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Moscow, Russia

Cosmoparticle physics - fundamental relationship of cosmology and particle physics and the platform of a Scientific-Educational complex of

Virtual Institute of Astroparticle physics (VIA)

The main ideas of the Open Online Course "Introduction to cosmoparticle physics" for the International PhD programme on Fundamental physics

Presented at the
International School for young scientists «Visions in Fundamental Physics»
Dedicated to the memory of Nikolay Narozhny
(12-16 December 2016, MEPHI, Moscow, Russia)

12 December 2016

The bedrocks of modern cosmology

Our current understanding of structure and evolution of the Universe implies three necessary elements of Big Bang cosmology that can not find physical grounds in the standard model of electroweak and strong interactions. They are:

- Inflation
- Baryosynthesis
- Dark matter/energy

All these phenomena imply extension of the Standard Model of Strong (QCD) and Electroweak Interactions. On the other hand, studies of physics Beyond the Standard Model involve Cosmology for their probe.

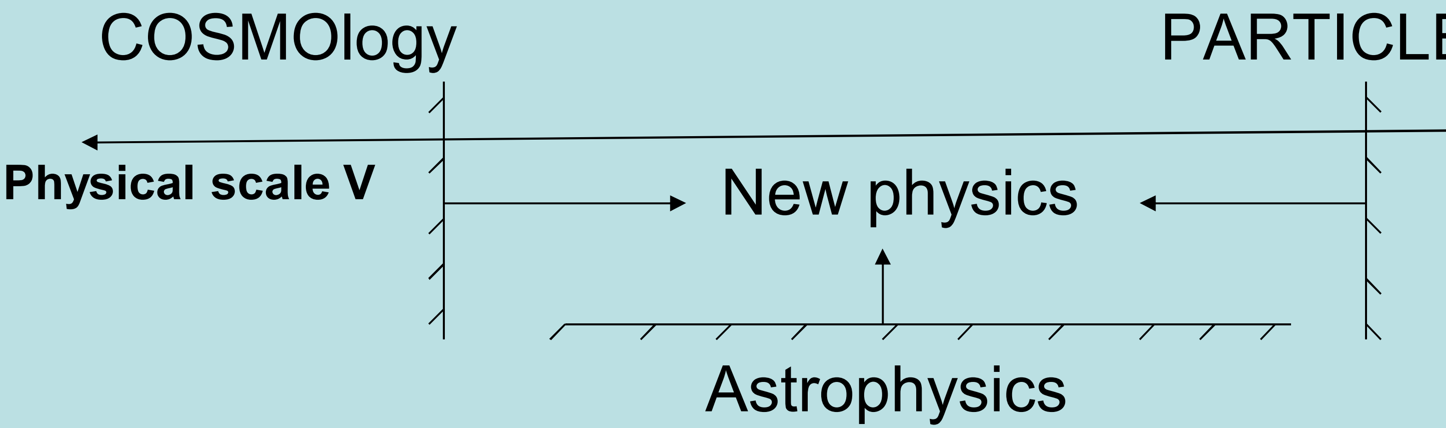
COSMOPARTICLE PHYSICS studies the fundamental relationship of

COSMOlogy and PARTICLE PHYSICS

in the complex cross-disciplinary physical and astronomical research

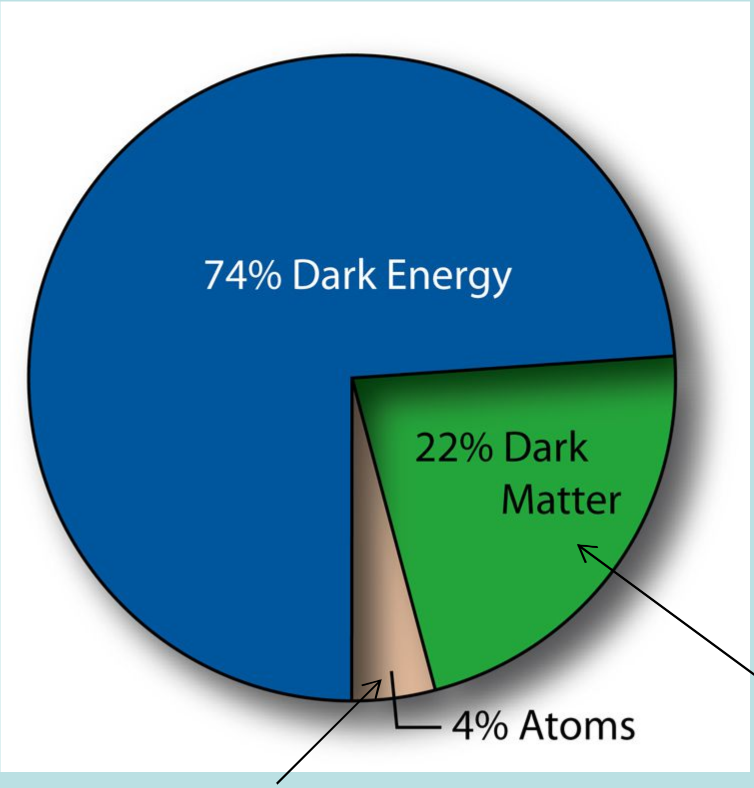
Basic ideas of cosmoparticle physics

- **Physics beyond the Standard model can be studied in combination of indirect physical, astrophysical and cosmological effects**
- **New symmetries imply new conserved charges. Strictly conserved charge implies stability of the lightest particle, possessing it.**
- **New stable particles should be present in the Universe. Breaking of new symmetries implies cosmological phase transitions. Cosmological and astrophysical constraints are supplementary to direct experimental search and probe the fundamental structure of particle theory at the scale V**
- **Combination of physical, cosmological and astrophysical effects provide an over-determined system of equations for parameters of particle theory**



Extremes of physical knowledge converge in the mystical Uhrohboros vicious circle of problems, which can be resolved by methods of Cosmoparticle physics

Composition of the Universe



$$\Omega \equiv \frac{\rho}{\rho_{cr}}$$

$$\Omega_{\mathrm{b}} \approx 0.044 \qquad \Omega_{\mathrm{CMB}} \approx 0.5 \cdot 10^{-4}$$

$$\Omega_{\mathrm{DM}} \approx 0.20$$

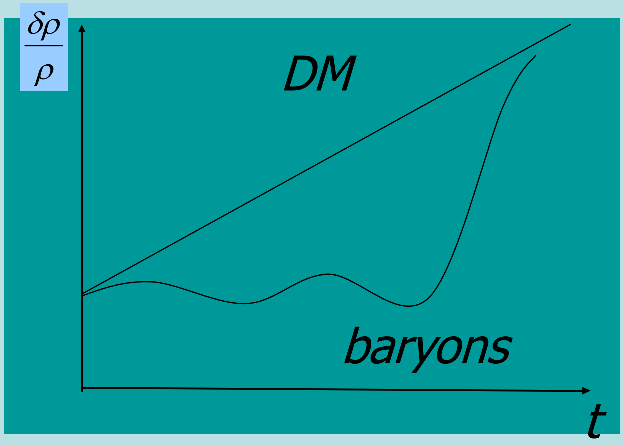
$$\Omega_{\Lambda} \approx 0.7$$

$$\boxed{\Omega_{\mathrm{tot}} \approx 1.0}$$

Baryonic matter consists of atoms

Can dark Matter consist of Dark atoms?

Cosmological Dark Matter



$$\frac{\delta\rho}{\rho} \Rightarrow \frac{\delta T}{T}$$

Cosmological Dark Matter explains:

- ***virial paradox in galaxy clusters,***
- ***rotation curves of galaxies***
- ***dark halos of galaxies***
- ***effects of macro-lensing***

But first of all it provides formation of galaxies from small density fluctuations, corresponding to the observed fluctuations of CMB

To fulfil these duties Dark Matter should interact sufficiently weakly with baryonic matter and radiation and it should be sufficiently stable on cosmological timescale

Dark Matter – Cosmological Reflection of Microworld Structure

Dark Matter should be present in the modern Universe, and thus is stable on cosmological scale.

This stabilty reflects some Conservation Law, which prohibits DM decay.

Following Noether's theorem this conservation law should correspond to a (nearly) strict symmetry of microworld.

Direct seaches for Dark Matter

Possibility of detecting relict massive neutrinos

V. F. Shvartsman, V. B. Braginskiĭ, S. S. Gershteĭn, Ya. B. Zel'dovich, and M. Yu. Khlopov

M. V. Keldysh Institute of Applied Mathematics, Academy of Sciences of the USSR

(Submitted 18 August 1982)

Pis'ma Zh. Eksp. Teor. Fiz. **36**, No. 6, 224–226 (20 September 1982)

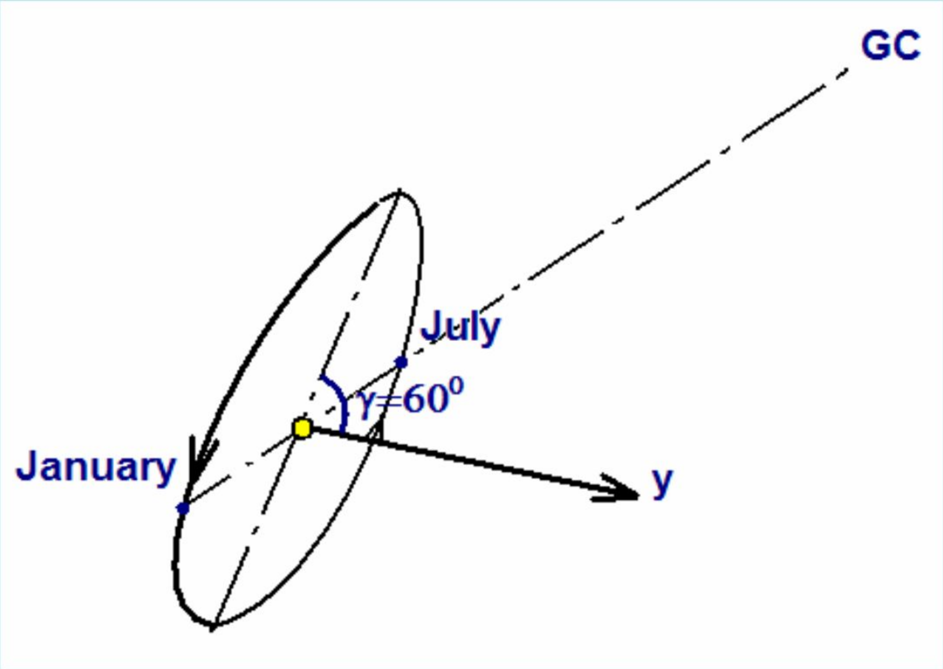
The coherent intensification of the interaction of relict massive neutrinos with grains of matter with a size on the order of the neutrino wavelength suggests that it might be possible to detect a galactic neutrino sea by virtue of the mechanical pressure which it exerts in the direction opposite that in which the solar system is moving in the galaxy.

Annual modulation of WIMP effects

Minimization of background

- Installation deeply underground
- Radioactively pure materials
- Annual modulation

DM does not participate in rotation around GC.



$$v_{Earth\ y} = v_{Sun\ y} + v_{orb} \cdot \cos\gamma \cdot \cos\omega(t - t_0)$$

$$v_{Sun\ y} = 220 + 16.5 \cdot \cos 25° \cdot \sin 53° \text{ (km/s)}$$

$$t_0 = 2 \text{ June}$$

$$Amplitude <\sim \frac{v_{orb} \cdot \cos\gamma}{v_{Sun\ y}} \sim \frac{15}{232} \sim 7\%$$

