TeV Leptogenesis

调研简报

---主要思路
---存在问题
---初步设想

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Outline

1. Introduction
   - **Baryogenesis**
   - **Leptogenesis**
2. TeV Leptogenesis
   - **Motivation**
   - **Difficulties**
   - **Way Out on Theoretical Side and LHC**
3. Comments

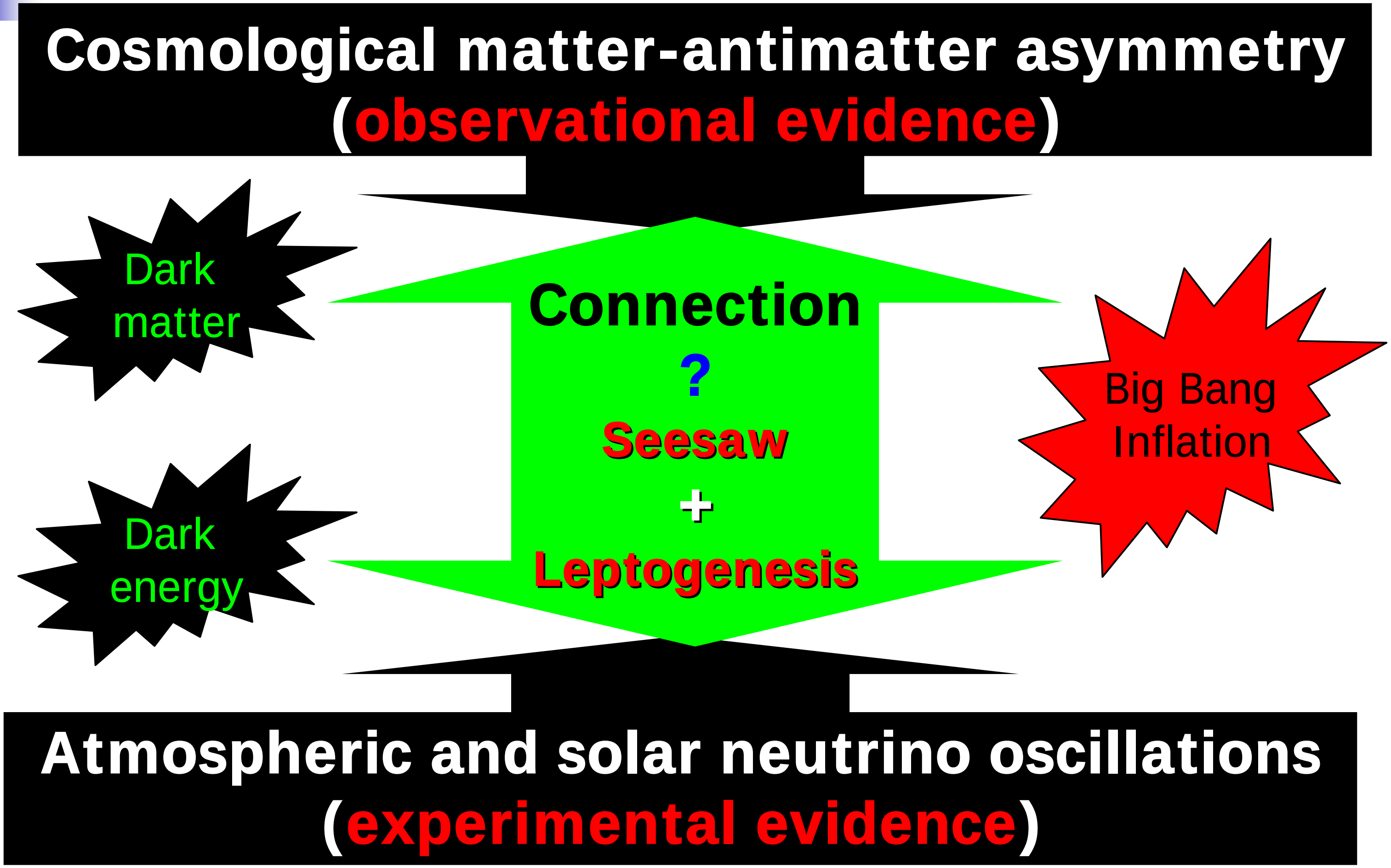
Established New Physics?

