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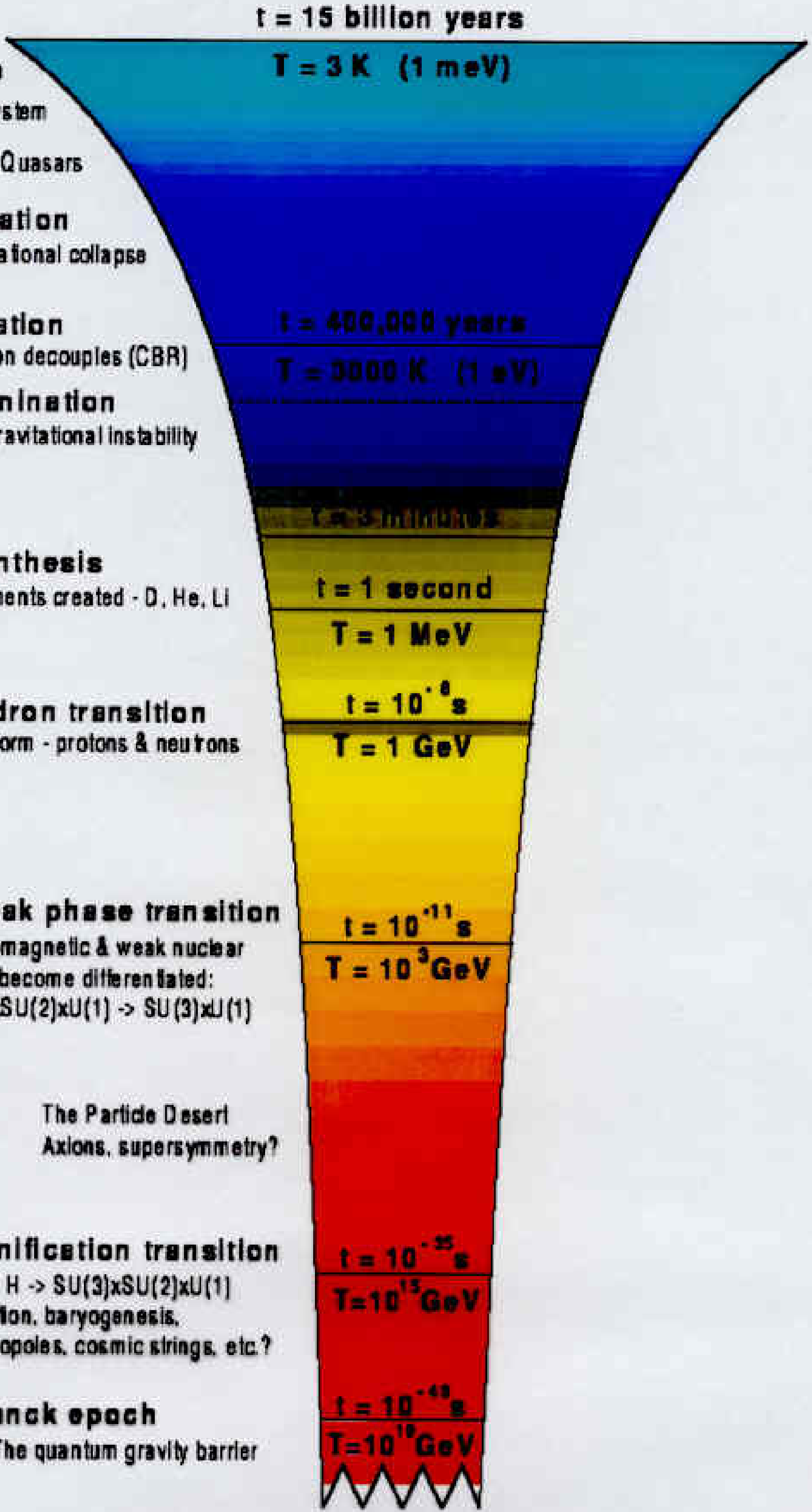
COSMOPHENOMENOLOGY
of
NEW PHYSICS

Big Bang history



Today t_0

Life on earth

Solar system

Quasars

Galaxy formation

Epoch of gravitational collapse

Recombination

Relic radiation decouples (CBR)

Matter domination

Onset of gravitational instability

Nucleosynthesis

Light elements created - D, He, Li

Quark-hadron transition

Hadrons form - protons & neutrons

Electroweak phase transition

Electromagnetic & weak nuclear forces become differentiated:
SU(3)xSU(2)xU(1) -> SU(3)xU(1)

The Particle Desert
Axions, supersymmetry?

