Brussels, June 5 2013

Grand unification - the quest for predictivity

Michal Malinský

Institute of Particle and Nuclear Physics, Charles University in Prague

based on

Phys.Rev.D80 015013 2009
Phys.Rev.D81 035015 2010
Phys.Rev.D85 095014 2012
Phys.Rev.D87 085020 2013

in collaboration with
Stefano Bertolini (SISSA/ISAS & INFN Trieste)
and Luca di Luzio (KIT Karlsruhe)

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MARIE CURIE ACTIONS

SEVENTH FRAMEWORK PROGRAMME

Outline

GUTs are spontaneously broken BSM gauge theories based on simple compact gauge groups

SU(5), SO(10), E_6 ...

Outline

- SU(5) as a prototype GUT
- What kind of physics are GUTs about?
- How were/are GUTs tested?
- Status of the minimal SO(10) models
- Recent developments

The Georgi-Glashow SU(5)

The Georgi-Glashow SU(5) as a prototype GUT

H. Georgi, S. Glashow, PRL 32, 1974

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

$$(1,2,-\tfrac{1}{2}) \quad \begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$

$$(1,1,+1) \quad e^c \quad \mu^c$$

$$(3,2,+\tfrac{1}{6}) \quad \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix}$$

$$(\bar{3},1,-\tfrac{2}{3}) \quad u^c \quad c^c$$

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$$\overline{5} \quad \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ -e \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} s_1^c \\ s_2^c \\ s_3^c \\ -\mu \\ \nu_\mu \end{pmatrix}$$

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Gauge sector:

$(8,1,0)$ G^μ

$(1,3,0)$ A^μ

$(1,1,0)$ B^μ

$\left.\begin{matrix} A^\mu \\ B^\mu \end{matrix}\right\} W^\pm, Z, \gamma$

$$24 = (8,1,0) \oplus (1,3,0) \oplus (1,1,0) \oplus (3,2,-\tfrac{5}{6}) \oplus (\overline{3},2,+\tfrac{5}{6})$$

G^μ A^μ B^μ $\begin{pmatrix} X^\mu \\ Y^\mu \end{pmatrix}$

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$\begin{pmatrix} X^\mu \\ Y^\mu \end{pmatrix}$ new gauge bosons

Higgs sector: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \to SU(3)_c \otimes U(1)_Q$

$(1,2,-\tfrac{1}{2})$ H

$$\overline{5} = \underset{i\tau_2 H^*}{(1,\overline{2},+\tfrac{1}{2})} \oplus \underset{\Delta_c}{(\overline{3},1,-\tfrac{1}{3})}$$

new coloured scalars

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$\overline{5} = (1,\overline{2},+\frac{1}{2}) \oplus (\overline{3},1,-\frac{1}{3})$

$i\tau_2 H^*$ Δ_c

new coloured scalars

GUT-breaking Higgs: $SU(5) \to SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

yet some extra scalars

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The Georgi-Glashow SU(5) as a prototype GUT

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.

of the GIM mechanism with the notion of colored quarks[4] 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 that there are no fundamental strongly interacting scalar-meson fields.[6] This insures that

- Georgi and Glashow have shown the uniqueness of SU(5) as a rank=4 GUT

What kind of physics are GUTs about?

Charge quantization

Generators of simple non-Abelian Lie groups are discrete & traceless

$\Downarrow$

charges obey non-trivial algebraic relations

Charge quantization

Generators of simple non-Abelian Lie groups are discrete & traceless

⇩

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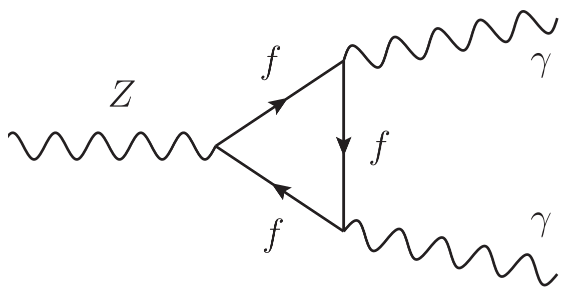
Wait; anomalies quantize (hyper)charge in the SM too!?



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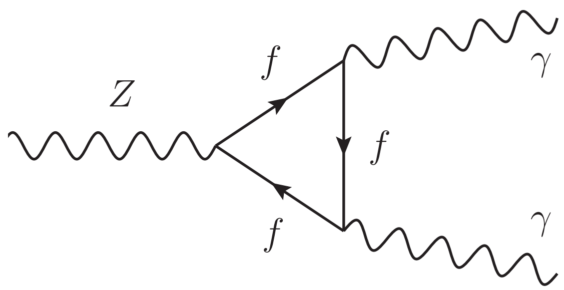

Not if you do believe in RH neutrinos...

$$Y = Y_{SM} + \varepsilon(B - L)$$

Foot, Lew, Volkas, Mod.Phys.Lett. A5 (1990) 2721

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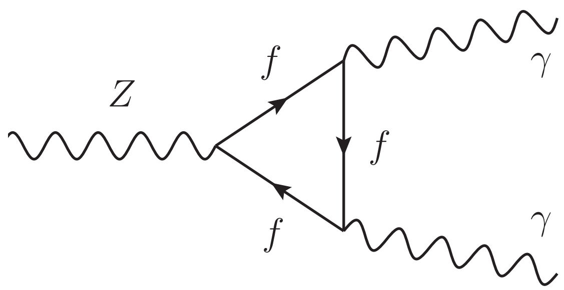

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Majorana OK...

Babu, Mohapatra, PRL 63 (1989) 938

Monopoles

Non-trivial vacuum manifold homotopy

$\Downarrow$

heavy topologically stable finite-energy extended Higgs/gauge configurations

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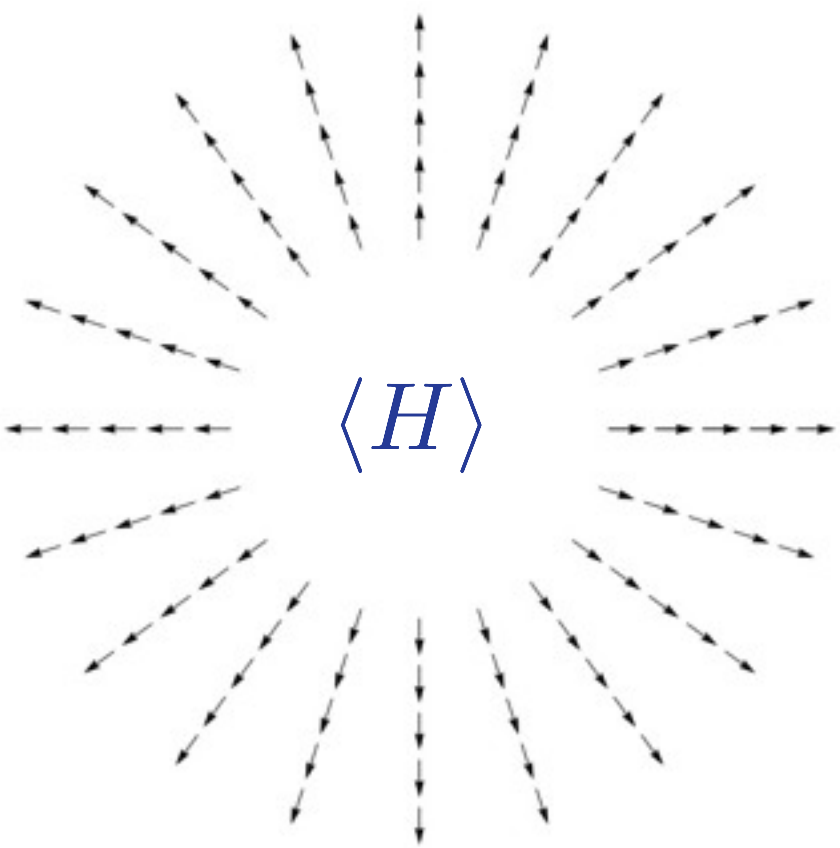
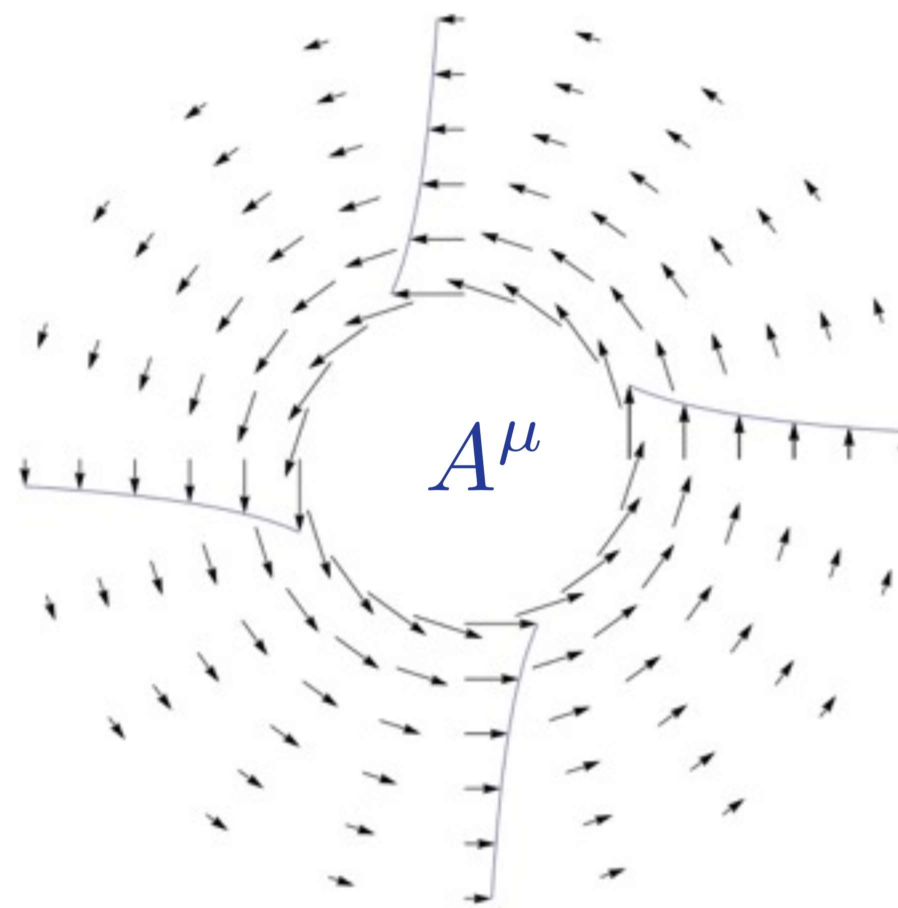


monopoles

vortices

domain walls

...

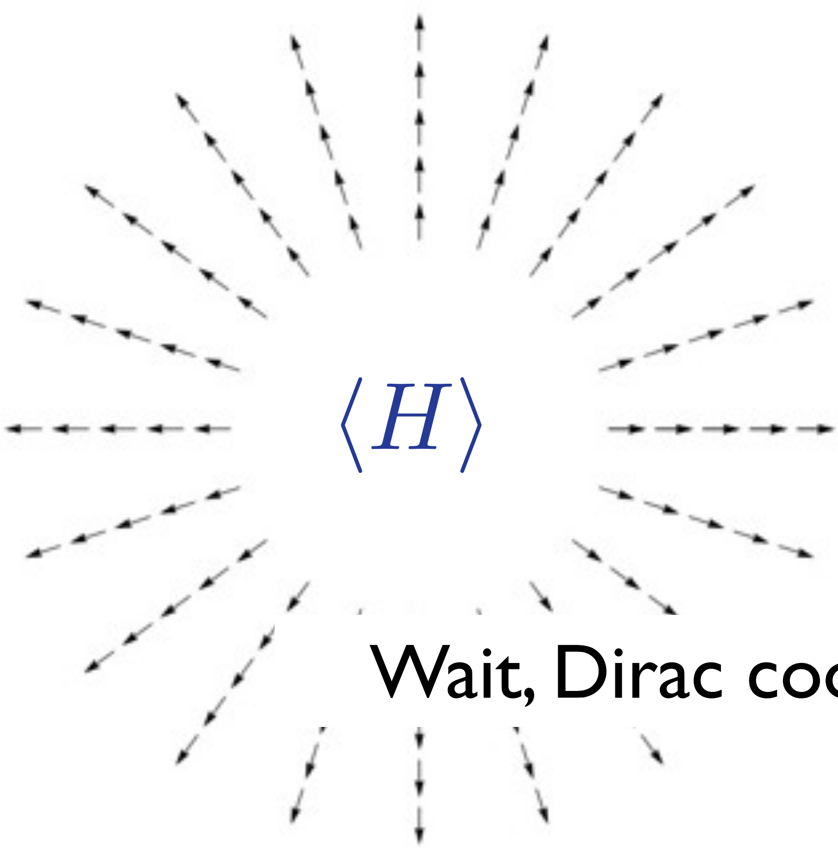


Monopoles

Non-trivial vacuum manifold homotopy

⇩

heavy topologically stable finite-energy extended Higgs/gauge configurations



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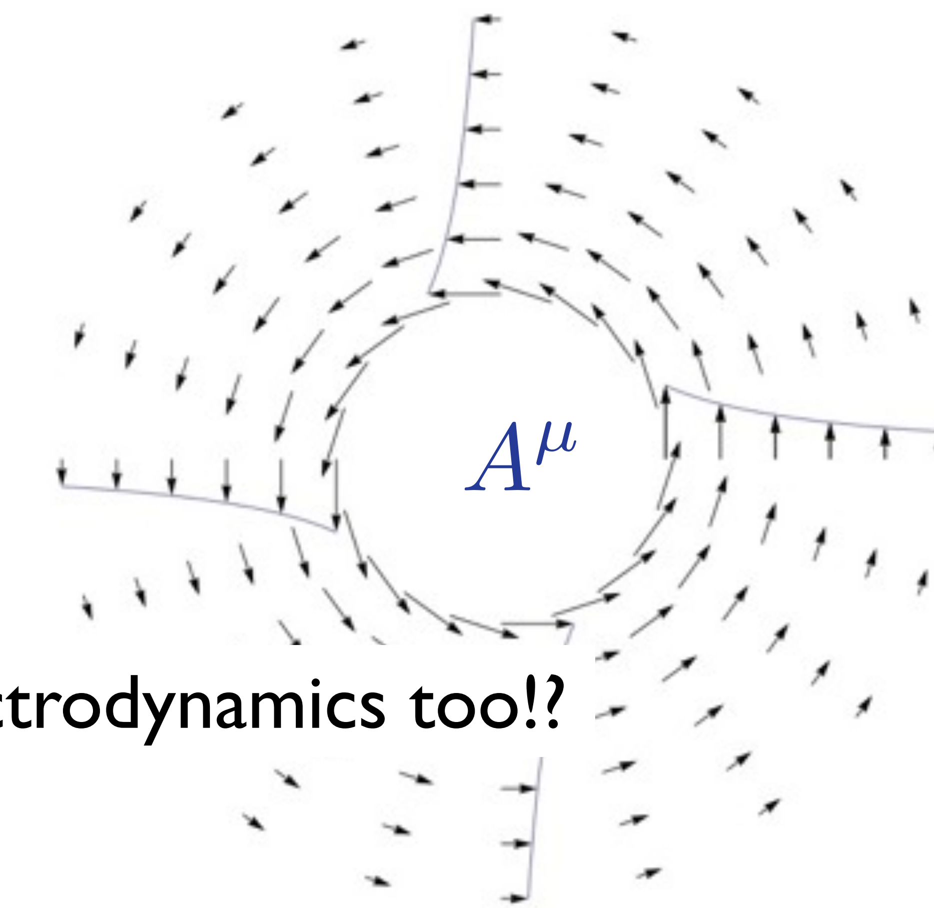

Wait, Dirac cooked a monopole in electrodynamics too!?

P. A. M. Dirac, Proc. Roy. Soc. A 33, 6, (1931)

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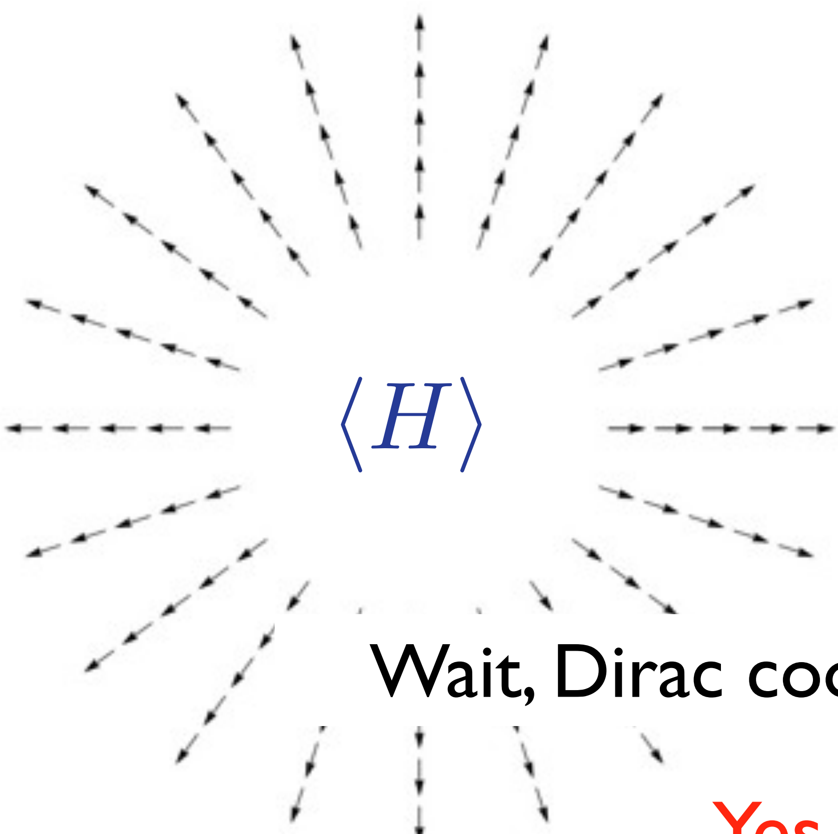

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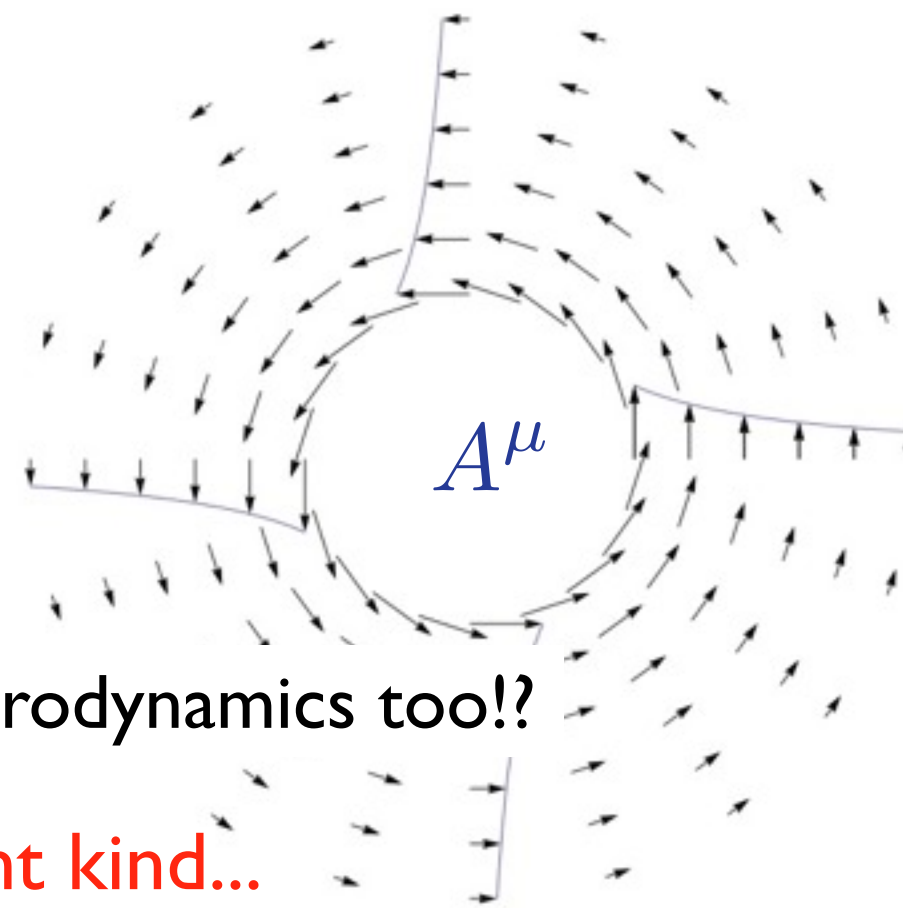

Wait, Dirac cooked a monopole in electrodynamics too!?

Yes, but of a slightly different kind...

P. A. M. Dirac, Proc. Roy. Soc. A 33, 6, (1931)

Baryon/lepton number violation & flavour

- Quarks and leptons share GUT multiplets

  - gauge bosons coupled to a universal charge

  - Yukawas do not care about who is who either

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quark to lepton transitions
proton decay
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SU(5) example: $Y_5 \overline{5}_F 10_F \overline{5}_H + Y_{10} 10_F 10_F * \overline{5}_H^\dagger$

$$M_d = M_l^T \qquad M_u = M_u^T$$

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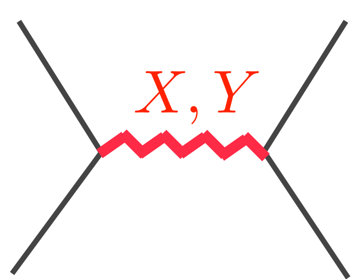
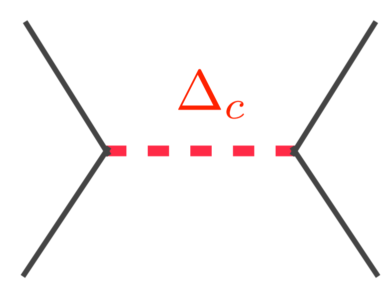
- d=6 proton decay:

gauge-induced



$$\frac{f_1}{M_G^2}\overline{Q}u^c\overline{Q}e^c, \quad \frac{f_2}{M_G^2}u^c\overline{Q}d^c\overline{L}$$

Higgs-induced



$$\frac{f_3}{M_G^2}QQQL, \quad \frac{f_4}{M_G^2}u^cu^cd^ce^c$$

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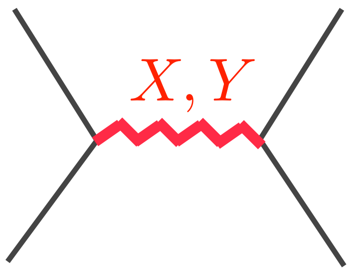

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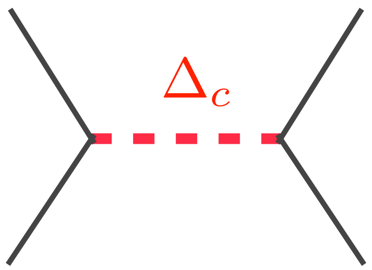

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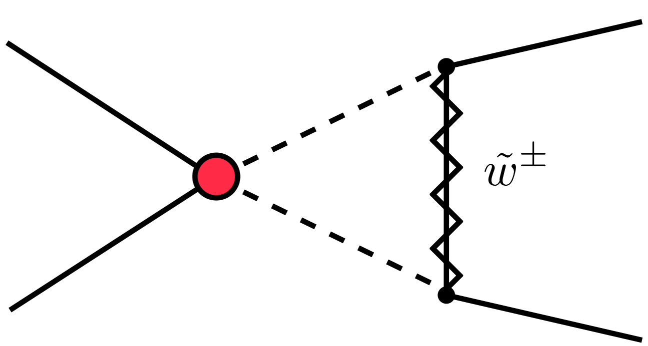
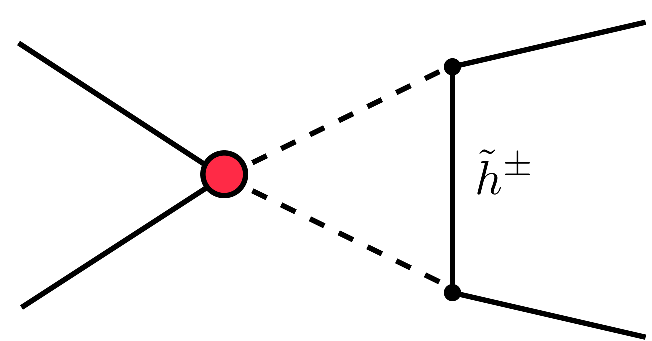
- d=5 proton decay in SUSY:



$$W_L \sim \frac{c_L}{M_{\Delta_c}} \hat{Q}\hat{Q}\hat{Q}\hat{L}$$



$$W_R \sim \frac{c_R}{M_{\Delta_c}} \hat{u}^c\hat{u}^c\hat{d}^c\hat{e}^c$$

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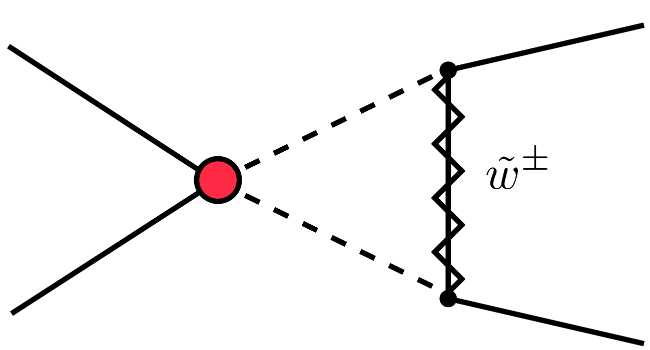

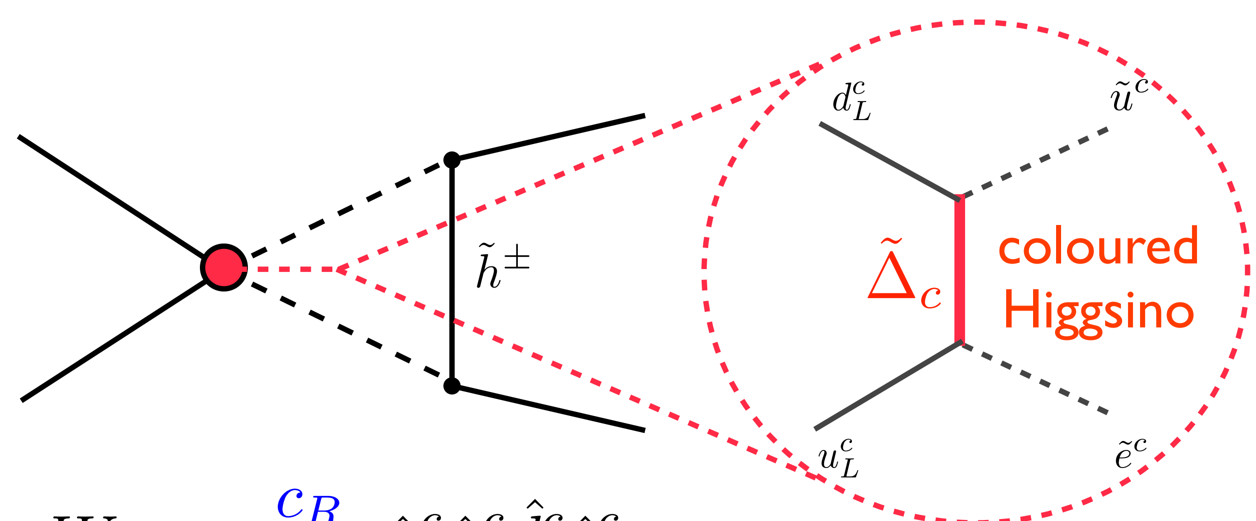

$$W_L \sim \frac{c_L}{M_{\Delta_c}} \hat{Q}\hat{Q}\hat{Q}\hat{L} \qquad W_R \sim \frac{c_R}{M_{\Delta_c}} \hat{u}^c \hat{u}^c \hat{d}^c \hat{e}^c$$

$$c_L,\, c_R \sim Y_u Y_d^\dagger,\, Y_u^\dagger Y_d$$

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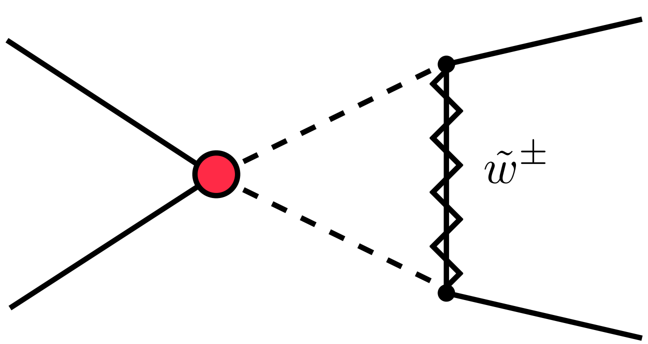
- d=5 proton decay in SUSY: Kaons favoured: $p^+ \to K^+ \bar{\nu}, \ldots$!!!



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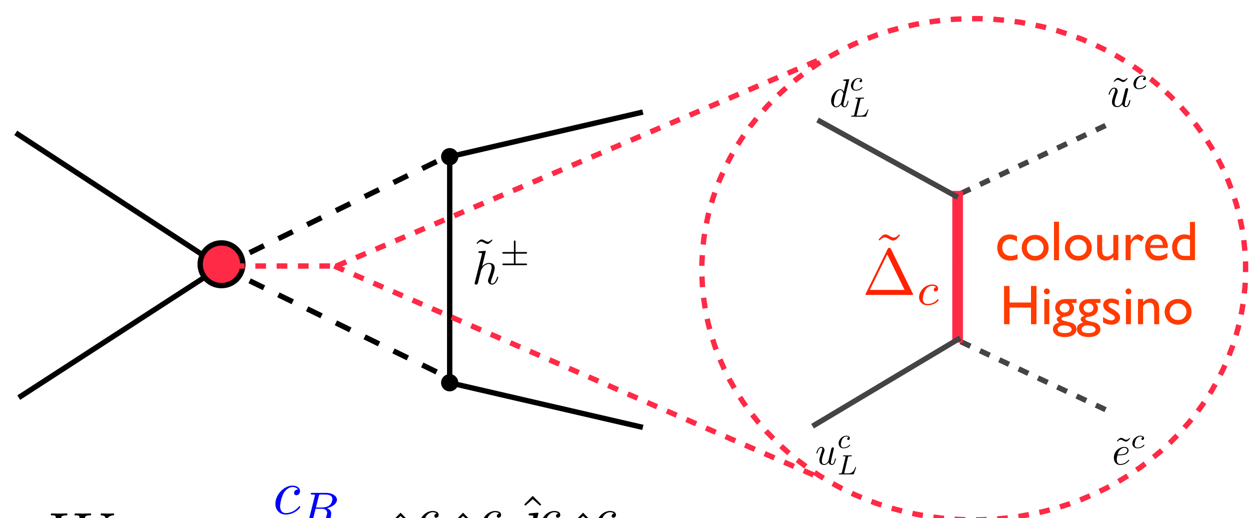

$$W_R \sim \frac{c_R}{M_{\Delta_c}} \hat{u}^c \hat{u}^c \hat{d}^c \hat{e}^c$$

$$c_L,\, c_R \sim Y_u Y_d^\dagger,\, Y_u^\dagger Y_d$$

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- Instantons (at zero T) cause $9q + 3l \leftrightarrow \emptyset$ with immesurably small rates

$$^3He \rightarrow e^+\mu^+\overline{\nu}_\tau$$

$$\mathcal{A} \sim e^{-2\pi/\alpha_w} \sim 10^{-80}$$

Baryon/lepton number violation & flavour

Wait; baryon/lepton numbers (B+L) are broken in the SM too !?

Yes, but only by anomalies (at renormalizable level)

- Instantons (at zero T) cause $9q + 3l \leftrightarrow \emptyset$ with immesurably small rates

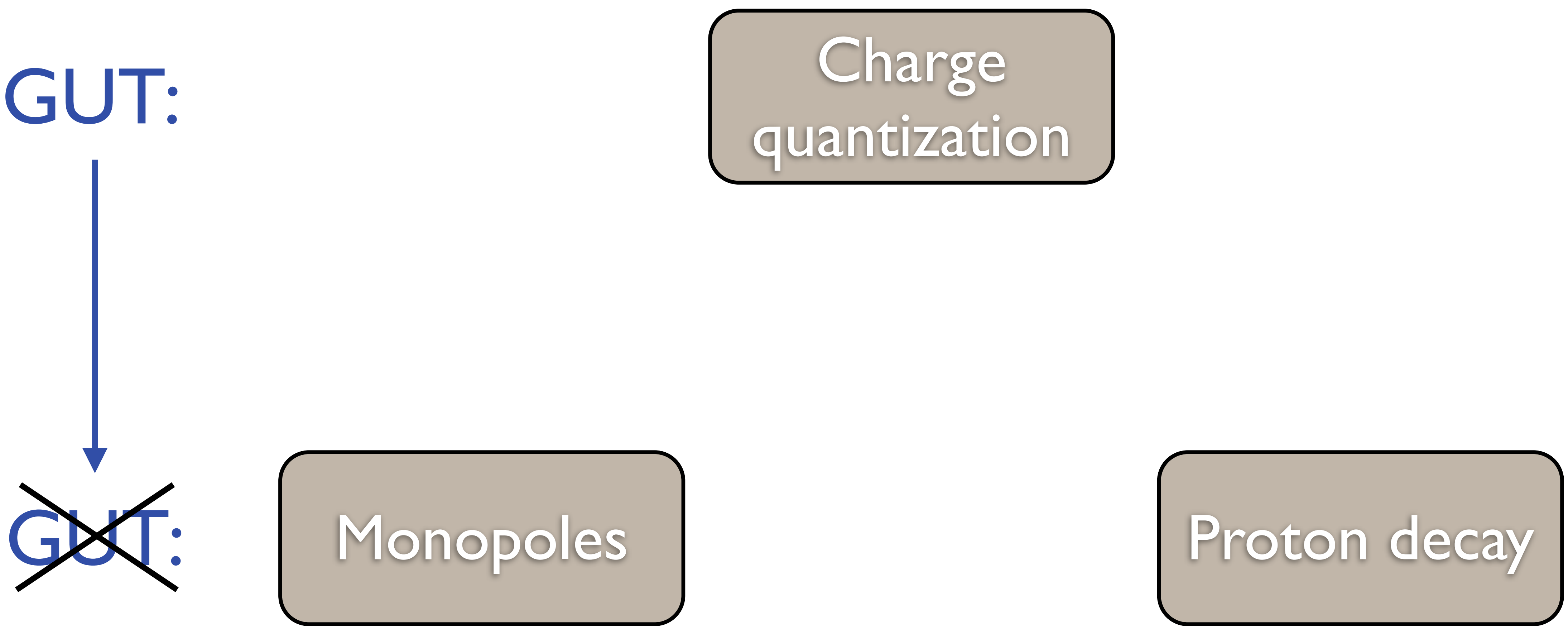
$$^3He \rightarrow e^+\mu^+\overline{\nu}_\tau$$

$$\mathcal{A} \sim e^{-2\pi/\alpha_w} \sim 10^{-80}$$

- Sphalerons (at high T) make the tunneling more efficient ⇨ leptogenesis

Kuzmin, V. Rubakov, M. Shaposhnikov, PLB155, 1985 Fukugita, Yanagida, PLB174, 1986

All these are tightly connected...



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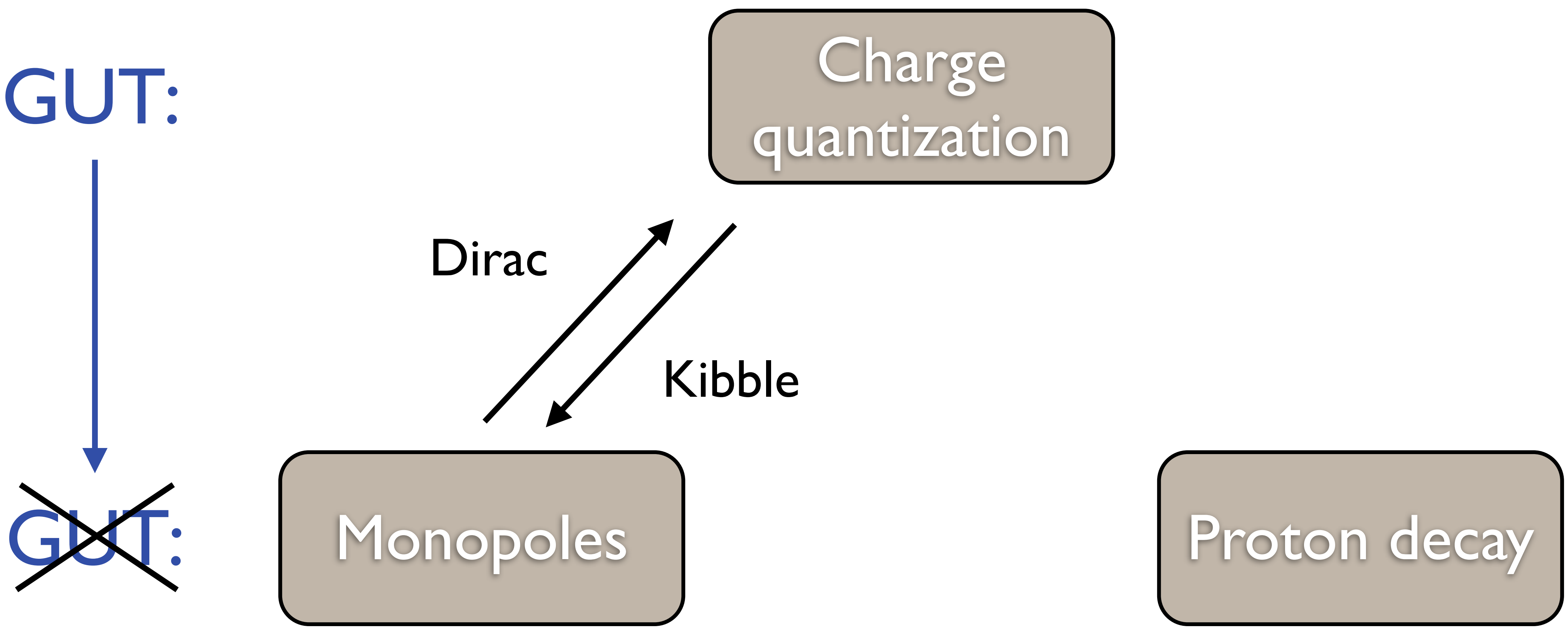

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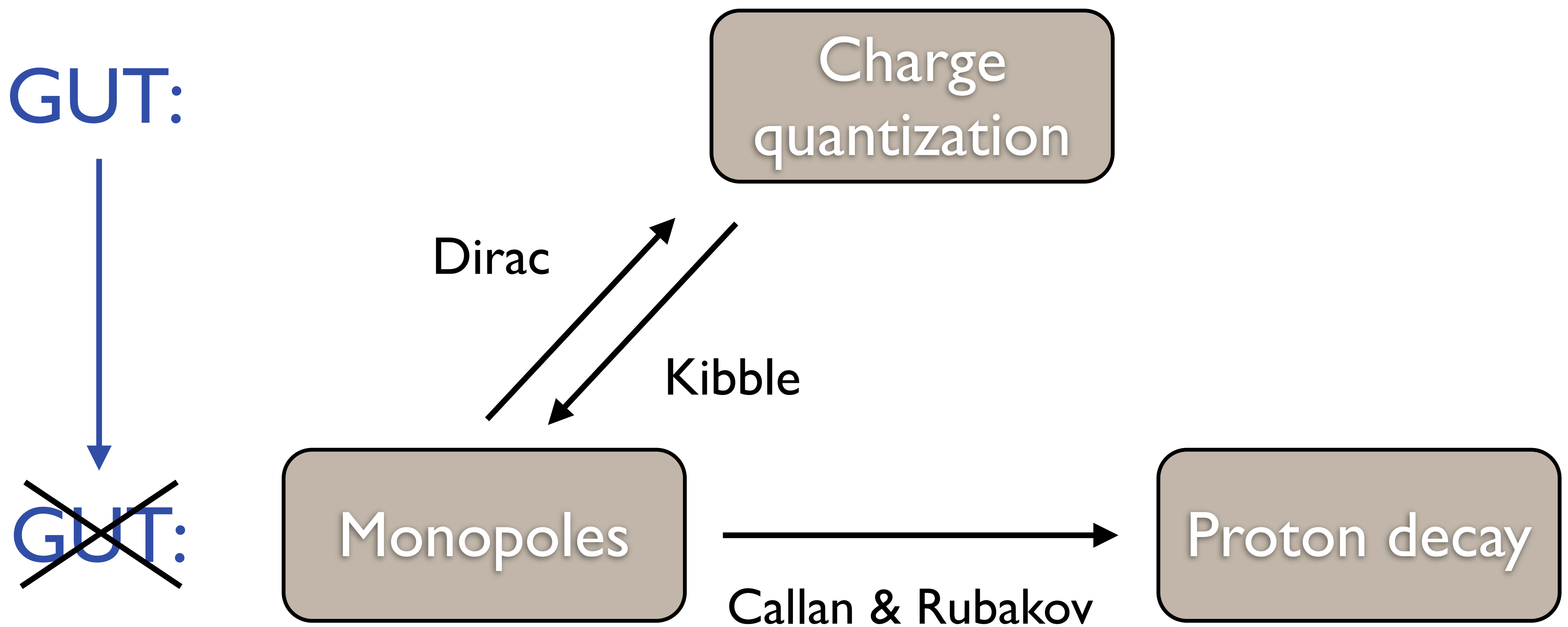

