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Der Wissenschaftsfonds.

D-brane model building and the holographic framework

Pascal Anastasopoulos

$$\left[\text{Diagram 1} + \text{Diagram 2} \right]^2 = 0$$

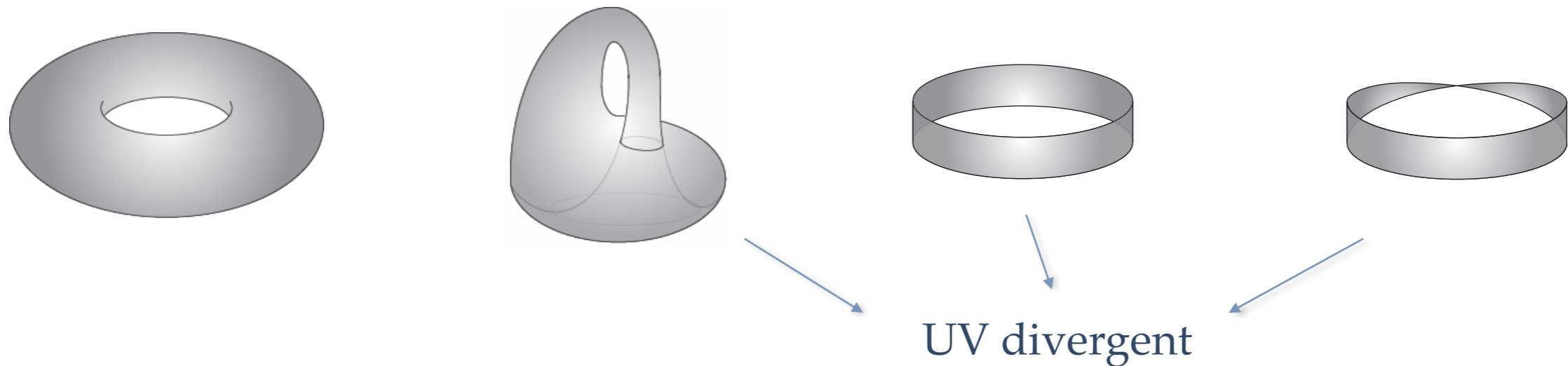
The diagram shows two 3D representations of a sphere with a wavy line extending from its left side, positioned on a vertical plane. The first diagram features a gray plane and a sphere with a light gray shading. The second diagram features a blue plane and a sphere with a light blue shading. The two diagrams are separated by a plus sign and enclosed in large blue square brackets. To the right of the closing bracket is a superscript '2', and below the bracket is an equals sign followed by a zero.

Orientifolds

Orientifolds

- * A very interesting class of models is the **orientifolds**.
- * These models contain **unoriented closed** and **open** strings.
- * The **1-loop partition function** of these models contain **four different amplitudes**.

Bianchi Pradisi Sagnotti



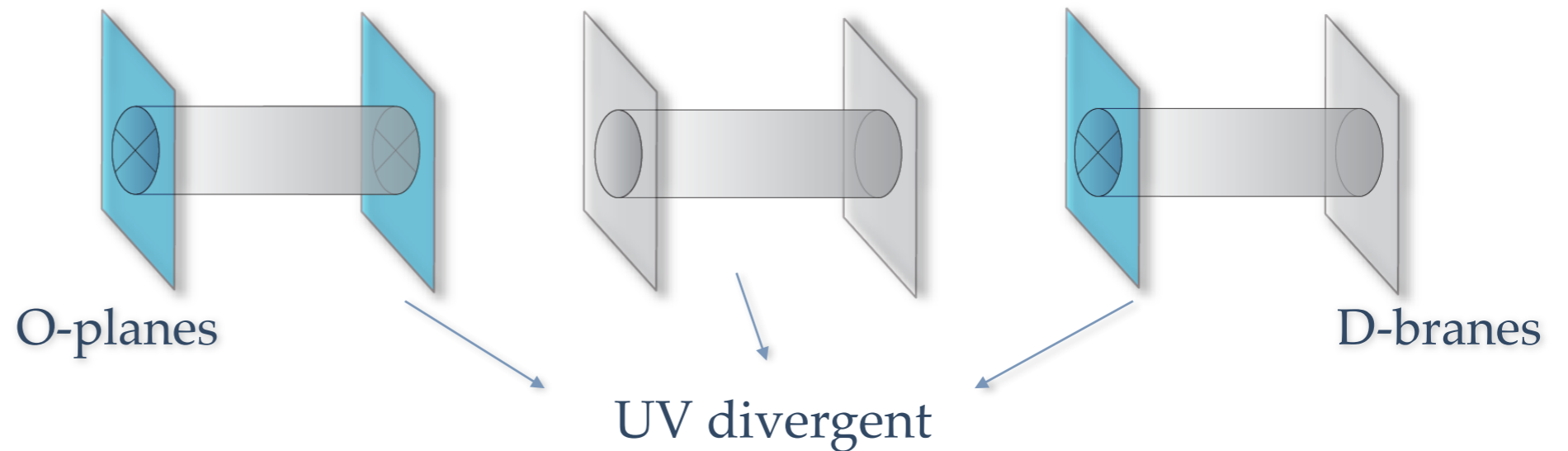
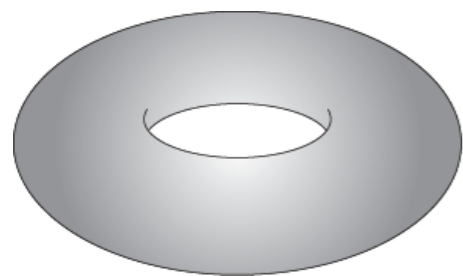
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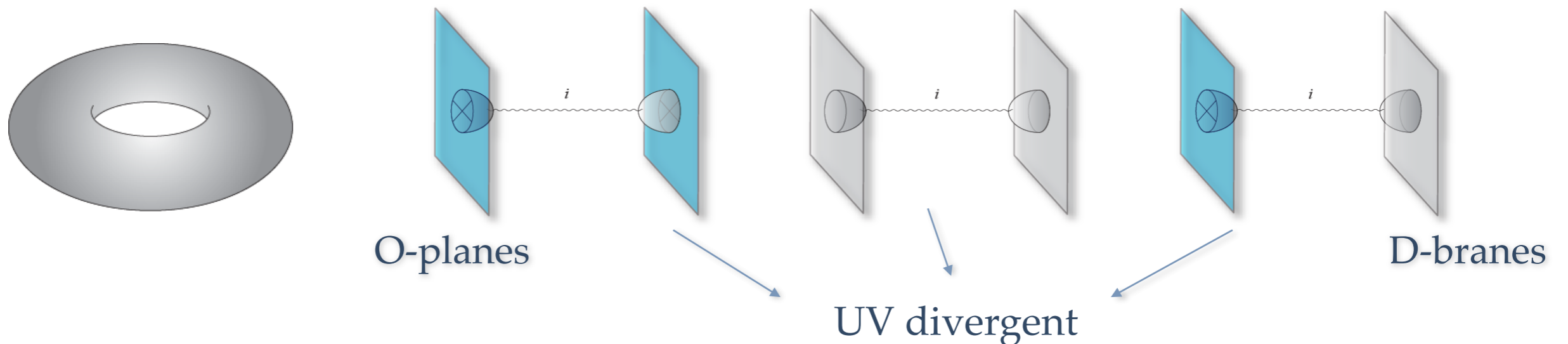
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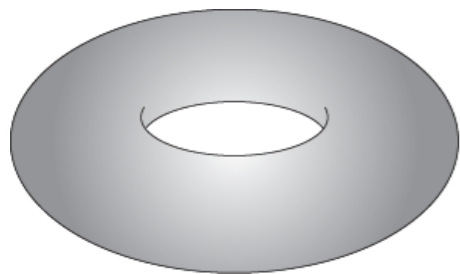
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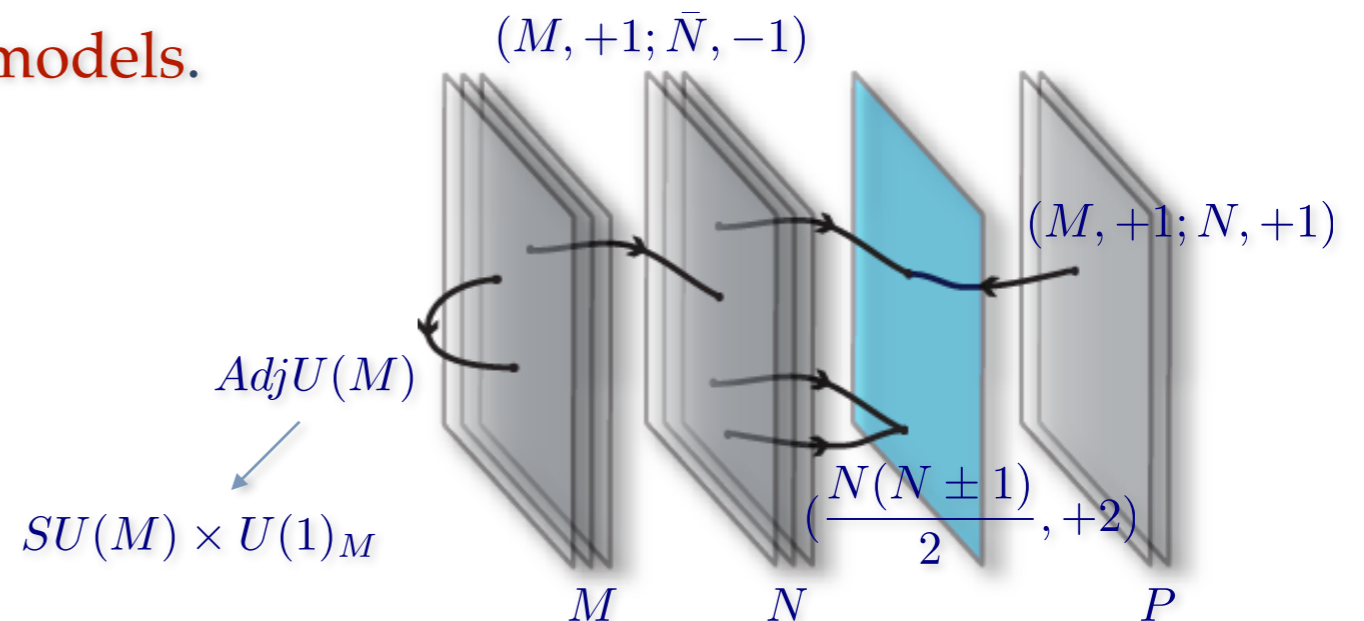


$$\left[\text{Diagram 1} + \text{Diagram 2} \right]^2 = 0$$

tadpole condition

The diagram shows two terms in brackets, each representing a tadpole diagram. The first term shows a sphere with a wavy line attached to a grey plane. The second term shows a sphere with a wavy line attached to a blue plane. The entire expression is squared and set equal to zero.

- Tadpole cancellation leads to **consistent models**.

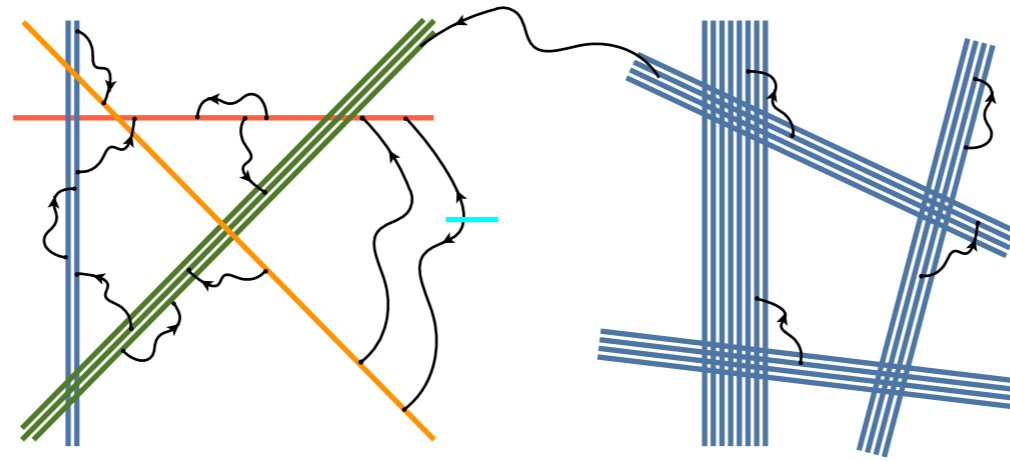


Orientifolds

- ❖ In this way, we construct Type I **consistent models** (free of irreducible anomalies).
- ❖ **Mixed anomalies** are cancelled by the combination of the **Green-Schwarz mechanism** and **generalized Chern-Simons terms**.
- ❖ Can we **embed the Standard Model in a D-brane configuration**?

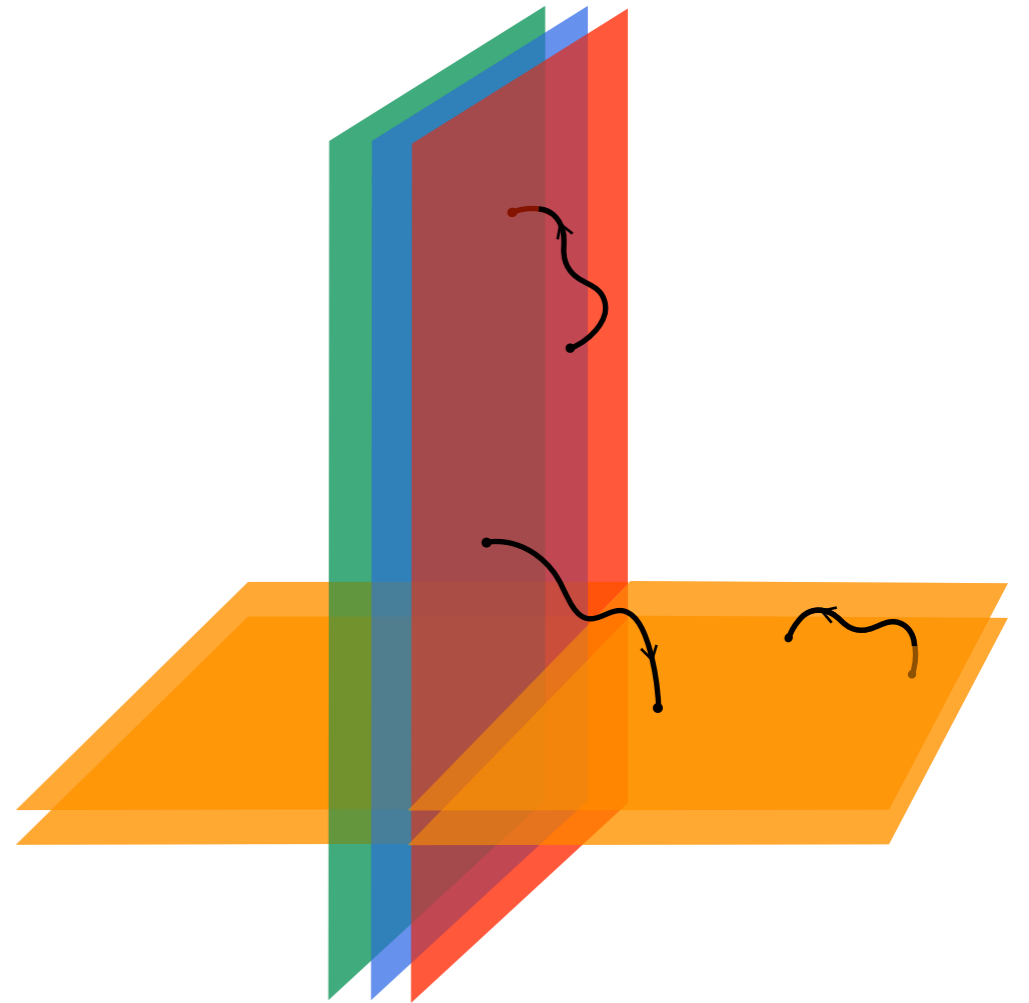
D-brane Standard Model

- ❖ Building a consistent model, and hoping that SM is at one corner is **not a good idea**.

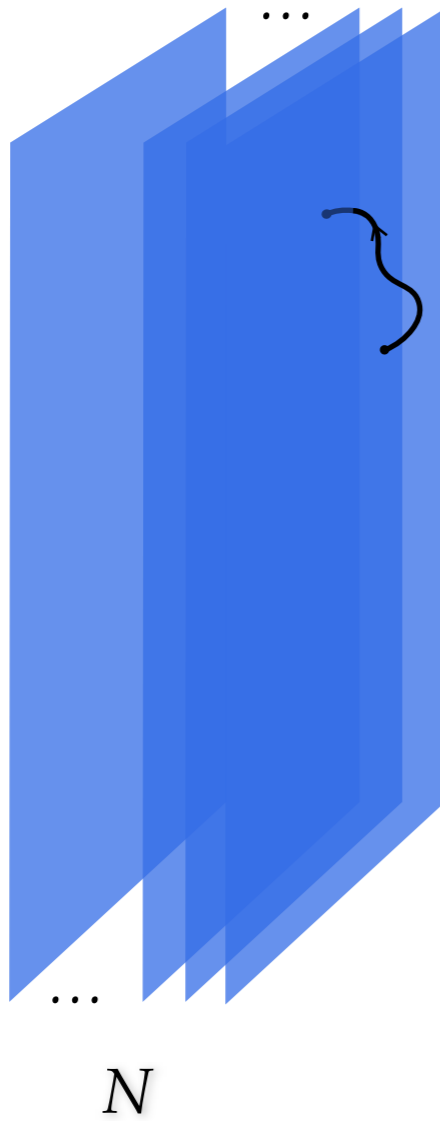


- ❖ Instead we can try a different technique.
 - ❖ Construct a **local model** which accommodates the SM.
 - ❖ Add extra **D-branes** until the **full model is consistent**.
- ❖ The rules for this procedure **are simple**.

