Q. Shafi

$\delta T/T$, Neutrino Oscillations And Proton Decay

- Introduction / Motivation

- Models
  - $\rightarrow$ $\delta T/T$ (inflation)
  - $\rightarrow$ ν Oscillations
  - $\rightarrow$ Baryon asymmetry

- Proton Decay

with Dvali, Lazarides, Kyae
Senoguz, Schaefer, ...

PHYSICS BEYOND THE STANDARD MODEL (SM) REQUIRED BY :

- Neutrino Oscillations

  $(\Delta m^2_{SM} \underset{\uparrow \dim 5}{\sim} 10^{-10}\, eV^2 \ll \Delta m^2_{ATM}, \Delta m^2$

- $\delta T/T$ (Inflation) $(\sim 10^{-5})$

- Non-baryonic DM $(\Omega_{CDM} \simeq 0.25$

- Baryon Asymmetry $(n_B/s \sim 10^{-10}$

Gauge(d) $U(1)_{B-L}$ (SM: global $U(1)_{B-L}$)

- Anomaly cancellation
  $\Rightarrow$ 3 (right handed) ν_R

- Seesaw Mechanism

- Leptogenesis

? B-L breaking scale

Hierarchy Problem(s)

- $M_W \ll M_{P(\text{lanck})}$

- $M_{B-L} \ll M_P$ (ν Osc)

- f_a(axion) $\sim 10^{10} - 10^{12}$ GeV ($\ll M_P$)
  $\uparrow$
  CDM

- $M_{\text{inflaton}} \ll M_{GUT}$ ($\delta\rho/\rho$, etc.

Supersymmetry can certainly help here, especially if the SUSY breaking scale (in the observable sector) is of order TeV.

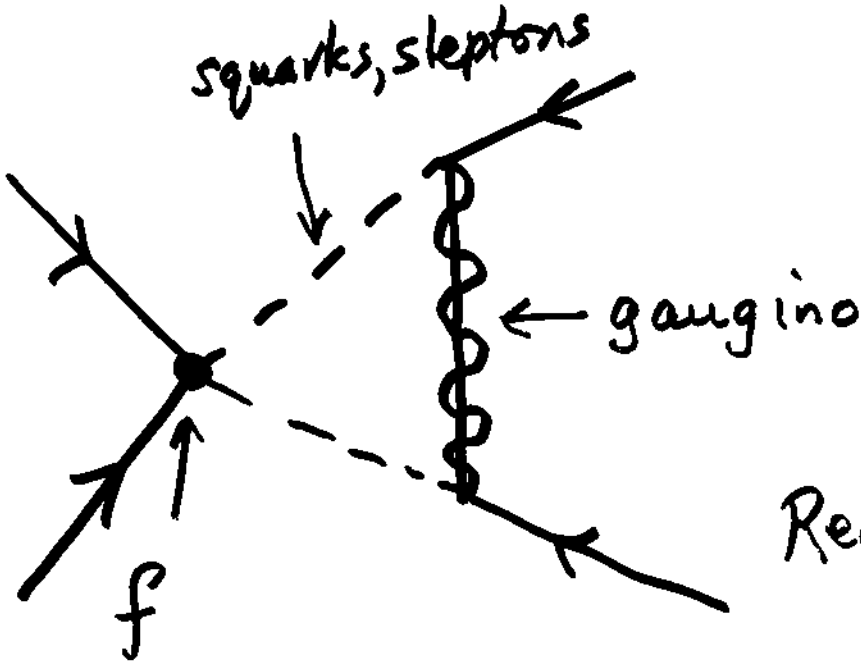
$\Rightarrow$ starting point could be MSSM $\times$ $U(1)_{B-L}$

- Z_2 'matter' parity eliminates rapid proton decay and delivers cold dark matter (LSP).

- But dim 5 p decay is still problematic because of superpotential terms such as

$$\frac{f}{M_P} Q\,Q\,Q\,L$$ (allowed by $U(1)_{B-L}$

$\left(\text{cf: } \frac{1}{M_P^2}\, qqql \text{ in SM} \Rightarrow \tau_p \gtrsim 10^{42}\,\text{yr} \right)$



Require $\tau_p \gtrsim 10^{33}$

$\Rightarrow$ Coefficient $f \lesssim 10^{-7}$ (how?)

One solution:

$$Z_2 \subset U(1)_R$$

Under R: Q, L carry charge $\frac{1}{2}$
& W (superpotential)
has unit charge

($\mathcal{L}(x) \to \int d^2\theta\, W$ invariant)

Working with MSSM $\times$
$U(1)_{B-L} \times U(1)_R$

one can

- easily realize inflation;
- determine M_{B-L} (from $\delta T/T$
  ↳ not possible from gauge coupl unification
- put bounds on right handed ν masses;
- resolve μ problem;
- explain n_b/s via leptogenesis.

Starting theory quite simple

$$W = W_{MSSM} + W_{INF} + W_{RH\nu}$$

$$W_{INF} = \kappa S\left(\bar{\phi}\phi - M_{B-L}^{2}\right)$$

Unique form at renormalizable level. Higher order terms dont affect conclusions regarding $\delta T/T$, M_{B-L}.

Inflation (101) (inflation linked to some phase transition

Recall that we deal with spontaneously broken gauge theories:

Example: $\mathcal{U}(1)_{B-L} \xrightarrow{\langle\phi\rangle} 1$

e.g. supercon

Consider the potential energy density

dimens

$$V \sim \kappa^2 \left|\phi^*\phi - M_{B-L}^2\right|^2 + 2\kappa^2 S^2 |\phi$$

req'd by S

Minimum corresponds to

$$|\phi| = M_{B-L}, \quad \langle S \rangle = 0 \quad (\Rightarrow V = 0)$$

$\Rightarrow$ $\mathcal{U}(1)$ spontaneously broken (today

To realize an inflationary epoch, some fields must be displaced from their present positions.