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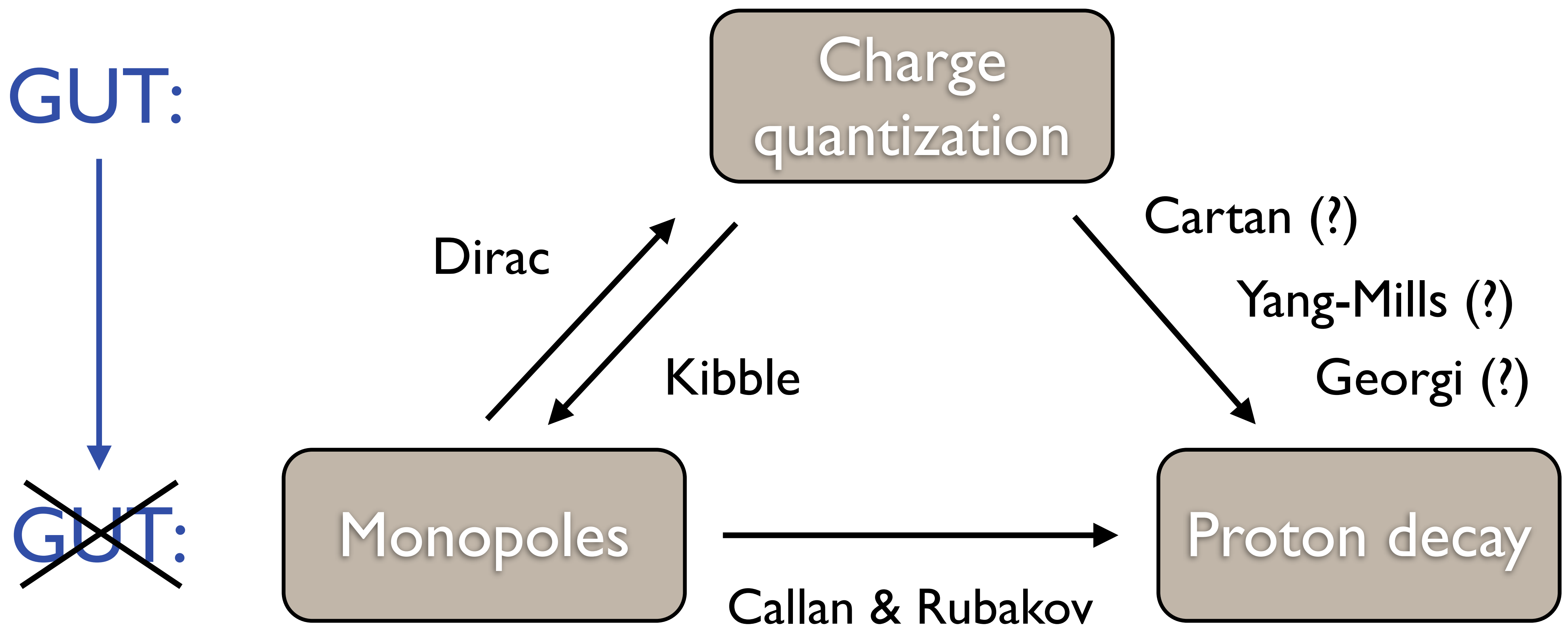

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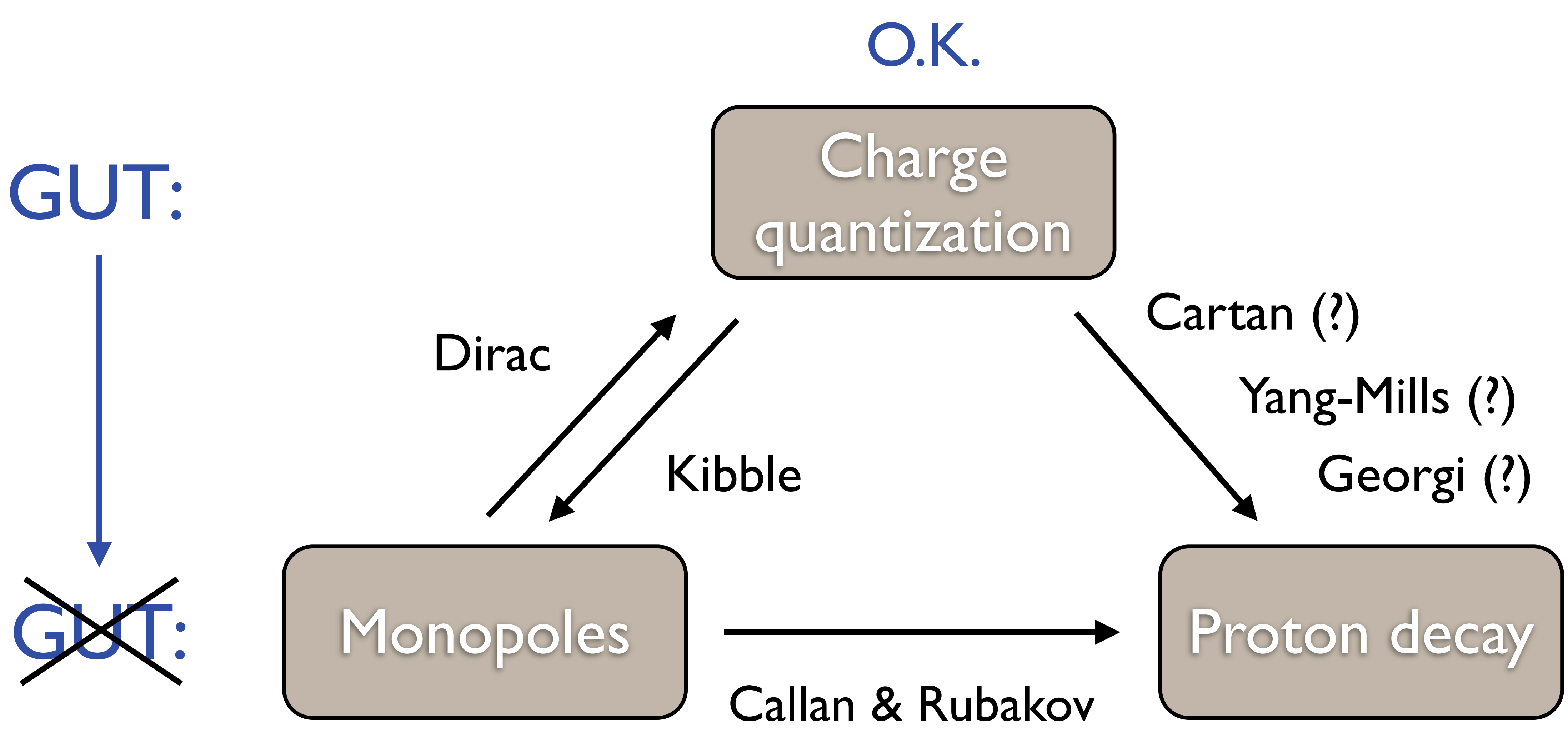

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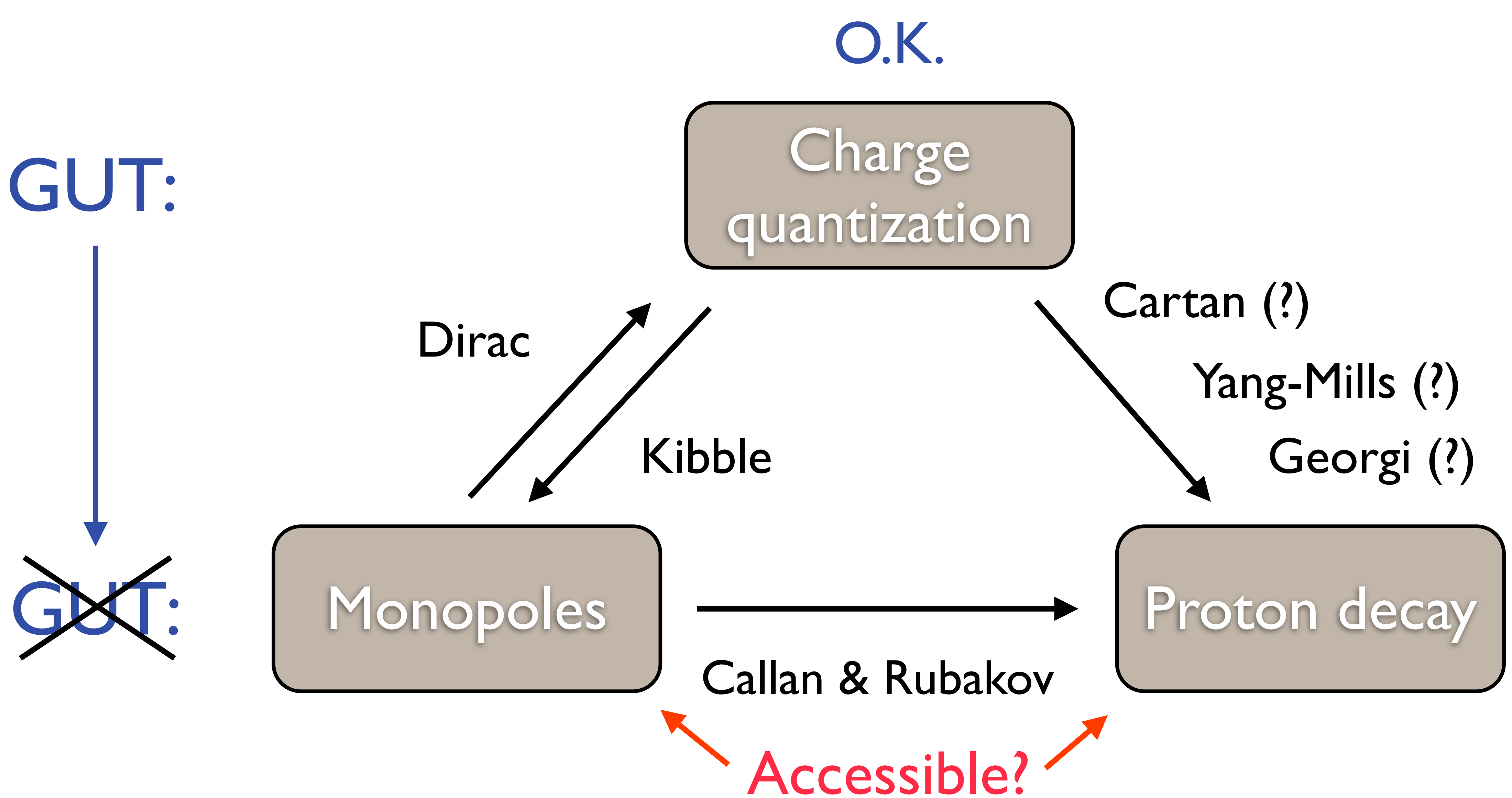

Prerequisites: GUT scale, symmetry breaking, flavour structure

Where do the GUTs live?

Simple gauge group broken down to 321 of the SM

⇩

the SM gauge couplings should converge at high energies

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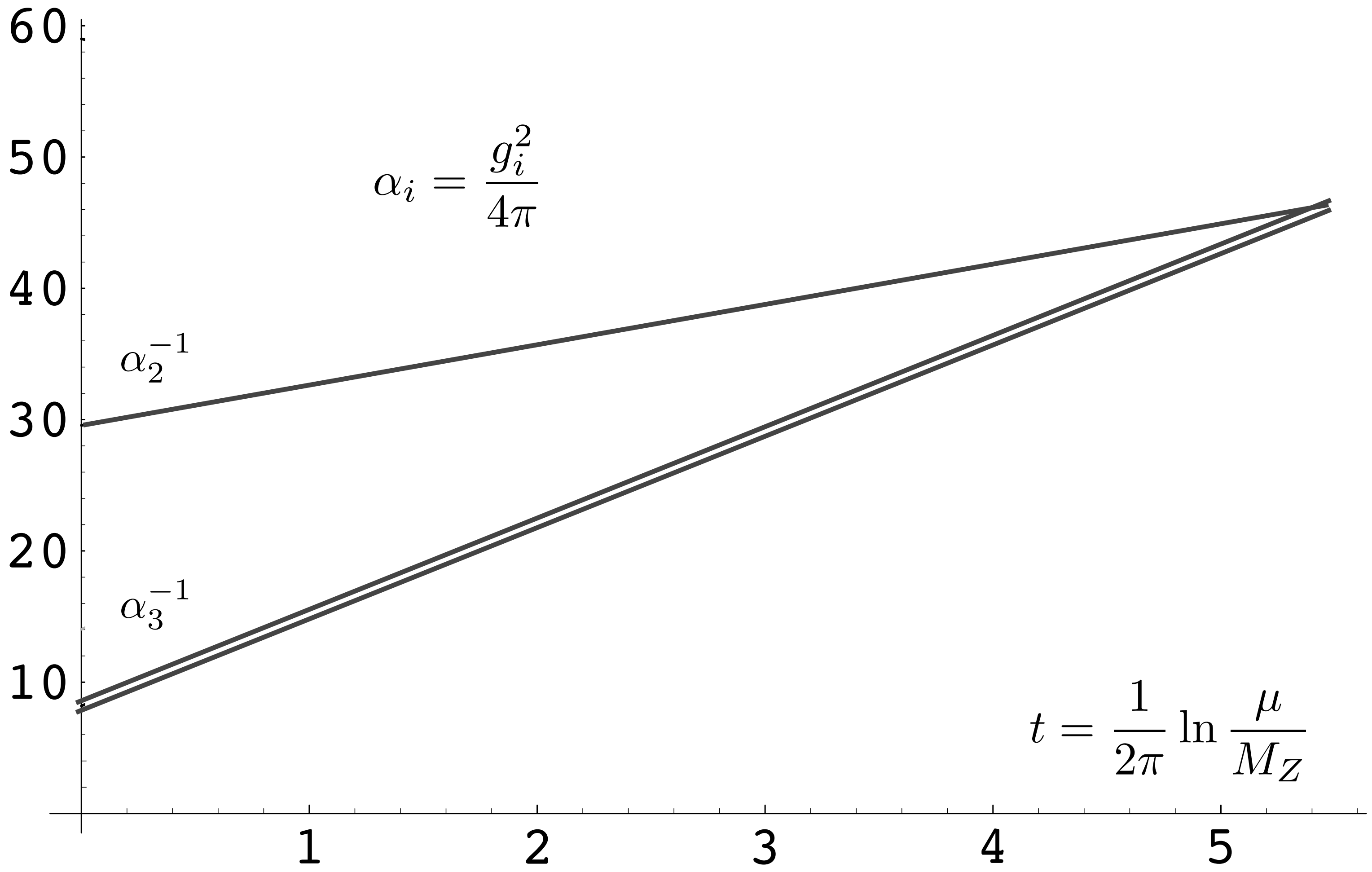

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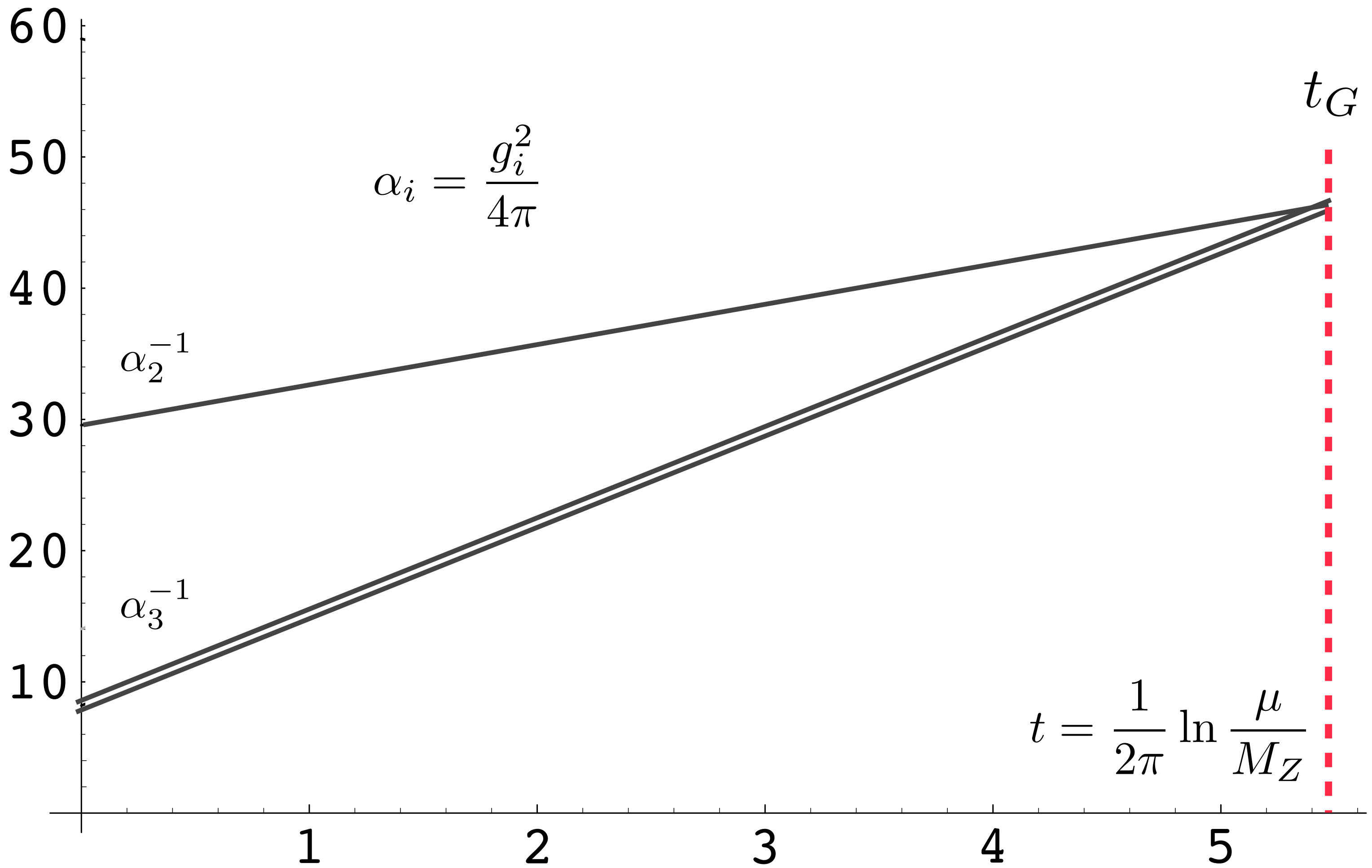

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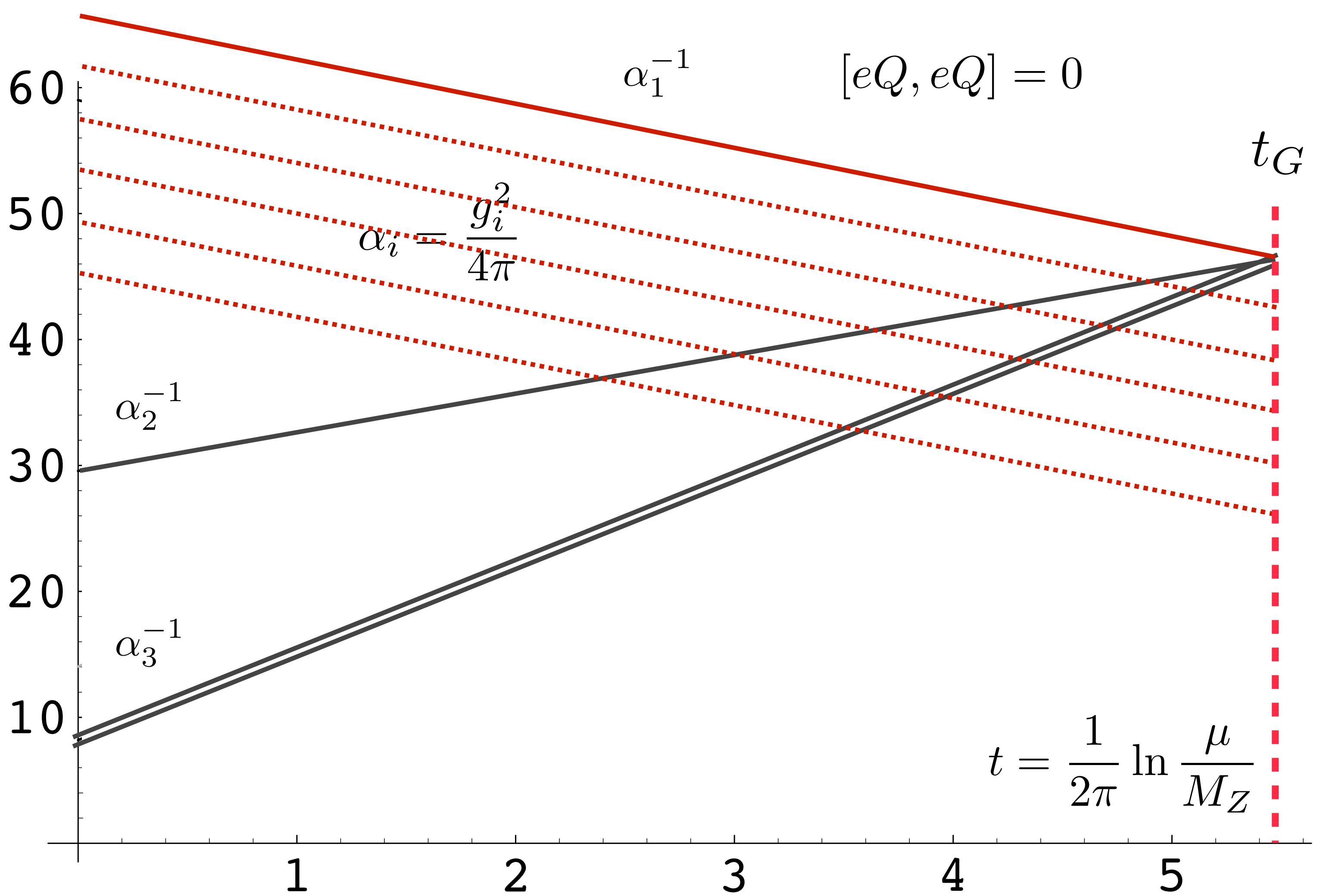

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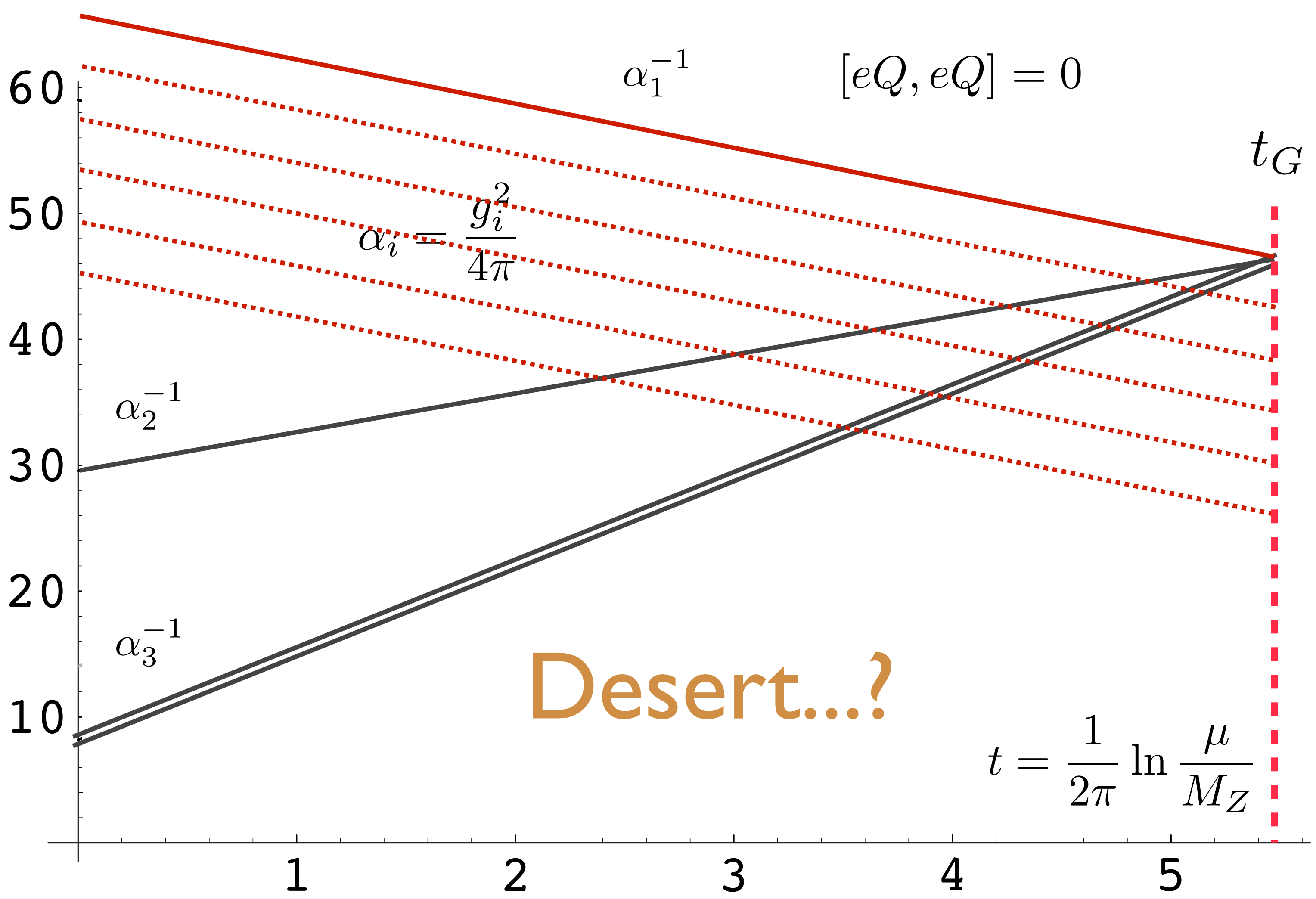

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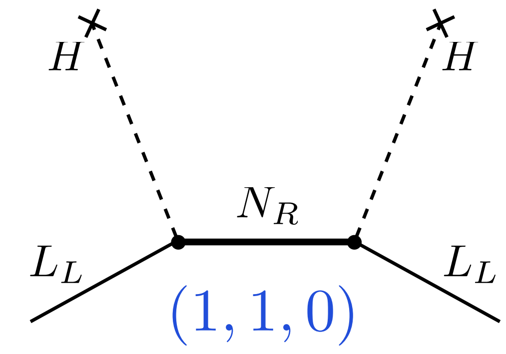
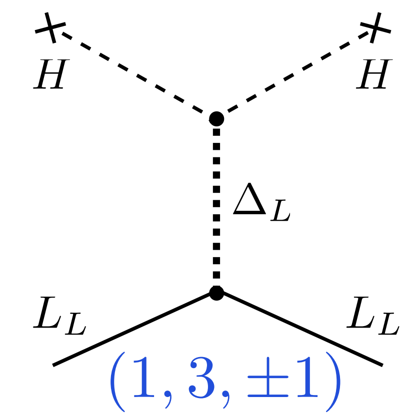
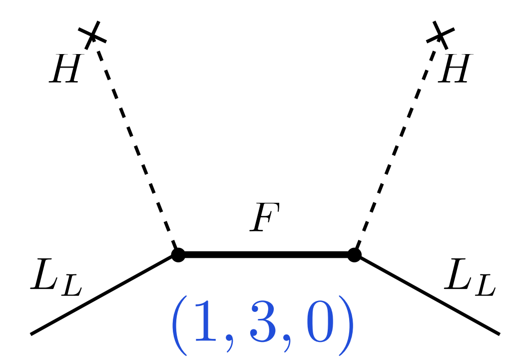


type-II seesaw



type-III seesaw



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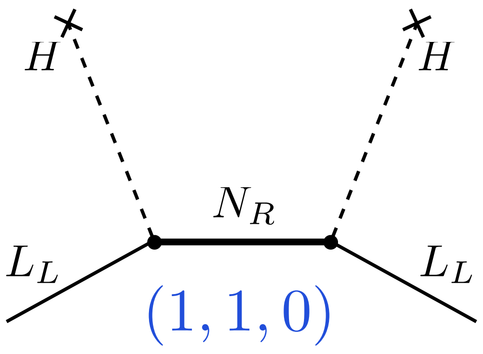

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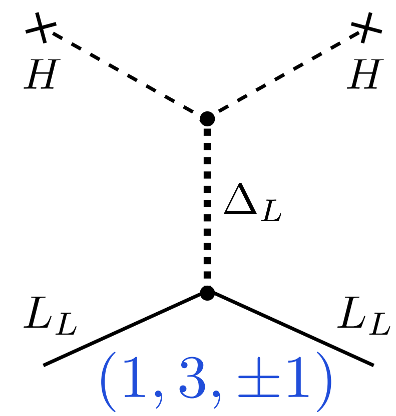

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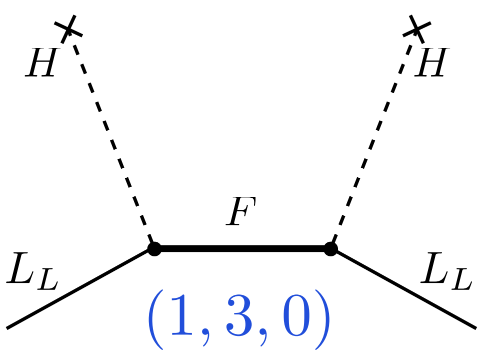

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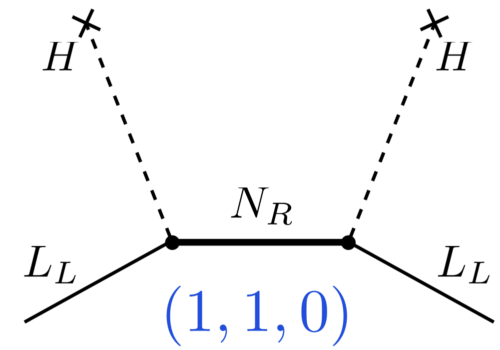

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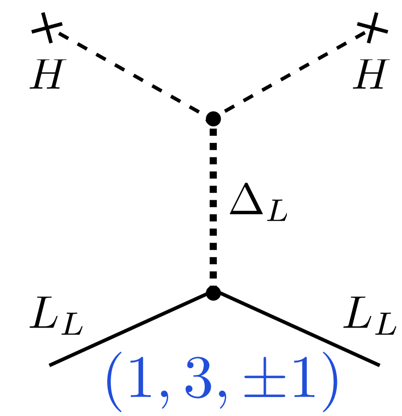

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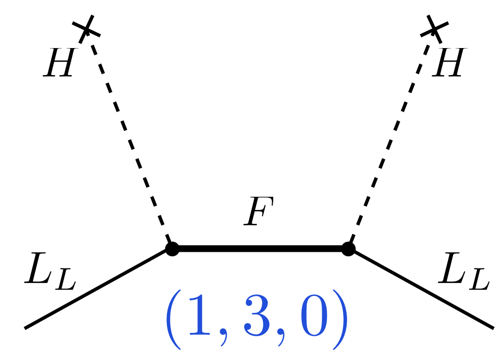

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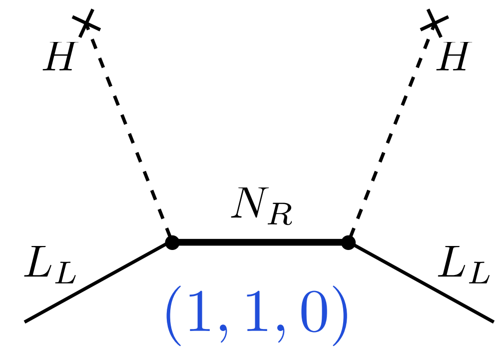

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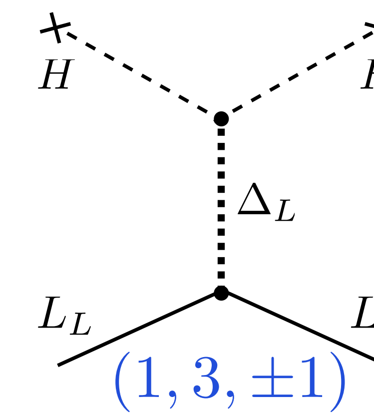

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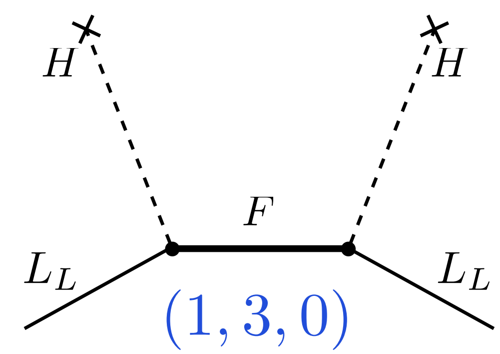

$$\Lambda \sim (10^{12} - 10^{14})\ \mathrm{GeV}$$

Remarkably close to the scale inferred from gauge unification!

How to test GUTs?

Monopoles(?)

No way to produce GUT monopoles in lab, only cosmics or Callan-Rubakov

G. Giacomelli, L. Patrizii, and Z. Sahnoun, arXiv:1105.2724

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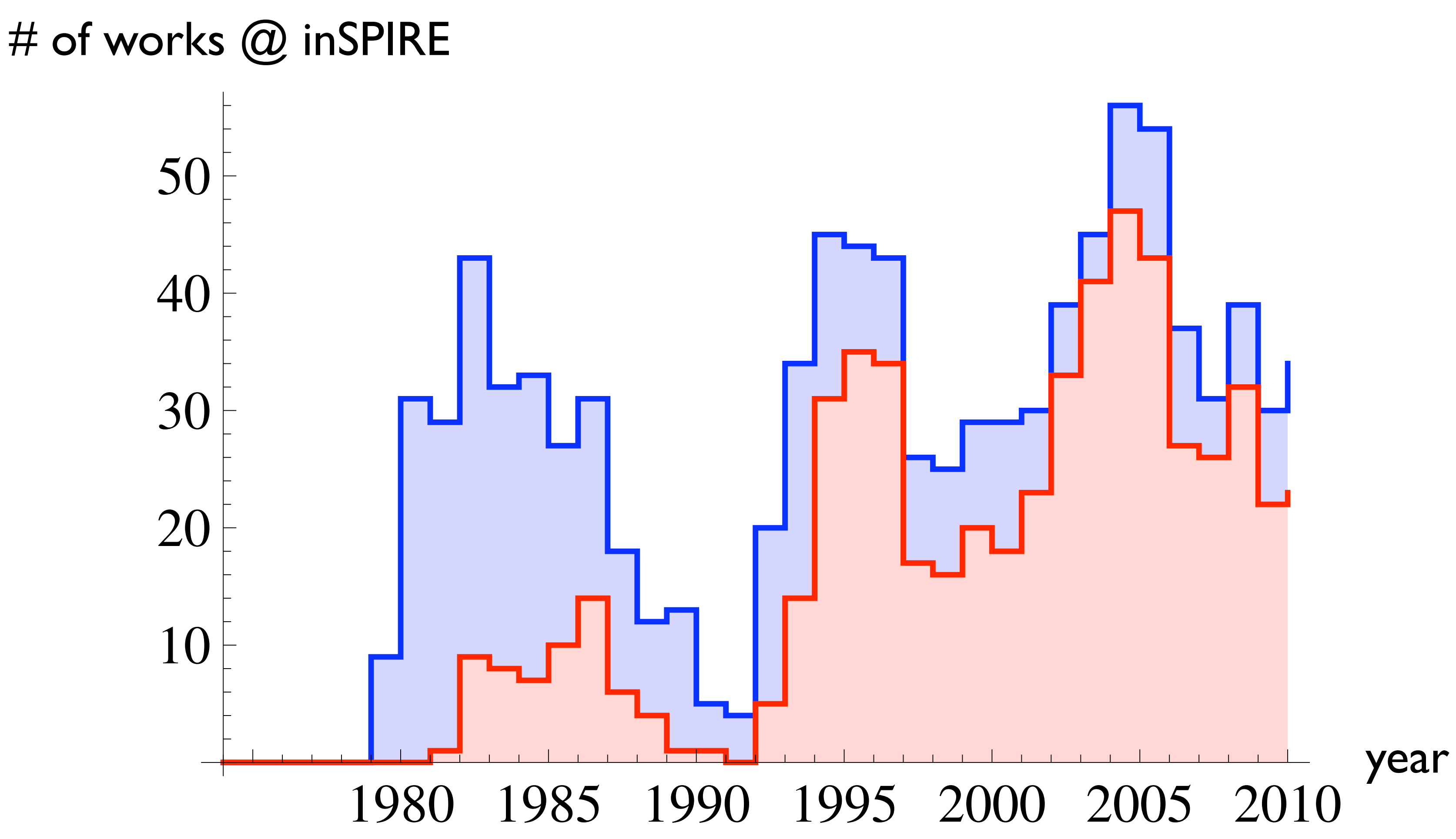
N.B. early (fake) monopole-like events Price et al. 1975

Proton decay



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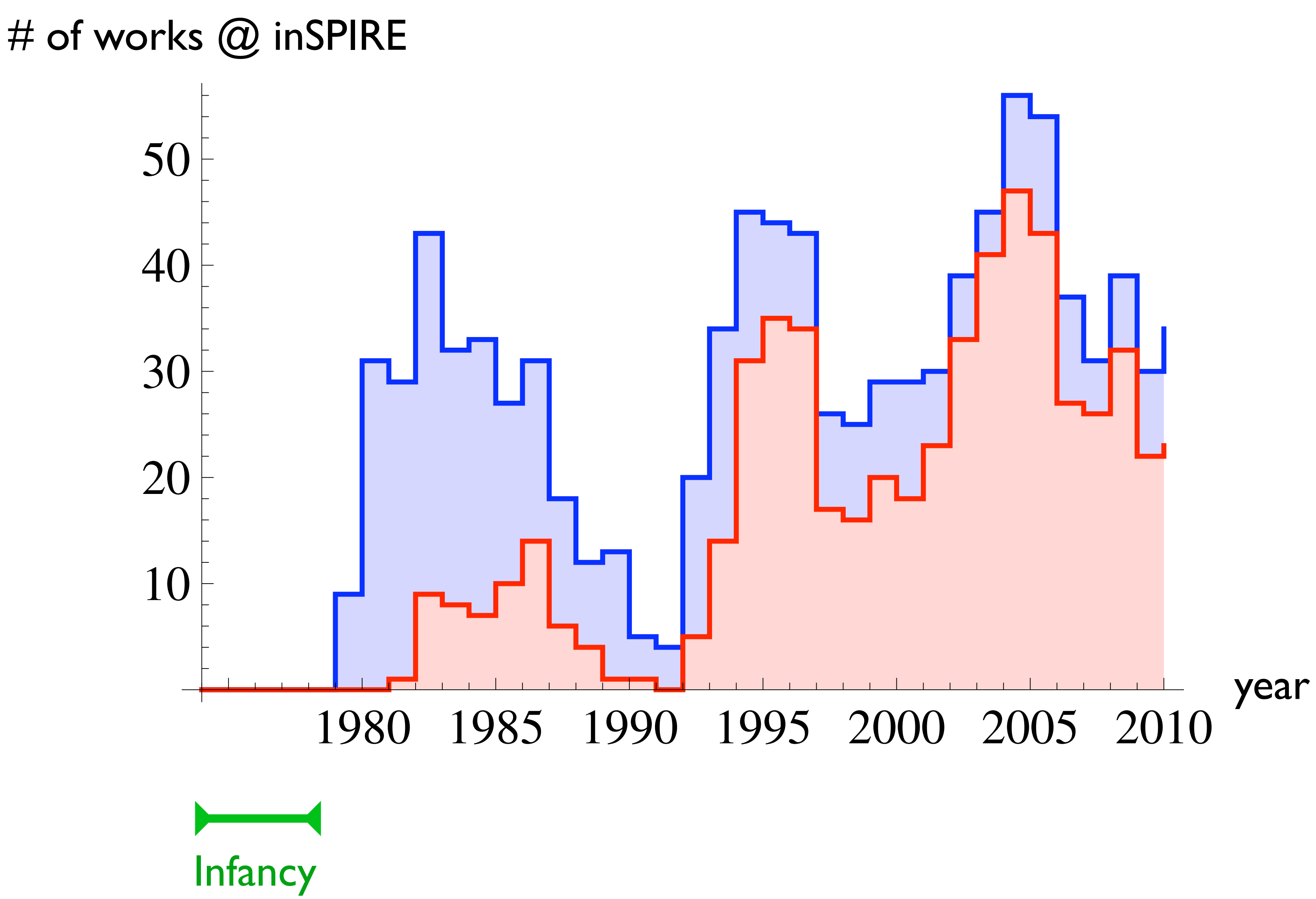

Birth: February 25 1974 - Georgi & Glashow PRL32

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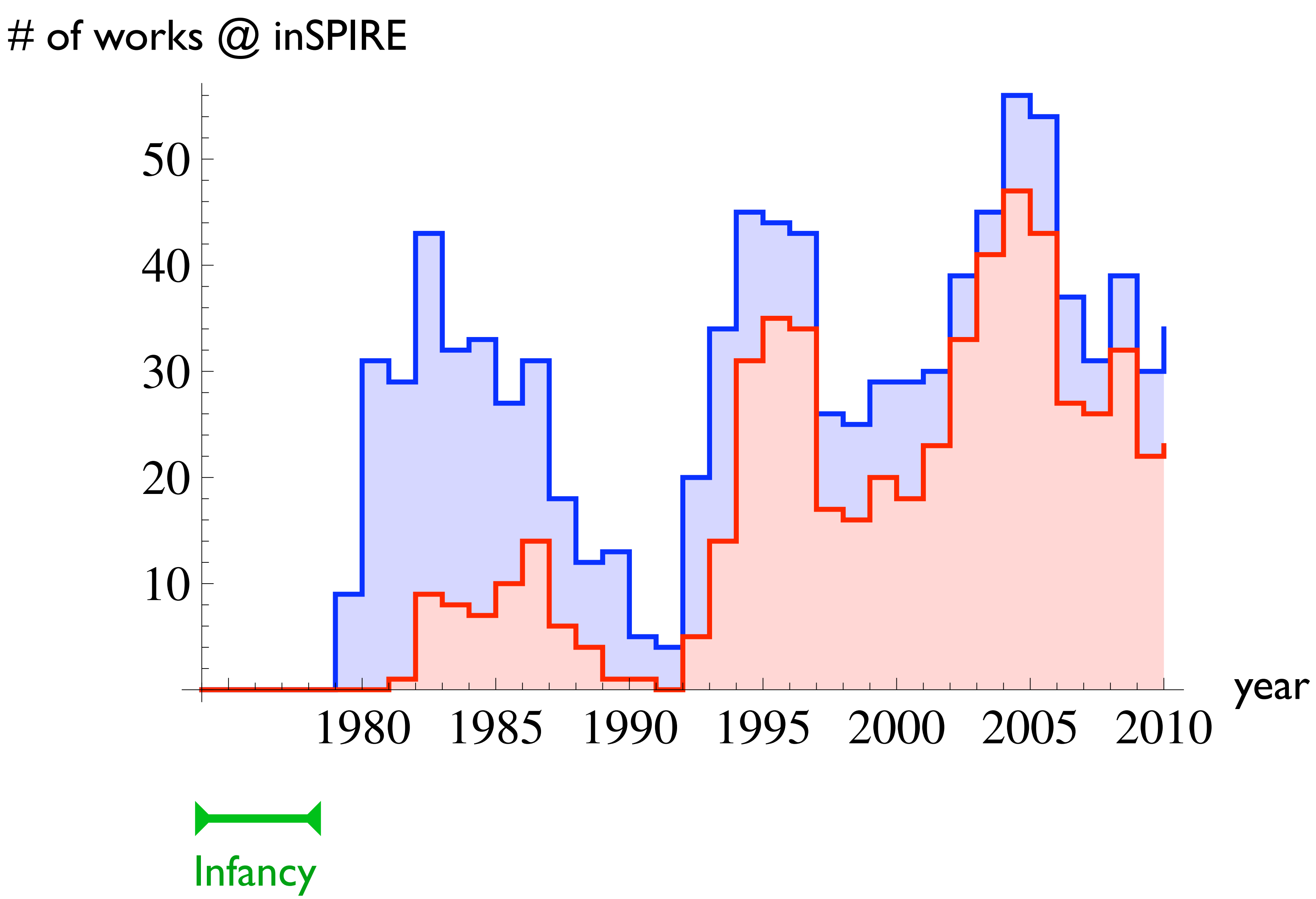

