Adding baryogenesis to minimal viable inflationary models

Alexei A. Starobinsky

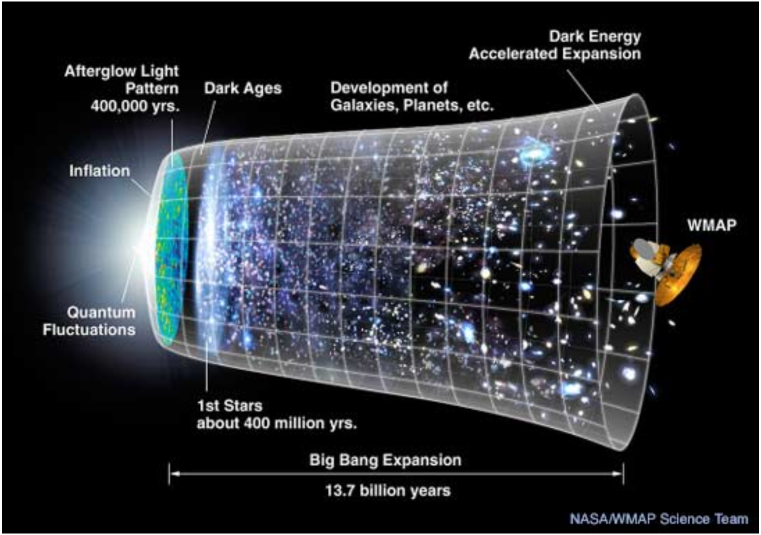
Landau Institute for Theoretical Physics RAS, Moscow - Chernogolovka, Russia

21th Lomonosov Conference on Elementary Particle Physics
Moscow State University, Moscow, 24.08.2023

The simplest viable one-parametric inflationary models

Reheating process in the R^2 inflationary model with the baryogenesis scenario

Conclusions



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

Inflation

The (minimal variant of the) inflationary scenario is based on the two cornerstone independent ideas (hypothesis):

1. Existence of inflation (or, quasi-de Sitter stage) – a stage of accelerated, close to exponential expansion of our Universe in the past preceding the hot Big Bang with decelerated, power-law expansion.

2. The origin of all inhomogeneities in the present Universe is the effect of gravitational creation of pairs of particles - antiparticles and field fluctuations during inflation from the adiabatic vacuum (no-particle) state for Fourier modes covering all observable range of scales (and possibly somewhat beyond).

Existing analogies in other areas of physics.

1. The present dark energy.

2. Creation of electrons and positrons in an external strong electromagnetic field.

Outcome of inflation

In the super-Hubble regime ($k \ll aH$) in the coordinate representation in the synchronous gauge with some additional conditions fixing it completely:

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

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

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

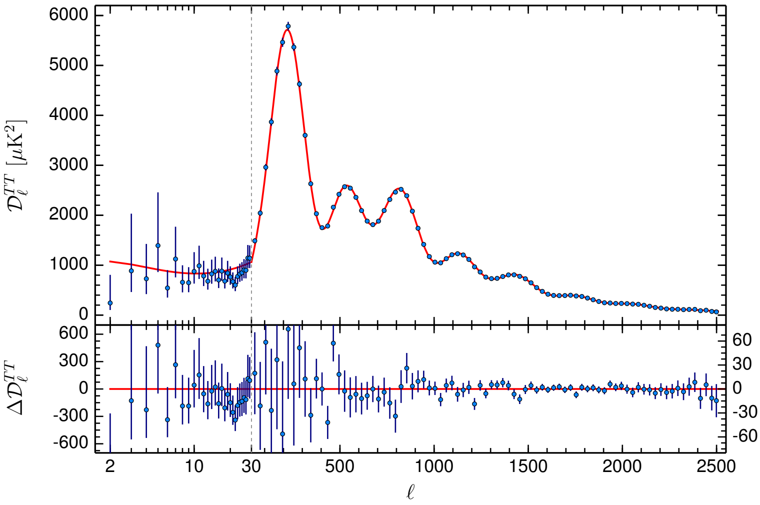
$\xi = -\mathcal{R}$ describes primordial scalar perturbations, g – primordial tensor perturbations (gravitational waves (GW)).

