COSMOLOGY AND NEW PHYSICS

A.D. Dolgov

ITEP, 117218, Moscow, Russia
INFN, Ferrara 40100, Italy

NBI Summer Institute

Copenhagen
August, 10, 2006

Presently there are two established models/theories which are in perfect or almost perfect agreement with experiment/observations but are mutually incompatible:

1. Minimal standard model in particle physics (MSM)

and

2. Standard cosmological model (SCM).

New physics is necessary.

WHAT IS NEW PHYSICS?

New objects and interactions.

Breaking of established rules or conservation laws.

New principles.

WHAT ELSE?

NATURAL NEW PHYSICS

Almost inevitable:

1. New fields or/and particles,

a) stable or quasistable

b) heavy or light,
dark matter, cold or warm, and maybe dark energy.

BH as DM are not excluded (thus no new fields) but DE demands something really new.

2. Breaking of charges/quantum numbers:

a) electric, (impossible? or at least nontrivial with hi D);
inevitable if $m_\gamma \neq 0$, the universe might be electrically charged.

b) baryonic (practically certain)

c) leptonic (expected)

d) leptonic family (discovered!).

Less probable but still expected:

3. Topological or non-topological solitons.

4. New types of interactions, especially new long range forces, modified gravity.

5. Higher dimensions?

UNNATURAL NEW PHYSICS:

1. **Breaking of Lorentz-invariance.**
2. **Violation of CPT.**
3. **Spin-statistics relation.**
4. **Unitarity, coherence.**
5. **Energy conservation.**
6. **Causality, time-mashine.**
7. **Breaking of least action principle, Hamilton and Lagrange dynamics.**

UNEXPECTED NEW PHYSICS

anything which is not in the list above and will never be there a priori.

WHY COSMOLOGY?

1. Cosmology surely shows that some new physics exists. Minimal standard model (MSM) of particle physics is incompatible with the standard cosmological model (SCM).

2. In the future cosmology may be the best laboratory to discovery and study new (unnatural) physics.

How reliable is SCM?
How much we can trust it?

STANDARD COSMOLOGICAL MODEL

Theoretical setting (very simple).

1. General Relativity.

2. Homogeneous and isotropic distribution of matter in zeroth approximation.

Perturbations in first order for small perturbations, or numerical simulation, when $\delta\rho/\rho \geq 1$.

3. Knowledge of cosmic particle content and form of their interaction, sometimes, but not always, equation of state exists and is sufficient:

$$\mathbf{p} = \mathbf{f}(\rho)$$

with p and ρ being pressure and energy densities of matter.

Isotropic homogeneous metric:

$$\mathbf{ds^2 = dt^2 - a^2(t)\, f(r) d\bar{r}^2}$$

is a solution of GR equations with $\mathbf{f(r) = 1 + kr^2/4}$ and $\mathbf{k = 0, \pm 1}$. Theory and observations agree that

$$\mathbf{k \approx 0}.$$

Hubble parameter:

$$\mathbf{H = \dot{a}/a}$$

BASIC EQUATIONS

1. 2nd Newton law (acceleration of test body):

$$\frac{\ddot{a}}{a} = -\frac{4\pi}{3m_{Pl}^2}(\rho + 3p)$$

$$G_N^{-1} \equiv m_{Pl}^2 = 1.2 \cdot 10^{19}\ \mathrm{GeV}.$$

NB **Not only mass (energy) creates gravitational force but also pressure.**

Equation $(\rho + \mathbf{3p}) < \mathbf{0}$, generates anti-gravity, expansion is accelerated and superluminal for l $>$ 1/H - true for any expansion regime.

With Newtonian gravity we would not exist.

2. Conservation of energy of test body

$$\mathbf{H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi\rho}{3m_{Pl}^2} - \frac{k}{a^2}}$$

Critical energy density:

$$\rho_{\mathbf{c}} = \frac{\mathbf{3H^2m_{Pl}^2}}{\mathbf{8}\pi}$$

Measure of real energy density of different species j:

$$\mathbf{\Omega_j} = \rho_{\mathbf{j}}/\rho_{\mathbf{c}}$$

If $\mathbf{k = 0}$, $\mathbf{\Omega_{tot} = 1}$.

Covariant energy-momentum conservation, $T^{\nu}_{\mu;\nu} = 0$:

$$\dot{\rho} + 3H(\rho + p) = 0.$$

(follows from 1 and 2).

For "normal " matter $\rho > 0$ and $|\rho| > |p|$, hence $\dot{\rho} < 0$ and energy density drops in the course of expansion.

Vacuum energy, $p_{\text{vac}} = -\rho_{\text{vac}}$ and

$$\rho_{\text{vac}} = \text{const}$$

Parametrize equation of state for different cases:

$$\mathbf{p = w\rho}$$

Physical examples with
$\mathbf{w = -1, -2/3, -1/3, 0, 1/3, 1}$
are known.

Where is $\mathbf{w = 2/3}$?

If w < -1, energy density rises in the course of expansion, "phantom" cosmology.

Everything will be turn apart in the future, not only galaxies and stellar bodies, but even atoms and particles.

Should be forbidden! All known models are pathological.

BACK TO THE PAST

(brief universe history)

1. Beginning, unknown. Maybe time did not exist?

2. Inflation. Surely existed, "experimental" fact.

3. Baryogenesis.

4. Thermally equilibrium universe, adiabatically cooled down. Some phase transitions on the way, GUT, EW, QCD, with possible formation of topological solitons.

Well known epochs:

5. Neutrino decoupling, $T \sim 1$ MeV.

6. Big bang nucleosynthesis (BBN), $T = 1 - 0.07$ MeV. One of the cornerstones of SCM.

6. Onset of structure formation at RD→MD, $z_{eq} \approx 10^4$, $T \sim$ eV.

7. Hydrogen recombination, $z \approx 10^3$, $T \sim 0.2$ eV. **Decoupling of CMBR. Infall of baryons into already evolved seeds of structures.**

8. Reionization, at $z = 10 - 20$? Formation of first stars.

9. Present time, $t_U = 12 - 15$ Gyr.

Universe today

1. Expansion rate:

$\mathbf{H = 100\,h\,km/sec/Mpc\ \ h = 0.73 \pm 0.05}$

2. Energy density:

$$\rho = \rho_{\mathbf{c}} = \mathbf{1.9 \cdot 10^{-29} h^2 \frac{g}{cm^3}} = \tag{1}$$

$$\mathbf{10.5\,h^2 \frac{keV}{cm^3} \approx 10^{-47}\,GeV^4}$$

MATTER INVENTORY

Total energy density:

$\Omega_{\mathrm{tot}} = 1 \pm 0.1$

from position of first peak of CMBR and LSS

Usual baryonic matter:

$\Omega_{\mathrm{B}} = 0.044 \pm 0.004$

from heights of CMBR peaks, BBN, onset of structure formation and small $\delta T/T$.

Total dark matter:
$\Omega_{\mathrm{DM}} \approx 0.22 \pm 0.04$
from galactic rotation curves, gravitational lensing, equilibrium of hot gas in rich galactic clusters, cluster evolution, LSS.

The rest:
$\Omega_{\mathrm{DE}} \approx 0.7$
- induces accelerated expansion; from dimming of hi-z supernovae, LSS, universe age.

Different pieces of data and their interpretation are independent. It diminishes probability of an error.

Cosmic microwave background radiation.

Perfect equilibrium Planck spectrum,
$\mathbf{T = 2.725 \pm 0.001\,K}$,
$\mathbf{n_\gamma = 410.4 \pm 0.5\ cm^{-3}}$,
$\mathbf{\Omega_\gamma = (4.9 \pm 0.5) \cdot 10^{-5}}$.

Small angular fluctuations of temperature, snapshot of the universe at $\mathbf{z \approx 10^3}$, allow to measure cosmological parameters.

