Connecting the baryons to the dark matter of the Universe

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

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Introduction

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

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

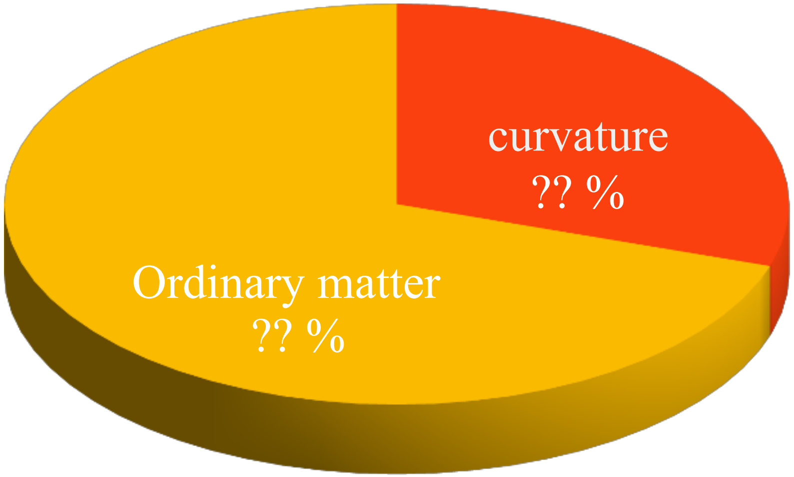
• A baryon asymmetry could be dynamically generated from a baryon symmetric Universe, if the following conditions are satisfied (Sakharov'67):

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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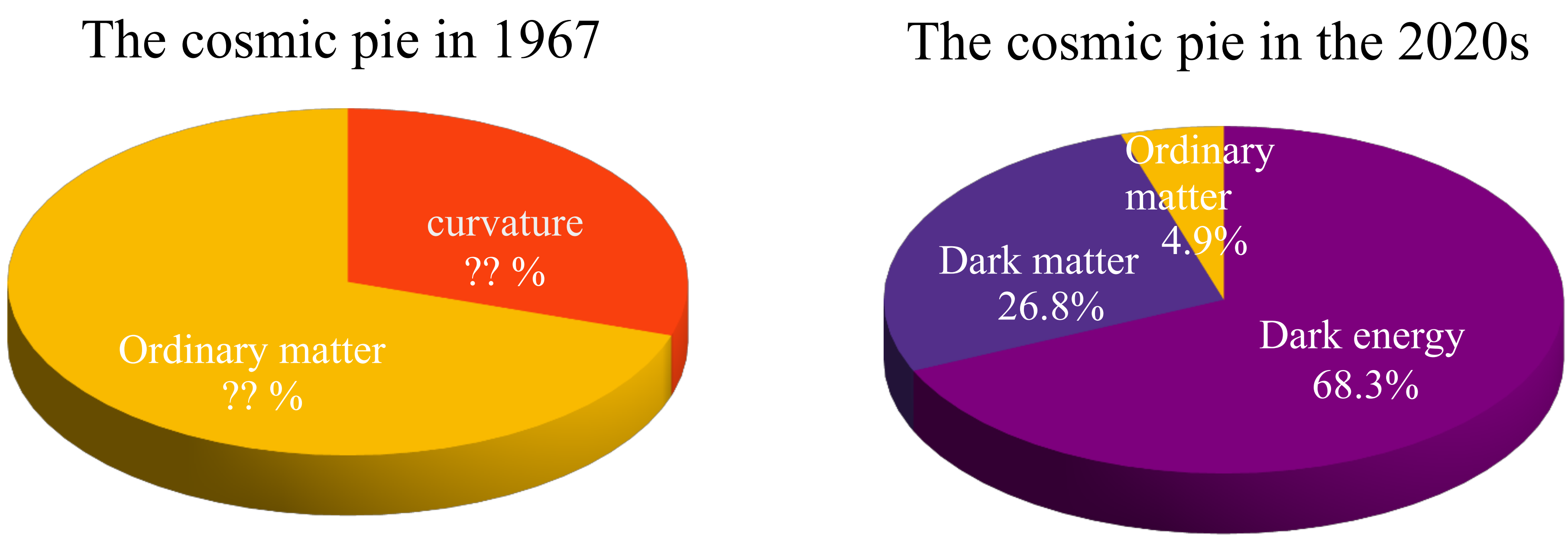

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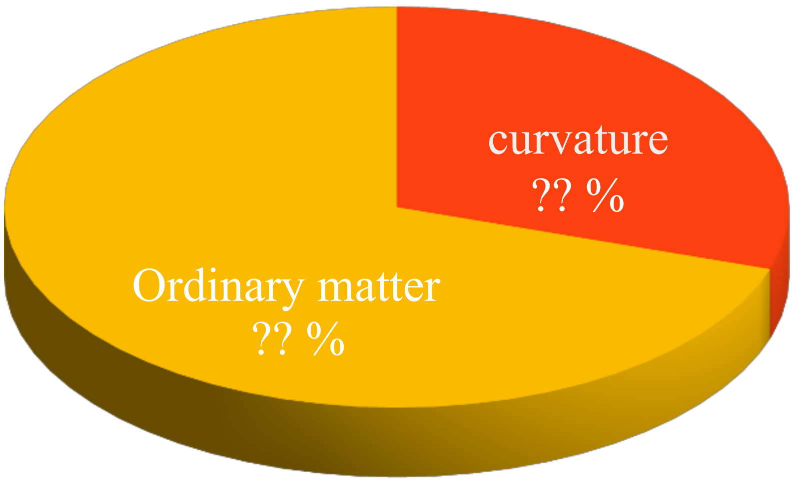
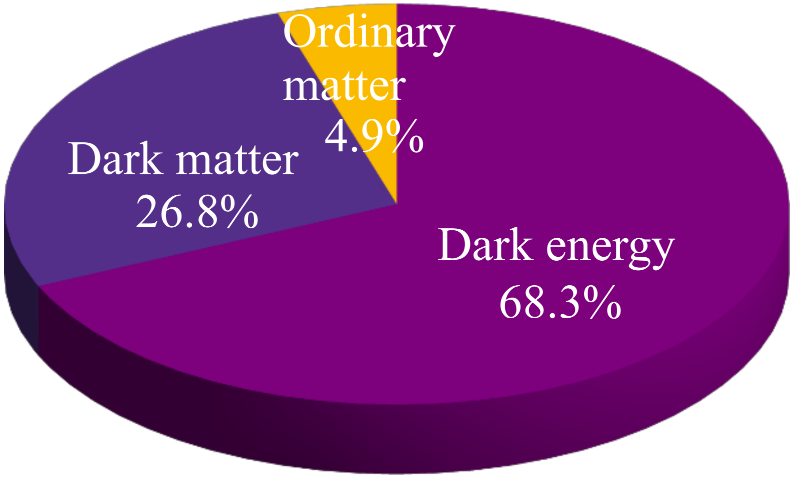


The cosmic pie in the 2020s



There is no evidence for a baryon asymmetry in our Universe

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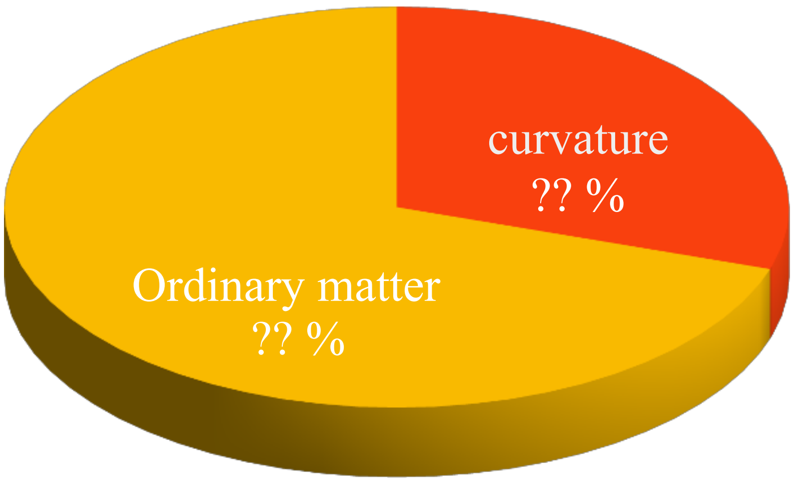

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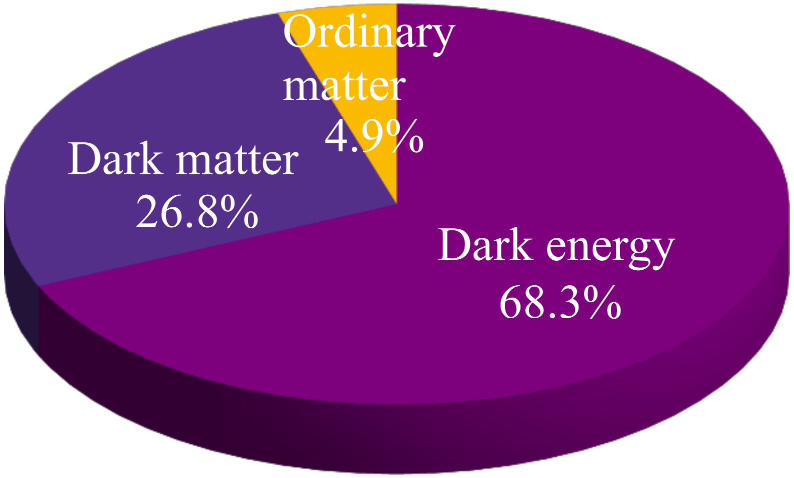

There is no evidence for a baryon asymmetry in our Universe

- 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.

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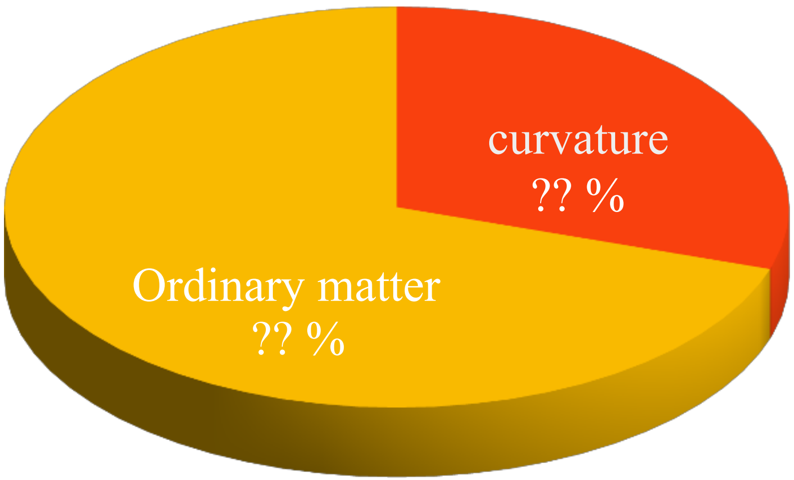

