Clockwork dark matter

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based on

T. Hambye, D. Teresi and M.H.G. Tytgat, JHEP 1707 (2017) 047

THE FUTURE OF SEARCHES FOR INVISIBLE PARTICLES, AACHEN, 14/12/17

Introduction

- **clockwork mechanism** $\rightarrow$ an elegant and economical way to generate **tiny numbers**/large hierarchies X with only $\mathcal{O}(1)$ **couplings** and $N \sim \log X$ **fields**
- originally introduced for relaxion models [Choi, Im, '15; Kaplan, Rattazzi, '15]
- a **framework** for model building: [Giudice, McCullough, '16]
  - low-scale invisible axions [Giudice, McCullough, '16; Farina, Pappadopulo, Rompineve, Tesi, '16]
  - **hierarchy problem** [Giudice, McCullough, '16] (**Matthew's talk**)
  - neutrino physics [Hambye, DT, Tytgat, '16; Carena, Li, Machado $\times$ 2, Wagner, '17]
  - inflation [Kehagias, Riotto, '16]
  - SUSY [Giudice, McCullough, DT, in prep.] and SUGRA [Kehagias, Riotto, '17; Antoniadis, Delgado, Markou, Pokorski, '17]
  - ... [not cited here for brevity]
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- dark matter cosmologically stable if decays by dim-5 ($\Lambda \gg M_{PL}$), dim-6 ($\Lambda \sim M_{GUT}$), tiny couplings $\Longrightarrow$ **all difficult to test**
- **clockwork** mechanism $\rightarrow$ dark matter cosmologically **stable** although it **decays into SM** via $\mathcal{O}(1)$ **interactions** with **TeV-scale** particles!
- large interactions $\Longrightarrow$ dark matter is a **thermal relic**, i.e. a **WIMP**

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The clockwork mechanism

Based on the simple observation that:

$1/2 \quad \times \quad 1/2 \quad \times \quad 1/2 \quad \times \quad 1/2 \quad \times \quad \dots \quad \times \quad 1/2$ can **easily** be **tiny**

Use a **chain** of N fields

$$\phi_0 \ \overset{1/q}{\text{——}} \ \phi_1 \ \overset{1/q}{\text{——}} \ \phi_2 \ \overset{1/q}{\text{——}} \ \phi_3 \ \overset{1/q}{\text{——}} \ \dots \ \overset{1/q}{\text{——}} \ \phi_N \ \text{——} \ \mathbf{SM}$$

if clever **symmetry** $\longrightarrow \quad \phi_{light} \approx \phi_0 \quad \Longrightarrow \quad \phi_{light} - \mathbf{SM} \sim \mathbf{1/q^N} \quad (q > 1)$

For **fermions** use chiral symmetries

$$R_0 \ \overset{m}{\text{——}} \ \underbrace{L_1 \quad R_1}_{qm} \ \overset{m}{\text{——}} \ \underbrace{L_2 \quad R_2}_{qm} \ \overset{m}{\text{——}} \ \underbrace{L_3 \quad R_3}_{qm} \ \overset{m}{\text{——}} \ \dots \ \overset{m}{\text{——}} \ \underbrace{L_N \quad R_N}_{qm} \ \text{——} \ L_{SM}$$

light $N \approx R_0 \quad \Longrightarrow \quad N - L_{SM} \sim \mathbf{1/q^N}$

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Clockwork fermion

- chiral symmetry group:

  $U(1)_{R_0} \times U(1)_{L_1} \times U(1)_{R_1} \times \ldots \times U(1)_{L_N} \times U(1)_{R_N}$ with $U(1)_{R_N} \equiv U(1)_{L_{SM}}$

- **scalars**:

  $S_i \sim (-1, 1)$ under $U(1)_{R_i} \times U(1)_{L_{i+1}}$ $\quad C_i \sim (1, -1)$ under $U(1)_{L_i} \times U(1)_{R_i}$

