Clockwork mechanisms

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CW mechanism

[Choi, Kim, Yun 14], [Choi, Im 15], [Kaplan, Rattazzi 15], [Giudice, McCullough 16]

A mechanism generating **exponentially small couplings/ large interaction scales** from O(1) couplings

CW models

A new useful tool to build a 'natural' model

- **CW Dimensions** [Ahmed, Dillon 16], [Giudice, Kats, McCullough, Torre, Urbano 17], [Choi, Im, Shin 17], [Craig, Garcia, Sutherland 17]…
- **CW Axion** [Choi, Kim, Yun 14], [Farina, et.al. 16],[Coy, Frigerio, Ibe 17],[Agrawal, Fan, Reece 18], [Long 18], [Bonnefoy, Dudas, Pokorski 19], [Bae, Kost, Shin 19]…
- **CW Inflation** [Kehagias, Riotto 17], [SCP, Shin 18] …
- **CW Dark matter** [Hambey, Teresi, Tytgat 17], [Marzora, Raidal, Urban 18], [Kim, McDonald 18], [Goudelis, Mohan, Sengupta 18]…
- **CW Neutrino** [SCP, Shin 17], [Ibarra, Kushwaha, Vempati 17], [Patel 17], [Banerjee, Ghosh, Ray 18], [Alonso, et.al. 18], [Hong, Kurup, Perelstein 19], [Kitabayashi 19]…
- **CW gravity** [Ibanez, Montero 17], [Saraswat17], [Hong, Kim, Shin 18], [Terresi 18], [Im, Nilles, Olechowski 19], [Sannino, Smirnov, Wang 19]…

Contents

- Basic ideas of CW mechanism
- CW models
- Summary & Discussion

Basic ideas

[Giudice, McCullough 16] [Choi, Im, Shin 17]

We can easily make an exponentially small number by multiplying small numbers multiple times:

$$\frac{1}{3} \times \frac{1}{3} \times \frac{1}{3} \cdots \times \frac{1}{3} = \frac{1}{3^N} = e^{-N \ln 3}$$

$$N = 15 : \text{book} \rightarrow \text{atom}$$

A chain of N-fields can generate small effective coupling:

$$\phi_0 \overset{1/q<1}{\overbrace{\longrightarrow}} \phi_1 \overset{1/q}{\overbrace{\longrightarrow}} \phi_2 \overset{1/q}{\overbrace{\longrightarrow}} \cdots \overset{1/q}{\overbrace{\longrightarrow}} \phi_N \overset{g}{\overbrace{\longrightarrow}} \mathcal{O}_{\rm SM}$$

$$\phi_{\rm light} \approx \phi_0 \quad \longrightarrow \quad \phi_{\rm light} - \mathcal{O}_{\rm SM} \sim \frac{g}{q^N}$$

light field by symmetry

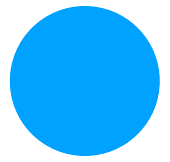
General CW mechanism

[Giudice, McCullough 16]

- 1D lattice in theory space with $(N+1)$ sites
- Each site has a symmetry S, $G=S^{N+1}$: symmetry of full theory space
- $(N+1)$ massless particles $P=(P_0,P_1,\ldots,P_{N+1})$
- At a scale m, G is broken due to mass mixings between site(i)-site(i+1); N-links ==> remaining one symmetry S_0, one massless particle P_0 (a linear combination of P's)
- **CW assumption: Symmetry breaking is asymmetrically with q (>1 or <1) for site(i) and site(i+1), $i=0,1,2,\ldots N-1$.**
- **P_0 is exponentially localized towards one of the boundaries. (P_0 is exponentially small ($\sim 1/q^N$) at the opposite site ==> leads to suppressed coupling with the localized operator)**

CW theory space

Basic ingredients:



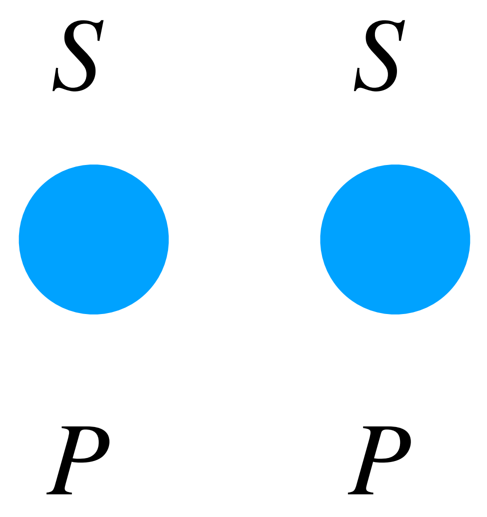
S **: symmetry group**

P **: massless particle**

“One-site” model

CW theory space

We can extend to 2 on 1D lattice

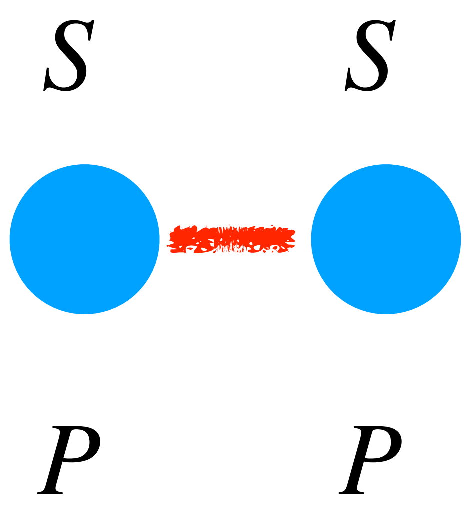


Full symmetry: $\mathscr{G} \supset S^2$

2 massless particles: $P = (P_0, P_1)$

CW theory space

asymmetric soft breaking parametrized by q>1



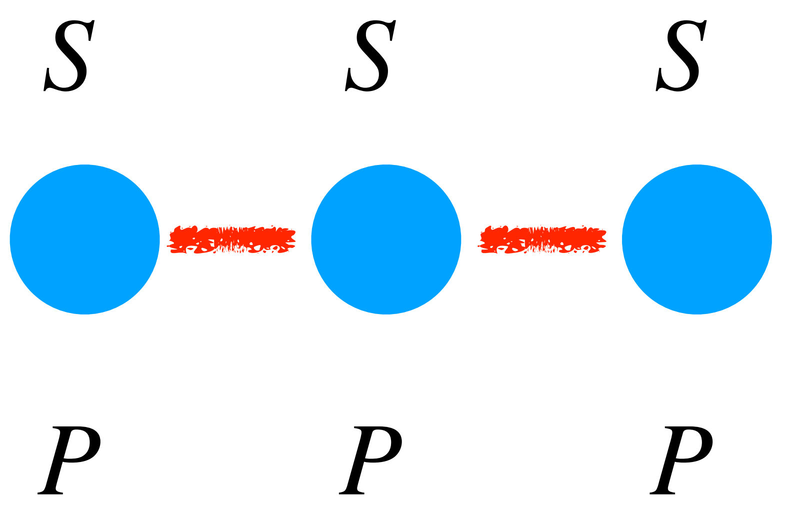
Full symmetry: $\mathcal{G} \supset S^2 \longrightarrow S_0$

