Emergent fields from Hidden sectors

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Plan of the talk

- Motivation
- Framework
- Emergent axions
- Gravi- / Dark- photons
- Emergent neutrinos
- Conclusions
**Motivation**

- Standard Model (SM) is an effective field theory.

- In the IR, we keep terms like low-dimensional operators of SM fields

\[ S_{SM} = \int d^4 x \ g_i(x) O_i(x) \]

- These couplings \( g_i(x) \) could be dynamical.
  - The coupling of the stress-energy tensor is the metric \( g_{\mu\nu}(x) \): dynamical (gravity).
  - The QCD \( \theta \)-angle is believed to be dynamical (axion).
  - In string theory, Yukawa couplings are also dynamical scalars (quasi)-moduli.

- In this talk we will explore these couplings in a generic holography-inspired framework.
Motivation

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

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

    

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

    

- The **Standard Model** (SM) is just a **small sector** of the Fundamental Theory.

- A **Hidden Sector** (HS) is a **(arbitrary) 4D QFT**, hidden from the SM in the IR.

- **Messengers** which couples the two sectors (SM and HS).
**Motivation**

- From the SM point of view, operators of the HS will appear as “fields”.

- Some of these operators/fields will be protected by symmetries and will remain light.

| HS point of view                                      | SM point of view                      |
|------------------------------------------------------|---------------------------------------|
| $\hat{T}_{\mu\nu}$ of the HS                         | $g_{\mu\nu}$ graviton                |
| $Tr[\hat{F} \wedge \hat{F}]$ of the HS              | $a$ axion                             |
| global conserved currents of the HS                   | abelian gauge fields                  |

- Occasionally, heavy operators/fields could provide interesting phenomenology.

| Fermionic operators of the HS/MS                      | RH-Neutrinos                          |
|------------------------------------------------------|---------------------------------------|
|                                                      | PA Kiritsis Niederweiser              |
Motivation

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 (graviton, axions, gauge fields, neutrinos) in this framework are composites, and they are distinct qualitatively from what has been considered so far.
Motivation

- This picture is quite generic in string theory.

- Consider D-brane realisations of the SM.
  - Standard Model is localized on a collection of stacks of D-branes,
  - Hidden D-branes are at some distance to ensure the stability of the construction (tadpole cancelation). Strings living on these D-branes consist a Hidden sector to the SM at the IR.
  - The closed string sector naturally provides the graviton, gravi-photons, (RR) axions and other moduli.
Framework
The Standard Model (SM):

- Contains all **known/standard fields** (quarks, leptons, gauge fields, Higgs).
- Later, we will **loosen** this standard definition by investigating **extensions**.
The Hidden $QFT_N$:

- It is **UV-complete**: At the UV it is either asymptotically free or conformal.

- **Size is enormous** and its structure is random.

- However, we will assume $SU(N)$ with $N$ - large (even astronomical) values.

- At **weak coupling (IR)** the hidden theory contains the simplest $QFT$s:
  
  vectors $\hat{A}^\mu$, scalars $\hat{\phi}$ and spin-1/2 particles $\hat{\psi}$
**Messengers**

- They are **charged under both** the SM and the HS.
- They are **massive** and they can be **heavy/light** (depending on the HS).
- In our case we assume to be heavy, with scale $M_{\text{messenger}}$.
- This scale is the largest of all other scales in this framework.

Kiritsis
Framework

UV picture

messengers

Hidden $QFT_N$

messenger mass

mixing terms between gauge invariant operators of the two sectors

IR picture

operators in Hidden Sector

weakly coupled fields for the SM

operators protected by symmetries

light particles
Emergent Axions
Emergent Axions

- Instanton density $\text{Tr} [\hat{F} \wedge \hat{F}] \sim a \implies$ is an ALP (axion-like-particle).
  - (pseudo-) scalar operator
  - protected by symmetries $\implies$ remains light
  - couples linearly to SM’s instanton densities

\[ S_{\text{eff}} = -\frac{g_{SM}^2 g_{QFT}^2}{90(4\pi)^2 M^4} \int d^4 x \left[ (F \cdot F)(\hat{F} \cdot \hat{F}) + 2(F \cdot \hat{F})^2 + \frac{7}{4} (F \wedge F)(\hat{F} \wedge \hat{F}) + \frac{7}{2} (F \wedge \hat{F})^2 \right] \]
  - associated U(1) symmetry which is broken by instantons.

