A CLOCKWORK WIMP

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PLAN

The Clockwork Mechanism illustrated

Construction of a Clockwork WIMP

Majorana neutrino masses

Relation to dimension deconstruction

Conclusions

Based on arXiv:1612.06411, in collaboration with Thomas Hambye and Daniele Teresi

ON SCALES AND MASSES

new physics (local) $\longrightarrow$ effective operators $\longrightarrow$ new scale

Weinberg operator $\longrightarrow$ L breaking scale

Proton decay $\longrightarrow$ GUT scale

Axion $\longrightarrow$ PQ symmetry breaking scale

Quantum gravity $\longrightarrow$ Planck scale

...

but **MASS ≠ SCALE**

$$G_F^{-1/2} \sim \frac{M_W}{g}$$

Fermi

$$\Lambda_\nu \sim \frac{M_R}{y^2}$$

Weinberg

$$M_P \sim \frac{M_s}{g_s}$$

Planck

THE CLOCKWORK MECHANISM

Kaplan & Ratazzi (2015); Choi & Im (2015) ; Giuidice & McCullough (2016)

$$\Lambda \sim \frac{M}{y^x}$$

large scale physics : large mass or tiny coupling?

We are often reluctant to introduce small parameters
(even if natural in the sense of 't Hooft)

The **Clockwork** is a possible mechanism
to generate **small numbers**
out of a theory with O(1) parameters

or **large effective scales** (e.g. M_P)
out of
dynamics at **much lower energies** (e.g. TeV)

perhaps experimentally accessible energies…

THE CLOCKWORK MECHANISM

Grand Goal : Addressing the Hierarchy Problem

Guidice & McCullough (2016)

THE CLOCKWORK MECHANISM

More prosaically, a framework for model builders….

THE CLOCKWORK MECHANISM

hierarchy problem Guidice & McCullough (2016)

low scale invisible axion Guidice & McCullough (2016); Farina *et al* (2016)

inflation Kehagias & Riotto (2016)

neutrino physics Hambye, Teresi & MT (2016); Carena *et al* (2017); Ibarra *et al* (2017)

dark matter Hambye, Teresi & MT (2016) (this talk)

…

THE CLOCKWORK MECHANISM

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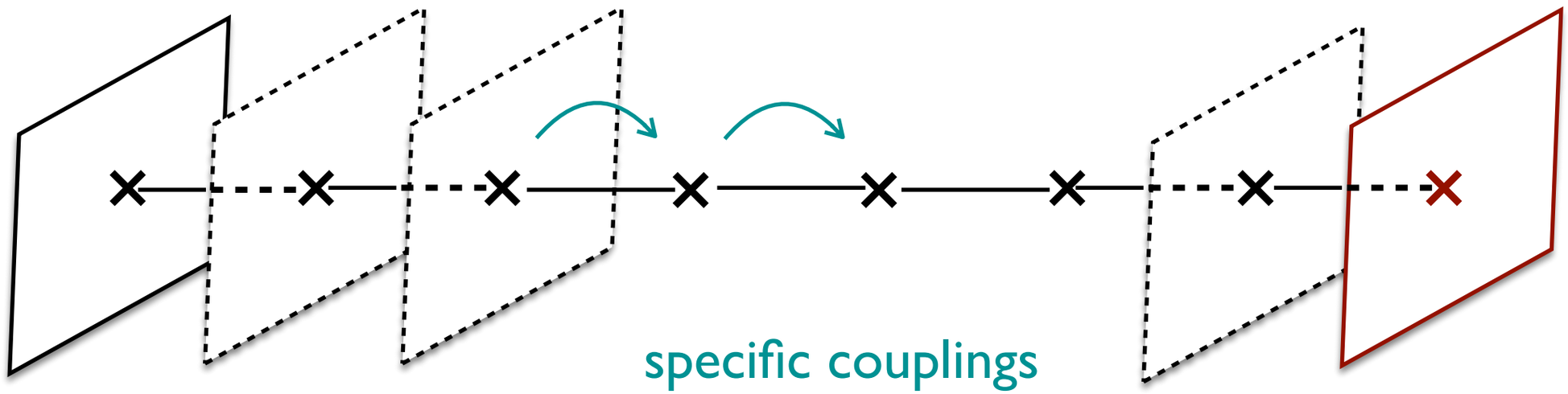
…

CLOCKWORK MECHANISM PICTORIALLY



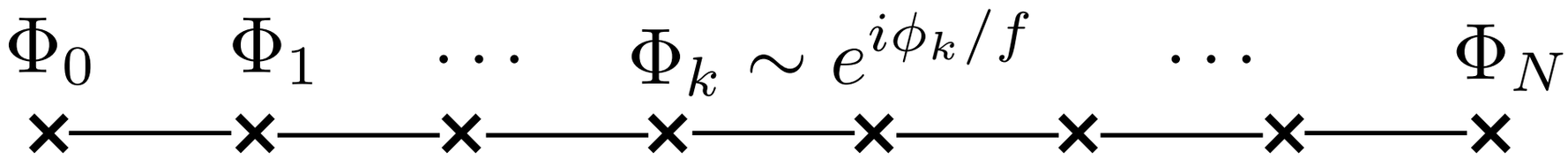
Hidden Sector
(e.g. DM)

specific couplings
lead to exponential
localization of the
lightest hidden field

Visible Sector
(SM)

We first illustrate this with a scalar model
or
Scalar Clockwork

CLOCKWORK MECHANISM ILLUSTRATED



$$\mathcal{L} = \frac{f^2}{2}\sum_{k=0}^{N}|\partial\Phi_k|^2 - \frac{m^2 f^2}{2}\sum_{k=0}^{N-1}(\Phi_k^\dagger \Phi_{k+1}^q + h.c.) \qquad \mathbf{q > 1}$$

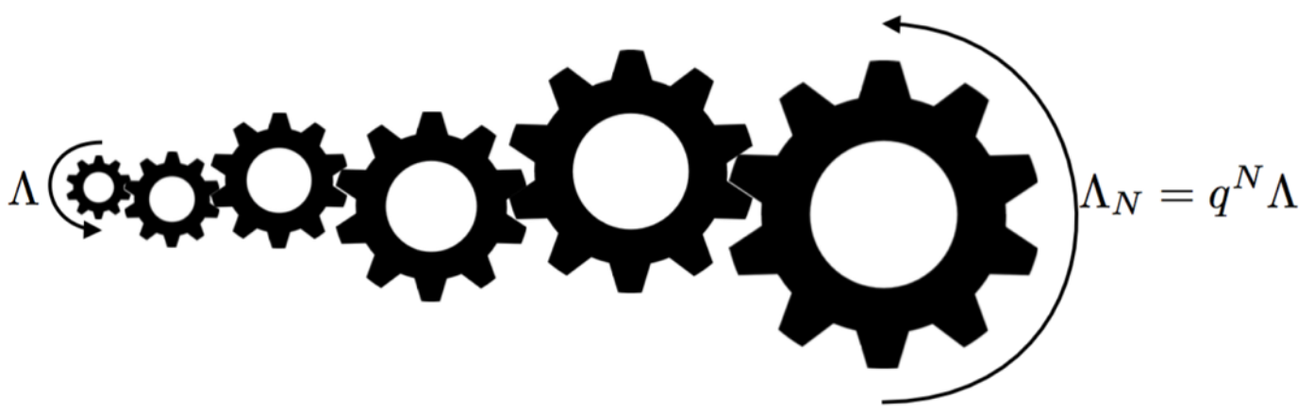
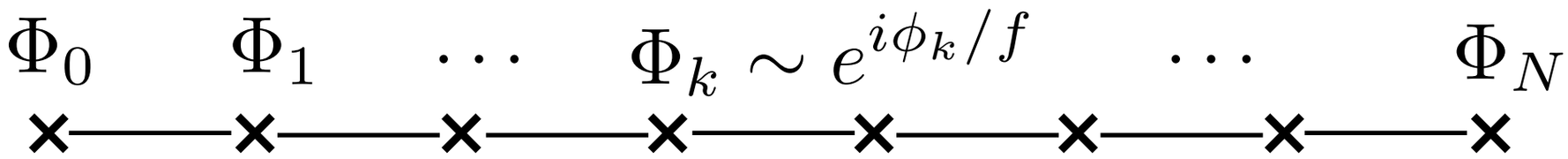


Figure 1: A schematic representation of the clockwork mechanism increasing the interaction scale of a non-renormalisable operator.

