28th International workshop
"What comes beyond the standard models"

Stable multicharged particles in the early Universe

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Dark atom model

- Stable lepton-like multicharged heavy particles X^{-2n} arise in several models [1,2].
- Only even values of charge are allowed [3].
- Such particles should form neutral bound states with ordinary matter nuclei.

$$X^{-2n} + n\,He^{+2} \rightarrow XHe + \gamma$$

[1] Hadronic and Hadron-Like Physics of Dark Matter / V. Beylin [et al.] //Symmetry. — 2019. — Vol. 11, no. 4. — P. 587. — ISSN 2073-8994.
[2] Khlopov M. What comes after the Standard Model? // Prog. Part. Nucl.Phys. — 2021. — Vol. 116. — P. 103824
[3] Belotsky K. M., Khlopov M. Y., Shibaev K. I. Composite Dark Mat-ter and its Charged Constituents // Gravitation and Cosmology. Vol.12. — Moscow : (KPS 06), 2006. — P. 1–7. — e-PrintArchive: astro-ph/0604518.

Outline

- Bound states and their description
  - Inner structure of dark ions
  - Estimations and applications
- Nuclear reactions with dark ions
  - Using analogies
  - Accurate calculation
- Primordial concentrations
  - Anomalous isotopes
  - Primordial metals
- Conclusions

Bound states and their description

- Isotopes produced in primordial nucleosynthesis [4]:

$$^{1}H, \quad ^{2}d, \quad ^{3}t,$$
$$^{3}He, \quad ^{4}He,$$
$$+ \ ^{7}Li, \quad ^{7}Be$$

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- What structure do dark XN ions have?

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Bound states and their description

Inner structure of dark ions

$$a = \frac{r_N}{r_B} \approx Z_X Z_N \, \alpha \, m_N \, r_0 \, A_N^{1/3}$$

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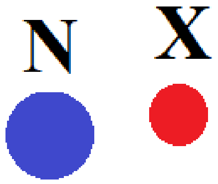

- Point-like particles

➢ Analogy with ordinary hydrogen:

$$E_{X-N}^{\mathrm{Bohr}} = 2n^2 Z^2 \alpha^2 m_N = \frac{1}{2 m_N r_B^2}$$

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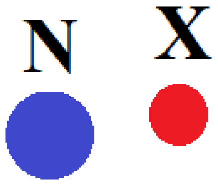

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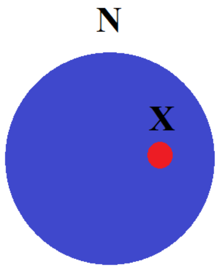


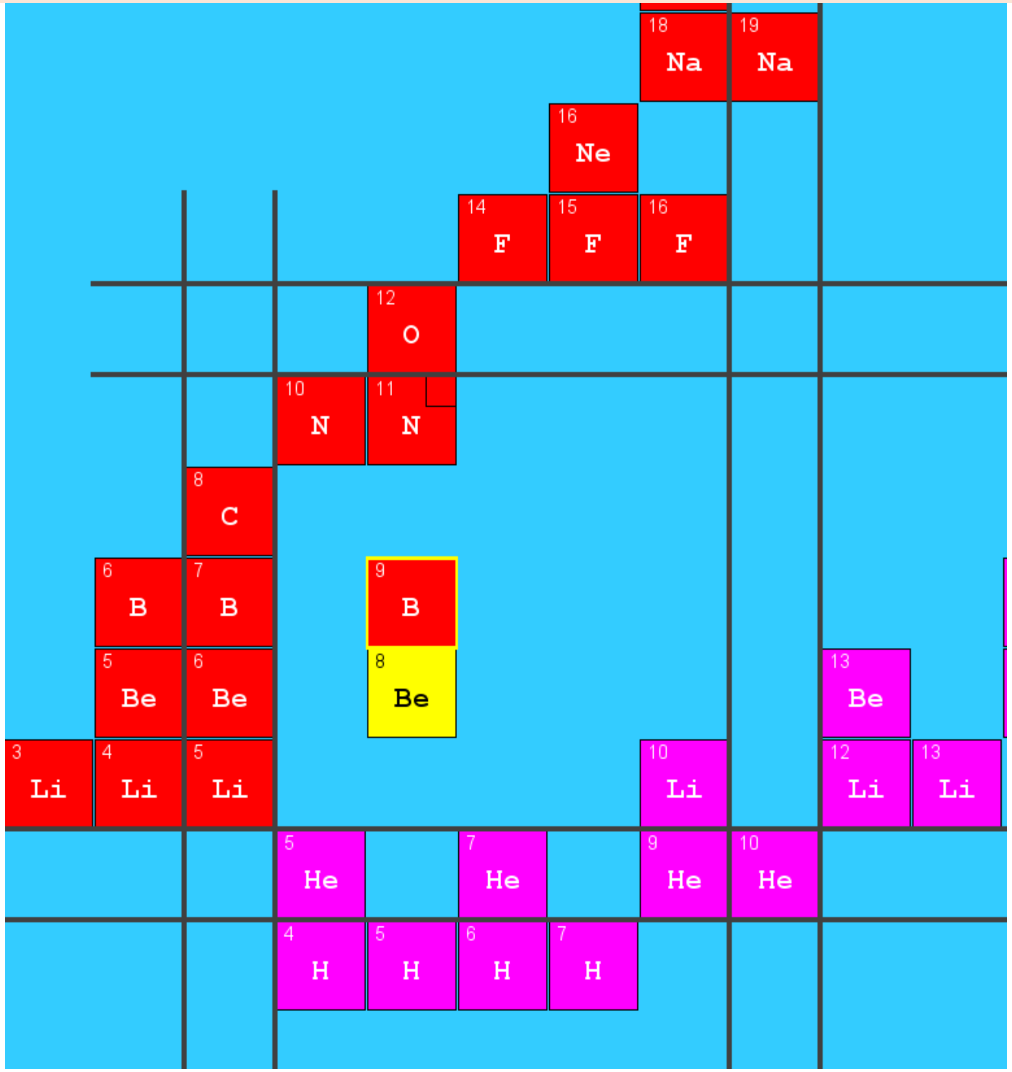
- Non-point nucleus in a shell

➢Nuclear analogies should be used.