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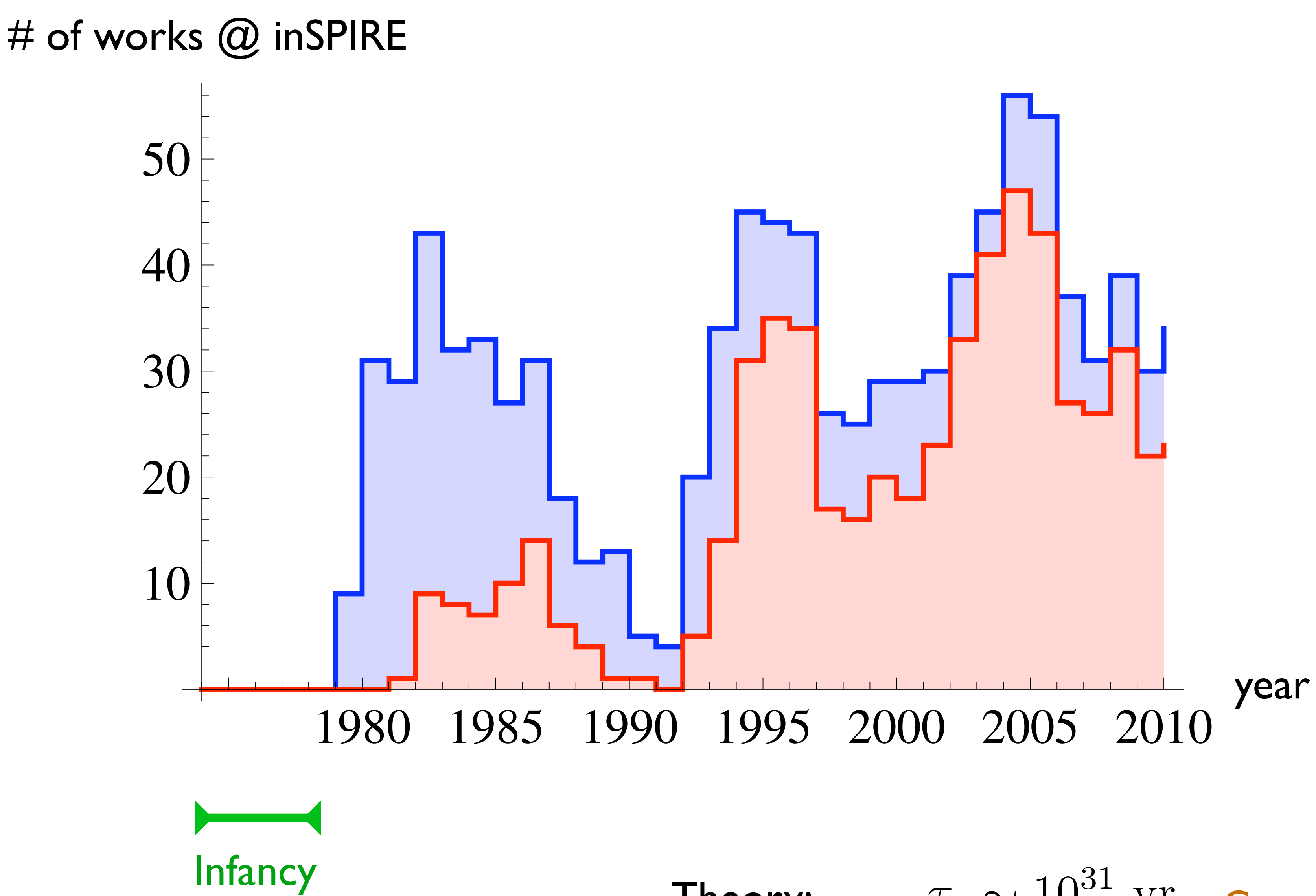

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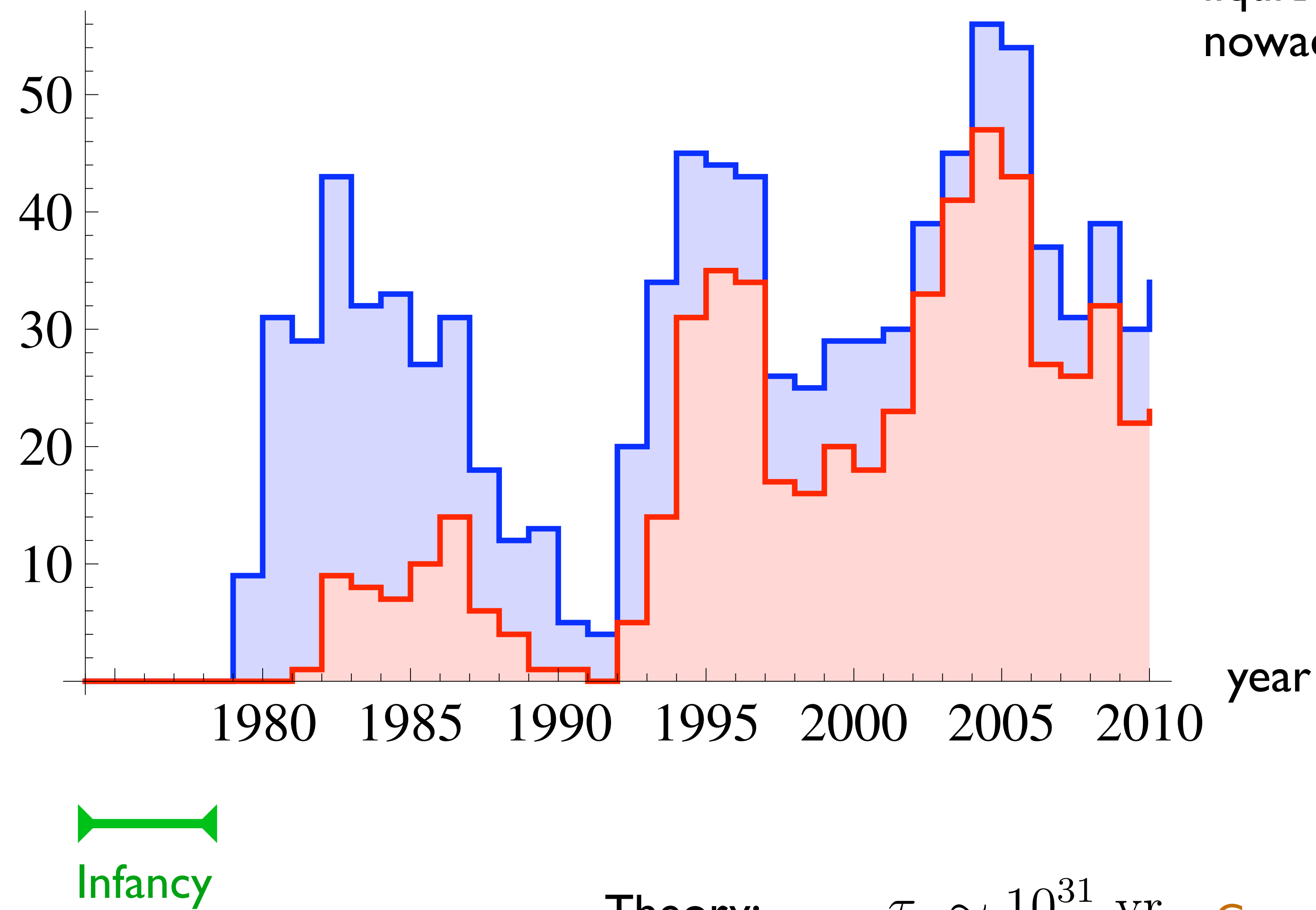
Proton decay

lifetimes enormous ⇨ need for large detectors

# of works @ inSPIRE

i.e., water Cherenkov, liquid scintilators, nowadays liquid argon...



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First large water-Cherenkov detectors

KamiokaNDE

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3,000 tons of pure water, about 1,000 PMs

1983-1985 - first phase (proton decay focused)

1987-1990 - solar neutrino deficit measurements

Feb. 23 1987 07:35 - 12 out of 10^{58} neutrinos from SN 1987A (170,000 ly)

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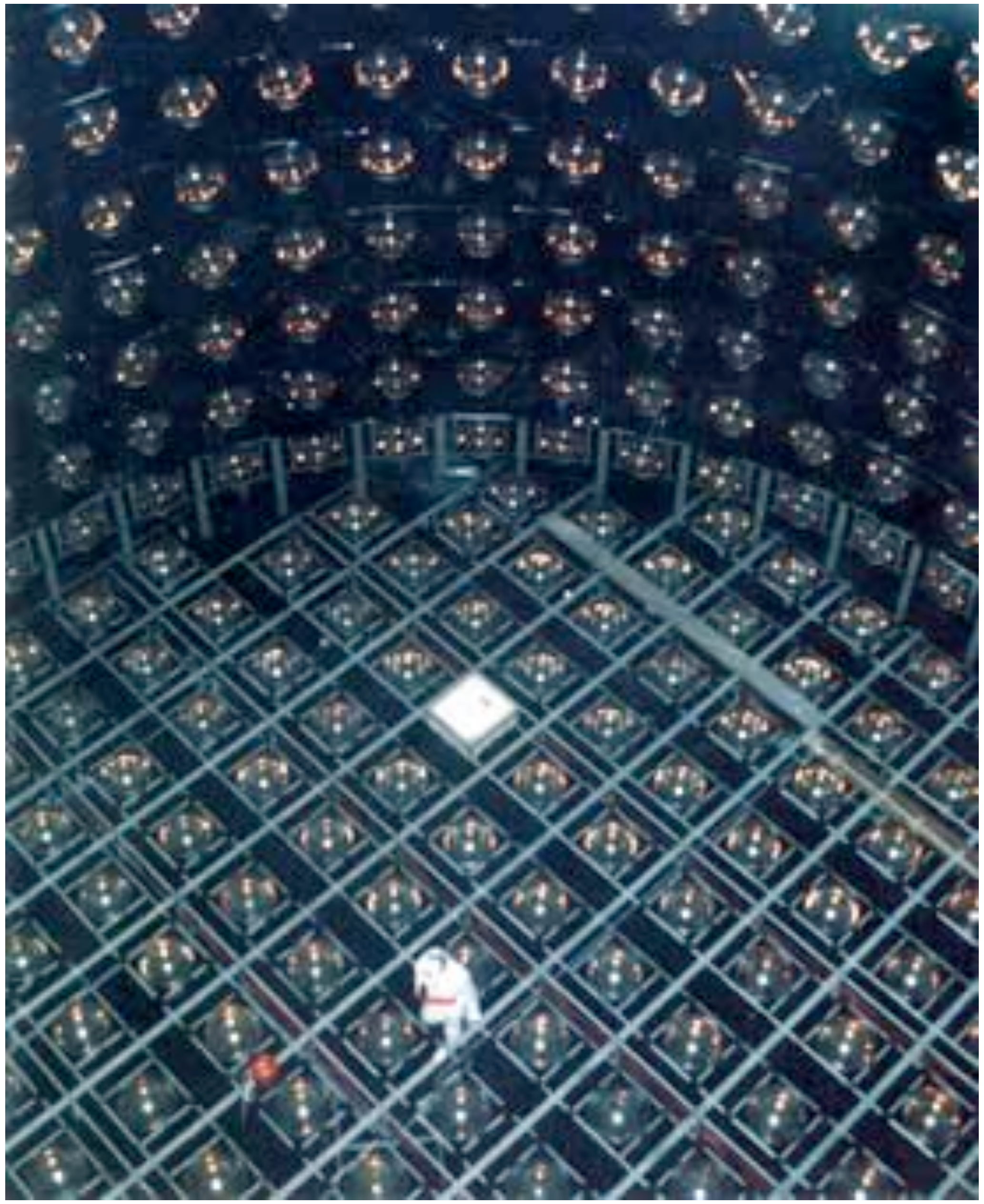

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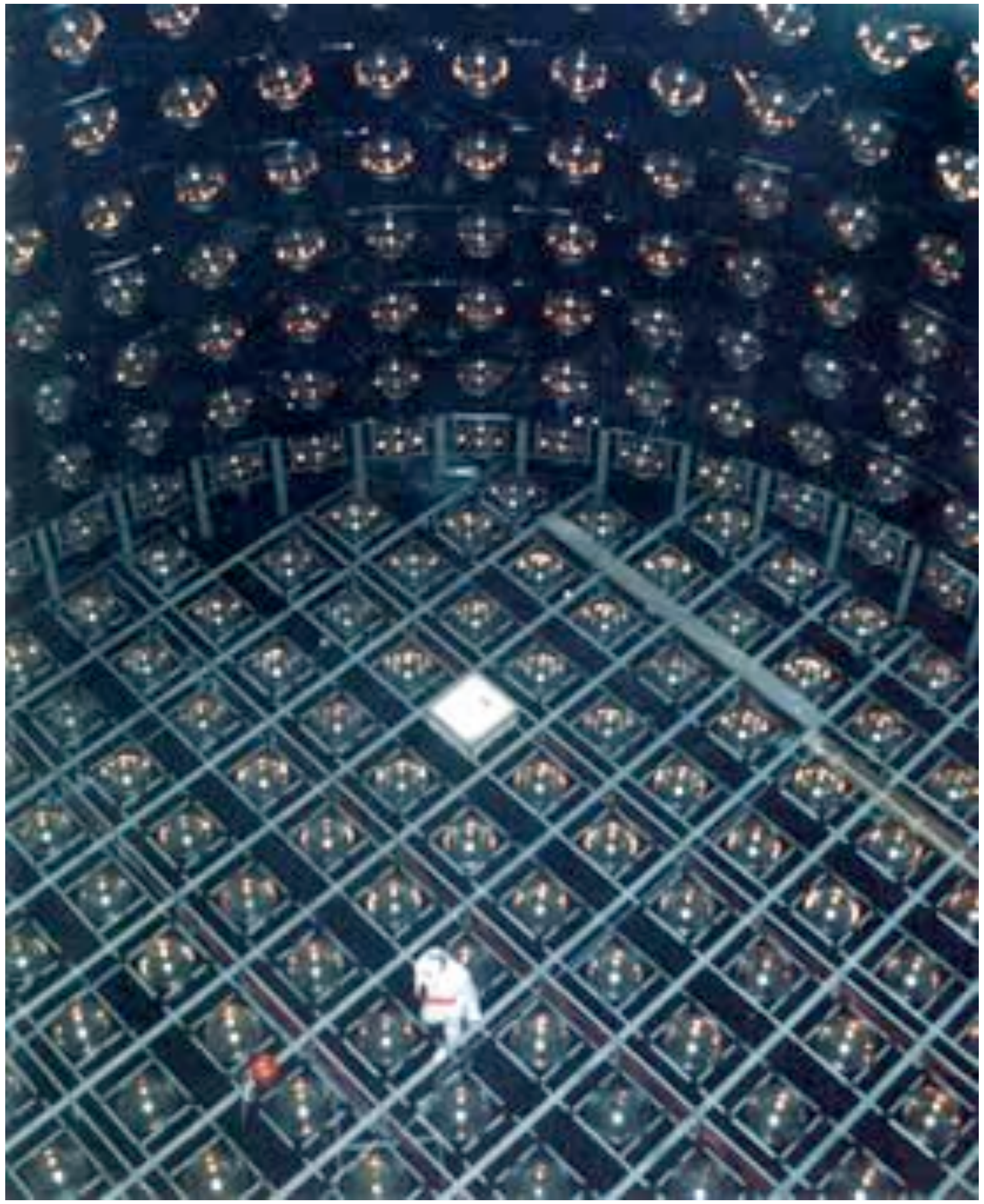

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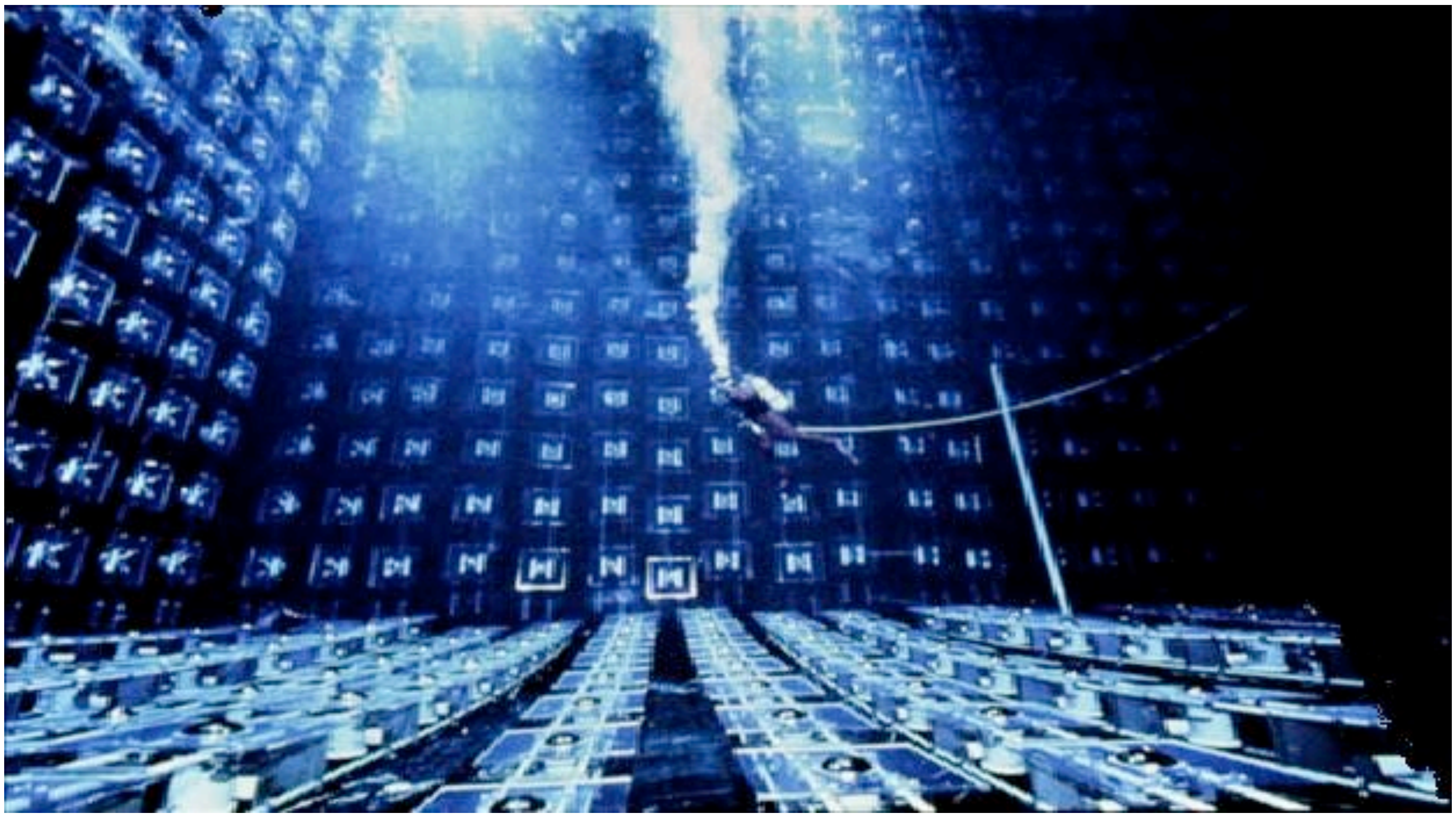

Morton salt mine, Mentor, Cleveland/Ohio

3x larger than KamiokaNDE

worse PM's though

(coverage about 1% only)

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few more years after upgrade (until about 1998)

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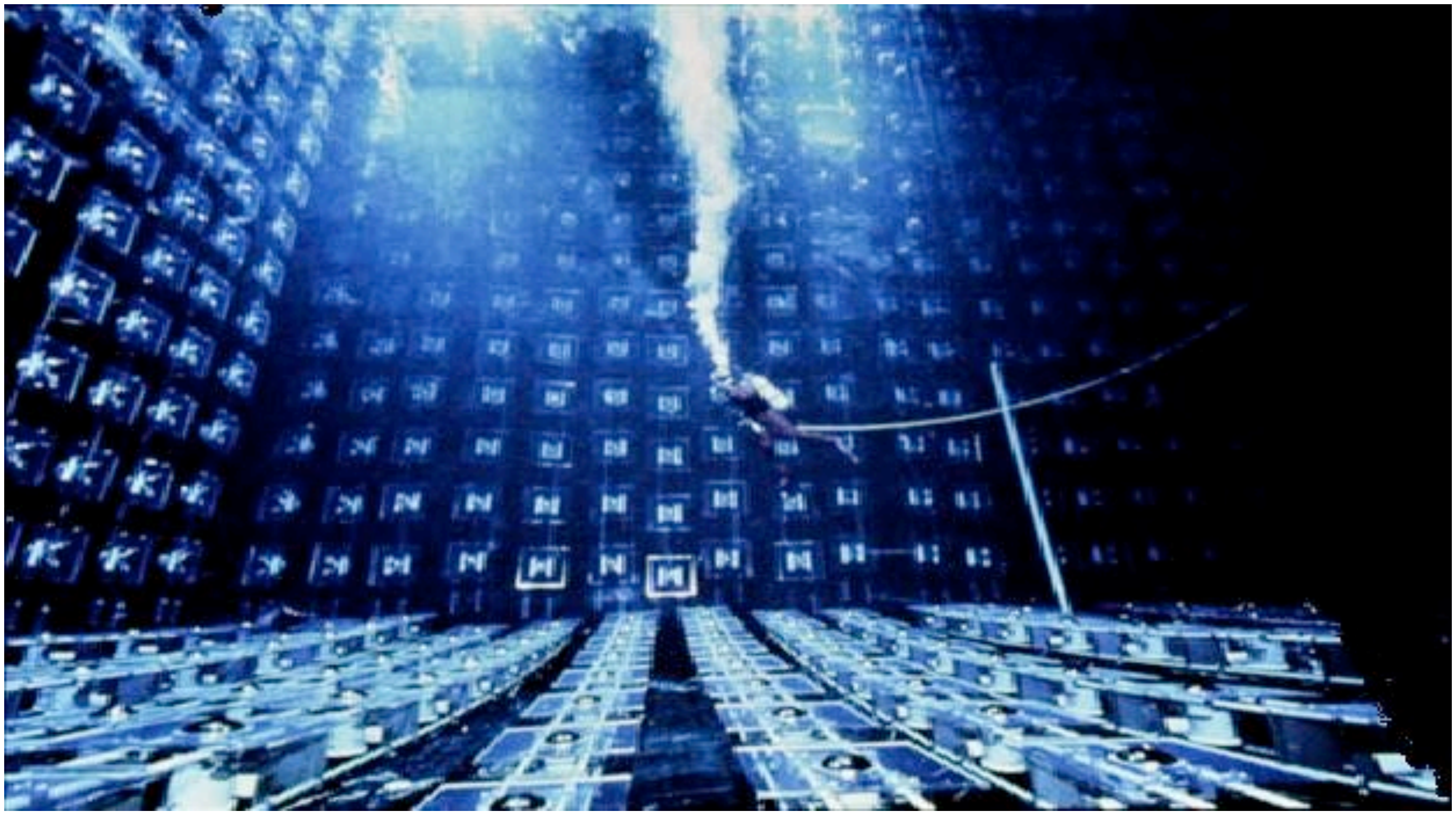

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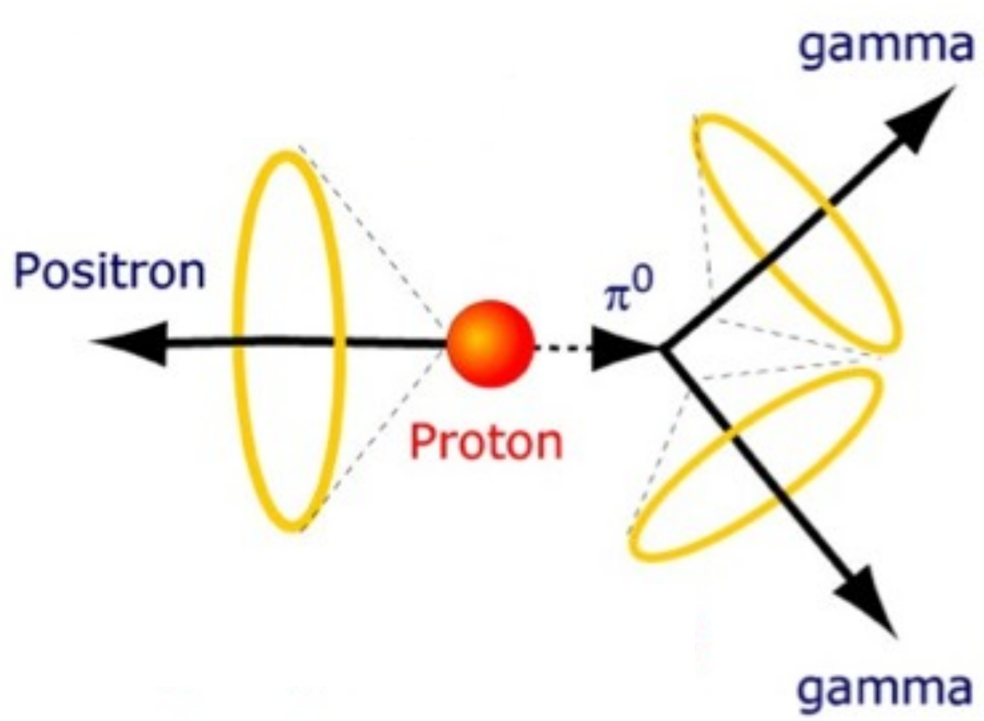
"Golden channel": $p \to \pi^0 e^+$

$\pi^0 \to 2\gamma$

$p_\pi = p_e = 459$ MeV

$p_{\gamma/\pi R} = 68$ MeV



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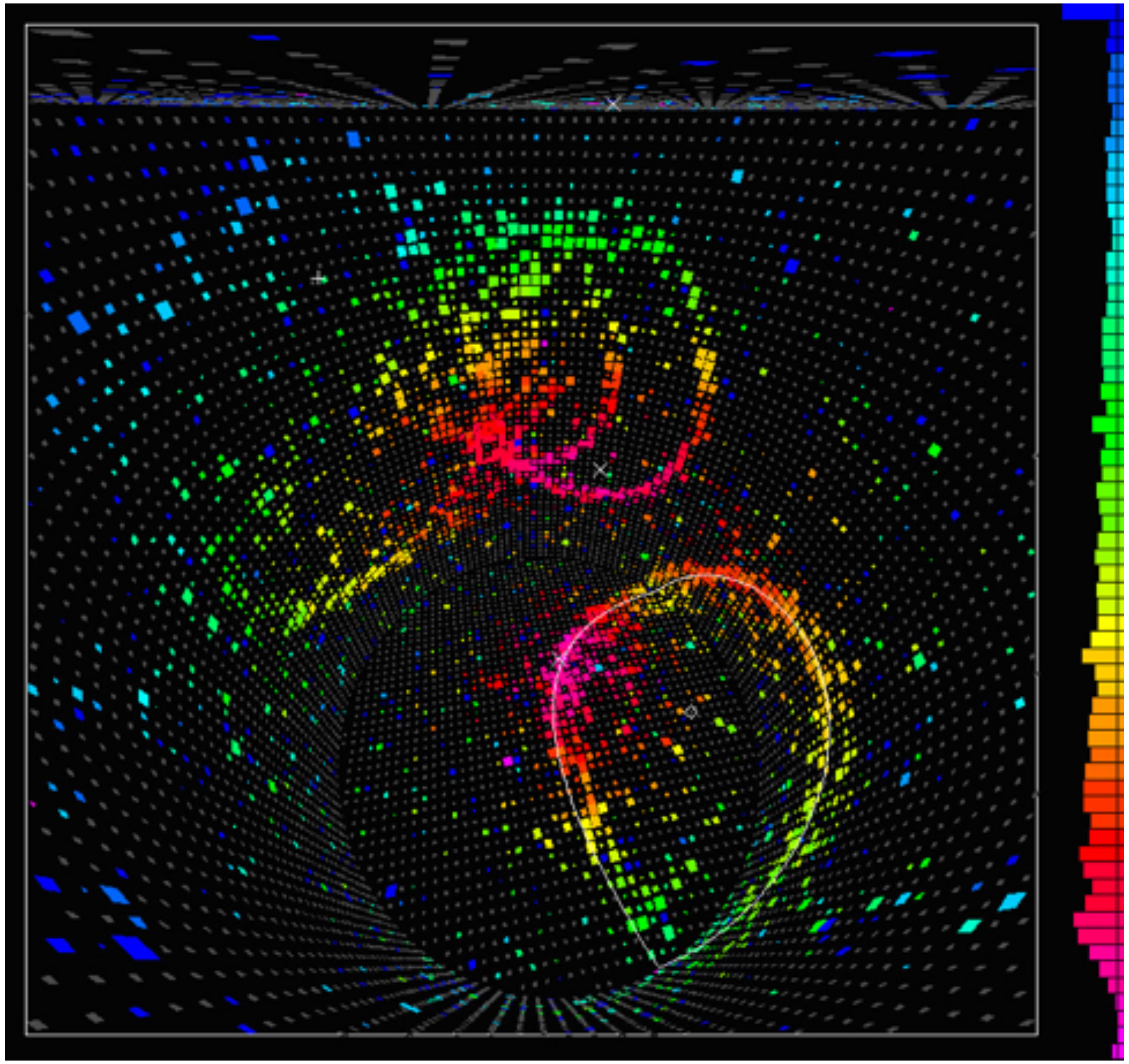

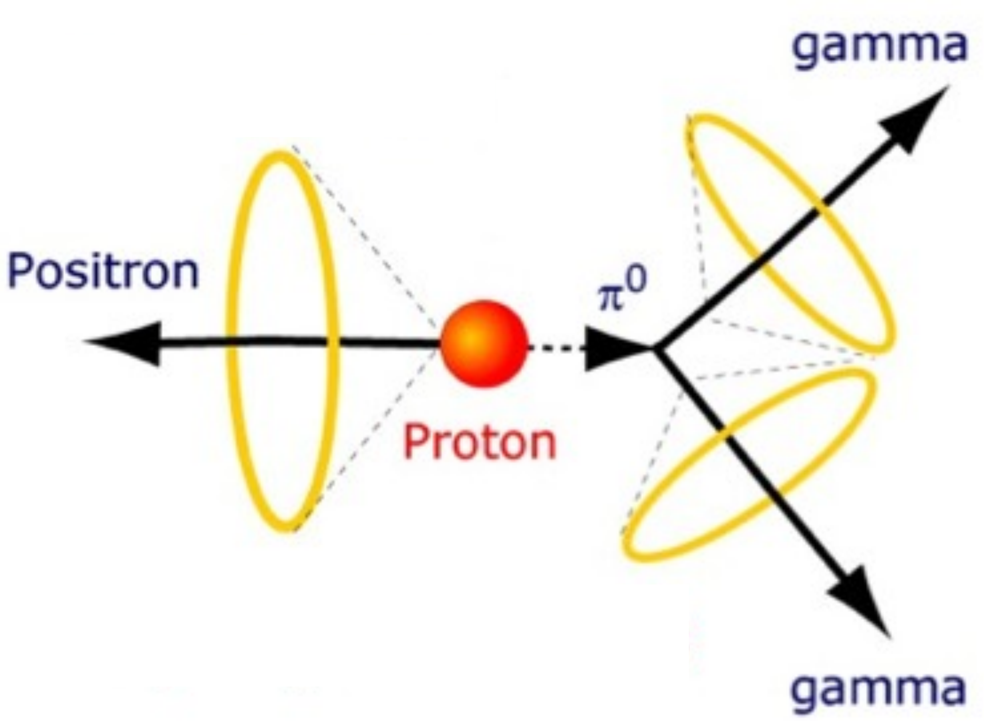

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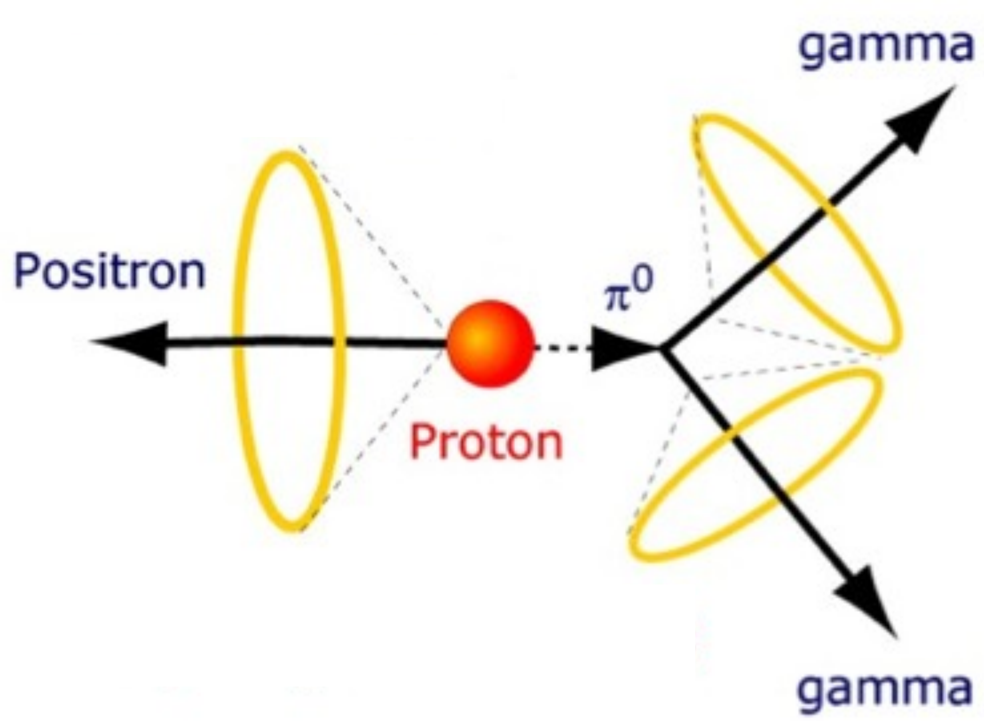

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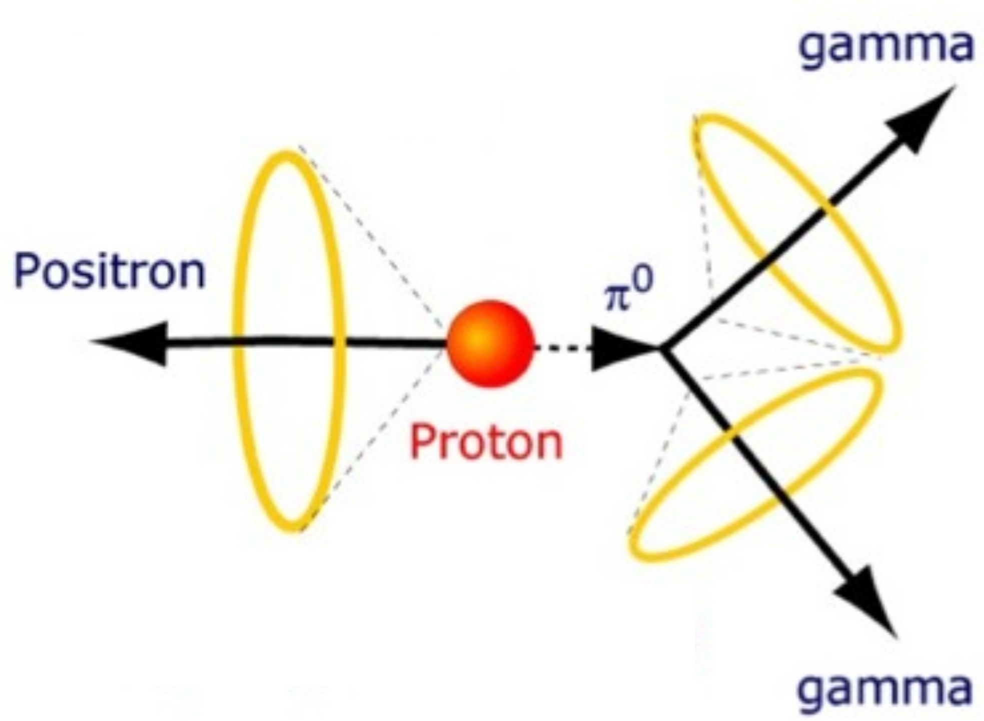
Other complication - nuclear effects

- majority of nucleons in oxygen
- Fermi motion
- pion charge exchange
- absorption



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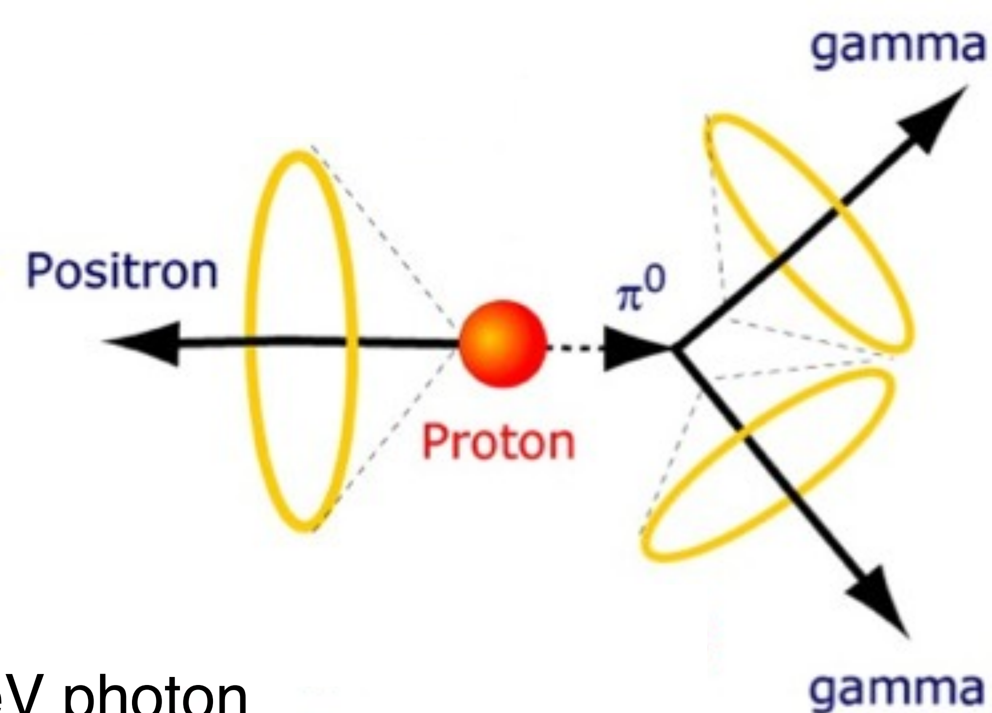
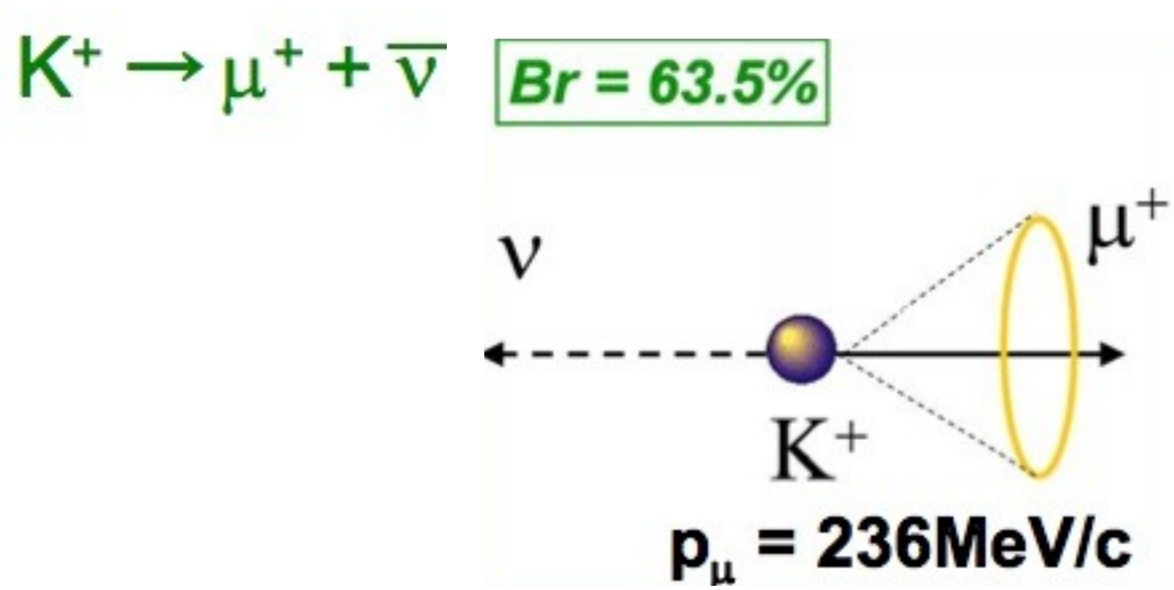


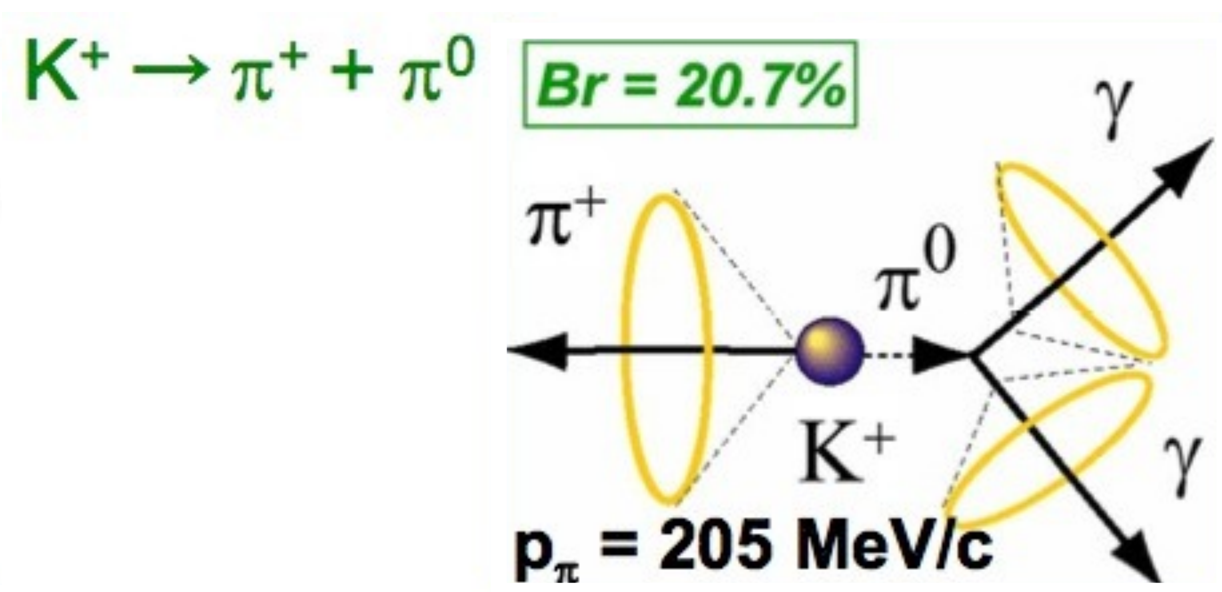
Other signals

- nuclear recombination - extra 6.3 MeV photon
- neutron capture at a dope (Gd, ...)

