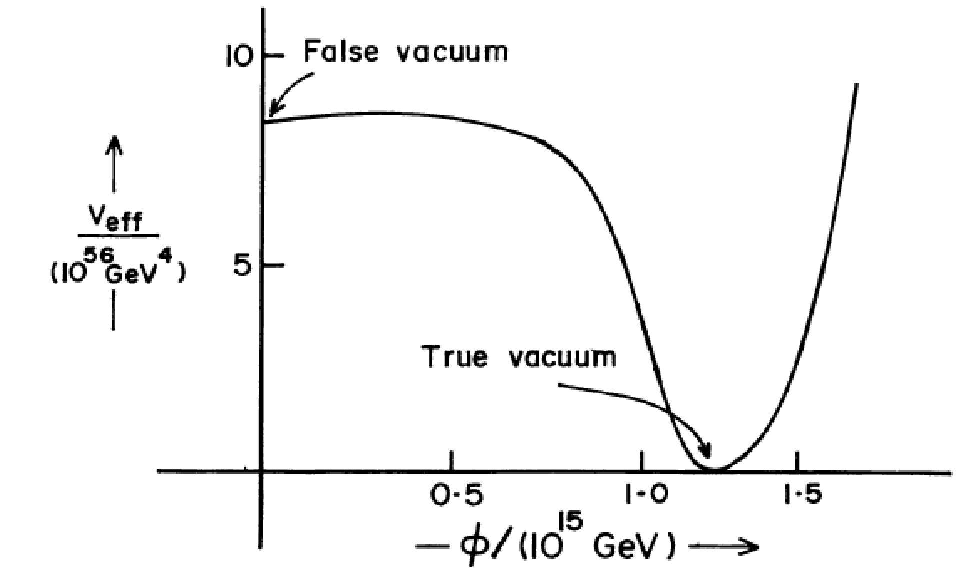

Inflation

- Fundamental problems: Friedman models
- Inflation: expectations
- Inflation: primordial density perturbations
- Inflation and CMB observations

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INFLATION FOR ASTRONOMERS

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The Cold Dark Matter Density Perturbation

Andrew R. Liddle† and David H. Lyth*

arXiv:astro-ph/9303019v1 31 Mar 1993

Coleman-Weinberg Potential In Good Agreement With WMAP

Q. Shafi* and V. N. Şenoğuz†

arXiv:astro-ph/0603830v4 5 Jun 2006

Supergravity based inflation models: a review

Masahide Yamaguchi

arXiv:1101.2488v2 [astro-ph.CO] 12 Apr 2011

The horizon problem

In an early, relativistic epoch of expansion the size of the region, which could have been smoothed out in a causal process is not larger than the photon free path:

$$R_{\mathrm{H}}(t) \equiv a(t) \int_0^t \frac{dx}{a(x)} = 2ct$$

which is less than a ~ million l.y. at recombination. CMB observations show that the last scattering sphere was homogeneous with the accuracy of 1:10000 despite the fact that its size

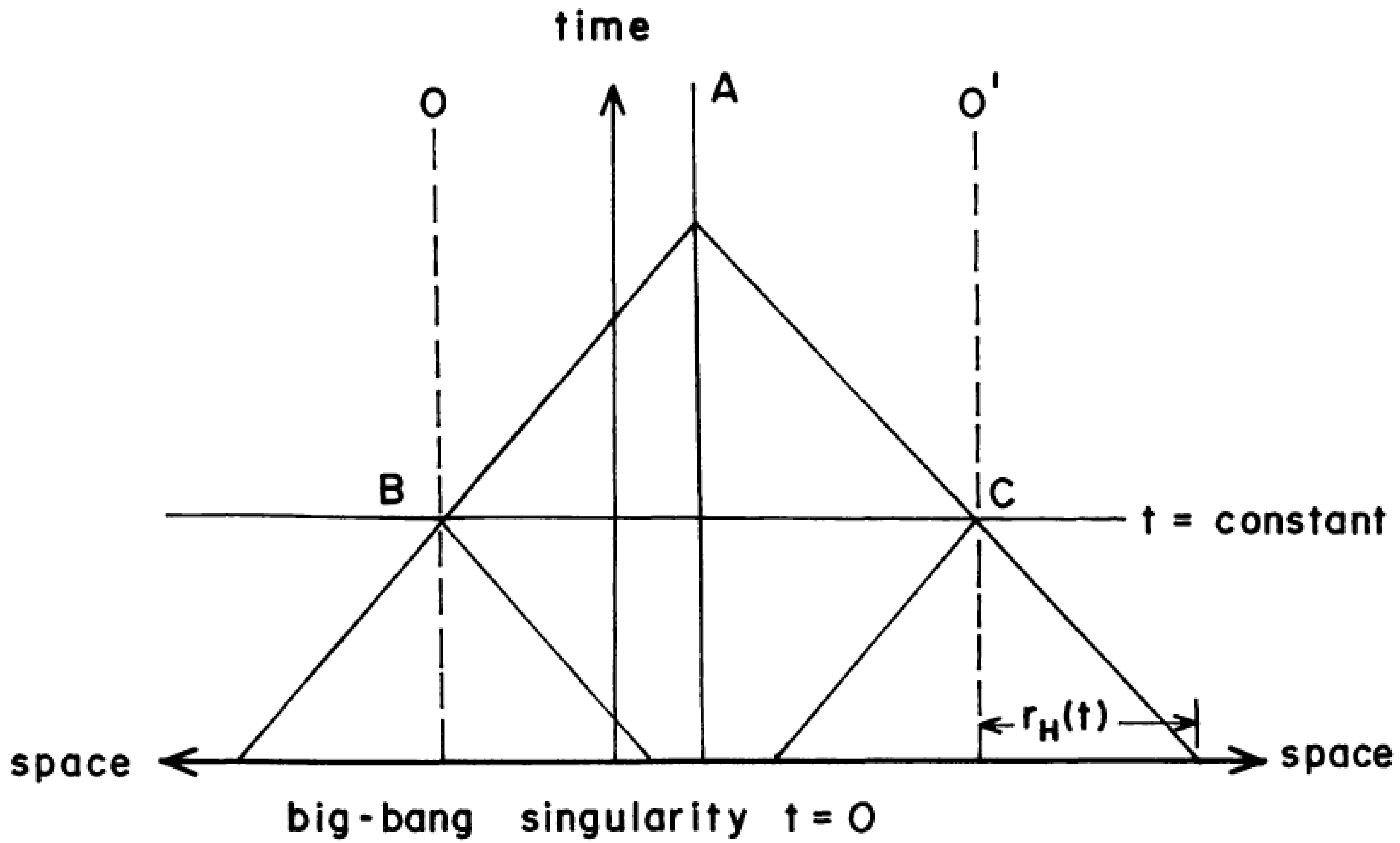
$$D_{\mathrm{rec}} = \frac{3ct_0}{1 + z_{\mathrm{rec}}} \approx 50 \times R_{\mathrm{H}}(t_{\mathrm{rec}})$$

was much larger than the causally connected region.

This is THE HORIZON PROBLEM

The horizon problem

330 NARLIKAR & PADMANABHAN (1991) ARA&A, 29, 325



The diagram uses comoving spatial coordinates and the conformal time (*eta*).
A observes similarity of regions close to B and C , which cannot be understood since the past cones of B and C have no common points. (Continuation to $t < 0$ makes no sense!)

