Remarks on Grand Unification and Proton Decay

Francesco Vissani

INFN, LNGS Theory Group

The idea is to provide some elements for a discussion of GUT and p-decay.

I gratefully acknowledge the suggestions and help of E. Bellotti, F. Cavanna, C. Galbiati, A. Ianni, O. Palamara; of Z. Berezhiani, F. Nesti, L. Pilo of the local theory group; and finally of my GUT collaborators C. Aulakh, B. Bajc, A. Melfo, G. Senjanović.

Contents

1 Historical Perspective and Introduction

Search since '60 (CERN). Sakharov expected $\tau_p = 10^{50}$ year.

Burst of interest after mid '70 (GUT) - '80 (SUSY GUT)

Explored $\tau_p = 10^{29} - 10^{33}$ year since then.

How to explore the next 1-2 orders of magnitudes?

GUT are still studied. No complete or fully convincing GUT yet.
Most HEP theorists work on other topics.

Here we speak only of gauge theories, in particular of GUT.

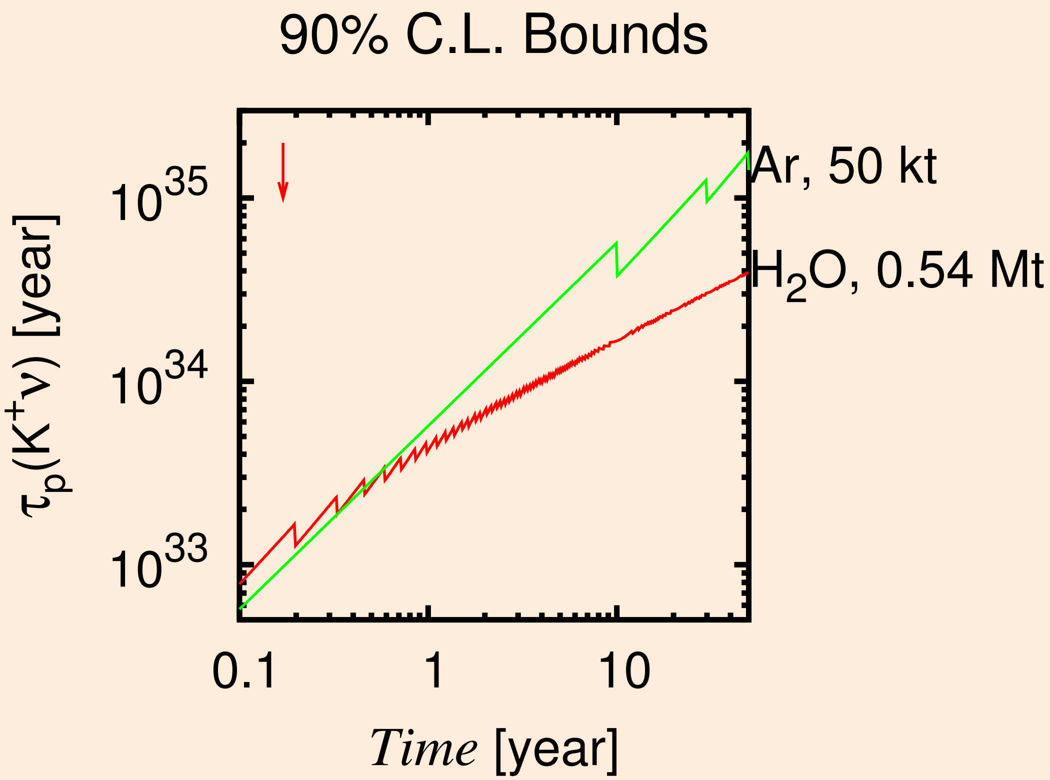
To proceed à la Super-Kamiokande (SK) it is essential to reduce the systematics we have today. Consider for instance $p \to K\bar{\nu}$.

