IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

Why Study Neutrinos?

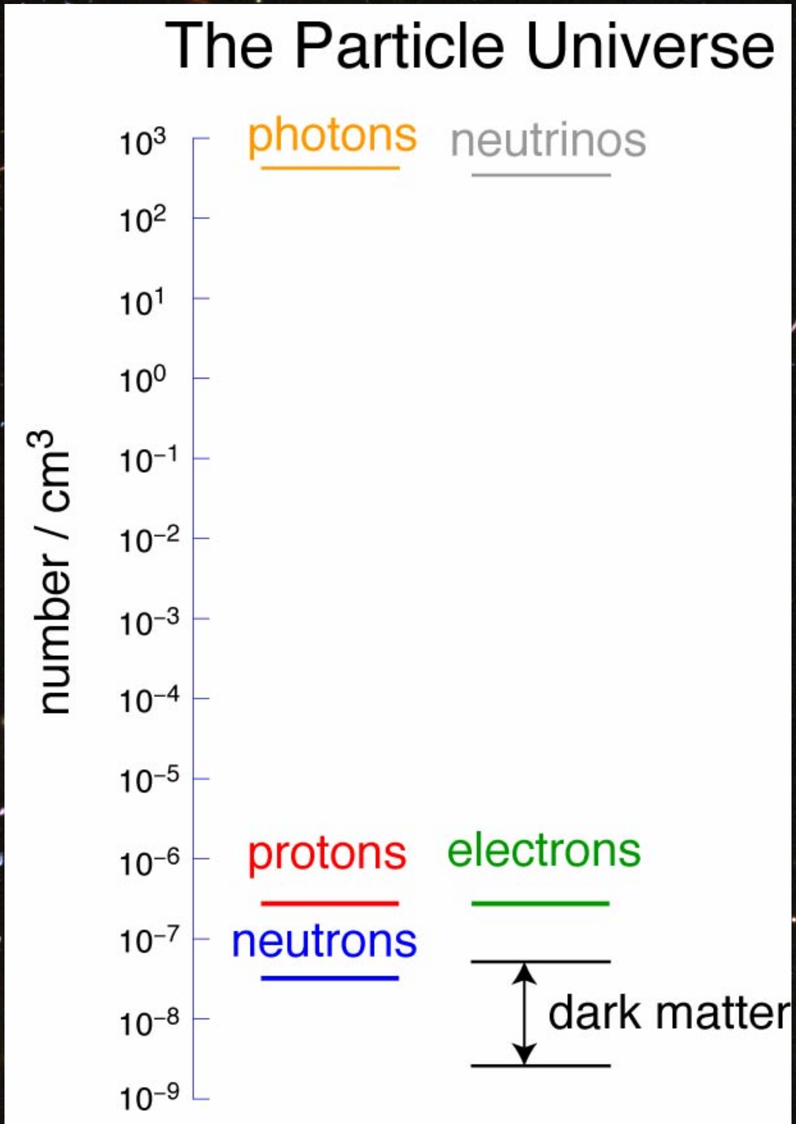
Hitoshi Murayama
(IPMU Tokyo & Berkeley)

将来検討小委員会 Sep 5, 2009

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

There are a lot of neutrinos out there



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)

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

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

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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 very high scales

Neutrinos are Left-handed

Helicity of Neutrinos*

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

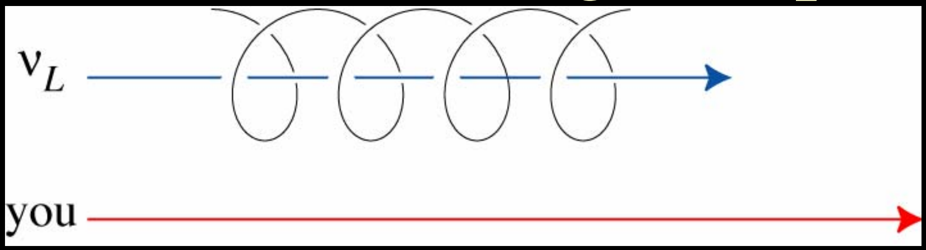
Brookhaven National Laboratory, Upton, New York

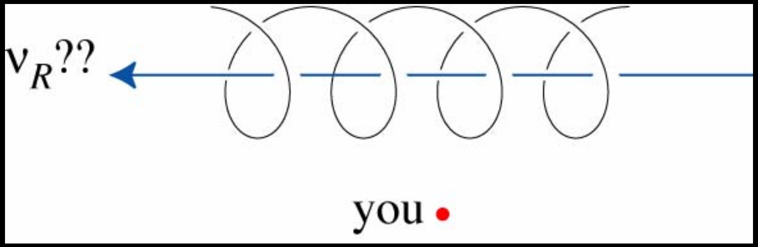
(Received December 11, 1957)

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 they have mass, can't go at speed of light.



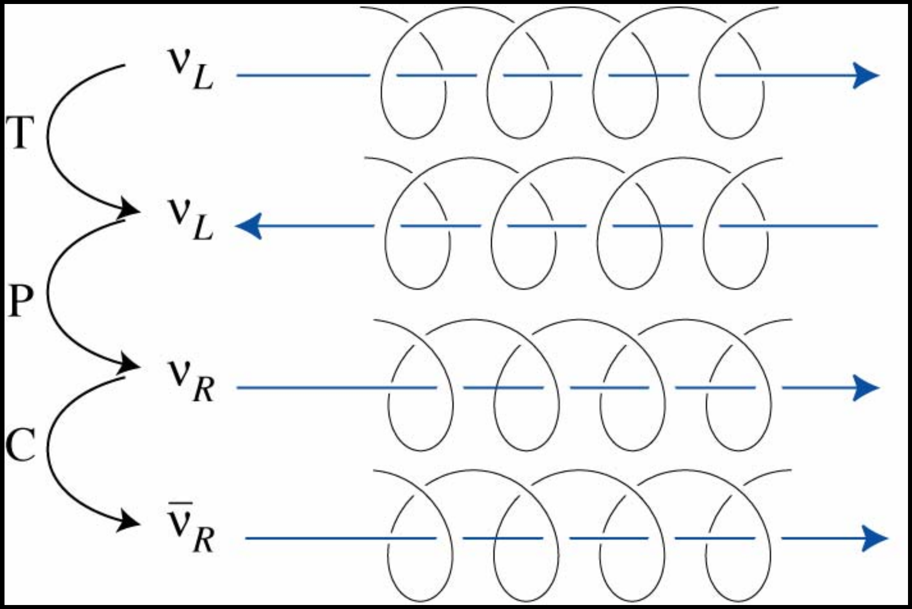


- Now neutrino right-handed??

⇒ 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?

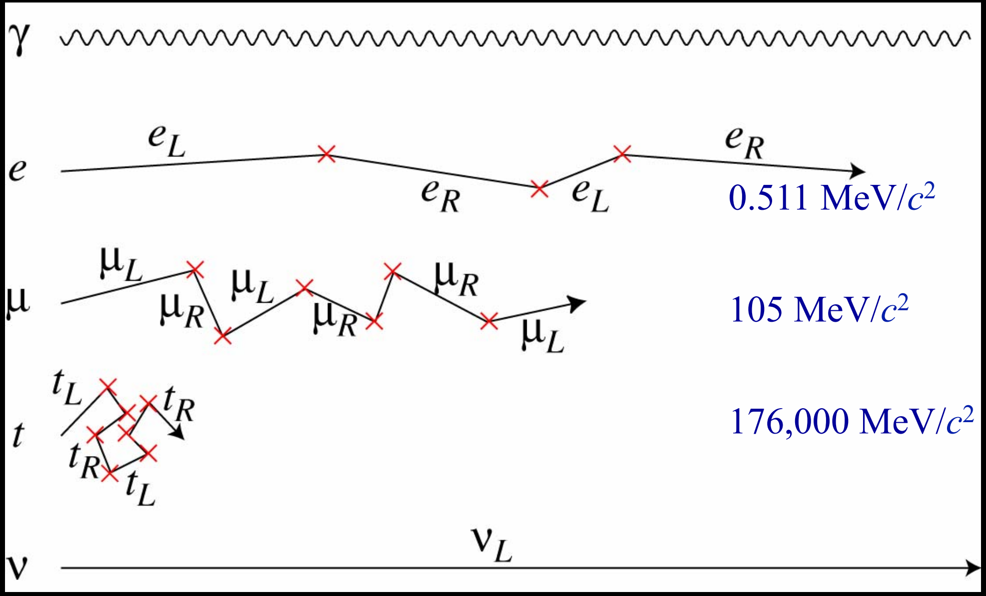
- What about other particles? Electron, muon, up-quark, down-quark, etc
- We say "weak force acts only on left-handed particles" yet they are massive.

Isn't this also a contradiction?

No, because we are swimming in a Bose-Einstein condensate in Universe

Universe is filled with Higgs

- "Empty" space filled with a BEC: cosmic superconductor
- Particles bump on it, but not photon because it is neutral.
- Can't go at speed of light (massive), and right-handed and left-handed particles mix ⇒ no contradiction