The flatness problem

Friedman equation and few definitions

$$\frac{\dot{a}^2}{a^2} + \frac{kc^2}{a^2} = \frac{8\pi G}{3c^2}\epsilon$$

$$H_0 = \frac{\dot{a}(t_0)}{a(t_0)} \qquad H(t) = \frac{\dot{a}(t)}{a(t)}$$

$$\rho_c = \frac{3H_0^2}{8\pi G} \qquad \rho_c(t) = \frac{3H^2(t)}{8\pi G}$$

$$\epsilon_0 = \Omega_0 \rho_c c^2 \qquad \epsilon(t) = \Omega(t)\rho_c(t)c^2$$

$$H^2(t) + \frac{a_0^2}{a^2}(\Omega_0 - 1)H_0^2 = \Omega(t)H^2(t)$$

give a formula for a dimensionless density in an earlier epoch:

$$\Omega(t) - 1 = (\Omega_0 - 1)\frac{a_0^2}{a^2}\frac{H_0^2}{H^2(t)}$$

Since at early relativistic epoch H(t)/H_0~(1+z)^2, the density parameter must be **=1** with enormous accuracy to give today's density of the order of critical density.

The flatness problem

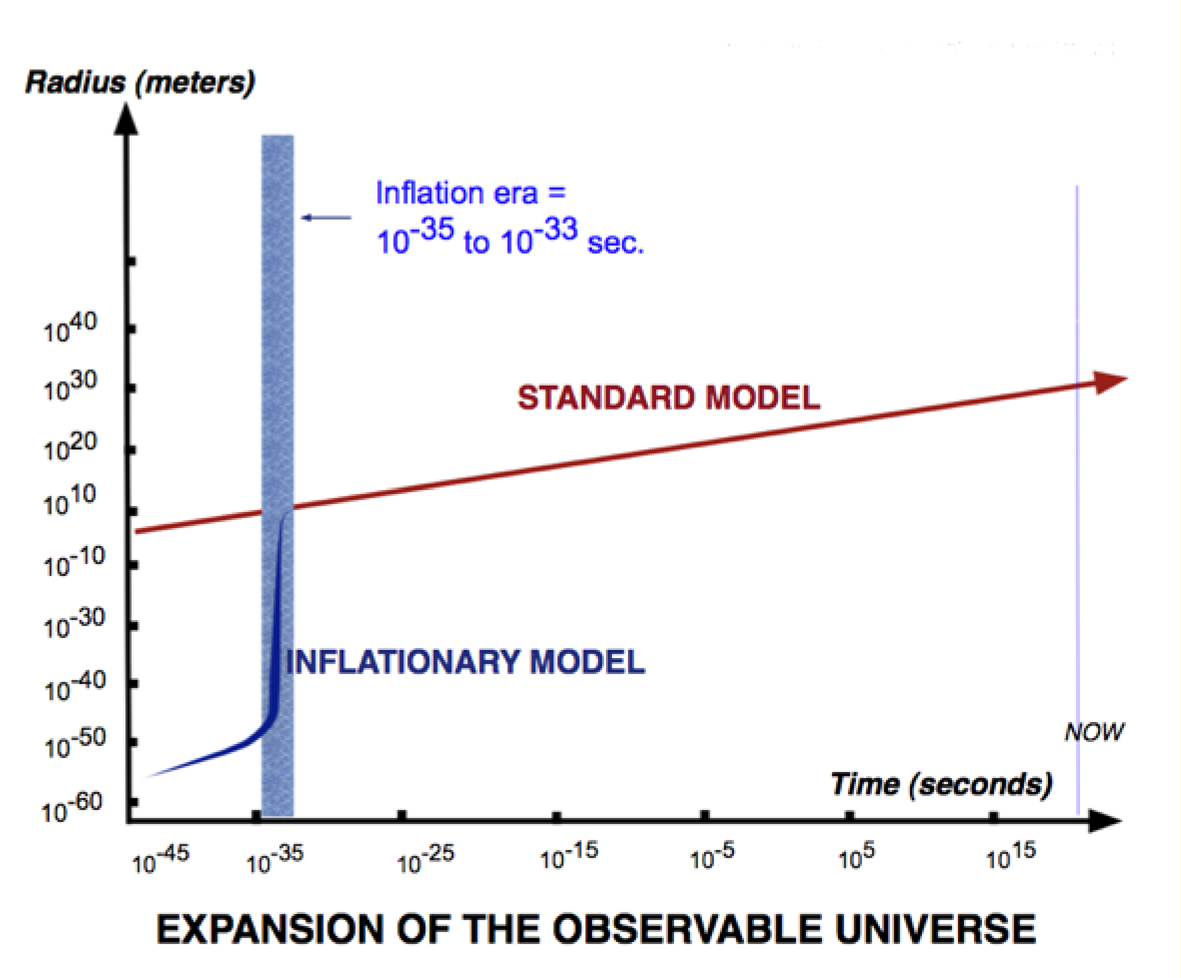
If the density at the beginning were defined with a tiny error, we would live today in a practically EMPTY Universe or its evolution would end long ago in a collapse leading to a final SINGULARITY

Problem of the structure

If astronomical objects formed in a causal process, their evolution could have started when the necessary material was accumulated in a causally connected region. For instance a galaxy mass becomes less than the *mass under the horizon* which happens at $z \sim 10^6$. Since then the perturbation could have grown ~10^6 times so at the *beginning of causality* they must have been *large* ~0.000 001. But the density (particle number) fluctuation this size cannot be a statistical fluctuation, which would be of the order of 1/sqrt(N), where N – a number of atoms in a galaxy:

$N \sim 10^{12} * 2 \times 10^{30} * 6 \times 10^{26} \sim 10^{69}$.

Inflation: a scenario



The horizon size

We ask how far from the source at the time t are the photons sent at $t = 0$. In a static space-time it would be ct, in an expanding universe it is:

$$R_H(t) = a(t) \int_0^t \frac{cdt'}{a(t')} \tag{1}$$

(The path traveled earlier gives relatively larger contribution because it is multiplied by a larger expansion factor.) Comparing the results of a power-law and exponential expansion laws we get:

$$a(t) = a_i (t/t_i)^\alpha \quad \Rightarrow \quad R_H(t) = \frac{1}{1-\alpha}\, ct \tag{2}$$

$$a(t) = a_i\; e^{t/\tau} \quad \Rightarrow \quad R_H(t) = c\tau \left(e^{t/\tau} - 1\right) \tag{3}$$

We assume $\alpha < 1$; typical EOS $P = \epsilon/3$ and $P = 0$ correspond to $\alpha = 1/2$ i $\alpha = 2/3$, respectively.

