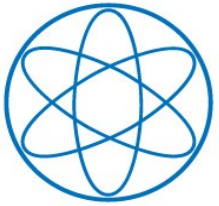
Connecting the baryons to the dark matter of the Universe

Alejandro Ibarra





In collaboration with Mar Císcar-Monsalvatje, Jérôme Vandecasteele and Martina Sabová

DISCRETE'26
Bratislava
November 2026

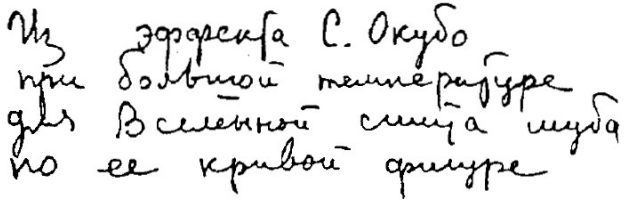
Introduction

Violation of *CP* invariance, *C* asymmetry, and baryon asymmetry of the universe

A. D. Sakharov

(Submitted 23 September 1966)
Pis'ma Zh. Eksp. Teor. Fiz. **5**, 32–35 (1967) [JETP Lett. **5**, 24–27 (1967).
Also S7, pp. 85–88]

Usp. Fiz. Nauk **161**, 61–64 (May 1991)



Literal translation: *Out of S. Okubo's effect*
At high temperature
A fur coat is sewed for the Universe
Shaped for its crooked figure.

The theory of the expanding universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the universe is asymmetrical with respect to the number of particles and antiparticles (*C* asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a nonzero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of *C* asymmetry in the hot model of the expanding universe (see Ref. 1) by making use of effects of *CP* invariance violation (see Ref. 2). To explain baryon asymmetry, we propose in addition an approximate negative in the excess of μ neutrinos over μ antineutrinos).

According to our hypothesis, the occurrence of *C* asymmetry is the consequence of violation of *CP* invariance in the nonstationary expansion of the hot universe during the superdense stage, as manifest in the difference between the partial probabilities of the charge-conjugate reactions. This effect has not yet been observed experimentally, but its existence is theoretically undisputed (the first concrete example, Σ_+ and Σ_- decay, was pointed out by S. Okubo as early as 1958) and should, in our opinion, have much cosmological significance.

We assume that the asymmetry has occurred in an earlier stage of the expansion, in which the particle, energy, and

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Из эффекта С. Окубо
при большой температуре
для Вселенной сшита шуба
по ее кривой фигуре

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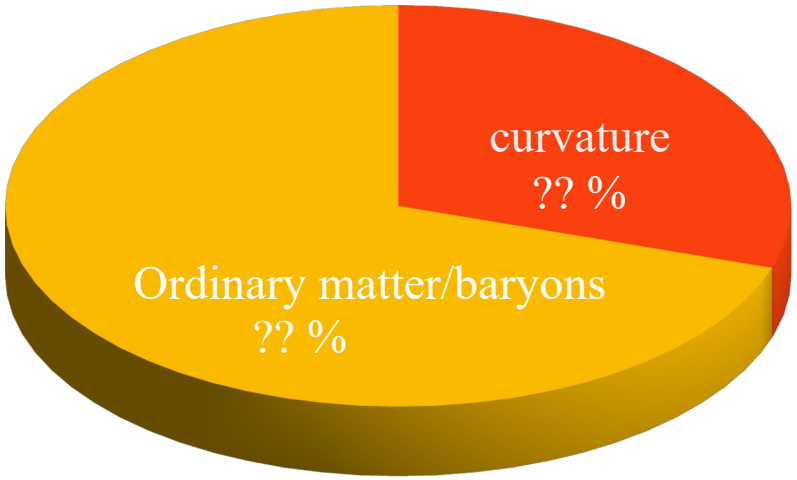
As of 2026, there is no evidence for a baryon asymmetry in our Universe

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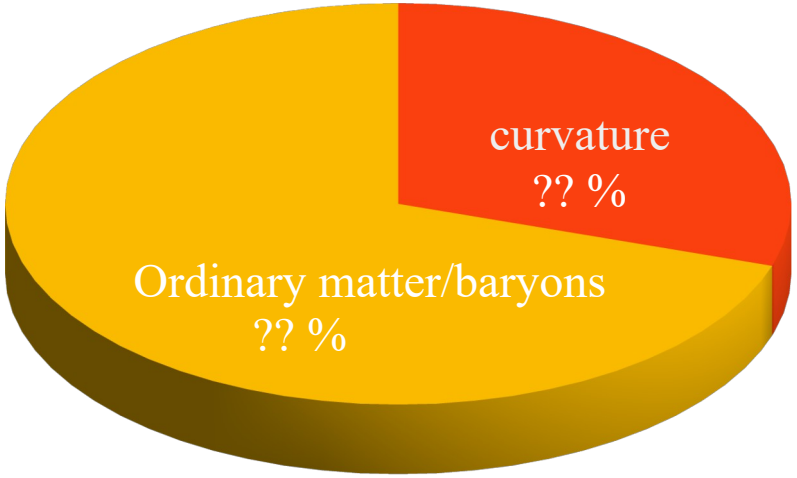
Rethinking the Sakharov conditions

The cosmic pie in 1967

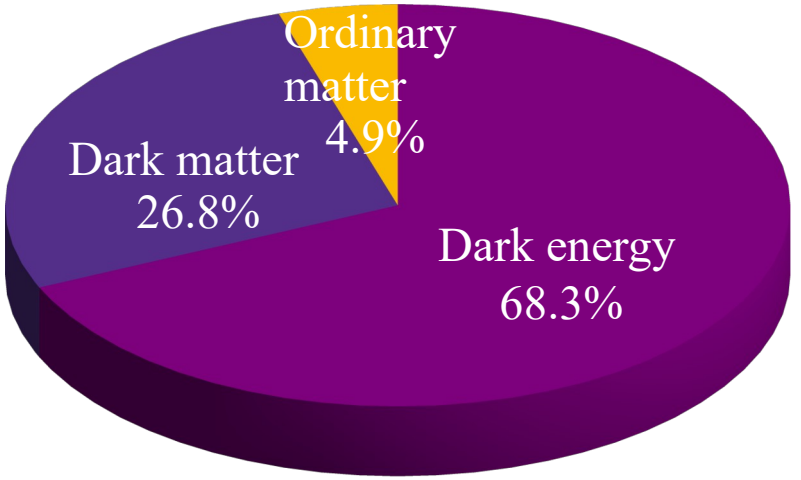


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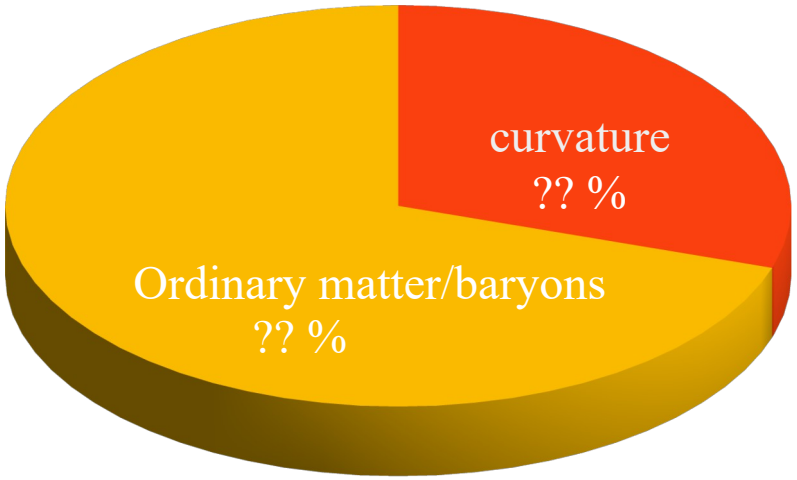


The cosmic pie in the 2020s

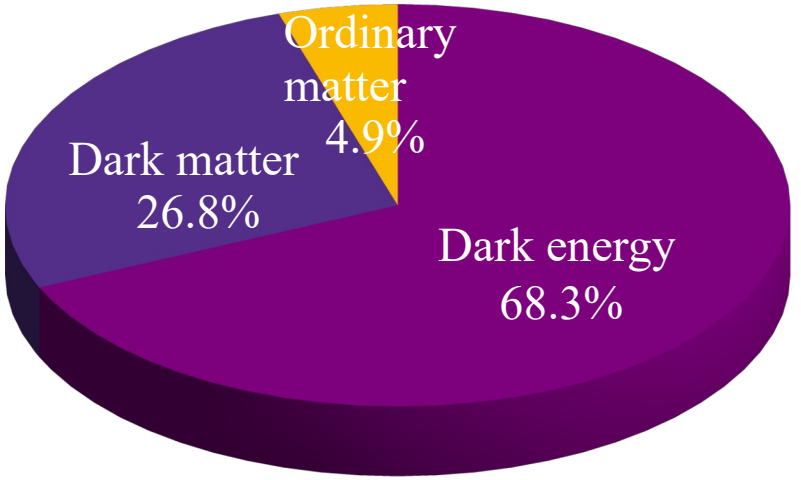


Rethinking the Sakharov conditions

The cosmic pie in 1967



The cosmic pie in the 2020s



- 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.

