Dark photon bounds in the dark EFT

Enrico Bertuzzo
(University of São Paulo, Brazil)

07/10/2021 - FNAL theory group seminar

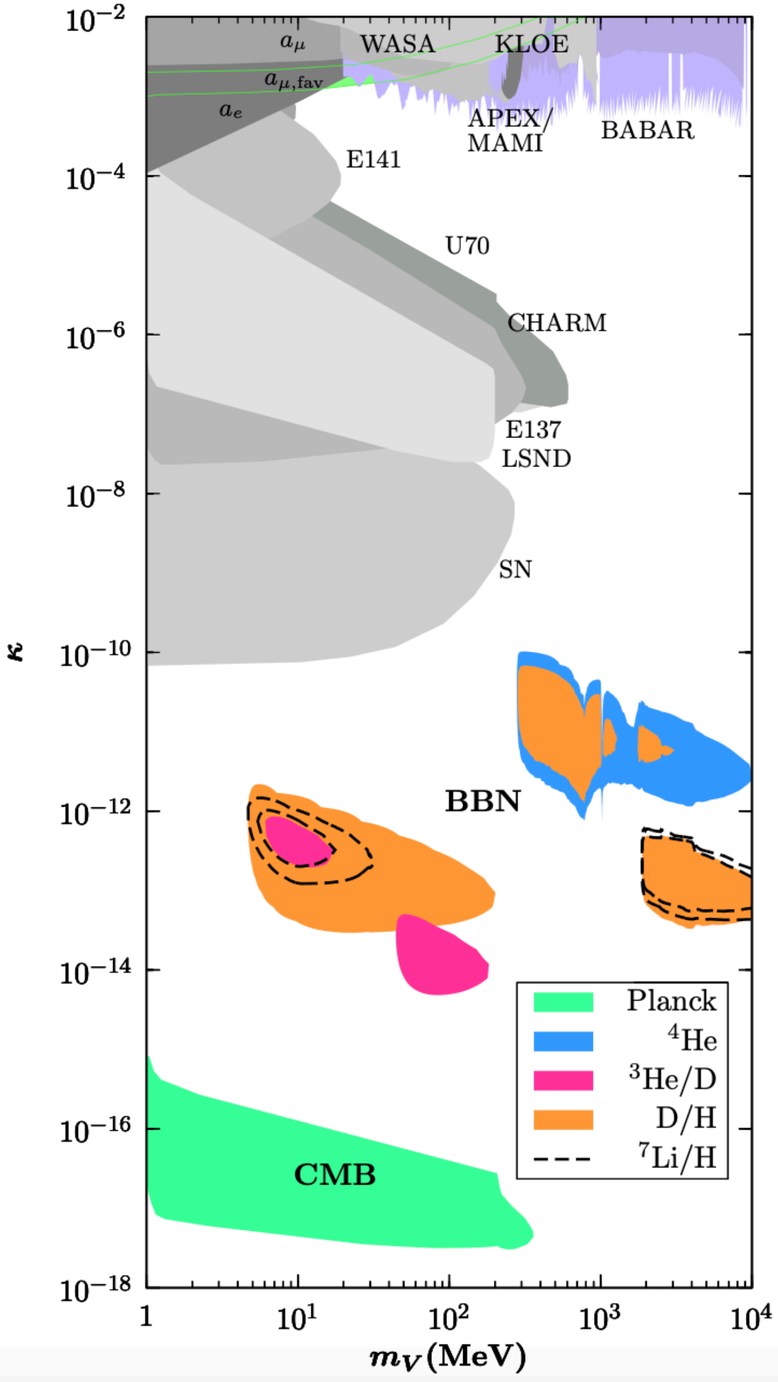
Setting the stage

- Dark photon: one of the simplest extension of the SM (just add a new $U(1)$)

$$\mathscr{L} \supset \frac{\epsilon}{2} A'_{\mu\nu} B^{\mu\nu} \qquad \Rightarrow \qquad \mathscr{L}_{phys} \supset \epsilon \, c_W \, e \, A'_{\mu} J^{\mu}_{EM}$$

- Today: focus on dark photons with $m_{A'} \geq 1$ MeV
  $\Rightarrow$ various possibility for detection/various bounds
- The bounds can be drastically modified by adding interactions (i.e. making the dark photon invisible with interactions $g_d A'_{\mu} J^{\mu}_{dark}$), typically becoming less restrictive

visible dark photon

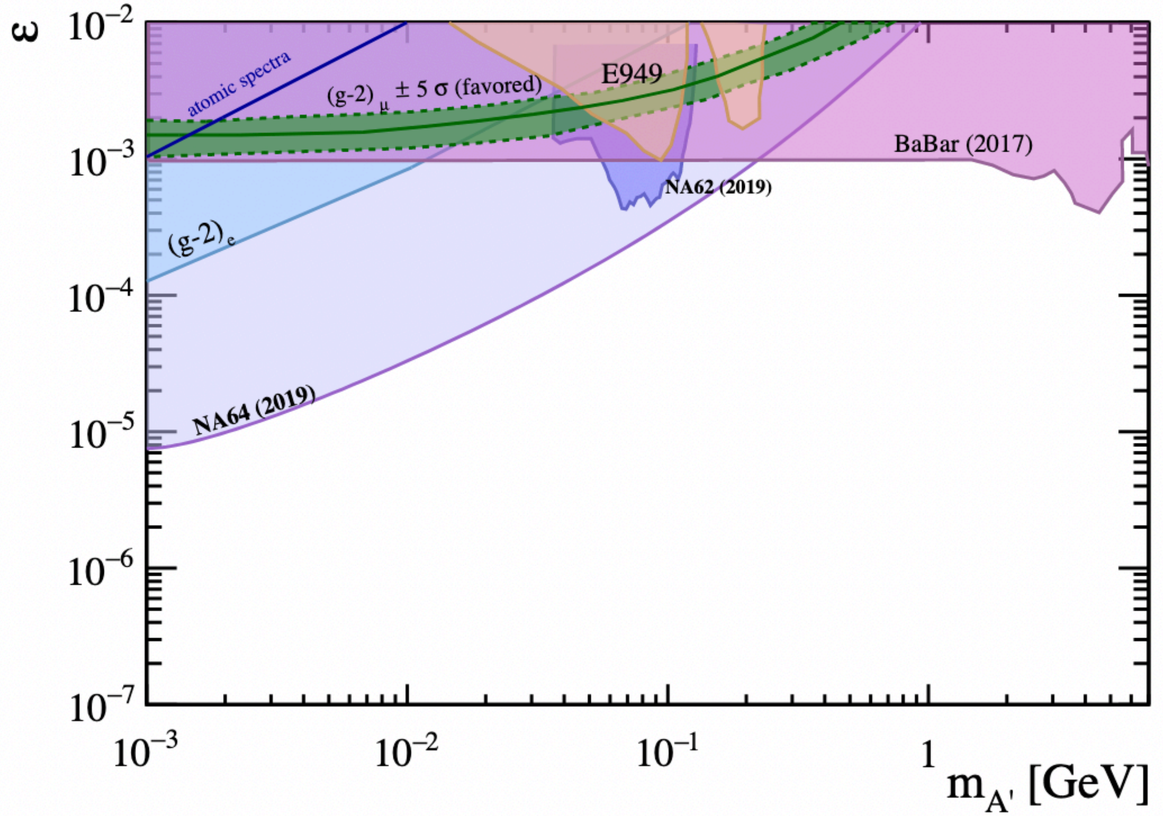


Fradette,Pospelov,Pradler,Ritz

Phys.Rev.D 90 (2014) 3, 035022

Fabbrichesi,Gabrielli,Lanfranchi

2005.01515



invisible dark photon ($BR_{\text{inv}} \simeq 1$)

Our question:

Have we exhausted all possibilities?

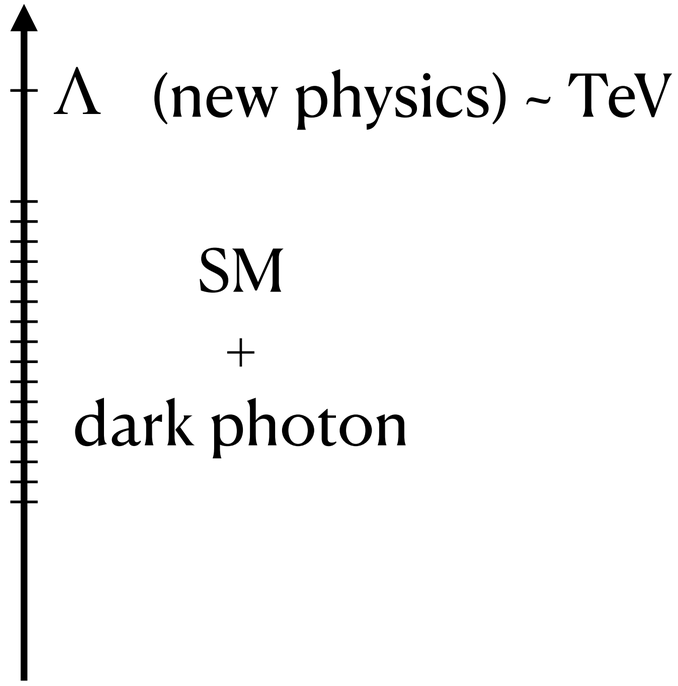
Or can we imagine different modifications of the dark photon couplings without making it invisible?

D. Barducci, EB, G. Grilli di Cortona, G.M. Salla

2109.04852

Framing better the question

- Given a $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$ symmetry, it is easy to imagine that additional states will be charged under it
- Suppose these states are **HEAVY**
  $\Rightarrow$ **we can use a EFT approach** (dark EFT)
- Further hypothesis: origin of the dark photon mass is left unspecified (i.e. lies above Λ)



The dark effective field theory

Dipole operators

	Operator
$\mathcal{O}_{Xu}$	$X_{\mu\nu}\bar{Q}\tilde{H}\sigma^{\mu\nu}u_R$
$\mathcal{O}_{Xd}$	$X_{\mu\nu}\bar{Q}H\sigma^{\mu\nu}d_R$
$\mathcal{O}_{Xe}$	$X_{\mu\nu}\bar{L}H\sigma^{\mu\nu}e_R$
$\mathcal{O}_{Bu}$	$B_{\mu\nu}\bar{Q}\tilde{H}\sigma^{\mu\nu}u_R$
$\mathcal{O}_{Bd}$	$B_{\mu\nu}\bar{Q}H\sigma^{\mu\nu}d_R$
$\mathcal{O}_{Be}$	$B_{\mu\nu}\bar{L}H\sigma^{\mu\nu}e_R$
$\mathcal{O}_{Wu}$	$W^a_{\mu\nu}\bar{Q}T^a_L\tilde{H}\sigma^{\mu\nu}u_R$
$\mathcal{O}_{Wd}$	$W^a_{\mu\nu}\bar{Q}T^a_LH\sigma^{\mu\nu}d_R$
$\mathcal{O}_{We}$	$W^a_{\mu\nu}\bar{L}T^a_LH\sigma^{\mu\nu}e_R$

Operators generating kinetic terms or kinetic mixing

	Operator
$\mathcal{O}_{XX}$	$H^\dagger HX_{\mu\nu}X^{\mu\nu}$
$\mathcal{O}_{BB}$	$H^\dagger HB_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{WW}$	$H^\dagger HW^a_{\mu\nu}W^{a\mu\nu}$
$\mathcal{O}_{XB}$	$H^\dagger HX_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{BW}$	$H^\dagger T^a_L HW^a_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{XW}$	$H^\dagger T^a_L HW^a_{\mu\nu}X^{\mu\nu}$