The most important quantities:

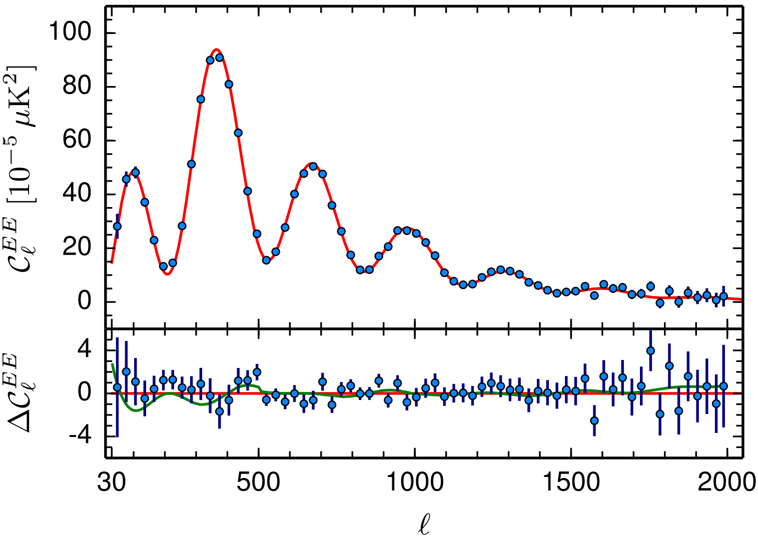
$$P_\xi(k), \;\; \frac{d \ln P_\xi(k)}{d \ln k} \equiv n_s(k) - 1, \;\; r(k) \equiv \frac{P_g}{P_\xi}$$

Both $|n_s - 1|$ and r are small during slow-roll inflation.

CMB temperature anisotropy multipoles



CMB E-mode polarization multipoles



New cosmological parameters relevant to inflation

Now we have numbers: N. Agranim et al., arXiv:1807.06209

The primordial spectrum of scalar perturbations has been measured and its deviation from the flat spectrum $n_s = 1$ in the first order in $|n_s - 1| \sim N_H^{-1}$ has been discovered (using the multipole range $\ell > 40$):

$$< \xi^2(\mathbf{r}) >= \int \frac{P_\xi(k)}{k}\, dk, \;\; P_\xi(k) = (2.10 \pm 0.03) \cdot 10^{-9} \left(\frac{k}{k_0}\right)^{n_s - 1}$$

$$k_0 = 0.05 \ \mathrm{Mpc}^{-1}, \;\; n_s - 1 = -0.035 \pm 0.004$$

Two fundamental observational constants of cosmology in addition to the three known ones (baryon-to-photon ratio, baryon-to-matter density and the cosmological constant). Existing inflationary models can predict (and predicted, in fact) one of them, namely $n_s - 1$, relating it finally to $N_H = \ln \frac{k_B T_\gamma}{\hbar H_0} \approx 67.2$. (note that $(1 - n_s) N_H \sim 2$).

The simplest models producing the observed scalar slope

1. The $R + R^2$ model (Starobinsky, 1980):

$$\mathcal{L} = \frac{f(R)}{16\pi G}, \quad f(R) = R + \frac{R^2}{6M^2}$$

$$M = 2.6 \times 10^{-6} \left(\frac{55}{N}\right) M_{Pl} \approx 3.1 \times 10^{13}\,\mathrm{GeV}$$

$$n_s - 1 = -\frac{2}{N} \approx -0.036, \quad r = 3(1-n_s)^2 = \frac{12}{N^2} \approx 0.004$$

$$N = \ln\frac{k_f}{k} = \ln\frac{T_\gamma}{k} - \mathcal{O}(10), \quad H_{dS}(N=55) = 1.4 \times 10^{14}\,\mathrm{GeV}$$

2. Scalar field models with $V(\phi) = \frac{\lambda\phi^4}{4}$ at large ϕ and strong non-minimal coupling to gravity $\xi R\phi^2$ with $\xi < 0,\ |\xi| \gg 1$ (Spokoiny, 1984), including the Higgs inflationary model (Bezrukov and Shaposhnikov, 2008) - the same predictions.

3. The mixed R^2-Higgs model

M. He, A. A. Starobinsky and J. Yokoyama, JCAP **1805**, 064 (2018).

$$\mathcal{L} = \frac{1}{16\pi G}\left(R + \frac{R^2}{6M^2}\right) - \frac{\xi R\chi^2}{2} + \frac{1}{2}\chi_{,\mu}\chi^{,\mu} - \frac{\lambda\chi^4}{4}, \;\; \xi < 0, \;\; |\xi| \gg 1$$

The same predictions for n_s, r in terms of N with the renormalized scalaron mass $M \to \tilde{M}$:

$$\frac{1}{\tilde{M}^2} = \frac{1}{M^2} + \frac{3\xi^2\kappa^2}{\lambda}$$

The reason for the same predictions: geometrization of the scalar. For a generic family of solutions during inflation, the scalar kinetic term can be neglected, so

$$\xi R\phi = -V'(\phi) + \mathcal{O}(|\xi|^{-1}) \; .$$

No conformal transformation, we remain in the the physical (Jordan) frame!

Modern trends and developments in the inflationary scenario

1. Exclusion of more (once popular) inflationary models using better and better upper bounds on r.
2. Development of more complicated inflationary models with transient breaking of the inflaton slow roll behaviour during inflation in order to produce localized peaks in $P_{\xi}(k)$ – to be prepared for possible discovery of PBHs and/or peaks in the primordial GW power spectrum (this requires at least two new fundamental cosmological parameters).
3. More detailed description of post-inflationary evolution of the Universe including creation, heating and thermalization of usual matter as a result of inflaton decay (leads to better predictions for N, n_s, relation to the Standard Model of elementary particles and generation of baryon asymmetry).
4. Thoughts about pre-inflationary history of our Universe (purely theoretical at this moment).