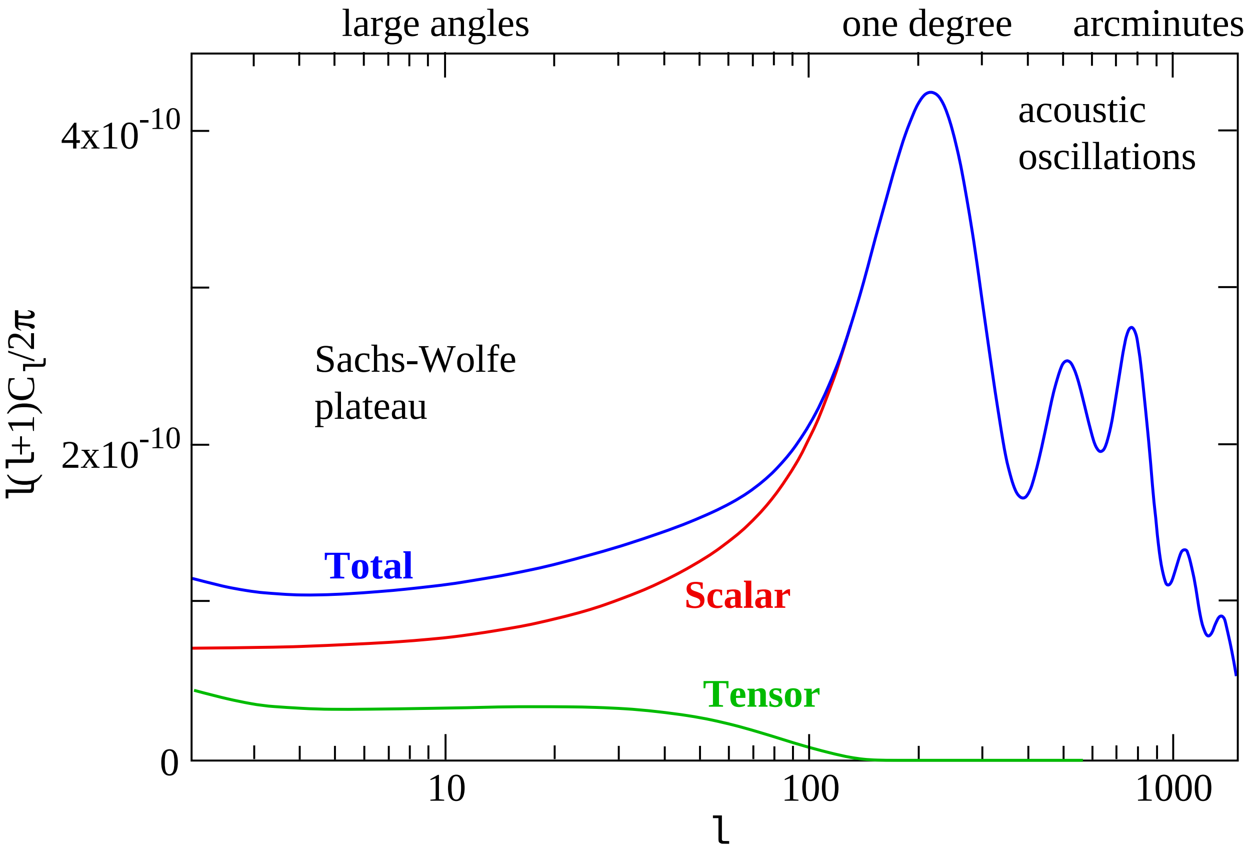


Figure 1: **Theoretical angular power spectrum for adiabatic initial perturbations and typical cosmological parameters. The scalar and tensor contributions to the anisotropies are also shown.**

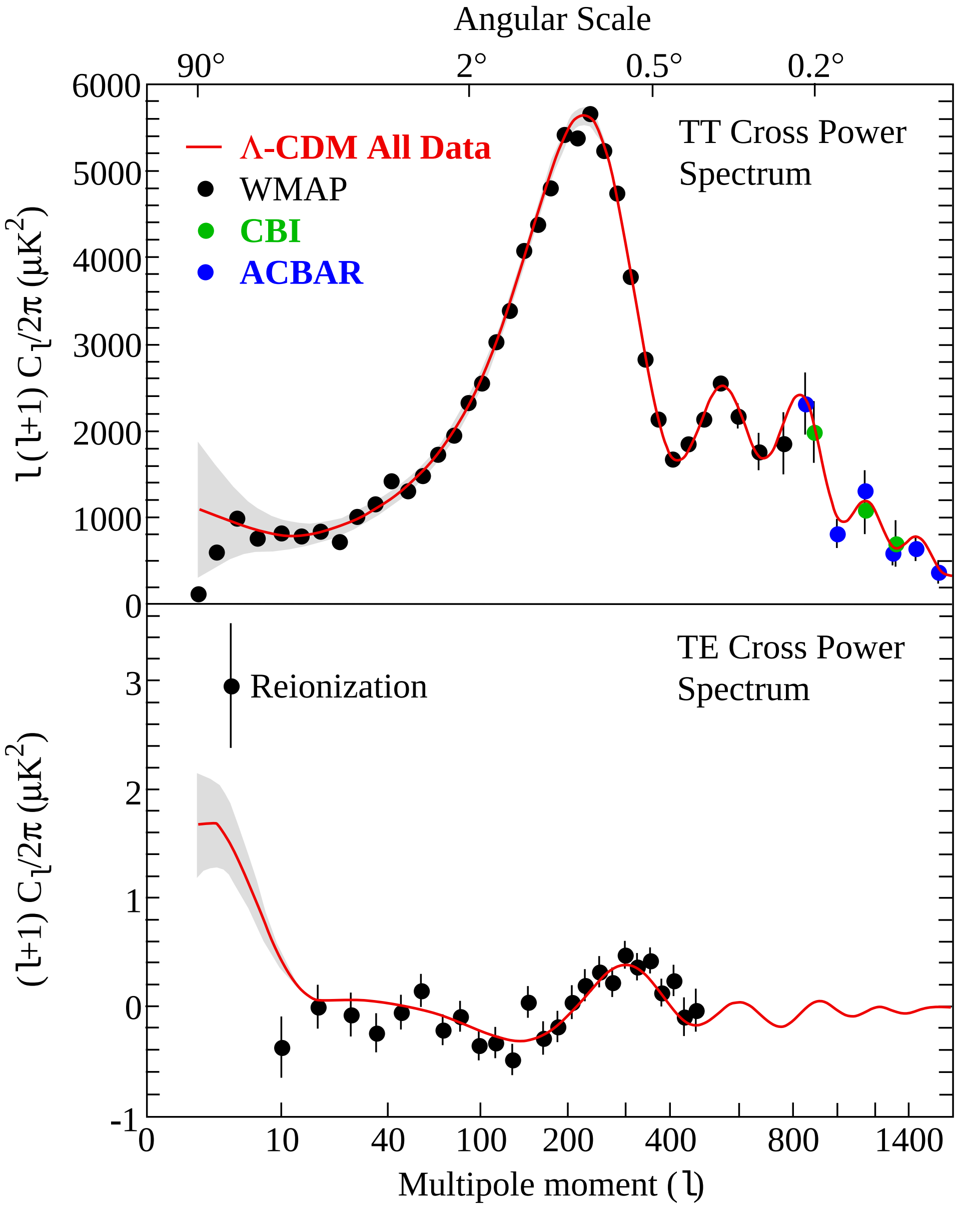


Figure 2: **Temperature-temperature (TT) and temperature-polarization TE power spectra. The best fit ΛCDM model is also shown. Alignment and small amplitudes of low multipoles. “Evil axis”? Cosmic variance.**

INFLATION

Period of exponential (or more generally accelerated) expansion in the early universe,

$$\mathbf{a(t) \sim \exp[Ht]}$$

with $\mathrm{H} \approx$ const.
Easy to realize by e.g. a scalar field:

$$\mathbf{T}_{\mu\nu} = \partial_\mu\phi\partial_\mu\phi - (\mathbf{1}/\mathbf{2})\mathbf{g}_{\mu\nu}\left[\partial_\alpha\phi\partial^\alpha\phi - \mathbf{U}(\phi)\right]$$

if $\mathrm{U}(\phi) \approx \mathrm{const} \gg (\partial_\mu\phi)^{\mathbf{2}}$ then
$\mathbf{p} \approx -\rho$

Inflation is the only known way to create the observed universe.

