Cosmological Matter-Antimatter Asymmetry and Neutrino Oscillations

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- A Conjecture + An Ansatz
- Seesaw + Leptogenesis
- ν-Mixing + Baryogenesis

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Motivation: the new minimal SM

Davoudiasl, Kitano, Li, Murayama, hep-ph/0405097

NMSM = MSM + New Physics

(Minimal number of new degrees of freedom)

Experimental/Observational Evidence for NP:

- Dark Matter
- Dark Energy
- Cosmic Inflation
- Cosmic Baryon Asymmetry
- Atmospheric & Solar Neutrino Oscillations

Can one stone kill two big birds?

The minimal seesaw model:
Frampton, Glashow, Yanagida, hep-ph/0208157; ……

2 Right-handed neutrinos added:

$$\nu_{\rm R} = \begin{pmatrix} N_1 \\ N_2 \end{pmatrix}$$

$$-\mathcal{L}_{\rm Y(SM)} = \bar{l}_{\rm L} Y_l e_{\rm R} H + \bar{l}_{\rm L} Y_\nu \nu_{\rm R} H^{\rm c} + \frac{1}{2} \overline{\nu^{\rm c}_{\rm R}} M_{\rm R} \nu_{\rm R} + {\rm h.c.}$$

- **Principle of minimal particle content**
- **SU(2)×U(1) gauge symmetry preserved**

Seesaw + Leptogenesis { **Neutrino Oscillations**, **Baryon Asymmetry** }

Is there special ν-mass hierarchy?

3 Right-handed neutrinos ⟹ more freedom

Conjecture: Universal Geometric Neutrino Mass Hierarchy

Z.Z.X., hep-ph/0406047 (for both light and heavy ν);
Kaus, Meshkov, hep-ph/0410024 (for light ν);
Tsujimoto, hep-ph/0501023 (for heavy ν).

