

Neutral hadrons disappearing into the darkness

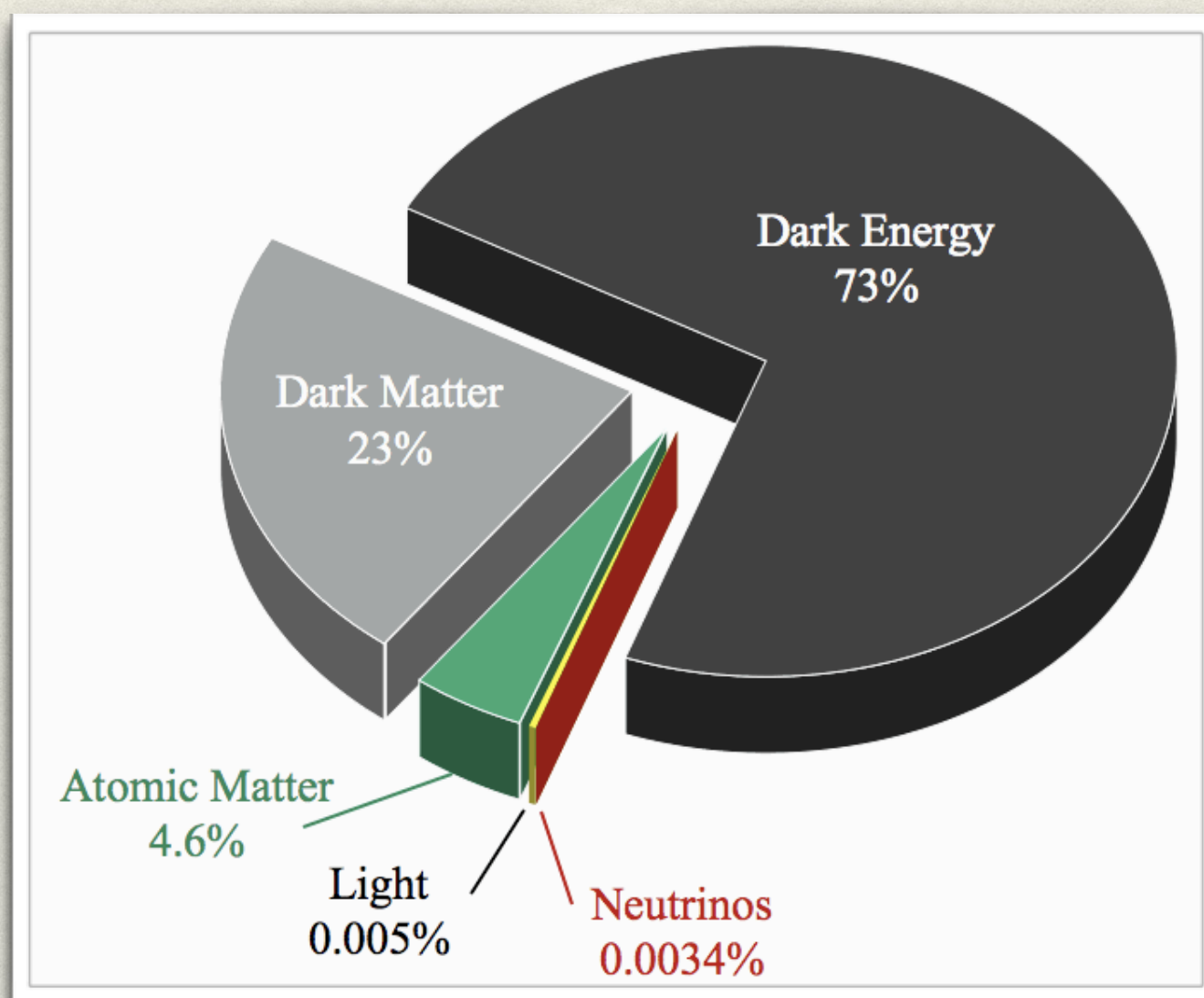
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outline

- motivations: dark sector
- implications for neutral meson decays
- other signatures
- conclusions