Other relevant operators

	Operator
$\mathcal{O}_T$	$\left\lvert H^\dagger D_\mu H\right\rvert^2$

The dark effective field theory

After properly going into the physical basis, we are left with

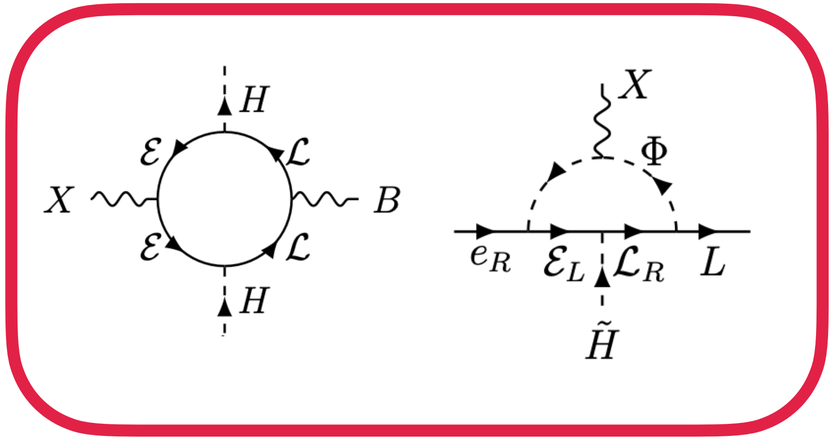
$$\mathcal{L}_{\text{int}} = e\, c_W\, \epsilon A'_\mu J^\mu_Q + \frac{d_\ell}{16\pi^2}\frac{v}{\Lambda^2}\bar{\ell}_L \sigma^{\mu\nu} \ell_R A'_{\mu\nu} + h.c.$$

usual coupling

dark dipole interaction

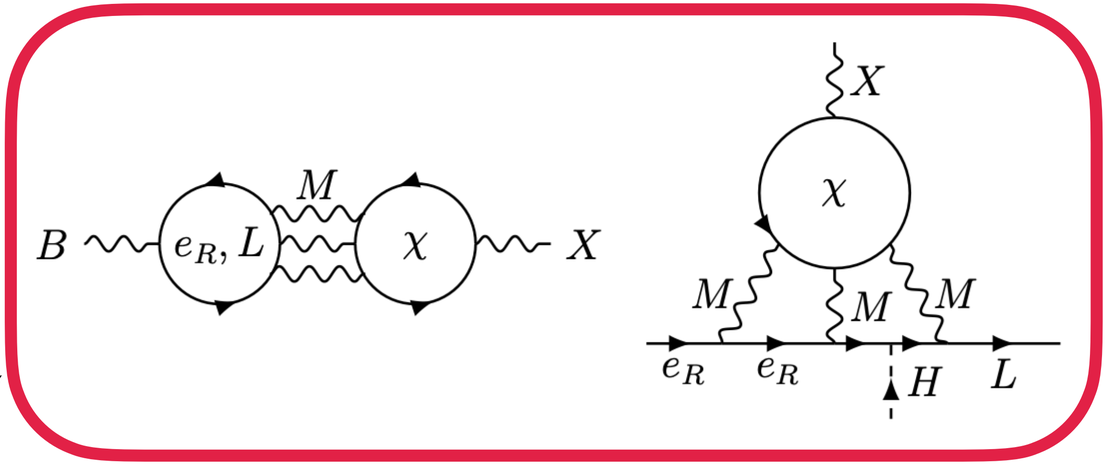
(here, only with leptons for simplicity)

Can we take ϵ and d_ℓ as independent parameters?



1-loop generation
(new heavy fermions
and scalars)

3 & 4-loop generation
(new heavy fermions
& new heavy gauge bosons)

