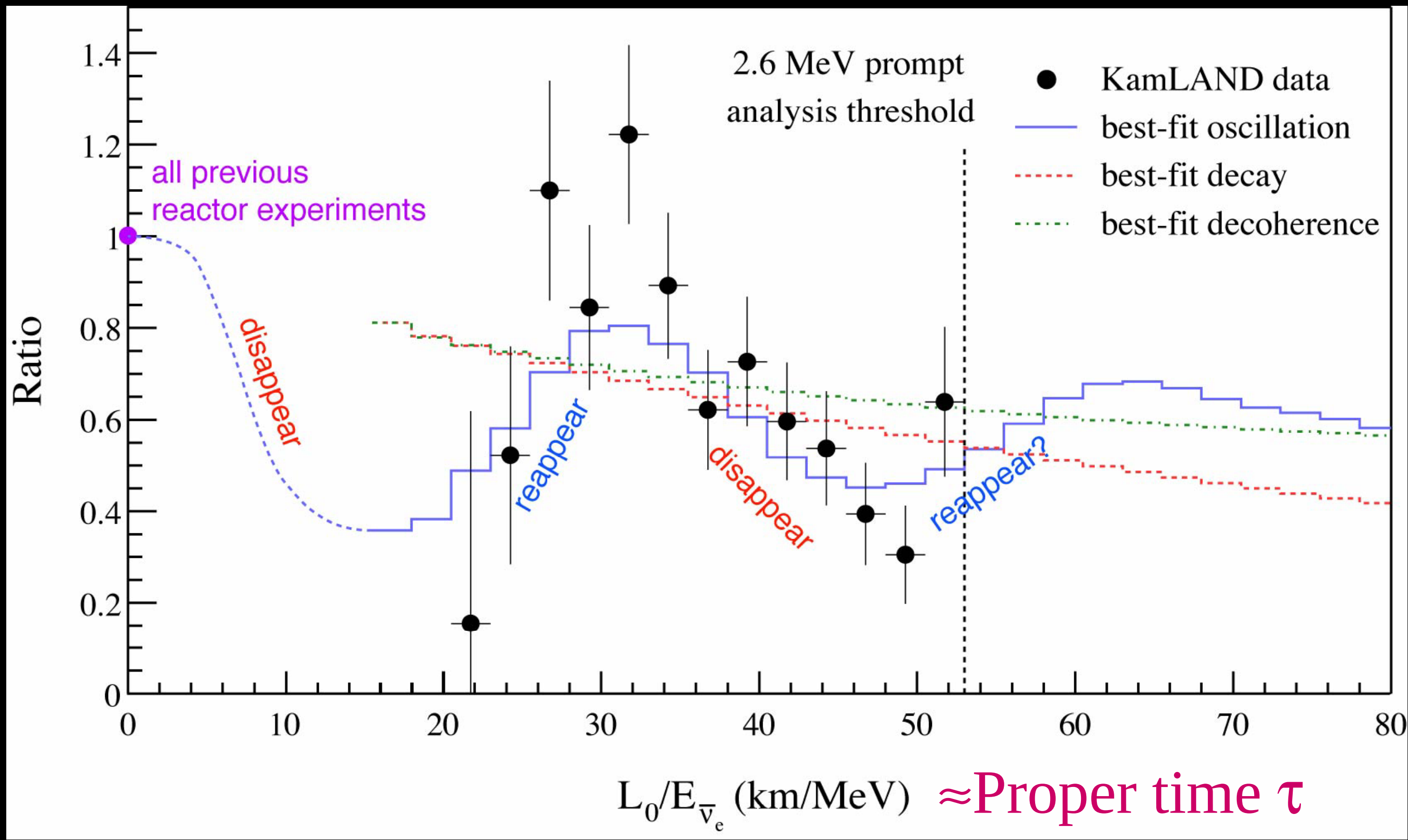
- Lepton Flavor is not conserved
- Neutrinos have tiny mass, not very hierarchical
- Neutrinos mix a lot

the first evidence for

incompleteness of Minimal Standard Model



Neutrinos do oscillate!



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

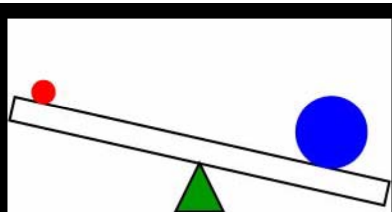
Seesaw and SUSY-GUT

Seesaw Mechanism

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

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

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



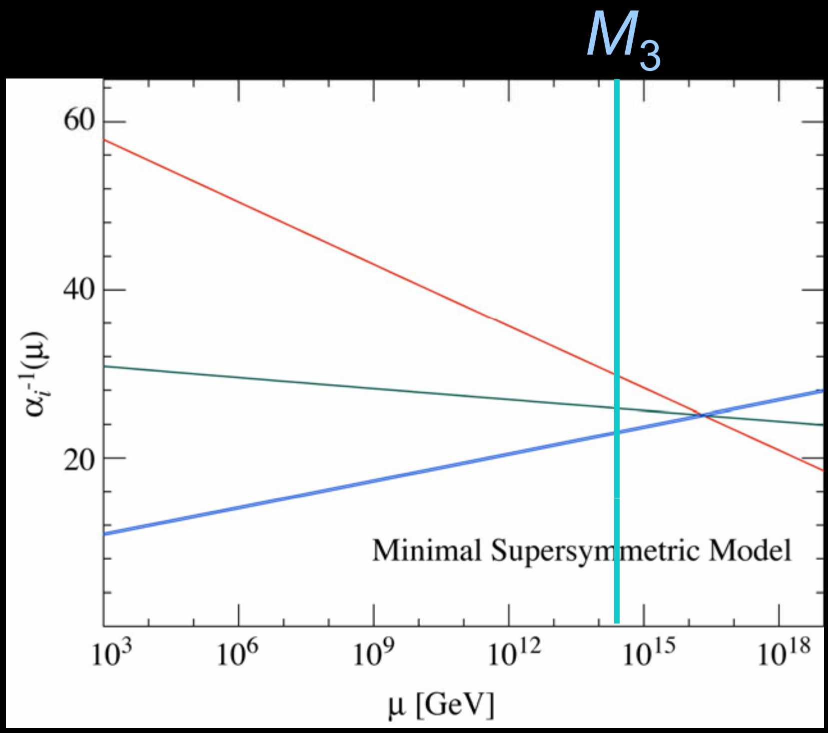
To obtain $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim m_t$, $M_3 \sim 10^{14}$GeV

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

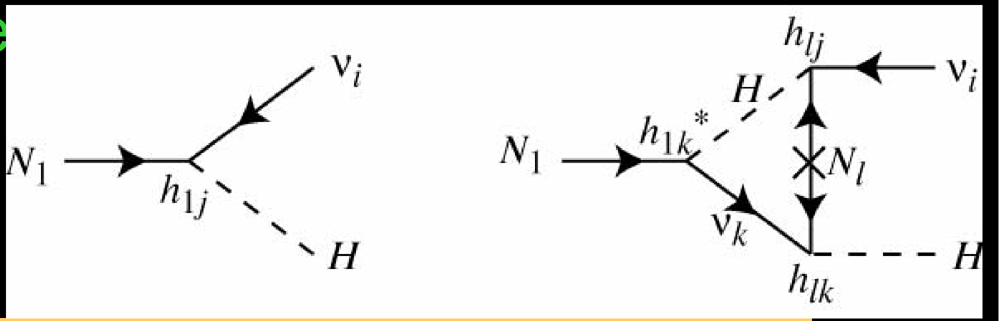
  $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim m_t$

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



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

  ⇒ More matter than anti-matter

  ⇒ *We have survived "The Great Annihilation"*
- Despite detailed information on neutrino masses, it still works (e.g., Bari, Buchmüller, Plümacher)

$\tilde{\nu}_R$

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?

amplitude

t

size of the universe

t

Experimental Tests

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

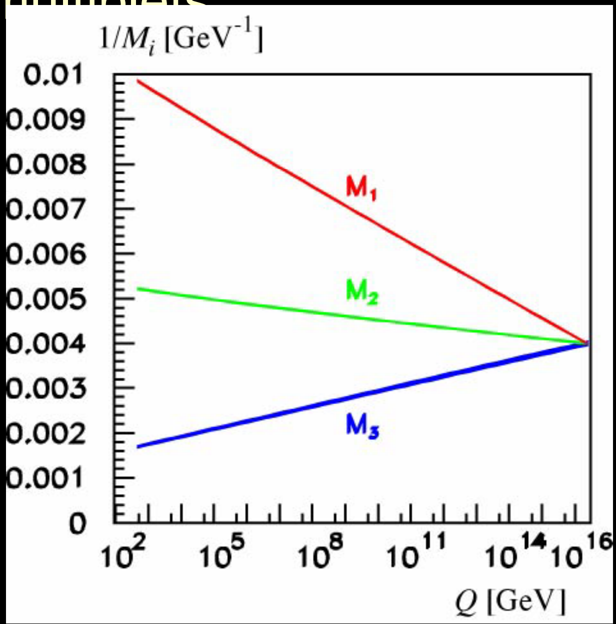
- LHC finds SUSY, ILC establishes SUSY
- no more particles beyond the MSSM at TeV scale
- Gaugino masses unify (two more coincidences)
- Scalar masses unify for 1st, 2nd generations (two for 10, one for 5*, times two)

