Confronting GUTs with Proton Decay and Gravitational Waves

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New observational windows om the high-scale origin of the matter-antimatter





Part I



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Part II

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Part I begins

The role of GUTs

- GUT unifies SM gauge interactions into a single gauge group SM fermionic multiplets into 1 or 2 representations of the GUT representation
- - \implies reduces number of SM parameters
- Many GUTs predict non-zero **neutrino masses**, dark matter candidate etc





- GUTs unify leptons and quarks into common multiplets.
- integrated out \implies proton decay

$$\frac{\epsilon_{\alpha\beta}}{\Lambda_1^2} \left[(\overline{u_R^c} \gamma^{\mu} Q_{\alpha}) (\overline{d_R^c} \gamma_{\mu} L_{\beta}) + (\overline{u_R^c} \gamma^{\mu} Q_{\alpha}) (\overline{e_R^c} \gamma_{\mu} Q_{\beta}) \right] + \frac{\epsilon_{\alpha\beta}}{\Lambda_2^2} \left[(\overline{d_R^c} \gamma^{\mu} Q_{\alpha}) (\overline{u_R^c} \gamma_{\mu} L_{\beta}) + (\overline{d_R^c} \gamma^{\mu} Q_{\alpha}) (\overline{\nu_R^c} \gamma_{\mu} Q_{\beta}) \right],$$

$$SU(3)_C \times SU(2)_L \times U(1)_Y \text{ invariant but}$$

• GUTs spontaneously broken to SM gauge group, heavy gauge boson Weinberg, 1979









- GUTs unify leptons and quarks into common multiplets.
- integrated out \implies proton decay





GUTs spontaneously broken to SM gauge group, heavy gauge boson <u>Weinberg, 1979</u>





Limits (or even finding!) proton decay

Neutrino experiments are large vats of proton sitting around for a long time. $au_{\pi^0 e^+} > 1.6 \times 10^{34} \, \text{years}$ <u>SK (1610.03597)</u>





Nucleon decay limits



11

During SSB from $G_{GUT} \rightarrow \cdots \rightarrow G_{SM}$ topological defects may form.

Domain wall





 $\pi_0(G/H) \neq 0$

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<u>cambridge</u> <u>cosmic structures</u>

 $\pi_1(G/H) \neq 0$



 $\pi_2(G/H) \neq 0$





During SSB from $G_{GUT} \rightarrow \cdots \rightarrow G_{SM}$ topological defects may form.







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Cosmic strings

 $\pi_1(G/H) \neq 0$







Cosmic strings induced via U(1) breaking are ubiquitously as GUT breaks to SM





- Inflation occurs after string formation → string network diluted and no GW signal
- Inflation occurs during string formation → partly diluted string network → GW spectrum broken power law behaviour (Cui, Lewicki, Morrissey) <u>1912.08832</u>



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• Inflation occurs before string formation \rightarrow string network gives "scaling" solution





Proton decay in non-supersymmetric SO(10)



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- 2005.13549 in collaboration with Stephen King, Silvia Pascoli, and Ye-Ling Zhou use PD and GWs to examine viable non-SUYS SO(10) GUT breaking chains.
- $G_{51} = SU(5) \times U(1)_X$,
- $G_{51}^{\text{flip}} = SU(5)_{\text{flip}} \times U(1)_{\text{flip}},$

 $G_{3211} = SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$

- $G'_{3211} = SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X,$
- $G_{422} = SU(4)_C \times SU(2)_L \times SU(2)_R$.

 $G_r = G_{3221}$ or G_{421}

(d)

Also work by Dror et al (1908.03227) Buchmuller et al (1912.03695)







Topological defects in non-supersymmetric SO(10)



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monopoles and domains walls are unwanted topological defects

$G_x = G_{3221} \text{ or } G_{421}$

Assumed inflation at highest scale to remove unwanted defects and preserve cosmic strings













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Further study in **2106.15634**





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Further study in 2106.15634

Non-SUSY SO(10) with unification and GW signal only provided with Pati-Salam intermediate group

