Matter-antimatter asymmetry and dark matter stability from baryon number conservation

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In collaboration with Mar Ciscar and Jérôme Vandecasteele. arXiv: 2307.02592

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October 2023

Introduction

• Cosmological observations suggest that our Universe contains many more baryons than antibaryons.

$$Y_{B,0} = \left.\frac{n_B - n_{\bar{B}}}{s}\right|_0 = (8.75 \pm 0.23) \times 10^{-11}$$

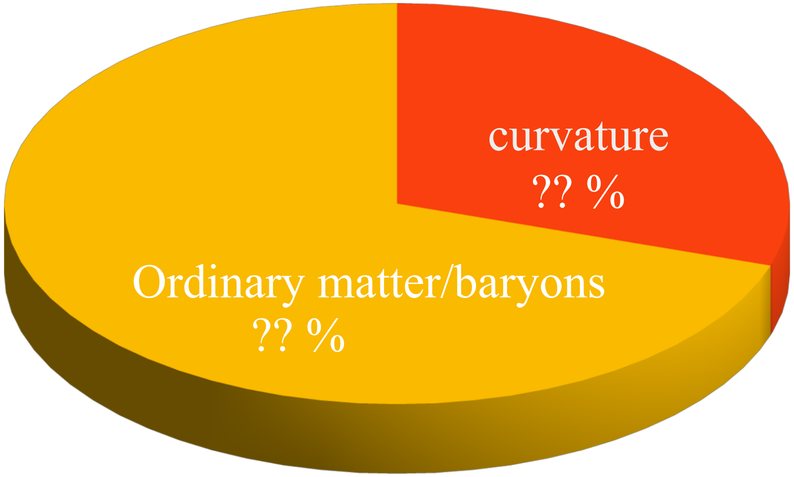
• A baryon asymmetry could be dynamically generated from a baryon symmetric Universe, if the following conditions are satisfied (Sakharov'67):

1) Violation of baryon number
2) C and CP violation.
3) Departure from thermal equilibrium.

Baryogenesis

Introduction

The cosmic pie in 1967



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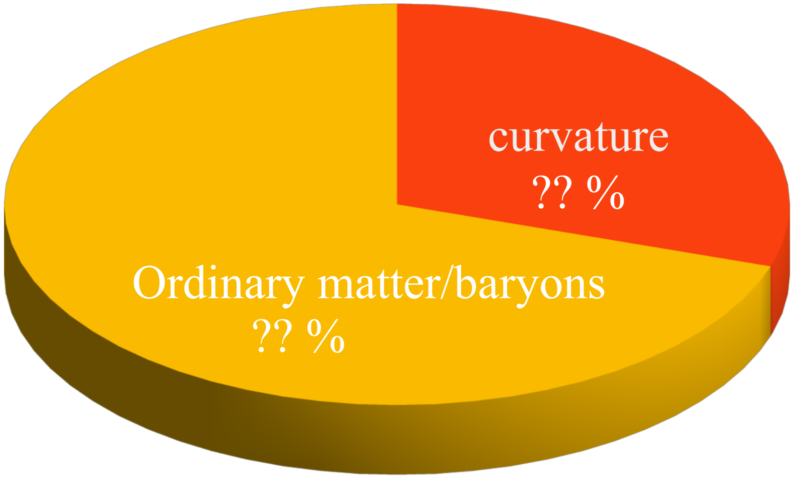
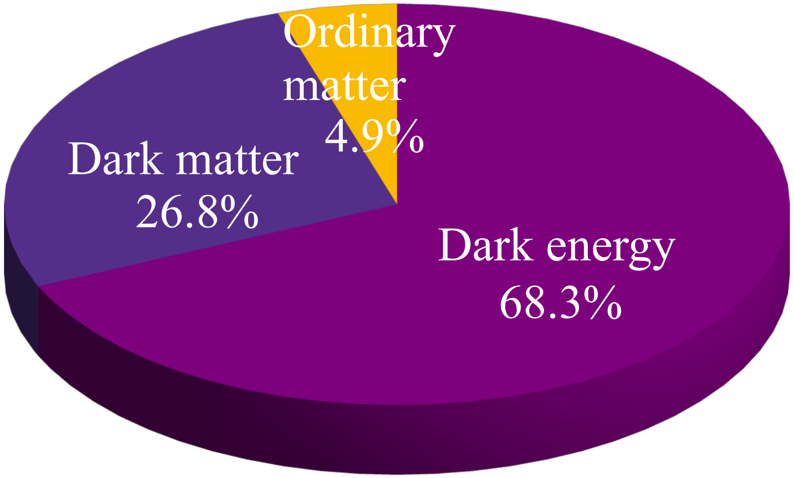


The cosmic pie in the 2020s



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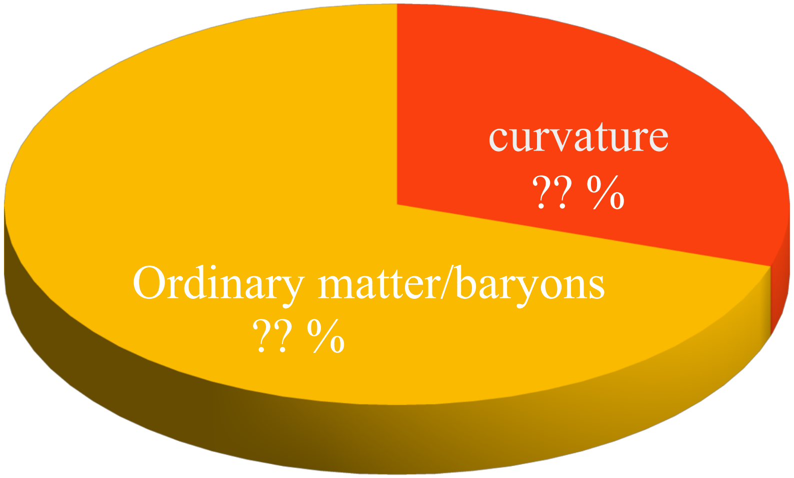

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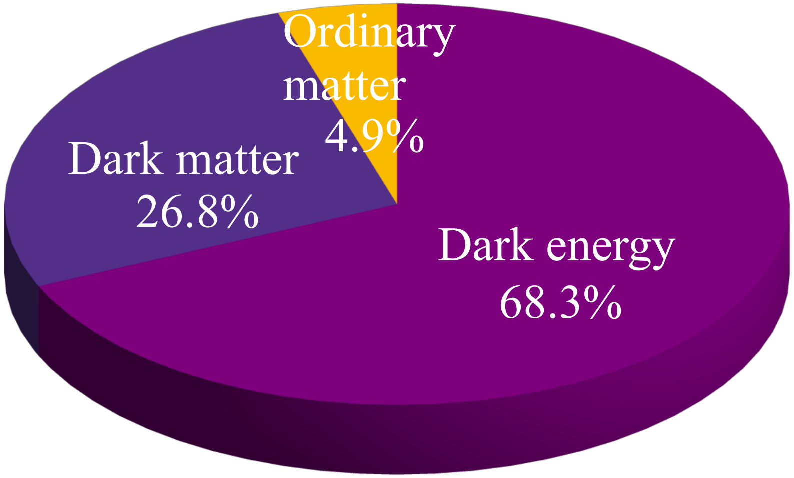
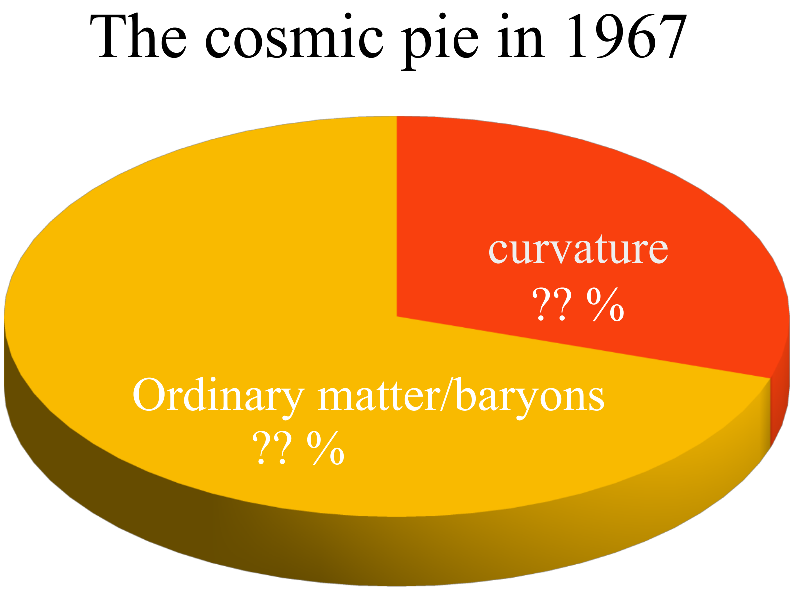
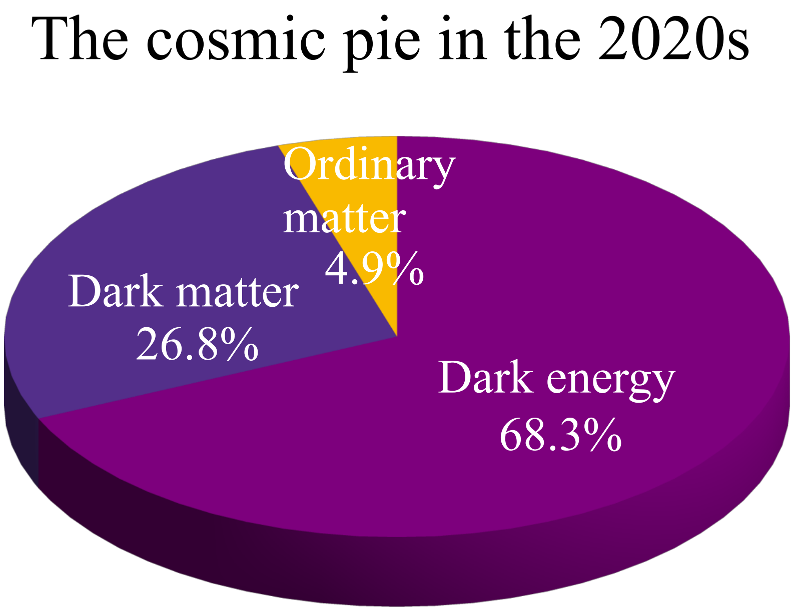


There is no evidence for a baryon asymmetry in our Universe

Introduction





There is no evidence for a baryon asymmetry in our Universe

- Dark sector particles could also carry baryon number
- Observations only show that there are more quarks than antiquarks.

$$Y_{\Delta q,0} = (2.63 \pm 0.07) \times 10^{-10}$$

- The Universe could even be baryon symmetric.