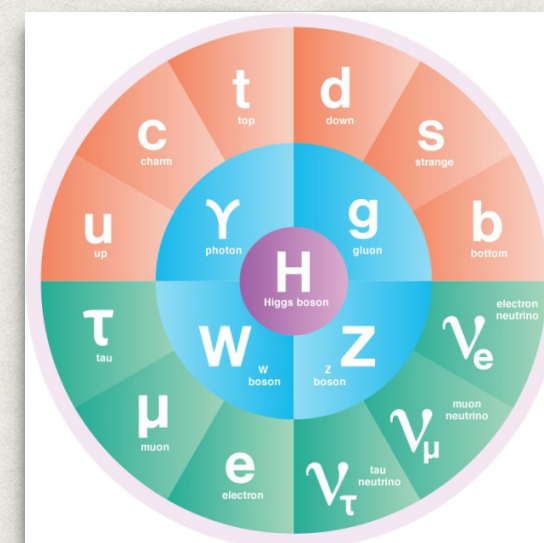
CERN, 12 October 2018, for NA64

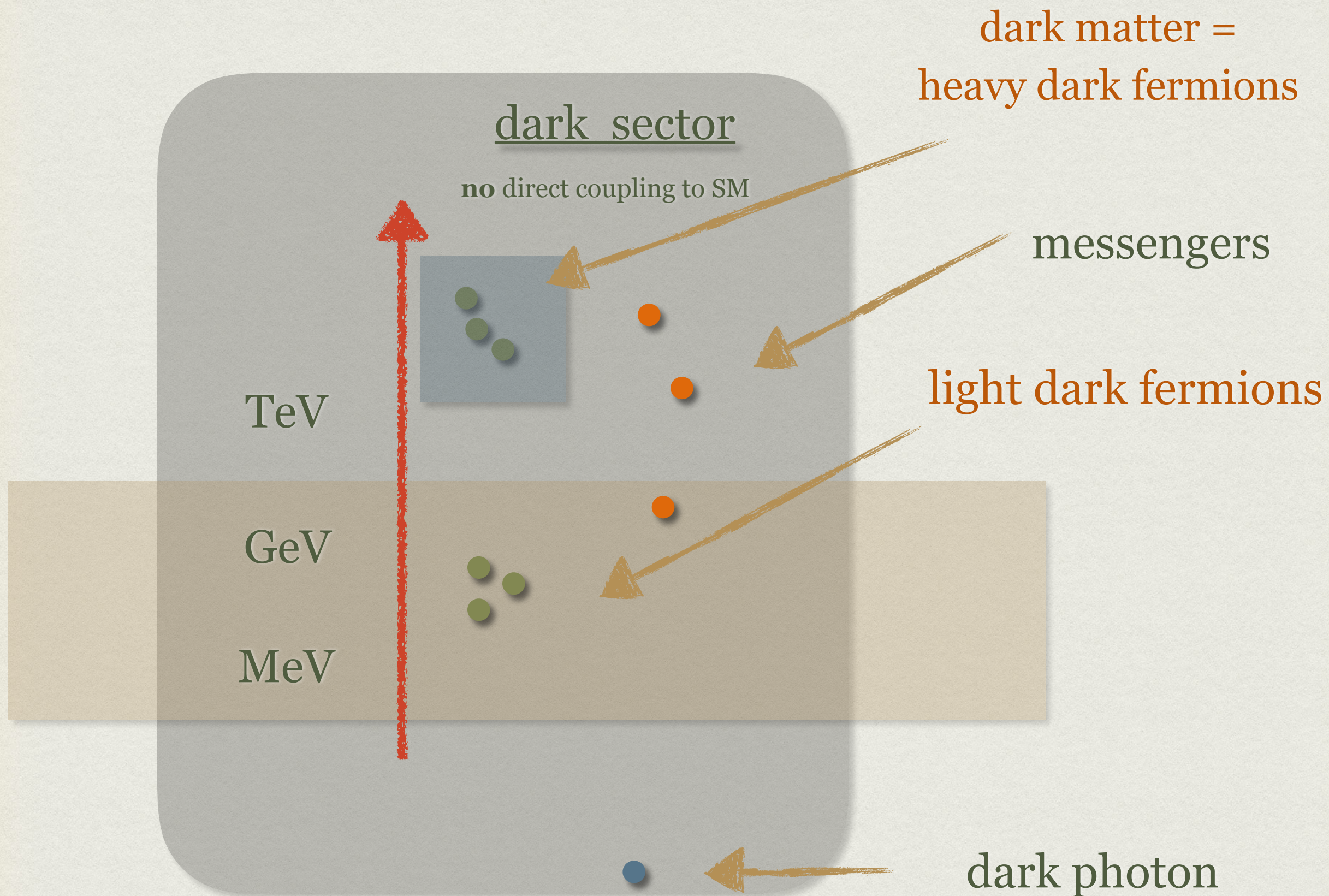


ordinary matter

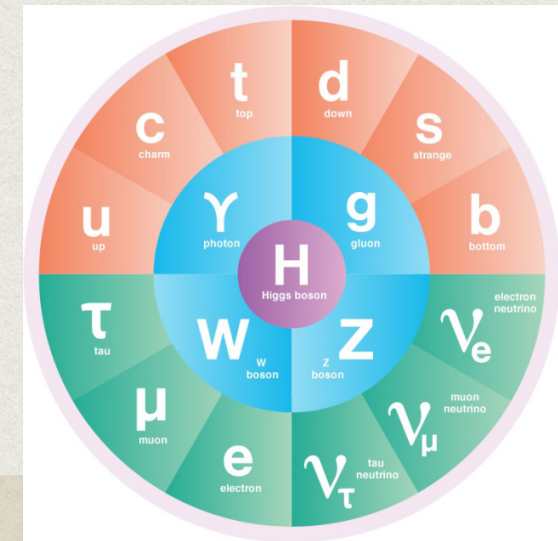
GeV

MeV





ordinary matter



dark sector

no direct coupling to SM

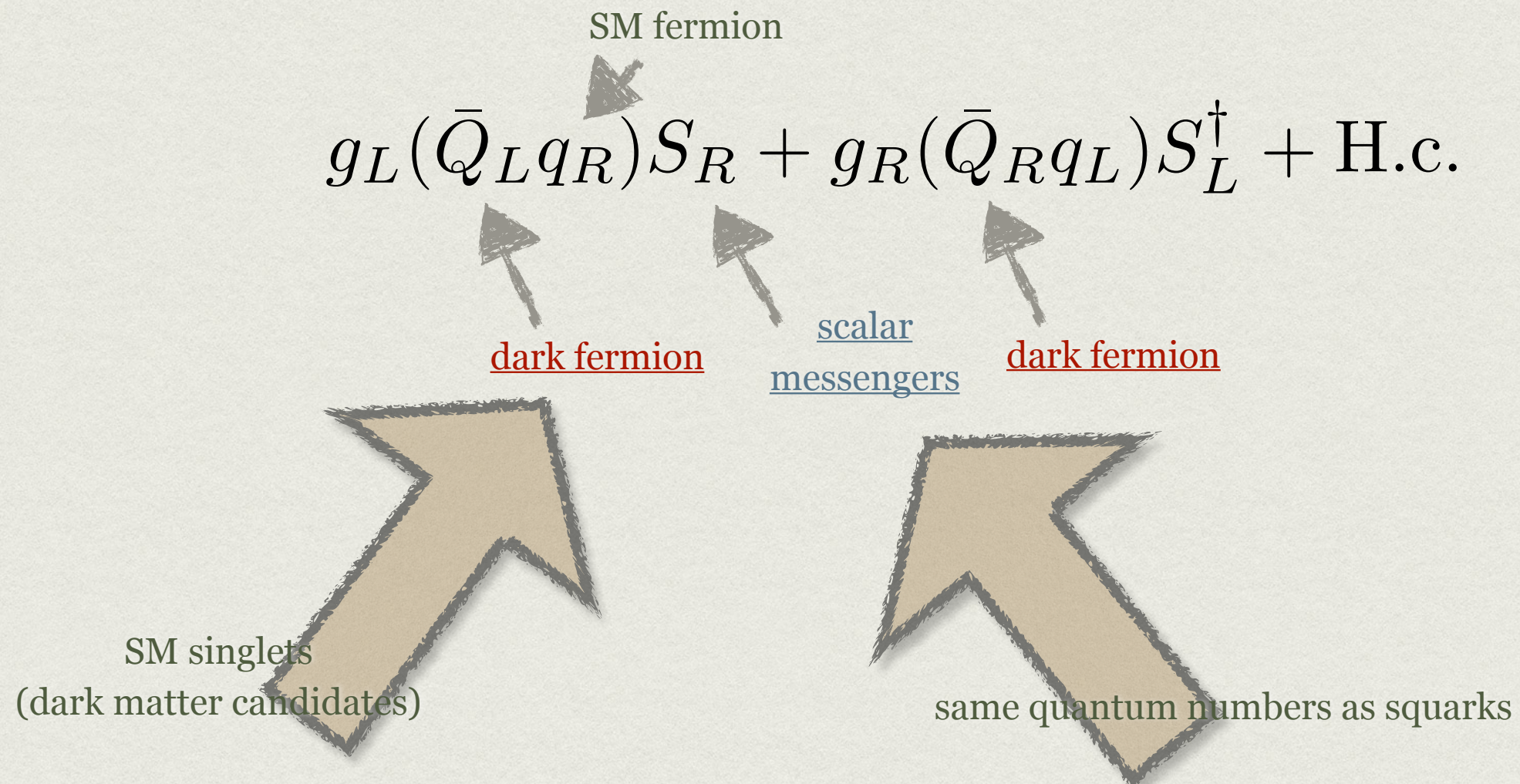
TeV

GeV

MeV

messengers make
the dark sector talk to SM

