Project-X
Intensity Frontier

Hitoshi Murayama (Berkeley/IPMU Tokyo)

THE BIG QUESTIONS

PROJECT X

0. What is the origin of mass for fundamental particles?
1. Are there undiscovered principles of nature: new symmetries, new physical laws?
2. How can we solve the mystery of dark energy?
3. Are there extra dimensions of space?
4. Do all the forces become one?
5. Why are there so many kinds of particles?
6. What is dark matter? How can we make it in the laboratory?
7. What are neutrinos telling us?
8. How did the universe come to be?
9. What happened to the antimatter?

Based on "The Quantum Universe," HEPAP 2004

Use SUSY

- In all of these questions, what we find at the LHC is crucial
- How do we set quantitative goals?
- Examples with SUSY
- Focus on *9. What happened to anti-matter?*
- But is related to other QU questions

Two Energy Scales

- We follow the clues provided by Nature
- the missing physics we are aware of:
  - Higgs
  - Dark Matter
  - Dark Energy
  - neutrino mass
  - matter asymmetry
  - inflation
- EWSB, Dark Matter ⇒ TeV
- neutrino mass, inflation ⇒ 10^{10}-10^{15} GeV

4. Do all the forces become one?

5. Why are there so many kinds of particles?

NEWSFLASH:

➡ We now know that new sources of heavy quark flavor or CP violation at sub-TeV energies are constrained to be small

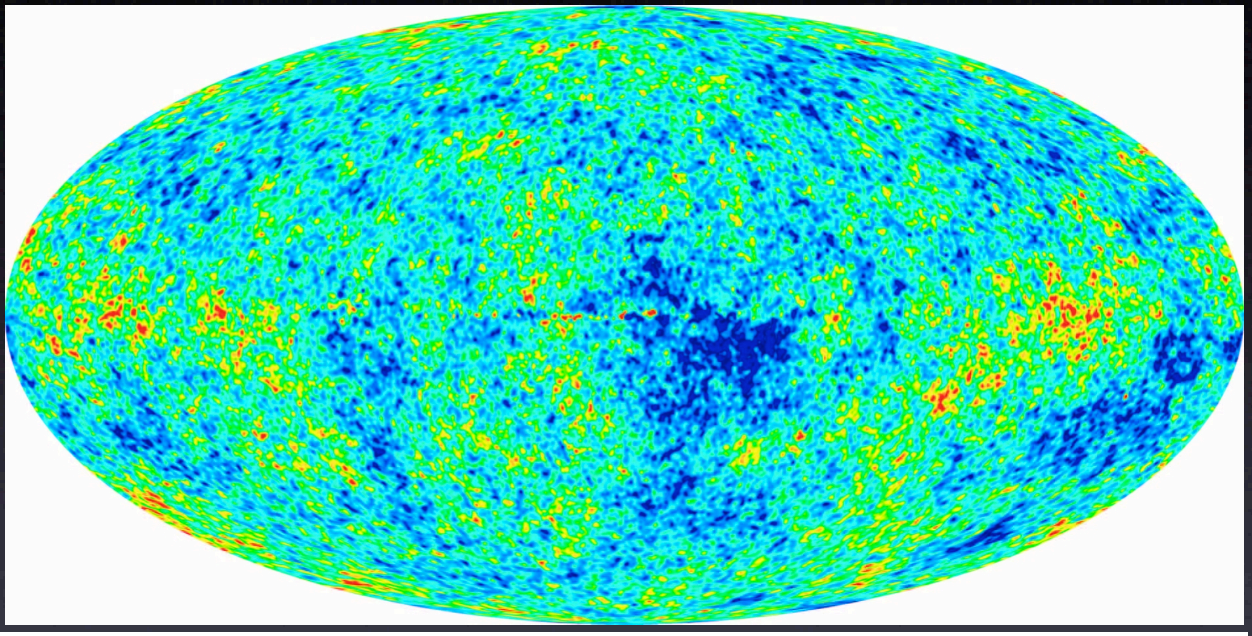
➡ Even a couple years ago this was not obvious! (B_s mixing, B -> tau + nu). From a theory point of view it is quite surprising

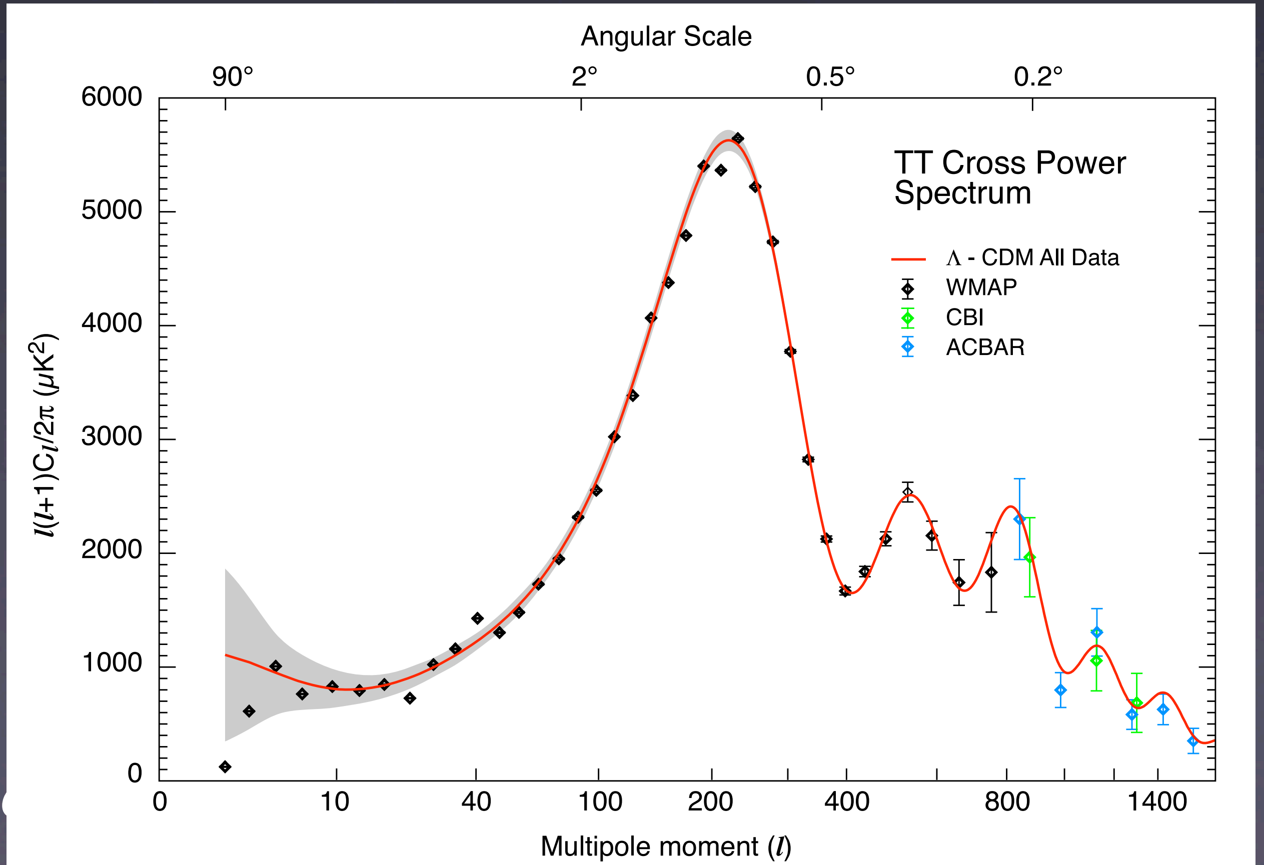
➡ We have discovered that the quark sector, which includes the unknown Terascale physics of electroweak symmetry breaking, is either Minimally Flavor Violating or close to it

- KM phase the dominant source of the *observed* CP violation!

Another NEWSFLASH

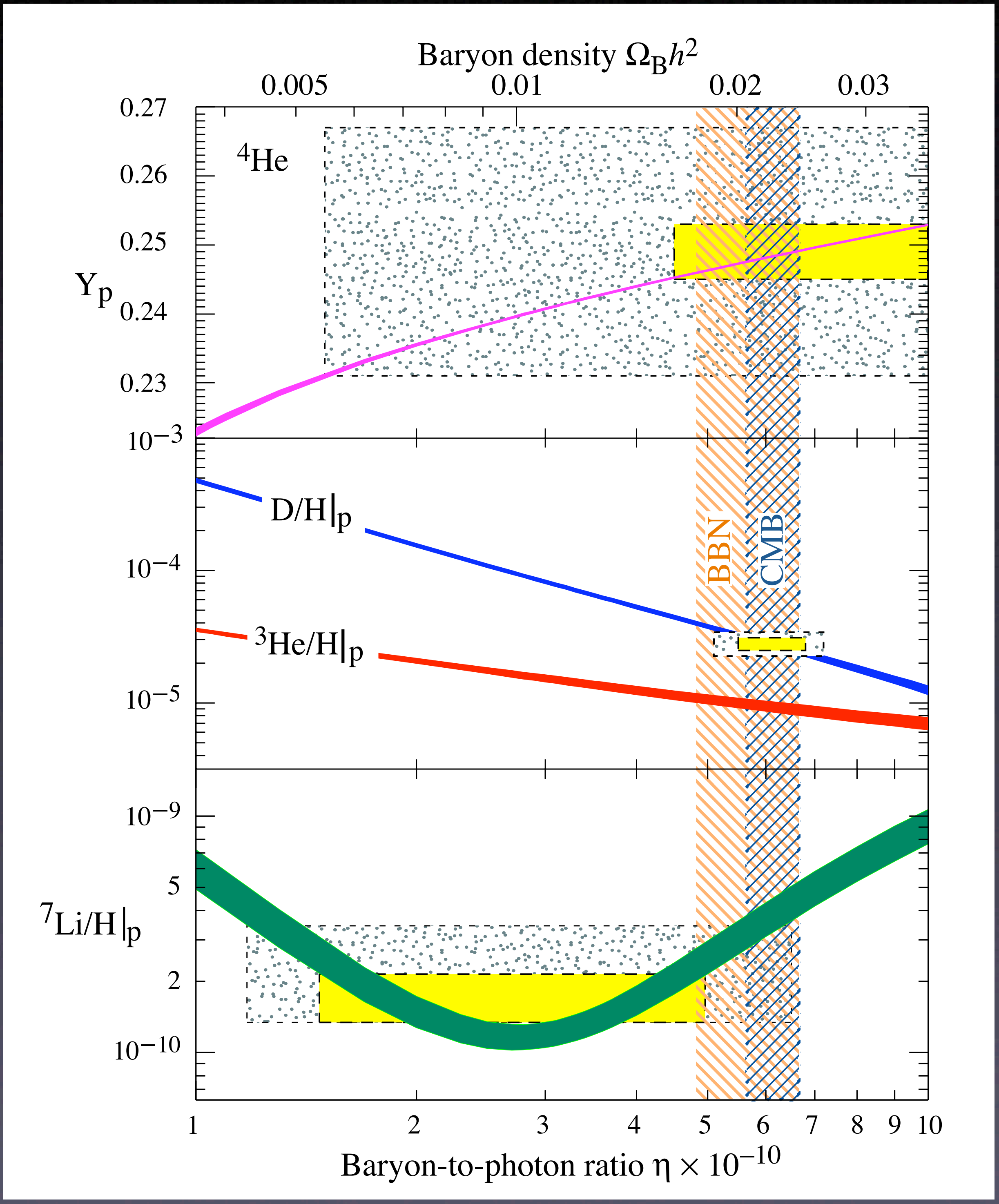
- Data on CMB anisotropy power spectrum
- Cosmic Inflation stretched the new-born microscopic space to our entire visible universe
- Big “reset” of the universe
- universe started anew after the end of inflation (“reheating”)





