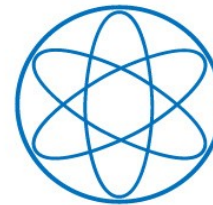
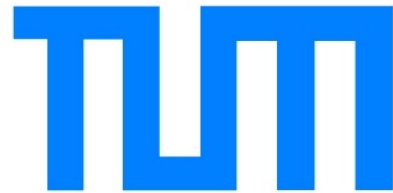


Connecting the baryons to the dark matter of the Universe

Alejandro Ibarra

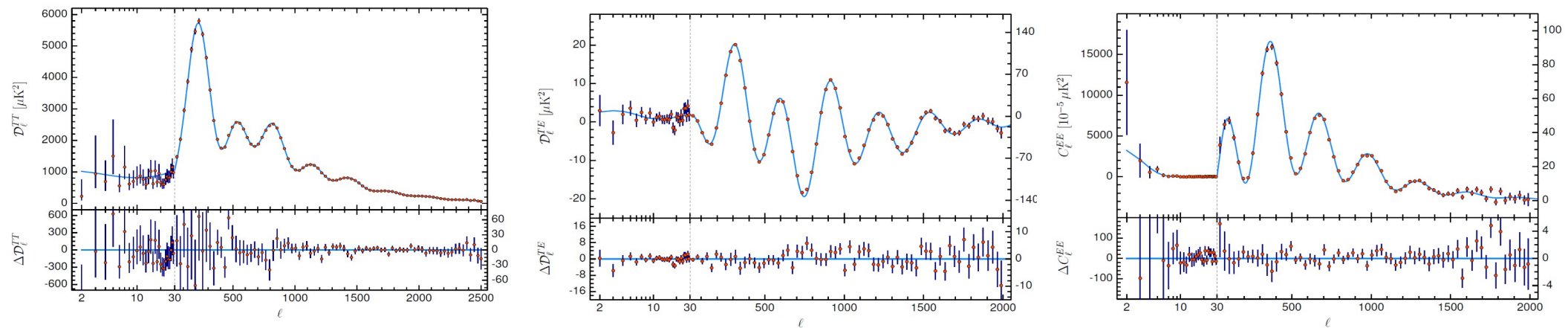
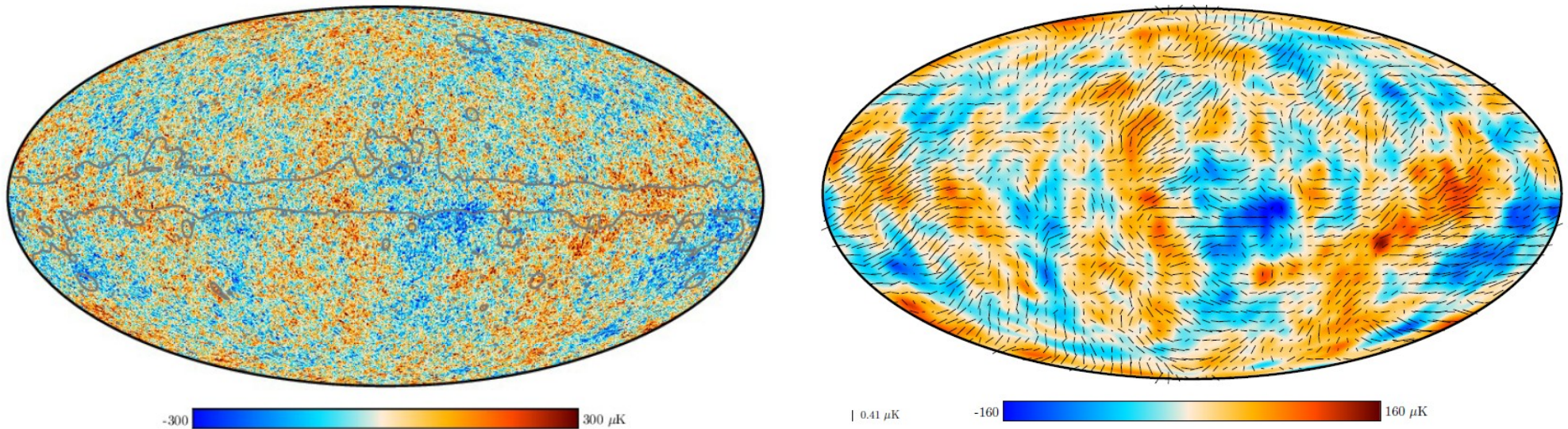


In collaboration Mar Ciscar, Jérôme Vandecasteele and Nick Proff

Summer Institute'26
Fujiyoshida
August 2026

Introduction

The Standard Model of Cosmology is well grounded physically and can explain with great accuracy a large number of cosmological data.



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Einstein field equations

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3D space homogeneous and isotropic

$$ds^2 = dt^2 - a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\Omega^2 \right)$$

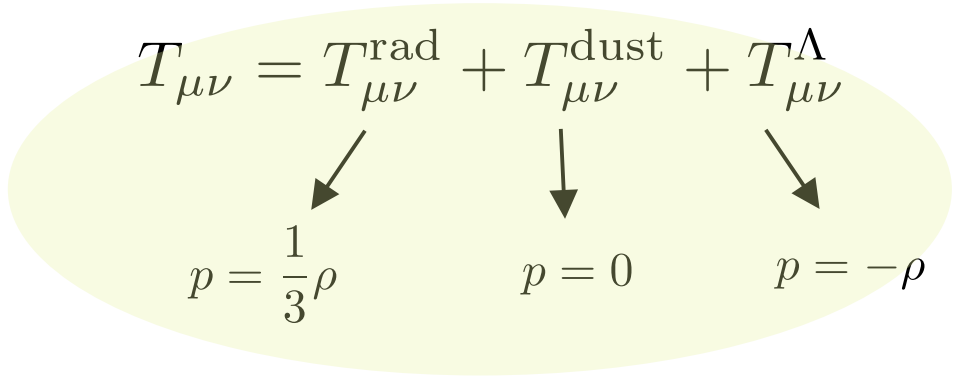
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$$p = \frac{1}{3}\rho$$

$$p = 0$$

$$p = -\rho$$

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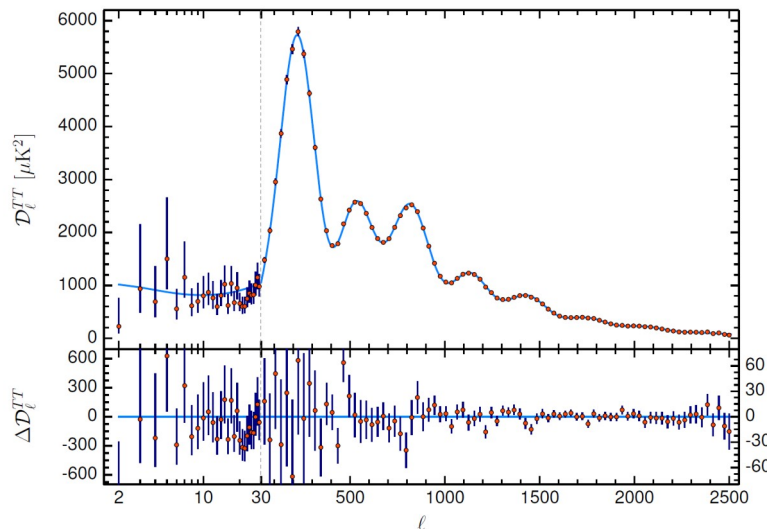
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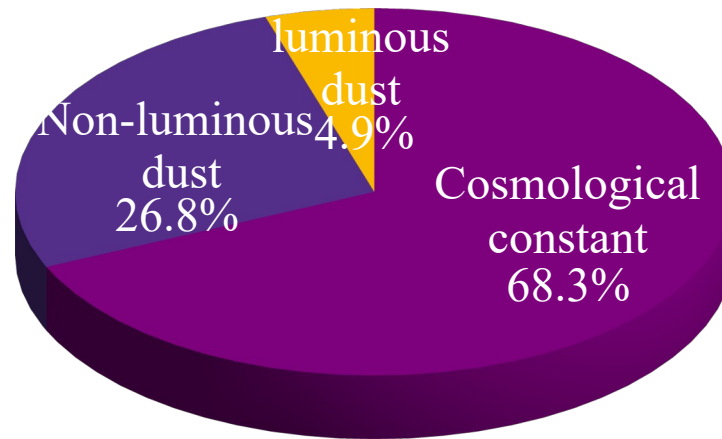
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$\swarrow$ $\downarrow$ $\swarrow$
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$$\begin{aligned} \rho^{\text{rad}} &\simeq 10^{-4} \rho_c \\ \rho^{\text{dust}} &\simeq 0.32 \rho_c \quad \begin{cases} \rightarrow 15\% \text{ luminous} \\ \rightarrow 85\% \text{ non-luminous} \end{cases} \\ \rho^{\Lambda} &\simeq 0.68 \rho_c \\ \rho^{\text{tot}} &\simeq \rho_c \simeq 2 \times 10^{-26} \text{ kg/m}^3 \text{ (spatially flat)} \end{aligned}$$

Introduction



Λ CDM works very well, but it leaves many open questions:

- ☐ Why is the universe spatially flat?
- ☐ Why the density contributions from the luminous and non-luminous matter components are comparable?
- ☐ Why the density contributions from the matter components and the cosmological constant are comparable *today*?
- ☐ What are the cosmic fluids made of? Can they be described in terms of quantum fields?

A tale of two Standard Models

The Standard Model of Particle Physics

Quantum Field Theory

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

Three Generations of Matter (Fermions) spin 1/2

	I	II	III	
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
name →	u Left up Right	c Left charm Right	t Left top Right	g gluon
	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
Quarks	d Left down Right	s Left strange Right	b Left bottom Right	γ photon
	0 eV	0 eV	0 eV	91.2 GeV
	0	0	0	0
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z weak force
	0.511 MeV	105.7 MeV	1.777 GeV	>114 GeV
	-1	-1	-1	0
Leptons	e Left electron Right	μ Left muon Right	τ Left tau Right	H Higgs boson
				spin 0
				80.4 GeV
				± 1
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Bosons (Forces) spin 1

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The Standard Model of Particle Physics explains the radiation content of our Universe.

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Many particles, but none of them non-luminous *and* cosmologically stable *and* producing a pressureless fluid.

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H	0	0
Higgs boson		

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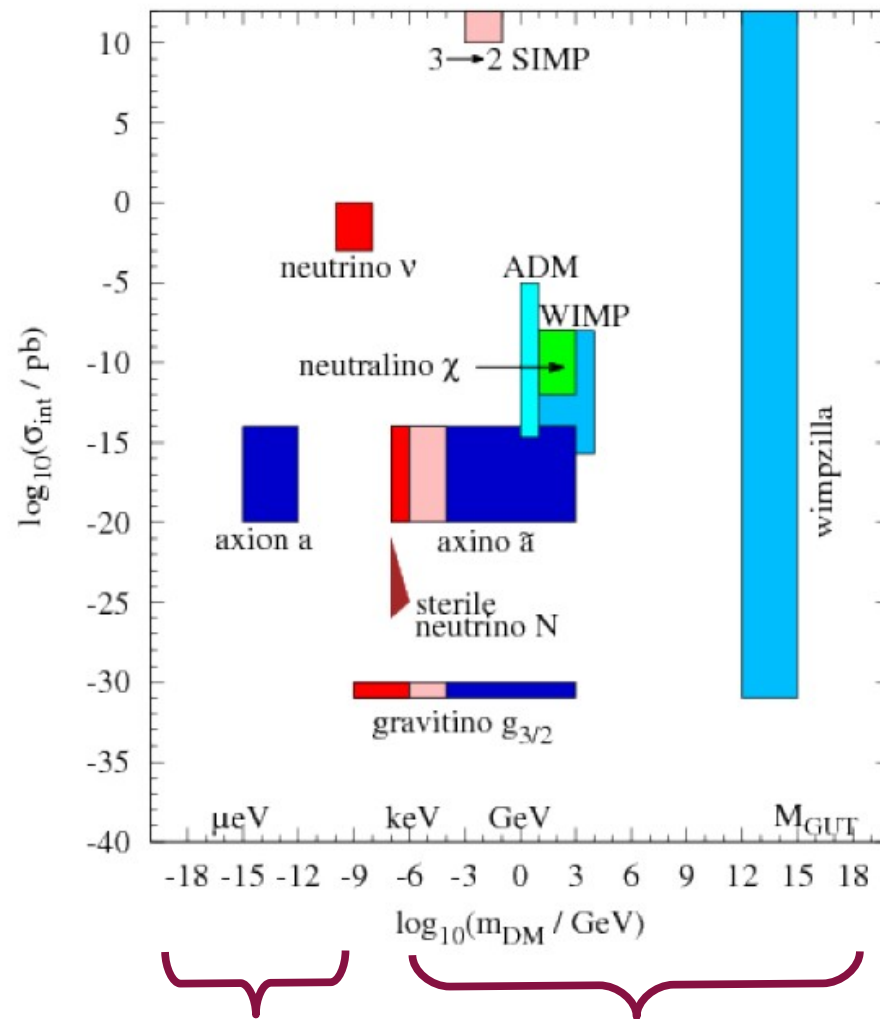
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Evidence for Physics beyond the Standard Model

A tale of two Standard Models

The dark matter zoo



Naturally long-lived
on cosmological
time-scales

Stability typically requires
an exact (or approximately exact)
new symmetry.

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Bosons (Forces) spin 1

spin 0

H Higgs boson

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Not even close. There is no known particle generating a fluid with equation of state $p = -\rho$

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II III

mass --
charge
name

Quarks

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171.2 GeV $\frac{2}{3}$ t top

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Bosons (Forces) spin 1

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The Standard Model leads to candidates for cosmologically stable luminous matter (protons, electrons, nuclei...)

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But where is the luminous *antimatter*??

A tale of two Standard Models

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

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

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

Baryogenesis

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Baryogenesis

All these conditions are fulfilled in the Standard Model, but not in sufficiently large amounts.