Light

$$\frac{m_1}{m_2} = \frac{m_2}{m_3} = \frac{M_1}{M_2} = \frac{M_2}{M_3}$$

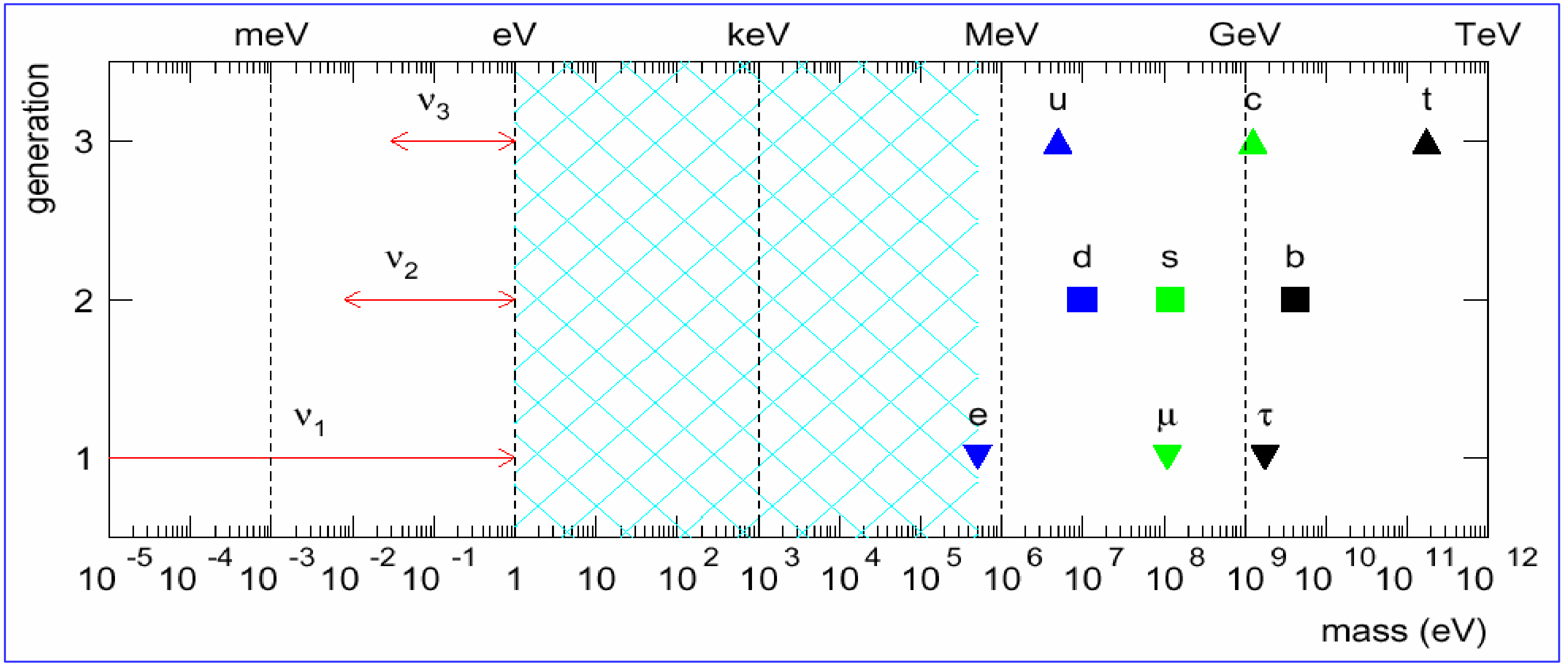
Heavy

Quarks

$$\frac{m_u}{m_c} \sim \frac{m_c}{m_t} \quad ; \quad \frac{m_d}{m_s} \sim \frac{m_s}{m_b}$$

?