Inflation solves the problems of:

1. Flatness and predicts $|\Omega - 1| < 10^{-4}$ (inhomogeneities on horizon).

Without inflation the fine-tuning 10^{-15} at BBN and 10^{-60} at Planck era is necessary.

2. Makes all the observed universe causally connected. If not inflation, the connected regions on the sky $< 1^{o}$, while CMBR comes almost the same from all the sky.

3. Explains the origin of expansion.

3. Makes the universe almost homogeneous and isotropic at the present-day Hubble scale.

4. Creates small inhomogeneities but at astronomically large scales, seeds of large scale structure (LSS) formation. The mass of inflaton should be $\mathbf{m_\phi \sim 10^{-5} m_{Pl}}$, or unnaturally weak self-coupling, $\lambda\phi^4$ with $\lambda \sim \mathbf{10^{-14}}$.

Scalar field, even with $\mathbf{m = 0}$, is not conformally invariant. Life is possible only because of that.

Predicted: adiabatic Gaussian density perturbations with almost flat Harrison-Zeldovich spectrum, $\delta\mathbf{\Psi} \sim \delta\mathbf{k}/\mathbf{k}$.

Deviations from flat spectrum agree with the data.

END OF INFLATION:

$m_\phi \sim H$ and inflaton starts to oscillate near origin and produce particles.

“Let there be light” - dark vacuum-like state exploded and created hot universe:

BIG BANG!!!

(Re)heating temperature is model dependent, most probably is not large, $T_{rh} < E_{GUT} \sim 10^{15}$ GeV.

No unwanted magnetic monopoles.

Initial hot universe might be far from thermal equilibrium.

INFLATIONARY CONCLUSION:

1. Inflation is an experimental fact!

1. Observed $\Omega = 1$.

2. Flat spectrum of perturbations.

3. No other way to create our universe. However, be aware of danger of no-go theorems in physics, e.g. impossibility to combine internal and space symmetries - SUSY!

INFLATION DEMANDS NEW FIELD INFLATON absent in MSM.

BARYOGENESIS

Inflation is impossible if baryonic charge is conserved.

Initial conditions with an excess of particles over antiparticles are not allowed.

Dynamical generation of excess of B over $\bar{\mathrm{B}}$ is necessary.

Inflation is incompatible with conserved nonzero baryonic charge density.

Sufficient inflation,

$\sim$ 70 Hubble times,

could proceed only if the energy density is approximately constant.

$$\mathbf{H} = \dot{\mathbf{a}}/\mathbf{a} \sim \sqrt{\rho}/\mathbf{m}_{\mathbf{Pl}}$$

and $\mathbf{a} \sim \exp(\mathbf{Ht})$ if $\mathbf{H} = \mathrm{const}$.

If baryons were conserved, the energy density associated with baryonic charge (baryonic number) could not be constant and inflation could last at most 4-5 Hubble times.

If baryonic charge were conserved:

$$\mathbf{B \sim 1/a^3,\ \ \rho_B \sim 1/a^n,\ n = 3 - 4}$$

At RD-stage $\rho_{\mathbf{B}} \approx \mathbf{10^{-7}}\rho_{\mathbf{tot}}$ **and**

$$\rho_{\mathbf{B}}/\rho_{\mathbf{tot}} \approx \mathbf{const}$$

till inflation, going backward in time.
At inflation $\rho_{\mathbf{tot}} = \mathbf{const}$
(baryons not included),
while $\rho_{\mathbf{B}} \sim \exp(-\mathbf{4Ht})$**.**
For $\mathbf{Ht} > 4 - \mathbf{5}$**: sub-dominant baryons became dominant,** $\rho_{\mathbf{tot}} \approx \rho_{\mathbf{B}}$ **and**

$$\rho \neq \mathbf{const}$$

Three Sakharov's conditions:

1. Nonconservation of baryons. **Theoretically natural; proved to be true in MSM and in GUT. Cosmology is an "experimental" proof: We exist** *ergo* **baryons are not conserved.**

2. Breaking of C and CP. **Established in particle physics.**

3. Deviation from thermal equilibrium. **Always true in expanding universe for massive particles or/and in the case of first order p.t.**

Baryogenesis: only one number to explain:

$$\beta = \frac{\mathbf{n_B - n_{\bar{B}}}}{\mathbf{n_\gamma}} = \frac{\mathbf{n_B}}{\mathbf{n_\gamma}}\Big|_{\mathbf{today}} \approx \mathbf{6 \cdot 10^{-10}}$$

Plethora of scenarios can do that but all require new physics.

MSM - baryogenesis is possible:

1. C and CP are known to be broken.

2. Baryons are not conserved because of chiral anomaly (and nonabelian theory).

3. Nonequilibrium, if EW phase transition is first order.

HOWEVER:

1. Heavy Higgs makes 1st order p.t. improbable.

Deviation from equilibrium due to non-zero masses of W and Z is too weak:

$$\frac{\delta f}{f_{eq}} \sim \frac{H}{\Gamma} \sim \frac{m_W}{\alpha\, m_{Pl}} \sim 10^{-15}$$

2. C and CP violation at high T, $T \sim T_{EW} \sim 100$ GeV, is tiny: the amplitude of CP-breaking is proportional to the product of the mixing angles and to the mass differences of all down and all up quarks:

$$A_- \sim \sin\theta_{12}\sin\theta_{23}\sin\theta_{31}\sin\delta$$
$$(m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)$$
$$(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)/T^{12}$$

At $T \geq 100$ GeV when sphalerons were operating

$$A_- \sim 10^{-19}.$$

Three quark families allow for natural CP-violation through CP-odd phase in CKM matrix and, thus, through baryogenesis could create suitable for life universe - an “explanation” why we need 3 families.

Now either CP breaking is different in particle physics and cosmology and we do not need three families or - see next page...

One may avoid these problems and create baryon asymmetry in EW theory with 3 families if one allows time variation of fundamental constants such that

$$\mathbf{m_{Pl} \sim m_{EW}}$$

$$\mathbf{m_{q_j} \sim m_{EW}} \text{ and } \delta \mathbf{m_{q_j} \sim m_{q_j}}$$

But this is very new physics.

May baryogenesis be an indication of time varying constants, TeV gravity, and large higher dimensions?!

Baryo-thru-lepto-genesis

Creation of lepton asymmetry by decays of heavy, $m \sim 10^{10}$ GeV, Majorana fermion and subsequent transformation of L into B by EW.
L is naturally nonconserved.
Heavy particles to break thermal equilibrium are present.
Three CP-odd phases of order unity might be there.

New heavy particles and new sources of CP violation are necessary.

CP VIOLATION IN COSMOLOGY.

Three possible mechanisms:

1. Usual, explicit.

2. Spontaneous. A complex scalar field with two (or several) degenerate vacuum states. The universe as a whole should be charge symmetric but locally could be asymmetric.
Domain wall problem.

3. Dynamical or stochastic. A scalar field displaced from minimum (e.g. by quantum oscillations during inflation), and not yet relaxed to the origin at baryogenesis. **A rich universe structure with isocurvature perturbations and even antimatter domains may be created.**

Probably the only chance to obtain an observational information about the mechanism of baryogenesis.

Phase transitions in the process of cosmological cooling down.

Gauge theories with spontaneously broken symmetries. Higgs potential:

$$\mathbf{U}(\mathbf{\Phi}) = \lambda \left(|\phi|^{\mathbf{2}} - \eta^{\mathbf{2}} \right)^{\mathbf{2}}$$

High T vacuum at $\phi = \mathbf{0}$.
Low T real vacuum at $|\phi| = \eta$.
Change of vacuum energy

$$\delta\rho_{\mathbf{EW}} = \lambda\eta^{\mathbf{4}} \sim \mathbf{10^8}\ \mathbf{GeV}^4$$

QCD gauge transition from free quarks and gluons to confinement phase. Formation of quark, $\langle \bar{q}q \rangle$, and gluon, $\langle G^2_{\mu\nu} \rangle$, condensates.