Evidence for Physics beyond the Standard Model

A tale of two Standard Models

Many extensions of the Standard Model have been proposed to explain baryogenesis, fulfilling the Sakharov conditions:

- Electroweak baryogenesis with extra scalar singlets/doublets.

Bochkarev, Kuzmin, Shaposhnikov '92,
Turok, Zadrozny '91,
Cline, Kainulainen Vischer '96

...

- Leptogenesis via the decay of heavy right-handed neutrinos

Fukugita, Yanagida '86

- Baryogenesis via neutrino oscillations

Akhmedov, Rubakov, Smirnov '98

- Affleck-Dine baryo/leptogenesis

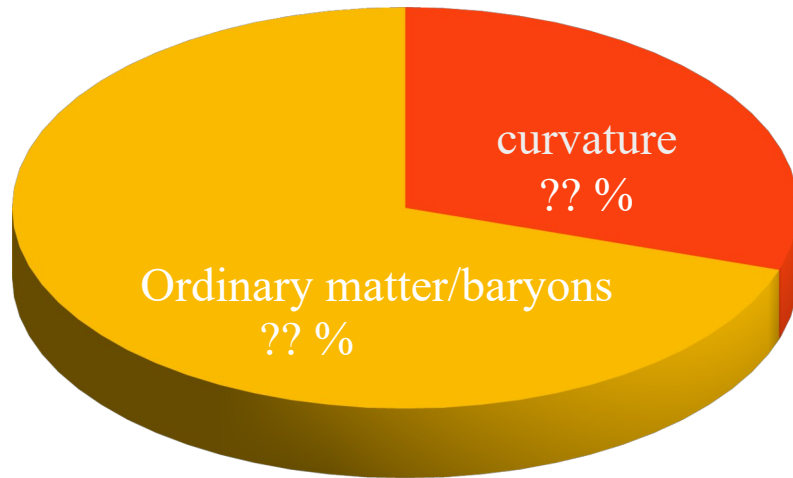
Affleck, Dine '85

- Many more

... however without a *direct* connection to other puzzles in cosmology (e.g. the dark matter puzzle)

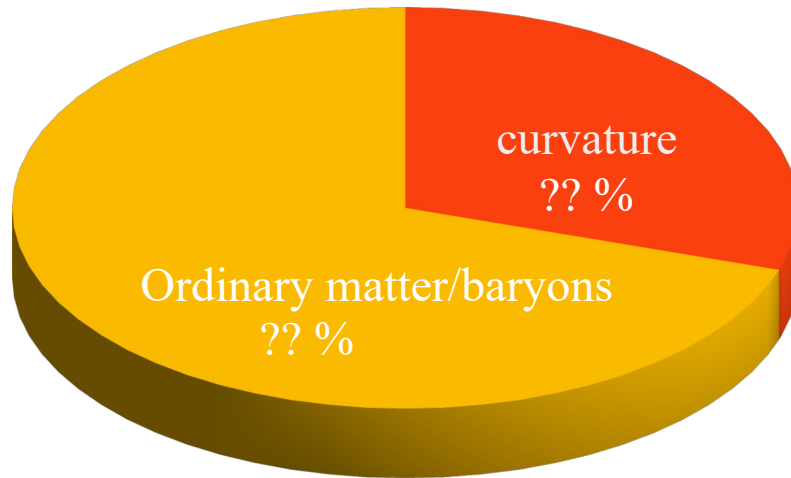
Rethinking the Sakharov conditions

The cosmic pie in 1967

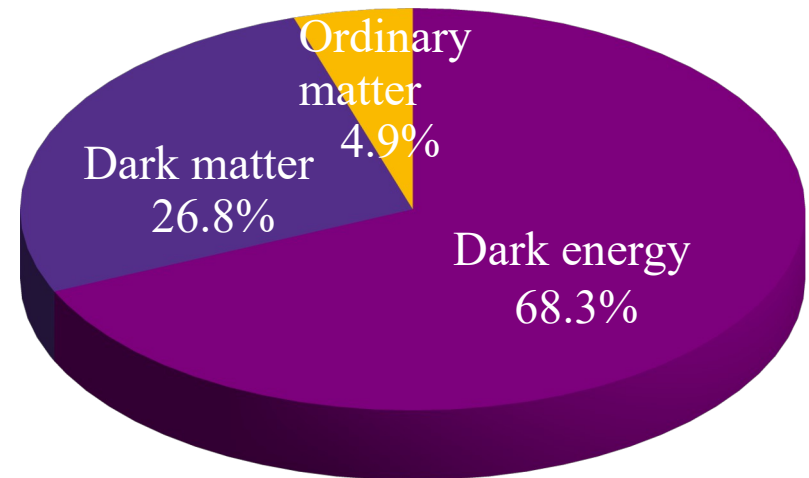


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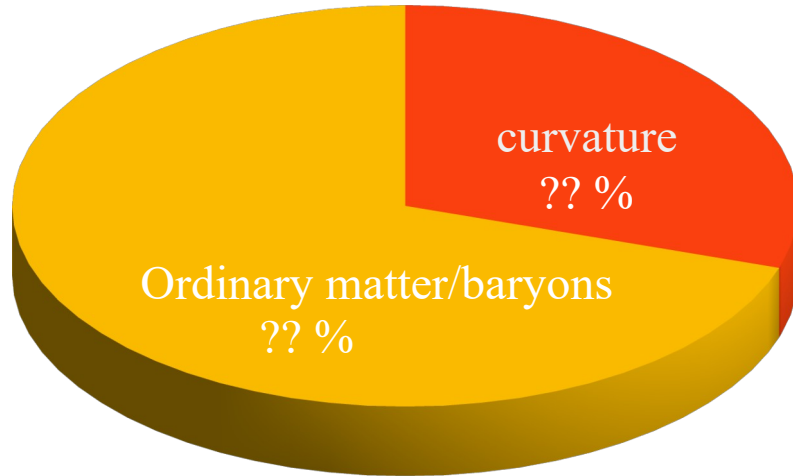


The cosmic pie in the 2020s

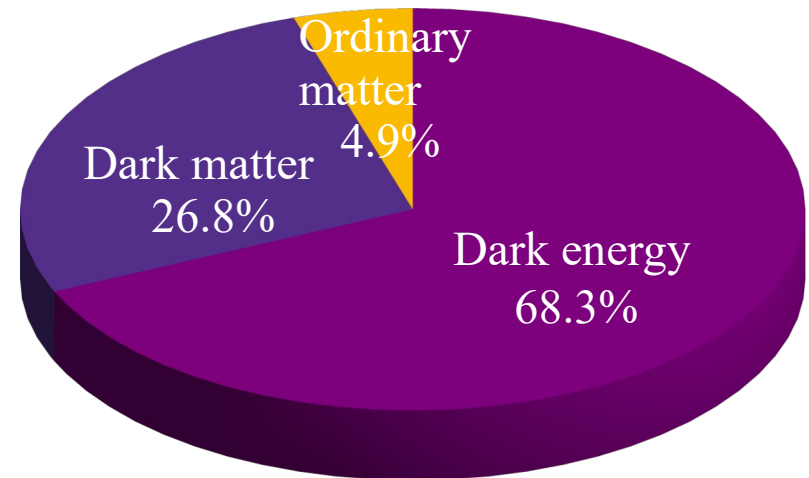


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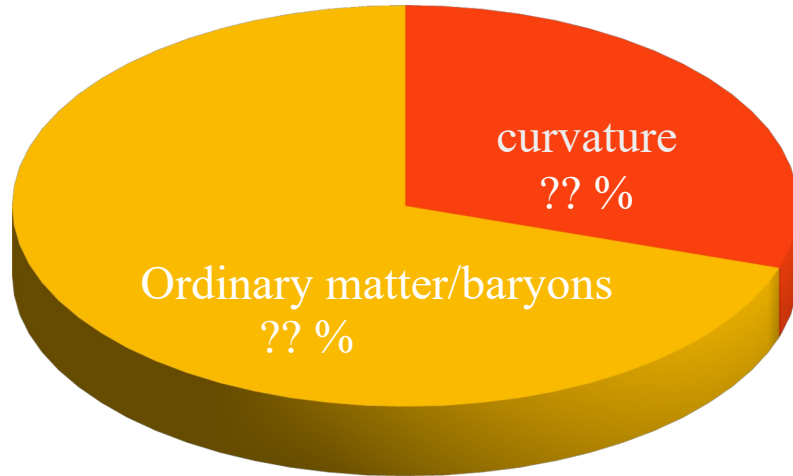
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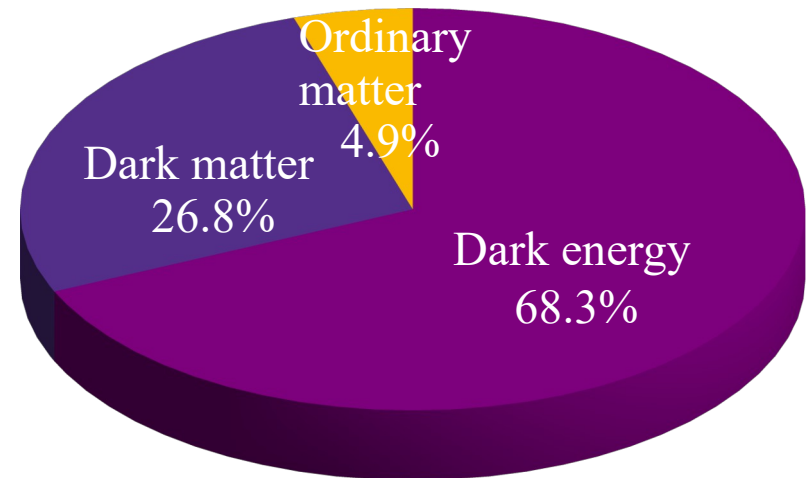
There is no evidence for a baryon asymmetry in our Universe

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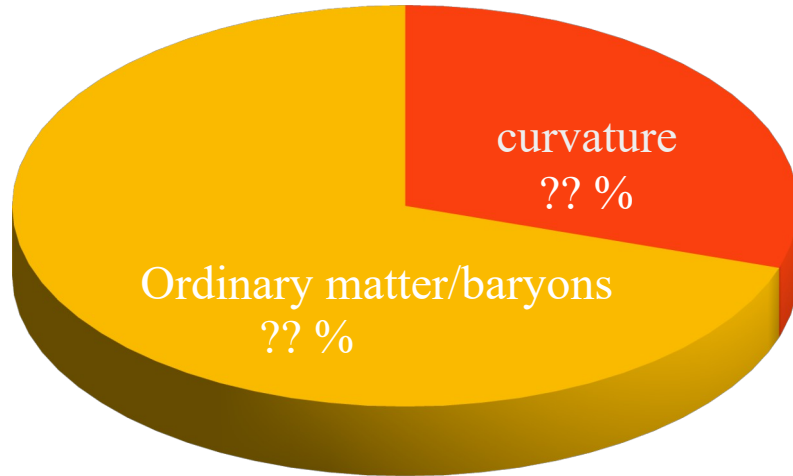


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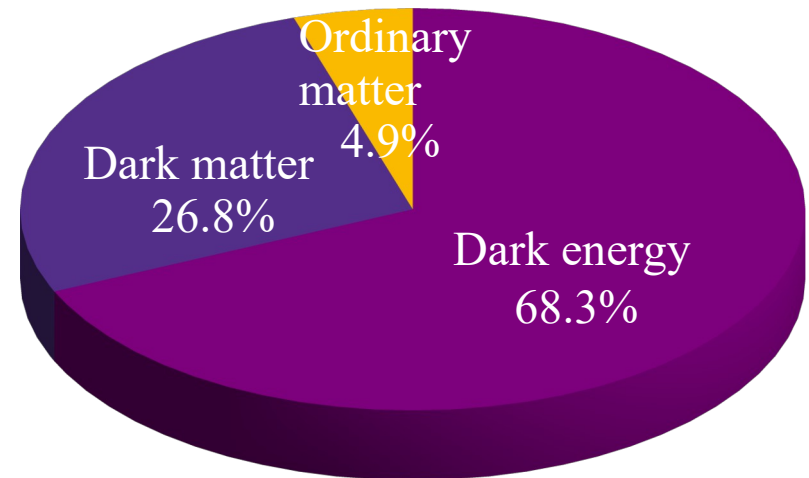
- Observations only show that there are more quarks than antiquarks.
$$Y_{\Delta q,0} = (2.63 \pm 0.07) \times 10^{-10}$$
- Dark sector particles could also carry baryon number
- The Universe could even be baryon symmetric.

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The 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

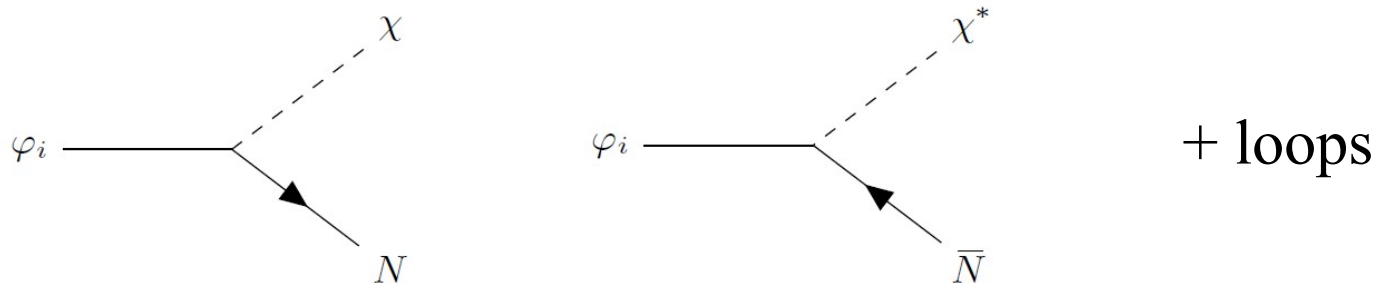
A corresponding asymmetry in χ ensures the conservation of the baryon number throughout the history of the Universe.

