Connecting the baryons to the dark matter of the Universe

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Fujiyoshida
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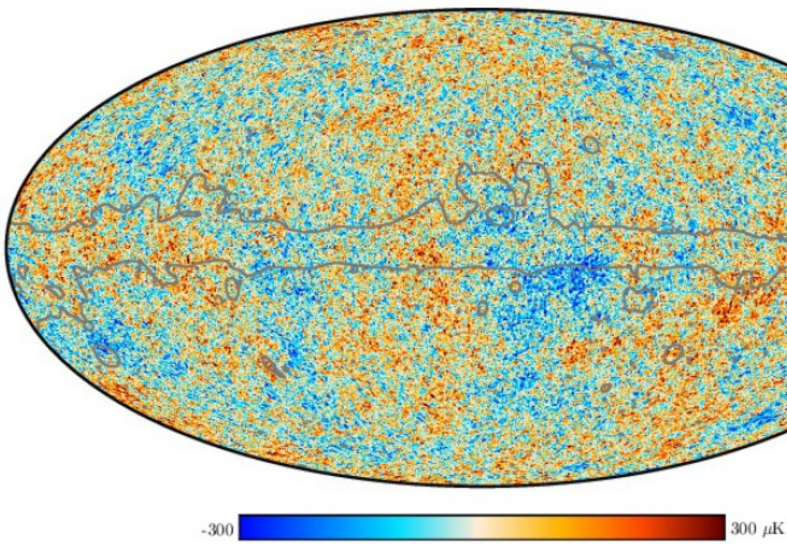
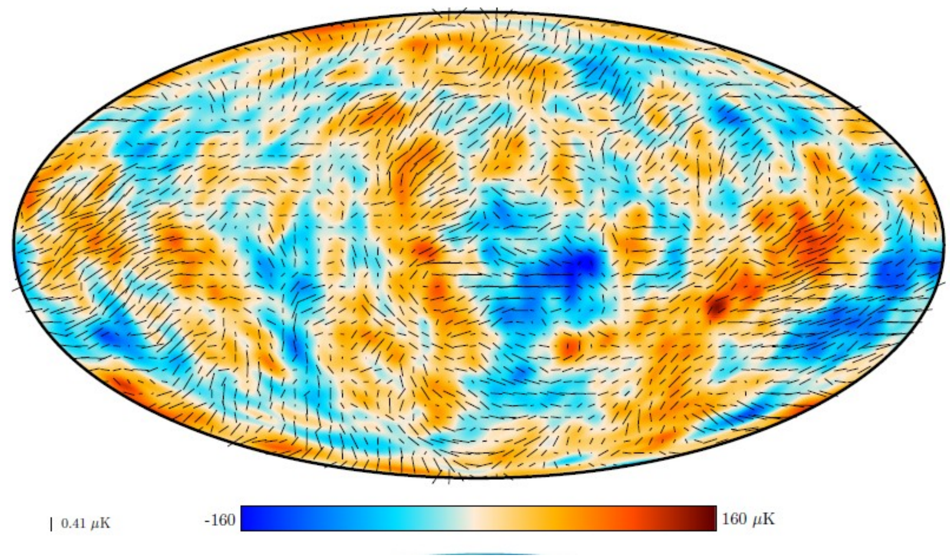
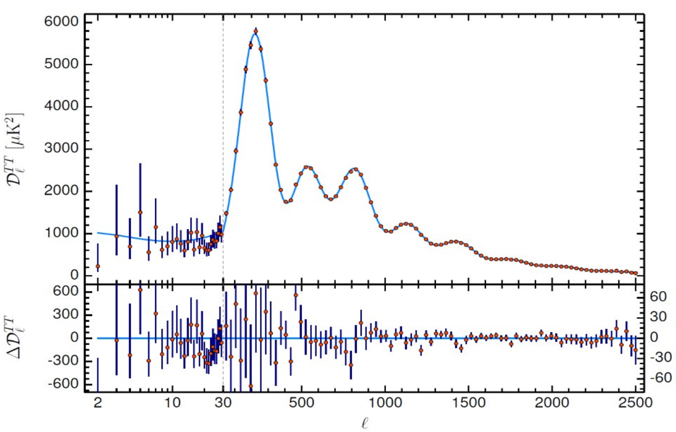
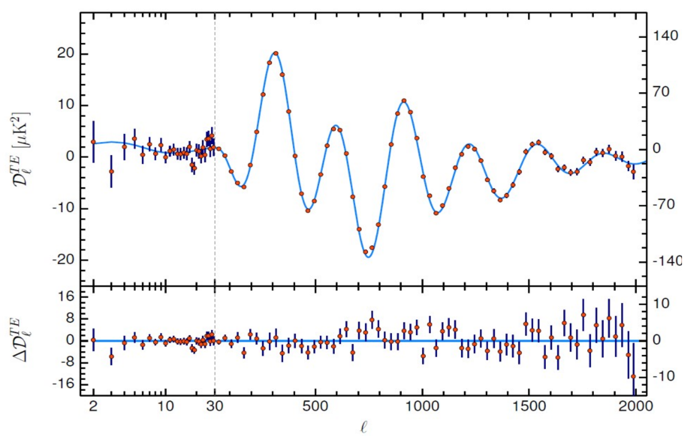
Introduction

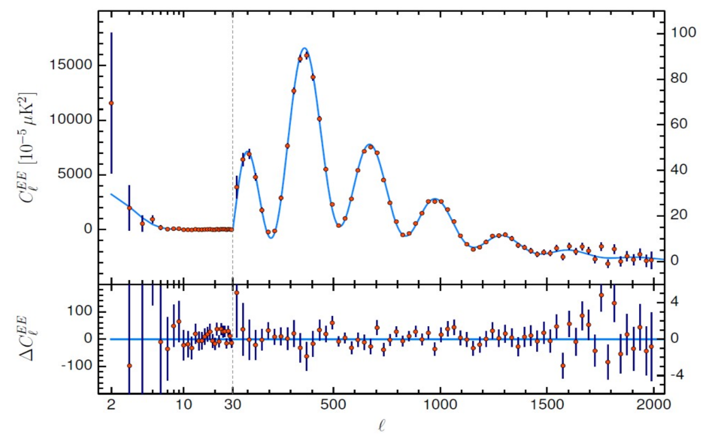
The Standard Model of Cosmology is well grounded physically and can explain with great accuracy a large number of cosmological data.











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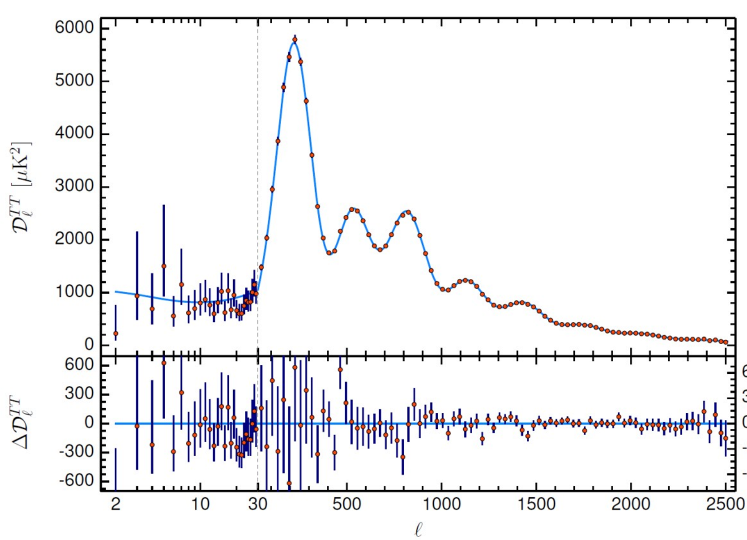

$$\rho^{\mathrm{rad}} \simeq 10^{-4} \rho_c$$

$$\rho^{\mathrm{dust}} \simeq 0.32 \rho_c$$

15% luminous

85% non-luminous

$$\rho^{\Lambda} \simeq 0.68 \rho_c$$

$$\rho^{\mathrm{tot}} \simeq \rho_c \simeq 2 \times 10^{-26} \mathrm{kg/m^3} \ \text{(spatially flat)}$$

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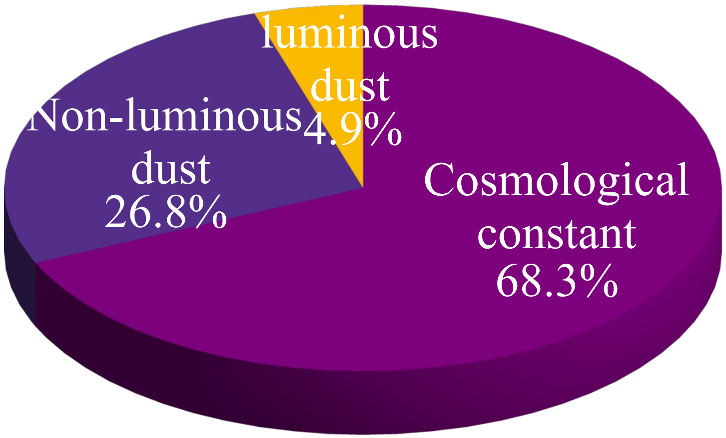


ΛCDM works very well, but it leaves many open questions:

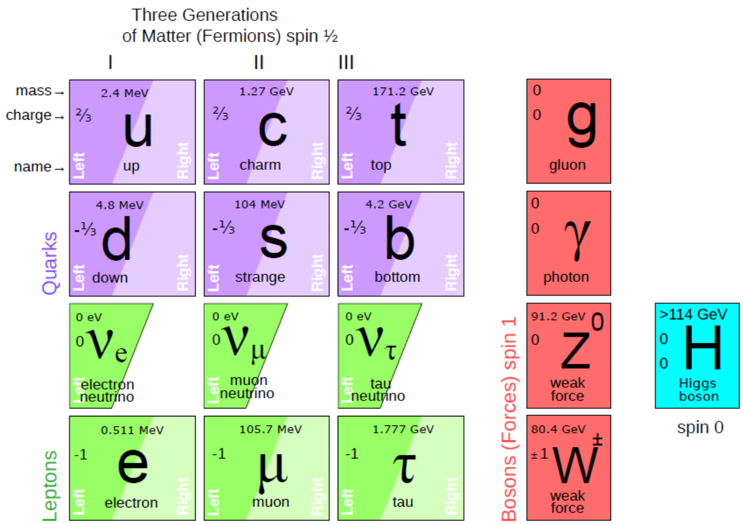
- Why is the universe spatially flat?
- Why the density contributions from the luminous and non-luminous matter components are comparable?
- Why the density contributions from the matter components and the cosmological constant are comparable *today*?
- What are the cosmic fluids made of? Can they be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

A tale of two Standard Models

The Standard Model of Particle Physics

Quantum Field Theory

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



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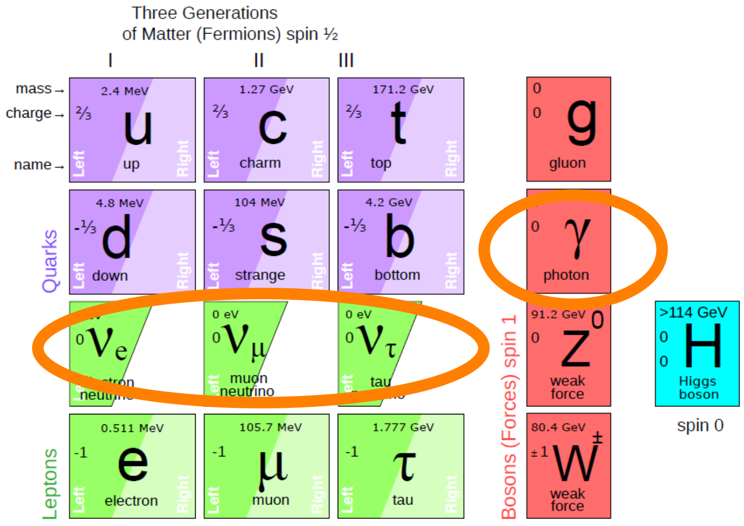

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The Standard Model of Particle Physics explains the radiation content of our Universe.

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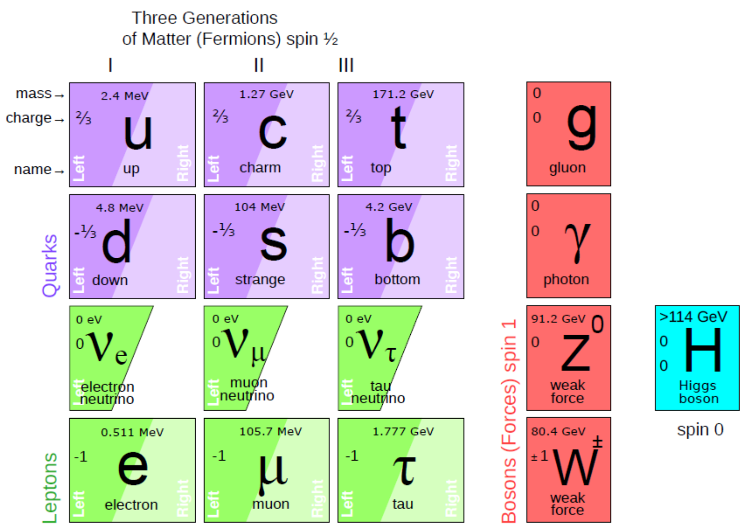

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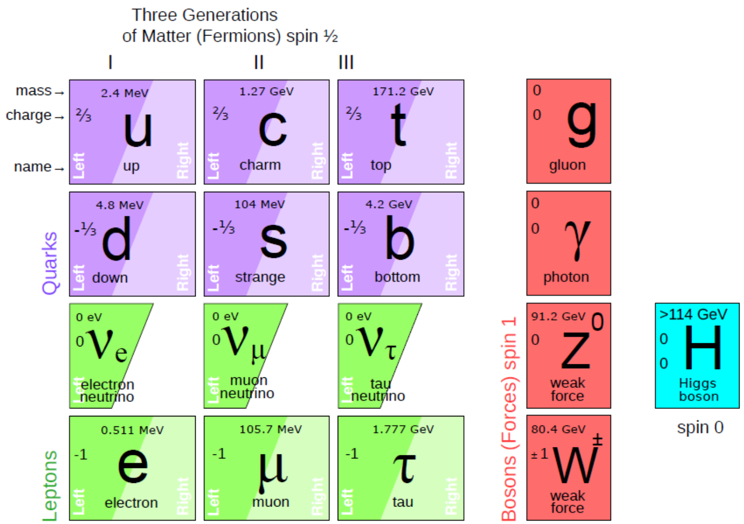

