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Emergent fields from Hidden sectors

Pascal Anastasopoulos

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Y. Mambrini, E. Niederweiser, S. Oribe

Susy 2022, Ioannina - 27/06/2022

Motivation

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

- In the IR, we keep terms like

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

low-dimensional operators of SM fields

couplings

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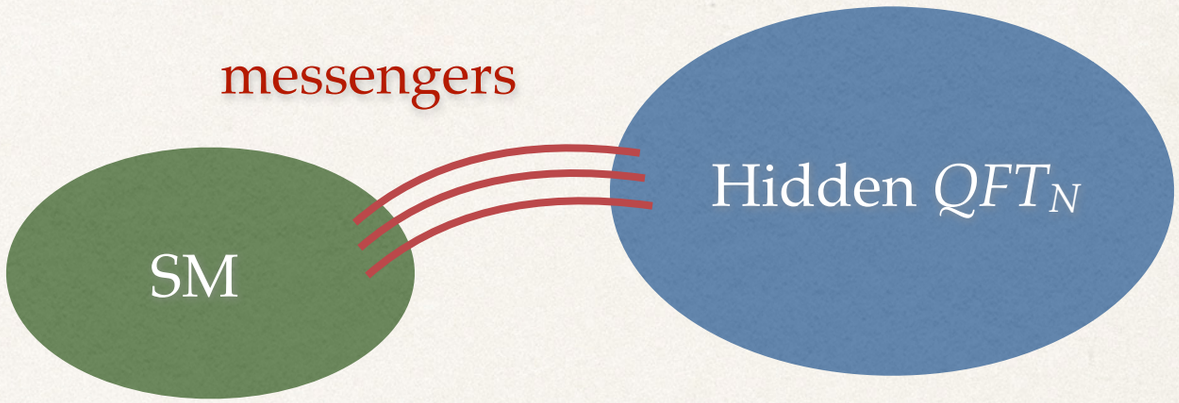
couplings

- 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.



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.

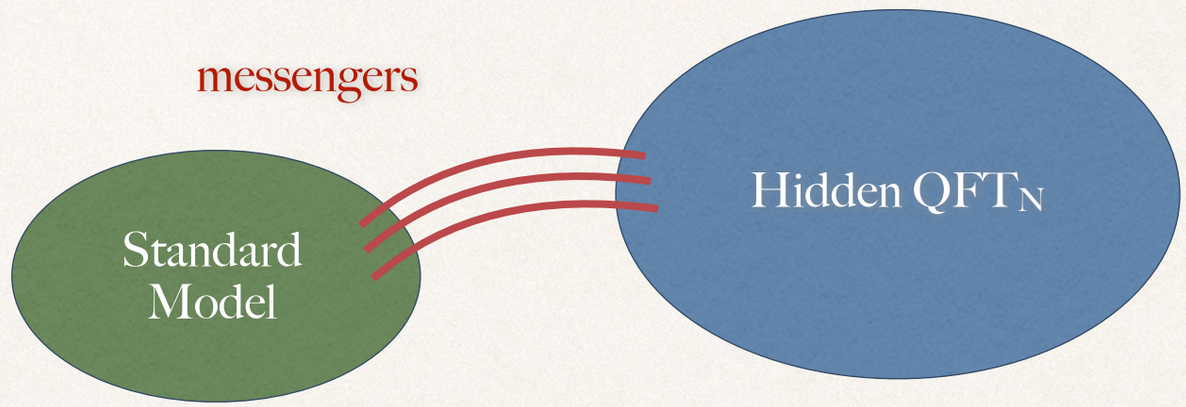
The Framework

- 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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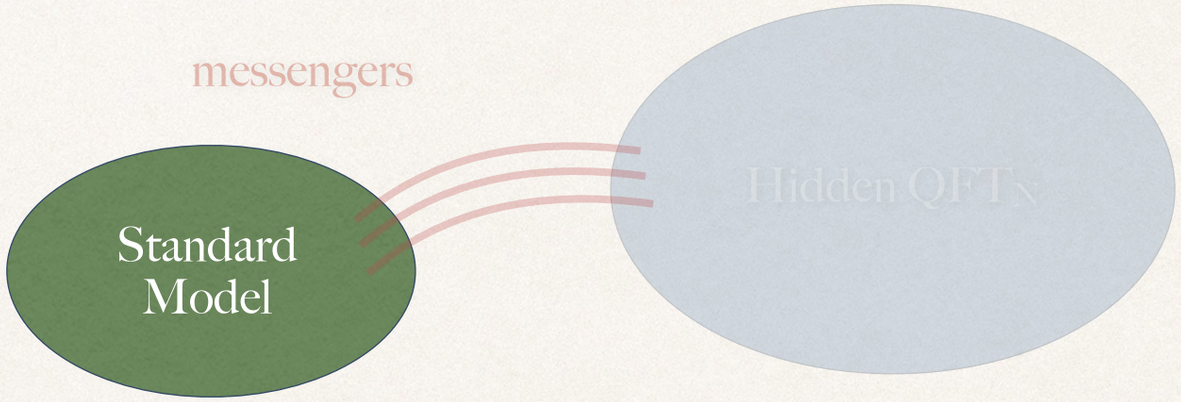

- The Standard Model (SM):
  - Contains all standard fields (quarks, leptons, gauge fields, Higgs).
  - We assume that all SM fields are described as bifundamentals.
  - That enlarges the gauge group to contain additional (anomalous) U(1)s.

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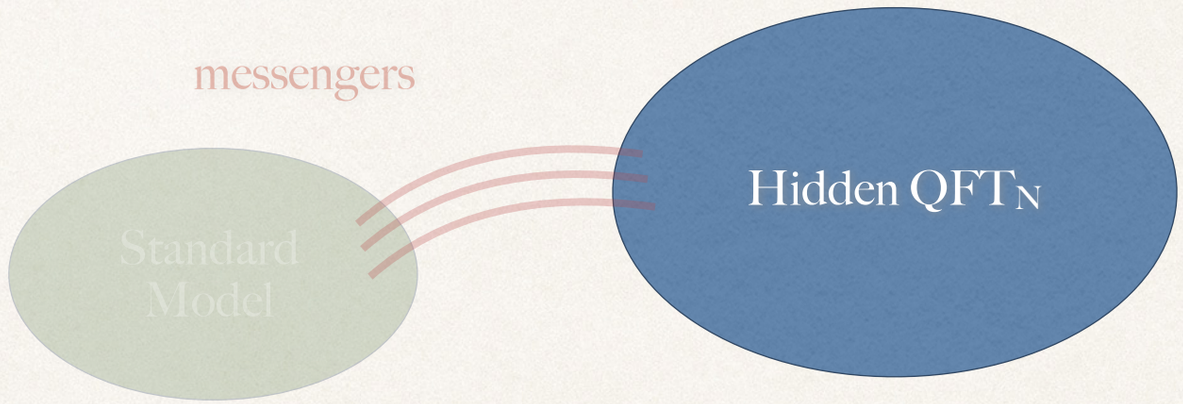

- The Hidden Sector (assume an SU(N) with N - Large):
  - It is UV-complete: can either be asymptotically free or conformal.
  - At low energies the hidden sector contains the simplest QFT: $\hat{A}^\mu, \hat{\phi}, \hat{\psi}$.

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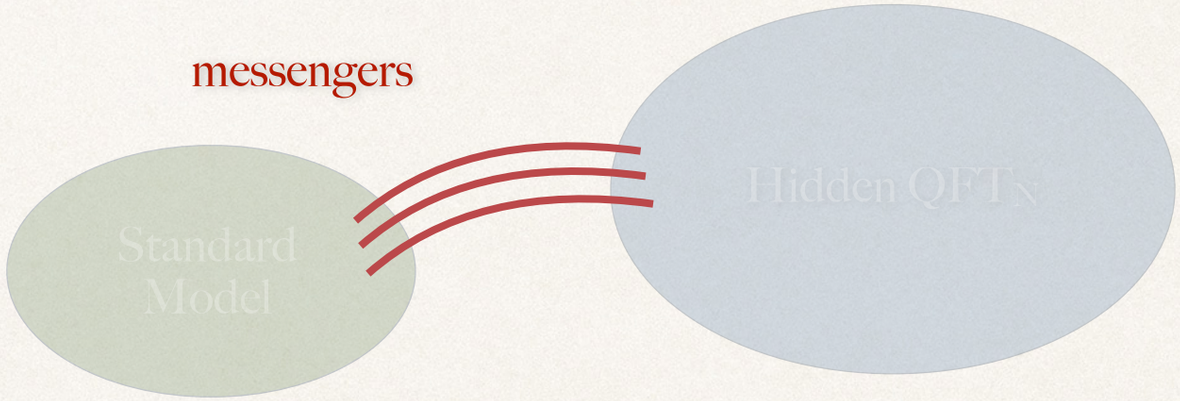

- Messenger sector
  - Charged particles under both sectors (SM and the HS).
  - They are massive, and $M_{messengers}$ is the highest scale of the whole framework.

The Framework

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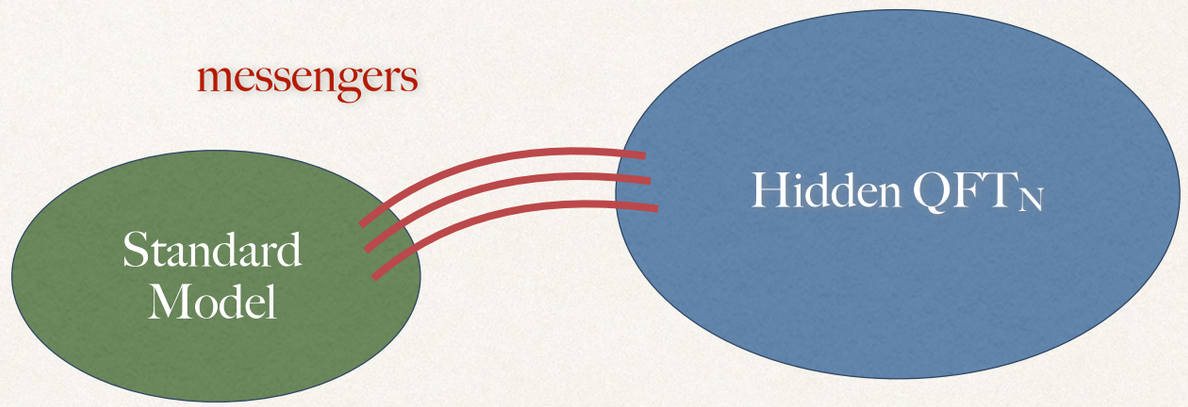

- This framework has many common features with D-brane models.

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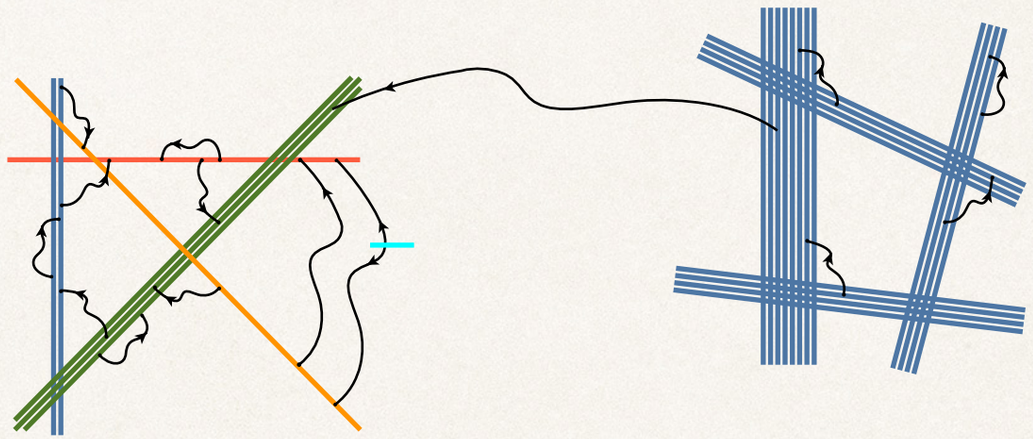
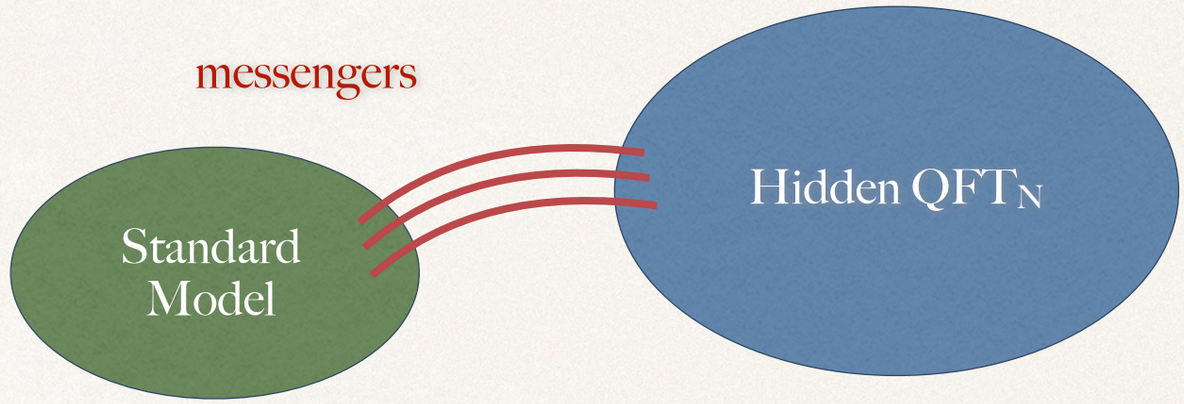


- This framework has many common features with D-brane models.