Think of S as temperature ($\simeq 0$ at present)

For $S \gg M_{B-L}$ (very early universe) we should have $|\phi| = 0$, so that

$$V \sim \kappa^2 M_{B-L}^4$$

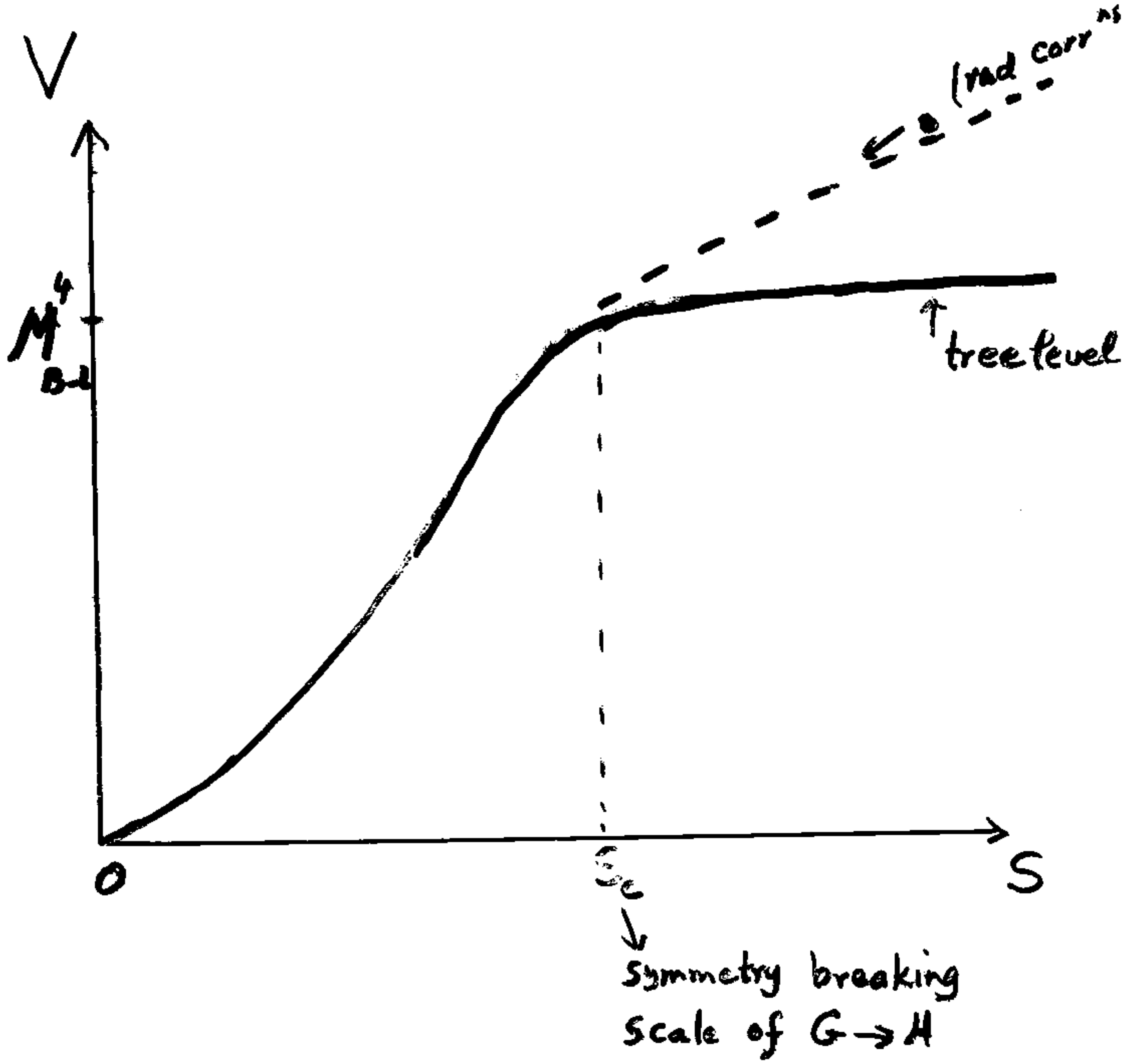
symmetry restoration (cf: superconducto

Thus, we expect to have gauge symmetry restoration above some 'critical' temperature $S_c > M_{B-}$

A non-zero vacuum energy density $\Rightarrow$ exponential expansion of the universe $\Rightarrow$ inflation.

? How does inflation terminate

Through quantum corrections that are calculable:



For $S > S_c$,

$$V_{eff}(S) \sim \mu^4 \left[1 + \frac{N\kappa^2}{32\pi^2} \ln\left(\frac{\kappa^2 S^2}{\Lambda^2}\right) \right]$$