a model of dark sector



both DF and messengers charged under unbroken U(1) dark interaction

massless dark photon

model motivated to solve flavour hierarchy problem

Higgs Yukawa radiatively generated at 1-loop order

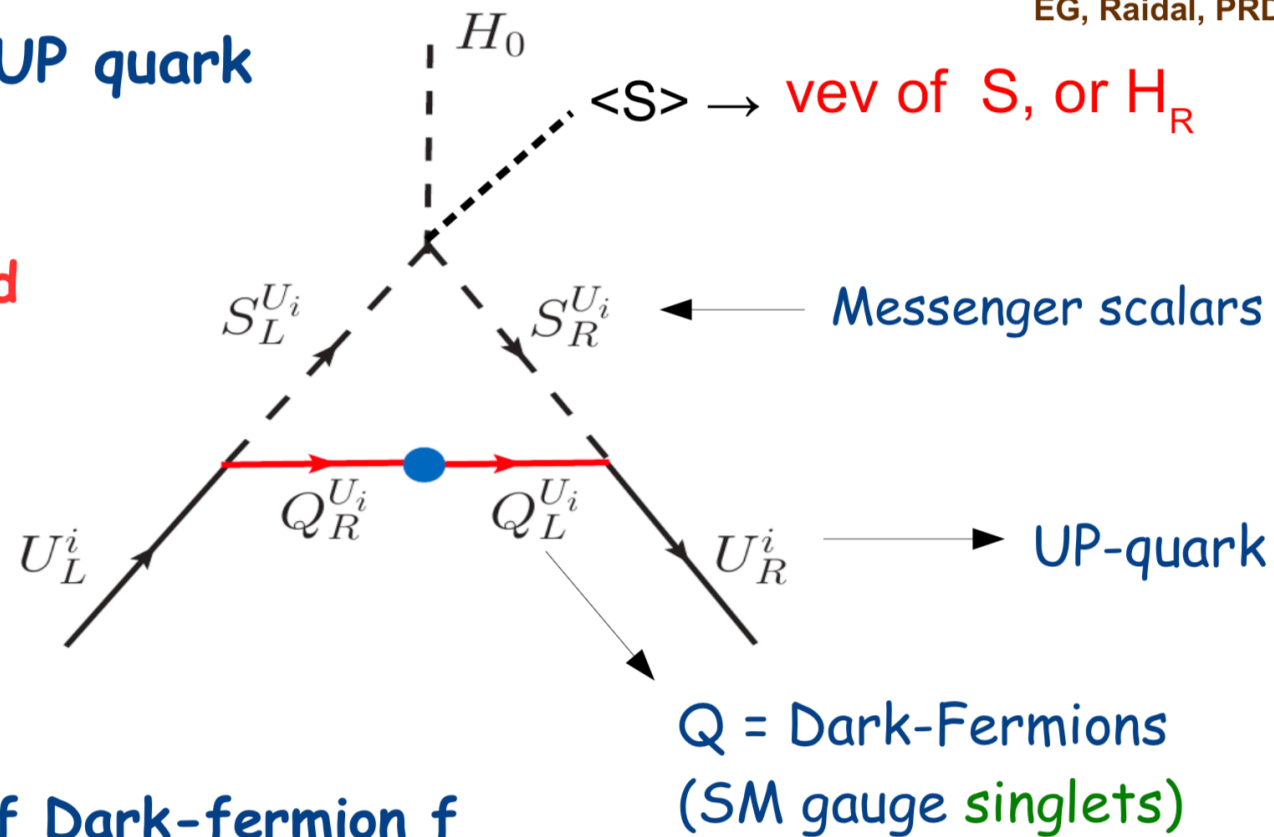
Via higher order dim. operators $\rightarrow \bar{U}_L U_R H S$ finite at any order