- We will focus on QFT's that we often meet in D-brane models (without being one of them).

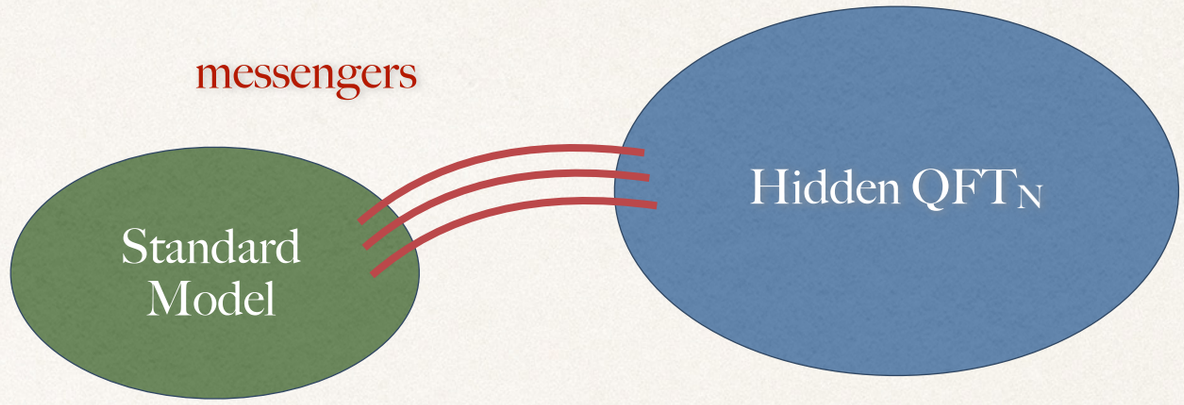
Our framework in different scales

UV picture



Our framework in different scales

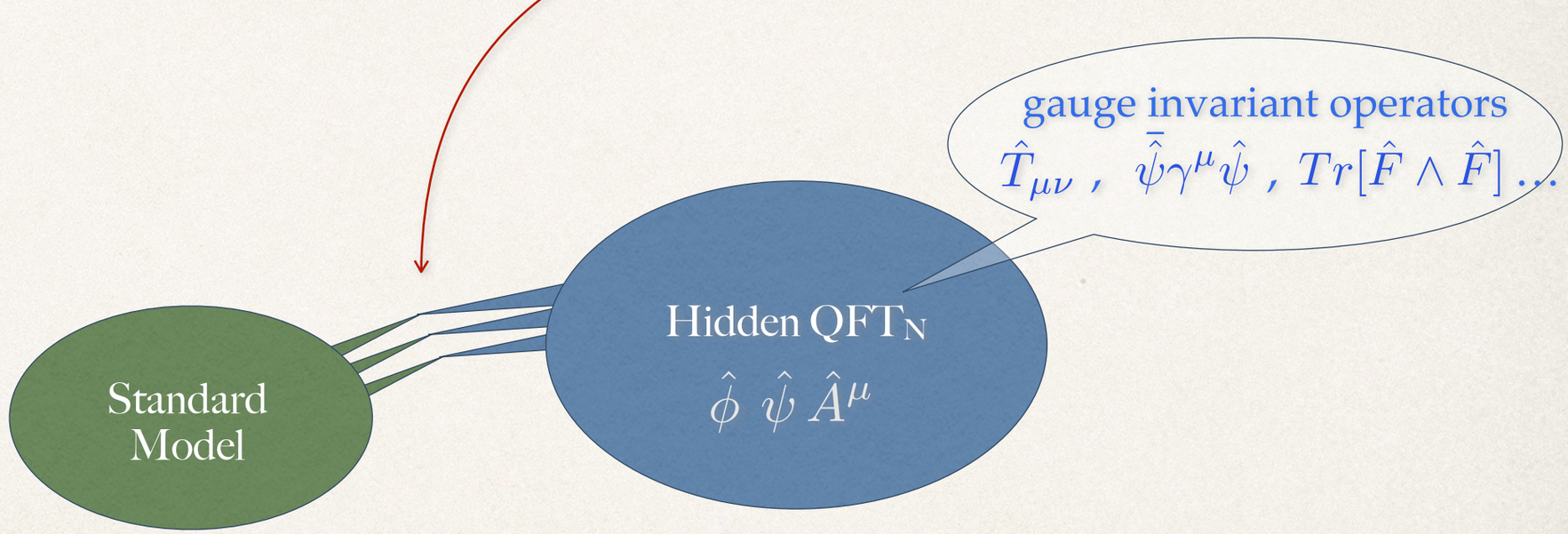
UV picture



mass of messengers

(gauge invariant) operators of the two sectors (weakly) mix

IR picture



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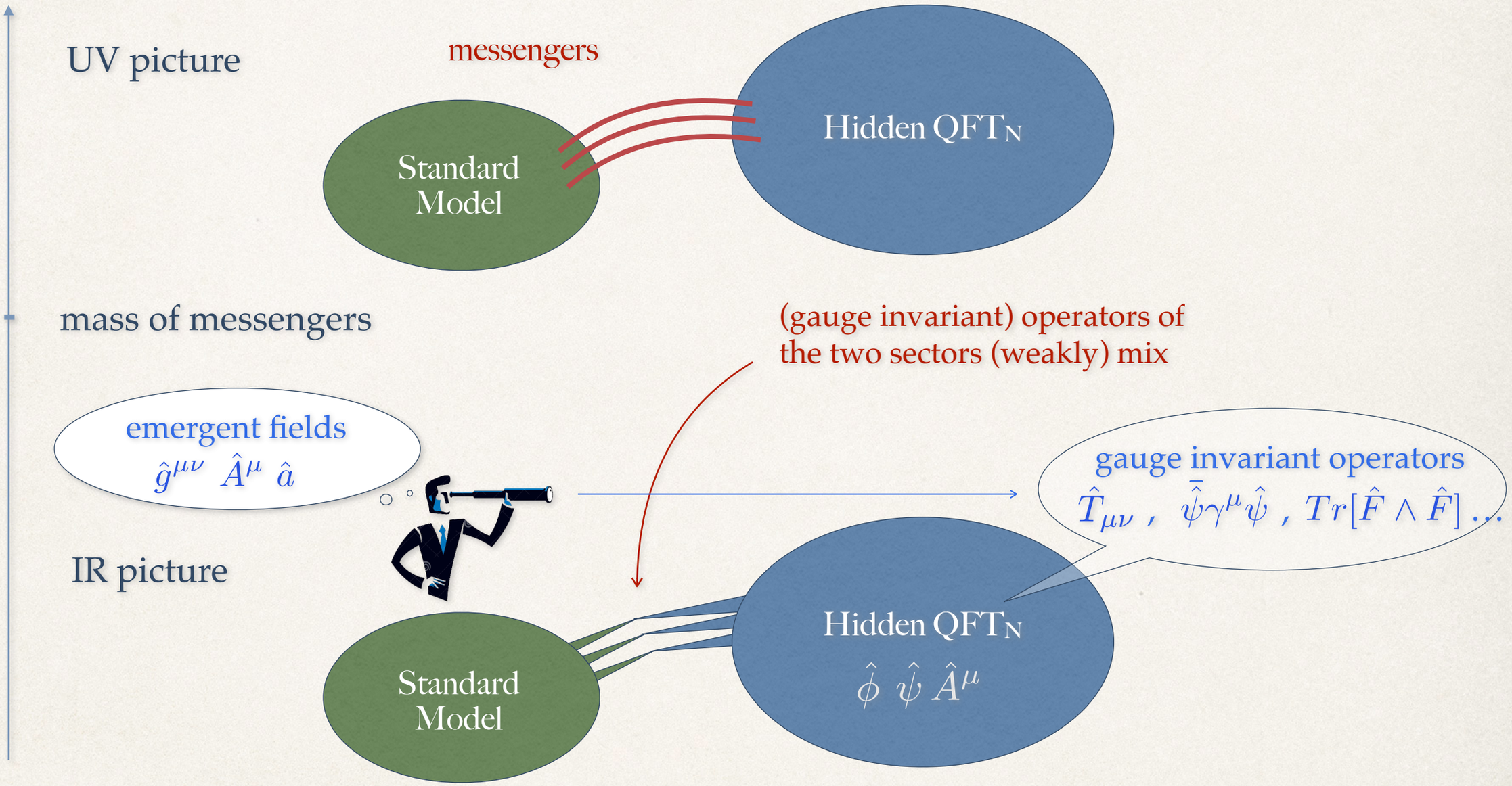