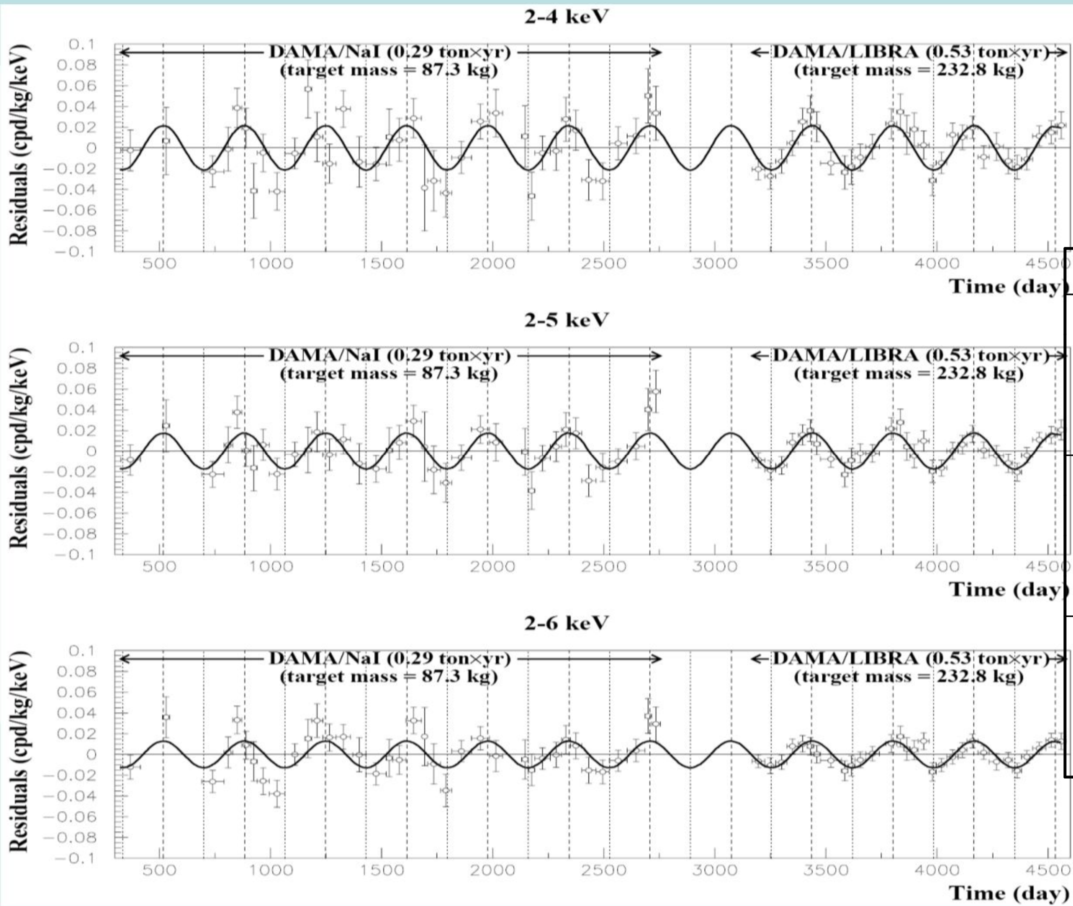
DAMA/NaI and DAMA/LIBRA

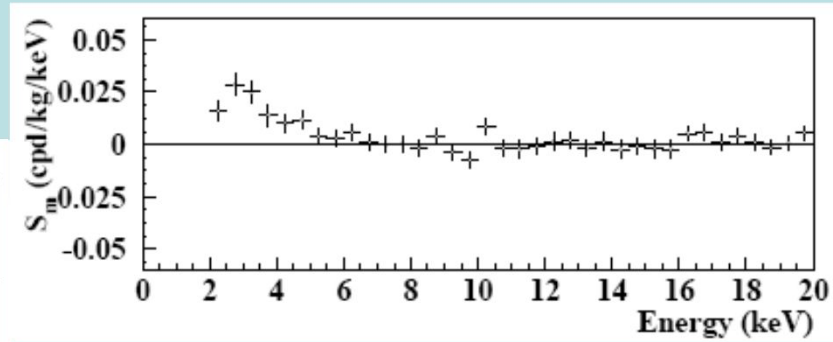
Experiment DAMA (*NaI*)

DAMA/NaI (7 years) + DAMA/LIBRA (4 years) total exposure: 300555 kg×day = 0.82 ton×yr

Results of 7 years of observation (1995-2002).

$$R(t) = S_0 + S_m \cos[\omega(t - t_0)]$$





$t_0 = 21\,\mathrm{May} \pm 22\,\mathrm{days}$

$T = 1.00 \pm 0.01\,\mathrm{year}$

$Amplitude = 0.020(3)\ \mathrm{cpd/kg/keV}$

$Confedence\ level = 6.3\sigma$

	A (cpd/kg/keV)	T= 2p/? (yr)	t_0 (day)	C.L.
DAMA/NaI (7 years)				
(2÷4) keV	0.0252 ± 0.0050	1.01 ± 0.02	125 ± 30	5.0s
(2÷5) keV	0.0215 ± 0.0039	1.01 ± 0.02	140 ± 30	5.5s
(2÷6) keV	0.0200 ± 0.0032	1.00 ± 0.01	140 ± 22	6.3s
DAMA/LIBRA (4 years)				
(2÷4) keV	0.0213 ± 0.0032	0.997 ± 0.002	139 ± 10	6.7s
(2÷5) keV	0.0165 ± 0.0024	0.998 ± 0.002	143 ± 9	6.9s
(2÷6) keV	0.0107 ± 0.0019	0.998 ± 0.003	144 ± 11	5.6s
DAMA/NaI + DAMA/LIBRA				
(2÷4) keV	0.0223 ± 0.0027	0.996 ± 0.002	138 ± 7	8.3s
(2÷5) keV	0.0178 ± 0.0020	0.998 ± 0.002	145 ± 7	8.9s
(2÷6) keV	0.0131 ± 0.0016	0.998 ± 0.003	144 ± 8	8.2s

Model Independent Annual Modulation Result

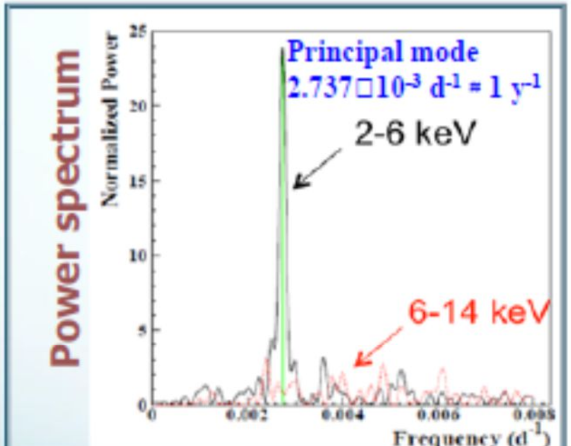
DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kg×day = **1.33 ton×yr**

EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648

The measured modulation amplitudes (A), period (T) and phase (t_0) from the single-hit residual rate vs time

	A(cpd/kg/keV)	$T=2\pi/\omega$ (yr)	t_0 (day)	C.L.
DAMA/NaI+DAMA/LIBRA-phase1				
(2-4) keV	**0.0190 ±0.0020**	**0.996 ±0.0002**	**134 ± 6**	**9.5σ**
(2-5) keV	**0.0140 ±0.0015**	**0.996 ±0.0002**	**140 ± 6**	**9.3σ**
(2-6) keV	**0.0112 ±0.0012**	**0.998 ±0.0002**	**144 ± 7**	**9.3σ**

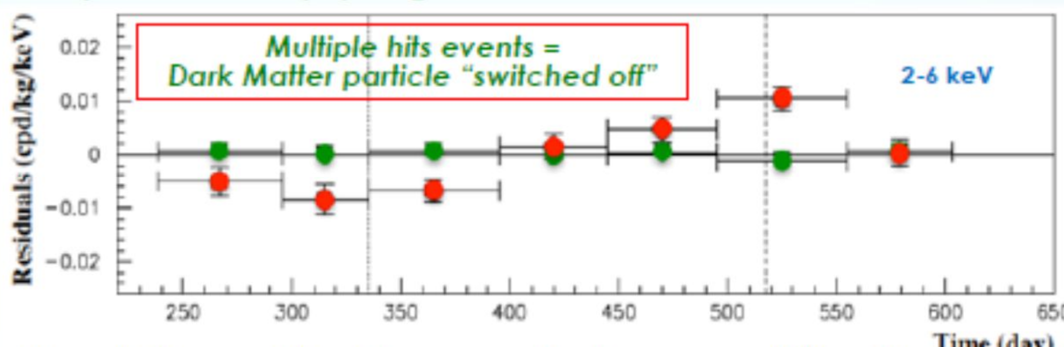
$A\cos[\omega(t-t_0)]$



No systematics or side reaction able to account for the measured modulation amplitude and to satisfy all the peculiarities of the signature

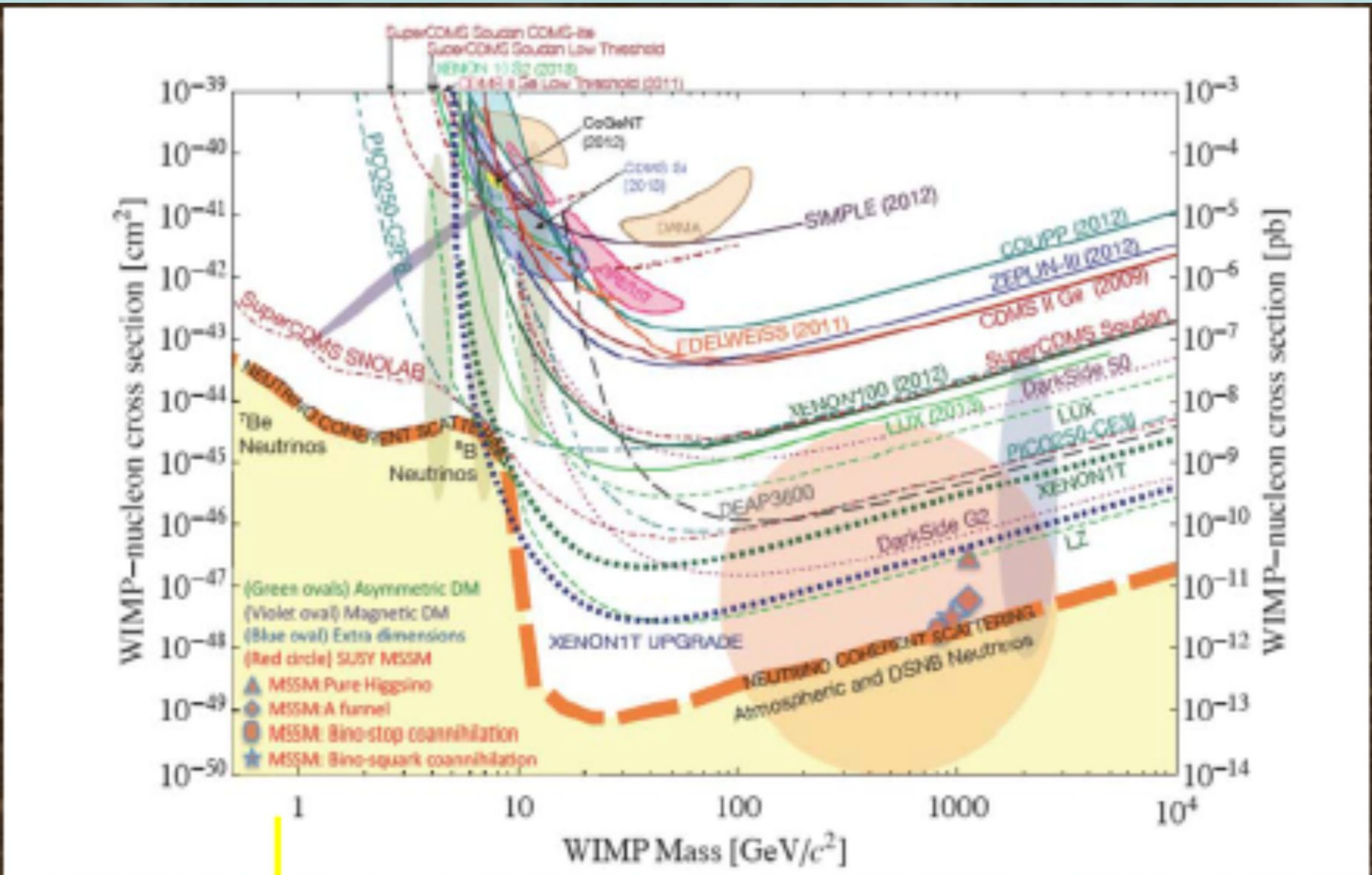
Comparison between **single hit residual rate (red points)** and **multiple hit residual rate (green points)**; Clear modulation in the single hit events; No modulation in the residual rate of the multiple hit events

A=-(0.0005±0.0004) cpd/kg/keV



This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about 9.2σ C.L.