Guidice & McCullough (2016)

CLOCKWORK MECHANISM ILLUSTRATED



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$$-\frac{m^2}{2}\sum_{0}^{N-1}(\phi_k - q\phi_{k+1})^2 + \ldots$$

$$G = U_0(1)\otimes U_1(1)\otimes \ldots \otimes U_N(1) \quad \xrightarrow{m^2 \neq 0} \quad U(1)$$

one Goldstone mode + N massive modes

CLOCKWORK MECHANISM ILLUSTRATED

$$\Phi_0 \qquad \Phi_1 \qquad \cdots \qquad \Phi_k \sim e^{i\phi_k/f} \qquad \cdots \qquad \Phi_N$$

$$\times\!\!-\!\!-\!\!-\!\!\times\!\!-\!\!-\!\!-\!\!\times\!\!-\!\!-\!\!-\!\!\times\!\!-\!\!-\!\!-\!\!\times\!\!-\!\!-\!\!-\!\!\times\!\!-\!\!-\!\!-\!\!\times\!\!-\!\!-\!\!-\!\!\times\!\!-\!\!-\!\!-\!\!\times$$

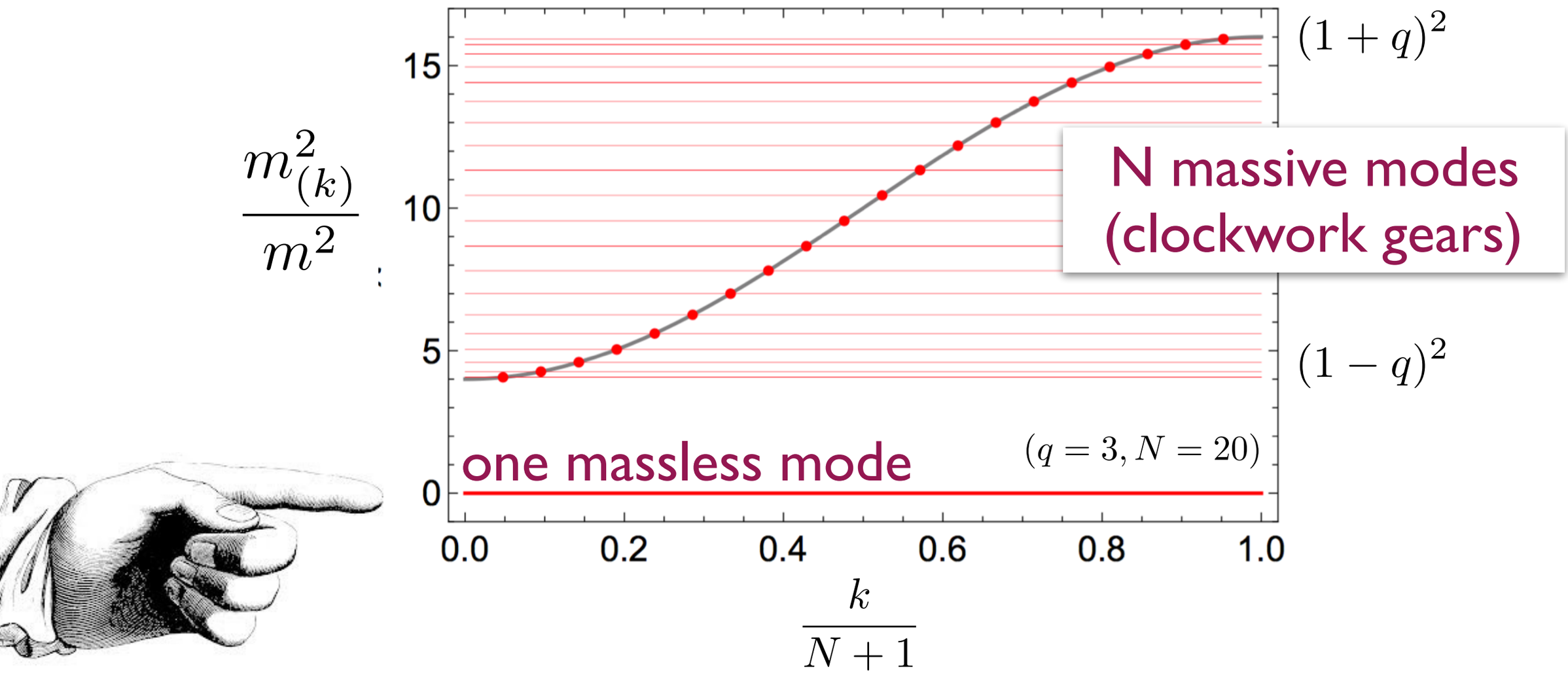
$$-\frac{m^2}{2}\sum_0^{N-1}(\phi_k - q\phi_{k+1})^2 + \ldots \quad \longrightarrow \quad M^2 = m^2 \begin{pmatrix} 1 & -q & 0 & \ldots & & 0 \\ -q & 1+q^2 & -q & \ldots & & 0 \\ 0 & -q & 1+q^2 & -q & & 0 \\ \vdots & \vdots & \vdots & \ddots & & \vdots \\ & & & -q & 1+q^2 & -q \\ 0 & 0 & 0 & \ldots & -q & q^2 \end{pmatrix}$$

$$M^2\varphi^{(0)} = 0 \quad \longrightarrow \quad \varphi^{(0)} \sim \phi_0 + \phi_1/q + \ldots + \phi_N/q^N$$

$$q > 1 \to q^N \gg 1$$

massless mode
localized towards site k=0

CLOCKWORK MECHANISM ILLUSTRATED



plot from Farina *et al* (2016)

CLOCKWORK MECHANISM ILLUSTRATED

$$\varphi^{(0)} \sim \phi_0 \quad \phi_1 \quad \cdots \quad \phi_N \text{ — SM}$$

massless mode localized towards site k=0

$$\mathcal{L} \supset \frac{\phi_N}{F} G\tilde{G} \quad \longrightarrow \quad \frac{\varphi^{(0)}}{q^N F} G\tilde{G}$$

very tiny coupling!

e.g.

$$N = 15, \quad q = 3 \quad \longrightarrow q^N F \sim 10^{10} \left(\frac{F}{\text{TeV}}\right) \quad \text{GeV}$$

thus large effective scale!

WHY A CLOCKWORK WIMP ?

Massive particle χ Real (~ Majorana neutrino) or Complex (~ Dirac neutrino)

Neutral (i.e. not seen, in a broad sense)

Very stable

$\tau \gtrsim 10^{18}\mathrm{sec}$ to be around today

$\tau \gtrsim 10^{26}\mathrm{sec}$ from constraints on decay products

easy as Z_2

Annihilate into Standard Model particles

$$\chi + \chi \leftrightarrow f + \bar{f}$$

directly or indirectly (i.e. secluded dark matter)

$$\langle \sigma v \rangle \sim 3 \cdot 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$$

WHY A CLOCKWORK WIMP ?

WIMP **stability** in general protected by a **symmetry**

discrete global ~ R-parity in SUSY SM & hundreds of toy models

discrete ~ SO(10) or **continuous gauge sym.** ~ hidden photons

accidental symmetry (like the proton)

ACCIDENTAL SYMMETRY ?

1. Proton stability (natural because it's not a fundamental particle)

$$\mathcal{L} \supset y\,\bar{p}e^+\pi_0 \longrightarrow \Gamma_p \propto y^2 m_p \longrightarrow y \lesssim 10^{-32}$$

$$\mathcal{O} \sim \frac{1}{\Lambda^2}\bar{\psi}_q\Gamma\psi_q\bar{\psi}_q\Gamma'\psi_e \longrightarrow \Gamma_p \propto \frac{1}{\Lambda^4}m_p^5$$

$$\tau_p \gtrsim 10^{40}\mathrm{sec} \longrightarrow \Lambda \gtrsim 10^{16}\mathrm{GeV} \qquad \Lambda_{\mathrm{gut}}?$$

2. Large SU(2) representation?

e.g. a Majorana SU(2) 5-plet (aka **Minimal Dark Matter**) $M_5 \sim \mathrm{TeV}$

dim-6 decay op. $\tau \sim \dfrac{\Lambda^4}{M^5}$ $\tau_5 \gtrsim 10^{26}\mathrm{sec} \longrightarrow \Lambda \gtrsim 10^{16}\mathrm{GeV}$

WHY A CLOCKWORK WIMP ?

Q: can we make a WIMP long lived with $\Lambda \sim$ TeV ?

CLOCKWORK WIMP - CONSTRUCTION

chiral chain

$R_0 \quad L_1 R_1 \quad \cdots \quad L_N R_N$

× × × × × × ×

complex scalars

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

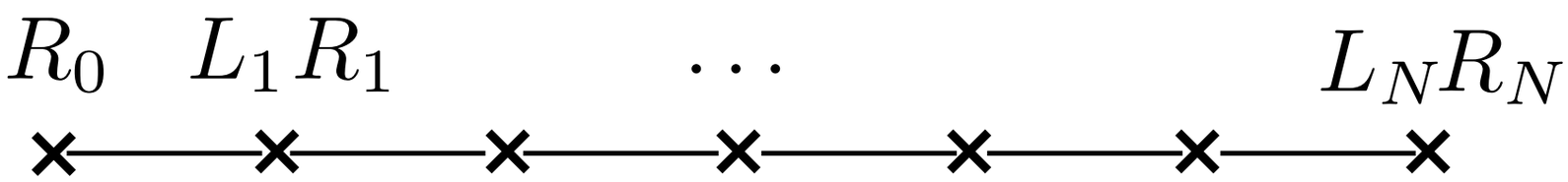
basic ingredients:

One chiral chain (L and R Weyl spinors)
+ 2 N complex scalars (spurions and/or dynamical)

The construction goes through 4 steps

CLOCKWORK WIMP - CONSTRUCTION

chiral chain



complex scalars

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

step 1: break the chiral symmetries

$$\begin{cases} m \to y_S \langle S_i \rangle \\ mq \to y_C \langle C_i \rangle \end{cases}$$