➢Binding energies: $E_{X-N}^{Thomson}$ and Q_N

Bound states and their description
Inner structure of dark ions

- Isotope stabilization



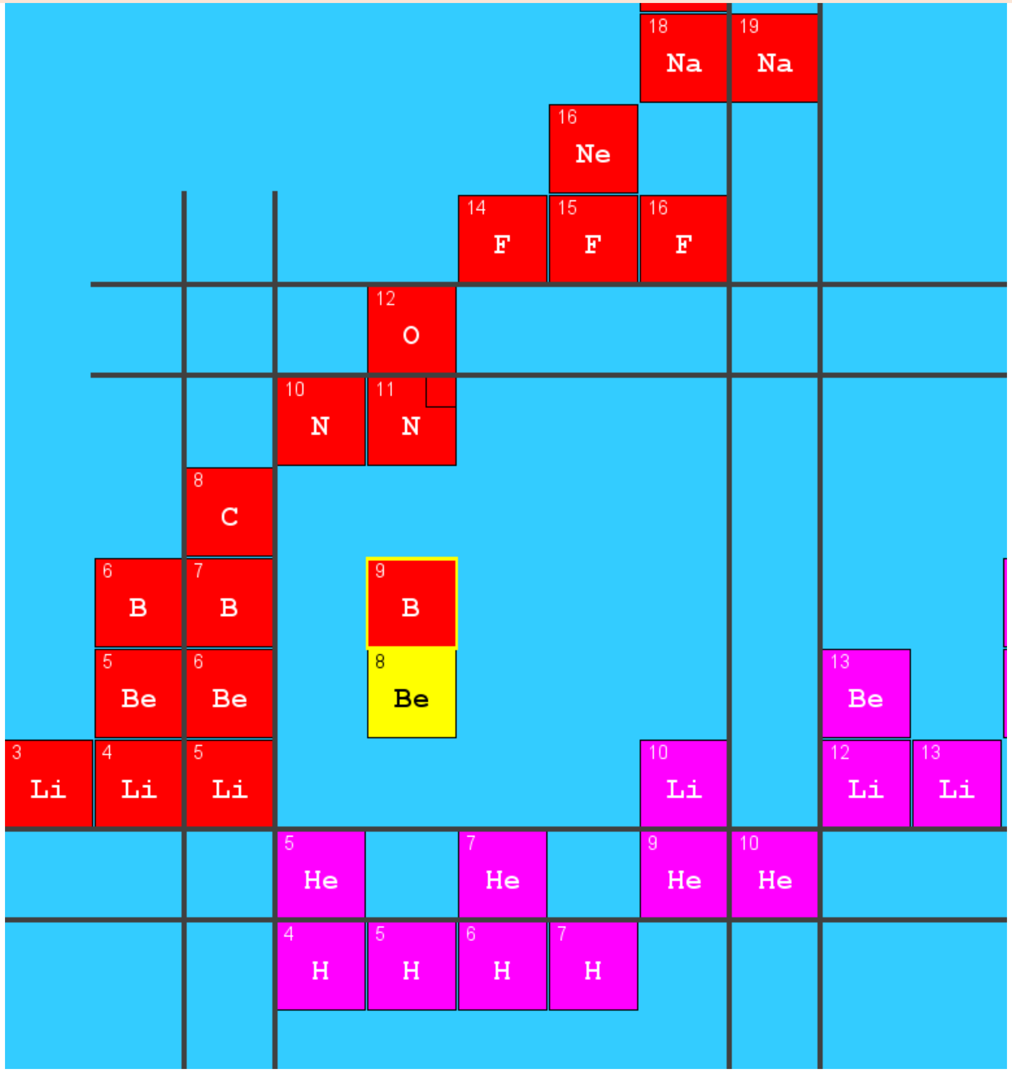
Bound states and their description

Inner structure of dark ions

- Isotope stabilization

- New stable-in-shall isotopes?

  (Xp_4 for instance)



Bound states and their description

Estimations and applications

- The most states are Thomson-like.

- There are a lot of $E_{X-N}^{Thomson}$ estimations [5,6,7], but no Q_N estimations .

$$\mathcal{H} = \begin{cases} \dfrac{p^2}{2m_N} - \dfrac{Z_X Z_N \alpha}{2r_N}\left(3 - \dfrac{r^2}{r_N^2}\right), & r < r_N \\ \dfrac{p^2}{2m_N} - \dfrac{Z_X Z_N \alpha}{r}, & r > r_N \end{cases}$$

$$E_{X-N}^{\text{Glashow}} = \begin{cases} \frac{3}{2}\frac{Z_X Z_N \alpha}{r_N}\left(1 - \sqrt{\frac{1}{a}}\right), & a \gtrsim 2 \\ \frac{1}{m_N r_N}\lambda\left(a\right), & a \approx 1 \\ \frac{1}{2}(Z_X Z_N \alpha)^2 m_N, & a < 1 \end{cases}$$

n	A			
	H	He	Li	Be
1	B	4	3	T
2	4	3	T	T
3	3	T	T	T
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[5] Cahn R. N., Glashow S. L. Chemical Signatures for Superheavy Elemen-tary Particles // Science. — 1981. — Vol. 213. — P. 607–611.
[6] Akhmedov E. Nuclear fusion catalyzed by doubly charged scalars: Implications for energy production // Phys. Rev. D – 2022. – Vol. 106, No. 03
[7] Akhmedov E., Pospelov M. BBN catalysis by doubly charged particles //JCAP. — 2024. — Vol. 08. — P. 028. — arXiv: 2405.06019 [hep-ph].

