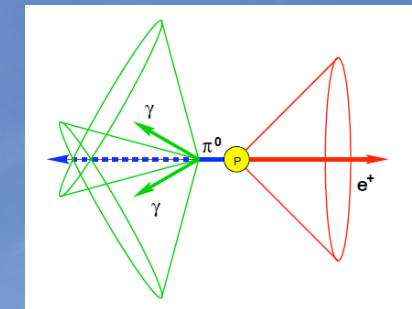


Physics beyond the Standard Model and Proton Stability

Pavel Fileviez Perez

(MPIK)

NNN14, Paris, 2014



MAX-PLANCK-GESELLSCHAFT



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FÜR KERNPHYSIK

References

P. F. P., Physics Reports (2015), in prep.

P. Nath, P. F. P., Physics Reports 441 (2007) 191

B. Bajc, P. F. P., G. Senjanovic (2002)

I. Dorsner, P. F. P., Nucl. Phys. B723 (2005) 53.

I. Dorsner, P. F. P., Phys. Lett. B 642 (2006) 248.

P. F. P., 2007 & 2004.

P. F. P., M. B. Wise, 2009, 2013.

The Desert Hypothesis in Particle Physics

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B and L Violation:

Seesaw Camel

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

$$p \rightarrow e^+ \gamma$$

P. Fileviez Perez

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

GUTs, Strings ?
 $\Lambda \sim 10^{15-19} \text{ GeV}$

Georgi-Glashow Model SU(5)

VOLUME 32, NUMBER 8

PHYSICAL REVIEW LETTERS

25 FEBRUARY 1974

Unity of All Elementary-Particle Forces

Howard Georgi* and S. L. Glashow

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

(Received 10 January 1974)

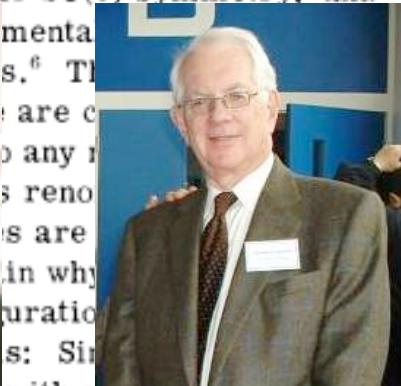
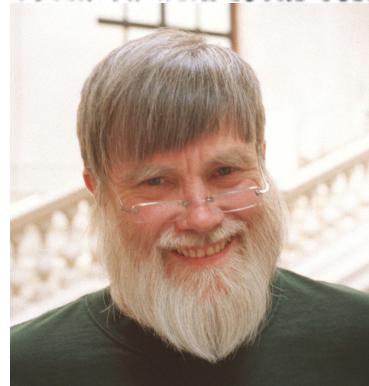
Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).

We present a series of hypotheses and speculations leading inescapably to the conclusion that SU(5) is the gauge group of the world—that all elementary particle forces (strong, weak, and electromagnetic) are different manifestations of the same fundamental interaction involving a single coupling strength, the fine-structure constant. Our hypotheses may be wrong and our speculations idle, but the uniqueness and simplicity of our scheme are reasons enough that it be taken seriously.

Our starting point is the assumption that weak and electromagnetic forces are mediated by the vector bosons of a gauge-invariant theory with spontaneous symmetry breaking. A model describing the interactions of leptons using the gauge group $SU(2) \otimes U(1)$ was first proposed by Glashow, and was improved by Weinberg and Salam who incorporated spontaneous symmetry breaking.¹ This scheme can also describe had-

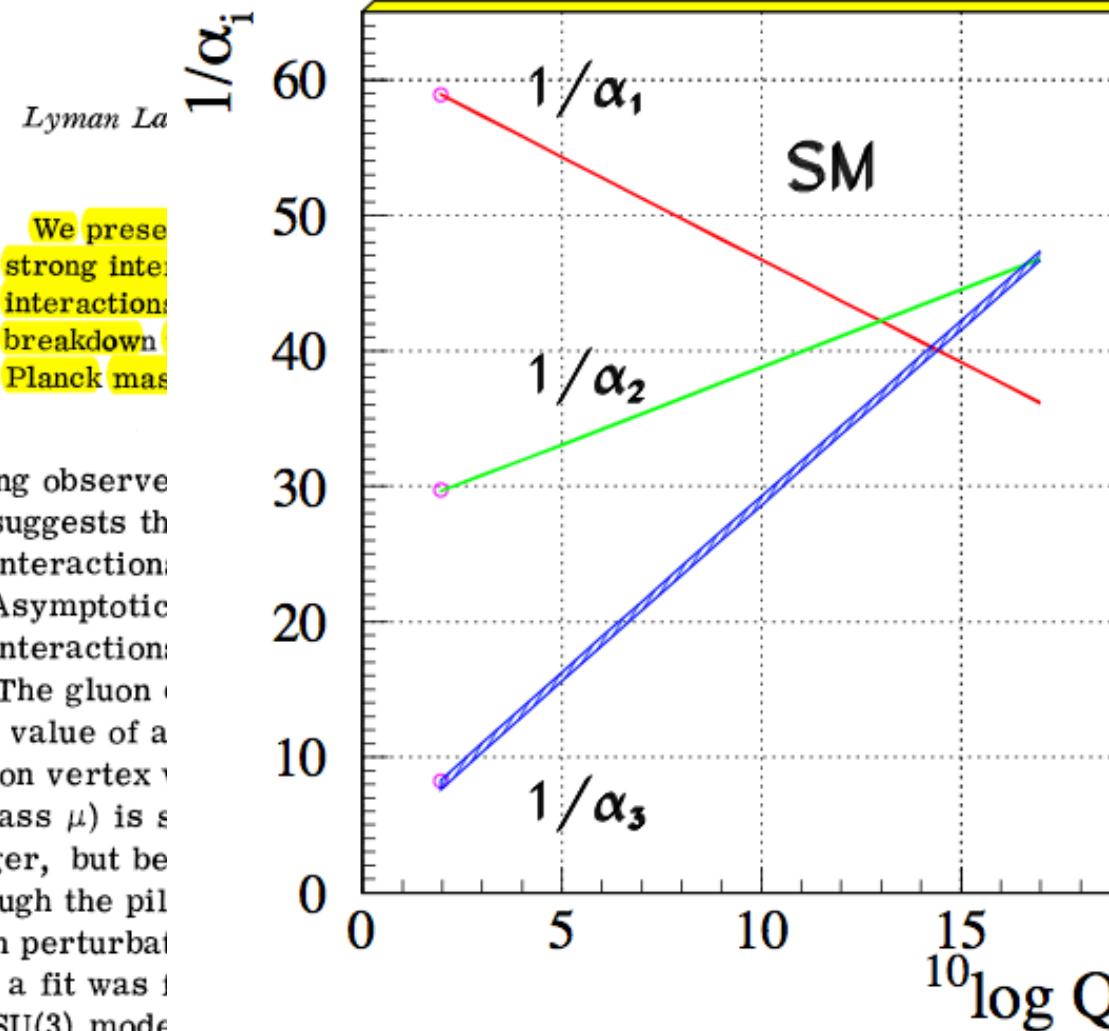
of the GIM mechanism with the notion of colored quarks⁴ keeps the successes of the quark model and gives an important bonus: Lepton and hadron anomalies cancel so that the theory of weak and electromagnetic interactions is renormalizable.⁵

The next step is to include strong interactions. We assume that *strong interactions are mediated by an octet of neutral vector gauge gluons associated with local color SU(3) symmetry*, and



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actions are associated with a non-Abelian theory, they may be asymptotically free.⁷