This is just a largely arbitrary, partial, incorrect exercise

Indirect searches for Dark Matter

Astrophysical bounds on the mass of heavy stable neutral leptons

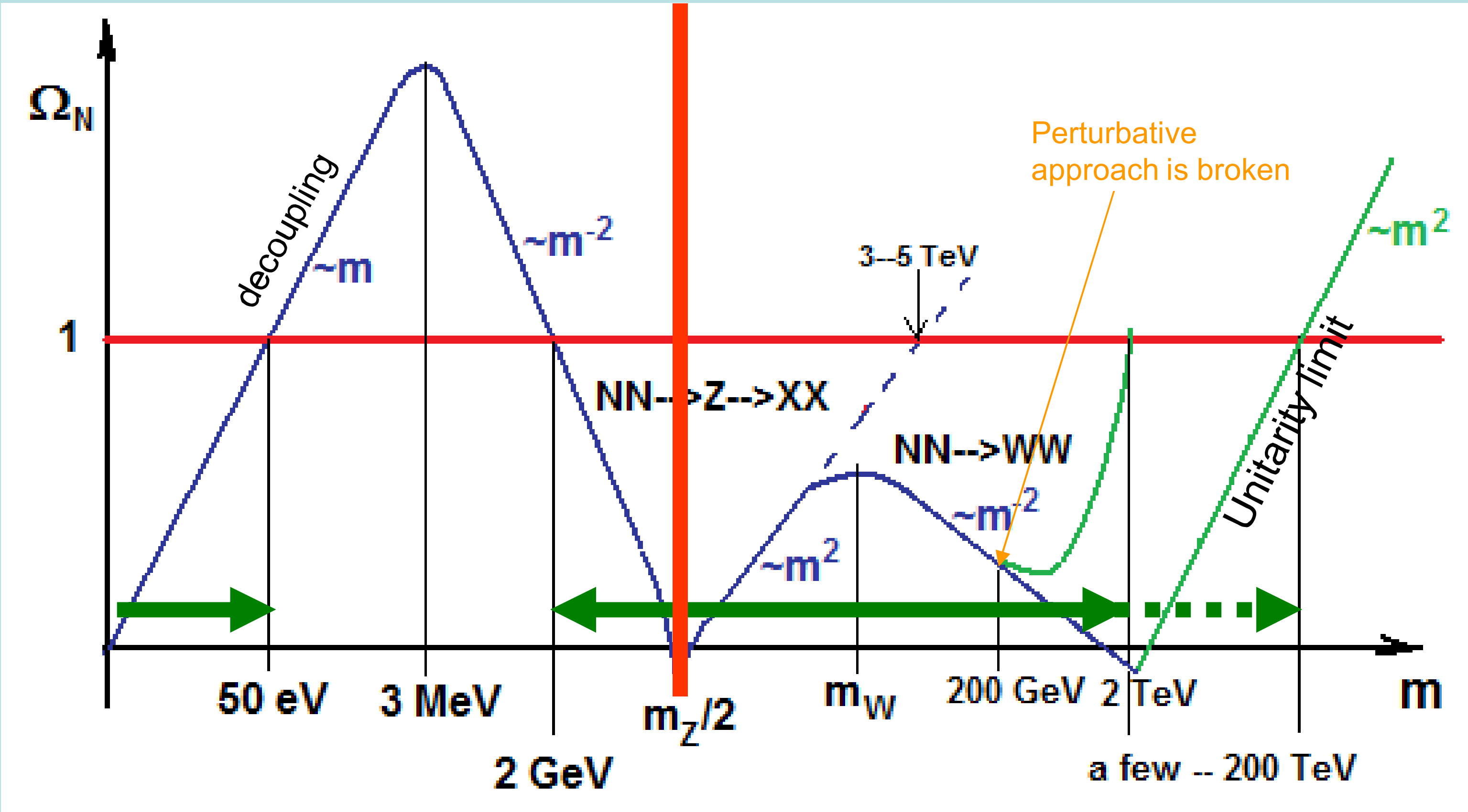
Ya. B. Zel'dovich, A. A. Klypin, M. Yu. Khlopov, and V. M. Chechetkin

Institute of Applied Mathematics, USSR Academy of Sciences
(Submitted 29 November 1979)
Yad. Fiz. **31**, 1286–1294 (May 1980)

Analytical and numerical calculations show that heavy neutral stable leptons are carried along by the collapsing matter during the formation of galaxies and possibly stars as well. The condensation in galaxies and stars results in appreciable annihilation of leptons and antileptons. Modern observations of cosmic-ray and γ-ray fluxes establish a limit $m_\nu \gtrsim 100$ GeV for the mass of neutral leptons, since annihilation of neutral leptons produces γ rays and cosmic rays. The obtained bound, in conjunction with ones established earlier, precludes the existence of stable neutral leptons (neutrinos) with $m_\nu > 30$ eV.

Constraint on the mass of neutrino

$$\Omega_N \sim \begin{cases} \dfrac{m_Z^4}{m_{Pl} m^2}, & m << \dfrac{m_Z}{2} \\ \dfrac{m^2}{m_{Pl}}, & \dfrac{m_Z}{2} << m < m_W \\ \dfrac{m_Z^4}{m_{Pl} m^2}, & m >> m_W \end{cases}$$



Thus 2 GeV < *m* < a few÷200 TeV is cosmologically allowable.

However *m* < 45 GeV is forbidden by accelerator data.

Condensation of heavy neutrinos in Galaxy

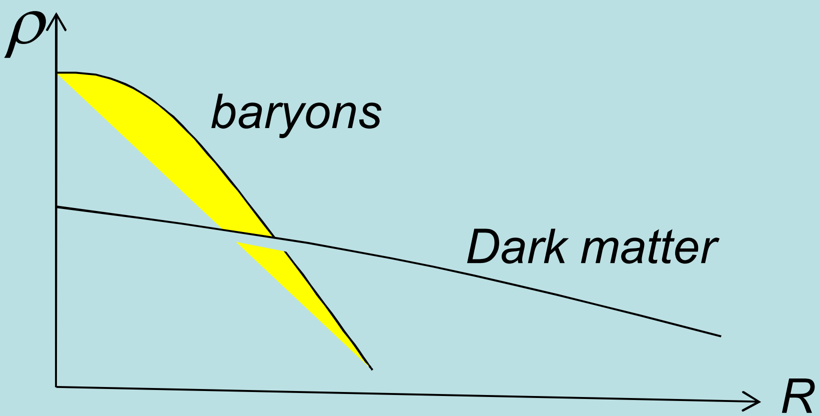
$$\ddot{R} + \omega^2 R = 0$$

$$\omega^2 = 4\pi G\left(\rho_\nu + \rho_b\right)$$

$$I = \frac{E(t)}{\omega(t)} = \frac{\omega^2 R^2}{2\omega} = const$$

$$\rho_\nu(t) \propto R^{-3} \propto \omega^{3/2} \propto \left[\rho_b(t)\right]^{3/4}$$

$$\rho_\nu(t) \propto \left[\rho_b(t)\right]^{3/4}$$



- Motion of collisionless gas in nonstationary field of baryonic matter, contracting owing to dissipation processes, provides effective dissipation and contraction of this gas.
- In result collisionless Dark Matter condences in Galaxy, but it is distributed more steeply, than baryonic matter.
- It gives qualitative explanation for formation of dark matter halo.
- Due to condensation effects of annihilation in Galaxy can be significant even for subdominant component as 4th neutrino.

Cosmic positron excess from DM?

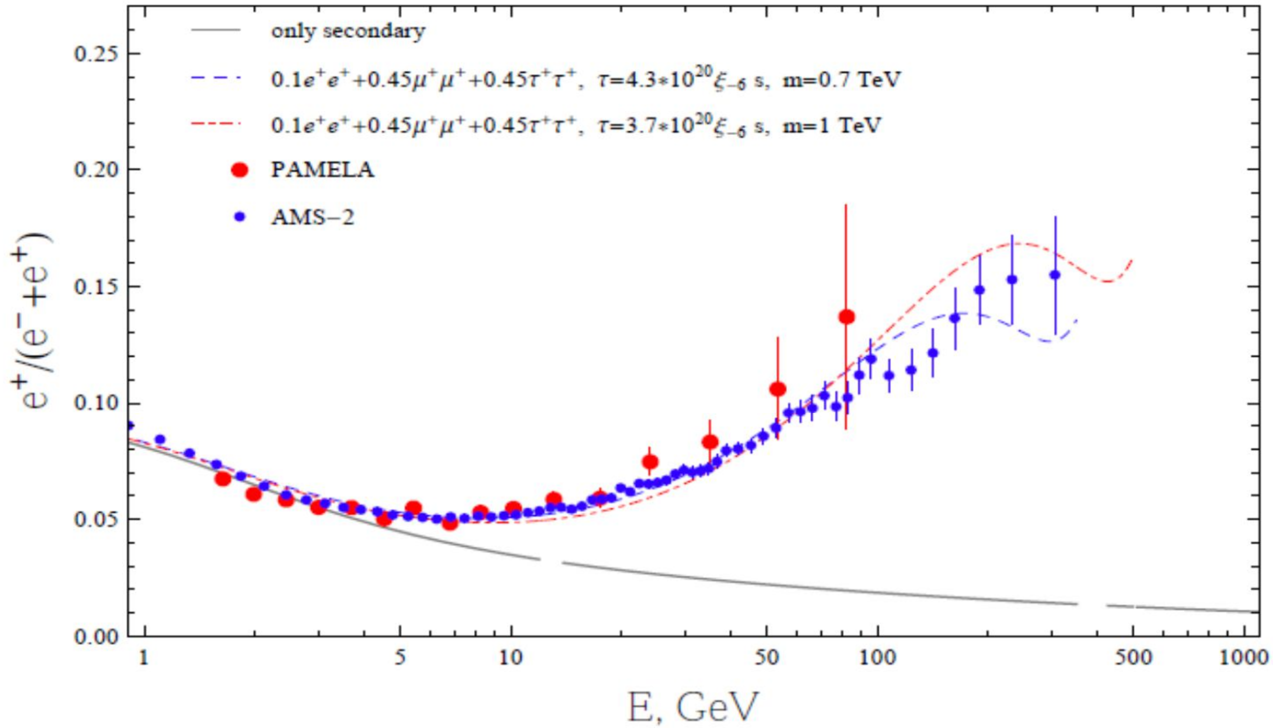


Figure 3: Positron excess due to $UU \to e^+e^+, \mu^+\mu^+, \tau^+\tau^+$ decays compared to PAMELA and AMS-02 data.

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

[figure from K.M.Belotsky et al. arXiv:1403.1212]

