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Cosmoparticle physics of dark matter

Talk at

The XXIV International Workshop

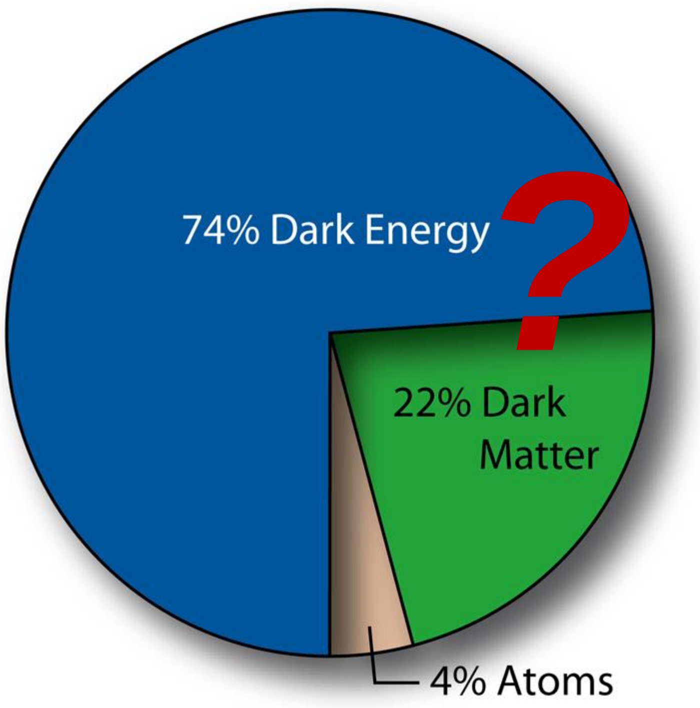
High Energy Physics and Quantum Field Theory

Sochi, Russia 27 September 2019

Outlines

- New symmetries of BSM Physics and DM candidates
- Axion-Like Particle physics and Primordial nonlinear structures
- Dark matter from Charged particles?
- Cosmoparticle physics of Dark atom solutions for puzzles of direct and indirect dark matter searches

Composition of the Modern Unverse



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

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

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

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

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

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

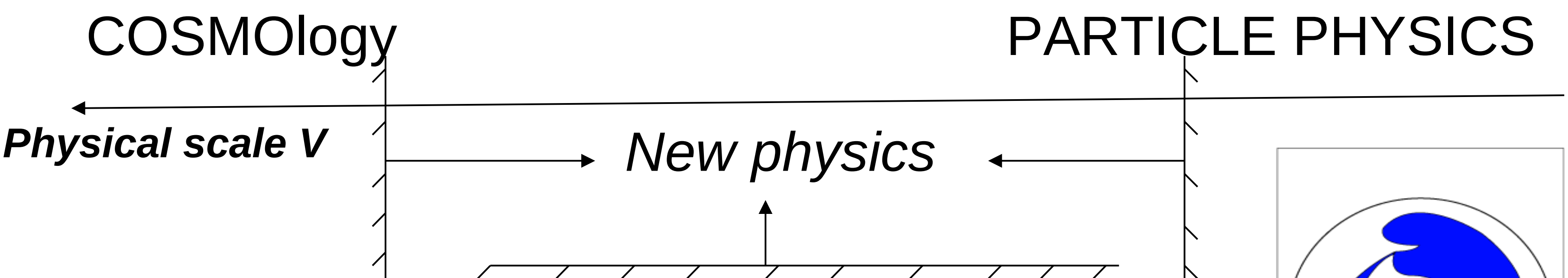
Our current understanding of structure and evolution of the Universe implies three necessary elements of Big Bang cosmology that can not find physical grounds in the standard model of electroweak and strong interactions. They are:

- Inflation
- Baryosynthesis
- Dark matter/energy

Physics beyond the Standard model, describing these phenomena inevitably predicts additional model dependent effects.

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**

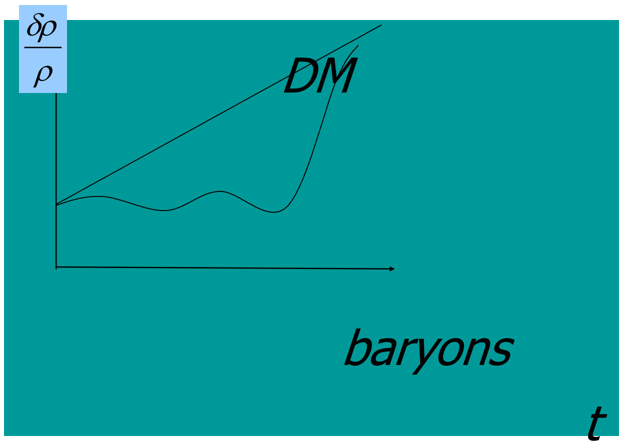


Extremes of physical knowledge converge in the mystical Ouroboros vicious cycle of problems, which can be resolved by methods of Cosmoparticle physics

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



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

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.

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 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.

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 characterstic scale

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

- At m>> 1 GeV this scale corresponds to Cold Dark Matter (CDM) scenario
- Supersymmetric (SUSY) models naturally predict several candidates for such Weakly Interacting Massive Particles (WIMP)
- SUSY WIMP candidates were linked to a set of supesymmetric partners of the known particles to be discovered at the LHC.

“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 supergavity
- KK-particles: B_{KK1}
- Anomalous hadrons, O-helium ← ***SIMP*** ***(strongly interacting massive particles)***
- Supermassive particles…
- Mirror and shadow particles,
- PBHs…

PRIMORDIAL STRUCTURES IN AXION-LIKE MODELS

U(1) model

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

After spontaneous symmetry breaking infinitely degenerated vacuum

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

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

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

to vacuum states

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

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

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

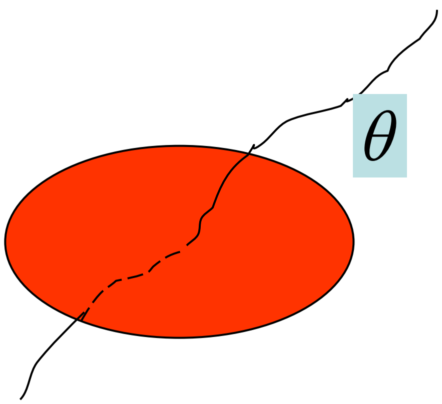
$$V(\varphi,\psi=0)=-\frac{m^2}{2}\varphi^2+\frac{\lambda}{4}\varphi^4 \Rightarrow V(\varphi,\psi)=\left(\varepsilon\psi^2-\frac{m^2}{2}\right)\varphi^2+\frac{\lambda}{4}\varphi^4$$

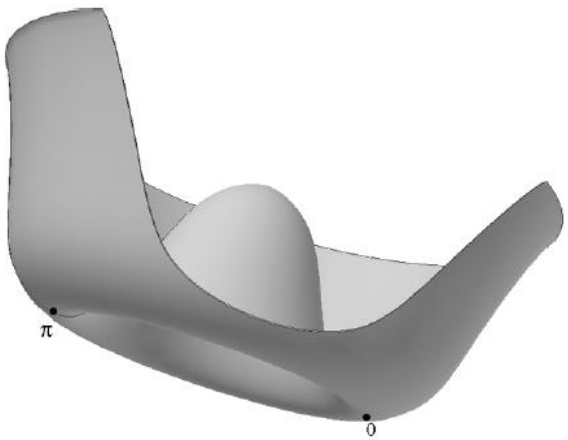
- When inflaton field rolls down below

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

transition to phase with broken symmetry takes place.

Topological defects





- Spontaneous breaking of U(1) symmetry results in the continuous degeneracy of vacua. In the early Universe after reheating 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.

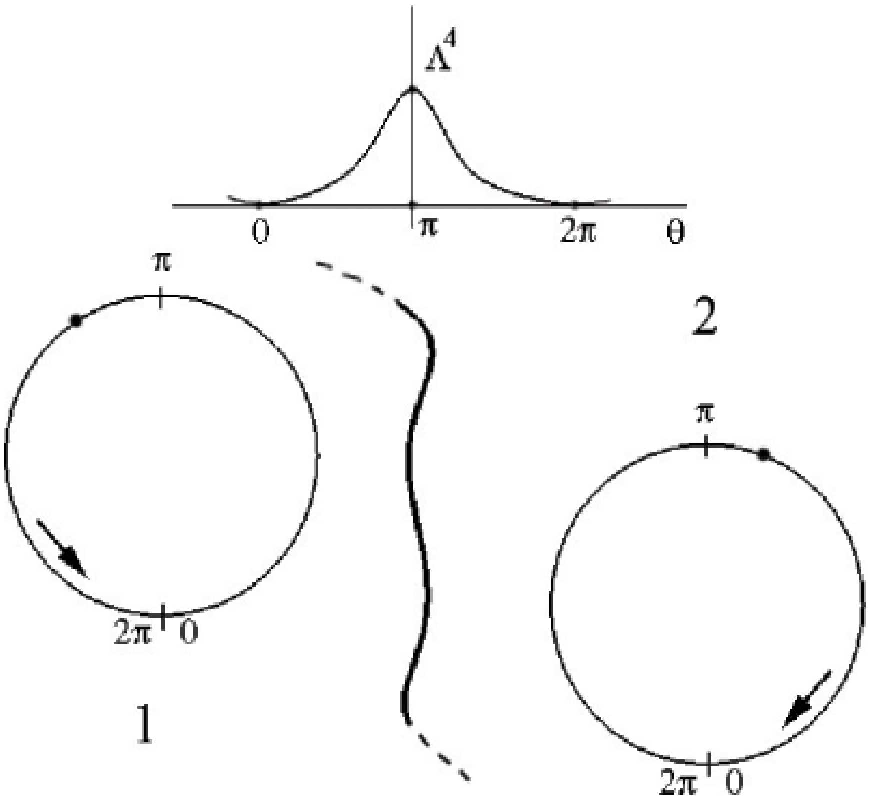
Unstable topological defects

- 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 α 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.

