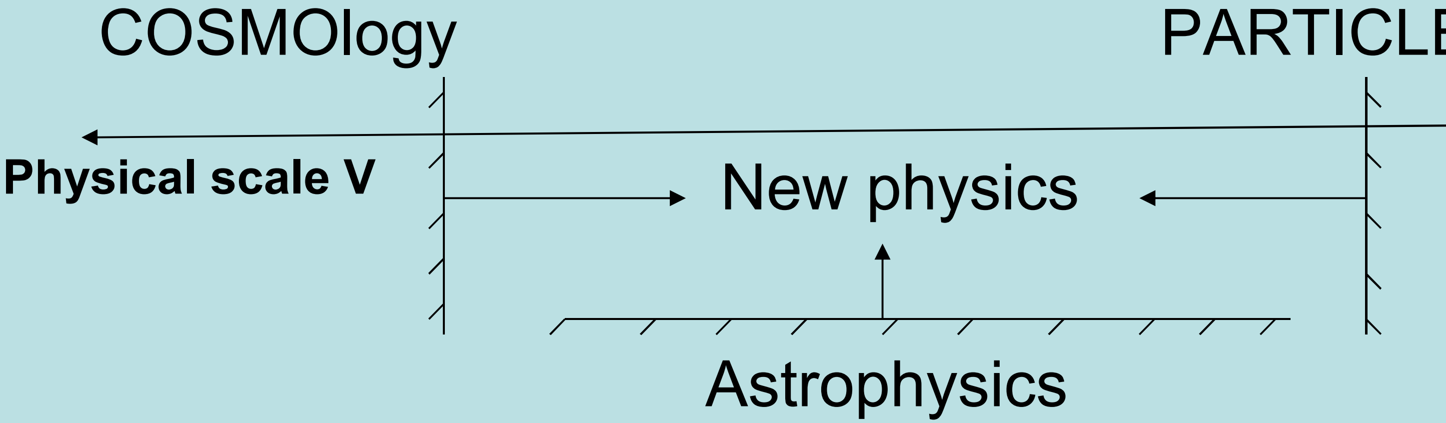
Cosmoparticle physics - the fundamental relationship of cosmology and particle physics

Lecture from the course

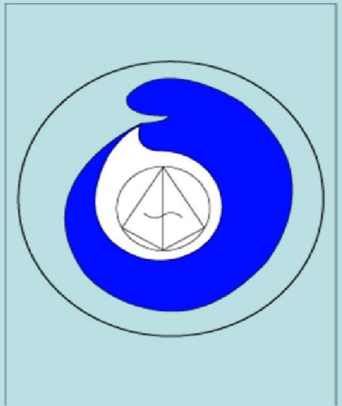
« Introduction to cosmoparticle physics »

Basic ideas of cosmoparticle physics

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



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



Problem of quark-lepton families

- There are free families of quarks and leptons with apparent symmetry of their interactions and apparent hierarchy of their mass states.

$$\begin{pmatrix} \nu_e \\ e \\ u \\ d \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \\ c \\ s \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \\ t \\ b \end{pmatrix}$$

Masses of fermions are determined by EW scale.

Masses of H-gauge bosons must be much heavier than this scale, due to the absence of flavor changing neutral currents (FCNC)

Gauge model of broken family symmetry

- To avoid symmetric mass terms L- and R-handed states of fermions should belong to different representations. It excludes orthogonal and vector-like groups of family symmetry and reduces the choice to SU(3) for 3 generations [8 H gauge bosons].
- Heavy partners F of ordinary fermions f acquire mass by Yukawa coupling with Higgs fields [3 multiplets $\langle \xi_i \rangle$ and singlet $h\langle \eta \rangle = \mu$]. Mixing of F and f induces SU(3) symmetry breaking pattern in mass pattern of quarks and leptons.
- To compensate anomalies heavy partners N of neutrinos are necessary. It provides the mechanism of neutrino mass.
- Natural choice of Higgs potential leads to additional global U(1) symmetry. It links physics of axion to physics of broken family symmetry.

Fermion masses

- Dirac see-saw mechanism of mass generation for quarks and charged leptons

$$f_L \quad g\langle\varphi\rangle \quad F_R \quad G\langle\xi_i\rangle \quad F_L \quad h\langle\eta\rangle \quad f_R$$

$$m_f = \frac{h\langle\eta\rangle}{G\langle\xi_i\rangle} g_f\langle\varphi\rangle$$

- Maiorana see-saw mechanism for neutrino mass.

$$\nu_L \quad g\langle\varphi\rangle \quad N_R \quad G\langle\xi_i\rangle_{sym} \quad \overline{N}_L \quad g\langle\varphi\rangle \quad \overline{\nu}_R$$

$$m_\nu = \frac{g_f\langle\varphi\rangle}{G\langle\xi_i\rangle} g_f\langle\varphi\rangle = m_f \frac{g_f\langle\varphi\rangle}{h\langle\eta\rangle}$$

- Pattern of symmetry breaking

$$SU(3)\otimes U(1) \xrightarrow[\langle\xi_0\rangle]{} SU(2)\otimes U'(1) \xrightarrow[\langle\xi_1\rangle]{} U''(1) \xrightarrow[\langle\xi_2\rangle\equiv V]{} I$$

- Results in mass pattern

$$m_i \propto \langle\xi_i\rangle^2$$

Reduction of number of parameters

Hierarchy of masses is not given by hands, but follows from pattern of family symmetry breaking