The horizon size

In the case of a power-law expansion the horizon radius $R_H(t) \sim ct$, but in the case of an exponential expansion ongoing long enough ($t \gg \tau$) one gets $R_H(t) \gg ct$. This is a recipe to enlarge causally connected region without enlarging the expansion time. In a standard (AD 2021) cosmological model the dark energy density and the cold matter energy density are comparable, so $\Lambda \approx H_0^2/c^2$. In the future, when the cosmological term becomes even more dominating than today, the first Friedman equation becomes:

$$\frac{\ddot{a}}{a} = \frac{1}{3}\Lambda c^2 \qquad \frac{\ddot{a}}{a} = \frac{1}{3}H_0^2 \quad \Rightarrow \tag{4}$$

$$a(t) \approx a(t_0)e^{H_0(t-t_0)/\sqrt{3}} \tag{5}$$

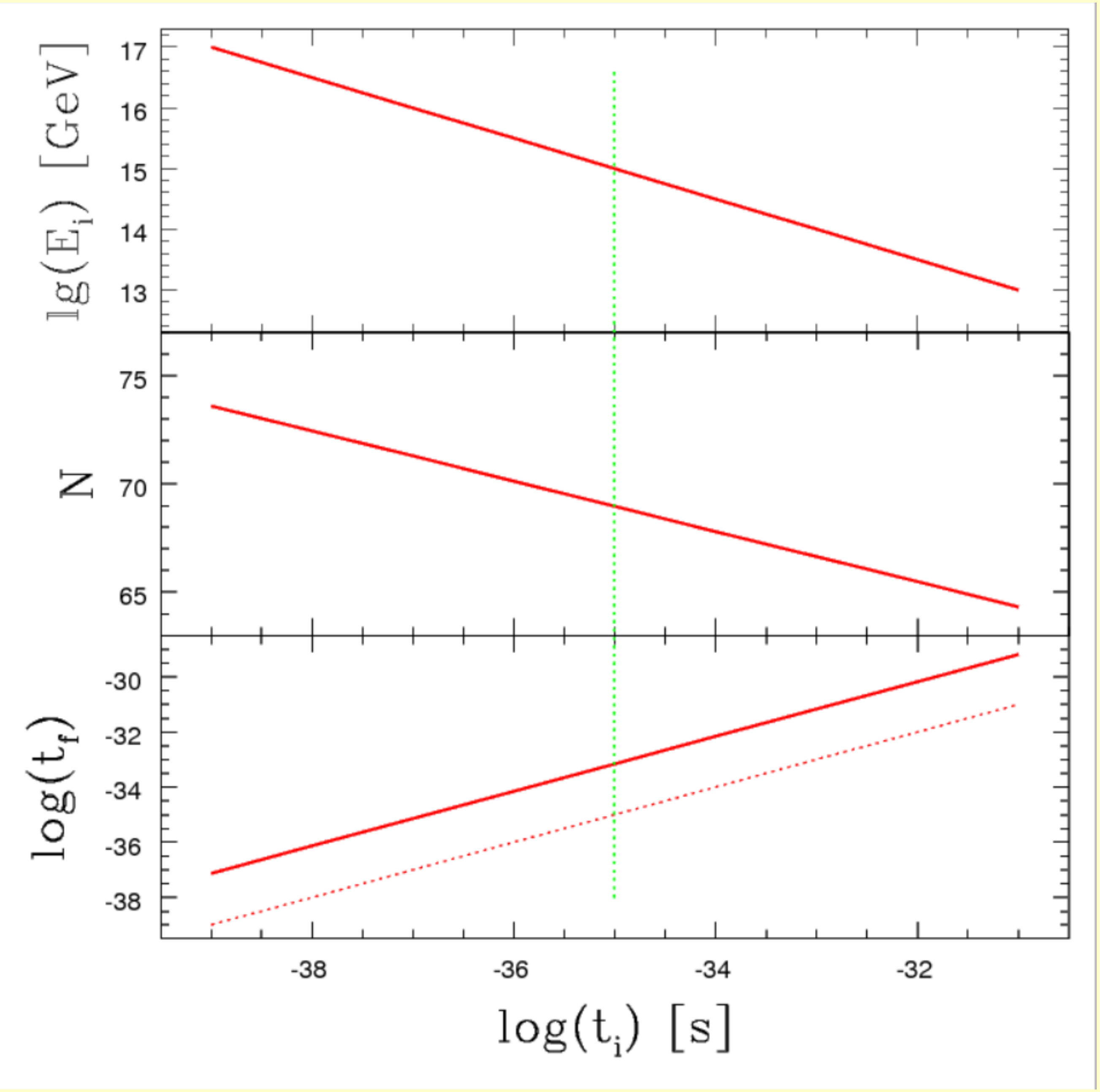
This will be a description of exponential expansion with a characteristic time-scale of $\sim 10^{10}$ y. But it will be (a slow) process in the future, having no relation to the horizon size in the early Universe. (Perhaps $\tau \approx t_{beginning}$ is their common feature.)

Inflation: expectations

- In an early, relativistic universe (according to GR) $\epsilon = 3c^2/(32\pi G t^2)$. For $t < t_{\rm Pl} = 10^{-43}{\rm s}$ classical description of gravity becomes inadequate. ($kT_{\rm Pl} \approx 10^{19}$ GeV)
- When $kT \approx 10^{15}$ GeV a *spontaneous symmetry breaking* could have taken place. (According to old GUT hypothesis a single interaction **electro-weak-strong** was replace by two of them: **electro-weak** and **strong**. Reactions lepton $\leftrightarrow$ hadron possible before became impossible after (lepton and hadron number conservation known after, up to the present days, were unknown before)).
- GUT epoch corresponds to $t_{\rm GUT} \approx 10^{-35}$ s. If the inflation took place at this time, the causally connected region should be expanded (during the inflation and after) to the size $\approx 10^4\ c/H_0$, much larger than the observable Universe today. The observed uniformity of such a small part of a causally connected region would not be a paradox.

Inflation: expectations

- At $t = 10^{-35}$ s the size of a causally connected region was $R_H(t) = 2ct = 6 \times 10^{-27}$ m. To get $10^4 c/H_0 \approx 10^{30}$ m the expansion factor should be 10^{56}.
- After the inflation the expansion proceeds classically. Let us assume that at $t_f = 10^{-33}$ s inflation ended. Until the equality time $t_{eq} \approx 2 \times 10^{12}$ s the region expands $\sqrt{t_{eq}/t_f} \approx 4 \times 10^{22}$ times and after that another $(t_0/t_{eq})^{2/3} \approx 3 \times 10^3$ times, or $\approx 10^{26}$ times total.
- It follows that the missing $10^{56}/10^{26} = 10^{30}$ should be an effect of inflation.



Back-engineering: what parameters meet expansion factor requirements for a given time of the beginning of inflation (t_i)

Inflation: expectations

We are not asking here why inflation could happen. We are only going to find out how long should it be going on (under the condition that it was very early, long before recombination, nucleosynthesis, baryogenesis etc).

The example describing the future of a standard model suggests that time scale of the exponential expansion is of the order of cosmic time at its beginning $\tau \sim t_i$. If the inflation goes on between t_i a t_f, we have:

$$\frac{a(t_f)}{a(t_i)} = e^{(t_f - t_i)/t_i} \approx e^{t_f/t_i} \equiv e^N \tag{6}$$

To avoid horizon and flatness problems one needs $N \approx 70$ exponential periods, which gives 2.5×10^{30} enlargement of a causally connected region.

"Physical" mechanism

The similarity (?) of the cosmological constant to a vacuum in the field theory suggests consideration of an abstract scalar (the simplest) field of an inflaton $\phi(t, \vec{x})$. The standard methods of the field theory give the energy density and the pressure related to the field:

$$\epsilon = \frac{1}{2}\dot{\phi}^2 + V(\phi) \qquad P = \frac{1}{2}\dot{\phi}^2 - V(\phi) \tag{7}$$

where $\dot{\phi}^2/2$ is the kinetic and $V(\phi)$ - the potential energy density of the field. If the field is static or changes "slowly" the potential term may dominate and then $P \approx -\epsilon$. Such an equation of state (compare the role of Λ) a dominating term in the RHS of the Friedman equation, which implies an exponential expansion.

