# Sub-GeV Dark Vector Bosons and their Impacts on Cosmology

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February 10, 2021

# Overview

- Introduction
- Dark Forces and Dark Vectors
- Branching Ratios
- EM Energy Spectra
- Application to Cosmology

# Introduction

It is well known that dark matter is present in the Universe and has shown itself interacting with its surroundings gravitationally.

- Bullet Cluster
- Rotation Curves
- Cosmic Microwave Background

Knowing that dark matter must exist in some capacity, we can ask another question:

**Why not also dark forces?**

# Dark Forces and Dark Vectors

Introducing a new dark force with a $U(1)$ gauge group that is weakly coupled to the SM, the effective Lagrangian is

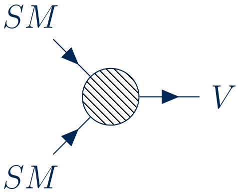
$$\mathcal{L}_{eff} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{\epsilon}{2}F_{\mu\nu}X^{\mu\nu} - g_V J^\mu_{SM} V_\mu + \mathcal{L}_{\mathsf{SM}}$$

Five new dark forces: $U(1)_{A'}$, $U(1)_{B-L}$, and $U(1)_{L_i - L_j}$, where $i \neq j = e, \mu, \tau$.

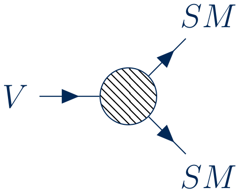
The third term is important for the $A'$ model and the fourth term is the main method for the other models to interact with the SM

# Dark Forces and Dark Vectors

In the early Universe:




Create




Decay

The decays are slow and can alter BBN and the CMB power spectrum.

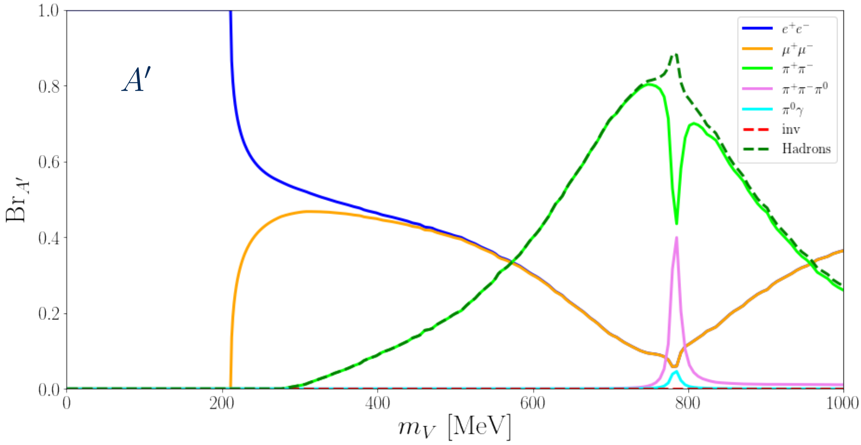
To compute these effects we need the decay spectra of electrons and photons.

The calculation has two steps:

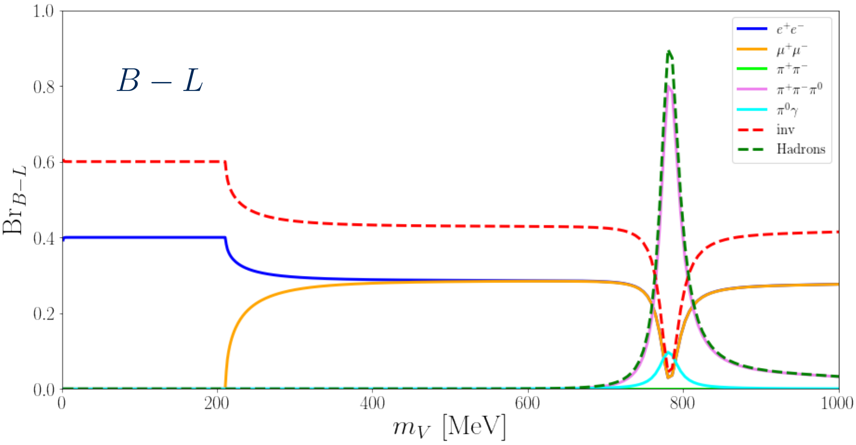
**How do the dark vectors decay?**

**What is the EM energy spectra of the decays?**

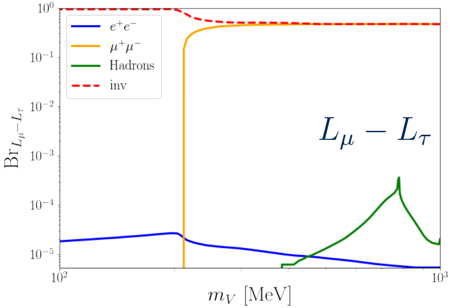
# Branching Ratios Results I

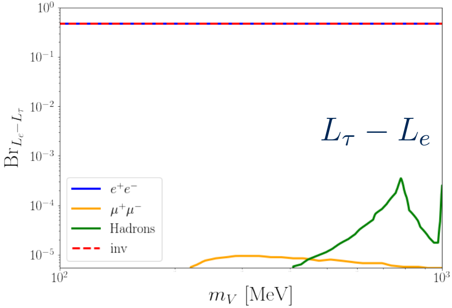


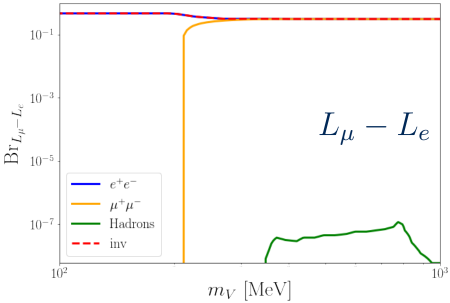
# Branching Ratios Results II



# Branching Ratios Results III



# Energy Spectra

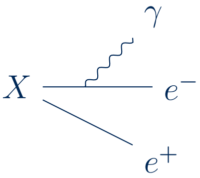
Focusing on the channels that produce electrons and photons:

$$e^-e^+,\ \mu^-\mu^+,\ \pi^0\gamma,\ \pi^-\pi^+, \text{ and } \pi^-\pi^+\pi^0$$

Boosts were applied to the final electrons and photons from the decay channels to be in the rest frame of the dark vector boson.

Non-leading terms, such as Final State Radiation, are not shown but they are included in the analysis since they produce photons.

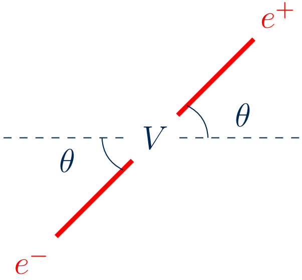
$$X \to e^+ + e^- + \gamma$$



# Energy Spectra

$V \to e^+e^-$

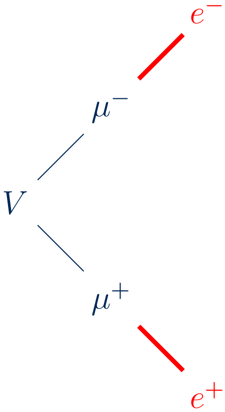
Both electrons come immediately from the decay

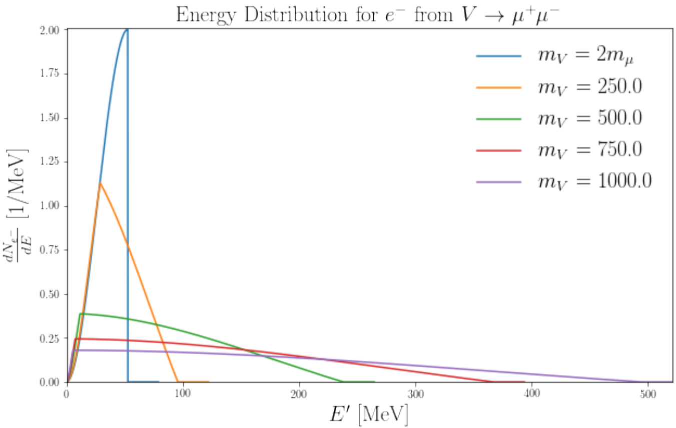



Sum of electron and positron wanted since we care about the total EM energy!

