Holography, Gravi-photons and Dark Photons

Massimo Bianchi
Physics Dept and I.N.F.N.
University of Rome “Tor Vergata”

based on w.i.p. with P. Anastasopoulos, D. Consoli and E. Kiritsis
and 1408.3541 by E. Kiritsis

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Foreword

Aristarchus-Copernicus principle: we are probably not at the center of the "world" [Kiritsis 1408.3541]

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although, thanks to Galileo and Einstein, we are surely entitled to be at the center of our own “world”
Hidden sectors, gauge/gravity correspondence, landscape of vacua … new postulates [Kiritsis 1408.3541]

- The ‘Theory of Everything’ is an UV-complete 4-d QFT (AF, conformal)
- The ‘Number of Colors’ is very large and the structure is almost random (yet constrained)

Plan

- Brief review of the basic ideas
- Focus on ‘gravi-photons’
  - String Theory setup
  - Holographic setup
  - Comparison
- Axions, just a hint
- Conclusions and outlook

Gravity, axions and more from random UV QFT

Basic ideas

UV-complete QFT4: Asymptotically free (AF) or Conformal (CFT)
Gauge fields $\sim N^2$, matter representations constrained by $\beta_N \leq 0$:
$\rightarrow$ (bi)fundamentals, (anti)symmetric tensors, adjoints
$\sim$ unoriented open strings!
Gauge group

- large N vs 'small' N
- many factors, the largest rank dominates
- strong coupling vs weak coupling
- (quasi) conformal (qCFT), asymptotically free (AF), IR free

Messenger sector(s)

- light ($M_m \sim M_{SM}$) vs heavy ($M_m >> M_{SM}$)
- elementary $\eta^a_i \in G_{hid} \times G_{SM}$, composite $\eta^a_i \sim \rho^i_\alpha \sigma^\alpha_a$ with $\rho^i_\alpha \in G_{hid} \times G_{inter}$ and $\sigma^\alpha_a \in G_{int} \times G_{inter}$, ... 'exceptional'
- multi-trace interactions, similar to $M_m \rightarrow \infty$ ... exclude relevant or (quasi)marginal (e.g. $\mathcal{N} = 4$ SYM not good)

‘Dominant’ hidden theory

- Dominant hidden theory: large N, quasi-conformal, at strong ’t Hooft coupling
- Messengers must be heavy $M_m >> M_{SM}$

AF ‘technicolour’ with light ($M_m \sim M_{SM}$) less plausible: hard, though not inconceivable, to have interesting IR fixed points with SM spectrum and interactions

Emergent gravity and other interactions

- Brane-world idea: negative cosmological constant can accommodate large extra dimensions [Randall, Sundrum; ...]
- Modified IR gravity: interplay between bulk and boundary [Dvali, Gabdadze, Porrati; ...]

Beyond $\Lambda_{UV} = M_m$ gravity must be replaced by its ancestor messenger interactions

Emergent gravity and geometry

'Minimal' coupling at linear level, diff-invariance at non-linear level

$$\int \frac{d^4x}{M_m^4} T_{\mu\nu}^{CFT_0} T_{SM}^{\mu\nu} \quad \leftrightarrow \quad h_{\mu\nu} = g_{\mu\nu} - \eta_{\mu\nu} \approx \frac{T_{\mu\nu}^{CFT_0}}{M_m^4}$$

non-conserved tensors with $\Delta = 4 + \delta$, for $\delta << 1$ (e.g. $1/N$)
dangerous Equivalence Principle Violations ... forbidden/excluded
5d 'holographic' dictionary: for $1/r_{SM} = \mu << M_m$

$$S = M^3 \int d^5x \sqrt{\hat{g}} \left(R^{(5)}(\hat{g}) + \frac{12}{\ell^2} \right) + \delta(r - r_{SM}) \int d^4x \sqrt{g} \mathcal{L}_{SM}(\psi_I, g_{\mu\nu})$$

with $g_{\mu\nu} = (M\ell)^{3/2} g_{\mu\nu}^{\mathrm{ind}}(r = r_{SM})$ and $(M\ell)^3 = \kappa_{CFT} N^2$
Similar to RS scenario, yet AdS without cutoff
5d vs 4d gravity, including SM loop corrections (à la DGP)

$$\mathcal{L}_{SM} \to \mathcal{L}_4 = \mathcal{L}_{SM} + \Lambda_4 + M_P^2 R(g) + \zeta R^2(g) + \ldots$$

with $M_P = NM_m$, $\Lambda_4 = N^2 M_m^4$, $\Lambda_{\mathrm{eff}} = \Lambda_4 - 24(M^3/\ell)$ 'tuneable'
5d/4d cross-over scale $r_c = M_P^2/M^3$