Inflation dynamics

The set of equations describing the evolution of the cosmological model and the inflaton field has the form:

$$\frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3c^2}\left(\frac{1}{2}\dot{\phi}^2 + V(t,\phi)\right) \tag{8}$$

$$\ddot{\phi} + 3\frac{\dot{a}}{a}\dot{\phi} + \frac{\partial V(t,\phi)}{\partial \phi} = 0 \tag{9}$$

Below the prime stands for the ϕ derivative. We require that the potential gradients are small:

$$\epsilon = \frac{3c^2}{16\pi G}\left(\frac{V'}{V}\right)^2 \ll 1 \;\; \eta = \frac{3c^2}{8\pi G}\left|\frac{V''}{V}\right| \ll 1 \;\; \xi^2 = \left(\frac{3c^2}{8\pi G}\right)^2\left|\frac{V'V'''}{V^2}\right| \ll 1 \tag{10}$$

These are the condition for a "slow" evolution, which guarantee a long enough inflation period.

Inflation dynamics

Under the "slow evolution of the field " requirement one can approximate the equations by:

$$H^2 \equiv \frac{\dot{a}^2}{a^2} \approx \frac{8\pi G}{3c^2} V(\phi) \qquad 3H\dot{\phi} \approx -V'(\phi)$$

Getting H from the second equation and dividing the first by the second we get:

$$H \approx -\frac{8\pi G}{c^2} \dot{\phi} \frac{V(\phi)}{V'(\phi)}$$

ne can also calculate the number of exponential growth periods:

$$N \equiv \int \frac{da}{a} \equiv \int \frac{\dot{a}dt}{a} \equiv \int Hdt \approx \frac{8\pi G}{c^2} \int dt\ \dot{\phi} \frac{V}{V'} \equiv \frac{8\pi G}{c^2} \int d\phi \frac{V}{V'}$$

Calculating the last integral between the local and the global minima of V, we check, whether any particular form of V may give inflation meeting our expectations.

Inflation dynamics

Density perturbations are related to Newtonian potential perturbations via the Poisson equation. For a single Fourier component one has:

$$-\frac{k^2}{a^2}\delta\Phi_{\vec{k}} = \frac{4\pi G}{c^2}\delta\epsilon_{\vec{k}} = \frac{3}{2}H^2\frac{\delta\epsilon_{\vec{k}}}{\epsilon} \qquad \delta\Phi_{\vec{k}} = -\frac{3}{2}\frac{a^2}{k^2}H^2\delta_{\vec{k}}$$

This latter form is called a *curvature perturbation*:

$$\delta\mathcal{K}_{\vec{k}} = \frac{9}{4}\left(\frac{aH}{k}\right)^2\delta_{\vec{k}} \qquad \frac{d}{dt}\delta\mathcal{K}_{\vec{k}} = 0$$

(Since $\delta\mathcal{K} \propto \delta\Phi$, it does not change with time.)

Inflation dynamics (following Planck XXII)

The evolution of the curvature perturbations is described by a rather complicated equation:

z is a function of *a* and its derivatives

$$\left(a\delta\phi_{\vec{k}}\right)'' + \left(k^2 - \frac{z''}{z}\right)\left(a\delta\phi_{\vec{k}}\right) = 0$$

Prime stands for the derivative relative to the conformal time τ, $d\tau = dt/a(t)$. Curvature and inflaton perturbations are related by:

$$\delta\mathcal{K} = -H\frac{\delta\phi}{\dot{\phi}}$$

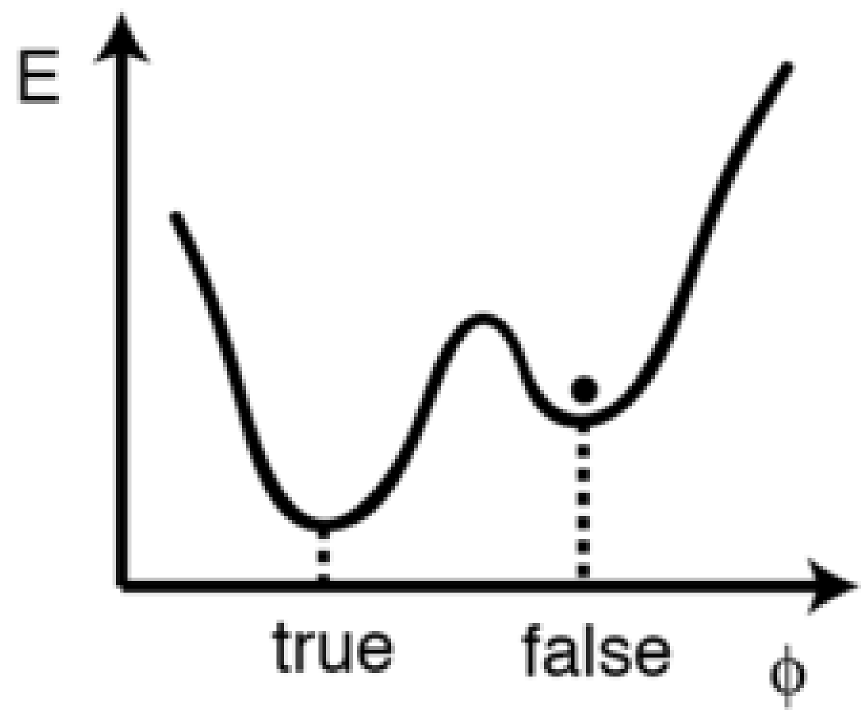
Tensor perturbations obey a similar equation:

$$\left(ah_{\vec{k}}^{+,\times}\right)'' + \left(k^2 - \frac{a''}{a}\right)\left(ah_{\vec{k}}^{+,\times}\right) = 0$$

When $k \ll aH$ (waves longer than the horizon scale) both curvature and tensor perturbations stay constant.

Slow evolution

Usually inflaton field ϕ takes the value which corresponds to a minimum of the potential V. The Universe evolution can change the potential shape and a new minimum may arise at a different value of ϕ. Slow changes of ϕ allow for the long lasting domination of the potential term, as in "old" inflation.



Guth (~1980): idea

•Experimental data (today E<10 TeV=10^4 GeV) electro-weak and strong interactions
•Extrapolation (behavior of the coupling constants which seem to approach a common value at ~ 10^15 GeV, far beyond measurements) → unification, single electro-weak-strong interaction? Hadrons and leptons not fundamentally different? A symmetric state of matter?
• And a I order phase transition when E ~ 10^15 GeV? (Going from a symmetric to unsymmetric state of matter, "spontaneous symmetry breaking")
• Heat of this transition powering inflation?
• Analogy: ferromagnet above/below (Pierre) Curie temperature? (cooling, spontaneous magnetization spin alignment in zones, little transition heat

Guth (~1980): idea

•Above kT=10^15 GeV single minimum V at *phi*=0. All directions in *phi* space “equivalent” ←→ all fermions “equal” (leptons and hadrons)
• At kT<3x10^14 GeV: a new minimum of V, arises but located beyond a barrier. The system remains in a state of *false vacuum* (*phi* =0); potential energy becomes dominating. These are the conditions for inflation.
•The temperature decreases further, the potential barrier lowers, *phi* moves to the true potential minimum V
• The potential energy of the inflaton field changes into its kinetic energy, inflation ends. Energy of *phi* oscillations is converted into particle production. (They have been diluted exp(3N) times during the inflation)

