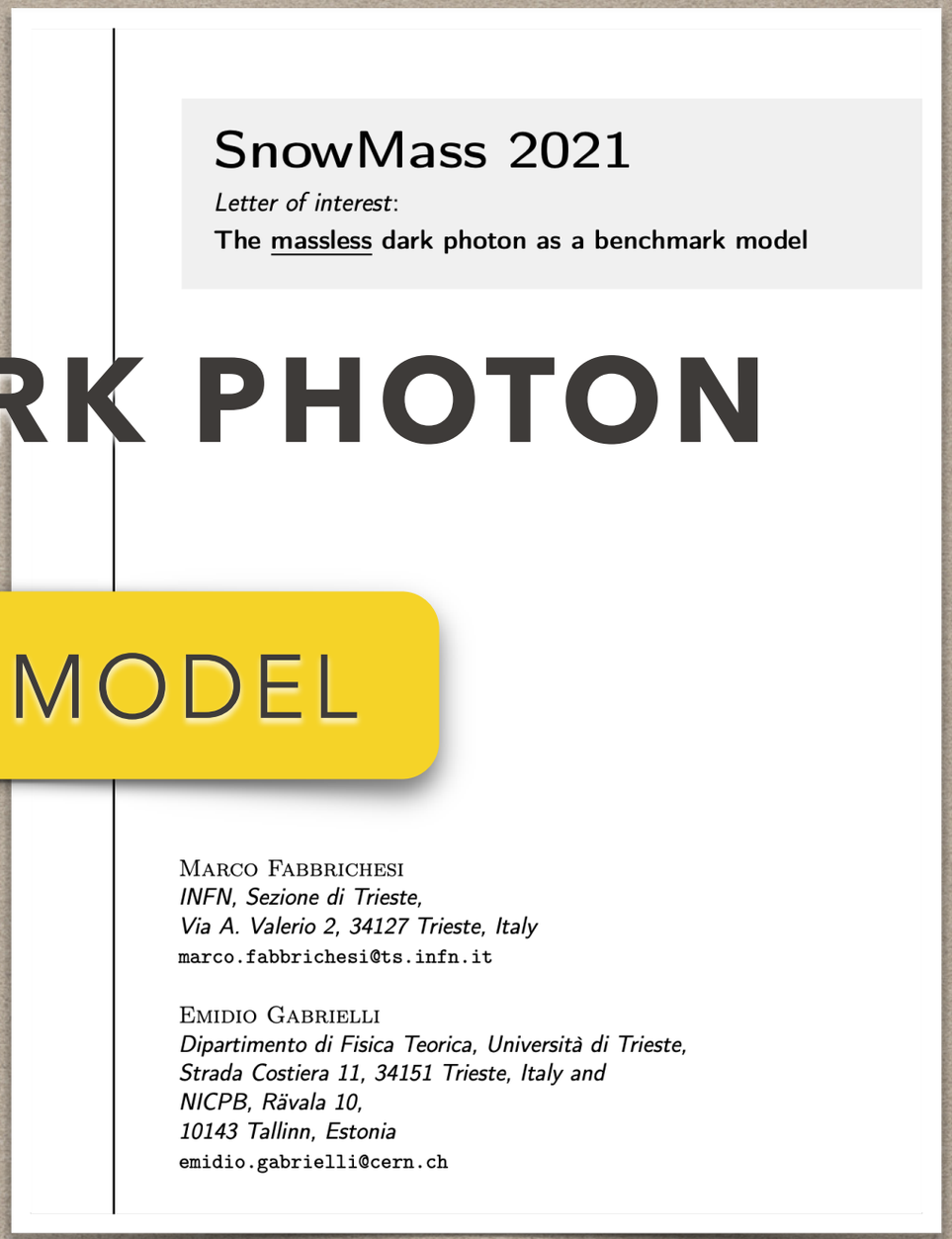
THE MASSLESS DARK PHOTON

AS A BENCHMARK MODEL



SnowMass 2021

Letter of interest:

The massless dark photon as a benchmark model

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Snowmass 2021

2 october 2000

see, arXiv:2005.01515

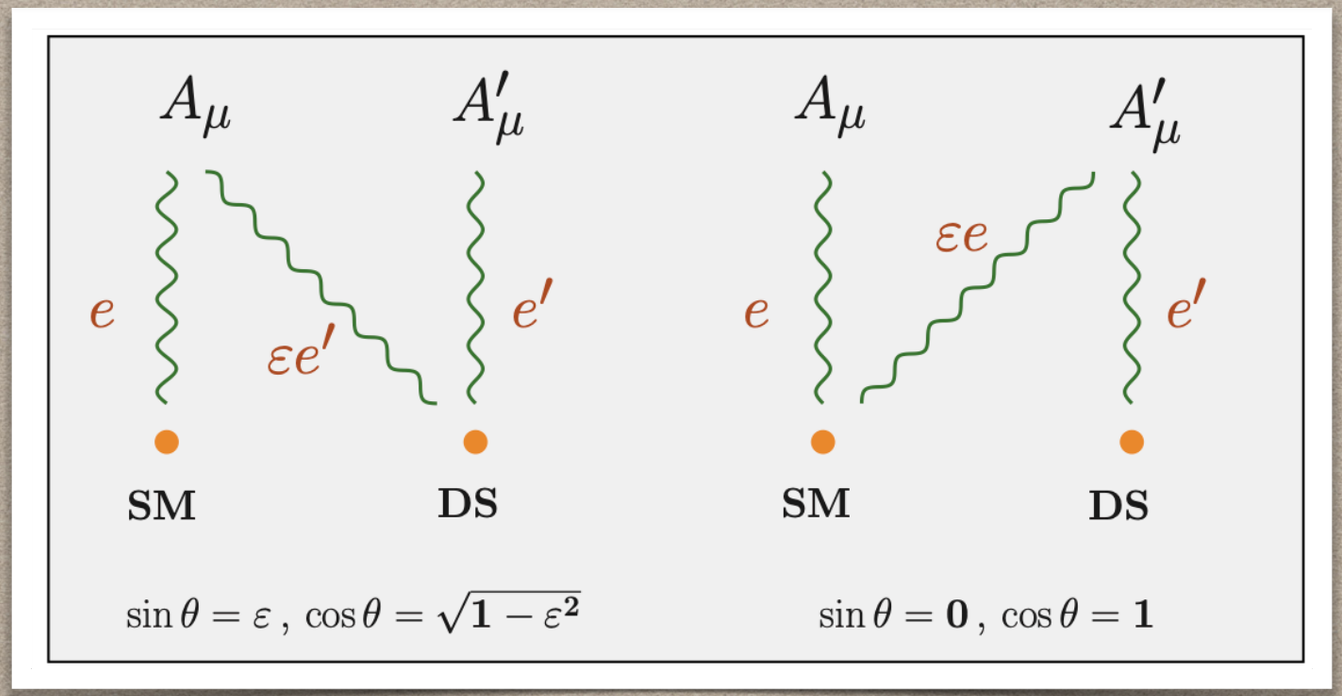
$$\mathcal{L}_0 = -\frac{1}{4}F_{a\mu\nu}F_a^{\mu\nu} - \frac{1}{4}F_{b\mu\nu}F_b^{\mu\nu} - \frac{\varepsilon}{2}F_{a\mu\nu}F_b^{\mu\nu}$$

$$\boxed{\mathcal{L} = e\, J_\mu A_b^\mu + e'\, J'_\mu A_a^\mu}$$

rotation

$$\begin{pmatrix} A_a^\mu \\ A_b^\mu \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{1-\varepsilon^2}} & 0 \\ -\frac{\varepsilon}{\sqrt{1-\varepsilon^2}} & 1 \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A'^\mu \\ A^\mu \end{pmatrix}$$

$$
\begin{aligned}
\mathcal{L}' = & \left[\frac{e'\cos\theta}{\sqrt{1-\varepsilon^2}} J'_\mu + e\left(\sin\theta - \frac{\varepsilon\cos\theta}{\sqrt{1-\varepsilon^2}}\right) J_\mu\right] A'^\mu \\
+ & \left[-\frac{e'\sin\theta}{\sqrt{1-\varepsilon^2}} J'_\mu + e\left(\cos\theta + \frac{\varepsilon\sin\theta}{\sqrt{1-\varepsilon^2}}\right) J_\mu\right] A^\mu .
\end{aligned}
$$



