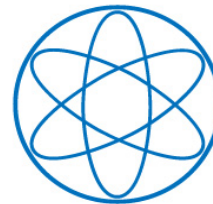


Connecting the baryons to the dark matter of the Universe

Alejandro Ibarra



In collaboration with Mar Ciscar and Jérôme Vandecasteele. JCAP 01 (2024) 028

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August 2024

Introduction

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

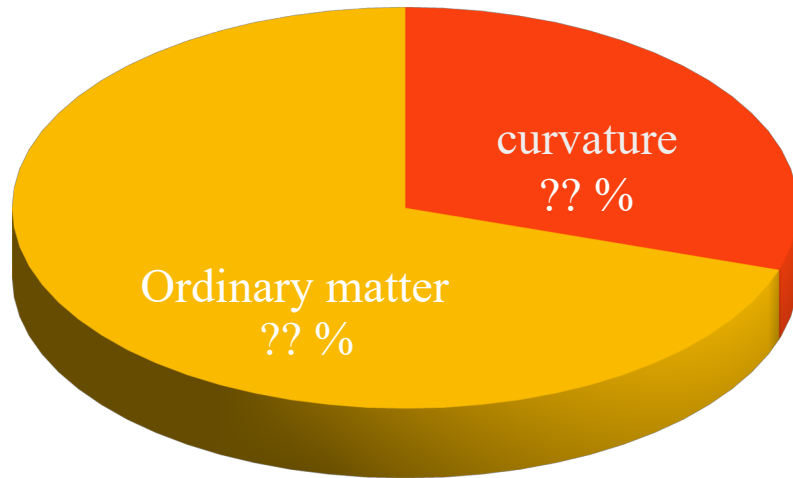
$$Y_{B,0} = \left. \frac{n_B - n_{\bar{B}}}{s} \right|_0 = (8.75 \pm 0.23) \times 10^{-11}$$

- 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

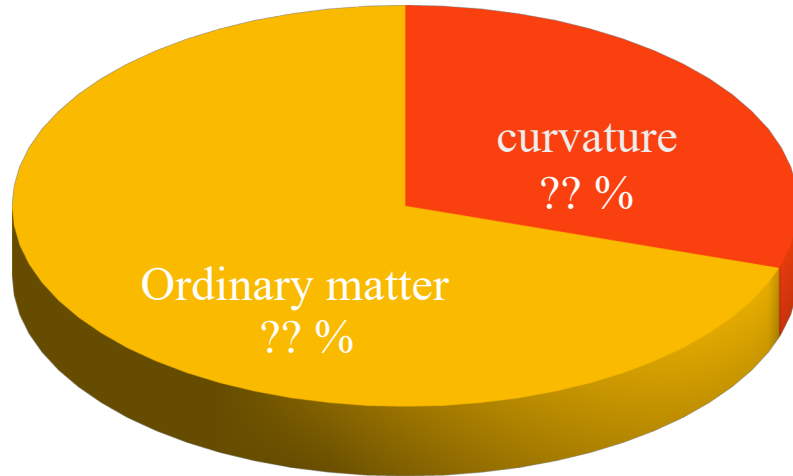
Introduction

The cosmic pie in 1967

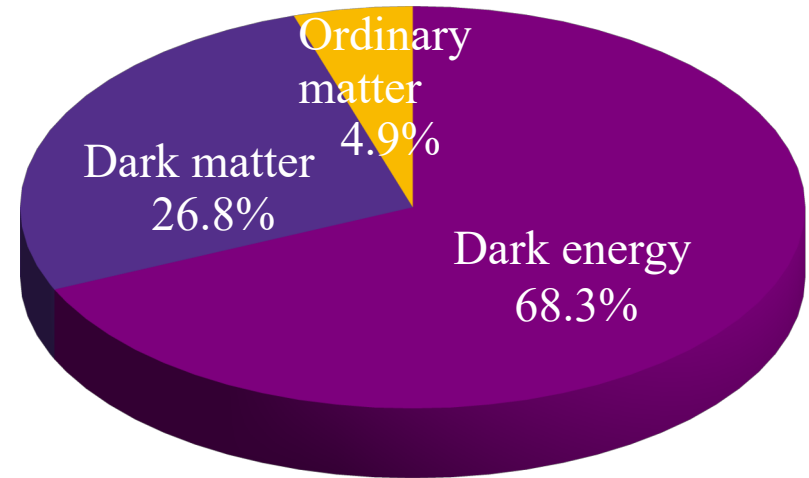


Introduction

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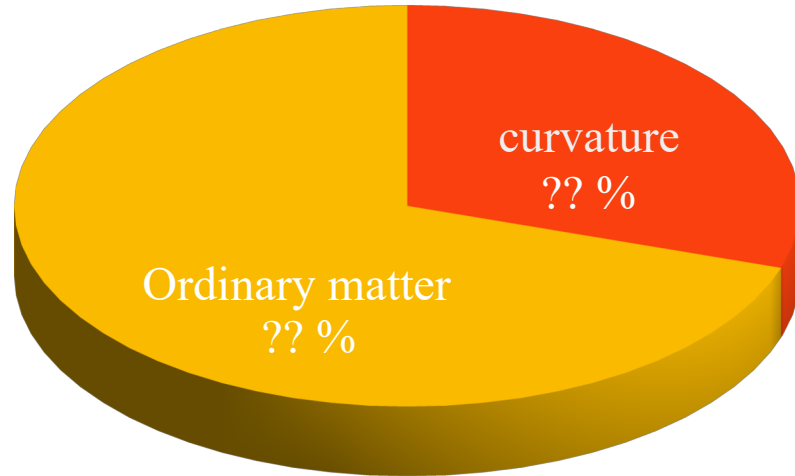


The cosmic pie in the 2020s

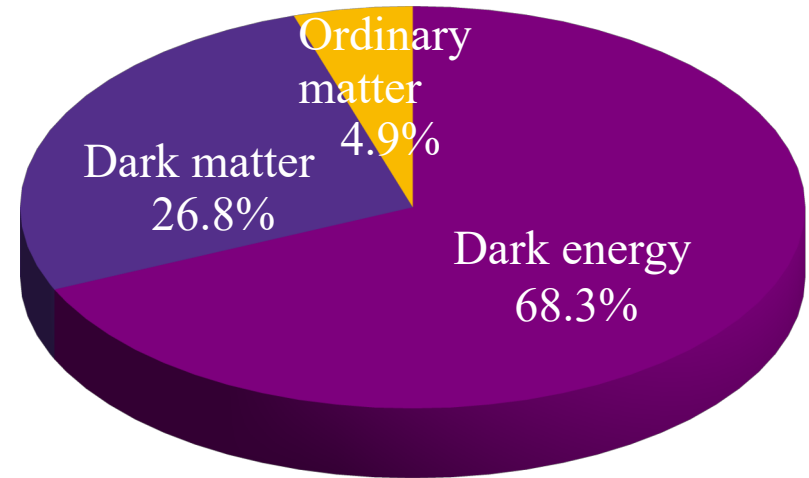


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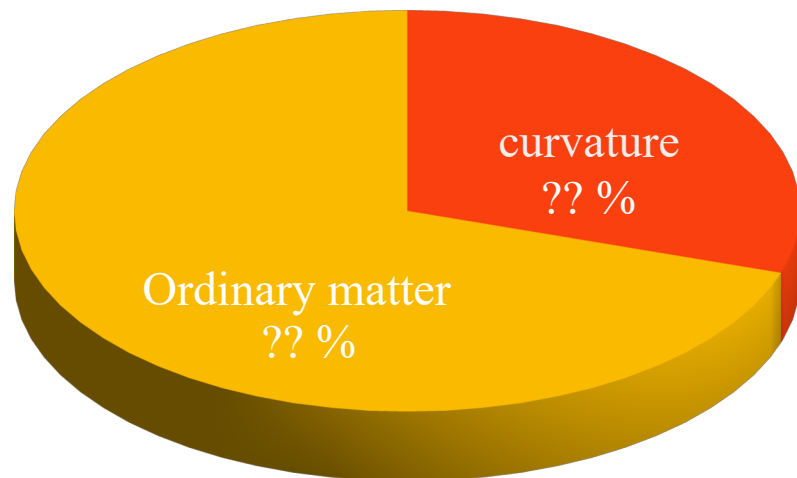
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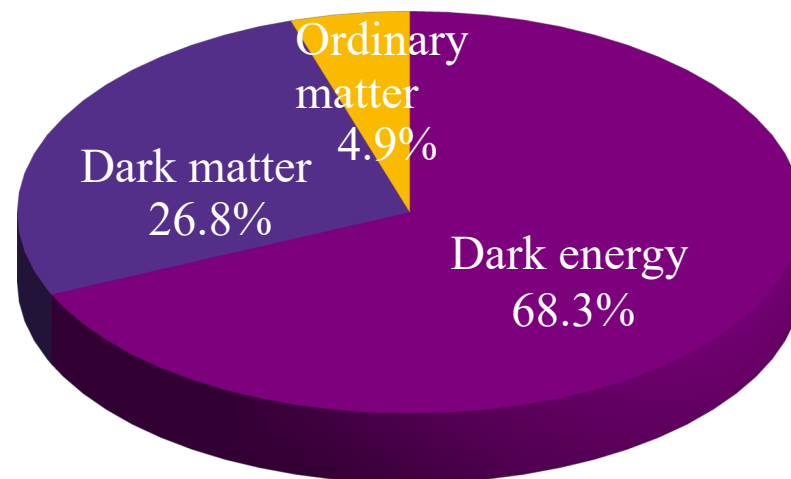
There is no evidence for a baryon asymmetry in our Universe

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The cosmic pie in the 2020s



There is no evidence for a baryon asymmetry in our Universe

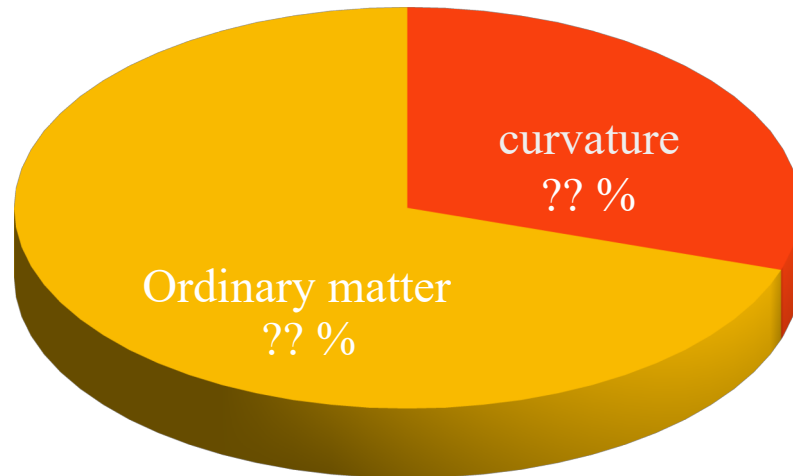
- Observations only show that there are more quarks than antiquarks.

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

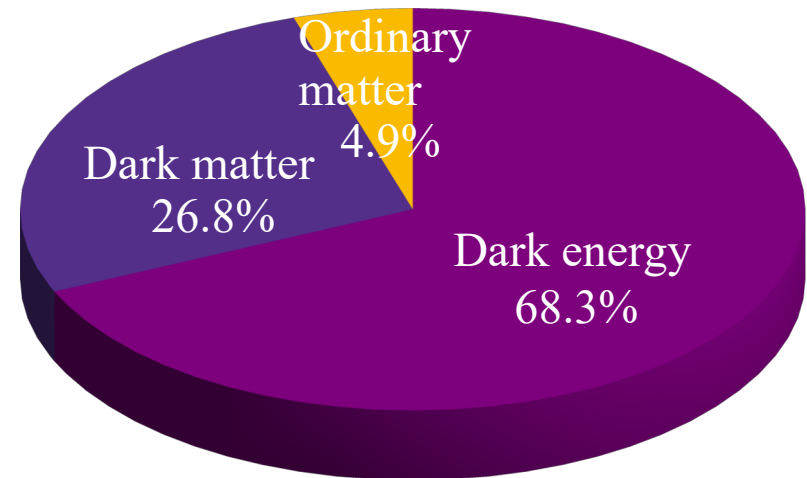
- Dark sector particles could also carry baryon number
- The Universe could even be baryon symmetric.