More NEWSFLASH

- Matter Asymmetry is now measured in two independent ways
- CMB anisotropy
- Big-Bang Nucleosynthesis
- Consistent!



Matter and Anti-Matter
Early Universe

1,000,000,001

q

1,000,000,000

$\bar{q}$

Matter and Anti-Matter Current Universe

us

q $\bar{q}$

The Great Annihilation

Matter Asymmetry

- Initial condition of the universe *cannot* be the explanation any more
- Matter Asymmetry *must* be created at or after the end of inflation
- Sakharov's necessary conditions
  - violation of matter number: $0\nu\beta\beta$, pdecay
  - CP violation
  - out of equilibrium

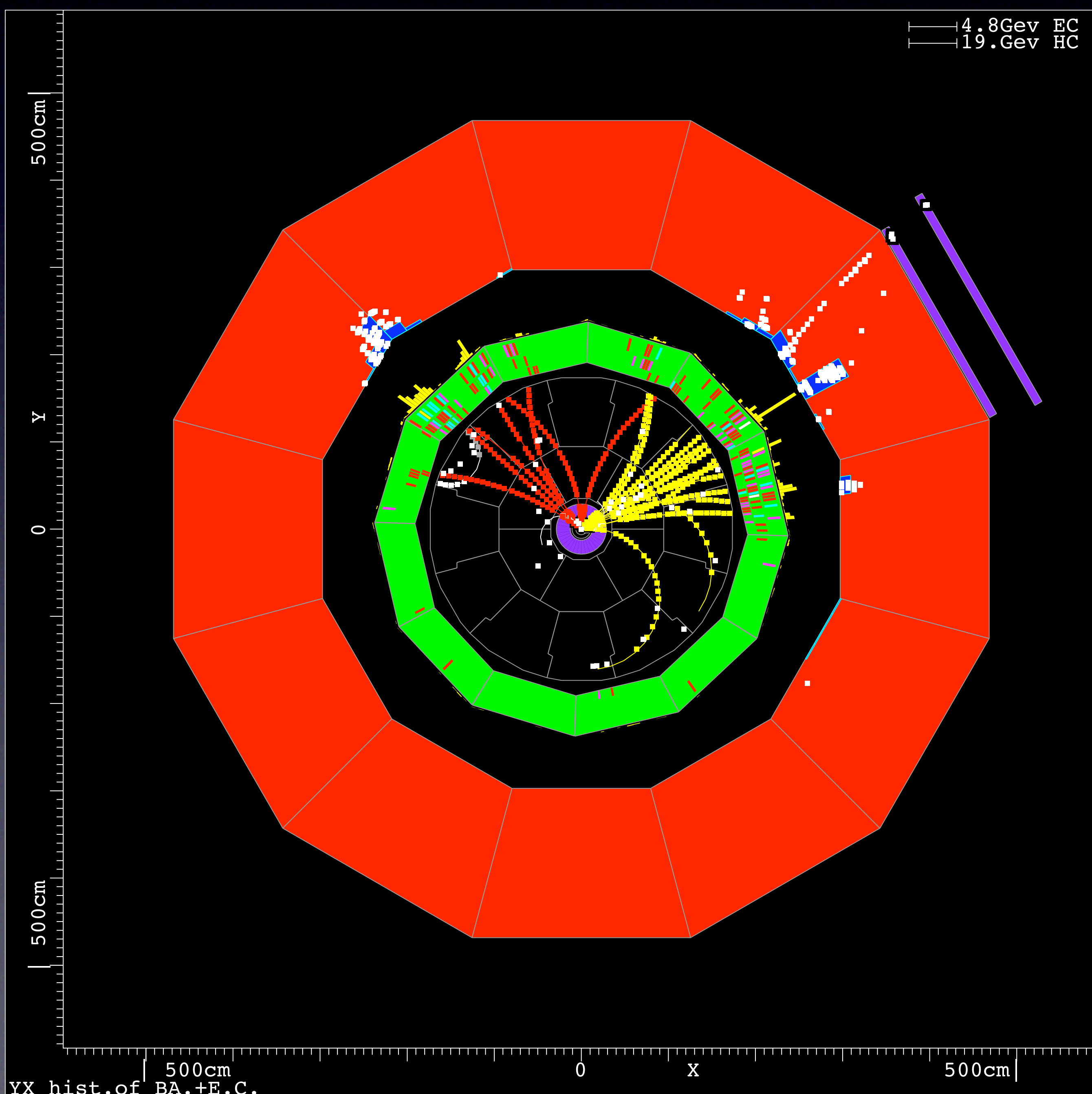
Need new source of $\not{C}\not{P}$

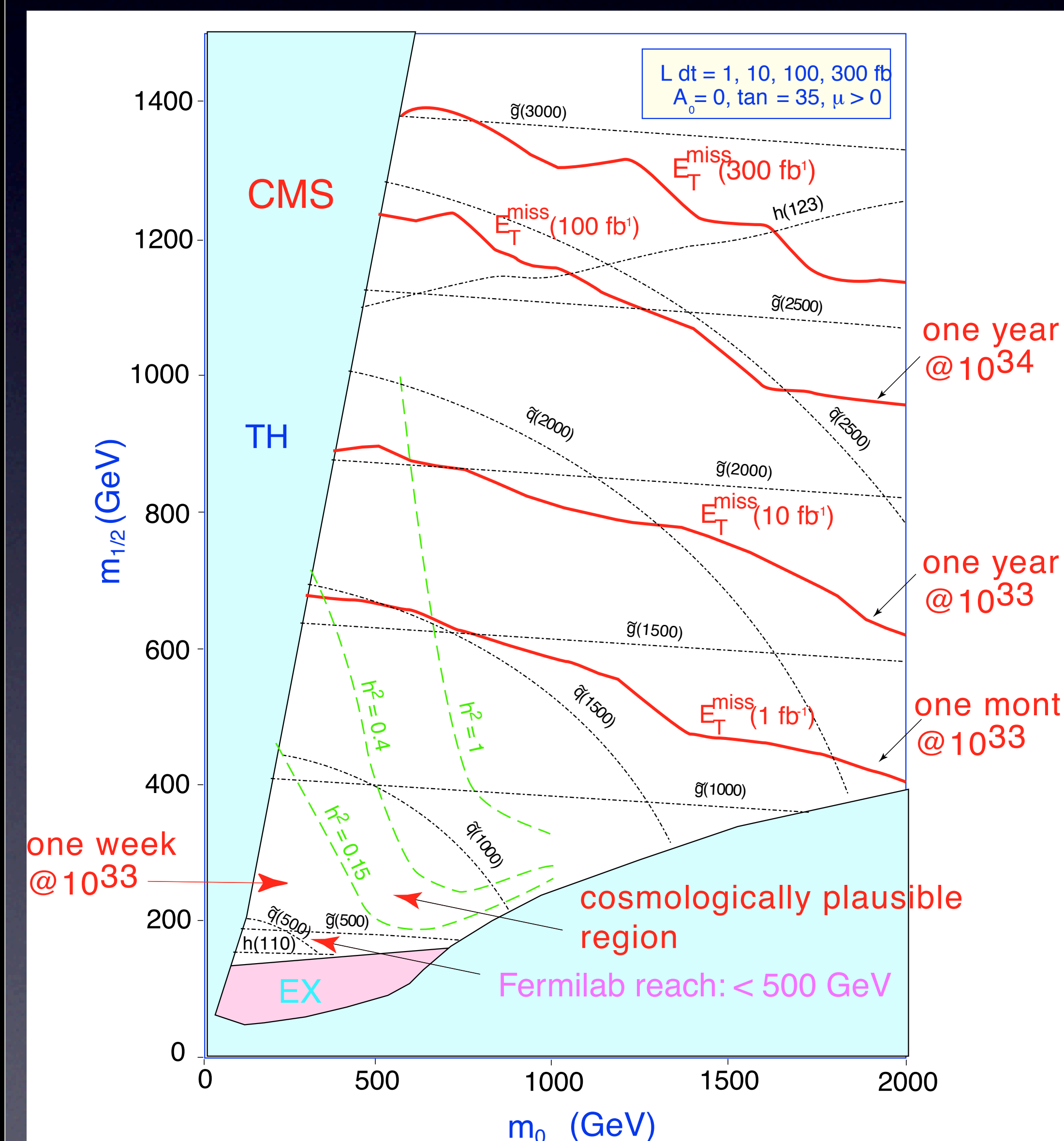
- Now that KM is established
- KM phase requires full three generations, quark mixing

$$J = \Im m \left(\det[M_u^2, V_{CKM}^\dagger M_d^2 V_{CKM}] \right) \approx 10^{-20}$$

- Absolutely not enough
- Need new source(s) of CP violation
- At TeV? 10^{10}-10^{15}GeV?

