Tracking Down the Route to the SM with Inflation and Gravitational Waves

EJ. Chun[1] *L. Velasco-Sevilla*[1,2]

[1]Korea Institute for Advanced Study, Seoul 02455, Korea

[2]Department of Physics and Technology, University of Bergen, PO Box 7803, 5020 Bergen, Norway

PASCOS 2021

Outline

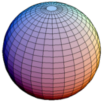
Motivation

1. LHC will not discern many LOW energy signatures of GUT models
2. Instead Gravitational Wave experiments can discern many models from each other
3. GUT have many predictions
   - 3.1 Gauge Coupling Unification, Proton Decay, etc.
   - 3.2 Topological Defects: Monopoles, Cosmic Strings, Domain Walls *(Intense Research in the last three years)*

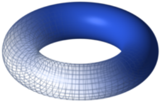
   Can we really distinguish models (uncertainties, Model Building fine-tuning) ?

Discerning SO(10) Models according their Topological Defects

Topological Defects are a measure of Homotopy Groups



$\pi(S^2) = 0$, No defect



$\pi(T \approx \mathbb{R}^2/\mathbb{Z}^2) = \mathbb{Z}^2$

Quasi-Complete Classification of GUT models according to their Topological Defects

Jeannerot, Rocher, Sakellariadou, ph/0308134

following T. W. B. Kibble, “Topology of Cosmic Domains and Strings”, J. Phys. A, vol. 9, pp. 1387-1398, 1976.

1 $\rightarrow$ Monopoles, 2 $\rightarrow$ Cosmic Strings, 3 $\rightarrow$ Domain Walls

$$
\mathrm{SO(10)} \begin{cases}
\xrightarrow{1} \; 5\;1_{\mathrm{V}} \begin{cases}
\xrightarrow{2\;(2)} \; 5\;(Z_2) \xrightarrow{1} \mathrm{G_{SM}}\;(Z_2) \\
\xrightarrow{1} \; 3_{\mathrm{C}}\;2_{\mathrm{L}}\;1_{\mathrm{Z}}\;1_{\mathrm{V}} \xrightarrow{2\;(2)} \mathrm{G_{SM}}\;(Z_2) \\
\xrightarrow{1,2\;(1,2)} \; \mathrm{G_{SM}}\;(Z_2)
\end{cases} \\
\xrightarrow{1} \; 5_{\mathrm{F}}\;1_{\mathrm{V}} \xrightarrow{2'\;(2)} \mathrm{G_{SM}}\;(Z_2) \\
\xrightarrow{0\;(2)} \; 5\;(Z_2) \xrightarrow{1} \mathrm{G_{SM}}\;(Z_2)
\end{cases}
$$

$$
\mathrm{SO}(10)\begin{cases}
\xrightarrow{1} & 4_\mathrm{C}\ 2_\mathrm{L}\ 2_\mathrm{R} & \longrightarrow & \\
\xrightarrow{1,2} & 4_\mathrm{C}\ 2_\mathrm{L}\ 2_\mathrm{R}\ Z_2^\mathrm{C} & \longrightarrow & \\
\xrightarrow{1,2} & 4_\mathrm{C}\ 2_\mathrm{L}\ 1_\mathrm{R}\ Z_2^\mathrm{C} & \longrightarrow & \cdots \\
\xrightarrow{1} & 4_\mathrm{C}\ 2_\mathrm{L}\ 1_\mathrm{R} & \longrightarrow & \cdots \\
\xrightarrow{1,2} & 3_\mathrm{C}\ 2_\mathrm{L}\ 2_\mathrm{R}\ 1_\mathrm{B-L}\ Z_2^\mathrm{C} & \longrightarrow & \cdots \\
\xrightarrow{1} & 3_\mathrm{C}\ 2_\mathrm{L}\ 2_\mathrm{R}\ 1_\mathrm{B-L} & \longrightarrow & \cdots \\
\xrightarrow{1} & 3_\mathrm{C}\ 2_\mathrm{L}\ 1_\mathrm{R}\ 1_\mathrm{B-L} & \xrightarrow{2\ (2)} & \mathrm{G}_\mathrm{SM}\ (Z_2) \\
\xrightarrow{1\ (1,2)} & \mathrm{G}_\mathrm{SM}\ (Z_2) & &
\end{cases}
$$