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The cosmic pie in 1967



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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.

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Generates more N than \bar{N} . For example, from the out of equilibrium decay of a heavy particle, à la leptogenesis.
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“Neutron portal” $\bar{N} d_R \overline{u_R^c} d_R$. Transmits the asymmetry in N to the visible sector and generates a quark-antiquark asymmetry
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A simple scenario

The role of the complex scalar χ

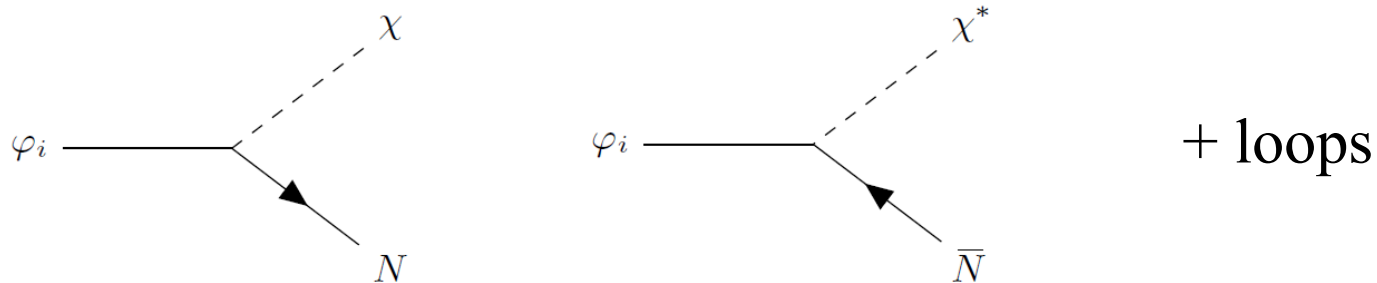
A corresponding asymmetry in χ ensures the conservation of the baryon number throughout the history of the Universe.

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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 .

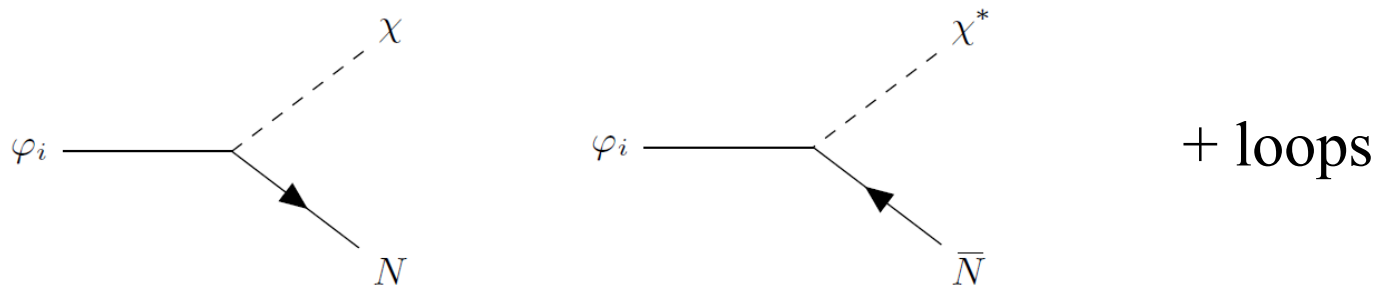


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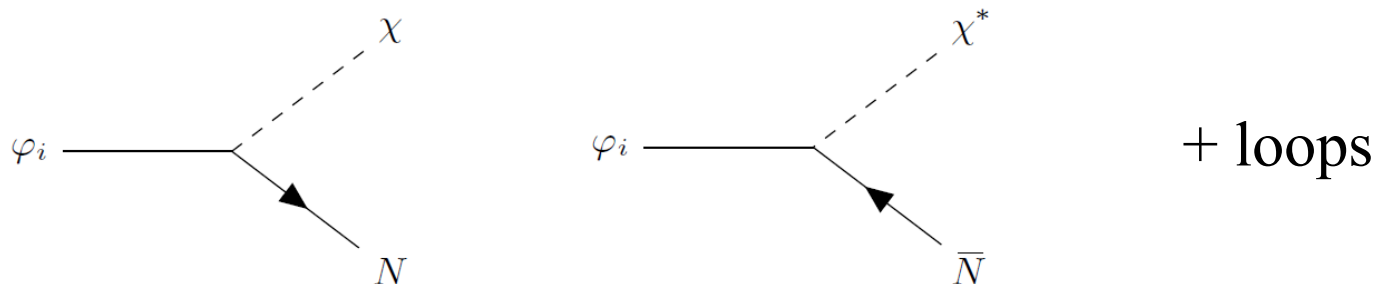
Bonus: χ is absolutely stable, due to the conservation of baryon number.

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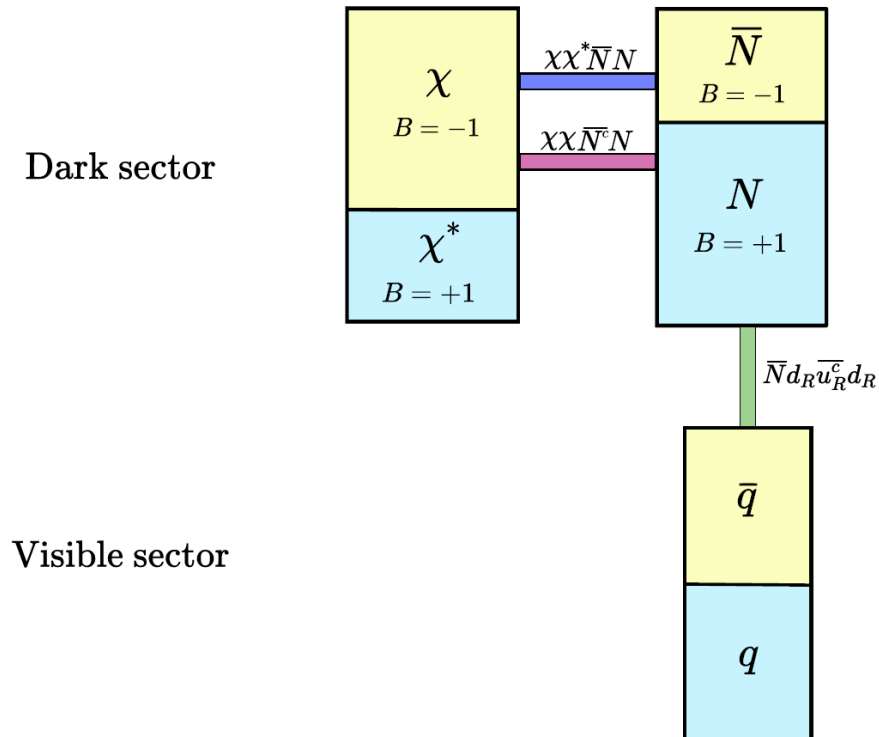
**quark-antiquark
asymmetry**