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

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

A quark-antiquark asymmetry will be generated if:

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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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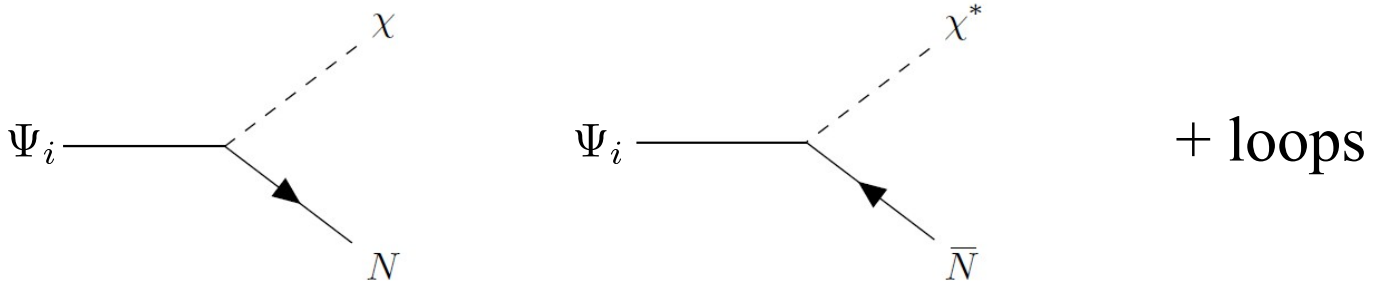
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A simple scenario

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.

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.

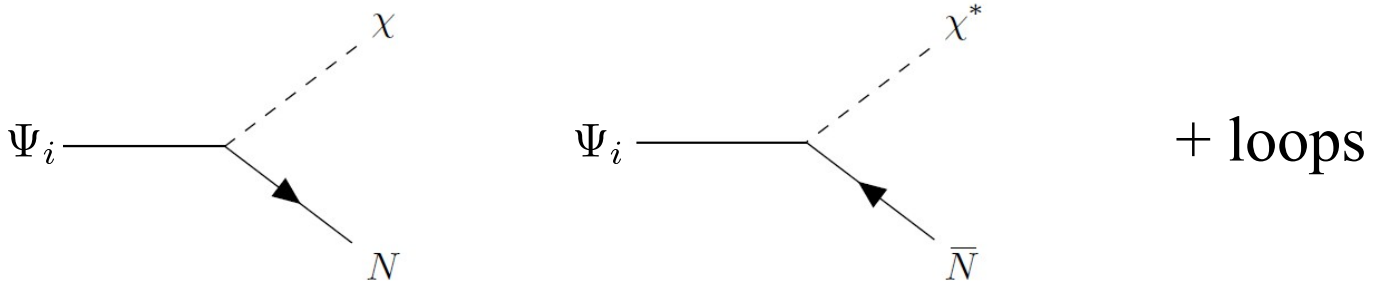


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Bonus: χ is absolutely stable, due to the conservation of baryon number.