Proton decay in water

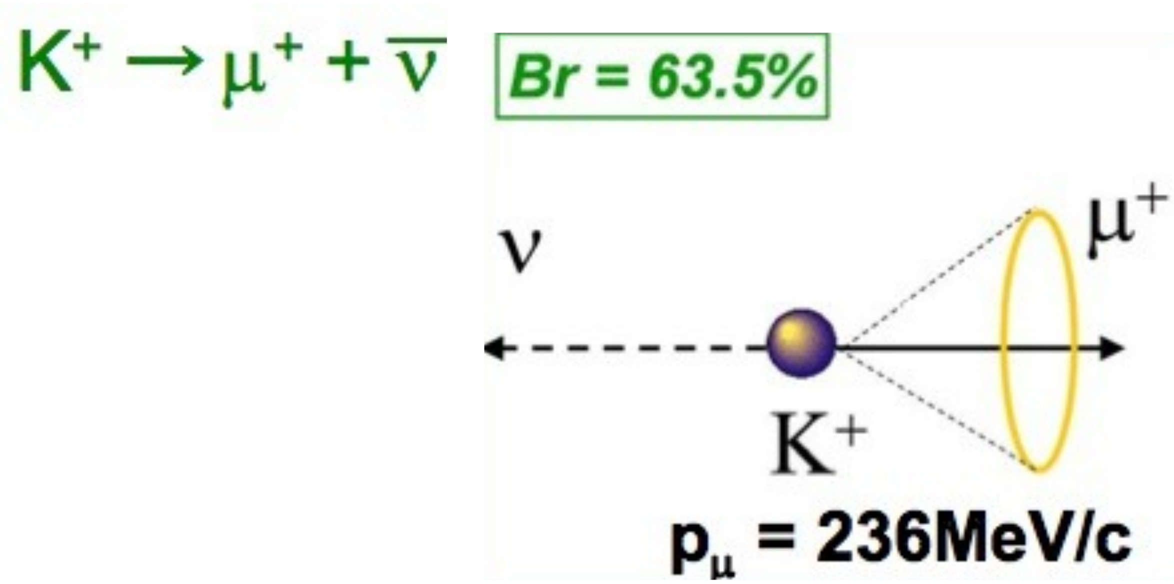
"Silver channel": $p \to K^+ \nu$ p_K = 340 MeV



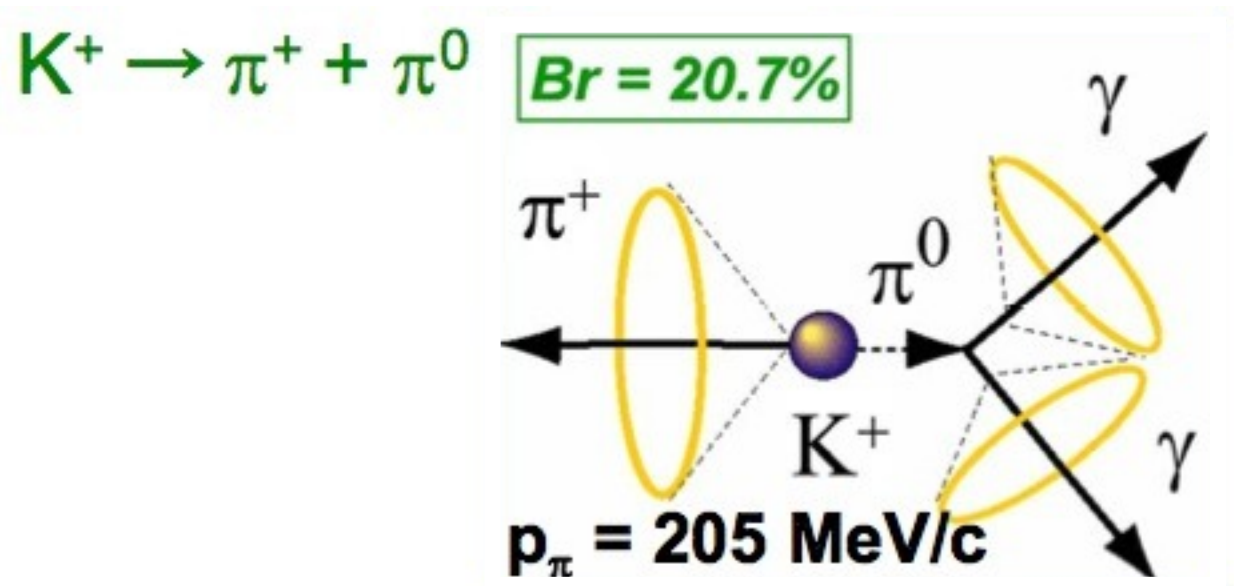


Proton decay in water

"Silver channel": $p \rightarrow K^+ \nu$ p_K = 340 MeV Kaons don't shine !



- single cone



- 2 EM cones
- little opposite-side activity

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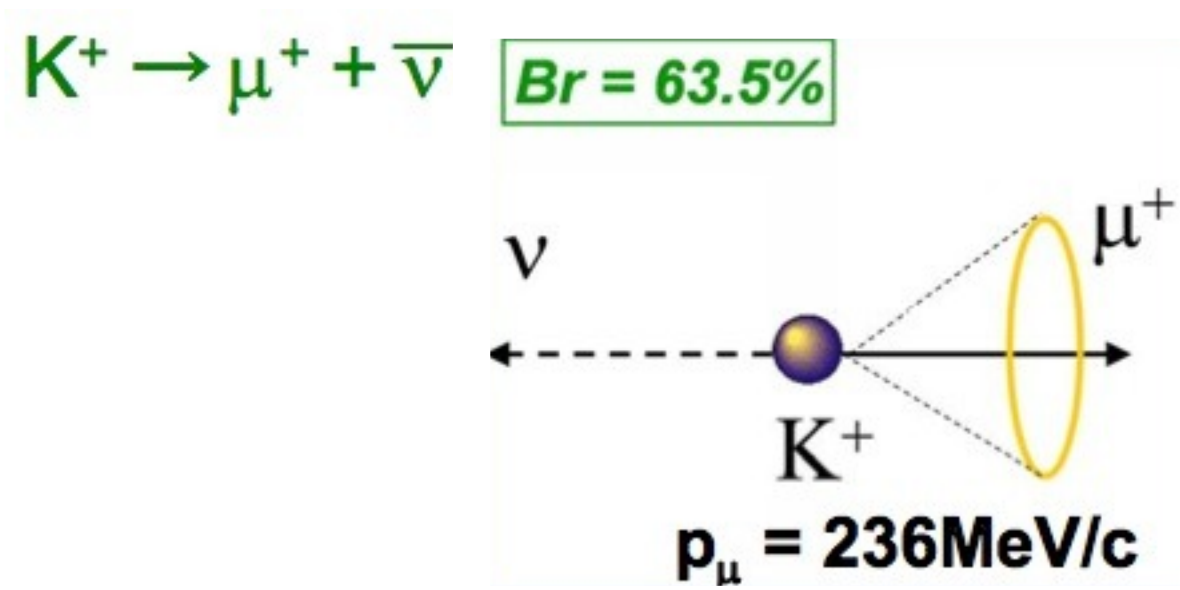

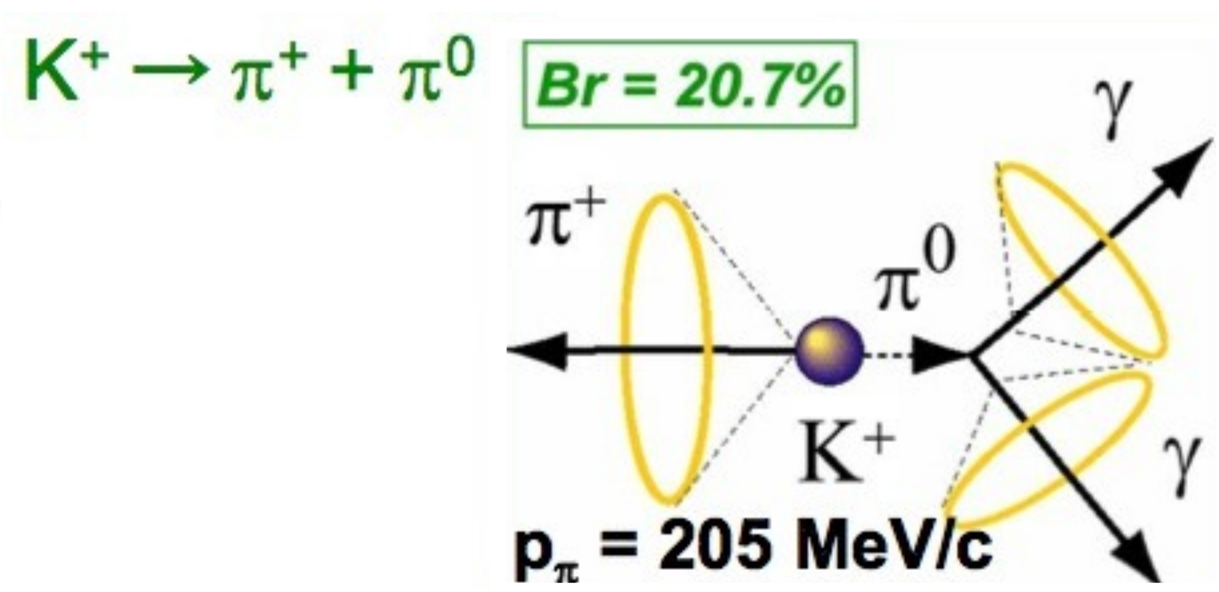

- single cone

- 2 EM cones
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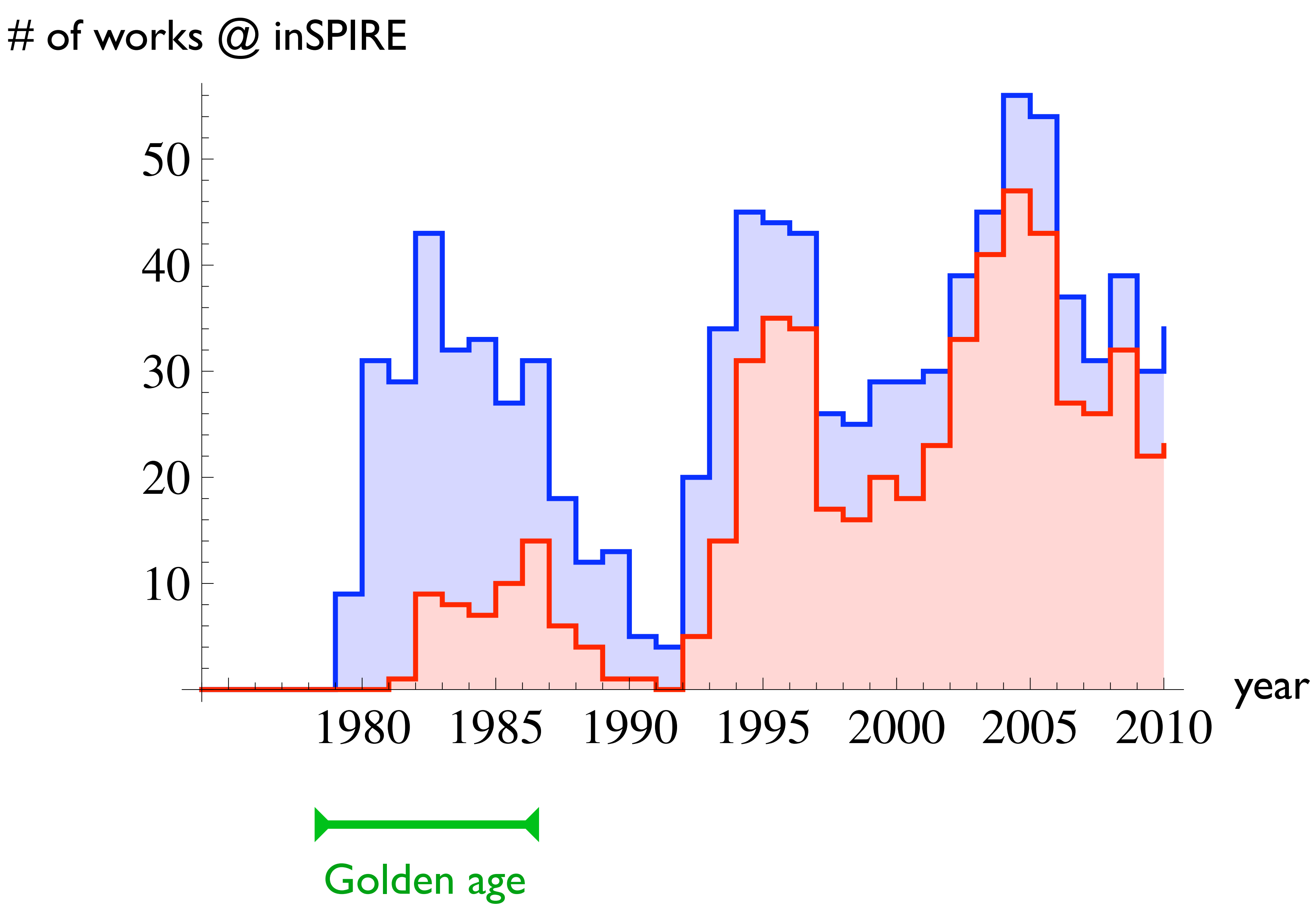
About one order of magnitude less sensitive than $p \to \pi^0 e^+$

Proton decay

The era of IMB (since 1982) & Kamiokande (since 1983)



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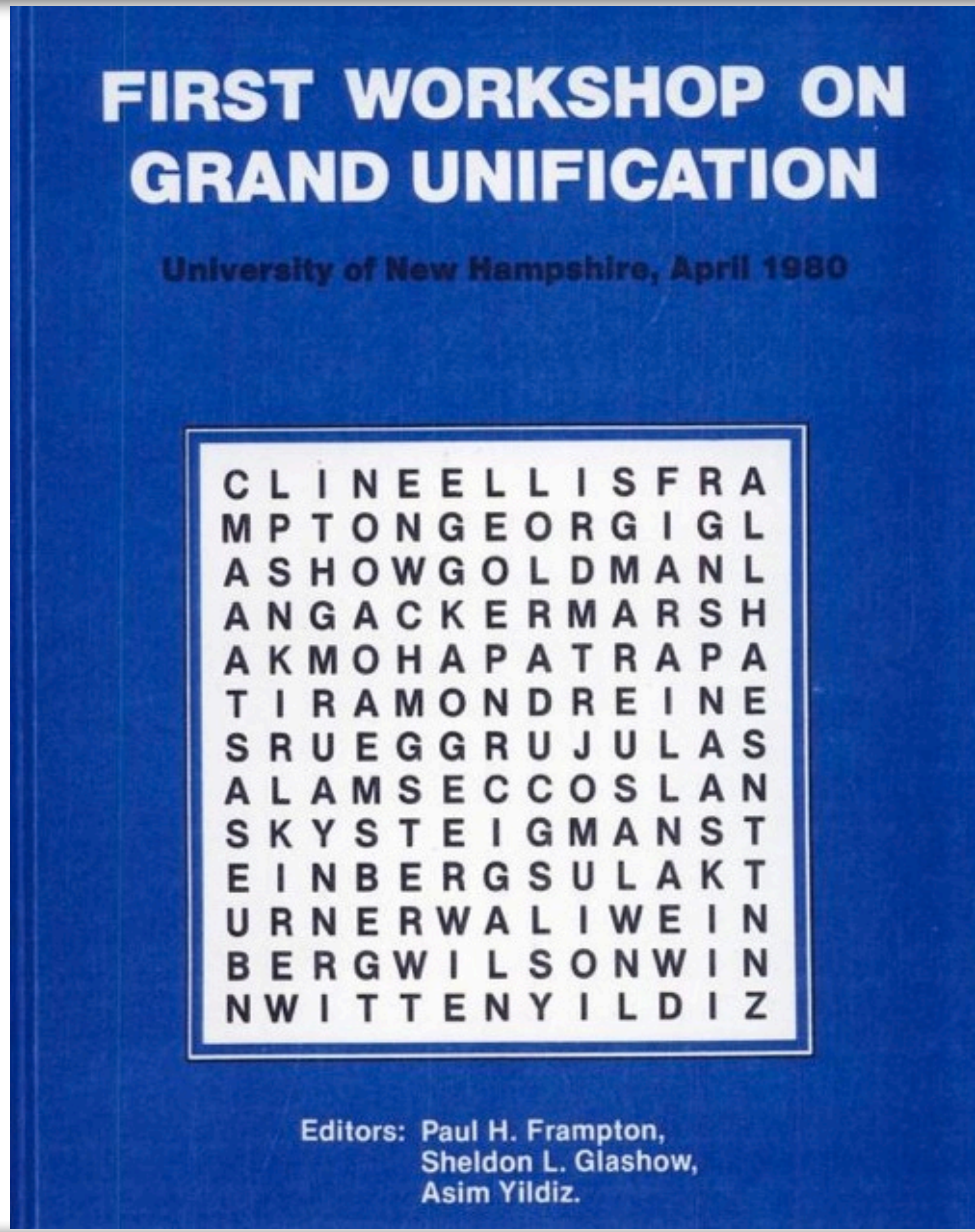

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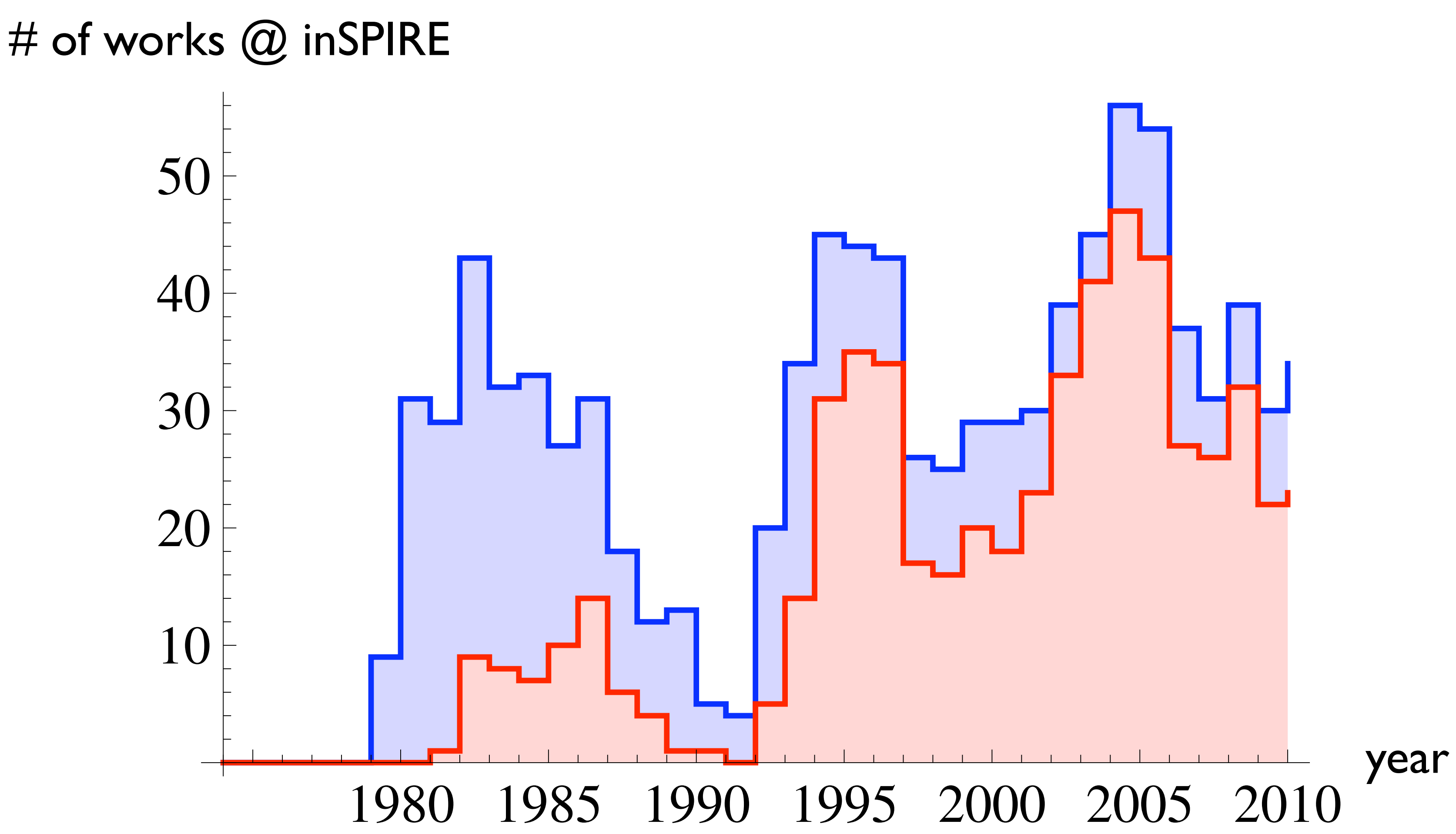

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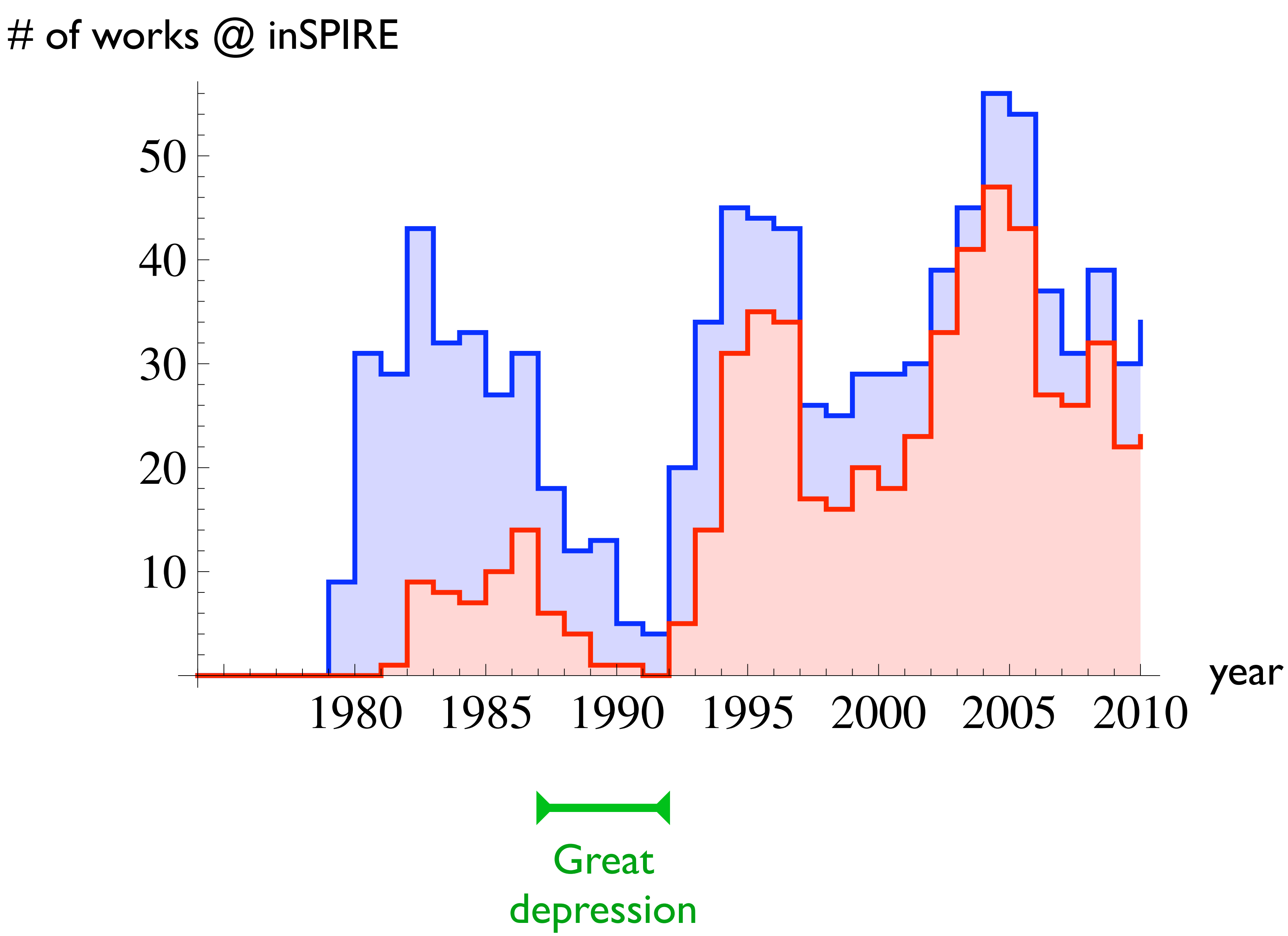

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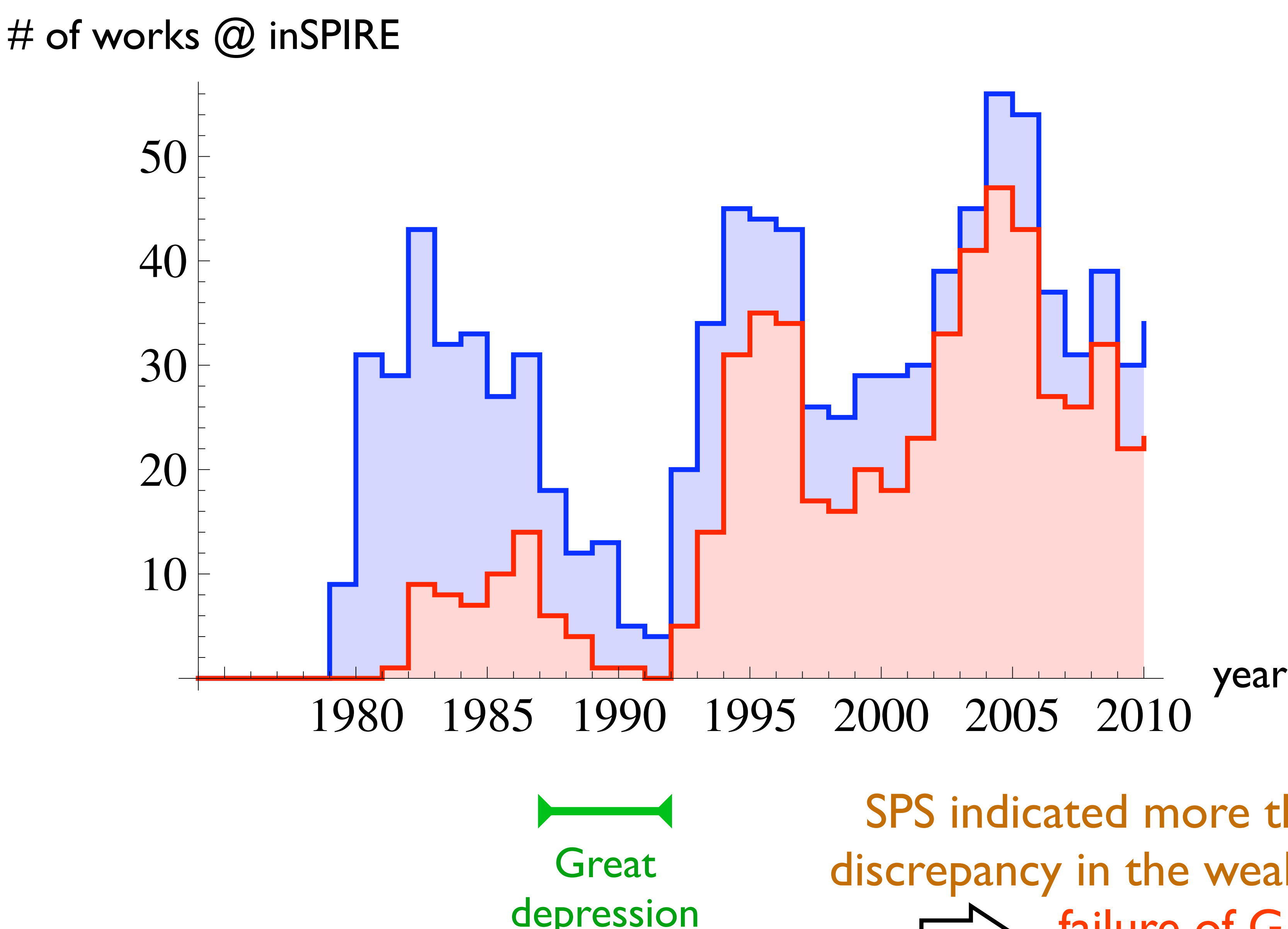

SPS indicated more that 10 sigma discrepancy in the weak mixing angle $\Rightarrow$ failure of G-G

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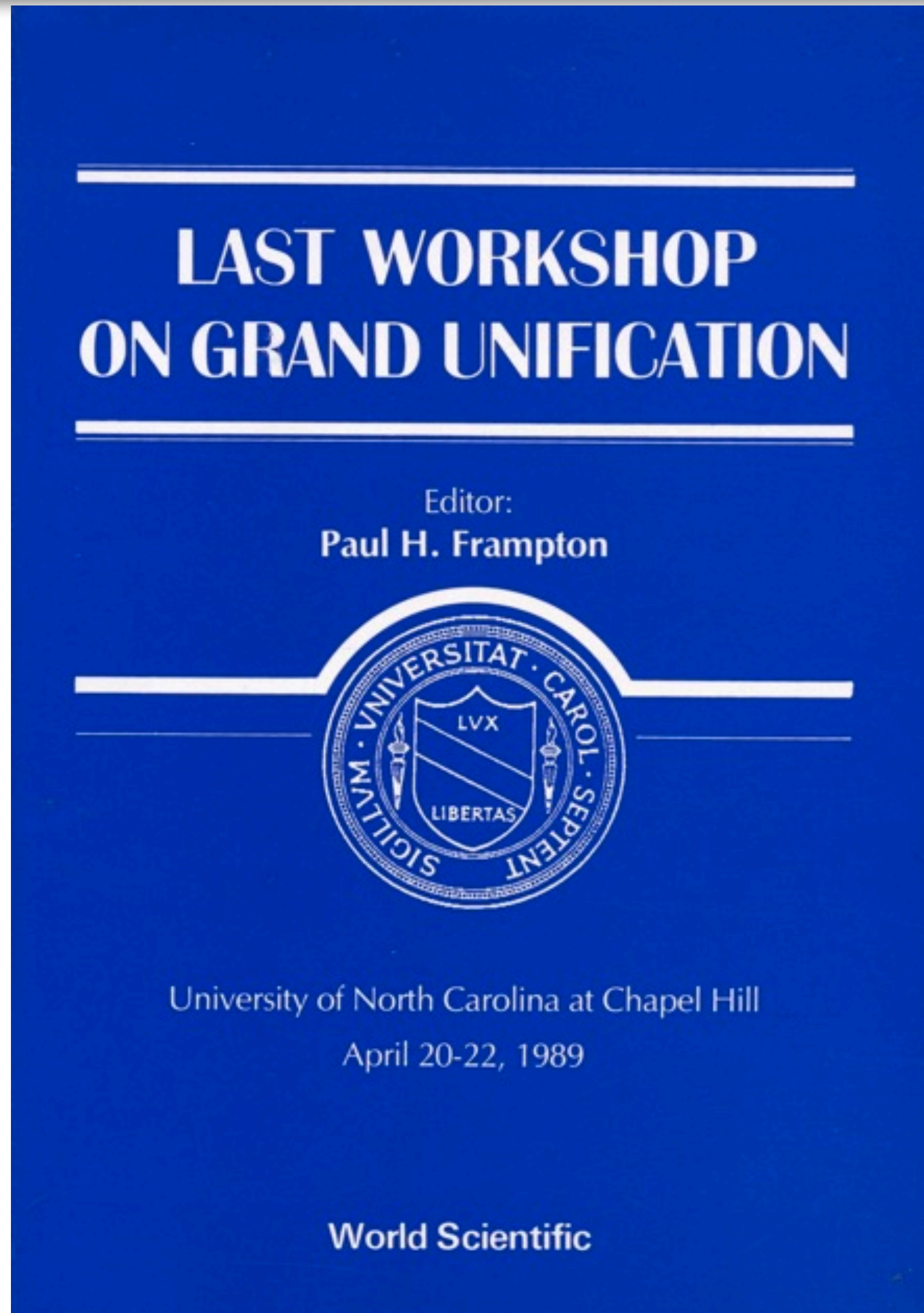

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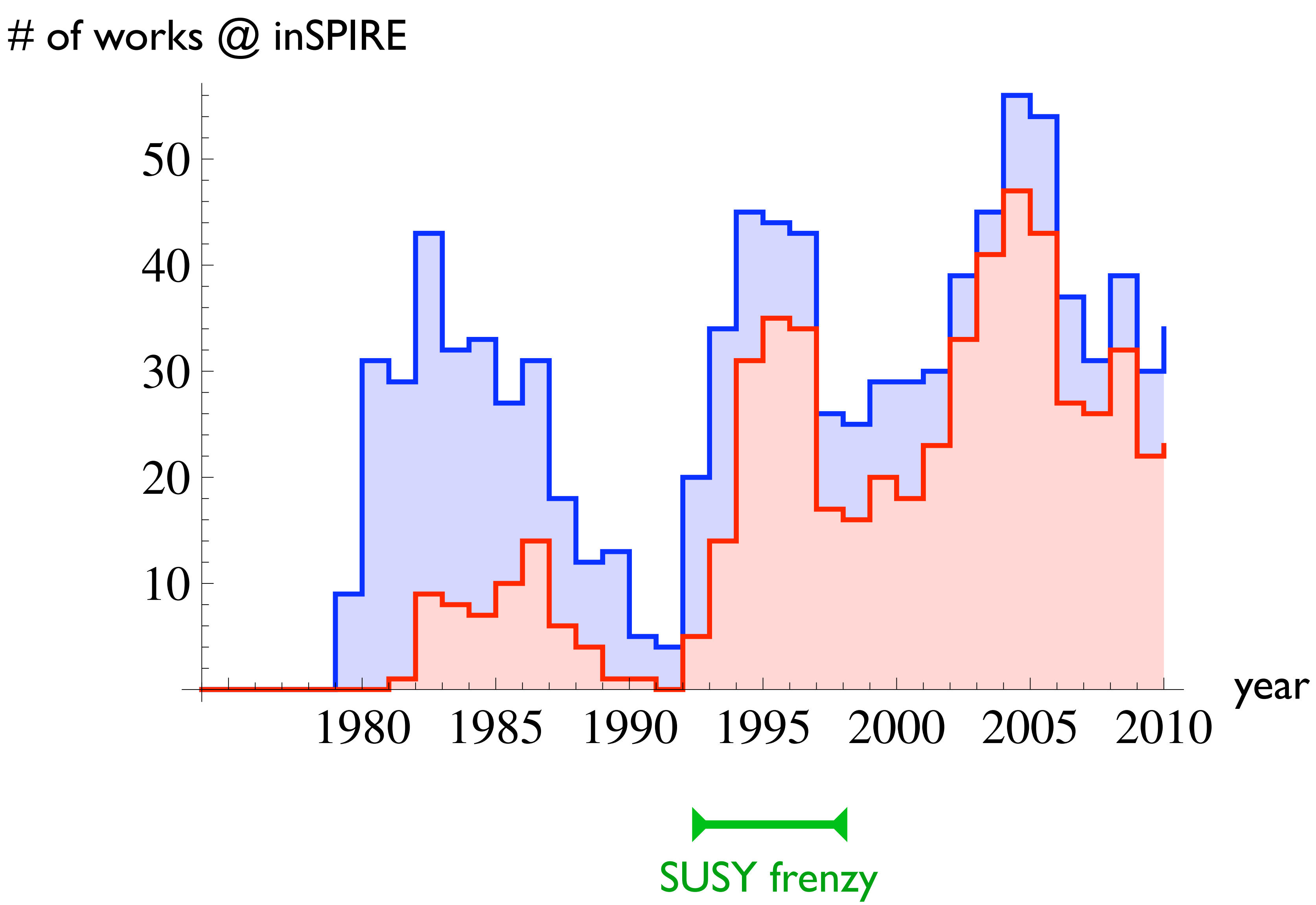

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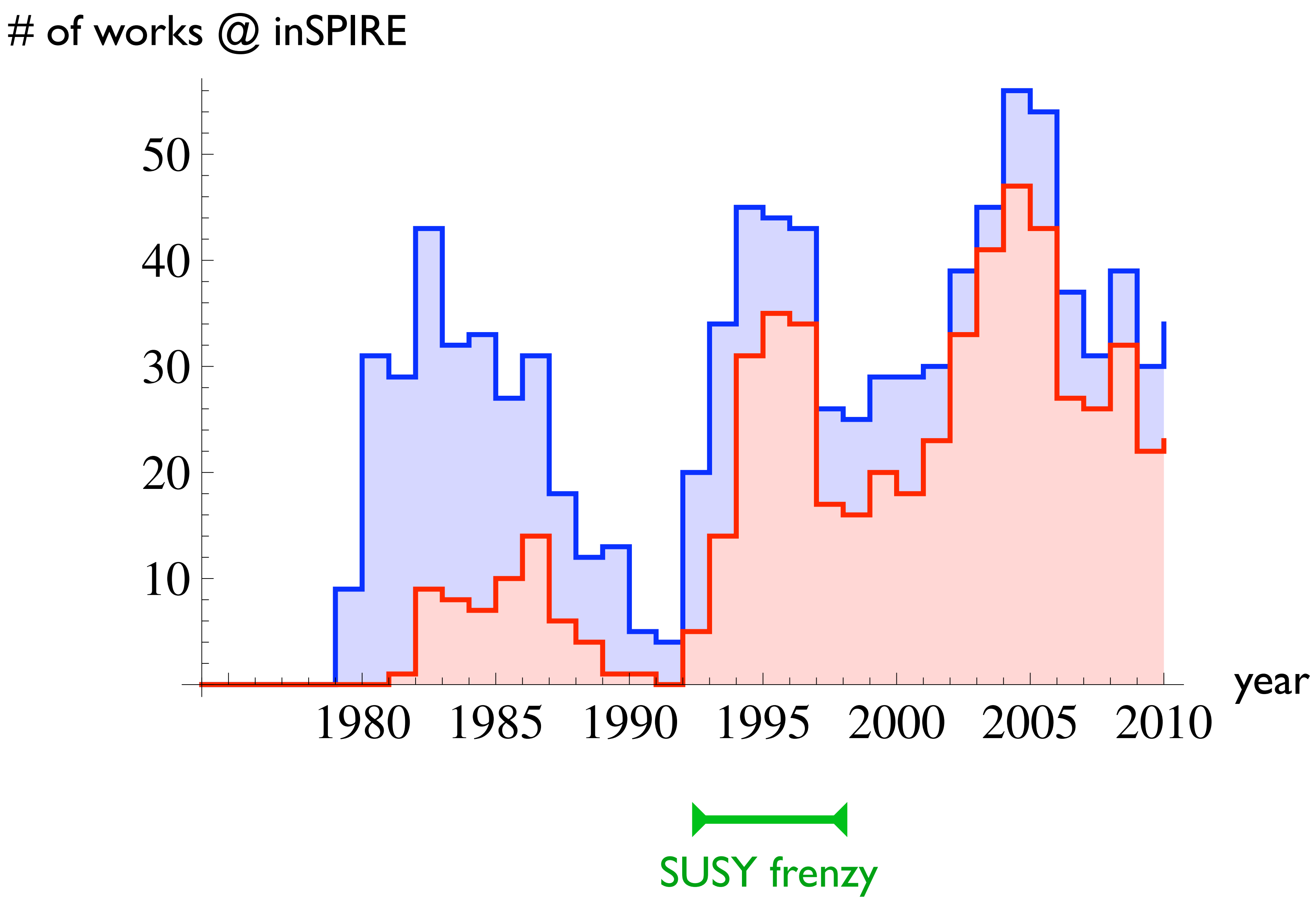
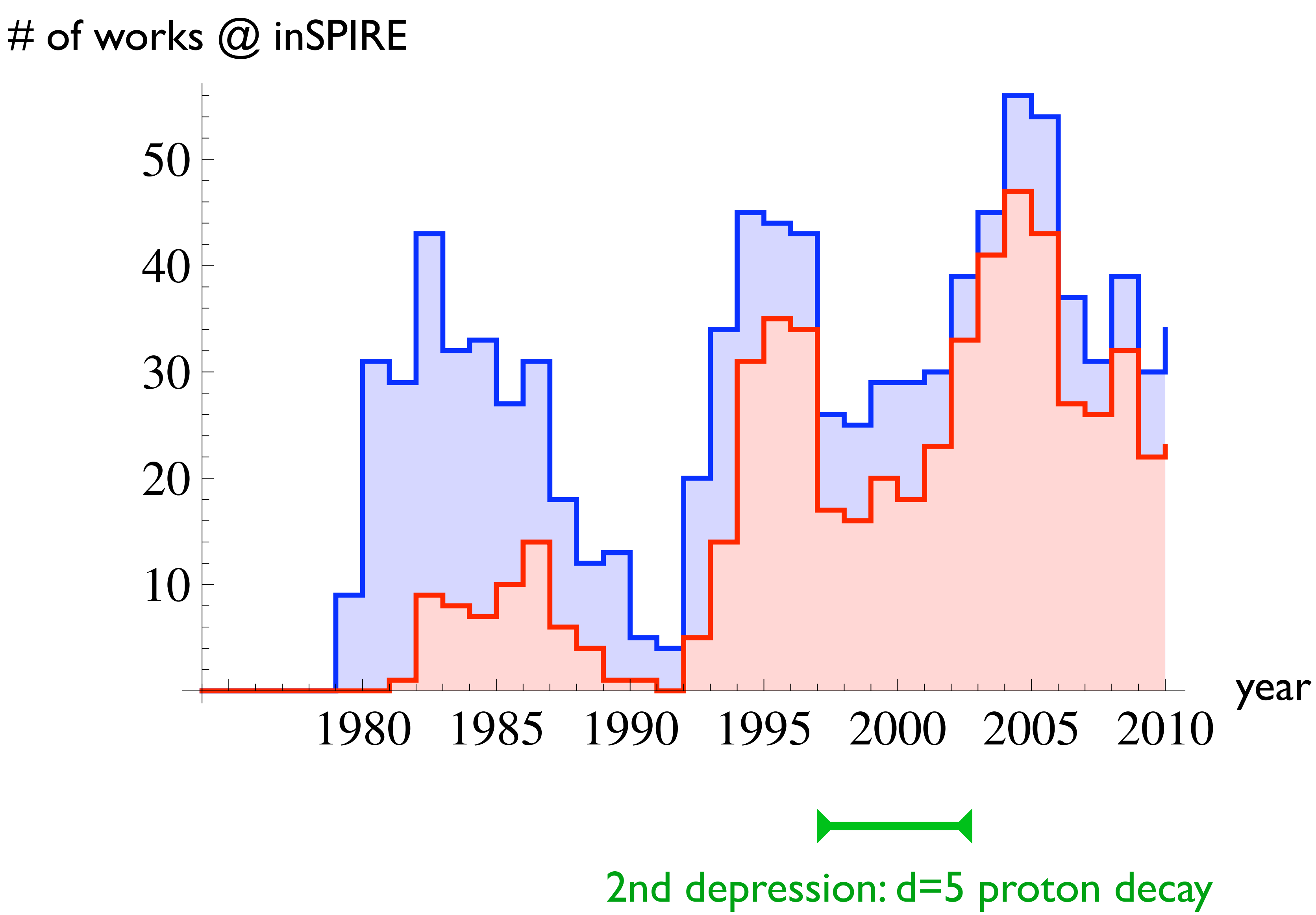


