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## Peculiar footprints of BSM physics and Cosmology

**Talk at XXVIII Bled Workshop**
**"What comes beyond the Standard models?"**
**Bled, Slovenia 6-17 July 2025**

# Outlines

- BSM Physical basis of the now Standard cosmology
- Mesengers of BSM cosmology that follow from BSM physics. Cosmoarcheology of new physics. Detectors of the Universe.
- Time changing DM and DE in UDM models
- Dark atoms and nuclearites
- Primordial Black Holes (PBHs) and Strong Primordial nonhomogeneities as cosmological reflection of particle symmetry and mechanims of its breaking
- Antimatter as profound signature for nonhomogeneous baryosynthesis. Antimatter stars with zero metallicity
- Cosmoparticle physics of Dark Universe

# 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

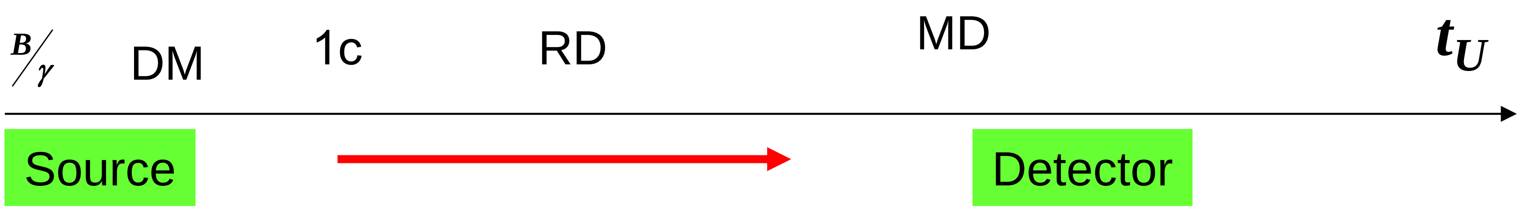
*All these phenomena imply extension of the Standard Model of Strong (QCD) and Electroweak Interactions. On the other hand, studies of physics Beyond the Standard Model involve Cosmology for their probe.*

COSMOPARTICLE PHYSICS studies the fundamental relationship of

COSMOlogy and PARTICLE PHYSICS

in the complex cross-disciplinary physical and astronomical research

**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 cosmophenomenology 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 astrophysical 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)**

# Detectors of the Universe

- Integral detectors (age of the Universe, primordial He, LSS, PBH) are sensitive to the contribution of a new form of matter (or products of its decay) to the total cosmological density.
- Differential detectors are sensitive to presence of decay products of definite type ( $\bar{p}, \gamma, \nu ...$ ).

# Weak and strong non-equilibrium sources

- If energy density of non-equilibrium particles is of the order or larger than the energy density of equilibrium radiation the source is strong.
- If their energy density is much smaller, than the total (equilibrium) energy density the source is weak.

# Kinetics of non-equilibrium processes

- System of kinetic equations of non-equilibrium processes is given by

$$\frac{\partial F_i}{\partial t} + 2HF_i - Hp_i \frac{\partial F_i}{\partial p_i} = I^+ - I^- + Q_i$$

Here $H(t)$ is Hubble constant in the period $t$, $Q(p,t,\tau)$ – the distribution function of source, characterized by the time scale $\tau$, $I$ – collision terms and $F$ - distribution functions.

# Distribution function for weak sources

- The condition of weak source is given by

$$\sum_i \int \varepsilon_i Q_i\left(p_i, t, \tau\right) dp_i \Delta t \ll \varepsilon_\gamma;$$

- The distribution function $F_i = f_i + \varphi_i$ takes into account both thermal equilibrium $f_i$ and non-equilibrium $\varphi_i$ components for particles of type *i*.

# Kinetic equation for weak sources

- For non-equilibrium particles of *i*-th type the equation runs

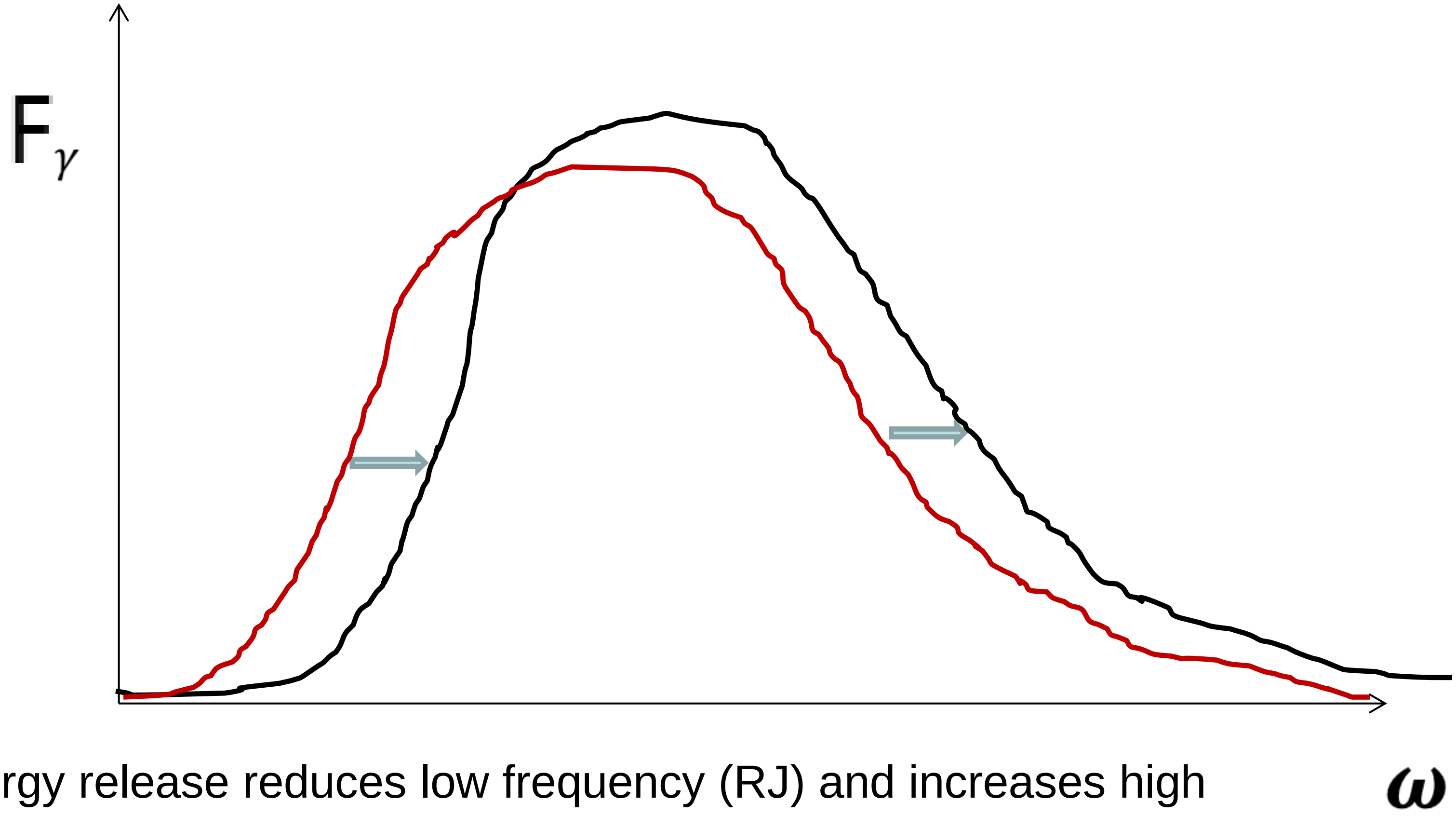
$$\frac{\partial \varphi_i}{\partial t} = \sum_{j,k} \varphi_j F_k \frac{d\left(\sigma v\right)^{i}_{jk}}{dp_i} dp_j dp_k + \sum_j \varphi_j \frac{d\Gamma_j}{dp_i} -$$

$$-\varphi_i \left( \Gamma_i + \sum_j \left( n_j \left(\sigma v\right)^{ij} \left(p_i\right) + \int \varphi_j \left(\sigma v\right)^{ij} dp_j \right) \right) + Q_i \left(p_i, t, \tau\right)$$

# CMB spectrum as electromagnetic calorimeter

- If electromagnetic energy release takes place at $z > 10^8 \Omega_b^{1/2}$ , Planck form of spectrum is restored due to $\gamma e \rightarrow 2\gamma e$ or $\gamma Z \rightarrow 2\gamma Z$ processes.
- When the rate of expansion exceeds the rate of these processes black body spectrum is distorted. The distortion is proportional to the energy release relative to the total energy density of the thermal background radiation.

