

**Maxim Yu. Khlopov**

VIA, APC Laboratory, Paris, France;

National Research Nuclear University “MEPHI” Moscow, Russia

and

Institute of Physics, Southern Federal University, Rostov on Don, Russia

# **Cosmological reflection of the BSM physics**

Talk at

**XXV Bled Workshop**

**“What comes beyond the Standard models?”**

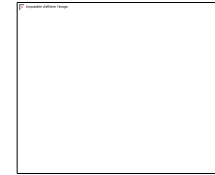
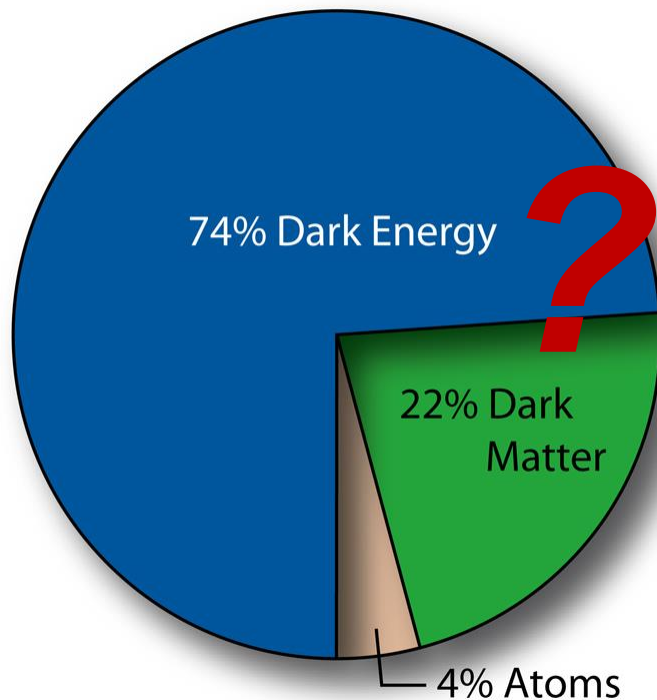
Bled, 7 July 2022

*Sponsored by « Symmetry »*

# Outlines

- BSM Physical basis of the SM cosmology
- BSM cosmology that follows from BSM physics.
- Dark atom solution for puzzles of direct DM searches
- Primordial Black Holes (PBHs) as cosmological reflection of particle symmetry.
- Strong Primordial nonhomogeneities and Massive PBH clusters from models of inflation.
- Antimatter as profound signature for nonhomogeneous baryosynthesis.

# Composition of the Modern Universe



$$\Omega_b \approx 0.044 \quad \Omega_{\text{CMB}} \approx 0.5 \cdot 10^{-4}$$

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

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

$$\Omega_{\text{tot}} \approx 1.0$$

**In the modern Universe dominate dark energy and dark matter – their nature is related to the new physics – physics beyond the Standard model, on which the bedrocks of modern cosmology are based**

# 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:*

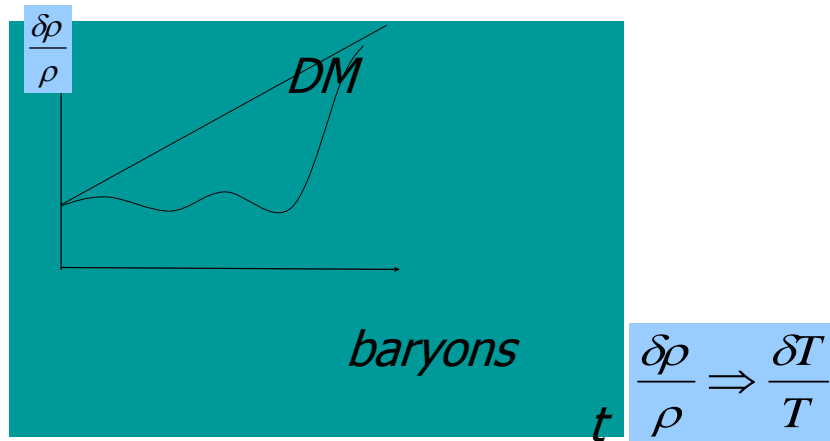
- Inflation
- Baryosynthesis
- Dark matter/energy

*Physics beyond the Standard model, describing these phenomena inevitably predicts additional model dependent effects, in which NS and BH play important role.*

# **Cosmological Reflections of Microworld Structure**

- **(Meta-)stability of new particles reflects some Conservation Law, which prohibits their rapid decay. Following Noether's theorem this Conservation Law should correspond to a (nearly) strict symmetry of microworld. Indeed, all the particles - candidates for DM reflect the extension of particle symmetry beyond the Standard Model.**
- **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...).**
- **Structures, arising from dominance of superheavy metastable particles and phase transitions in early Universe, can give rise to Black Holes, retaining in the Universe after these structures decay.**

# Cosmological Dark Matter



***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.*

*Baryon density estimated from the results of BBN (mainly from Primordial deuterium) is not sufficient to explain the matter content of the modern Universe*

# **Dark Matter – Cosmological Reflection of Microworld Structure**

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

**This stability reflects some Conservation Law, which prohibits DM decay.**

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

# BSM physics of dark matter

- Extension of SM symmetry provides new conservation laws and stability of lightest particles that possess new conserved charges (R-parity in Supersymmetry, mirrority of mirror (shadow) matter, PQ symmetry in axion models etc)
- Mechanisms of symmetry breaking in the early Universe lead to primordial nonlinear structures and macroscopic forms of DM – like PBHs and PBH clusters



# Dark Matter from Elementary 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 characteristic 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 also play the role of specific composite Dark matter (Dark atoms).
- Physical models, underlying dark atom scenarios, their problems and nontrivial solutions as well as the possibilities for their test will be the subject of the successive talks.

# “WIMP miracle”

- Freezing out of particles with mass of few hundred GeV and annihilation cross section of the order of weak interaction leads to their primordial abundance, which can explain dark matter.
- However direct search for such WIMPs doesn't give positive result, as well as no SUSY particles are detected at the LHC
- It can imply a much wider list of DM candidates

# The list of some physical candidates for DM

- Sterile neutrinos – physics of neutrino mass
- Axions – problem of CP violation in QCD
- Gravitinos – SUGRA and Starobinsky supergravity
- KK-particles:  $B_{KK1}$
- Anomalous hadrons, O-helium
- Supermassive particles...
- Mirror and shadow particles,
- PBHs...

***SIMP***

*(strongly interacting  
massive particles)*



# **THE PUZZLES OF DIRECT DARK MATTER SEARCHES**

# Direct searches for Dark Matter

## **Possibility of detecting relict massive neutrinos**

V. F. Shvartsman, V. B. Braginskii, S. S. Gershtein, Ya. B. Zel'dovich, and  
M. Yu. Khlopov

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

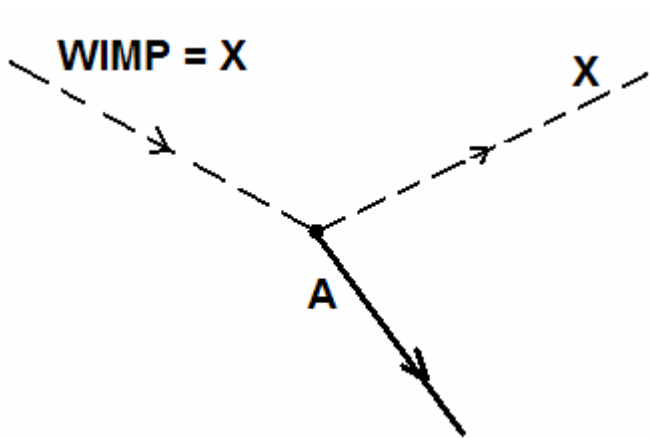
(Submitted 18 August 1982)

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.

# WIMP-nucleus interaction

CDM can consist of Weakly Interacting Massive Particles (WIMPs).  
Such particles can be searched by effects of WIMP-nucleus interactions.



$$\Delta T = 0 \div \Delta T_{\max} = \frac{q_{\max}^2}{2m_A} = \frac{2\mu^2 v^2}{m_A} \xrightarrow{m_X \gg m_A} 2m_A v^2$$

$$v \sim 300 \frac{\text{km}}{\text{s}}, \quad \Delta T \sim 10 \text{keV}$$

$$\Delta T_{\max} < E_A^* \Rightarrow \text{elastic scattering}$$

$$q_{(\max)} R_A > 1 \Rightarrow \text{non-pointlike nucleus}$$

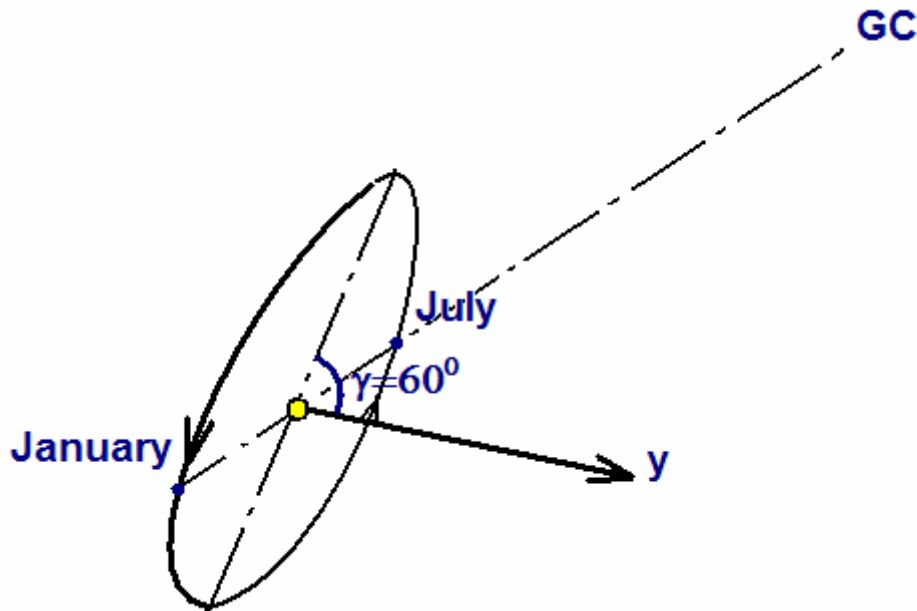
$$\text{Interaction amplitude} \equiv A_{AX} = A_{AX}^{\text{point}} \cdot F_A(q^2)$$

# Annual modulation of WIMP effects

## Minimization of background

- Installation deeply underground
- Radioactively pure materials
- Annual modulation

DM does not participate in rotation around GC.

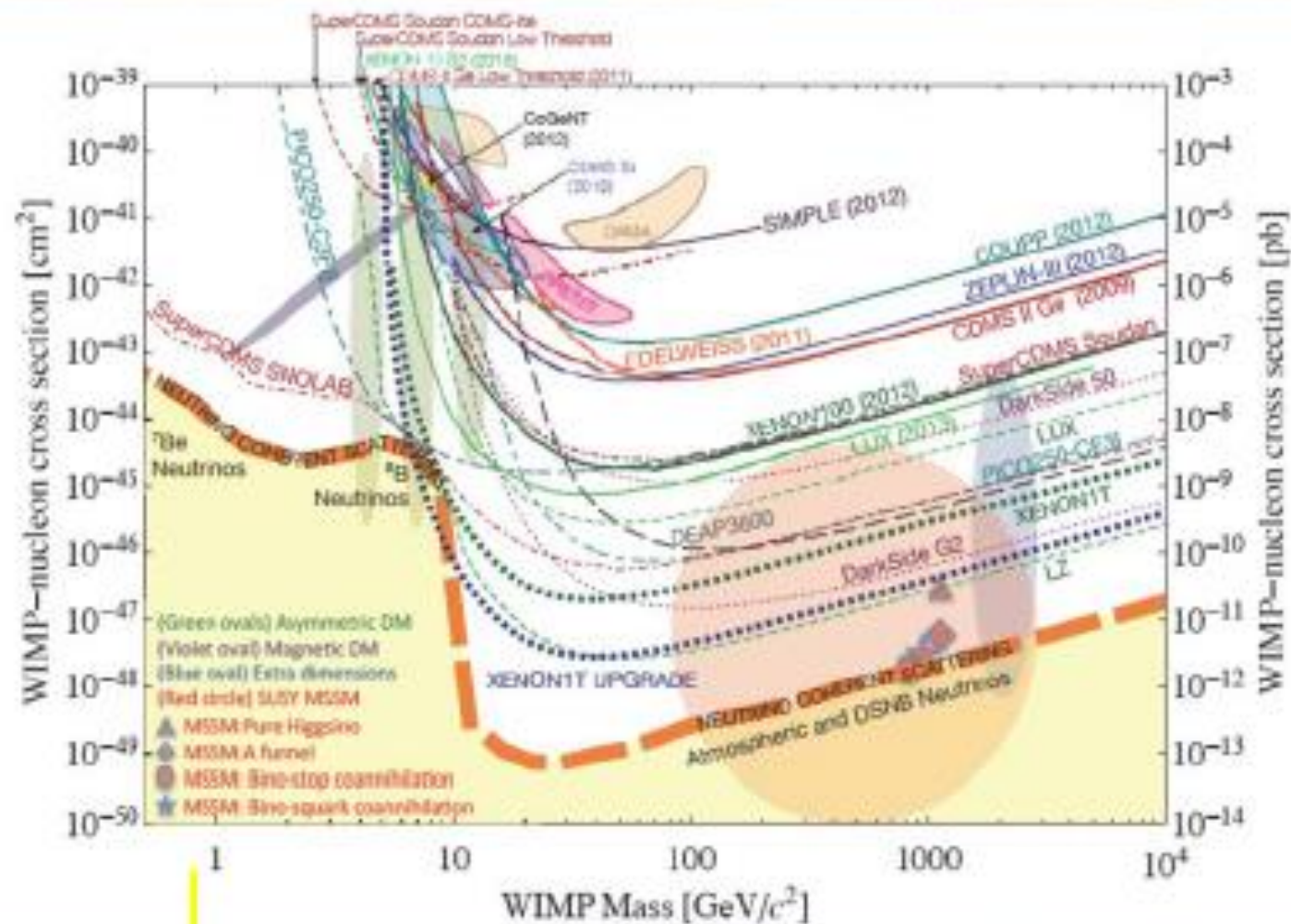


$$v_{Earth\ y} = v_{Sun\ y} + v_{orb} \cdot \cos \gamma \cdot \cos \omega(t - t_0)$$

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

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

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



This is just a largely arbitrary, partial, incorrect exercise



# **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 characteristic 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.
- Some aspects of DM effects are the subject of the talk by V.A.Beylin.