LEP precision data support MSSM-like unification ⇨ interest in SUSY GUTs

Proton decay

The era of IMB 3 (beg. of 1990's) & Super-K (since 1996)



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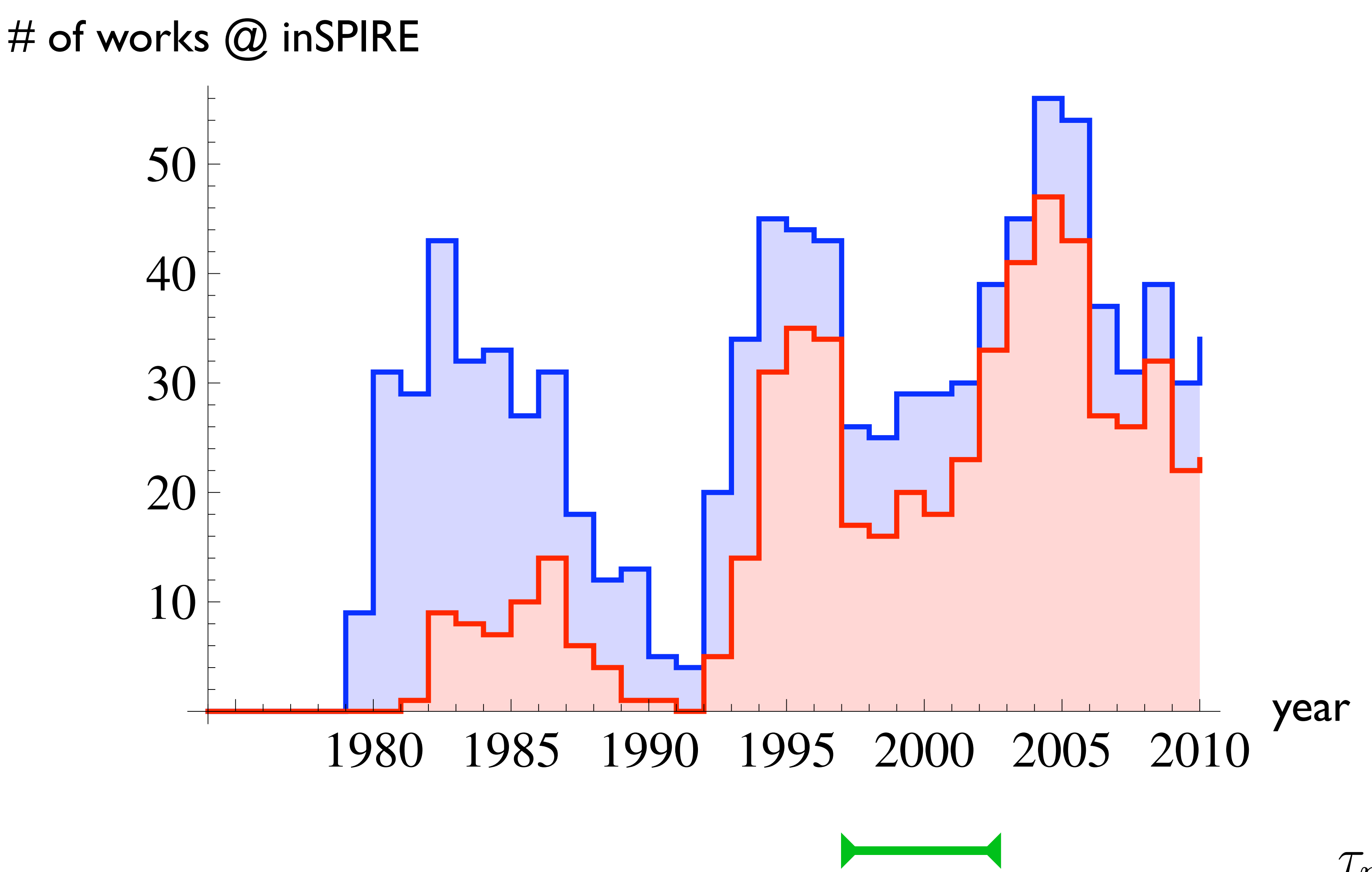

2nd depression: d=5 proton decay

$\tau_p \gtrsim 8.5 \times 10^{32}$ yr

IMB-3 1999

First reliable calculations & new proton & flavour data ⇨ failure of the SUSY GG

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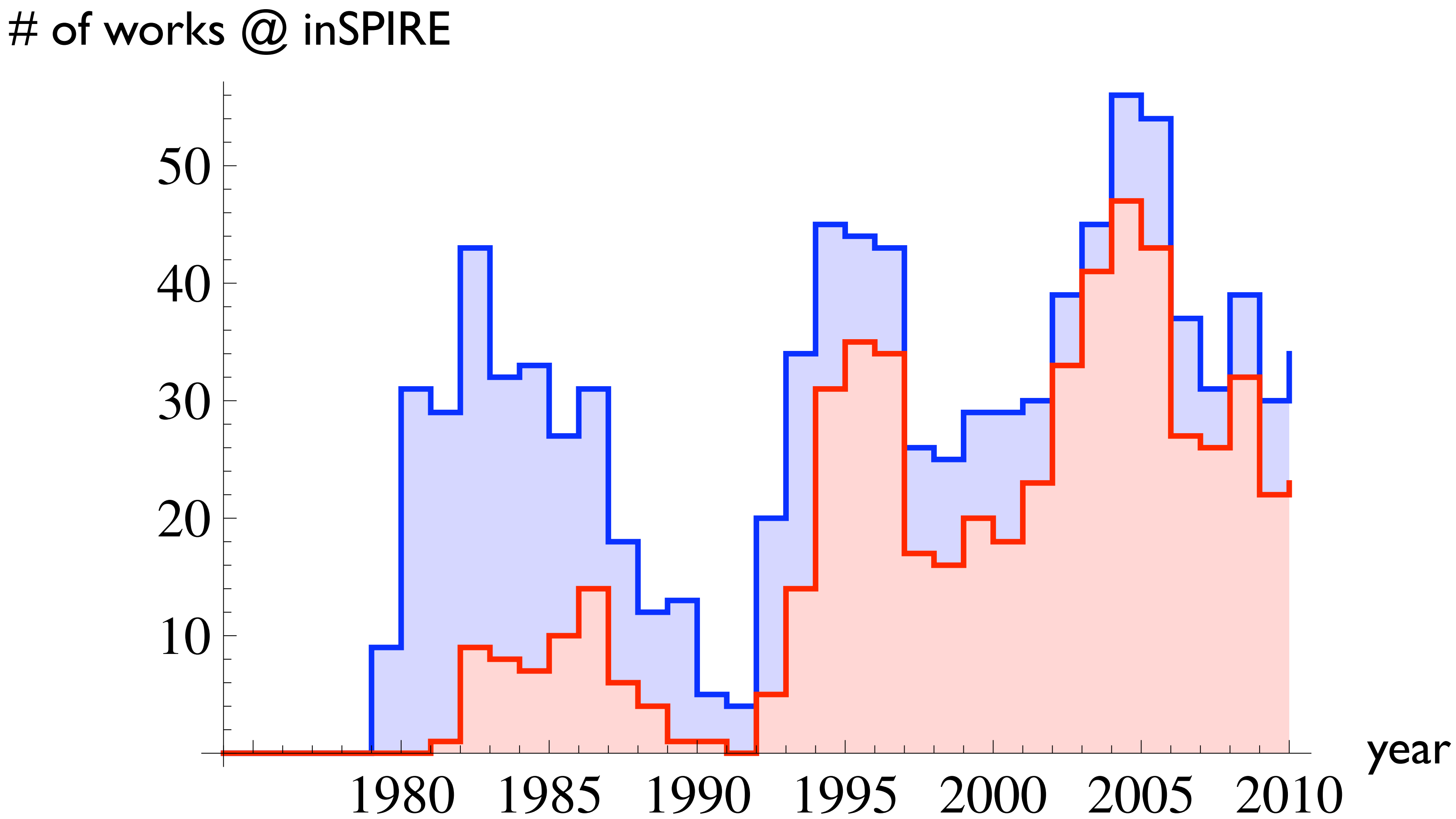

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to some extent

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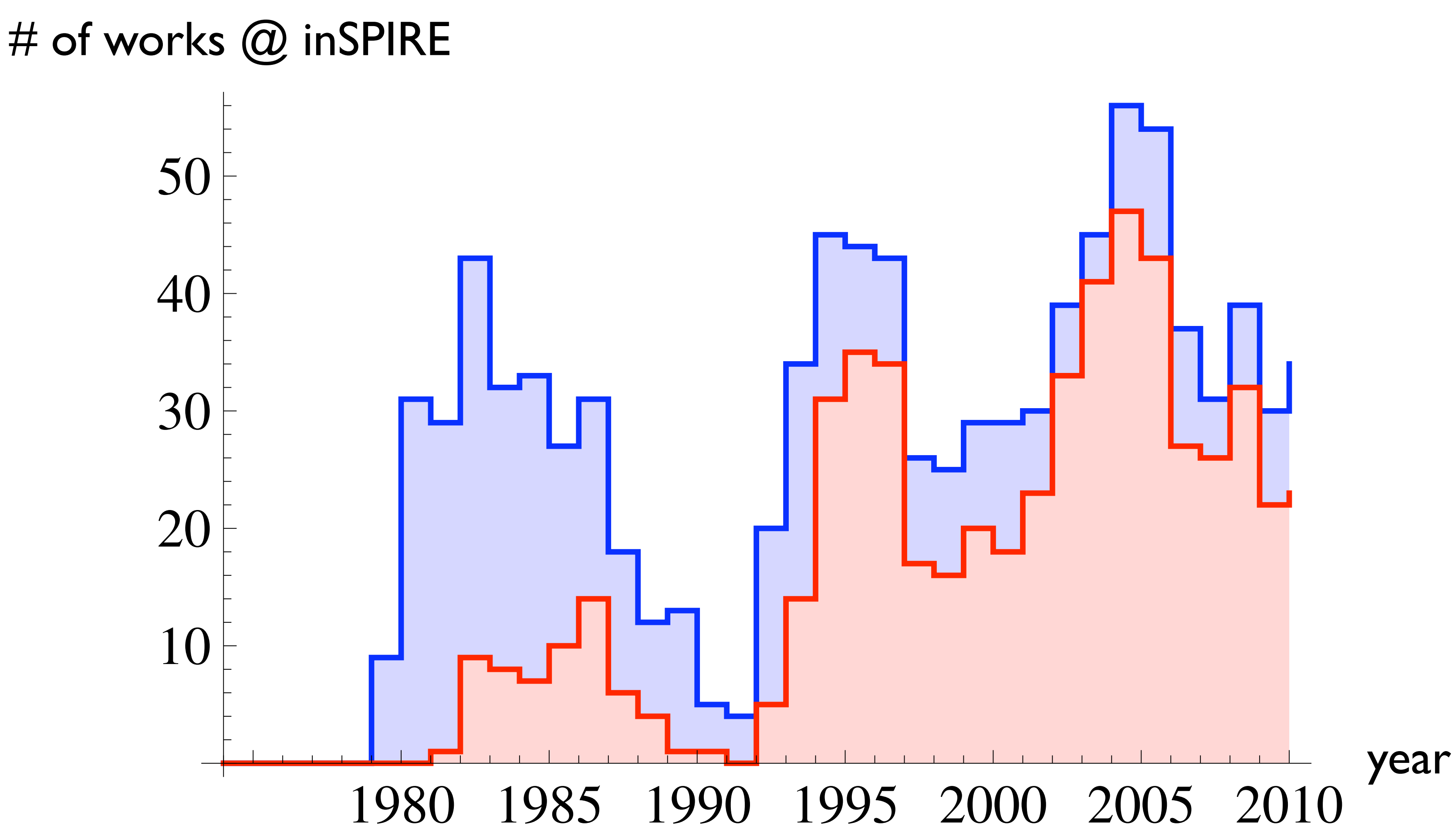


"SO(10) era"

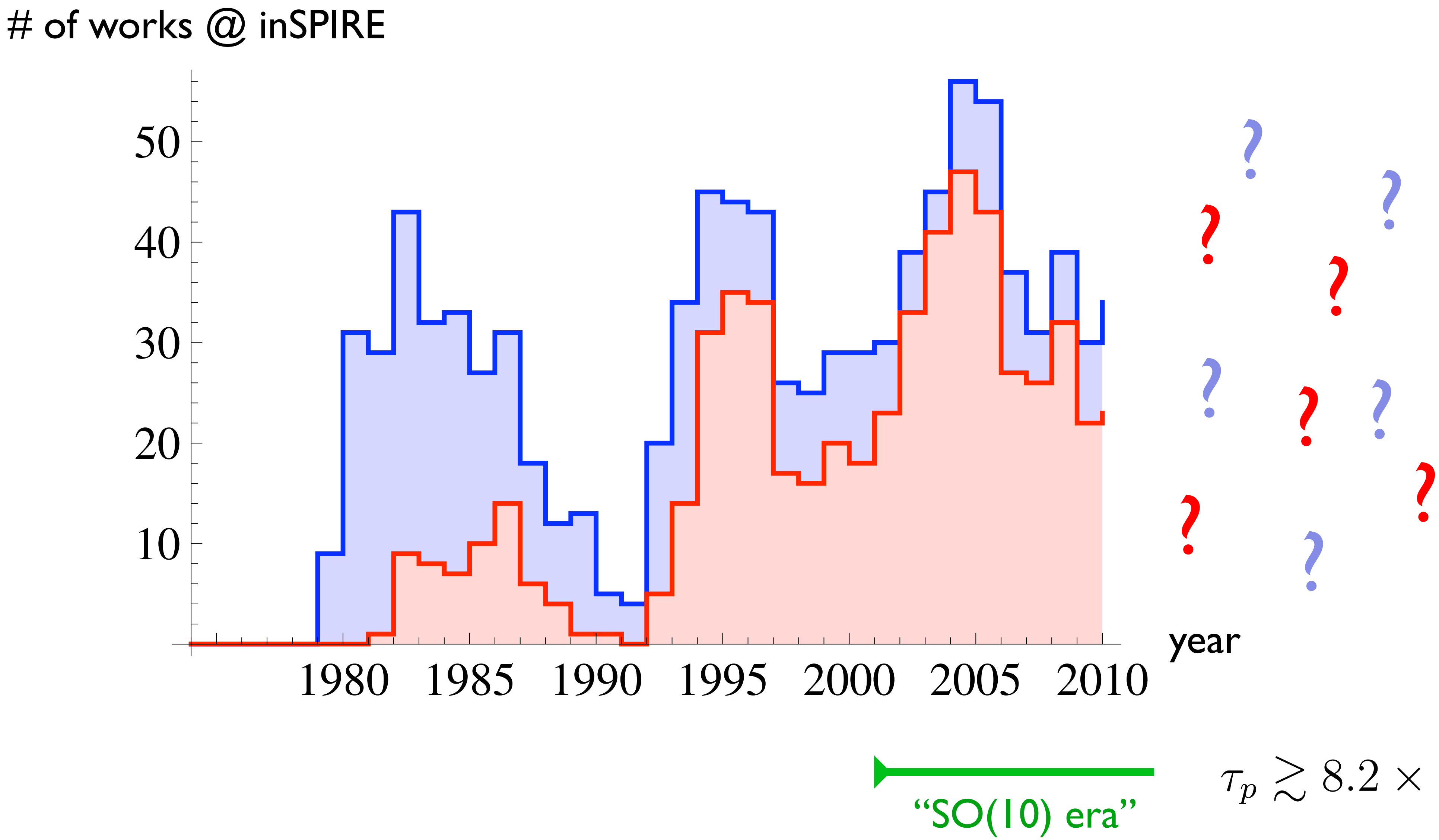
$\tau_p \gtrsim 8.2 \times 10^{33}$ yr

Super-K (2009)

neutrino masses and mixing constraints

Proton decay

future: Hyper-Kamiokande(?), LAGUNA(?), LBNE (?)



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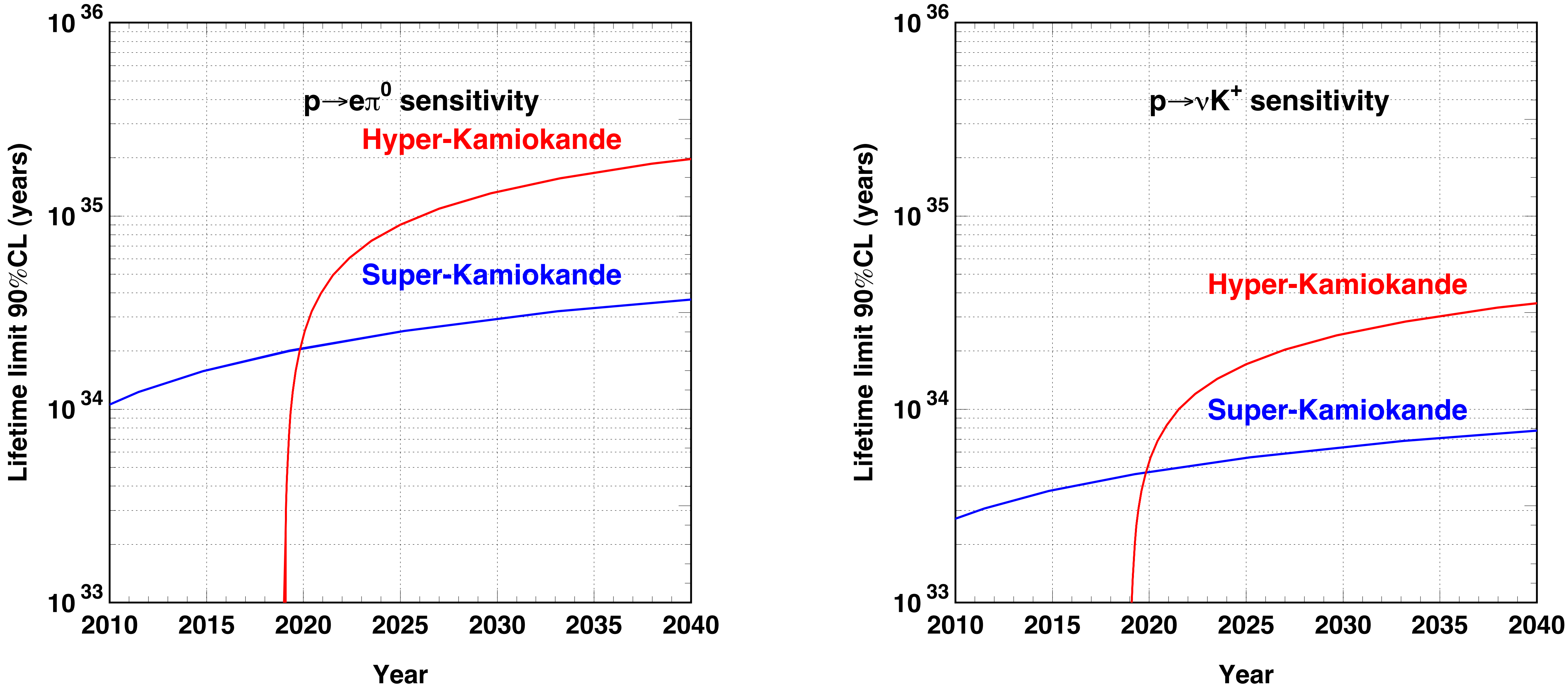
Optimistic scenario: Hyper-Kamiokande @ around 2020

Hyper-K letter of intent: Abe et al., arXiv:1109.3262 [hep-ex]



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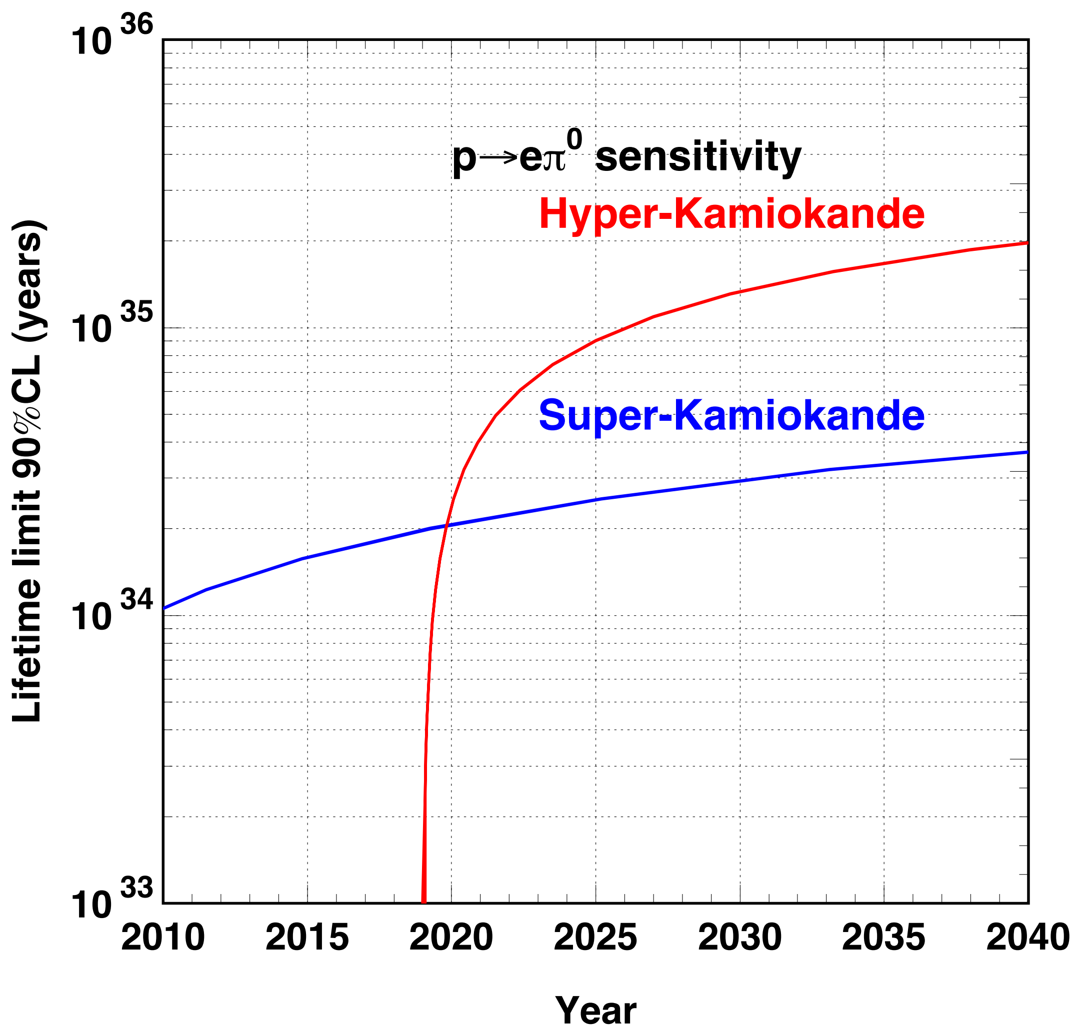

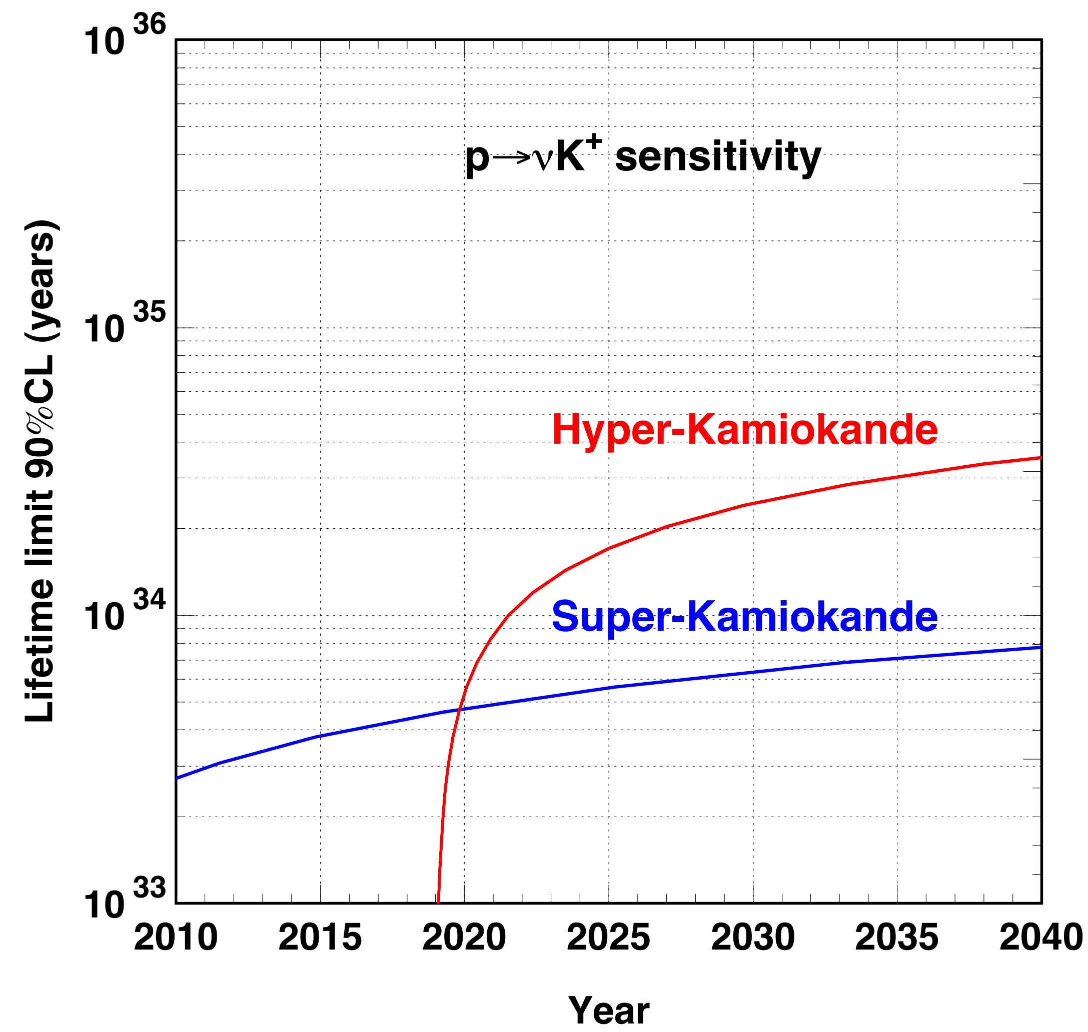

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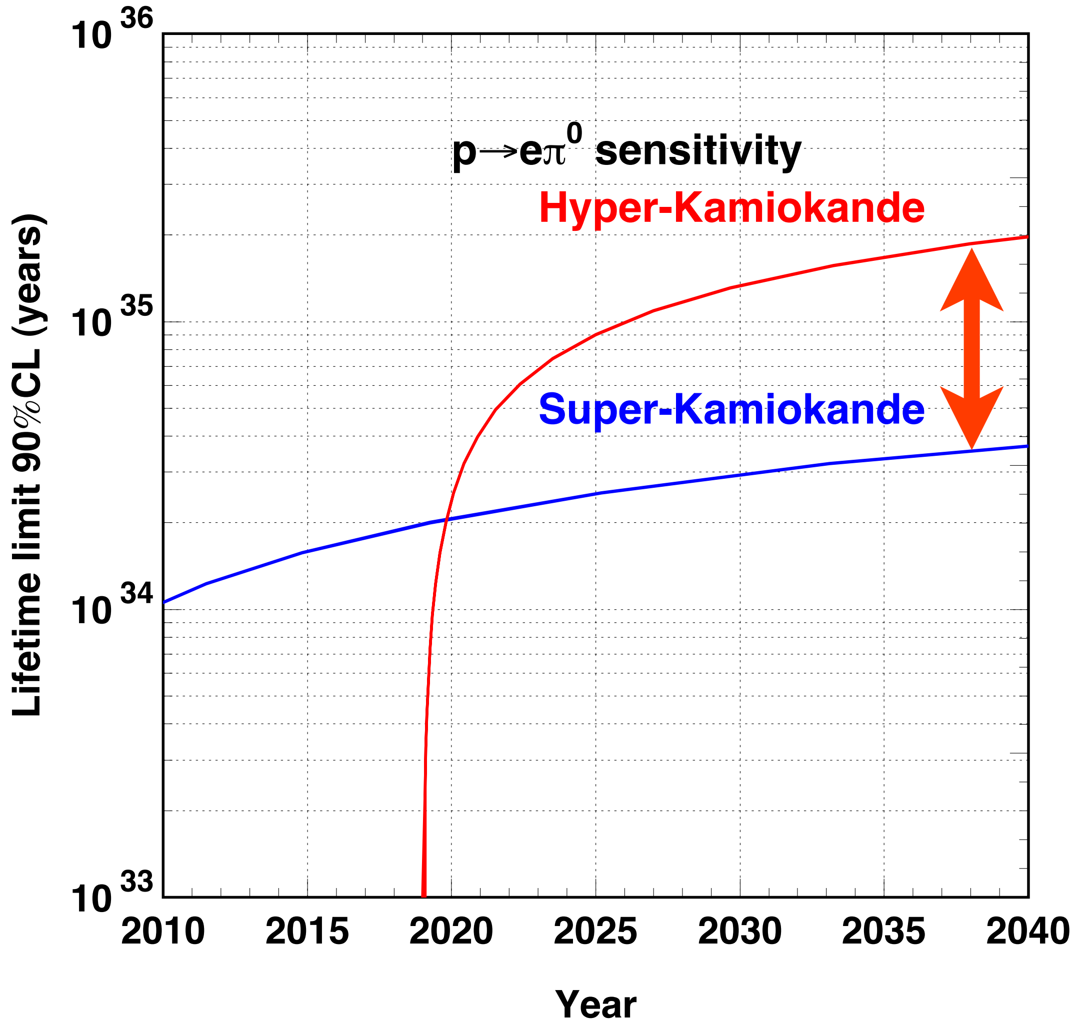

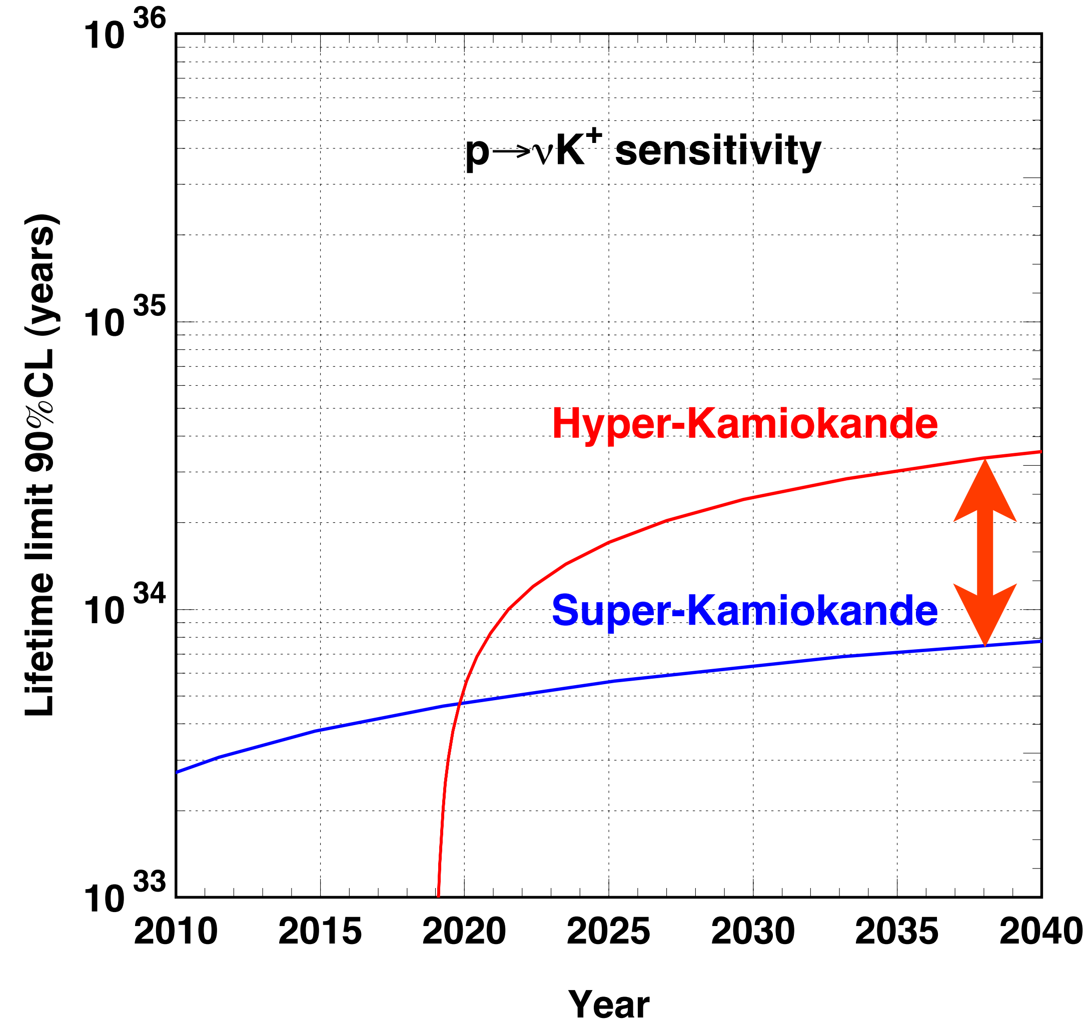

Accuracy of a **factor of few** in Γ_p needed to make a case !

The status of SO(10) GUTs

(again, just minimal models)

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(again, just minimal models)

||

"wrong at the right time"

SO(10) basics

Georgi & Glashow 1974
Fritzsch & Minkowski 1975

- Matter family in a single spinor

$$16_F = (3,2,+\tfrac{1}{6}) \oplus (1,2,-\tfrac{1}{2}) \oplus (\bar{3},1,+\tfrac{1}{3}) \oplus (\bar{3},1,-\tfrac{2}{3}) \oplus (1,1,+1) \oplus (1,1,0)$$

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- Strongly correlated Yukawa's:

$$10_H = (1,2,-\tfrac{1}{2}) \oplus (1,2,+\tfrac{1}{2}) \oplus (\bar{3},1,+\tfrac{1}{3}) \oplus (3,1,-\tfrac{1}{3})$$

$16_F 16_F 10_H \ni$ Dirac masses for everybody can be obtained with a single coupling!

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$16_F 16_F 10_H \ni$ Dirac masses for everybody can be obtained with a single coupling!

- RH neutrinos automatic, renormalizable type I+II seesaw natural

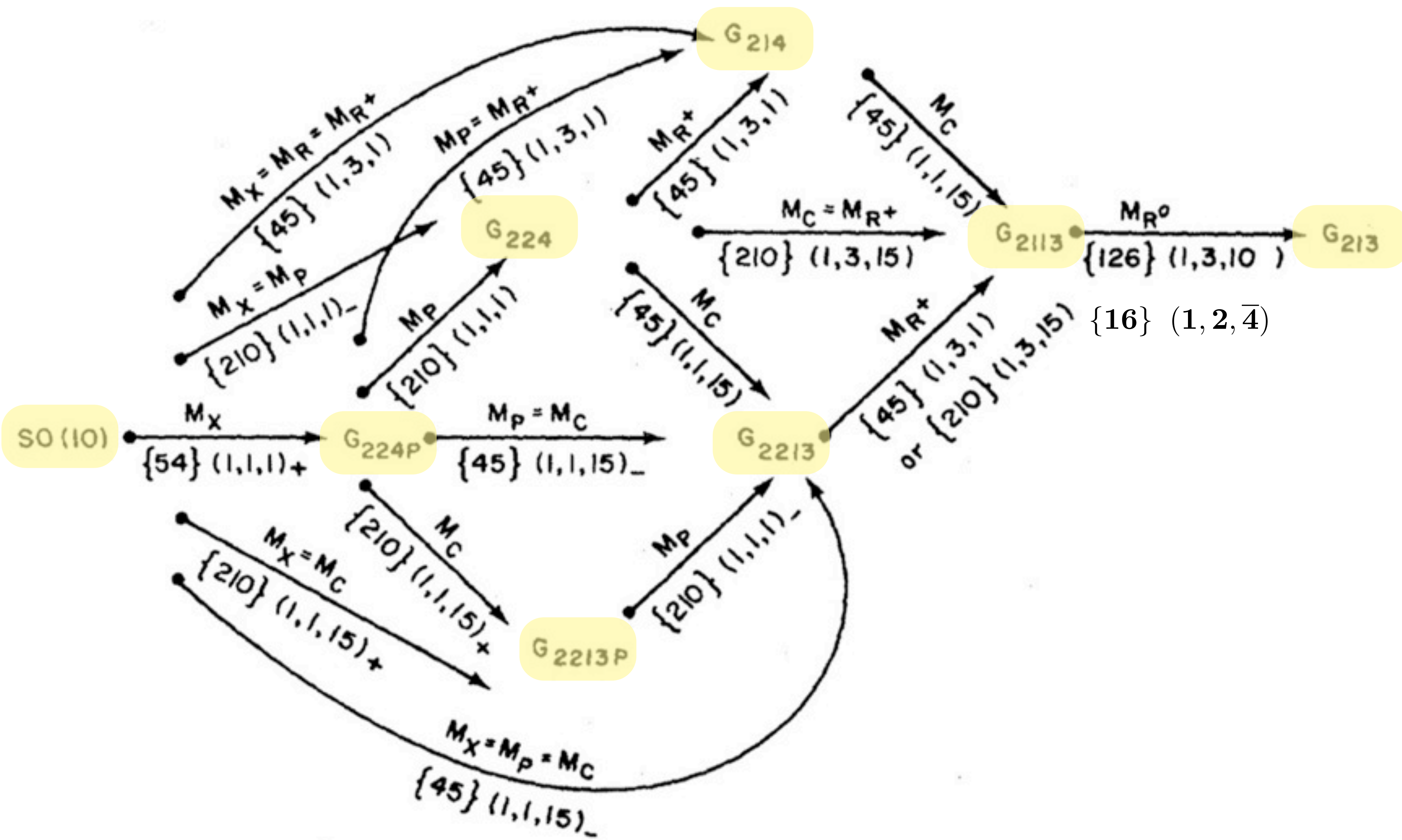
$$\overline{126}_H \ni (1,2,-\tfrac{1}{2}) \oplus (1,2,+\tfrac{1}{2}) \oplus (1,1,0) \oplus (1,3,+1) \oplus \ldots$$

$16_F 16_F \overline{126}_H \ni$ LH and RH Majorana neutrino masses, extra Dirac contributions

SO(10) symmetry breaking

Chang, Mohapatra, Gipson, Marshak, Parida 1985

SU(5) branches omitted



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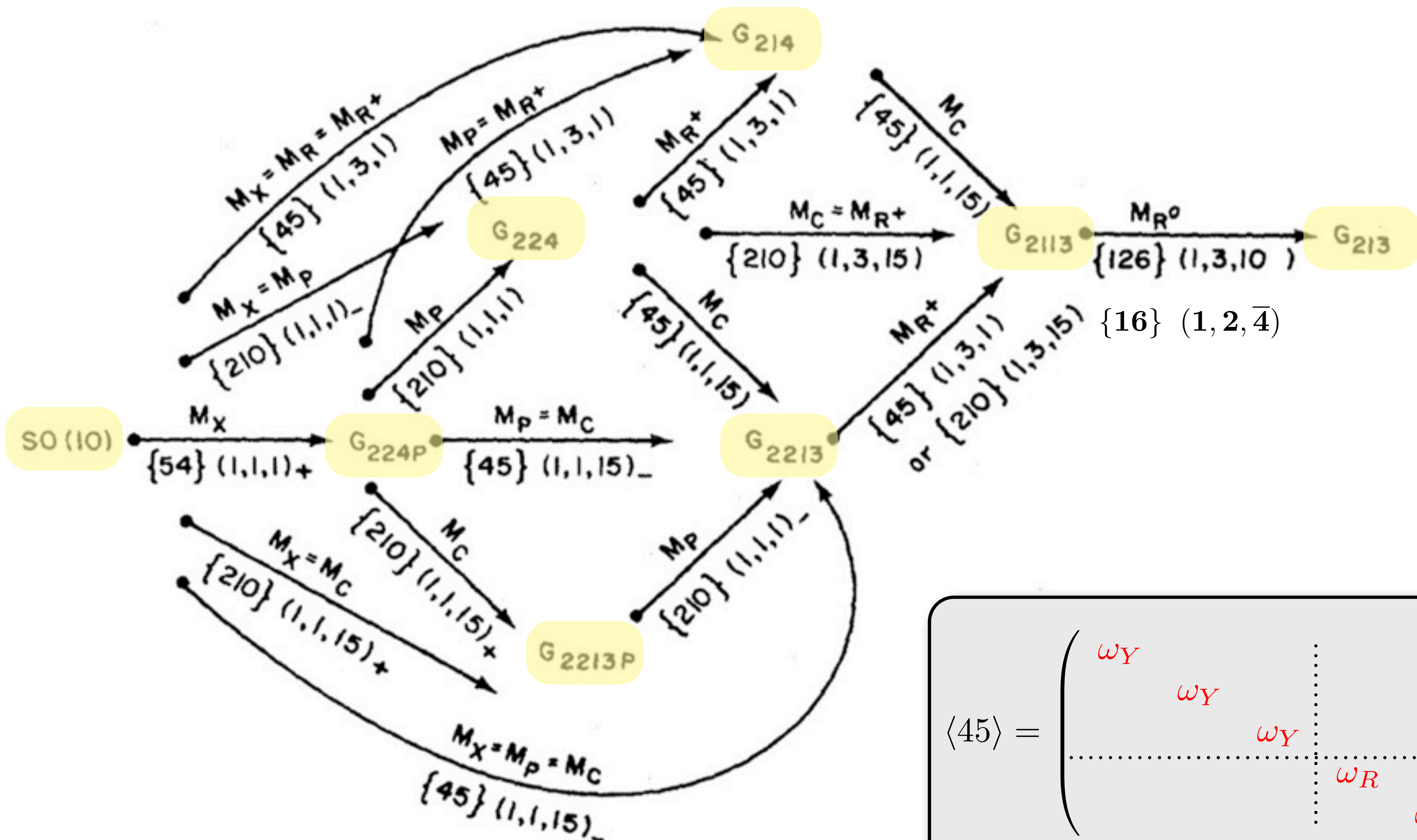

$$\langle 45\rangle = \left(\begin{array}{ccc|cc} \omega_Y & & & & \\ & \omega_Y & & & \\ & & \omega_Y & & \\ \hline & & & \omega_R & \\ & & & & \omega_R \end{array}\right) \otimes \tau_2$$