With the best search method, the CL for $\tau_p > 10^{34}$ y is:

time	4 y	20 y	100 y	500 y
$\mathcal{L}(\sigma)$	10%	34%	45%	49%
$\mathcal{L}(\sigma/3)$	11%	43%	73%	90%

using $\sigma_{\text{signal}} = 20\%$ and $\sigma_{\text{background}} = 59\%$ for Gaussian smearing (500 y SK means 11 Mton y and $S/B = 32/85$)

In other decay modes such as $p \to \pi^0 e^+$ detectors of this type is known to perform better.



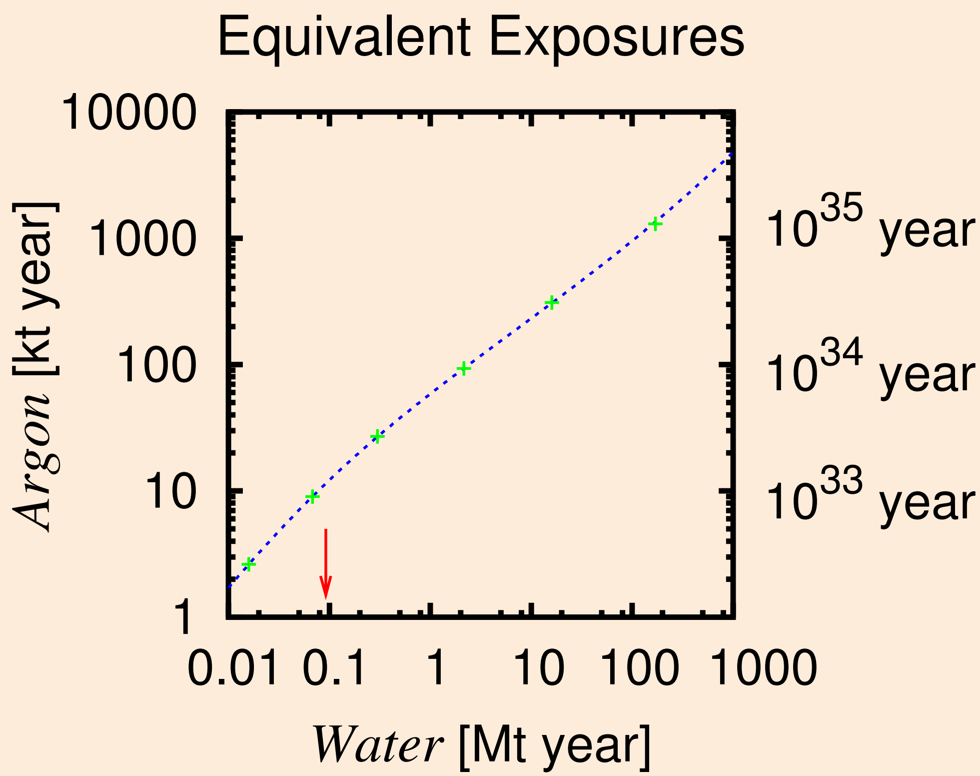


Figure 1: Sensitivity to $p \to K\bar{\nu}$; syst. not included. Water, $\epsilon = 14.6\%$ and $b = 14/(\mathrm{Mton\ y})$ (2 methods, summed); Argon, $\epsilon = 97\%$ and $b = 1/(\mathrm{Mton\ y})$. Impact of stat. fluctuations ≈ 2.

2 Standard Model

Fermion content (each family):

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{matrix} u_R \\ d_R \end{matrix} \quad \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \quad \begin{matrix} \bullet \\ e_R \end{matrix}$$

Scalar content:

$$\begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$

2.1 Features

For each family, 5 fermionic representations

Just 1 scalar doublet *(remarkably simple, not always appreciated)*

Number of parameters:

- 1 mass scale *(1 Higgs, 1 scale)*
- 17 couplings = 3 gauge, 1 Higgs, 13 Yukawa *(a lot)*

Theorem:

> Neutrinos are massless and the proton is stable:
>
> B-L exactly conserved; B or L only perturbatively.