# « 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  $\text{He-4}$ , as soon as helium is created in SBBN.*
- *Particles  $E$  with electric charge -1 form +1 ion  $[E \text{ He}]$ .*
- *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 isotopes*
- *Positively charged ion is not formed, if negatively charged particles  $E$  have electric charge -2.*

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

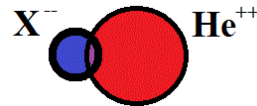
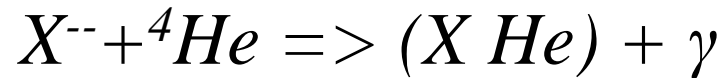
If we have a stable double charged particle  $X^{--}$  in excess over its partner  $X^{++}$  it may create Helium like neutral atom (O-helium) at temperature  $T < I_o$

Where:



${}^4\text{He}$  is formed at  $T \sim 100 \text{ keV}$  ( $t \sim 100 \text{ s}$ )

This means that it would rapidly create a neutral atom, in which all  $X^{--}$  are bound



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



## 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 ( $\sim 1$  TeV range):*

- *AC « leptons » from almost commutative geometry*

D. Fargion, M.Khlopov, C.Stephan, Class. Quantum Grav. 23 (2006) 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

# WTC-model

*The ideas of Technicolor (TC) are revived with the use of  $SU(2)$  group for “walking” (not running ) TC gauge constant \*.*

- 1.  $U$  and  $D$  techniquarks bound by Technicolor give mass to  $W$  and the  $Z$  bosons.*
- 2.  $UU$ ,  $UD$ ,  $DD$  and their corresponding antiparticles are technibaryons and corresponding anti-technibaryons.*
- 3. The electric charges of  $UU$ ,  $UD$ , and  $DD$  are in general  $y+1$ ,  $y$  and  $y-1$  respectively, where  $y$  is an arbitrary real number.*
- 4. In order to cancel the **Witten global anomaly** the model requires in addition an existence of a fourth family of leptons.*
- 5. Their electric charges are in terms of  $y$  respectively  $(1 - 3y)/2$  and  $(-1 - 3y)/2$ .  
If  $y=1$ , both **stable doubly charged** technibaryons and technileptons are possible\*\*.*

*All these stable techniparticles will look like stable multiple charged leptons at LHC*

## References

\*

F. Sannino and K. Tuominen, *Phys. Rev. D* 71 (2005) 051901 ;  
D. K. Hong *et al.*, *Phys. Lett. B* 597 (2004) 89 ;  
D. D. Dietrich *et al.*, *Phys. Rev. D* 72 (2005) 055001 ;  
S. B. Gudnason *et al.*, *Phys. Rev. D* 73 (2006) 115003 ;  
S. B. Gudnason *et al.*, *Phys. Rev. D* 74 (2006) 095008]

\*\*

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

# Techniparticle excess

- The advantage of WTC framework is that it provides definite relationship between baryon asymmetry and techniparticle excess.

$$\frac{TB}{B} = -\sigma_{UU} \left( \frac{L'}{B} \frac{1}{3\sigma_{\zeta}} + 1 + \frac{L}{3B} \right)$$

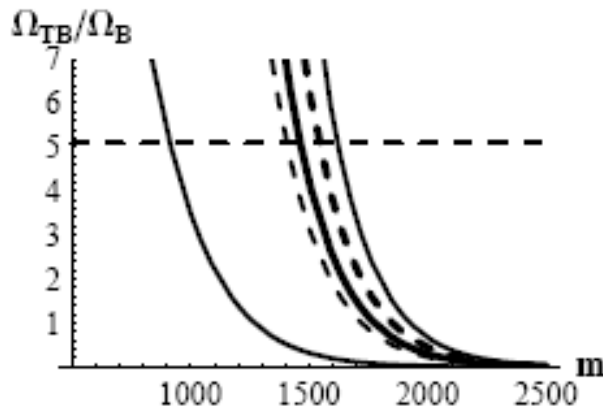
Here  $\sigma_i$  ( $i = UU, \zeta$ ) are statistical factors in equilibrium relationship between, TB, B, L and L'

*The equilibrium is maintained by electroweak SU(2) sphalerons and similar relationship can hold true for any SU(2) dublets (like U quarks of 4th family or stable quarks of 5th family) [See talk by D.Sopini]*



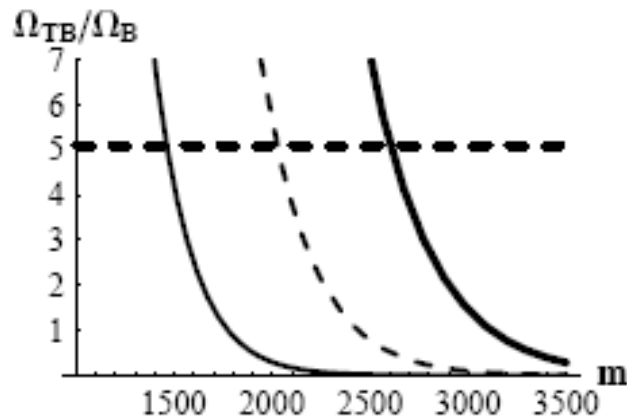
# Relationship between TB and B

$$\xi = \frac{L'}{3B\sigma_\zeta} + 1 + \frac{L}{3B}$$



- $L'=0$ ,  $T^*=150$  GeV  
 $\xi = 0.1; 1; 4/3; 2; 3$

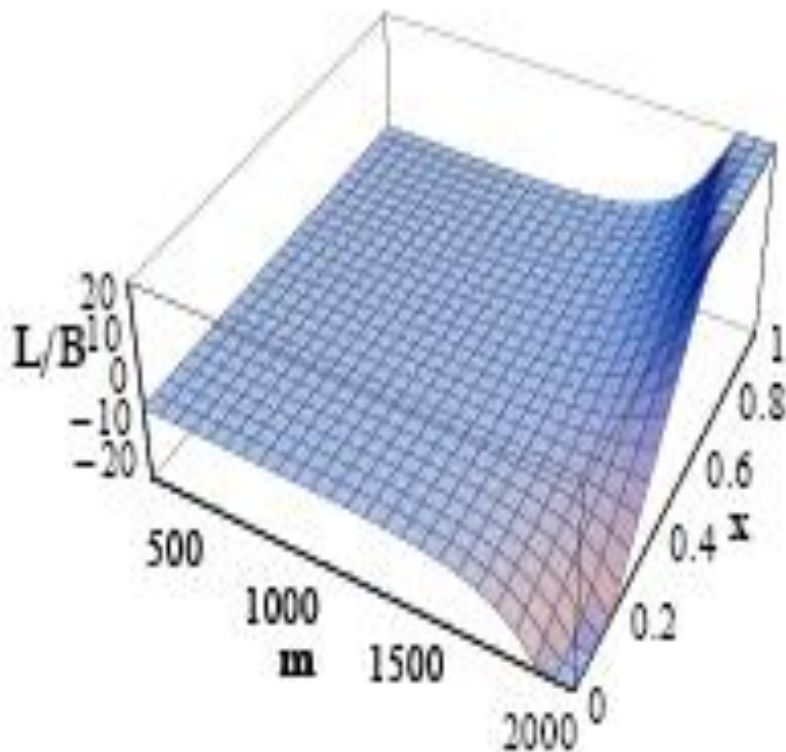
$\xi$



$$\xi = 4/3$$

- $L'=0$ ,  
 $T^*=150, 200, 250$  GeV

# Relationship between TB, L' and B



- $x$  denotes the fraction of dark matter given by the technibaryon
- $TB < 0, L' > 0$  – two types of -2 charged techniparticles.

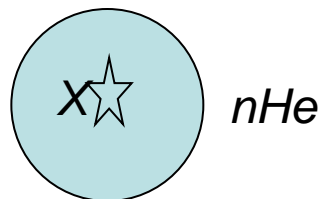
*The case  $TB > 0, L' > 0$  ( $TB < 0, L' < 0$ ) gives an interesting possibility of (-2 +2) atom-like WIMPs, similar to AC model. For  $TB > L'$  ( $TB < L'$ ) no problem of free +2 charges*

# Stable multiple charged particles

*WTC can lead to techniparticles with multiple charge*

$q$	$UU(q+1)$	$UD(q)$	$DD(q-1)$	$\nu'(\frac{1-3q}{2})$	$\zeta(\frac{-1-3q}{2})$
1	<b>2</b>	1	0	-1	<b>-2</b>
3	<b>4</b>	3	<b>2</b>	-4	-5
5	<b>6</b>	5	4	-7	<b>-8</b>
7	<b>8</b>	7	<b>6</b>	<b>-10</b>	-11

*-2n charged particles in WTC bound with n nuclei of primordial He form Thomson atoms of XHe*



# From WIMP miracle to DM reality?

- The lack of positive evidence of SUSY particles at the TeV scale may reflect the super high energy SUSY scale.
- It can provide alternative ways to solve the SM problems.
- Composite Higgs boson is another possibility to solve the SM problems, involving, in particular, stable multiple charged particles.

**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

# New component of cosmic ray

- XHe atoms can be captured and ionized in stars and free multiple charged X particles can be accelerated in shocks at SN explosion.
- It leads to creation of a new exotic lepton-like multiple-charged component of cosmic rays.\*
- The advantage of cosmic ray search for X, as compared with their collider searches is that there is no suppression related with the energy threshold of their formation since they are of primordial origin.

# 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,  $\sigma v$  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  $\overline{V_h}$  is velocity of Solar System relative to DM halo (220 km/s),  $\overline{V_E}$  is velocity of orbital motion of Earth (29.5 km/s) and

$n_0 = 3 \cdot 10^{-4} S_3^{-1} \text{ cm}^{-3}$  is the local density of O-helium dark matter.