We want to evaluate the mass and the decay constant of these emergent axions
Evaluating the mass and the decay constant

* From different sides we have different approaches.

- **HS side:** operators \( S = S_{SM}[O] + S_{HS}[\hat{O}] + \lambda \int d^4 x \ O(x)\hat{O}(x) \)
- **SM side:** fields \( S = S_{SM}[O] + \frac{1}{2} \int d^4 x \ a(x)K_\alpha a(x) + g \int d^4 x \ a(x)O(x) \)

* Comparing the same quantity from the two sides (the inverse propagator)

\[
\frac{1 - \lambda^2 \langle O(p)O(-p) \rangle \langle \hat{O}(p)\hat{O}(-p) \rangle}{\langle \hat{O}(p)\hat{O}(-p) \rangle} \rightarrow \text{HS point of view}
\]

\[
iK_\alpha(p) = f_\alpha^2 (p^2 + m_\alpha^2) + O[p^4] \rightarrow \text{SM point of view}
\]

and get the mass \( m_\alpha \) and the decay constant \( f_\alpha \) for the axion (SM point of view).
Fixing $m_a$ & $f_a$

* Results depend on various scales of our framework.

* Assuming a strongly coupled HS, with scale $m_{HS}$ we have:

  - At scales $p \ll m_{HS}$, we get
    \[ m_a^2 \sim m_{HS}^2, \quad f_a^2 = \frac{m_{HS}^2}{\lambda_0^2} \left( \frac{M_{messenger}}{m_{HS}} \right)^8 \]

  - At scales $p \gg m_{HS}$, the kinetic term of the axion is well-defined but non-local
    \[ S_{eff} \simeq \frac{M_{messenger}^8}{2} \int d^4 x_1 d^4 x_2 \ a(x_1) \log \left( \frac{|x_1 - x_2|}{m_{HS}} \right) a(x_2) + \int d^4 x \ a(x) O_{SM}(x) \]

  - In this category we also have the case of a conformal hidden theory ($m_{HS} \to 0$).

* Therefore, $m_{HS}$ is the “compositeness” scale.
Comments and directions

- **Instanton densities as axions** is a new idea, never studied in the past.

- Our goal is to extend our research towards **phenomenology** (all are works in progress)
  - Study the $a \to \gamma\gamma$ decay and compare with data.
  - The hierarchy of couplings of the **emergent axions** and the SM gauge fields.
  - The couplings of the **emergent axions** to the SM fermions.

- If the **scale of the hidden theory** is low, emergent axions are **spread out**.
  - Reconstruct the **effective action** of these non-local axions.
  - Modify the couplings of these axions with SM fields.
  - Study their **phenomenological implications**.

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Graviphotons/Dark-photons

**messengers**

**SM** ➔ **Hidden QFT$_N$**
Gravi/Dark-photons

* Back to our setup

UV picture

Global (exact) U(1) symmetry

Messengers

Hidden $QFT_N$

HS point of view

Global conserved currents ($\hat{J}^\mu = \bar{\psi} \gamma^\mu \psi$)

SM point of view

Abelian gauge fields $\hat{A}^\mu$

* Such emergent/composite vectors have (like the composite axions)

- (very) light masses
- A compositeness scale
Gravi/Dark-photons

- Back to our setup

- **Emergent gauge fields** couple to all gauge invariant antisymmetric tensors of the SM.

\[ W_6 \sim \frac{1}{NM^2} Tr[D_\mu H D_\nu H^\dagger] F_{\alpha}^{\mu \nu} + \frac{1}{N^{\frac{3}{2}}M^2} F_{\alpha}^{\mu \nu} [\bar{\psi} \gamma_{\mu \nu} H \psi + \text{c.c.}] \]
\[ + \frac{1}{N^{\frac{3}{2}}M^2} F_{\mu \nu} A_{\alpha} F_{Y,\mu \nu} H H^\dagger + \frac{1}{N^2M^4} F_{\mu \nu} A_{\alpha} F_{Y,\mu \nu} [\bar{\psi} H \psi + \text{c.c.}] + \ldots \]

- **Couplings** are taken after using **EFT principles** and **large-N expansions**.

