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Emergent Axions

Pascal Anastasopoulos

with P. Betzios, M. Bianchi, D. Consoli, E. Kiritsis

Corfu - 12/09/2019

Plan of the talk

- Motivation
- Framework
- Emergent gravity
- Emergent axions
- Phenomenological considerations
- Conclusions

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- Until now, the only theory that gives a consistent description of quantum gravity is string theory, which provides a natural cutoff, the string scale, protecting the theory from divergences.
- On the other hand, new holographic ideas relate large-N gauge theories to string theories (which contain gravity) providing a different approach to this problem.

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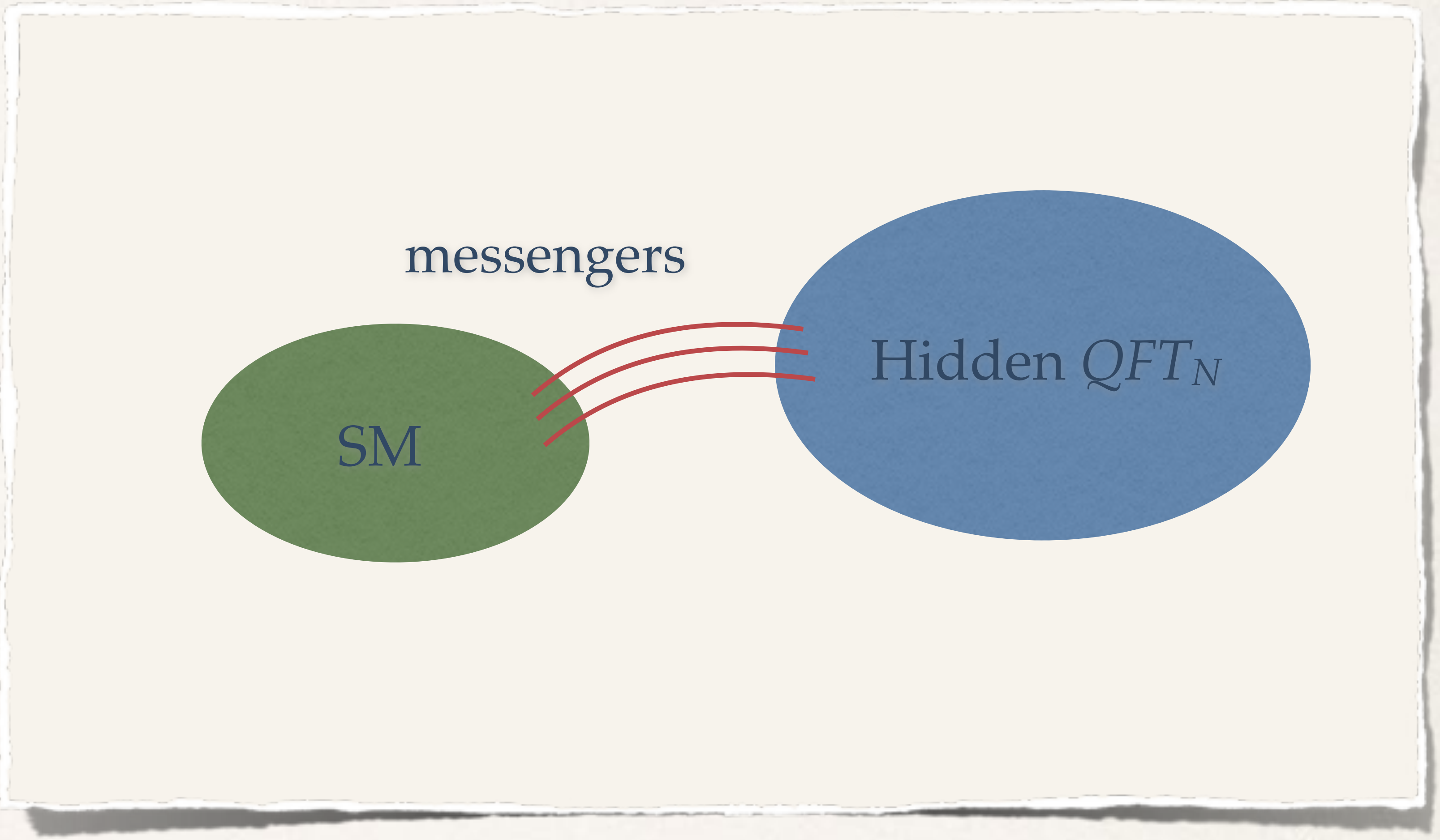
- These fields are the instanton densities $a \sim Tr[\hat{F} \wedge \hat{F}]$ of the hidden sector.

- They are protected by their topological invariance and therefore they do not acquire heavy masses in contrary to other scalar operators.



Framework

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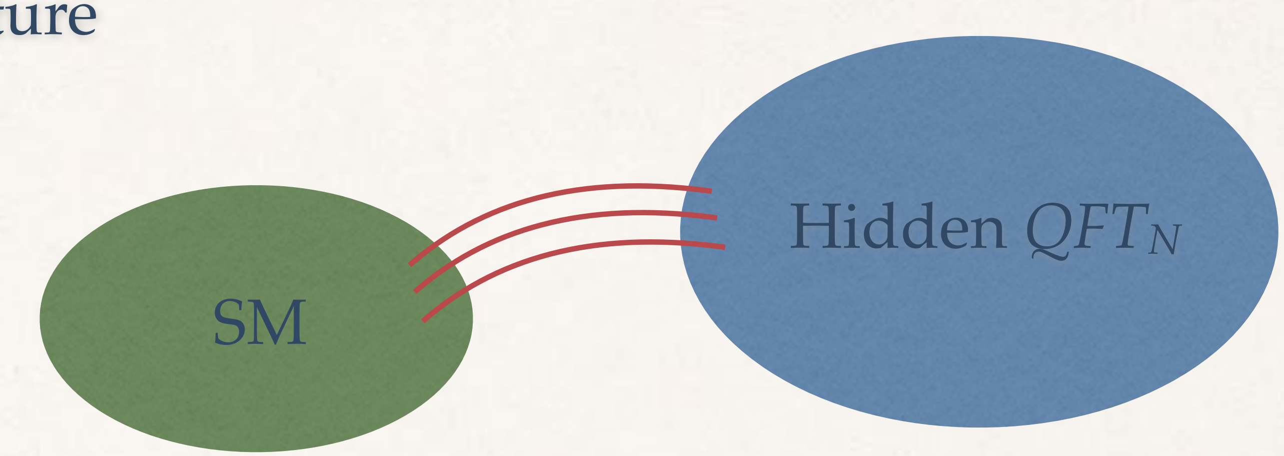
UV picture



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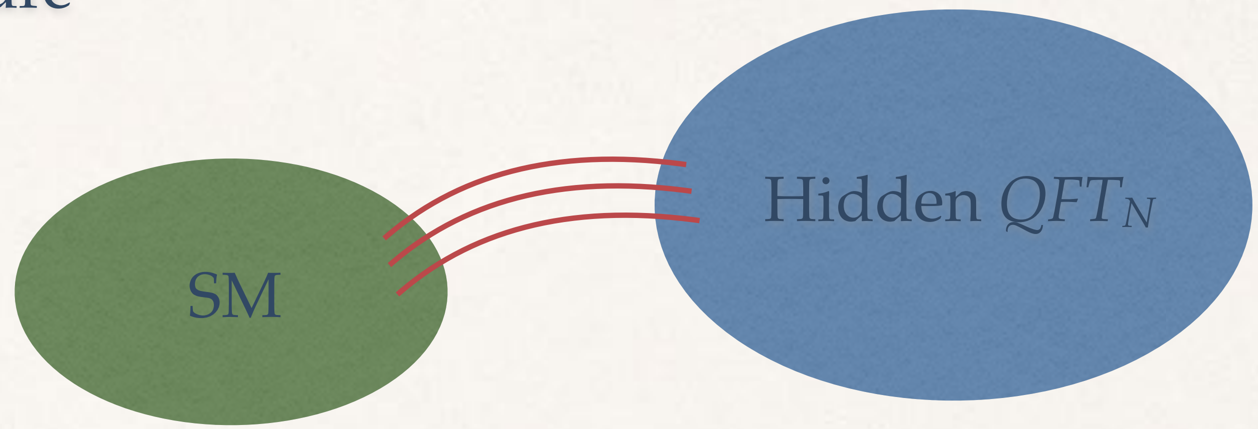

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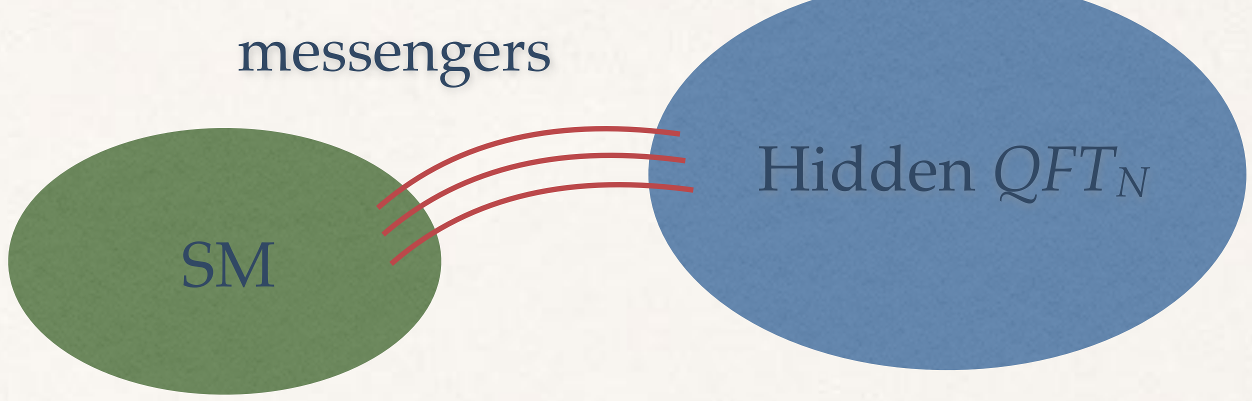