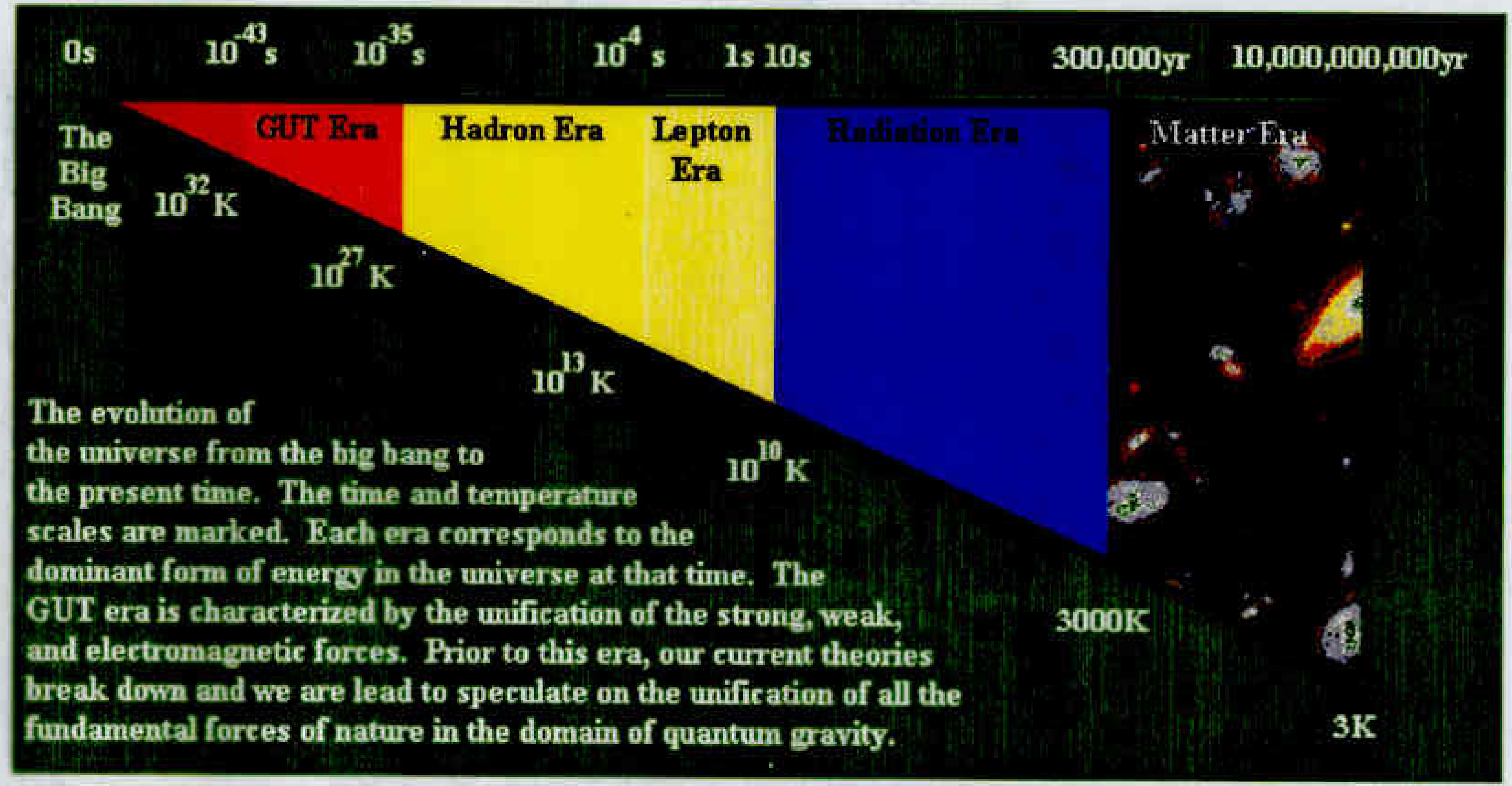
Grand unification transition

G -> H -> SU(3)xSU(2)xU(1)
Inflation, baryogenesis, monopoles, cosmic strings, etc.?

The Planck epoch

The quantum gravity barrier

The thermal history of the Universe

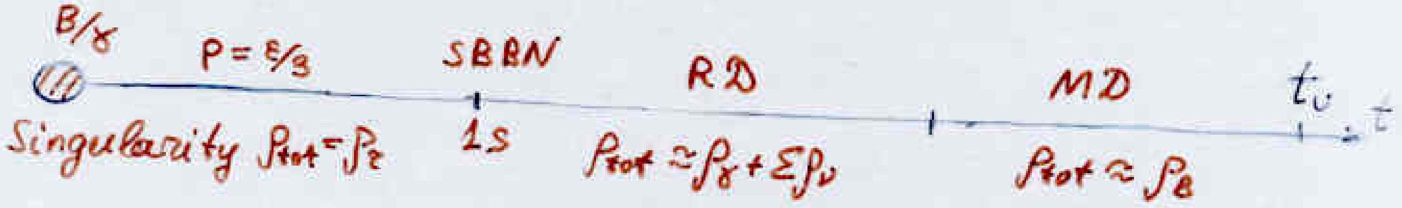


The evolution of the universe from the big bang to the present time. The time and temperature scales are marked. Each era corresponds to the dominant form of energy in the universe at that time. The GUT era is characterized by the unification of the strong, weak, and electromagnetic forces. Prior to this era, our current theories break down and we are lead to speculate on the unification of all the fundamental forces of nature in the domain of quantum gravity.

New standards in cosmology

New paradygma of inflational Universe with baryosynthesis and nonbaryonic dark matter

Old big bang scenario



New big bang scenario

Trivial comment - The true history of the Universe should account for all the three phenomena (all the three are based on the extentions of the SM on new particle physics), necessar for the modern cosmology $\Longrightarrow$ Nontrivial consequence - No practical realization of New big bang scenario can be reduced to these three phenomena only. The true history of the Universe should be much more complicated.

The true mystery of the crisis of the old big bang scenario is that it happens (if does, c.f. SBBN - ?) so late. The true cosmological picture is effectively masked by the old scenario.

We should refine the astrophysical probes for new cosmological phenomena to the extent, sufficient for their discrimination

Inflation

To solve the problems of Big Bang Universe (horizon, flatness, initial $\delta\rho/\rho$, primordial magnetic monopoles, ...)

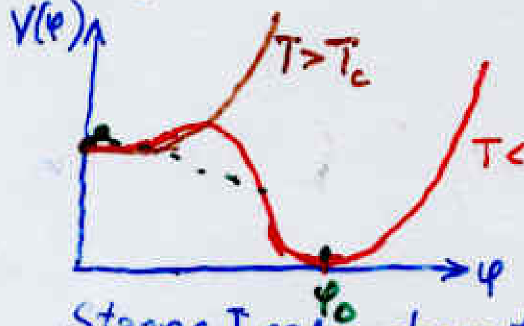
$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\varepsilon + 3p)$ if $p < -\varepsilon/3$ $\frac{\ddot{a}}{a} > 0$

deceleration acceleration

Inflaton? Its physical nature?

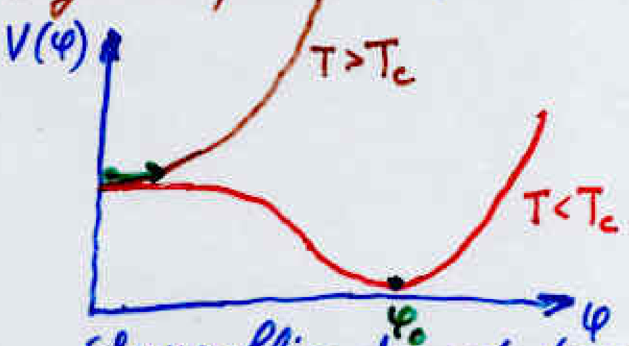
New elementary scalar field.

GUT Higgs scalar φ, $V(\varphi, T)$



Strong I order phase transition.
"Old" inflational scenario

High temperature phase transitions



slow rolling down to true vacuum
"New" inflational scenario

Chaotic inflation

Slow rolling down to true vacuum for any scalar field φ

c.f. $V(\varphi) = \frac{1}{2}m^2\varphi^2$

$\varphi = \Phi \cos mt$

at $t \ll \frac{1}{m}$ $p = -\varepsilon$

Extended inflation.