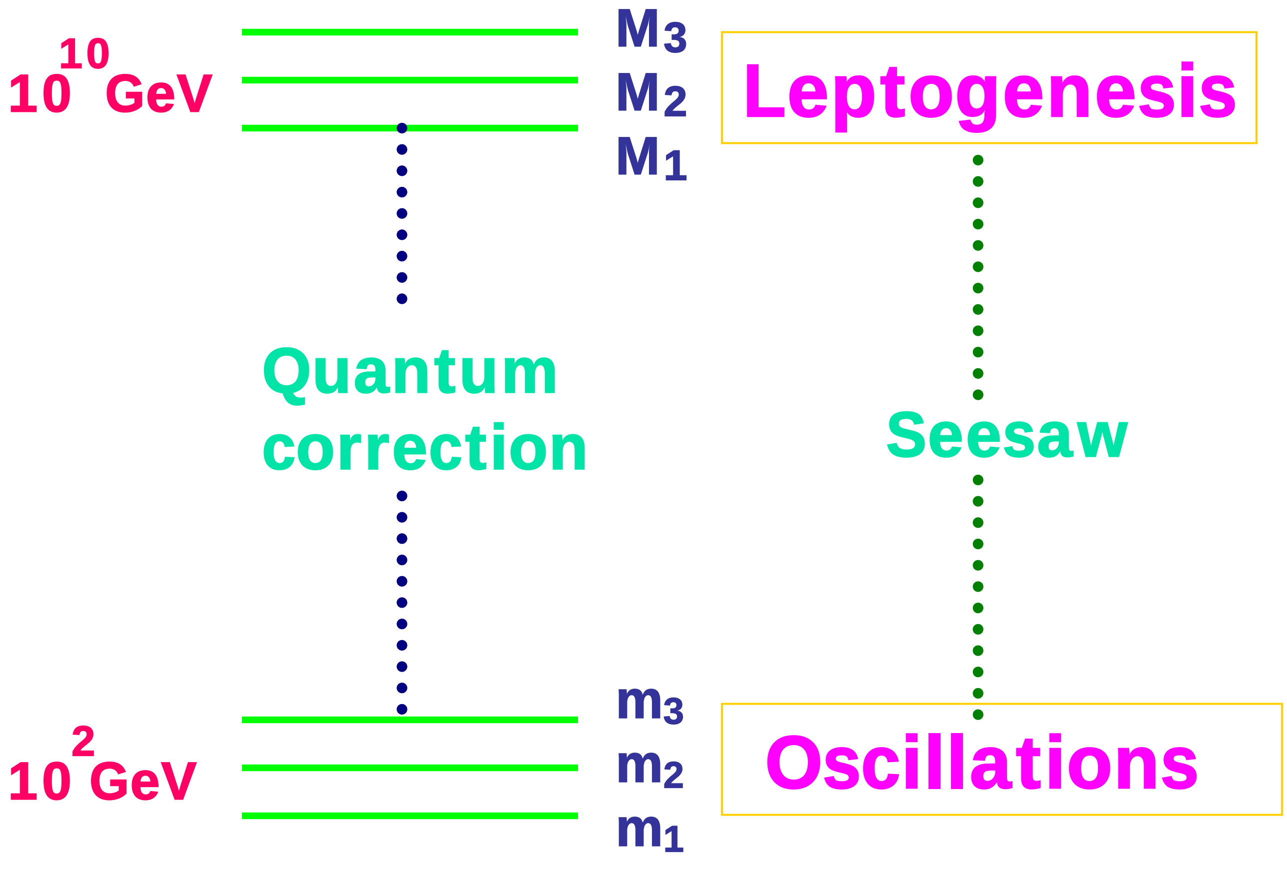
A plot of fermion mass spectrum



(a nomal neutrino mass hierarchy is assumed)

Gaps: eV — MeV; and TeV — RH ν-mass scale

A phenomenological picture:



Geometric ν-mass hierarchy:

$$m_1 : m_2 : m_3 = r^2 : r : 1$$

at electroweak scale

★ **Atm**

★ **Sun**

$$\Delta m^2_{31} = m^2_3 - m^2_1 \sim 2.3 \times 10^{-3} \mathrm{eV}^2$$

$$\Delta m^2_{21} = m^2_2 - m^2_1 \sim 6.9 \times 10^{-5} \mathrm{eV}^2$$

$$m_1 = \frac{r^2}{\sqrt{1-r^4}} \sqrt{\Delta m^2_{31}}$$

$$m_2 = \frac{r}{\sqrt{1-r^4}} \sqrt{\Delta m^2_{31}}$$

$$m_3 = \frac{1}{\sqrt{1-r^4}} \sqrt{\Delta m^2_{31}}$$

$$r = \sqrt{\frac{\Delta m^2_{21}}{\Delta m^2_{31} - \Delta m^2_{21}}}$$

$$0.122 \lesssim r \lesssim 0.270$$

3σ

Renormalization-group equations

$$m_i(M_1) \approx m_i(M_Z)\mathcal{I}_\alpha$$

$$\mathcal{I}_\alpha = \exp\left[\int_{\ln M_Z}^{\ln M_1} \frac{1}{16\pi^2}(\lambda_H - 3g_2^2 + 6f_t^2)\mathrm{d}\tau\right]$$

Minimal SM case

$$\Rightarrow \quad m_1(M_1)/m_2(M_1) \approx m_2(M_1)/m_3(M_1) \approx r$$

Further Conjecture:

$$M_1/M_2 = M_2/M_3 = r$$

$$D_1/D_2 = D_2/D_3 = r$$

at the seesaw scale

D_i: Eigenvalues of Y_ν

M_i:Eigenvalues of M_R

$$\Rightarrow \quad m_i \propto \frac{D_i^2}{M_i}\langle\phi\rangle^2$$

Seesaw-invariant Fritzsch texture

Seesaw relation:

$$M_\nu \approx Y_\nu M_{\rm R}^{-1} Y_\nu^T \langle\phi\rangle^2$$

Conjecture: *Y_ν* and *M*_R Fritzsch Texture

$$Y_\nu = D_3 F_{\rm D}$$
$$M_{\rm R} = M_3 F_{\rm R}$$

$$F_\lambda = \begin{pmatrix} 0 & ce^{i\varphi_\lambda} & 0 \\ ce^{i\varphi_\lambda} & 0 & be^{i\phi_\lambda} \\ 0 & be^{i\phi_\lambda} & a \end{pmatrix}$$

$$a = 1 - r + r^2$$
$$b = (1-r)\sqrt{r(1+r^2)/a}$$
$$c = r\sqrt{r/a}$$

Phase condition

$$\phi_{\rm D} - \phi_{\rm R} = \varphi_{\rm D} - \varphi_{\rm R}$$

$$M_\nu \approx Y_\nu M_{\rm R}^{-1} Y_\nu^T \langle\phi\rangle^2 = m_3 \mathcal{I}_\alpha F_\nu$$

Seesaw invariance!

