A Clockwork WIMP

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based on

T. Hambye, D. Teresi and M.H.G. Tytgat, arXiv:1612.06411 [hep-ph]

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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 in the context of weak-scale relaxation [Choi, Im, '15; Kaplan, Rattazzi, '15] (**talk by Perez**)
- mechanism **more general** than that [Giudice, McCullough, '16] (**talk by McCullough**), useful for:
  - low-scale invisible axions [Giudice, McCullough, '16; Farina, Pappadopulo, Rompineve, Tesi, '16]
  - hierarchy problem [Giudice, McCullough, '16]
  - flavour puzzle?
  - inflation [Kehagias, Riotto, '16]
  - **dark matter** [Hambye, DT, Tytgat, '16] (**this talk!**)
- 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:

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

Use a **chain** of N fields

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

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

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

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

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Clockwork dark matter

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

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- **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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The spectrum

Take $q \gg 1$ for simplicity, clockwork works for $m_N \lessapprox qm$

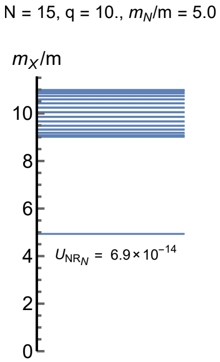
- the **dark-matter** Majorana fermion N with mass $\approx m_N$:

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

- 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)



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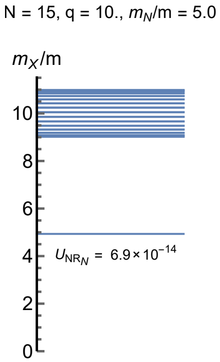

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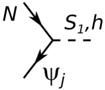

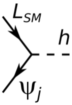

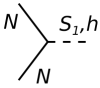

Cosmological (meta)stability of dark matter

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

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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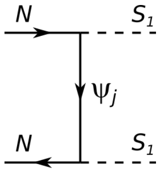
Scenario A: $m_S < m_N$

Dominant process:



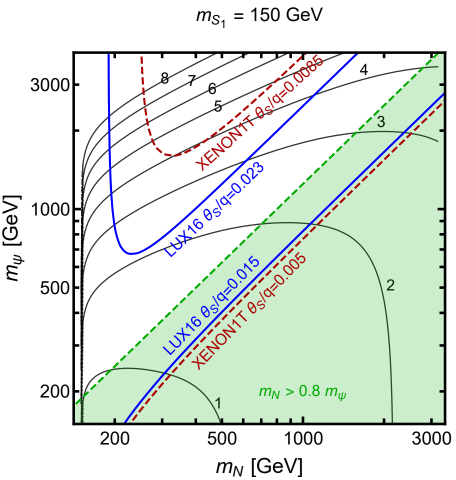
from $N \sim R_0$, $\Psi_j \supset L_1$
and $y_S\, S_1 \overline{L}_1 R_0$

not clockwork-suppressed!

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

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

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



y_S needed for correct Ω_{DM}

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

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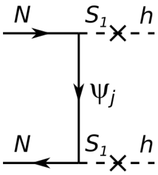
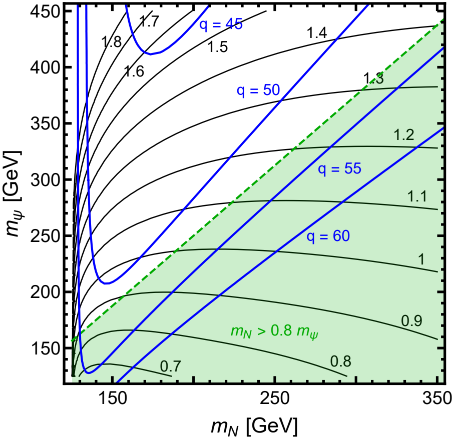


$\propto \quad (y_S \theta_S)^4$

$\theta_S \lessapprox 0.4$ **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 $m_S < 500\,\mathrm{GeV}$: $\theta_S < 0.3 - 0.4$ from direct searches
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More fun with the clockwork...

- Extra-dimensional origin?
  - the clockwork Lagrangian can come from a **discretized 5th dimension**
  - curved metric with 1 5D field + SM (**talk by McCullough**) or
  - **flat-spacetime** construction:
    - 1 Dirac fermion with mass M in the 5D bulk $\to L_i, R_i$
    - 1 chiral fermion on one brane $\to R_0$
    - SM chiral leptons on the other brane $\to L_{SM}$
    - Lagrangian $\mathcal{L} \supset \sum_{i=0}^{N-1} \frac{1}{a} \bar{L}_{i+1} R_i - \sum_{i=1}^{N} \left(\frac{1}{a} + M \right) \bar{L}_i R_i$
    - clockwork with $m = \frac{1}{a}, \quad qm = \frac{1}{a} + M, \quad q^N = (1 + \frac{\pi RM}{N})^N \ \to \ e^{\pi RM}$
- **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**:

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

  - ≥ 2 nonzero $m_\nu \Longrightarrow$ at least 2 clockwork chains
  - a **suggestive possibility**: 1 chain for dark matter, 2 chains for neutrino masses (+ leptogenesis?)

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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
- highly non-trivial features, e.g. loop decays suppressed too
- **N** pseudo-Dirac “**RH neutrinos**” at the $\lesssim$ **TeV range** with **large couplings**
- **rich phenomenology** at dark-matter experiments, colliders and LFV
- can originate rather minimally from deconstructed flat 5D
- Majorana neutrino masses can be incorporated, and are clockwork-suppressed