2.2 Looking beyond

W/o renormalizability, much alike Fermi interactions: 1 operator for ν-masses (dim.5), 6 possible operators for p-decay (dim.6), *etc.*

M_{Planck} as the cutoff? *(Sakharov's* 10^{50}*; but* ν *mass too small)*

Adding the right handed neutrinos ν_R to SM:

- recover a renormalizable lagrangian
- obtain the effective operator for ν-masses
- baryogenesis through non-perturbative (B+L)-violations

3 Minimal SU(5) (Georgi-Glashow)

Fermion content (each family):

$$\bar{5}_M = (d^c, l), \quad 10_M = (u^c, q, e^c)$$

Scalar content:

$$24_H, \quad 5_H$$

(meaning of the indices: M stays for matter, H for Higgs field)

3.1 Features

2 Fermions per family; *quark and leptons unified*

2 Scalars: 1 to break SU(5)→SM; 1 for fermion masses

Theorem 1:

incompatible with observed gauge couplings

Theorem 2:

compatible with observed gauge couplings
if SM→ MSSM near ~ 100 GeV

can be seen as prediction of low energy SUSY. That's why SUSY oft-included in the definition of 'minimal SU(5)' that we follow.

3.2 Expectations for p-Decay

p-decay through gauge bosons ($G_{\rm eff} = g^2/M_X^2$) and/or Higgs triplets. The last dominate in Minimal (SUSY) SU(5):

$$G_{\rm eff} = \frac{g^2}{(4\pi)^2} \frac{''Y_{\rm up}'' \; ''Y_{\rm down}''}{M_{\rm tripl} M_{\rm SUSY}}, \quad \tau_p \sim 1/(G_{\rm eff}^2 \Lambda_{\rm QCD}^5)$$

Uncertainties are considerable. Expect $p \to K^+ \bar{\nu}$ among the faster channels. In actual calculations, τ_p can range till 10^{33} years.

Is minimal SU(5) ruled out by Super-Kamiokande?
Different claims in literature, wait 1 page for my view.

3.3 Criticisms to "Minimal SU(5)"

1. ν-mass is zero *(so: yes, just as the SM, it is ruled out by SK)*
2. Even worse: $M_{\rm down\ quarks} = M_{\rm charged\ leptons}$ as implied by the higgs choice. It works for $m_b = m_\tau$, for lighter fermions fails.
3. R-parity (needed to have DM candidate) must be imposed

$$\bar{5}_{\rm matter} \sim \bar{5}_{\rm Higgs}$$

Minimal SU(5) is not a complete theory but I suspect that its failures should be thought as valuable keys for the construction of a reliable GUT. Even more, I doubt we can hit a theory of p-decay without hitting a theory of fermion masses.

4 Left-right and Pati-Salam Groups

Other groups offer some understanding of fermions and include ν_R:

$\star$ SU(3)$_c\times$SU(2)$_L\times$SU(2)$_R\times$U(1)$_{B-L}$ (left-right)
Fields of the 2 chiralities are arranged symmetrically, e.g.,

$$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \text{ and } \begin{pmatrix} \nu_{eR} \\ e_R \end{pmatrix}$$

The left-right group, in turn, is included in the Pati-Salam group

⋆ SU(4)×SU(2)$_L$×SU(2)$_R$ (Pati-Salam)

Quarks and leptons fit together in a very elegant manner:

$$(4,2,1)_L = \begin{pmatrix} u_{1L} & u_{2L} & u_{3L} & \nu_{eL} \\ d_{1L} & d_{2L} & d_{3L} & e_L \end{pmatrix},$$

$$(4,1,2)_R = \begin{pmatrix} u_{1R} & u_{2R} & u_{3R} & \nu_{eR} \\ d_{1R} & d_{2R} & d_{3R} & e_R \end{pmatrix}.$$

Next, we show a group that contains both SU(5) and Pati-Salam group, inheriting their appealing features.