Change of vacuum energy

$$\delta\rho_{\mathbf{QCD}} = \mathbf{0.1 - 0.01\ \ GeV}^4$$

If QCD phase transition is 1st order, bubbles with different proton-to neutron ratio may be formed and lead to inhomogeneous BBN.

PROBLEM OF VACUUM ENERGY.

$$\mathbf{R}_{\mu\nu} - \frac{\mathbf{1}}{\mathbf{2}}\mathbf{g}_{\mu\nu}\mathbf{R} - \mathbf{\Lambda}\,\mathbf{g}_{\mu\nu} = \mathbf{8}\pi\mathbf{G}_{\mathbf{N}}\,\mathbf{T}_{\mu\nu}$$

Λ is equivalent to vacuum energy density,

$$\mathbf{T}_{\mu\nu}^{(\mathbf{vac})} = \rho_{\mathbf{vac}}\mathbf{g}_{\mu\nu},$$

$$\mathbf{\Lambda} = \mathbf{8}\pi\rho_{\mathbf{vac}}/\mathbf{m}_{\mathbf{Pl}}^{\mathbf{2}}.$$

1. Theoretically: $\Lambda \approx \infty$.
Mismatch between theory and data:
50-100 ORDERS OF MAGNITUDE.

2. Majority point of view during long time and maybe even now:

$$\infty = \mathbf{0}$$

“Corrections are infinite but small” (R. Feynman).

3. New independent pieces of data: EMPTY SPACE (ANTI)GRAVITATES. Is it vacuum with nonvanishing energy density?

4. Close proximity of $\rho_{\mathbf{vac}} = \mathbf{const}$ to $\rho_{\mathbf{c}} \sim \mathbf{1/t^2}$ exactly today.

5. If antigravitating substance is not vacuum energy then WHAT?

Biographical notes

Name(s):
Cosmological constant, Λ-term, vacuum energy
or, maybe, dark energy.

Date of birth: 1918
Father A. Einstein: "The biggest blunder of my life" (after Hubble's discovery of cosmological expansion).

Many times assumed dead, probably erroneously.
Well alive today.
Still not safe - many want to kill it.

SOME MORE QUOTATIONS:

Lemaitre: "greatest discovery, worth to make Einstein's name famous".

Gamow: "λ raises its nasty head again" (after indications that quasars are accumulated near $z = 2$ in the 60s)

Covariant conservation:

$$\mathbf{D}_\mu \left(\mathbf{R}^\mu_\nu - \frac{\mathbf{1}}{\mathbf{2}} \mathbf{g}^\mu_\nu \mathbf{R} \right) \equiv \mathbf{0}$$

automatic in metric theories.

Analogy to electrodynamics:

$$\partial_\mu \mathbf{F}^{\mu\nu} = \mathbf{4}\pi \mathbf{J}^\nu$$

Owing to anti-symmetry of $\mathbf{F}^{\mu\nu}$,

$$\partial_\mu \partial_\nu \mathbf{F}^{\mu\nu} \equiv \mathbf{0}$$

and the current MUST be conserved,

$$\partial_\mu \mathbf{J}^\mu = \mathbf{0}.$$

Automatic conservation of r.h.s. of Einstein equations:

$$\mathbf{D}_{\mu}\left[\mathbf{T}_{\nu}^{(\mathbf{m})\mu}/(\mathbf{8}\pi\mathbf{m}_{\mathbf{Pl}}^{\mathbf{2}})+\boldsymbol{\Lambda}\mathbf{g}_{\mu\nu}\right]=\mathbf{0}$$

Due to covariant conservation of energy-momentum tensor:

$$\mathbf{D}_{\mu}\mathbf{T}_{\nu}^{\mu\,(\mathbf{m})}=\mathbf{0},$$

and the condition (in metric theory):

$$\mathbf{D}_{\mu}\mathbf{g}_{\nu}^{\mu}\equiv\mathbf{0},$$

the cosmological constant must be CONSTANT:

$$\boldsymbol{\Lambda}=\mathbf{const}$$

Models with $\Lambda = \Lambda(t)$ are not innocent, new fields to respect energy conservation condition are necessary or serious modifications of the theory, e.g. non-metric theories.

First attempts to make time-dependent Lambda, 1935 by Bronshtein (Leningrad); strongly criticized by Landau.

RISE AND FALL
OF LAMBDA-TERM

1. Birth: $\Omega_{\rm v} \approx 1$.

2. Hubble discovery of expansion, earlier Friedman solution: $\Omega_{\rm v} \equiv 0$.

3. Lemaitre, De Sitter, later Eddington: one of the most important discoveries in GR.

4. Still non-zero Lambda is not accepted by majority.

5. QSO accumulation near z=2 explained by $\Omega_{\rm v} \sim 1$. Later rejected.

6. From 60s to the end of the Millennium Lambda was identically zero.

Only a few treated it seriously, starting from Zeldovich.

7. End of 90s:

a) Universe age crisis.

With H $\geq$ 70 km/sec/Mpc the universe would be too young, $t_U < 10$ Gyr, while stellar evolution and nuclear chronology demand $t_U \geq 13$ Gyr.

b) $\Omega_m = 0.3$, measured by several independent ways: mass-to-light ratio, gravitational lensing, galactic clusters evolution (number of clusters for different red-shifts z).

On the other hand:

inflation predicts $\Omega_{tot} = 1$.

Spectrum of angular fluctuations of CMBR (position of the first peak) "measures" $\Omega_{tot} = 1 \pm 0.05$.

c) Dimming of high redshift supernovae.

Cannot be explained by dust absorption because it was found that the effect is non-monotonic in z. At larger z dimming decreases. Indeed,

$\rho_{\mathrm{m}} \sim 1/a^3$,

while $\rho_{\mathrm{vac}} = \mathrm{const.}$

Equilibration at $z \approx 0.7$.

d) LSS and CMBR well fit theory if $\Omega_{\mathrm{v}} \approx 0.7$.

Theory: gravitational instability, flat spectrum of primordial fluctuations, cold dark matter (non-interactive?).

CONCLUSION:

$$\Omega_{\mathrm{v}} = 0.7$$

$$\rho_{\mathrm{vac}} \approx 10^{-47}\,\mathrm{GeV}^4$$

$$\Omega_{\mathrm{m}} = 0.3$$

EVOLUTION OF VACUUM(-LIKE) ENERGY DURING COSMIC HISTORY

1. At inflation $\rho_{\mathbf{vac}} \sim 10^{100} \rho_{\mathbf{v}}^{\mathbf{now}}$ and was DOMINANT. But it was not real vacuum energy but vacuum-like energy of almost constant scalar field inflaton.

2. At GUT p.t. (if such era existed)

$$\delta\rho_{\mathbf{vac}} \approx 10^{60}\,\mathrm{GeV}^4$$

3. At electro-weak p.t.

$$\delta\rho_{\mathbf{vac}} \approx 10^{8}\,\mathrm{GeV}^4$$

4. At QCD p.t.

$$\delta\rho_{\mathbf{vac}} \approx \mathbf{10^{-2}\,GeV^4}$$

The magnitude of vacuum energies of gluon and chiral condensates are known from experiment!

After inflation till almost the present epoch ρ_{vac} was always sub-dominant

ρ_{vac} started to dominate energy density only recently at $\mathbf{z \approx 0.3}$.

CONTRIBUTIONS TO VACUUM ENERGY

1. Bosonic vacuum fluctuations:

$$\langle \mathcal{H}_{\mathrm{b}} \rangle_{\mathrm{vac}} = \int \frac{d^3k}{(2\pi)^3} \frac{\omega_k}{2} \langle a_k^\dagger a_k + b_k b_k^\dagger \rangle_{\mathrm{vac}}$$

$$= \int \frac{d^3k}{(2\pi)^3} \omega_k = \infty^4$$

2. Fermionic vacuum fluctuations:

$$\langle \mathcal{H}_{\mathrm{f}} \rangle_{\mathrm{vac}} = \int \frac{d^3k}{(2\pi)^3} \frac{\omega_k}{2} \langle a_k^\dagger a_k - b_k b_k^\dagger \rangle_{\mathrm{vac}}$$

$$= \int \frac{d^3k}{(2\pi)^3} \omega_k = -\infty^4$$

Bosonic/fermionic cancellation - Zeldovich prior to SUSY.