1 massless particle remains $P = (P_1, P_2) \longrightarrow P_0 = P_1 + \frac{1}{q} P_2$

(semi-localization)

CW theory space

“3-sites model”



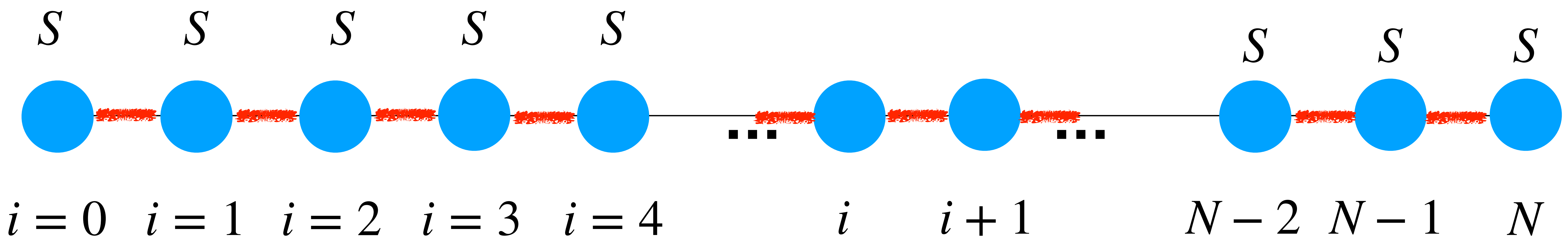
Symmetry breaking by 2 links: $\mathcal{G} \supset S^3 \longrightarrow S_0$

1 massless particle remains: $P = (P_0, P_1, P_2) \longrightarrow P_0 = P_1 + \frac{1}{q}P_2 + \frac{1}{q^3}P_3$

(semi-localization)

CW theory space

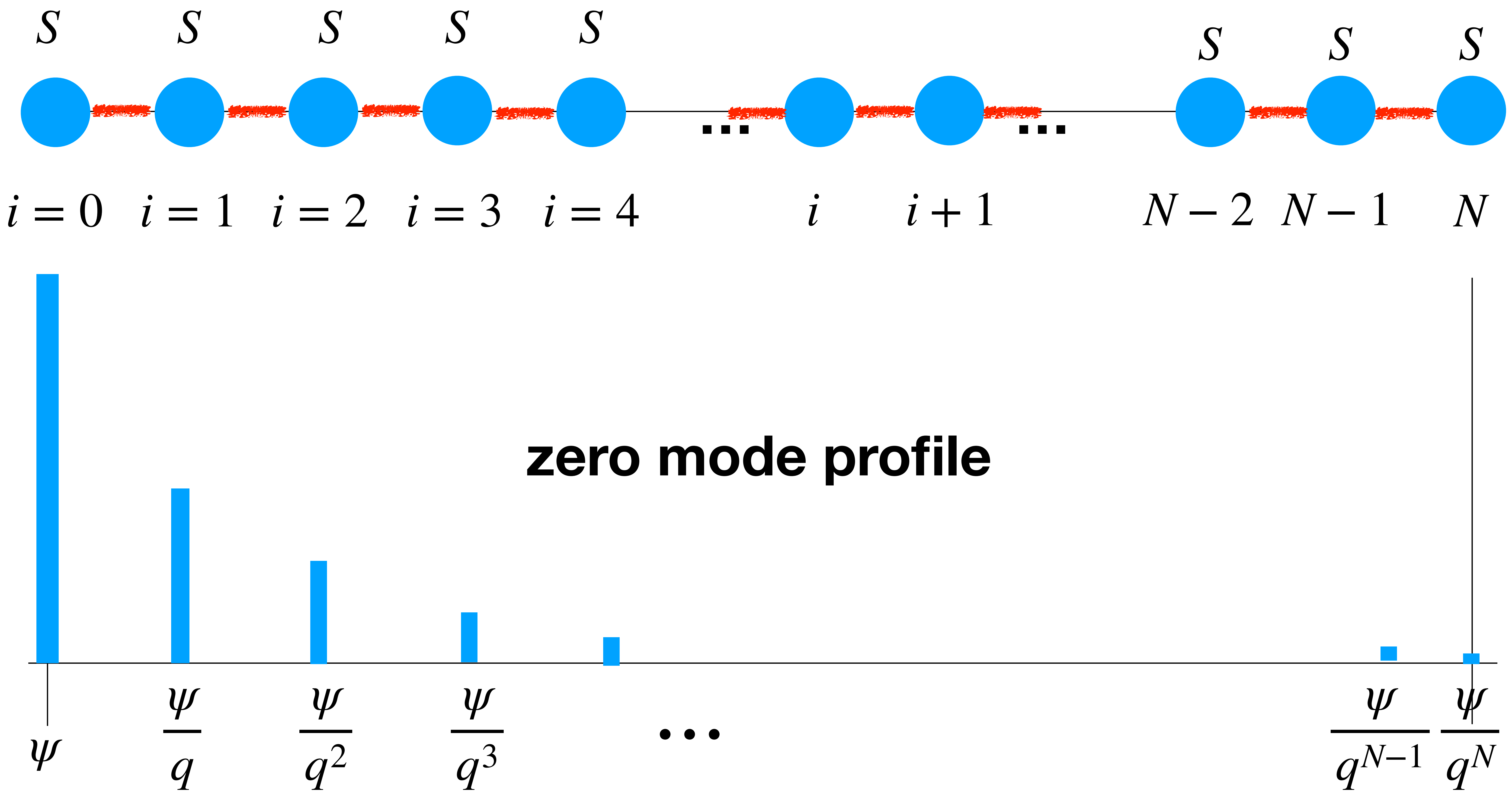
“(N+1) sites”



