A CLOCKWORK WIMP

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PLAN

- the clockwork mechanism illustrated
- construction of a clockwork wimp
- Majorana neutrino masses
- a bit of 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

$\dots$

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
out of
dynamics at **much lower energies**

reading accessible energies…

THE CLOCKWORK MECHANISM

a framework for model building….

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)
- sugra Antoniadis, Delgado, Markou & Pokorski (2016)
- dark matter Hambye, Teresi & MT (2016) (this talk)

- …

THE CLOCKWORK MECHANISM ILLUSTRATED

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

$$\times \quad \times \quad \times \quad \times \quad \times \quad \times \quad \times \quad \times$$

The Scalar Clockwork

THE CLOCKWORK MECHANISM ILLUSTRATED

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

$$\times \quad \times \quad \times \quad \times \quad \times \quad \times \quad \times \quad \times$$

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

$q > 1$

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

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

one massless + N massive modes

THE CLOCKWORK MECHANISM ILLUSTRATED

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

× × × × × × × ×

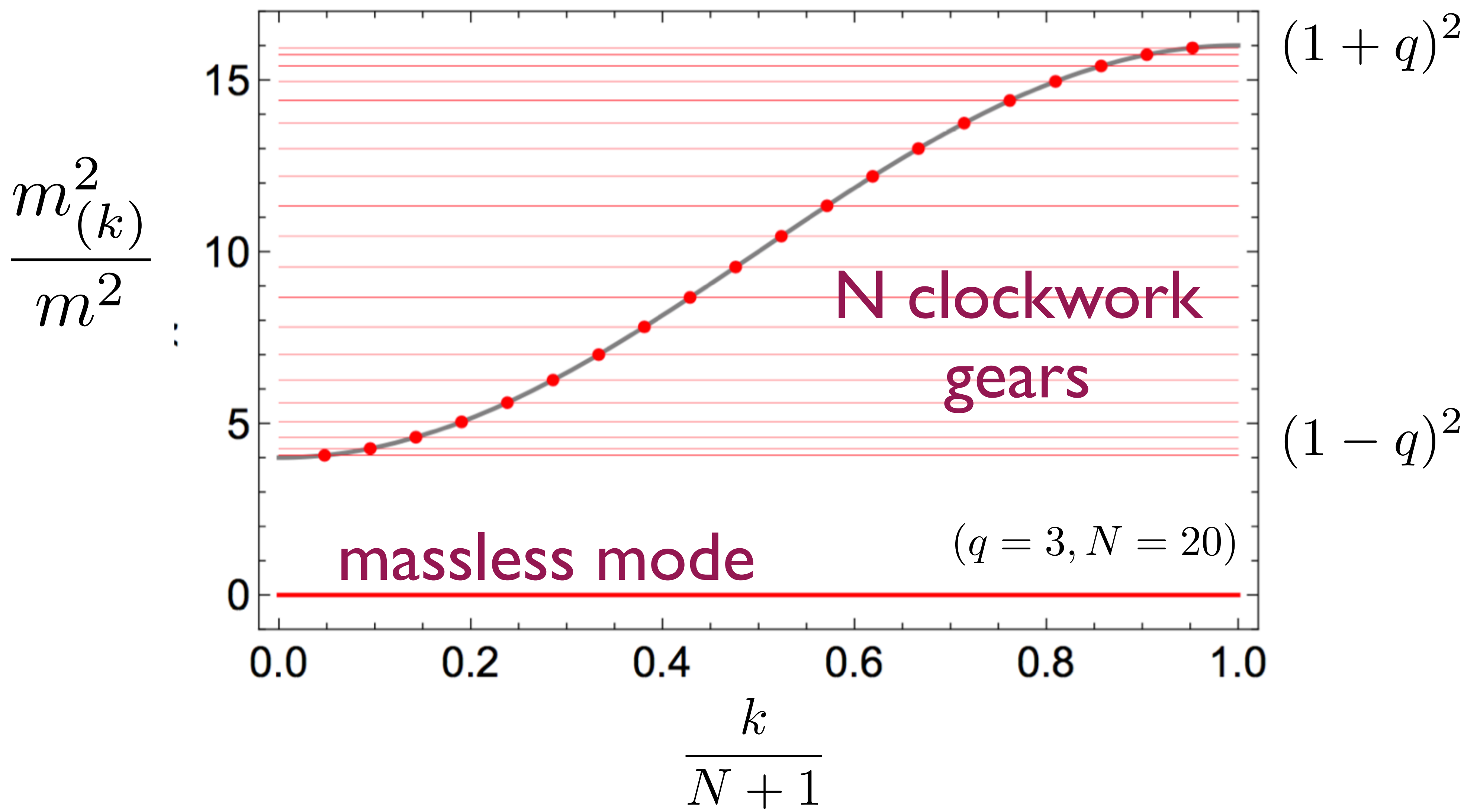
$$-\frac{m^2}{2}\sum_{0}^{N-1}(\phi_k - q\phi_{k+1})^2 + \ldots \quad \longrightarrow \quad M^2 = m^2 \begin{pmatrix} 1 & -q & 0 & \ldots & & 0 \\ -q & 1+q^2 & -q & \ldots & & 0 \\ 0 & -q & 1+q^2 & -q & & 0 \\ \vdots & \vdots & \vdots & \ddots & & \vdots \\ & & & -q & 1+q^2 & -q \\ 0 & 0 & 0 & \ldots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

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

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

massless mode
localized towards site k=0

THE CLOCKWORK MECHANISM ILLUSTRATED



plot from Farina *et al* (2016)

THE CLOCKWORK MECHANISM ILLUSTRATED

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

$\times \quad \times \quad \times \quad \times \quad \times \quad \times \quad \times$

massless mode
localized towards
site k=0

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

tiny
coupling

e.g.

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

large effective scale

A CLOCKWORK WIMP ?

WIMP abundance from thermal freeze-out

$$\langle \sigma v \rangle \sim \frac{\alpha^2}{M^2}$$

mass in hundreds
of GeV-TeV range

WIMP stability protected by a symmetry

SUSY, SO(10), exact gauge symmetry,
accidental symmetry,…

e.g. a Majorana SU(2) 5-plet (aka Minimal Dark Matter)

possible decay through
dim-6 op.

$$\tau \sim \frac{\Lambda^4}{M^5} \longrightarrow \Lambda \gtrsim 10^{16}\,\mathrm{GeV}$$

a large, difficult
to test scale

CAN WE STABILIZE A WIMP THROUGH THE CLOCKWORK MECHANISM ?