The First Five years of AMS on the International Space Station

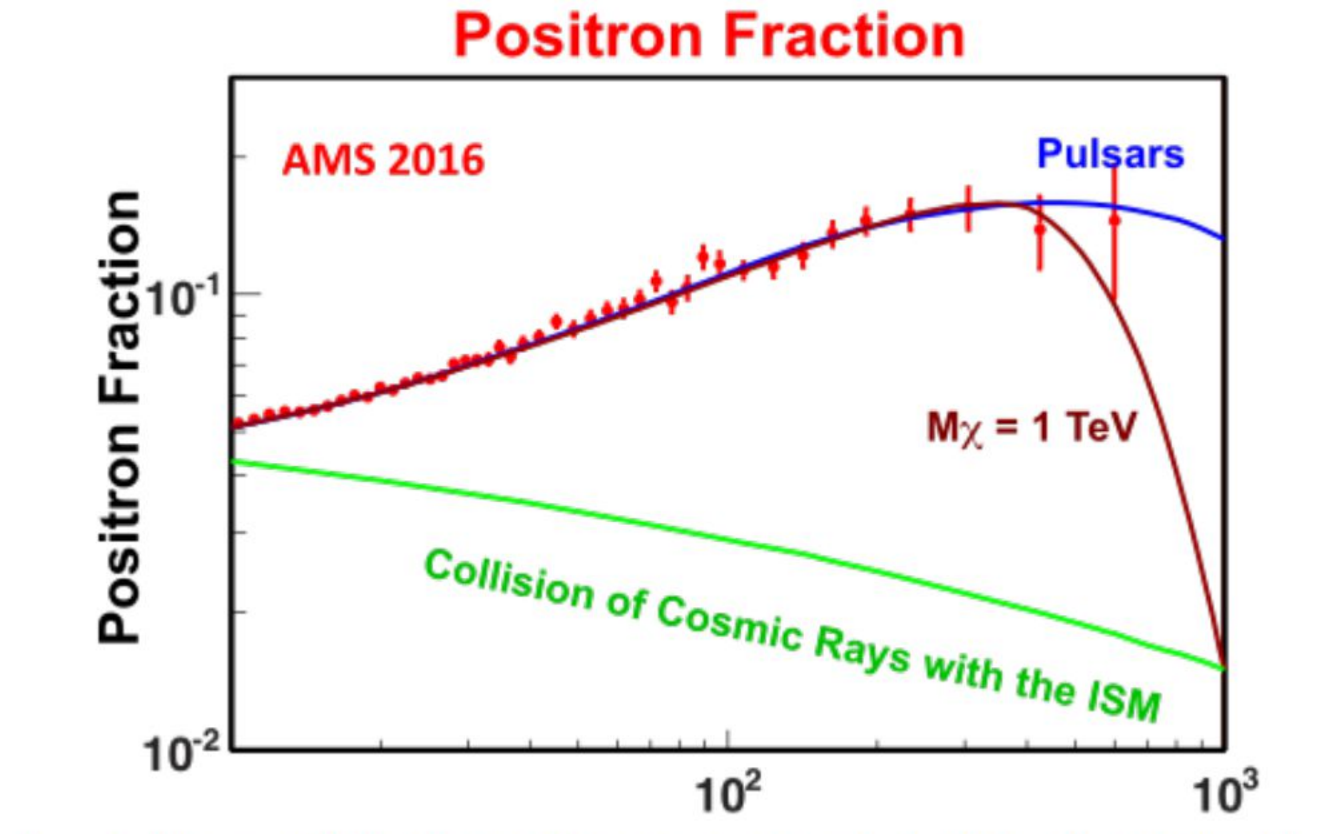
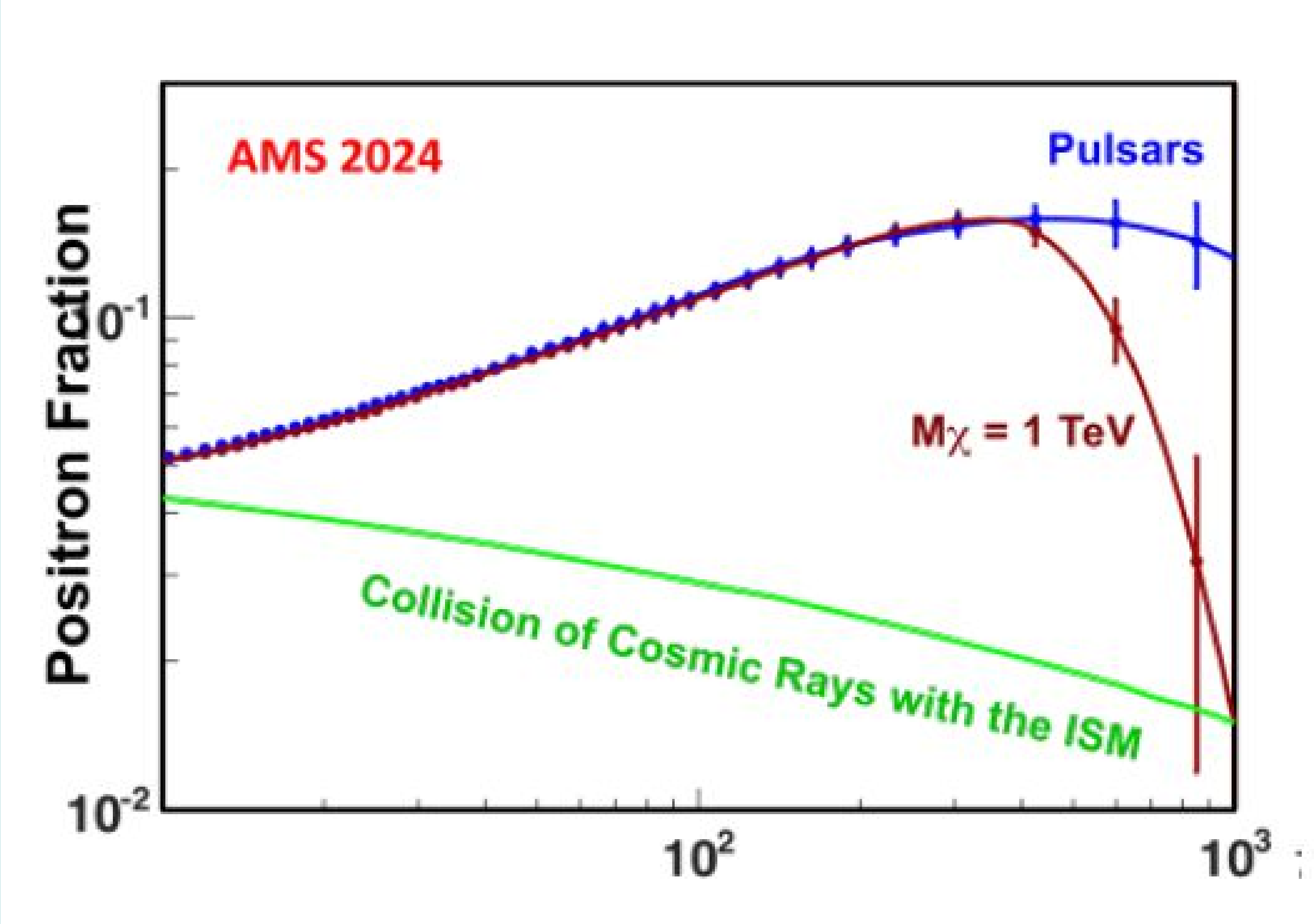


Figure 5. The current AMS positron fraction measurement compared with three theoretical models.

Presented in CERN on 08.12.2016 by Prof. S.Ting

AMS02 in the next decade



Presented in CERN on 08.12.2016 by Prof. S.Ting

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 »

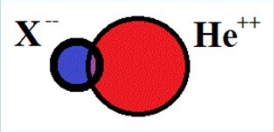
If we have a stable double charged particle X^{--} *in excess over its partner* X^{++}
it may create Helium like neutral atom (O-helium) at temperature $T > I_o$

Where:

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

^{4}He 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

$$X^{--} + {}^4He \Rightarrow (X\,He) + \gamma$$



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

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

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

$$T_{RM} = 1eV$$

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

- 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 more close to warm 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

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

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 $g = 980 \ \mathrm{cm/s^2}$.

OHe solution for puzzles of direct DM search

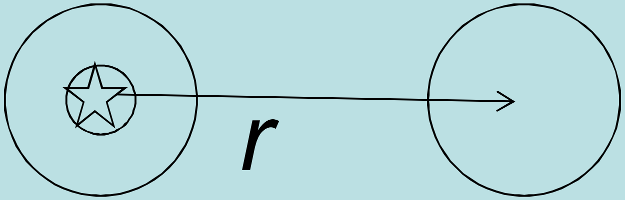
- OHe equilibrium concentration in the matter of DAMA detector is maintained for less than an hour
- Annual modulations in inelastic processes, induced by OHe in matter. No signal of WIMP-like recoil
- The process

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

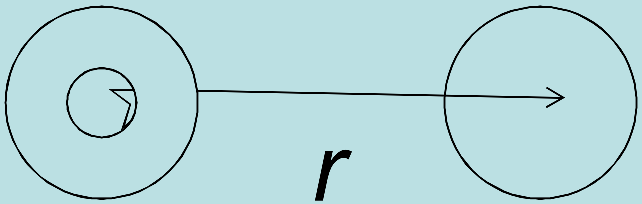
is possible, in which only a few keV energy is released. Other inelastic processes are suppressed

- 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

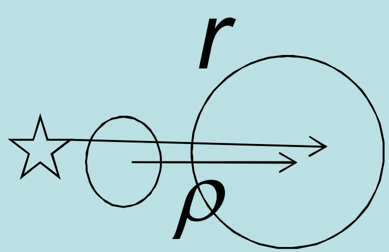
Potential of OHe-nucleus interaction



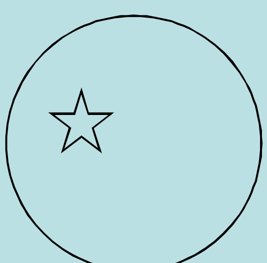
$$U_{Xnuc} = -2Z\alpha\left(\frac{1}{r} + \frac{1}{r_o}\right)\exp\left(-2r/r_o\right)$$



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

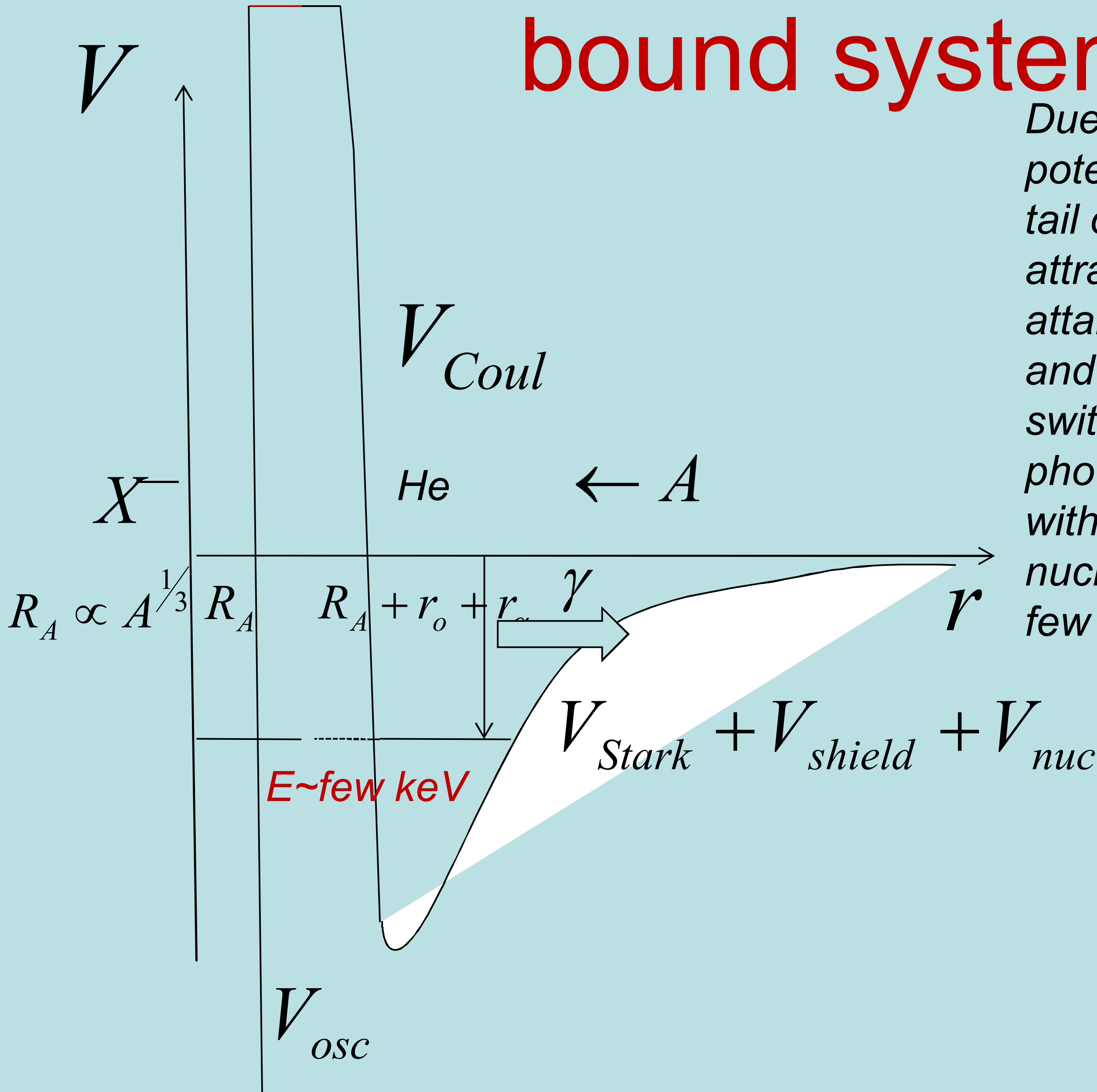


$$U_{Coul} = +\frac{2\alpha Z}{\rho} - \frac{2\alpha Z}{r}$$



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

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.*

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

$$E_{Na} = 3keV$$

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:

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

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

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

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

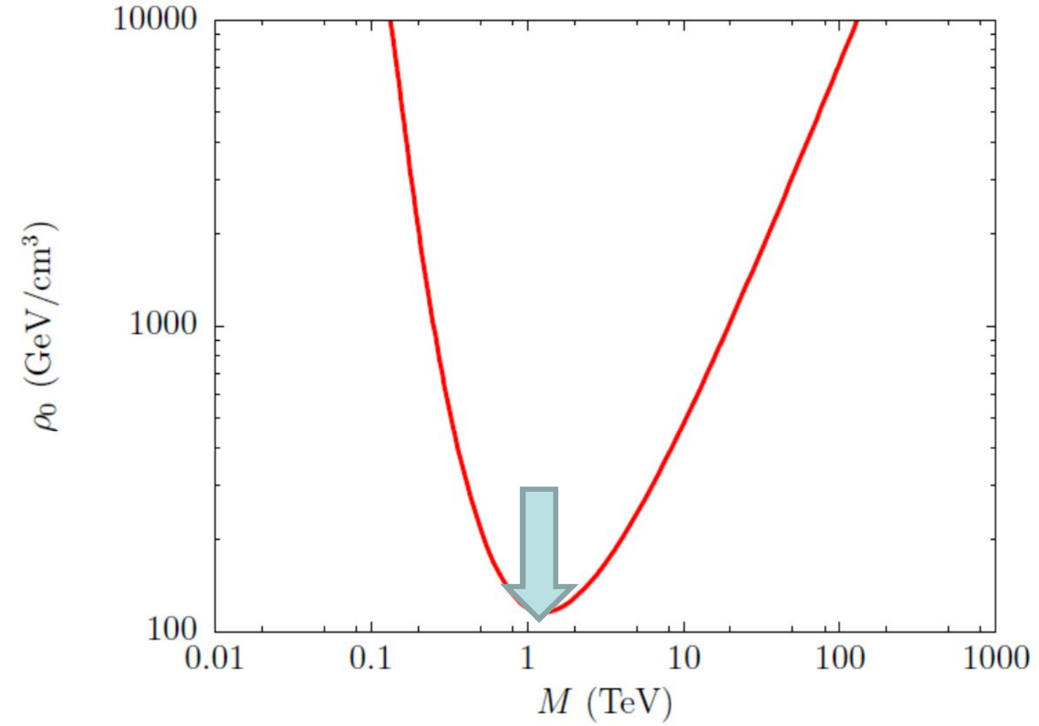


Figure 1: Values of the central dark matter density ρ_0 (GeV/cm^3) and of the OHe mas
M (TeV) reproducing the excess of e^+e^- pairs production in the galactic bulge. Belov
the red curve, the predicted rate is too low.