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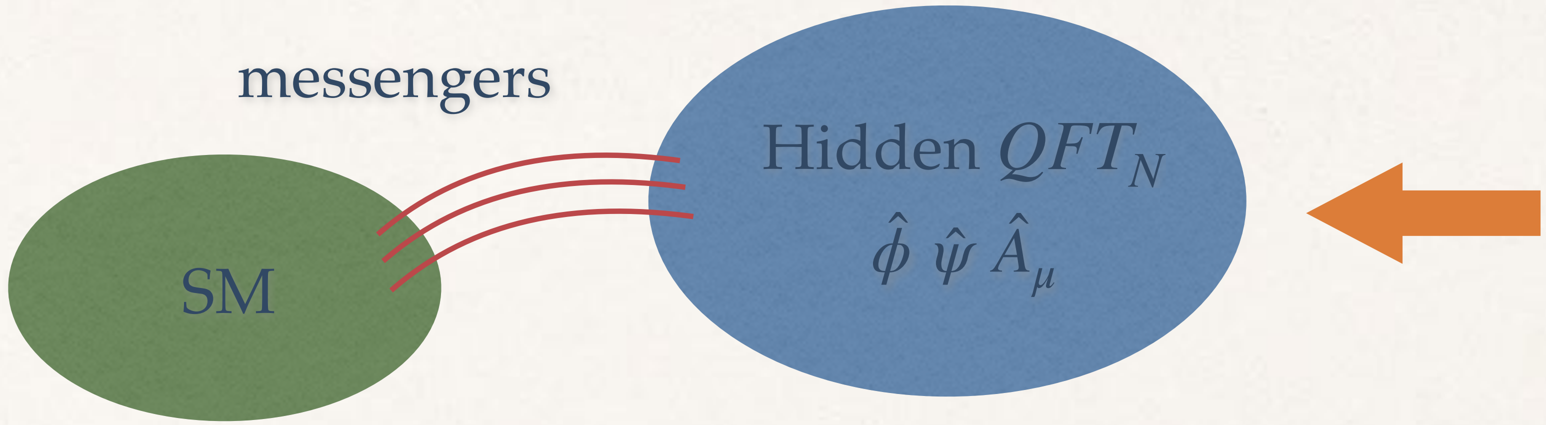
- The "rest of the universe" is a hidden in the IR (and consequently to us) 4D quantum field theory which is in principle arbitrary.
- The two separate sectors are connected via messenger fields.

Framework



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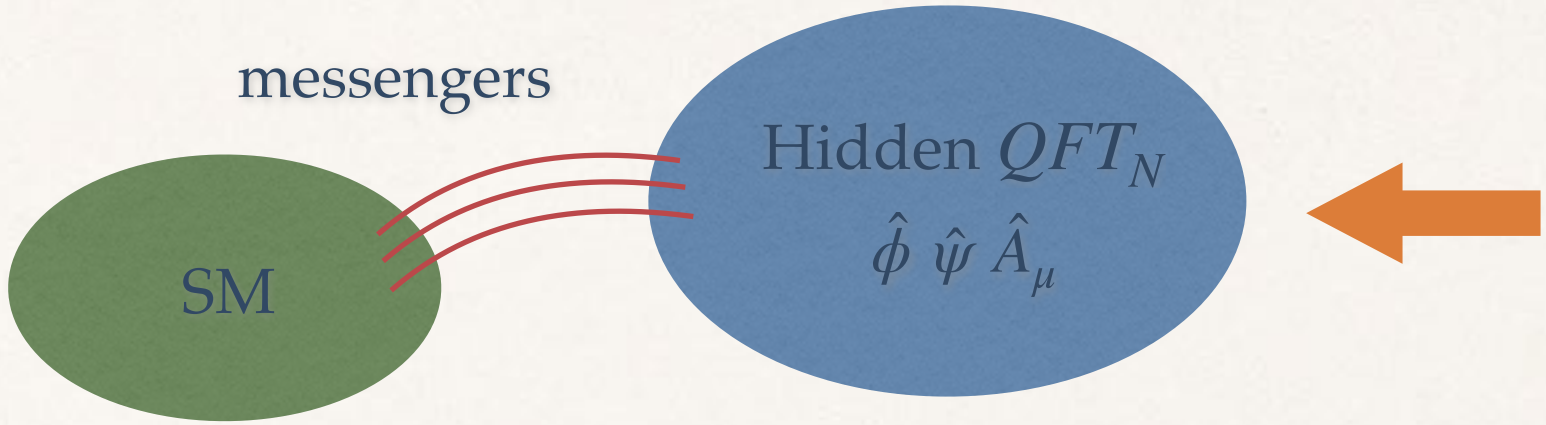
Framework



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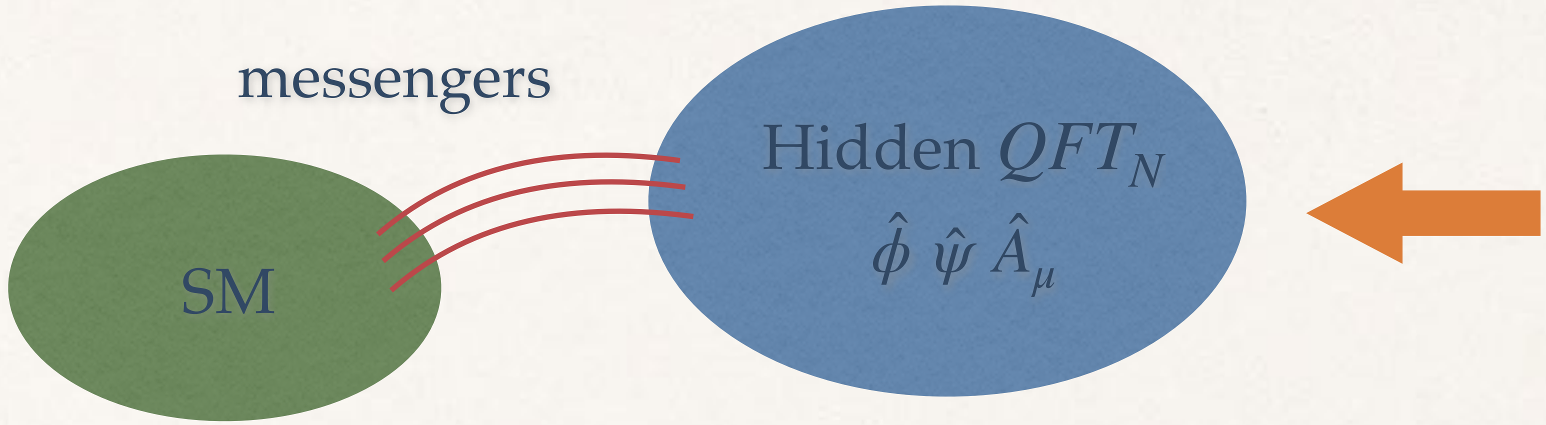

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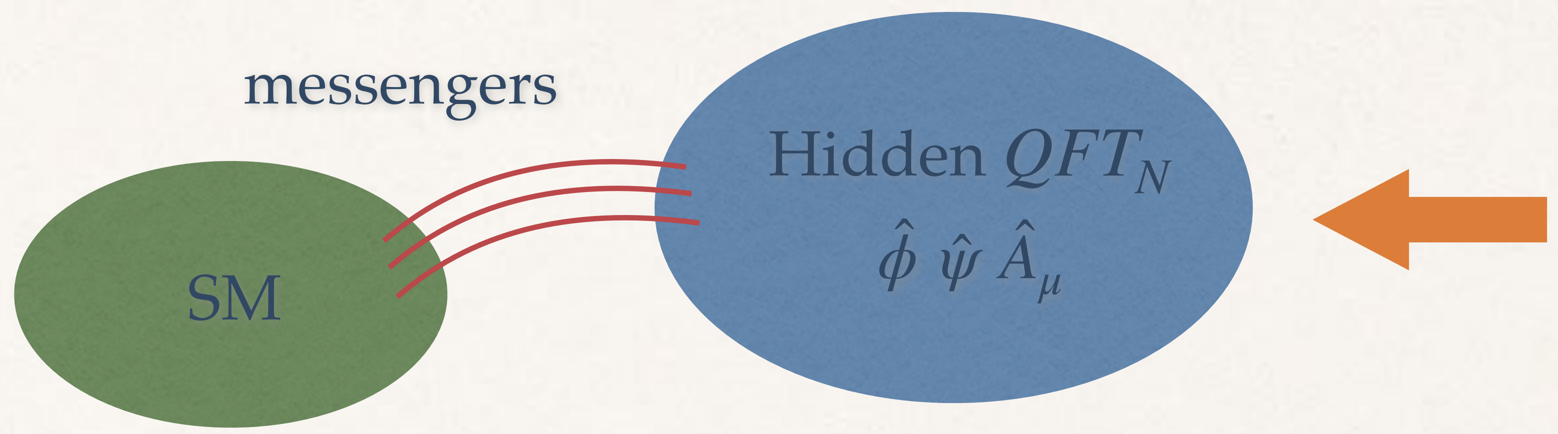

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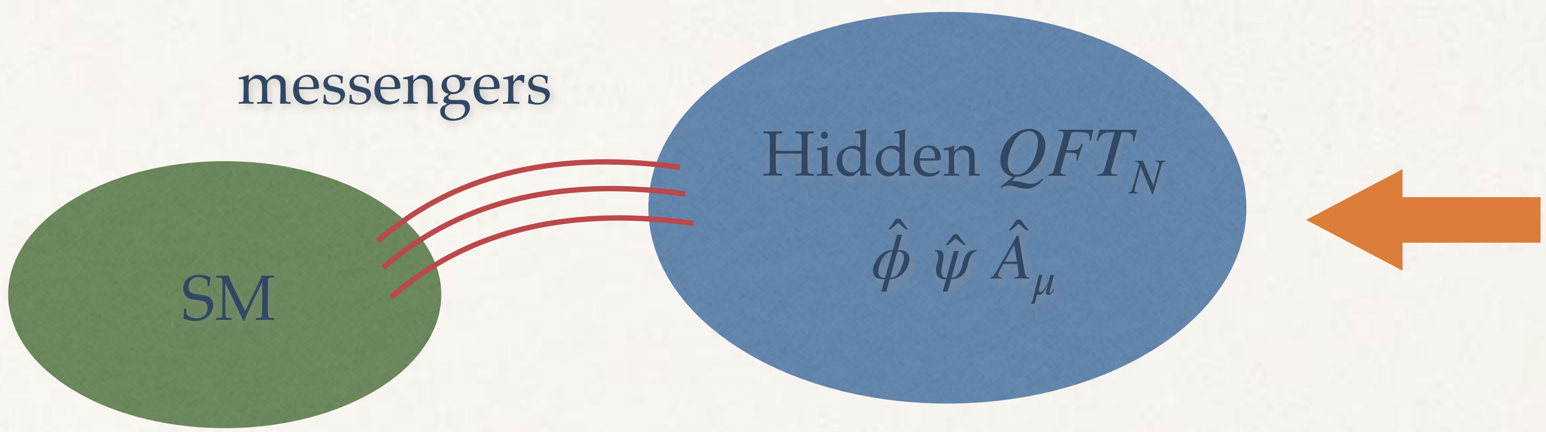

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  - However, we will assume $SU(N_i)$ with N_i from large (to astronomical) values.
  - At weak coupling (IR) the hidden theory contains: vectors $\hat{A}^\mu$, scalars $\hat{\phi}$ and spin-1/2 particles $\hat{\psi}$ (the simplest QFTs).