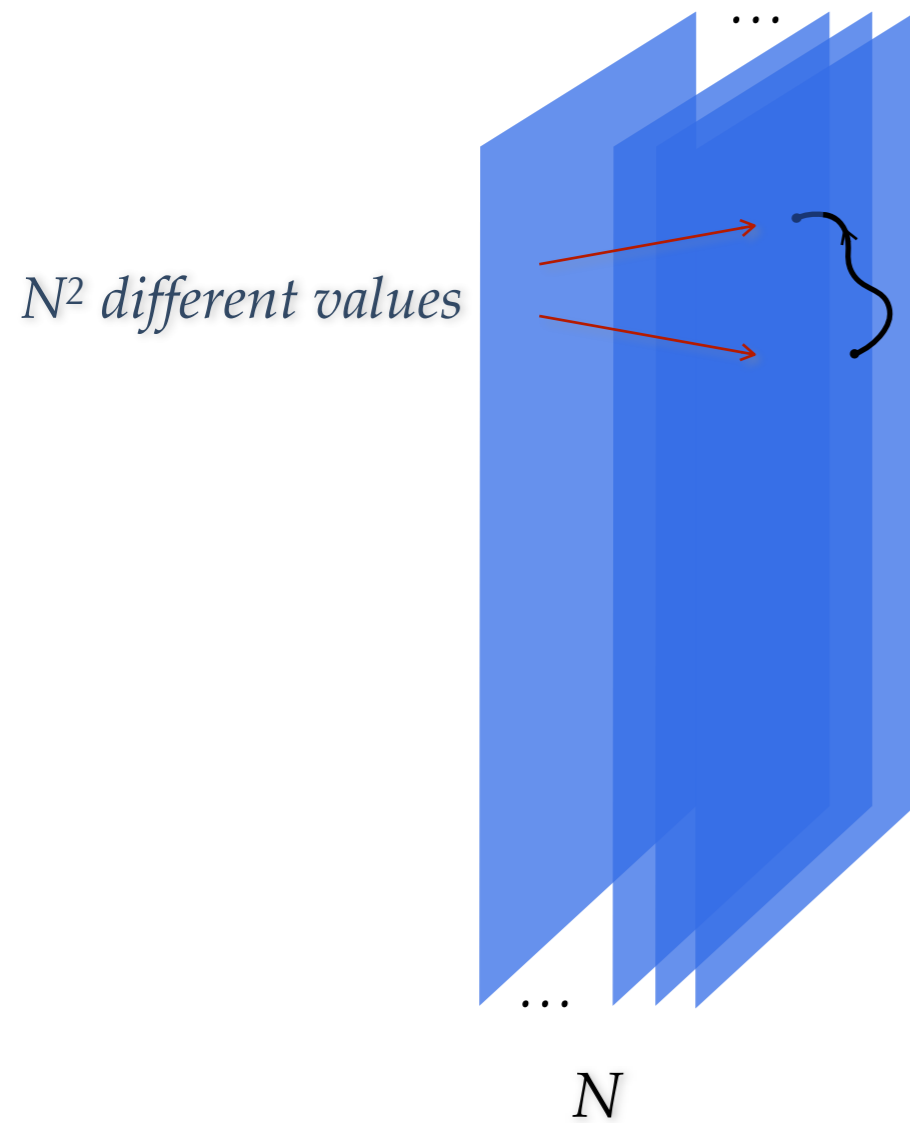
From bottom to up



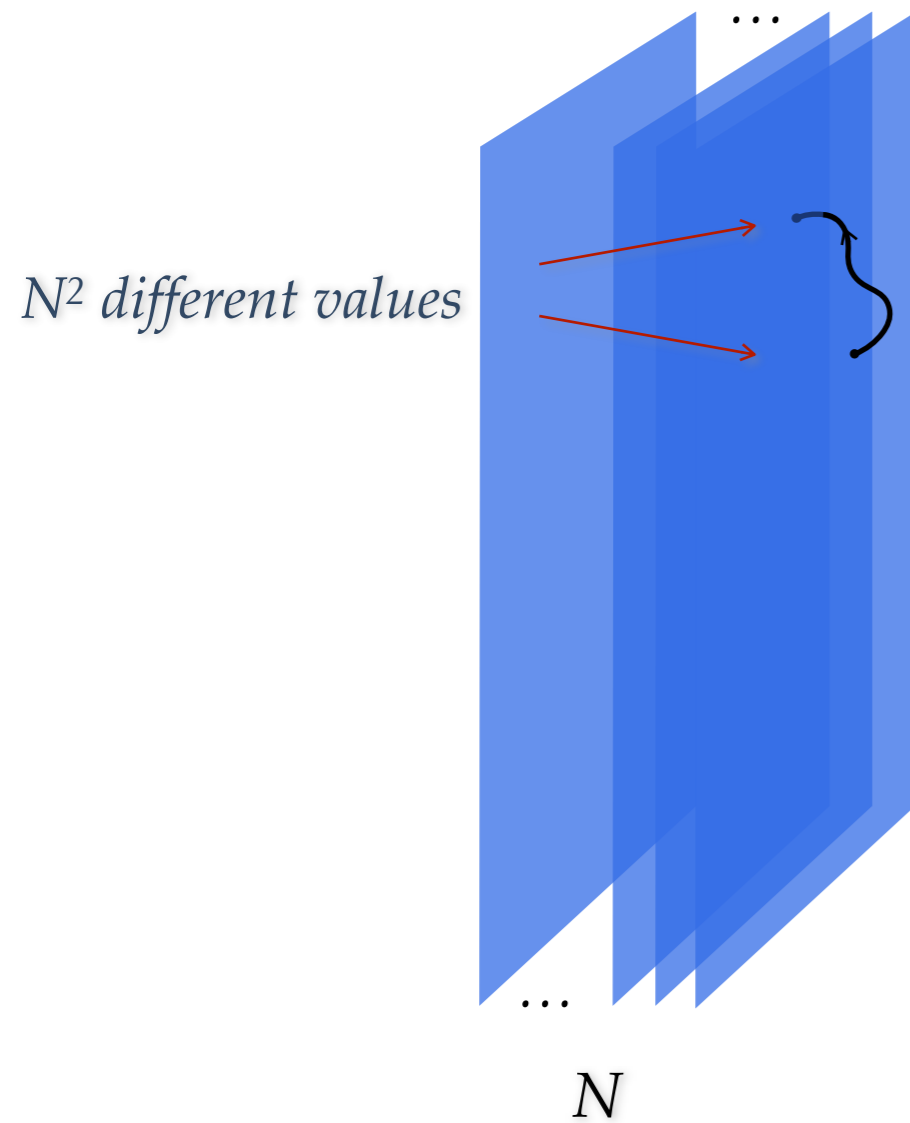
Force mediators



Force mediators

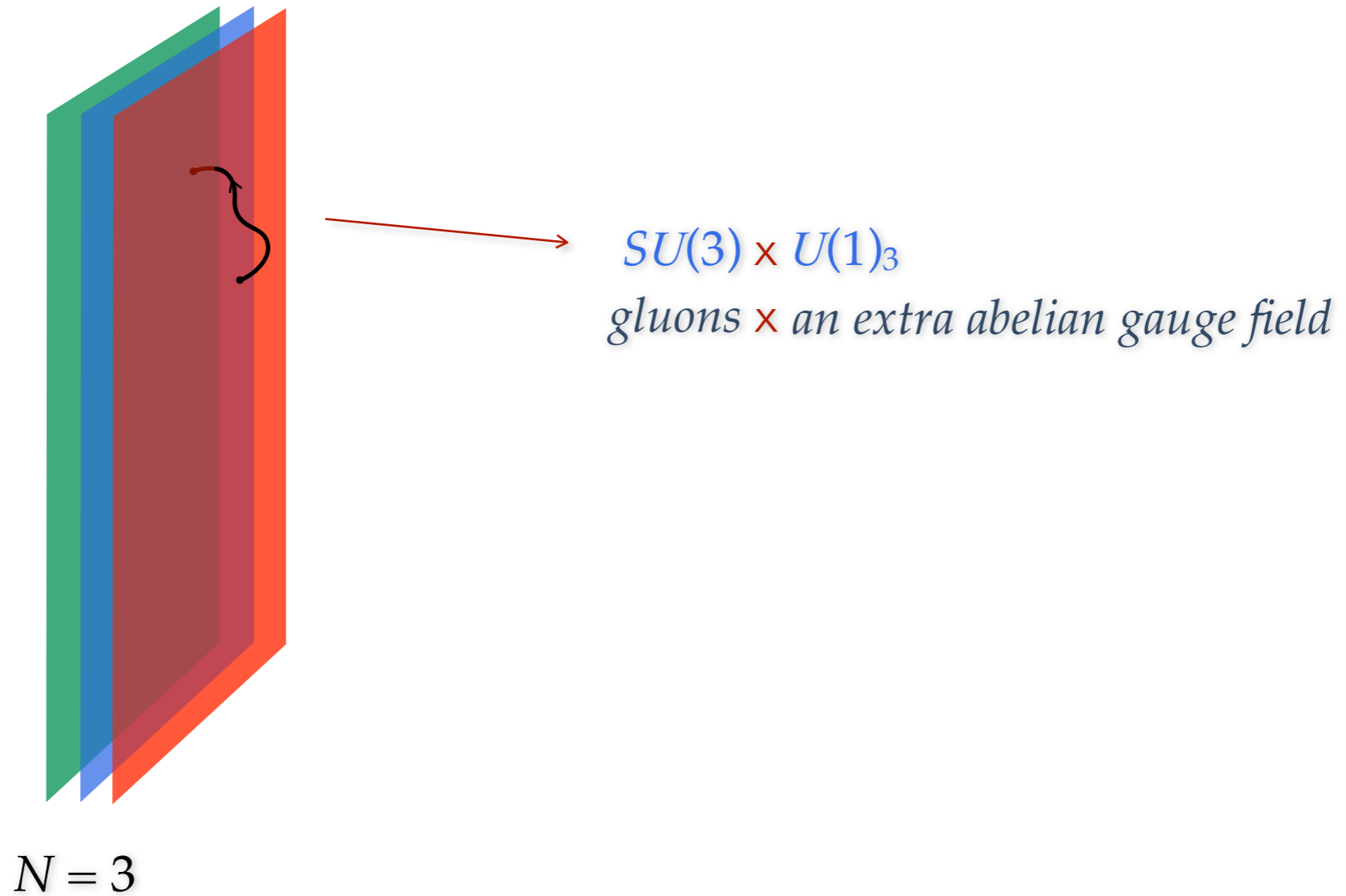


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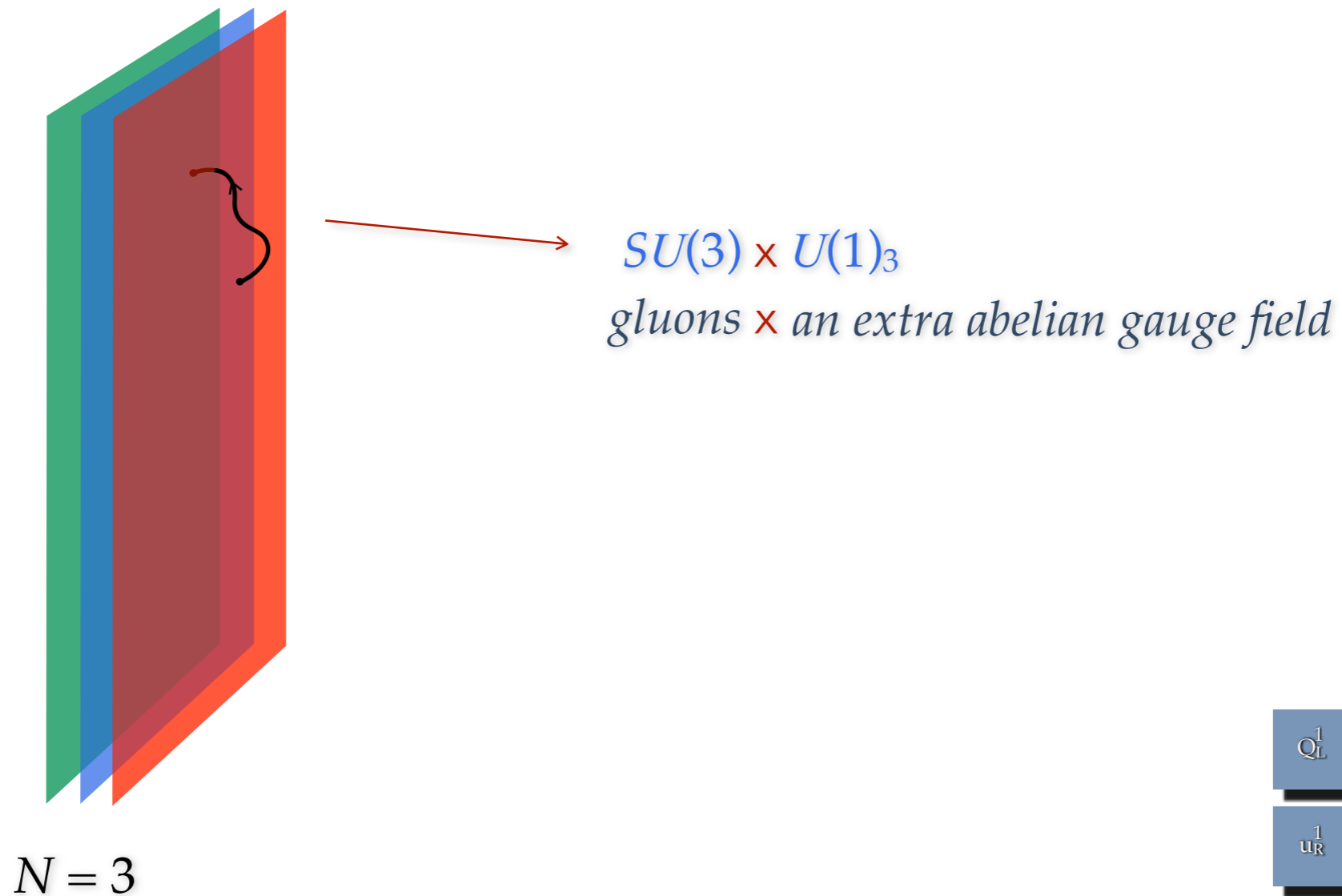


gauge fields $U(N) \rightarrow SU(N) \times U(1)_N$

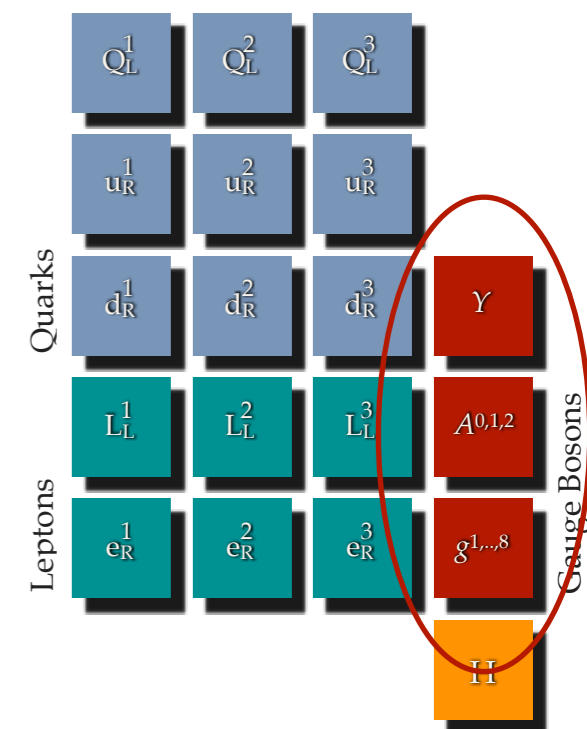
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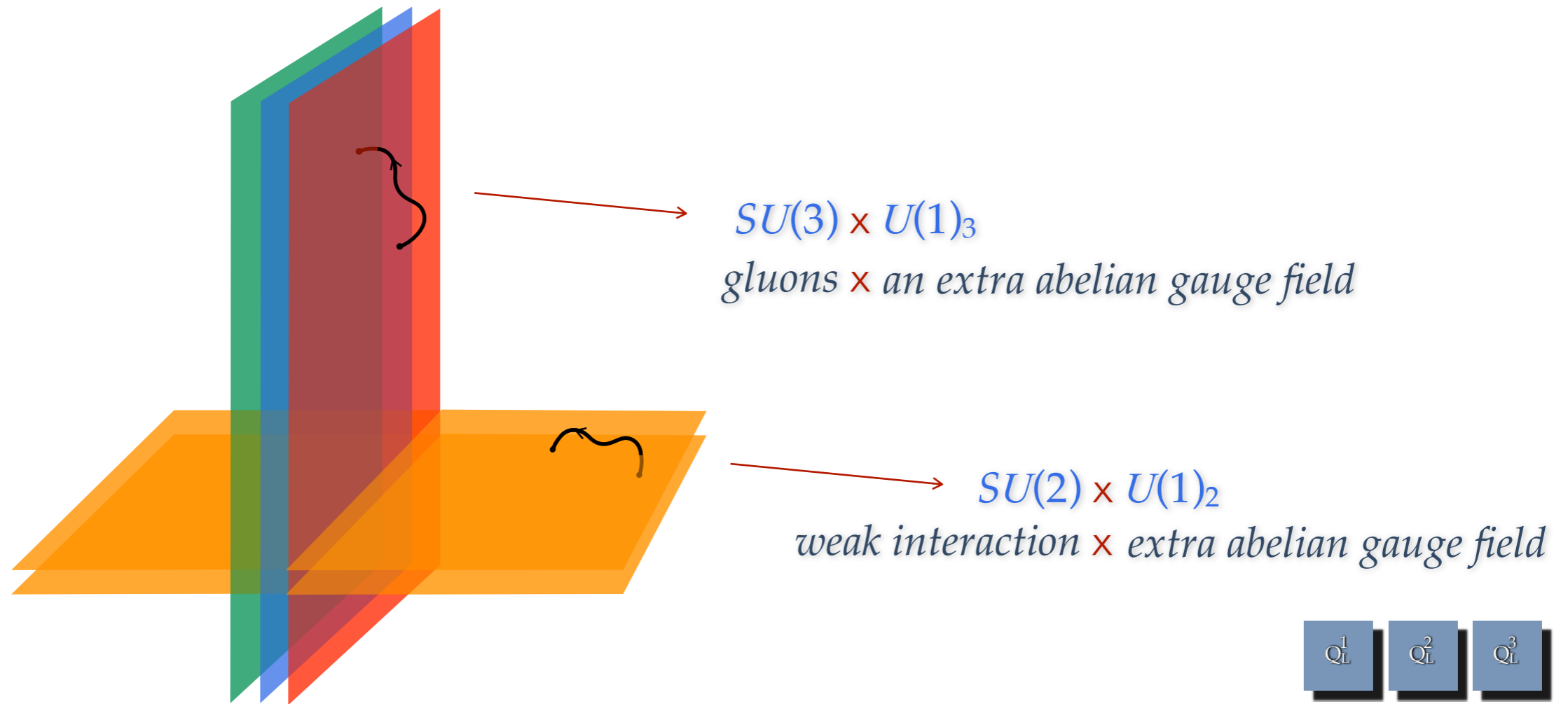
Force mediators



- ❖ All force mediators can be described by **such open strings**.
- ❖ For example the full $SU(3) \times SU(2) \times U(1)_Y$ needs **3+ such stacks**.



