A model for **Dark Matter, Naturalness** and a complete Gauge Unification

NDM’15, Jyväskylä/1.6.2015

**Kimmo Kainulainen** / University of Jyväskylä / HIP

in collaboration with

**Kimmo Tuominen** / University of Helsinki / HIP

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HIERARCHY PROBLEM = ?
UNIFICATION = ?
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**TCDM**
- JCAP 1002 (2010) 029
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- JCAP 1310 (2013) 036
- arXiv:1504.07197
Naturality in TC is “trivial”

\[ m_h^2 \sim g^2 \Lambda^2 \]
\[ m_f^2 \sim m_f^2 (1 + c g^2 \log \Lambda^2) \]

No fundamental light scalar: TC-breaking scale \( \Lambda_{TC} \sim \mathcal{O}(\text{TeV}) \)

\[ Q < \Lambda_{TC} \]

DOF’s: SM-Higgs + singlet + …

\[ H, S, \ldots \]

\[ Q > \Lambda_{TC} \]

Fundamental DOF’s

\[ Q, U, D, \eta_1, \eta_2 \]

Fermions
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Many new bound states in scale

\[ m_i \sim \Lambda_{TC} \]

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Fundamental DOF’s

Fermions
**THE Model** 
Free from Gauge and global anomalies

New low energy fields beyond the SM:

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<tr>
<th></th>
<th>( \text{SU}(3)_c )</th>
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*Discrete symmetry to ensure stability of DM and absence of fractionally charged TC-baryons*

TC-symmetry group
Here \( N_{TC} = 3 \)
### The Model: Free from Gauge and Global Anomalies

New low energy fields beyond the SM:

<p>| |</p>
<table>
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<tr>
<td><strong>Table 1</strong></td>
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<tr>
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<td><strong>Field</strong></td>
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Avoid Witten anomaly

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- **Avoid Witten anomaly**
- **“Bino”: to make the WIMP**
- **Discrete symmetry** to ensure **stability of DM** and absence of fractionally charged TC-baryons

- **TC for composite $H$**
- **TC for composite $S$**

($=\text{”bino” mass}$)

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“Wino” and “Gluino” SM gauge Unification

TC for composite H

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(=>”bino” mass)
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*Discrete symmetry to ensure stability of DM and absence of fractionally charged TC-baryons*

- Avoid Witten anomaly
- “Bino”: to make the WIMP
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<td>1</td>
<td>1</td>
<td>1</td>
<td>-1</td>
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<tr>
<td>$\omega$</td>
<td>1</td>
<td>adj.</td>
<td>0</td>
<td>1</td>
<td>-1</td>
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<tr>
<td>$\beta$</td>
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<td>1</td>
<td>0</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td>adj.</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>$Q_L$</td>
<td>1</td>
<td>2</td>
<td>1/6</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>$U_R^c$</td>
<td>1</td>
<td>1</td>
<td>-2/3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>$D_R^c$</td>
<td>1</td>
<td>1</td>
<td>1/3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>$\eta_1$</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>-1</td>
</tr>
<tr>
<td>$\eta_2$</td>
<td>1</td>
<td>1</td>
<td>0</td>
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<td>-1</td>
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<tr>
<td>$\tilde{G}$</td>
<td>1</td>
<td>1</td>
<td>0</td>
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<td>-1</td>
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</table>

Avoid Witten anomaly

“Bino”: to make the WIMP

*DM-sector*

3 neutral Majorana fields + 2 charged Dirac fields

Discrete symmetry to ensure stability of DM and absence of fractionally charged TC-baryons

“Wino” and “Gluino” SM gauge Unification

TC for composite $H$

TC for composite $S$

(=)”bino” mass

“TC-gluino” SM+TC gauge Unification

TC-symmetry group

Here $N_{TC} = 3$
**THE Model** Free from Gauge and global anomalies

New low energy fields beyond the SM:

<table>
<thead>
<tr>
<th>Field</th>
<th>SU(3)$_c$</th>
<th>SU(2)$_L$</th>
<th>U(1)$_Y$</th>
<th>SU(N$_{TC}$)</th>
<th>$Z_2$</th>
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<td>1</td>
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**DM-sector**

- Avoid Witten anomaly
- "Bino": to make the WIMP
- Can be relatively heavy

**Discrete symmetry to ensure stability of DM and absence of fractionally charged TC-baryons**

3 neutral Majorana fields + 2 charged Dirac fields

"Wino" and "Gluino" SM gauge Unification

TC for composite $H$

TC for composite $S$ ($\Rightarrow \text{"bino" mass}$)