Bound states and their description
Estimations and applications

- In [7] was used E_{X-N} instead of Q_N
- The simplest estimation of ΔQ_N

$$\Delta m \ \to \Delta m + 0.711 \frac{Z(Z-1)}{A^{1/3}}$$

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- Reaction: $\mathrm{X}N_1 \rightarrow XN_2 + N_3$
- Energy: $(Z_1 m_p + (A_1 - Z_1)m_n - \Delta {m_1}^{shell}) - (Z_2 m_p + (A_2 - Z_2)m_n - \Delta {m_2}^{shell}) - (Z_3 m_p + (A_3 - Z_3)m_n)$

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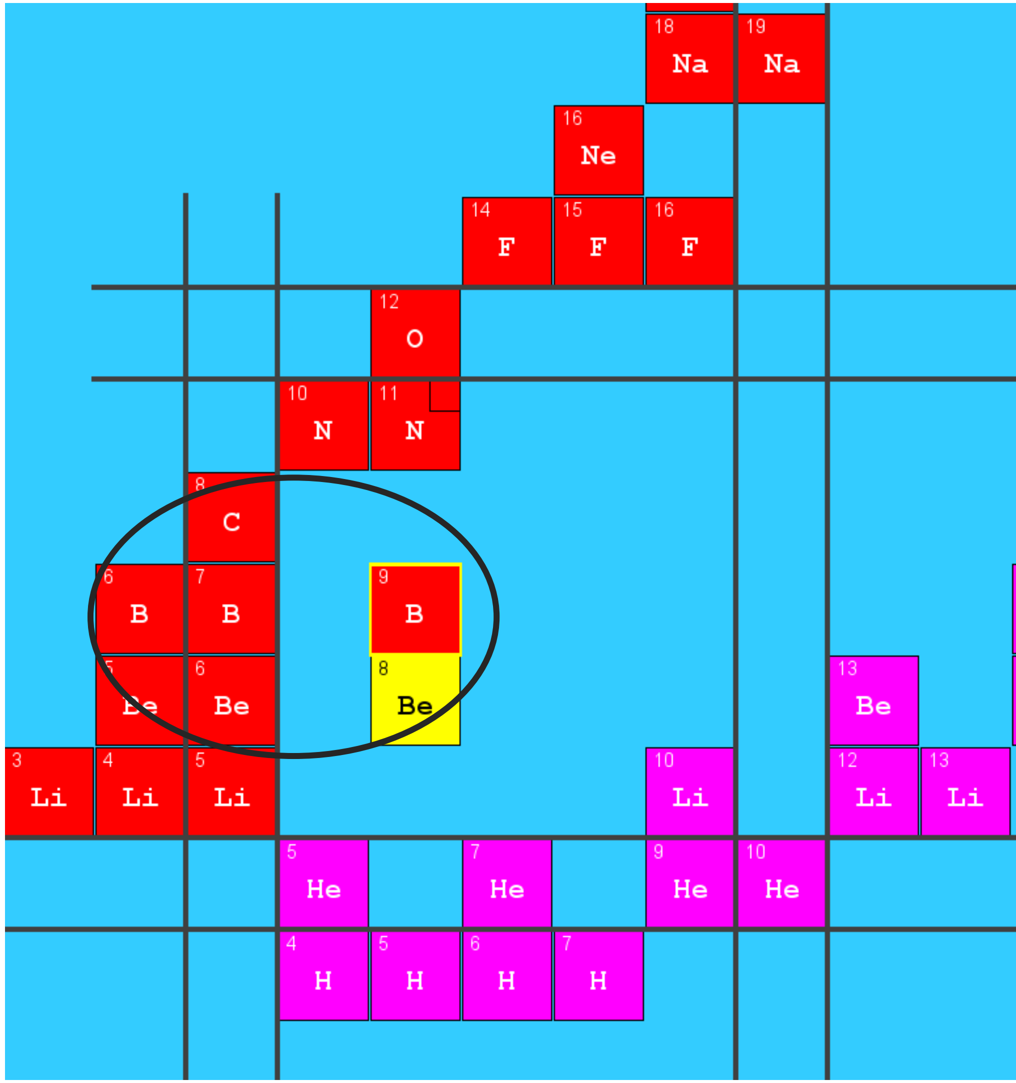
  - n-emission is not prevented