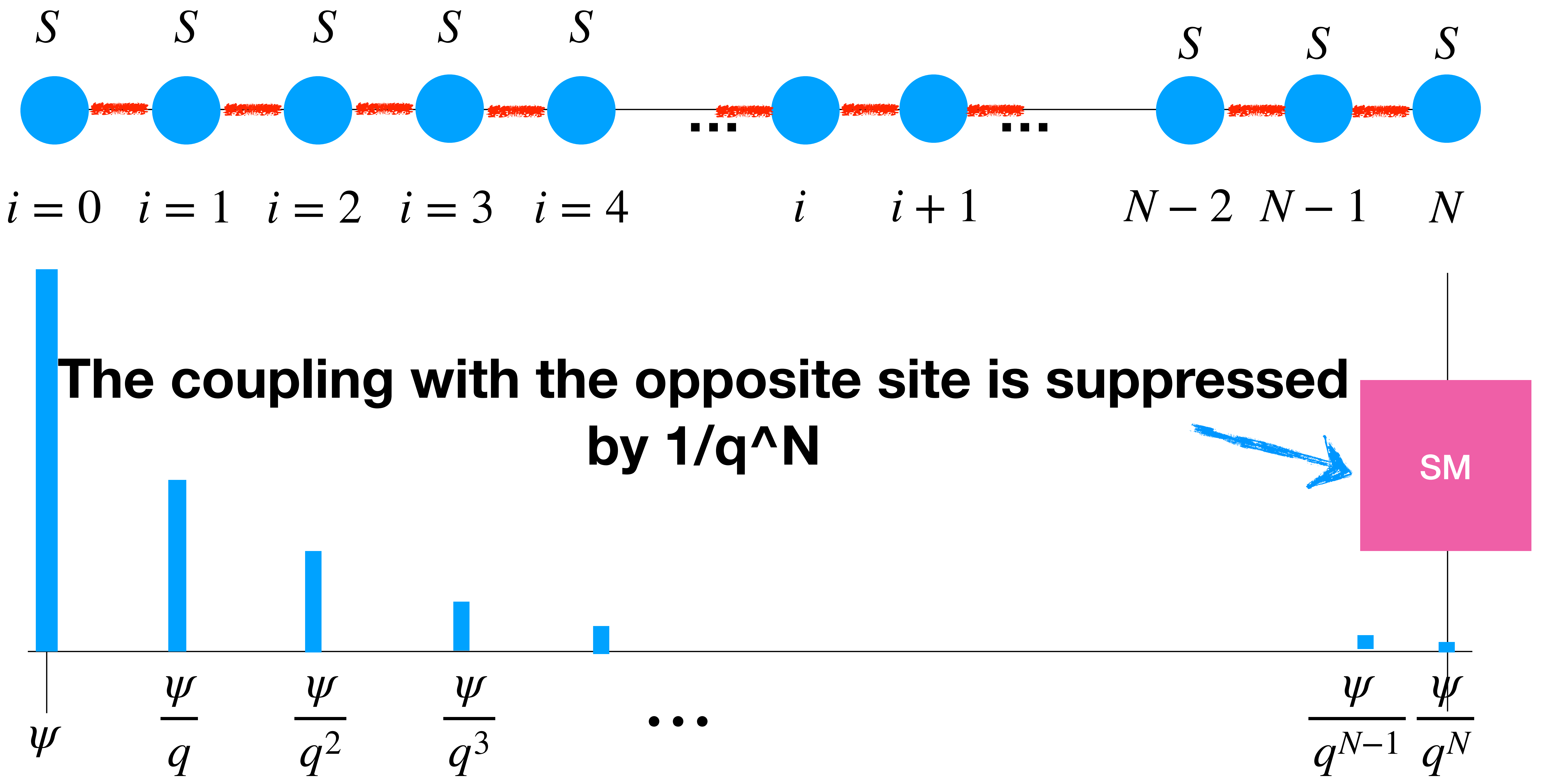
Symmetry breaking by N-links: (asymmetric) $\mathscr{G} \supset S^{N+1} \rightarrow S_0$

1 massless particle remains: $P_0 = \sum_{i=0}^{N} C_i P_0^i \qquad C_i \approx \frac{1}{q^i}$

CW theory space



CW theory space



CW	s=0	s=1/2	s=1	s=2
symmetry S	Shift	Chiral	gauge	4D diffeomorphism
CW model	axion	neutrino mass, flavor	tiny gauge coupling	CW graviton, naturalness problem

Scalar CW potential

Introduce (N+1)-‘gear fields’ in CW sector

$$\{\phi_0, \phi_1, \phi_2, \phi_3, \cdots, \phi_N\}$$

$$V_{\rm CW}(\phi_i) = \sum_{i=0}^{N} \frac{1}{2} m_{\rm CW}^2 \left(\phi_i - q\phi_{i+1}\right)^2$$