A CLOCKWORK WIMP - CONSTRUCTION

chiral chain

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

$\times \quad \times \quad \times \quad \times \quad \times \quad \times \quad \times$

complex scalars

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

basic ingredients:

a chiral chain (Weyl spinors) and complex scalars (spurions or dynamical)

construction goes through 4 steps

A CLOCKWORK WIMP - CONSTRUCTION

chiral chain

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

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

complex scalars

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rem: these fields are spurions
in the original framework
they are dynamical in our case

step 1: break the chiral symmetries

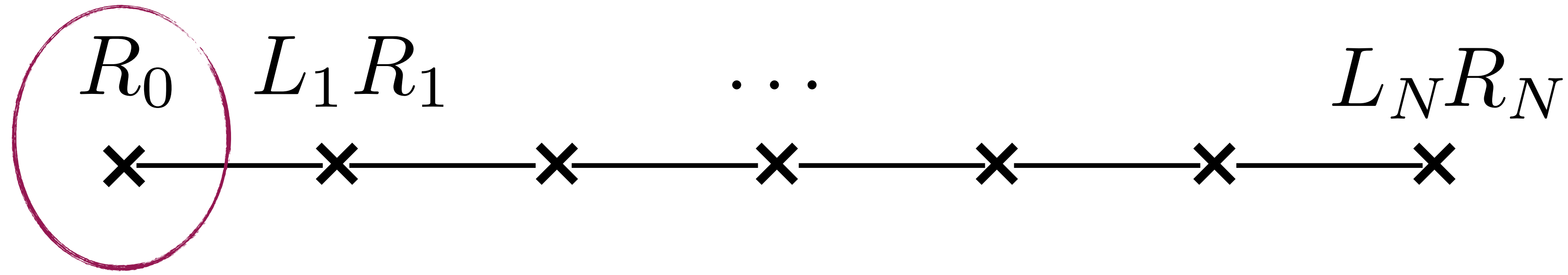
$$\begin{cases} m \to y_S \langle S_i \rangle \\ mq \to y_C \langle C_i \rangle \end{cases}$$

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

one **massless** mode

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

A CLOCKWORK WIMP - CONSTRUCTION



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

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

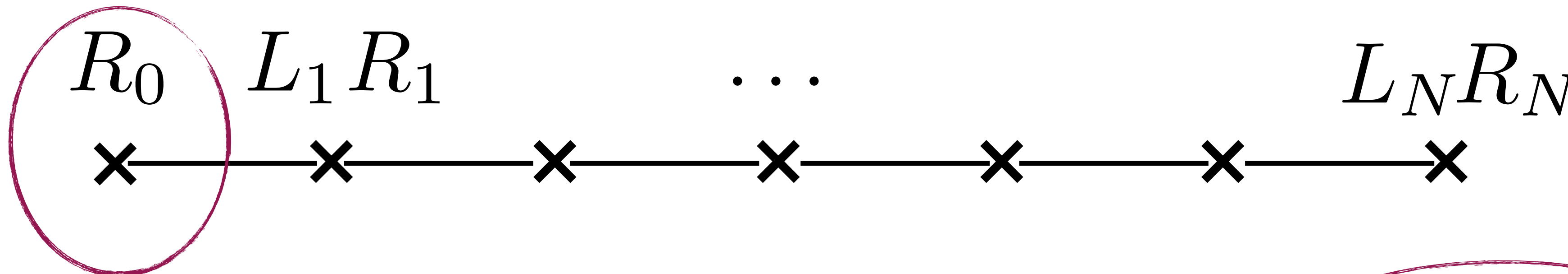
massless chiral mode

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

N Dirac gears
mass ~ q m

i.e. pretty much like the scalar clockwork

A CLOCKWORK WIMP - CONSTRUCTION



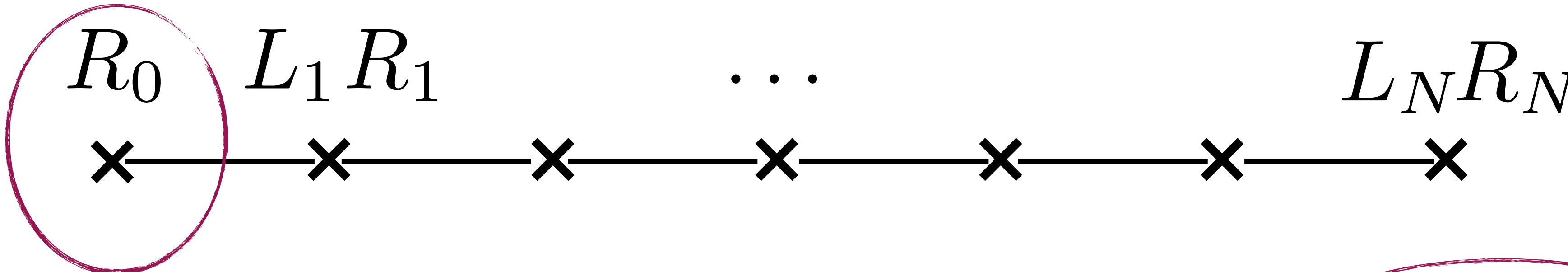
$$\mathcal{L} \supset -m \sum_{i=1}^{N} \left(\bar{L}_i R_{i-1} - q \bar{L}_i R_i \right) + h.c. - \frac{1}{2} m_N \bar{R}_0^c R_0$$

step 2: break the residual chiral symmetry

i.e.