$$
4_\mathrm{C}\ 2_\mathrm{L}\ 2_\mathrm{R}\begin{cases}
\xrightarrow{1}\ 3_\mathrm{C}\ 2_\mathrm{L}\ 2_\mathrm{R}\ 1_\mathrm{B-L} \begin{cases} \xrightarrow{1}\ 3_\mathrm{C}\ 2_\mathrm{L}\ 1_\mathrm{R}\ 1_\mathrm{B-L} \xrightarrow{2\ (2)} \mathrm{G}_\mathrm{SM}\ (Z_2) \\ \xrightarrow{2'\ (2)}\ \mathrm{G}_\mathrm{SM}\ (Z_2) \end{cases} \\
\xrightarrow{1}\ 4_\mathrm{C}\ 2_\mathrm{L}\ 1_\mathrm{R} \begin{cases} \xrightarrow{1}\ 3_\mathrm{C}\ 2_\mathrm{L}\ 1_\mathrm{R}\ 1_\mathrm{B-L} \xrightarrow{2\ (2)} \mathrm{G}_\mathrm{SM}\ (Z_2) \\ \xrightarrow{2'\ (2)}\ \mathrm{G}_\mathrm{SM}\ (Z_2) \end{cases} \\
\xrightarrow{1}\ 3_\mathrm{C}\ 2_\mathrm{L}\ 1_\mathrm{R}\ 1_\mathrm{B-L} \xrightarrow{2\ (2)} \mathrm{G}_\mathrm{SM}\ (Z_2) \\
\xrightarrow{1\ (1,2)}\ \mathrm{G}_\mathrm{SM}\ (Z_2)
\end{cases}
$$

$$
4_\mathrm{C}\ 2_\mathrm{L}\ 2_\mathrm{R}\ Z_2^\mathrm{C}\begin{cases}
\xrightarrow{1}\ 3_\mathrm{C}\ 2_\mathrm{L}\ 2_\mathrm{R}\ 1_\mathrm{B-L}\ Z_2^\mathrm{C} \begin{cases} \xrightarrow{3}\ 3_\mathrm{C}\ 2_\mathrm{L}\ 2_\mathrm{R}\ 1_\mathrm{B-L} \longrightarrow \cdots \\ \xrightarrow{1,3}\ 3_\mathrm{C}\ 2_\mathrm{L}\ 1_\mathrm{R}\ 1_\mathrm{B-L} \xrightarrow{2\ (2)} \mathrm{G}_\mathrm{SM}\ (Z_2) \\ \xrightarrow{2',3\ (2,3)}\ \mathrm{G}_\mathrm{SM}\ (Z_2) \end{cases} \\
\xrightarrow{1}\ 4_\mathrm{C}\ 2_\mathrm{L}\ 1_\mathrm{R}\ Z_2^\mathrm{C} \begin{cases} \xrightarrow{3}\ 4_\mathrm{C}\ 2_\mathrm{L}\ 1_\mathrm{R} \longrightarrow \cdots \\ \xrightarrow{1,3}\ 3_\mathrm{C}\ 2_\mathrm{L}\ 1_\mathrm{R}\ 1_\mathrm{B-L} \xrightarrow{2\ (2)} \mathrm{G}_\mathrm{SM}\ (Z_2) \\ \xrightarrow{3\ (2,3)}\ \mathrm{G}_\mathrm{SM}\ (Z_2) \end{cases} \\
\xrightarrow{3}\ 4_\mathrm{C}\ 2_\mathrm{L}\ 2_\mathrm{R} \longrightarrow \text{Eq. (4.10)} \\
\xrightarrow{1}\ 4_\mathrm{C}\ 2_\mathrm{L}\ 1_\mathrm{R} \longrightarrow \cdots \\
\xrightarrow{1,3}\ 3_\mathrm{C}\ 2_\mathrm{L}\ 2_\mathrm{R}\ 1_\mathrm{B-L} \longrightarrow \cdots \\
\xrightarrow{1,3}\ 3_\mathrm{C}\ 2_\mathrm{L}\ 1_\mathrm{R}\ 1_\mathrm{B-L} \xrightarrow{2\ (2)} \mathrm{G}_\mathrm{SM}\ (Z_2) \\
\xrightarrow{1,3\ (1,2,3)}\ \mathrm{G}_\mathrm{SM}\ (Z_2).
\end{cases}
$$