Closed walls formation in Inflationary Universe



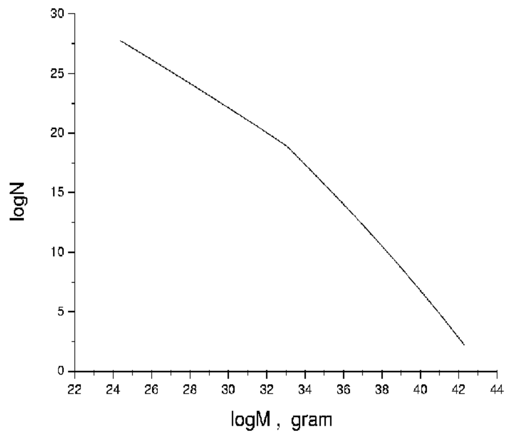
If the first U(1) phase transition takes place on inflationary stage, the value of phase θ , corresponding to e-folding N~60, fluctuates

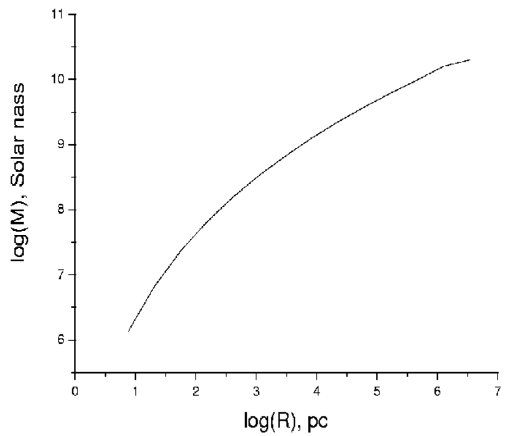
$$\Delta\theta \approx H_{\text{infl}} / (2\pi f)$$

Such fluctuations can cross π

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

Massive PBH clusters





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

Spectrum of Massive BHs

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

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

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

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

GW signals from closed wall collapse and BHs merging in clouds

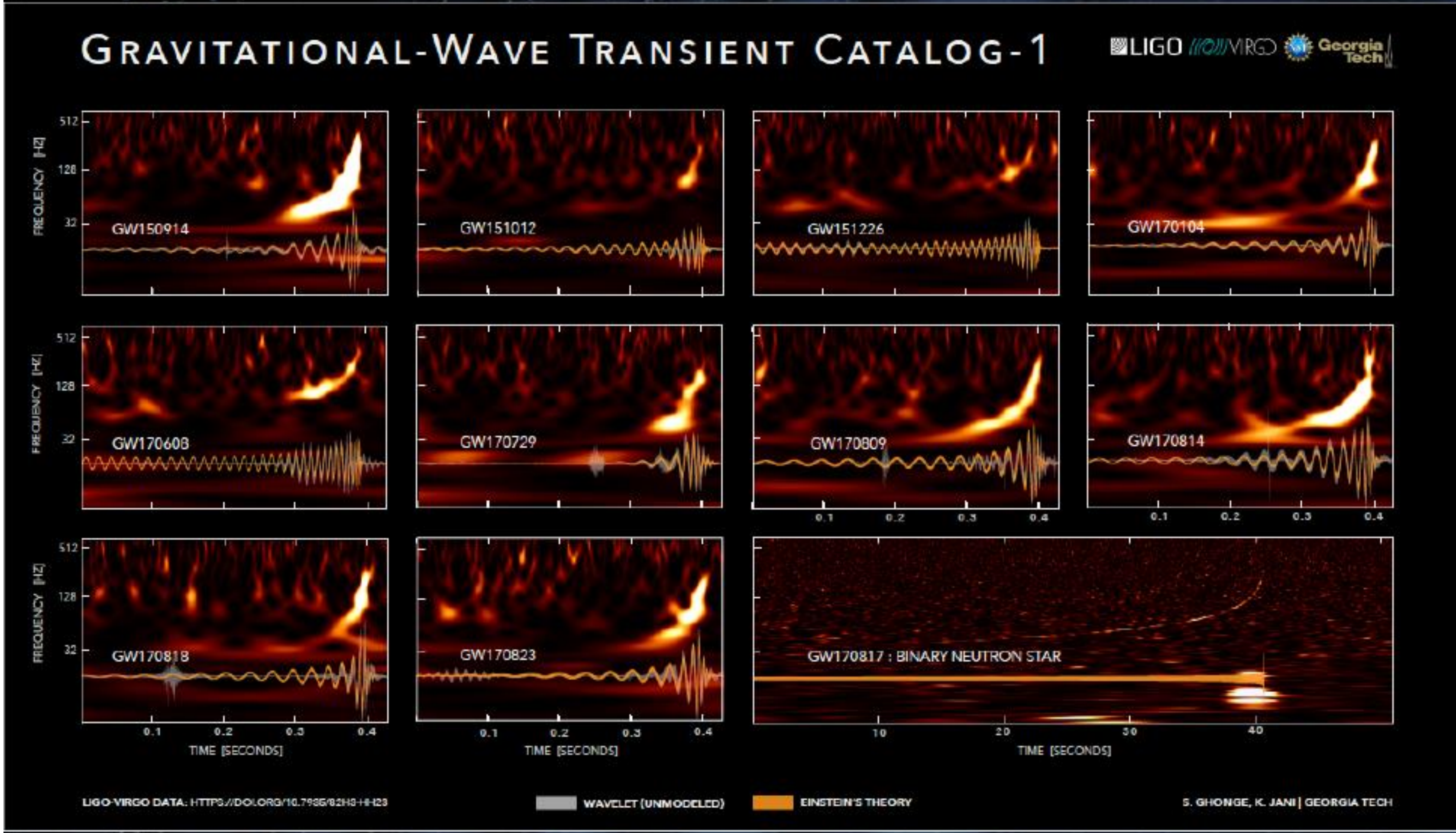
- Closed wall collapse leads to primordial GW spectrum, peaked at $\nu_0 = 3 \cdot 10^{11} (\Lambda / f) Hz$ with energy density up to

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

- 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 is probably detected by LIGO!.

GWTC-1



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	$m_1/\mathrm{M}_\odot$	$m_2/\mathrm{M}_\odot$	$\mathcal{M}/\mathrm{M}_\odot$	χ_{eff}	$M_{\mathrm{f}}/\mathrm{M}_\odot$	a_{f}	$E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$	d_L/Mpc	z	$\Delta\Omega/\mathrm{deg}^2$
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	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 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 may be an interesting hot topic for a PhD thesis

