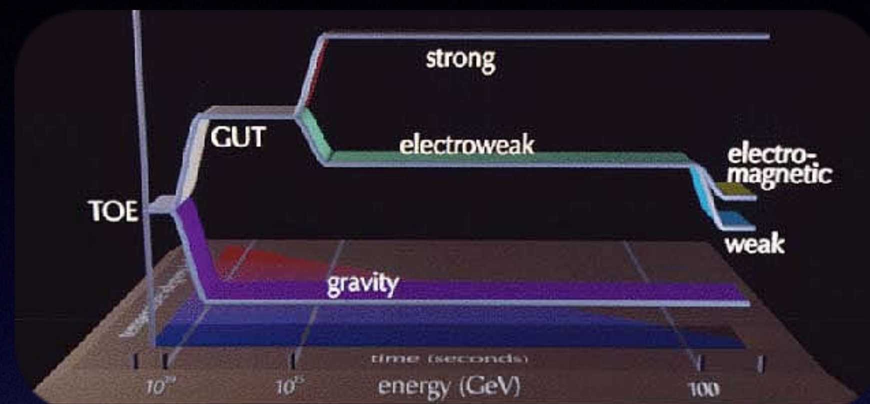
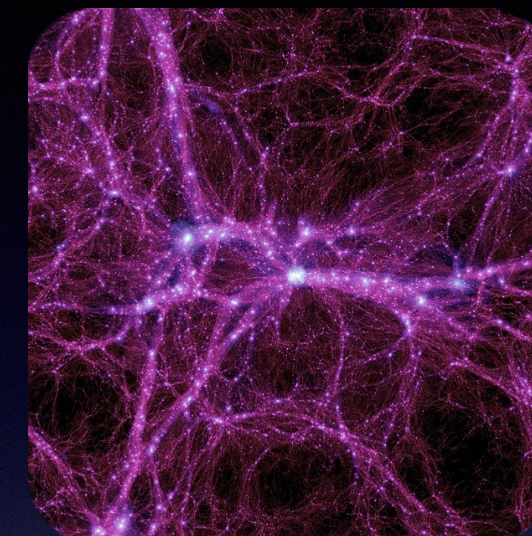
Unification and dark matter





Yann Mambrini

http://www.ymambrini.com/My_World/Physics.html

ERC Higgs@LHC

MultiDark
Multimessenger Approach for Dark Matter Detection

LPT Orsay

cnrs dépasser les frontières

P2IO
Physique des 2 Infinis et des Origines

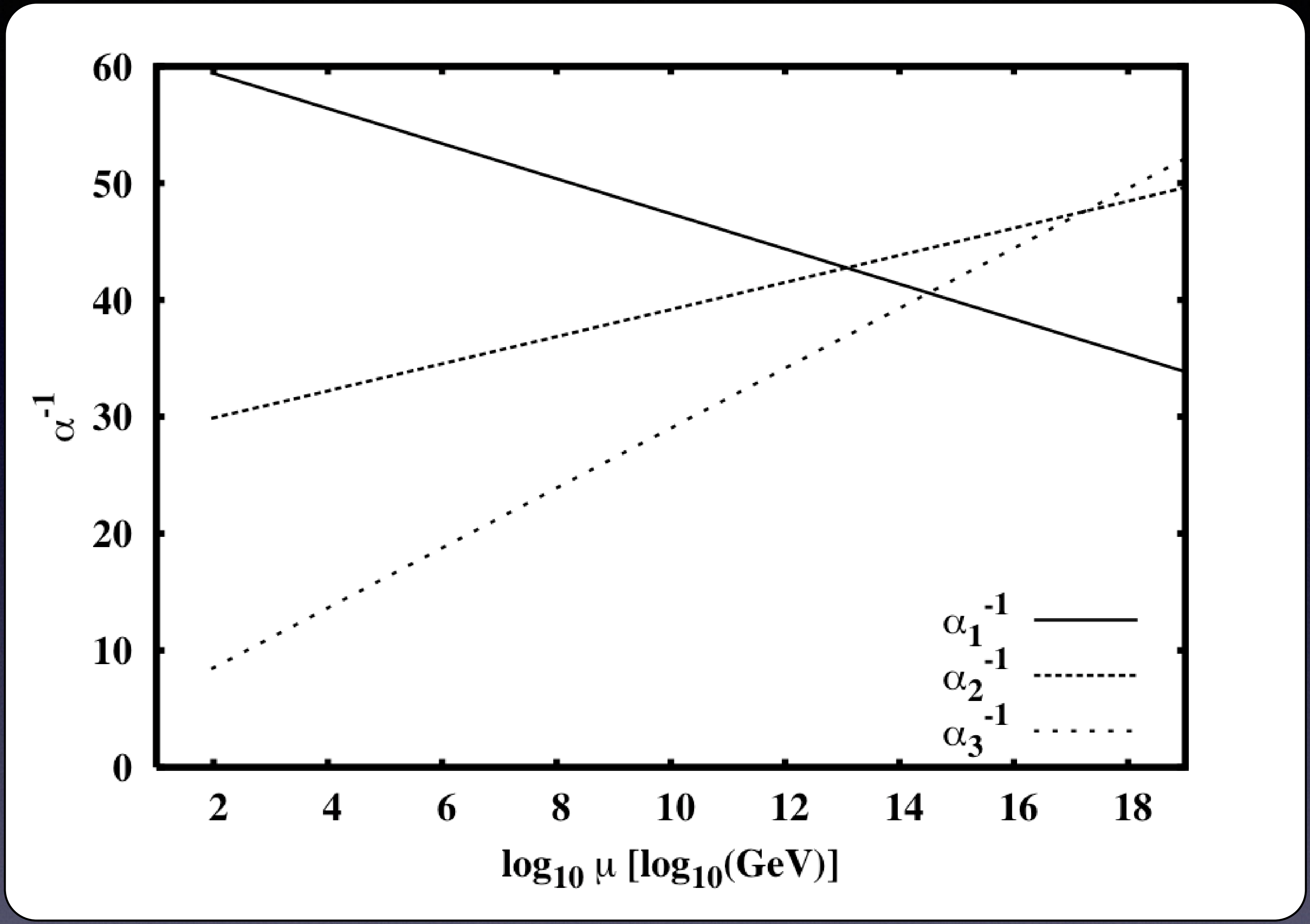
invisibles
neutrinos, dark matter & dark energy physics

