

27th International workshop
“What comes beyond the standard models”

Problems of dark atom cosmology

Authors: Vitaly A. Beylin ^{*,1}; Maxim Yu. Khlopov ^{*,+,x,2}; Danila O. Sopin ^{+,x,3}

* Virtual Institute of Astroparticle Physics, 75018, Paris, France

+ National Research Nuclear University MEPhI 115409 Moscow, Russia

x Research Institute of Physics, Southern Federal University, 344090 Stachki 194, Rostov on Don, Russia

1. vitbeylin@gmail.com
2. khlopov@apc.in2p3.fr
3. sopindo@mail.ru

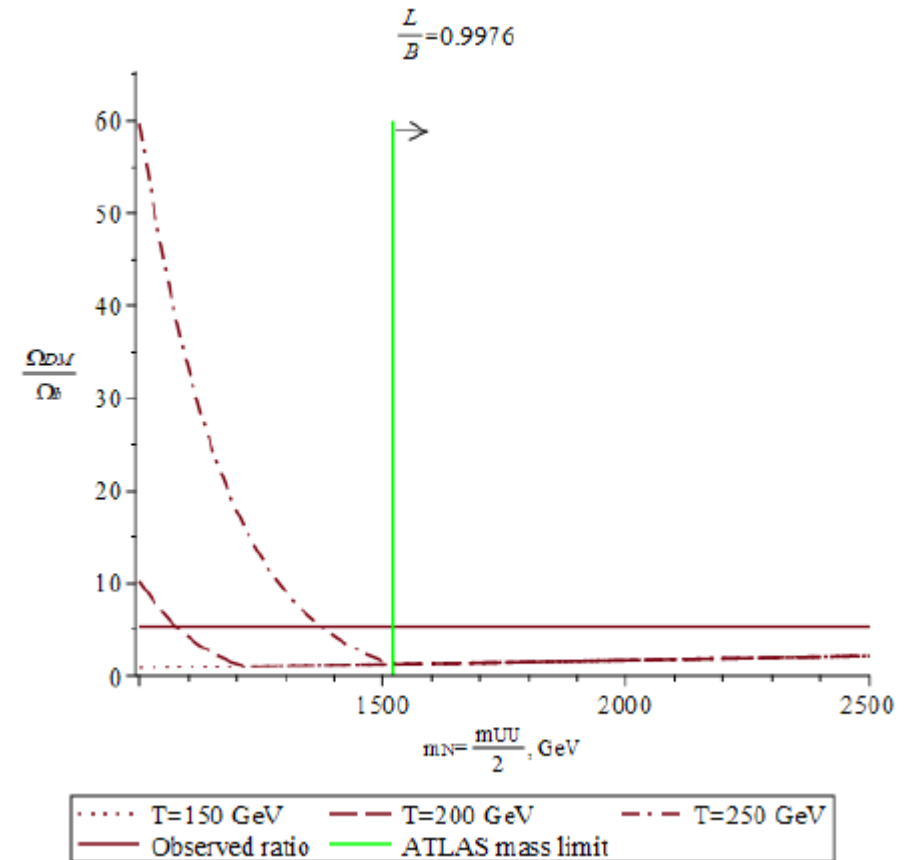
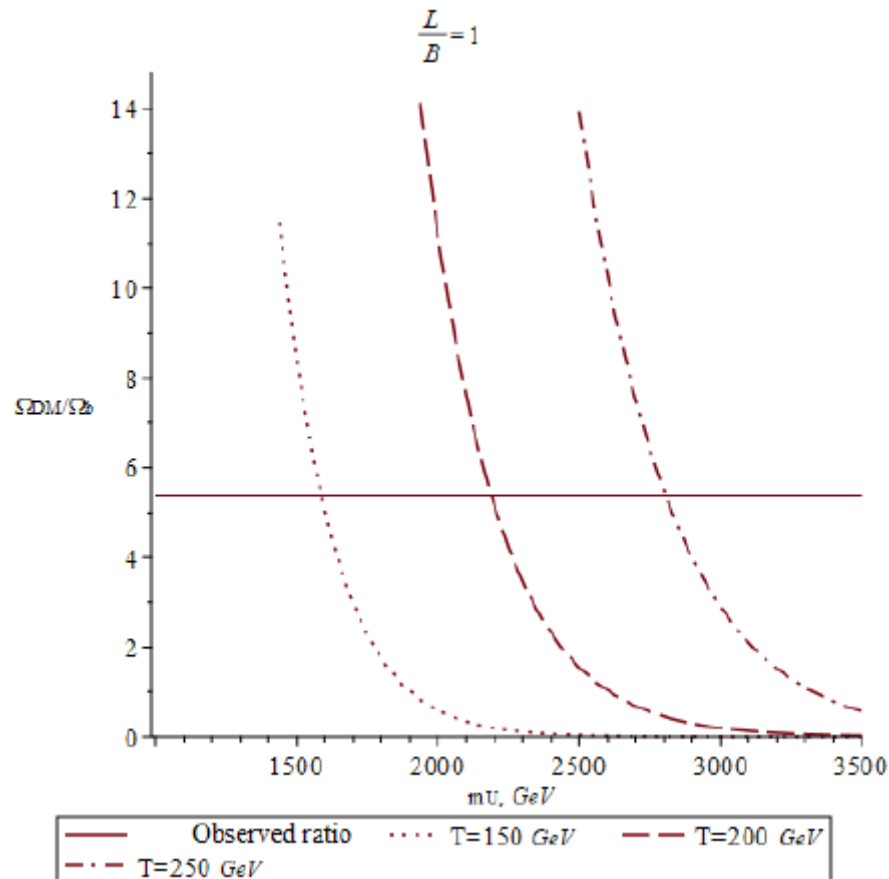
Dark atom