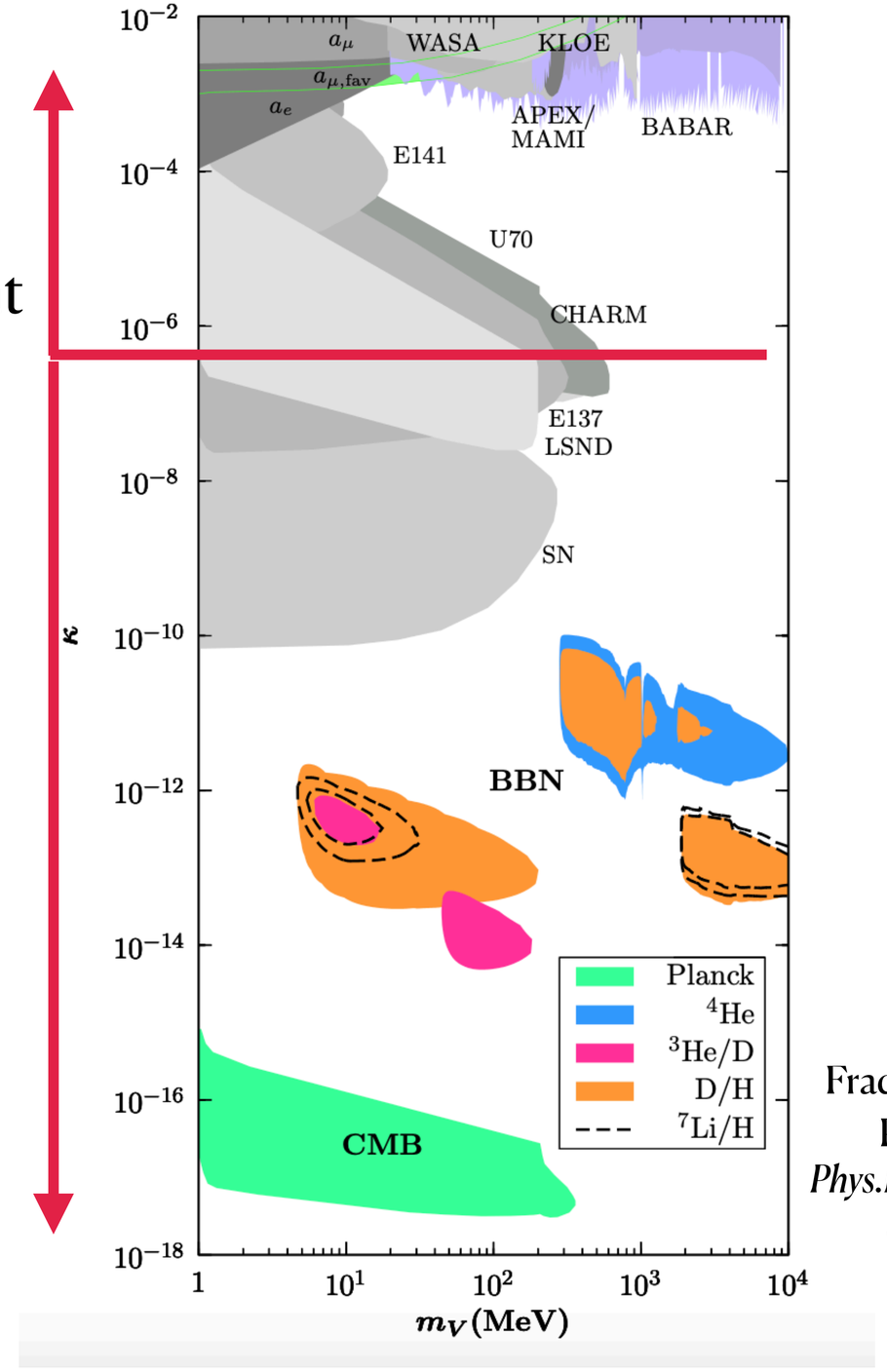


Gherghetta,Kersten,Olive,Pospelov
Phys.Rev.D 100 (2019) 9, 095001

The big picture

dark dipole
too small
to be relevant

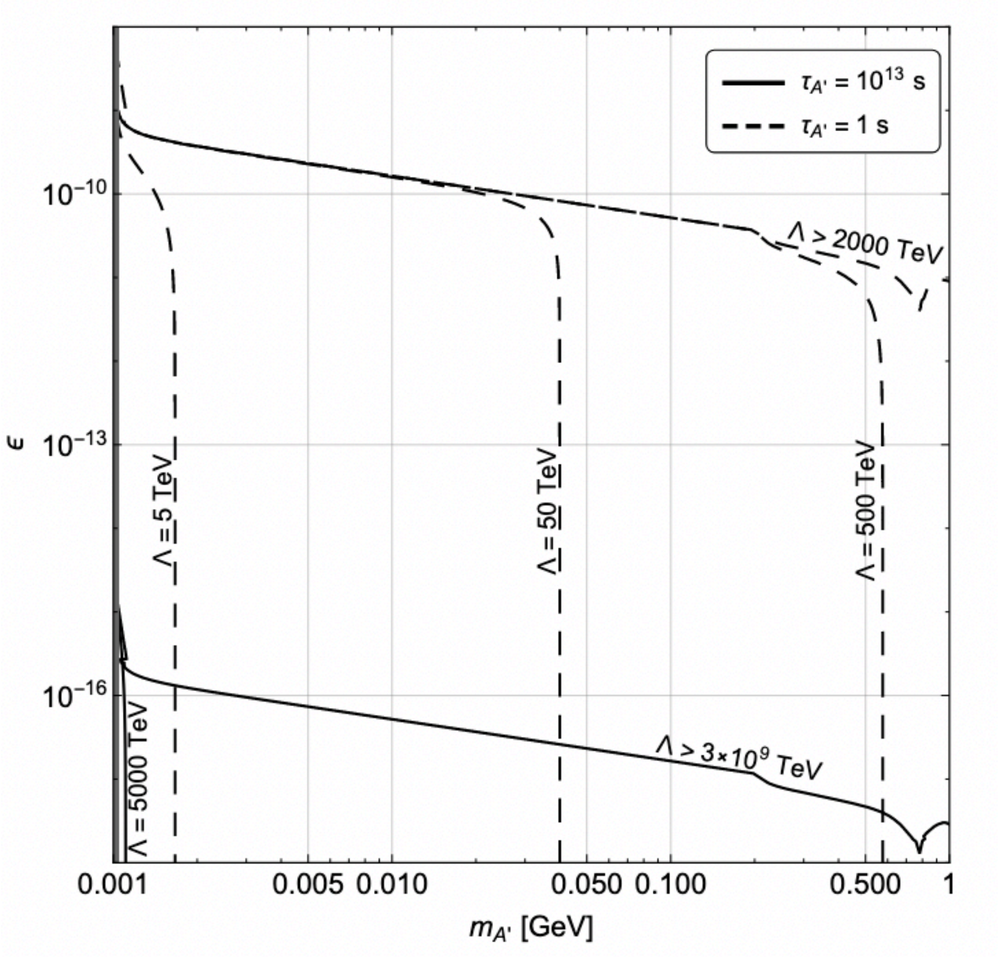
dark dipole
may have
DISRUPTIVE
effects

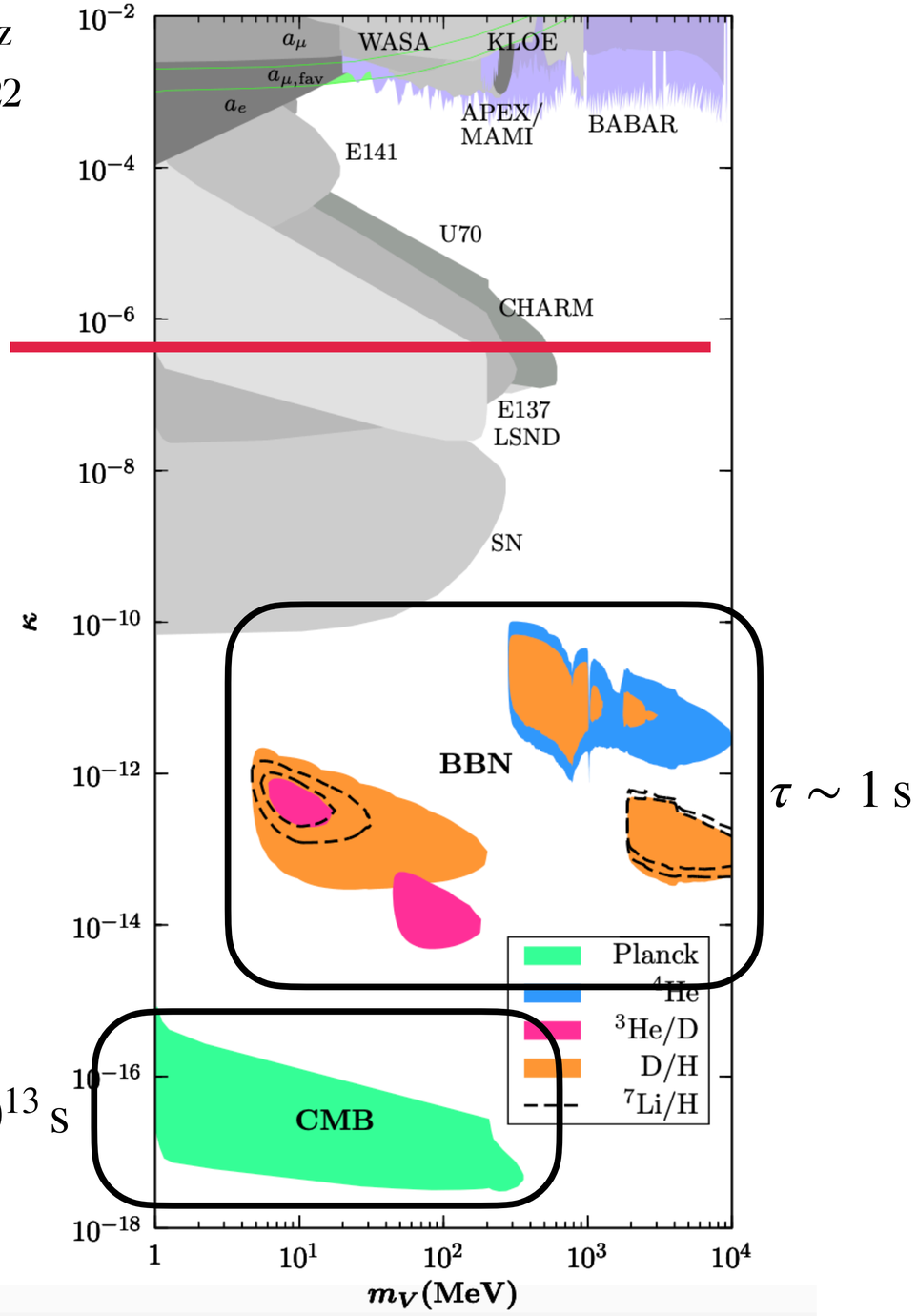


Fradette,Pospelov,
Pradler,Ritz
Phys.Rev.D 90 (2014)
3, 035022

BBN & CMB

Fradette,Pospelov,Pradler,Ritz
Phys.Rev.D 90 (2014) 3, 035022





$\tau \sim 1$ s

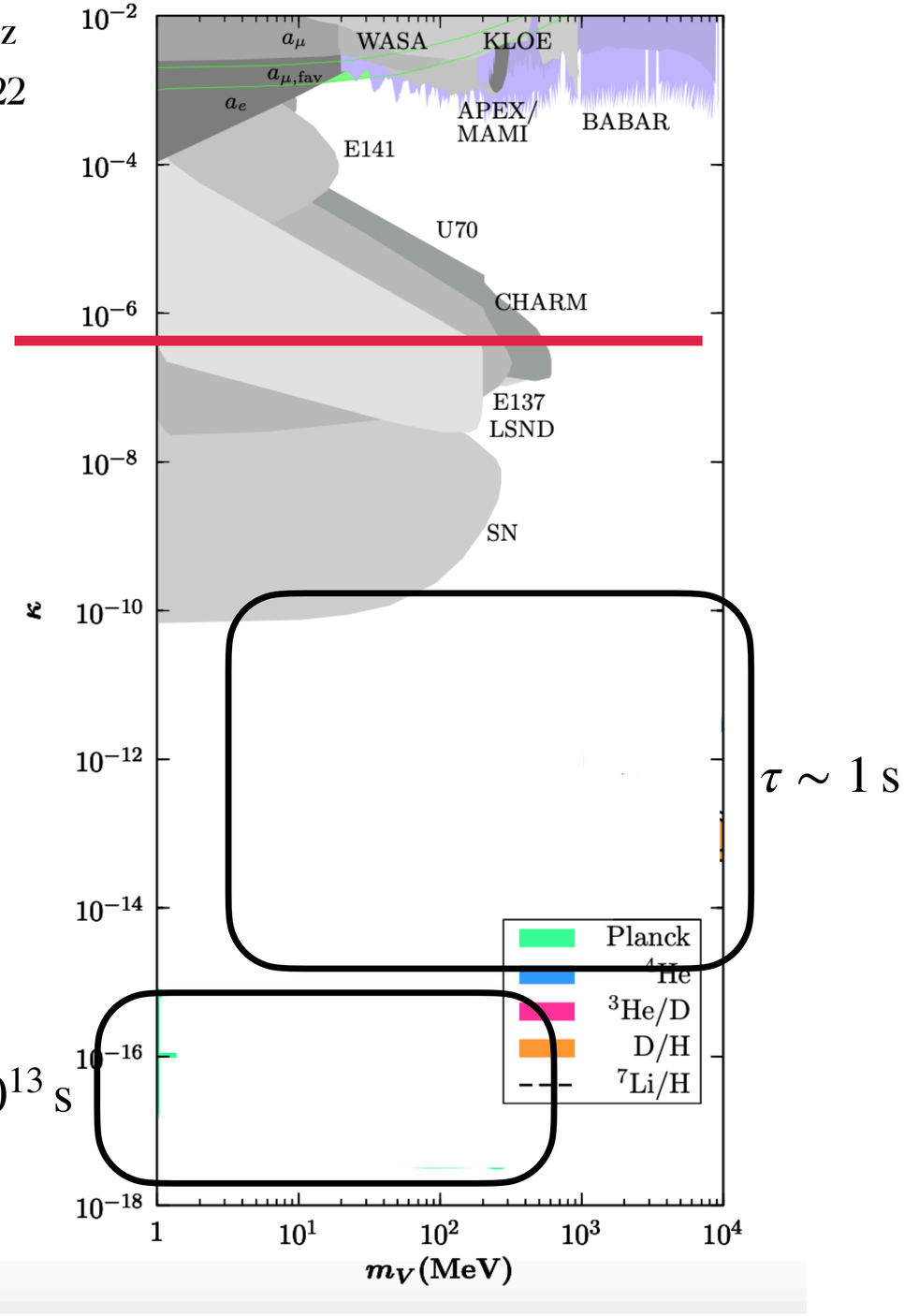
$\tau \sim 10^{13}$ s

Fradette,Pospelov,Pradler,Ritz

Phys.Rev.D 90 (2014) 3, 035022

BBN & CMB

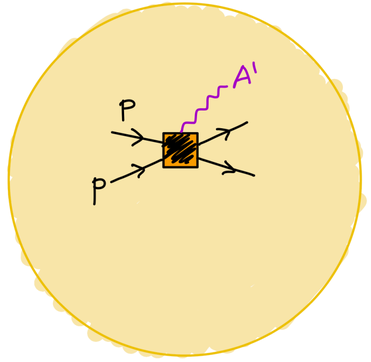
bounds disappear for $\Lambda \lesssim (50 \div 100)$ TeV



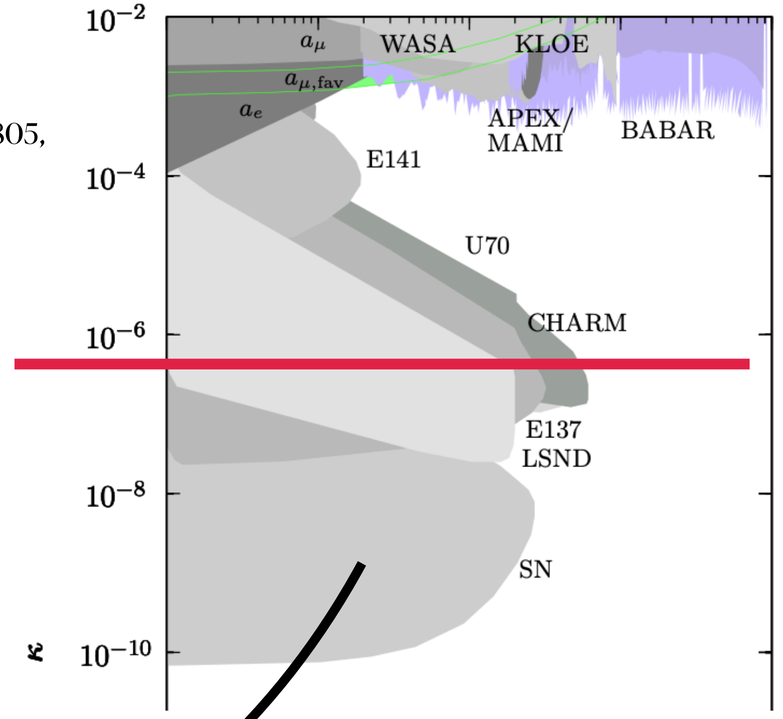
$\tau \sim 1$ s

$\tau \sim 10^{13}$ s

Supernova



1201.2683,
Nucl. Phys. B 890 (2014) 17,
Phys. Rev. C 94 (2016) 045805,
JHEP 01 (2017) 107
JHEP 02 (2017) 033
...



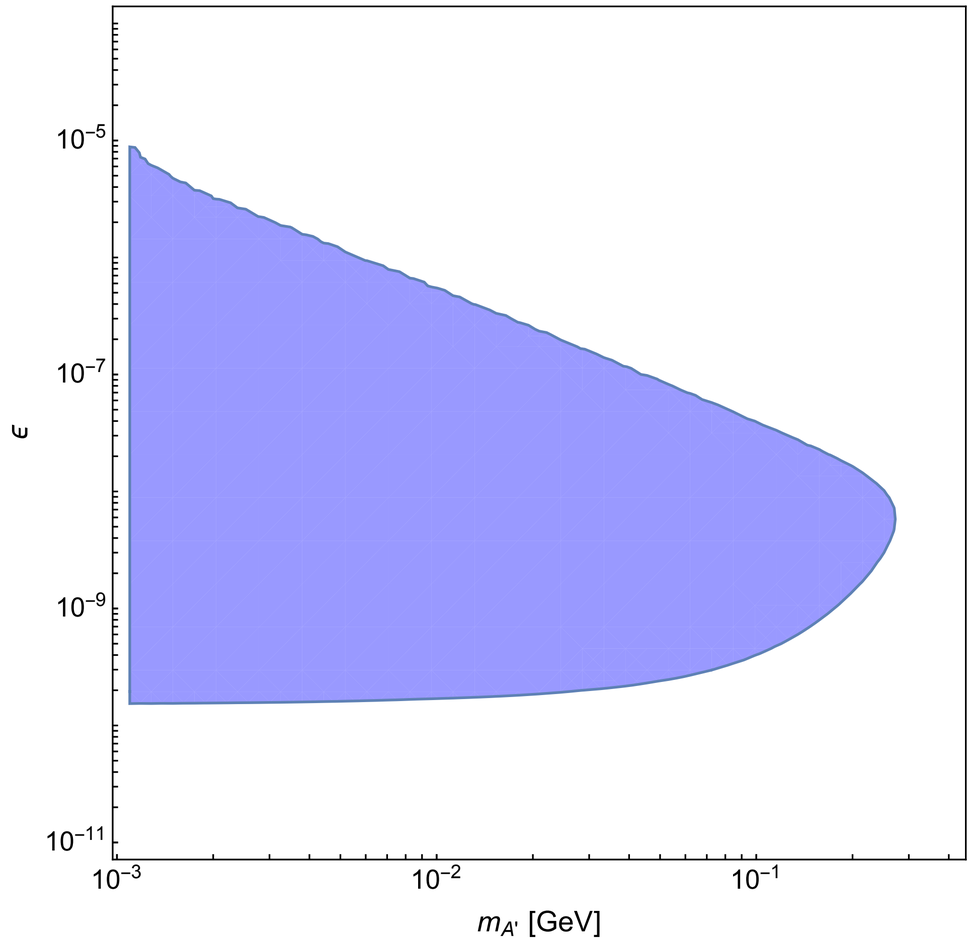
$$L_{A'} = \left\langle Q_{A'}\, e^{-R_c/(c\tau_{A'})} \right\rangle V_c < L_\nu \simeq 3 \times 10^{53}\,\mathrm{erg/s}$$