The most recent upper limit on r

G. Galloni et al., JCAP 04 (2023) 062; arXiv:2208.00188:

$$r_{0.01} < 0.028 \text{ at the 95\% CL.}$$

For comparison, in the chaotic inflationary model $V(\varphi) \propto |\varphi|^n$, $r = \frac{4n}{N}$, $1 - n_s = \frac{n+2}{2N}$. The r upper bound gives $n < 0.5$ for $N_{0.01} = (55 - 60)$, but then $1 - n_s \leq 0.022$. Thus, this model is disfavoured by observational data.

The target prediction for r in the 3 simplest (one-parametric) inflationary models having $n_s - 1 = -\frac{2}{N}$ (the $R + R^2$, Higgs and combined Higgs-R^2 models) is

$$r = \frac{12}{N^2} = 3(n_s - 1)^2 \approx 0.004$$

Reheating in the R^2 model

Previously the channel of scalaron decay into light scalar particles minimally or non-minimally coupled to gravity was considered mainly. The decay rate to the non-minimally coupled complex Higgs doublet is

$$\Gamma_{\phi\to h} = \frac{GM^3}{6}\sqrt{1-\frac{4m_h^2}{M^2}}\left(6\xi - 1 + \frac{2m_h^2}{M^2}\right)^2$$

Now, according to the leptogenesis scenario (M. Fukugita and T. Yanagida, 1986), let us add right-handed Majorana neutrinos with a large mass to the matter sector of the Standard Model to explain the neutrino oscillation experiments and the baryon asymmetry of the Universe (H. Jeong, K. Kamada, A. A. Starobinsky and J. Yokoyama, arXiv:2305.14273).

The scalaron decay rate to Majorana neutrinos ($\alpha = 1, 2, 3$):

$$\Gamma_{\phi \to N_\alpha} = \frac{GMM_{N_\alpha}^2}{12} \left(1 - \frac{4M_{N_\alpha}^2}{M^2}\right)^{\frac{3}{2}}$$

Assuming the hierarchy $M_{N1} \ll M_{N2} \ll M_{N3}$, it is maximal for $M_{N1} \approx 10^{13}$ GeV.

Scalaron decay to gauge bosons occurs due to the EMT trace anomaly proportional to beta functions of SM gauge fields, its rate is

$$\Gamma_{\phi \to g} \simeq \sum_F b_{\alpha_F}^2 \alpha_F^2 \mathcal{N}_{\alpha_F} \frac{GM^3}{96\pi^2}$$

where $\mathcal{N}_{\alpha_F}$ is the number of SM gauge bosons with the charge α_F and b_{α_F} is the first coefficient of the beta function of these fields.

Scalaron decay into two gravitons is strongly suppressed in the pure $R + R^2$ gravity (AS, 1981); it still occurs due to the term in the conformal trace anomaly proportional to the square of the Weyl tensor but this effect is very small.

Effect of non-minimal coupling

Regarding ξ, two cases $\xi = 0$ (minimal coupling) and $\xi = 1/6$ (conformal coupling) were investigated. In the former case, the decay to scalar particles dominates and the reheating temperature $T_{reh} \approx 3 \times 10^9$ GeV is maximal and practically independent of the Majorana mass M_{N1}. Decay to Majorana neutrinos become much more important in the latter case, and the reheating temperature is lower, $T_{reh} \sim (0.2 - 1) \times 10^9$ GeV and depends on M_{N1} significantly for $M_{N1} > 10^{12}$ GeV. The change in n_s and r is very small. On the other hand, lepton asymmetry, which is produced when the heavy Majorana neutrinos decay and then converted to baryon asymmetry by the subsequent sphaleron processes, is about two orders of magnitude larger in the conformally coupled case.

Conclusions

- 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: $H_{55} \sim 10^{14}\,\mathrm{GeV},\ m_{infl} \sim 10^{13}\,\mathrm{GeV}$.
- In $f(R)$ gravity, the simplest $R + R^2$ model is one-parametric and has the preferred values $n_s - 1 = -\frac{2}{N}$ and $r = \frac{12}{N^2} = 3(n_s - 1)^2 \approx 0.004$. The first value produces the best fit to present observational CMB data. The same prediction follows for the Higgs and the mixed R^2-Higgs models though actual values of $N(k)$ are slightly different for these 3 cases.
- The $R + R^2$ inflationary model can be supplemented with the realistic leptogenesis scenario by adding right-handed Majorana neutrinos with a large mass $\sim 10^{13}$ GeV to the matter sector of the Standard Model to explain the baryon asymmetry of the Universe.