How to Give Chiral Fermions a Mass

David Tong
String Pheno 2021

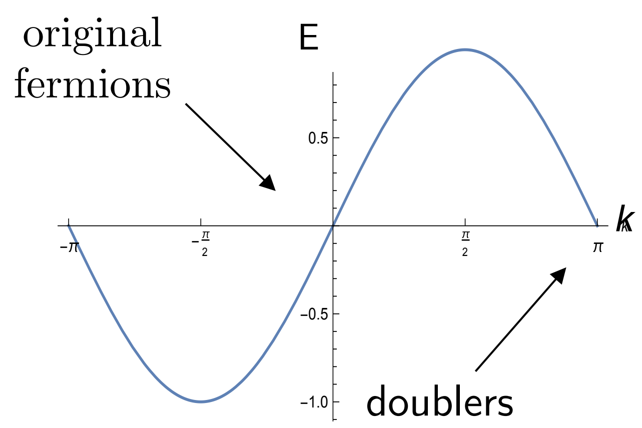
Based on 2009.05037 with Shlomo Razamat, and 2104.03997

Symmetric Mass Generation

Giving masses to fermions preserving symmetries that you might naively think should be broken.

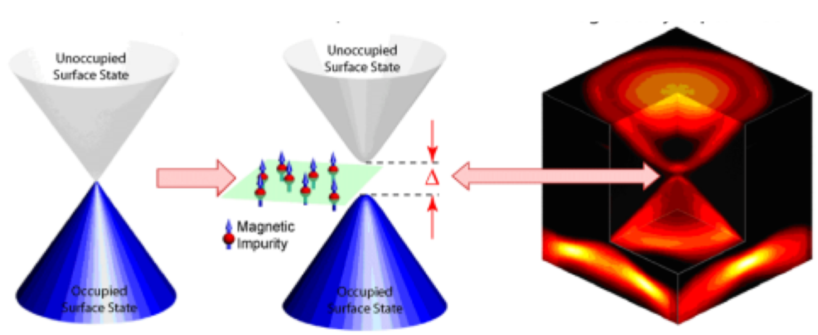
Motivation

- Nielsen-Ninomiya theorem



c.f. Eichten and Preskill '86

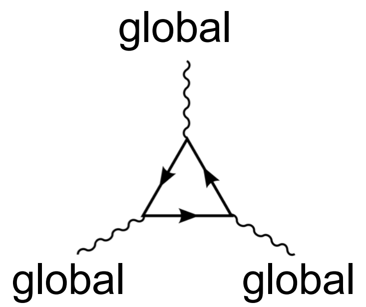
- Interacting topological insulators



c.f. Fidkowski and Kitaev, '09

The Obstacle: the 't Hooft Anomaly

Consider a global symmetry G



‘t Hooft anomaly = obstruction to gauging

The ‘t Hooft anomaly characterises the symmetry and does not change under deformations or RG.

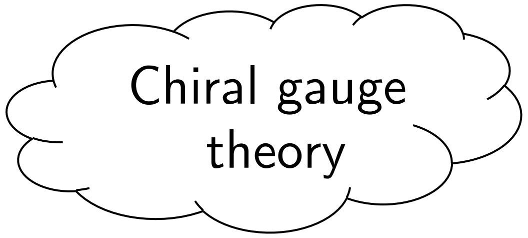
The Obstacle: the 't Hooft Anomaly

- If the the ‘t Hooft anomaly for a continuous global symmetry is non-vanishing then the theory must be gapless.

- In a chiral gauge theory, the ‘t Hooft anomaly necessarily vanishes! So there is no obstacle to gapping fermions.