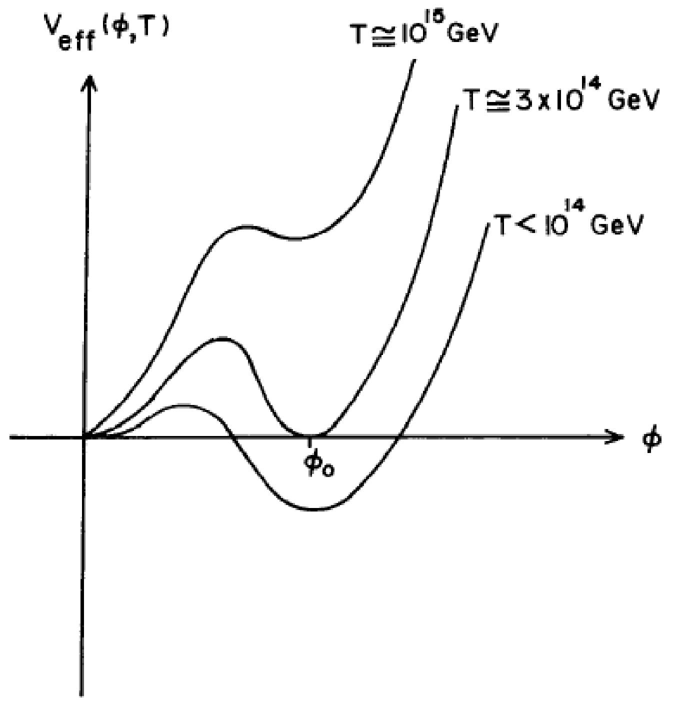
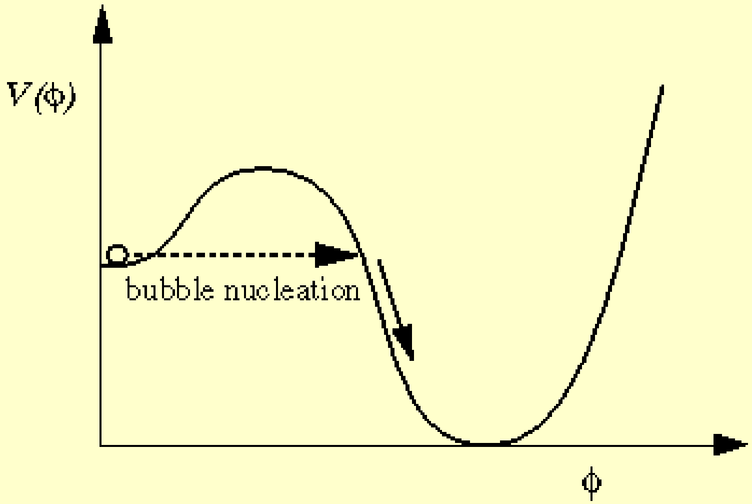
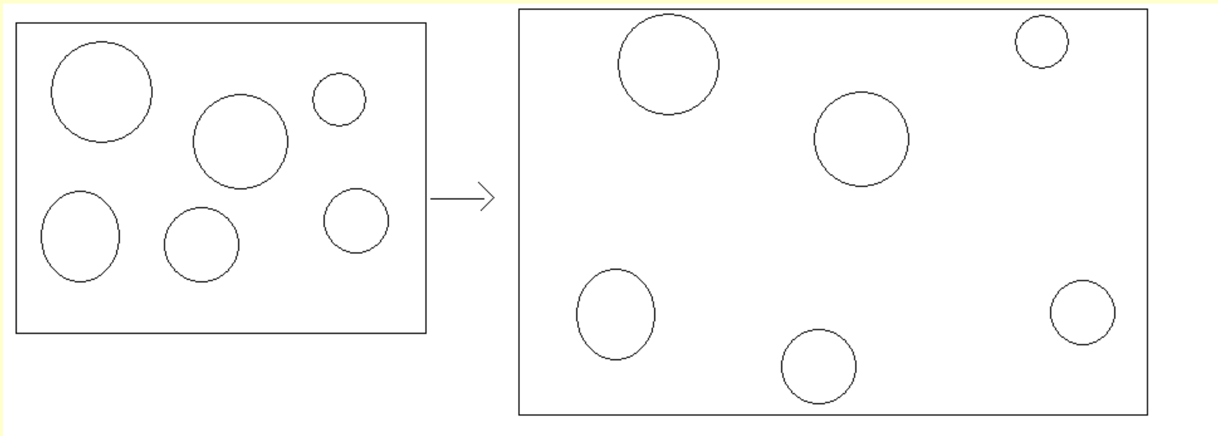


Figure 3 The potential energy of the Higgs field ϕ at various temperatures in the original model proposed by Guth.

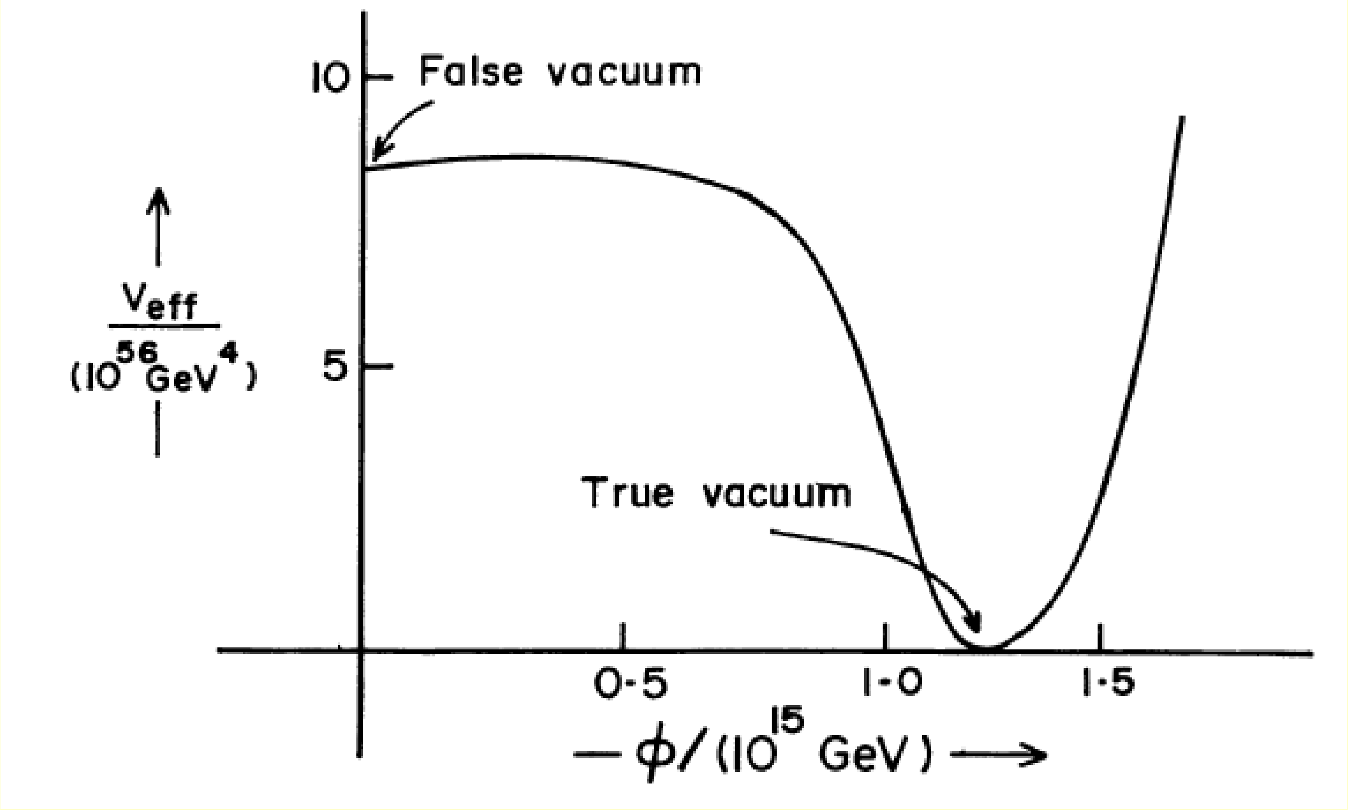
Guth (old inflation): problems





- The tunnel effect produces separate "bubbles" of new phase
- False vacuum around bubbles expands as during inflation causing the increase of their distances
- Beginning of a multi-verse?
- Another problem: this GUT hypothesis implies a finite proton lifetime (~10^33 s), which has been disproved by KAMIOKANDE

Inflation: another version



• This potential form (proposed in other context by Coleman and Weinberg) has a lower barrier and is very flat near the state of false vacuum. It allows for the slow evolution of the inflaton field.
• Steep walls of the potential well around the global minimum lead to violent oscillations and particle creation at the end of inflation

Inflation: still another...