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 Birds?



Cosmological matter-antimatter asymmetry
(observational evidence)

Dark matter

Dark energy

Connection
?
Seesaw
+
Leptogenesis

Big Bang Inflation

Atmospheric and solar neutrino oscillations
(experimental evidence)

Baryogenesis

¶ **WMAP** The baryon-to-photon ratio of number densities has been measured to the precision of less than 10%:

$$\eta_B = \frac{n_B}{n_\gamma} = 6.1^{+0.3}_{-0.2} \times 10^{-10}$$

¶ Sakharov Conditions for Baryogenesis

1. Baryon-number-violating interactions
2. C and CP violation
3. Departure from thermal equilibrium

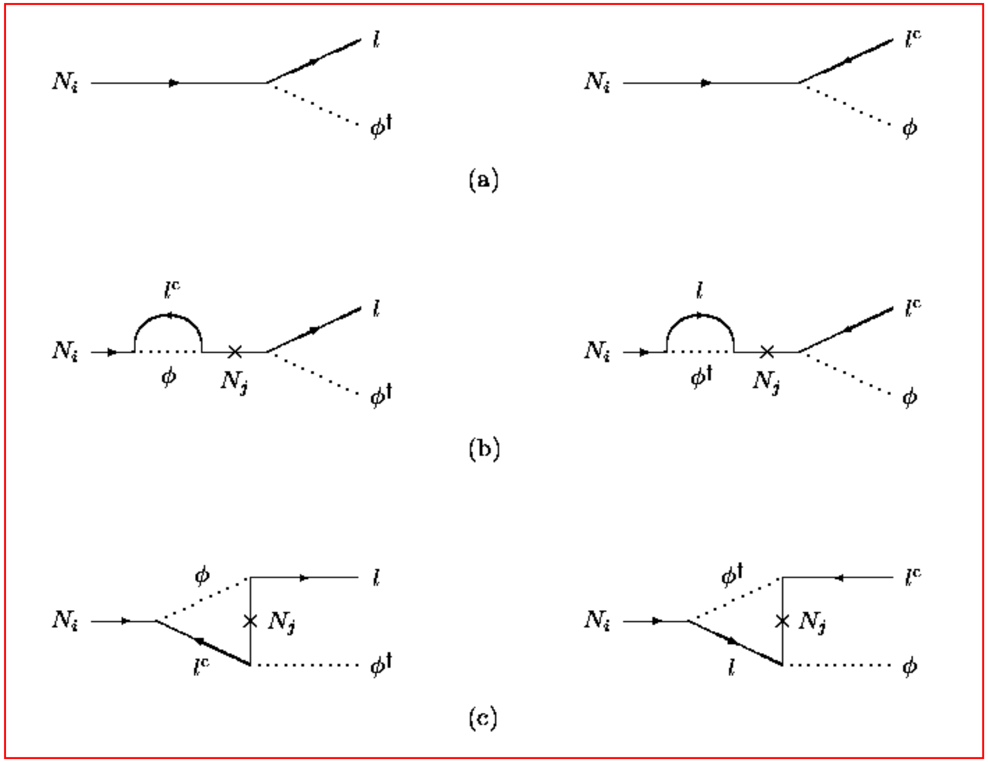
¶ Dynamical Generation of Baryon Number Asymmetry

1. Planck Scale, GUT and Electroweak Baryogenesis
2. Affleck-Dine Mechanism
3. Baryogenesis via Leptogenesis

Leptogenesis

- **Heavy right-handed Majorana neutrinos *N_i***
- **Out of thermal equilibrium and *N_i* decay**

$$\Gamma_1 < H(T \sim M_1)$$



- **Net lepton asymmetry**

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

- **Sphaleron process**

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

Motivation for TeV leptogenesis

The Fukugita-Yanagida mechanism has an intrinsic problem for phenomenology: Its lack of testability.