Use to calculate

$\delta T/T$, n, S/T $\left(n = 1 - \frac{1}{N_\ell} \simeq 0.98 \right)$

Predictions

- $\delta T/T \;\propto\; \left(M_{B-L}/M_{Planck}\right)^2$

  $$\Longrightarrow\; M_{B-L} \sim 10^{16}\,\text{GeV}$$
  $$(\sim M_{GUT})$$

- $n_s \simeq 1 - \dfrac{1}{N}$ ($N \sim 60$ e-foldi

  $\simeq 0.98 - 0.99$

- $r \equiv T/S \ll 1$

- Lepto/Baryo-genesis / ν Oscilla

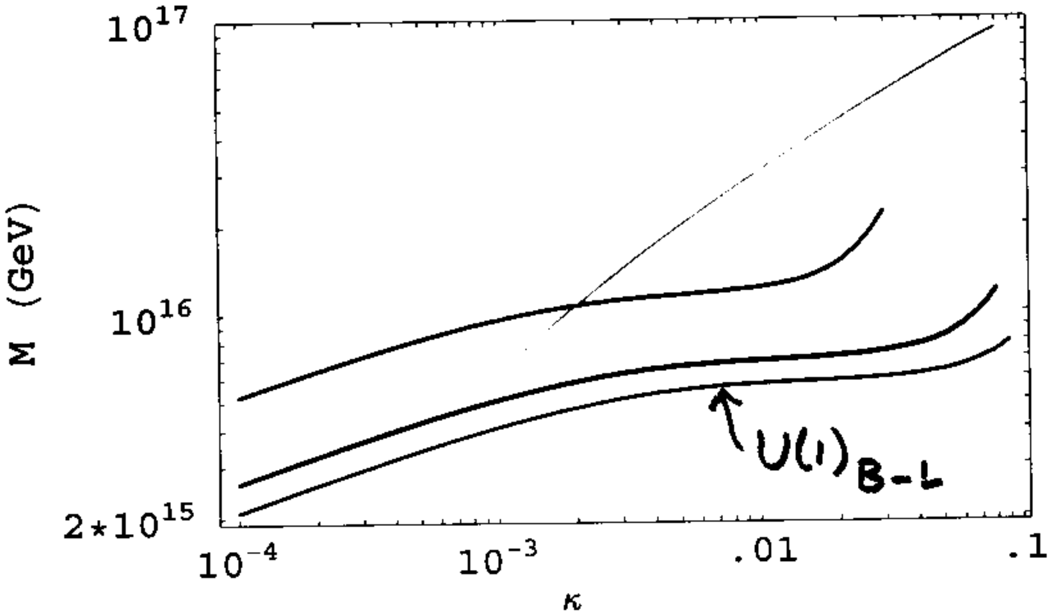


FIG. 2: The symmetry breaking scale M vs. κ, for $\mathcal{N}=1$ (green), $\mathcal{N}=2$ (blue), $\mathcal{N}=16$ (purple), and for shifted hybrid inflation (orange).

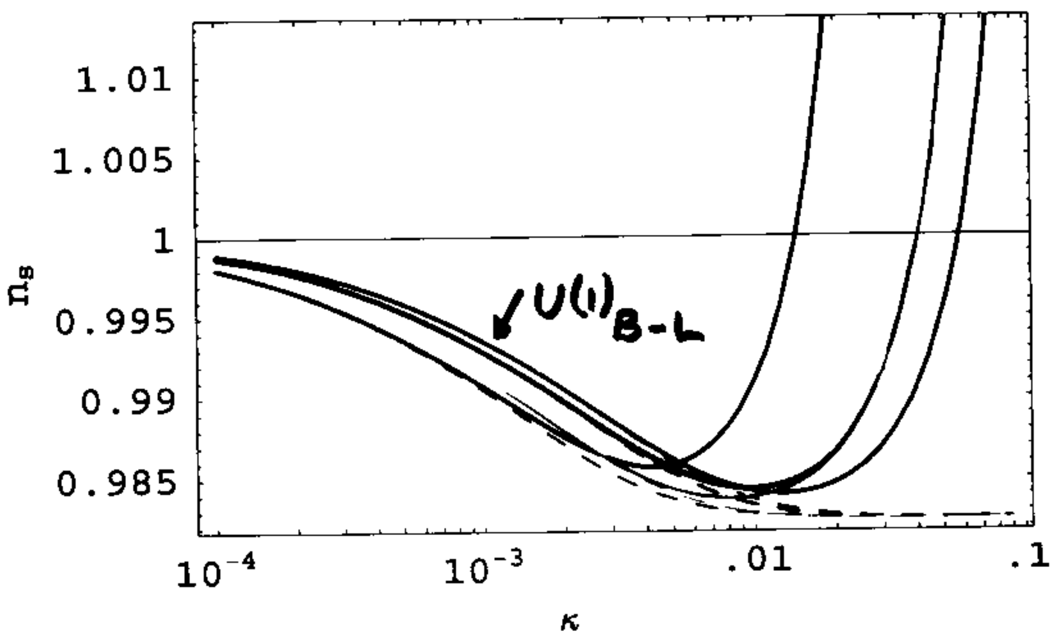


FIG. 1: The spectral index n_s vs. κ, for $\mathcal{N} = 1$ (green), $\mathcal{N} = 2$ (blue), $\mathcal{N} = 16$ (purple), and for shifted hybrid inflation (orange). Solid lines - with SUGRA correction, dashed lines - without SUGRA correction.

Note: $K \simeq \dfrac{\text{inflaton mass}}{M} \lesssim 10^{-2}$

(from T_{reheat})

Table 1 Power Law ΛCDM Model Parameters- *WMAP* Data Only

Parameter		Mean (68% confidence range)	Maximum Likelihood
Baryon Density	$\Omega_b h^2$	0.024 ± 0.001	0.023
Matter Density	$\Omega_m h^2$	0.14 ± 0.02	0.15
Hubble Constant	h	0.72 ± 0.05	0.68
Amplitude	A	0.9 ± 0.1	0.80
Optical Depth	τ	$0.166^{+0.076}_{-0.071}$	0.11
Spectral Index	n_s	0.99 ± 0.04	0.97
	χ^2_{eff}/ν		1431/1342

[a]Fit to *WMAP* data only

Table 2. Derived Cosmological Parameters

Parameter	Mean (68% confidence range)
Amplitude of Galaxy Fluctuations	$\sigma_8 = 0.9 \pm 0.1$
Characteristic Amplitude of Velocity Fluctuations	$\sigma_8 \Omega_m^{0.6} = 0.44 \pm 0.10$
Baryon Density/Critical Density	$\Omega_b = 0.047 \pm 0.006$
Matter Density/Critical Density	$\Omega_m = 0.29 \pm 0.07$
Age of the Universe	$t_0 = 13.4 \pm 0.3$ Gyr
Redshift of Reionization[b]	$z_r = 17 \pm 5$
Redshift at Decoupling	$z_{dec} = 1088^{+1}_{-2}$
Age of the Universe at Decoupling	$t_{dec} = 372 \pm 14$ kyr
Thickness of Surface of Last Scatter	$\Delta z_{dec} = 194 \pm 2$
Thickness of Surface of Last Scatter	$\Delta t_{dec} = 115 \pm 5$ kyr
Redshift at Matter/Radiation Equality	$z_{eq} = 3454^{+385}_{-392}$
Sound Horizon at Decoupling	$r_s = 144 \pm 4$ Mpc
Angular Diameter Distance to the Decoupling Surface	$d_A = 13.7 \pm 0.5$ Gpc
Acoustic Angular Scale[c]	$\ell_A = 299 \pm 2$
Current Density of Baryons	$n_b = (2.7 \pm 0.1) \times 10^{-7}$ cm^{-3}
Baryon/Photon Ratio	$\eta = (6.5^{+0.4}_{-0.3}) \times 10^{-10}$

[a]Fit to the *WMAP* data only

[b]Assumes ionization fraction, $x_e = 1$

[c] $l_A = \pi d_A / r_s$

• μ Problem

Consider the Superpotential

$$W = S\,(\underbrace{\kappa\bar{\phi}\phi}_{\substack{\text{breaks}\\ U(1)_{B-L}}} + \lambda H_u H_d - M_{B-L}^2)$$

- SUSY unbroken with $|\langle\phi\rangle| = \kappa\langle\bar{\phi}\rangle| \neq 0$
  $\langle H_u\rangle$, $\langle H_d\rangle$ and $\langle S\rangle$:

- After SUSY breaking, S acquires vev $\propto m_{3/2}$
  $\Rightarrow$ μ term $\propto m_{3/2}$.