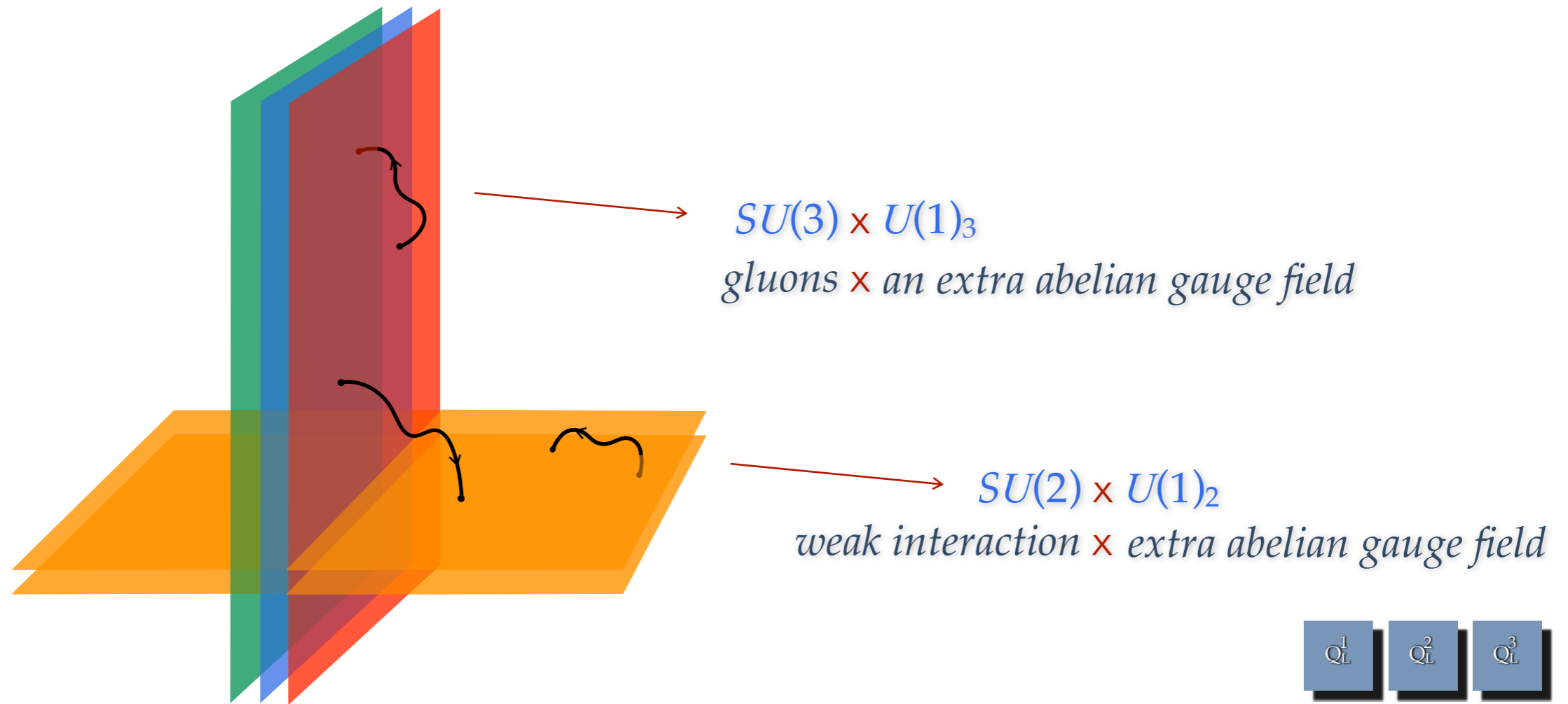
Matter at D-brane intersections



	Q_L^1	Q_L^2	Q_L^3	
	u_R^1	u_R^2	u_R^3	
Quarks	d_R^1	d_R^2	d_R^3	Y
	L_L^1	L_L^2	L_L^3	$A^{0,1,2}$
Leptons	e_R^1	e_R^2	e_R^3	$g^{1,\dots,8}$
				H

Gauge Bosons

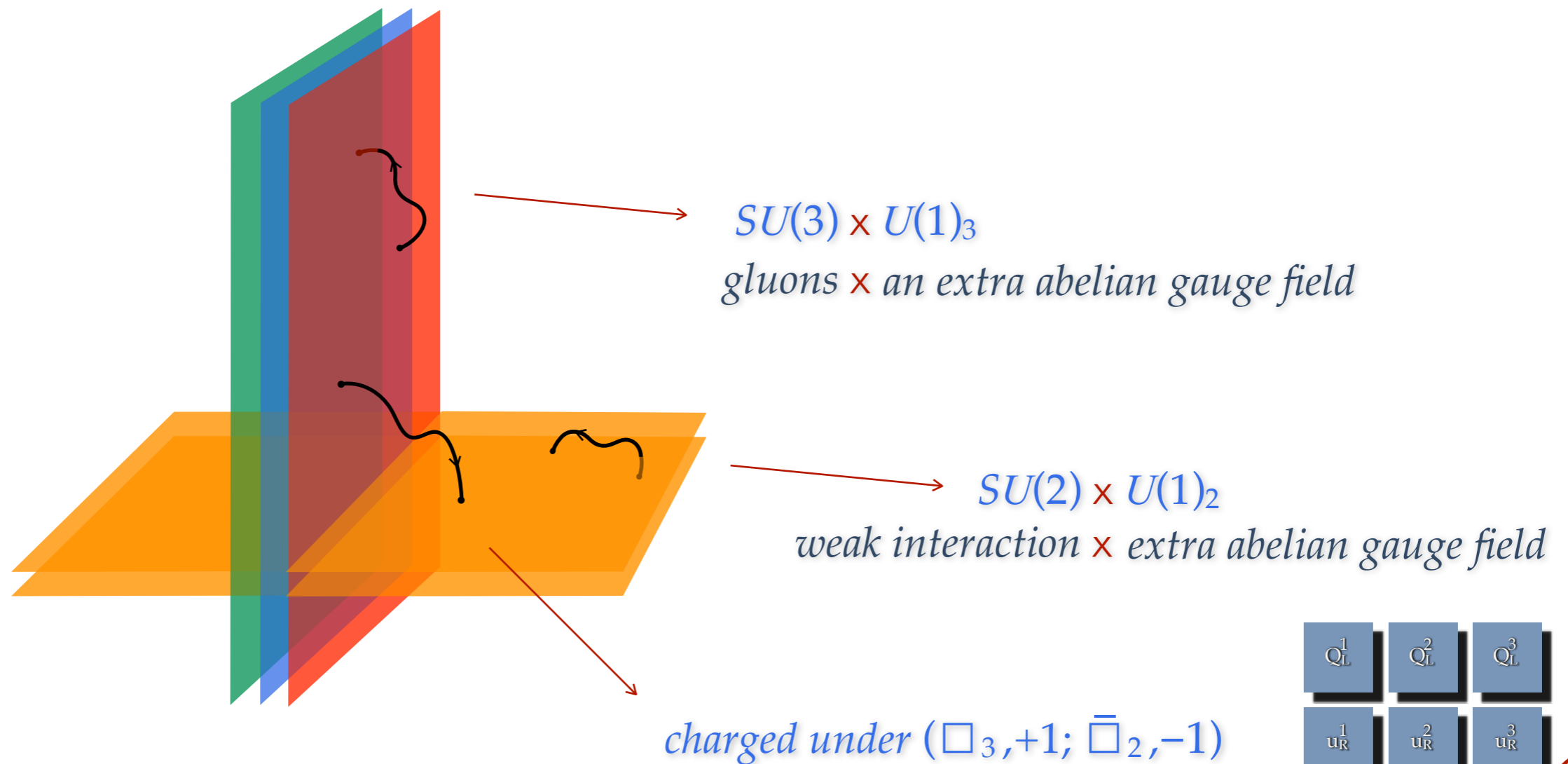
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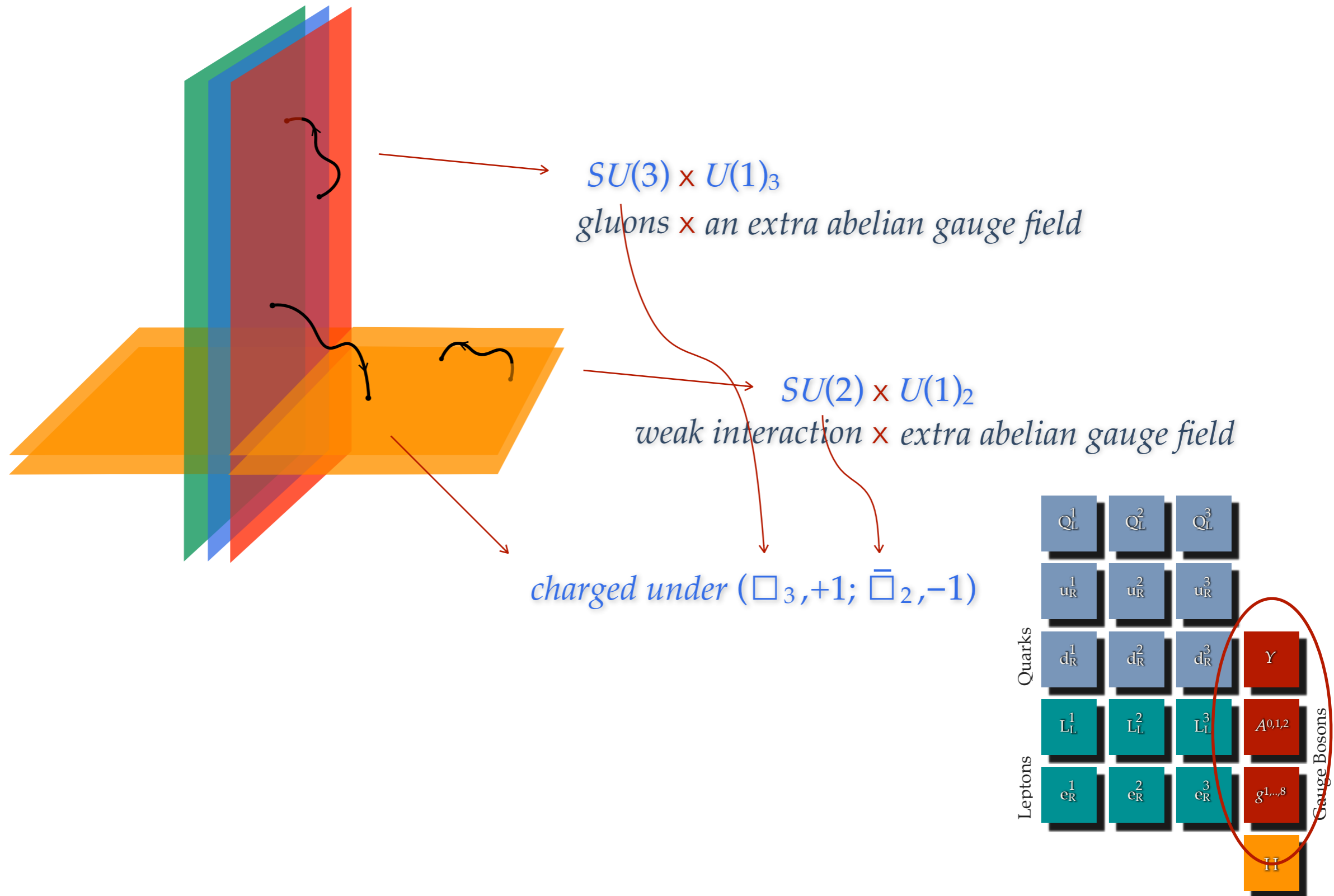
Matter at D-brane intersections



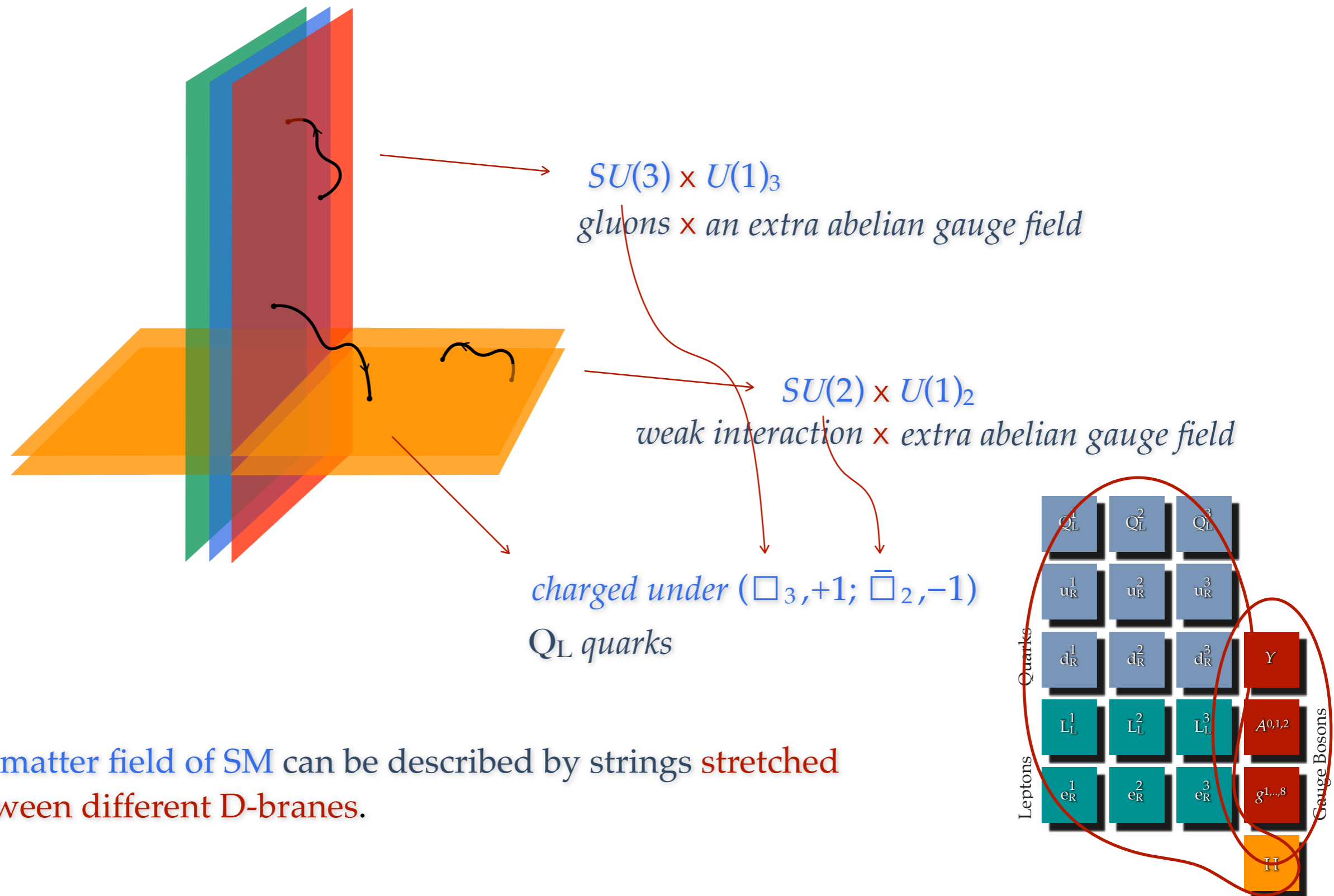
	Q_L^1	Q_L^2	Q_L^3	
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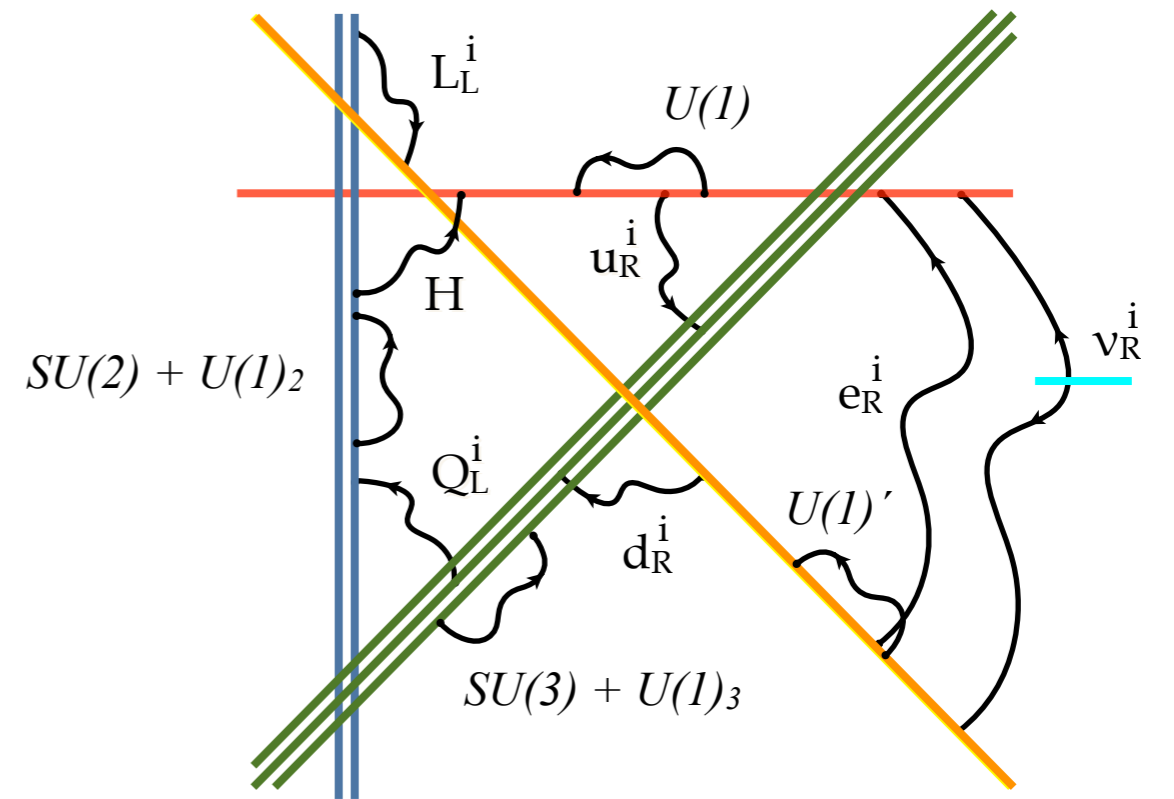
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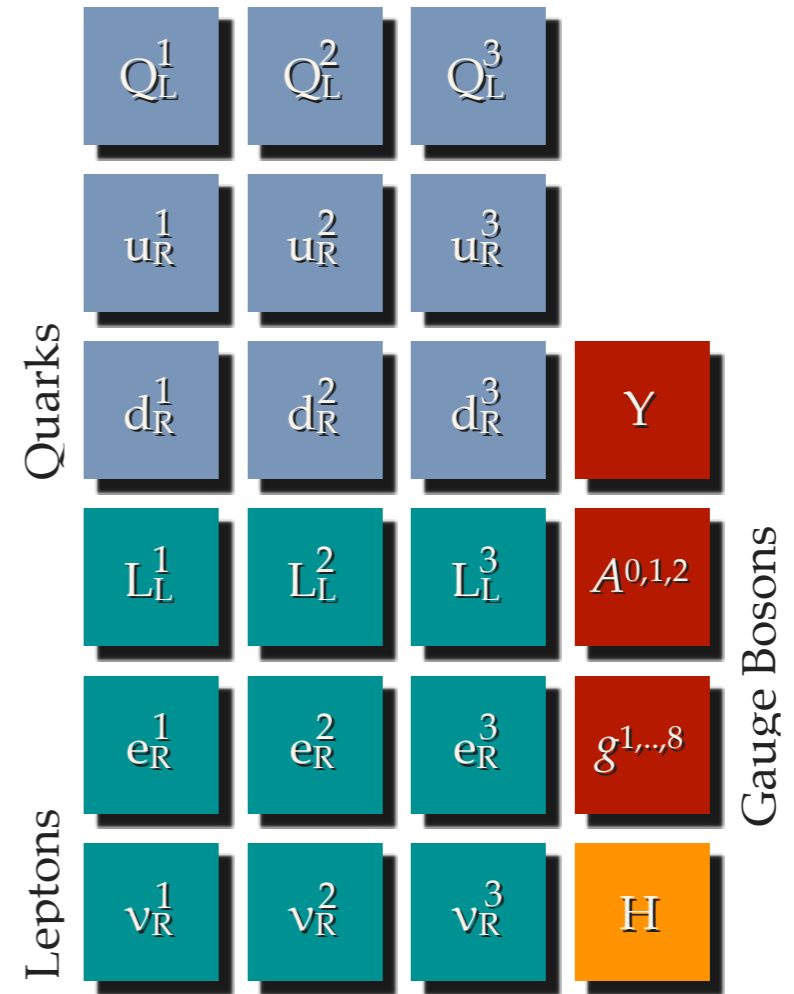
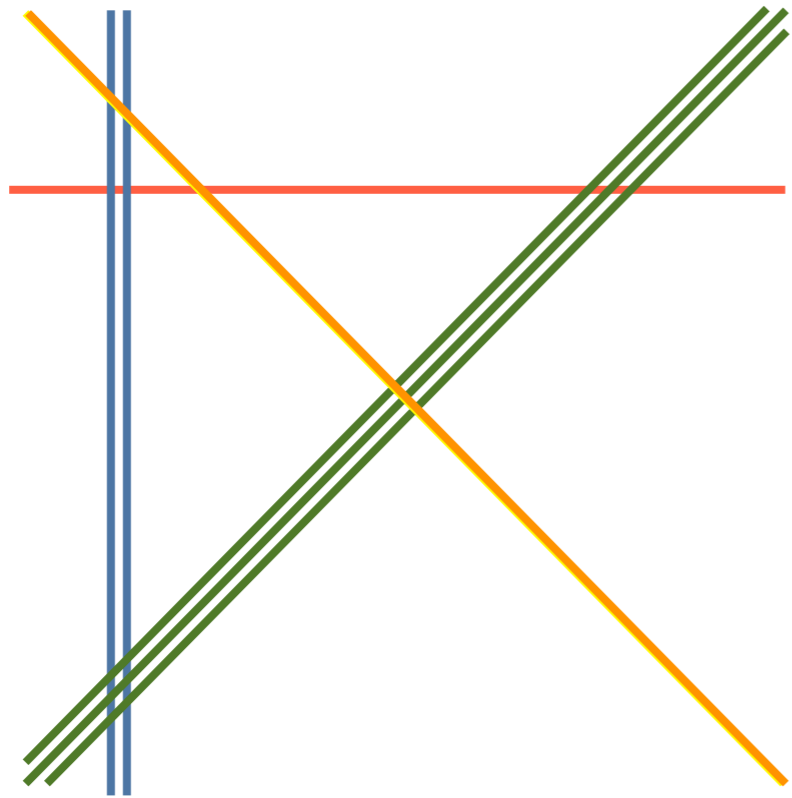