give a mass to the N state

A CLOCKWORK WIMP - CONSTRUCTION



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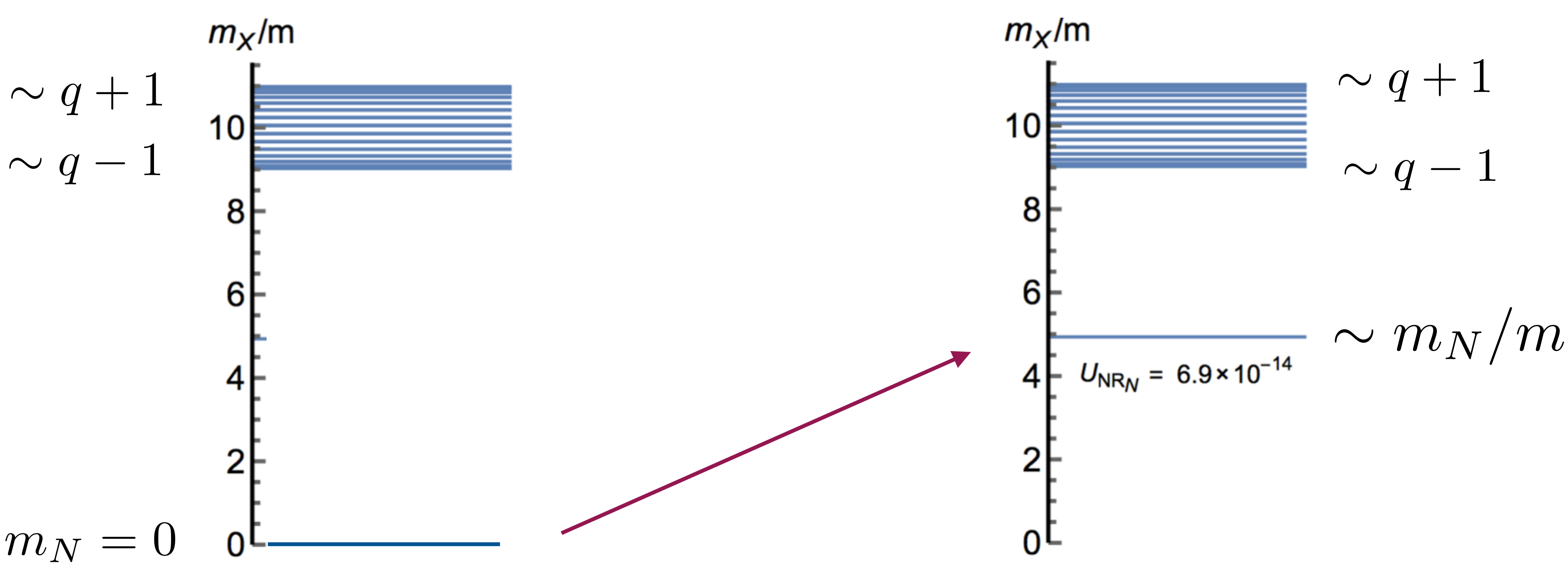
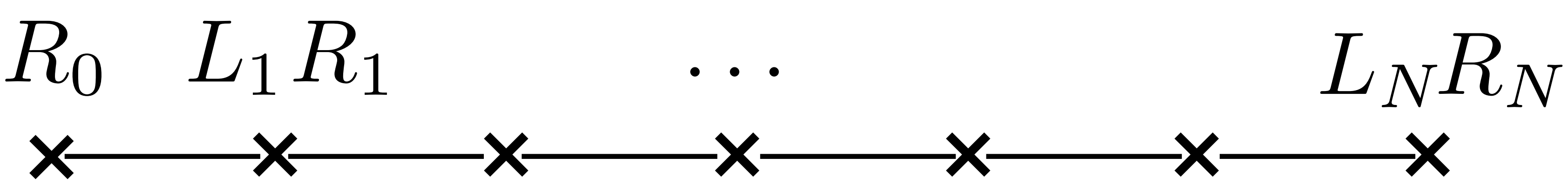
$(q = 10, N = 15, m_N = 0)$ $(q = 10, N = 15, m_N = 5m)$



A CLOCKWORK WIMP - CONSTRUCTION



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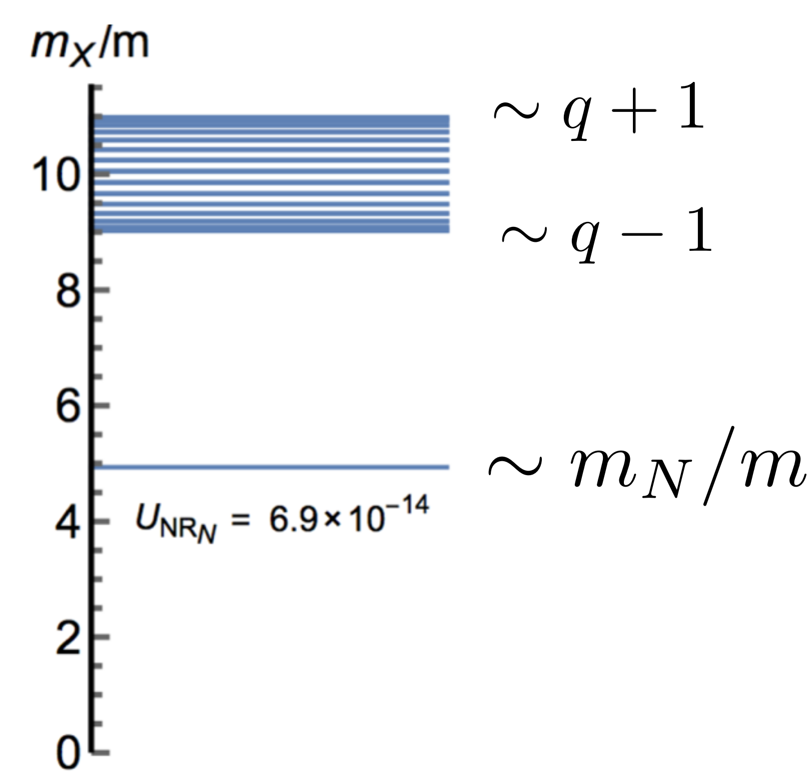
clockwork mechanism unaffected provided

$$m_N \lesssim qm$$

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

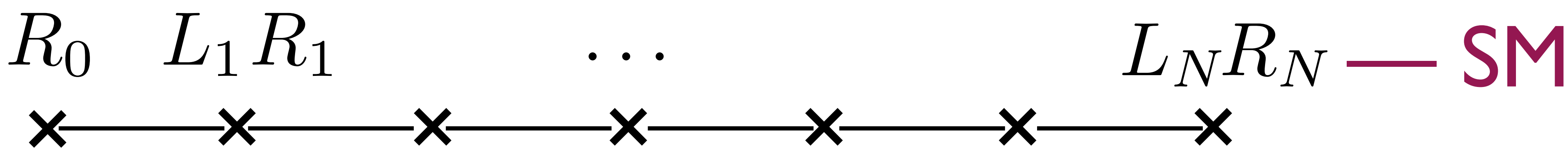


{ one light & localized mode
N gears with O(1) couplings

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

Hambye, Teresi & MT (2016)

A CLOCKWORK WIMP - CONSTRUCTION

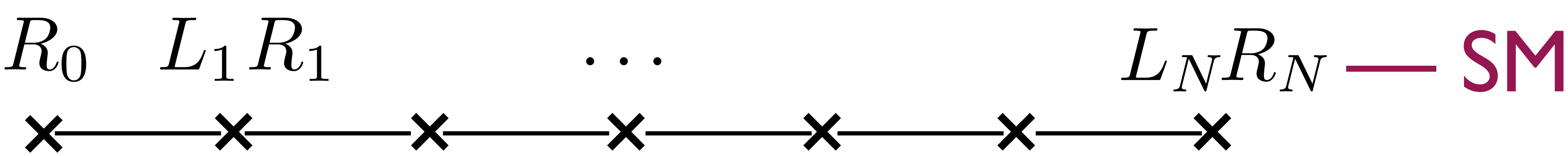


$$\mathcal{L} \supset -m \sum_{i=1}^{N} \left(\bar{L}_i R_{i-1} - q \bar{L}_i R_i \right) + h.c. - \frac{1}{2} m_N \bar{R}_0^c R_0$$