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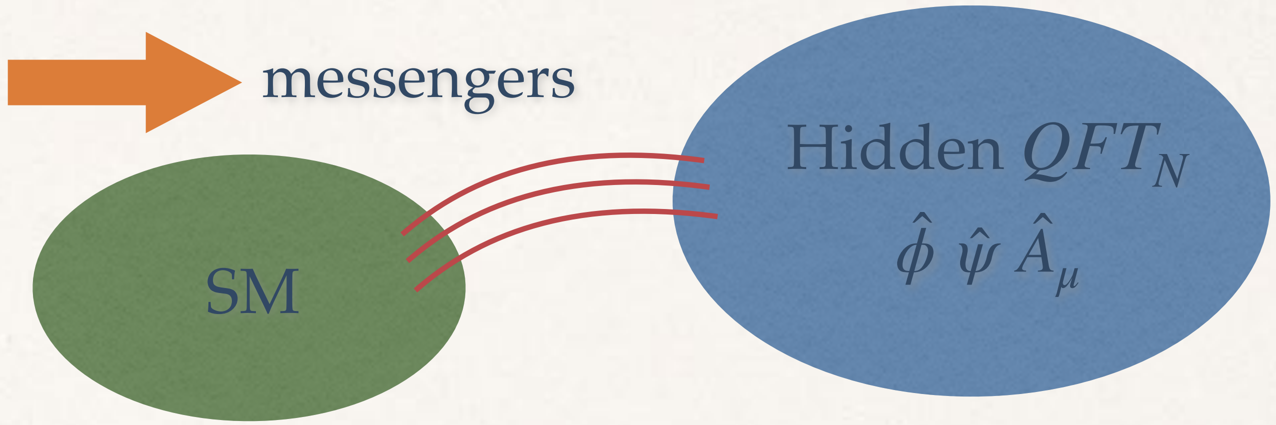
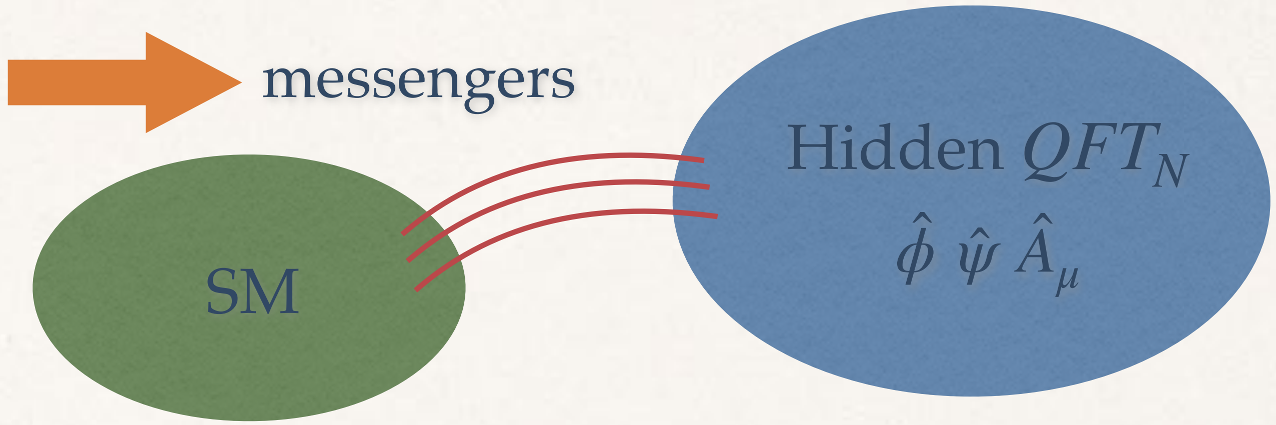


- Messengers

Framework



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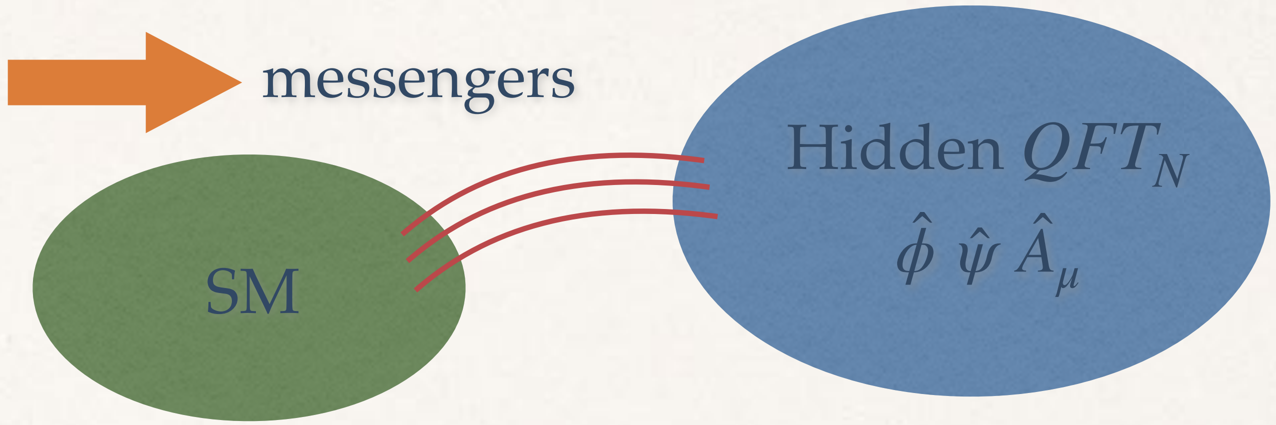

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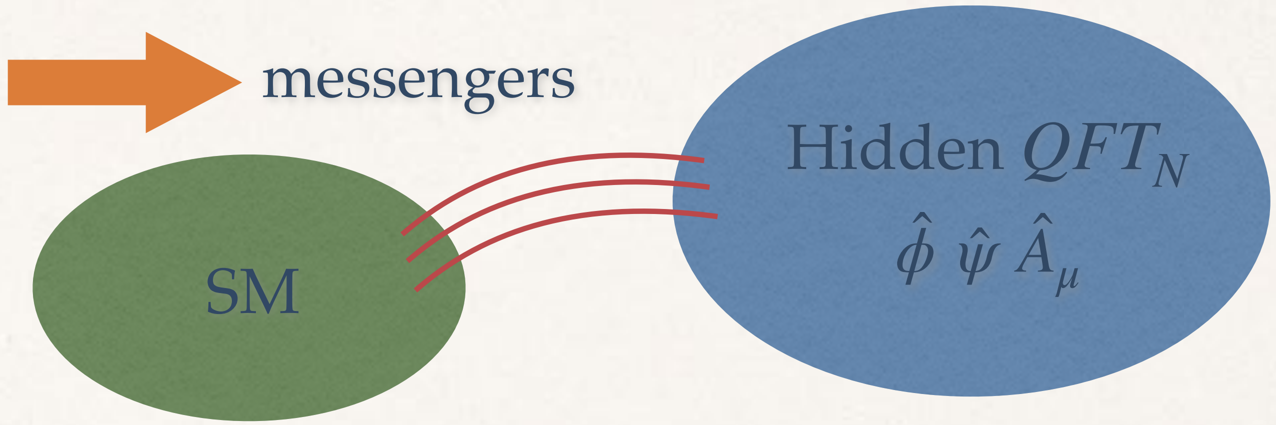

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  - In our case we assume to be heavy.