31 possible breaking chains



	CO(10)	defect	\mathcal{O}	defect	\mathcal{O}	Observ	vable
	50(10) Higgs	G_1	Higgs	$G_{\rm SM}$	string	gs?
	I1:	$\xrightarrow{\mathrm{m}}$	G_{3221}	$\xrightarrow{\mathrm{S}}$		\checkmark	
	I2:	$\xrightarrow[]{\text{m,s}}{\textbf{210}}$	G_{3221}^{C}	$egin{array}{c} 126 \\ \xrightarrow{\mathrm{S,W}} \\ \overline{126} \end{array}$		X	
	I3:	$\xrightarrow{\mathrm{m}}$	G_{421}	$\xrightarrow{\mathrm{S}}$		\checkmark	
	I4:	$\begin{array}{c} {\bf 45} \\ {f m} \\ {f 210} \end{array}$	G_{422}	$egin{array}{c} 126 \\ \stackrel{ m m}{\longrightarrow} \\ \overline{126}.45 \end{array}$		X	
	I5:	$\xrightarrow[54]{\mathrm{m,s}}$	G_{422}^{C}	$\xrightarrow[]{\text{m,w}}{126,45}$		×	
	I6:	$\xrightarrow[]{\text{m}}{\textbf{210}}$	G_{3211}	$\stackrel{\mathrm{s}}{\longrightarrow}$ 126		\checkmark	
SO((10) $\xrightarrow{\text{defect}}_{\text{Higgs}}$	$G_3 \stackrel{ ext{defea}}{=} ext{Higg}$	$\stackrel{\text{ct}}{\rightarrow} G_2$	$\stackrel{\text{defect}}{\longrightarrow} G$ $\stackrel{\text{Higgs}}{\longrightarrow}$	1 defec Higgs	$\frac{t}{s} G_{SM}$)bservable strings?
III1:	$: \qquad \xrightarrow{\mathrm{m,s}} 54$	$G_{422}^C = \frac{W}{210}$	$\rightarrow G_{422}$	$\xrightarrow{\mathrm{m}} G$	$421 \xrightarrow{s} \overline{126}$		1
III2:	$: \qquad \xrightarrow{\mathrm{m,s}} 54$	$G_{422}^C = \frac{W}{210}$	$\rightarrow G_{422}$	$\xrightarrow{\mathrm{m}}$ G	$\begin{array}{c} 120\\ 3221 \end{array} \xrightarrow{s} \\ \hline 126 \end{array}$	•	\checkmark
III3:	$: \qquad \xrightarrow{\mathrm{m,s}} 54$	$G_{422}^C = \frac{W}{210}$	$\rightarrow G_{422}$	m C			_
III4:	• =	210	122	$210 \qquad \qquad$	$3211 \xrightarrow{3} 126$	•	
	$: \qquad \xrightarrow{\mathrm{m,s}} 54$	$G_{422}^C = \frac{m}{210}$	$\rightarrow G^C_{3221}$	$\begin{array}{c} & G \\ 210 \\ & W \\ 45 \end{array} \qquad G$	$ \begin{array}{c} 3211 & \xrightarrow{\mathbf{s}} \\ 126 \\ 3221 & \xrightarrow{\mathbf{s}} \\ 126 \end{array} $		✓ ✓
1115	$\begin{array}{c} \xrightarrow{\mathrm{m,s}} \\ 54 \\ \xrightarrow{\mathrm{m,s}} \\ 54 \end{array}$	$ \begin{array}{ccc} & 210 \\ & G_{422}^C & \frac{m}{210} \\ & G_{422}^C & \frac{m}{210} \end{array} $	$\rightarrow G^C_{3221}$ $\rightarrow G^C_{3221}$	$\begin{array}{c} & G \\ 210 \\ & W \\ 45 \\ & M, W \\ 45 \end{array} \qquad G$	$ \begin{array}{c} 3211 & \xrightarrow{\mathbf{s}} \\ 126 \\ 3221 & \xrightarrow{\mathbf{s}} \\ 126 \\ 3211 & \xrightarrow{\mathbf{s}} \\ 126 \end{array} $	•	✓ ✓ ✓
1115: 1116:	$\begin{array}{c} \xrightarrow{\mathrm{m,s}} \\ 54 \\ \xrightarrow{\mathrm{m,s}} \\ 54 \\ \xrightarrow{\mathrm{m,s}} \\ 54 \\ \end{array}$	$ \begin{array}{cccc} & 210 \\ G_{422} & \frac{m}{210} \\ G_{422} & \frac{m}{210} \\ G_{422} & \frac{m}{210} \\ G_{422} & \frac{m,w}{45} \end{array} $	$\begin{array}{c} & & G^{C}_{3221} \\ \rightarrow & G^{C}_{3221} \\ \rightarrow & G^{C}_{3221} \\ \rightarrow & G_{3221} \end{array}$	$\begin{array}{c} & G \\ 210 \\ & 210 \\ \hline \\ & & 45 \\ \hline \\ & & M \\ \hline \\ & & 45 \\ \hline \\ & & 6 \\ \hline \\ & & \hline \\ & & \hline \\ & & & \hline \\ & & & \hline \\ & & & &$	$\begin{array}{c} 3211 & \xrightarrow{\mathbf{s}} \\ 126 \\ 3221 & \xrightarrow{\mathbf{s}} \\ 126 \\ 3211 & \xrightarrow{\mathbf{s}} \\ 126 \\ 3211 & \xrightarrow{\mathbf{s}} \\ 126 \\ \end{array}$	•	✓ ✓ ✓
1115: 1116: 1117:	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{c} & 210\\ G_{422}^C & \frac{m}{210}\\ G_{422}^C & \frac{m}{210}\\ G_{422}^C & \frac{m}{210}\\ G_{422}^C & \frac{m,w}{45}\\ G_{3221}^C & \frac{w}{45} \end{array}$	$\begin{array}{c} & & G_{3221}^C \\ \hline & & G_{3221}^C \\ \hline & & G_{3221}^C \\ \hline & & G_{3221} \\ \hline & & G_{3221} \end{array}$	$\begin{array}{c} \xrightarrow{\mathbf{w}} & G \\ \xrightarrow{\mathbf{w}} & \mathbf{f} \\ \xrightarrow{\mathbf{w}} & \mathbf{f} \\ \xrightarrow{\mathbf{m}, \mathbf{w}} & G \\ \xrightarrow{\mathbf{m}, \mathbf{w}} & \mathbf{f} \\ \xrightarrow{\mathbf{m}} & \mathbf{f} \end{array}$	$ \begin{array}{c} 3211 \\ \hline 126 \\ \hline 3221 \\ \hline 3221 \\ \hline 3211 \\ \hline 126 \\ \hline$	•	✓ ✓ ✓ ✓
1115: 1116: 1117: 1117: 1118:	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{c} & 210\\ G_{422}^C & \frac{m}{210}\\ G_{422}^C & \frac{m}{210}\\ G_{422}^C & \frac{m}{210}\\ G_{422}^C & \frac{m,w}{45}\\ G_{3221}^C & \frac{w}{45}\\ G_{422} & \frac{m}{45}\\ \end{array}$	$\begin{array}{ccc} & & & & \\ & & & & \\ & & & & \\ & & & & $	$\begin{array}{c} \xrightarrow{\mathbf{w}} & G \\ \xrightarrow{\mathbf{w}} & \mathbf{f} \\ \xrightarrow{\mathbf{w}} & \mathbf{f} \\ \xrightarrow{\mathbf{m}} & \mathbf{f} \end{array}$	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	•	
 1115: 1116: 1117: 1117: 1118: 1119: 	$ \begin{array}{c} \begin{array}{c} \begin{array}{c} m,s\\ \overline{54}\\ \hline \underline{m,s}\\ \overline{210}\\ \hline \underline{m,s}\\ \overline{210}\\ \underline{m,s}\\ \overline{54}\\ 54$	$\begin{array}{c} \begin{array}{c} & 210\\ G_{422}^{C} & \frac{m}{210}\\ \hline & \\ G_{422}^{C} & \frac{m}{210}\\ \hline & \\ G_{422}^{C} & \frac{m}{45}\\ \hline & \\ G_{3221}^{C} & \frac{w}{45}\\ \hline & \\ G_{422}^{C} & \frac{m}{45}\\ \hline & \\ G_{422}^{C} & \frac{m}{45}\\ \end{array}$	$\begin{array}{ccc} & & & & & \\ & & & & & & \\ & & & & & $	$\begin{array}{c} \xrightarrow{\mathbf{w}} & G \\ \xrightarrow{\mathbf{w}} & \mathbf{f} \\ \xrightarrow{\mathbf{w}} & \mathbf{f} \\ \xrightarrow{\mathbf{m}} \\ \xrightarrow{\mathbf{m}} & \mathbf{f} \\ \xrightarrow{\mathbf{m}} & \mathbf{f} \\ \xrightarrow{\mathbf{m}} & \mathbf{f} \\ \xrightarrow{\mathbf{m}} \\ \xrightarrow{\mathbf{m}} & \mathbf{f} \\ \xrightarrow{\mathbf{m}} \\ \xrightarrow{\mathbf{m}} & \mathbf{f} \\ \xrightarrow{\mathbf{m}} \\ \xrightarrow{\mathbf{m}}$	$ \begin{array}{c} 3211 \\ \hline 126 \\ \hline 3221 \\ \hline 126 \\ \hline 3211 \\ \hline 126 \\ \hline 3211 \\ \hline 3211 \\ \hline 126 \\ \hline 1$	· · ·	

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SO(10)IV1: IV2: IV3:

SO(10)	$\stackrel{\rm defect}{\longrightarrow}$	G_{2}	$\stackrel{\rm defect}{\longrightarrow}$	G_1	$\stackrel{\text{defect}}{\longrightarrow}$	Gon	Observable
50(10)	Higgs	02	Higgs	ΟŢ	Higgs	USM	strings?
II1:	$\stackrel{ m m}{\longrightarrow}$ 210	G_{422}	$rac{\mathrm{m}}{45}$	G_{3221}	$\xrightarrow{\mathrm{s}}$ $\overline{126}$		\checkmark
II2:	$\stackrel{\mathrm{m,s}}{\longrightarrow}$	G_{422}^{C}	$\stackrel{ m m}{\longrightarrow}$ 210	G_{3221}^{C}	$\xrightarrow{\overline{s,w}}{\overline{126}}$		×
II3:	$\xrightarrow{\mathrm{m,s}}$ 54	G_{422}^{C}	$\stackrel{\mathrm{m,w}}{\longrightarrow}$	G_{3221}	$\xrightarrow{S}{126}$		\checkmark
II4:	$\xrightarrow{\text{m,s}}{\textbf{210}}$	G_{3221}^{C}	$\stackrel{\mathrm{w}}{\longrightarrow}$ 45	G_{3221}	$\xrightarrow{S}{126}$		\checkmark
II5:	$\stackrel{ ext{m}}{\longrightarrow}$ 210	G_{422}	$\stackrel{\mathrm{m}}{\longrightarrow}$ 45	G_{421}	$\xrightarrow{S}{\overline{126}}$		\checkmark
II6:	$\stackrel{\mathrm{m,s}}{\longrightarrow}$	G_{422}^{C}	$rac{\mathrm{m}}{45}$	G_{421}	$\xrightarrow{S}{126}$		\checkmark
II7:	$\stackrel{\mathrm{m,s}}{\longrightarrow}$ 54	G_{422}^{C}	$\stackrel{ ext{w}}{ ext{210}}$	G_{422}	$\xrightarrow{\text{m}}$ $\xrightarrow{126}$ 45		×
II8:	$\xrightarrow{\mathrm{m}}$ 45	G_{3221}	$\xrightarrow{\mathrm{m}}$ 45	G_{3211}	$\xrightarrow{S}{126}$,	\checkmark
II9:	$\xrightarrow{\text{m,s}} 210$	G_{3221}^{C}	$\xrightarrow{\text{m,w}}$ 45	G_{3211}	$\xrightarrow{S}{\overline{126}}$		\checkmark
II10:	$\xrightarrow{\text{m}}$ 210	G_{422}	$\xrightarrow{\text{m}}$ 210	G_{3211}	$\xrightarrow{S}{126}$		\checkmark
II11:	$\xrightarrow{\text{m,s}}{54}$	G_{422}^{C}	$\xrightarrow{\text{m,w}} 210$	G_{3211}	$\xrightarrow{S}{126}$		\checkmark
II12:	$\xrightarrow{\mathrm{m}}{45}$	G_{421}	$\stackrel{ ext{m}}{ ext{45}}$	G_{3211}	$\xrightarrow{\text{S}}{126}$		\checkmark