- <u>**P decay**</u>: 'Matter' fields have R-charge = $\frac{1}{2}$
  Thus, QQQL is eliminated.

Note: Z_2 subgroup of $U(1)_R$ acts as 'matter' parity

T_{reheat} (T_r) / Leptogenesis

- Inflaton consists of S and $\phi, \bar{\Phi}$ fields;

- Relevant couplings include

$$\begin{cases} N_i N_j \bar{\phi} \bar{\phi} & \text{(masses for right handed } \nu \text{)} \\ S H_u H_d & \leftarrow \text{suppose this is absent} \\ S \bar{\Phi} \phi & \end{cases}$$

then

inflaton decays into right handed ν & $\tilde{\nu}$.

If $S H_u H_d$ present then T_r is somewhat higher.

Then

$$T_r \sim \left(\frac{1}{10} - \frac{1}{50}\right) M_i$$

$(2M_i \le m$

Thus, we require at least one $M_i \lesssim 10^{10} - 10^{11}$ GeV.

Suppose $M_3 \sim 10^{14}$ GeV $(16_3 16_3 \overline{16}\, \overline{16}$

so that $m_3 \sim m_D^2/M_3 \sim 10^{-1}$ eV $(\Delta m_{AT}$

Then, we could have

$$T_r \sim 10^9 \text{ GeV}$$

$$m_\phi \sim 10^{12} - 10^{13} \text{ GeV}$$

$$M_1, M_2 \sim 10^{10} - 10^{11} \text{ GeV}$$

$\Rightarrow$ non-thermal leptogenesis possible.

With $T_r \ll M_1, M_2 \ll M_3$,

$$n_L/s \lesssim 3\times 10^{-10}\left(\frac{T_r}{m_\phi}\right)\left(\frac{M_i}{10^6\,\mathrm{GeV}}\right)\left(\frac{m_{\nu_3}}{0.05}\right.$$

$$\Rightarrow T_r \gtrsim 2\times 10^7\,\mathrm{GeV}\left(\frac{10^{16}\,\mathrm{GeV}}{M}\right)^{1/2}\left(\frac{m_\phi}{10^{11}\,\mathrm{GeV}}\right)^{3/4}\left(\frac{.05\,\mathrm{eV}}{m_{\nu_3}}\right.$$

For the simplest models, $T_r \gtrsim 3\times 10^7\,\mathrm{GeV}$

Note: For quasi-degenerate right handed neutrinos, the lepton asymmetry ϵ per neutrino decay can be of order unity, so that $T_r \gtrsim 10^2\,\mathrm{GeV}$ (TeV scale leptogenesis)

$$\boxed{n_L/s \sim \frac{T_r}{m_\phi}\epsilon}$$

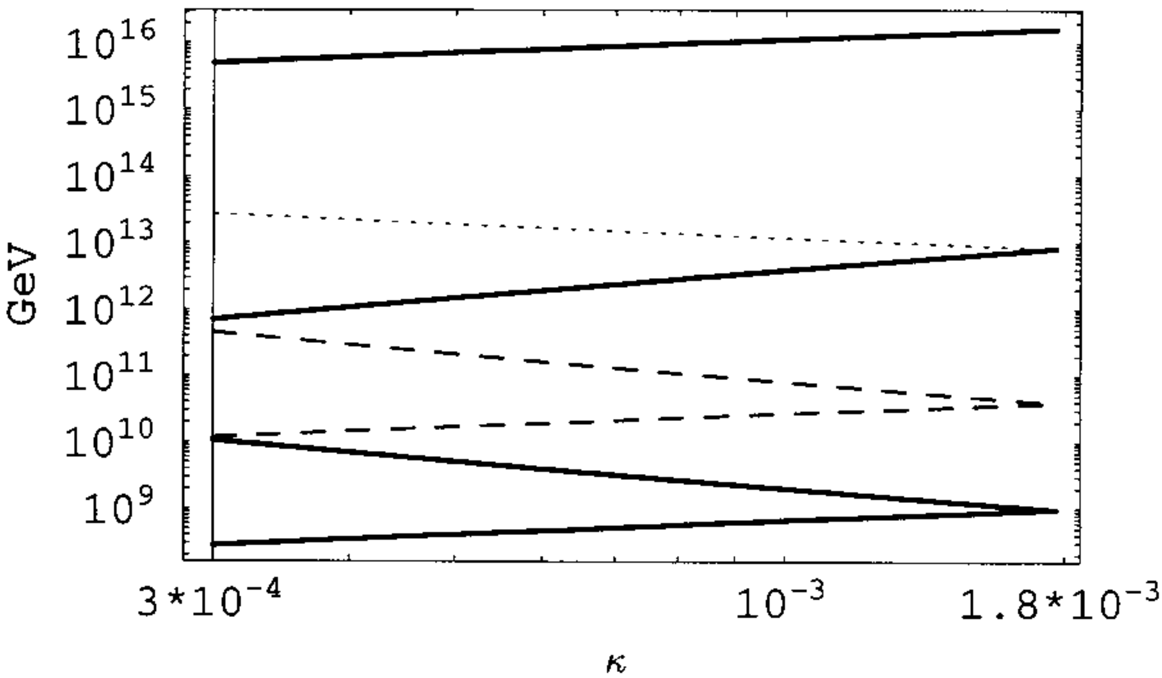


Figure 6: From bottom to top, T_r, M_2 (dashed lines), $m_\chi/2$, M_3 (dotted lines) and M as functions of κ, for shifted hybrid inflation with $G = G_{PS}$ and degenerate left handed Majorana neutrinos. The regions for T_r, M_2 and M_3 are bound by the baryon asymmetry and near maximal atmospheric mixing ($\sin^2 2\theta_{23} \geq 0.95$) constraints. Note that M_3 is bound below by $m_\chi/2$, and $\kappa > 3 \times 10^{-4}$ is required for the inflationary trajectory for $\beta = 0.5$.