How to Gap Chiral Fermions

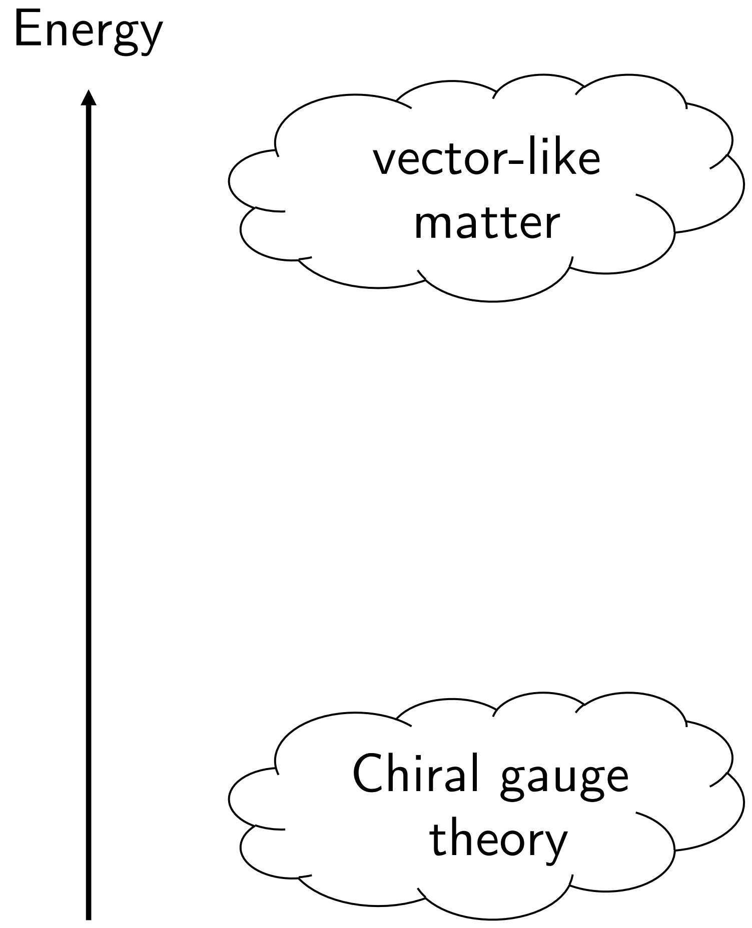
Razamat and Tong '20



How to Gap Chiral Fermions

We must typically add new degrees of freedom.