Other interactions

- Non-minimal Higgs-gravity coupling ... can drive inflation [Shaposhnikov, Bezrukov]

$$\int d^4x\sqrt{g}[M_H^2 + \zeta' R^{(4)}]|H|^2$$

  with $M_H = M_P = NM_m$, $\zeta' = N^2 \log(M_m^2/\mu^2)$
- Extra (anomalous) U(1)'s
  Assuming bi-fundamental / open-string rule, one extra U(1) is necessarily present beyond Y. In brane constructions typically several U(1)'s massive though not anomalous in 4d.
  E.g. B-L get mass from 6d anomaly [Anastasopoulos, Kiritsis].
  Generalized Chern-Simons couplings [Anastasopoulos, MB, Dudas, Kiritsis]
  Mass scale suppressed by g_s coupling to closed-string 'axions' at disk level and by large internal volumes $g^2_{YM,p}{=}g_s/\mathcal{V}_{p-3}$
- Axions ...

Basic Operators

- scalar operators, exclude relevant, yet (quasi) marginal dangerous (for EPV) e.g.

$$\mathcal{O}_\Phi = TrF^2 \rightarrow \Phi = N\mathcal{O}_\Phi / M_m^2$$

  $m_\Phi = M_m = \Lambda_{UV}$, EPV harmless: appear only for $\mu >> M_m$ where gravity description breaks down anyway

- pseudo-scalar(s) e.g.

$$\mathcal{A} = TrF\tilde{F} \rightarrow a = A/M_m^4$$

  continuous PQ symmetry: perturbatively exact, broken by (D-)instantons, Non-Perturbative potential $V_{NP} = \Lambda^4 \cos(a/f_a)$ with $f_a = M_m = M_P/N$

- vector operator(s) $\mathcal{J}_\mu$ dual to 5d gauge field(s) A_μ: no minimal coupling to messengers and (anomalous) U(1)'s

Open questions

- $N = M_P/M_m$? Nature/structure (at all scales?) of hidden CFT_0 (or more) and messenger sector(s)
- Cosmology: SM 'brane' will fall in the bulk (à la mirage cosmo), new perspectives on cosmo-constant, (early-time) inflation (e.g. axion, 'dilaton', Higgs, ...) [talk by Charmousis]
- Equivalence Principle and possible violations, 5d (above M_m) vs 4d (below M_m) nature of gravity
- Gravi-photons and extra U(1)'s, ... axions

... our focus henceforth and in the near future

‘Gravi-photons’

Focus on 'gravi-photons'

Dark or heavy photons represent natural and interesting extensions of SM, ubiquitous in (unoriented) string theory, viable candidates for dark matter in string cosmology, mixing with axions
Usually coupled with gravitational strength to SM, hence the name: 'gravi-photons'
Relevant parameters: mass M and kinetic mixing ε with visible gauge bosons (ie 'our' photon or Y)
In a 'caricature' model: SM lives on intersecting/magnetized D7-branes, hidden sector on D3-branes

- 'SM' visible matter would correspond to D7-D7
- gravity and BSM will 'emerge' from D3-D3 and D3-D7

Relevant Questions

- What kind of couplings ‘gravi-photons’ have to SM fields at dimension 4, 5 and 6?
- From which surfaces or at which order in the relevant expansion parameter these couplings get contributions from?
- Are there couplings in one description that do not appear in the other and *vice versa*?
- What are the consequences of these couplings for Physics Beyond the SM?

Two setups

- Unoriented String Theory setup [MB, Sagnotti; ...]
- Holographic setup [Kiritsis; ...]

Let us analyse them in turn

String Theory setup

Extra (anomalous) U(1)'s
Assuming bi-fundamental open-strings, one extra U(1) is necessarily present beyond Y. In brane constructions typically several U(1)'s massive though not anomalous in 4d. E.g. B-L get mass from 6d anomaly [Anastasopoulos, Kiritsis] and Generalized Chern-Simons couplings in 4d [Anastasopoulos, Bianchi, Dudas, Kiritsis]
Mass scale suppressed by g_s coupling to closed-string 'axions' at disk level and by large internal volume factors $g^2_{YM,p} = g_s/\mathcal{V}_{p-3}$
Two main possibilities

- Closed-strings eg 'RR photons' see e.g. [Camara, Ibanez, Marchesano; ...]
- Flavour or Hidden sector open-string bosons see e.g. [MB, Inverso, Morales, Ricci-Pacifici; ...]