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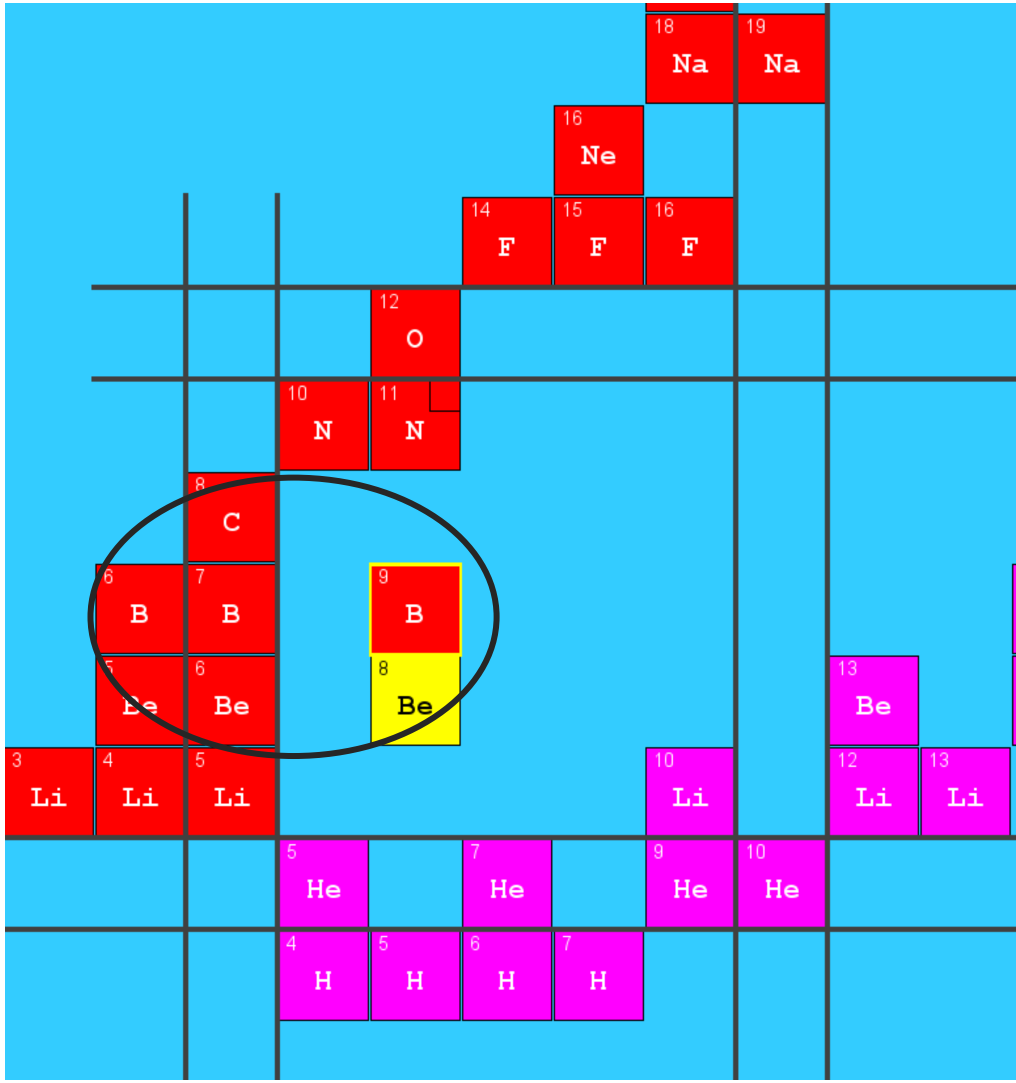
- An error should be rather large



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Bound states and their description

Estimations and applications

How to describe XN more accurate?

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- Cluster approach:
  - Consider nucleus as a bound state of n, p, α clusters
  - Use **experimental** $V_{\alpha-\alpha}, V_{\alpha-N,}$ and V_{N-N} potentials to improve predictions for Li, Be, C isotopes

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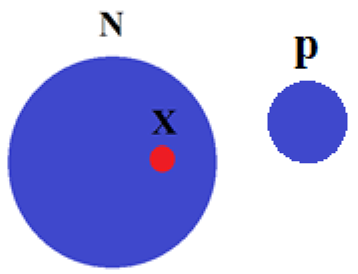

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+ Analogy with ordinary / bosonic atoms [8,9]
  - Use Hartree-Fock method to describe nonstandard states like Xp_2

[8] Amusia M. Y., Chernysheva L. V. On the Bosonic Atoms // JETP Let-ters. — 2018. — Vol. 107, no. 2. — ISSN 1090-6487
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➢ Expected results:
  - ➢ the energy of p-, α- separation
  - ➢ wave functions of bound states

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Bound states and their description
Estimations and applications

How to describe XN more accurate?

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➢Expected results:

  - ➢the energy of p-, α- separation
  - ➢wave functions of bound states

➢Potential problems:

  - ➢Is not applicable on high charges (n>1) because of non-point helium
  - ➢Bad predictions for spherical nuclei (???)

Bound states and their description
Estimations and applications

How to describe XN more accurate?

- *Ab-initio* approach [10,11]
    - Simulate nucleus by solving a many-body quantum problem
    - Use mesonic potential, modified by Coulomb term arising from the interaction with X^{-2n}

[10] Ab initio study of Z(N) = 6 magicity* / H. Li [и др.] // Chinese PhysicsC. — 2024. — Т. 48, № 12. — С. 124103. — ISSN 2058-6132.
[11] Ab Initio Study of the Beryllium Isotopes Be7 to Be12 / S. Shen [и др.] //Physical Review Letters. — 2025. — Т. 134, № 16. — ISSN 1079-7114.

Nuclear reactions with dark ions

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

(2) $XN_1 + N_2 \rightarrow XN_3 + N_4/\gamma$

(3) $XN_1 + XN_2 \rightarrow X_2N_3 + N_4/\gamma$

(1) The first stage of dark atom recombination

(2) Nuclear interaction of ordinary matter with dark ions

(3) Dark chemistry: interaction of two dark ions

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What does we need?

- List (network) of reactions
- Cross sections/rates

Nuclear reactions with dark ions

Using analogies

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

- Bohr states (point-like nucleus!):
  Recombination of hydrogen-like atom [13]

The exact analogy can be used for capturing of:

- n=1: *p, d, t,* ^3He
- n=2: *p, d, t*
- n=3,4: *p, d*
- n≥5: *p*

$$\langle \sigma v \rangle_{\rm rec} = \frac{32}{3}\sqrt{\frac{2\pi E_{X-N}}{3\,m_N}}\,(Z_X Z_N\,\alpha)^3\, r_B^2 \cdot \left(\frac{E_{X-N}}{T}\right)^{\frac{1}{2}} \left(\ln\left(\frac{E_{X-N}}{T}\right) + \gamma\right)$$

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- Thomson states (non-point-like nucleus)

  The picture changes completely.

  it is impossible to use the hydrogen-like wave function, and therefore the cross section **must change**.

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Nuclear reactions with dark ions

Using analogies

(2) $XN_1 + N_2 \to XN_3 + N_4/\gamma$

- If the similar ordinary reaction is exist [4]

$$\langle \sigma v \rangle^{ij}(T) = \frac{2}{T}\sqrt{\frac{2}{\pi T}\frac{m_i + m_j}{m_i m_j}}\int_0^\infty \sigma^{ij}(E)\, E\, e^{-\frac{E}{T}} dE$$

$$\sigma^{ij}(E) = \frac{S^{ij}(E)}{E} e^{-2\pi\eta_{ij}},$$

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In [7] the accurate calculations for X^- [14] was rescaled.

