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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

$$S_{SM} = \int d^4x \; g_i(x) O_i(x)$$

couplings

- 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 θ-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.

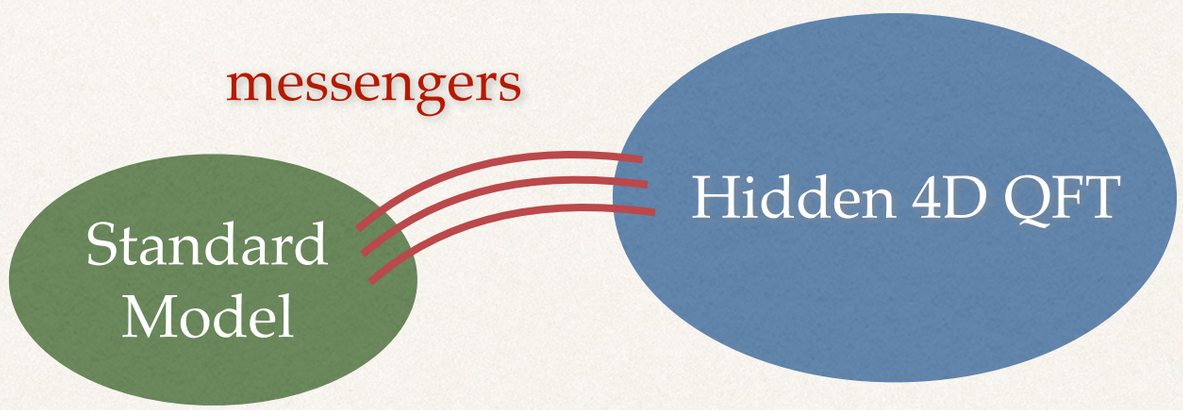
Motivation

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

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

Kiritsis

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



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

Nielsen

- 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	$\longrightarrow$	$g_{\mu\nu}$ graviton Betzios, Kiritsis, Niarchos
$Tr[\hat{F} \wedge \hat{F}]$ of the HS	$\longrightarrow$	a axion PA Betzios Bianchi Consoli Kiritsis
global conserved currents of the HS	$\longrightarrow$	abelian gauge fields Betzios Kiritsis Niarchos Papadoulaki PA Bianchi Consoli Kiritsis

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

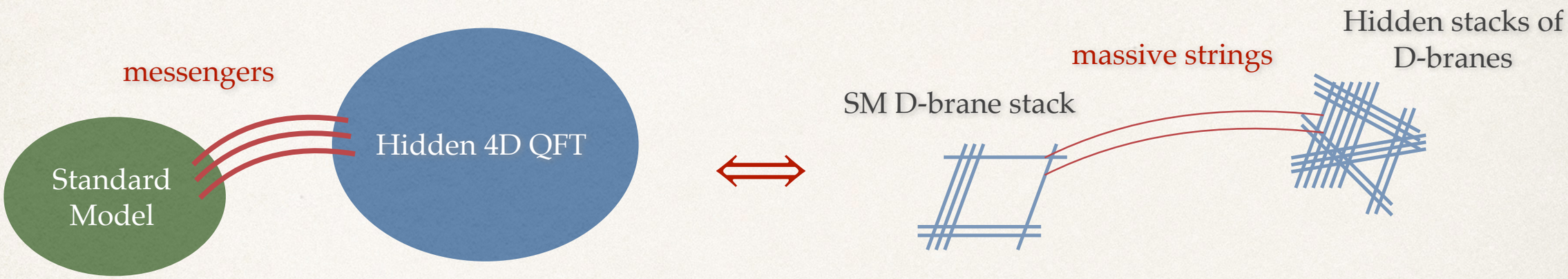
Fermionic operators of the HS/MS	$\longrightarrow$	RH-Neutrinos PA Kiritsis Niederweiser

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.

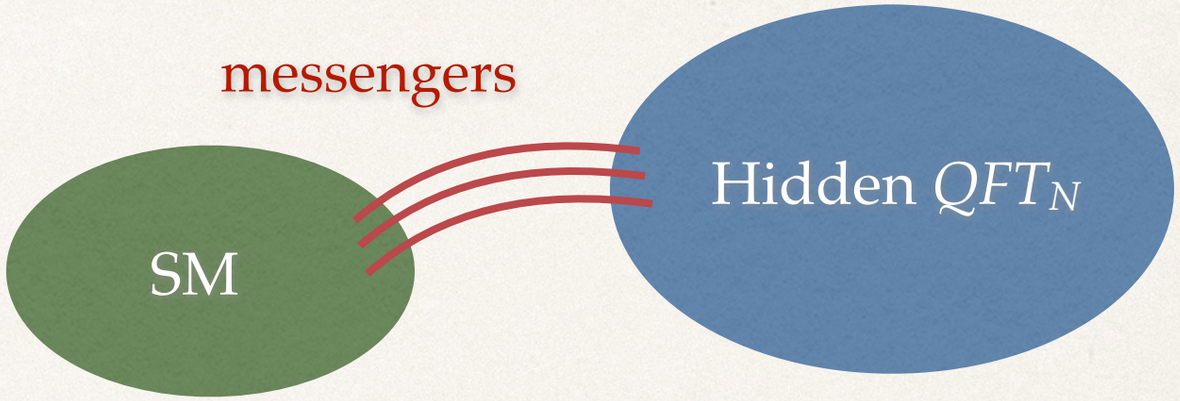
Motivation

- This picture is quite generic in string theory.

