Role of modern cosmology for fundamental physics and for BNO research

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International conference "Physics and Fundamental Interactions"
dedicated to the 50th anniversary of Baksan Neutrino Observatory
Nalchik, Kabardino-Balkaria, Russian Federation,
08.06.2017

Four epochs of the history of the Universe

$H \equiv \frac{\dot{a}}{a}$ where $a(t)$ is a scale factor of an isotropic homogeneous spatially flat universe (a Friedmann-Lemaître-Robertson-Walker background):

$$ds^2 = dt^2 - a^2(t)(dx^2 + dy^2 + dz^2) + small\ perturbations$$

The history of the Universe in one line: four main epochs

$$? \longrightarrow DS \Longrightarrow FLRWRD \Longrightarrow FLRWMD \Longrightarrow \overline{DS} \longrightarrow ?$$

Geometry

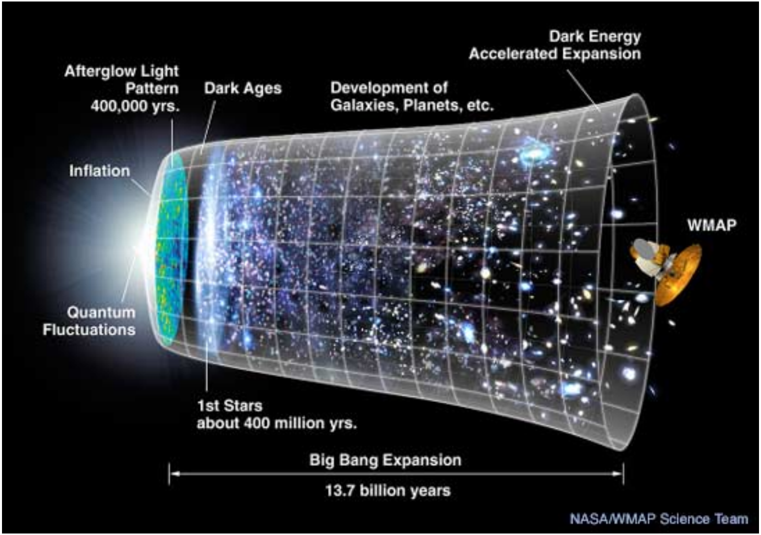
$$|\dot{H}| << H^2 \Longrightarrow H = \frac{1}{2t} \Longrightarrow H = \frac{2}{3t} \Longrightarrow |\dot{H}| << H^2$$

Physics

$$p \approx -\rho \Longrightarrow p = \rho/3 \Longrightarrow p \ll \rho \Longrightarrow p \approx -\rho$$

Duration in terms of the number of e-folds $\ln(a_{fin}/a_{in})$

$$> 60 \qquad \sim 55 \qquad 7.5 \qquad 0.5$$


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

Main epochs of the Universe evolution – before 1979

The history of the Universe in one line: two main epochs

$$? \longrightarrow FLRWRD \Longrightarrow FLRWMD \longrightarrow ?$$

Geometry

$$H = \frac{1}{2t} \Longrightarrow H = \frac{2}{3t}$$

Physics

$$p = \rho/3 \Longrightarrow p \ll \rho$$

Present matter content of the Universe

In terms of the critical density

$\rho_{crit} = \frac{3H_0^2}{8\pi G} = 0.920 \times 10^{-29} \left(\frac{H_0}{70}\right)^2 \mathrm{g/cm^3}$

$\Omega_i = \frac{\rho_i}{\rho_{crit}}, \quad \sum_i \Omega_i = 1$

where the Hubble constant $H_0 = 70 \pm 3$ km/s/Mpc

(neglecting spatial curvature - less than 0.5%):

- Baryons (p,n) and leptons (e^-) $\approx 5\%$
  No primordial antimatter.
- Photons (γ) 4×10^{-5}
  $T_\gamma = (2.72548 \pm 0.00057)\mathrm{K}$
- Neutrinos ($\nu_e, \ \nu_\mu, \ \nu_\tau$) $< 0.5\%$

$$\sum_i m_{\nu i} < 0.2 \ \mathrm{eV}, \quad \sum_i m_{\nu i} = 46\Omega_\nu \left(\frac{H_0}{70}\right) \ \mathrm{eV}.$$

- Non-relativistic non-baryonic dark matter $\approx 25\%$
- Dark energy $\approx 70\%$

Dark matter

Dark matter and dark energy are seen through gravitational interaction only – we know the structure of their effective energy-momentum tensor.