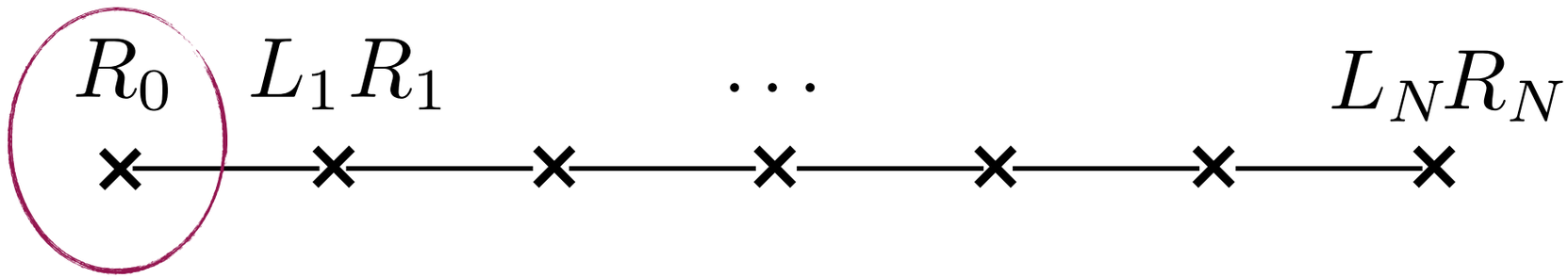
These fields are spurions in the original framework
They are dynamical in our case

$$U(1)_{R_0} \times U(1)_{L_1} \times U(1)_{R_1} \times \ldots \times U(1)_{L_N} \times U(1)_{R_N} \longrightarrow U(1)_R$$

one **massless** mode

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

CLOCKWORK WIMP - CONSTRUCTION



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

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

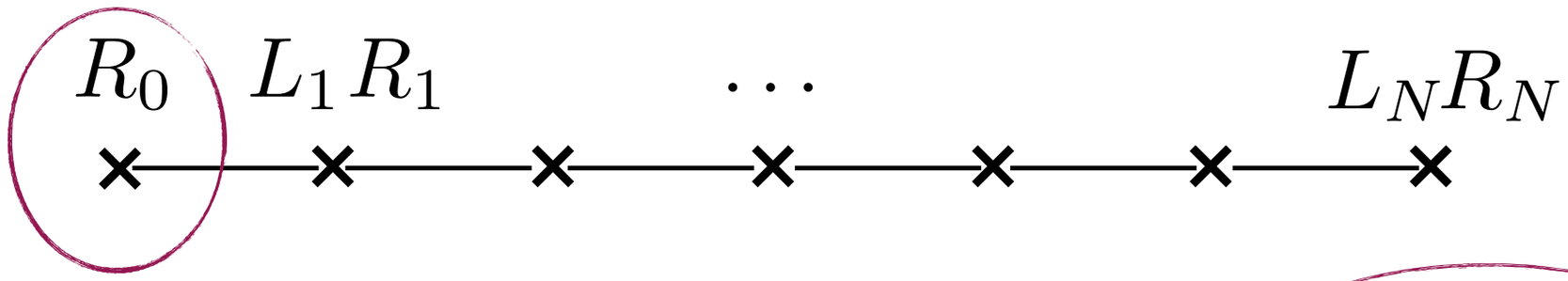
massless chiral mode

$$\psi^{(n)} \approx \frac{1}{\sqrt{N}} \sum_k \left[\mathcal{O}(1) L_k + \mathcal{O}(1) R_k \right]$$

N Dirac gears
mass ~ q m

i.e. pretty much like the scalar clockwork

CLOCKWORK WIMP - CONSTRUCTION



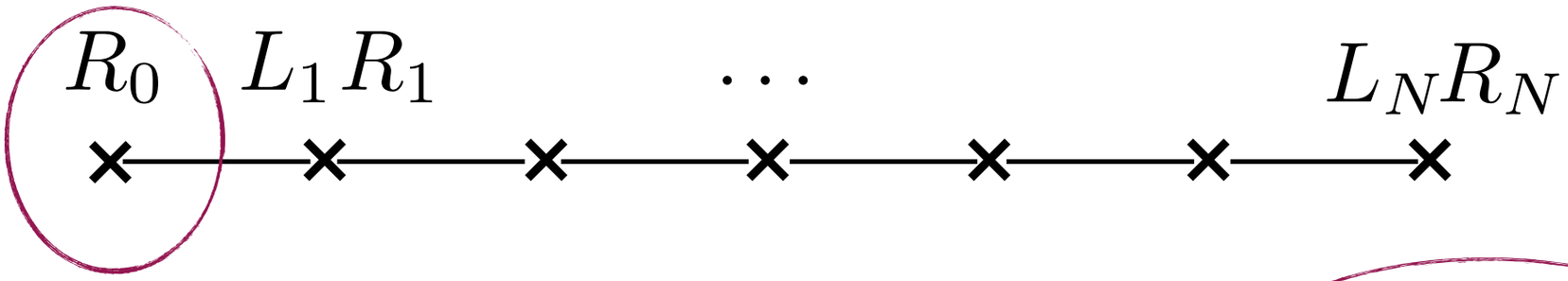
$$\mathcal{L} \supset -m \sum_{i=1}^{N} \left(\bar{L}_i R_{i-1} - q \bar{L}_i R_i \right) + h.c. - \frac{1}{2} m_N \bar{R}_0^c R_0$$

step 2: break the residual chiral symmetry

i.e.

give a mass to the N ~ DM state

CLOCKWORK WIMP - CONSTRUCTION



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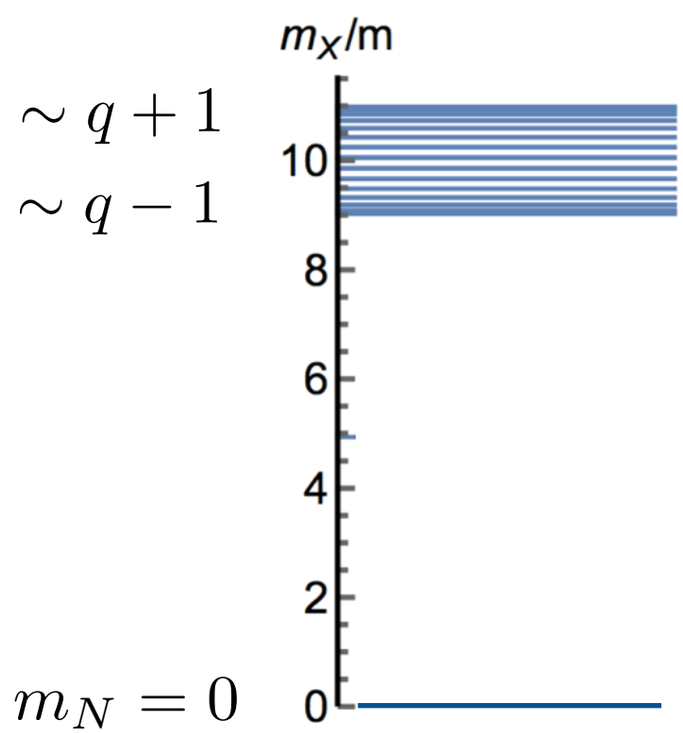
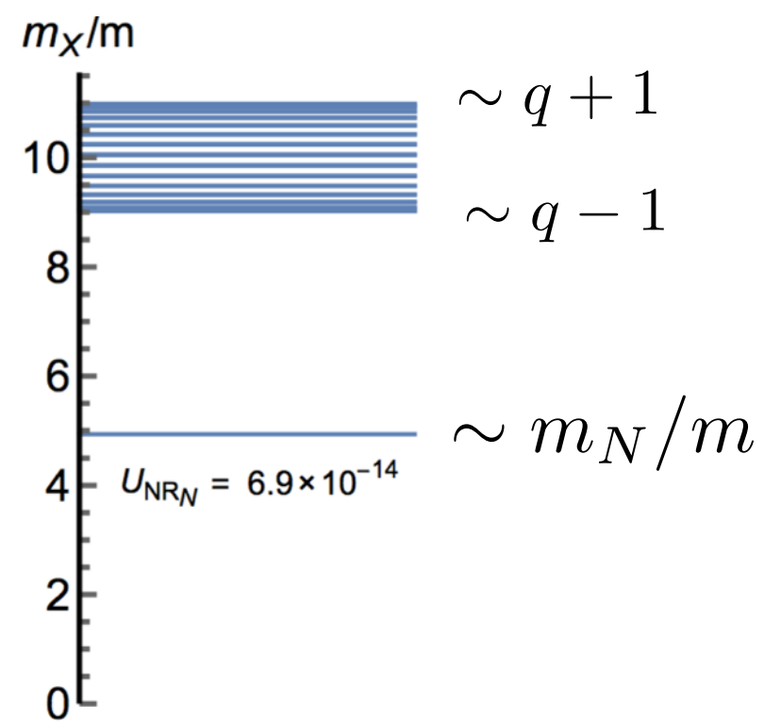
$(q = 10, N = 15, m_N = 0)$