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Evidence for Physics beyond the Standard Model

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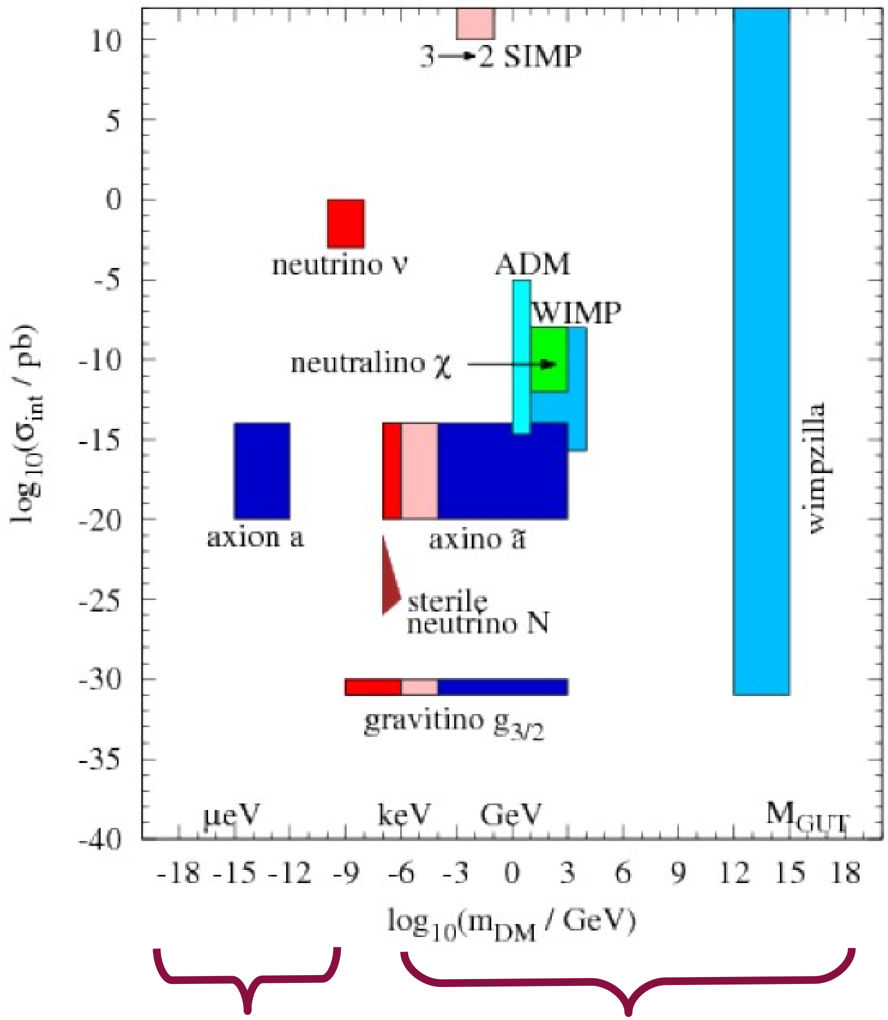
The dark matter zoo



Naturally long-lived on cosmological time-scales

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

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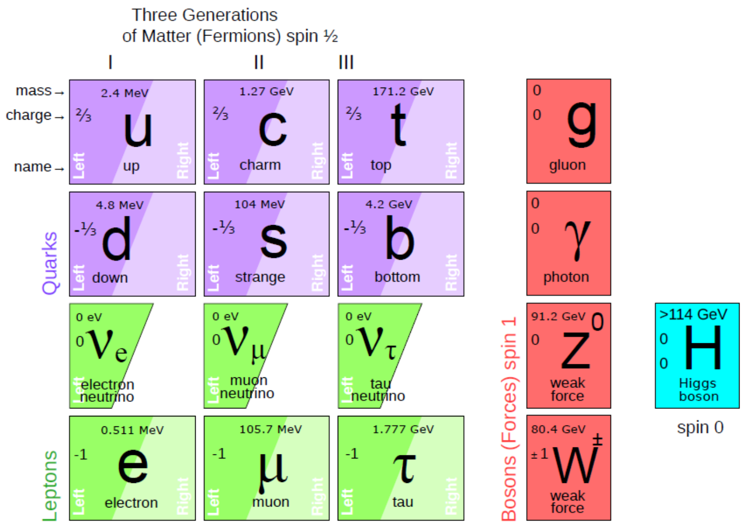

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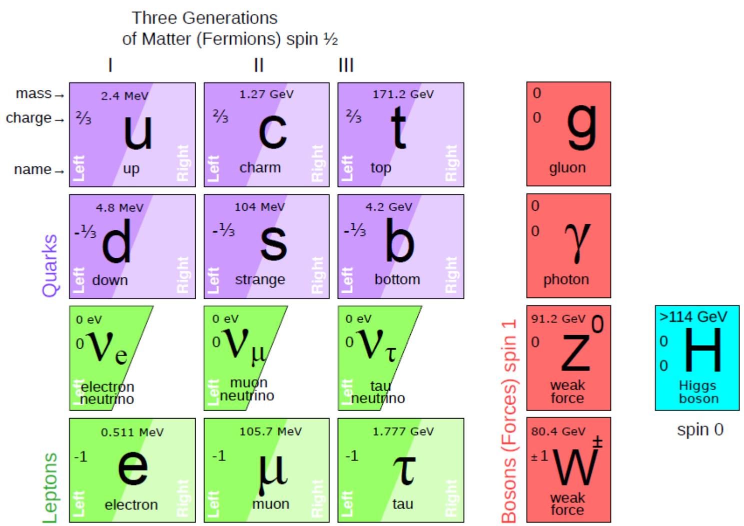

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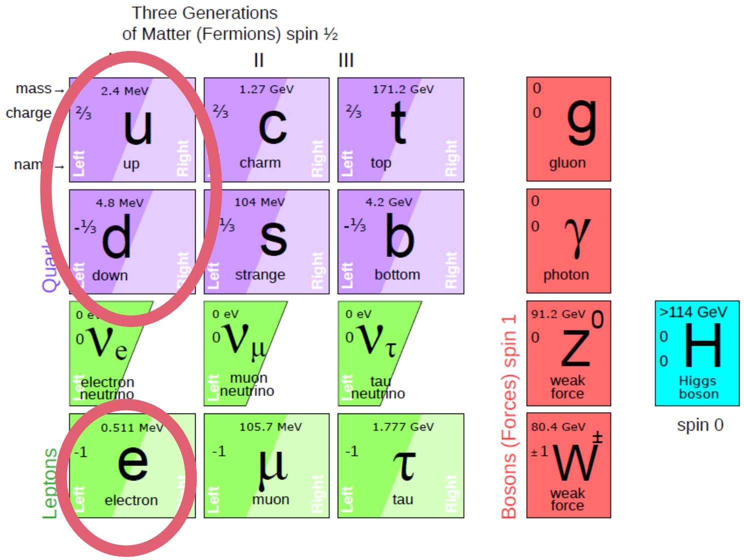

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The Standard Model leads to candidates for cosmologically stable luminous matter (protons, electrons, nuclei...)

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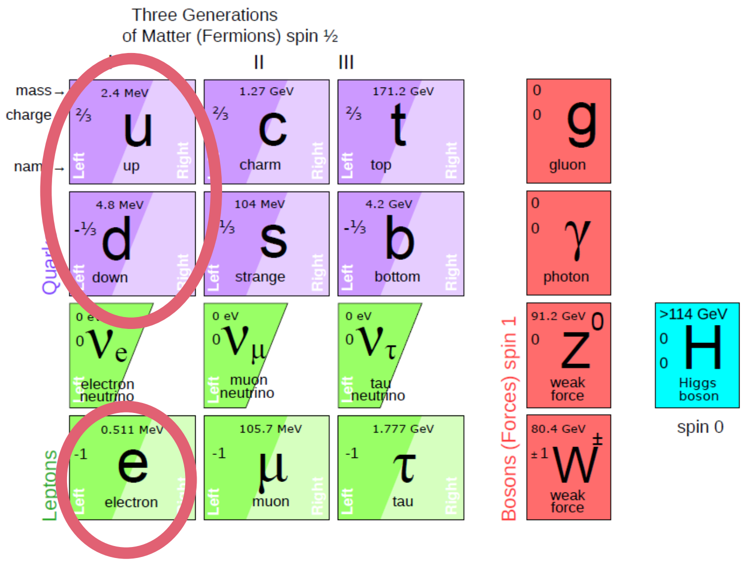

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The Standard Model leads to candidates for cosmologically stable luminous matter (protons, electrons, nuclei...)

But where is the luminous *antimatter*??

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• 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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• 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.

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Baryogenesis

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

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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

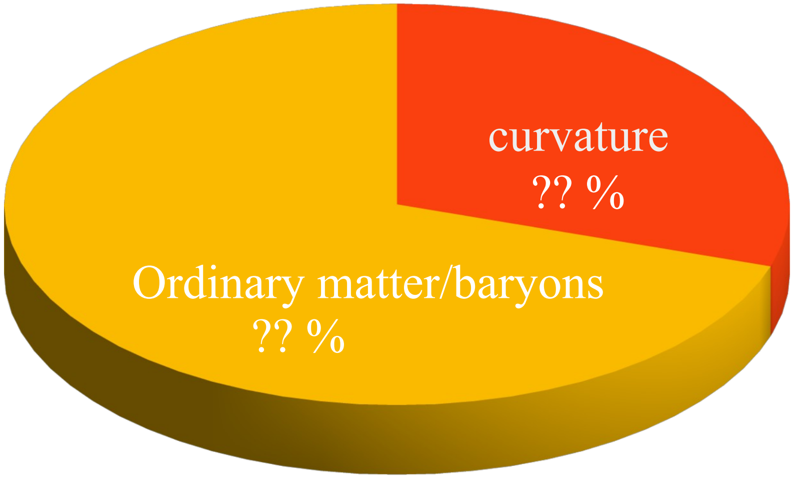
  Affleck, Dine '85

- 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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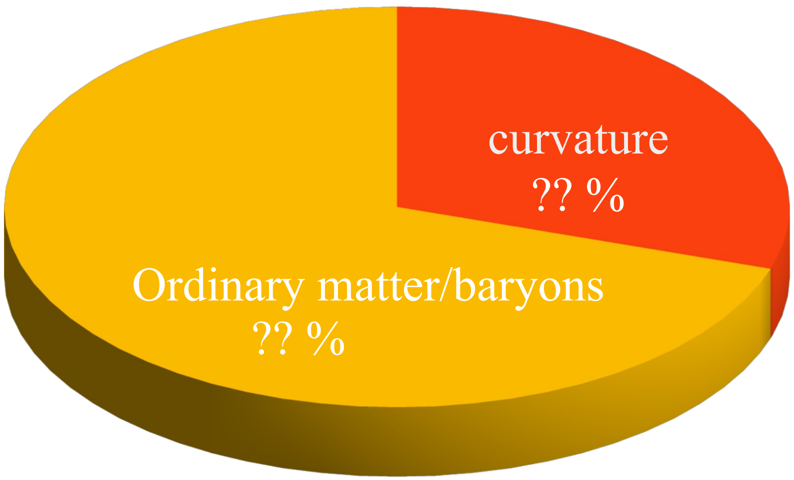

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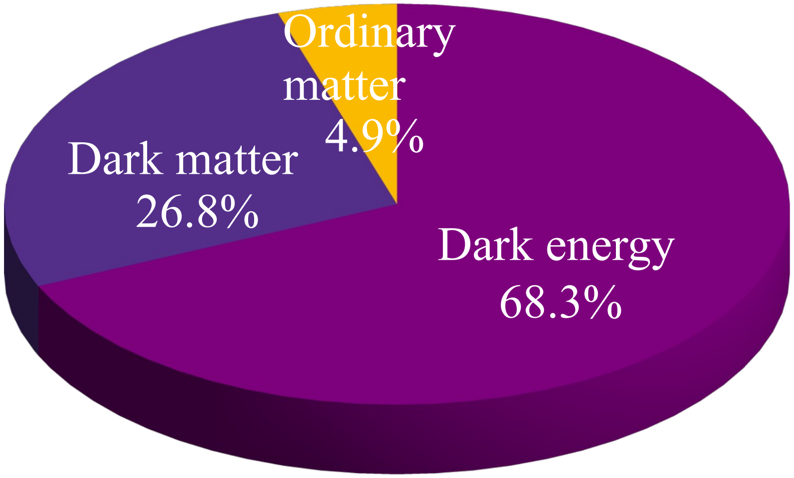

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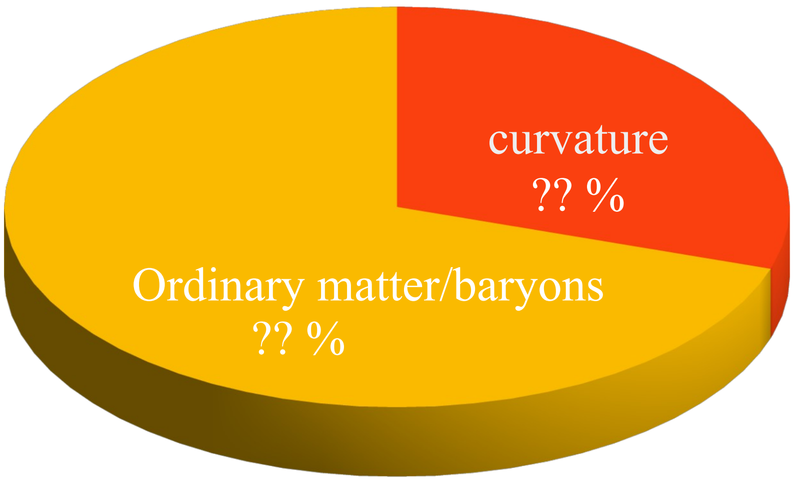

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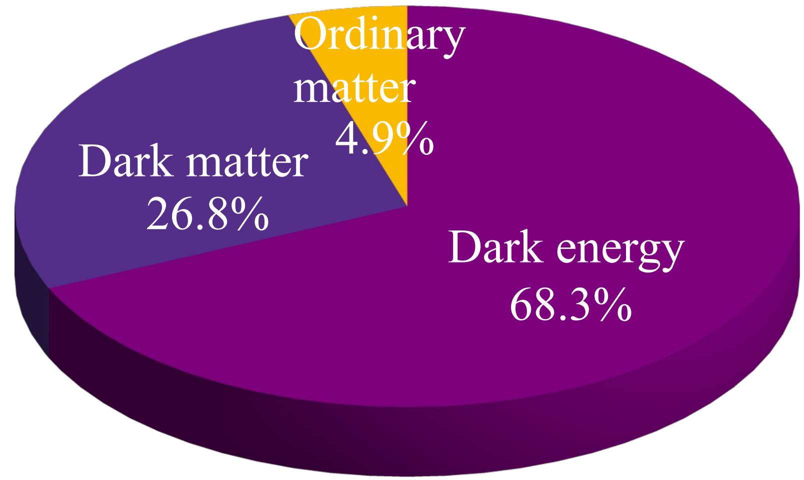