Running of the gauge couplings in the SM



effects. This will lead us to an estimate of the

hs 02138

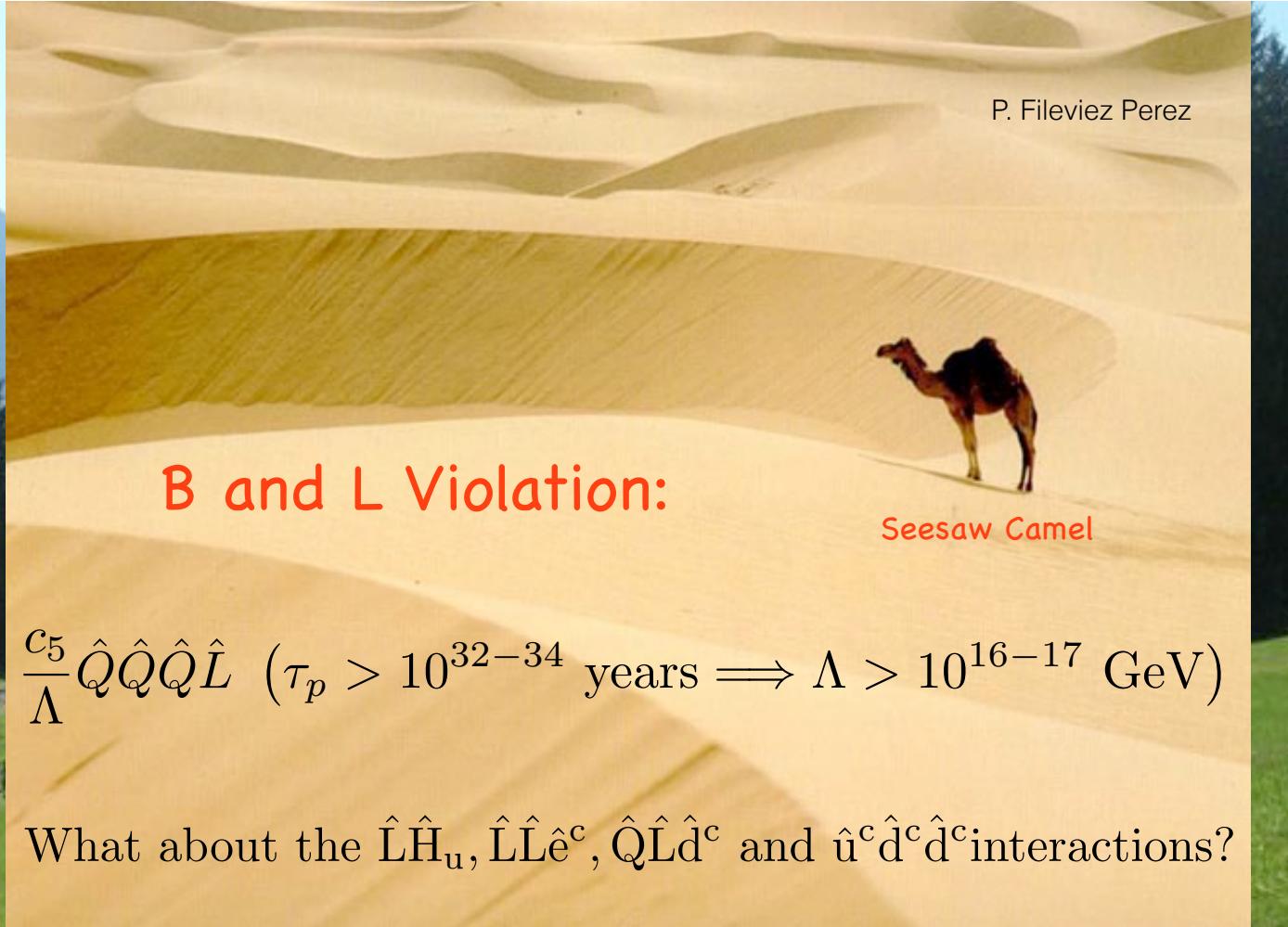
which make
and weak
instantaneous
most the

1. In order to support this, Georgi and Glashow⁷ assumed that some single gauge group unitary, magnetic interaction. However, as we show, the success of an understanding of the obvious disparity between the weak and strong at ordinary energies is evident in this paper. Calculation of such

The Desert Hypothesis and Supersymmetry

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MSSM

10 TeV ? 100 TeV ? ...

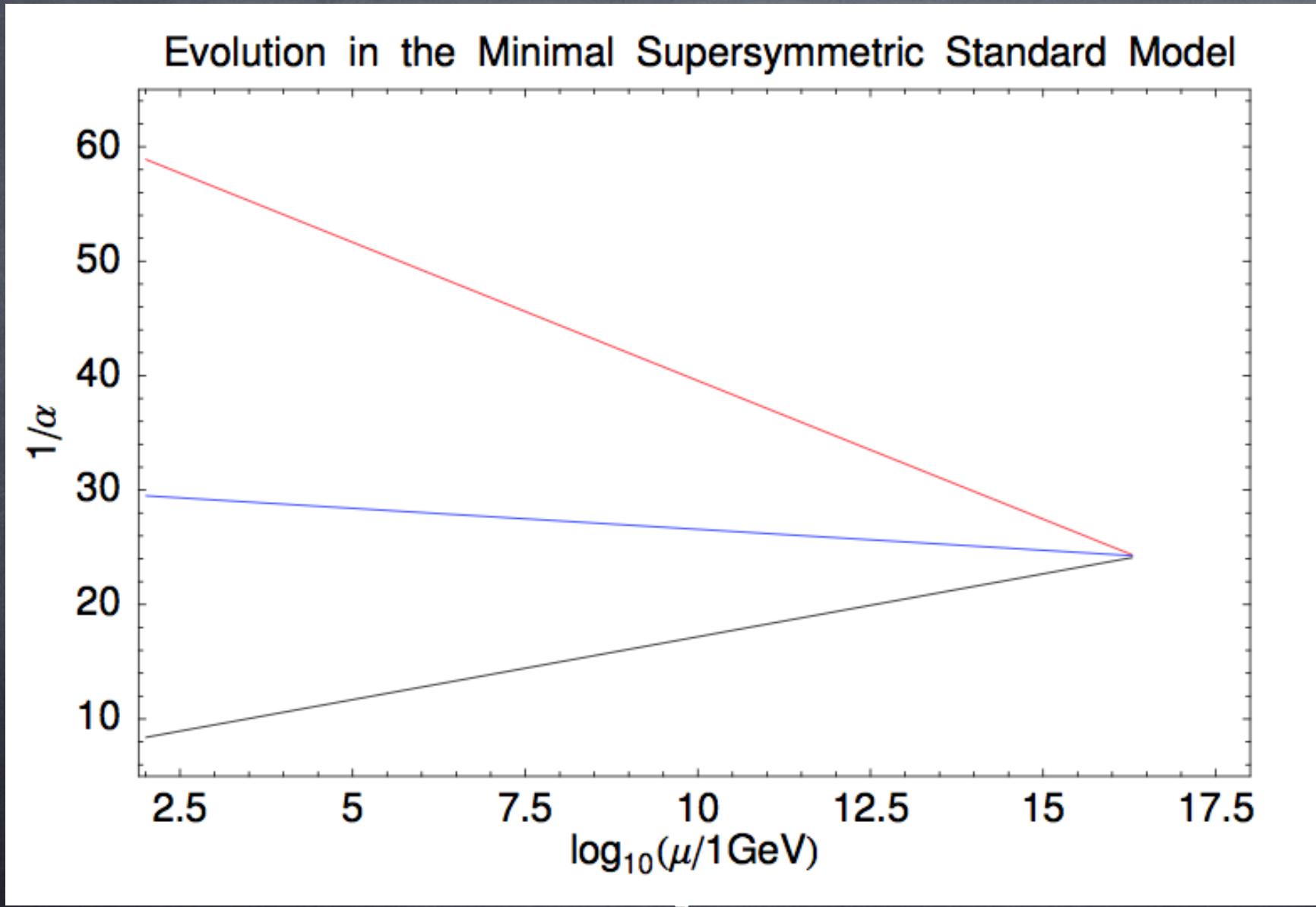
Unification of Gauge Couplings !

