Gauge Theories for Baryon and Lepton Numbers

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MAX-PLANCK-GESELLSCHAFT

From Majorana to the LHC: Workshop on the Origin of Neutrino Masses
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MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Collaborators:

2009 - M. B. Wise (Caltech, USA)

2013 - M. Duerr (MPIK, Germany)

2013 - M. Lindner (MPIK, Germany)

References:

P. F. P., M. B. Wise,
Phys. Rev. D 82, 011901 (2010);
JHEP 08 (2011) 068

M. Duerr, P. F. P., M. B. Wise,
Physical Review Letters 110,231801 (2013)

M. Duerr, P. F. P., M. Lindner,
Phys. Rev. D 88, 051701(R) (2013)

M. Duerr, P. F. P., 1309.3970

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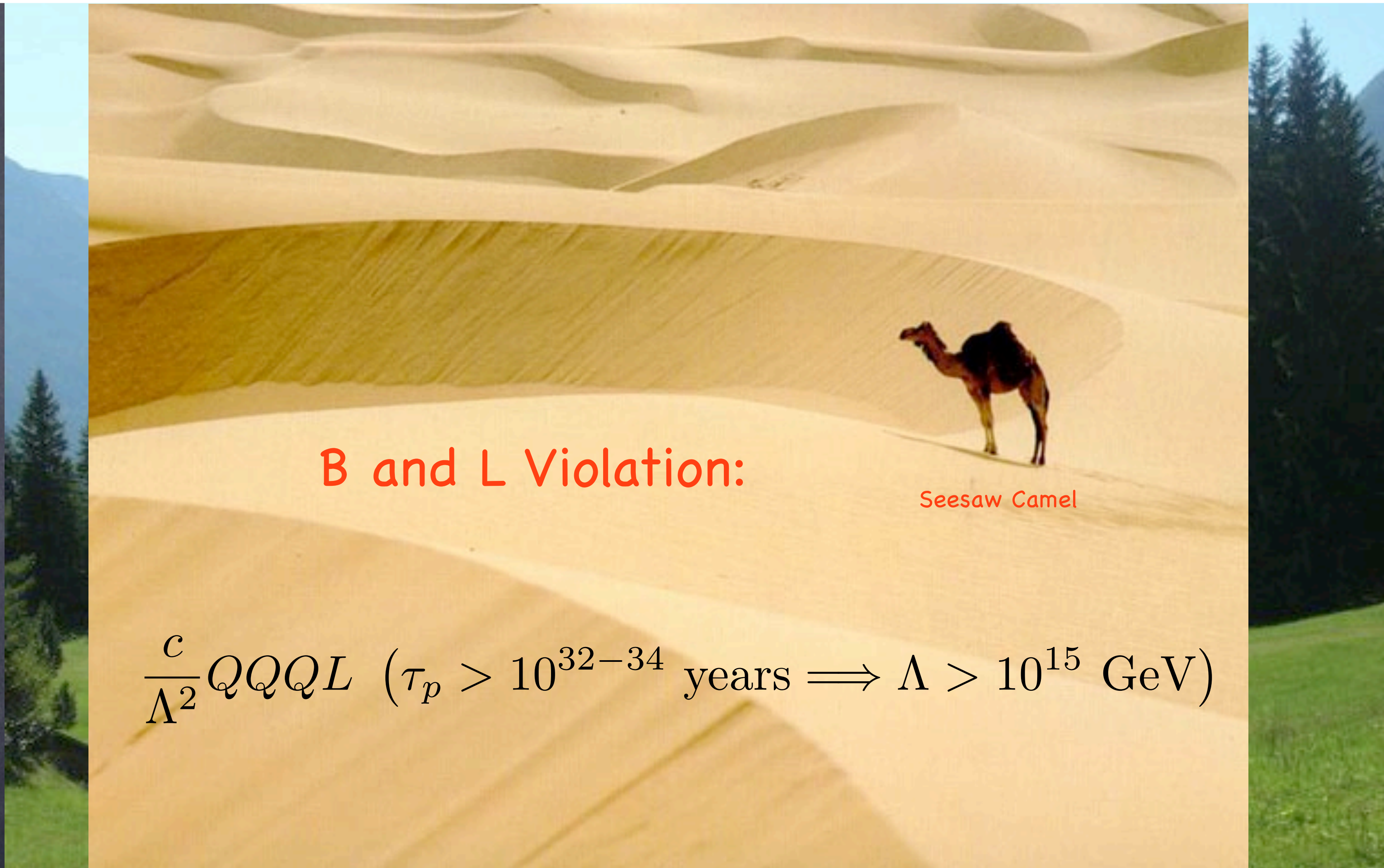
The Desert Hypothesis in Particle Physics

LOW SCALE



HIGH SCALE

B and L Violation:

$$\frac{c}{\Lambda^2} QQQL \ \left(\tau_p > 10^{32-34} \ \text{years} \Longrightarrow \Lambda > 10^{15} \ \text{GeV}\right)$$

Standard Model

$\Lambda_{\text{Weak}} \sim 100 \ \text{GeV}$

GUTs, Strings ?