- * All matter field of SM can be described by strings stretched between different D-branes.

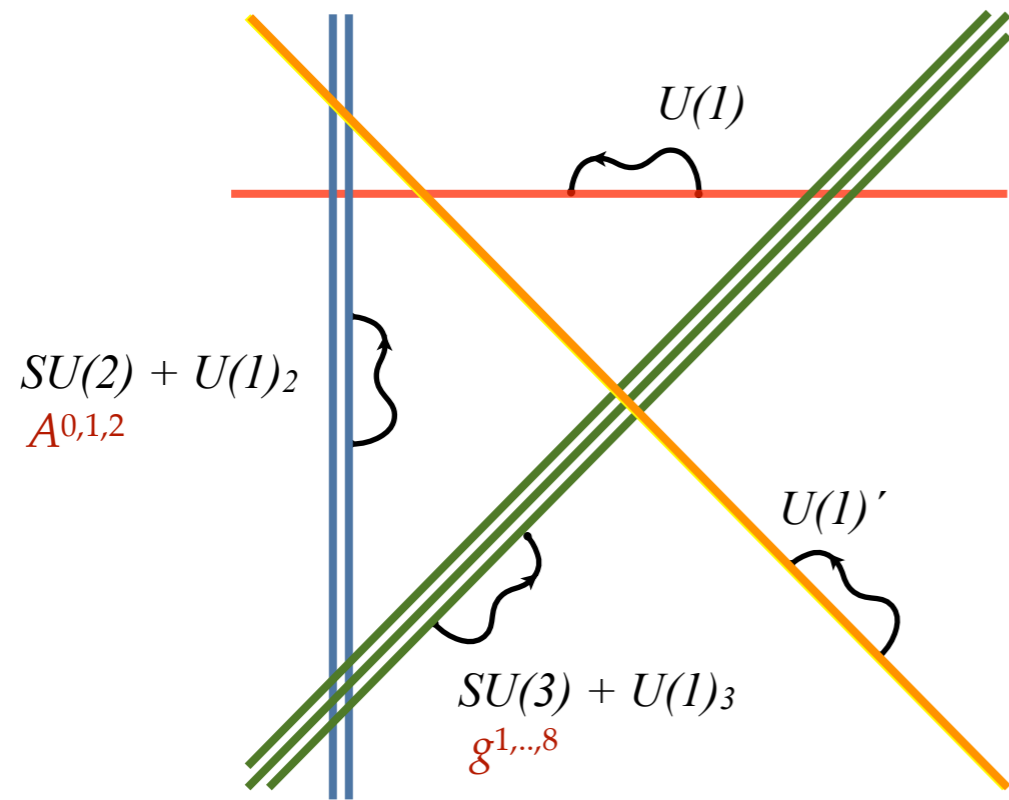


An example of a local construction

An (local) example



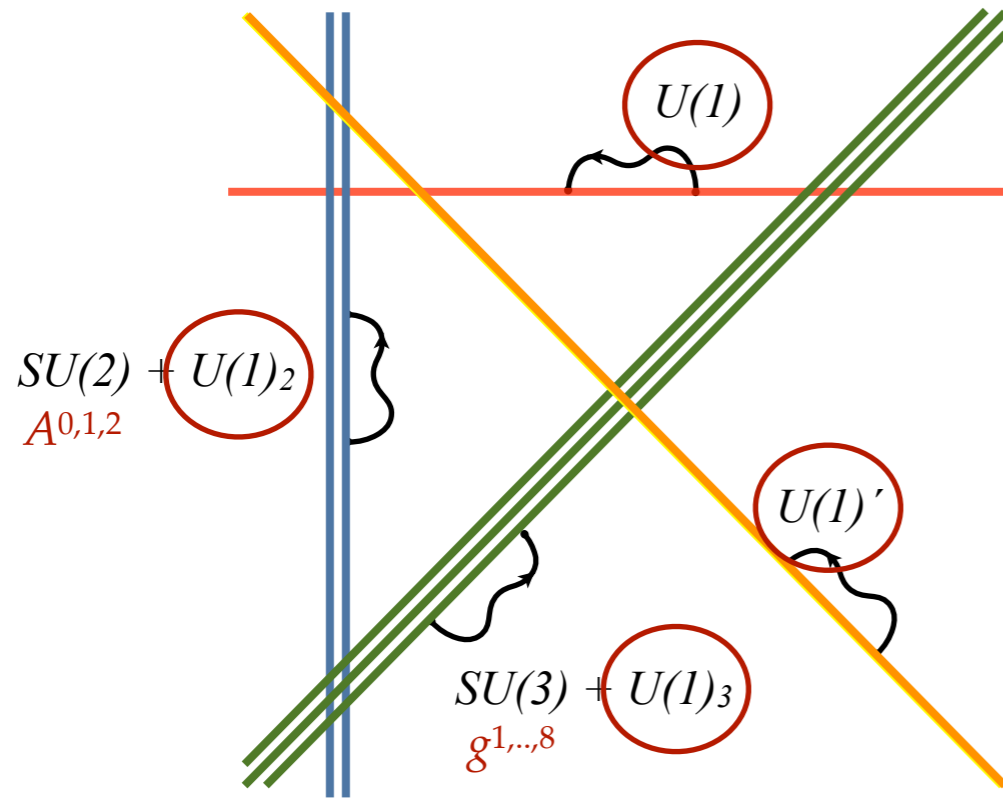
An (local) example



	Q_L^1	Q_L^2	Q_L^3	
	u_R^1	u_R^2	u_R^3	
Quarks	d_R^1	d_R^2	d_R^3	Y
	L_L^1	L_L^2	L_L^3	$A^{0,1,2}$ ✓
	e_R^1	e_R^2	e_R^3	$g^{1,\dots,8}$ ✓
Leptons	ν_R^1	ν_R^2	ν_R^3	H
				Gauge Bosons

An (local) example

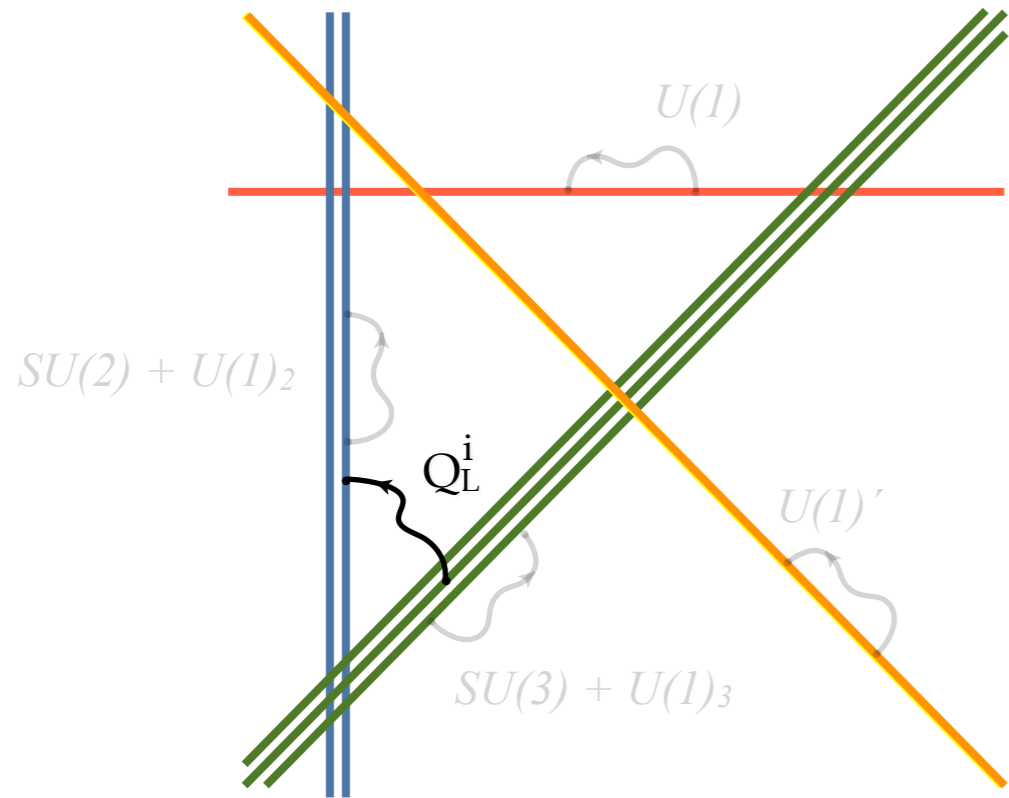
$$Y = \frac{1}{6}U(1)_3 - \frac{1}{2}U(1) + \frac{1}{2}U(1)'$$



				$U(1)_u$	New Massive Gauge Bosons
	Q_L^1	Q_L^2	Q_L^3	$U(1)_b$	
	u_R^1	u_R^2	u_R^3	$U(1)_c$	
Quarks	d_R^1	d_R^2	d_R^3	Y ✓	Gauge Bosons
	L_L^1	L_L^2	L_L^3	$A^{0,1,2}$ ✓	
	e_R^1	e_R^2	e_R^3	$g^{1,\dots,8}$ ✓	
Leptons	ν_R^1	ν_R^2	ν_R^3	H	

An (local) example

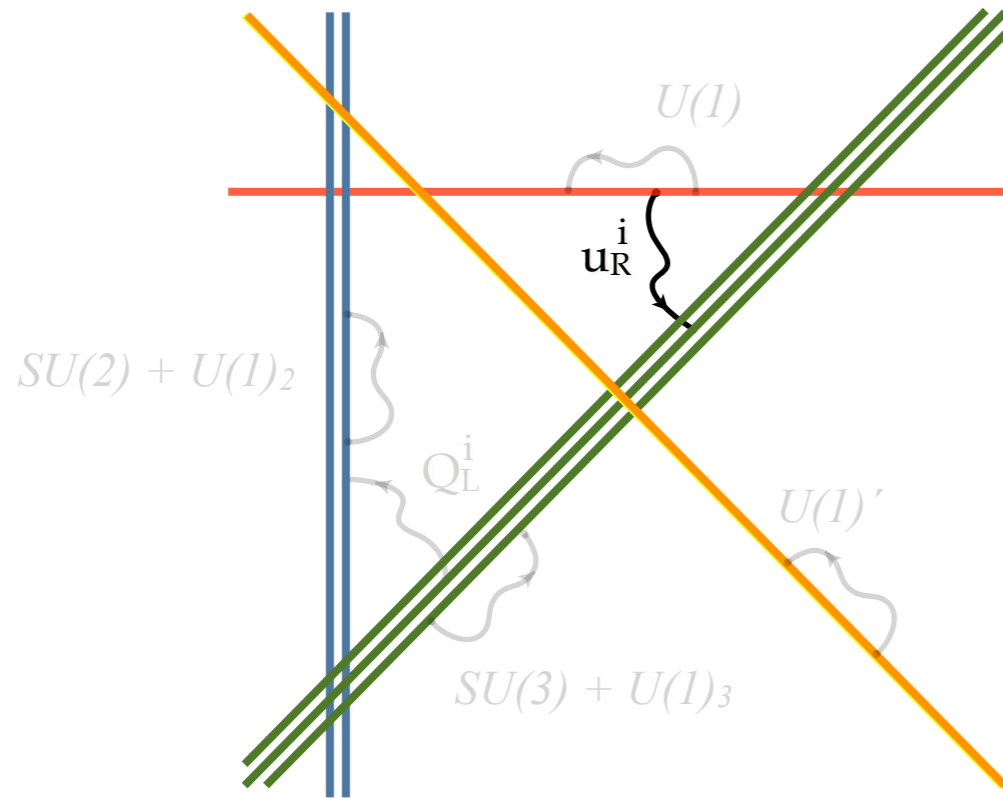
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			$U(1)_a$	New Massive Gauge Bosons
	Q_L^1 ✓	$(\square_3, \bar{\square}_2, \frac{1}{6})$	$U(1)_b$	
	u_R^1	$(\bar{\square}_3, \cdot, -\frac{2}{3})$	$U(1)_c$	
Quarks	d_R^1	$(\bar{\square}_3, \cdot, \frac{1}{3})$	Y ✓	
	L_L^1	$(\cdot, \square_2, -\frac{1}{2})$	$A^{0,1,2}$ ✓	Gauge Bosons
Leptons	e_R^1	$(\cdot, \cdot, 1)$	$g^{1,..,8}$ ✓	
	ν_R^1	$(\cdot, \cdot, 0)$	H	$(\cdot, \square_2, +\frac{1}{2})$

An (local) example

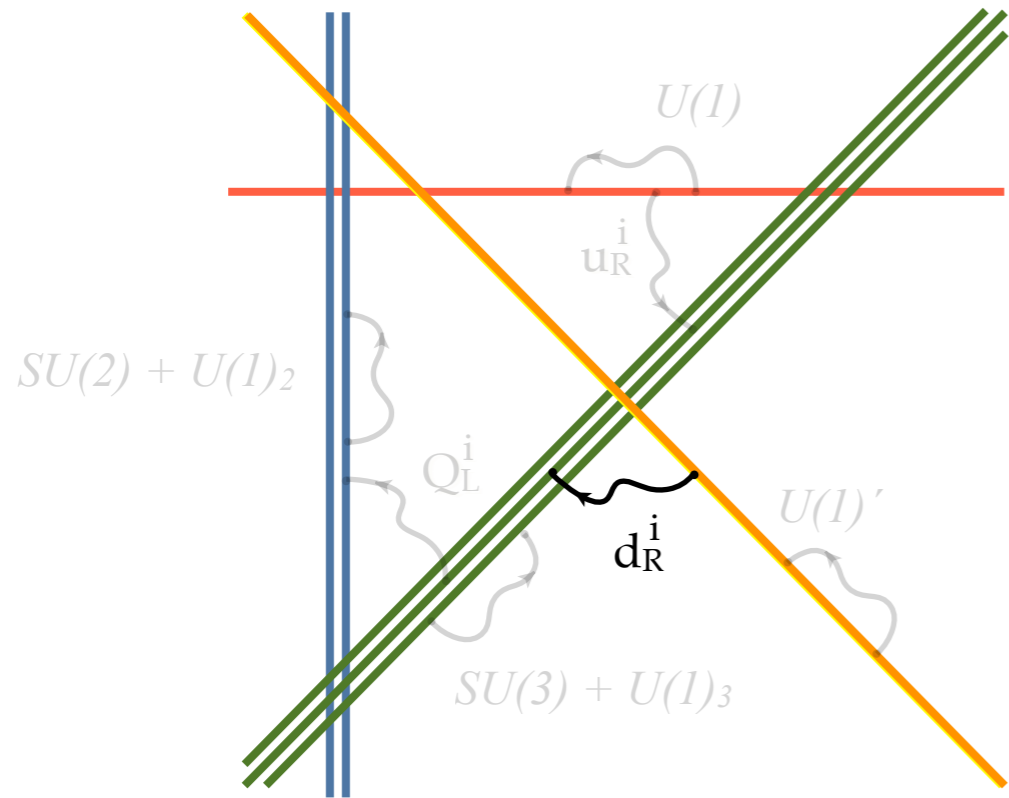
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Quarks	d_R^i	$(\bar{\square}_3, \cdot, \frac{1}{3})$	Y ✓	
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	e_R^i	$(\cdot, \cdot, 1)$	$g^{1,..,8}$ ✓	
Leptons	ν_R^i	$(\cdot, \cdot, 0)$	H	$(\cdot, \square_2, +\frac{1}{2})$