In collaboration with

G. Arcadi, E. Dudas, L. Heurtier, N. Nagata, K. Olive, M. Tytgat, B. Zaldivar, J. Zheng

GDR Terascale, Paris Saclay, 31st of March 2015

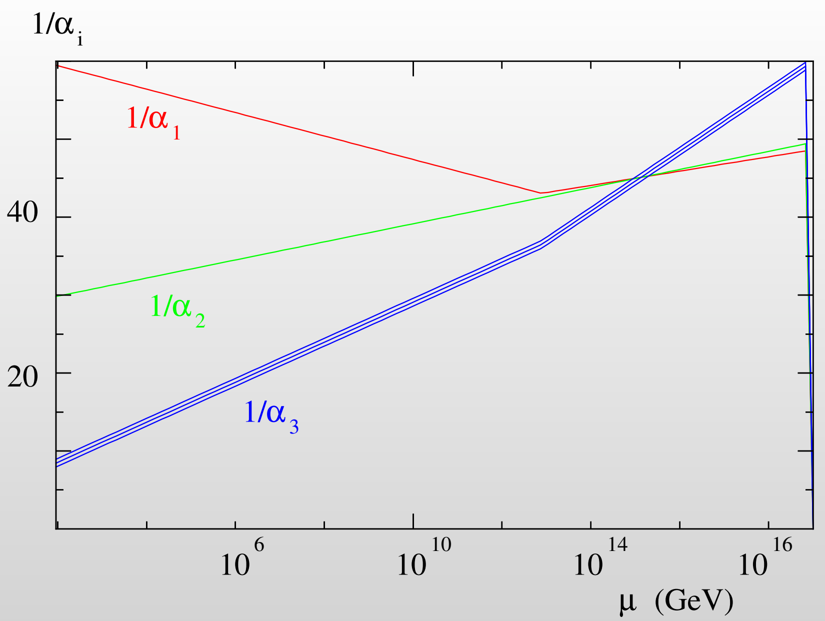
Gauge coupling unification



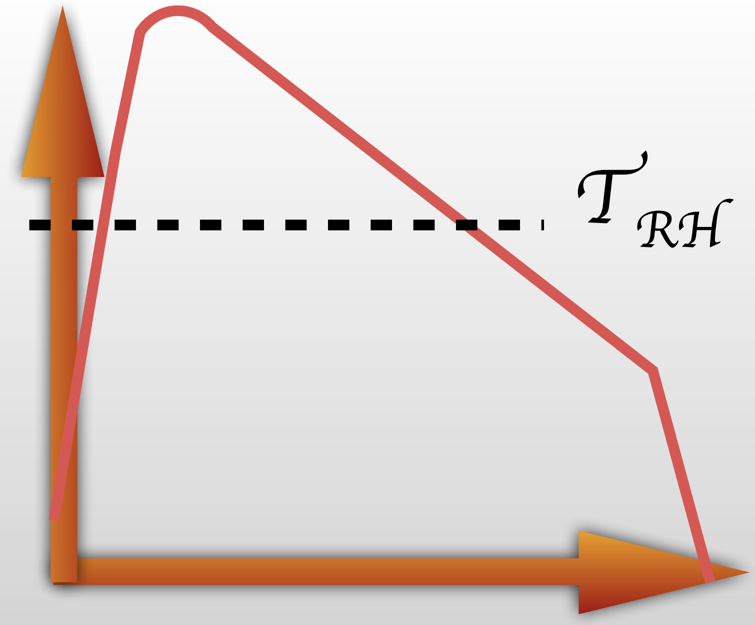
First motivation for GUT-like models

Two medications: modifying the **particle content** (SUSY) or the **gauge structure** (GUT), or **both** (SUSY-GUT)

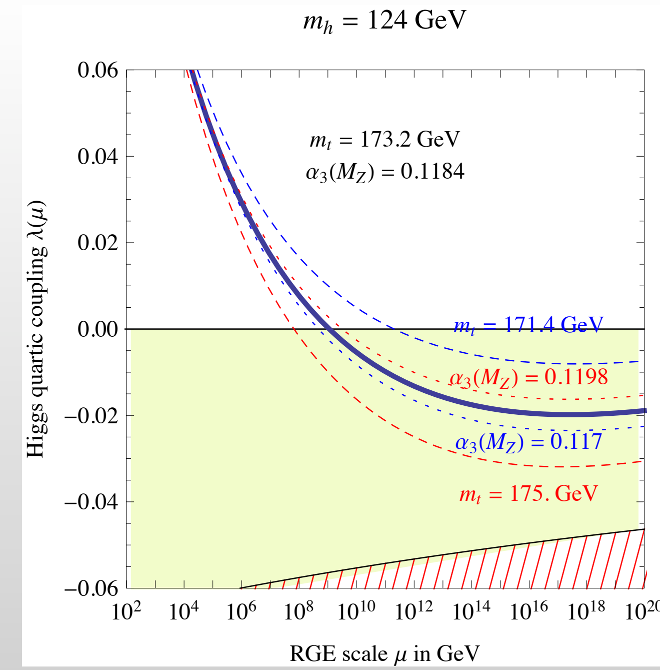
Care should be taken concerning the proton decay in GUT models as electrons and quarks belong to **same multiplets**



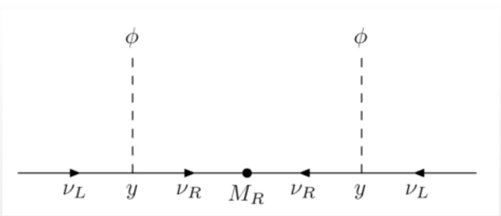
Unification :
Intermediate scale ~ 10^{10} GeV



Reheating process:
T_{RH} ~ 10^{10} GeV



Higgs quartic coupling
μ ~ 10^{10} GeV



$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D & M^R \end{pmatrix}$$

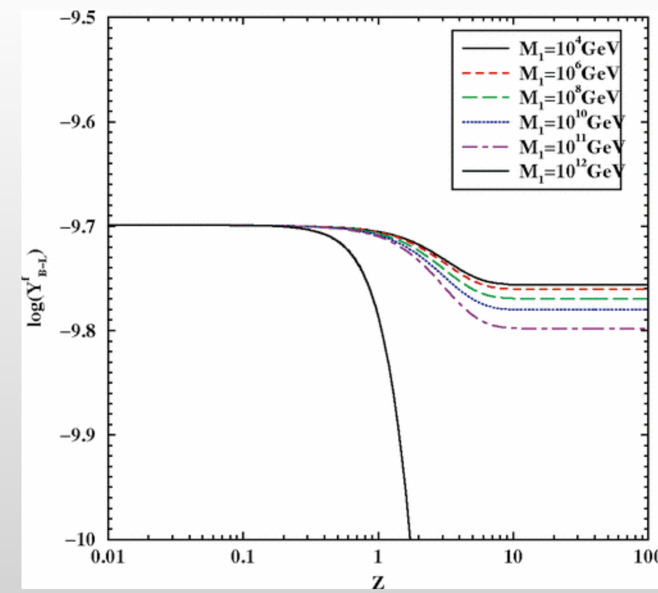
$$\mathcal{L}_\nu = -(\frac{1}{2}M^R + \frac{ih}{\sqrt{2}}A)\bar{\nu}^c_R \nu_R - \frac{y_{LR}}{\sqrt{2}}\bar{\nu}_L H \nu_R + h.c.$$

$$m_1 = \frac{1}{2}\left[M^R - \sqrt{(M^R)^2 + 4m_D^2}\right] \simeq -\frac{m_D^2}{M^R} \simeq -\frac{y_{LR}^2 v_H^2}{2M^R}$$

See-saw mechanism with ν_R:
m_ν=0.1 eV => M^R ~ 10^{10} GeV

Nature seems to point toward an intermediate scale around 10^{10} GeV

« Unification is one thing, and stability [in Northeast Asia] is another thing. »
Kim Dae Jung, president of South Korea



Leptogenesis/baryogenesis
μ ~ 10^{10} GeV

Stability of dark matter

« There is nothing stable in the world; uproar's your only music. »
John Keats

A large number of models introduce a $\mathbf{Z_2}$ adhoc symmetry to justify the **stability** of their dark matter candidate (Higgs-portal, Z'-portal, Rp SUSY..)

However, a $\mathbf{Z_2}$ symmetry **appear naturally** once a local **U(1)** symmetry is **spontaneously** broken by a Higgs-mechanism

toy example

$$\psi \mapsto e^{i\alpha(x)}\psi \qquad \phi \mapsto e^{iq\alpha(x)}\phi.$$

$$\beta\phi\phi^*\psi\psi^*, \quad \gamma\psi^q\phi^*, \quad \delta\psi^{*q}\phi$$

$$\phi(x) \xrightarrow{SSB} v + \phi'(x).$$

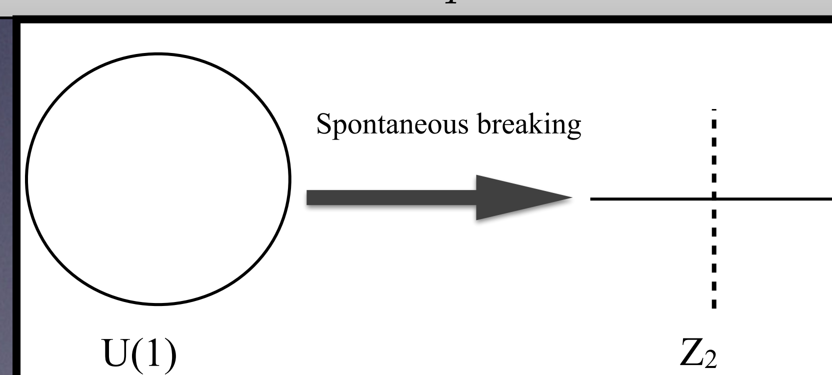
$$\psi \to e^{\frac{2i\pi}{q}m}\psi, \quad m \in \mathbb{Z}$$

residual discrete Abelian symmetry $\mathbb{Z}_q$.