A sample of models studied in the literature

$$SO(10) \xrightarrow[54]{M_{\rm GUT}} \left(SU(4)_C \times SU(2)_L \times SU(2)_R\right)/Z_2 \times Z_2^C \xrightarrow[126]{M_{\rm R}} G_{SM} \xrightarrow[10]{M_{\rm EW}} G_{SU(3)_C \times U(1)_Y},$$

$$SO(10) \xrightarrow[126]{M_{\rm GUT}} SU(5) \times Z_2 \xrightarrow[45]{M_{\rm R}} G_{SM} \xrightarrow[10]{M_{\rm EW}} G_{SU(3)_C \times U(1)_Y},$$

$$SO(10) \xrightarrow[16]{M_{\rm GUT}} SU(5) \xrightarrow[45]{M_{\rm R}} G_{SM} \xrightarrow[10]{M_{\rm EW}} G_{SU(3)_C \times U(1)_Y},$$

$$SO(10) \xrightarrow[210,126,\overline{126}]{M_{\rm GUT}} SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \xrightarrow[16]{M_{\rm GUT}} G_{SM} \xrightarrow[10]{M_{\rm EW}} G_{SU(3)_C \times U(1)_Y},$$

$$SO(10) \xrightarrow[210,126,\overline{126}]{M_{\rm GUT}} SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L} \xrightarrow[16]{M_{\rm GUT}} G_{SM} \xrightarrow[10]{M_{\rm EW}} G_{SU(3)_C \times U(1)_Y},$$

$$SO(10) \xrightarrow[210]{M_{\rm GUT}} SU(4)_C \times SU(2)_L \times SU(2)_R \times Z_2^C \xrightarrow[210]{M_{\rm In}} SU(3)_C \times SU(2)_L \times SU(2)_R \times Z_2^C \xrightarrow[\overline{126}]{M_{\rm B-L}} G_{\rm SM}$$

A sample of models studied in the literature

Kibble, Lazarides, Shafi, Phys. Rev. D 26, 1982

$$SO(10) \quad \xrightarrow[54]{M_{\rm GUT}} \left(SU(4)_C \times SU(2)_L \times SU(2)_R\right)/Z_2 \times Z_2^C \xrightarrow[126]{M_{\rm R}} G_{SM} \xrightarrow[10]{M_{\rm EW}} G_{SU(3)_C\times U(1)_Y}$$

$$SO(10) \quad \xrightarrow[126]{M_{\rm GUT}} SU(5) \times Z_2 \xrightarrow[45]{M_{\rm R}} G_{SM} \xrightarrow[10]{M_{\rm EW}} G_{SU(3)_C\times U(1)_Y},$$

$$SO(10) \quad \xrightarrow[16]{M_{\rm GUT}} SU(5) \xrightarrow[45]{M_{\rm R}} G_{SM} \xrightarrow[10]{M_{\rm EW}} G_{SU(3)_C\times U(1)_Y},$$

$$SO(10) \quad \xrightarrow[210,126,\overline{126}]{M_{\rm GUT}} SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \xrightarrow[16]{M_{\rm GUT}} G_{SM} \xrightarrow[10]{M_{\rm EW}} G_{SU(3)_C\times U(1)_Y},$$

$$SO(10) \quad \xrightarrow[210,126,\overline{126}]{M_{\rm GUT}} SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L} \xrightarrow[16]{M_{\rm GUT}} G_{SM} \xrightarrow[10]{M_{\rm EW}} G_{SU(3)_C\times U(1)_Y},$$

$$SO(10) \quad \xrightarrow[210]{M_{\rm GUT}} SU(4)_C \times SU(2)_L \times SU(2)_R \times Z_2^C \xrightarrow[210]{M_{\rm In}} SU(3)_C \times SU(2)_L \times SU(2)_R \times Z_2^C \xrightarrow[\overline{126}]{M_{\rm B-L}} G_{\rm SM}$$

Chakrabortty, Lazarides, Maji, Shafi, 2011.01838

A sample of models studied in the literature

$$SO(10) \xrightarrow[54]{M_{\text{GUT}}} (SU(4)_C \times SU(2)_L \times SU(2)_R)/Z_2 \times Z_2^C \xrightarrow[126]{M_{\text{R}}} G_{SM} \xrightarrow[10]{M_{\text{EW}}} G_{SU(3)_C \times U(1)_Y},$$

$$SO(10) \xrightarrow[126]{M_{\text{GUT}}} SU(5) \times Z_2 \xrightarrow[45]{M_{\text{R}}} G_{SM} \xrightarrow[10]{M_{\text{EW}}} G_{SU(3)_C \times U(1)_Y},$$

$$SO(10) \xrightarrow[16]{M_{\text{GUT}}} SU(5) \xrightarrow[45]{M_{\text{R}}} G_{SM} \xrightarrow[10]{M_{\text{EW}}} G_{SU(3)_C \times U(1)_Y},$$

$$SO(10) \xrightarrow[210,126,\overline{126}]{M_{\text{GUT}}} SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \xrightarrow[16]{M_{\text{GUT}}} G_{SM} \xrightarrow[10]{M_{\text{EW}}} G_{SU(3)_C \times U(1)_Y},$$