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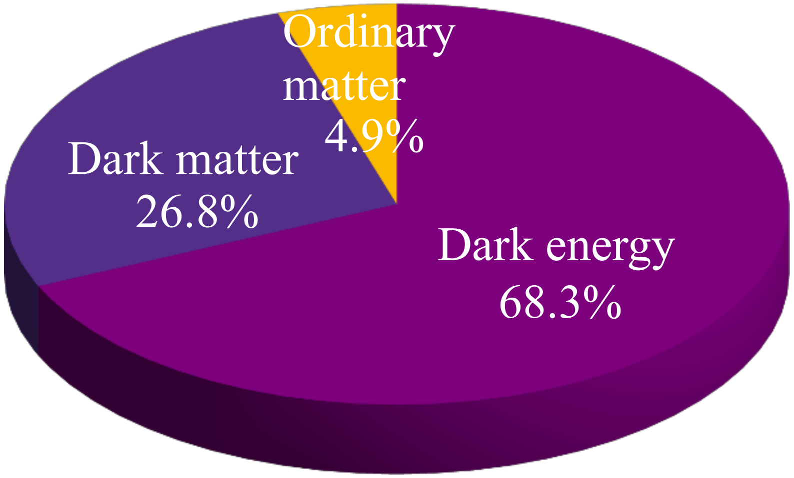

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The Sakharov conditions may not be necessary

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
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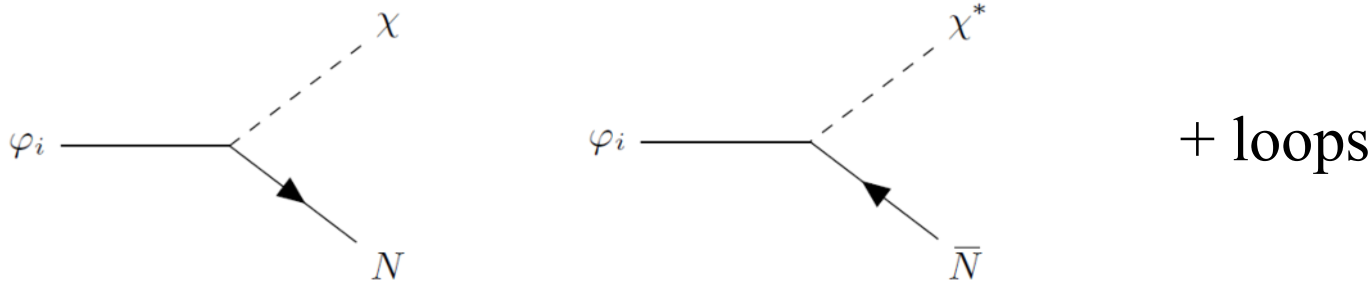

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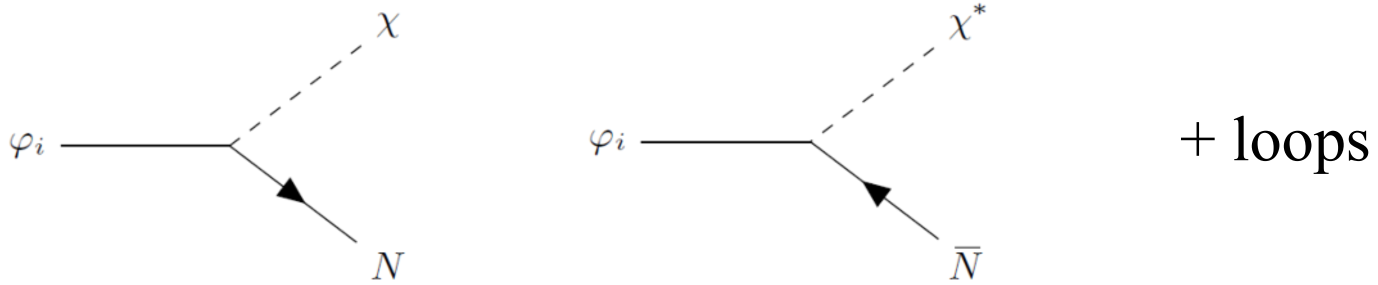

Bonus: χ is absolutely stable, due to the conservation of baryon number.

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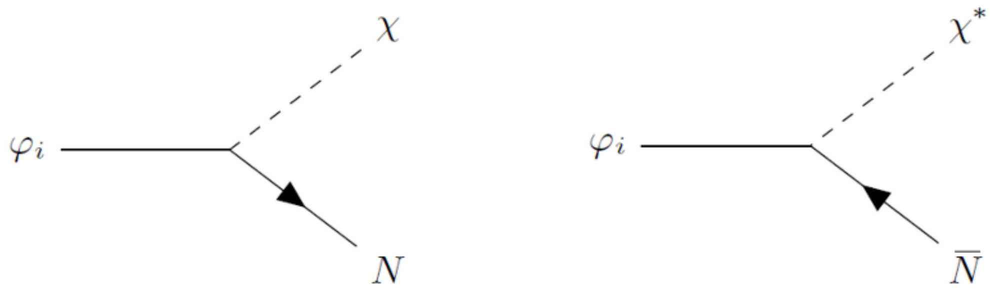

+ loops

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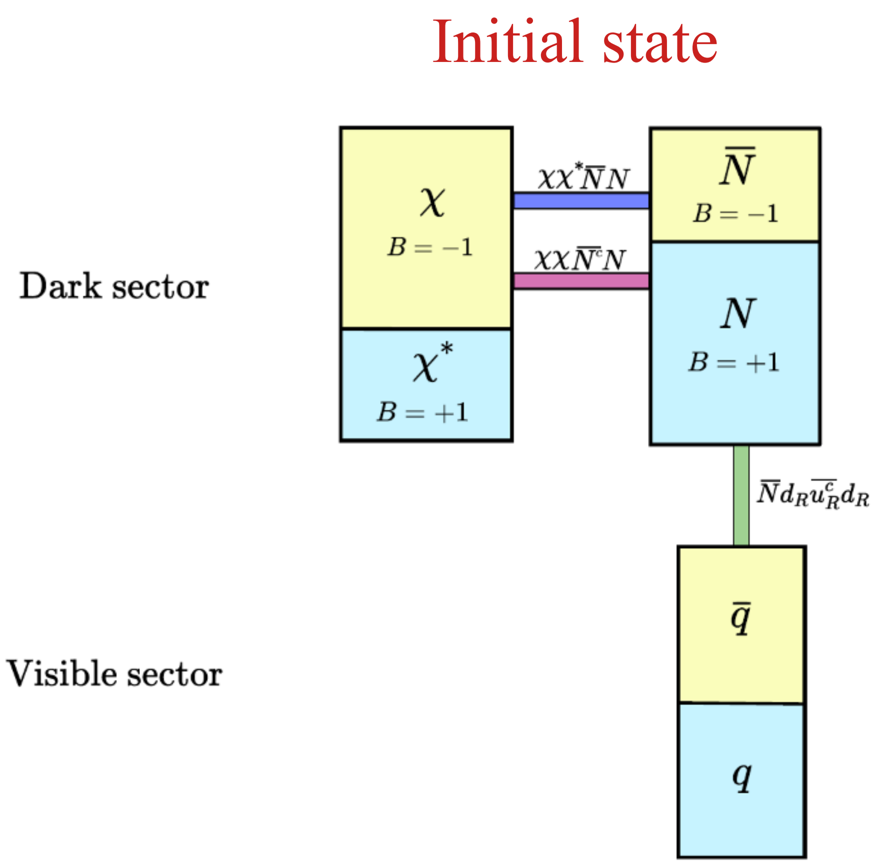
quark-antiquark asymmetry ⟺ **dark matter stability**

A simple scenario



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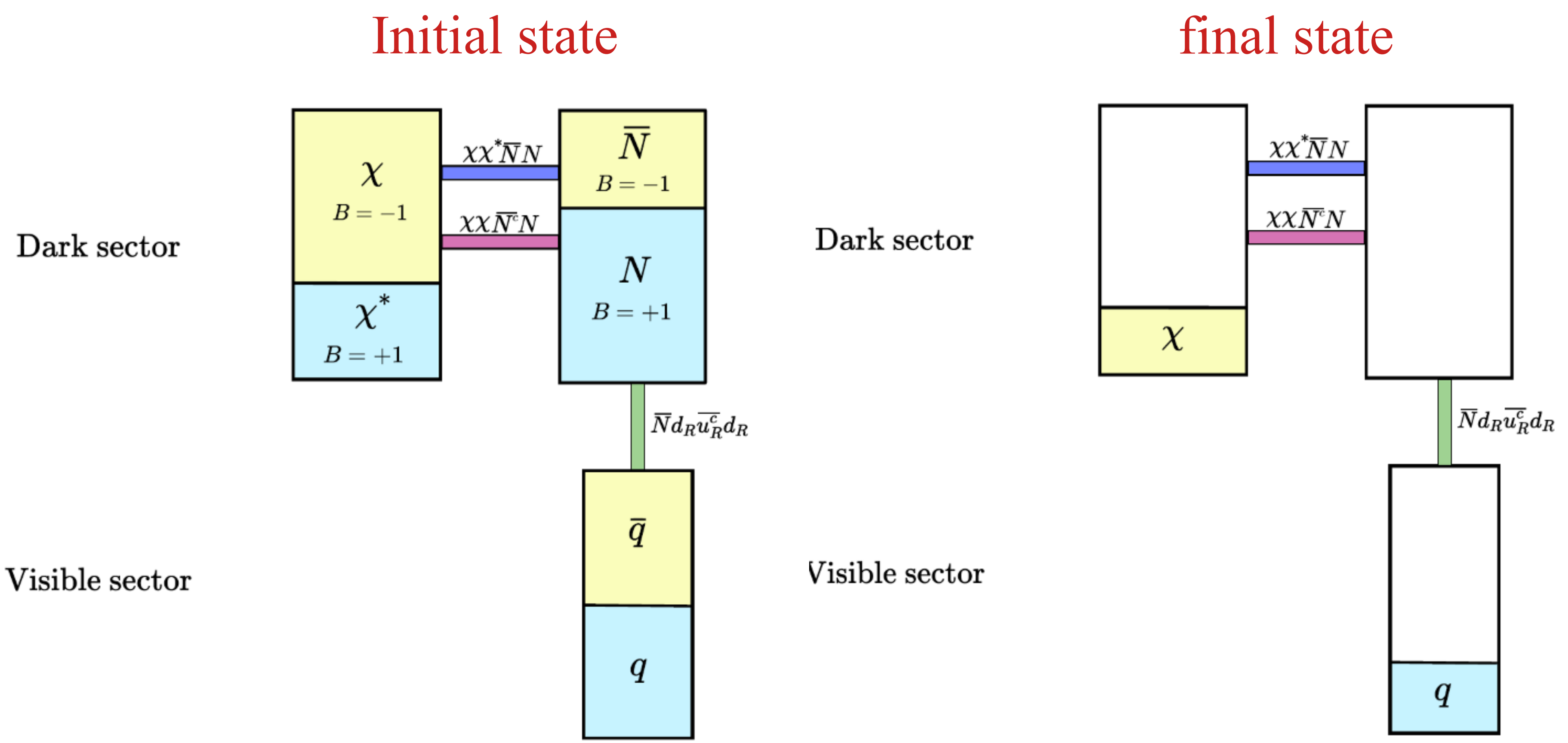
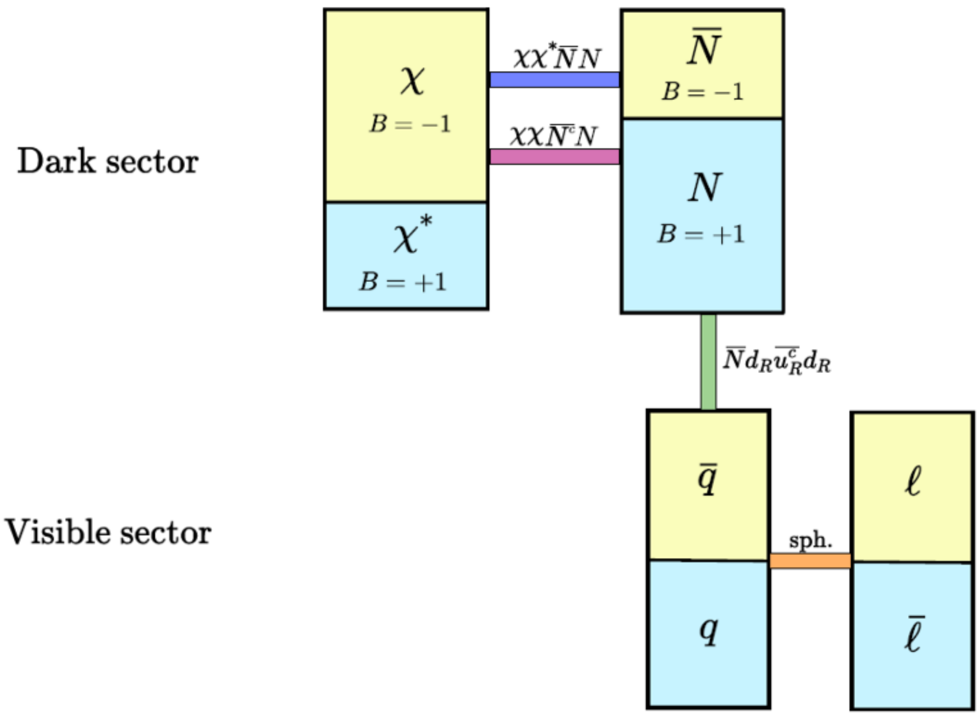