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

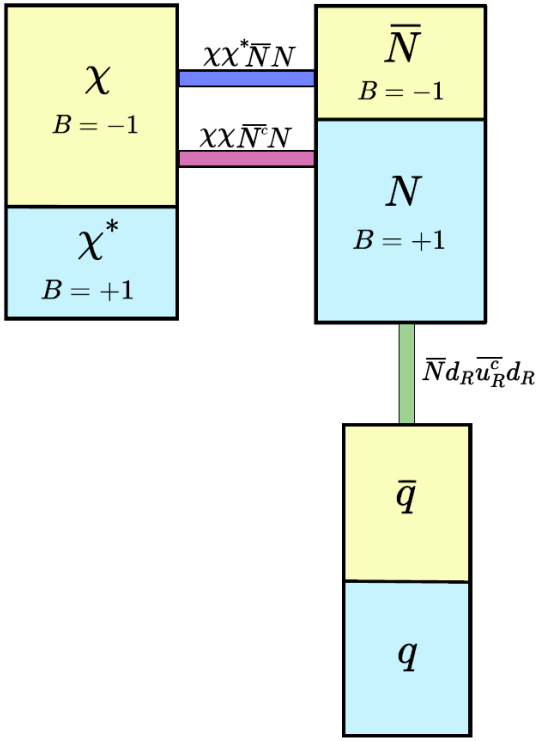
A simple scenario

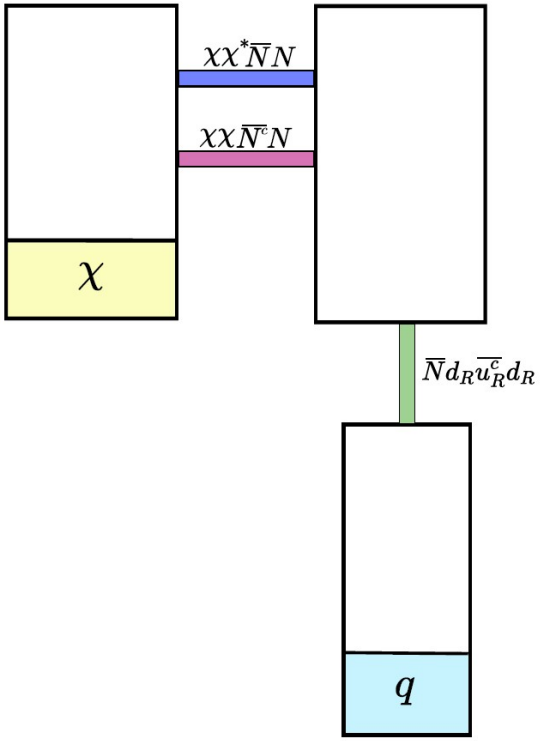
high T

Low T

Dark sector

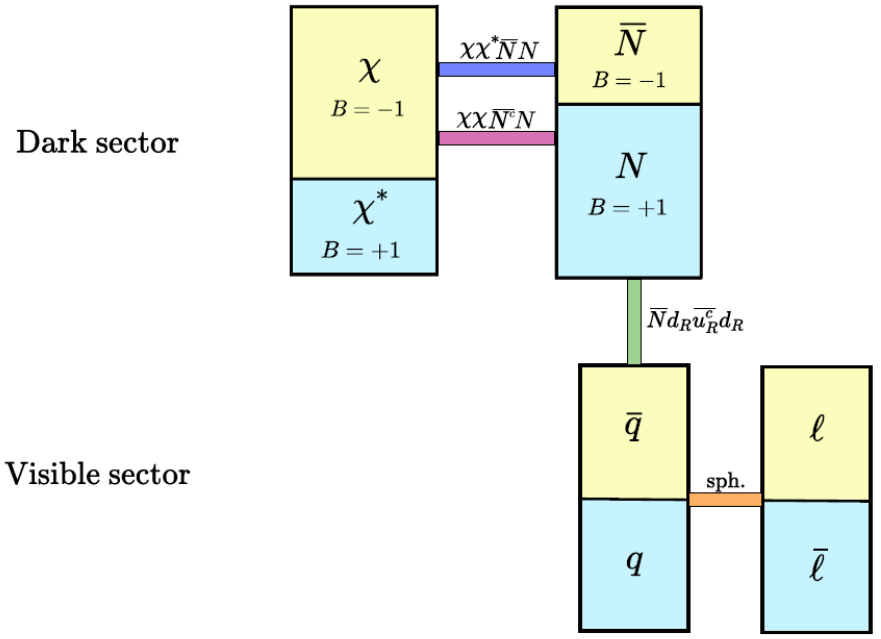
Visible sector



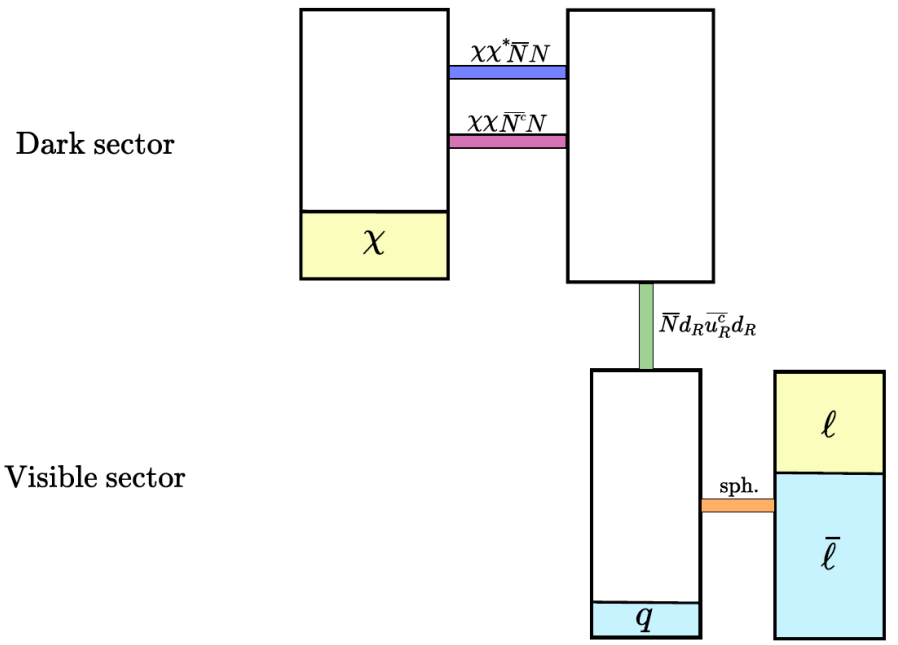


A more refined scenario

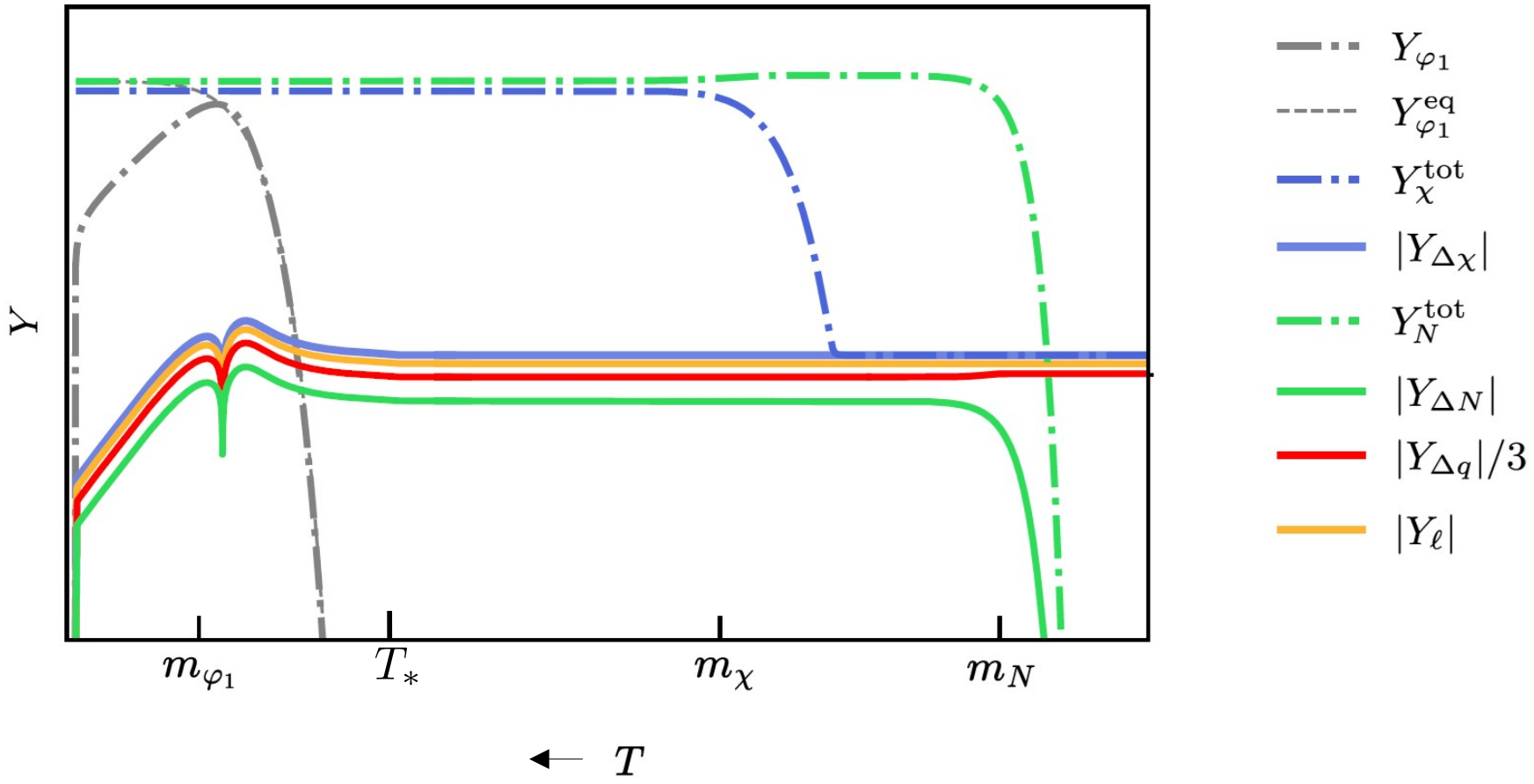
high T



