Connecting the baryons
to the dark matter of the Universe

Alejandro Ibarra
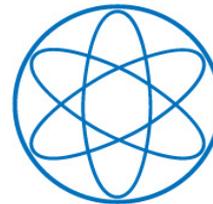
CATCH22+2
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Introduction

• 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
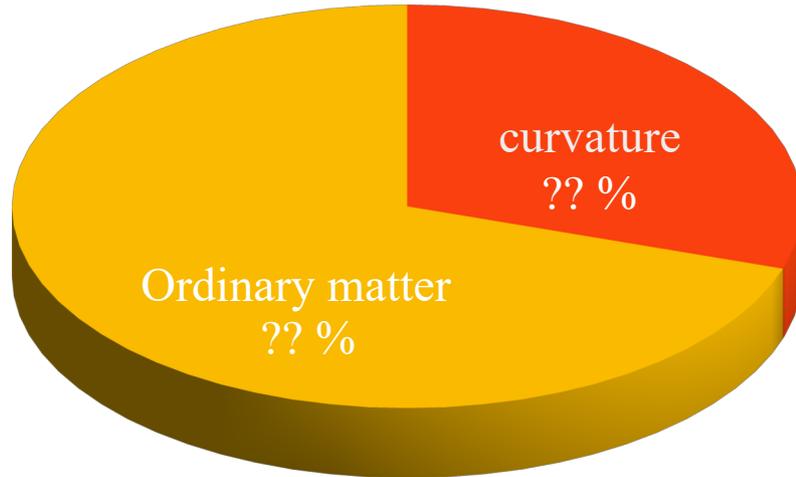
The cosmic pie in 1967

curvature
?? %

Ordinary matter
?? %

Introduction

The cosmic pie in 1967

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The cosmic pie in the 2020s

Ordinary matter 4.9%

Dark matter 26.8%

Dark energy 68.3%

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**There is no evidence for a baryon asymmetry in our Universe**

Introduction

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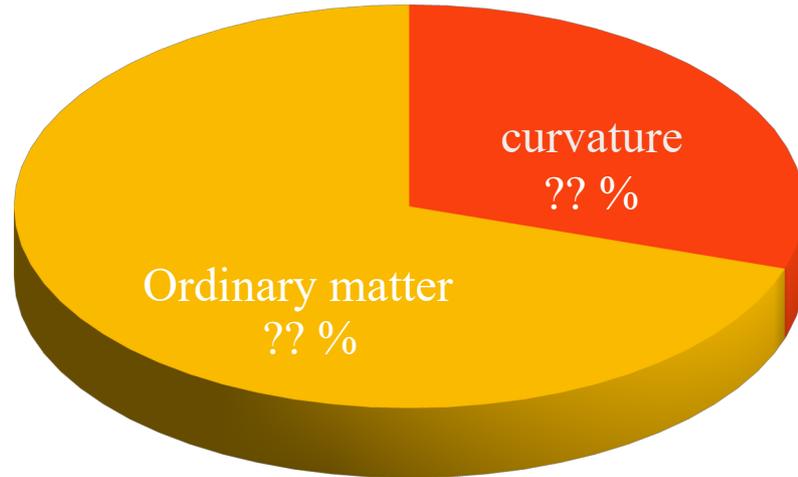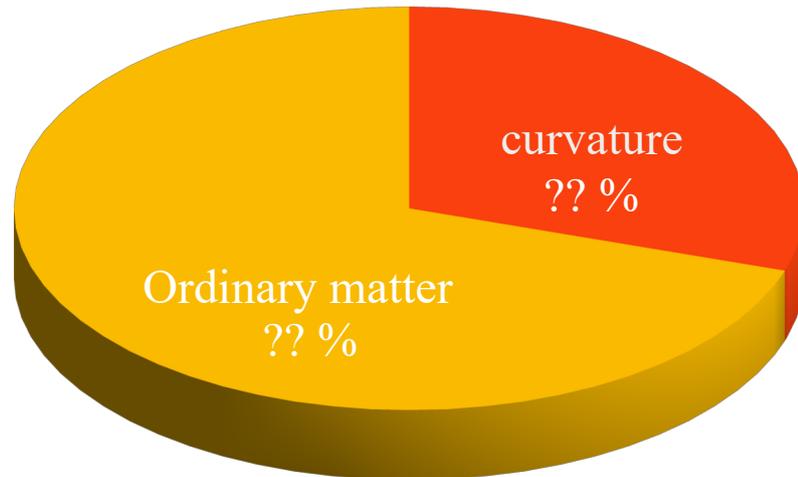
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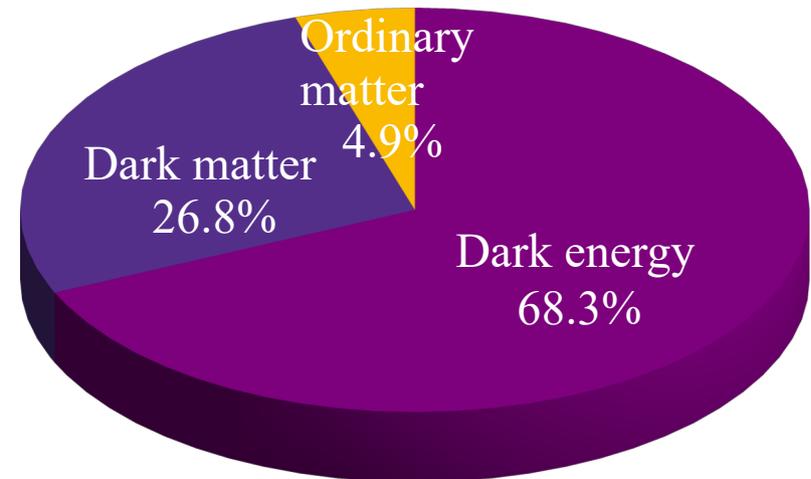
There is no evidence for a baryon asymmetry in our Universe

- Observations only show that there are more quarks than antiquarks.

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

- Dark sector particles could also carry baryon number
- The Universe could even be baryon symmetric.

Introduction

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> ## There is no evidence for a baryon asymmetry in our Universe

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- The Universe could even be baryon symmetric.

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.

A simple scenario

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• C- and CP-violation in the dark sector.
  Generates more N than $\overline{N}$. For example, from the out of equilibrium decay of a heavy particle, à la leptogenesis.

• Portal interactions between dark sector and visible sector.
  "Neutron portal" $\overline{N} d_{\mathrm{R}} \, \overline{u_{\mathrm{R}}^c} d_{\mathrm{R}}$. Transmits the asymmetry in N to the visible sector and generates a quark-antiquark asymmetry

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The role of the complex scalar χ

A corresponding asymmetry in χ ensures the conservation of the baryon number throughout the history of the Universe.

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$+$ loops

A simple scenario

The role of the complex scalar χ

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For instance, if the asymmetry in N is generated from the decays of a heavy Majorana fermion, the same decay generates an identical asymmetry in χ.

$$\varphi_i \longrightarrow \begin{array}{c} \chi \\ \diagup \\ \diagdown \\ N \end{array} \qquad \qquad \varphi_i \longrightarrow \begin{array}{c} \chi^* \\ \diagup \\ \diagdown \\ \overline{N} \end{array} \qquad + \text{ loops}$$
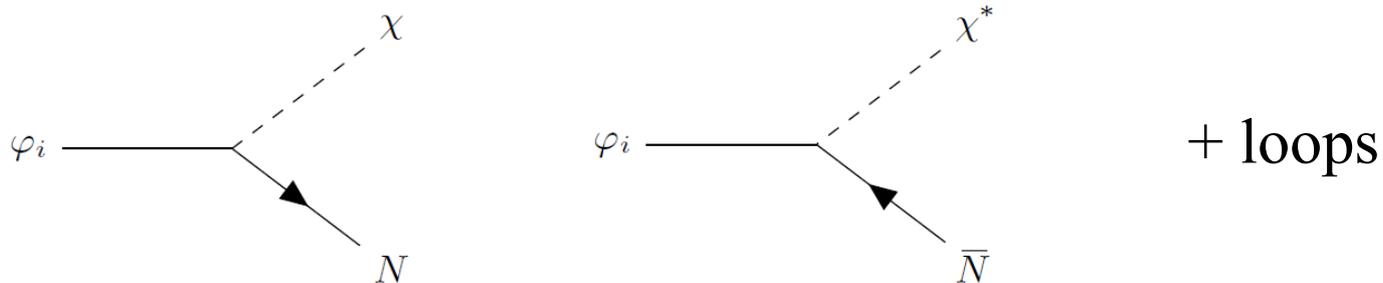
Bonus: χ is absolutely stable, due to the conservation of baryon number.