- chain of fields:

$$\mathbf{R_0} \ \underline{\ S_1\ } \ L_1 \ \underline{\ C_1\ } \ R_1 \ \underline{\ S_2\ } \ L_2 \ \underline{\ C_2\ } \ \ldots \ \underline{\ C_N\ } \ R_N \ \underline{\qquad} \ \mathbf{L_{SM}}$$

- **clockwork** mechanism when scalars acquire a **vev**:

$$m = y_S \langle S_i \rangle \qquad qm = y_C \langle C_i \rangle$$

- **Majorana mass** m_N for R_0, eigenstate $N \approx R_0$ is the **dark-matter** candidate

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Clockwork Lagrangian

- the Lagrangian is

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kinetic} - \sum_{i=1}^{N} \left(y_S S_i \bar{L}_i R_{i-1} - y_C C_i \bar{L}_i R_i + h.c. \right)$$
$$- \left(y\, \bar{L}_{SM} \widetilde{H} R_N + h.c. \right) - \frac{1}{2} \left(m_N \overline{R_0^c}\, R_0 + h.c. \right)$$

- after the scalars acquire vevs $m = y_S \langle S_i \rangle\,, \quad qm = y_C \langle C_i \rangle$:

$$\mathcal{L} \supset -m \sum_{i=1}^{N} \left(\bar{L}_i R_{i-1} - q\, \bar{L}_i R_i \right) - \frac{m_N}{2}\, \overline{R_0^c}\, R_0 + h.c.$$

- clockwork mechanism for $m_N \lessapprox qm$ (for $q \gg 1$)

The spectrum

Take $q \gg 1$ for simplicity

- the **dark-matter** Majorana fermion N with mass $\approx m_N$:

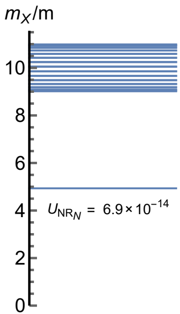
$$N \approx R_0 + \frac{1}{q^1} R_1 + \frac{1}{q^2} R_2 + \ldots + \frac{1}{q^N} R_N$$

- a **band** of N **pseudo-Dirac** ψ_i with mass $\approx qm$:

$$\psi_i \approx \frac{1}{\sqrt{N}} \sum_k \mathcal{O}(1) L_k + \mathcal{O}(1) R_k$$

- N scalars S_i and C_i expected in the same mass range (not necessarily dynamic, but not discussed here)

N = 15, q = 10., m_N/m = 5.0



Relevant **sizeable** interactions:

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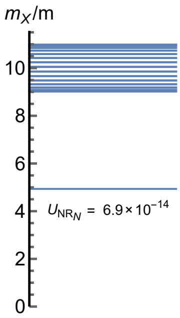

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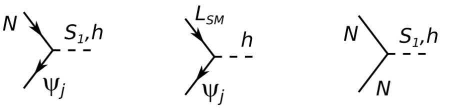

Cosmological (meta)stability of dark matter

$$\mathbf{R_0} \xrightarrow{y_S\langle S_1\rangle} L_1 \xrightarrow{y_C\langle C_1\rangle} R_1 \xrightarrow{y_S\langle S_2\rangle} L_2 \xrightarrow{y_C\langle C_2\rangle} \dots \xrightarrow{y_C\langle C_N\rangle} R_N \xrightarrow{y\,h} \mathbf{L_{SM}}$$

N can **decay**, e.g. $N \to \nu h, \nu Z, lW$, but

The coupling of **dark matter** to **SM fermions** is **clockwork suppressed**:

$$\mathcal{L} \supset -\frac{y}{q^N}\bar{L}_{SM}\widetilde{H}N_R$$

Dark matter cosmologically stable

The decay lifetime of N longer than the age of the Universe with $\mathcal{O}(1)$ **couplings** and $\lesssim$ **TeV-scale** states

- indirect detection $\Longrightarrow q^{2N} > 1.5 \times 10^{50}\ \left(\frac{m_N}{\text{GeV}}\right) y^2$
  for example: $m_N \sim 100\,\text{GeV}$, $y \sim 1$, $q \sim 10$, $N \sim 26$
- effect of **clockwork gears** ψ_j in loop diagrams also **clockwork-suppressed**