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

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

# 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  $\omega = 2\pi/T$ ,  $T=1yr$  and  $t_0$  is the phase. The averaged concentration is given by

$$n_{oE}^{(1)} = \frac{n_o}{320S_3A_{med}^{1/2}}V_h$$

and the annual modulation of OHe concentration is characterized by

$$n_{oE}^{(2)} = \frac{n_o}{640S_3A_{med}^{1/2}}V_E$$

**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**.

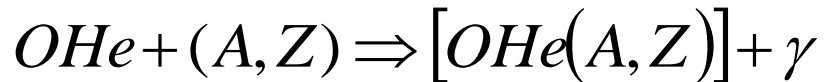
# OHe solution for puzzles of direct DM search

- OHe equilibrium concentration in the matter of DAMA detector is maintained for less than an hour



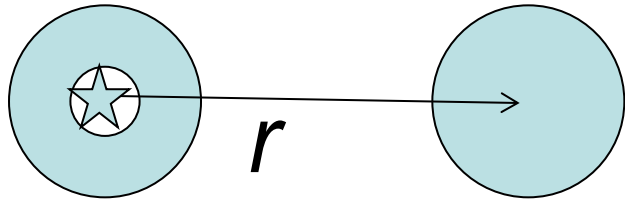
- Annual modulations in inelastic processes, induced by OHe in matter. No signal of WIMP-like recoil
- Signal in DAMA detector is not accompanied by processes with large energy release. This signal corresponds to a formation of anomalous isotopes with binding energy of few keV

- The process

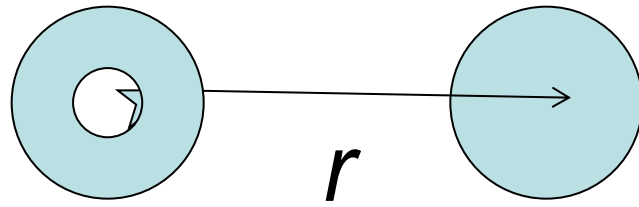


is possible, in which only a few keV energy is released. Other inelastic processes are suppressed

# Potential of OHe-nucleus interaction



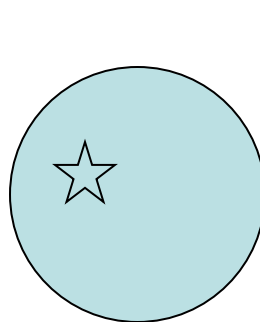
$$U_{Xnuc} = -2Z\alpha \left( \frac{1}{r} + \frac{1}{r_o} \right) \exp(-2r/r_o)$$



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

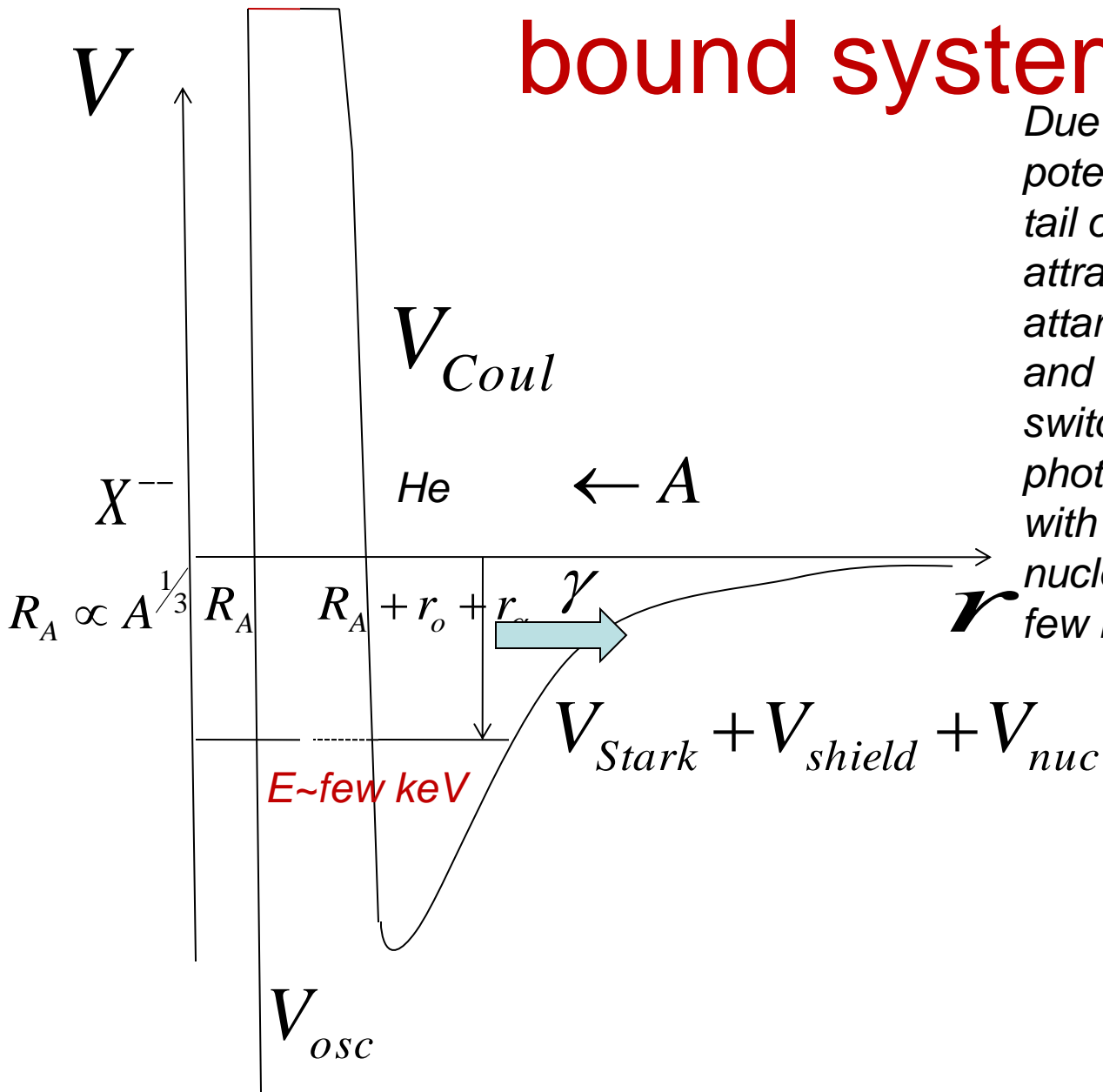


$$U_{Coul} = +\frac{2\alpha Z}{\rho} - \frac{2\alpha Z}{r}$$



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

# 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 attraction 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

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

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

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

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*

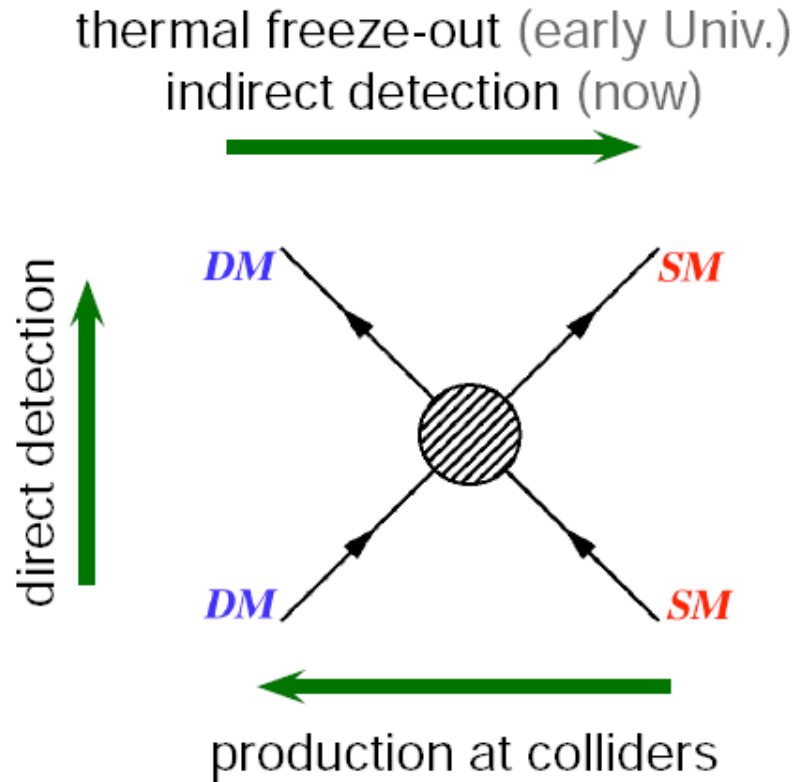
*Some Potential Problems of OHe Composite Dark Matter,*

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

# **COMPOSITE DARK MATTER CONSTITUENTS AT ACCELERATORS**



# Complementarity in searches for Dark Matter

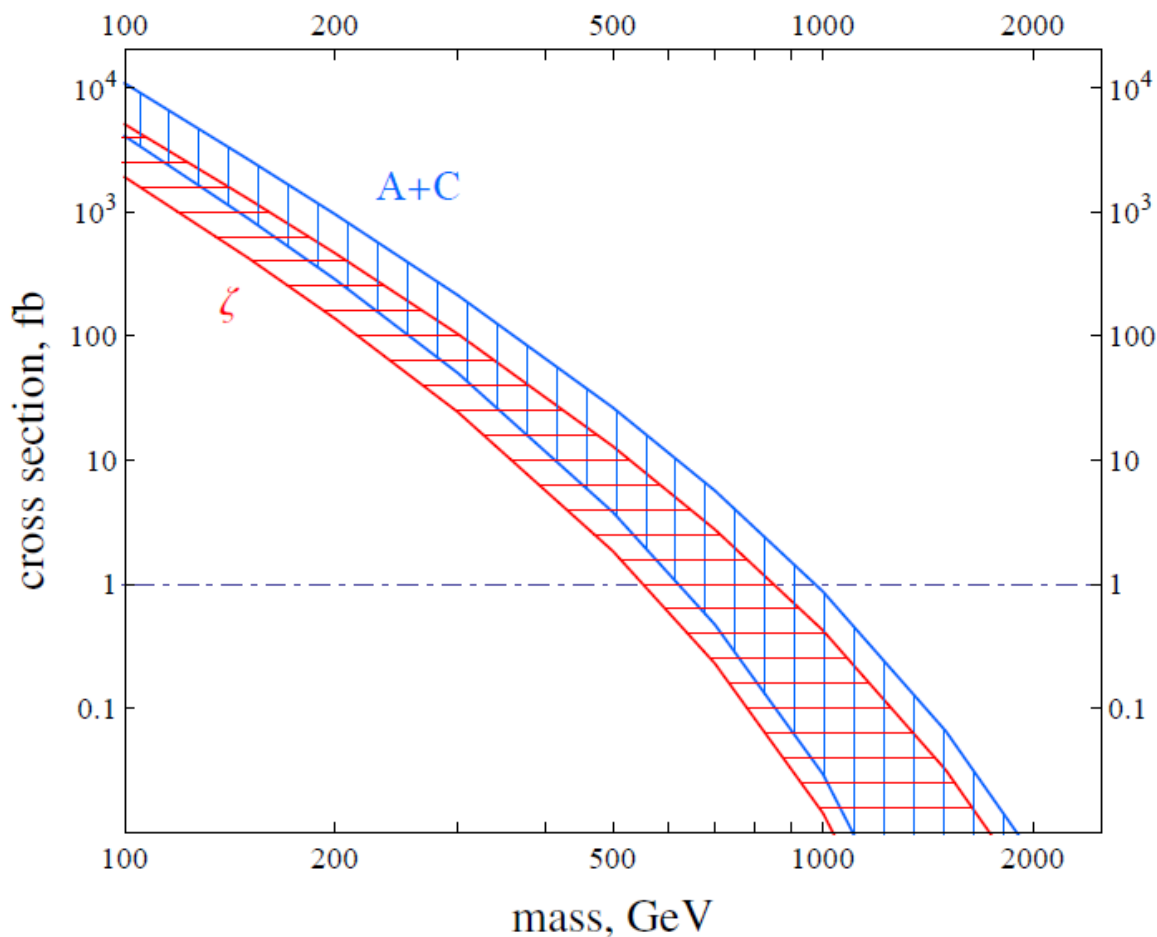


*Usually, people use this illustration for complementarity in direct, indirect and accelerator searches for dark matter. However, we see that in the case of composite dark matter the situation is more nontrivial. We need charged particle searches to test dark atom model*

# 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.

# LHC discovery potential for charged components of composite dark matter



The shaded strips correspond to production cross sections of technileptons and A,C leptons with  $Q=2$  at  $7 \text{ teV} < \sqrt{s} < 14 \text{ TeV}$

# 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<sup>a</sup>, O. Bulekov<sup>a</sup>, M. Jüngst<sup>b</sup>, M.Yu.Khlopov<sup>a,h</sup>, C. Marino<sup>c</sup>, P. Mermod<sup>d</sup>, H. Ogren<sup>e</sup>, A. Romaniouk<sup>a</sup>, Y. Smirnov<sup>a</sup>, W. Taylor<sup>f</sup>, B. Weinert<sup>g</sup>, D. Zieminska<sup>e</sup>, S. Zimmermann<sup>g</sup>