# Effect of energy release in CMB spectrum




The energy release reduces low frequency (RJ) and increases high frequency (W) parts of spectrum

# Bose-Einstein distortion

- Early energy release at $4 \cdot 10^4 \Omega_b^{1/2} < z < 10^8 \Omega_b^{1/2}$

leads to equilibrium distribution at fixed number of photons – i.e. to the Bose-Einstein distribution with photon chemical potential proportional to energy release:

$$F_{em}(\nu) = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left\{\frac{h\nu + \mu k T_e}{k T_e}\right\} - 1}$$

Measurements of SMB spectrum provide the constraint

$$\frac{\delta\varepsilon}{\varepsilon_\gamma} < \frac{1}{3}|\mu| < 1.1 \cdot 10^{-4}$$

# y-distortions of CMB spectrum

- Late energy release at

$$z < 4 \cdot 10^4 \,\Omega_b^{1/2}$$

cannot support equilibrium Bose – Einstein distribution and spectral *y* distortions are determined by kinetics of heating of photon gas by hot electrons. COBE data give

$$\frac{\delta\varepsilon}{\varepsilon_\gamma} < 12\left|y\right| < 3 \cdot 10^{-4}$$

# High energy neutrino background from decays of superheavy particles

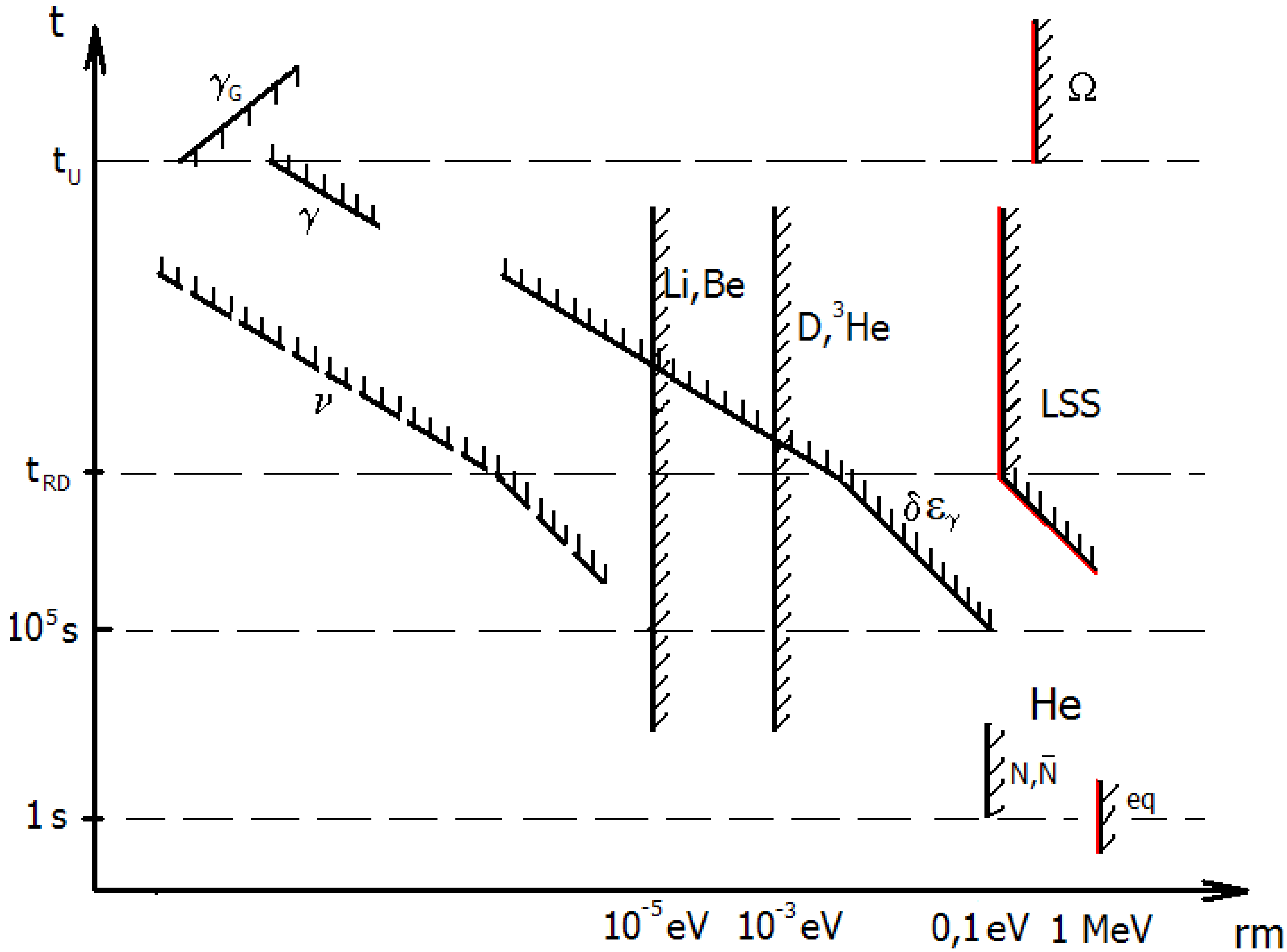
- If superheavy particles of mass *M* decay in early Universe after 1 s, high energy neutrinos – their decay products and high energy neutrinos from interaction of decay products quarks and leptons with thermal neutrino background form high energy neutrino background.
- Interaction of high energy neutrinos with thermal neutrino background and their redshift put upper limit on the maximal energy of these high energy neutrinos in the modern Universe:

$$E_{\max}^{\text{mod}} = 2 \cdot 10^{-10}\ \text{GeV} \left( \frac{\tau}{1\text{s}} \right)^{3/2}$$

For $\tau > 10^5\ s$

such neutrinos can be detected in neutrino observatories.

# Laboratory of the Universe




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

# Unstable dark matter (UDM)

*A. G. Doroshkevich and M. Yu. Khlopov*

*Mon. Not. R. astr. Soc.* (1984) **211,** 277–282

**Formation of structure in a universe with unstable neutrinos**

*A. G. Doroshkevich, A. A. Klypin and M. U. Khlopov*

*Mon. Not. R. astr. Soc.* (1989) **239,** 923–938

**Large-scale structure of the Universe in unstable dark matter models**

# UDM+Lambda

$$\Omega_{\mathrm{d}} + \Omega_{\mathrm{R}} + \Omega_{\mathrm{hot}} + \Omega_{\mathrm{cold}} + \Omega_{\Lambda} = 1$$

$$\left(\text{at } t \ll \tau\ \Omega_{\mathrm{d}} = 1 - \Omega_{\mathrm{st}} \text{ and } \Omega_{\mathrm{cold}} = \Omega_{\mathrm{st}}\right).$$

$$1 + z_{\mathrm{max}} = (3\Omega_{\Lambda}/\Omega_{R})^{0.25}, \qquad \Omega_{\mathrm{max}}^{-1} - 1 = 4(\Omega_{\Lambda}/\Omega_{\mathrm{cold}})\,(\Omega_{\mathrm{R}}/3\Omega_{\Lambda})^{0.75}$$

$$\Omega_{\Lambda\,\mathrm{max}} = 0.25(1 - \Omega_{\mathrm{max}}), \qquad \Omega_{\mathrm{R}} = 1 - \Omega_{\mathrm{cold}} - \Omega_{\Lambda}.$$

# UDM versus LCDM

- **UDM:**
- H<50, age of Universe does not need Lamda
- LSS evolution slows down **absolutely** due to decrease of density in it
- Homogeneously distributed dark matter – products of decay of unstable dark matter
- SN data are interpreted in terms of non-accelerated expansion

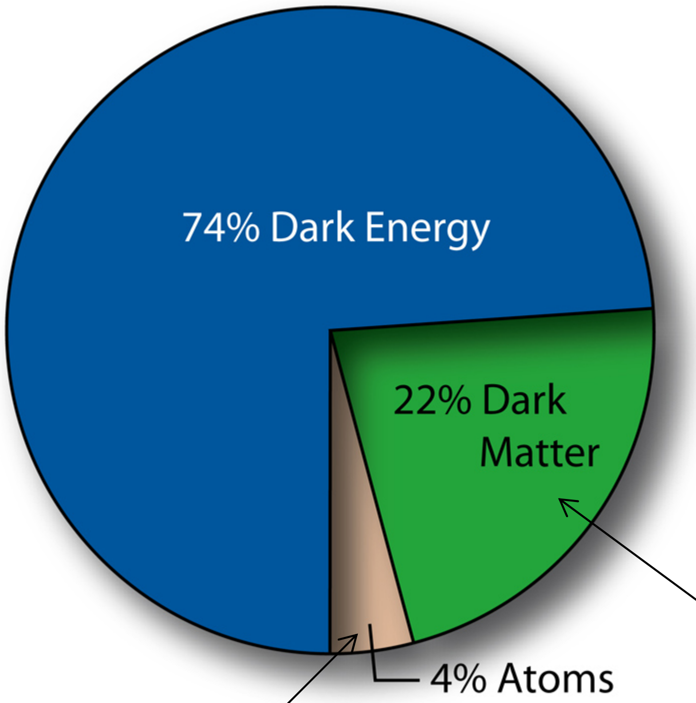
- **LCDM:**
- H>50, age of Universe needs Lamda
- LSS evolution slows down **relative** to accelerated expansion
- Homogeneous dark energy is provided by Lambda-term, quintessence…
- SN data are interpreted in terms of accelerated expansion

# UDM+Lambda

- In the light of the current data UDM cannot be alternative for LambdaCDM
- Neutrino oscillations exclude the masses for UDM scenario for known neutrinos.
- However, for sterile neutrinos such a scenario is possible.
- Effect of UDM leads to time variation of the equation state for unclustered energy density and deserves interest for our analysis of the observational data.