Kiritsis

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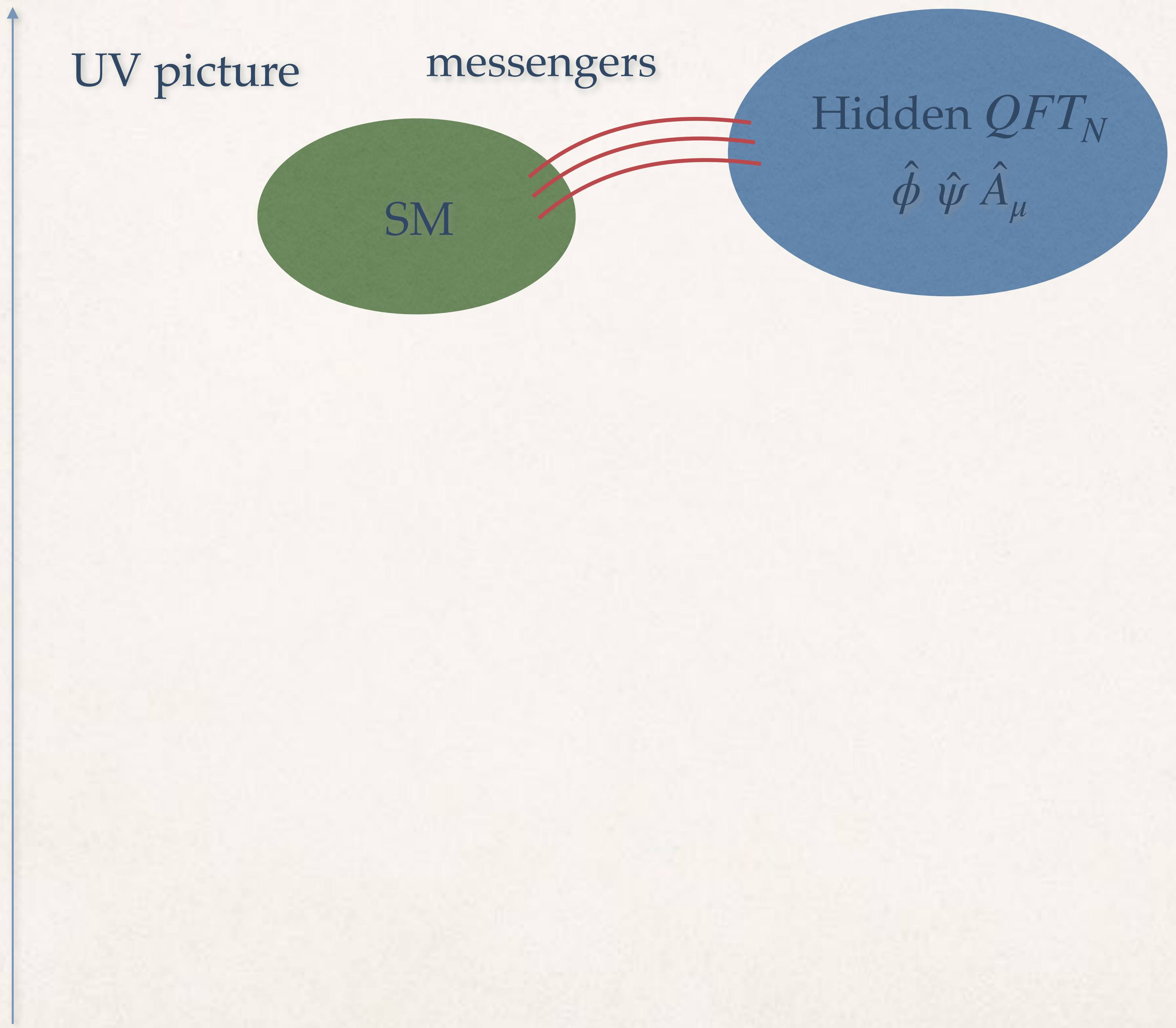

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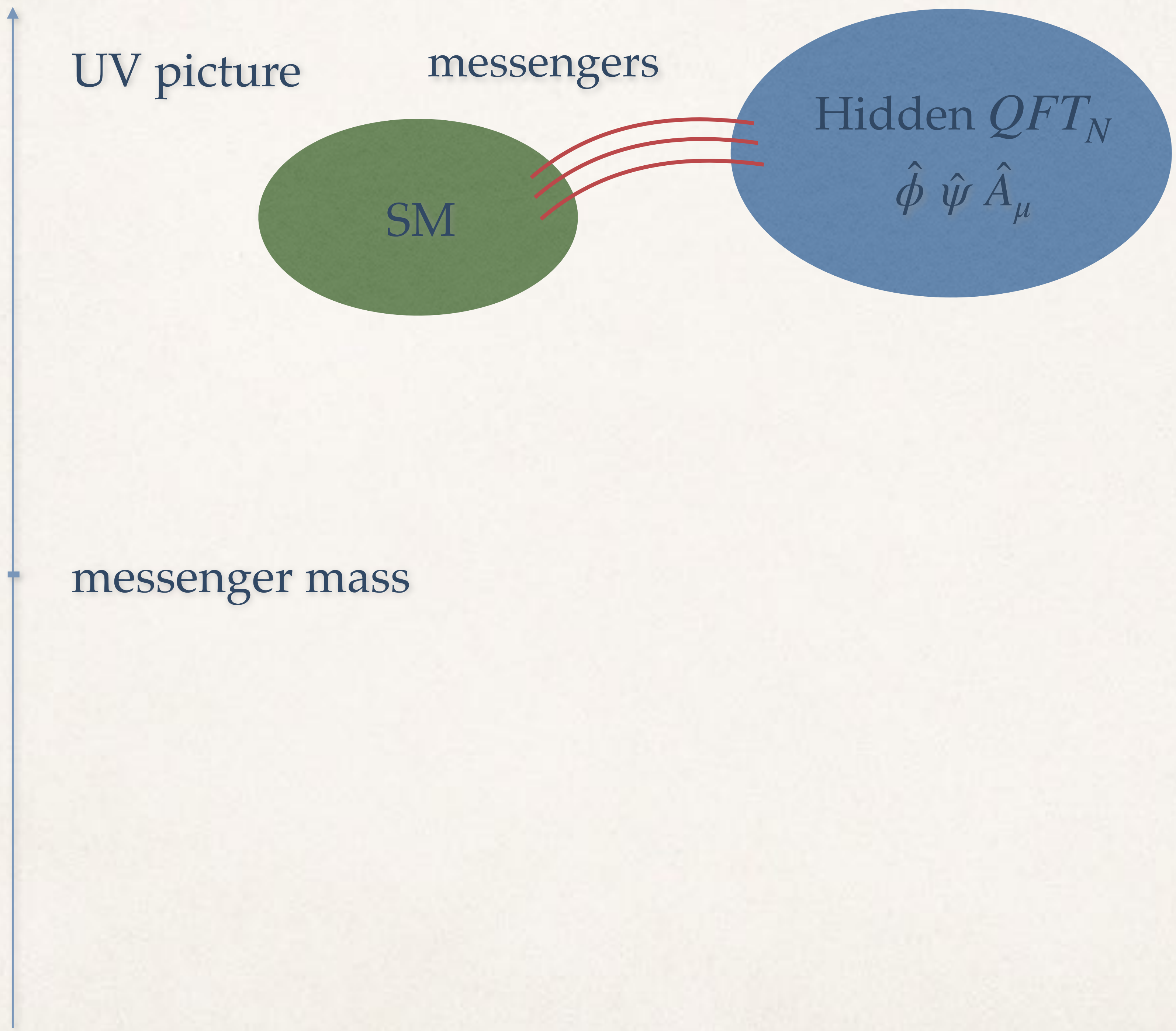
UV picture
messengers
Hidden QFT_N
$\hat{\phi}\ \hat{\psi}\ \hat{A}_\mu$
SM
messenger mass