Is it any difference and why?

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- If not:
  - rough analogies [15]:

$$(XN_1)^0 + N_2^{+q} \to (XN_3)^{+q} + \gamma \quad \text{and} \quad n + p \to d + \gamma$$

$$\langle \sigma v \rangle = \frac{f\pi\alpha}{m_p^2}\frac{3}{\sqrt{2}}\left(\frac{Z}{A}\right)^2 \frac{T}{\sqrt{A m_p E}};$$

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$$OHe + He \to OBe + \gamma$$

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[15] Khlopov M. Y., Mayorov A. G., Soldatov E. Y. Dark Atoms of the Uni-verse: towards OHe nuclear physics. — 2010. — arXiv: 1011 . 4586[astro-ph.CO].

Nuclear reactions with dark ions

Accurate calculation

- Accurate calculation of reaction rates [6,14] requires to know wave functions of particles
- To find it
  - In [6] the variation method was used
  - In [14] the quantum three-body problem was solved

[6] Akhmedov E. Nuclear fusion catalyzed by doubly charged scalars: Implications for energy production // Phys. Rev. D – 2022. – Vol. 106, No. 03
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Primordial concentrations

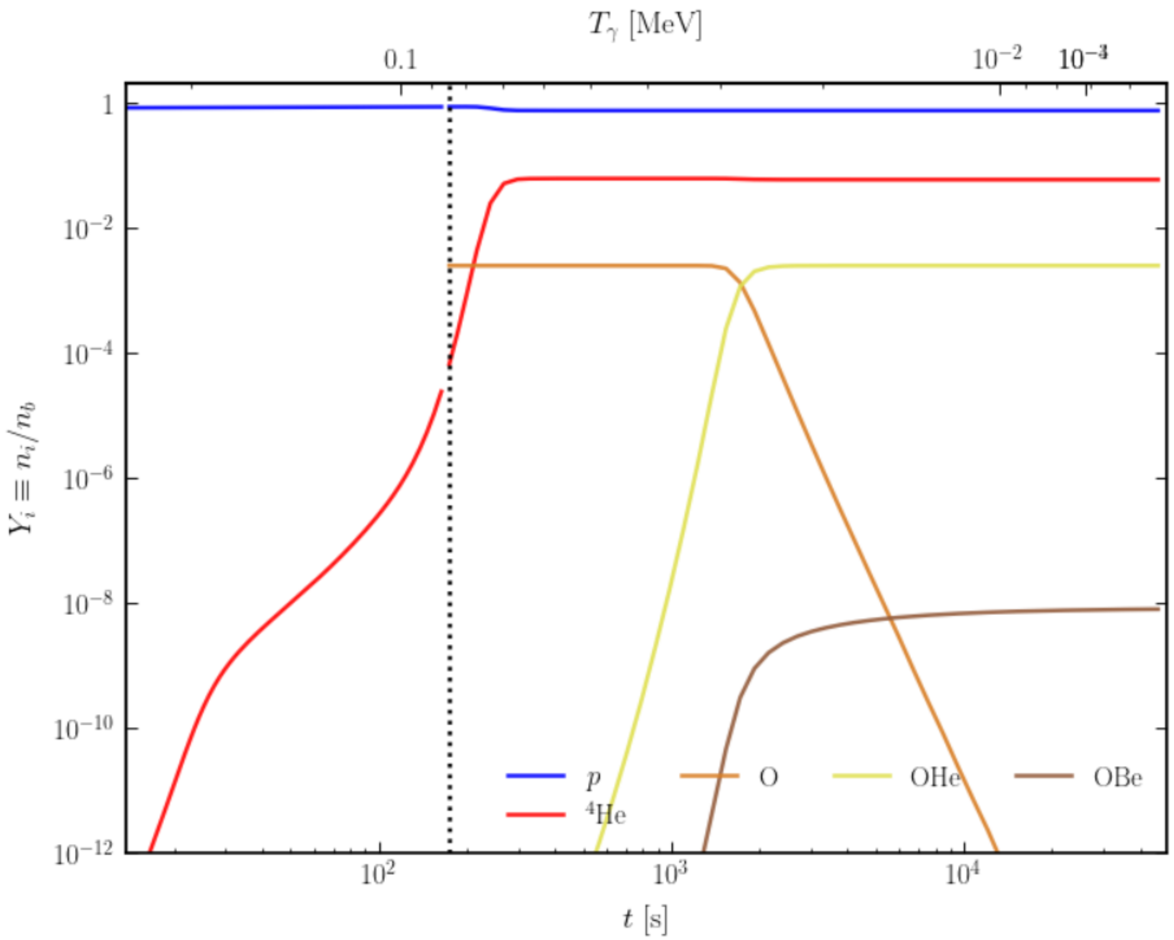
Anomalous isotopes

1) $O^{--} + {}^4\mathrm{He} \rightarrow OHe + \gamma;$
2) $OHe + {}^4\mathrm{He} \rightarrow OBe + \gamma.$

$$\langle\sigma v\rangle_{\rm rec} = \frac{32}{3}\sqrt{\frac{2\pi E_{X-N}}{3\,m_N}}\,(Z_X Z_N\,\alpha)^3\, r_B^2 \cdot \left(\frac{E_{X_N}}{T}\right)^{\frac{1}{2}} \left(\ln\left(\frac{E_{X_N}}{T}\right) + \gamma\right),$$

$$\langle\sigma v\rangle = \frac{f\pi\alpha}{m_p^2}\frac{3}{\sqrt{2}}\left(\frac{Z}{A}\right)^2 \frac{T}{\sqrt{Am_p E}},$$

$$\frac{n_O}{n_b} \approx 8.7\cdot 10^{-19}, \qquad \frac{n_{OHe}}{n_b} \approx 2.5\cdot 10^{-3}, \qquad \frac{n_{OBe}}{n_b} \approx 8.1\cdot 10^{-9}.$$