An (local) example

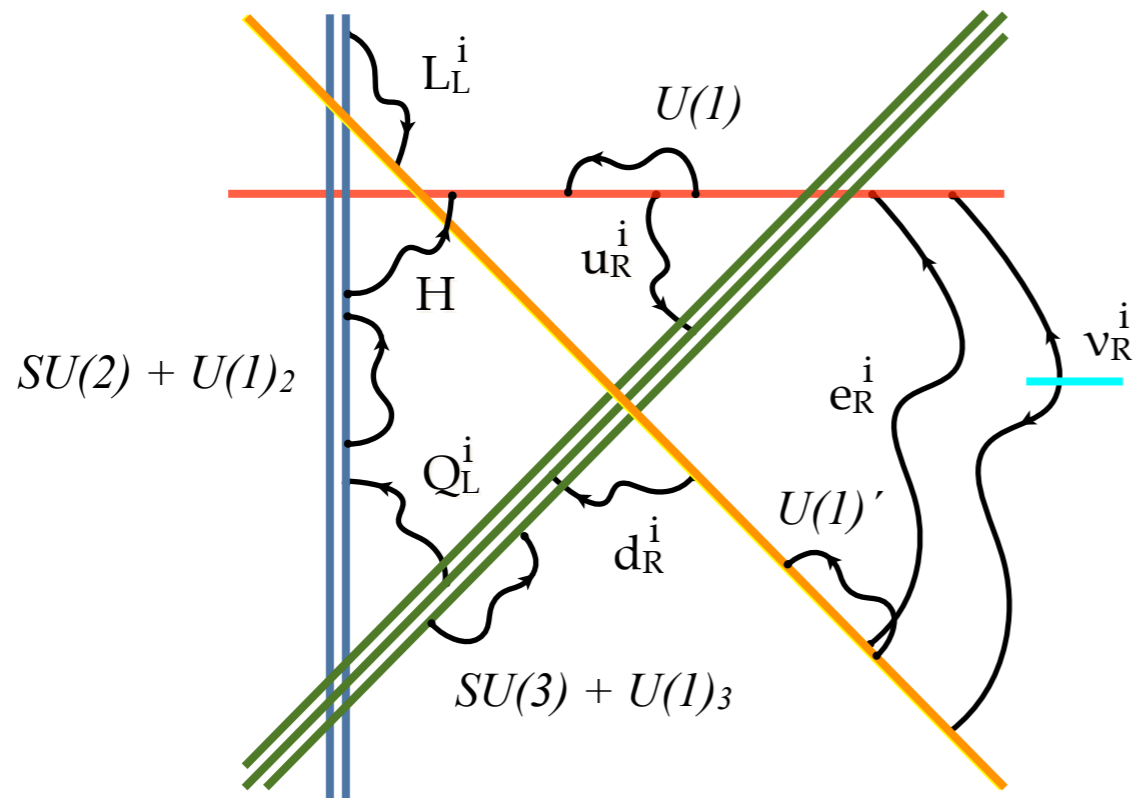
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	d_R^1 ✓	$(\bar{\square}_3, \cdot, \frac{1}{3})$	Y ✓	
Leptons	L_L^1	$(\cdot, \square_2, -\frac{1}{2})$	$A^{0,1,2}$ ✓	Gauge Bosons
	e_R^1	$(\cdot, \cdot, 1)$	$g^{1,..,8}$ ✓	
	ν_R^1	$(\cdot, \cdot, 0)$	H	

An (local) example

$$Y = \frac{1}{6}U(1)_3 - \frac{1}{2}U(1) + \frac{1}{2}U(1)'$$



				$U(1)_u$	New Massive Gauge Bosons
	Q_L^1 ✓	Q_L^2 ✓	Q_L^3 ✓	$U(1)_b$	
	u_R^1 ✓	u_R^2 ✓	u_R^3 ✓	$U(1)_c$	
Quarks	d_R^1 ✓	d_R^2 ✓	d_R^3 ✓	Y ✓	Gauge Bosons
	L_L^1 ✓	L_L^2 ✓	L_L^3 ✓	$A^{0,1,2}$ ✓	
	e_R^1 ✓	e_R^2 ✓	e_R^3 ✓	$g^{1,..,8}$ ✓	
Leptons	v_R^1 ✓	v_R^2 ✓	v_R^3 ✓	H ✓	

- * SM can be embedded in **D-brane models** (in various different ways).
- * To construct a **fully consistent and stable** configuration we need to **add extra branes**.

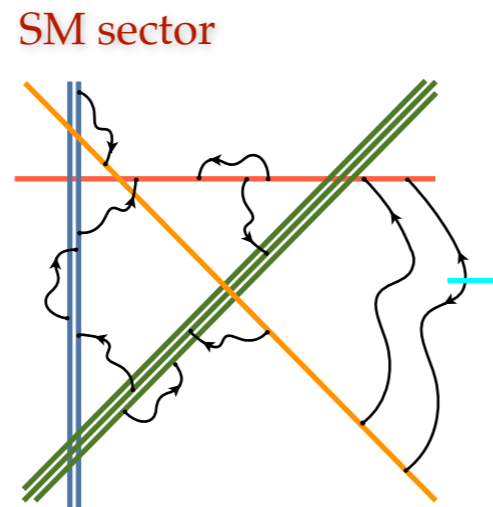
Aldazabal Ibanez Marchesano Quevedo Rabadan Uranga Cvetic
 Richter Shiu Blumenhagen Honecker Kors Lust Ott Antoniadis
 Dimopoulos Kiritsis Tomaras Rizos Schellekens et al..

SM in Gepner orientifolds

- ❖ With Best, we looked for SM embeddings in D-brane models, in rational boundary CFT.
Anastasopoulos Dijkstra Kiritsis Schellekens
- ❖ Bert had already developed the CFT techniques for building CFTs as parts of the closed strings and BCFTs as parts of orientifolds of string theory.
- ❖ He algorithmized these techniques allowing for large scale searches.

SM in Gepner orientifolds

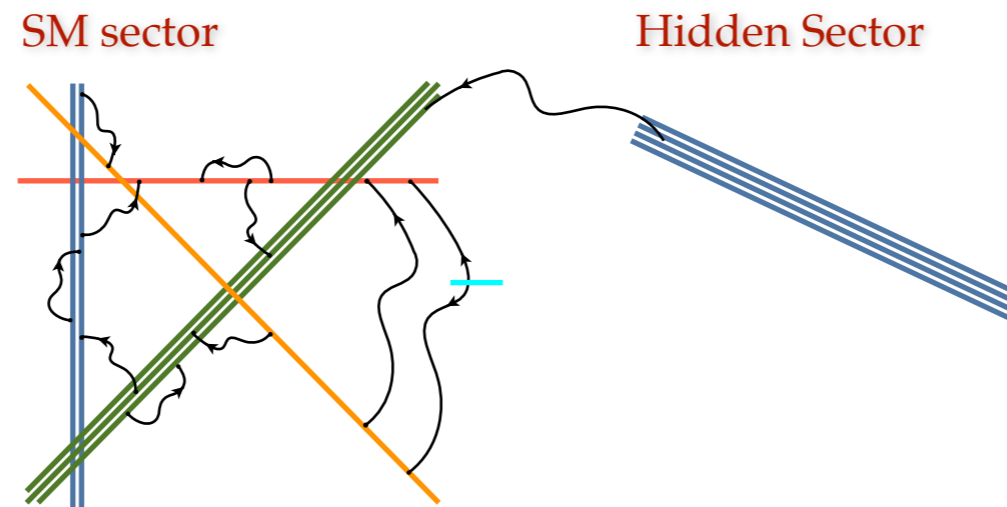
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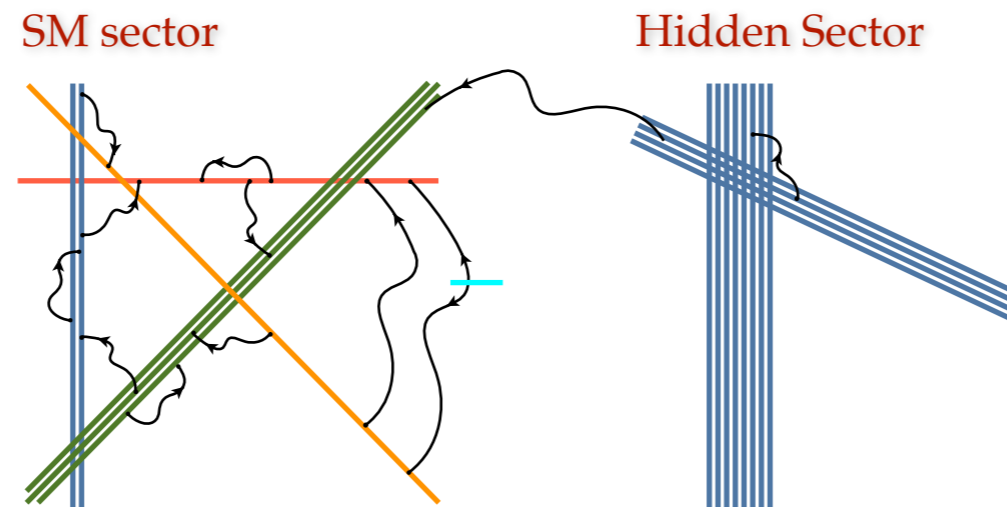
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- we added Hidden sectors for the global consistency of the models.

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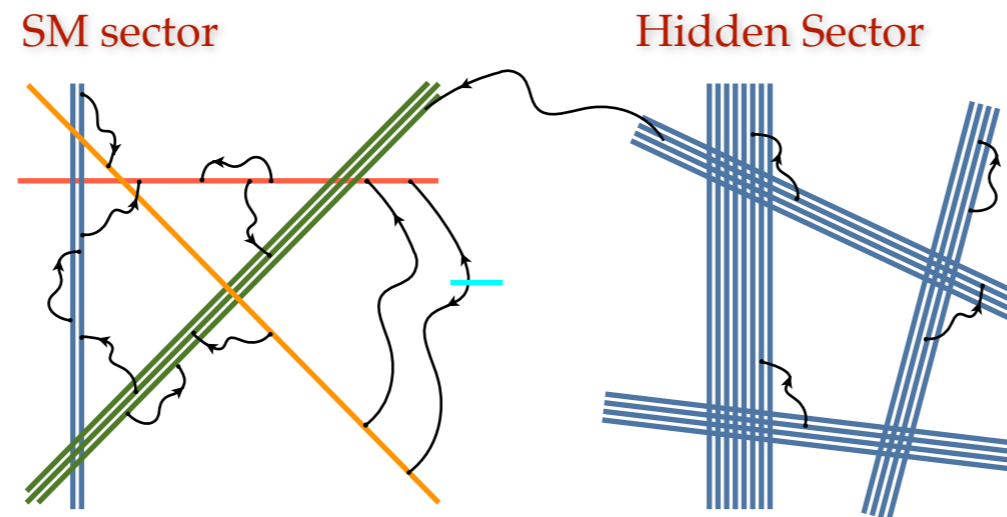
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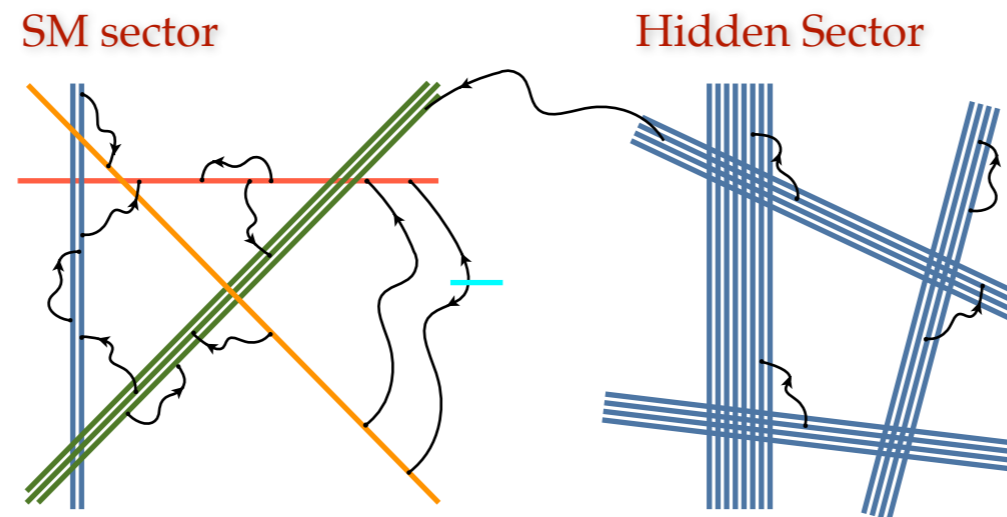


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global consistency! Next..

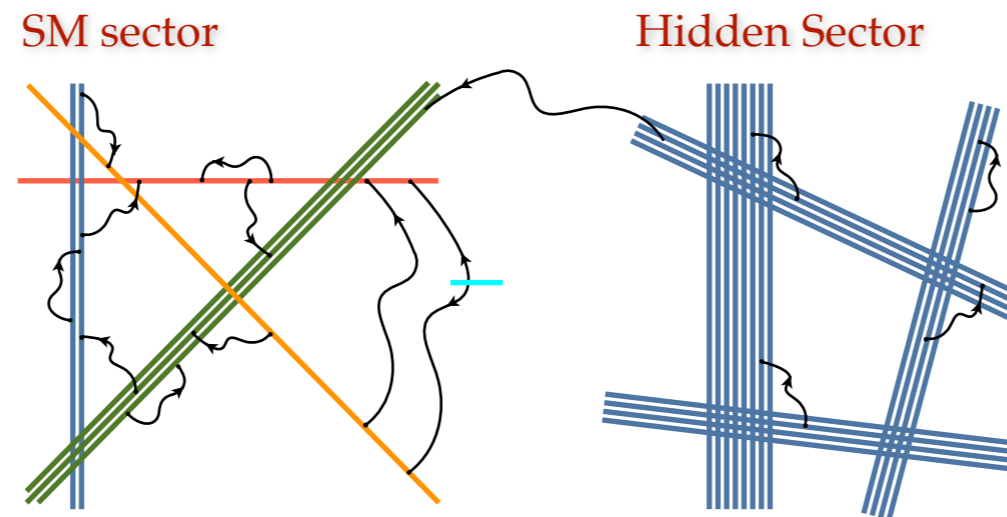


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1900 different classes of SM embeddings



global consistency! Next..

at least 1 HS, so that the full model is consistent

- we constructed phenomenologically acceptable SM sectors,
- we added Hidden sectors for the **global consistency** of the models.

$$U(3) \times U(2) \times U(1) \times U(1)'$$

Model: 2.4.22.22

Orientifolds: 1

Type: U U U U U S S
 Dimension: 3 2 1 1 2 4 2

Stacks of D-branes

6 x	(0 , V , 0 , V , 0 , 0 , 0)	chirality -6	→	3L + 3H _d
3 x	(0 , V , 0 , V* , 0 , 0 , 0)	chirality -3	→	3H _u
3 x	(V , V , 0 , 0 , 0 , 0 , 0)	chirality 3	→	3Q
7 x	(V , 0 , V* , 0 , 0 , 0 , 0)	chirality -3	→	3u ^c
7 x	(V , 0 , V , 0 , 0 , 0 , 0)	chirality -3	→	3d ^c
5 x	(0 , 0 , V , V , 0 , 0 , 0)	chirality 3	→	3ν ^c
5 x	(0 , 0 , V , V* , 0 , 0 , 0)	chirality -3	→	3l ^c
6 x	(Ad , 0 , 0 , 0 , 0 , 0 , 0)	chirality 0	}	Non-Chiral matter (needed to cancel tadpoles)
5 x	(0 , Ad , 0 , 0 , 0 , 0 , 0)	chirality 0		
15 x	(0 , 0 , Ad , 0 , 0 , 0 , 0)	chirality 0		
6 x	(0 , 0 , 0 , Ad , 0 , 0 , 0)	chirality 0		
6 x	(A , 0 , 0 , 0 , 0 , 0 , 0)	chirality 0		
8 x	(S , 0 , 0 , 0 , 0 , 0 , 0)	chirality 0		
10 x	(0 , 0 , S , 0 , 0 , 0 , 0)	chirality 0		
2 x	(0 , V , 0 , 0 , V , 0 , 0)	chirality 0		
8 x	(V , 0 , 0 , V* , 0 , 0 , 0)	chirality 0		
2 x	(0 , 0 , 0 , S , 0 , 0 , 0)	chirality 0		
4 x	(V , V* , 0 , 0 , 0 , 0 , 0)	chirality 0		
40 x	(0 , 0 , V , 0 , 0 , 0 , V)	chirality 0		
4 x	(V , 0 , 0 , V , 0 , 0 , 0)	chirality 0		
6 x	(0 , 0 , A , 0 , 0 , 0 , 0)	chirality 0		
2 x	(V , 0 , 0 , 0 , 0 , V , 0)	chirality 0		
2 x	(0 , 0 , 0 , V , 0 , V , 0)	chirality 0		
6 x	(0 , V , V , 0 , 0 , 0 , 0)	chirality 0		
6 x	(0 , V , V* , 0 , 0 , 0 , 0)	chirality 0		
8 x	(0 , 0 , 0 , V , 0 , 0 , V)	chirality 0		
12 x	(V , 0 , 0 , 0 , 0 , 0 , V)	chirality 0		
2 x	(0 , V , 0 , 0 , 0 , 0 , V)	chirality 0		
42 x	(0 , 0 , 0 , 0 , 0 , 0 , A)	chirality 0		
37 x	(0 , 0 , 0 , 0 , 0 , 0 , S)	chirality 0		
2 x	(0 , 0 , 0 , 0 , 0 , V , V)	chirality 0		

Just $SU(5)$

Model: 1.4.4.4.4

Orientifolds: 1

Type: U O O

Dimension: 5 1 1

3 x	(A , 0 , 0)	chirality 3
11 x	(V , V , 0)	chirality -3
8 x	(S , 0 , 0)	chirality 0
3 x	(Ad, 0 , 0)	chirality 0
1 x	(0 , A , 0)	chirality 0
3 x	(0 , V , V)	chirality 0
8 x	(V , 0 , V)	chirality 0
2 x	(0 , S , 0)	chirality 0
4 x	(0 , 0 , S)	chirality 0
4 x	(0 , 0 , A)	chirality 0

→ $3Q + 3d^c + 3l^c$

→ $3L + 3u^c$

Non-Chiral matter
(needed to cancel tadpoles)

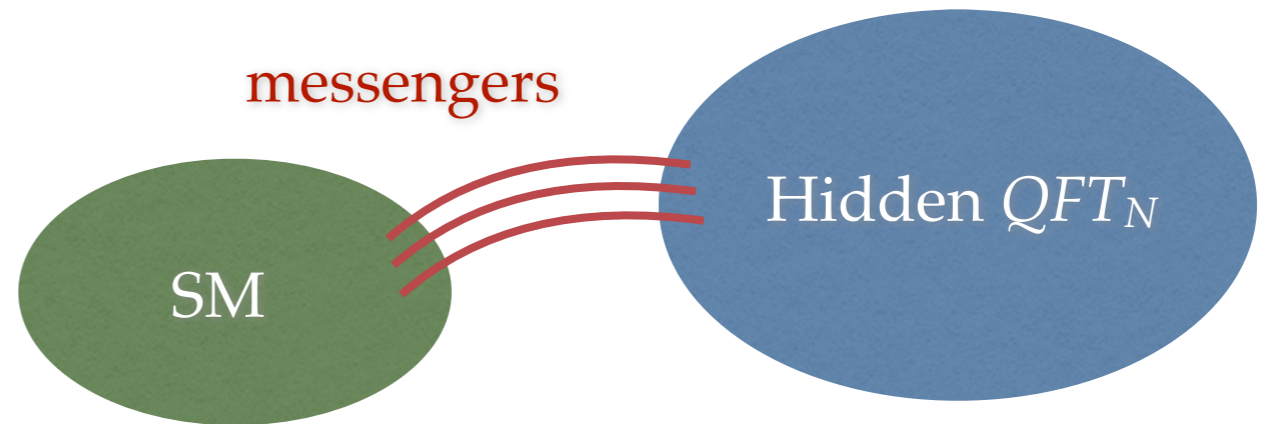
Some additional works

- ❖ With these classes of SM embeddings in string theory, we can study **additional properties**.
 - ❖ With Bert, we studied **Georgi-Glashow** and the **flipped SU(5)** model (among the 1900 models) and analyze them with respect to their Yukawa couplings.