# THE PUZZLES
# OF DARK MATTER SEARCH

# Composition of the Universe




*Baryonic matter consists of atoms*

*Can dark Matter consist of Dark atoms?*

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

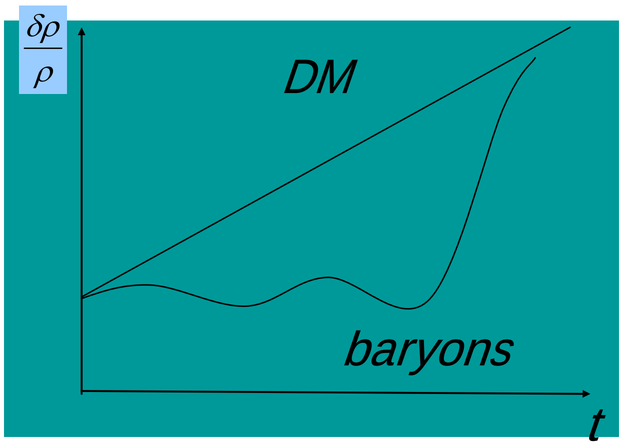
$$\Omega_{\mathrm{b}} \approx 0.044 \qquad \Omega_{\mathrm{CMB}} \approx 0.5 \cdot 10^{-4}$$

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

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

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

# 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.

# Dark matter and the mass of neutrino

**Astrophysical implications of the neutrino rest mass. III. Nonlinear growth of perturbations and the missing mass**

A. G. Doroshkevich, Ya. B. Zel'dovich, R. A. Syunyaev, and M. Yu. Khlopov

*Keldysh Institute of Applied Mathematics, USSR Academy of Sciences, Moscow, and Institute for Space Research, USSR Academy of Sciences, Moscow*

(Submitted May 28, 1980)

Pis'ma Astron. Zh. **6**, 465–469 (August 1980)

A discussion is given of the influence that a finite rest mass for the neutrino would have on the phenomenon of "missing mass" in galaxies and clusters of galaxies, on the nonlinear stage in the evolution of primordial irregularities, and on the problem of observing neutral hydrogen in the spectrum of distant quasars.

In 1980 the experimental claims on the existence of the mass of electron neutrino about 30 eV lead to immediate cosmological consequence of the neutrino dominated Universe, In which massive neutrinos play the role of dark matter.

# 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)

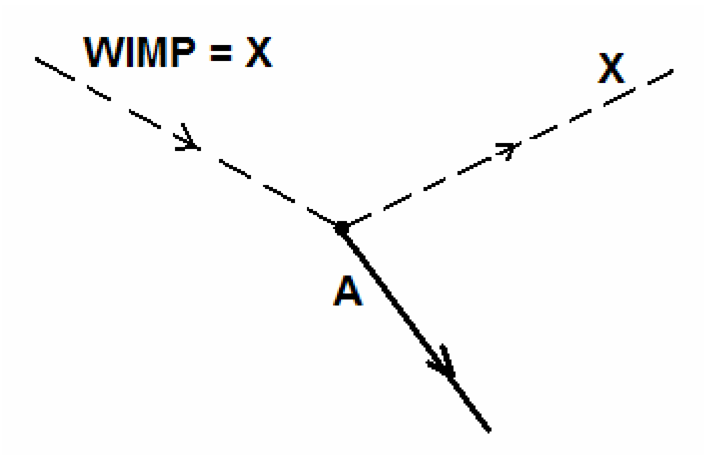
The coherent intensification of the interaction of relict massive neutrinos with grains of matter with a size on the order of the neutrino wavelength suggests that it might be possible to detect a galactic neutrino sea by virtue of the mechanical pressure which it exerts in the direction opposite that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

# “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

# WIMP-nucleus interaction

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




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

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

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

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

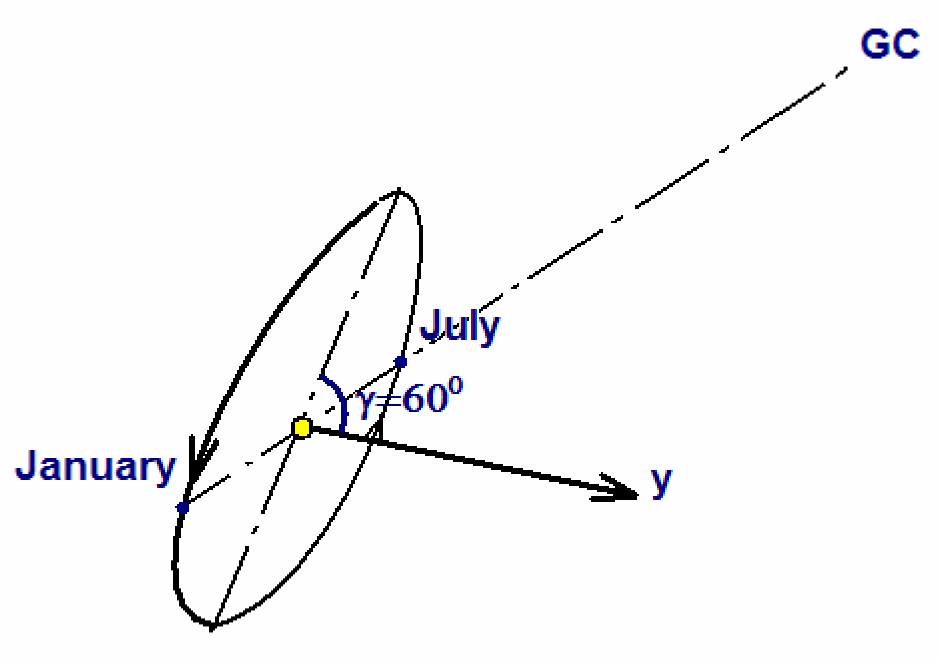
$$Interaction\ amplitude \equiv A_{AX} = A_{AX}^{\text{point}} \cdot F_A(q^2)$$

# Annual modulation of WIMP effects

## Minimization of background

- Installation deeply underground
- Radioactively pure materials
- Annual modulation

DM does not participate in rotation around GC.




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

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

$$t_0 = 2\,\mathrm{June}$$

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

See talk by R. Bernabei

# 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 supergavity
- KK-particles: $B_{KK1}$
- Anomalous hadrons, O-helium ⟵ **_SIMP_** _**(strongly interacting massive particles)**_
- Supermassive particles…
- Mirror and shadow particles,
- PBHs…

# DARK MATTER FROM CHARGED PARTICLES?

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

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

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

# Dark Matter from Charged Particles?

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

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

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

# « No go theorem » for -1 charge components

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

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

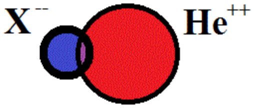
If we have a stable double charged particle $X^{--}$ *in excess over its partner* $X^{++}$ *it may create* *Helium like neutral atom (O-helium) at temperature* $\boldsymbol{T > I_o}$