6

GUTs, Strings ?

Running of the gauge couplings in the MSSM

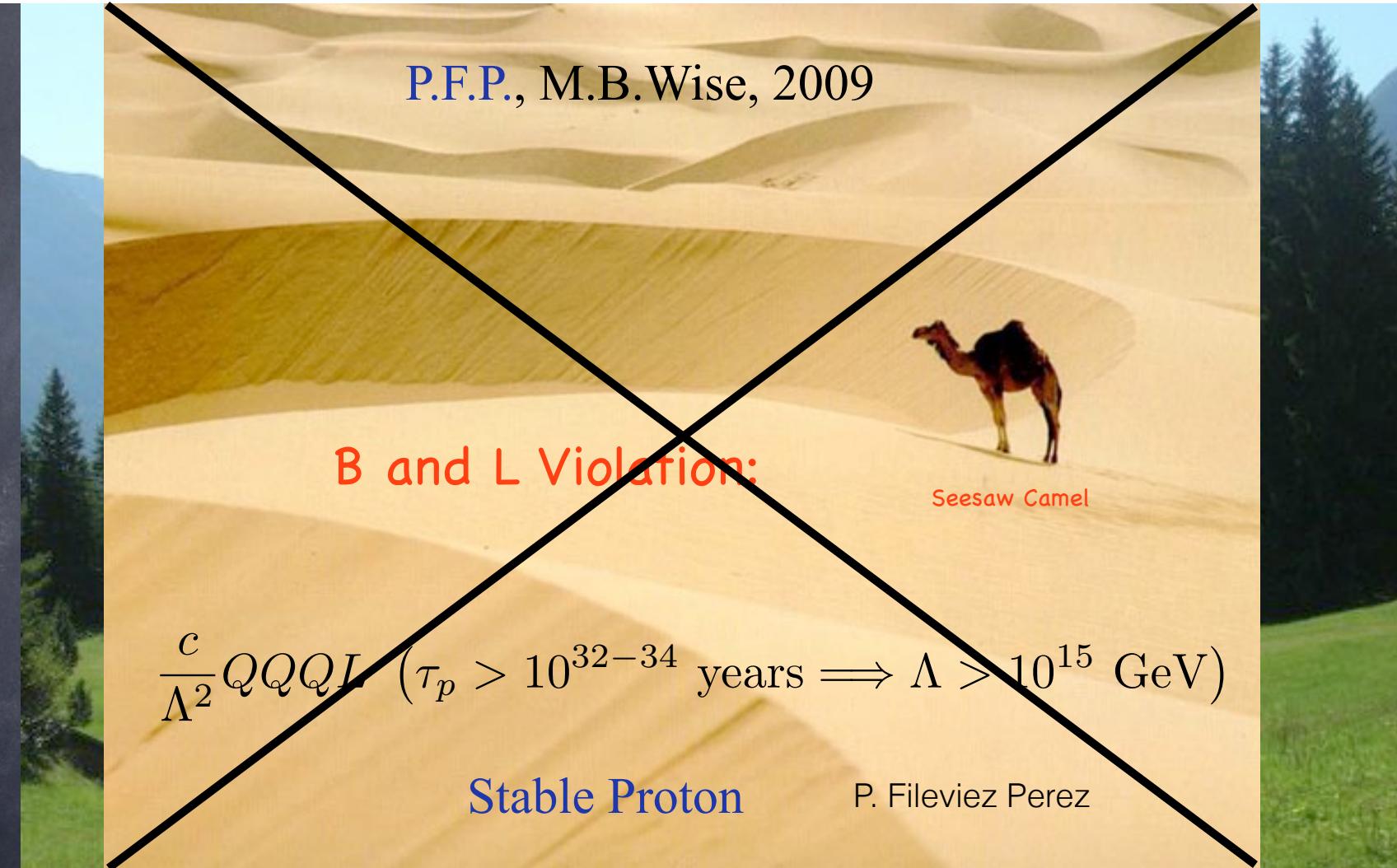
Dimpolous, Raby, Wilczek, 1981; Ibanez, Ross, 1981; Marciano, Senjanovic, 1982; Einhorn, Jones, 1982.



The Desert Hypothesis in Particle Physics

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

GUTs, Strings ?
 $\Lambda \sim 10^{15-19} \text{ GeV}$

Aim

Physics beyond the SM vs. Proton Stability



Scenario I:
The proton decays and the
Desert Hypothesis is maybe
true !



Scenario II:
The proton is stable and there
is no Desert !

Main focus of this talk !

P. Fileviez Perez

Outline

- Introduction
- Grand Unification vs. Proton Decay
- Nucleon Decay in Supersymmetry
- Summary

Introduction

Proton Stability

SM: In the renormalizable SM the proton is stable !
Baryon number is a global symmetry broken at the quantum level by SU(2) instanton processes in 3 units ($\Delta B = 3$)

Matter Unification: In theories where quarks and leptons are unified one can have B violating interactions which mediate proton decay
(Pati, Salam, 1973)

$$p \rightarrow \gamma e^+, \pi^0 e^+, \dots (\Delta B = 1)$$

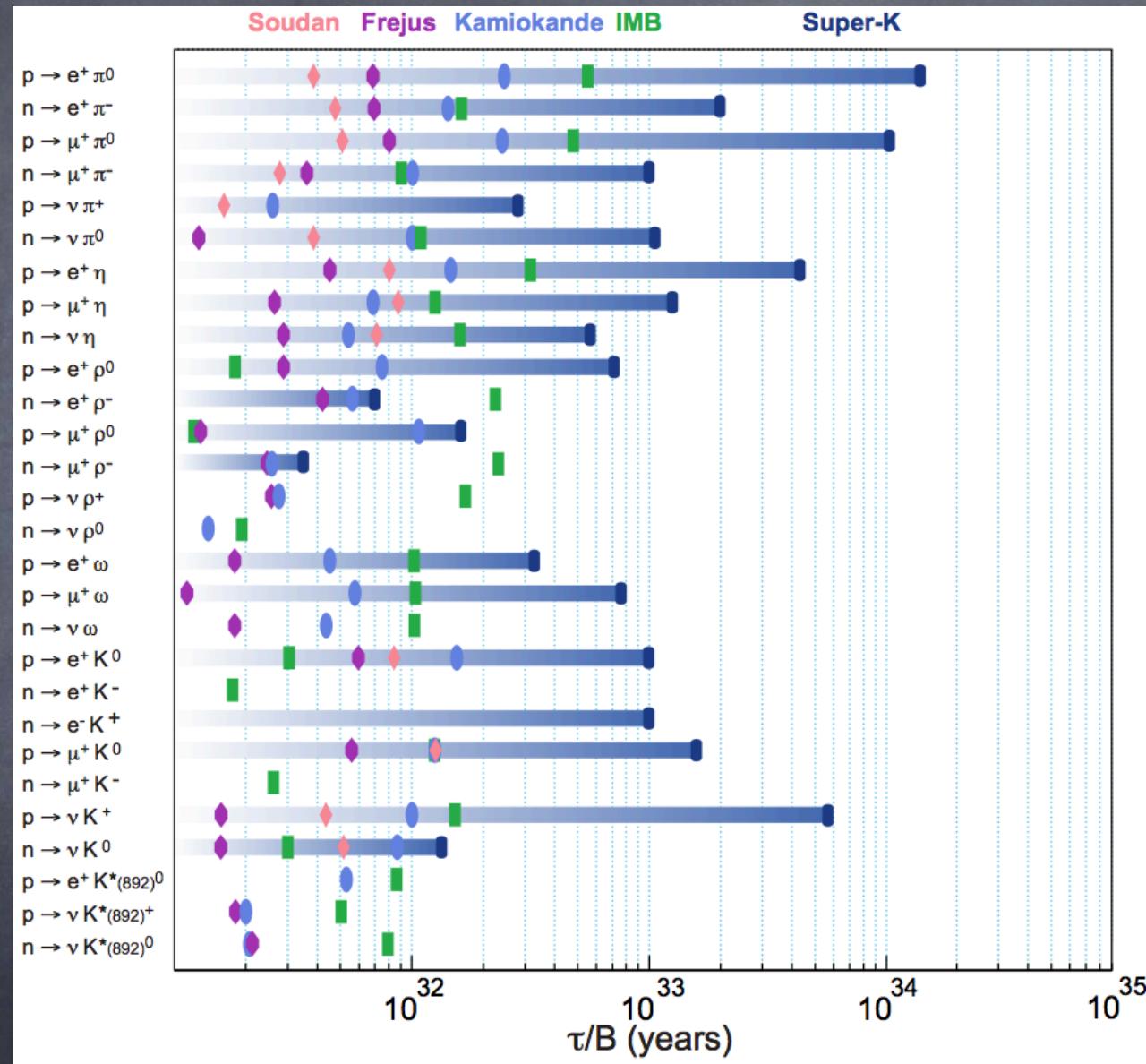
GUTs: In grand unified theories (SU(5), SO(10),..) B is explicitly broken at the high scale and generically one predicts proton decay.

