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Dark atom solution for puzzles of direct dark matter searches

Talk at

9th Symposium on Large TPCs for Low-Energy Rare Events

Paris, France, 13 December 2018

Outlines

- Dark atoms – bound states of electrically charged particles?
- O-helium – nuclear interacting dark matter
- O-helium interpretation of the puzzles of direct dark matter searches
- OHe indirect effects – explaining excess of low and high energy cosmic positrons.
- Accelerator probes for OHe model

DARK MATTER FROM CHARGED PARTICLES?

Baryonic Matter – atoms of stable quarks and charged lepton (electron)

- Ordinary matter consists of atoms
- Atoms consist of nuclei and electrons.
- Electrons are lightest charged particles – their stability is protected by the conservation of electric charge.
- Nuclei consist of nucleons, whose stability reflects baryon charge conservation.

In ordinary matter stable elementary particles are electrically charged, but bound in neutral atoms.

Dark Matter from Charged Particles?

By definition Dark Matter is non-luminous, while charged particles are the source of electromagnetic radiation. Therefore, neutral weakly interacting elementary particles are usually considered as Dark Matter candidates. If such neutral particles with mass m are stable, they freeze out in early Universe and form structure of inhomogeneities with the minimal characterstic scale

$$M = m_{Pl}\left(\frac{m_{Pl}}{m}\right)^2$$

- However, if charged particles are heavy, stable and bound within neutral « atomic » states they can play the role of composite Dark matter.
- Physical models, underlying such scenarios, their problems and nontrivial solutions as well as the possibilities for their test are the subject of the present talk.

« No go theorem » for -1 charge components

- *If composite dark matter particles are « atoms », binding positive P and negative E charges, all the free primordial negative charges E bind with He-4, as soon as helium is created in SBBN.*
- *Particles E with electric charge -1 form +1 ion [E He].*
- *This ion is a form of anomalous hydrogen.*
- Its Coulomb barrier prevents effective binding of positively charged particles P with E. These positively charged particles, bound with electrons, become atoms of anomalous istotopes
- *Positively charged ion is not formed, if negatively charged particles E have electric charge -2.*

Nuclear-interacting composite dark matter: O-helium « atoms »

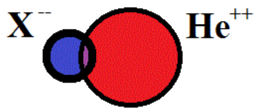
If we have a stable double charged particle X^{--} *in excess over its partner* X^{++} *it may create Helium like neutral atom (O-helium) at temperature* $\boldsymbol{T < I_o}$

Where:

$$I_o = Z_{He}^2 Z_\Delta^2 \alpha^2 m_{He} = 1.6 MeV$$

^4He is formed at T ~100 keV (t~100 s)
This means that it would rapidly create a neutral atom, in which all X^{--} are bound

$$X^{--} + {}^4He => (X\ He) + \gamma$$



The Bohr orbit of O-helium « atom » is of the order of radius of helium nucleus.

$$R_o = 1/\left(Z Z_{He} \alpha m_{He}\right) = 2 \cdot 10^{-13} cm$$

References
1. M.Yu. Khlopov, *JETP Lett.* 83 (2006) 1;
2. D. Fargion, M.Khlopov, C.Stephan, *Class. Quantum Grav.* 23 (2006) 7305;
2. M. Y. Khlopov and C. Kouvaris, *Phys. Rev.* D 77 (2008) 065002]

Constituents of composite dark matter

Few possible candidates for -2 charges:

Stable doubly charged "leptons" with mass >100 GeV (~1 TeV range):

- *AC « leptons » from almost commutative geometry*

D. Fargion, M.Khlopov, C.Stephan, Class. Quantum Grav. 23 (206) 7305

- *Technibaryons and technileptons from Walking Technicolor (WTC)*

M. Y. Khlopov and C. Kouvaris, Phys. Rev. D 77 (2008) 065002; M. Y. Khlopov and C. Kouvaris, Phys. Rev. D 78 (2008) 065040

Hadron-like bound states of:

- *Stable U-quark of 4-th family in Heterotic string phenomenology*

M.Yu. Khlopov, *JETP Lett.* 83 (2006) 1

- *Stable U-quarks of 5th family in the approach, unifying spins and charges*

N.S. Mankoc Borstnik, Mod. Phys. Lett. A 10 (1995) 587

M.Yu.Khlopov, A.G.Mayorov, E.Yu.Soldatov (2010), arXiv:1003.1144

O-HELIUM DARK MATTER

O-helium dark matter

$$T < T_{od} = 1keV$$

$$n_b \langle \sigma v \rangle \left(m_p / m_o \right) t < 1$$

$$T_{RM} = 1eV$$

$$M_{od} = \frac{T_{RM}}{T_{od}} m_{Pl} \left(\frac{m_{Pl}}{T_{od}} \right)^2 = 10^9 M_{Sun}$$