	e	μ	τ
e	m_e	s_{12}	s_{13}
μ	s_{12}	m_μ	s_{23}
τ	s_{13}	s_{23}	m_τ

	e	μ	τ
e	0	p	0
μ	p	0	q
τ	0	q	r

3 parameters instead of 9

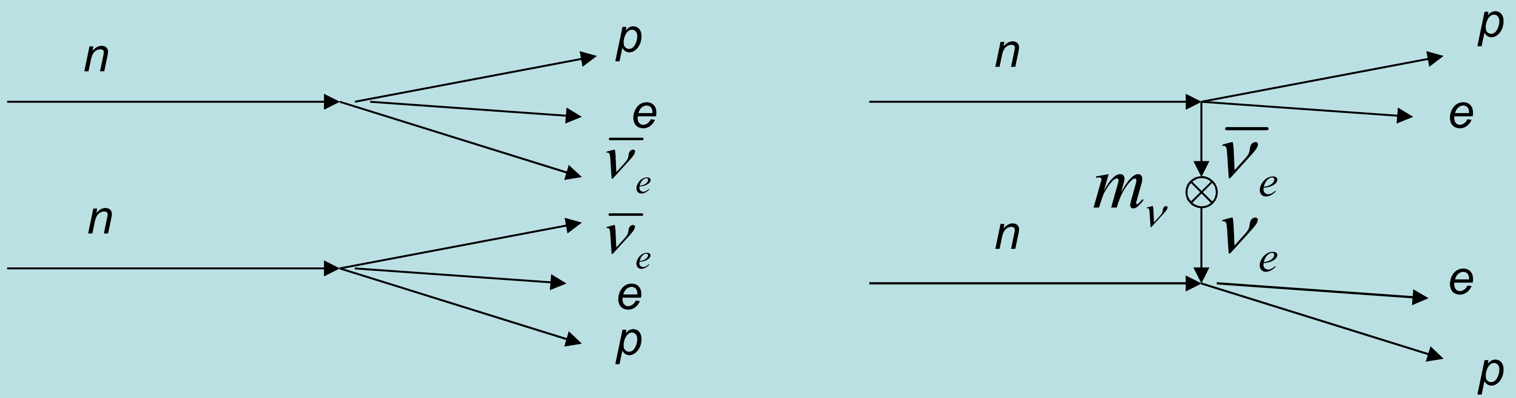
Archion

- The assumption that Higgs potential contains only terms, which can be generated by radiative effects of gauge and Yukawa couplings excludes the term $\propto p\xi_i\xi_j\xi_k$.
- It leads to additional global U(1) symmetry. Breaking of this symmetry results in the existence of Goldstone boson α .
- This boson shares the properties of Majoron, familon and axion and was called archion.
- Archion couplings are proportional to 1/*V* and its mass is given by

$$m_\alpha = C\frac{f_\pi}{V}m_\pi$$

Physical consequences

- FCNC, due to H-bosons $K \to \mu e; \overline{D}^0 \leftrightarrow D^0; \ldots$
- Mass of neutrino $m_\nu \propto V^{-1}$, neutrino oscillations, double neutrinoless beta-decay due to Majorana mass



- Archion decays $K \to \pi\alpha; \mu \to e\alpha; \ldots$
- Archion decays of massive neutrinos

$$\nu_H \to \nu_L \alpha \qquad \tau = \frac{V^2}{a_{HL}^2 m_H^3} \propto V^5$$

Astrophysical consequences

- Archion emission speeds up stellar evolution

$$t_s = \frac{Q}{L + L_\alpha} < t_s = \frac{Q}{L} \qquad L_\alpha \propto 1/V^2$$

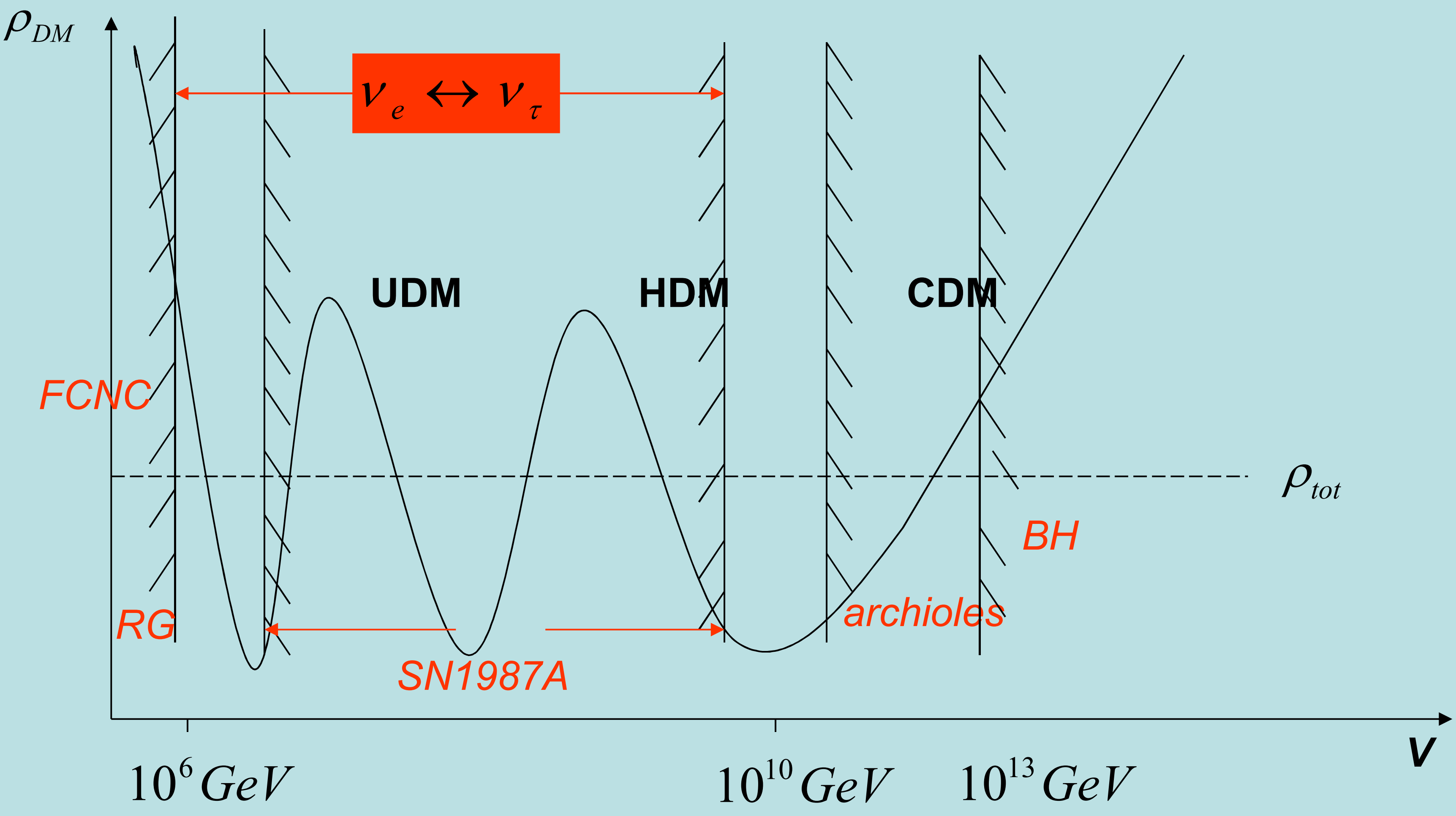
It puts lower limit $V > 10^6\,GeV$ from observation of red giants.