# Energy Spectra

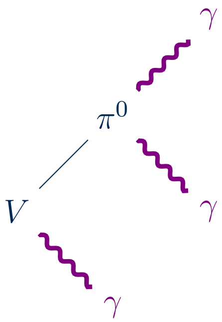
$V \to \mu^+\mu^-$

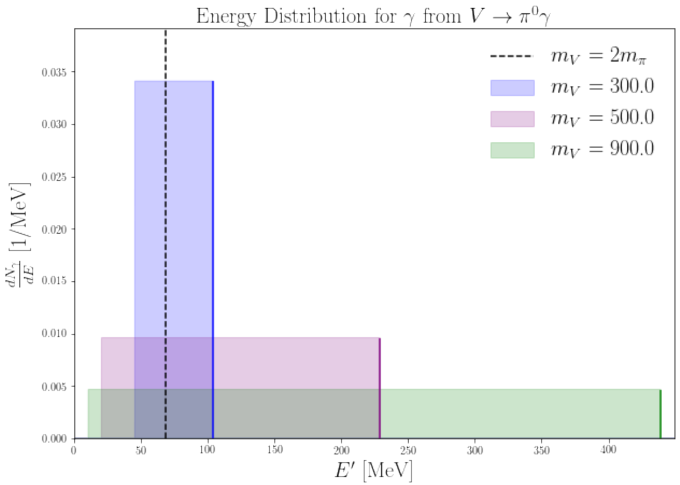


# Energy Spectra

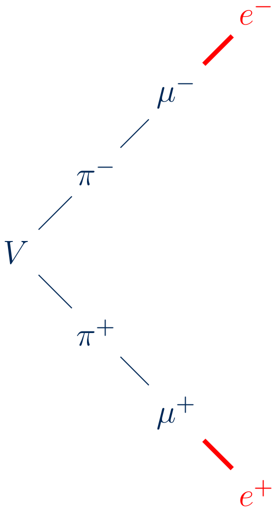
$V \to \pi^0\gamma$

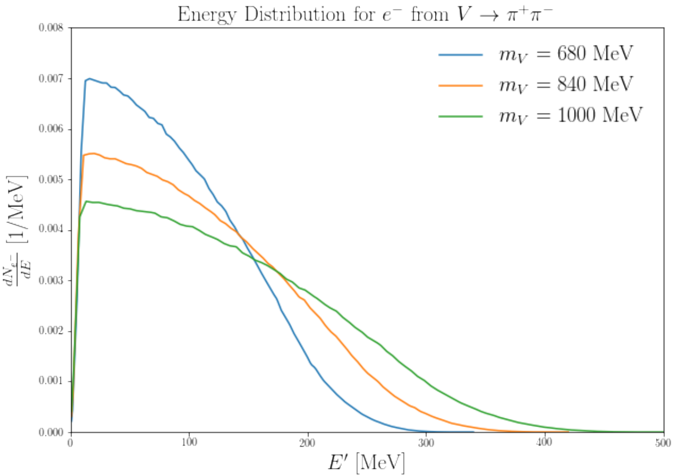


# Energy Spectra

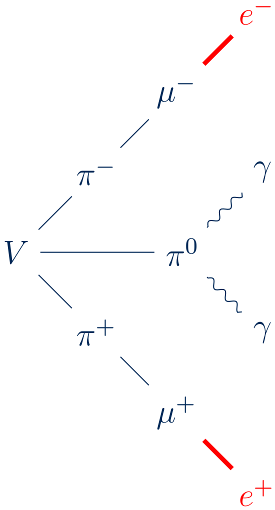
$V \to \pi^+\pi^-$

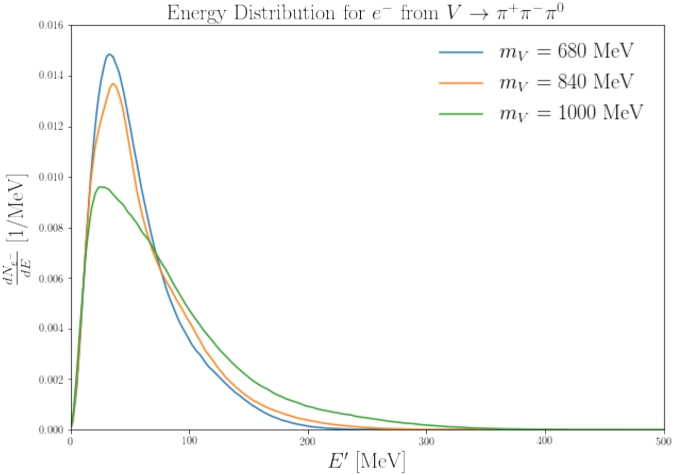


# Energy Spectra

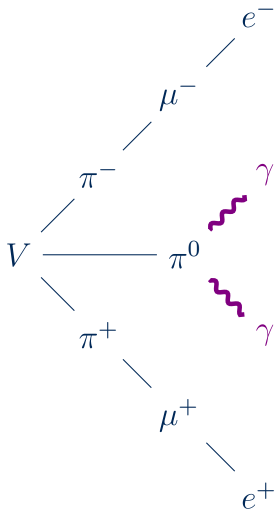
$V \to \pi^+\pi^-\pi^0$

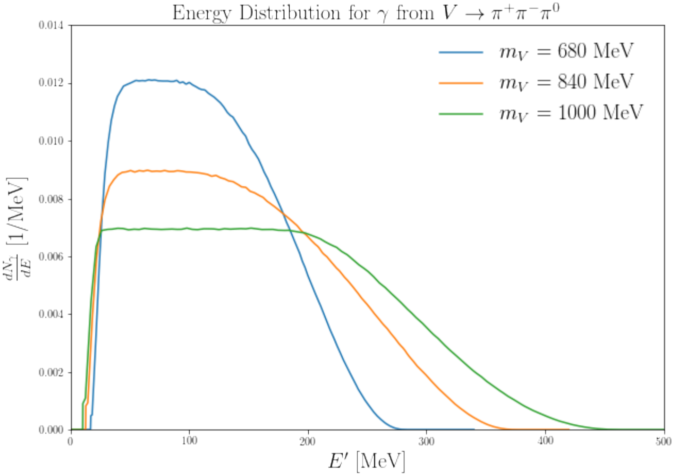


# Energy Spectra

$V \to \pi^+\pi^-\pi^0$



# Application to Cosmology

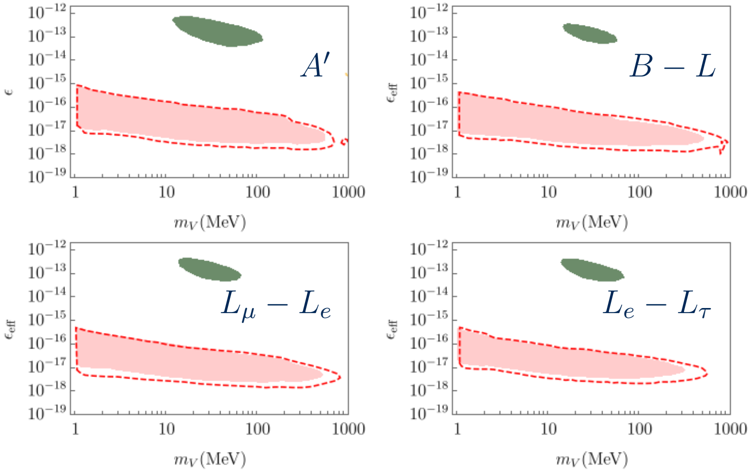
We applied these results to constrain sub-GeV dark vectors against measurements of BBN and CMB.

BBN $\rightarrow$ destroying light elements (photodissociation)

CMB $\rightarrow$ modify recombination (ionization of hydrogen)

For both, the total EM energy spectra from electrons and photons are required inputs.

# Summary of BBN and CMB




Where we define $\epsilon_{\text{eff}} = \sqrt{\alpha_V/\alpha}$. Green is for BBN exclusion, red is for CMB power spectrum exclusion and the dotted red line is projected limits for a cosmic variance limited experiment.

# Conclusion

- Five dark forces were explored in the sub-GeV region
- EM energy spectra for the channels were calculated and constrained by BBN and CMB measurements
- Extensions of the parameter space were implemented.

Thank you!

Merci!

Questions?