Typical scale of usual leptogenesis → $M_1 > 10^8 \,\mathrm{GeV}$

In MSSM, The number of the produced right-handed neutrinos depends strongly upon the reheating temperature. A successful leptogenesis scenario requires:

The yield variable of the gravitino is proportional to T_{RH} .

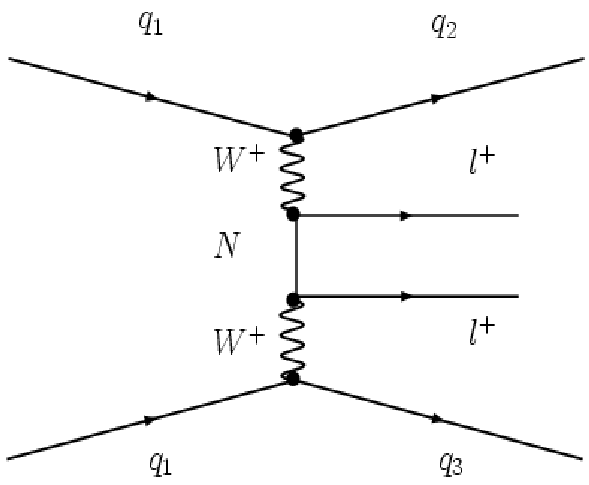
In order to avoid gravitino overproduction, $T_{\mathrm{RH}} \leq 10^9 \,\mathrm{GeV}$

It is particularly interesting to look for possible leptogenesis at much lower energy scales, of order TeV, which would be directly testable in the upcoming TeV experiments.

Possible processes at LHC

If the mass of a right-handed neutrino is of the order of TeV scale, then its potential effects can be searched for in a number of rare processes.

A. Ali, A. V. Borisov, N. B. Zamorin, Eur. Phys. J. C 21, 123 (2001)



- Like-sign dilepton states produced in rare meson decay.
- Dilepton production in proton-proton collisions.

$$M^+ \to \tilde{M}^- \mu^+ \mu^+$$

$$pp \to l^\pm l^\pm X$$

Experimental upper bound → $B_{\mu\mu}(K) < 3.0 \times 10^{-9}$

$$\langle m_{ll'}^{-1} \rangle = \left| \sum_N U_{lN} U_{l'N} \eta_N \frac{1}{m_N} \right|$$

Theoretical estimate

$$\langle m_{ll'}^{-1} \rangle^{-1} > 300\,\mathbf{KeV}$$

$$B_{\mu\mu}(K) \equiv B\left(K^+ \to \pi^- \mu^+ \mu^+\right) = 2.5 \times 10^{-10}\,\mathbf{MeV}^2 \cdot \langle m_{\mu\mu}^{-1} \rangle^2$$

Difficulties in TeV Leptogenesis

- ε_1 **sufficient large**
- **Satisfy** $\Gamma_1 < H(T \sim M_1)$

$$M_1 \geq 10^8\,\mathrm{GeV}$$

$$\begin{aligned}
\Gamma_1 &= \frac{(M_D^\dagger M_D)_{11}}{8\pi v^2} M_1 \\
H &= \frac{4\pi^3 g_*}{45} \frac{M_1^2}{M_P} \\
\epsilon_1 &\approx -\frac{3}{16\pi v^2} \frac{M_1}{M_2} \frac{\mathrm{Im}[(M_D^\dagger M_D)_{12}^2]}{(M_D^\dagger M_D)_{11}}, \\
&\quad (\text{for } M_1 \ll M_2 \ll M_3)
\end{aligned}$$

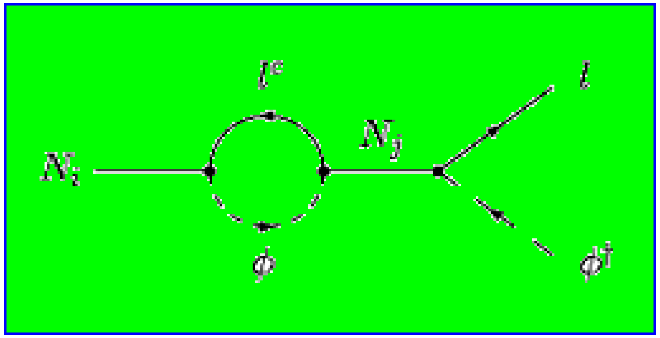
If $M_1 \sim \mathrm{TeV}$, these two conditions can not simultaneously be satisfied.