"TC-gluino" SM+TC gauge Unification

TC-symmetry group

Here $N_{TC} = 3$
Unification

\[ \sin^2 \theta_W(M_Z) = 0.23126 \pm 0.00005 \]
\[ M_Z = 91.1876 \pm 0.0021 \text{ GeV} \]
\[ \alpha^{-1}(M_Z) = 127.940 \pm 0.014 \]
\[ \alpha_3(M_Z) = 0.1193 \pm 0.0016 \]

SM-gauge unification (1-loop)

\[ \alpha_n^{-1}(\mu) = \alpha_n^{-1}(M_Z) - \frac{b_n}{2\pi} \ln \left( \frac{\mu}{M_Z} \right) \]

Standard Model

\[ b_1 = b_1^{\text{SM}} \]
\[ b_2 = b_3^{\text{SM}} \]
\[ b_3 = b_3^{\text{SM}} \]
Unification

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**Standard Model**

$$b_1 = b_1^{SM} + \frac{37}{30}$$

$$b_2 = b_3^{SM} + \frac{5}{2}$$

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TCDM-model

\[ b_1 = b_1^{\text{SM}} + \frac{37}{30} \]
\[ b_2 = b_3^{\text{SM}} + \frac{5}{2} \]
\[ b_3 = b_3^{\text{SM}} + 2 \]
The beta function coefficient (as in extended TC models) or scalars decoupled at high energies (as in SUSY models). The hypercharge assignment of our model renders the Technicolor sector identical to the SM hypercharge gauge group. With this choice the estimates for the value of the QCD-coupling at electroweak scale.

\[ \alpha_n^{-1}(\mu) = \alpha_n^{-1}(M_Z) - \frac{b_n}{2\pi} \ln \left( \frac{\mu}{M_Z} \right) \]

The beta function coefficients for the gauge couplings are given by:

- \( b_1 = b_1^{SM} + \frac{37}{30} \)
- \( b_2 = b_2^{SM} + \frac{5}{2} \)
- \( b_3 = b_3^{SM} + 2 \)

For completeness we will first briefly review the argument for the unification of the SM gauge couplings. Starting from the running of all four couplings in the MWTC-DM model under consideration, including the TC-coupling, the unification scale can be determined from the lattice. The running of the SM couplings will be a constant. This must be determined from the lattice. The unification scale will be close to conformality. The latter choice fits well in with the gauge coupling unification considered in the next subsection.

The real part, \( R = \left( \frac{\mu}{M_Z} \right) \), is an interesting possibility, we shall here assume that the field is heavy with respect to the masses in the dark matter sector. If the field is light with respect to the masses in the dark matter sector, it can be heavy with respect to the masses in the Technicolor sector. If the field is light with respect to the masses in the dark matter sector, it can be heavy with respect to the masses in the Technicolor sector. If the field is light with respect to the masses in the Technicolor sector, it can be heavy with respect to the masses in the Technicolor sector.

Using Eq. (3.5) we can now derive the following relation:

\[ \frac{\alpha_3}{\alpha_1} = \frac{\alpha_3^{SM}}{\alpha_1^{SM}} \]

The unification scale of the SM-gauge unification (1-loop) is given by:

\[ M_U = (2.20 \pm 0.03) \times 10^{15} \text{ GeV}, \quad \text{and} \quad \alpha_U = 0.03042 \pm 0.00002 \]
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- Proton life-time (SK): \( \tau_p > 10^{34} \text{ y} \) \text{ OK (borderline)}
Unification of all couplings

TC-coupling unification:

\[ b_4 = (4 + 2) \times \frac{1}{3} + 2 - 11 = -7 \]

\[ \alpha_4^{-1}(\mu) = \alpha_4^{-1}(\Lambda_{TC}^{1-\text{loop}}) - \frac{b_4}{2\pi} \ln \left( \frac{\mu}{\Lambda_{TC}^{1-\text{loop}}} \right) \]
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Determine \( \Lambda_{\text{TC}}^{1-\text{loop}} \) from 2-4-unification

\[ \Lambda_{\text{TC}}^{1-\text{loop}} = 341 \pm 5 \text{GeV} \]
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\equiv 0
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Our TC is QCD-like and \( \Lambda_{QCD}^{1-\text{loop}} = 57 \text{ MeV} \) while \( \Lambda_{QCD} \sim 700 \text{ MeV} \). This suggests that:

\( \Lambda_{TC} \sim 3 \text{ TeV} \) !!!