Stuekelberg masses

$$\mathcal{L}_{Stu} = -\frac{1}{2}M_a^2 A_{a\mu}A_a^\mu - \frac{1}{2}M_b^2 A_{b\mu}A_b^\mu - M_a M_b A_{a\mu}A_b^\mu$$

$$\sin\theta = \frac{\delta\sqrt{1-\varepsilon^2}}{\sqrt{1-2\delta\varepsilon+\delta^2}} \qquad \cos\theta = \frac{1-\delta\varepsilon}{\sqrt{1-2\delta\varepsilon+\delta^2}}$$

$$\begin{aligned}\mathcal{L}'' = & \frac{1}{\sqrt{1-2\delta\varepsilon+\delta^2}}\left[\frac{e'\left(1-\delta\varepsilon\right)}{\sqrt{1-\varepsilon^2}}J'_\mu + \frac{e\left(\delta-\varepsilon\right)}{\sqrt{1-\varepsilon^2}}J_\mu\right]A'^\mu \\ + & \frac{1}{\sqrt{1-2\delta\varepsilon+\delta^2}}\left[eJ_\mu - \delta e' J'_\mu\right]A^\mu\end{aligned}$$

massless

NOT the $m_{A'} \to 0$ limit

$$\mathcal{L}' = e' J'_\mu A'^\mu + \left[-\frac{e'\varepsilon}{\sqrt{1-\varepsilon^2}} J'_\mu + \frac{e}{\sqrt{1-\varepsilon^2}} J_\mu \right] A^\mu$$

no direct interaction with visible sector

massive

$$\mathcal{L} \supset -\frac{e\varepsilon}{\sqrt{1-\varepsilon^2}} J_\mu A'^\mu \simeq -e\,\varepsilon\, J_\mu A'^\mu$$

benchmark model: ***the dipole operator***

$$d_M^{ij} \equiv |\mathbb{D}_M^{ij}|$$

$$\mathcal{L} = \frac{e_D}{2\Lambda^2} \overline{\psi}_L^i \, \sigma_{\mu\nu} \left(\mathbb{D}_M^{ij} + i\gamma_5 \, \mathbb{D}_E^{ij} \right) H \psi_R^j \, F'^{\mu\nu} + \text{H.c.}$$

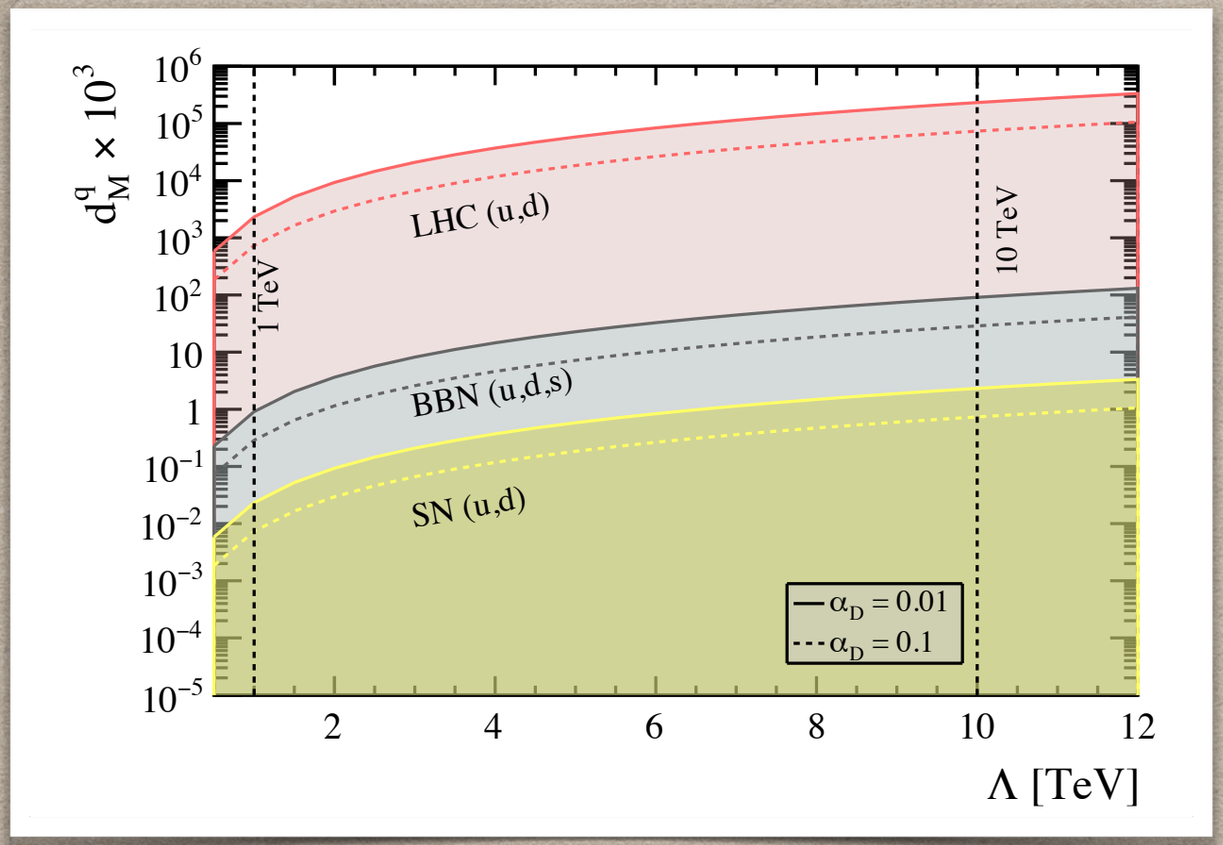
effective scale Λ

as for a very light
axion or massive dark photon

<u>many constraints</u>:

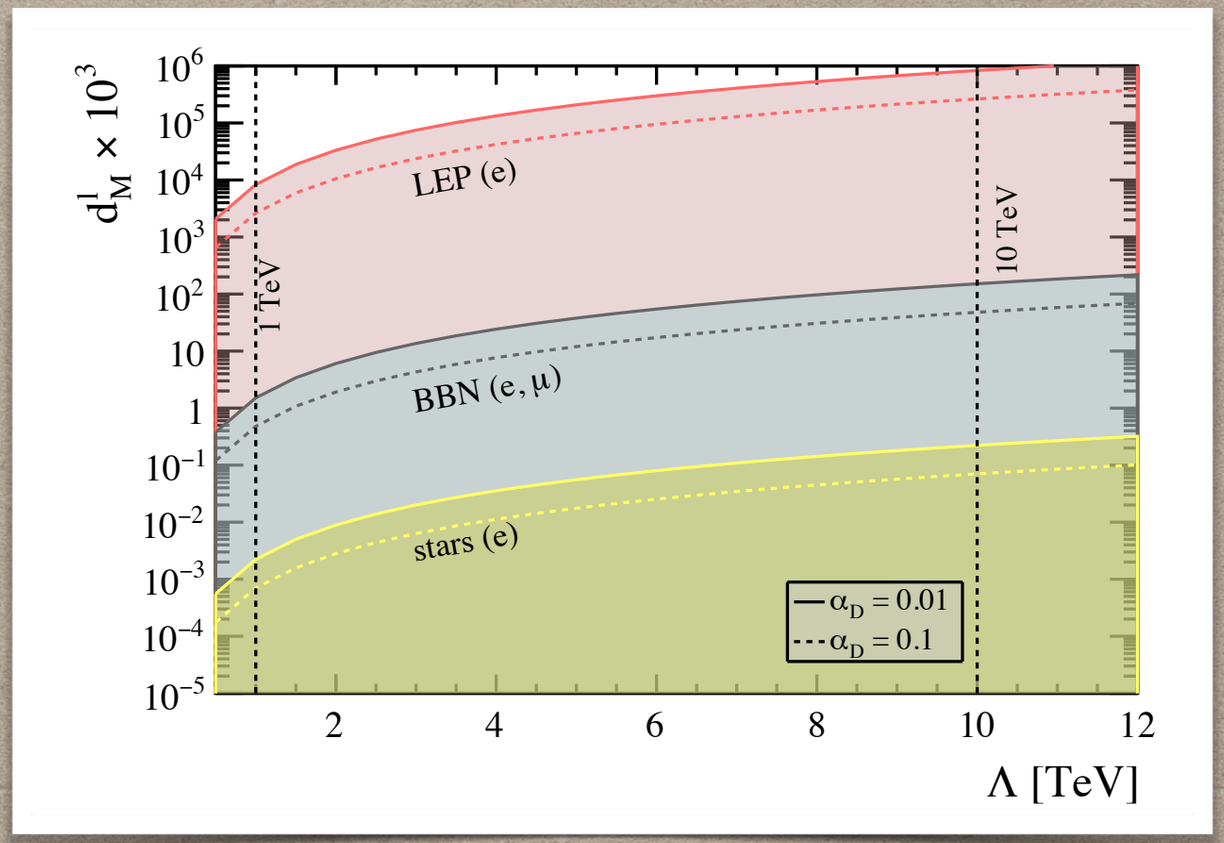
- *energy losses in stars and supernovae*
- *primordial nucleosynthesis*
- *precision and flavor physics*

figures from
F., Gabrielli, Lanfranchi, arXiv:2005.01515



quarks

leptons



implementation of the benchmark model

NA62, NA64, KOTO, BESIII, BaBar, BELLE

$$K^+ \to \pi^0 \pi^+ A'$$
$$K^+ \to \pi^+ \nu\bar{\nu}$$
$$K_L \to \pi^0 \nu\bar{\nu}$$

$$H^0 \to \gamma A'$$
$$Z^0 \to \gamma A'$$

- Flavor physics
- Higgs and Z physics
- Pair annihilation
- Magnons
- Astrophysics

$$e^+ e^- \to \gamma A'$$

present and future colliders

snowmass 2021

most work already on arXiv:
e.g. 2006.15945,1911.03755,
1806.05678,1712.05412,
1705.03470

