Radiative SM Yukawas from dark dynamics

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Status of the Standard Models

- The SM of particle physics:
    - Flavor sector is the last not understood SM sector
- The SM of cosmology – ΛCDM:
    - Universe is dominated by DM and DE
    - Inflation is our only handle of the early Universe
- General Relativity describes gravity
    - No renormalizable quantum theory of gravity exist

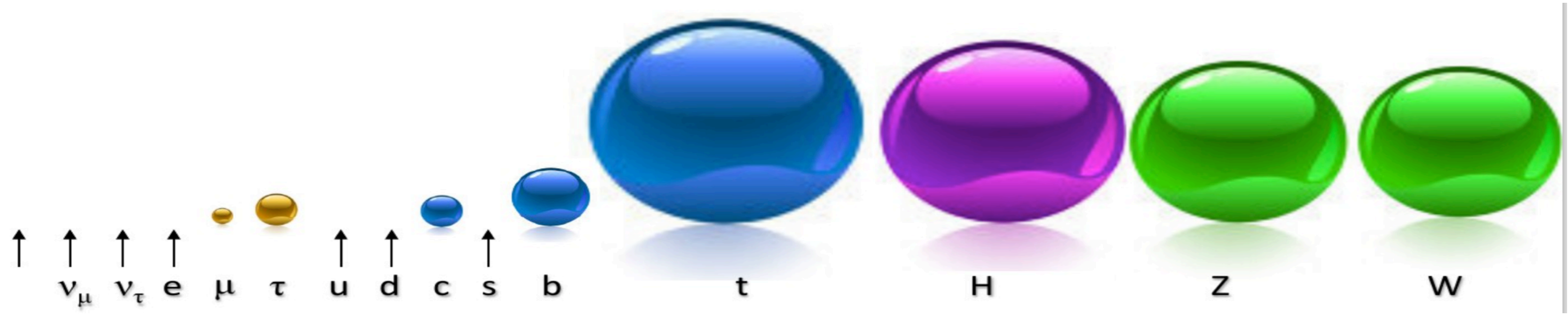
The role and the connection between these three sectors in Nature is not clear yet

What about flavour?

Higgs and flavour

- In the SM flavour is described by Yukawa interact.

$$H\psi_L^i Y_{ij} \psi_R^j$$



- Yukawa couplings are hierarchical, up and down, quark and lepton sectors are all different
- No symmetry or other fundamental principle exist to describe them
- Despite of huge amount of data, we have no understanding of the origin of flavour physics

Dominant idea: the Froggatt-Nielsen mechanism

- Based on U(1) flavour symmetry and non-renormalizable operators of the form

$$\left(\frac{\phi}{M}\right)^2 H\psi_2\psi_2 + \left(\frac{\phi}{M}\right)^3 H\psi_1\psi_3 + \left(\frac{\phi}{M}\right)^4 H\psi_1\psi_2 +$$

- Choosing $\varepsilon = \frac{\langle\phi\rangle}{M}$ and appropriate particle quantum numbers results in:

$$Y = \begin{pmatrix} \varepsilon^6 & \varepsilon^4 & \varepsilon^3 \\ \varepsilon^4 & \varepsilon^2 & \varepsilon \\ \varepsilon^3 & \varepsilon & 1 \end{pmatrix}$$

- Extendable to SU(2), SU(3) and discrete flavour symmetry groups
- Is this paradigm testable? Falsifiable?

Implications of the Higgs discovery

- The discovery of 125 GeV elementary Higgs,
  - Mass fixes only one SM parameter
  - All its properties are in agreement with the SM

together with

- the absence of any signal of physics stabilizing its mass against radiative corrections (SUSY)

exclude NP with strong coupling to Higgs at high Λ

  - Grand Unification is strongly disfavoured
  - Gravity must remain weakly coupled to Higgs at M_P

Any alternative?