Selfsupported inflation

Phenomenology of inflation (A.D. Linde) should find physical grounds and cosmoparticle relevance

Baryosynthesis

quarks and antiquarks $T \gg m_N$ $\xrightarrow{\hspace{4cm}}$ $T \lesssim m_N$ baryons, no antimatter $\rightarrow t$

$\Delta B/\gamma$ initial baryon excess $\longrightarrow$ B/γ baryon asymmetry of the Universe

$$\left.\begin{array}{l}\Delta B \neq 0\\ \text{CP violation}\\ \text{out of equilibrium}\end{array}\right\} \frac{\Delta B}{\gamma} \neq 0 \quad \text{in baryon symmetric Universe}$$

GUT

$\Delta B \neq 0$

baroleptonic gauge fields, X $\longleftrightarrow$ $p \to e^+ \pi^0$ decay

$$n_X = n_{\bar X} \quad \left.\begin{array}{lll} X \to qq & & r\\ \searrow \bar q l & & 1-r\\ \bar X \to \bar q \bar q & & \bar r\\ \searrow q \bar l & & 1-\bar r \end{array}\right\}$$

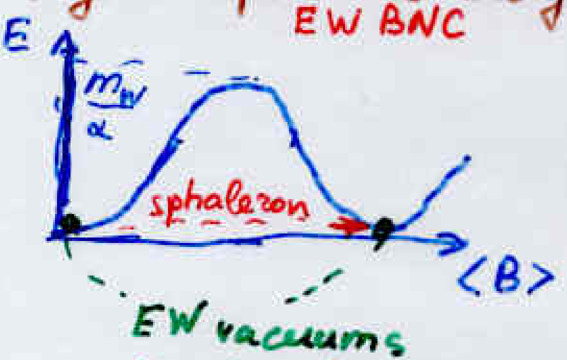
Owing to CP violation $r \neq \bar r$

$$\frac{\Delta B}{\gamma} = (r - \bar r)\frac{n_X}{\gamma}$$

SUSY

squarks, baryons with $s=0$, $\langle n_{sq} \rangle \neq 0$ squark condensate

High Temperature Baryon Nonconservation in Electroweak Theory



At $T \gg m_W$ sphalerons are in the equilibrium leading to $B+L \to 0$.

$\frac{\Delta B}{\gamma}$ with $(B-L)=0$ can be washed down

No direct relation to proton decay, but maybe (?) related to strong BNC at high energies. High temperature BNC takes place even in the standard model, but respective baryosynthesis seem to need smth beyond it.

$(\Delta L = 2)$ and EW BNC

Physics of Majorana neutrino mass $\underset{\Delta L = 2}{\overset{\nu_L \; m_\nu \; \bar\nu_R}{\longrightarrow}}$

Out of equilibrium $\Delta L = 2$ processes together with $(B+L) \to 0$ due to EW BNC can induce the observed baryon asymmetry of the Universe

Different physical models for inflation and baryosynthesis are not, in fact, alternative. They follow from different physical grounds and should be treated (in general) independently

Inflation

Strong I order phase transition → GUT Higgs potentials
Hierarchy of GUT sym. breaking

New or chaotic inflation scenario → refined GUT Higgs potentials
SUSY, R^2 gravity

extended inflation → Kaluzza-Klein models or superstrings

. . .

Baryosynthesis

CP violation in nonequilibrium
$X \begin{array}{l} \rightarrow qq \\ \searrow \bar{q}\,l \end{array} \rightarrow \frac{\Delta B}{\gamma}$ → GUT B-nonconservation

(sq) condensate with $\langle B \rangle \neq 0$ → SUSY GUT models

$(B+L) \to 0$ → extended SM
high T B nonconservation in EW model

$\Delta L \neq 0$ → Majorana neutrino mass physics

. . . . .

They should be selfconsistently considered together with the physics of nonbaryonic dark matter.

Hidden parameters of the modern Cosmology

The parameters ρ_{tot}, ρ_{b}, ρ_{dm} finding physical basis in inflation

$$\rho_{tot} = \rho_{crit} \quad \text{(simplest case)}$$

baryosynthesis

$$\rho_{b} = f\left(\frac{\Delta B}{\gamma}\right)$$

and nonbaryonic dark matter

$$\rho_{d.m.} = m_{d.m.} \cdot n_{d.m.}$$

are accompanied by additional (HIDDEN) parameters ρ_{PBH}, $\rho_{\bar{b}}$, ...

In particle physics $(\hbar = c = 1)$

metastable particles : $\tau \gg \frac{1}{m}$

In Cosmology, to be of cosmological significance

$$\tau \gg t(T \sim m) = \boxed{\frac{m_{Pl}}{m}} \cdot \frac{1}{m}$$

Following Noether's theorem:

Strict symmetry

$$\Downarrow$$

Conserved charge

The lightest particle, possessing strictly conserved quantum number should be absolutely stable.

So, conservation of electron charge $\Rightarrow$ stability of electron

baryon charge (approximate) conservation (meta) stability of proton

New strict (approximate) particle symmetries lead to new (meta)stable particle.

In this way cosmology probes the most fundamental structure of particle theory.

Very early Universe

Necessary elements

Inflation

$\frac{\delta\rho}{\rho}$ initial

overall homogeneity and isotropy

Baryosynthesis

B/γ

EW phase transition

QCD phase transition

$q, g \to N\bar{N}, \pi$

$\begin{pmatrix} e^+n \leftrightarrow \bar{\nu}p \\ ep \leftrightarrow \nu n \end{pmatrix} \to {}^4He$

Nucleo-Synthesis

Possible processes

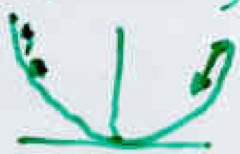
Spontaneous breaking of symmetry at $T < T_{cr}$

Topological defects (strings, walls, monopoles...)

Early dust-like stages

post-inflational stage $\langle p \rangle = 0$

$\varphi = \varphi_0 \cos mt \qquad t \gg \frac{1}{m}$



Freezing of metastable particles

$T \gg m$ - equilibrium

$T < m \qquad n_m/n_\gamma \propto \exp(-m/T) \xrightarrow[\text{at } T=T_f]{\text{freezing}} \exp(-m/T_f)$

freezing $\tau(m\bar{m} \to \dots) > t$

$n_m \cdot (\sigma_{ann} v)\, t < 1$

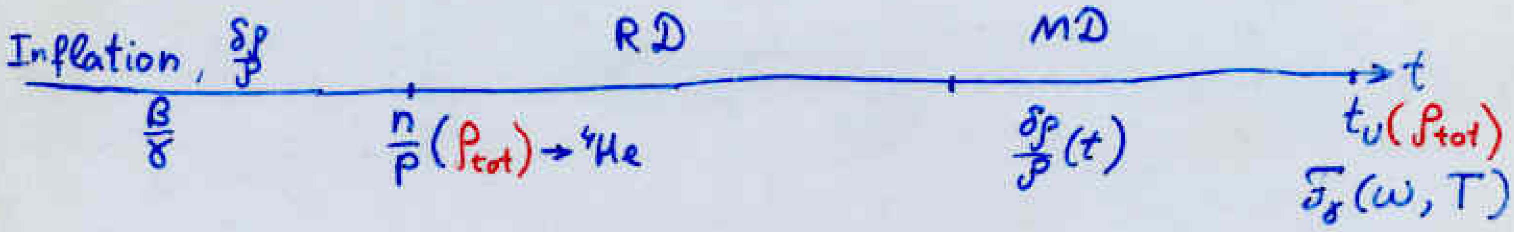
$$\nu = \frac{n_m}{n_\gamma}\Big|_{\text{frozen}} \sim \frac{1}{m \cdot \sigma_{ann} \cdot m_{pl}}$$

At $\nu m > T$

$\rho_m = m \cdot \nu \cdot n_\gamma > \rho_\gamma \sim T \cdot n_\gamma$

m-domination in the Universe until $t \sim \tau$

Gedanken experiment



$\boxed{\text{Source}} \longrightarrow \boxed{\text{Detector}}$

Astrophysical data as the sample of experimental data from this Gedanken experiment.