# Kinetic Term in Effective Lagrangian

$$
\begin{aligned}
-\frac{\epsilon}{2}F^{\mu\nu}X_{\mu\nu} &= -\frac{\epsilon}{2}F^{\mu\nu}\left(\partial_\mu V_\nu - \partial_\nu V_\mu\right) \\
&= -\frac{\epsilon}{2}\left(F^{\mu\nu}\partial_\mu V_\nu - F^{\mu\nu}\partial_\nu V_\mu\right) \\
&= \epsilon\left(\partial_\mu F^{\mu\nu}\right)V_\nu - \epsilon\partial_\mu\left(F^{\mu\nu}V_\nu\right) \\
&= \epsilon e V_\mu J^\mu_{\text{em}}
\end{aligned}
$$

# Dark Forces and Dark Vectors

The $A'$ vector couples exclusively to the SM photon below the weak scale. The effective coupling can be found using $J^\mu_{A'} = 0$ and examining the kinetic term

$$\alpha_{A'} = \epsilon^2 \alpha_{\text{em}}$$

The other four forces couple to a specific current with an effective coupling

$$\begin{aligned} J^\mu_{B-L} &= \frac{1}{3}\bar{Q}\gamma^\mu Q + \frac{1}{3}\bar{u}_R\gamma^\mu u_R + \frac{1}{3}\bar{d}_R\gamma^\mu d_R - \bar{L}\gamma^\mu L - \bar{e}_R\gamma^\mu e_R; \quad U(1)_{B-L} \\ J^\mu_{L_i-L_j} &= \bar{L}_i{}^\mu_\gamma L_i + \bar{l}_i\gamma^\mu l_i - \bar{L}_j\gamma^\mu L_j - \bar{l}_j\gamma^\mu l_j \qquad ; \quad U(1)_{L_i-L_j} \end{aligned}$$

$$\alpha_V = g_V^2/4\pi$$

Where $V = B - L, L_\mu - L_e, L_e - L_\tau,$ or $L_\mu - L_\tau$

# Branching Ratios

To compute the physical effects of dark vectors, we need to know how they decay. The decay channels of interest in the sub-GeV region are: $e^+e^-$, $\mu^+\mu^-$, $\pi^0\gamma$, $\pi^+\pi^-$ and $\pi^+\pi^-\pi^0$. The decay width to fermion - anti-fermion is easily calculable following Feynman Rules:

$$\Gamma(V \to f\bar{f}) = \frac{Q_f^2 C_f \alpha_X}{3} m_V \left(1 + 2\frac{m_f^2}{m_V^2}\right)\sqrt{1 - 4\frac{m_f^2}{m_V^2}}$$

$$C_f = \begin{cases} 1, & l^+l^- \\ 3, & q\bar{q} \\ 1/2, & \nu\bar{\nu} \end{cases}$$

The hadronic channels require more care for their branching ratios.

# Branching Ratios

The $A'$ and $B-L$ models can mix with the $\rho$ and $\omega$ mesons. Couplings can be found by applying VMD.

$$\mathbf{T}_\rho = \frac{1}{2}\boldsymbol{\lambda}_3, \quad \mathbf{T}_\omega = \frac{1}{3}\mathbb{I}_{3\times 3} + \frac{1}{2\sqrt{3}}\boldsymbol{\lambda}_8$$

$$\mathbf{T}_A = \text{diag}(1/2, \pm 1/2, 0), \quad A = \omega, \rho$$

Can be reduced to a hidden $U(2)$ symmetry since the mesons are comprised of only up and down quarks, and the coupling of these quarks to the forces are needed

$$\mathbf{Q}_{A'} = \text{diag}(2/3, -1/3), \quad \mathbf{Q}_{B-L} = \text{diag}(1/3, 1/3)$$

Finally, the induced kinetic mixing can be found

$$\kappa_{A,V} = 2\text{tr}(\mathbf{T}_A\mathbf{Q}_V) = \begin{cases} 1 & A = \rho, V = A' \\ 1/3 & A = \omega, V = A' \\ 0 & A = \rho, V = B-L \\ 2/3 & A = \omega, V = B-L \end{cases}$$

# Branching Ratios

The simpliest hadronic decay channel is the $\pi^0\gamma$ channel.

$$\Gamma(V \to \pi^0\gamma) = \kappa_{\omega,V}^2 \frac{3\alpha_V}{128\pi^3} \frac{m_V^3 \alpha_{\text{em}}}{f_\pi^2} \left(1 - \frac{m_\pi^2}{m_V^2}\right)^3 \left|F_\omega(m_V^2)\right|^2$$