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

A solution for cosmic positron excess?

- In WTC: if both technibaryons UU and technileptons ζ are present, CDMS, LUX results constrain WIMP-like ($UU\zeta$) component to contribute no more than 0,0001% of total DM density.
- Decays of positively charged UU->$l^+ l^+$ with a lifetime of about $10^{20} s$ and mass 700-1000 GeV can explain the excess of cosmic positrons, observed by PAMELA and AMS02

Cosmic positron excess from DM?

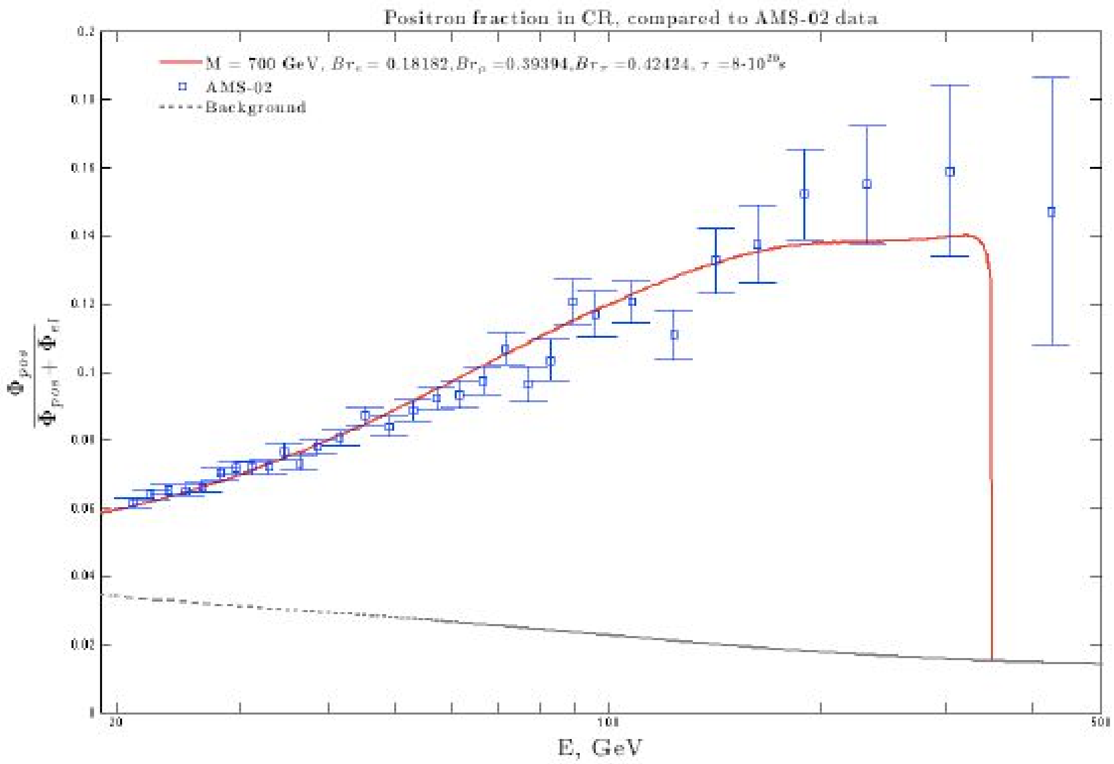


Figure 3: Positron fraction in the cosmic rays from decays of dark matter particles (red curve), corresponding to the best-fit values of model parameters ($M = 700\,\mathrm{GeV}, \tau = 8 \cdot 10^{20}\,\mathrm{s}, Br_{ee} = 0.182, Br_{\mu\mu} = 0.394, Br_{\tau\tau} = 0.424$), and fraction of secondary 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

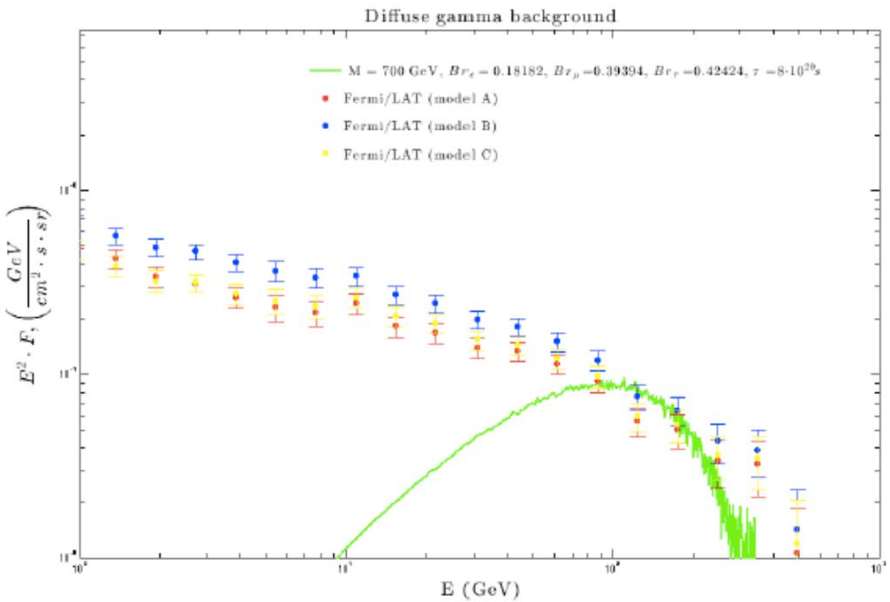


Figure 4: Gamma-ray flux multiplied by E^2 from decays of dark matter particles in the Galaxy and beyond (green curve), corresponding to the best-fit values of model parameters ($M = 700\,\mathrm{GeV}, \tau = 8 \cdot 10^{20}\,\mathrm{s}, Br_{ee} = 0.182, Br_{\mu\mu} = 0.394, Br_{\tau\tau} = 0.424$), 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.

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

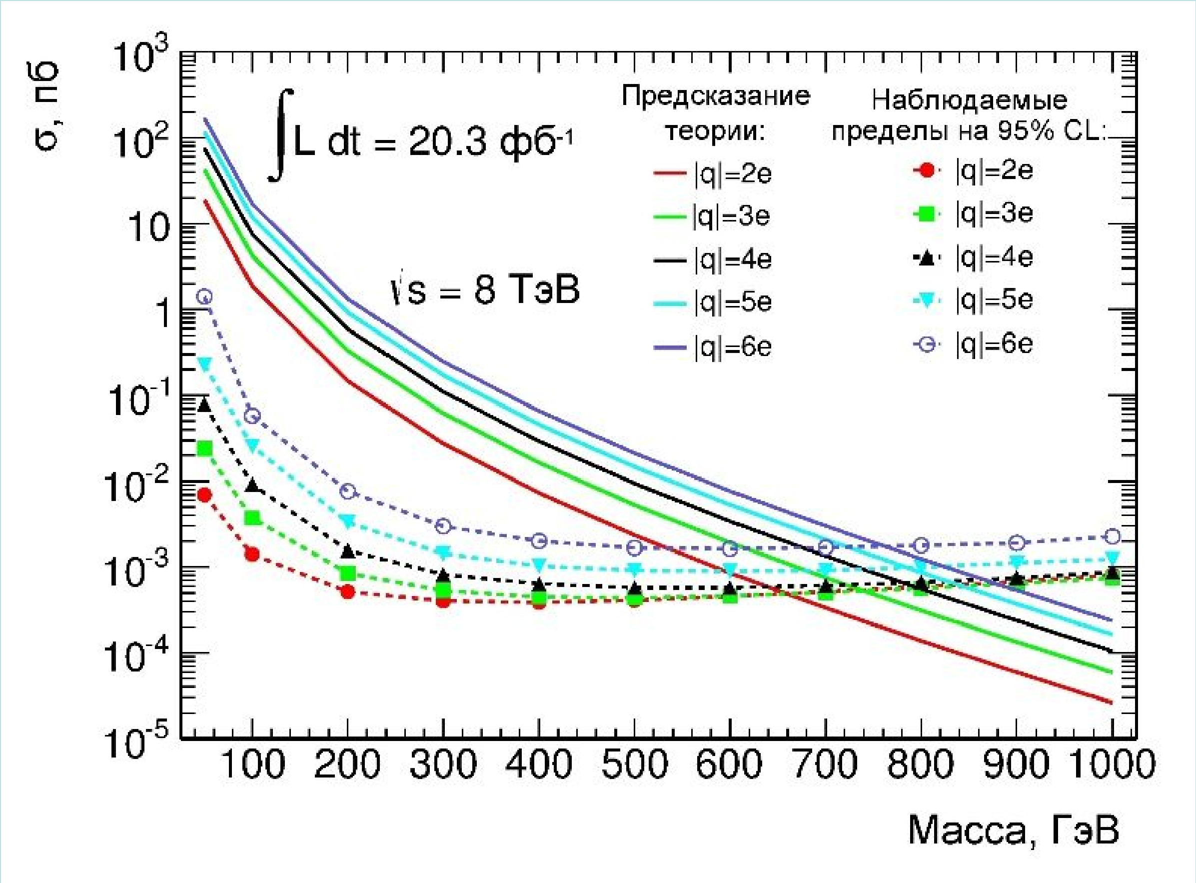
Some Potential Problems of OHe Composite Dark Matter,

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

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 either explain some possible 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 current run of the LHC.

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]

Hot problems in BSM physics of dark matter

- The simplest WIMP solution based on SUSY models doesn’t seem to be proved.
- It makes us to turn to ‘nonstandard’ cosmological scenarios, involving composite, unstable decaying and multicomponent dark matter.
- Physical motivations for such scenarios and their experimental and observational probes are the hot topics for scientific research

PRIMORDIAL NONLINEAR STRUCTURES

Strong nonhomogeneities in nearly homogeneous and isotropic Universe

- The standard approach is to consider homogeneous and isotropic world and to explain development of nonhomogeneous structures by gravitational instability, arising from small initial

$\delta << 1$

$$\delta \equiv \delta\rho / \rho << 1$$

- However, if there is a tiny component, giving small contribution to total density,

$\rho_i << \rho$ its strong nonhomogeneity $\delta_i \equiv (\delta\rho / \rho)_i > 1$

is compatible with small nonhomogeneity of the total density

$$\delta = (\delta\rho_i + \delta\rho)/\rho \approx (\delta\rho_i / \rho_i)(\rho_i / \rho) << 1$$

Such components naturally arise as consequences of particle theory, shedding new light on galaxy formation and reflecting in cosmic structures the fundamental structure of microworld.

Cosmological Reflection of the Structure of symmetry breaking

- **In the early Universe at high temperature particle symmetry was restored. Transition to phase of broken symmetry in the course of expansion is the source of topological defects (monopoles, strings, walls…).**
- **Even unstable, macroscopic cosmological defects can leave observable signatures**

Cosmological Phase transitions 1.

- At high temperature $T > T_{cr}$ spontaneously broken symmetry is restored, owing to thermal corrections to Higgs potential

$$V(\varphi, T=0) = -\frac{m^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4 \Rightarrow V(\varphi, T) = \left(C\lambda T^2 - \frac{m^2}{2}\right)\varphi^2 + \frac{\lambda}{4}\varphi^4$$

- When temperature falls down below

$$T = T_{cr} \cong \langle \varphi \rangle = \frac{m}{\sqrt{\lambda}}$$

transition to phase with broken symmetry takes place.

Cosmological Phase transitions 2.

- Spontaneously broken symmetry can be restored on chaotic inflationary stage, owing to corrections in Higgs potential due to interaction of Higgs field with inflaton

$$V(\varphi,\psi=0)=-\frac{m^2}{2}\varphi^2+\frac{\lambda}{4}\varphi^4 \Rightarrow V(\varphi,\psi)=\left(\varepsilon\psi^2-\frac{m^2}{2}\right)\varphi^2+\frac{\lambda}{4}\varphi^4$$

- When inflaton field rolls down below

$$\psi=\psi_{cr}\cong\frac{m}{\sqrt{\varepsilon}}$$

transition to phase with broken symmetry takes place.