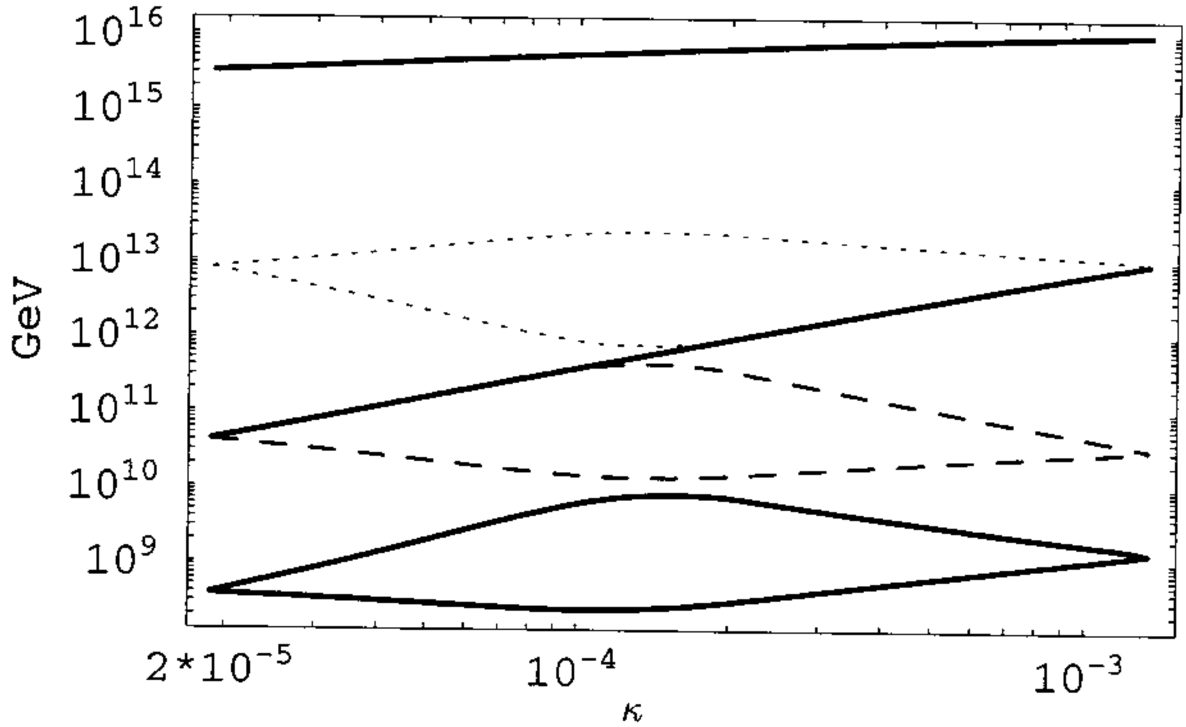


Figure 4: From bottom to top, T_r, M_2 (dashed lines), $m_\chi/2$, M_3 (dotted lines) and M as functions of κ, for SUSY hybrid inflation with $G = SO(10)$ and degenerate left handed Majorana neutrinos. The regions for T_r, M_2 and M_3 are bound by the baryon asymmetry and near maximal atmospheric mixing ($\sin^2 2\theta_{23} \geq 0.95$) constraints.

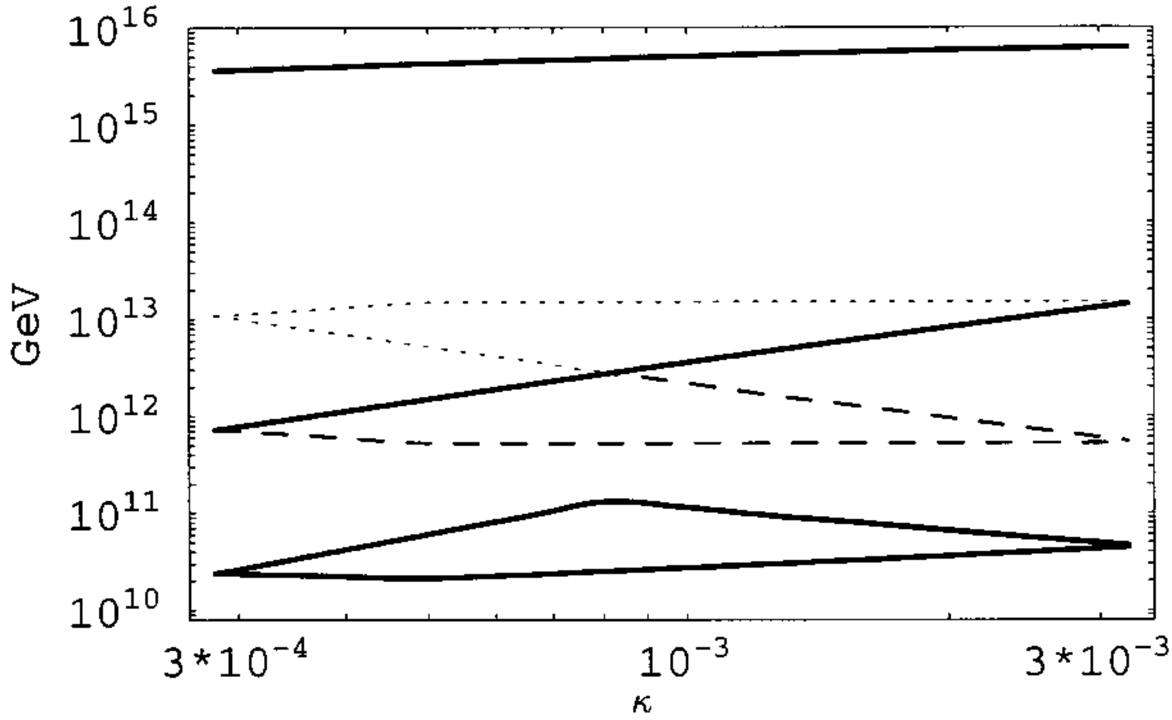


Figure 3: From bottom to top, T_r, M_2 (dashed lines), $m_\chi/2$, M_3 (dotted lines) and M as functions of κ, for degenerate left handed Majorana neutrinos. The regions for T_r, M_2 and M_3 are bound by the baryon asymmetry and near maximal atmospheric mixing ($\sin^2 2\theta_{23} \geq 0.95$) constraints. Note that the allowed regions for M_2 and M_3 are also constrained by $M_2 \leq M_\chi/2 < M_3$.