A more refined scenario

Initial state



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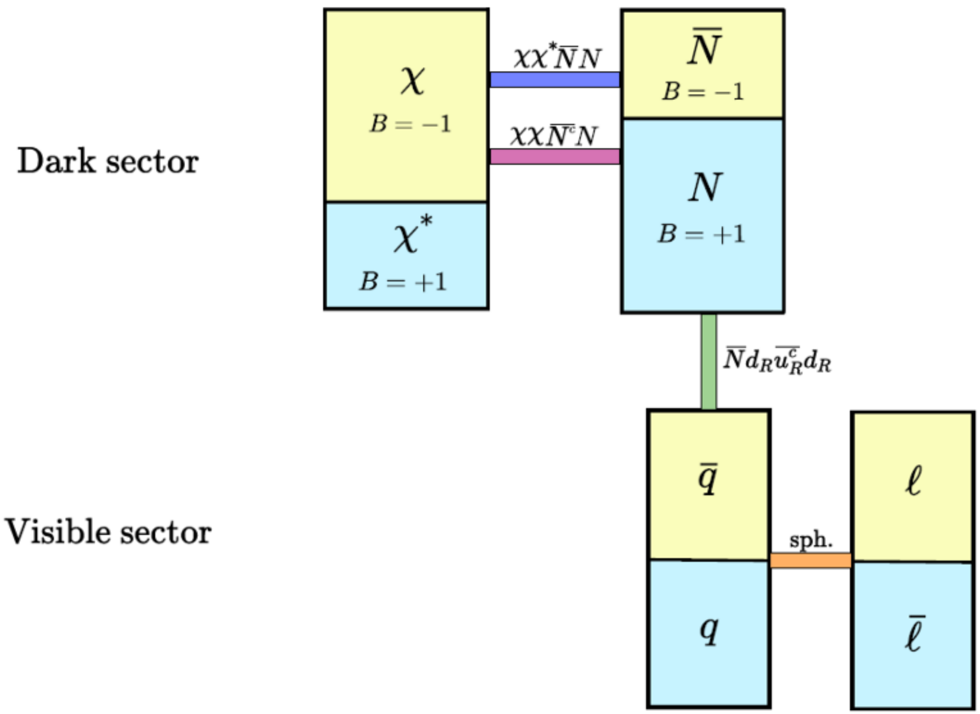

Consider for simplicity:

- 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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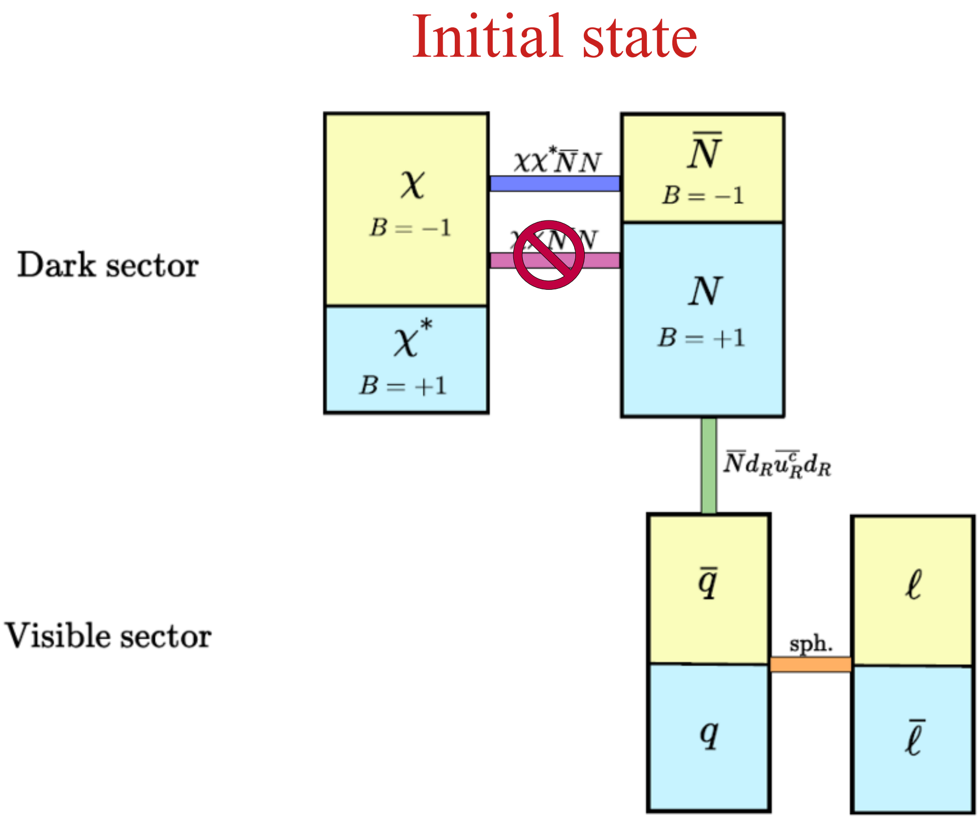

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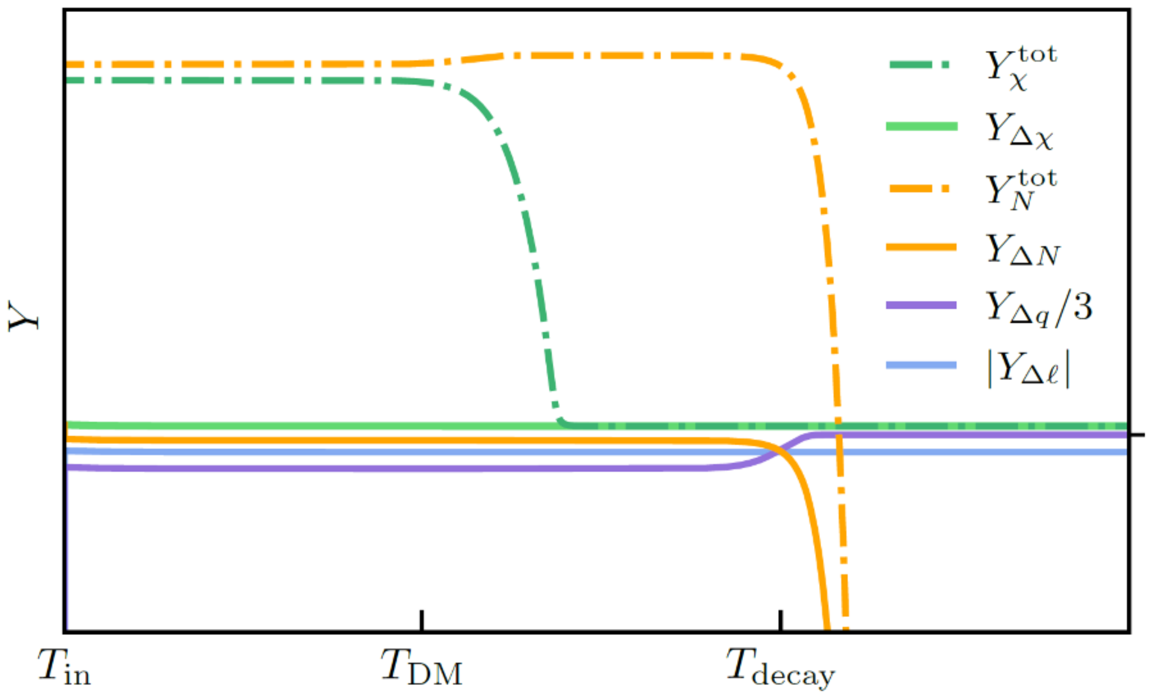
A more refined scenario