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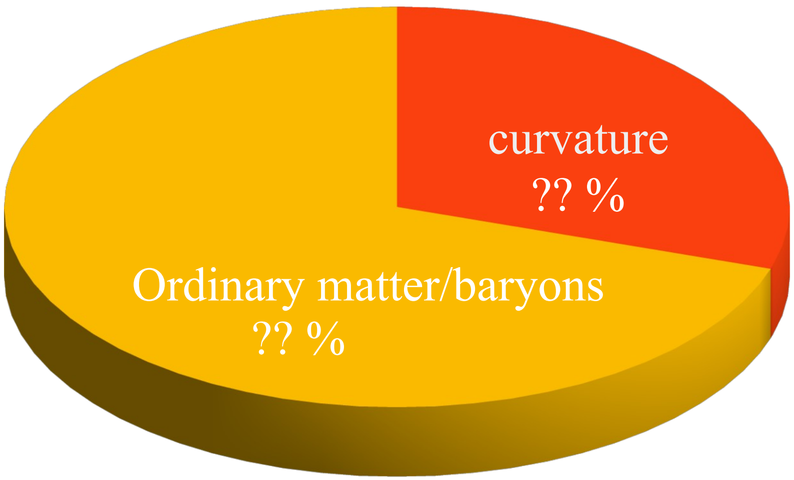

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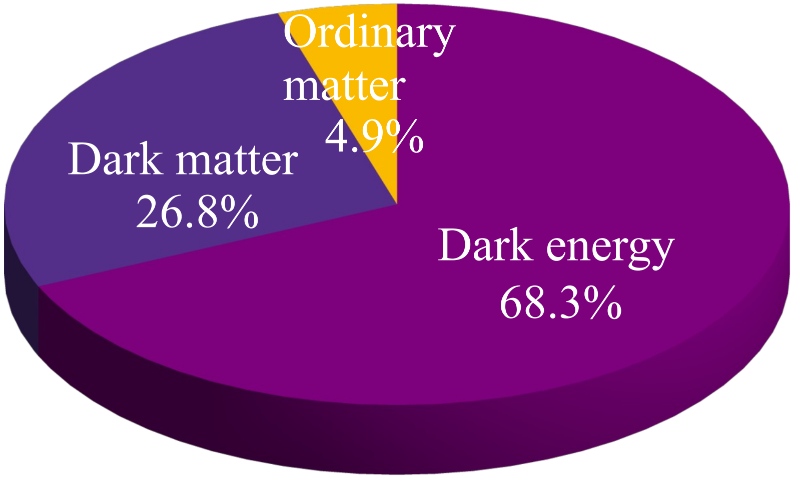

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- Observations only show that there are more quarks than antiquarks.

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

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

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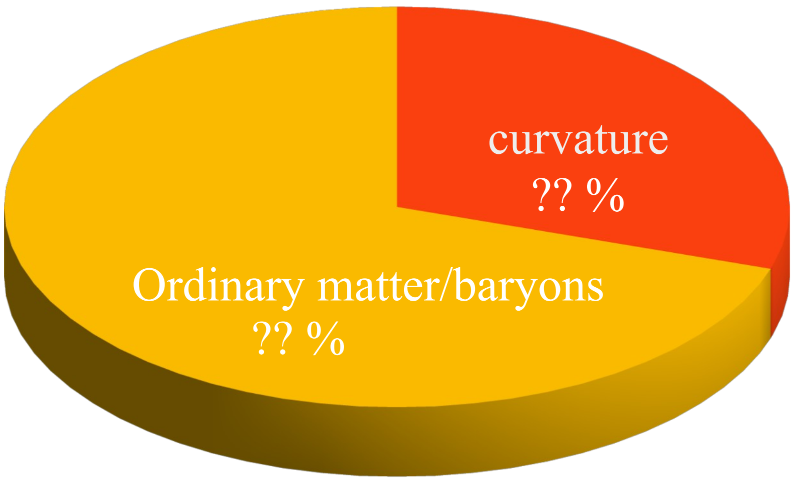

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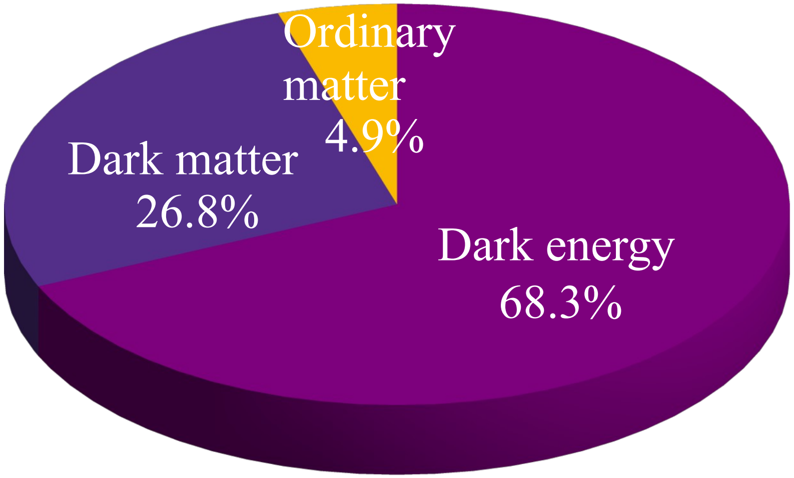

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The Sakharov conditions may not be necessary

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
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  "Neutron portal" $\overline{N} d_{\mathrm{R}} \, \overline{u^c_{\mathrm{R}}} d_{\mathrm{R}}$. Transmits the asymmetry in N to the visible sector and generates a quark-antiquark asymmetry

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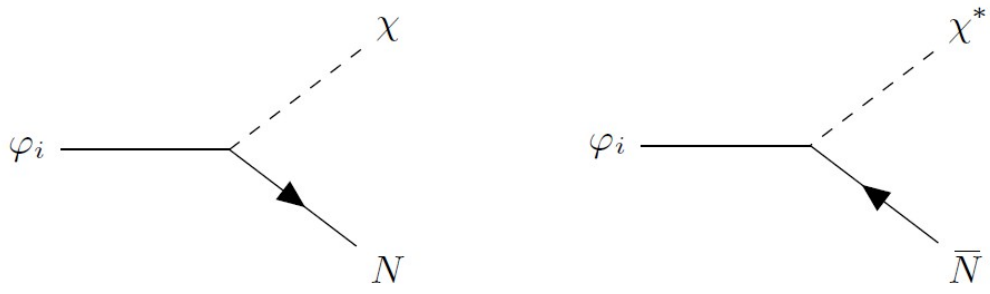

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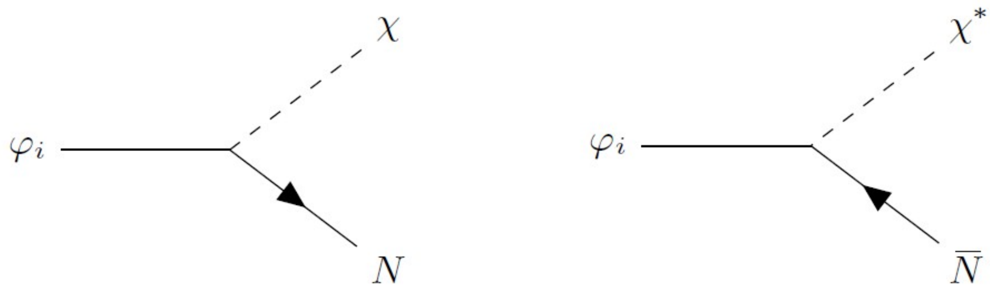

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Bonus: χ is absolutely stable, due to the conservation of baryon number.

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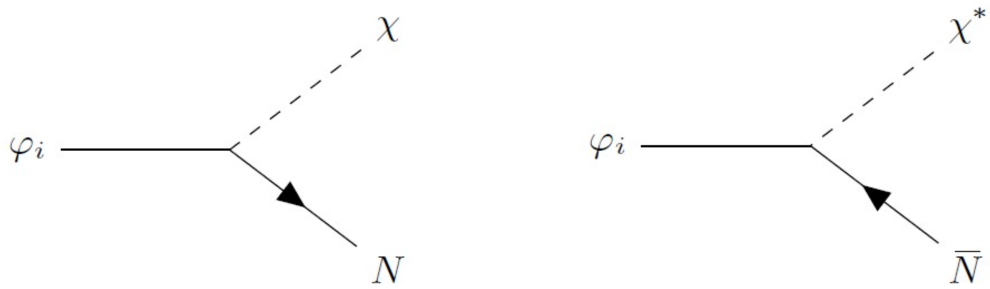

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quark-antiquark asymmetry ⟺ **dark matter stability**

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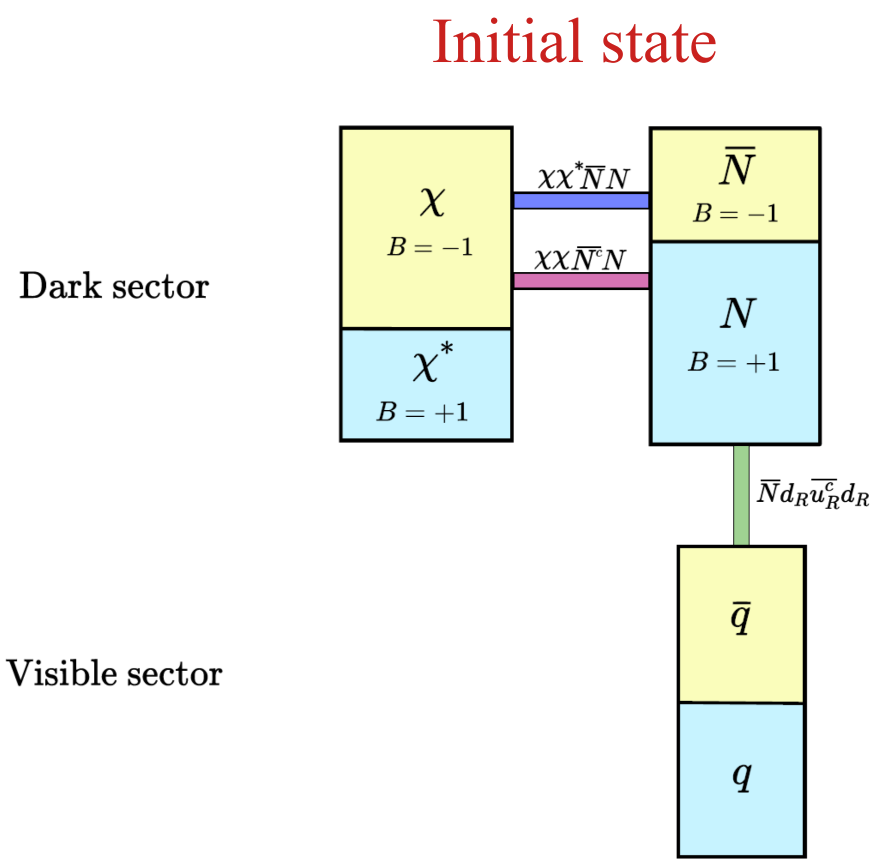

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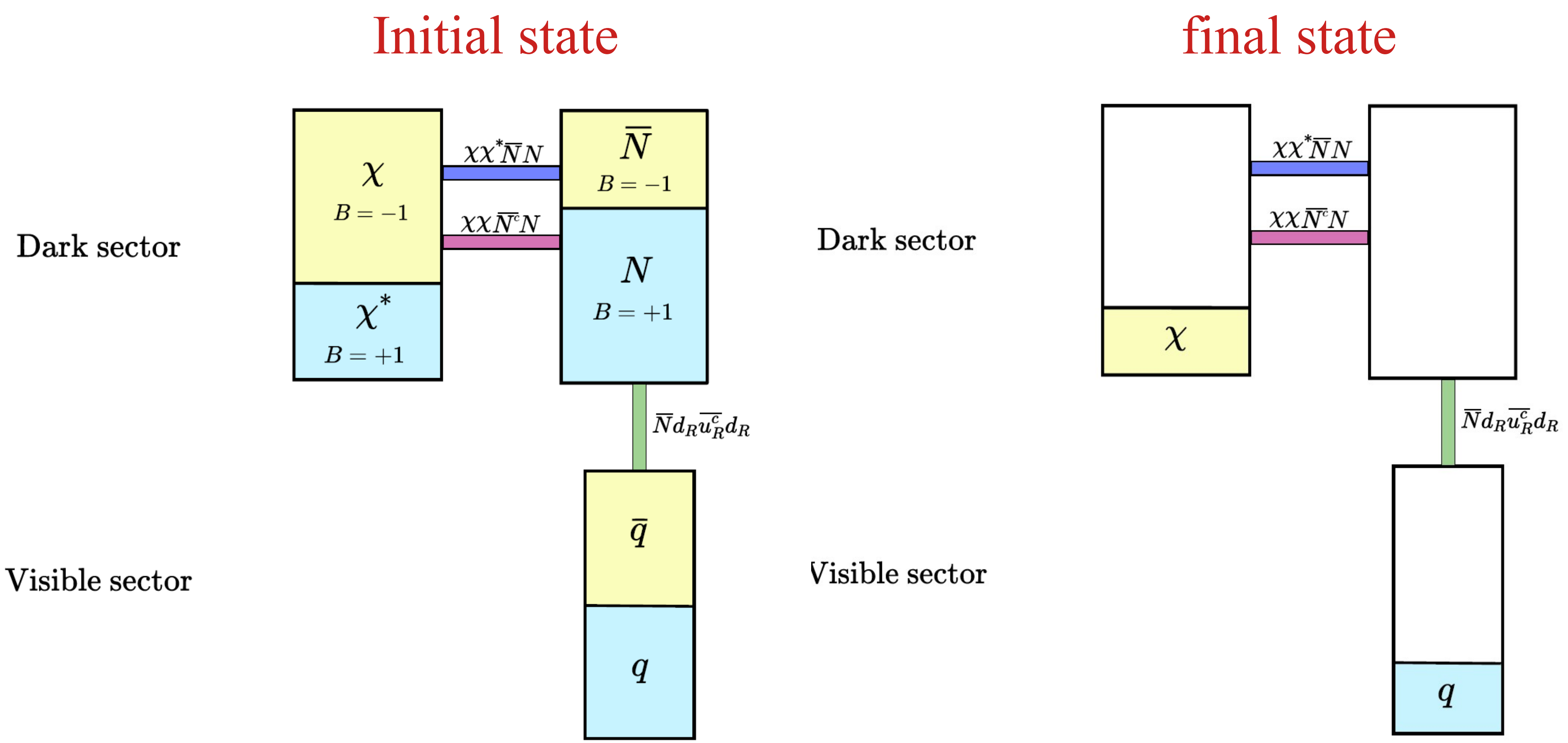
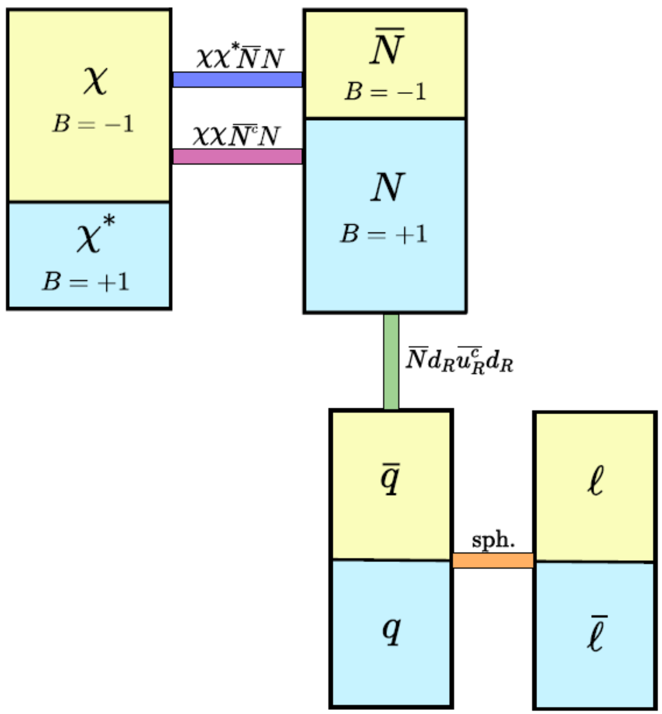