**dark matter
stability**

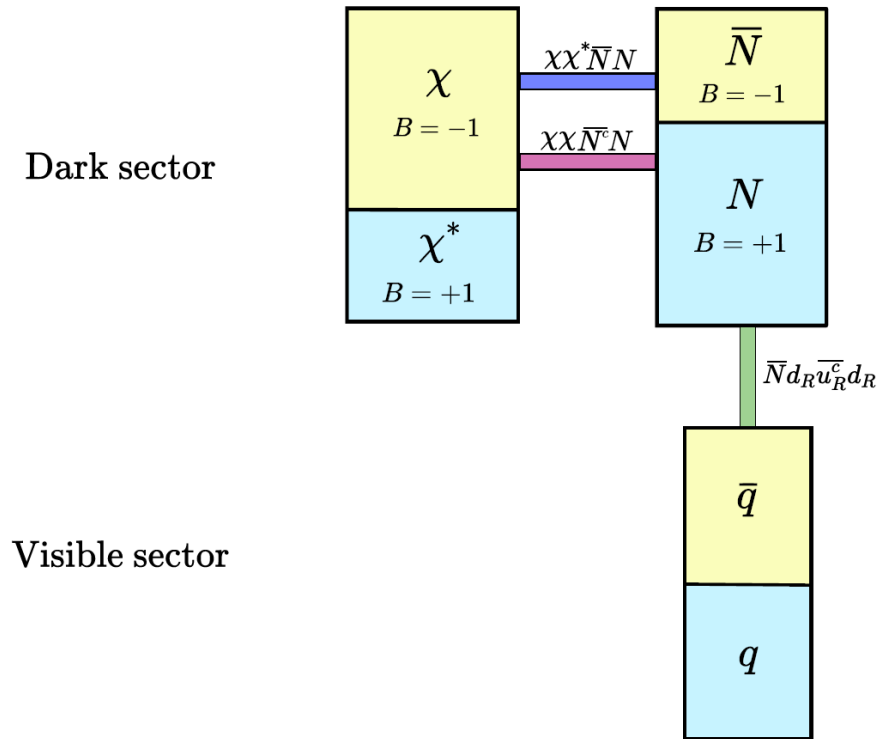
A simple scenario

Initial state

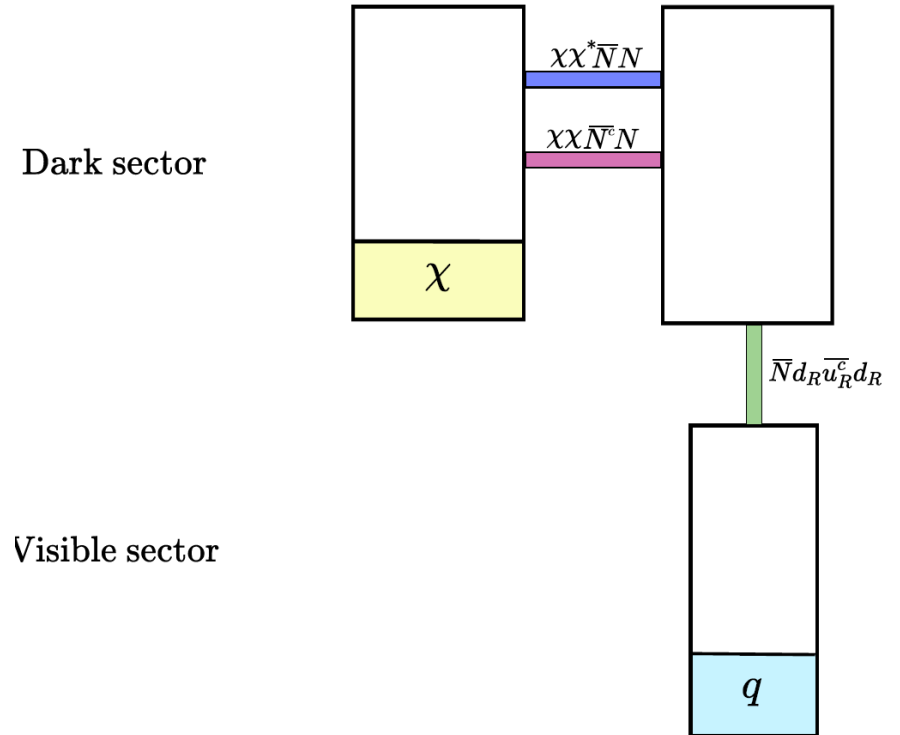


A simple scenario

Initial state

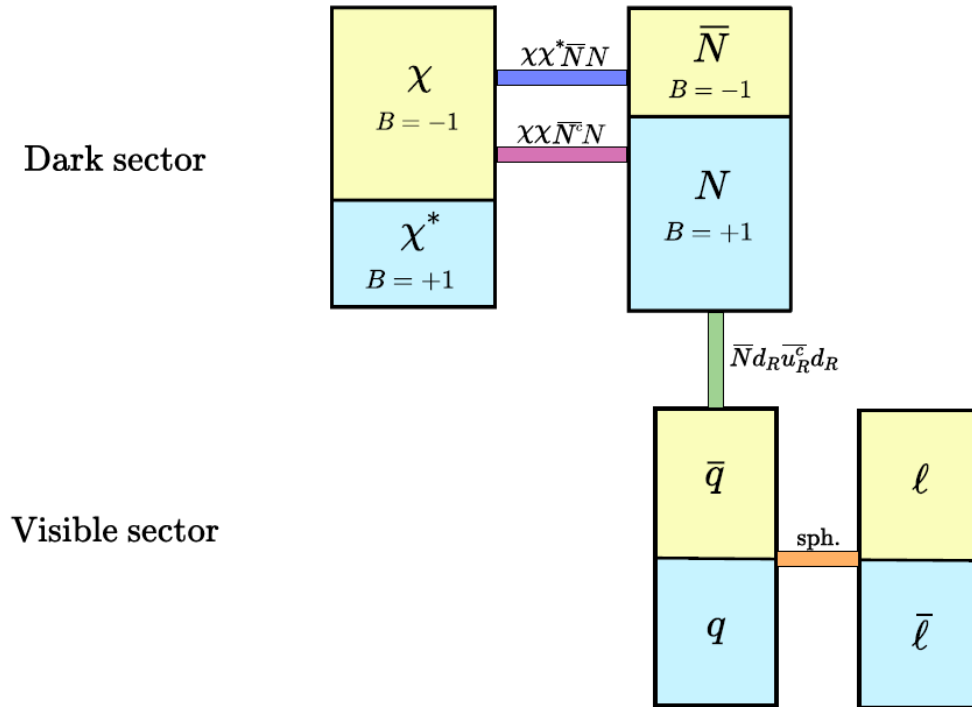


final state



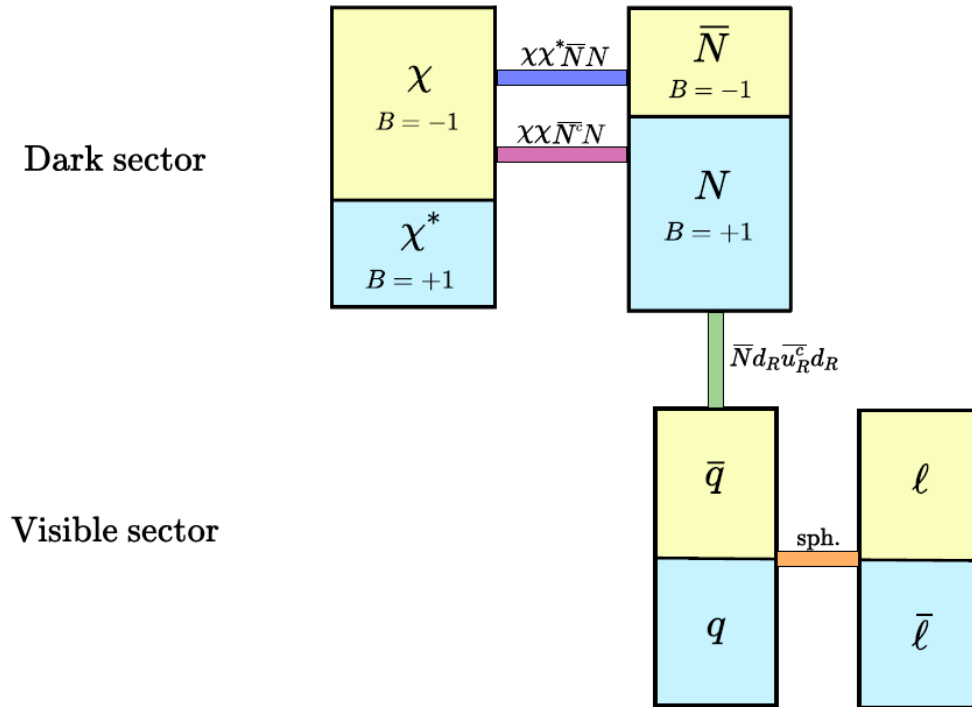
A more refined scenario

Initial state



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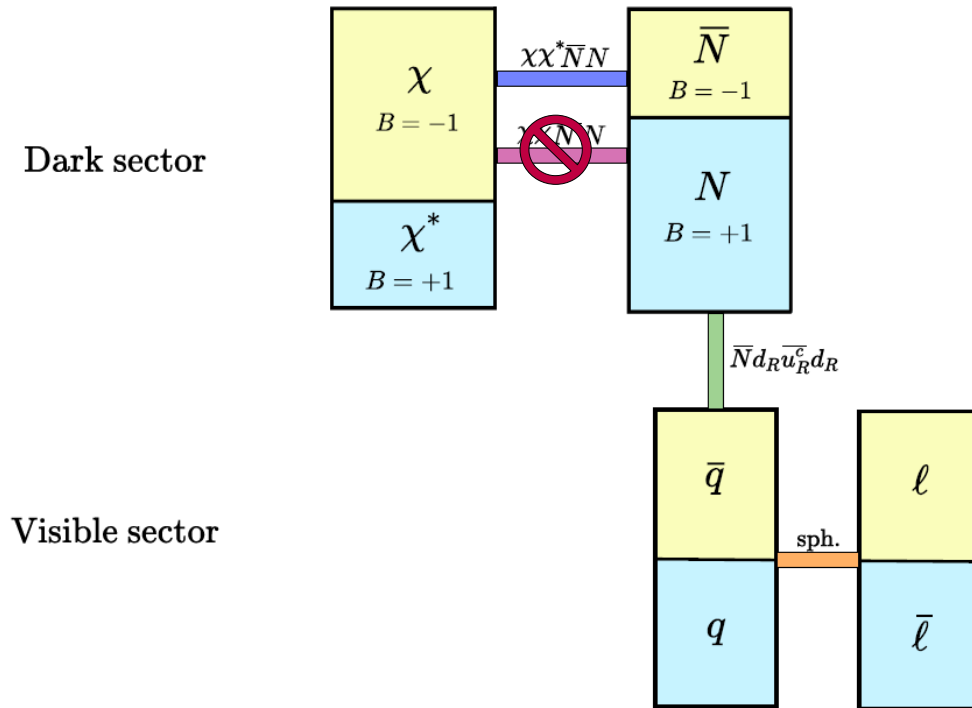


Consider for simplicity:

- 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

A more refined scenario

Initial state

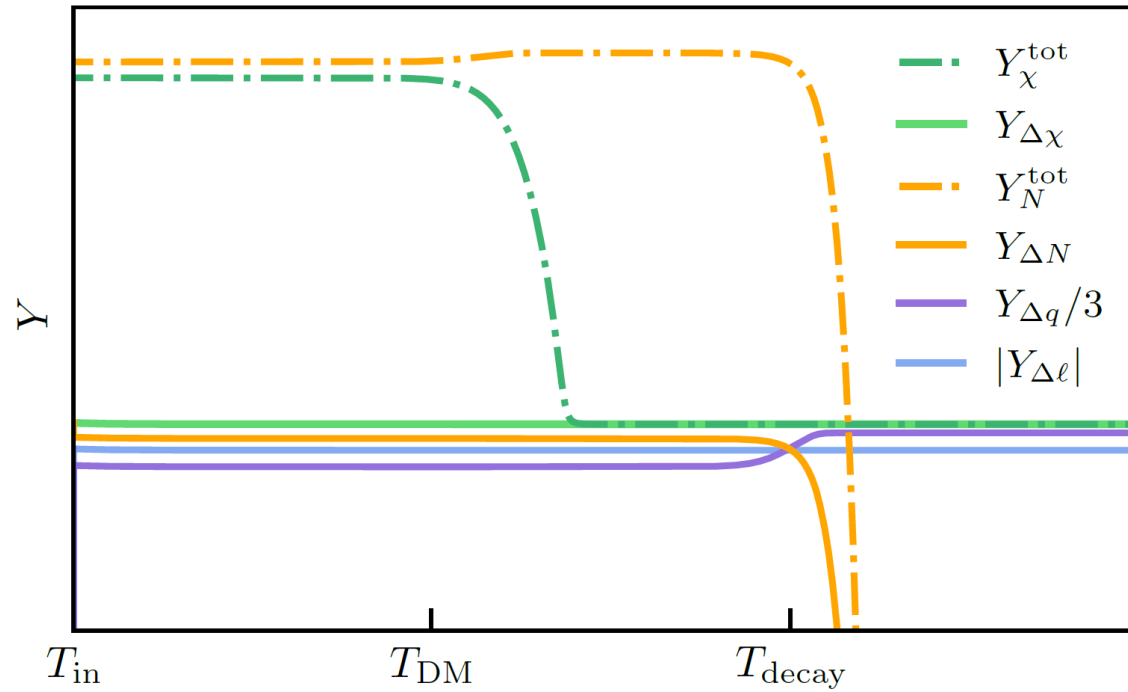


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A more refined scenario

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

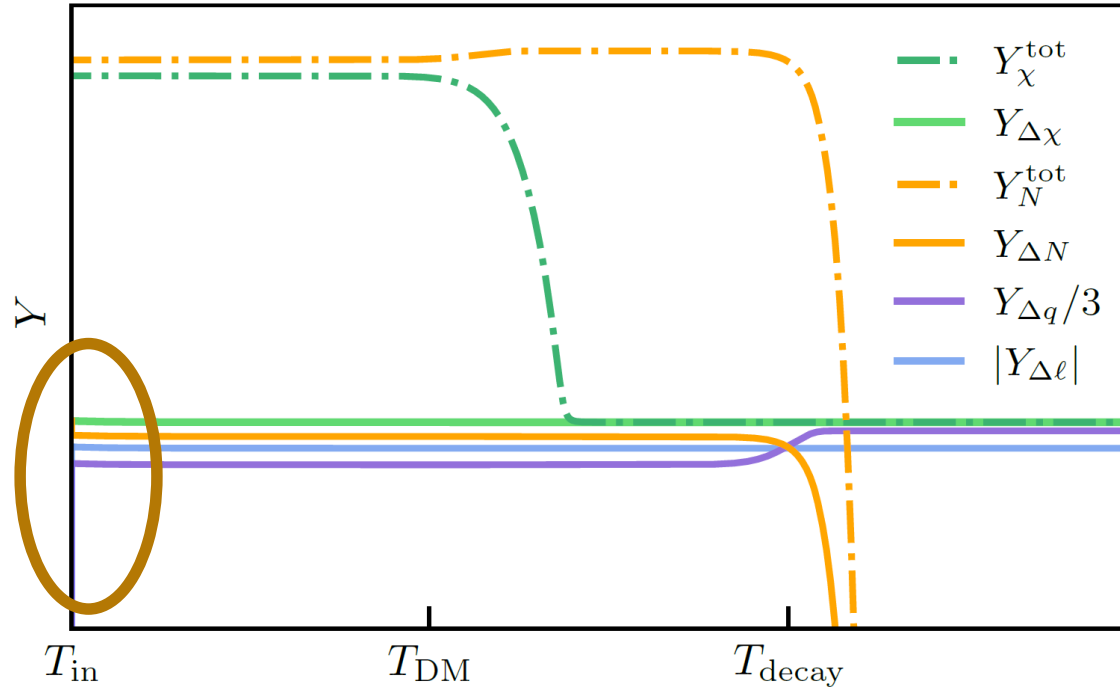


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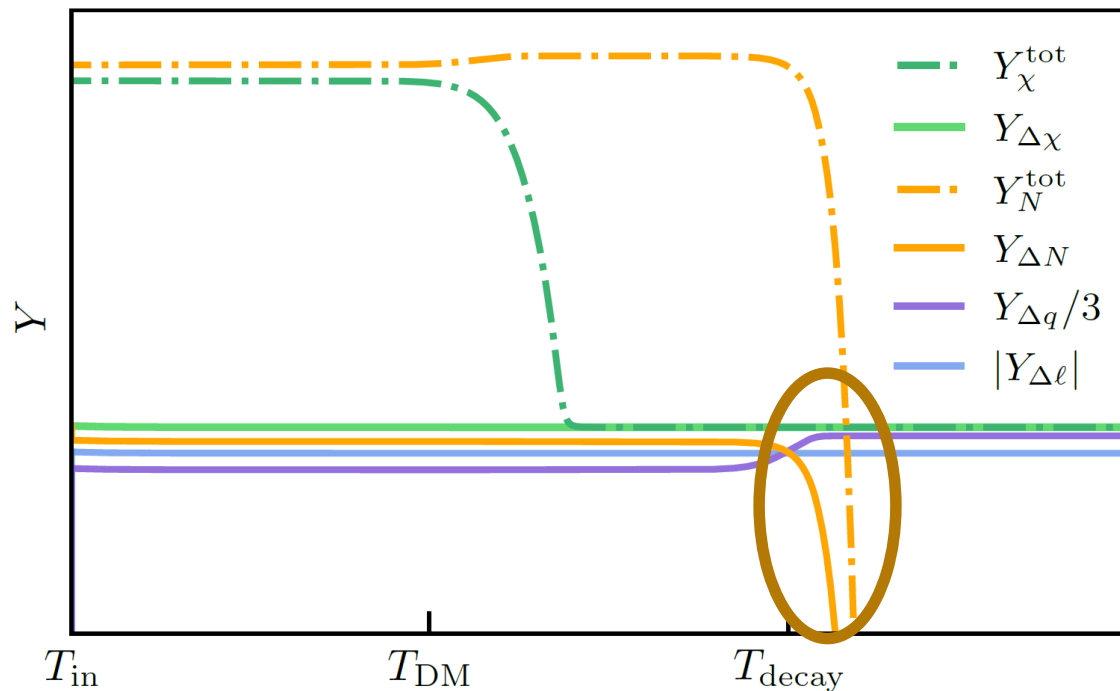
The asymmetry in N is quickly transmitted to the quark sector via scatterings $N\bar{d} \leftrightarrow ud$, $N\bar{u} \leftrightarrow dd$

$$Y_{\Delta N}(T) = \frac{11}{122} Y_{\Delta N}^{\text{in}},$$

$$Y_{\Delta q}(T) = \frac{54}{61} Y_{\Delta N}^{\text{in}},$$

$$Y_{\Delta\ell}(T) = -\frac{75}{122} Y_{\Delta N}^{\text{in}}.$$

A more refined scenario



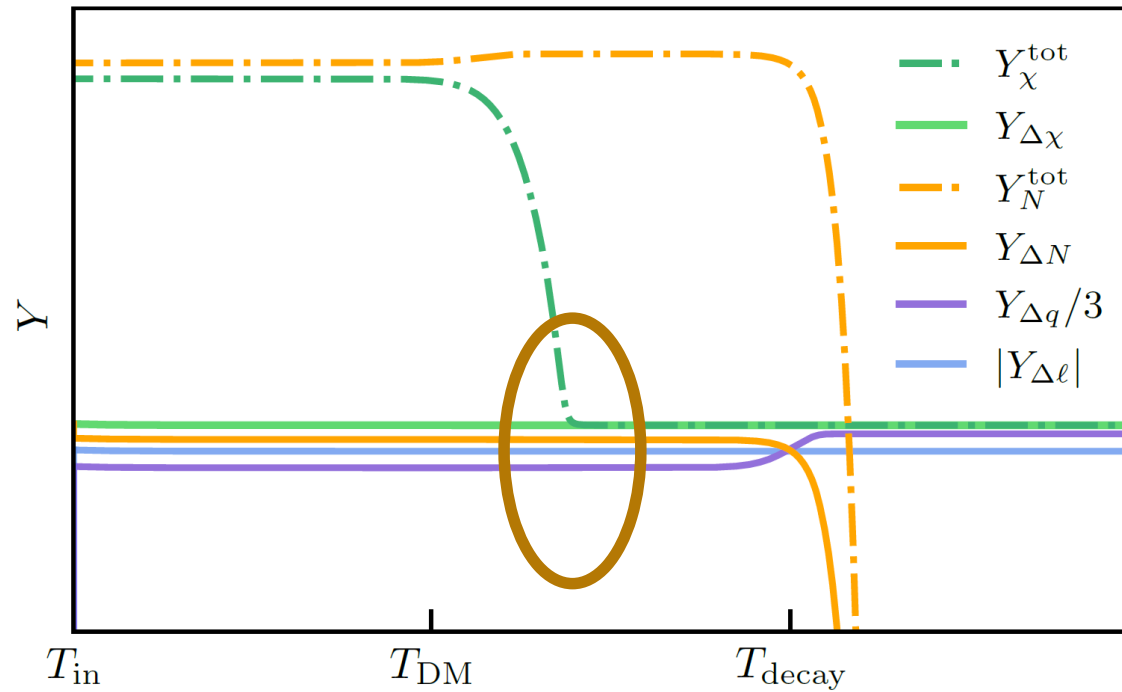
The decay $N \rightarrow udd$ increases the quark-antiquark asymmetry.

$$Y_{\Delta q,0} = 3 \frac{11}{122} Y_{\Delta N}^{in} + \frac{54}{61} Y_{\Delta N}^{in} = \frac{141}{122} Y_{\Delta N}^{in}$$

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

$$Y_{\Delta e,0} = -\frac{75}{122} Y_{\Delta N}^{in}$$

A more refined scenario

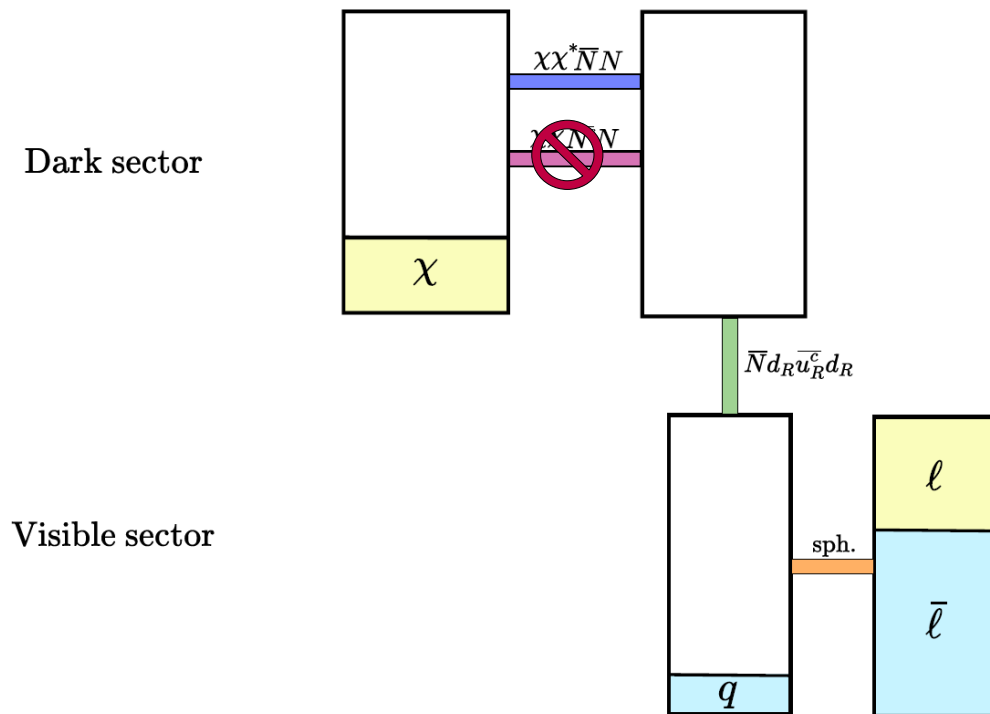


Freeze-out of $\chi\chi^* \rightarrow N\bar{N}$

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

A more refined scenario

Final state, when all χ^* are annihilated

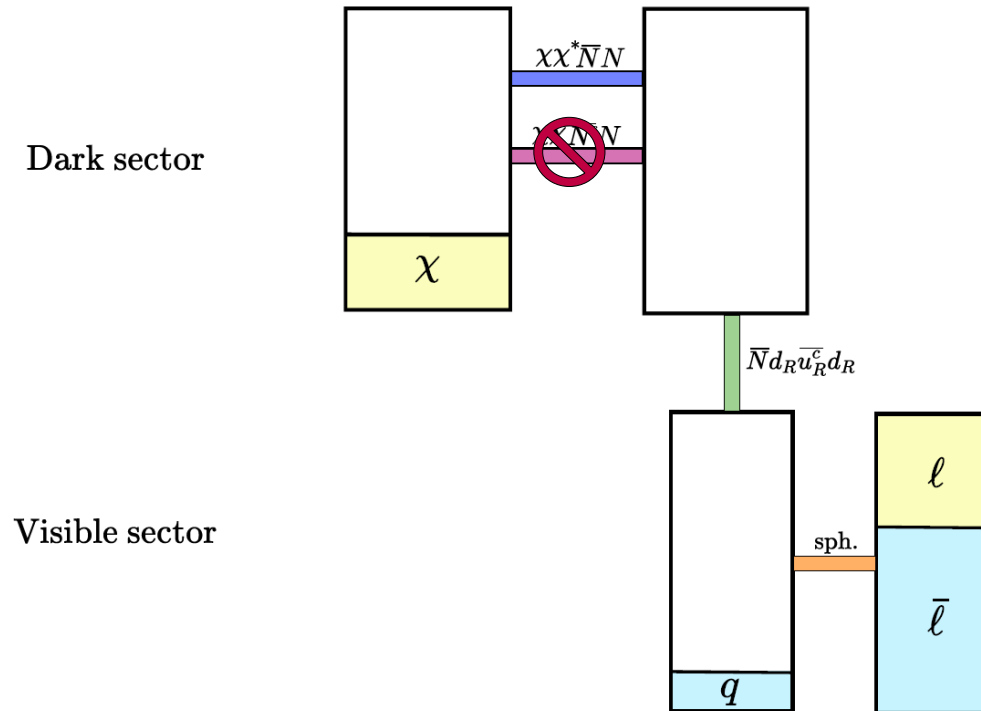


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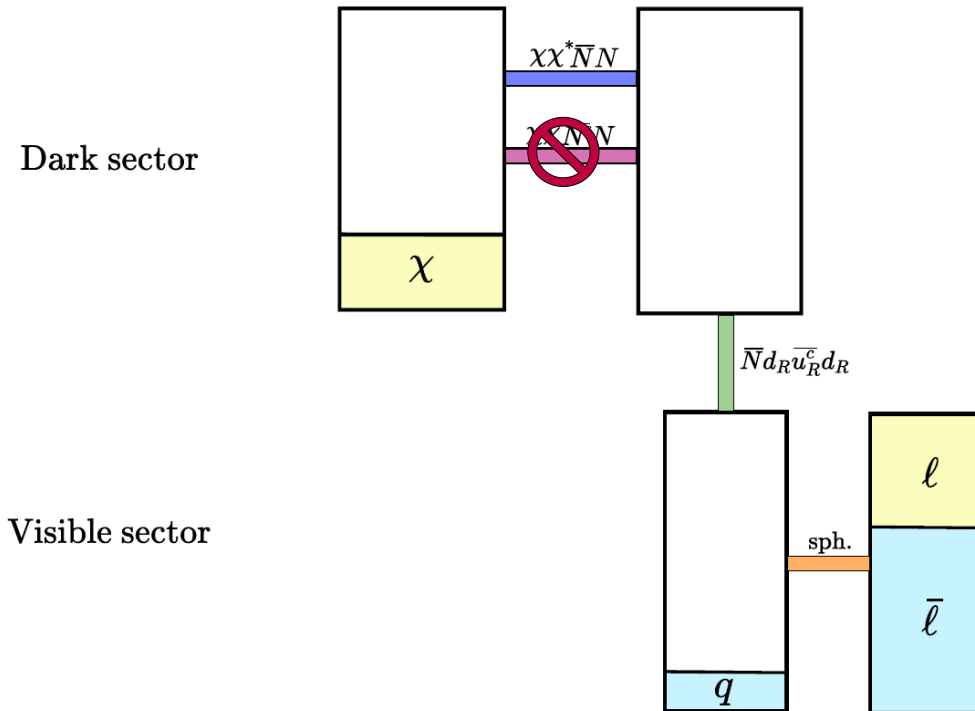