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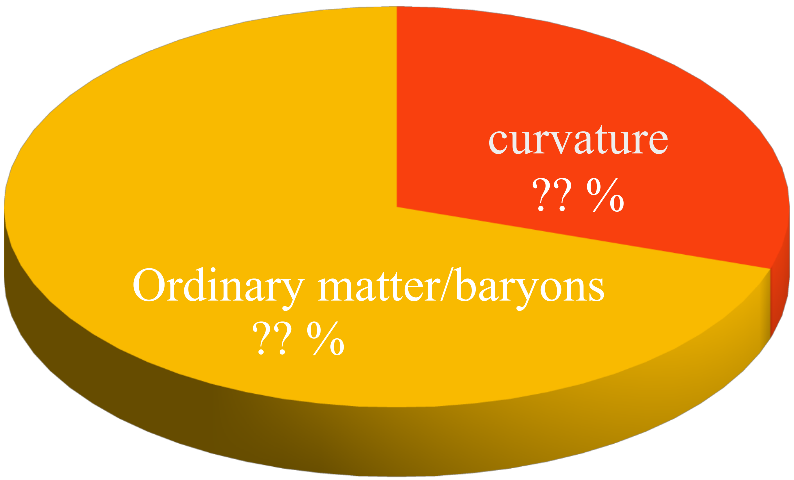

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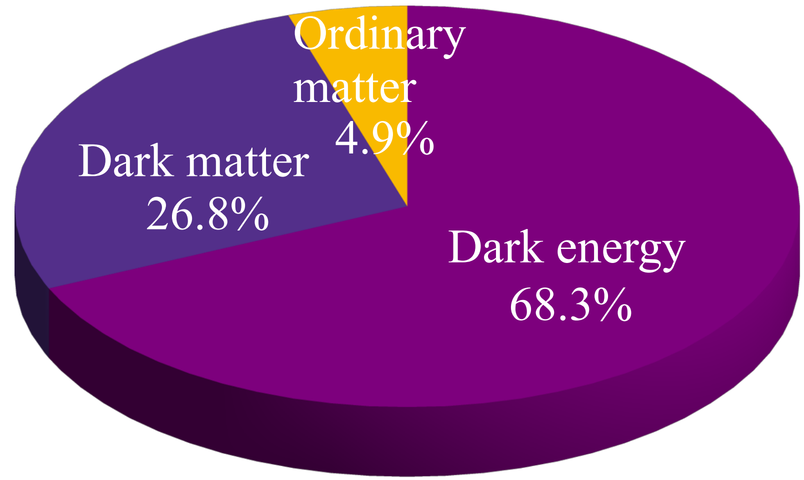

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The Sakharov conditions may not be necessary

An alternative recipe to cook the cosmic pie

Assume that there are dark sector particles with baryon number.

A quark-antiquark asymmetry will be generated if:

- C- and CP-violation in the dark sector.
  To generate an asymmetry between a particle carrying baryon number and its antiparticle

- Portal interactions between dark sector and visible sector.
  To transmit the asymmetry to the visible sector.

- Departure from thermal equilibrium.

A simple scenario

- Complex scalar, χ, with baryon number -1
- Dirac fermion, N, with baryon number +1
- Standard Model quarks, with baryon number 1/3
- Baryon number conservation.

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  Generates more N than $\overline{N}$. For example, from the out of equilibrium decay of a heavy particle, à la leptogenesis.

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  "Neutron portal" $\overline{N} d_{\rm R} \, \overline{u^c_{\rm R}} d_{\rm R}$. Transmits the asymmetry in N to the visible sector and generates a quark-antiquark asymmetry

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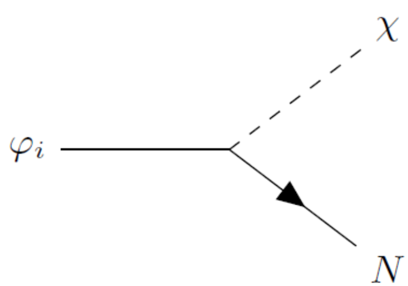

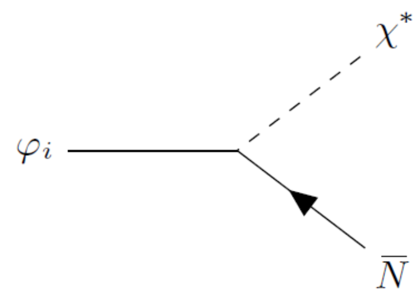

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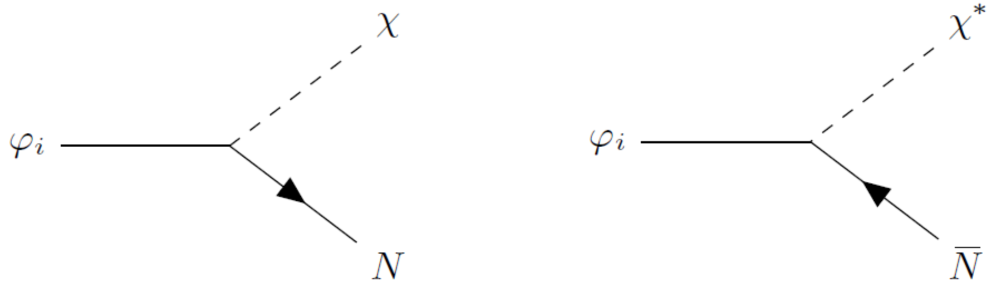

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Bonus: χ is absolutely stable, due to the conservation of baryon number.

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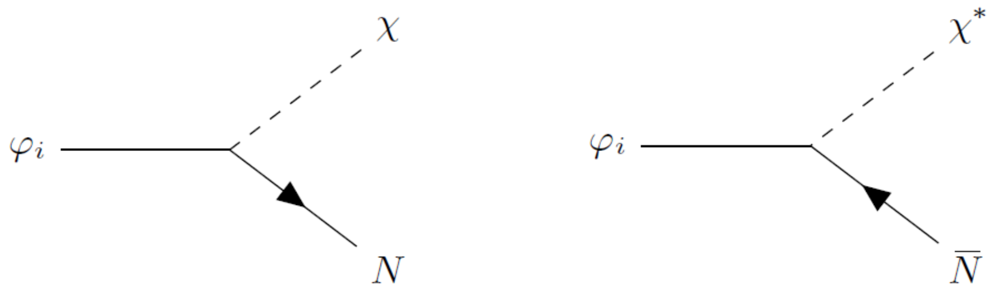

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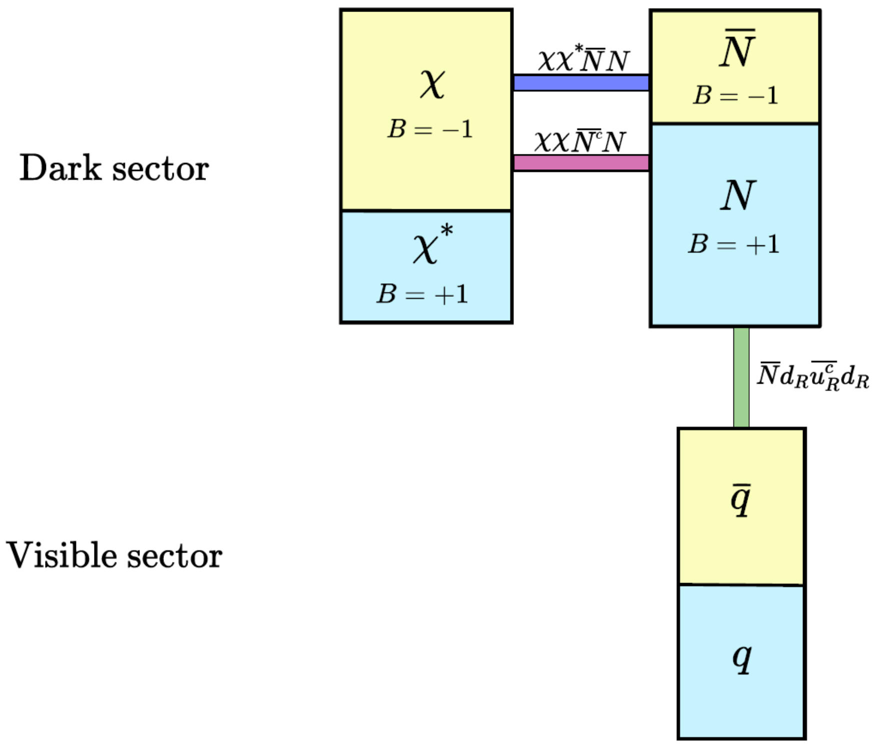
quark-antiquark asymmetry ⟺ **dark matter stability**

A simple scenario

Initial state



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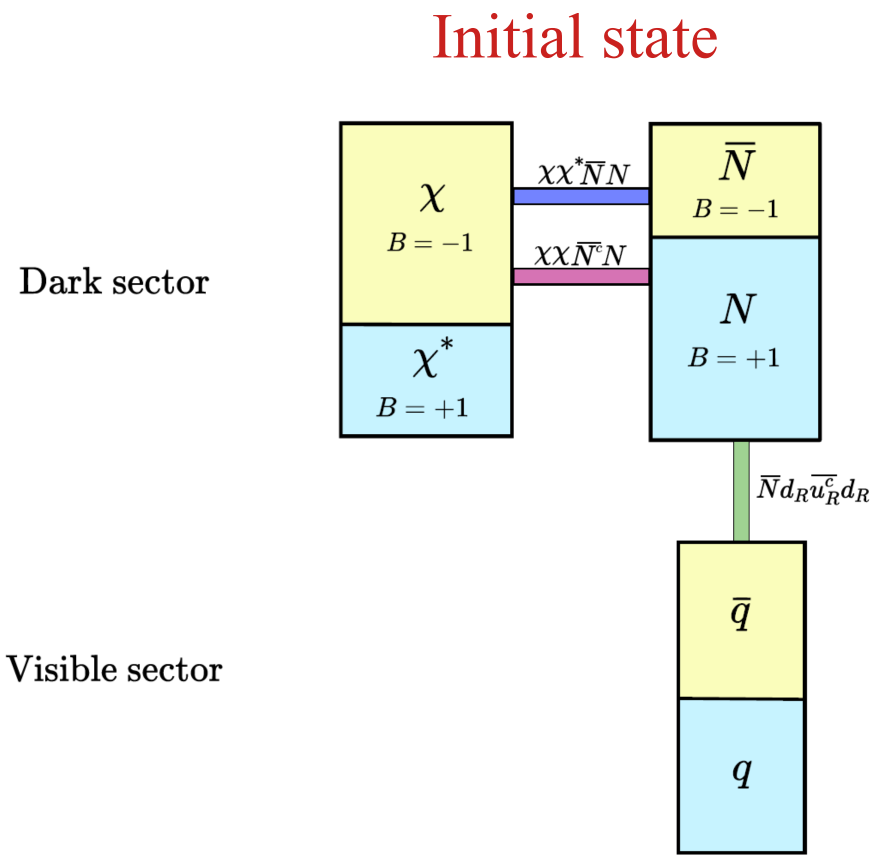
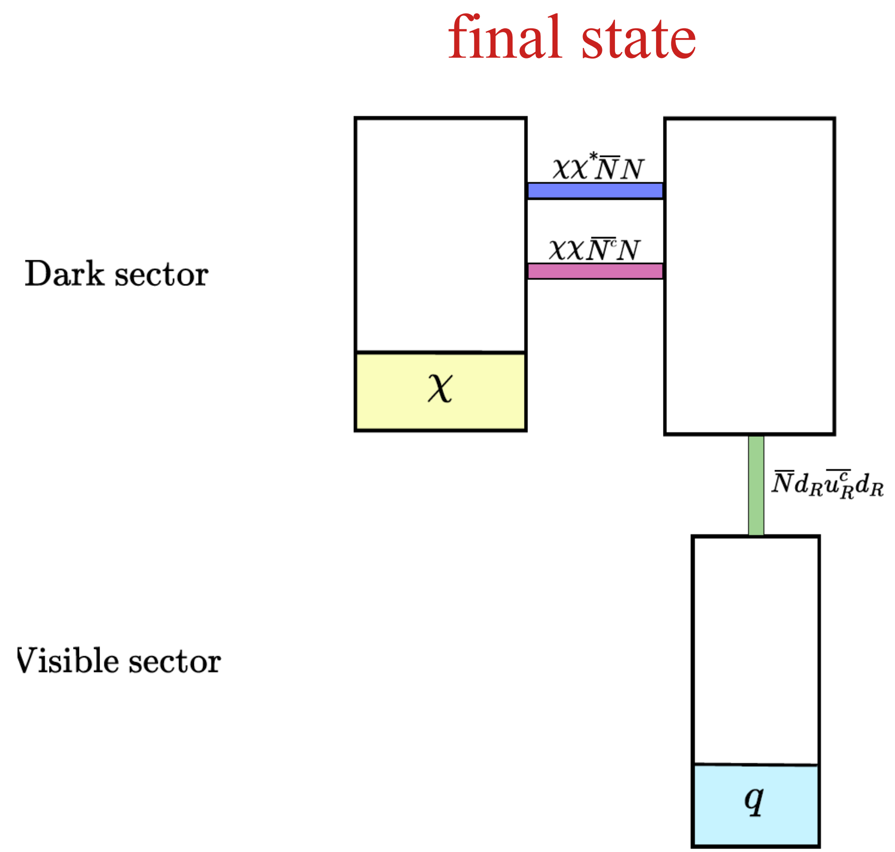
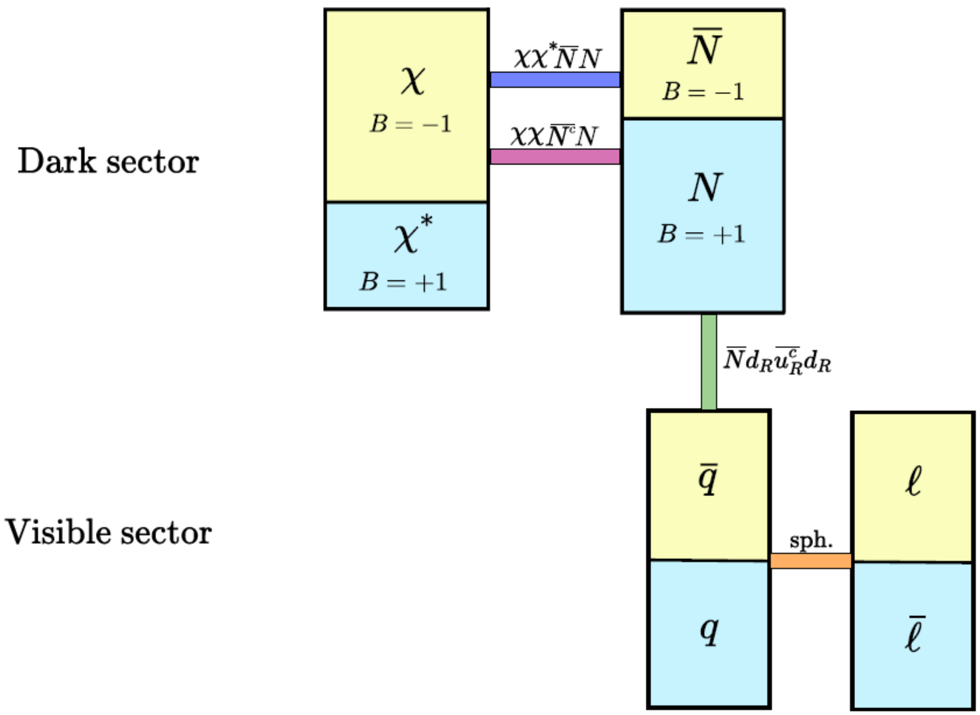




