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# Multi-messenger cosmology of new physics

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# Outlines

- Messengers from physics of very early Universe
- Multi-component dark matter from new particle symmetries
- Dark atoms of Dark Matter
- Primordial black holes
- Topological defects from BSM symmetry breaking
- Strong primordial inhomogeneities as messenger of particle symmetry breaking
- Multimessenger cosmology in the context of cosmoparticle physics

# 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 originated from very early Universe, inevitably predicts additional model dependent effects, which we can call multimessenger cosmology of new physics*

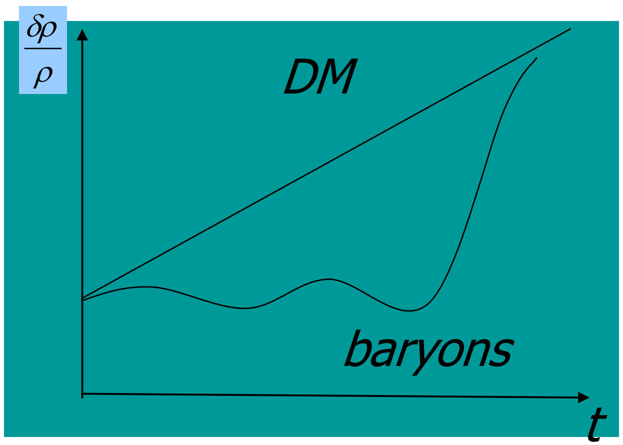
# Our existence is the main messenger of new physics

- The fact of our existence originated in inflationary Universe with baryosynthesis and dark matter/ energy appears as the main signature of new physics.
- Involvement of additional model dependent messengers of new physics can specify its features.

# 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 (NOTE that nuclear strong interaction is sufficiently weak in hot Big Bang Universe) 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*

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

- However, if charged particles are heavy, stable and hidden within neutral « atomic » states they can also play the role of specific composite Dark matter (Dark atoms).

# “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
- Supermassive particles…
- Mirror and shadow particles,
- PBHs…

***SIMP***

***(strongly interacting massive particles)***

They follow from different motivations to extend the symmetry of SM and can co-exist in multi-component dark matter.

The models predicting these particles also predict next to lightest metastable particles, which can play the role of cosmological messengers for the underlying dark matter physics.

# From WIMP miracle to DM reality?

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

# 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 and predicting new stable charged particles are severely constrained.

# « 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 or any even value -2n.*

# Constituents of composite dark matter

## *Few possible candidates for -2n charges:*

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

- *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 n=1:*

- *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*

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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;*

# 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)*

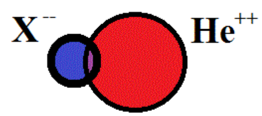
# Nuclear-interacting composite dark matter: O-helium « atoms »

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

$$T < I_o = 1.6\ MeV$$

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

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




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

$$R_0 = 1/(ZZ_{He}\alpha m_{He}) = 2\ 10^{-13} cm$$

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References

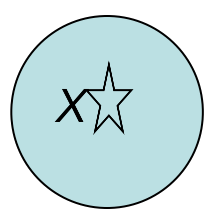
1. M.Yu. Khlopov, *JETP Lett.* 83 (2006) 1;
2. D. Fargion, M.Khlopov, C.Stephan, *Class. Quantum Grav.* 23 (2006) 7305;
2. M. Y. Khlopov and C. Kouvaris, *Phys. Rev.* D 77 (2008) 065002]

# 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*




*nHe*

# 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

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

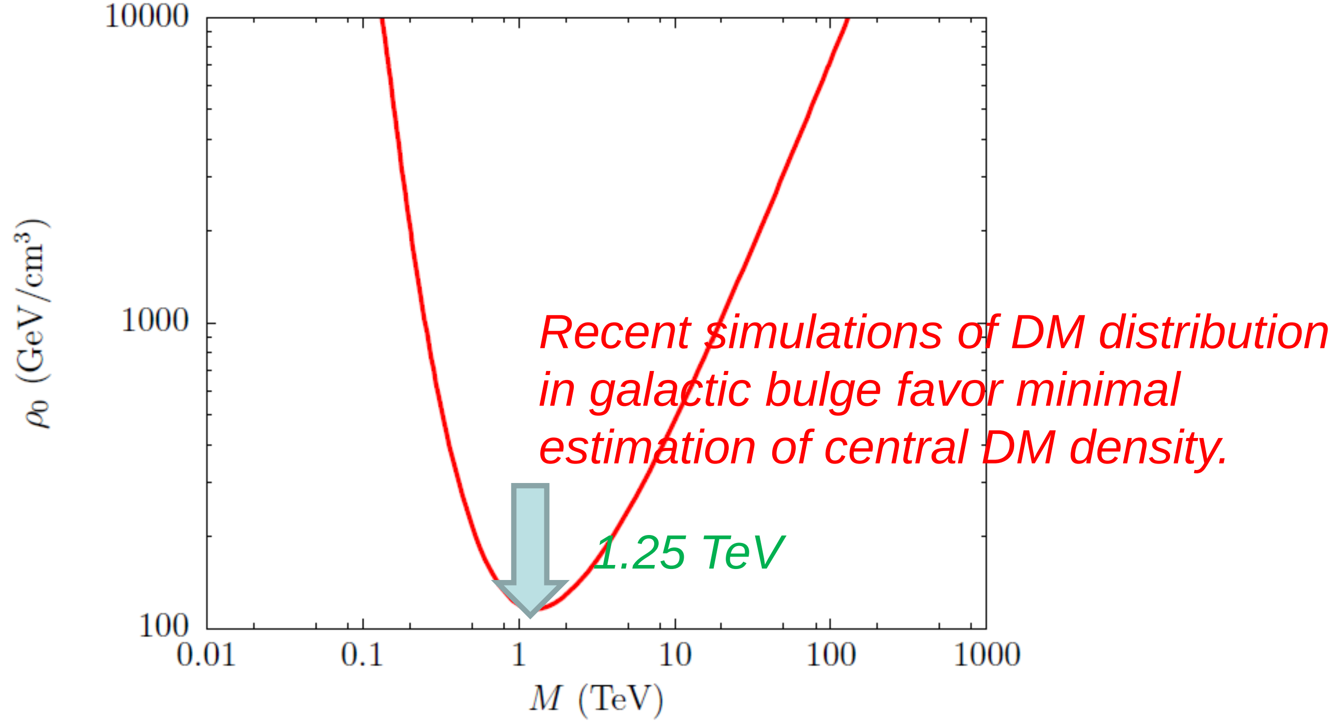



Figure 1: Values of the central dark matter density $\rho_0$ (GeV/cm$^3$) and of the OHe mas $M$ (TeV) reproducing the excess of $e^+e^-$ pairs production in the galactic bulge. Belo the red curve, the predicted rate is too low.

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

# Composite dark matter explanation for low energy positron excess

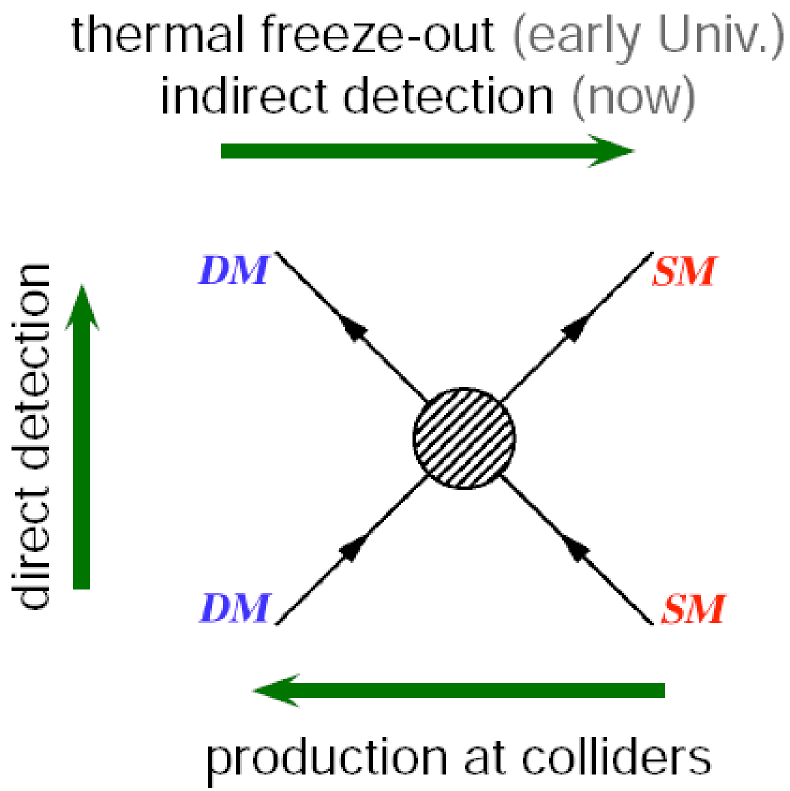
- In spite of large uncertainty of DM distribution in galactic bulge, where baryonic matter dominates and DM dynamical effects are suppressed, realistic simulations favor lower value of DM central density around $\rho_0 \simeq 115\ \mathrm{GeV/cm^3}$. Then observed excess of positron annihilation line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

