

Standard cosmological model – the present status

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History of the Universe

Present matter content of the Universe

Dark matter and dark energy

4 fundamental cosmological constants

New fundamental constants expected

Viable one-parameter inflationary models

Conclusions

4 stages of the Universe evolution

The history of the Universe in one line according to the present paradigm:

$$? \longrightarrow DS \Longrightarrow FRWRD \Longrightarrow FRWMD \Longrightarrow \overline{DS} \longrightarrow ?$$

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

$H \equiv \frac{\dot{a}}{a}$ where $a(t)$ is a scale factor of an isotropic homogeneous universe.

Present matter content of the Universe

In terms of the critical density

$$\rho_{crit} = \frac{3H_0^2}{8\pi G} \approx 0.9 \times 10^{-29} \text{ g/cm}^3, \quad \Omega_i = \frac{\rho_i}{\rho_{crit}}, \quad \sum_i \Omega_i = 1$$

(neglecting spatial curvature - less than 1%):

- ▶ Baryons (p, n) and leptons (e^-) 4.5%
No primordial antimatter.
- ▶ Photons (γ) 4×10^{-5}
 $T_\gamma = (2.72548 \pm 0.00057)\text{K}$ (arxiv:0911.1955)
- ▶ Neutrinos (ν_e, ν_μ, ν_τ) $< 1\%$

$$\sum_i m_{\nu i} < 0.6 \text{ eV}, \quad \sum_i m_{\nu i} = 94\Omega_\nu h^2 \text{ eV}.$$

- ▶ Non-relativistic non-baryonic dark matter 23%
- ▶ Dark energy 73%

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:

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

$\Phi(\mathbf{r}, t)$ is measured using the motion of 'test particles' in it.

- Stars if galaxies → rotation curves.
- Galaxies → peculiar velocities.
- Hot gas in galaxies → X-ray profiles.
- Photons → gravitational lensing (strong and weak).

Observations: DM is non-relativistic, has a dust-like EMT – $p \ll \epsilon = \rho c^2$, $p > 0$, collisionless in the first approximation – $\sigma/m < 1 \text{ cm}^2/\text{g}$, and has the same spatial distribution as visible matter for scales exceeding a few Mpc.

Ground experiments: very weakly interacting with baryonic matter, $\sigma < 10^{-43} \text{ cm}^2$ for $m \sim (50 - 100) \text{ GeV}$ (however, there exist an interesting window with $m \sim 7 \text{ GeV}$ and $\sigma \sim 10^{-40} \text{ cm}^2$ consistent with the results of DAMA, CDMS and CoGeNT).

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:

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

$G = G_0 = \text{const}$ - 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: $T_{\mu}^{\nu}(DE)$ is very close to $\Lambda\delta_{\mu}^{\nu}$ for the concrete solution describing our Universe;

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

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”).

$f(R)$ gravity – the simplest form of geometrical DE

$$S = \frac{1}{16\pi G} \int f(R) \sqrt{-g} d^4x + S_m$$

$$f(R) = R + F(R), \quad R \equiv R^\mu{}_\mu .$$

The effective energy-momentum tensor of DE in $f(R)$ gravity:

$$8\pi G T_{\mu}^{\nu}{}_{(DE)} = F'(R) R^\nu{}_\mu - \frac{1}{2} F(R) \delta^\nu{}_\mu + (\nabla_\mu \nabla^\nu - \delta^\nu{}_\mu \nabla_\gamma \nabla^\gamma) F'(R) .$$

The most critical test for all $f(R)$ models of present dark energy: anomalous growth of density perturbations in the non-relativistic matter component at recent redshifts $z \sim (1 - 3)$.

4 fundamental cosmological constants

One-to-one relation to the 4 cosmological stages.

A fundamental theory beyond each of these constants.

- ▶ Characteristic amplitude of primordial scalar (adiabatic) perturbations.

$$\Delta_{\mathcal{R}}^2 = 2.4 \times 10^{-9}, \quad P_s(k) = \int \frac{\Delta_{\mathcal{R}}^2}{k} dk .$$

Theory of initial conditions – inflation.

- ▶ Baryon to photon ratio.

$$\frac{n_b}{n_\gamma} = 6.28 \times 10^{-10} \frac{\Omega_b h^2}{0.0023} \left(\frac{2.725}{T_\gamma(\text{K})} \right)^3 .$$

Theory of baryogenesis.