<sup>a</sup>*Moscow Engineering Physics Institute*

<sup>b</sup>*CERN*

<sup>c</sup>*University of Victoria*

<sup>d</sup>*Oxford University*

<sup>e</sup>*Indiana University*

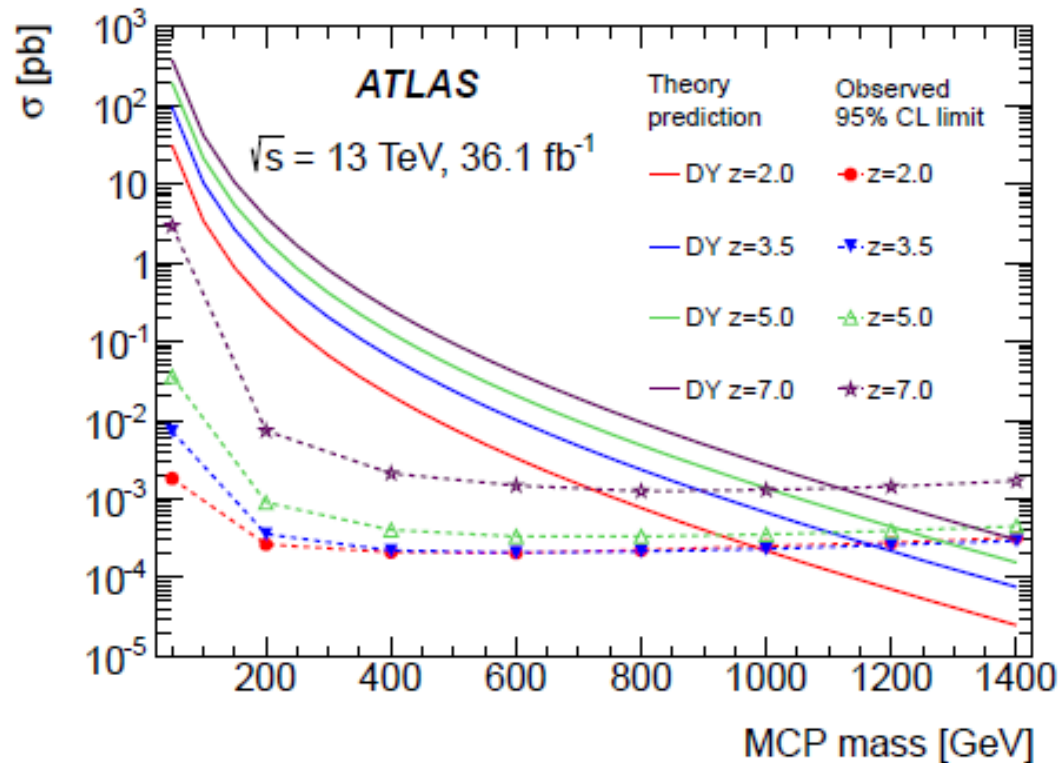
<sup>f</sup>*York University*

<sup>g</sup>*University of Bonn*

<sup>h</sup>*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



$M > 980 \text{ GeV}$   
for  $|q|=2e$   
at 95% c.l.

[ATLAS Collaboration, Search for heavy long-lived multi-charged particles in proton-proton collisions at  $\sqrt{s} = 13 \text{ TeV}$  using the ATLAS detector. Phys. Rev. D 99, 052003 (2019)]

# 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 positron annihilation line in Galactic bulge,*

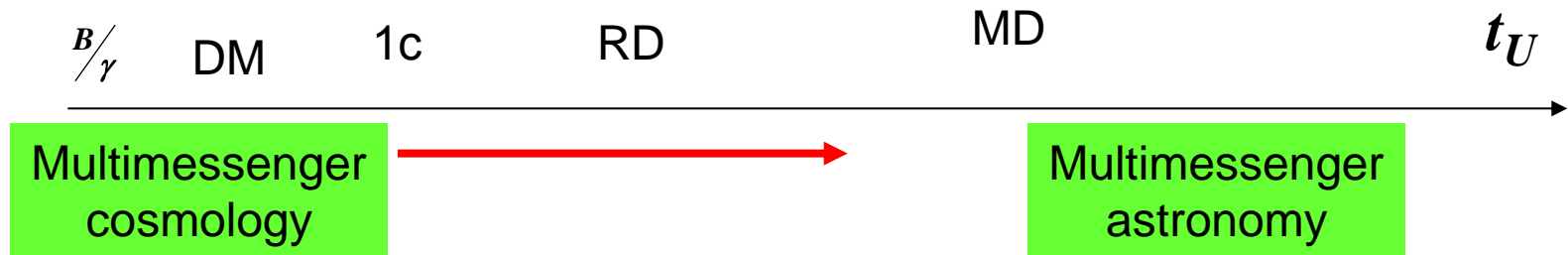
$ q /e$	$z$											
	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	
Lower mass limit [TeV]	0.98	1.06	1.13	1.17	1.20	1.22	1.22	1.21	1.19	1.16	1.12	

*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. The latter is already excluded for double charged constituents.*

*[ATLAS Collaboration, Search for heavy long-lived multi-charged particles in proton-proton collisions at  $\sqrt{s}=13$  TeV using the ATLAS detector.*

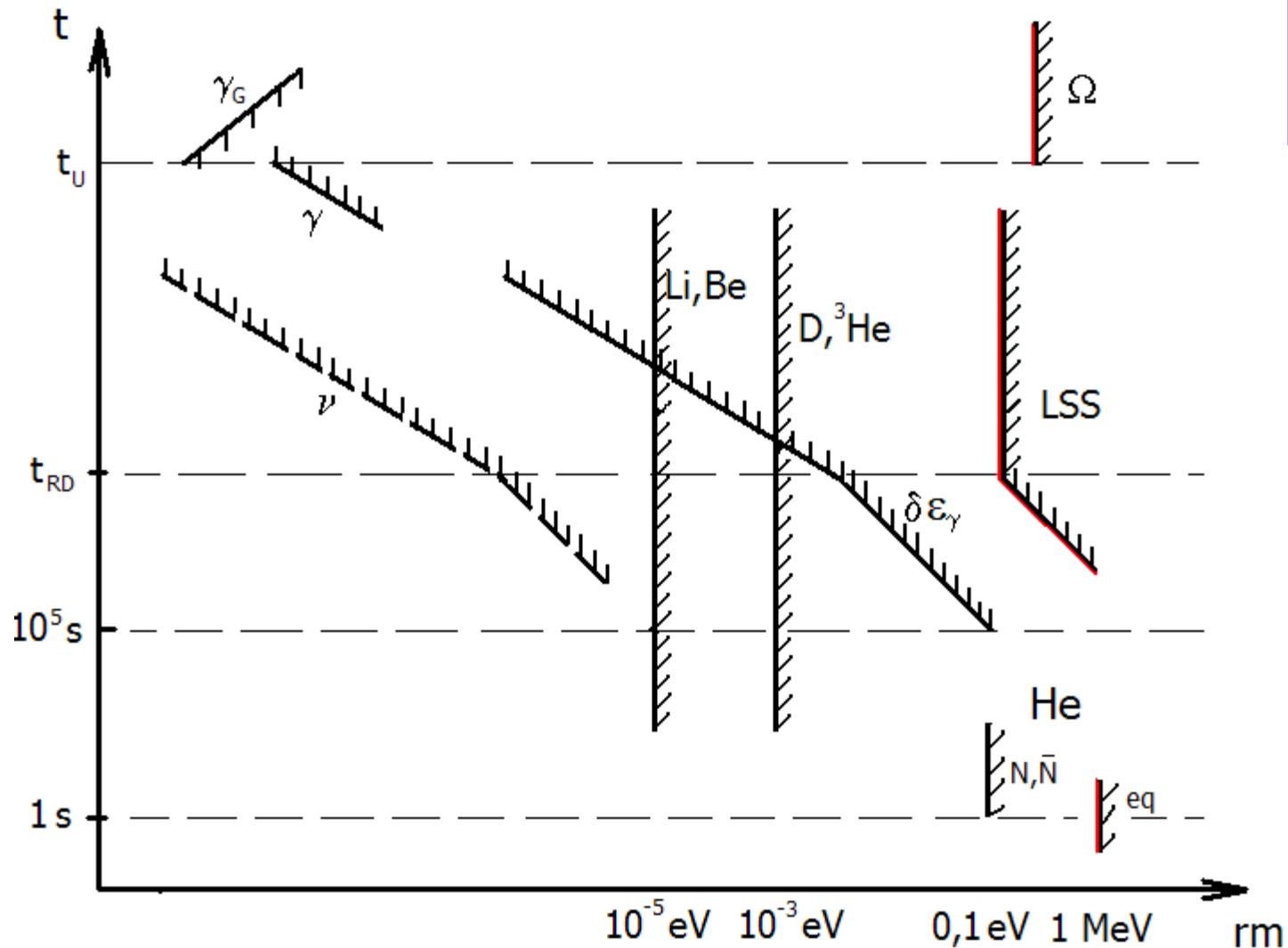
*Phys. Rev. D 99, 052003 (2019)*

**Cosmoarcheology** treats the set of astrophysical data as the experimental sample shedding light on possible properties of new physics. Its methods provide *Gedanken Experiment*, in which multimessenger cosmology of new physics is considered as the source, while its effects on later stages of expansion are considered as detector, fixing the signatures for these effects in the multimessenger astronomical data.



These « detectors of the Universe » can be « integral » (sensitive to very existence of new forms of matter) and « differential » (sensitive to some particular effect of such forms of matter)

# Laboratory of the Universe



$$r \equiv \frac{n_X}{n_\gamma}$$



# Non-equilibrium particles

- Decays of unstable particles, antimatter domain annihilation, PBH evaporation... are the source of particles with energy  $E \gg T$  or of such particles, which are absent in equilibrium at this temperature  $T$  (e.g. antiprotons in baryon asymmetrical Universe after the first microsecond of expansion).
- Late sources of non-equilibrium particles directly contribute in fluxes of cosmic rays.
- If the source of particles acts sufficiently early, interaction of non-equilibrium particles with plasma and radiation can lead to observable effect

# **PBH PROBES FOR PHYSICS OF EARLY UNIVERSE**

# Primordial Black Holes

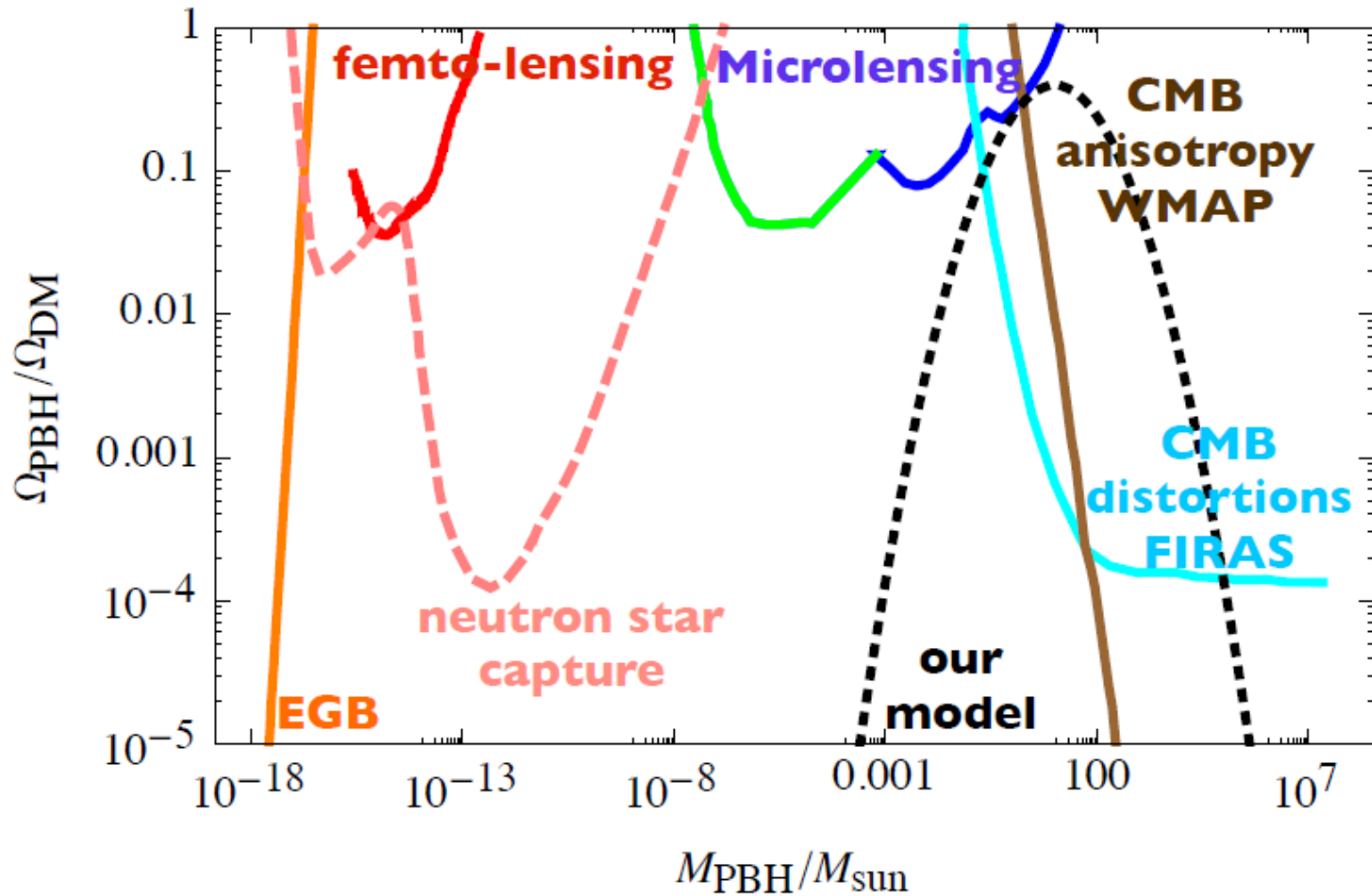
- Any object of mass  $M$  can form Black hole, if contracted within its gravitational radius.