Let us study their masses and mixings with 'visible' gauge bosons

Mixing between visible gauge bosons and closed-string 'graviphotons'

Starting from Type I open and unoriented superstrings and/or more-or-less standard D-brane actions one can derive the mixing resulting from compactifications with(out) fluxes

Mixing in the absence of closed-string "bulk" fluxes

Type I in $D = 10$, un-oriented open strings couple to un-oriented closed strings: metric G_{MN} in NS-NS sector, 2-form C_{MN} in R-R sector. Starting with the terms

$$G^{MN} G^{KL} Tr(F_{MK} F_{NL}) \quad , \quad \partial^L C^{MN} Tr(A_M F_{NL})$$

decomposing $G_{MN} \to \{g_{\mu\nu}, G_{i\mu}, g_{ij}\}$, $C_{MN} \to \{c_{\mu\nu}, C_{i\mu}, c_{ij}\}$ get

$$\mathcal{F}^{\mu\nu}_{NSNS,i} Tr(\varphi^i F_{\mu\nu}) \quad , \quad \mathcal{F}^{\mu\nu}_{RR,i} Tr(\varphi^i F_{\mu\nu})$$

for toroidal compactifications with $\mathcal{N} = 4$ supersymmetry and $O(d, d + n_a)$ symmetry.

In compactifications with lower supersymmmetry

- For $\mathcal{N} = 2$ in $D = 4$ (both R-R and NS-NS vectors)

$$\mathcal{F}^{\mu\nu}_{NSNS/RR,I} Tr(\phi^I F_{\mu\nu})$$

  where $I = 1, 2$ denote 'untwisted' directions ($\sim T^2$)

- For $\mathcal{N} = 1$ in $D = 4$ (only R-R vectors from h^-_{21}, odd under Ω)

$$\mathcal{F}^{\mu\nu}_{RR,h^-_{21}} Tr(\phi_{Adj} F_{\mu\nu})$$

Mixing in the absence of closed-string "bulk" fluxes with 'discrete' Wilson lines

In (supersymmetric) orbifold compactifications, discrete Wilson lines

$$\mathcal{F}^{\mu\nu}_{RR,h_{21}^{-},k}\, Tr(\gamma^k F_{\mu\nu}) \quad \leftrightarrow \quad \mathcal{W}^{RR}_{k-\mathrm{twist},\alpha}\, Tr(\gamma^k W^{\alpha}) + \mathrm{h.c.}$$

Alternatively one can have supersymmetric couplings to pairs of bi-fundamentals (like the Higgses in the MSSM)

$$\mathcal{F}^{\mu\nu}_{RR,h_{21}^{-}}\, Tr(\phi_{H}\phi_{\tilde{H}} F_{\mu\nu}) \quad \leftrightarrow \quad \mathcal{W}^{\alpha}_{RR,h_{21}^{-}}\, Tr(\Phi_{H}\Phi_{\tilde{H}} W_{\alpha}) + \mathrm{h.c.}$$

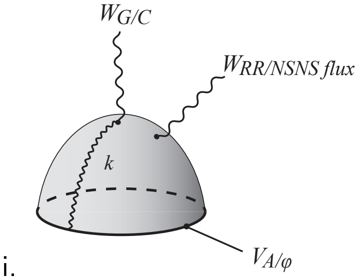
usually forbidden by additional (anomalous) U(1) symmetries acting on $H, \tilde{H}$

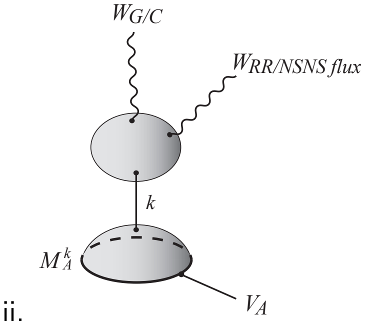
Mixing in the presence of closed-string "bulk" fluxes

