Clockwork theory and phenomenology

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What's the clockwork mechanism?

- **clockwork mechanism** $\rightarrow$ an elegant and economical way to generate **tiny numbers**/large hierarchies X with only $\mathcal{O}(1)$ **couplings** and $\mathcal{N} \sim \log X$ **fields**
- Originally introduced in the context of relaxation models, to solve technical issues present in these [Choi, Im, '15; Kaplan, Rattazzi, '15]
- Then realized as a **framework** for model building: [Giudice, McCullough, '16]
  - low-scale invisible axions [Giudice, McCullough, '16; Farina, Pappadopulo, Rompineve, Tesi, '16; Giudice, Katz, McCullough, DT, Urbano, in prep.]
  - **hierarchy problem** [Giudice, McCullough, '16; Giudice, McCullough, Katz, Torre, Urbano, '17; DT, '18]
  - inflation [Kehagias, Riotto, '16; . . .]
  - **dark matter** [Hambye, DT, Tytgat, '16; . . .]
  - neutrino physics [Hambye, DT, Tytgat, '16; Ibarra, Kushwaha, Vempati, '17; . . .]
  - UV/EFT relation [Craig, Garcia Garcia, Sutherland, '17; Giudice, McCullough, '17]
  - supergravity [Kehagias, Riotto, '17; Antoniadis, Delgado, Markou, Pokorski, '17]
  - **UV origin** [DT, '18]
  - **collider pheno** and cosmology [Giudice, McCullough, Katz, Torre, Urbano, '17; Giudice, McCullough, Katz, DT, Urbano, in prep.]
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How the clockwork works (made easy)

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

$$\phi_0 \; \frac{1/q}{\quad} \; \phi_1 \; \frac{1/q}{\quad} \; \phi_2 \; \frac{1/q}{\quad} \; \phi_3 \; \frac{1/q}{\quad} \; \ldots \; \frac{1/q}{\quad} \; \phi_{\mathcal{N}} \; \frac{}{\quad} \; \mathbf{SM}$$

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

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For **fermions** use chiral symmetries

$$R_0 \ \underline{\ m\ } \ \underbrace{L_1 \quad R_1}_{qm} \ \underline{\ m\ } \ \underbrace{L_2 \quad R_2}_{qm} \ \underline{\ m\ } \ \underbrace{L_3 \quad R_3}_{qm} \ \underline{\ m\ } \ \ldots \ \underline{\ m\ } \ \underbrace{L_{\mathcal{N}} \quad R_{\mathcal{N}}}_{qm} \ \underline{\qquad} \ L_{SM}$$

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

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Chain to have **clockwork dark matter** [Hambye, DT, Tytgat, '16]

$$\mathbf{R_0} \;\underline{\;S_1\;}\; L_1 \;\underline{\;C_1\;}\; R_1 \;\underline{\;S_2\;}\; L_2 \;\underline{\;C_2\;}\; \ldots \;\underline{\;C_N\;}\; R_{\mathcal{N}} \;\underline{\qquad}\; \mathbf{L_{SM}}$$

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The spectrum

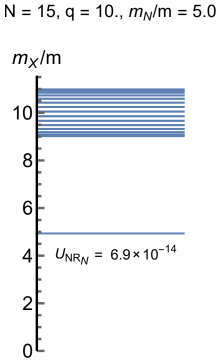
- the **dark-matter** Majorana fermion N with mass $\approx m_N$:

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

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

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

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



$\mathbf{R_0}$ $\overset{S_1}{\text{———}}$ L_1 $\overset{C_1}{\text{———}}$ R_1 $\overset{S_2}{\text{———}}$ L_2 $\overset{C_2}{\text{———}}$ $\ldots$ $\overset{C_{\mathcal{N}}}{\text{———}}$ $R_{\mathcal{N}}$ ——— $\mathbf{L_{SM}}$

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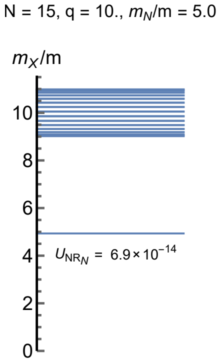
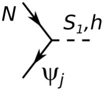
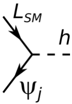