A simple scenario

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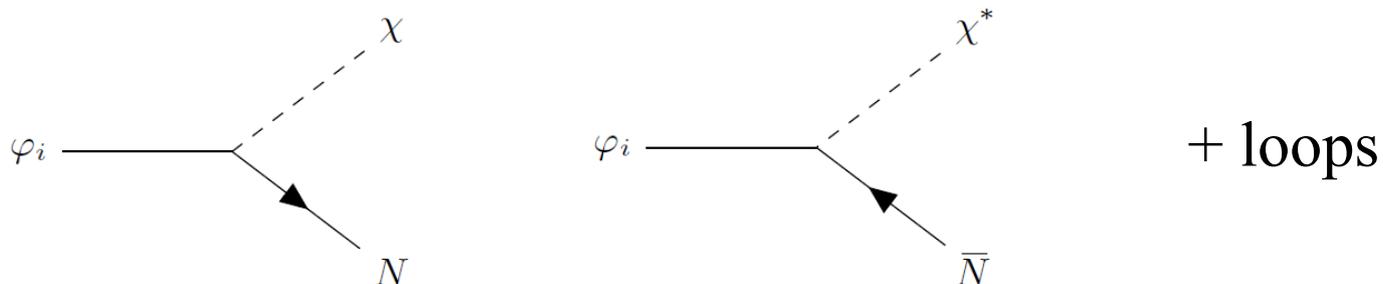
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**quark-antiquark asymmetry** $\Longleftrightarrow$ **dark matter stability**

A simple scenario
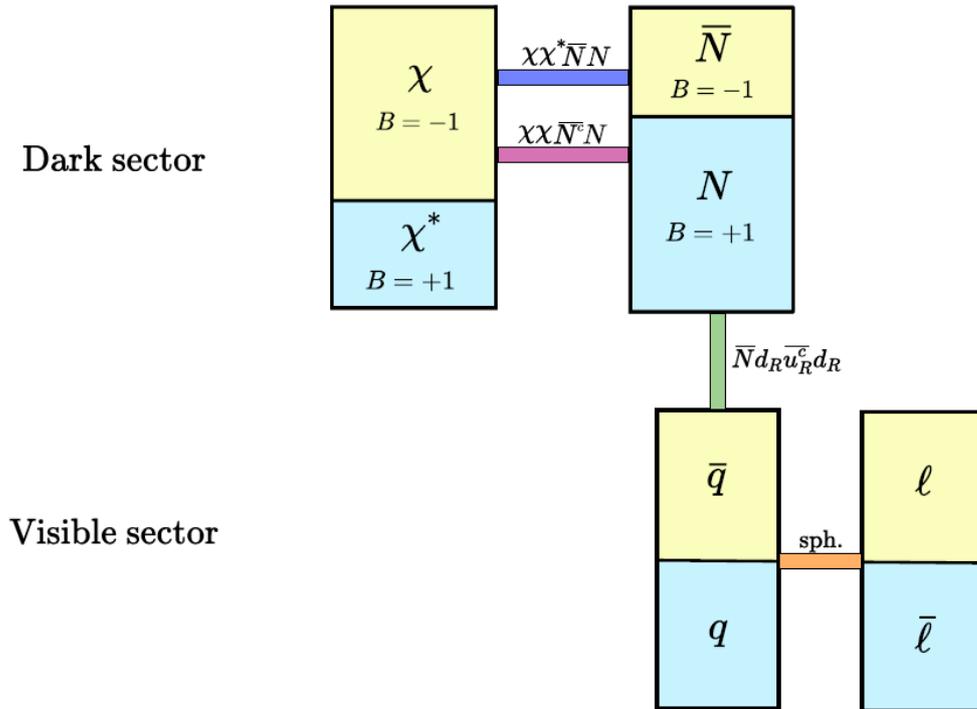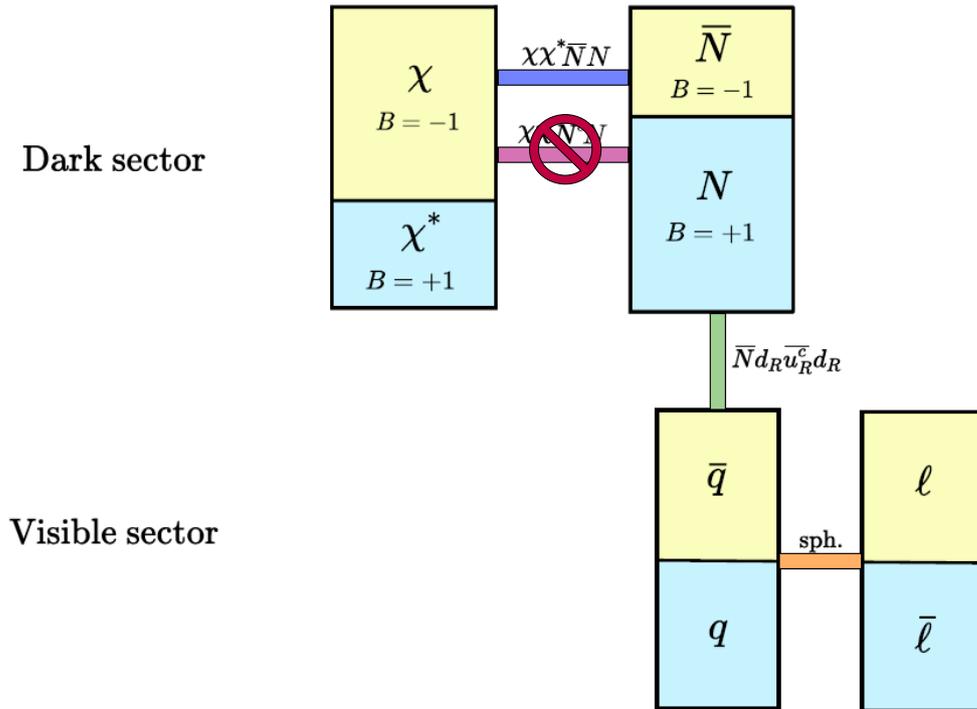
Initial state

Dark sector

Visible sector

χ
$B = -1$

χ^*
$B = +1$

$\overline{N}$
$B = -1$

N
$B = +1$

$\chi\chi^*\overline{N}N$

$\chi\chi\overline{N^c}N$

$\overline{N}d_R\overline{u_R^c}d_R$

$\overline{q}$

q

ℓ

$\overline{\ell}$

sph.

A simple scenario

Initial state

Dark sector

Visible sector

$$\chi\chi^*\overline{N}N$$
$$\overline{N}$$
$$B = -1$$
$$\chi$$
$$B = -1$$
$$\chi\overline{N}N$$
$$N$$
$$B = +1$$
$$\chi^*$$
$$B = +1$$
$$\overline{N}d_R\overline{u^c_R}d_R$$
$$\overline{q}$$
$$\ell$$
sph.
$$q$$
$$\overline{\ell}$$

A simple scenario

Initial state

Final state

Dark sector

χ
$B = -1$

$\chi\chi^*\overline{N}N$

$\overline{N}$
$B = -1$

$\chi N N$

N
$B = +1$

χ^*
$B = +1$

$\overline{N}d_R\overline{u}_R^c d_R$

$\chi\chi^*\overline{N}N$

$\chi N N$

χ

$\overline{N}d_R\overline{u}_R^c d_R$

Visible sector

$\overline{q}$

q

sph.

ℓ

$\overline{\ell}$

sph.

q

ℓ

$\overline{\ell}$

A simple scenario

Initial state   **Final state**

Dark sector

χ, $B = -1$ $\chi\chi^*\overline{N}N$ $\overline{N}$, $B = -1$

χ^*, $B = +1$ N, $B = +1$

$\overline{N}d_R\overline{u}_R^c d_R$

Visible sector

$\overline{q}$ ℓ sph. q $\overline{\ell}$

χ

$\overline{N}d_R\overline{u}_R^c d_R$

ℓ sph. $\overline{\ell}$ q

Legend:
- Y_χ^{tot}
- $Y_{\Delta\chi}$
- Y_N^{tot}
- $Y_{\Delta N}$
- $Y_{\Delta q}/3$
- $|Y_{\Delta\ell}|$

Y

T_{in} T_{DM} T_{decay}

A simple scenario

Initial state   Final state

Dark sector

$\chi \chi^* \overline{N} N$

$\overline{N}$, $B = -1$

χ, $B = -1$

χ^*, $B = +1$

N, $B = +1$

$\overline{N} d_R \overline{u}_R^c d_R$

Visible sector

$\overline{q}$ ℓ sph.

q $\overline{\ell}$

χ

ℓ sph.