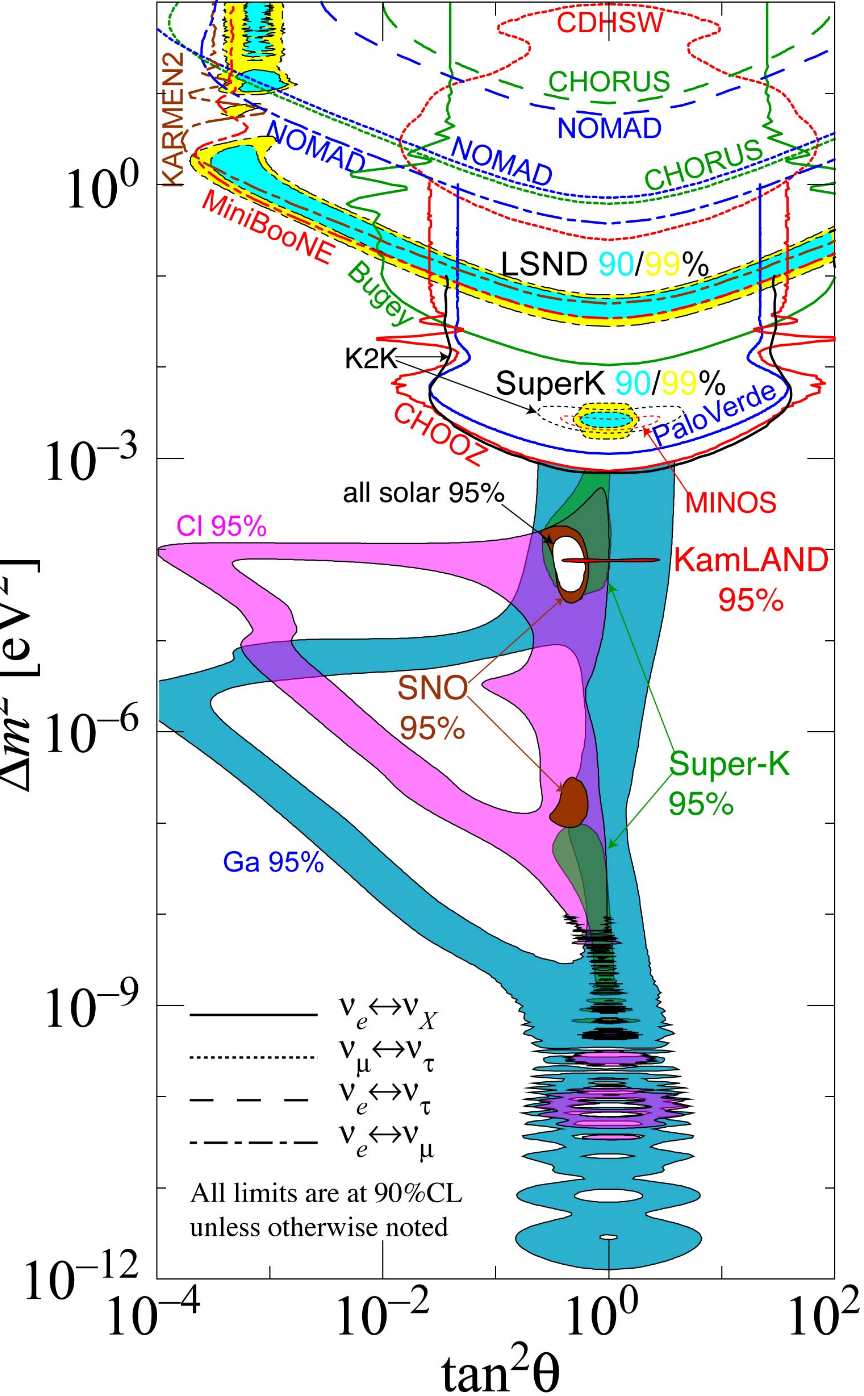


But neutrinos can't bump because there isn't a right-handed one ⇒ stays massless

Lot of effort since ‘60s

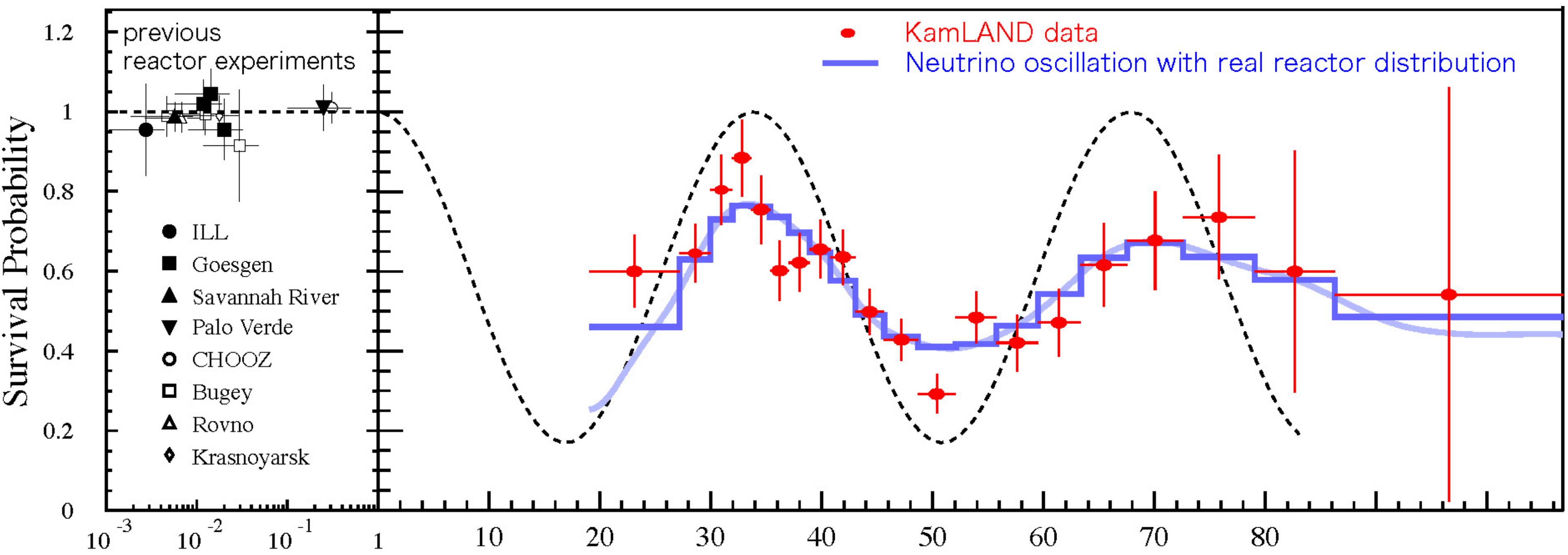
Finally convincing evidence for “neutrino oscillation”

Neutrinos have tiny but finite mass



http://hitoshi.berkeley.edu/neutrino

KamLAND '08
neutrinos do oscillate!