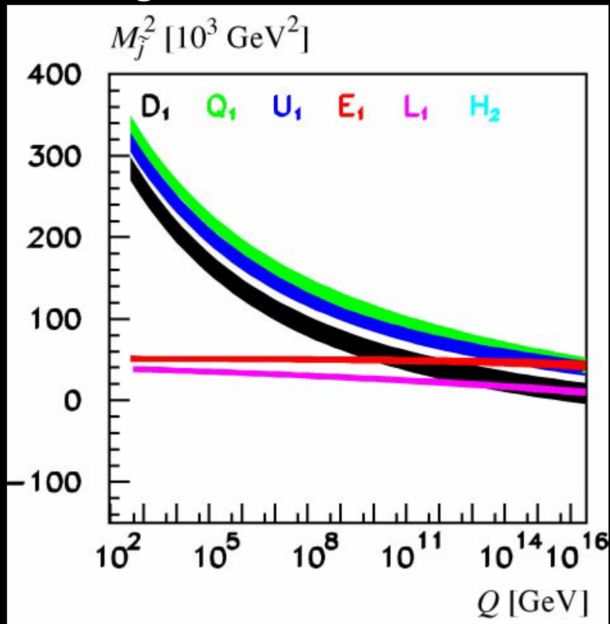
$\Rightarrow$ strong hint that there are no additional particles beyond the MSSM below M_{GUT} except for gauge singlets.

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





gauginos, higgsinos

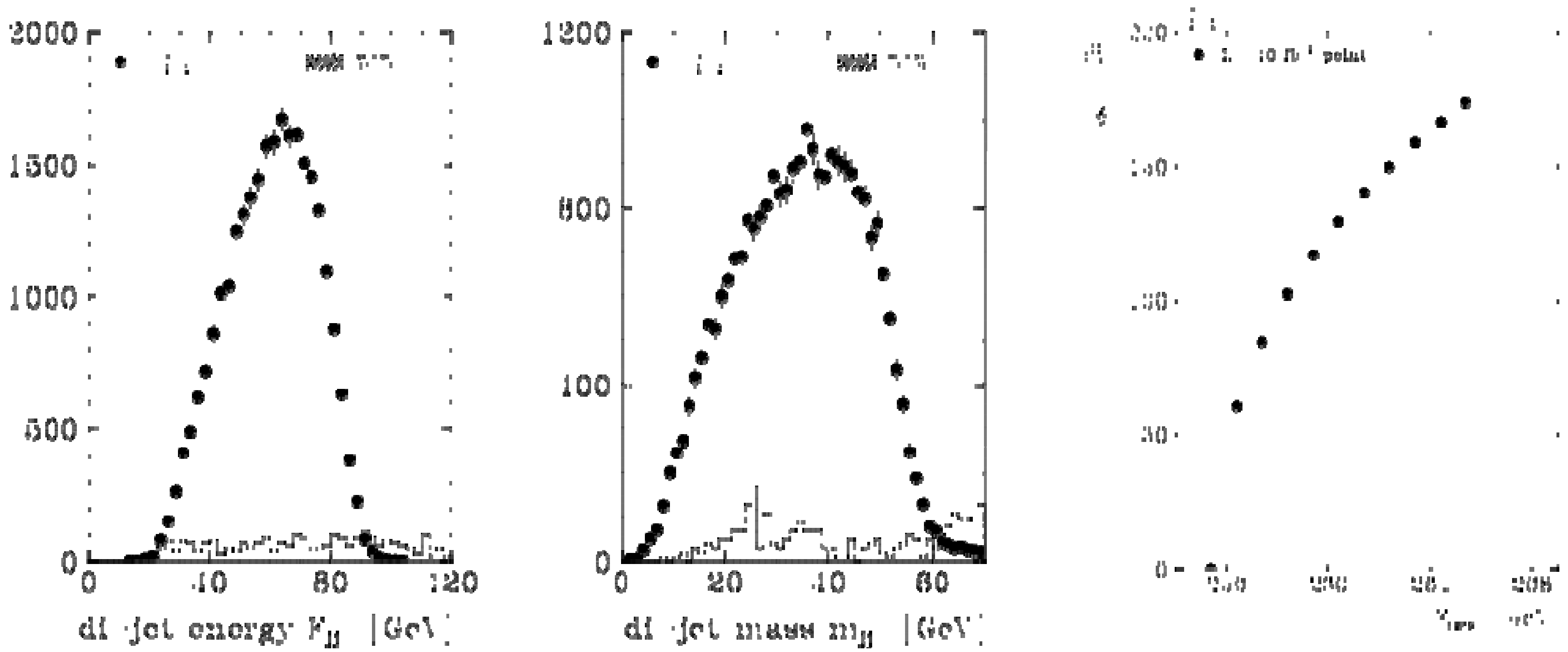
- charged ones "charginos"

$$(\tilde{W}^- \; \tilde{H}_d^-) \begin{pmatrix} M_2 & \sqrt{2} m_W \sin\beta \\ \sqrt{2} m_W \cos\beta & \mu \end{pmatrix} \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}_u^+ \end{pmatrix}$$

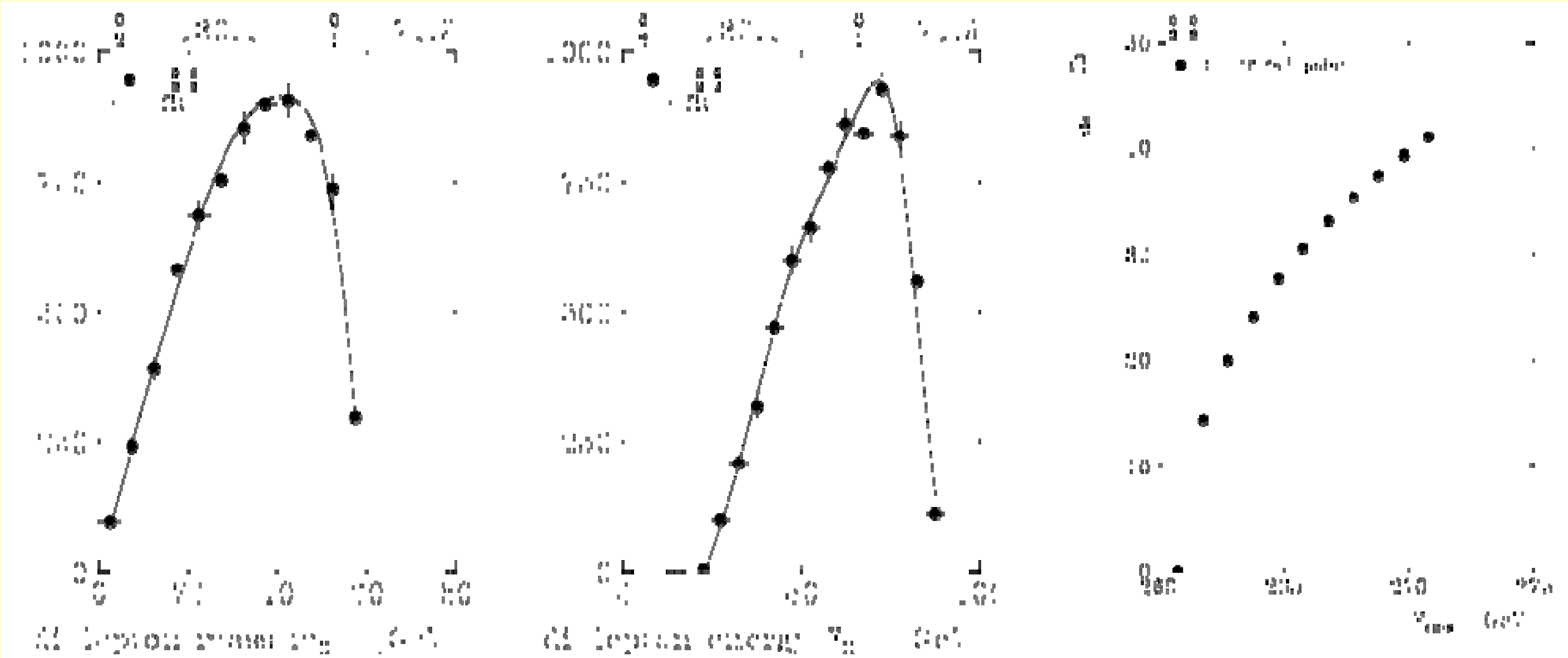
- neutral ones "neutralinos"

$$(\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0) \begin{pmatrix} M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -\mu \\ m_Z s_W s_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W}^0 \\ \tilde{H}_d^0 \\ \tilde{H}_u^0 \end{pmatrix}$$

$$e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow (\tilde{\chi}_1^0 l^\pm \nu_l)(\tilde{\chi}_1^0 q\bar{q}')$$



$$e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow (\tilde{\chi}_1^0 l^+ l^-)(\tilde{\chi}_1^0 l'^+ l'^-)$$