Density of dark atoms

4-th stable generation

WTC



Outline

- **Problems**
- **Generation of multicharged superheavy particles X^{-2n}**
 - Sphaleron in WTC model
 - System of equations
- **Formation of dark atoms XHe**
 - Recombination temperatures
 - Kinetic equations
 - Interaction of dark ions XN
- **Conclusion**

Problems

Generation of multicharged superheavy particles X^{-2n}

- Properties of the sphaleron transitions
 - Value of the sphaleron energy E_{sph} should change [1]
 - Which also result in
 - Rate of sphaleron transitions changing
 - Freezing out temperature changing
- Additional solutions
 - Second branch of sphaleron transitions [1]
 - New nontopological solutions [2]

Formation of dark atoms XHe

- Recombination of XHe dark atoms [3]
- Interactions
 - Capturing of primordial nucleus
 - Interaction of two dark atoms

- [1] M. Spannowsky, C. Tamarit: Sphalerons in composite and nonstandard Higgs models, Phys. Rev. D **95** (2017)
- [2] G. Nolte, J. Kunz: Sphaleron barrier in the presence of fermions, Phys. Rev. D **48** (1993)
- [3] E. Akhmedov, M. Pospelov: BBN catalysis by doubly charged particles, arXiv: 2405.06019

Sphaleron solution

Sphaleron transitions are the nonperturbative electroweak processes violating the baryon and lepton numbers.

To find the properties of the sphaleron transitions we need to

- write out the lagrangian and energy functional of the model;
- find the corresponding field equations;
- find the saddle point solution (sphaleron) using an ansatz;
- calculate the energy of the barrier between topologically unequal vacua;
- estimate the rate and freezing out temperature of sphaleron transitions.

WTC model

$$\begin{aligned}\mathcal{L}_{\text{Higgs}} = & \frac{1}{2}\text{Tr} [D_\mu M D^\mu M^\dagger] + \frac{m^2}{2}\text{Tr}[M M^\dagger] \\ & - \frac{\lambda}{4}\text{Tr} [M M^\dagger]^2 - \lambda'\text{Tr} [M M^\dagger M M^\dagger] + 2\lambda'' [\text{Det}(M) + \text{Det}(M^\dagger)] \\ & + \frac{m_{\text{ETC}}^2}{4} \text{Tr} [M B M^\dagger B + M M^\dagger] ,\end{aligned}$$