$\stackrel{\rm defect}{\longrightarrow}$	G_{\star}	$\stackrel{\rm defect}{\longrightarrow}$	C_{2}	$\stackrel{\rm defect}{\longrightarrow}$	C_{2}	$\stackrel{\rm defect}{\longrightarrow}$	C_1	$\stackrel{\rm defect}{\longrightarrow}$	$C_{\rm CD}$	Observable
Higgs	\mathbf{G}_4	Higgs	U 3	Higgs	02	Higgs	GŢ	Higgs	USM	strings?
$\xrightarrow{\mathrm{m,s}}$	G_{422}^{C}	$\xrightarrow{\mathrm{m}}$	G_{3221}^{C}	$\xrightarrow{\mathrm{W}}$	G_{3221}	$\xrightarrow{\mathrm{m}}$	G_{3211}	$\xrightarrow{\mathrm{S}}$		\checkmark
54		210		45		45		126		
$\xrightarrow{\mathrm{m,s}}$	G_{A22}^C	$\xrightarrow{\mathrm{W}}$	G_{422}	$\xrightarrow{\mathrm{m}}$	G_{3221}	$\xrightarrow{\mathrm{m}}$	G_{3211}	$\xrightarrow{\mathrm{S}}$		\checkmark
54	422	210		45	0	45	0-11	$\overline{126}$		
$\xrightarrow{\mathrm{m,s}}$	G^{C}	$\xrightarrow{\mathrm{W}}$	G_{499}	$\xrightarrow{\mathrm{m}}$	G_{491}	\xrightarrow{m}	G_{2211}	$\xrightarrow{\mathrm{S}}$		1
$54^{'}$	₩422	$210^{'}$	$\bigcirc 422$	$45^{'}$	V 421	$45^{'}$	₩3211	$\overline{126}'$		▼



ſ	SO(10)	$\stackrel{\rm defect}{\longrightarrow}$	C_{\perp}	defect		bservable	Monop	ole	SO(10)	$\stackrel{\text{defect}}{\longrightarrow}$	$G_2 \stackrel{\mathrm{d}}{\longrightarrow}$	$\xrightarrow{\text{efect}} G_1$	$\stackrel{\text{defect}}{\longrightarrow}$ ($\frac{1}{2}$ Ob	oservable		
	50(10)	Higgs	G	Higgs	rSM s	strings?				Higgs	- F.	liggs –	Higgs	S	trings?		
}			0	S					II1:	$\xrightarrow{\mathrm{m}}$	G_{422} .	$\xrightarrow{\mathrm{m}} G_{32}$	$221 \xrightarrow{s}$		\checkmark		
	11:	$\stackrel{\longrightarrow}{45}$ m s	G_{3221}	$\xrightarrow{126}_{\mathrm{S} \mathrm{W}}$					II2:	$\begin{array}{c} 210 \\ \xrightarrow{\text{m,s}} \\ 54 \end{array}$	G^{C}_{422} :	$\xrightarrow{\text{m}} G_{32}^{C}$	$\begin{array}{c} 126 \\ s,w \\ \hline 221 \\ \hline 126 \\ \hline \end{array}$		×		
	I2:	$\stackrel{\mathrm{III},\mathrm{S}}{\longrightarrow}$ 210	G_{3221}^{C}	$\xrightarrow{3,w}$ $\overline{126}$		×	cosmic	;	II3:	$\begin{array}{c} 04 \\ \mathbf{m,s} \\ 54 \end{array}$	$G^{C}_{422} \stackrel{r}{-}$	$\xrightarrow{\mathrm{m,w}} G_{3}$	$221 \xrightarrow[126]{\text{S}} 126$		\checkmark		
	I3:	$rac{\mathrm{m}}{45}$	G_{421}	$\xrightarrow{\mathrm{S}}$ $\overrightarrow{126}$			strings		II4:	$\stackrel{\mathrm{m,s}}{\longrightarrow}$ 210	G^{C}_{3221} -	$\xrightarrow{\mathrm{w}} G_3$	$221 \xrightarrow[126]{s}$		√		
	I4:	$\stackrel{ m m}{\longrightarrow}$ 210	G_{422}	$\xrightarrow{\text{m}} \overline{126} 45$		×	Doma	ain	II5:	$\xrightarrow{\mathrm{m}}$ 210	G_{422} -	$\xrightarrow{\mathrm{m}} G_{42}$	$21 \xrightarrow{s}{\mathbf{\overline{126}}}$		√		
	I5:	$\xrightarrow{\mathrm{m,s}}$	G^{C}_{A22}	$\xrightarrow{\text{m,w}}$		X	wall	S	II6:	$rac{\mathrm{m,s}}{54}$ (G^{C}_{422} -	$\xrightarrow{\mathrm{m}} G_{45}$	$21 \xrightarrow{\mathrm{S}} \overline{126}$		\checkmark		
	То	54 m	$\overline{\mathbf{C}}$	$\overline{126},\!45$					II7:	$\begin{array}{c} { m m,s} \\ { m 54} \end{array}$	G^{C}_{422}	$\xrightarrow{\mathrm{w}}$ G_{42}	$22 \xrightarrow{\mathrm{m}} \overline{126.45}$		×		
	16:	$\overrightarrow{210}$	G_{3211}	$\overrightarrow{126}$					II8:	$\stackrel{\mathrm{m}}{\longrightarrow}$ (G_{3221} .	$\xrightarrow{\mathrm{m}} G_{3}$	211 $\xrightarrow{s}{126}$		\checkmark		
SO($10) \xrightarrow[\text{Higgs}]{\text{defect}} C$	\vec{a}_3 defe	$\stackrel{\text{ct}}{} G_2$	$\stackrel{\text{defect}}{\longrightarrow} G_1$	$\stackrel{\text{defect}}{} G$	$G_{\rm SM}$ Observable strings?			II9:	$\stackrel{\mathrm{m,s}}{\longrightarrow}$ 210	$G_{3221}^C \stackrel{r}{\cdot}$	$\xrightarrow{\mathrm{m,w}} G_{3}$	$211 \xrightarrow[]{s}{126}$		\checkmark		
III1:	$\xrightarrow{\text{m,s}} ($	$\frac{1000}{2422} \frac{W}{1000}$	$\rightarrow G_{422}$	$\xrightarrow{\text{m}} G_{42}$	$1 \xrightarrow{s} 1$	strings:			II10:	$\xrightarrow{\mathrm{m}}$ 210	G_{422}	$\xrightarrow{\mathrm{m}} G_{32}$	211 $\xrightarrow{s}{126}$		\checkmark		
III2:	$\xrightarrow{\begin{array}{c} 54 \\ \mathbf{m,s} \\ 54 \end{array}} \mathbf{(}$	$\begin{array}{ccc} \widehat{\mathcal{G}}_{422}^C & \underline{\mathcal{W}}_{210} \\ \overline{\mathcal{G}}_{422}^C & \underline{\mathcal{W}}_{210} \end{array}$	$\rightarrow G_{422}$	$\xrightarrow{\text{d5}} G_{32}$	$21 \xrightarrow{s}{126}$	\checkmark			II11:	$rac{\mathrm{m,s}}{54}$	G_{422}^C $\frac{r}{2}$	$\xrightarrow{\mathrm{m,w}} G_{32}$	$211 \xrightarrow[]{s}{126}$		√		
III3:		$\widetilde{\mathcal{F}}_{422}^C = \frac{\mathbb{W}}{210}$	$\rightarrow G_{422}$	$\xrightarrow{\mathrm{m}}$ G_{32}	$11 \xrightarrow[126]{\text{S}} 11 \xrightarrow[126]{\text{S}}$	\checkmark			II12:	$rac{\mathrm{m}}{45}$ (G_{421} -	$\xrightarrow{\mathrm{m}} G_{3}$	$211 \xrightarrow{\mathrm{s}} \\ \overline{126}$		1		
III4:	$\xrightarrow{\mathrm{m,s}}$ 6	$G_{422}^C \frac{\mathrm{m}}{210}$	$\rightarrow G^C_{3221}$	$\xrightarrow{\mathrm{w}} G_{32}$	$21 \xrightarrow[126]{s}$	\checkmark		de de	efect	defec	t a	defect	det	feçt	defect	~	Observable
III5:	$\xrightarrow{\mathrm{m,s}}$ ($r_{422}^C = \frac{\mathrm{m}}{210}$	$\rightarrow G^C_{3221}$	$\xrightarrow{\mathrm{m,w}} G_{32}$	$11 \xrightarrow{\mathrm{s}} \\ \overline{126}$	\checkmark		SO(10) = H	$ G_4$	Higg	$\rightarrow G_3$	Higgs	$G_2 = -$ Hi	$\rightarrow G_1$	Higgs	$G_{\rm SM}$	strings?
III6:	$\begin{array}{c} \stackrel{\mathrm{m,s}}{\longrightarrow} & 0 \\ 54 \end{array}$	$\mathcal{L}_{422}^{C} \frac{\mathrm{m,v}}{45}$	$\stackrel{V}{\rightarrow} G_{3221}$	$\xrightarrow{\mathrm{m}} G_{32}$	$11 \xrightarrow{\mathrm{s}} \\ \overline{126}$	✓	Ι	[V1: -	$\xrightarrow{\mathbf{m},\mathbf{s}} G_{42}^C$	$2 \frac{m}{210}$	$\rightarrow G^C_{322}$	$21 \xrightarrow{\text{W}} 45$	$G_{3221} - \frac{r}{4}$	$\xrightarrow{\mathrm{n}} G_{32}$	$211 \xrightarrow{\text{S}} 126$		\checkmark
III7:	$\xrightarrow{\mathrm{m,s}}$ $\overbrace{210}$	$\mathcal{G}_{3221}^C \frac{\mathrm{w}}{45}$	$\rightarrow G_{3221}$	$\xrightarrow{\mathrm{m}} G_{32}$	11 $\xrightarrow{s}{126}$			[V2: -	$\xrightarrow{\mathrm{m,s}} G_{42}^C$	$2 \frac{W}{210}$	$\rightarrow G_{422}$	$2 \xrightarrow{\text{m}} 2$	G_{3221} -	$\xrightarrow{\mathrm{n}} G_{32}$	$211 \xrightarrow{S}{S}$		\checkmark
III8:	$\xrightarrow{\mathrm{m}}$ C	$\tilde{f}_{422} \frac{m}{45}$	\rightarrow G_{3221}	$\xrightarrow{\text{III}} G_{32}$	11 $\xrightarrow{\mathbf{s}}$ 126			[V3: -	$\xrightarrow{\mathrm{m,s}} G^C_{42}$	$\frac{210}{2}$	$\rightarrow G_{A2'}$	$2 \xrightarrow{\mathbf{H}5} $	$G_{421} - \frac{1}{2}$	$\stackrel{\text{a}}{\to} G_{22}$	$\begin{array}{c} 126 \\ s \\ 11 \end{array} \xrightarrow{\mathrm{S}}$		
III9:	$\xrightarrow{\mathrm{III},\mathrm{S}}$ C	$\mathcal{G}_{422}^C \frac{\mathrm{m}}{45}$	$\rightarrow G_{421}$	$\xrightarrow{\mathrm{m}} G_{32}$	11 $\xrightarrow{s}{126}$	\checkmark			54 54	² 210	~ 422	45	4	5	$\overline{126}$		-
III1(): $\xrightarrow{\mathrm{m}}$ C	$\frac{1}{422} \frac{m}{45}$	$\rightarrow G_{421}$	$\xrightarrow{\mathrm{m}} G_{32}$	$11 \xrightarrow{\mathrm{s}} \\ 126$	✓											