Possible hint is provided by the SM

- The SM particle content is special:

ChSB=EWSB

- The hierarchy of Yukawas suggests some non-perturbative mechanism for ChSB

- In topcolour type models, based on NJL,

composite Higgs does not imply confinement

Nambu & Jona-Lasinio mechanism

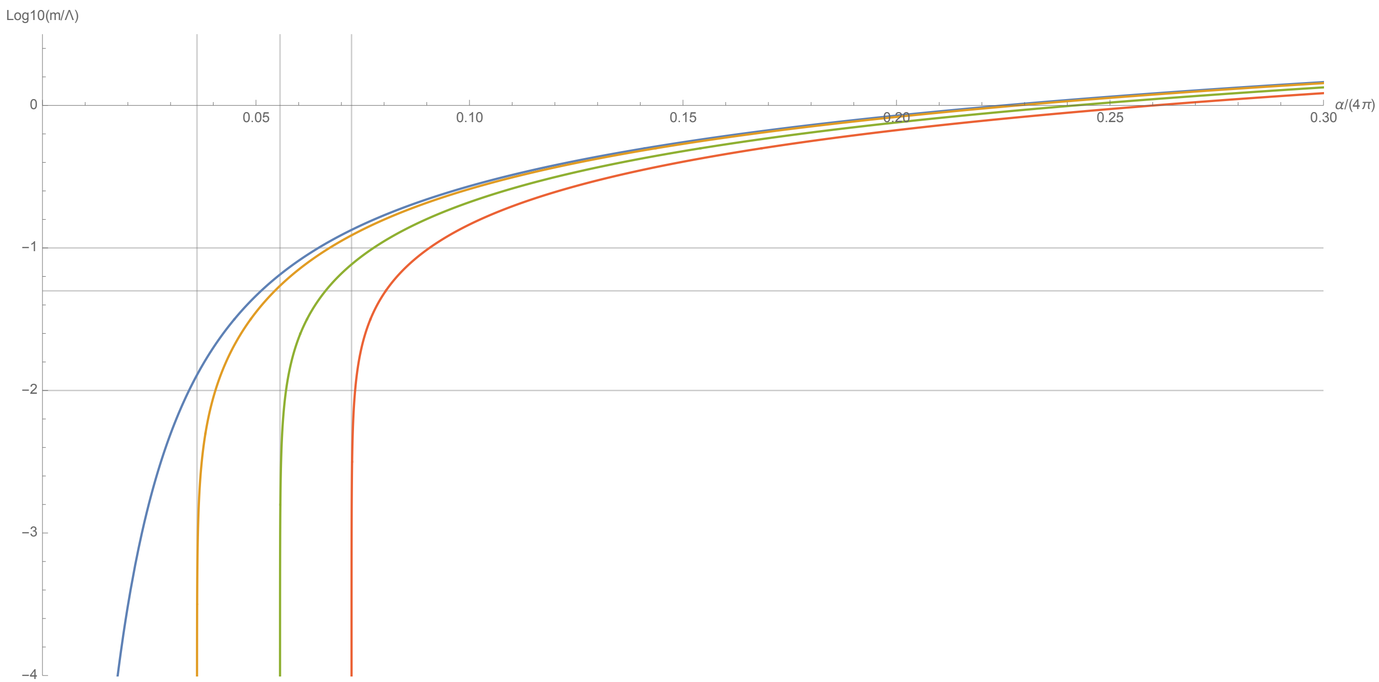
- Assume 4-fermion interaction $g(\bar{\psi}\psi)^2$ and solve mass-gap eq. for 
- Two solutions exist, m=0 and

$$G^{-1}=\frac{N_c}{8\pi^2}[\Lambda^2-m_t^2\ln(\Lambda^2/m_t^2)]$$

- Solution exists for $G > G_C$
- Chiral symmetry is spontaneously broken – composite Goldstone boson must exist

The solution admits hierarchies

- Close to critical int., stable hierarchies arise



- No viable NJL realizations in the SM exist because of the constraints on the SM interactions

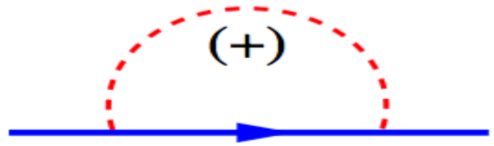
Turn to the dark side!