# 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

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

# Complementarity in searches for Dark Matter

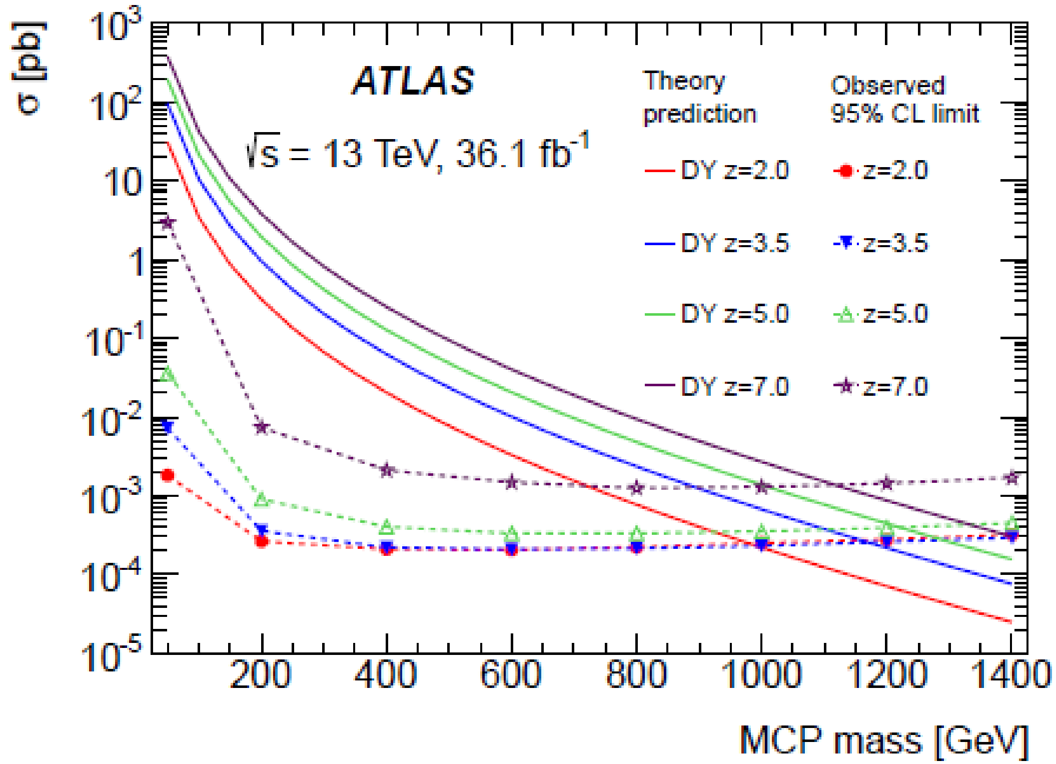



*Usually, people use this illustration for complementarity in direct, indirect and accelerator searches for dark matter. However, we see that in the case of composite dark matter the situation is more nontrivial. We need charged particle searches to test dark atom model*

# Collider test for dark atoms

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

# 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

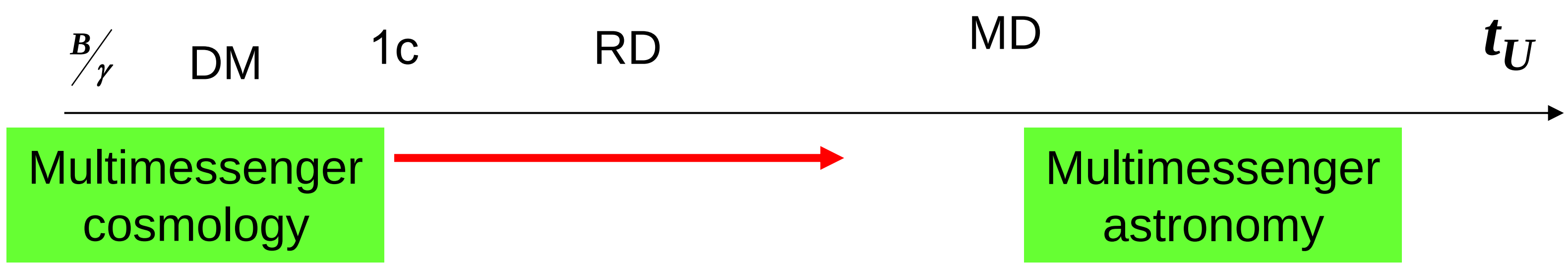
*Coming analysis of results of double charged particle searches at the LHC can cover all the range of masses, at which composite dark matter can explain excess of positron annihilation line in Galactic bulge,*

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

*Composite dark matter can explain excess of low energy positrons at M=1.25 TeV and high energy positrons at M<1 TeV. The latter is already excluded for double charged constituents.*

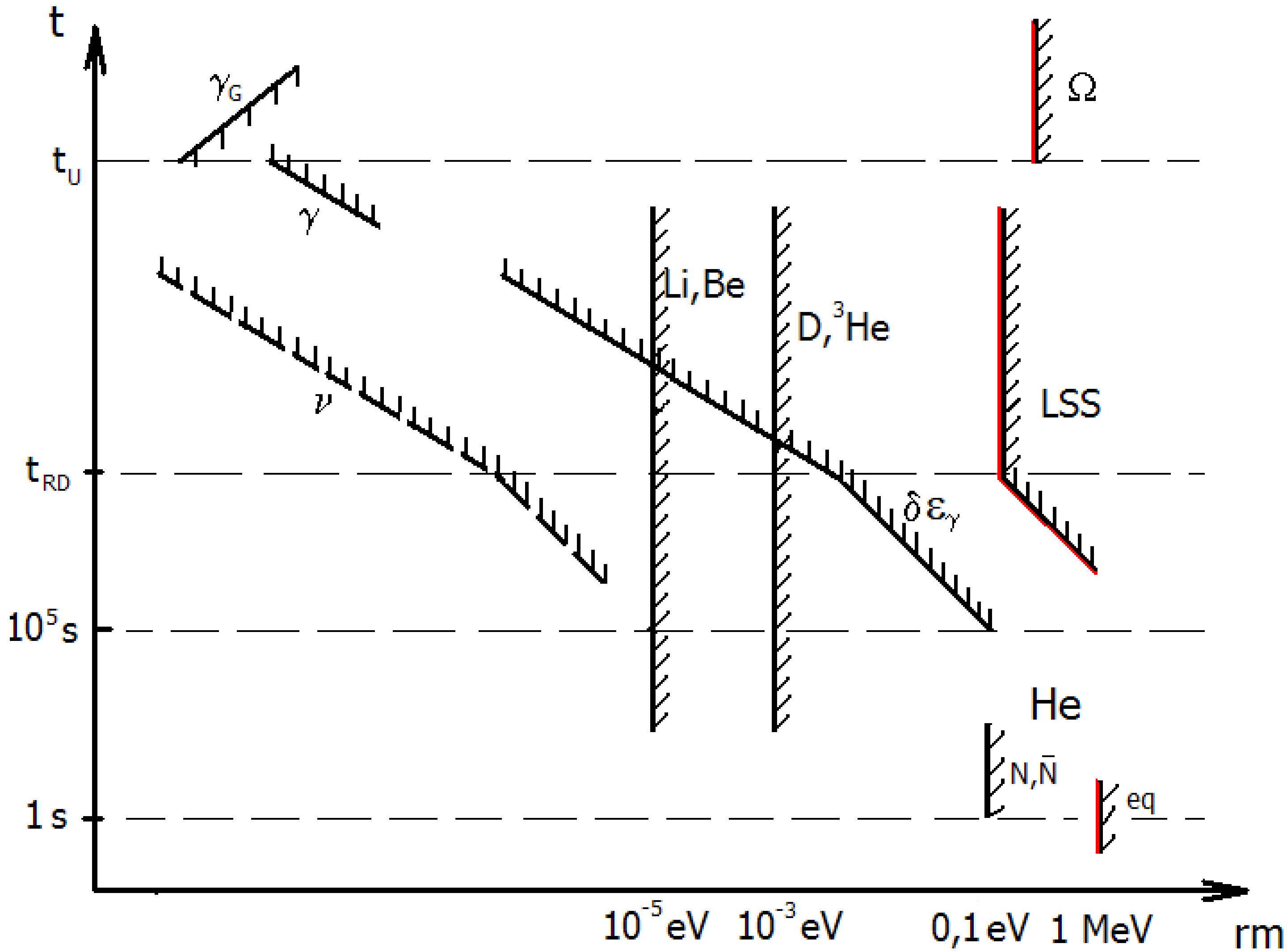
*[ATLAS Collaboration, Search for heavy long-lived multi-charged particles in proton-proton collisions at $\sqrt{s}$= 13 TeV using the ATLAS detector. Phys. Rev. D 99, 052003 (2019)*