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SO(10)	$\stackrel{\rm defect}{\longrightarrow}$	G_{2}	$\stackrel{\rm defect}{\longrightarrow}$	G_1	$\stackrel{\text{defect}}{\longrightarrow}$	Gon	Observable
50(10)	Higgs	02	Higgs	ΟŢ	Higgs	USM	strings?
II1:	$\stackrel{ m m}{\longrightarrow}$ 210	G_{422}	$rac{\mathrm{m}}{45}$	G_{3221}	$\xrightarrow{\mathrm{s}}$ $\overline{126}$		\checkmark
II2:	$\xrightarrow[54]{\mathrm{m,s}}$	G_{422}^{C}	$\stackrel{ m m}{\longrightarrow}$ 210	G_{3221}^{C}	$\xrightarrow{\overline{s,w}}{\overline{126}}$		×
II3:	$\xrightarrow{\mathrm{m,s}}$ 54	G_{422}^{C}	$\stackrel{\mathrm{m,w}}{\longrightarrow}$	G_{3221}	$\xrightarrow{S}{126}$		\checkmark
II4:	$\xrightarrow{\text{m,s}}{\textbf{210}}$	G_{3221}^{C}	$\stackrel{\mathrm{w}}{\longrightarrow}$ 45	G_{3221}	$\xrightarrow{S}{126}$		\checkmark
II5:	$\stackrel{ ext{m}}{\longrightarrow}$ 210	G_{422}	$\stackrel{\mathrm{m}}{\longrightarrow}$ 45	G_{421}	$\xrightarrow{S}{\overline{126}}$		\checkmark
II6:	$\stackrel{\mathrm{m,s}}{\longrightarrow}$	G_{422}^{C}	$rac{\mathrm{m}}{45}$	G_{421}	$\xrightarrow{S}{126}$		\checkmark
II7:	$\stackrel{\mathrm{m,s}}{\longrightarrow}$ 54	G_{422}^{C}	$\stackrel{ ext{w}}{ ext{210}}$	G_{422}	$\xrightarrow{\text{m}}$ $\xrightarrow{126}$ 45		×
II8:	$\xrightarrow{\mathrm{m}}$ 45	G_{3221}	$\xrightarrow{\mathrm{m}}$ 45	G_{3211}	$\xrightarrow{S}{126}$,	\checkmark
II9:	$\xrightarrow{\text{m,s}} 210$	G_{3221}^{C}	$\xrightarrow{\text{m,w}}$ 45	G_{3211}	$\xrightarrow{S}{\overline{126}}$		\checkmark
II10:	$\xrightarrow{\text{m}}$ 210	G_{422}	$\xrightarrow{\text{m}}$ 210	G_{3211}	$\xrightarrow{S}{126}$		\checkmark
II11:	$\xrightarrow{\text{m,s}}{54}$	G_{422}^{C}	$\xrightarrow{\text{m,w}} 210$	G_{3211}	$\xrightarrow{S}{126}$		\checkmark
II12:	$\xrightarrow{\mathrm{m}}{45}$	G_{421}	$\stackrel{ ext{m}}{ ext{45}}$	G_{3211}	$\xrightarrow{\text{S}}{126}$		\checkmark