LHC finds SUSY



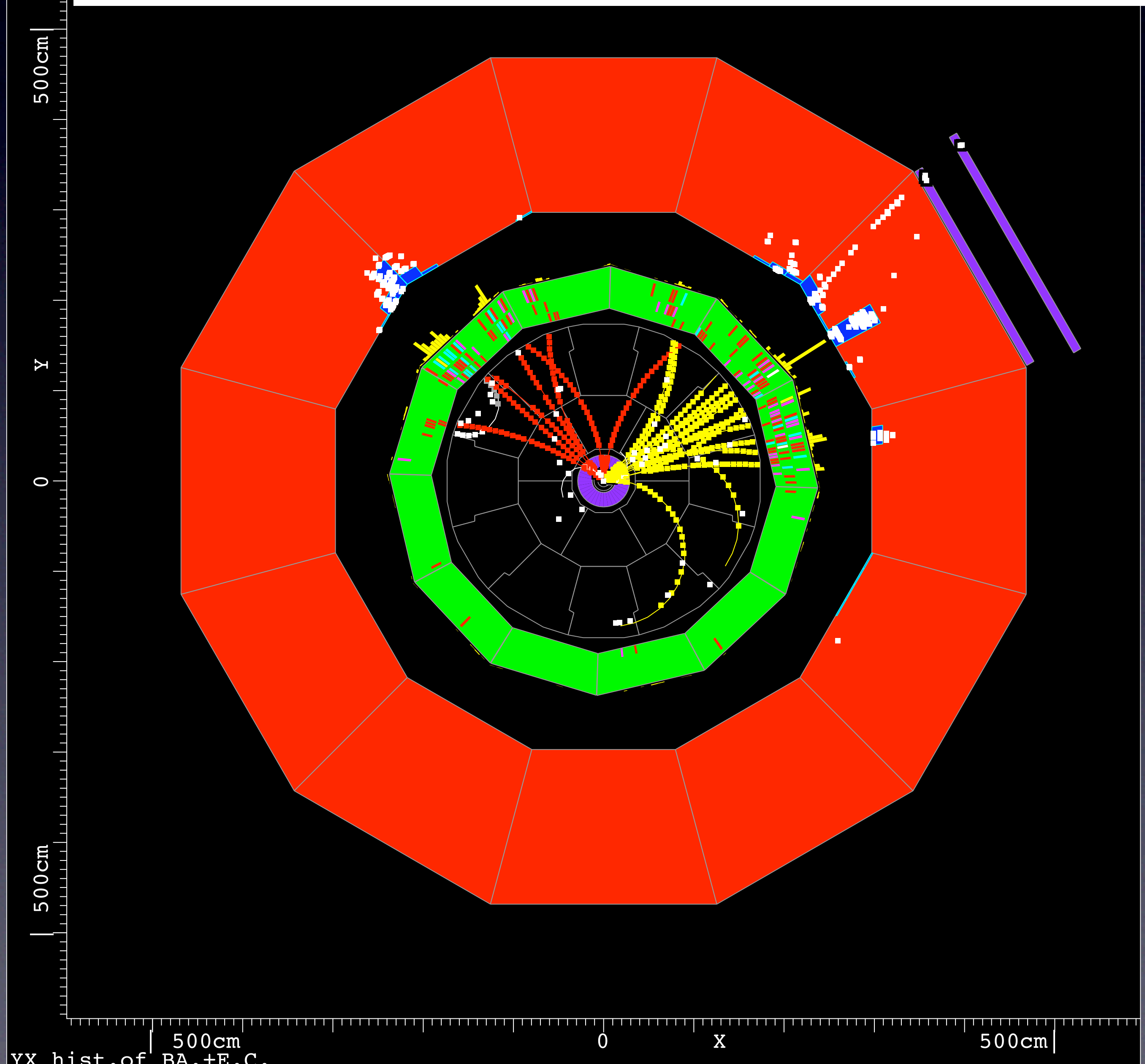


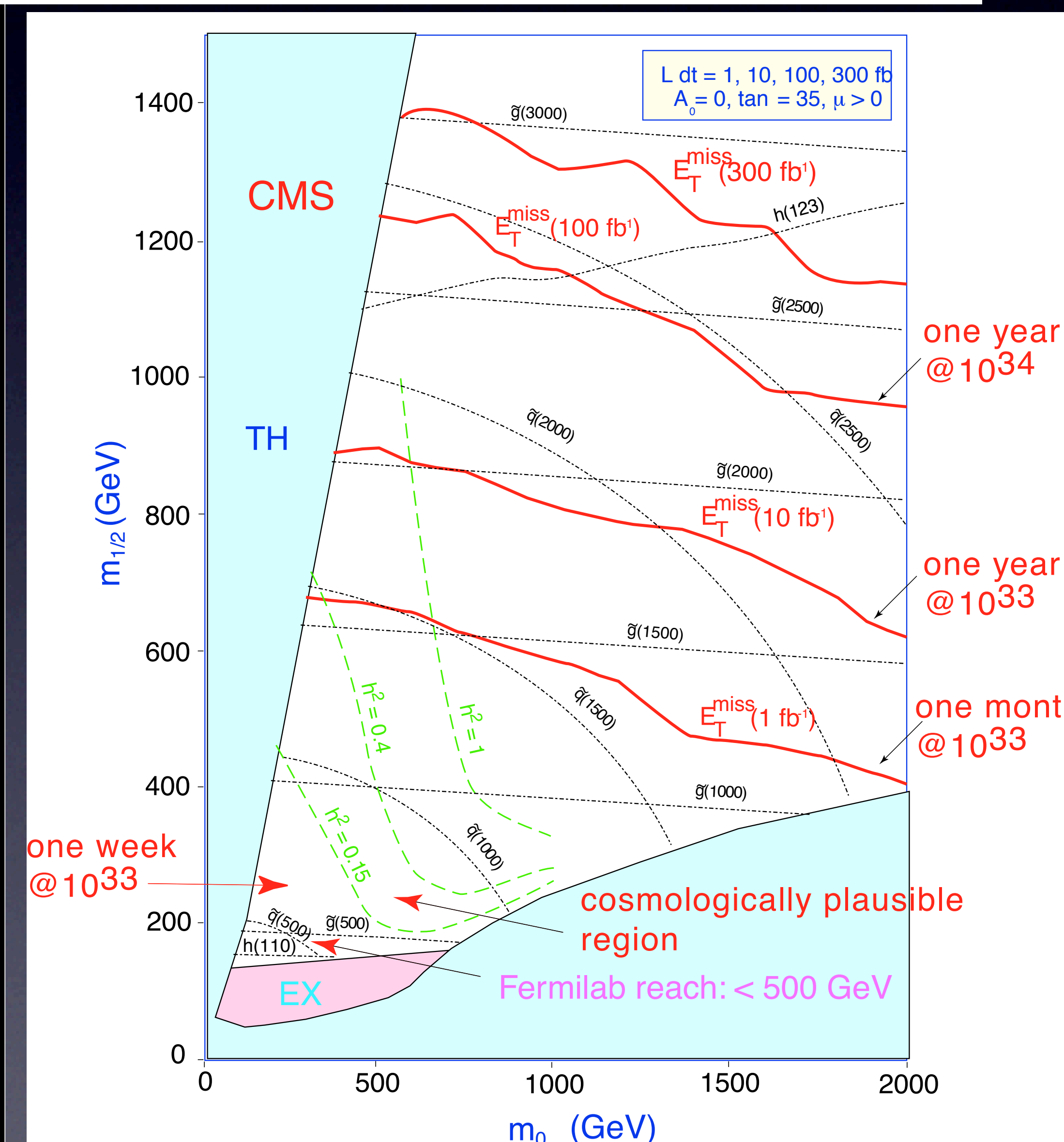
The New York Times

July 23, 2008

The Other Half of the World Discovered

Geneva, Switzerland





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The Other Hal

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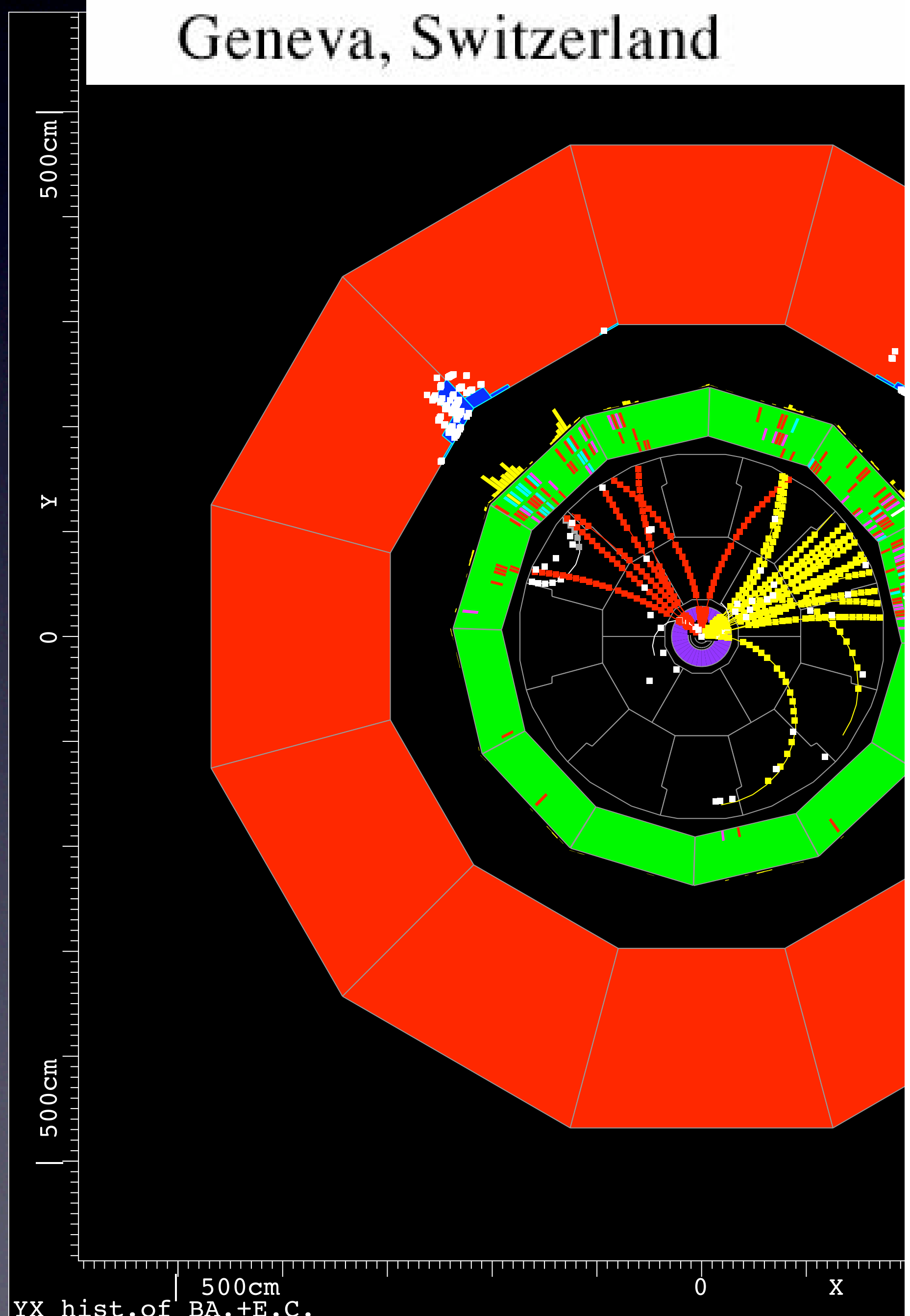