Resonant Leptogenesis

A. Pilaftsis, *et al*. Nucl. Phys. B 692, 303 (2004)

Resonance conditions: $M_1 \approx M_2 << M_3$, $M_{N_i} \sim \mathrm{TeV}$

$$\varepsilon_i^{s} = \frac{\mathrm{Im}[(\lambda^+\lambda)_{ij}^2]}{(\lambda^+\lambda)_{ii}(\lambda^+\lambda)_{jj}} \frac{(M_{N_i}^2 - M_{N_j}^2)M_{N_i}\Gamma_{N_j}}{(M_{N_i}^2 - M_{N_j}^2)^2 + M_{N_i}^2\Gamma_{N_j}^2}$$



$$\frac{\left|\mathrm{Im}[(\lambda^+\lambda)_{ij}^2]\right|}{(\lambda^+\lambda)_{ii}(\lambda^+\lambda)_{jj}} \sim 1$$

$$\left|M_{N_i} - M_{N_j}\right| \sim \frac{\Gamma_{N_{i,j}}}{2}$$

$$\Gamma_{N_i} = \frac{(\lambda^+\lambda)_{ii}}{8\pi} M_{N_i}$$

Questions:

1. Why are the Yukawa couplings so small?
2. Why do the right-handed neutrinos have nearly degenerate masses?

When the masses of heavy right-handed neutrinos are a few TeV, the Yukawa couplings should be reduced by more than six orders of magnitude in order to generate tiny masses of light neutrinos via seesaw mechanism, or equivalently to satisfy the out-of-equilibrium condition, the CP asymmetries can still be enhanced by the resonance effects.

Supersymmetry Breaking

T. Hambye, *et al*. JHEP 0407, 070 (2004)

Heavy Standard Model singlet fields: X_{ij} and Y

i , j flavor indices

Superpotential

$$\int d^2\theta \left(g \frac{X_{ij}}{M_{\mathrm{P}}} L_i N_j H_{\mathrm{u}} + g' \frac{Y}{M_{\mathrm{P}}} L_i N_j H_{\mathrm{u}} + \cdots \right)$$

$$M_{\mathrm{P}} = 1/\sqrt{8\pi G_{\mathrm{N}}} \approx 2 \cdot 10^{18}\ \mathrm{GeV}$$

Kähler terms

$$\int d^4\theta \left(h \frac{Y^+}{M_{\mathrm{P}}} N_i N_i + h_{\mathrm{B}} \frac{Y^+ Y X_{ij}^+}{M_{\mathrm{P}}^3} N_i N_j + h_x \frac{X_{ik} X_{kj}^+ Y^+}{M_{\mathrm{P}}^3} N_i N_j + \cdots \right)$$

$$< Y >_F = F_Y = f_Y m_{\mathrm{I}}^2$$

$$< X_{ij} >_A = A_{X_{ij}} = a_{X_{ij}} m_{\mathrm{I}}$$

$$< Y >_A = < X_{ij} >_F = 0$$

Supersymmetry → Breaking

$$\int d^2\theta \left(\lambda_{ij} L_i N_j H_{\mathrm{u}} + M_N N_i N_j + \Delta M_{Nij} N_i N_j \right)$$

$$+ A \tilde{L}_i \tilde{n}_i h_{\mathrm{u}} + B_{ij}^2 \tilde{n}_i \tilde{n}_j + \cdots$$

Explanation for small Yukawa couplings and high degree of mass degeneracy

$$m_{\mathrm{I}} = \sqrt{m_{3/2} M_{\mathrm{P}}} \approx 10^{11}\mathrm{GeV}$$

$$m_{3/2} \approx 1\mathrm{TeV}$$

$$g, h, a_X, f_Y \approx O(1)$$

→

$$\lambda_{ij} = g a_{X_{ij}} \left(\frac{m_{3/2}}{M_{\mathrm{P}}} \right)^{1/2} \approx 10^{-7} \sim 10^{-8}$$

$$M_N = h f_Y m_{3/2} \approx 1\mathrm{TeV}$$

$$\Delta M_{Nij} = h_x a_{X_{ik}} a_{X_{kj}}^+ \frac{f_Y m_{3/2}^2}{M_{\mathrm{P}}} \approx 10^{-3}\mathrm{eV}$$