5 SO(10) (Fritzsch-Minkowski, Georgi)

Fermion content (each family):

$$16_M$$

SU(5) and Pati-Salam $\subset$ SO(10). Fermion field decomposition:

$$16 = (4, 2, 1) + (\bar{4}, 1, 2) = 10 + \bar{5} + 1$$

The choice of Higgs is crucial, not simple and not unique.

An advert: in Bern on May 6, 2006, workshop in honor of Peter Minkowski *"SO(10) 2006: Neutrino & Fermion Masses, p-Decay & Leptogenesis"*

5.1 Features

1. (try the smaller Higgs representation first)

The 'smallest' higgs is a 10-plet, but it fails immediately:

$$16_M \; \mathbf{10_H} \; 16_M \Rightarrow m_\nu = m_{top}$$

2. (Higgs for ν_R masses)

In fact, there is no choice:

> *if we have to give large mass to ν_R, we need a higgs which contains an SU(2)$_L$ singlet: this is the $\overline{\mathbf{126}}_\mathbf{H}$*

We assume the existence of a fundamental $\overline{\mathbf{126}}_\mathbf{H}$ field, but recall that an effective field $\overline{\mathbf{126}}_\mathbf{H} \sim \mathbf{16_H 16_H}$ could be sufficient.

3. (*new possibilities for gauge coupling unification*)

Intermediate gauge scales are possible, so that even non-SUSY SO(10) could work. Note that:

- The scale of SO(10) breaking controls proton decay;
- the scale of $SU(2)_R$ and B-L breaking control the mass of ν_R.

4. (*tight constraints on fermion masses*)

The fermions fit in 16-plets $\Leftrightarrow$ the flavor group is just U(3). This means that fermion masses are more constrained. Possibly the flavor group has a dynamical meaning *(we do not discuss this)*

5.2 Minimal non-SUSY Model

The first SO(10) model I present is non-supersymmetric and includes a $\mathbf{54_H}$. Unification takes place through:

$$\text{SO(10)} \to \text{Pati-Salam} \times \text{Parity} \to \text{SM}$$

Fermion masses require another Higgs among other, e.g., $\mathbf{10_H}$.

$p \to e^+\pi^0$ is induced and expected to be relatively fast, but:

1. *The scale is not so precisely known due to possible deviations from 'survival principle';*
2. *Fermion masses implies further relevant effects, similar to appearance of quark mixing in Fermi interactions.*