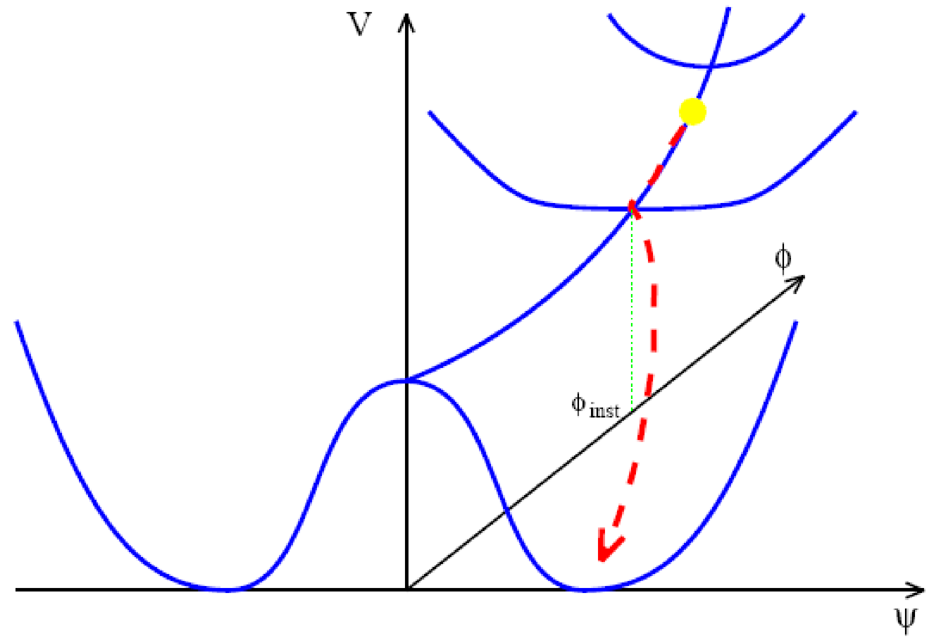
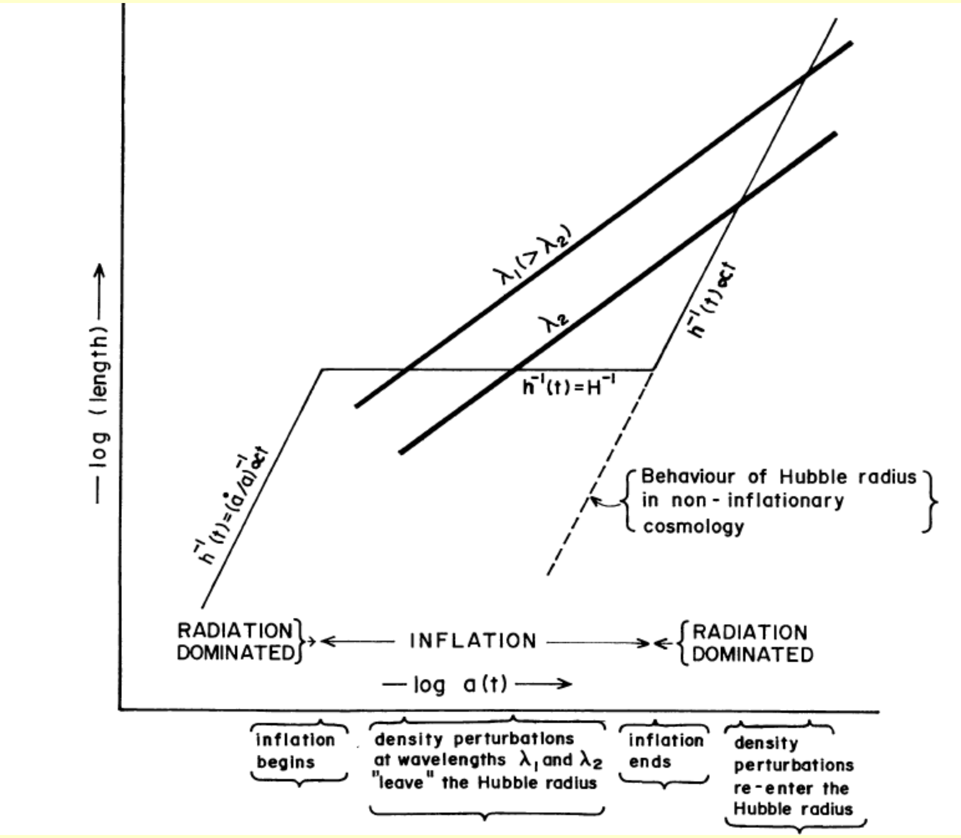


Figure 4: The potential for the hybrid inflation model. The field rolls down the channel at $\psi = 0$ until it reaches the critical ϕ value, then falls off the side to the true minimum at $\phi = 0$ and $\psi = \pm M$.

$$V(\phi, \psi) = \frac{\lambda}{4}\left(\psi^2 - M^2\right)^2 + \frac{1}{2}m^2\phi^2 + \frac{1}{2}\lambda'\phi^2\psi^2 \,.$$

- Hybrid model: inflaton potential + some other field
- Example: interaction with GUT fields
- (Infinite number of possibilities ...)

The structure formation



Perturbation sizes remain proportional to the scale factor *a(t)* . The Hubble radius is c/H(t) ~ ct before and after the inflation and is constant during the inflation [*a* (*t*) ~ exp(*Ht*)] We are interested in perturbations on th scales <c/H_0 – we are not able to observe larger ones. Now they are smaller than the Hubble radius, but they were larger in the past. During the inflation (and a “bit” earlier) there was a first period, when the interesting scales could be fitted under the Hubble radius and could be formed in a causal way.

The structure formation

- Since the largest causally connected region at the beginning of inflation is now $\sim 10^4$ times larger than the observable Universe the latter became larger than the Hubble radius later, after $\ln(10^4) \approx 9$ exponential growth times.
- The CMB anisotropy is measured up to $l \leqslant 9000$ (South Pole Telescope), which corresponds to perturbations of the size of ≈ 0.5 Mpc. These smallest scales have sizes $\approx 10^4$ times smaller than the observable Universe today, so they became larger than the Hubble radius after another $\ln(10^4) \approx 9$ exponential growth times.
- The interesting for us perturbations were becoming larger than the Hubble radius during the inflation at 10 - 20 exponential growth times since its beginning and 60 - 50 before its end

The structure formation

- After > 10 exponential growth times the vacuum term is strongly dominating. Until the end of inflation there are still 60 -50 characteristic times, so the final stages of inflation "similarly" influence perturbations on all interesting scales.
- When the perturbation size is much larger than the Hubble radius, the pressure gradients are unimportant ($c_S t < ct \ll \lambda$)
- During this time the curvature and tensor perturbation amplitudes remain constant

The structure formation

Since the curvature and tensor perturbations have constant amplitudes while their sizes remain super-horizontal, it is enough to calculate the amplitudes at the moment of "horizon crossing" (when they become larger than the Hubble radius). Curvature perturbations of the very large scales, which return under the horizon late, during the matter domination era, remain unchanged forever. (As Newtonian potential perturbations in an equivalent approach.)