A more refined scenario

Initial state



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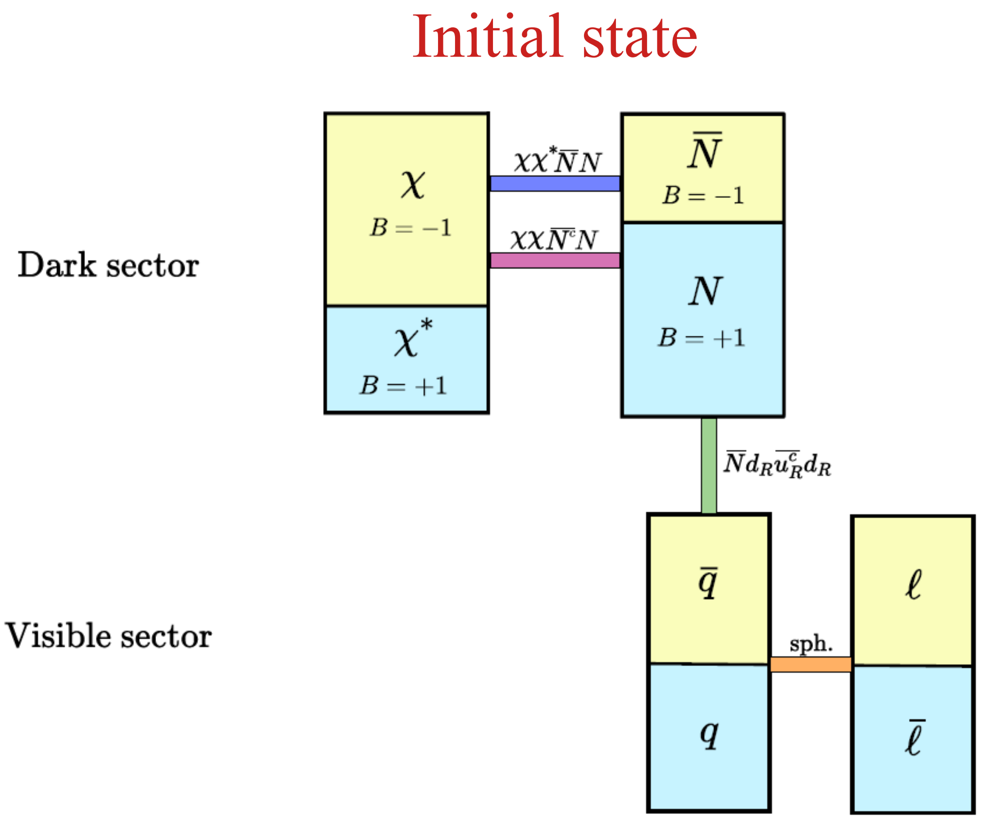

Consider for simplicity:

- Neutron portal sufficiently strong to bring the dark sector baryons into thermal equilibrium with the visible sector
- Wash-out scatterings $\chi\chi \leftrightarrow NN, \chi N \leftrightarrow \chi^* N$ suppressed

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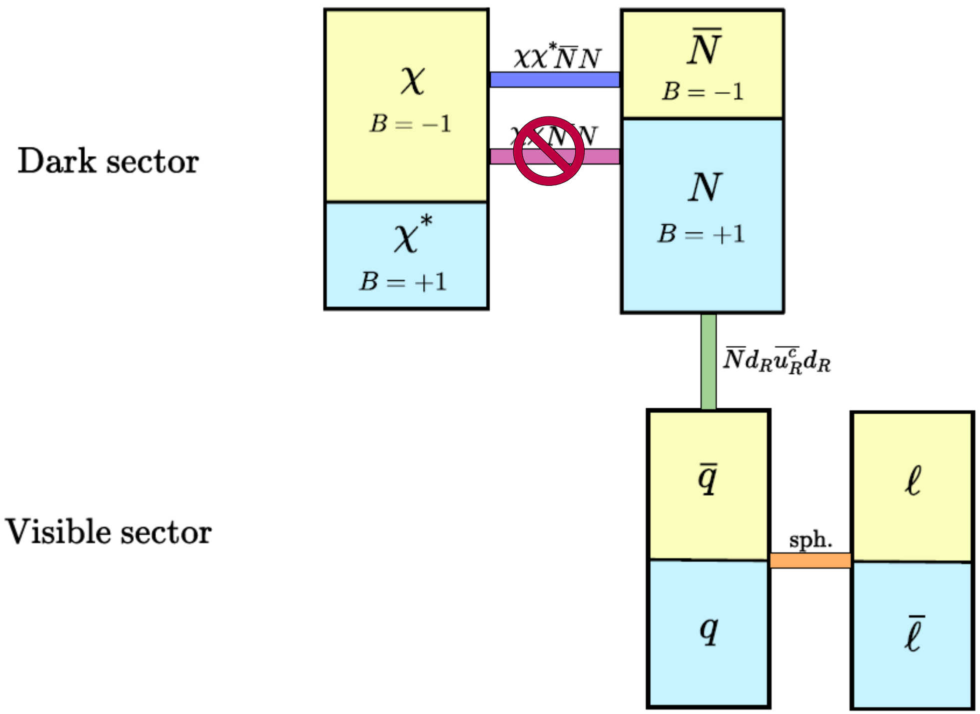

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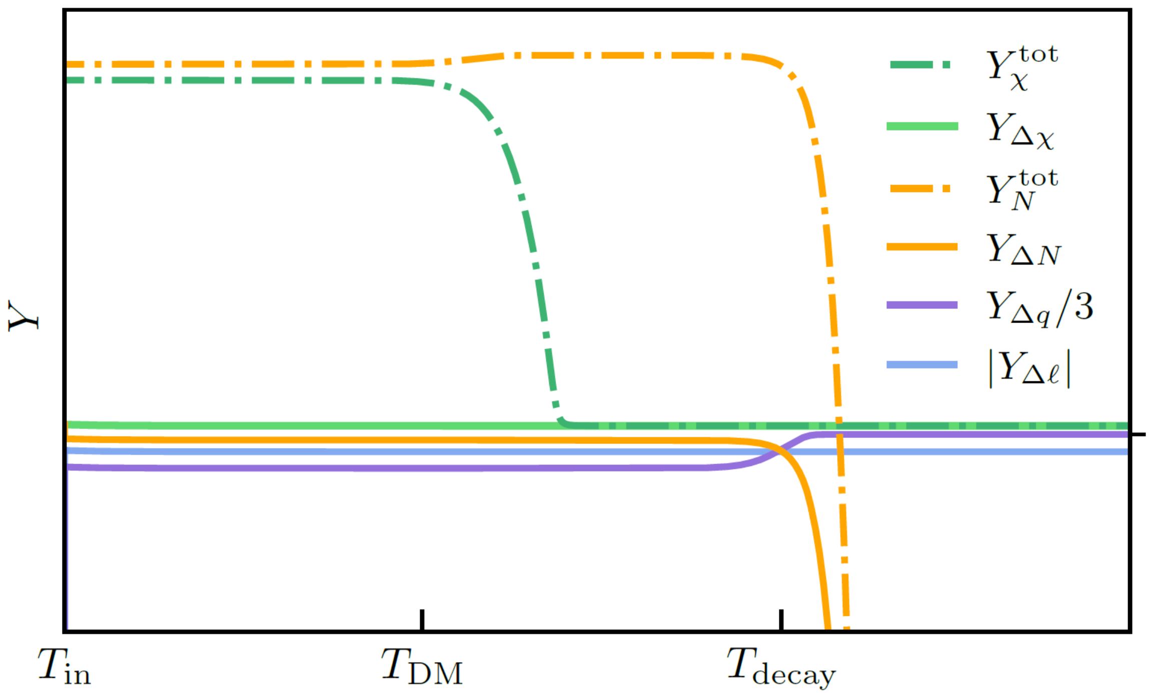
A more refined scenario

$$Y_N^{\rm eq} = 2Y_\chi^{\rm eq}$$
$$Y_{\Delta N}^{\rm in} = Y_{\Delta\chi}^{\rm in},$$
$$Y_{\Delta q}^{\rm in} = Y_{\Delta\ell}^{\rm in} = 0.$$