*Where:*

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

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

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




*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

# 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.

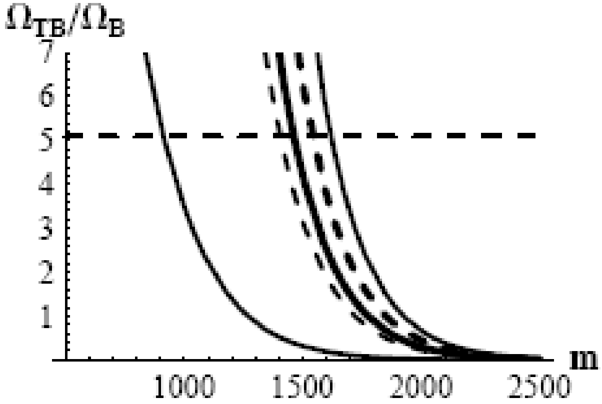
$$\frac{TB}{B} = -\sigma_{UU}\left(\frac{L'}{B}\frac{1}{3\sigma_\zeta} + 1 + \frac{L}{3B}\right)$$

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)*

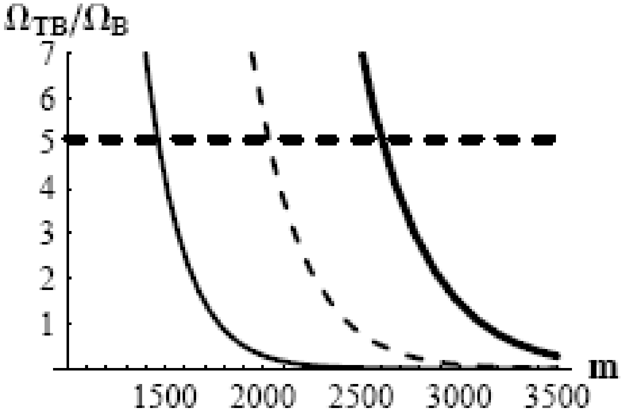
# Relationship between TB and B

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




- L'=0, T*=150 GeV

$\xi$ =0.1; 1; 4/3; 2; 3

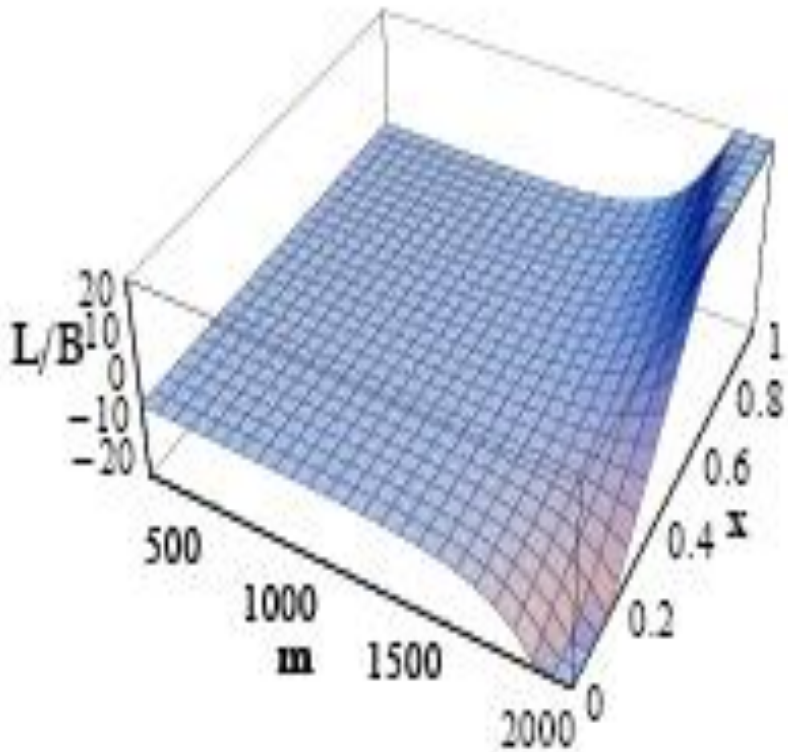



$\xi = 4/3$,

- 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.

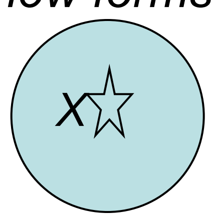
*The case TB>0, L’>0 (TB<0, L’<0 ) gives an interesting possibility of (-2 +2) atom-like WIMPs, similar to AC model. For TB>L’ (TB<L’) no problem of free +2 charges*

# Stable multiple charged particles

*WTC can lead to techniparticles with multiple charge*

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

*-2n charged particles in WTC bound with n nuclei of primoridal He form Thomson atoms of XHe. They represent new forms of neutral superheavy nuclear matter.*




*nHe*

# O-HELIUM DARK MATTER

# O-helium dark matter

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

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

$$T_{RM} = 1eV$$

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

- 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, $\sigma v$ is the rate of nuclear collisions and $g = 980\ \mathrm{cm/s^2}$.

# O-helium experimental search?

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

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

# O-HELIUM DARK MATTER IN UNDERGROUND DETECTORS

# O-helium concentration in Earth

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

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

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

where ***V**_h* is velocity of Solar System relative to DM halo (220 km/s), ***V**_E* is velocity of orbital motion of Earth (29.5 km/s) and

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

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

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

See talk by A.Kharakhashyan

# Annual modulation of O-helium concentration in Earth

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

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

where $\omega = 2\pi/T$, *T*=1*yr* and ***t**$_o$* is the phase. The averaged concentration is given by

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

and the annual modulation of OHe concentration is characterized by

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

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

# OHe solution for puzzles of direct DM search

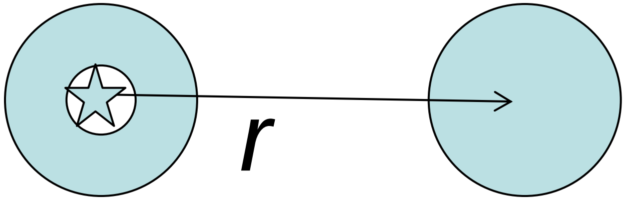
- OHe equilibrium concentration in the matter of DAMA detector is maintained for less than an hour
- Annual modulations in inelastic processes, induced by OHe in matter. No signal of WIMP-like recoil
- The process

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

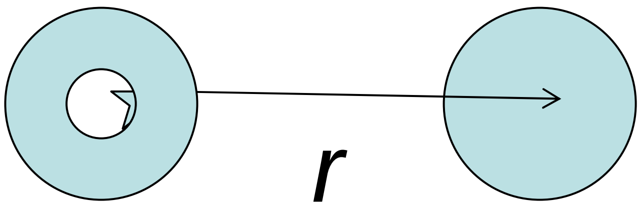
is possible, in which only a few keV energy is released. Other inelastic processes are suppressed

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

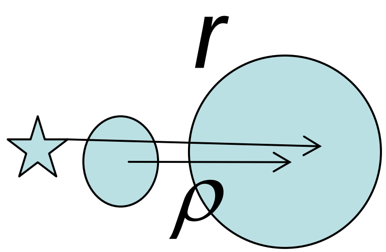
# Potential of OHe-nucleus interaction



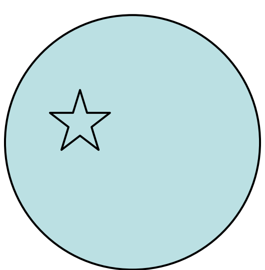

$$U_{Xnuc} = -2Z\alpha\left(\frac{1}{r} + \frac{1}{r_o}\right)\exp\left(-2r/r_o\right)$$