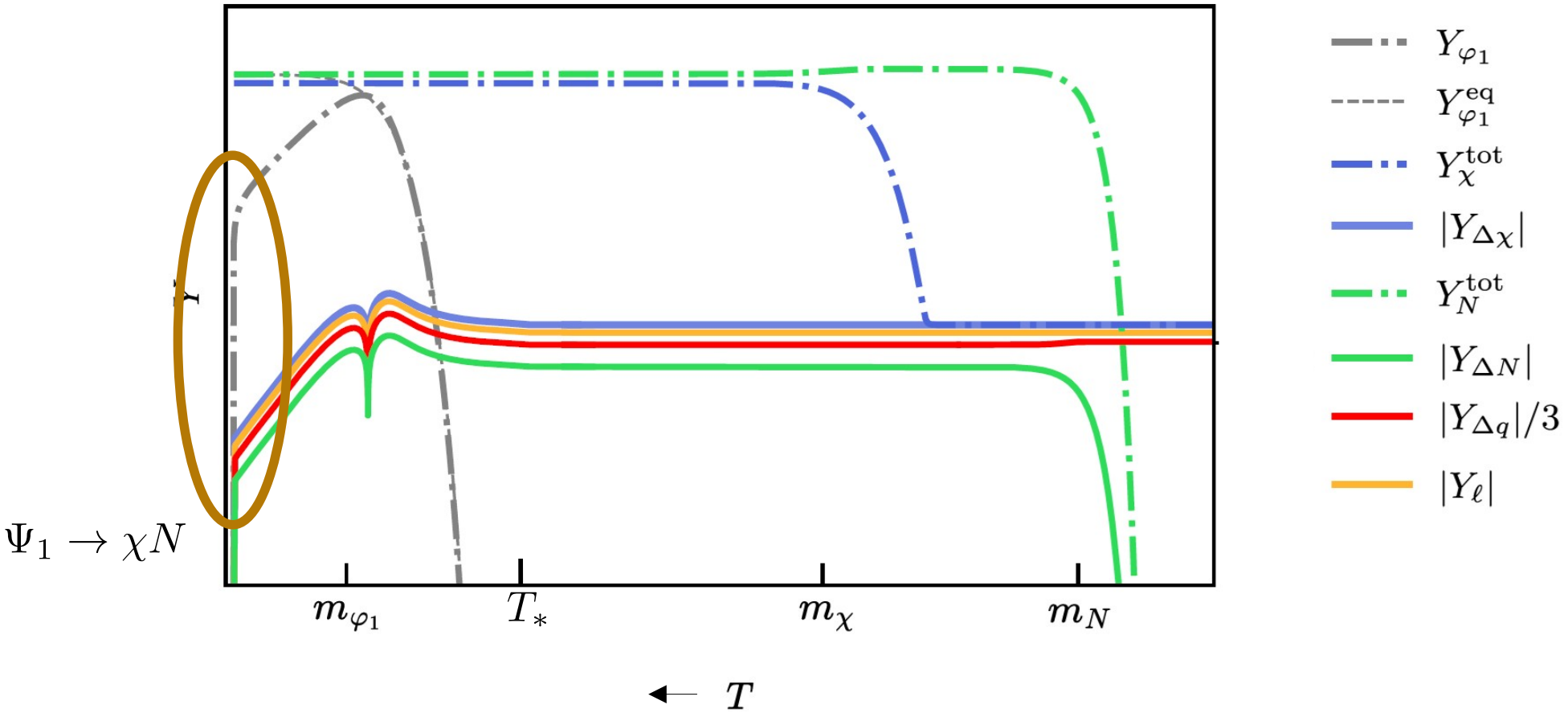
Low T



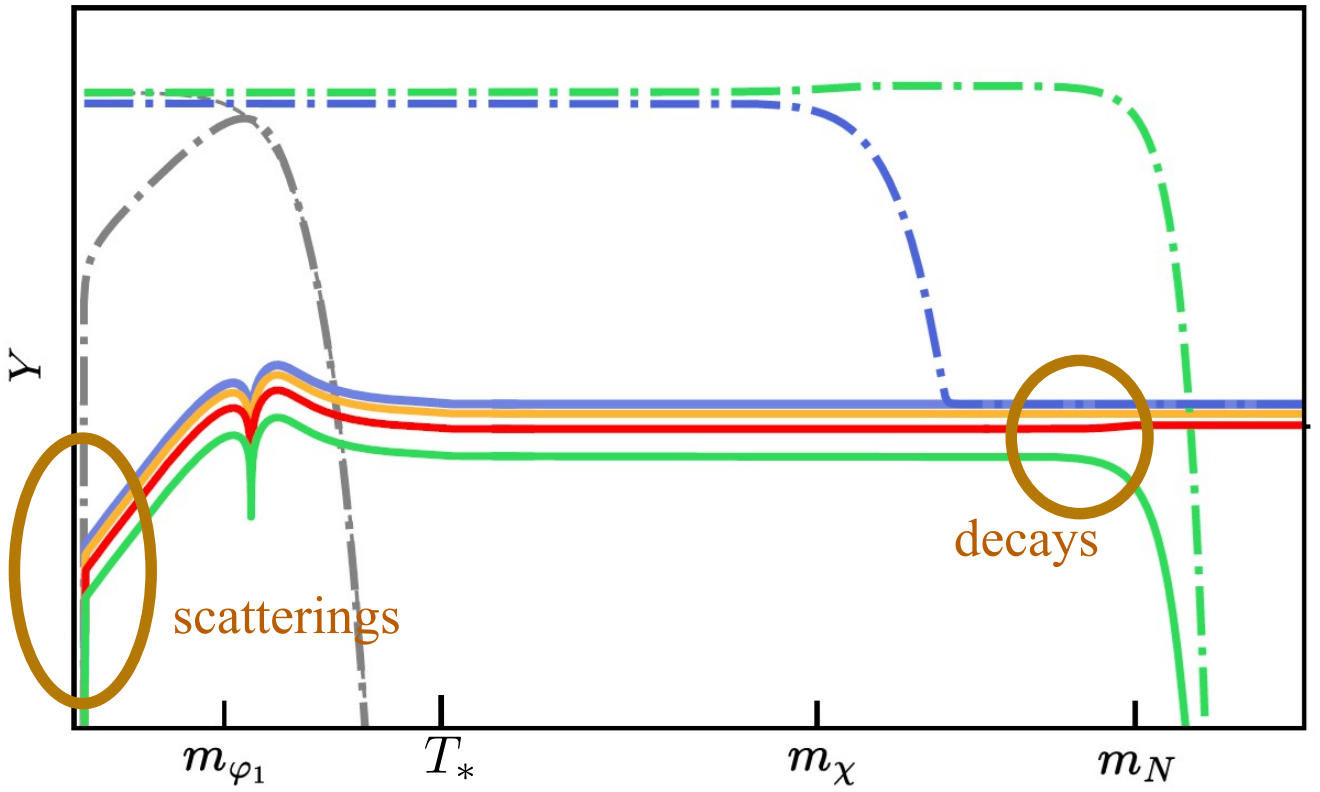
Evolution of the various yields



Evolution of the various yields



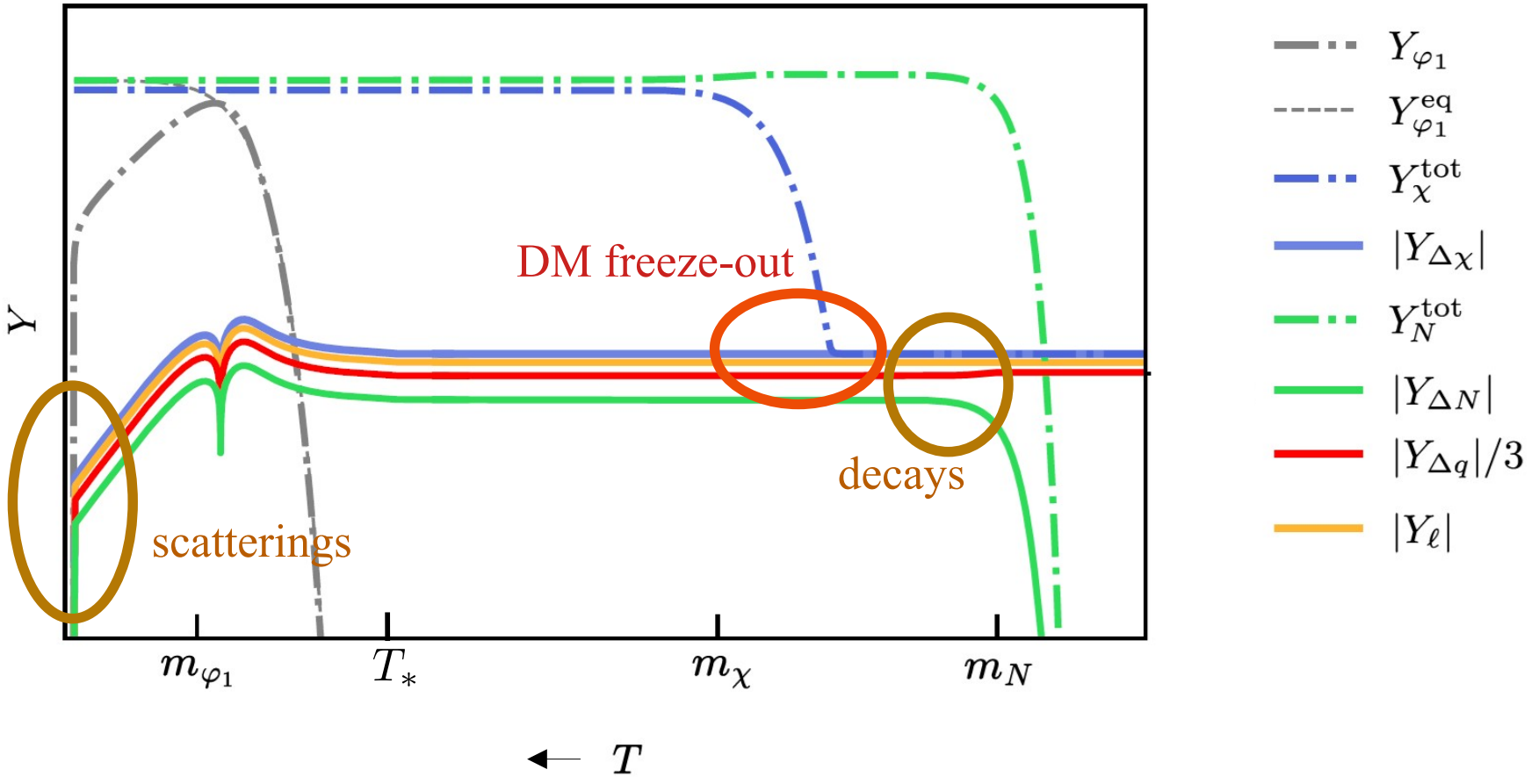
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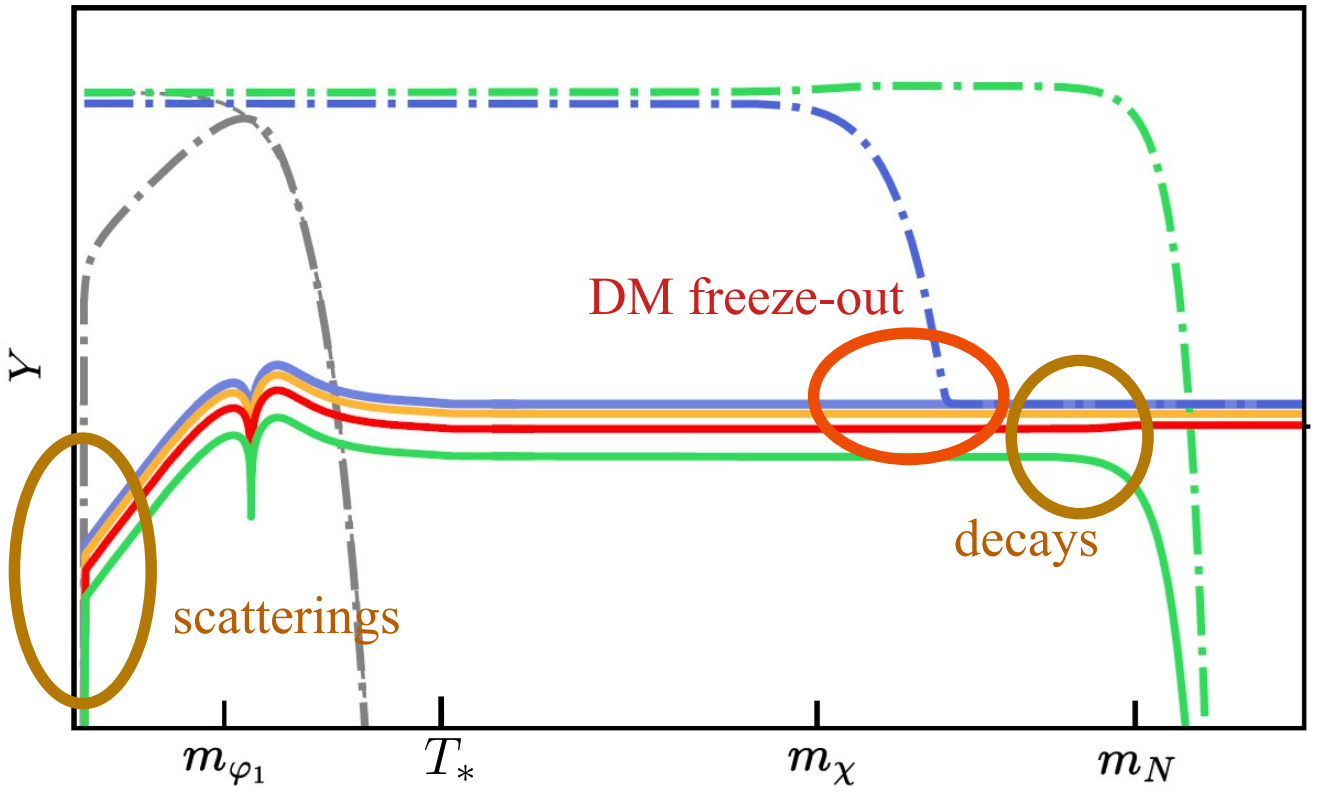
$N\bar{d} \leftrightarrow ud,$
$N\bar{u} \leftrightarrow dd$