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	CO(10)	defect	\mathcal{O}	defect	\mathcal{C}	Observable			SO(10)	$\stackrel{\rm defect}{\longrightarrow}$	G_2	$\stackrel{\rm defect}{\longrightarrow}$	G_1	$\stackrel{\rm defect}{\longrightarrow}$	GSM	Obser	vable			
	SO(10)	Higgs	G_1	Higgs	$G_{\rm SM}$	strings?				Higgs		Higgs	0.1	Higgs		strin	lgs?			
	T1·	\xrightarrow{m}	G_{22221}	\xrightarrow{S}					II1:	$\stackrel{ ext{in}}{ ext{210}}$	G_{422}	$rac{111}{45}$	G_{3221}	$\xrightarrow{3}{126}$		\				
	11.	45 ′	03221	$\overline{126}'$					II2:	$\xrightarrow{\mathrm{m,s}}$	G_{422}^{C}	$\xrightarrow{\mathrm{m}}$	G_{3221}^{C}	$\xrightarrow{s,w}$		X	,			
	I2:	$\begin{array}{c} \stackrel{\mathrm{III},\mathrm{S}}{\longrightarrow} \\ 210 \end{array}$	G_{3221}^{C}	$\xrightarrow{\text{S,W}}$ $\overline{126}$		×			II3:	$\xrightarrow{\text{m,s}}$	G_{422}^{C}	$\xrightarrow{\text{m,w}}$	G_{3221}	$\stackrel{126}{\longrightarrow}$		√	,			
	I3:	$\xrightarrow{\mathrm{m}}$	G_{421}	\xrightarrow{S}		\checkmark			II4:	$\xrightarrow{54}{\overset{\mathrm{m,s}}{\longrightarrow}}$	G_{3221}^{C}	$\begin{array}{c} 45 \\ \xrightarrow{\mathrm{W}} \end{array}$	G_{3221}	$\stackrel{126}{\underline{\hspace{0.5mm}}}{\overset{\mathrm{S}}{\longrightarrow}}$		1	•			
	I4:	$\xrightarrow{\text{m}}$	G_{422}	$\stackrel{ ext{126}}{ ext{m}}$		X	SO(10)	Higgs	II5:	$\begin{array}{c} 210 \\ \xrightarrow{\mathrm{m}} \\ 210 \end{array}$	G_{422}	$\begin{array}{c} 45 \\ \underline{\mathrm{m}} \\ 45 \end{array}$	G_{421}	$\begin{array}{c} 126 \\ \xrightarrow{\mathrm{S}} \\ \overline{126} \end{array}$		1	,			
	15.	$\xrightarrow{\text{m,s}}$	G^{C}_{122}	126,45 m,w	2	X			II6:	$\stackrel{\mathrm{m,s}}{\longrightarrow}$ 54	G_{422}^{C}	$\stackrel{ m m}{\longrightarrow}$ 45	G_{421}	$\xrightarrow{s}{\overline{126}}$		1	·			
	10.	54 ′ m	C 422	$\overline{126}, 45$	5				II7:	$\xrightarrow[54]{\mathrm{m,s}}$	G_{422}^{C}	$\stackrel{ ext{w}}{ ext{210}}$	G_{422}	$\xrightarrow{\text{m}} 126 45$		X	,			
	16:	$\stackrel{ ext{in}}{ ext{210}}$	G_{3211}	$\stackrel{ ightarrow}{\overline{126}}$					II8:	$\xrightarrow{\mathrm{m}}$ 45	G_{3221}	$\xrightarrow{\mathrm{m}}$ 45	G_{3211}	$\xrightarrow{S}{126}$		✓				
SO((10) $\xrightarrow{\text{defect}}$ C		$\stackrel{\text{fect}}{\to} G_2$	$\stackrel{\text{defect}}{\longrightarrow} C$	defec	$G_{\rm SM}$ Observat	ole		II9:	$\xrightarrow[]{\text{m,s}}{\textbf{210}}$	G_{3221}^{C}	$\stackrel{\mathrm{m,w}}{\longrightarrow}$ 45	G_{3211}	$\xrightarrow{s}{\overline{126}}$		✓	·			
TTT1-	$\xrightarrow{\text{m,s}} ($	$\gamma C = v$	$\stackrel{\text{Sgs}}{\longrightarrow} G_{400}$	$\xrightarrow{\text{m}}$ (γ				II10:	$\xrightarrow{\mathrm{m}}$	G_{422}	$\xrightarrow{\mathrm{m}}$	G_{3211}	$\xrightarrow{s}{120}$		\checkmark	•			
	54 m,s	2^{422} 21 γC V	10°	45 m	$\overline{126}$	•			II11:	$\xrightarrow{\text{m,s}}$	G^{C}_{422}	$\xrightarrow{\text{m,w}}$	G_{2211}	$\stackrel{126}{\longrightarrow}$,			
1112:		x_{422}^{\prime} 2 1	$\rightarrow G_{422}$	$rac{\longrightarrow}{45}$ ($\overrightarrow{3221} \xrightarrow{\overrightarrow{126}}$					$54^{'}$ m	C 422	210 m	C 3211	$\overline{126}_{\mathrm{S}}^{'}$						
III3:	$: \qquad \xrightarrow{\mathrm{III},\mathrm{S}} C$	$\begin{array}{cc} \widehat{\mathcal{F}}_{422}^C & \stackrel{\mathrm{v}}{=} \\ 2 \end{array}$	$\stackrel{\scriptstyle \scriptstyle V}{\longrightarrow} G_{422}$	$\frac{\mathrm{m}}{210}$ ($\overrightarrow{3211} \xrightarrow{\mathrm{s}} \overline{126}$				1112:	$\overrightarrow{45}$	G_{421}	$\overrightarrow{45}$	G_{3211}	$\stackrel{\longrightarrow}{\overline{126}}$		v				
III4:	$: \qquad \xrightarrow{\mathrm{m,s}} \qquad \overleftarrow{54}$	$r_{422}^C = \frac{n}{21}$	$\stackrel{\text{a}}{\longrightarrow} G^C_{3221}$	\xrightarrow{W} ($73221 \xrightarrow{\frac{1}{3}}{\frac{1}{3}}$				defect	defe	oct	de	fect	de	ofect		defect		Observ	vable
III5	$: \qquad \xrightarrow{\mathrm{m,s}} C$	$r_{422}^C = \frac{n}{21}$	$\stackrel{\text{n}}{\to} G^C_{3221}$	$\xrightarrow{\mathrm{m,w}}$ ($\gamma_{3211} \xrightarrow{s}{126}$			SO(10)	$\xrightarrow{\text{Higgs}} G_4$	Hig	$\stackrel{\sim}{\rightarrow} G_3$	Hi	$\stackrel{\text{recu}}{\longrightarrow} G$	$2 \frac{1}{12}$	$\xrightarrow{\text{iggs}}$ (G_1	$\stackrel{\text{defect}}{\longrightarrow}$ ($G_{\rm SM}$	strin	gs?
III6:	$: \qquad \xrightarrow{\mathrm{m,s}}{54} \qquad \mathcal{C}$	$rac{m}{f_{422}}$ $\frac{m}{4}$	$\xrightarrow{W} G_{3221}$	$\xrightarrow{\text{m}}$ ($\overrightarrow{3211} \xrightarrow{126}{3}$			IV1:	$\xrightarrow{\mathrm{m,s}} G_{42}^C$	$\frac{m}{2}$	$\rightarrow G_3^{()}$	$\frac{7}{221}$	$\xrightarrow{\mathrm{w}}$ G	3221 -	$\xrightarrow{\mathrm{m}}$ (G_{3211}	$\xrightarrow{\mathrm{S}}$		√	,
III7:	$ \begin{array}{ccc} & \xrightarrow{\mathrm{m,s}} \\ & \xrightarrow{\mathrm{m,s}} \\ & \xrightarrow{\mathrm{210}} \end{array} $	r_{3221}^{C}	$\xrightarrow{v}{5}$ G_{3221}	$\xrightarrow{\text{m}}$ ($\gamma_{3211} \xrightarrow{S}{120}$			IV3·	$\xrightarrow{\text{54}} C^C$	- 210 W	$\begin{array}{c} U \\ \to \\ C \end{array}$	4	$\stackrel{\text{H5}}{\longrightarrow} \bigcirc$	4 1 1 1 1 1 1 1 1 1 1	$ \stackrel{\text{15}}{\longrightarrow} \textbf{\ell} $	γ_{20011}	126 $\stackrel{\text{S}}{\longrightarrow}$,
III8	$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	$rac{1}{422}$	$\xrightarrow{n}{5} G_{3221}$	$\xrightarrow{\mathrm{m}}$ ($\gamma_{3211} \xrightarrow{s}{\frac{126}{125}}$				54 m,s ~C	22 21 w		נ∠∠ ז	45 () m ~	3221 4	45 ′ 、 m	\sim 3211	$\overline{126}'_{\mathrm{S}}$		•	,
III9:	$: \qquad \xrightarrow{\mathrm{m,s}} \qquad ($	$\mathcal{G}_{422}^C \stackrel{\text{a}}{}$	$\xrightarrow{n}{\mathfrak{s}} G_{421}$	$\xrightarrow{\mathrm{m}}$ ($73211 \xrightarrow{s}{126}$			IV3:	$\overrightarrow{54}$ G_{42}°	$22 \frac{1}{210}$	$\rightarrow G_4$	22 -4	\rightarrow G	421	$rac{1}{45}$ (<i>J</i> 3211	$\overrightarrow{126}$		_	
III1	$0: \frac{\overset{34}{\longrightarrow}}{210} 0$	$\begin{array}{c} 4\\ 3\\ 422 \end{array} \begin{array}{c} 1\\ -\\ 4 \end{array}$	$\stackrel{\text{a}}{\longrightarrow} G_{421}$	$\begin{array}{c} \overset{45}{\longrightarrow} & \mathbf{(} \\ \overset{\mathbf{m}}{45} & \mathbf{(} \end{array}$	$ \begin{array}{c} \begin{array}{c} \begin{array}{c} 126\\ s\\ \end{array}\\ 3211\\ \end{array}\\ \begin{array}{c} \begin{array}{c} \end{array}\\ \hline 126\\ \end{array}\\ \hline 126\\ \end{array} $															