- Neutrino radiation from collapsing stars is suppressed due to energy loss by archion emission
- Detection of neutrino from SN1987A constrains $10^{10}\,GeV > V \geq 3 \cdot 10^6\,GeV$ (at low *V* archion energy losses decrease due to opacity of stellar matter)

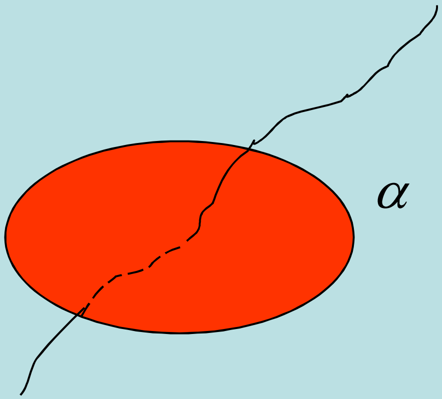
Dark matter candidates

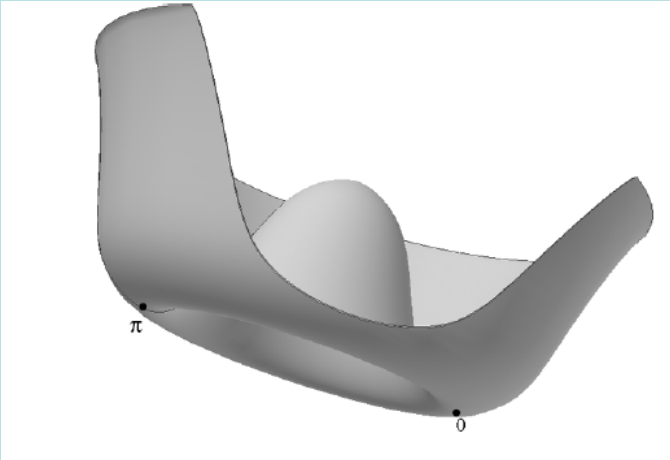
- Massive neutrinos $n_\nu = \frac{3}{11} n_\gamma , \quad \rho_\nu = m_\nu n_\nu \propto V^{-1}$
- Unstable massive neutrinos. Due to strong dependence $\tau(\nu_H \to \nu_L \alpha) \propto V^5$ at lower *V* neutrino lifetime can become $\tau < t_U$
- Primordial archion field oscillations $\rho_\alpha \propto V$
- Density of all the candidates is determined by the same scale of family symmetry breaking *V* and they can be treated within the unique framework.

Unified model of dark matter



Topological defects in axion cosmology





- **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 axion cosmic string network.**
- **The tilt in potential, generated by instanton effects at T~1GeV breaks continuous degeneracy of vacua. In the result axion field acquires mass, while string network converts into walls-bounded-by-strings structure in this second phase transition.**

Unstable topological defects

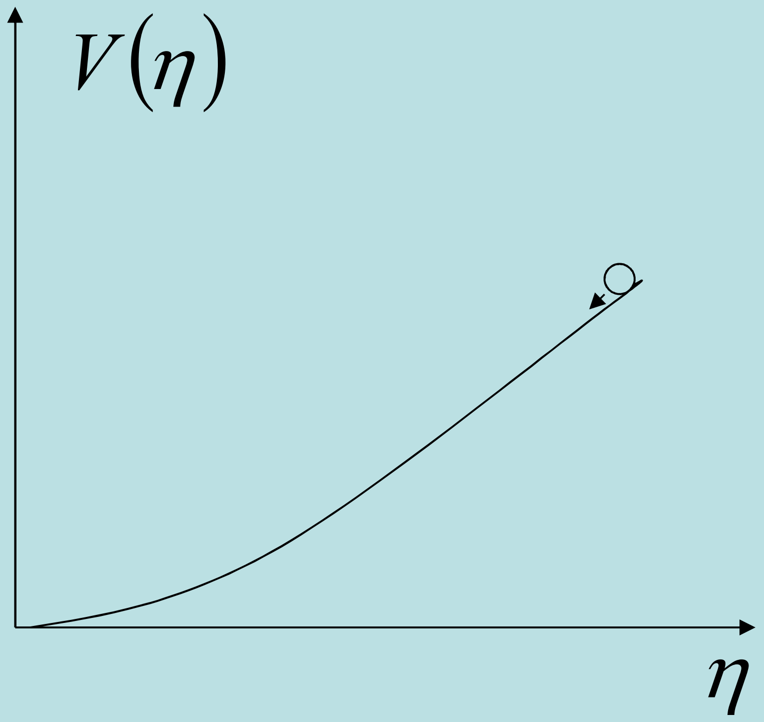
- The first phase transition gives rise to cosmic axion string network.
- This network converts in the second phase transition into walls-bounded-by-strings structure (walls are formed between strings along the surfaces $\alpha = \pi$), which is unstable.
- However, the energy density distribution of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

Inflation from horizontal unification

- Gauge theory of broken family symmetry also provides mechanisms for inflation and baryogenesis. It provides horizontal unification of physical basis for cosmology.



Singlet field η can play the role of inflaton and provide the mechanism for chaotic inflation. At large values of

$$\langle \xi_i \rangle > 10^{13}\,GeV$$

horizontal phase transitions can take place on inflationary stage, thus preventing formation of archioles.

Effects of horizontal phase transitions on inflationary stage

- After horizontal phase transition on inflationary stage closed circles, along which $\Delta\alpha = 2\pi$, inflate exponentially and axion string network can not arise on scale of the modern cosmological horizon, preventing archioles formation.
- However, such phase transitions provide several mechanisms for massive, intermediate and even supermassive BH formation.