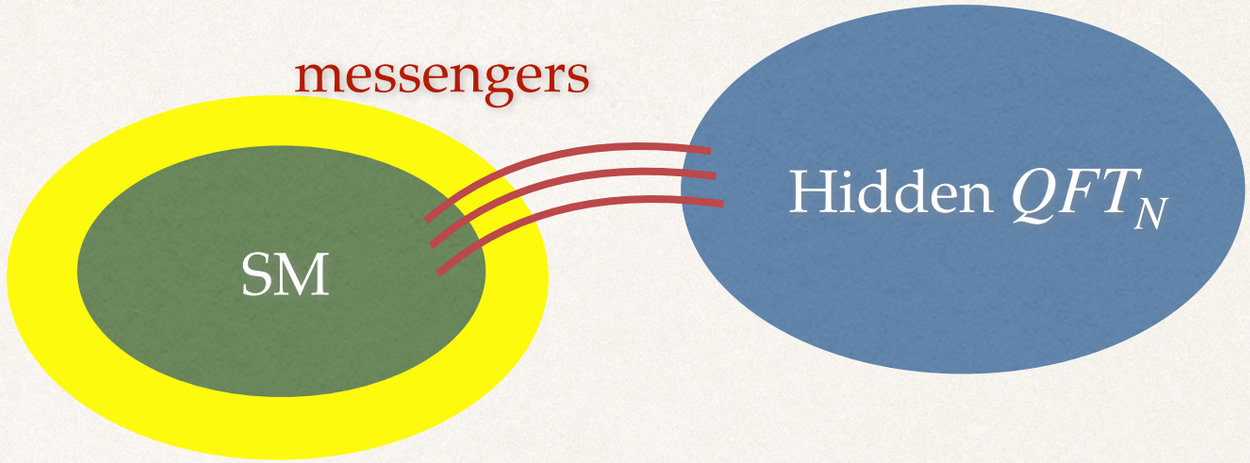


- Consider D-brane realisations of the SM.
  - Standard Model is localized on a collection of stacks of D-branes,
  - Hidden D-branes are at some distance to ensure the stability of the construction (tadpole cancelation). Strings living on these D-branes consist a Hidden sector to the SM at the IR.
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

Framework

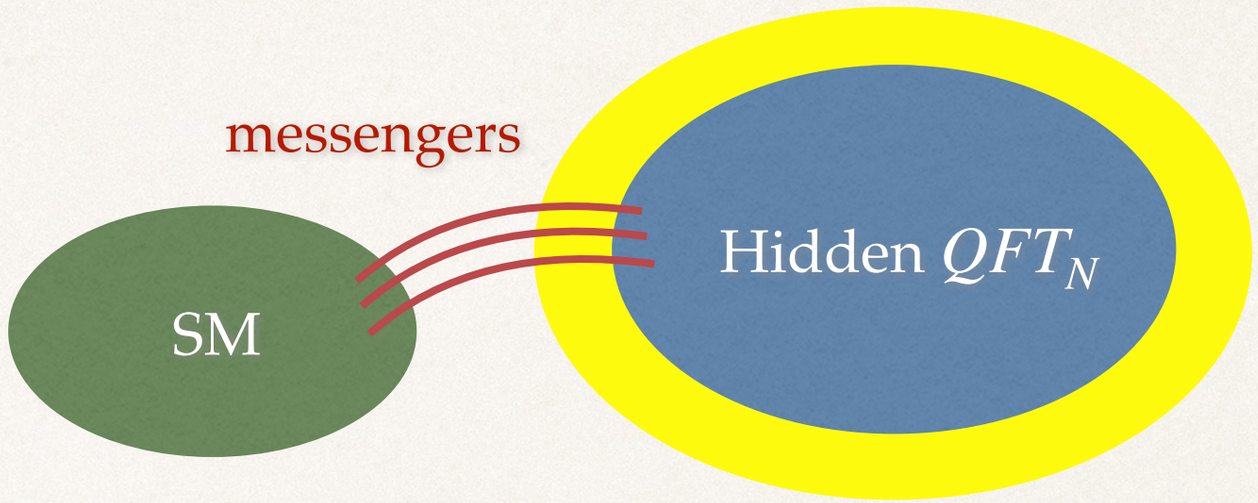


Framework



- The Standard Model (SM):
  - Contains all known/standard fields (quarks, leptons, gauge fields, Higgs).
  - Later, we will loosen this standard definition by investigating extensions.

Framework

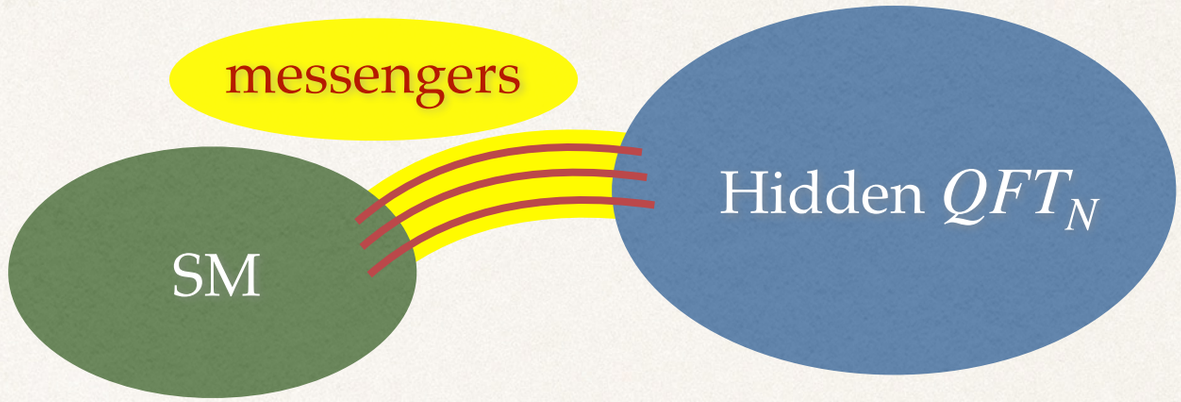


- The Hidden QFT_N :
  - It is UV-complete: At the UV it is either asymptotically free or conformal.
  - Size is enormous and its structure is random.
  - However, we will assume SU(N) with N - large (even astronomical) values.
  - At weak coupling (IR) the hidden theory contains the simplest *QFT*s:

Nielsen

vectors $\hat{A}^\mu$, scalars $\hat{\phi}$ and spin-1/2 particles $\hat{\psi}$

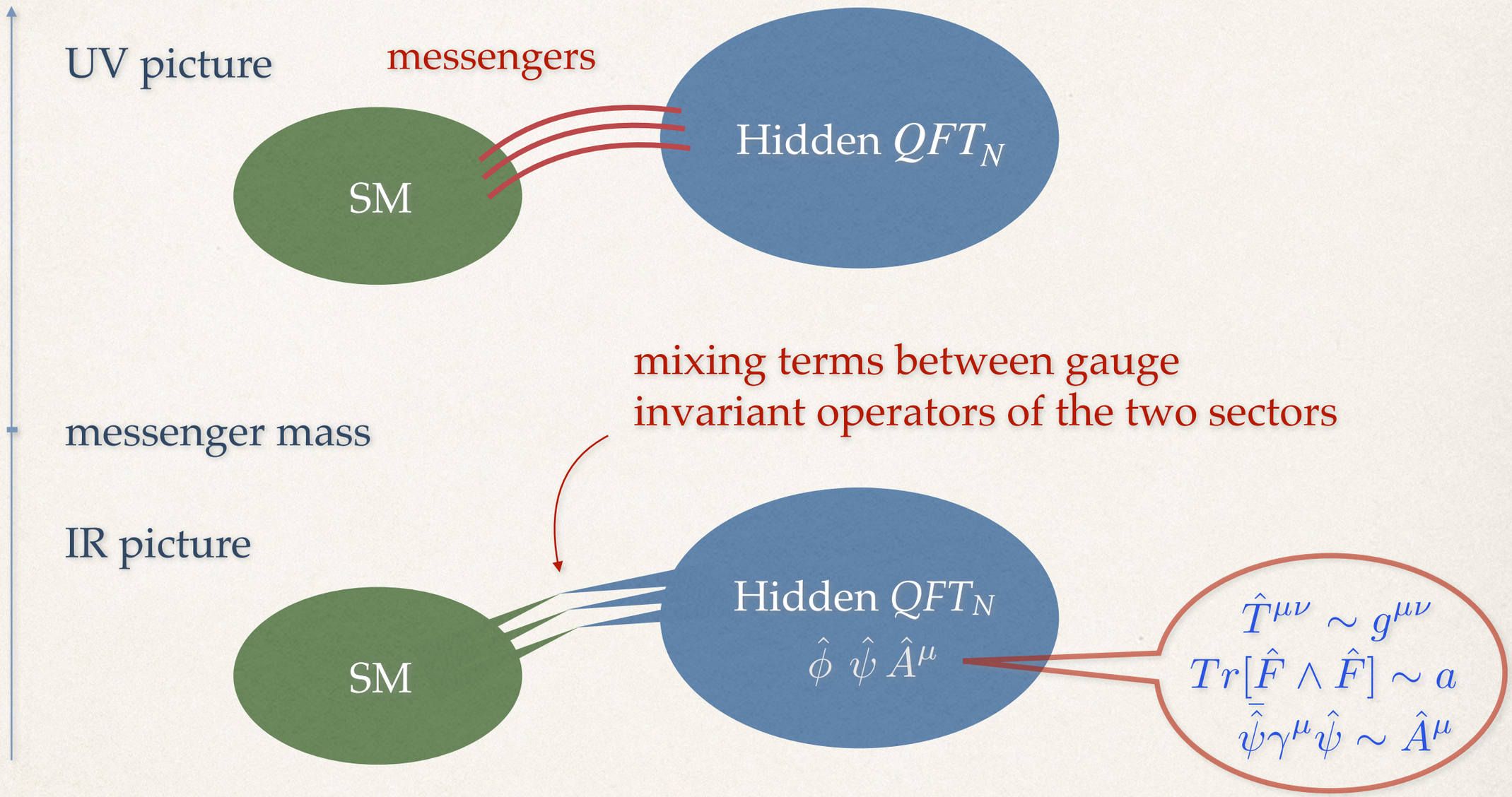
Framework



- 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 $M_{messenger}$.
  - This scale is the largest of all other scales in this framework.

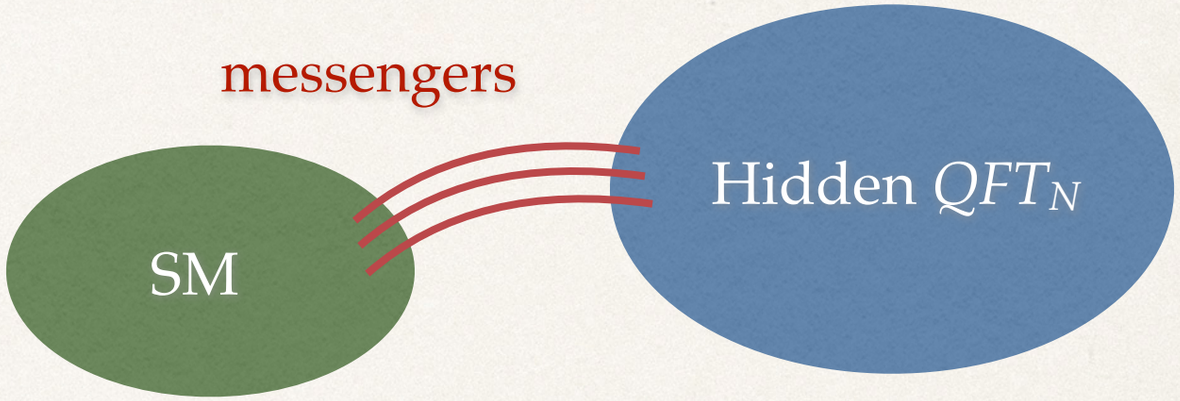
Kiritsis

Framework



operators in Hidden Sector → weakly coupled fields for the SM

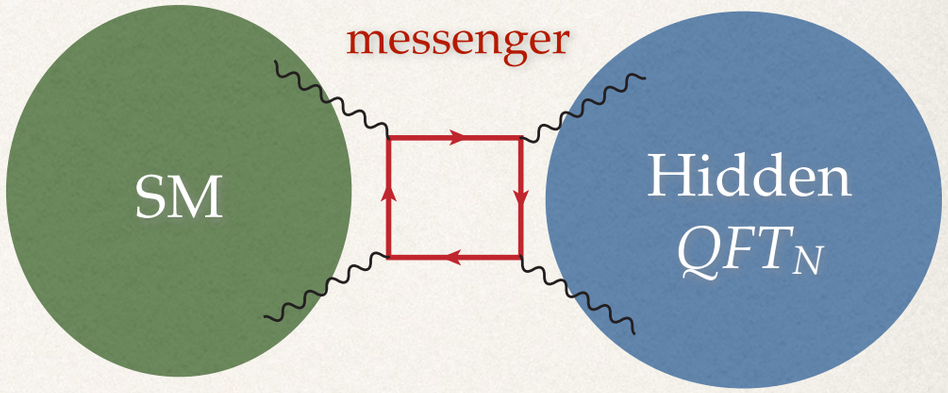
operators protected by symmetries → light particles



Emergent Axions

Emergent Axions

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



$$S_{eff} = -\frac{g_{SM}^2 g_{QFT}^2}{90(4\pi)^2 M^4} \int d^4x \Big[(F \cdot F)(\hat{F} \cdot \hat{F}) + 2(F \cdot \hat{F})^2 + \frac{7}{4}(F \wedge F)(\hat{F} \wedge \hat{F}) + \frac{7}{2}(F \wedge \hat{F})^2 \Big]$$

~ Euler-Heisenberg

$a\ Tr[F \wedge F]$

- 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.