Necessary conditions for resonant leptogenesis

Hierarchy of Couplings

Assumptions: $m_{\mathbf{B}} >> m_{\mathbf{A}}$ and $g_{\mathbf{B}} >> g_{\mathbf{A}}$

$$\left.\begin{array}{l} A \xrightarrow{g_{\mathbf{A}}} C+D \\ B \xrightarrow[g_{\mathbf{B}}]{} C+D \end{array}\right\}$$

When A decays, all B has decayed away

$$A \longrightarrow B^* \longrightarrow C+D \quad \Rightarrow \quad \varepsilon_{\mathbf{CP}} \propto g_{\mathbf{B}}^2$$

Basic idea

- Mass of particle A is much smaller than that of particle B. Then A can decay to C and D through a virtual B.
- The CP asymmetry is proportional to $g_{\mathbf{B}}^2$, at the same time, A decay is still out-of-equilibrium.
- The naturalness of the hierarchy of couplings between two particles A and B, which are very similar since they couple to the same decay products, is debatable.

T. Hambye, E. Ma, U. Sarkar, N.P.B 590 (2000) 429; P.R.D 62 (2000) 015010

Three Body Decays

$$\boxed{m_C > m_A > m_B}$$

For example, A is the right-handed neutrino and C is the Higgs scalar field

$$\left.\begin{array}{l} C \xrightarrow{g_1} A+B \\ C \xrightarrow[g_2]{} D+E \end{array}\right\} \quad \boxed{A \longrightarrow B+C^* \longrightarrow B+D+E} \quad \Rightarrow \quad \begin{array}{l} \boxed{\Gamma_{\mathbf{A}} \propto g_1^2 g_2^2} \\ \boxed{\varepsilon_{\mathbf{CP}} \propto g_2^2} \end{array}$$

Basic idea

- Mass of particle A is smaller than that of particle C. Then A can only decay to B, D and E through a virtual C.
- The decay width of A is proportional to $g_1^2 g_2^2$, and the CP asymmetry is proportional to g_2^2 .
- Two-body scattering must be checked to ensure that the CP asymmetry is not erased.

LEPTOGENESIS AT THE TEV SCALE, T. Hambye, hep-ph/0111089

Flaton decay

S. Dar, Q. Shafi and A. Sil, hep-ph/0508037

$$G_{221} = SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

Spontaneously broken at $M_I \sim 10^{12}\,\mathrm{GeV}$

1. Flaton $\phi, \bar{\phi}$ decays produce **Ni**
2. **Ni** decay --> CP asymmetry
3. Resonant leptogenesis

Nonthermal leptogenesis

$SU(2)_R \to \mathrm{Triplet}\ \phi, \bar{\phi}$

$$\phi = \begin{bmatrix} \frac{\phi^-}{\sqrt{2}} & \phi^0 \\ \phi^{--} & -\frac{\phi^-}{\sqrt{2}} \end{bmatrix} \text{ and } \bar{\phi} = \begin{bmatrix} \frac{\bar{\phi}^+}{\sqrt{2}} & \bar{\phi}^{++} \\ \bar{\phi}^0 & -\frac{\bar{\phi}^+}{\sqrt{2}} \end{bmatrix} \Rightarrow \begin{array}{c|cc} & \phi^{++} & \bar{\phi}^{++} \\ \hline \phi^{--} & \frac{1}{7}M_s^2 + M_s^2 & \frac{6}{7}M_s^2 \\ \bar{\phi}^{--} & \frac{6}{7}M_s^2 & \frac{1}{7}M_s^2 + M_s^2 \end{array},$$