STRONG PRIMORDIAL INHOMOGENEITY PROBES FOR INFLATION AND BARYOSYNTHESIS

Primordial Black Holes

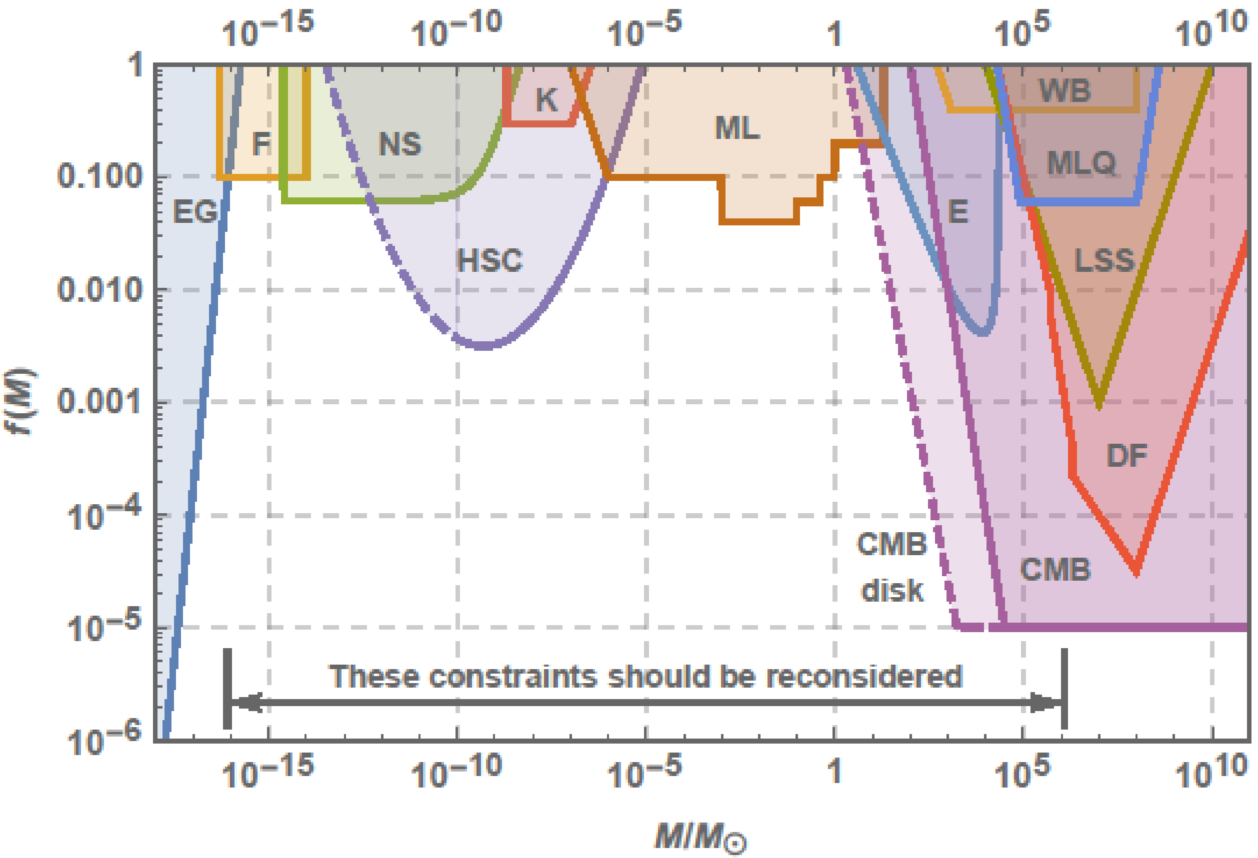
- Any object of mass M can form Black hole, if contracted within its gravitational radius.

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

- 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

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

Constraints on PBH dark matter



The critical analysis of constraints on Primordial Black Holes (PBH) dark matter releases a wide range of PBH masses for PBH DM

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

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

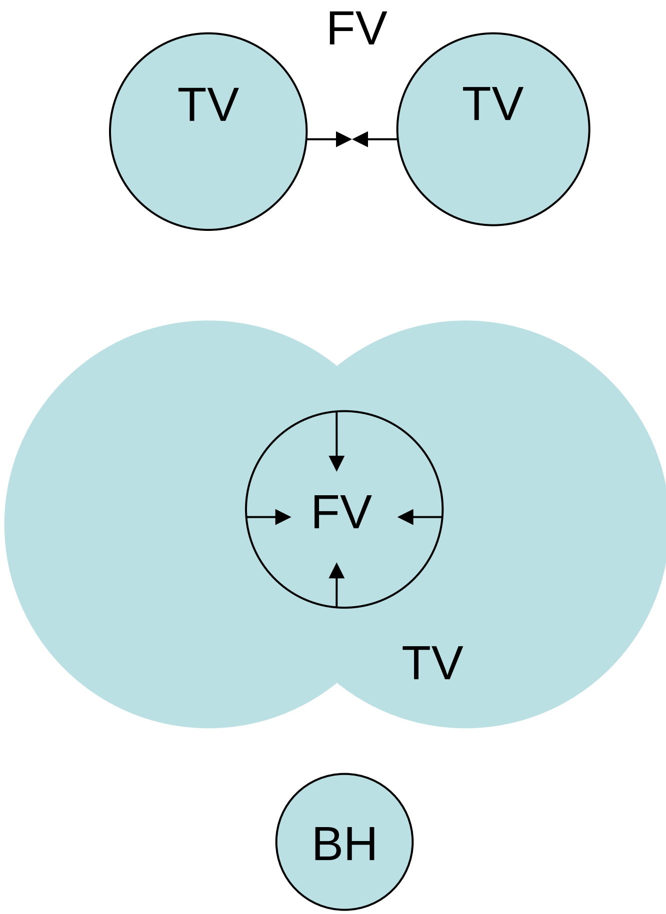
- At *k=0* on dust-like stage exponential suppression is absent. The minimal estimation is determined by direct production of BHs

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

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 »).

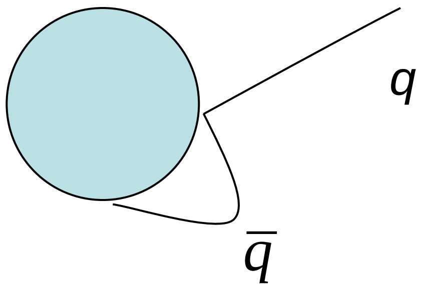
PBHs as indicator of first order phase transitions



- 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 gravitational field. Products of evaporation have black body spectrum with



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

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

- 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 $m \leq T_{PBH}$ 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 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.**

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

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

$\rho_i << \rho$ **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.

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.

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, we see that cosmological consequences of particle theory can lead to mechanisms of intermediate and even supermassive BH formation.

THE PUZZLES
OF DIRECT DARK MATTER
SEARCHES

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

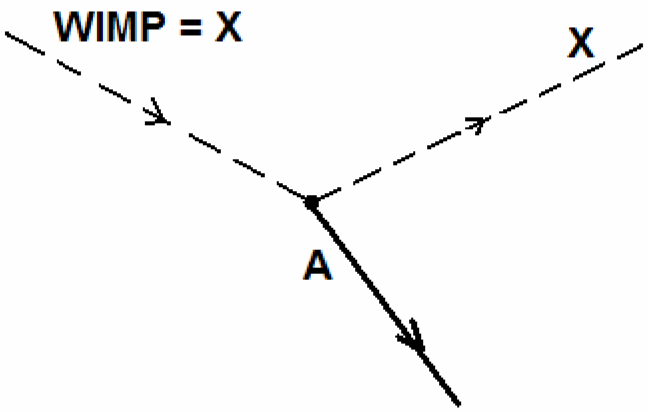
M. V. Keldysh Institute of Applied Mathematics, Academy of Sciences of the USSR

(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-nucleus interaction

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



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

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

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

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

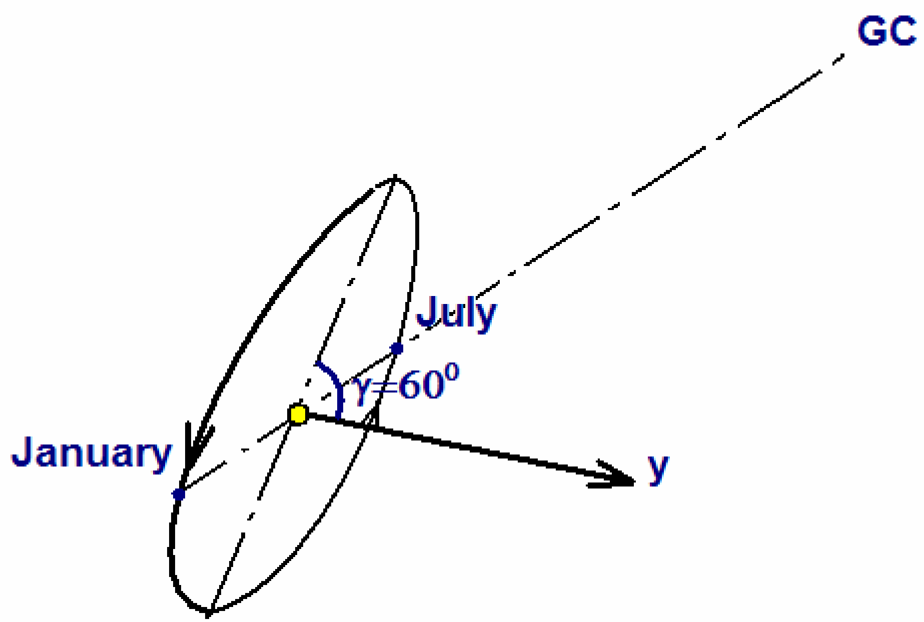
$$\textit{Interaction amplitude} \equiv A_{AX} = A^{\text{point}}_{AX} \cdot F_A(q^2)$$

Annual modulation of WIMP effects

Minimization of background

- Installation deeply underground
- Radioactively pure materials
- Annual modulation

DM does not participate in rotation around GC.