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The role of the complex scalar χ

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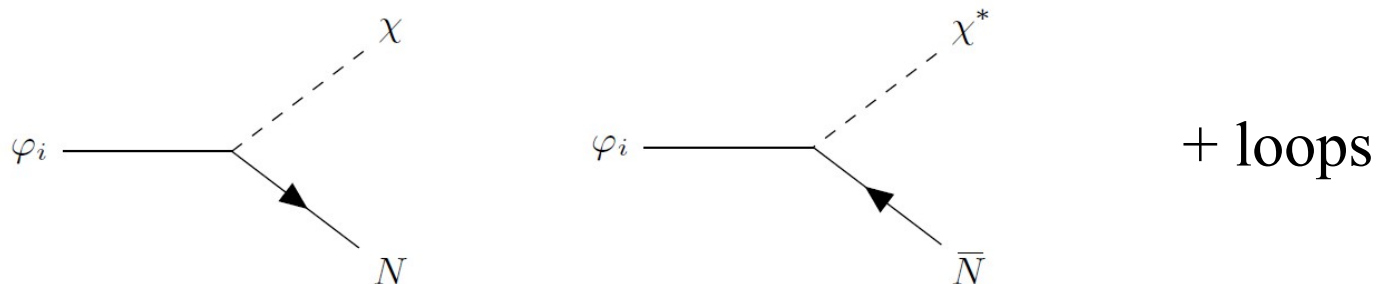


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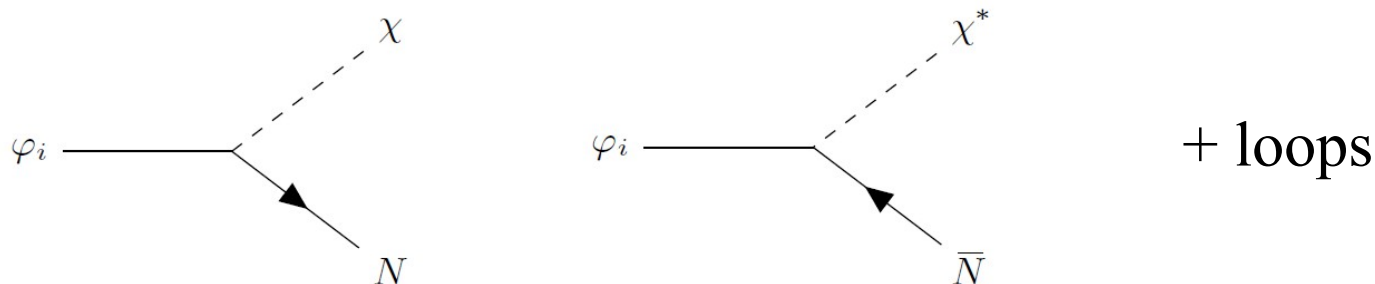
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For instance, if the asymmetry in N is generated from the decays of a heavy Majorana fermion, the same decay generates an identical asymmetry in χ .



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

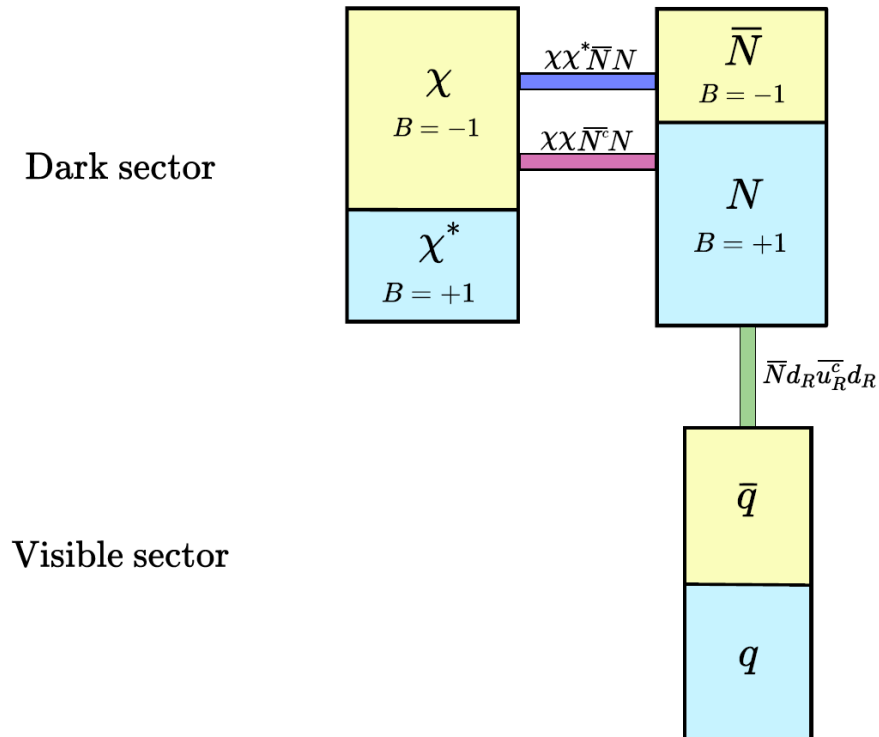
**quark-antiquark
asymmetry**



**dark matter
stability**

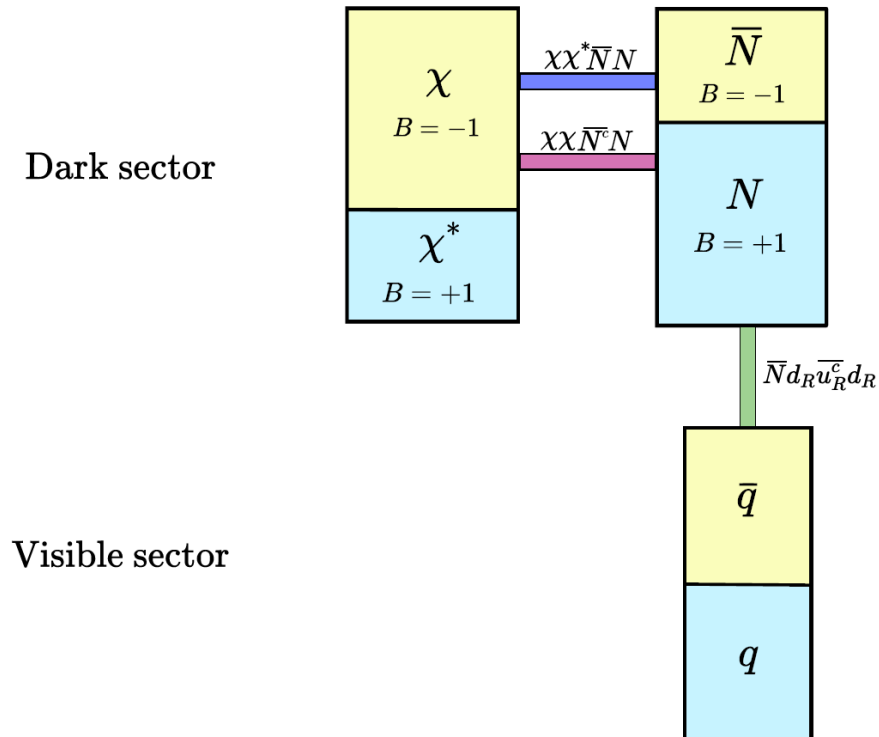
A simple scenario

Initial state

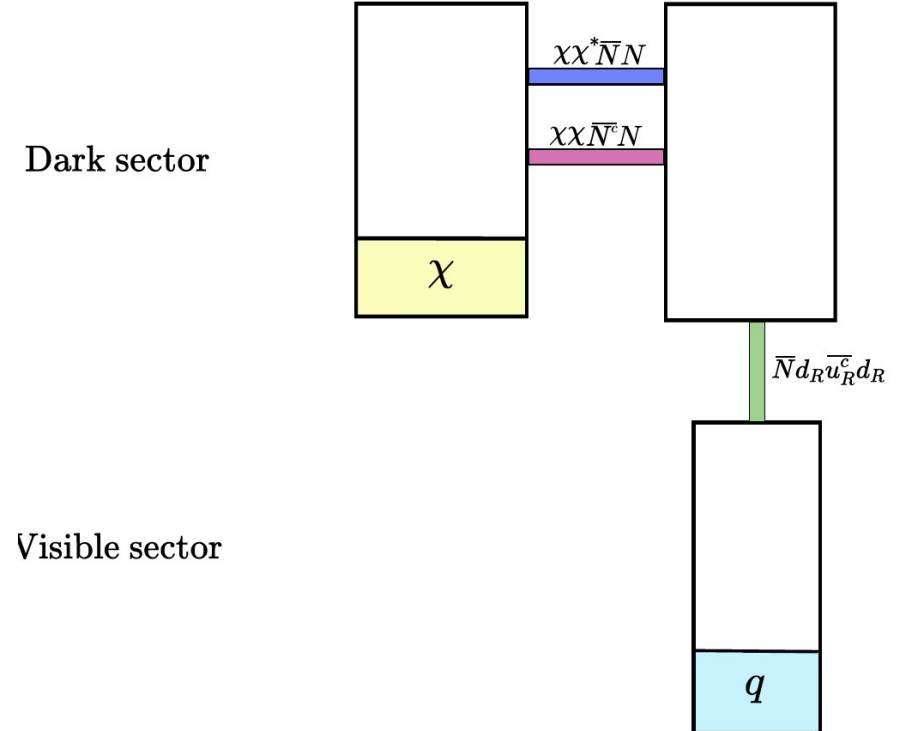


A simple scenario

Initial state

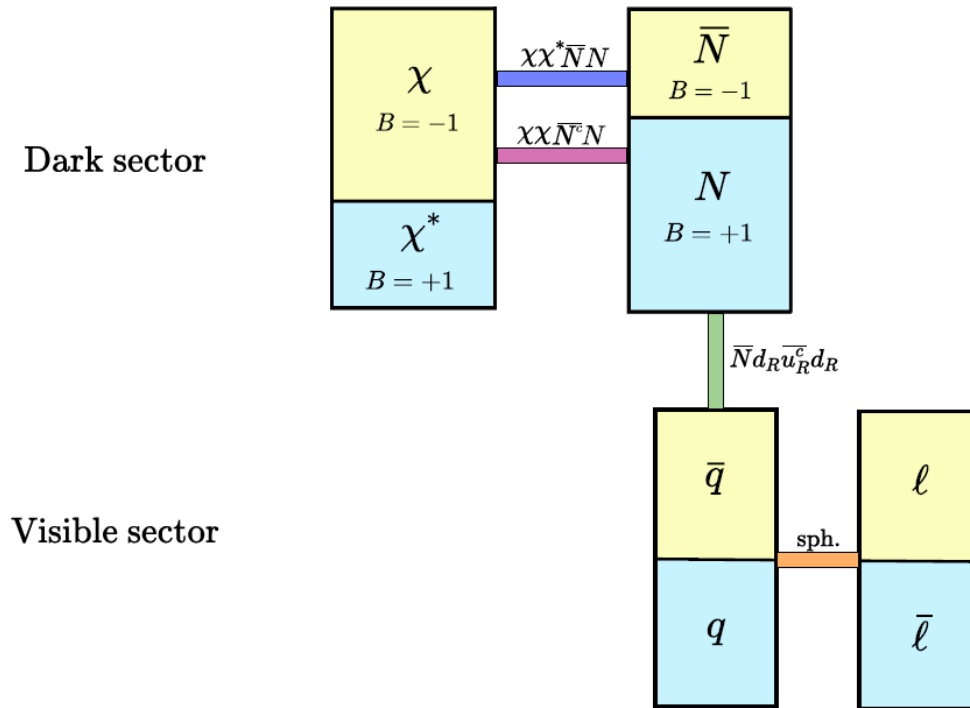


final state



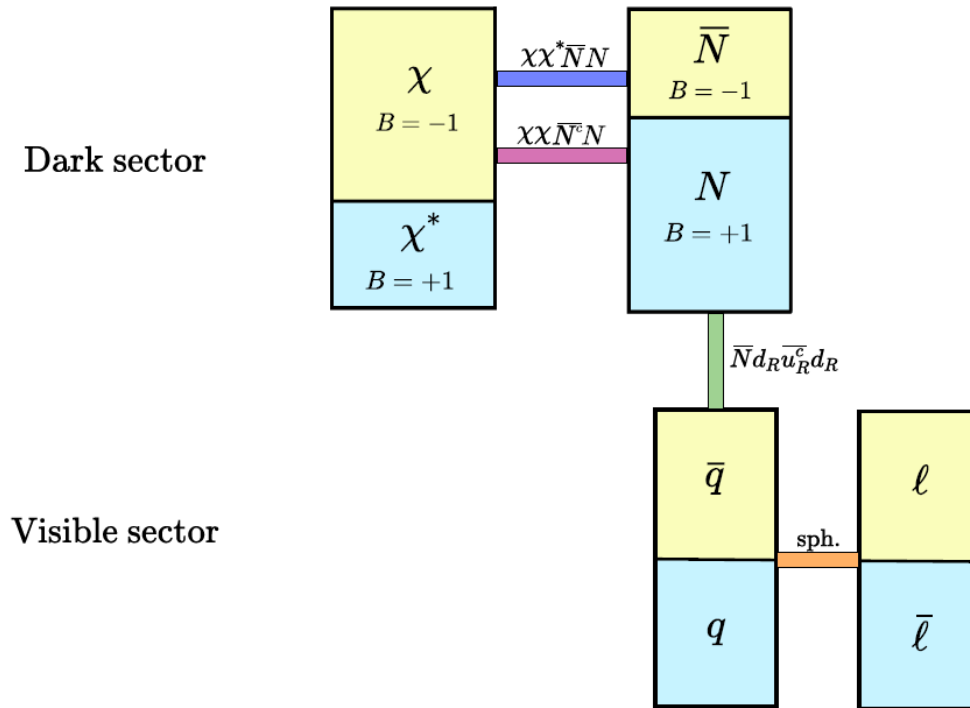
A more refined scenario

Initial state



A more refined scenario

Initial state

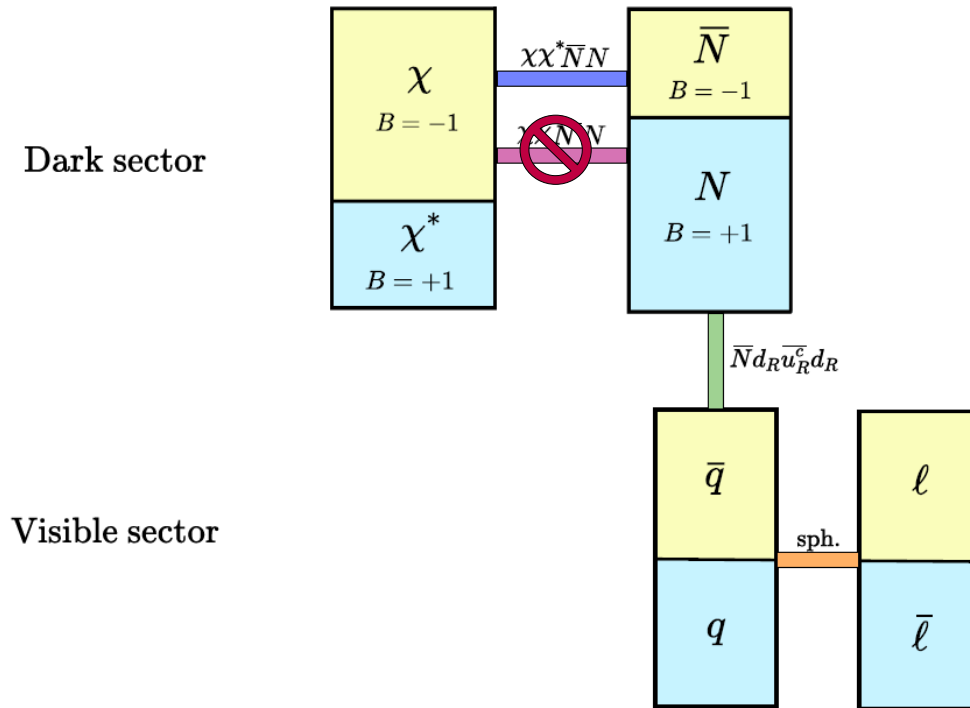


Consider for simplicity:

- 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



Consider for simplicity:

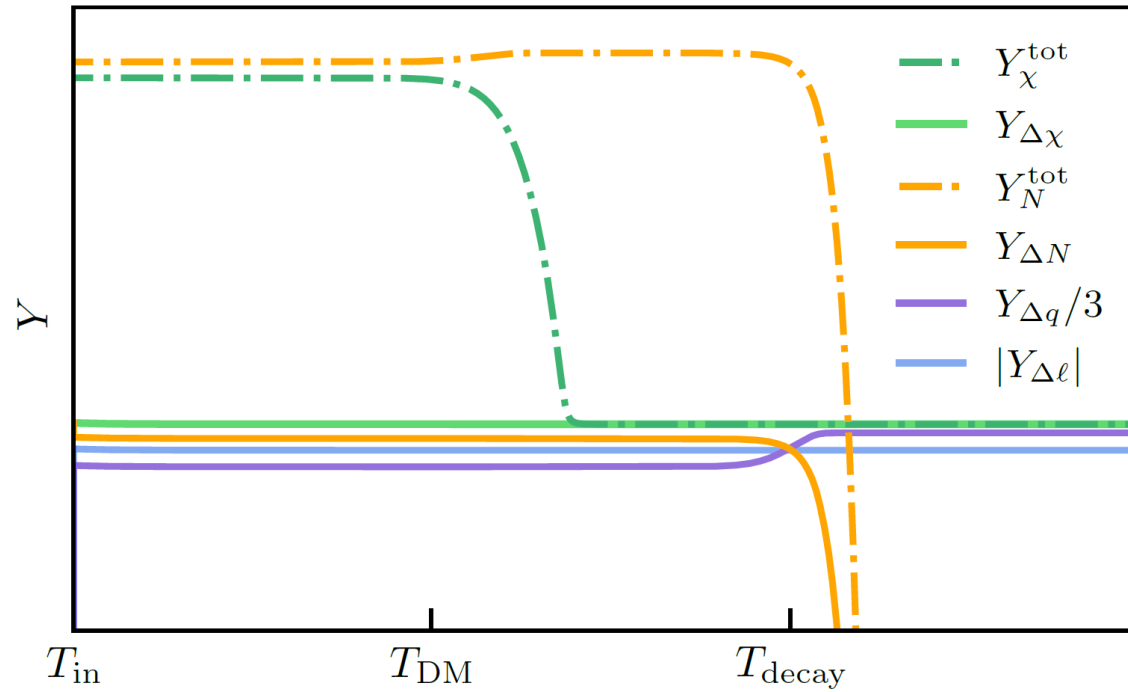
- Neutron portal sufficiently strong to bring the dark sector baryons into thermal equilibrium with the visible sector
- Wash-out scatterings $\chi\chi \leftrightarrow NN$, $\chi N \leftrightarrow \chi^* N$ suppressed

A more refined scenario

$$Y_N^{\text{eq}} = 2Y_\chi^{\text{eq}}$$

$$Y_{\Delta N}^{\text{in}} = Y_{\Delta\chi}^{\text{in}},$$

$$Y_{\Delta q}^{\text{in}} = Y_{\Delta\ell}^{\text{in}} = 0.$$

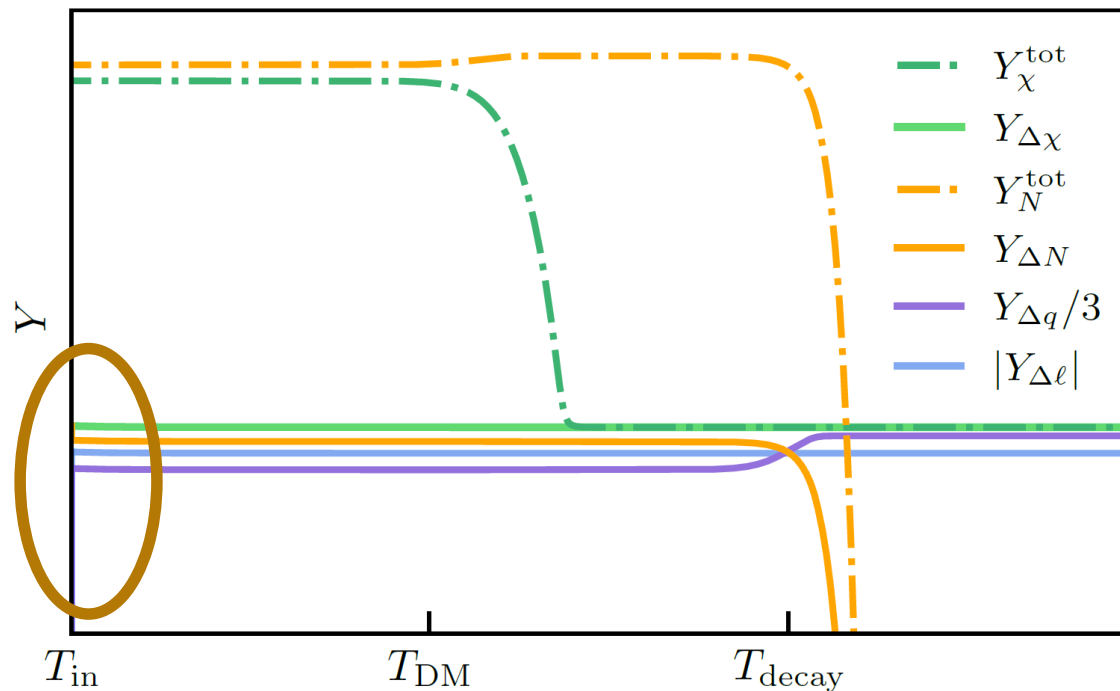


A more refined scenario

$$Y_N^{\text{eq}} = 2Y_\chi^{\text{eq}}$$

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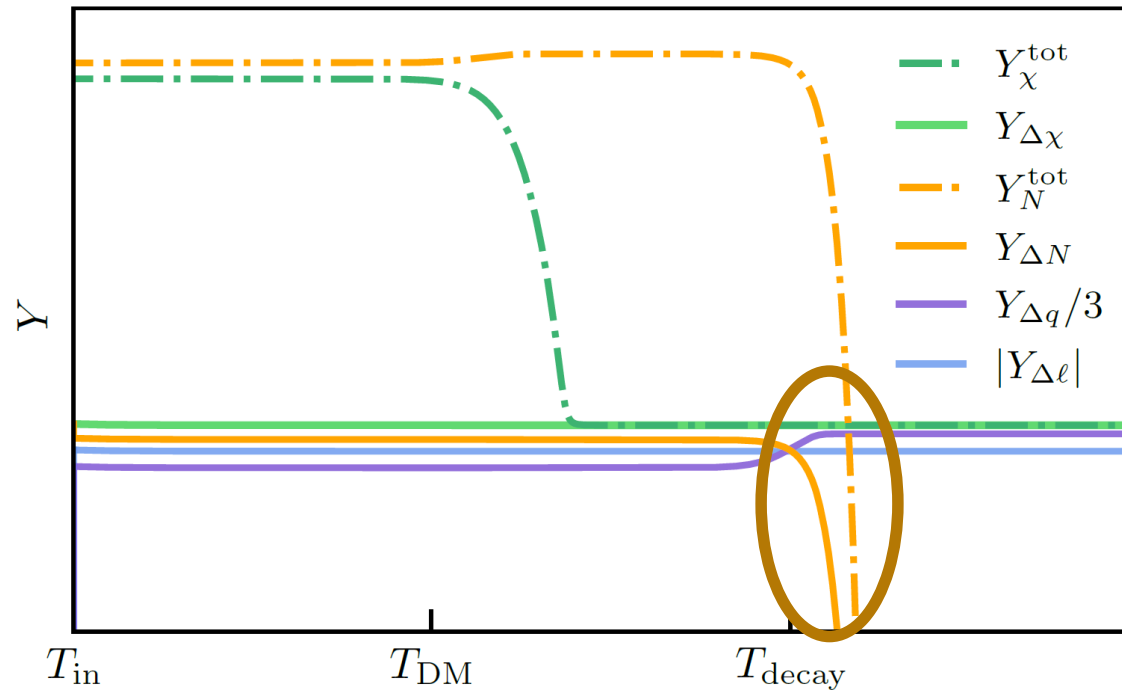
The asymmetry in N is quickly transmitted to the quark sector via scatterings $N\bar{d} \leftrightarrow ud$, $N\bar{u} \leftrightarrow dd$

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

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

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

A more refined scenario



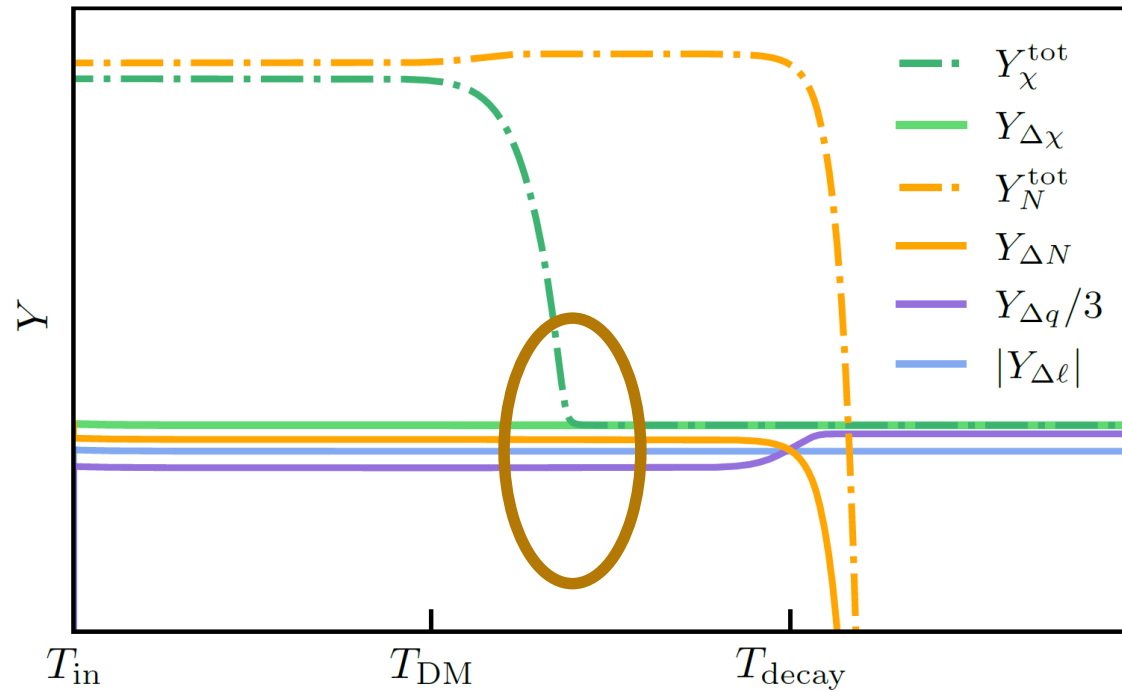
The decay $N \rightarrow udd$ increases the quark-antiquark asymmetry.