$\Lambda \sim 10^{15-19} \ \text{GeV}$

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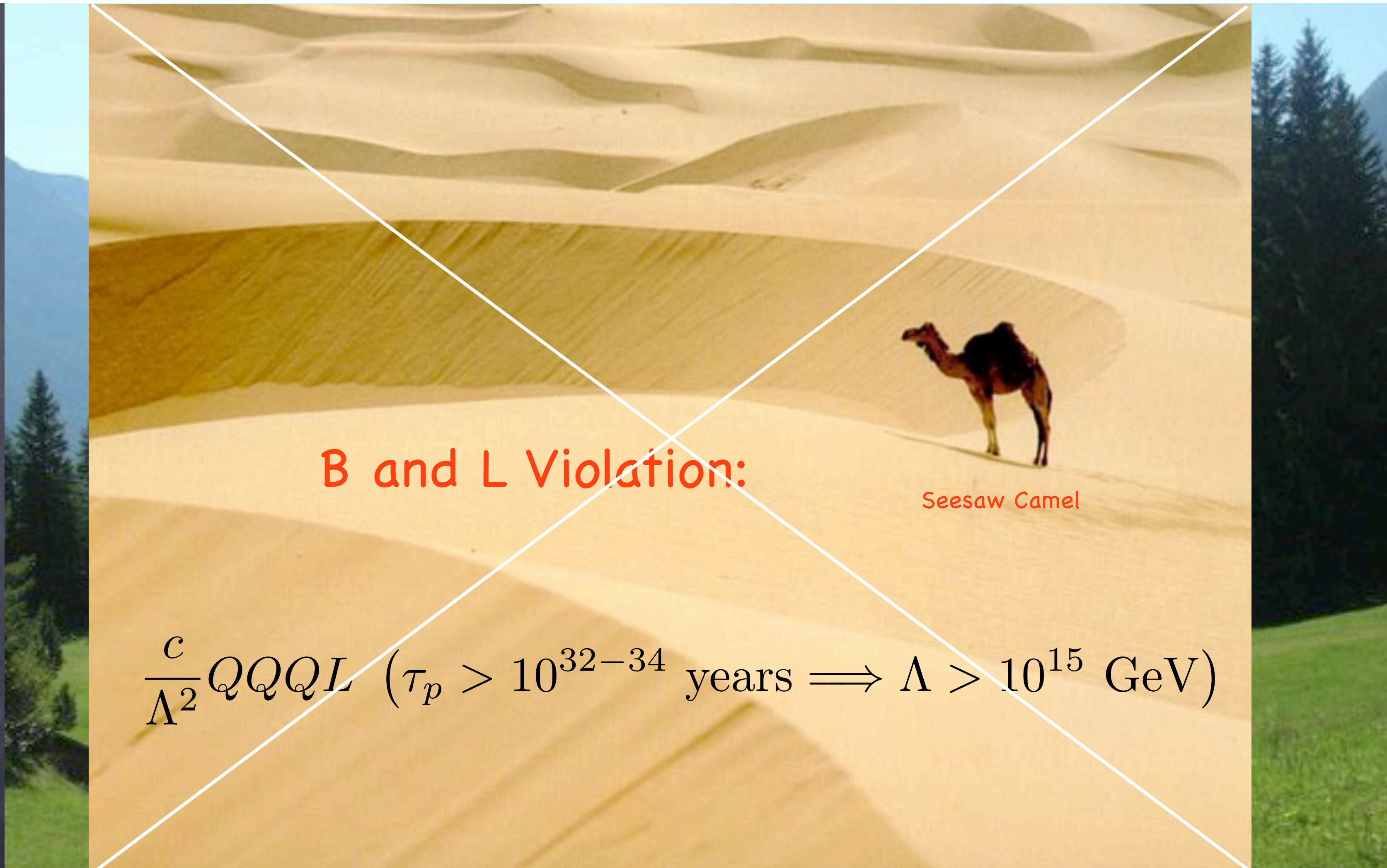
Can we break B and L at the TeV scale?

LOW SCALE



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HIGH SCALE

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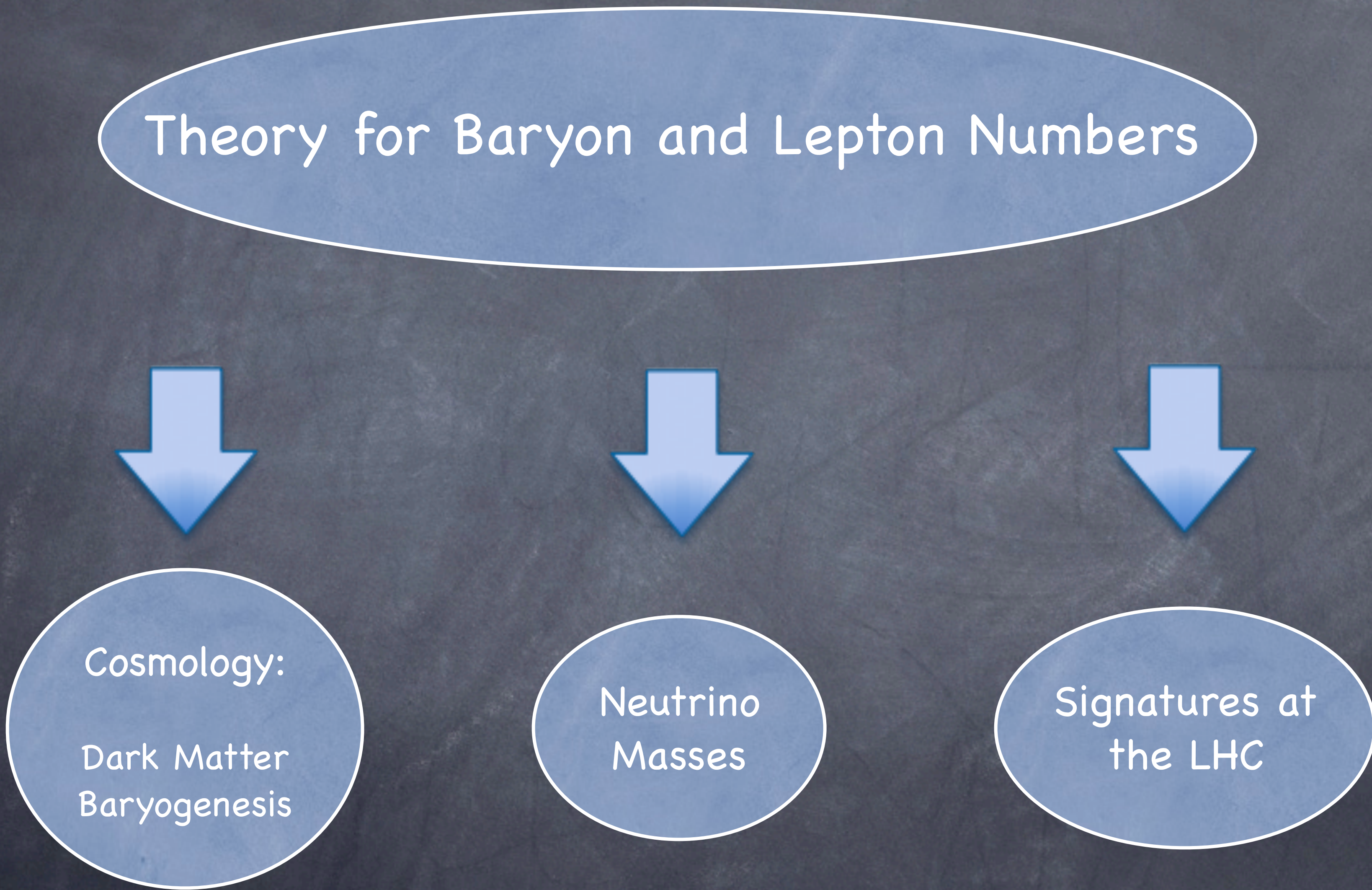
Aim