$$D_3 = \sqrt{m_3 M_3 \mathcal{I}_\alpha} / \langle\phi\rangle$$

$$\mathcal{I}_\alpha \sim 1.4 \;\; \text{for} \;\; M_1 \sim 10^{10}\text{GeV}$$

MNS lepton flavor mixing matrix

Charged leptons:
at the seesaw scale

$$Y_l = \begin{pmatrix} \mathbf{0} & \tilde{c}e^{i\varphi_l} & \mathbf{0} \\ \tilde{c}e^{i\varphi_l} & \mathbf{0} & \tilde{b}e^{i\phi_l} \\ \mathbf{0} & \tilde{b}e^{i\phi_l} & \tilde{a} \end{pmatrix}$$

$$\tilde{a} \approx m_\tau/\langle\phi\rangle, \; \tilde{b} \approx \sqrt{m_\mu m_\tau}/\langle\phi\rangle \text{ and } \tilde{c} \approx \sqrt{m_e m_\mu}/\langle\phi\rangle$$

The MNS matrix V arises from mismatch between the diagonalizations of Y_l and Y_ν. Due to the normal hierarchy of m_i, RGE effects on V is negligibly small from seesaw to electroweak scales.

At low scales, the Fritzsch-like texture of lepton mass matrices is found to be compatible with the present neutrino data at the 3σ level.
(Z.Z.X. 02; Z.Z.X., S. Zhou 04)

$$0.215 \lesssim r \lesssim 0.270$$

Isomeric textures and FTY seesaw

If M_l and M_ν take a parallel and Fritzsch-like form, there are 6 different combinations. Their consequences on lepton flavor mixing are exactly the same --- an isomeric feature! (This feature is also true when the leptogenesis is concerned.)

(A)	$M = \begin{pmatrix} 0 & Ce^{i\varphi} & 0 \\ Ce^{i\varphi} & 0 & Be^{i\phi} \\ 0 & Be^{i\phi} & A \end{pmatrix}$
(B)	$M = \begin{pmatrix} 0 & 0 & Ce^{i\varphi} \\ 0 & A & Be^{i\phi} \\ Ce^{i\varphi} & Be^{i\phi} & 0 \end{pmatrix}$
(C)	$M = \begin{pmatrix} 0 & Ce^{i\varphi} & Be^{i\phi} \\ Ce^{i\varphi} & 0 & 0 \\ Be^{i\phi} & 0 & A \end{pmatrix}$
(D)	$M = \begin{pmatrix} 0 & Be^{i\phi} & Ce^{i\varphi} \\ Be^{i\phi} & A & 0 \\ Ce^{i\varphi} & 0 & 0 \end{pmatrix}$
(E)	$M = \begin{pmatrix} A & 0 & Be^{i\phi} \\ 0 & 0 & Ce^{i\varphi} \\ Be^{i\phi} & Ce^{i\varphi} & 0 \end{pmatrix}$
(F)	$M = \begin{pmatrix} A & Be^{i\phi} & 0 \\ Be^{i\phi} & 0 & Ce^{i\varphi} \\ 0 & Ce^{i\varphi} & 0 \end{pmatrix}$

A seesaw ansatz with Fritzsch form of M_l and M_D, but $M_R = 1$ (3 degenerate heavy neutrinos) by Fukugita, Tanimoto, Yanagida (93, 03):
At low scales: better fit to current neutrino oscillations;
At seesaw scale: no leptogenesis due to N-degeneracy.