$\overline{\ell}$

q
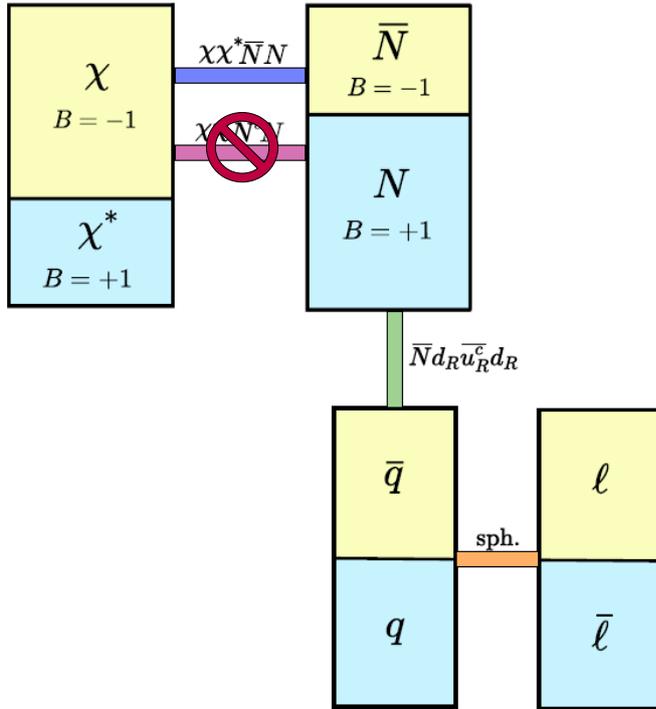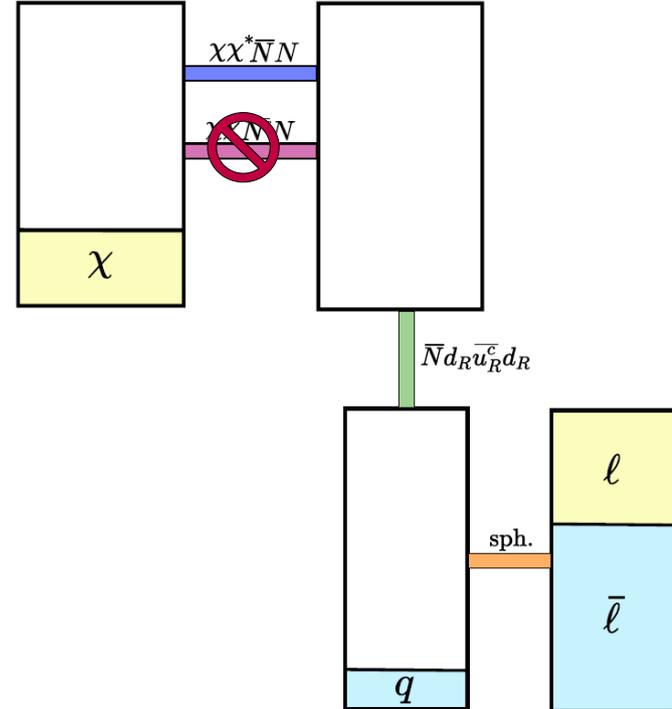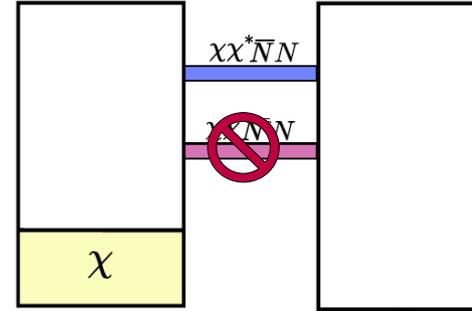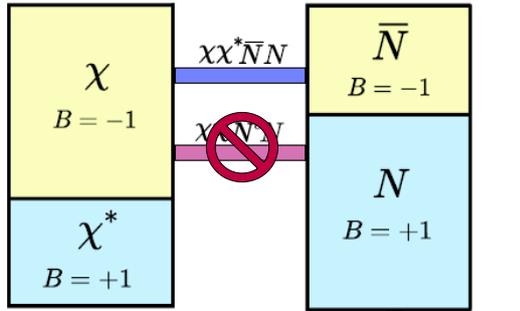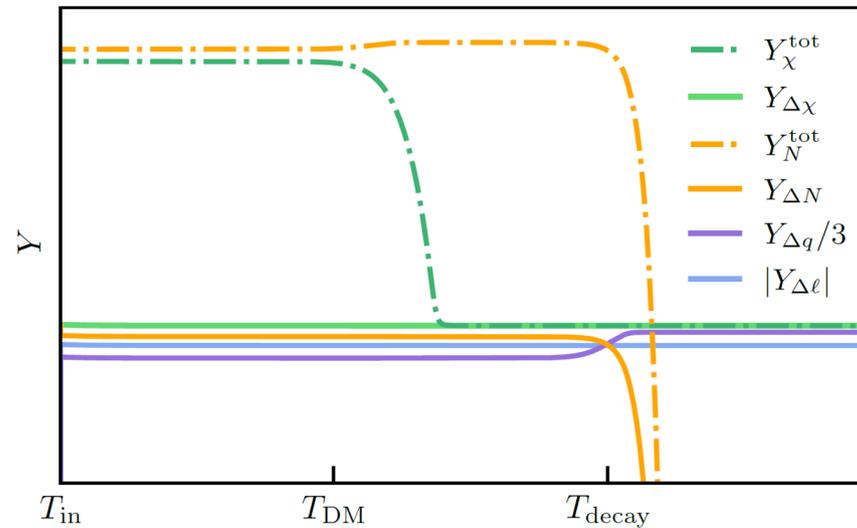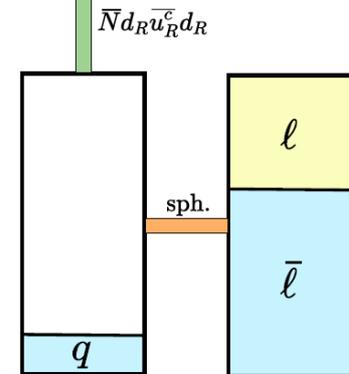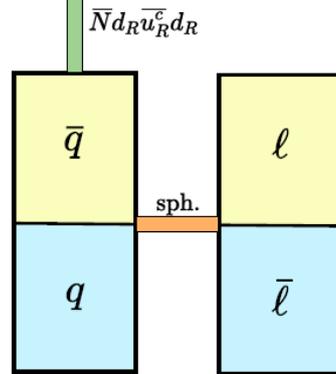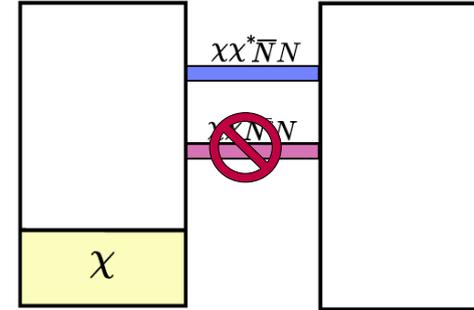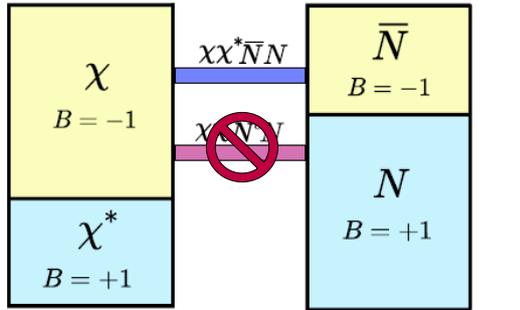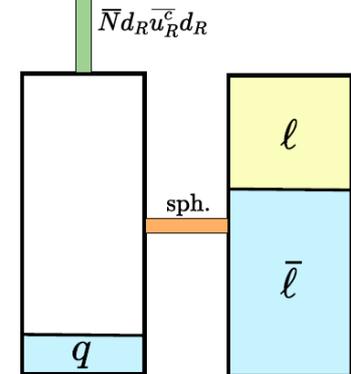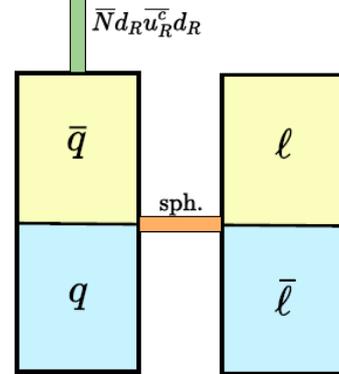
The asymmetry in N transmitted to the quark sector via scatterings

$$N\overline{d} \leftrightarrow ud$$

$$N\overline{u} \leftrightarrow dd$$

- Y_χ^{tot}
- $Y_{\Delta\chi}$
- Y_N^{tot}
- $Y_{\Delta N}$
- $Y_{\Delta q}/3$
- $|Y_{\Delta\ell}|$