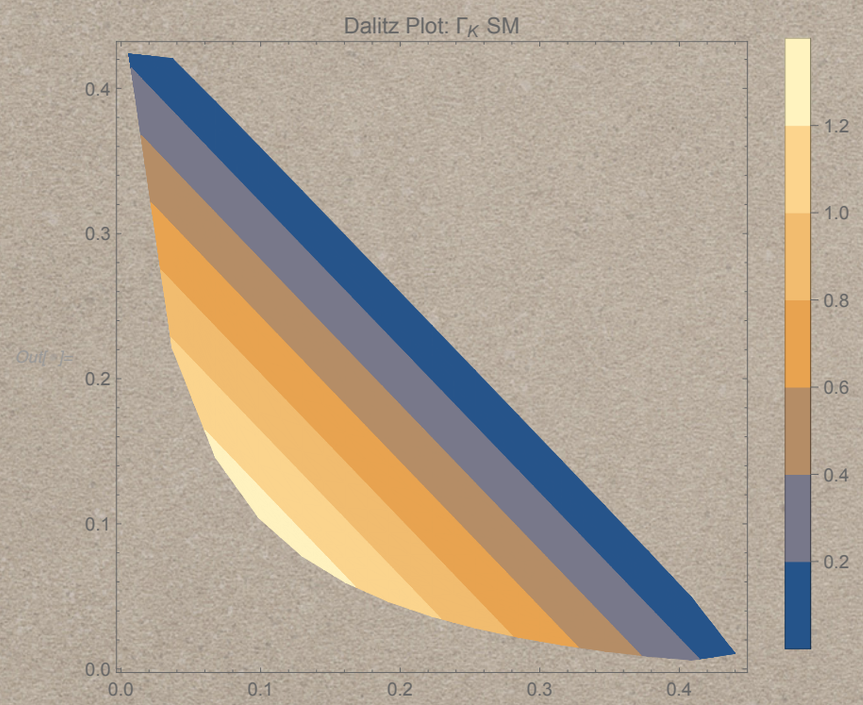
plan:

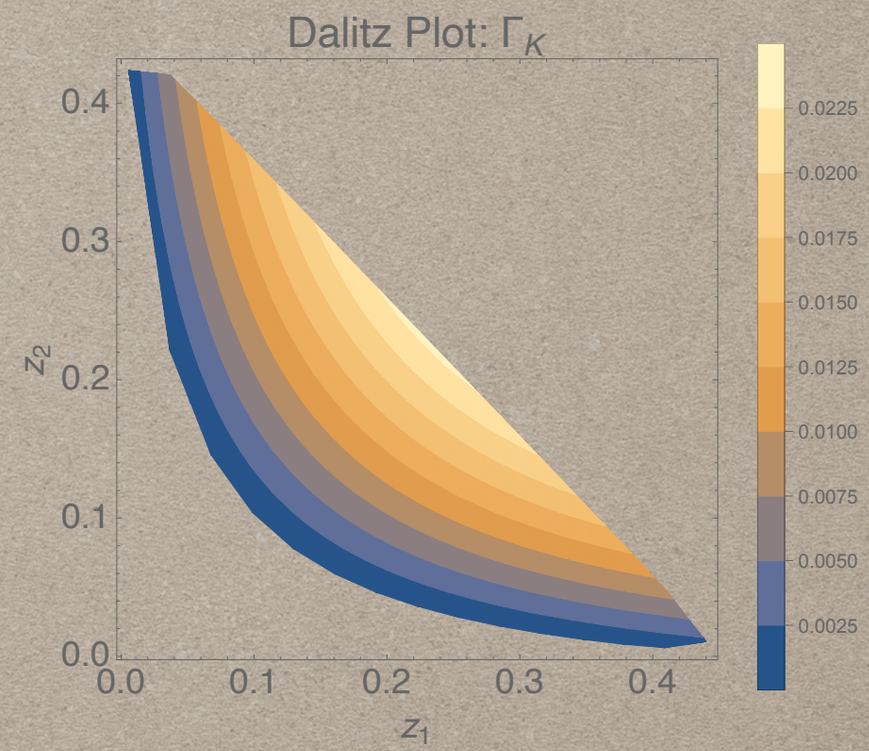
- *write a contributed paper (first half of 2021)*
  (motivations and characteristic signature)