Turning on 'bulk' (closed-string) R-R flux (bi-spinors)

$$f_{AB} = f_{MNP}\Gamma^{MNP}_{[AB]} + \ldots \rightarrow f_{ijk}\varepsilon_{\alpha\beta}\Gamma^{ijk}_{(ab)} + \ldots = f_{ab}\varepsilon_{\alpha\beta} + \ldots$$

$A, B{=}1, \ldots 16$, $a, b{=}1, \ldots 4$, $\alpha, \beta{=}1, 2$ of $SO(1{,}9) \supset SO(1{,}3) \times SO(6)$





subtract axion pole $2\epsilon{\cdot}p_3{=}p_1^2$ (ii) from (i), get finite contribution

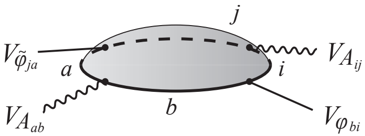
$$\mathcal{A}^{disk,flux}_{RR,vis} = f_{(ab)}\mathcal{F}^{(ab)}_{\mu\nu,RR}F^{\mu\nu}_{vis}\left[\frac{\pi}{2\alpha'\epsilon{\cdot}p_3} + \frac{\pi}{16}\right] Tr(\gamma^k Q) + \cdots$$

Similar analysis in presence of NS-NS flux ... ISD fluxes, warping

Mixing between visible and dark open-string vectors

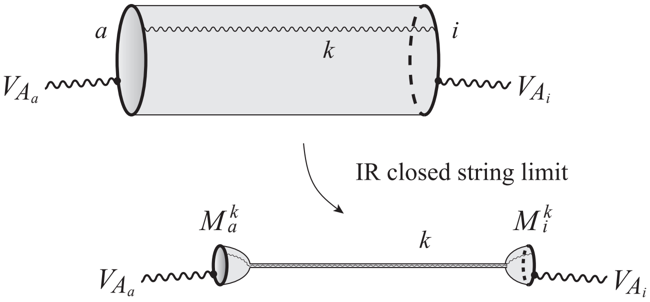
Suppose hidden gauge boson be open-string vector.
At tree-level (disk) mass mixing if scalar 'messengers' get VEVs

$$\left\langle V^{(0)}_{ab} V^{(-1)}_{\phi_{bi}} V^{(0)}_{ij} V^{(-1)}_{\tilde{\phi}_{ja}} \right\rangle_{disk} = Tr[T_{ab} T_{\phi_{bi}} T_{ij} T_{\tilde{\phi}_{ja}}] \ \langle \phi \tilde{\phi} \rangle \ a^{hid} \cdot a^{vis} + \ldots$$



Get kinetic mixing from $\alpha' p_1 p_3$ terms in ...

Mixing at 1-loop



get mass mixing

$$\mathcal{M}_{ia}^2 = \sum_{k,k'} \mathcal{M}_i^k \widetilde{\mathcal{M}}_a^{k'} h_{k,k'}^{ax}$$

with $\mathcal{M}_i^s = M_s Tr(\gamma_{(i)}^k Q_i)$, $\widetilde{\mathcal{M}}_a^k = M_s Tr(\gamma_{(a)}^k \widetilde{Q}_a)$
as well as kinetic mixing ($\sim$ threshold corrections)

Magnetic dipole couplings vs SUSY

At the same (two-derivative) order in low energy expansion
$\mathcal{N} = 4$ supersymmetry

$$\mathcal{A}^{disk}_{\mathcal{F}\lambda\lambda} = \mathcal{F}^{\mu\nu}_{RR,i}[\Gamma^i_{ab} Tr(\lambda^a \gamma_{\mu\nu} \lambda^b) + \text{h.c.}]$$

$\mathcal{N} = 2$ supersymmetry: only with gaugino bi-linear!

$$\mathcal{A}^{disk}_{\mathcal{F}\lambda\lambda} = \mathcal{F}^{\mu\nu}_{RR} Tr(\lambda^r \sigma_{\mu\nu} \lambda^s)\varepsilon_{rs} \qquad \text{while} \qquad \mathcal{A}^{disk}_{\mathcal{F}\zeta\zeta} = 0$$

$\mathcal{N} = 1$ supersymmetry: only with 'mixed' bi-linear!

$$\mathcal{A}^{disk}_{\mathcal{F}\lambda\lambda} = \mathcal{F}^{\mu\nu}_{RR,(-\frac{1}{2},-\frac{1}{2})} Tr(\lambda_{+\frac{3}{2}} \sigma_{\mu\nu} \chi_{-\frac{1}{2}})$$