T_{in} T_{DM} T_{decay}
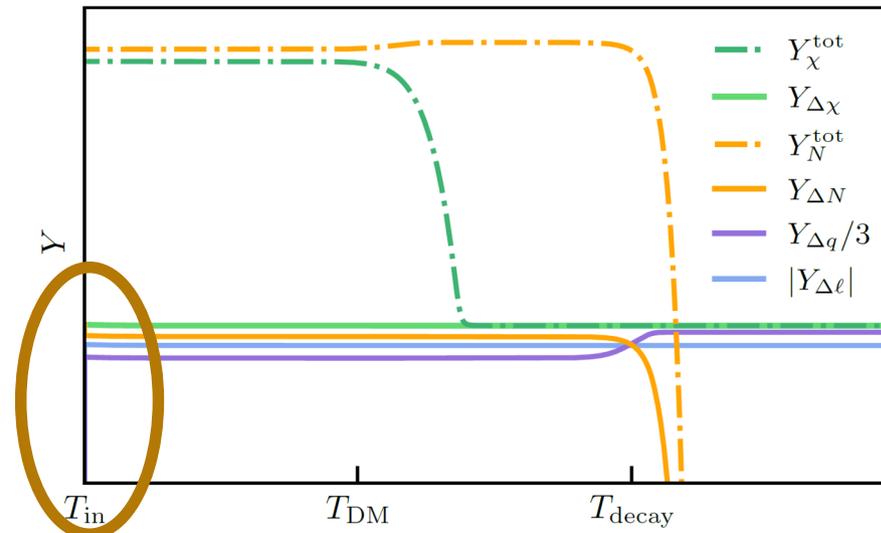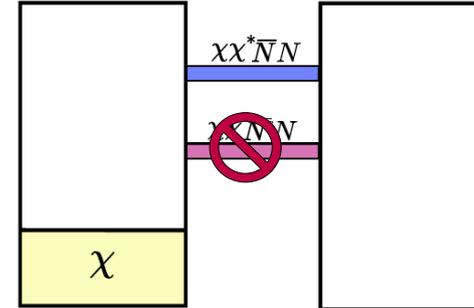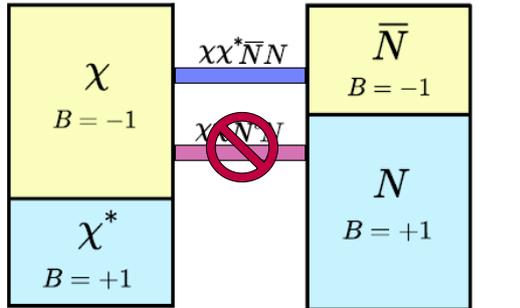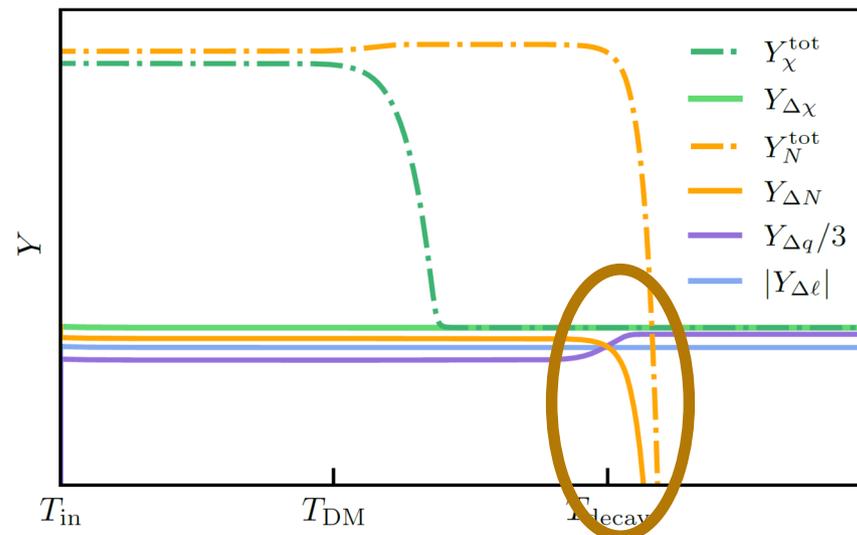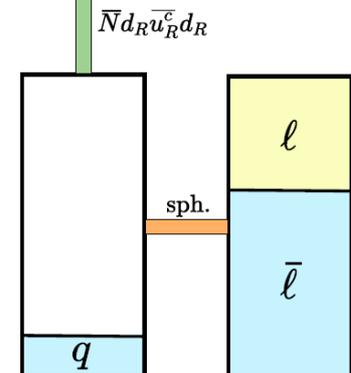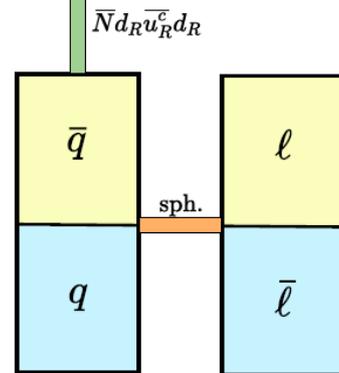
A simple scenario

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

A simple scenario
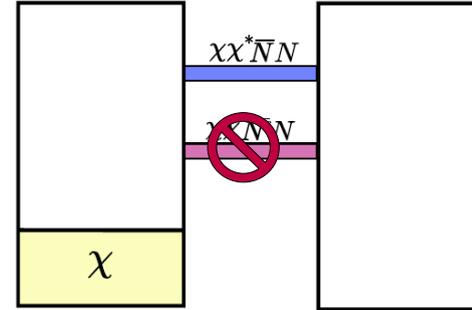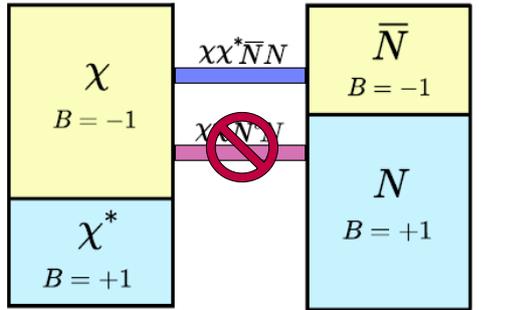
Initial state

Final state

Dark sector

Visible sector

$\chi\chi^*\overline{N}N$

χ $B = -1$

χ^* $B = +1$

$\overline{N}$ $B = -1$

N $B = +1$

$\overline{N}d_R\overline{u}_R^c d_R$

$\overline{q}$ ℓ sph. q $\overline{\ell}$

DM freeze-out
$\chi\chi^* \to N\bar{N}$

Y

T_{in} T_{DM} T_{decay}

Y_χ^{tot}
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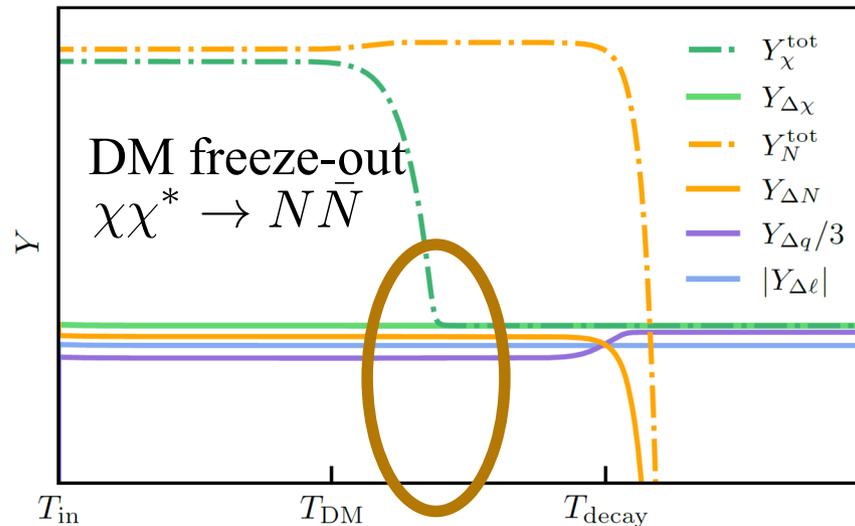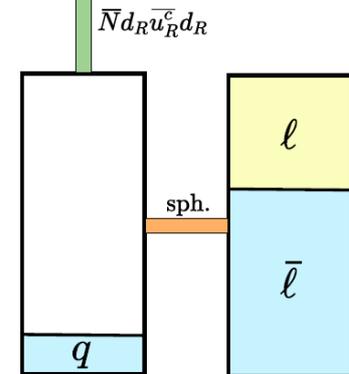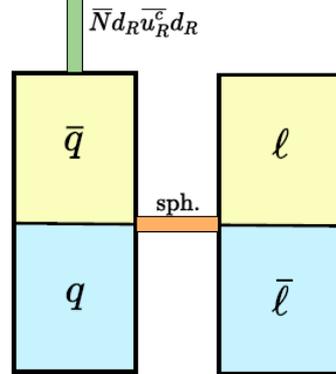
A simple scenario