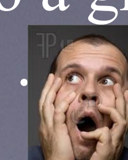
generalization

$$\langle\phi\rangle \xrightarrow{U(1)} \langle\phi\rangle \quad \Rightarrow \quad e^{iQ_\phi\alpha}\langle\phi\rangle = e^{iNq\alpha}\langle\phi\rangle = \langle\phi\rangle \quad \Rightarrow \quad \alpha = \frac{2\pi}{q}$$

$$\psi \to e^{i\alpha p}\psi = e^{i\frac{2\pi}{q}p} \qquad e^{i\frac{2\pi}{q}} \equiv \mathbb{Z}_q$$



Conclusion: if one wants to include a naturally stable candidate (Z_2 symmetry) one needs to extend the rank of the Standard Model SU(3) X SU(2)L X U(1) of rank **2+1+1=4** to a group of rank (at least) **5**. **SO(10)** is the minimal candidate and **not SU(5)** which is of **rank 4** .



Looking for a model..

Unification of gauge couplings

Respecting proton lifetime

Intermediate scale giving natural neutrino mass and Higgs stability

Natural stable neutral candidate (dark matter)

Dark matter respecting WMAP/PLANCK constraint

SO(10) seems to do honestly the job

SO(10) in a nutshell

« It is a genius, but one should always check his calculations »
Gustav Kirchhoff about the numerous mathematical errors of Maxwell

SO(N) is the group of the (NxN) orthogonal [$O^TO=1$] matrices with determinant = 1

Orthogonal matrices are generated by antisymmetric tensors.
There are N(N-1)/2 antisymmetric generators, and 5 commuting **Cartan** generators

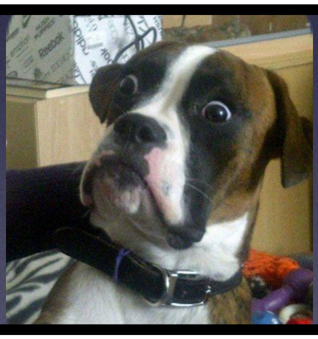
$$\frac{10(10-1)}{2} = 45$$

$$10 \otimes 10 = 1 \oplus 45 \oplus 54$$

45 antisymmetric representation
and 54 symmetric representation

$$\{\Gamma_i, \Gamma_j\} = 2\delta_{i,j}\ \mathbb{I}$$

Clifford algebra (conservation of length)



$$\Gamma_1 = \sigma_1 \otimes \sigma_1 \otimes \sigma_1 \otimes \sigma_1 \otimes \sigma_1$$

Dimension $2^5 = 32$ + « left-right » symmetrization : 16 + 16

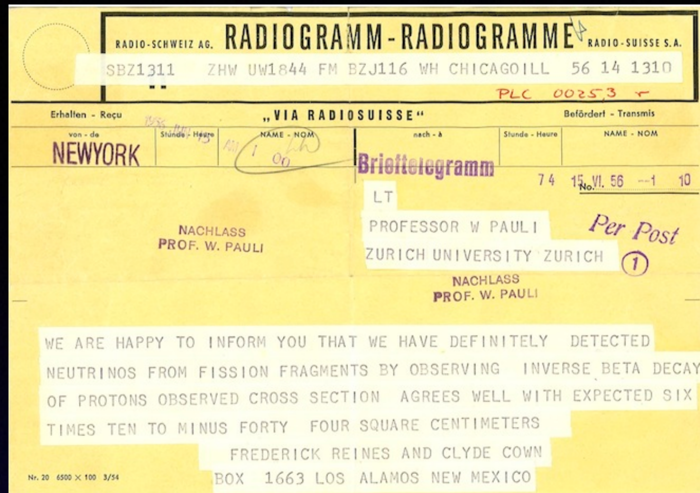
$$16 \otimes 16 = 10 \oplus 120 \oplus 126$$

dimensionality	IR	indices
10	vector	Γ_μ
16	spinor	ψ
45	adjoint	$\Sigma_{\mu\nu}$
54	symmetric second-rank tensor	$\Gamma_{\{\mu\nu\}}$
120	antisymmetric third-rank tensor	$\Gamma_{[\mu\nu\lambda]}$
126	antisymmetric fifth-rank tensor	$\Gamma_{[\mu\nu\lambda\rho\sigma]}$
210	antisymmetric fourth-rank tensor	$\Gamma_{[\mu\nu\lambda\kappa]}$

$$\Psi_L = \begin{bmatrix} u_r \\ u_g \\ u_b \\ \nu \\ d_r \\ d_g \\ d_b \\ e \\ d_r^c \\ d_g^c \\ d_b^c \\ e^c \\ -u_r^c \\ -u_g^c \\ -u_b^c \\ -\nu^c \end{bmatrix}_L$$

SO(10)	SU(5)	$SU(2)_L \times SU(2)_R \times SU(4)$
10	5+5*	(2,2,1)+(1,1,6)
16	1+5*+10	(2,1,4)+(1,2,4*)
45	1+10+10*+24	(3,1,1)+(1,3,1)+(1,1,15)+(2,2,6)
54	15+15*+24	(1,1,1)+(3,3,1) +(1,1,20)+(2,2,6)
126	1+5*+10+15*+45+50*	(1,1,6)+(3,1,10*)+(1,3,10)+(2,2,15)
210	1+5+5*+10+10*+24 +40+40*+75	(1,1,1)+(1,1,15)+(2,2,6)+(3,1,15) +(1,3,15)+ (2,2,10)+(2,2,10*)

SO(10) and neutrino physics



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„VIA RADIOSUISSE"