Primordial spectrum of the density perturbations

The Harrison - Zeldovich postulate says that the power of the perturbations of Newtonian potential at every scale should be the same:

$$k^3 \left\langle \delta\Phi_k^2 \right\rangle \sim k^3 \frac{\langle \delta_k^2 \rangle}{k^4} = \frac{\langle \delta_k^2 \rangle}{k} \sim k^{n-1}$$

so it corresponds to $n = 1$. Using inflation theory one can calculate the amplitude at the moment of "horizon crossing". Calculation is based on the investigation of the inflaton field, which we are not following here. As a result one gets:

$$\frac{\langle \delta_k^2 \rangle}{k} = \frac{32}{75} \frac{V_*}{m_{Pl}^4} \frac{1}{\epsilon_*}$$

where the star (*) stands for the values at horizon crossing.

Inflationary perturbation spectrum: phenomenology

There are three parameters which define the shape of the inflaton potential in the third order, sufficient to investigate the astronomically interesting range of scales:

$$\epsilon = \frac{1}{2} m_{Pl}^2 \left(\frac{V'}{V} \right)^2 , \quad \eta = m_{Pl}^2 \left(\frac{V''}{V} \right) , \quad \xi^2 = m_{Pl}^4 \left(\frac{V' V'''}{V^2} \right)$$

If these parameters are small, it is possible to get the slope of the spectrum n at the scale of observable Universe, its logarithmic derivative α and the ratio of the tensor to curvature power spectrum r:

$$\begin{aligned} n &\approx 1 - 6\epsilon + 2\eta \\ \alpha &\approx 16\epsilon\eta - 24\epsilon^2 - 2\xi^2 \qquad \alpha \equiv \frac{dn}{d \ln k} \\ r &\approx 16\epsilon \end{aligned}$$

Planck XXII: Inflation

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1 + \frac{1}{2}\, dn_s/d\ln k \ln(k/k_*) + \frac{1}{6}\, d^2 n_s/d\ln k^2 (\ln(k/k_*))^2 + \ldots}$$

$$\mathcal{P}_t(k) = A_t \left(\frac{k}{k_*}\right)^{n_t + \frac{1}{2}\, dn_t/d\ln k \ln(k/k_*) + \ldots},$$

$$A_s \approx \frac{V}{24\pi^2 M_{pl}^4 \epsilon_V}$$

$$A_t \approx \frac{2V}{3\pi^2 M_{pl}^4}$$

$$M_{pl} = (8\pi G)^{-1/2}$$

Power spectra of the scalar (curvature) and tensor (gravitational waves) in Planck convention

Planck XXII: Inflation

$$
\begin{aligned}
n_s - 1 &\approx 2\eta_V - 6\epsilon_V \\
n_t &\approx -2\epsilon_V \\
\mathrm{d}n_s/\mathrm{d}\ln k &\approx -16\epsilon_V\eta_V + 24\epsilon_V^2 + 2\xi_V^2 \\
\mathrm{d}n_t/\mathrm{d}\ln k &\approx -4\epsilon_V\eta_V + 8\epsilon_V^2
\end{aligned}
$$

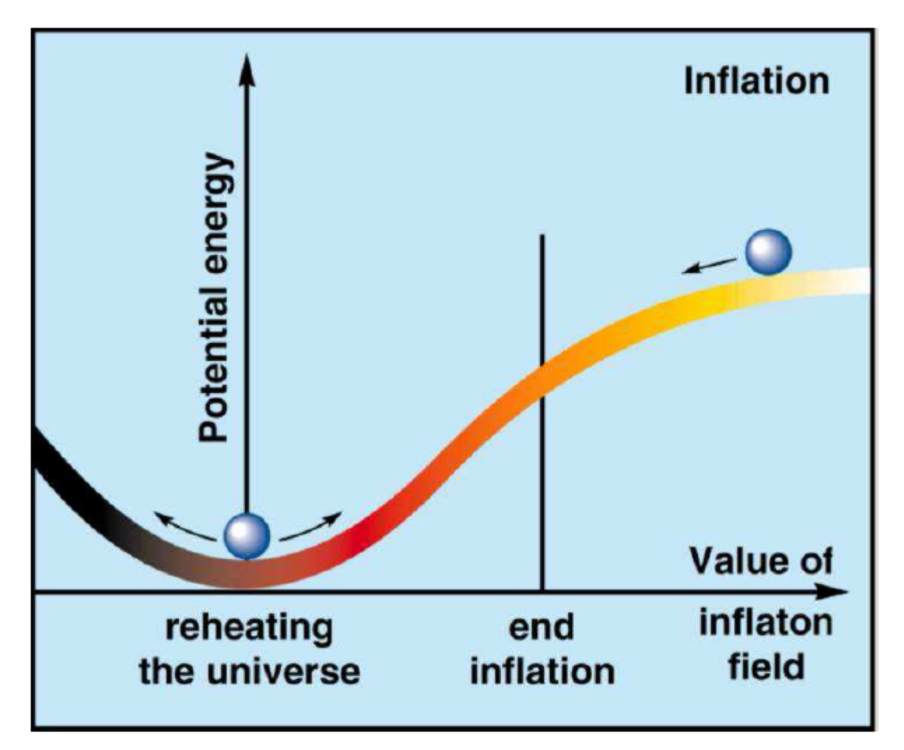
$$
r = \frac{\mathcal{P}_t(k_*)}{\mathcal{P}_{\mathcal{R}}(k_*)} \approx 16\epsilon \approx -8n_t
$$

The values of parameters defining the spectrum are directly related to the inflaton potential parameters introduced earlier. (The subscript "V" makes no difference, they are the same) . Every nontrivial inflaton potential implies the slope of the spectrum in disagreement with Harrison – Zeldovich postulate. The spectrum is not exactly power-law since its slope changes.
The tensor perturbation spectrum is close to but different from flat (n_t =0) and its slope also changes.

Perturbation spectrum

$$\frac{\langle \delta_k^2 \rangle}{k} \sim k^{n-1}$$

$$\frac{\langle \delta_k^2 \rangle}{k} = \frac{32}{75} \frac{V_*}{m_{Pl}^4} \frac{1}{\epsilon_*}$$



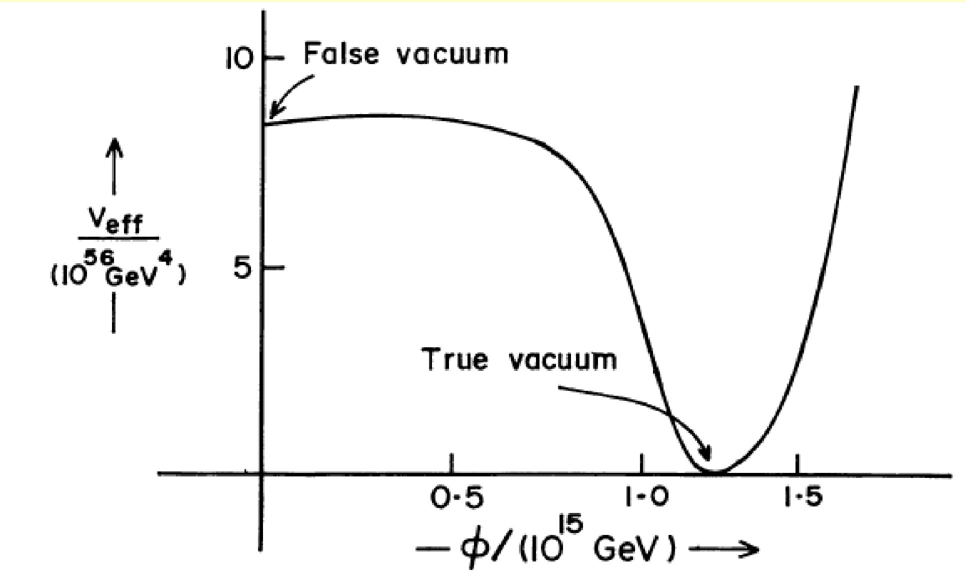
• During the inflation the potential at the "position of inflaton" decreases → smaller scales, which leave the horizon later correspond to lower values of V_*