$$M = \begin{pmatrix} i\Pi_{UU} + \tilde{\Pi}_{UU} & \frac{i\Pi_{UD} + \tilde{\Pi}_{UD}}{\sqrt{2}} & \frac{\sigma + i\Theta + i\Pi^0 + A^0}{2} & \frac{i\Pi^+ + A^+}{\sqrt{2}} \\ \frac{i\Pi_{UD} + \tilde{\Pi}_{UD}}{\sqrt{2}} & i\Pi_{DD} + \tilde{\Pi}_{DD} & \frac{i\Pi^- + A^-}{\sqrt{2}} & \frac{\sigma + i\Theta - i\Pi^0 - A^0}{\sqrt{2}} \\ \frac{\sigma + i\Theta + i\Pi^0 + A^0}{2} & \frac{i\Pi^- + A^-}{\sqrt{2}} & i\Pi_{\overline{UU}} + \tilde{\Pi}_{\overline{UU}} & \frac{i\Pi_{\overline{UD}} + \tilde{\Pi}_{\overline{UD}}}{\sqrt{2}} \\ \frac{i\Pi^+ + A^+}{\sqrt{2}} & \frac{\sigma + i\Theta - i\Pi^0 - A^0}{2} & \frac{i\Pi_{\overline{UD}} + \tilde{\Pi}_{\overline{UD}}}{\sqrt{2}} & i\Pi_{\overline{DD}} + \tilde{\Pi}_{\overline{DD}} \end{pmatrix}$$

[4] R. Foadi, M. T. Frandsen, T. A. Ryttov, F. Sannino: Minimal walking technicolor: Setup for collider physics, Phys. Rev. D **76** (2007)

[5] F. Sannino: Conformal Dynamics for TeV Physics and Cosmology, arXiv: 0911.0931.

System of equations

- 25 nonlinear differential equations of the second order
- Higgs boson equation:

$$\partial_\mu^2 \sigma(x_\mu) + a\sigma^3(x_\mu) + b(x_\mu)\sigma(x_\mu) + f(x_\mu) = 0,$$

$$a = \lambda + \lambda' - \lambda'',$$

$$\begin{aligned} b = & (\lambda + \lambda' - \lambda'')(2|\Pi_{UU}|^2 + 2|\Pi_{DD}|^2 + 2|\Pi_{UD}|^2 + (\Pi^0)^2) + \\ & + (\lambda + 3\lambda' + \lambda'')(2|P_{UU}|^2 + 2|P_{DD}|^2 + 2|P_{UD}|^2 + (A^0)^2) + \\ & + (\lambda + \lambda' + 3\lambda'')\Theta^2 + \\ & + (\lambda + 2\lambda')((A^-)^2 + (A^+)^2 + (\Pi^-)^2 + (\Pi^+)^2) + \\ & + 2(\lambda' + \lambda'')(A^+ A^- - \Pi^+ \Pi^-) + \\ & + g_W^2(W_\mu^1 W^{1\mu} - W_\mu^2 W^{2\mu} + W_\mu^3 W^{3\mu}) + \frac{g_e^2}{4}B_\mu B^\mu - g_W g_e B_\mu W^{3\mu} - m^2, \end{aligned}$$

Formation of dark atoms

$$(0) \quad N^1 + N^2 \rightarrow N^3 + N^4,$$

$$(1) \quad X + N \rightarrow XN + \gamma,$$

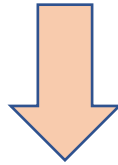
$$(2) \quad XN^1 + N^2 \rightarrow XN^3 + \gamma \setminus N^4,$$

$$(3) \quad XN^1 + XN^2 \rightarrow X_2N^3 + \gamma \setminus N^4.$$

Recombination temperatures

$$(1) X^{-2n} + N^{+q} \rightarrow (XN)^{-2n+q} + \gamma$$

$$n_i^{\text{now}} \left(\frac{T}{T_{\text{now}}} \right)^3 = g_i \left(\frac{m_i T^{\frac{3}{2}}}{2\pi} \right) e^{-\frac{m_i}{T}}$$

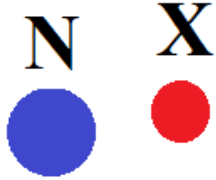


$$T_{\text{rec}} = W_{X-N} \left(\ln \left(\frac{g_X g_N}{g_{XN}} \left(\frac{m_N T_{\text{now}}^2}{2\pi W_{X-N}} \right)^{\frac{3}{2}} \frac{1}{n_N^{\text{now}}} \right) \right)^{-1}.$$