DM - non-relativistic, gravitationally clustered.
DE - relativistic, unclustered.
Definition of their effective EMT – through equations (conventional).
DM - through the generalized Poisson equation:

$$\frac{\triangle\Phi}{a^2} = 4\pi G(\rho - \rho_0(t)).$$

$\Phi(\mathbf{r}, t)$ is measured using the motion of 'test particles' in it.
a) Stars in galaxies $\to$ rotation curves.
b) Galaxies $\to$ peculiar velocities.
c) Hot gas in galaxies $\to$ X-ray profiles.
d) Photons $\to$ gravitational lensing (strong and weak).

Observations: DM is non-relativistic, has a dust-like EMT – $p \ll \epsilon = \rho c^2, \quad p > 0$, collisionless in the first approximation – $\sigma/m \lesssim 0.5\ \mathrm{cm}^2/\mathrm{g}$, and has the same spatial distribution as visible matter for scales exceeding a few Mpc.

Ground experiments: very weakly interacting with baryonic matter, $\sigma < 10^{-43}\ \mathrm{cm}^2$ for $m \sim (50 - 100)$ GeV.

Dark energy

Two cases where DE shows itself:
1) inflation in the early Universe – primordial DE,
2) present accelerated expansion of the Universe – present DE.

Quantitative and internally self-consistent definition of its effective EMT - through gravitational field equations conventionally written in the Einstein form:

$$\frac{1}{8\pi G}\left(R_\mu^\nu - \frac{1}{2}\,\delta_\mu^\nu R\right) = \left(T^\nu_{\mu\,(vis)} + T^\nu_{\mu\,(DM)} + T^\nu_{\mu\,(DE)}\right) \;,$$

$G = G_0 = const$ - the Newton gravitational constant measured in laboratory.
In the absence of direct interaction between DM and DE:

$$T^\nu_{\mu\,(DE);\nu} = 0 \;.$$

Possible forms of DE

- Physical DE.
  New non-gravitational field of matter. DE proper place – in the rhs of gravity equations.
- Geometrical DE.
  Modified gravity. DE proper place – in the lhs of gravity equations.
- Λ - intermediate case.

Observations: $T_{\mu\,(DE)}^{\nu}$ is very close to $\Lambda\delta_{\mu}^{\nu}$ for the concrete solution describing our Universe;

$$|<w_{DE}>+1|<0.1\ ,$$

where $w_{DE}\equiv p_{DE}/\epsilon_{DE}$.
$w_{DE}>-1$ – normal case,
$w_{DE}<-1$ – phantom case,
$w_{DE}\equiv -1$ – the exact cosmological constant ("vacuum energy").

Four fundamental cosmological constants

One-to-one relation to the four epochs of the history of the Universe.

A fundamental theory beyond each of these constants.

- Characteristic amplitude of primordial scalar (adiabatic) perturbations.

$$< \zeta^2(\mathbf{r}) >= \int \frac{P_\zeta(k)}{k}\, dk, \quad P_\zeta(k) = 2.2 \times 10^{-9} \left(\frac{k}{k_0}\right)^{n_s - 1}$$

$$k_0 = 0.05\mathrm{Mpc}^{-1}, \quad n_s - 1 = -0.035 \pm 0.005$$

Theory of initial conditions – inflation. Its simplest model (Starobinsky, 1980) predicted the slope of the spectrum relating it finally to $N_H = \ln \frac{k_B T_\gamma}{\hbar H_0} \approx 67.2$:

$$n_s - 1 = -\frac{2}{N}$$

where $N = N_H - \mathcal{O}(10)$ is the number of e-folds from the end of inflation.

- Baryon to photon ratio.

$$\frac{n_b}{n_\gamma} = 6.01 \times 10^{-10}\,\frac{\Omega_b h^2}{0.0022}\,\left(\frac{2.725}{T_\gamma(\mathrm{K})}\right)^3, h = \frac{H_0}{100}\,.$$

Theory of baryogenesis.

- Baryon to total non-relativistic matter density.

$$\frac{\rho_b}{\rho_m} = 0.167\,\frac{\Omega_b}{0.05}\,\frac{0.3}{\Omega_m}\,.$$

Theory of dark matter.