$(q = 10, N = 15, m_N = 5m)$



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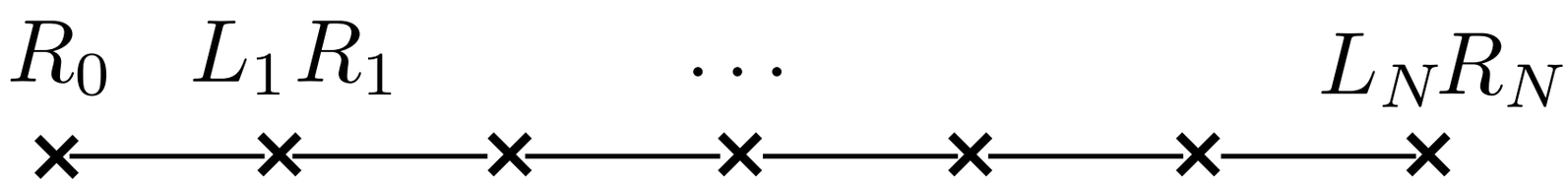

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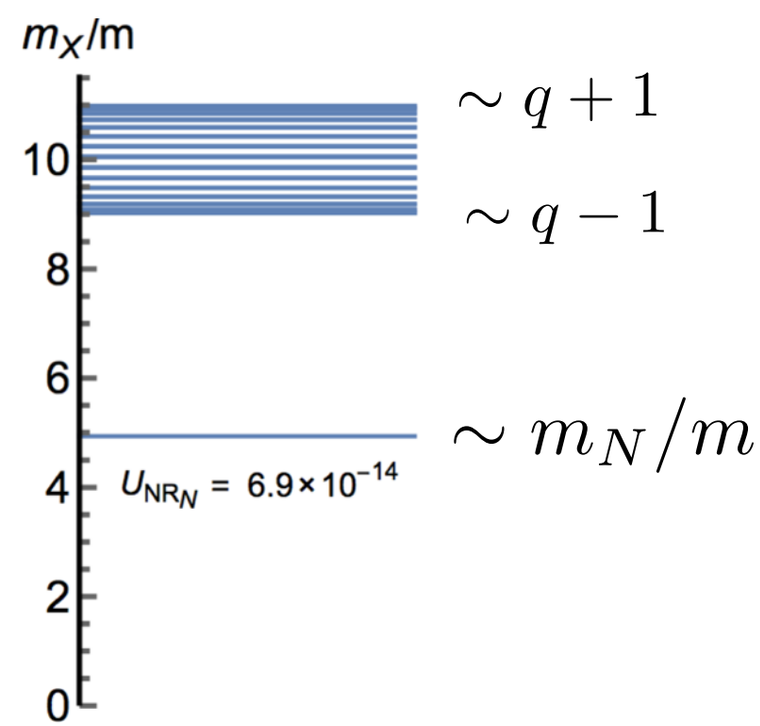
clockwork mechanism unaffected provided

$$m_N \lesssim qm$$

$$\left\{ \begin{array}{l} \text{one light \& localized mode} \\ \text{N gears with O(1) couplings} \end{array} \right.$$

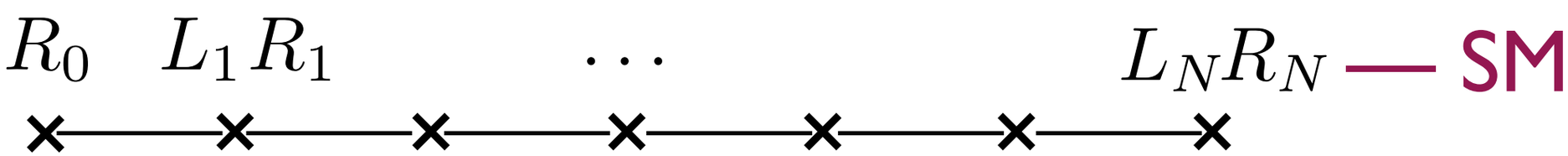
(pseudo-Dirac if $q \gg m_N/m$)

$(q = 10, N = 15, m_N = 5m)$



Hambye, Teresi & MT (2016)

CLOCKWORK WIMP - CONSTRUCTION



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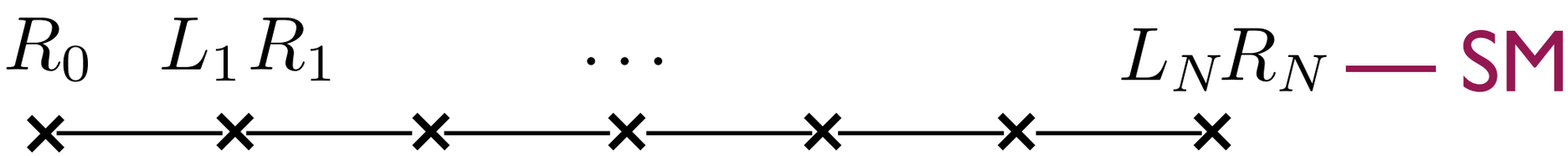
$$-y(\bar{L}_{SM} H \tilde{R}_N + h.c.)$$

step 3: couple the chain to the SM

CLOCKWORK WIMP - CONSTRUCTION



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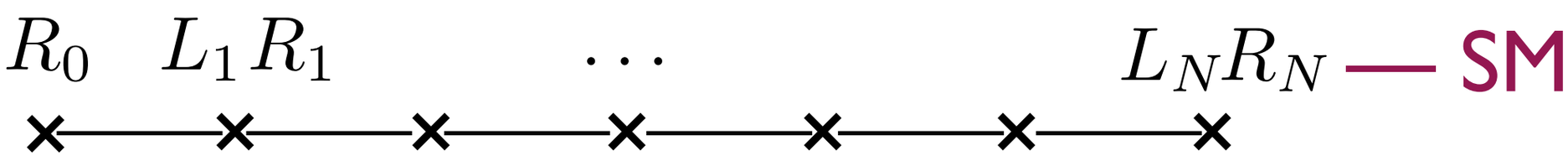
$$-y(\bar{L}_{SM} \tilde{H} R_N + h.c.)$$

step 3: couple the chain to the SM

$$N \approx R_0 + \frac{1}{q} R_1 + \frac{1}{q^2} R_2 + \ldots + \frac{1}{q^N} R_N \rightarrow \mathcal{L} \supset -\frac{y}{q^N} \bar{L}_{SM} \tilde{H} N + h.c.$$

tiny coupling

CLOCKWORK WIMP - CONSTRUCTION



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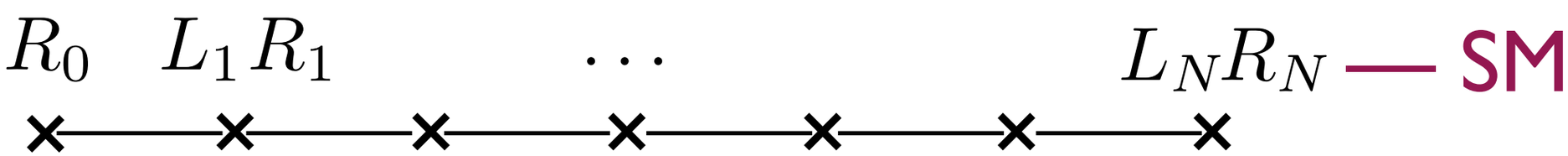
$$-y(\bar{L}_{SM} H \bar{R}_N + h.c.)$$

$$\mathcal{L} \supset \frac{-y}{q^N} \bar{L}_{SM} \tilde{H} N + h.c. \longrightarrow \Gamma(N \to \nu h, \nu Z, lW) \sim \frac{m_N}{8\pi} \frac{y^2}{q^{2N}}$$

The N mode is **unstable** but lifetime $\gtrsim 10^{26}\mathrm{sec}$ (gamma's, etc.)

if $q^{2N} \gtrsim 10^{52} \left(\frac{m_N}{100\mathrm{GeV}} \right) y^2$ **e.g.** $(q = 10, N = 26, y = 1)$

CLOCKWORK WIMP - CONSTRUCTION



$$\mathcal{L} \supset -m \sum_{i=1}^{N} \left(\bar{L}_i R_{i-1} - q \bar{L}_i R_i \right) + h.c. - \frac{1}{2} m_N \bar{R}_0^c R_0$$

$$-y(\bar{L}_{SM} H \tilde{R}_N + h.c.)$$

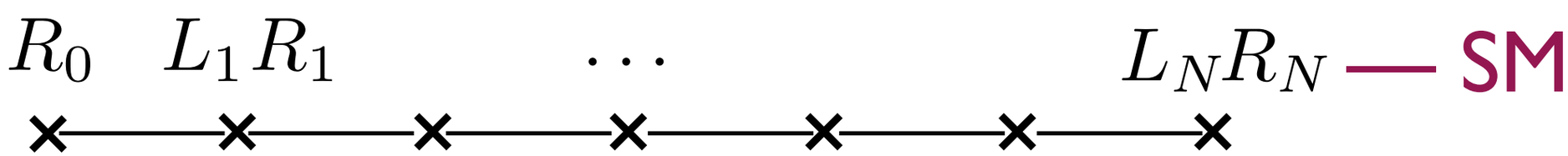
last (but not the least) **step**:

abundance from thermal freeze-out?

$$NN \to hh, hZ, l\bar{l}, \ldots \quad \textbf{but rate} \quad \propto \frac{y^4}{q^{4N}}$$

i.e. very much suppressed…

CLOCKWORK WIMP - AT LAST



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kinetic}$$

$$- \sum_{i=1}^{N} \left(y_S S_i \bar{L}_i R_{i-1} - y_C C_i \bar{L}_i R_i + h.c. \right)$$

$$- \left(y \, \bar{L}_{SM} \widetilde{H} R_N + h.c. \right) - \frac{1}{2} \left(m_N \overline{R_0^c} \, R_0 + h.c. \right)$$

$$- \sum_{i=1}^{N} \left(\lambda_S \, S_i^\dagger S_i \, H^\dagger H + \lambda_C \, C_i^\dagger C_i \, H^\dagger H \right)$$