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



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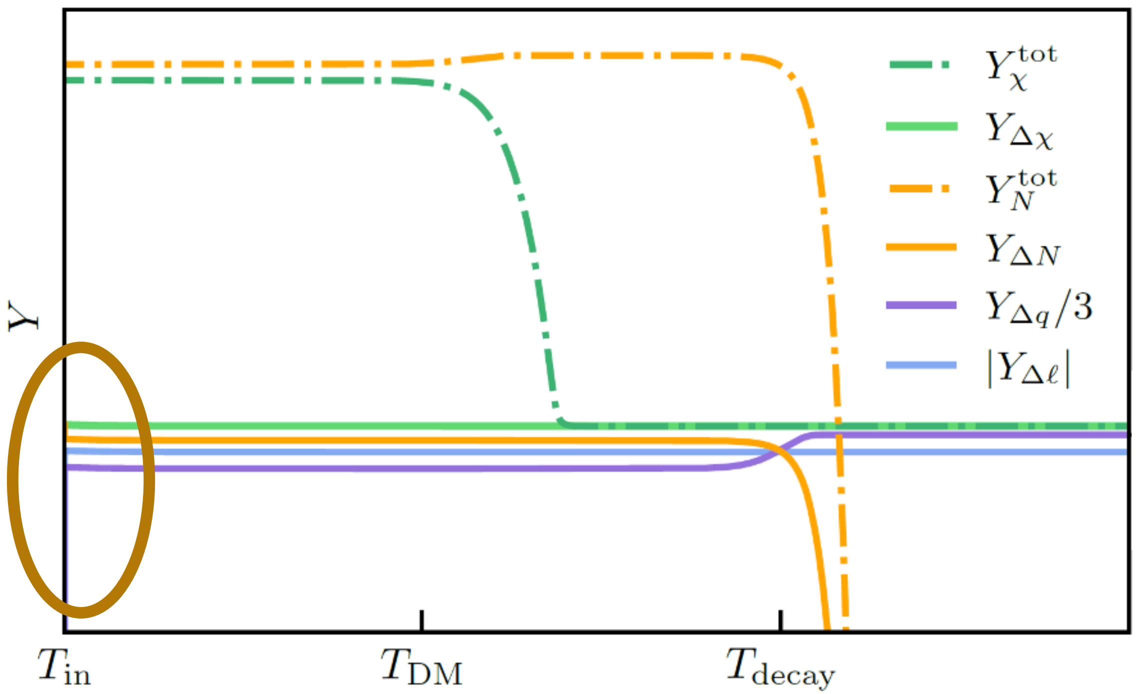
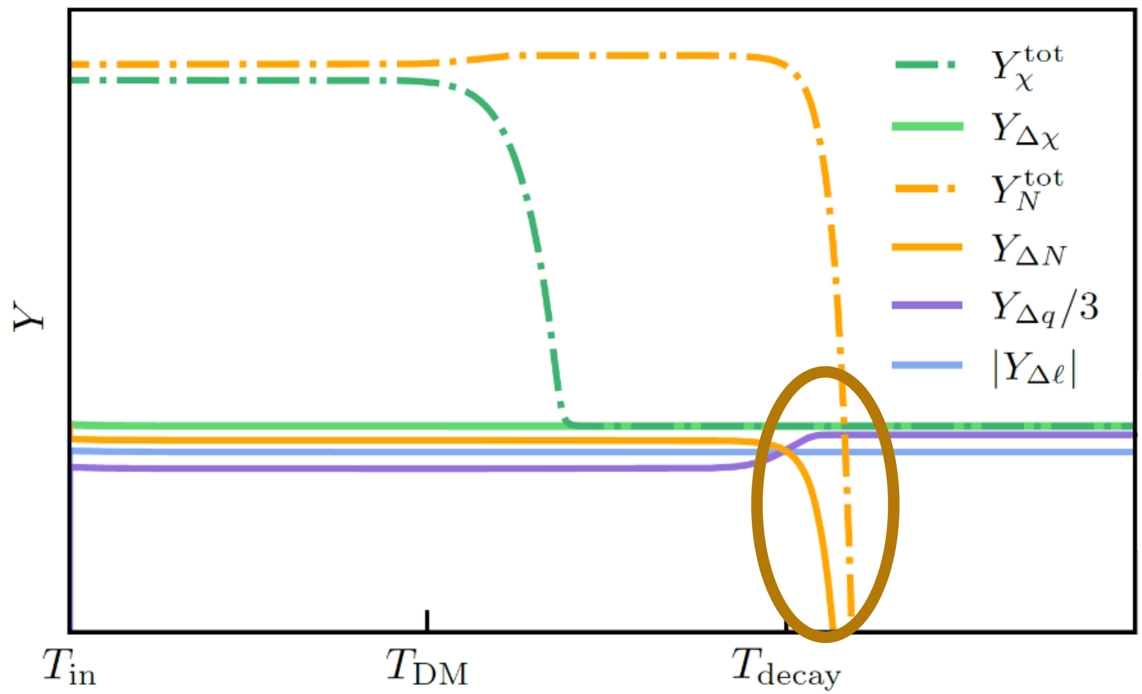


The asymmetry in N is quickly transmitted to the quark sector via scatterings $N\bar{d} \leftrightarrow ud, \;\; N\bar{u} \leftrightarrow dd$

$$Y_{\Delta N}(T) = \frac{11}{122} Y_{\Delta N}^{\rm in},$$
$$Y_{\Delta q}(T) = \frac{54}{61} Y_{\Delta N}^{\rm in},$$
$$Y_{\Delta \ell}(T) = -\frac{75}{122} Y_{\Delta N}^{\rm in}.$$

A more refined scenario



The decay $N \to udd$ 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

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

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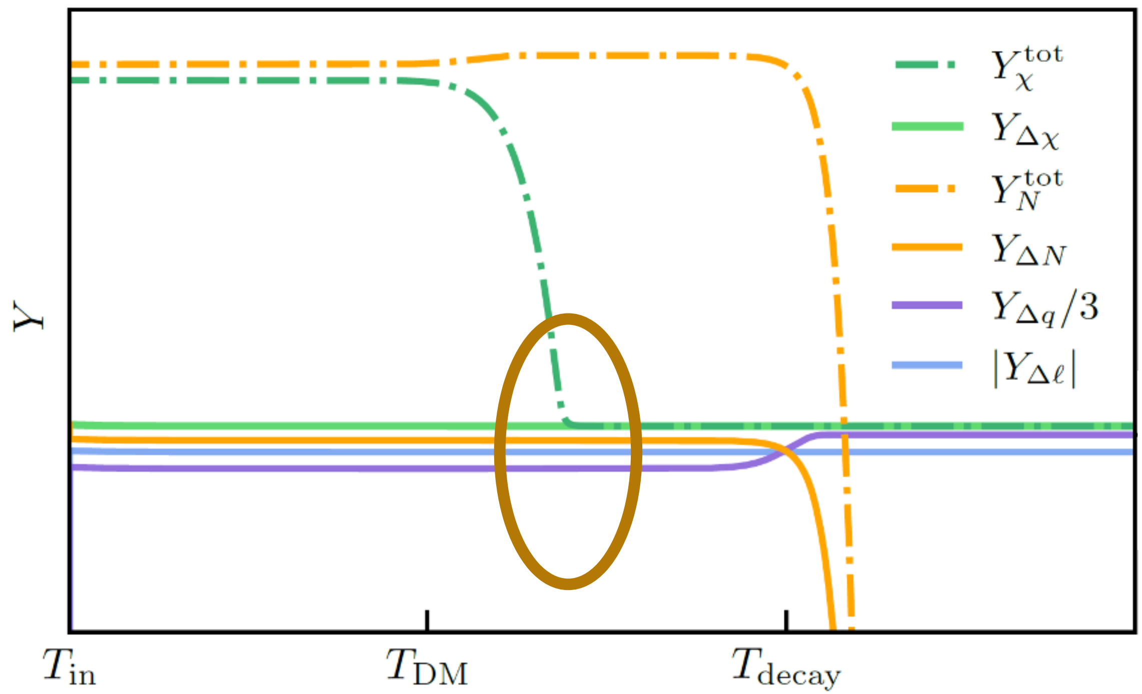
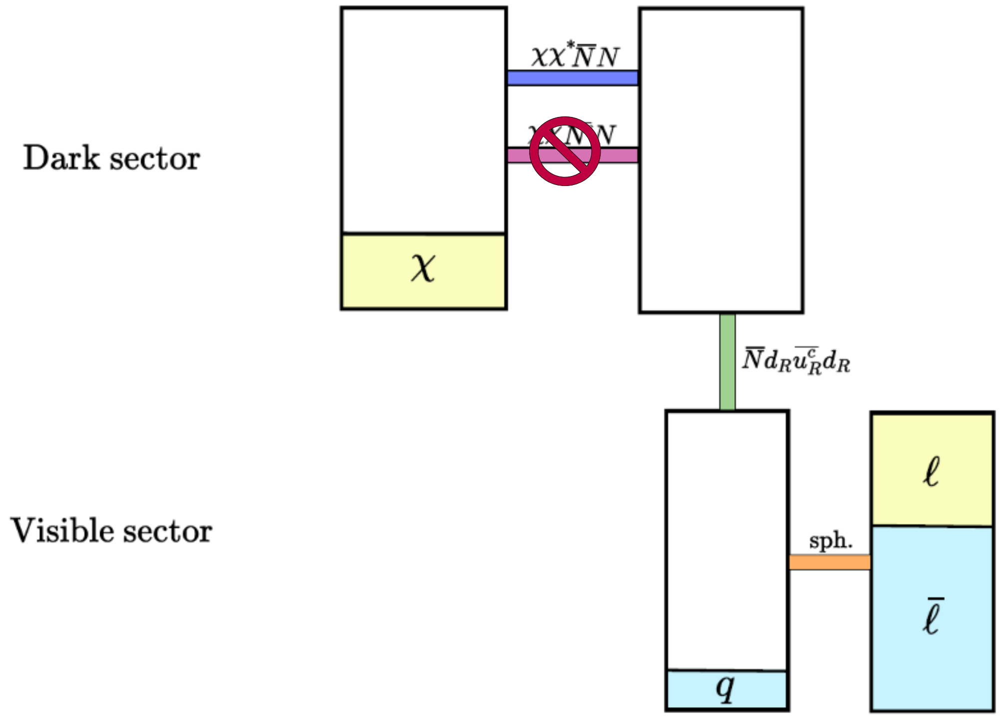


Freeze-out of $\chi\chi^* \to N\bar{N}$

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

A more refined scenario

Final state, when all χ^* are annihilated



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

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

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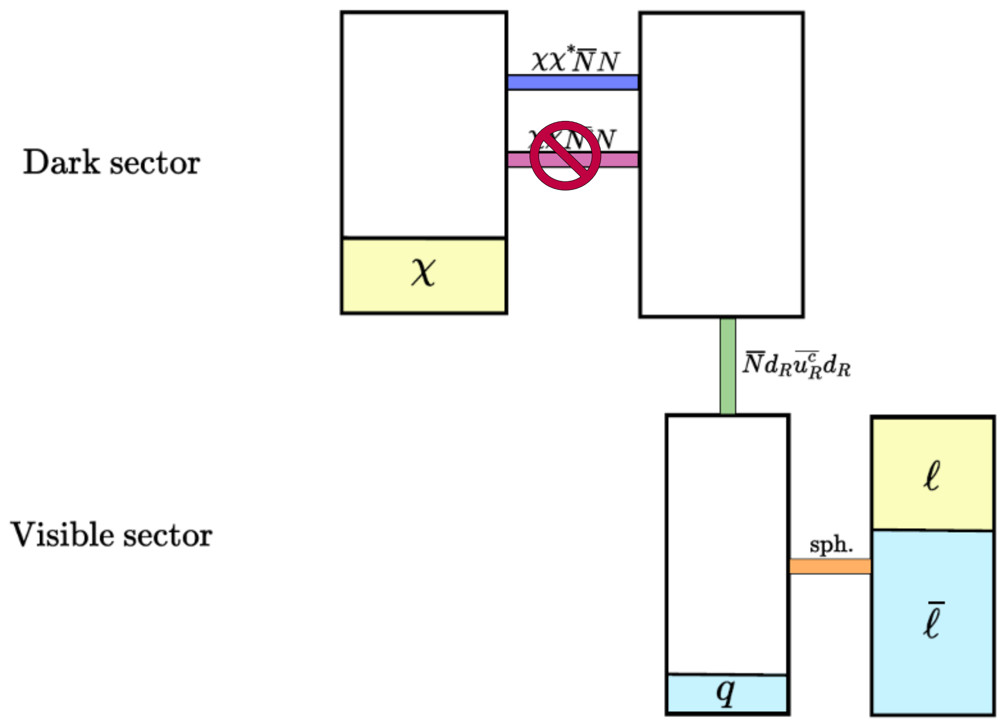

$$\Omega_{\mathrm{DM},0}h^2 \simeq 2.8 \times 10^8 \, Y^{\mathrm{in}}_{\Delta N} \frac{m_\chi}{\mathrm{GeV}} .$$