Topological defects

- In cosmological phase transition false (symmetric) vacuum goes to true vacuum with broken symmetry. Degeneracy of true vacuum states results in formation of topological defects.
- Discrete symmetry of true vacuum $\langle\varphi\rangle = \pm f$ leads to domains of true vacuum with +*f* and -*f* and false vacuum wall on the border. [Zeldovich, Kobzarev, Okun, 1975]
- Continuous degeneracy $\langle\varphi\rangle = f\exp(i\theta)$ results in succession of singular points surrounded by closed paths with $\Delta\theta = 2\pi$. Geometrical place of these points is line – cosmic string.
- SU(2) degeneracy results in isolated singular points – in GUTs they have properties of magnetic monopoles.

Strong Primordial nonhomogeneities from the early Universe

- Cosmological **phase transitions** in inflationary Universe can give rise to unstable cosmological defects, retaining a replica in the form of primordial **nonlinear** structures (massive PBH clusters, archioles).
- Nonhomogenous baryosynthesis (including spontaneous baryosynthesis and leptogensis) in its extreme form can lead to **antimatter** domains in baryon asymmetrical inflationary Universe.

Strong nonhomogeneities of total density and baryon density are severely constrained by CMB data at large scales (and by the observed gamma ray background in the case of antimatter). However, their existence at smaller scales is possible.

U(1) model

$$V(\psi) = \frac{\lambda}{2}\left(\psi^2 - f^2\right)$$

After spontaneous symmetry breaking infinitely degenerated vacuum

$$\psi = f e^{i\varphi/f}$$

experiences second phase transition due to the presence (or generation by instanton effects)

$$V(\varphi) = \Lambda^4\left(1 - \cos(\varphi/f)\right)$$

to vacuum states

$$\theta \equiv \varphi/f = 0, 2\pi, \ldots$$

In particular, this succession of phase transitions takes place in axion models

Axion

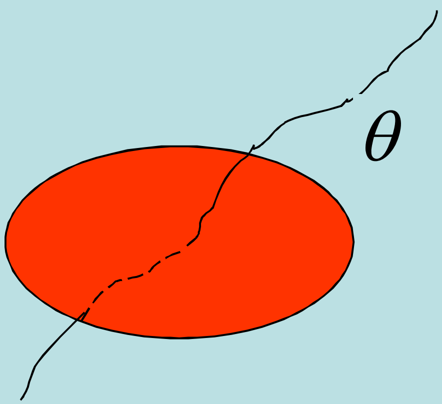
Some astrophysical limitations on the axion mass

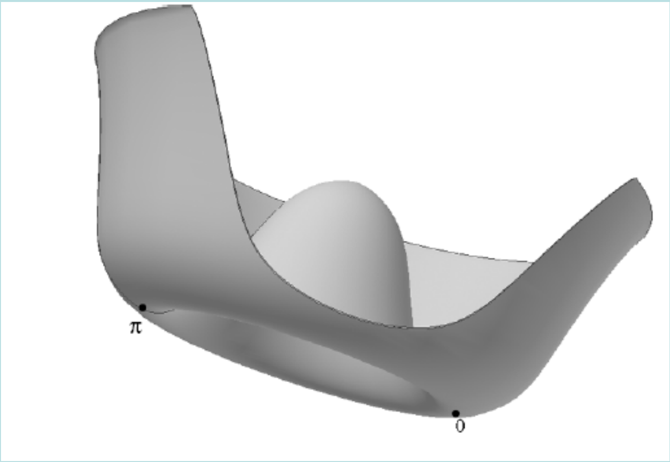
M. I. Vysotsskii, Ya. B. Zel'dovich, M. Yu. Khlopov, and
V. M. Chechetkin

Institute of Applied Mathematics, USSR Academy of Sciences
(Submitted 27 March 1978)
Pis'ma Zh. Eksp. Teor. Fiz. **27**, No. 9, 533–536 (5 May 1978)

A comparison of the axion luminosity of the sun with the observed photon luminosity leads to the lower bound $\mu_a > 25$ keV. This bound can be raised to $\mu_a > 200$ keV by resorting to modern ideas concerning the structure of supergiants.

Topological defects





- Spontaneous breaking of U(1) symmetry results in the continuous degeneracy of vacua. In the early Universe the transition to phase with broken symmetry leads to formation of cosmic string network.
- The tilt in potential breaks continuous degeneracy of vacua. In the result string network converts into walls-bounded-by-strings structure in the second phase transition.

Unstable topological defects

- The first phase transition gives rise to cosmic string network.
- This network converts in the second phase transition into walls-bounded-by-strings structure (walls are formed between strings along the surfaces $\theta = \pi$), which is unstable.
- However, the energy density distribution of coherent oscillations of the field φ follows the walls-bounded-by-strings structure.

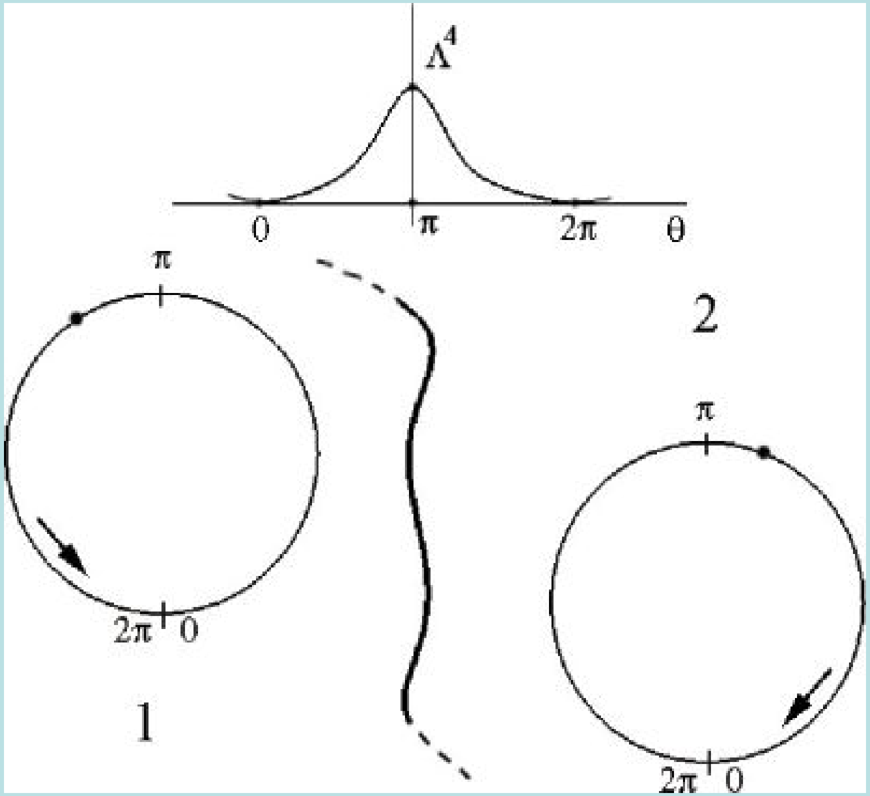
Archioles structure

- Numerical studies revealed [Vachaspati,Vilenkin, 1984] that ~80% of string length corresponds to infinite Brownian lines, while the remaining ~20% of this length corresponds to closed loops with large size loops being strongly suppressed. It corresponds to the well known scale free distribution of cosmic strings.
- The fact that the energy density of coherent oscillations reflects this property is much less known. It leads to a large scale correlation in this distribution, called archioles [Khlopov,Sakharov, 1994; Khlopov, Sakharov, Sokoloff, 1996; 1999]
- Archioles offer possible seeds for large scale structure formation.

Massive Primordial Black Holes

- Any object can form Black hole, if contracted within its gravitational radius. It naturally happens in the result of evolution of massive stars (possibly, star clusters).
- In the early Universe Black hole can be formed, if within cosmological horizon expansion can stop [Zeldovich, Novikov, 1966]. Since in the early Universe the total mass within horizon is small, it seems natural to expect that such Primordial Black holes should have very small mass (much smaller, than the mass of stars).
- However, cosmological consequences of particle theory can lead to mechanisms of intermediate and even supermassive BH formation.

Closed walls formation in Inflationary Universe



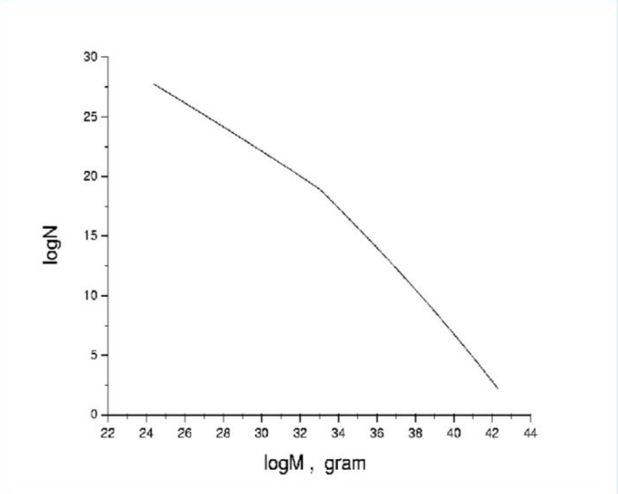
If the first U(1) phase transition takes place on inflationary stage, the value of phase θ , corresponding to e-folding N~60, fluctuates

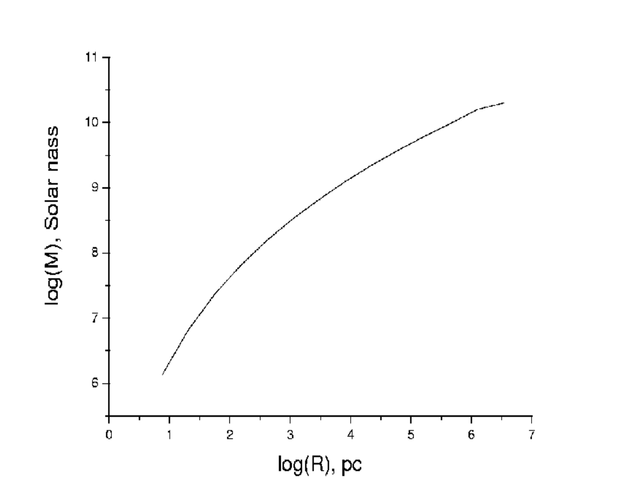
$$\Delta\theta \approx H_{\text{infl}} / (2\pi f)$$

Such fluctuations can cross π

and after coherent oscillations begin,regions with $\theta > \pi$ occupying relatively small fraction of total volume are surrounded by massive walls

Massive PBH clusters





Each massive closed wall is accompanied by a set of smaller walls.
As soon as wall enters horizon, it contracts and collapses in BH.
Each locally most massive BH is accompanied by a cloud of less massive BHs.
The structure of such massive PBH clouds can play the role of seeds for galaxies and their large scale distribution.