$$\Omega_{\mathrm{DM},0}h^2 \simeq 2.8 \times 10^8 \, Y^{\mathrm{in}}_{\Delta N} \frac{m_\chi}{\mathrm{GeV}}.$$
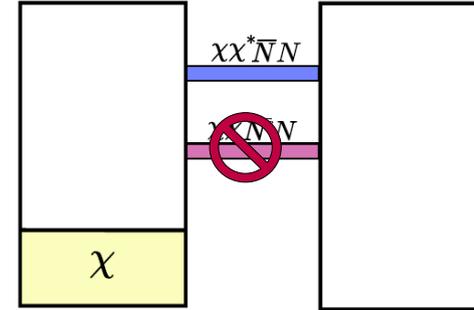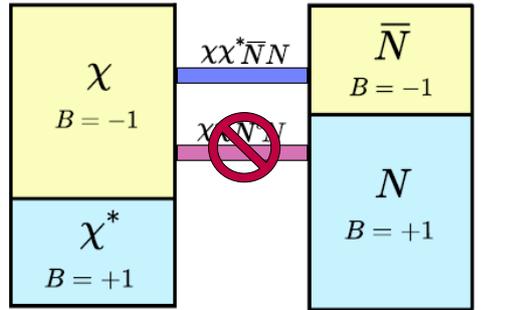
$$Y_{\Delta q,0} = \frac{162}{79} Y^{\mathrm{in}}_{\Delta N},$$
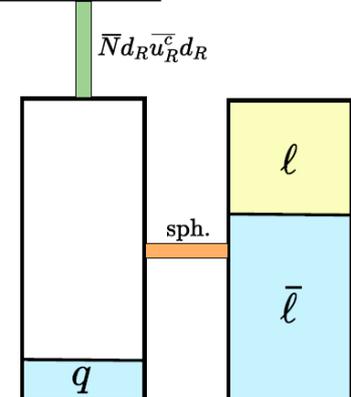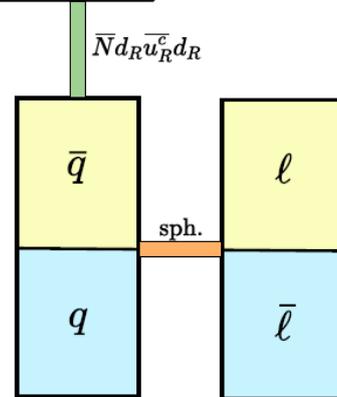
A simple scenario

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

$$Y_{\Delta q,0} = \frac{162}{79} Y_{\Delta N}^{\mathrm{in}},$$

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

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

Experimental tests

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

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

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

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- Direct detection: same analysis as for the singlet scalar DM model
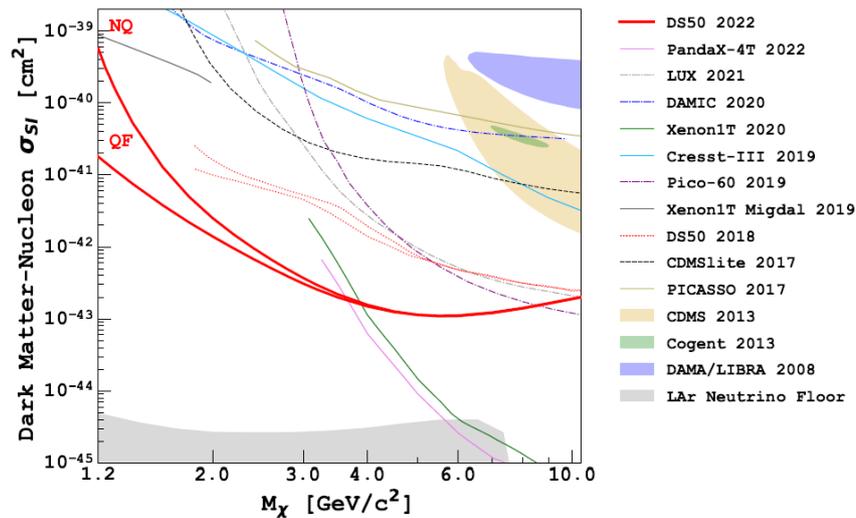
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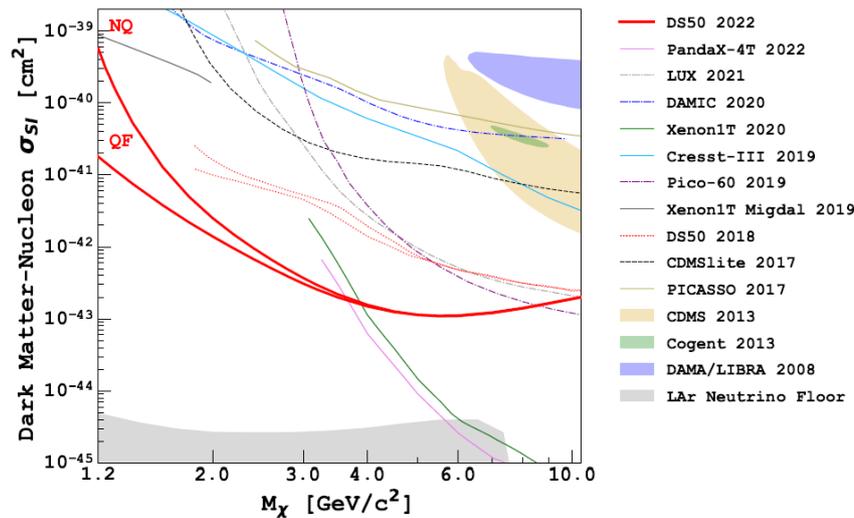
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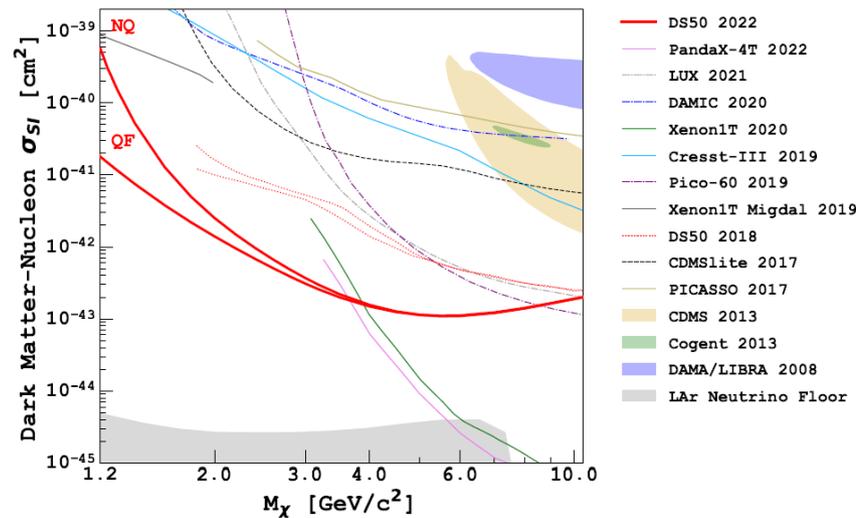
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- If DM partially asymmetric, indirect detection signals.