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Outline

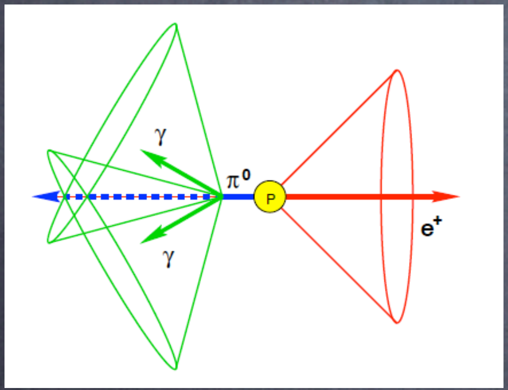
- Introduction
- Living without the Great Desert
- Left-Right Symmetry and Type III Seesaw
- Summary

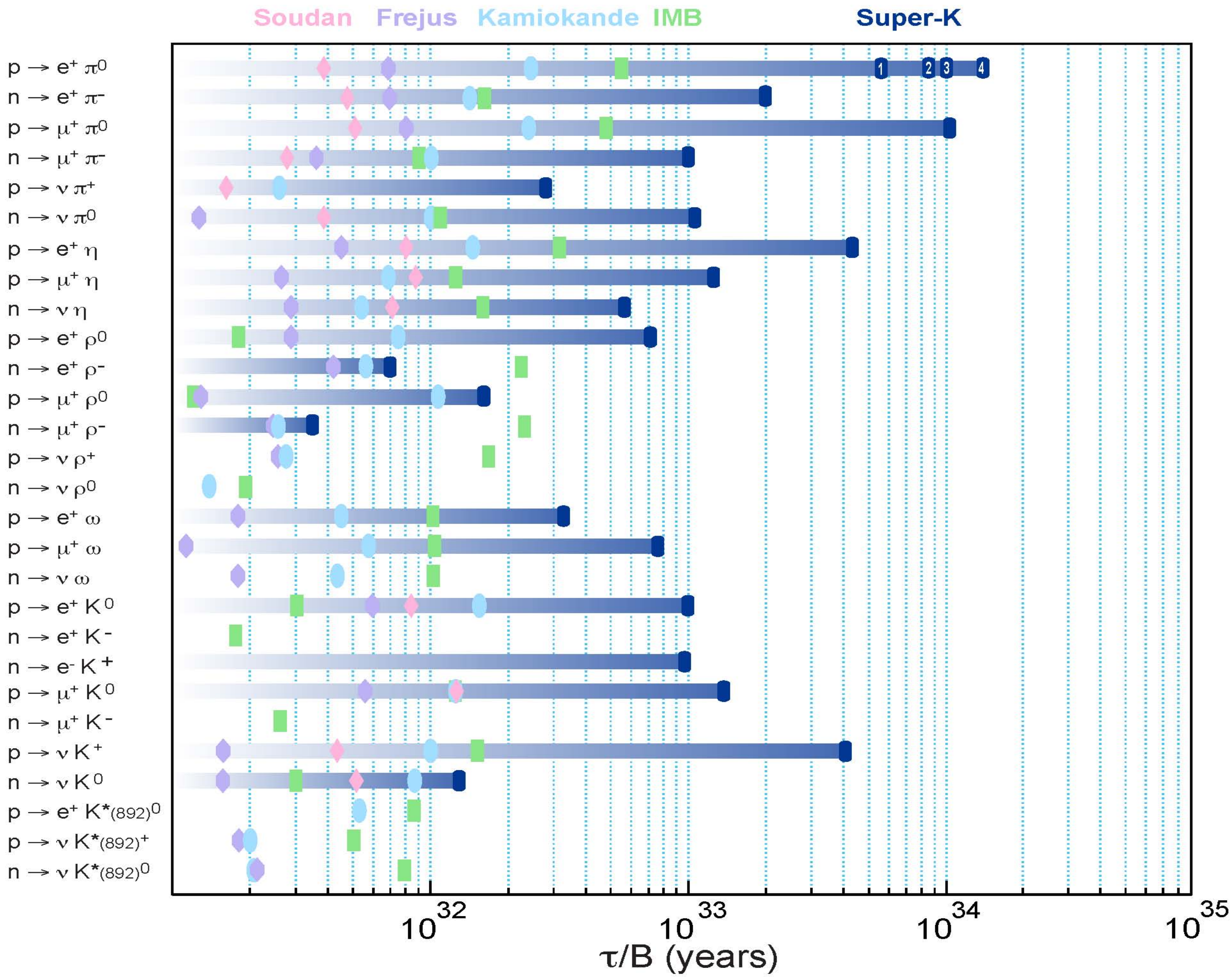
Introduction

Experimental Results

- Proton Decay:

$$\Delta B = 1, \; \Delta L = \text{odd}$$





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- Neutrino Oscillations:

$$\Delta L_e \neq 0, \Delta L_\mu \neq 0, \Delta L_\tau \neq 0$$

Cosmology

Baryon Asymmetry:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$

→

BARYON NUMBER VIOLATION

$$\Delta B \neq 0$$

Sakharov's Condition, 1967

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Living without the Great Desert