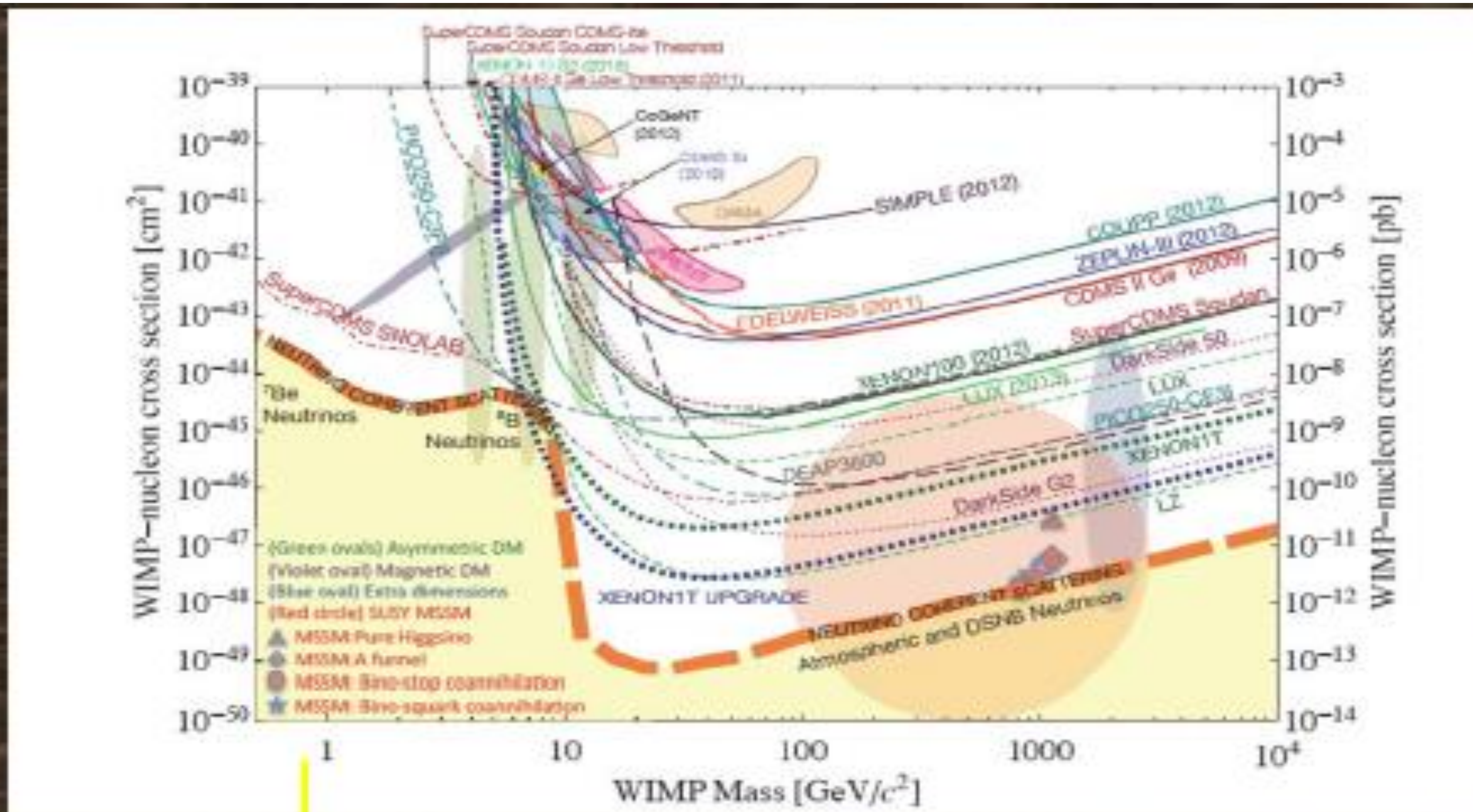
$$v_{Earth\ y} = v_{Sun\ y} + v_{orb} \cdot \cos\gamma \cdot \cos\omega(t - t_0)$$

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

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

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

Controversial results of direct DM searches



This is just a largely arbitrary, partial, incorrect exercise

THE PUZZLES
OF INDIRECT DARK MATTER
SEARCHES

Indirect searches for Dark Matter

Astrophysical bounds on the mass of heavy stable neutral leptons

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

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

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

Condensation of Dark Matter in Galaxy

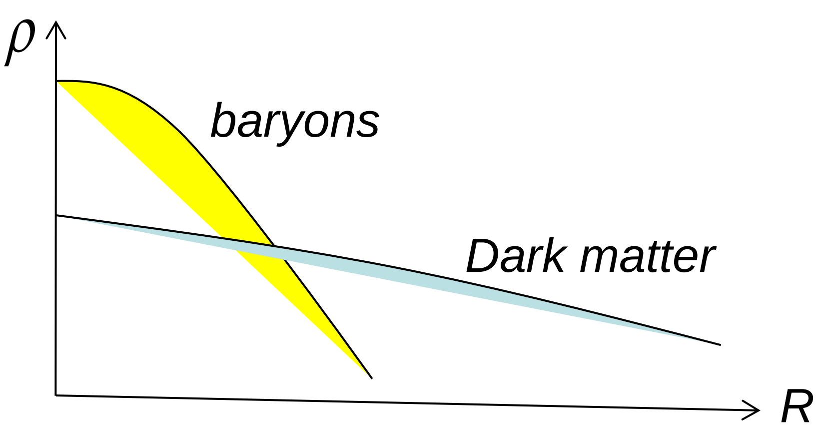
$$\ddot{R} + \omega^2 R = 0$$

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

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

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

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



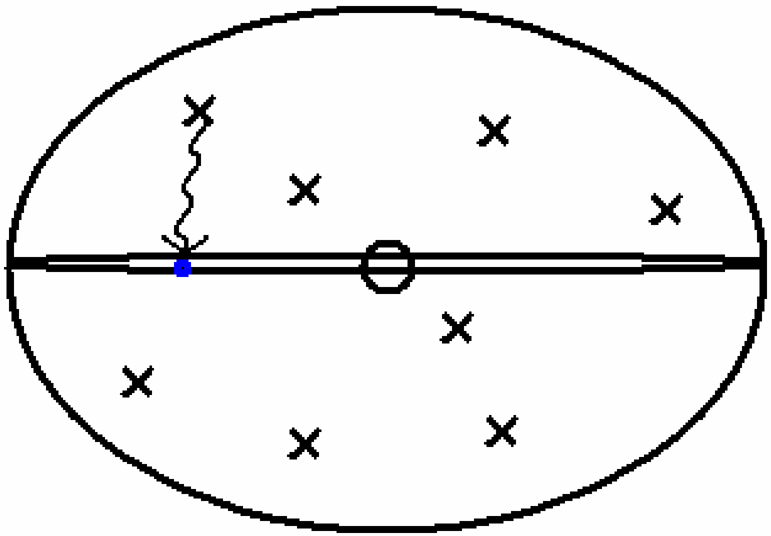
- Motion of collisionless gas in nonstationary field of baryonic matter, contracting owing to dissipation processes, provides effective dissipation and contraction of this gas.
- In result collisionless Dark Matter condences in Galaxy, but it is distributed more steeply, than baryonic matter.
- It qualitatively explains the difference in distribution of baryons and dark matter.
- Due to condensation effects of annihilation in Galaxy can be significant even for subdominant DM components (e.g.4th neutrino).

Annihilation and decays of DM as a source of CR.

Stable DM particles can annihilate

$$\dot{n}_{sources} = n_X n_{\tilde{X}} \langle \sigma_{ann} v \rangle$$

$$X\tilde{X} \to e^+ e^- + \ldots$$



Metastable neutral particles decay with equal amount of positrons and electrons

$$X \to e^+ e^- + \ldots$$

At the level of elementary process metastable double charged particles can decay to same sign leptons only

$$X^{++} \to l^+ l^+$$

The excess of high energy positrons detected in PAMELA, FERMI/LAT and AMS02 experiments may be considered as an evidence for indirect effect of dark matter, first predicted by Zeldovich et al (1980).

Cosmic positron excess from DM?