Matter - structure of spatial distribution
- chemical composition

Thermal background - spectrum
- isotropy

Nonthermal background - Xray, γ-ray, UV, IR, optical, radio

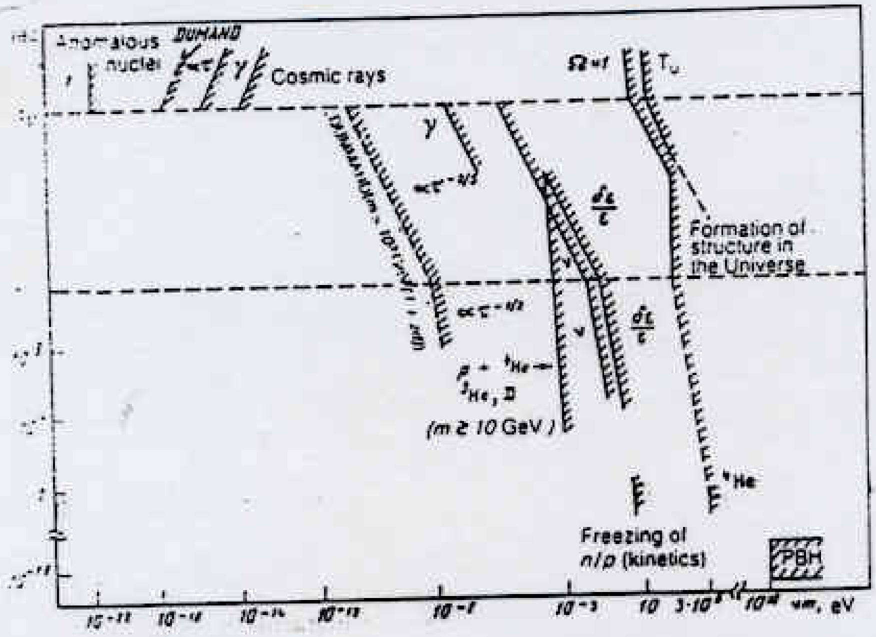
Cosmic rays - e^+e^-, N, nuclei
antiprotons, antinuclei?

galactic magnetic fields
Dark matter fluxes
Magnetic monopole fluxes
ν - background
Cosmic axions

Different properties of hypothetical particles and fields cause different effects in these data

Cosmoarcheology

Astrophysical data as experimental sample from the Gedanken experiment with cosmological consequences of new physics



Integral methods

t_U - age of the Universe, constraining the total density of the modern Universe

Y - primordial light element abundances constrain the total (^4He, ^7Li) and baryon (D) densities in the period of SBBN

$\left(\frac{\Delta T}{T}\right)_e$ - total and baryon densities in the period of recombination

MD stage in the period of LSS formation

Differential methods

$\left(\frac{\Delta T}{T}\right)_\nu \rightarrow \frac{\delta \varepsilon_\gamma}{\varepsilon_\gamma}$ electromagnetic calorimeter $\delta \varepsilon_\gamma$

Inequilibrium cosmological nucleosynthesis $F(p\rangle, \langle\varepsilon\rangle)$

$n_{\bar{p}}$; $f_i(P)$ $\langle E \rangle \gg T$

Cosmological nonthermal cosmic ray, γ, $\nu\bar{\nu}$ backgrounds

COSMOARCHEOLOGY

We can put constraints on hypothetical effects at different stages of cosmological evolution from

UNIVERSAL TOOLS

1. Age of the Universe $\rho_{tot} \le \rho_{max}$ for any form of matter in the modern Universe
2. Primordial ^4He abundance $\rho_{tot} \le \rho_{max}$ for any form of matter at $t \sim 1s$
3. Formation of Large Scale Structure
   Excludes radiation dominancy in the period of large scale structure formation. $\rho_{tot} \le \rho_{max}$ at $10^4 \le t \le 10^{16} s$

HYPOTHETICAL UNIVERSAL TOOL

4. Absence of primordial black holes and effects of their evaporation
   Probes early dust like stages and inhomogeneity of early Universe, starting from $t \sim 10^{-28} s$

DIFFERENTIAL TOOLS

5. Spectrum of Black Body Radiation Background
   Absence of $\Delta T/T(\nu)$ distorsions constrain electromagnetic energy release, starting from $z > 10^8$
6. Nonthermal electromagnetic cosmic backgrounds
   Probes sources of inequilibrium particles at $z > 10^2$
7. D, ^3He, ^6Li, ^7Be... abundances, probing inequilibrium cosmological nucleosynthesis at $t > 10^2 s$
8. Cosmic rays, cosmic $\bar{p}$ and γ fluxes, sensitive to hypothetical sources of inequilibrium particles at $z < 10^3$
   [M.Yu. Kh. se Evgenyi Sedelnikov, Gamov Seminar]
9. Cosmic High Energy Neutrino Background, probing hypothetical sources of superhigh energy particles at $t > 10^5 s$

Inhomogeneous Baryosynthesis

CP violation in the standard model of EW interaction is ascribed to KM mass matrix.

But

$$m_f = h_f \langle \varphi \rangle = 0 \text{ at } T > T_{EW}$$

when $\langle \varphi \rangle = 0$

Spontaneous CP violation may lead to spatial variation of CP violating phase $\chi(x)$

GUT: $\frac{\Delta B}{\gamma} \propto \mathrm{Im}\,\chi(x) \Rightarrow \frac{\Delta B(x)}{\gamma}$

SUSY: $V(\cancel{B}) \Rightarrow n_{sq} \rightarrow \Delta n_B$

$$n_{sq}(x) \Rightarrow \Delta n_B(x)$$

Spatial variation of baryonic density of scalar quark condensate

EW BVC $+ (\Delta L = 2)$:

axions are CP violating phase in the period

$$T_{PQ} > T > \Lambda \sim 1\,\mathrm{GeV}$$

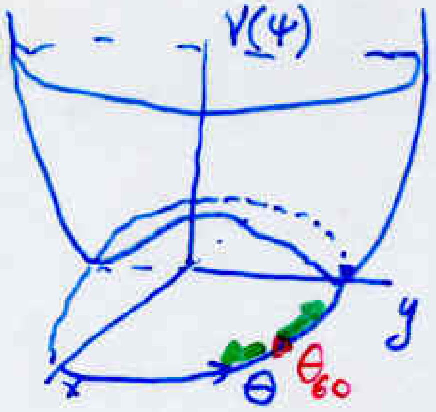
$$\Delta L(x) \Rightarrow \Delta B(x)$$

Coexistence of $\varphi_0(x) = \mathrm{const}$ and $\varphi_1(x)$ can lead to local antibaryosynthesis in the Universe with global dominancy of baryons.