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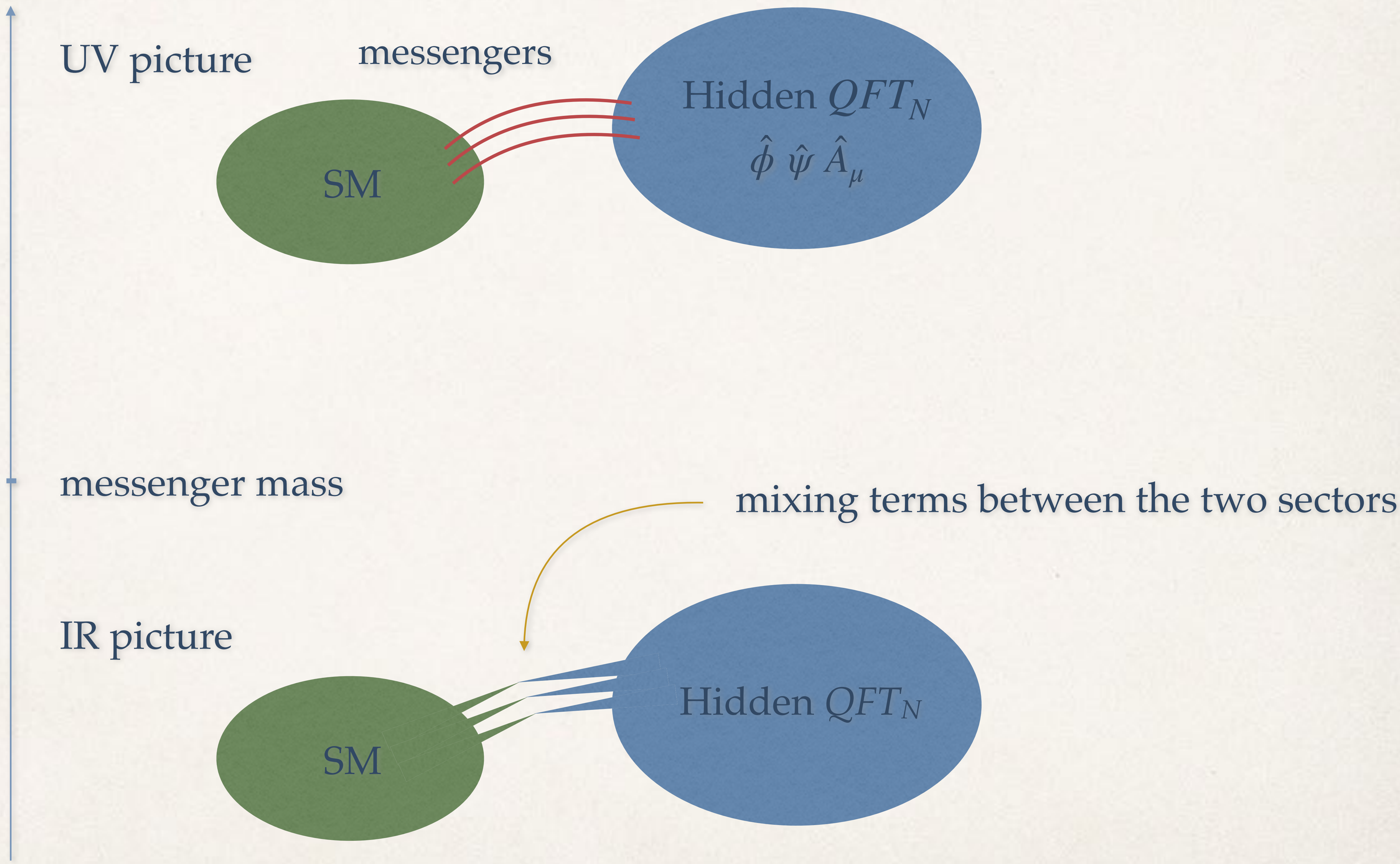
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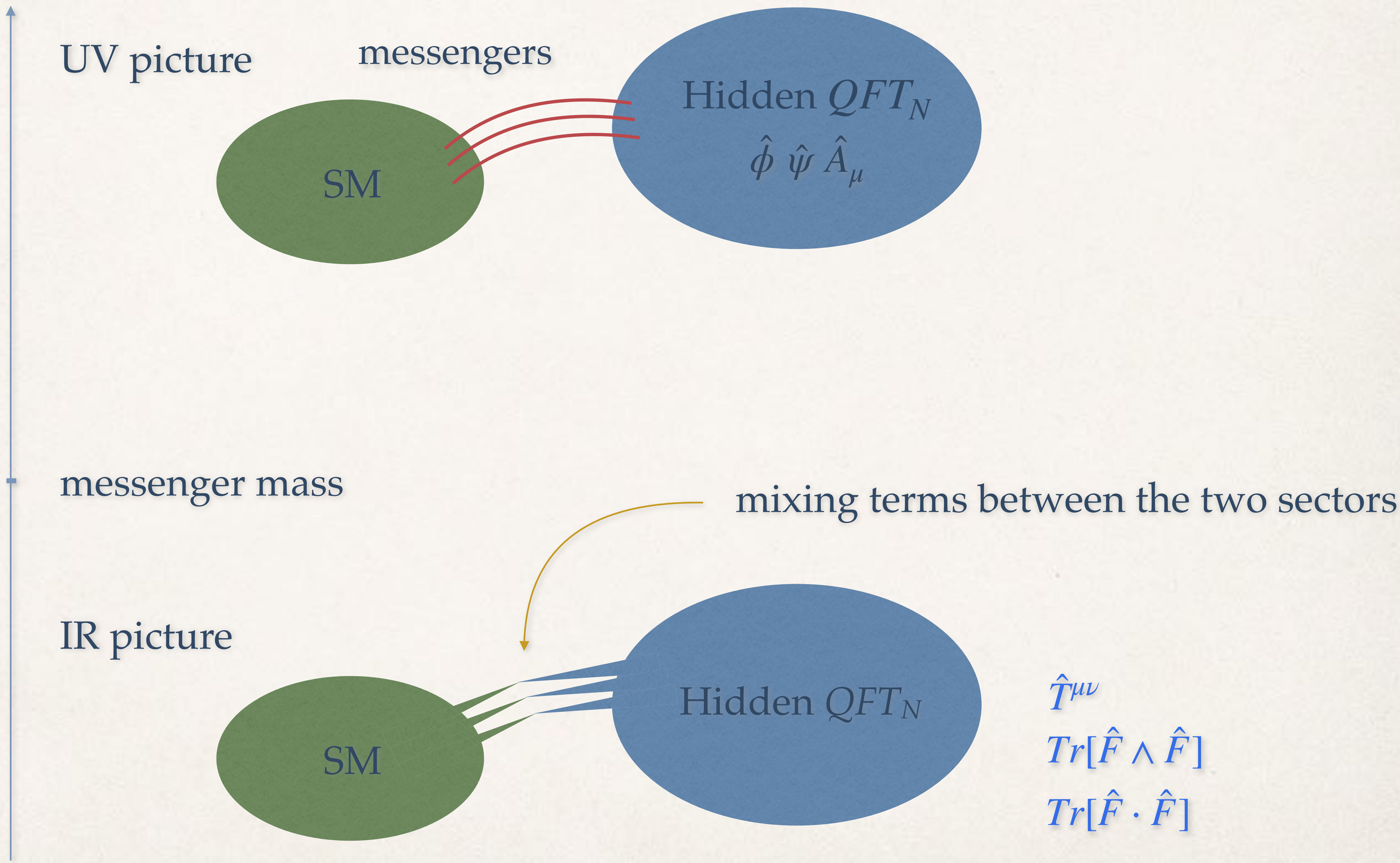
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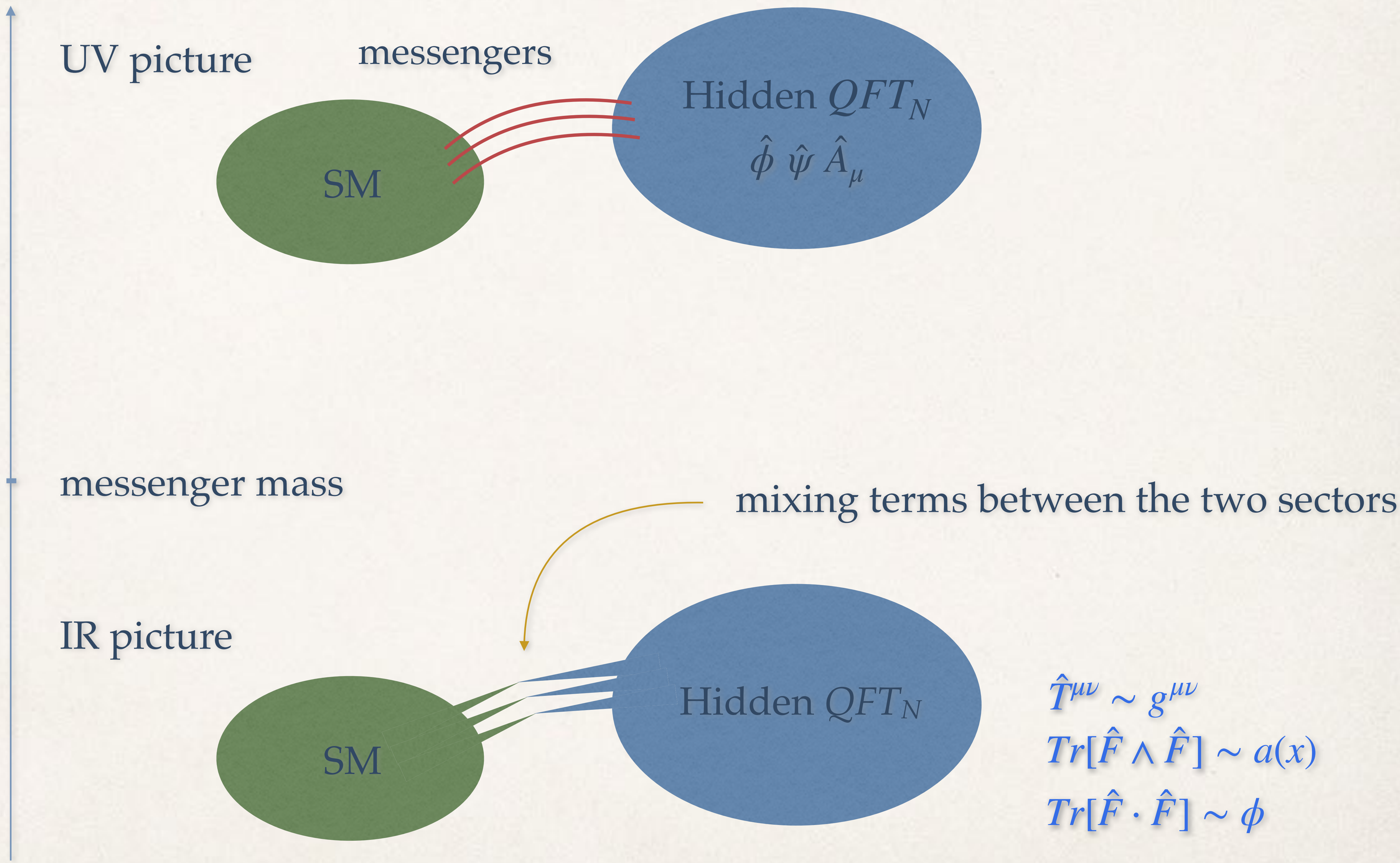
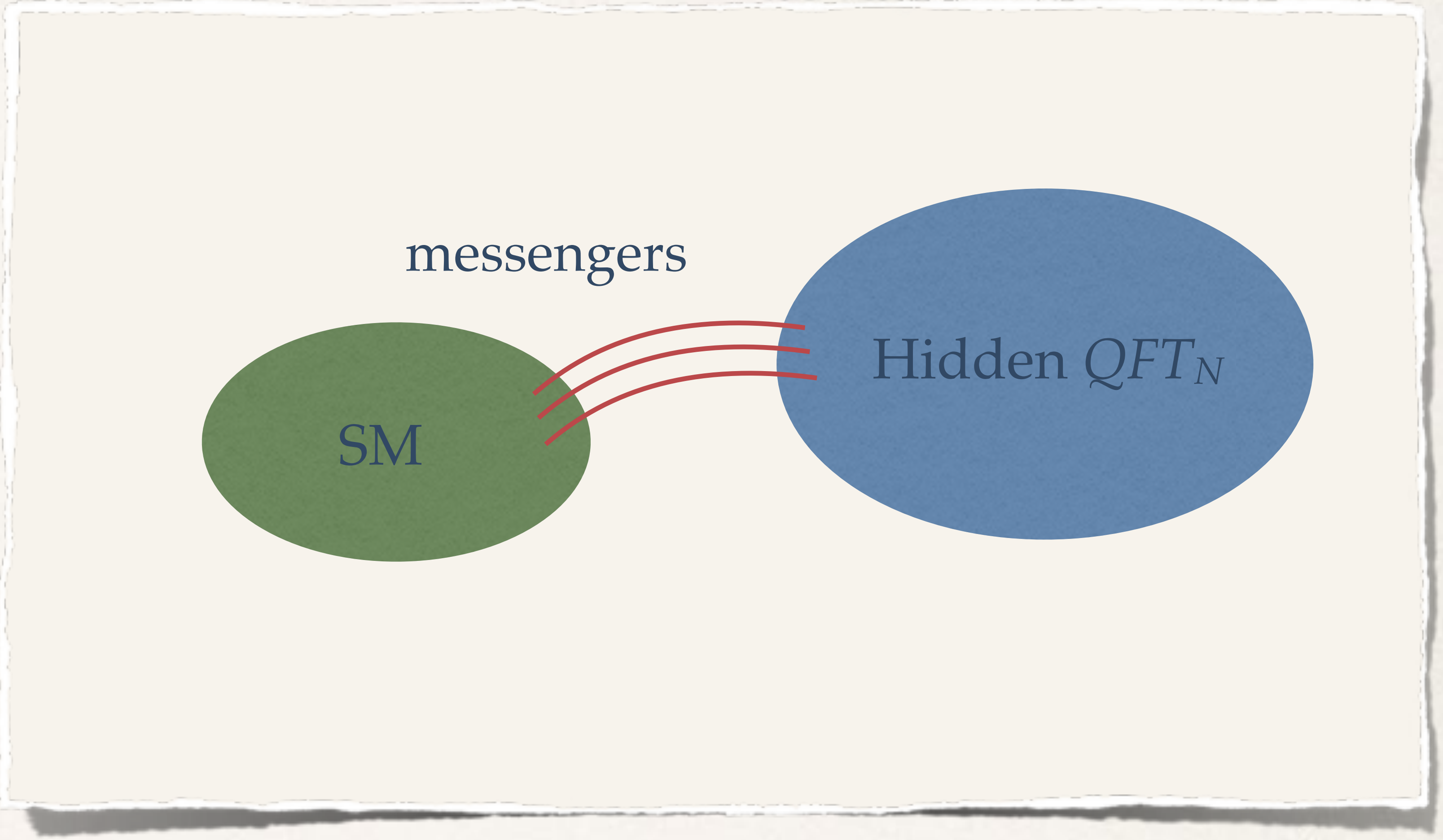