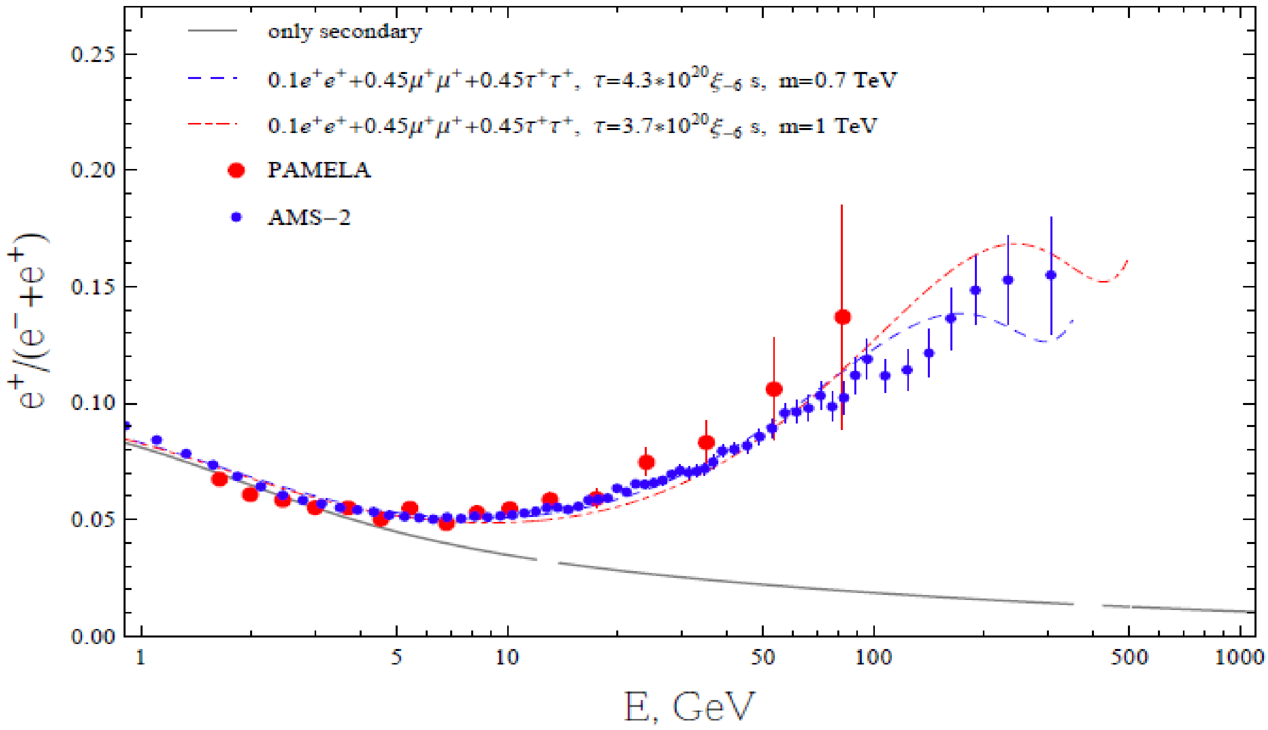
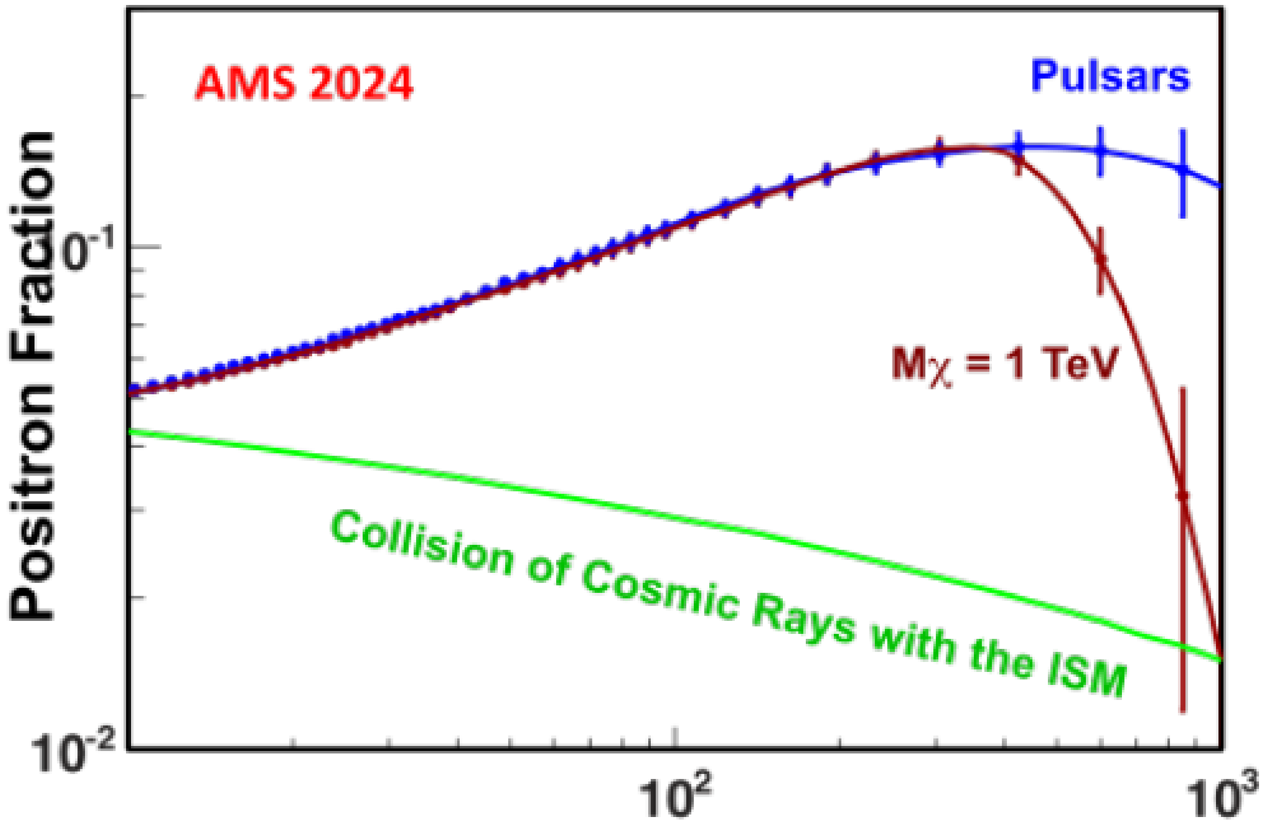


Figure 3: Positron excess due to $UU \to e^+e^+, \mu^+\mu^+, \tau^+\tau^+$ decays compared to PAMELA and AMS-02 data.

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

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

AMS02 in the next decade



Presented in CERN on 08.12.2016 by Prof. S.Ting

INTEGRAL excess of positron annihilation line

- In the galactic bulge the excess of positron annihilation line is observed by INTEGRAL.
- This effect may be due to extra positrons originated from dark matter.

DARK MATTER FROM CHARGED PARTICLES?

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

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

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

Dark Matter from Charged Particles?

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

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

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

« No go theorem » for -1 charge components

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

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

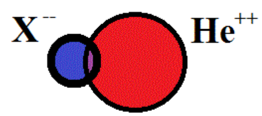
If we have a stable double charged particle X^{--} *in excess over its partner* X^{++} *it may create Helium like neutral atom (O-helium) at temperature* $T < I_o$

Where :

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

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

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



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

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

References

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

-2n charged particles

- Multiple charged particles can appear as constituents of composite Higgs boson – a possible alternative to SUSY solution for Higgs mass divergence and EW breaking scale
- Such particles, if produced in excess over their +*2n* charged partners, can capture *n* primordial helium nuclei.
- Such bound states are not like Bohr atom, but look like Thomson atom with negatively charged core and nuclear droplet oscillating around it.

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]

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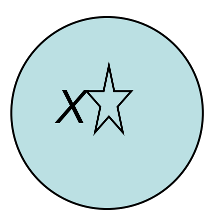
M. Y. Khlopov and C. Kouvaris, Phys. Rev. D 77 (2008) 065002;

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	**2**	1	0	-1	$\mathbf{-2}$
3	**4**	3	**2**	$\mathbf{-4}$	-5
5	**6**	5	**4**	-7	$\mathbf{-8}$
7	**8**	7	**6**	$\mathbf{-10}$	-11

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



nHe

Techniparticle excess

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

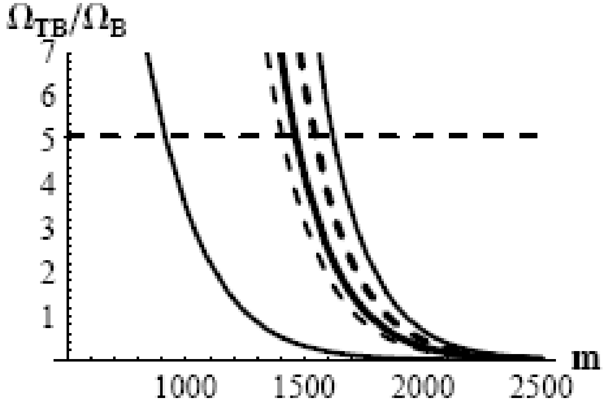
$$\frac{TB}{B} = -\sigma_{UU}\left(\frac{L'}{B}\frac{1}{3\sigma_\zeta} + 1 + \frac{L}{3B}\right)$$

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)