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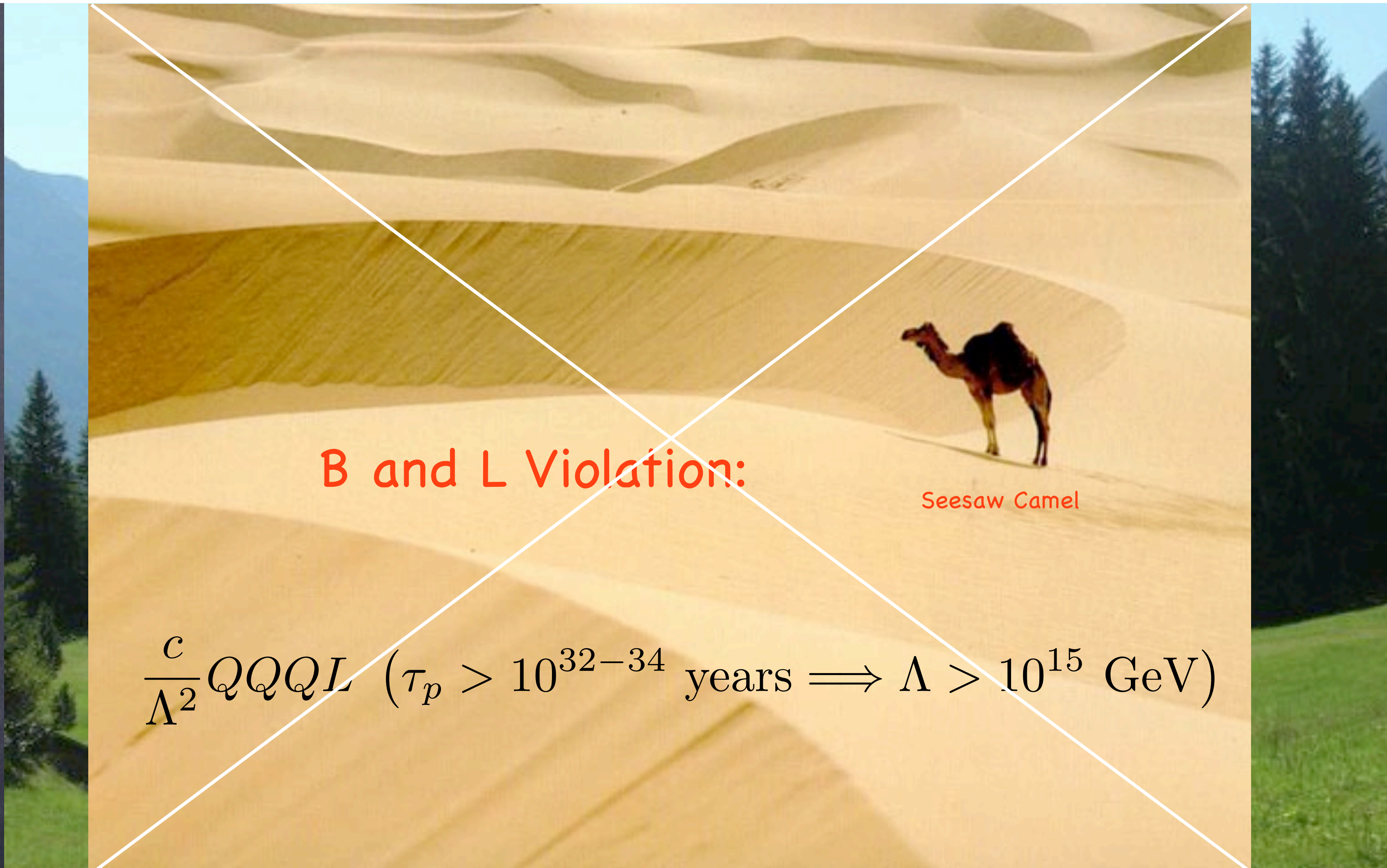
Aim: Can we break B and L at the TeV scale?

LOW SCALE



B and L Violation:

$$\frac{c}{\Lambda^2} QQQL \ \left(\tau_p > 10^{32-34} \text{ years} \Longrightarrow \Lambda > 10^{15} \text{ GeV}\right)$$

HIGH SCALE

Standard Model

$\Lambda_{\text{Weak}} \sim 100$ GeV

GUTs, Strings ?

$\Lambda \sim 10^{15-19}$ GeV

B and L as Local Symmetries

A. Pais, 1973 (B as a Local Symmetry)

S. Rajpoot, 1987; Foot, Joshi, Lew, 1989

Carone, Murayama, 1995

Breaking Local Baryon and Lepton Numbers at the TeV Scale (NO Desert !!)

P. F. P., M.B. Wise, 2010

P. F. P., M. B. Wise, JHEP 1108(2011) 068

M. Duerr, P. F. P., M. B. Wise, arXiv:1304.0576 (Phys. Rev. Lett. 2013)

P. F. P., M. B. Wise, PRD82 (2010)011901; JHEP1108(2011)068

Breaking B and L at the TeV scale !

$$G_{SM} \otimes U(1)_B \otimes U(1)_L$$

where: $U(1)_B$ and $\mathrm{U}(1)_\mathrm{L}$ can be broken at the TeV Scale !

$$Q_L \sim (3,2,1/6,1/3,0), \; u_R \sim (3,1,2/3,1/3,0), \; d_R \sim (3,1,-1/3,1/3,0)$$

$$\ell_L \sim (1,2,-1/2,0,1), \; e_R \sim (1,1,-1,0,1), \nu_R \sim (1,1,0,0,1)$$

How to define an anomaly free theory ?

Anomalies Cancellation

Baryonic Anomalies:

$$\mathcal{A}_1\left(SU(3)^2\otimes U(1)_B\right),\ \mathcal{A}_2\left(SU(2)^2\otimes U(1)_B\right),$$
$$\mathcal{A}_3\left(U(1)_Y^2\otimes U(1)_B\right),\ \mathcal{A}_4\left(U(1)_Y\otimes U(1)_B^2\right),$$
$$\mathcal{A}_5\left(U(1)_B\right),\ \mathcal{A}_6\left(U(1)_B^3\right),$$

Leptonic Anomalies:

$$\mathcal{A}_7\left(SU(3)^2\otimes U(1)_L\right),\ \mathcal{A}_8\left(SU(2)^2\otimes U(1)_L\right),$$
$$\mathcal{A}_9\left(U(1)_Y^2\otimes U(1)_L\right),\ \mathcal{A}_{10}\left(U(1)_Y\otimes U(1)_L^2\right),$$
$$\mathcal{A}_{11}\left(U(1)_L\right),\ \mathcal{A}_{12}\left(U(1)_L^3\right),$$

Mixed:

$$\mathcal{A}_{13}\left(U(1)_B^2\otimes U(1)_L\right),\mathcal{A}_{14}\left(U(1)_L^2\otimes U(1)_B\right),$$
$$\mathcal{A}_{15}\left(U(1)_Y\otimes U(1)_L\otimes U(1)_B\right),$$

In the SM: $\mathcal{A}_2 = -\mathcal{A}_3 = 3/2 \qquad \mathcal{A}_8 = -\mathcal{A}_9 = 3/2$

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P. F. P., M. B. Wise, PRD82 (2010)011901; JHEP1108(2011)068

Possible Solutions

- Sequential Family (B=-1, L=-3)
- Mirror Family (B=1, L=3)
- Vector-like Family with Seesaw

Now they are in disagreement with LHC Constraints !

What about Fermionic Leptoquarks ?

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M. Duerr, P. F. P., M. B. Wise, arXiv:1304.0576 (Phys. Rev. Lett. 2013)

One can define an anomaly free theory using the Fermionic Lepto-quarks:

$$\Psi_L \sim (1, 2, -1/2, -3/2, -3/2), \ \Psi_R \sim (1, 2, -1/2, 3/2, 3/2)$$

$$\eta_L \sim (1, 1, -1, 3/2, 3/2), \ \eta_R \sim (1, 1, -1, -3/2, -3/2)$$

$$\chi_L \sim (1, 1, 0, 3/2, 3/2), \ \chi_R \sim (1, 1, 0, -3/2, -3/2)$$

They can have vector-like masses and cancel all anomalies !