EG, Raidal, PRD 89 (2014)

Yukawa coupling UP quark

H_0 = Higgs field

$U(1)_F$ charge flows
only inside loop



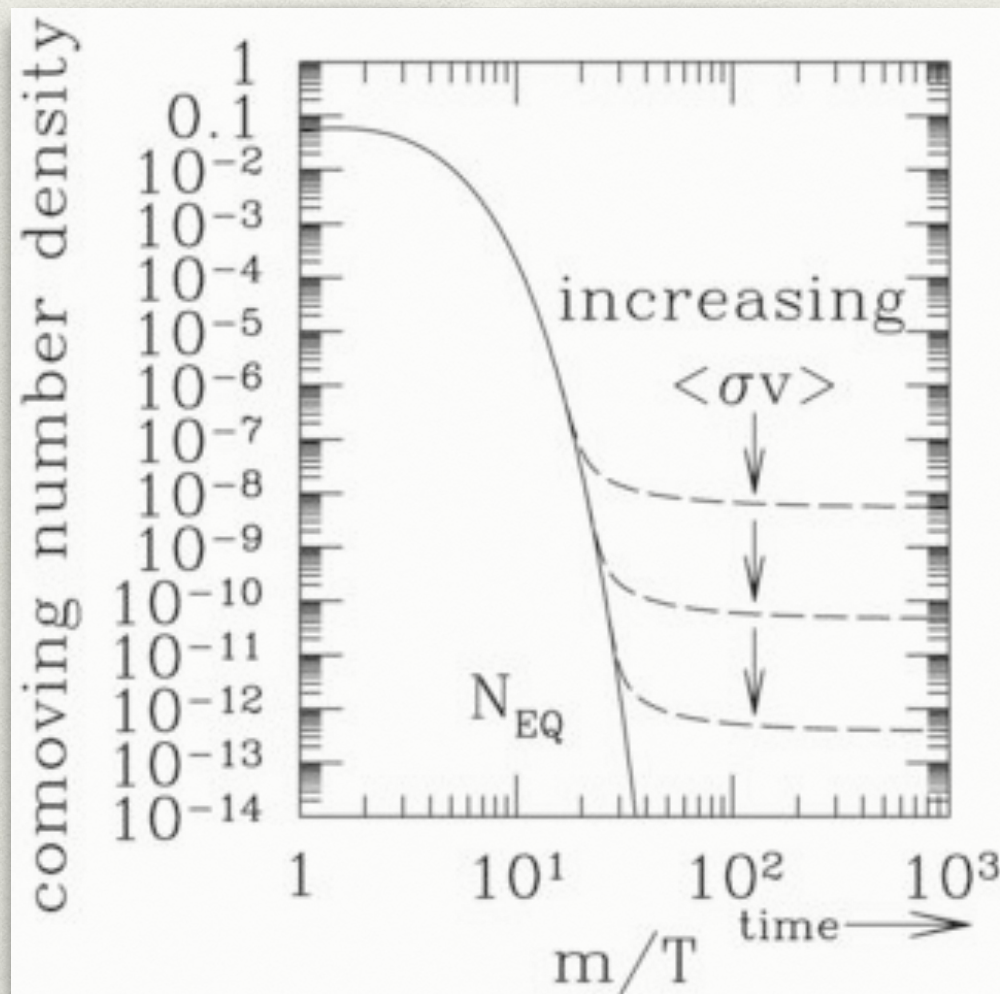
● $\rightarrow M_f$ = mass of Dark-fermion f

$$Y_f \sim \frac{M_f}{\Lambda_{\text{eff}}}$$

Yukawas follow M_f hierarchy !