Antibaryon domains are in this case probes for the mechanisms of baryosynthesis and CP violation at high temperatures

Inflationary Model with Spontaneous Baryosynthesis

(KHLOPOV, RUBIN, SAKHAROV, Phys. Rev D, 2000)



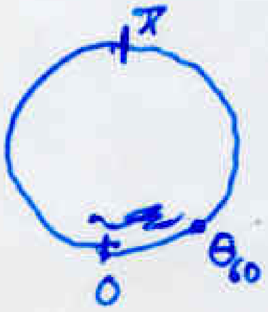
$$\mathcal{L} = h\theta\bar{l}Q$$

$\Delta L \neq 0$
$\Delta B \neq 0$

$$\psi = f\,e^{i\theta}$$

$N = 60 \rightarrow$ e-folding, corresponding to the modern horizon.

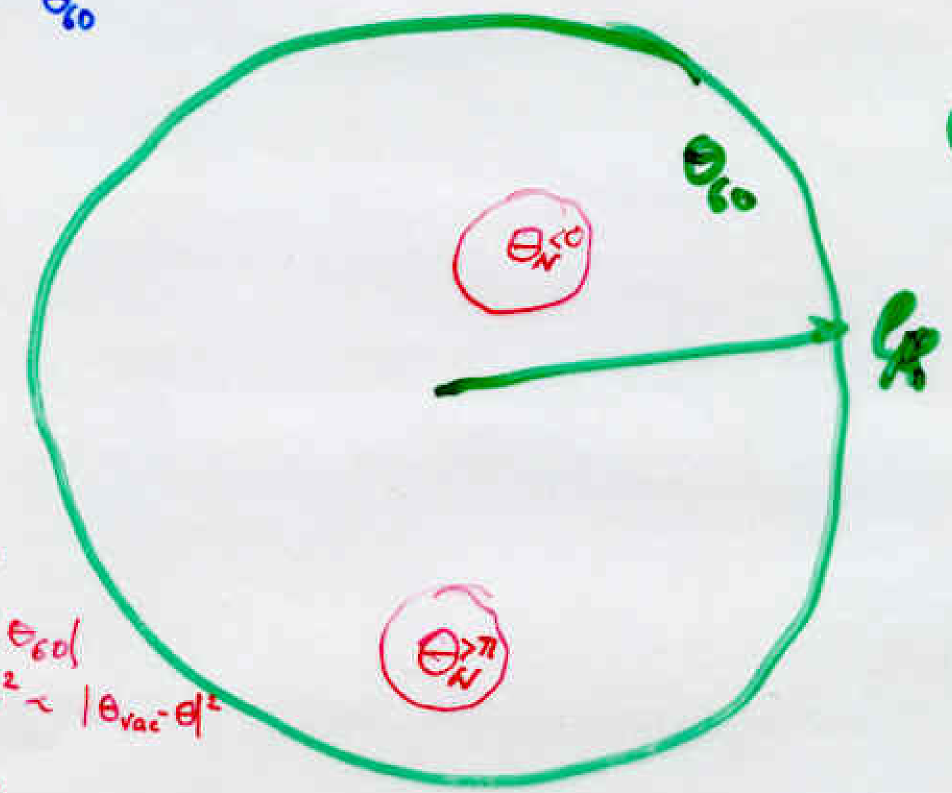
$\theta_{60} \longrightarrow l_h(t_U)$ $\Delta\theta \sim \dfrac{M_{infl}}{2\pi f}$

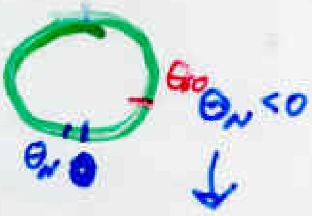


$\theta_N < 0$, or $\theta_N > \pi$

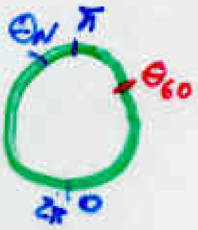
$\theta_N < 0$
$|\theta_N| < |\theta_{60}|$
$\Delta B \propto \theta^3$
$\rho_{\bar{B}} \ll \rho_B$

$\theta_N > \pi$
$|2\pi - \theta_N| > |\theta_{60}|$
$\Delta B \propto \theta^2 \sim |\theta_{vac} - \theta|^2$
$\rho_{\bar{B}} > \rho_B$





$\Delta B < 0$



$\Delta B < 0$

Antimatter in the Baryon asymmetrical Universe

Diffused Antiworld

Local antibaryosynthesis in baryon asymmetrical Universe may lead to antimatter domains with $\Omega_{\bar{B}} \ll \Omega_{B}$

SBB Nucleosynthesis results in this case in "unnatural" abundances of antinuclei

$$\bar{H} : \bar{D} : {}^{3}\overline{He} : {}^{4}\overline{He} \neq H : D : {}^{3}He : {}^{4}He$$

In diffused antiworld $\bar{D}$ and ${}^{3}\overline{He}$ may be most abundant (after $\bar{H}$) and serve as the signature of antimatter.

At $\Omega_{\bar{B}} \ll 1$, $\Omega_{\bar{B}} \ll \Omega_{B}$ antigalaxy formation may not take place (At $\Omega_{\bar{B}} < 10^{-5}$ recombination may be strongly suppressed and the Jeans scale of ionized antimatter is of the order of cosmological horizon)

Statistical analysis of antimatter domain distribution is needed.

Preliminary estimates show, that domains as small as 1kpc can survive and even be present in the Galaxy.

Gravitation and Cosmology,
V. 4, ~~N~~1, (1998) pp. 69-72

Antimatter globular cluster in our Galaxy – the probe for the matter origin

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Abstract

The existence of a globular cluster of antimatter stars in our Galaxy is shown to be a probable signature of the mechanism of inhomogeneous baryosynthesis. The observed gamma ray flux puts the constraint on the total mass of such anti- cluster. The expected signatures in cosmic ray experiments are discussed.

1 Introduction

Baryon asymmetry of the Universe is considered as the one of the most important features of the modern cosmology. It is commonly based on the statement that no macroscopic amount of antimatter is present around us at least on the scale of the local supercluster of galaxies. The statement is generally supported by the negative results of the direct searches for antimatter in the vicinity of the Solar system and by the severe constraint on matter-antimatter annihilation, following both from the observed gamma background and from the analysis of the influence of annihilation in the early Universe on the spectrum of relic radiation and on the light element abundance. However, the both types of evidences, definitely excluding the equal amounts of matter and antimatter around us, do not exclude the principal possibility of the existence of macroscopic amount of antimatter, putting only upper limit on its average density and possible distribution.