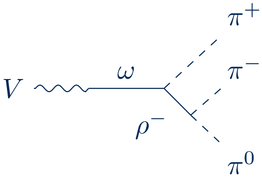
The $\pi^+\pi^-$ channel was difficult to calculate analytically and BaBar results were used.

$$\Gamma(A' \to \pi^+\pi^-) = \Gamma(A' \to \mu^+\mu^-)\mathcal{R}_\mu^{\pi^+\pi^-}(m_{A'}^2)$$

Where $\mathcal{R}_\mu^{\pi^+\pi^-} \equiv \frac{\sigma(e^+e^- \to \pi^+\pi^-)}{\sigma(e^+e^- \to \mu^+\mu^-)}$

# Branching Ratios

$$\Gamma(V \to \pi^+\pi^-\pi^0) = \kappa^2_{\omega,V}\frac{3\alpha_V}{16\pi^4}\left(\frac{g^2_{\rho\pi\pi}}{4\pi}\right)^2\frac{m_V}{f_\pi^2}\mathcal{I}(m_V^2)\left|F_\omega(m_V^2)\right|^2$$




$$\mathcal{I}(m_V^2) = \int dE_+ dE_- [|\mathbf{p}_+|^2|\mathbf{p}_-|^2 - (\mathbf{p}_+\cdot\mathbf{p}_-)^2] \times \left|\frac{1}{m_\rho^2-(p_++p_-)^2-i\Gamma_\rho m_\rho}\right.$$
$$\left.+\frac{1}{m_\rho^2-(p_++p_0)^2-i\Gamma_\rho m_\rho}+\frac{1}{m_\rho^2-(p_++p_0)^2-i\Gamma_\rho m_\rho}\right|^2$$

The branching ratio in the sub-GeV region can now be found using:

$$\mathrm{Br}_c = \frac{\Gamma_c}{\Gamma_T}, \quad \Gamma_T = \sum_c \Gamma_c$$

# Energy Spectra

$V \to \mu^+\mu^-$

Electrons are a final state for this decay, but the muons must decay first. The electrons from muons decays are Michel electrons and follow the distribution

$$f(y) = 2y^2\Big[(3-2y) + P(1-2y)\cos\theta\Big]\Theta(1-y)$$

Where $y = E_{e^\pm}/E_{max}$, $E_{max} = m_\mu/2$ and the energy spectra of the electrons is

$$\left.\frac{dN_{e^-}}{dE}\right|_{\mu^-} = \frac{f(y)}{E_{max}}$$

# Energy Spectra

$V \to \mu^+\mu^-$

Applying boosts and solving the integrals we find the sum of electron and positron spectra

$$\left.\frac{dN_e}{dE}\right|_V = \frac{2}{E_{max}} \begin{cases} 0 & : \quad y' > B \\ \frac{2y'^2}{\gamma}\left[\frac{3}{1-\beta^2} - 2y'\frac{1+\beta^2/3}{(1-\beta^2)^3/2}\right] & : \quad y' < \frac{1}{B} \\ \frac{1}{\beta\gamma}\left(\frac{3}{2}\left(1 - y'^2\frac{1-\beta}{1+\beta}\right) - \frac{2}{3}\left[1 - y'^3\left(\frac{1-\beta}{1+\beta}\right)^{3/2}\right]\right) & : \quad \frac{1}{B} < y' < B \end{cases}$$

Where $B = \sqrt{\frac{1+\beta}{1-\beta}}$. The $P$ terms are not included as they cancel since the positron spectrum is the same form but the sign of $P$ is flipped.