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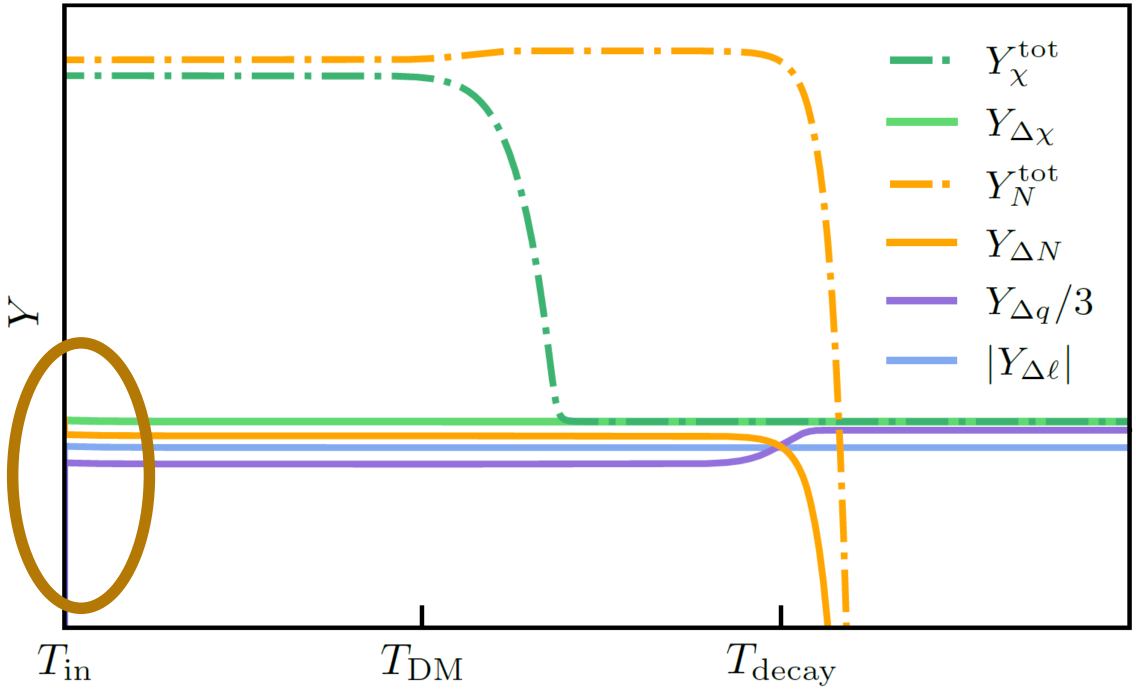

The asymmetry in N is quickly transmitted to the quark sector via scatterings $N\bar{d} \leftrightarrow ud,\ \ N\bar{u} \leftrightarrow dd$

$$Y_{\Delta N}(T) = \frac{42}{79} Y_{\Delta N}^{\rm in},$$
$$Y_{\Delta q}(T) = \frac{36}{79} Y_{\Delta N}^{\rm in},$$
$$Y_{\Delta \ell}(T) = -\frac{25}{79} Y_{\Delta N}^{\rm in}.$$

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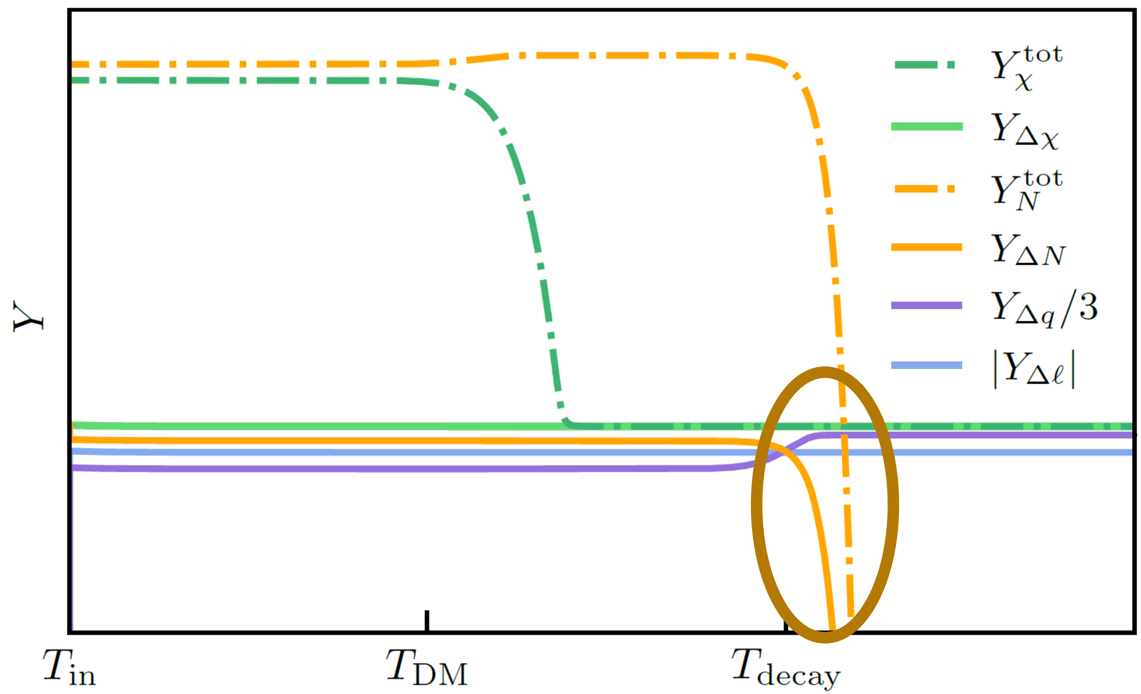

The decay $N \to udd$ increases the quark-antiquark asymmetry.

$$Y_{\Delta q,0} = 3\frac{42}{79}Y_{\Delta N}^{\rm in} + \frac{36}{79}Y_{\Delta N}^{\rm in} = \frac{162}{79}Y_{\Delta N}^{\rm in},$$

The decay typically occurs when the sphalerons are out-of-equilibrium, and the lepton asymmetry remains the same

$$Y_{\Delta\ell,0} = -\frac{25}{79}Y_{\Delta N}^{\rm in}$$

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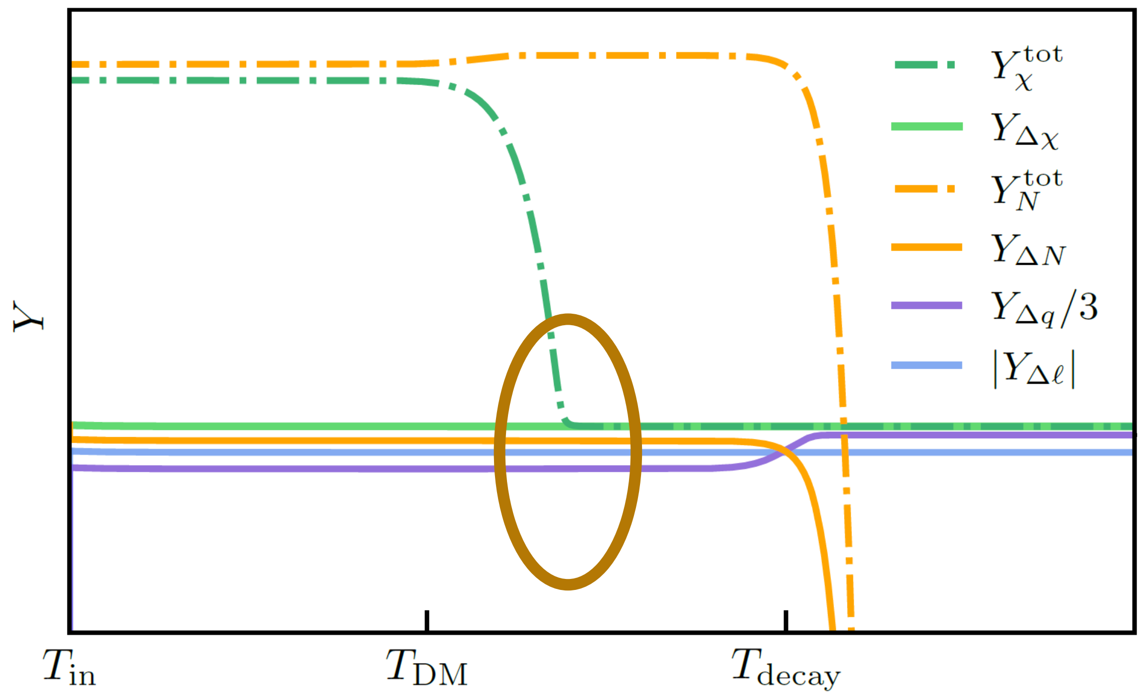
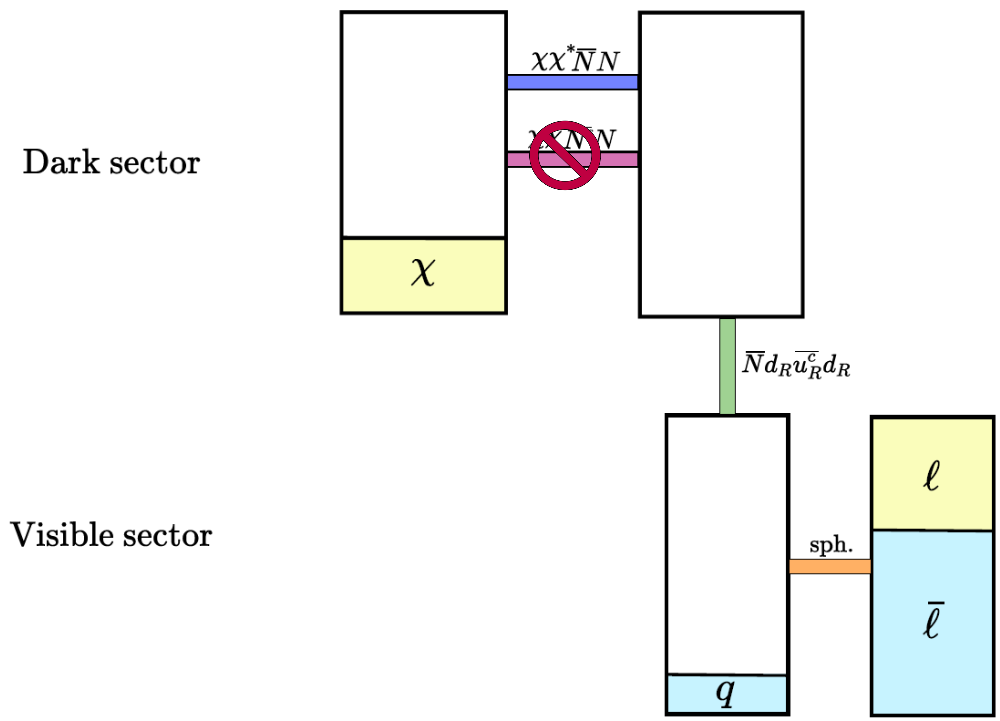


Freeze-out of $\chi\chi^* \to N\bar{N}$

$$\Omega_{\rm DM,0}h^2 \simeq 2.8\times 10^8\, Y_\chi^{\rm tot}(x_{\rm f.o.})\frac{m_\chi}{\rm GeV}.$$

A more refined scenario

Final state, when all χ^* are annihilated



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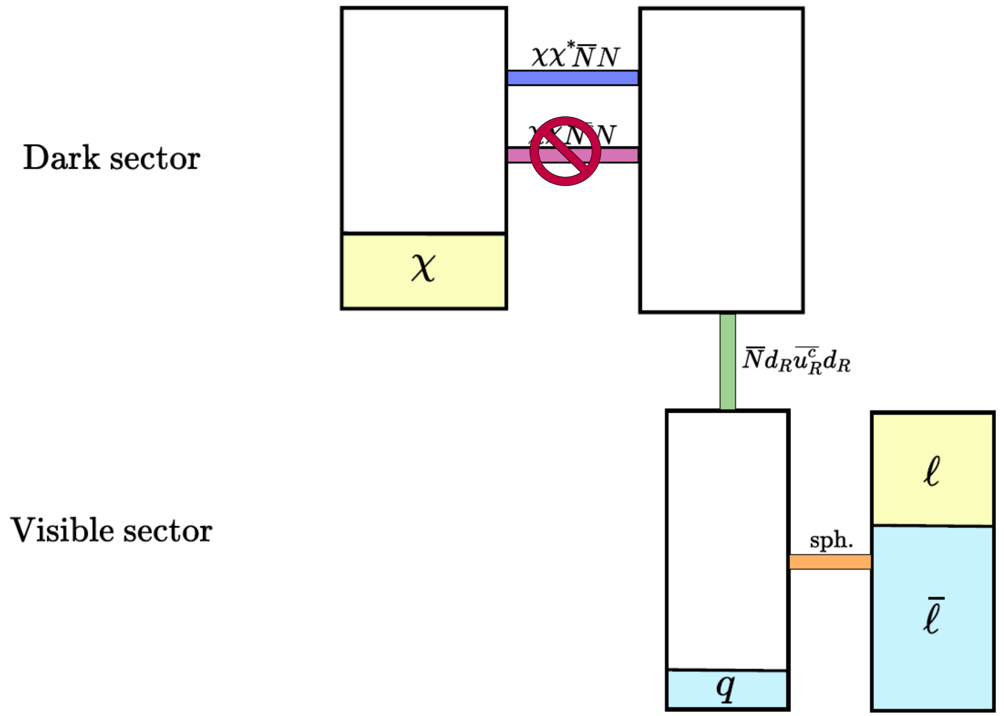

$$\Omega_{\mathrm{DM},0}h^2 \simeq 2.8 \times 10^8\, Y^{\mathrm{in}}_{\Delta N}\,\frac{m_\chi}{\mathrm{GeV}}\,.$$

$$Y^{\mathrm{tot}}_{\chi}(x_{\mathrm{f.o.}}) = Y_{\Delta\chi}(x_{\mathrm{f.o.}}) = Y^{\mathrm{in}}_{\Delta\chi} = Y^{\mathrm{in}}_{\Delta N}$$