dark fermions, dark matter and relic density

$$\Omega h^2 \approx \frac{2.5 \times 10^{-10} \text{ GeV}^{-2}}{\langle \sigma v_0 \rangle}$$



light dark fermions

$$\langle \sigma v_0 \rangle \simeq \frac{\pi \alpha_D^2}{2m_Q^2}$$

$$\langle \sigma v_0 \rangle \simeq \left(\frac{g_{L,R}^2}{4\pi} \right)^2 \frac{\pi}{2m_S^2}$$

heavy dark fermions

thermally averaged cross section

$$\left(\frac{g_{L,R}^2}{4\pi}\right)^2 \left(\frac{10 \text{ TeV}}{m_S}\right)^2 \simeq 0.1 \quad \longrightarrow \quad \Omega h^2 \simeq 0.12$$

constraint on long-range interaction from galaxy dynamics

$$\frac{G_N^2 m_Q^4 N}{8\alpha_D^2} \left[\ln \left(\frac{G_N m_Q^2 N}{2\alpha_D^2} \right) \right]^{-1} \gtrsim 50$$

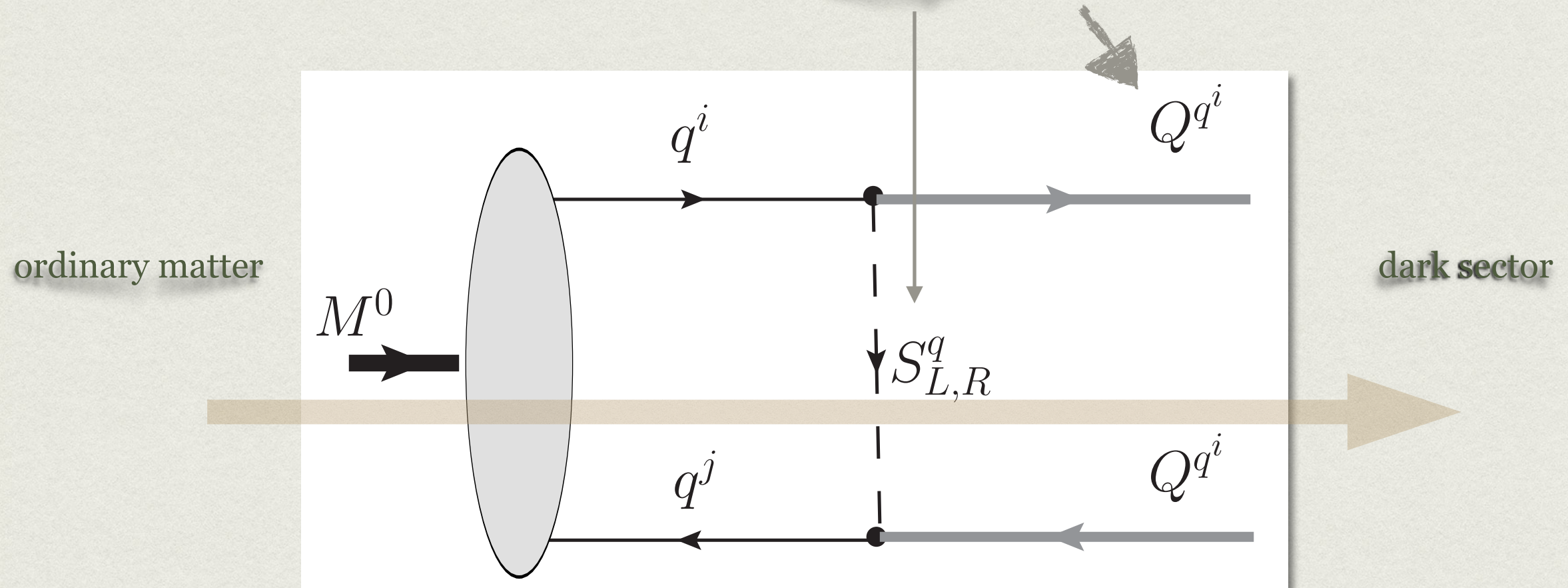
$$\alpha_D \simeq 0.1$$

$$m_Q > 8 \text{ TeV}$$

invisible decay of kaons

$$g_L(\bar{Q}_L q_R) S_R + g_R(\bar{Q}_R q_L) S_L^\dagger + \text{H.c.}$$

SM fermion
 dark fermion messenger dark fermion



effective operators

$$\hat{Q}_L^{ij} = \bar{Q}_L^i \gamma^\mu Q_L^i \bar{q}_R^j \gamma_\mu q_R^i \quad \hat{Q}_R^{ij} = \bar{Q}_R^i \gamma^\mu Q_R^i \bar{q}_L^j \gamma_\mu q_L^i$$

$$(c_L^D)_{ij} = \frac{g_L^2 P_{ij}^L}{2m_{D_L}^2} \quad \text{and} \quad (c_R^D)_{ij} = \frac{g_R^2 P_{ij}^R}{2m_{D_R}^2}$$


$$\mathcal{M}_{M^0}^{ij} = -\frac{i}{4} \left(\frac{g_L^2 P_{ij}^L}{m_{D_L}^2} [\bar{u}_{Q^i} \gamma_R^\mu v_{Q^i}] - \frac{g_R^2 P_{ij}^R}{m_{D_R}^2} [\bar{u}_{Q^i} \gamma_{LL}^\mu v_{Q^i}] \right) \langle 0 | \bar{q}^j \gamma_5 \gamma_\mu q^i | M_{ij}^0(p) \rangle$$

$$\Gamma(M_{ij}^0 \rightarrow Q^i \bar{Q}^i) = \frac{1}{8\pi} \frac{|\bar{\mathcal{M}}_{M^0}^{ij}|^2 |\vec{k}_i|}{m_{M^0}^2} \Omega_C(\beta_{ij})$$

$$|\mathcal{M}_{M^0}^{ij}|^2 = \frac{f_{M^0}^2 m_{M^0}^2 m_{Q^i}^2}{8m_S^4} P_{ij}^2 (g_L^2 + g_R^2)^2$$