# Energy Spectra

$V \to \pi^0 \gamma$

The initial photon is a delta spike

$$\left.\frac{dN_\gamma}{dE}\right|_V = \delta\left(E_\gamma - \frac{m_V}{2}\left(1 - \frac{m_\pi^2}{m_V^2}\right)\right)$$

The two photons from the pion decay

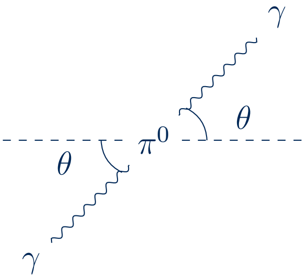
$$\left.\frac{dN_\gamma}{dE}\right|_{\pi^0} = 2\delta(E_\gamma - E_o)$$

Boosting to the $V$ rest frame with

$$\gamma = \frac{E_\pi}{m_\pi} = \frac{m_V}{2m_\pi}(1+\frac{m_\pi^2}{m_V^2}), \quad \beta = \frac{\sqrt{\gamma^2 - 1}}{\gamma}$$

$$\left.\frac{dN_\gamma}{dE}\right|_V = \begin{cases} \frac{1}{\beta\gamma}\frac{1}{E_o} & : B_- \le \frac{E'}{E_o} \le B_+ \\ 0 & : \text{otherwise} \end{cases}$$

Where $B_\pm = \gamma(1 \pm \beta)$



# Energy Spectra

$V \to \pi^+\pi^-$

The pions decay to muons which in turn decay to Michel electrons, thus one more boost must be applied to the results of the $V \to \mu^+\mu^-$ channel resulting in the integral

$$\left.\frac{dN_{e^-}}{dE}\right|_V = \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2\pi} \int dz \int dx \int d\phi \left|\frac{\partial(E'', z, x, \phi)}{\partial(E, z, x, \phi)}\right|^{-1} \left(\left.\frac{dN_{e^-}}{dE''}\right|_{\mu^-}\right)$$

This is a complicated integral to solve, and a Monte Carlo method can be used to find the distribution of the electrons. P $= +1$ for muons and -1 for anti-muons

$$\left.\frac{dN_e}{dE}\right|_V = 2\left.\frac{dN_{e^-}}{dE}\right|_V$$

# Big Bang Nucleosynthesis Results I

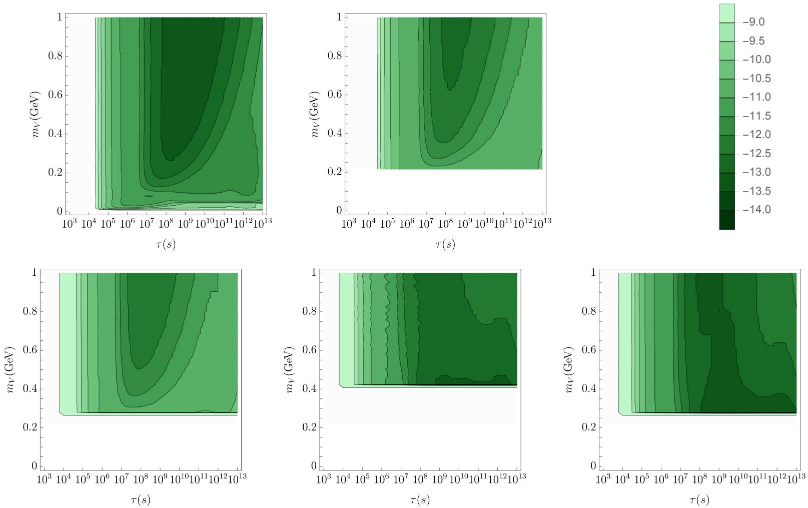



Figure: BBN limits for $m_V Y_V$ in the parameter space of mass and lifetime on exclusive decay channels $V \to e^+e^-$ (upper left), $V \to \mu^+\mu^-$ (upper middle), $V \to \pi^+\pi^-$ (lower left), $V \to \pi^+\pi^-\pi^0$ (lower middle), $V \to \pi^0\gamma$ (lower right).