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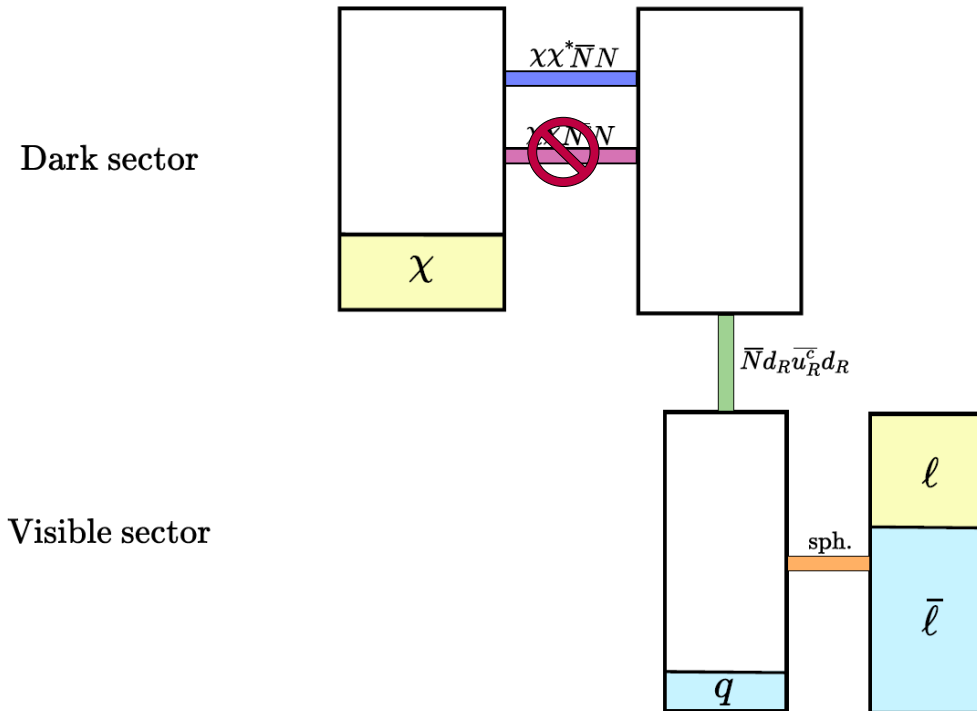


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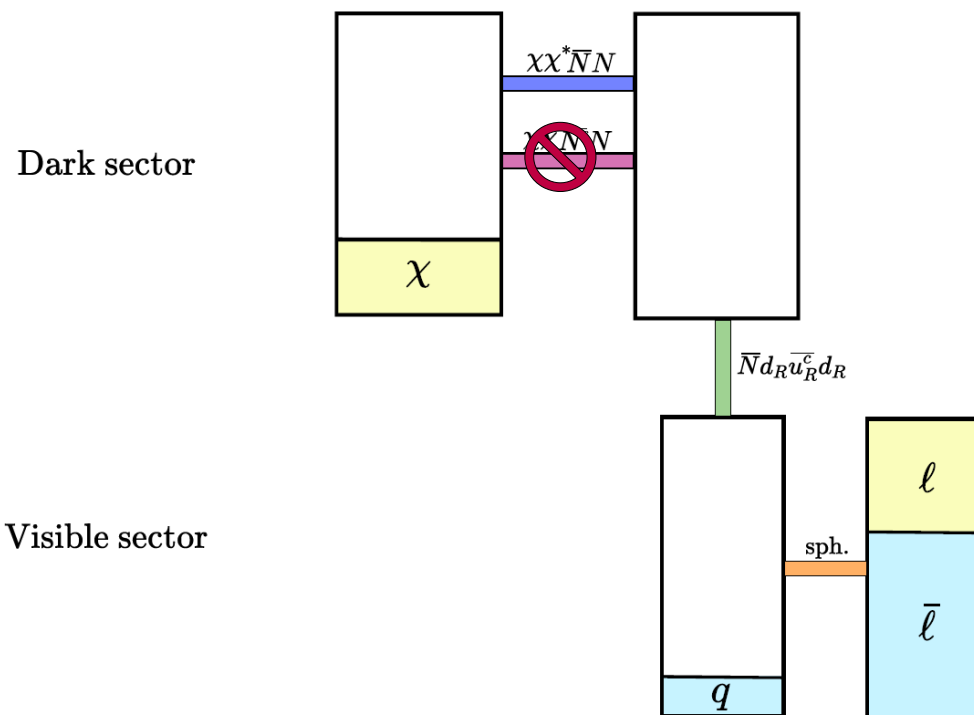


$$\Omega_{\text{DM},0} h^2 \simeq 1.4 \times 10^8 Y_{\Delta q,0} \frac{m_\chi}{\text{GeV}} .$$

$$Y_{\Delta q,0} = \frac{141}{122} Y_{\Delta N}^{\text{in}} ,$$

A more refined scenario

Final state, when all χ^* are annihilated



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

$$Y_{\Delta q,0} = \frac{141}{122} Y_{\Delta N}^{\text{in}},$$

$$Y_{\Delta\chi}^{\text{in}} \simeq 2.3 \times 10^{-10},$$

$$m_\chi \simeq 1.9 \text{ GeV}.$$

Experimental tests

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

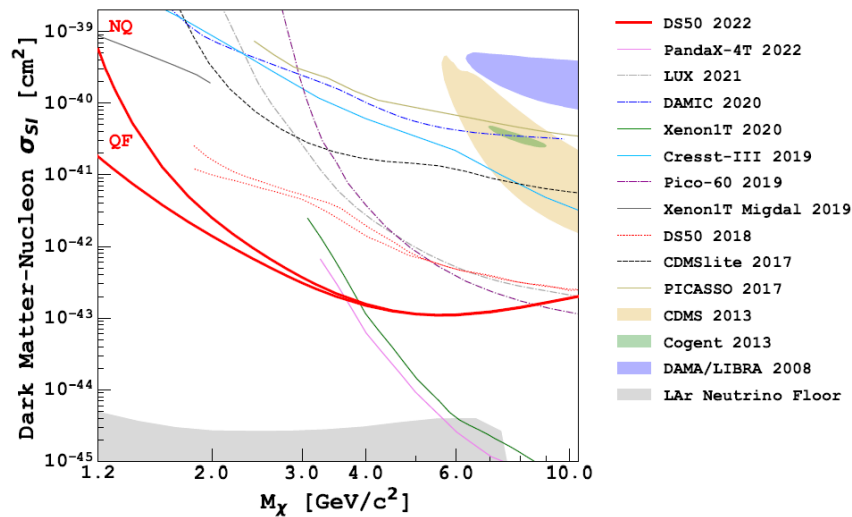
- Higgs invisible decay $h \rightarrow \chi\chi^*$

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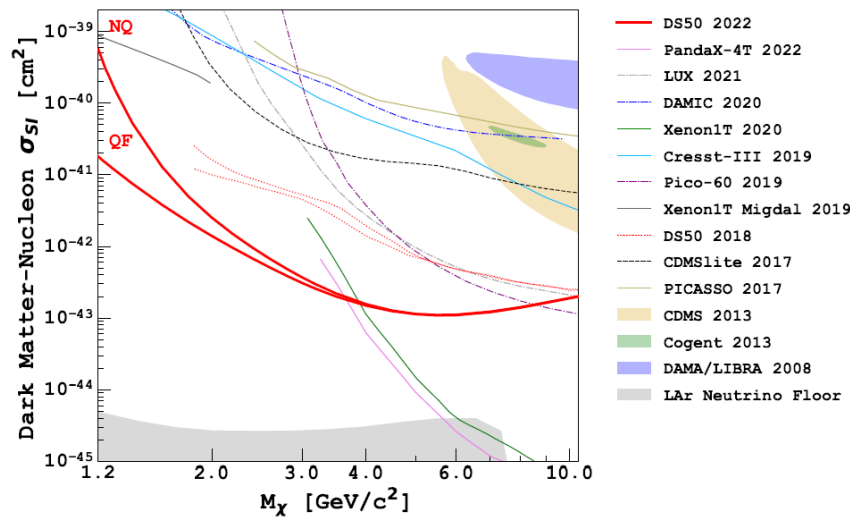


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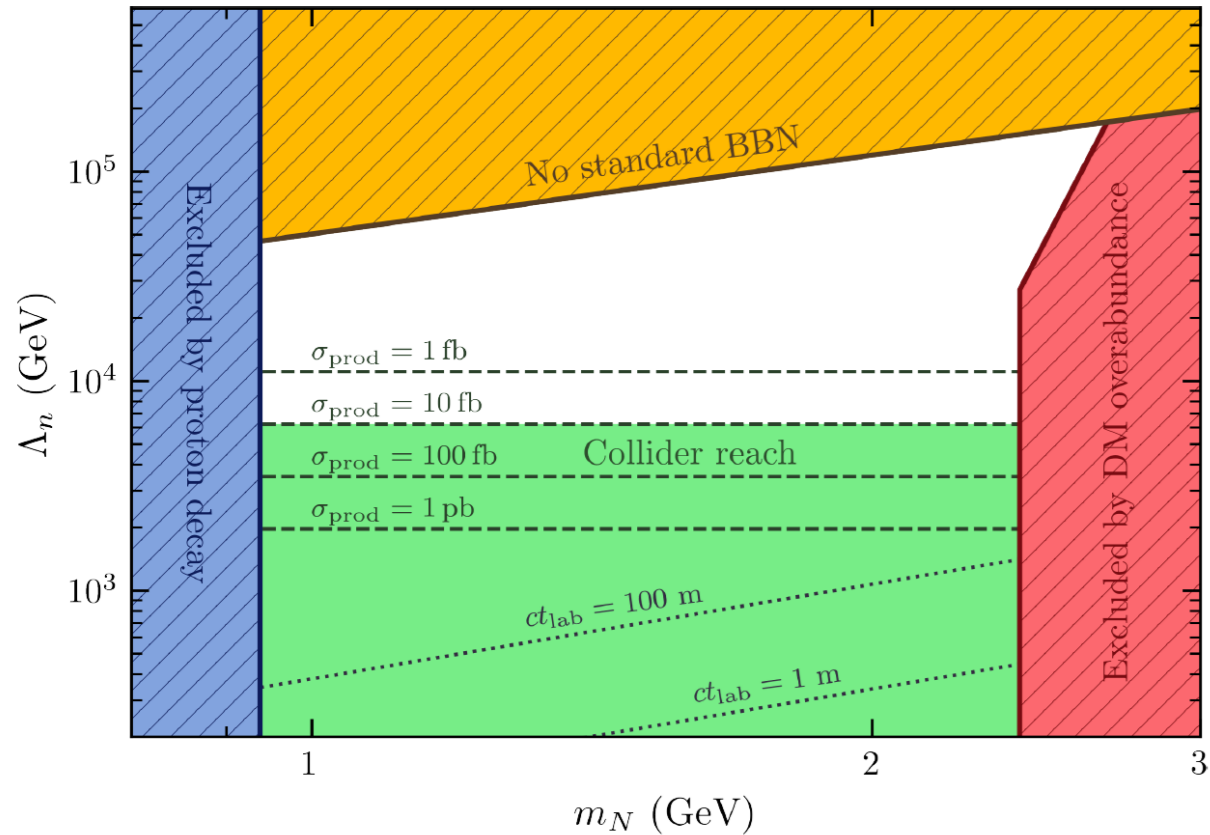