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	CO(10)	defect	C	defect	Q	Observ	vable						Г		defect		defect		defect		Observable	٦
	SO(10)) Higgs	G_1	Higgs	$G_{\rm SM}$	strin	gs?							SO(10)	$) \xrightarrow{\text{defect}}_{\text{Higgs}}$	G_2	$\xrightarrow{\text{Higgs}}$	G_1	$\xrightarrow{\text{Higgs}}$	$G_{\rm SM}$	strings?	
	I1:	$\xrightarrow{\mathrm{m}}$	G_{3221}	\xrightarrow{s}		1								II1:	$\xrightarrow[]{\text{m}}{210}$	G_{422}	$\xrightarrow{\mathrm{m}}$ 45	G_{3221}	$\xrightarrow{\text{S}}$ 126		\checkmark	
	I2:	$\xrightarrow{\text{M},\text{S}}$	G^{C}_{2221}	$\stackrel{{\bf 126}}{\longrightarrow}$		x		If upw	anted	dofo	ct cr	roate	bd	II2:	$\xrightarrow[]{\text{m,s}}{\textbf{54}}$	G_{422}^{C}	$\stackrel{\mathrm{m}}{\longrightarrow}$ 210	G_{3221}^{C}	$\xrightarrow{\text{s,w}} \overline{126}$		×	
	10	210 m	⊂ <u>3221</u>	$\overline{126}$						uere				II3:	$\xrightarrow{\mathrm{m,s}}$ 54	G_{422}^{C}	$\xrightarrow{\mathrm{m,w}}$	G_{3221}	$\xrightarrow{s}{100}$		\checkmark	
	13:	$rac{11}{45}$	G_{421}	$\stackrel{\sim}{\overline{126}}$				in tina	I 22R =	$ \rightarrow $	no G	i VV		II4:	$\xrightarrow{\text{m,s}}$	G_{3221}^{C}	\xrightarrow{W}	G_{3221}	\xrightarrow{s}		\checkmark	
	I4:	$\xrightarrow{\mathrm{m}}$ 210	G_{422}	$\xrightarrow{\mathrm{m}}$ $\overrightarrow{126}$ 4^{p}	5	×		else G	VV					II5:	210 $\xrightarrow{\text{m}}$ 210	G_{422}	$\xrightarrow{\begin{array}{c} 45\\ m\\ \hline 45\end{array}}$	G_{421}	$\begin{array}{c} 126 \\ \xrightarrow{\mathrm{S}} \\ \hline 126 \end{array}$		\checkmark	
	I5:	$\xrightarrow{\mathrm{m,s}}$	G_{422}^{C}	$\xrightarrow{\text{m,w}}$		×								II6:	$\xrightarrow[\mathbf{m,s}]{54}$	G_{422}^{C}	$\xrightarrow{\mathrm{m}}{45}$	G_{421}	$ \xrightarrow{\text{S}} \overline{126} $		\checkmark	
	IG.	54 m	C	126,48	5									II7:	$\xrightarrow[54]{\mathrm{m,s}}$	G_{422}^{C}	$\stackrel{ ext{w}}{\longrightarrow}$ 210	G_{422}	$\xrightarrow{\text{m}}$ $\overrightarrow{126}$ 45		×	
	10.	$\overrightarrow{210}$	G3211	$\overrightarrow{126}$		V								II8:	$\xrightarrow{\mathrm{m}}$ 45	G_{3221}	$\xrightarrow{\mathrm{m}}$ 45	G_{3211}	$\xrightarrow{s}{\overline{126}}$		\checkmark	
SO($10) \stackrel{\text{defect}}{\longrightarrow} 0$	$G_3 \stackrel{\mathrm{def}}{=}_{\mathrm{Hig}}$	$\stackrel{\text{fect}}{\to} G_2$	$\stackrel{\text{defect}}{\longrightarrow} C$ Higgs	$ \vec{J}_1 \xrightarrow{\text{defec}}_{\text{Higgs}} $	$\stackrel{\mathrm{t}}{\simeq} G_{\mathrm{SM}}$	Observable strings?							II9:	$\xrightarrow[]{\text{m,s}}{\textbf{210}}$	G_{3221}^{C}	$\xrightarrow[]{\text{m,w}}{45}$	G_{3211}	$ \xrightarrow{\text{S}} \overline{126} $		\checkmark	
III1:	$\xrightarrow{\text{m,s}}$	$\overline{G^C_{422}}$ $\frac{\mathbf{v}}{\mathbf{v}}$	$\xrightarrow{v} G_{422}$	$\xrightarrow{\mathrm{m}}$ ($G_{421} \xrightarrow{s}$	•	<u>√</u>	_						II10:	$\stackrel{ m m}{\longrightarrow}$ 210	G_{422}	$\xrightarrow{\mathrm{m}}$ 210	G_{3211}	$\xrightarrow{s}{\overline{126}}$		\checkmark	
III2:	$\xrightarrow{\text{m,s}}^{54}$	$G_{422}^C = \frac{v}{21}$	$\stackrel{\text{v}}{\to} G_{422}$	$\xrightarrow{\text{m}}$ ($ \begin{array}{c} 126 \\ _{3221} \xrightarrow{\mathrm{s}} \end{array} $	•	√							II11:	$\xrightarrow{\mathrm{m,s}}{54}$	G^C_{422}	$\stackrel{\mathrm{m,w}}{\longrightarrow}$	G_{3211}	$\xrightarrow{s}{\overline{126}}$		\checkmark	
III3:	$egin{array}{c} {f 54} \ {f m,s} \ {f 54} \ {f 54} \end{array}$	$G_{422}^C = \frac{v}{21}$	$\stackrel{\text{lo}}{\longrightarrow} G_{422}$	$\begin{array}{c} 45 \\ \mathbf{\frac{m}{210}} \end{array} $	$ \begin{array}{c} \begin{array}{c} \begin{array}{c} 126\\ s\\ \end{array}\\ 3211 \end{array} \xrightarrow{s}\\ 126 \end{array} $		\checkmark							II12:	$\xrightarrow{\mathrm{m}}{45}$	G_{421}	$\xrightarrow{\mathrm{m}}$ 45	G_{3211}	$\xrightarrow[]{S}{126}$		\checkmark	
III4:	$rac{\mathrm{m,s}}{54}$ ($G_{422}^C = \frac{n}{21}$	$\stackrel{\text{a}}{\longrightarrow} G^C_{3221}$	$\frac{\mathrm{w}}{45}$ ($\widetilde{f}_{3221} \xrightarrow[]{s}{126}$	•	\checkmark			defect		defect		defect		defect		defe	ct	O	bservable	
III5:	$\xrightarrow{\mathrm{m,s}}$ ($G_{422}^C = \frac{n}{21}$	$\stackrel{\text{a}}{\longrightarrow} G^C_{3221}$	$\begin{array}{c} \xrightarrow{\mathrm{m,w}} & \mathbf{C} \\ 45 \end{array}$	$G_{3211} \xrightarrow[]{s}{126}$	•	\checkmark		SO(10)	\longrightarrow Higgs	G_4	\longrightarrow Higgs	G_3	Higgs	G_2	\longrightarrow Higgs	G_1	Higg	$\stackrel{\rightarrow}{}_{\mathrm{gs}} G_{\mathrm{SI}}$	M s	strings?	
III6:	$rac{\mathrm{m,s}}{54}$ ($G_{422}^C \frac{\mathrm{m}}{4}$	$\xrightarrow{\mathbf{w}} G_{3221}$	$\frac{\mathrm{m}}{45}$ ($\begin{array}{c} 3211 \\ \hline 126 \end{array}$	•	\checkmark		IV1:	$\xrightarrow{\text{m,s}} 54$	G_{422}^{C}	$\xrightarrow{\mathrm{m}}$ 210	G^{C}_{3221}	\xrightarrow{W}	G_{3221}	$\xrightarrow{\text{m}}$	G_{321}	$11 \frac{s}{100}$	\rightarrow		✓	
III7:	$\stackrel{\mathrm{m,s}}{\longrightarrow}$ ($G_{3221}^C \frac{v}{4}$	$\xrightarrow{v} G_{3221}$	$\frac{\mathrm{m}}{45}$ ($ \widehat{J}_{3211} \xrightarrow{\mathrm{s}} \overline{126} $	•	\checkmark		IV2:	$\xrightarrow{\mathrm{m,s}}$	G_{422}^{C}	\xrightarrow{W}	G_{422}	$\xrightarrow{\mathrm{m}}$	G_{3221}	$\xrightarrow{\mathrm{m}}$	G_{321}		\rightarrow		✓	
III8:	$\frac{\mathrm{m}}{210}$ ($G_{422} = \frac{n}{4}$	$\xrightarrow{n}{5} G_{3221}$	$\frac{m}{45}$ ($ \widehat{J}_{3211} \xrightarrow{\mathrm{s}} \overline{126} $	•	\checkmark		IV3·	$\stackrel{54}{\longrightarrow}$	G^{C}_{422}	$\begin{array}{c} 210 \\ \xrightarrow{\mathrm{W}} \end{array}$	G_{499}	$\stackrel{\textbf{45}}{\longrightarrow}$	G_{491}	$\begin{array}{c} 45 \\ \mathrm{m} \\ \longrightarrow \end{array}$	G_{201}	126	6 →		<u>,</u>	
III9:	$rac{\mathrm{m,s}}{54}$ ($G_{422}^C - \frac{n}{4}$	$\xrightarrow{n}{5} G_{421}$	$\frac{\mathrm{m}}{45}$ ($ \widehat{f}_{3211} \xrightarrow{\mathrm{s}} \overline{126} $	•	\checkmark			54	₩422	$210^{'}$	₩422	45	₩421	$45^{'}$	₩ 32]	$11 \overline{126}$	<u>;</u>		▼	J
III10	$\therefore \frac{\mathrm{m}}{210} 0$	$G_{422} = \frac{n}{4}$	$\xrightarrow{n} G_{421}$	$\begin{array}{c} { m m} { m \overline{45}} \end{array} \qquad \qquad$	$ \widehat{J}_{3211} \xrightarrow{s}{126} $	•	✓															