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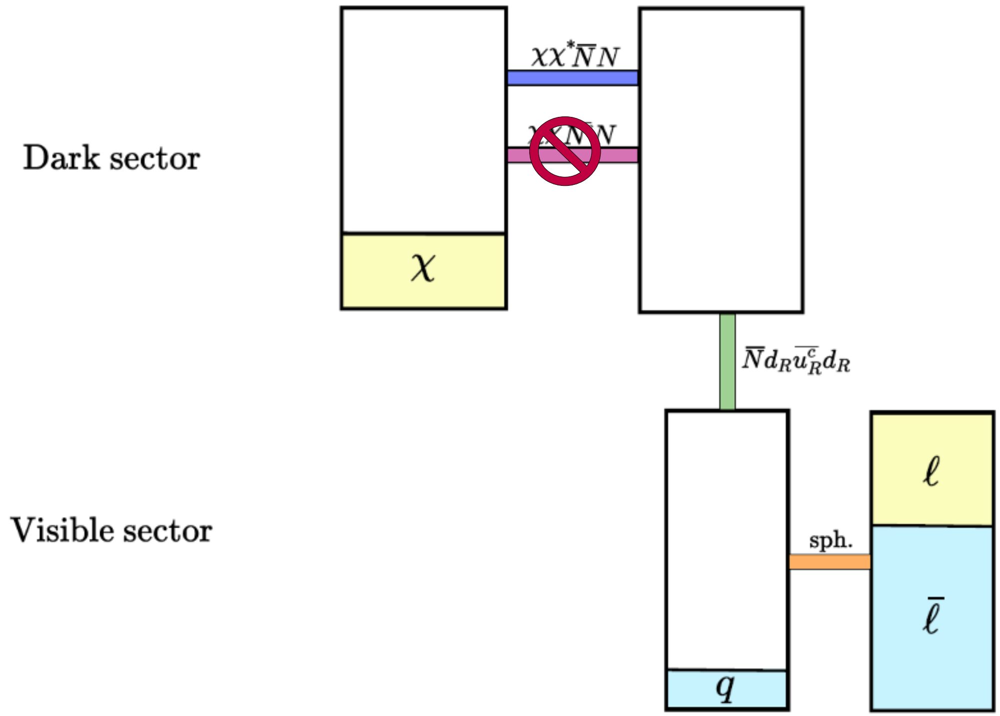
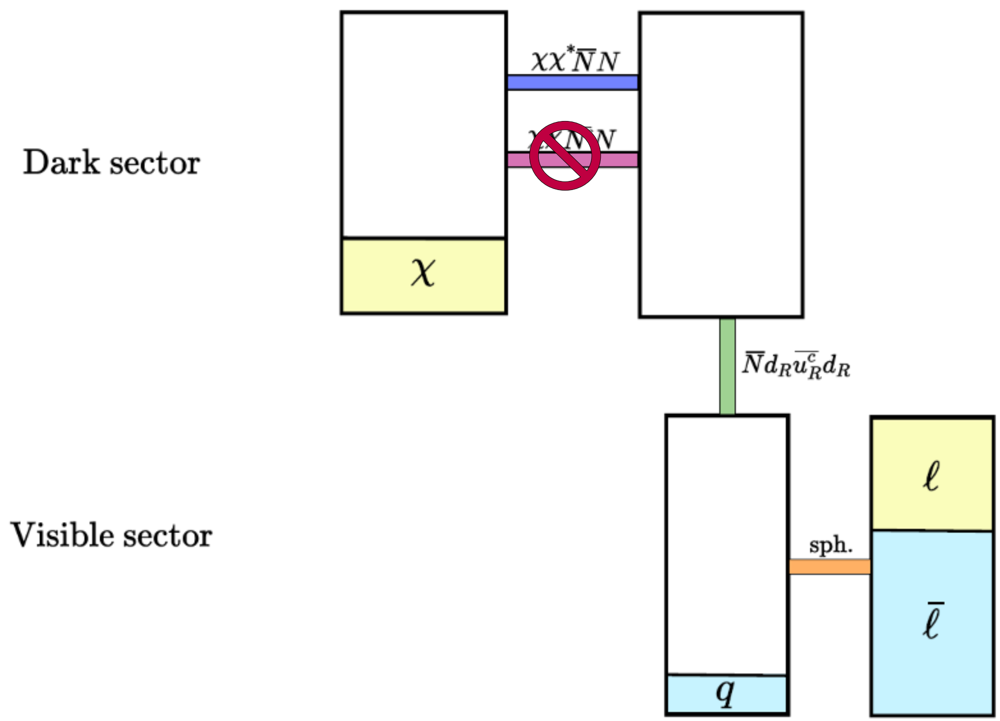


$$\Omega_{\rm DM,0}h^2 \simeq 2.8\times 10^8\, Y^{\rm in}_{\Delta N}\,\frac{m_\chi}{\rm GeV}.$$

$$Y_{\Delta q,0} = \tfrac{141}{122} Y^{\rm in}_{\Delta N},$$

A more refined scenario

Final state, when all χ^* are annihilated



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

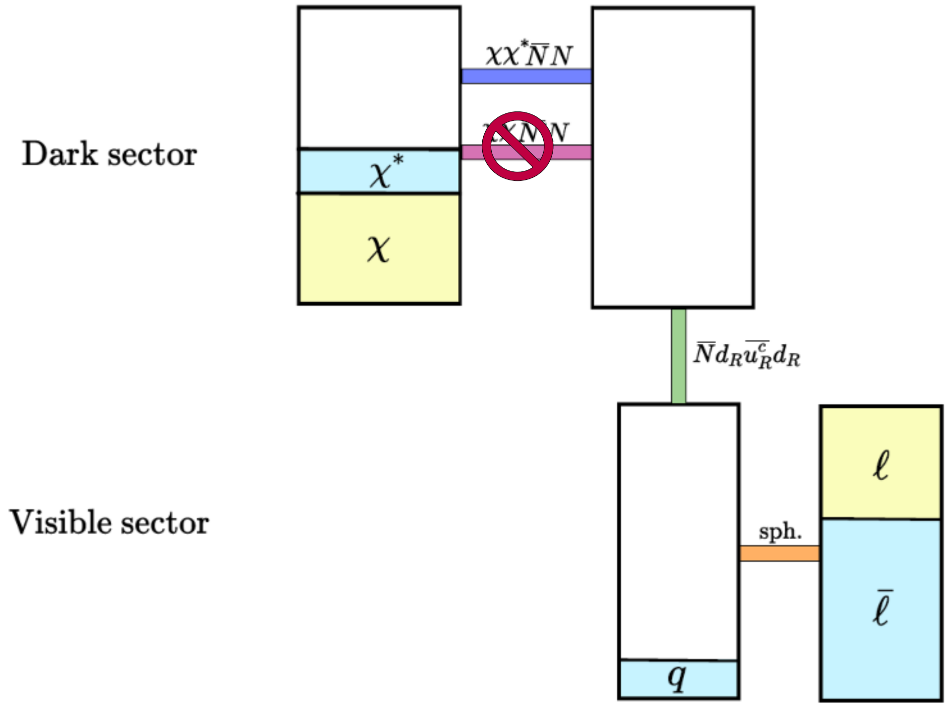
$$Y_{\Delta q,0} = \tfrac{141}{122} Y^{\rm in}_{\Delta N},$$

$$Y^{\rm in}_{\Delta\chi} \simeq 2.3 \times 10^{-10},$$

$$m_\chi \simeq 1.9\,{\rm GeV}.$$

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

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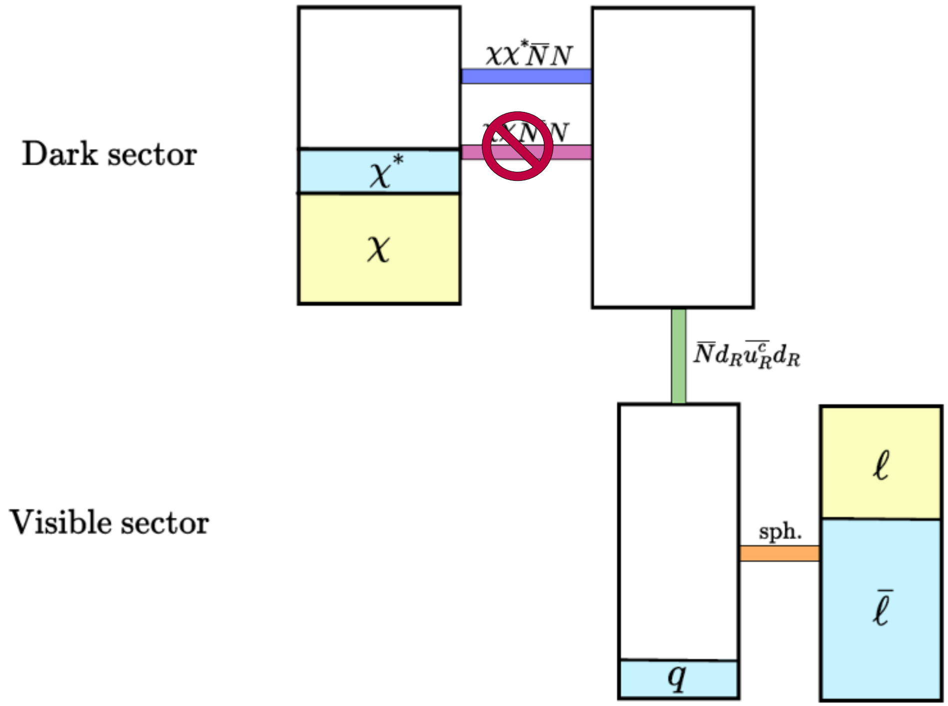

$$\Omega_{\rm DM,0}h^2 \gtrsim 2.8\times 10^8\, Y^{\rm in}_{\Delta N}\,\frac{m_\chi}{\rm GeV}\,.$$

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

$$Y^{\rm in}_{\Delta\chi} \simeq 2.3\times 10^{-10}$$

$$m_\chi \lesssim 1.9\,{\rm GeV}$$

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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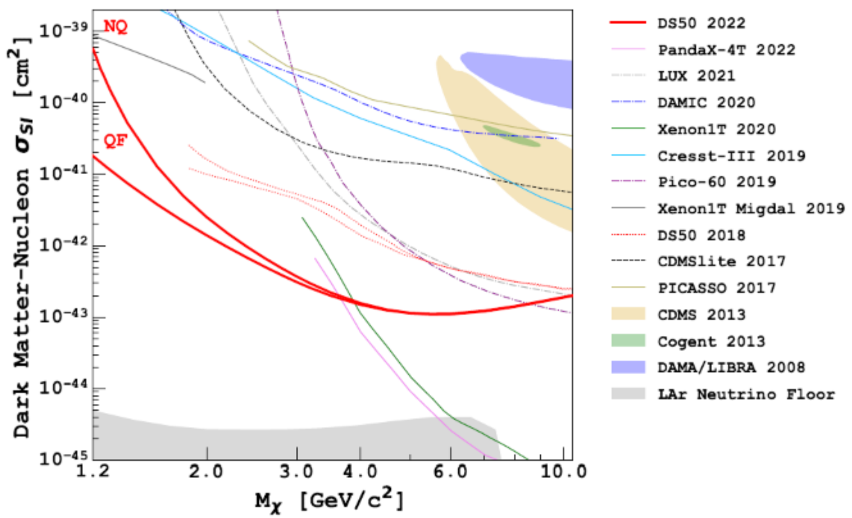