- Energy and momentum transfer from baryons to O-helium is not effective and O-helium gas decouples from plasma and radiation
- O-helium dark matter starts to dominate
- On scales, smaller than this scale composite nature of O-helium results in suppression of density fluctuations, making O-helium gas Warmer than Cold Dark Matter

O-helium in Earth

- Elastic scattering dominates in the (OHe)-nucleus interaction. After they fall down terrestrial surface the in-falling OHe particles are effectively slowed down due to elastic collisions with the matter. Then they drift, sinking down towards the center of the Earth with velocity

$$V = \frac{g}{n\sigma v} \approx 80 S_3 A_{med}^{1/2} \text{ cm/ s}.$$

Here $A_{med} \sim 30$ is the average atomic weight in terrestrial surface matter, $n = 2.4 \cdot 10^{24}/A_{med}$ is the number of terrestrial atomic nuclei, σv is the rate of nuclear collisions and $g = 980 \text{ cm/ s}^2$.

O-helium experimental search?

- In underground detectors, (OHe) “atoms” are slowed down to thermal energies far below the threshold for direct dark matter detection. However, (OHe) nuclear reactions can result in observable effects.
- O-helium gives rise to less than 0.1 of expected background events in XQC experiment, thus avoiding severe constraints on Strongly Interacting Massive Particles (SIMPs), obtained from the results of this experiment.

It implies development of specific strategy for direct experimental search for O-helium.

O-HELIUM DARK MATTER IN UNDERGROUND DETECTORS

O-helium concentration in Earth

The O-helium abundance the Earth is determined by the equilibrium between the in-falling and down-drifting fluxes.

The in-falling O-helium flux from dark matter halo is

$$F = \frac{n_0}{8\pi} \cdot |\overline{V_h} + \overline{V_E}|,$$

where **V_h** is velocity of Solar System relative to DM halo (220 km/s), **V_E** is velocity of orbital motion of Earth (29.5 km/s) and $n_0 = 3 \cdot 10^{-4} S_3^{-1}\,\mathrm{cm}^{-3}$ is the local density of O-helium dark matter.

At a depth *L* below the Earth's surface, the drift timescale is ~*L/V.* It means that the change of the incoming flux, caused by the motion of the Earth along its orbit, should lead at the depth L ~ 10^5 cm to the corresponding change in the equilibrium underground concentration of OHe on the timescale

$$t_{dr} \approx 2.5 \cdot 10^2 S_3^{-1}\,\mathrm{s}$$

Annual modulation of O-helium concentration in Earth

The equilibrium concentration, which is established in the matter of underground detectors, is given by

$$n_{oE} = \frac{2\pi \cdot F}{V} = n_{oE}^{(1)} + n_{oE}^{(2)} \cdot sin(\omega(t - t_0)),$$

where $\omega = 2\pi/T$, T=1*yr* and $\boldsymbol{t_o}$ is the phase. The averaged concentration is given by

$$n_{oE}^{(1)} = \frac{n_o}{320 S_3 A_{med}^{1/2}} V_h$$

and the annual modulation of OHe concentration is characterized by

$$n_{oE}^{(2)} = \frac{n_o}{640 S_3 A_{med}^{1/2}} V_E$$

The rate of nuclear reactions of OHe with nuclei is proportional to the local concentration and the energy release in these reactions leads to ionization signal containing both constant part and annual modulation.

OHe solution for puzzles of direct DM search

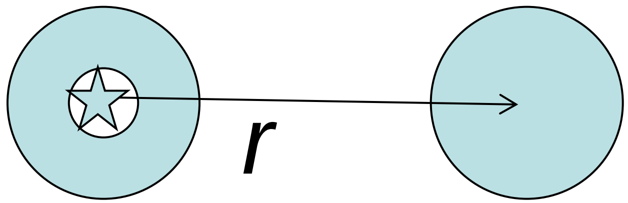
- OHe equilibrium concentration in the matter of DAMA detector is maintained for less than an hour
- Annual modulations in inelastic processes, induced by OHe in matter. No signal of WIMP-like recoil
- The process

$$OHe + (A,Z) \Rightarrow [OHe(A,Z)] + \gamma$$

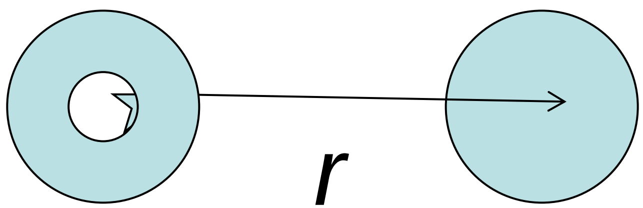
is possible, in which only a few keV energy is released. Other inelastic processes are suppressed

- Signal in DAMA detector is not accompanied by processes with large energy release. This signal corresponds to a formation of anomalous isotopes with binding energy of few keV