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




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

# Laboratory of the Universe




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

# Non-equilibrium particles

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

# Primordial Black Holes

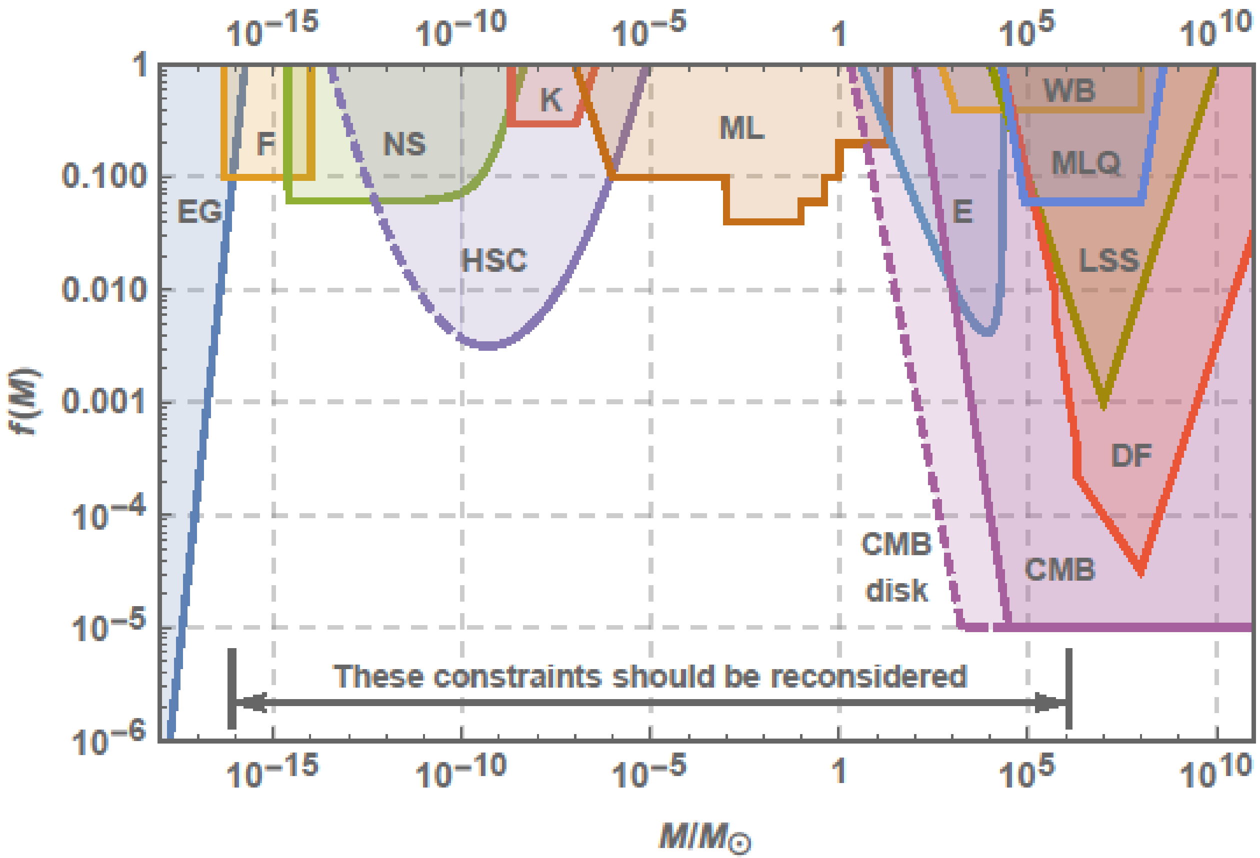
- Any object of mass M can form Black hole, if contracted within its gravitational radius.

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

- 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 PBH dark matter releases a wide range of PBH masses for PBH DM, if PBH clustering is taken into account (K.Belotsky et al Clusters of primordial black holes. Eur. Phys. J. C (2019) 79: 246)*

# 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

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

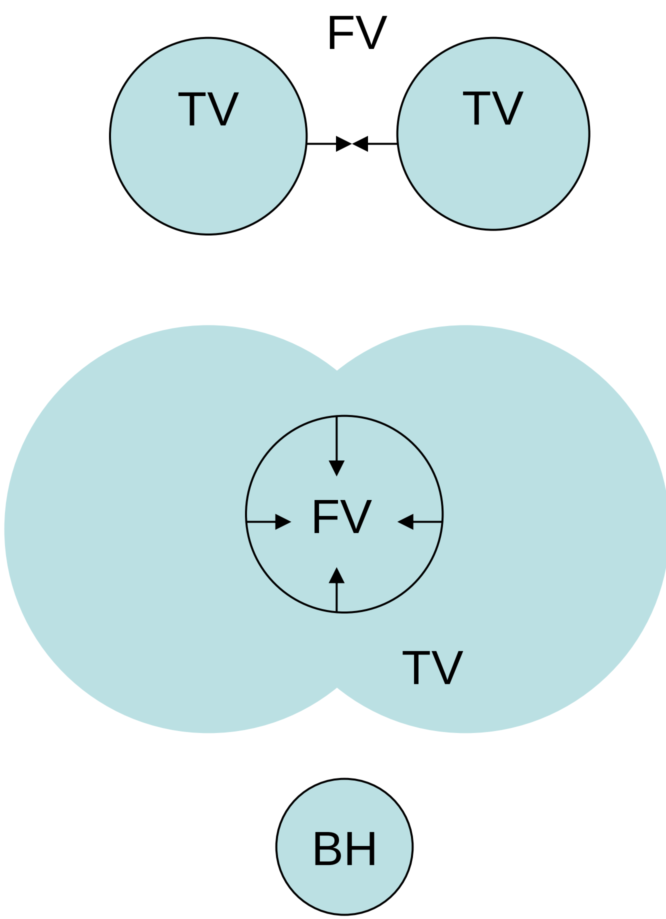
- At *k=0* on dust-like stage exponential suppression is absent. The minimal estimation is determined by direct production of BHs

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

# 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 »).

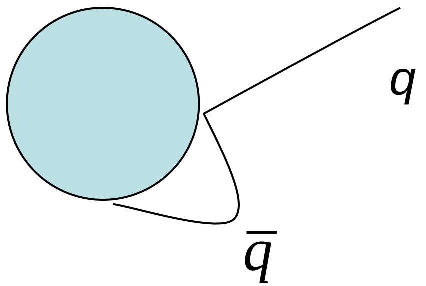
# PBHs as indicator of first order phase transitions




- 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 formation can correlate with primordial spectrum of gravitational waves, originated from this phase transition.