  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 $\dfrac{1}{\Lambda_n^2}\,\overline{N}d_R\,\overline{u_R^c}d_R$
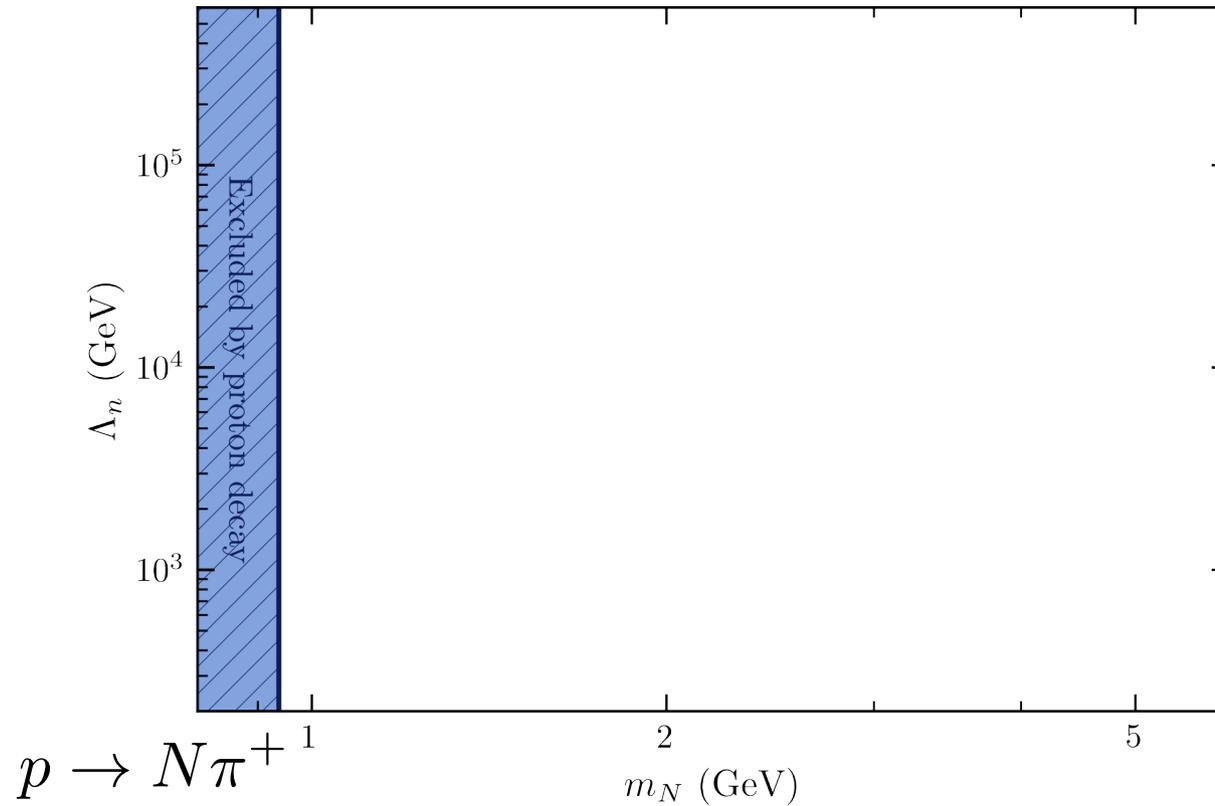
Experimental tests

2) Neutron portal $\dfrac{1}{\Lambda_n^2}\, \overline{N} d_R\, \overline{u_R^c} d_R$
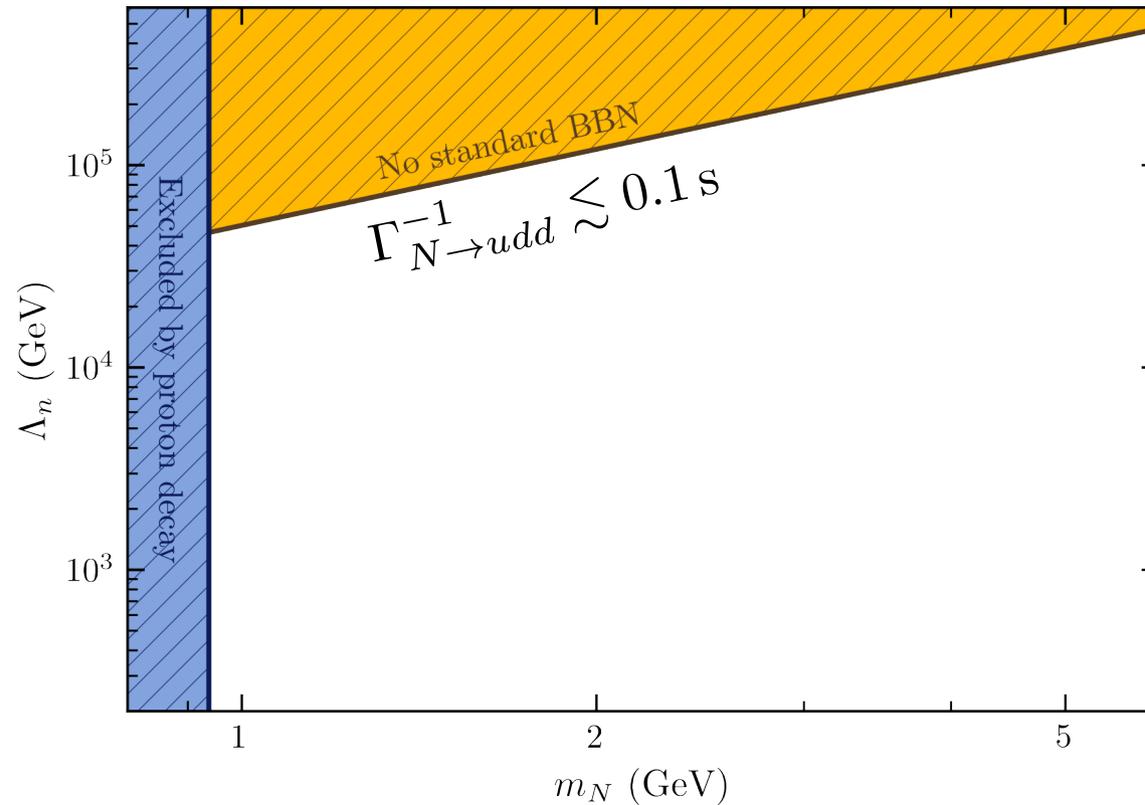
$$\Gamma^{-1}_{N\to udd} \approx 1.6 \ \text{s} \left(\frac{\Lambda_n}{10^5 \ \text{GeV}}\right)^4 \left(\frac{\text{GeV}}{m_N}\right)^5 ,$$

Experimental tests

2) Neutron portal $\dfrac{1}{\Lambda_n^2}\overline{N}d_R\,\overline{u_R^c}d_R$
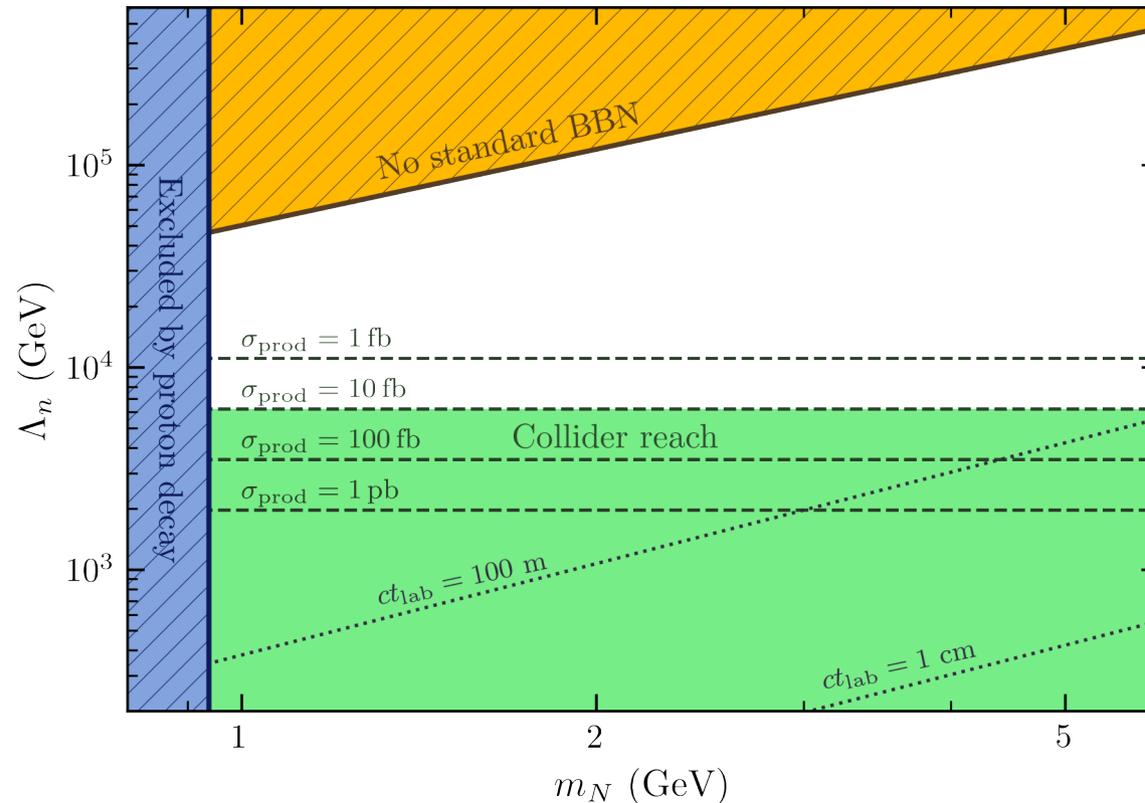
N production in pp collisions through $ud \to N\bar{d}, dd \to N\bar{u}$