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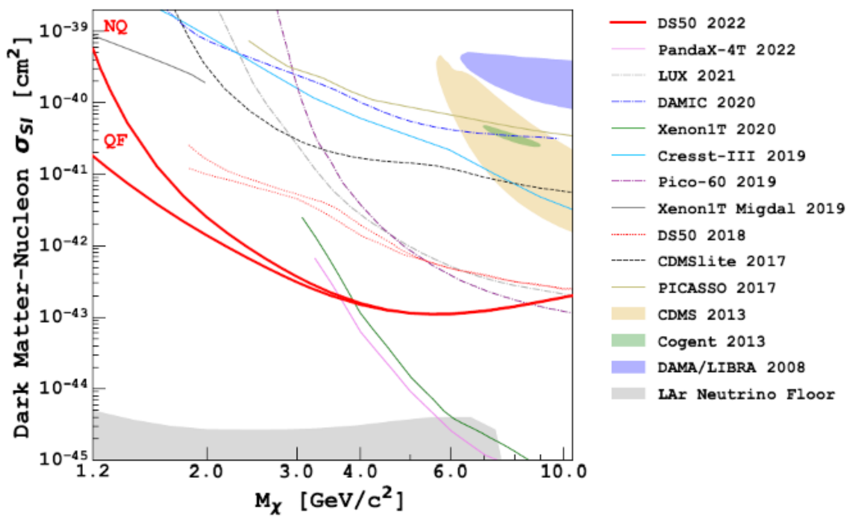

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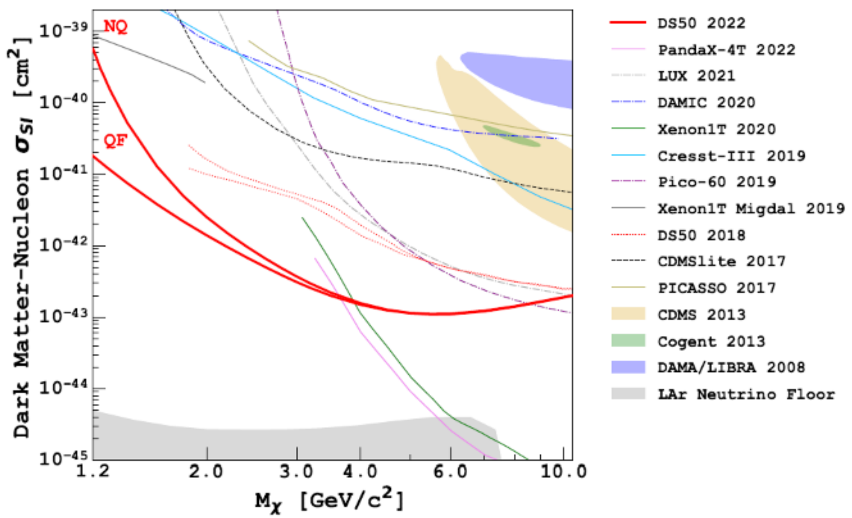

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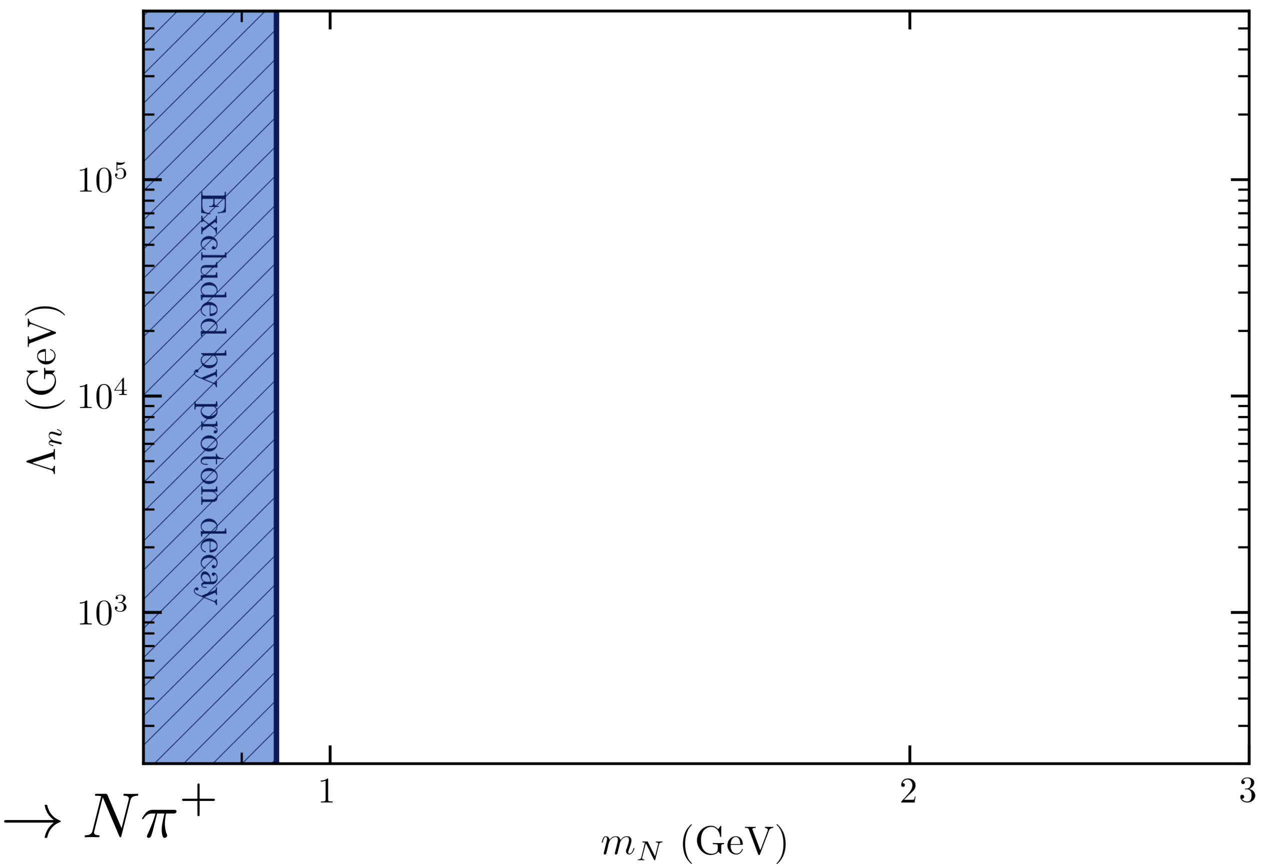
- If DM partially asymmetric, indirect detection signals.

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 $\frac{1}{\Lambda_n^2}\overline{N}d_R\,\overline{u^c_R}d_R$



$p \to N\pi^+$

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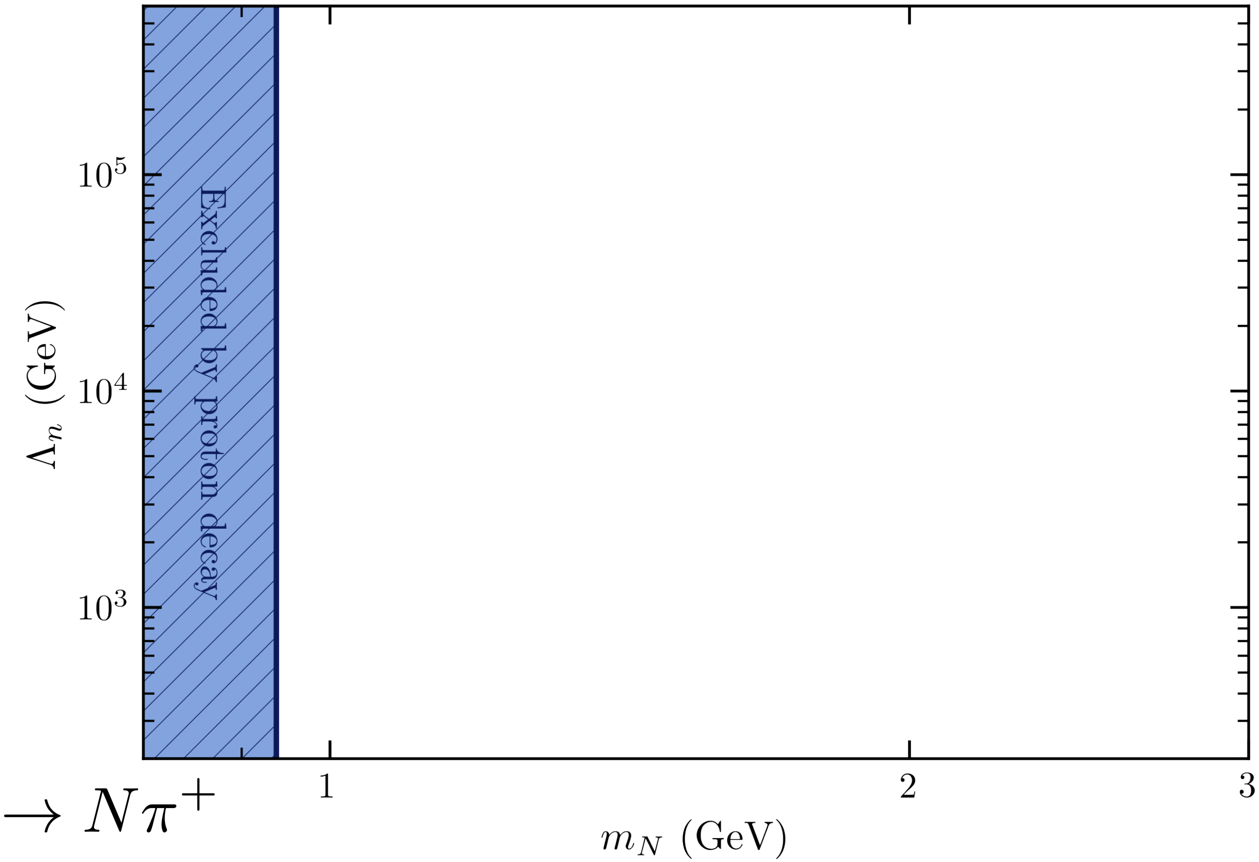

$p \to N\pi^+$

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

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

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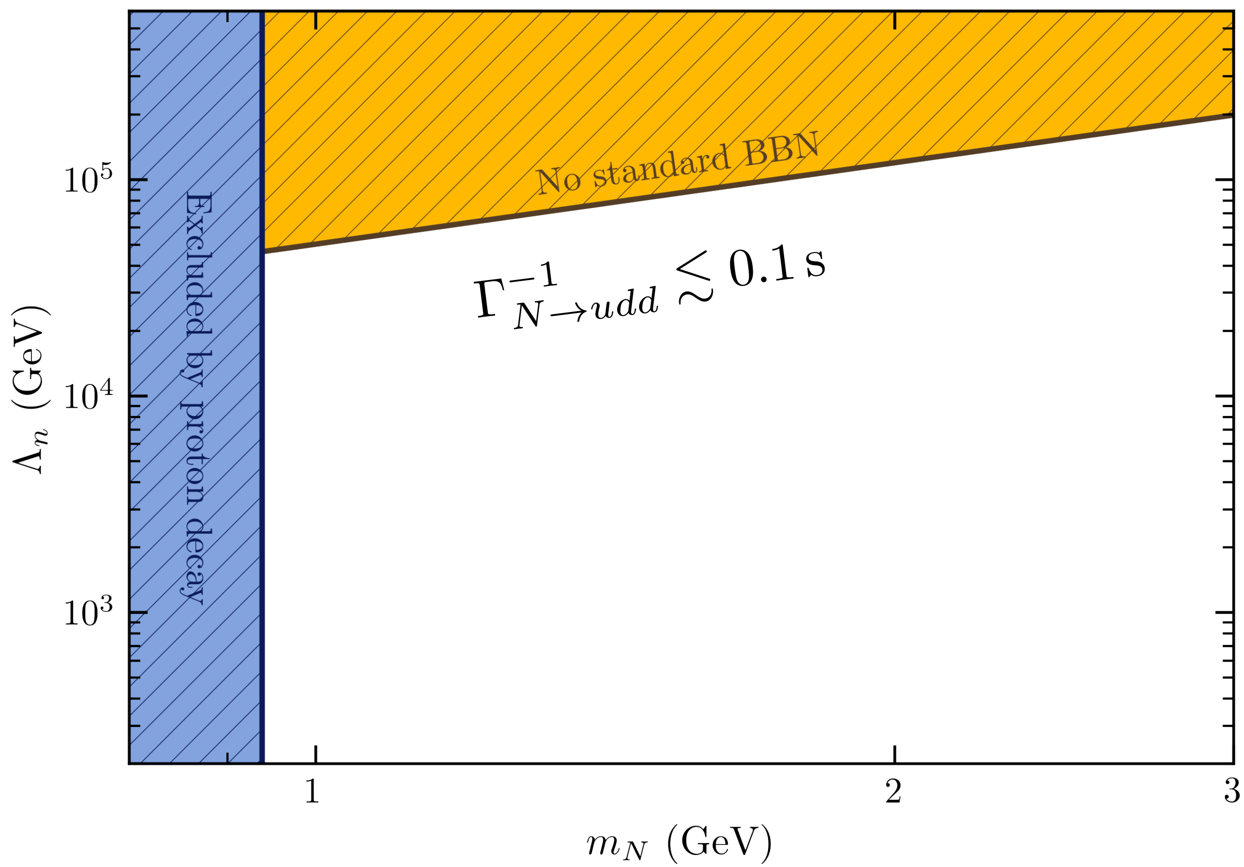