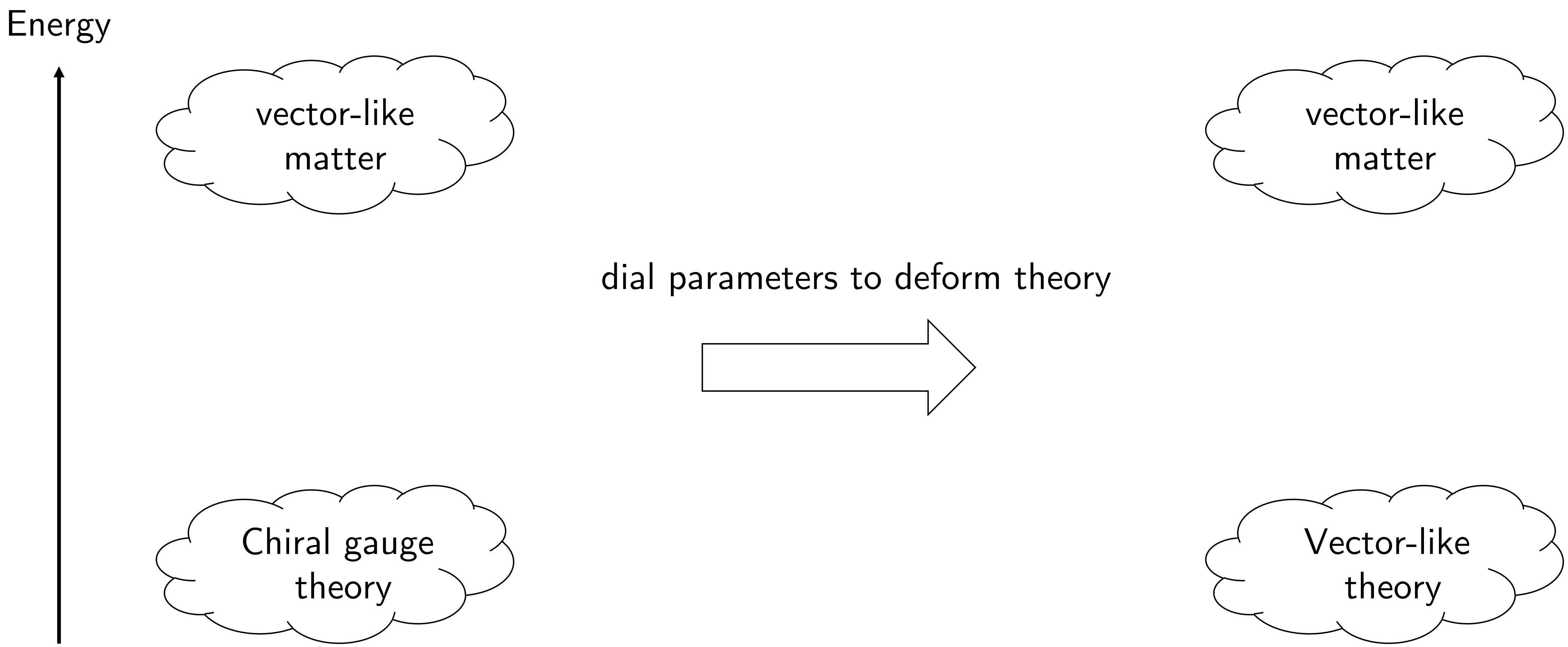
Razamat and Tong '20



How to Gap Chiral Fermions

We must typically add new degrees of freedom.

Razamat and Tong '20



i.e. chiral + vector-like = vector-like

Basic idea

Take a collection of chiral fermions transforming under some symmetry, let's call it G

$$\psi_L \ , \quad \chi_L \ , \quad \lambda_L \quad \text{and} \quad \psi_R$$

Now introduce a new additional confining force that acts on some subset of the fermions, say just the left-handed ones above.

In certain, very special circumstances, these fermions can bind together into a new massless composite fermion.

$$\psi_{\rm new} = \psi_L \chi_L \rho_L$$

where, if you're lucky, $\psi_{\rm new}$ transforms under G in the same way as ψ_R . Then

$$\mathcal{L}_{4-{\rm fermi}} \sim \psi_L \chi_L \rho_L \psi_R^\dagger \ \longrightarrow \ \psi_{\rm new} \psi_R^\dagger$$

And this is a mass term!

The Catch

- Usually confinement comes along with chiral symmetry breaking.
- In the present context, this typically means G is spontaneously broken, ruining our hard work.

<u>Upshot</u>

Symmetric mass generation $\Longleftrightarrow$ Confinement without chiral symmetry breaking

Example: The Standard Model

$$G = SU(3) \times SU(2) \times U(1)$$

(left-handed)^c		right-handed		
leptons	quarks	electron	up quark	down quark
$(\mathbf{1}, \mathbf{2})_{-3}$	$(\bar{\mathbf{3}}, \mathbf{2})_{+1}$	$(\mathbf{1}, \mathbf{1})_{+6}$	$(\mathbf{3}, \mathbf{1})_{-4}$	$(\mathbf{3}, \mathbf{1})_{+2}$

Example: The Standard Model

$$G = SU(3) \times SU(2) \times U(1)$$

(left-handed)^c		right-handed			
leptons	quarks	electron	up quark	down quark	neutrino
$(\mathbf{1},\mathbf{2})_{-3}$	$(\bar{\mathbf{3}},\mathbf{2})_{+1}$	$(\mathbf{1},\mathbf{1})_{+6}$	$(\mathbf{3},\mathbf{1})_{-4}$	$(\mathbf{3},\mathbf{1})_{+2}$	$(\mathbf{1},\mathbf{1})_{0}$
$(\mathbf{1},\mathbf{2})_{-3}$				$(\mathbf{3},\mathbf{1})_{+2}$	$(\mathbf{1},\mathbf{1})_{0}$
$(\mathbf{1},\mathbf{2})_{+3}$				$(\bar{\mathbf{3}},\mathbf{1})_{-2}$	

- Add three further pairs of fermions
  - Note: these are all vector-like and can be made heavy

Example: The Standard Model

$$G = SU(3) \times SU(2) \times U(1)$$

(left-handed)^c | right-handed

leptons	quarks	electron	up quark	down quark	neutrino
$(\mathbf{1}, \mathbf{2})_{-3}$	$(\bar{\mathbf{3}}, \mathbf{2})_{+1}$	$(\mathbf{1}, \mathbf{1})_{+6}$	$(\mathbf{3}, \mathbf{1})_{-4}$	$(\mathbf{3}, \mathbf{1})_{+2}$	$(\mathbf{1}, \mathbf{1})_{0}$
$(\mathbf{1}, \mathbf{2})_{-3}$				$(\mathbf{3}, \mathbf{1})_{+2}$	$(\mathbf{1}, \mathbf{1})_{0}$
$(\mathbf{1}, \mathbf{2})_{+3}$				$(\bar{\mathbf{3}}, \mathbf{1})_{-2}$	

- Add three further pairs of fermions
- Gauge the H = SU(2) symmetry.
  - We should also introduce a scalar to ensure that H = SU(2) is initially broken and the gauge bosons heavy.