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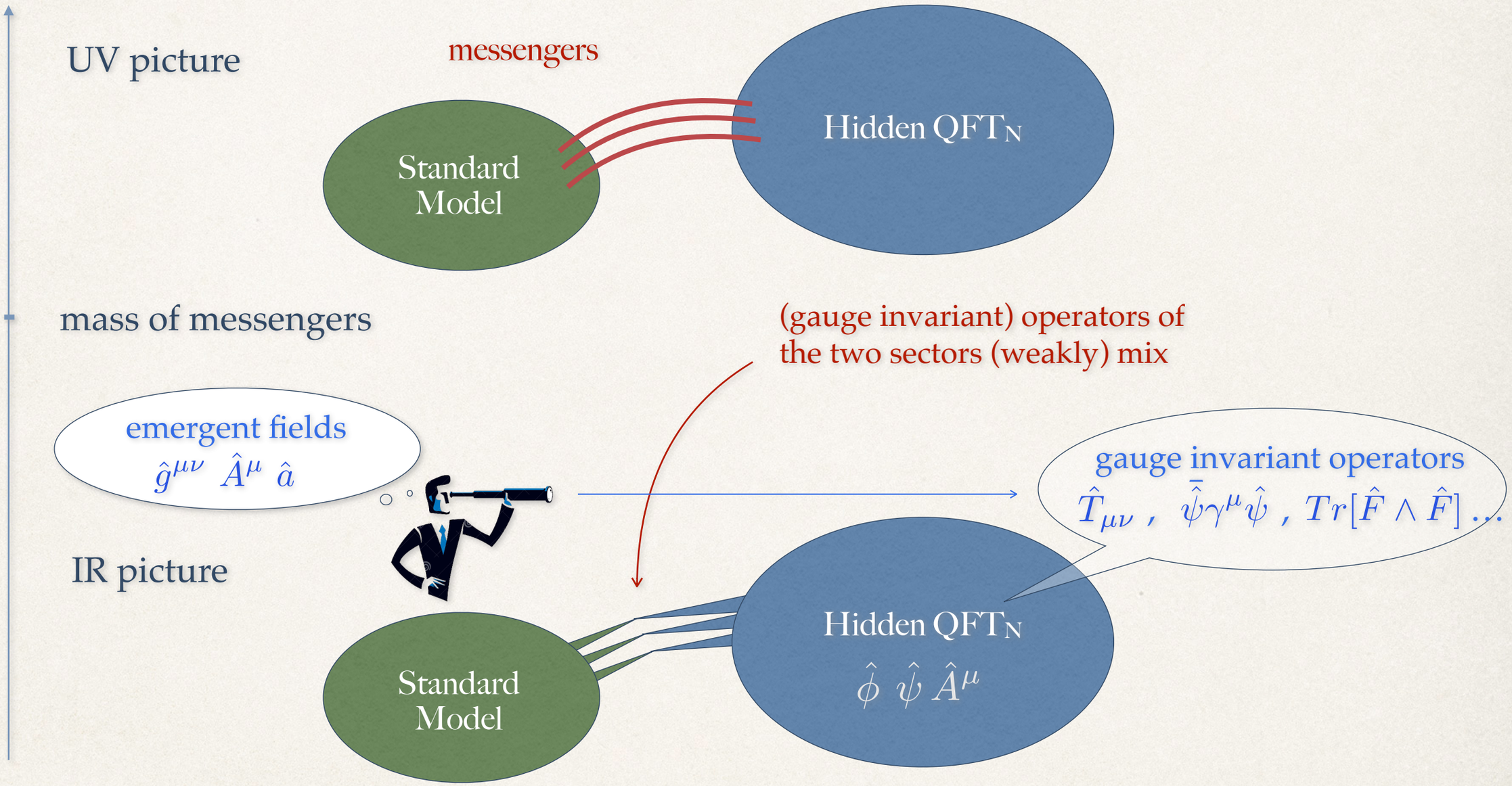
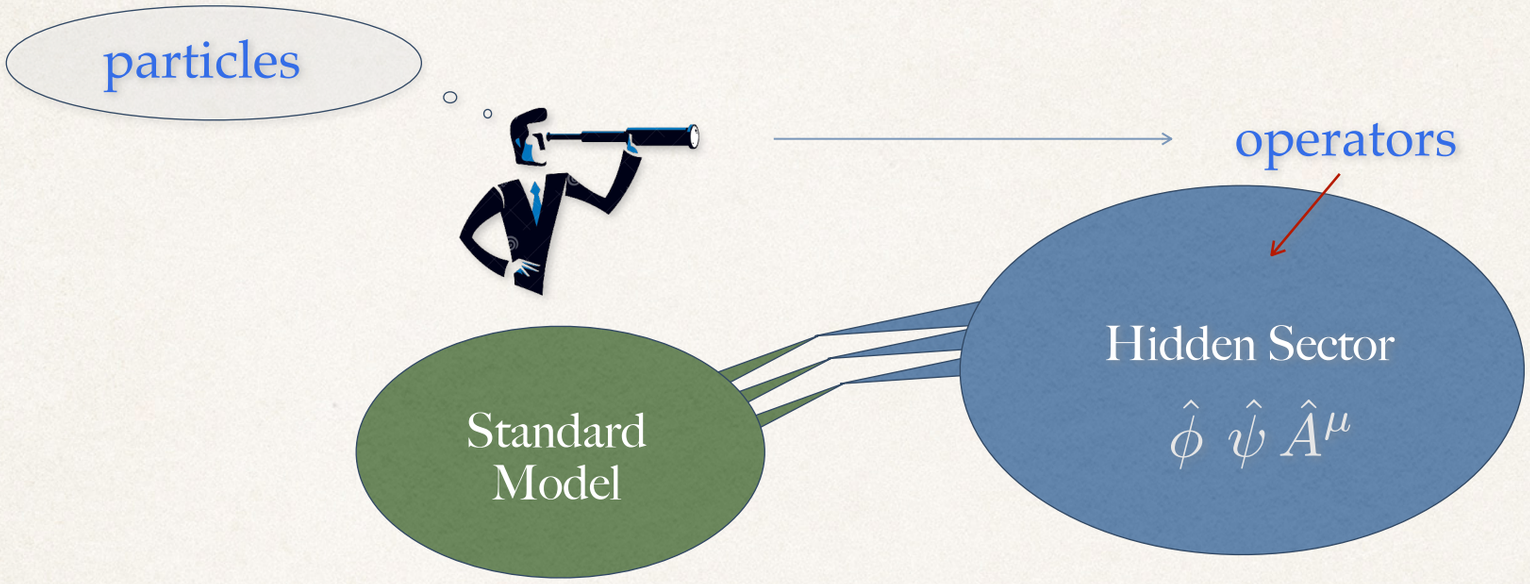


Operators of the HS, protected by symmetries ⟶ light (emergent) particles

Light emergent fields



- Operators/particles protected by symmetries remain light.

HS point of view		HS 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
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.

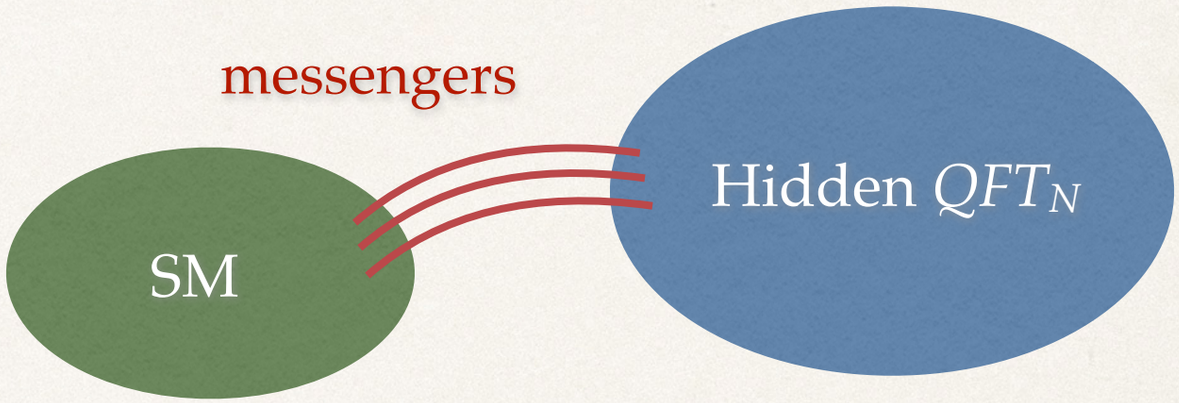
- Our goal is:

  - To build the effective action for these emergent fields.

  - To investigate the phenomenological implications.

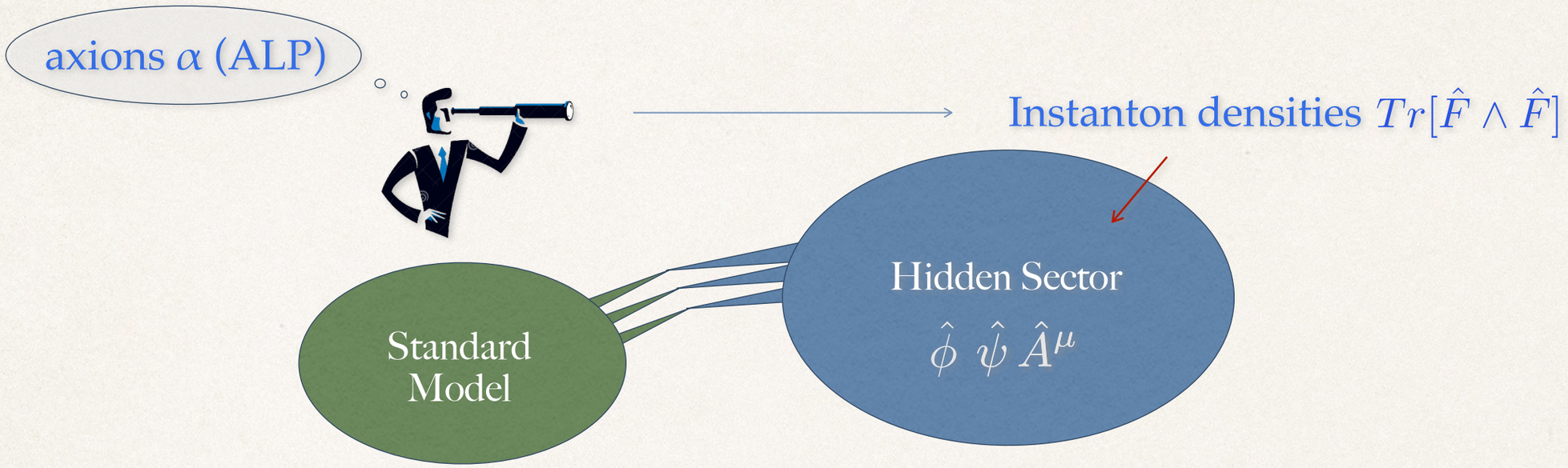
- In various cases, we assume a holographic hidden sector.

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



Emergent Axions

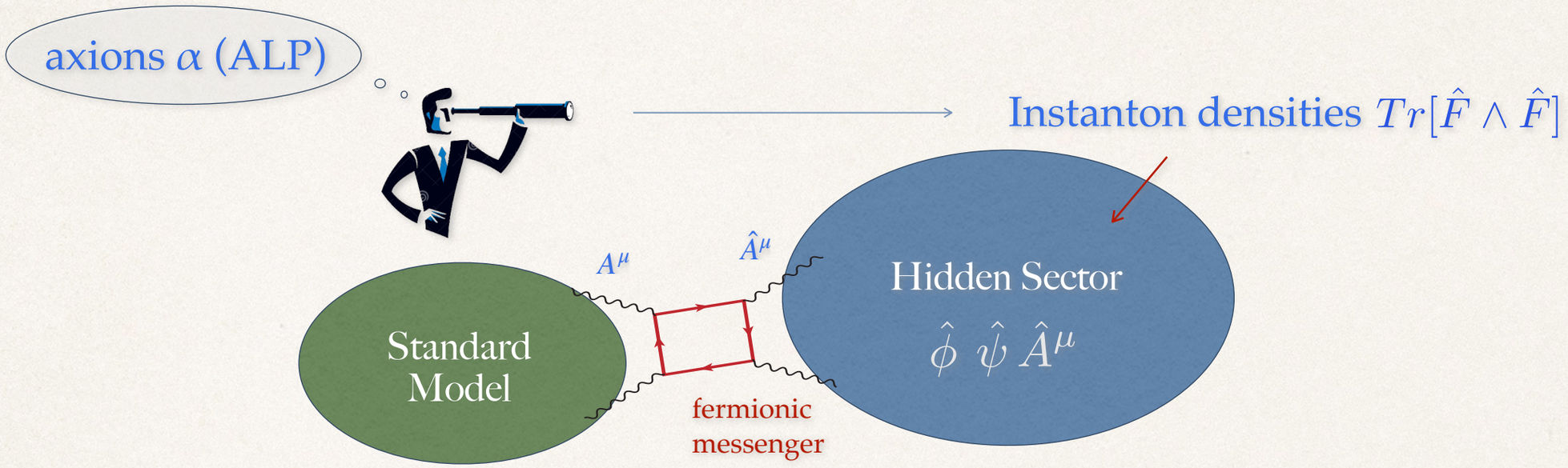
Emergent Axions - future plans



(pseudo-) scalar operator

protected by symmetries (remains light)