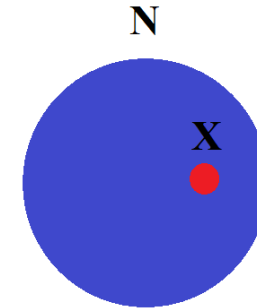
Structure of the dark atoms

$$a \approx Z_X Z_N \alpha m_p r_0 A_N^{\frac{4}{3}}$$

$$0 < a < 1$$



$$1 < a < \infty$$



$$W_{X-N}^{Bohr} = 2n^2 Z^2 \alpha^2 m_N$$

$$W_{X-N}^{Thomson} = \left\langle \frac{2nZ\alpha}{2R_N} \left(3 - \frac{R_N^2 \sin^2(\omega t)}{R_N^2} \right) \right\rangle = \frac{5nZ\alpha}{2r_0 A^{\frac{1}{3}}}$$

$$W_{X-N}^{Bohr} > W_{X-N}^{Thomson}$$

Structure of the dark ions XN

$$a \approx Z_X Z_N \alpha m_p r_0 A_N^{\frac{4}{3}}$$

n	A					
	H	He	Li	Be	B	C
1	B	B	B	8	T	T
2	B	B	6	T	T	T
3	B	5	T	T	T	T
4	B	5	T	T	T	T
5	B	4	T	T	T	T

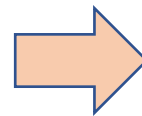
Recombination temperatures

$$T_{\text{rec}} = W_{X-N} \left(\ln \left(\frac{g_X g_N}{g_{XN}} \left(\frac{m_N T_{\text{now}}^2}{2\pi W_{X-N}} \right)^{\frac{3}{2}} \frac{1}{n_N^{\text{now}}} \right) \right)^{-1}$$

$$W_{X-N}^{\text{Bohr}} = 2n^2 Z^2 \alpha^2 m_N$$

n	$T \text{ keV}$			
	p	D	${}^3\text{He}$	${}^4\text{He}$
1	3	5	28	47
2	13	19	≈ 116	198
3	29	44	≈ 270	464
4	54	79	≈ 490	848
5	86	126	≈ 780	580

- For $n < 4$ the dominant branch is
 $X + \text{He} \rightarrow X\text{He} + \gamma$



- But for $n \geq 4$ it is
 $X + \text{H} \rightarrow X\text{H} + \gamma$

Kinetic equations

$$(0) \quad N^1 + N^2 \rightarrow N^3 + N^4,$$

$$(1) \quad X + N \rightarrow XN + \gamma,$$

$$(2) \quad XN^1 + N^2 \rightarrow XN^3 + \gamma \setminus N^4,$$

$$(3) \quad XN^1 + XN^2 \rightarrow X_2N^3 + \gamma \setminus N^4.$$



$$\left\{ \begin{array}{l} \frac{dn_i}{dt} + 3Hn_i = \sum_{i,k} n_j n_k (\sigma v)_i^{jk} - n_i \sum_j n_j (\sigma v)_{ij}, \\ \frac{\partial \phi_{N_i}}{\partial t} = \sum_{j,k} n_j n_k \frac{d(\sigma v)_{N_i}^{jk}}{dp_{N_i}} - \phi_{N_i} \sum_j n_j (\sigma v)^{N_i j}(p_{N_i}) - \phi_{N_i} \sum_j \int \phi_{N_j} (\sigma v)^{N_i N_j} dp_{N_j}. \end{array} \right.$$

$$\frac{dn_N^*}{dp_N} = \phi_N(p_N, t).$$

$$n_N = n_N^{\text{eq}} + n_N^*$$

Interaction of dark ions

$$(2) \quad XN^1 + N^2 \rightarrow XN^3 + \gamma \setminus N^4,$$

$$(3) \quad XN^1 + XN^2 \rightarrow X_2N^3 + \gamma \setminus N^4.$$

$$n_{XHe} \sigma v t = \frac{3}{2\pi^2} \frac{\rho_c \Omega_{DM}^{\text{now}} M_{Pl} \sigma}{m T_{\text{now}}^3} \sqrt{\frac{10 T^3}{g m_N}} \approx 3040.3 \frac{\sigma}{m_{XHe} \sqrt{m_N}} > 1$$

$$n_{XHe} = \frac{\rho_c}{m_{XN}} \Omega_{DM}^{\text{now}} \left(\frac{T}{T_{\text{now}}} \right)^3 \quad t = \frac{3 M_{Pl}}{4 T^2} \sqrt{\frac{5}{\pi^3 g_*}} \quad \langle v \rangle = \sqrt{\frac{8T}{\pi m_N}}$$

$$\sigma \approx 2 \cdot 10^{-25} \text{ cm}^2 = 500 \text{ GeV}^{-2} \quad \Rightarrow \quad m_{XHe} < 14 \text{ TeV}.$$

Conclusion

To describe the dark atom formation completely in extensions of SM it is necessary to

- Solve the system of field equations and find the sphaleron energy;
- To consider the effect of helium capture processes on nucleosynthesis.

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