Yet the QED-like dipole coupling

$$\frac{q_e}{2m_e}(g_e - 2)\mathcal{F}^{\mu\nu}_{RR} Tr(\bar{\psi}_e \gamma_{\mu\nu} \psi_e)$$

forbidden prior to supersymmetry breaking

Holographic setup

Suppose QFT_N has a global exact symmetry $\rightarrow$ emergent symmetry for SM, as for 'gravi-photons' in ST setup

SM fields do not transform under such a symmetry, NO minimal couplings. Yet quadratic mixing of emergent A_μ to SM gauge fields

Preliminary classification:

SM perspective

1. U(1) non-anomalous symmetries: SM has only hypercharge Y ('massless') and B-L ('massive')
2. U(1) "anomalous" symmetries $Tr(Q) \neq 0$ (e.g. B-L in ST setups)
3. Non-abelian gauge symmetries, e.g. SU(2) or SU(3).

QFT_N/messenger perspective

a. Global symmetries that act only on messengers (irrelevant at $\mu < M_m$).
b. R-like symmetries that act both on large-N QFT and on messengers (survive at $\mu < M_m$).
c. Flavor symmetries of the large-N QFT that do not act on messengers.

Leading couplings to visible sector

Consider abelian case with un-charged messengers: 1c, 2c. Generating functional of QFT_N + messengers $\{\eta_{ai}, \zeta_{ai}, \omega^{\mu}_{ai}\}$ with 'source' A_μ for the global current J_μ and for messenger composite operators $\{\Phi_{ij}, \Psi_{ij}, J^{\mu}_{ij}\}$ (QFT_N singlets, SM 'bi-fundamentals') that couple to SM fields $\{\phi^{ij}, \psi^{ij}, a^{ij}_{\mu}\}$

- Scalar operators Φ_{ij}: if SM singlets and UV dimension $\Delta \leq 2$ can couple to $|H|^2$. However, for stability expect QFT_N not to have any relevant scalar operators!
- Spin 1/2, fermion operators Ψ_{ij} with $\Delta \geq 3/2$ for unitarity, yet $\Delta < 5/2$ at weak coupling and $\Delta > 3/2$ at strong coupling. Couple to SM fermions ψ^{ij}. Exceptionally, $\Delta \approx 3/2$ (at strong coupling), couple to SM fermions-Higgs composites.
- Spin-1 bosonic operators J^{μ}_{ij} coupled to SM vectors a^{ij}_{μ}. For renormalizability such couplings must be gauge couplings of conserved vector currents to SM gauge fields.

Coupling to messengers

For 'bi-fundamental' messengers $\{\eta_{ai}, \zeta_{ai}, \omega^{\mu}_{ai}\}$

$$S_m = \int d^4x [\Phi_{ij}\phi^{ij} + \bar{\Psi}_{ij}\psi^{ij} + J^{\mu}_{ij} a^{ij}_{\mu} + \cdots]$$

where ϕ^{ij}, ψ^{ij}, a^{ij}_{μ} denote SM fields, while $\Phi_{ij}, \Psi_{ij}, J^{\mu}_{ij}$ messenger composite operators

$$\Phi_{ij} \sim \sum_{a=1}^{N} \eta^{\dagger}_{ai}\eta_{aj} \quad , \quad \Psi_{ij} \sim \sum_{a=1}^{N} \eta^{\dagger}_{ai}\zeta_{aj} \quad , \quad J^{\mu}_{ij} \sim \sum_{a=1}^{N} \bar{\zeta}_{ai}\gamma^{\mu}\zeta_{aj}$$

Generating functional, integrating out QFT$_N$ and messenger fields

$$\left\langle e^{\int d^4x [J_{\mu}A^{\mu} + (J^{\Phi}_{ij} + \phi_{ij})\Phi^{ij} + (\bar{J}^{\Psi}_{ij} + \bar{\psi}_{ij})\Psi^{ij} + (B^{\mu}_{ij} + a^{\mu}_{ij})J^{ij}_{\mu}]} \right\rangle$$

$$= e^{W(A_{\mu}, J^{\Phi}_{ij} + \phi_{ij}, J^{\Psi}_{ij} + \psi_{ij}, B^{\mu}_{ij} + a^{\mu}_{ij})}$$