Emergent Axions - future plans



(pseudo-) scalar operator

~ Euler-Heisenberg

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

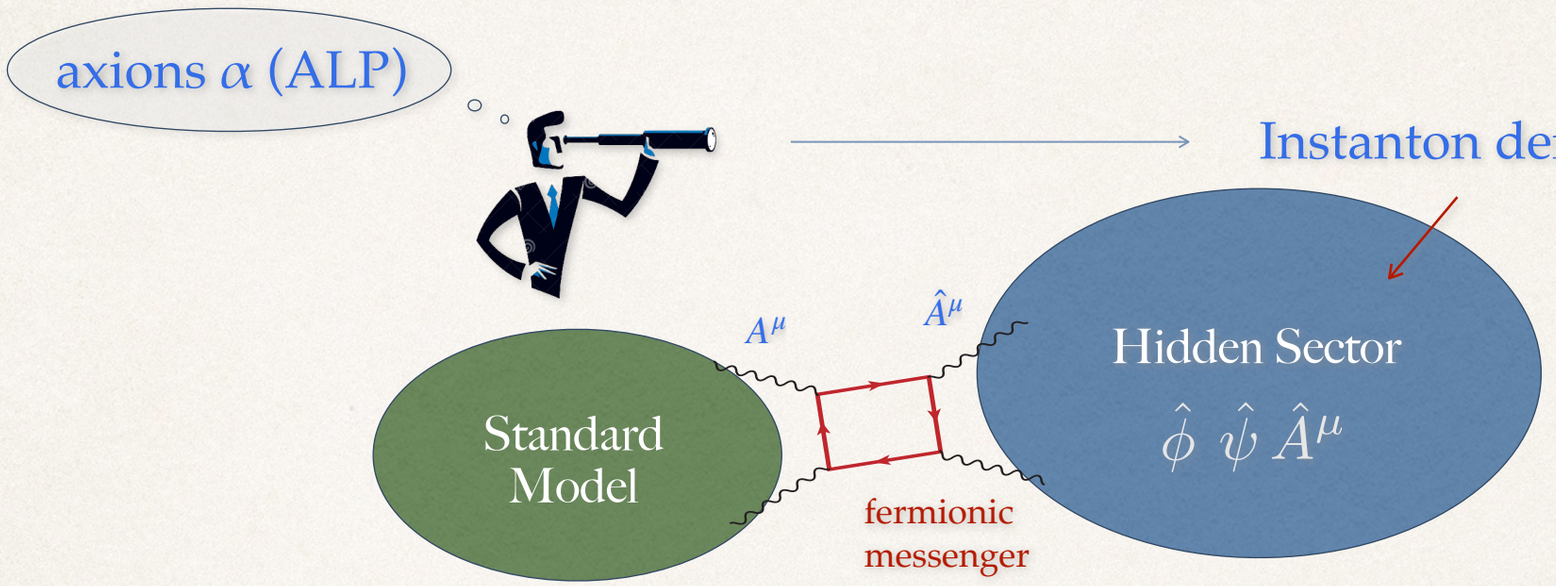
$$a\, Tr[F \wedge F]$$

protected by symmetries (remains light)

couples linearly to SM's instanton densities

associated U(1) symmetry (broken by instantons)

Emergent Axions - future plans



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$a\, Tr[F \wedge F]$

protected by symmetries (remains light)

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- Axions from instanton densities is a new idea/approach.

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- Composite axions have been considered in the past, being of the mesonic type η'.

- We aim to study their phenomenological implications (in progress).

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)

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  - 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 (ex: boson stars).

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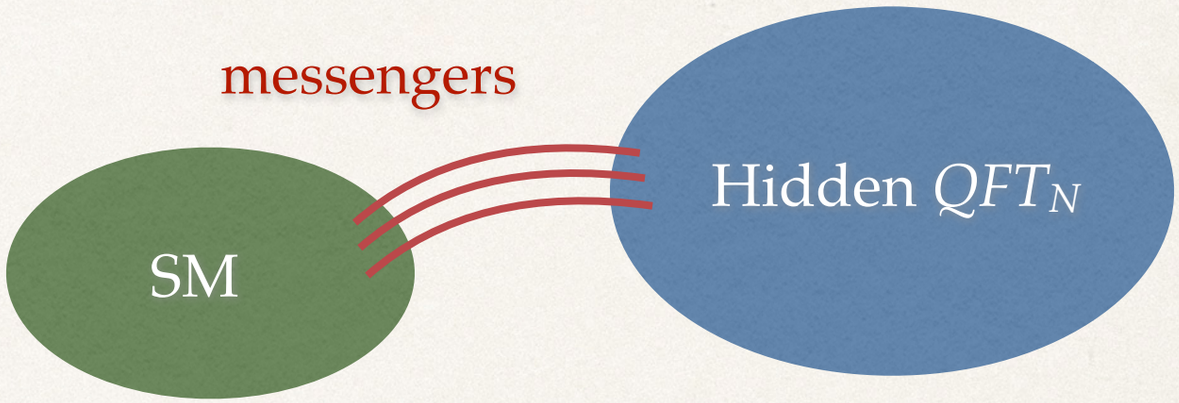
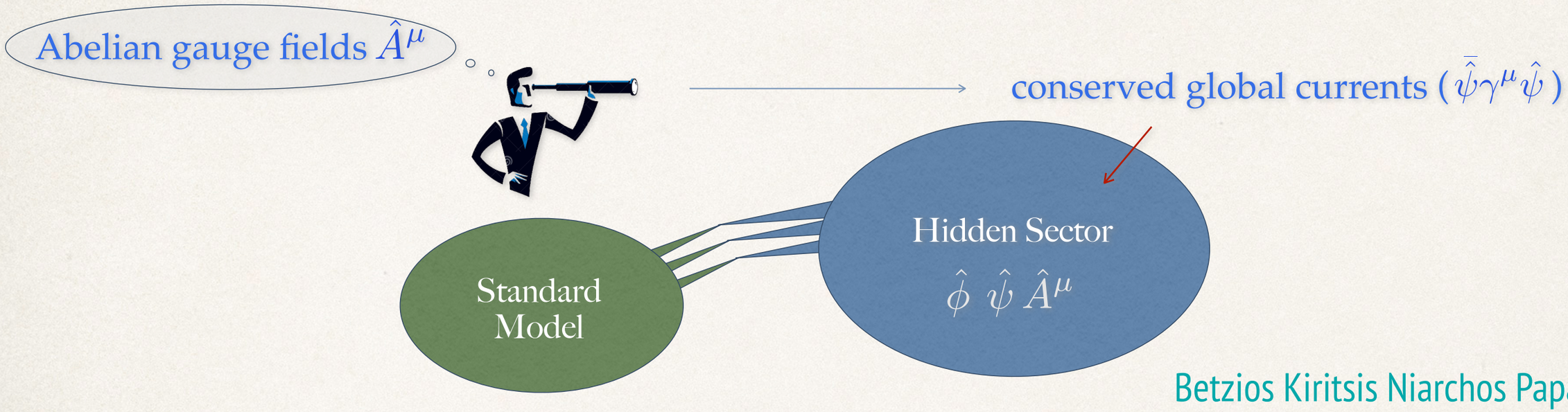


Graviphotons/Dark-photons

Gravi/Dark-photons - future plans

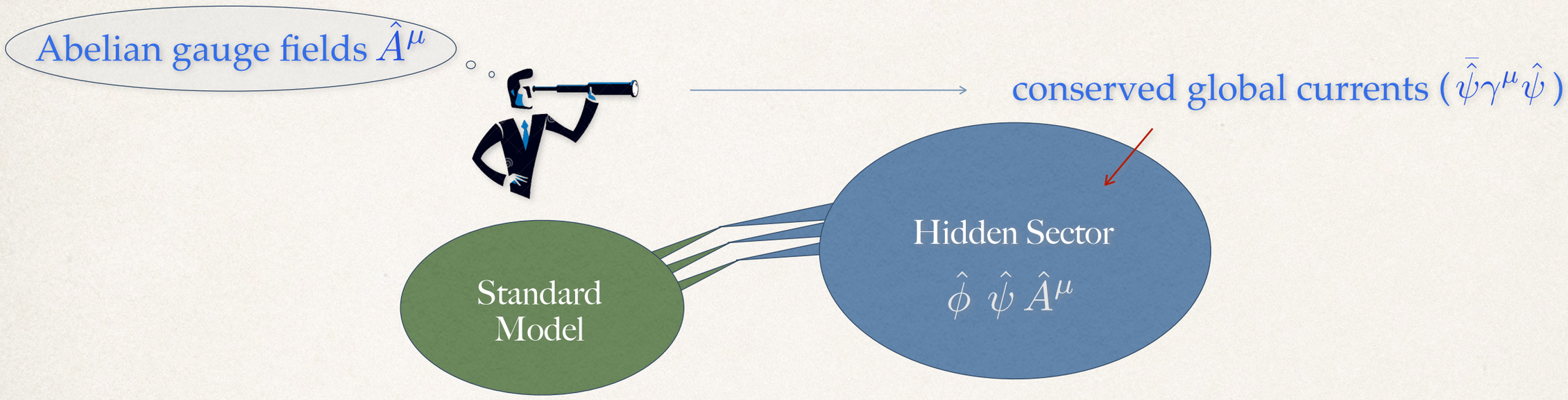


Betzios Kiritsis Niarchos Papadoulaki

Anastasopoulos Betzios Bianchi Consoli Kiritsis

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

Gravi/Dark-photons - future plans



- 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.

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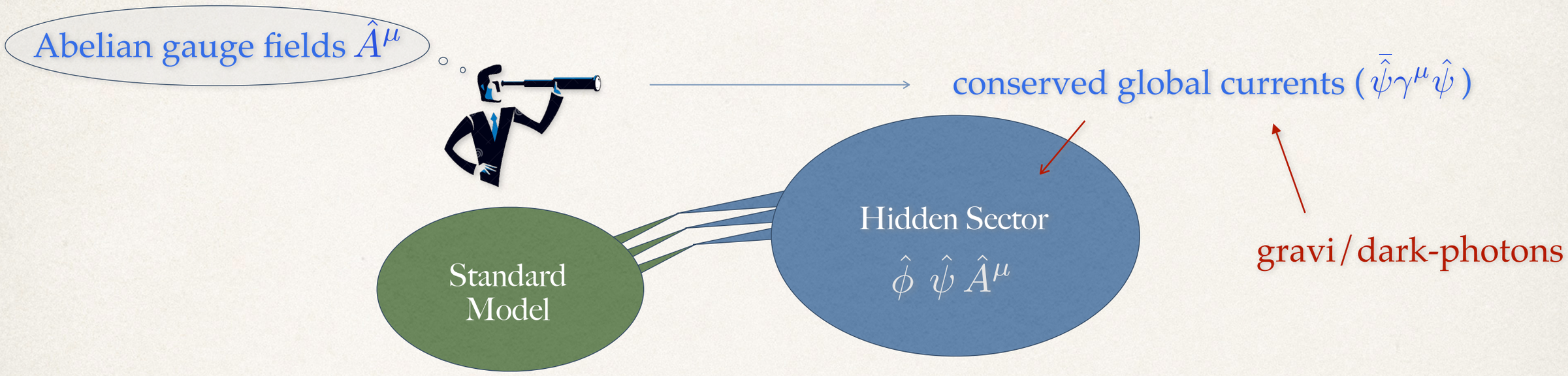
Gravi/Dark-photons - future plans



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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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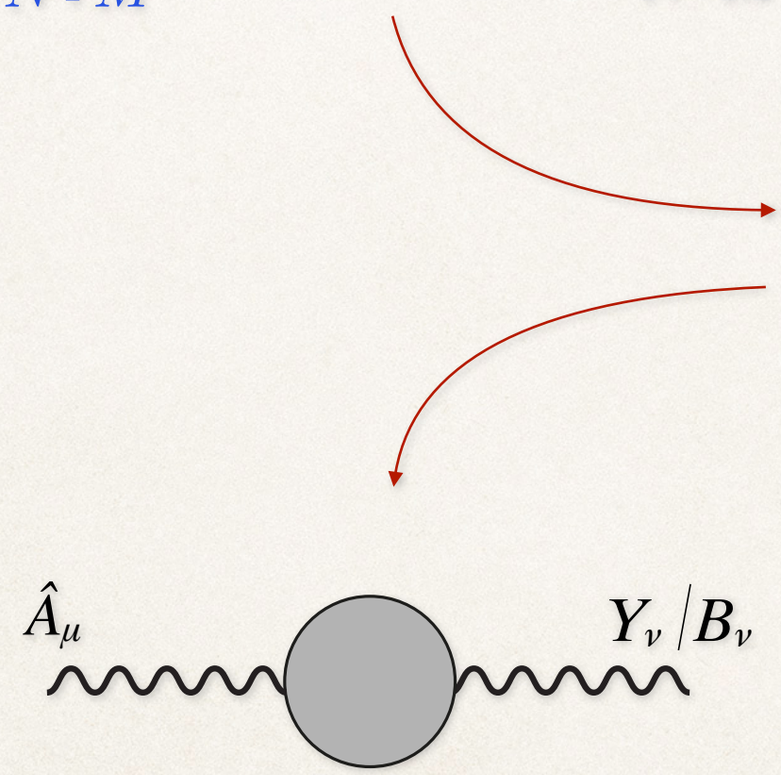
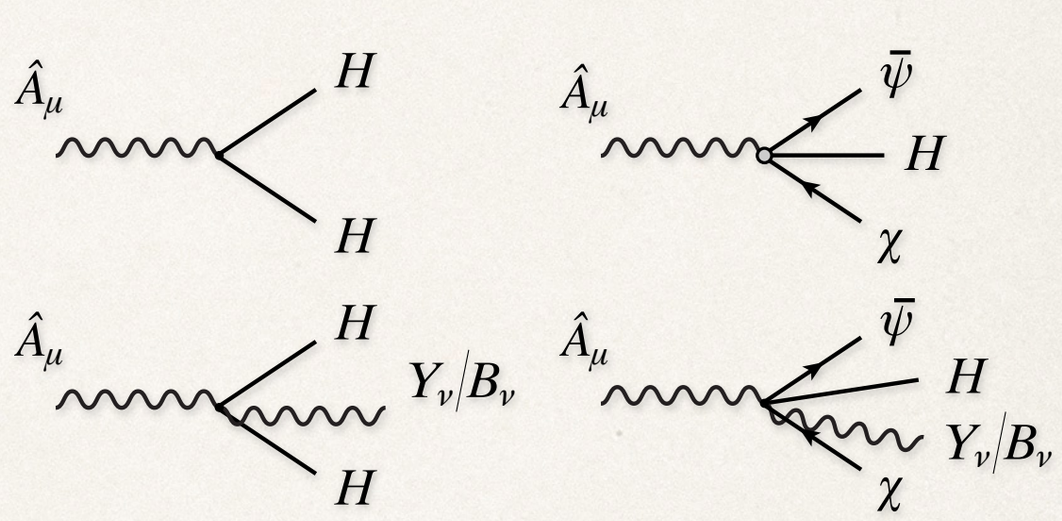
Mixings

- 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).