$$r \leq r_g = \frac{2GM}{c^2}$$

- It naturally happens in the result of evolution of massive stars (and, possibly, dense star clusters).
- In the early Universe Black hole can be formed, if expansion can stop within cosmological horizon [Zeldovich, Novikov, 1966]. It corresponds to strong nonhomogeneity in early Universe

$$\delta \equiv \frac{\delta\rho}{\rho} \sim 1$$

# Constraints on PBHs



# PBHs as indicator of early dust-like stages

- In homogeneous and isotropic Universe ( $\delta_0 \ll 1$ ) with equation of state  $p = k\varepsilon$  probability of strong nonhomogeneity  $\delta \sim 1$  is exponentially suppressed

$$P(\delta) = A(\delta, \delta_0) \exp\left(-\frac{k^2 \delta^2}{2\delta_0^2}\right)$$

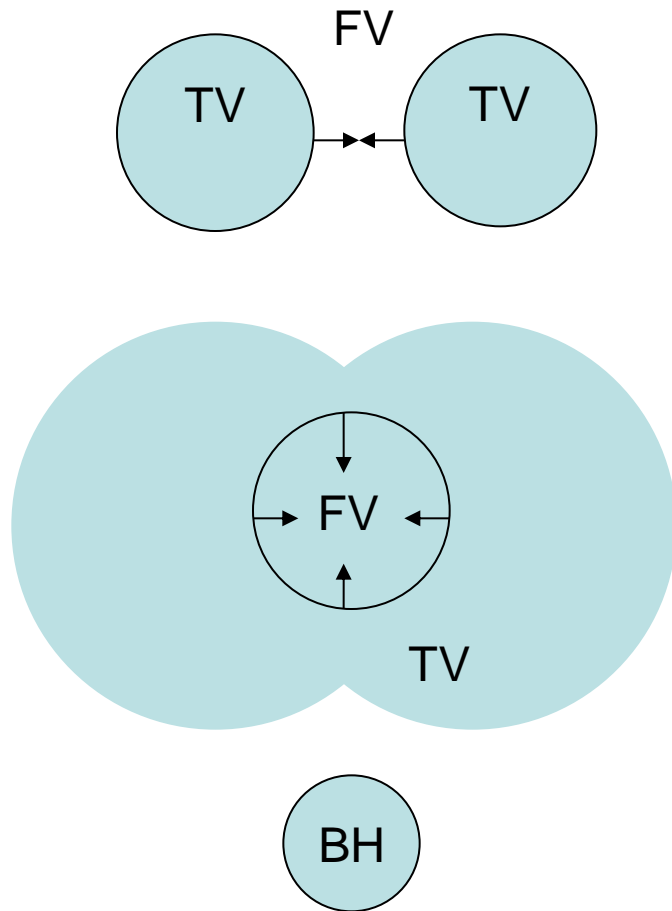
- At  $k=0$  on dust-like stage exponential suppression is absent. The minimal estimation is determined by direct production of BHs

$$A(\delta, \delta_0) \geq \left(\frac{\delta_0}{\delta}\right)^5 \left(\frac{\delta_0}{\delta}\right)^{3/2} = \left(\frac{\delta_0}{\delta}\right)^{13/2}$$

# Dominance of superheavy particles

- Superheavy particles with mass  $m$  and relative concentration  $r = \frac{n}{n_\gamma}$  dominate in the Universe at  $T < r m$ .
- Coherent oscillations of massive scalar field also behave as medium with  $p=0$ .
- They form BHs either directly from collapse of symmetric and homogeneous configurations, or in the result of evolution of their gravitationally bound systems (pending on particle properties they are like « stars » or « galaxies »).

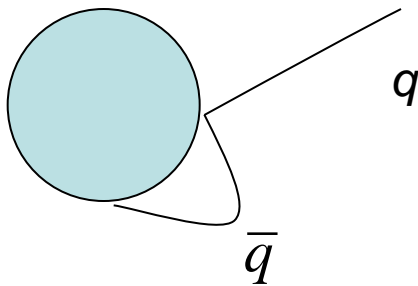
# PBHs as indicator of first order phase transitions



- Collision of bubbles with True Vacuum (TV) state during the first-order phase transition results in formation of False Vacuum (FV) bags, which contract and collapse in Black Holes (BH).

# PBH evaporation

- According to S. Hawking PBH with mass  $M$  evaporate due to creation of pairs by its nonstationary gravitational field. Products of evaporation have black body spectrum with



$$T_{PBH} \propto \frac{1}{r_g}$$

$$T_{PBH} \approx 10^{13} \text{ GeV} \left( \frac{1g}{M} \right)$$

- The rate of evaporation is given by

$$\frac{dM}{dt} = -\kappa T_{PBH}^4 r_g^2 \propto \frac{1}{r_g^2} \propto \frac{1}{M^2}$$

- The evaporation timescale is

$$t_{PBH} \approx 10^{27} \text{ s} \left( \frac{M}{1g} \right)^3$$

Any particle with  $m \leq T_{PBH}$   
is created – UNIVERSAL source



# Effects of Primordial Black Holes

- PBHs behave like a specific form of Dark Matter
- 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). PBHs with mass  $M < 10^{15} g$  evaporate and their astrophysical effects are similar to effects of unstable particles.
- However, cosmological consequences of particle theory can lead to mechanisms of intermediate and even supermassive BH formation.

**STRONG PRIMORDIAL  
INHOMOGENEITY PROBES  
FOR INFLATION AND  
BARYOSYNTHESIS**

# 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 fluctuations.

$$\delta \equiv \delta\rho / \rho \ll 1$$

- However, if there is a tiny component, giving small contribution to total  $\rho_i \ll \rho$  its strong nonhomogeneity  $\delta_i \equiv (\delta\rho / \rho)_i > 1$

is compatible with small nonhomogeneity of the total density

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

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.

# 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 leptogenesis) 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.

# 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.
- 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.

# U(1) model (ALP cosmology)

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

**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)**

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

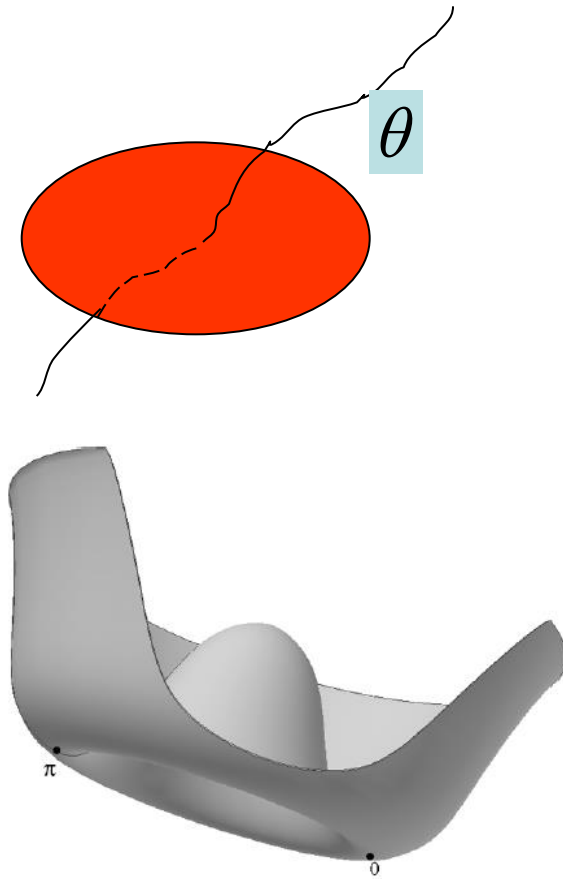
**to vacuum states**

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

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



# 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. This structure is unstable and decay, but the initial values of phase define the energy density of field oscillations.

# Unstable topological defects

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

# Archioles structure

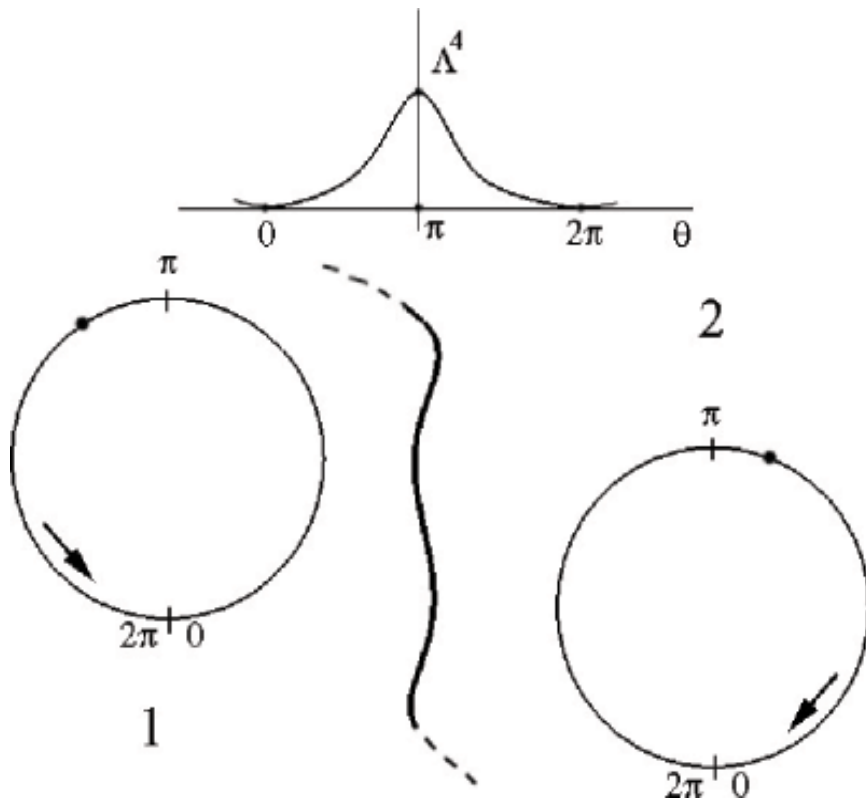


- Numerical studies revealed that ~80% of string length corresponds to infinite Brownian lines, while the remaining ~20% of this length corresponds to closed loops with large size loops being strongly suppressed. It corresponds to the well known scale free distribution of cosmic strings.
- The fact that the energy density of coherent axion field oscillations reflects this property is much less known. It leads to a large scale correlation in this distribution, called archioles.
- Archioles offer possible seeds for large scale structure formation.
- However, the observed level of isotropy of CMB puts constraints on contribution of archioles to the total density and thus puts severe constraints on axions as dominant form of Dark Matter.

# 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 (and, 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



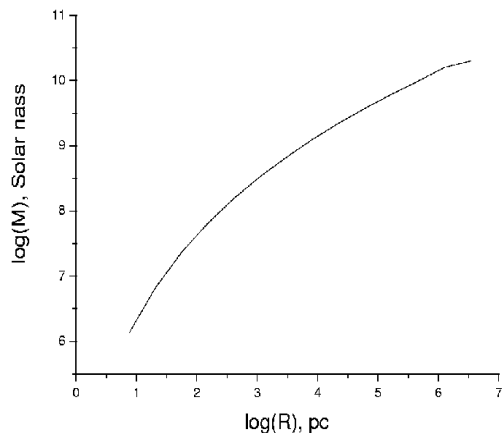
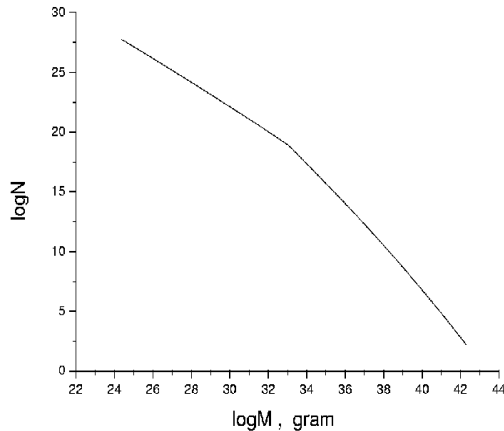
If the first U(1) phase transition takes place on inflationary stage, the value of phase  $\theta$ , corresponding to e-folding  $N \sim 60$ , fluctuates

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

Such fluctuations can cross  $\pi$

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  $\nu_0 = 3 \cdot 10^{11} (\Lambda / f) \text{ Hz}$  with energy density up to