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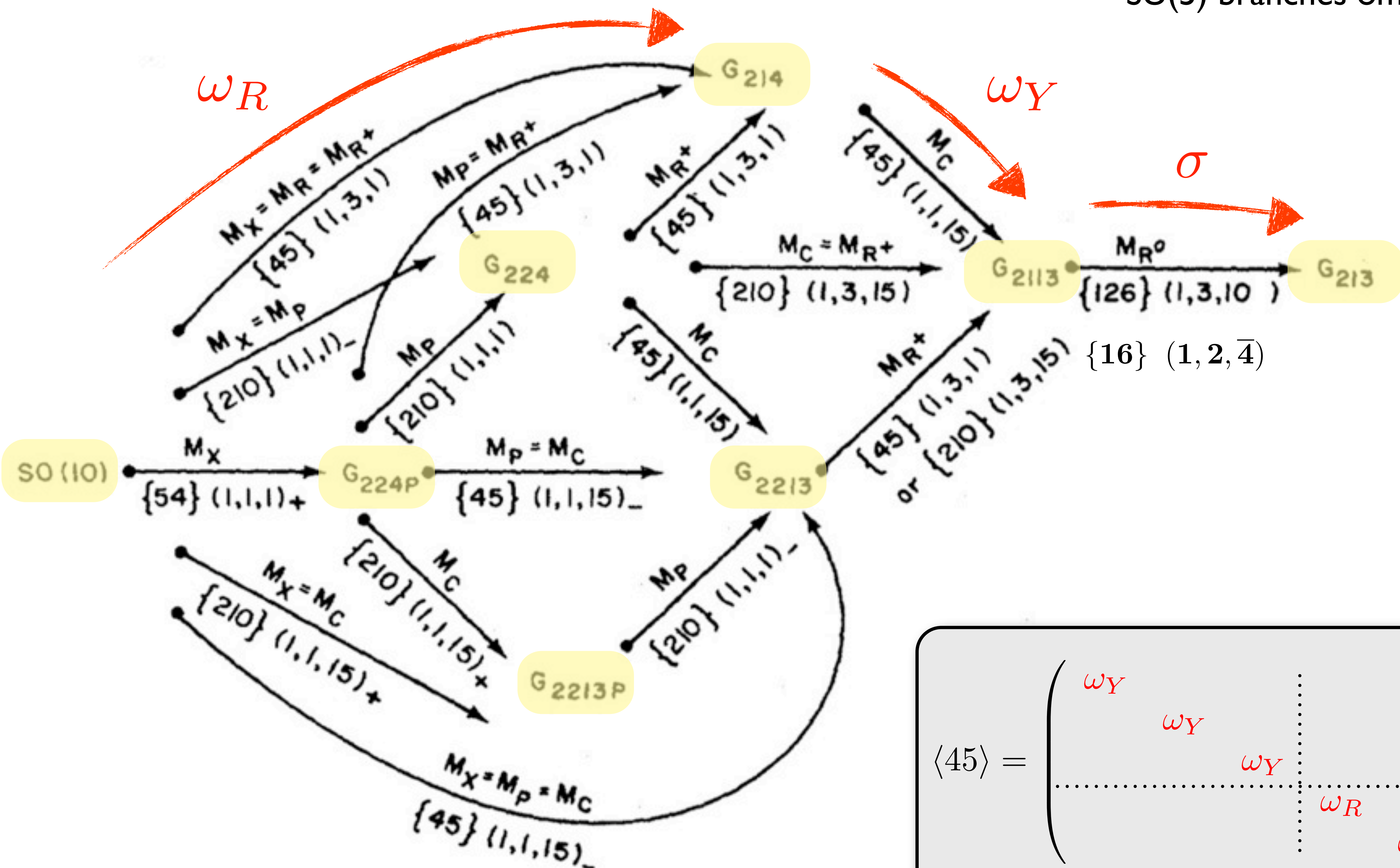

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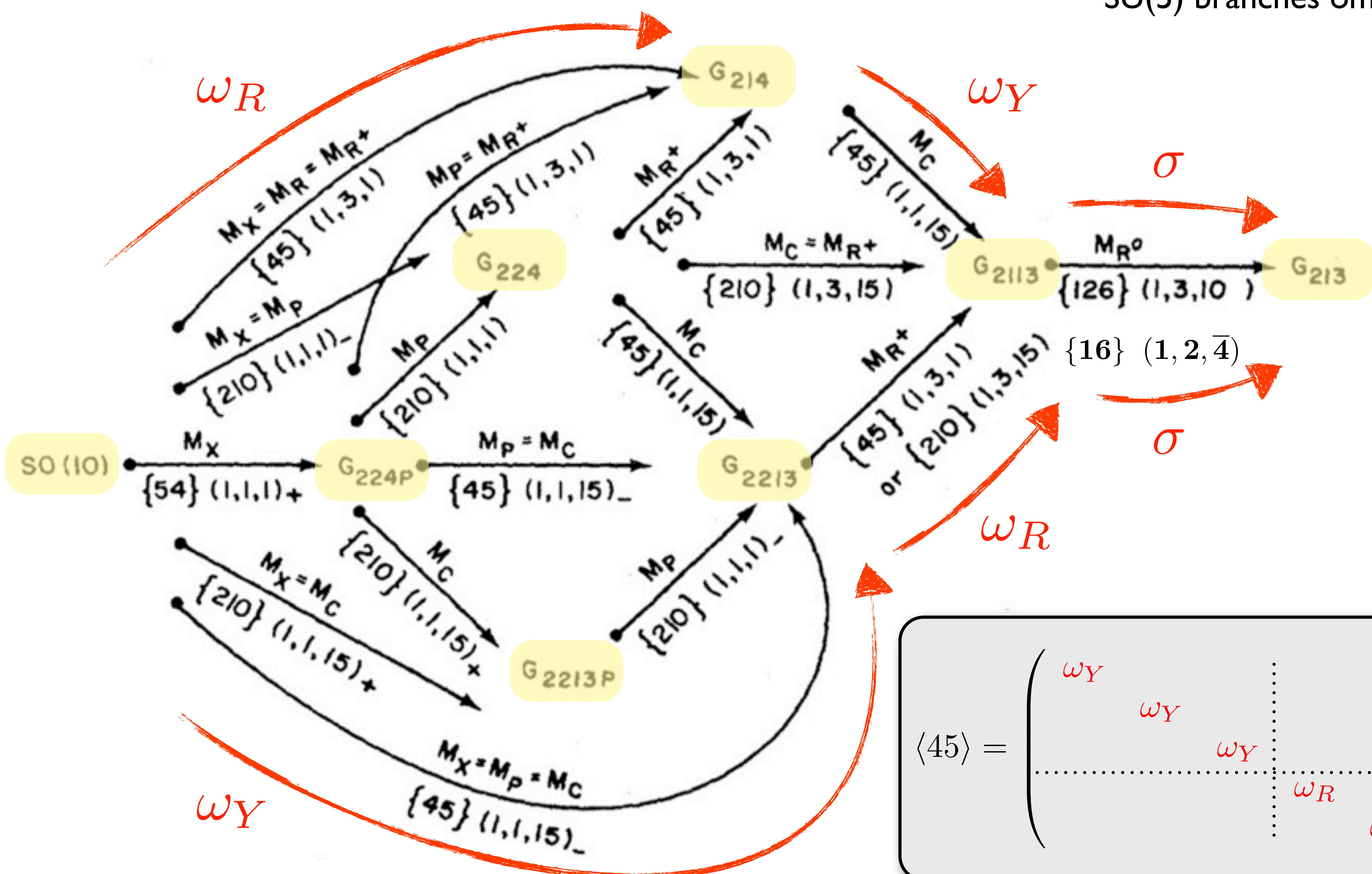

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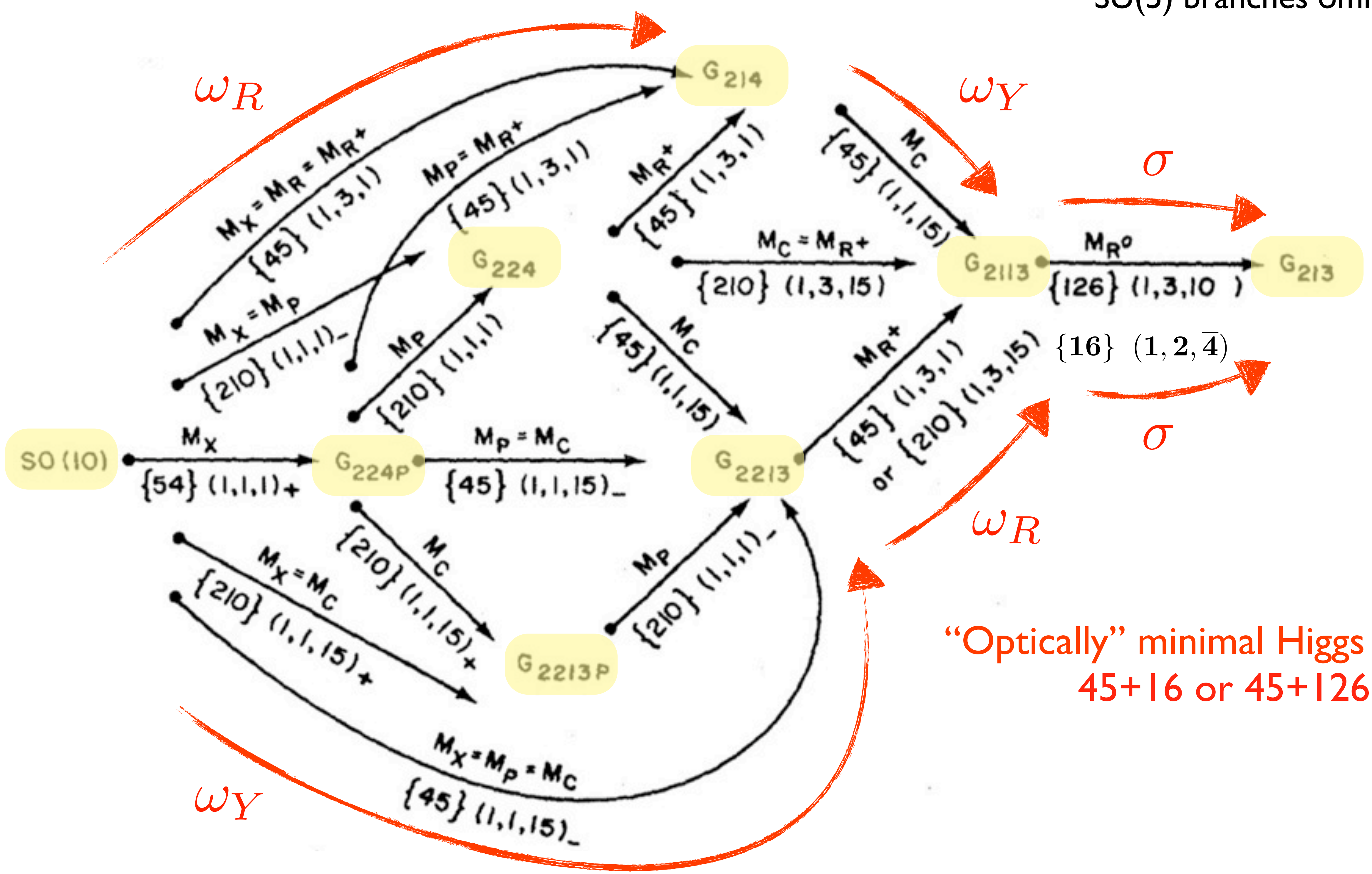

"Optically" minimal Higgs models:
45+16 or 45+126

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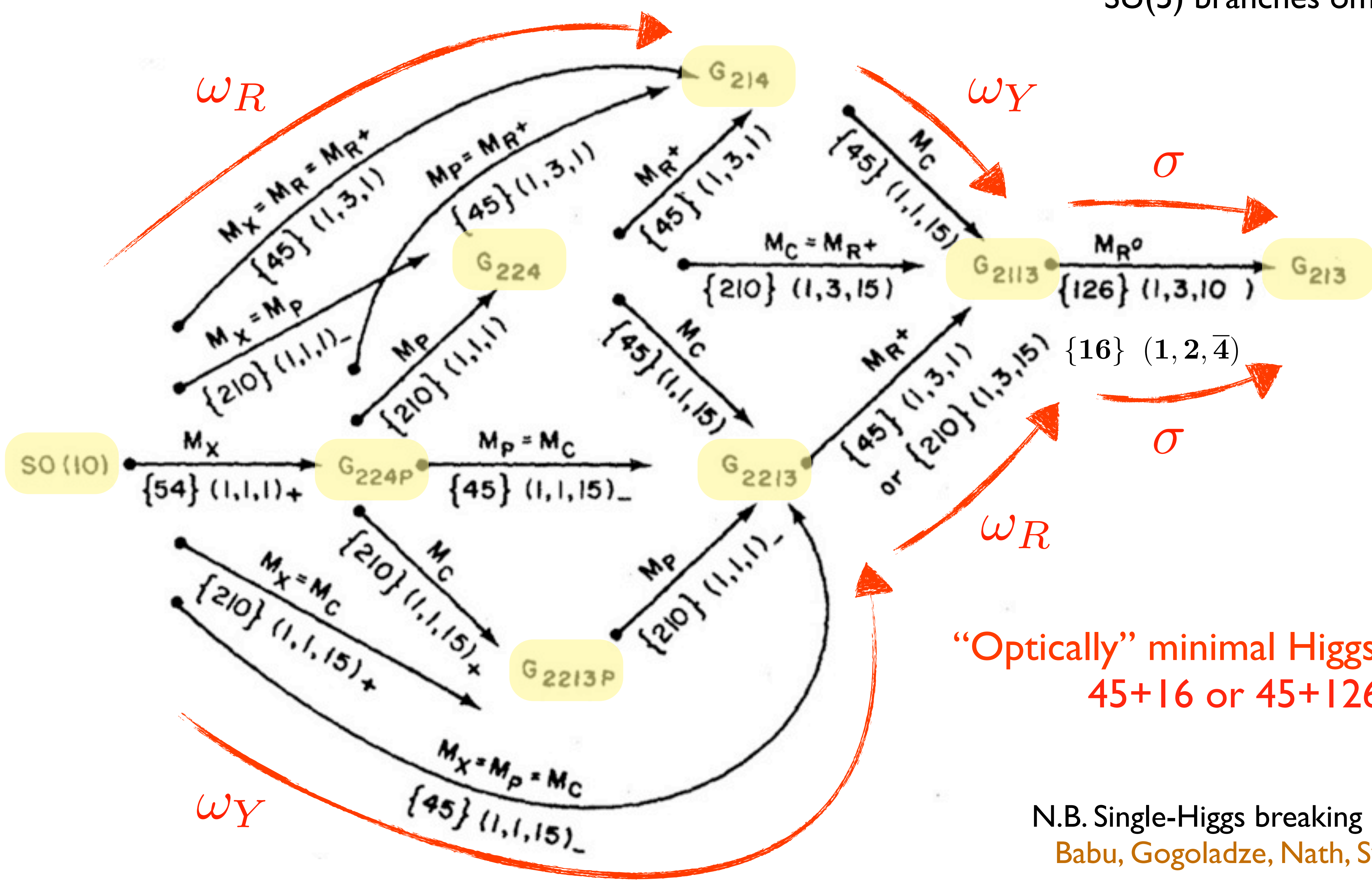

“Optically” minimal Higgs models: 45+16 or 45+126

N.B. Single-Higgs breaking (144)
Babu, Gogoladze, Nath, Syed

Minimal SUSY SO(10)?

45+16	45+126
+ technically simpler	- much more complicated
- nonrenormalizable	+ renormalizable Yukawas!
- d=4 proton decay	+ automatic R-parity

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*The Higgs models with just 16+45 or 126+45 are nonrenormalizable!

The spectacular failure of the minimal SUSY SO(10)

renormalizable

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Minimal renormalizable SUSY SO(10)

Babu, Mohapatra, Fukuyama, Ilakovac, Kikuchi, Okada, Macesanu, Aulakh, Bajc, Senjanovic, Vissani, Melfo, Ng, Gargh, Frigerio, Bertolini, MM Schwetz, and many others...

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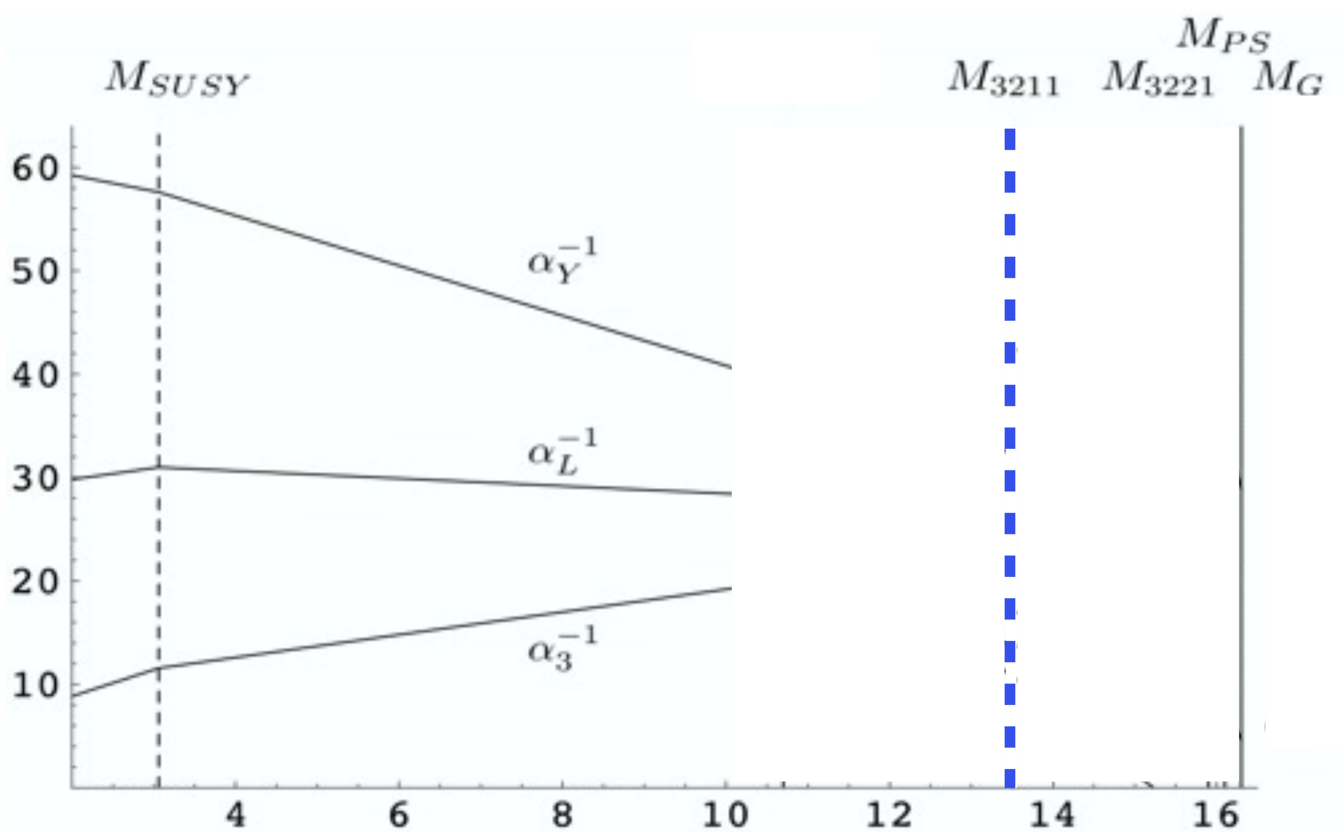

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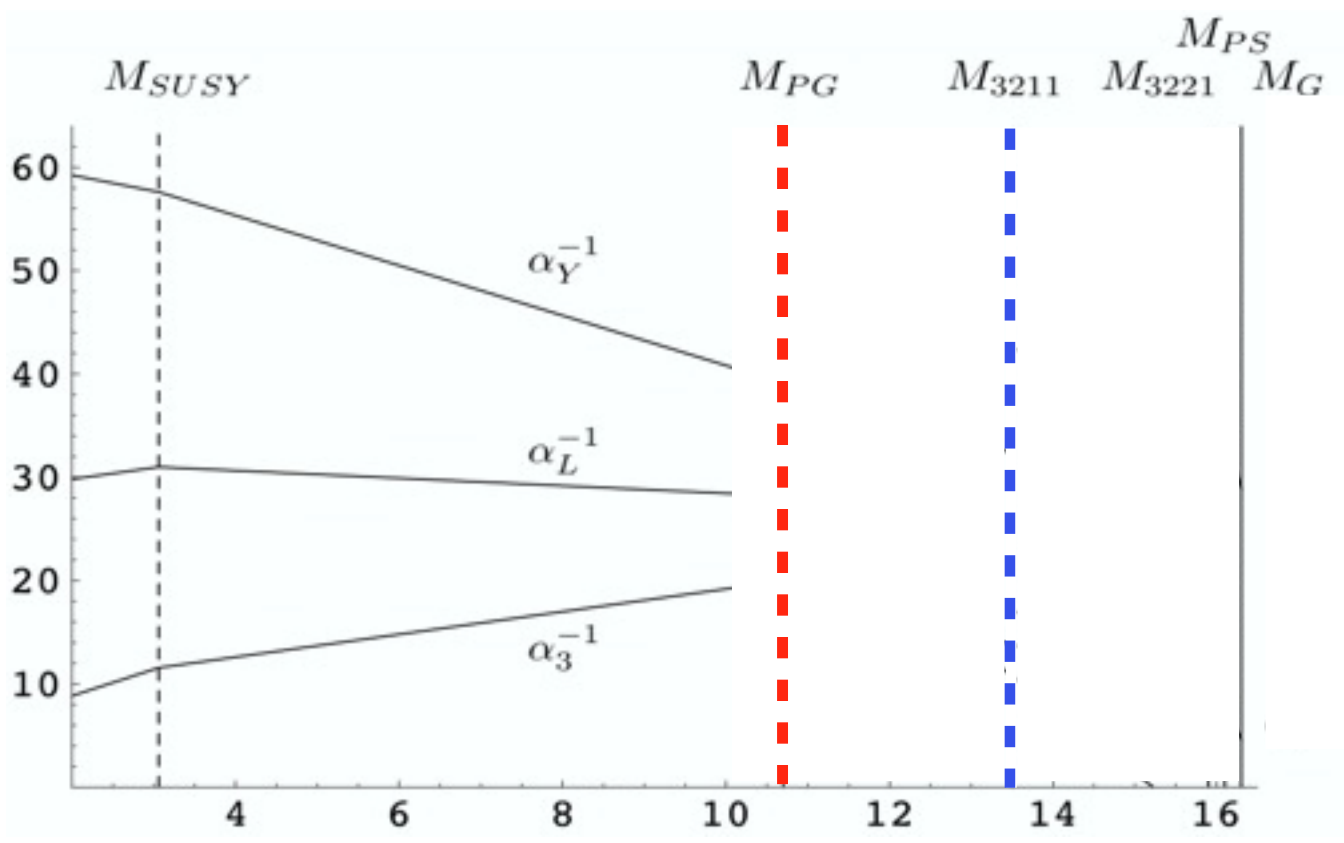

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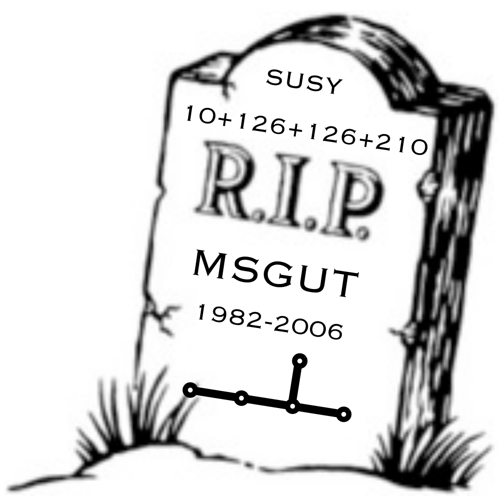

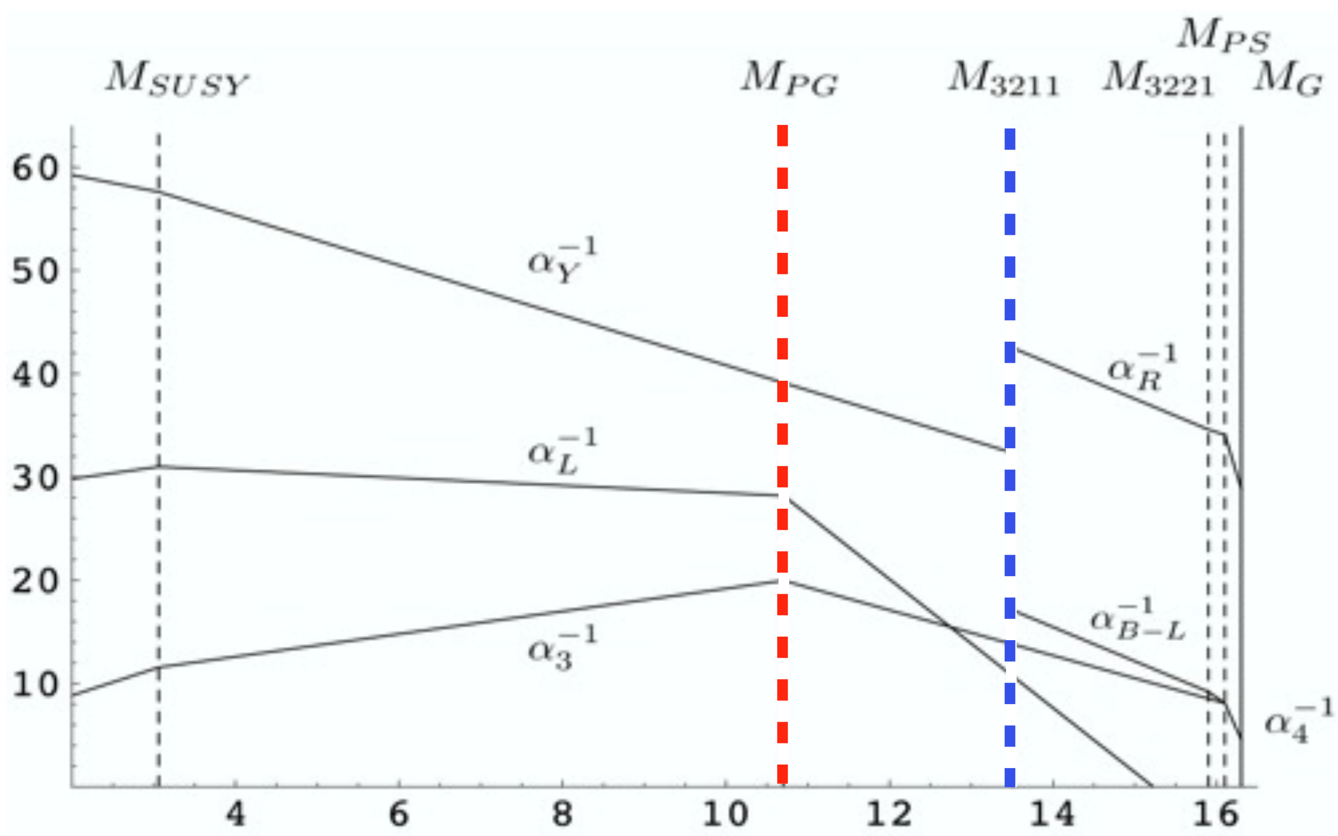

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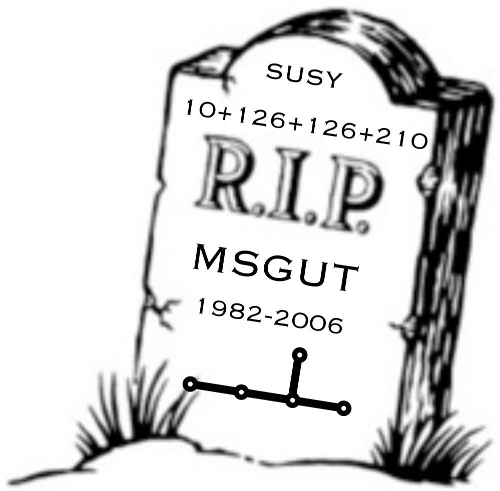
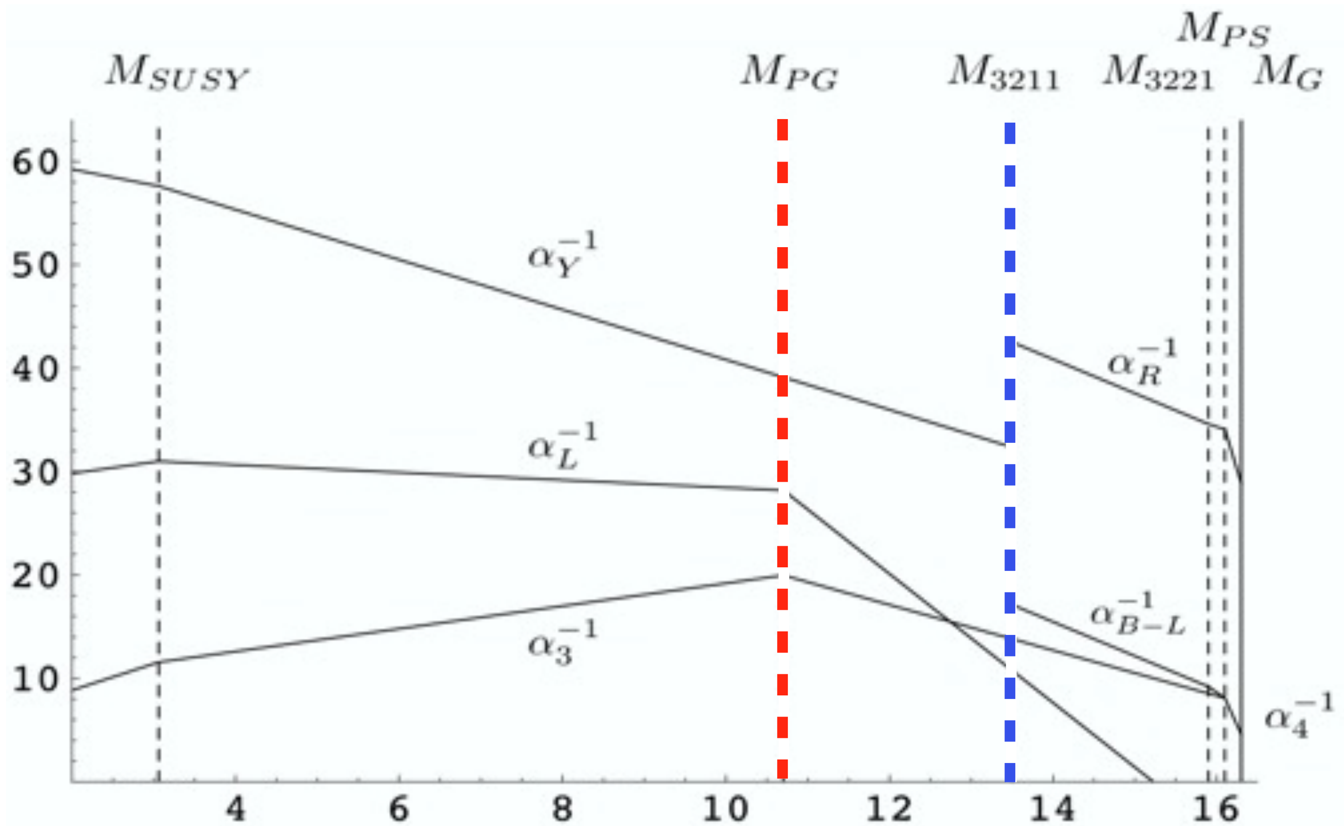


N.B. low cut-off!



Non-SUSY SO(10)

Is the tension between seesaw and unification alleviated w/o SUSY?

Non-SUSY SO(10)

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Maybe; unification pattern is different here...

Non-SUSY SO(10)

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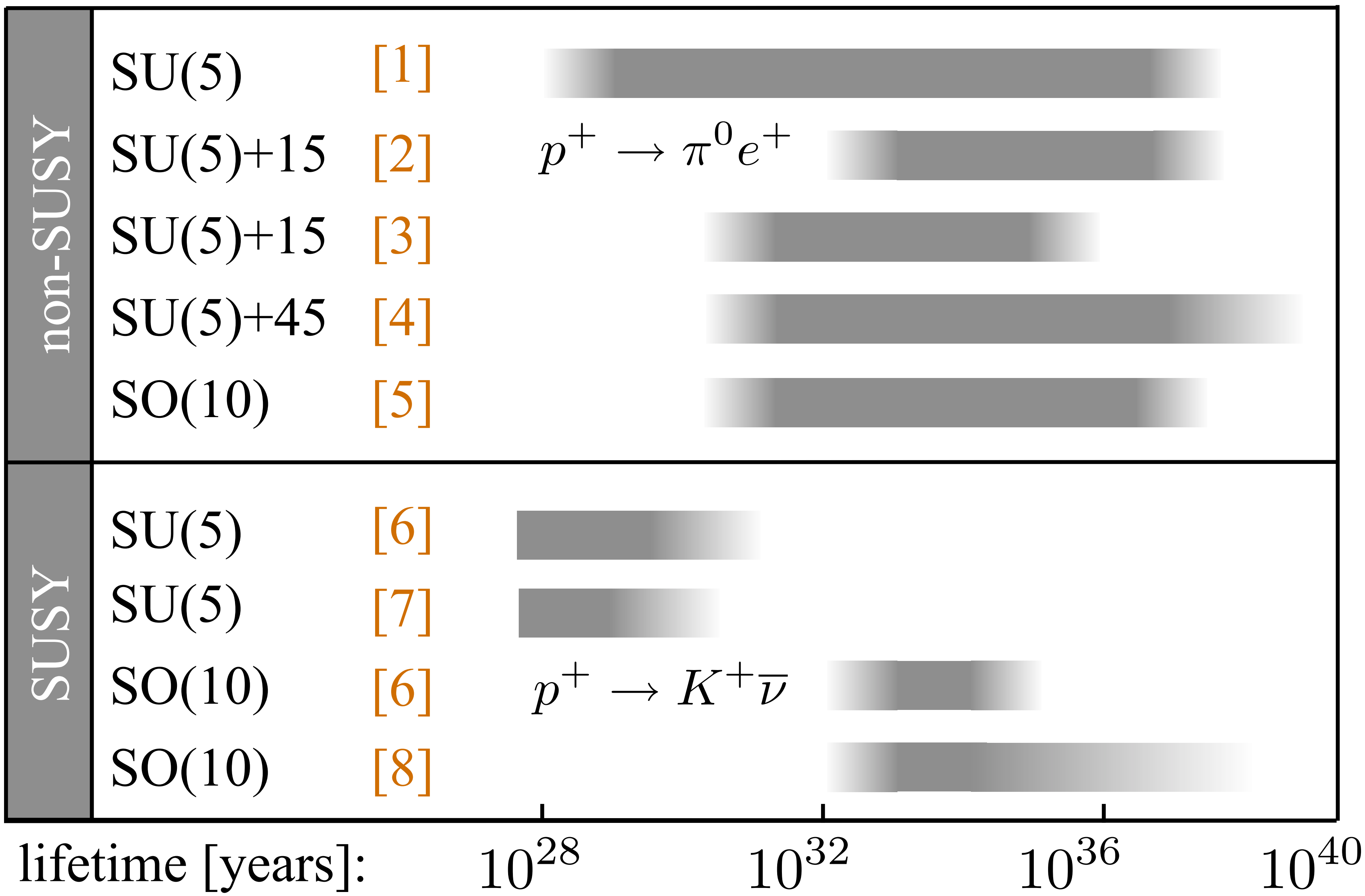
Actually, there is much more to the minimal non-SUSY SO(10)...

SO(10) & the quest for predictivity...

Proton lifetime calculations in GUTs



[1] Georgi, Quinn, Weinberg, PRL 33, 451 (1974)
[2] Dorsner, Fileviez Perez, NPB 723, 53 (2005)
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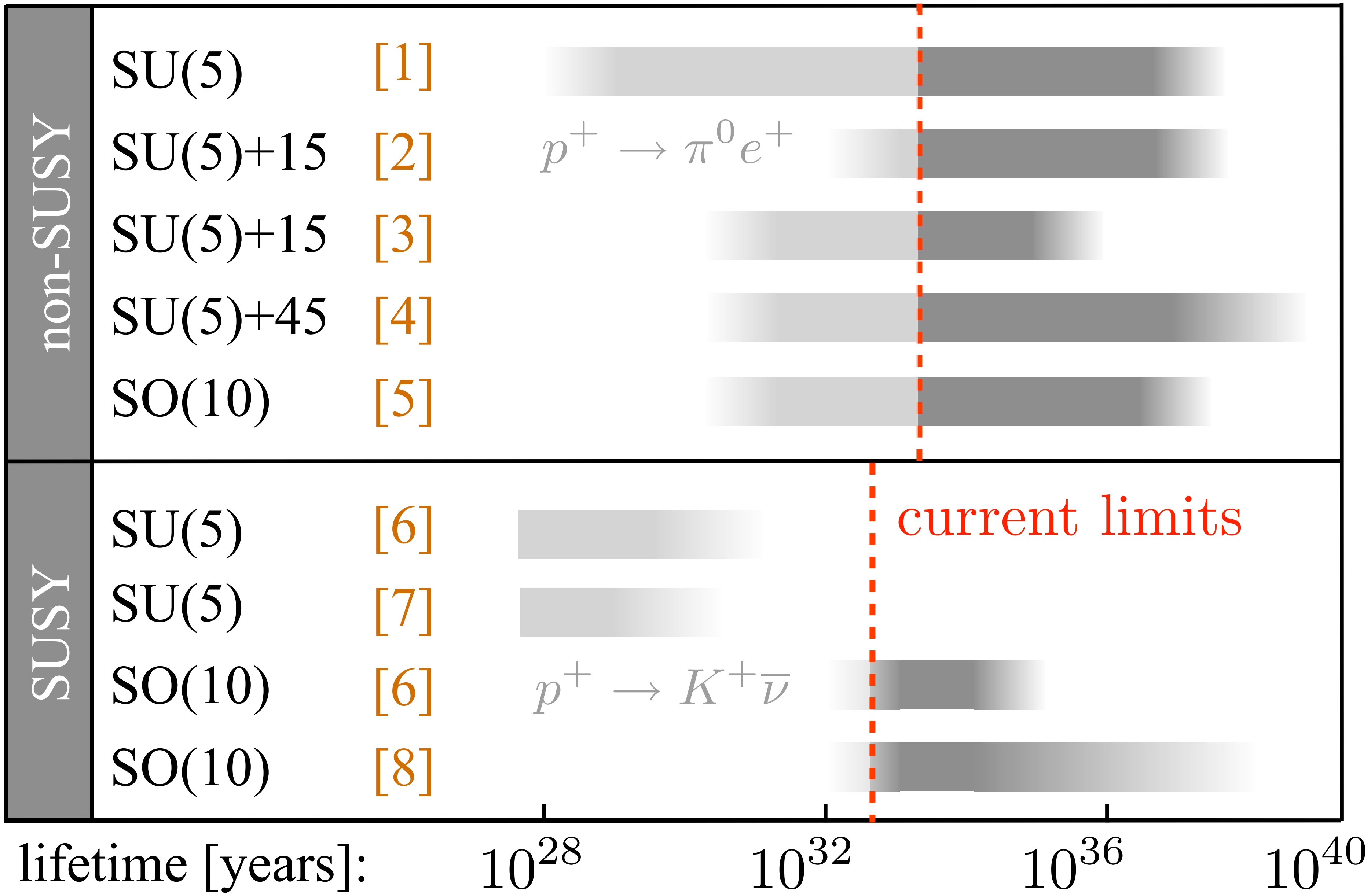

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Main theoretical uncertainties:

GUT scale determination

- at least two loops

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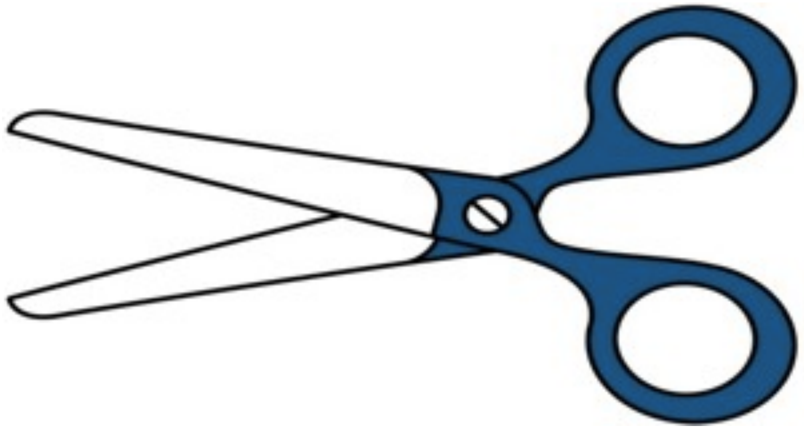

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Planck scale effects

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Planck scale effects

$$\mathcal{L} \ni \frac{\kappa}{\Lambda} F^{\mu\nu} \langle \Phi \rangle F_{\mu\nu}$$

- finite shifts in the gauge matching

- can be as large as $\Delta\alpha_i^{-1} \sim 1$

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Larsen, Wilczek, NPB 458, 249 (1996)
G. Veneziano, JHEP 06 (2002) 051
Calmet, Hsu, Reeb, PRD 77, 125015 (2008)
G. Dvali, Fortsch. Phys. 58 (2010) 528-536

Planck scale effects

$$\mathcal{L} \ni \frac{\kappa}{\Lambda} F^{\mu\nu} \langle \Phi \rangle F_{\mu\nu}$$

- finite shifts in the gauge matching

- can be as large as $\Delta\alpha_i^{-1} \sim 1$

easily half an order of magnitude uncertainty in M_G !

Main theoretical uncertainties:

Flavour structure of the BLV currents

Precision proton lifetime calculations in GUTs

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- some channels more sensitive than others

Example:

$$\frac{g^2}{M_{1/6}^2} C_{ijk}\, \overline{u^c}\gamma^\mu d_i\, \overline{d_j^c}\gamma_\mu \nu_k \qquad C_{ijk} = (V_{d^c}^\dagger V_d)_{ji}(V_{u^c}^\dagger V_\nu)_{1k}$$

Precision proton lifetime calculations in GUTs

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Supersymmetry

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forget... 