The idea of antimatter probing the origin of the matter in baryon asymmetrical Universe was first put forward in Ref. [1] (see also Ref. [2]). It was shown (see for review Ref. [3]) that practically all the existing mechanisms of baryosynthesis Ref. [4] can under some condition lead to antibaryon excess. In the other words the idea of inhomogeneous baryosynthesis was put forward in Ref. [1] and in Ref. [2]. From this viewpoint antimatter represents the high amplitude

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Forms of Antimatter Domains

$\Omega_{\bar{B}} = \frac{\langle \rho_{\bar{B}} \rangle}{\rho_{cr}}$ inside domain

$\Omega_{\bar{B}} < 10^{-4}$ Diffused Antiworld

SBBN: $10^{-5} < \Omega_{\bar{B}} < 10^{-4}$ $\quad {}^4\overline{He} < \bar{D}$; $\bar{H}, \bar{D}$

$\Omega_{\bar{B}} < 10^{-5}$ $\quad \bar{H}$

No recombination

$\rho_{\bar{B}} < \rho_{\gamma}$ inside domain at $\Omega_{\bar{B}} < 10^{-4}$

No gravitational instability

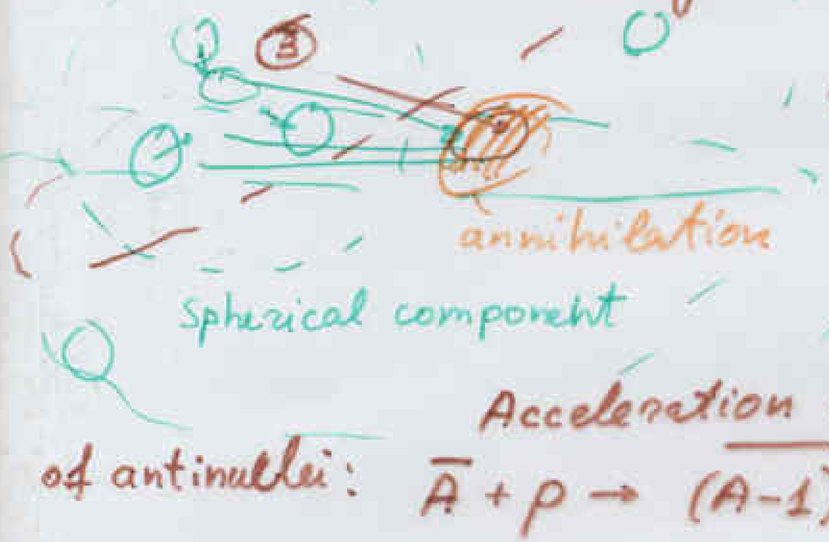
Such domains can not be in the supercluster of galaxies and should be in voids

$10\,\mathrm{kpc} < R < 1 \div 10\,\mathrm{Mpc}$

γ - sources from voids

$\Omega_{\bar{B}} > 10^{-4}$ after recombination and gravitational instability can lead to antistar formation

○ Globular cluster of antistars in the Galaxy



$M \sim 10^4 \div 10^6 M_\odot$

low $\rho_{\bar{B}}$ gas

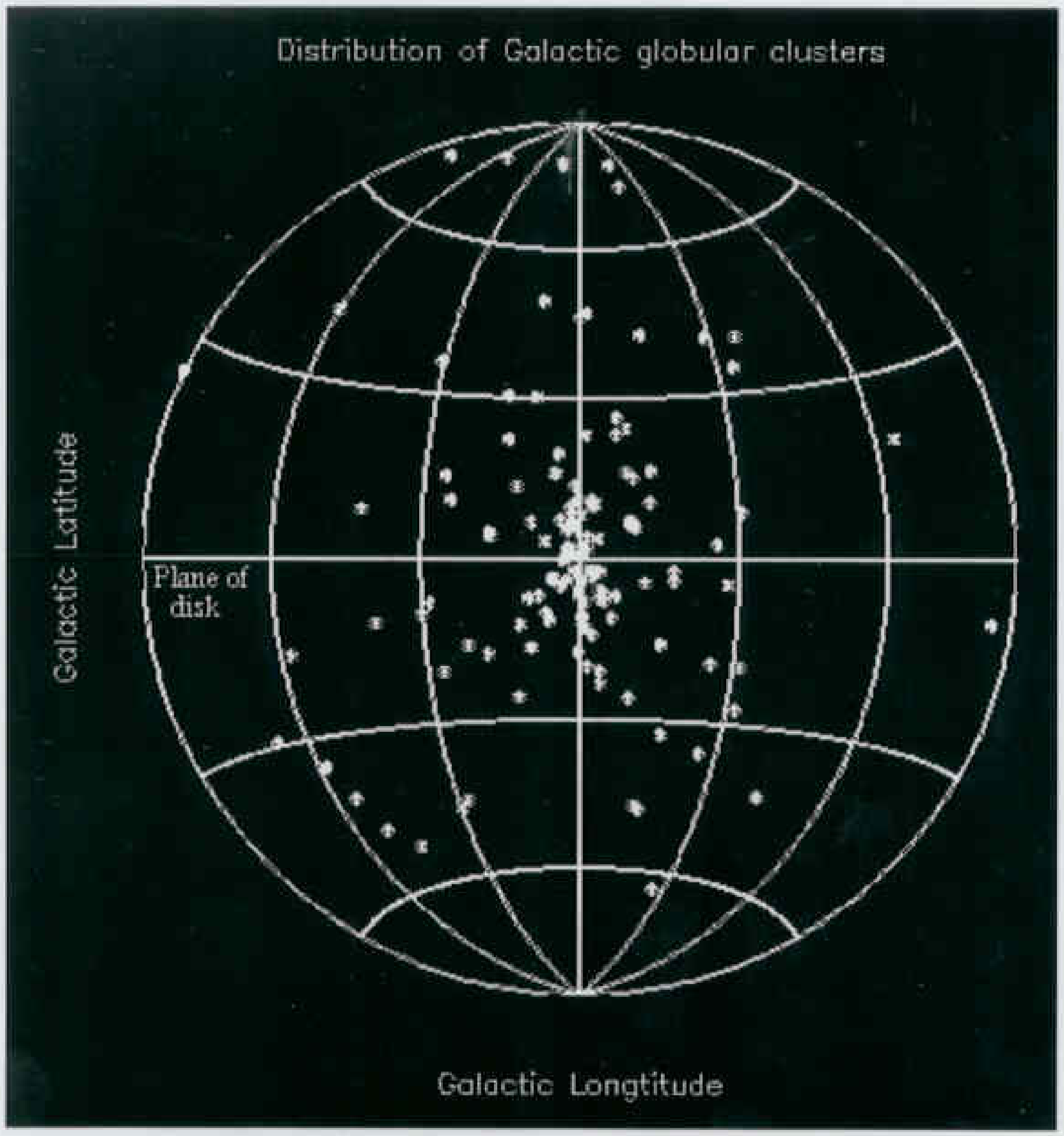
low ρ_B of gas

Can survive

No antistars in disc

Acceleration in multiple annihilation of antinuclei: $\bar{A} + p \to \overline{(A-1)}$

Globular clusters



Globular cluster population in our Galaxy consists of 147 confirmed globular clusters. In the spherical component of Galaxy the globular clusters move with velocity 150km/s – 170km/s.