# Big Bang Nucleosynthesis Results II

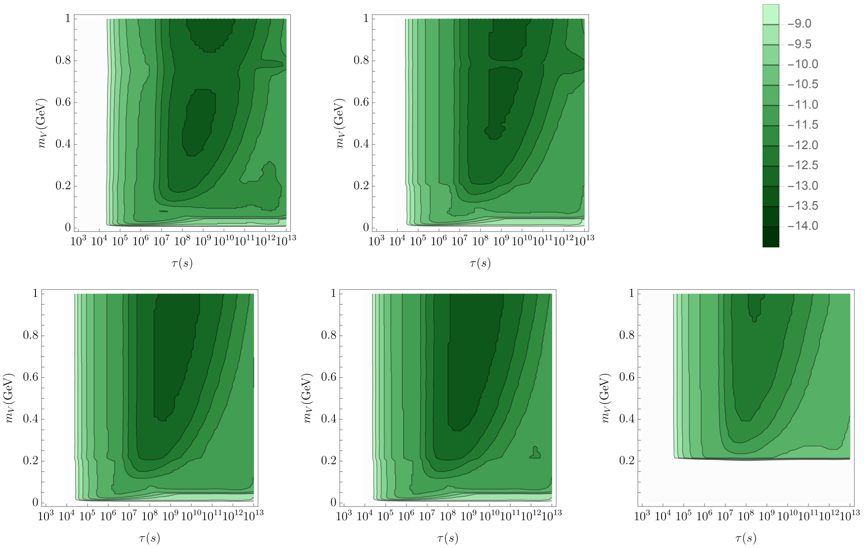



Figure: BBN limits for $m_V Y_V$ in the parameter space of mass and lifetime on models $A'$ (upper left), $B-L$ (upper middle), $L_\mu - L_e$ (lower left), $L_e - L_\tau$ (lower middle), $L_\mu - L_\tau$ (lower right).

# Applications and Results

## Cosmic Microwave Background

EM energy injection can also be constrained by the power spectrum of the CMB. For a decaying particle it injects energy into the cosmological background. The energy is not deposited immediately and is spread into specific channels.

The largest contribution to distortions of the CMB power spectra is from hydrogen ionization. This process ionzies newly-formed atoms and alters recombination.

# Cosmic Microwave Background Results

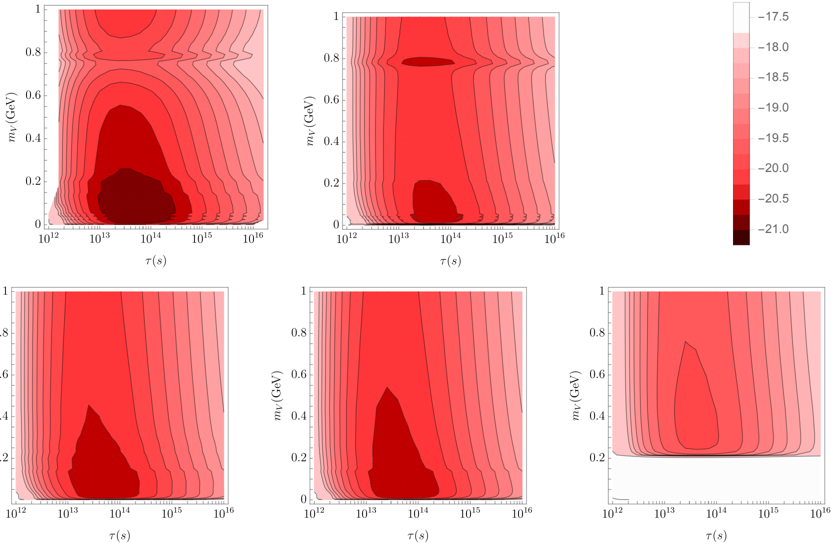



Figure: CMB limits on models $A'$ (upper left), $B-L$ (upper middle), $L_\mu - L_e$ (lower left), $L_e - L_\tau$ (lower middle), $L_\mu - L_\tau$ (lower right).

# Summary of BBN and CMB

The dark vector can decay to the covered particle, but the exact opposite can occur where the particles annihilate into the dark vector.
Assuming a thermal freeze in abundance of the dark vector, the parameter space can be changed to an effective coupling, mass and pre-decay yield

$$Y_V = (Y_V)_I + (Y_V)_{II}$$

$$(Y_V)_I = \frac{3}{2\pi^2} m_V^3 \tilde{\Gamma}_V \int_0^{x_{\mathsf{QCD}}} dx \frac{K_1(x)}{x^2 s H}$$

$$(Y_V)_{II} = \frac{3}{2\pi^2} m_V^3 \Gamma_V \int_{x_{\mathsf{QCD}}}^{\infty} dx \frac{K_1(x)}{x^2 s H}$$

Where the effective coupling for the different dark vectors is defined as:

$$\epsilon_{eff} = \sqrt{\alpha_V / \alpha_{\mathsf{em}}}$$