The minimal SO(10) blessing

SO(10) broken by 45, rank reduced by 126

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Scalar potential: $V = V_{45} + V_{126} + V_{\mathrm{mix}}$

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SO(10) broken by 45, rank reduced by 126

Scalar potential: $V = V_{45} + V_{126} + V_{\rm mix}$

$$V_{45} = -\frac{\mu^2}{2}(\phi\phi)_0 + \frac{a_0}{4}(\phi\phi)_0(\phi\phi)_0 + \frac{a_2}{4}(\phi\phi)_2(\phi\phi)_2\,,$$

$$\begin{aligned} V_{126} = & -\frac{\nu^2}{5!}(\Sigma\Sigma^*)_0 \\ & + \frac{\lambda_0}{(5!)^2}(\Sigma\Sigma^*)_0(\Sigma\Sigma^*)_0 + \frac{\lambda_2}{(4!)^2}(\Sigma\Sigma^*)_2(\Sigma\Sigma^*)_2 \\ & + \frac{\lambda_4}{(3!)^2(2!)^2}(\Sigma\Sigma^*)_4(\Sigma\Sigma^*)_4 + \frac{\lambda'_4}{(3!)^2}(\Sigma\Sigma^*)_{4'}(\Sigma\Sigma^*)_{4'} \\ & + \frac{\eta_2}{(4!)^2}(\Sigma\Sigma)_2(\Sigma\Sigma)_2 + \frac{\eta_2^*}{(4!)^2}(\Sigma^*\Sigma^*)_2(\Sigma^*\Sigma^*)_2\,, \end{aligned}$$

$$\begin{aligned} V_{\rm mix} = & \frac{i\tau}{4!}(\phi)_2(\Sigma\Sigma^*)_2 + \frac{\alpha}{2\cdot 5!}(\phi\phi)_0(\Sigma\Sigma^*)_0 \\ & + \frac{\beta_4}{4\cdot 3!}(\phi\phi)_4(\Sigma\Sigma^*)_4 + \frac{\beta'_4}{3!}(\phi\phi)_{4'}(\Sigma\Sigma^*)_{4'} \\ & + \frac{\gamma_2}{4!}(\phi\phi)_2(\Sigma\Sigma)_2 + \frac{\gamma_2^*}{4!}(\phi\phi)_2(\Sigma^*\Sigma^*)_2\,. \end{aligned}$$

$$(\phi\phi)_0(\phi\phi)_0 \equiv \phi_{ij}\phi_{ij}\phi_{kl}\phi_{kl}$$

$$(\phi\phi)_2(\phi\phi)_2 \equiv \phi_{ij}\phi_{ik}\phi_{lj}\phi_{lk}$$

$$(\phi\phi)_0 \equiv \phi_{ij}\phi_{ij}\,, \quad (\Sigma\Sigma^*)_0 \equiv \Sigma_{ijklm}\Sigma^*_{ijklm}$$

$$(\Sigma\Sigma^*)_0(\Sigma\Sigma^*)_0 \equiv \Sigma_{ijklm}\Sigma^*_{ijklm}\Sigma_{nopqr}\Sigma^*_{nopqr}$$

$$(\Sigma\Sigma^*)_2(\Sigma\Sigma^*)_2 \equiv \Sigma_{ijklm}\Sigma^*_{ijkln}\Sigma_{opqrm}\Sigma^*_{opqrn}$$

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The minimal SO(10) ~~blessing~~ nightmare

SO(10) broken by 45, rank reduced by 126

Scalar potential: $V = V_{45} + V_{126} + V_{\rm mix}$

$$V_{45} = -\frac{\mu^2}{2}(\phi\phi)_0 + \frac{a_0}{4}(\phi\phi)_0(\phi\phi)_0 + \frac{a_2}{4}(\phi\phi)_2(\phi\phi)_2\,,$$

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???

$$(\phi\phi)_0(\phi\phi)_0 \equiv \phi_{ij}\phi_{ij}\phi_{kl}\phi_{kl}$$

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The minimal SO(10) ~~blessing~~ nightmare

Ruled out in 1980's

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$$m^2_{(8,1,0)} = 2a_2(\omega_R - \omega_Y)(\omega_R + 2\omega_Y)$$
$$m^2_{(1,3,0)} = 2a_2(\omega_Y - \omega_R)(\omega_Y + 2\omega_R)$$

Yasuè 1981, Anastaze, Derendinger, Buccella 1983, Babu, Ma 1985

$$\langle 45 \rangle = \begin{pmatrix} \omega_Y & & & & \\ & \omega_Y & & & \\ & & \omega_Y & & \\ & & & \omega_R & \\ & & & & \omega_R \end{pmatrix} \otimes \tau_2$$

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$\omega_Y \gg \omega_R$

$$SO(10) \underset{\omega_Y}{\overset{45}{\rightarrow}} SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \underset{\omega_R}{\overset{45}{\rightarrow}} SU(3)_c \otimes SU(2)_L \otimes U(1)_R \otimes U(1)_{B-L} \overset{16}{\rightarrow} SM$$

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Aaarrrggh... tachyonic spectrum unless $\frac{1}{2} < |\omega_Y/\omega_R| < 2$

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SU(5)-like vacua only, not far from the "SM running"!

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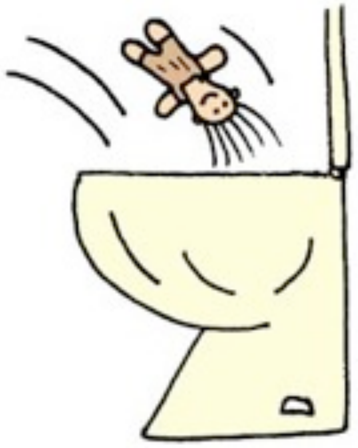

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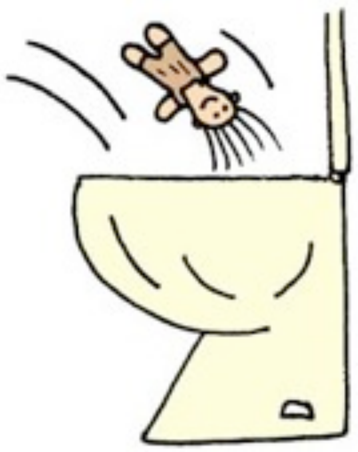

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The minimal SO(10) ~~blessing~~ nightmare

"Do not trust arguments based on the lowest order of perturbation theory."

S.Weinberg , "Why RG is a good thing"
in "Asymptotic Realm of Physics", MIT press 1983

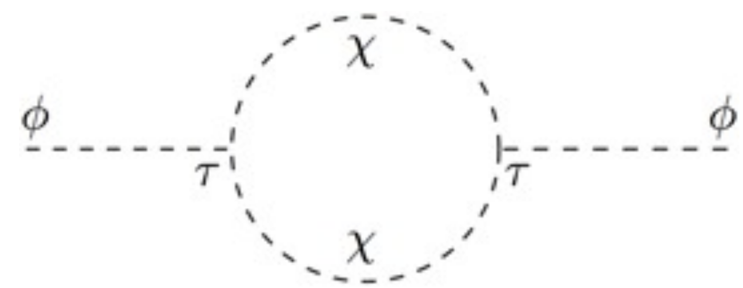
The minimal SO(10) ~~blessing~~ nightmare

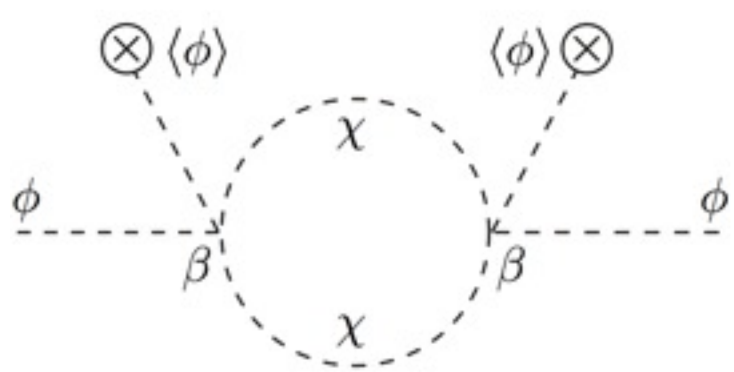
Quantum salvation in 2010

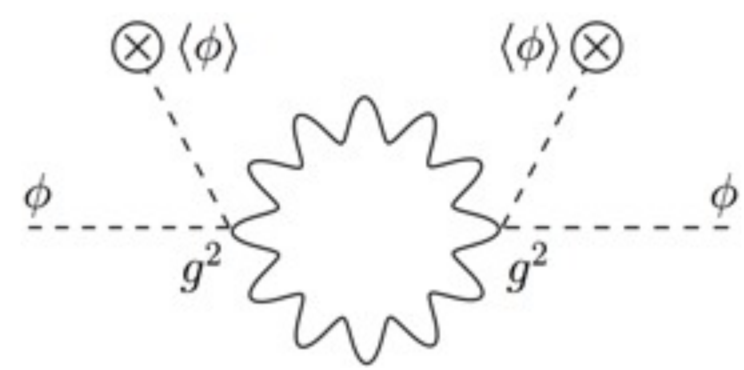
The minimal SO(10) ~~blessing~~ nightmare

Quantum salvation in 2010

One-loop effective potential:







$$\Delta m^2_{(1,3,0)} = \frac{1}{4\pi^2}\left[\tau^2 + \beta^2(2\omega_R^2 - \omega_R\omega_Y + 2\omega_Y^2) + g^4\left(16\omega_R^2 + \omega_Y\omega_R + 19\omega_Y^2\right)\right] + \text{logs}\,,$$

$$\Delta m^2_{(8,1,0)} = \frac{1}{4\pi^2}\left[\tau^2 + \beta^2(\omega_R^2 - \omega_R\omega_Y + 3\omega_Y^2) + g^4\left(13\omega_R^2 + \omega_Y\omega_R + 22\omega_Y^2\right)\right] + \text{logs}\,,$$

Bertolini, Di Luzio, MM, PRD 81, 035015 (2010)

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Leading Planck-scale effects in M_G absent

$$\mathcal{L} \ni \frac{\kappa}{\Lambda} F^{\mu\nu} \langle 45 \rangle F_{\mu\nu} = 0$$

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The minimal SO(10) blessing

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Towards a consistent & potentially realistic SO(10) scenario

"Consistency is the last refuge of people without imagination"
Oscar Wilde

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Two potentially realistic minimally finetuned & consistent options:

Bertolini, Di Luzio, MM, PRD85 095014 2012

Towards a consistent & potentially realistic SO(10) scenario

multiplet	type	eigenstate	Δb^{321}	mass [GeV]
$(\mathbf{6},\mathbf{3},+\frac{1}{3})$	**CS**	1	$(\frac{5}{2},4,\frac{2}{5})$	$\mathbf{5.6\times10^{11}}$
$(1,1,-1)$	VB	1	$(0,0,-\frac{11}{5})$	1.3×10^{14}
$(1,1,+1)$	VB	1	$(0,0,-\frac{11}{5})$	1.3×10^{14}
$(1,1,+1)$	GB	1	$(0,0,\frac{1}{5})$	1.3×10^{14}
$(1,1,0)$	VB	1	$(0,0,0)$	2.8×10^{14}
$(1,1,0)$	GB	1	$(0,0,0)$	2.8×10^{14}
$(8,1,0)$	RS	1	$(\frac{1}{2},0,0)$	7.7×10^{14}
$(3,2,+\frac{1}{6})$	CS	2	$(\frac{1}{3},\frac{1}{2},\frac{1}{30})$	1.1×10^{15}
$(3,2,+\frac{7}{6})$	CS	1	$(\frac{1}{3},\frac{1}{2},\frac{49}{30})$	1.2×10^{15}
$(1,1,0)$	RS	2	$(0,0,0)$	4.3×10^{15}
$(1,1,+2)$	CS	1	$(0,0,\frac{4}{5})$	4.5×10^{15}
$(\overline{\mathbf{3}},\mathbf{2},-\frac{1}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{11}{30})$	$\mathbf{5.2\times10^{15}}$
$(\mathbf{3},\mathbf{2},+\frac{1}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{11}{30})$	$\mathbf{5.2\times10^{15}}$
$(\mathbf{3},\mathbf{2},+\frac{1}{6})$	**GB**	1	$(\frac{1}{3},\frac{1}{2},\frac{1}{30})$	$\mathbf{5.2\times10^{15}}$
$(\overline{\mathbf{3}},\mathbf{2},+\frac{5}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{55}{6})$	$\mathbf{5.2\times10^{15}}$
$(\mathbf{3},\mathbf{2},-\frac{5}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{55}{6})$	$\mathbf{5.2\times10^{15}}$
$(\mathbf{3},\mathbf{2},-\frac{5}{6})$	**GB**	1	$(\frac{1}{3},\frac{1}{2},\frac{5}{6})$	$\mathbf{5.2\times10^{15}}$
$(1,1,+1)$	CS	2	$(0,0,\frac{1}{5})$	5.6×10^{15}
$(1,1,0)$	RS	3	$(0,0,0)$	5.7×10^{15}
$(1,3,0)$	RS	1	$(0,\frac{1}{3},0)$	6.1×10^{15}
$(\overline{3},1,+\frac{1}{3})$	CS	1	$(\frac{1}{6},0,\frac{1}{15})$	6.4×10^{15}
$(8,2,+\frac{1}{2})$	CS	1	$(2,\frac{4}{3},\frac{4}{5})$	9.3×10^{15}
$(\overline{3},1,+\frac{4}{3})$	CS	1	$(\frac{1}{6},0,\frac{16}{15})$	9.6×10^{15}
$(\overline{3},1,+\frac{1}{3})$	CS	2	$(\frac{1}{6},0,\frac{1}{15})$	9.6×10^{15}
$(\overline{3},1,-\frac{2}{3})$	CS	2	$(\frac{1}{6},0,\frac{4}{15})$	9.6×10^{15}

multiplet	type	eigenstate	Δb^{321}	mass [GeV]
$(\mathbf{8},\mathbf{2},+\frac{1}{2})$	**CS**	1	$(2,\frac{4}{3},\frac{4}{5})$	$\mathbf{2.3\times10^{4}}$
$(\overline{3},1,-\frac{2}{3})$	VB	1	$(-\frac{11}{6},0,-\frac{44}{15})$	2.8×10^{13}
$(3,1,+\frac{2}{3})$	VB	1	$(-\frac{11}{6},0,-\frac{44}{15})$	2.8×10^{13}
$(\overline{3},1,-\frac{2}{3})$	GB	1	$(\frac{1}{6},0,\frac{4}{15})$	2.8×10^{13}
$(1,1,0)$	VB	1	$(0,0,0)$	6.1×10^{13}
$(1,1,0)$	GB	1	$(0,0,0)$	6.1×10^{13}
$(3,2,+\frac{7}{6})$	CS	1	$(\frac{1}{3},\frac{1}{2},\frac{49}{30})$	2.6×10^{14}
$(3,2,+\frac{1}{6})$	CS	3	$(\frac{1}{3},\frac{1}{2},\frac{1}{30})$	2.8×10^{14}
$(1,2,+\frac{1}{2})$	RS	1	$(0,\frac{1}{12},\frac{1}{20})$	3.3×10^{14}
$(1,1,0)$	RS	2	$(0,0,0)$	2.2×10^{15}
$(\overline{3},1,-\frac{2}{3})$	CS	2	$(\frac{1}{6},0,\frac{4}{15})$	2.3×10^{15}
$(6,3,+\frac{1}{3})$	CS	1	$(\frac{5}{2},4,\frac{2}{5})$	2.3×10^{15}
$(3,3,-\frac{1}{3})$	CS	1	$(\frac{1}{2},2,\frac{1}{5})$	2.3×10^{15}
$(1,3,-1)$	CS	1	$(0,\frac{2}{3},\frac{3}{5})$	2.3×10^{15}
$(\overline{6},1,-\frac{4}{3})$	CS	1	$(\frac{5}{6},0,\frac{32}{15})$	3.2×10^{15}
$(1,1,0)$	RS	3	$(0,0,0)$	3.3×10^{15}
$(8,1,0)$	RS	1	$(\frac{1}{2},0,0)$	4.6×10^{15}
$(1,3,0)$	RS	1	$(0,\frac{1}{3},0)$	6.1×10^{15}
$(\overline{\mathbf{3}},\mathbf{2},+\frac{5}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{55}{6})$	$\mathbf{8.7\times10^{15}}$
$(\mathbf{3},\mathbf{2},-\frac{5}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{55}{6})$	$\mathbf{8.7\times10^{15}}$
$(\mathbf{3},\mathbf{2},-\frac{5}{6})$	**GB**	1	$(\frac{1}{3},\frac{1}{2},\frac{5}{6})$	$\mathbf{8.7\times10^{15}}$
$(\overline{\mathbf{3}},\mathbf{2},-\frac{1}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{11}{30})$	$\mathbf{8.7\times10^{15}}$
$(\mathbf{3},\mathbf{2},+\frac{1}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{11}{30})$	$\mathbf{8.7\times10^{15}}$
$(\mathbf{3},\mathbf{2},+\frac{1}{6})$	**GB**	1	$(\frac{1}{3},\frac{1}{2},\frac{1}{30})$	$\mathbf{8.7\times10^{15}}$
$(\overline{3},1,+\frac{1}{3})$	CS	1	$(\frac{1}{6},0,\frac{1}{15})$	1.1×10^{16}

Towards a consistent & potentially realistic SO(10) scenario

	multiplet	type	eigenstate	Δb^{321}	mass [GeV]
Light	$(\mathbf{6},\mathbf{3},+\frac{1}{3})$	CS	1	$(\frac{5}{2},4,\frac{2}{5})$	$\mathbf{5.6\times10^{11}}$
	$(1,1,-1)$	VB	1	$(0,0,-\frac{11}{5})$	1.3×10^{14}
	$(1,1,+1)$	VB	1	$(0,0,-\frac{11}{5})$	1.3×10^{14}
	$(1,1,+1)$	GB	1	$(0,0,\frac{1}{5})$	1.3×10^{14}
	$(1,1,0)$	VB	1	$(0,0,0)$	2.8×10^{14}
	$(1,1,0)$	GB	1	$(0,0,0)$	2.8×10^{14}
	$(8,1,0)$	RS	1	$(\frac{1}{2},0,0)$	7.7×10^{14}
	$(3,2,+\frac{1}{6})$	CS	2	$(\frac{1}{3},\frac{1}{2},\frac{1}{30})$	1.1×10^{15}
	$(3,2,+\frac{7}{6})$	CS	1	$(\frac{1}{3},\frac{1}{2},\frac{49}{30})$	1.2×10^{15}
	$(1,1,0)$	RS	2	$(0,0,0)$	4.3×10^{15}
	$(1,1,+2)$	CS	1	$(0,0,\frac{4}{5})$	4.5×10^{15}
	$(\bar{\mathbf{3}},\mathbf{2},-\frac{1}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{11}{30})$	$\mathbf{5.2\times10^{15}}$
	$(\mathbf{3},\mathbf{2},+\frac{1}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{11}{30})$	$\mathbf{5.2\times10^{15}}$
	$(\mathbf{3},\mathbf{2},+\frac{1}{6})$	**GB**	1	$(\frac{1}{3},\frac{1}{2},\frac{1}{30})$	$\mathbf{5.2\times10^{15}}$
	$(\bar{\mathbf{3}},\mathbf{2},+\frac{5}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{55}{6})$	$\mathbf{5.2\times10^{15}}$
	$(\mathbf{3},\mathbf{2},-\frac{5}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{55}{6})$	$\mathbf{5.2\times10^{15}}$
	$(\mathbf{3},\mathbf{2},-\frac{5}{6})$	**GB**	1	$(\frac{1}{3},\frac{1}{2},\frac{5}{6})$	$\mathbf{5.2\times10^{15}}$
	$(1,1,+1)$	CS	2	$(0,0,\frac{1}{5})$	5.6×10^{15}
	$(1,1,0)$	RS	3	$(0,0,0)$	5.7×10^{15}
	$(1,3,0)$	RS	1	$(0,\frac{1}{3},0)$	6.1×10^{15}
	$(\bar{3},1,+\frac{1}{3})$	CS	1	$(\frac{1}{6},0,\frac{1}{15})$	6.4×10^{15}
	$(8,2,+\frac{1}{2})$	CS	1	$(2,\frac{4}{3},\frac{4}{5})$	9.3×10^{15}
	$(\bar{3},1,+\frac{4}{3})$	CS	1	$(\frac{1}{6},0,\frac{16}{15})$	9.6×10^{15}
	$(\bar{3},1,+\frac{1}{3})$	CS	2	$(\frac{1}{6},0,\frac{1}{15})$	9.6×10^{15}
	$(\bar{3},1,-\frac{2}{3})$	CS	2	$(\frac{1}{6},0,\frac{4}{15})$	9.6×10^{15}

multiplet	type	eigenstate	Δb^{321}	mass [GeV]	
$(\mathbf{8},\mathbf{2},+\frac{1}{2})$	CS	1	$(2,\frac{4}{3},\frac{4}{5})$	$\mathbf{2.3\times10^{4}}$	Light
$(\bar{3},1,-\frac{2}{3})$	VB	1	$(-\frac{11}{6},0,-\frac{44}{15})$	2.8×10^{13}	
$(3,1,+\frac{2}{3})$	VB	1	$(-\frac{11}{6},0,-\frac{44}{15})$	2.8×10^{13}	
$(\bar{3},1,-\frac{2}{3})$	GB	1	$(\frac{1}{6},0,\frac{4}{15})$	2.8×10^{13}	
$(1,1,0)$	VB	1	$(0,0,0)$	6.1×10^{13}	
$(1,1,0)$	GB	1	$(0,0,0)$	6.1×10^{13}	
$(3,2,+\frac{7}{6})$	CS	1	$(\frac{1}{3},\frac{1}{2},\frac{49}{30})$	2.6×10^{14}	
$(3,2,+\frac{1}{6})$	CS	3	$(\frac{1}{3},\frac{1}{2},\frac{1}{30})$	2.8×10^{14}	
$(1,2,+\frac{1}{2})$	RS	1	$(0,\frac{1}{12},\frac{1}{20})$	3.3×10^{14}	
$(1,1,0)$	RS	2	$(0,0,0)$	2.2×10^{15}	
$(\bar{3},1,-\frac{2}{3})$	CS	2	$(\frac{1}{6},0,\frac{4}{15})$	2.3×10^{15}	
$(6,3,+\frac{1}{3})$	CS	1	$(\frac{5}{2},4,\frac{2}{5})$	2.3×10^{15}	
$(3,3,-\frac{1}{3})$	CS	1	$(\frac{1}{2},2,\frac{1}{5})$	2.3×10^{15}	
$(1,3,-1)$	CS	1	$(0,\frac{2}{3},\frac{3}{5})$	2.3×10^{15}	
$(\bar{6},1,-\frac{4}{3})$	CS	1	$(\frac{5}{6},0,\frac{32}{15})$	3.2×10^{15}	
$(1,1,0)$	RS	3	$(0,0,0)$	3.3×10^{15}	
$(8,1,0)$	RS	1	$(\frac{1}{2},0,0)$	4.6×10^{15}	
$(1,3,0)$	RS	1	$(0,\frac{1}{3},0)$	6.1×10^{15}	
$(\bar{\mathbf{3}},\mathbf{2},+\frac{5}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{55}{6})$	$\mathbf{8.7\times10^{15}}$	
$(\mathbf{3},\mathbf{2},-\frac{5}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{55}{6})$	$\mathbf{8.7\times10^{15}}$	
$(\mathbf{3},\mathbf{2},-\frac{5}{6})$	**GB**	1	$(\frac{1}{3},\frac{1}{2},\frac{5}{6})$	$\mathbf{8.7\times10^{15}}$	
$(\bar{\mathbf{3}},\mathbf{2},-\frac{1}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{11}{30})$	$\mathbf{8.7\times10^{15}}$	
$(\mathbf{3},\mathbf{2},+\frac{1}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{11}{30})$	$\mathbf{8.7\times10^{15}}$	
$(\mathbf{3},\mathbf{2},+\frac{1}{6})$	**GB**	1	$(\frac{1}{3},\frac{1}{2},\frac{1}{30})$	$\mathbf{8.7\times10^{15}}$	
$(\bar{3},1,+\frac{1}{3})$	CS	1	$(\frac{1}{6},0,\frac{1}{15})$	1.1×10^{16}	

Towards a consistent & potentially realistic SO(10) scenario

	multiplet	type	eigenstate	Δb^{321}	mass [GeV]
Light	$(6,3,+\frac{1}{3})$	CS	1	$(\frac{5}{2},4,\frac{2}{5})$	$\mathbf{5.6\times10^{11}}$
	$(1,1,-1)$	VB	1	$(0,0,-\frac{11}{5})$	1.3×10^{14}
Seesaw	$(1,1,+1)$	VB	1	$(0,0,-\frac{11}{5})$	1.3×10^{14}
	$(1,1,+1)$	GB	1	$(0,0,\frac{1}{5})$	1.3×10^{14}
	$(1,1,0)$	VB	1	$(0,0,0)$	2.8×10^{14}
	$(1,1,0)$	GB	1	$(0,0,0)$	2.8×10^{14}
	$(8,1,0)$	RS	1	$(\frac{1}{2},0,0)$	7.7×10^{14}
	$(3,2,+\frac{1}{6})$	CS	2	$(\frac{1}{3},\frac{1}{2},\frac{1}{30})$	1.1×10^{15}
	$(3,2,+\frac{7}{6})$	CS	1	$(\frac{1}{3},\frac{1}{2},\frac{49}{30})$	1.2×10^{15}
	$(1,1,0)$	RS	2	$(0,0,0)$	4.3×10^{15}
	$(1,1,+2)$	CS	1	$(0,0,\frac{4}{5})$	4.5×10^{15}
	$(\mathbf{\bar{3}},\mathbf{2},-\frac{1}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{11}{30})$	$\mathbf{5.2\times10^{15}}$
	$(\mathbf{3},\mathbf{2},+\frac{1}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{11}{30})$	$\mathbf{5.2\times10^{15}}$
	$(\mathbf{3},\mathbf{2},+\frac{1}{6})$	**GB**	1	$(\frac{1}{3},\frac{1}{2},\frac{1}{30})$	$\mathbf{5.2\times10^{15}}$
	$(\mathbf{\bar{3}},\mathbf{2},+\frac{5}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{55}{6})$	$\mathbf{5.2\times10^{15}}$
	$(\mathbf{3},\mathbf{2},-\frac{5}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{55}{6})$	$\mathbf{5.2\times10^{15}}$
	$(\mathbf{3},\mathbf{2},-\frac{5}{6})$	**GB**	1	$(\frac{1}{3},\frac{1}{2},\frac{5}{6})$	$\mathbf{5.2\times10^{15}}$
	$(1,1,+1)$	CS	2	$(0,0,\frac{1}{5})$	5.6×10^{15}
	$(1,1,0)$	RS	3	$(0,0,0)$	5.7×10^{15}
	$(1,3,0)$	RS	1	$(0,\frac{1}{3},0)$	6.1×10^{15}
	$(\bar{3},1,+\frac{1}{3})$	CS	1	$(\frac{1}{6},0,\frac{1}{15})$	6.4×10^{15}
	$(8,2,+\frac{1}{2})$	CS	1	$(2,\frac{4}{3},\frac{4}{5})$	9.3×10^{15}
	$(\bar{3},1,+\frac{4}{3})$	CS	1	$(\frac{1}{6},0,\frac{16}{15})$	9.6×10^{15}
	$(\bar{3},1,+\frac{1}{3})$	CS	2	$(\frac{1}{6},0,\frac{1}{15})$	9.6×10^{15}
	$(\bar{3},1,-\frac{2}{3})$	CS	2	$(\frac{1}{6},0,\frac{4}{15})$	9.6×10^{15}

multiplet	type	eigenstate	Δb^{321}	mass [GeV]	
$(8,2,+\frac{1}{2})$	CS	1	$(2,\frac{4}{3},\frac{4}{5})$	$\mathbf{2.3\times10^{4}}$	Light
$(\bar{3},1,-\frac{2}{3})$	VB	1	$(-\frac{11}{6},0,-\frac{44}{15})$	2.8×10^{13}	
$(3,1,+\frac{2}{3})$	VB	1	$(-\frac{11}{6},0,-\frac{44}{15})$	2.8×10^{13}	Seesaw
$(\bar{3},1,-\frac{2}{3})$	GB	1	$(\frac{1}{6},0,\frac{4}{15})$	2.8×10^{13}	
$(1,1,0)$	VB	1	$(0,0,0)$	6.1×10^{13}	
$(1,1,0)$	GB	1	$(0,0,0)$	6.1×10^{13}	
$(3,2,+\frac{7}{6})$	CS	1	$(\frac{1}{3},\frac{1}{2},\frac{49}{30})$	2.6×10^{14}	
$(3,2,+\frac{1}{6})$	CS	3	$(\frac{1}{3},\frac{1}{2},\frac{1}{30})$	2.8×10^{14}	
$(1,2,+\frac{1}{2})$	RS	1	$(0,\frac{1}{12},\frac{1}{20})$	3.3×10^{14}	
$(1,1,0)$	RS	2	$(0,0,0)$	2.2×10^{15}	
$(\bar{3},1,-\frac{2}{3})$	CS	2	$(\frac{1}{6},0,\frac{4}{15})$	2.3×10^{15}	
$(6,3,+\frac{1}{3})$	CS	1	$(\frac{5}{2},4,\frac{2}{5})$	2.3×10^{15}	
$(3,3,-\frac{1}{3})$	CS	1	$(\frac{1}{2},2,\frac{1}{5})$	2.3×10^{15}	
$(1,3,-1)$	CS	1	$(0,\frac{2}{3},\frac{3}{5})$	2.3×10^{15}	
$(\bar{6},1,-\frac{4}{3})$	CS	1	$(\frac{5}{6},0,\frac{32}{15})$	3.2×10^{15}	
$(1,1,0)$	RS	3	$(0,0,0)$	3.3×10^{15}	
$(8,1,0)$	RS	1	$(\frac{1}{2},0,0)$	4.6×10^{15}	
$(1,3,0)$	RS	1	$(0,\frac{1}{3},0)$	6.1×10^{15}	
$(\mathbf{\bar{3}},\mathbf{2},+\frac{5}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{55}{6})$	$\mathbf{8.7\times10^{15}}$	
$(\mathbf{3},\mathbf{2},-\frac{5}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{55}{6})$	$\mathbf{8.7\times10^{15}}$	
$(\mathbf{3},\mathbf{2},-\frac{5}{6})$	**GB**	1	$(\frac{1}{3},\frac{1}{2},\frac{5}{6})$	$\mathbf{8.7\times10^{15}}$	
$(\mathbf{\bar{3}},\mathbf{2},-\frac{1}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{11}{30})$	$\mathbf{8.7\times10^{15}}$	
$(\mathbf{3},\mathbf{2},+\frac{1}{6})$	**VB**	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{11}{30})$	$\mathbf{8.7\times10^{15}}$	
$(\mathbf{3},\mathbf{2},+\frac{1}{6})$	**GB**	1	$(\frac{1}{3},\frac{1}{2},\frac{1}{30})$	$\mathbf{8.7\times10^{15}}$	
$(\bar{3},1,+\frac{1}{3})$	CS	1	$(\frac{1}{6},0,\frac{1}{15})$	1.1×10^{16}	

Towards a consistent & potentially realistic SO(10) scenario

	multiplet	type	eigenstate	Δb^{321}	mass [GeV]
Light	$(6,3,+\frac{1}{3})$	CS	1	$(\frac{5}{2},4,\frac{2}{5})$	5.6×10^{11}
Seesaw	$(1,1,-1)$	VB	1	$(0,0,-\frac{11}{5})$	1.3×10^{14}
Seesaw	$(1,1,+1)$	VB	1	$(0,0,-\frac{11}{5})$	1.3×10^{14}
Seesaw	$(1,1,+1)$	GB	1	$(0,0,\frac{1}{5})$	1.3×10^{14}
	$(1,1,0)$	VB	1	$(0,0,0)$	2.8×10^{14}
	$(1,1,0)$	GB	1	$(0,0,0)$	2.8×10^{14}
	$(8,1,0)$	RS	1	$(\frac{1}{2},0,0)$	7.7×10^{14}
	$(3,2,+\frac{1}{6})$	CS	2	$(\frac{1}{3},\frac{1}{2},\frac{1}{30})$	1.1×10^{15}
	$(3,2,+\frac{7}{6})$	CS	1	$(\frac{1}{3},\frac{1}{2},\frac{49}{30})$	1.2×10^{15}
	$(1,1,0)$	RS	2	$(0,0,0)$	4.3×10^{15}
	$(1,1,+2)$	CS	1	$(0,0,\frac{4}{5})$	4.5×10^{15}
GUT	$(\bar{3},2,-\frac{1}{6})$	VB	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{11}{30})$	5.2×10^{15}
GUT	$(3,2,+\frac{1}{6})$	VB	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{11}{30})$	5.2×10^{15}
GUT	$(3,2,+\frac{1}{6})$	GB	1	$(\frac{1}{3},\frac{1}{2},\frac{1}{30})$	5.2×10^{15}
GUT	$(\bar{3},2,+\frac{5}{6})$	VB	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{55}{6})$	5.2×10^{15}
GUT	$(3,2,-\frac{5}{6})$	VB	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{55}{6})$	5.2×10^{15}
GUT	$(3,2,-\frac{5}{6})$	GB	1	$(\frac{1}{3},\frac{1}{2},\frac{5}{6})$	5.2×10^{15}
	$(1,1,+1)$	CS	2	$(0,0,\frac{1}{5})$	5.6×10^{15}
	$(1,1,0)$	RS	3	$(0,0,0)$	5.7×10^{15}
	$(1,3,0)$	RS	1	$(0,\frac{1}{3},0)$	6.1×10^{15}
	$(\bar{3},1,+\frac{1}{3})$	CS	1	$(\frac{1}{6},0,\frac{1}{15})$	6.4×10^{15}
	$(8,2,+\frac{1}{2})$	CS	1	$(2,\frac{4}{3},\frac{4}{5})$	9.3×10^{15}
	$(\bar{3},1,+\frac{4}{3})$	CS	1	$(\frac{1}{6},0,\frac{16}{15})$	9.6×10^{15}
	$(\bar{3},1,+\frac{1}{3})$	CS	2	$(\frac{1}{6},0,\frac{1}{15})$	9.6×10^{15}
	$(\bar{3},1,-\frac{2}{3})$	CS	2	$(\frac{1}{6},0,\frac{4}{15})$	9.6×10^{15}

	multiplet	type	eigenstate	Δb^{321}	mass [GeV]
Light	$(8,2,+\frac{1}{2})$	CS	1	$(2,\frac{4}{3},\frac{4}{5})$	2.3×10^{4}
Seesaw	$(\bar{3},1,-\frac{2}{3})$	VB	1	$(-\frac{11}{6},0,-\frac{44}{15})$	2.8×10^{13}
Seesaw	$(3,1,+\frac{2}{3})$	VB	1	$(-\frac{11}{6},0,-\frac{44}{15})$	2.8×10^{13}
Seesaw	$(\bar{3},1,-\frac{2}{3})$	GB	1	$(\frac{1}{6},0,\frac{4}{15})$	2.8×10^{13}
	$(1,1,0)$	VB	1	$(0,0,0)$	6.1×10^{13}
	$(1,1,0)$	GB	1	$(0,0,0)$	6.1×10^{13}
	$(3,2,+\frac{7}{6})$	CS	1	$(\frac{1}{3},\frac{1}{2},\frac{49}{30})$	2.6×10^{14}
	$(3,2,+\frac{1}{6})$	CS	3	$(\frac{1}{3},\frac{1}{2},\frac{1}{30})$	2.8×10^{14}
	$(1,2,+\frac{1}{2})$	RS	1	$(0,\frac{1}{12},\frac{1}{20})$	3.3×10^{14}
	$(1,1,0)$	RS	2	$(0,0,0)$	2.2×10^{15}
	$(\bar{3},1,-\frac{2}{3})$	CS	2	$(\frac{1}{6},0,\frac{4}{15})$	2.3×10^{15}
	$(6,3,+\frac{1}{3})$	CS	1	$(\frac{5}{2},4,\frac{2}{5})$	2.3×10^{15}
	$(3,3,-\frac{1}{3})$	CS	1	$(\frac{1}{2},2,\frac{1}{5})$	2.3×10^{15}
	$(1,3,-1)$	CS	1	$(0,\frac{2}{3},\frac{3}{5})$	2.3×10^{15}
	$(\bar{6},1,-\frac{4}{3})$	CS	1	$(\frac{5}{6},0,\frac{32}{15})$	3.2×10^{15}
	$(1,1,0)$	RS	3	$(0,0,0)$	3.3×10^{15}
	$(8,1,0)$	RS	1	$(\frac{1}{2},0,0)$	4.6×10^{15}
	$(1,3,0)$	RS	1	$(0,\frac{1}{3},0)$	6.1×10^{15}
GUT	$(\bar{3},2,+\frac{5}{6})$	VB	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{55}{6})$	8.7×10^{15}
GUT	$(3,2,-\frac{5}{6})$	VB	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{55}{6})$	8.7×10^{15}
GUT	$(3,2,-\frac{5}{6})$	GB	1	$(\frac{1}{3},\frac{1}{2},\frac{5}{6})$	8.7×10^{15}
GUT	$(\bar{3},2,-\frac{1}{6})$	VB	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{11}{30})$	8.7×10^{15}
GUT	$(3,2,+\frac{1}{6})$	VB	1	$(-\frac{11}{3},-\frac{11}{2},-\frac{11}{30})$	8.7×10^{15}
GUT	$(3,2,+\frac{1}{6})$	GB	1	$(\frac{1}{3},\frac{1}{2},\frac{1}{30})$	8.7×10^{15}
	$(\bar{3},1,+\frac{1}{3})$	CS	1	$(\frac{1}{6},0,\frac{1}{15})$	1.1×10^{16}

Towards a consistent & potentially realistic SO(10) scenario

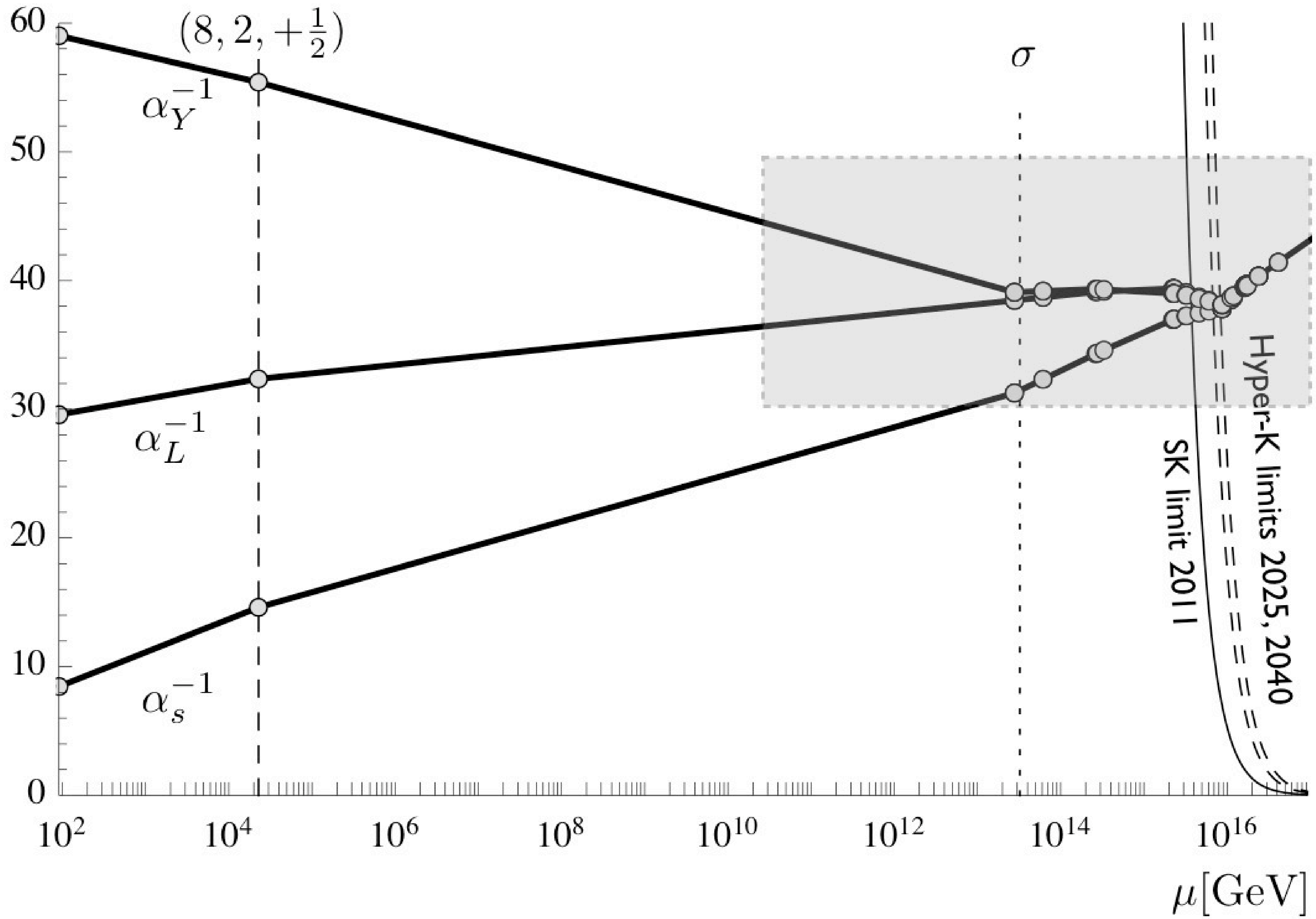
Case I: light $(8, 2, +\frac{1}{2})$

Bertolini, Di Luzio, MM, PRD 85, 095014 (2012)

Towards a consistent & potentially realistic SO(10) scenario

Case I: light $(8, 2, +\frac{1}{2})$

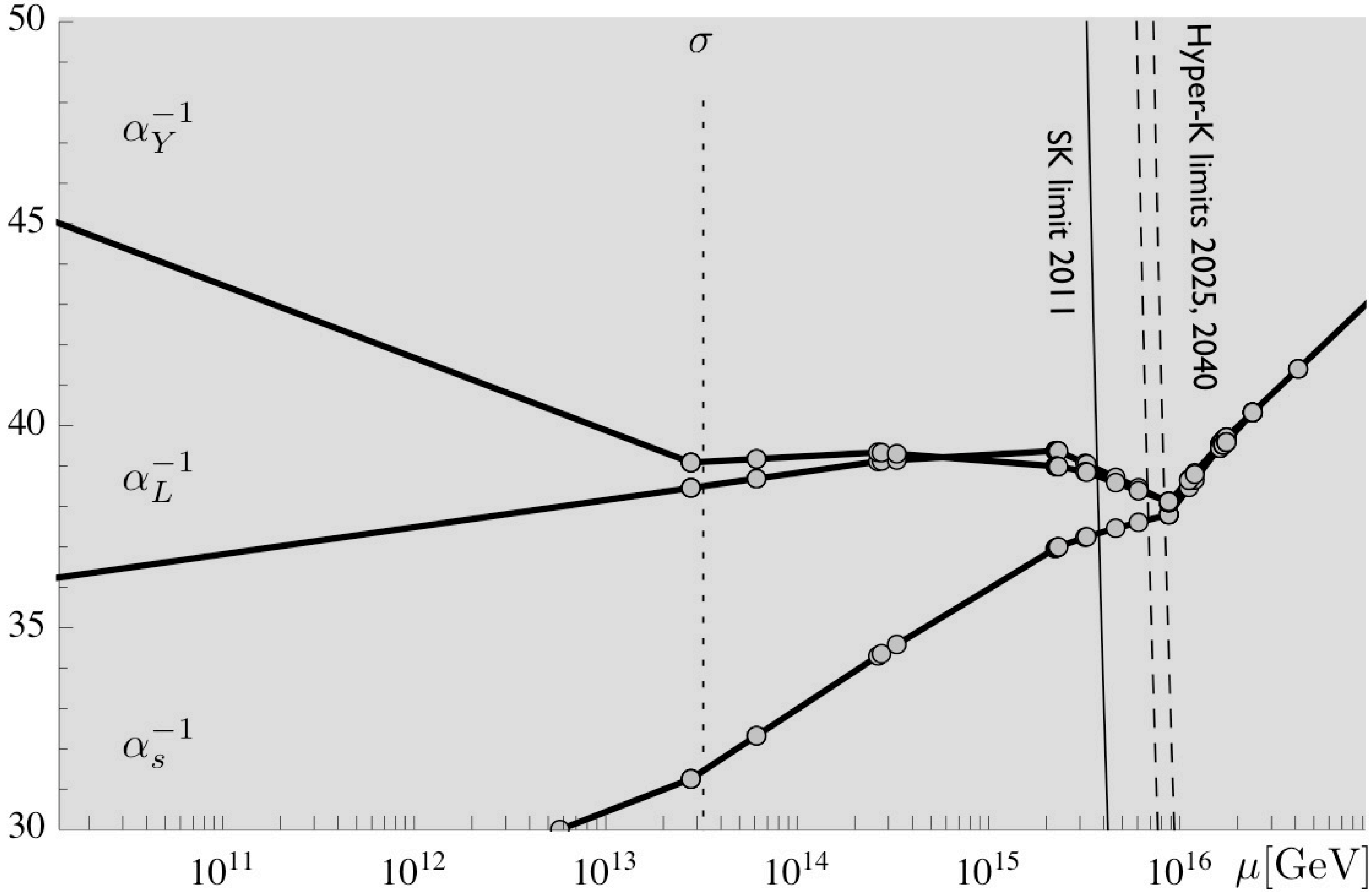
Bertolini, Di Luzio, MM, PRD 85, 095014 (2012)