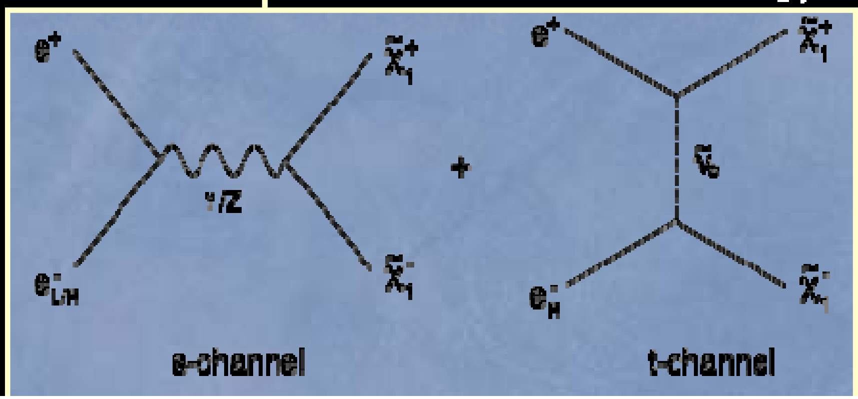


Model-independent parameter determination

- Chargino/neutralino mass matrices have four parameters M_1, M_2, μ, tanβ
- Can measure 2+4 masses
- can measure 10x2 neutralino cross sections

$$\sigma_{L,R}(e^+e^- \to \tilde{\chi}^0_i\tilde{\chi}^0_j) \quad \sigma_{L,R}(e^+e^- \to \tilde{\chi}^+_i\tilde{\chi}^-_j)$$

- can measure 3x2 chargino cross sections
- depend on masses of $\tilde{\nu}$, $\tilde{e}_L$, $\tilde{e}_R$



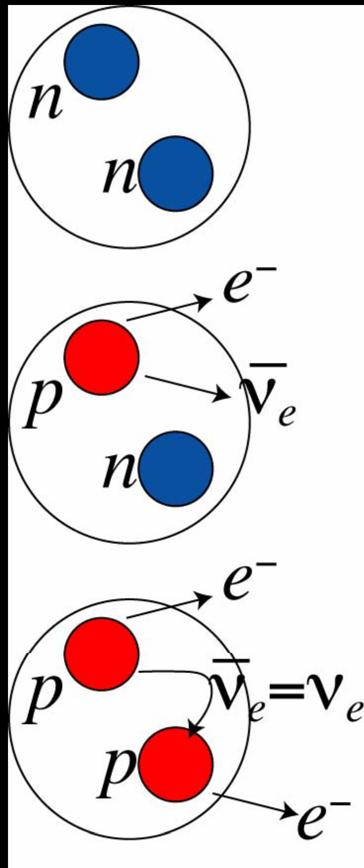
	input	fit
M_2	152 GeV	152 ±1.8 GeV
μ	316 GeV	316 ±0.9 GeV
tanβ	3	3 ±0.7
M_1	78.7 GeV	78.7 ±0.7 GeV

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

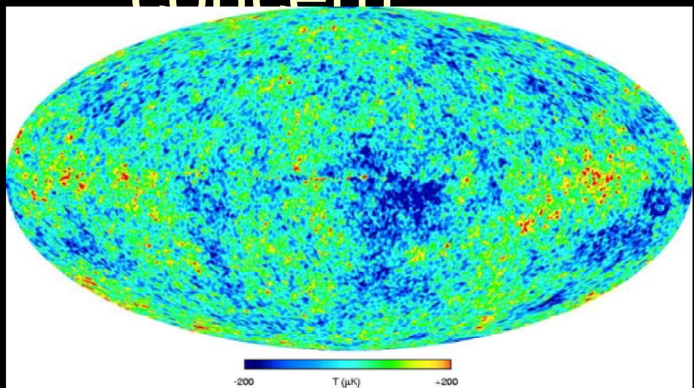
$$\mathcal{L}_5 = (LH)(LH) \to \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

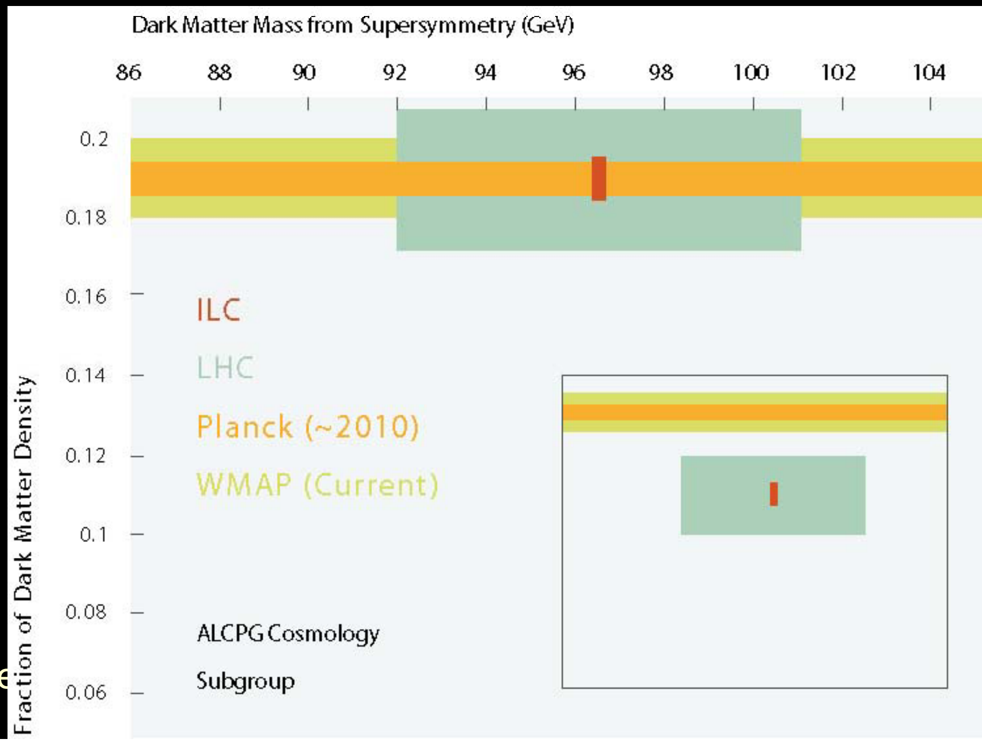
- But it can also happen with R-parity violating SUSY



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





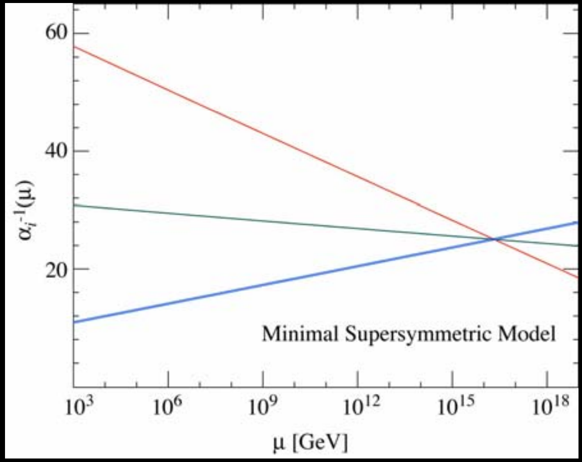
$$\Omega_M = \frac{0.756(n+1)x_f^{n+1}}{g^{1/2}\sigma_{ann}M_{Pl}{}^3}\frac{3s_0}{8\pi H_0^2} \approx \frac{\alpha^2/(TeV)^2}{\sigma_{ann}}$$