$N \to udd$

Evolution of the various yields



Evolution of the various yields

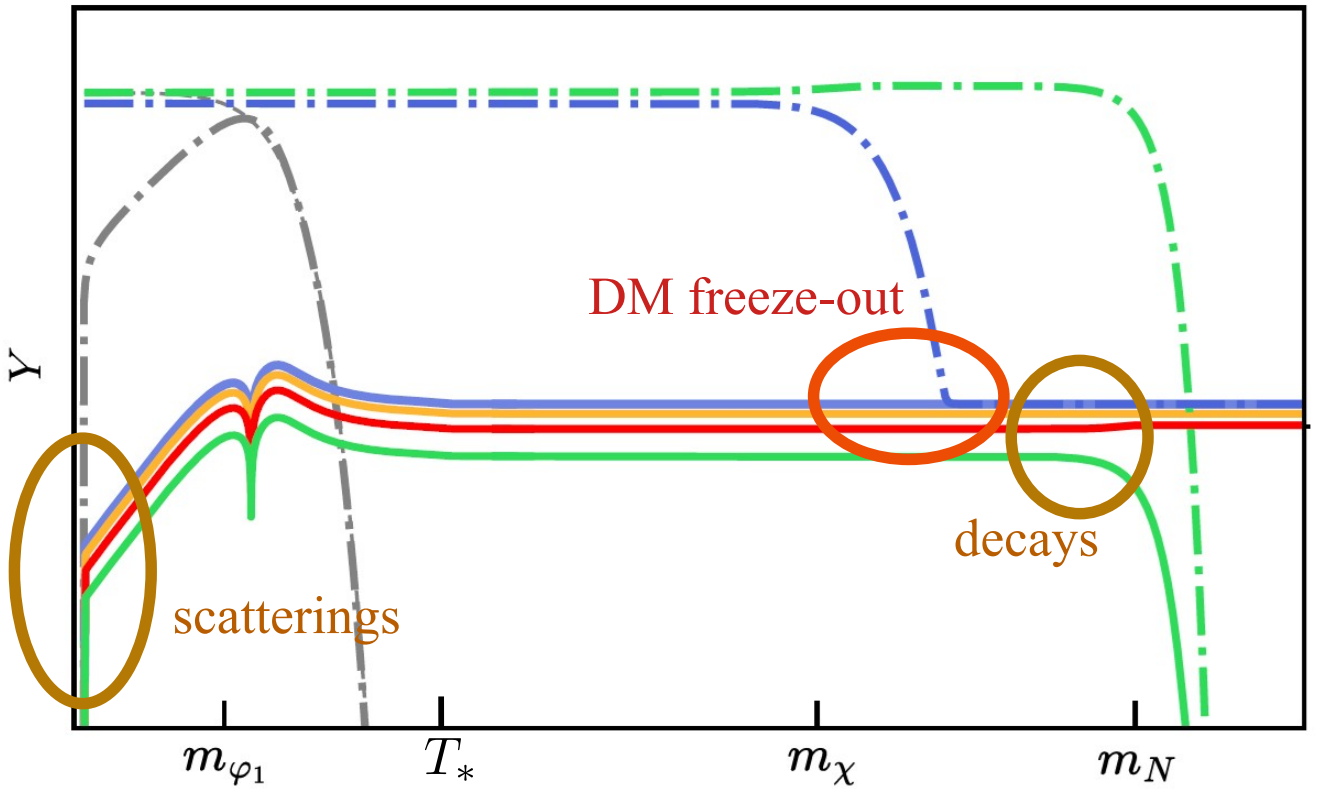


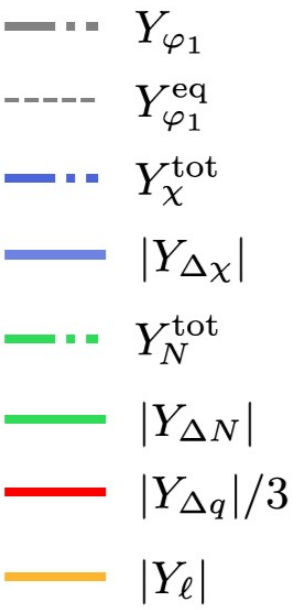
$$Y_{\Delta q,0} = \frac{141}{122} Y_{\Delta N}(T_*)$$

$$\Omega_{\rm DM,0} h^2 \simeq 2.8 \times 10^8 \, Y_{\Delta N}(T_*) \frac{m_\chi}{\rm GeV}.$$

$$Y_{\Delta N}(T_*) \simeq 2.3 \times 10^{-10}$$
$$m_\chi \simeq 1.9\,{\rm GeV}.$$

Evolution of the various yields





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

why should $m_\chi/m_p = \mathcal{O}(1)$??

A model of composite scalar dark matter

In progress with M. Sabová

Particle content:

	spin	$SU(2)_D$	B
ϕ_1	0	**2**	$-1/2$
ϕ_2	0	**2**	$-1/2$
N	1/2	**1**	$+1$

The symmetry allows the gauge singlet invariant $\epsilon_{ab}\phi_1^a\phi_2^b$ with B=-1 and $\epsilon^{ab}\phi_{1a}^\dagger\phi_{2b}^\dagger$ with B=+1.

If $SU(2)_D$ is strongly coupled, the bound state of ϕ_1 and ϕ_2 has spin 0 and B=-1:

$$\epsilon_{ab}\phi_1^a\phi_2^b \to f_\chi\chi$$

χ has the correct properties

A model of composite scalar dark matter

In progress with M. Sabová

Remarks:

1) The dark matter stability is not due to $SU(2)_D$, but due to the baryon number conservation

If B conservation is not imposed, the gauge symmetry allows

$$\mathcal{L} = \lambda_{\phi H} \left(\epsilon_{ab} \phi_1^a \phi_2^b\right) H^\dagger H$$

$$\mathcal{L} = \frac{\lambda_{\phi H} f_\chi v}{\sqrt{2}} \chi h \longrightarrow \text{DM decay}$$

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2) The scale of confinement of the $SU(2)_D$ is comparable to the one of $SU(3)_C$

$$b = \frac{11}{3} C_2(G) - \frac{4}{3} \sum_f T(R_f) - \frac{1}{3} \sum_s T(R_s)$$

$SU(3)_C$ with six quarks in **3**: $b = 7$

$SU(2)_D$ with two scalars in **2**: $b = 7$

If the couplings are comparable, $\Lambda_{QCD} \sim \Lambda_D$

If $m_{\phi_i} \ll \Lambda_D$, then $m_\chi / m_p = \mathcal{O}(1)$

A model of composite scalar dark matter

In progress with M. Sabová

3) To generate the initial asymmetries we introduce a Majorana fermion with zero baryon number.

The C and CP violating decays

$$\Psi_i \to \epsilon_{ab}\phi_1^a \phi_2^b N, \epsilon_{ab}\phi_1^{a*} \phi_2^{b*} \bar{N}$$

Generate asymmetries $(Y_{\phi_1} - Y_{\phi_1^*}) = (Y_{\phi_2} - Y_{\phi_2^*}) = (Y_N - Y_{\bar{N}})$ while keeping the total baryon number conserved.

A model of composite scalar dark matter

In progress with M. Sabová

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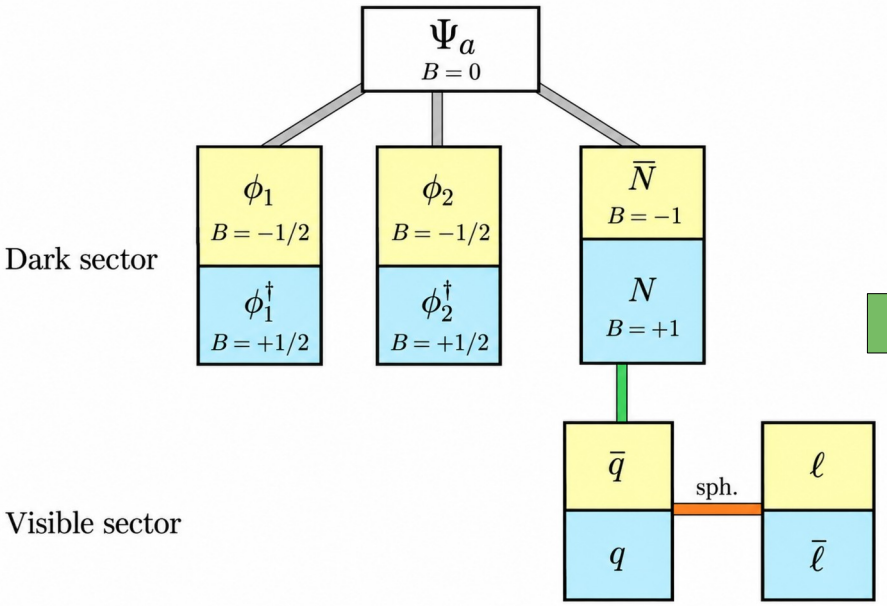
Generate asymmetries $(Y_{\phi_1} - Y_{\phi_1^*}) = (Y_{\phi_2} - Y_{\phi_2^*}) = (Y_N - Y_{\bar{N}})$ while keeping the total baryon number conserved.

4) ϕ and ϕ^* do not have time to totally annihilate into gluons before confinement. χ and χ^* annihilate into dark mesons very fast.