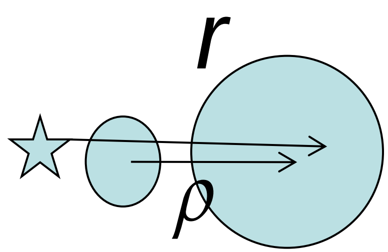
Potential of OHe-nucleus interaction



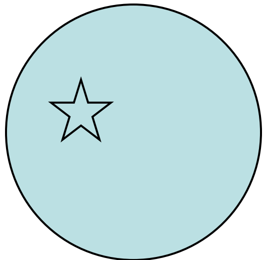
$$U_{Xnuc} = -2Z\alpha\left(\frac{1}{r} + \frac{1}{r_o}\right)\exp\left(-2r/r_o\right)$$



$$U_{Stark} = -\frac{2Z\alpha}{r^4}\frac{9}{2}r_o^3$$

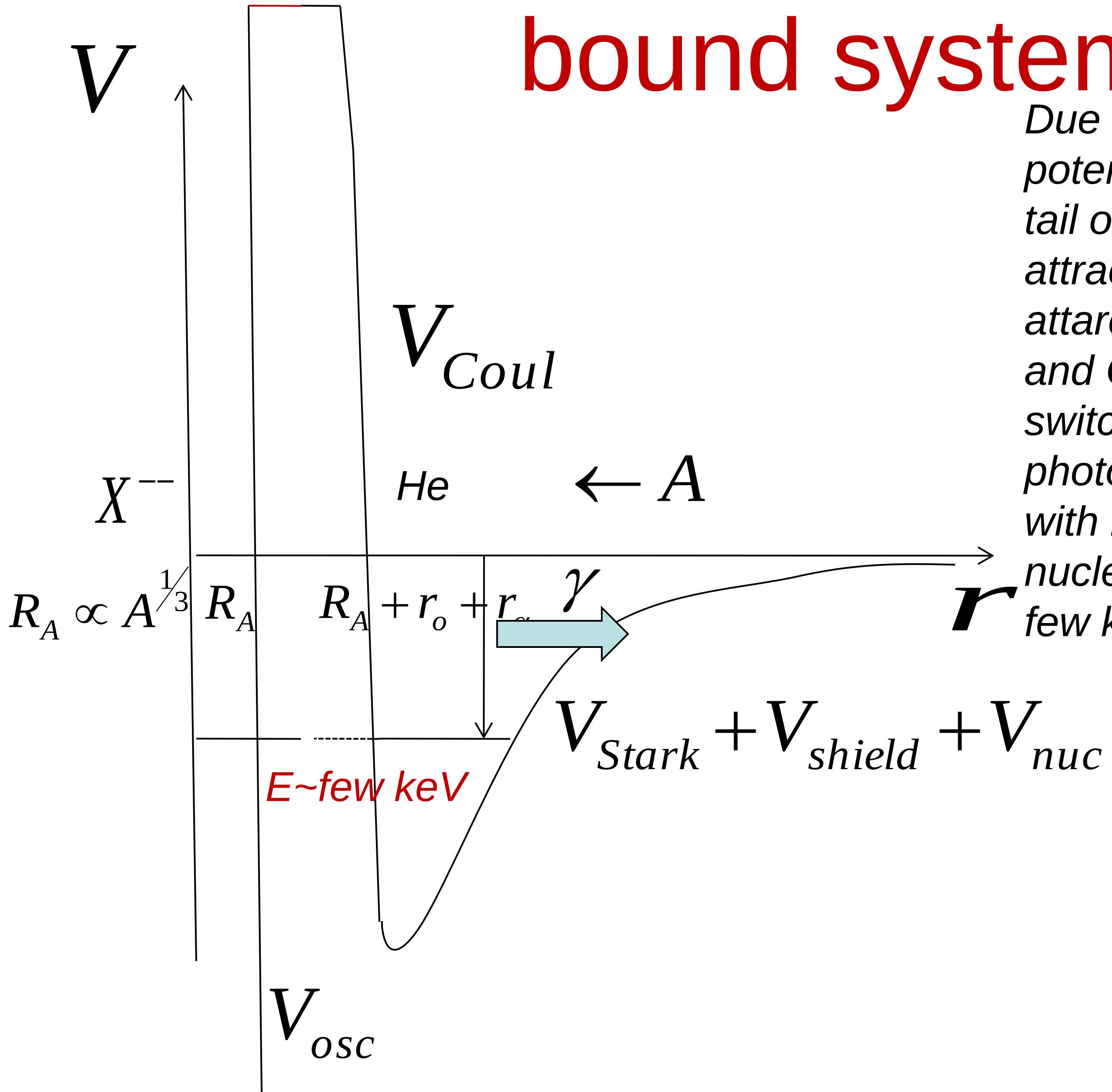


$$U_{Coul} = +\frac{2\alpha Z}{\rho} - \frac{2\alpha Z}{r}$$



$$U_{osc} = -\left[\frac{(Z+2)\alpha}{R}\left(1-\left(\frac{r}{R}\right)^2\right)\right]$$