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

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

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

A more refined scenario

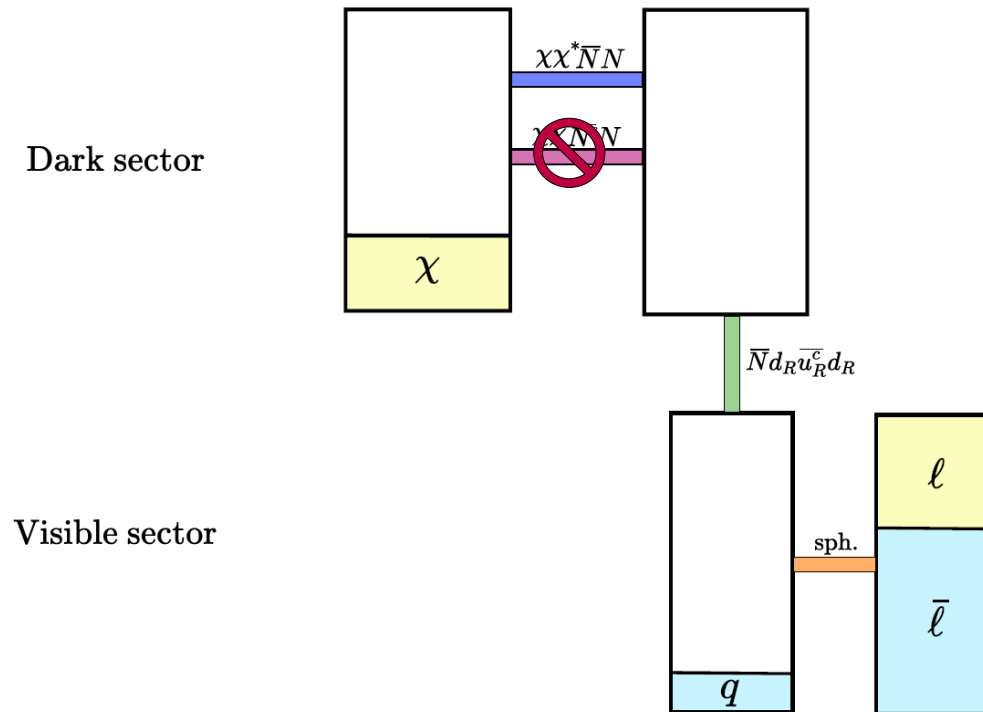


Freeze-out of $\chi\chi^* \rightarrow N\bar{N}$

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

A more refined scenario

Final state, when all χ^* are annihilated

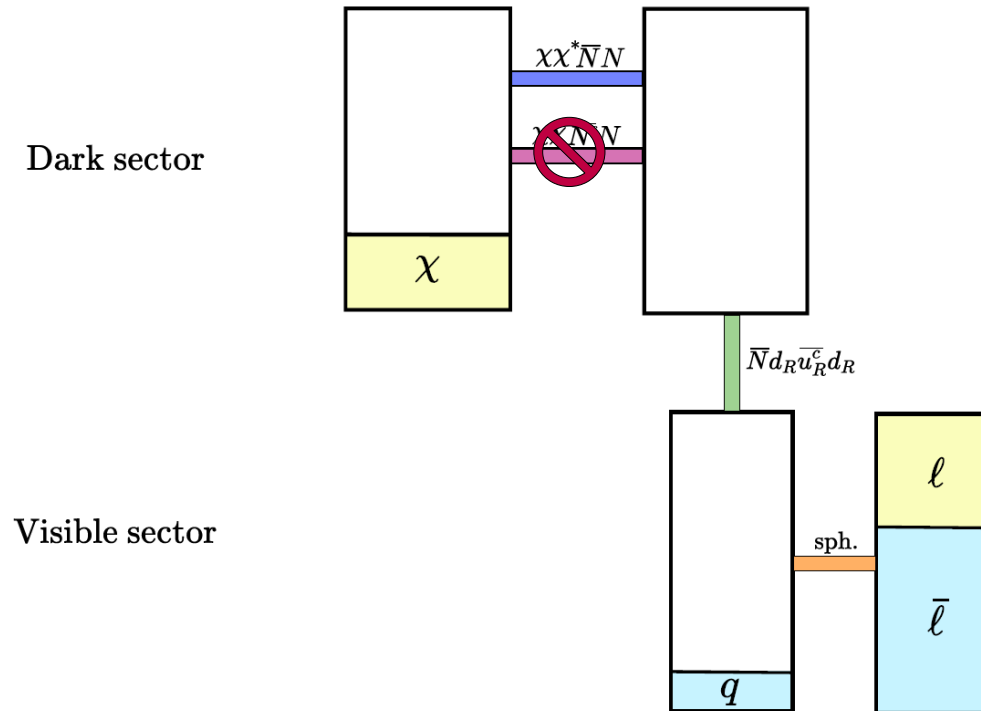


$$\Omega_{\text{DM},0} h^2 \simeq 2.8 \times 10^8 Y_{\chi}^{\text{tot}}(x_{\text{f.o.}}) \frac{m_{\chi}}{\text{GeV}}.$$

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

A more refined scenario

Final state, when all χ^* are annihilated

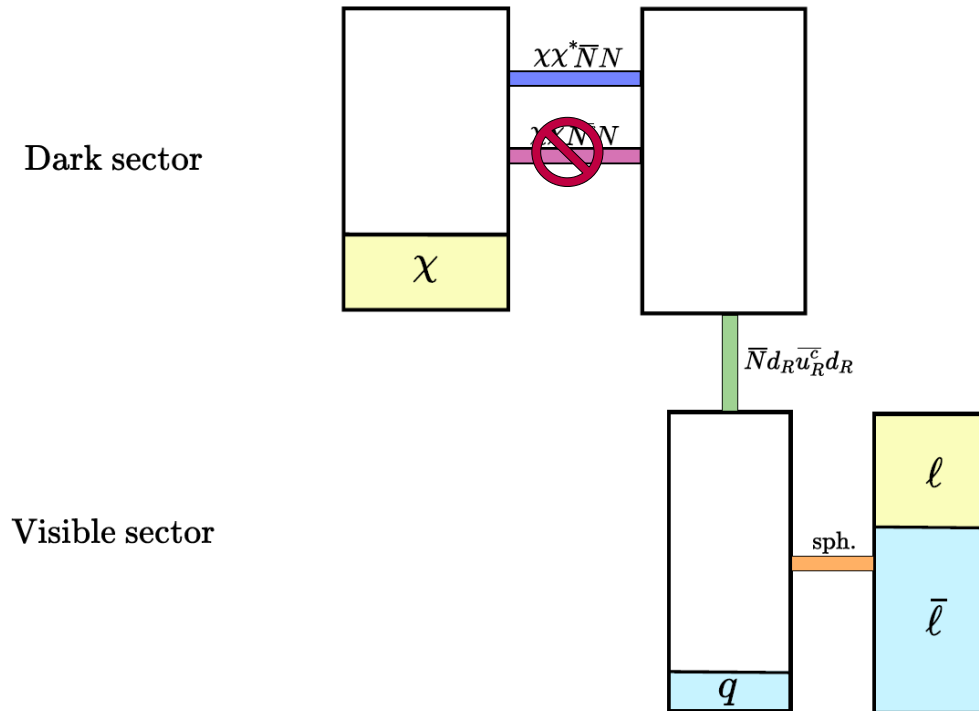


$$\Omega_{\text{DM},0} h^2 \simeq 2.8 \times 10^8 Y_{\Delta N}^{\text{in}} \frac{m_\chi}{\text{GeV}}.$$

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Final state, when all χ^* are annihilated

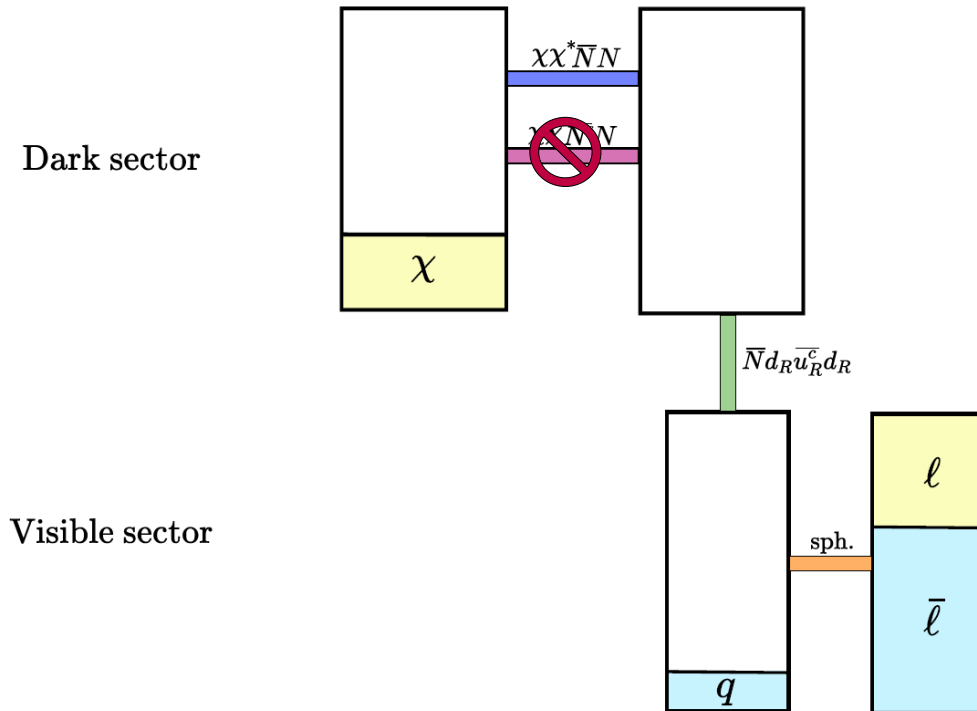


$$\Omega_{\text{DM},0} h^2 \simeq 2.8 \times 10^8 Y_{\Delta N}^{\text{in}} \frac{m_\chi}{\text{GeV}}.$$

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

A more refined scenario

Final state, when all χ^* are annihilated

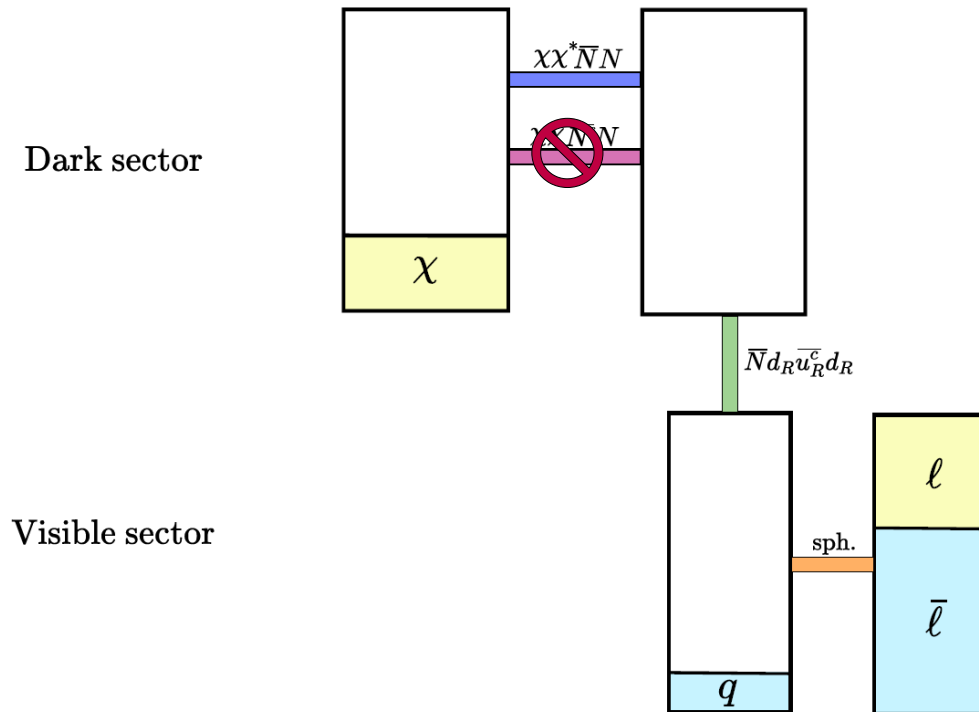


$$\Omega_{\text{DM},0} h^2 \simeq 1.4 \times 10^8 Y_{\Delta q,0} \frac{m_\chi}{\text{GeV}}.$$

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

A more refined scenario

Final state, when all χ^* are annihilated



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

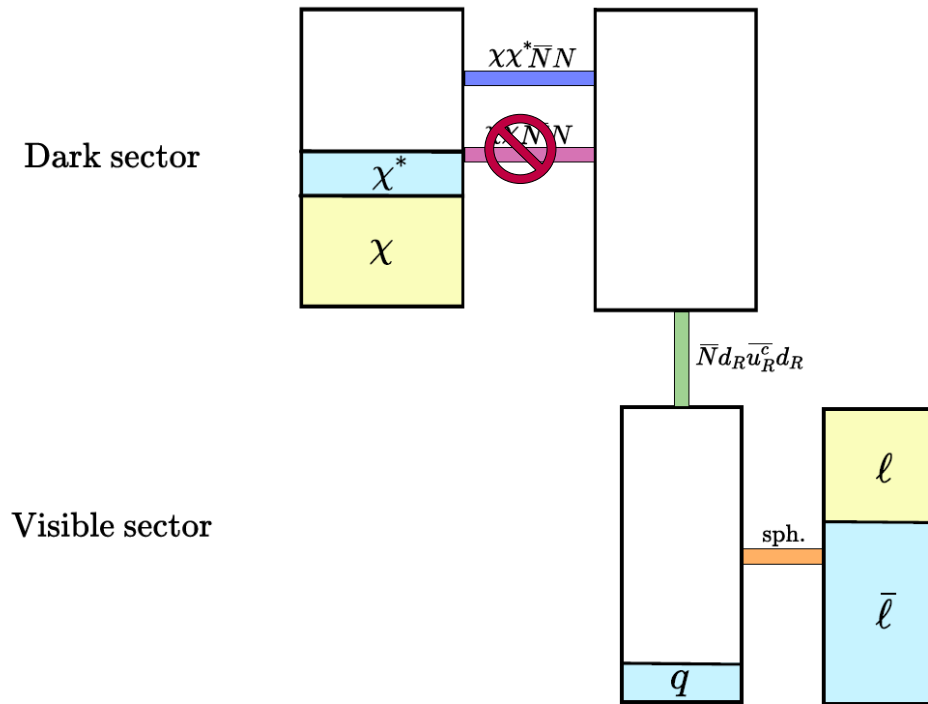
$$Y_{\Delta q,0} = \frac{141}{122} Y_{\Delta N}^{\text{in}},$$