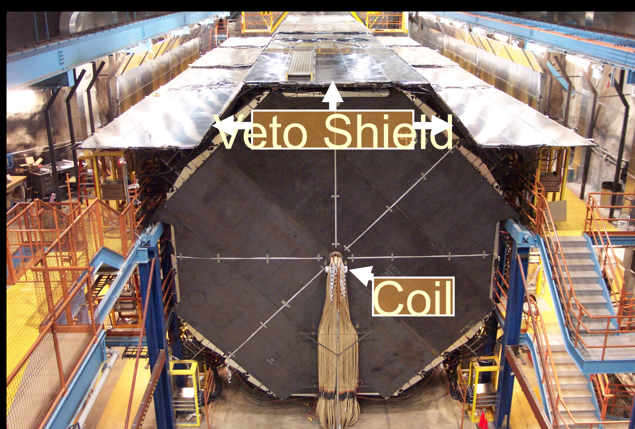


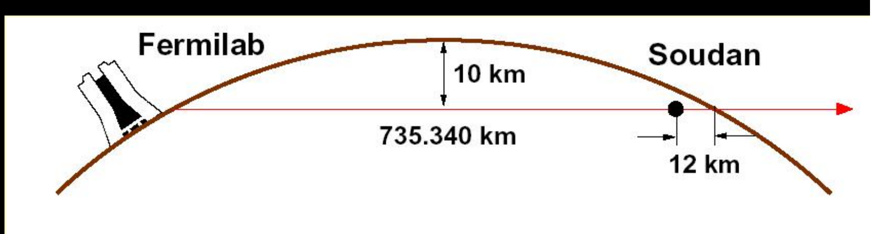
L_0/E (km/MeV) ≈Proper time τ

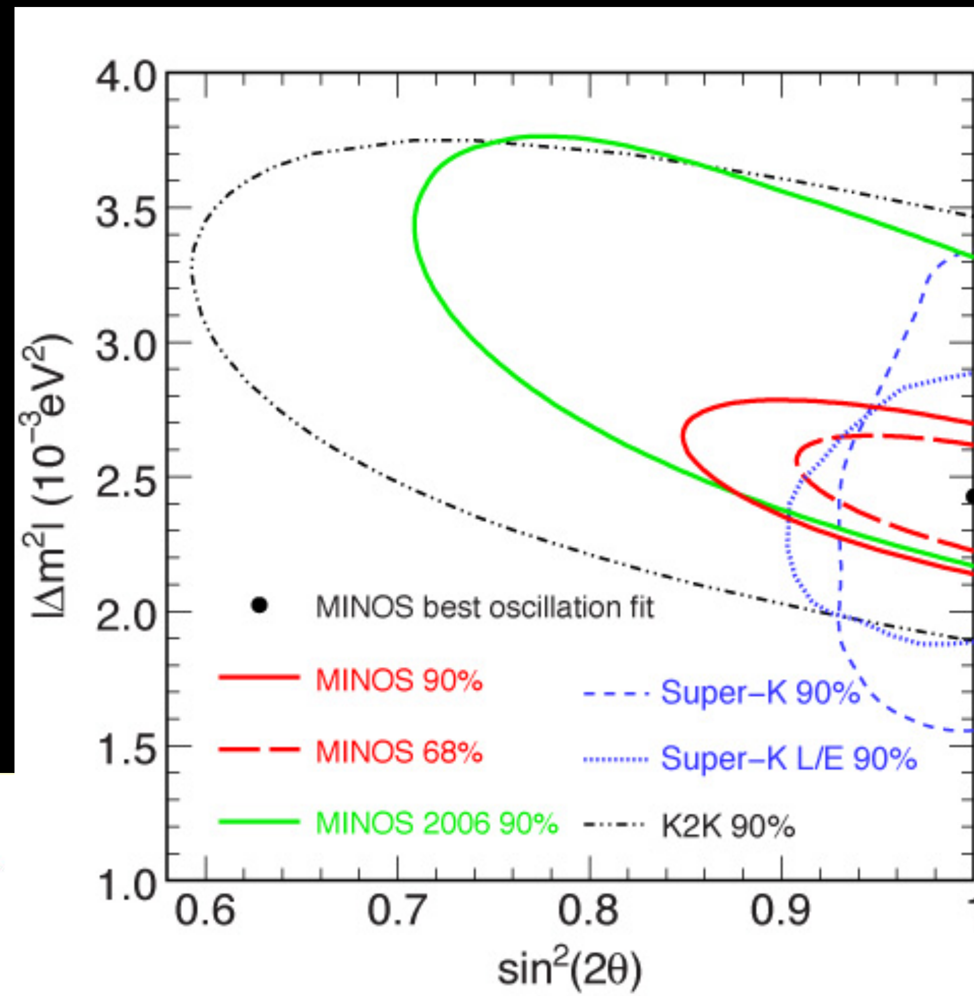
L_0=180 km

MINOS '08

- SuperK atmospheric neutrino result confirmed with manmade neutrinos

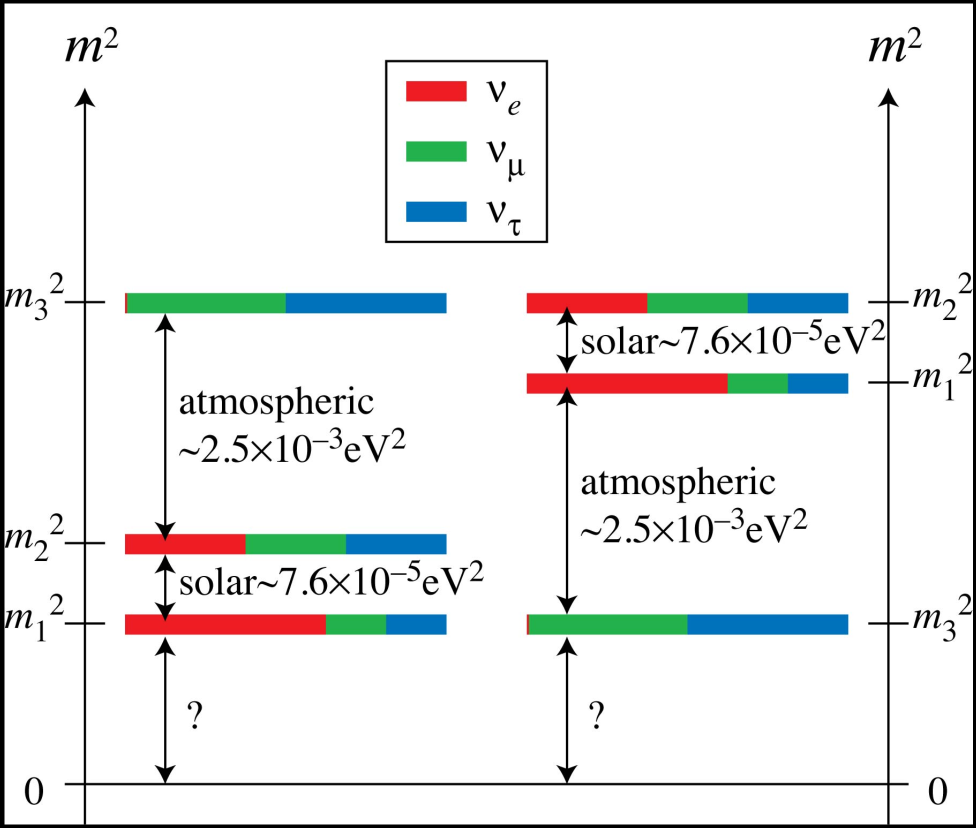






Raised More Questions

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



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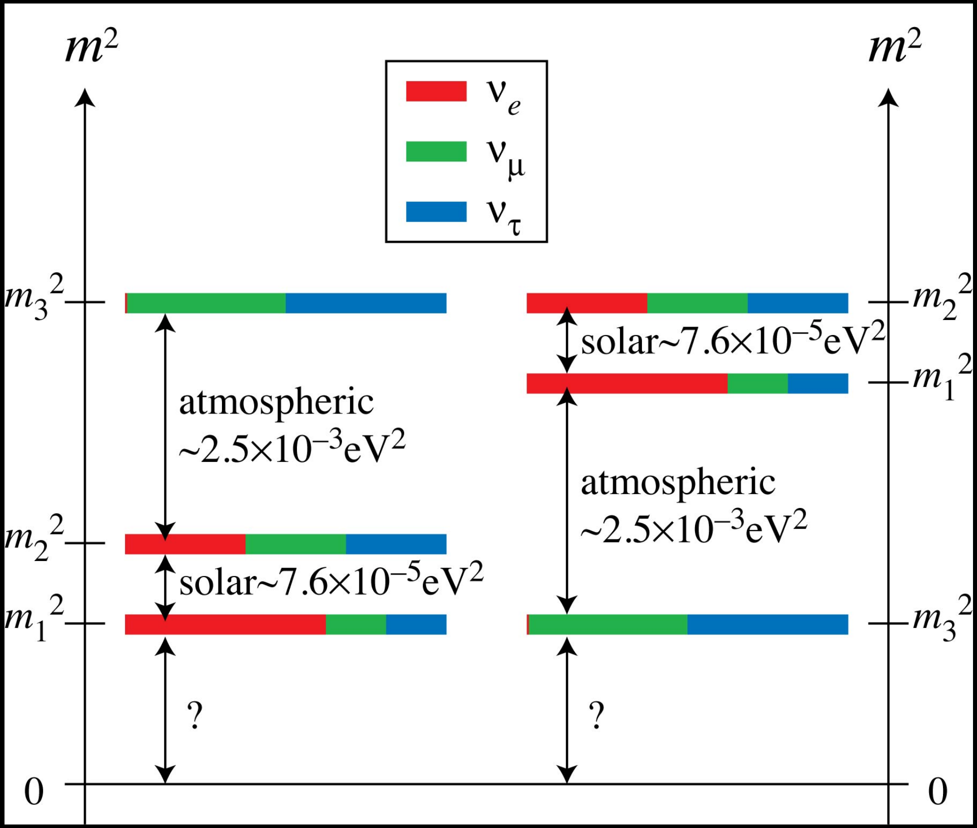
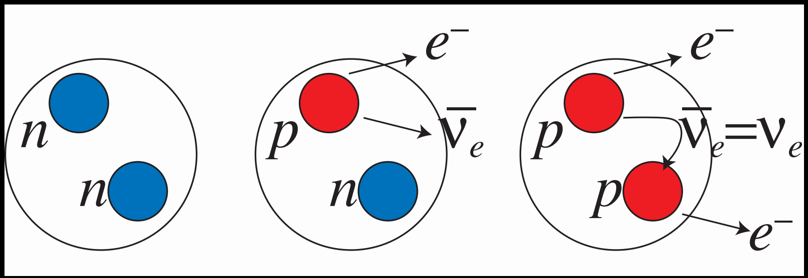
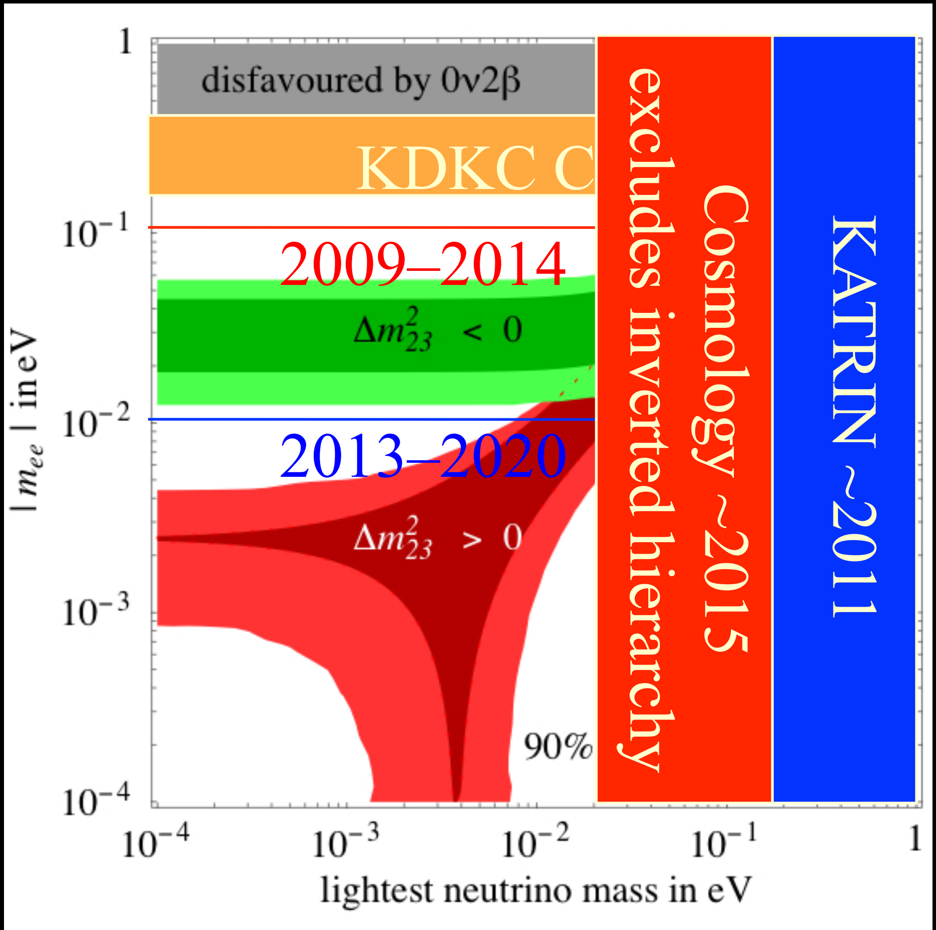


Dirac vs Majorana

- Many neutrinoless double beta decay experiments aiming at below 0.1eV





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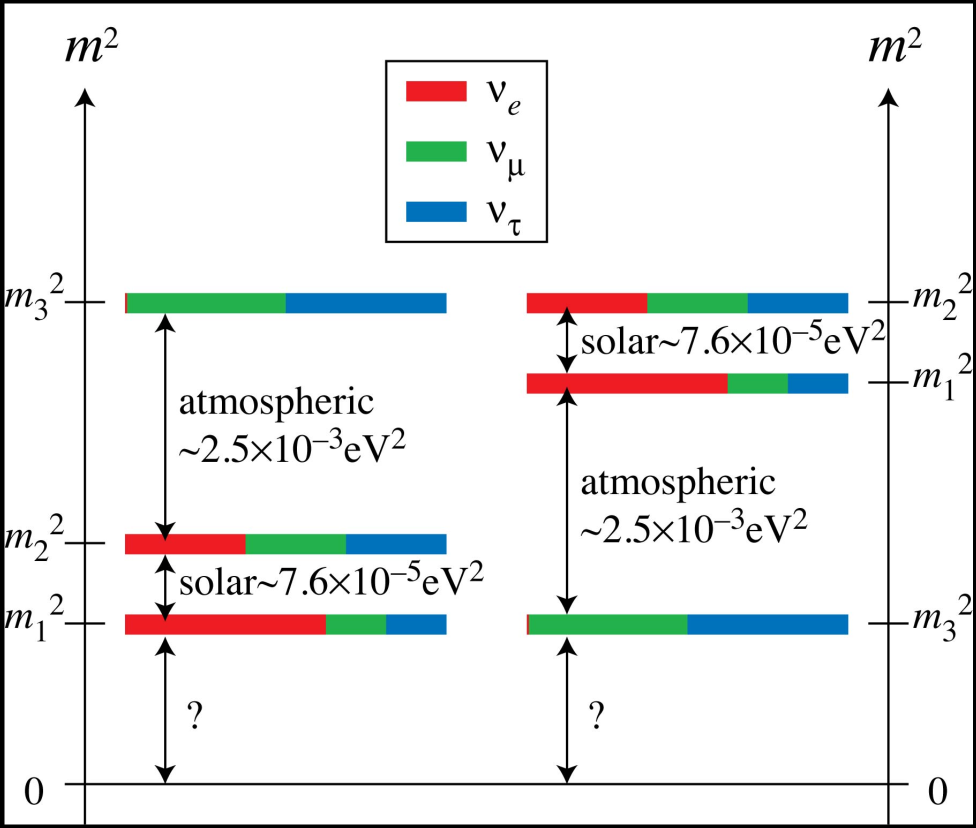
$\Rightarrow$1%@T2K



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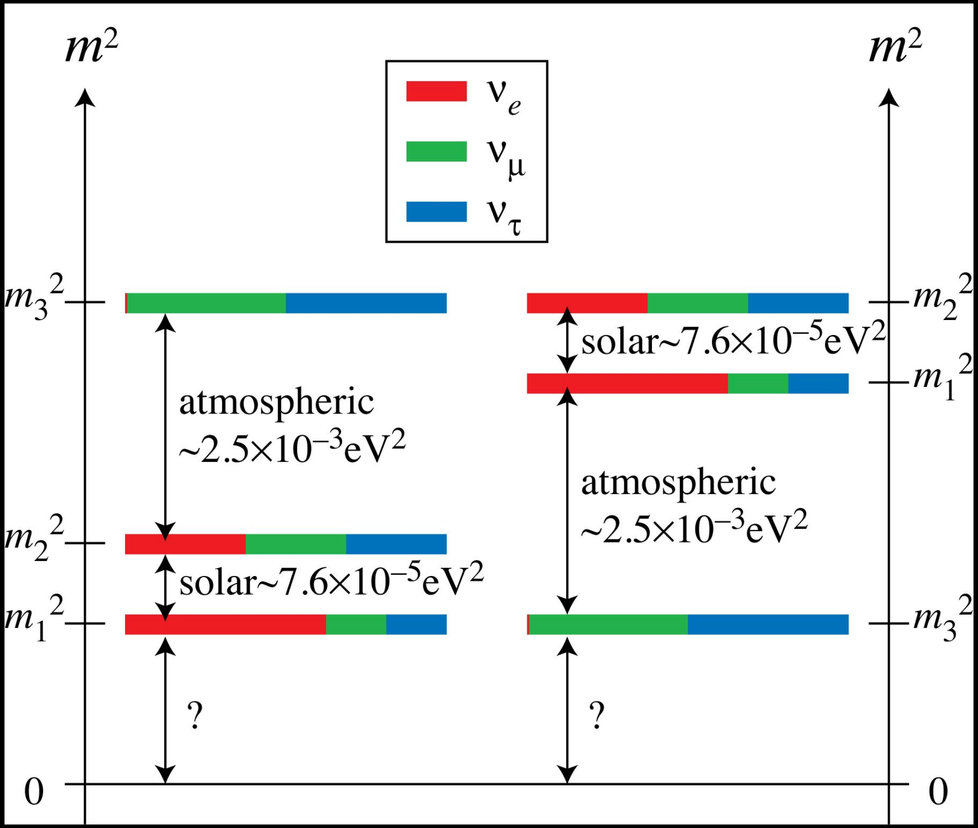
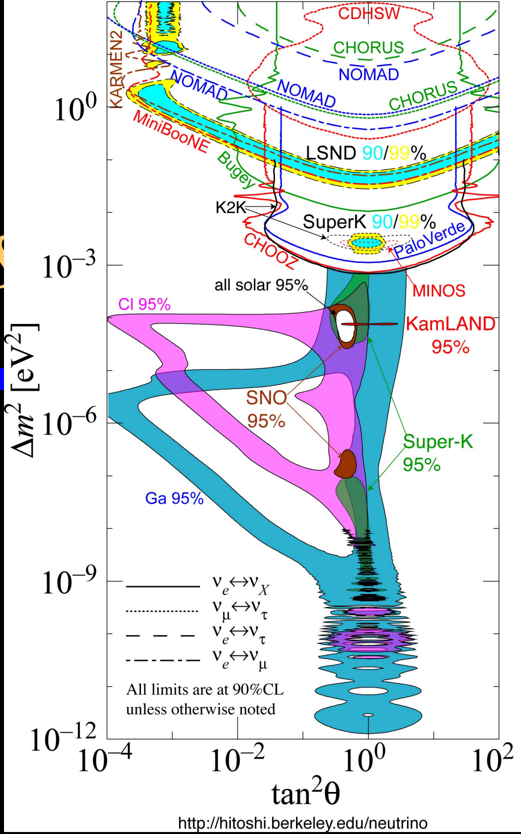


Now that LMA is establis



- Dream case for neutrino oscillation physics!
- $\Delta m^2_{\text{solar}}$ within reach of long-baseline expts
- Even CP violation may be probed by
  - neutrino superbeam
  - muon-storage ring neutrino factory
  - beta beam

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

- Possible only if:
  - $\Delta m_{23}{}^2$, s_{23} large (near maximal)
  - $\Delta m_{12}{}^2$, s_{12} also large (LMA)
  - θ_{13} large enough: *it decides the future!*

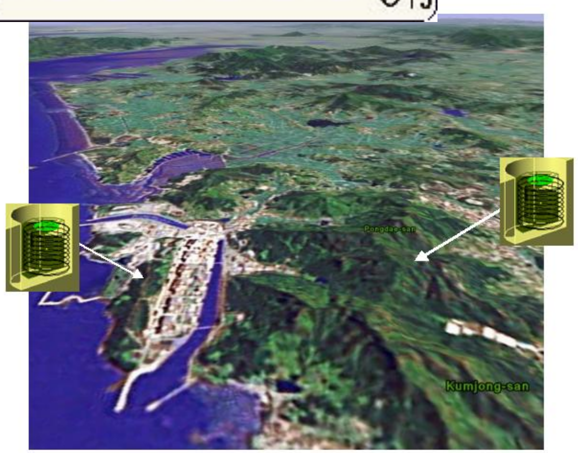
Reactor neutrino experiments looking for θ_{13}