Squarks $J=0$? PDG 2012

The following data are averaged over all light flavors, presumably u, d, s, c with both chiralities. For flavor-tagged data, see listings for Stop and Sbottom. Most results assume minimal supergravity, an untested hypothesis with only five parameters. Alternative interpretation as extra dimensional particles is possible. See KK particle listing.

SQUARK MASS

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
538±10	**OUR FIT**		**mSUGRA assumptions**
532±11	[1]ABBIENDI 11D	CMS	Missing ET with mSUGRA assumptions
541±14	[2]ADLER 11O	ATLAS	Missing ET with mSUGRA assumptions
• • • We do not use the following data for averages, fits, limits, etc • • •			
652±105	[3]ABBIENDI 11K	CMS	extended mSUGRA with 5 more parameters

[1]ABBIENDI 11D assumes minimal supergravity in the fits to the data of jets and missing energies and set $A_0=0$ and $\tan\beta = 3$. See Fig. 5 of the paper for other choices of A_0 and $\tan\beta$. The result is correlated with the gluino mass M_3. See listing for gluino.
[2]ADLER 11O uses the same set of assumptions as ABBIENDI 11D, but with $\tan\beta = 5$.
[3]ABBIENDI 11K extends minimal supergravity by allowing for different scalar masses-squared for Hu, Hd, 5* and 10 scalars at the GUT scale.

SQUARK DECAY MODES

MODE	BR(%)	DOCUMENT ID	TECN	COMMENT
j+miss	32±5	ABE 10U	ATLAS	
j l+miss	73±10	ABE 10U	ATLAS	lepton universality
j e+miss	22±8	ABE 10U	ATLAS	
j μ +miss	25±7	ABE 10U	ATLAS	
q χ^+	seen	ABE 10U	ATLAS	

Immediate question

- OK, there are new particles ~ TeV
- We see them created by *gauge interactions*
  - mostly QCD, some via Drell-Yan (E&W)
- What do they do with flavor?
  - Do they come in three families?
  - Do they mix? Do they violate CP?
  - Do they tell us something about the origin of flavor?

5. Why are they so many kinds of particles?

- Well-defined question with *known* mass scale
- cf. Right now we don't know the mass scale of flavor physics!

5. Why are they so many kinds of particles?

Need precision

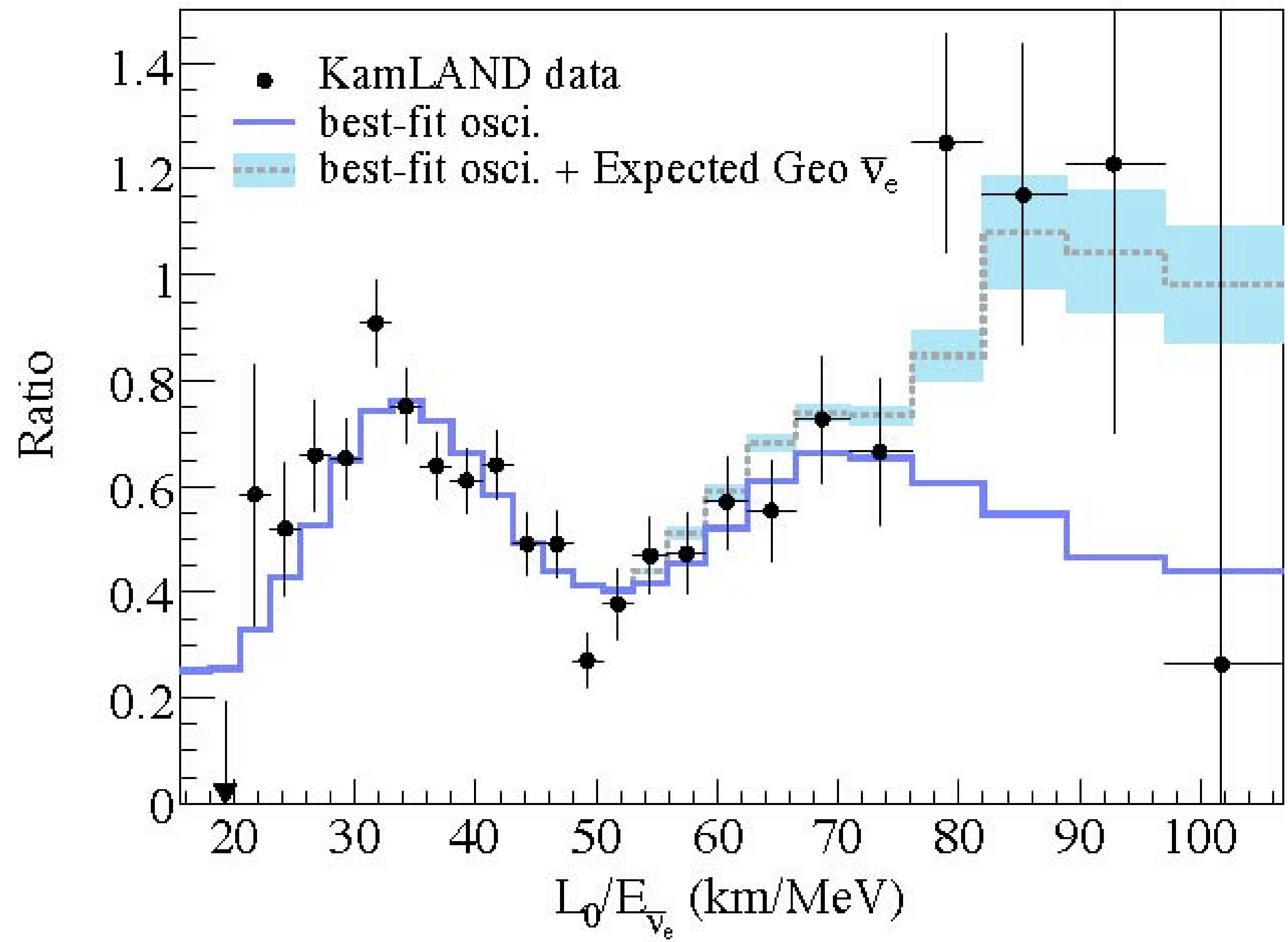
- All flavor data so far suggest KM the only source of CP violation (B_d, B_s, K)
- Need precise measurements to see small deviations
- Need large statistics
- Need high intensity machine!
- Approach theoretical uncertainty
- K→pi nu nu with small uncertainties
- Mismatch with B-sector?
- See if there are new CP violation at TeV scale!

Quantiative Goals

- Match the theoretical uncertainties
- Will know the mass scale and nature of physics that comes into the loop diagrams from LHC
- More confidence on what to expect
- Level of deviations expected: see Joe's wrap-up

More NEWSFLASH

KamLAND 2007



$c_{13}^2 s_{23} c_{23}$

More NEWSFLASH

- neutrino oscillation discovered
- 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) => verified!
  - θ_{13} large enough

CP Violation in ν osc

- Need intense source of neutrinos > MW
- Need large detector > 100 kt
- Suppose we see CP violation
- What do we learn?
- Dirac phase is not necessarily tied to Majorana phase relelvant to leptogenesis
- Again it depends on LHC/ILC

7. What are neutrinos telling us?

A possibility to “establish” seesaw

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A possibility to “establish” seesaw