$\hat{T}^{\mu\nu} \sim g^{\mu\nu}$

$Tr[\hat{F} \wedge \hat{F}] \sim a(x)$

$Tr[\hat{F} \cdot \hat{F}] \sim \phi$

operators in Hidden Sector $\longrightarrow$ weakly coupled fields for the visible Sector



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$$+ \int d^4x\sqrt{g}\Big(\Lambda + \frac{1}{16\pi G}R\Big)\Big|_{g_{\mu\nu}+\eta_{\mu\nu}+h_{\mu\nu}}$$

where λ the coupling between the stress tensors of the hidden and visible theories.

Baggioli, Betzios, Kiritsis, Niarchos

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- The theorem of Weinberg-Witten is inapplicable in this case since the final gravitational theory has a non-trivial cosmological constant.

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- Our goal is to study their properties in various different cases and compare with data.

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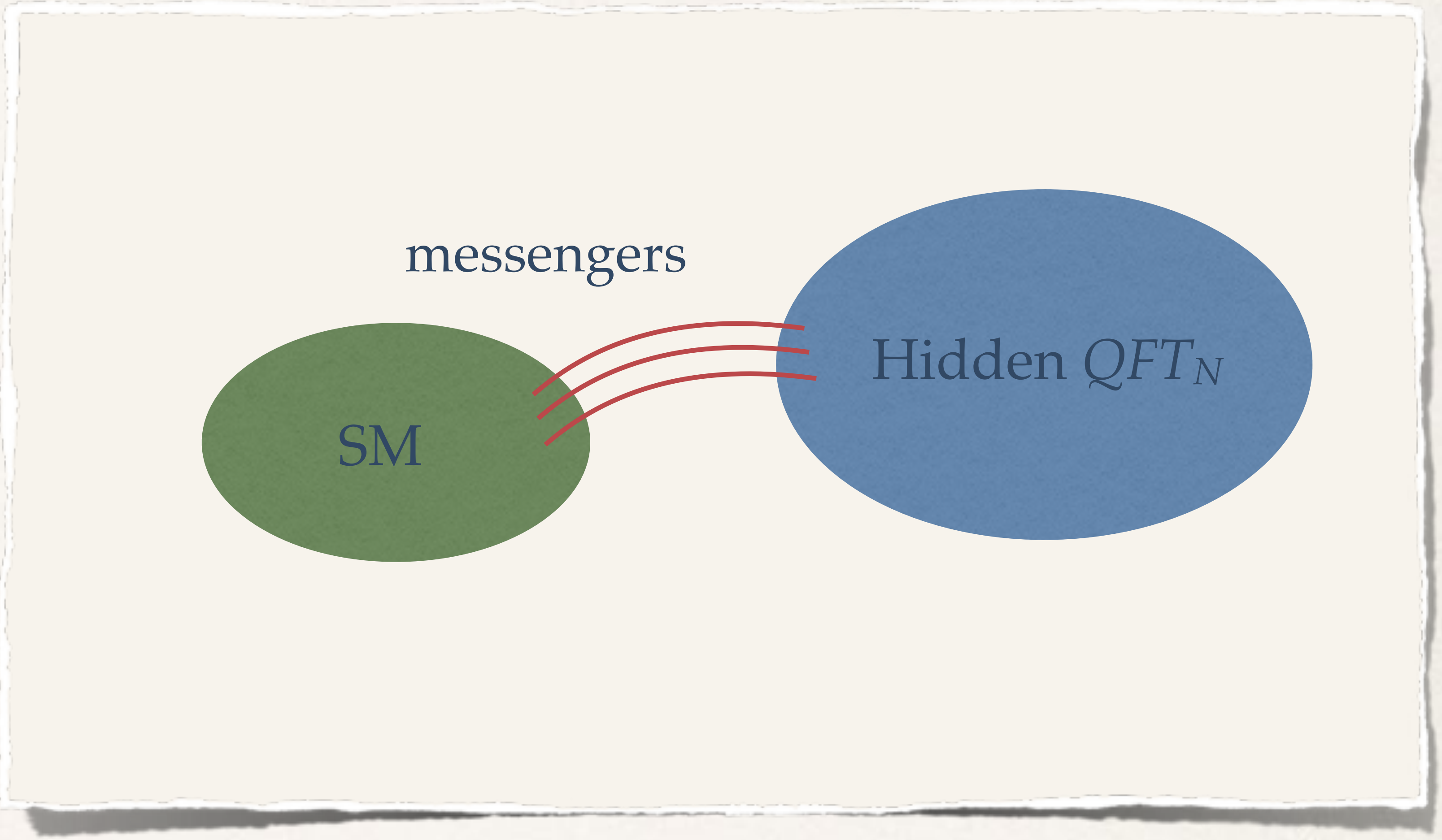
- Therefore we certainly have an ALP (axion-like-particle).
- Whether it is a QCD axion (potential has a min at 0) has to be checked.



Emergent Axions

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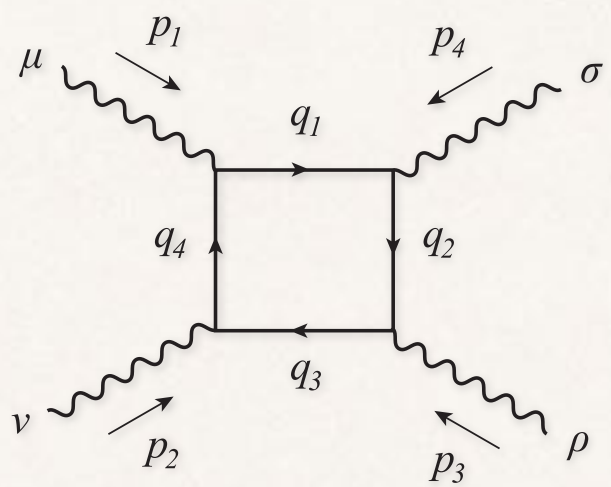

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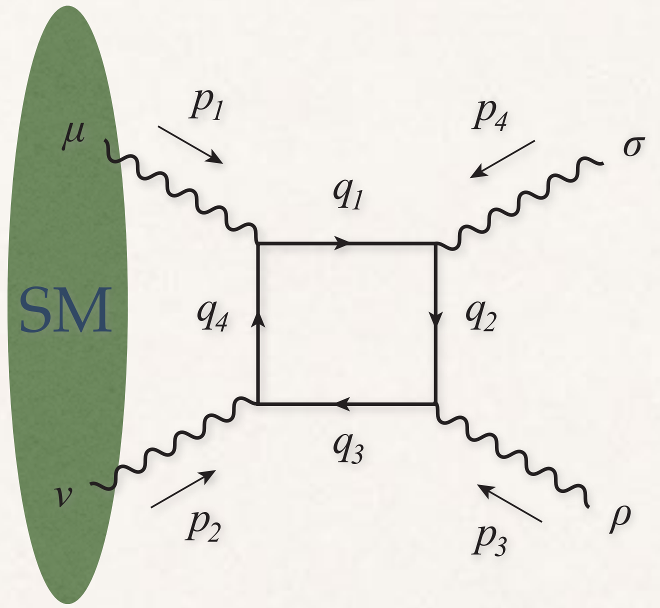

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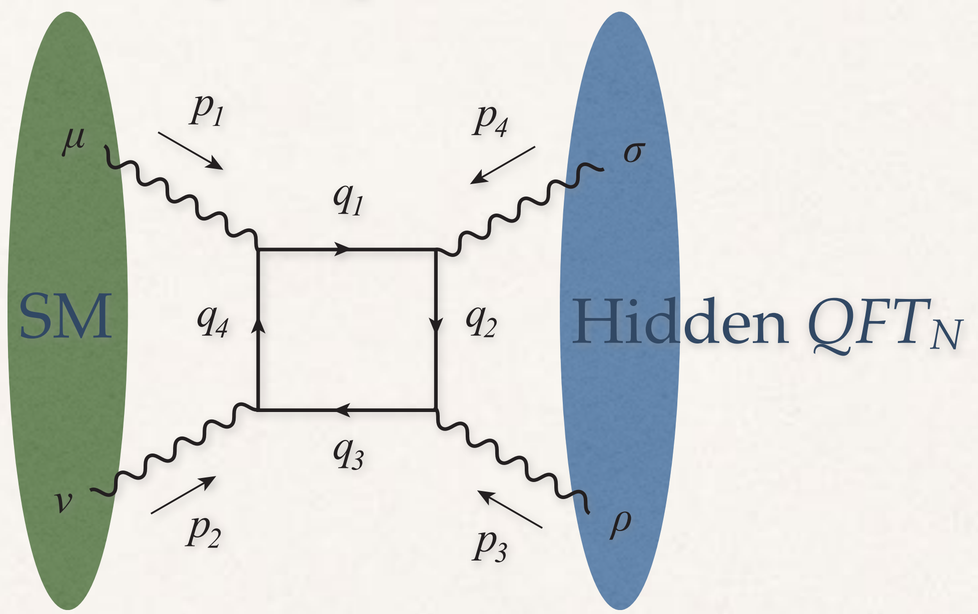