$$\Gamma^{-1}_{N\to udd} \approx 1.6 \text{ s} \left(\frac{\Lambda_n}{10^5 \text{ GeV}}\right)^4 \left(\frac{\text{GeV}}{m_N}\right)^5,$$

Experimental tests

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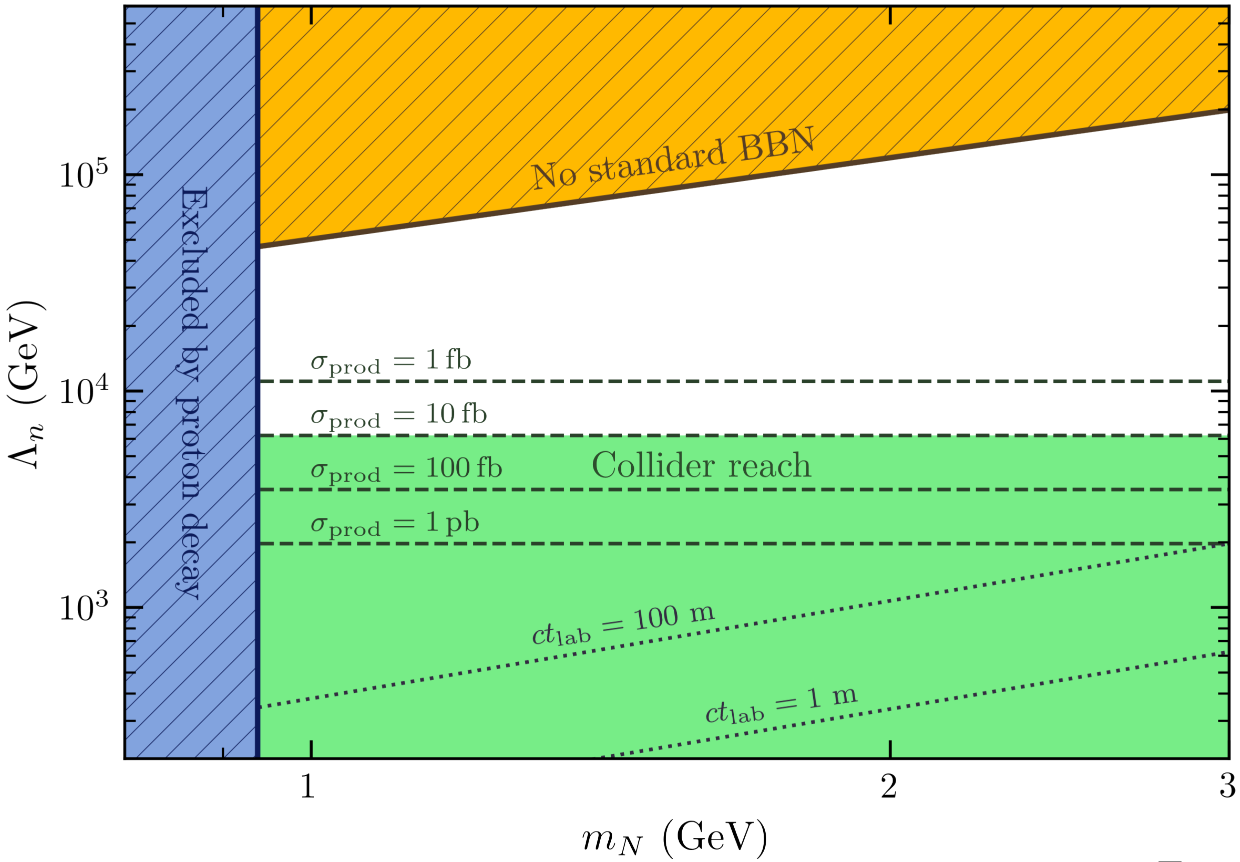

N production in pp collisions through $ud \to N\bar{d}, dd \to N\bar{u}$

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

Experimental tests

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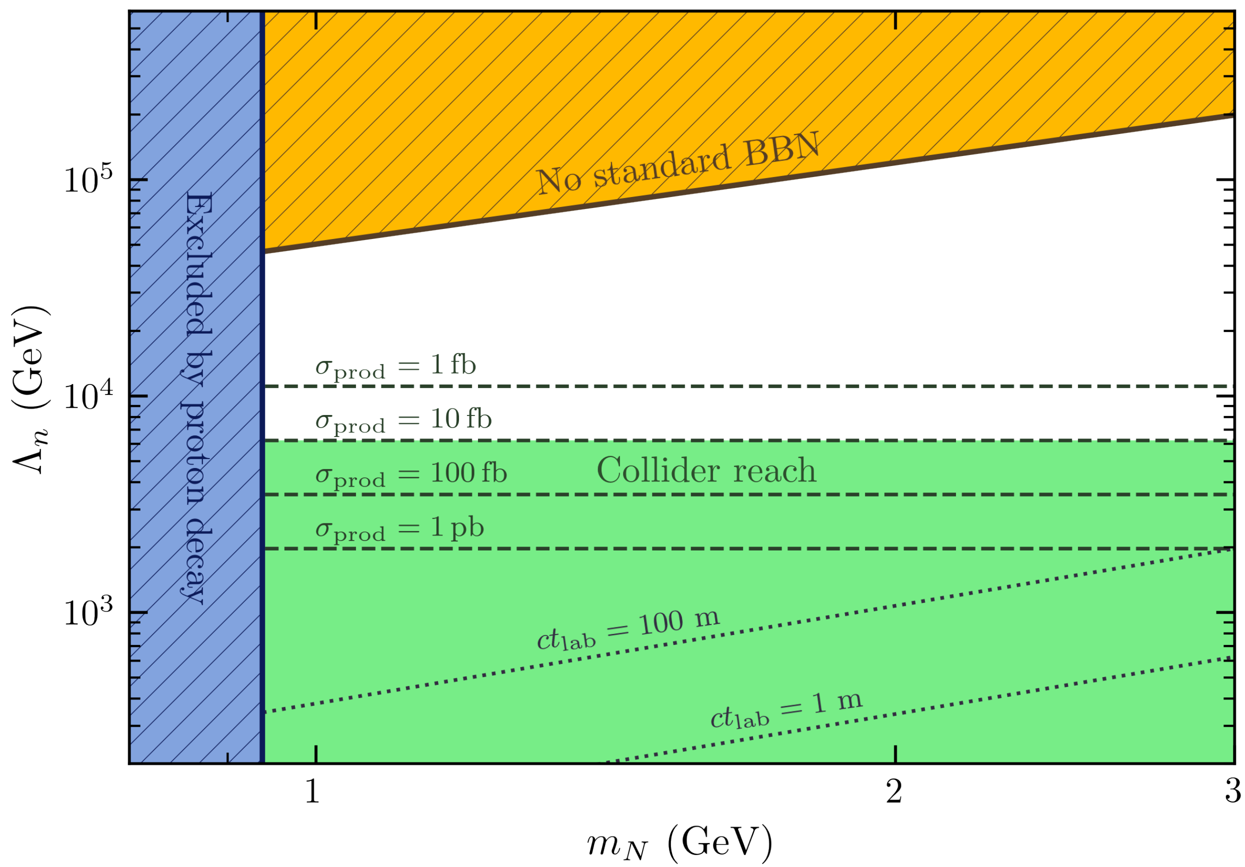

- The EFT may break down. Additional signatures from the production of the mediator.
- These constraints are not valid for different baryon-portals, e.g. the "charmed-Omega" portal $\overline{N}s_R\overline{c^c_R}s_R$
- No search exists on baryon → meson + invisible

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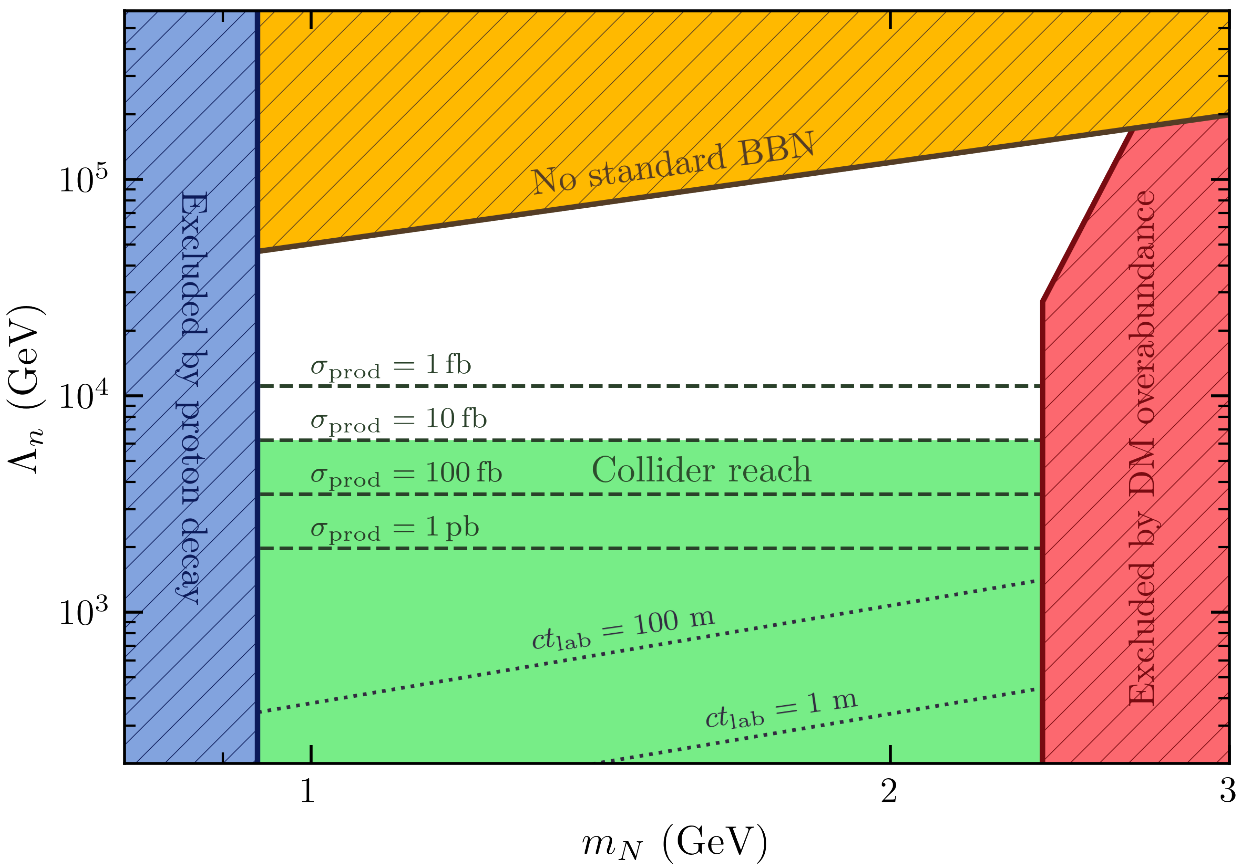

The rate of annihilations $\chi\chi^* \to N\overline{N}$ must be sufficiently efficient at freeze-out.