M. Duerr, **P. F. P.**, M. B. Wise, arXiv:1304.0576 (Phys. Rev. Lett. 2013)

Interactions:

$$-\mathcal{L} \supset h_1 \overline{\Psi}_L H \eta_R + h_2 \overline{\Psi}_L \tilde{H} \chi_R + h_3 \overline{\Psi}_R H \eta_L + h_4 \overline{\Psi}_R \tilde{H} \chi_L$$
$$+ \lambda_1 \overline{\Psi}_L \Psi_R S_{BL} + \lambda_2 \overline{\eta}_R \eta_L S_{BL} + \lambda_3 \overline{\chi}_R \chi_L S_{BL}$$
$$+ a_1 \chi_L \chi_L S_{BL} + a_2 \chi_R \chi_R S_{BL}^\dagger + \text{h.c.}$$

$$-\mathcal{L}_\nu = Y_\nu \bar{\ell}_L \tilde{H} \nu_R + \frac{\lambda_R}{2} \nu_R \nu_R S_L + \text{h.c.}$$

Higgs: $S_{BL} \sim (1, 1, 0, -3, -3), \quad S_L \sim (1, 1, 0, 0, -2)$

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M. Duerr, P. F. P., M. B. Wise, arXiv:1304.0576 (Phys. Rev. Lett. 2013)

Some Features:

Symmetry Breaking: $S_{BL} \sim (1,1,0,-3,-3), \quad S_L \sim (1,1,0,0,-2)$

$$\Delta B = \pm 3, \Delta L = \pm 2, \Delta L = \pm 3$$

NO Proton Decay !

NO DESERT !

Dark Matter: Ψ^0_{LF} can be a cold dark matter candidate !

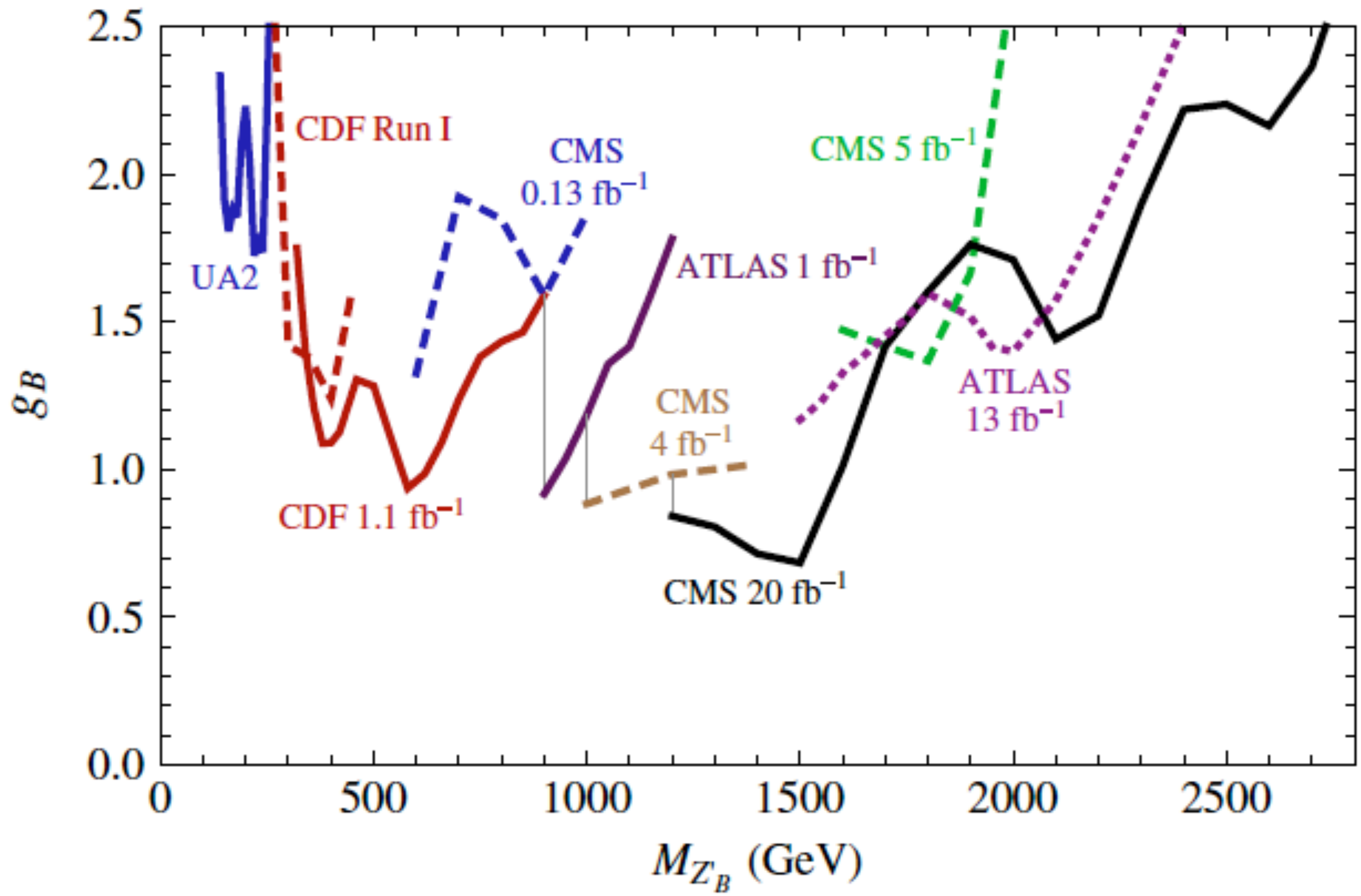
NO extra Flavour violation !

New Gauge Bosons: Z_L, Z_B

Dobrescu, Yu, PRD 88, 035021 (2013)

An, Hou, Wang, DU 2 (2013) 50

Bounds on the Baryonic Breaking Scale !