Supersymmetry:
$\mathbf{N_b = N_f}$ **and** $\mathbf{m_b = m_f}$**, then**

$$\rho_{\mathbf{vac}} = \mathbf{0}$$

if the symmetry is UNBROKEN.

Soft SUSY breaking necessarily leads to

$$\rho_{\mathbf{vac}} \sim \mathbf{10^8\ GeV^4} \neq \mathbf{0}$$

Broken SUGRA allows for $\rho_{vac} = 0$ **but the natural value is**

$$\rho_{\mathbf{vac}} \sim \mathbf{m_{Pl}^4} \sim \mathbf{10^{76}\ GeV^4}$$

Phase transitions in the course of cosmological cooling

$$\delta\rho_{\mathbf{vac}} \gg \mathbf{10^{-47}\ GeV^4}$$

QCD is well established and experimentally verified science leads to conclusion that vacuum is not empty but filled with quark and gluon condensates:

$$\langle \bar{q}q \rangle \neq 0$$
$$\langle G_{\mu\nu} G^{\mu\nu} \rangle \neq 0$$

both having NEGATIVE vacuum energy

$$\rho_{\mathrm{vac}}^{\mathrm{QCD}} \approx -10^{45} \rho_c$$

Vacuum condensate is destroyed by quarks and the proton mass is:

$$\mathbf{m_p = 2m_u + m_d - \rho_{vac} l_p^3}$$

$\mathbf{m_u \sim m_d \sim 5\ eV.}$

Who adds the necessary "donation" to make the OBSERVED $\rho_{\mathrm{vac}} > 0$ and what kind of matter is it?

INTERMEDIATE SUMMARY

1. Known and huge contributions to ρ_{vac} but unknown mechanism of their compensation down to (almost) zero.

2. Observed today $\rho_{\mathbf{vac}} \sim \rho_{\mathbf{c}}$. WHY?

3. What is the nature of antigravitating matter? Consistent with $\mathbf{w} = -1$, vacuum?

Mostly only problems 2 and 3 are addressed:
a) modification of gravity;
b) new field (quintessence) leading to accelerated expansion.

Most probably all three problems are strongly coupled and can be solved only after adjustment of ρ_{vac} down to ρ_c is understood.

POSSIBLE SOLUTIONS

1. Subtraction constant.
2. Anthropic principle.
3. Infrared instability of massless fields (gravitons) in DS space-time.
4. Dynamical adjustment.
5. Drastic modification of existing theory - breaking of general covariance, Lorentz invariance, rejection of the Lagrange/Hamiltonian principle, ... ???

Remember: we need to explain only one number or a function if w $\neq 1$.

Dynamical adjustment, as axionic solution of strong CP problem:
New field Φ (scalar of higher spin) coupled to gravity is necessary.
1) Vacuum energy → condensate of $\mathbf{\Phi}$
2) $\rho(\mathbf{\Phi})$ compensates original ρ_{vac}.
3) Negative energy density of Phi.

Byproducts of dynamical adjustment have many features of less ambitious models of modified gravity, e.g.
explicit breaking of Lorentz invariance,
and
time dependent unstable background and stable fluctuations over it.

DYNAMICAL ADJUSTMENT

Generic predictions (before discovery of DE):

1. Change exponential expansion to power law one.

2. Compensation of vacuum energy is not complete but only down to terms of the order of $\rho_c(t)$.

3. Non-compensated energy may have an unusual equation of state.

Unfortunately, no realistic model found starting from 1982.

EXAMPLES OF ADJUSTMENT

1. Non-minimally coupled scalar field (AD, 1982):

$$\ddot{\phi} + 3H\dot{\phi} + U'(\phi, R) = 0$$

with e.g. $U = \xi R\phi^2/2$.

Solutions are unstable if $\xi R < 0$.

Asymptotically:

$$\phi \sim \mathbf{t}$$

and DS turns into Friedman, but

$$\mathbf{T}_{\mu\nu}(\phi) \neq \mathbf{F}\mathbf{g}_{\mu\nu}$$

and the change of the regime is achieved due to weakening of gravitational coupling:

$$\mathbf{G_N \sim 1/t^2}$$

Such a rise of $\mathbf{M_{Pl}}$ was recently suggested as a mechanism to explain hierarchy between EW and Planck.

2. Vector field V_μ (AD, 1985):

$$\mathcal{L}_\infty = \eta\left[\mathbf{F}^{\mu\nu}\mathbf{F}_{\mu\nu}/\mathbf{4} + (\mathbf{V}^{\mu}_{;\mu})^{\mathbf{2}}\right] + \xi\mathbf{R}\mathbf{m}^{\mathbf{2}}\ln\left(\mathbf{1}+\frac{\mathbf{V}^{\mathbf{2}}}{\mathbf{m}^{\mathbf{2}}}\right)$$

Unstable solution:

$$\mathbf{V_t} \sim \mathbf{t} + \mathbf{c}/\mathbf{t}$$

and

$$\mathbf{T}_{\mu\nu}(\mathbf{V_t}) \sim \mathbf{g}_{\mu\nu} + \textbf{vanishing terms}$$

Logarithmic variation of gravitational coupling with time.

3. Second rank tensor field $\mathbf{S}_{\mu\nu}$ (AD, 1994):

$$\mathcal{L}_2 = \eta_1 \mathbf{S}_{\alpha\beta;\gamma}\mathbf{S}^{\alpha\gamma;\beta} + \eta_2 \mathbf{S}^{\alpha}_{\beta;\alpha}\mathbf{S}^{\gamma\beta}_{\;;\gamma} + \eta_3 \mathbf{S}^{\alpha}_{\alpha;\beta}\mathbf{S}^{\gamma;\beta}_{\gamma}$$

Components $\mathbf{S_{tt}}$ and isotropic part of $\mathbf{S_{ij}} \sim \delta_{\mathbf{ij}}$ are unstable:

$$(\partial_t^2 + 3H\partial_t - 6H^2)S_{tt} - 2H^2 s_{jj} = 0$$

$$(\partial_t^2 + 3H\partial_t - 6H^2)s_{tj} = 0$$

$$(\partial_t^2 + 3H\partial_t - 2H^2)s_{ij} - 2H^2\delta_{ij}S_{tt} = 0$$

where $\mathbf{s_{tj} = S_{tj}/a(t)}$ and $\mathbf{s_{ij} = S_{ij}/a^2(t)}$.

Ill-defined theory with “non-physical” components, T_{tt} and/or T_{ii} becoming physical?

Ogievetsky and Polubarinov: “Photon and Notoph” - gauge theory of scalar field described by t-component of vector V_μ.

In all the cases after some period of exponential expansion DS is changed into Friedman
and the dominant term in $T_{\mu\nu} \sim g_{\mu\nu}$ but G_N is time-dependent.

More important: in all the models above expansion rate is not related to the usual matter.

4. Scalar with "crazy" coupling to gravity (Mukohayama, Randall, 2003; AD, Kawasaki, 2003:)

$$A = \int d^4x\sqrt{g}\left[-\frac{1}{2}(R+2\Lambda)+F_1(R) + \frac{D_\mu\phi D^\mu\phi}{2\,R^2} - U(\phi,R)\right]$$

Solution tends to

$$R \sim \rho_{vac} + U(\phi) = 0$$

It has some nice features ("almost realistic"), $H = 1/2t$, *etc*
but unstable with respect to small fluctuations.