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

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

A more refined scenario

Final state, when χ^* are partially annihilated

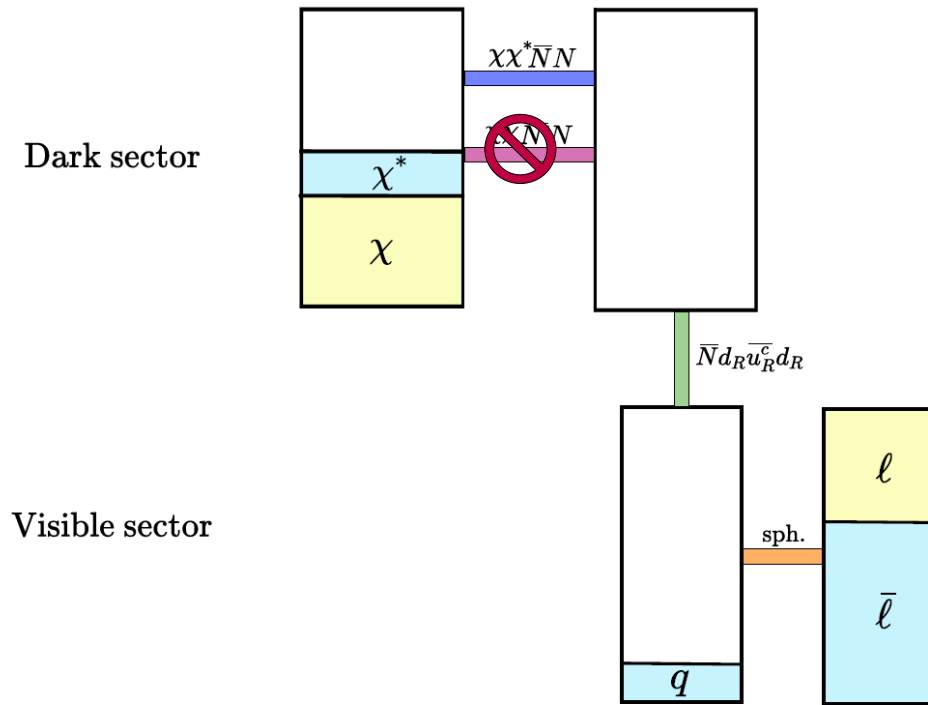


$$\Omega_{\text{DM},0} h^2 \simeq 2.8 \times 10^8 Y_{\chi}^{\text{tot}}(x_{\text{f.o.}}) \frac{m_{\chi}}{\text{GeV}}.$$

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

A more refined scenario

Final state, when χ^* are partially annihilated

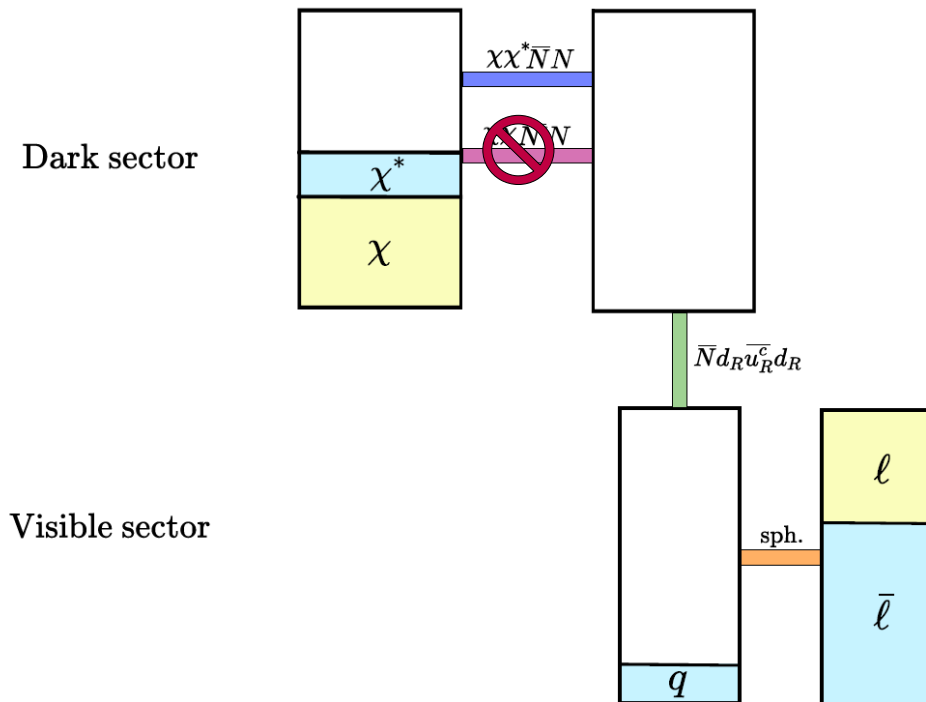


$$\Omega_{\text{DM},0} h^2 \gtrsim 2.8 \times 10^8 Y_{\Delta N}^{\text{in}} \frac{m_\chi}{\text{GeV}}.$$

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

A more refined scenario

Final state, when χ^* are partially annihilated



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

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

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

$$m_\chi \lesssim 1.9 \text{ GeV}$$

Experimental tests

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

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

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

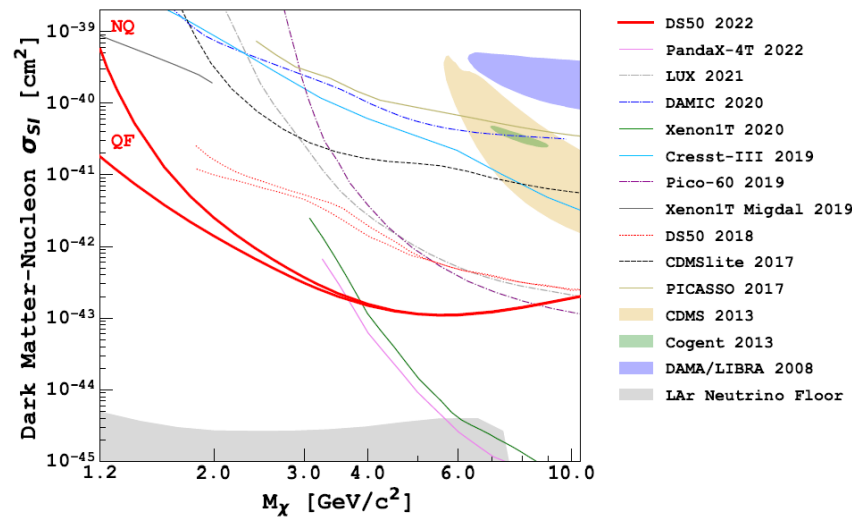
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□ Direct detection: same analysis as for the singlet scalar DM model



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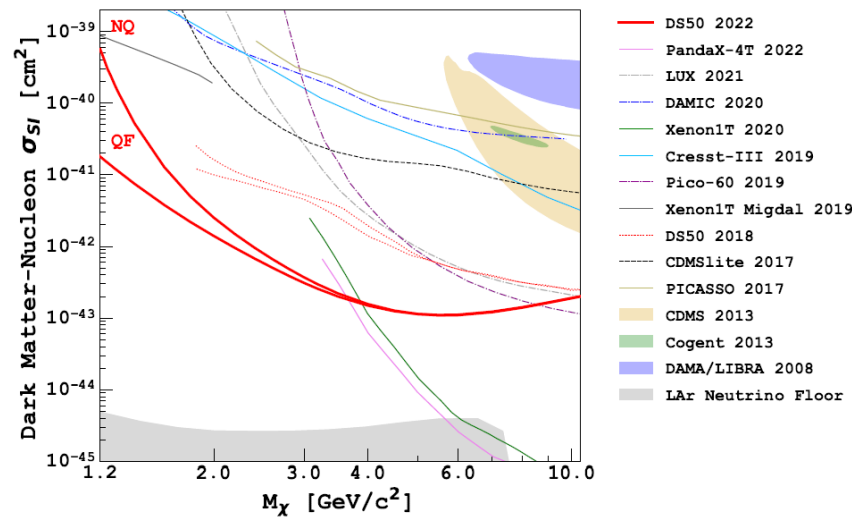
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□ If DM partially asymmetric, indirect detection signals.

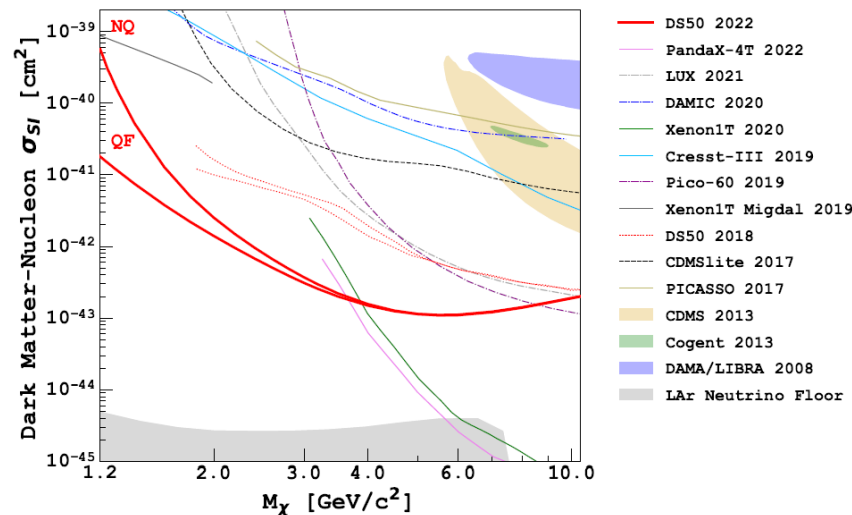
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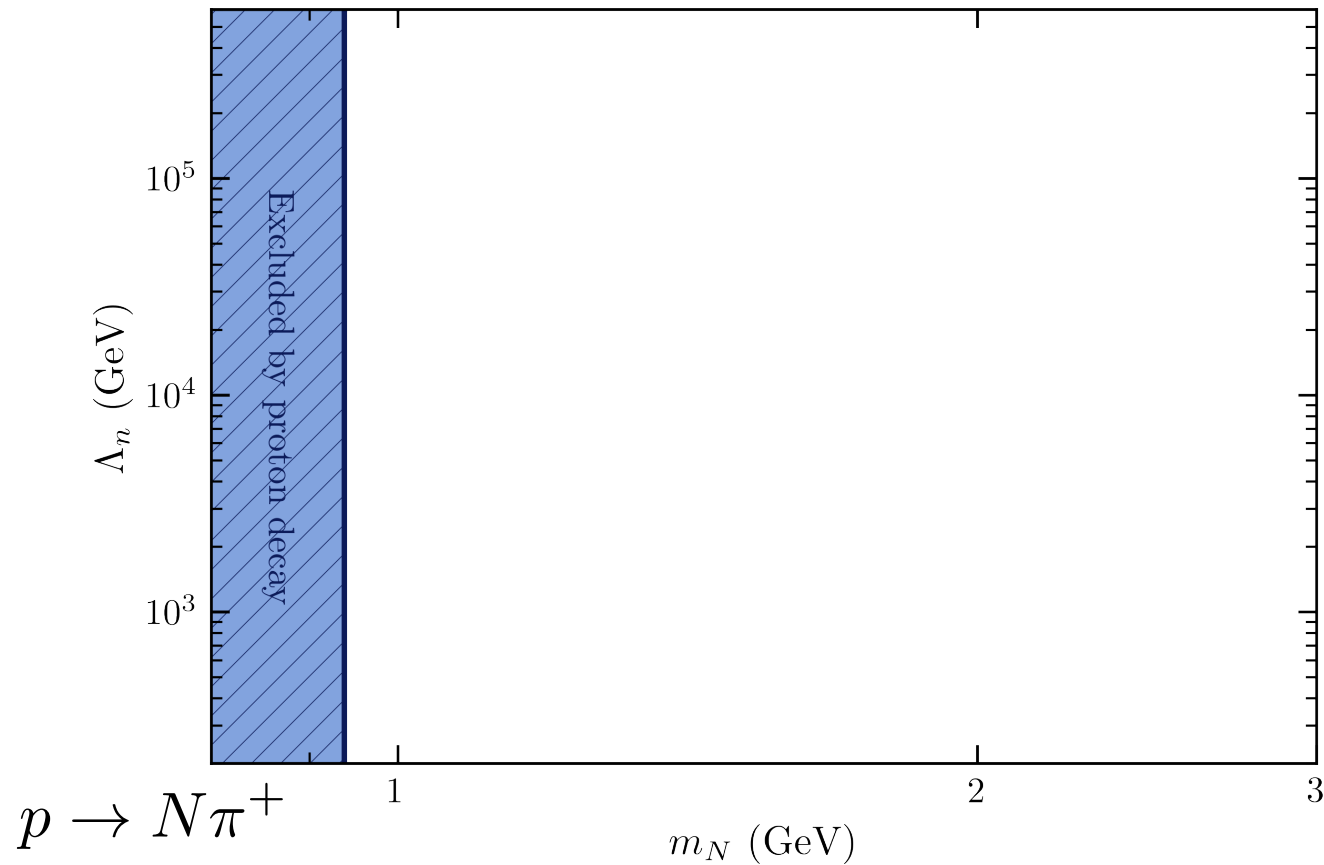
□ If DM partially asymmetric, indirect detection signals.

Note: the Higgs portal generates a contribution to the dark matter mass.