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

Experimental tests

2) Neutron portal $\frac{1}{\Lambda_n^2} \overline{N} d_R \, \overline{u_R^c} d_R$
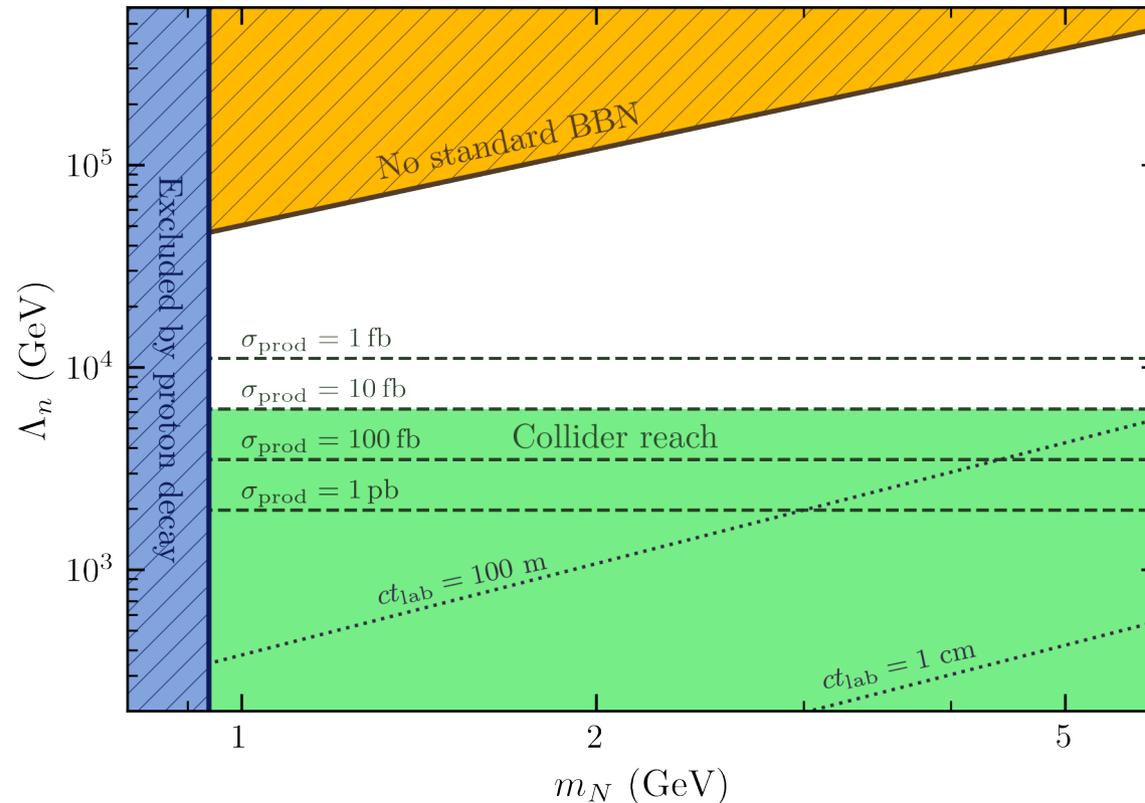
- The EFT may break down. Additional signatures from the production of the mediator.
- These constraints are not valid for different baryon-portals, e.g. the "charmed-Omega" portal $\overline{N} s_R \overline{c_R^c} s_R$

Experimental tests

2) Neutron portal $\frac{1}{\Lambda_n^2}\overline{N}d_R\,\overline{u_R^c}d_R$
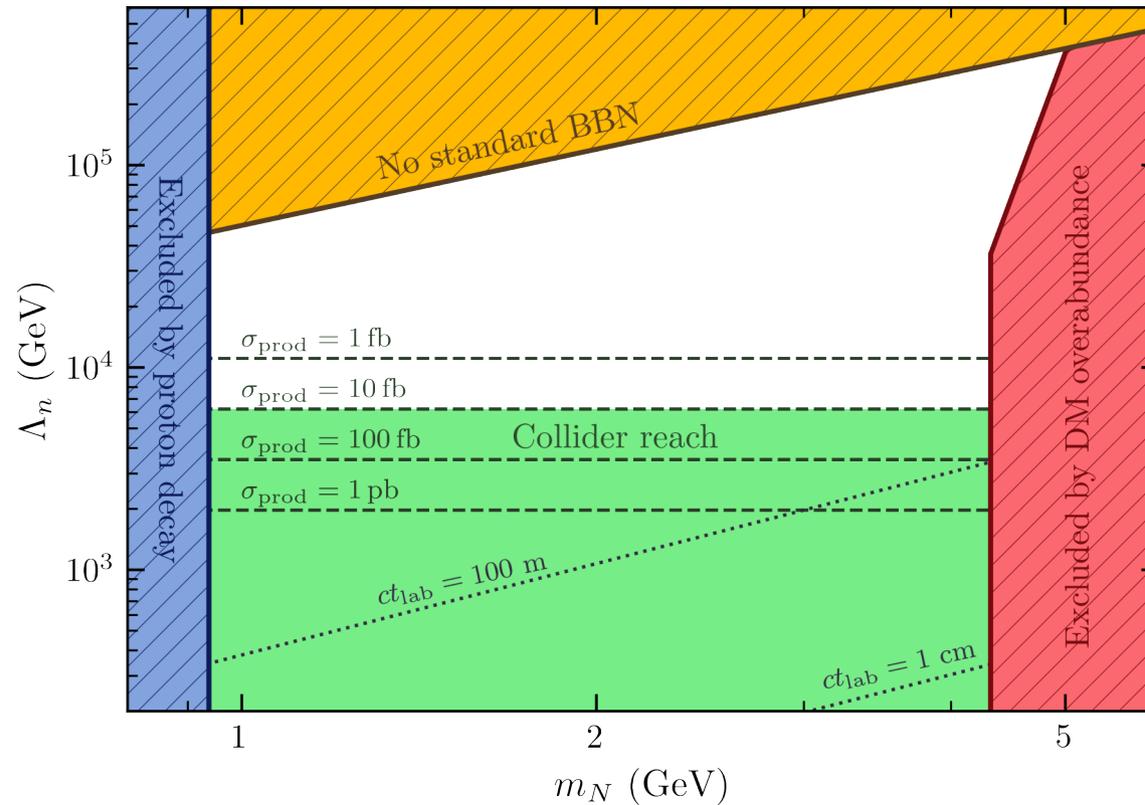
The rate of annihilations $\chi\chi^* \to N\overline{N}$ must be sufficiently efficient at freeze-out.

Experimental tests

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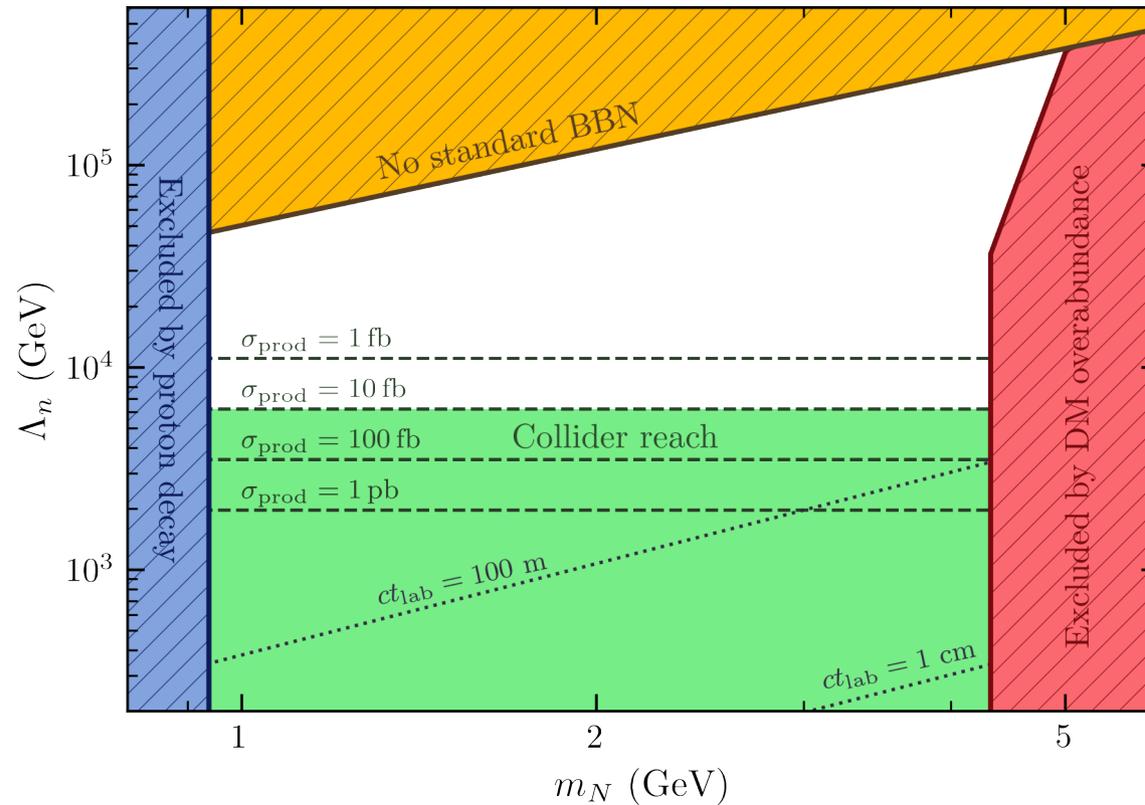


The rate of annihilations $\chi\chi^* \to N\overline{N}$ must be sufficiently efficient at freeze-out.