- These **emergent vectors** can play the role of gravi-/dark-photons.
Mixings

With the effective action of couplings between gravi/dark-photons and SM fields we can evaluate mixing with SM abelian fields (hypercharge or anomalous U(1)'s).

\[
W_6 \sim \frac{1}{N M^2} Tr[D_{\mu} H D_{\nu} H^\dagger] F_{A}^{\mu\nu} + \frac{1}{N \frac{3}{2} M^2} F_{A}^{\mu\nu} [\bar{\psi} \gamma_{\mu\nu} H \psi + c.c.]
+ \frac{1}{N^2 M^2} F_{\hat{A}}^{\mu\nu} F_{\mu\nu}^{Y,\mu\nu} H H^\dagger + \frac{1}{N^2 M^4} F_{\hat{A}}^{\mu\nu} F_{\mu\nu}^{Y,\mu\nu} [\bar{\psi} H \psi + c.c.] + \cdots
\]

We explore two different cases: the unbroken and the broken phase.

\[
\hat{A}_\mu \quad Y^\mu \text{ hypercharge}
\]

\[
\hat{A}_\mu \quad B^\mu \text{ anomalous U(1)}
\]
Unbroken phase

* At leading order, we have the 1-loop Higgs diagram

\[
\hat{A}_\mu \rightarrow H \rightarrow Y \chi \rightarrow Y \chi
\]

\[\sim \frac{\Omega_3}{8} \frac{Q_Y^H}{N} \frac{\Lambda^2}{M^2} \int d^4p \ F_{\mu\nu}^\hat{A}(p) F_{\mu\nu}^Y(-p) + \cdots\]

* At next order, we have 2-loop diagrams (where SM fermions can contribute)

\[W_6 \sim \frac{1}{NM^2} Tr[D_\mu H D_\nu H^\dagger] F_{\mu\nu}^\hat{A} + \frac{1}{N^{3/2}M^2} F_{\mu\nu}^\hat{A} [\bar{\psi} \gamma_{\mu\nu} H \psi + c.c.] + \cdots\]

\[+ \frac{1}{N^{3/2}M^2} F_{\mu\nu}^{\hat{A}} F_{\rho\sigma}^{Y,\mu\nu} H H^\dagger + \frac{1}{N^2M^4} F_{\mu\nu}^{\hat{A}} F_{\rho\sigma}^{Y,\mu\nu} [\bar{\psi} H \psi + c.c.] + \cdots\]
Broken phase

The action in the broken phase becomes

\[
W_{\text{BROKEN}} \sim \frac{4g_w^2}{NM^2} (h+v)^2 F^\hat{A}_\mu W^- + \frac{4ie}{NM^2} (h+v) F^\hat{A}_\mu A^\nu \partial^\nu h
\]
\[
+ \frac{4e}{NM^2} \sqrt{g_w^2 + g_Y^2} (h+v)^2 F^\hat{A}_\mu A^\nu Z^\nu + \frac{1}{N^3 \frac{3}{2} M^2} F^\mu_\nu (h+v) \bar{\psi} \gamma_\mu \nu \psi + \text{c.c.}
\]
\[
+ \frac{1}{N^2 M^4} F^\hat{A}_\mu (\cos \theta_w F^{\gamma,\mu\nu}_w - \sin \theta_w F^{Z,\mu\nu}_w)(h+v)^2
\]
\[
+ \frac{1}{N^2 M^4} F^\hat{A}_\mu (\cos \theta_w F^{\gamma,\mu\nu}_w - \sin \theta_w F^{Z,\mu\nu}_w) [\bar{\psi} \psi (h+v) + \text{c.c.}]
\]

The mixing is coming at tree- and 1-loop level from the diagrams

\[
\sim \frac{\nu^2}{NM^2} \int d^4 p F^\hat{A}_{\mu\nu}(p) \left( \cos \theta_w F^{\gamma,\mu\nu}_w - \sin \theta_w F^{Z,\mu\nu}_w \right) (-p)
\]
\[
\sim 4\Omega_3 Tr_y \left[ \frac{Q_Y m_\psi v}{N^3 \frac{3}{2} M^2} \right] \log \frac{\Lambda^2}{m_\psi^2}
\]
\[
\sim -e \frac{\Lambda^2}{NM^2} \frac{8i\Omega_3}{(2\pi)^4}
\]

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The holographic-inspired scenario is similar to string theory picture.

Our goal is to compare couplings between U(1)’s and SM fields in the two scenarios.