Shift symmetry: $\phi_i \to \phi_i + q^{-i} C$

↓

massless mode $m_0^2 = 0$

Scalar CW potential

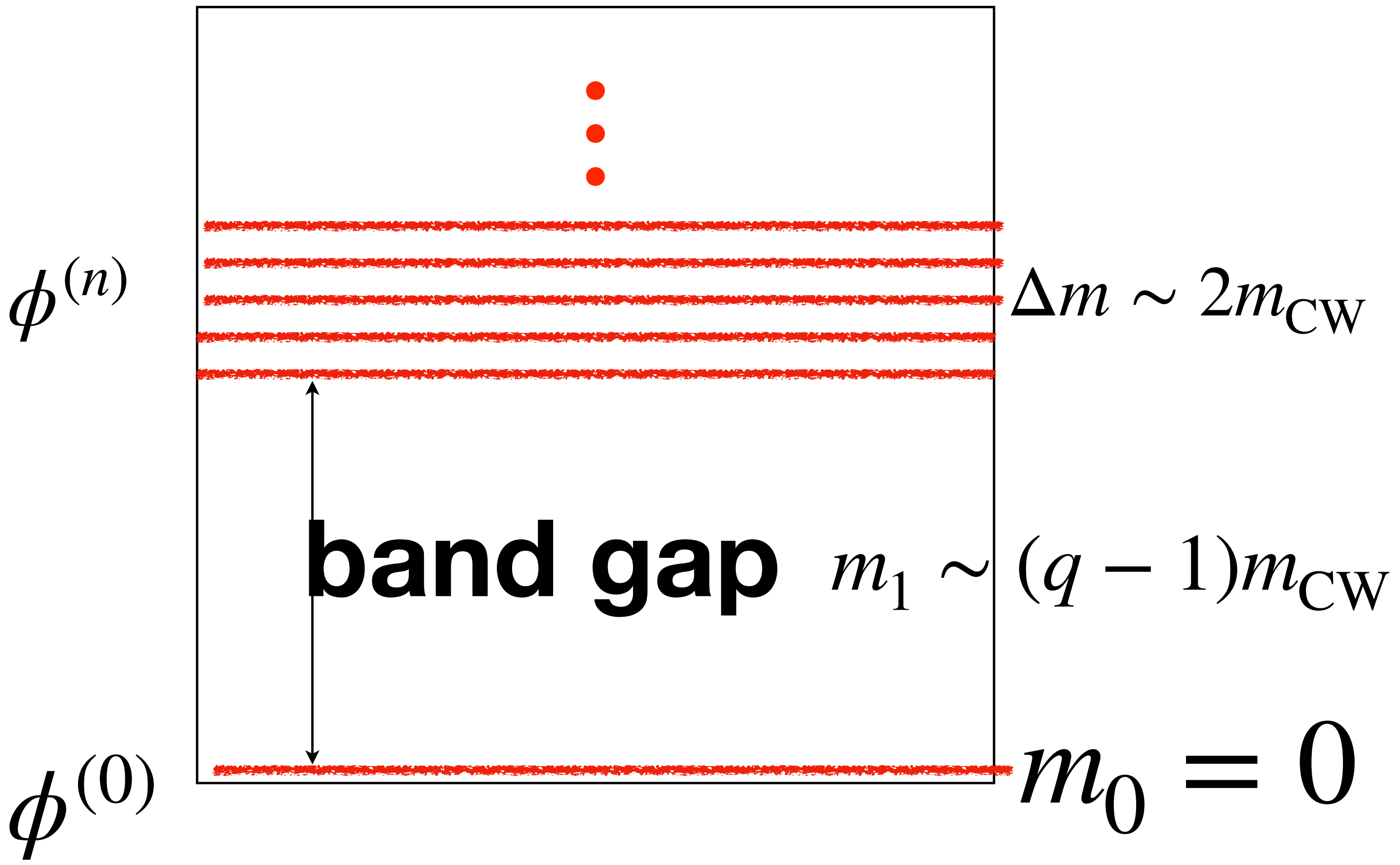
Spectrum of CW gears

$$\mathcal{M}_\phi^2 = m_{\rm CW}^2 \begin{pmatrix} 1 & -q & 0 & \cdots & & 0 \\ -q & 1+q^2 & -q & \cdots & & 0 \\ 0 & -q & 1+q^2 & \cdots & & 0 \\ \vdots & \vdots & \vdots & \ddots & & \vdots \\ & & & & 1+q^2 & -q \\ 0 & 0 & 0 & \cdots & -q & q^2 \end{pmatrix}$$

$$m_0 = 0$$

$$m_n^2 = m_{\rm CW}^2 \left(q^2 - 1 - 2q \cos \frac{n\pi}{N+1} \right)$$

$$\phi^{(0)} \approx \sum_{i=0}^{N} \frac{\phi_N}{q^N}$$



KK spectrum of extra dimension,
or Deconstructed 5D theory.

Continuum limit

$$\mathscr{L}_{\text{CW}} = -\sum_{i=0}^{N}\frac{1}{2}\left(\partial_\mu\phi_i\right)^2 - \sum_{i=0}^{N}\frac{1}{2}m_i^2\left(\phi_i - q\phi_{i+1}\right)^2$$

$N \to \infty$

$\phi_i(x) \to \Phi(x, y)$

$\phi_{i+1}(x) - \phi_i(x) \to \partial_y\Phi(x, y)$

$q - 1 \to k, m_i^2 \to m(y)^2$

$$\mathscr{L}_{\text{CW}} = -\int dy\,\frac{1}{2}\left(\partial_\mu\Phi(x,y)\right)^2 + \frac{1}{2}m(y)^2\left(\partial_y\Phi(x,y) - k\Phi(x,y)\right)^2$$

Extra dimension

$$\mathscr{L}_{\mathrm{CW}} = -\int dy \frac{1}{2}\left(\partial_\mu \Phi(x,y)\right)^2 + \frac{1}{2} m(y)^2 \left(\partial_y \Phi(x,y) - k\Phi(x,y)\right)^2$$

Field redefinition $\Phi(x,y) = e^{ky}\Psi(x,y)$

$$\mathscr{L}_{\mathrm{CW}} = -\int dy \frac{1}{2} e^{2ky} \left[\left(\partial_\mu \Psi(x,y)\right)^2 + \frac{1}{2} m(y)^2 \left(\partial_y \Phi(x,y)\right)^2\right]$$

"CW geometry"

$$ds^2 = \left(\frac{e^{2ky}}{m^2(y)}\right)^{2/3} \left(m(y)^2 dx^2 + dy^2\right)$$

Linear dilaton+Warped geometry

$$ds^2 = \left(\frac{e^{2ky}}{m^2(y)}\right)^{2/3} \left(m(y)^2 dx^2 + dy^2\right)$$

$$k = \frac{1}{2}k_{\text{LD}} - p \qquad m(y) = e^{-py}$$

$$ds^2 = e^{\frac{3}{2}k_{\text{LD}}y} \left(e^{-2py} dx^2 + dy^2\right)$$

address Hierarchy Problem

á la Randall-Sundrum/LED/Linear dilaton (little string)

CW dictionary

Discrete (N=finite)	Continuum (N->∞)
1D-Lattice in theory space	5th-dimension
CW gears	KK modes
interaction with the boundary site	localized interaction on a brane at the boundary of compact dimension

CW axion

[Choi, Kim, Yun 14], [Farina, et.al. 16],[Coy, Frigerio, Ibe 17],[Agrawal, Fan, Reece 18], [Long 18], [Bonnefoy, Dudas, Pokorski 19], [Bae, Kost, Shin 19]…

$$\mathcal{L} = \frac{\pi_N}{16\pi^2 f}\tilde{G}_{\mu\nu}G^{\mu\nu}$$

$$= \frac{\pi_0}{16\pi^2 q^N f}\tilde{G}_{\mu\nu}G^{\mu\nu}$$

CW: $\frac{1}{f} \to \frac{1}{q^N f}$

CW graviton

[Ibanez, Montero 17], [Hong, Kim, Shin 18], [Terresi 18], [Im, Nilles, Olechowski 19]

Pauli-Fierz theory of massive graviton with Gears

$$\mathcal{L} = -\frac{m^2}{2}\sum_{j=0}^{N-1}\left(\left[h_j^{\mu\nu} - q h_{j+1}^{\mu\nu}\right]^2 - \left[\eta_{\mu\nu}(h_j^{\mu\nu} - q h_{j+1}^{\mu\nu})\right]^2\right)$$

$$-\frac{1}{M_N} h_N^{\mu\nu} T_{\mu\nu} \to -\frac{1}{M_P}\tilde{h}_0^{\mu\nu} T_{\mu\nu} \qquad M_P = \frac{q^N M_N}{\mathcal{N}_0}$$

CW inflation

[Kegagias, Riotto 16]

A large field inflation

$$V_{inf} = m^3 \phi_{inf}$$

The problem: $\left(\frac{m}{M_P}\right)^3 \sim 10^{-10}$

The CW solution: $\frac{1}{q^N}\left(\frac{m}{M_P}\right)^3 \sim 10^{-10}$

$$V(\pi_1, \cdots, \pi_N) = \frac{M_1^2}{2} \sum_{i=0}^{N-1} (\pi_i - q\,\pi_{i+1})^2 + M_2^3 \pi_N$$

CW Higgs inflation

[SCP, Shin 18]

The 'Higgs inflation'

$$S = \int d^4x\sqrt{-g}\left(-\frac{M_P^2 + \xi\phi^2}{2}R - \frac{1}{2}(\partial_\mu\phi)^2 - \frac{\lambda}{4}\phi^4\right)$$

The problem: $\lambda = 4.4 \times 10^{-10}\xi^2$

The CW solution: $\lambda = \dfrac{\lambda}{q^{4N}}\xi^2$

$$K(\phi_i) \equiv \sum_{i=1}^{N+1} \xi_i\phi_i^2,$$

$$V_{CW}(\phi_i) = \sum_{i=1}^{N} \frac{m^2}{2}(\phi_{i+1} - q\phi_i)^2$$

CW mechanisms for neutrino mass

[SCP, Shin 17]

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- CW Dirac mass, Type-0

$$m_\nu \approx \left(\frac{y}{q^N}\right) v$$

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- CW EW scale seesaw, Type-1 $$m_\nu \approx \left(\frac{y}{q^N}\right)^2 \frac{v^2}{m_M}$$