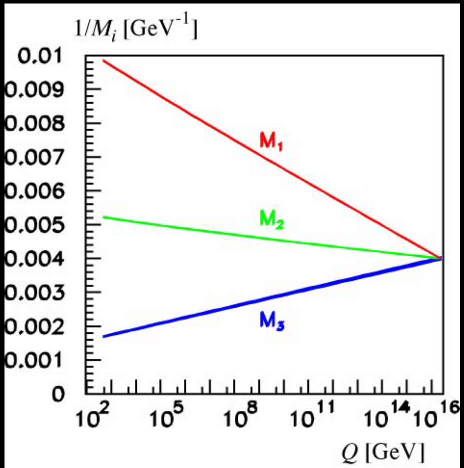
Need "New Physics" Λ<10^{14}GeV

- 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}

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

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

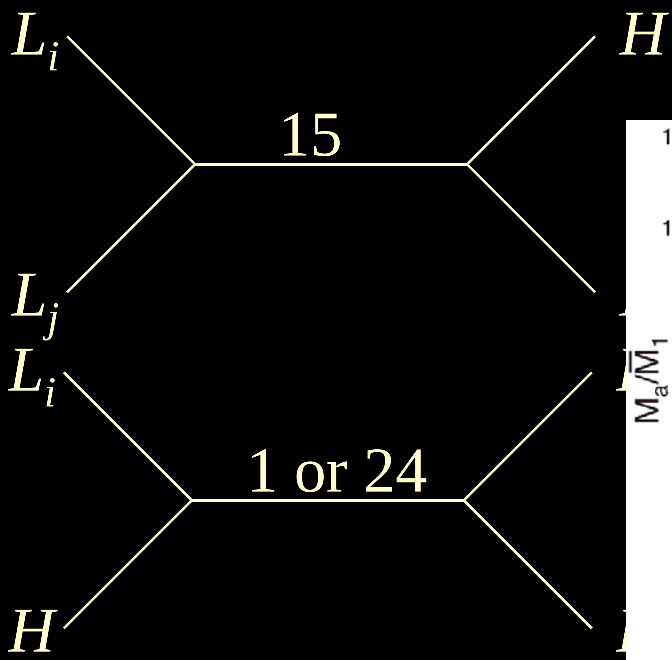


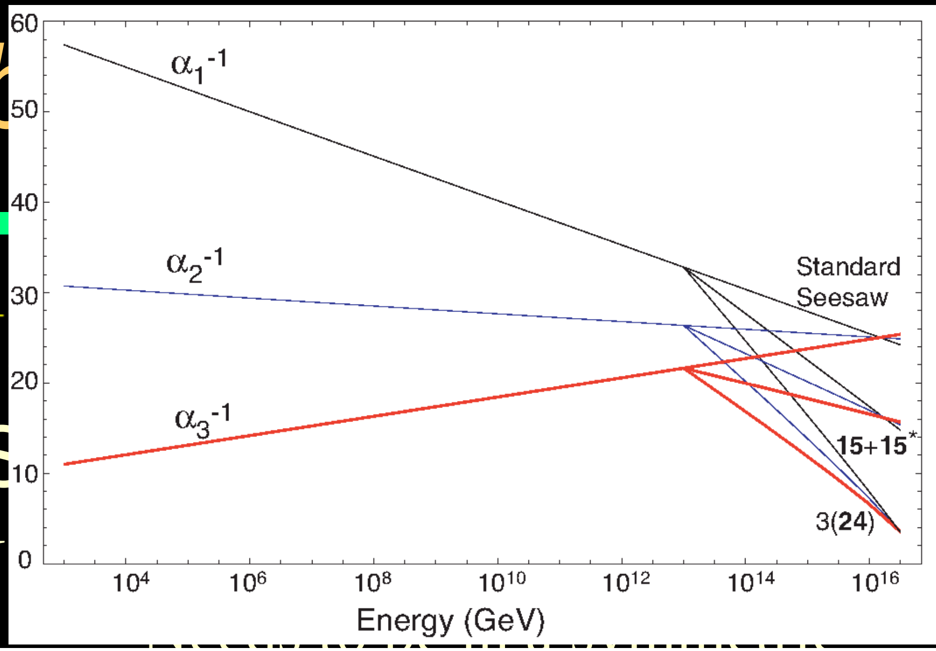


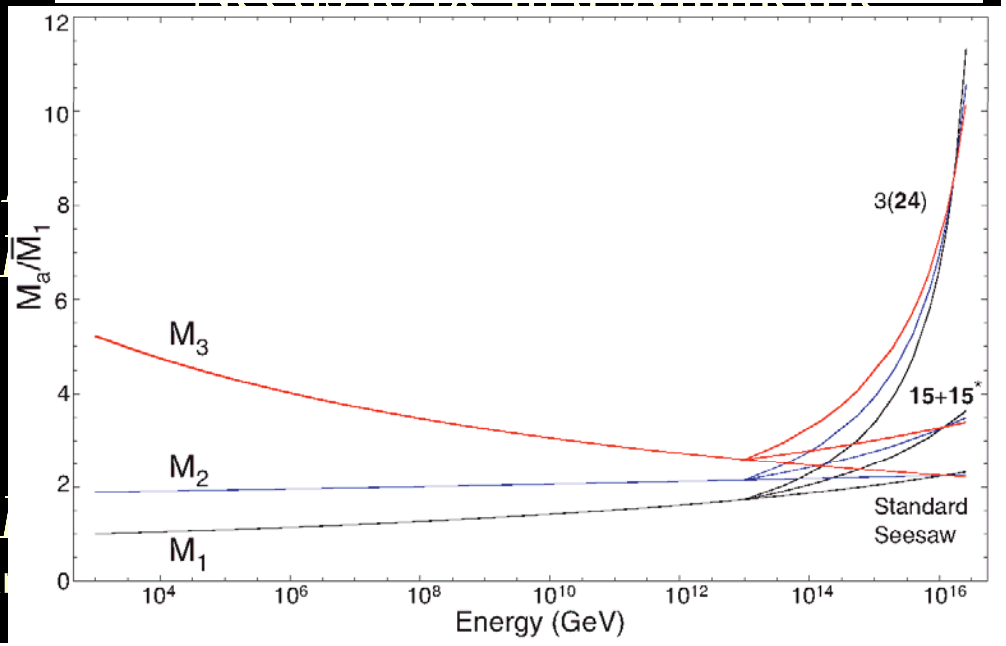
Possib

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

- L is in 5*, H in 5 of S







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

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
[illegible]	[illegible]	[illegible]	[illegible]

Matt Buckley, HM

High precision needed

$\Lambda = 10^{13}$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
[illegible]	[illegible]	[illegible]	[illegible]

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

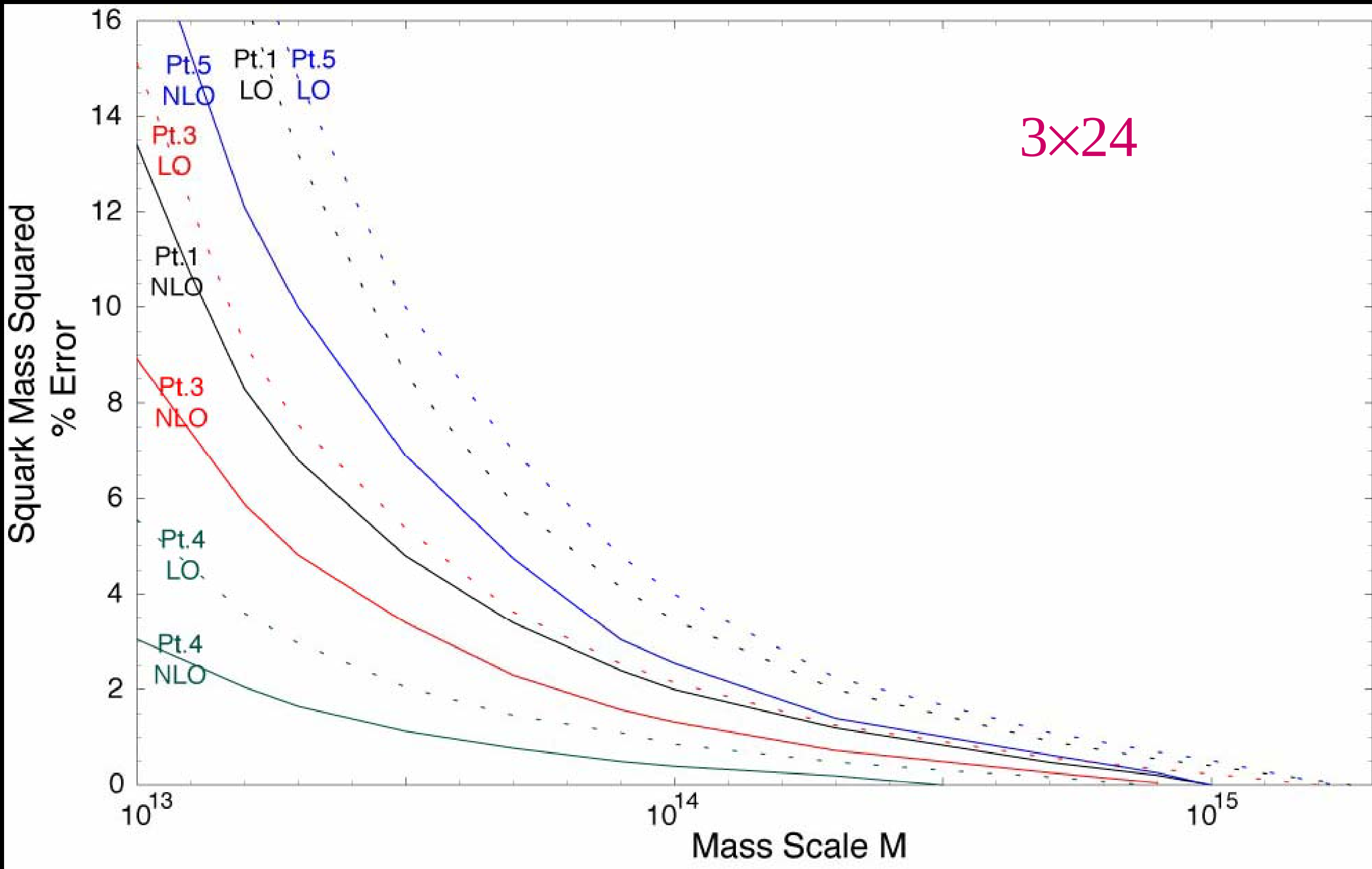
- Threshold behavior for squark-pair production has not been calculated with QCD effects (à la ttbar threshold)
- Mass differences presumably better measured
  - Jet energy scale uncertainties cancel
  - Difference in end points
  - But flavor tagging a challenge