A strategy to build flavour models

- Assume dark sector with non-trivial dynamics
- Generate dark chiral symmetry breaking non-perturbatively so that mass hierarchies exist
- Transfer fermion mass hierarchy to the SM using appropriate messenger sector
- Study the associated phenomenology

Dark U(1) symmetry

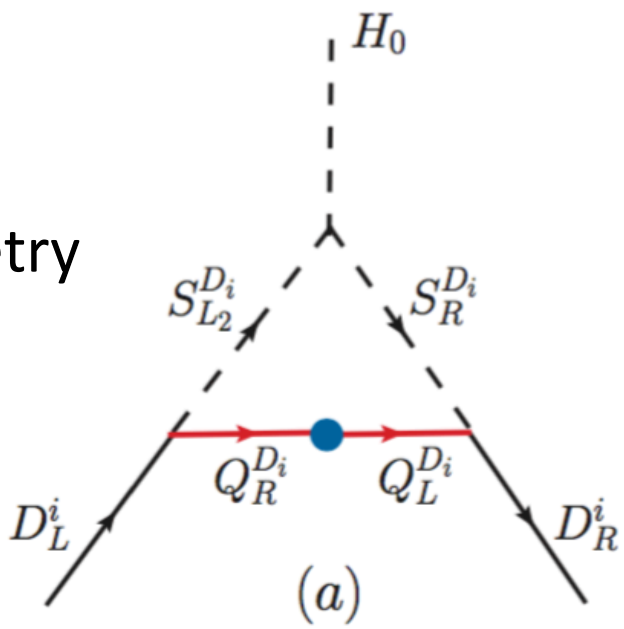
- Dark SM singlet fermions charged under $U_F(1)$
- Renormalizable mass gap equation:



- U(1) charges allow the hierarchy $m_1 << m_2 << m_3$
- Cosmological implications:
  - Lightest fermion is DM
  - Dark long-range forces may solve halo formation problems
- Particle physics implications:
  - Missing E_T signatures at colliders (DM, dark photon etc.)
  - FCNC processes for dark photons $q_2 \to q_1 \Upsilon_D$

The mechanism

- Forbid the SM Yukawas using Z_2 symmetry H-> -H
- Transfer to the SM fermions using the messengers (SUSY quantum numb.)



Fields	Spin	$SU(2)_L$	$U(1)_Y$	$SU(3)_c$	$U(1)_F$
$\hat{S}^{D_i}_L$	0	1/2	1/3	3	$-q_{D_i}$
$\hat{S}^{U_i}_L$	0	1/2	1/3	3	$-q_{U_i}$
$S^{D_i}_R$	0	0	-2/3	3	$-q_{D_i}$
$S^{U_i}_R$	0	0	4/3	3	$-q_{U_i}$
Q^{D_i}	1/2	0	0	0	q_{D_i}
Q^{U_i}	1/2	0	0	0	q_{U_i}
S_0	0	0	0	0	0

$$\mathcal{L}^I_{MS} = g_L \left(\sum_{i=1}^{N_f} [\bar{q}^i_L Q^{U_i}_R]\, \hat{S}^{U_i}_L + \sum_{i=1}^{N_f} [\bar{q}^i_L Q^{D_i}_R]\, \hat{S}^{D_i}_L \right) + $$
$$+ \; g_R \left(\sum_{i=1}^{N_f} [\bar{U}^i_R Q^{U_i}_L]\, S^{U_i}_R + \sum_{i=1}^{N_f} [\bar{D}^i_R Q^{D_i}_L]\, S^{D_i}_R \right) + $$
$$+ \; \lambda_S S_0 \left(\tilde{H}^\dagger S^{U_i}_L S^{U_i}_R + H^\dagger S^{D_i}_L S^{D_i}_R \right) + h.c., \qquad (20)$$