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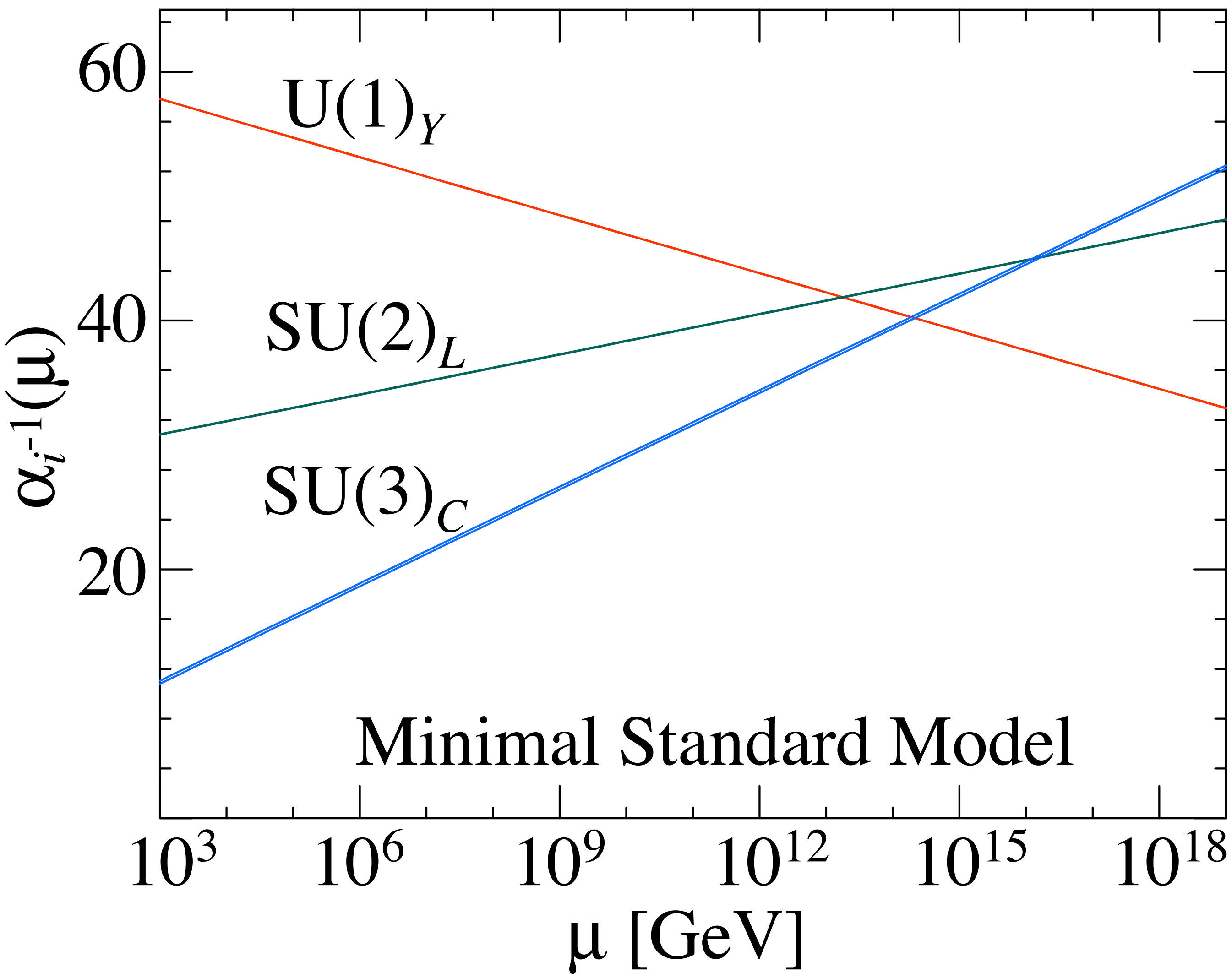
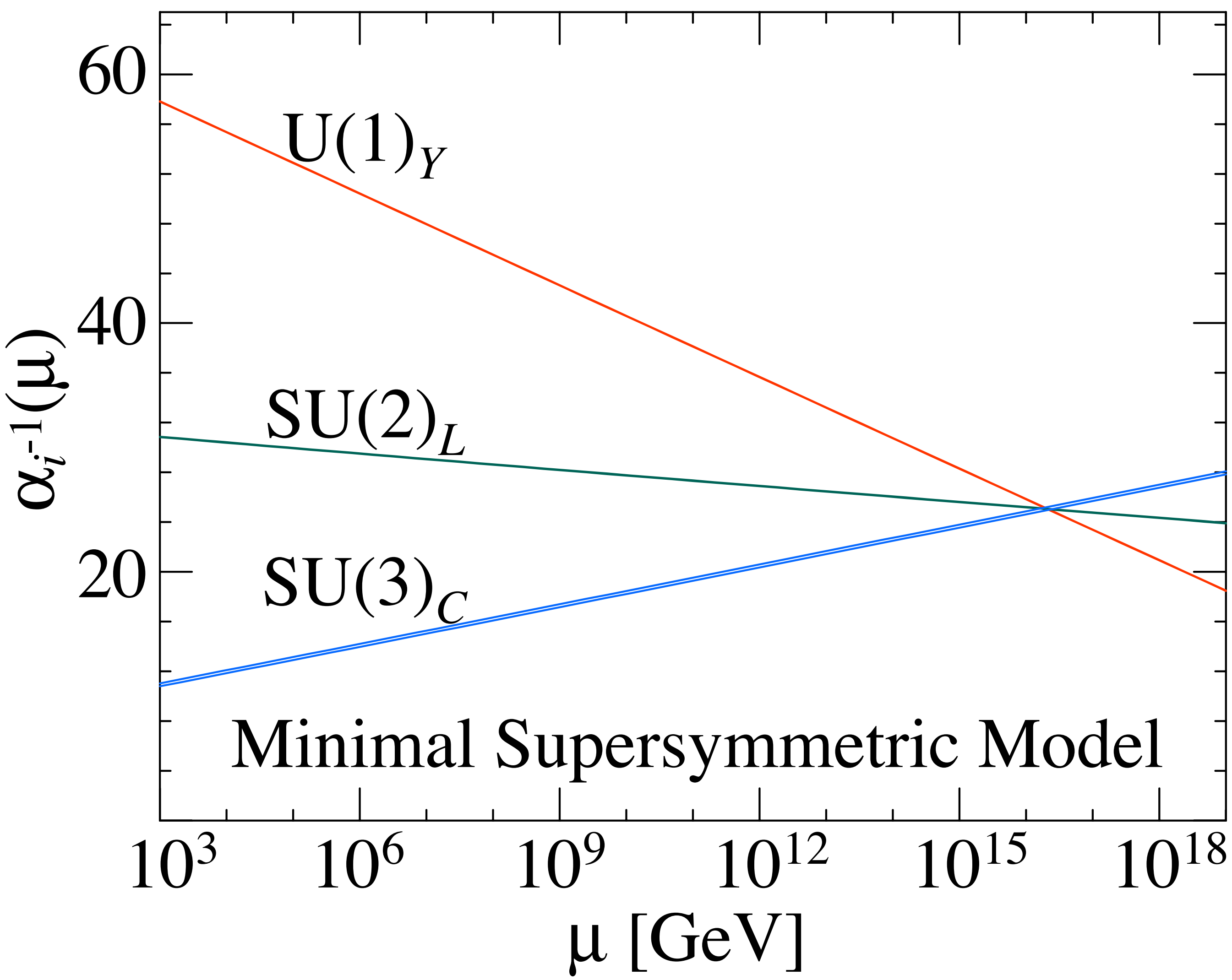
- Scalar masses unify for 1st, 2nd generations (two for 10, one for 5*, times two)

$\Rightarrow$ strong hint that there are no additional particles beyond the MSSM below M_{GUT} except for gauge singlets, i.e. right-handed neutrinos.