If the high – density antimatter region was present in our Galaxy, it could survive in the form of globular cluster at large galactocentric distance.

Antimatter globular cluster

$$M_{surv} \le M < M_{max}$$

$$M_{surv} \sim \rho_{\bar{B}}\, l_s^3 \sim 10^3 M_\odot$$

for $\rho_{\bar{B}} \sim \rho_B$

$$M_{max} \le 10^5 M_\odot$$

from $\mathcal{F}_\gamma^{obs} \Rightarrow \mathcal{F}_\gamma(\bar{p}\ \text{ann})$

$n_{gas} = 5\cdot 10^{-4}\ \text{cm}^{-3}$

$$\mathcal{F}_\gamma(\bar{p}\ \text{ann}) \propto \dot{\bar{p}}$$

Elliptical galaxies

$$\dot{m} = \frac{0.1\, M_\odot}{10^{11} M_\odot}$$

Antimatter pollution

- **The integral effect of antimatter globular clusters may be estimated by the analysis of antimatter pollution of the galaxy by that globular clusters** (K.M.Belotzky, Yu.A.Golubkov, M.Yu.Khlopov, R.V.Konoplich, A.S.Sakharov 1998)

- **There are two main mechanisms of antimatter loss by the globular clusters**

I. The stationary mass loss by antimatter stars in the form of stellar wind

$$\dot{M} \approx 10^{-12} M_{SUN} - \text{per solar mass per year}$$

II. The antimatter supernova explosion $\dot{M} \approx 10^{-13} M_{SUN}$ – per solar mass per year.

Appendix-4

The model of galactic annihilation

- **The $\overline{p}p$ annihilation cross section**

$$\sigma_{ann}(P<300\,MeV/c)=\frac{2\pi c\alpha}{v_c^2\left(1-\exp(-2\pi c\alpha/v_c)\right)}\cdot(160\,mb)$$

- **The model of halo**

$$n_H(z)=n_H^{halo}+\Delta_H(z);\quad \Delta_H(z)=\frac{n_H^{disk}}{1+(z/D)^2};\quad n_H^{halo}=5\cdot10^{-4}cm^{-3};$$

$$n_H^{disk}=1cm^{-3};\ D=100pc;$$

90% of the halo mass is a non – baryonic dark matter

- **For the $\overline{p}$ with velocities $\cong 10^3\ km/s$ (stellar wind) the confinement time in the halo, starting from the distances $z\cong 2\ kpc$ is less then annihilation time ("two – zone" leaky box model)**
In the gaseous disk the situation is opposite

- **The $\overline{p}$ are collecting in the halo during the confinement time $\approx 5\cdot10^8\ yrs$ increasing the gamma flux**

- **During the large confinement time the $\overline{p}$ are being spread over the halo with constant number density not dependent on the position of antistar cluster and under the usual acceleration mechanisms in the halo their spectrum comes to the stationary form**

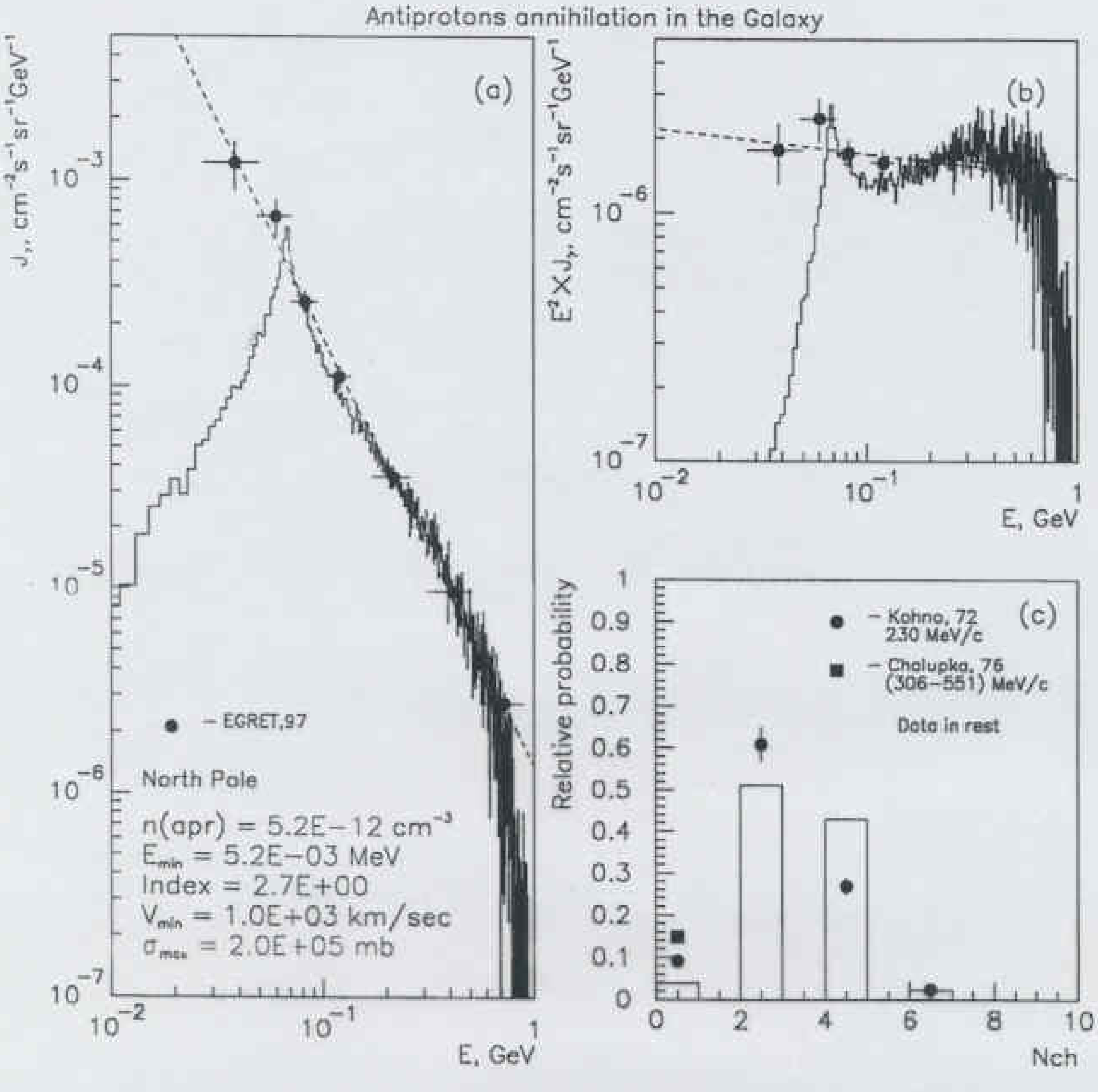


Figure 3: Comparison of the calculated differential fluxes of γ quanta from $\bar{p}p$ annihilation with experimental data *EGRET* [20] on diffuse gamma background (a,b). There is also shown the comparison of the charged multiplicity distribution in the annihilation model described in the text with the existent experimental data (c).