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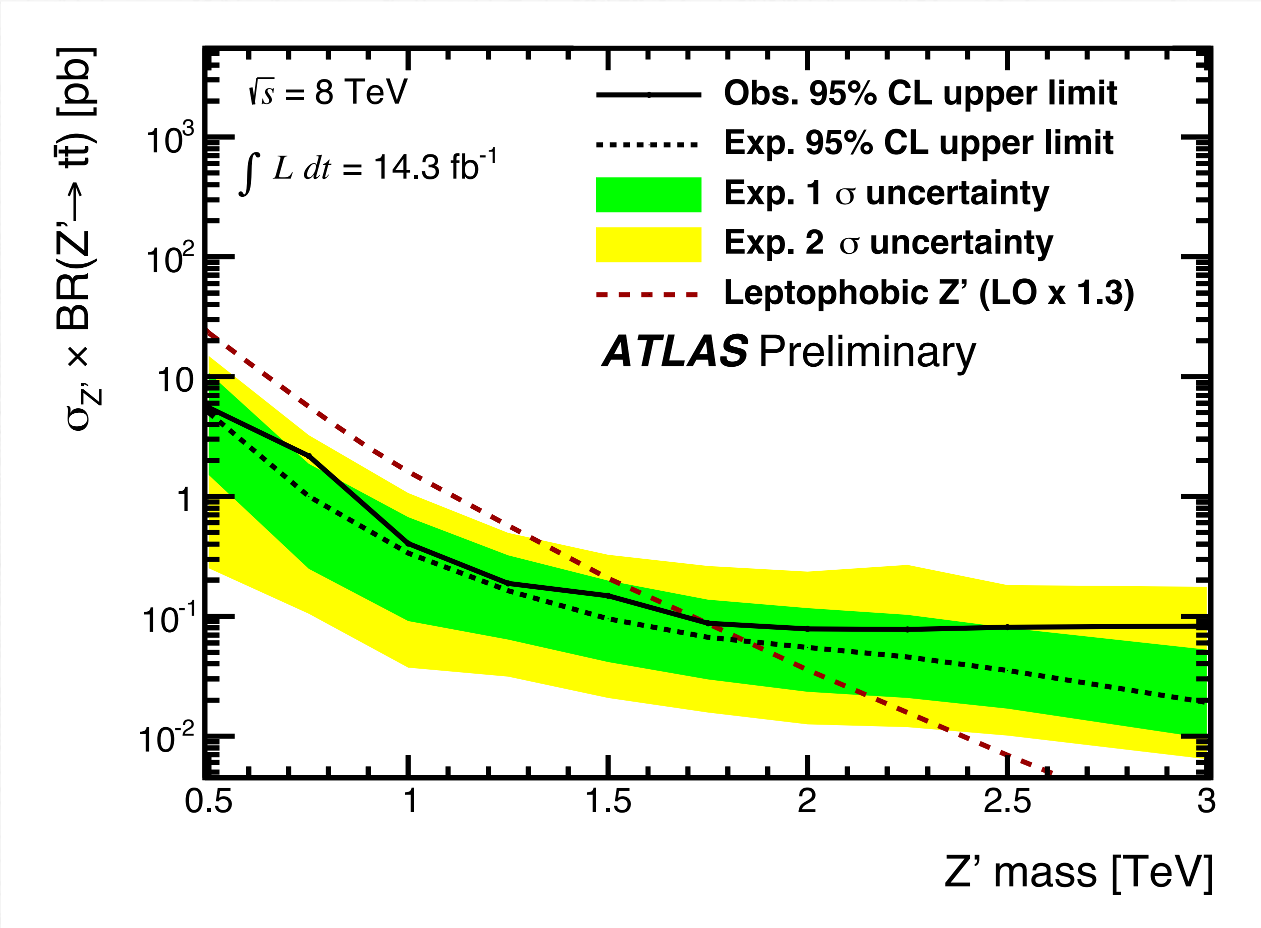
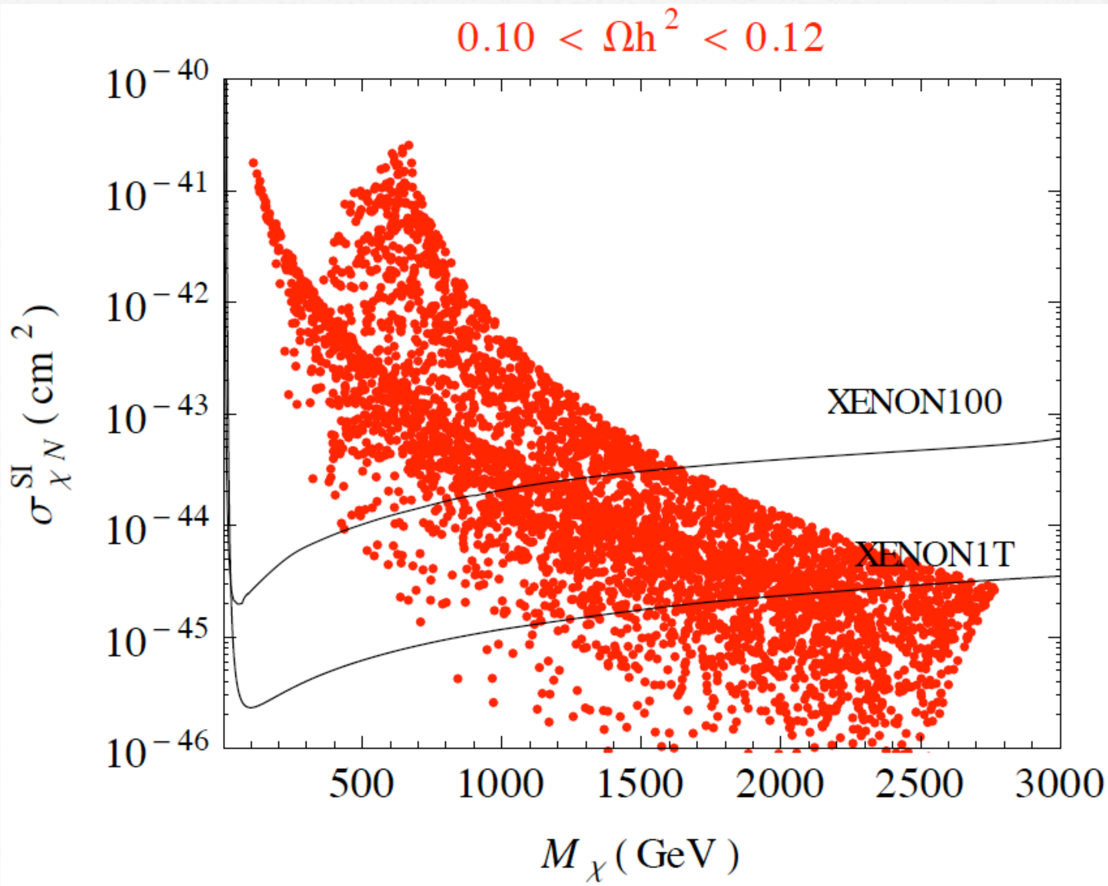


(a) Z' upper cross section limits.