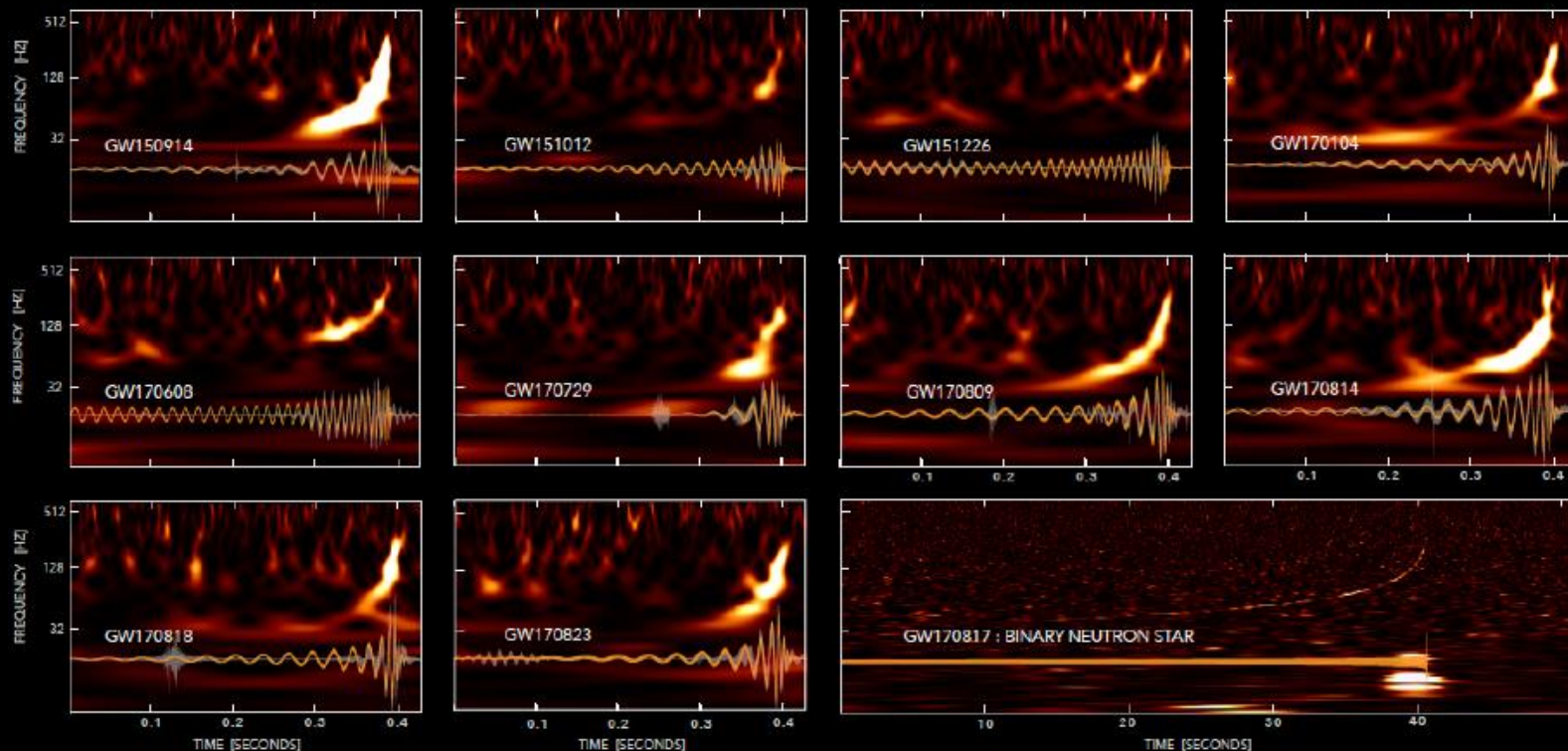
$$\Omega_{GW} \approx 10^{-4} (f / m_{Pl})$$

- At  $f \sim 10^{14} \text{ GeV}$   $\Omega_{GW} \sim 10^{-9}$
- For  $1 < \Lambda < 10^8 \text{ GeV}$   $3 \cdot 10^{-3} \text{ Hz} < \nu_0 < 3 \cdot 10^5 \text{ Hz}$
- Merging of BHs in BH cluster is probably detected by LIGO!.



# GWTC-1

## GRAVITATIONAL-WAVE TRANSIENT CATALOG-1



LIGO-VIRGO DATA: [HTTPS://DOI.ORG/10.7926/82410-14-123](https://doi.org/10.7926/82410-14-123)

WAVELET (UNMODELED)

EINSTEIN'S THEORY

S. GHONGE, K. JANI | GEORGIA TECH

LVC, arXiv:1811.12907 [astro-ph]  
submitted to PRX

# Parameter estimation

- ▶ Median values and 90% credible intervals based on two GR waveform models
- ▶ GW170729: highest mass and most distant BBH observed to date (median values); has moderate spin
- ▶ GW170818: best localised BBH to date - HLV detection
- ▶ Results consistent with previously published ones

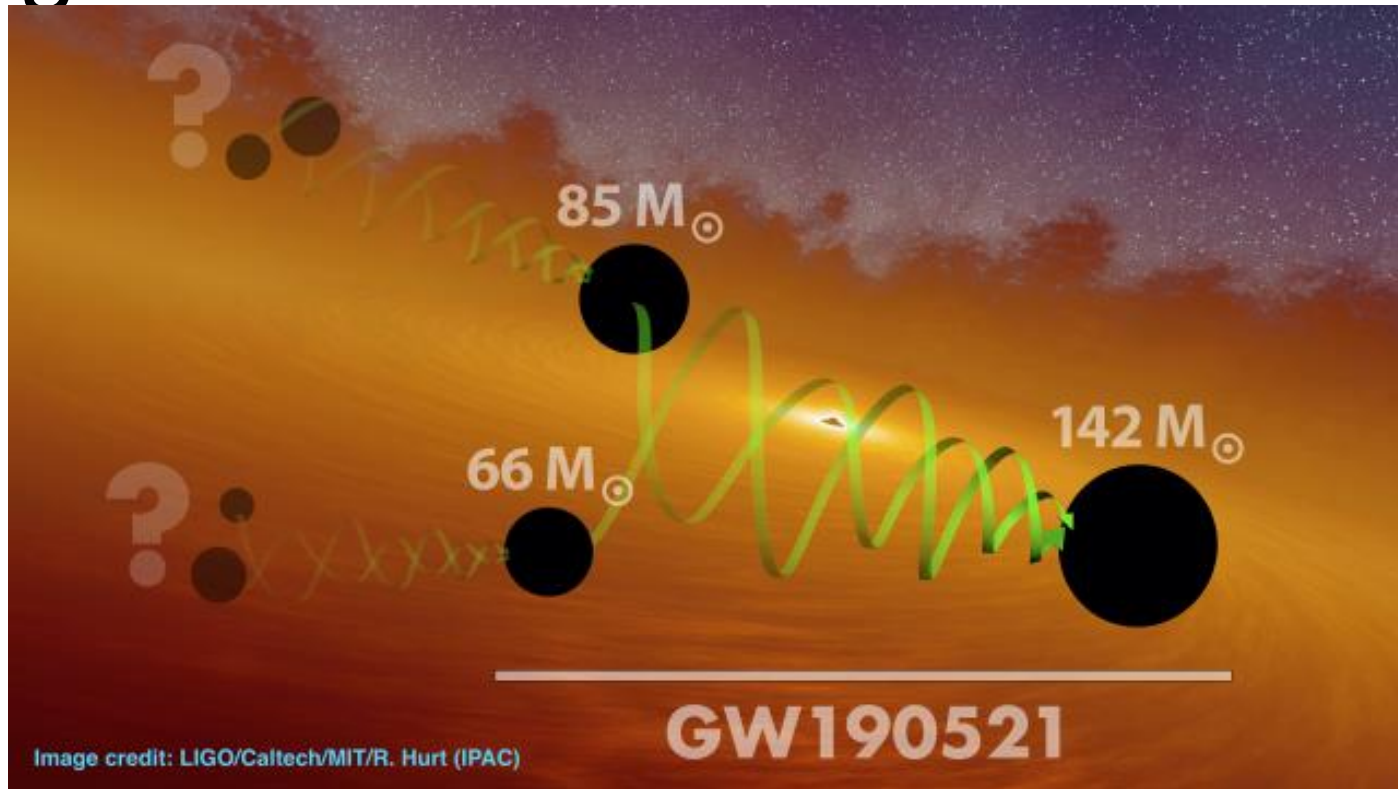
Event	$m_1/M_\odot$	$m_2/M_\odot$	$M/M_\odot$	$\chi_{\text{eff}}$	$M_f/M_\odot$	$a_f$	$E_{\text{rad}}/(M_\odot c^2)$	$\ell_{\text{peak}}/(\text{erg s}^{-1})$	$d_L/\text{Mpc}$	$z$	$\Delta\Omega/\text{deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	$430^{+150}_{-170}$	$0.09^{+0.03}_{-0.03}$	179
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7} \times 10^{56}$	$1060^{+540}_{-480}$	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7} \times 10^{56}$	$440^{+180}_{-190}$	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-0.9} \times 10^{56}$	$960^{+430}_{-410}$	$0.19^{+0.07}_{-0.08}$	924
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.0}_{-0.1}$	$3.5^{+0.4}_{-1.3} \times 10^{56}$	$320^{+120}_{-110}$	$0.07^{+0.02}_{-0.02}$	396
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5} \times 10^{56}$	$2750^{+1350}_{-1320}$	$0.48^{+0.19}_{-0.20}$	1033
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9} \times 10^{56}$	$990^{+320}_{-380}$	$0.20^{+0.05}_{-0.07}$	340
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5} \times 10^{56}$	$580^{+160}_{-210}$	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	$\leq 2.8$	$\leq 0.89$	$\geq 0.04$	$\geq 0.1 \times 10^{56}$	$40^{+10}_{-10}$	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7} \times 10^{56}$	$1020^{+430}_{-360}$	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9} \times 10^{56}$	$1850^{+840}_{-840}$	$0.34^{+0.13}_{-0.14}$	1651

# 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 is of special interest\*



# GW190521: A Binary Black Hole Merger with a Total Mass of $150 M_{\odot}$



The LIGO Scientific Collaboration, the Virgo Collaboration: Phys. Rev. Lett. 125, 101102 (2020)

Masses natural for PBHs in the gap for BHs of astrophysical origin

# **ANTIMATTER STARS IN BARYON ASYMMETRIC UNIVERSE**

# 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.

# Survival of antimatter domains

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

$$\partial n_b / \partial t = D(t) \partial^2 n_b / \partial x^2 - \alpha n_b \quad \text{where} \quad D(t) \approx \frac{3T_\gamma c}{2\rho_\gamma \sigma_T}$$

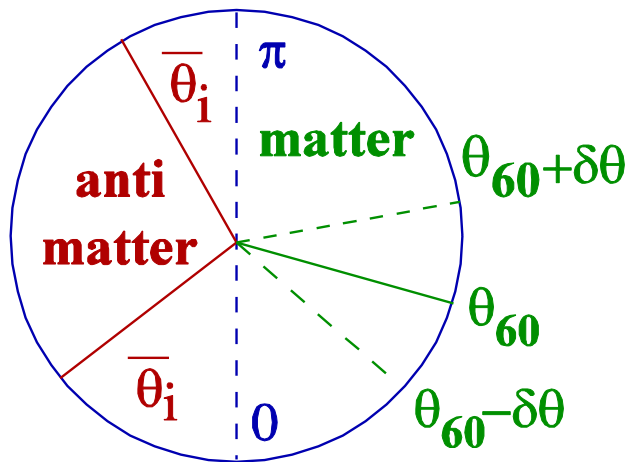
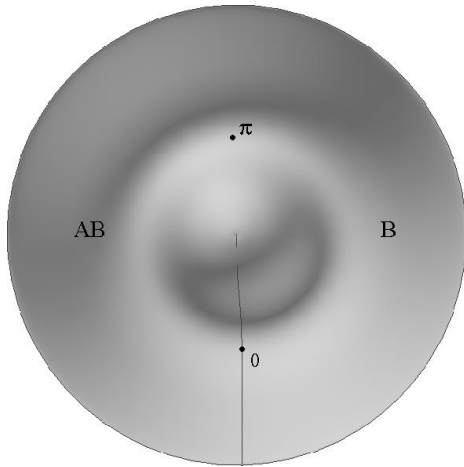
**The minimal surviving scale is given by**

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

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

\*See talk by O.M.Lecian

# Nonhomogeneous spontaneous baryosynthesis



- Model of spontaneous baryosynthesis provides quantitative description of combined effects of inflation and nonhomogeneous baryosynthesis, leading to formation of antimatter domains, surviving to the present time.