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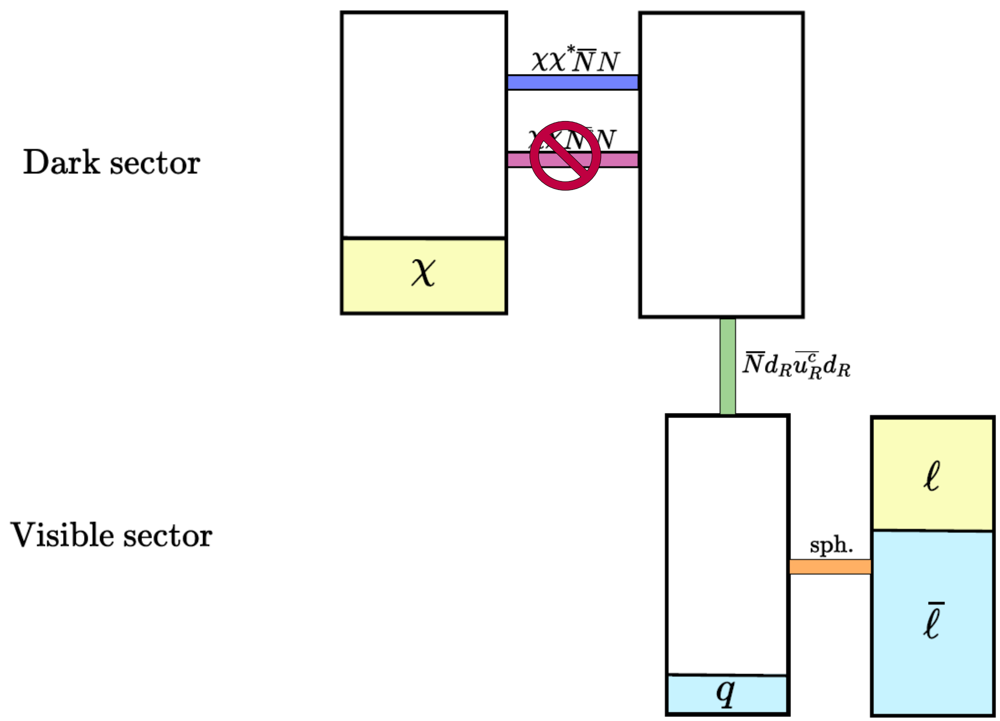

$$\Omega_{\mathrm{DM},0}h^2 \simeq 2.8\times 10^8\, Y^{\mathrm{in}}_{\Delta N}\frac{m_\chi}{\mathrm{GeV}}\,.$$

$$\mathrm{Y}_{\Delta q,0} = \tfrac{162}{79}Y^{\mathrm{in}}_{\Delta N},$$

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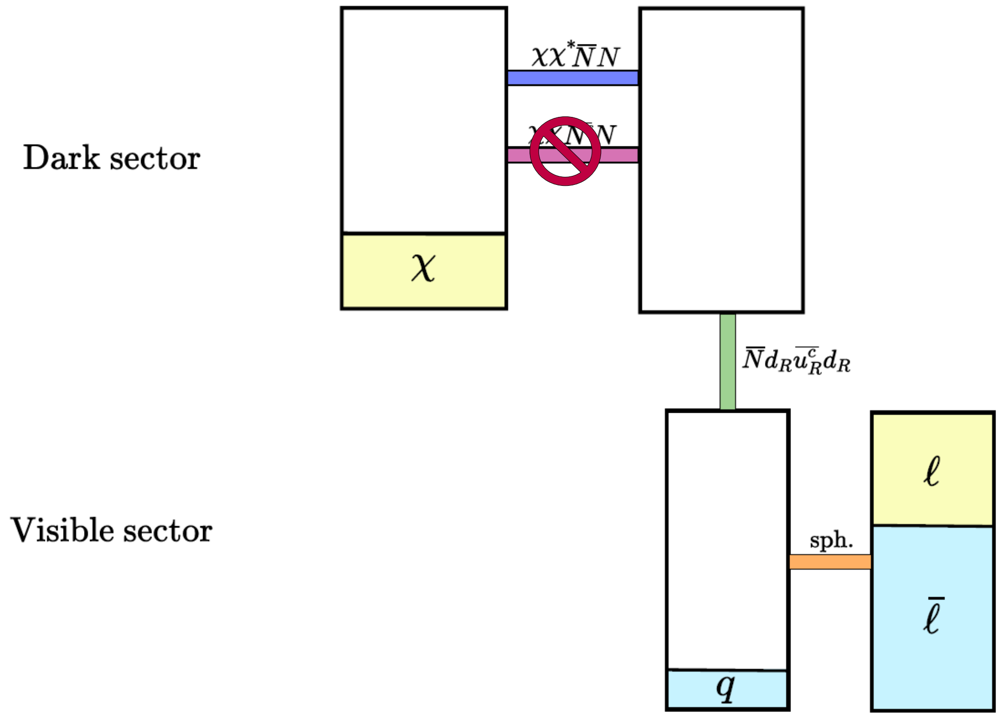
Final state, when all χ^* are annihilated



$$\Omega_{\rm DM,0}h^2 \simeq 1.4\times 10^8\, Y_{\Delta q,0}\frac{m_\chi}{\rm GeV}\ .$$

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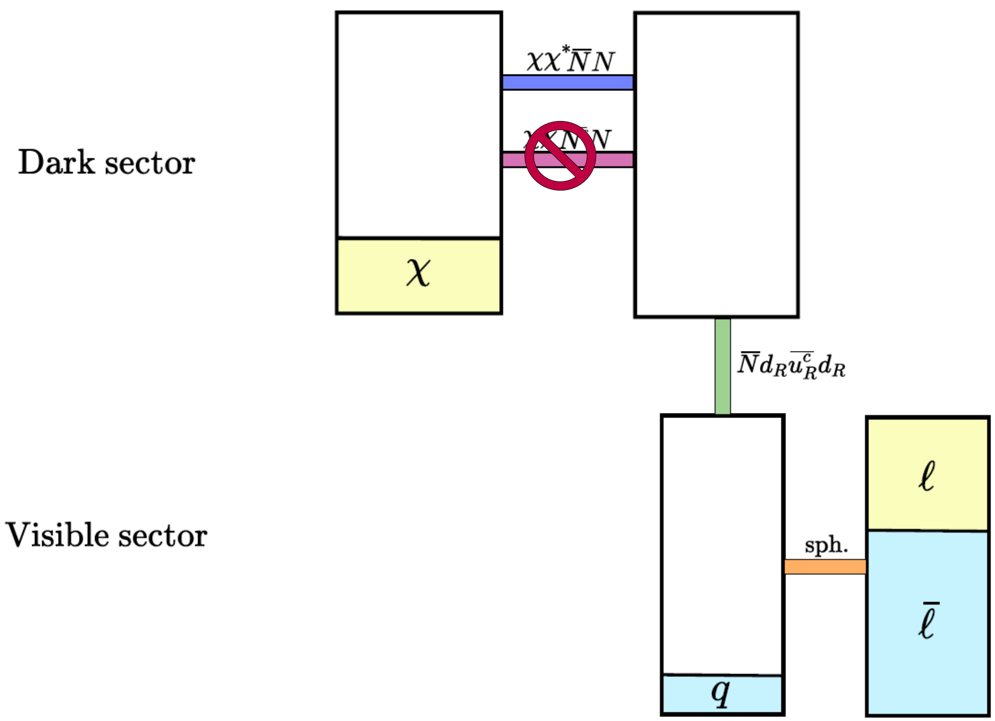

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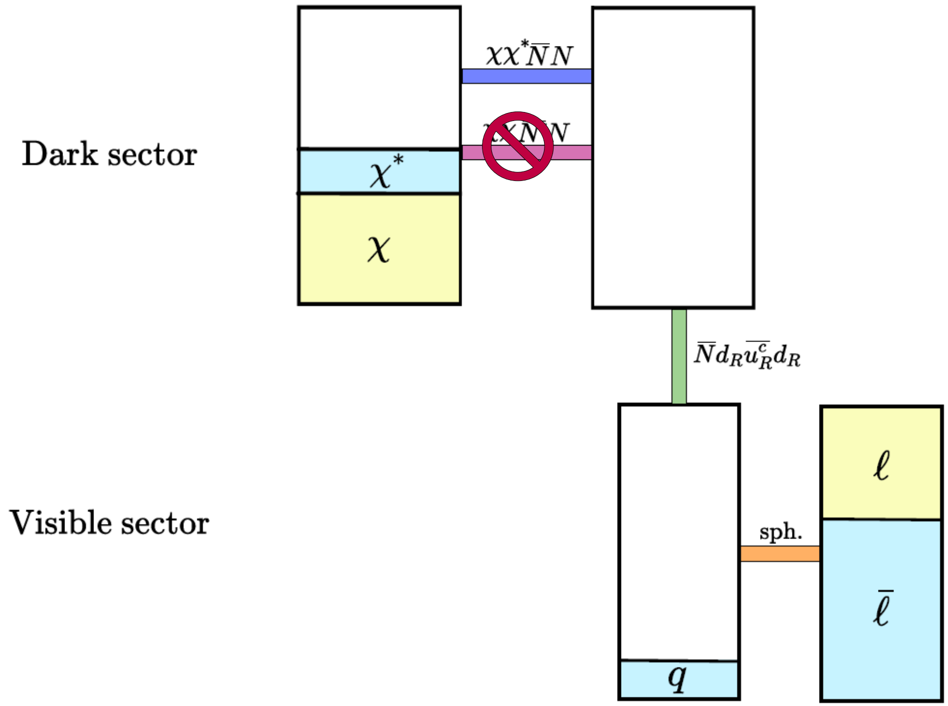
$$\mathrm{Y}_{\Delta q,0} = \tfrac{162}{79} Y^{\mathrm{in}}_{\Delta N},$$