Baryonic Dark Matter

M. Duerr, P. F. P., arXiv: 1309.3970



$$g_B, \ M_{Z_B}, \ M_\chi \ \& \ B$$

Annihilation:

$$\bar{\chi}\chi \to Z_B \to \bar{q}q$$

Direct Detection:

$$\chi N \to Z_B \to \chi N$$

LHC Signatures:

$$pp \to Z_B \to \bar{\chi}\chi, \ \bar{q}q, \ \bar{\chi}\chi j, ..$$

Left-Right Symmetry and Type III Seesaw

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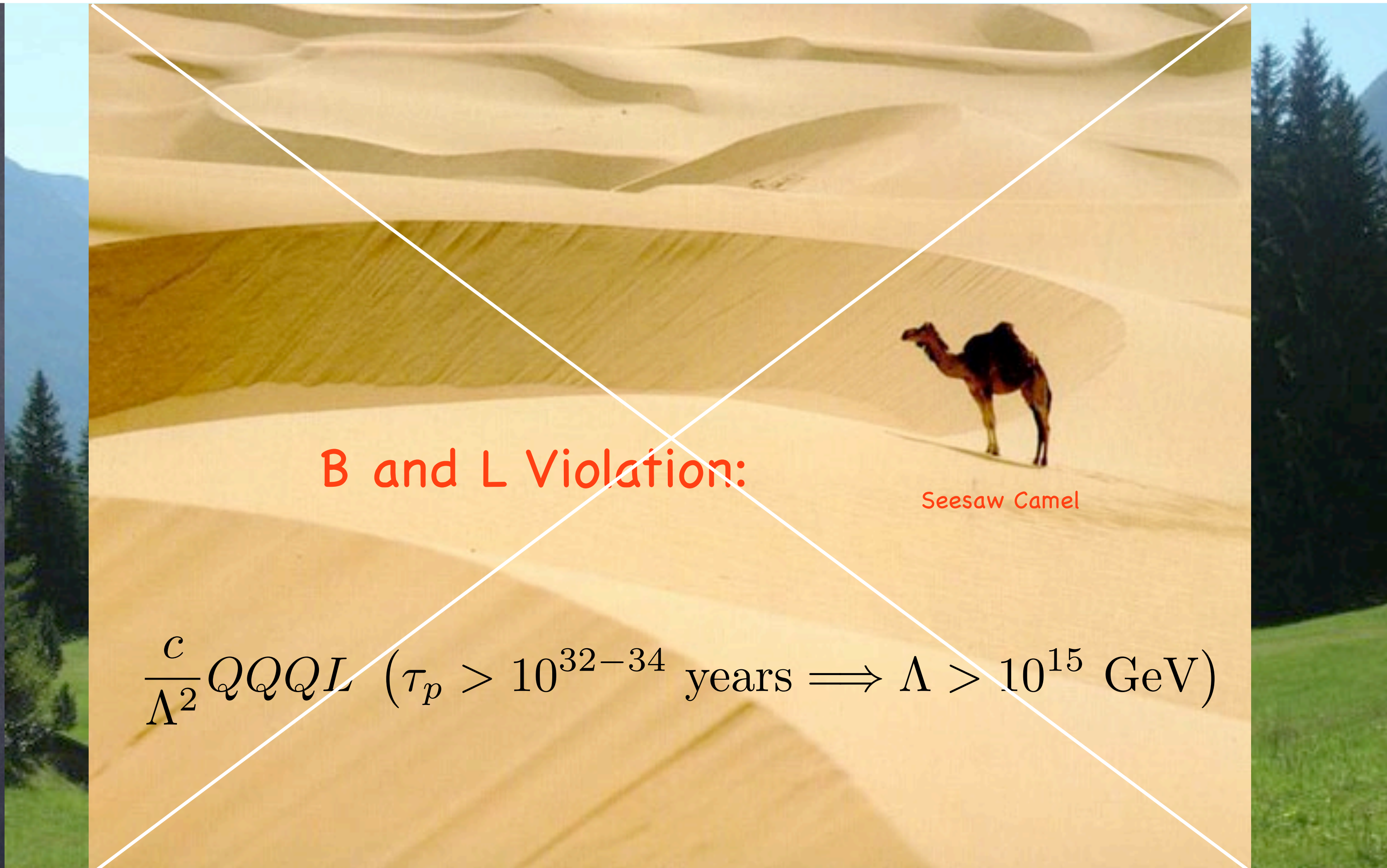
Again: Can we break B and L at the TeV scale?

LOW SCALE



B and L Violation:

$$\frac{c}{\Lambda^2} QQQL \;\; \left(\tau_p > 10^{32-34} \text{ years} \Longrightarrow \Lambda > 10^{15} \text{ GeV}\right)$$

HIGH SCALE

Left-Right Symmetric Theory

GUTs, Strings ?

$$\Lambda \sim 10^{15-19} \text{ GeV}$$

Pati, Salam; Pati, Mohapatra; Senjanovic, Mohapatra

Left-Right Symmetry

$$SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

- Connection between Neutrino Masses and the Scale of Parity Violation
- Minimal Model has Type I and Type II Seesaw Mechanisms
- Doorway to SO(10) Unification
- If the scale is low one has ‘exotic’ signals at the LHC

He, Rajpoot, 1990 M. Duerr, P. F. P., M. Lindner, 1306.0568 (PRD)

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_B \otimes U(1)_L$$

SM Fermions:

$$Q_L \sim (2,1,1/3,0),\ Q_R \sim (1,2,1/3,0),\ \ell_L \sim (2,1,0,1),\ \ell_R \sim (1,2,0,1)$$

Anomalies:

$$\mathcal{A}_1\left(SU(2)_L^2 \otimes U(1)_B\right) = 3/2,$$
$$\mathcal{A}_2\left(SU(2)_L^2 \otimes U(1)_L\right) = 3/2,$$
$$\mathcal{A}_3\left(SU(2)_R^2 \otimes U(1)_B\right) = -3/2,$$
$$\mathcal{A}_4\left(SU(2)_R^2 \otimes U(1)_L\right) = -3/2.$$

The Simplest Solution is ....

P. F. P., JHEP 03 (2009) 142

M. Duerr, P. F. P., M. Lindner, 1306.0568 (PRD)

Type III Seesaw Fields

$$\rho_L \sim (3, 1, -3/4, -3/4), \;\; \& \; \rho_R \sim (1, 3, -3/4, -3/4),$$

$$\rho_L = \frac{1}{2} \begin{pmatrix} \rho_L^0 & \sqrt{2}\rho_L^+ \\ \sqrt{2}\rho_L^- & -\rho_L^0 \end{pmatrix} \text{ and } \rho_R = \frac{1}{2} \begin{pmatrix} \rho_R^0 & \sqrt{2}\rho_R^+ \\ \sqrt{2}\rho_R^- & -\rho_R^0 \end{pmatrix}.$$

The theory is anomaly free !