Spectrum of Massive BHs

- The minimal mass of BHs is given by the condition that its gravitational radius exceeds the width of wall ($d \approx 2f/\Lambda^2$)

$$r_g = \frac{2M}{m_{Pl}^2} > d = \frac{2f}{\Lambda^2} \Rightarrow M_{\min} = f\left(\frac{m_{Pl}}{\Lambda}\right)^2$$

- The maximal mass is given by the condition that pieces of wall do not dominate within horizon, before the whole wall enters the horizon

$$R < \frac{3\sigma_w}{\rho_{tot}} \Rightarrow M_{\max} = f\left(\frac{m_{Pl}}{f}\right)^2\left(\frac{m_{Pl}}{\Lambda}\right)^2 \Rightarrow \frac{M_{\max}}{M_{\min}} = \left(\frac{m_{Pl}}{f}\right)^2$$

GW signals from closed wall collapse and BHs merging in clouds

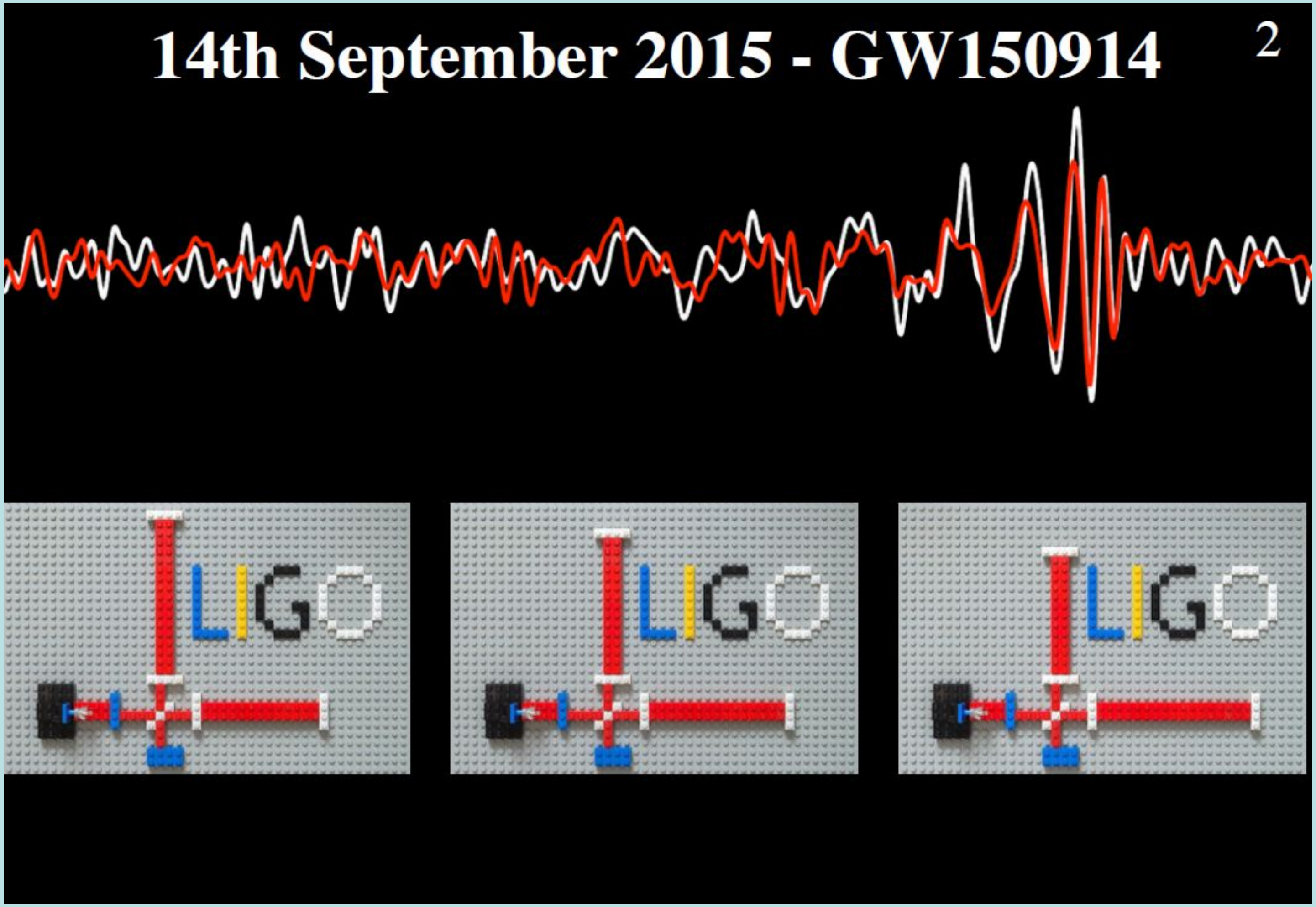
- Closed wall collapse leads to primordial GW spectrum, peaked at $\nu_0 = 3 \cdot 10^{11} (\Lambda / f) Hz$ with energy density up to

$$\Omega_{GW} \approx 10^{-4} (f / m_{Pl})$$

- At $f \sim 10^{14} GeV$ $\Omega_{GW} \sim 10^{-9}$
- For $1 < \Lambda < 10^8 GeV$ $3 \cdot 10^{-3} Hz < \nu_0 < 3 \cdot 10^5 Hz$

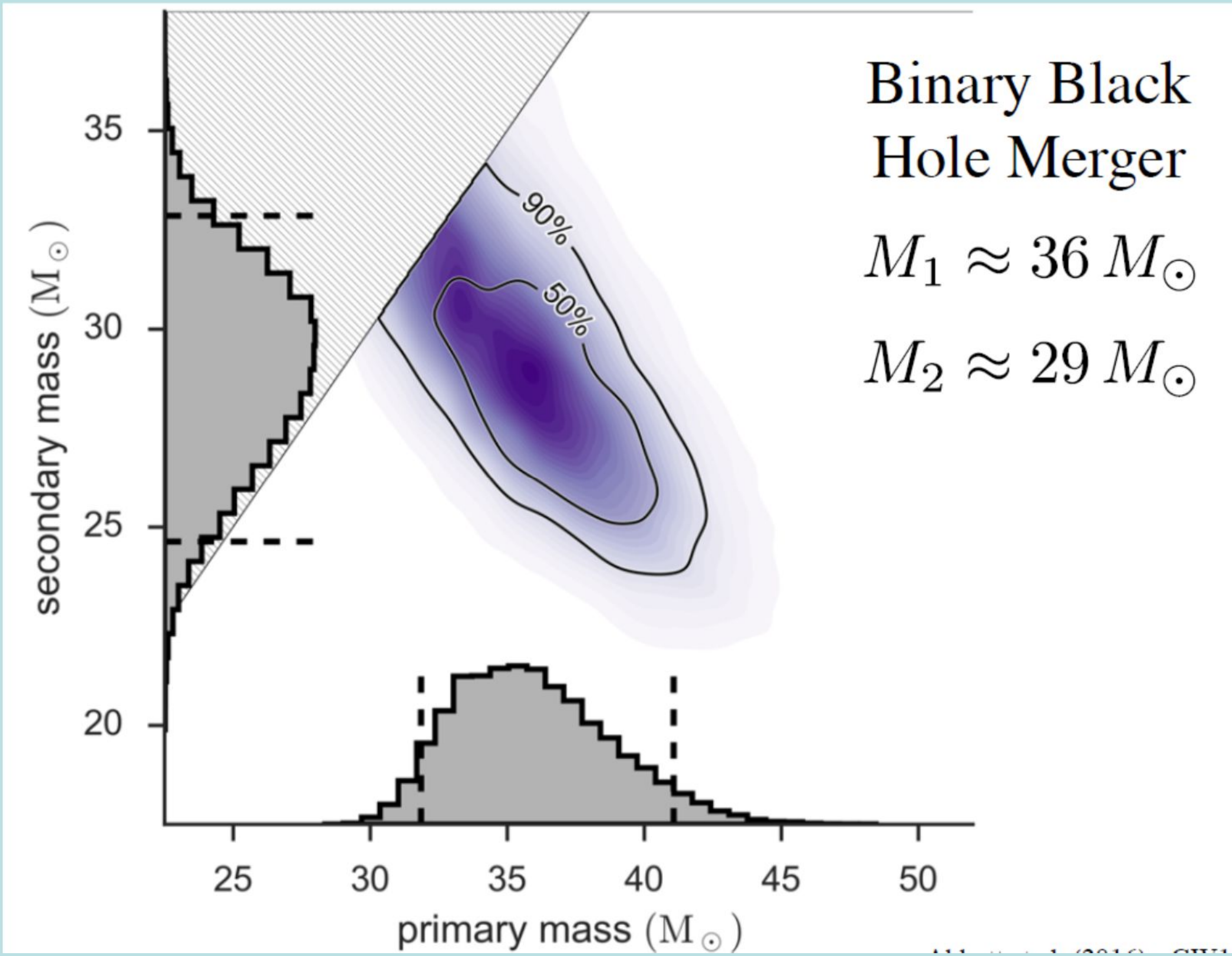
- Merging of BHs in BH cluster is probably detected by LIGO!.

The first GW signal!



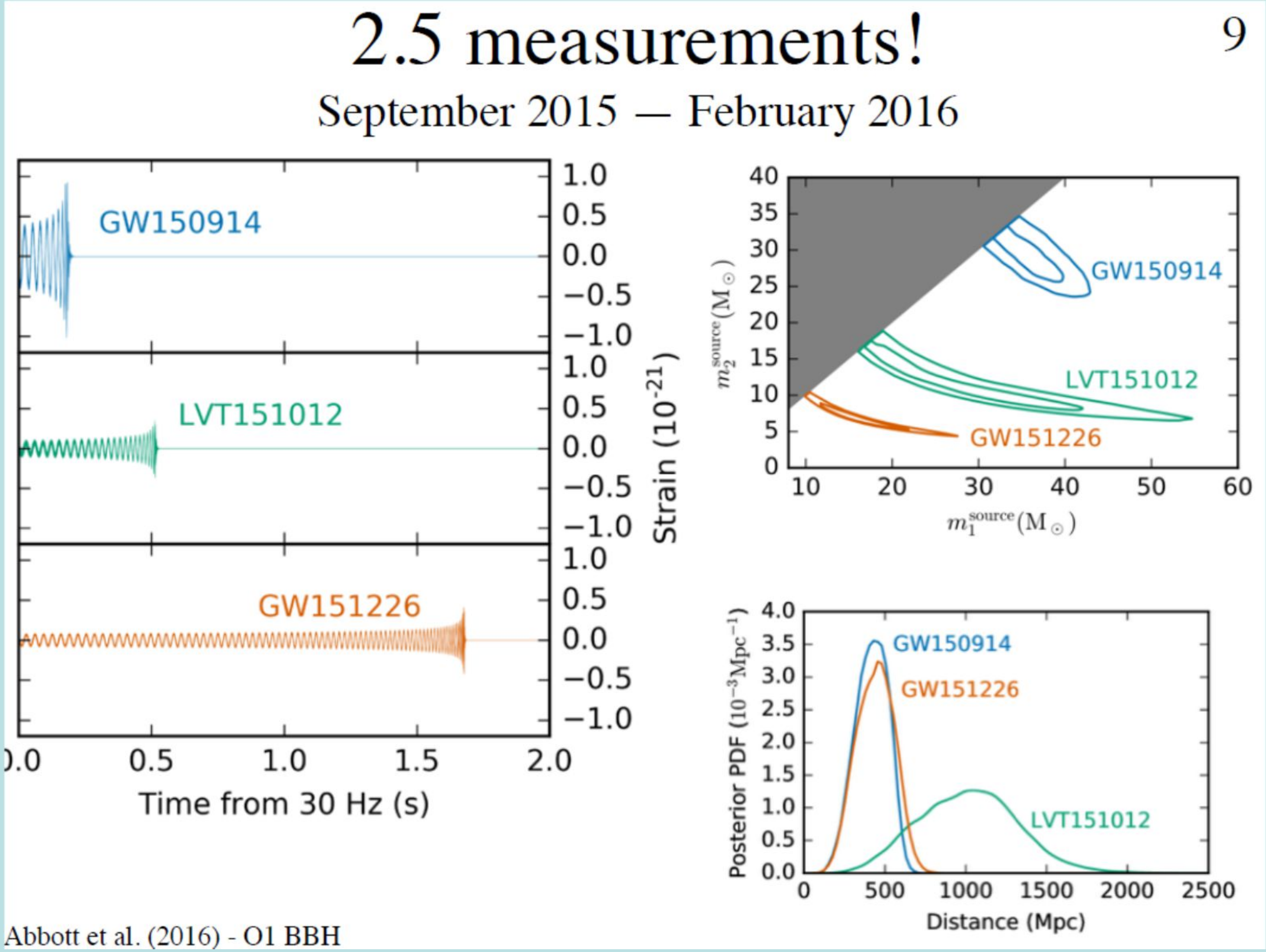
From VIA talk 09.12.2016 by P.Lasky

Abbott et al. (2016) - GW150914



From VIA talk 09.12.2016 by P.Lasky

GW astronomy!



From VIA talk 09.12.2016 by P.Lasky

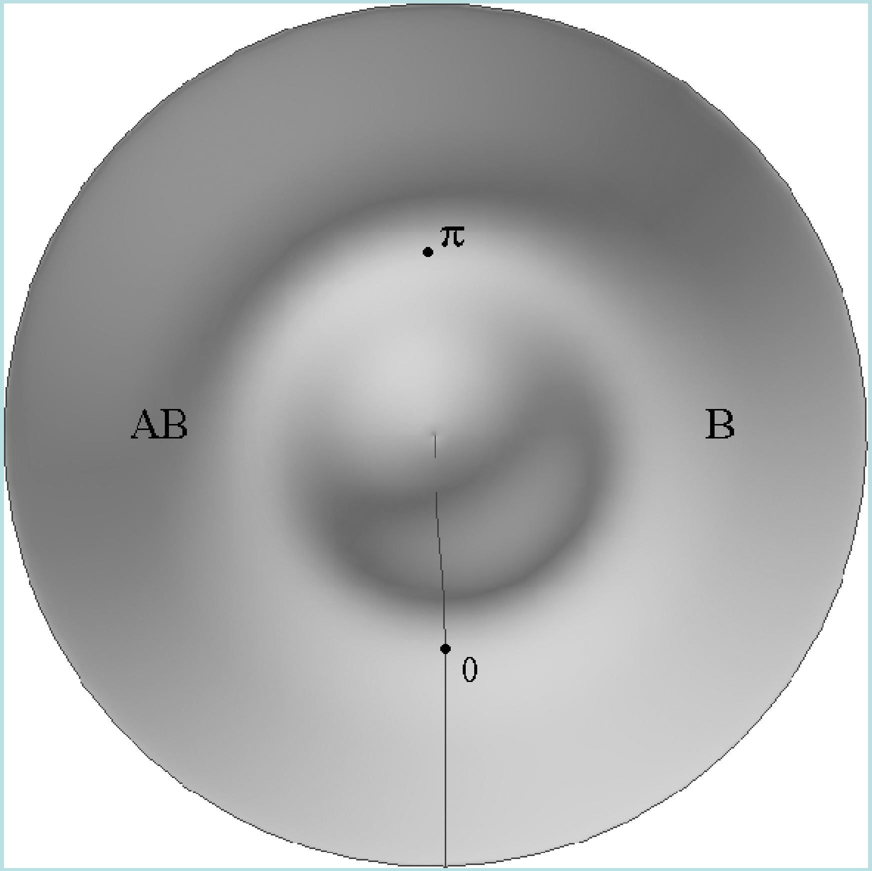
Binaries of massive PBHs?