Next Leading Order

- At NLO, things depends on more details
- Use Snowmass benchmark points to study

	1	2	3	4	5
m_0	400	400	200	800	100
$M_{1/2}$	400	400	100	200	300
A_0	0	0	0	0	300
$\tan\beta$	2	10	2	10	2.1
sgn μ	+	+	−	+	+

Needed accuracy (3σ)



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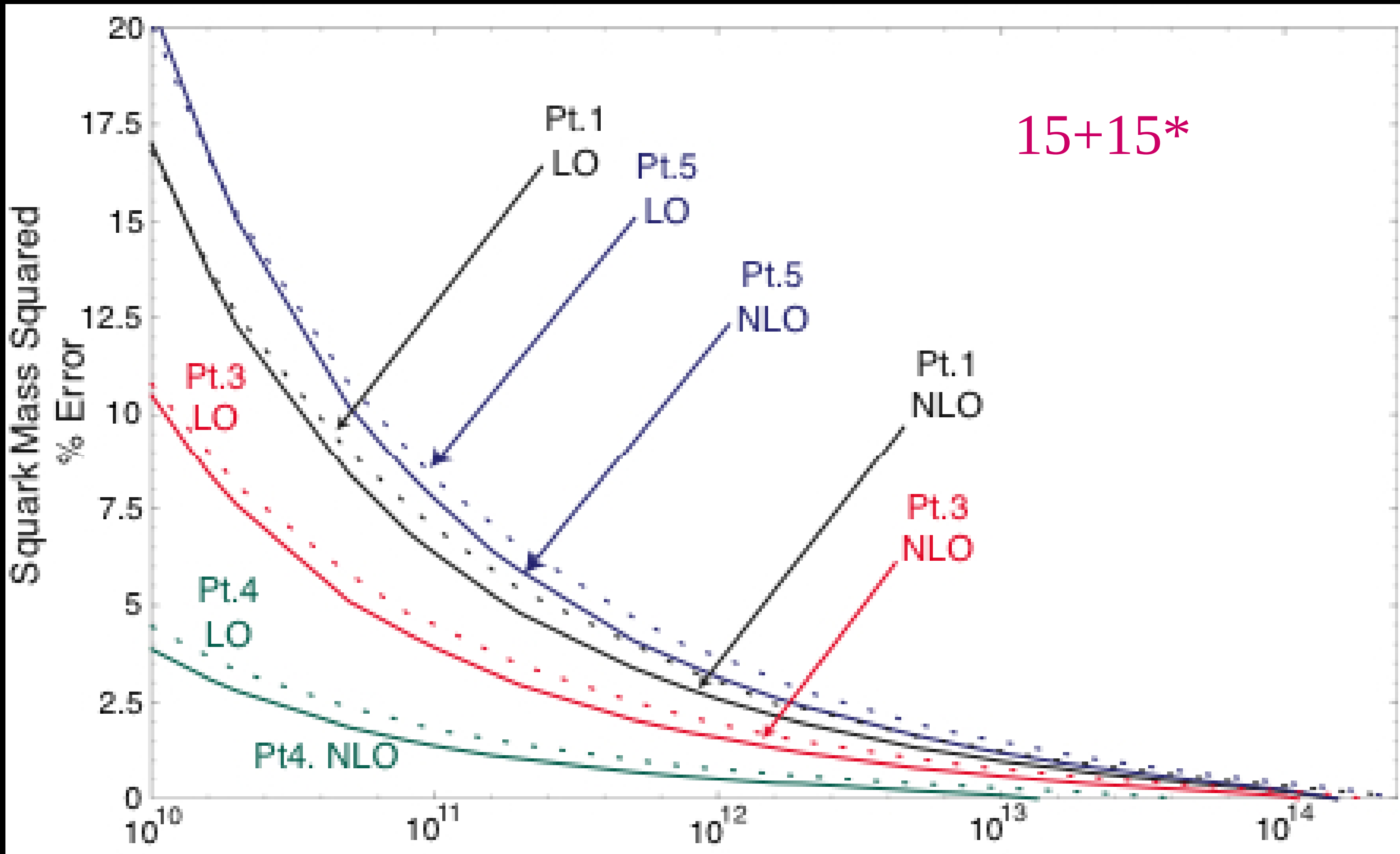
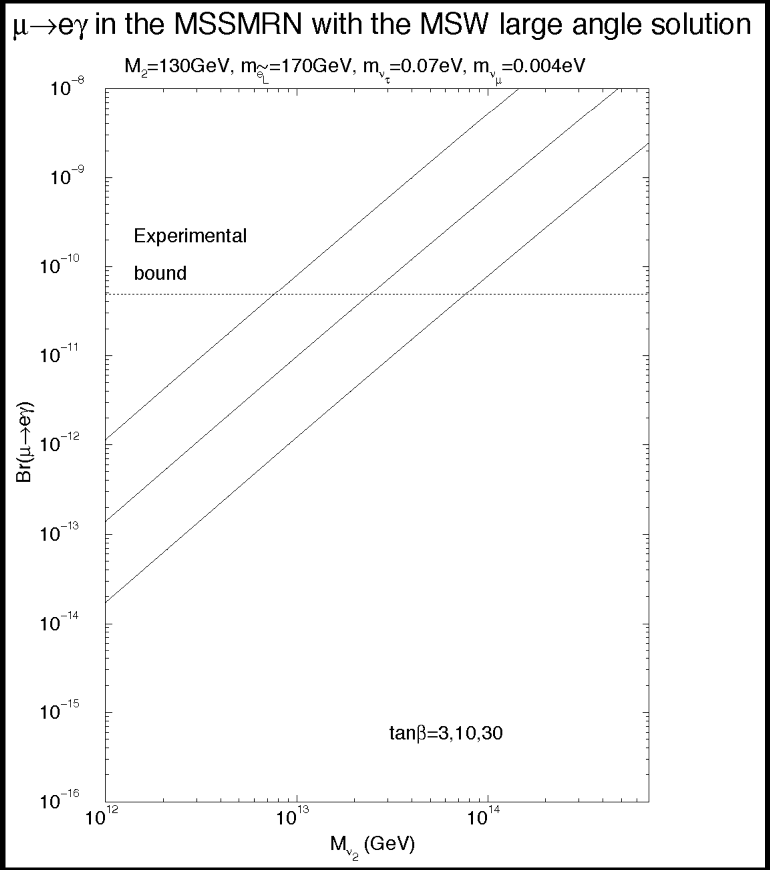


What about Yukawa couplings?