χSB

N mass
& DM-SM

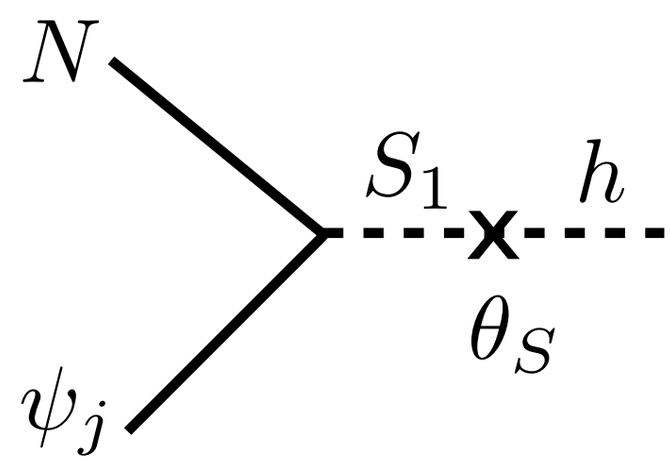
Higgs
portal

not sure I would put that Lagrangian on a t-shirt

CLOCKWORK WIMP - AT LAST

$$\mathcal{L} \supset -\frac{\xi_j^S}{\sqrt{2}} S_1 \bar{\psi}_j P_R N + h.c.$$

$$-\frac{\xi_j}{\sqrt{2}} h \bar{\psi}_j P_R N + h.c.$$



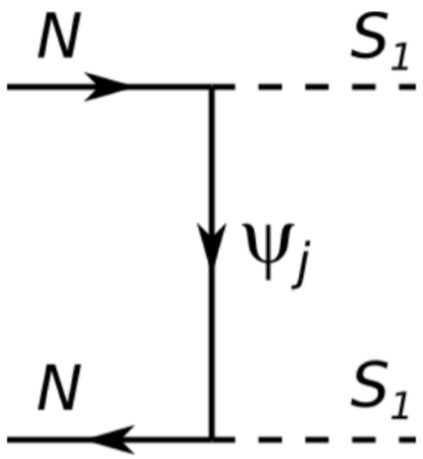
with $\xi_j^S \approx \sqrt{\frac{2}{N+1}} \sin\left(\frac{j\pi}{N+1}\right) y_S$ and $\xi_j \approx \theta_S \xi_j^S$

O(1) couplings with gears can be used to make N a WIMP!

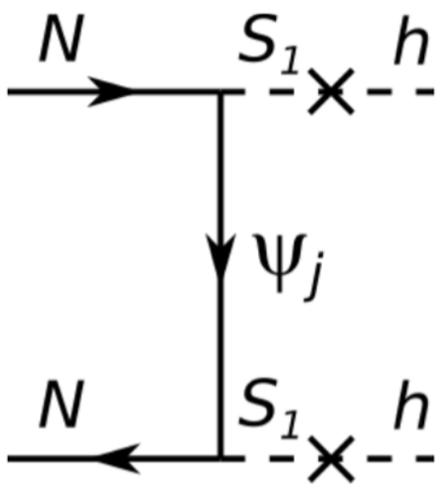
Hambye, Teresi & MT (2016)

CLOCKWORK WIMP - RECAP

Abundance



(Secluded scenario)



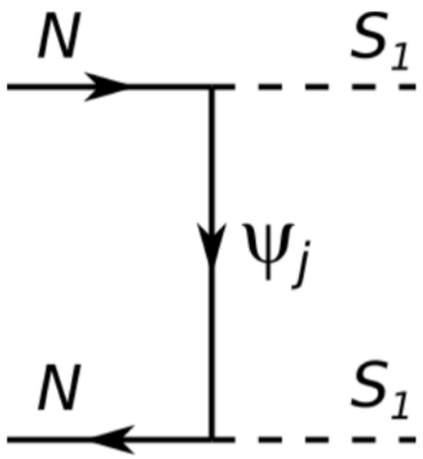
(Higgs portal scenario)

annihilation through the chiral gears

$\langle \sigma v \rangle \sim 3 \cdot 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$

CLOCKWORK WIMP - RECAP

Abundance



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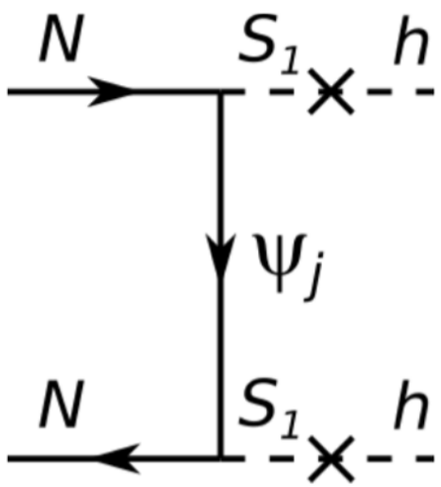

(Higgs portal scenario)

annihilation through the chiral gears

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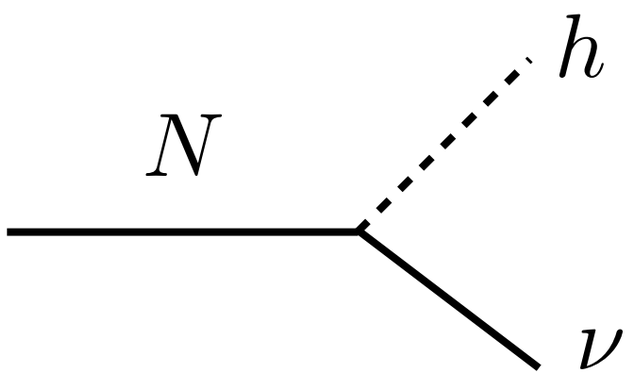
Stability/decay



$$\frac{1}{q^N}$$

suppressed by the chiral chain

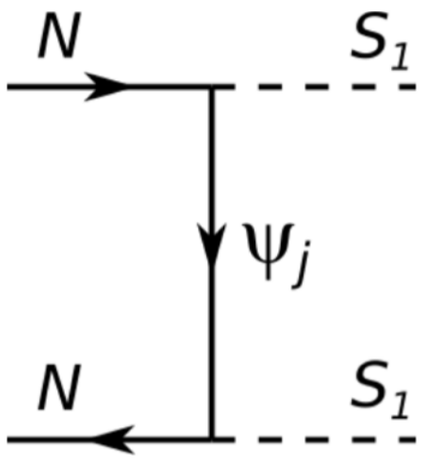
Diagonal coupling to Higgs

(taking into account the pseudo-Dirac nature of the clockwork gears)

$$\mathcal{L} \supset \frac{m_N}{\sqrt{2}m} \frac{\xi}{q^2} \bar{N}^c N\, h + h.c.$$

CLOCKWORK WIMP - RECAP

Abundance



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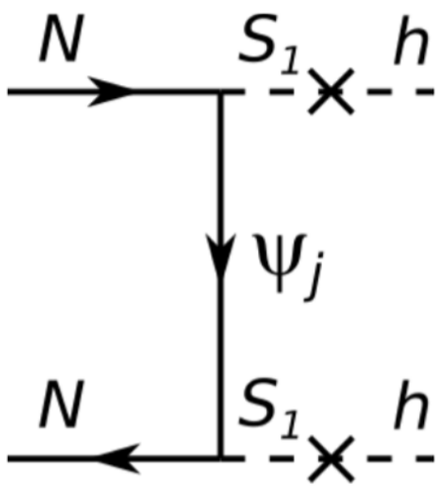
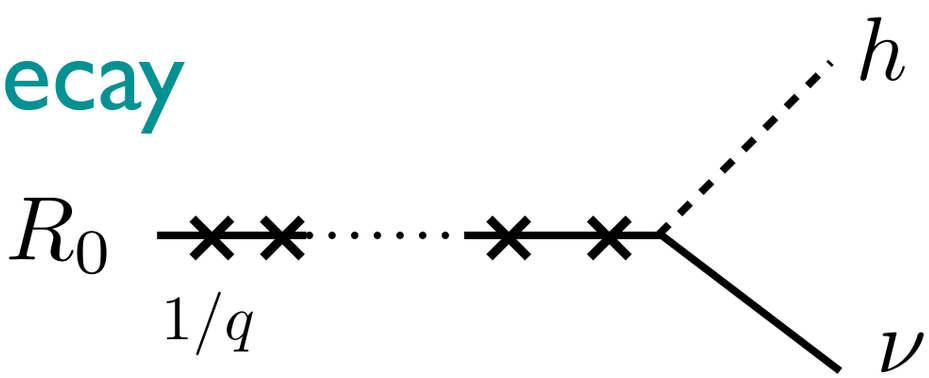


(Higgs portal scenario)

annihilation through the chiral gears

$\langle \sigma v \rangle \sim 3 \cdot 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$