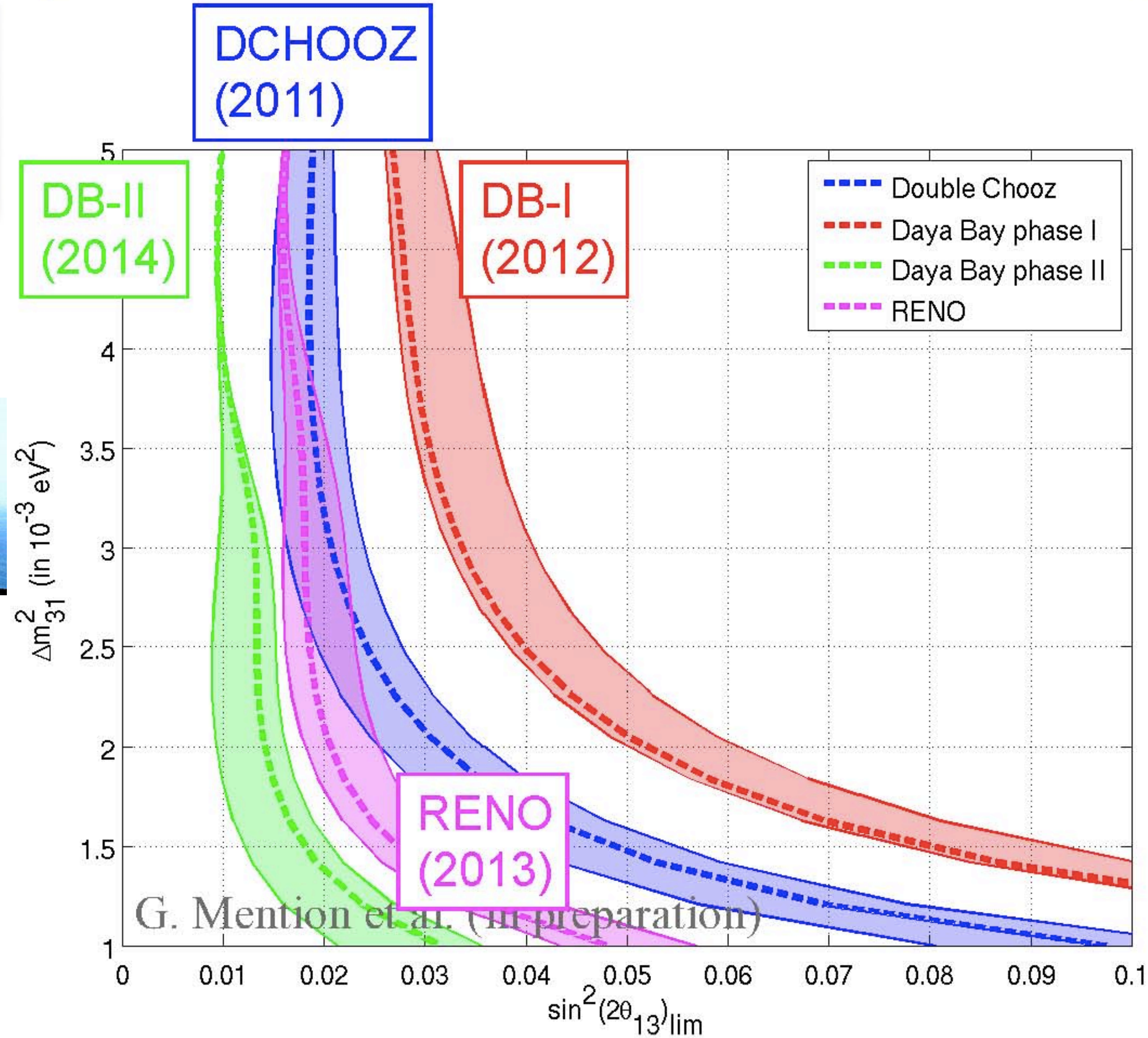
Sensitivity & Achievable year

France

Hong Kong

Korea



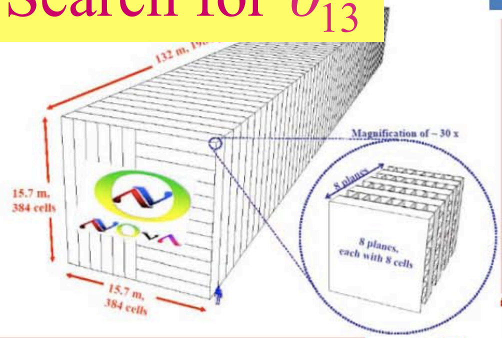


F.Suekane @AAP09

Near future LBL θ_{13} experiments

Precision θ_{23}
Search for θ_{13}

Need much higher sensitivity experiments



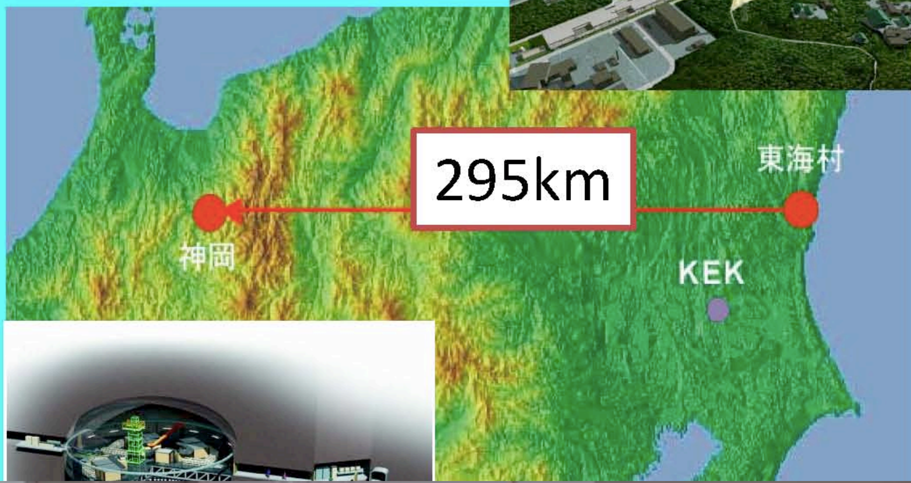
15 kton totally active detector

NOνA
(~2013 -)

NuMI beam intensity upgrade to 700 kW

T2K
(2009 -)

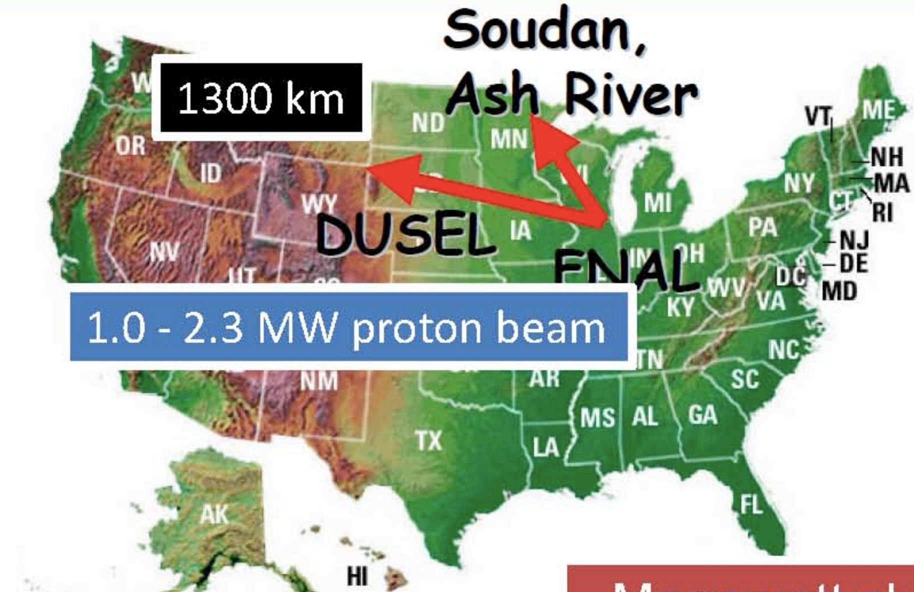
J-PARC
(750kW design)



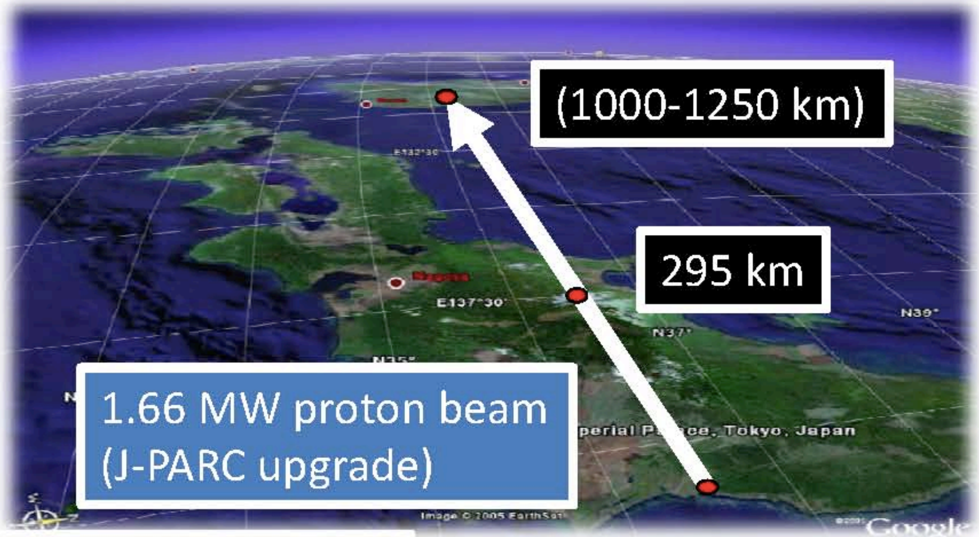
iolation
archy

Future LBL possibilities (assuming $\sin^2 2\theta_{13}$ is larger than 0.01)

Kajita@TAUP09

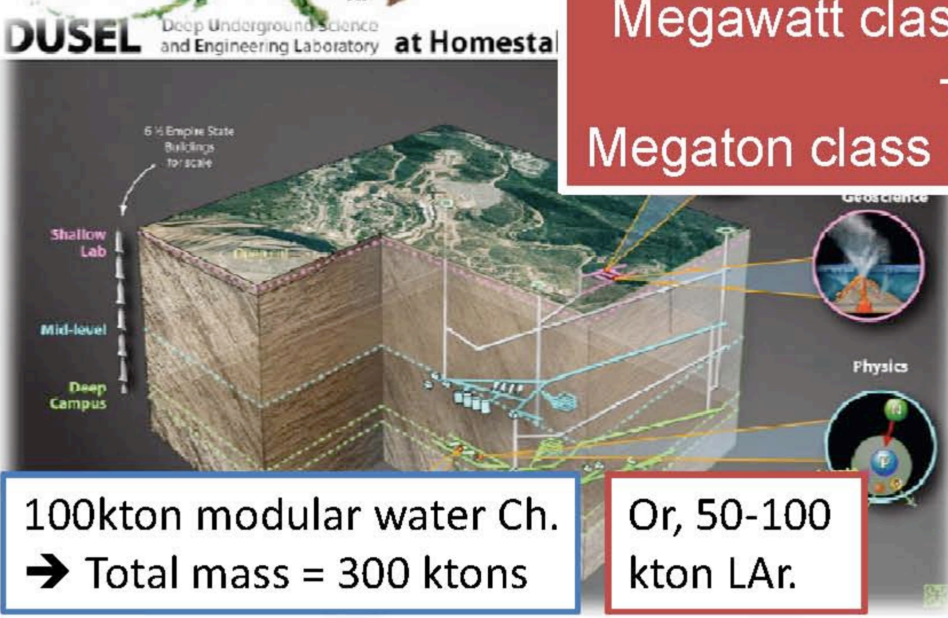


1.0 - 2.3 MW proton beam



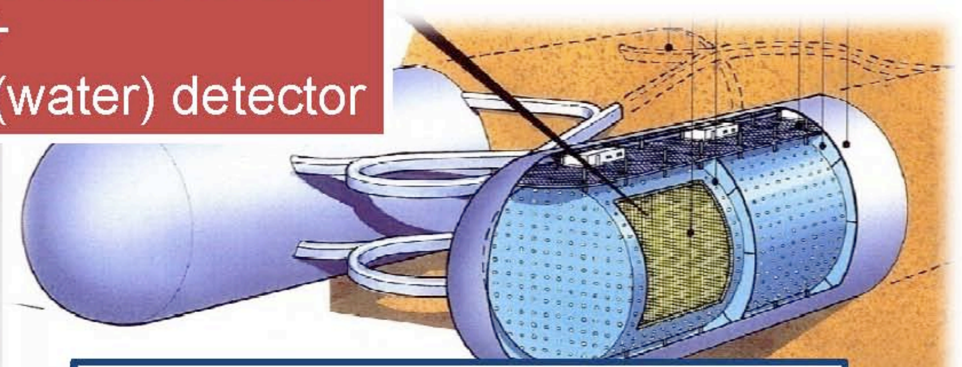
1.66 MW proton beam
(J-PARC upgrade)