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

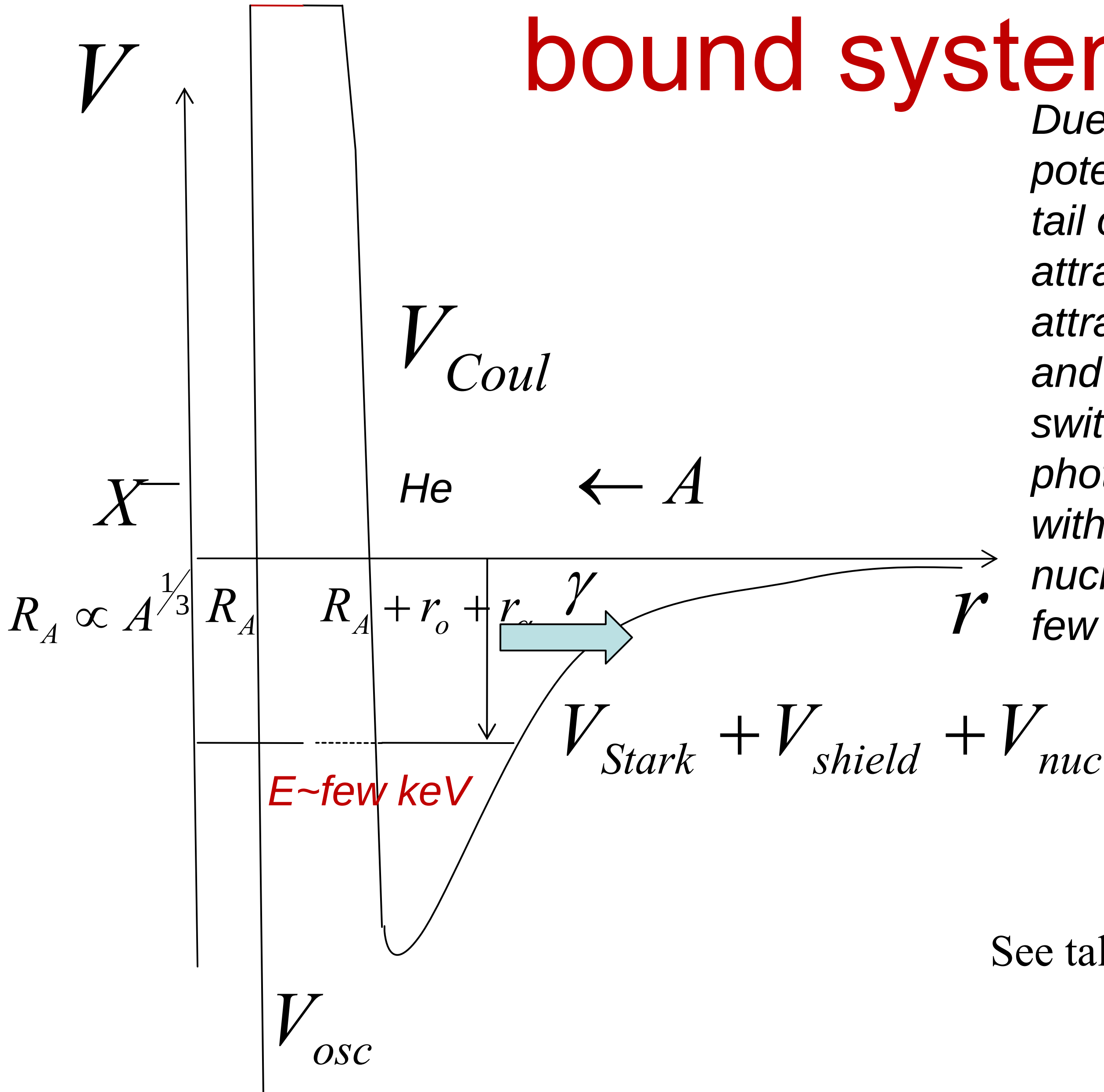



$$U_{Coul} = +\frac{2\alpha Z}{\rho} - \frac{2\alpha Z}{r}$$



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

# Formation of OHe-nucleus bound system




*Due to shielded Coulomb potential of X, Stark effect and tail of nuclear Yukawa force OHe attracts the nucleus. Nuclear 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.*

See talks by T.Bikbaev, J.Mwilima

# Few keV Level in OHe-nucleus system

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

# Rate of OHe-nucleus radiative capture

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

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

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

# Reproduction of DAMA/NaI and DAMA/LIBRA events

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

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

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

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

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

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

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

$$E_{Na} = 3keV$$

P. Belli et al. Phenomenology on Dark atom model. To be published

# Problems of multiple He and p capture in early Universe

See talks by D.Sopin and M.Baligno

# Problems of release of multiple charged components in SN and forms , in which they are accelerated

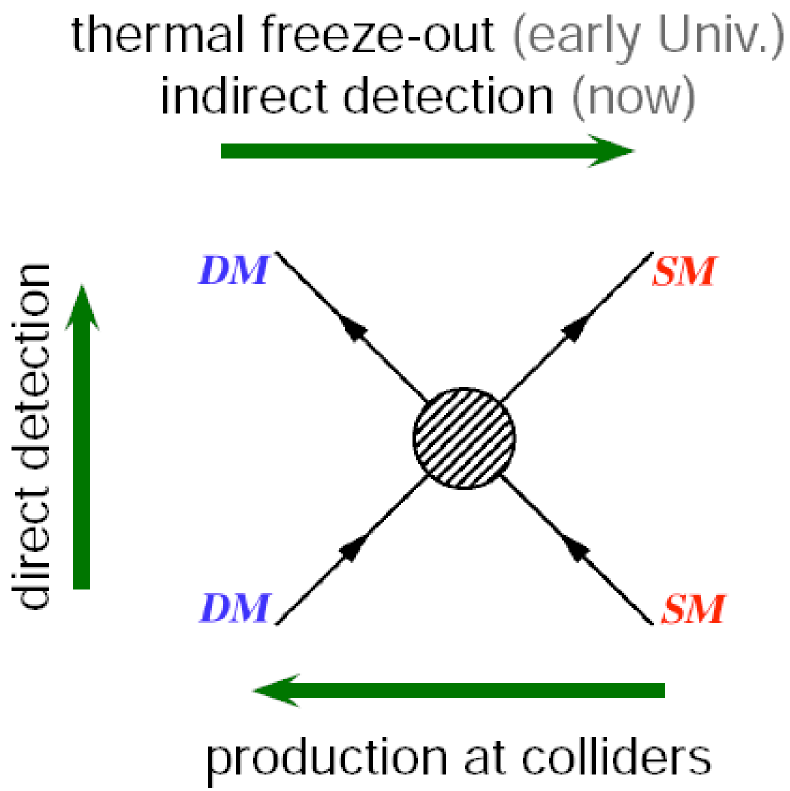
See talk by L.Basov

# Problem of Bose-Einstein nature of He in dark atoms

See talk by A.Haque

# DARK ATOM 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. The latter explanation implies a very narrow range of masses of (meta-) stable double charged particles in vicinity of 1 TeV, what is the challenge for their search at the experiments at the LHC.

# Search for multi-charge particles in the ATLAS experiment

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

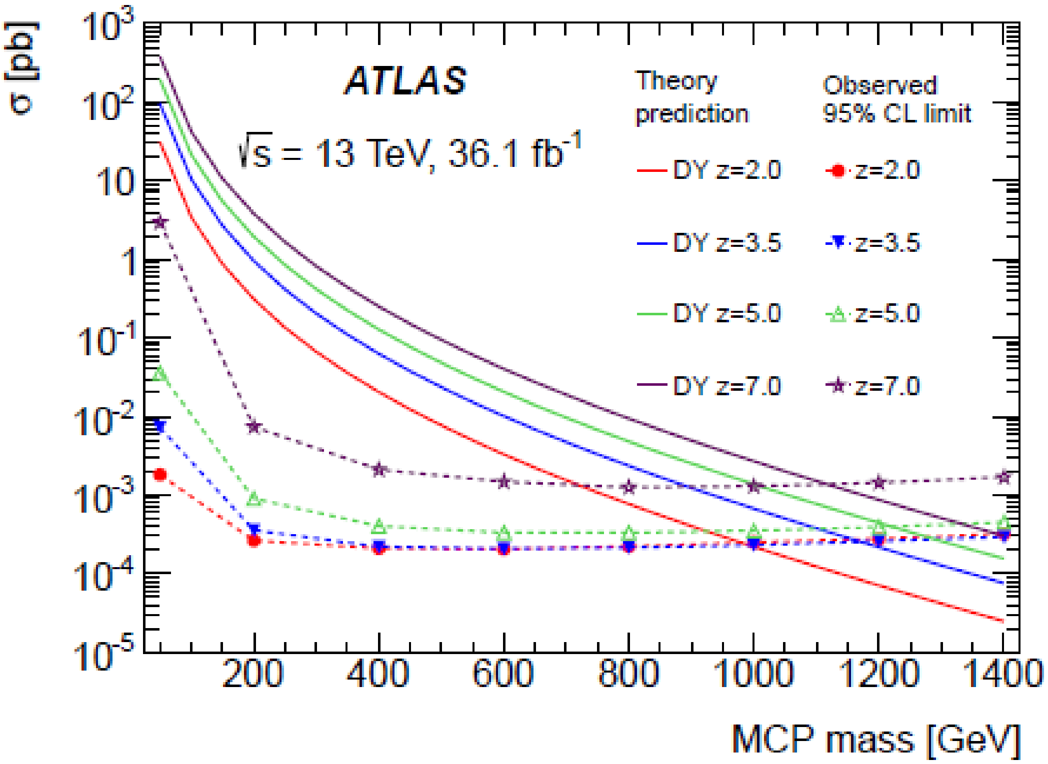
**Search for Multi-charge Objects in *pp* collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector**

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

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

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

# Searches for multiple charged particles in ATLAS experiment




*M>980 GeV*
*for |q|=2e*
*at 95% c.l.*

*[ATLAS Collaboration, Search for heavy long-lived multi-charged particles in proton-proton collisions at √ s= 13 TeV using the ATLAS detector. Phys. Rev. D 99, 052003 (2019)*