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

step 3: couple the chain to the SM

A CLOCKWORK WIMP - CONSTRUCTION



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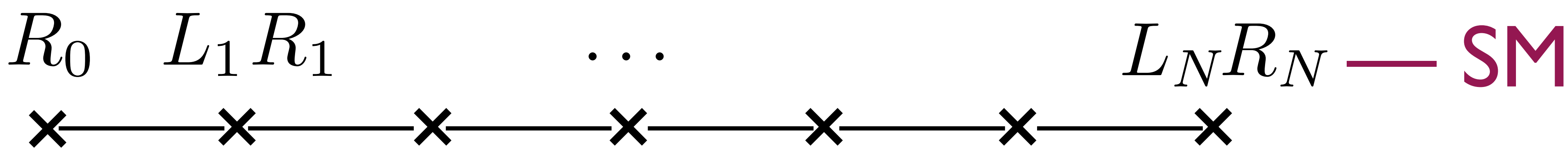
$$-y(\bar{L}_{SM} \tilde{H} R_N + h.c.)$$

step 3: couple the chain to the SM

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

tiny coupling

A CLOCKWORK WIMP - CONSTRUCTION



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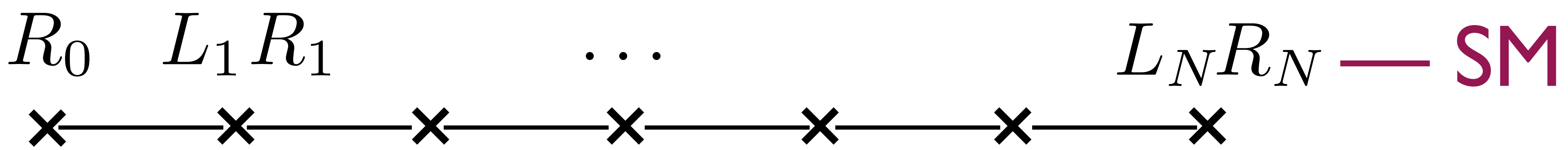
$$-y(\bar{L}_{SM} \tilde{H} R_N + h.c.)$$

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

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

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

A CLOCKWORK WIMP - CONSTRUCTION



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

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

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

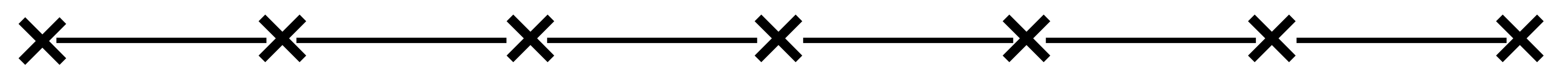
abundance from thermal freeze-out?

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

i.e. quite suppressed…

A CLOCKWORK WIMP - AT LAST

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



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

χSB

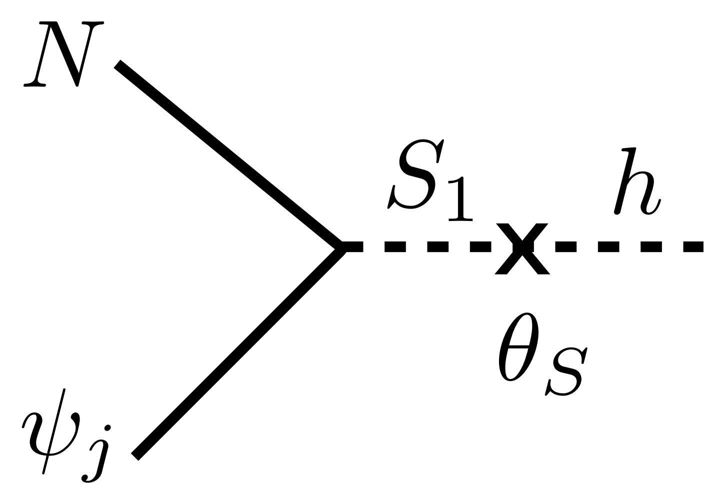
$$- \left(y\, \bar{L}_{SM} \widetilde{H} R_N + h.c. \right) - \frac{1}{2} \left(m_N \overline{R_0^c}\, R_0 + h.c. \right)$$
$$- \sum_{i=1}^{N} \left(\lambda_S\, S_i^\dagger S_i\, H^\dagger H + \lambda_C\, C_i^\dagger C_i\, H^\dagger H \right)$$

Higgs portal

A CLOCKWORK WIMP - AT LAST

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

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



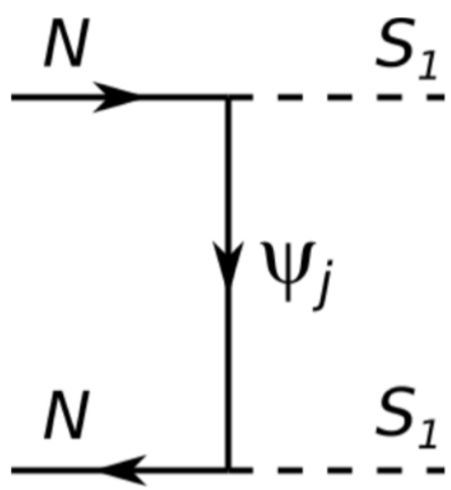
with $\xi_j^S \approx \sqrt{\frac{2}{N+1}} \sin\left(\frac{j\pi}{N+1}\right) y_S$ **and** $\xi_j \approx \theta_S \xi_j^S$

$$NN \leftrightarrow S_1 S_1, S_1 h, hh, \ldots \quad \rightarrow \quad \propto \xi_S^2 \ (\xi^2) = \sum_{j=1}^{N} |\xi_j^S|^2 \approx y_S^2 \ (\theta_S)^2$$

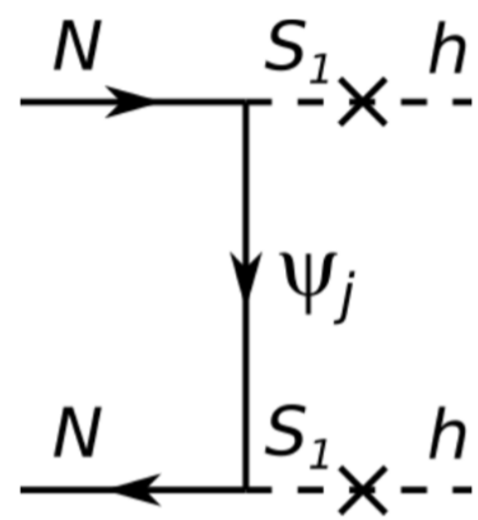
O(1) couplings, the N could be a WIMP!