Megawatt class super-beam
+
Megaton class (water) detector



100kton modular water Ch.
➔ Total mass = 300 ktons

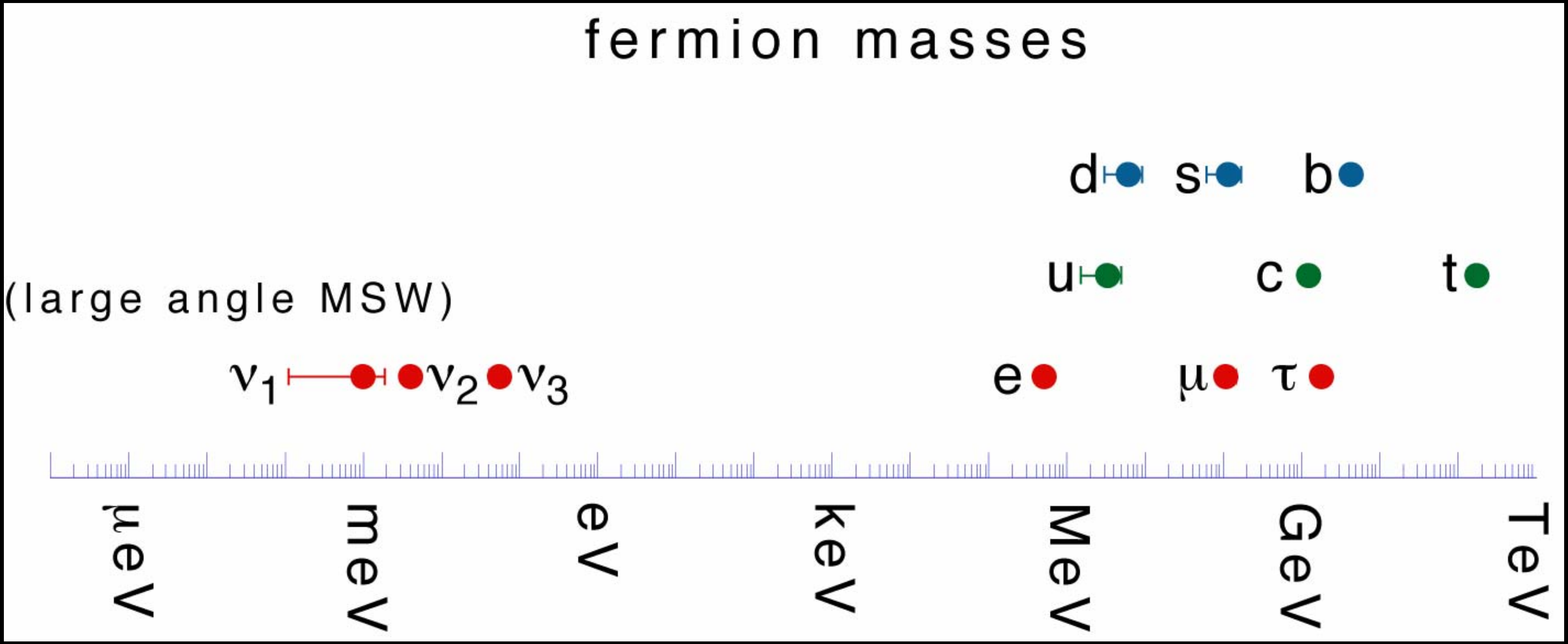
Or, 50-100 kton LAr.



0.54Mton detector in Kamioka, or
0.27 Mton water Cherenkov detector
in Kamioka and Korea.

What do we learn from neutrinos?

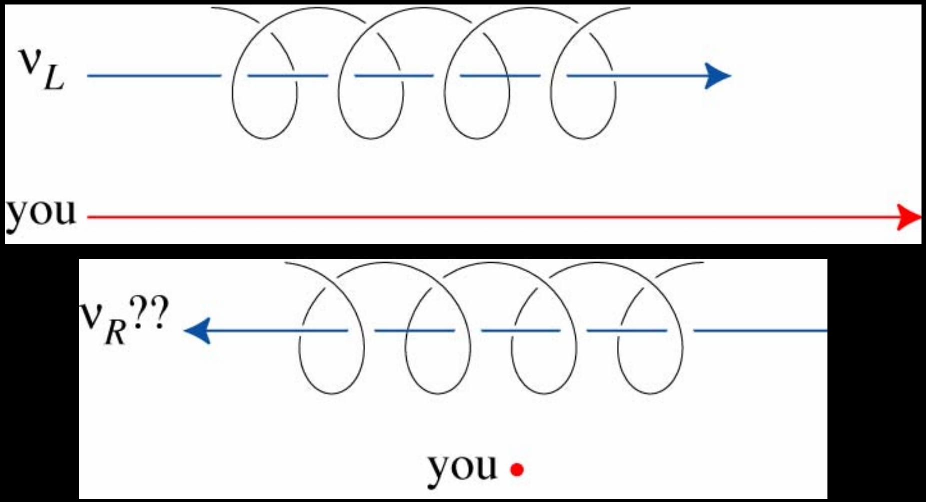
Mass Spectrum



What do we do now?

Neutrinos have mass

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

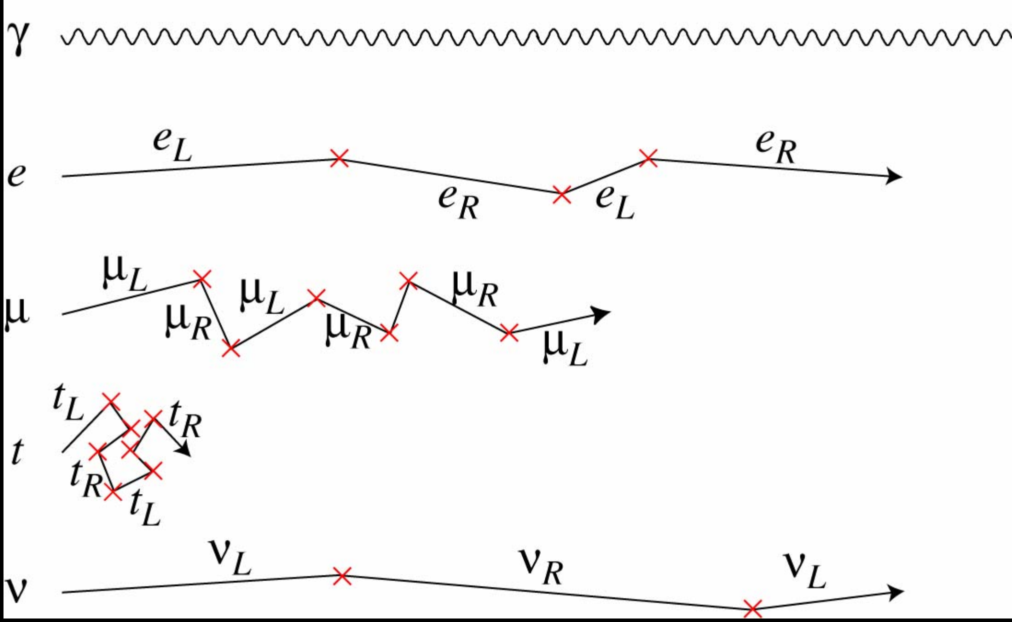


- What is this right-handed particle?
  - New particle: right-handed neutrino (Dirac)
  - Old anti-particle: right-handed anti-neutrino (Majorana)

Two ways to go

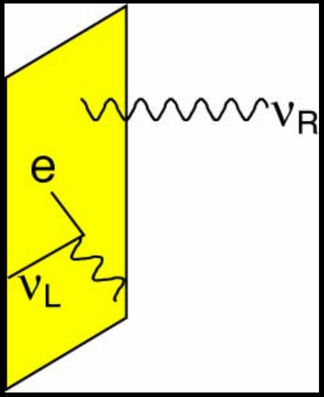
(1) Dirac Neutrinos:

- 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

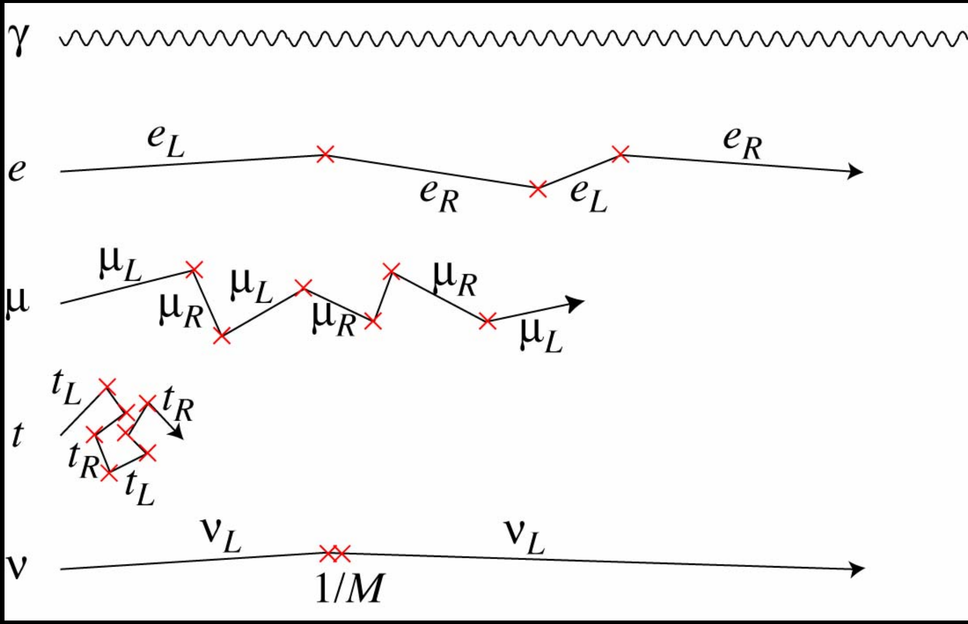


$$\int d^4\theta \frac{S^*}{M}(LH_uN)$$

Two ways to go

(2) Majorana Neutrinos:

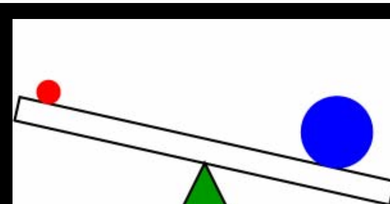
- There are no new light particles
- What if I pass a neutrino and look back?
- Must be right-handed *anti*-neutrinos
- No fundamental distinction between neutrinos and anti-neutrinos!



Seesaw Mechanism

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

$$\begin{pmatrix} \nu_L & \nu_R \end{pmatrix} \begin{pmatrix} & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \qquad m_\nu = \frac{m_D^2}{M} << m_D$$



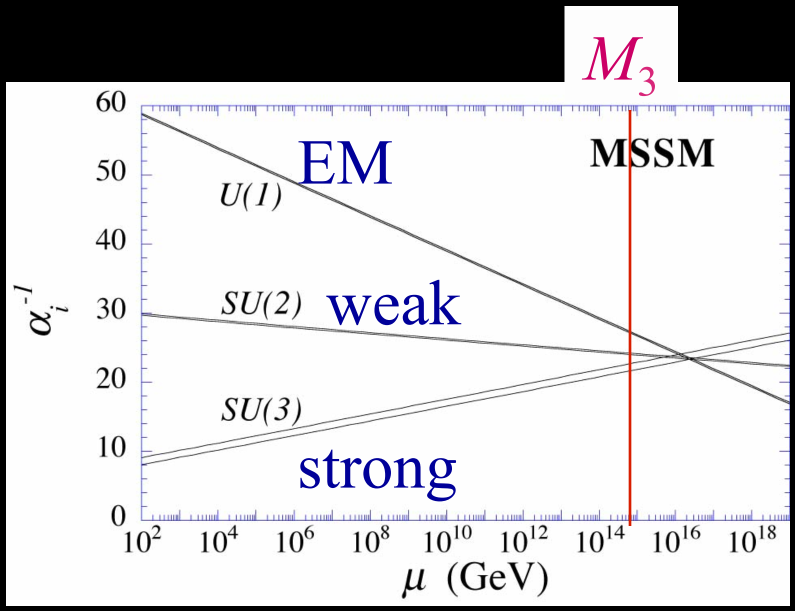
To obtain $m_3 \sim (\Delta m^2_{\mathrm{atm}})^{1/2}$, $m_D \sim m_t$, $M_3 \sim 10^{15}$GeV (GUT!)