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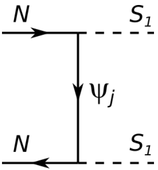
Scenario A: $m_S < m_N$

Dominant process:



from $N \sim R_0$, $\Psi_j \supset L_1$
and $y_S\, S_1 \overline{L}_1 R_0$

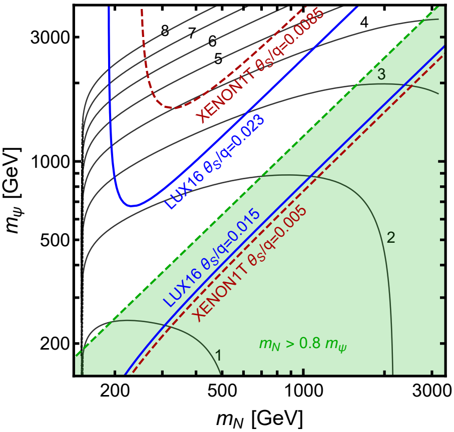
not clockwork-suppressed!

$\Longrightarrow$ **N is a WIMP**

perturbative $y_S < \sqrt{4\pi} \simeq 3.5$

$\Longrightarrow$ **N and ψ_j light enough**

m_{S_1} = 150 GeV



y_S needed for correct Ω_{DM}

Scenario B: $m_N < m_S$ and $2m_N < m_S + m_h$

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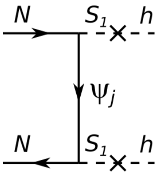
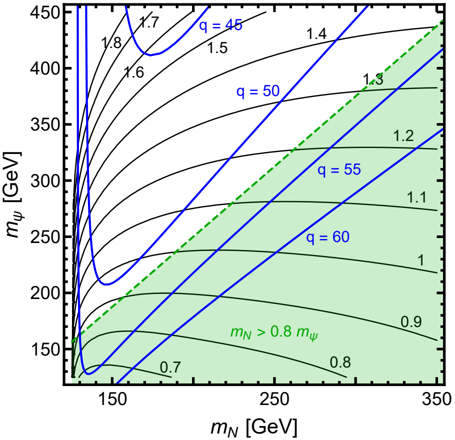


$\propto \quad (y_S \theta_S)^4$

$\theta_S \lessapprox 0.4$ **from colliders**

y_S non-perturbative for universal θ_S:
$\theta_S \lessapprox 0.4/\sqrt{N}$

it works also near the h and S resonances, for universal θ_S too



$y_S \theta_S$ needed for correct Ω_{DM}

Other limits and prospects

- Indirect detection: annihilation is p-wave, but decays $N \to h\nu$ monochromatic
- ψ_j in the hundreds of GeV range, coupled via $y \overline{L}_{SM} H R_N$ and $\psi_j \supset R_N$
  $\Longrightarrow$ pseudo-Dirac **RH neutrinos** in the **observable range**, **y sizeable**
  - EWPT: $|B_{l\psi}|^2 \equiv y^2 v^2/(2m_\psi^2) \lesssim 10^{-3}$
  - LFV: $BR(\mu \to e\gamma) \approx 8 \times 10^{-4} |B_{e\Psi}|^2 |B_{\mu\Psi}|^2 < 4.2 \times 10^{-13}$
  - direct L-conserving searches: up to $m_\psi \approx 200$ GeV with 300 fb^{-1} [Das, Dev, Okada, '14]
  - if $m_N \lll m_\psi$ L-violating searches: up to $m_\psi \approx 300$ GeV with 300 fb^{-1} [Deppisch, Dev, Pilaftsis, '15]
- In scenario B S_1 **needs** to have **large mixing with h**, in A it can
  $\Longrightarrow$ limits and searches for scalar singlets [Falkowski, Gross, Lebedev, '15; Robens, Stefaniak, '15]
  - for $m_S < 500\,\text{GeV}$: $\theta_S < 0.3 - 0.4$ from direct searches
  - for $m_S > 500\,\text{GeV}$: $\theta_S \lesssim 0.3 - 0.4$ from EWPT