- ▶ Baryon to total non-relativistic matter density.

$$\frac{\rho_b}{\rho_m} = 0.167 \frac{\Omega_b}{0.045} \frac{0.27}{\Omega_m} .$$

Theory of dark matter.

- ▶ Energy density of present dark energy.

$$\rho_{DE} = \frac{\epsilon_{DE}}{c^2} = 6.72 \times 10^{-30} \frac{\Omega_{DE}}{0.73} \left(\frac{H_0}{70} \right)^2 \text{ g/cm}^3 ,$$

$$\frac{G^2 \hbar \epsilon_{DE}}{c^7} = 1.30 \times 10^{-123} \frac{\Omega_{DE}}{0.73} \left(\frac{H_0}{70} \right)^2 .$$

Theory of present dark energy (of a cosmological constant).

The minimal present standard cosmological model

Λ CDM + ($\mathcal{K} = 0$) + ($n_s = 1$ adiabatic perturbations)

contains two more parameters:

- ▶ H_0 – not a constant, but a present value of $H(t)$;
- ▶ τ – optical width after recombination – a constant, but not fundamental.

4 fundamental constants \implies no more than 4 "coincidences".

New fundamental constants from cosmology soon?

In case of primordial dark energy (inflation) – **yes**.

The basic prediction from inflation is that the primordial spectrum of adiabatic scalar perturbations is generically only **approximately** flat (i.e. Harrison-Zeldovich like), namely, $n_s - 1$ is a small and slowly varying function of scale, apart from one exceptional and very specific form of an inflaton potential (Starobinsky, 2005).

WMAP has got some first evidence for a non-zero value of this function: $\langle n_s \rangle - 1 \approx -0.04$ at 3σ level, but only under the additional assumption that the tensor-to-scalar ratio $r = 0$. Thus, no definite statement about the value of $\langle n_s \rangle - 1$ may be made at present. But this quantity will be certainly measured with 10% accuracy by Planck in less than 2 years. So, at least one new fundamental constant is guaranteed to be measured soon. More optimistically, the constant r and primordial gravitational waves may be discovered, too.

Keeping the same number of fundamental constants

Observations tend to increase the number of fundamental constants, but theory can counteract it by "unification", by expressing these new constants through already existing ones.

Inflationary theory can keep the number of fundamental cosmological constants equal to 4, since there exists viable one-parameter inflationary models. Incidentally, they are also the pioneering ones.

- ▶ Geometrical primordial dark energy – the $f(R) = R + R^2/(6M^2)$ inflationary model (Starobinsky, 1980).

$M = 3.0 \times 10^{-6} (50/N) M_{Pl}$ – from $\Delta_{\mathcal{R}}$. Then

$$n_s - 1 = -2/N = -0.04 (50/N) ,$$

$$r = 12/N^2 = 0.005 (50/N)^2 .$$

- ▶ Scalar field inflation with a phase transition – the "new" inflationary model (Linde, 1982; Albrecht and Steinhardt, 1982) with $V(\phi) = V_0 - \lambda\phi^4/4$.

$\lambda = 2.8 \times 10^{-13} (50/N)^{3/2}$ – from $\Delta_{\mathcal{R}}$. Then

$$n_s - 1 = -3/N = -0.06 (50/N), \quad r \ll 1.$$

- ▶ Scalar field inflation without a phase transition – the simplest chaotic inflationary model with $V(\phi) = m^2\phi^2/2$ (Linde, 1983, though its mathematical solution was known since Starobinsky, 1978, where this model was used for a bouncing universe scenario).

$m = 1.4 \times 10^{-6} (50/N) M_{Pl}$ – from $\Delta_{\mathcal{R}}$. Then

$$n_s - 1 = -2/N = -0.04 (50/N),$$

$$r = 8/N = 0.16 (50/N).$$

The present 2σ upper bound: $r < 0.24$.

No more than one of these models may remain after the Planck data.

Conclusions

- ▶ At present, cosmology requires **4** fundamental dimensionless constants to describe observational data.
- ▶ At least one new fundamental constant will be discovered before the next VAK conference, but the theory is ready to express it through the existing constants.
- ▶ 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 adjustable parameter can explain all existing observational data.