$$Y^{U_i} = \frac{\lambda_S\, g_L\, g_R\, \mu\, M_{Q^{U_i}}}{16\pi^2\, \bar{m}^2} C_0(x_i) \qquad M_{Q_t} \gtrsim \left(\frac{55}{g_L g_R}\right) \text{TeV}$$

Natural realization- left-right symmetry

- Gauge group $SU(2)_L \times SU(2)_R \times U(1)_Y$ forbids Yukawas for Higgs content H_L and H_R

$$\mathcal{L}_H = (D_\mu H_L)(D^\mu H_L)^\dagger + (D_\mu H_R)(D^\mu H_R)^\dagger - \lambda_L (H_L H_L^\dagger)^2 - \lambda_R (H_R H_R^\dagger)^2$$
$$- \lambda_{LR}(H_R H_R^\dagger)(H_L H_L^\dagger) + \mu_R^2 (H_R H_R^\dagger)\,,$$

Fields	Spin	$SU(2)_L$	$SU(2)_R$	$U(1)_Y$	$SU(3)_c$	$U(1)_F$
$\hat{S}_L^{D_i}$	0	1/2	0	1/3	3	$-q_{D_i}$
$\hat{S}_L^{U_i}$	0	1/2	0	1/3	3	$-q_{U_i}$
$\hat{S}_R^{D_i}$	0	0	1/2	1/3	3	$-q_{D_i}$
$\hat{S}_R^{U_i}$	0	0	1/2	1/3	3	$-q_{U_i}$
Q^{D_i}	1/2	0	0	0	0	q_{D_i}
Q^{U_i}	1/2	0	0	0	0	q_{U_i}

$$Y_f = \left(\frac{g_{LR}^2}{16\pi^2}\right)\left(\frac{\xi M_{Q_f}\sqrt{2}}{v_L}\right) f_1(x_f,\xi)$$

Lower bound on RH breaking scale

- Quark masses imply lower bound on $SU(2)_R$ scale

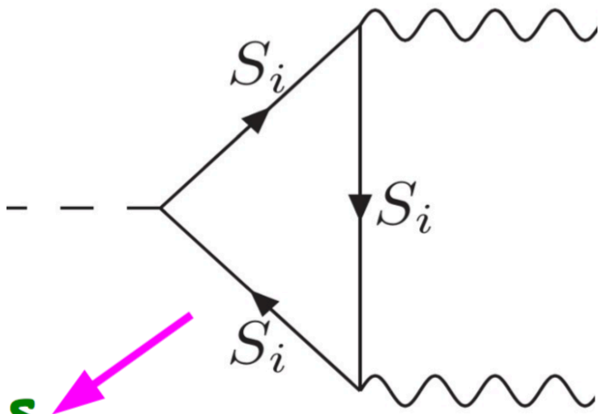
$$v_R \geq \frac{2m_t^2}{\lambda v_L} \left(\frac{16\pi^2}{g_{LR}^2} \right)^2 \xi F(\xi)^2$$

ξ	$v_R^{\min}$[TeV]	$M_{W_R}^{\min}$[TeV]	$\bar{m}^{\min}$[TeV]	$m_-^{\min}$[TeV]
0.1	1581	169	554	526
0.2	799	85	279	249
0.3	529	56	185	155
0.5	293	31	107	75
0.7	164	17	67	37
0.8	110	12	52	23
0.9	57	6	35	11
0.95	30	3	25	6