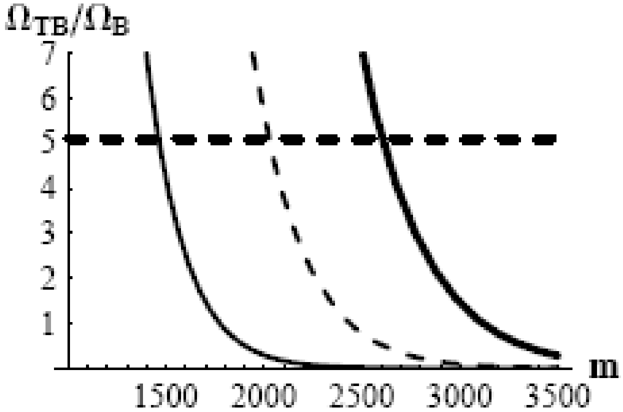
Relationship between TB and B

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



- L'=0, T*=150 GeV

ξ =0.1; 1; 4/3; 2; 3

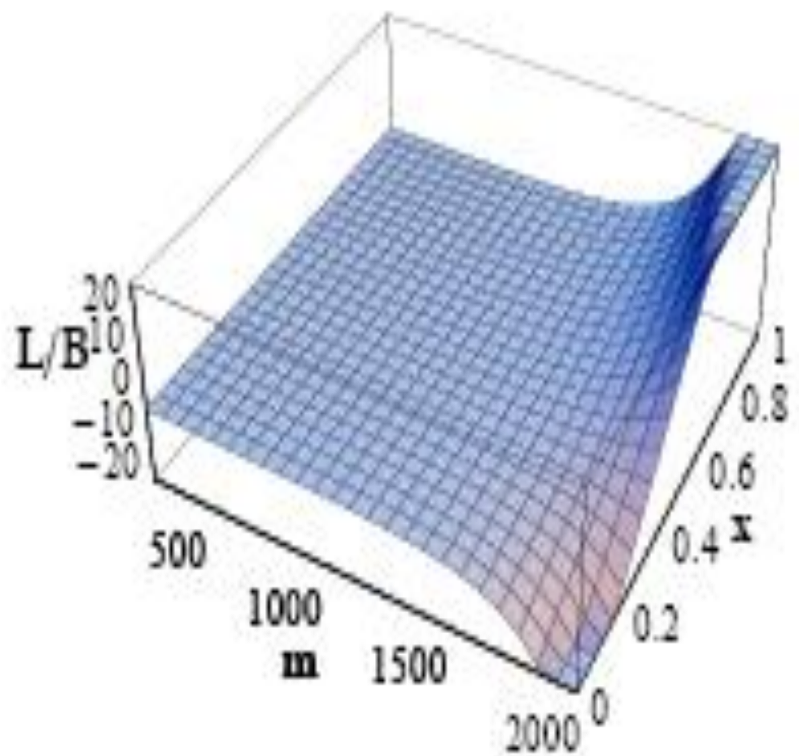


$\xi = 4/3$

- 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

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 Warmer than Cold Dark Matter

O-helium in Earth

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

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

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

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

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

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

Annual modulation of O-helium concentration in Earth

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

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

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

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

and the annual modulation of OHe concentration is characterized by

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

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

OHe solution for puzzles of direct DM search

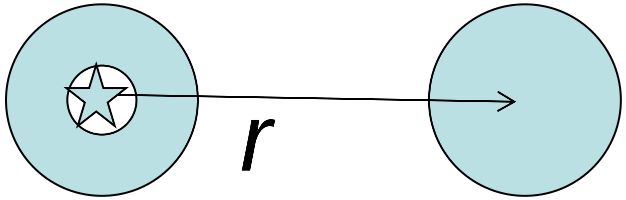
- OHe equilibrium concentration in the matter of DAMA detector is maintained for less than an hour
- Annual modulations in inelastic processes, induced by OHe in matter. No signal of WIMP-like recoil
- The process

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

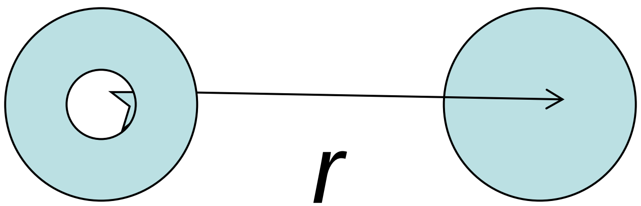
is possible, in which only a few keV energy is released. Other inelastic processes are suppressed

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

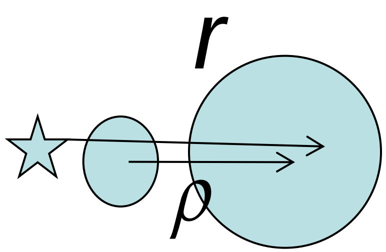
Potential of OHe-nucleus interaction



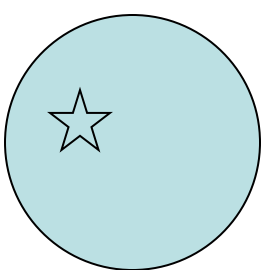
$$U_{Xnuc} = -2Z\alpha\left(\frac{1}{r} + \frac{1}{r_o}\right)\exp\left(-2r/r_o\right)$$



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

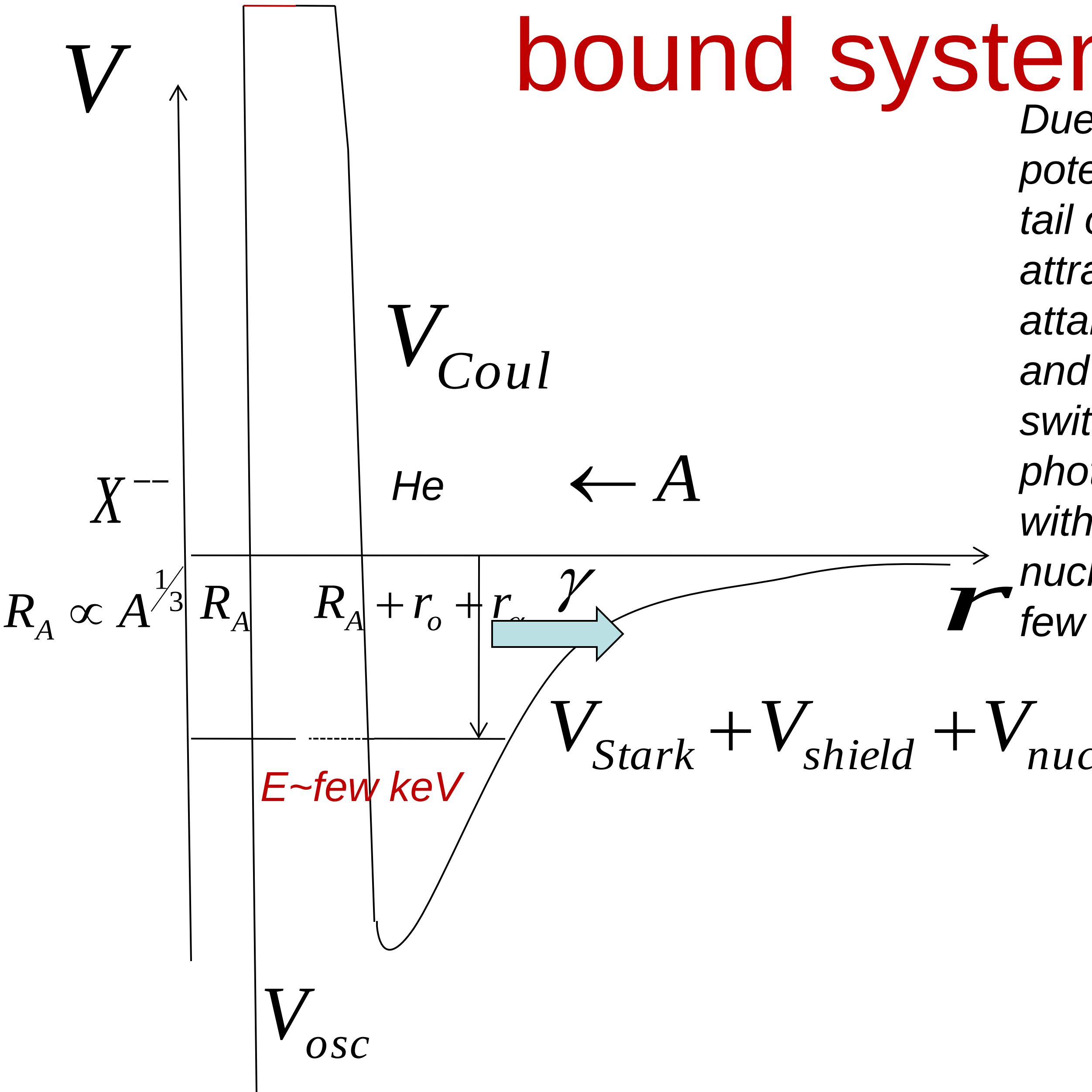


$$U_{Coul} = +\frac{2\alpha Z}{\rho} - \frac{2\alpha Z}{r}$$



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

Formation of OHe-nucleus bound system



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

Few keV Level in OHe-nucleus system

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

Rate of OHe-nucleus radiative capture

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

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

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

Reproduction of DAMA/NaI and DAMA/LIBRA events

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

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

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

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

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

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

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.