Brieftelegramm

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

NACHLASS PROF. W. PAULI

Per Post

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

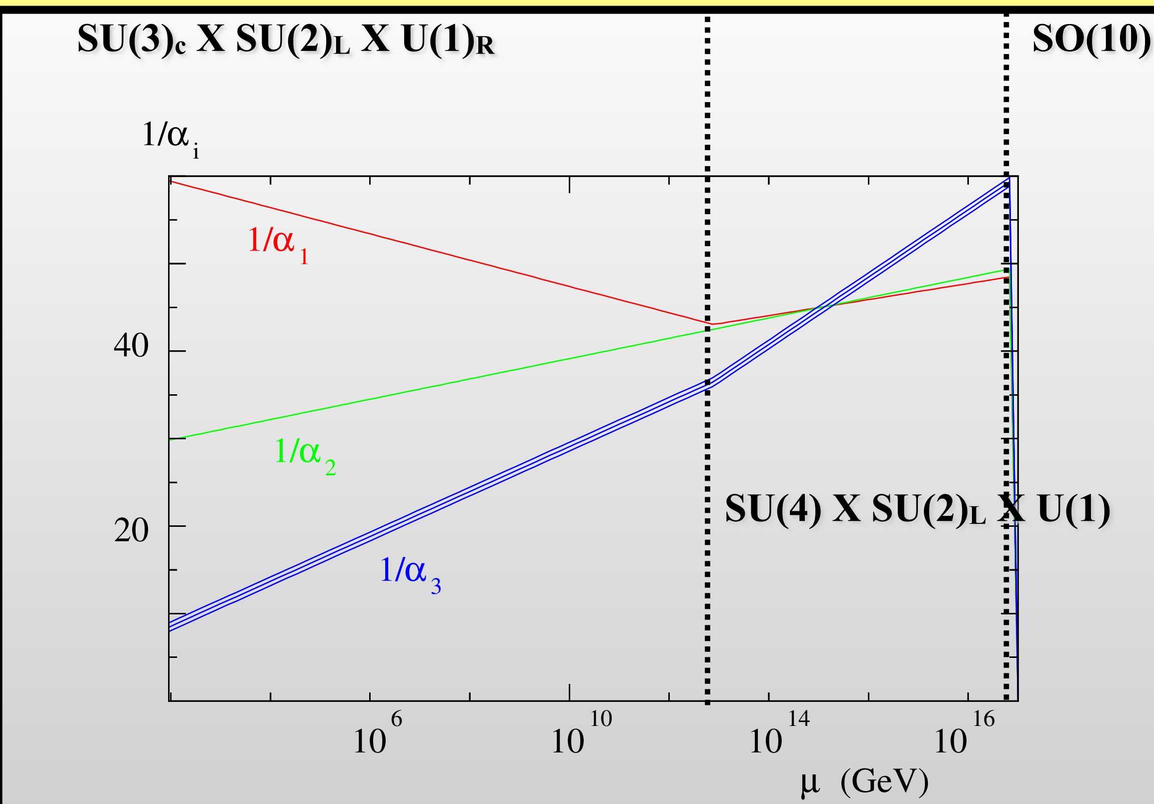
FREDERICK REINES AND CLYDE COWN BOX 1663 LOS ALAMOS NEW MEXICO

To: professor W. Pauli, Zurich University
We are happy to inform you that we have definitively detected neutrinos from fission fragments (..)

F. Reines and C. Cowan,
Los Alamos, June 14th 1956

The SO(10) spinor in the 16 representation naturally embed a ***right handed neutrino*** ν_R. The breaking of SO(10) into an *intermediate group*, at an intermediate (~10^{10} GeV) scale provides then the best framework for a natural see-saw mechanism (natural means $y_\nu \sim 1$)

As a free bonus, one also obtain unification at GUT scale!



Asking for unification imposes the intermediate scale (~10^{10} GeV) and leads to natural see-saw

$$SO(10) \longrightarrow G_{\rm int} \longrightarrow G_{\rm SM} \otimes \mathbb{Z}_N$$

$$\mathcal{L}_Y = \frac{g}{2}\mathbf{16}_L.\mathbf{16}_L.\mathbf{10} + \frac{h}{2}\mathbf{16}_L.\mathbf{16}_L.\mathbf{126}$$

$$M^R = h\langle \mathbf{126} \rangle$$

TABLE I. Possible breaking schemes of SO(10).

	$SO(10) \to \mathcal{G}\times$ [Higgs]	M_{int}(GeV)	T_{RH}(GeV)
A	$4 \times 2_L \times 1_R$ [**16**]	$10^{12.9}$	3×10^9
A	$4 \times 2_L \times 1_R$ [**126**]	$10^{11.8}$	1×10^8
B	$4 \times 2_L \times 2_R$ [**16**]	$10^{14.4}$	3×10^{11}
B	$4 \times 2_L \times 2_R$ [**126**]	$10^{13.8}$	5×10^{10}
C	$3_C \times 2_L \times 2_R \times 1_{B-L}$ [**16**]	$10^{10.6}$	3×10^6
C	$3_C \times 2_L \times 2_R \times 1_{B-L}$ [**126**]	$10^{8.6}$	6×10^3

(Y. Mambrini, K. Olive, J. Quevillon, B. Zaldivar 2013)

To do list

"To Do Today,
1. Sit and think
2. Reach enlightenment
3. Feed the cats"

Jarod Kintz

Unification ☑ DONE!

Neutrino Mass ☑ DONE!

[+ Higgs stability J. Elias-Miro, J.R. Espinosa, G. Giudice, H.M. Lee, A. Strumia 2012]

Intermediate scale ☑ DONE!

Dark Matter?

What is left?

« Nous partîmes trois mille; mais par un prompt renfort, Nous nous vîmes cinq cent en arrivant au port,»

Modified quote by Don Rodrigue in « Le Cid », Racine

From all the possible representations where a neutral candidate can exist, asking for

Natural stability [U(1) broken to Z_2 symmetry]

Non degeneracy in the multiplet [to avoid long lived charged particles]

Natural seesaw [Higgs in **126** representation]

Higgs stability [Intermediate scale ~10^{10} GeV]

Proton lifetime [> 10^{34} years]

What is left?

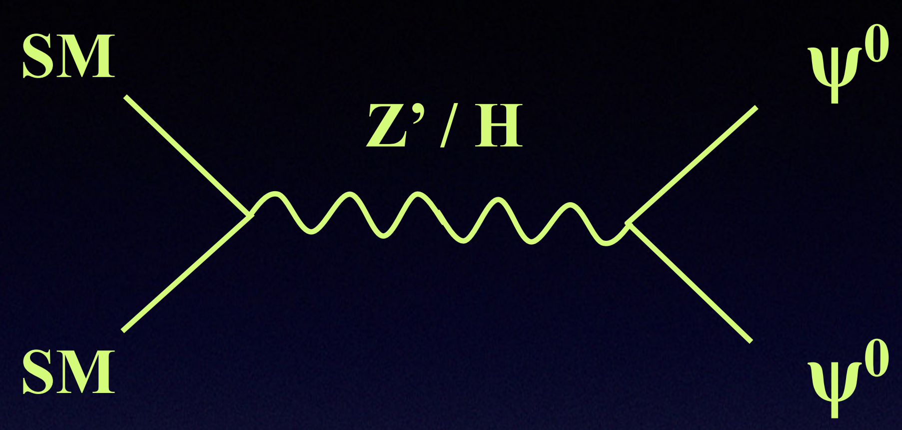
$G_{\rm int}$	R_1
$\mathrm{SU}(4)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R$	**210**
$\mathrm{SU}(4)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes D$	**54**

$$\mathrm{SO}(10) \longrightarrow G_{\rm int} \longrightarrow G_{\rm SM} \otimes \mathbb{Z}_N$$

Y. Mambrini, N. Nagata, K. Olive, J. Quevillon, J. Zheng 2015

Computing the relic abundance

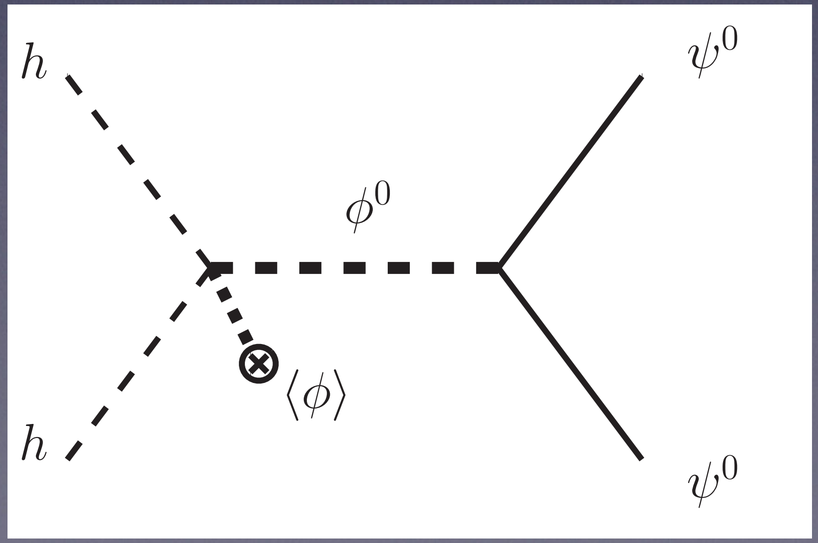
Non-equilibrium Thermal Dark Matter (NET DM)