- Strong CP problem solved by LR symmetry

Collider phenomenology

- "Squark" and "slepton" mediators at the LHC, pheno resembles the one of SUSY without gluino
- Resonant mono-photon from $H \to \gamma\bar{\gamma}$



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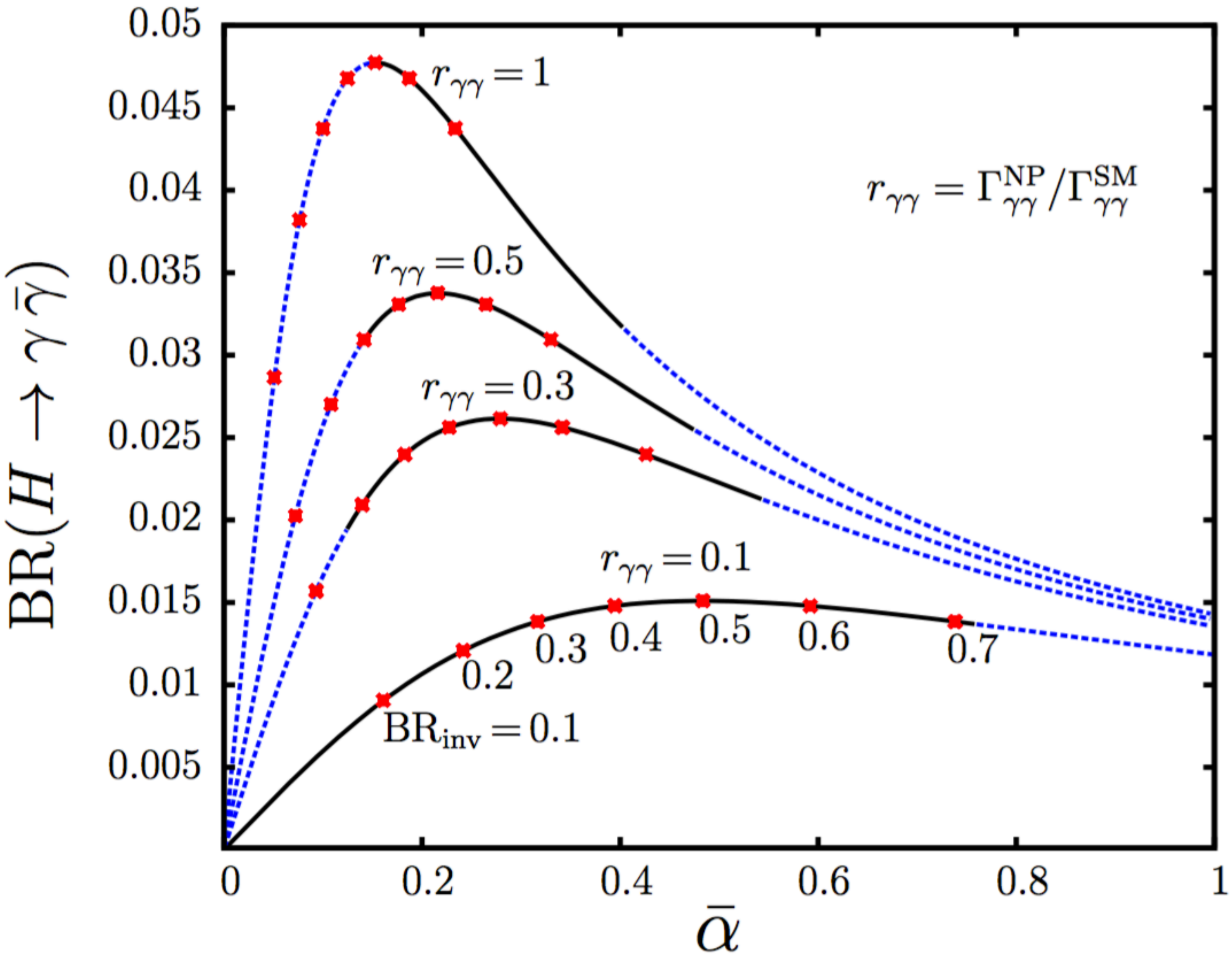
Mediators

$$\mathcal{L}_{\rm eff}^{H} = \frac{\sqrt{\alpha\bar{\alpha}}}{\Lambda_{\gamma\bar{\gamma}}}\left[H \bar{F}_{\mu\nu} F_{\mu\nu}\right]$$