SUSY: In the MSSM B and L are explicitly broken at the renormalizable level by R_pV interactions and generically one predicts proton decay.

$$R = (-1)^{3(B-L)+2S}$$

P. Fileviez Perez

Experimental Results: $\Delta B = 1$, $\Delta L = \text{odd}$



J. Raaf @ NNN13

SK Results and papers on proton decay

2014: $p \rightarrow e^+ \nu \nu, \mu^+ \nu \nu$

2014: $p \rightarrow K^+ \bar{\nu}$

2013: $n \rightarrow \bar{\nu} \pi^0, p \rightarrow \bar{\nu} \pi^+$

2012: $p \rightarrow \mu^+ K^0$

2012: $p \rightarrow \ell^+ \pi^0, \ell^+ \eta, \ell^+ \rho, \ell^+ \omega$

2009: $p \rightarrow e^+ \pi^0, \mu^+ \pi^0$

2005: $p \rightarrow K^+ \bar{\nu}, \mu^+ K^0, e^+ K^0$

1999: $p \rightarrow K^+ \bar{\nu}$

In my opinion, if SK wants to discover proton decay, more effort is needed !

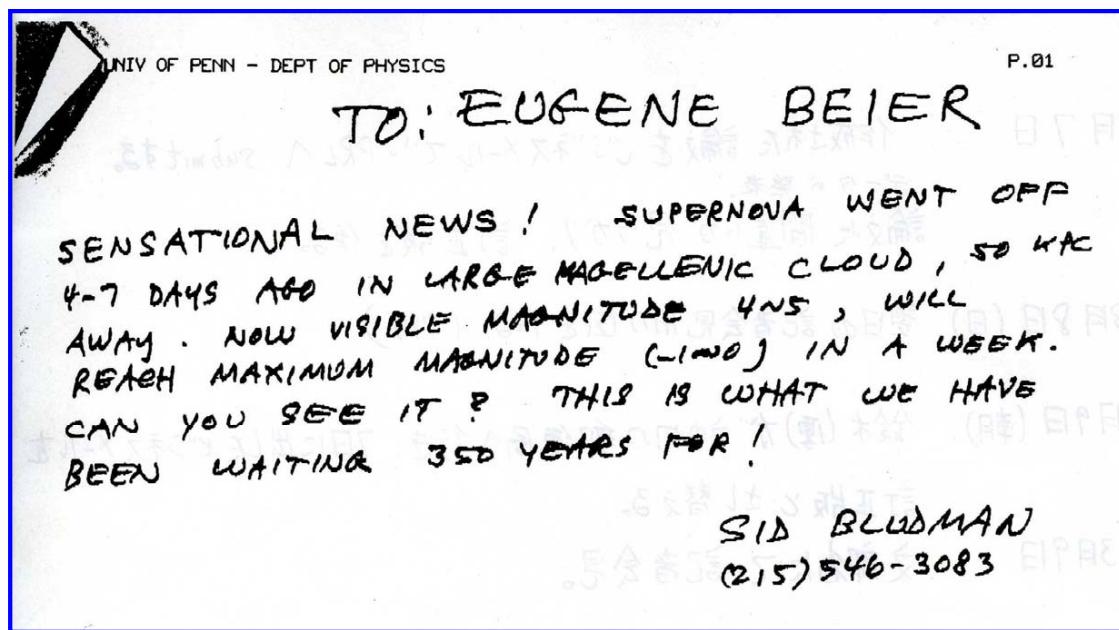
As I will explain, we have no idea which is the dominant channel.
Therefore, it is important to investigate all possible decay channels !

Kamiokande and the Supernova Discovery

25 February 1987

Curtain of SN1987A neutrino drama was raised.

Fax from Sid Bludman to E. Beier



Unfortunately, I cannot send a fax to tell you which proton decay channel you will see at SK ;)

I have no idea !

P. Fileviez Perez

Grand Unification vs. Proton Decay

Non-SUSY GUTs

d=6 gauge:

$$\begin{aligned} O(e_\alpha^C, d_\beta) &= \underline{c(e_\alpha^C, d_\beta)} \epsilon_{ijk} \overline{u_i^C} \gamma^\mu u_j \overline{e_\alpha^C} \gamma_\mu d_{k\beta}, \\ O(e_\alpha, d_\beta^C) &= \underline{c(e_\alpha, d_\beta^C)} \epsilon_{ijk} \overline{u_i^C} \gamma^\mu u_j \overline{d_{k\beta}^C} \gamma_\mu e_\alpha, \\ O(\nu_l, d_\alpha, d_\beta^C) &= \underline{c(\nu_l, d_\alpha, d_\beta^C)} \epsilon_{ijk} \overline{u_i^C} \gamma^\mu d_{j\alpha} \overline{d_{k\beta}^C} \gamma_\mu \nu_l \end{aligned}$$

after integrating out the superheavy gauge bosons.

$$c(e^c, d), c(e, d^c) \& c(\nu, d, d^c) \sim g_{GUT}^2/M_V^2$$

$$M_V > 10^{14-15} \text{ GeV} \quad \text{naive !}$$

in agreement with gauge coupling unification at the high scale.

Unfortunately, the values of the Wilson coefficients can change dramatically in different models !