Stability/decay



$$\frac{1}{q^N}$$

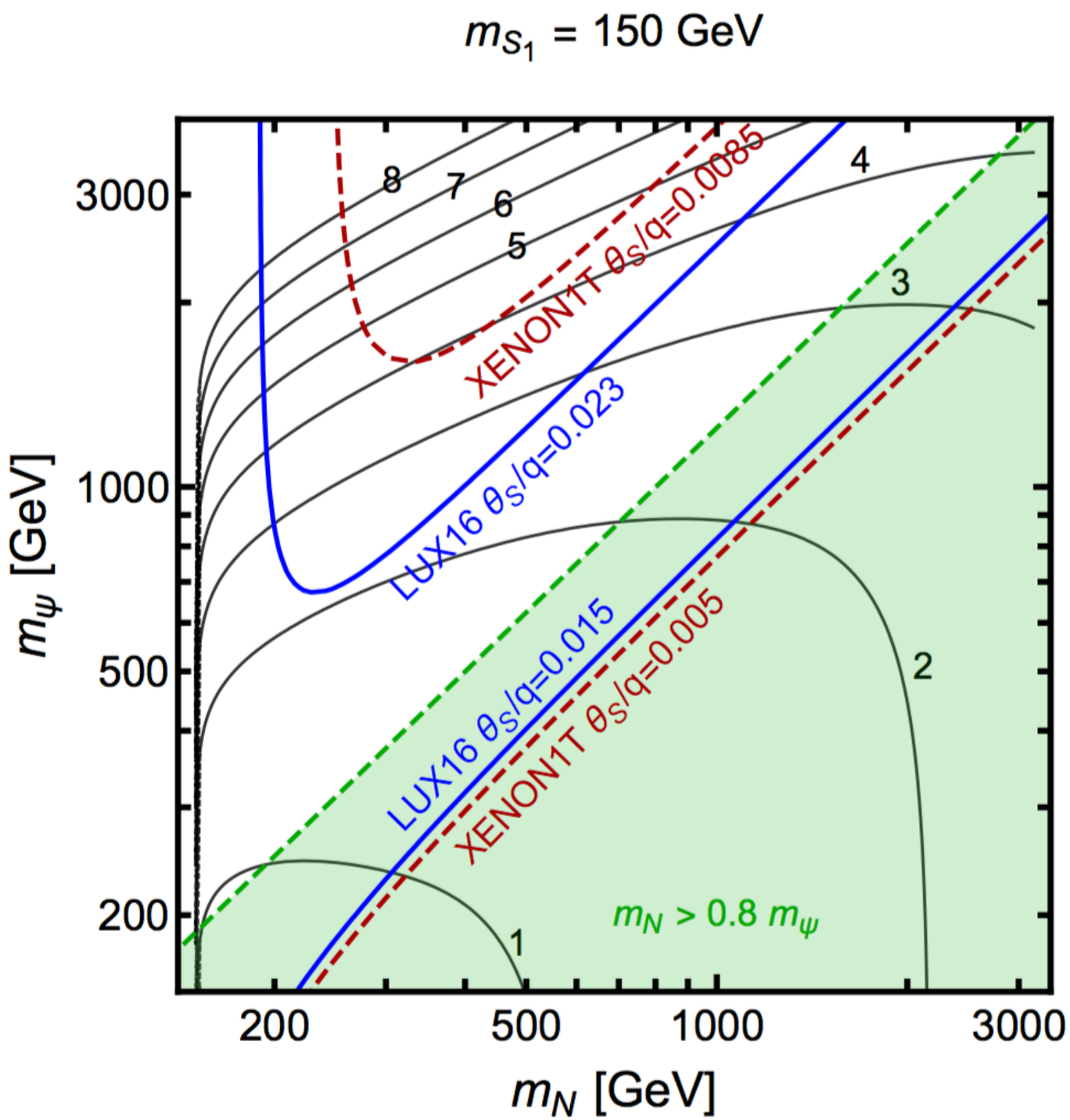
suppressed by the chiral chain

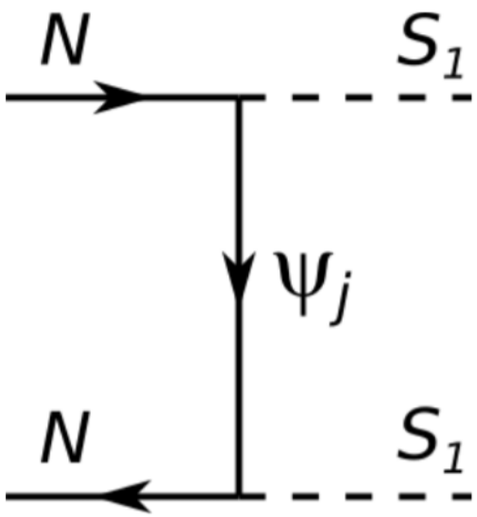
Diagonal coupling to Higgs

(taking into account the pseudo-Dirac nature of the clockwork gears)

$$\mathcal{L} \supset \frac{m_N}{\sqrt{2}m} \frac{\xi}{q^2} \bar{N}^c N\, h + h.c.$$

CLOCKWORK WIMP PHENO - ex. SECLUDED





black solid: y_S required for $\Omega_{dm} \approx 0.25$

blue solid: LUX16 exclusions (below lines)

red dashed: Xenon1T reach

Higgs mediated $\propto (\theta_S/q)^2$

CLOCKWORK WIMP PHENO

The clockwork gears ψ_i are essentially

a bunch of **TeV pseudo-Dirac sterile neutrinos**

with O(1) coupling to the SM leptons and the Higgs

<u>L conserving searches @ LHC</u> ~ 3 charged leptons

$$pp \to l_1^+ \Psi_i \to l_1^+ l_2^- W^+ \to l_1^+ l_2^- l_3^+ \nu \qquad m_\psi \lesssim 200 \text{ GeV} \quad (300\,\text{fb}^{-1})$$

Das, Dev & Okada (2014)

<u>L violating searches @ LHC</u> ~ 2 same sign leptons

$$pp \to l_1^+ \Psi_i \to l_1^+ l_2^+ W^- \to l_1^+ l_2^+ \text{jets} \qquad m_\psi \lesssim 300\text{GeV} \quad (300\,\text{fb}^{-1})$$

Deppisch, Dev & Pilaftsis (2015)

CLOCKWORK WIMP PHENO

DM indirect detection

p-wave annihilation, but decay into mono-energetic neutrinos

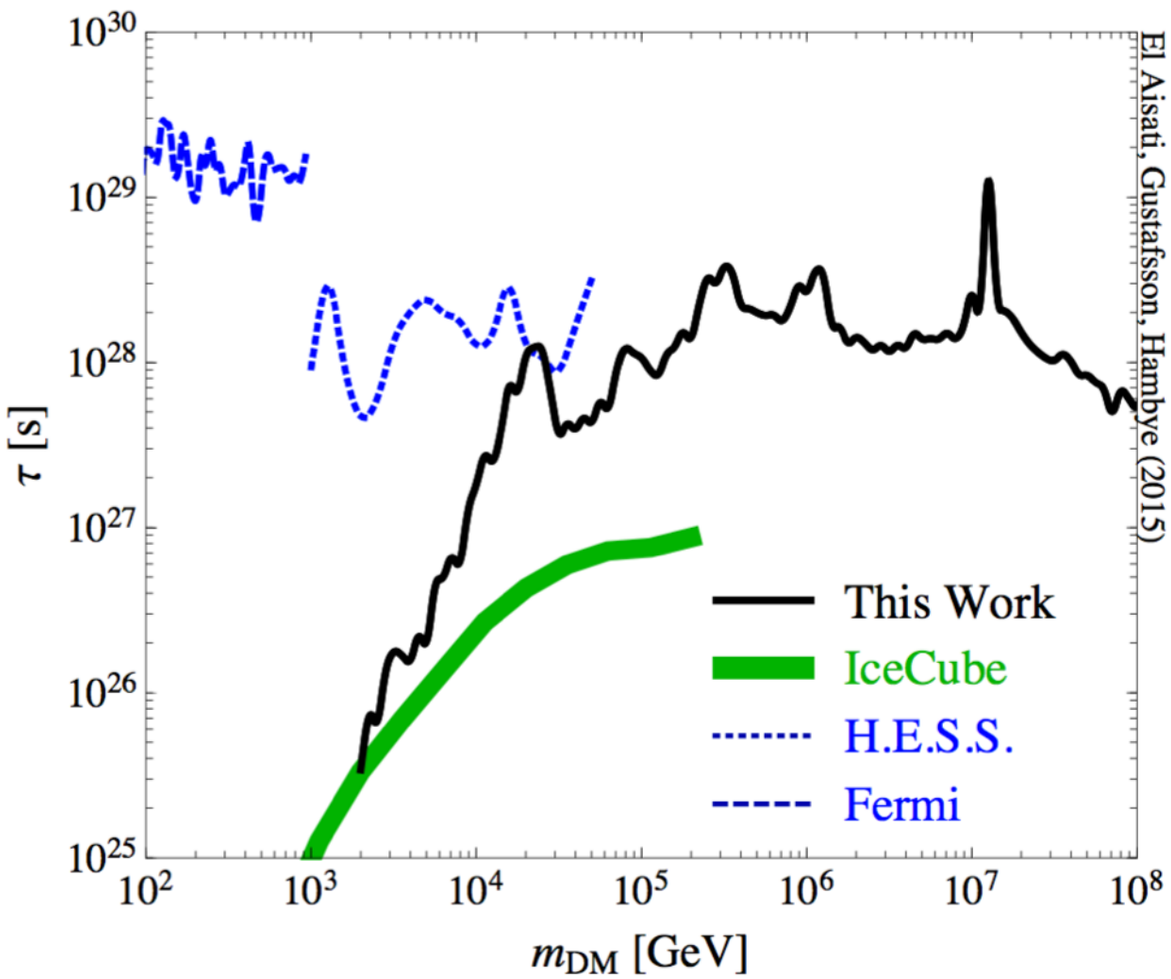


FIG. 8: Lifetime limits on DM particle decay into monochromatic lines $\nu + \gamma$. From Fermi-LAT [78] (blue, dashed) and H.E.S.S. [12, 28] (blue, dotted) using gamma-ray data compared to the neutrino line bounds derived in this study (solid black) as well as previous IceCube limits [31] (thick green).

$$N \to \nu + H$$

To recap, the <u>same</u> degrees of freedom that fix N abundance make N long-lived!