A more refined scenario

Initial state

Dark sector

Visible sector



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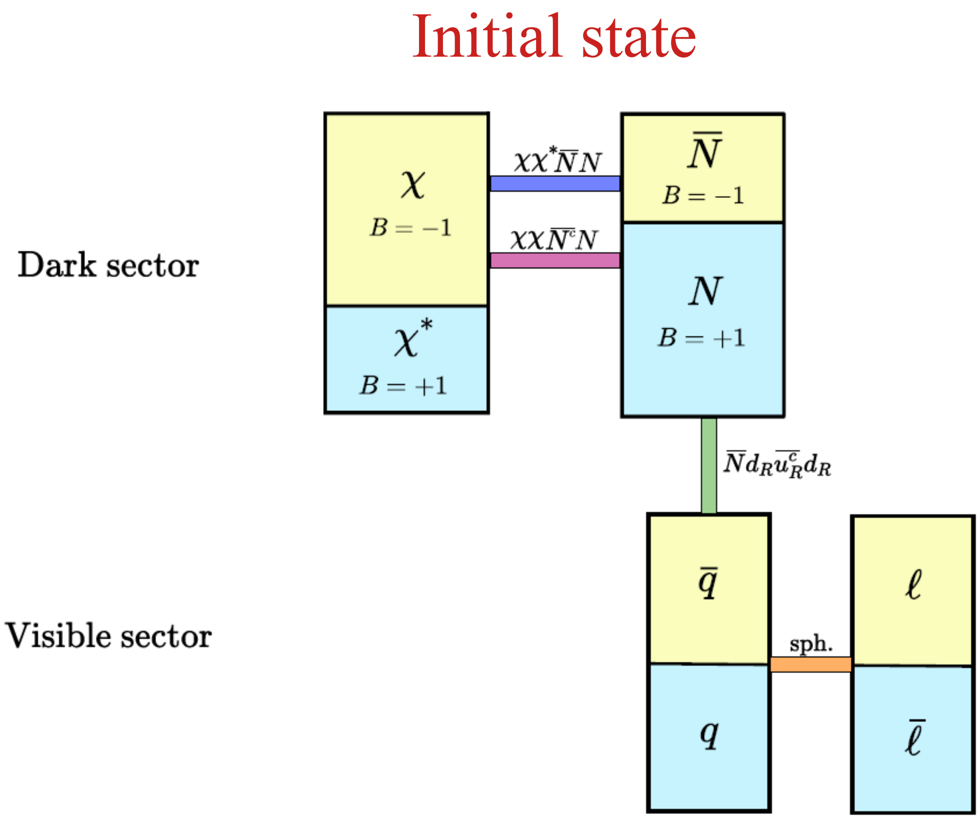

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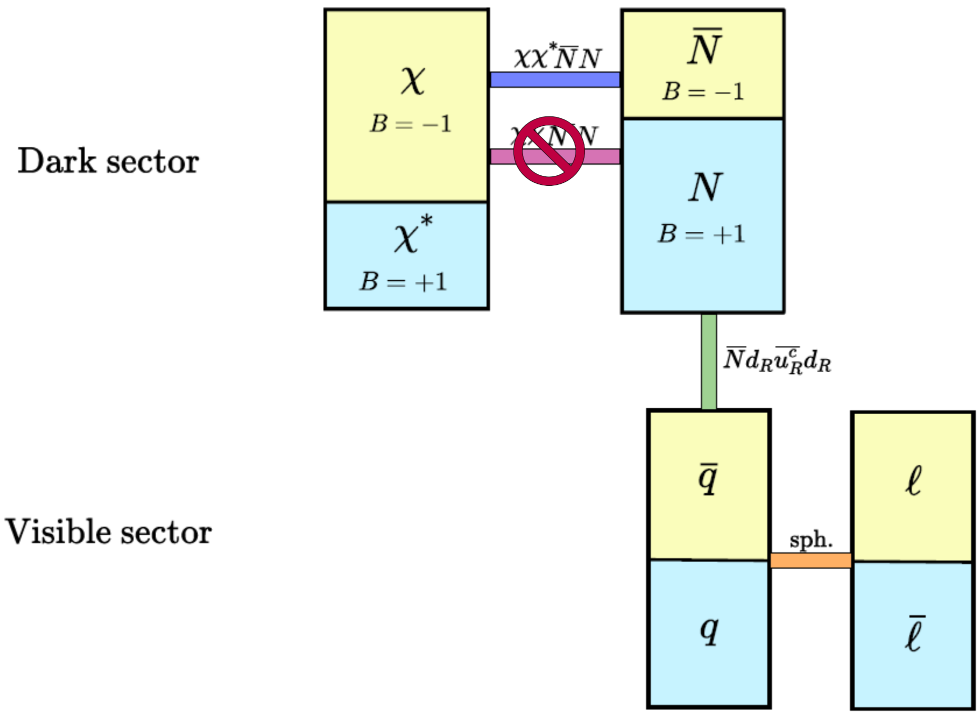

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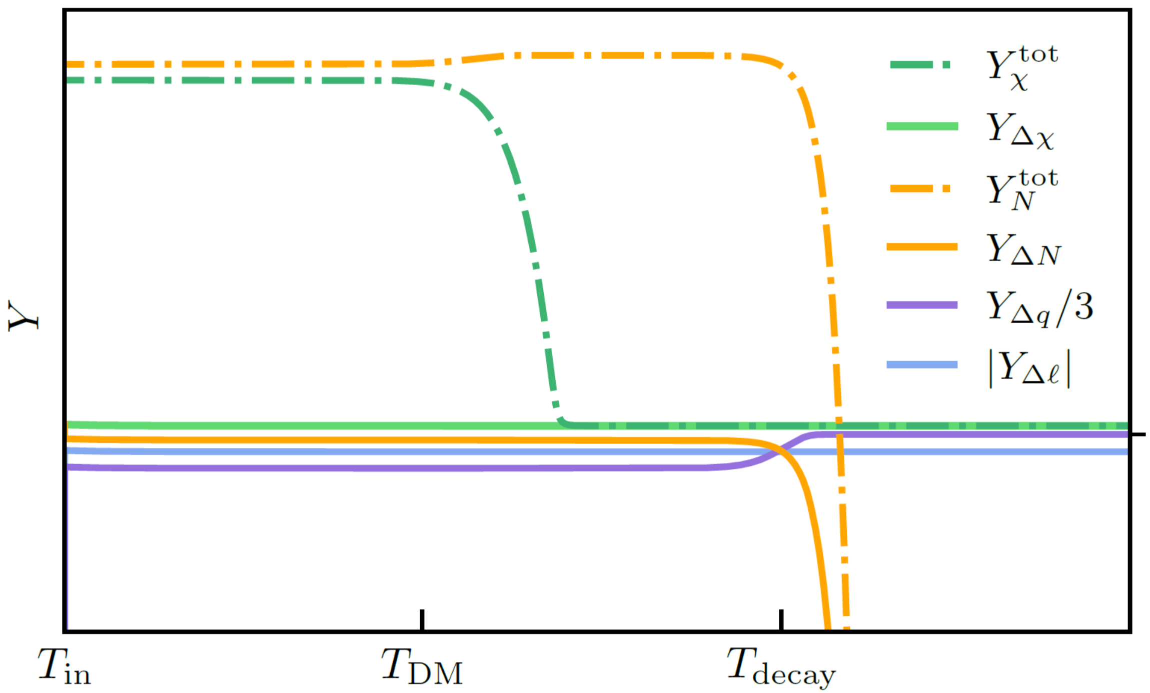
$$Y_N^{\mathrm{eq}} = 2Y_\chi^{\mathrm{eq}}$$

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

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



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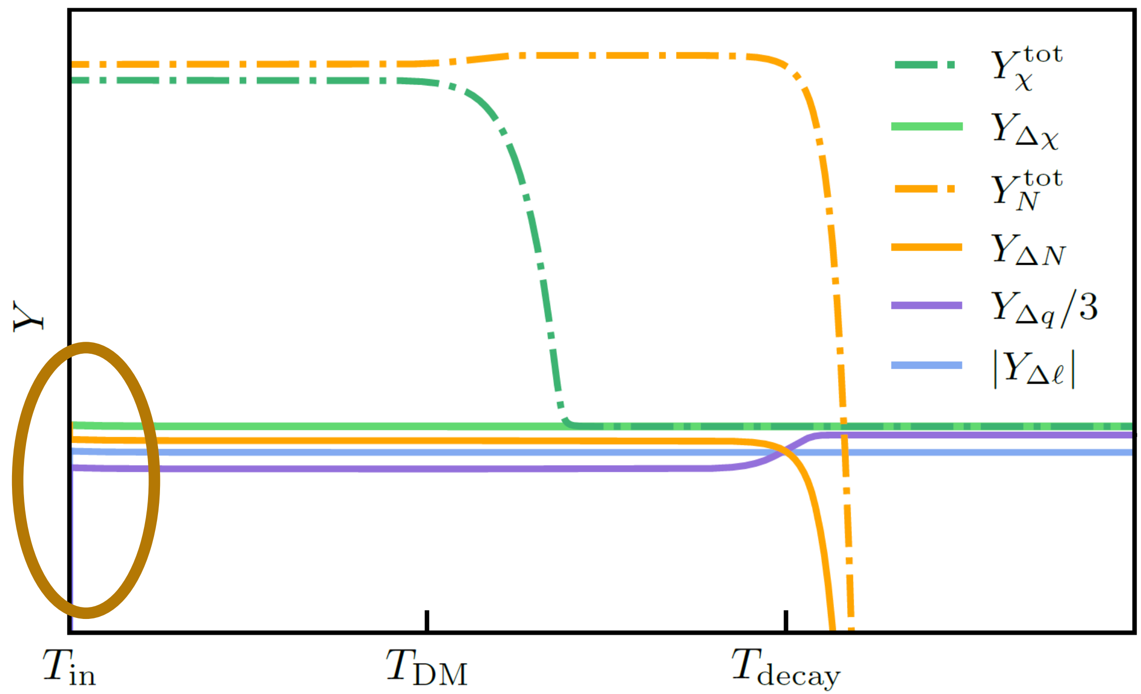
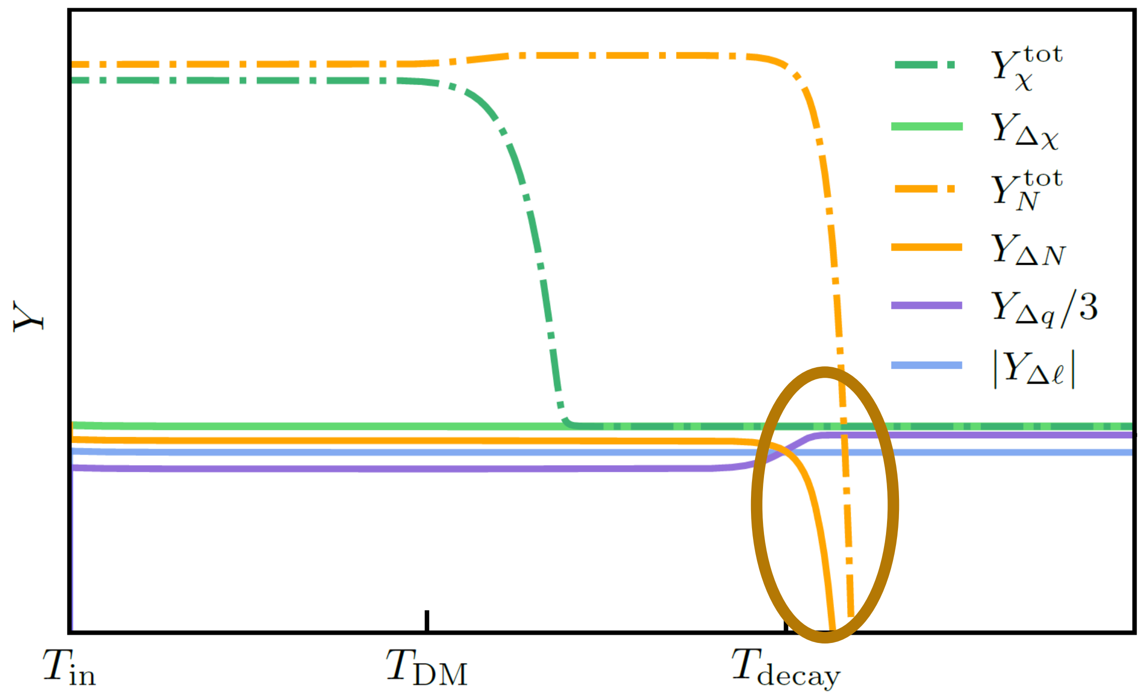