Georgi-Glashow Model

Georgi, Glashow, Phys.Rev.Lett.32:438-441,1974

$$G_{SM} = SU(3) \otimes SU(2) \otimes U(1) \subset SU(5)$$

$$\alpha_3 \quad \alpha_2 \quad \alpha_1 \quad \rightarrow \quad \alpha_5$$

Matter Assignment

$$\bar{\mathbf{5}} = \begin{pmatrix} d_1^C \\ d_2^C \\ d_3^C \\ e \\ -\nu \end{pmatrix}_L \quad \mathbf{10} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & u_3^C & -u_2^C & u_1 & d_1 \\ -u_3^C & 0 & u_1^C & u_2 & u_2 \\ u_2^C & -u_1^C & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^C \\ -d_1 & -d_2 & -d_3 & -e^C & 0 \end{pmatrix}_L$$

Higgs Bosons

$$\mathbf{5}_H = \begin{pmatrix} \textcolor{red}{T_1} \\ \textcolor{red}{T_2} \\ \textcolor{red}{T_3} \\ H^+ \\ H^0 \end{pmatrix} \quad \mathbf{24}_H = \begin{pmatrix} \Sigma_8 & \Sigma_{(3,2)} \\ \Sigma_{(\bar{3},2)} & \Sigma_3 \end{pmatrix} + \frac{1}{2\sqrt{15}} \begin{pmatrix} 2 & 0 \\ 0 & -3 \end{pmatrix} \Sigma_{24}$$

Georgi-Glashow Model

Georgi, Glashow, Phys.Rev.Lett.32:438-441,1974

$$A_\mu = \frac{1}{2} \lambda_a A_\mu^a = \frac{1}{2} \begin{pmatrix} G_\mu, B_\mu & V_\mu \\ V_\mu^* & W_\mu, B_\mu \end{pmatrix} \quad V_\mu = \sqrt{2} \begin{pmatrix} X_{1\mu} & Y_{1\mu} \\ X_{2\mu} & Y_{2\mu} \\ X_{3\mu} & Y_{3\mu} \end{pmatrix}$$

- New B violating interactions → THE PROTON IS UNSTABLE !!!

$$\bar{5}^\dagger \gamma^0 i \gamma^\mu D_\mu \bar{5} \rightarrow g_5 \overline{(d^C)_L} \gamma^\mu (\textcolor{blue}{X}_\mu e_L - \textcolor{blue}{Y}_\mu \nu_L) / \sqrt{2}$$

$$Tr \overline{10} i \gamma^\mu D_\mu 10 \rightarrow g_5 \overline{(e^C)_L} \gamma^\mu (\textcolor{blue}{X}_\mu d_L - \textcolor{blue}{Y}_\mu u_L) / \sqrt{2} +$$

$$g_5 \left(\overline{u}_L \gamma^\mu \textcolor{blue}{X}_\mu (u^C)_L + \overline{d}_L \gamma^\mu \textcolor{blue}{Y}_\mu (u^C)_L \right) / \sqrt{2}$$



$$\mathcal{O}(e_\alpha^C, d_\beta) = k_1^2 \textcolor{red}{c}(e_\alpha^C, d_\beta) \epsilon_{ijk} \overline{u_i^C} \gamma^\mu u_j \overline{e_\alpha^C} \gamma_\mu d_{k\beta}$$

Why the Georgi-Glashow model is ruled out ?

- The unification of gauge couplings in disagreement with the experiments
- $M_E = M_D^T$ at the GUT scale in disagreement with the experiments
- $M_\nu = 0$

What are the simplest realistic extensions of the Georgi-Glashow Model ?

Type II-SU(5)

I. Dorsner, [P. F. P.](#), Nucl. Phys. B723 (2005)53

Type III-SU(5)

B. Bajc, G. Senjanovic, JHEP 0708 (2007) 014

Adjoint-SU(5)

[P. F. P.](#), Phys. Lett. B654 (2007) 189

P. Fileviez Perez

Type II-SU(5)

I. Dorsner, P.F.P Nucl.Phys.B723:53-76,2005

Matter: $\bar{5} = (d^C, e, \nu)$, $10 = (u^C, Q, e^C)$ Higgs Sector: 5_H , 24_H , 15_H

$$15 = \underbrace{(1, 3, 1)}_{\Delta} \oplus \underbrace{(3, 2, 1/6)}_{\Phi_b} \oplus \underbrace{(6, 1, -2/3)}_{\Phi_c}$$

Neutrino Mass through the Type II seesaw mechanism:

$$Y_\nu \bar{5} \bar{5} 15_H + \mu 5_H^* 5_H^* 15_H + \text{h.c.}$$

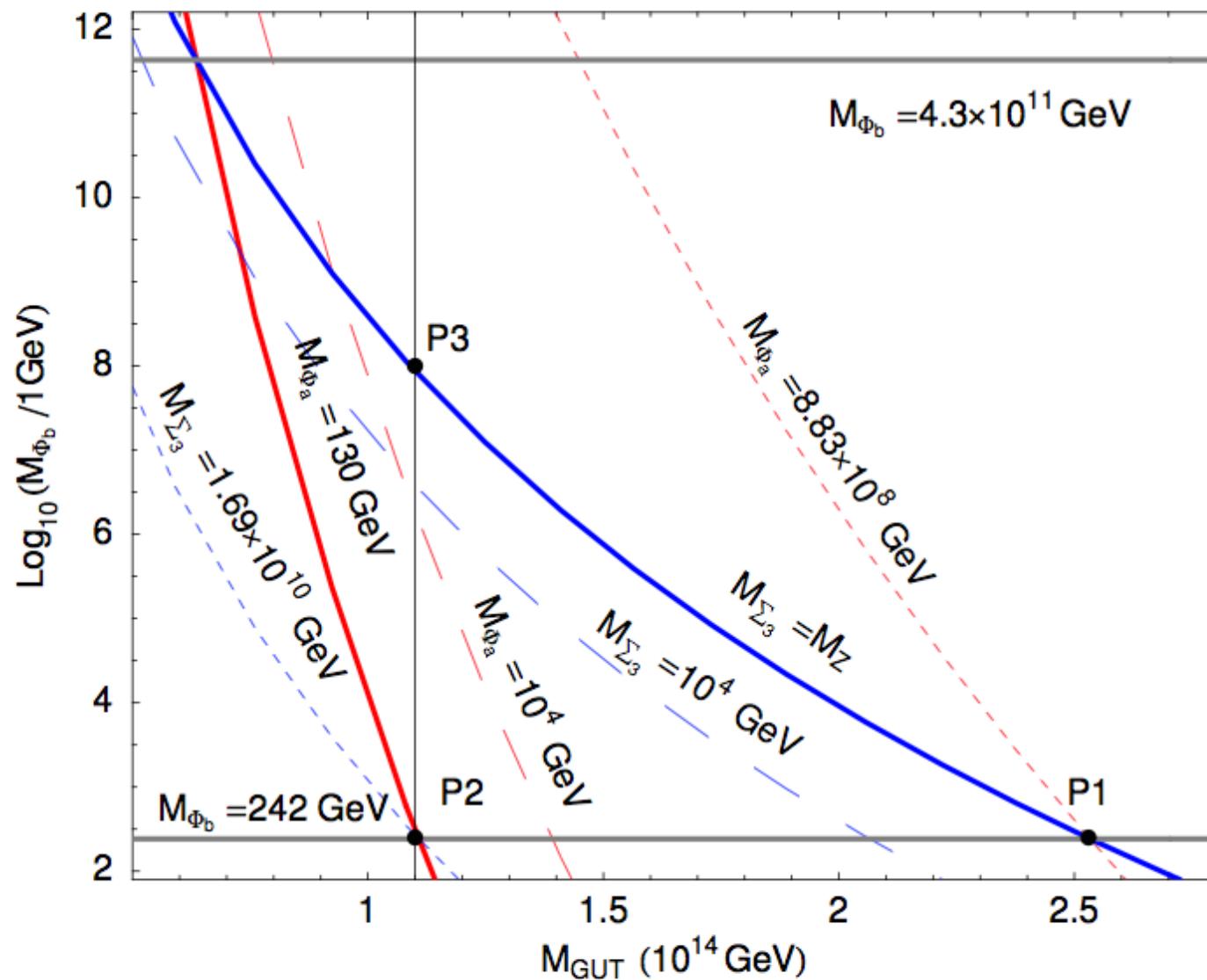
$$M_\nu = Y_\nu \langle \Delta \rangle = Y_\nu \mu v_W^2 / M_\Delta^2$$