- 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-flavor violation



Hisano&Nomura, hep-ph/9810479

If this works out

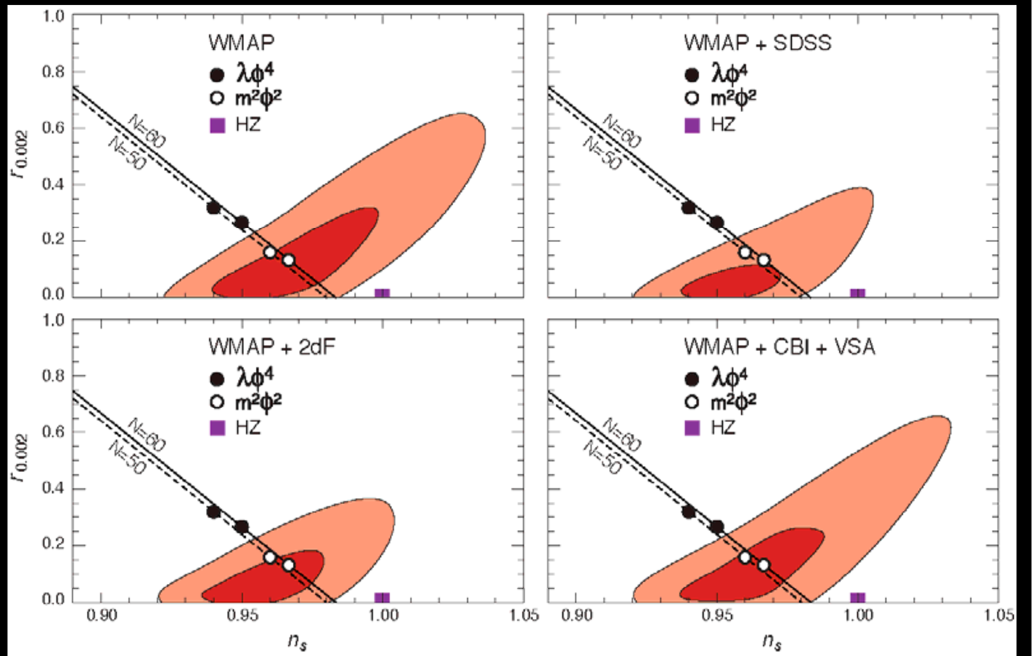
- Evidence for SU(5)-like unification hard to ignore
- Only three possible origins of Majorana neutrino mass < 10^{14} GeV consistent with gauge coupling and gaugino unification
- Only one consistent with scalar mass unification
- Could well “establish” the standard seesaw mechanism this way

Leptogenesis?

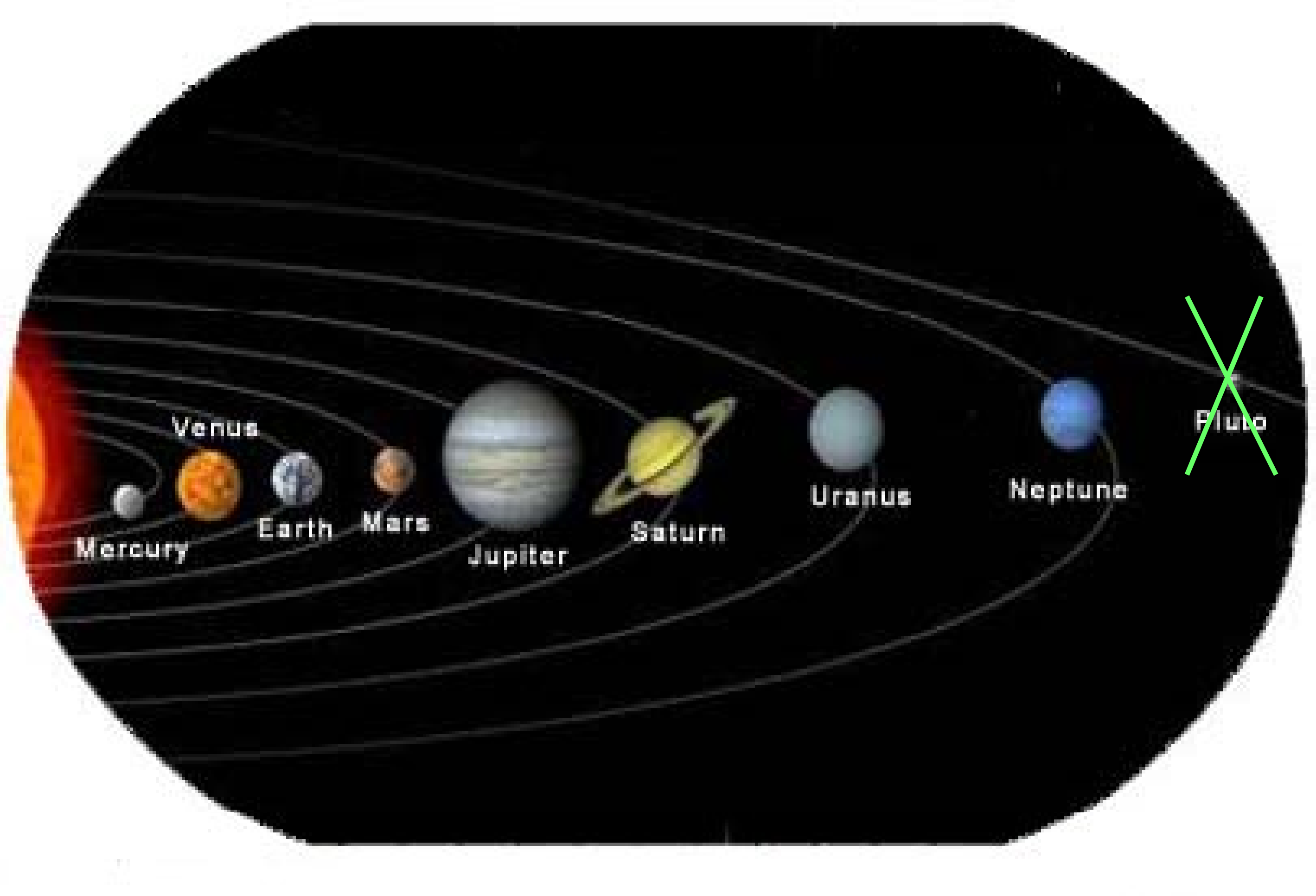
- No new gauge non-singlets below M_{GUT}
- Either
  - Baryogenesis due to particles we know at TeV scale, *i.e.*, electroweak baryogenesis
  - Baryogenesis due to gauge-singlets well above TeV, *i.e.*, leptogenesis by ν_R
- The former can be excluded by colliders & EDM
- The latter gets support from 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
- Completely consistent with latest WMAP
- Detection possible in the near future



Alignment of the Planets

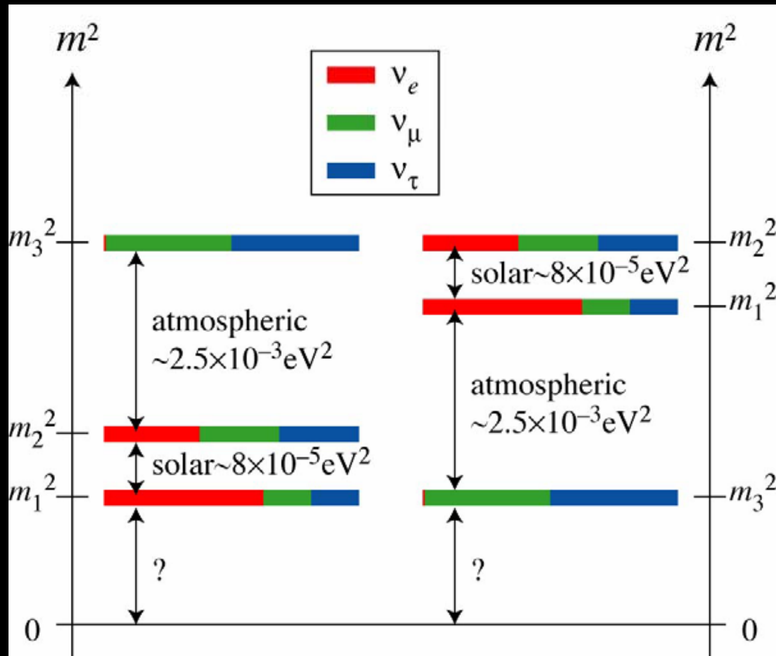


Conclusions

- *Revolutions in neutrino physics*
- Neutrino mass probes very high-energy physics
- But how do we know?
- By collection of experiments, with surprisingly important role of colliders
- We could well find convincing enough experimental evidence for seesaw mechanism
- May even learn something about our existence, the birth of the universe itself

Immediate Questions

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



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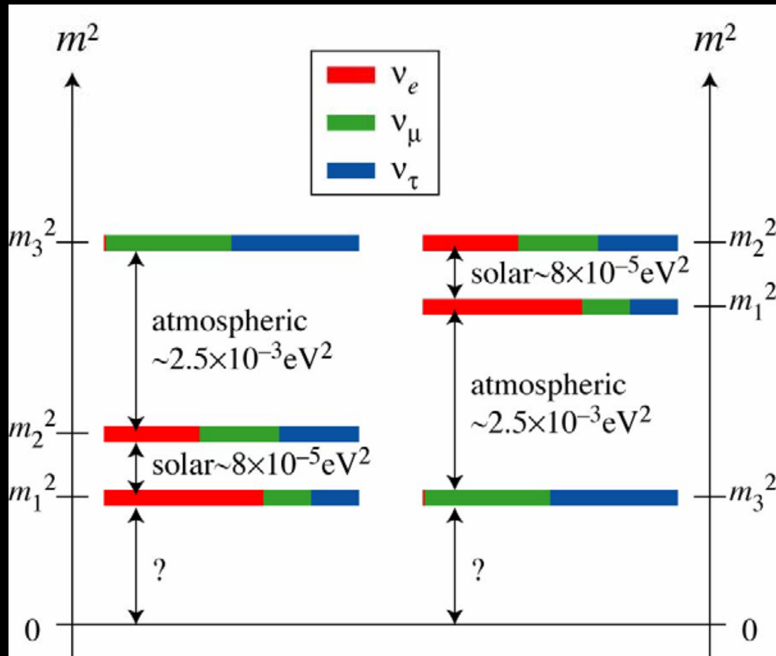