Dark photon Fermi-Sommerfeld

Coulomb distortion of final-state states

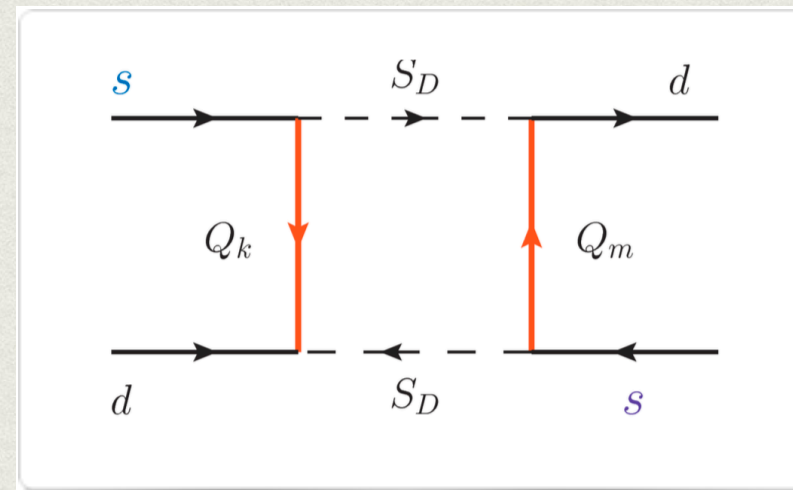
$$\Omega_C(\beta_{ij}) = \prod_{0 < i < j} \frac{2\pi\alpha_D q_i q_j}{\beta_{ij}} \frac{1}{\exp\left[\frac{2\pi\alpha_D q_i q_j}{\beta_{ij}}\right] - 1}$$

constraint from flavor physics

$$\langle M^0 | (\bar{q}_L^i \gamma^\mu q_L^j) (\bar{q}_L^i \gamma_\mu q_L^j) | \bar{M}^0 \rangle = \frac{1}{3} m_{M^0} f_{M^0}^2 B_{M^0} \eta_{\text{QCD}}$$

$$\Delta m_{M^0} = \left[\frac{g_L^4 (\rho_{ij}^L)^2 \rho_{ii}^L \rho_{jj}^L + g_R^4 (\rho_{ij}^R)^2 \rho_{ii}^R \rho_{jj}^R}{m_S^2} \right] \frac{f_{M^0}^2 m_{M^0}}{192 \pi^2}$$

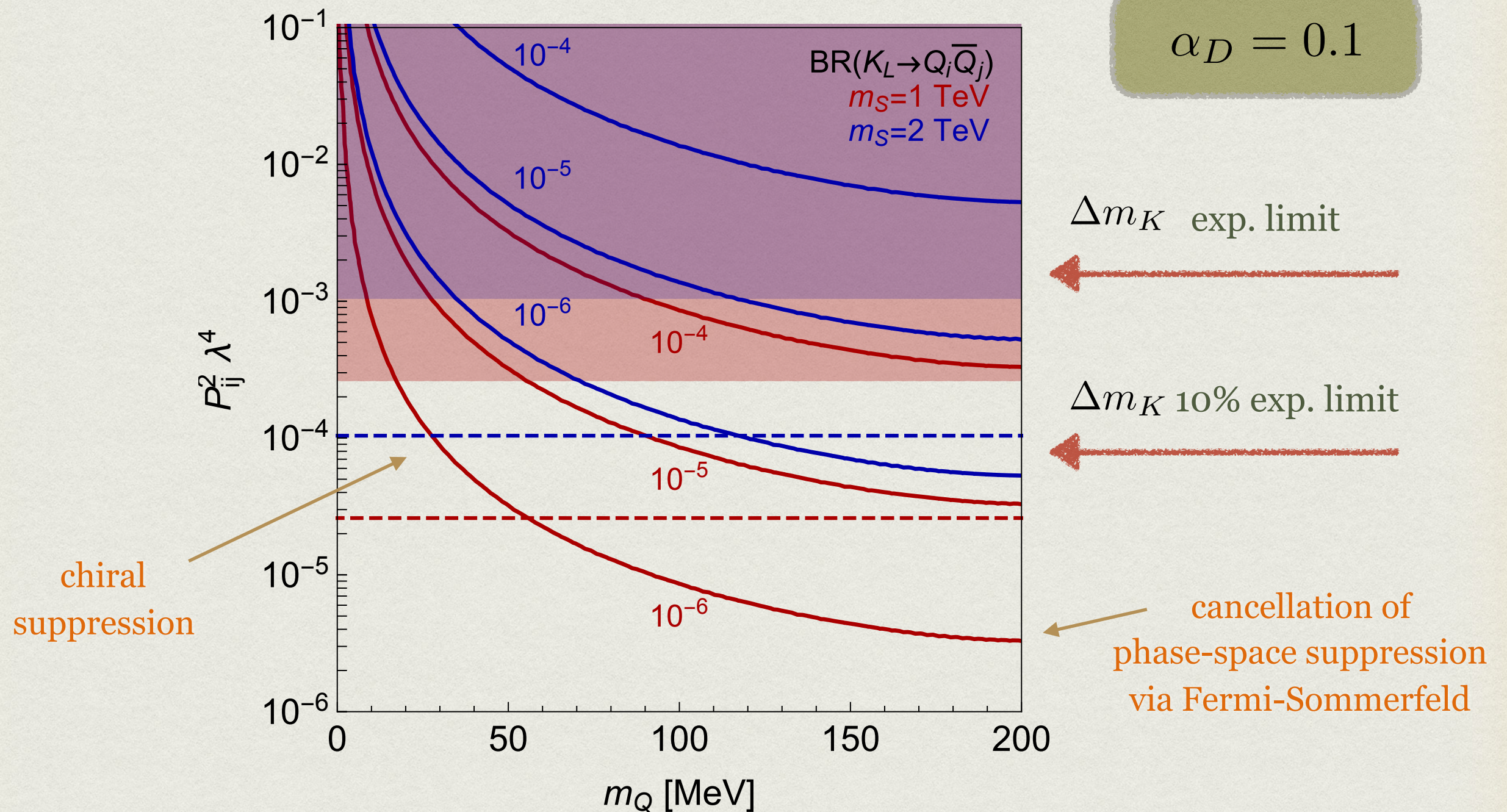
$$P_{ij}^{L,R} = \rho_{ij}^{L,R} \rho_{ii}^{L,R}$$