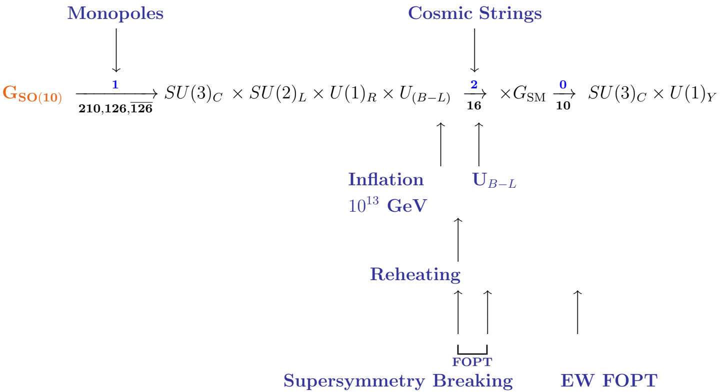
$$SO(10) \xrightarrow[210,126,\overline{126}]{M_{\text{GUT}}} SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L} \xrightarrow[16]{M_{\text{GUT}}} G_{SM} \xrightarrow[10]{M_{\text{EW}}} G_{SU(3)_C \times U(1)_Y},$$

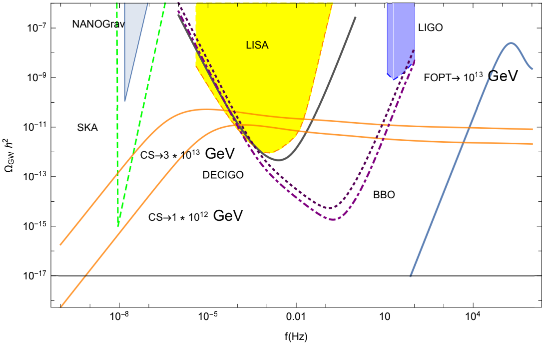
$$SO(10) \xrightarrow[210]{M_{\text{GUT}}} SU(4)_C \times SU(2)_L \times SU(2)_R \times Z_2^C \xrightarrow[210]{M_{\text{In}}} SU(3)_C \times SU(2)_L \times SU(2)_R \times Z_2^C \xrightarrow[\overline{126}]{M_{\text{B-L}}} G_{\text{SM}}$$

$$SO(10) \xrightarrow[210,126,\overline{126}]{M_{\mathrm{GUT}}} SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L} \xrightarrow[16]{M_{\mathrm{GUT}}} G_{SM}$$

$$\xrightarrow[10]{M_{\mathrm{EW}}} G_{SU(3)_C \times U(1)_Y},$$

One model of Olive et al. 2009.01709 with Starobinksy-like inflation

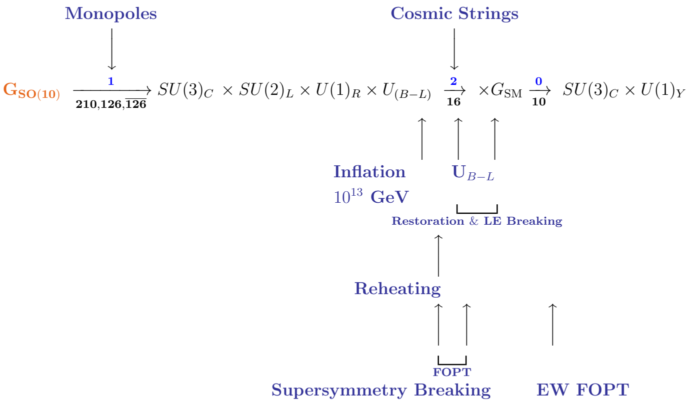


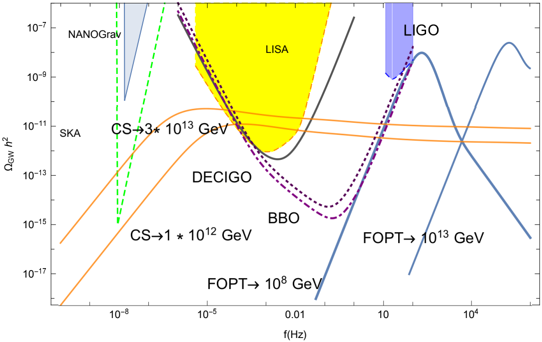

NANOGrav
LISA
LIGO
FOPT→ 10^{13} GeV
SKA
CS→3 * 10^{13} GeV
DECIGO
BBO
CS→1 * 10^{12} GeV
$\Omega_{GW}\, h^2$
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-8}
10^{-5}
0.01
10
10^4
f(Hz)