energy emission rate

core radius

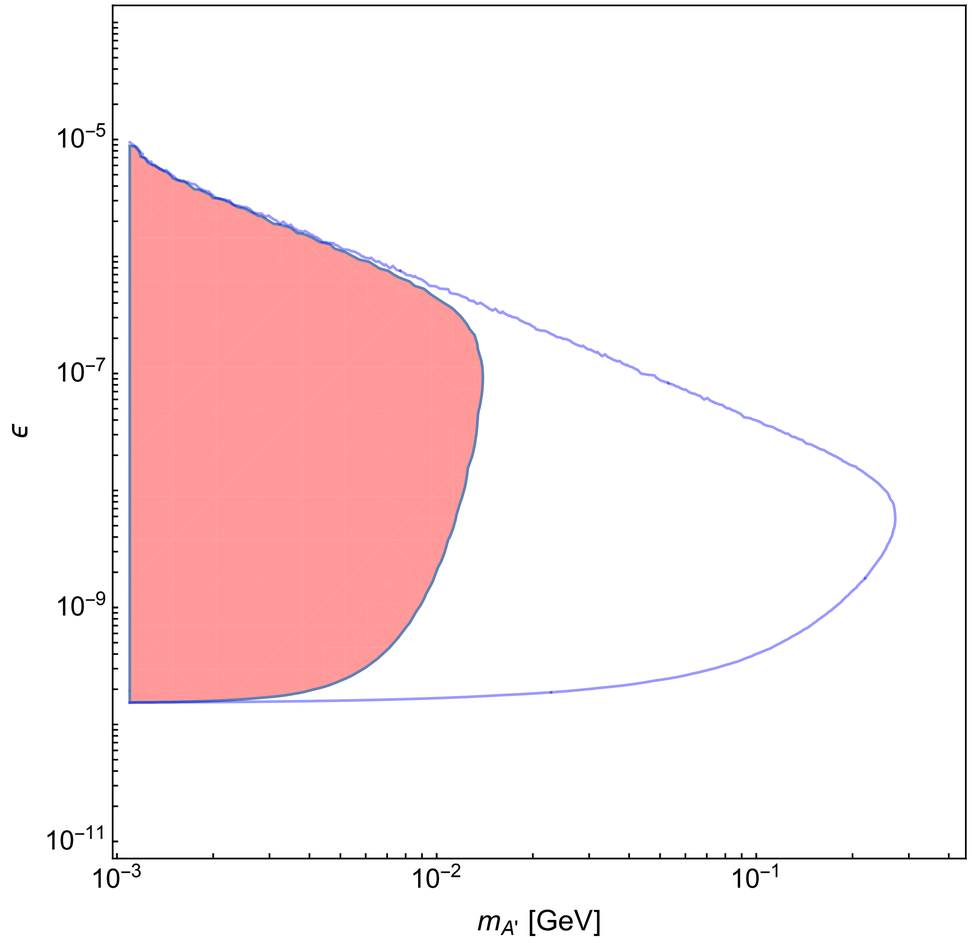
For simplicity, we neglect finite temperature effects