Extended Standard Model

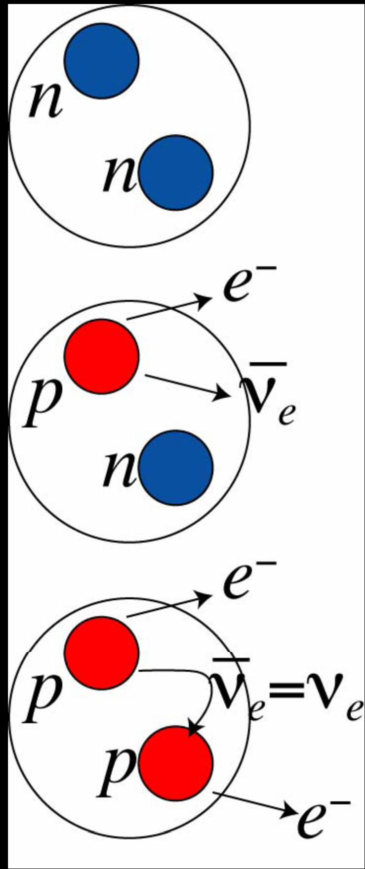
- Massive Neutrinos $\Rightarrow$ Minimal SM incomplete
- How exactly do we extend it?
- Abandon either
  - Minimality: introduce new unobserved light degrees of freedom (right-handed neutrinos)
  - Lepton number: abandon distinction between neutrinos and anti-neutrinos and hence matter and anti-matter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

$0\nu\beta\beta$: $nn \rightarrow ppe^- e^-$ with no neutrinos

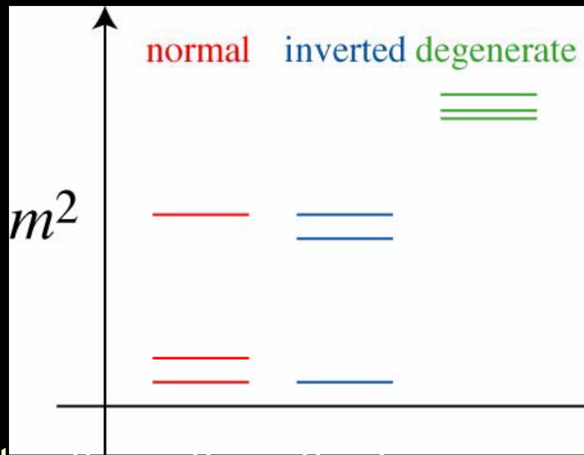
Neutrinoless Double Beta Decay

- $2\nu\beta\beta$: $nn \to ppe^-e^-\bar{\nu}\bar{\nu}$ happens in the SM (very rare)
- $0\nu\beta\beta$: $nn \to ppe^-e^-$ with no neutrinos does not happen in the SM, violates lepton number
- Possible if neutrinos Majorana
- Matrix element proportional to

$$<m_{\nu e}>=\Sigma_i m_{\nu i} U_{ei}^2$$



Three Types of Mass Spectrum

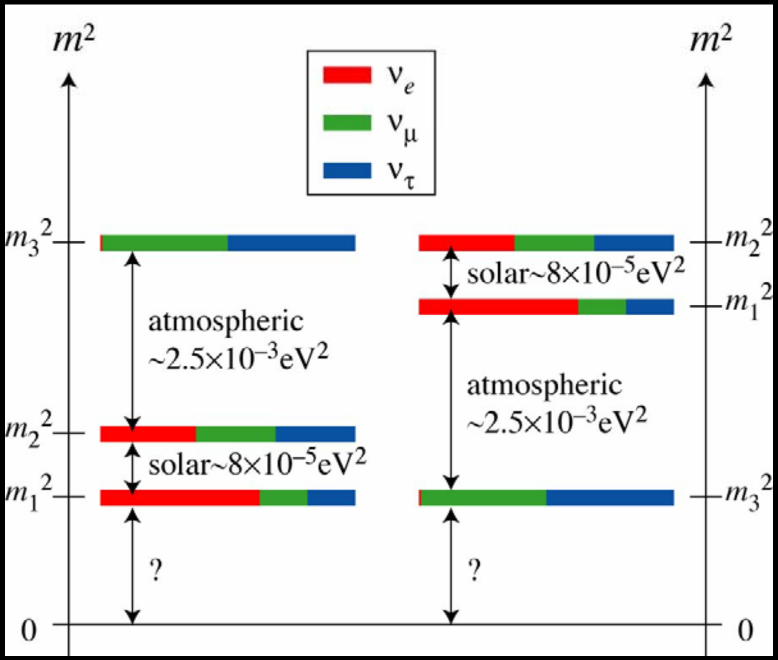


- Degenerate
  - All three around >0.1eV with small splittings
  - Possible even after WMAP+2dF: m<0.23eV
  - May be confirmed by KATRIN, cosmology
  - $|\langle m_{\nu e}\rangle| = |\Sigma_i m_{\nu i} U_{ei}^2| > m \cos^2 2\theta_{12} > 0.07m$
- Inverted
  - $m_3 \sim 0$, $m_1 \sim m_2 \sim (\Delta m^2_{23})^{1/2} \approx 0.05$eV
  - May be confirmed by long-baseline experiment with matter effect
  - $|\langle m_{\nu e}\rangle| = |\Sigma_i m_{\nu i} U_{ei}^2| > (\Delta m^2_{23})^{1/2} \cos^2 2\theta_{12} > 0.0035$eV
- Normal
  - $m_1 \sim m_2 \sim 0$, $m_3 \sim (\Delta m^2_{23})^{1/2} \approx 0.05$eV
  - $|\langle m_{\nu e}\rangle| = |\Sigma_i m_{\nu i} U_{ei}^2|$ may be zero even if Majorana

HM, Peña-Garay

Immediate Questions

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



T2K (Tokai to Kamioka)

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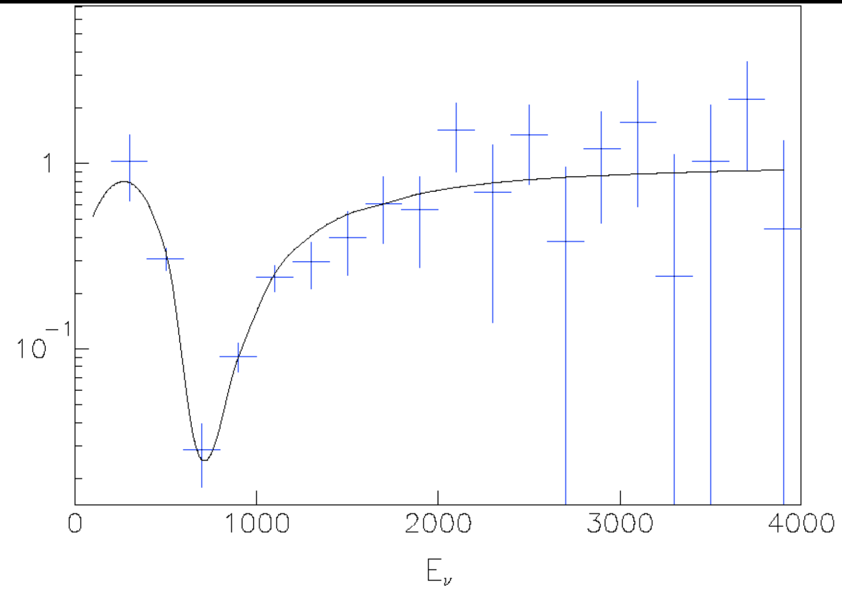
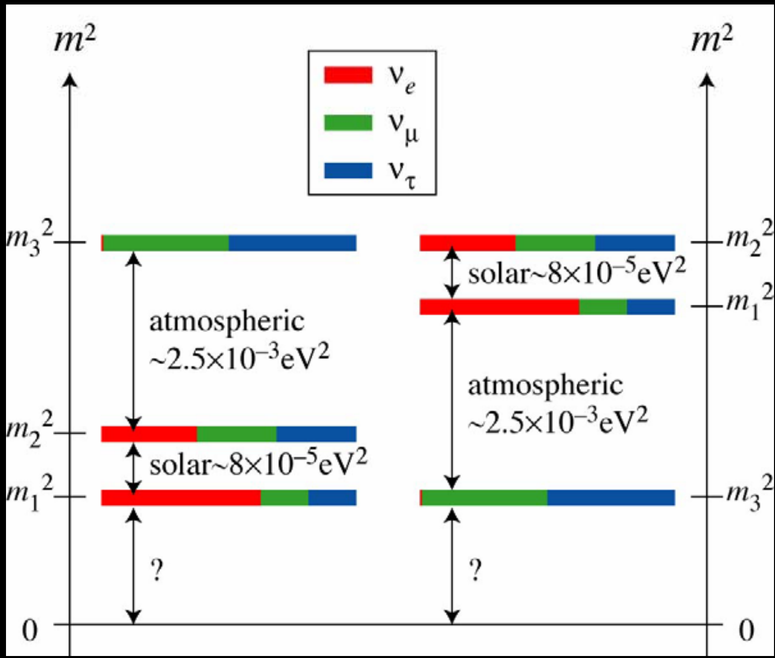


Can measure $\sin^2 2\theta_{23}$
at 1% level

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...