$$a \sim \hat{O} = Tr[\hat{F} \wedge \hat{F}]$$

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

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

$$i\langle a(p)a(-p)\rangle|^{-1}_{total} \longrightarrow \frac{1-\lambda^2\langle O(p)O(-p)\rangle\langle\hat{O}(p)\hat{O}(-p)\rangle}{\langle\hat{O}(p)\hat{O}(-p)\rangle} \longrightarrow \text{HS point of view}$$

$$i\langle a(p)a(-p)\rangle|^{-1}_{total} \longrightarrow iK_a(p) = f_a^2(p^2 + m_a^2) + \mathcal{O}[p^4] \longrightarrow \text{SM point of view}$$

and get the mass m_a and the decay constant f_a 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

$$m_a^2 \sim m_{HS}^2 \quad , \quad f_a^2 = \frac{m_{HS}^2}{\lambda_0^2} \left(\frac{M_{messenger}}{m_{HS}} \right)^8$$

  - At scales $p \gg m_{HS}$, the kinetic term of the axion is well-defined but non-local

$$S_{eff} \simeq \frac{M_{messenger}^8}{2} \int d^4x_1 d^4x_2 \; a(x_1) \log \frac{|x_1 - x_2|}{m_{HS}} a(x_2) + \int d^4x \; a(x) O_{SM}(x)$$

  - 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)

PA Kiritsis Mambrini Oribe

  - Study the $a \to \gamma\gamma$ decay and compare with data.

  - The hierarchy of couplings of the emergent axions and the SM gauge fields.

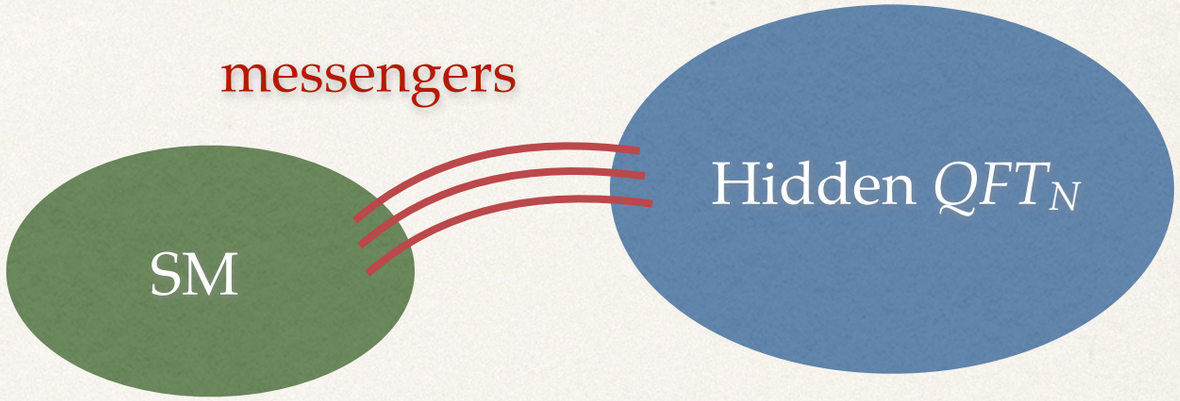
  - The couplings of the emergent axions to the SM fermions.

- 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.