Peaks of density fluctuations from phase transitions

- Owing to weak $\nu\eta^2\xi^2; \nu > \frac{h^2 G^2}{8\pi^2}$ interaction, on chaotic

inflationary stage corrections in Higgs potential

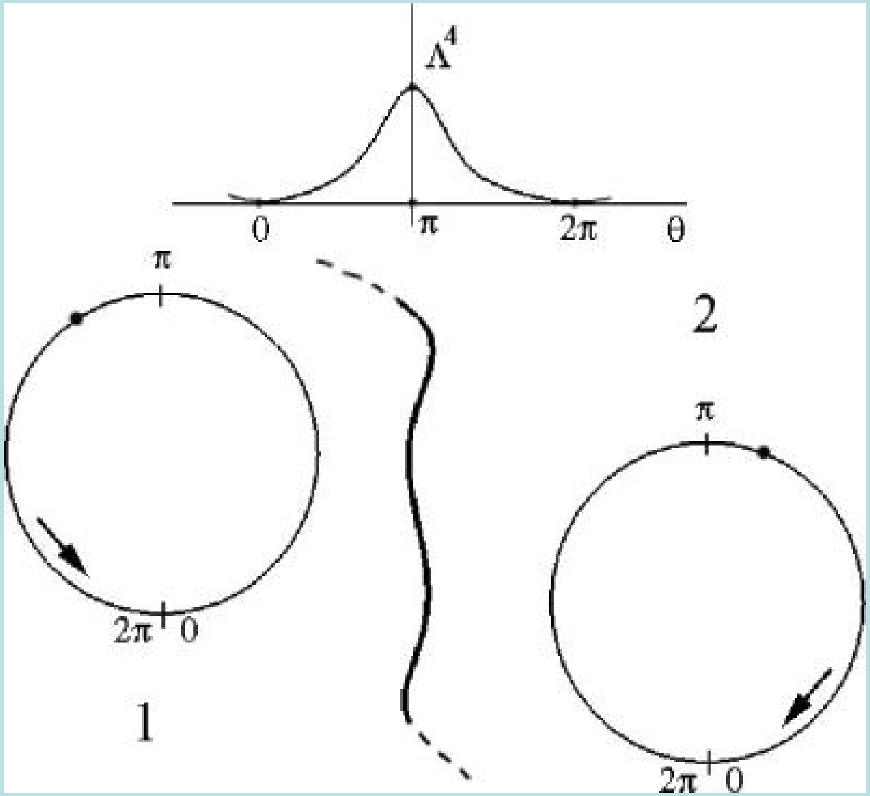
$$V(\xi,\eta) = \nu\xi^2\eta^2 - \frac{m^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4 \Rightarrow V(\xi,\eta) = \left(\nu\eta^2 - \frac{m^2}{2}\right)\xi^2 + \frac{\lambda}{4}\xi^4$$

result in horizontal phase transition, when inflaton field rolls down below

$$\eta = \eta_{cr} \cong \frac{m}{\sqrt{2\nu}}$$

It leads to peaks with $\delta_0 \geq 0.1$ on corresponding scales in spectrum of density fluctuations. Such peaks give rise to copius production of massive BHs.

Closed walls formation in Inflationary Universe

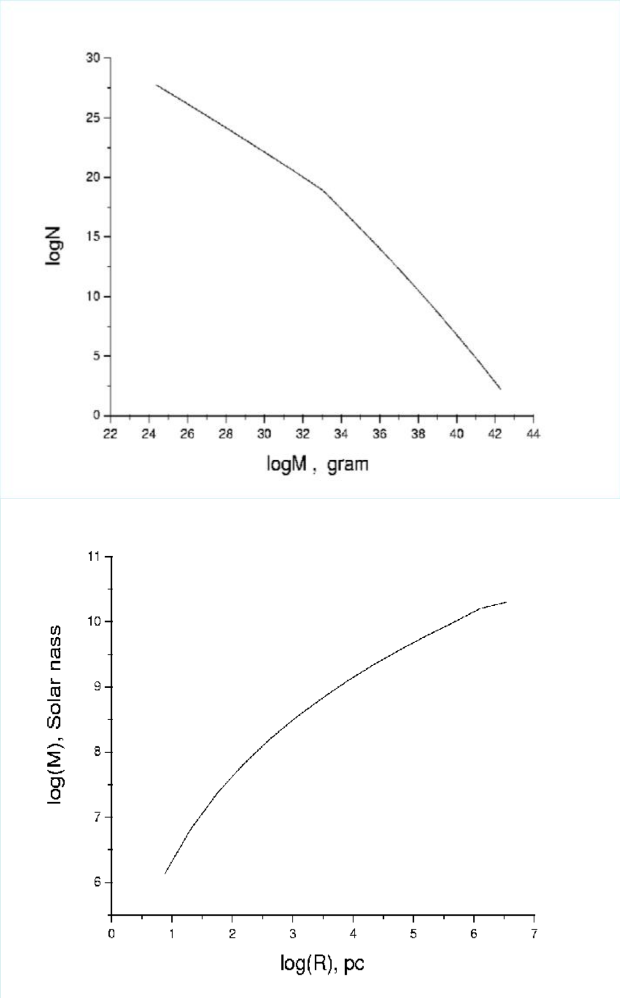


If horizontal phase transition takes place on inflationary stage, the value of phase α , corresponding to e-folding N~60, fluctuates

$$\Delta\alpha \approx H_{\text{infl}} / (2\pi V)$$

Such fluctuations can cross π and after coherent oscillations begin, regions with $\alpha > \pi$ occupying relatively small fraction of total volume are surrounded by massive walls. Collapse of such walls also lead to massive BH formation