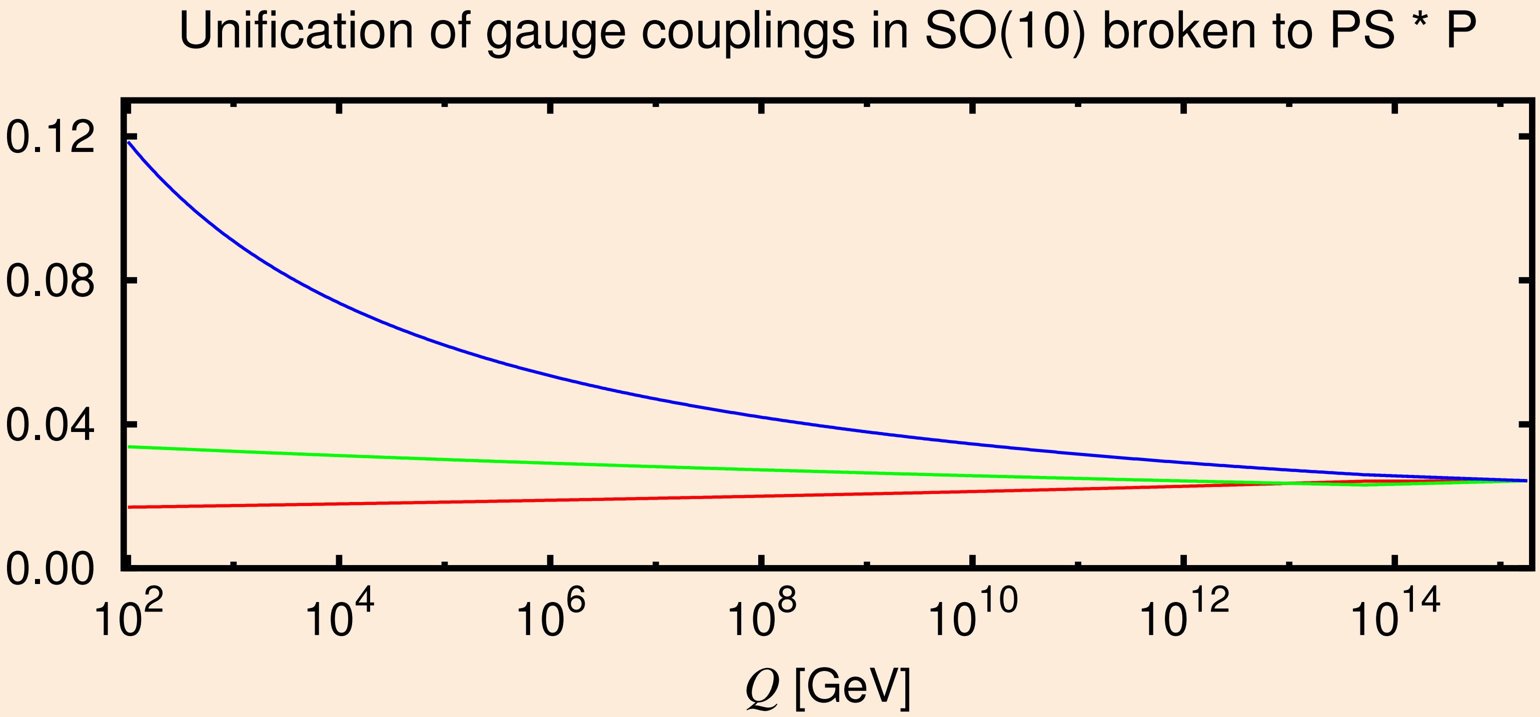


Figure 2: Evolution of the gauge coupling constants in a GUT model with intermediate scale. Here, $M_{\text{interm.}} \approx 5 \times 10^{13}$ GeV.

5.3 Minimal SUSY Model

The second SO(10) model is SUSY. We select $\mathbf{10_H}$ for b-tau unification and take care of SUSY by having $\overline{\mathbf{126}}_\mathbf{H}$ *and* $\mathbf{126_H}$. Adding one last Higgs, the $\mathbf{210_H}$, completes the model and gives chance of realistic fermion masses (ν included) e.g.,

$$\begin{aligned} M_{\rm down\ quarks} &= Y_{10}\,\langle H_{10}\rangle \quad + \quad Y_{126}\,\langle H_{126}\rangle \\ M_{\rm charged\ leptons} &= Y_{10}\,\langle H_{10}\rangle \quad -3 \quad Y_{126}\,\langle H_{126}\rangle \end{aligned}$$

Quantitative studies are in progress.

5 different triplets can mediate p-decay; however, this has to be studied after we are sure that fermion masses come out right.

6 Summary

It is much more difficult to test GUT than SM, but we *need* to formulate complete GUT. We discussed certain SO(10) GUT, of which we are studying fermion masses; if OK, next step is p-decay.

I did not even try to be exhaustive. Indeed there are
more approaches and principles: naturalness, mechanism for doublet-triplet splitting, flavor physics, other/higher unification (e.g., SU(6), E6), systematic inclusion of higher dim. opp., string selection criteria... More observables as well: higgs mass, $0\nu2\beta$, ν oscillations, collider exps., baryogenesis, FCNC, $\mu \to e\gamma$, nature of DM...

Rather I tried to argue we can still rely on old good gauge principle, i.e., on GUT. Simplest possibilities should be explored in detail. In any case, I believe it is important to adopt precisely defined frameworks, for $M_X \times 2$ means τ_p(gauge)$\times 16$.

7 Offline Discussion

Here I collect a number of interesting questions raised by the participants in the meeting after the talk, thanking them warmly for offering an occasion of clarify certain important points.