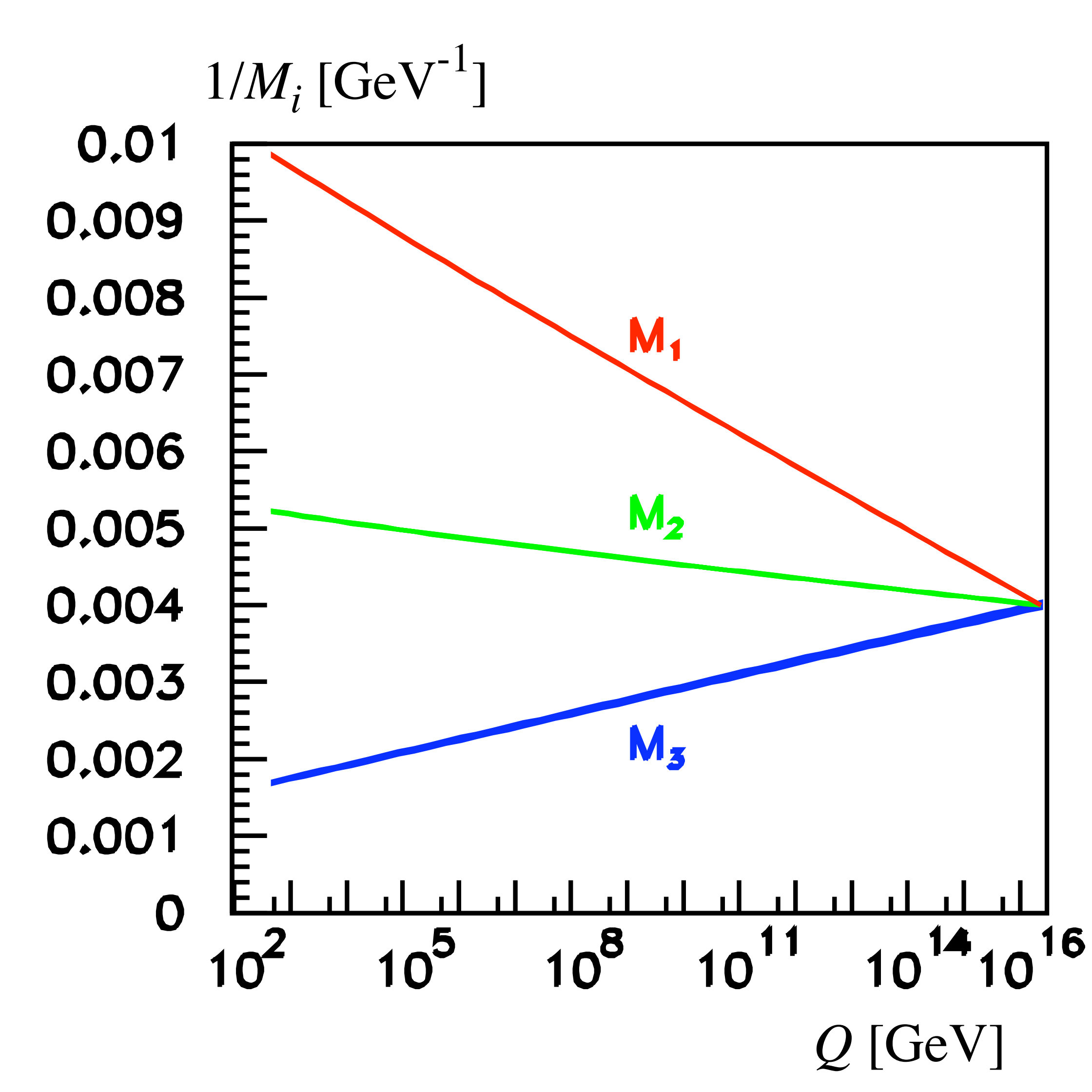
unification

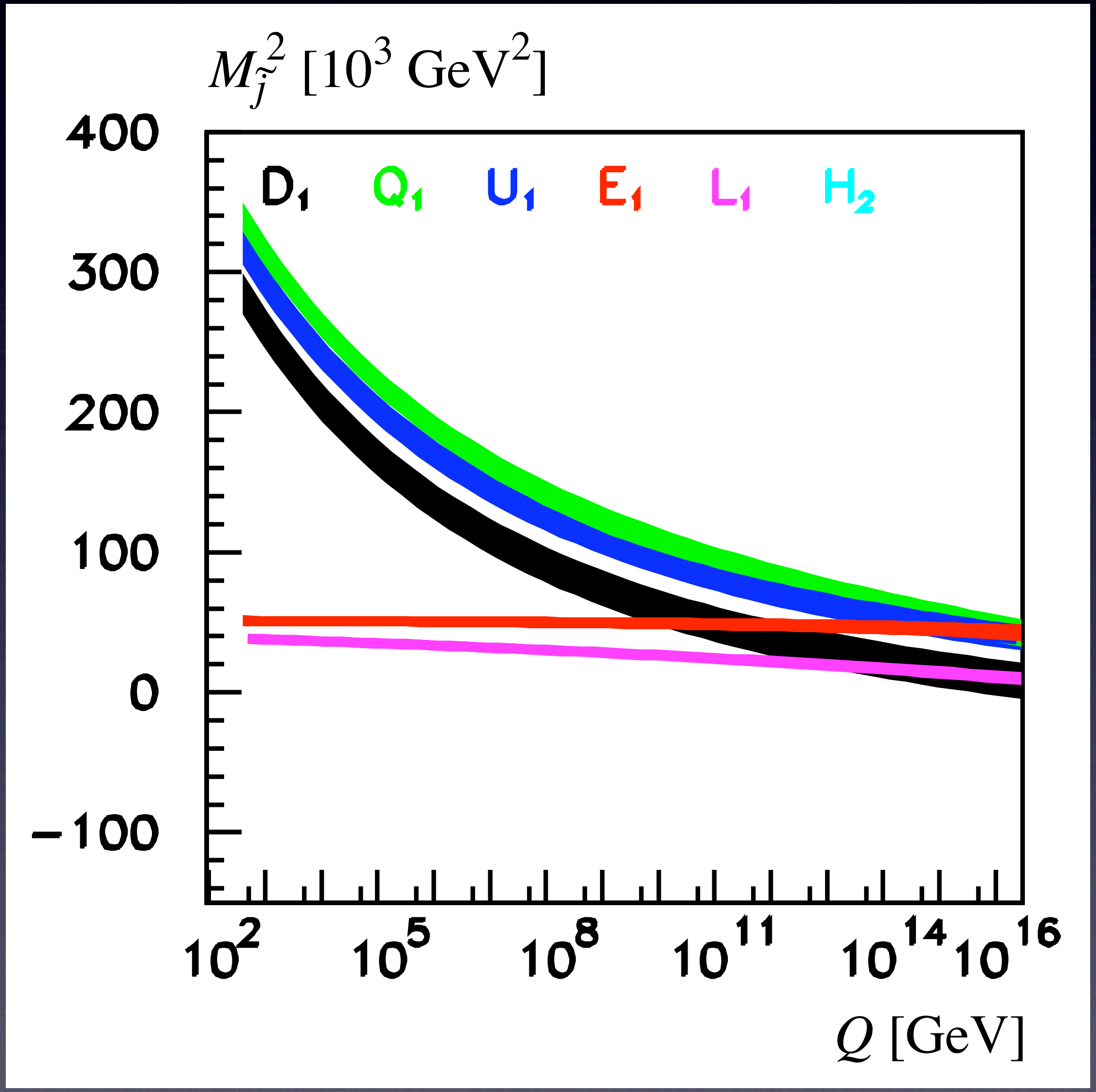




4. Do all the forces become one?

Gaugino and scalars



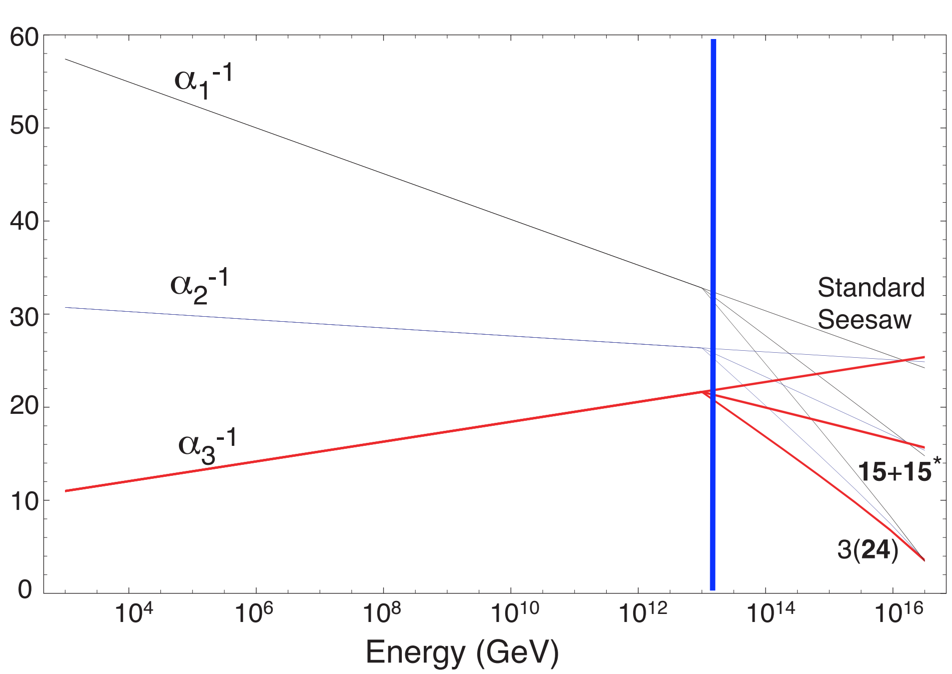


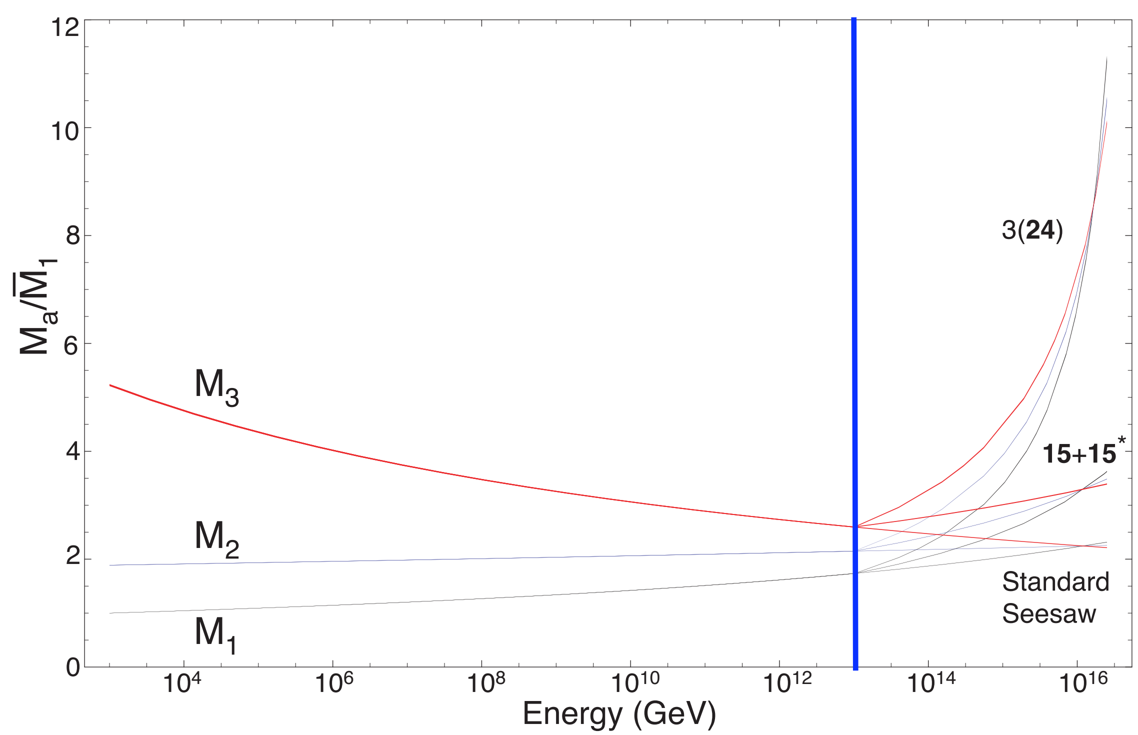
Can't be an accident!