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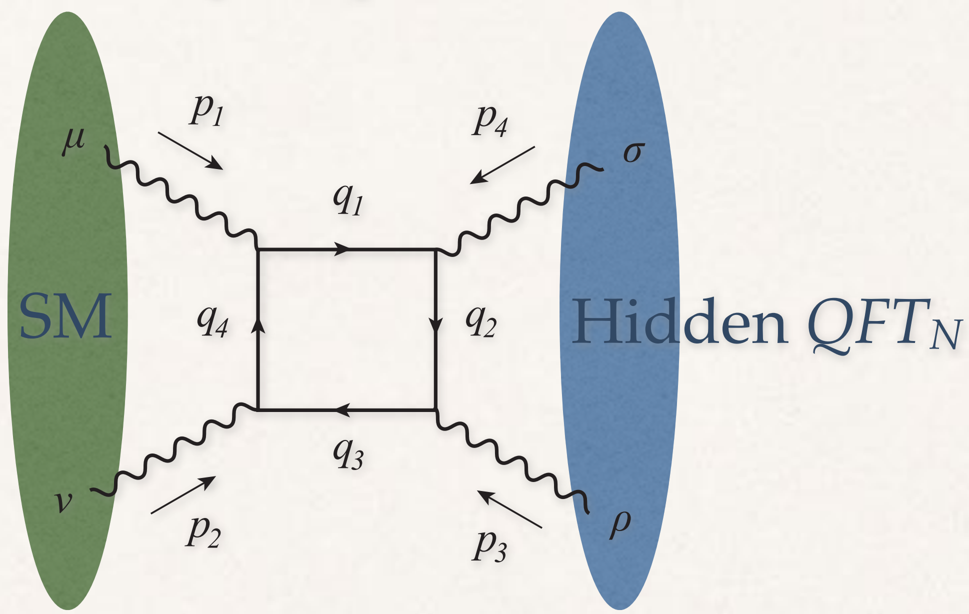

- The effective action finally is

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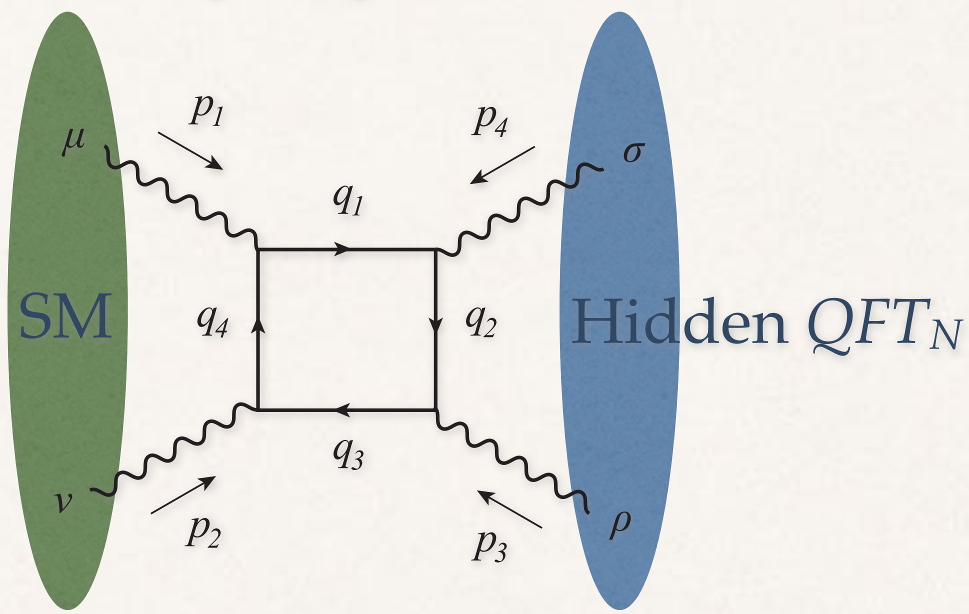

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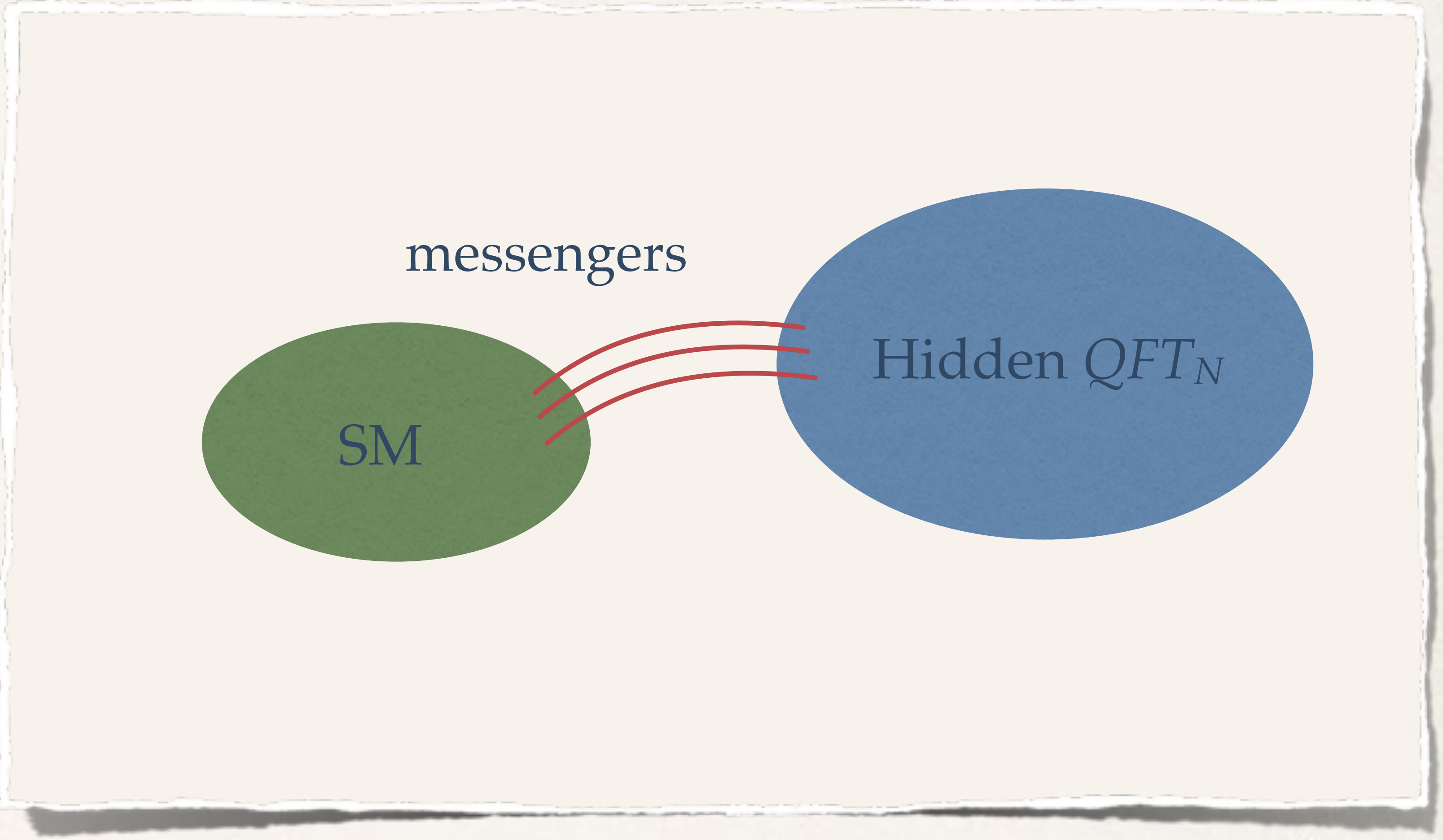
- Our goal is to focus in this coupling.



Effective theory

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- Consider the interaction between two theories T_1 (= Hidden) and T_2 (= SM)

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where $O_i = Tr[F_i \wedge F_i]$ are operators of dimension Δ_i ($= 4$).

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where $O_i = Tr[F_i \wedge F_i]$ are operators of dimension Δ_i (= 4).

- Following the standard procedure (Schwinger functional, Legendre transformations) we get

$$i\langle O_1(p) O_1(-p)\rangle\big|_{total} = \frac{G_{11}(p)}{1 - \lambda^2 G_{11}(p) G_{22}(p)} = G_{11}(p) + \lambda^2 \frac{G_{22}(p) G_{11}^2(p)}{1 - \lambda^2 G_{11}(p) G_{22}(p)}$$

where $G_{ii}(p) = \langle O_i(p) O_i(-p)\rangle_i$.

2-point function

- We want to examine the effect of a generic scalar-scalar interaction between two theories and the IR "resolution".

- Consider the interaction between two theories T_1 (= Hidden) and T_2 (= SM)

$$S = S_1[O_1] + S_2[O_2] + \lambda \int d^4x \; O_1(x) O_2(x)$$

where $O_i = Tr[F_i \wedge F_i]$ are operators of dimension Δ_i (= 4).

- Following the standard procedure (Schwinger functional, Legendre transformations) we get

$$i\langle O_1(p) O_1(-p)\rangle\big|_{total} = \frac{G_{11}(p)}{1-\lambda^2 G_{11}(p) G_{22}(p)} = G_{11}(p) + \lambda^2 \frac{G_{22}(p) G_{11}^2(p)}{1-\lambda^2 G_{11}(p) G_{22}(p)}$$

where $G_{ii}(p) = \langle O_i(p) O_i(-p)\rangle_i$.

- This is the propagator of the O_1, in the presence of the interaction term $\lambda O_1 O_2$.

Integrating out a pseudo-scalar

- Next, we want to evaluate the effective mass and decay constant of the operator O_1 of the T_1 theory as being an axion field a coupled to T_2.

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- We have several different options/regimes.

Fixing m_a & f_a

$$\frac{1-\lambda^2 G_{hh}(p) G_{SMSM}(p)}{G_{hh}(p)} = f_a^2(p^2+m_a^2) + \mathcal{O}[p^4]$$

- We will assume from now on that T_1 = hidden and T_2 = SM.