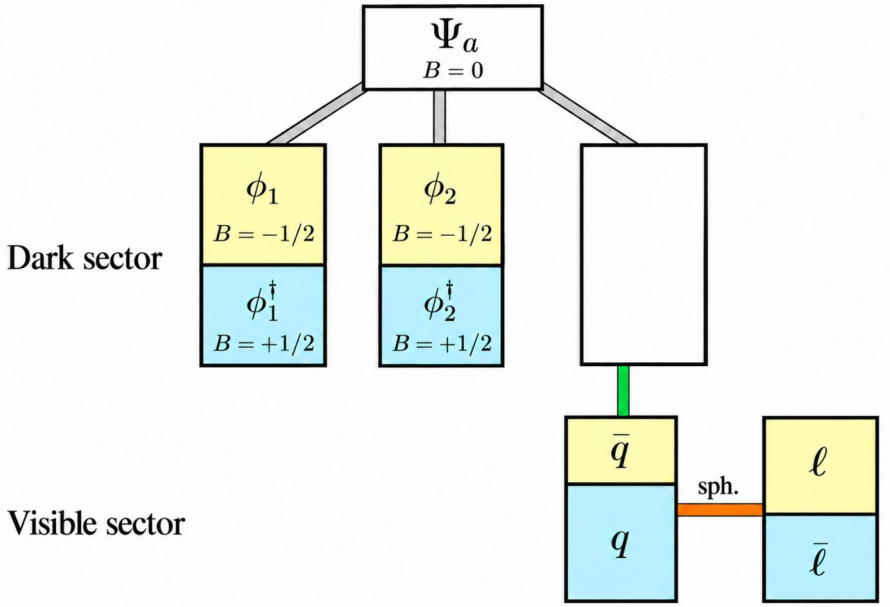
$$\chi\chi^* \to M_{ij}M_{ij}$$

A model of composite scalar dark matter

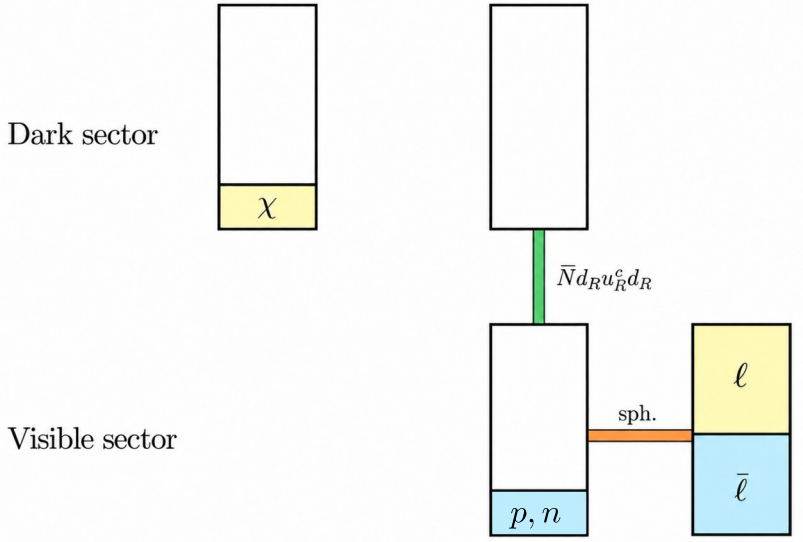
Generation of asymmetries from ψ decay



Transmission of the asymmetry in N to the visible sector



Annihilation of the symmetric parts
Confinement of ϕ and quarks



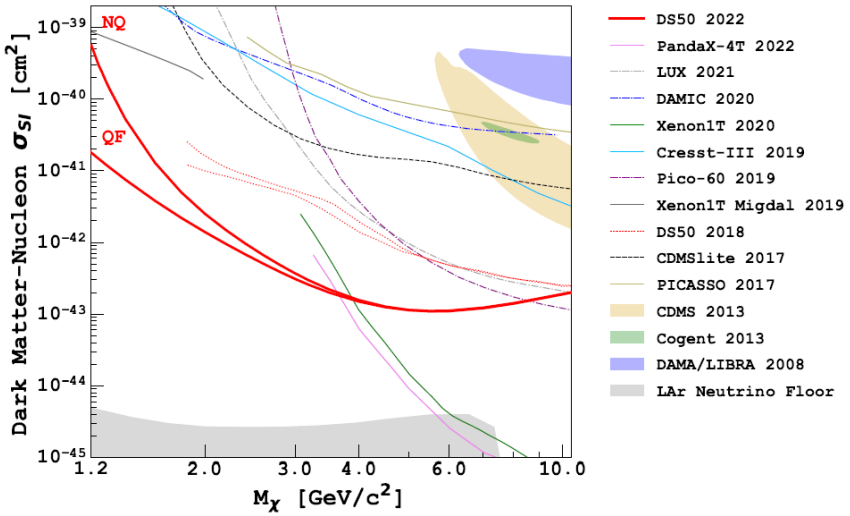
Experimental tests

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

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

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

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

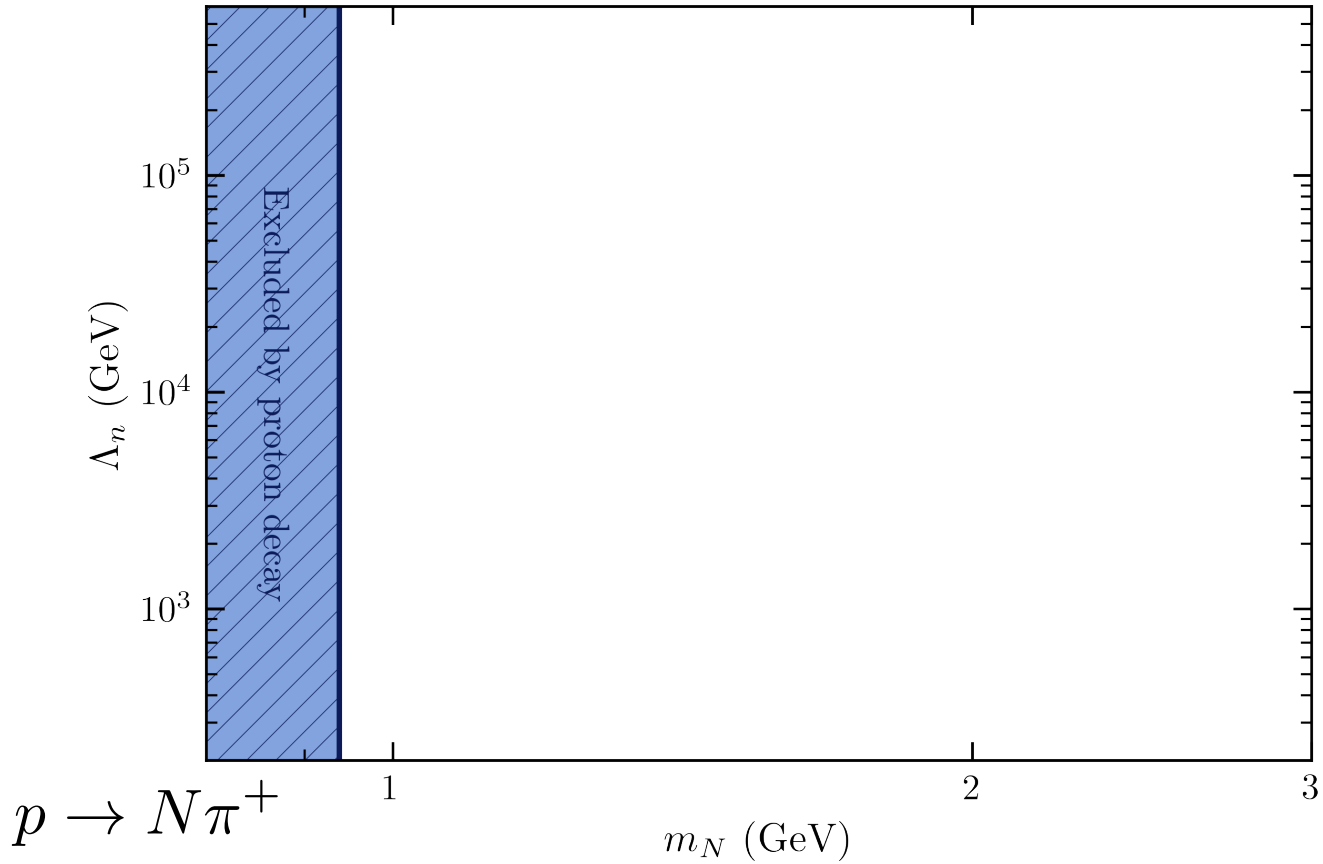


$\Rightarrow \lambda_{\chi H} \lesssim 10^{-2}$