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- CW Inverse seesaw, Type-ia $$m_\nu \approx m_M \left(\frac{y}{q^N}\right)^2 \frac{v^2}{m_D^2}$$

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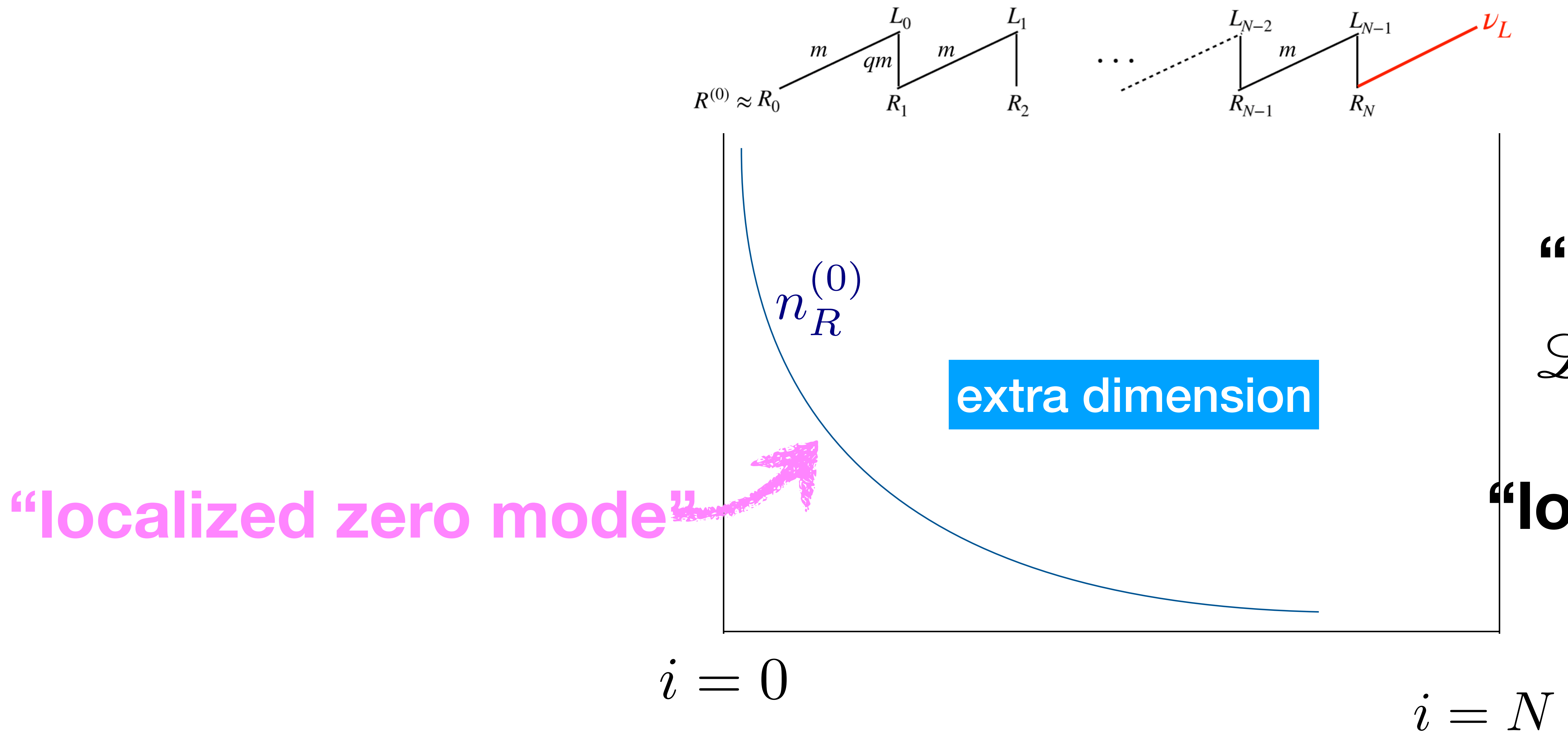
- CW Inverse seesaw, Type-ia $\quad m_\nu \approx m_M \left(\frac{y}{q^N}\right)^2 \frac{v^2}{m_D^2}$
- CW Inverse seesaw, Type-ib $\quad m_\nu \approx \left(\frac{m_M}{q^{2N}}\right) \frac{y^2 v^2}{m_D^2 + y^2 v^2}$

Type-0 CW diagram

$$\mathscr{L} = \mathscr{L}_{\text{kin}} - m\sum_{i=1}^{N}\left(\bar{L}_i R_{i-1} - q\bar{L}_i R_i + h.c.\right) - yH\bar{\ell}_L R_N + h.c.$$

Type-0 CW



"SM"

$$\mathscr{L} = - y v \nu_L R_N$$

"localized Yukawa"

$$m_\nu \approx \left(\frac{y}{q^N}\right) v$$

$y \approx 1, q = 3, N = 25$

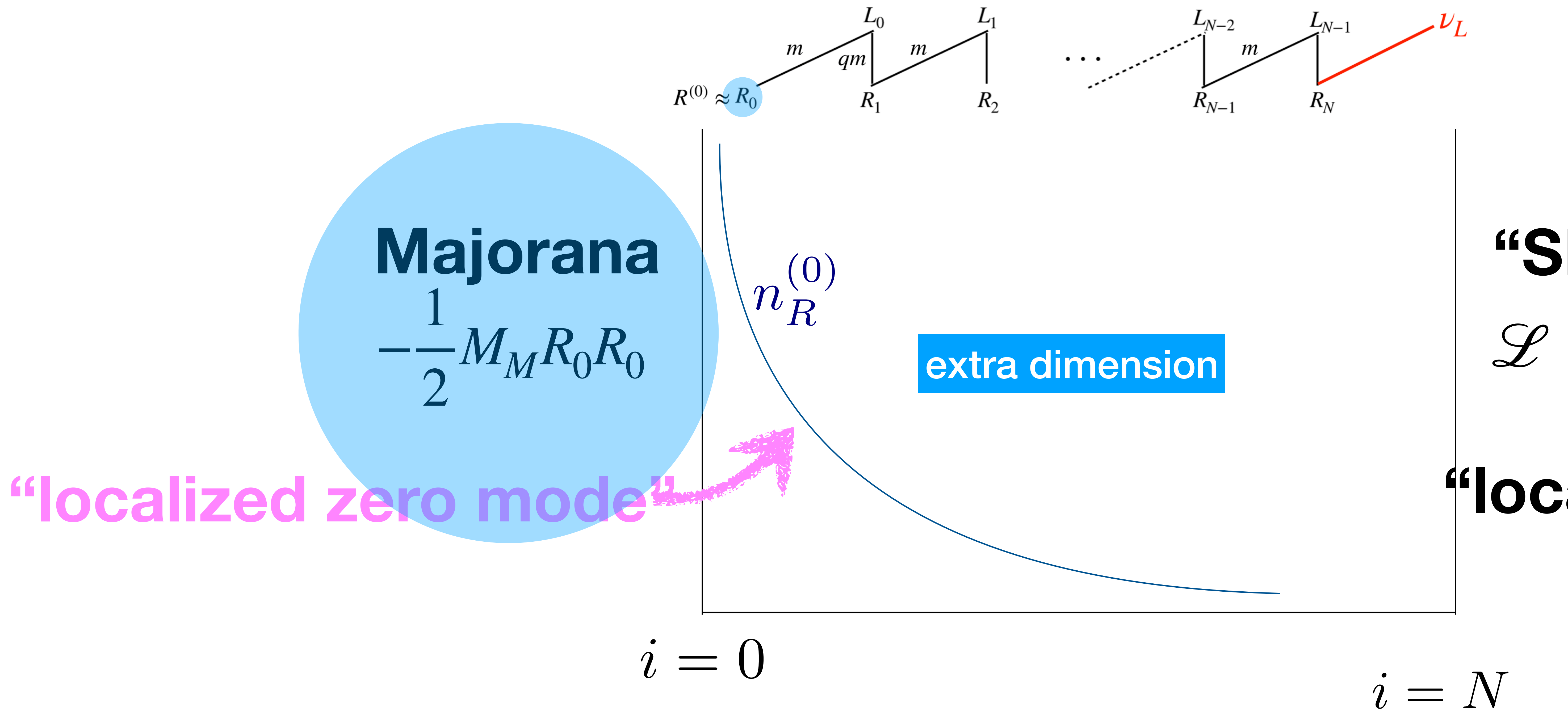
(cf) Grossmann, Neubert (2000)