A CLOCKWORK WIMP - TO RECAP

Abundance



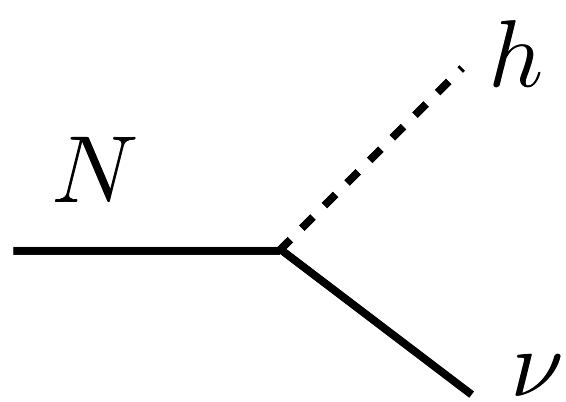
(scenario A)



(scenario B)

annihilation through the chiral gears

Stability/decay

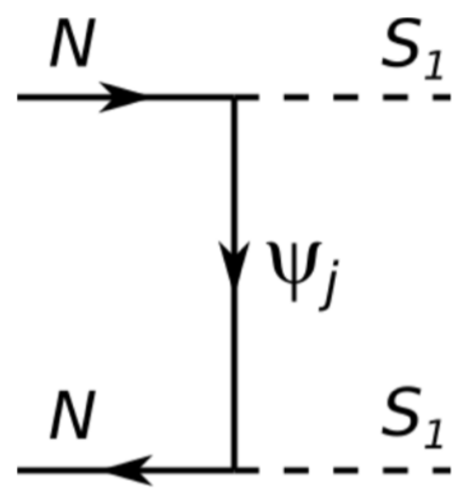


$$\frac{1}{q^N}$$

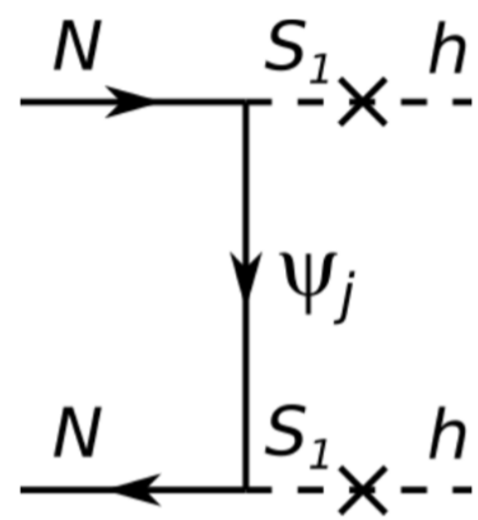
suppressed by the chiral chain

A CLOCKWORK WIMP - TO RECAP

Abundance



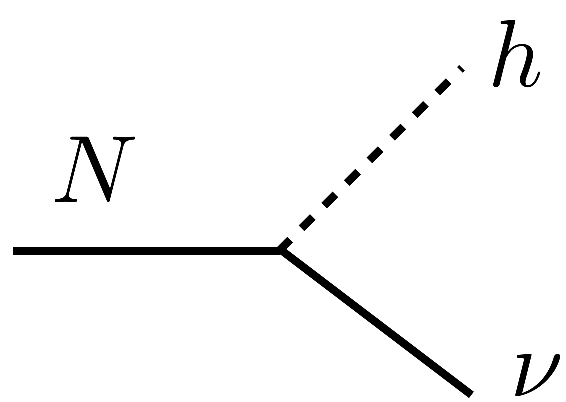
(scenario A)



(scenario B)