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

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Baryogenesis

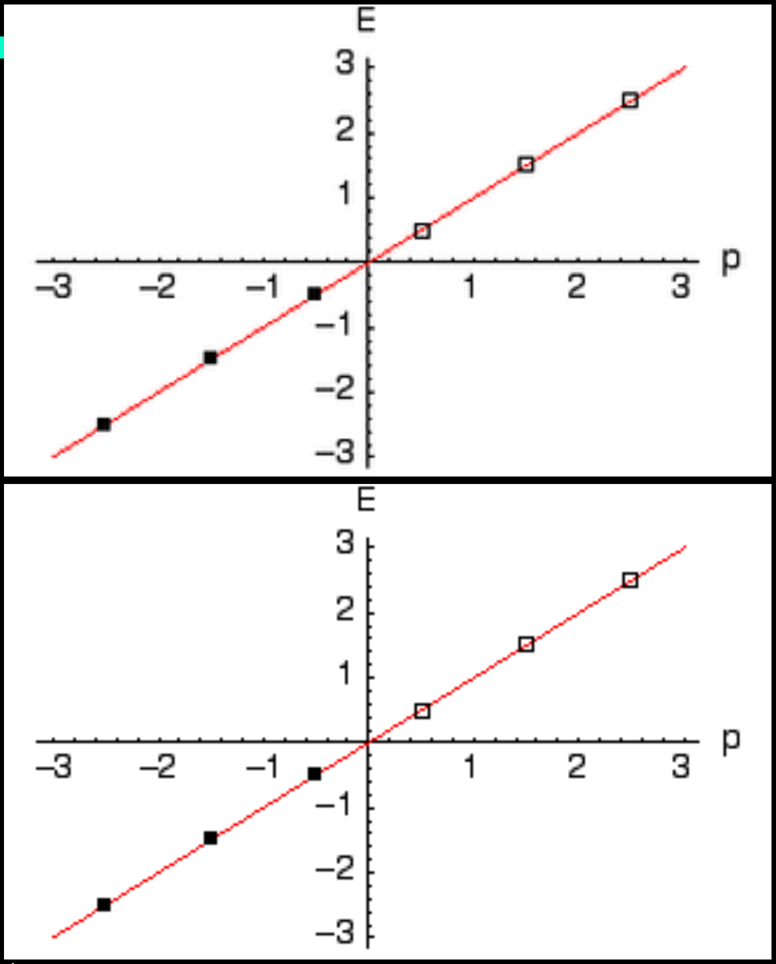
- What created this tiny excess matter?
- *Necessary* conditions for baryogenesis (Sakharov):
  - Baryon number non-conservation
  - CP violation

    (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

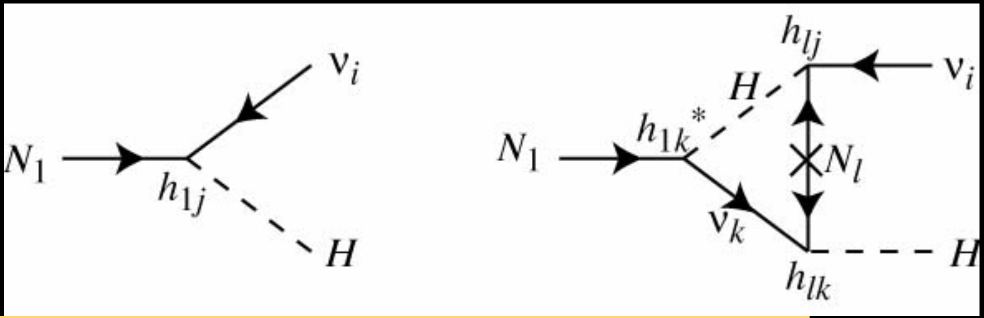
- Actually, SM converts L (ν) to B (quarks).
  - In Early Universe ($T >$ 200GeV), W is massless and fluctuate in W *plasma*
  - Energy levels for left-handed quarks/leptons fluctuate correspon-dingly



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

Leptogenesis

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



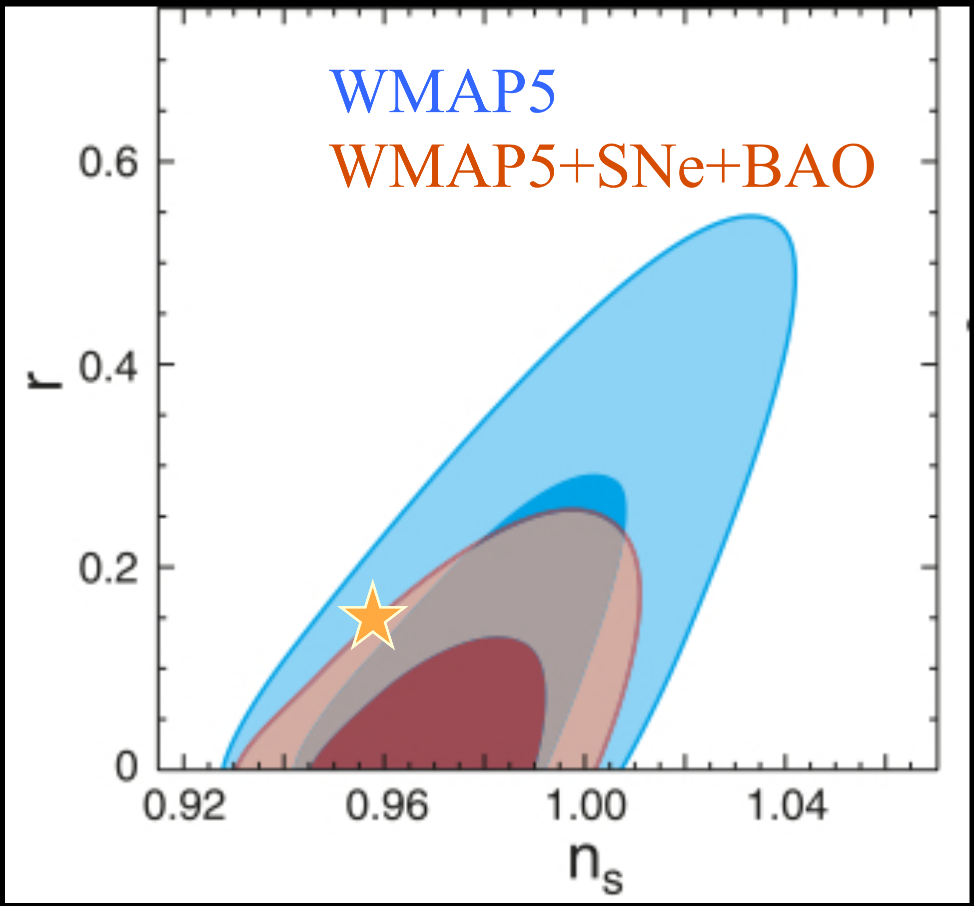
$$\Gamma(N_1 \to \nu_i H) - \Gamma(N_1 \to \bar{\nu}_i H) \propto \mathrm{Im}(h_{1j} h_{1k} h_{lk}^* h_{lj}^*)$$

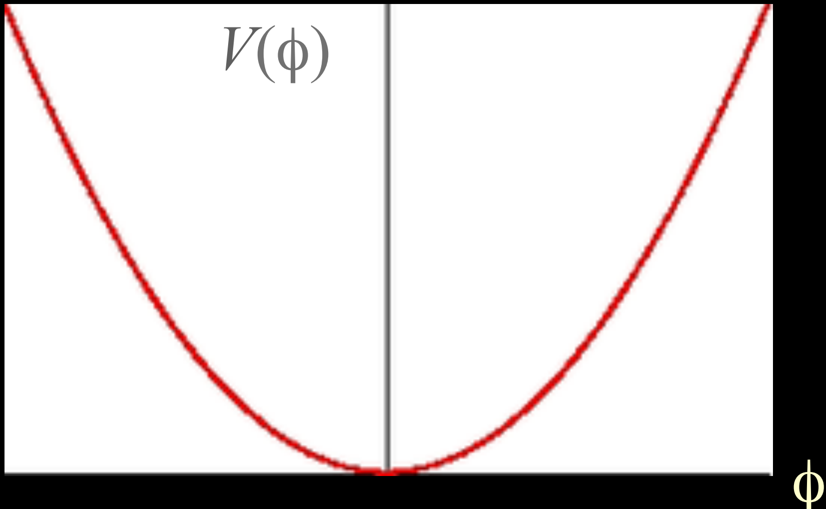
- L gets converted to B via EW anomaly

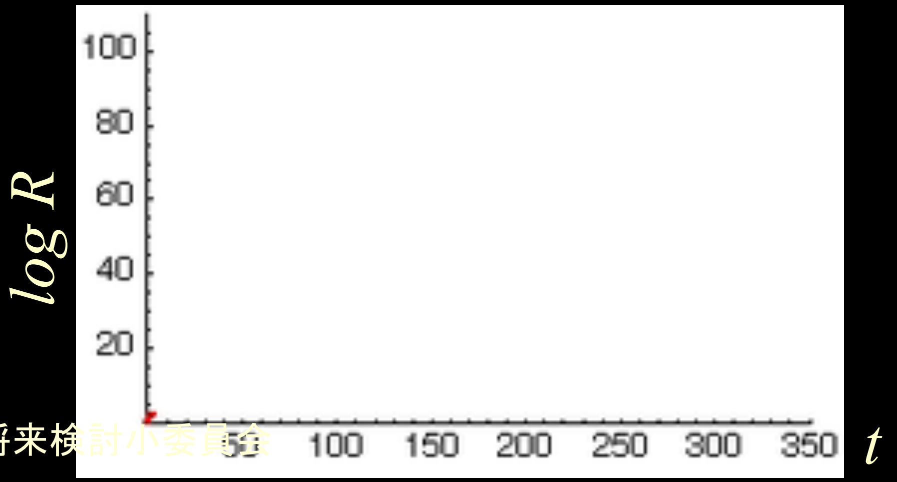
  ⇒ More matter than anti-matter

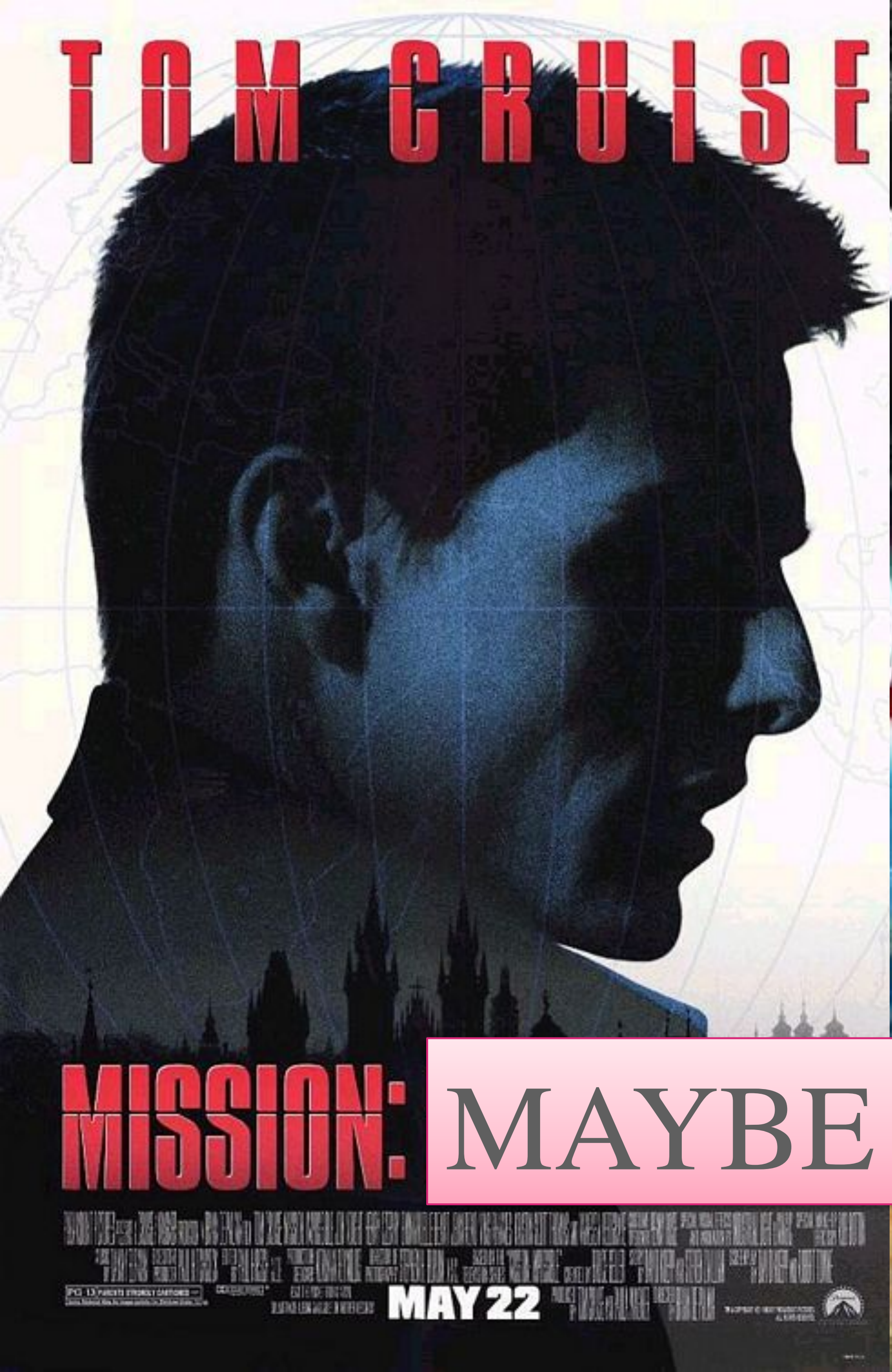
  ⇒ *We have survived "The Great Annihilation"*