With $G = MSSM \times U(1)_{B-L}$ $(\times U(1)_R)$:

- Proton is stable;

- Electric charge quantization is unexplained;

- Quark - Leptons not unified. (Gauge coupling unification)

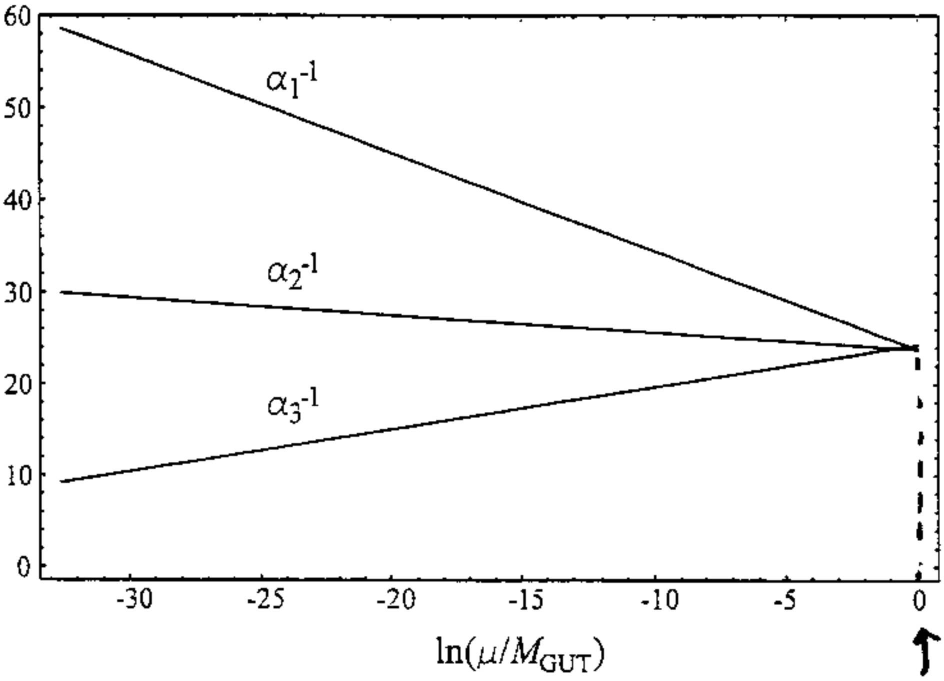
Obvious Generalization:

$$G = SO(10) \supset SU(4)_c \times SU(2)_L \times SU(2)_R$$

or $$G = E_6 \supset SU(3)_c \times SU(3)_L \times SU(3)_R$$

Evolution of Gauge Couplings

$$\alpha_i \equiv g_i^2/4\pi$$



↑
Unified Theory ?
(single gauge coupling)

- Unification of couplings $\Longrightarrow$
- Charge Quantization
  ($\Rightarrow$ monopoles)
- Quark-Lepton Unification
  $\Rightarrow$ Proton Decay

$$G = SU(4)_c \times SU(2)_L \times SU(2)_R$$

Pati & Salam
⋮

- Quark – lepton unification

$$\begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}_L \quad \begin{pmatrix} u^c & u^c & u^c & \nu^c \\ d^c & d^c & d^c & e^c \end{pmatrix}_R$$

- Charge Quantization (monopole carr… two Dirac quan…

- Gauge bosons do not mediate proton decay

- Doublet – Triplet problem absent (huge advantage over $SO(10)$)

Proton Decay ?

Minimal (higgs) Model

King, Shaf

- $\phi(\bar{4},1,2)$, $\bar{\phi}(4,1,2)$ break $G_{422} \to$ M:

- $h(1,2,2) \leftarrow$ EW doublets

- μ-problem solved as before.

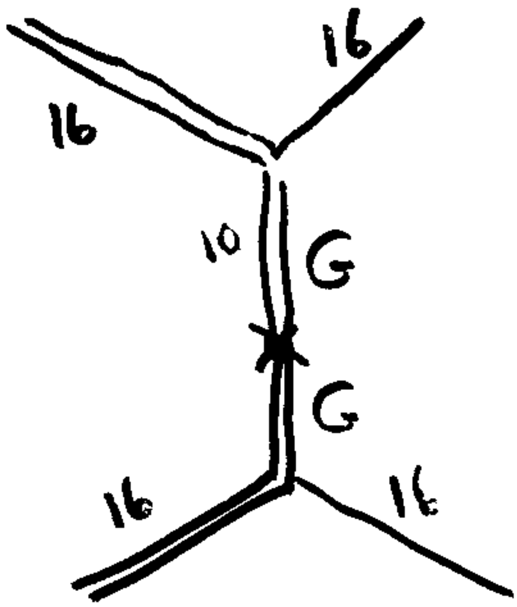
$$W \supset S(\kappa\bar{\phi}\phi + \lambda h^2 - \kappa M^2)$$

$$+ G\bar{\phi}\bar{\phi} + G\phi\phi$$

$(6,1,1) \leftarrow$ in principle, these mediate p decay (required to realis MSSM spectrum at low energies)

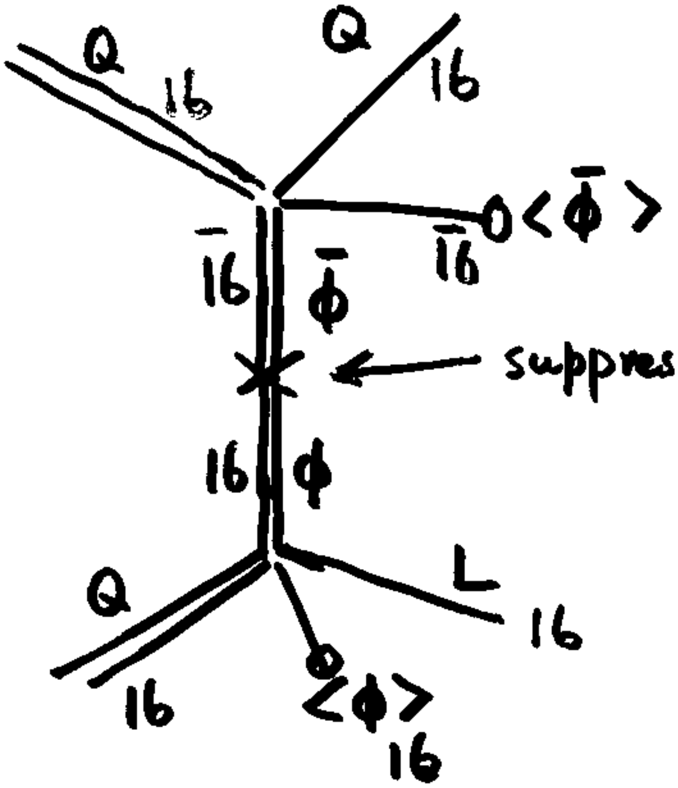
Dimension Five Nucleon Decay

(i)



Allowed by G_{422}, but absent due to $U(1)_R$.