El Aisati, Gustafsson & Hambye (2015)

LOT OF FIELDS, WITH **VERY** SPECIFIC COUPLINGS…

CLOCKWORK CHIRAL CHAIN FROM DECONSTRUCTION

our Lagrangian is related to a discretized **flat** 5th dimension (Z)

1) $\mathcal{L}_5 \supset \bar{\psi}(i\overleftrightarrow{\partial\!\!\!/} - M)\psi = i\bar{\psi}\gamma^\mu\partial_\mu\psi + \left[\frac{1}{2}\left(\bar{L}\partial_Z R - \partial_Z \bar{L} R\right) - M\bar{L}R + h.c.\right]$

2) naive discretization ⇒ fermion doubling

⇒ add a Wilson term $-\frac{a}{2}\partial_Z\bar{\psi}\partial_Z\psi$ with lattice spacing $a = \frac{\pi R}{N} \to 0$

3) Dirichlet condition $L(0) = 0$ ⇒ surviving chiral mode R_0

4) Standard Model degrees of freedom at $Z = \pi R$ (~ braneworld)

$$\mathcal{L} \supset \sum_{i=0}^{N-1} \underbrace{\frac{1}{a}}_{m} \bar{L}_{i+1} R_i - \sum_{i=1}^{N} \underbrace{\left(\frac{1}{a} + M\right)}_{qm} \bar{L}_i R_i$$

well-defined continuum limit

$$q^N = \left(1 + \frac{\pi R M}{N}\right)^N \quad \to \quad e^{\pi R M}$$

$1/M \ll \pi R$

Hambye, Teresi & MT (2016)

MORE ON DECONSTRUCTION

Clockwork (CW) scalar ☞ Linear Dilaton (LD)

Giuidice & McCullough (2016)

warped, conformally flat 5D $$ds^2 = e^{\frac{4}{3}k|y|}\left(\eta_{\mu\nu}dx^\mu dx^\nu + dy^2\right)$$

LargeExtraDim < CW/LD < Randall-Sundrum

hierarchy from volume

$$M_P^2 \propto R M_5^3$$

hierarchy from warping

Giuidice, Kats, McCullough, Torre & Urbano (2017)

MORE ON DECONSTRUCTION

Clockwork (CW) scalar ☞ Linear Dilaton (LD)

Giuidice & McCullough (2016)

warped, conformally flat 5D $$ds^2 = e^{\frac{4}{3}k|y|}\left(\eta_{\mu\nu}dx^\mu dx^\nu + dy^2\right)$$

LargeExtraDim < CW/LD < Randall-Sundrum

hierarchy from volume	**hierarchy from volume & warping**	**hierarchy from warping**
$M_P^2 \propto RM_5^3$		

Giuidice, Kats, McCullough, Torre & Urbano (2017)

CONCLUSIONS

We have built a clockwork WIMP
It is accidentally stable (not protected by a symmetry)

Its decay is mediated by the very same degrees of freedom that determine its abundance

These many degrees of freedom lie in the 100 GeV-TeV range

They could be seen @ LHC as sterile RHN

There are also (possibly) plenty of scalars to search for @ LHC

It is also a framework for low scale SM neutrino Majorana mass and potentially for much of BSM physics

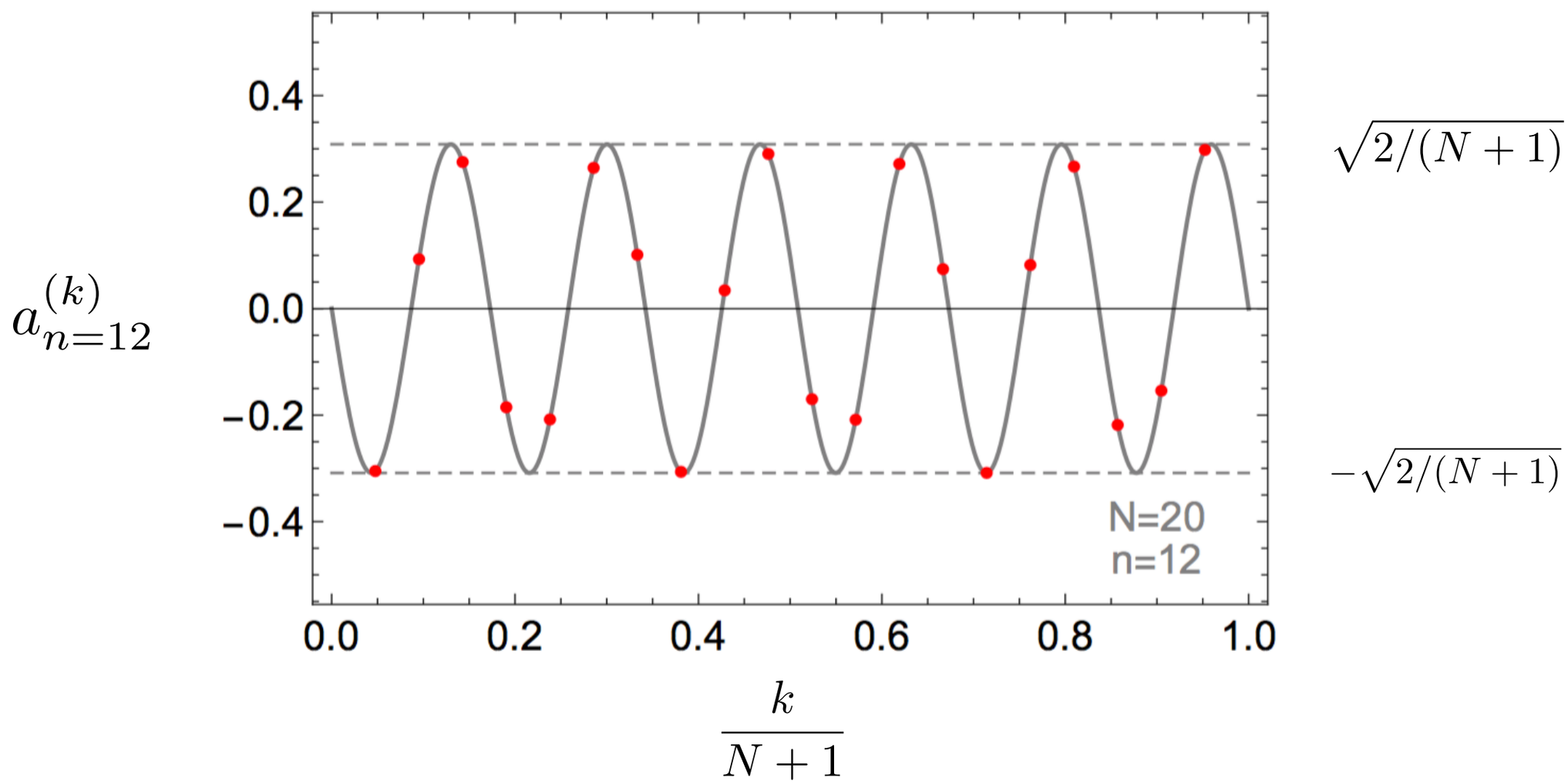
The clockwork could be seen as a (discrete) spatial dimension
May lead to unusual signatures, which are worth being studied further

Backup slides

CLOCKWORK MECHANISM ILLUSTRATED

$$\varphi^{(k)} = \sum_{n=0}^{N} a_n^{(k)} \phi_n$$

Clockwork Gears have unsuppressed overlap (eventually coupling) at all sites!