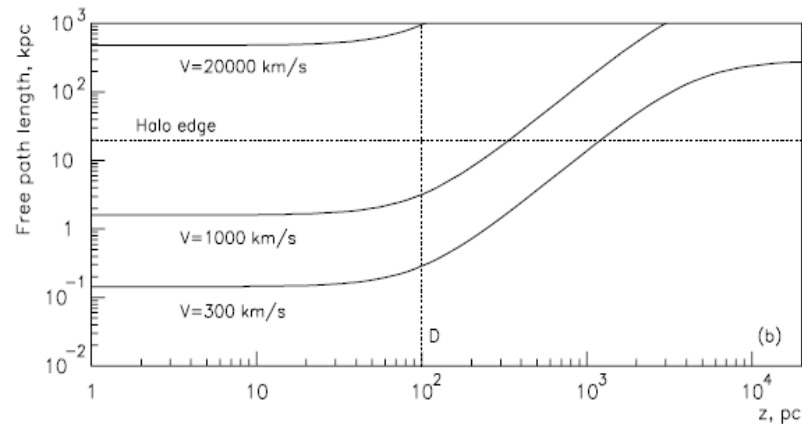
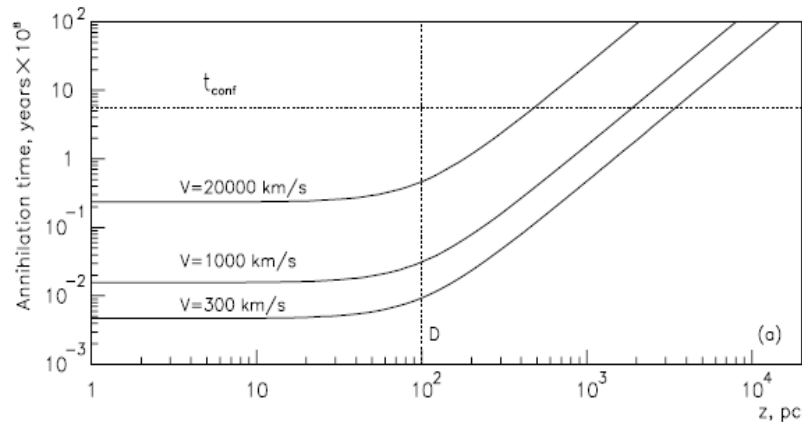
# Antimatter in galaxies

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

**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.**

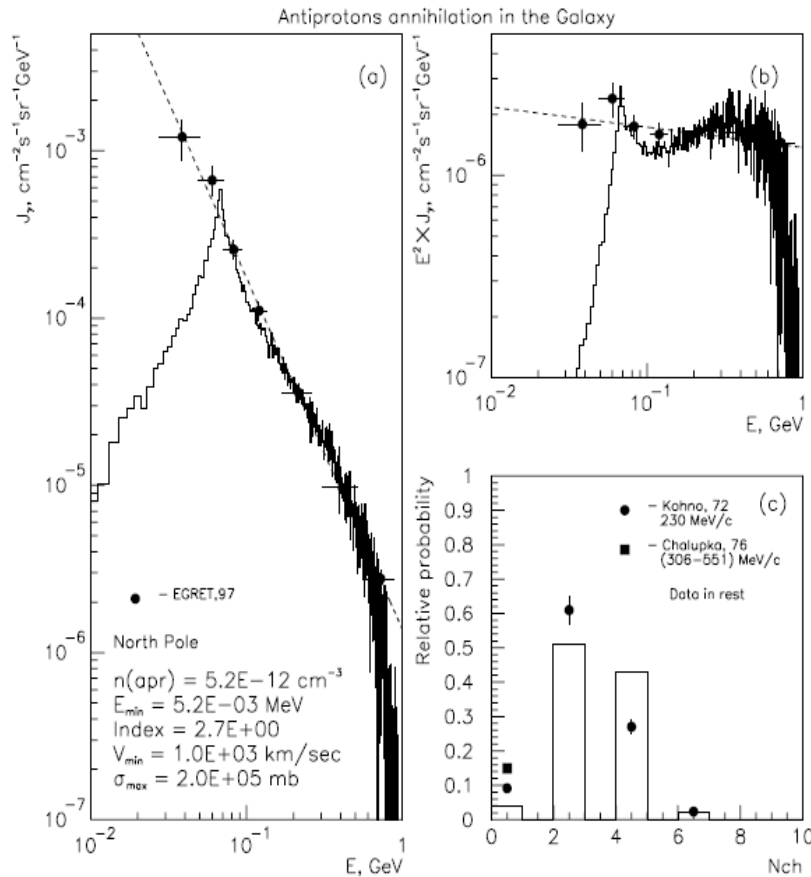
**In our Galaxy from 1000 to 100000 antimatter stars can exist in a form of antimatter globular cluster (Khlopov, 1998). Being in halo, such cluster is a faint gamma ray source, but antimatter from it pollutes Galaxy and can be observed indirectly by annihilation, or directly as anti-meteorites or antinuclei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

# Antimatter pollution of Galaxy



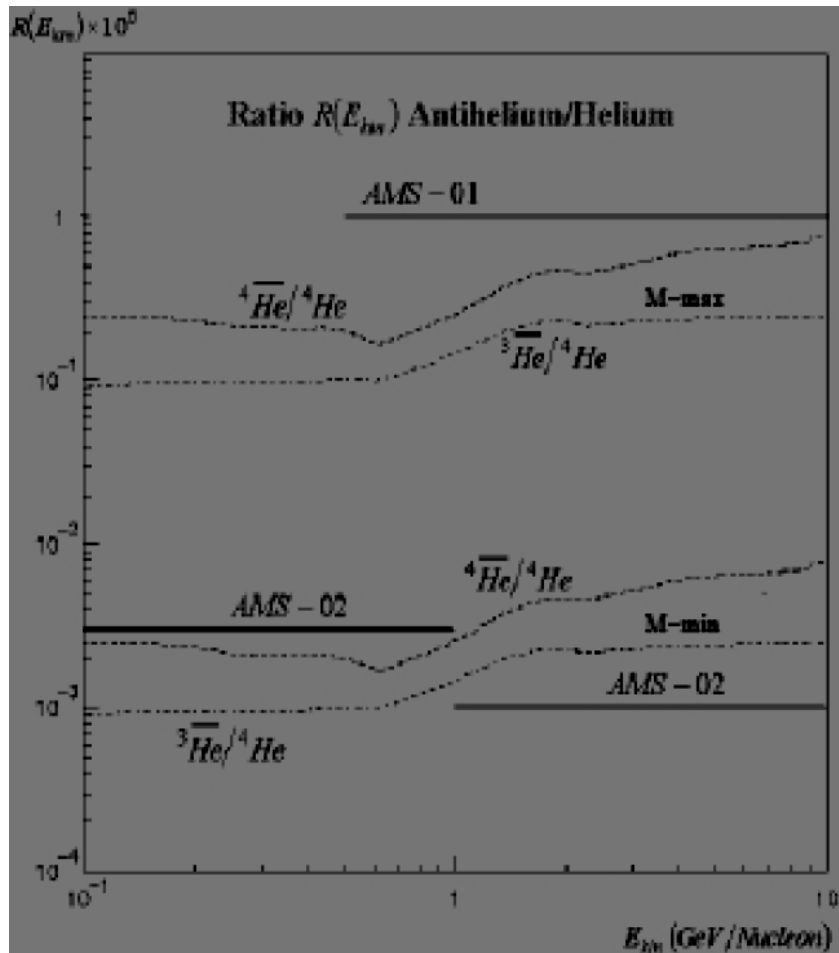
- Since antihydrogen is dominant in antimatter composition, the Galaxy is dominantly polluted by antiprotons.
- Their lifetime in Galaxy depends on their velocity and density of surrounding matter.

# Gamma background from antimatter annihilation in Galaxy



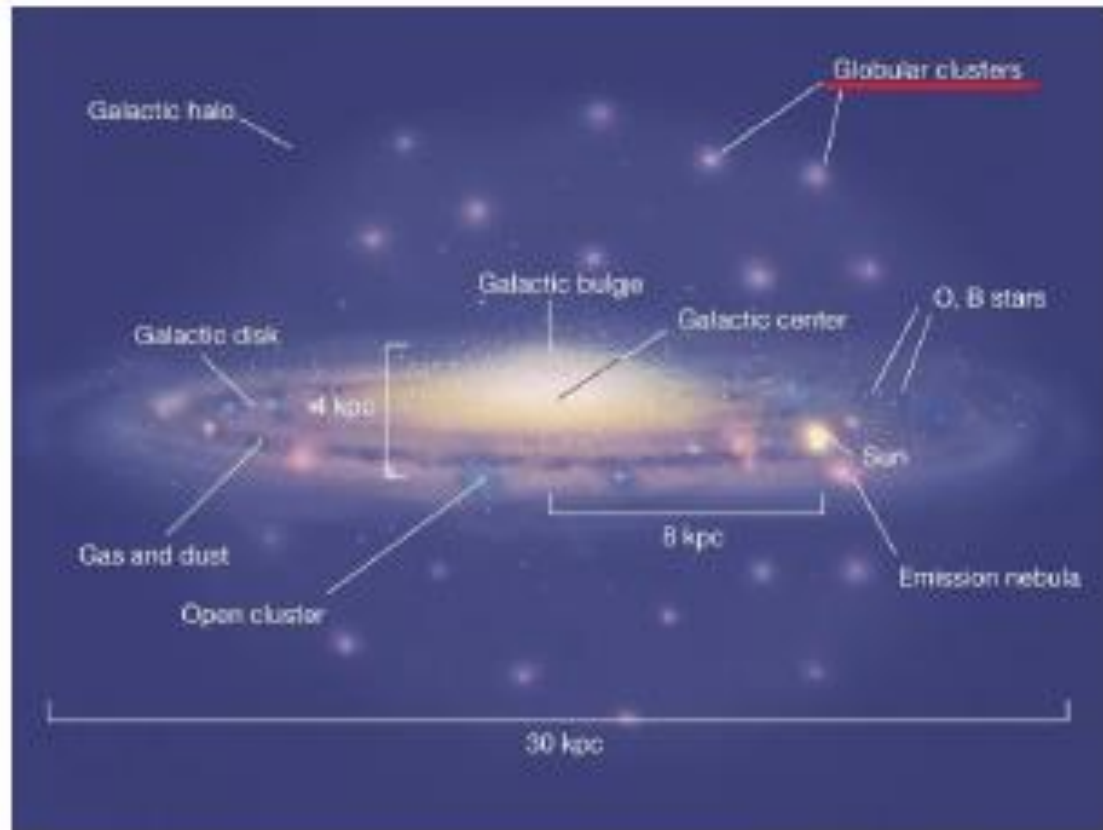
- Antiproton annihilation can reproduce gamma background observed by EGRET in the range tens-hundreds MeV.
- It can not be considered as PROOF for existence of antimatter stars – only pieces of antimatter (antihelium nuclei, antimeteorites) can provide such PROOF.

# Cosmic antihelium test for antimatter stars in Galaxy



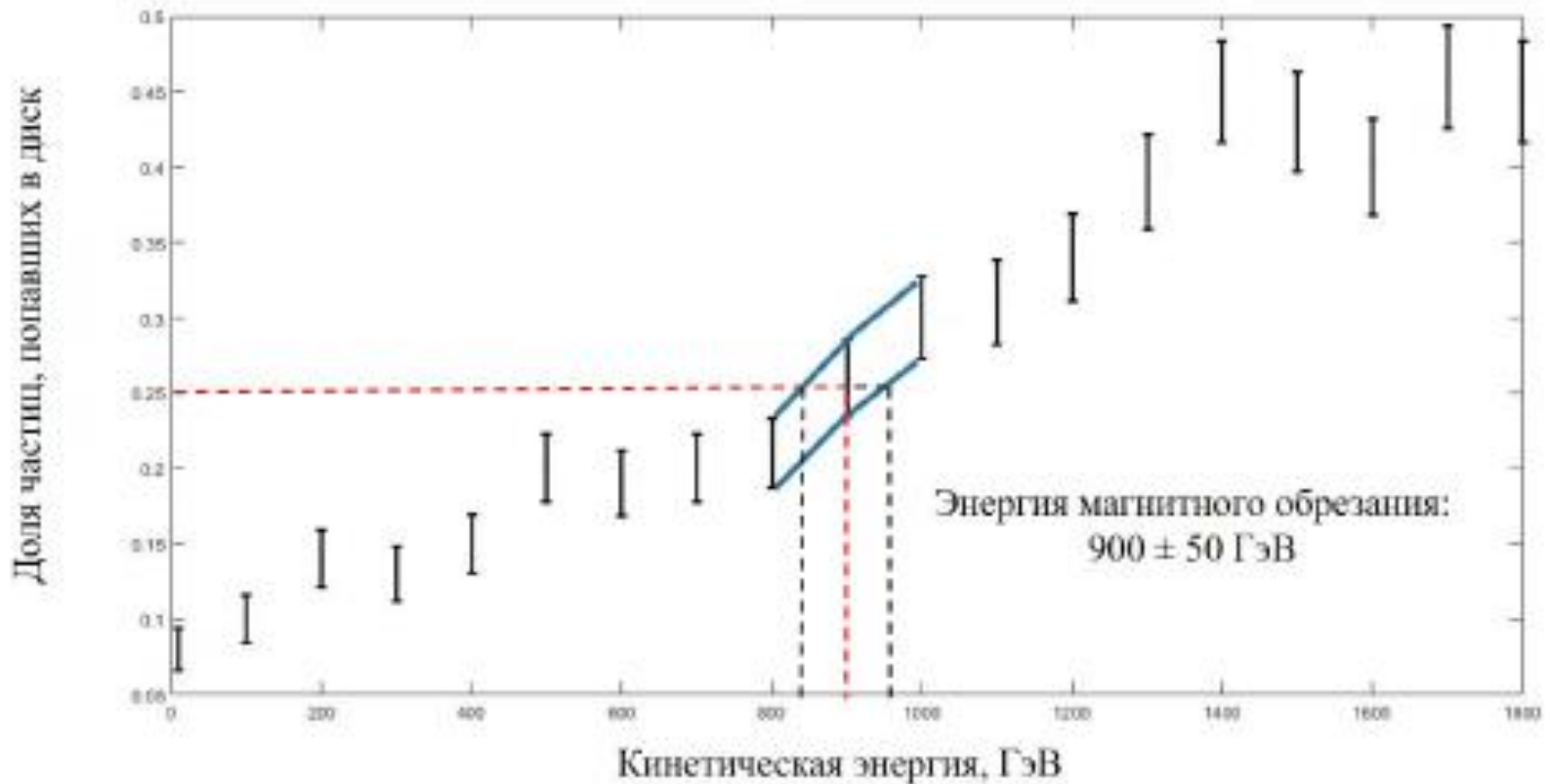
- **Nonhomogeneous baryosynthesis in extreme form leads to antimatter domains in baryon asymmetrical Universe**
- **To survive in the surrounding matter domain should be sufficiently large, and to have sufficiently high internal antibaryon density to form stars. It gives minimal estimation of possible 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 initially in PAMELA and then completely in AMS-02 experiment**