The dark atom model can be probed due to upper limit on the mass of multiple charged constiuents (D.Sopin)

# 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.

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

- 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

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

# PBHs as indicator of early dust-like stages

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

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

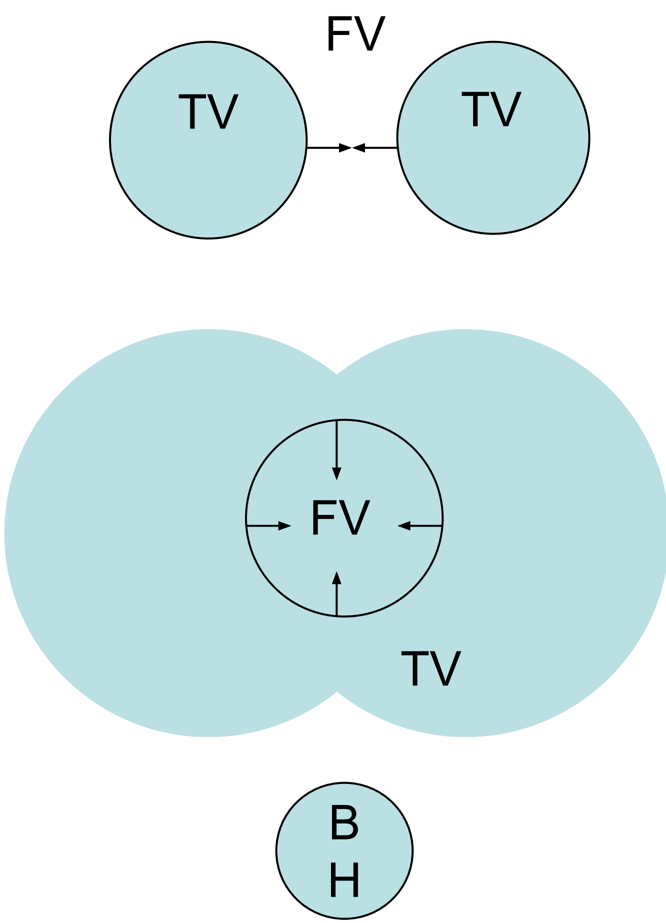
- At *k=0* on dust-like stage exponential suppression is absent. The minimal estimation is determined by direct production of BHs

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

# Dominance of superheavy particles

- Superheavy particles with mass *m* and relative concentration $r = n/n_{\gamma}$ 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 »).

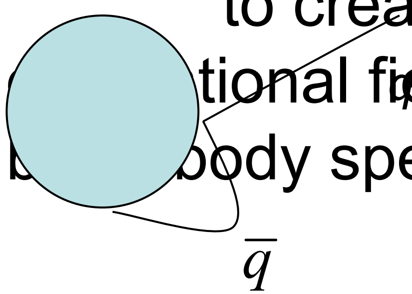
# PBHs as indicator of first order phase transitions




- 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 g… tional field. Products of evaporation have b… body spectrum with




$$T_{PBH} \propto 1/r_g \qquad T_{PBH} \approx 10^{13}\, GeV \left(\frac{1g}{M}\right)$$

- The rate of evaporation is given by

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

- The evaporation timescale is

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

Any particle with $m \le T_{PBH}$ 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 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.

# PRIMORDIAL NONLINEAR STRUCTURES

# Cosmological Reflections of Microworld Structure

- **Dark Matter should be present in the modern Universe, and thus be 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. 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…).**

# 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

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

After spontaneous symmetry breaking infinitely degenerated vacuum

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

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

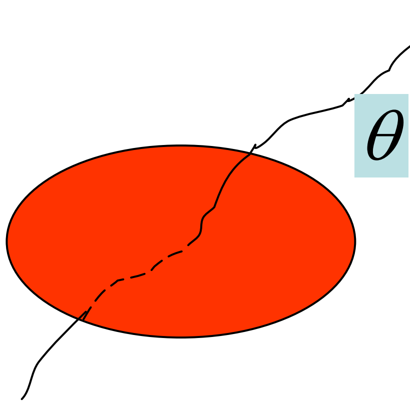
## Some astrophysical limitations on the axion mass

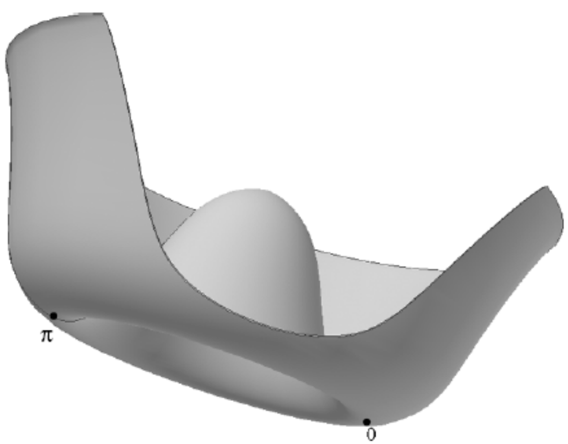
M. I. Vysotsskii, Ya. B. Zel'dovich, M. Yu. Khlopov, and
V. M. Chechetkin

*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.

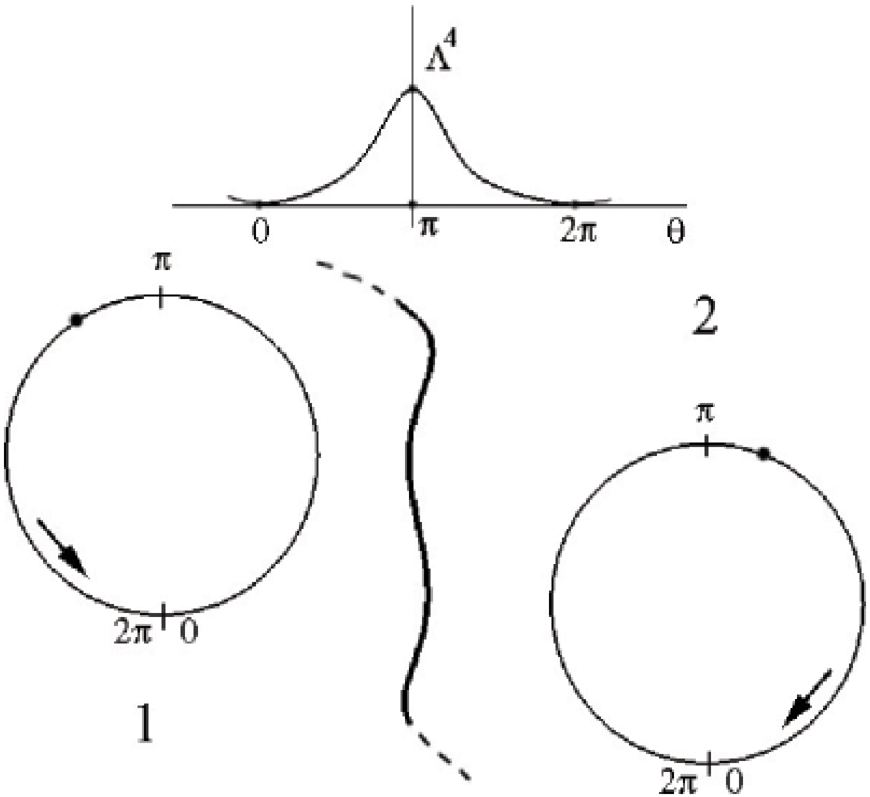
# Unstable topological defects

- 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 $\varphi$ 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.