- Massive PBHs are not distributed homogeneously in space, but are in clouds.
- It makes more probable formation of massive PBHs binaries.
- The problem of creation of stellar mass PBH clouds, their evolution and formation of BH binaries in them may be an interesting hot topic for a PhD thesis

Antimatter from nonhomogeneous baryosynthesis

- Baryon excess B>0 can be generated nonhomogeneously B(x).
- Any nonhomogeneous mechanism of BARYON excess generation B(x) leads in extreme form to ANTIBARYON excess in some regions.

Nonhomogeneous spontaneous baryosynthesis



Model of spontaneous baryosynthesis

$$L = -\frac{f^2}{2}\partial_\mu\theta\partial^\mu\theta + i\bar{Q}\gamma^\mu\partial_\mu Q + i\bar{L}\gamma^\mu\partial_\mu L$$

$$-m_Q\bar{Q}Q - m_L\bar{L}L + (\frac{g}{\sqrt{2}}f\bar{Q}L + h.c.) + \partial_\mu\theta\bar{Q}\gamma^\mu Q$$

naturally leads to nonhomogeneity of baryon excess and to generation of antibaryon excess in some regions

$$n_{B(\bar{B})} = \frac{g^2}{\pi^2}\int_{m_Q+m_L}^{\infty}\omega d\omega\left|\int_{-\infty}^{\infty}dt\chi(t)e^{\pm 2i\omega t}\right|^2$$

Sufficiently large domains of antimatter survive to the present time

Survival of antimatter domains

Diffusion of baryons and antibaryons to the border of domain results in eating of antimatter by surrounding baryonic matter.

$$\partial n_b / \partial t = D(t) \partial^2 n_b / \partial x^2 - \alpha n_b$$

where

$$D(t) \approx \frac{3T_\gamma c}{2\rho_\gamma \sigma_T}$$

The minimal surviving scale is given by

$$d \approx \frac{c}{\sqrt{\frac{8\pi}{3} G\rho_0}} \frac{T_p}{m} \sqrt{\frac{m}{T_{rec}}} \int_{T_p/T_{rec}}^{1} \frac{dy}{y^{3/2}} = \frac{2c}{\sqrt{\frac{8\pi}{3} G\rho_0}} \sqrt{\frac{T_p}{m}}$$

which is about $d \sim 3/h$ kpc..

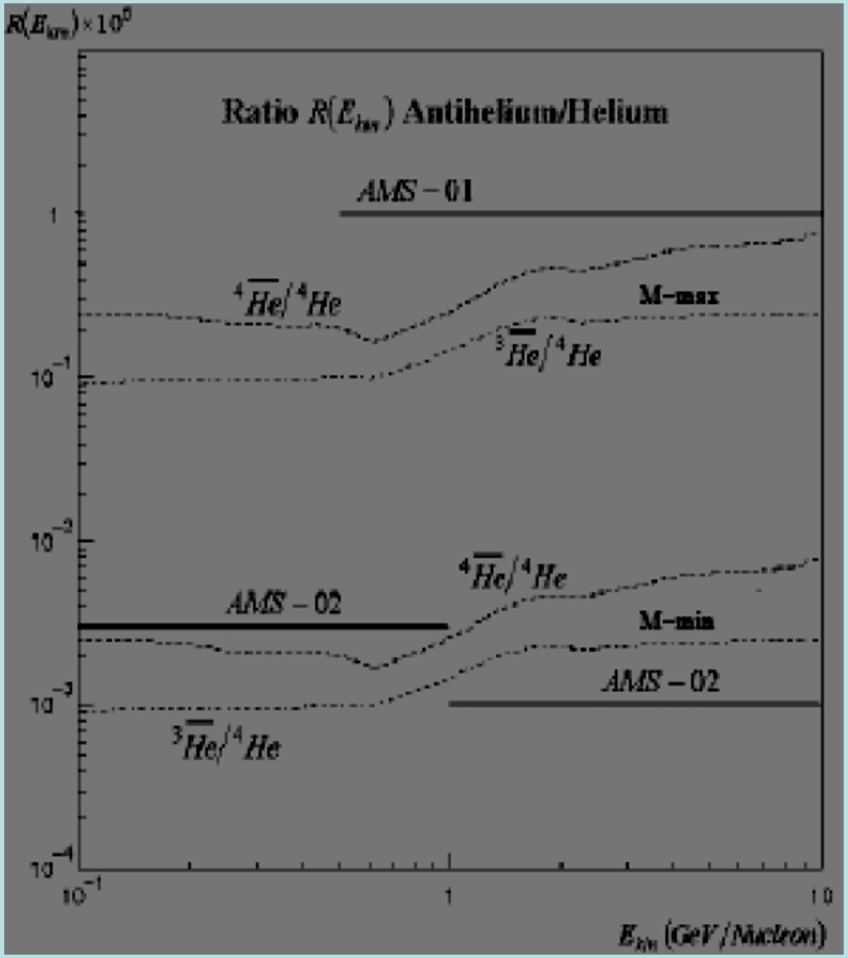
Antimatter in galaxies

Number of e-fold	Number of domains	Size of domain
59	0	$1103 Mpc$
55	$5.005 \cdot 10^{-14}$	$37.7 Mpc$
54	$7.91 \cdot 10^{-10}$	$13.9 Mpc$
52	$1.291 \cdot 10^{-3}$	$1.9 Mpc$
51	0.499	$630 kpc$
50	74.099	$255 kpc$
49	$8.966 \cdot 10^{3}$	$94 kpc$
48	$8.012 \cdot 10^{5}$	$35 kpc$
47	$5.672 \cdot 10^{7}$	$12 kpc$
46	$3.345 \cdot 10^{9}$	$4.7 kpc$
45	$1.705 \cdot 10^{11}$	$1.7 kpc$

Numerical simulations show that within the modern horizon possible amount of antimatter domains, with the size exceeding the survival scale and thus surviving to the present time, can be comparable with the total number of galaxies.

In our Galaxy from 1000 to 100000 antimatter stars can exist in a form of antimatter globular cluster (Khlopov, 1998). Being in halo, such cluster is a faint gamma ray source, but antimatter from it pollutes Galaxy and can be observed indirectly by annihilation, or directly as anti-meteorites or antinuclei in cosmic rays.

Cosmic antihelium test for antimatter stars in Galaxy



- Nonhomogeneous baryosynthesis in extreme form leads to antimatter domains in baryon asymmetrical Universe
- To survive in the surrounding matter domain should be sufficiently large, and to have sufficiently high internal antibaryon density to form stars. It gives minimal estimation of possible amount of antimatter stars in Galaxy
- The upper limit comes from observed gamma background
- Assuming that antihelium component of cosmic rays is proportional to the fraction of antimatter stars in the total mass of Galaxy, it is possible to test this hypothesis in AMS-02 experiment

First signal from antimatter stars in AMS02?

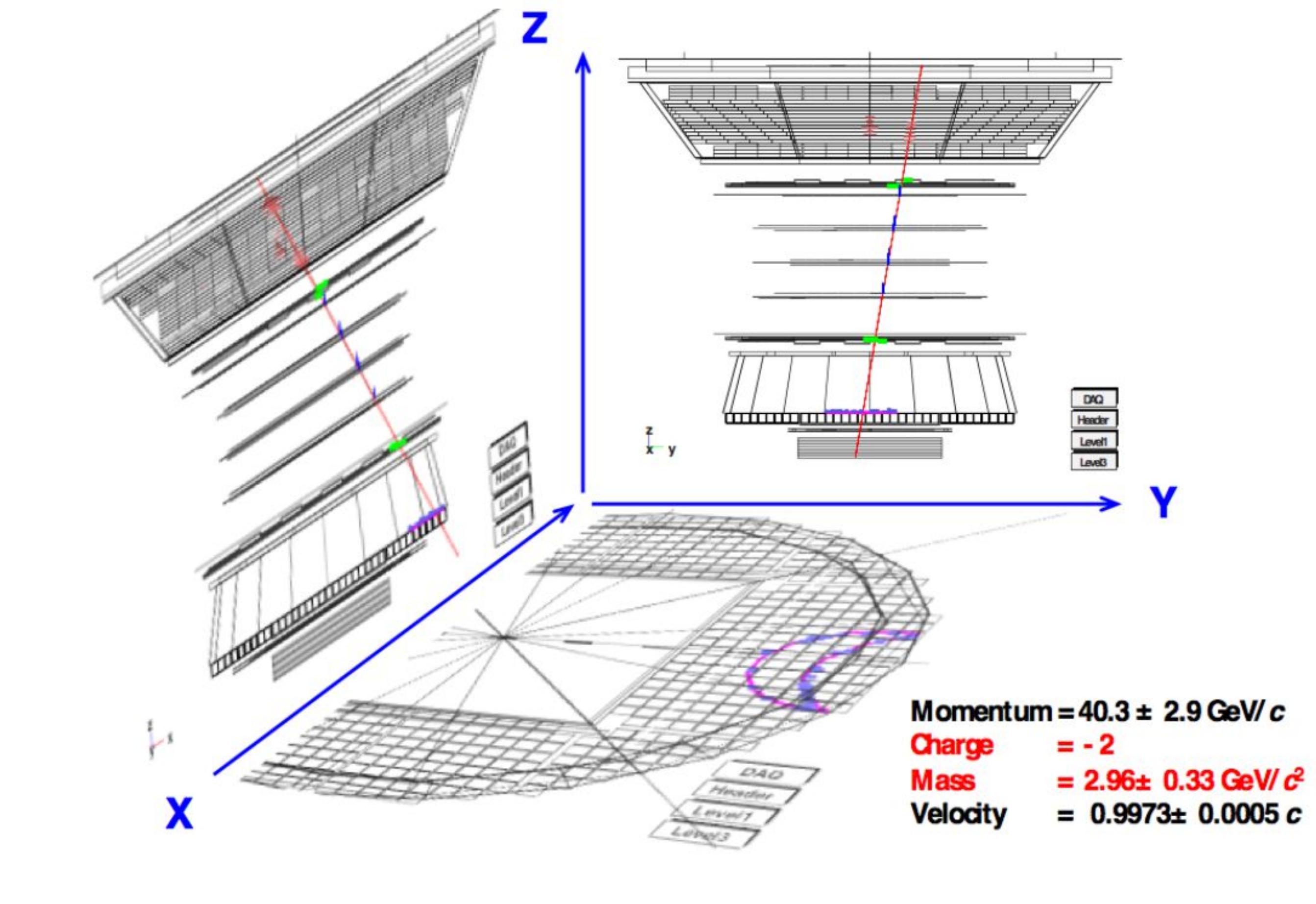


Figure 14. An antihelium candidate.

Presented in CERN on 08.12.2016 by Prof. S.Ting

Conclusion

The puzzle of our origin and existence still retains in the multiverse of cosmological scenarios and particle physical models underlying them.

The progress in the precision astronomical observations and physical experiments supports development of cosmoparticle physics.

We expect exciting discoveries in the relationship of micro- and macro-worlds during the next decade and their theoretical interpretation is the challenge for the Fundamental physics.

International PhD programme may put important contribution in this development

International Virtual Institute of Astroparticle Physics (CosmoVIA)

Scientific-Educational complex of interactive online education and collaboration in cross-disciplinary study of fundamental relationship between micro- and macro-worlds

Open Online Course
‘’Introduction to cosmoparticle physics’’

It will include, in particular, such topics as:

- Frontiers of particle physics
- Inflation, baryosynthesis, dark matter and BSM physics
- Cosmoarcheology (cosmological probes for particle physics)
- Cosmophenomenology of new physics
- Dark matter direct and indirect searches
- Composite dark matter, Dark atoms, Unstable dark matter
- Extra dimensions and Brane world cosmology
- Cosmoparticle physics - the fundamental realtionship of cosmology and particle physics