Example: The Standard Model

$$G = SU(3) \times SU(2) \times U(1)$$

(left-handed)^c		right-handed			
leptons	quarks	electron	up quark	down quark	neutrino
$(\mathbf{1},\mathbf{2})_{-3}$	$(\bar{\mathbf{3}},\mathbf{2})_{+1}$	$(\mathbf{1},\mathbf{1})_{+6}$	$(\mathbf{3},\mathbf{1})_{-4}$	$(\mathbf{3},\mathbf{1})_{+2}$	$(\mathbf{1},\mathbf{1})_{0}$
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- Add three further pairs of fermions
- Gauge the H = SU(2) symmetry. This gauge theory has an SU(6) flavour symmetry

$$G \subset SU(6)_{\text{flavour}}$$

- When SU(2) confines, it will spontaneously break SU(6) and hence, sadly, *G*.

Example: The Standard Model

$$G = SU(3) \times SU(2) \times U(1)$$

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leptons	quarks	electron	up quark	down quark	neutrino
$(\mathbf{1},\mathbf{2})_{-3}$	$(\bar{\mathbf{3}},\mathbf{2})_{+1}$	$(\mathbf{1},\mathbf{1})_{+6}$	$(\mathbf{3},\mathbf{1})_{-4}$	$(\mathbf{3},\mathbf{1})_{+2}$	$(\mathbf{1},\mathbf{1})_{0}$
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- Add three further pairs of fermions
- Gauge the H = SU(2) symmetry
- Supersymmetrize.
  - Add scalar superpartners for all fermions and a H = SU(2) gaugino

Example: The Standard Model

	L	Q	E	U	D	N
	leptons	quarks	electron	up quark	down quark	neutrino
	$(\mathbf{1},\mathbf{2})_{-3}$	$(\bar{\mathbf{3}},\mathbf{2})_{+1}$	$(\mathbf{1},\mathbf{1})_{+6}$	$(\mathbf{3},\mathbf{1})_{-4}$	$(\mathbf{3},\mathbf{1})_{+2}$	$(\mathbf{1},\mathbf{1})_{0}$
	$(\mathbf{1},\mathbf{2})_{-3}$				$(\mathbf{3},\mathbf{1})_{+2}$	$(\mathbf{1},\mathbf{1})_{0}$
$L' \longrightarrow$	$(\mathbf{1},\mathbf{2})_{+3}$			$D' \longrightarrow$	$(\bar{\mathbf{3}},\mathbf{1})_{-2}$	

- The H = SU(2) gauge theory is coupled to six doublets.
- This confines without breaking the global symmetry.
- The low-energy physics consists of 15 free mesons:

Seiberg '94

$$\epsilon_{ab}L^aL^b \qquad \epsilon_{ijk}D^iD^j \qquad L^aD^i \qquad L^aN \qquad D^iN$$

Example: The Standard Model

L	Q	E	U	D	N
leptons	quarks	electron	up quark	down quark	neutrino
$(\mathbf{1},\mathbf{2})_{-3}$	$(\bar{\mathbf{3}},\mathbf{2})_{+1}$	$(\mathbf{1},\mathbf{1})_{+6}$	$(\mathbf{3},\mathbf{1})_{-4}$	$(\mathbf{3},\mathbf{1})_{+2}$	$(\mathbf{1},\mathbf{1})_{0}$
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$L' \longrightarrow (\mathbf{1},\mathbf{2})_{+3}$				$D' \longrightarrow (\bar{\mathbf{3}},\mathbf{1})_{-2}$	

If we add the superpotential, invariant under G = SU(3) x SU(2) x U(1)