Anastasopoulos Leondaris Richter Schellekens
 - ❖ **Adding an additional single D-brane** we solve various pheno problems.
 - ❖ Also **rigid O(1) instantons** provide the missing Yukawas.
- ❖ We study the presence of **abelian discrete symmetries**, by allowing the U(1)s to be **combinations of the visible and hidden sector**.

We find multiple models that allow for **matter parity** or **Baryon triality**.

Anastasopoulos Richter Schellekens
- ❖ In all cases, SM fields are described by **bifundamentals** in D-brane configurations.
- ❖ The same description applies also in the **next framework** which we will discuss.
- ❖ A **holography-inspired scenario**.



Holography-inspired scenario

Motivation

- ❖ The gauge/gravity duality gave **new possibilities** for model building.
- ❖ In this framework, we study **4D quantum field theories** (UV-complete) without gravity.
- ❖ **All fields beyond the SM** (graviton, axions, vector fields) are **composite** and **emerge** from a Hidden sector.
- ❖ They are very **different** from what **has been considered so far**.
- ❖ Their **theoretical** and **phenomenological** study is very **interesting**.

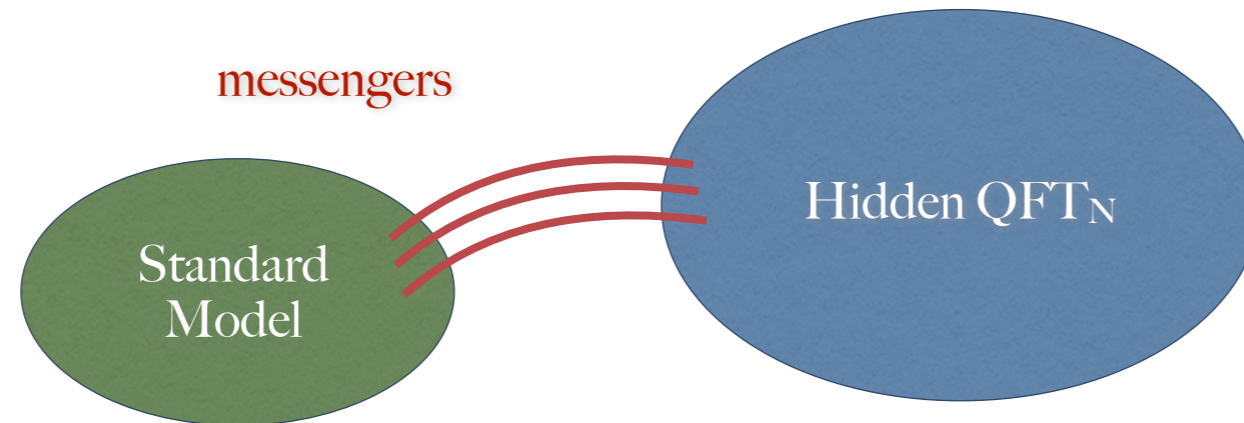
The Framework

- ❖ In this **holography-inspired scenario**, and we will *assume* that

all interaction in nature are described by 4D Quantum Field Theories

Kiritsis

- ❖ In this framework, the **Fundamental Theory** consists of **three parts**



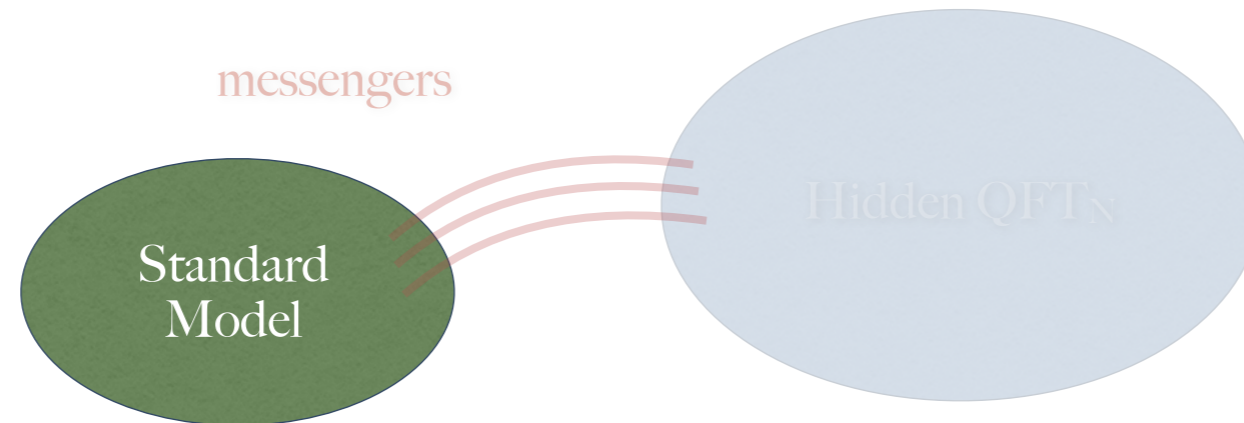
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- ❖ The **Standard Model (SM)**:
 - Contains all **standard fields** (quarks, leptons, gauge fields, Higgs).
 - We assume that all SM fields are described as **bifundamentals**.
 - That **enlarges** the gauge group to contain **additional** (anomalous) U(1)s.

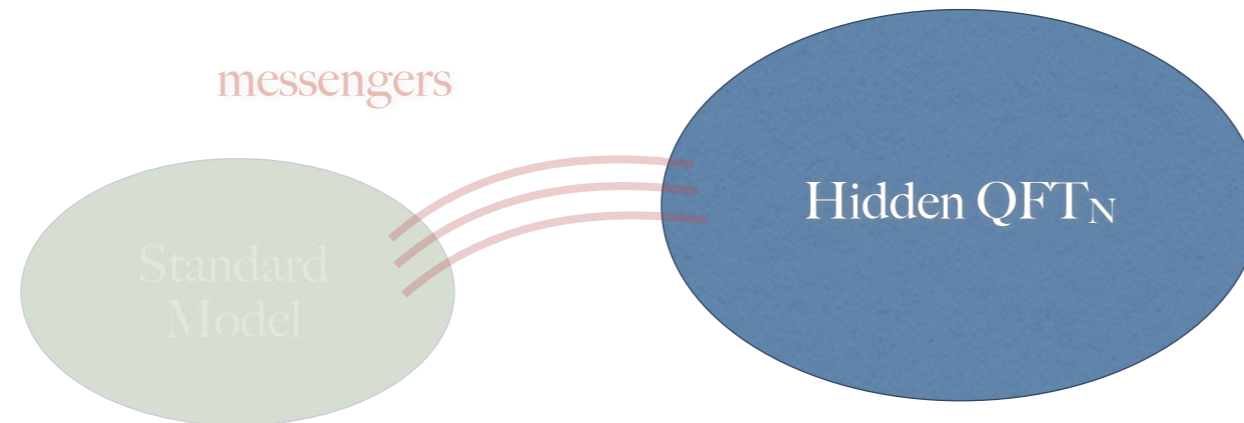
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- ❖ The **Hidden Sector** (assume an $SU(N)$ with N - Large):
 - It is **UV-complete**: can either be **asymptotically free** or **conformal**.
 - At **low energies** the hidden sector contains the **simplest QFT**: $\hat{A}^\mu, \hat{\phi}, \hat{\psi}$.

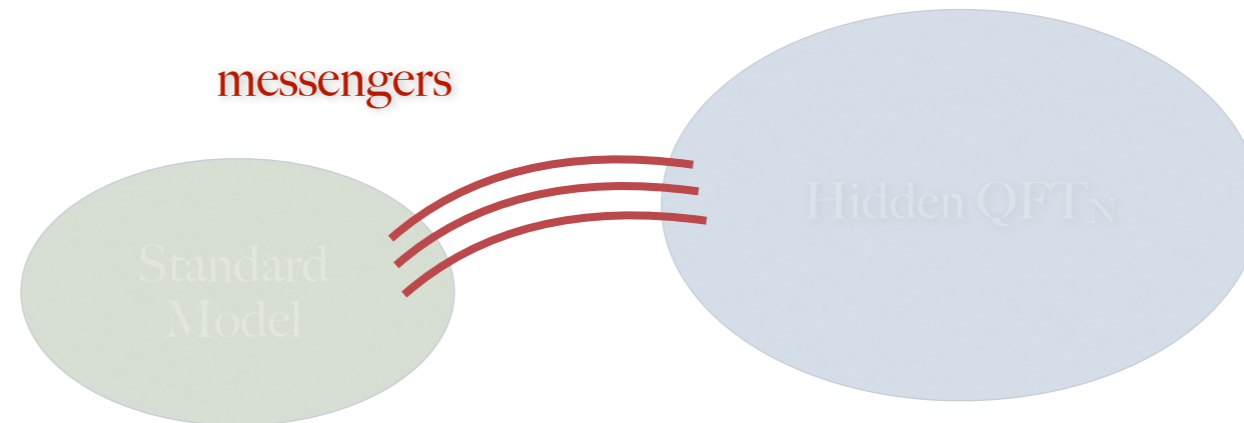
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Kiritsis

- ❖ In this framework, the **Fundamental Theory** consists of **three parts**



- ❖ **Messenger sector**
 - Charged particles under **both sectors** (SM and the HS).
 - They are **massive**, and $M_{\text{messengers}}$ is the **highest scale** of the whole framework.

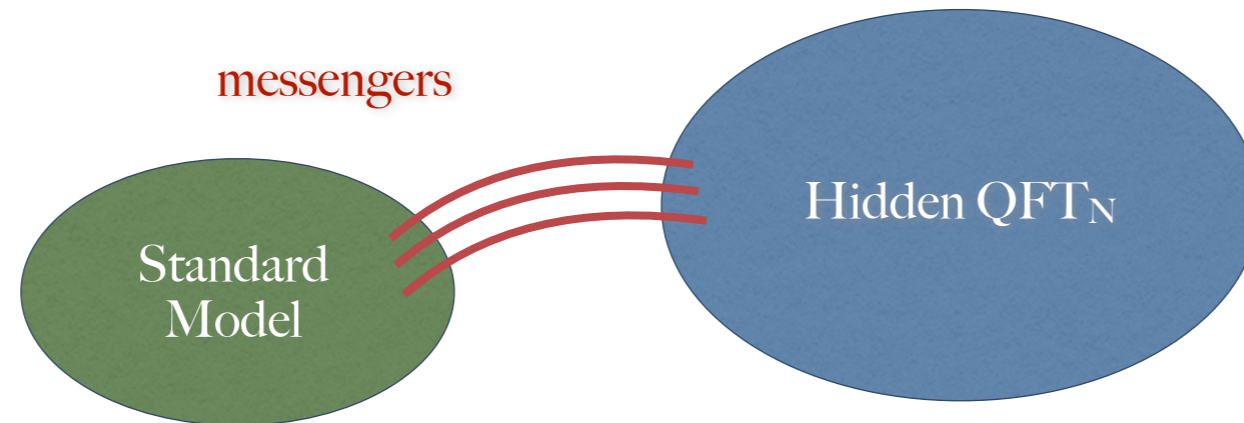
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- ❖ This framework has many **common features** with **D-brane models**.

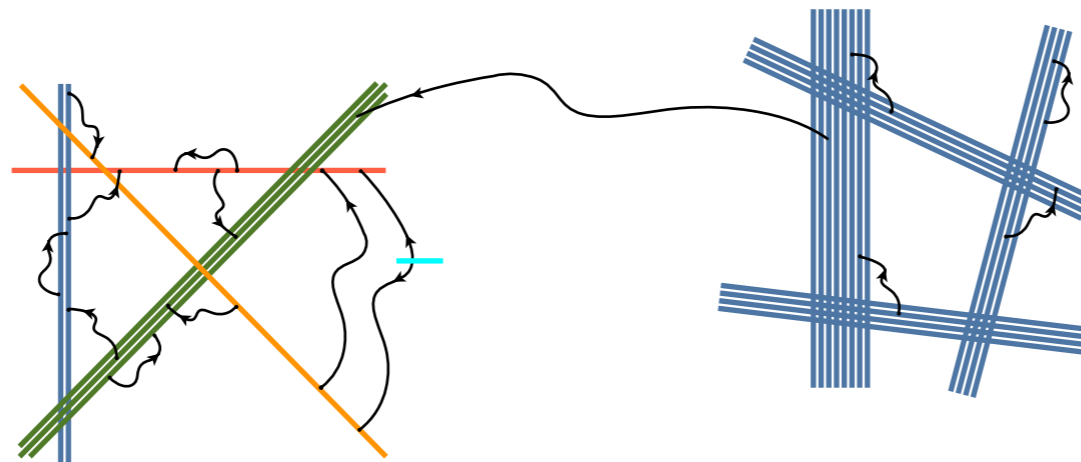
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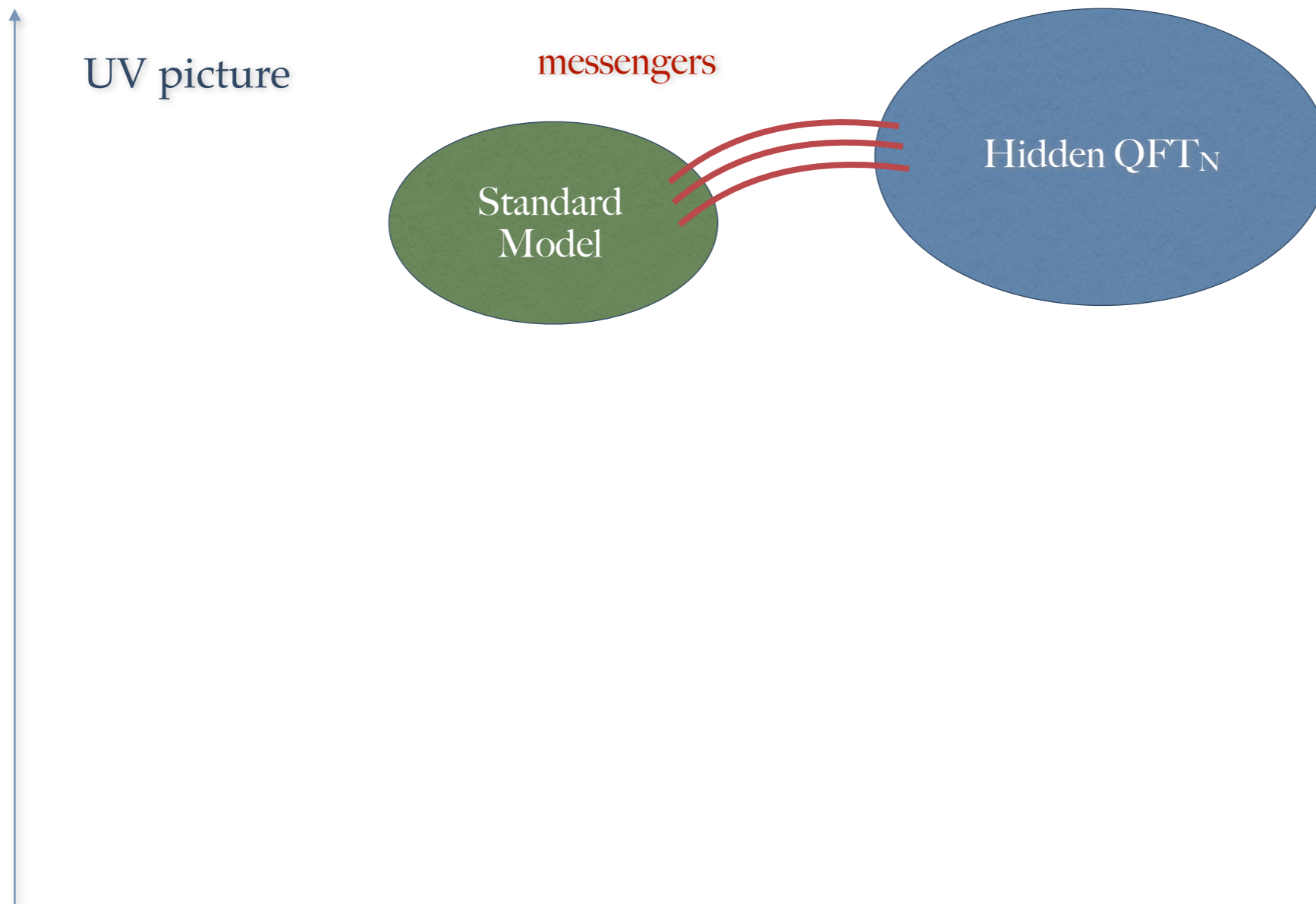
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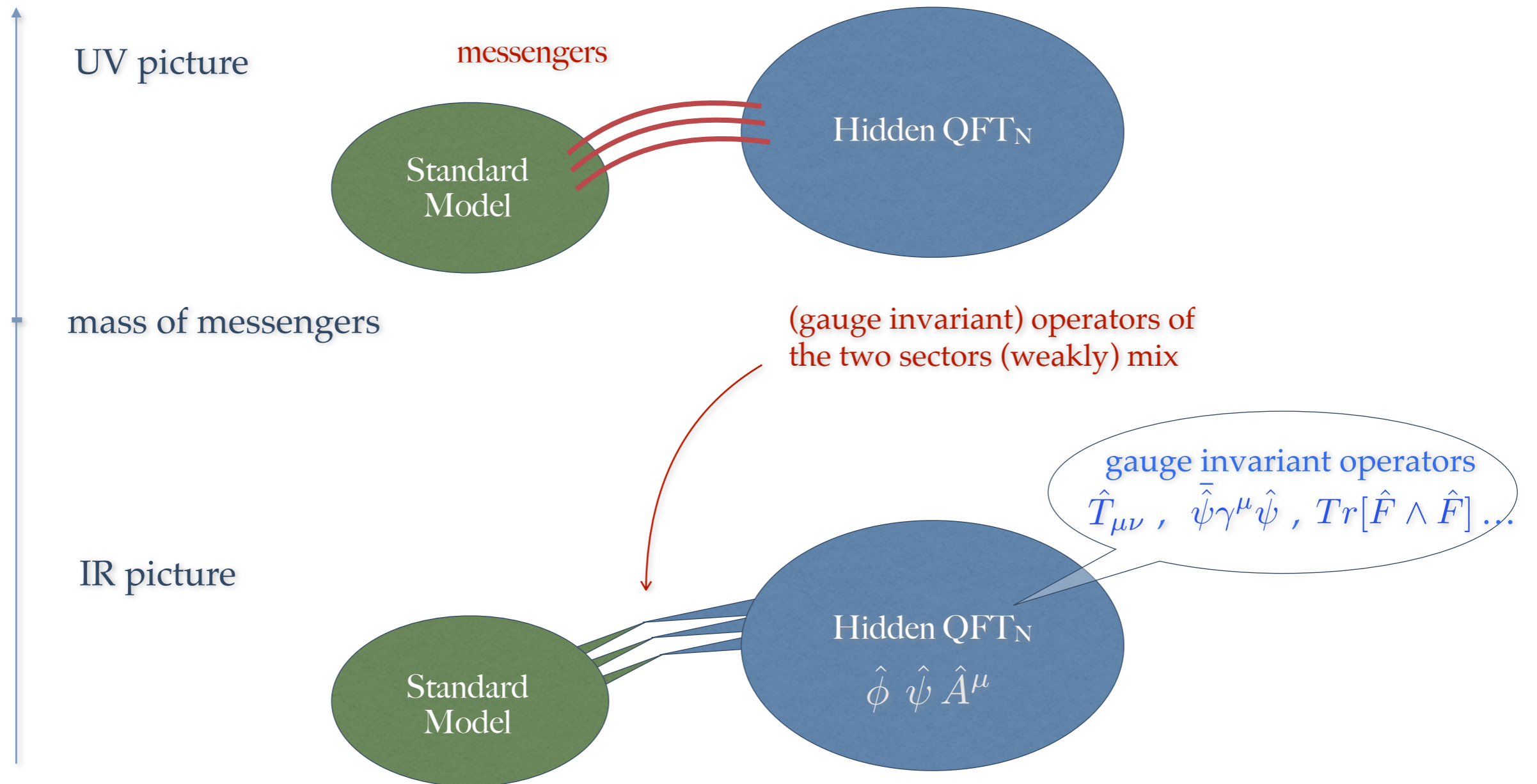