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

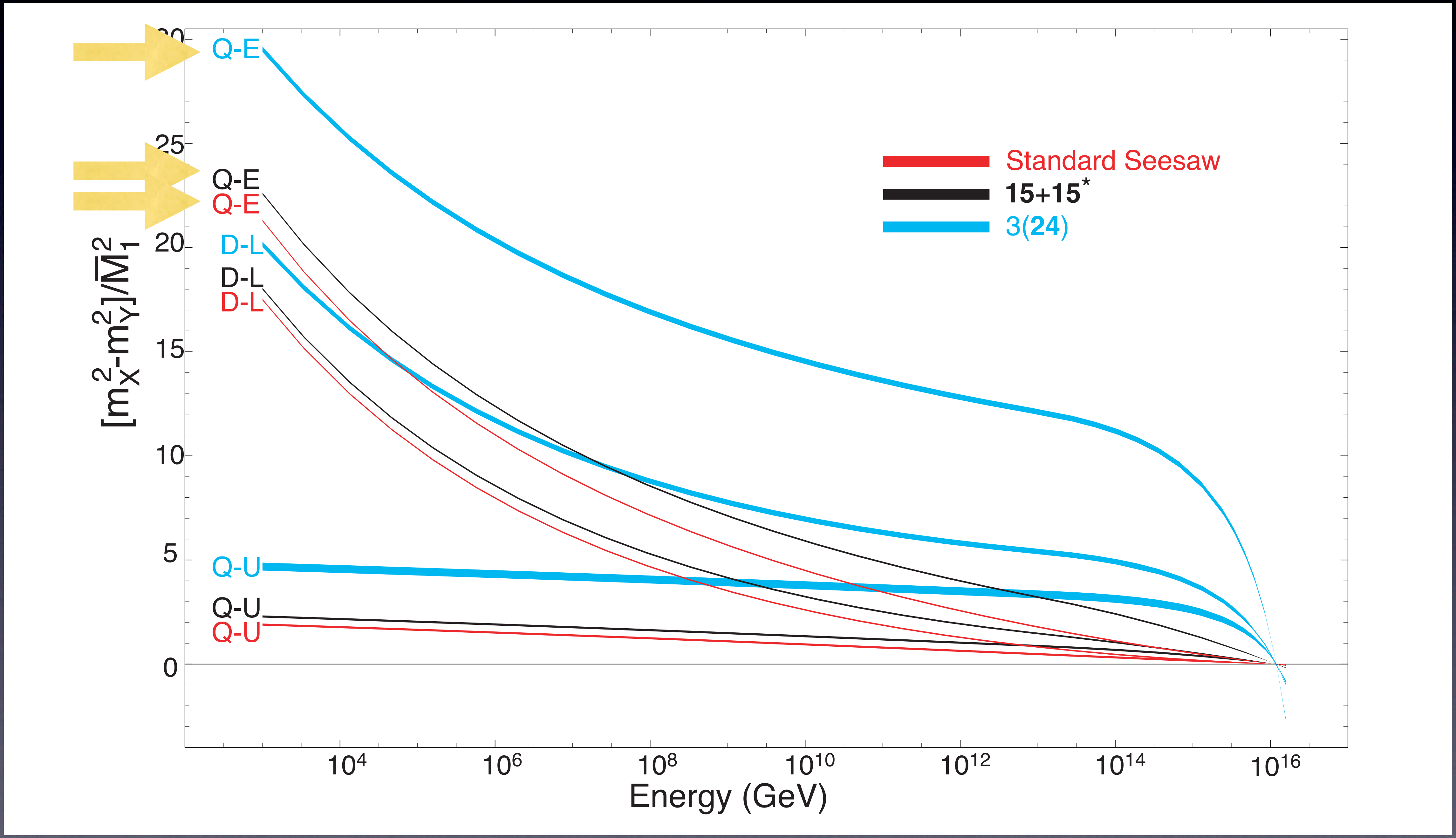
- If 0nbb found, there must be Majorana operator at $\Lambda <$a few $\times 10^{14}$GeV < M_{GUT}, we need new particles below M_{GUT}

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





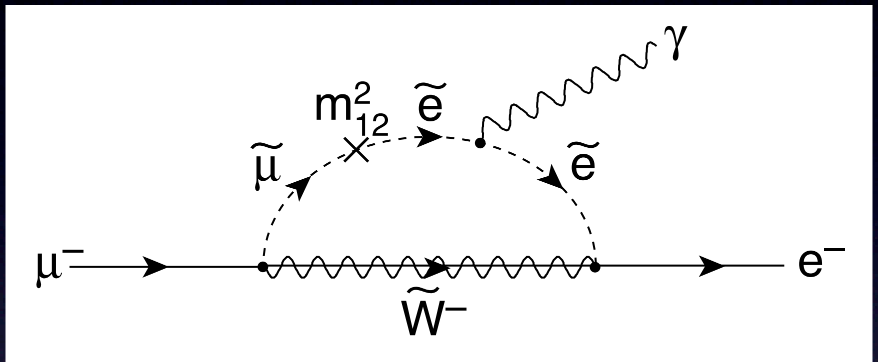
scalar masses tell them apart



Gauge singlets! proving seesaw

What is the seesaw scale?

- ν_R loops induce lepton flavor violation
- large mixings make the effect big
- The current limit on $\mu \to e\gamma$ prefer $M < 10^{13}$ GeV
- uncertainties in SUSY parameters will be removed
- Positive detection suggest what M is!



$$m_{12}^2 \propto (G_F m_\nu M)^2 \sin 2\theta_{12}$$

$$\Gamma(\mu \to e\gamma) \propto \frac{m_\mu^5}{m_{SUSY}^4}(G_F m_\nu M)^2$$

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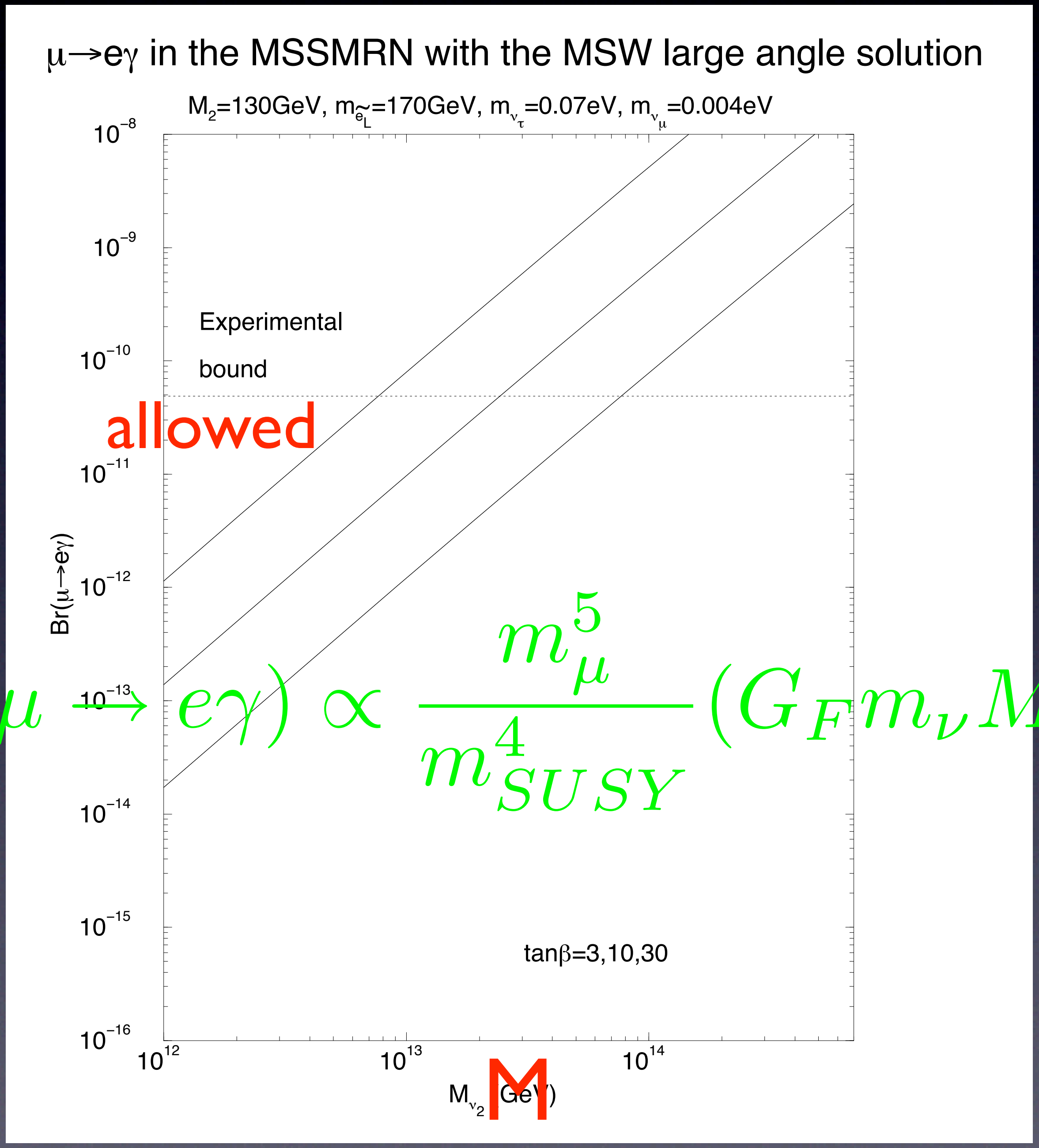

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Hisano&Nomura, hep-ph/9810479

Quantitative Goal

- How far do we need to go with LFV?
- mu e gamma limited by background
- mu e conversion promising