Massive PBH clusters



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

Spectrum of Massive BHs

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

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

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

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

GW signals from closed wall collapse and BHs merging in clouds

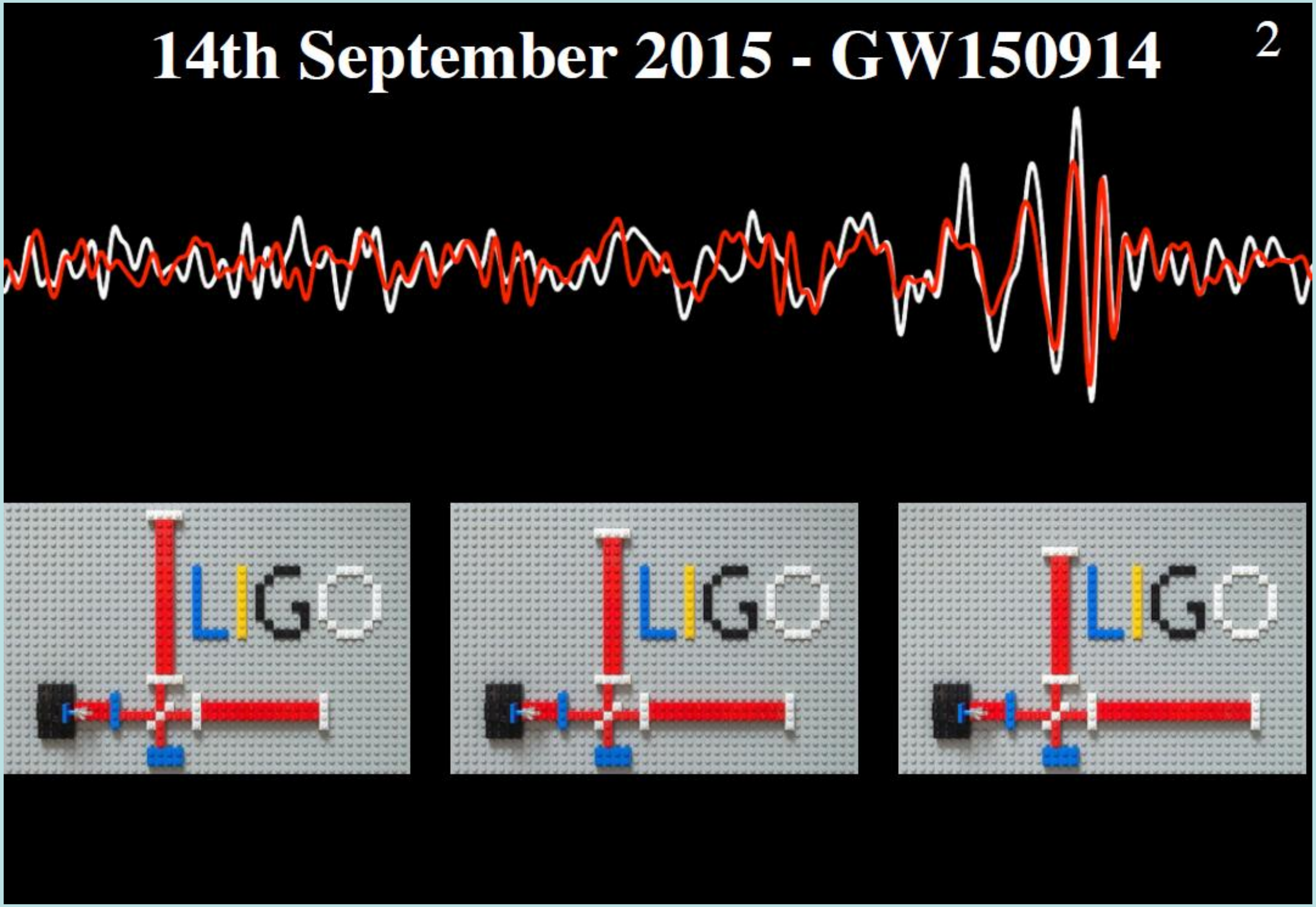
- Closed wall collapse leads to primordial GW spectrum, peaked at $\nu_0 = 3 \cdot 10^{11} (\Lambda / f) Hz$ with energy density up to

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

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

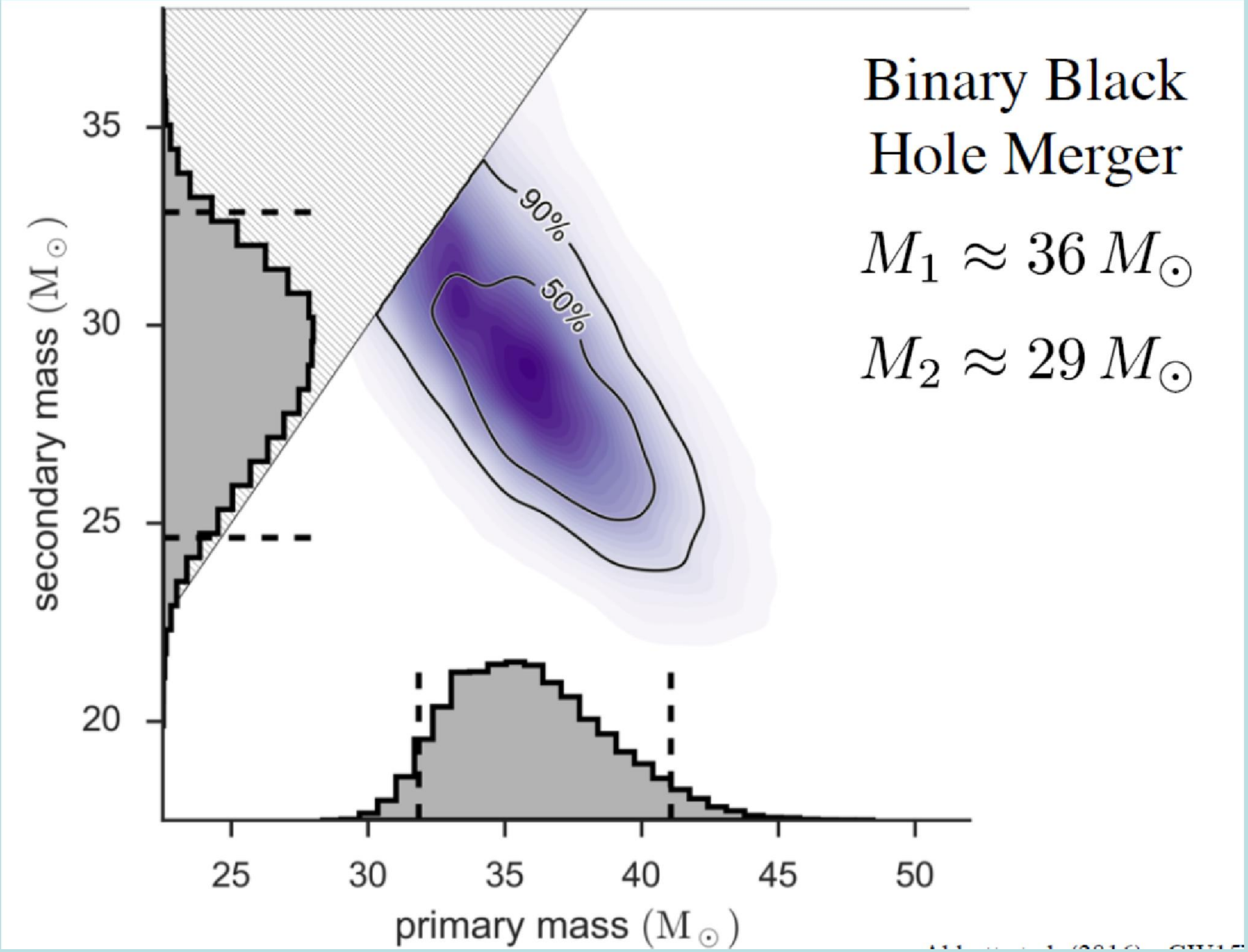
- Merging of BHs in BH cluster is probably detected by LIGO!.