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





Y^μ hypercharge

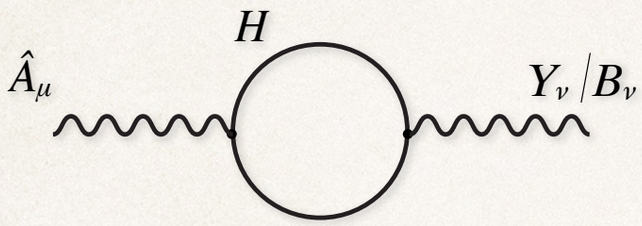
B^μ anomalous U(1)

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

Unbroken phase

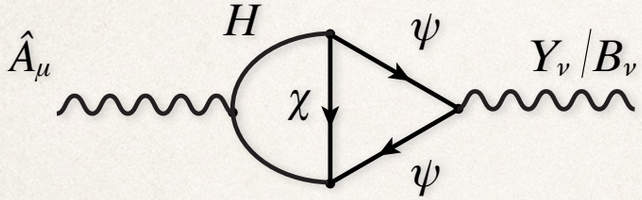
$$W_6 \sim \frac{1}{NM^2} Tr[D_\mu H D_\nu H^\dagger] F^{\mu\nu}_{\hat{A}} + \frac{1}{N^{\frac{3}{2}} M^2} F^{\mu\nu}_{\hat{A}} [\bar{\psi} \gamma_{\mu\nu} H \psi + c.c.]$$
$$+ \frac{1}{N^{\frac{3}{2}} M^2} F^{\hat{A}}_{\mu\nu} F^{Y,\mu\nu} H H^\dagger + \frac{1}{N^2 M^4} F^{\hat{A}}_{\mu\nu} F^{Y,\mu\nu}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

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

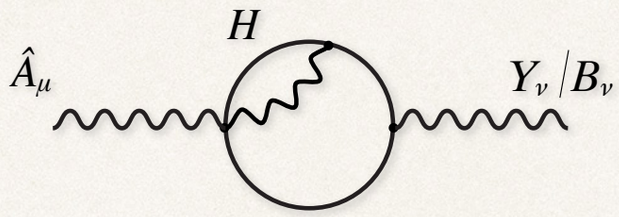


$$\sim \frac{\Omega_3}{8} \frac{Q_Y^H}{N} \frac{\Lambda^2}{M^2} \int d^4p \, F^{\hat{A}}_{\mu\nu}(p) F_Y^{\mu\nu}(-p) + \cdots$$

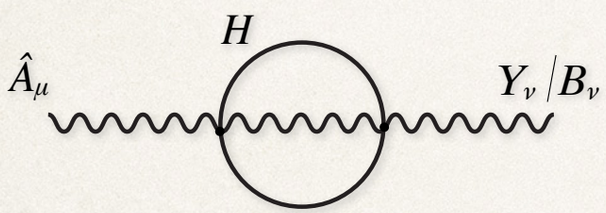
- At next order, we have 2-loop diagrams (where SM fermions can contribute)

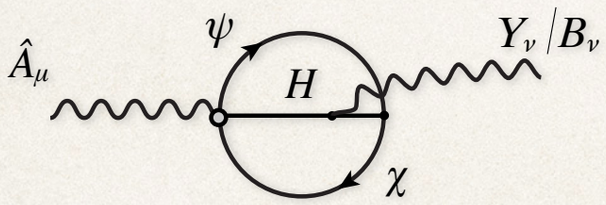


$$\sim Q_Y^\psi |g_{H\psi\chi}|^2 \frac{\Lambda^2}{NM^2}$$

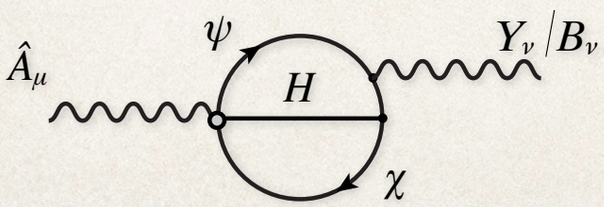


$$\sim \frac{(Q_Y^H)^2}{N}$$





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



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

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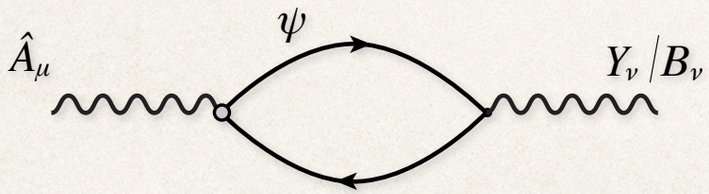
Broken phase

- The action in the broken phase becomes

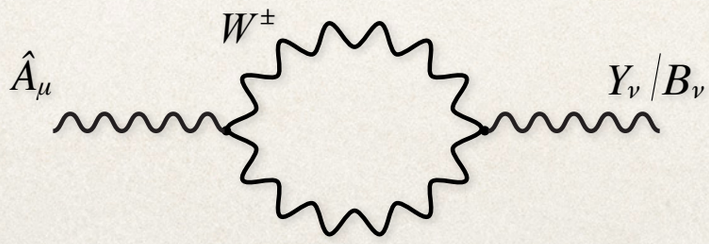
$$
\begin{aligned}
W_{BROKEN} \sim\ & \frac{4g_w^2}{NM^2}(h+v)^2\, F^{\hat{A}}_{\mu\nu} W^{\mu}_{+} W^{\nu}_{-} + \frac{4ie}{NM^2}\,(h+v) F^{\hat{A}}_{\mu\nu} A^{\mu}_{\gamma} \partial^{\nu} h \\
& + \frac{4e}{NM^2}\sqrt{g_w^2+g_Y^2}(h+v)^2 F^{\hat{A}}_{\mu\nu} A^{\mu}_{\gamma} Z^{\nu} + \frac{1}{N^{\frac{3}{2}}M^2}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

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

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



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



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

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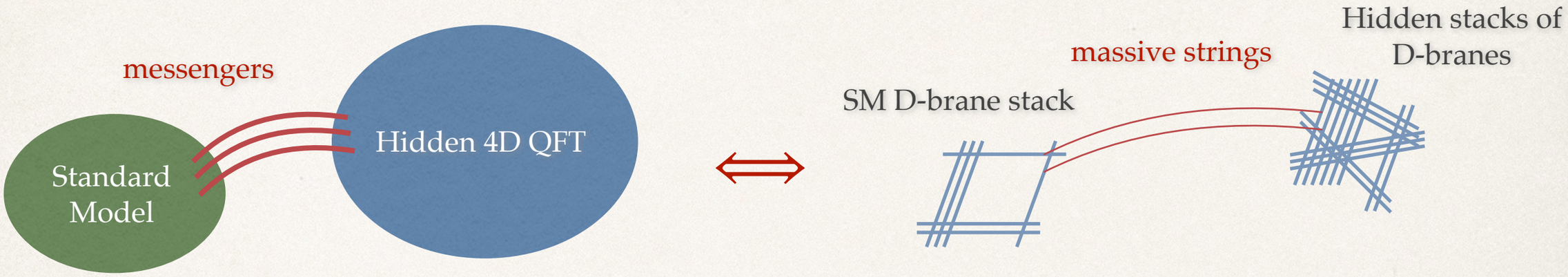
String theory vs QFT pictures

- 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.

- 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.

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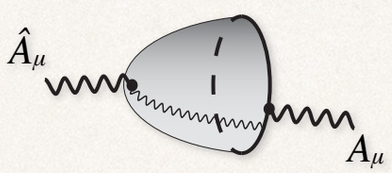
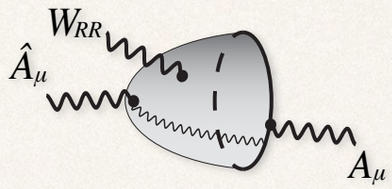
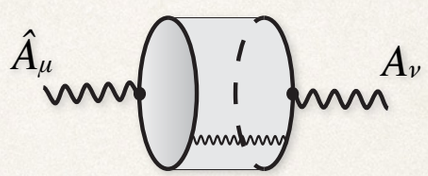
EFT couplings from ST amplitudes

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

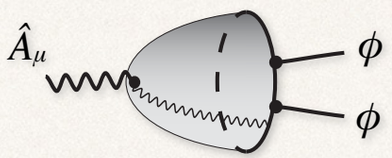
$$\frac{\Lambda^2}{NM^2} F^{\mu\nu}\hat{F}^{\mu\nu}$$

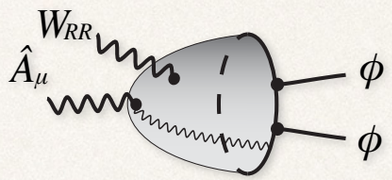


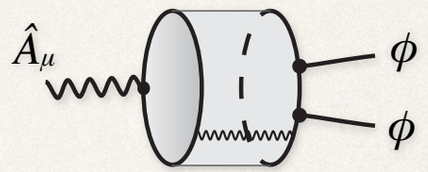




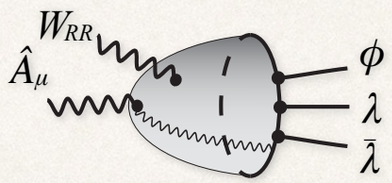
$$\frac{1}{NM^2} D_\mu H^\dagger D_\nu H \hat{F}^{\mu\nu}$$

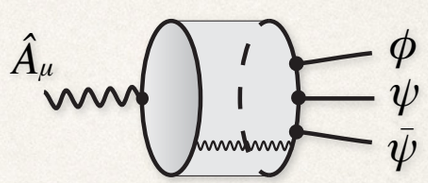






$$\frac{1}{N^{\frac{3}{2}}M^2} \bar{\psi}\gamma_{\mu\nu} H\psi \hat{F}^{\mu\nu}$$





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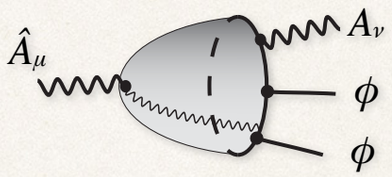

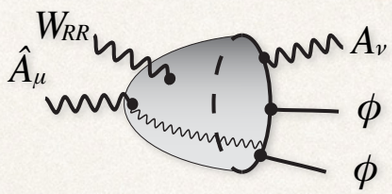

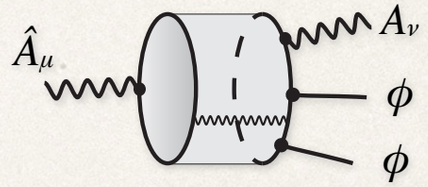

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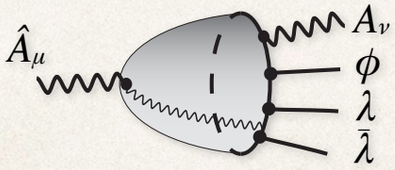