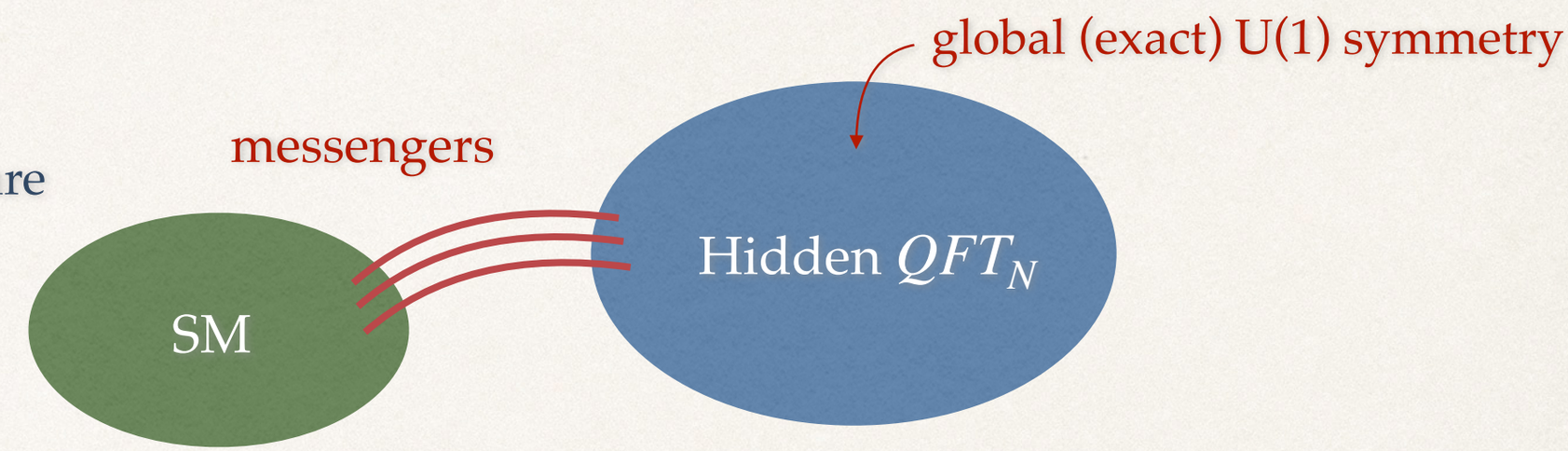


Graviphotons/Dark-photons

Gravi/Dark-photons

- Back to our setup

UV picture



HS point of view

SM point of view

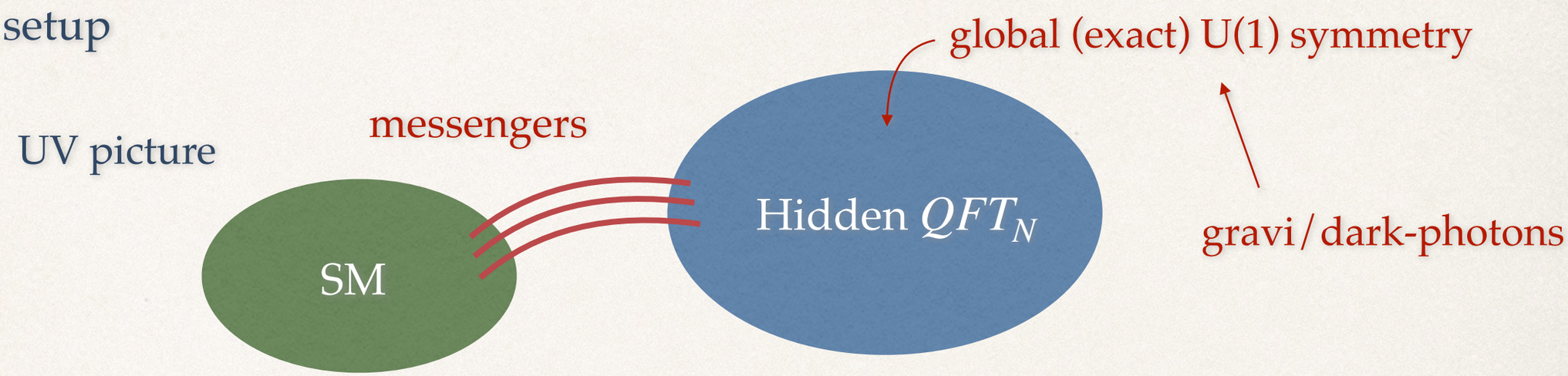
global conserved currents ($\hat{J}^\mu = \bar{\hat{\psi}}\gamma^\mu\hat{\psi}$) $\longrightarrow$ abelian gauge fields $\hat{A}^\mu$

- Such emergent/composite vectors have (like the composite axions)
  - (very) light masses
  - a compositeness scale

Betzios Kiritsis Niarchos Papadoulaki

Gravi/Dark-photons

- Back to our setup



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

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

emergent gauge fields

SM fields

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

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

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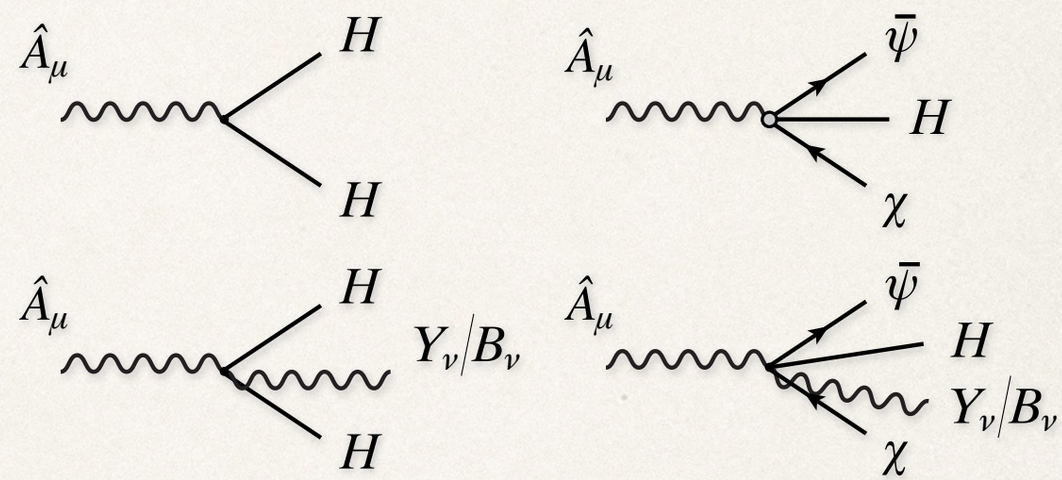
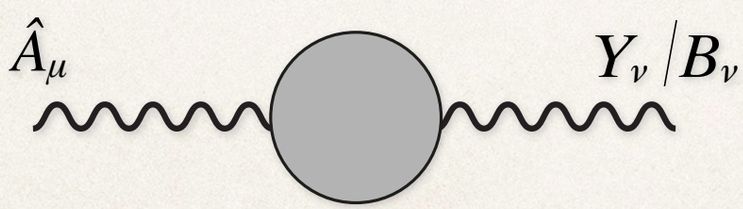
Mixings

- 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).

$$
\begin{aligned}
W_6 \quad \sim \quad & \frac{1}{NM^2} Tr[D_\mu H D_\nu H^\dagger] F^{\mu\nu}_{\hat{A}} + \frac{1}{N^{\frac{3}{2}} M^2} F^{\mu\nu}_{\hat{A}} [\bar{\psi}\gamma_{\mu\nu} H \psi + c.c.] \\
& + \frac{1}{N^{\frac{3}{2}} M^2} F^{\hat{A}}_{\mu\nu} F^{Y,\mu\nu} H H^\dagger + \frac{1}{N^2 M^4} F^{\hat{A}}_{\mu\nu} F^{Y,\mu\nu} [\bar{\psi} H \psi + c.c.] + \cdots
\end{aligned}
$$





Y^μ hypercharge

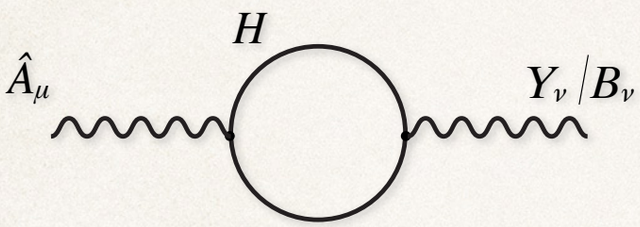
B^μ anomalous U(1)

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

Unbroken phase

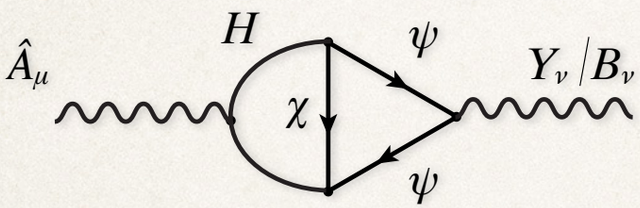
$$W_6 \sim \frac{1}{NM^2} Tr[D_\mu H D_\nu H^\dagger] F^{\mu\nu}_{\hat{A}} + \frac{1}{N^{\frac{3}{2}} M^2} F^{\mu\nu}_{\hat{A}} [\bar{\psi}\gamma_{\mu\nu} H\psi + c.c.] + \frac{1}{N^{\frac{3}{2}} M^2} F^{\hat{A}}_{\mu\nu} F^{Y,\mu\nu} HH^\dagger + \frac{1}{N^2 M^4} F^{\hat{A}}_{\mu\nu} F^{Y,\mu\nu} [\bar{\psi}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