Origin of Universe








TOM CRUISE
MISSION:
MAYBE
MAY 22

TOM CRUISE
M:i:III
THE MISSION BEGINS MAY 5

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)

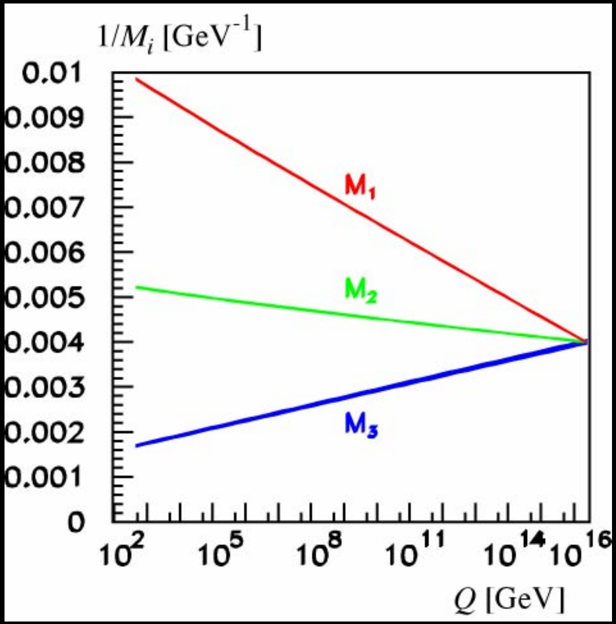
⇒ strong hint that there are no additional particles beyond the MSSM below M_{GUT} except for gauge singlets.