Formation of OHe-nucleus bound system



Due to shielded Coulomb potential of X, Stark effect and tail of nuclear Yukawa force OHe attracts the nucleus. Nuclear attarction causes OHe excitation and Coulomb repulsion is switched on. If the system emits a photon, OHe forms a bound state with nucleus but **beyond** *the nucleus with binding energy of few keV.*

Few keV Level in OHe-nucleus system

- The problem is reduced to a quantum mechanical problem of energy level of OHe-nucleus bound state in the potential well, formed by shielded Coulomb, Stark effect and Yukawa tail attraction and dipole-like Coulomb barrier for the nucleus in vicinity of OHe. The internal well is determined by oscillatory potential of X in compound (Z+2) nucleus, in which He is aggregated.
- The numerical solution for this problem is simplified for rectangular wells and walls, giving a few keV level for Na.

Rate of OHe-nucleus radiative capture

As soon as the energy of level is found one can use the analogy with radiative capture of neutron by proton with the account for:

- Absence of M1 transition for OHe-nucleus system (which is dominant for n+p reaction)
- Suppression of E1 transition by factor $f \sim 10^{-3}$, corresponding to isospin symmetry breaking

(in the case of OHe only isoscalar transition is possible, while E1 goes due to isovector transition only)

Reproduction of DAMA/NaI and DAMA/LIBRA events

The rate of OHe radiative capture by nucleus with charge Z and atomic number A to the energy level E in the medium with temperature T is given by

$$\sigma v = \frac{f\pi\alpha}{m_p^2}\frac{3}{\sqrt{2}}\left(\frac{Z}{A}\right)^2\frac{T}{\sqrt{Am_pE}}.$$

Formation of OHe-nucleus bound system leads to energy release of its binding energy, detected as ionization signal. In the context of our approach the existence of annual modulations of this signal in the range 2-6 keV and absence of such effect at energies above 6 keV means that binding energy of Na-Ohe system in DAMA experiment should not exceed 6 keV, being in the range 2-4 keV.

Annual modulation of signals in DAMA/NaI and DAMA/LIBRA events

The amplitude of annual modulation of ionization signal (measured in counts per day per kg, cpd/kg) is given by

$$\zeta = \frac{3\pi\alpha \cdot n_o N_A V_E t Q}{640\sqrt{2} A_{med}^{1/2}(A_I + A_{Na})} \frac{f}{S_3 m_p^2} (\frac{Z_i}{A_i})^2 \frac{T}{\sqrt{A_i m_p E_i}} = 4.3 \cdot 10^{10} \frac{f}{S_3^2} (\frac{Z_i}{A_i})^2 \frac{T}{\sqrt{A_i m_p E_i}}.$$

This value should be compared with the integrated over energy bins signals in DAMA/NaI and DAMA/LIBRA experiments and the results of these experiments can be reproduced for

$$E_{Na} = 3keV$$

OPEN QUESTIONS OF THE OHE SCENARIO

Earth shadow effect

- OHe is nuclear interacting and thus should cause the Earth shadow effect.
- The studies, whether we can avoid recent DAMA constraints are under way.

THE PROBLEM OF POTENTIAL BARRIER

The crucial role of potential barrier in OHe-nucleus interaction

- Due to this barrier elastic OHe-nucleus scattering strongly dominates.
- If such barrier doesn’t exist, overproduction of anomalous isotopes is inevitable.
- Its existence should be proved by proper quantum mechanical treatment

J.-R. Cudell, M.Yu;Khlopov and Q.Wallemacq

Some Potential Problems of OHe Composite Dark Matter,

Bled Workshops in Physics (2014) V.15, PP.66-74; e-Print: arXiv: 1412.6030.

SENSITIVITY OF INDIRECT EFFECTS OF COMPOSITE DARK MATTER TO THE MASS OF THEIR DOUBLE CHARGED CONSTITUENTS

Excessive positrons in Integral

Taking into account that in the galactic bulge with radius ~ 1 kpc the number density of O-helium can reach the value

$$n_o \approx 3 \cdot 10^{-3} / S_3 \, \mathrm{cm}^{-3}$$

one can estimate the collision rate of O-helium in this central region:

$$dN/dt = n_o^2 \sigma v_h 4\pi r_b^3/3 \approx 3 \cdot 10^{42} S_3^{-2} \, s^{-1}$$

At the velocity of particules in halo, energy transfer in such collisions is E ~ 1MeV. These collisions can lead to excitation of O-helium. If 2S level is excited, pair production dominates over two-photon channel in the de-excitation by E0 transition and positron production with the rate

$$3 \cdot 10^{42} S_3^{-2} \, s^{-1}$$

is not accompanied by strong gamma signal. This rate of positron production is sufficient to explain the excess of positron production in bulge, measured by Integral.