$$\frac{\lambda^4 P_{sd}^2}{(m_S [\text{TeV}])^2} < 2.6 \times 10^{-4}$$

invisible decay of kaons: branching ratios

13

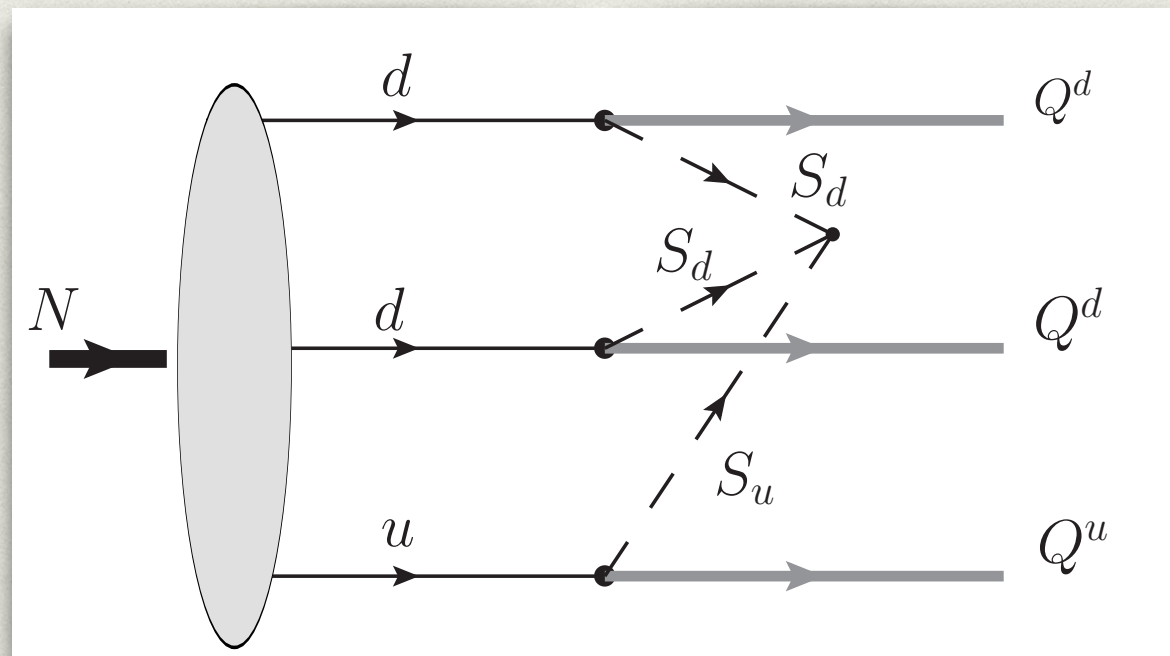


depending on the messenger mass, values between 10^{-4} and 10^{-5} can be reached