Equation of motion for Φ:

$$\mathbf{D}_\mu \left[\mathbf{D}^\mu \phi \left(\frac{\mathbf{1}}{\mathbf{R}}\right)^{\mathbf{2}}\right] + \mathbf{U}'(\phi) = \mathbf{0}.$$

GR equations for the trace,
with $\mathbf{F_1 = C_1 R^2}$:

$$-\mathbf{R} + \mathbf{3}\left(\frac{\mathbf{1}}{\mathbf{R}}\right)^{\mathbf{2}} (\mathbf{D}_\alpha \phi)^{\mathbf{2}} - \mathbf{4}\left[\mathbf{U}(\phi) + \rho_{\mathbf{vac}}\right]$$

$$-\mathbf{6D^2}\left[\mathbf{2C_1R} - \left(\frac{\mathbf{1}}{\mathbf{R}}\right)^{\mathbf{2}} \frac{(\mathbf{D}_\alpha\phi)^{\mathbf{2}}}{\mathbf{R}}\right] = \mathbf{T}^\mu_\mu$$

A desperate attempt to improve the model:

$$\frac{(\mathbf{D}\phi)^{\mathbf{2}}}{\mathbf{R}^{\mathbf{2}}} \to -\frac{(\mathbf{D}\phi)^{\mathbf{2}}}{\mathbf{R}\,|\mathbf{R}|}.$$

More general action with scalar field (AD, Kawasaki, 2003) not yet explored:

$$\mathbf{A} = \int \mathbf{d^4x}\sqrt{-\mathbf{g}}[-\mathbf{m_{Pl}^2}(\mathbf{R}+\mathbf{2\Lambda})/\mathbf{16}\pi \\ +\mathbf{F_1}(\mathbf{R})+\mathbf{F_2}(\phi,\mathbf{R})\mathbf{D}_\mu\phi\mathbf{D}^\mu\phi \\ +\mathbf{F_3}(\phi,\mathbf{R})\mathbf{D}_\mu\phi\mathbf{D}^\mu\mathbf{R}-\mathbf{U}(\phi,\mathbf{R})]$$

Moreover $R_{\mu\nu}$ and $R_{\mu\nu\alpha\beta}$ can be also included.

LAMBDA-SUMMARY

1. Some compensating agent must exist!
QCD demands that.

2. Quite natural to expect that ρ_{vac} is not completely compensated and

$$\Delta\rho \sim \rho_{\mathbf{c}}$$

3. Realistic model is needed, it can indicate what is w: is it (-1) or different.

4. Theoretical prior:
A STRANGE FORM OF ENERGY LIVES IN THE UNIVERSE it must be included into data analysis.

BIG BANG NUCLEOSYNTHESIS

(formation of light elements in the early universe)

Neutron-proton transformations:

$$\mathbf{n} + \mathbf{e}^+ \leftrightarrow \mathbf{p} + \bar{\nu}_\mathbf{e}$$
$$\mathbf{n} + \nu_\mathbf{e} \leftrightarrow \mathbf{p} + \mathbf{e}^-$$

frozen at $T \approx 0.7$ MeV, determine starting value of n/p-ratio.

When T drops down to 60-70 keV all neutrons quickly form ^{4}He (about 25% by mass) and a little ^{2}H (3×10^{-5} by number), ^{3}He (similar to ^{2}H) and ^{7}Li ($10^{-9} - 10^{-10}$) - span by 9 orders of magnitude, well confirmed by the data.

INTERESTING FINE-TUNING: IF FERMI COUPLING CONSTANT CHANGES BY A FACTOR OF FEW THE WORLD WOULD BE VERY DIFFERENT:

EITHER NO HELIUM OR NO HYDROGEN

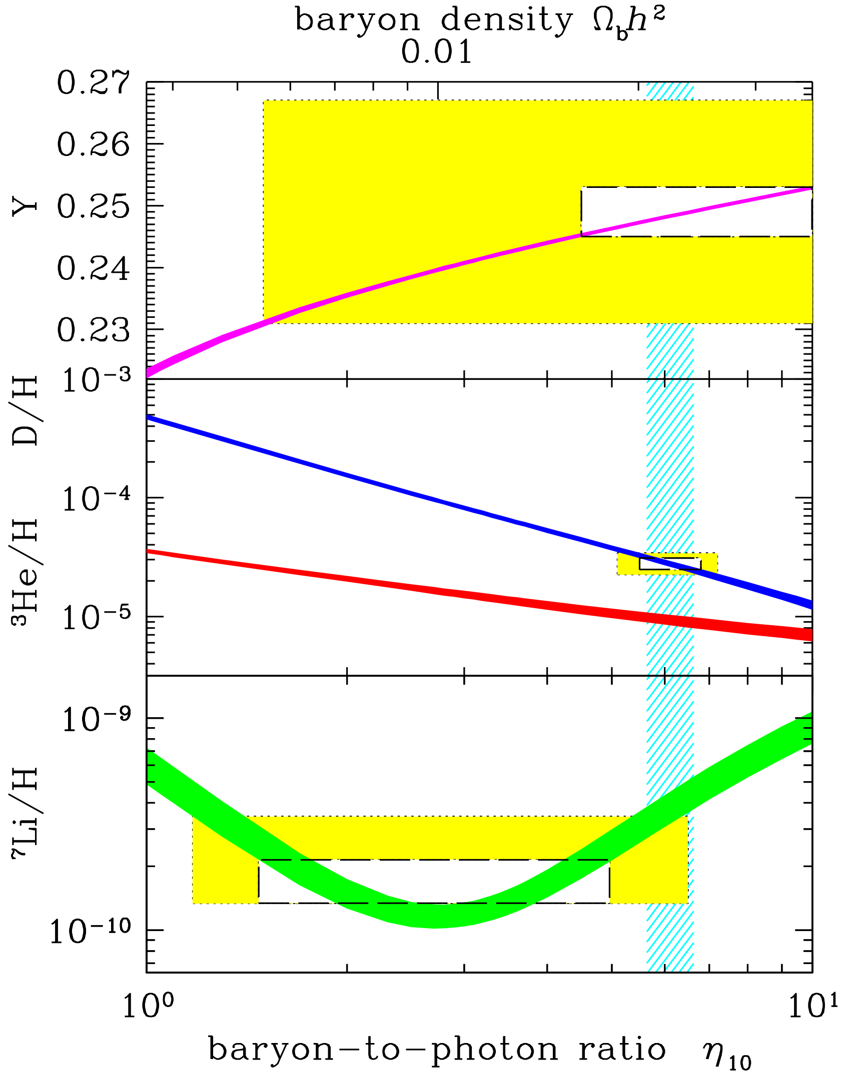
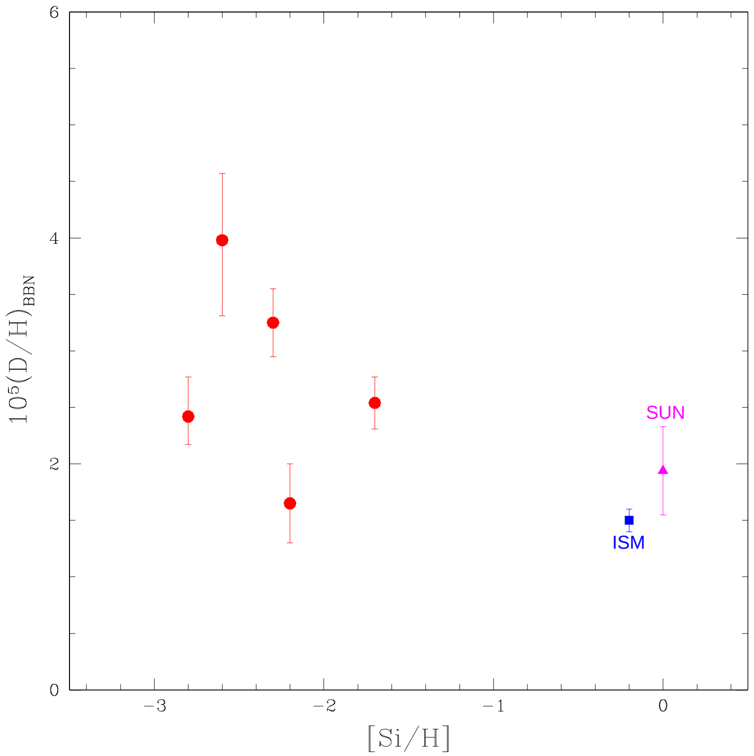