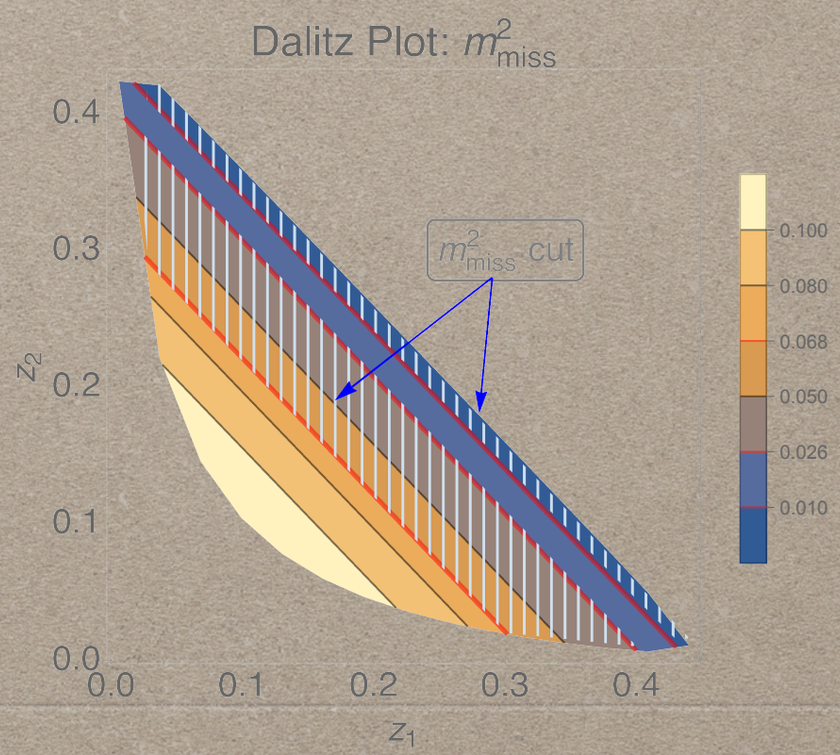
- *have experiments include new kinematics*
  in their data analysis

(next slide, please)