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

Excessive positrons in Integral

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

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

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

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

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

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

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

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

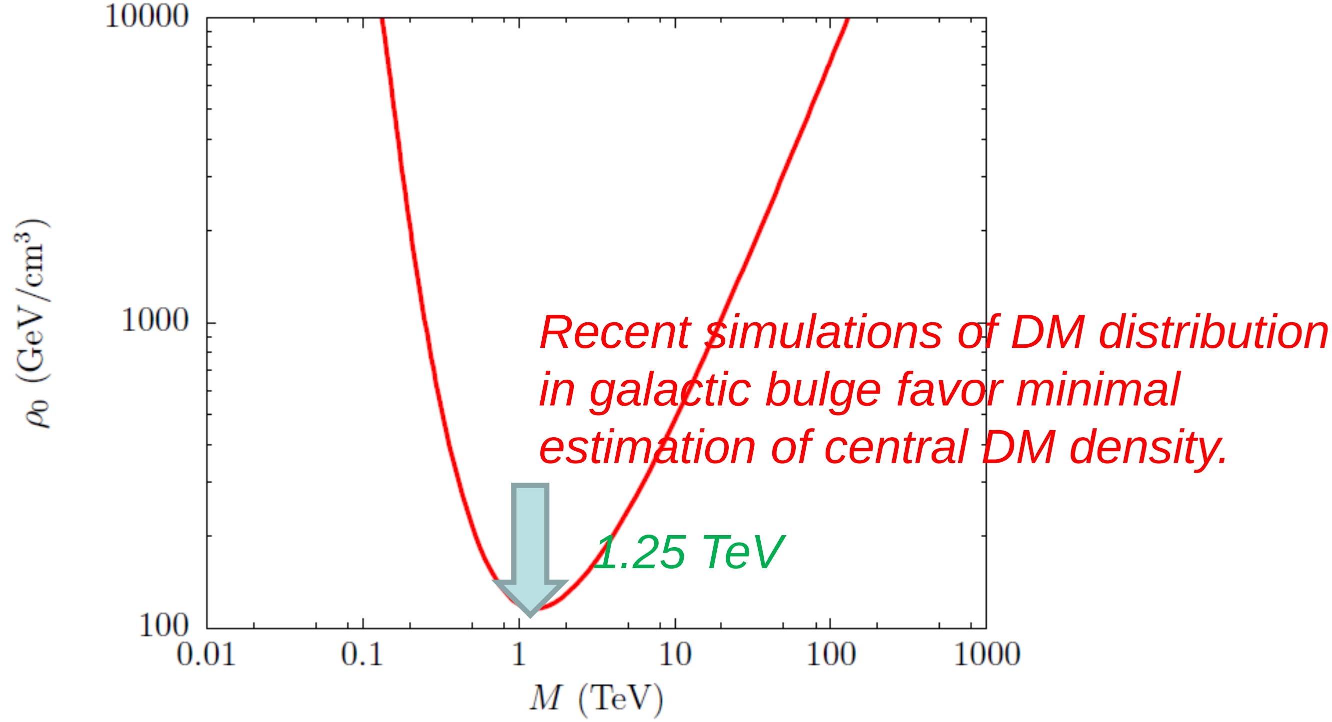


Figure 1: Values of the central dark matter density ρ_0 (GeV/cm^3) and of the OHe mas
M (TeV) reproducing the excess of e^+e^- pairs production in the galactic bulge. Belo
the red curve, the predicted rate is too low.

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

Gamma lines from bulge

- If OHe levels with nonzero orbital momentum are excited, gamma lines should be observed from the transitions

$$(n > m)\ E_{nm} = 1.598\,\mathrm{MeV}\,(1/m^2 - 1/n^2)$$

at the level

$$3 \cdot 10^{-4} S_5^{-2} (\mathrm{cm}^2\,\mathrm{s}\,\mathrm{MeV}\,\mathrm{ster})^{-1}$$

Search for these lines may be a challenge for SRG mission

Composite dark matter explanation for low energy positron excess

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

A solution for cosmic positron excess?

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

Cosmic positron excess from double charged constituents of dark atoms

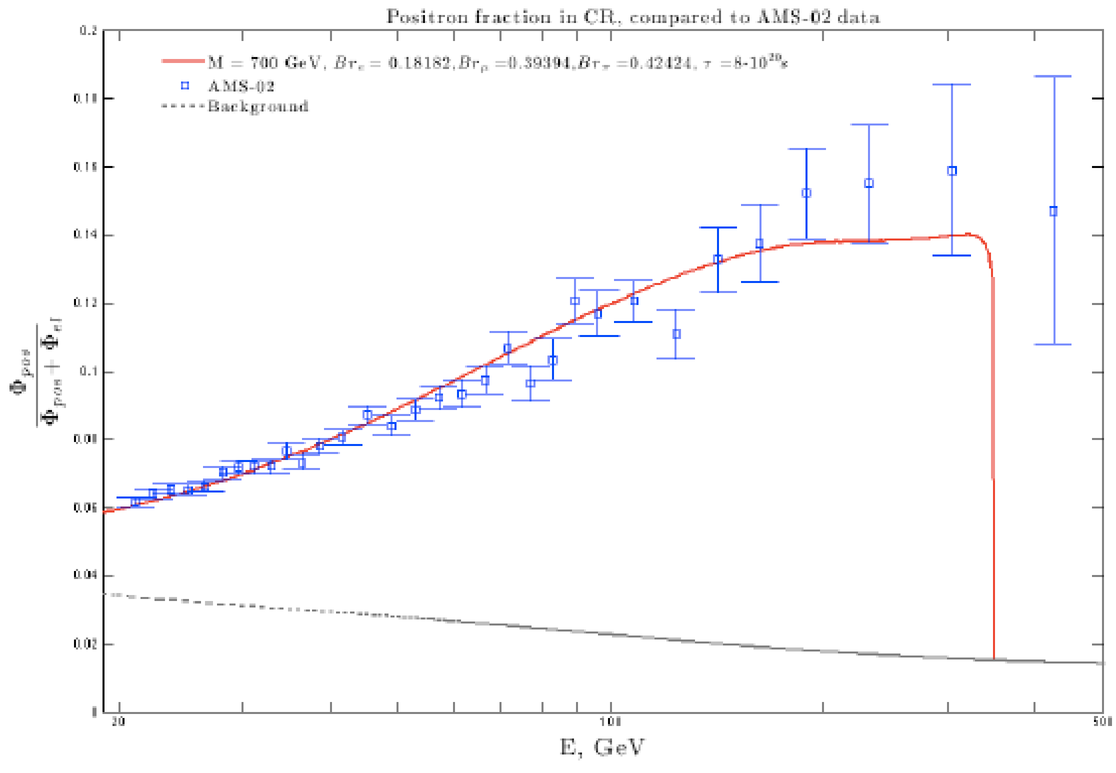


Figure 3: Positron fraction in the cosmic rays from decays of dark matter particles (red curve), corresponding to the best-fit values of model parameters ($M = 700\,\mathrm{GeV}, \tau = 8 \cdot 10^{20}\,\mathrm{s}, Br_{ee} = 0.182, Br_{\mu\mu} = 0.394, Br_{\tau\tau} = 0.424$), and fraction of secondary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

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

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

Diffuse Gamma ray background

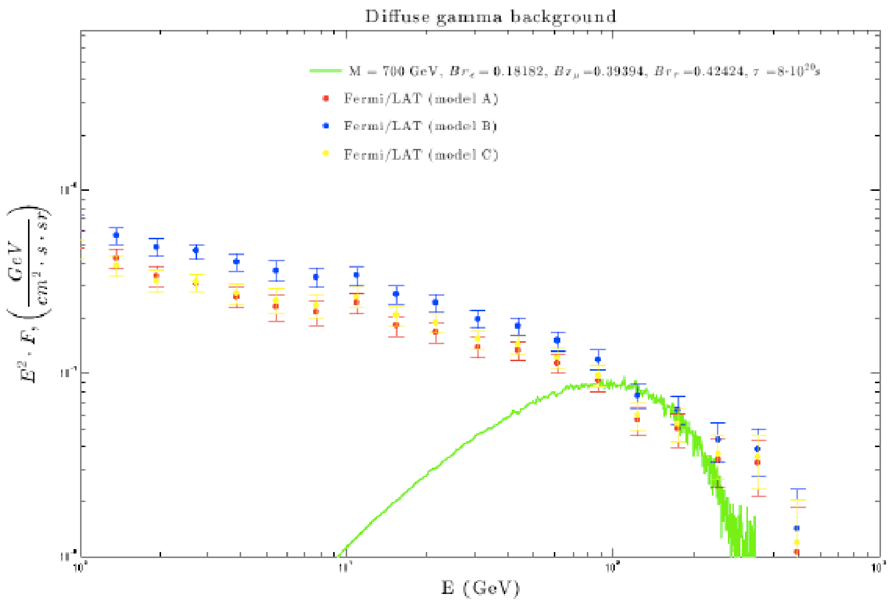


Figure 4: Gamma-ray flux multiplied by E^2 from decays of dark matter particles in the Galaxy and beyond (green curve), corresponding to the best-fit values of model parameters ($M = 700\,\mathrm{GeV}, \tau = 8 \cdot 10^{20}\,\mathrm{s}, Br_{ee} = 0.182, Br_{\mu\mu} = 0.394, Br_{\tau\tau} = 0.424$),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