Figure 3: **He^4, D, He^3 and Li^7 predicted by the standard BBN. Boxes indicate the observed light element abundances (smaller boxes: 2σ statistical errors; larger boxes: $\pm 2\sigma$ statistical and systematic errors). The vertical band is the CMB measure of the cosmic baryon density.**

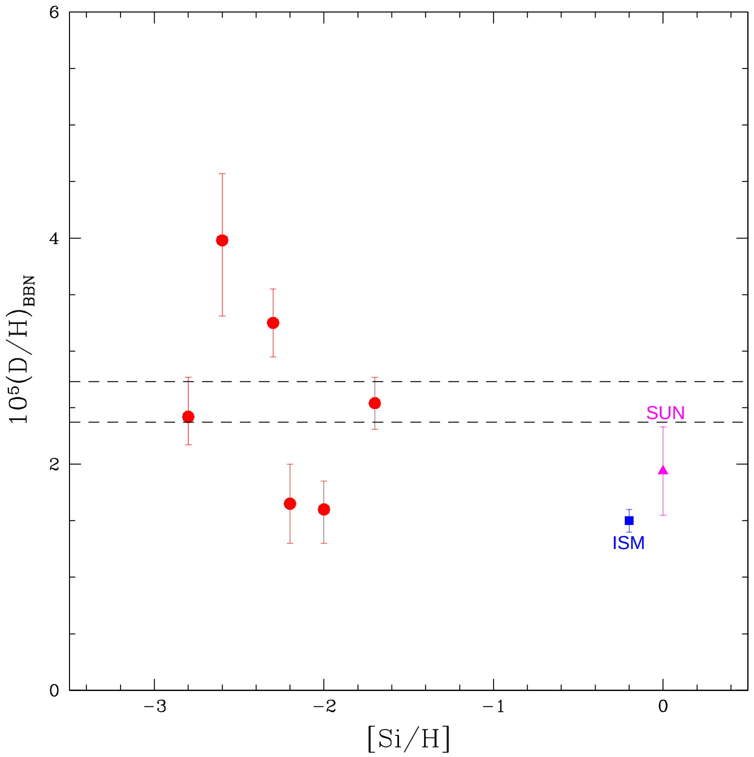
Possibly the accuracy in the previous figure is too high. Individual measurements are much more dispersed.

Problems in comparing theory with observations: calculate at $\mathbf{t_U \sim 300\,sec}$ and observe now.
Evolutionary effects are poorly known.

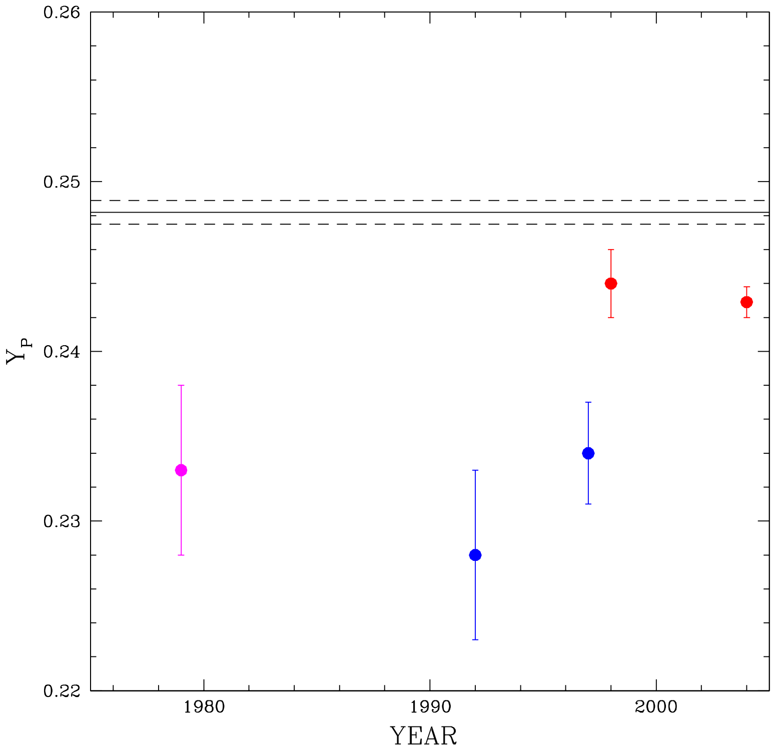
Helium is not destroyed, the observed abundance is larger than the primordial one. Extrapolation to zero metallicity. Unknown ionization corrections.
Deuterium destroyed in the course of evolution, in contrast to helium may be observed at high red-shifts, i.e. possibly primordial deuterium. Data are rather dispersed from $1.6 \cdot 10^{-5}$ up to $3.5 \cdot 10^{-5}$.
Lithium, potential problem, but difficult to observe, in first generation stars?



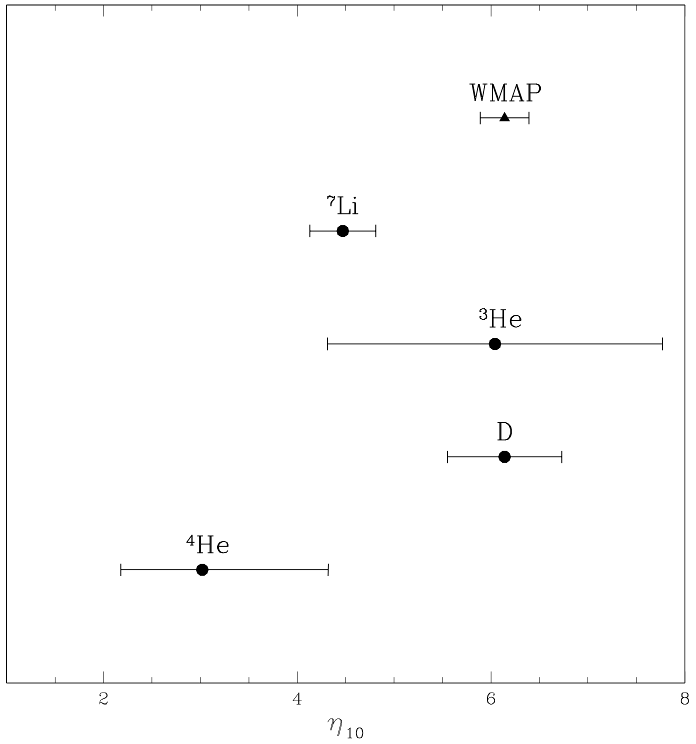
Observationally inferred primordial ^{2}H abundances (D/H by number) versus a logarithmic measure of the metallicity, relative to solar ([Si/H]), for five high redshift, 2003. Also shown for comparison are the D/H ratios inferred from observations of the local interstellar medium (ISM; filled square) and that for the pre-solar nebula (Sun; filled triangle).



Previous figure updated to 2004 to include the one new deuterium abundance determination for a high redshift, low metallicity QSOALS. The dashed lines show the SBBN-predicted 1σ band for the WMAP baryon abundance.



The observationally inferred primordial ^{4}He mass fractions from 1978 until 2004. The error bars are the quoted 1σ uncertainties. Also shown is the SBBN-predicted relic abundance (solid line) for the WMAP baryon abundance, along with the 1σ uncertainty (dashed lines) of the SBBN prediction.



The SBBN values for the early universe ($\sim$ 20 minutes) baryon abundance parameter η_{10} inferred from the adopted primordial abundances of D, ^{3}He, ^{4}He, and ^{7}Li. Also shown is the WMAP-derived CMBR and LSS value ($\sim$ 400 kyr).

BBN with wrong statistics

If neutrinos obey Bose statistics:
1) their energy density would be 8/7 of normal fermionic ν, giving $\mathbf{\Delta}\mathrm{N}_\nu = \mathbf{3/7}$;
2) larger density of ν_e would lead to smaller temperature of n/p-freezing.