Excessive positrons in Integral from dark atoms– high sensitivity to DM distribution

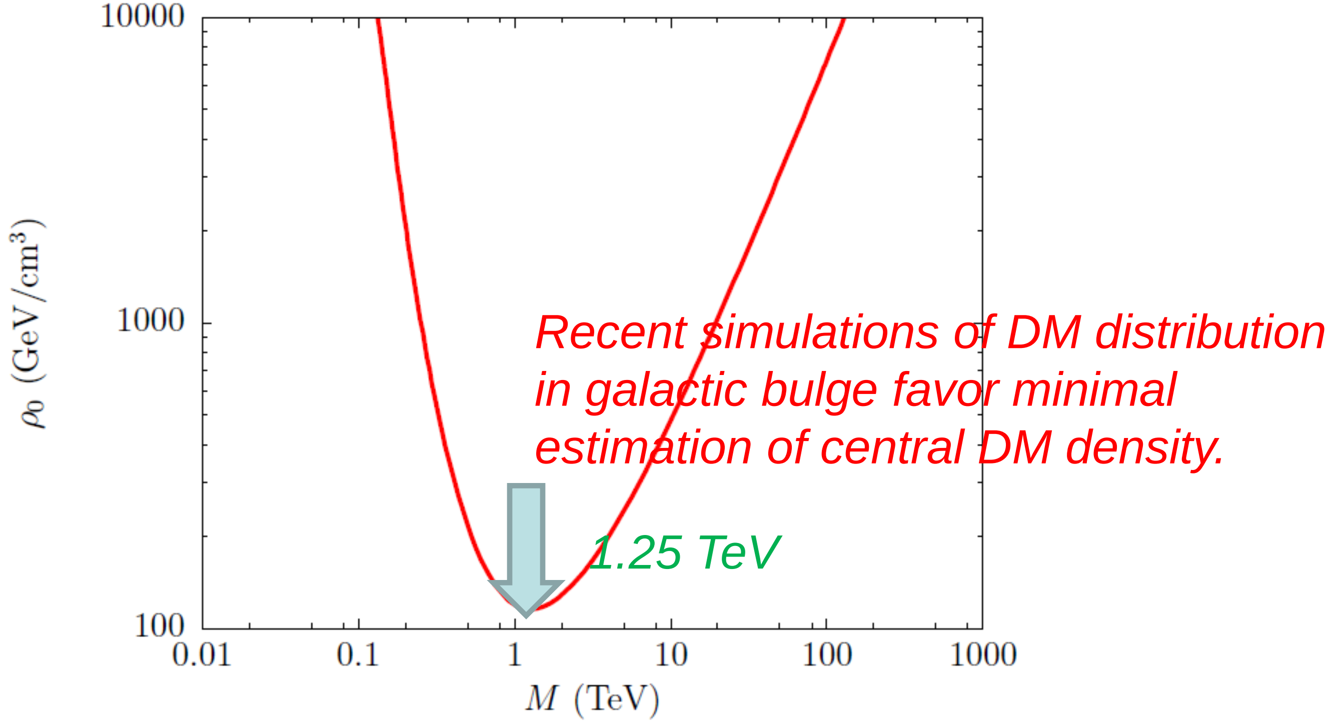


Figure 1: Values of the central dark matter density ρ_0 (GeV/cm^3) and of the OHe mas M (TeV) reproducing the excess of e^+e^- pairs production in the galactic bulge. Belo the red curve, the predicted rate is too low.

J.-R. Cudell, M.Yu.Khlopov and Q.Wallemacq
Dark atoms and the positron-annihilation-line excess in the galactic bulge.
Advances in High Energy Physics, vol. 2014, Article ID 869425, : arXiv: 1401.5228

Composite dark matter explanation for low energy positron excess

- In spite of large uncertainty of DM distribution in galactic bulge, where baryonic matter dominates and DM dynamical effects are suppressed, realistic simulations favor lower value of DM central density around $\rho_0 \simeq 115$ GeV/cm^3. Then observed excess of positron annihilation line can be reproduced in OHe model only at the mass of its heavy double charged constituent:
- $$M \simeq 1.25 \text{ TeV}$$

A solution for cosmic positron excess?