$$Y^{\mathrm{in}}_{\Delta\chi} \simeq 1.3 \times 10^{-10},$$

$$m_\chi \simeq 3.4\,\mathrm{GeV}.$$

A more refined scenario

Final state, when χ^* are partially annihilated

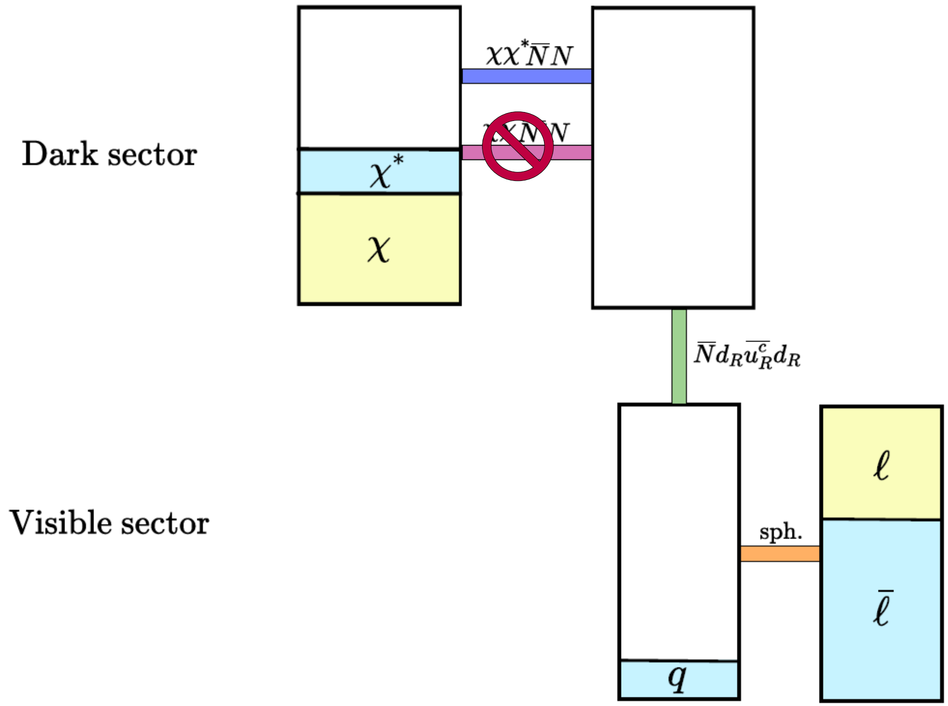


$$\Omega_{\mathrm{DM},0}h^2 \simeq 2.8\times 10^8\, Y_\chi^{\mathrm{tot}}(x_{\mathrm{f.o.}})\,\frac{m_\chi}{\mathrm{GeV}}.$$

$$Y_\chi^{\mathrm{tot}}(x_{\mathrm{f.o.}}) > Y_{\Delta\chi}(x_{\mathrm{f.o.}}) = Y_{\Delta\chi}^{\mathrm{in}} = Y_{\Delta N}^{\mathrm{in}}$$

A more refined scenario

Final state, when χ^* are partially annihilated



$$\Omega_{\mathrm{DM},0}h^2 \gtrsim 2.8\times 10^8\, Y_{\Delta N}^{\mathrm{in}}\frac{m_\chi}{\mathrm{GeV}}.$$

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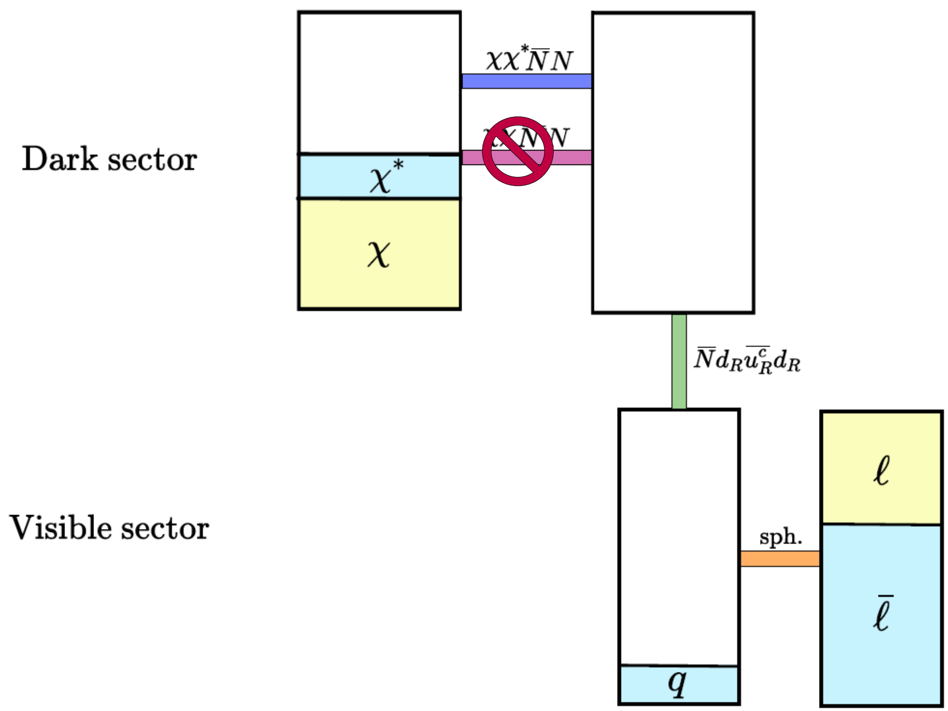

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$$m_\chi \lesssim 3.4\,\mathrm{GeV}$$

Experimental tests

1) Higgs portal $\lambda_{\chi H}|\chi|^2|H|^2$

- Higgs invisible decay $h \to \chi\chi^*$

  From BR(h→ inv) <0.18, $\Rightarrow \lambda_{\chi H} \lesssim 10^{-2}$

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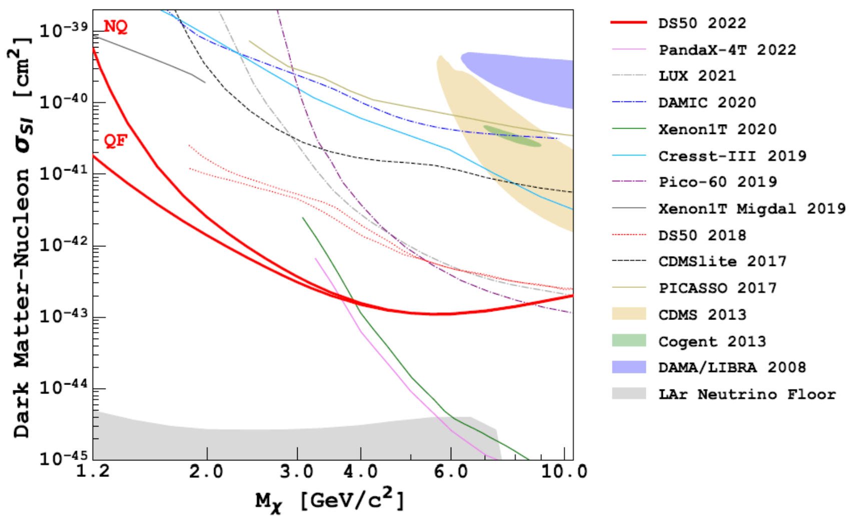

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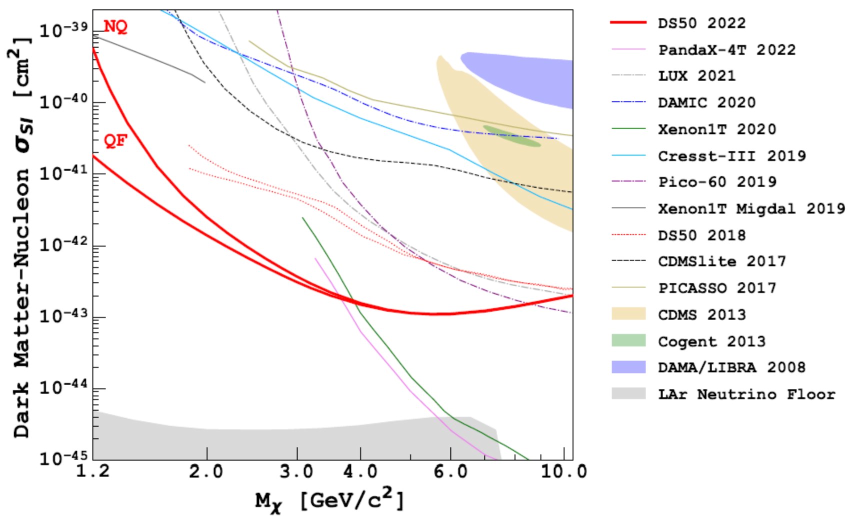

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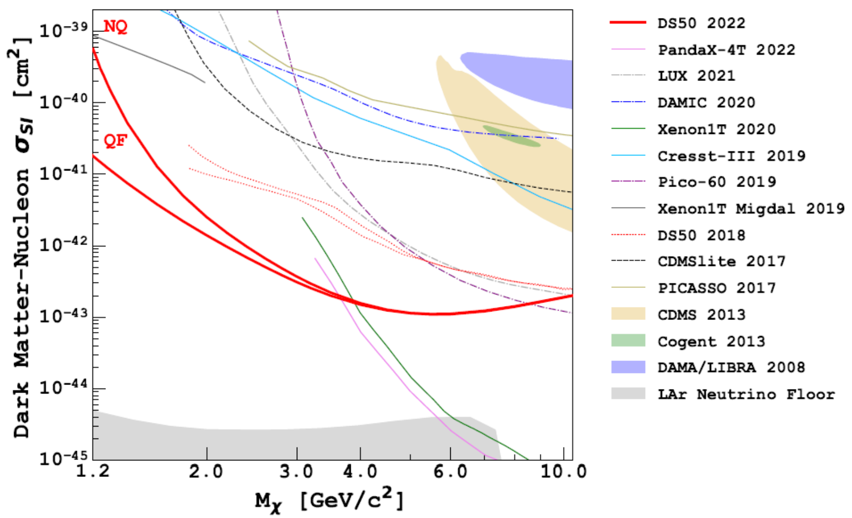

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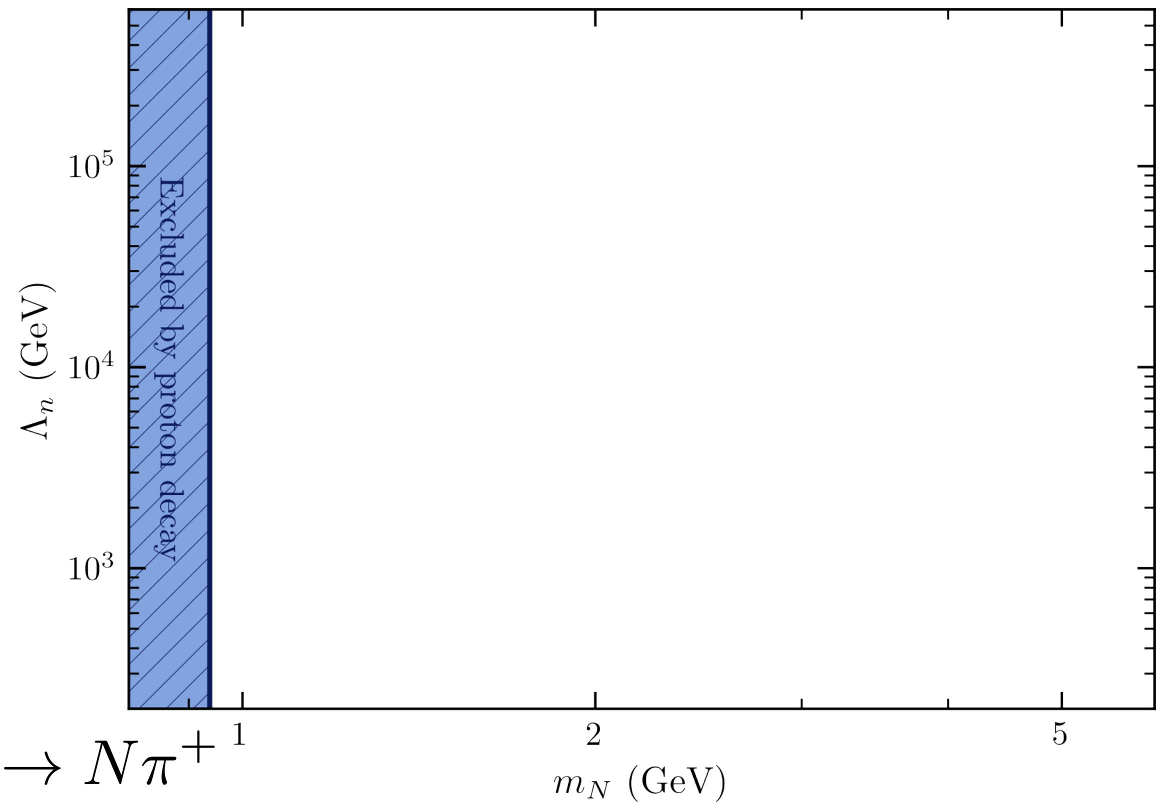
- If DM partially asymmetric, indirect detection signals.