The asymmetry in N is quickly transmitted to the quark sector via scatterings $N\bar{d} \leftrightarrow ud,\ \ N\bar{u} \leftrightarrow dd$

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

A more refined scenario



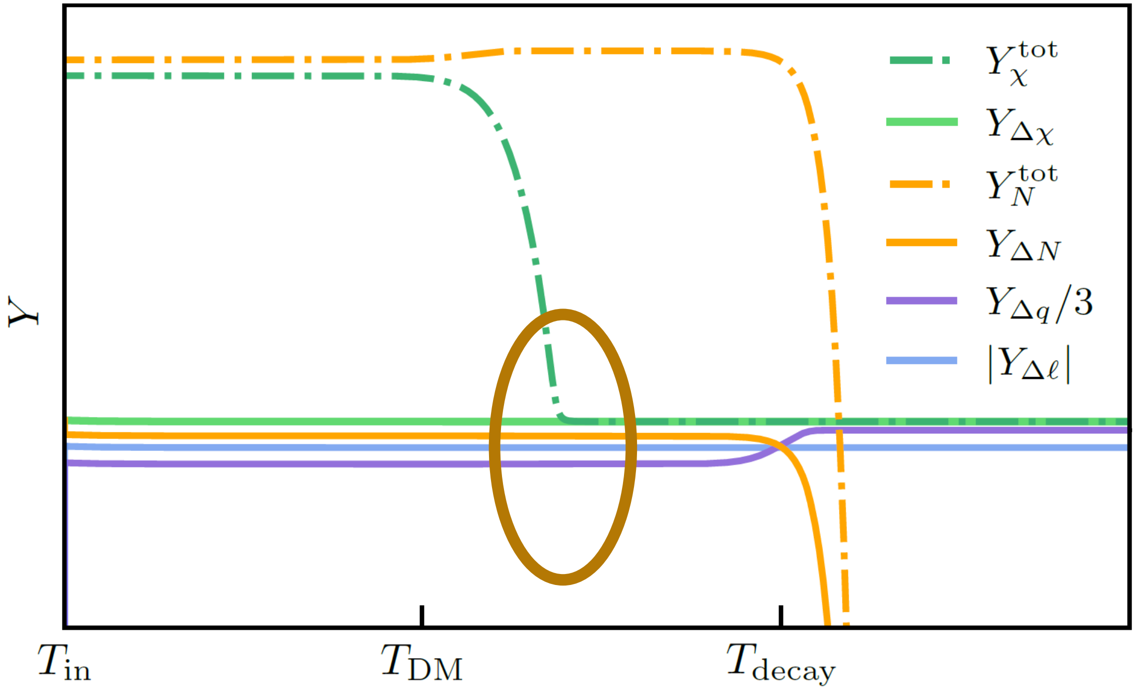
The decay $N \to udd$ increases the quark-antiquark asymmetry.

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

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

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

A more refined scenario

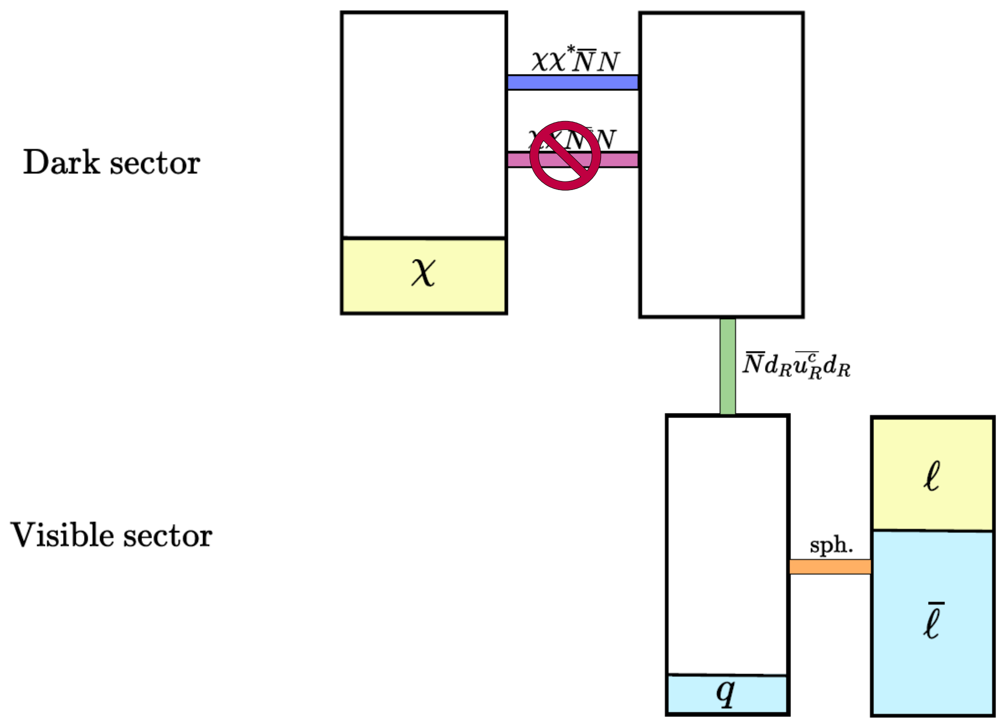


Freeze-out of $\chi\chi^* \to N\bar{N}$

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

A more refined scenario

Final state, when all χ* are annihilated

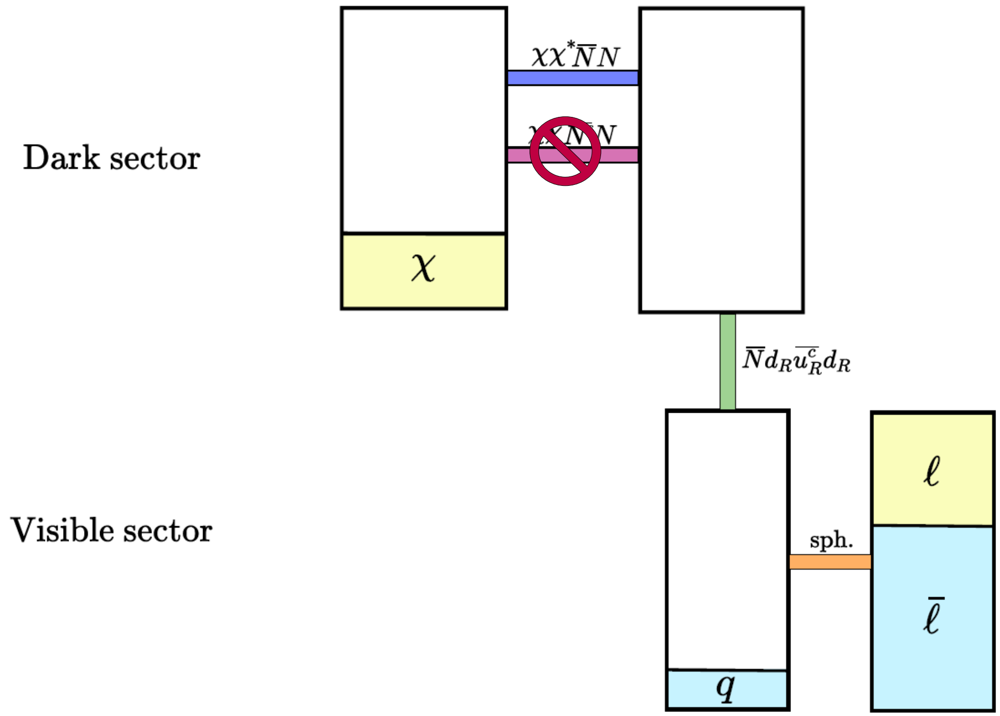


$$\Omega_{\mathrm{DM},0}h^2 \simeq 2.8 \times 10^8\, Y_\chi^{\mathrm{tot}}(x_{\mathrm{f.o.}})\frac{m_\chi}{\mathrm{GeV}}.$$

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

A more refined scenario

Final state, when all χ^* are annihilated

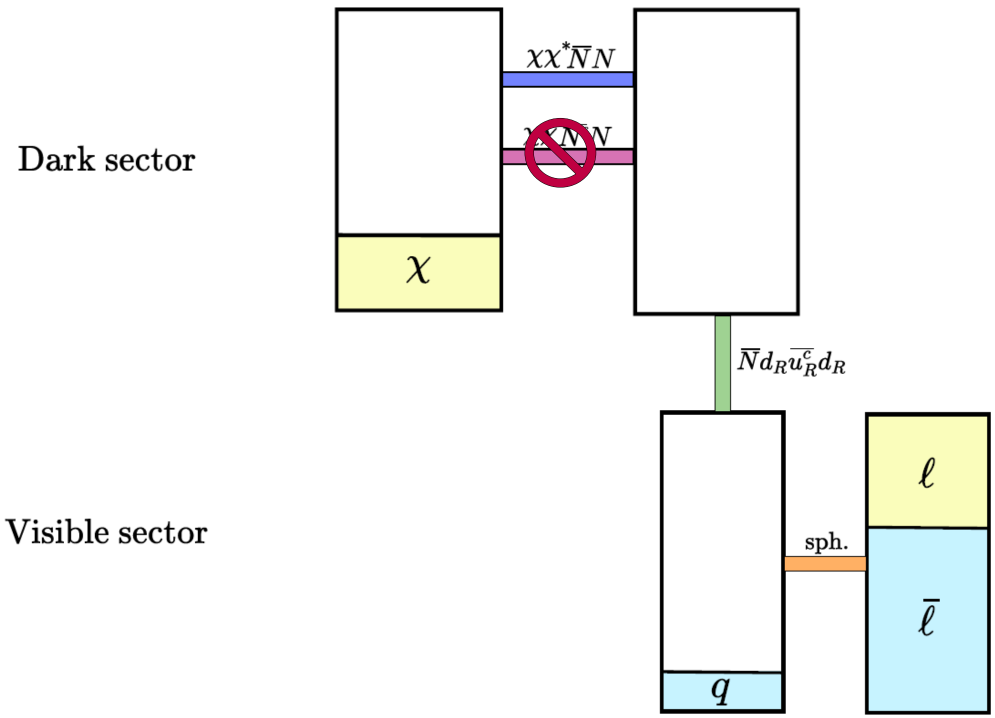


$$\Omega_{\mathrm{DM},0}h^2 \simeq 2.8\times 10^8\, Y^{\mathrm{in}}_{\Delta N}\frac{m_\chi}{\mathrm{GeV}}.$$

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

A more refined scenario

Final state, when all χ^* are annihilated

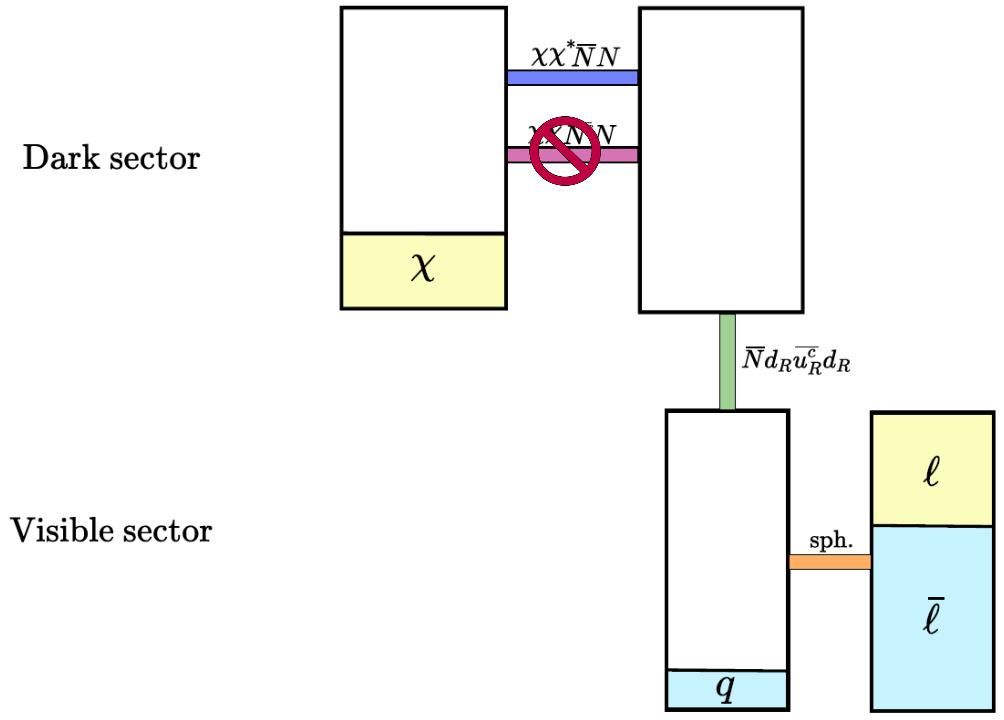


$$\Omega_{\rm DM,0}h^2 \simeq 2.8\times 10^8\, Y^{\rm in}_{\Delta N}\frac{m_\chi}{\rm GeV}.$$

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

A more refined scenario

Final state, when all χ^* are annihilated

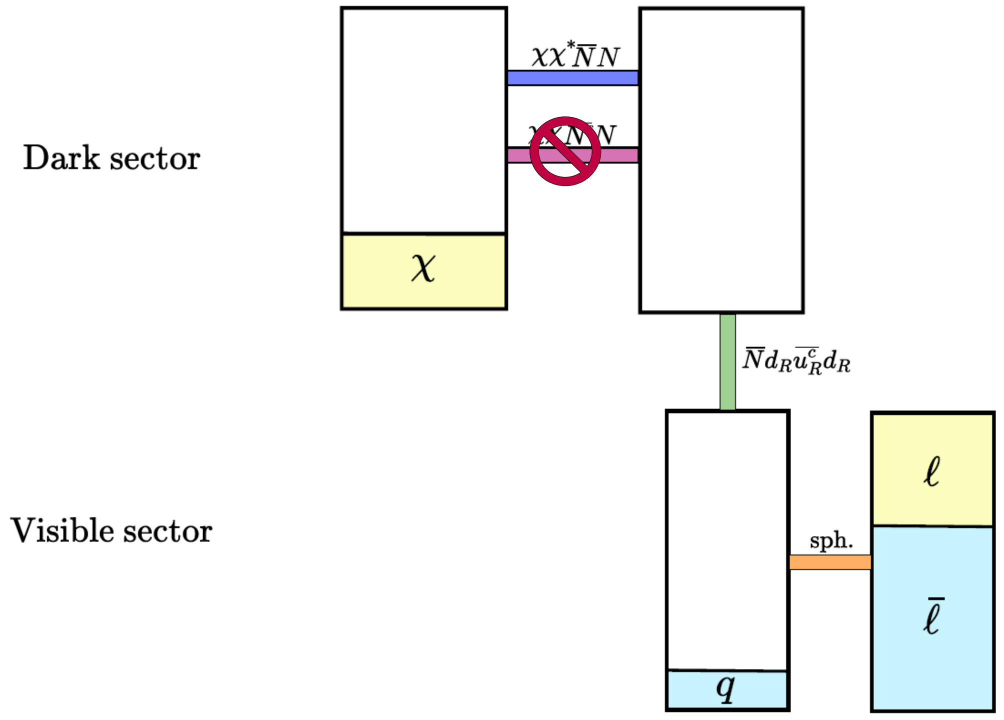


$$\Omega_{\mathrm{DM},0}h^2 \simeq 1.4 \times 10^8\, Y_{\Delta q,0}\frac{m_\chi}{\mathrm{GeV}}\,.$$