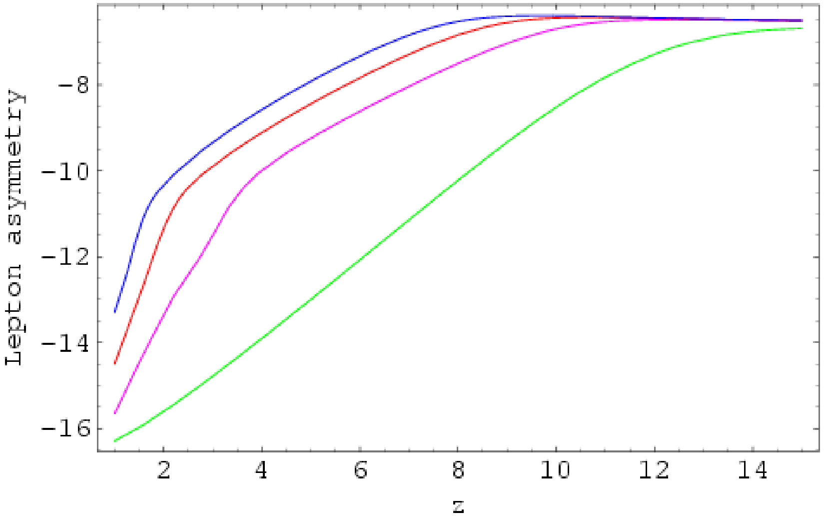
$M_s \sim \mathrm{TeV}$

Lightest doubly-charged particles have masses ~ 2.9 TeV and can be found at the LHC.

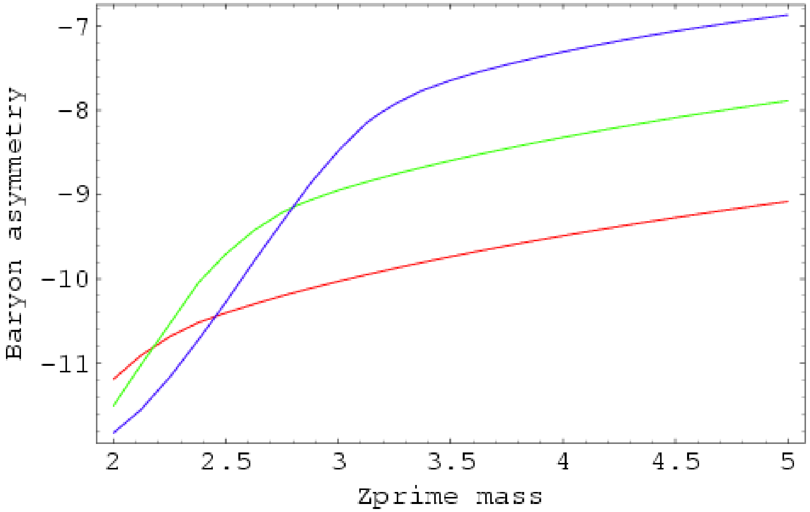
Extra gauged symmetry

E.J. Chun, hep-ph/0508050

1. Introduce extra gauged symmetry
2. Sneutrinos $\tilde{N}, \tilde{N}^{+}$ decay $U(1)' \to Z'$
3. Resonant leptogenesis
4. $\tilde{N}\tilde{N}^{+} \to Z' \to f\bar{f}$ gauge annihilation