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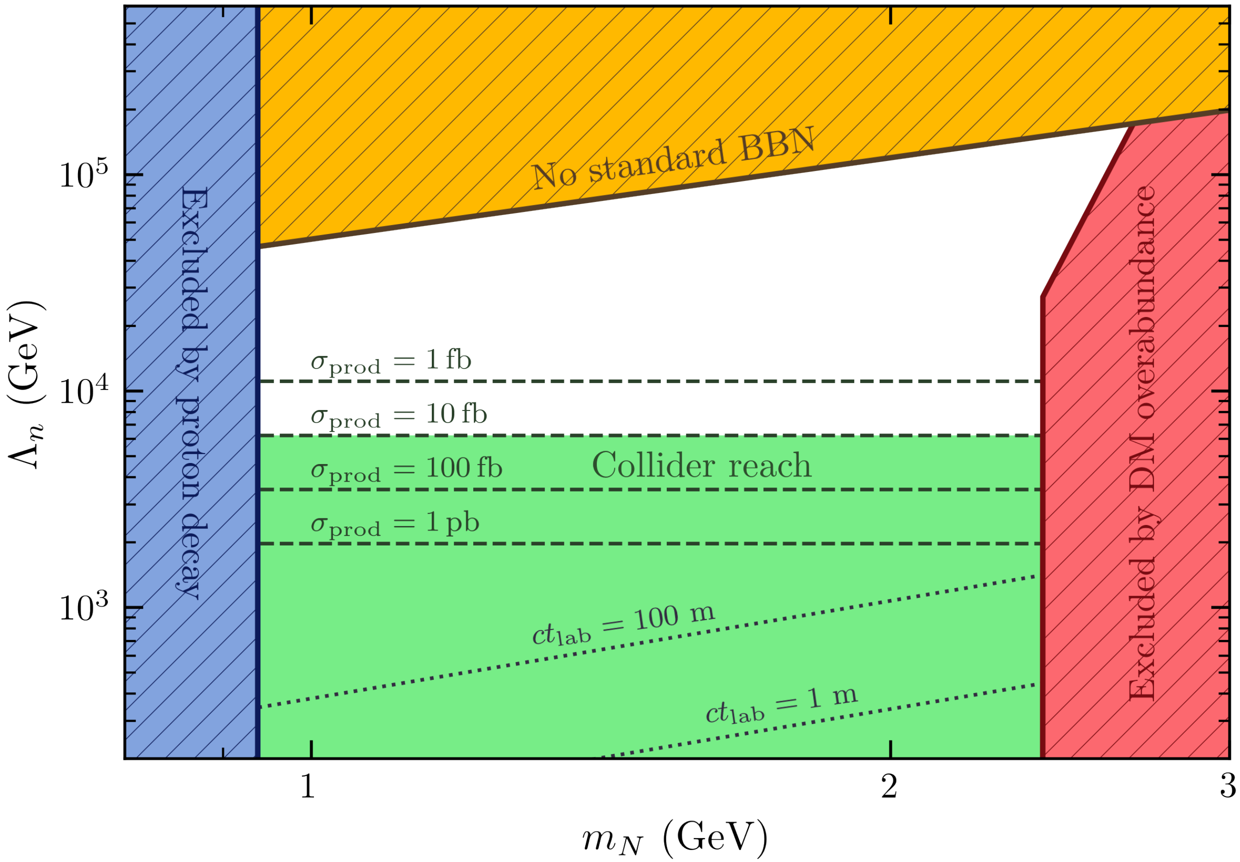
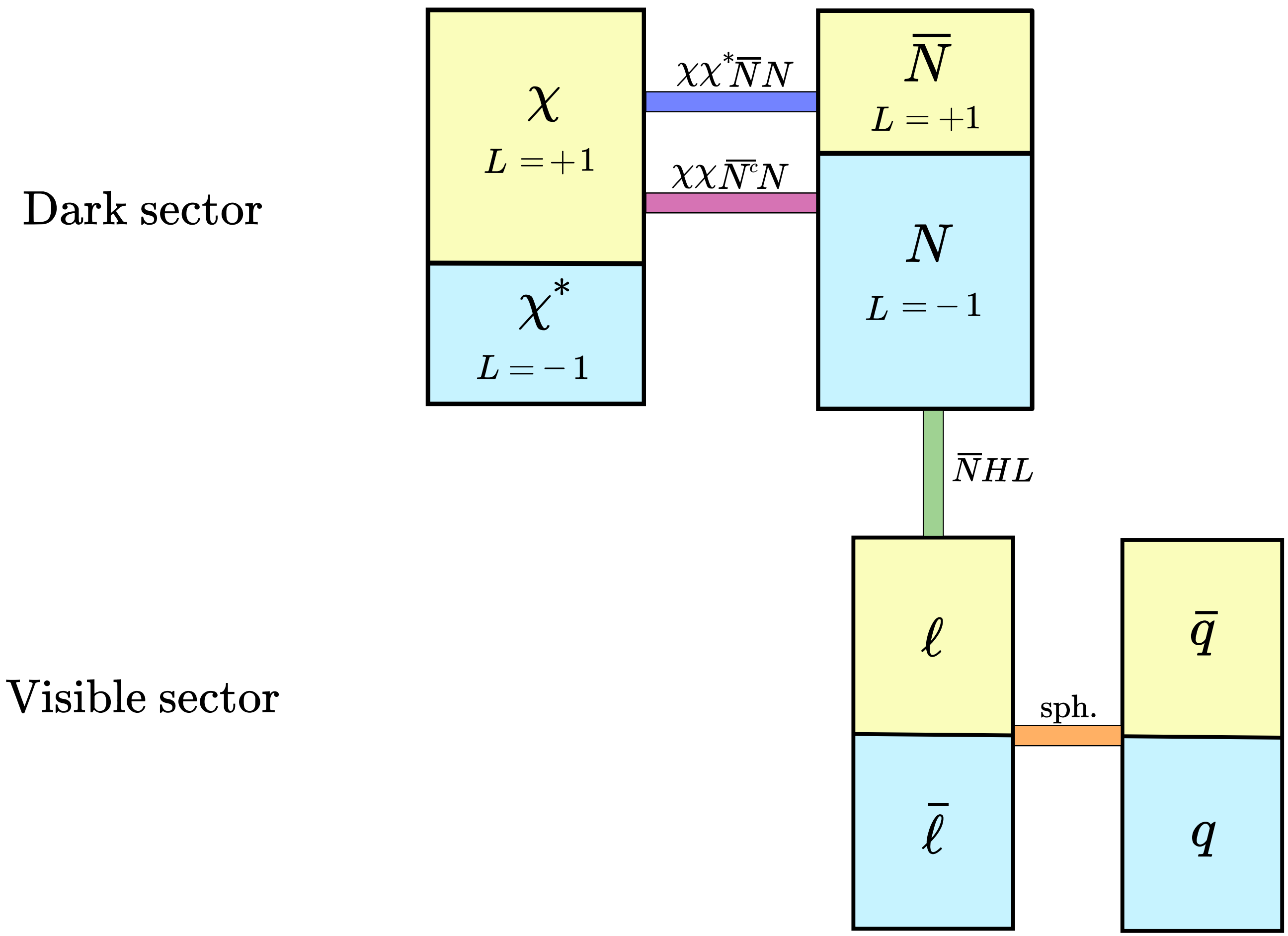


The rate of annihilations $\chi\chi^* \to N\overline{N}$ must be sufficiently efficient at freeze-out.

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

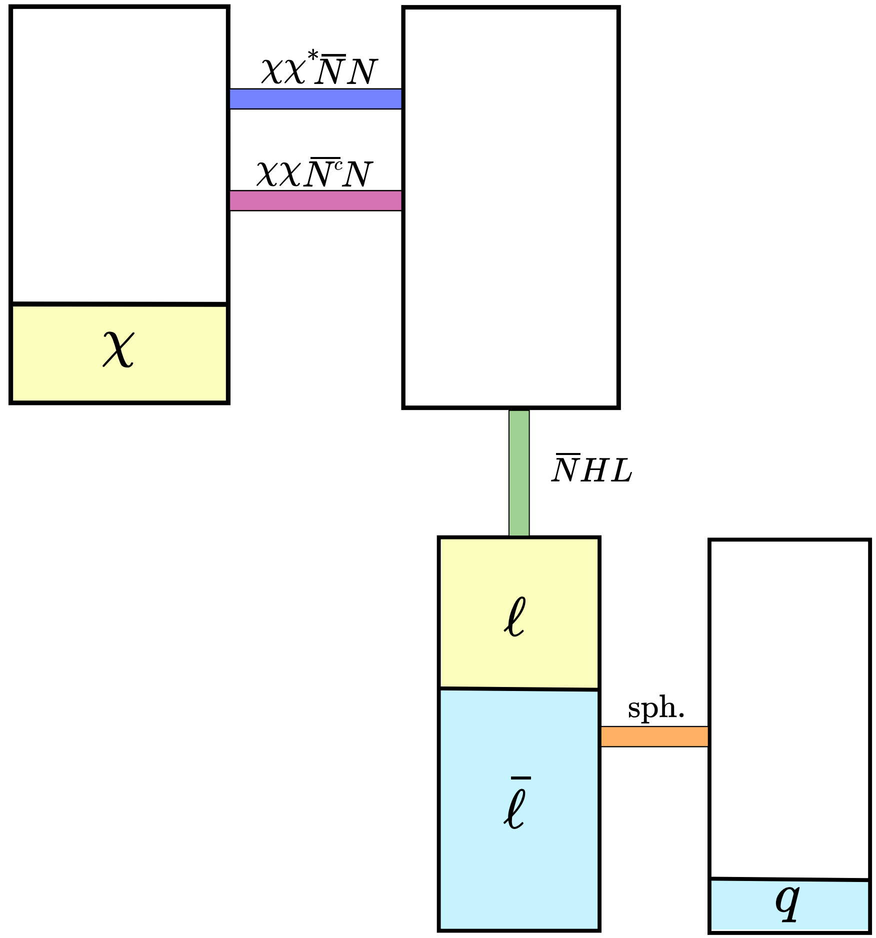
A leptonic portal



A leptonic portal

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.