- Dream case for neutrino oscillation physics!
- Δm^2_{solar} within reach of long-baseline expts
- Even CP violation may be probable
  - neutrino superbeam
  - muon-storage ring neutrino factory

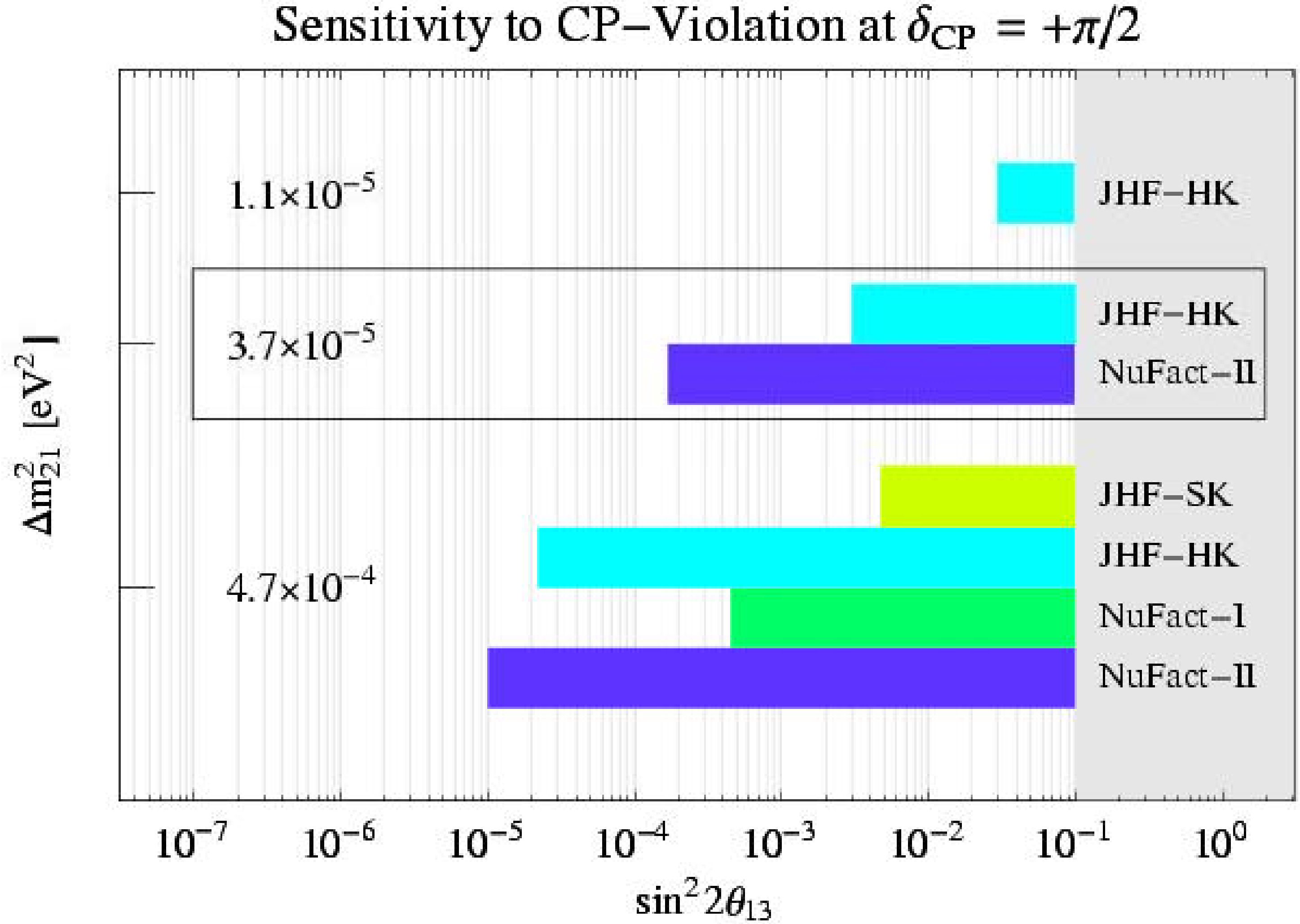
$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23}$$
$$\sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

- Possible only if:
  - $\Delta m_{12}{}^2$, s_{12} large enough (LMA)
  - θ_{13} large enough

θ_{13} decides the future

- The value of θ_{13} crucial for the future of neutrino oscillation physics
- Determines the required facility/parameters/baseline/energy
- Two paths to determine θ_{13}
  - Long-baseline accelerator neutrino oscillation
  - Reactor neutrino experiment with two detectors

Measurements of CP-violation



- CP violation with high luminosity superbeams feasable
- sensitivity is δ_{CP} dependent

Huber, ML, Winter, hep-ph/020435:

Reactor experiments

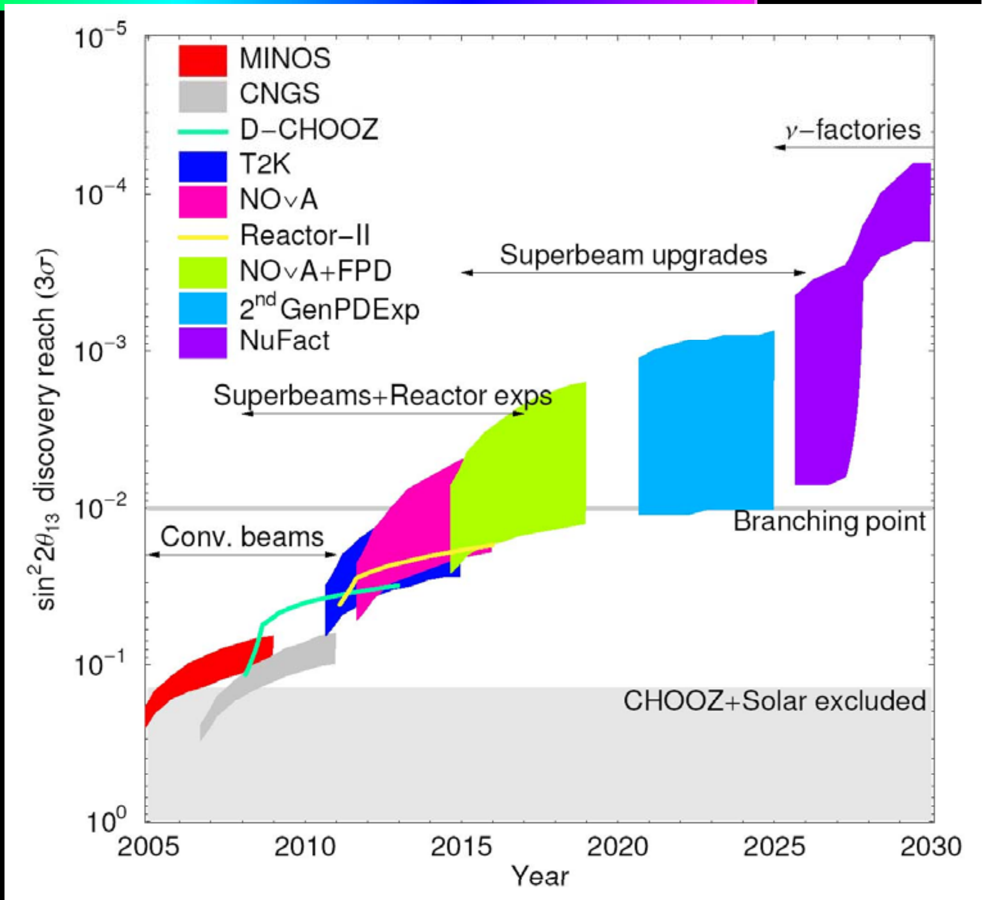
- Double-CHOOZ
  - Aiming at $\sin^2 2\theta_{13} \sim 0.03$
- Daya Bay
  - Aiming at $\sin^2 2\theta_{13} \sim 0.01$

Daya Bay

Reactor experiment to look for $\sin^2 2\theta_{13}$ down to ~0.01

Need for new facilities

- The answer depends on what we will find in the near future



What about 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