The first GW signal!



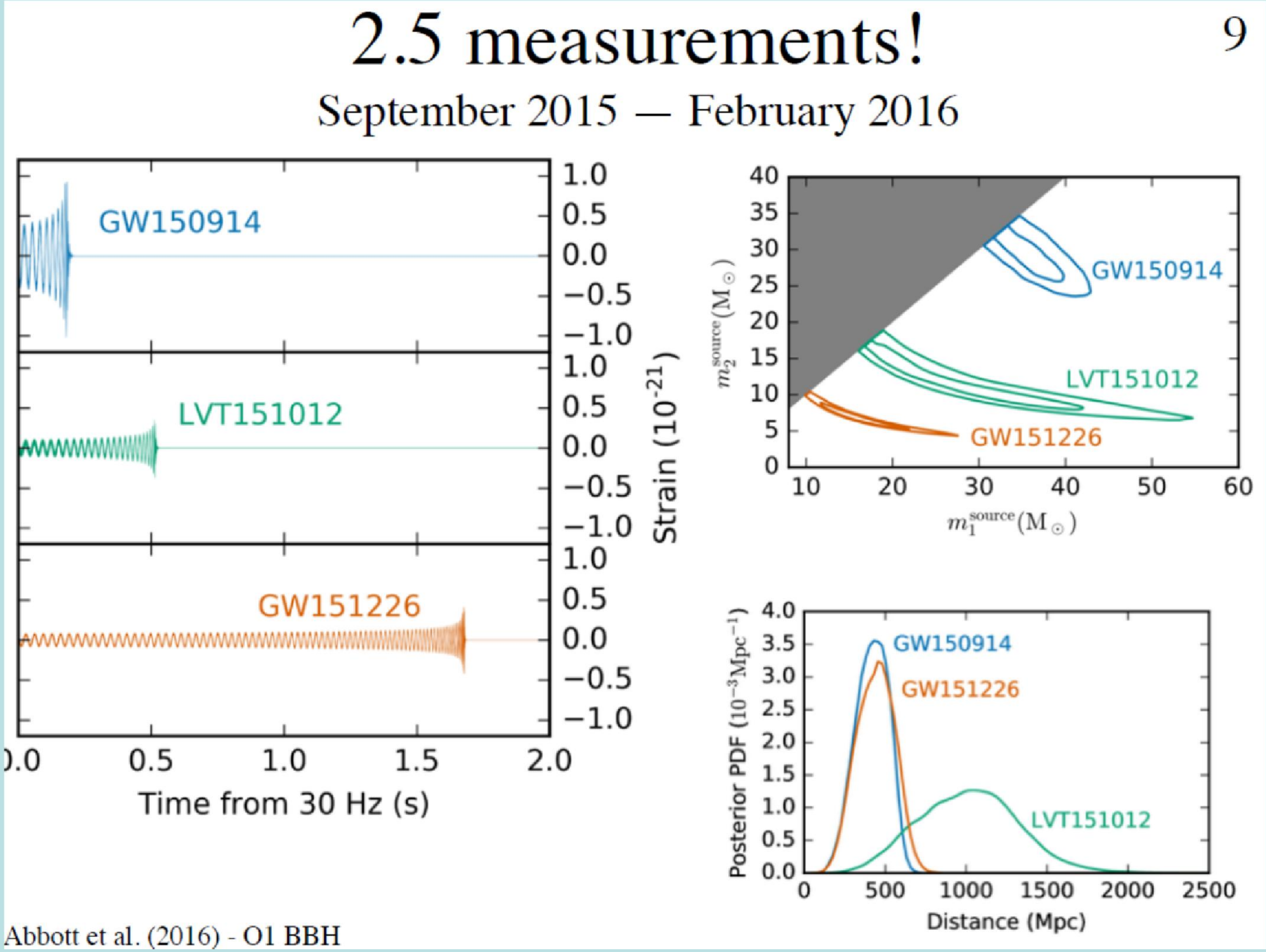
From VIA talk 09.12.2016 by P.Lasky

Abbott et al. (2016) - GW150914



From VIA talk 09.12.2016 by P.Lasky

GW astronomy!



From VIA talk 09.12.2016 by P.Lasky

Binaries of massive PBHs?

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

Baryogenesis from leptogenesis

- EW baryon charge nonconservation washes out baryon asymmetry with B-L=0.
- Majorana mass of neutrino corresponds to

$$\Delta L = 2$$

- Leptogenesis: CP violating effects in nonequilibrium L-nonconserving decays of N can lead to generation of lepton excess. Due to EW baryon charge nonconservation baryon excess is generated from lepton excess in processes, making

$$B + L \Rightarrow 0$$

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

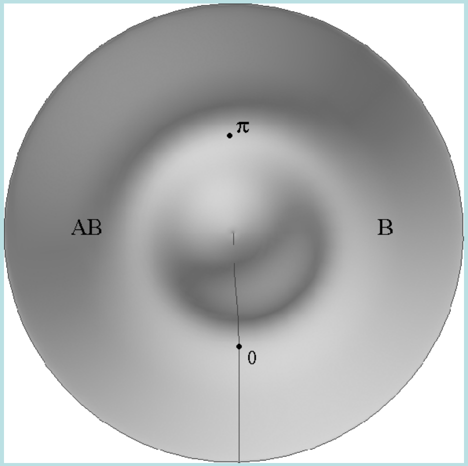
$$D(t) \approx \frac{3T_\gamma c}{2\rho_\gamma \sigma_T}$$

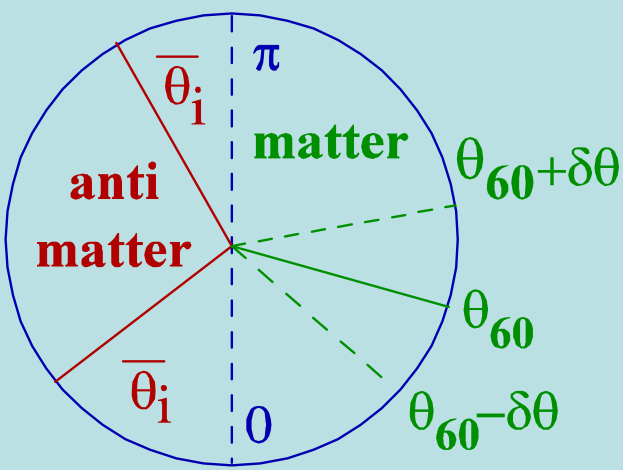
The minimal surviving scale is given by

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

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.