# 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 PRIMORDIAL INHOMOGENEITY PROBES FOR INFLATION AND BARYOSYNTHESIS

# Strong nonhomogeneities in nearly homogeneous and isotropic Universe

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

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

- **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.

# Cosmological Phase transitions 1.

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

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

- When temperature falls down below

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

transition to phase with broken symmetry takes place.

# Cosmological Phase transitions 2.

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

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

- When inflaton field rolls down below

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

transition to phase with broken symmetry takes place.

# Topological defects

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

# 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)**

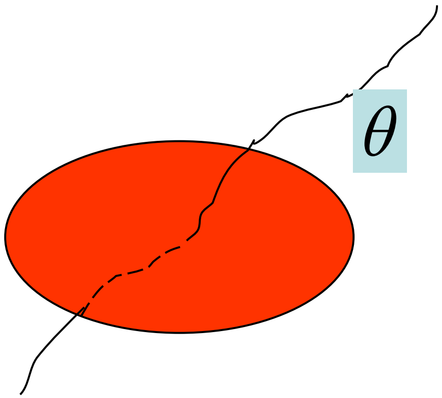
$$V(\varphi) = \Lambda^4\left(1 - \cos(\varphi/f)\right)$$

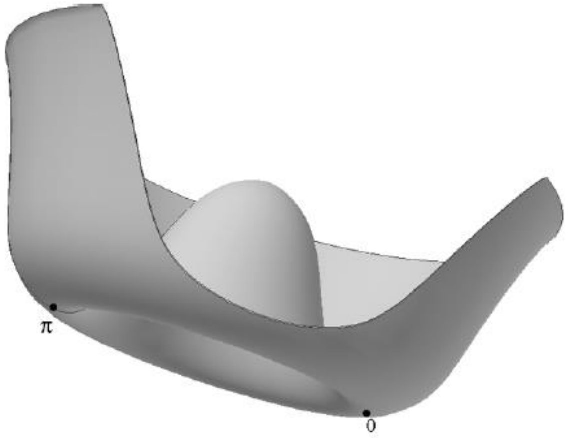
**to vacuum states**

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

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

# Topological defects



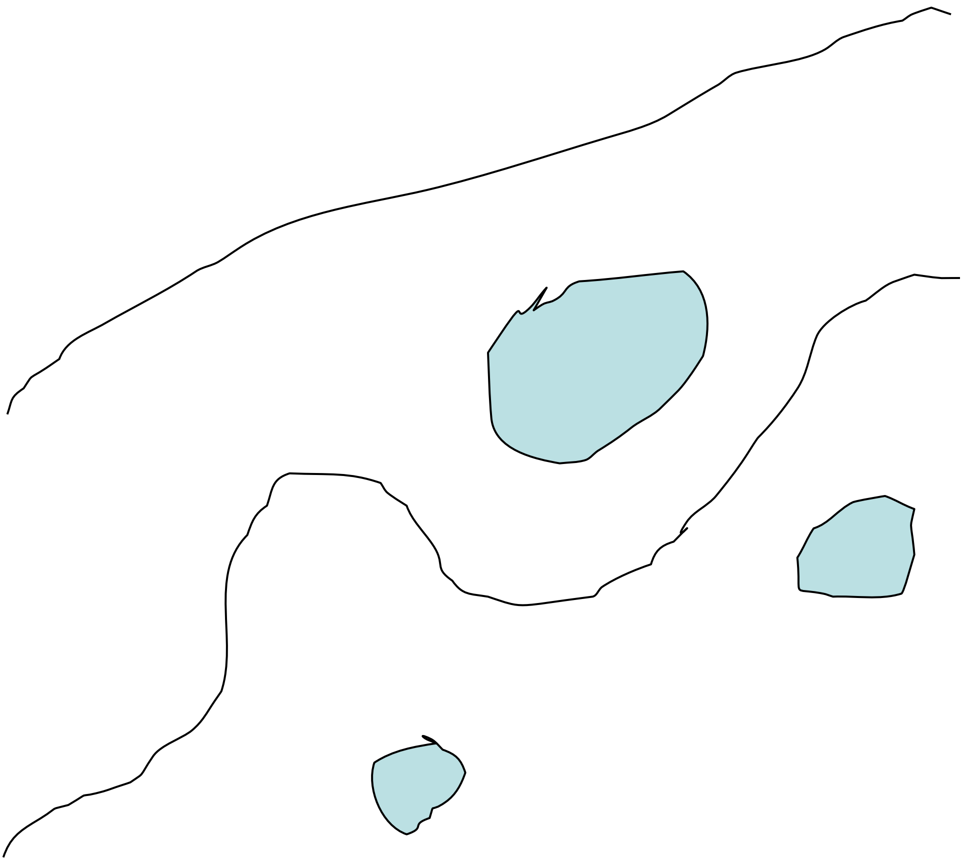




- Spontaneous breaking of U(1) symmetry results in the continuous degeneracy of vacua. In the early Universe the transition to phase with broken symmetry leads to formation of cosmic string network.
- The tilt in potential breaks continuous degeneracy of vacua. In the result string network converts into walls-bounded-by-strings structure in the second phase transition. This structure is unstable and decay, but the initial values of phase define the energy density of field oscillations.

# Unstable topological defects

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

# Archioles structure

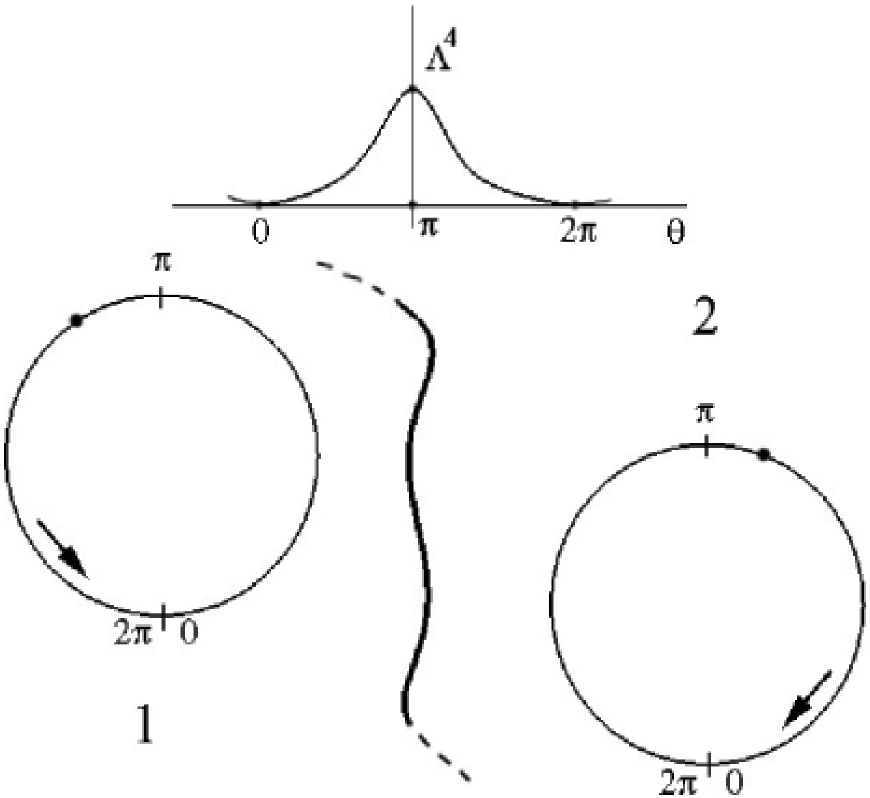


- Numerical studies revealed that ~80% of string length corresponds to infinite Brownian lines, while the remaining ~20% of this length corresponds to closed loops with large size loops being strongly suppressed. It corresponds to the well known scale free distribution of cosmic strings.
- The fact that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