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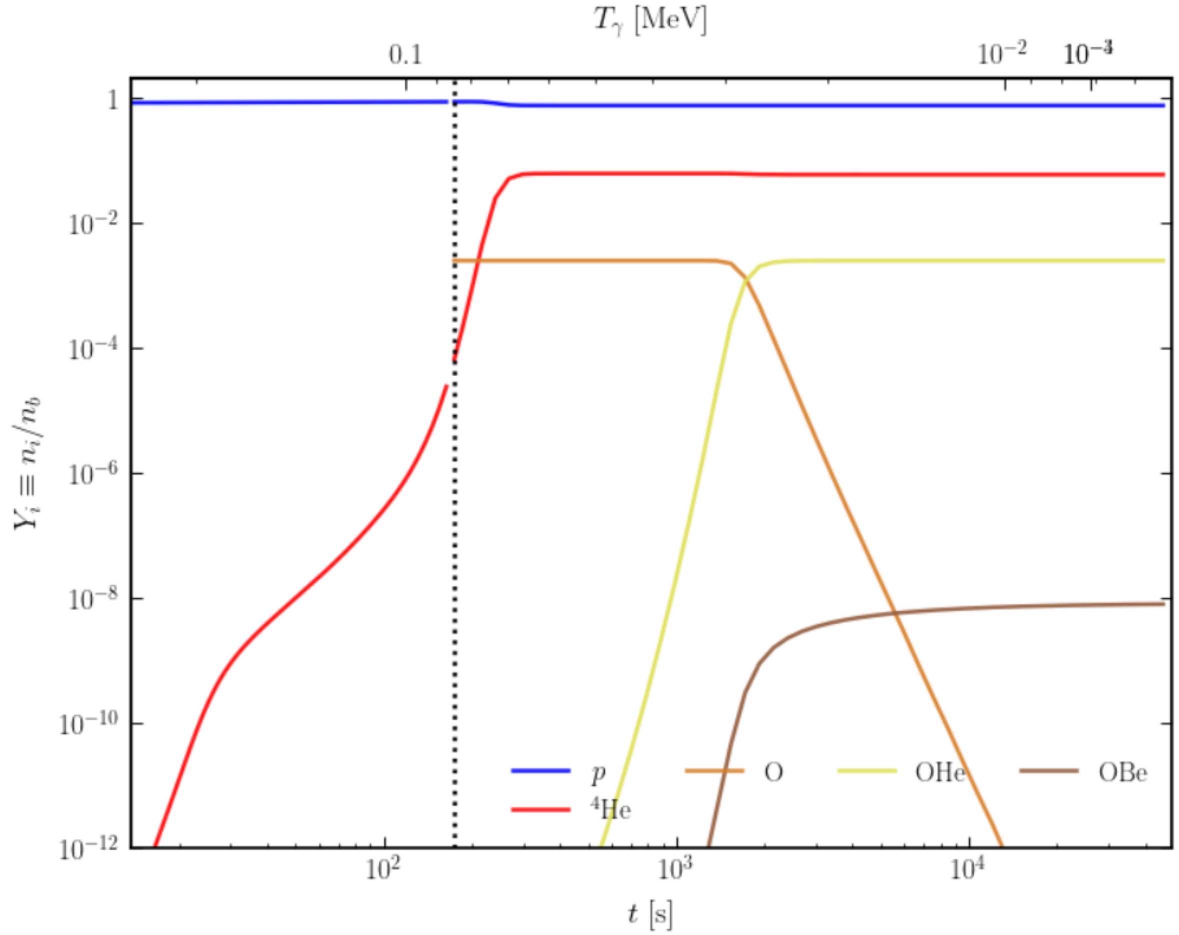


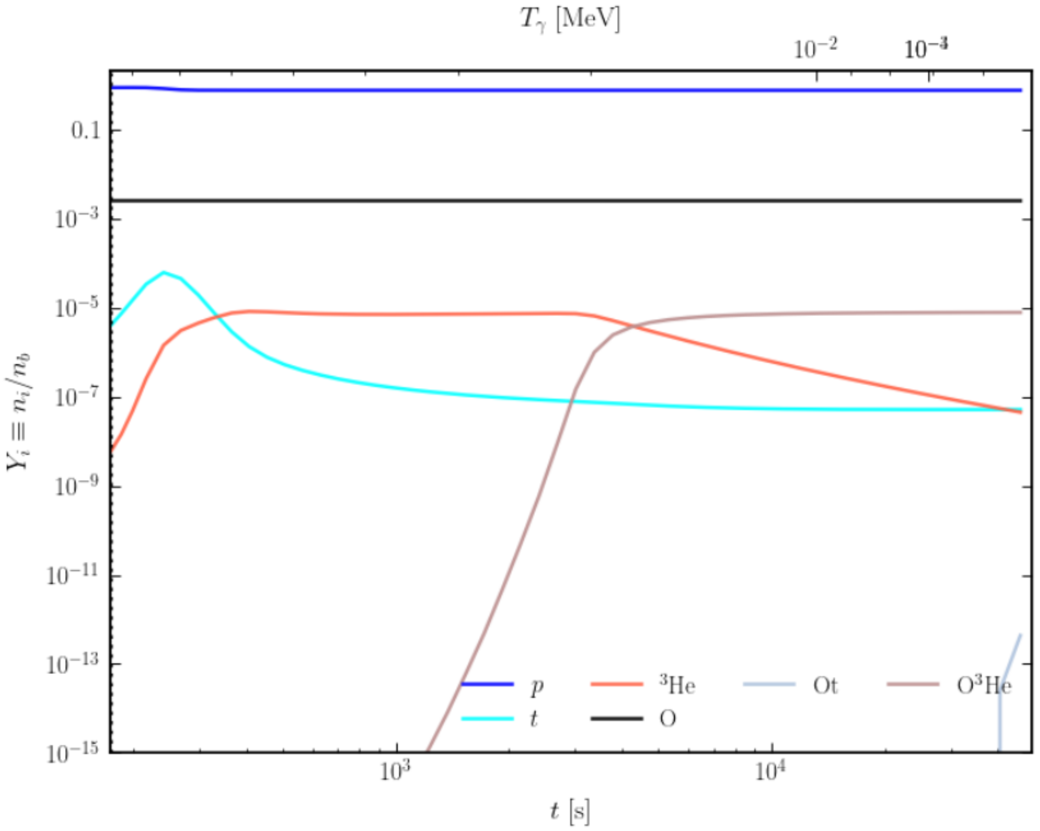
[16] LINX: A Fast, Differentiable, and Extensible Big Bang Nucleosynthe-sis Package / C. Giovanetti [et al.]. — 2024. — arXiv: 2408 . 14538[astro-ph.CO].