e.g.: the NA62 experiment $K^+ \to \pi^+ \nu \bar{\nu}$





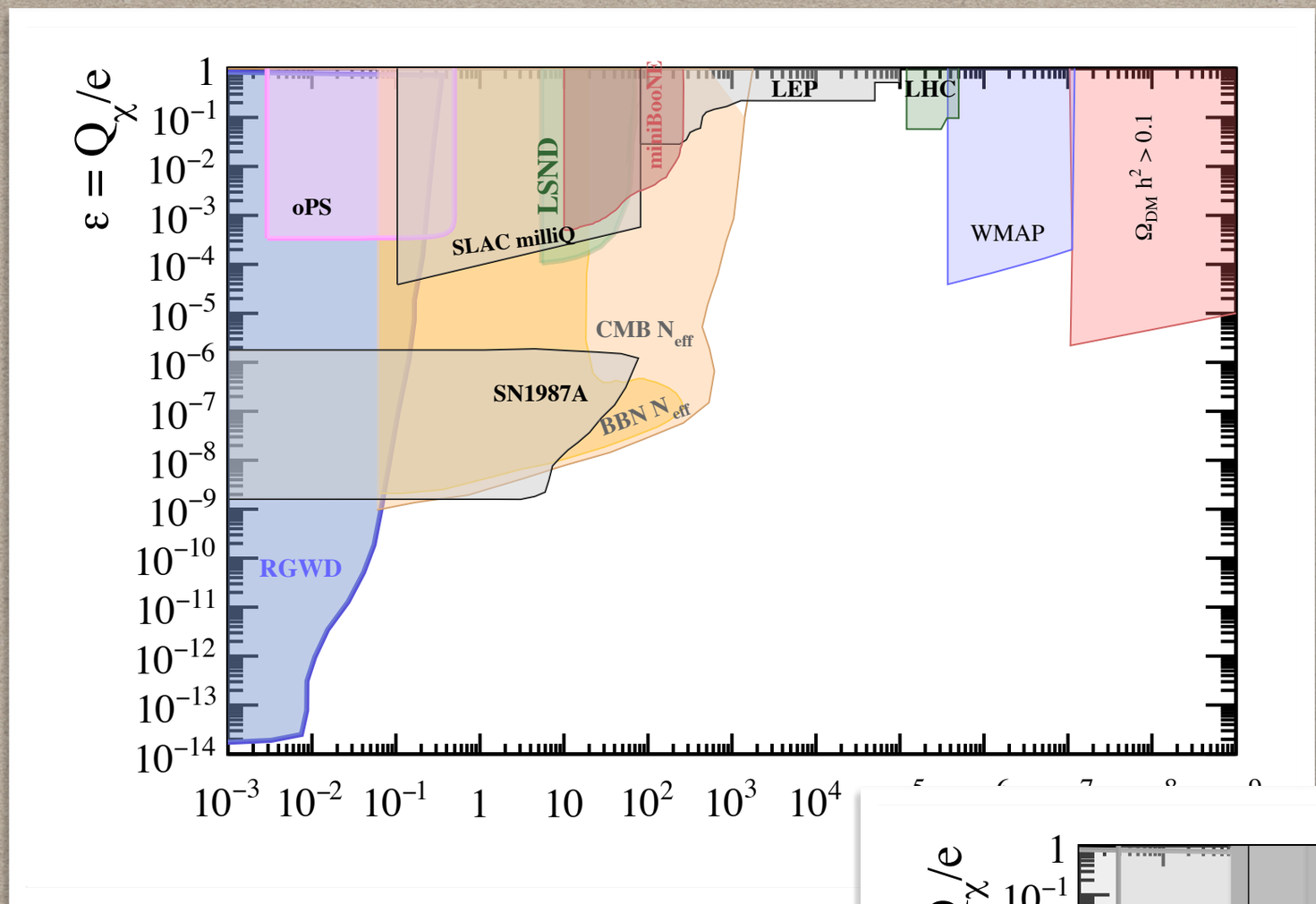


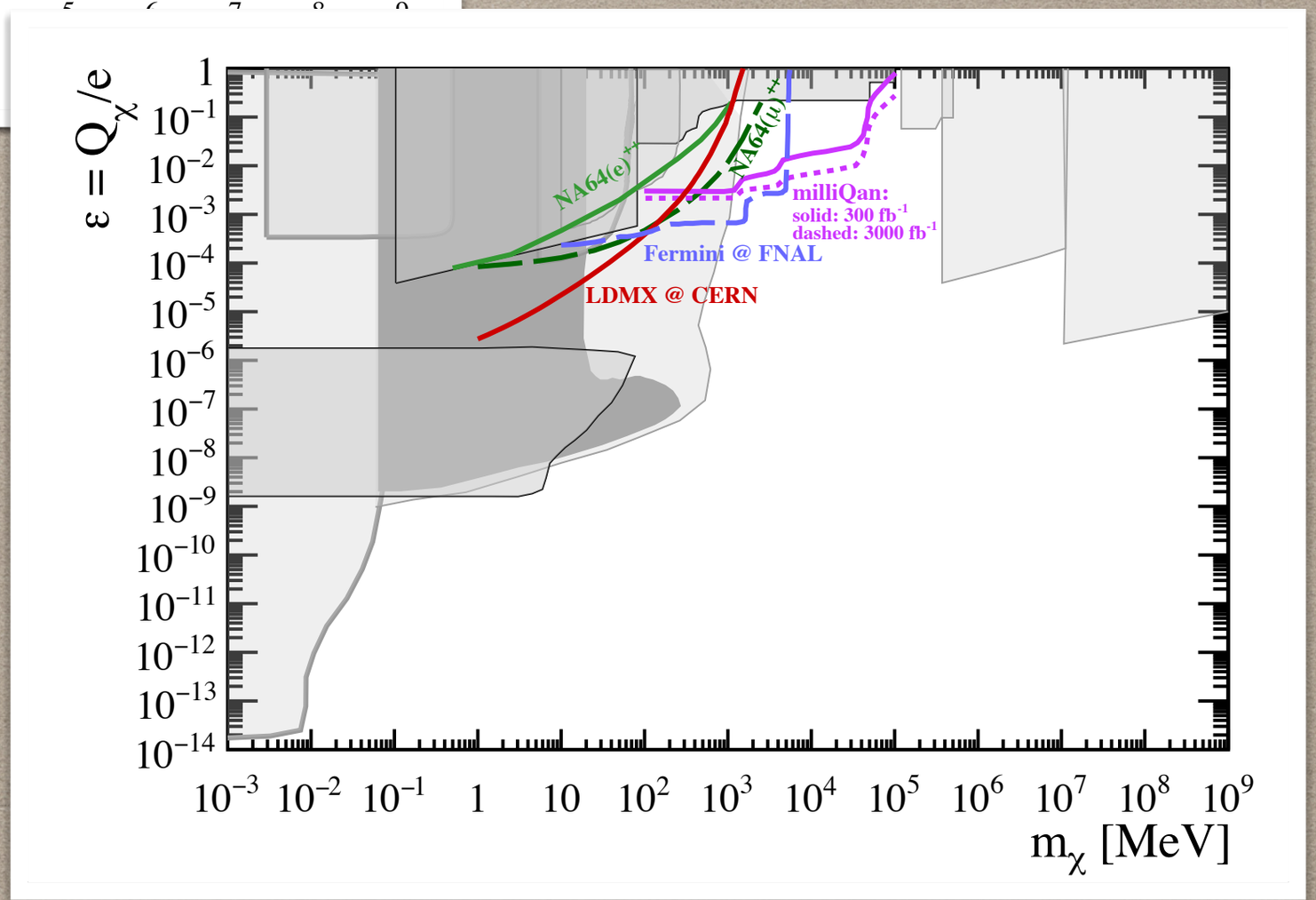
contact interaction

vs.

long distance

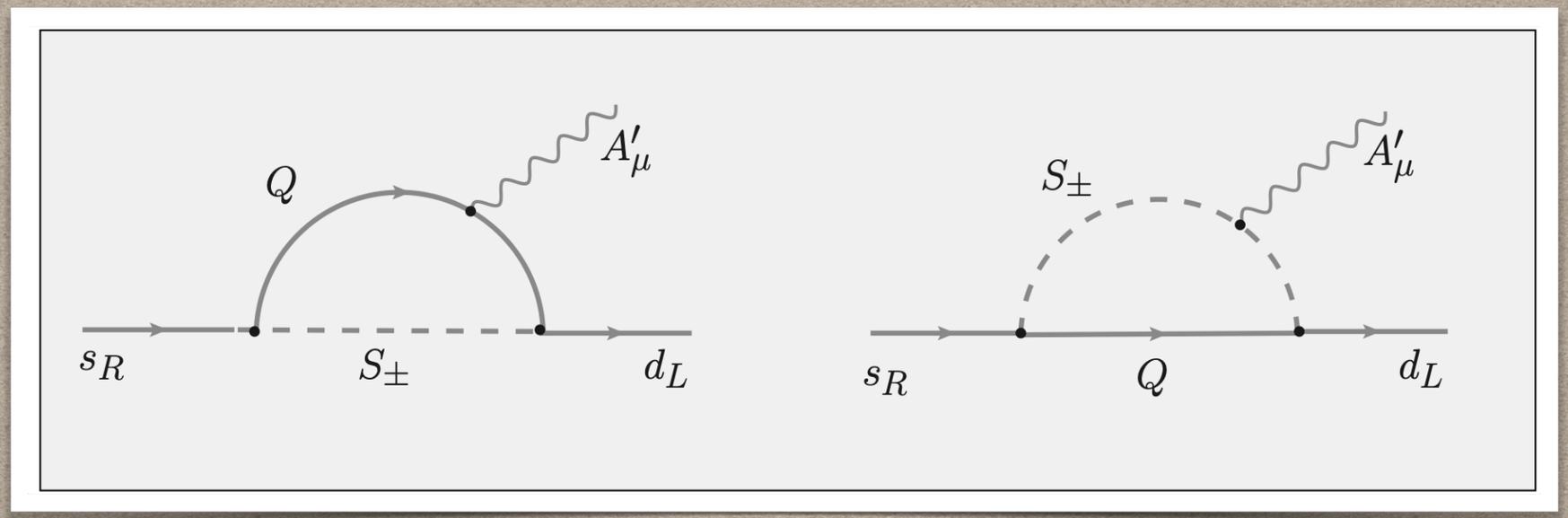
in case someone asks





millicharge

simple UV model

dark sector: fermions and scalars

$$\mathcal{L} \supset -g_L \left(\phi_L^\dagger \bar{\chi}_R l_L + S_L^{U\dagger} \bar{Q}_R^U q_L + S_L^{D\dagger} \bar{Q}_R^D q_L\right) - g_R \left(\phi_R^\dagger \bar{\chi}_L e_R + S_R^{U\dagger} \bar{Q}_L^D u_R + S_R^{U\dagger} \bar{Q}_L^D d_R\right) + \text{h.c.}$$