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Assume minimal survival hypothesis



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Assume minimal survival hypothesis



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- Assume minimal survival hypothesis
- intermediate breaking scales (see backup details)

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• Perform two-loop RGE analysis to determine GUT scale (i.e. proton decay rate) in terms

Breaking chains allowed by Super-K: IV2 & IV3

IV2 : SO (10) $\xrightarrow{M_X} G_{422}^C \xrightarrow{M_4} G_{422} \xrightarrow{M_3} G_{3221} \xrightarrow{M_2} G_{3211} \xrightarrow{M_1} G_{SM}$ IV3 : SO(10) $\xrightarrow{M_X} G_{422}^C \xrightarrow{M_4} G_{422} \xrightarrow{M_3} G_{421} \xrightarrow{M_2} G_{3211} \xrightarrow{M_1} G_{SM}$

Regions due to more free parameters

10¹⁷

- RGE provide information on GUT but also intermediate scale breaking.
- For type (c) chains an observable GW signal is produced in the final SSB.
- We assume Nambu-Goto string \implies gravitational radiation primary emission.

• Determine M_1 we can determine when cosmic string formed \implies string tension

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Summary

- non-SUSY SO(10) Pati Salam type provide unification: **31 breaking chains**

Two-loop RGE, 17 not excluded by Super-K lower bound PD.

Chain	$G\mu$ after Hyper-K (no prot	on decay)
I1	excluded	
II1:	$G\mu \lesssim 1.5 \times 10^{-17}$	
II3:	excluded	
II4:	excluded	
II5:	$G\mu \simeq 5.1 \times 10^{-18} - 6.3 \times$	$\times 10^{-17}$
II8:	excluded	
III1:	$G\mu \simeq 1.3 \times 10^{-18} 1.6 \times$	(10^{-15})
III2:	$G\mu \lesssim 5.0 imes 10^{-12}$	
III3:	$G\mu \lesssim 6.2 imes 10^{-14}$	
III4:	excluded	Festable by LIGO ,
III6:	excluded	DECIGO, AEDGE,
III7:	excluded	C, ET, MAGIS
III8:	excluded	
III10:	$G\mu \lesssim 1.1 \times 10^{-21}$	
IV1:	excluded	
IV2:	$G\mu \lesssim 9.4 \times 10^{-13}$	
IV3:	$G\mu \lesssim 9.4 \times 10^{-13}$	

rovide unification: **31 breaking chains** uper-K lower bound PD.

If HyperK **does not** observe PD, 9 chains excluded

8 survivors! If we observe GW signal from cosmic string larger upper bounds (see table) we can exclude those breaking chains

If we observe PD, M_1 determined and so is GW signal. Correlations matters!

will probe the ultrahigh GUT scale determination of the proton lifetime.

- cosmic strings are "well behaved" and can generate GW.
- The presence/absence and nature is determined by the inflationary scale.
- key.

Summary

Proton decay is a smoking gun of GUTs and the next generation of neutrino oscillation experiments

• Topological defects are prodigiously produced during GUT symmetry breaking. The undesirable kind are monopoles and domain walls which, if existent, must have been inflated away. As defects

 Non-observation is useful and can exclude many GUT breaking chains. Naturally observation would be more exciting in which case correlation between terrestrial and cosmological observables is

Part I ends Part II begins

Matter-antimatter asymmetry

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Standard Model is an effective theory which contains non-renormalisable operators

 $\mathcal{L} \supset -Y_{ij} \frac{L^i H L^j H}{2M} + \mathcal{O}\left(\frac{1}{M^2}\right) + \text{h.c}$

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After SSB a Majorana mass is produced for the active neutrinos

 \mathcal{N}

Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic

> Magg, Wetterich, Lazarides, Shafi. Mohapatra, Senjanovic, Schecter, Valle

H...

H

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<u>Weinberg, 1979</u>

After SSB a Majorana mass is produced for the active neutrinos

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<u>Weinberg, 1979</u>

Schecter, Valle

 $\mathcal{L} \supset -L_{\alpha}Y_{\alpha i}N_{i}F$

After diagonalising the mass mat

$$\tilde{H} - \frac{1}{2} \overline{N_i^C} M_{N_i} N_i + \text{h.c.}$$

$$\operatorname{trix} \qquad m_{\nu} \approx \frac{m_D m_D^T}{M_N} = \frac{Y^2 v^2}{M_N}$$

Sakharov's Conditions

Departure from thermal equilibrium

Fukugita, Yanagida

Thermal leptogenesis

Thermal leptogenesis

lepton asymmetry

Thermal leptogenesis

B-L conserving sphaleron processes

lepton asymmetry

Decay asymmetry from interference between tree and loop level diagrams

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Thermal leptogenesis

Washout and scattering processes

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Thermal leptogenesis

Work in collaboration with Yuber Perez Gonzalez: 2010.03565

Astrophysical BHs require $M > 3M_{\odot}$ For smaller BH mass require large perturbations in the early Universe : bubble collision, collapse of density perturbations...

PBHs evaporate by emitting thermal spectrum of particles **Hawking**, **1975**

$$\frac{dM}{dt} = -\sum_{a} \frac{g_a}{2\pi^2} \int_0^\infty \frac{\sigma_{\rm abs}^{s_a}(GMp) \, p^3 \, dp}{\exp[E_a(p)/T_{\rm BH}] - (-1)^{2s_a}} \qquad T_{\rm BH} = \frac{1}{8\pi GM} \approx 1.06 \left(\frac{10^{13} \text{ g}}{M}\right) \, G_{\rm BH}$$

PBHs are totally indiscriminate in their particle production: just need T_{BH} to be close to particle mass

Carr et al (0912.5297)

$$aH\frac{dn_{\alpha\beta}^{\mathrm{B-L}}}{da} = \epsilon_{\alpha\beta}^{(1)} \left[\left(n_{N_1} - n_{N_1}^{\mathrm{eq}} \right) \Gamma_{N_1}^T + n_{\mathrm{BH}} \widetilde{\Gamma}_{N_1}^{\mathrm{BH}} \right] - \mathcal{W}_{\alpha}$$

$$aH\frac{dn_{\alpha\beta}^{\mathrm{B-L}}}{da} = \epsilon_{\alpha\beta}^{(1)} \left[\left(n_{N_1} - n_{N_1}^{\mathrm{eq}} \right) \Gamma_{N_1}^T + n_{\mathrm{BH}} \widetilde{\Gamma}_{N_1}^{\mathrm{BH}} \right] - \mathcal{W}_{\alpha}$$

$$aH\frac{dn_{\alpha\beta}^{\mathrm{B-L}}}{da} = \epsilon_{\alpha\beta}^{(1)} \left[\left(n_{N_1} - n_{N_1}^{\mathrm{eq}} \right) \Gamma_{N_1}^T + n_{\mathrm{BH}} \widetilde{\Gamma}_{N_1}^{\mathrm{BH}} \right] - \mathcal{W}_{\alpha}$$