Type-1 CW diagram

$$\mathscr{L} = \mathscr{L}_{\rm kin} - m \sum_{i=1}^{N} \left(\bar{L}_i R_{i-1} - q \bar{L}_i R_i + h.c.\right) - y H \bar{\ell}_L R_N + h.c. - \frac{1}{2} m_M R_0 R_0$$

Type-1 CW ‘seesaw’

[SCP, Shin 17]



“SM”

$\mathscr{L} = -yv\nu_L R_N$

“localized Yukawa”

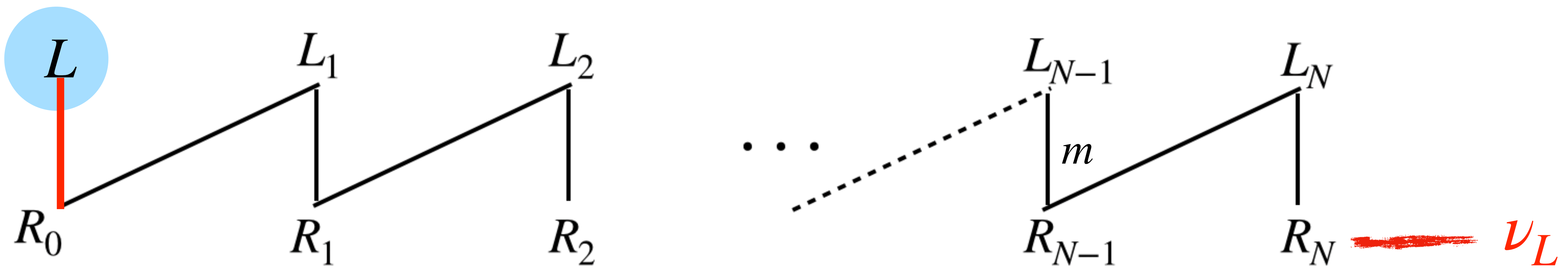
$$m_\nu \approx \left(\frac{y}{q^N}\right)^2 \frac{v^2}{m_M}$$

Unsuppressed Majorana mass, suppressed Yukawa

Type-ia diagram

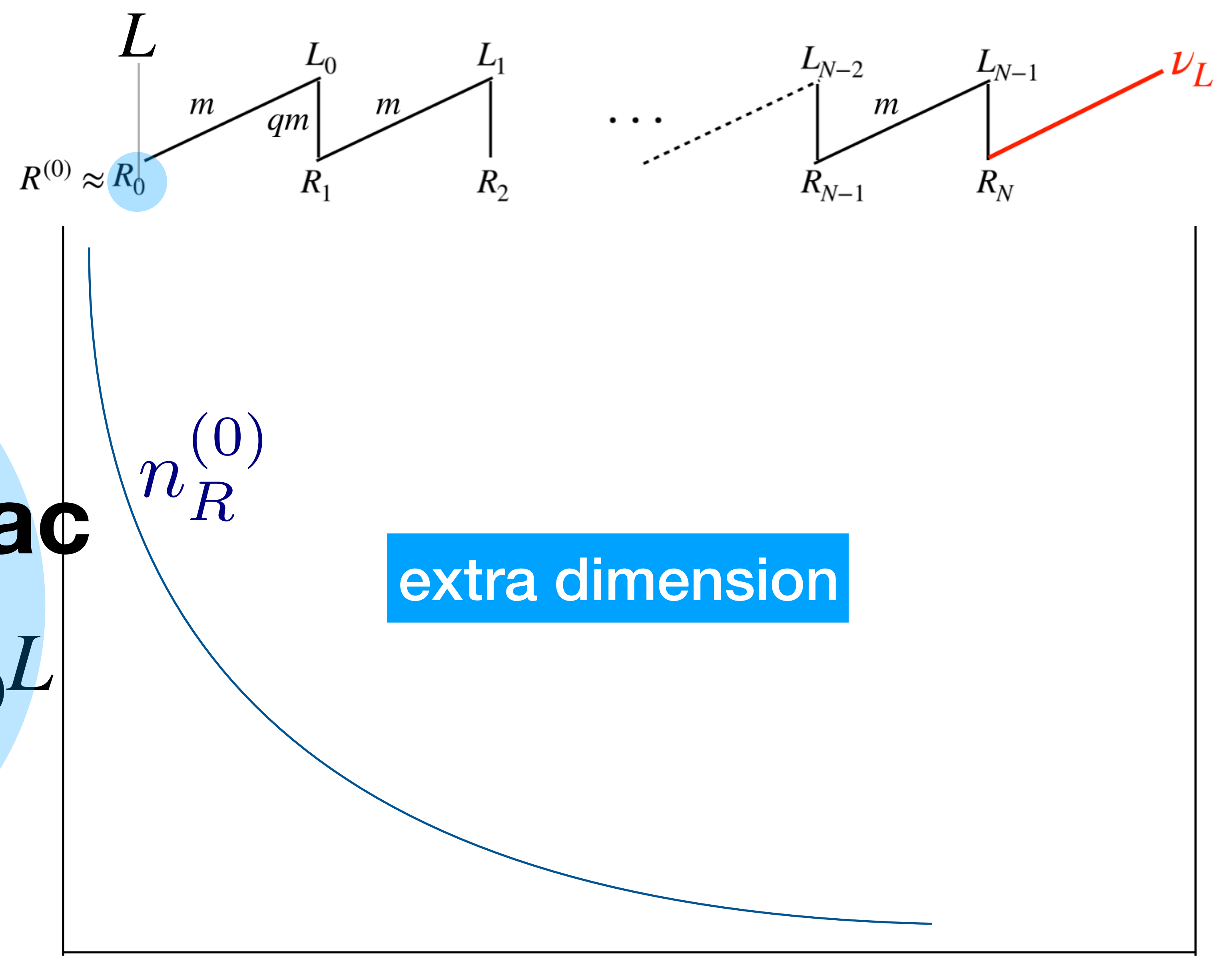
$$\mathscr{L} = \mathscr{L}_{\text{kin}} - m\sum_{i=1}^{N}\left(\bar{L}_i R_{i-1} - q\bar{L}_i R_i + h.c.\right) - yH\bar{\ell}_L R_N + h.c. - \frac{1}{2}m_M LL - m_D \bar{L} R_0$$