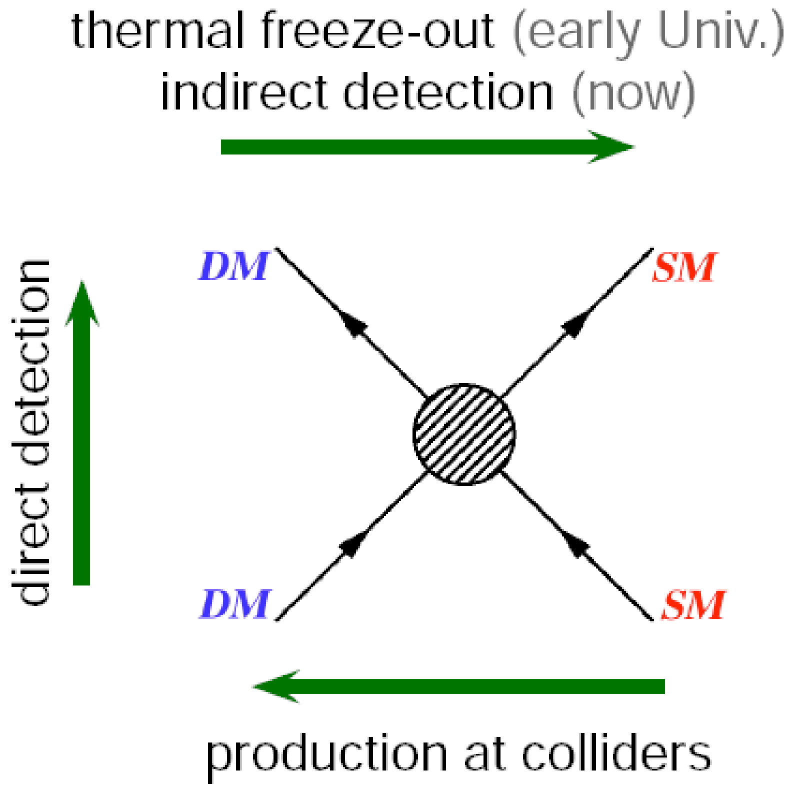
Composite dark matter explanation for high energy positron excess

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

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

COMPOSITE DARK MATTER CONSTITUENTS AT ACCELERATORS

Complementarity in searches for Dark Matter

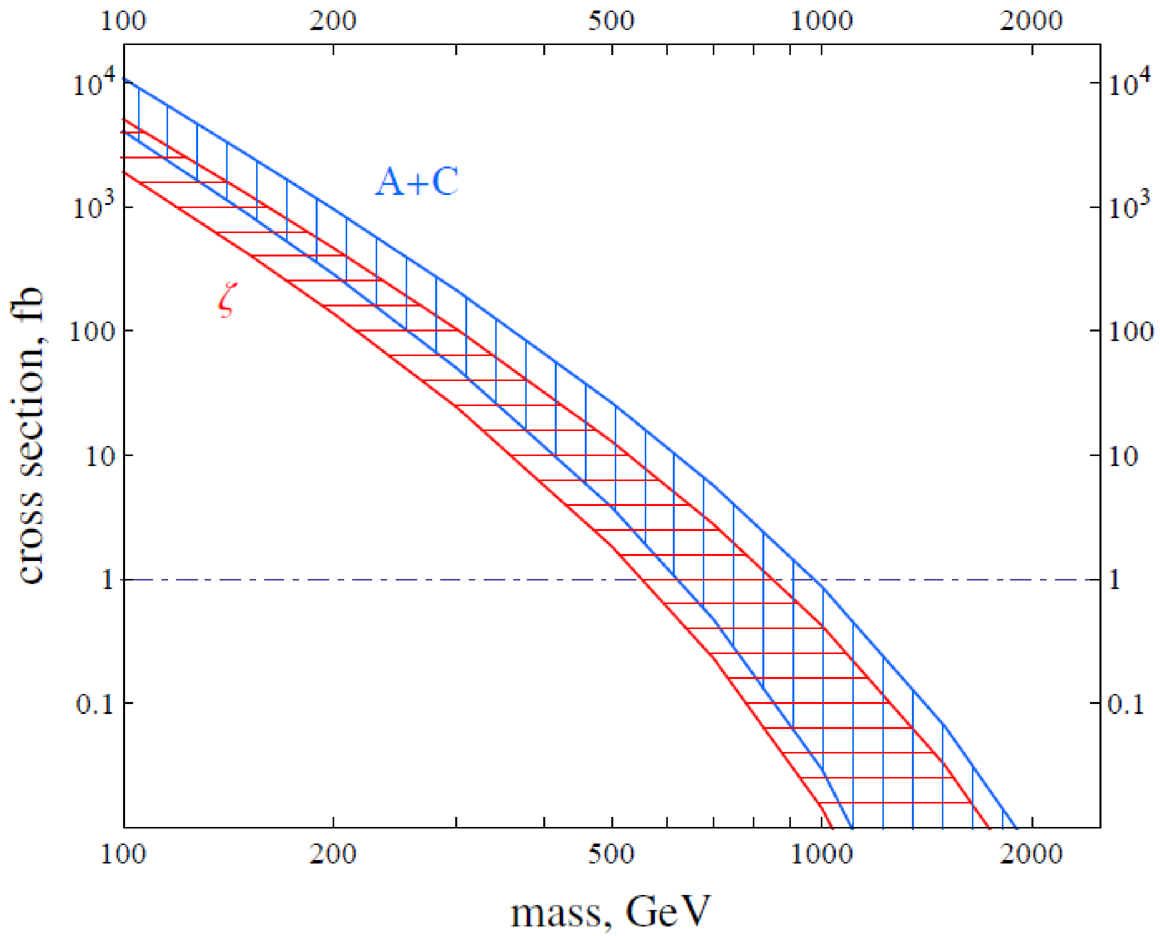


Usually, people use this illustration for complementarity in direct, indirect and accelerator searches for dark matter. However, we see that in the case of composite dark matter the situation is more nontrivial. We need charged particle searches to test dark atom model

Collider test for dark atoms

- Being the simplest dark atom model OHe scenario can not only explain the puzzles of direct dark matter searches, but also explain some possible observed indirect effects of dark matter. 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.

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 teV < $\sqrt{s}$ < 14 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

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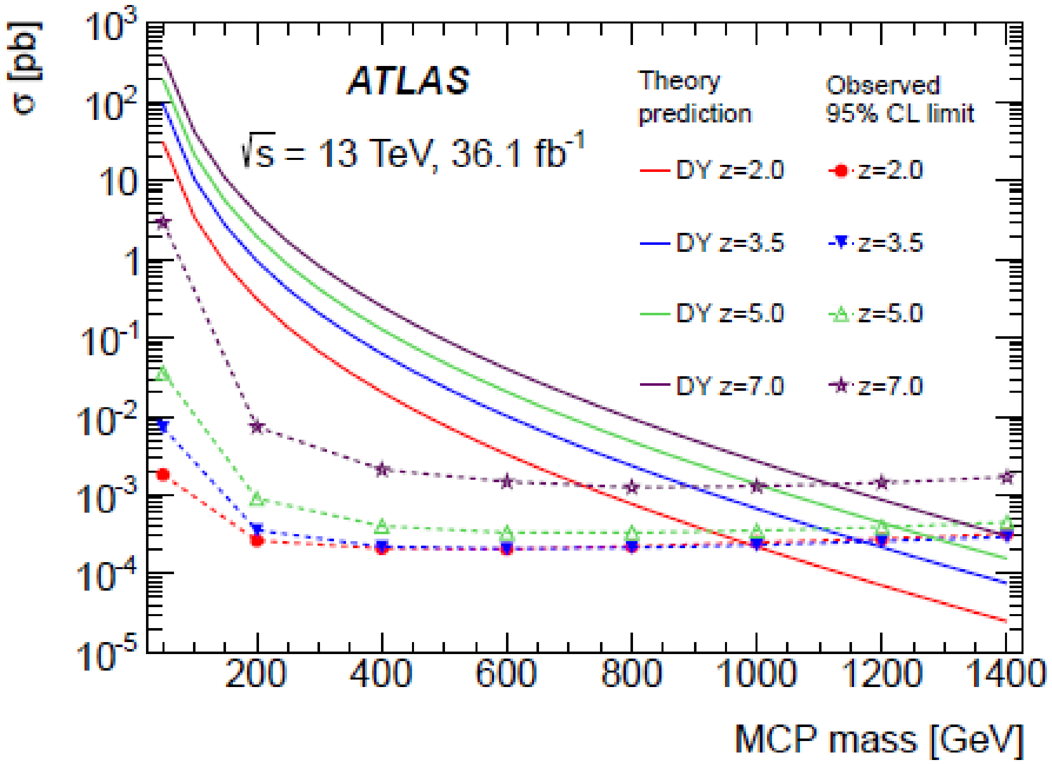
[a]*Moscow Engineering Physics Institute*
[b]*CERN*
[c]*University of Victoria*
[d]*Oxford University*
[e]*Indiana University*
[f]*York University*
[g]*University of Bonn*
[h]*University of Paris*

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)

Experimentum crucis for composite dark matter at the LHC

Coming analysis of results of double charged particle searches at the LHC can cover all the range of masses, at which composite dark matter can explain excess of slow and high energy positrons,

$\lvert q\rvert/e$	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.

[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)

Conclusions

- **Physical nature of dark matter involves various aspects of physics beyond the standard model.**

- **Strong primordial nonlinear structures (PBHs, archioles or massive PBH clouds) provide cosmological probes for BSM physics of dark matter in axion-like models.**

- **Dark atom hypothesis can explain puzzles of direct dark matter searches and cosmic positron anomalies. The latter can be directly probed at the LHC, offering nontrivial collider probes for dark matter physics in searches for stable multiple charged particles.**