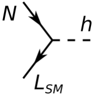
$$\mathbf{R_0} \;\underline{\;S_1\;}\; L_1 \;\underline{\;C_1\;}\; R_1 \;\underline{\;S_2\;}\; L_2 \;\underline{\;C_2\;}\; \ldots \;\underline{\;C_{\mathcal{N}}\;}\; R_{\mathcal{N}} \;\underline{\quad}\; \mathbf{L_{SM}}$$

sizeable:





suppressed $\sim 1/q^{\mathcal{N}}$:



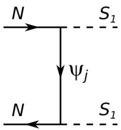
A clockwork WIMP [Hambye, DT, Tytgat, '16]

for $q \sim 10$, $\mathcal{N} \sim 26$

$\Longrightarrow$ N cosmologically **stable**

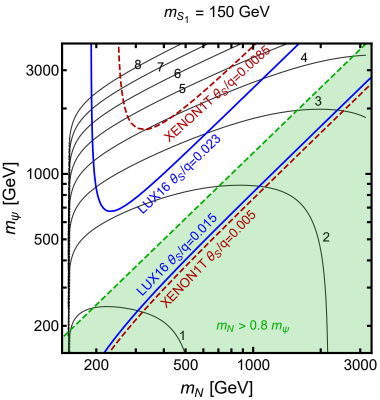
The decay lifetime of N longer than the age of the Universe with $\mathcal{O}(1)$ **couplings** and $\lesssim$ **TeV-scale** states

but large



N is produced thermally in the early Universe and freezes out

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



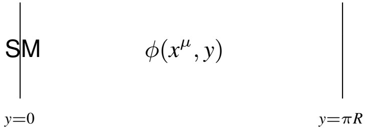
Yukawa needed for correct Ω_{DM}

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

Clockwork chain from an extra dimension

$$\phi_0 \;\frac{1/q}{\quad}\; \phi_1 \;\frac{1/q}{\quad}\; \phi_2 \;\frac{1/q}{\quad}\; \phi_3 \;\frac{1/q}{\quad}\; \dots \;\frac{1/q}{\quad}\; \phi_{\mathcal{N}} \;\frac{}{\quad}\; \mathbf{SM}$$

- the different fields ϕ_i could be a **single** field on different points of a discretized **extra dimension** $y_i = i \times \pi R/\mathcal{N}$
- 5th dimension $0 \leq y \leq \pi R$ with a single ϕ in the bulk, 2 branes $y = 0, \pi R$ and the SM localized at $y = 0$:



- a well-defined continuum limit exists and selects either
  - massless field in curved **clockwork** metric $ds^2 = e^{\frac{4}{3}ky}(dx^2 + dy^2)$ [Giudice, McCullough, '16]
  - **massive** field in flat spacetime [Hambye, DT, Tytgat, '16; Craig, Garcia Garcia, Sutherland, '17]
  - the two are equivalent from EFT perspective, related by field redefinitions [Giudice, McCullough, '17; Giudice, Katz, McCullough, DT, Urbano, in prep.]

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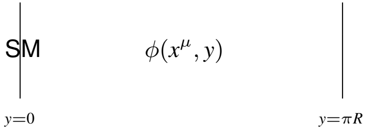

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Clockwork naturalness [Giudice, McCullough, '16]

- we want massless 5D gravity with **clockwork metric** $ds^2 = e^{\frac{4}{3}ky}(dx^2 + dy^2)$
- metric must be obtained dynamically!
- linear **dilaton** model (Jordan frame): [Antoniadis, Dimopoulos, Giveon, '01]

$$\mathcal{S} = \int d^4x\, dy \sqrt{-g}\, \frac{M_5^3}{2}\, e^S (\mathcal{R} + g^{MN}\partial_M S\, \partial_N S + 4k^2) + \text{brane terms}$$

- go to Einstein frame by $g_{MN} \to e^{-2S/3} g_{MN}$:

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- solve EoMs: $S = 2\,k\,y\,,\quad ds^2 = e^{\frac{4}{3}ky}(dx^2 + dy^2)$
- SM at $y = 0$ feels a Planck mass $M_P \simeq \frac{M_5^{3/2}}{k^{1/2}}\, e^{\pi kR} \simeq 10^{19}$ GeV
- but fundamental one is $M_5 \sim$ TeV for $kR \approx 10$
  $\Longrightarrow$ **hierarchy** problem **solved**