Note: the Higgs portal generates a contribution to the dark matter mass.
To keep $m_\chi \sim$ a few GeV, $\Rightarrow \lambda_{\chi H} \lesssim 2 \times 10^{-4}$

Experimental tests

2) Neutron portal $\dfrac{1}{\Lambda_n^2}\overline{N}d_R\,\overline{u_R^c}d_R$



$p \to N\pi^+$

Experimental tests

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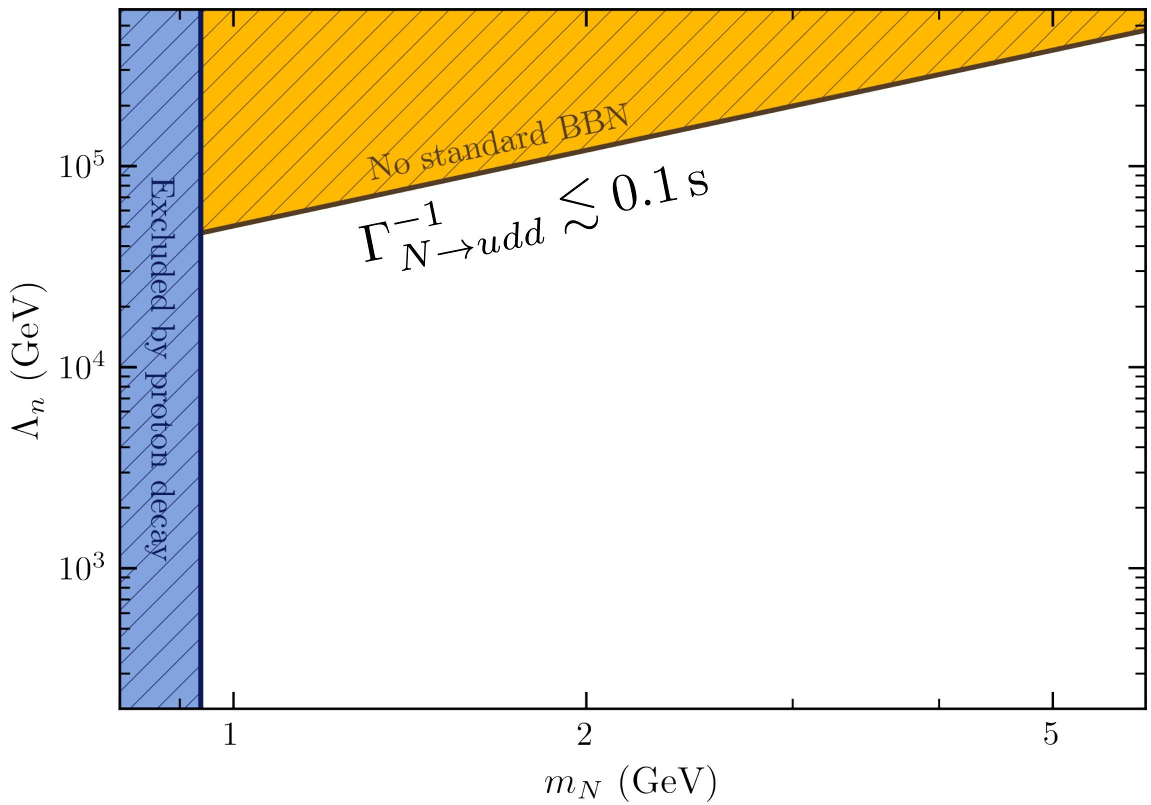

$$\Gamma^{-1}_{N\to udd} \approx 1.6\ \mathrm{s}\left(\frac{\Lambda_n}{10^5\ \mathrm{GeV}}\right)^4\left(\frac{\mathrm{GeV}}{m_N}\right)^5,$$

Experimental tests

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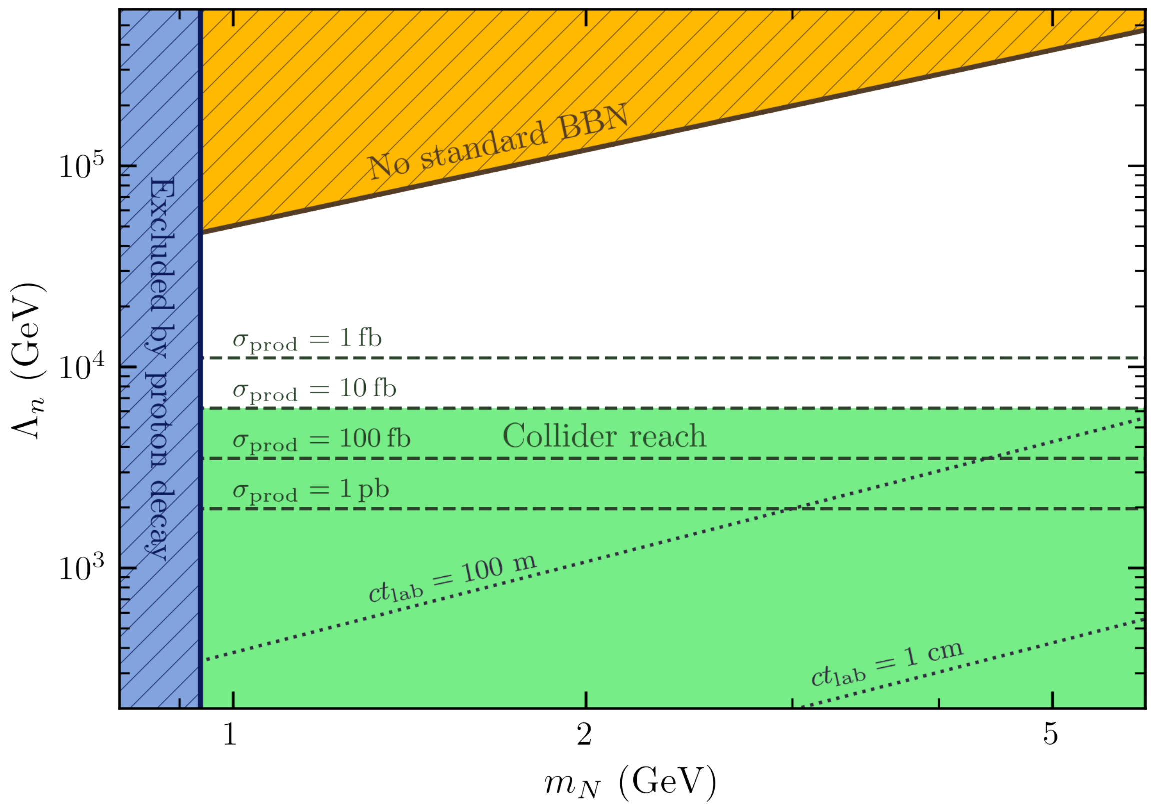

N production in pp collisions through $ud \to N\bar{d}, dd \to N\bar{u}$

$$\sigma_{pp\to N+\text{jet}} \approx 2\,\text{fb} \left(\frac{f_{\rm PDF}}{10^{-2}}\right) \left(\frac{10^4\,\text{GeV}}{\Lambda_n}\right)^4$$

Experimental tests

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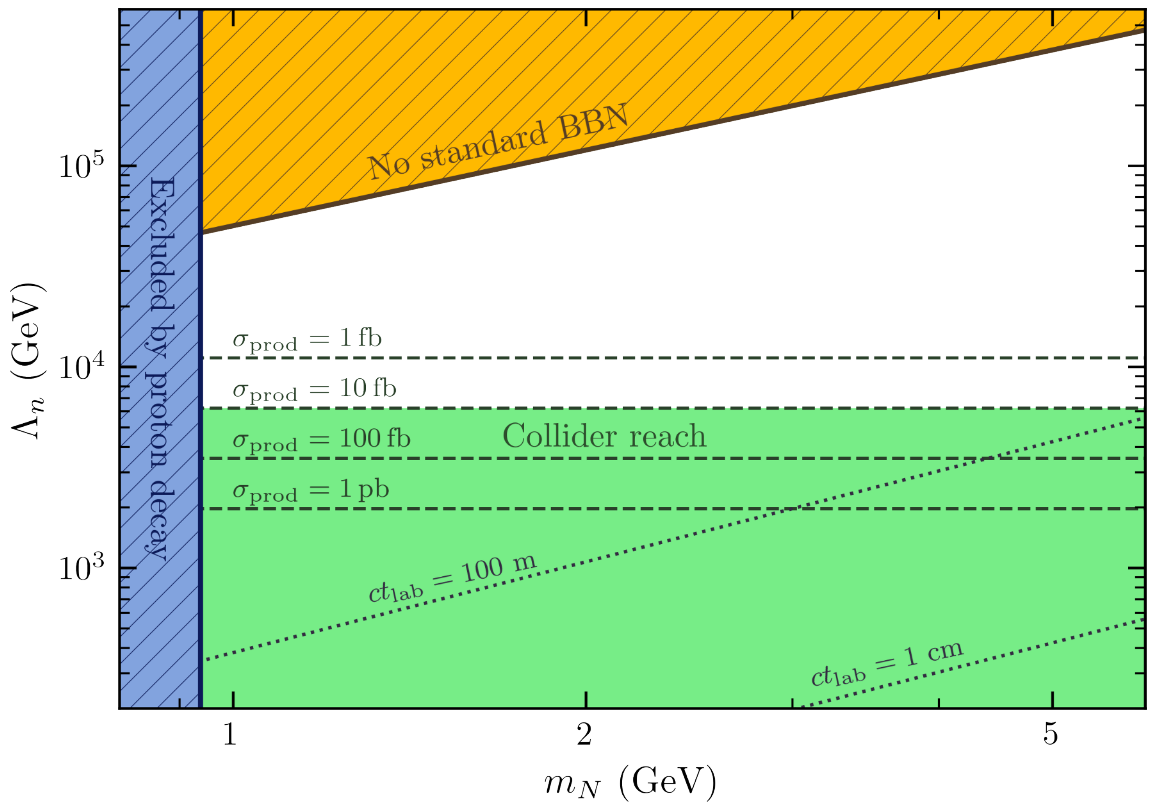

- The EFT may break down. Additional signatures from the production of the mediator.
- These constraints are not valid for different baryon-portals, e.g. the "charmed-Omega" portal $\overline{N} s_R \overline{c_R^c} s_R$

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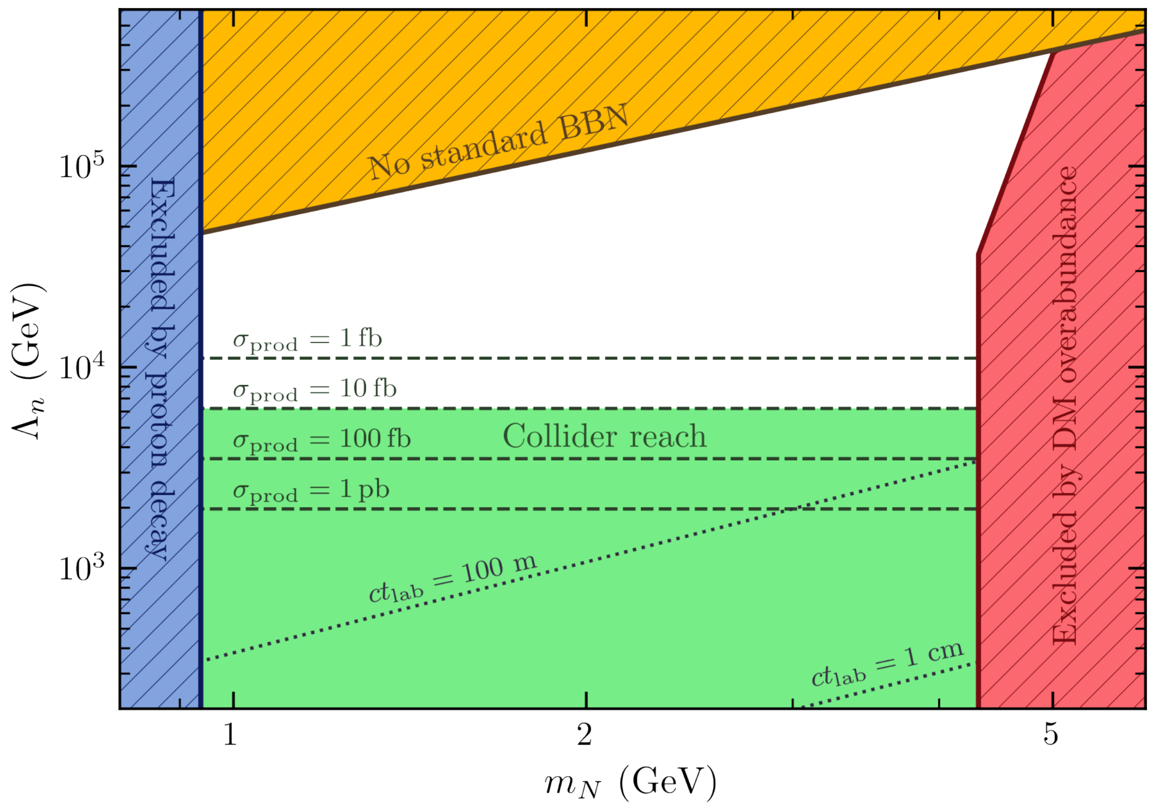

The rate of annihilations $\chi\chi^* \to N\overline{N}$ must be sufficiently efficient at freeze-out.