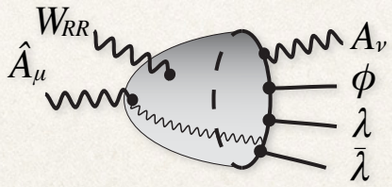

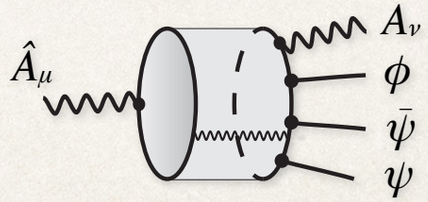

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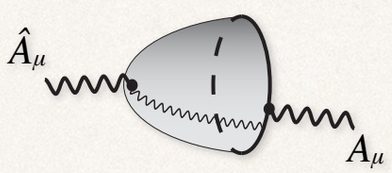
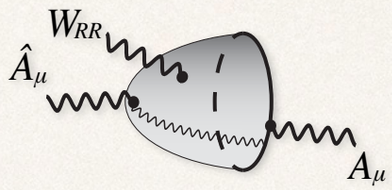
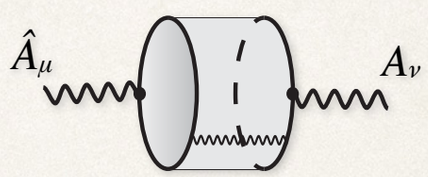
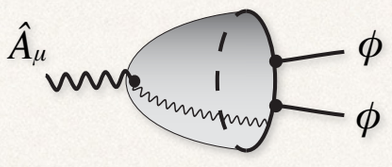
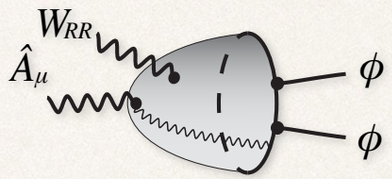


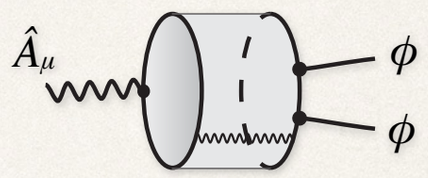




$$\frac{1}{NM^2} D_\mu H^\dagger D_\nu H \hat{F}^{\mu\nu}$$







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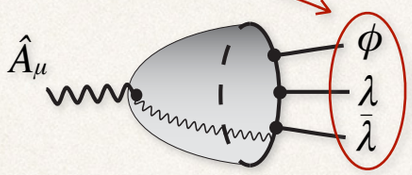

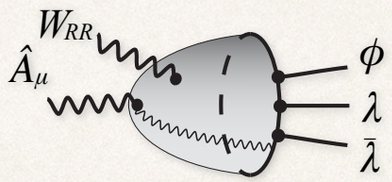

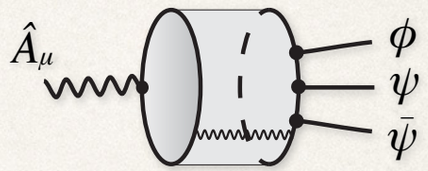

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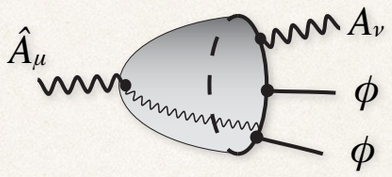

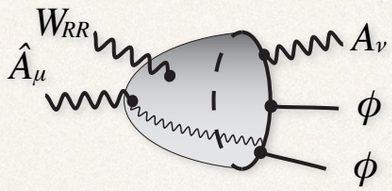

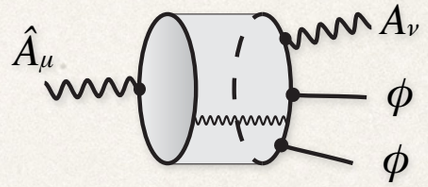

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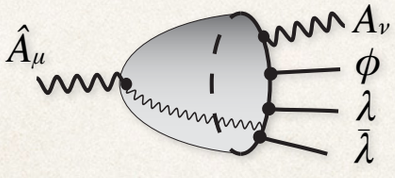

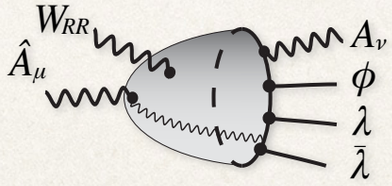

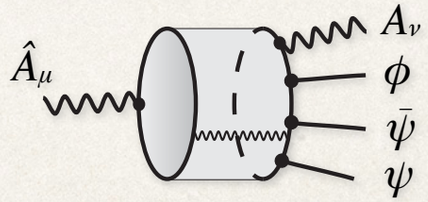

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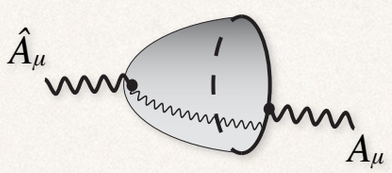

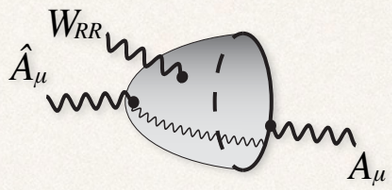

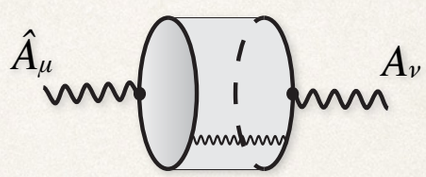

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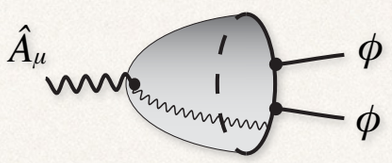

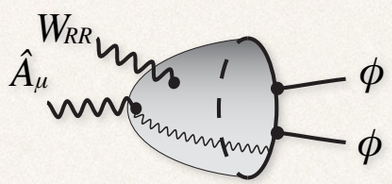

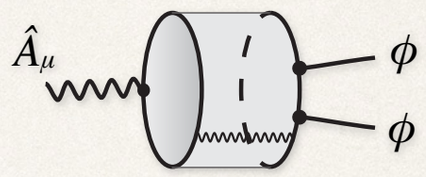

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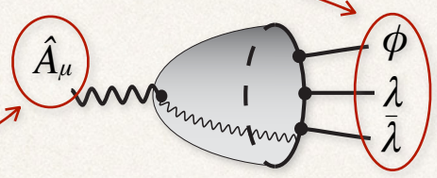

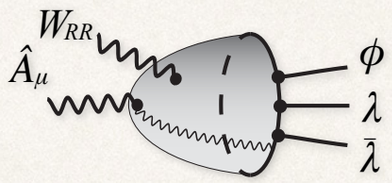

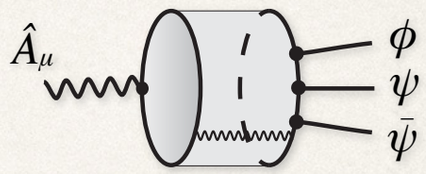

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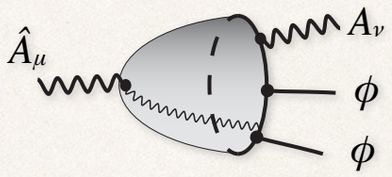

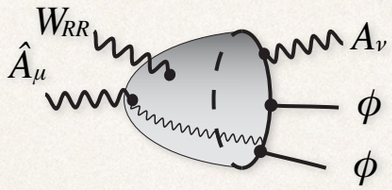

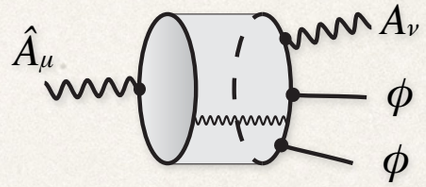

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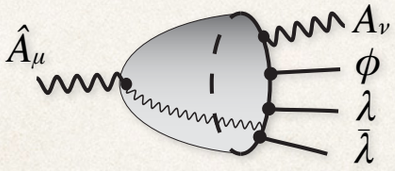

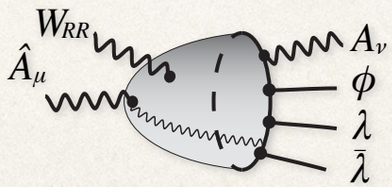

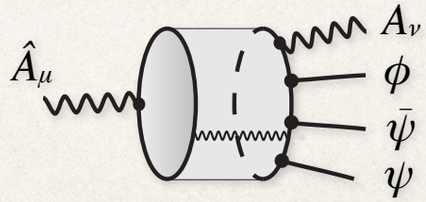

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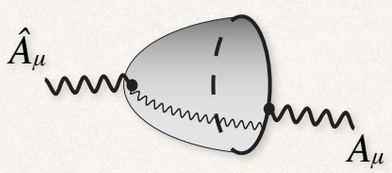

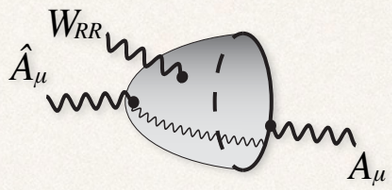

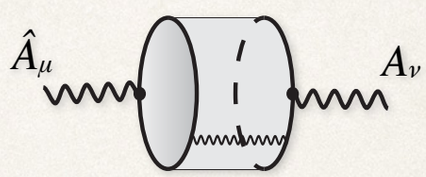

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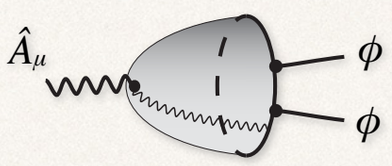

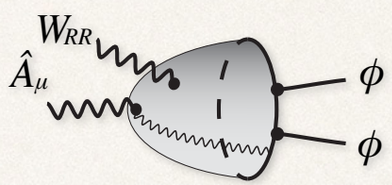

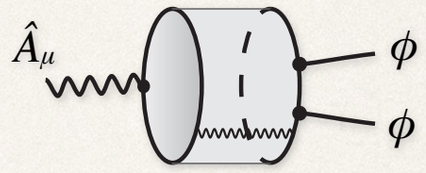

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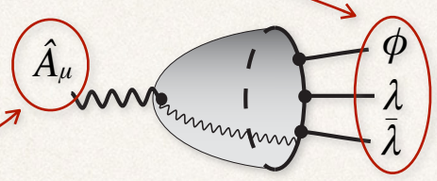

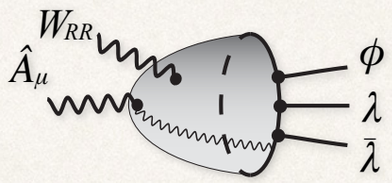

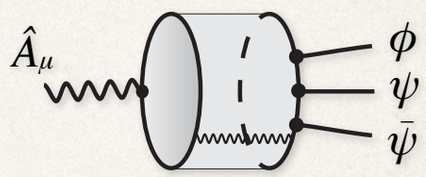

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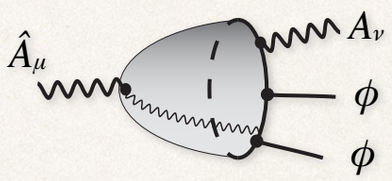
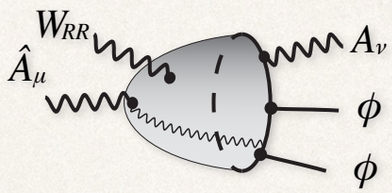
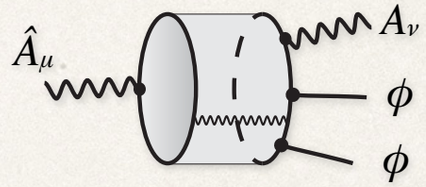
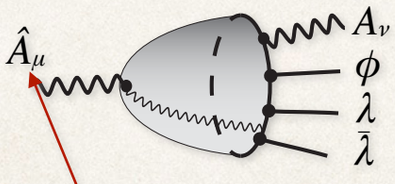
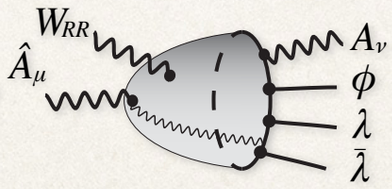