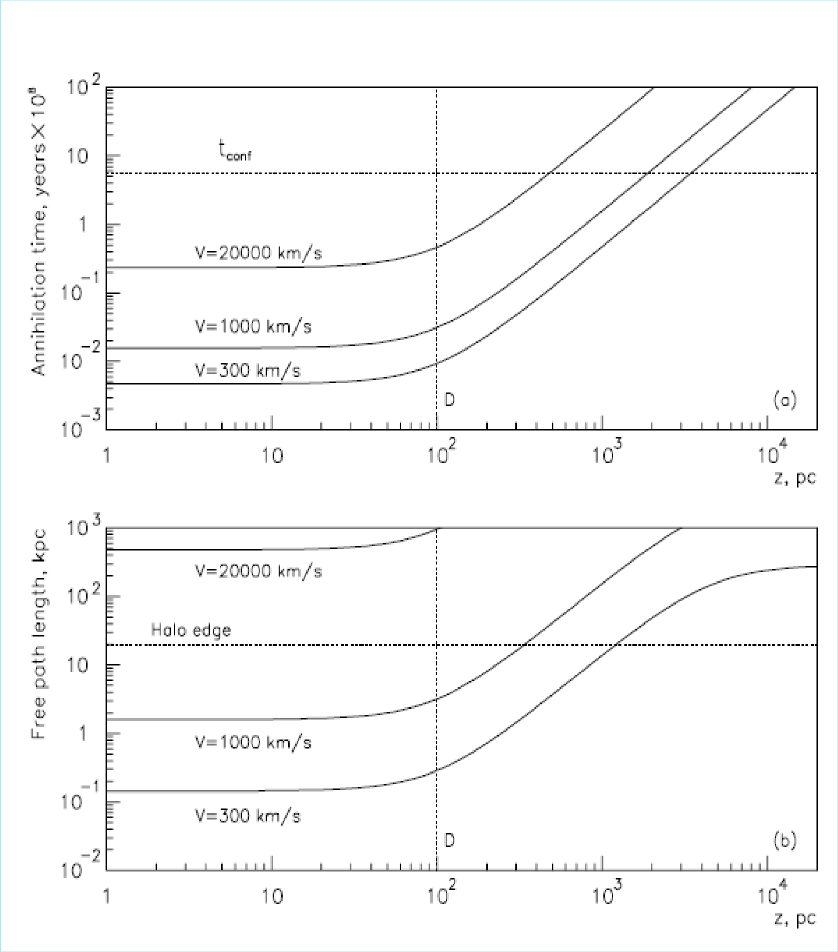
Antimatter in galaxies

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.

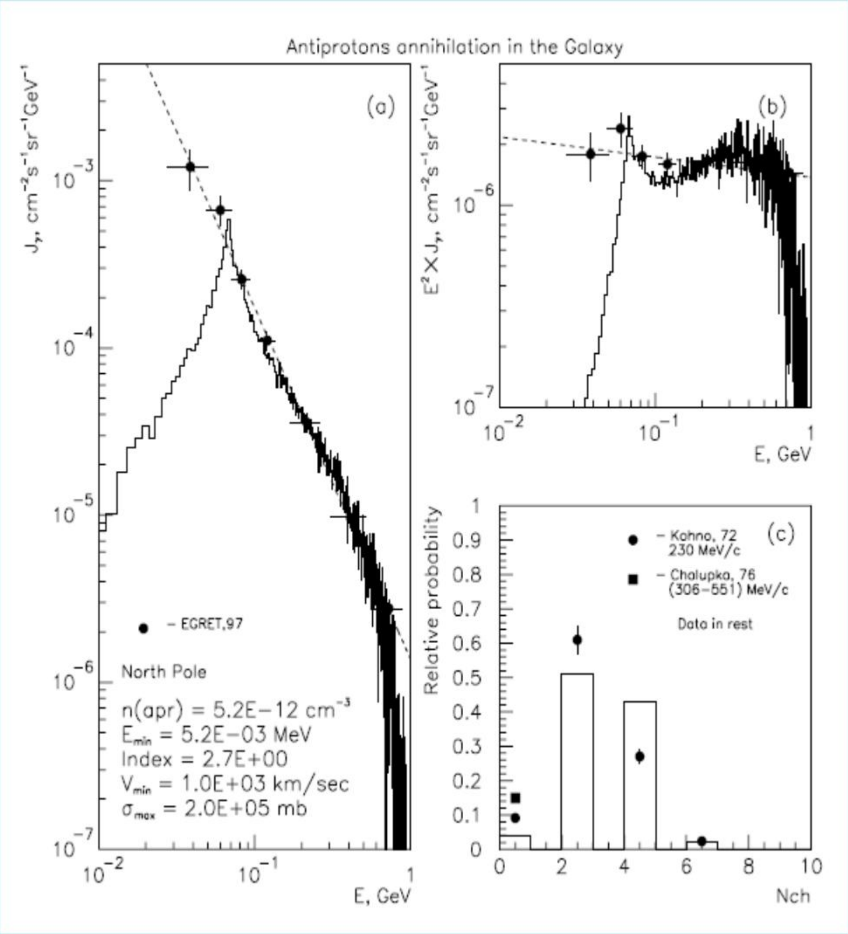
In our Galaxy from 1000 to 100000 antimatter stars can exist in a form of antimatter globular cluster (Khlopov, 1998). Being in halo, such cluster is a faint gamma ray source, but antimatter from it pollutes Galaxy and can be observed indirectly by annihilation, or directly as anti-meteorites or antinuclei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