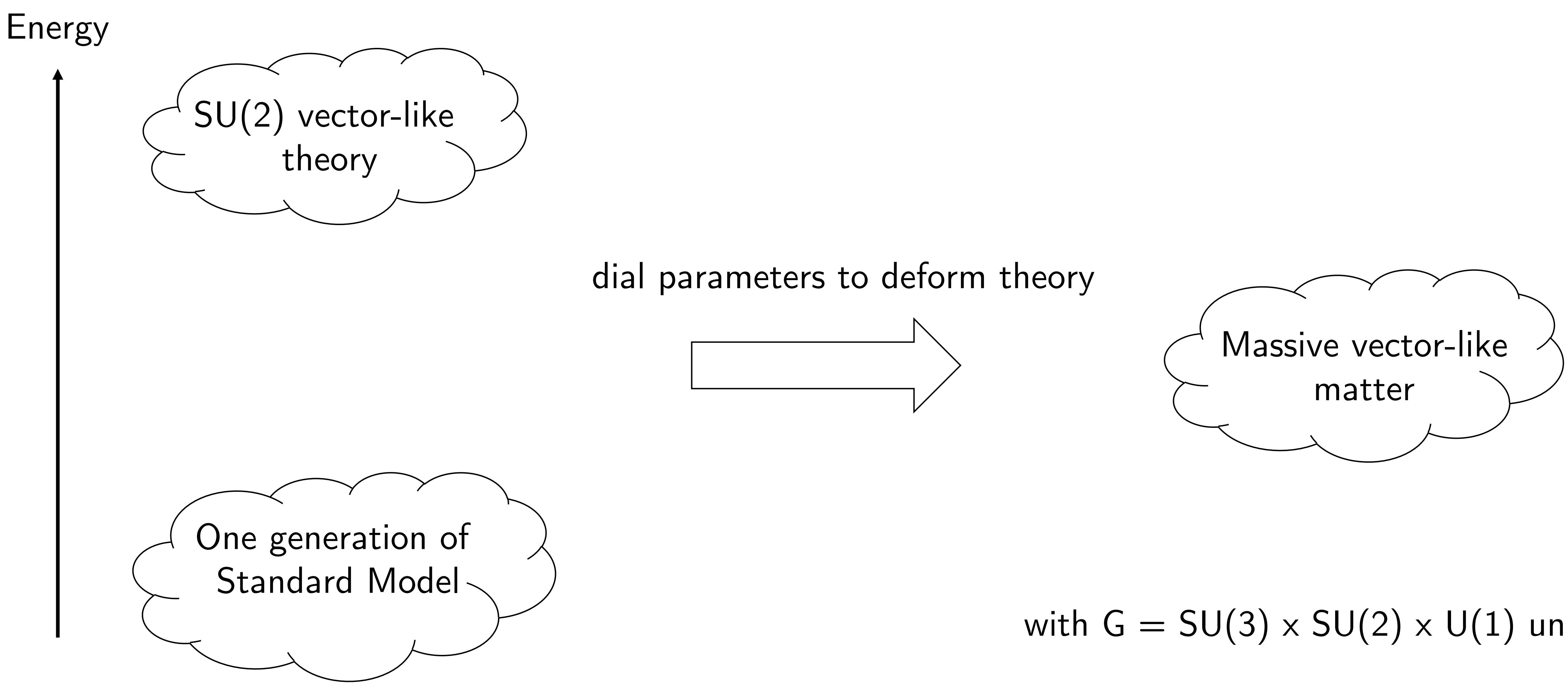
$$\mathcal{W}_{UV} = \epsilon_{ab} L^a L^b E + \epsilon_{ijk} D^i D^j U^k + \epsilon_{ab} L^a D^i Q_i^b + \epsilon_{ab} L^a N L'^b + D^i N D'_i$$

But, in the infra-red, this becomes

$$\mathcal{W}_{IR} = \widetilde{E} E + \widetilde{U}_k U^k + \widetilde{Q}_b^i Q_i^b + \widetilde{L}^b L'^b + \widetilde{D}_i D'_i$$

This gaps all fermions without breaking G = SU(3) x SU(2) x U(1)

A Gapping Mechanism for the Standard Model



with G = SU(3) x SU(2) x U(1) unbroken

Note: Supersymmetry just a crutch. The mechanism survives supersymmetry breaking.

Thank you for your attention