- In WTC: if both technibaryons UU and technileptons ζ are present, CDMS, LUX results constrain WIMP-like (UUζ) component to contribute no more than 0,0001% of total DM density.
- Decays of positively charged UU->$l^+ l^+$ with a lifetime of about $10^{21} s$ and mass 700-1000 GeV can explain the excess of cosmic positrons, observed by PAMELA and AMS02

Cosmic positron excess from double charged constituents of dark atoms

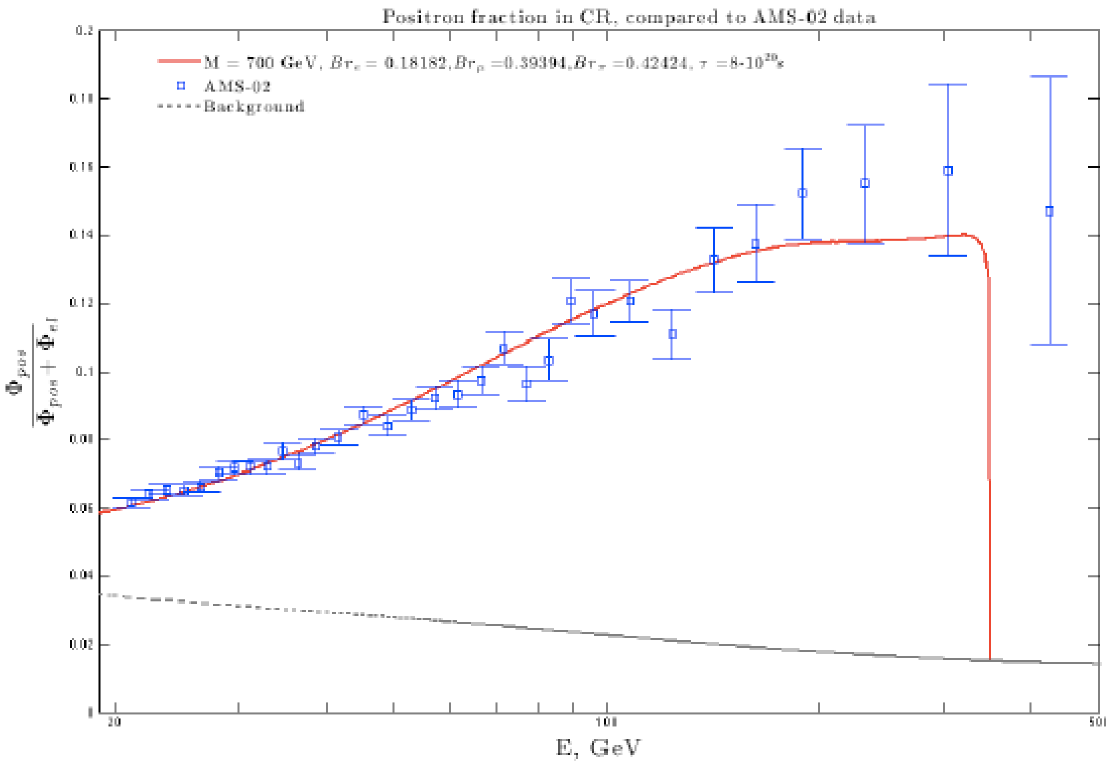


Figure 3: Positron fraction in the cosmic rays from decays of dark matter particles (red curve), corresponding to the best-fit values of model parameters ($M = 700\,\mathrm{GeV}, \tau = 8 \cdot 10^{20}\,\mathrm{s}, Br_{ee} = 0.182, Br_{\mu\mu} = 0.394, Br_{\tau\tau} = 0.424$), and fraction of secondary positrons (gray line), compared to the latest AMS-02 data [34] (blue dots).

Probably such indirect effect is detected in the cosmic positron fluxes.

[figure from K.M.Belotsky et al. Int.J.Mod.Phys. D24 (2015) 1545004 arXiv:1508.02881]

