Clockwork theory and phenomenology

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based on

D. Teresi, *"Clockwork without supersymmetry"*, arXiv:1802.01591

and

T. Hambye, D. Teresi and M.H.G. Tytgat, *"A Clockwork WIMP"*, JHEP 1707 (2017) 047

D. Teresi, *"Clockwork Dark Matter"*, Proceedings of Moriond Electroweak 2017

SUSY 2018, BARCELONA, 26/07/18

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; Niedermann, Padilla, Saffin, '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

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

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Fermion chain [Hambye, DT, Tytgat, '16]

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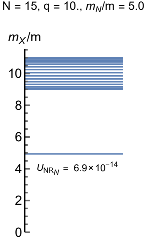
An example: a clockwork WIMP [Hambye, DT, Tytgat, '16]

- the spectrum:
  - a light **clockwork mode** N
  - a band of $\mathcal{N}$ **clockwork gears** ψ_i with mass $\approx qm$



$\mathrm{R}_0 \; \underline{\;S_1\;} \; L_1 \; \underline{\;C_1\;} \; R_1 \; \underline{\;S_2\;} \; L_2 \; \underline{\;C_2\;} \; \ldots \; \underline{\;C_\mathcal{N}\;} \; R_\mathcal{N} \; \underline{\qquad} \; \mathrm{L_{SM}}$

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

$\Longrightarrow$ N cosmologically **stable** with $q, \mathcal{N} \sim 10$
$\Longrightarrow$ **clockwork dark matter**

- sizeable:

$\Longrightarrow$ N is **produced** thermally and freezes out
$\Longrightarrow$ **clockwork WIMP**! Rich phenomenology

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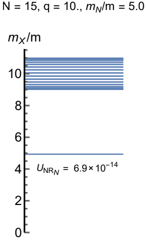

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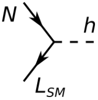

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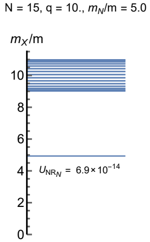

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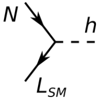

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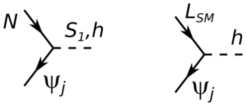

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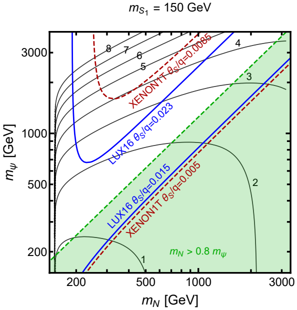
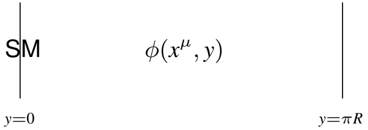


Clockwork chain from an extra dimension

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

- 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]
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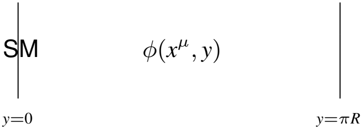

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Clockwork solution to the hierarchy problem [Giudice, McCullough, '16]

- 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 $g_{MN} \to e^{-2S/3} g_{MN}$, solve EoMs

$$S = 2ky\,, \quad ds^2 = e^{\frac{4}{3}ky}(dx^2 + dy^2)$$

- 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
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Fragility of the clockwork

- linear-dilaton action in the Jordan frame:

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- "brane terms" tuned to have $\Lambda_{4D} \simeq 0$ (like in Randall-Sundrum)

- Einstein-frame action:

$$\mathcal{S} = \int d^4x\, dy \sqrt{-g}\, \frac{M_5^3}{2} \left(\mathcal{R} - \frac{1}{3} g^{MN} \partial_M S\, \partial_N S + 4k^2\, e^{-2S/3} \right) + \text{brane terms}$$

- 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 ($\Longrightarrow \Lambda_{5D} = 0$) $\longrightarrow$ **only possibility?**

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- clockwork is robust if a symmetry gives $\Lambda_{5D} = 0$ (SUSY could do, but still...)
- consider 5 dimensions as before, with branes at $y = 0, \pi R$, SM at $y = 0$
- **additional** $D - 5$ flat dimensions $\sim L \ll R$
- **UV origin**: **dilaton** is the volume of these extra dimensions:

$$\sqrt{-g^{(D)}} = \sqrt{-g^{(5)}}\, e^{S(y)}$$

- **robustness**: in this setup **GR** in D dimensions **forbids** cosmological constant:

$$\sqrt{-g^{(D)}}\,\Lambda_D \longrightarrow \sqrt{-g^{(5)}}\, e^{S(y)}\,\Lambda_D \quad \text{in 5D}$$

- pure gravity with $\Lambda_D = -2k^2$:

$$\begin{aligned} \mathcal{S} &= \frac{M_D^{D-2}}{2} \int d^D X \sqrt{-g^{(D)}} \left(\mathcal{R}^{(D)} + 4k^2\right) \\ &\longrightarrow \frac{M_5^3}{2} \int d^5 x \sqrt{-g^{(5)}}\, e^S \left(\mathcal{R}^{(5)} + \frac{D-6}{D-5}\,\partial_m S\, \partial^m S + 4k^2\right) \end{aligned}$$

$\longrightarrow$ **linear dilaton** action for $D \to \infty$

$\longrightarrow$ linear dilaton as a **limit** of a non-stringy theory, **robust** without SUSY

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- consider 5 dimensions as before, with branes at $y = 0, \pi R$, SM at $y = 0$
- **additional** $D - 5$ flat dimensions $\sim L \ll R$
- **UV origin**: **dilaton** is the volume of these extra dimensions:

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- **robustness**: in this setup **GR** in D dimensions **forbids** cosmological constant:

$$\sqrt{-g^{(D)}}\, \Lambda_D \longrightarrow \sqrt{-g^{(5)}}\, e^{S(y)} \Lambda_D \quad \text{in 5D}$$

- pure gravity with $\Lambda_D = -2k^2$:

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$\longrightarrow$ **linear dilaton** action for $D \to \infty$

$\longrightarrow$ linear dilaton as a **limit** of a non-stringy theory, **robust** without SUSY

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Quasi linear-dilaton model [DT, '18]

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a theory with no exponential hierarchy in the fundamental parameters along the chain/extra dimension, that gives rise to an exponential hierarchy between the coupling of the light mode and of the clockwork gears to the same external sector

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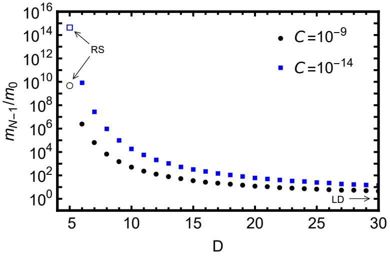

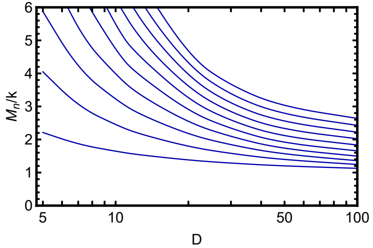

for large D still a **clockwork theory**!

The End