The uncertainty

The actual distribution of magnetic field in our Galaxy.

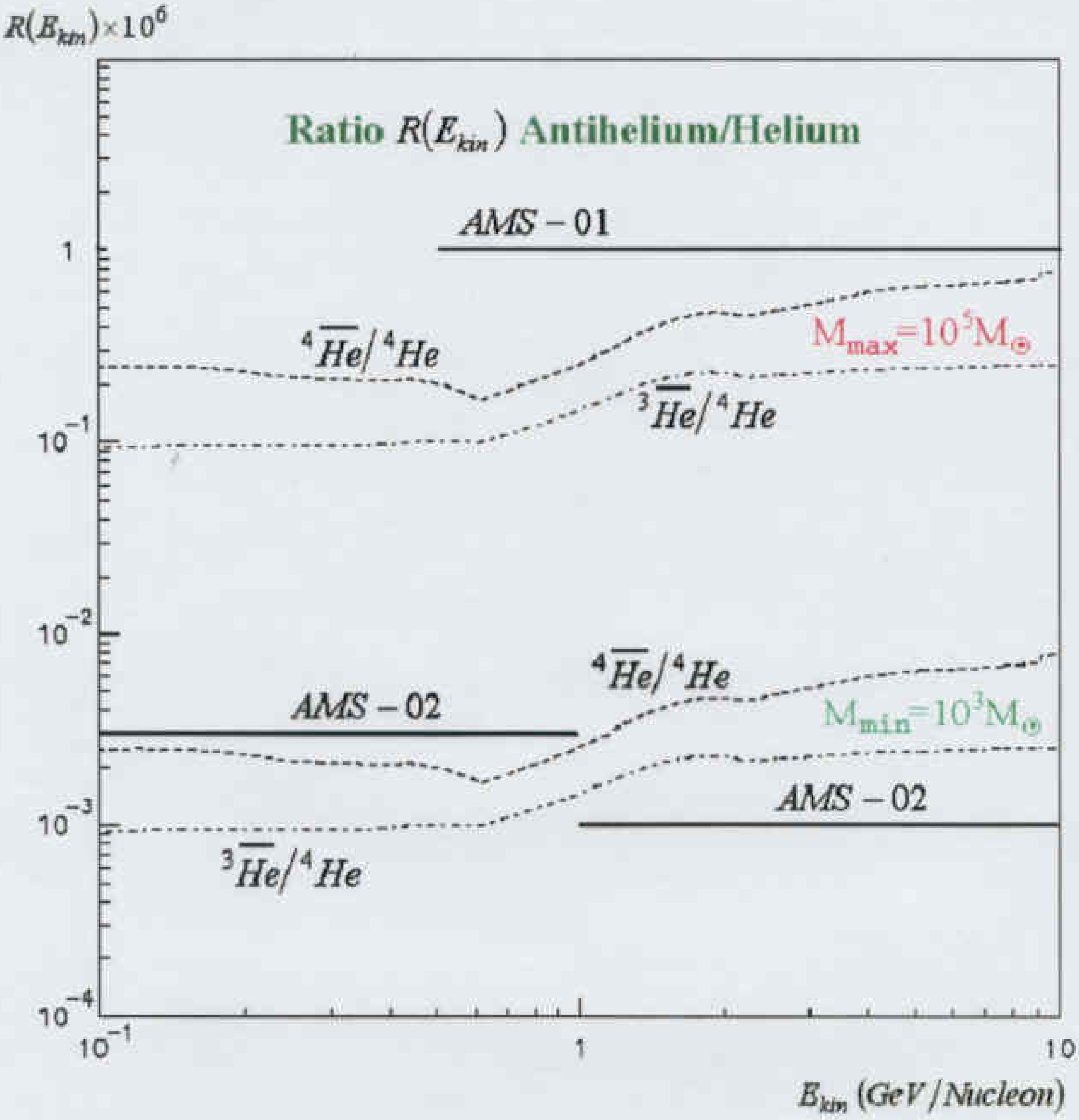
The mechanism of cosmic–ray acceleration

The relative contribution of disc and halo particles into the cosmic–ray spectrum

The acceleration of matter and antimatter cosmic rays are similar

The contribution of antinuclei into the cosmic–ray fluxes is proportional to the mass ratio of globular cluster and Galaxy.

Anti-helium flux



Khlopov

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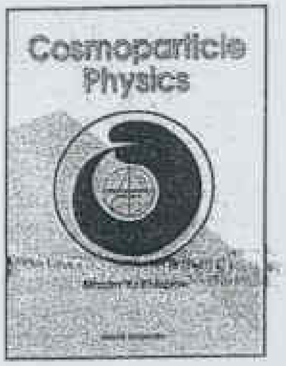

COSMOPARTICLE PHYSICS

by **Maxim Yu Khlopov** *(Centre for Cosmoparticle Physics, "Cosmion", Russia)*

Since the 1980s the cross-disciplinary, multidimensional field of links between cosmology and particle physics has been widely recognised by theorists, studying cosmology, particle and nuclear physics, gravity, as well as by astrophysicists, astronomers, space physicists, experimental particle and nuclear physicists, mathematicians and engineers.

This book outlines the principal ideas of the modern particle theory and cosmology, their mutual relationship and the nontrivial correspondence of their physical and astrophysical effects.

"The relationship between cosmology and particle physics is now one of the important topics of discussion at any scientific meeting both on astrophysics and high energy physics."

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596pp **Apr 1999**
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Contents: Introduction; The Lorentz Transformation; Kinematic and Optical Effects; Classical Dynamics; Relativistic Dynamics I; Relativistic Dynamics II; 4–Vectors; Classical Electromagnetism; Electromagnetism and Relativity; Relativistic Dynamics III; The Principle of Least Action.

Readership: Graduate and undergraduate students in general physics.

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Readership: Undergraduates and graduates in astronomy and astrophysics.

204pp Jan 1995
981-02-1929-6 US$32 £23

World Scientific Lecture Notes in Physics – Vol. 33

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by **U E Schröder** *(Univ. Frankfurt)*

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Few-Body Systems (Austria), 19

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Carl Bra
Mathematical Revie

This book provides a thorough discussion of th concepts and main consequences of special relativity. Treated in detail are the Lorentz transformations, their kinematical consequenc (the so-called paradoxes), relativistic mechanic electrodynamics as an example of a relativistic field theory, and the principal features of relativistic hydrodynamics. The book offers a logical development of special relativity from Einstein's principle of relativity alone; arrives a the essential statements of the theory by a dire approach – this emphasis is different from that most books; and offers a concise introduction

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