In string theory, we have two classes of abelian gauge fields

- Closed sector (NSNS and RR sectors) \implies gravi-photons
- Open sector (strings living on D-branes) \implies dark-brane-photons

We will list the terms in the action and the corresponding string amplitudes.
EFT couplings from ST amplitudes

* Couplings from the EFT picture and the corresponding string amplitudes.

\[ \frac{\Lambda^2}{N M^2} F_{\mu\nu} \hat{F}_{\mu\nu} \]

\[ \frac{1}{N M^2} D_\mu H^\dagger D_\nu H \hat{F}_{\mu\nu} \]

\[ \frac{1}{N^{3/2} M^2} \bar{\psi} \gamma_{\mu\nu} H \psi \hat{F}_{\mu\nu} \]

\[ \frac{1}{N^{3/2} M^2} F_{\mu\nu} \hat{F}_{\mu\nu} H^\dagger H \]

\[ \frac{1}{N^2 M^4} F_{\mu\nu} \hat{F}_{\mu\nu} \bar{\psi} H \psi \]

closed strings

RR/NSNS fluxes

open string

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Comparison with results

- Our results, regarding the couplings $g_s = \frac{1}{N}$ in String Theory and the Large-N

| EFT coupling          | EFT estimate | graviphoton         | graviphoton + bulk fluxes | dark photon |
|------------------------|--------------|----------------------|----------------------------|-------------|
| $F \hat{F}$            | $O(\frac{1}{N})$ | $O(g_s^2)$            | $O(g_s^{3/2})$             | $O(g_s)$    |
| $\phi F \hat{F}$       | $O(\frac{1}{N})$ | $O(g_s)$              | $O(g_s^2)$                 |             |
| $DHDH^\dagger \hat{F}$ | $O(\frac{1}{N})$ | $O(g_s)$              | $O(g_s^{3/2})$             | $O(g_s^2)$  |
| $HH^\dagger F \hat{F}$ | $O(\frac{1}{N^{3/2}})$ | $O(g_s^{5/2})$       | $O(g_s^{5/2})$             | $O(g_s^2)$  |
| $\bar{\psi} H \gamma^{\mu\nu} \psi \hat{F}_{\mu\nu}$ | $O(\frac{1}{N^{3/2}})$ | $O(g_s^{3/2})$       | $O(g_s^{3/2})$             | $O(g_s^2)$  |
| $\bar{\psi} H \psi F \hat{F}_{\mu\nu}$          | $O(\frac{1}{N^2})$ | $O(g_s^2)$            | $O(g_s^2)$                 | $O(g_s^{5/2})$ |

agreement in circles

zero at leading order

sub-leading

- Same couplings are expected if we substitute the hypercharge with some anomalous $U(1)$ accompanying the SM (a usual case in semi-realistic D-brane configurations).

PA Bianchi Consoli Kiritsis
Comments and future directions

- **Emergent U(1)’s weakly couple to the SM fields and they can play the role of graviphotons/dark-photons.**
  - PA Bianchi Consoli Kiritsis

- **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.**
  - Björken

- **Non-local kinetic terms appear like in the axionic case.**
  - Effective action will be **rebuilt.**
  - Spread-out of the wavefunction provides different couplings (weaker) from the point-like case.
  - New limits on graviphoton/dark-photon couplings to the SM fields.
Composite Neutrinos
Neutrinos

- RH-neutrinos can also emerge in this framework.

- They can have two different realizations
  - bound state (baryonic) of $N$ (odd number) fermions from the hidden sector.
  - bound state (mesonic) of messengers.

- The effective action of these composite fermions triggers the seesaw mechanism

$$ S \sim \int d^4 x \left( \bar{L}_L H N_R + \bar{N}_R N_R \right) $$
RH-neutrinos as mesonic messengers

* We assume that mesonic scalars get vevs (of order of the messenger scale).

* Playing with the various parameters, we get (via type I seesaw mechanism)
  - Models with heavy sterile neutrinos
  - Models with light/ultra-light sterile neutrinos.

* Study cases where type II/III (inverse/radiative) seesaw mechanisms can apply.

* Phenomenological implications (leptonic mixing matrix, leptogenesis).

* Additionally, we can span over semi realistic D-brane configurations for patterns that fall in one of the heavy/light categories.
Conclusions
**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**.

* **Phenomenological implications** are **on the go**.

* **Emergent fields** in this framework are **composites**, and they are **distinct qualitatively** from what has been **considered so far**.