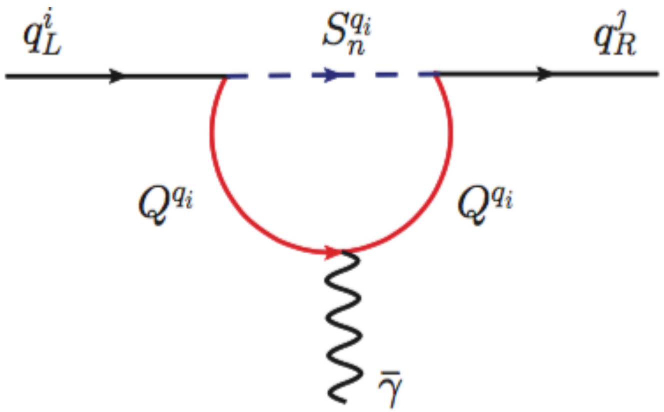
- Exp. signature $pp \to \gamma + \not{E}_T$ at the Higgs resonance has not been searched for at the LHC

Branchings can be as large as 1%

- 

FCNC decays of fermions to dark photons

- Top decay example



$$\Gamma(q^i \to q^j \bar{\gamma}) = \frac{m_{q_i}^3}{16\pi^3} \left(\frac{1}{(\Lambda_L^q)_{ij}^2} + \frac{1}{(\Lambda_R^q)_{ij}^2} \right)$$

$$\mathcal{L}_{\rm eff} = \sum_{q=U,D} \sum_{i,j=1}^{3} \left(\frac{1}{2(\Lambda_L^q)_{ij}} \left[\bar{q}_R^j(x) \sigma_{\mu\nu} \bar{F}^{\mu\nu}(x) q_L^i(x) \right] + \frac{1}{2(\Lambda_R^q)_{ij}} \left[\bar{q}_L^j(x) \sigma_{\mu\nu} \bar{F}^{\mu\nu}(x) q_R^i(x) \right] \right),$$

$$\begin{aligned} {\rm BR}^{\rm exp}(t \to u\,\gamma) &< 1.3 \times 10^{-4} \\ {\rm BR}^{\rm exp}(t \to c\,\gamma) &< 1.7 \times 10^{-3}\,. \end{aligned}$$

Max expected HL LHC sensitivity 10^{-7}

ξ_D	${\rm BR}^{\rm max}(t \to q\,\bar{\gamma})$	$\bar{m}_D^{\rm min}$[TeV]	$m_{D_-}^{\rm min}$[TeV]
0.1	1.2×10^{-14}	15	14
0.2	2.1×10^{-13}	7.7	6.9
0.3	1.3×10^{-12}	5.1	4.3
0.5	1.8×10^{-11}	2.9	2.1
0.7	2.4×10^{-10}	1.9	1.0
(0.8)	1.3×10^{-9}	1.4	0.64
(0.9)	2.0×10^{-8}	0.97	0.31
(0.95)	3.1×10^{-7}	0.68	0.15
(0.99)	1.8×10^{-4}	0.30	0.03

Conclusions

- Flavour sector remains the last not understood sector of the SM
- Dark side may be the source of flavour
- Mass hierarchy may arise non-perturbatively in the dark side and be mediated to the SM
- Most natural scenario is the left-right model with the RH breaking scale 100 TeV
- Rich phenomenology: DM with long range interact., “squarks” and “sleptons,” dark photon at colliders and in FC processes, millicharged phenomenology