Variation Following Khalil and Sil, 1108.1973 with Chaotic inflation

$$SO(10) \xrightarrow[210,126,\overline{126}]{M_{\rm GUT}} SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L} \xrightarrow[16]{M_{\rm GUT}} G_{SM}$$

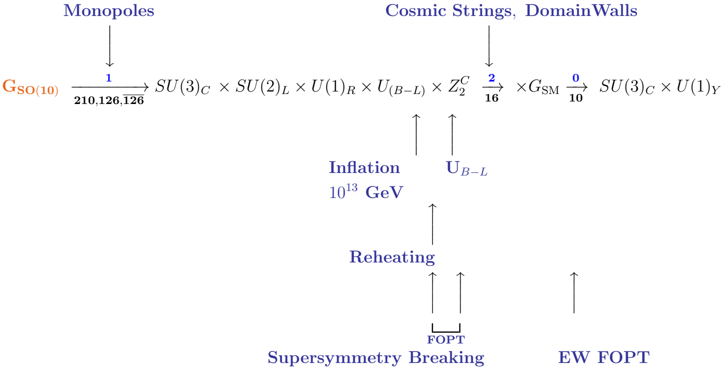
$$\xrightarrow[10]{M_{\rm EW}} G_{SU(3)_C \times U(1)_Y},$$

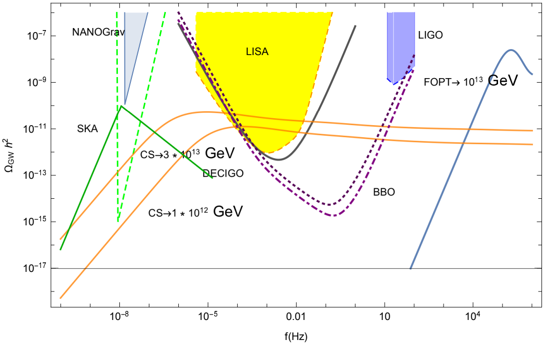



NANOGrav
SKA
LISA
LIGO
DECIGO
BBO
CS→3 * 10^{13} GeV
CS→1 * 10^{12} GeV
FOPT→ 10^{13} GeV
FOPT→ 10^{8} GeV
$\Omega_{GW} h^2$
f(Hz)
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-8}
10^{-5}
0.01
10
10^{4}

Variation with Low Energy Domain walls

Possible when introducing a bias parameter (which renders approximate a symmetry)



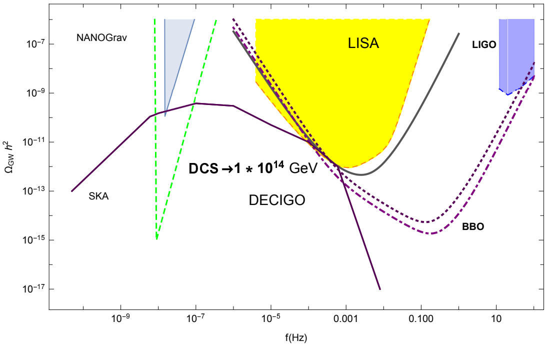


Very extreme case of DW annihilation Temperature of 0.1 GeV

$$SO(10) \xrightarrow[210]{M_{\rm GUT}} SU(4)_C \times SU(2)_L \times SU(2)_R \times Z_2^C \xrightarrow[210]{M_{\rm In}}$$
$$SU(3)_C \times SU(2)_L \times SU(2)_R \times Z_2^C \xrightarrow[\overline{126}]{M_{\rm B-L}} G_{\rm SM}$$

Chakrabortty, Lazarides, Maji, Shafi, 2011.01838

CS appear before inflation



Summary/ Outlook: Computational Improvements

1. Rather than a general analysis we focus on models that have been developed and satisfy phenomenological constraints
2. Possible to discern models from each other but need to improve both theoretical calculations
   - 2.1 For example, as far as theoretical uncertainties from model building we have

	Uncertainty (A)	Uncertainty (B)
Cosmic String	30%	30%
FOPT		
β	15%	30%
α	10%	30%

     New approach of computing FOPT parameters in Croon, Gould, Schicho, Tenkanen, White, 2009.10080

   - 2.2 And simulations: bring the attention of a more detailed simulation of CS growth, understanding DW scenarios and characterizing better FPOT parameters
3. We are just at the beginning of an exciting era of SGWB in the context of models BSM