Charged Fermion Masses: $Y_E \neq Y_D^T$ higher-dimensional operatorsUnification: O.K. The theory predicts a light scalar leptoquark Φ_b

See also: I. Dorsner, P.F.P, R. González Felipe, Nucl.Phys.B747:312-327,2006

I. Dorsner, P.F.P, G. Rodrigo, Phys. Rev. D75 (2007) 125007

$\tau_p < 2 \times 10^{36}$ years



Type III seesaw and Non-SUSY Unification

B. Bajc, G. Senjanović, hep-ph/0612029

Matter: $\bar{5} = (d^C, e, \nu)$, $10 = (u^C, Q, e^C)$, 24



Higgs Sector: 5_H , 24_H

$$24 = \underbrace{(8, 1, 0)}_{\rho_8} \oplus \underbrace{(1, 3, 0)}_{\rho_3} \oplus \underbrace{(3, 2, -5/6)}_{\rho_{(3,2)}} \oplus \underbrace{(\bar{3}, 2, 5/6)}_{\rho_{(\bar{3},2)}} \oplus \underbrace{(1, 1, 0)}_{\rho_0}$$

Neutrino Mass:

$$Y_0^i \bar{5}_i 24 5_H + \frac{1}{\Lambda} \bar{5}_i \times (Y_1^i 24 24_H + Y_2^i 24_H 24 + Y_3^i Tr(24 24_H)) 5_H$$

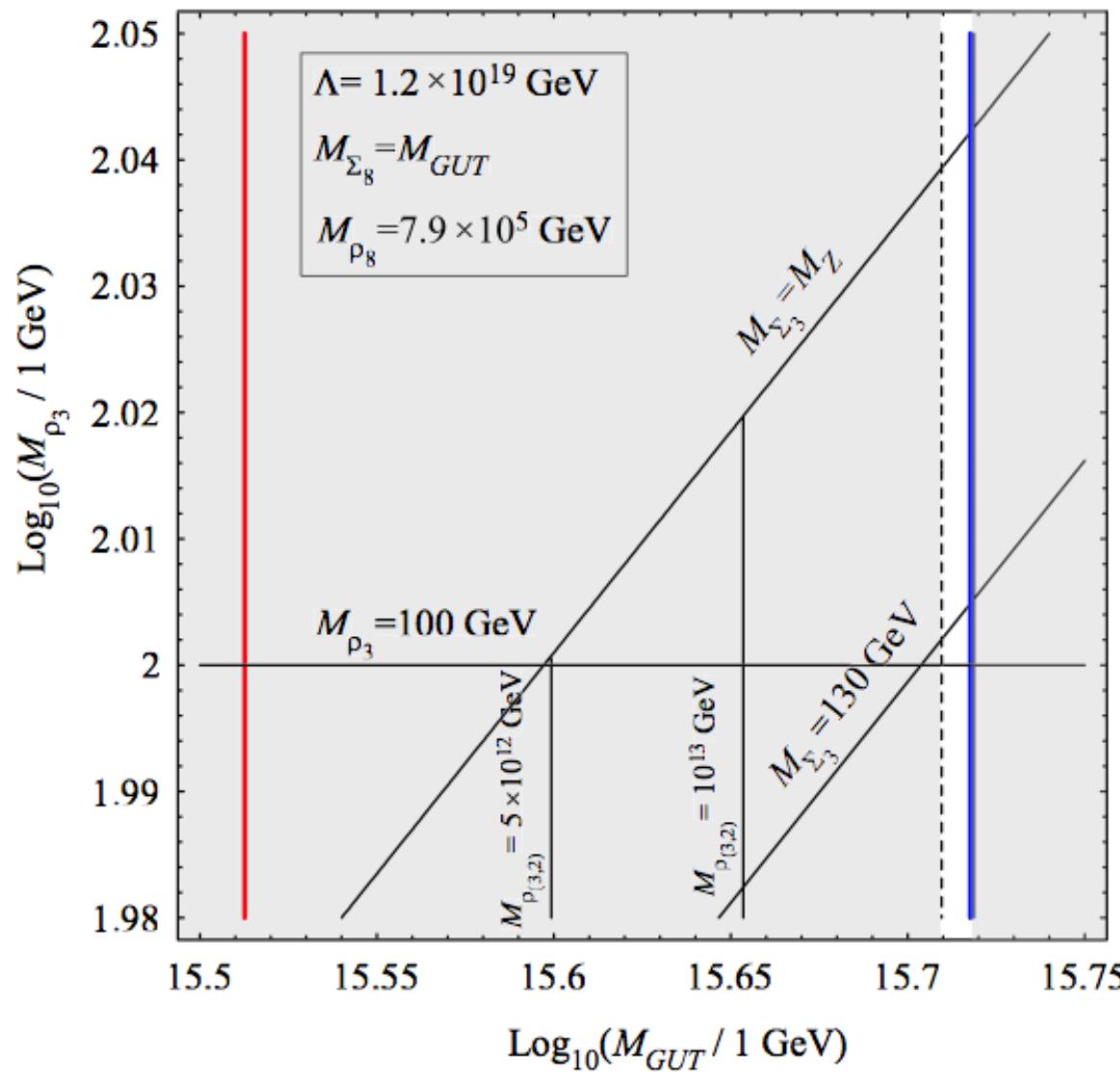
Charged Fermion Masses: $Y_E \neq Y_D^T$ using higher-dimensional operators

Unification: O.K. The theory predicts a light fermionic SU(2) triplet ρ_3

See also: I. Dorsner, P.F.P, JHEP 0706:029,2007.

$$\tau_p < 10^{36-37} \text{ years}$$

I. Dorsner, P.F.P, JHEP 0706:029,2007



See also: B.Bajc, Nemevsek, Senjanovic, Phys. Rev. D 76 (2007) 055011; L. Di Luzio, L . Mihaila, 1305.7034

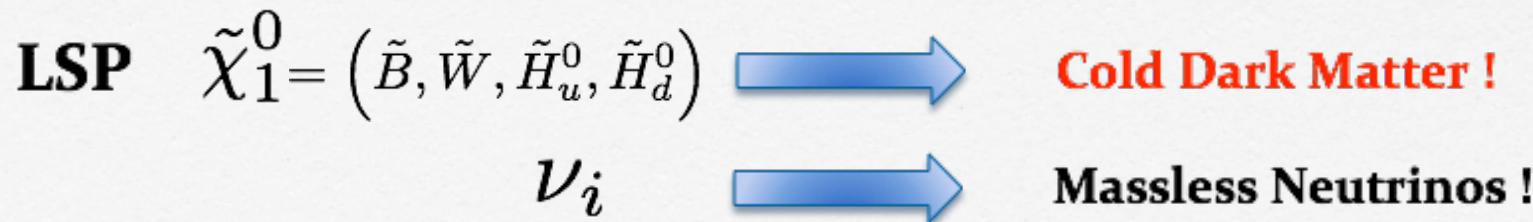
Nucleon Decay in Supersymmetry

MSSM Interactions

$$\mathcal{W}_{RpC} = Y_u Q H_u u^c + Y_d Q H_d d^c + Y_e L H_d e^c + \mu H_u H_d$$

$$\mathcal{W}_{RpV} = \epsilon L H_u + \lambda' L L e^c + \lambda'' Q L d^c + \lambda''' u^c d^c d^c$$

$$R = (-1)^{3(B-L)+2S} = (-1)^{2S} M$$



B and L violation in the MSSM

$$\mathcal{W}_{RpV} = \epsilon LH_u + \lambda LLe^c + \lambda' QLd^c + \lambda'' u^cd^cd^c$$