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

A more refined scenario

Final state, when all χ^* are annihilated



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

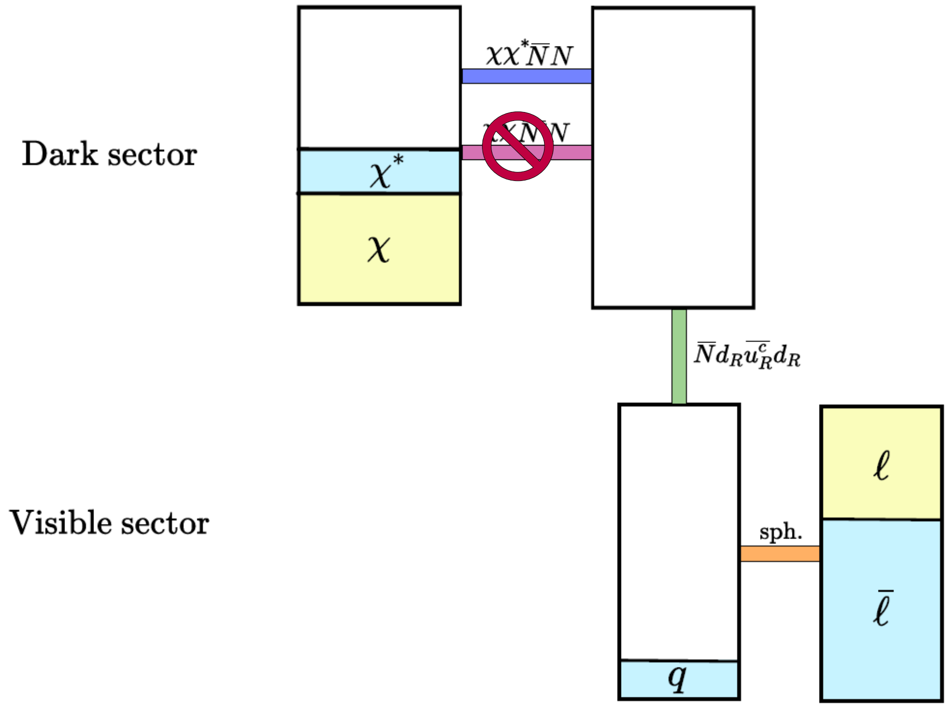
$$Y_{\Delta q,0} = \tfrac{141}{122} Y^{\mathrm{in}}_{\Delta N},$$

$$Y^{\mathrm{in}}_{\Delta N} \simeq 2.3 \times 10^{-10},$$

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

A more refined scenario

Final state, when χ^* are partially annihilated

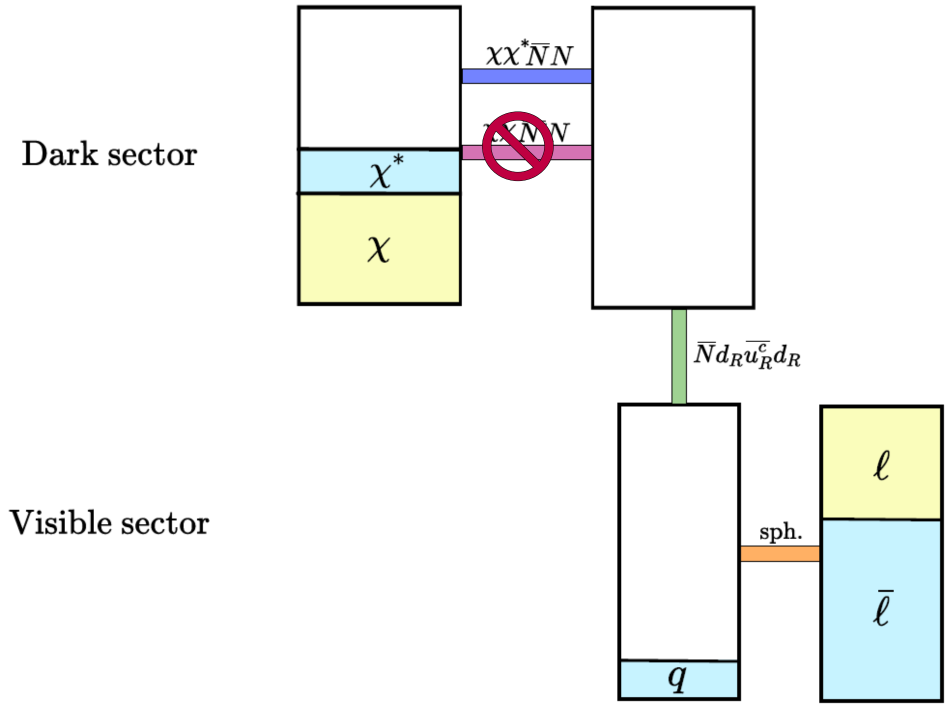


$$\Omega_{\mathrm{DM},0}h^2 \simeq 2.8\times 10^8\, Y_\chi^{\mathrm{tot}}(x_{\mathrm{f.o.}})\,\frac{m_\chi}{\mathrm{GeV}}.$$

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

A more refined scenario

Final state, when χ^* are partially annihilated

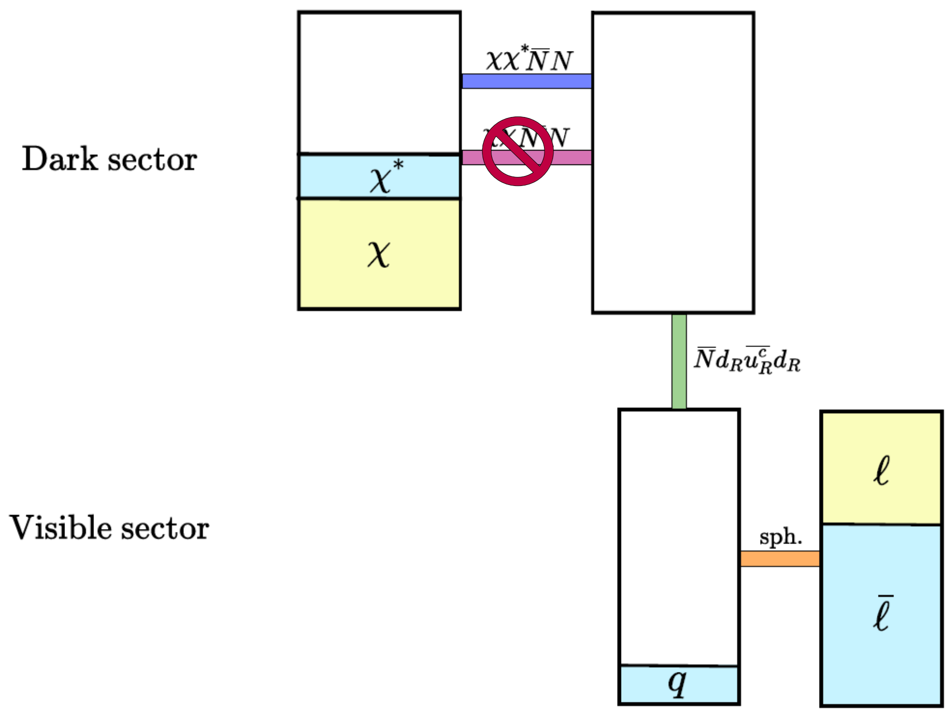


$$\Omega_{\rm DM,0}h^2 \gtrsim 2.8\times 10^8\, Y_{\Delta N}^{\rm in}\,\frac{m_\chi}{\rm GeV}\,.$$

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

A more refined scenario

Final state, when χ^* are partially annihilated



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

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

$$Y^{\mathrm{in}}_{\Delta N} \simeq 2.3\times 10^{-10}$$

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

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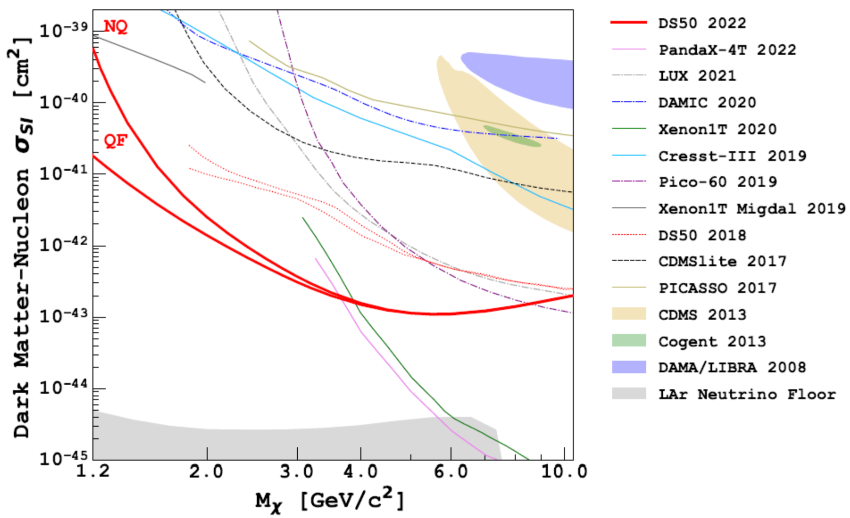
□ Direct detection: same analysis as for the singlet scalar DM model



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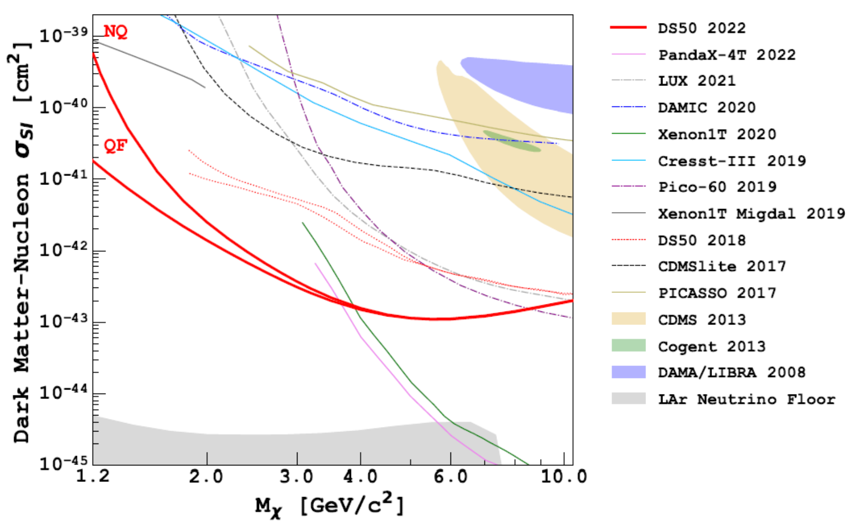

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- If DM partially asymmetric, indirect detection signals.

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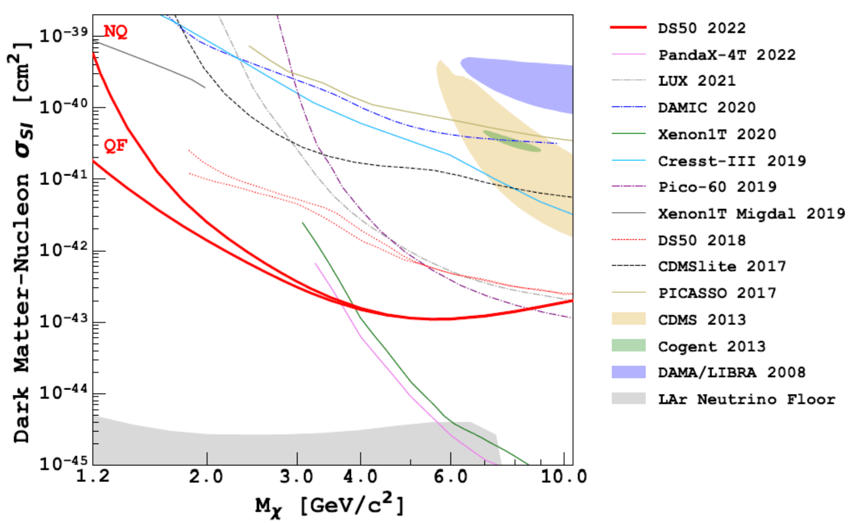