Annihilation is too weak to reach the thermal equilibrium

Scattering process is too weak to reach kinetic equilibrium with the thermal bath

The dark matter is produced from the thermal bath but at a very slow rate, until the expansion rate dominates the annihilation (H > Γ)



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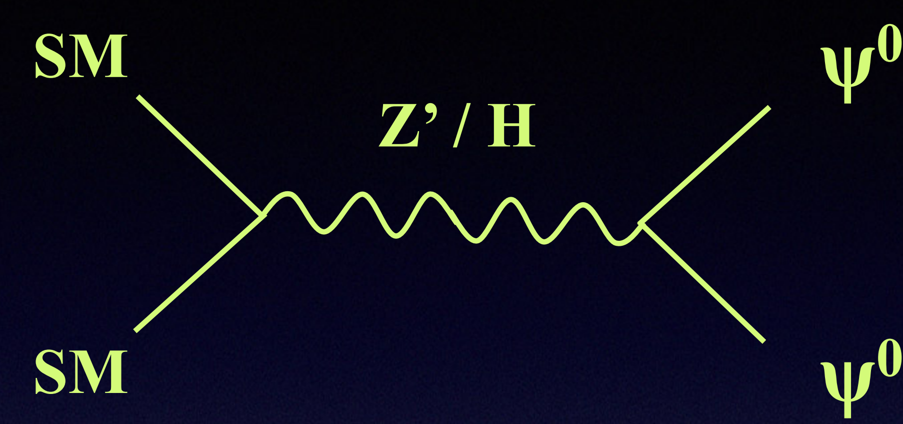

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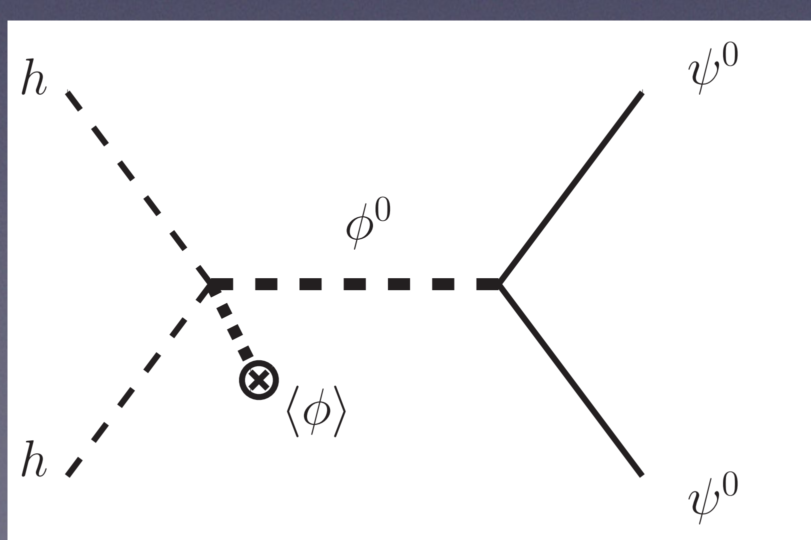
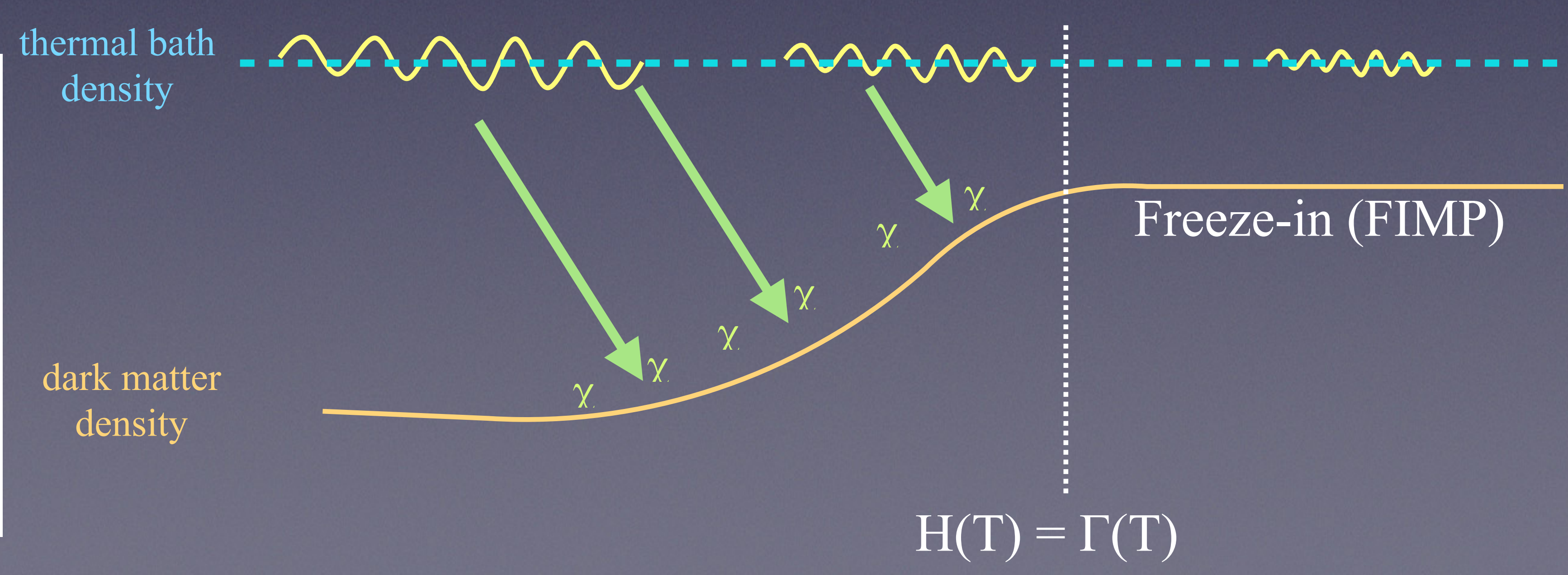




Computation of the relic abundance

Boltzman equation for the production rate (Y ~0 so no second part in the equation)

$$\frac{dY_\chi}{dx} = \sqrt{\frac{\pi}{45}}\frac{g_s}{\sqrt{g_\rho}} m_\chi M_P \frac{\langle \sigma v\rangle}{x^2} Y_{eq}^2$$

with

$$\langle \sigma v\rangle n_{eq}^2 \approx \frac{\kappa^2\, T}{2048\pi^6}\int_{4m_\chi^2}^{\infty} ds d\Omega \sqrt{s-4m_\chi^2}|\mathcal{M}|^2 K_1(\sqrt{s}/T)\,.$$

$$\sum |\mathcal{M}|^2 \simeq c\,\frac{\hat{s}-4M_{\rm DM}^2}{M_{\rm int}^2}$$

which gives

$$Y_{\rm DM}^{(0)} \simeq \frac{c}{64\pi^7}\left(\frac{45}{\pi g_*}\right)^{\frac{3}{2}}\frac{M_{\rm Pl}T_{\rm RH}}{M_{\rm int}^2}$$

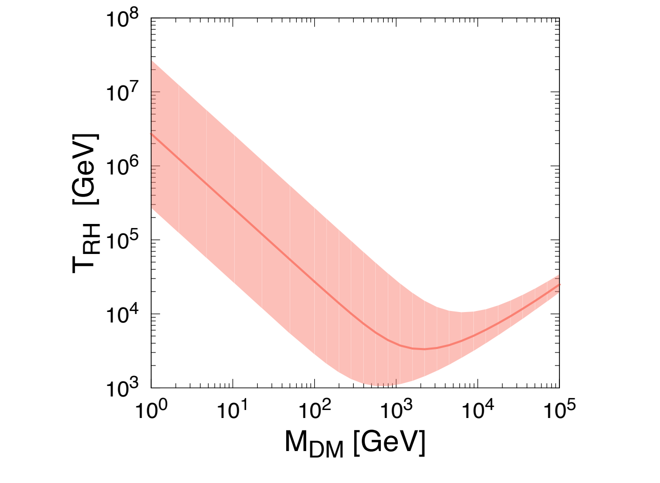
$\Omega h^2 = 0.1$

$$T_{\rm RH} \simeq 1.3\times 10^9~{\rm GeV}\times\left(\frac{\Omega_{\rm DM}h^2}{0.12}\right)\left(\frac{g_*^{\frac{3}{2}}c^{-1}}{10^4}\right)\left(\frac{M_{\rm DM}}{100~{\rm GeV}}\right)^{-1}\left(\frac{M_{\rm GUT}}{10^{16}~{\rm GeV}}\right)^2.$$