Towards a consistent & potentially realistic SO(10) scenario

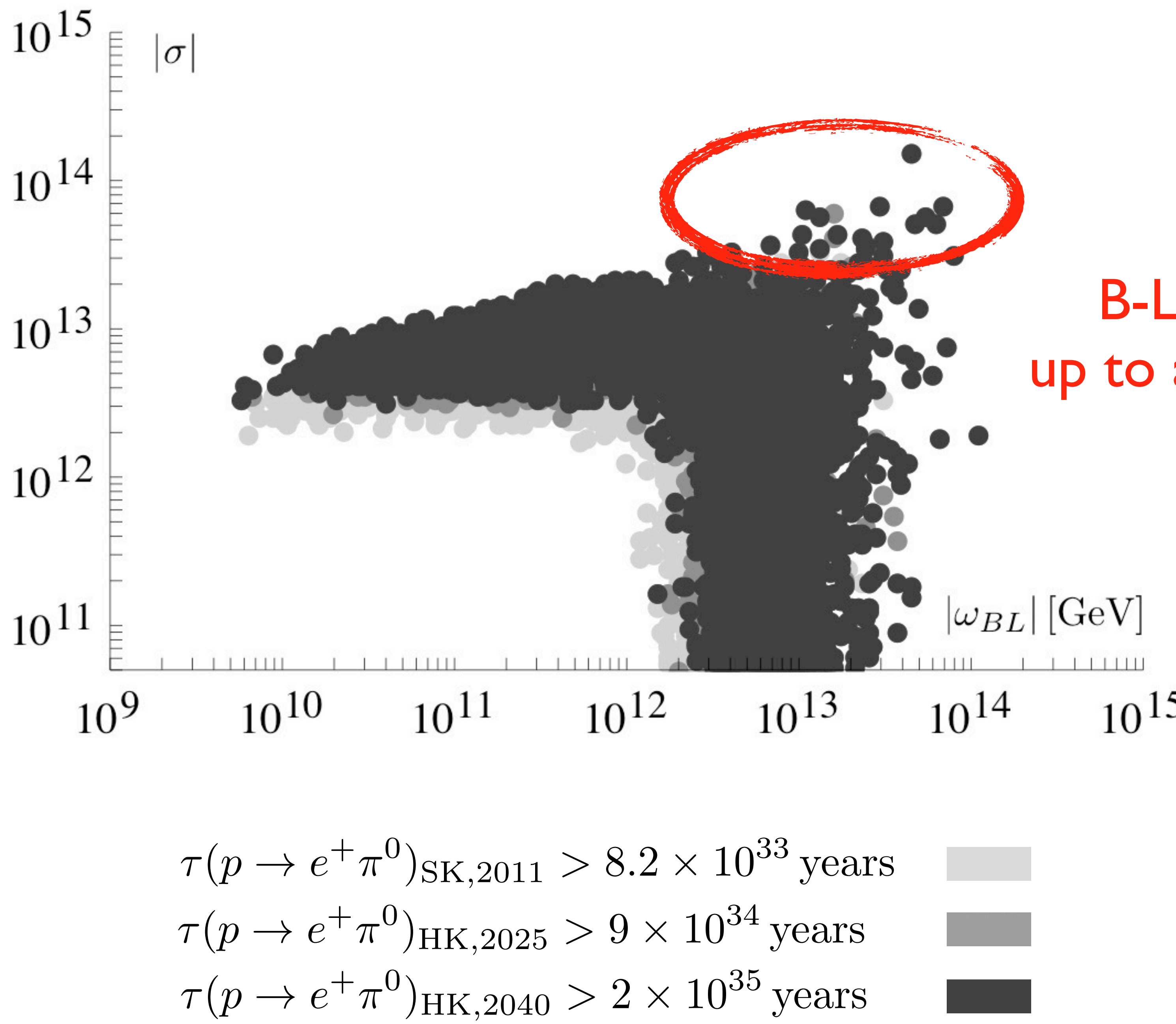
Case I: light $(8, 2, +\frac{1}{2})$

Bertolini, Di Luzio, MM, PRD 85, 095014 (2012)



Case I: light $(8, 2, +\frac{1}{2})$

Bertolini, Di Luzio, MM, PRD 85, 095014 (2012)

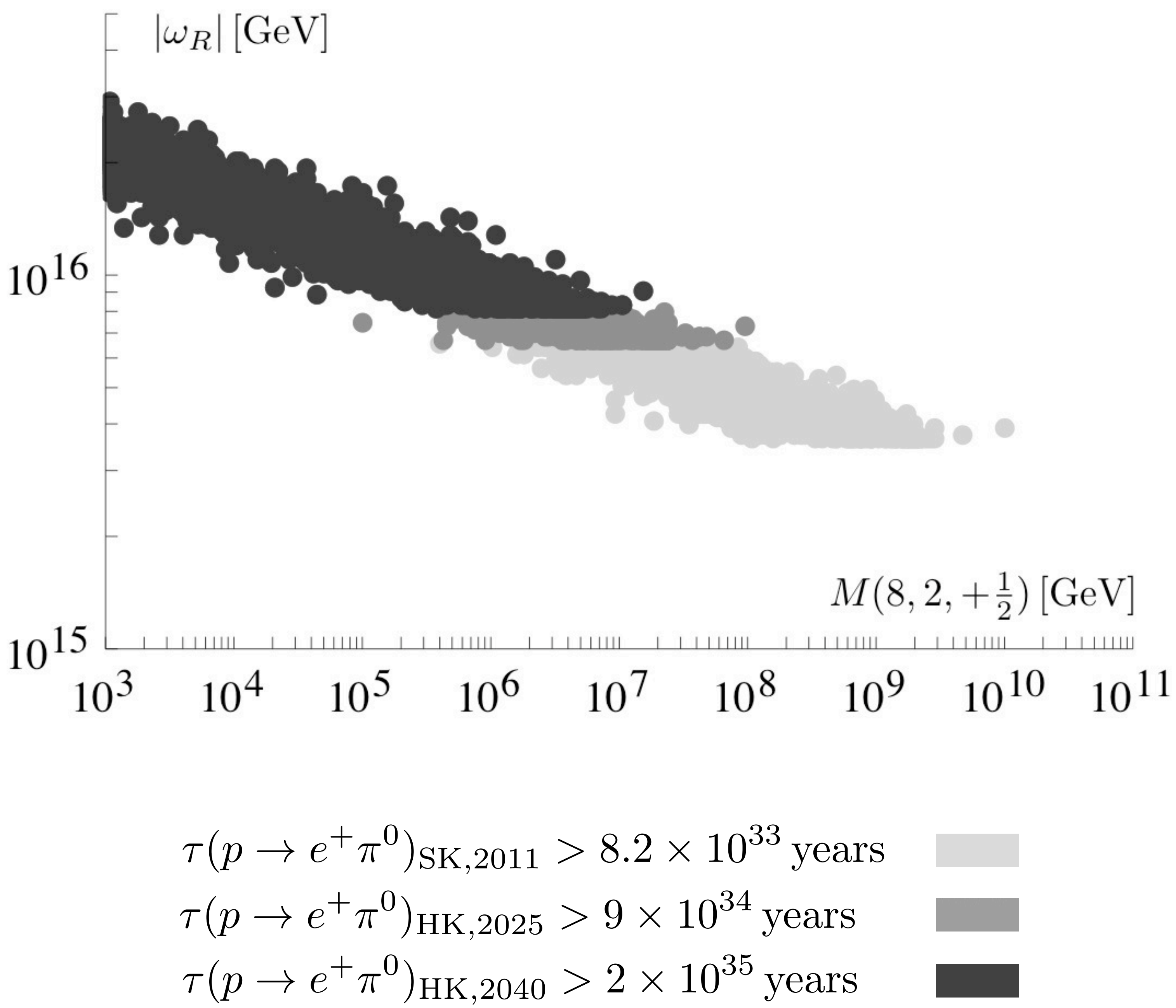


B-L scale reaches up to about 10^{14}GeV.

Towards a consistent & potentially realistic SO(10) scenario

Case I: light $(8, 2, +\frac{1}{2})$

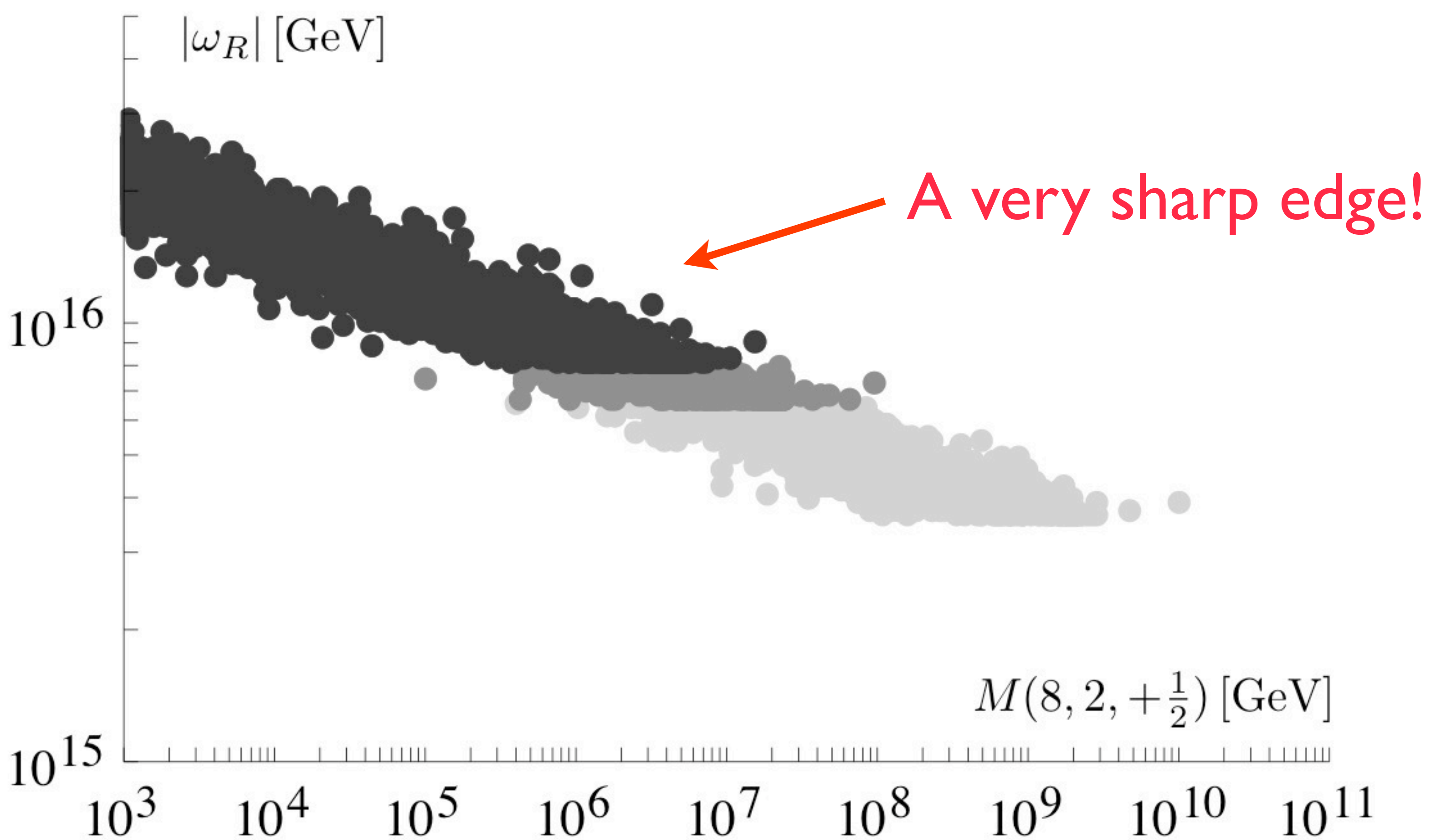
Bertolini, Di Luzio, MM, PRD 85, 095014 (2012)



Towards a consistent & potentially realistic SO(10) scenario

Case I: light $(8, 2, +\frac{1}{2})$

Bertolini, Di Luzio, MM, PRD 85, 095014 (2012)



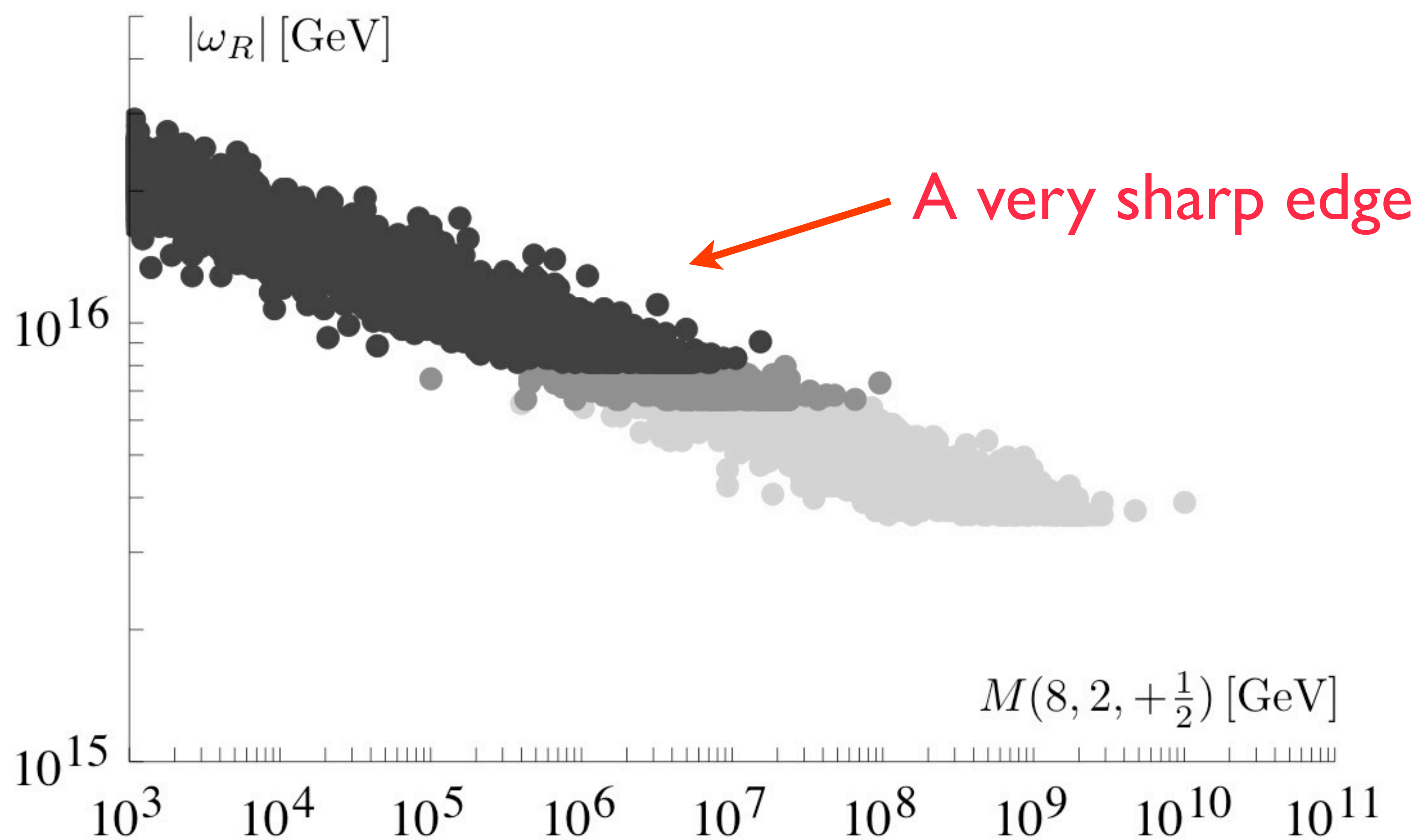
$\tau(p \to e^+\pi^0)_{\mathrm{SK},2011} > 8.2 \times 10^{33}$ years

$\tau(p \to e^+\pi^0)_{\mathrm{HK},2025} > 9 \times 10^{34}$ years

$\tau(p \to e^+\pi^0)_{\mathrm{HK},2040} > 2 \times 10^{35}$ years

Towards a consistent & potentially realistic SO(10) scenario

Case I: light $(8,2,+\frac{1}{2})$ **@ one loop** Bertolini, Di Luzio, MM, PRD 85, 095014 (2012)



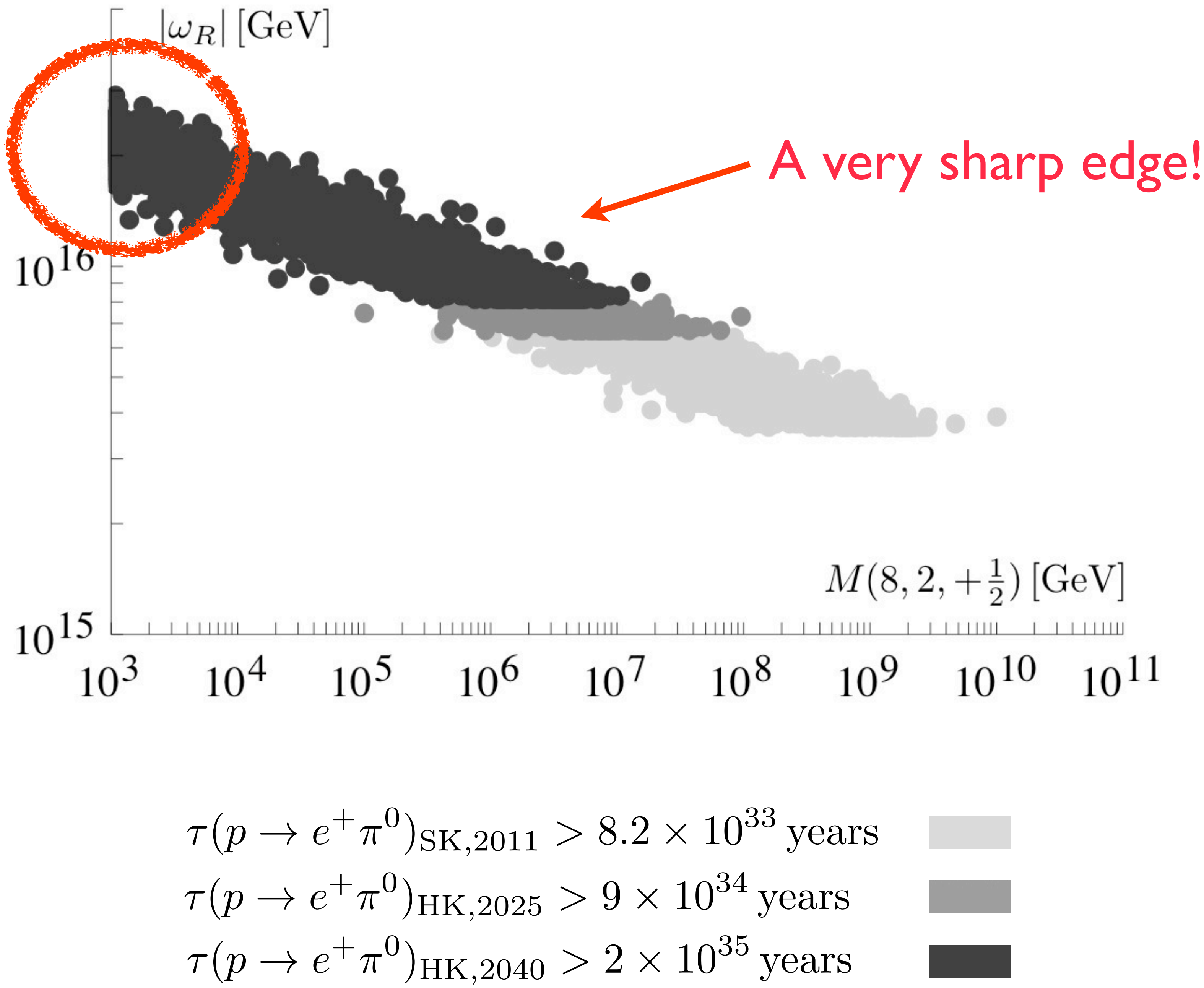
$\tau(p \to e^+\pi^0)_{\mathrm{SK},2011} > 8.2 \times 10^{33}$ years (light grey)

$\tau(p \to e^+\pi^0)_{\mathrm{HK},2025} > 9 \times 10^{34}$ years (medium grey)

$\tau(p \to e^+\pi^0)_{\mathrm{HK},2040} > 2 \times 10^{35}$ years (dark grey)

Towards a consistent & potentially realistic SO(10) scenario

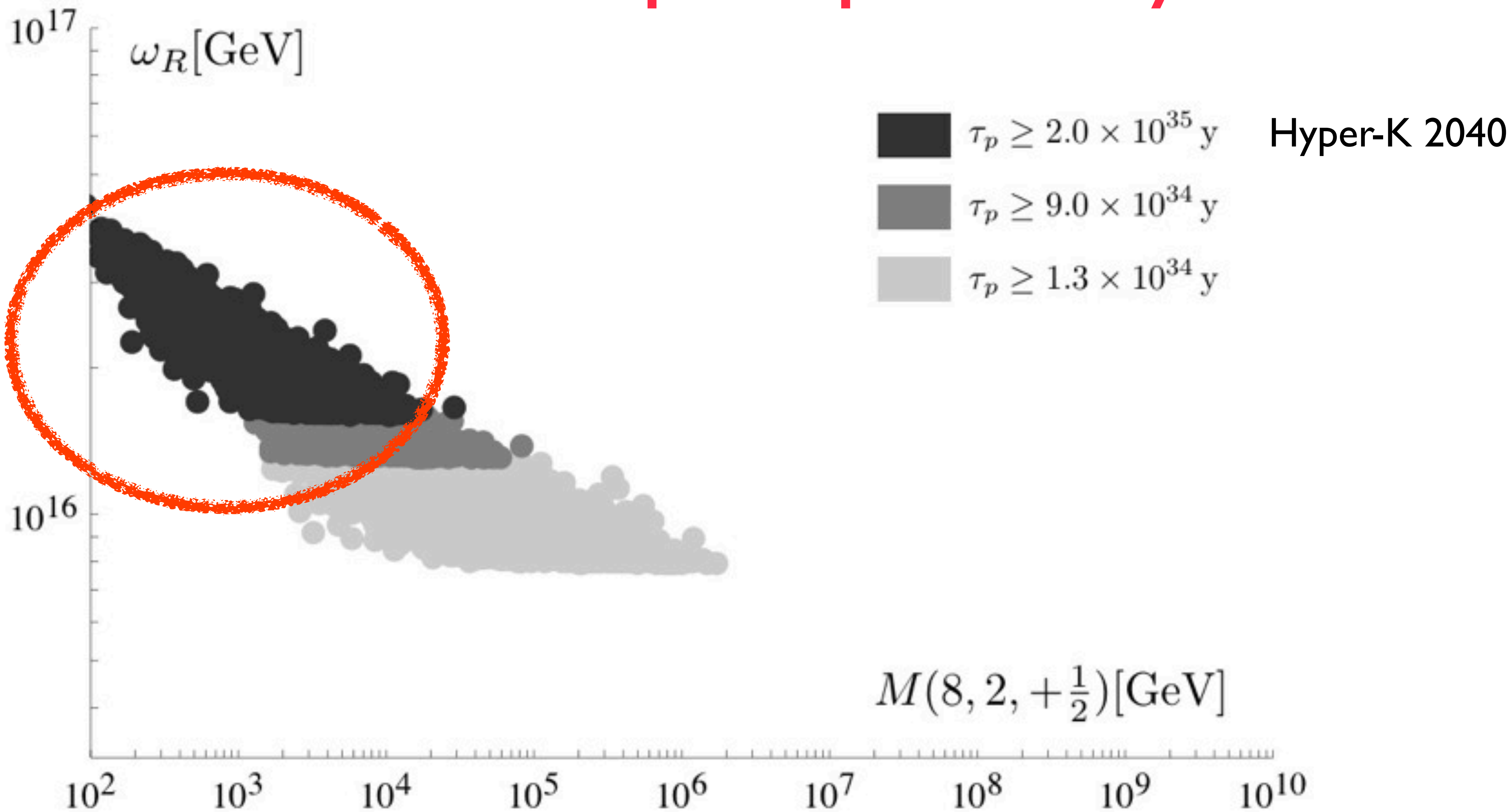
Case I: light $(8, 2, +\frac{1}{2})$ **@ one loop** Bertolini, Di Luzio, MM, PRD 85, 095014 (2012)



Towards a consistent & potentially realistic SO(10) scenario

Case I: light $(8, 2, +\frac{1}{2})$ **@ two loops** Bertolini, Di Luzio, MM, PRD 85, 095014 (2012)

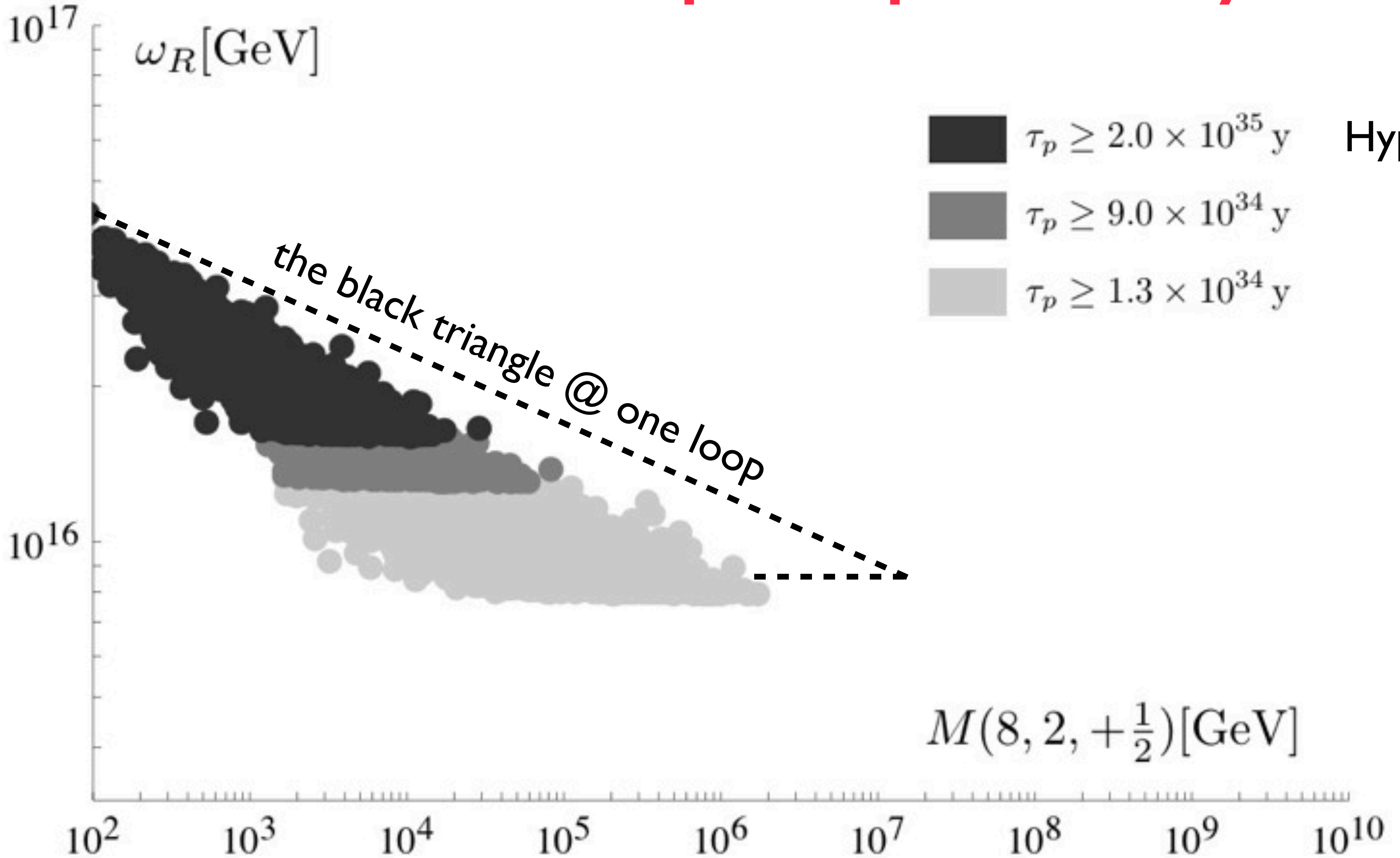
+ improved proton decay



Towards a consistent & potentially realistic SO(10) scenario

Case I: light $(8, 2, +\frac{1}{2})$ **@ two loops** Bertolini, Di Luzio, MM, PRD 85, 095014 (2012)

+ improved proton decay

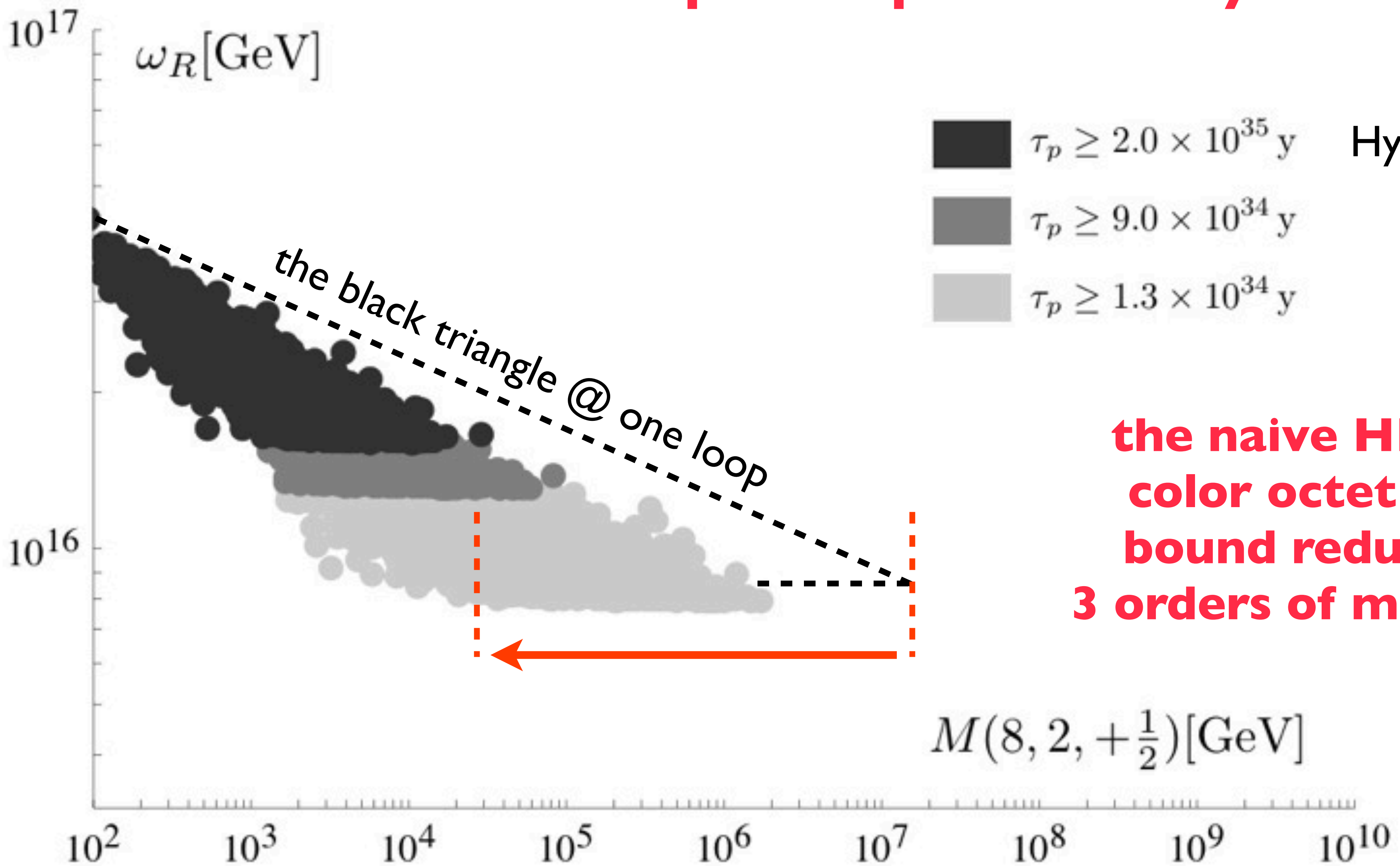


Hyper-K 2040

Towards a consistent & potentially realistic SO(10) scenario

Case I: light $(8, 2, +\frac{1}{2})$ **@ two loops** Bertolini, Di Luzio, MM, PRD 85, 095014 (2012)

+ improved proton decay

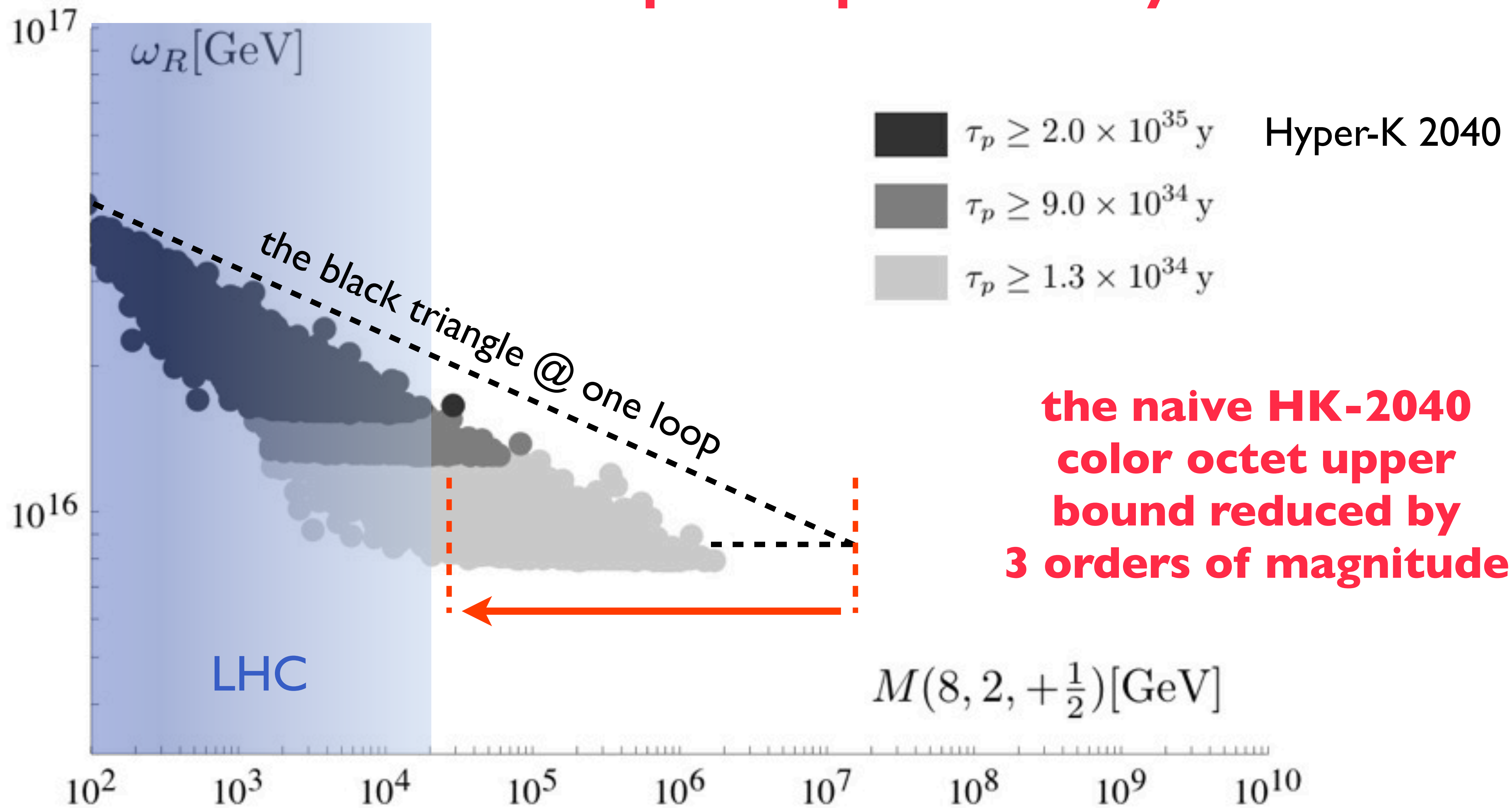


the naive HK-2040 color octet upper bound reduced by 3 orders of magnitude

Towards a consistent & potentially realistic SO(10) scenario

Case I: light $(8, 2, +\frac{1}{2})$ **@ two loops** Bertolini, Di Luzio, MM, PRD 85, 095014 (2012)

+ improved proton decay



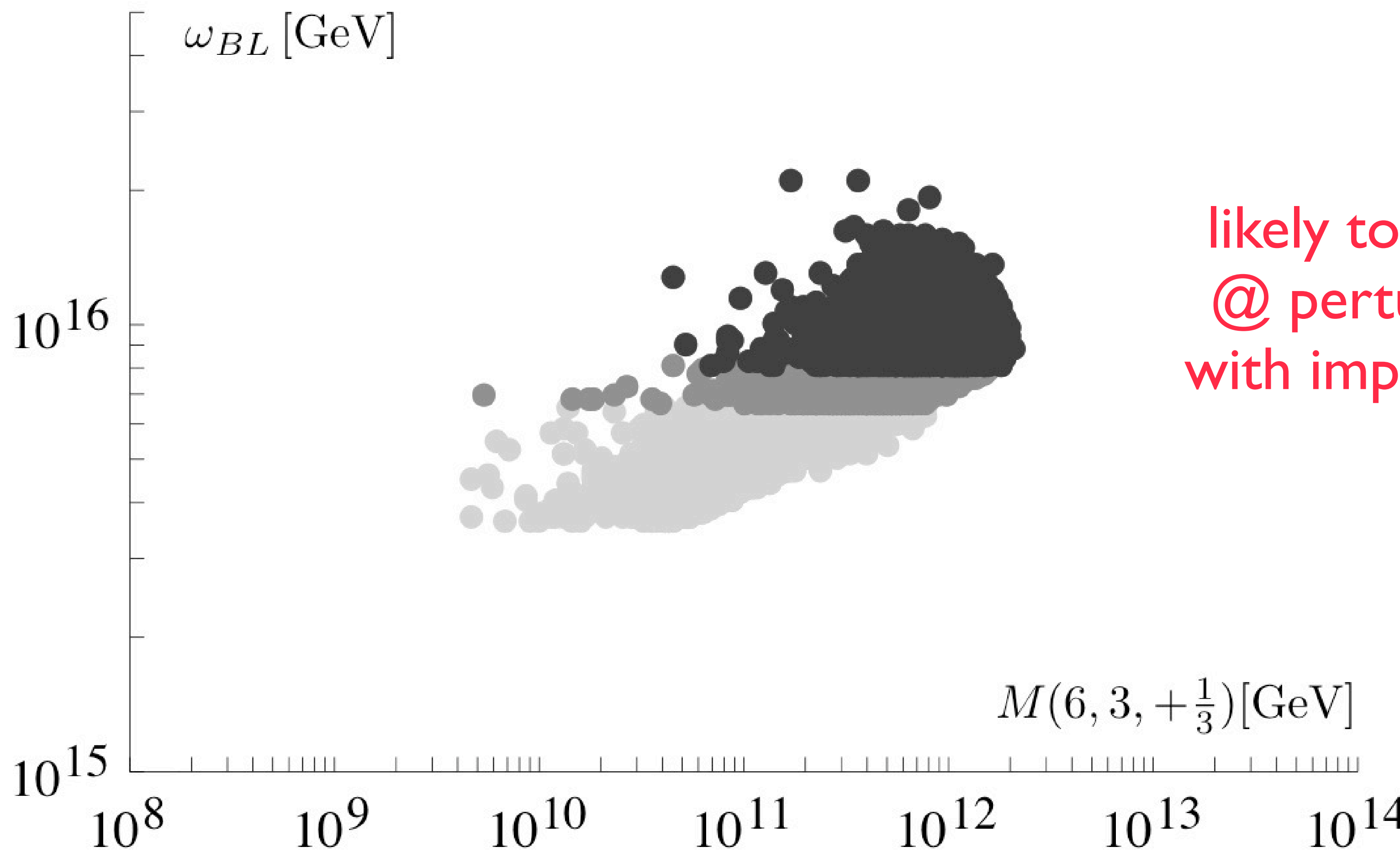
the naive HK-2040 color octet upper bound reduced by 3 orders of magnitude

CMS JHEP 1301, 013 (2013); ATLAS, JHEP 1301, 029 (2013)

Towards a consistent & potentially realistic SO(10) scenario

Case II: light $(6, 3, +\frac{1}{3})$

Bertolini, Di Luzio, MM, PRD 85, 095014 (2012)



likely to be ruled out
@ perturbative level
with improved p-decay

$\tau(p \to e^+\pi^0)_{\mathrm{SK},2011} > 8.2 \times 10^{33}$ years (light grey)

$\tau(p \to e^+\pi^0)_{\mathrm{HK},2025} > 9 \times 10^{34}$ years (grey)

$\tau(p \to e^+\pi^0)_{\mathrm{HK},2040} > 2 \times 10^{35}$ years (dark)

Conclusions / outlook

3rd GUT renaissance? Probably a wishful thinking...

Minimal SO(10) GUT:

Either

we should see a scalar color octet @ LHC

or

we should see proton decay @ Hyper-Kamiokande

Thanks for your kind attention!

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(and sorry for taking extra time)