The net result:

$$\mathbf{N}_\nu^{(\mathbf{eff})} = \mathbf{2.43}$$

Equilibrium distribution for mixed statistics:

$$\mathbf{f}_\nu^{(\mathbf{eq})} = \left[\exp(\mathbf{E}/\mathbf{T}) + \kappa\right]^{-\mathbf{1}}.$$

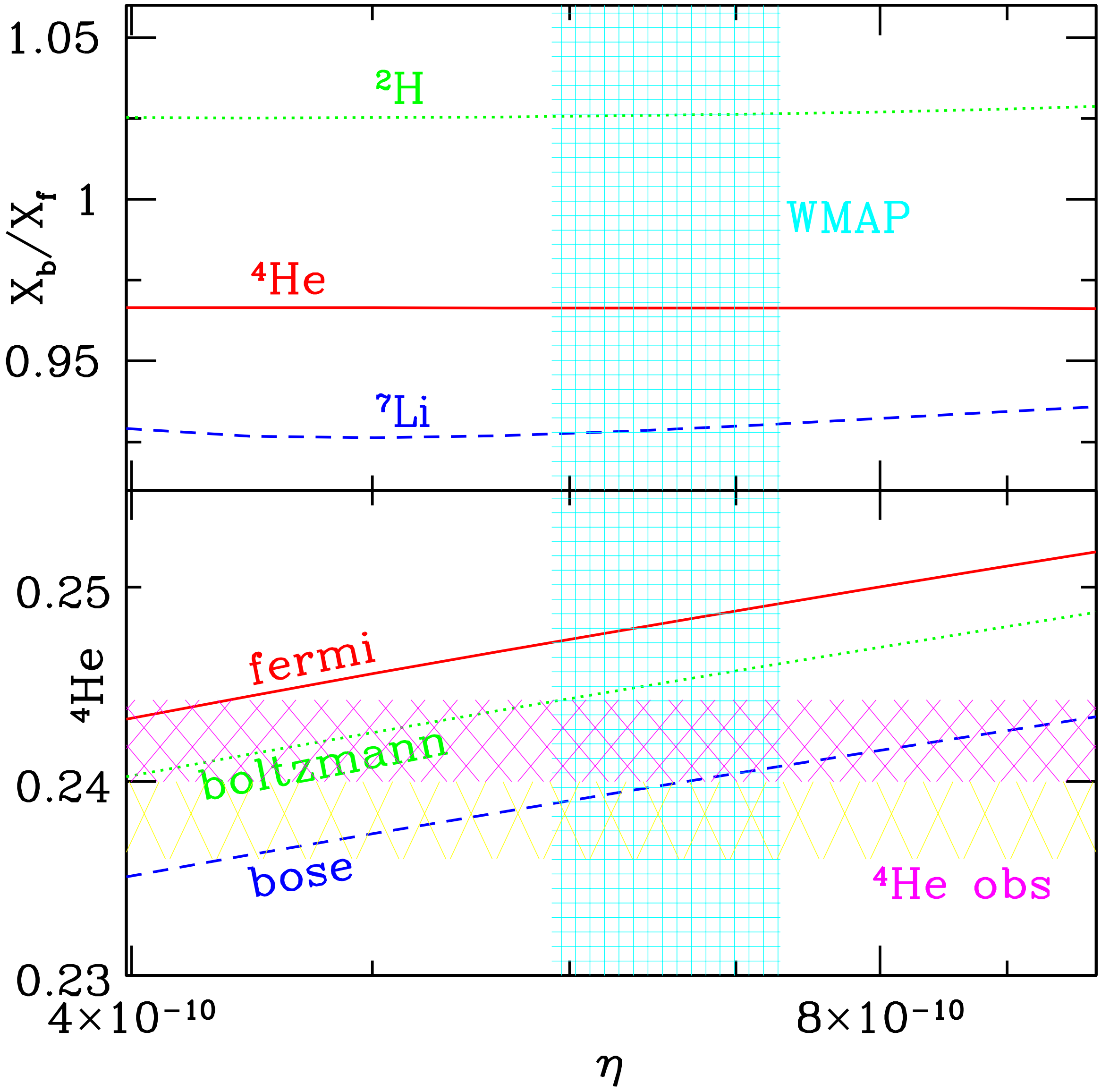

1.05
1
0.95
X_b/X_f
^{2}H
WMAP
^{4}He
^{7}Li
0.25
0.24
0.23
^{4}He
fermi
boltzmann
bose
^{4}He obs
4×10^{-10}
8×10^{-10}
η

Figure caption: Upper: ratios of nuclear abundances for pure bosonic neutrinos with respect to fermionic ones as functions of $\eta = N_B/N_\gamma$. Vertical cyan region is WMAP 2σ determination of η. Lower: ^{4}He mass fraction for the purely bosonic, Boltzmann, and fermionic neutrinos. ($\kappa = -1, 0, +1$ respectively). The two skew hatched regions show the observation of primordial ^{4}He helium from Fields-Olive (lower, yellow) and Izotov-Thuan (upper, magenta)

FORMATION OF LARGE SCALE STRUCTURE

Theoretical input: rise of initial density perturbations because of gravitational instability.

Assumptions

1. Spectrum of primordial fluctuations. Usually assumed flat, **Harrison-Zeldovich** type. Predicted by inflation. Confirmed by CMBR at large scales ≥ 10Mpc.

2. Properties of dark matter. Usually non-interacting **CDM+Lambda**. **Self-interacting dark matter, e.g. mirror?**

3. Analytical calculations at linear regime, when $\delta\rho/\rho \ll 1$. Standard physics: GR and hydrodynamics. Not distorted at large scales accessible to CMBR.

4. Numerical simulations at nonlinear regime, when $\delta\rho/\rho \geq 1$. Necessary at smaller scales, ~ 10 Mpc.

All above is confirmed (not proven?) by the data.

Necessity of nonbaryonic matter.

Fluctuations of baryonic matter can rise only after recombination, i.e in neutral matter. Photonic pressure prevents baryons and electrons from gravitational coupling otherwise.

Fluctuations at MD regime can rise as scale factor. Thus density contrast in purely baryonic universe may rise at most by 10^3.

In the case of adiabatic fluctuations (proven by CMB)

$$\frac{\delta\rho}{\rho} \sim \frac{\delta \mathbf{T}}{\mathbf{T}} < \mathbf{10^{-4}}$$

and fluctuations cannot reach unity by today.

Fluctuations in nonbaryonic DM not interacting with light do not suffer from the pressure of CMBR and fluctuations can rise at MD-stage, i.e. at redshift $\mathbf{z \sim 10^4}$.

Possible forms of dark (invisible) matter

Several (too many?) candidates.

Cold dark matter (CDM):

1. **LSP, $m = 0.1 - 1$ TeV.**
2. **Axion, $m = 10^{-5}$ eV.**
3. **Mirror world.**
4. **Black holes.**

Warm dark matter (WDM):

Sterile neutrino $m = 0.1 - 1$ keV.

Hot dark matter (HDM):

Usual neutrinos, must be subdominant.

What if ν obeys Bose statistics?

A.D., A. Smirnov, hep-ph/0501066;
A.D. hep-ph/0504238

Neutrinos might form cosmological Bose condensate:

$$\mathbf{f}_{\nu_\mathbf{b}} = \frac{\mathbf{1}}{\exp[(\mathbf{E} - \mu_\nu)/\mathbf{T} - \mathbf{1}]} + \mathbf{C}\delta(\mathbf{k}),$$

and make
ALL COLD DARK MATTER
plus
HOT DARK MATTER

DM out of OLD KNOWN particles but NEW PHYSICS.

CONCLUSION

Cosmology proves that there is NEW PHYSICS:

a) inflation,
b) baryogenesis,
c) dark matter,
d) dark antigravitating energy.

QCD "measures" vacuum energies of quark and gluon condensate which have vacuum energy $\sim$ 50 orders of magnitude larger than that observed.

Who killed it?

If unitarity and spin-statistics are broken then the usual equilibrium distributions may be broken too and the effects can be accumulated and large. One should be aware of Pandora box of consequences if sacred principles are destroyed.

"If God does not exist anything is allowed." Dostoevsky.