“inverse seesaw”



Type-ia CW

[SCP, Shin 17]



Majorana Dirac

$$-\frac{1}{2}M_M LL - m_D \bar{R}_0 L$$

$i = 0$

$i = N$

“SM”

$$\mathscr{L} = -y v \nu_L R_N$$

“localized Yukawa”

$$m_\nu \approx m_M \left(\frac{y}{q^N}\right)^2 \frac{v^2}{m_D^2}$$

Inverse seesaw-like

w/ suppressed Yukawa,

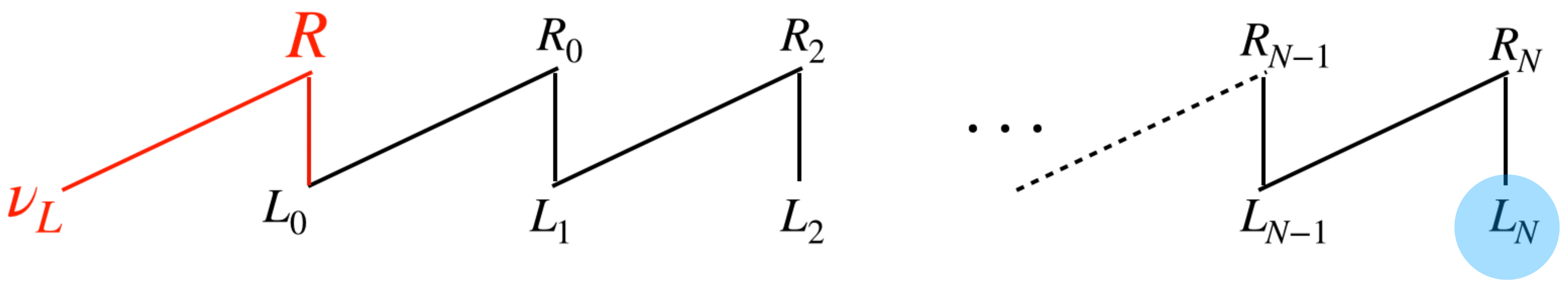
Unsuppressed Majorana

(cf) [SCP, Wang, Yanagida 10]

Type-ib diagram

$$\mathscr{L} = \mathscr{L}_{\text{kin}} - m\sum_{i=1}^{N}\left(\bar{L}_i R_{i-1} - q\bar{L}_i R_i + h.c.\right) - yH\bar{\ell}_L R_N + h.c. - \frac{1}{2}m_M L_N L_N - m_D \bar{L}_0 R$$

“inverse seesaw”



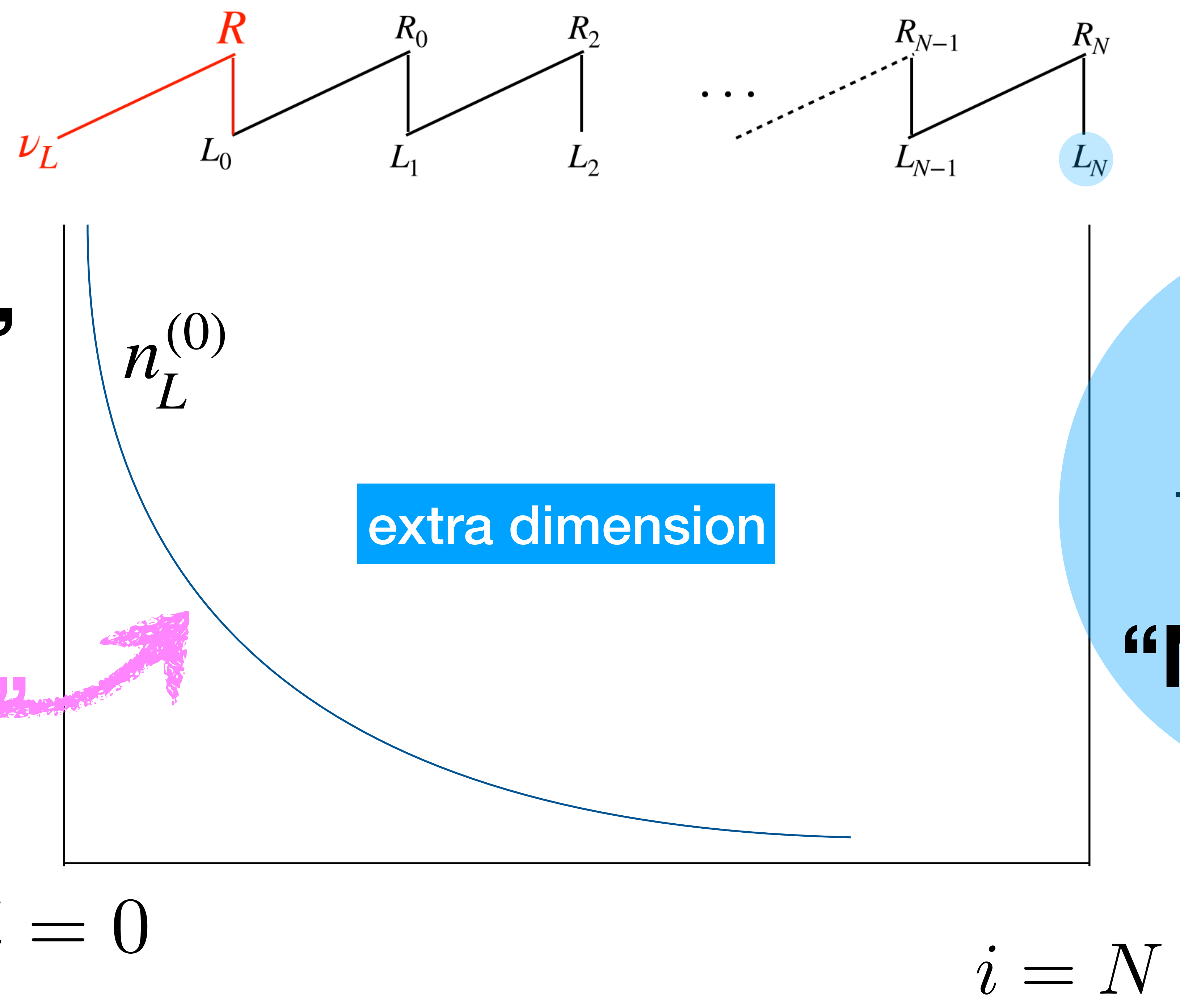
Type-ib CW

[SCP, Shin 17]