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

Experimental tests

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

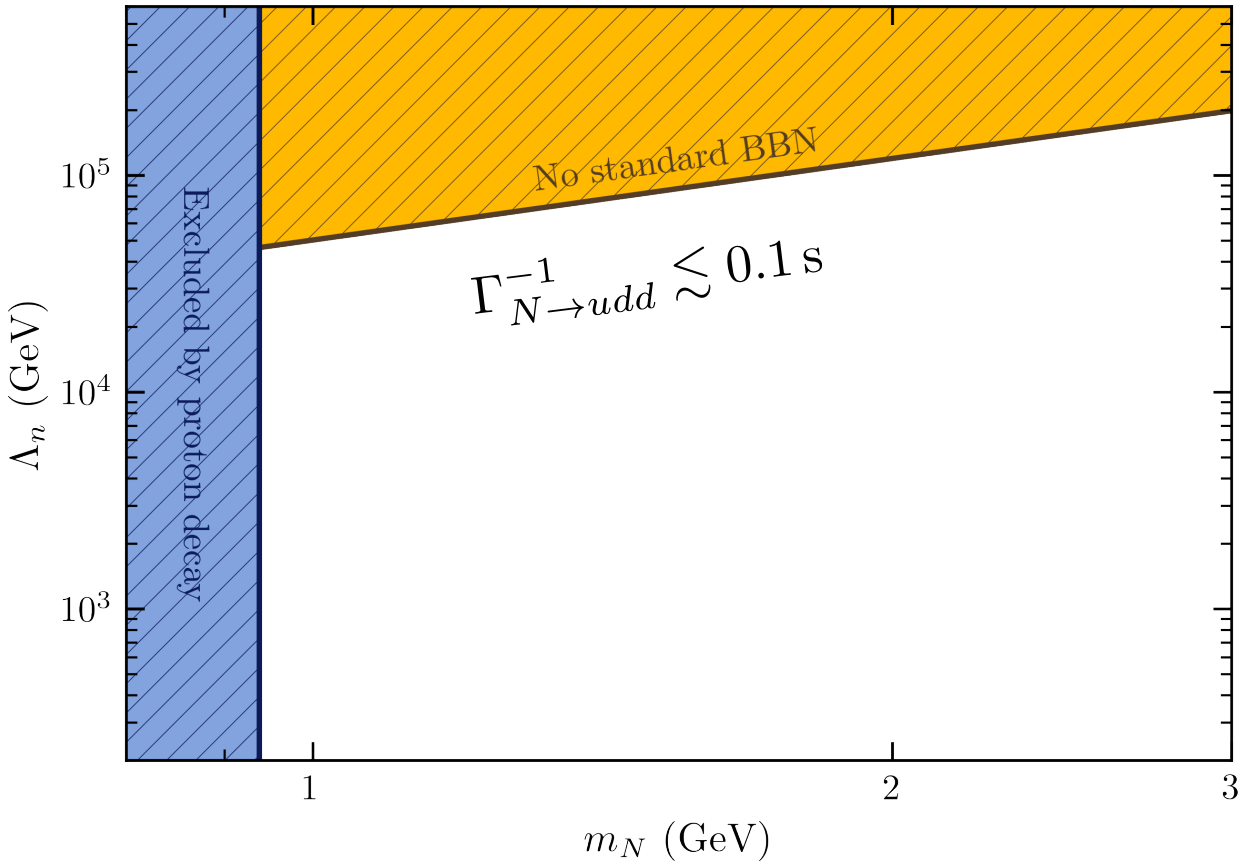


Larger N masses could be probed searching for $\Delta^+ \to N\pi^+$

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

Experimental tests

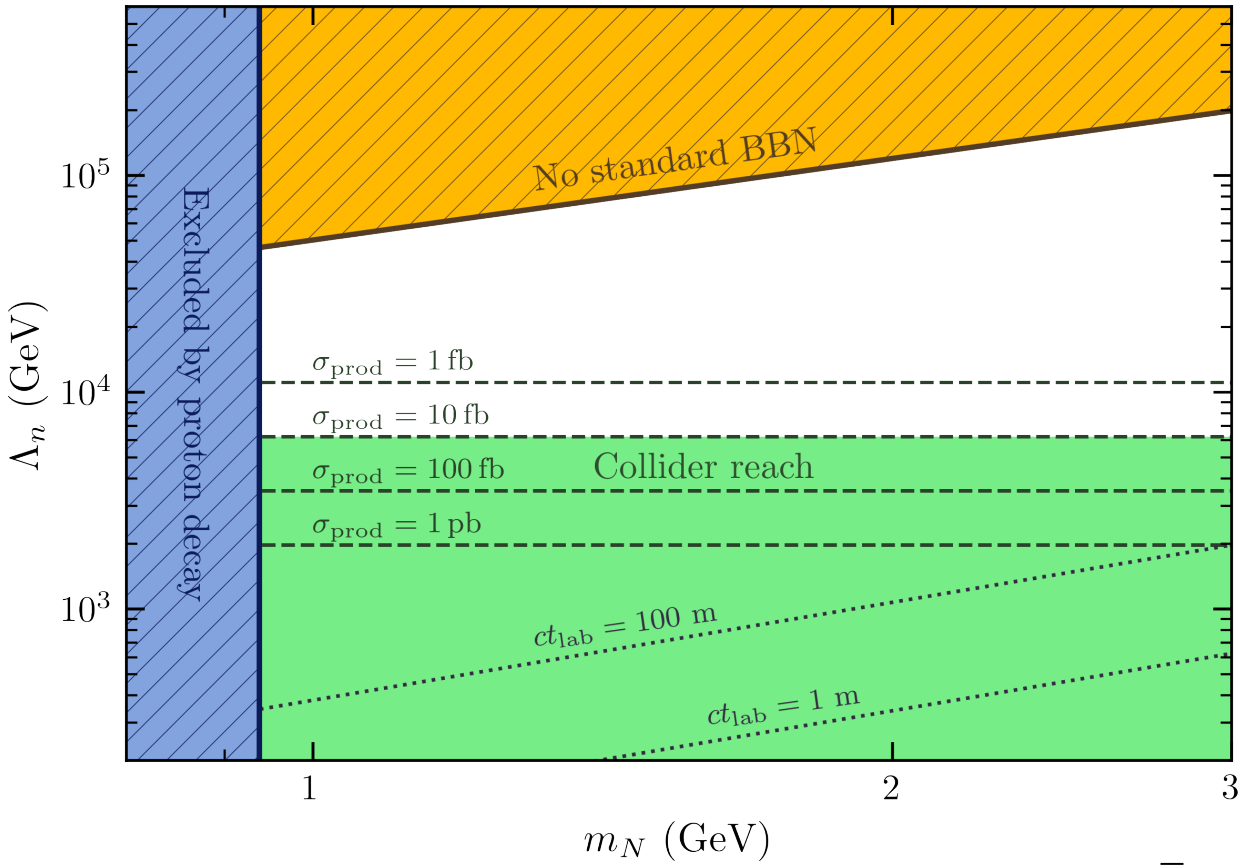
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$$\Gamma^{-1}_{N\to udd} \approx 1.6\ \mathrm{s}\left(\frac{\Lambda_n}{10^5\ \mathrm{GeV}}\right)^4\left(\frac{\mathrm{GeV}}{m_N}\right)^5,$$

Experimental tests

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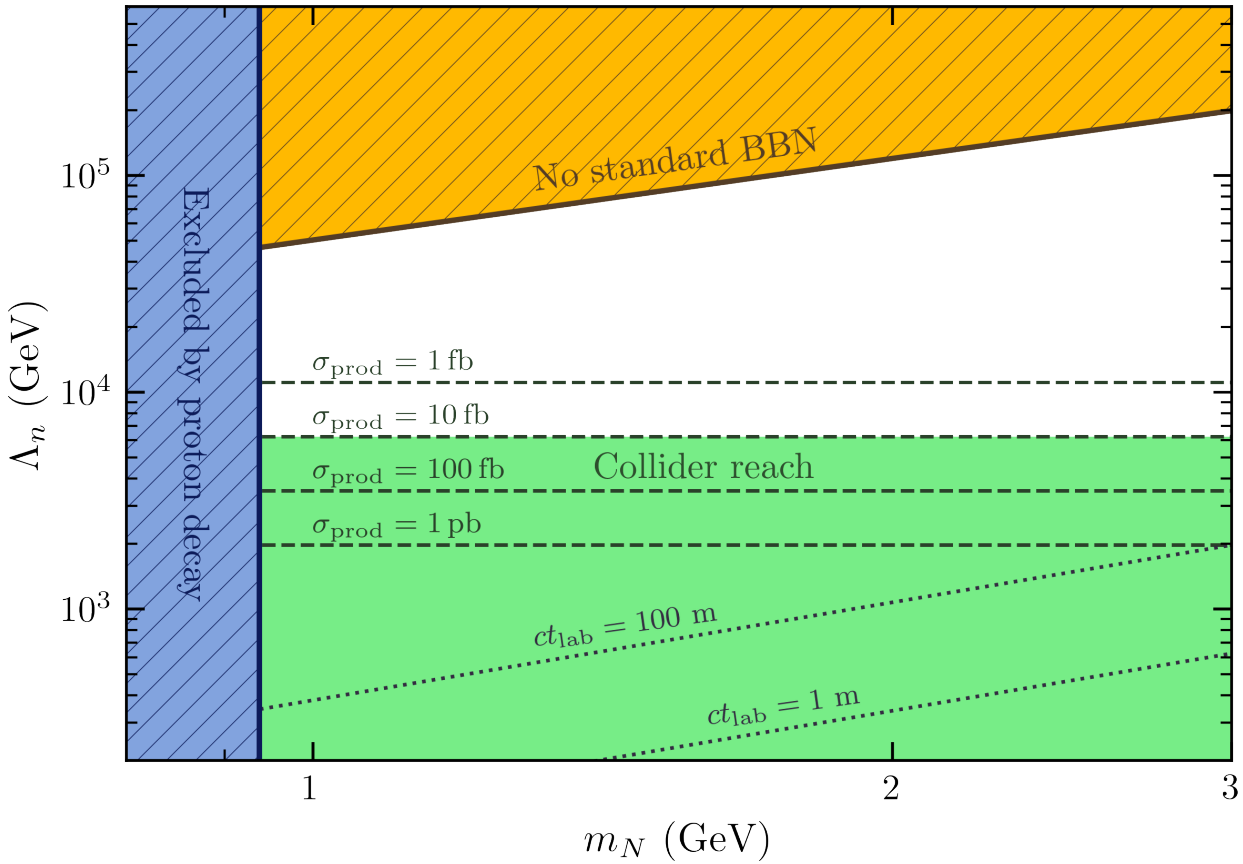