M. Duerr, P. F. P., M. Lindner, 1306.0568 (PRD)

Higgs Sector: $\Phi \sim (2, 2, 0, 0)$

$$H_L \sim (2, 1, 3/4, -1/4), \;\; H_R \sim (1, 2, 3/4, -1/4)$$

$$S_{BL} \sim (1, 1, 3/2, 3/2)$$

Relevant Interactions for Neutrino Masses:

$$\begin{aligned} -\mathcal{L} \supset \; & \bar{\ell}_L \left(Y_3 \Phi + Y_4 \tilde{\Phi} \right) \ell_R \\ + \; & \lambda_D \left(\ell_L^T C i \sigma_2 \rho_L H_L \; + \; \ell_R^T C i \sigma_2 \rho_R H_R \right) \\ + \; & \lambda_\rho \, \mathrm{Tr} \left(\rho_L^T C \rho_L + \rho_R^T C \rho_R \right) S_{BL} \; + \; \text{h.c.}, \end{aligned}$$

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M. Duerr, P. F. P., M. Lindner, 1306.0568 (PRD)

Type III Seesaw and Left-Right Symmetry

Parity Violation !

$v_L \ll v_R$

$$M^{III}_{\nu_L} \ll M^{III}_{\nu_R}.$$

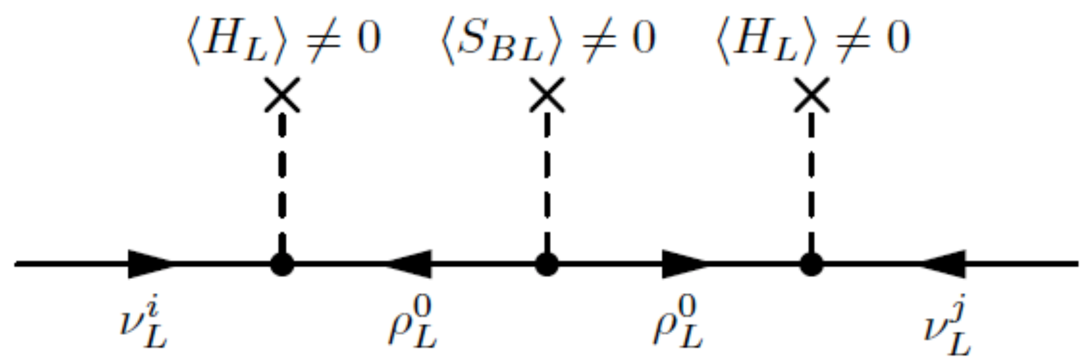

FIG. 1: Type III seesaw for the left-handed neutrinos.

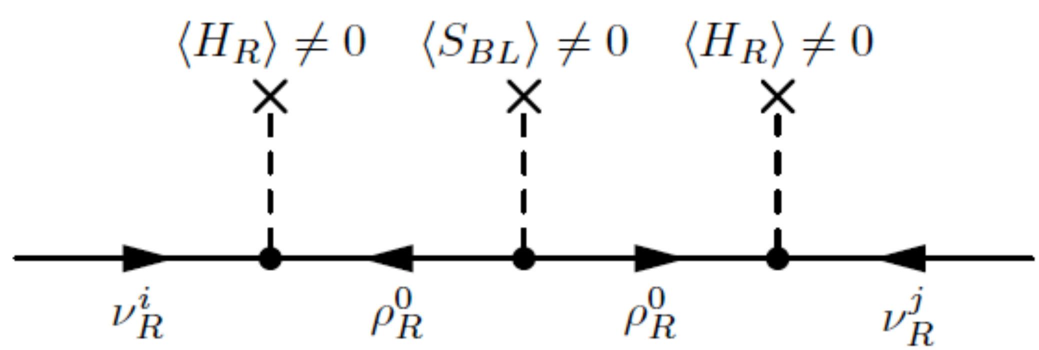

FIG. 2: Type III seesaw for the right-handed neutrinos.

M. Duerr, P. F. P., M. Lindner, 1306.0568 (PRD)

Neutrino Masses

$$-\mathcal{L}_\nu = \tilde{M}_\nu^D \overline{\nu}_L \nu_R - \frac{1}{2} M_{\nu_L}^{III} \nu_L^T C \nu_L - \frac{1}{2} M_R \nu_R^{3T} C \nu_R^3 + \text{h.c.},$$

3 + 2 System

$$-\mathcal{L}_\nu = -\frac{1}{2} M_{\nu_L}^{LL} \nu_L^T C \nu_L + \left(\tilde{M}_\nu^D\right)^{i\alpha} \overline{\nu}_L^i \nu_R^\alpha + \text{h.c.},$$

$$\mathcal{M}_\nu^{3+2} = \begin{pmatrix} 0 & 0 & 0 & m_D^1 & m_D^2 \\ 0 & m_1 & 0 & m_D^3 & m_D^4 \\ 0 & 0 & m_2 & m_D^5 & m_D^6 \\ m_D^1 & m_D^3 & m_D^5 & 0 & 0 \\ m_D^2 & m_D^4 & m_D^6 & 0 & 0 \end{pmatrix}.$$

Two light sterile neutrinos at the renormalizable level !!

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M. Duerr, P. F. P., M. Lindner, 1306.0568 (PRD)

Effect of higher-dimensional operators

$$\mathcal{O}_{\nu_L} = c_L \ell_L \ell_L H_L H_L S_{BL}^{\dagger} / \Lambda^2$$

$$\mathcal{O}_{\nu_R} = c_R \ell_R \ell_R H_R H_R S_{BL}^{\dagger} / \Lambda^2 .$$

Example:

$$\text{if } \mathrm{v_L} \sim 1 \text{ GeV}, \text{ and } \mathrm{v_{BL}} \sim 10 \text{ TeV} \rightarrow \Lambda \gtrsim 3 \times 10^3 \text{ TeV}$$

$$\text{Using } \mathrm{v_R} \sim 1 \text{ TeV and } \mathrm{v_{BL}} \sim 10 \text{ TeV} \rightarrow \mathrm{M}_{\nu_\mathrm{R}} < 1 \text{ MeV}.$$

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Summary

- The Desert Hypothesis plays a major role in our view of the relation between the physics at the low and high scales. However, this picture can be WRONG !

- One can define a consistent theory where B and L are local symmetries broken at the low scale in agreement with the experiments and there is no need to postulate the Great Desert. One has a simple theory for dark matter (and baryogenesis) which can be tested at LHC.

- Local B and L Symmetries together with Left-Right Symmetry requires Type III Seesaw. The Minimal Model predicts light sterile neutrinos at the renormalizable level.

THANK YOU !

This is my contribution to the GoranFest which took place in 2010 !

Sorry, I am a bit late ;)