“localized Yukawa”

$$\mathscr{L} = -\,y v \nu_L R$$
$$-M_D L_0 R$$

“localized zero mode”



$$-\frac{1}{2} M_M L_N L_N$$

“Majorana”

$$m_\nu \approx \left(\frac{m_M}{q^{2N}}\right) \frac{y^2 v^2}{m_D^2 + y^2 v^2}$$

Inverse seesaw-like
w/ unsuppressed Yukawa,
Suppressed Majorana

(cf) [SCP, Wang, Yanagida 10]

CW models for neutrino mass

$m_\nu = \begin{cases} \\ \\ \\ \end{cases}$

Type-0

Type-I

Inverse seesaw
Type-ia
Type-ib

CW models for neutrino mass

$$m_\nu = \begin{cases} \left(\frac{y}{q^N}\right) v & \textbf{Type-0} \\ \left(\frac{y}{q^N}\right)^2 \frac{v^2}{m_M} & \textbf{Type-I} \\ \left(\frac{m_M}{q^{2N}}\right) \frac{y^2 v^2}{m_D^2 + y^2 v^2} & \textbf{Inverse seesaw, Type-ia, Type-ib} \end{cases}$$

heavy modes

$$m_{\text{heavy}} \begin{cases} \text{Type I}: \; M_{\text{I}} = m_M \\ \\ \text{Type Ia}: \; M_{\text{Ia}\pm} = M_D \pm \dfrac{m_M}{2} + \dfrac{m_M^2}{8M_D} \pm \dfrac{y_{\text{eff}}^4 v^4 m_M^3}{2M_D^6}, \\ \text{Type Ib}: \; M_{\text{Ib}\pm} = \sqrt{M_D^2 + \lambda^2 v^2} \pm \dfrac{m_M^{\text{eff}} M_D^2}{2(M_D^2 + \lambda^2 v^2)}. \end{cases}$$

with unsuppressed Yukawa coupling!

Summary

- **CW mechanisms** are newly proposed to ‘solve’ naturalness problems using ‘CW gears’ and ‘localized interactions’.

$$\lambda \to \frac{\lambda}{q^N} \qquad q > 1, N \sim 10$$

- **CW phenomenology** is rich with gear fields (N>1) at CW scale, that often leads to observational consequences.

Discussion

CW	s=0	s=1/2	s=1	s=3/2	s=2
symmetry S	Shift	Chiral	gauge	SUSY?	4D diffeomorphism
CW model	axion	neutrino mass, flavor	tiny gauge coupling	??	CW graviton, naturalness problem

25th International Summer Institute on Phenomenology of Elementary Particle Physics and Cosmology (SI2019)

Invited Lecturers (topics):
Tongyan Lin (Light dark matter),
Hitoshi Murayama (overview),
Misao Sasaki(inflation and cosmology),
Chang Sub Shin (BSM theories)
Carsten Rott (Multi-messenger physics)

Register NOW! (due May 31)

https://indico.cern.ch/event/752582/

Contact me!

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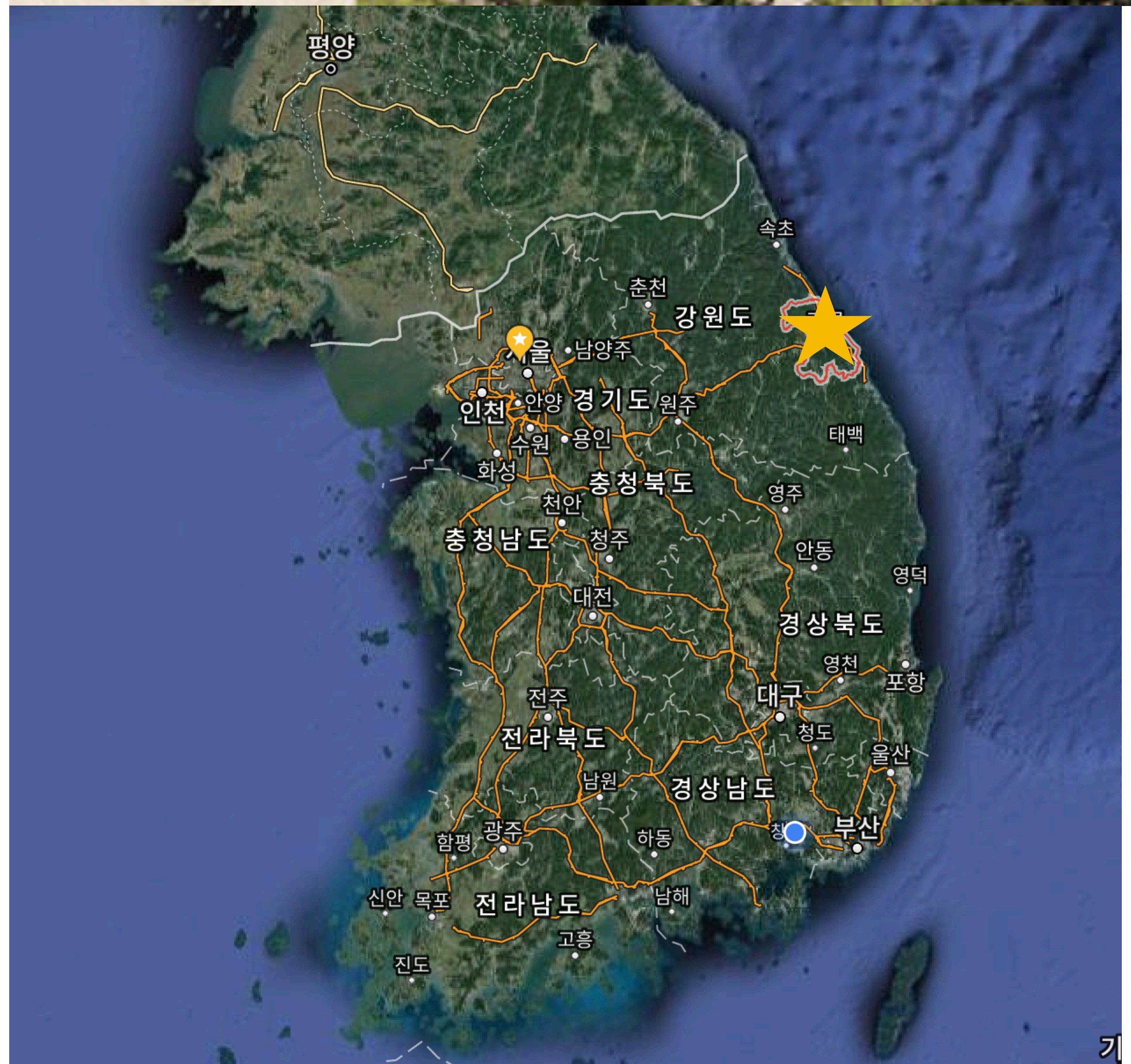

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