Q1 Aren't the nuclear uncertainties in proton decay considerable?

A1 I was intentionally vague in the talk on this point, but now I must admit my ignorance. However, borrowing from what I know from beta and double beta decay I would be surprised if the matrix elements are better known than a factor of a few (which should be squared to get the lifetime).

Q2 Which Argon exposure would be competitive with present SK result on $p \to K\bar{\nu}$?

A2 From the exposure of 92 kt year I get 11 kt year (from the lifetime $2\ 10^{33}$ year, 18 kt year). This is easy to understand from the efficiency 6 % and 8.6 % in the two best methods (that, we recall, have still no candidate event).

Q3 Why the research on GUT is not pushed with more strenght?

A3 I don't know. Certainly, there is a specific know-how accumulated since eighties that, with the time, risks to be abandoned. I am very grateful to my collaborators and in particular to Senjanovic and Berezhiani who work in the field since a quarter of a century and who taught me a lot.

Q4 In which sense you say that Minimal SU(5) is 'ruled out'?

A4 In the sense that it contradicts some well-known experimental facts (in particular neutrino masses). This contradiction does not mean that SU(5) is not a useful starting point to investigate unified theories, but certainly, it warns us from taking SU(5) too literaly. In particular, for what concerns τ_p.

Q5 Can we modify SU(5) to include massive neutrinos?

A5 Yes we can, in much the same manner that we can do for the SM (just for the record one could even relax R-parity and get massive neutrinos if we wish so). In my view, the real concern is whether using SU(5) we can produce a predictive setup or if we cannot.

Q6 What are the advantages of SO(10)?

A6 There is the aesthetic point I described, that the fermions look to be more ordered, and also a more practical consideration that SO(10) could provide a more predictive theory of fermion masses, to be eventually tested with leptogenesis and proton decay. In short SO(10) option is nicer but certainly I do not believe it is a unique possibility; furthermore does not help to understand family replication.

Q7 Isn't the 126-plet too big to be believable?

A7 I agree that the 126-plet is not appealing at first sight (and it is not so easy to work with it) but I do not see a real reason for this hypothesis not to be explored. String people claim that it is not so easy to get a 126-plet: if correct, this would be one of the few useful results from string theory. At the moment I believe we should not forget this possibility.

Q8 Are there other SO(10) models?

A8 Yes several ones. Many of them replace the 126-plet with a pair of 16-plet. E.g., this is done in a renormalizable model (Witten), or using the U(3) flavor symmetry to understand the fermion masses (Berezhiani & Nesti). The models I described in the talk have been selected by the criterion of simplicity, or more honestly by the fact that I happened to work on them.

Q9 Why not to include effective operators in SM, SU(5) and/or SO(10)?

A9 I have a personal preference toward renormalizable models and this is the type of models I emphasized, but I agree that this could be important. In particular, effects order $M_{\rm GUT}/M_{Planck}$ (with the conventional definition of M_{Planck}) are large and should possibly be understood or included.

Recall that, since Weinberg and Wilczek-Zee, the SM itself is often regarded as an effective theory where all possible effective operators are present at some scale. In this extended sense, we are not entitled to say that SM (or SU(5)) is ruled out by the observation of ν masses, whereas it is ruled out when it is defined as a renormalizable theory with a certain particle content.

Q10 Can you comment on R-parity in the context of SUSY GUT models.

A10 In SU(5) (or SM) R-parity has to be imposed by hand. Certain SO(10) models (like those with 126) predict the existence of R-parity as a theorem, instead.

Q11 Can you suggest useful references to go more into details (Or: for an introduction to GUT)?

A11 I recommend to use SPIRES

`http://www.slac.stanford.edu/spires/hep/`

for a personalized bibliographic search (in particular if you are interested in the results I described in the last slides). In case you want, please just pay me an email at the address:

`vissani@lngs.infn.it`

Q12 Why you use LaTeX to prepare your slides?

A12 Because it is not forbidden–is it?