Primordial concentrations
Anomalous isotopes

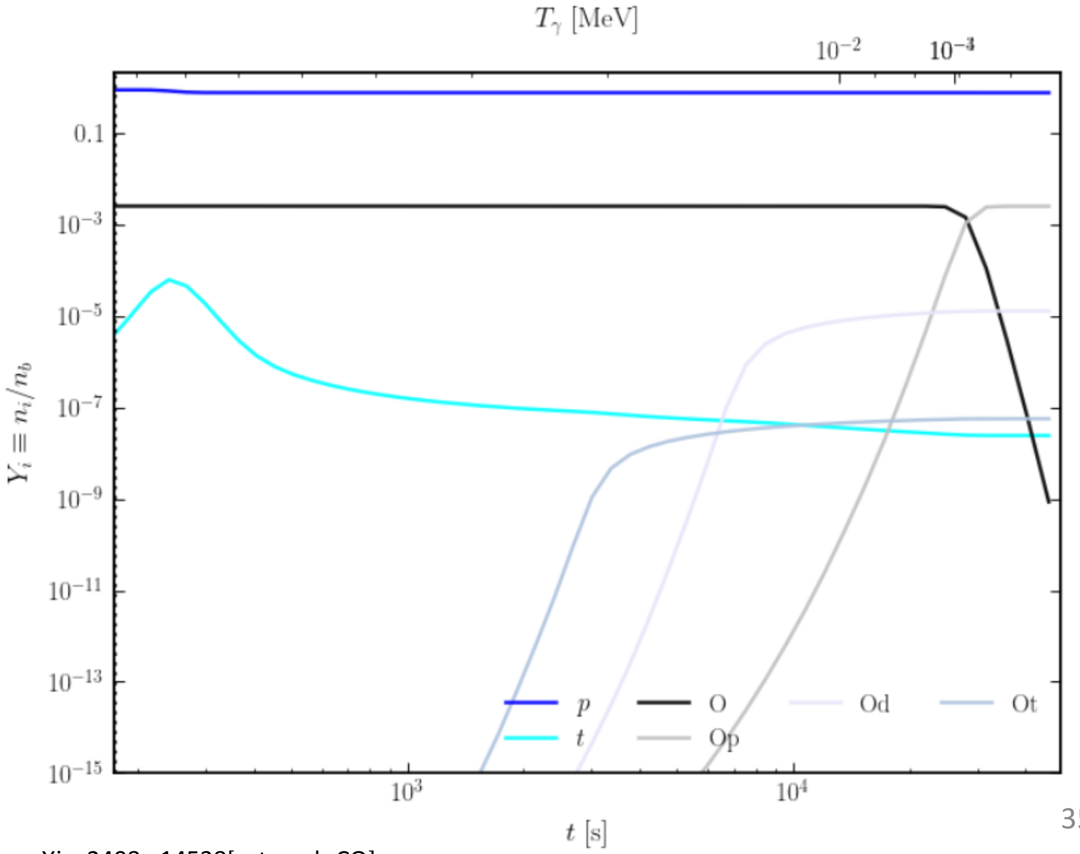
Exact rates are known only for capturing of:

- n=1: $p, d, t, {}^{3}He$
- n=2: p, d, t

n=1



n=2



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Primordial concentrations
Anomalous isotopes

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

$$E_{X-N}^{\rm Bohr} = 2n^2 Z^2 \alpha^2 m_N = \frac{1}{2m_N r_B^2}$$

$$E_{W-N}^{\rm Thompson} = \frac{3}{2}\frac{Z_X Z_N \alpha}{r_N}\left(1 - \sqrt{\frac{r_B}{r_N}}\right)$$