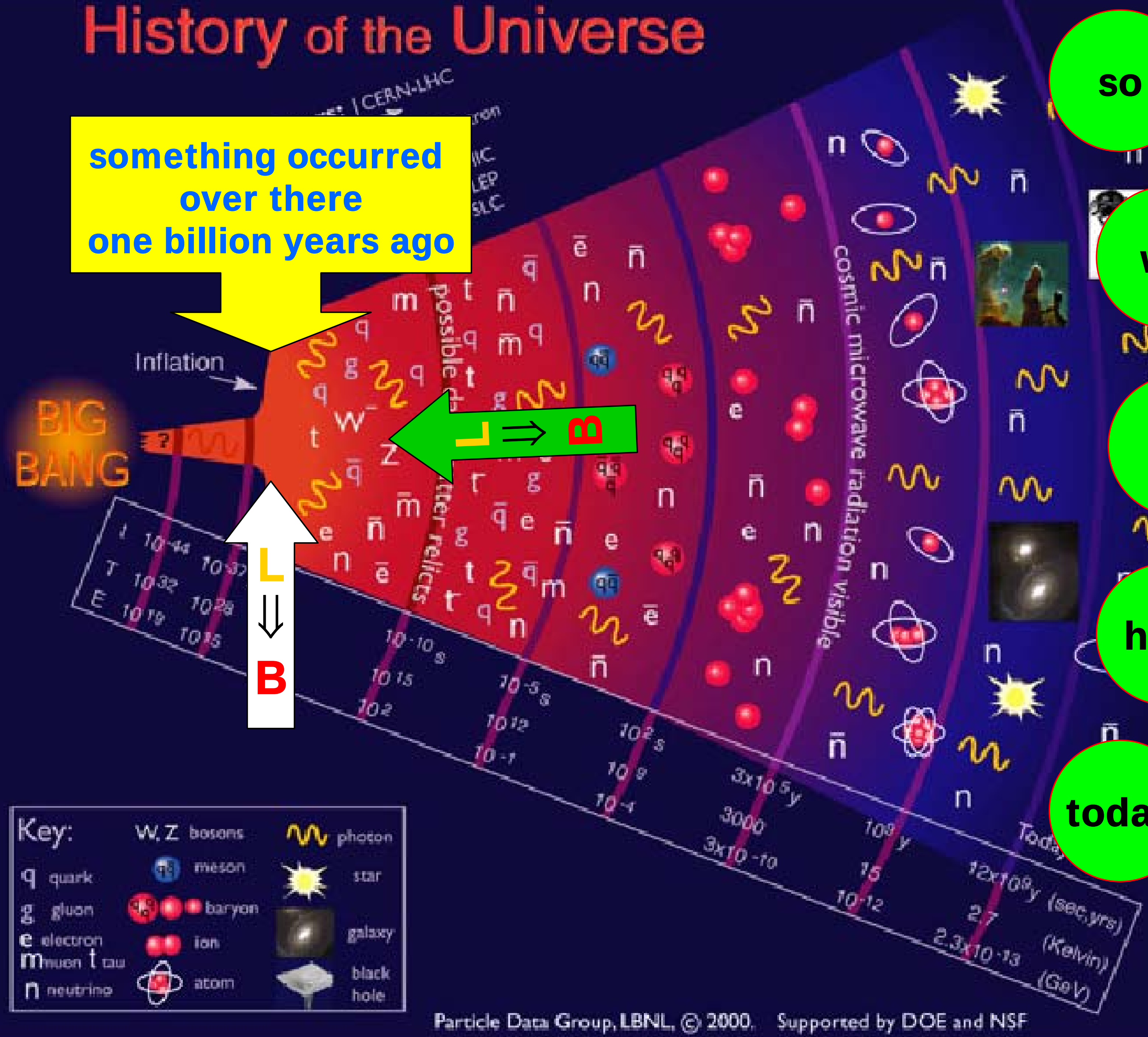
$M_{z'} = 1,2,3,4\text{TeV}$ $M_{\tilde{N}} = 0.3\text{TeV}$



$M_{\tilde{N}} = 0.3,0.6,0.9\text{TeV}$

A few hundred ~ a few events
for **LHC** with Luminosity 100 fb^-1

$Z' \to NN$



something occurred
over there
one billion years ago

$L \Rightarrow B$

$L \Downarrow B$

so

we

are

here

today

结束语

总体感觉

1 **TeV Leptogenesis** 想法本身是唯象有趣的
2 目前的各种模型存在很多问题，可信度很低
3 自然、自恰、一石多鸟：唯象学的不平庸性
4 “只可证伪不可证实”的难题：等待完整理论

初步设想

1 掌握**Leptogenesis** 的全部知识
2 在**TeV**尝试更简洁有趣的**scenarios**
3 考虑**TeV Majorana**中微子的其他过程
4 向专家们学习更多的**TeV**物理并开展合作