- Energy density of present dark energy.

$$\rho_{DE} = \frac{\epsilon_{DE}}{c^2} = 6.44 \times 10^{-30}\,\frac{\Omega_{DE}}{0.7}\,\left(\frac{H_0}{70}\right)^2\,\mathrm{g/cm^3}\,,$$

$$\frac{G^2\hbar\epsilon_{DE}}{c^7} = 1.25 \times 10^{-123}\,\frac{\Omega_{DE}}{0.7}\,\left(\frac{H_0}{70}\right)^2\,.$$

Theory of present dark energy.

The minimal present standard cosmological model

ΛCDM + ($\mathcal{K} = 0$)+(scale-invariant adiabatic perturbations) contains two more parameters:

- H_0 – not a constant, but a present value of $H(t)$;
- $\tau \approx 0.07$ – optical width after recombination – a constant, but not fundamental.

4 fundamental cosmological constants $\Longrightarrow$ no more than 4 cosmological "coincidences", all other "coincidences" exist already at the level of usual laboratory physics.

Outcome of inflation

In the super-Hubble regime ($k \ll aH$) in the coordinate representation:

$$ds^2 = dt^2 - a^2(t)(\delta_{lm} + h_{lm})dx^l dx^m, \quad l, m = 1, 2, 3$$

$$h_{lm} = 2\zeta(\mathbf{r})\delta_{lm} + \sum_{a=1}^{2} g^{(a)}(\mathbf{r})\, e_{lm}^{(a)}$$

$$e_l^{l(a)} = 0, \;\; g^{(a)}_{\;\;,l}\, e_m^{l(a)} = 0, \;\; e_{lm}^{(a)}\, e^{lm(a)} = 1$$

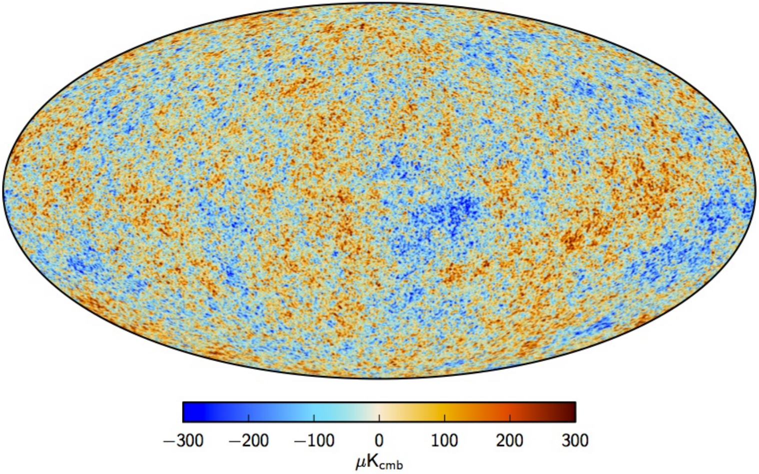
ζ describes primordial scalar perturbations, g – primordial tensor perturbations (primordial gravitational waves (GW)).

The most important quantities:

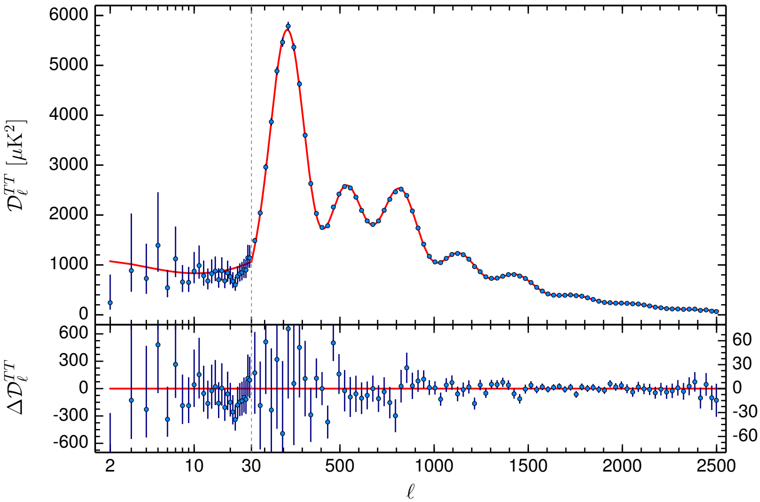
$$n_s(k) - 1 \equiv \frac{d \ln P_\zeta(k)}{d \ln k}, \quad r(k) \equiv \frac{P_g}{P_\zeta}$$