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Majorana neutrino masses

- SM leptons interact with TeV-scale ψ_i with large Yukawas $\Longrightarrow$ **huge** m_ν???
- Clockwork at work: if there were no $R_0 \Longrightarrow$ no chiral partner for νs but effect of R_0 has to go through the **whole clockwork chain**:

$$m_\nu \simeq \frac{m_D^2}{q^{2N} m_N}$$

- suppression here is smaller than for DM: $q = 10, m_N = 1$ TeV $\Longrightarrow N \approx 7$
- ≥ 2 nonzero $m_\nu \Longrightarrow$ at least **2 clockwork chains**
- a **suggestive possibility**: 1 chain for dark matter, 2 chains for neutrino masses
- + resonant leptogenesis? Starting from 2 degenerate, a small mass splitting can be generated by interactions with the clockwork gears...
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Clockwork from a flat extra dimension

- the clockwork Lagrangian can come from a **discretized 5th dimension**
- **flat-spacetime** construction for fermion:
- 1 Dirac fermion with mass M in the 5D bulk $\to L_i, R_i$

$$\mathcal{L}_5 \supset \bar{\psi}(i\overleftrightarrow{\not{\partial}}_D - M)\psi = i\overline{\psi}\gamma^\mu\partial_\mu\psi + \left[\frac{1}{2}\left(\overline{L}\,\partial_Z R - (\partial_Z\overline{L})R\right) - M\overline{L}R + h.c.\right]$$

- + **Wilson term** $-\frac{a}{2}\,\partial_Z\overline{\psi}\,\partial_Z\psi = -\frac{a}{2}\,\partial_Z\overline{L}\,\partial_Z R$ removes 1 hopping direction
- to get light mode: orbifold with Dirichlet b.c. $L(0) = 0$ (1 spare **chiral fermion** on one brane $\to R_0$)
- **SM chiral leptons** on the other brane $\to L_{SM}$
- discretized Lagrangian $\mathcal{L} \supset \sum_{i=0}^{N-1} \frac{1}{a}\overline{L}_{i+1}R_i - \sum_{i=1}^{N}\left(\frac{1}{a} + M\right)\overline{L}_i R_i$
- clockwork with $m = \frac{1}{a}, \quad qm = \frac{1}{a} + M, \quad q^N = \left(1 + \frac{\pi RM}{N}\right)^N \to e^{\pi RM}$

Clockwork from a flat extra dimension

- the clockwork Lagrangian can come from a **discretized 5th dimension**
- **flat-spacetime** construction for fermion:
- 1 Dirac fermion with mass M in the 5D bulk $\to L_i, R_i$

$$\mathcal{L}_5 \supset \bar{\psi}(i\overleftrightarrow{\not{\partial}}_D - M)\psi = i\overline{\psi}\gamma^\mu\partial_\mu\psi + \left[\frac{1}{2}\left(\overline{L}\,\partial_Z R - (\partial_Z\overline{L})R\right) - M\overline{L}R + h.c.\right]$$

- + **Wilson term** $-\frac{a}{2}\,\partial_Z\overline{\psi}\,\partial_Z\psi = -\frac{a}{2}\,\partial_Z\overline{L}\,\partial_Z R$ removes 1 hopping direction
- to get light mode: orbifold with Dirichlet b.c. $L(0) = 0$
  (1 spare **chiral fermion** on one brane $\to R_0$)
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Conclusions

- unstable dark matter requires huge suppression for the decay
- the **clockwork mechanism** can provide that
- **large couplings** with new **TeV-scale** states
- decaying dark matter as a **thermal relic** (a WIMP)
- direct connection between decay and annihilations
- **rich phenomenology** at dark-matter experiments, colliders and LFV
- **N** pseudo-Dirac "**RH neutrinos**" at the $\lesssim$ **TeV range** with **large couplings**
- Majorana neutrino masses are generated, and are clockwork-suppressed
- the construction can originate minimally from extra dimension
- extra-dimensional origin for fermions particularly interesting
  [Giudice, McCullough, DT, in preparation]