Supernova bounds



no dipole

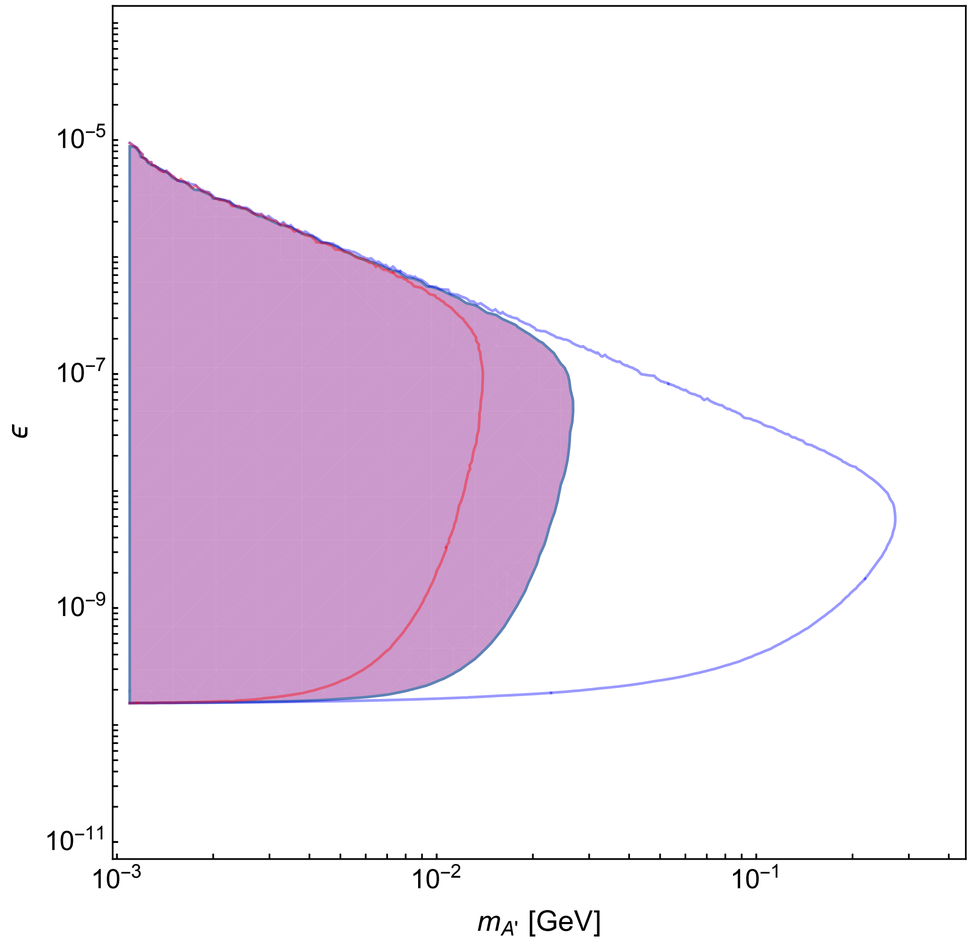
Supernova bounds



$\Lambda = 0.5$ TeV

less constraining because the lifetime diminishes

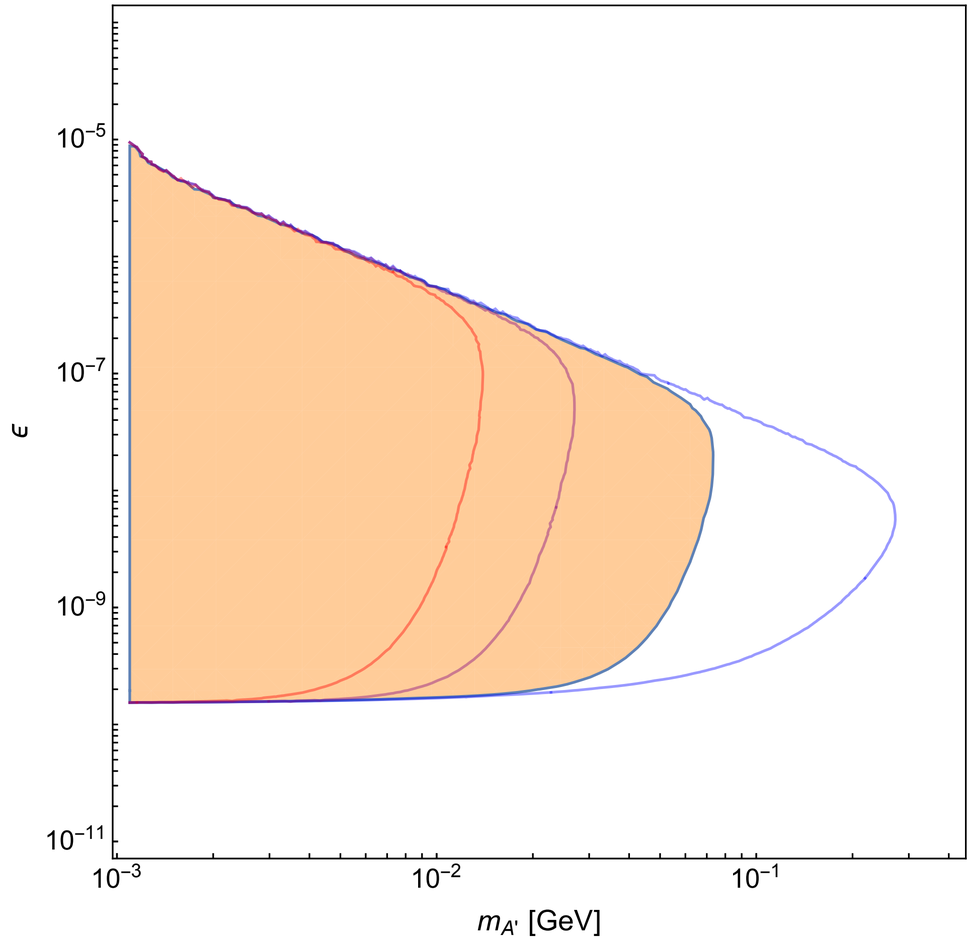
Supernova bounds



$\Lambda = 1\,\mathrm{TeV}$

less constraining because the lifetime diminishes

Supernova bounds

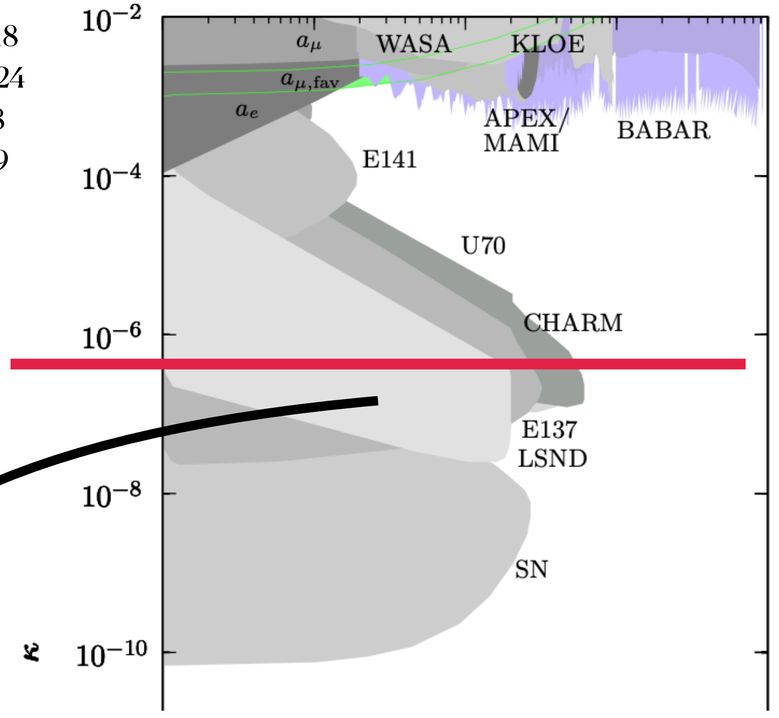


$\Lambda = 3$ TeV

less constraining because the lifetime diminishes

LSND

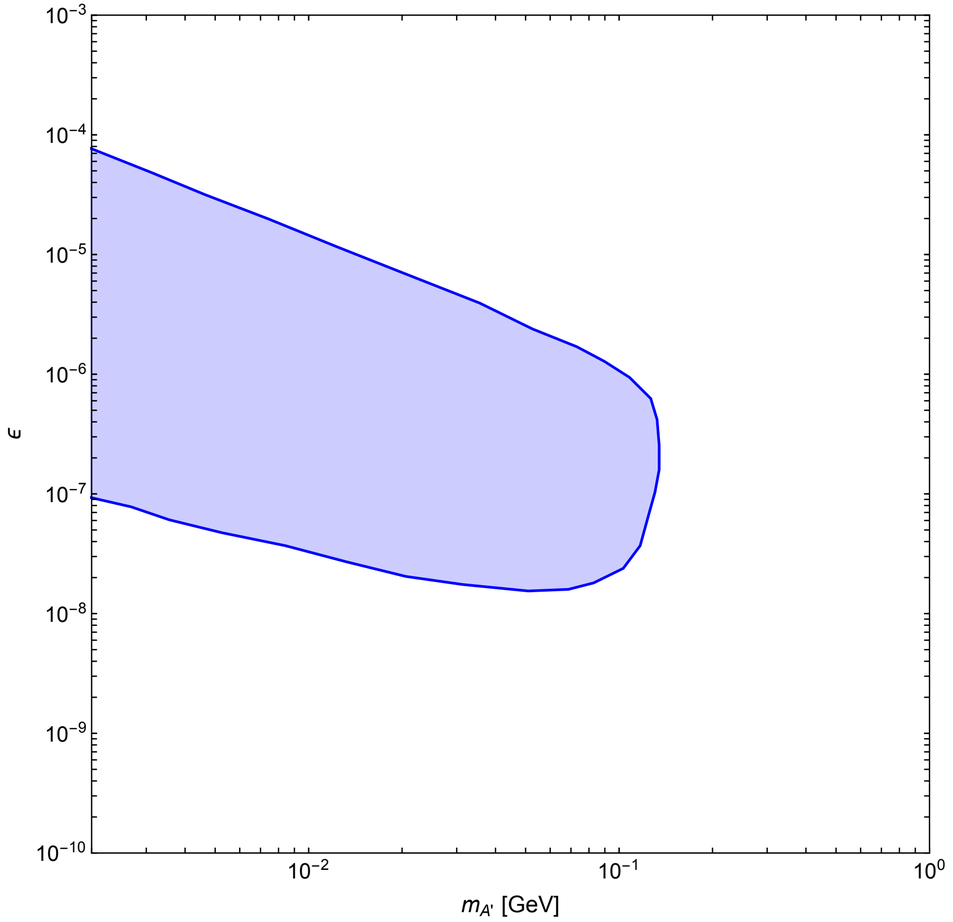
Phys. Rev. D 80 (2009) 075018
Phys. Rev. D 80 (2009) 095024
Phys. Rev. D 82 (2010) 113008
Phys. Rev. D 86 (2012) 095019
...