- ❖ This framework has many **common features** with **D-brane models**.
- ❖ We will focus on **QFT's** that we often meet in **D-brane models** (without being one of them).

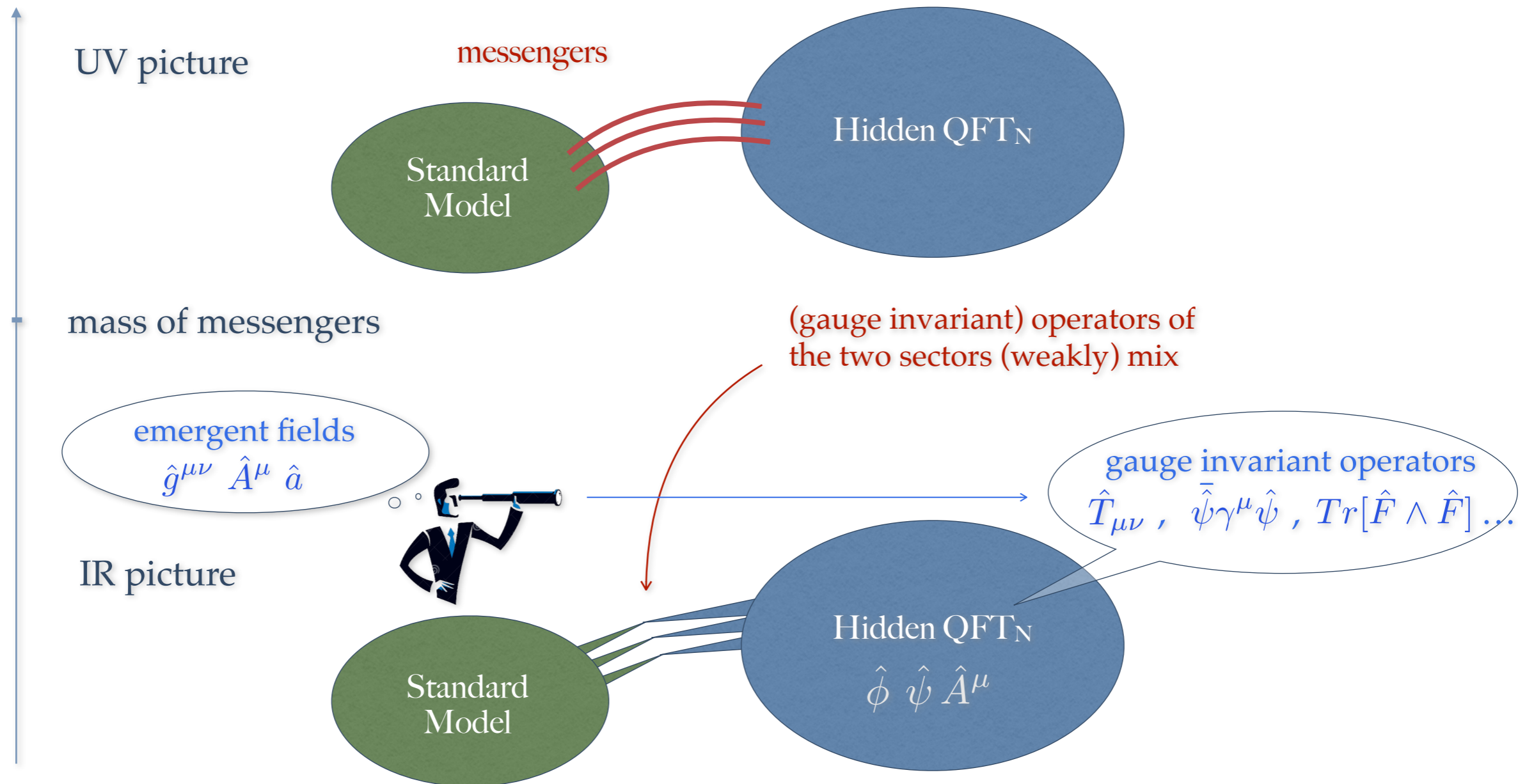
Our framework in different scales



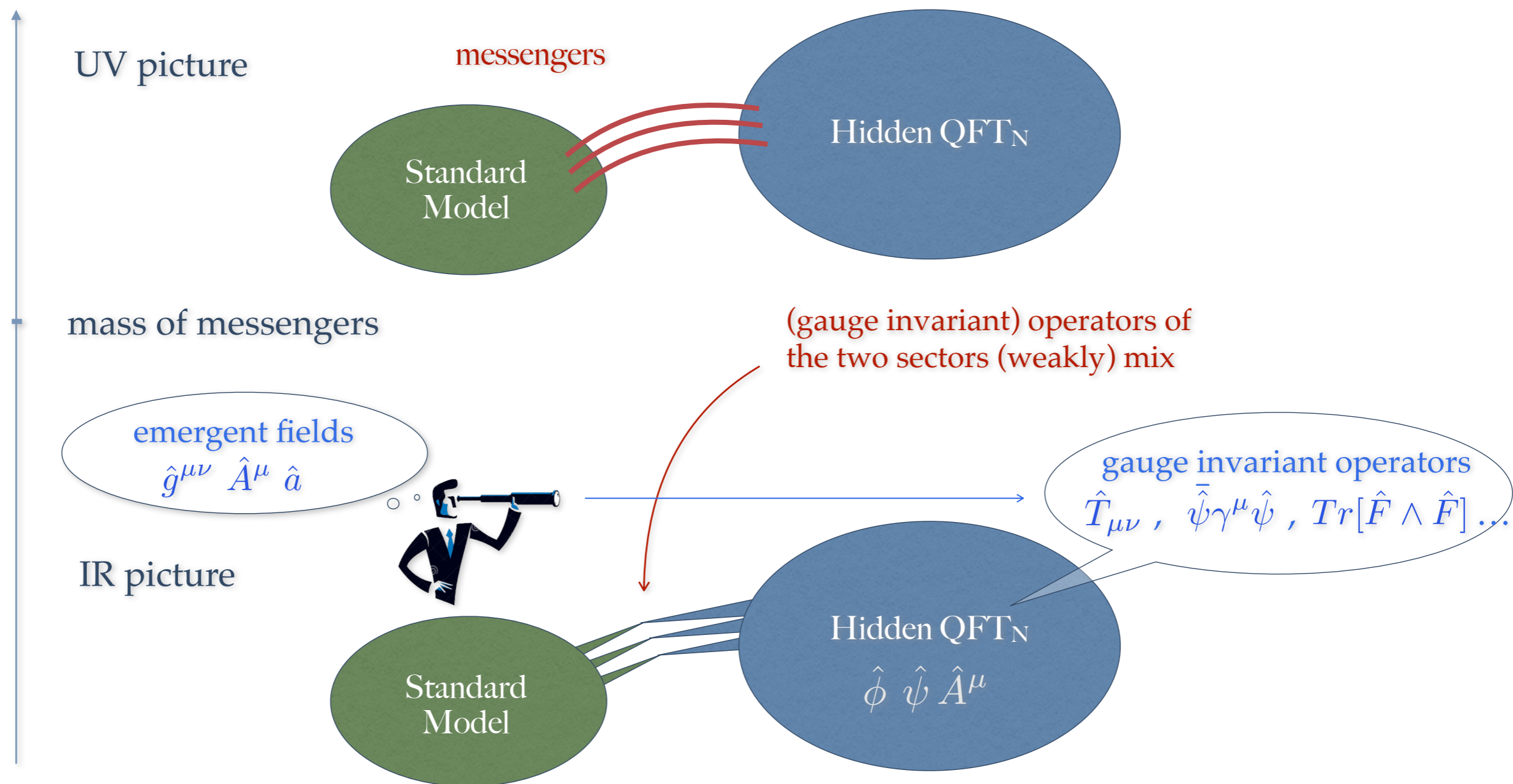
Our framework in different scales



Our framework in different scales

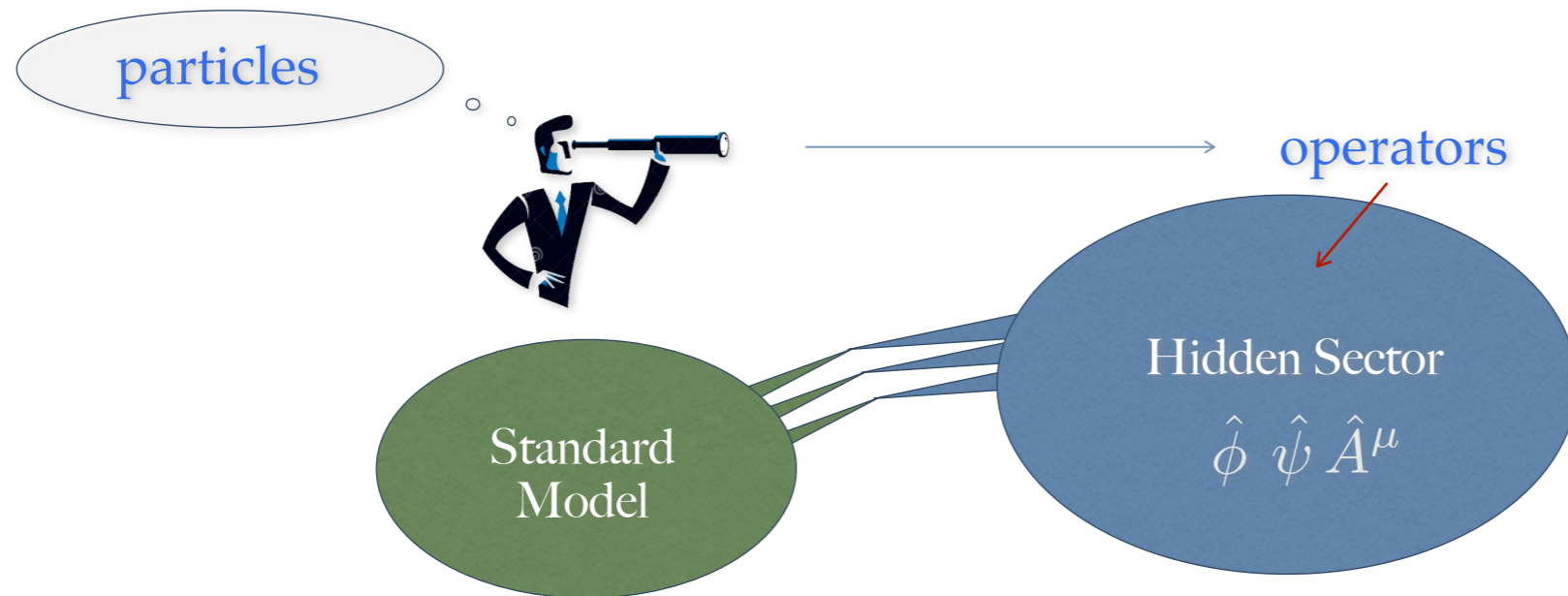


Our framework in different scales



Operators of the HS, protected by symmetries \longrightarrow light (emergent) particles

Light emergent fields



- ❖ Operators / particles protected by **symmetries** remain **light**.

HS point of view

Οπτική γωνία ΚΠ

$\hat{T}_{\mu\nu}$ of the HS

→ $g_{\mu\nu}$ graviton

$Tr[\hat{F} \wedge \hat{F}]$ of the HS

→ a axion

conserved global currents of the HS

→ abelian fields

- ❖ Occasionally, heavy operators / fields have **interesting phenomenology**.

Fermionic operators

→

R-H neutrinos

Light emergent fields

❖ All emergent fields are **composite**, bound states of the **HS** or the **messengers**.

❖ Therefore, they have a “compositeness scale”

compositeness scale



they have non-local kinetic terms.

behave like normal point-like particles.

❖ Our goal is:

- To build the effective action for these emergent fields.

- To investigate the phenomenological implications.

❖ In various cases, we assume a **holographic hidden sector**.

❖ **Emergent fields** **differ qualitatively** from what has been **considered so far**.

Emergent Gravity

- ❖ In this framework, **gravity** is an avatar of the Hidden QFT.

Kiritsis

$$S_{int} = \lambda \int d^4x \left(T_{\mu\nu}(x) \hat{T}^{\mu\nu}(x) + c T(x) \hat{T}(x) \right) \longrightarrow h_{\mu\nu} \sim \frac{\hat{T}_{\mu\nu}}{M^4}$$

- ❖ In the far IR, the graviton is **massless** and realise the action

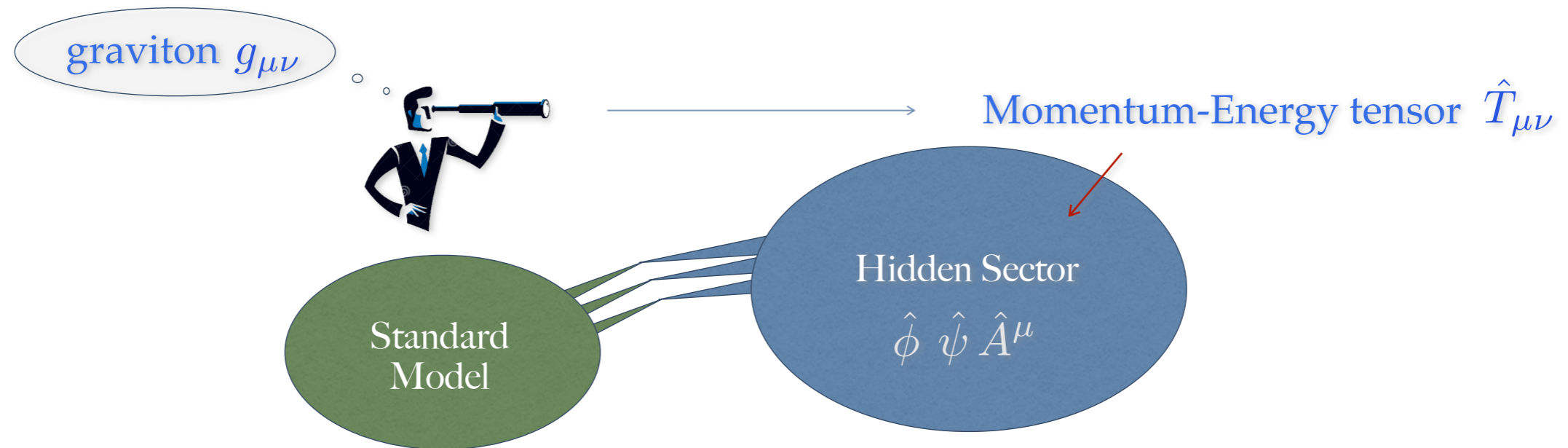
$$S_{eff} = S_{vis} + \int d^4x h_{\mu\nu} \left(T^{\mu\nu} + (2\pi)^4 \lambda^{-1} \left(1 + \frac{1}{2} \lambda^{-1} \Lambda^{-1} \right) \eta^{\mu\nu} \right) \\ + \int d^4x \sqrt{g} \left(\Lambda + \frac{1}{16\pi G} R \right) \Big|_{g_{\mu\nu} + \eta_{\mu\nu} + h_{\mu\nu}}$$

- ❖ The **cosmological constant** is given by $\Lambda = -\frac{(2\pi)^8}{\lambda^2 \langle \hat{T} \rangle}$.