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

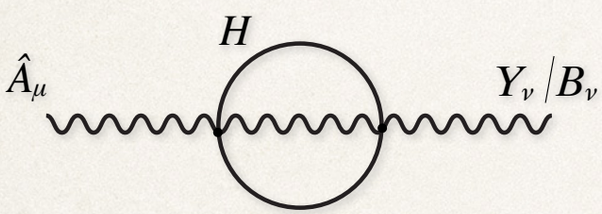


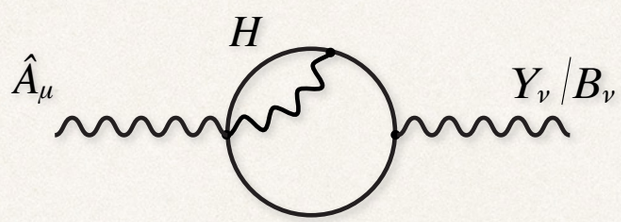
$$\sim \frac{\Omega_3}{8} \frac{Q_Y^H}{N} \frac{\Lambda^2}{M^2} \int d^4p \, F^{\hat{A}}_{\mu\nu}(p) F^{\mu\nu}_Y(-p) + \cdots$$

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

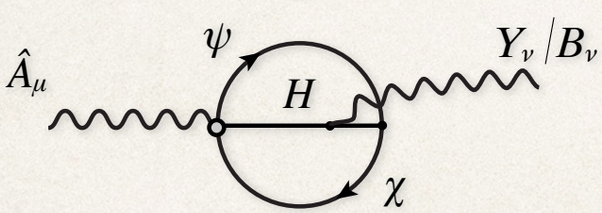


$$\sim Q_Y^\psi |g_{H\psi\chi}|^2 \frac{\Lambda^2}{NM^2}$$

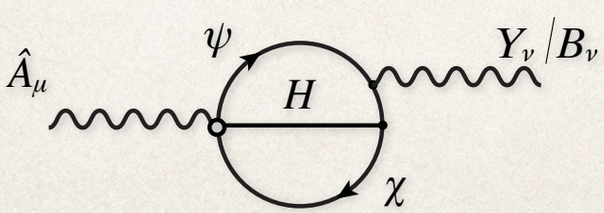




$$\sim \frac{(Q_Y^H)^2}{N}$$



$$\sim \frac{g_{H\psi\chi} m^2}{M^2 N^{\frac{3}{2}}} \log \frac{\Lambda^2}{m^2}$$



$$\sim \frac{Q_Y^H g_{H\psi\chi}}{N^{\frac{3}{2}}}$$

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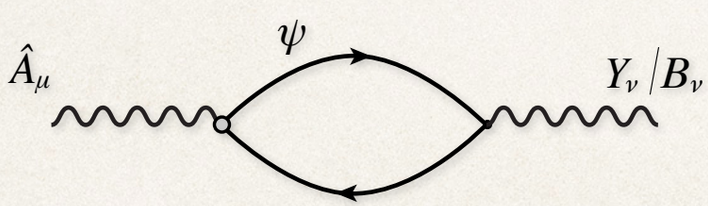
Broken phase

- The action in the broken phase becomes

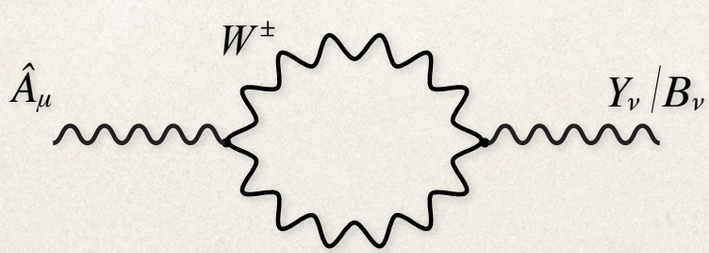
$$
\begin{aligned}
W_{BROKEN} \sim\ & \frac{4g_w^2}{NM^2}(h+v)^2\, F^{\hat{A}}_{\mu\nu} W^{\mu}_{+} W^{\nu}_{-} + \frac{4ie}{NM^2}\,(h+v) F^{\hat{A}}_{\mu\nu} A^{\mu}_{\gamma} \partial^{\nu} h \\
& + \frac{4e}{NM^2}\sqrt{g_w^2+g_Y^2}\,(h+v)^2 F^{\hat{A}}_{\mu\nu} A^{\mu}_{\gamma} Z^{\nu} + \frac{1}{N^{\frac{3}{2}}M^2}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

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

$$\sim \frac{v^2}{NM^2}\int d^4p\, F^{\hat{A}}_{\mu\nu}(p)\left(\cos\theta_w F^{\gamma,\mu\nu} - \sin\theta_w F^{Z,\mu\nu}\right)(-p)$$



$$\sim 4\Omega_3 Tr_Y\left[\frac{Q_Y m_\psi v}{N^{\frac{3}{2}}M^2}\right]\log\frac{\Lambda^2}{m_\psi^2}$$



$$\sim -e\frac{\Lambda^2}{NM^2}\frac{8i\Omega_3}{(2\pi)^4}$$

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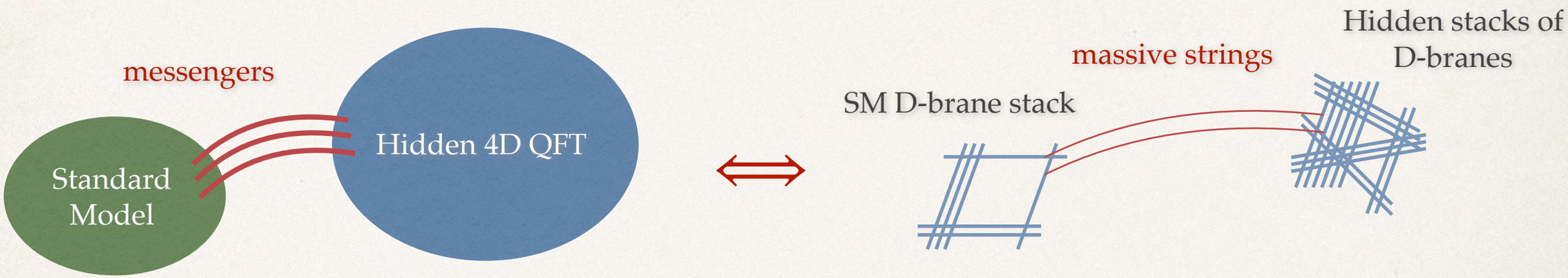
String theory vs QFT pictures

- 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.