production: NOT affected by the dark dipole

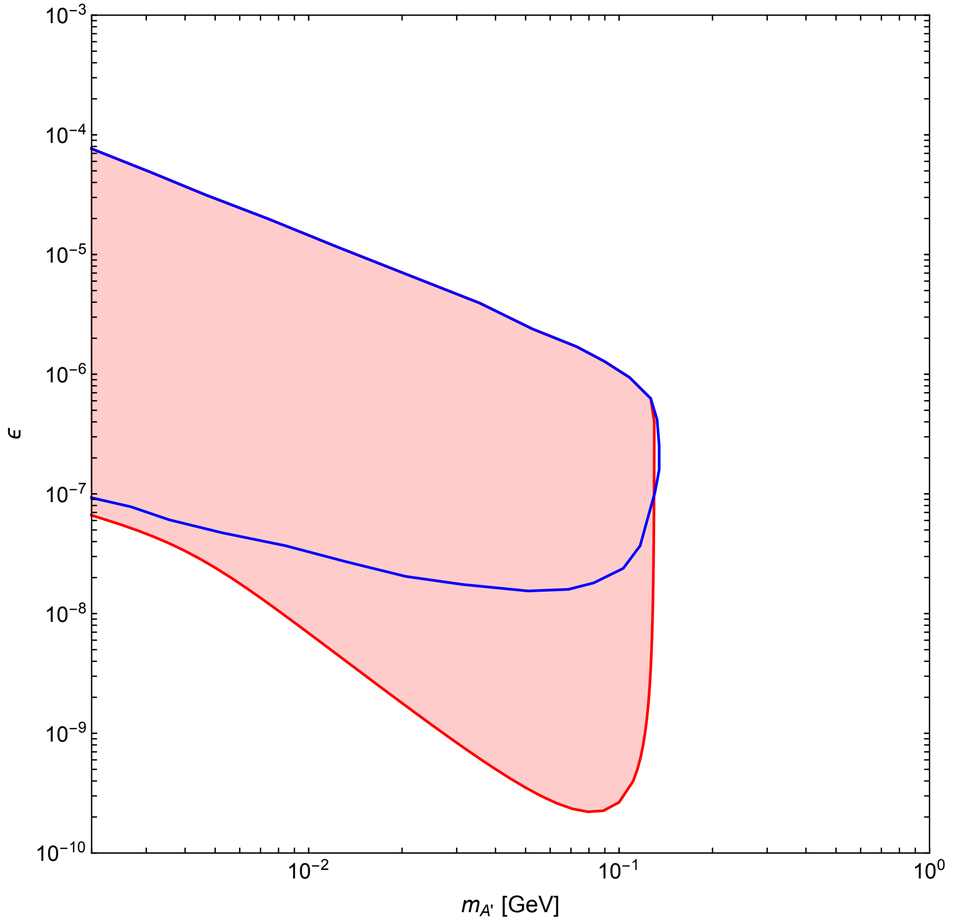
decay: modified by the dark dipole

LSND bounds



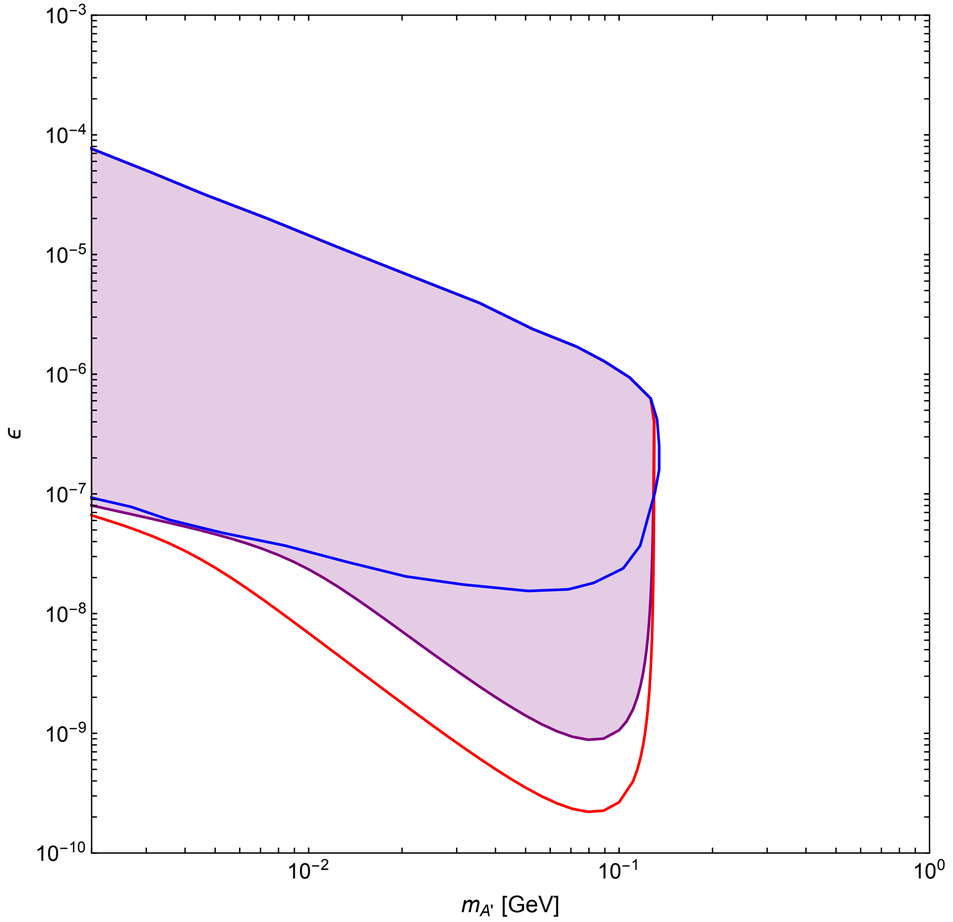
no dipole

LSND bounds



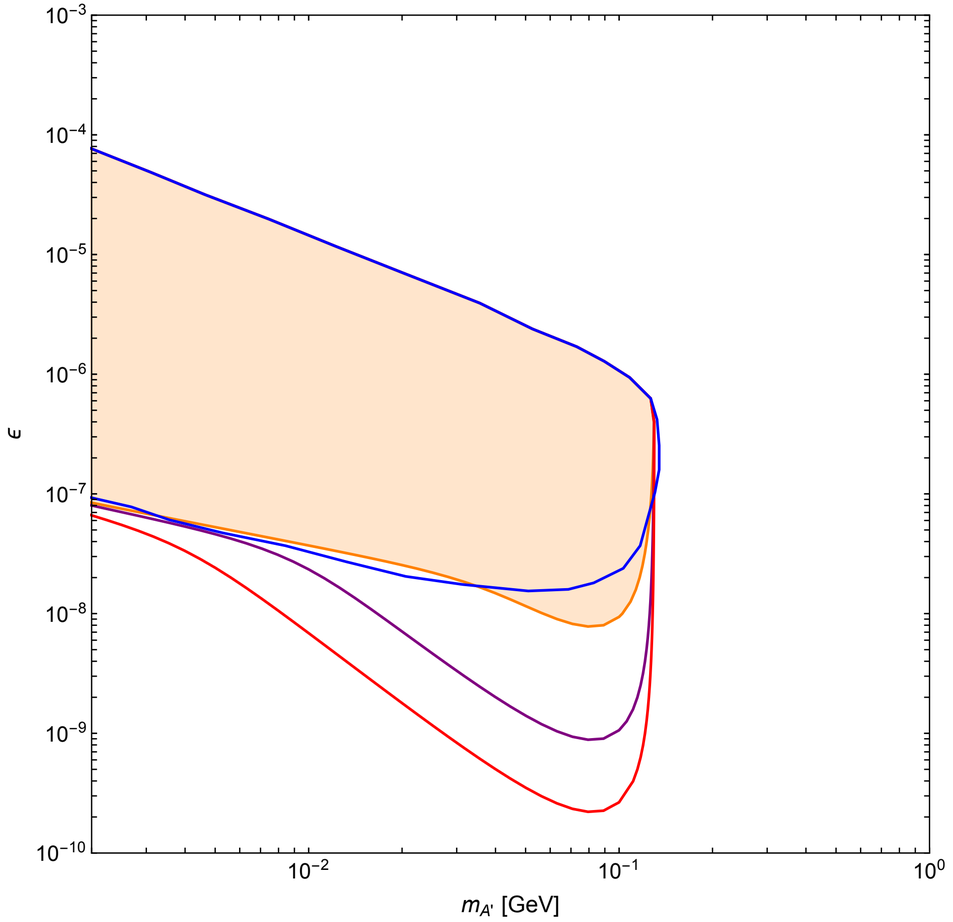
$\Lambda = 0.5$ TeV

LSND bounds



$\Lambda = 1\,\mathrm{TeV}$

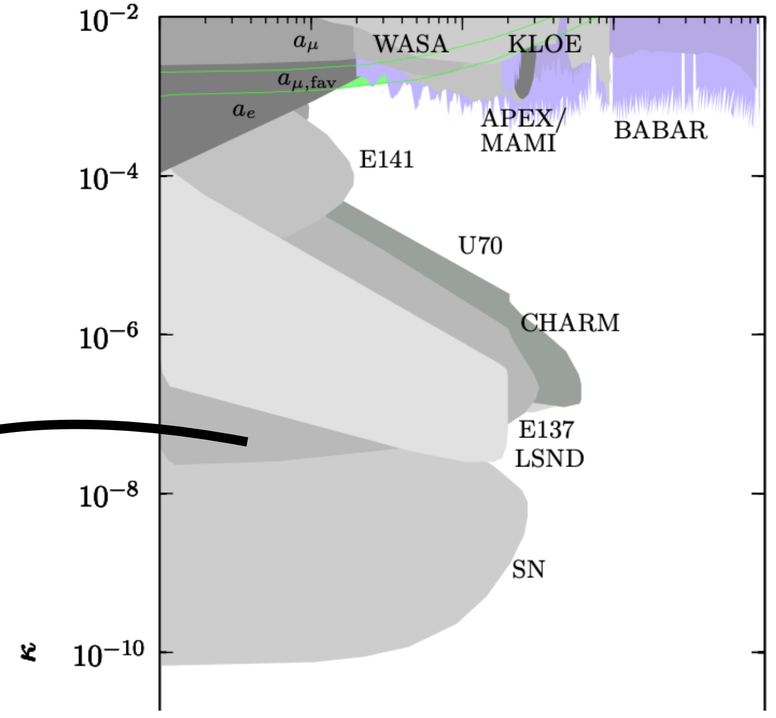
LSND bounds



$\Lambda = 3$ TeV

will explain shortly
this behavior

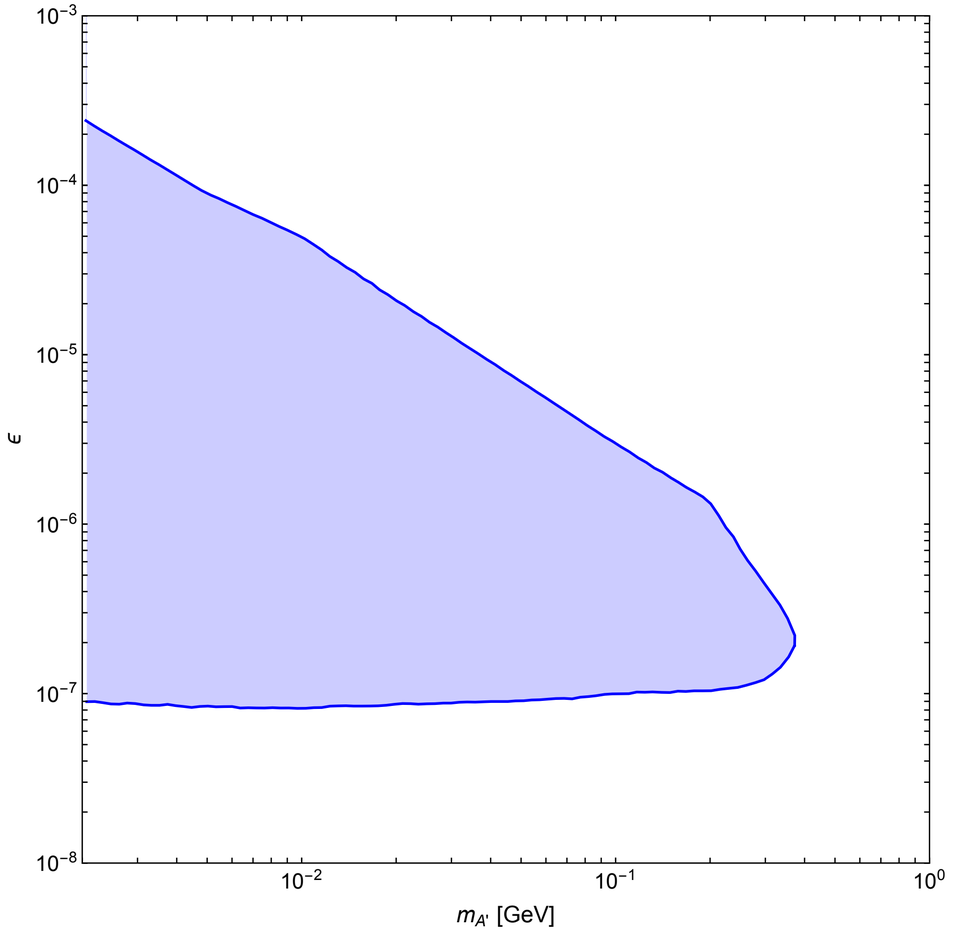
E137



production: modified by the dark dipole

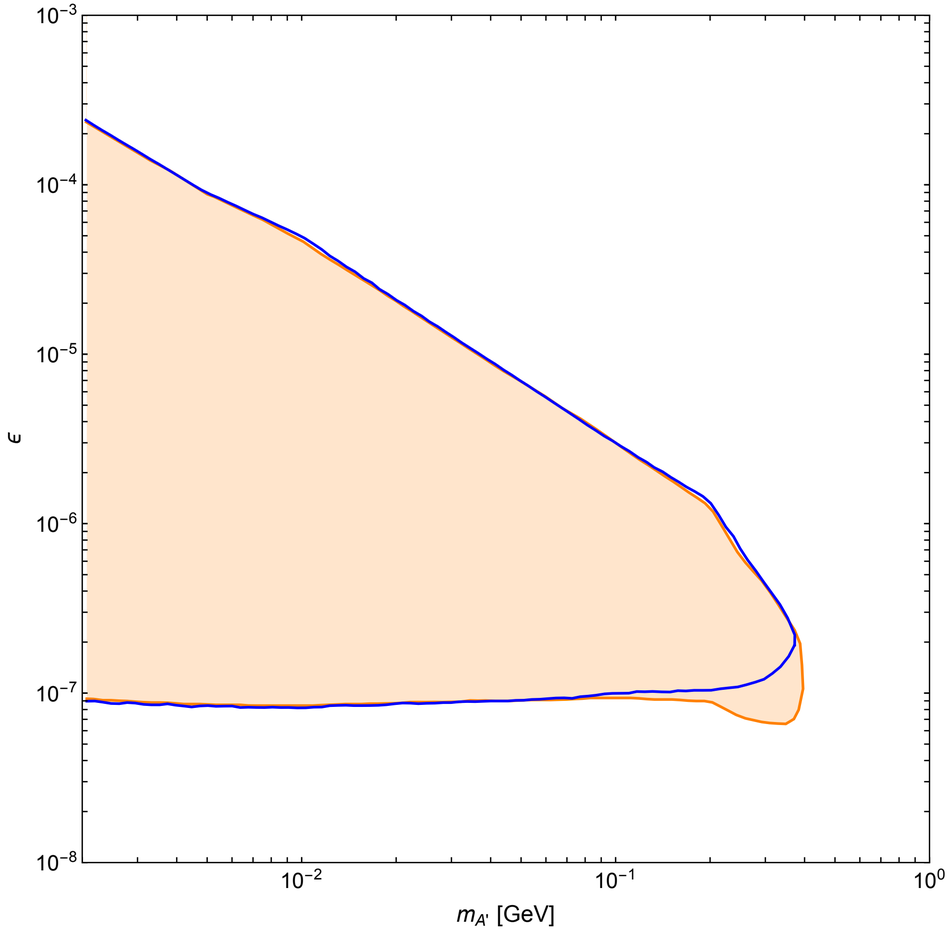
decay: modified by the dark dipole

E137 bounds



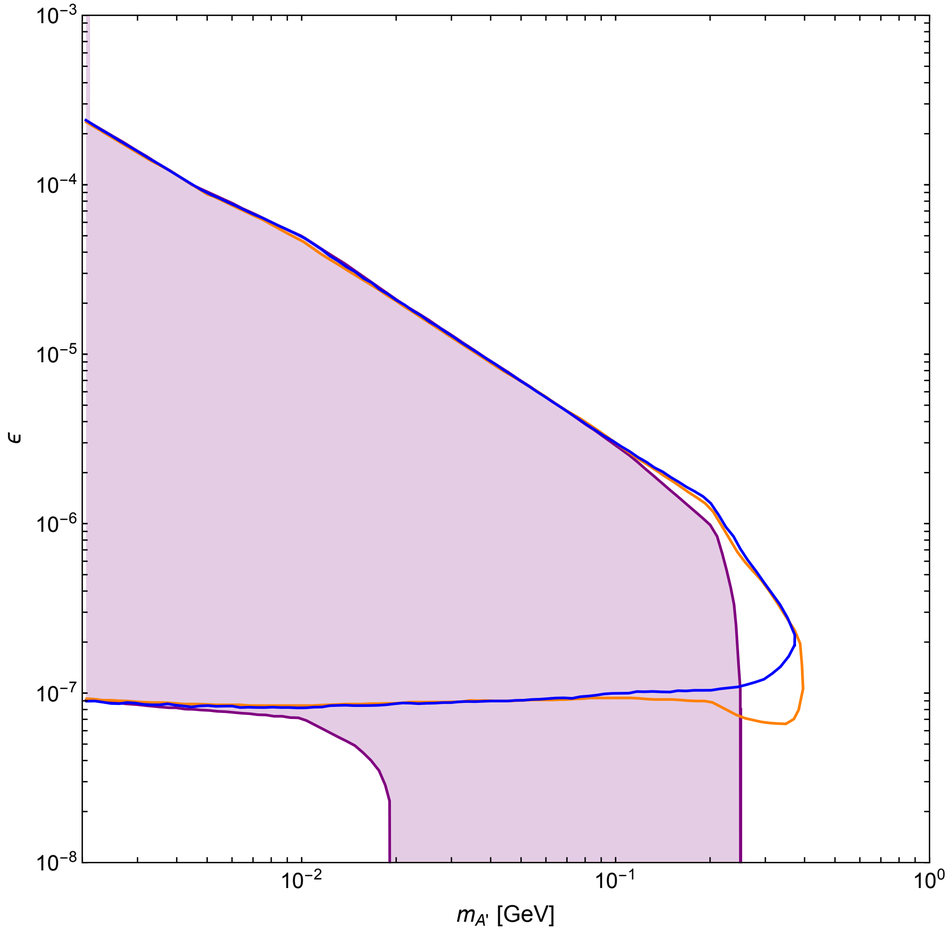