A. PBH evaporate **before/during** RHNs are thermally produced from plasma \rightarrow PBH evaporation creates an initial condition which gets erased by fast interactions in the plasma

B. PBH evaporation happens **shortly after** thermal leptogenesis

$$M_i = 1.7 \,\mathrm{g} \quad \beta_i = 10^{-3} \quad M_N = 10^{11}$$

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- creates an initial condition which gets erased by fast interactions in the plasma
- B. PBH evaporation happens **shortly after** thermal leptogenesis

A. PBH evaporate **before/during** RHNs are thermally produced from plasma \rightarrow PBH evaporation

$$M_i = 1.7 \,\mathrm{g} \quad \beta_i = 10^{-3} \quad M_N = 10^{11}$$

- creates an initial condition which gets erased by fast interactions in the plasma

A. PBH evaporate **before/during** RHNs are thermally produced from plasma \rightarrow PBH evaporation

B. PBH evaporation happens shortly after thermal leptogenesis $M_i = 1.7 \text{ g}$ $\beta_i = 10^{-3}$ $M_N = 10^{11} \text{ GeV}$

D. PBH evaporation occurs way after thermal leptogenesis era

$$M_i = 10^4 \,\mathrm{g} \quad \beta_i = 10^{-3} \quad M_N = 10^{-3}$$

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D. PBH evaporation occurs way after thermal leptogenesis era

$$M_i = 10^4 \,\mathrm{g} \quad \beta_i = 10^{-3} \quad M_N = 10^{-3}$$

Chose Yukawa matrix for maximal baryon asymmetry

Smaller PBH evaporate earlier and experience more redshift

GW spectrum produced directly from PBHs very high frequency.

Interesting proposal to detect GHz GWs via microwave cavity Berlin et al (2112.11465)

We could potentially observe GWs from curvature perturbations: PBH's $\approx 10 - 1000 \, \text{kg}$ GW detectable by LIGO & DECIGO (Papanikolaou et al, 2010.11573, Domenech et al **2012.08151**)

- Leptogenesis is one of the leading explanations of the matter anti-matter asymmetry. Added bonus is that light neutrino masses are also explained.
- It is entirely feasible the Universe underwent some non-standard cosmology such as **PBH** domination
- Due to the democratic nature of PBH, all particle degrees of freedoms are produced if the PBH is sufficiently hot.
- Non-trivial interplay between leptogenesis era and PBH evaporation. PBHs heavier than O(1) kg dilute baryon asymmetry of intermediate-scale leptogenesis.
- While thermal leptogenesis is a very scale mechanism and therefore difficult to test, future probes of GWs could falsify the certain regimes of leptogenesis.

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Arigato gozaimasu!

H

П

Beta function coefficients 1 and 2-loop respectively

$$b_{i} = -\frac{11}{3}C_{2}(H_{i}) + \frac{2}{3}\sum_{F}T(F_{i}) + \frac{1}{3}\sum_{S}T(S_{i}),$$

$$b_{ij} = -\frac{34}{3}[C_{2}(H_{i})]^{2}\delta_{ij} + \sum_{F}T(F_{i})[2C_{2}(F_{j}) + \frac{10}{3}C_{j}]$$

Two-loop RGE equation

$$\alpha_i(\mu)^{-1} = \alpha_i(\mu_0)^{-1} - \frac{b_i}{2\pi} \log \frac{\mu}{\mu_0} + \sum_j \frac{b_{ij}}{4\pi b_i} \log \left(1 - b_j \alpha_j(\mu_0) \log \frac{\mu}{\mu_0}\right) \,,$$

Matching condition

$$H_i \to H_j$$
, $\frac{1}{\alpha_{H_i}(M_I)} - \frac{C_2(1)}{12}$

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RGE

$$C_2(H_i)\delta_{ij}] + \sum_S T(S_i)[4C_2(S_j) + \frac{2}{3}C_2(H_i)\delta_{ij}],$$

 $\frac{C_2(H_i)}{12\pi} = \frac{1}{\alpha_{H_j}(M_I)} - \frac{C_2(H_j)}{12\pi} \,.$

 $II2: SO(10) \xrightarrow{M_X} G_{422}^C \xrightarrow{M_2} G_{3221}^C \xrightarrow{M_1} G_{SM}$

Intersection of M2 and Mx reduces II2 to I2

I2 : $SO(10) \rightarrow G_{3221}^C \rightarrow G_{SM}$

 $M_X \equiv M_2$

At right side blue curve

 $M_2 \equiv M_1$

II2 becomes I5

I5 : $SO(10) \rightarrow G_{422}^C \rightarrow G_{SM}$

$$\begin{split} \epsilon^{ijk} \epsilon_{\alpha\beta} \Big(\frac{1}{\Lambda_1^2} (\overline{u_R^{jc}} \gamma^{\mu} Q_{\alpha}^k) (\overline{d_R^{ic}} \gamma_{\mu} L_{\beta}) + \frac{1}{\Lambda_1^2} (\overline{u_R^{jc}} \gamma^{\mu} Q_{\alpha}^k) (\overline{e_R^c} \gamma_{\mu} Q_{\beta}^i) \\ + \frac{1}{\Lambda_2^2} (\overline{d_R^{jc}} \gamma^{\mu} Q_{\alpha}^k) (\overline{u_R^{ic}} \gamma_{\mu} L_{\beta}) + \frac{1}{\Lambda_2^2} (\overline{d_R^{jc}} \gamma^{\mu} Q_{\alpha}^k) (\overline{\nu_R^c} \gamma_{\mu} Q_{\beta}^i) + \text{h.c.} \Big) \,, \end{split}$$

$$\Gamma(p \to \pi^0 + e^+) = \frac{m_p}{32\pi} \left(1 - \frac{m_{\pi^0}^2}{m_p^2} \right)^2 A_L^2 \times \left[A_{SL} \Lambda_1^{-2} (1 + |V_{ud}|^2) \left| \langle \pi^0 | (ud)_R u_L | p \rangle \right|^2 + A_{SR} (\Lambda_1^{-2} + |V_{ud}|^2 \Lambda_2^{-2}) \left| \langle \pi^0 | (ud)_L u_L | p \rangle \right|^2 \right],$$

$$A_{SL(R)} = \prod_{A}^{M_Z \leqslant M_A \leqslant M_X} \prod_{i} \left[\frac{\alpha_i(M_{A+1})}{\alpha_i(M_A)} \right]^{\frac{\gamma_{iL(R)}}{b_i}} ,$$

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$$\Lambda_1 = \Lambda_2 \simeq \left(g_X M_X\right)/2$$

Example of correlation of string parameter with lowest intermediate scale / GW scale M1

$$G_{3211} \to G_{\rm SM}$$

$$U(1)_R \times U(1)_X \xrightarrow{M_1} U(1)_Y$$

 $M_1^2 \simeq 4\pi (\alpha_{1R}(M_1) + \alpha_{1X}(M_1))v^2 \qquad G\mu \simeq \frac{1}{2(\alpha_{1R}(M_1) + \alpha_{1X}(M_1))} \frac{M_1^2}{M_{\rm pl}^2}$ Gauge boson mass squared

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 $M_{N_1} = 10^{11} \text{ GeV}$ 10-2 - $|\eta_B|$ 10-4 PBH Domination 10-6 β 10-8 10^{-10} - 10^{2} 10^{3} 10^{4} 10^{-1} 10^{0} 10^{5} 10^{1} M_i [g]

Dilution effect present as long as there is PBH domination

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 $M_{N_1} = 10^8 \text{ GeV}$

System of equations

$$\frac{dM}{dt} = -\sum_{a} \frac{g_a}{2\pi^2} \int_0^\infty \frac{\sigma_{abs}^{s_a}(GMp) p^3 dp}{\exp[E_a(p)/T_{BH}] - (-1)^{2s_a}}$$
$$= -\kappa \varepsilon(M) \left(\frac{1 \text{ g}}{M}\right)^2$$
$$\varepsilon(M) = \varepsilon_{SM}(M) + \varepsilon_N(M)$$
$$\varepsilon_N(M) \approx 2 n_{N_i} f_{1/2}^0 \sum_{i=1}^{n_{N_i}} \exp\left[-\frac{8\pi GMM_{N_i}}{4.53}\right]$$

System of equations

66