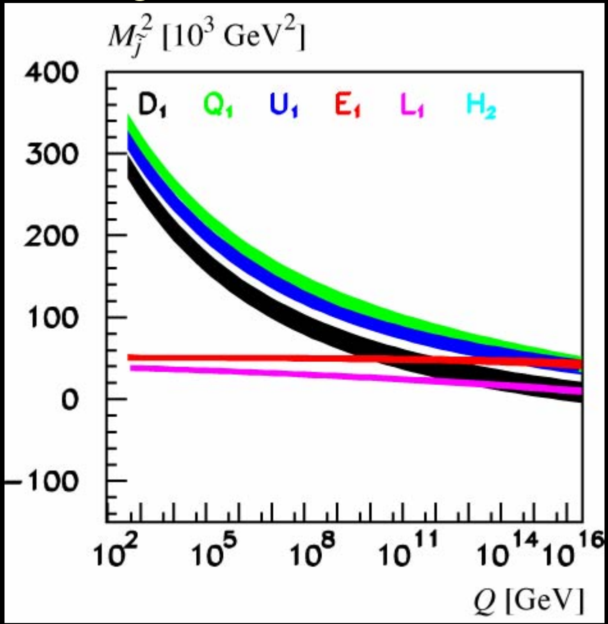
Buckley & HM, 2006 and in preparation

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



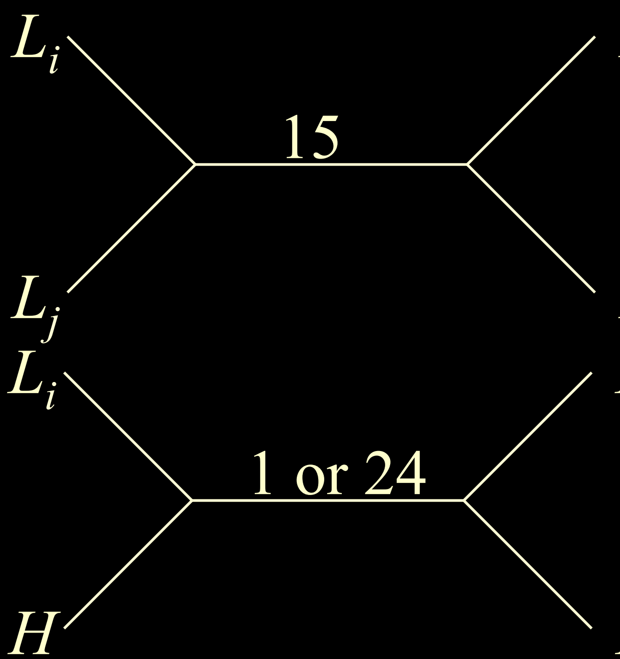


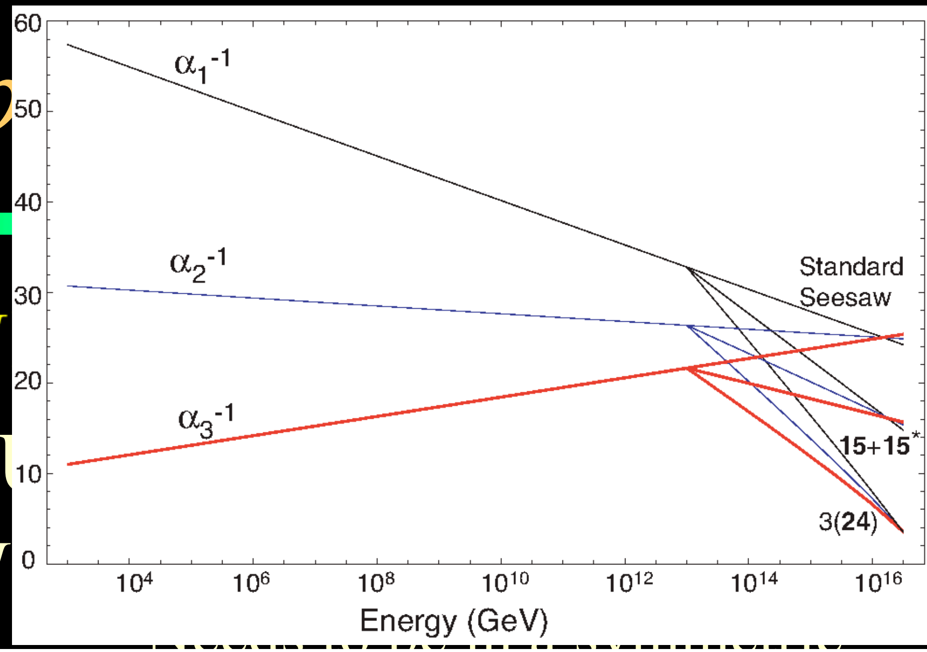
Zerwas and co

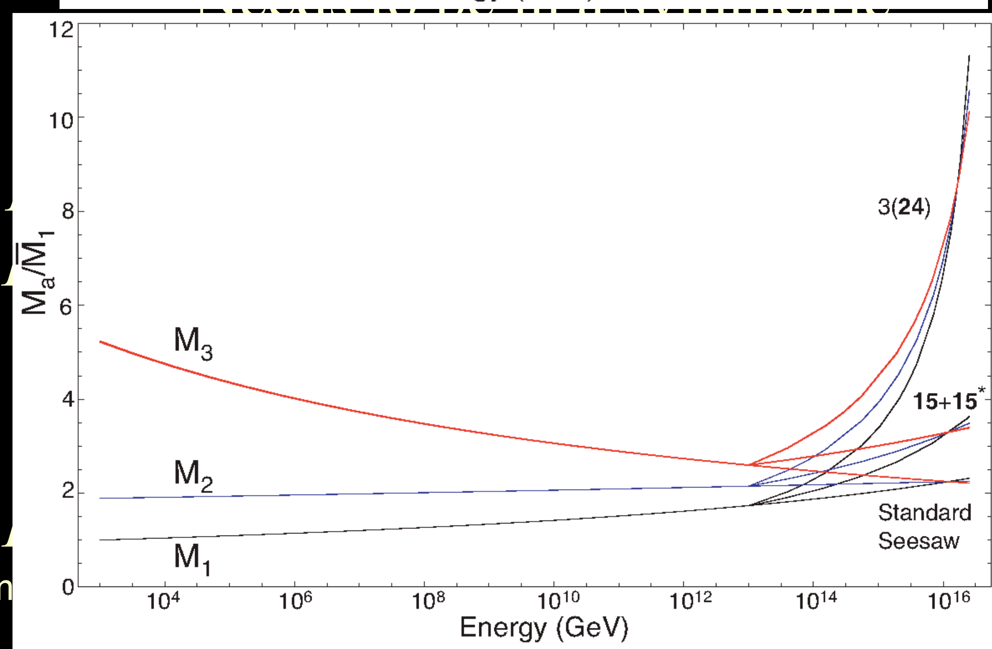
Possib

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

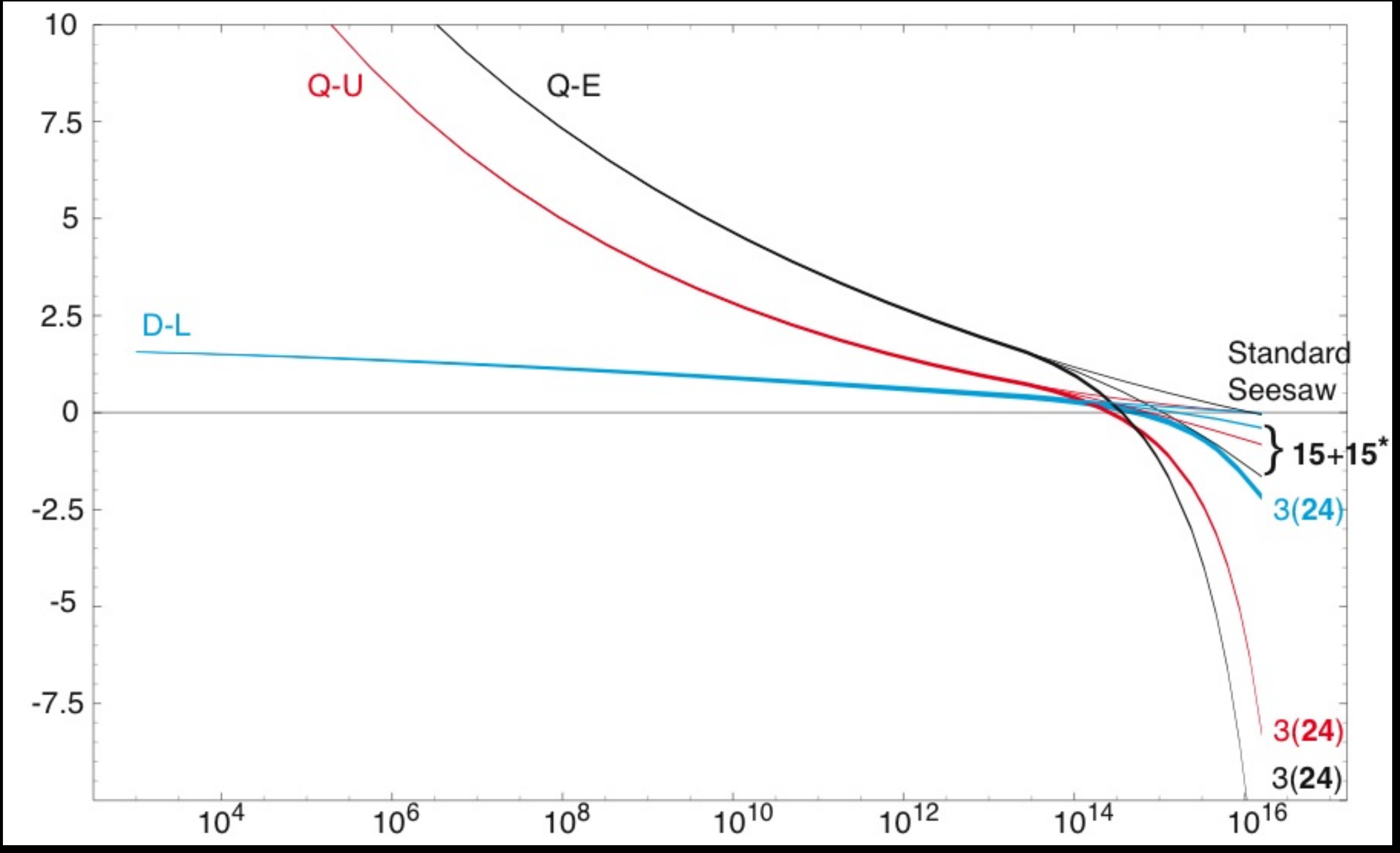
- L is in 5^*, H in 5 of SU





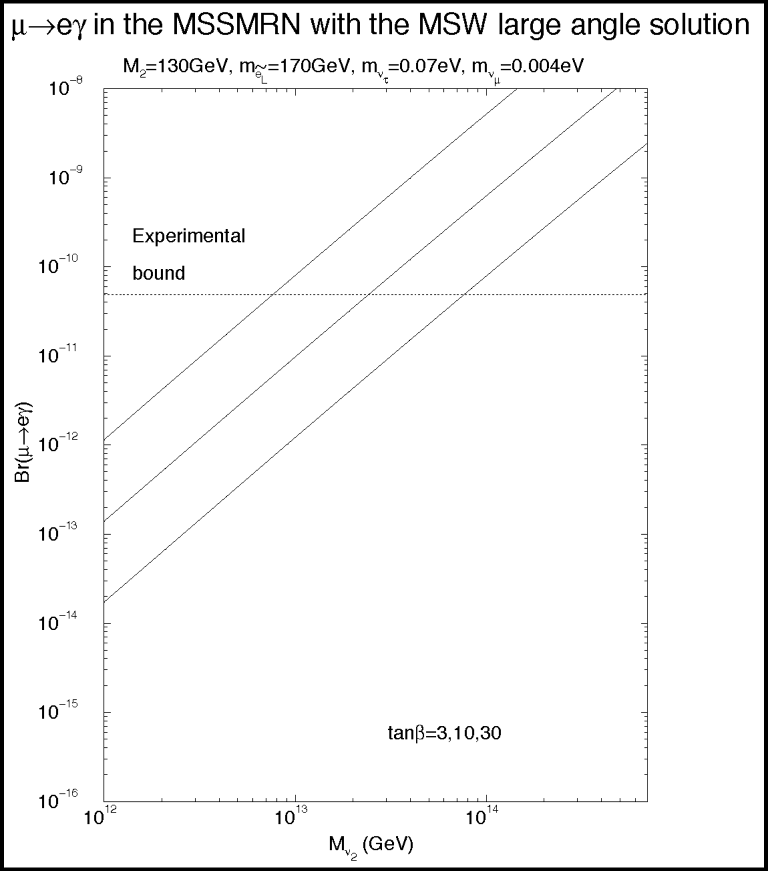


Scalar Masses



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

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

Can ν_R be non-singlets?

- Right-handed neutrinos can come with gauge groups *after inflation*
  - ~~SO(10)~~ Proton decay and monopoles
  - ~~$SU(4)\times SU(2)_L\times SU(2)_R$~~ monopoles
  - $SU(3)_C\times SU(2)_L\times SU(2)_R\times U(1)_{B-L}$
  - $SU(3)_C\times SU(2)_L\times U(1)_Y\times U(1)_{B-L}$

Jing Shu, HM, 2009

BERKELEY CENTER FOR THEORETICAL PHYSICS

Kibble-Zurek Mechanism

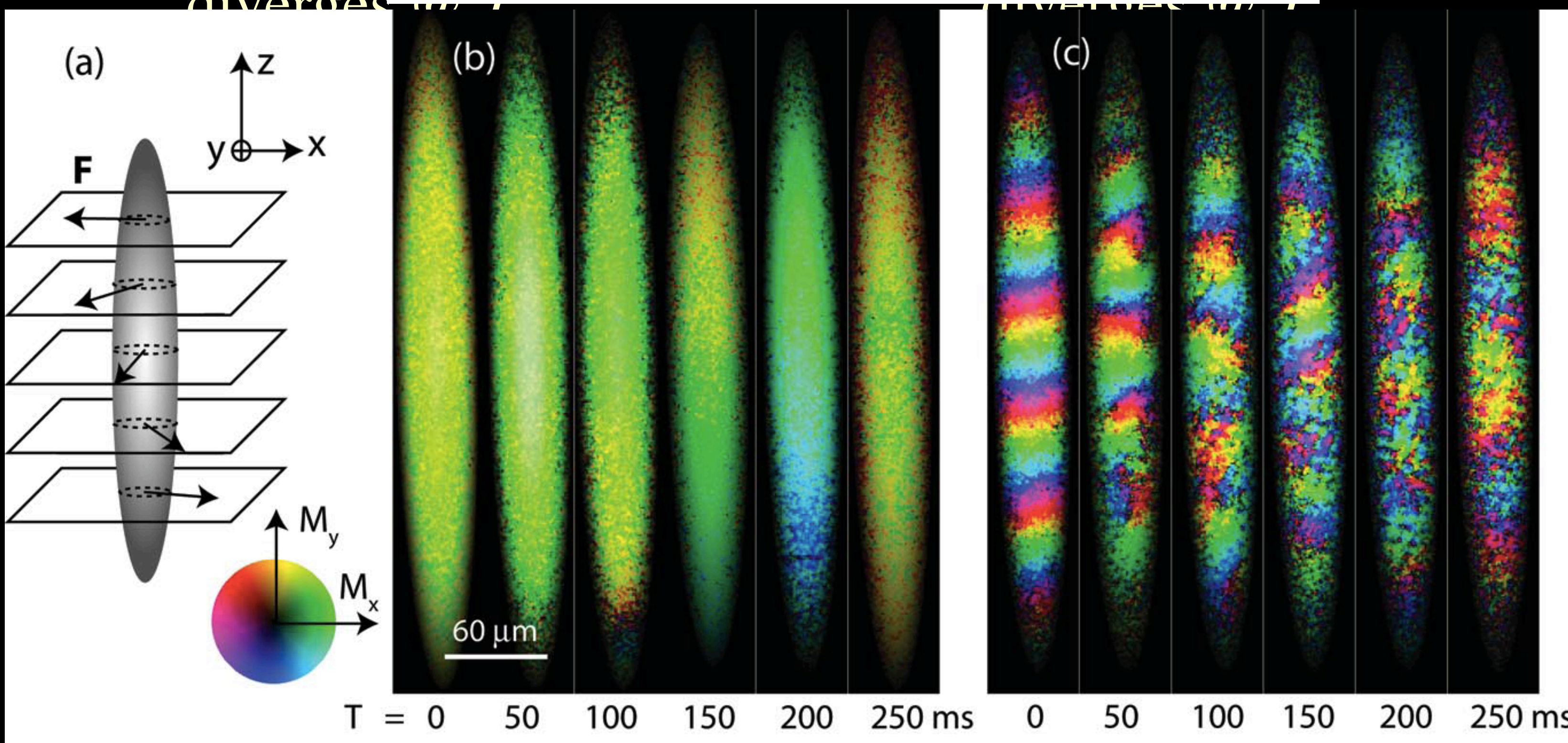
BEC of ^{87}Rb in *F*=1 hyperfine state

SO(2) symmetry to ferromagnet

Many vortices

Stamper-Kurn and collaborators

- Kibble:
  - Correlat … ne also diverges …

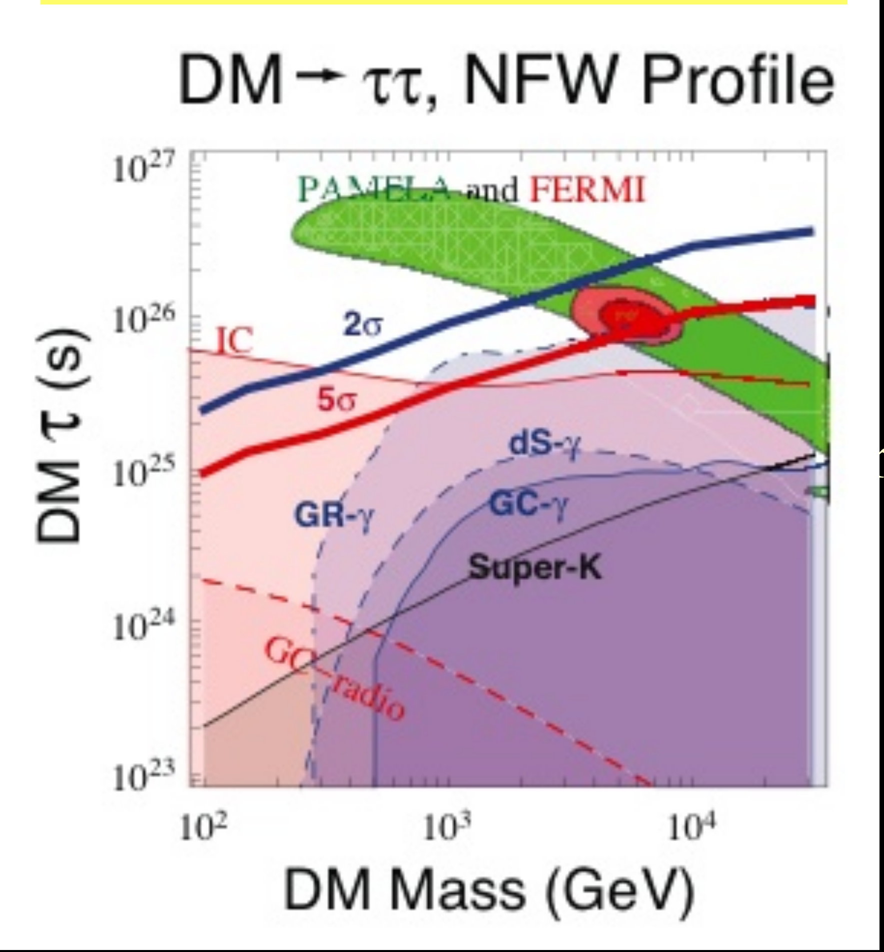


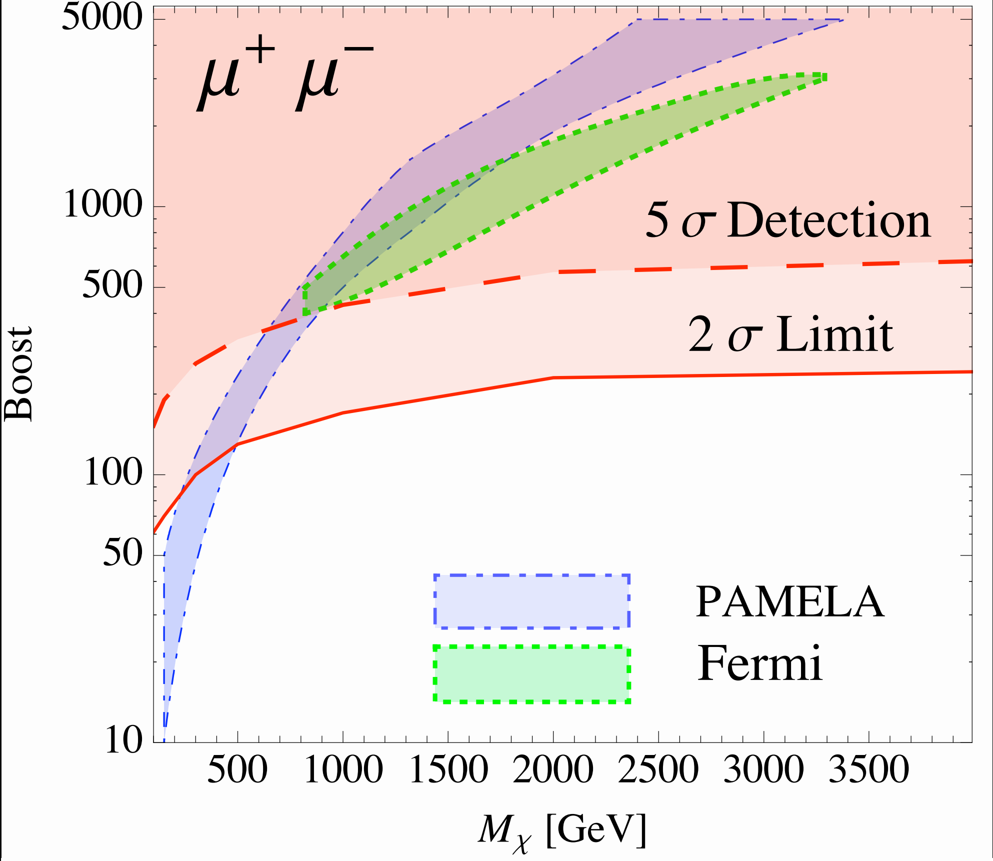
Indirect Dark Matter Detection

Dark Matter Heavy?

Superimposed on plots by
Meade, Papucci, Strumia, Volansky

Galactic Center





Spolyar, Buckley, Freese, Hooper, HM

Conclusions

- Neutrino oscillation firmly established
- Yet many more imoportant questions remain
- Well-defined near-future experimental program
- 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

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Hitoshi Murayama, 将来検討小委員会