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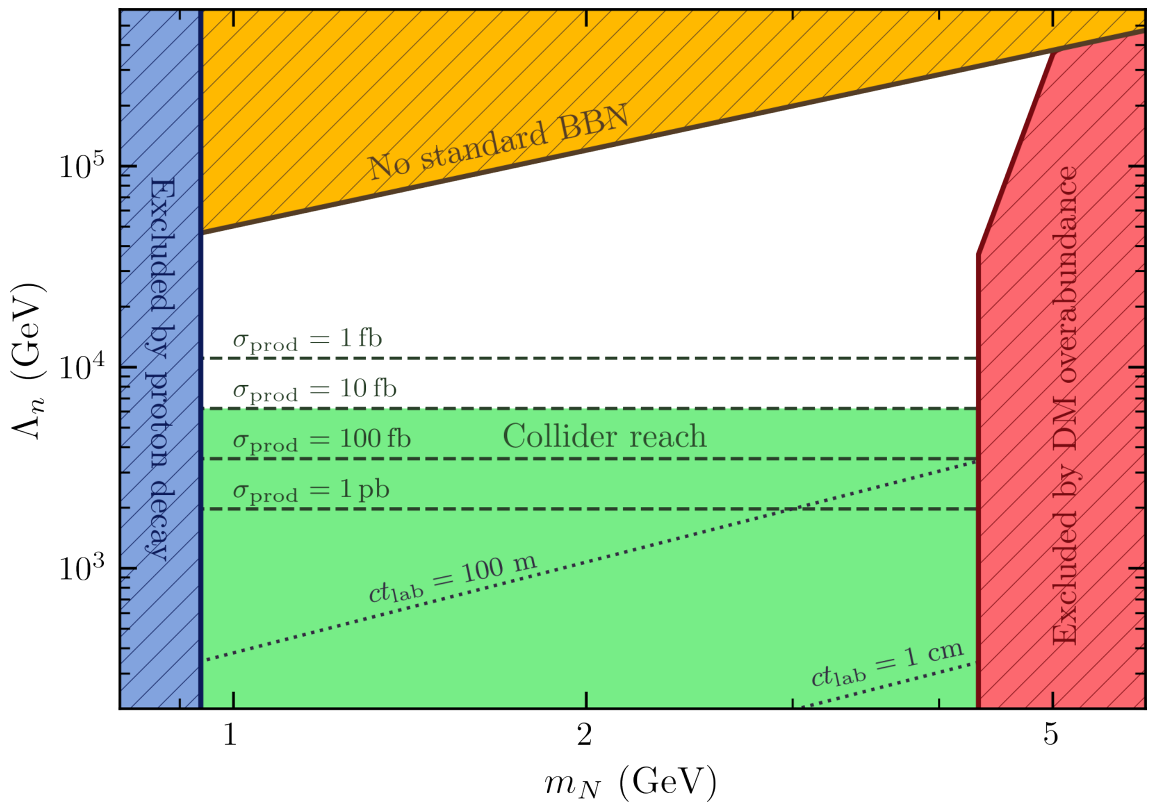

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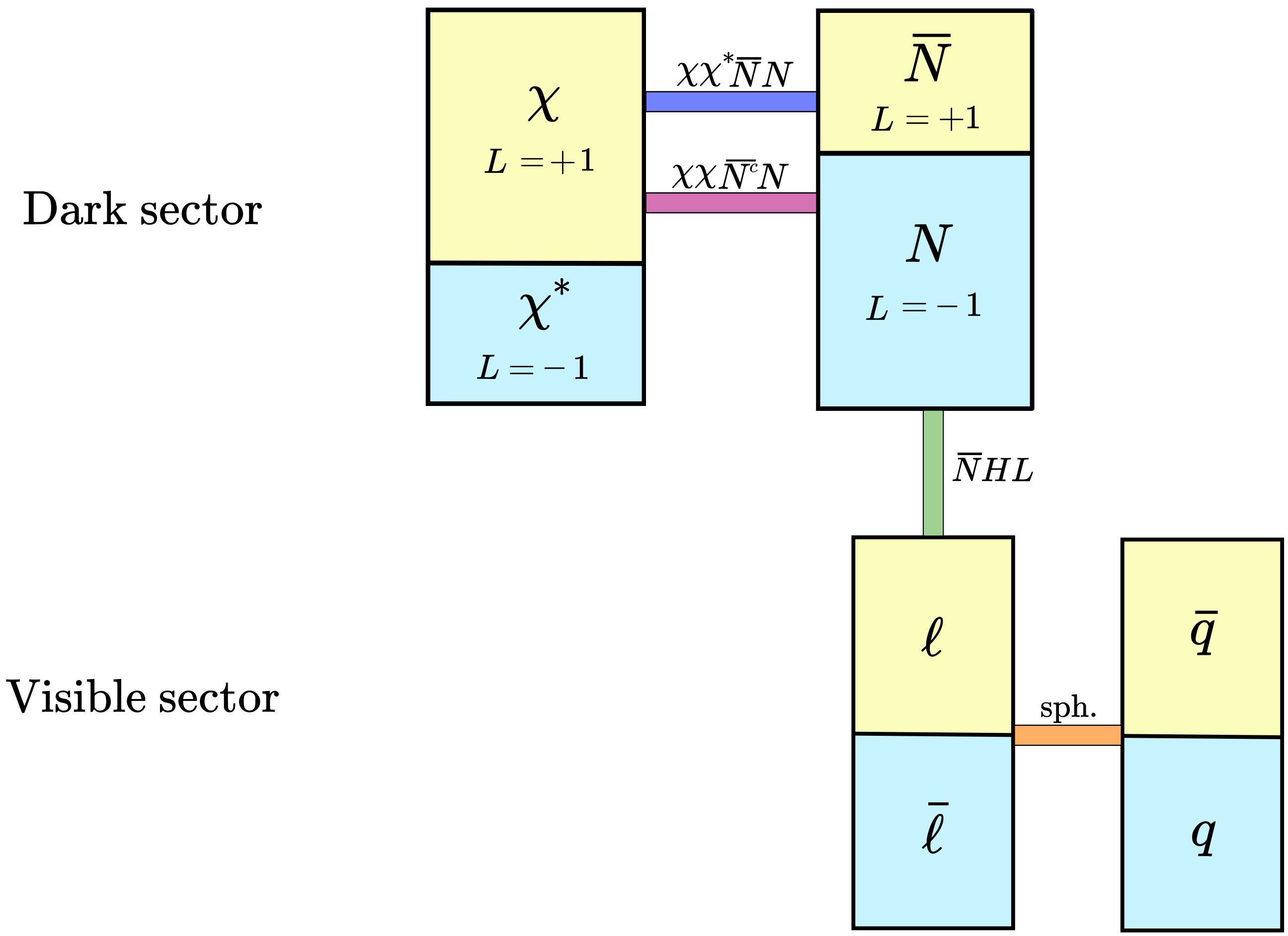
This limit can be avoided if the DM annihilates into other dark sector particles.

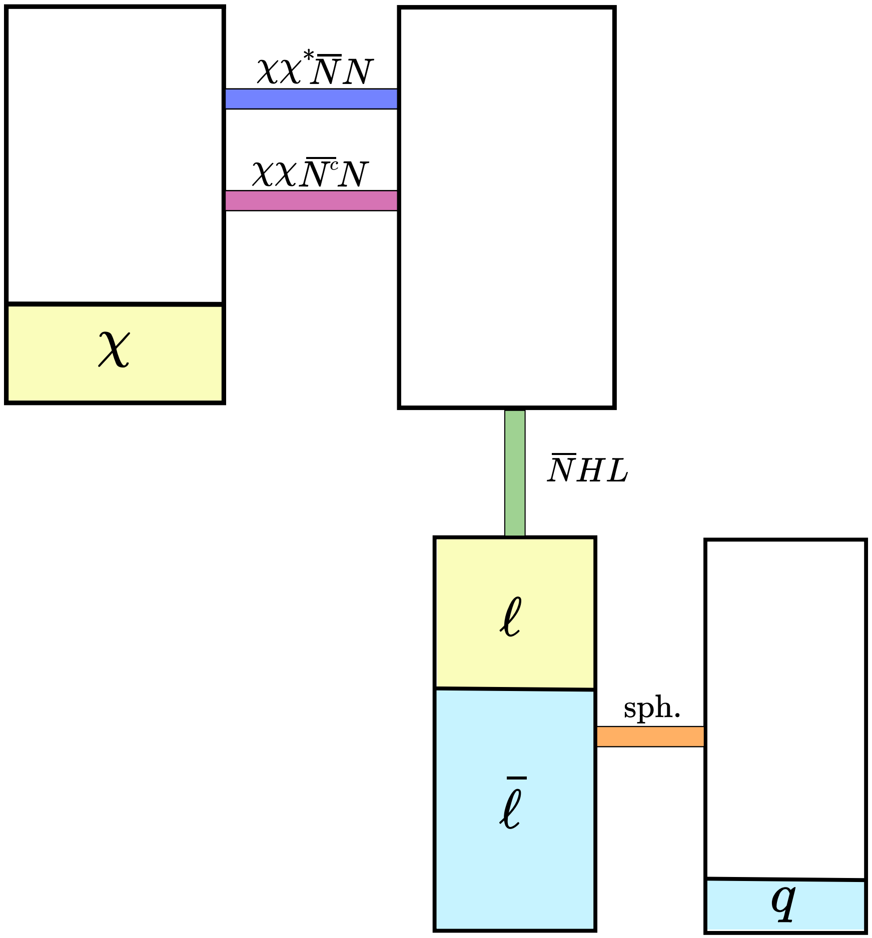
A leptonic portal



A leptonic portal

Dark sector

Visible sector



Conclusions

- There is no evidence for a baryon asymmetry in our Universe. Observations only show that there are more quarks than antiquarks.

- Dark sector particles could also carry baryon number. If this is the case, a quark-antiquark asymmetry could be generated without fulfilling the Sakharov conditions.

- We have presented a simple scenario where the baryon number is conserved, and that generates a quark-antiquark asymmetry. As a bonus, the dark matter particle is stable due to the baryon number conservation, and is predicted to have a mass of a few GeV. The scenario leads to signals at collider experiments and in flavor physics.