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Robust clockwork

- Einstein-frame action:

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- a 5D cosmological constant dominates and **destroys** the clockwork solution $\Longrightarrow$ implicit additional tuning $\Lambda_{5D}/k^2 \lesssim 10^{-16}$ [Giudice, Katz, McCullough, Torre, Urbano, '17]
- robust clockwork if **SUSY** in the bulk ($\Longrightarrow \Lambda_{5D} = 0$)

or

- **robust clockwork** without supersymmetry [DT, '18]:
  - **additional** $D-5$ flat dimensions $\sim L \ll R$
  - **dilaton** is the **volume** of these extra dimensions: $\sqrt{-g^{(D)}} = \sqrt{-g^{(5)}}\, e^{S(y)}$
  - in this setup GR in D dimensions **forbids** cosmological constant: $\sqrt{-g^{(D)}}\, \Lambda_D \longrightarrow \sqrt{-g}\, e^{S(y)} 4k^2$ in 5D
  - **pure gravity with** Λ_D $\longrightarrow$ linear dilaton action for $D \to \infty$, clockwork for D large enough

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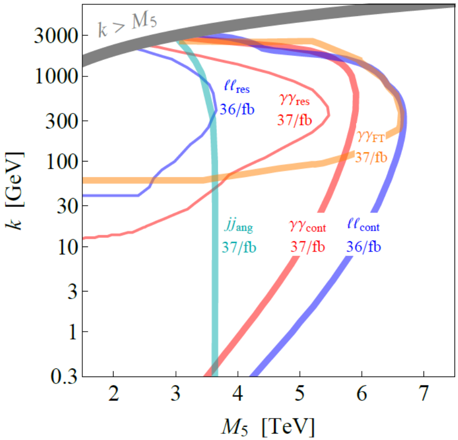

[Giudice, Katz, McCullough, Torre, Urbano, '17]

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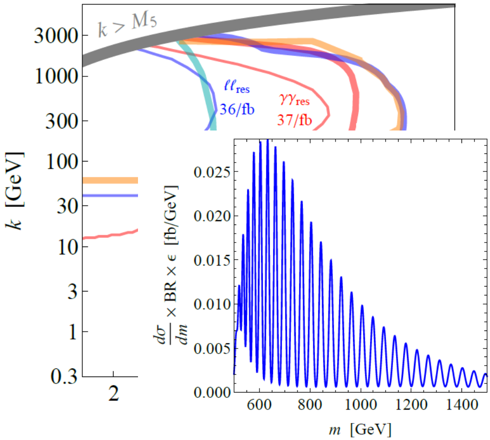

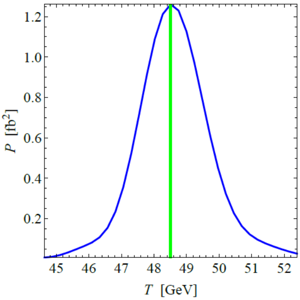

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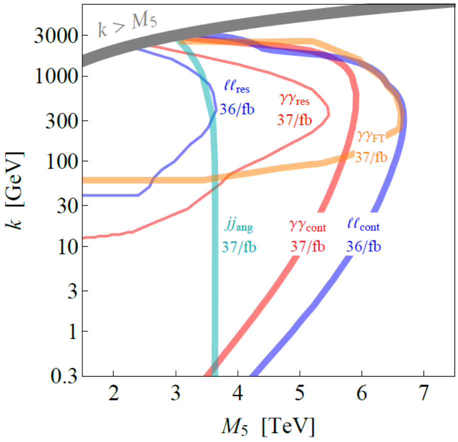

[Giudice, Katz, McCullough, Torre, Urbano, '17]

Preliminary - **novel** smoking-gun signatures:

- **s-channel** displaced vertices
- **chains** of **displaced** vertices
- long decay chains with many **soft** objects

Stay tuned:

[Giudice, Katz, McCullough, DT, Urbano, in prep.]

The End ?

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Many theory/pheno/cosmology developments on their way...

[Giudice, Kats, McCullough, DT, Urbano, in preparation]