(ii)



suppressed by $(m_{3/2}/$

Proton decay may arise through loop diagrams using dim 5 operators:

$$\frac{1}{M_*} F^c F^c \phi \phi \; (\supset u^c_\phi d^c_\phi u^c e^c$$

$$\frac{1}{M_*} F F \phi \phi \; (\supset u^c_\phi d^c_\phi u d)$$

(Add'l suppression from flavor symmetries.)

$$\tau_{p \to K \nu} \gtrsim 10^{38} \, \mathrm{yr}$$

More Elaborate 4-2-2 Model

(including quark-lepton masses, mixing

Mackawa,

- This means a non-minimal Higgs sector. In $SO(10)$ notation:

	Higgs	Matter
$\underset{\sim}{16}$	C, C'	$\psi_1 \quad \psi_2 \quad \psi_3$
$\underset{\sim}{\overline{16}}$	$\bar{C}, \bar{C}'$	
$\underset{\sim}{10}$	H, H'	T
$\underset{\sim}{1}$	$\theta, Z, \bar{Z}, S$	

- Fields now also carry anomalous $U(1)$ charge

$U(1)_A$ charges (4 - 2 - 2)

	HIGGS	SCALARS (no vev)	
$\underset{\sim}{16}$	$C(-3)$	$C'(3)$	
$\overline{\underset{\sim}{16}}$	$\bar{C}(1)$	$\overline{C'}(5)$	
$\underset{\sim}{10}$	$H(-3)$	$H'(3)$	
$\underset{\sim}{1}$	$Z(-1)$	$\bar{Z}(-1)$	$S(2)$

MATTER

$\underset{\sim}{16}_1$	$9/2$
$\underset{\sim}{16}_2$	$7/2$
$\underset{\sim}{16}_3$	$3/2$
$T(\underset{\sim}{10})$	$3/2$

By assigning suitable $U(1)_A / U(1)_R$ charges :

$$U_{CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

.

$$U_{MNS} \sim \begin{pmatrix} 1 & \lambda^{0.5} & \lambda \\ \lambda^{0.5} & 1 & \lambda^{0.5} \\ \lambda & \lambda^{0.5} & 1 \end{pmatrix}$$

with $\lambda^{0.5} \simeq 0.5$

- dim 5 p decay is heavily suppressed with an estimated lifetime $\sim 10^{39}$ yrs.

- Higher dimensional terms in the Kähler potential, if not suppressed by small coefficients, can induce dimension six proton decay

$$\tau_{p \to e^+ \pi^0} \sim 10^{34-38} \text{ yrs}$$

if the cutoff is not far above th GUT scale.

SO(10)

- B−L gauged ;
- $\nu^c \Rightarrow$ seesaw ;
- D−T splitting 'easier' (than SU(5))
- Two GUT scale vevs ;
- Matter parity $\subset$ SO(10) $\left\{\begin{array}{c}\text{only tensor fields} \\ \text{have vevs}\end{array}\right\}$

As an example consider

$$\begin{array}{ccc} 45_H & , & 16_H, \overline{16}_H \\ \downarrow & & \downarrow \\ 3-2_L-2_R-1 & & SU(5) \text{ (no monopole or strings)} \\ \text{(monopoles)} & & \end{array}$$

DW Mechanism

$$\langle 45_H \rangle = \begin{pmatrix} 0 & & & & \\ & 0 & & & \\ & & a & & \\ & & & a & \\ & & & & a \end{pmatrix} \otimes i\tau_2$$

Then, from $\overset{\text{10-plet}}{T_1\, 45_H\, T_2}$,

doublets remain massless (finally one pa

triplets become superheavy.

But $\overline{16}_H\, 45_H\, 16_H$ can destabilize the mechanism.

[redacted]

To accomplish

- D-T splitting
- MSSM spectrum at low energies
- Inflation
- Complete absence of monopoles
- Absence of moduli ,

One needs (it seems):

2 pairs of $16, \overline{16}$;

2 45-plets ;

2 10-plets ;

Plus a bunch of singlets & add'l symmetries (such as $U(1)_A$).

One Solution (Barr, Raby)