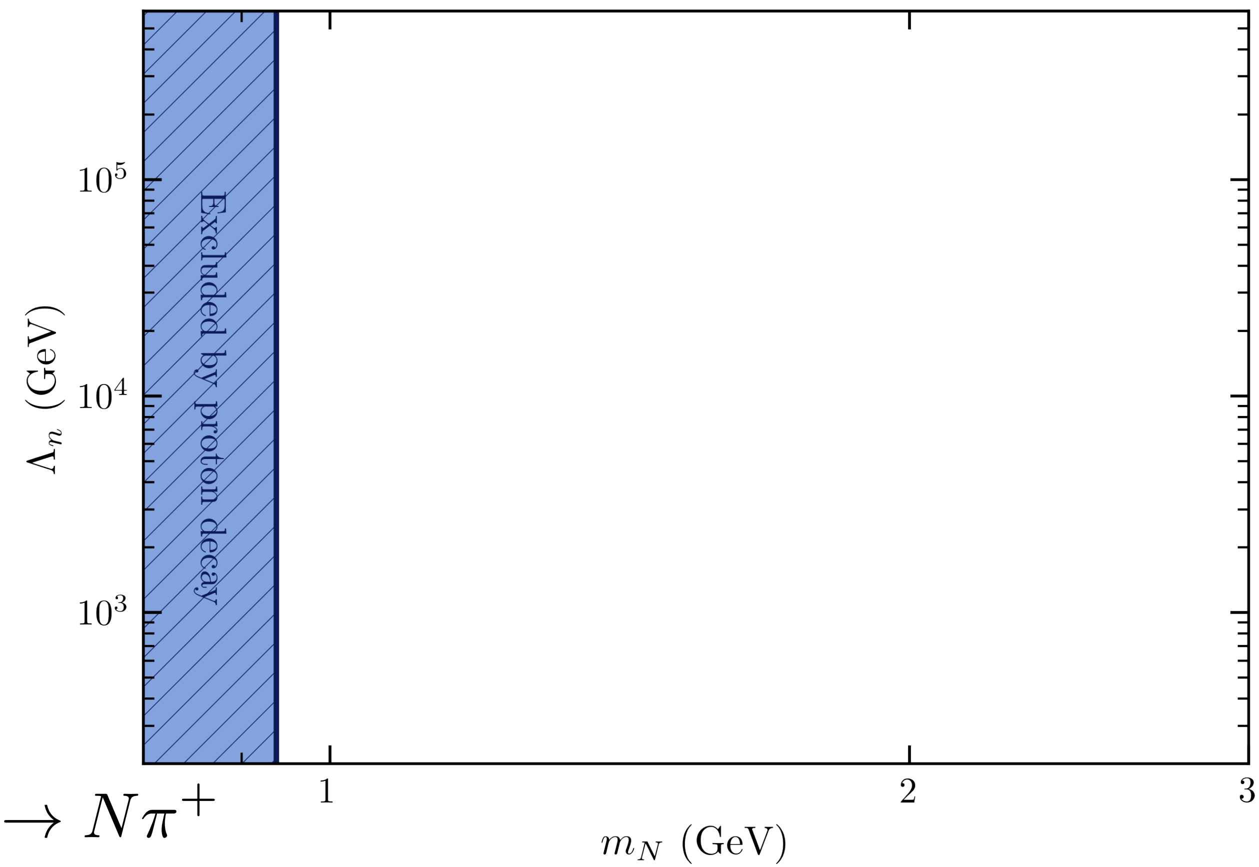
$\Rightarrow \lambda_{\chi H} \lesssim 10^{-2}$

□ 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

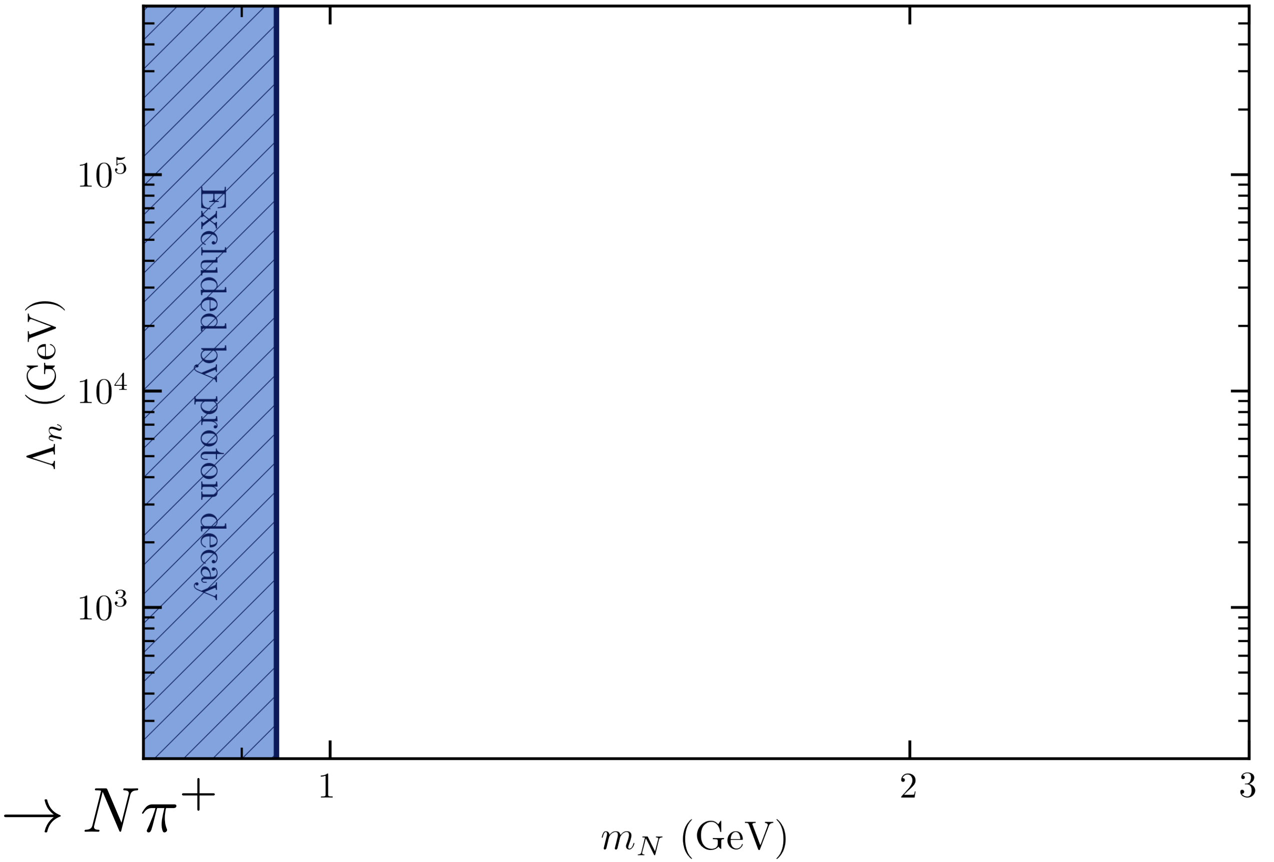
2) Neutron portal $\frac{1}{\Lambda_n^2}\overline{N}d_R\,\overline{u_R^c}d_R$



$p \to N\pi^+$

Experimental tests

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



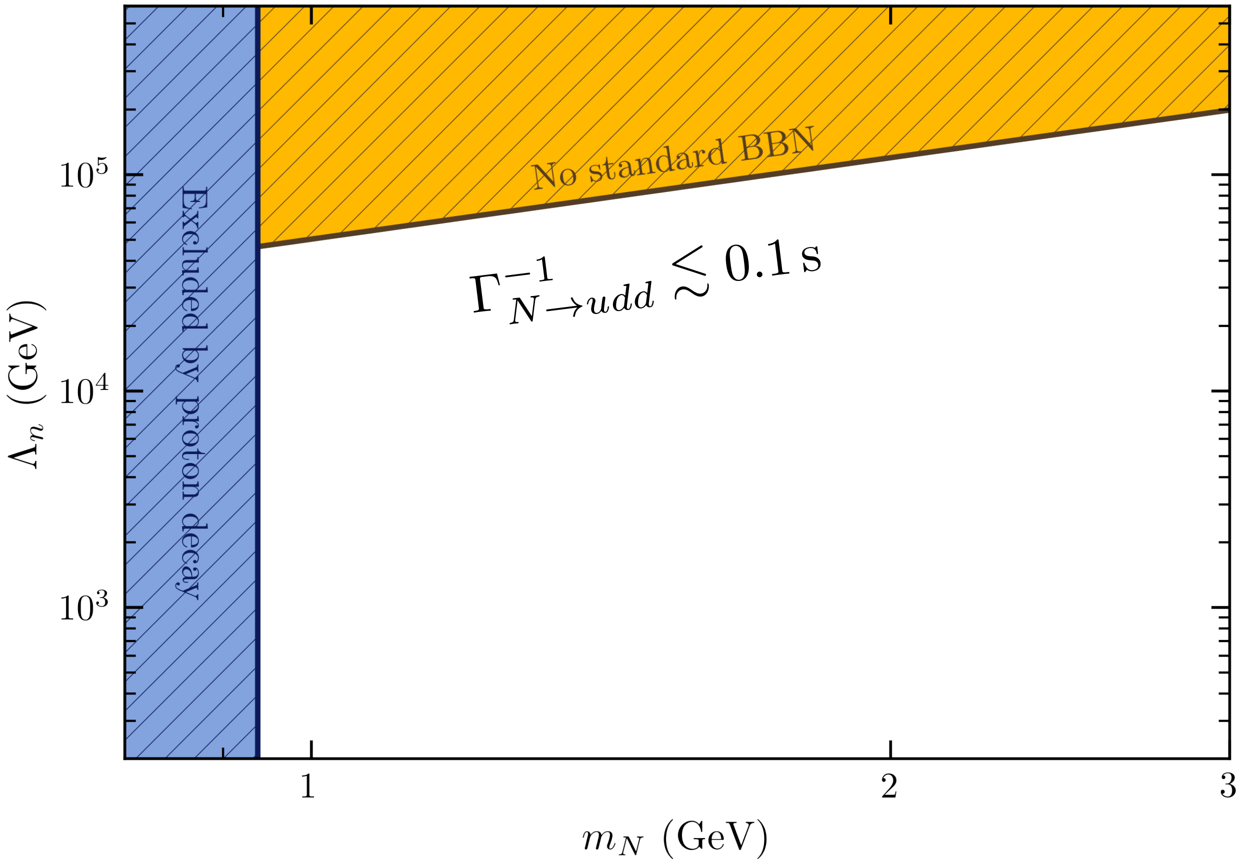
$p \to N\pi^+$

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

Experimental tests

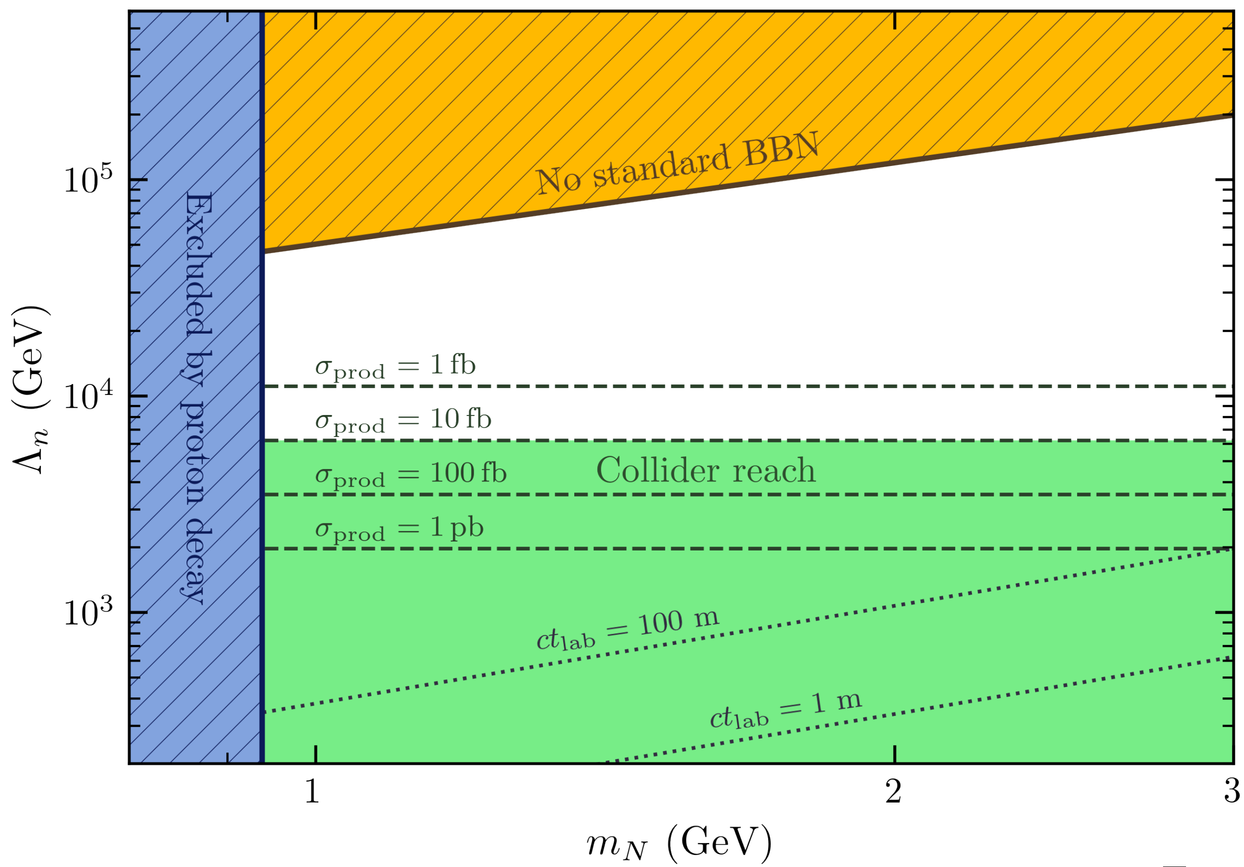
2) Neutron portal $\frac{1}{\Lambda_n^2} \overline{N} d_R \overline{u_R^c} d_R$