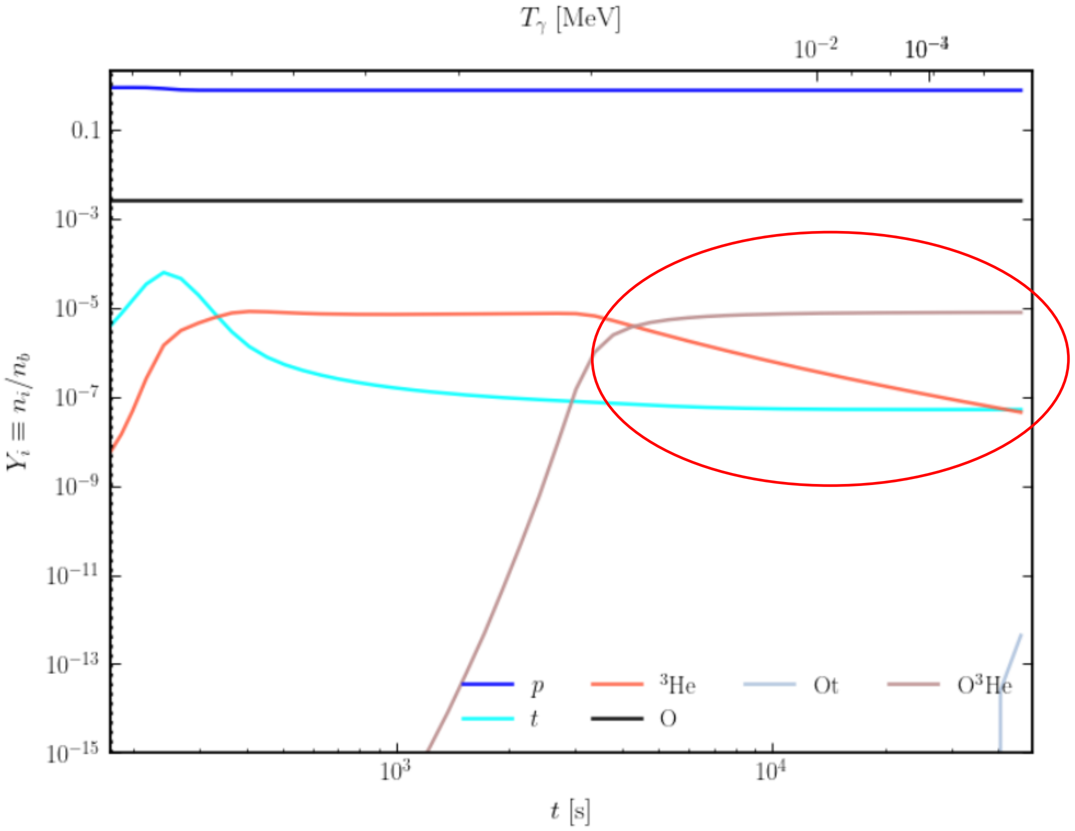
n	$T_{\rm rec}$, кэВ			
	p	D	^3He	^4He
1	3 (B)	4 (B)	28 (B)	37 (B)
2	13 (B)	19 (B)	$\sim$ 42 (T)	85 (T)
3	29 (B)	44 (B)	$\sim$ 116 (T)	180 (T)
4	54 (B)	79 (B)	$\sim$ 198 (T)	285 (T)
5	86 (B)	$\sim$ 126 (B)	$\sim$ 286 (T)	395 (T)

Primordial concentrations
Anomalous isotopes

Exact rates are known only for capturing of:

- n=1: $p, d, t, {}^{3}He$
- n=2: p, d, t

n=1



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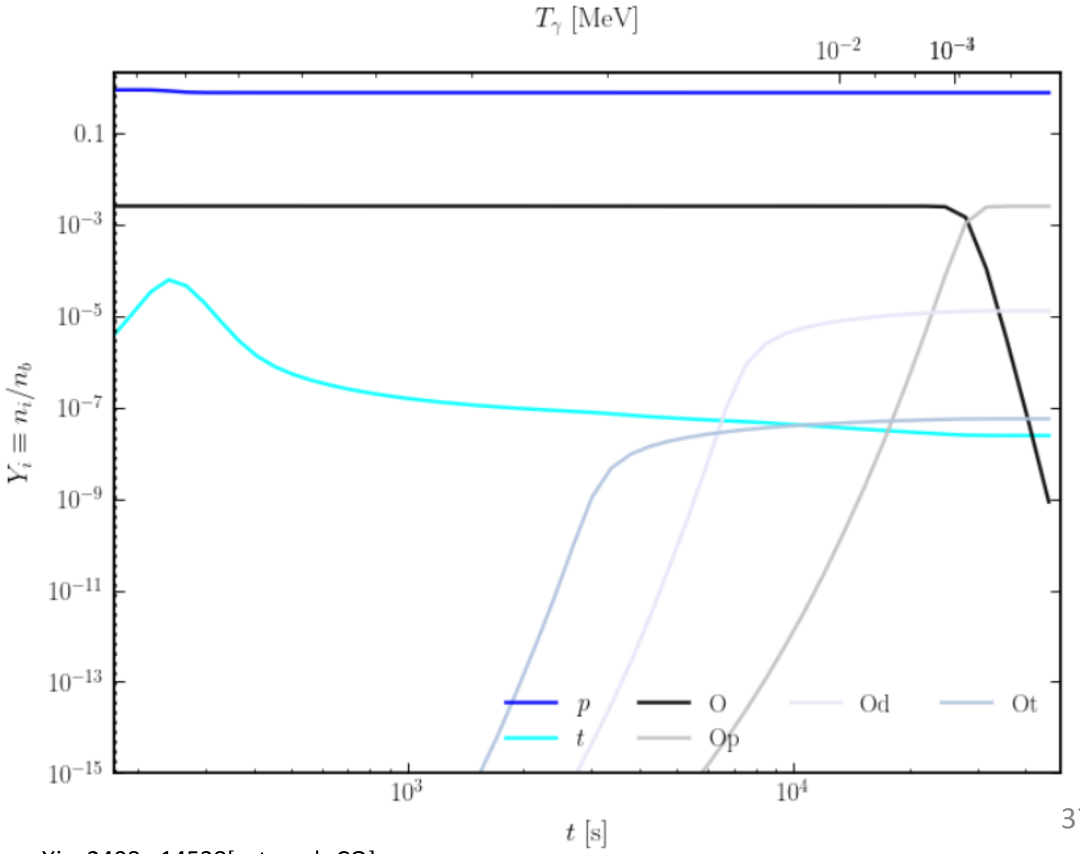

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Conclusions

- To predict the primordial concentrations of dark ions, it is necessary to describe both **the reactions of nuclear shell formation** and **the internal structure:**
  - kinetic equations require reaction rates, which for the most part can be found by rescaling
  - Both binding energies E_{X-N} and Q_N are needed to create an accurate network of reactions
  - The nuclear shell can be described using the methods of modern nuclear physics.
- The overproduction of anomalous isotopes and primordial metals may constrain the dark atom model, but the standard model of nucleosynthesis should be revised

28th International workshop
''What comes beyond the standard models''

Stable multicharged particles in the early Universe

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