CMB temperature anisotropy

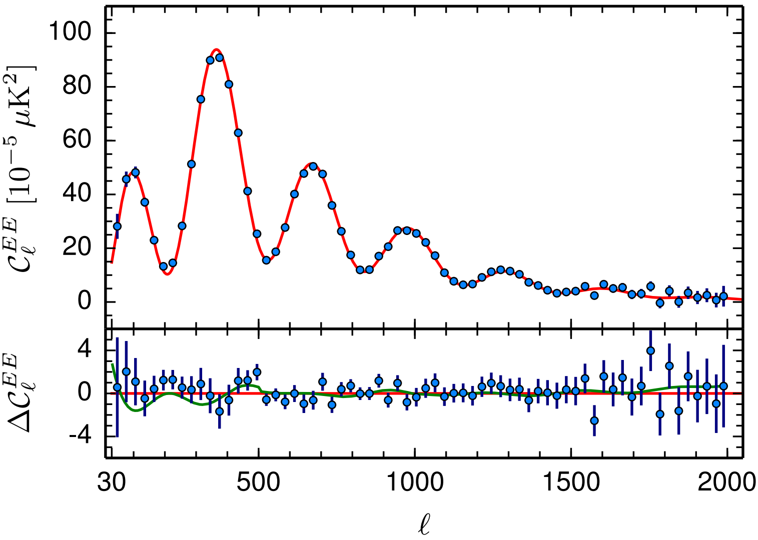
Planck-2015: P. A. R. Ade et al., arXiv:1502.01589



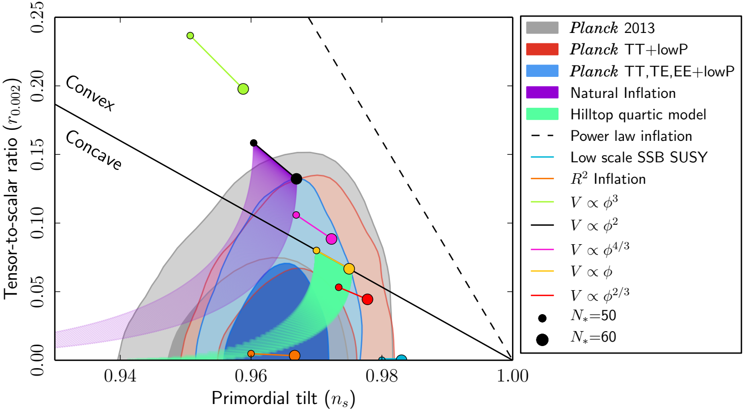
CMB temperature anisotropy multipoles



CMB E-mode polarization multipoles

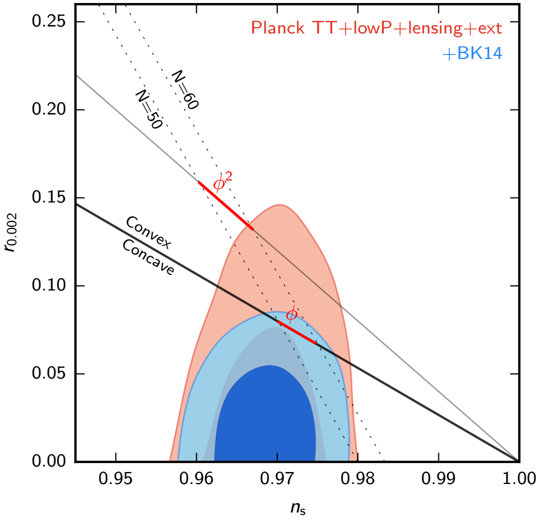


Comparison of the Planck results with simple smooth models



Combined BICEP2/Keck Array/Planck results

P. A. R. Ade et al., Phys. Rev. Lett. 116, 031302 (2016); arXiv:1510.09217



The simplest models producing the observed scalar slope

$$f(R) = R + \frac{R^2}{6M^2}$$

$$M = 2.6 \times 10^{-6} \left(\frac{55}{N}\right) M_{Pl} \approx 3.2 \times 10^{13}\,\mathrm{GeV}$$

$$n_s - 1 = -\frac{2}{N} \approx -0.036, \quad r = \frac{12}{N^2} \approx 0.004, \quad N = \ln\frac{k_f}{k}$$

$$H_{dS}(N = 55) = 1.4 \times 10^{14}\,\mathrm{GeV}$$

The same prediction from a scalar field model with $V(\phi) = \frac{\lambda\phi^4}{4}$ at large ϕ and strong non-minimal coupling to gravity $\xi R\phi^2$ with $\xi < 0, \ |\xi| \gg 1$, including the Brout-Englert-Higgs inflationary model.