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

A leptonic portal
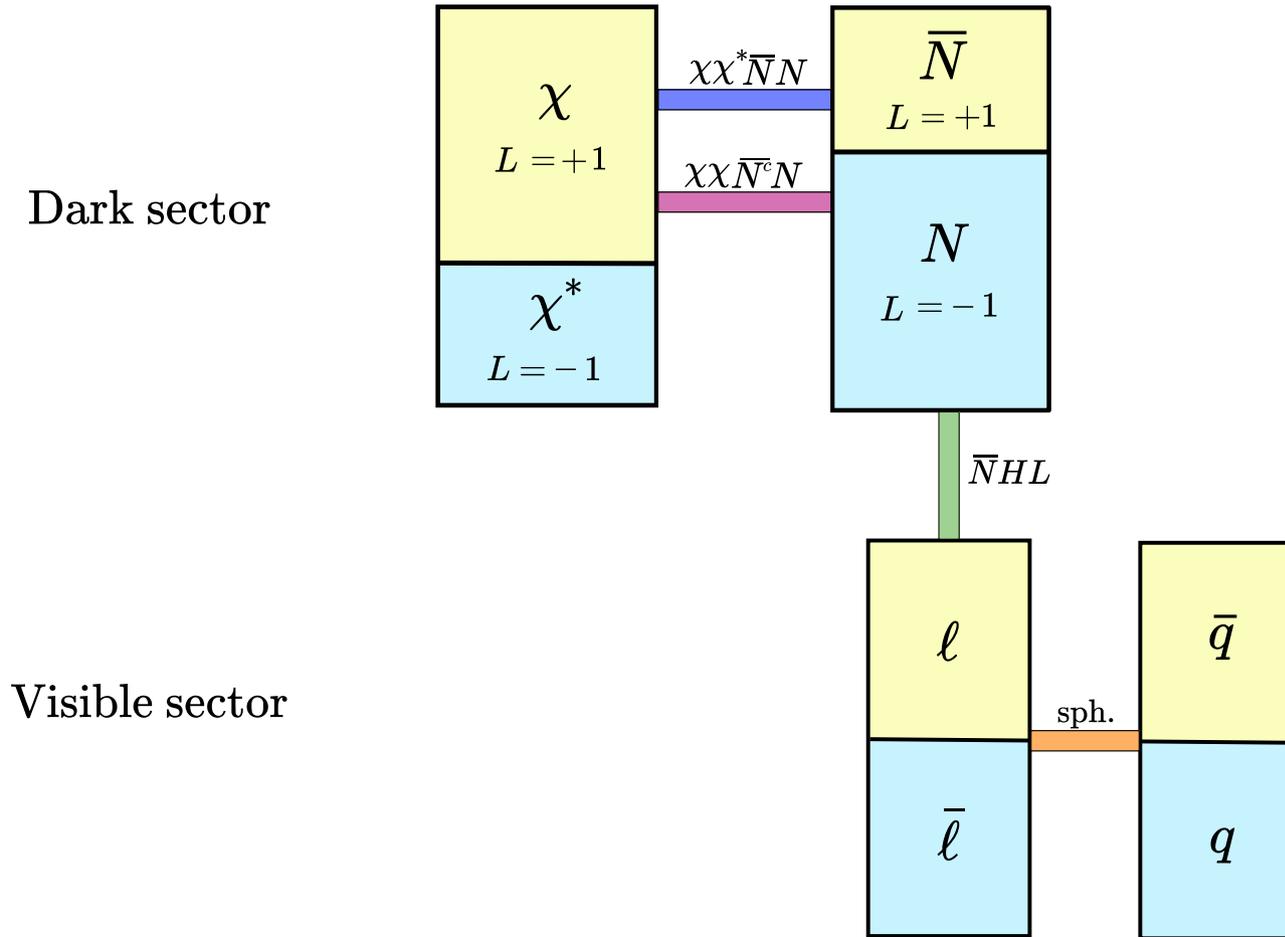
A leptonic portal
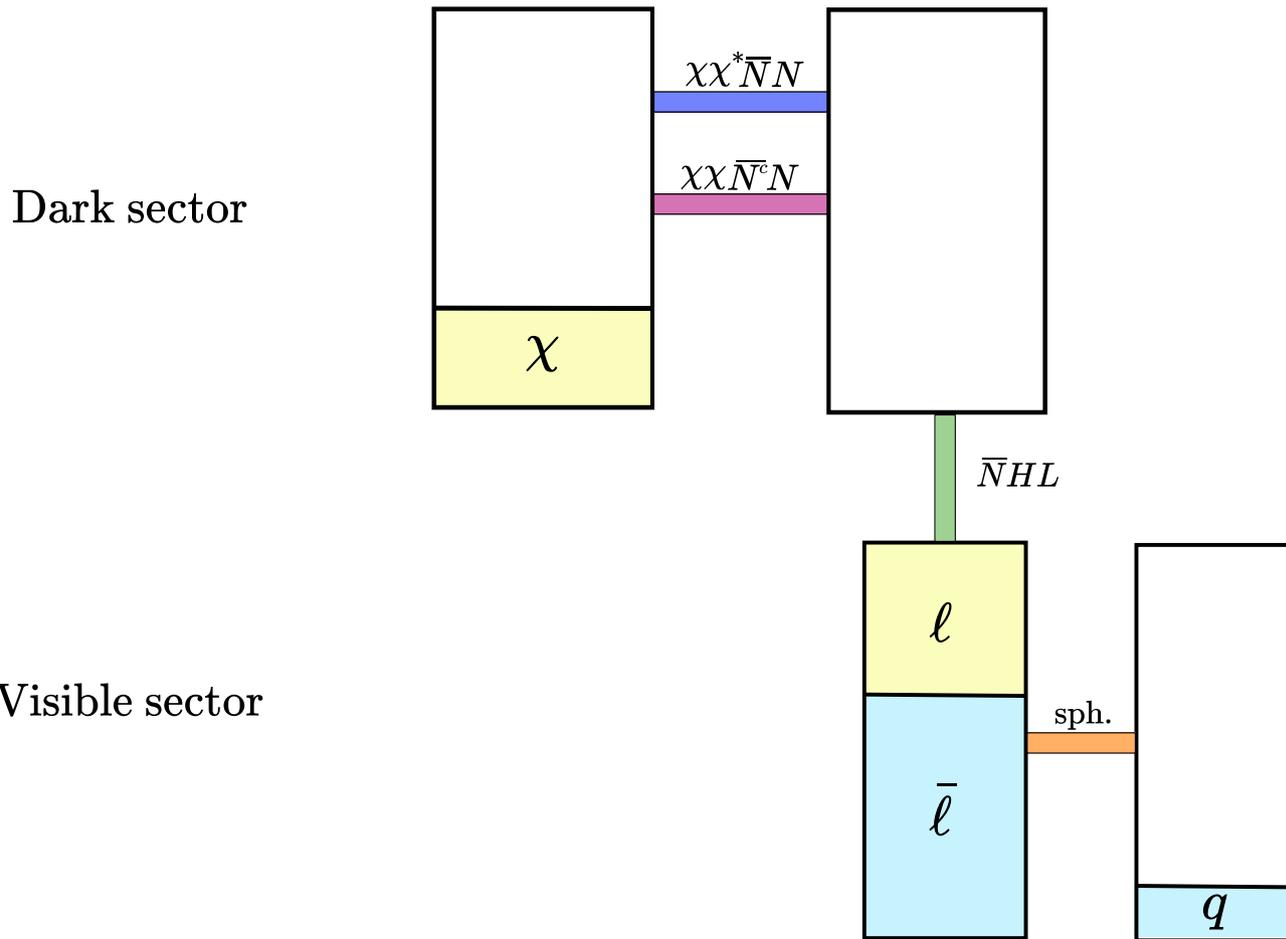
Conclusions

- 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.