Mixing emergent A_μ with SM vector boson(s) a^μ_{ij}

- Neither SM fields $\phi_{ij}, \psi_{ij}, a^\mu_{ij}$ nor messenger composite operator Φ^{ij}, Ψ^{ij}, J^{ij}_μ minimally coupled to A_μ
- Bi-fundamental (massive) messenger between QFT$_N$ and SM, charged under both the $U(1)_A$ and Y, one-loop computation can produce mixing F_A, F_Y if $Tr(Q_A)Tr(Q_Y) \neq 0$ (unlikely)

Low-dimension couplings to messenger bi-linears (here $M \approx M_m$)

$$W(A_\mu, \Phi_{ij}, \Psi_{ij}, B^\mu_{ij}) \sim \frac{1}{N}\left[\frac{1}{M^2}\partial_\mu\Phi\partial_\nu\Phi^* F^{\mu\nu}_A + \frac{1}{M}\bar{\Psi}\gamma_{\mu\nu}F^{\mu\nu}_A\Psi\right] +$$

$$+\frac{1}{N^{3/2}M^2}F^A_{\mu\nu}F^{B,\mu\nu}\Phi\Phi^* + \frac{1}{N^{3/2}M^3}F^A_{\mu\nu}F^{B,\mu\nu}\bar{\Psi}\Psi + \cdots$$

$\mathcal{O}(N^{-1})$ since coupling of one "gluonic" and two "mesonic" operators, while last term involves three mesonic operators. Yet, no mixing term for $Tr(Q_A)Tr(Q_B) = 0$

Integrating out massive messengers, i.e. setting Φ^{ij}, Ψ^{ij}, J_μ^{ij} to zero

$$W(A_\mu, \phi_{ij}, \psi_{ij}, a_{ij}^\mu) \sim \frac{1}{NM^2}\partial_\mu\phi\partial_\nu\phi^* F_A^{\mu\nu} + \frac{1}{NM}\bar{\psi}\gamma_{\mu\nu}F_A^{\mu\nu}\psi$$
$$+\frac{1}{N^{3/2}M^2}F_{\mu\nu}^A F^{Y,\mu\nu}HH^\dagger + \frac{1}{N^{3/2}M^3}F_{\mu\nu}^A F^{Y,\mu\nu}\bar{\psi}\psi + \cdots$$

Get A_μ coupling to a conserved topological current

$$J_\nu^T = \partial^\mu\left[\frac{1}{M^2}(\partial_\mu\phi\partial_\nu\phi^* - \partial_\mu\phi^*\partial_\nu\phi) + \frac{1}{M}\bar{\psi}\gamma_{\mu\nu}\psi\right]$$

Integrating out SM fields, kinetic mixing between F_A and F_Y

$$\int\frac{d^4x d^4y}{NM^2}F_{\mu\nu}(x)a_\rho^Y(y)[\langle\partial^\mu H\partial^\nu H^\dagger(x)J_H^\rho(y)\rangle + M\sum_\psi\langle\bar{\psi}\gamma^{\mu\nu}\psi(x)J_\psi^\rho(y)\rangle]$$

Higgs contribution has as leading term

$$\frac{1}{NM^2}\Lambda^2 F_{\mu\nu}^A F_Y^{\mu\nu} \quad \text{with} \quad \Lambda \simeq M$$

Fermionic contribution is smaller and proportional to

$$\frac{1}{NM}\sum_\psi Q_\psi^Y m_\psi \log\frac{m_\psi^2}{\Lambda^2}F_{\mu\nu}^A F_Y^{\mu\nu}$$

Kinetic Mixing of two U(1)'s: massless case

$$S = \int d^4x\{\frac{1}{4}\left[(F_1)^2 + (F_2)^2 + 2\epsilon F_1 \cdot F_2\right] + J_1 A_1 + J_2 A_2\}$$

After diagonalization

$$\widetilde{J}_1 = \frac{J_1 - \epsilon J_2}{\sqrt{1-\epsilon^2}} \approx J_1 - \epsilon J_2 \quad , \quad \widetilde{J}_2 = J_2$$

Therefore states charged only under J_2 with charge q acquire a charge under the visible C_1: $q' \simeq -\epsilon q$ for $\epsilon \ll 1$