Leptogenesis at the seesaw scale

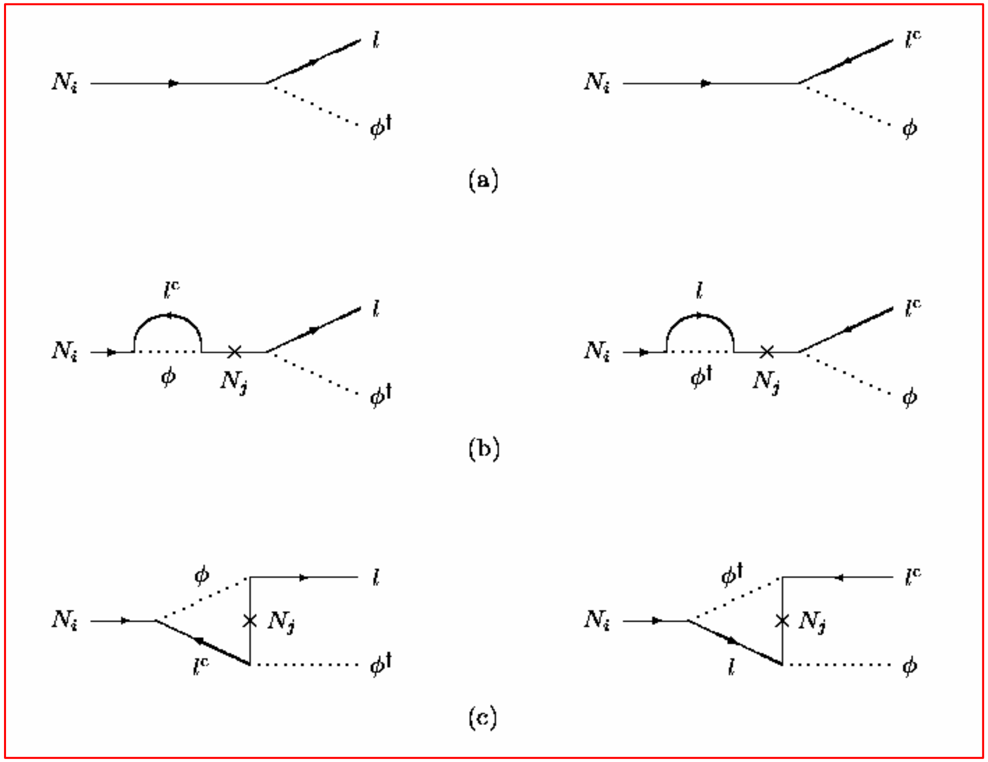
Lepton-number-violating decays:

$$N_i \rightarrow l + \phi^+$$

$$N_i \rightarrow l^c + \phi$$

CP violation

Fukugita, Yanagida 86



Baryogenesis via Leptogenesis

- ★ **Out of thermal equilibrium and *N_1* decay**

$$T \sim M_1 \gg T_{EW}\ ,\ \Gamma_1 < H(T \sim M_1)$$

- ★ **Net lepton asymmetry**

$$Y_{\rm L} \equiv \frac{n_l - n_{\bar{l}}}{s} \approx \varepsilon_1 \frac{d}{g_*}$$

- ★ **Net baryon asymmetry via sphaleron**

$$Y_{\rm B} \equiv \frac{n_B - n_{\bar{B}}}{s} \approx -0.35 Y_{\rm L}$$

Observation:

$$Y_{\rm B} \equiv \frac{1}{7}\frac{n_{\rm B}}{n_\gamma} \equiv \frac{10^{-10}}{7}\eta_{10}$$

$$\eta_{10} = \begin{cases} 5.6 \pm 0.5 & ({\rm BBN,\ T \sim 1MeV}) \\ 5.1 \pm 1.6 & ({\rm SNIa,\ T \sim 1meV}) \\ 6.0 \pm 0.6 & ({\rm CMB,\ T \sim 0.1eV}) \\ 6.1^{+0.3}_{-0.2} & ({\rm WMAP,}\qquad) \end{cases}$$

CP asymmetry in our ansatz

$$\varepsilon_1 \approx -\frac{3M_1}{16\pi}\left[\frac{\mathrm{Im}[(Y_\nu^\dagger Y_\nu)_{12}]^2}{M_2(Y_\nu^\dagger Y_\nu)_{11}} + \frac{\mathrm{Im}[(Y_\nu^\dagger Y_\nu)_{13}]^2}{M_3(Y_\nu^\dagger Y_\nu)_{11}}\right]$$

$$M_1^2 \ll M_2^2 \ll M_3^2$$

$$r^2 \leq 0.1$$

$$\varepsilon_1 = -\frac{3M_1 m_3 \mathcal{I}_\alpha (1-r)^2(1+r^2)\sin^3\omega\cos\omega}{2\pi\langle\phi\rangle^2\left[r^2(1+r)^2 + 4(1-r)(1+r^2)\sin^2\omega\right]}$$

where $\omega \equiv (\phi_{\mathrm{D}} - \phi_{\mathrm{R}})/2$

Dilution factor

$$d \approx 0.02 \times (0.01\ \mathrm{eV}/\tilde{m}_1)^{1.1}$$ **(A)**

$$\frac{1}{d} \approx \frac{3.3\times10^{-3}\ \mathrm{eV}}{\tilde{m}_1} + \left(\frac{\tilde{m}_1}{5.5\times10^{-4}\ \mathrm{eV}}\right)^{1.16}$$ **(B)**

in which $\tilde{m}_1 \equiv \frac{(\mathbf{Y}_\nu^\dagger \mathbf{Y}_\nu)_{11}}{M_1}\langle\phi\rangle^2 = m_1\mathcal{I}_\alpha\left[1 + \frac{4(1-r)(1+r^2)\sin^2\omega}{r^2(1+r)^2}\right]$