Antimatter pollution of Galaxy



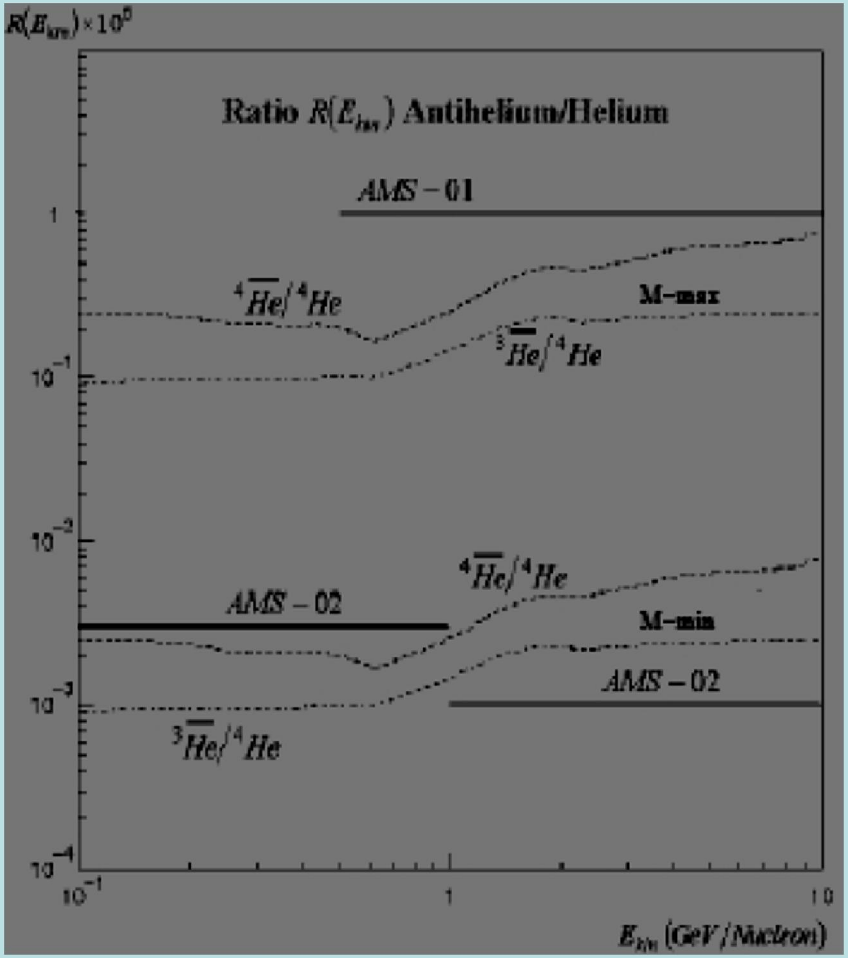
- Since antihydrogen is dominant in antimatter composition, the Galaxy is dominantly polluted by antiprotons.
- Their lifetime in Galaxy depends on their velocity and density of surrounding matter.

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?

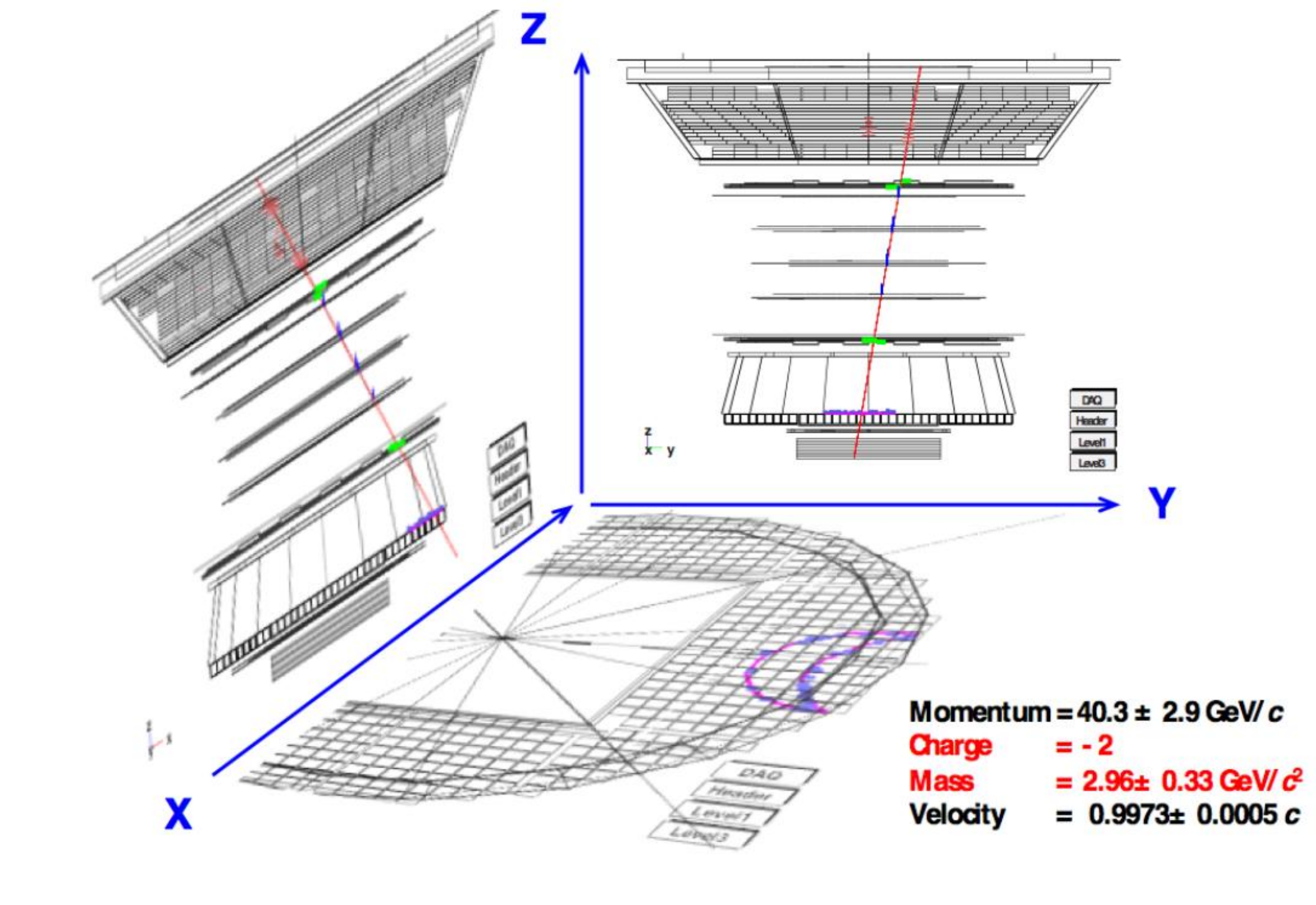


Figure 14. An antihelium candidate.

Presented in CERN on 08.12.2016 by Prof. S.Ting

Cosmological reflection of fundamental physical parameters

- Inflation driven by singlet field η is related to the mechanism of quark-charged leptons mass generation.
- Mechanism of neutrino Majorana mass is related to mechanism of baryosynthesis.
- Cold, warm and hot forms of dark matter, both stable and unstable follow from the unique theoretical framework and are realised pending of the scale V of family symmetry breaking.
- This model can hardly explain the dominant form of dark matter, but it illustrates methods of cosmoparticle physics.