Hints for super-high-energy particle physics

If no new fundamental dimensionless constants not found in experiments and observations are introduced, the simplest inflationary models predicts the existence of a particle (or a quasi-particle like plasmon) with the characteristic mass $\sim 10^{13}$ GeV. However, this mass occurs in curved space-time with $H \sim 10^{14}$ GeV.

On the the other hand, and independently, the electroweak vacuum of the SM of particle physics seems to be unstable for energies $E \gtrsim 10^{11}$ GeV in the Minkowski space-time due to high-order quantum corrections to the Higgs potential.

Some discrepancy between these numbers. However, possible new particles with masses in between ($\sim 10^{12}$ GeV) may remove it. Then inflation might save SM. These particles may be useful for effective baryosynthesis, too.

Upper limits on the $\sum m_\nu$ and N_ν

Follow from the (absence of) small-scale cut-off in the Fourier power spectrum of matter non-homogeneity (seen using $\Delta T/T$, galaxy counts, cluster redshift abundance, etc.). In the case of N_ν, data on primordial abundance of light elements produced by BBN are used, too.

The present conservative result for the standard cosmological model: $\sum_i m_{\nu i} < 0.23\ \mathrm{eV}$.
Expected to be lowered to $\sum_i m_{\nu i} \lesssim 0.05\ \mathrm{eV}$ during next several years.

The Planck-2015 result for the effective number of neutrino types: $N_{eff} = 3.15 \pm 0.23$.
Standard cosmology does not favor sterile neutrinos.

Why interest in one sterile neutrino?

Anomalies in some ground experiments though with marginal statistical significance:

1. The MiniBoone anomaly.
2. Gallium anomaly in the SAGE and GALLEX experiments.
3. Reactor anomalies.

If confirmed, their explanation requires a fourth (sterile) neutrino with the restmass $m \sim 1$ eV.

Will this destroy cosmology completely?

Possibility of one sterile neutrino with $m_4 \sim 1$ eV in modified gravity

Modified gravity, in particular the $f(R)$ gravity (but more complicated than $R + R^2$ model used for inflation), permits one sterile neutrino with $m \lesssim 1.5$ eV.

1. H. Motohashi, A. A. Starobinsky and J. Yokoyama, Phys. Rev. Lett. **110**, 121302 (2013).
2. A. S. Chudaikin, D. S. Gorbunov, A. A. Starobinsky, R. A. Burenin, JCAP **1505**, 004 (2015) - data on rich cluster abundance added.

An example of a cosmological model satisfying all viability conditions in the present Universe (Starobinsky, 2007):

$$f(R) = R + \lambda R_0 \left(\frac{1}{\left(1 + \frac{R^2}{R_0^2}\right)^n} - 1 \right)$$

with $n \geq 2$. $f(0) = 0$ is put by hand to avoid the appearance of a cosmological constant in the flat space-time.

However, cosmological data by themselves (with marginalization over m_4) do not give preference to this model over the standard cosmology with 3 neutrino types. It is only if m_4 is fixed, then cosmology with one sterile neutrino much heavier than standard neutrinos fits cosmological observational data significantly better than the standard ΛCDM model.

Conclusions

- At present, cosmology requires the introduction of at least four fundamental constants to describe observational data, additional to those known from ground and Solar system experiments.
- One new fundamental cosmological parameter $n_s - 1$ has been measured recently, but the theory had been able to predict it more than 30 years before the discovery.
- Regarding the present dark energy:
  a) still no statistically significant deviation from an exact cosmological constant;
  b) one constant is sufficient to describe its properties;
  c) no more than one new "coincidence problem".
- Regarding the primordial dark energy driving inflation in the early Universe:
  a number of inflationary models having only one free parameter can explain all existing observational data.

- The typical inflationary predictions that $|n_s - 1|$ is small and of the order of N_H^{-1}, and that r does not exceed $\sim 8(1 - n_s)$ are confirmed. Typical consequences following without assuming additional small parameters: $H_{55} \sim 10^{14}\,\mathrm{GeV},\ m_{infl} \sim 10^{13}\,\mathrm{GeV}$.
- The standard cosmological model bounds the sum of neutrino masses to $\sum_i m_{\nu i} \lesssim 0.2\ \mathrm{eV}$ and does not favor sterile neutrinos.
- Cosmology based on $f(R)$ gravity admits one massive sterile neutrino with the mass $m_4 \sim 1$ eV, and for a fixed mass $m_4 = 1$ eV, it fits cosmological observational data significantly better than the standard ΛCDM model.