$$\Rightarrow \lambda_{\chi H} \lesssim 10^{-2}$$

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

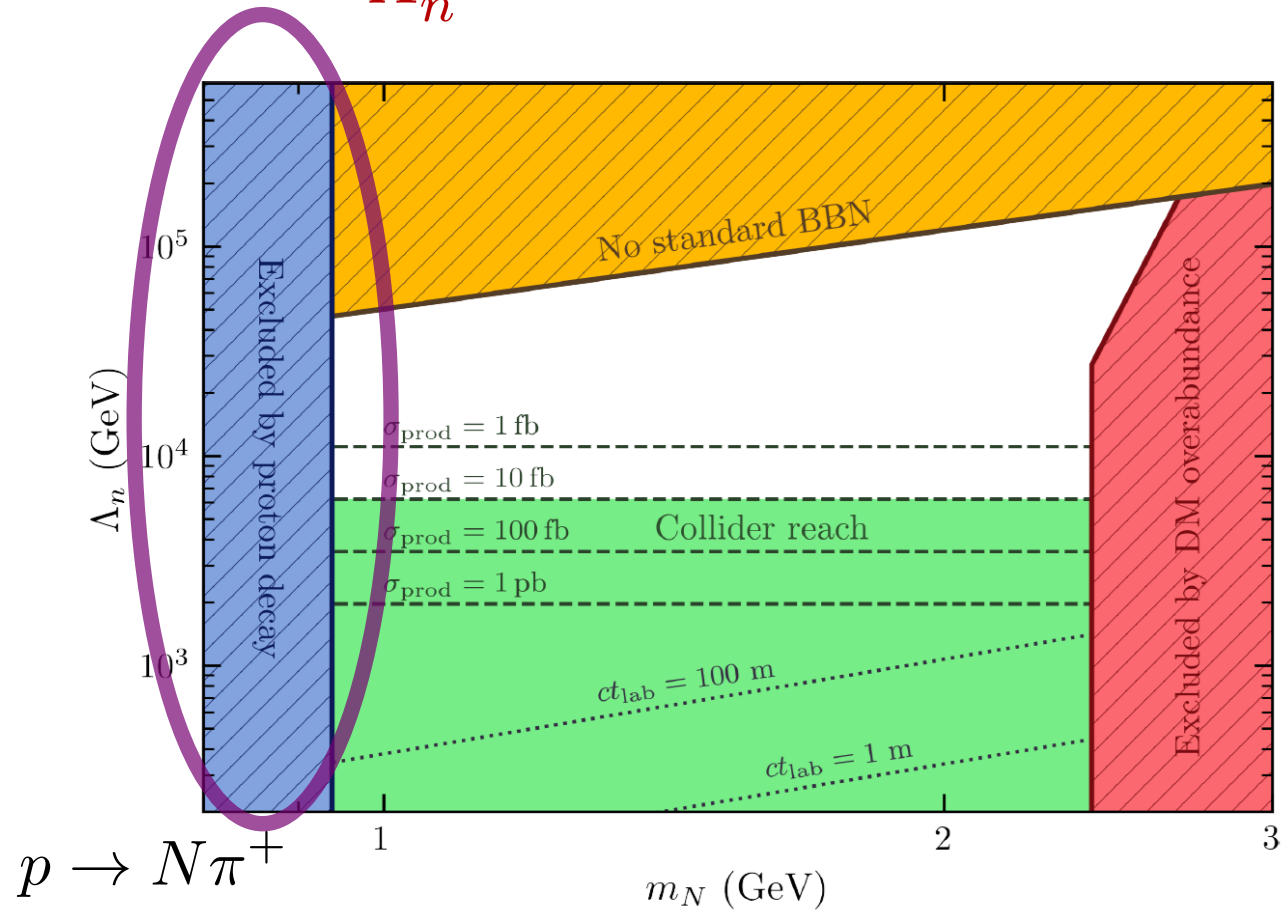
Experimental tests

2) Neutron portal $\frac{1}{\Lambda_n^2} \overline{N} d_R \overline{u}_R^c d_R$



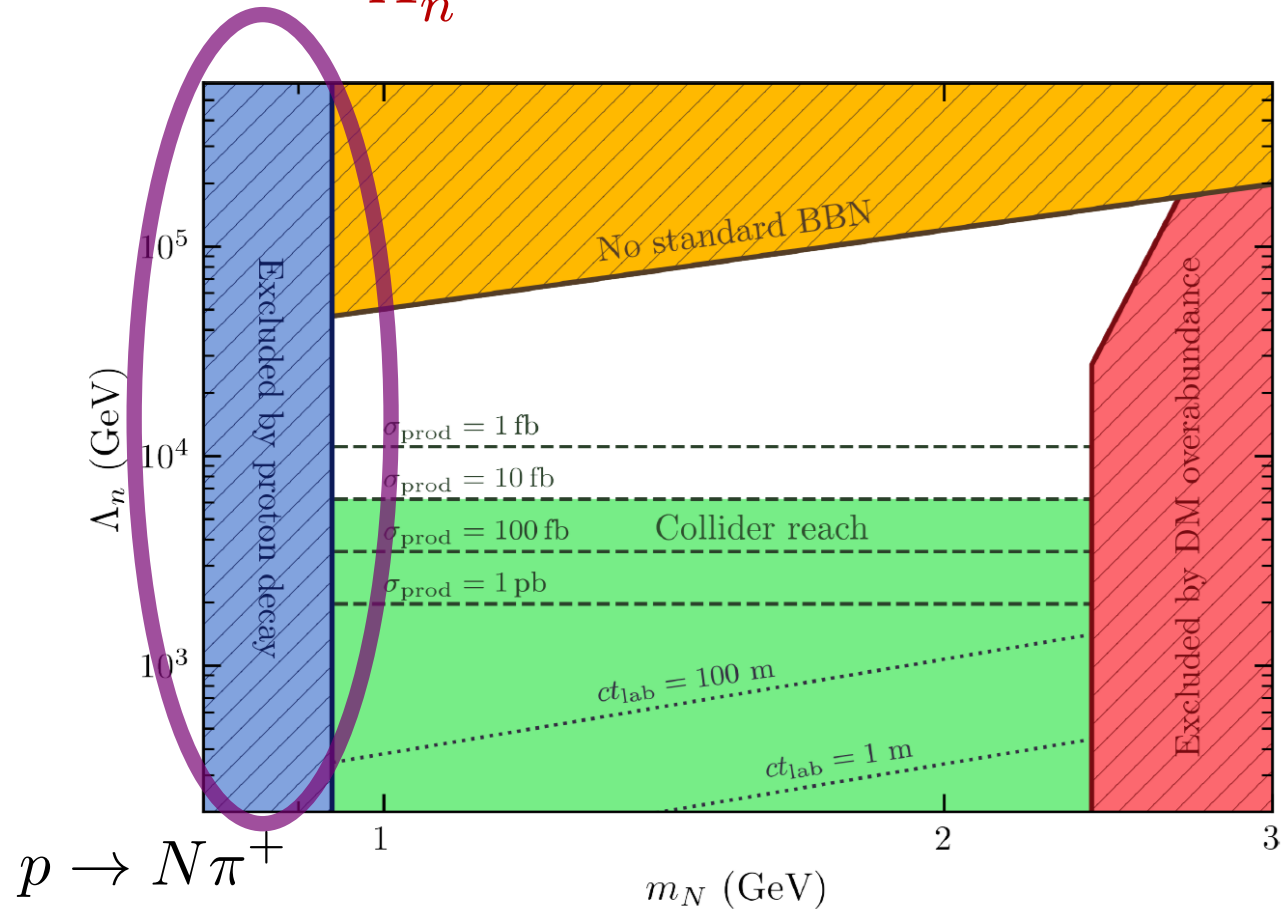
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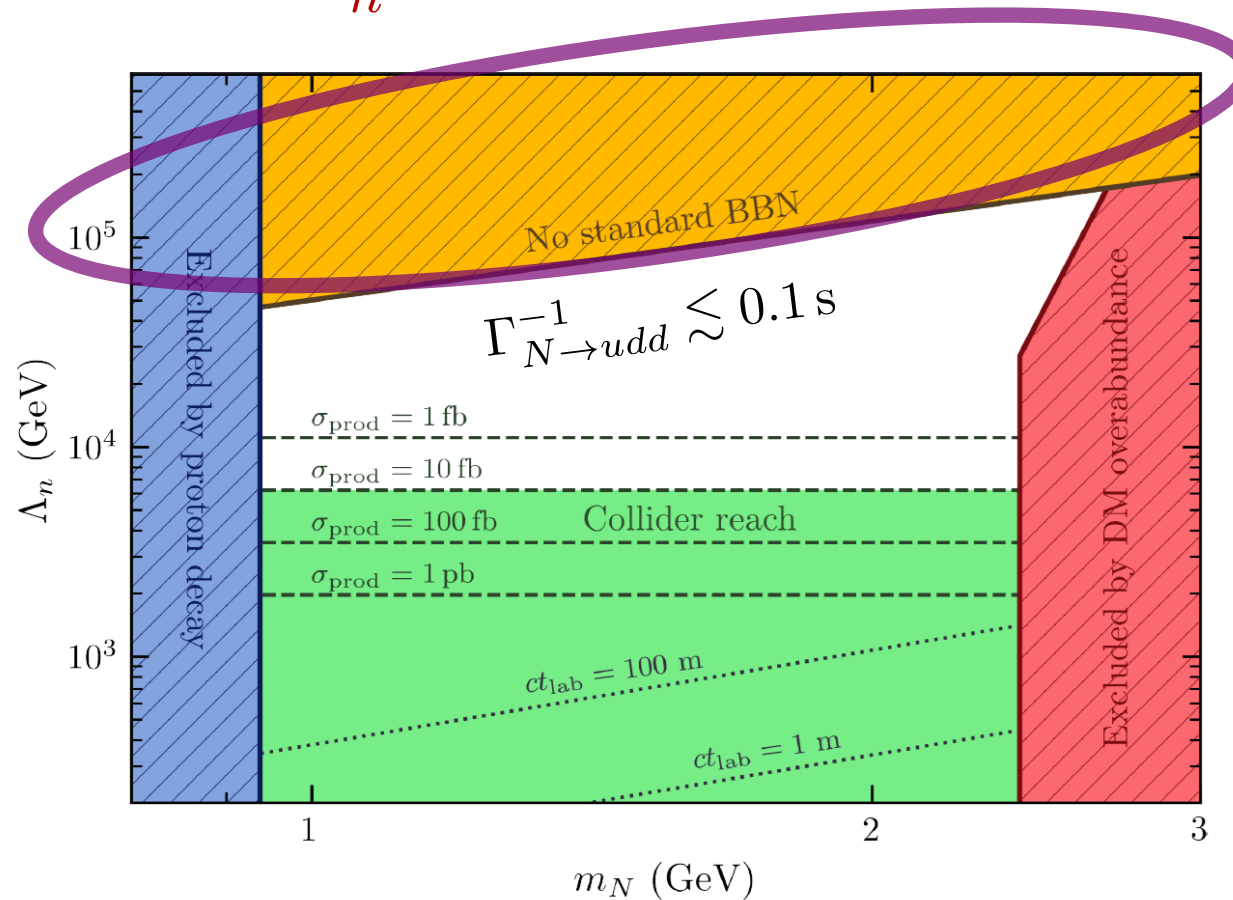