Kinetic Mixing of two U(1)'s: massive case

$$S = \int d^4x \{ \frac{1}{4} \left[(F_1)^2 + (F_2)^2 + 2\epsilon F_1 F_2 \right] + \frac{1}{2}(m_1^2 A_1^2 + m_2^2 A_2^2) + J_1 A_1 + J_2 A_2 \}$$

In particular $m_1 = 0$ (e.g. Y) while $m_2 \neq 0$ corresponding to a SM-'anomalous' U(1).
After diagonalization

$$\int d^4x \frac{1}{4} \left[(F_{C_1})^2 + (F_{C_2})^2 \right] + \frac{m_2^2}{2(1-\epsilon^2)}(C_2)^2 +$$

$$+\frac{1}{2} C_2 \left[\sqrt{\frac{(1-\epsilon)}{(1+\epsilon)}}(J_1 + J_2) - \sqrt{\frac{(1+\epsilon)}{(1-\epsilon)}}(J_1 - J_2) \right] + C_1 J_1$$

If SM spectrum un-charged under A_1 (unlike B-L), SM fields still remain uncharged after diagonalization

Messenger coupling to emergent U(1)

Look for non-trivial correlator of messenger bi-linear to QFT$_N$ global current $\langle J^{\mu}_{IJ} \eta^i_a \eta^j_a \rangle$ start from (schematically)

$$S_{int} = \int d^4x \left[\lambda \chi^{ij}_{SM} \sum_{a \in N} \eta_{ai}\eta_{aj} + \lambda' A^{ab}_{QFT_N} \sum_{i \in SM} \eta_{ai}\eta_{bi} \right]$$

The global (R-like) currents of QFT$_N$

$$J^{IJ}_{\mu} = Tr_N[\Phi^I \partial_\mu \Phi^J - \Phi^J \partial_\mu \Phi^I]$$

Coupling to messengers via triangle diagram

$$G^{\mu,IJ}(x_1, x_2, x_3) \equiv \left\langle Tr_N[\Phi^I(x_1)\Phi^J(x_2)] a^{\mu}_{ii}(x_3) \right\rangle$$

where a^{ii}_{μ} SM U(1)'s: Y (non-anomalous), else (anomalous). Renormalizable couplings of Φ^I to messengers ... may be non-zero for abelian currents

Comparison

The two setups offer complementary perspectives

- mixing terms (kinetic and mass): tree level (disk) for RR photons with 'discrete' Wilson lines or 'bulk' fluxes, for 'hidden' brane gauge fields: tree level (disk) if messengers get VEV's, one-loop via axio-dilaton exchange.
- mixing terms (kinetic): at order 1/N, with Λ^2/M^2 (Higgs loops) and $(m/M)\log(m^2/\Lambda^2)$ (fermion loops)
- qualitative match in the holographic picture with $M_s = M_m$ and $g_s = 1/N$
- ... much left to do

Axions, just a hint

Pseudo-scalar(s) $\mathcal{A}(x) = TrF\tilde{F} \rightarrow a = A/M_m^4$, continuous PQ symmetry: perturbatively exact, broken by (D-)instantons, non-perturbative potential $V_{NP}(a) = \Lambda^4 \cos(a/f_a)$ with $f_a = M_m = M_P/N$

$$S_{ax} = \frac{M^3}{N^2}\int d^5x\sqrt{\hat{g}}Z(\partial a)^2 +$$

$$N^2\delta(r - r_{SM})\int d^4x\sqrt{g}\{[f_a^2 + \xi|H|^2 + \ldots](\partial a)^2 + V_{NP}(a) + \sum_i \mathcal{I}_i a F_i \tilde{F}_i\}$$

with $\mathcal{I}_i\delta^{ab} = Tr(T_i^a T_i^b T_{U(1)})$, axial $U(1)_A$ act on messengers

Conclusions and outlook

- The 'Theory of Everything' can be a UV-complete, large N CFT, at strong coupling
- Messengers can be heavy $M_m >> M_{SM}$
- Gravity can emerge with $M_P = N M_m$ together with axions and 'gravi-photons'
- Dark or heavy photons represent natural and interesting extensions of SM, ubiquitous in (unoriented) string theory, mixing with axions, ...
- Two scenari:
  - String Theory setup: closed-string 'RR photons', open-string hidden sectors
  - Holographic setup: global flavour or R-symmetries
- Mixing with visible gauge bosons, new interactions with SM fields and milli-charged
- Axions can enter the game ... stay tuned