annihilation through the chiral gears

Stability/decay



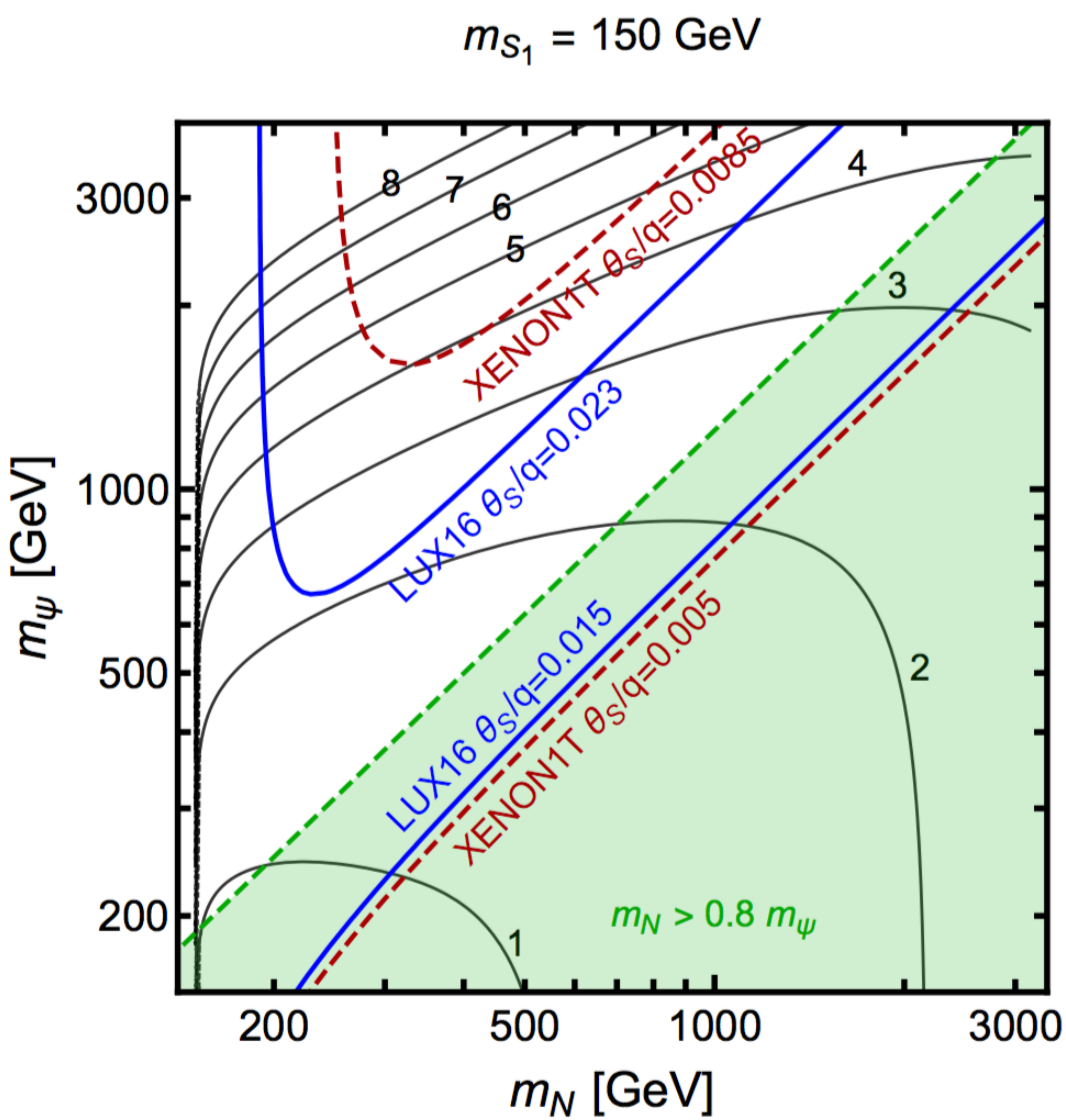
$$\frac{1}{q^N}$$

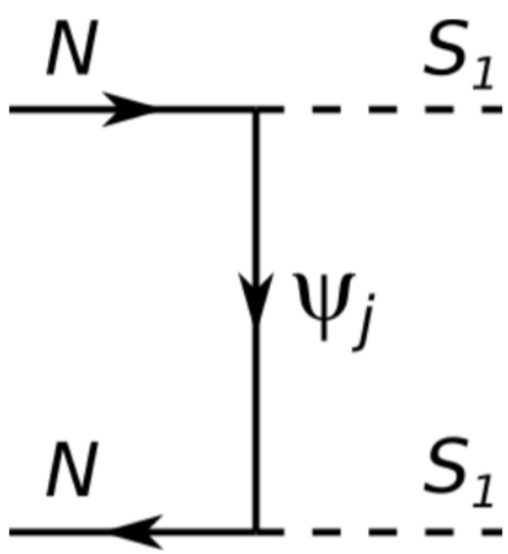
suppressed by the chiral chain

Diagonal coupling to Higgs
(taking into account the pseudo-Dirac nature of the clockwork gears)

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

A CLOCKWORK WIMP — SCENARIO A





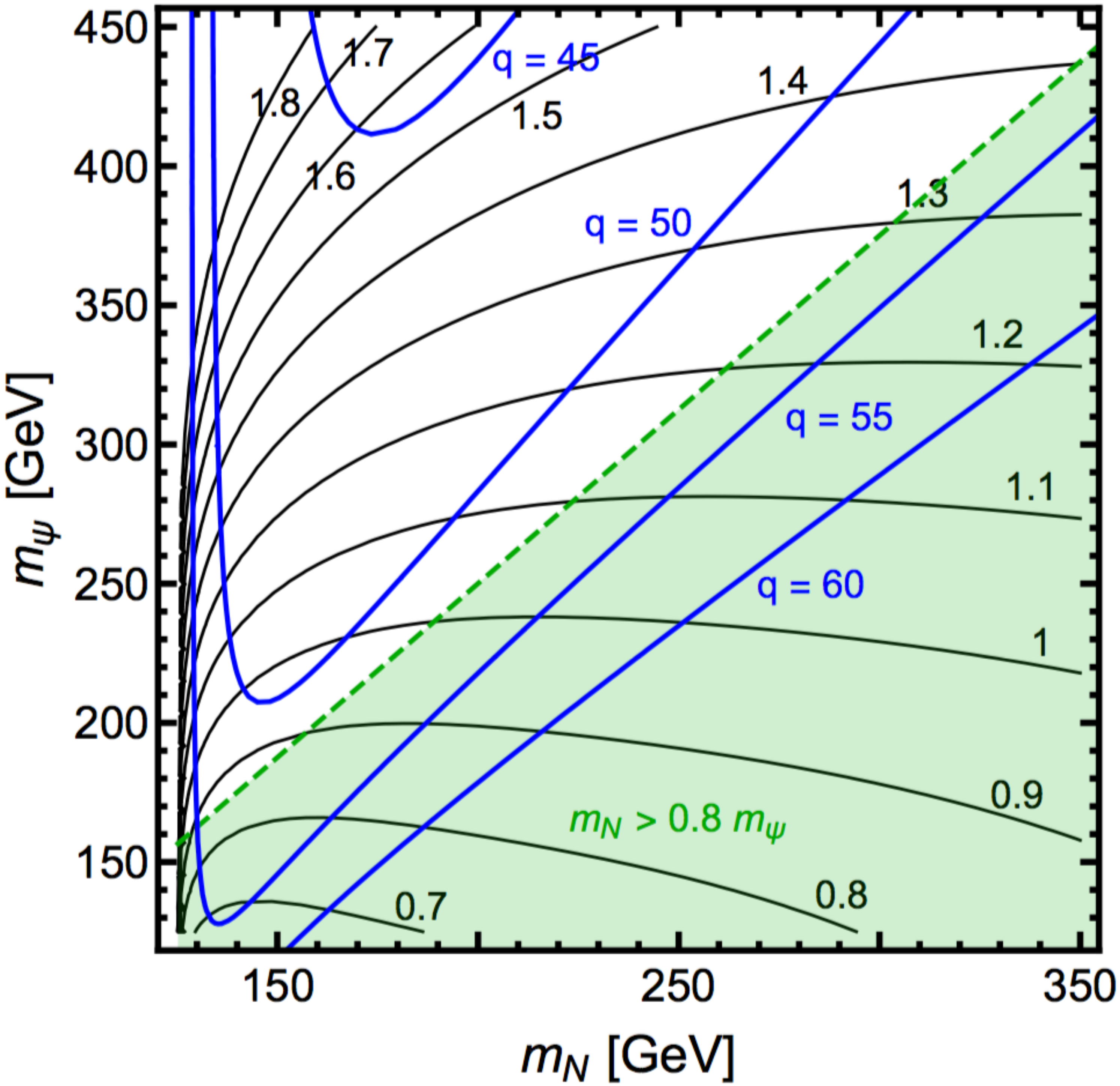
black solid: y_S required for $\Omega_{dm} \approx 0.25$

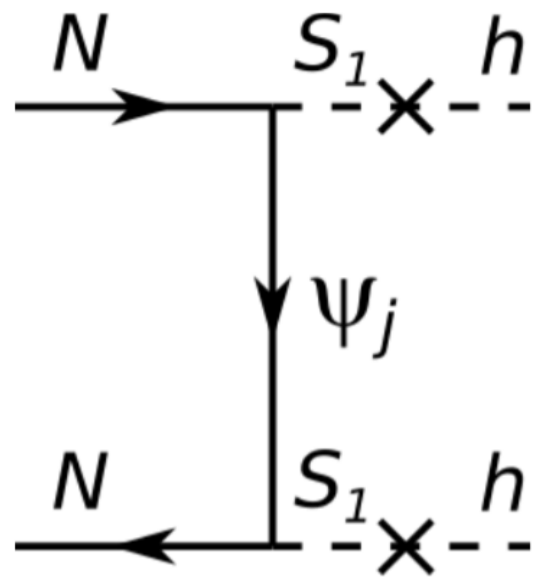
blue solid: LUX16 exclusions (below lines)

red dashed: Xenon1T reach

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

A CLOCKWORK WIMP — SCENARIO B





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

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

blue solid: LUX16 exclusions (below lines)