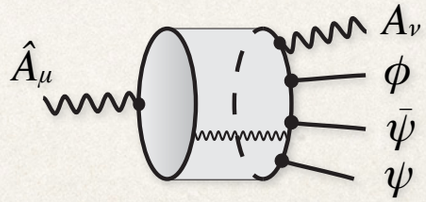




$$\frac{1}{N^2M^4} F^{\mu\nu}\hat{F}_{\mu\nu}\bar{\psi} H \psi$$







closed strings

PA Bianchi Consoli Kiritsis

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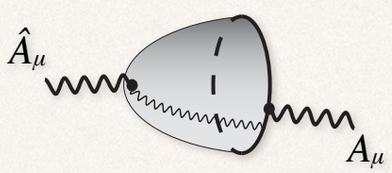
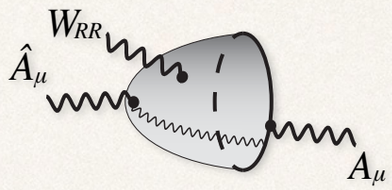
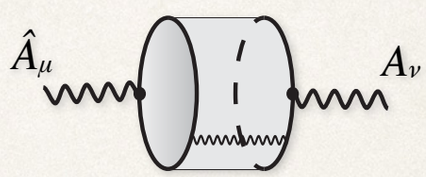
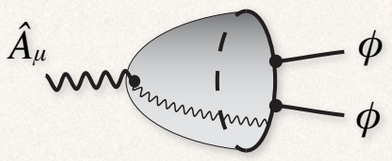
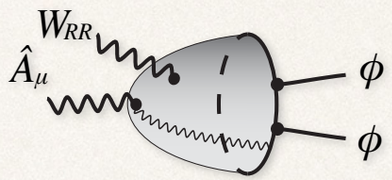


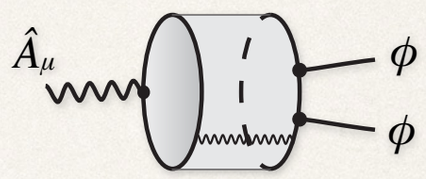




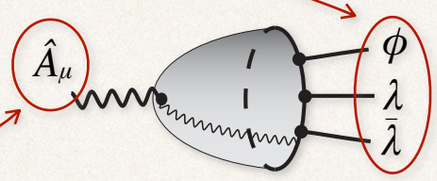
$$\frac{1}{NM^2} D_\mu H^\dagger D_\nu H \hat{F}^{\mu\nu}$$

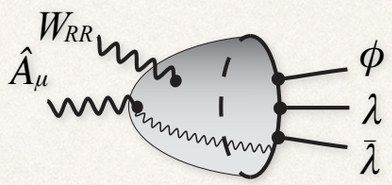


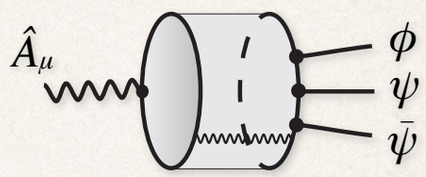




$$\frac{1}{N^{\frac{3}{2}}M^2} \bar{\psi}\gamma_{\mu\nu} H \psi \hat{F}^{\mu\nu}$$







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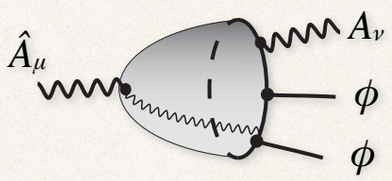

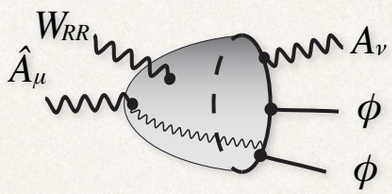

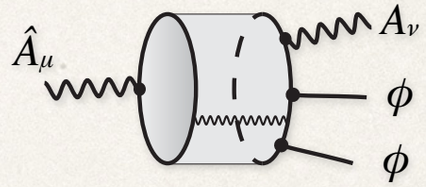

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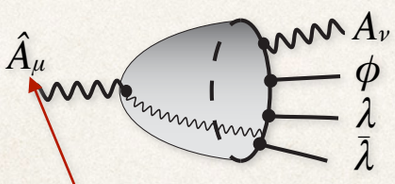

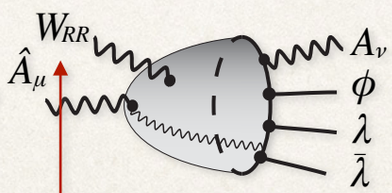

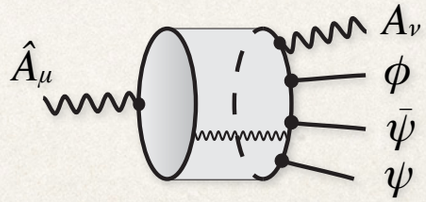

closed strings

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PA Bianchi Consoli Kiritsis

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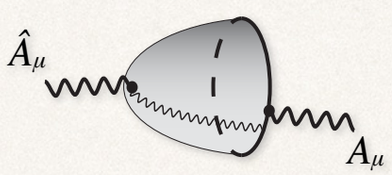

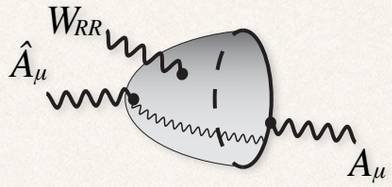

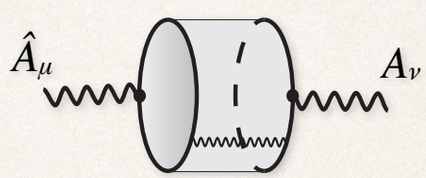

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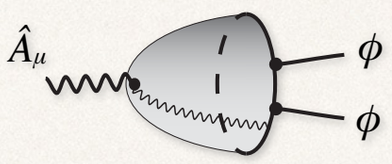

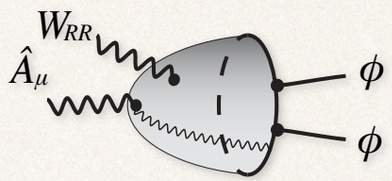

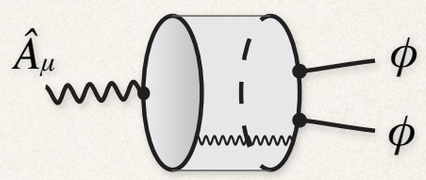

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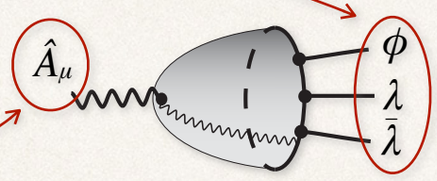

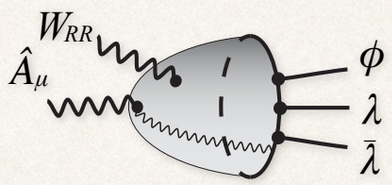

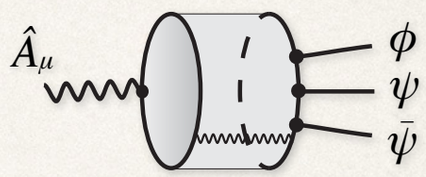

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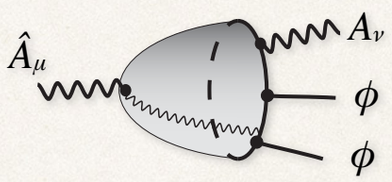

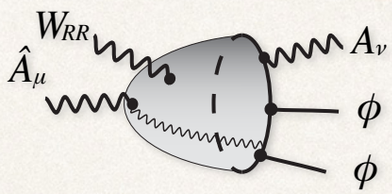

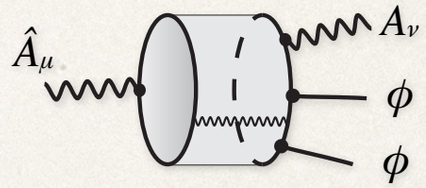

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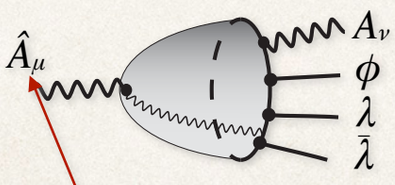

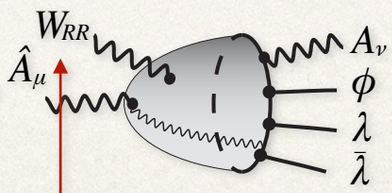

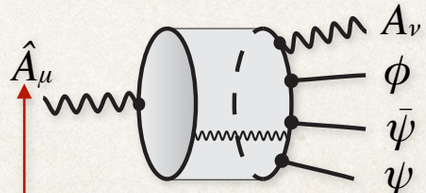

closed strings

RR/NSNS fluxes

open string

PA Bianchi Consoli Kiritsis

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

Anastasopoulos Bianchi Consoli Kiritsis

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agrement in circles

zero at leading order

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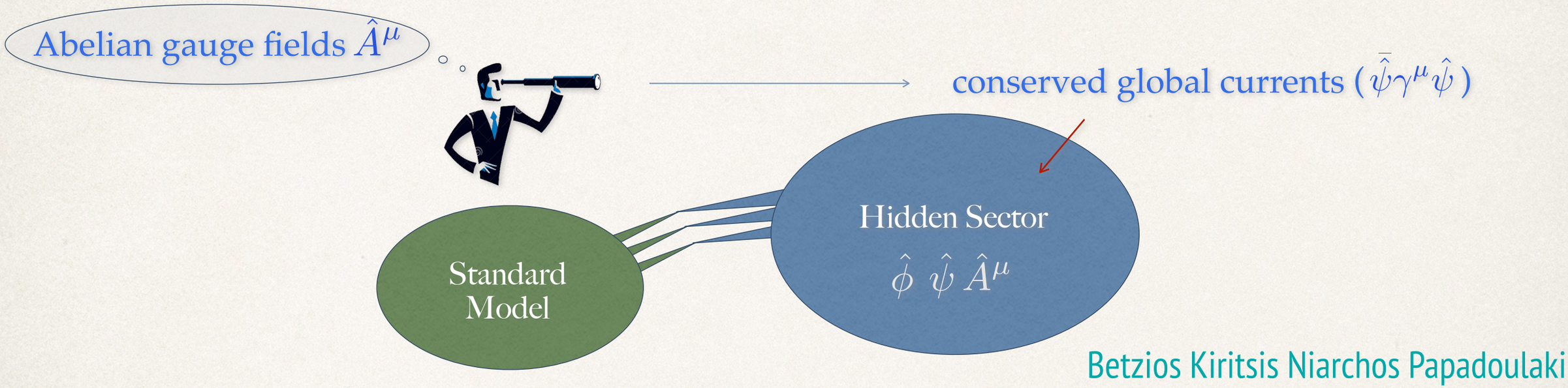
sub-leading

- 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).

Anastasopoulos Bianchi Consoli Kiritsis

Gravi/Dark-photons



Betzios Kiritsis Niarchos Papadoulaki

- No particle of the SM is directly charged under these U(1).
- They have very weak interactions. They have kinetic mixing with the hypercharge.