- ❖ The **Weinberg-Witten theorem** is **inapplicable**: the final gravitational theory has a **non-trivial cosmological constant**.

Betzios, Kiritsis, Niarchos

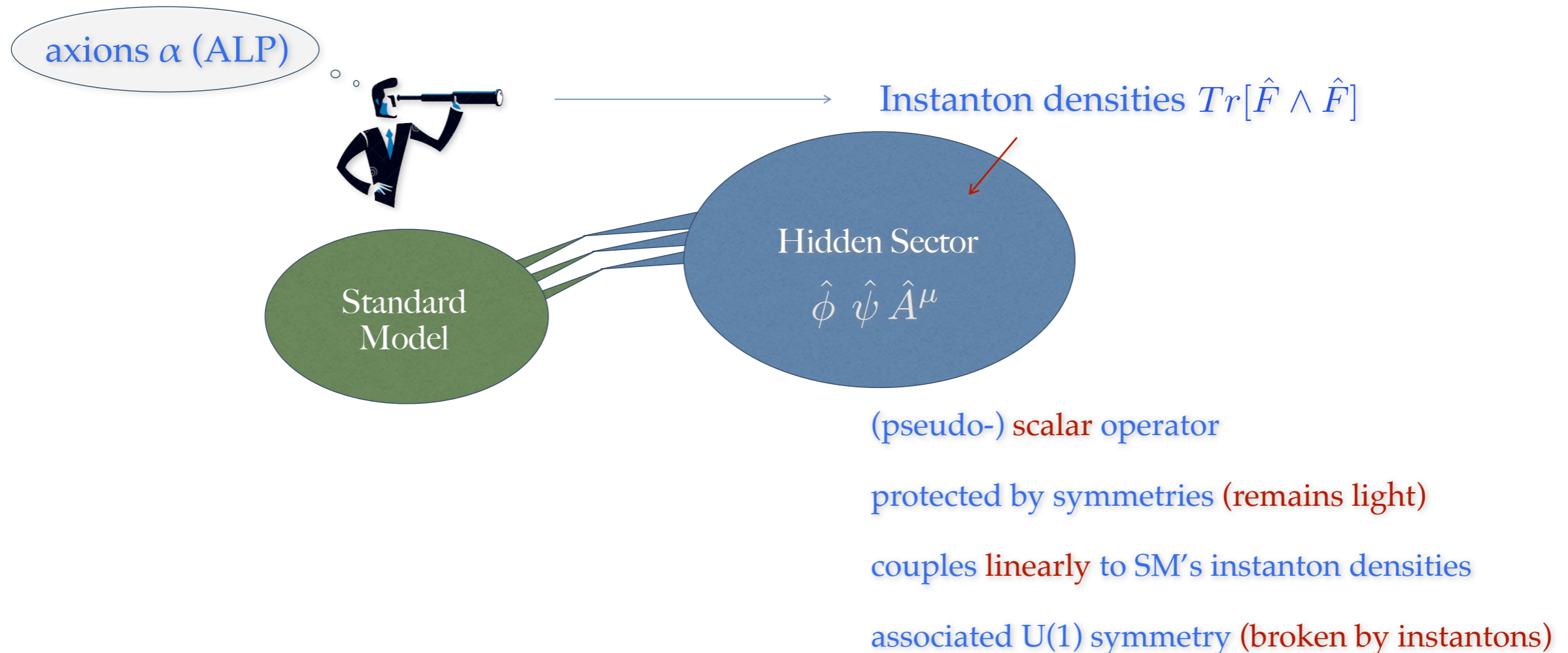
Emergent Gravity - Future plans



- ❖ Full analysis of the 2-point function shows that **the emergent graviton is massive**.
Betzios, Kiritsis, Niarchos
- ❖ The mass depends on various parameters of the model and can be **tuned to zero**.
- ❖ Even if emergent gravity **is not our known gravity**, **it is a prediction** of these holographic models with Hidden Sectors.
- ❖ In **combination** with a (massless) graviton, it can be studied as a **very interesting** (and new) two-metric/graviton model (bigravity).

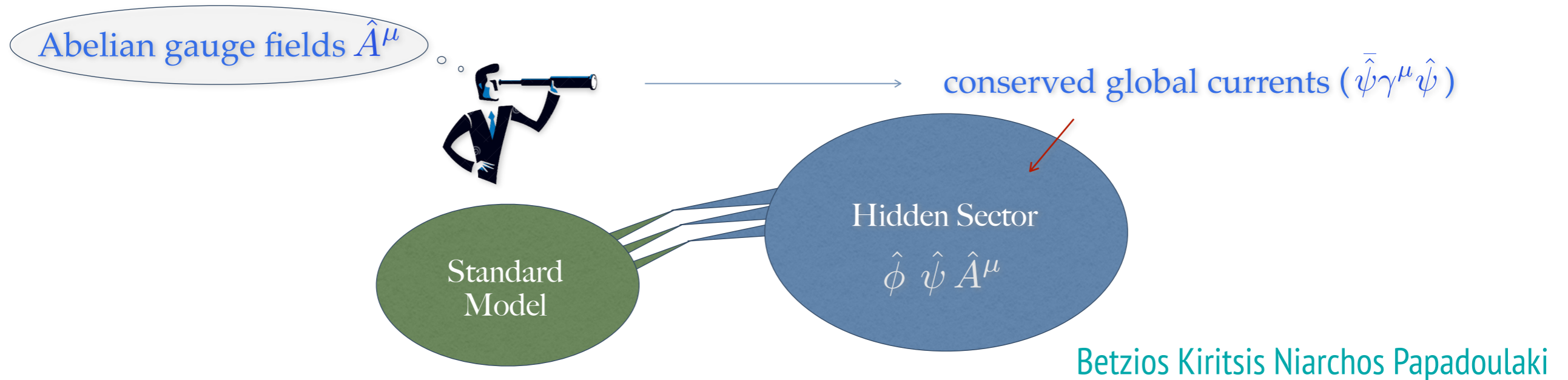
Anastasopoulos Markou

Emergent Axions - future plans



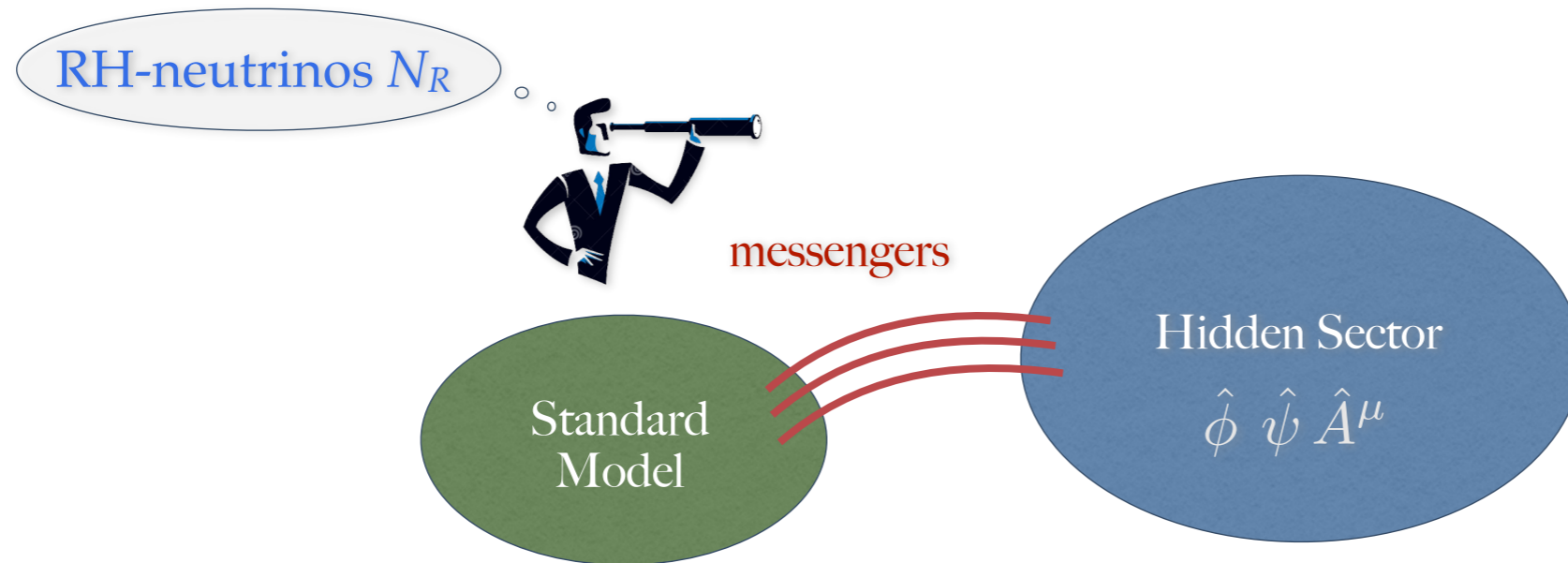
- * Axions from instanton densities is a **new idea / approach**.
Anastasopoulos Betzios Bianchi Consoli Kiritsis
- * Composite axions have been considered in the past, being of the **mesonic** type η' .
- * We aim to study their **phenomenological implications** (in progress).

Gravi/Dark-photons - future plans



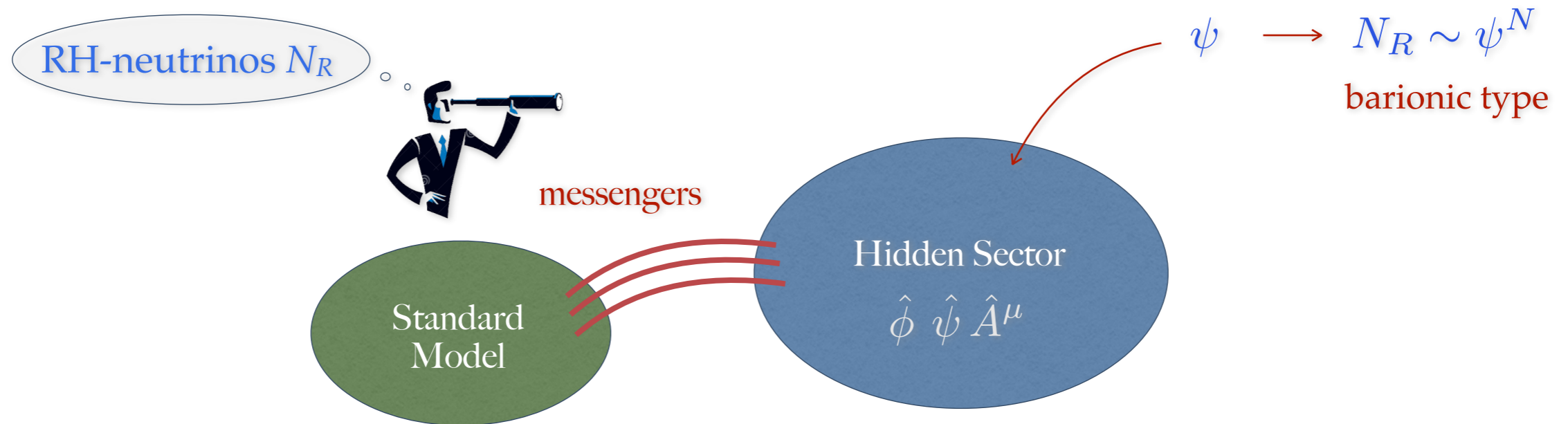
- ❖ No particle of the SM is **directly charged** under these U(1).
- ❖ They have **very weak interactions**. They have **kinetic mixing** with the hypercharge.
Anastasopoulos Betziros Bianchi Consoli Kiritsis
- ❖ Our goal to study this “**fifth force**” (can play the role of **gravi / dark-photons**).
- ❖ Emergent U(1)’s could **acquire non-vanishing vevs**. A very interesting option.
Kraus Tomboulis
- ❖ Emergent U(1)’s option is **not very much studied**.

Emergent Neutrinos - future plans



- ❖ Two different ways

Emergent Neutrinos - future plans

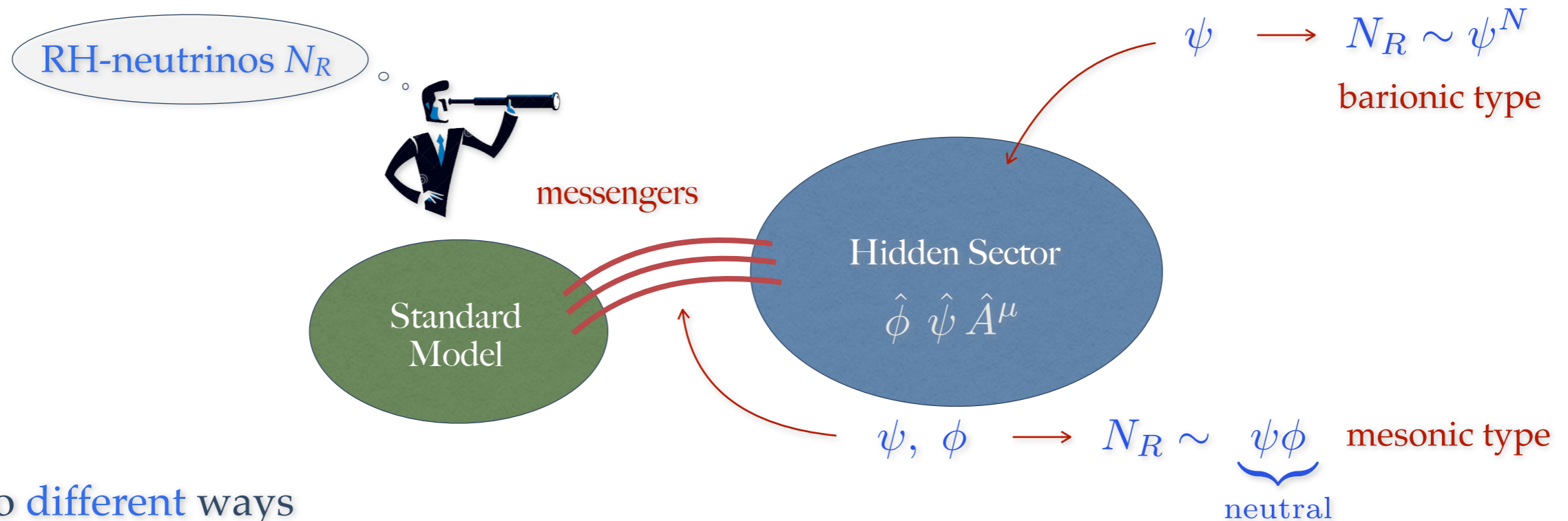


❖ Two different ways

- **baryonic type**: fermions of the HS.

Arkani-Hamed Grossman Robinson, Okui,...

Emergent Neutrinos - future plans



❖ Two different ways

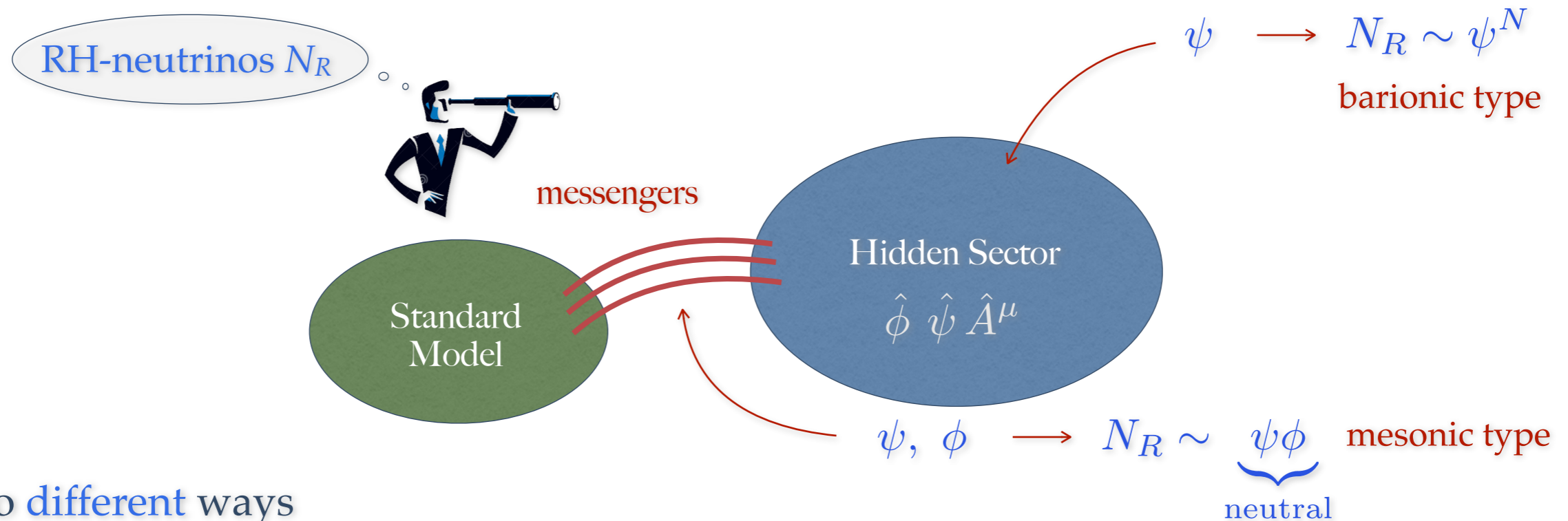
- **baryonic type:** fermions of the HS.

Arkani-Hamed Grossman Robinson, Okui, ...

- **mesonic type:** from a bosonic and a fermionic messenger.

Anastasopoulos Kiritsis

Emergent Neutrinos - future plans



- Two different ways

- baryonic type**: fermions of the HS.

Arkani-Hamed Grossman Robinson, Okui, ...

- mesonic type**: from a bosonic and a fermionic messenger.

Anastasopoulos Kiritsis

- The effective action of these emergent neutrinos triggers the **seesaw mechanism**

$$S \sim \int d^4x \left(\bar{L}_L H N_R + N_R N_R \right)$$

light (SM) neutrinos

sterile neutrinos

messenger scale

Conclusions

- * We consider a **holography-inspired scenario** of the **SM** and a **hidden 4D QFT** which communicate via **massive messengers**.
- * In this framework **operators of the HS** appear as **weakly coupled particles to the SM**.
- * Special interest: **operators protected by symmetries** \implies **light particles**.
- * We focus on: **gravitons, axions, graviphotons / dark-photons and neutrinos**.
- * Such emergent fields are **distinct** from **elementary / composite versions** studied in the past.