# Massive Primordial Black Holes

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

# Closed walls formation in Inflationary Universe



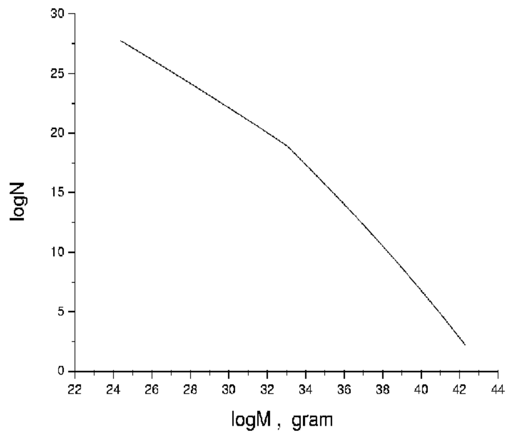

If the first U(1) phase transition takes place on inflationary stage, the value of phase $\theta$ , corresponding to e-folding N~60, fluctuates

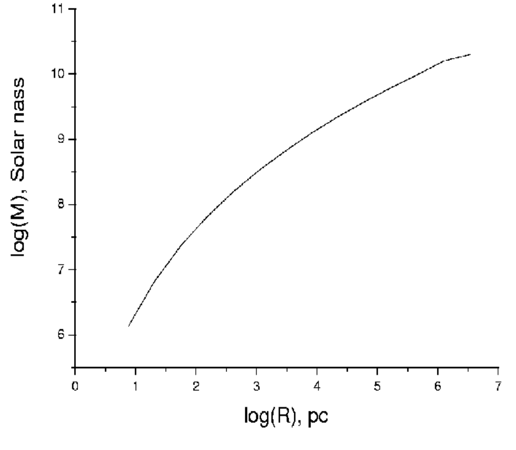
$$\Delta\theta \approx H_{\text{infl}}/(2\pi f)$$

Such fluctuations can cross $\pi$

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

# Massive PBH clusters




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

# Spectrum of Massive BHs

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

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

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

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

# GW signals from closed wall collapse and BHs merging in clouds

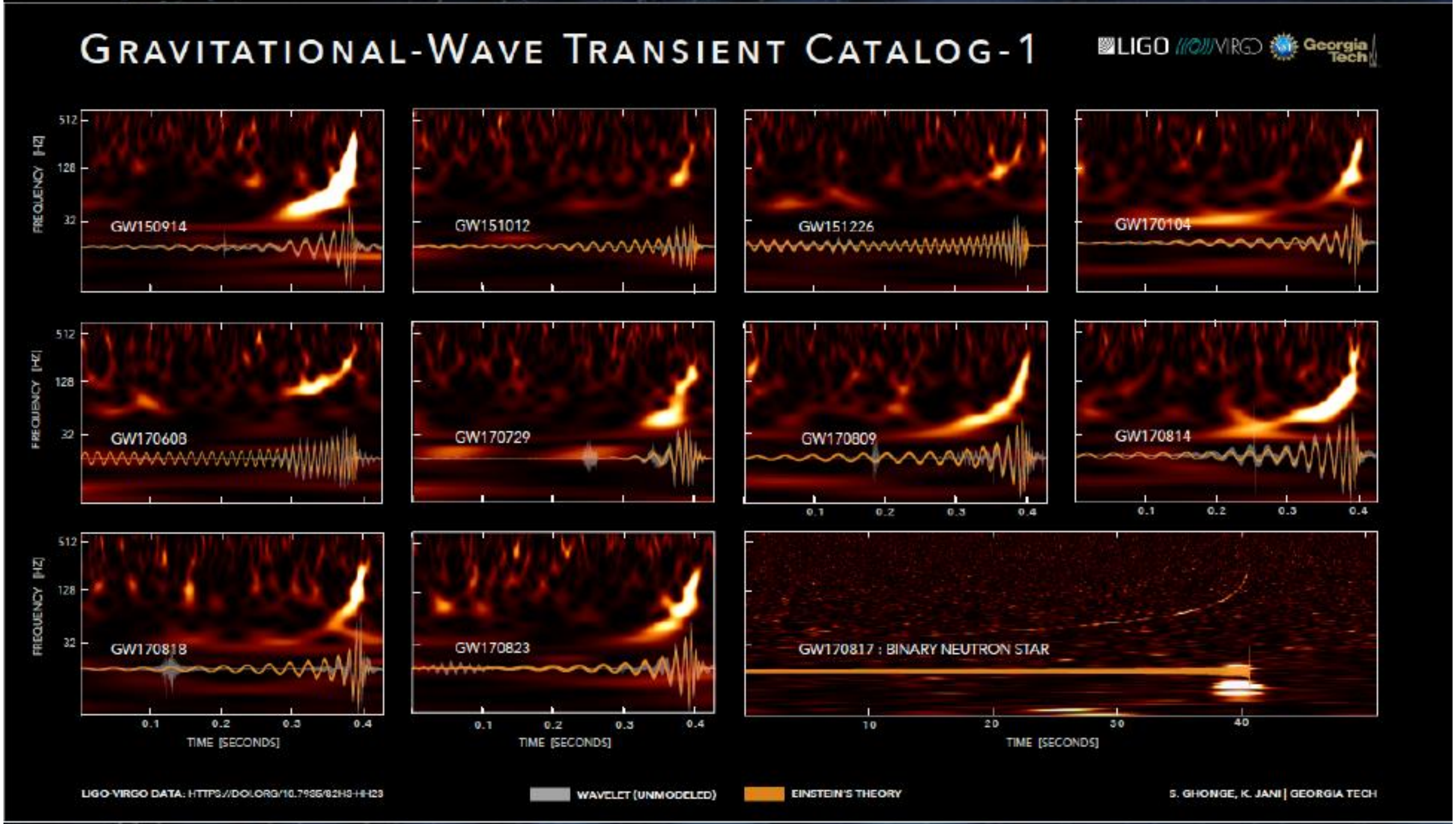
- Closed wall collapse leads to primordial GW spectrum, peaked at $\nu_0 = 3 \cdot 10^{11} (\Lambda / f) Hz$ with energy density up to

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

- 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

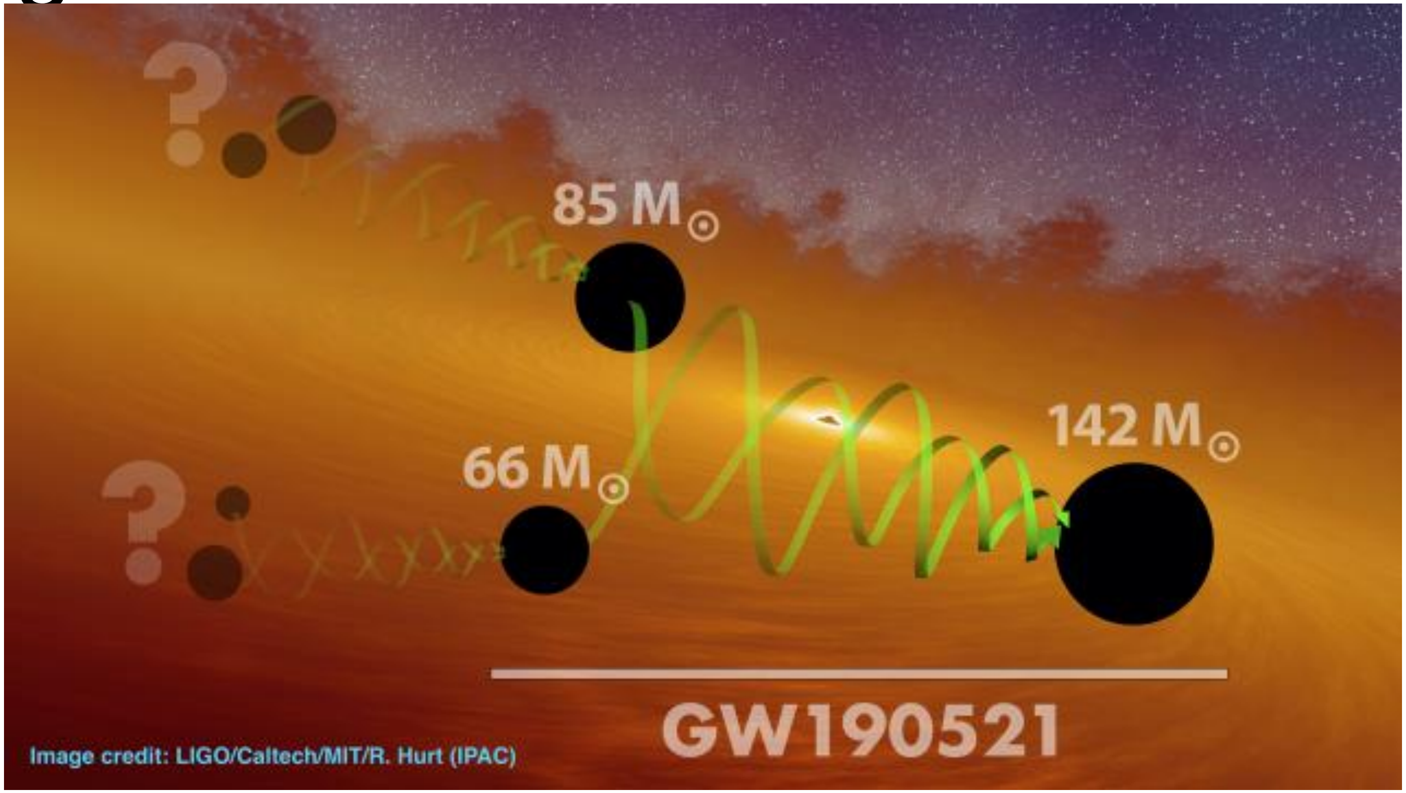
- Median values and 90% credible intervals based on two GR waveform models
- GW170729: highest mass and most distant BBH observed to date (median values); has moderate spin
- GW170818: best localised BBH to date - HLV detection
- Results consistent with previously published ones