N production in pp collisions through $ud \to N\bar{d}, dd \to N\bar{u}$

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

Experimental tests

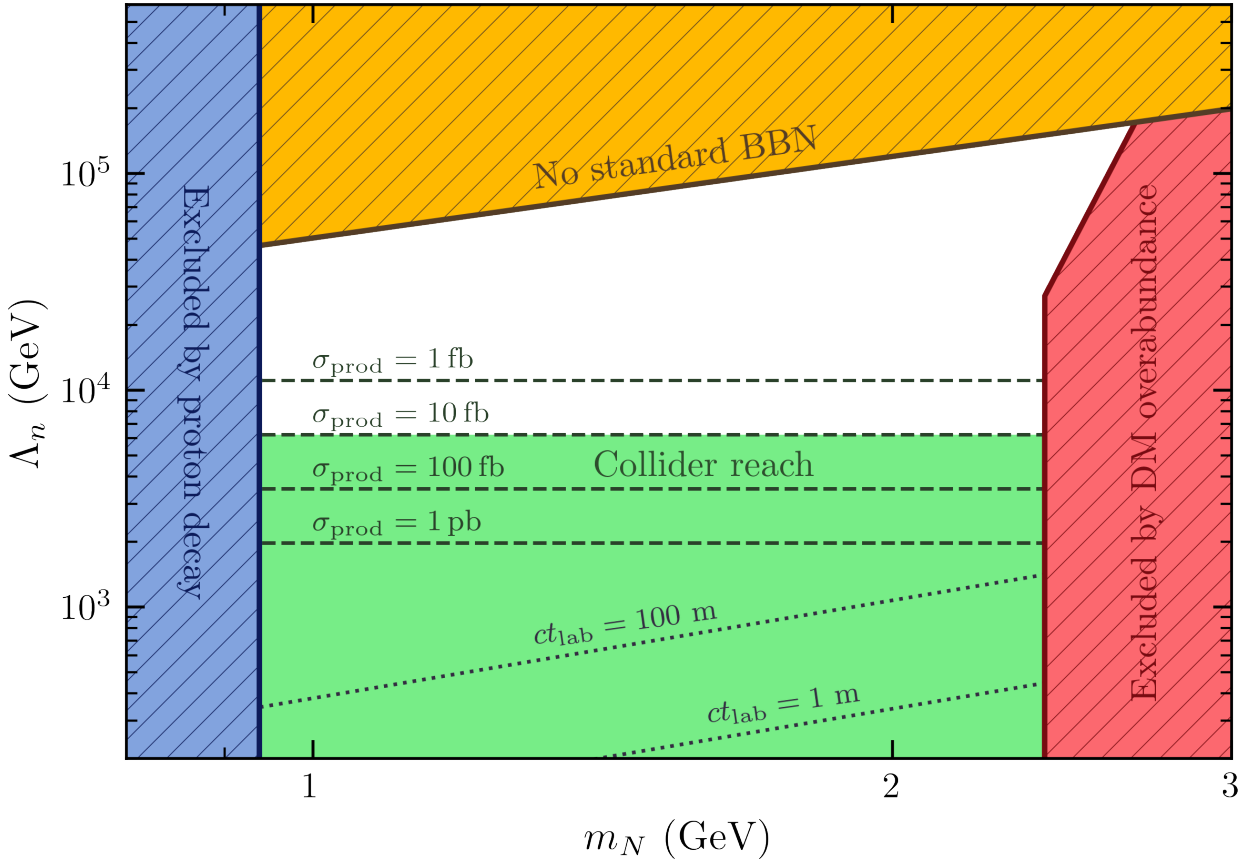
2) Neutron portal $\frac{1}{\Lambda_n^2}\overline{N} d_R \overline{u_R^c} d_R$



- 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 → meson + invisible

Experimental tests

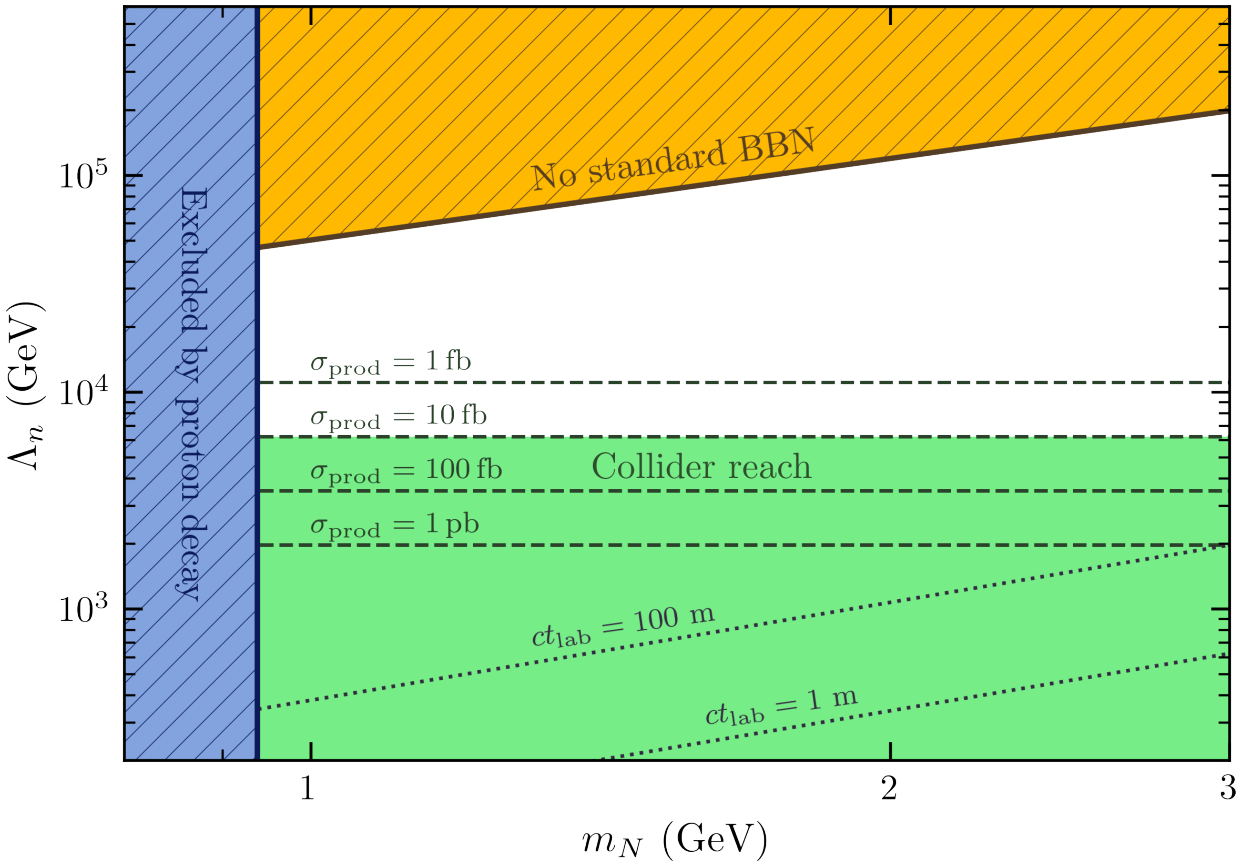
2) Neutron portal $\frac{1}{\Lambda_n^2}\overline{N}d_R\,\overline{u_R^c}d_R$



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

Experimental tests

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.

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

Conclusions

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

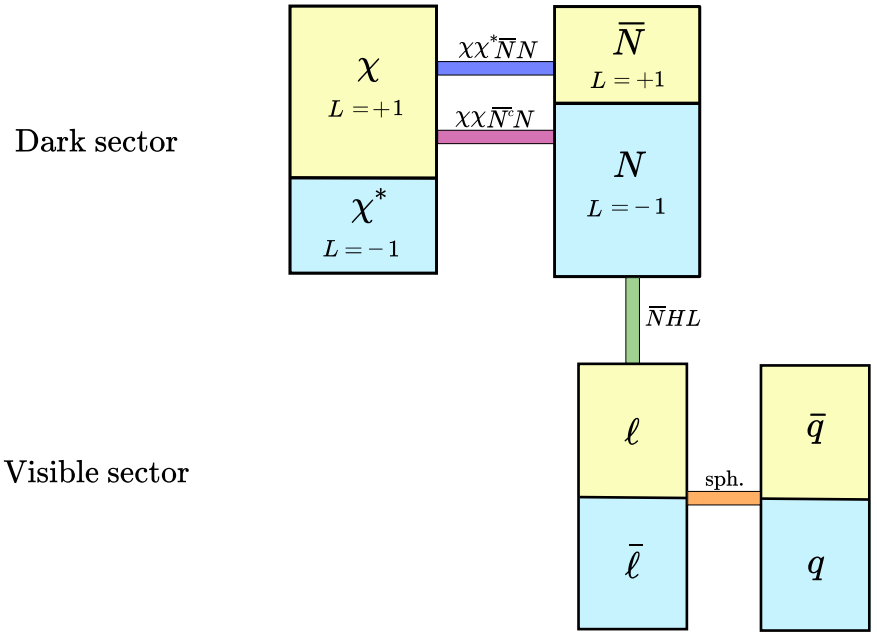
- Dark sector particles could also carry baryon number. If this is the case, a quark-antiquark asymmetry could be generated without fulfilling the Sakharov conditions.

- 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. This scenario can be realized in simple models of composite dark matter with scalar constituents.

A leptonic version

AI. Proff. To appear

high T



Low T