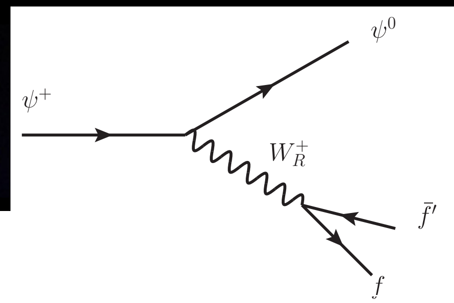
T_{RH} is determined by the relic abundance condition

Our result

« Did anybody read on the front page of Times that matter is decaying? » Woody Allen, 1980

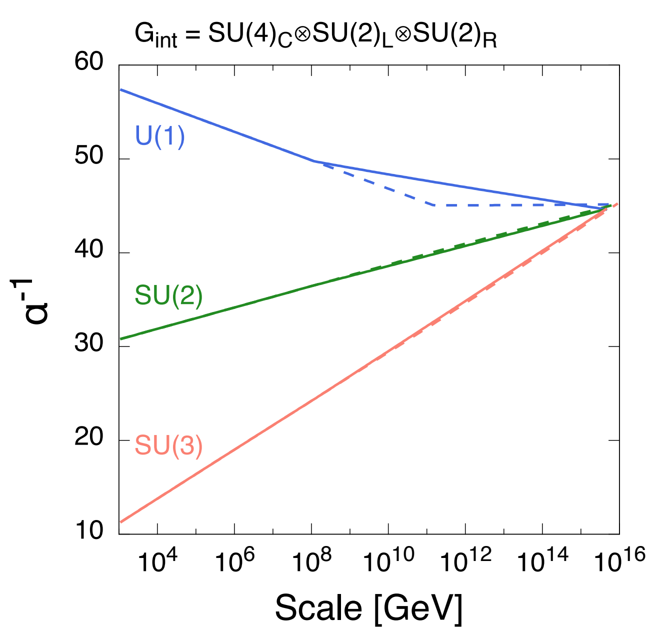


(b) Model II

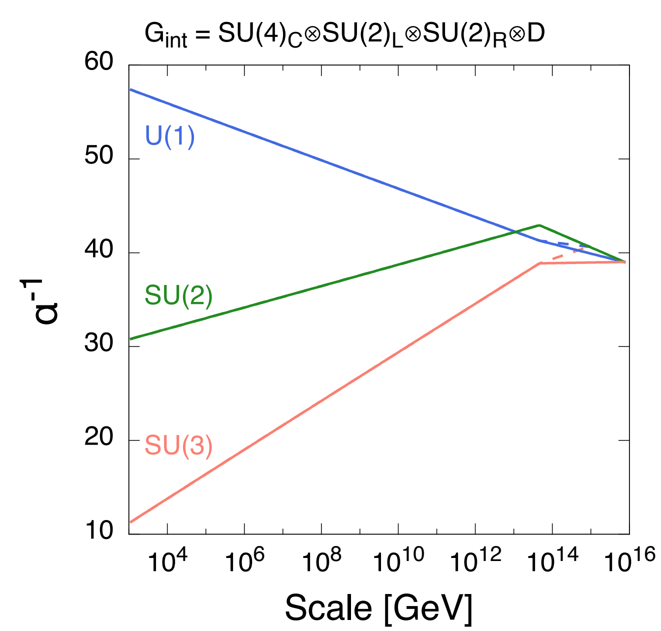


	Model I	Model II
$G_{\rm int}$	$SU(4) \otimes SU(2)_L \otimes SU(2)_R$	$SU(4) \otimes SU(2)_L \otimes SU(2)_R \otimes D$
$R_{\rm DM}$	$(\mathbf{1},\mathbf{1},\mathbf{3})_D$ in $\mathbf{45}_D$	$(\mathbf{15},\mathbf{1},\mathbf{1})_W$ in $\mathbf{45}_W$
R_1	$\mathbf{210}_R$	$\mathbf{54}_R$
R_2	$(\mathbf{10},\mathbf{1},\mathbf{3})_C \oplus (\mathbf{1},\mathbf{1},\mathbf{3})_R$	$(\mathbf{10},\mathbf{1},\mathbf{3})_C \oplus (\mathbf{10},\mathbf{3},\mathbf{1})_C \oplus (\mathbf{15},\mathbf{1},\mathbf{1})_R$
$\log_{10}(M_{\rm int})$	8.08(1)	13.664(5)
$\log_{10}(M_{\rm GUT})$	15.645(7)	15.87(2)
$g_{\rm GUT}$	0.53055(3)	0.5675(2)

2-loops RGE
Unification
Respecting τ_p
Intermediate scale giving m_ν
No degeneracy
PLANCK relic abundance



(a) Model I



(b) Model II

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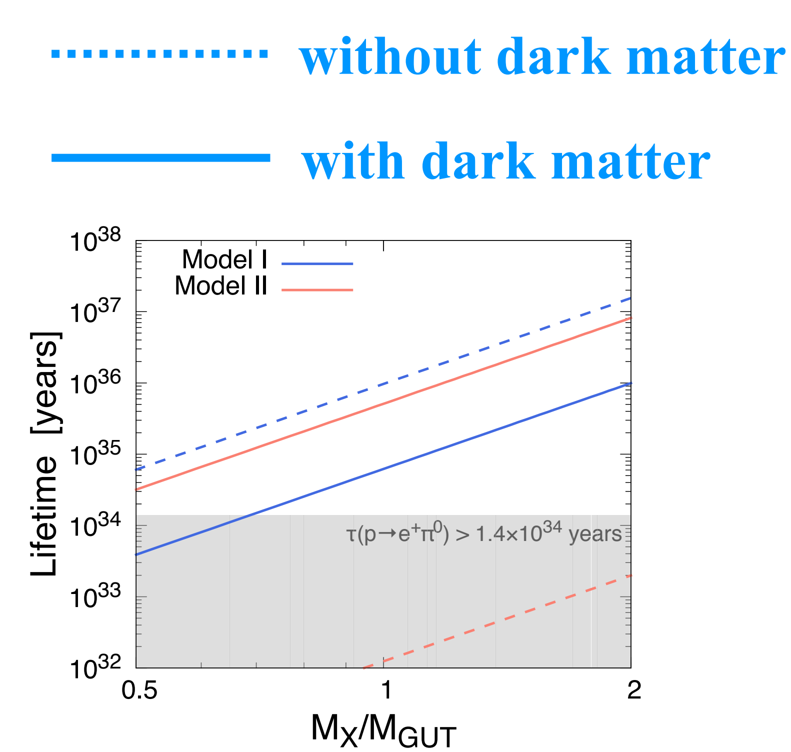

proton lifetime

Our result

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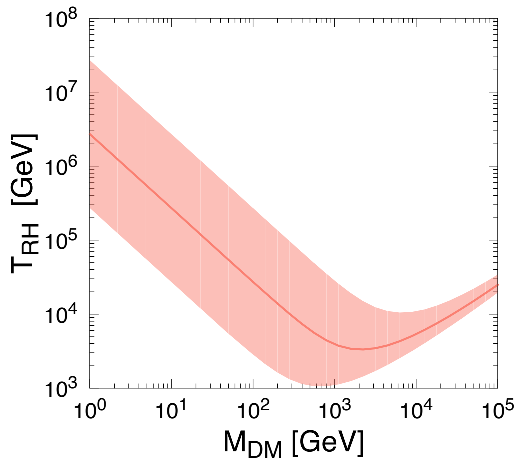