\( Q, U, D \quad \eta_{1.2} \quad \tilde{G} \quad G \)

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without:

\[ \begin{align*}
\eta_{1,2} & \quad \Lambda_{TC}^{1-\text{loop}} \approx 4.3 \text{ TeV} \\
\tilde{G} & \quad \Lambda_{TC}^{1-\text{loop}} \approx 235 \text{ TeV} \\
\text{bot} & \quad \Lambda_{TC}^{1-\text{loop}} \approx 1140 \text{ TeV}
\end{align*} \]
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- \( \tilde{G} \):
  - \( \Lambda_{TC}^{1-\text{loop}} \approx 235 \text{ TeV} \)
- bot:
  - \( \Lambda_{TC}^{1-\text{loop}} \approx 1140 \text{ TeV} \)

Particle spectrum/unification consistency coupled to existence of a TeV TC-scale.
Dark sector

• **3x3-mixing neutral mass lagrangian in 4D-notation:**

\[
\mathcal{L}_{\text{mass}} = \frac{1}{2} \left( \overline{N_R}, \overline{w^0_R}, \overline{\beta_R} \right) \left( \begin{array}{ccc} M_{NN} & m_{Nw} & m_{N\beta} \\ m_{Nw} & M_{ww} & m_{w\beta} \\ m_{N\beta} & m_{w\beta} & M_{\beta\beta} \end{array} \right) \left( \begin{array}{c} N_L \\ w^0_L \\ \beta_L \end{array} \right) + \text{h.c.}
\]

\[
M_{NN} \equiv \lambda_{NN} v^2 / \Lambda, \quad M_{ww} \equiv \lambda_{ww} v^2 / 4 \Lambda, \quad m_{N\beta} \equiv y_{\beta} v / \sqrt{2} \quad \text{etc.}
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- **MCMC scan with priors**

\[ |M_{ij}| \leq 3000 \text{ GeV}; \quad |m_{ij}| \leq 2000 \text{ GeV} \quad \text{and} \quad 200 \text{ GeV} \leq m_E \leq 2000 \text{ GeV} \]
Constraints

Decay constraints

\[ |U_{1i}|^4 \left(1 - \frac{4m_i^2}{m_Z^2}\right)^{3/2} < 0.008 \quad \text{LEP} \]

\[ R_i \equiv \frac{\Gamma_{H,DM}}{\Gamma_{H,DM} + \Gamma_{SM,\text{tot}}} \lesssim 0.17 \quad \text{LHC} \]

Direct mass constraints

\[ m_E, m_{\omega_D} > 500\text{GeV} \quad \text{LHC} \]

Precision electroweak constraints

\[ S = 0.00 \pm 0.08, \quad \text{and} \quad T = 0.05 \pm 0.07 \quad \text{(combined PDG)} \]
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Decay constraints

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Direct and indirect DM search constraints

WIMP has complex couplings to both \( h \) and \( Z \) giving rise to both SI and SD direct detection channels.
Direct-detection reach: SI-channel

Effective SI WIMP-nucleon x-section

\[ \sigma_{\text{SD,SI}}^{\text{eff}} \equiv f_{\text{rel}} \sigma_{\text{SD,SI}} \]

\[ f_{\text{rel}} \equiv \Omega \chi h^2 / \Omega_{\text{DM}} h^2 \]

DM abundance \( f_{\text{rel}} \) was computed including all available final states

\( XX \rightarrow f\bar{f}, W^+W^-, ZZ, hh, Zh \)
**Direct-detection reach:** SI-channel

*Effective SI WIMP-nucleon x-section*

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Only
SK hard WW / 11 and
SK tau tau / 15
give significant constraint
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Only
- **SK hard WW / 11** and
- **SK tau tau / 15**
give significant constraint

**ALSO included:**

- Gamma-ray limits from **Fermi-LAT / 15**
- And bounds on pp-ratio from **AMS-2 / 15**
EW-precision constraints

- All accepted models give a positive S-parameter

\[ S \geq 0.12 \]

In tension, but consistent with the current limits:

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Model ruled out if one finds that \( S < 0.1 \)!
Conclusions

We have presented an anomaly free, UV-safe model with:

• A TC-solution to Hierarchy Problem and complete gauge unification with

\[ M_U = 2.2 \times 10^{15} \text{ GeV} \quad \text{and (unification "\Rightarrow")} \quad \Lambda_{TC} \sim \mathcal{O}(\text{TeV}) \]
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• \textbf{Thermal WIMP-DM}, somewhat like a neutralino in the MSSM
  
  • A dominant or subdominant DM evading all current bounds
  • Most of the PM-space can be ruled out by XENON1t/LUX…
  • Model can be completely ruled out by finding $S < 0.1$
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  - A dominant or subdominant DM evading all current bounds
  - Most of the PM-space can be ruled out by XENON1t/LUX…
  - Model can be completely ruled out by finding \( S < 0.1 \)

- **Electroweak Baryogenesis** is likely to work in the model
THANK YOU !