no dipole

E137 bounds



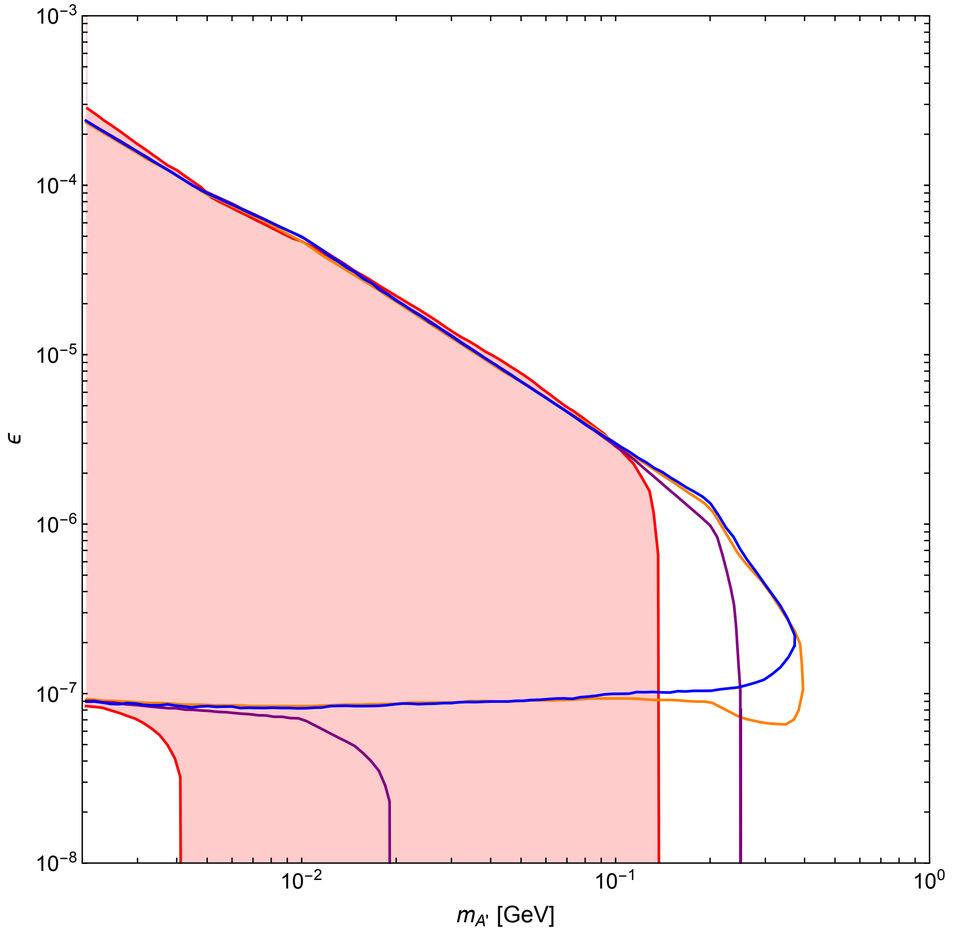
$\Lambda = 3$ TeV

E137 bounds



$\Lambda = 1\,\mathrm{TeV}$

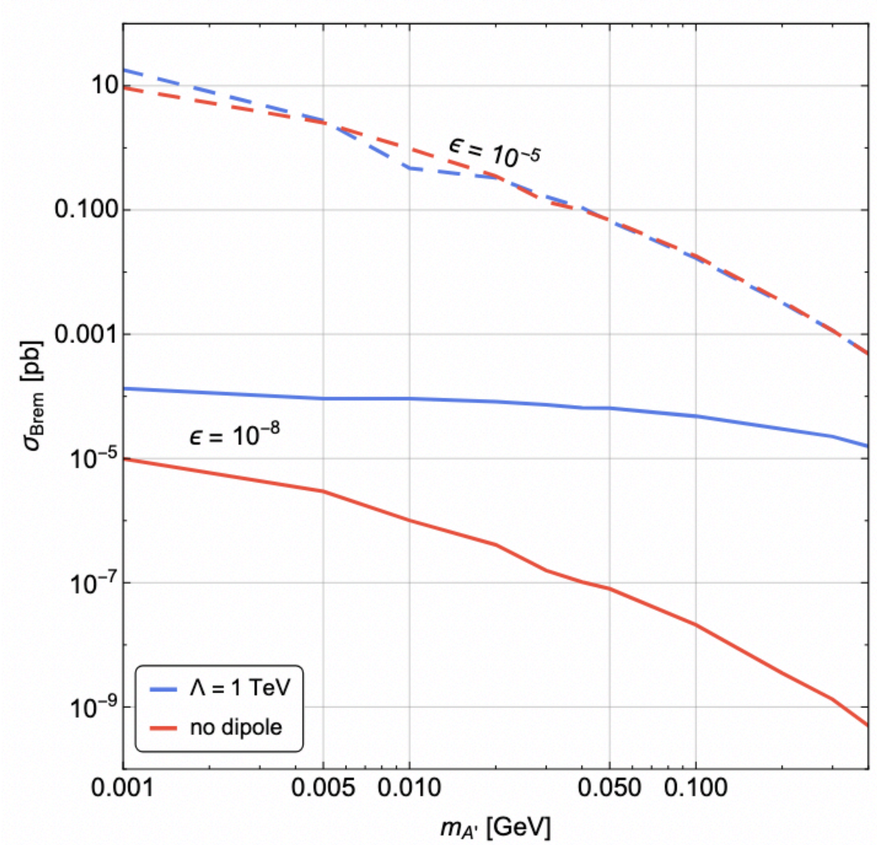
E137 bounds

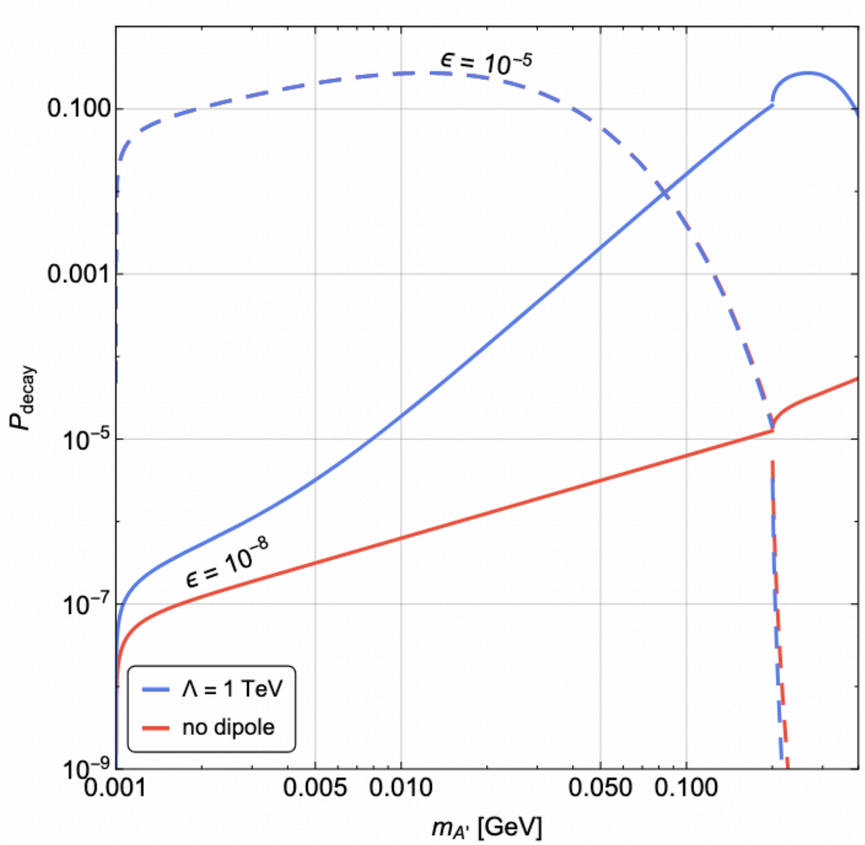


$\Lambda = 0.5$ TeV

LSND/E137 bounds: what is going on?

$$N_{\rm evts} = N_{A'}\, f_{\rm geom}\, P_{\rm dec} \qquad P_{\rm dec} = e^{-\frac{d}{\lambda}}\left(1 - e^{-\frac{d+l}{\lambda}}\right)\mathrm{BR}(A' \to X)$$





Time to answer our question:

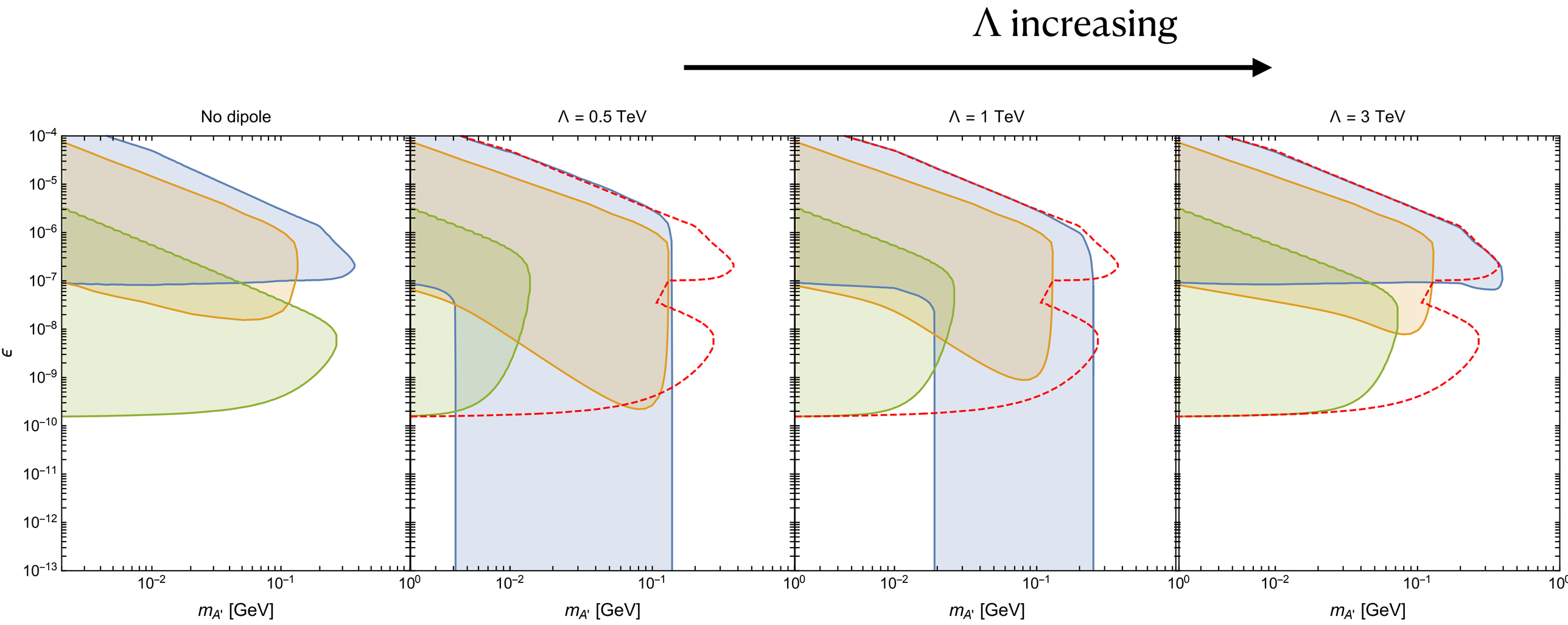
Can we imagine modifications of the dark photon couplings without making it invisible?