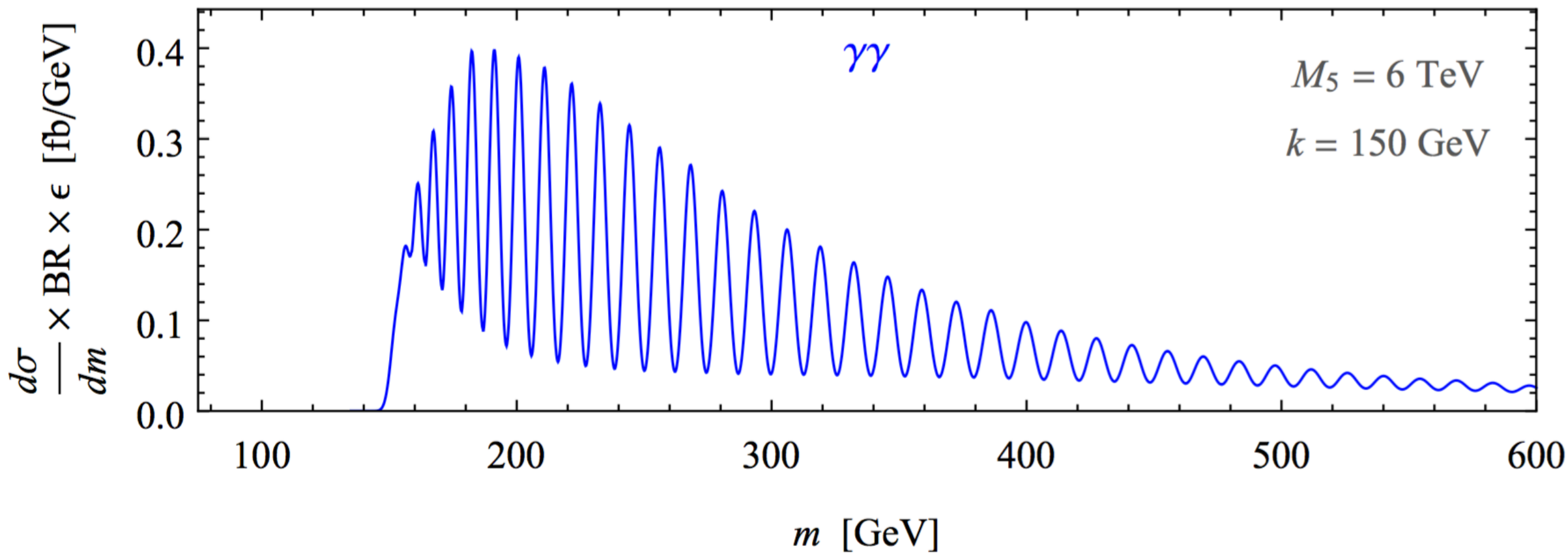


plot from Farina, Pappadopulo, Rompineve & Tesi (2016)

MORE ON DECONSTRUCTION

Clockwork (CW) scalar ☞ Linear Dilaton (LD)

KK graviton → γγ

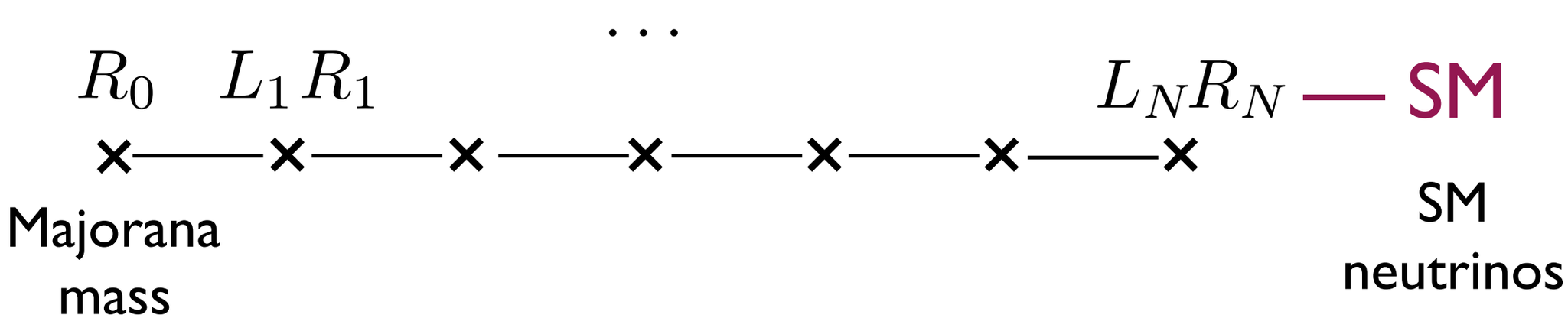


plot from Giuidice, Kats, McCullough, Torre & Urbano (2017)

CLOCKWORK NEUTRINO

Hambye, Teresi & MT (2016)

another chain…



Majorana character has to go through the whole chain

$$m_\nu \sim y^2 \frac{v^2}{q^N M}$$

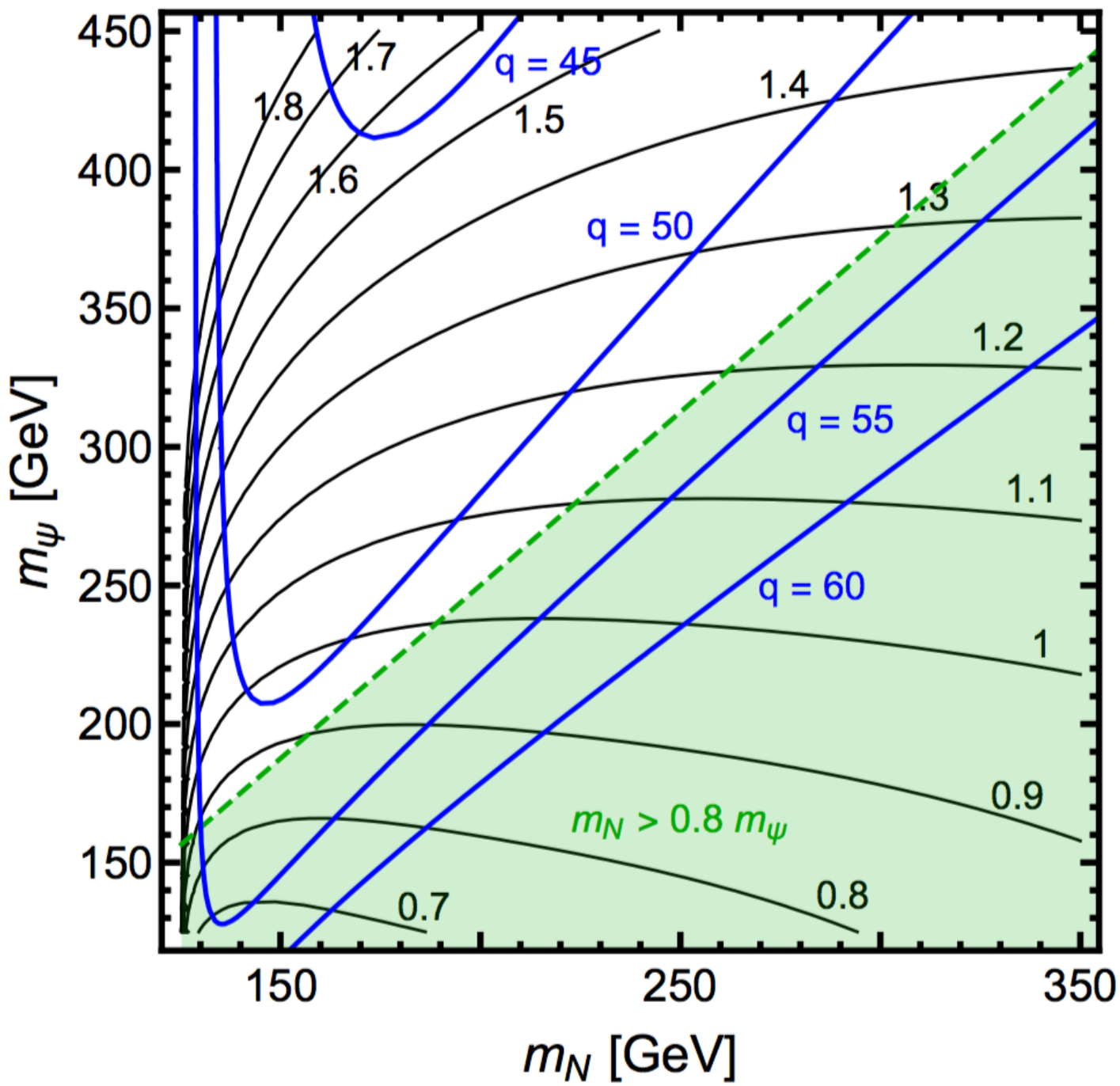
Smaller chain than for DM stability $(q = 10, N = 7, M = 1\,\mathrm{TeV})$

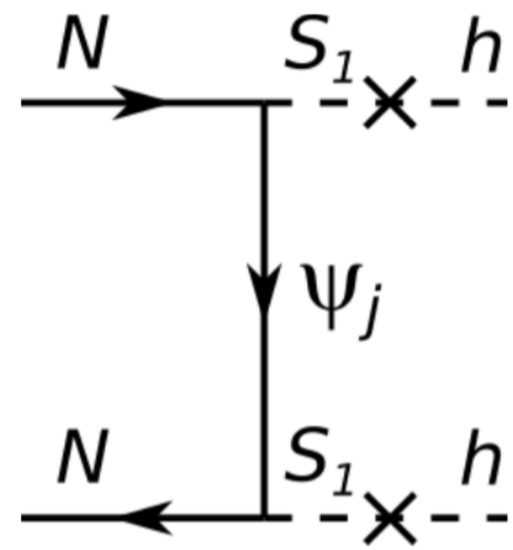
but need one per SM neutrino mass!

(i.e. at least 2 chains for neutrino, one for the DM…)

See also Carena, Li, Machado, Machado & Wagner (2017); Ibarra, Kushwaha & Vempati (2017)

CLOCKWORK WIMP PHENO - HIGGS PORTAL





$$\theta_S \lesssim \frac{0.4}{\sqrt{N}}$$

<u>black solid</u>: $y_S \theta_S$ required for $\Omega_{dm} \approx 0.25$

<u>blue solid</u>: LUX16 exclusions (below lines)

(no time to put the new Xenon1T limits, sorry)