A CLOCKWORK WIMP — BASIC PHENO

Indirect detection p-wave annihilation, but decay into monochromatic neutrinos $N \to h\nu$

e.g. El Aisati, Gustafsson & Hambye (2015)

A CLOCKWORK WIMP — BASIC PHENO

Indirect detection p-wave annihilation, but decay into monochromatic neutrinos $N \to h\nu$

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Collider searches ψ_j in the hundred GeV/TeV range, coupled via $y\bar{L}_{SM}HR_N$ with y sizable and $\psi_j \supset R_N$

observable pseudo-Dirac sterile RH neutrinos!

assuming single state approximation

EWPT: $|\theta_{l\psi}|^2 \equiv y^2v^2/(2m_\psi^2) \lesssim 10^{-3}$

LFV: $BR(\mu \to e\gamma) \sim 10^{-3}|\theta_{e\psi}|^2|\theta_{\mu\psi}|^2 \lesssim 10^{-13}$

L conserving searches: $m_\psi \lesssim 200 \text{ GeV}$ with 300 fb^{-1}

Das, Dev & Okada (2014)

L violating searches: $m_\psi \lesssim 300\text{GeV}$ with 300 fb^{-1}

$m_N \lesssim m_\psi$

Deppisch, Dev & Pilaftsis (2015)

A CLOCKWORK WIMP — BASIC PHENO

Indirect detection p-wave annihilation, but decay into monochromatic neutrinos $N \to h\nu$

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$m_N \lesssim m_\psi$

Deppisch, Dev & Pilaftsis (2015)

large mixing h-S in scenario B $\theta_S \lesssim 0.3 - 0.4$ (direct or EWPT)

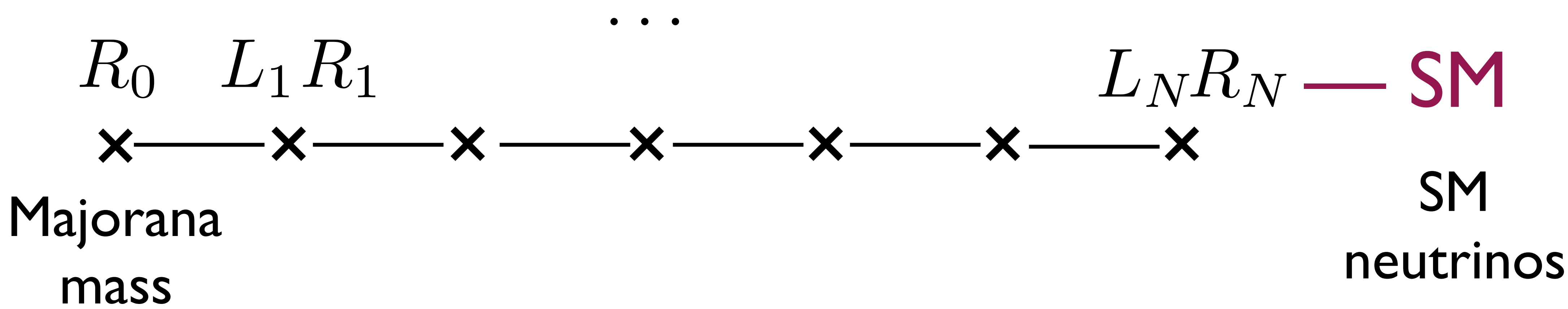
e.g. Falkowski, Gross & Lebedev (2015)

A CLOCKWORK WIMP IS POSSIBLE

CLOCKWORK MAJORANA NEUTRINO MASS

Hambye, Teresi & MT (2016)

another chain…



has to go through the whole chain $\quad m_\nu \sim y^2 \dfrac{v^2}{q^N M}$

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

but one/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)

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

A CLOCKWORK WIMP FROM DECONSTRUCTION

Lagrangian can be related to a discretized <u>flat</u> 5th dimension (Z)

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

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)

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

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)

CONCLUSIONS

We have build **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 at the LHC as RHN

There are also (possibly) plenty of **scalars**

Notice that it's also a framework for low scale SM neutrino Majorana mass

If you care, the clockwork could be seen as an extra spatial dimension

A Clockwork Wimp

by Lord_Gino_X ©

A Clockwork Wimp (Book 1 of 2)

Chapter 1

I slowly slide the large window open and climbed inside without making any noise. But there were noises. Noises that were tearing my ear drums apart. Noises that were directly coming from my chest. I knew I have to control my breathing in order to slow down my heart. It was becoming a distraction. A distraction I cannot afford. Luckily, I need less than a minute to do what I am here to do.

ON SCALES AND MASSES

following Giuidice & McCullough

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

a mass

$$\mathcal{L} \sim \frac{M^4}{g^2} \quad \longrightarrow \quad [\phi] = \frac{M}{g} \quad , \quad [\psi] = \frac{M^{3/2}}{g}$$

a scale

$$\mathcal{O} = \frac{1}{\Lambda^{d-4}} \phi^{n_B} \psi^{n_F} \quad \longrightarrow \quad \Lambda = \frac{M}{g^{\frac{n_B + n_F - 2}{d-4}}}$$