To keep $m_\chi \sim$ a few GeV, $\Rightarrow \lambda_{\chi H} \lesssim 2 \times 10^{-4}$

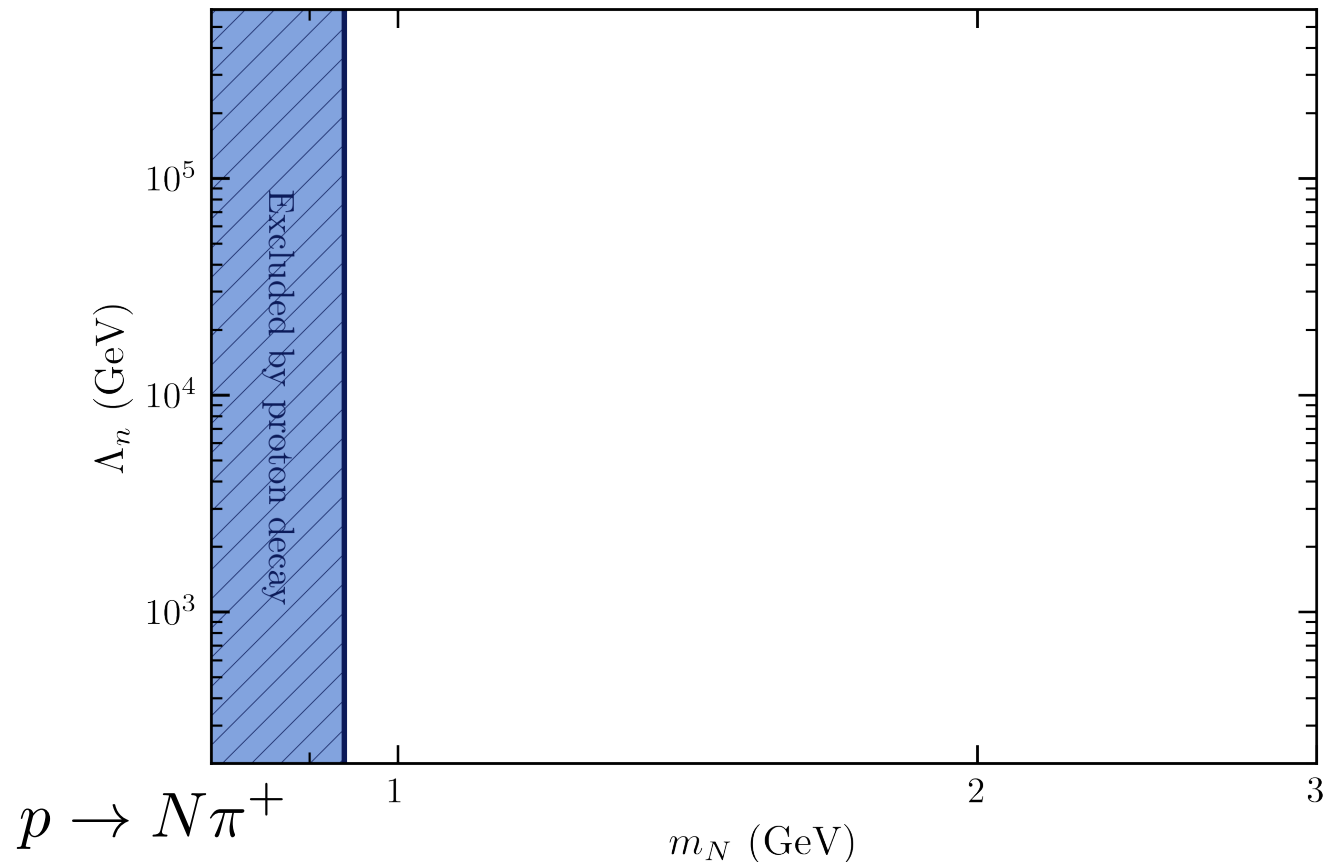
Experimental tests

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



Experimental tests

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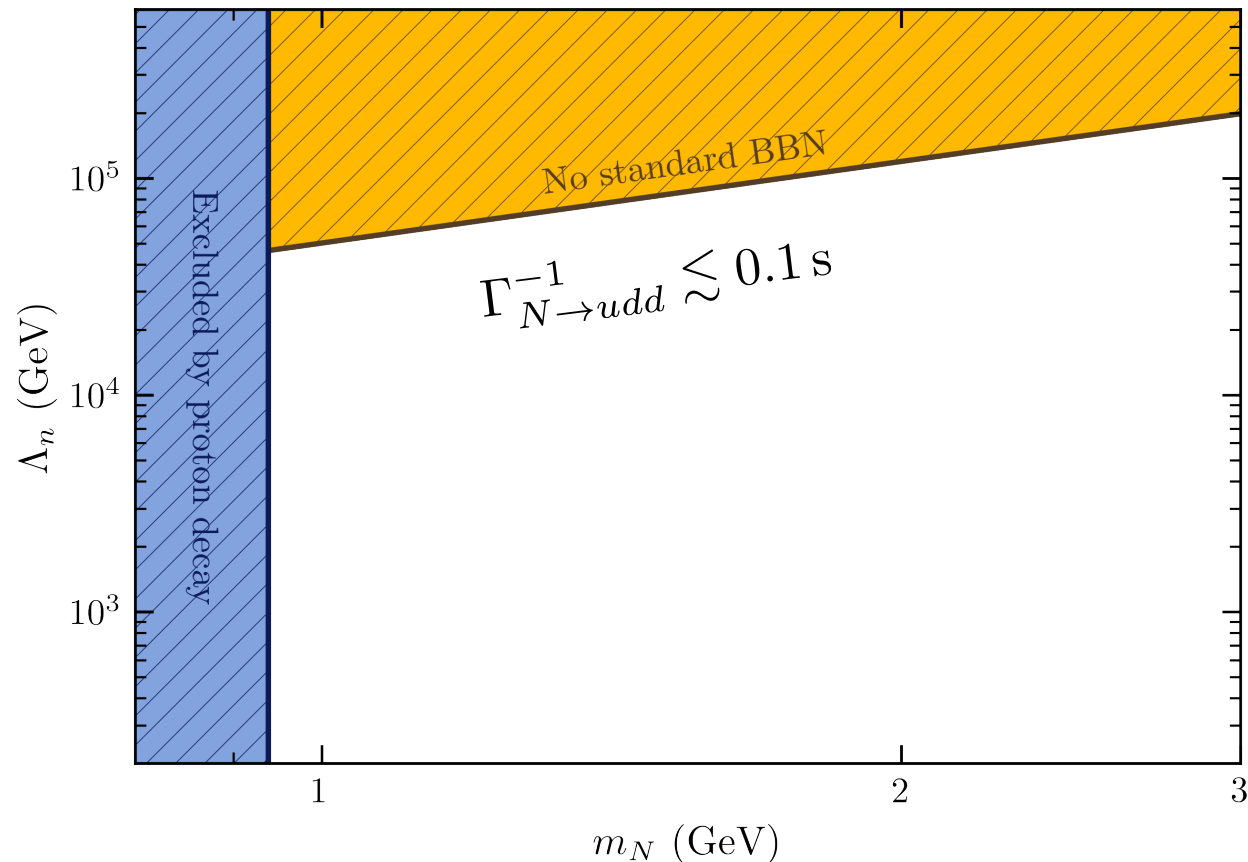


Larger N masses could be probed searching for $\Delta^+ \rightarrow N \pi^+$

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

Experimental tests

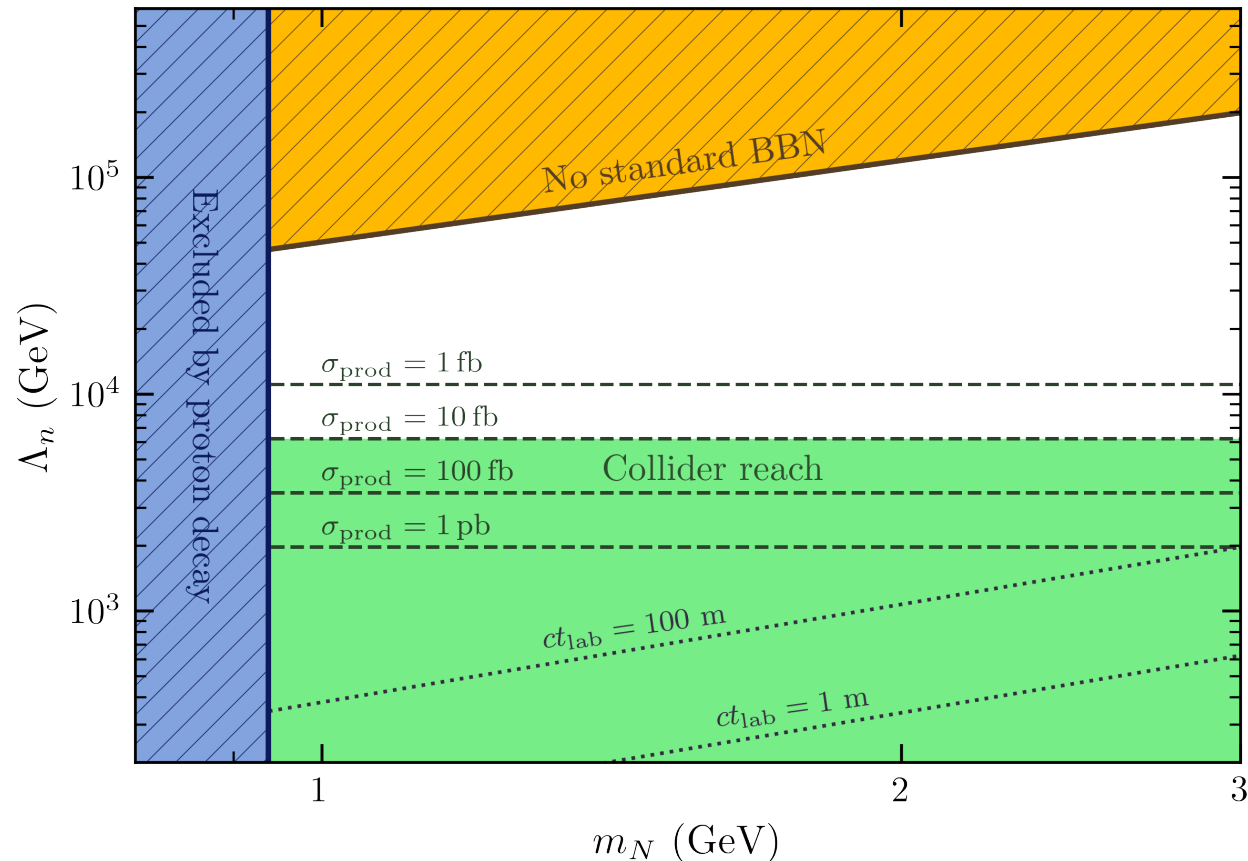
2) Neutron portal $\frac{1}{\Lambda_n^2} \overline{N} d_R \overline{u}_R^c d_R$



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

Experimental tests

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

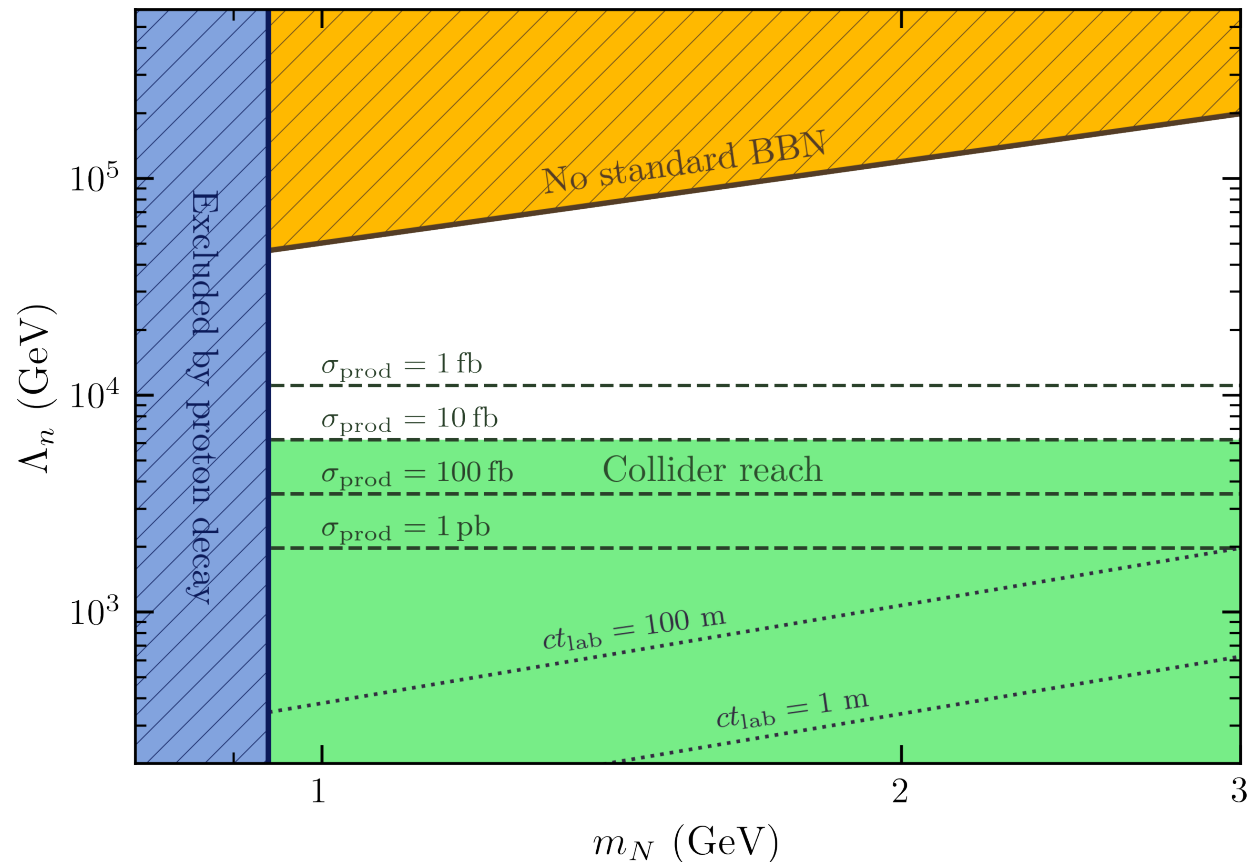


N production in pp collisions through $ud \rightarrow N\bar{d}, dd \rightarrow N\bar{u}$