Diffuse Gamma ray background

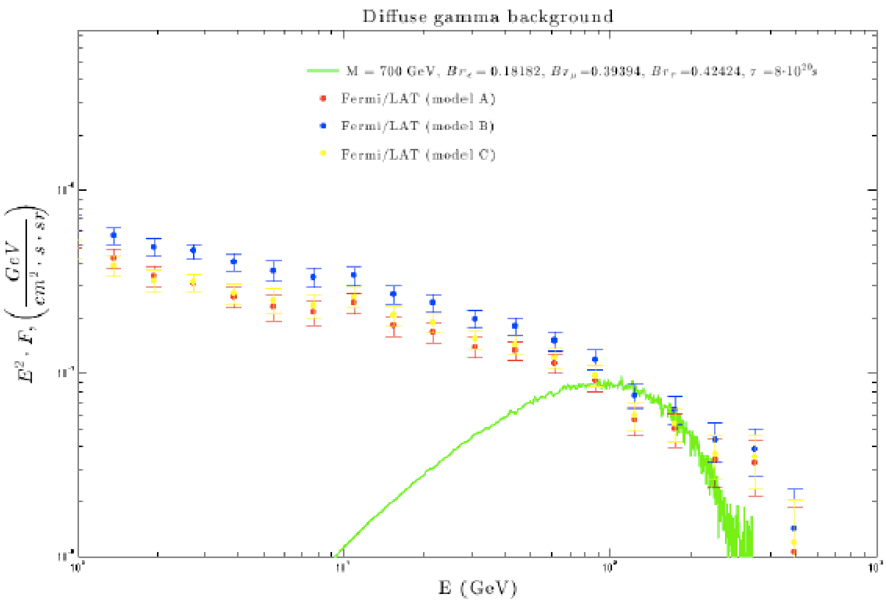


Figure 4: Gamma-ray flux multiplied by E^2 from decays of dark matter particles in the Galaxy and beyond (green curve), corresponding to the best-fit values of model parameters ($M = 700\,\mathrm{GeV}, \tau = 8 \cdot 10^{20}\,\mathrm{s}, Br_{ee} = 0.182, Br_{\mu\mu} = 0.394, Br_{\tau\tau} = 0.424$), compared to the latest FERMI/LAT data on isotropic diffuse gamma-ray background [42] ($|b| > 20°, 0° \leq l < 360°$ with point sources removed and without diffuse emission attributed to the interactions of Galactic cosmic rays with gas and radiation fields (foreground); here three different foreground models A (red dots), B (blue dots) and C (yellow dots) are shown). In our analysis we have used model B.

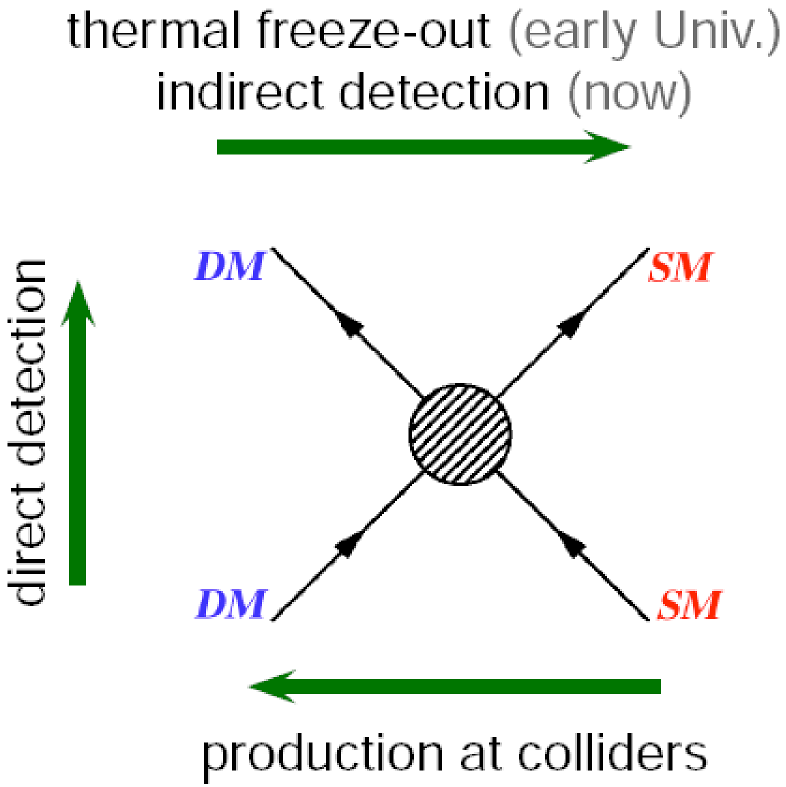
Composite dark matter explanation for high energy positron excess

- Any source of high energy positrons, distributed in galactic halo is simultaneously the source of gamma ray background, measured by FERMI/LAT.
- Not to exceed the measured gamma ray background the mass of decaying double charged particles should not exceed

$$M < 1\ \text{TeV}$$

COMPOSITE DARK MATTER CONSTITUENTS AT ACCELERATORS

Complementarity in searches for Dark Matter



Usually, people use this illustration for complementarity in direct, indirect and accelerator searches for dark matter. However, we see that in the case of composite dark matter the situation is more nontrivial. We need charged particle searches to test dark atom model

Collider test for dark atoms

- Being the simplest dark atom model OHe scenario can not only explain the puzzles of direct dark matter searches, but also explain some possible observed indirect effects of dark matter. Such explanation implies a very narrow range of masses of (meta-) stable double charged particles in vicinity of 1 TeV, what is the challenge for their search at the experiments at the LHC.