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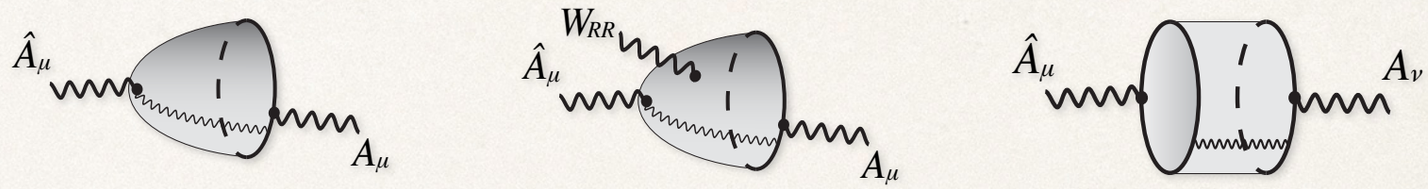
- In string theory, we have two classes of abelian gauge fields
  - Closed sector (NSNS and RR sectors) $\Longrightarrow$ gravi-photons
  - Open sector (strings living on D-branes) $\Longrightarrow$ dark-brane-photons
- We will list the terms in the action and the corresponding string amplitudes.

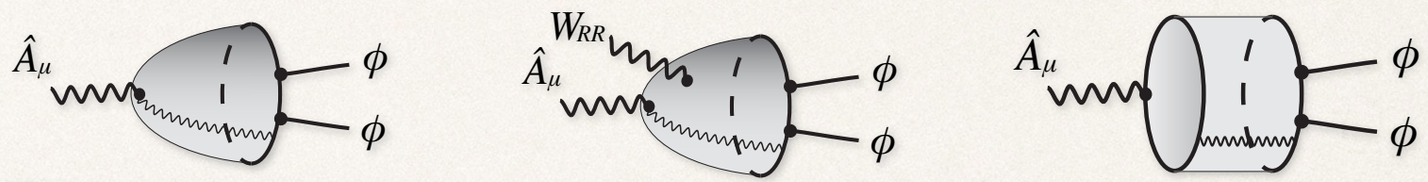
EFT couplings from ST amplitudes

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

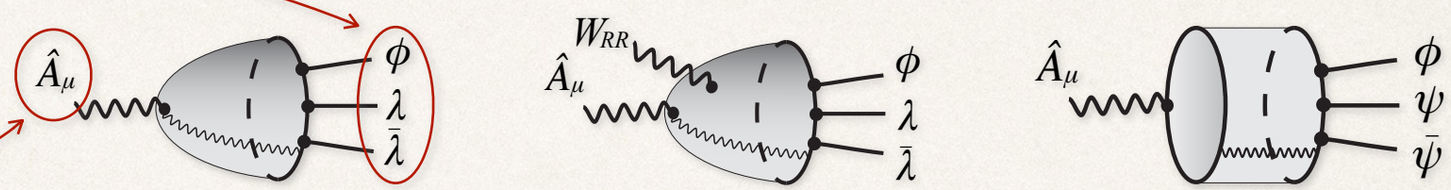
$$\frac{\Lambda^2}{NM^2} F^{\mu\nu}\hat{F}^{\mu\nu}$$



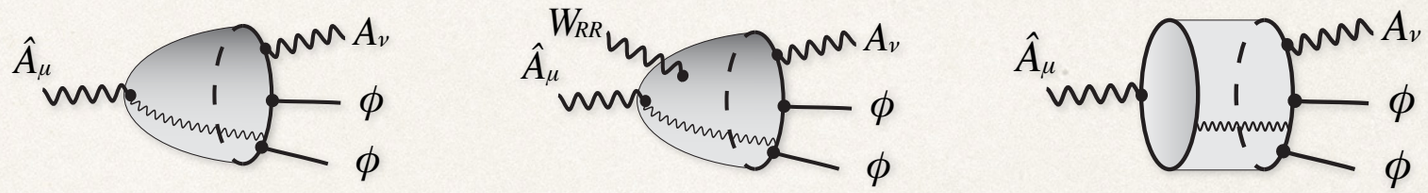
$$\frac{1}{NM^2} D_\mu H^\dagger D_\nu H \hat{F}^{\mu\nu}$$



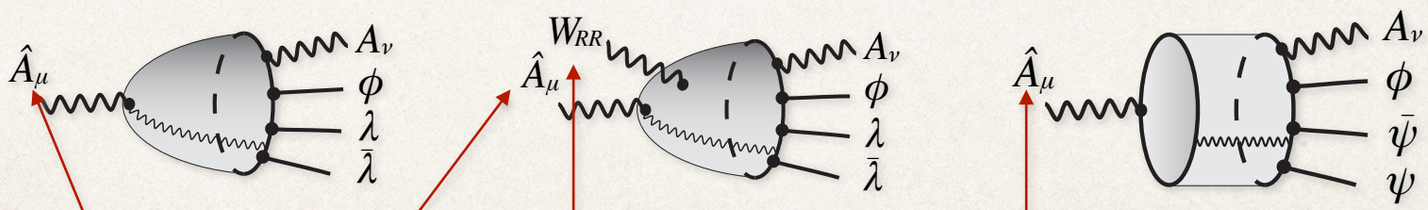
$$\frac{1}{N^{\frac{3}{2}}M^2} \bar{\psi}\gamma_{\mu\nu}H\psi\hat{F}^{\mu\nu}$$



$$\frac{1}{N^{\frac{3}{2}}M^2} F^{\mu\nu}\hat{F}_{\mu\nu}H^\dagger H$$



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



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**
$F\hat{F}$	$\mathcal{O}\left(\frac{1}{N}\right)$	$\mathcal{O}\left(g_s^2\right)$	$\mathcal{O}(g_s^{3/2})$	$\mathcal{O}\left(g_s\right)$
$\phi\ F\hat{F}$	$\mathcal{O}\left(\frac{1}{N}\right)$	$\mathcal{O}\left(g_s\right)$		
$DHDH^\dagger\hat{F}$	$\mathcal{O}\left(\frac{1}{N}\right)$	$\mathcal{O}\left(g_s^2\right)$	$\mathcal{O}\left(g_s^2\right)$	$\mathcal{O}(g_s^{3/2})$
$HH^\dagger F\hat{F}$	$\mathcal{O}\left(\frac{1}{N^{3/2}}\right)$	$\mathcal{O}(g_s^{5/2})$	$\mathcal{O}(g_s^{5/2})$	$\mathcal{O}\left(g_s^2\right)$
$\bar{\psi}H\gamma^{\mu\nu}\psi\hat{F}_{\mu\nu}$	$\mathcal{O}\left(\frac{1}{N^{3/2}}\right)$	$\mathcal{O}(g_s^{3/2})$	$\mathcal{O}(g_s^{5/2})$	$\mathcal{O}\left(g_s^2\right)$
$\bar{\psi}H\psi F\hat{F}_{\mu\nu}$	$\mathcal{O}\left(\frac{1}{N^2}\right)$	$\mathcal{O}\left(g_s^2\right)$	$\mathcal{O}\left(g_s^3\right)$	$\mathcal{O}(g_s^{5/2})$

agrement 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).