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

Experimental tests

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

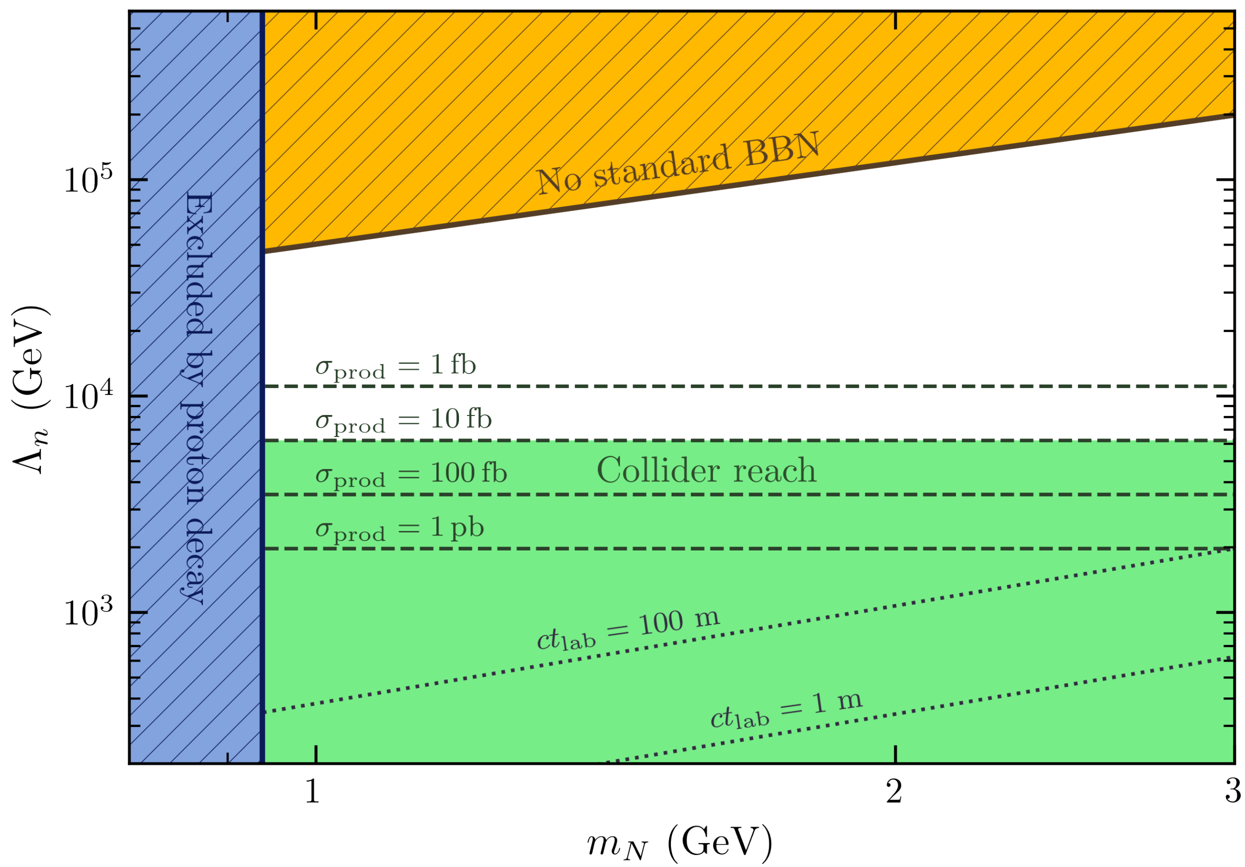


N production in pp collisions through $ud \to N\bar{d}, dd \to N\bar{u}$

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

Experimental tests

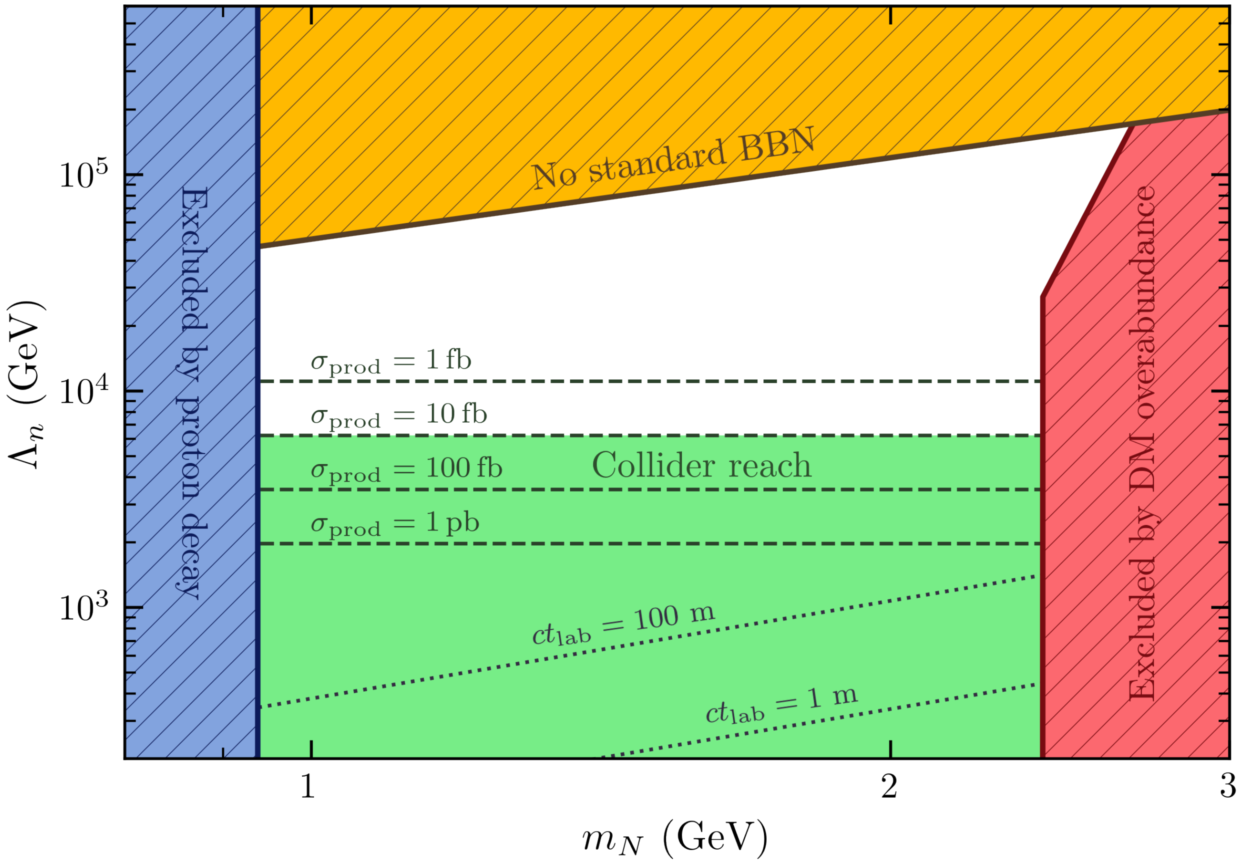
2) Neutron portal $\frac{1}{\Lambda_n^2}\overline{N}d_R\,\overline{u_R^c}d_R$



- 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

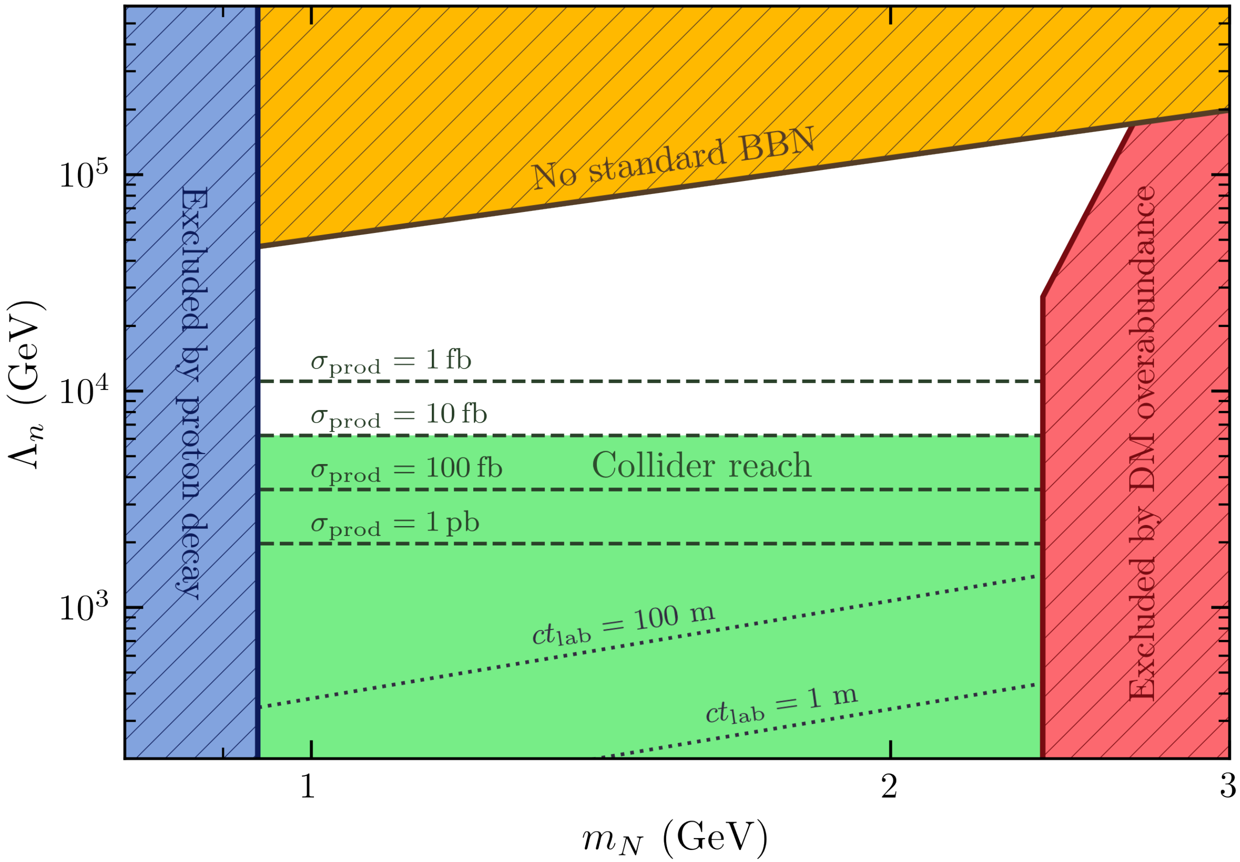
2) Neutron portal $\frac{1}{\Lambda_n^2}\overline{N}d_R\,\overline{u_R^c}d_R$



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

Experimental tests

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



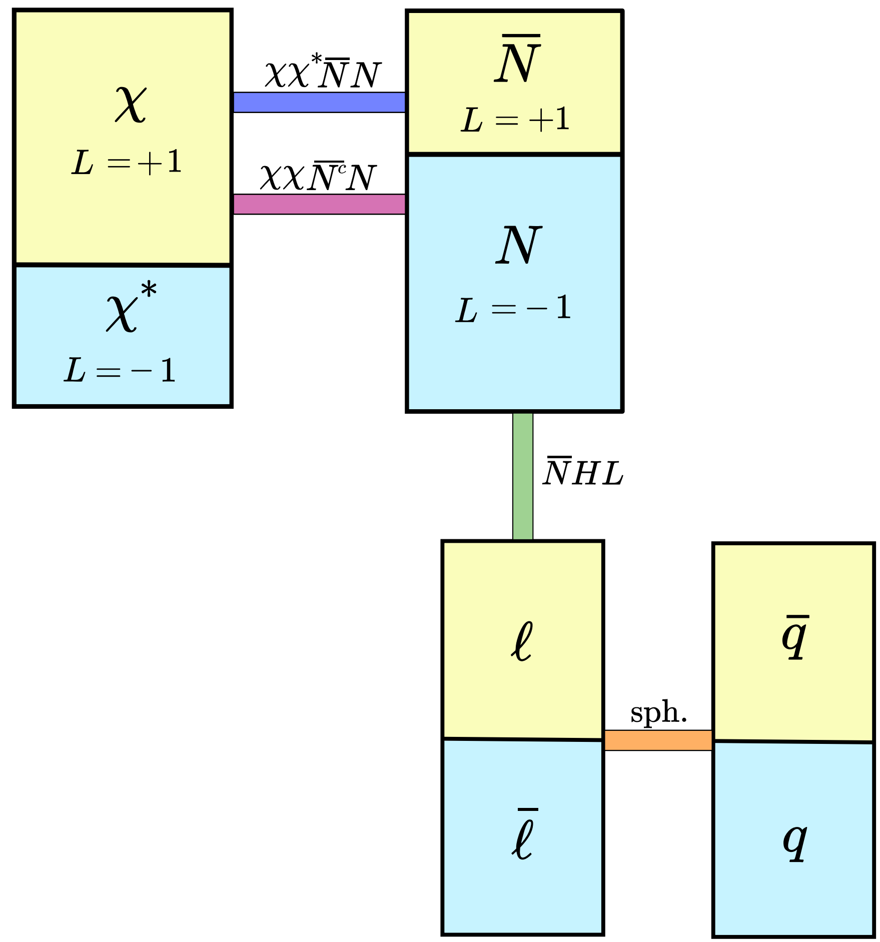
The rate of annihilations $\chi\chi^* \to N\overline{N}$ must be sufficiently efficient at freeze-out.

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

A leptonic portal

Dark sector

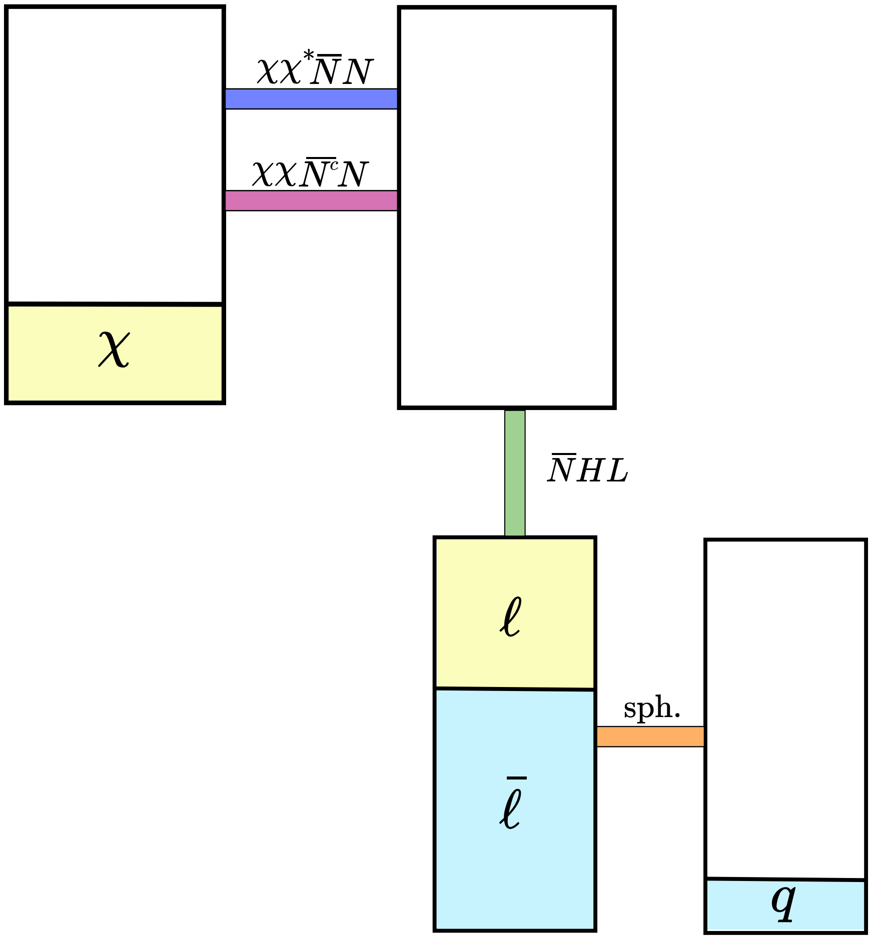
Visible sector



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.