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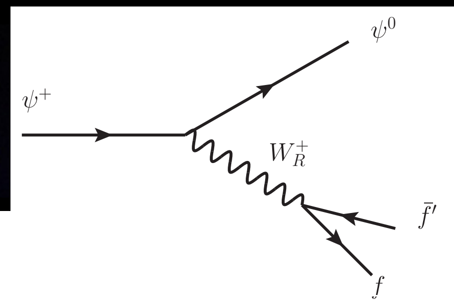

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R_1	$\mathbf{210}_R$	$\mathbf{54}_R$
R_2	$(\mathbf{10},\mathbf{1},\mathbf{3})_C\oplus(\mathbf{1},\mathbf{1},\mathbf{3})_R$	$(\mathbf{10},\mathbf{1},\mathbf{3})_C\oplus(\mathbf{10},\mathbf{3},\mathbf{1})_C\oplus(\mathbf{15},\mathbf{1},\mathbf{1})_R$
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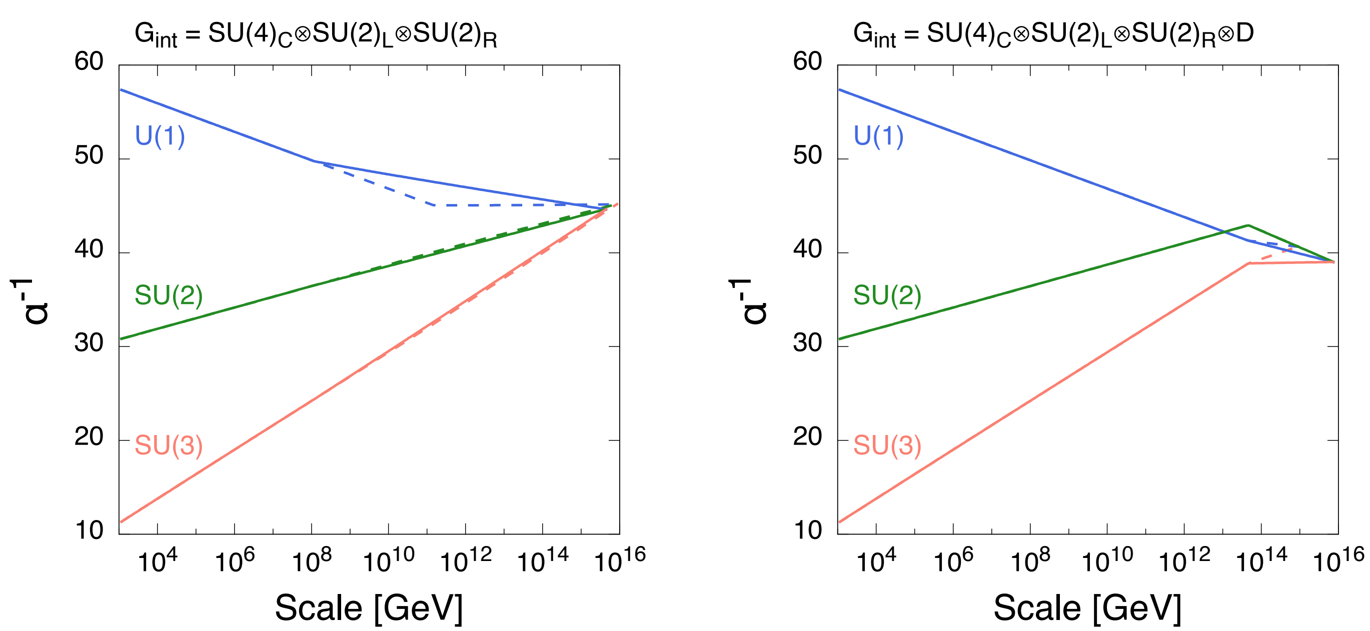

(a) Model I (b) Model II

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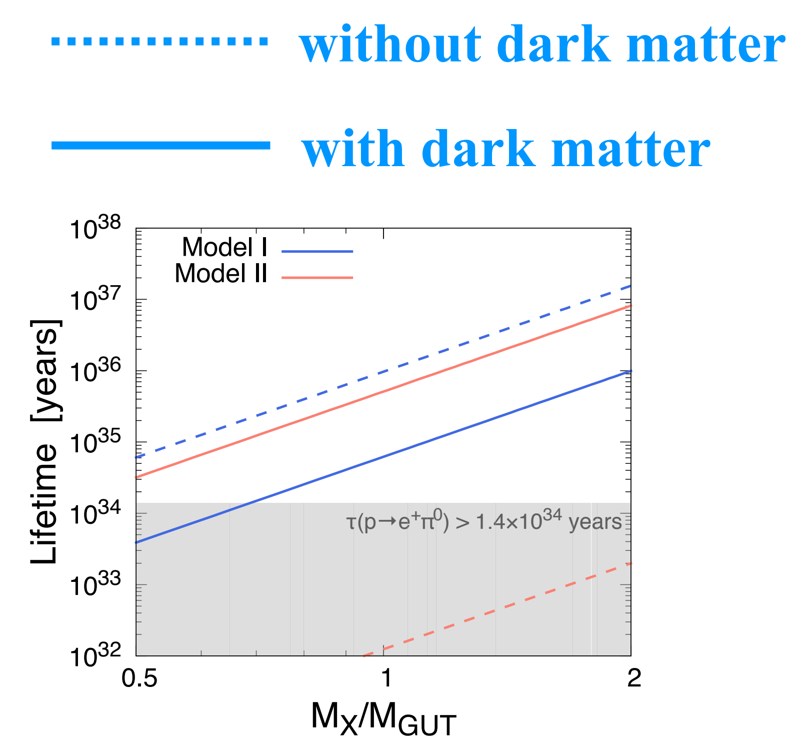


proton lifetime

Beyond SO(10): phenomenology of E6

$$E_6 \to SO(10) \times U(1)_\psi \qquad SO(10) \to SU(5) \times U(1)_\chi$$

$$\mathbf{27} \to \mathbf{16} + \mathbf{10} + \mathbf{1} \to (\mathbf{10} + \mathbf{5}^* + \mathbf{1}) + (\mathbf{5} + \mathbf{5}^*) + \mathbf{1}$$

Exceptional group of order 6: one extra Z'