Search for multi-charge particles in the ATLAS experiment

Work is done in a frame of Multi-Charge Analysis Group

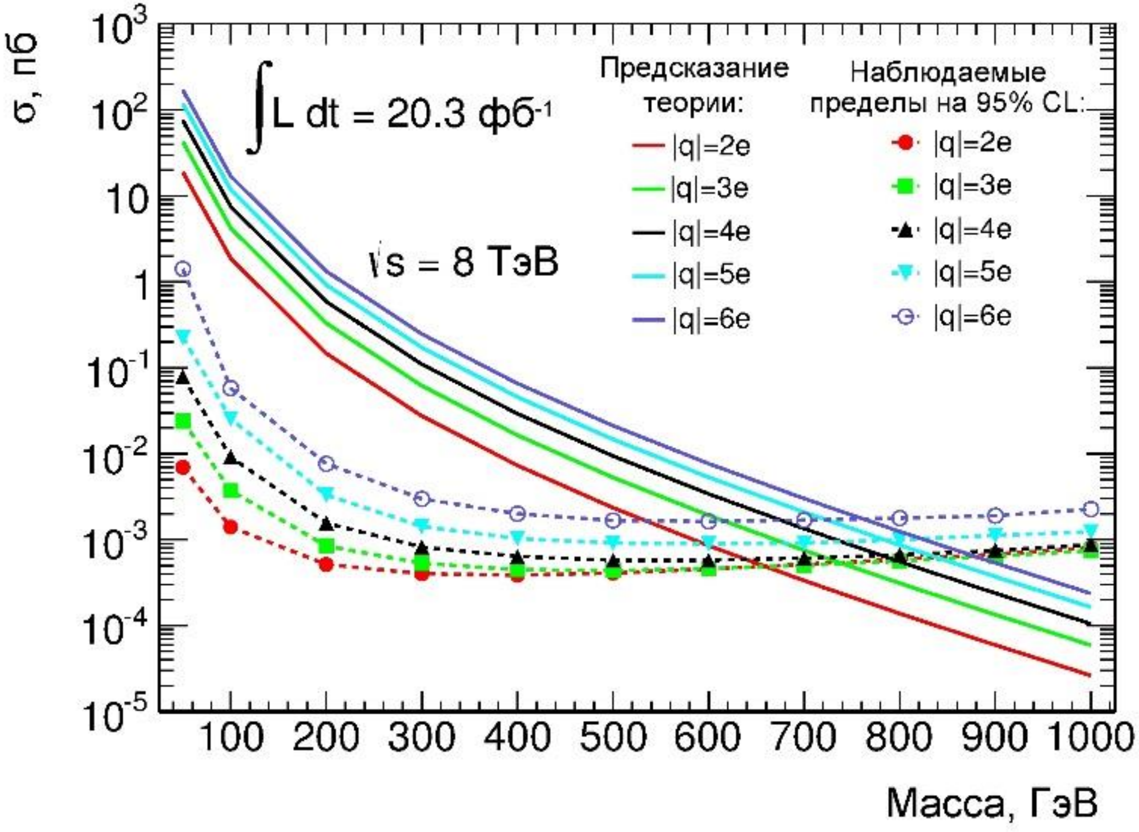
Search for Multi-charge Objects in *pp* collisions at $\sqrt{s}$ = 7 TeV using the ATLAS detector

K.M. Belotsky[a], O. Bulekov[a], M. Jüngst[b], M.Yu.Khlopov[a,h], C. Marino[c], P. Mermod[d], H. Ogren[e], A. Romaniouk[a], Y. Smirnov[a], W. Taylor[f], B. Weinert[g], D. Zieminska[e], S. Zimmermann[g]

[a]*Moscow Engineering Physics Institute*
[b]*CERN*
[c]*University of Victoria*
[d]*Oxford University*
[e]*Indiana University*
[f]*York University*
[g]*University of Bonn*
[h]*University of Paris*

Our studies favor good chances for detection of multi-charge species in ATLAS detector

Searches for multiple charged particles in ATLAS experiment



M>659 GeV for |q|=2e at 95% c.l. [Yu. Smirnov, PhD Thesis]

[ATLAS Collaboration, Search for heavy long-lived multi-charged particles in pp collisions at √s=8 TeV using the ATLAS detector, Eur. Phys. J. C 75 (2015) 362]

Experimentum crucis for composite dark matter at the LHC

Coming analysis of results of double charged particle searches at the LHC can cover all the range of masses, at which composite dark matter can explain excess of slow and high energy positrons, assuming the independent statistics In CMS and ATLAS experiments.

Data period	Estimated lower mass limit, GeV	
	ATLAS or CMS separately	ATLAS and CMS combined
2015–2016	1000	1110
2015–2018	1190	1300

Remind that composite dark matter can explain excess of low energy positrons at M=1.25 TeV and high energy positrons at M<1 TeV.

Conclusions

- **Physical basis of the modern cosmology implies new physics.**
- **Dark atom hypothesis can explain puzzles of direct dark matter searches and cosmic positron anomalies.**
- **It can be directly probed at the LHC in searches for stable double charged particles.**
- **It involves minimal number of parameters of new physics (mass of double charged constituents of dark atoms), but the known atomic and nuclear physics appears in such a complicated combination of effects in OHe-nucleus interaction that its proper quantum mechanical treatment is still an open problem for this approach.**