Larger N masses could be probed searching for $\Delta^+ \rightarrow N\pi^+$

No search reported in the PDG. In our framework, it is B-conserving

Experimental tests

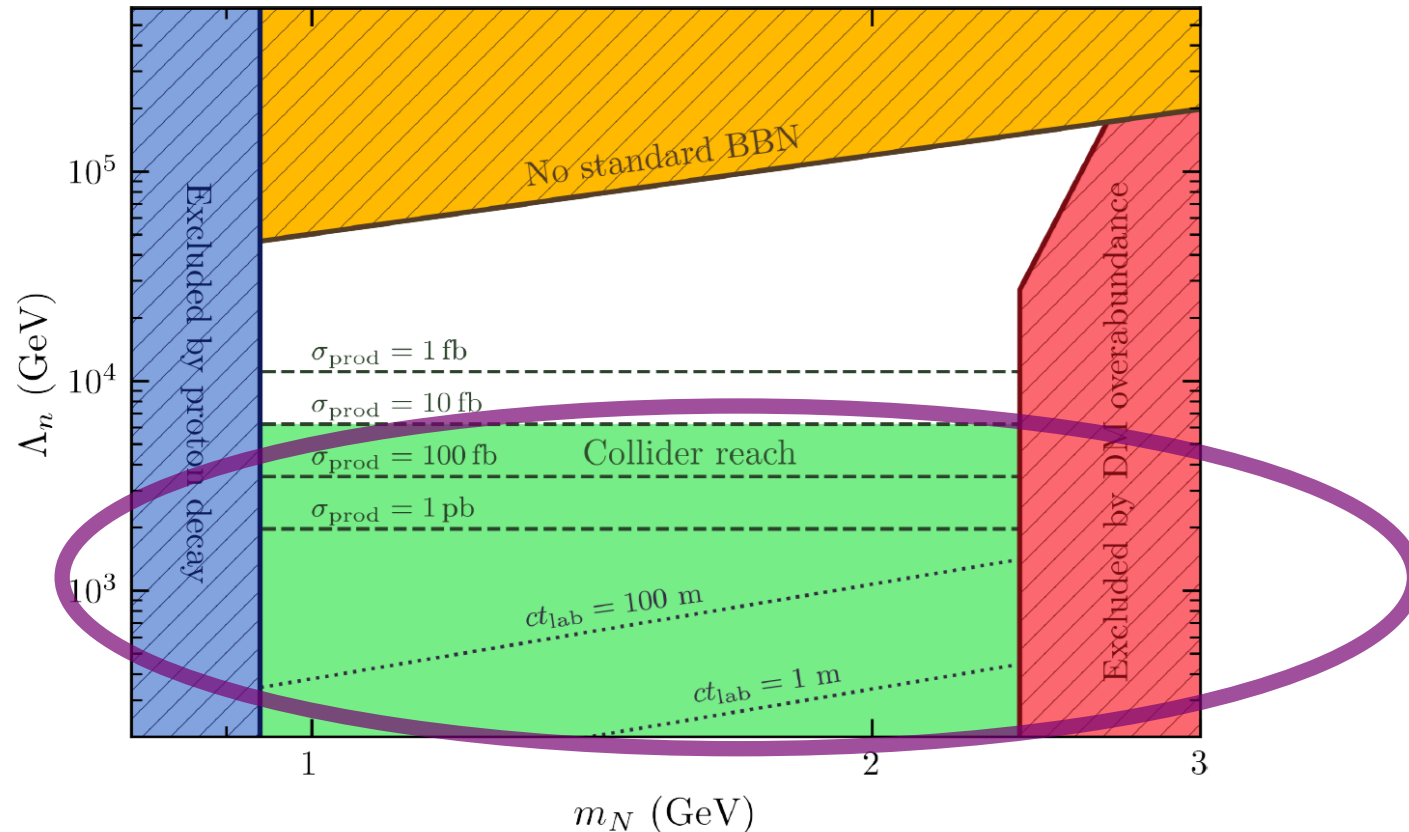
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$$\Gamma_{N \rightarrow udd}^{-1} \approx 1.6 \text{ s} \left(\frac{\Lambda_n}{10^5 \text{ GeV}} \right)^4 \left(\frac{\text{GeV}}{m_N} \right)^5,$$

Experimental tests

2) Neutron portal $\frac{1}{\Lambda_n^2} \overline{N} d_R \overline{u}_R^c d_R$

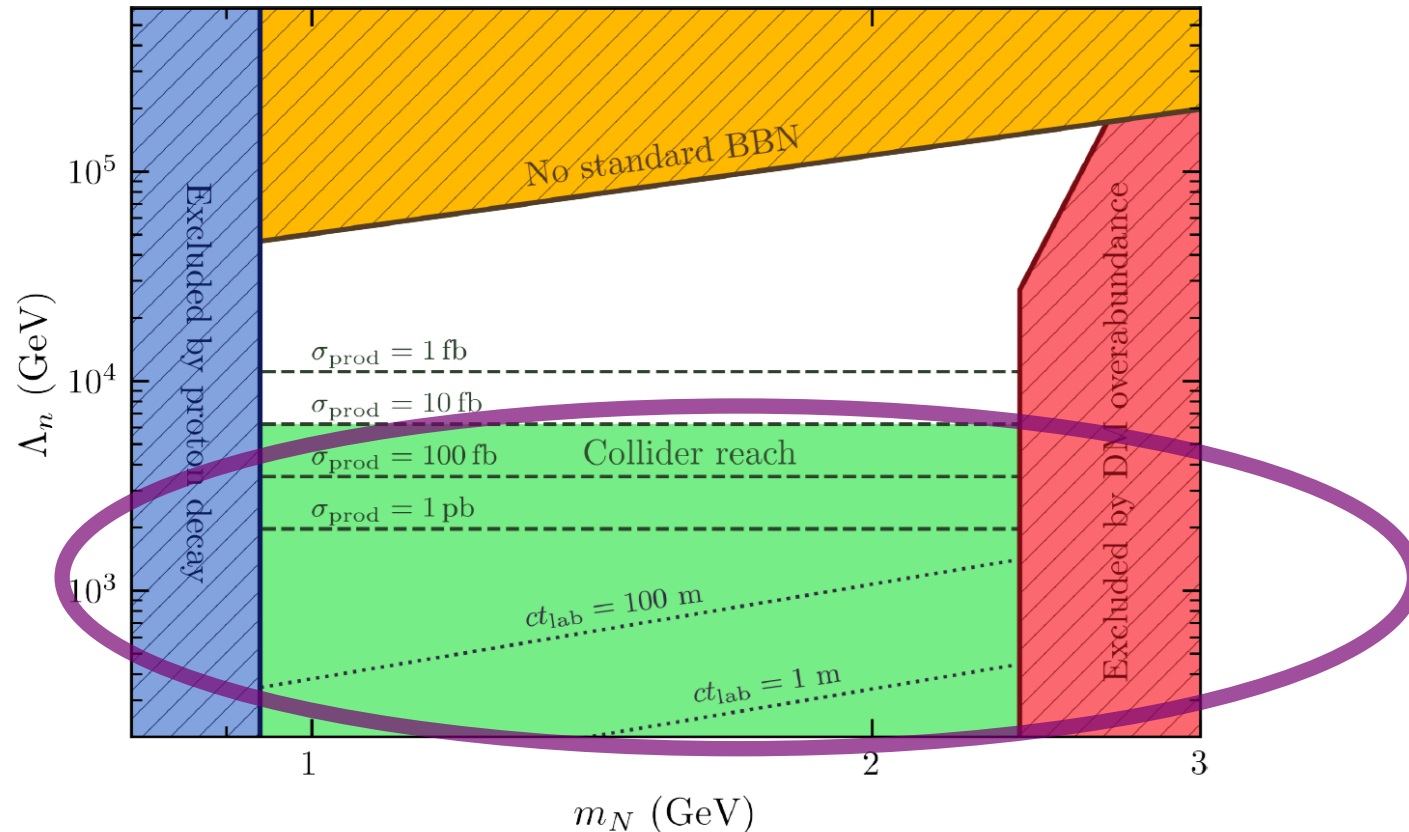


N production in pp collisions through $ud \rightarrow N\bar{d}, dd \rightarrow N\bar{u}$

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

Experimental tests

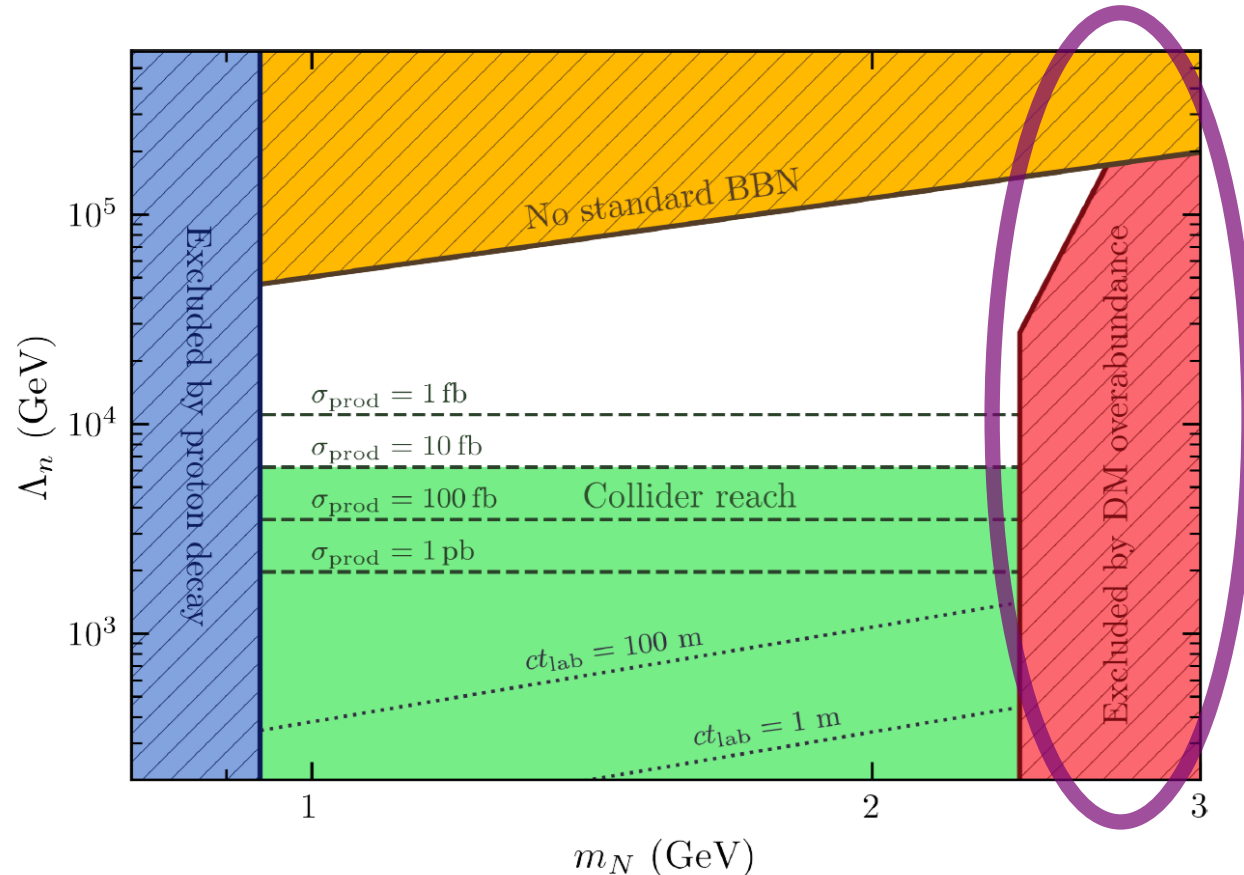
2) Neutron portal $\frac{1}{\Lambda_n^2} \overline{N} d_R \overline{u}_R^c d_R$