other signatures

neutron decay

proton is stable by charge conservation

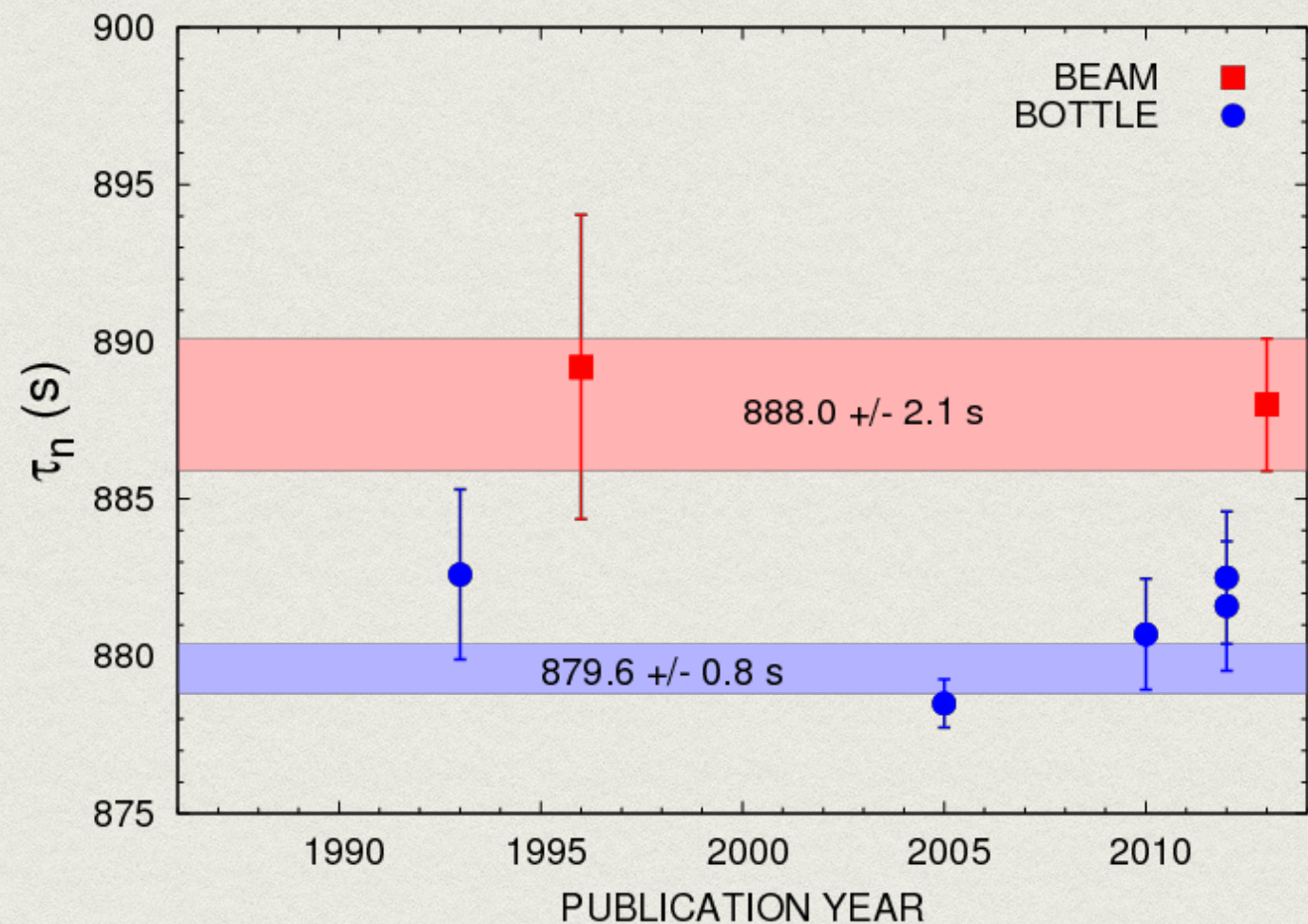


$$2Q_D = -Q_U$$

$$\Gamma_{N \rightarrow \text{invisible}} \simeq 4.9 \times 10^{-55} \left(\frac{\lambda \rho}{4\pi} \right)^6 \left(\frac{100 \text{ TeV}}{m_S} \right)^{10} \text{ GeV}$$

neutron decay naturally suppressed at $100 \text{ TeV} \ll \text{GUT}$

neutron life-time puzzle



Beryllium-8 stability

$$937.900 \text{ MeV} < 2m_D + m_U < 939.565 \text{ MeV}$$

neutron mass

$$\Gamma_{N \rightarrow Q^U Q^D Q^D} \simeq 4.9 \times 10^{-35} \left(\frac{\lambda \rho}{4\pi} \right)^6 \left(\frac{1 \text{ TeV}}{m_S} \right)^{10} \text{ GeV}$$

dark photon ★

massive

direct coupling to SM

$$\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$



$$g' q_f \bar{\psi}_i \gamma^\mu \psi_f A'_\mu$$

massless

no direct coupling to SM

only
higher dimensional
operators



$$\frac{g}{\Lambda} \bar{\psi} \sigma^{\mu\nu} \psi \bar{F}_{\mu\nu}$$

B. Holdom, *Phys. Lett.* **166B** (1986) 196



possible role in galaxy formation and dynamics

vector **massless** dark photon

unbroken U(1) symmetry

possible signature in Kaon physics

M. Fabbrichesi, EG, B. Mele

Phys. Rev. Lett. **119** (2017) 031801 [arXiv:1705.03470]



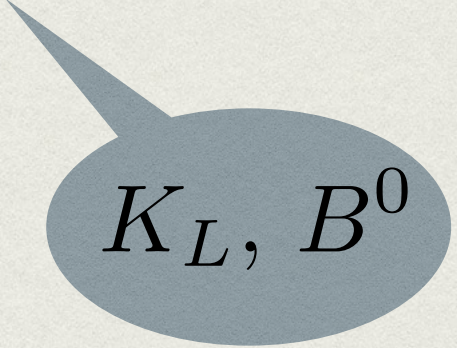
$$K^+ \rightarrow \pi^+ \pi^0 \bar{\gamma}$$

massless invisible system

$$\left(K^+ \rightarrow \pi^+ \bar{\gamma} \right. \text{forbidden} \left. \text{with a 'no' symbol} \right)$$

conclusions

- **dark matter** constituents:
heavy dark fermion interacting (via dark photon)
- **light dark fermions**:
can be produced in low-energy experiments
remarkable signature: invisible decays into the dark sector
- other signatures:
neutron decay (life-time puzzle)
dark photon in $K^+ \rightarrow \pi^+ \pi^0 \bar{\gamma}$



K_L, B^0