| Event | $m_1/\mathrm{M}_\odot$ | $m_2/\mathrm{M}_\odot$ | $\mathcal{M}/\mathrm{M}_\odot$ | $\chi_{\mathrm{eff}}$ | $M_\mathrm{f}/\mathrm{M}_\odot$ | $a_\mathrm{f}$ | $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$ | $\ell_{\mathrm{peak}}/(\mathrm{erg\,s}^{-1})$ | $d_L/\mathrm{Mpc}$ | $z$ | $\Delta\Omega/\mathrm{deg}^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 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 | $1.46^{+0.12}_{-0.10}$ | $1.27^{+0.09}_{-0.09}$ | $1.186^{+0.001}_{-0.001}$ | $0.00^{+0.02}_{-0.01}$ | $\leq 2.8$ | $\leq 0.89$ | $\geq 0.04$ | $\geq 0.1 \times 10^{56}$ | $40^{+10}_{-10}$ | $0.01^{+0.00}_{-0.00}$ | 16 |
| GW170818 | $35.5^{+7.5}_{-4.7}$ | $26.8^{+4.3}_{-5.2}$ | $26.7^{+2.1}_{-1.7}$ | $-0.09^{+0.18}_{-0.21}$ | $59.8^{+4.8}_{-3.8}$ | $0.67^{+0.07}_{-0.08}$ | $2.7^{+0.5}_{-0.5}$ | $3.4^{+0.5}_{-0.7} \times 10^{56}$ | $1020^{+430}_{-360}$ | $0.20^{+0.07}_{-0.07}$ | 39 |
| GW170823 | $39.6^{+10.0}_{-6.6}$ | $29.4^{+6.3}_{-7.1}$ | $29.3^{+4.2}_{-3.2}$ | $0.08^{+0.20}_{-0.22}$ | $65.6^{+9.4}_{-6.6}$ | $0.71^{+0.08}_{-0.10}$ | $3.3^{+0.9}_{-0.8}$ | $3.6^{+0.6}_{-0.9} \times 10^{56}$ | $1850^{+840}_{-840}$ | $0.34^{+0.13}_{-0.14}$ | 1651 |

# Binaries of massive PBHs?

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

# GW190521: A Binary Black Hole Merger with a Total Mass of 150 M_o




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

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

# ANTIMATTER STARS IN BARYON ASYMMETRIC UNIVERSE

# Antimatter from nonhomogeneous baryosynthesis

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

# Survival of antimatter domains

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

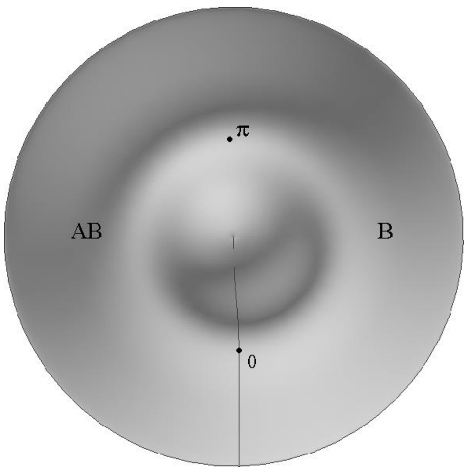
$$\partial n_b/\partial t = D(t)\partial^2 n_b/\partial x^2 - \alpha n_b$$ where $$D(t) \approx \frac{3T_\gamma c}{2\rho_\gamma \sigma_T}$$

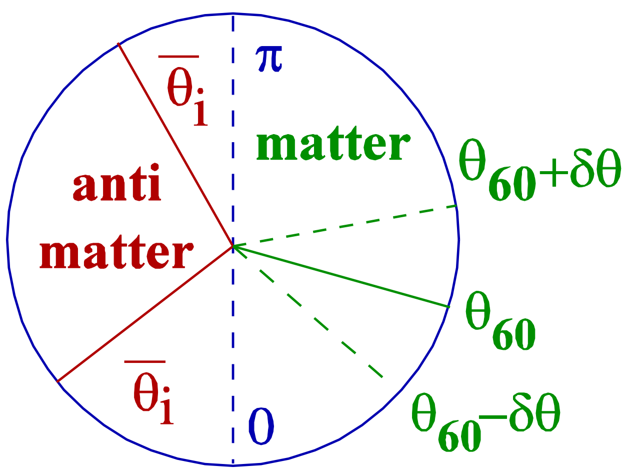
**The minimal surviving scale is given by**