Answer: YES

- In the context of the dark EFT we still have a visible dark photon

  Couplings: J_{EM} + dipoles
- Dipoles are generated by heavy new physics: bounds just slightly “deformed”?
- NOT IN GENERAL: since experiments probe also very small ϵ, the dipole effects may be dramatic

Overall effect



Backup

The full lagrangian

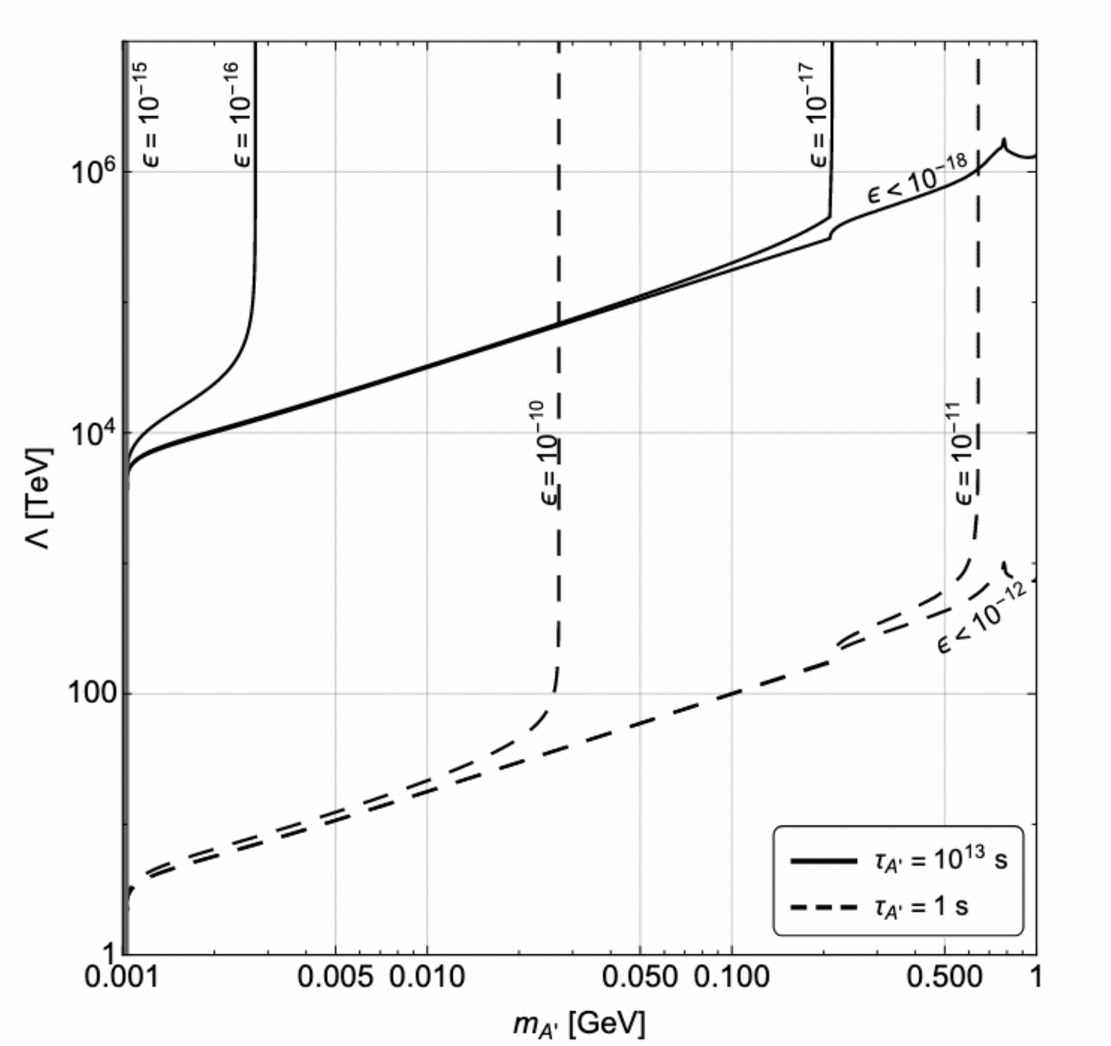
$$\begin{aligned}\mathcal{L}_{\rm int} &= eA_\mu J^\mu_Q + e\left(c_W\epsilon - s_W\mathcal{S}_d\right) J^\mu_Q A'_\mu \\ &+ \left(\sqrt{g^2+g'^2}\left(1+s_W c_W \mathcal{S}\right)\left[J^\mu_3 - s^2_W J^\mu_Q\right] - e(c^2_W - s^2_W)\mathcal{S} J^\mu_Q\right) Z_\mu \\ &+ \frac{d_\ell}{16\pi^2}\frac{v}{\Lambda^2}\bar{\ell}_L\sigma^{\mu\nu}\ell_R A'_{\mu\nu} + h.c.\,.\end{aligned}$$

$$\mathcal{S} = \frac{c_{BW}}{16\pi^2}\frac{g g' v^2}{\Lambda^2}, \qquad \mathcal{S}_d = \frac{c_{XW}}{16\pi^2}\frac{g g_d v^2}{\Lambda^2}\,.$$

Modified decay width

$$\Gamma(A' \to \ell^- \ell^+) = \left[\frac{\alpha_{EM}\, c_W^2\, \epsilon^2}{3} m_{A'} \left(1 + 2\frac{m_\ell^2}{m_{A'}^2}\right) + \frac{\alpha_{EM}^{1/2} c_W \epsilon\, d_\ell}{8\pi^{5/2}} \frac{m_\ell\, m_{A'}\, v}{\Lambda^2} \right.$$
$$\left. + \frac{d_\ell^2}{1536\pi^5} m_{A'}^3 \frac{v^2}{\Lambda^4} \left(1 + 8\frac{m_\ell^2}{m_{A'}^2}\right) \right] \sqrt{1 - \frac{4m_\ell^2}{m_{A'}^2}}\,.$$

Lifetime: letting the cutoff vary



Supernova bound from the emissivity

$$L_{A'} = \left\langle Q_{A'}\, e^{-R_c/(c\tau_{A'})} \right\rangle V_c < L_\nu \simeq 3 \times 10^{53}\,\mathrm{erg/s}$$

$$V_c \overset{'}{=} 4/3\,\pi R_c^3$$

$R_c \sim 10$ km is the core radius

Terrestrial bounds

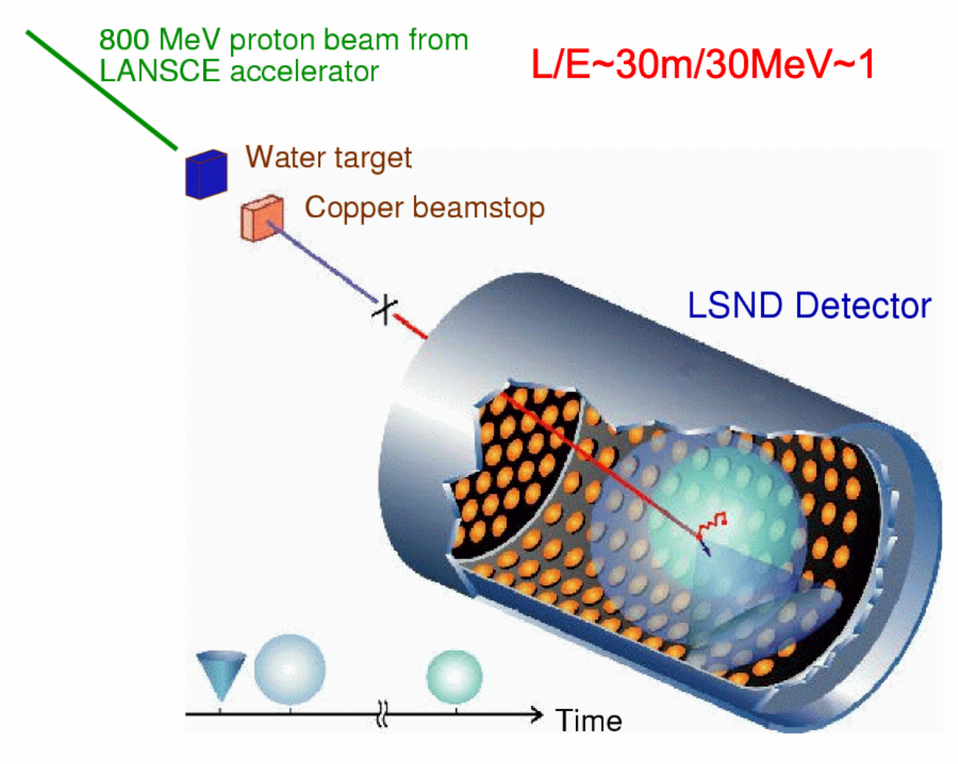
$$N_{\text{evts}} = N_{A'}\, f_{\text{geom}}\, P_{\text{dec}}$$

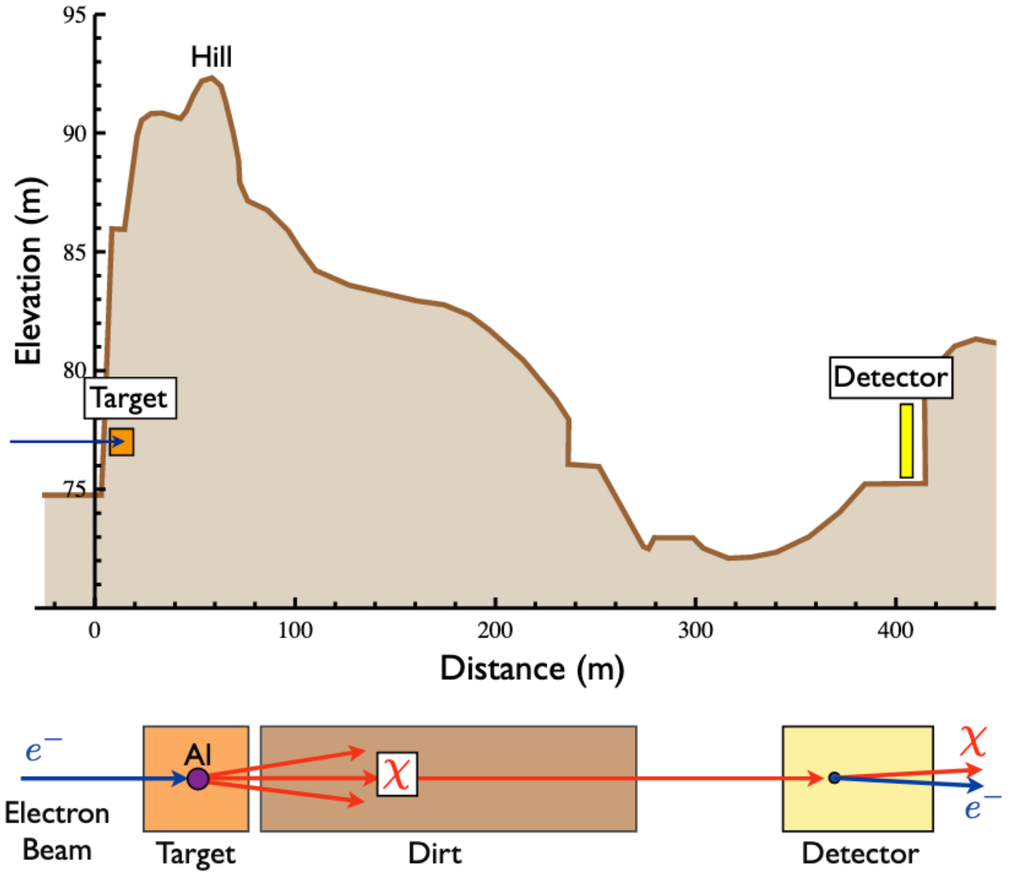
$$P_{\text{dec}} = e^{-\frac{d}{\lambda}}\left(1 - e^{-\frac{d+l}{\lambda}}\right)\text{BR}\left(A' \to X\right)$$

$$N_{A'} = N_{\pi^0}\text{Br}(\pi^0 \to \gamma A'), \qquad \text{Br}(\pi^0 \to \gamma A') \simeq 2\epsilon^2\left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3$$

$$N_{A'} = \mathcal{L}\sigma_{\text{prod}},$$

Terrestrial bounds





LSND

$d = 30$ m $\quad l = 8.75$ m

E137

hill (179 m) $\quad$ open region (204 m)