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Comments and future directions

- Emergent U(1)'s weakly couple to the SM fields and they can play the role of graviphotons/dark-photons.

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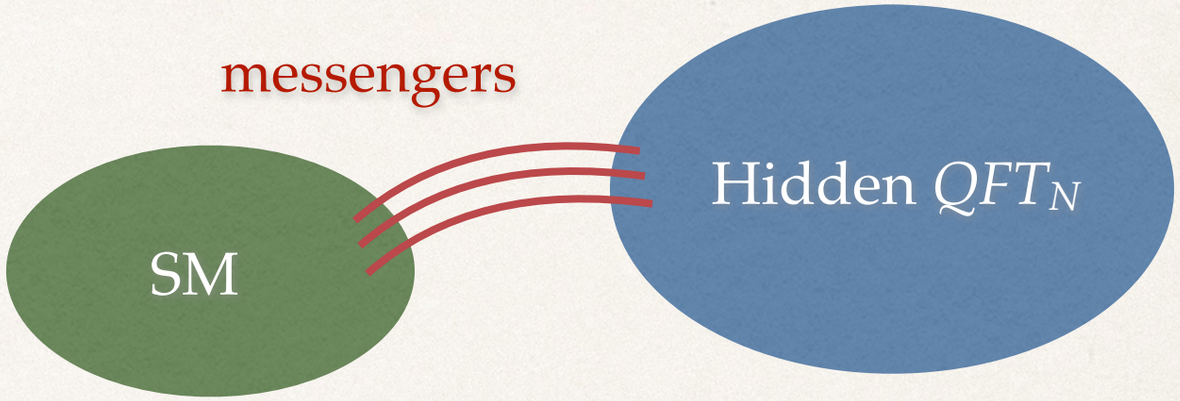
- Non-local kinetic terms appear like in the axionic case.
  - Effective action will be rebuilt.
  - Spread-out of the wavefunction provides different couplings (weaker) from the point-like case.
  - New limits on graviphoton/dark-photon couplings to the SM fields.
- Emergent U(1)'s could acquire non-vanishing vevs. A very interesting option.

Kraus Tomboulis

- Emergent U(1)'s option is not very much studied.

Björken



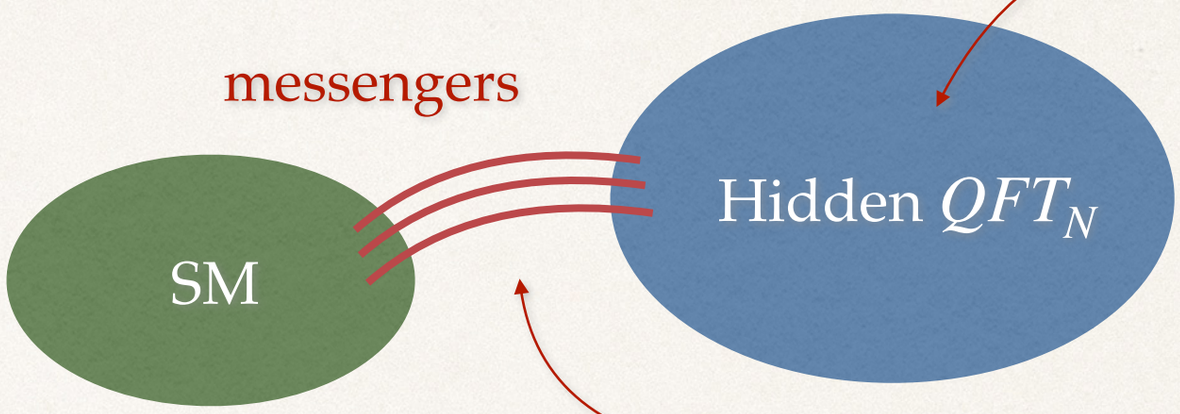
Composite Neutrinos

Neutrinos

- RH-neutrinos can also emerge in this framework.

$\psi \longrightarrow N_R \sim \psi^N$

baryonic type



$\psi,\ \phi \longrightarrow N_R \sim \underbrace{\psi\phi}_{\text{neutral}}$ mesonic type

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

    Arkani-Hamed Grossman Robinson, Okui, ...
  - bound state (mesonic) of messengers.

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

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

SM neutrino

sterile neutrino

messenger scale

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.

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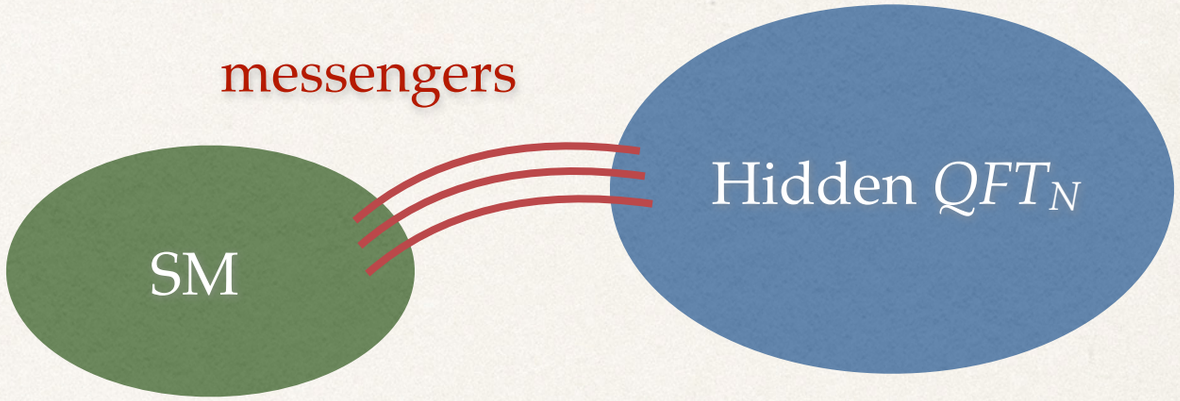
- Study cases where type II/III (inverse/radiative) seesaw mechanisms can apply.
- Phenomenological implications (leptonic mixing matrix, leptogenesis).
- Additionally, we can span over semi realistic D-brane configurations for patters that fall in one of the heavy/light categories.



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 $\Longrightarrow$ 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.