Backup slides

Clockwork scalar

- For **scalars**, use a chain of $N+1$ symmetries: $U(1)_0 \times U(1)_1 \times \ldots \times U(1)_N$
- broken by N spurions $m_k^2 \equiv m^2$ with $\quad Q_k(m_k^2) = 1, \quad Q_{k+1}(m_k^2) = -q \quad (q > 1)$
- $\mathcal{L} = -\frac{f^2}{2} \sum_{k=0}^{N} |\partial U_k|^2 + \frac{m^2 f^2}{2} \sum_{k=0}^{N-1} \left(U_k^\dagger U_{k+1}^q + h.c. \right)$
- for the Goldstones ϕ_k, $U_k \propto e^{i\phi_k/f}$: $\quad -\mathcal{L} \supset \frac{m^2}{2} \sum_{k=0}^{N-1} \left(\phi_k - q\phi_{k+1} \right)^2$
- **unbroken** $U(1)$ with $\mathcal{Q} = \sum_k \frac{Q_k}{q^k} \quad \Longrightarrow \quad$ **massless** $\varphi_0 = \mathcal{N} \sum_k \frac{\phi_k}{q^k}$
- For instance, if $\mathcal{L} \supset \frac{\phi_N}{16\pi^2 f} G\widetilde{G} \quad \Longrightarrow \quad \frac{\varphi_0}{16\pi^2 F} G\widetilde{G}$ with $F = f\frac{q^N}{\mathcal{N}} \gg f$

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Clockwork from the metric [Giudice, McCullough, ’16]

- **curved-spacetime** construction for scalar:
- curved **metric** $ds^2 = X(|Z|)\, dx^2 + Y(|Z|)\, dZ^2$
- **massless** scalar in the 5D bulk:

$$\mathcal{S} = -2 \int_0^R dZ \int d^4x \sqrt{-g}\, \frac{1}{2}\, g^{MN} \partial_M\phi\, \partial_N\phi = -\int_0^R dZ \int d^4x\, X^2 Y^{1/2} \left[\frac{(\partial_\mu\phi)^2}{X} + \frac{(\partial_Z\phi)^2}{Y} \right]$$

- discretized Lagrangian:

$$\mathcal{L} \supset \sum_{j=0}^{N-1} m_j^2 (\phi_j - q_j\phi_{j+1})^2 \qquad \text{with } m_j^2 = \frac{X_j}{a^2 Y_j}, \quad q_j = \frac{X_j^{1/2} Y_j^{1/4}}{X_{j+1}^{1/2} Y_{j+1}^{1/4}}$$

- clockwork if $X_j \propto Y_j$
  finite for $N \to \infty$ if $X_j \propto Y_j \propto e^{-\frac{4}{3}k\,a\,j}$
- $m = \frac{1}{a}, \quad q = e^{k\,a}, \quad q^N = e^{\pi k R}$

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The clockwork metric

- in the **continuum**: $ds^2 = e^{\frac{4}{3}k|Z|}\,(dx^2 + dZ^2)$
- Kaluza-Klein modes for massless scalar

$$\psi_0(Z) \simeq \sqrt{k\pi R}\, e^{-k\pi R} \quad \Longrightarrow \quad \frac{dP}{dZ} \propto e^{2kZ}$$

$$\psi_n(Z) = e^{-kZ} \times \text{oscillatory} \quad \Longrightarrow \quad \frac{dP}{dZ} = \text{oscillatory}$$

- what about **Large Extra Dimension** or **Randall-Sundrum**?

	m_j	q_j
LED	$\frac{1}{a}$	1
RS	$\frac{1}{a}\, e^{-\hat{k}aj}$	$e^{\hat{k}a}$
clockwork	$\frac{1}{a}$	$e^{\hat{k}a}$

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