# Closed walls formation in Inflationary Universe



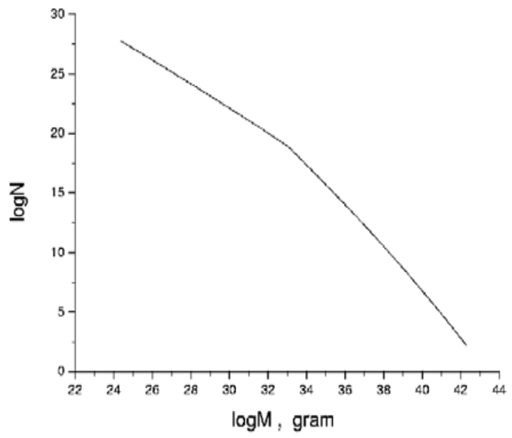

If the first U(1) phase transition takes place on inflationary stage, the value of phase $\theta$ , corresponding to e-folding N~60, fluctuates

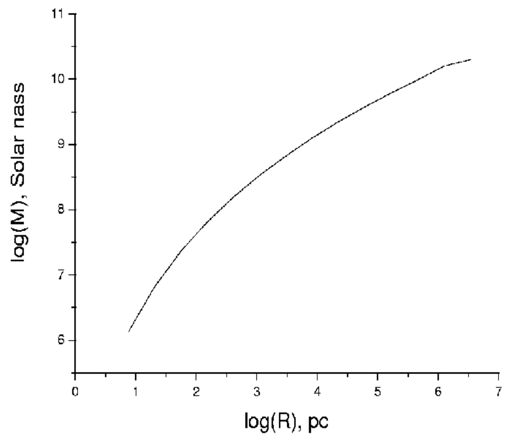
$$\Delta\theta \approx H_{\text{infl}} / (2\pi f)$$

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

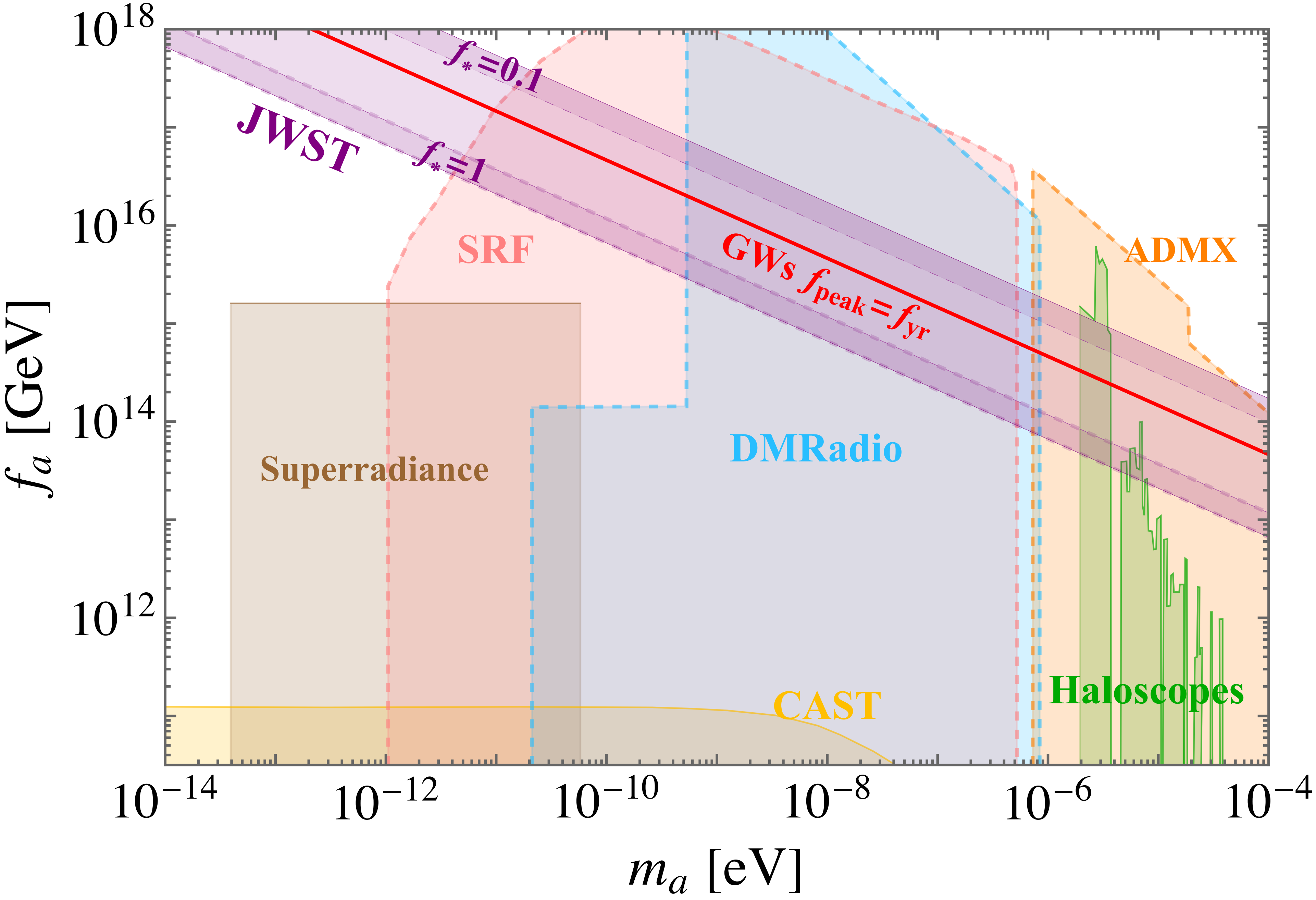
- Closed wa s to primordial GW spectrum, peaked at $\nu_0 = 3\cdot 10^{11}\left(\Lambda/f\right)Hz$ with energy density up to

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

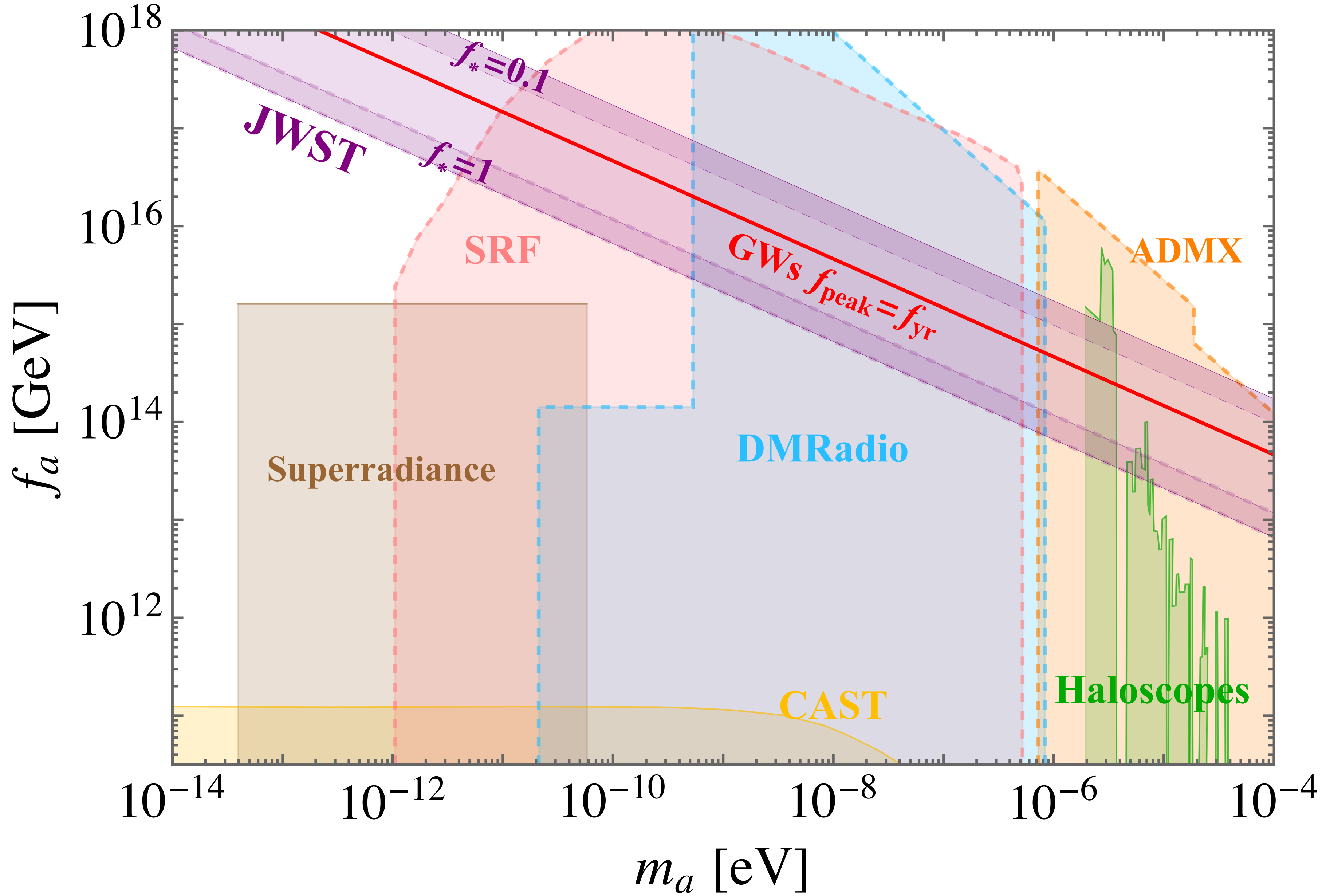
- At $f \sim 10^{14}\,GeV$ $\Omega_{GW} \sim 10^{-9}$
- For $1 < \Lambda < 10^{8}\,GeV$ $3\cdot 10^{-3}\,Hz < \nu_0 < 3\cdot 10^{5}\,Hz$

- Merging of BHs in BH cluster leads to signals accesible to LISA test.