45_H

16_H, $\overline{16}_H$, $\underbrace{16', \overline{16}'}$

Zero vev along the SU(5) singlet dir^n

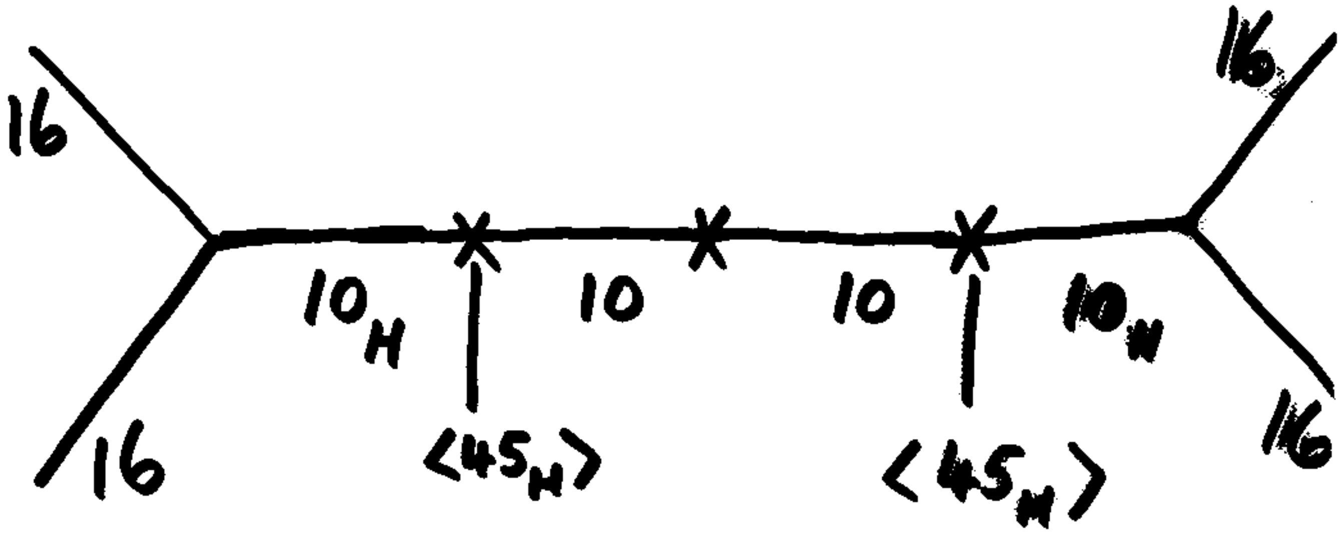
10_1, 10_2

+ bunch of singlets (avoid singlets with large vev & small (~Te masses somewhat suppressed ;

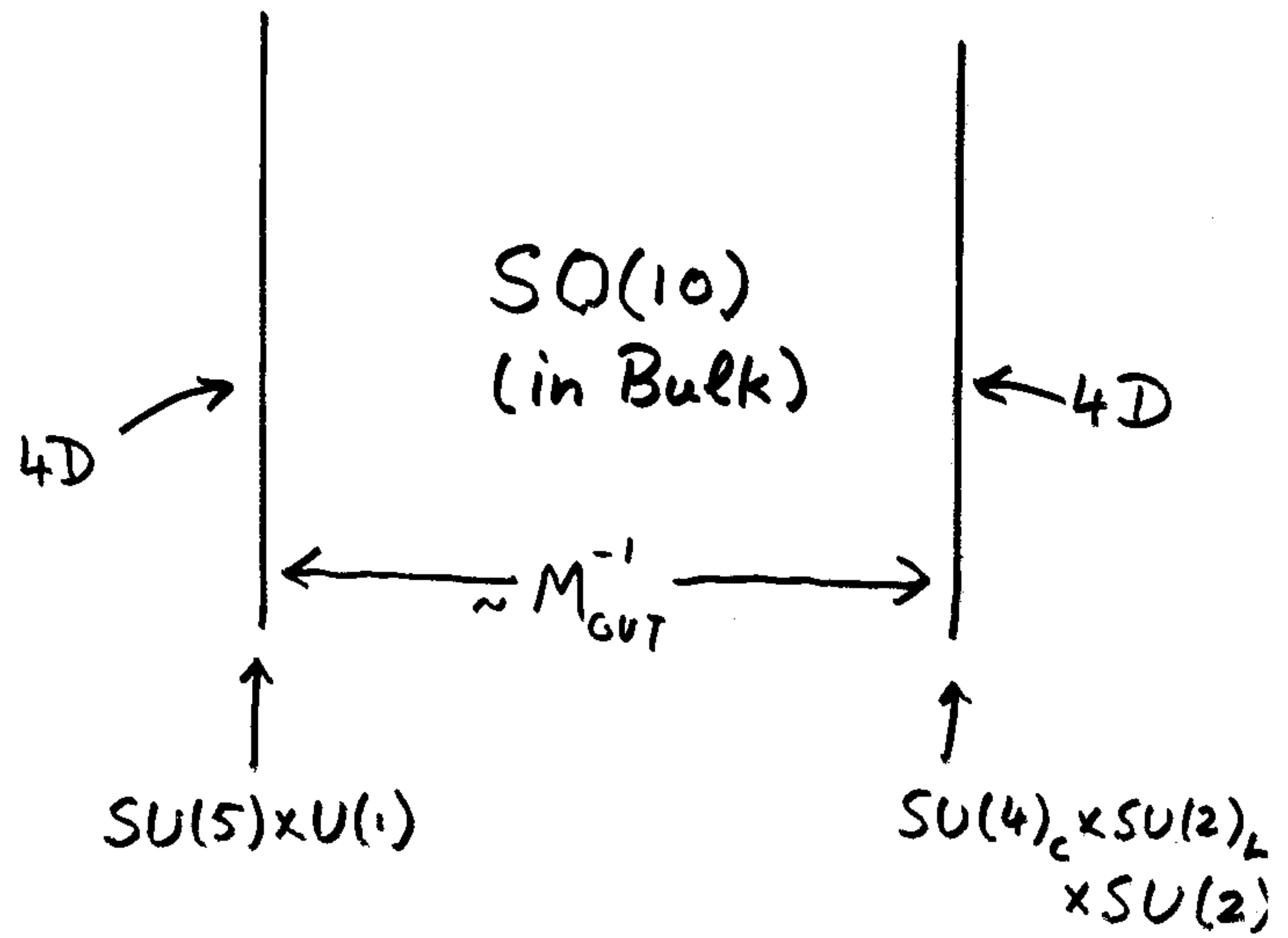
- To suppress it by a significant amount, one can include an additional 45-plet.

- Gauge boson mediated decay $p \to e\,\pi^0$ then becomes dominant ($\tau_p \sim 10^{35} - 10^{36}$ yrs).

dim 5 p decay



5-D SO(10)



- 5D SO(10) compactified on $S^1/Z_2 \times Z$
- 4D model is MSSM $\times$ U(1), with $N=1$ supersymmetry; ↳ break before
- Dim 5 p decay heavily suppressed
- But $p \to e^+ \pi^0$ enhanced relative to susy SU(5) by a factor ~ 10-10^2

SUMMARY

- MSSM $\times$ $U(1)_{B-L}$ is a compelling extension for implementing: inflation, $\delta T/T$, leptogenesis;
- resolving MSSM μ problem; stabilizing proton
- Dim 5 p decay is model dependent; heavily suppressed in some models (including SO(10)).
- $\tau_{p \to e^+ \pi^0} \sim 10^{34-36}$ yrs in some schemes.

FIND IT!