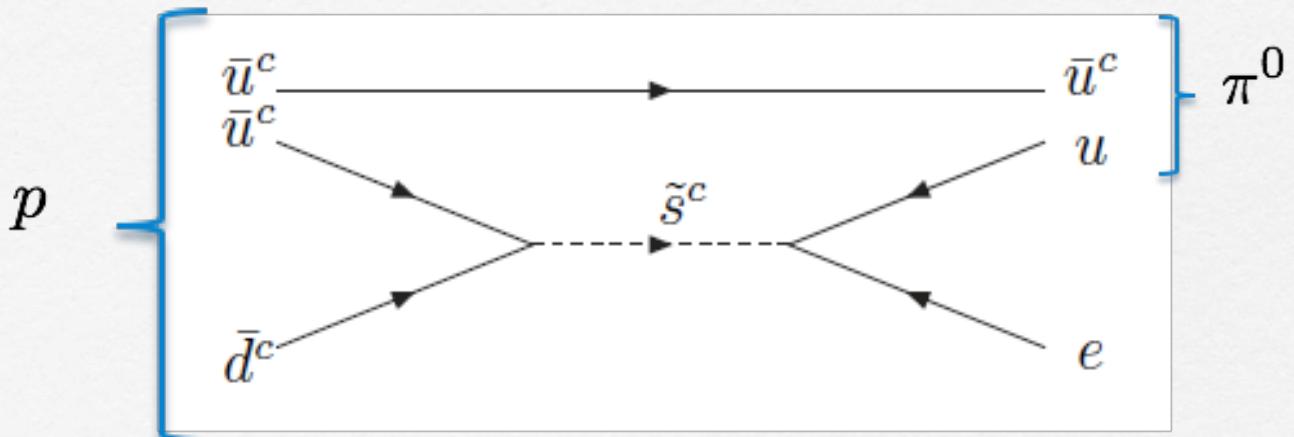
$$\mathcal{W}_{RPC}^5 = \frac{\lambda_\nu}{\Lambda} LLH_u H_u + \frac{\lambda_L}{\Lambda} QQQL + \frac{\lambda_R}{\Lambda} u^cd^cu^ce^c$$

Missing energy at the LHC (DM) vs Neutrino Masses ?

See e.g. P. Nath, [P. Fileviez Perez](#), Physics Reports 441:191,2007

Proton Decay and M-Parity

$$\lambda' Q L d^c$$
$$\lambda'' u^c d^c d^c$$



Channel : $\tau_{p \rightarrow \pi^0 e^+} > 10^{33}$ years

$$M_{\tilde{q}} \sim 10^3 \text{ GeV}$$

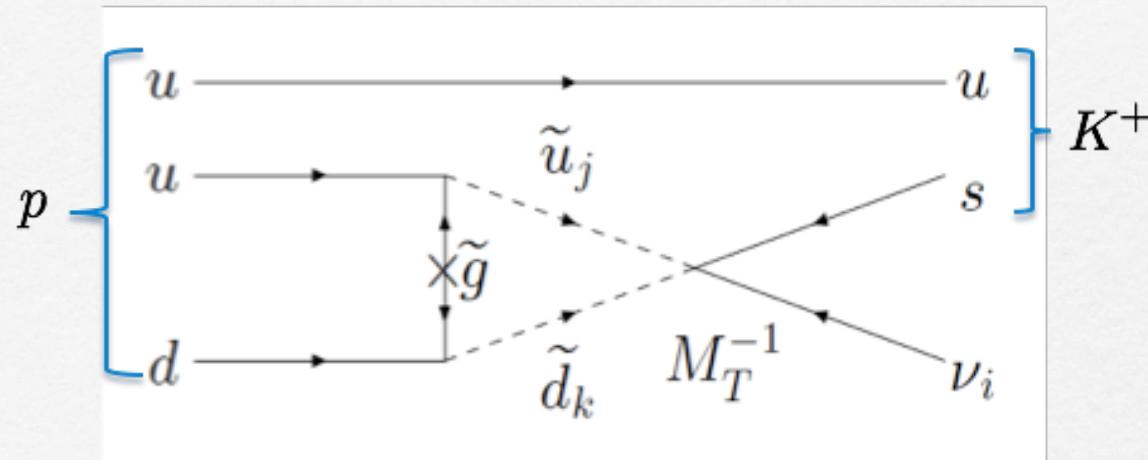


$$\tau_4 \sim 10^{-20} \text{ years}$$

$d=5$ operators

Example: $p \rightarrow K^+ \bar{\nu}$ ($\tau > 2.3 \times 10^{33}$ years)

$$\frac{\lambda_L}{M_T} QQQL$$

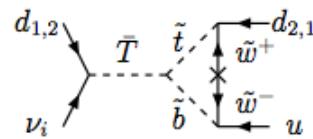


$M_T > 10^{17}$ GeV (NAIVE)

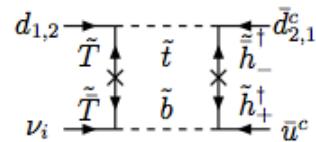
Dimopoulos, Raby, Wilczek; Arnowitt,
Chamseddine, Nath; Goto, Nihei; Lucas, Raby;
Bajc, P.F.P., Senjanovic

d=5 contributions

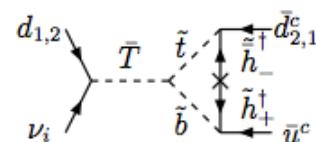
Bajc, P.F.P., Senjanovic



$$\propto (D^T \underline{C} N)_{1i,2i} (U^T \tilde{D}^*)_{13} (\tilde{D}^T \underline{A} \tilde{U})_{33} (\tilde{U}^\dagger D)_{32,31}$$

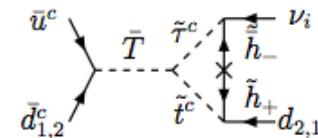


$$\propto (D^T \underline{A} \tilde{U})_{13,23} (\tilde{U}^\dagger Y_D^* D_c^*)_{32,31} (U_c^\dagger Y_U^* \tilde{D}^*)_{13} (\tilde{D}^T \underline{C} N)_{3i}$$

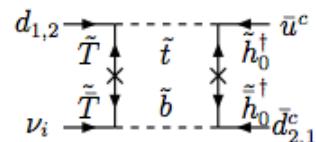


$$\propto (D^T \underline{C} N)_{1i,2i} (U_c^\dagger Y_U^* \tilde{D}^*)_{13} (\tilde{D}^T \underline{A} \tilde{U})_{33} (\tilde{U}^\dagger Y_D^* D_c^*)_{32,31}$$

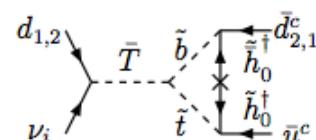
Many contributions !