$$P(\mu \to e) \sim 10^{-2}\Gamma(\mu \to e\gamma)$$

- how far do we need to go depends on SUSY masses from LHC
- See Joe's wrap-up

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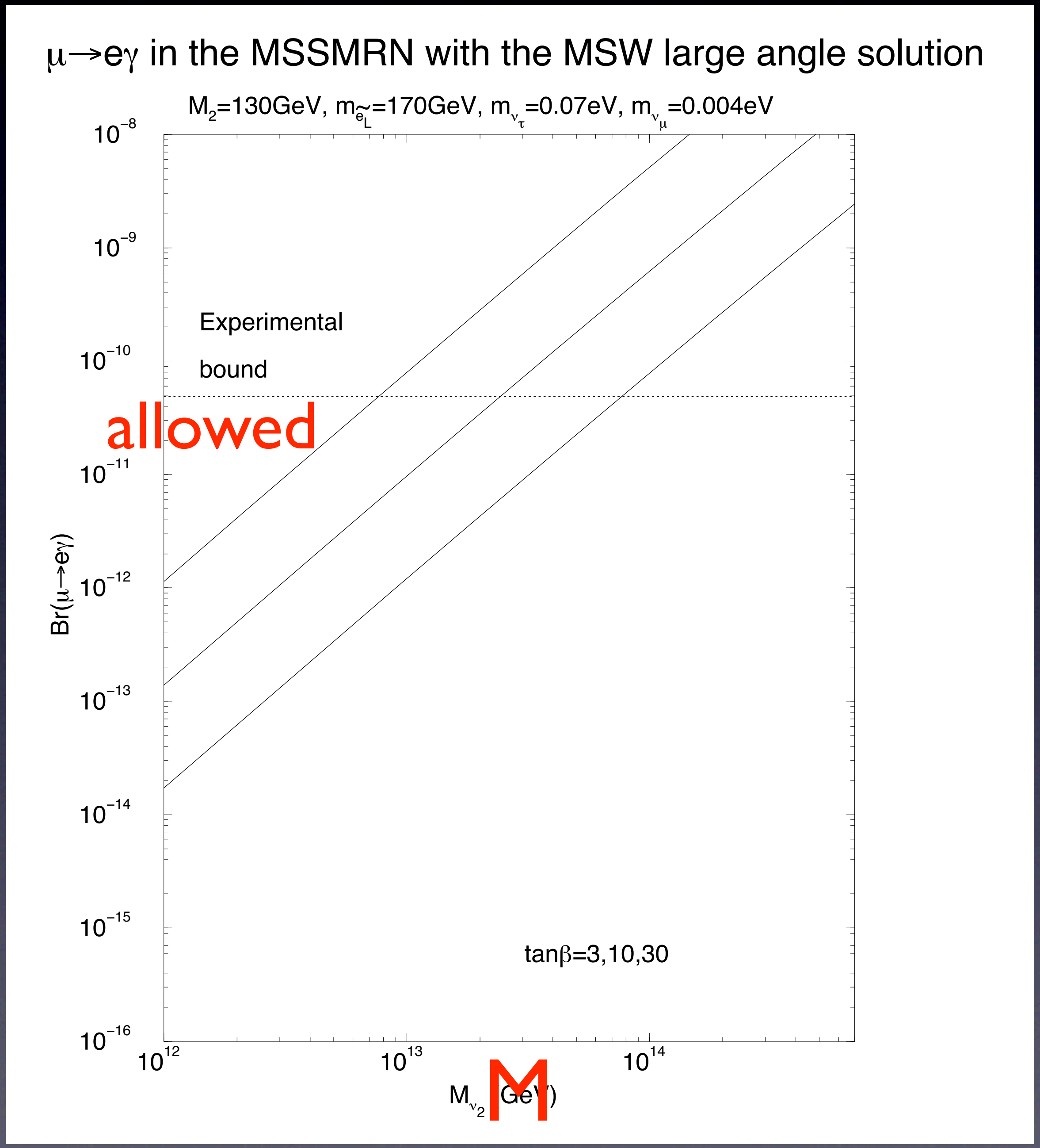
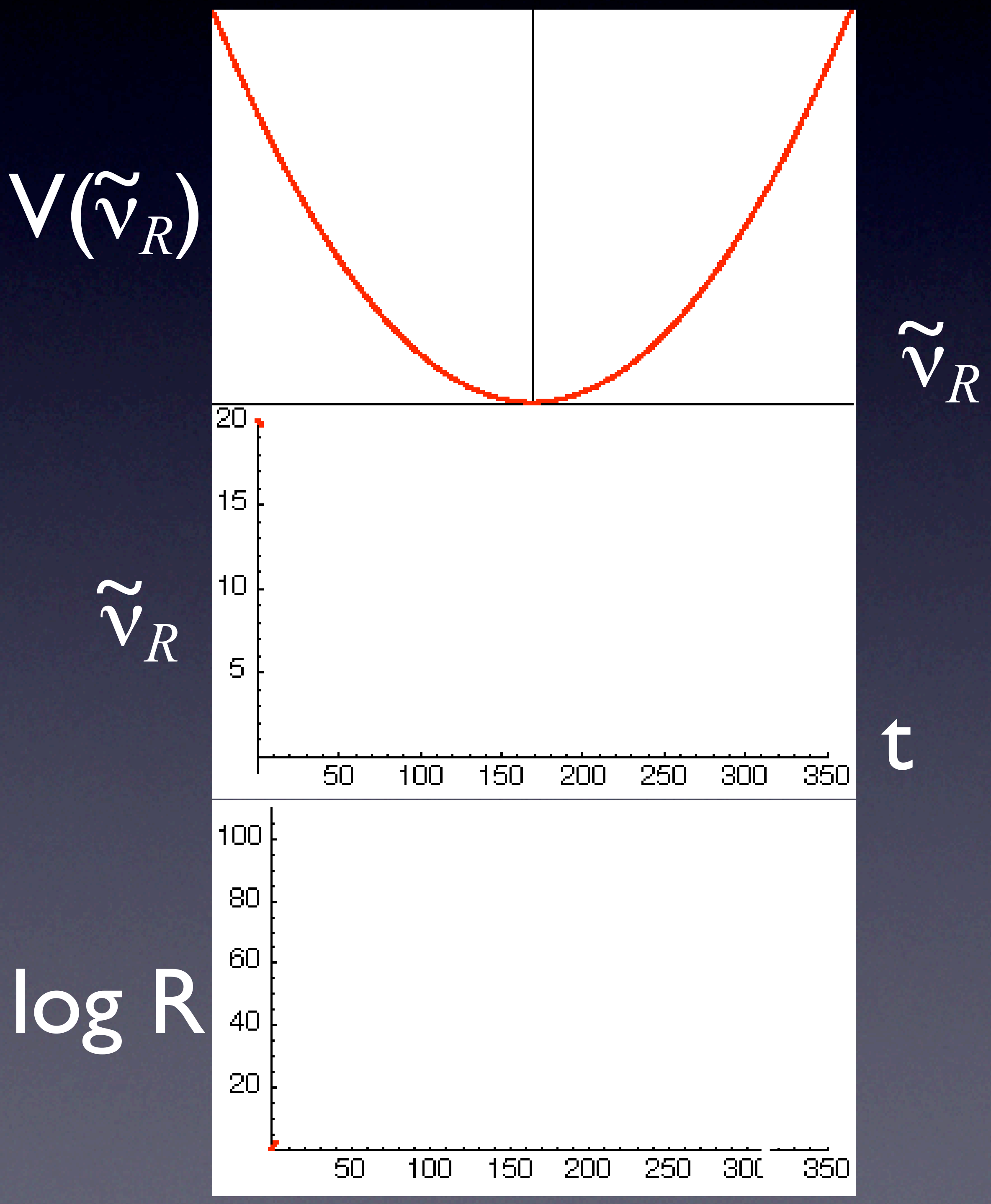


Hisano&Nomura, hep-ph/9810479

Origin of Universe

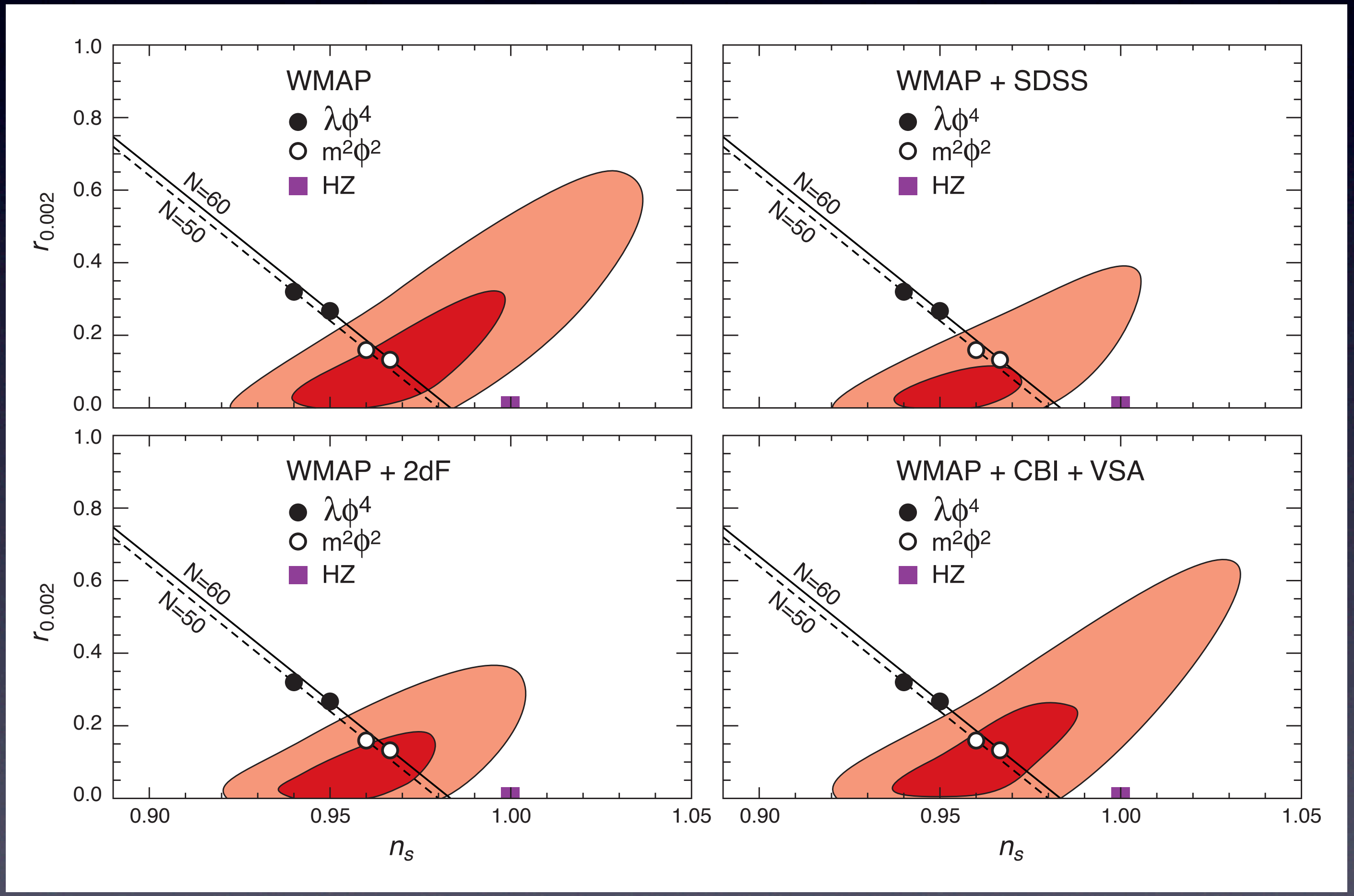
- Maybe an *even bigger* role: inflation
- Need a spinless field that
  - slowly rolls down the potential
  - oscillates around it minimum
  - decays to produce a thermal bath
- The superpartner of right-handed neutrino fits the bill
- When it decays and reheats the Universe, it produces the lepton asymmetry at the same time

Neutrino is mother of the Universe?



Origin of the Universe

- Right-handed scalar neutrino: $V = m^2\phi^2$
- $n_s \sim 0.96$
- $r \sim 0.16$
- Need $m \sim 10^{13}$GeV
- Maybe LFV will tell us that
- Completely consistent with latest WMAP
- Detection possible in the near future



8. How did the universe come to be?

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Conclusion

- Positive signal of new physics from the LHC requires new flavor experiments
- Many NEWSFLASH give us clues
- LHC will determine the mass scale, quantiative goals
- If nature is kind, we can approach the QU questions from *multi-prong* attack