# Antimatter GC in galactic halo?



*See talk by A. Kravtsova*

# Effect of magnetic cut off



See talk by A. Kirichenko

# First signal from antimatter stars in AMS02?

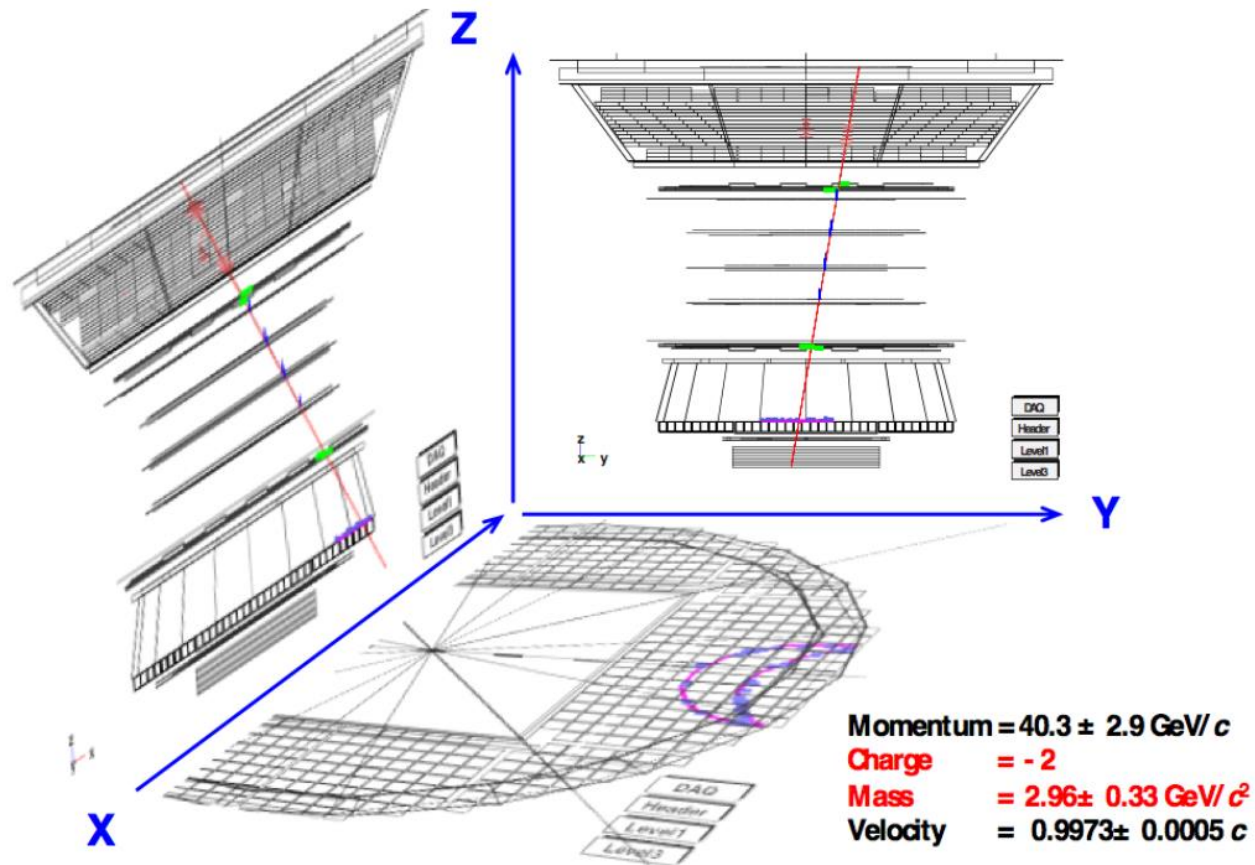


Figure 14. An antihelium candidate.

*Presented in CERN on 08.12.2016 by Prof. S.Ting*

# Latest Results from the AMS Experiment on the International Space Station

## ABSTRACT

In seven years on the Space Station, AMS has collected more than 115 billion charged cosmic rays with energies up to multi TeV. The measured positron spectra agrees well with dark matter models. The energy dependence of elementary particles (electrons, positrons, protons and antiprotons) as well as the rigidity dependence of primary cosmic rays and secondary cosmic rays are unique and distinct. These results require a new understanding of the cosmos.

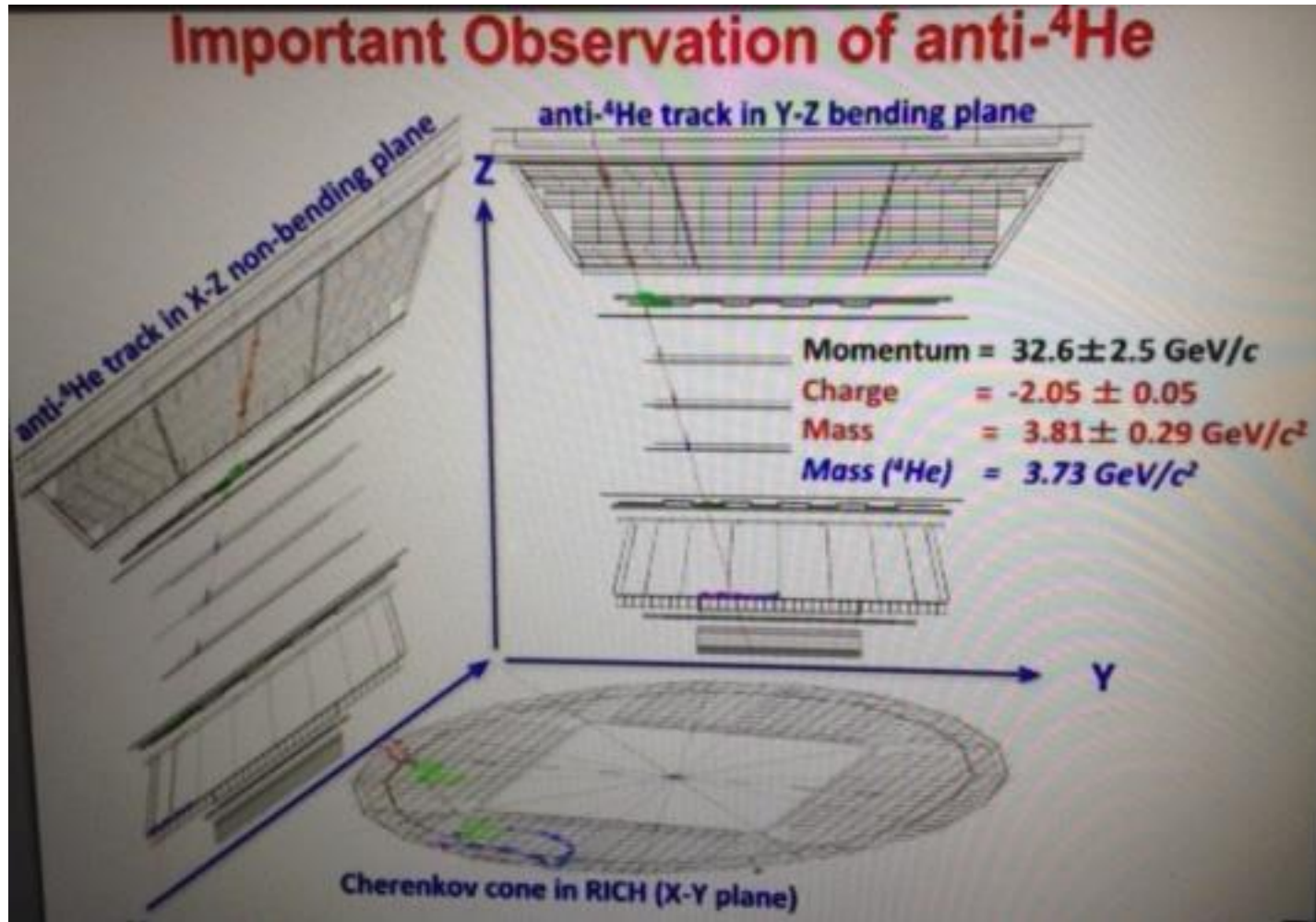
*Samuel Ting*  
*24 May 2018*



# Antihelium events

- 8 clear single track events with  $Z=-2$  within helium mass region
- Momentum resolution better than 10%

# Antihelium-4 candidates!



*Samuel Ting 24 May 2018*

## Puzzle of antiHe-3 and antiHe-4 ratio

Two anti-Helium-4 events are announced on 24.05.2018 with background probability 1/300.

Continuing to take the data through 2024 would reduce background probability, putting such candidate events above 5-sigma significance

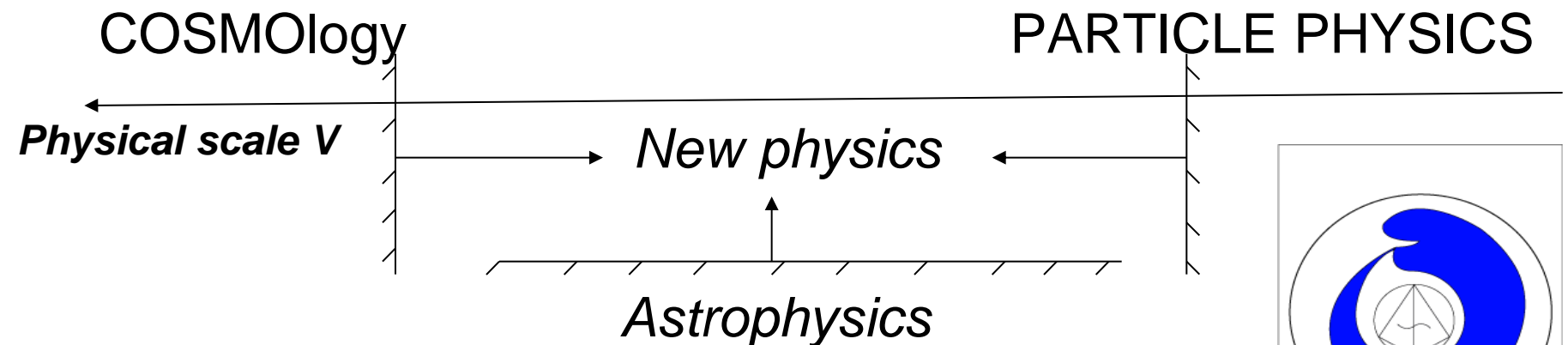
Though He3/He4 ratio is 0.1-0.2, the antiHe3/antiHe4 ratio looks now like 3. More data will resolve this puzzle

# 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.**
- **PBHs provide probes for physics of very early Universe**
- **Strong primordial nonlinear structures (massive PBH clouds, strong nonhomogeneities of baryonic matter and even antimatter stars) provide cosmological probes for physics of inflationary models with baryosynthesis and dark matter.**
- **These probes of new physics reflect the basic ideas of cosmoparticle physics**

# 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 Ouroboros vicious cycle of problems, which can be resolved by methods of Cosmoparticle physics*