- 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 $\overline{N} s_R \overline{c}_R^c s_R$
- **No search exists for baryon \rightarrow meson + invisible**

Experimental tests

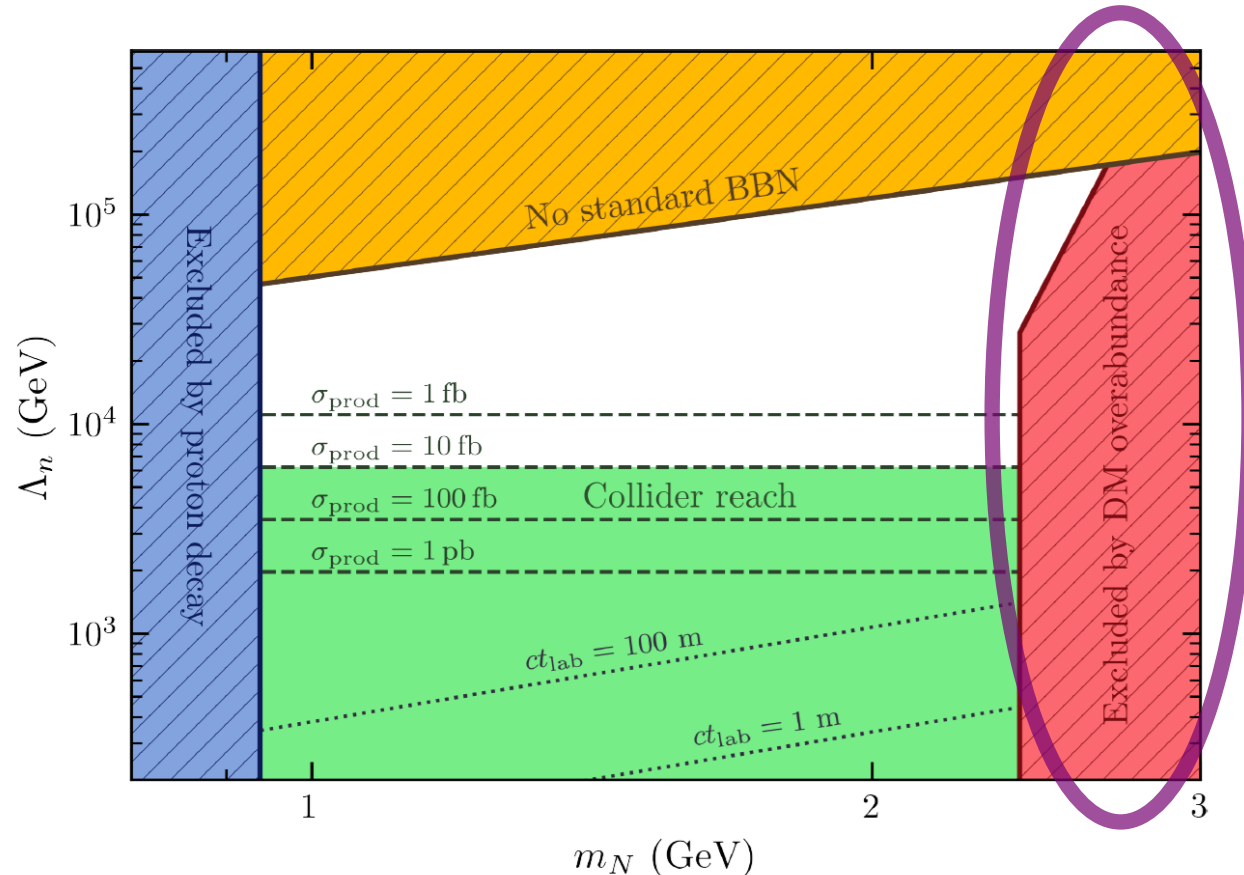
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The rate of annihilations $\chi\chi^* \rightarrow NN$ must be sufficiently efficient at freeze-out.

Experimental tests

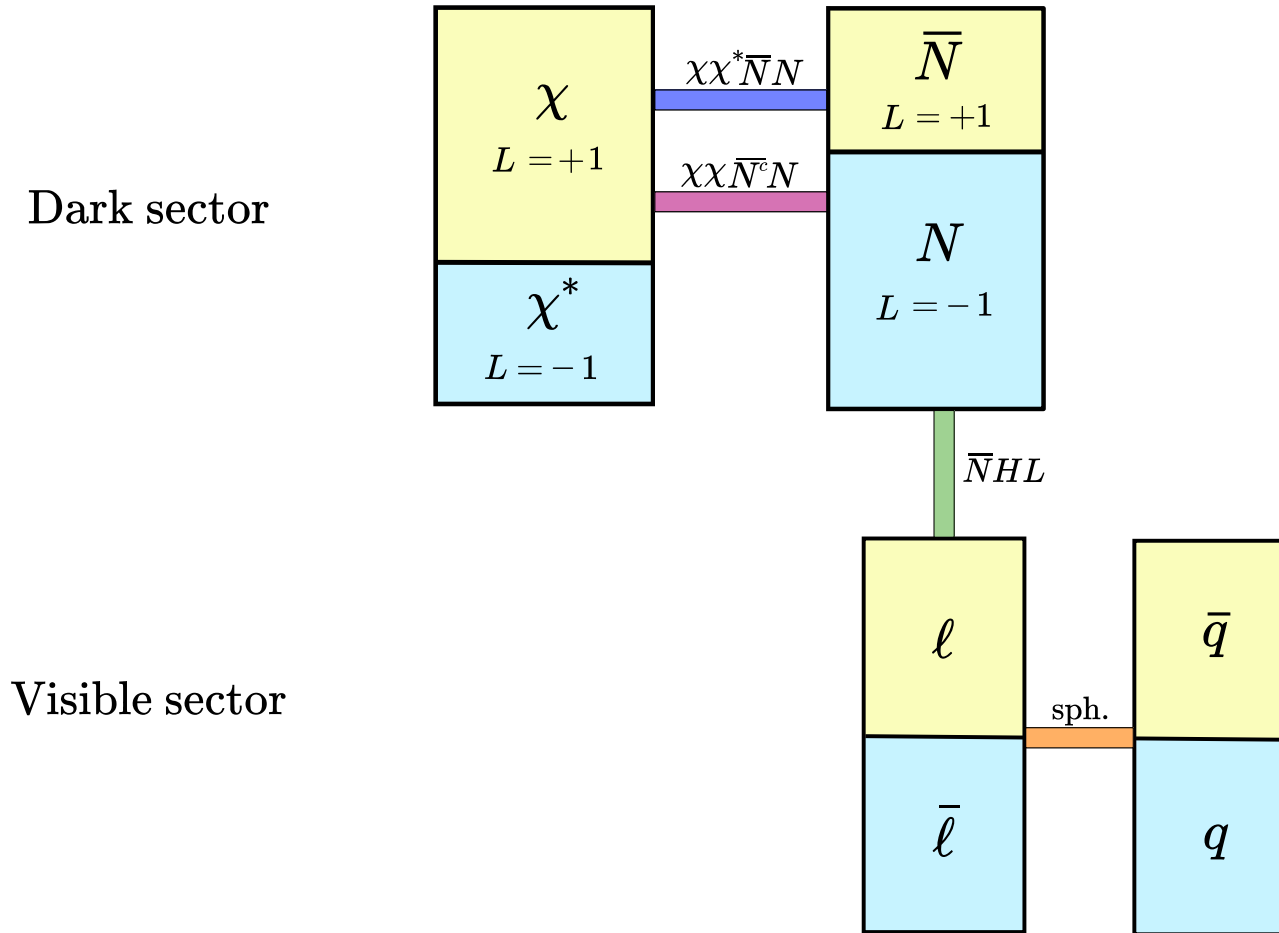
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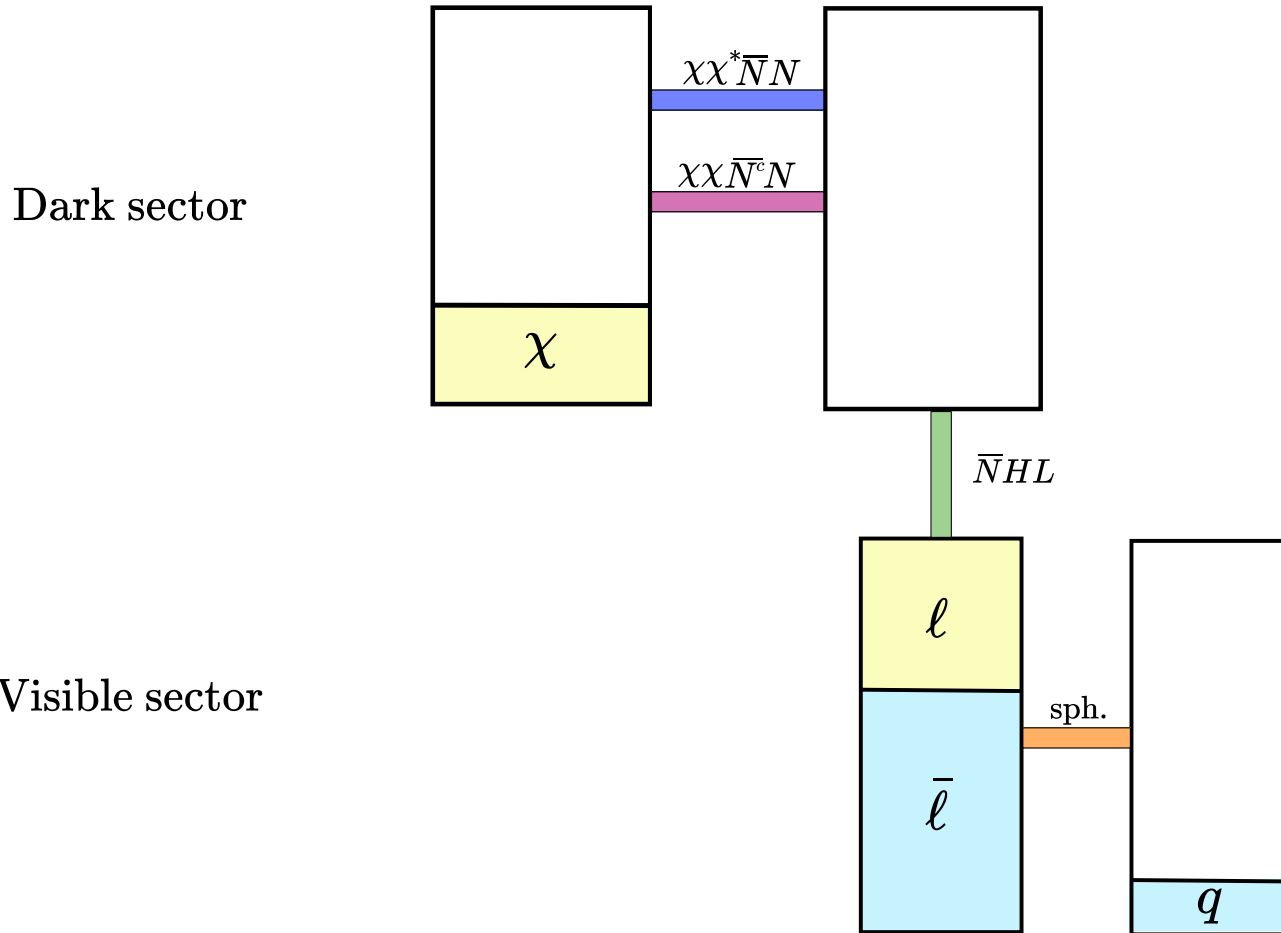
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This limit can be avoided if the DM annihilates into other dark sector particles.

A leptonic portal



A leptonic portal



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.