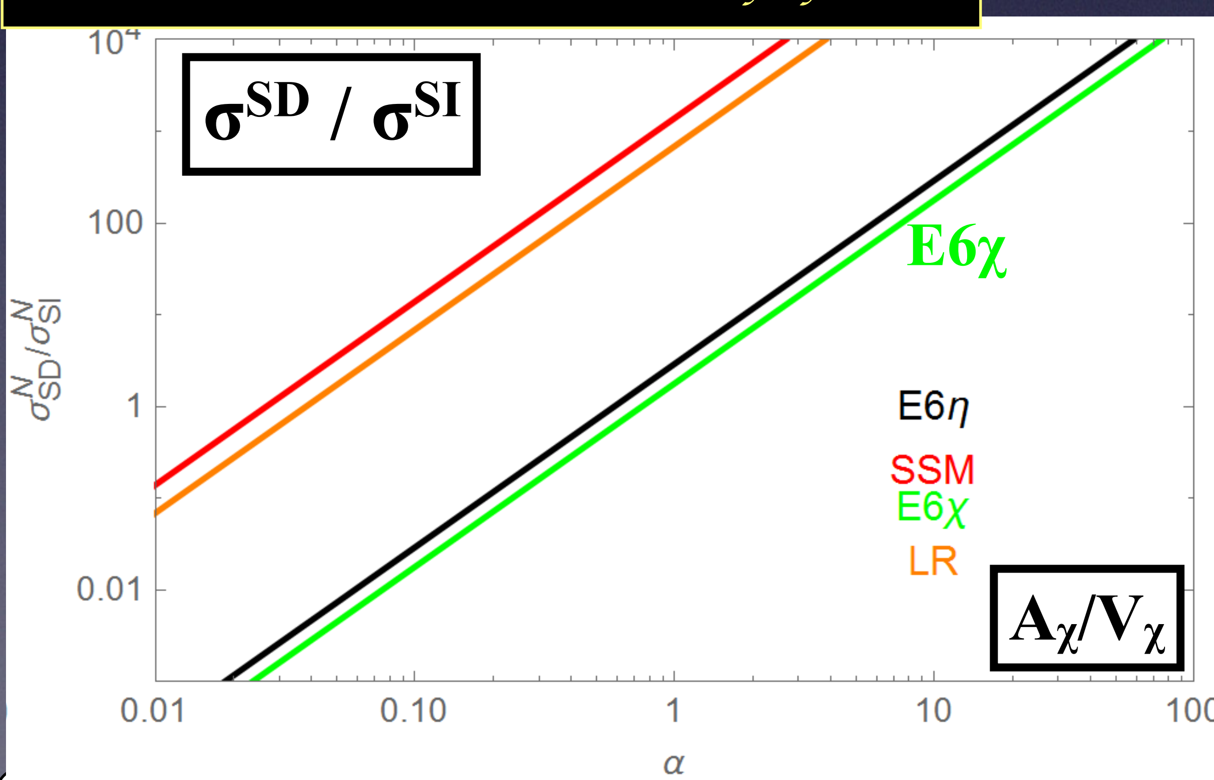
(G. Arcadi, Y. Mambrini, M. Tytgat, B. Zaldivar 2014)

E6 : Z'_χ Z'_ψ

$SO(10)$	$SU(5)$	$2\sqrt{10}Q_\chi$	$2\sqrt{6}Q_\psi$
16	$10\ (u, d, u^c, e^+)$	-1	1
	$5^*\ (d^c, \nu, e^-)$	3	1
	ν^c	-5	1
10	$5\ (D, H_u)$	2	-2
	$5^*\ (D^c, H_d)$	-2	-2
1	$1\ S$	0	4

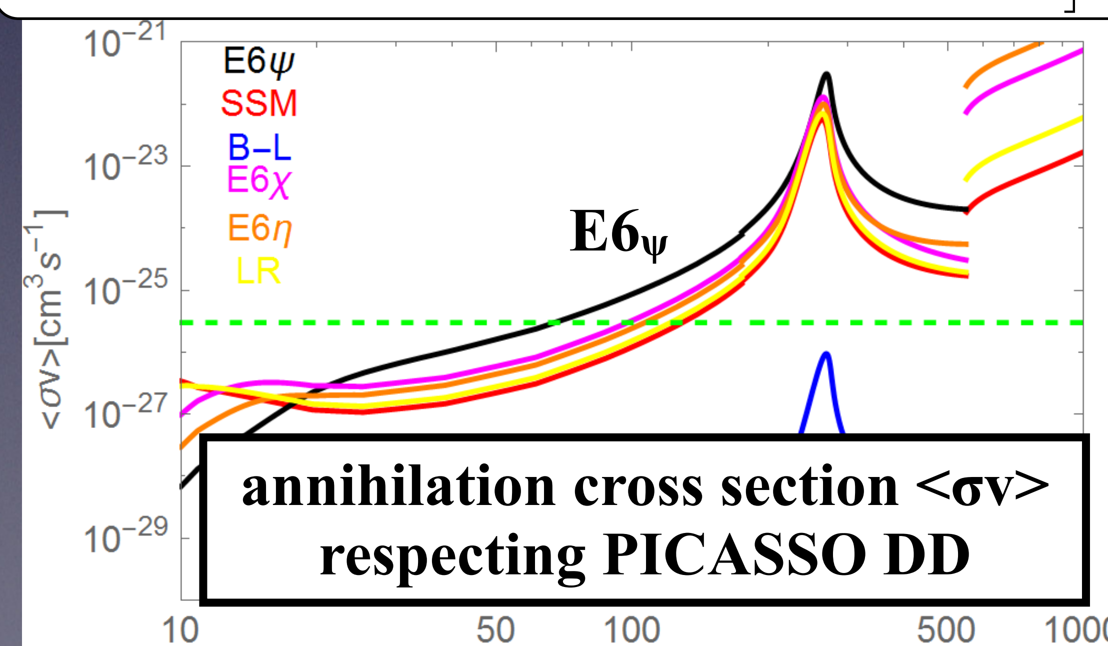
If dark matter is charged under $U(1)_\psi$, **pure axial** $\gamma^\mu\gamma^5$ coupling to the SM particles: only **spin-dependent** interaction. Constraints from direct detection becomes **very weak**. Opposite to $U(1)_{B-L}$ which gives **pure vectorial** γ^μ coupling.

G. Arcadi, Y. Mambrini, M. Pierre, in preparation



$$\frac{\sigma^p_{SD}}{\sigma^p_{SI}} = 3\alpha^2 \frac{\alpha_{SD}}{\alpha_{SI}}, \qquad \frac{\sigma^n_{SD}}{\sigma^n_{SI}} = 3\alpha^2 \frac{\alpha_{SD}}{\alpha_{SI}} \left|\frac{2V'_d + V'_u}{2V'_u + V'_d}\right|^2 \left|\frac{A'_u\Delta^p_u + A'_d(\Delta^p_d + \Delta^p_s)}{A'_u\Delta^n_u + A'_d(\Delta^n_d + \Delta^n_s)}\right|^2$$

$$\mathcal{L}_{\rm eff} \supset \frac{g_D^2}{M_{Z'}^2}\Big[V_D^\chi(2V_D^u + V_D^d)\ \bar\chi\gamma^\mu\chi\,\bar p\gamma_\mu p + A_D^\chi(\Delta_u^p A_D^u + (\Delta_d^p + \Delta_s^p)A_D^d)\bar\chi\gamma^\mu\gamma^5\chi\,\bar p\gamma_\mu\gamma^5 p\Big],$$



G. Arcadi, Y. Mambrini, C. Weniger, in preparation

Other work

M. Frigerio and T. Hambye (2009)

Dark matter stability and unification without supersymmetry

Michele Frigerio[a,b], Thomas Hambye[c]

In the absence of low energy supersymmetry, we show that (a) the dark matter particle alone at the TeV scale can improve gauge coupling unification, raising the unification scale up to the lower bound imposed by proton decay, and (b) the dark matter stability can automatically follow from the grand unification symmetry. Within reasonably simple unified models, a unique candidate satisfying these two properties is singled out: a fermion isotriplet with zero hypercharge, member of a 45 (or larger) representation of $SO(10)$. We discuss the phenomenological signatures of this TeV scale fermion, which can be tested in direct and indirect future dark matter searches. The proton decay rate into $e^+\pi^0$ is predicted close to the present bound.

Habemus Unified Standard Model including dark matter

- Unification ☑ DONE!
- Neutrino Mass ☑ DONE!
- Proton lifetime ☑ DONE!
- Dark Matter ☑ DONE!

Conclusion

Who made the (real) work

Natsumi Nagata, post-doc
University of Minneapolis
SO(10) w/o dark matter

Giorgio Arcadi, post-doc ERC
LPT Orsay
direct detection, LHC constraints, E6 Z'

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SO(10), NETDM, 2-loops RGE

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Lucien Heurtier, PhD student
Ecole Polytechnique
guitar player

Historical setup

Maxwell (citation, photo, paper)

SO(10) paper (+ photos)

Georgi Glashow SU(5) paper (+ photo)