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

Fermi

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

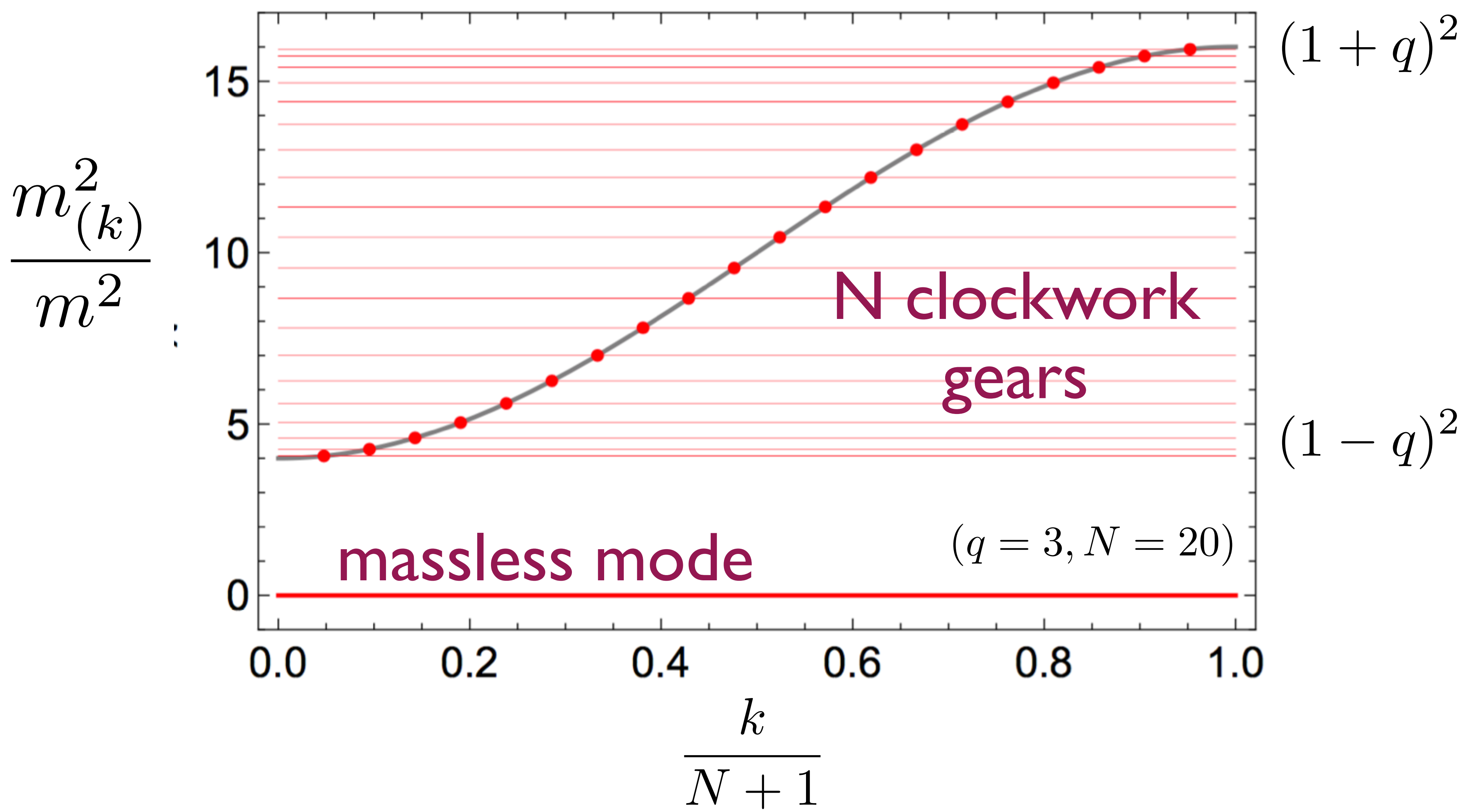
Weinberg

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

Planck

THE CLOCKWORK MECHANISM ILLUSTRATED

$$m^2_{(k)} = m^2 \left(1 + q^2 - 2q\cos\left(\frac{k\pi}{N+1}\right)\right)$$



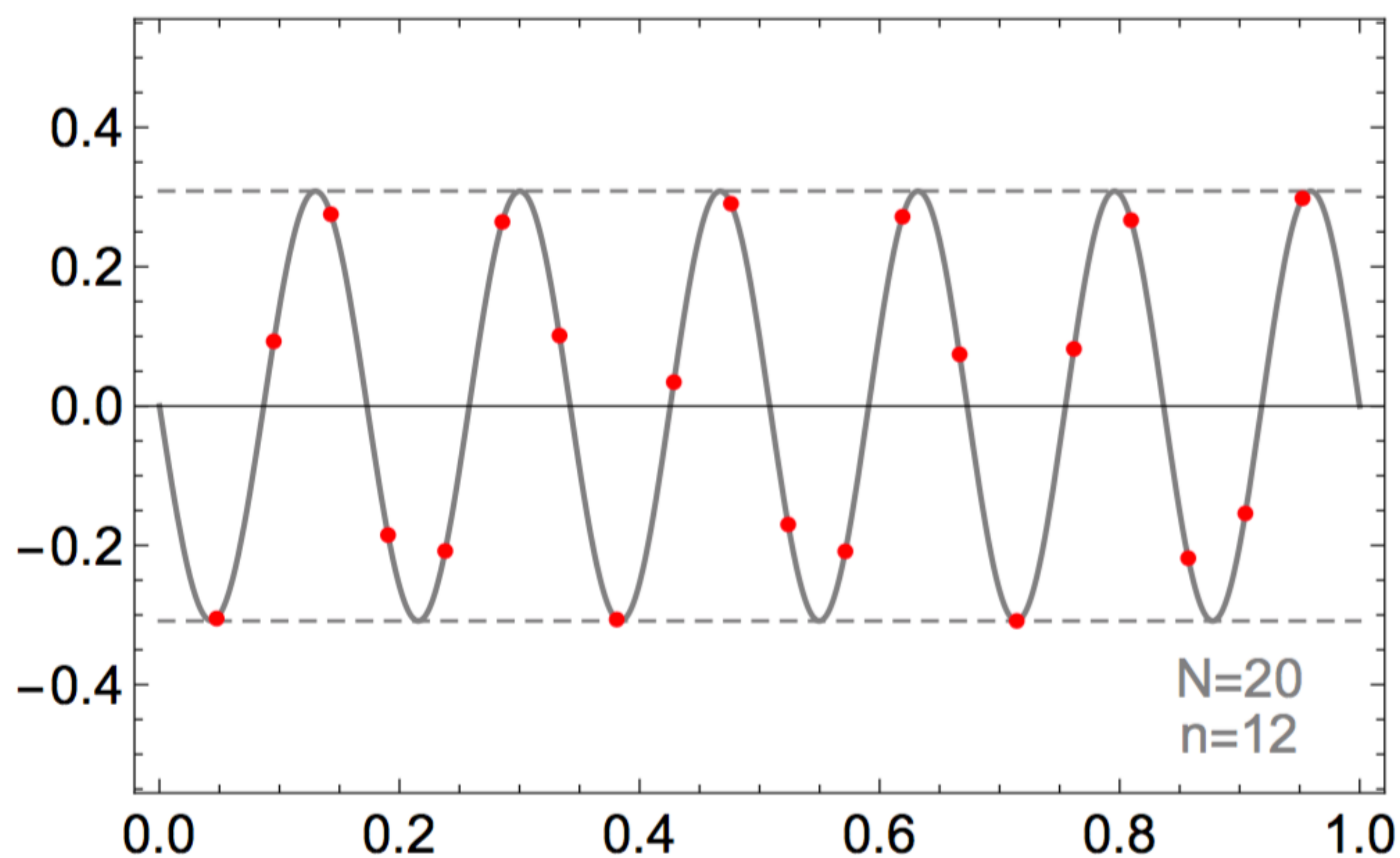
plot from Farina *et al* (2016)

THE CLOCKWORK MECHANISM ILLUSTRATED

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

clockwork gears
have **unsuppressed**
overlap at all sites

$a_{n=12}^{(k)}$



$\sqrt{2/(N+1)}$

$-\sqrt{2/(N+1)}$

$$\frac{k}{N+1}$$

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