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

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

# Nonhomogeneous spontaneous baryosynthesis




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

**see also talk by AM Lecian*

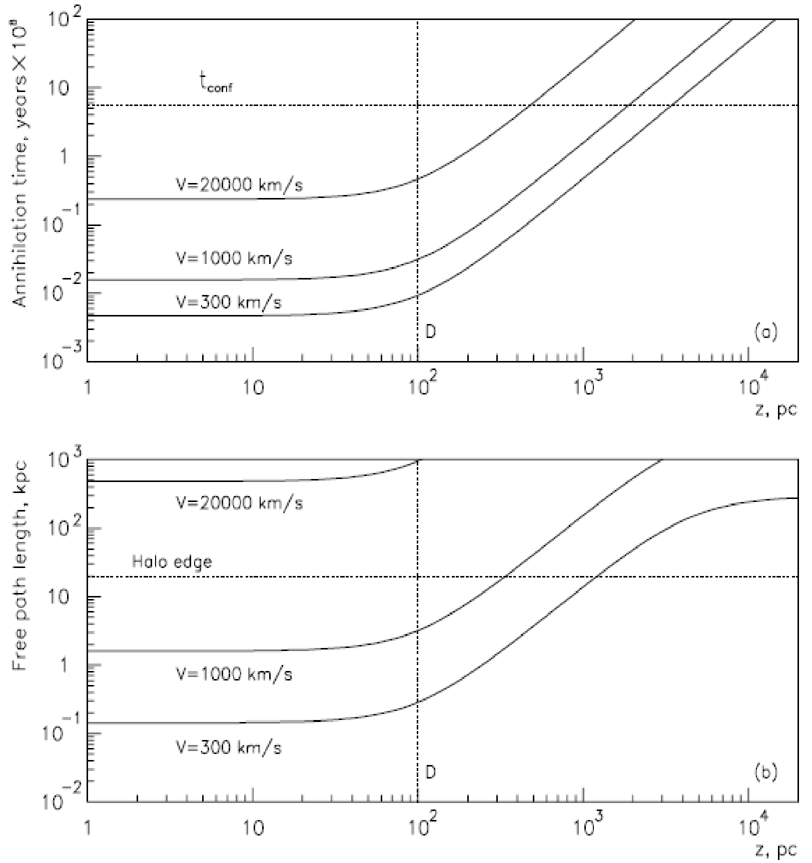
# Antimatter in galaxies

| 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.**

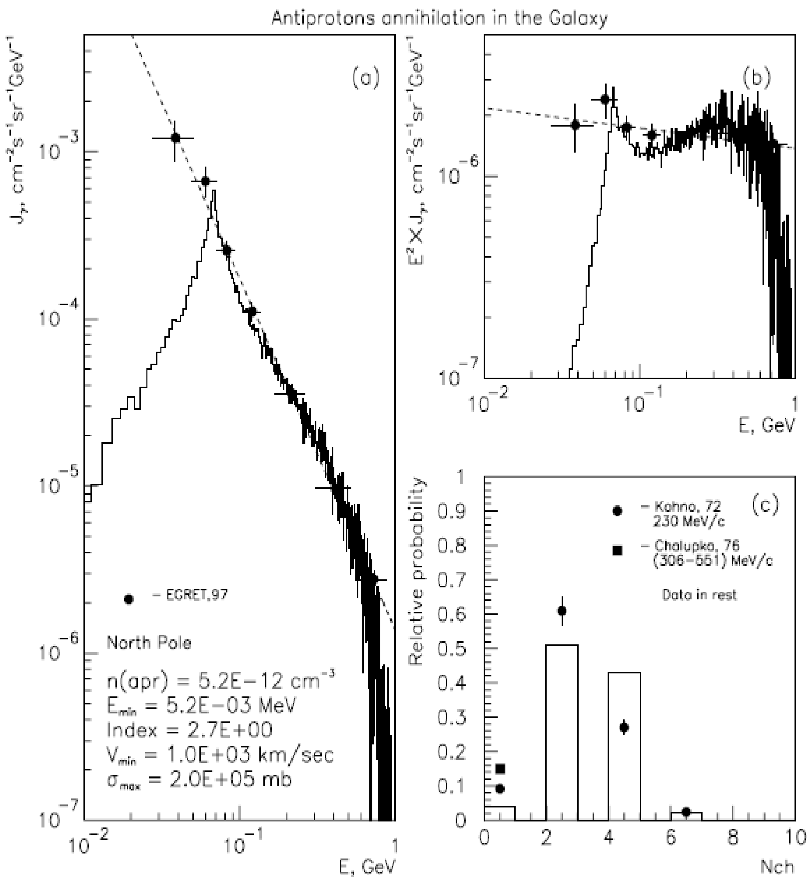
**In our Galaxy from 1000 to 100000 antimatter stars can exist in a form of antimatter globular cluster (Khlopov, 1998). Being in halo, such cluster is a faint gamma ray source, but antimatter from it pollutes Galaxy and can be observed indirectly by annihilation, or directly as anti-meteorites or antinuclei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

# Antimatter pollution of Galaxy



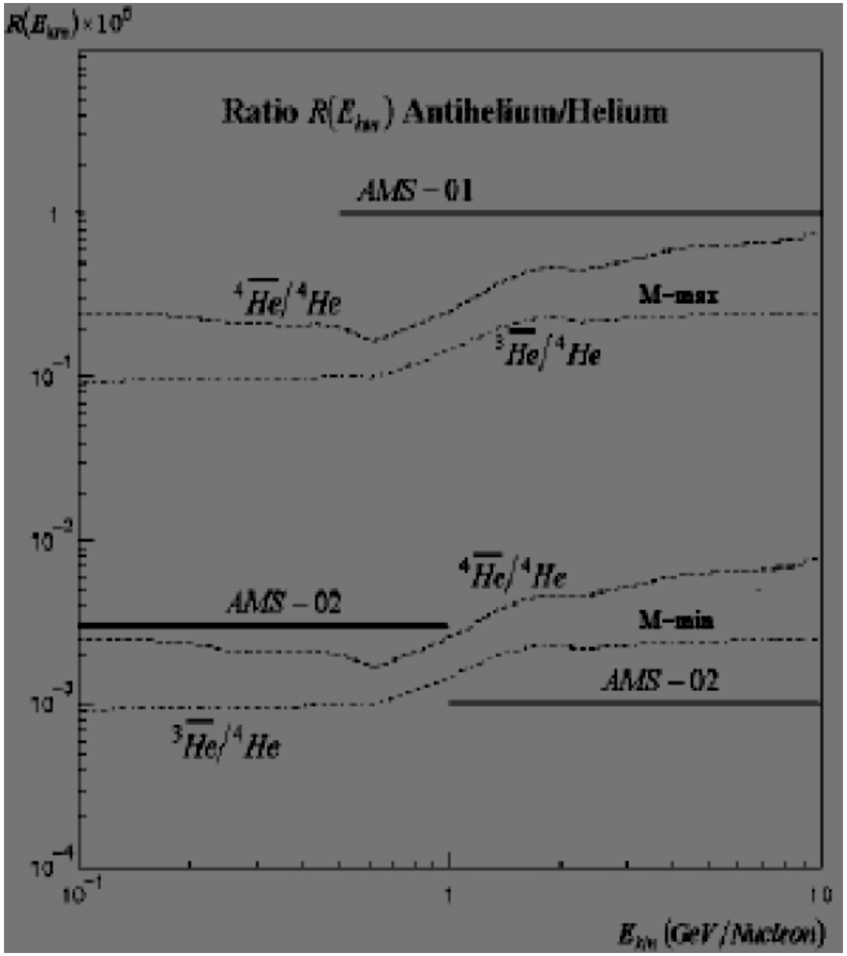

- Since antihydrogen is dominant in antimatter composition, the Galaxy is dominantly polluted by antiprotons.
- Their lifetime in Galaxy depends on their velocity and density of surrounding matter.

# Gamma background from antimatter annihilation in Galaxy




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

# Cosmic antihelium test for antimatter stars in Galaxy




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

# First signal from antimatter stars in AMS02?

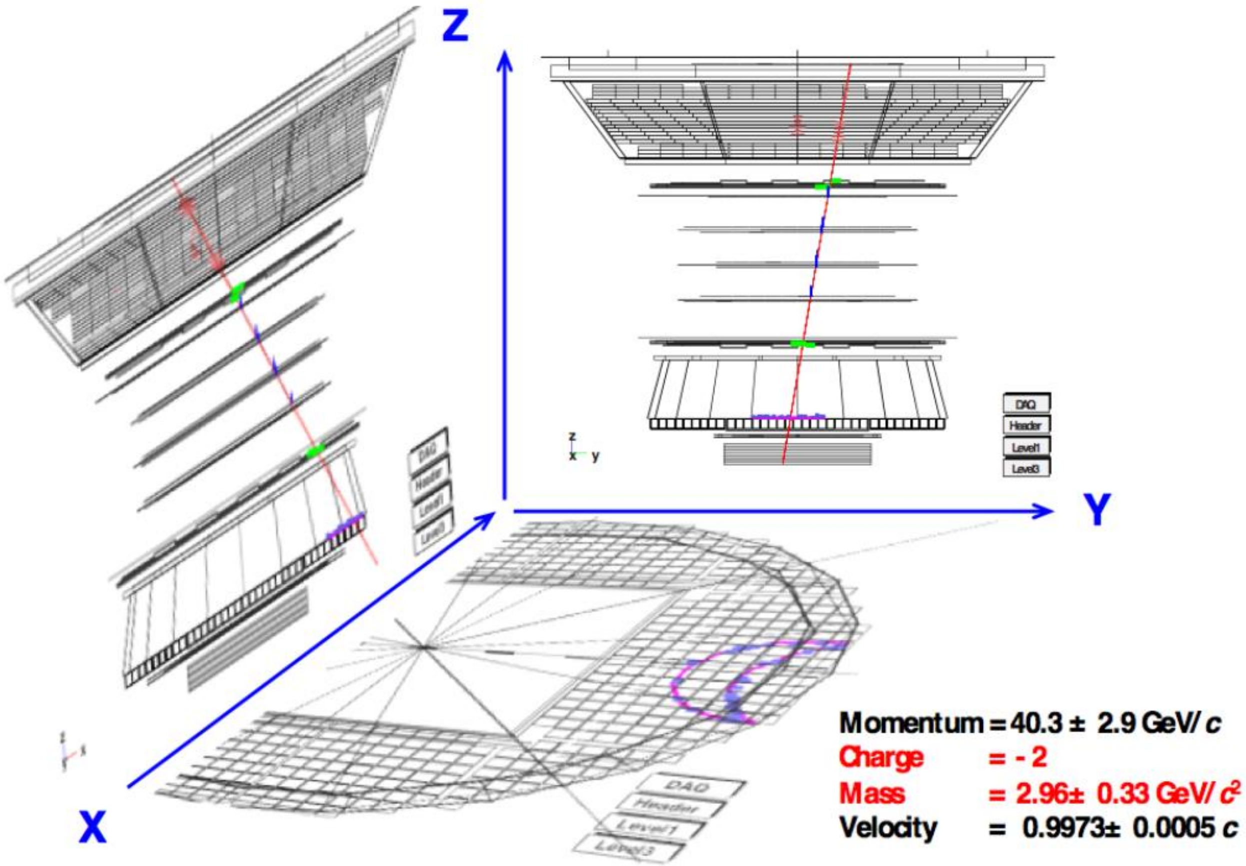



Figure 14. An antihelium candidate.