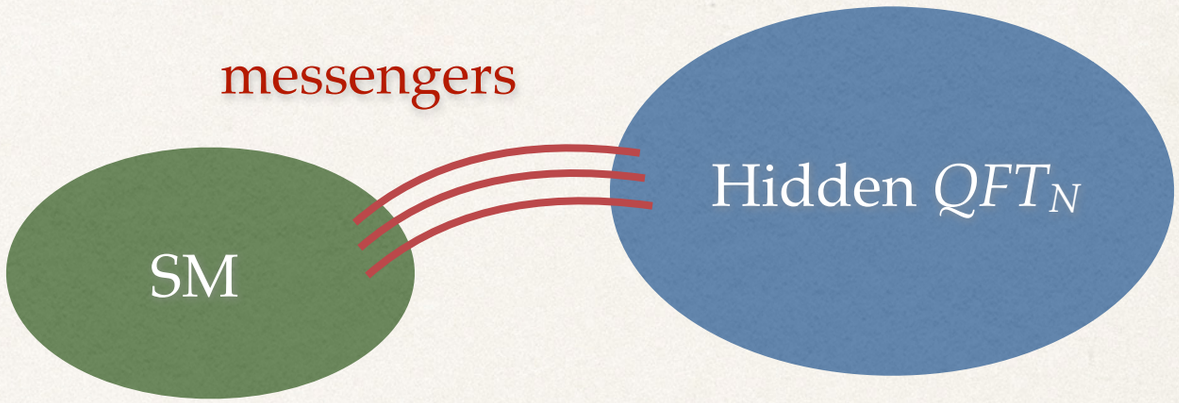
Anastasopoulos Betzios Bianchi Consoli Kiritsis

- 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

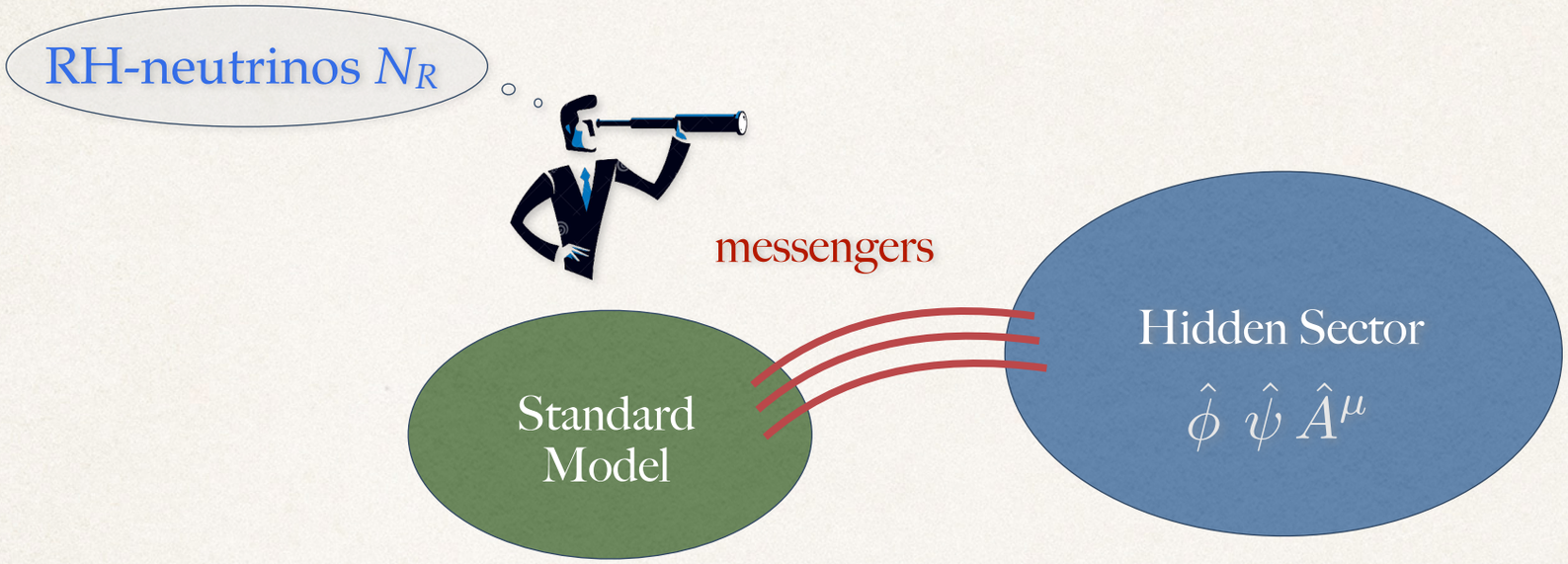
- Emergent U(1)'s option is not very much studied.

Bjorken



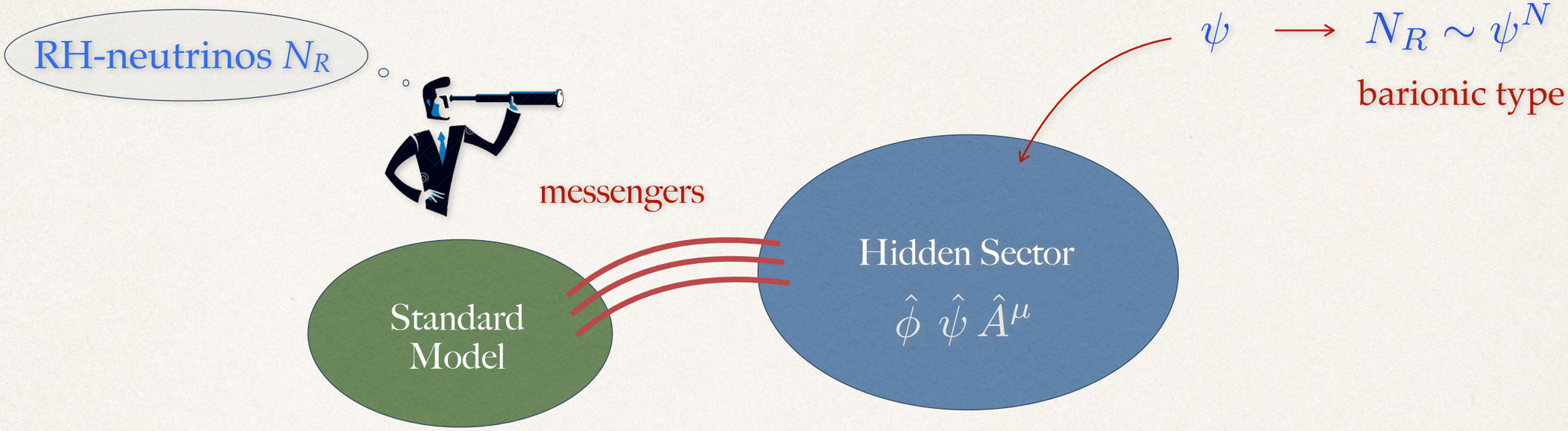
Composite Neutrinos

Emergent Neutrinos



- Two different ways

Emergent Neutrinos

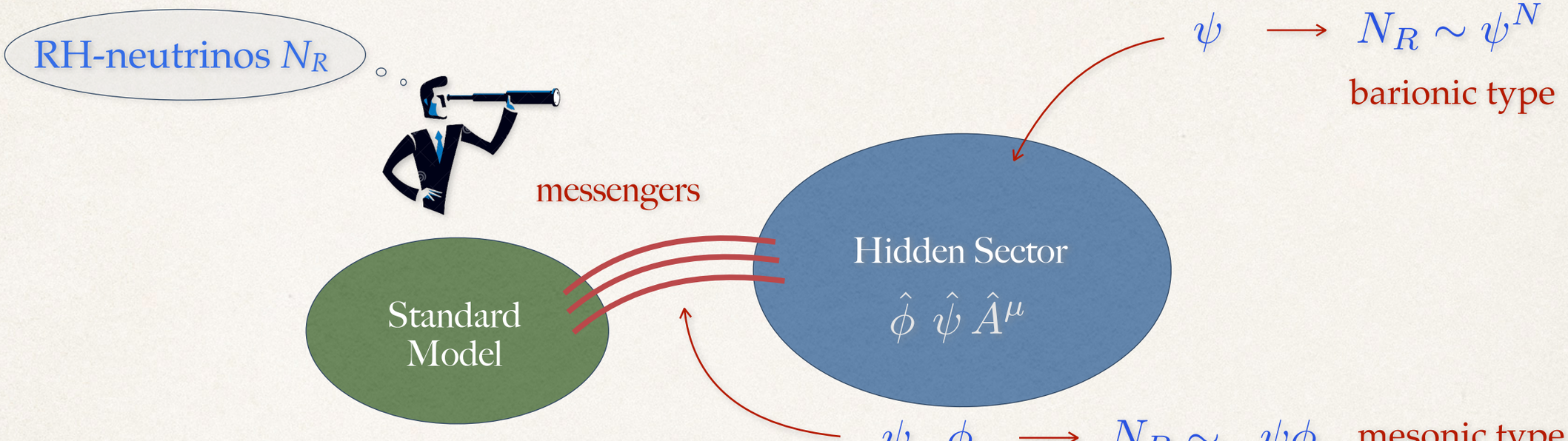


- Two different ways

  - baryonic type: fermions of the HS.

Arkani-Hamed Grossman Robinson, Okui, ...

Emergent Neutrinos



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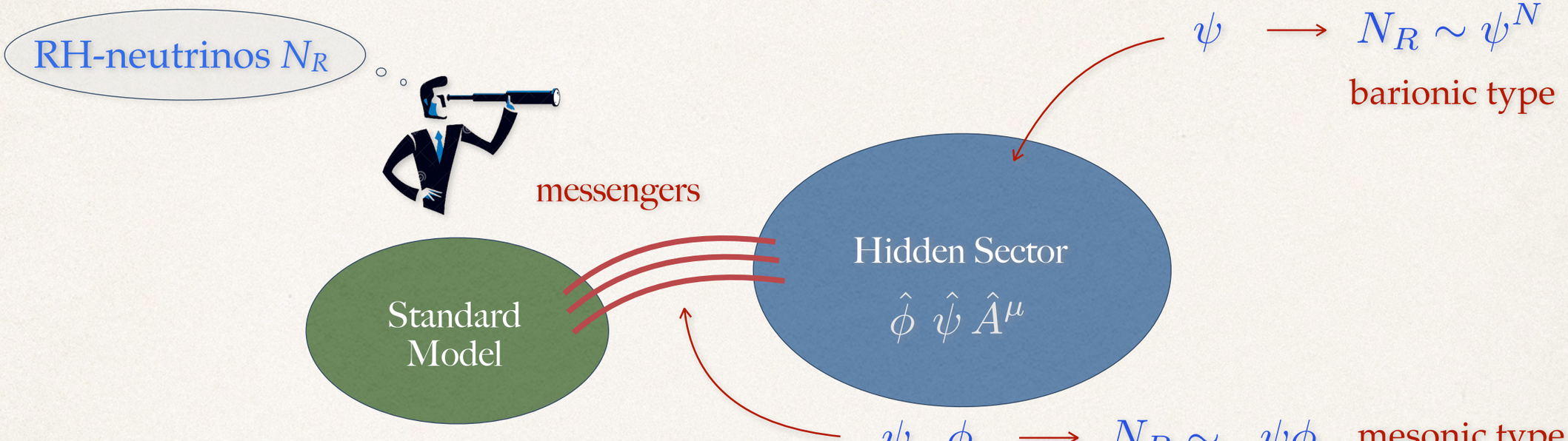
    Anastasopoulos Kiritsis

Emergent Neutrinos



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- The affective action of these emergent neutrinos triggers the seesaw mechanism

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

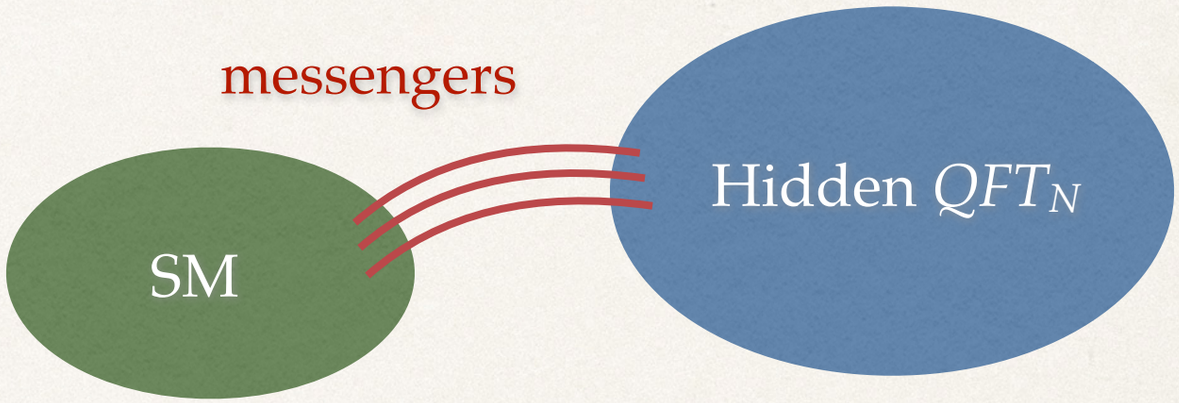
light (SM) neutrinos

sterile neutrinos

messenger scale

RH-neutrinos as mesonic messengers

- In our scenario, R-H neutrino can come from the (heavy) messenger sector.
- 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

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- 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.