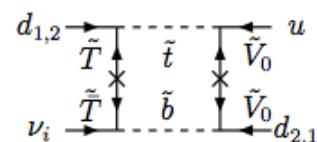
$$\propto (U_c^\dagger \underline{D}^* D_c^*)_{11,12} (D^T Y_U \tilde{U}_c)_{23,13} (\tilde{U}_c^\dagger \underline{B}^* \tilde{E}_c^*)_{33} (\tilde{E}_c^T Y_E N)_{3i}$$



$$\propto (D^T \underline{A} \tilde{U})_{13,23} (\tilde{U}^\dagger Y_U^* U_c^*)_{31} (D_c^\dagger Y_D^* \tilde{D}^*)_{23,13} (\tilde{D}^T \underline{C} N)_{3i}$$



$$\propto (D^T \underline{C} N)_{1i,2i} (U_c^\dagger Y_U^* \tilde{U}^*)_{13} (\tilde{U}^T \underline{A} \tilde{D})_{33} (\tilde{D}^\dagger Y_D^* D_c^*)_{32,31}$$



$$\propto (D^T \underline{A} \tilde{U})_{13,23} (\tilde{U}^\dagger U)_{31} (D^T \tilde{D}^*)_{23,13} (\tilde{D}^T \underline{C} N)_{3i}$$

Minimal Supersymmetric $SU(5)$

S. Dimopoulos and H. Georgi NPB(1981); N. Sakai Z. Phys. C (1981)

Chiral Superfields: $\hat{\bar{5}}_i$, $\hat{10}_i$, $\hat{5}_H$, $\hat{\bar{5}}_H$, $\hat{24}_H$

Vector Superfields: $\hat{24}_G$

$$\hat{10} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & U_3^C & -U_2^C & U_1 & D_1 \\ -U_3^C & 0 & U_1^C & U_2 & U_2 \\ U_2^C & -U_1^C & 0 & U_3 & D_3 \\ -U_1 & -U_2 & -U_3 & 0 & E^C \\ -D_1 & -D_2 & -D_3 & -E^C & 0 \end{pmatrix}_L$$

$$\hat{\bar{5}} = \begin{pmatrix} D_1^C \\ D_2^C \\ D_3^C \\ E \\ -N \end{pmatrix}_L \quad \hat{5}_H = \begin{pmatrix} T_1 \\ T_2 \\ T_3 \\ H_2^+ \\ H_2^0 \end{pmatrix} \quad \hat{\bar{5}}_H = \begin{pmatrix} \bar{T}_1 \\ \bar{T}_2 \\ \bar{T}_3 \\ H_1^- \\ -H_1^0 \end{pmatrix}$$

$$\hat{24}_H = \begin{pmatrix} \Sigma_8 & \Sigma_{(3,2)} \\ \Sigma_{(\bar{3},2)} & \Sigma_3 \end{pmatrix} + \frac{1}{2\sqrt{15}} \begin{pmatrix} 2 & 0 \\ 0 & -3 \end{pmatrix} \Sigma_{24}$$

- Unification: O.K.
- $M_E = M_D^T$ ($b - \tau$ unification O.K.)
- $M_\nu = 0$ if R-parity is conserved

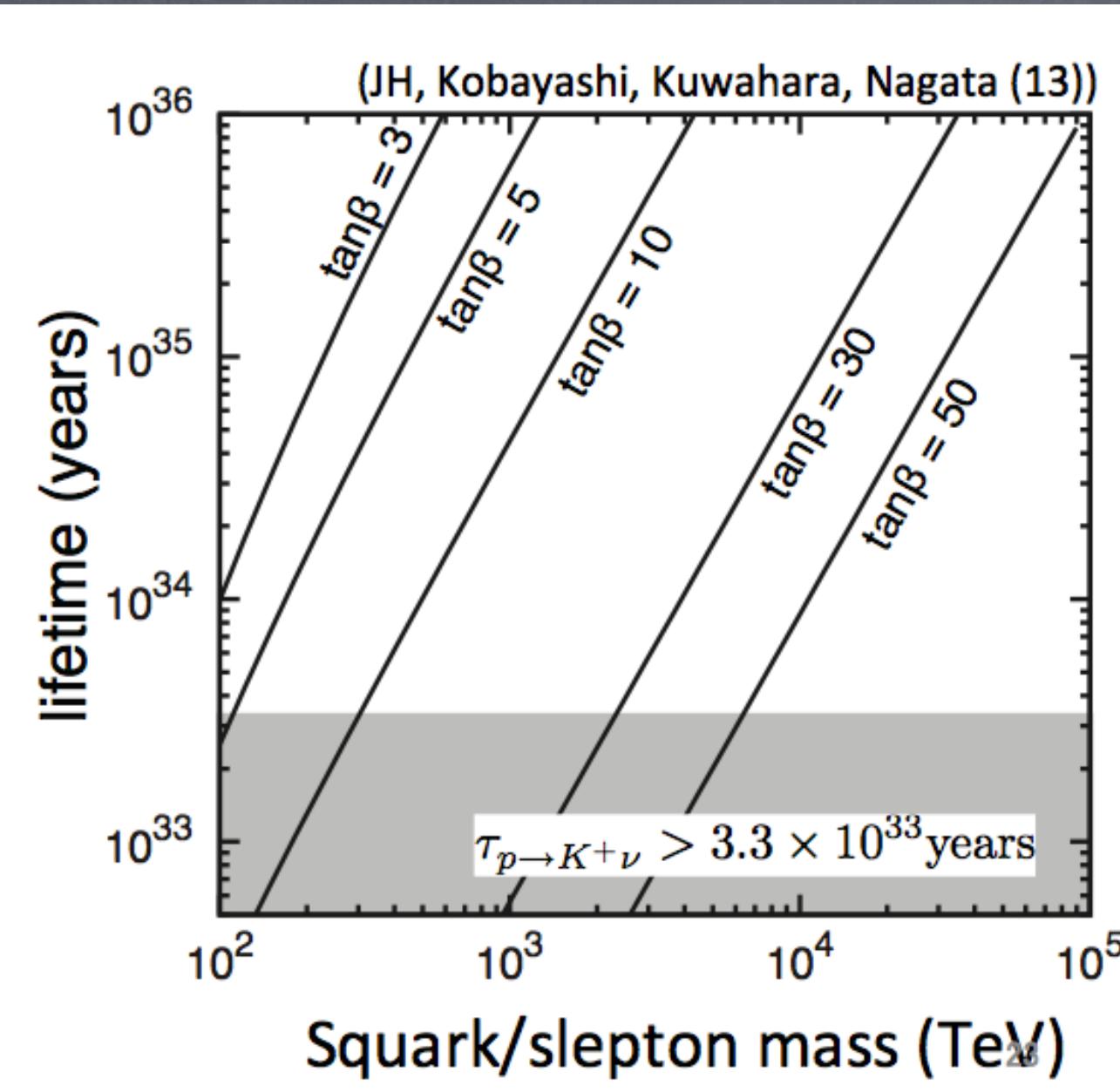
The Minimal Renormalizable SUSY $SU(5)$ is ruled out !!

The non-renormalizable SUSY $SU(5)$ model is OK,
see: Bajc, P.F.P., Senjanovic, 0210374; 0204311.

Unfortunately, the proton decay lifetime cannot be predicted in SUSY because one needs to know the full spectrum of supersymmetric particles !

In minimal SUSY $SU(5)$, assuming $m_{\tilde{q}, \tilde{l}} \sim 1$ TeV: $M_T > 10^{17}$ GeV

Note that in general we do not know $(\tilde{U}^\dagger U)_{j1} (\tilde{D}^\dagger D)_{k1} !!!$



J. Hisano @ BLV2013

$SO(10)$ GUTs and proton decay

$16_F, 10_H, 126_H, 210_H, \dots$

These theories are considered very appealing because the fermions are unified in the 16 representation. However, one has different breaking scales and it is very difficult to predict the lifetime of the proton.

For recent studies see:

G. Senjanovic, 2012

H. Kolesova, M. Malinsky, 1409.4961

Mohapatra et al, 1202.4012

Babu, Pati, Tavartkiladze, 1003.2625

Summary

P. Fileviez Perez

The Desert Hypothesis plays a major role in our view of the relation between the physics at the low and high scales. Proton decay could tell us if this picture is correct !

There are two realistic SU(5) models which predict a proton lifetime around 10^{36} years.

Proton decay bounds set a severe constraint on SUSY GUTs and together with the LHC results one can understand if they are viable.

More effort is needed in the experimental community. SK can use the data to constraint all possible decay channels. They could make the data public and other experimental groups could make independent analyses.

Proton Decay

by David Halliday

A proton once said, "I'll fulfill
My long-term belief in free will.
Though theorists (may) say
That I ought to decay
I'm damned if I think that I will."

P. Fileviez Perez