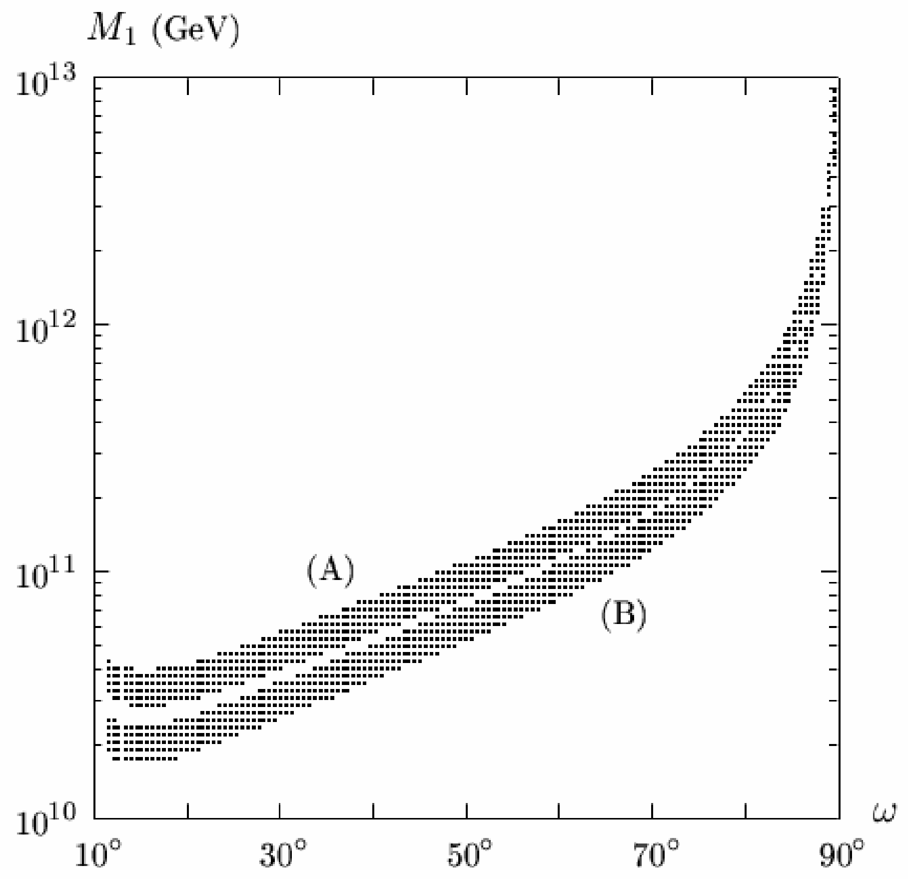
The allowed ranges of *M_1* and ω

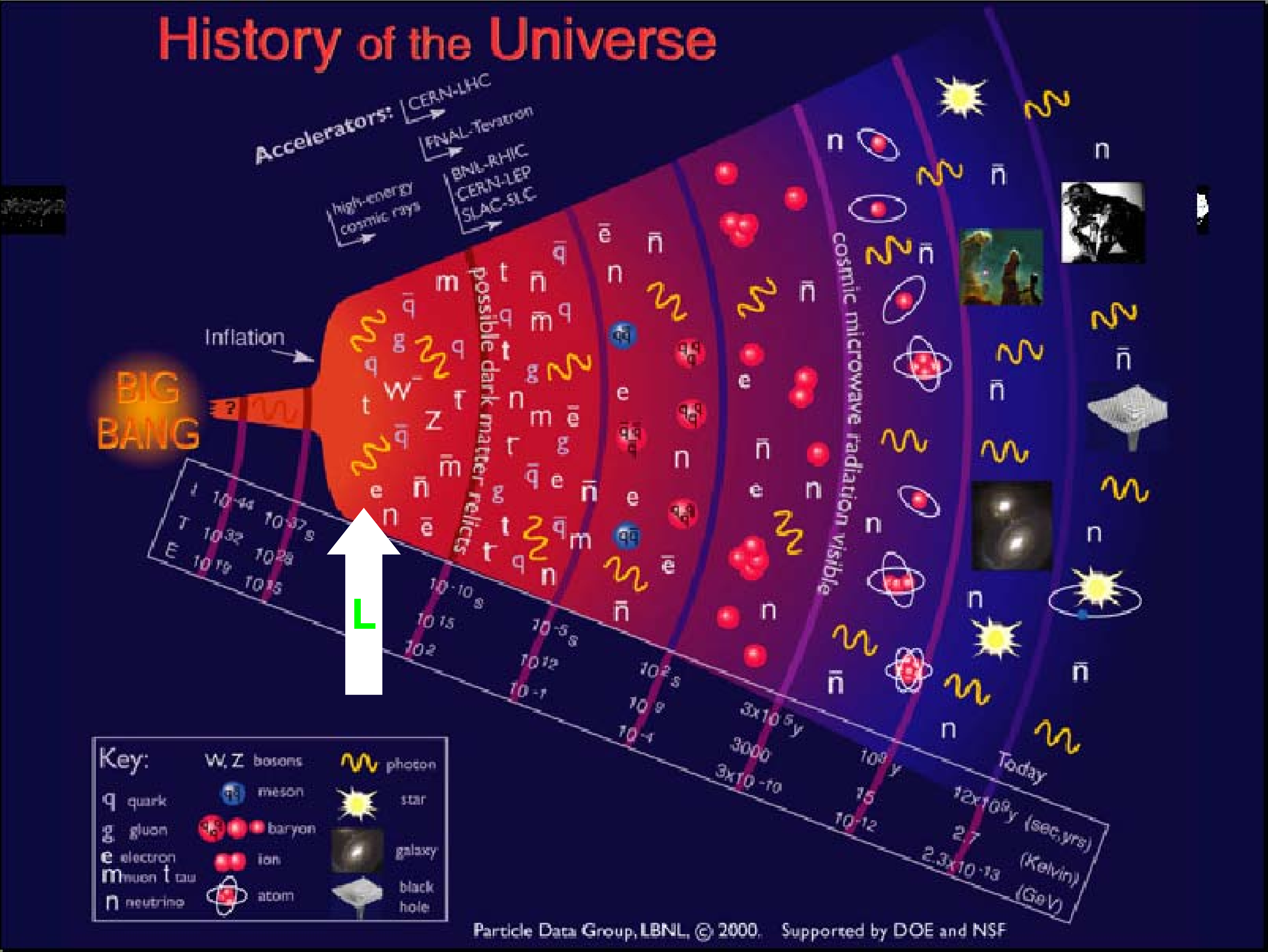
Input

$$\Delta m_{31}^2 = 2.5 \times 10^{-3} \mathrm{eV}^2$$
$$m_{\mathrm{H}} = 144 \ \mathrm{GeV}$$
$$r = 0.25$$
$$g_* = 106.75$$

M_1, ω random

$$7 \times 10^{-11} \lesssim Y_{\mathrm{B}} \lesssim 10^{-10}$$





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)
L
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

Some further comments:

- The cosmological baryon asymmetry and the present ν-oscillation data can simultaneously be interpreted in this phenomenological ansatz

- Y_B can be extended to the MSSM for $\tan\beta \leq 50$

- The CP-violating asymmetry ε_1 has no direct connection with the low-energy CP violation in neutrino oscillations

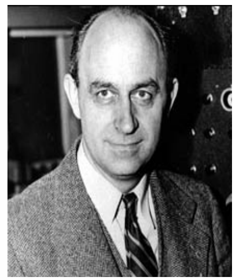
- Replace $\frac{m_1}{m_2} = \frac{m_2}{m_3} = \frac{M_1}{M_2} = \frac{M_2}{M_3}$ by $\frac{m_1}{m_2} \sim \frac{m_2}{m_3} \sim \frac{M_1}{M_2} \sim \frac{M_2}{M_3}$

The result is stable, but more free parameters.

Concluding question

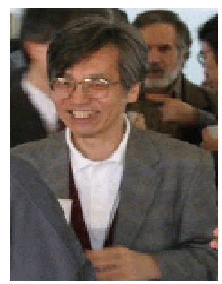
Leibniz: **why is there something rather than nothing?**











Thanks

For neutrino masses, the considerations have always been qualitative, and, despite some interesting attempts, there has never been a convincing quantitative model of the neutrino masses.