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

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

**ABSTRACT**

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

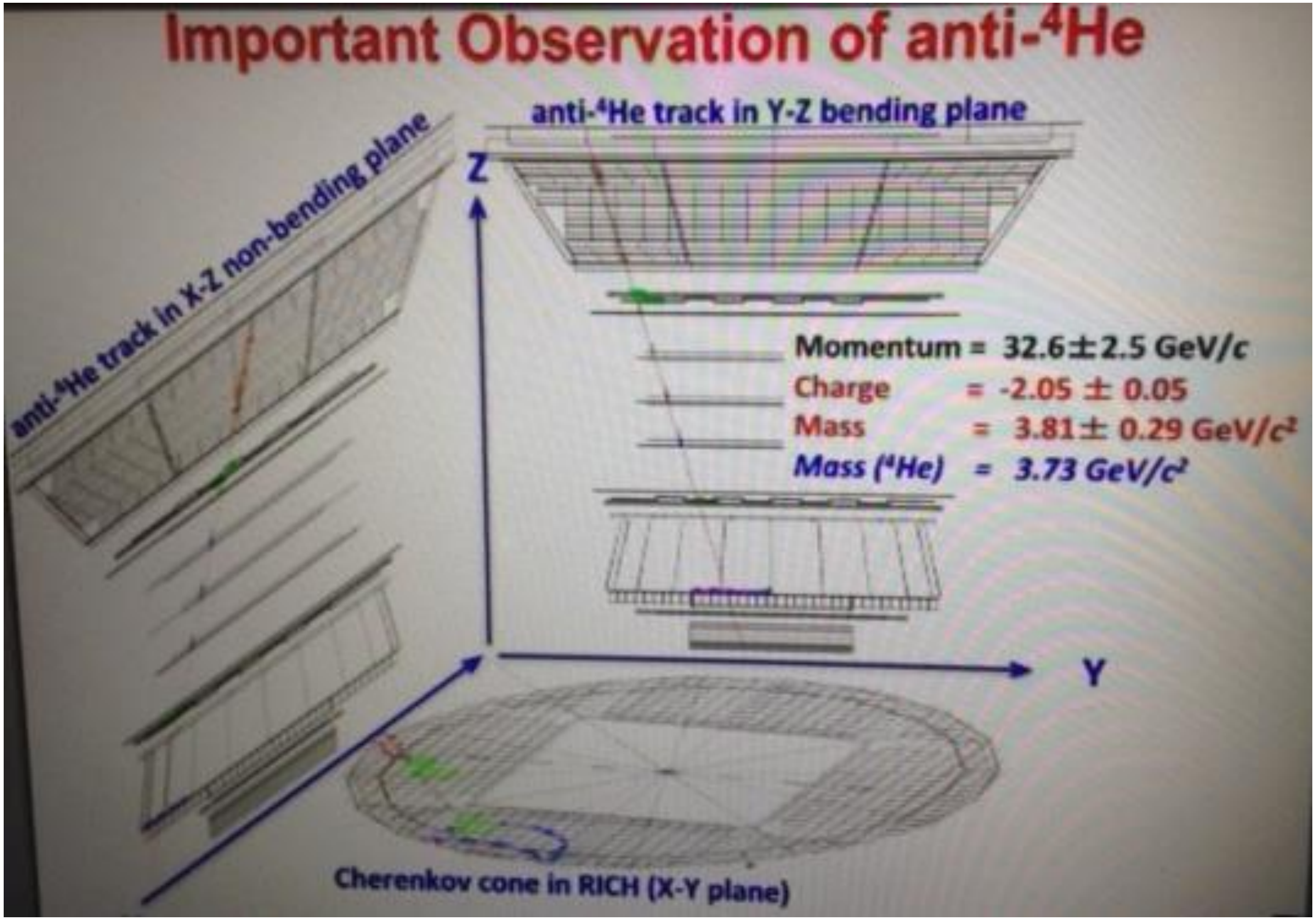
*Samuel Ting*

*24 May 2018*

# Antihelium events

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

# Antihelium-4 candidates!




*Samuel Ting 24 May 2018*

# Puzzle of antiHe-3 and antiHe-4 ratio

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

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

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

# Conclusions

• **Physical basis of the modern cosmology implies processes in very early Universe, which involve new physics.**

•**Dfferent dark matter candidates follow from different motivations to extend he Standard model and can co-exist in multi-component dark matter**

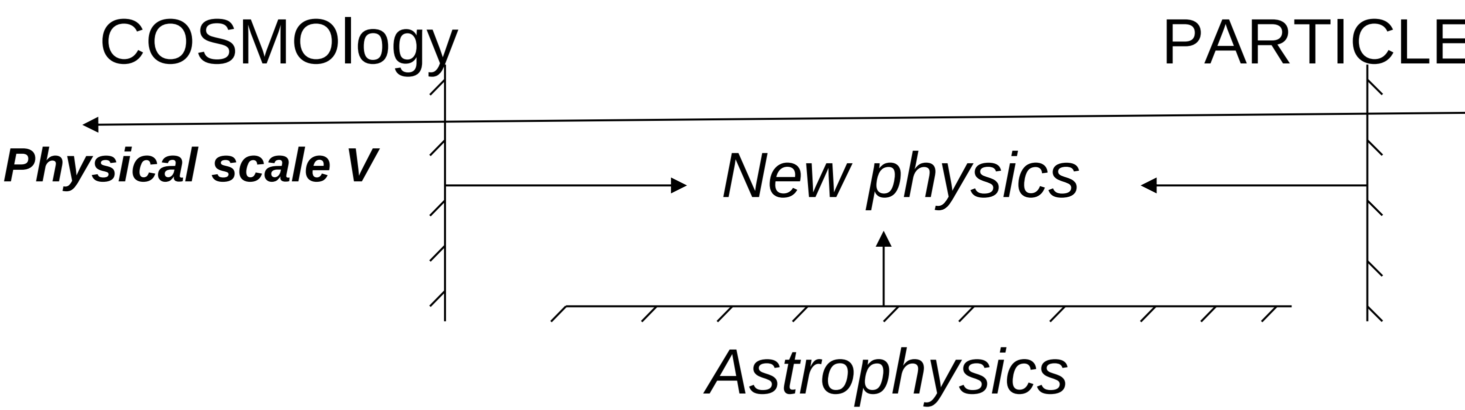
•**New stable and metastable particles, topological defects, evaporating PBHs provide probes for physics of very early Universe**

•**Strong primordial nonlinear structures (massive PBH clouds, strong nonhomogeneities of baryonic matter and even antimatter stars) can provide multimessenger cosmological probes for physics of inflationary models with baryosynthesis and dark matter.**

•**The set of these probes of new physics reflects the basic ideas of cosmoparticle physics in studies of fundamental relationship of cosmology and particle physics.**

# Basic ideas of cosmoparticle physics

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




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

# 2021 – UN announced as the A.D.Sakharov’s year

- It may be a good occasion for us to celebrate 100$^{th}$ Anniversary of A.D.Sakharov by new achievements in studies of physics and cosmology beyond the Standard models.

Session 8: The Universe of Andrei Sakharov

universe
an Open Access Journal by MDPI

at the 1st Electronic Conference on Universe

to be held online 22/02/2021 - 28/02/2021

may be one of possible platforms for such discussion