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- Since $m_{SM} = \Lambda_{QCD}$, there are three different remaining scales m_h, M, p in the problem.
- We have the following options to explore:
  - $p \ll m_{SM}, m_h \ll M$
  - $m_h \ll p \ll m_{SM}$
  - $m_{SM} \ll p \ll m_h$
  - $m_{SM}, m_h \ll p \ll M$

For $p \ll m_{SM}, m_h \ll M$

$$\frac{1-\lambda^2 G_{hh}(p) G_{SMSM}(p)}{G_{hh}(p)} = f_a^2(p^2+m_a^2) + \mathcal{O}[p^4]$$

- In that region we need the IR expansion of the correlators.

$$i\langle O(p)O(-p)\rangle = a_0 + a_2 p^2 + a_4 p^4 + \cdots$$

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$$a_n \sim M^{2(\Delta-2)-n}\left[1+\mathcal{O}\left(\frac{m}{M}\right)\right]$$

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- Therefore, their masses are given by the mass gap of the hidden theory and not by the large messenger masses M.

For $p \ll m_{SM}, m_h \ll M$

$$\frac{1 - \lambda^2 G_{hh}(p) G_{SMSM}(p)}{G_{hh}(p)} = f_a^2(p^2 + m_a^2) + \mathcal{O}[p^4]$$

- Therefore, we have the expansions

$$iG_{h,h}(p) = m_h^{2\Delta_h - 4}\left[\bar{a}_0 - \bar{a}_2 \frac{p^2}{m_h^2} + \mathcal{O}\left(\frac{p^4}{m_h^4}\right)\right]$$

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- We finally get

$$m_a^2 = \bar{a}_0 m_h^2 \left(1 + \frac{\bar{b}_0 \bar{a}_0 \lambda_0^2}{\bar{a}_2}\frac{m_h^4 m_{SM}^4}{M^8} - \frac{\bar{b}_2 \bar{a}_0^2 \lambda_0^2}{\bar{a}_2}\frac{m_h^6 m_{SM}^2}{M^8} + \cdots\right)$$

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- Assume that $\bar{a}_i, \bar{b}_i \sim 1$ we have m_a & f_a as functions of our parameters m_{SM}, m_h, M.

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- Therefore, the mass m_a has two contributions:
  - the SM quantum effects $\sim \Lambda_{QCD}^2/f_a$ as with standard axions and
  - a contribution from the hidden theory order m_{hidden} (unlike fundamental axions).

For $m_{SM} \ll p \ll m_h$

$$\frac{1-\lambda^2 G_{hh}(p) G_{SMSM}(p)}{G_{hh}(p)} = f_a^2(p^2+m_a^2) + \mathcal{O}[p^4]$$

- In that case, SM glueballs are fat and unstable and hidden ones are pointlike with expansions

$$iG_{h,h}(p) = m_h^{2\Delta_h - 4}\left[\bar{a}_0 - \bar{a}_2 \frac{p^2}{m_h^2} + \mathcal{O}\left(\frac{p^4}{m_h^4}\right)\right]$$

$$iG_{_{SM},_{SM}} = p^4 \log\frac{p^2}{m_{_{SM}}^2}\left[\hat{b}_0 + \hat{b}_2 \frac{m_{_{SM}}^2}{p^2} + \mathcal{O}\left(\frac{m_{_{SM}}^4}{p^4}\right)\right] \quad , \quad p \gg m_{_{SM}}$$

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- In that regime

$$\frac{1}{G_{hh}(p)} \gg \lambda^2 G_{SMSM}(p)$$

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- In that regime

$$\frac{1}{G_{hh}(p)} \gg \lambda^2 G_{SMSM}(p)$$

- And we get (the SM contribution is tiny)

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- And we get (the SM contribution is tiny)

$$m_a^2 = \frac{\bar{a}_0}{\bar{a}_2} m_h^2 \quad , \quad f_a^2 = \frac{\bar{a}_2}{\bar{a}_0^2}\frac{m_h^2}{\lambda_0^2}\left(\frac{M}{m_h}\right)^{2\Delta_h}$$

- The result is similar to the previous case. The leading contribution is coming from the hidden theory.

For $m_h \ll p \ll m_{SM}$

$$\frac{1-\lambda^2 G_{hh}(p) G_{SMSM}(p)}{G_{hh}(p)} = f_a^2(p^2+m_a^2) + \mathcal{O}[p^4]$$

- In that case, hidden glueballs are fat and unstable but SM ones are pointlike with

$$iG_{h,h}(p) = p^4 \log\frac{p^2}{m_h^2}\left[-\hat{a}_0 + \hat{a}_2\frac{m_h^2}{p^2} + \mathcal{O}\left(\frac{m_h^4}{p^4}\right)\right] \quad , \quad p \gg m_h$$

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- In that regime, $\langle aa\rangle^{-1} \sim M^8 \log|x|$ is a non-standard non-local axion kinetic term and

$$S_{eff} \simeq \frac{M^8}{2}\int d^4x_1 d^4x_2\ a(x_1)\log\frac{|x_1-x_2|}{m_h}a(x_2) + \int d^4x\ \chi(x)O_{SM}(x)$$

which is valid only for $m_{SM}^{-1} < \ell < m_h^{-1}$.

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- In this category we also have the case where the hidden theory is conformal ($m_h \to 0$).

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- In that case, *both* glueballs are fat and unstable with expansions

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we get again the non-local non-standard

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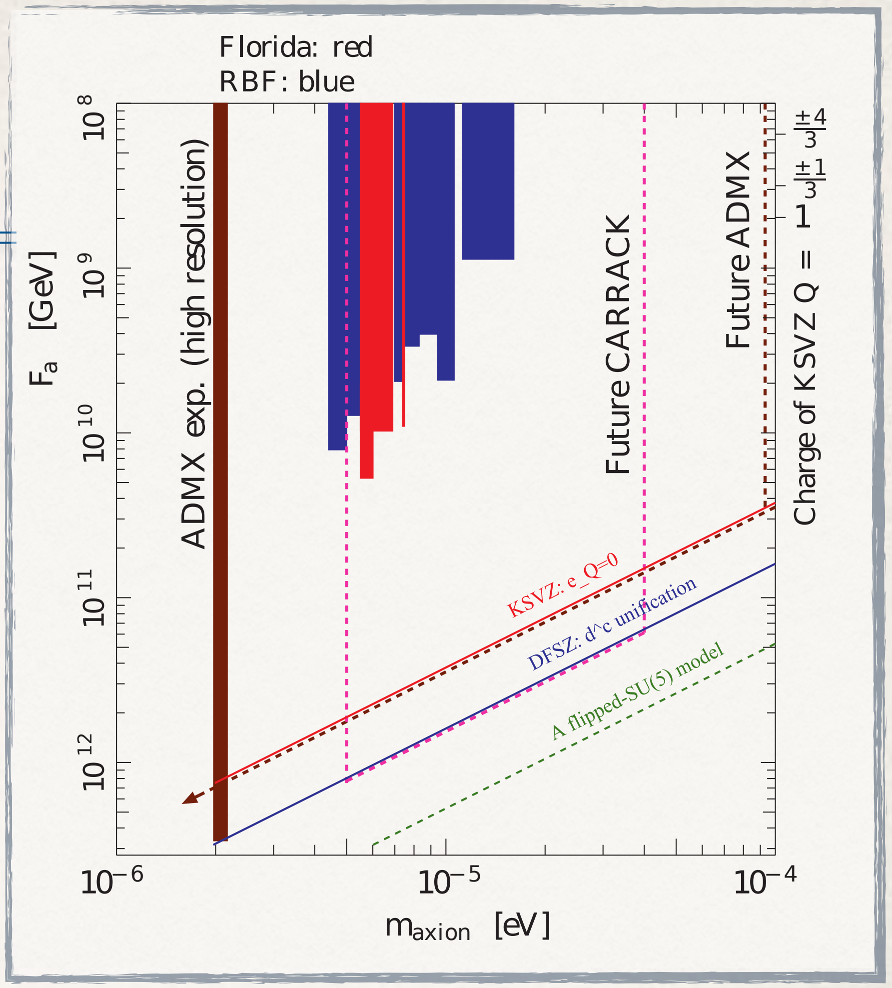
- Again, deeper analysis is needed for these models.

Phenomenological Windows



- Dark Matter axions

$$10^{-25}\ \text{eV} < m_a^{DM} < 10^{-18}\ \text{eV}$$

- Dark Energy axions

$$10^{-33}\ \text{eV} < m_a^{DE} < 10^{-30}\ \text{eV}$$

- Axions as Inflatons: (very much model dependent)

- Heavy Axions ($m_a > 1\text{eV}$)

$$m_a > 10\ \text{MeV} \quad \text{and} \quad \tau_{a\gamma} < 10^{-2}\ \text{s} \qquad \text{or} \qquad m_a < 10\ \text{eV} \quad \text{and} \quad \tau_{a\gamma} > 10^{24}\ \text{s}$$

- QCD axions

$$10^{-12}\ \text{eV} < m_a^{QCD} < 10^{-3}\ \text{eV}$$

$$10^{9}\ \text{GeV} < f_a^{QCD} < 10^{15}\ \text{GeV}$$

Comparison with data

- For $m_{SM}, m_h \ll M$ (only these can be compared with experimental data), we have

$$m_a \sim m_h \qquad\qquad M^4 \sim f_a m_a^3$$

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- For QCD axions we have: $(m_a f_a)^{1/2} \sim (m_u \Lambda_{QCD}^3)^{1/4} \sim 10^{-1} GeV \sim m_{SM}$

In our case $M^2 \sim m_a (m_a f_a)^{1/2} \sim m_h m_{SM}$ violating our initial assumption.

Conclusions

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- In this frame work gravity is emerging via the stress tensor of the hidden sector.
- As a byproduct we have axions (instanton densities) which, in contrary to other scalar operators, are not suppressed by the large messenger masses.
- The hidden instanton density generates an emergent axion coupled to the SM. The characteristic decay constant of the emergent axion is

$$f \sim m_{\rm hidden} \left(\frac{M}{m_{\rm hidden}} \right)^4 \quad \gg \quad m_{\rm hidden}$$

where m_{hidden} the characteristic scale of the hidden theory.

Conclusions

- The mass of the emergent axion has two contributions.
  - One due to SM quantum effects $\sim \Lambda_{QCD}^2/f_a$ as with standard axions.
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  - One due to SM quantum effects $\sim \Lambda^2_{QCD}/f_a$ as with standard axions.
  - In addition (unlike fundamental axions), has also a contribution from the hidden theory order m_{hidden} .
- Some regions of the parameter space of our models provide non-standard non-local kinetic terms and deeper study is required.