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

Experimental tests

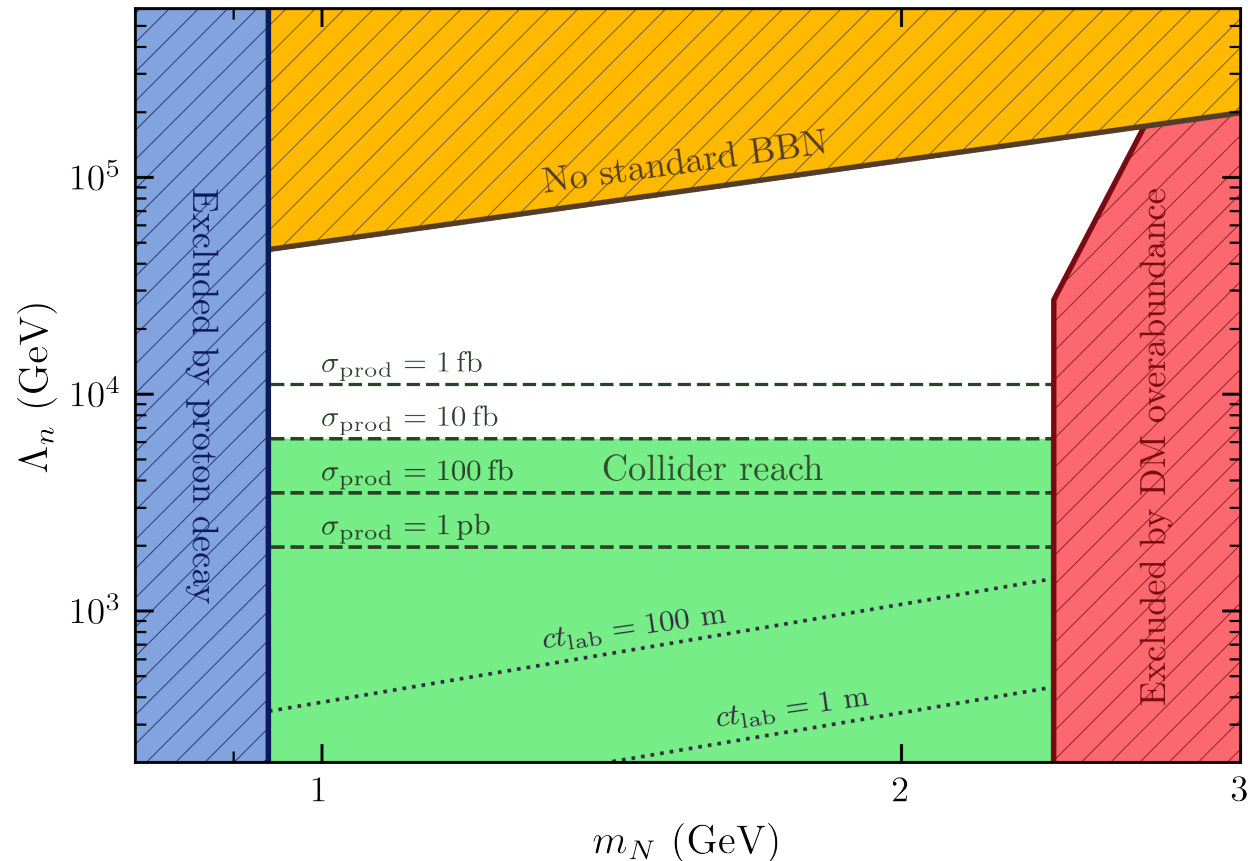
2) Neutron portal $\frac{1}{\Lambda_n^2} \overline{N} d_R \overline{u}_R^c d_R$



- 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 on baryon $\rightarrow$ meson + invisible**

Experimental tests

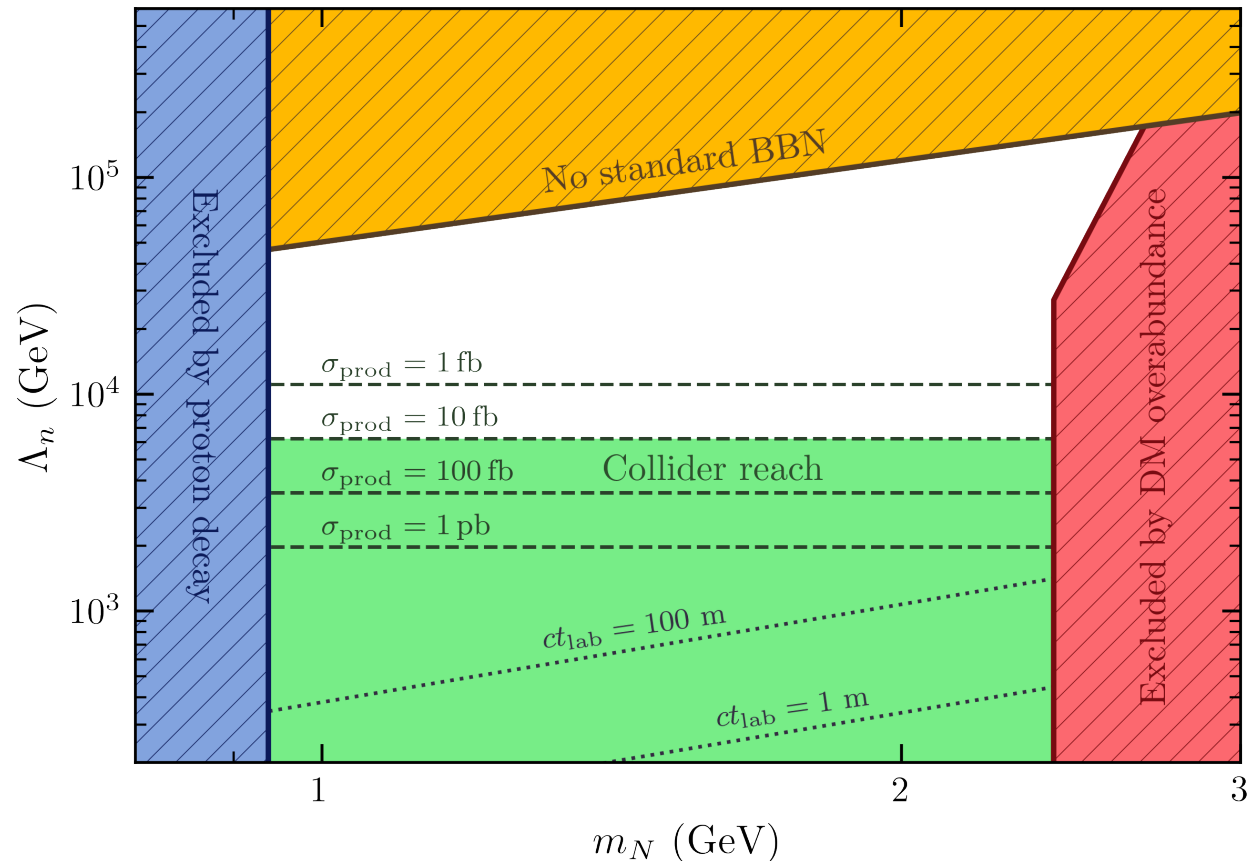
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The rate of annihilations $\chi\chi^* \rightarrow N\overline{N}$ must be sufficiently efficient at freeze-out.

Experimental tests

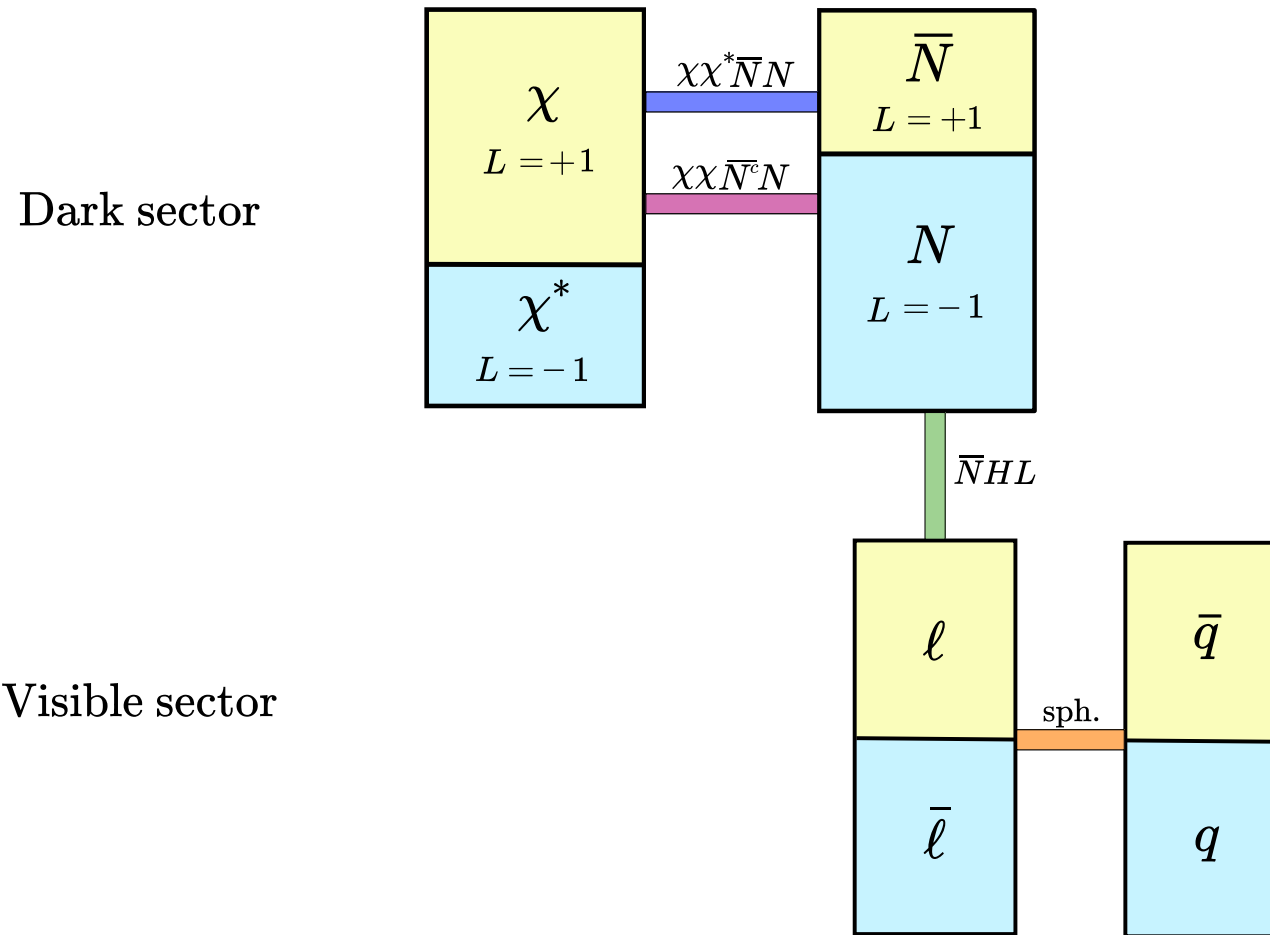
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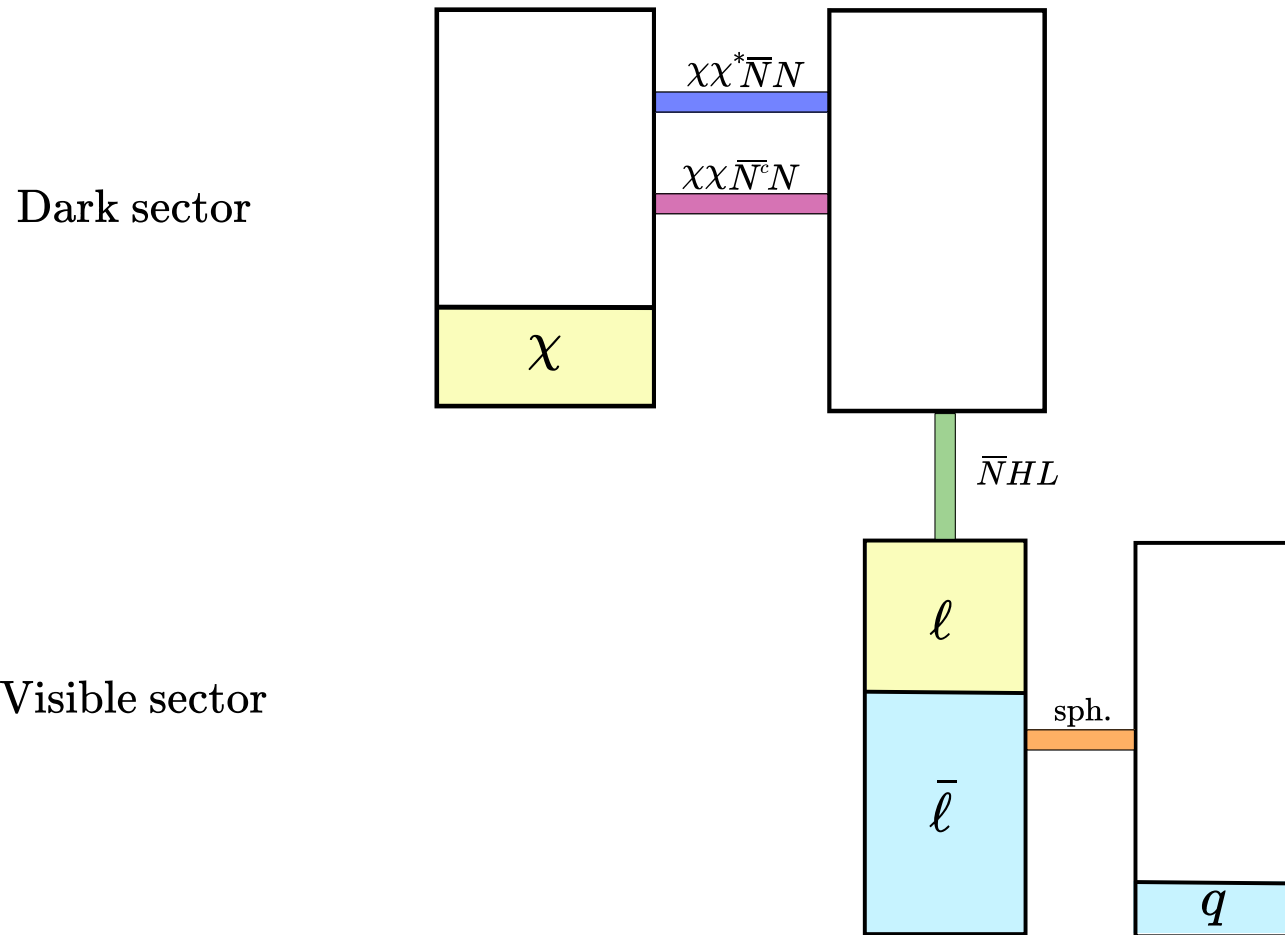
The rate of annihilations $\chi\chi^* \rightarrow N\overline{N}$ must be sufficiently efficient at freeze-out.

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.