# Joint constraints from JWST and ALP searching

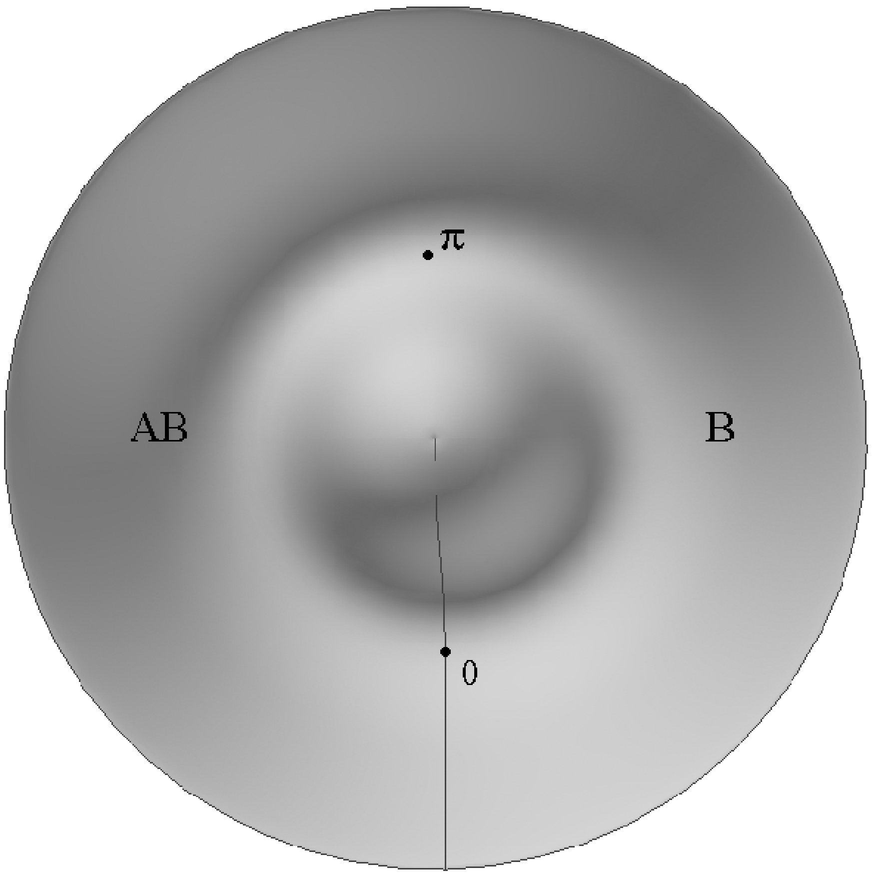


# Joint constraints from JWST and ALP searching




- The $(f_a, m_a)$, which provide suitable GWs peak frequency, lie in the allowed parameter region to give out the JWST observations. And could be probed by the future axion experiments.

# 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

See talk by M.Krasnov

# 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.

See talk by Anna Dembitskaya

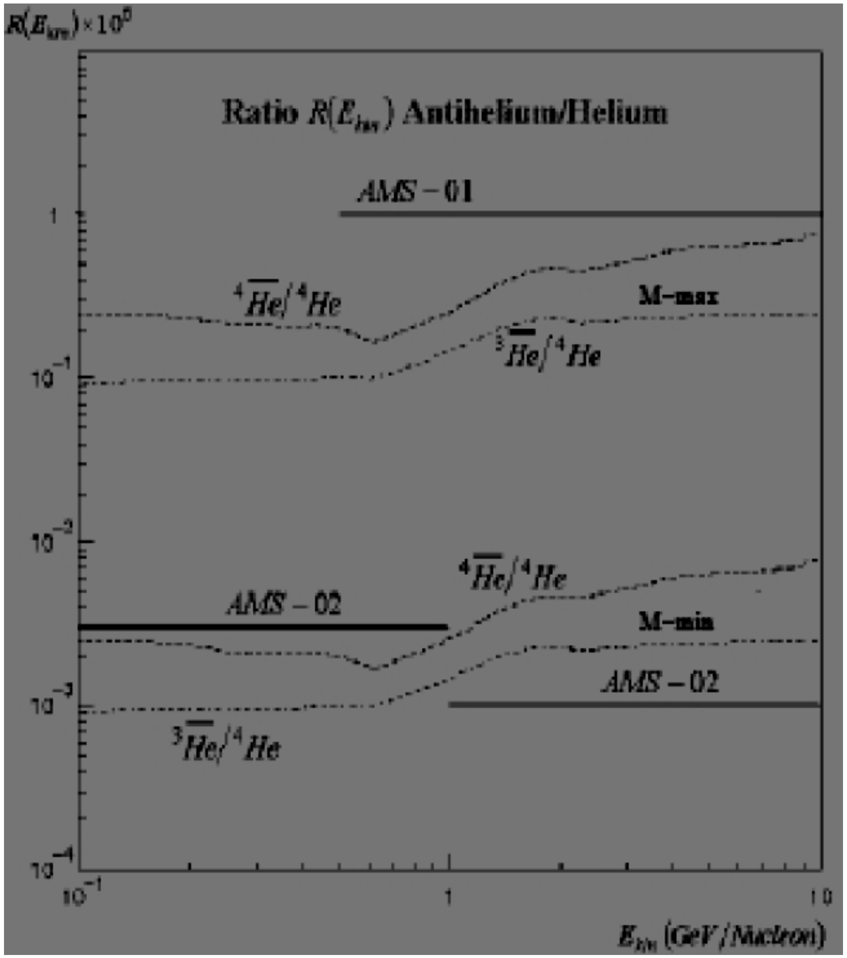
# Antimatter in galaxies

| 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

# Future confirmation of cosmic antiHe-4?

AMS02 has an unprecedented sensitivity to antinuclear component of cosmic rays.
It puts on the collaboration high responsibility for quality its published results.
The experiment is continued until 2028 to increase the statistics, reject all the possible backgrounds and publish highly reliable data on the existence of antiHe-4 component of cosmic rays, shedding light on the form of antimatter celestial objects in our Galaxy.

# Conclusions

Modern Standard cosmology corresponds to Dark Universe from the beginning to the present time. It is based on BSM physics, which can be studied by methods of Cosmoparticle physics.
There should be no surprize that BSM features start to appear in the data of DM direct searches, PTA, JWST, DESI and AMS02, revealing nontrivial forms and structures of BSM physics.
We are coming to the era of great cosmological discoveries, which will be subject of our future discussions at Bled meetings.
These discoveries involve very nontrivial tasks in studying new forms of matter and corresponding cosmologiocal scenarios

# Basic ideas of cosmoparticle physics in studies of New Physics, underlying Modern Cosmology

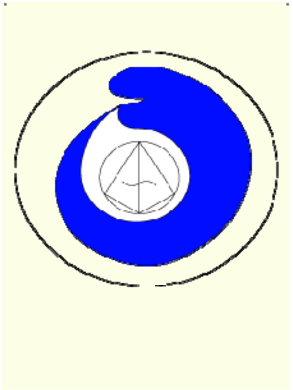
- Physics beyond the Standard model can be studied in combination of indirect physical, astrophysical and cosmological effects
- New symmetries imply new conserved charges. Strictly conserved charge implies stability of the lightest particle, possessing it.
- New **stable particles** should be present 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
- Combination of physical, cosmological and astrophysical effects provide an over-determined system of equations for parameters of particle theory

COSMOlogy PARTICLE PHYSICS

*Physical scale*

*New physics*

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



# International Virtual Institute of Astroparticle Physics (CosmoVIA)

A possible regular interactive form of collaboration in cross-disciplinary study of fundamental relationship between micro- and macro-worlds

# Possible submissions

MDPI Symmetry special issue

**Cosmoparticle Physics—Dedicated to Ya. B. Zeldovich's 110 Anniversary**

https://www.mdpi.com/journal/symmetry/special_issues/Q66F59L1NS

MDPI Physics special issue

**Beyond the Standard Models of Physics and Cosmology: 2nd Edition**

https://www.mdpi.com/journal/physics/special_issues/7041MZC873

MDPI Encyclopedia special collection

**Cosmology and particle physics**

https://www.mdpi.com/journal/encyclopedia/topical_collections/6C0EJH7RSD

You are invited to contribute these issues

Please send me proposals of your submissions

khlopov@apc.univ-paris7.fr