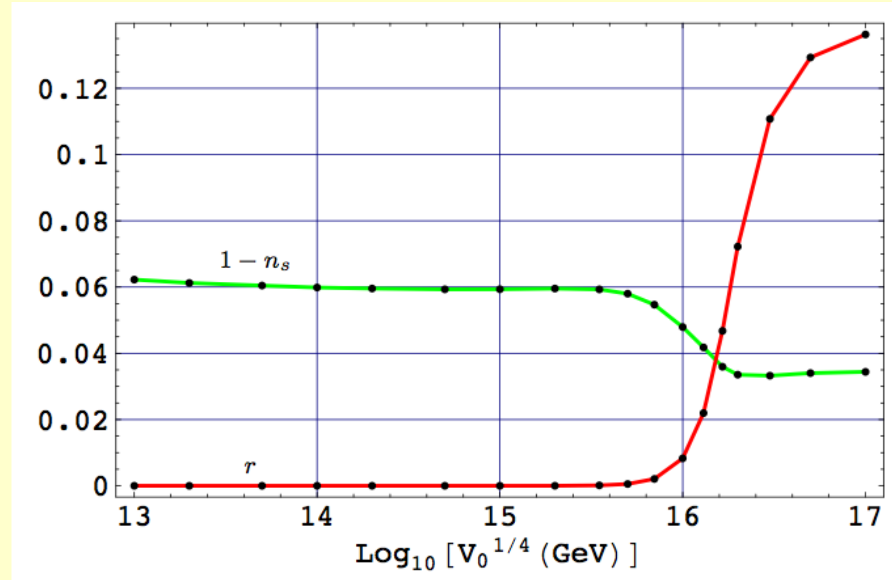
• If the shape of the potential resembles the plot above, the slope of the potential increases with time → *epsilon_** becomes larger

• It means that the RHS of equation decreases with *k*

• → $n < 1$

Inflation, spectrum, phenomenology





Coleman-Weinberg Potential In Good Agreement With WMAP

Q. Shafi* and V. N. Şenoğuz†

WMAP Cosmological Parameters

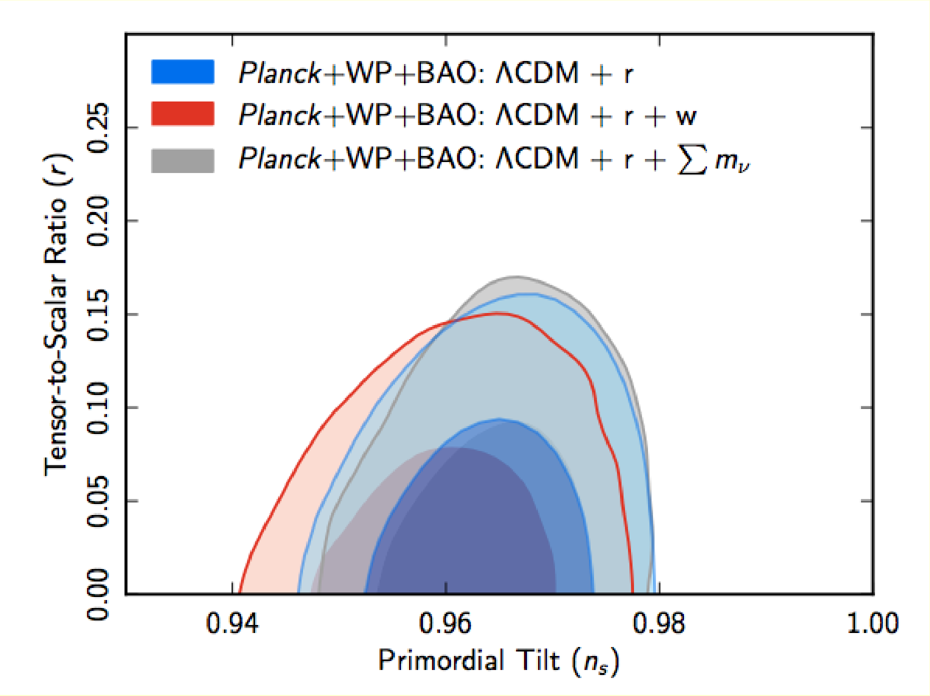
Model: lcdm+sz+lens

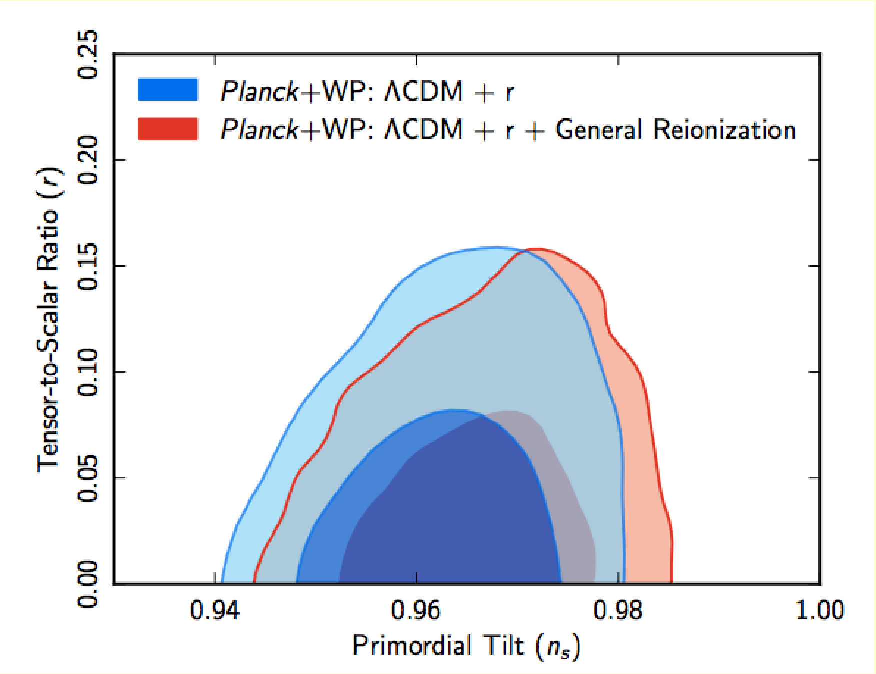
Data: wmap7

$1-n_s$		$0.0079 < 1-n_s < 0.0642$ (95% CL)	
$dn_s/d\ln k$	$\cdots$	-0.034 ± 0.026	-0.048 ± 0.029

CMB observations in principle can limit the possible inflation scenarios. When the primary (not lensing induced, nor due to dust) B-mode polarization is measured the ratio of tensor and scalar power spectra (r) can be defined

Planck XXII: Inflation



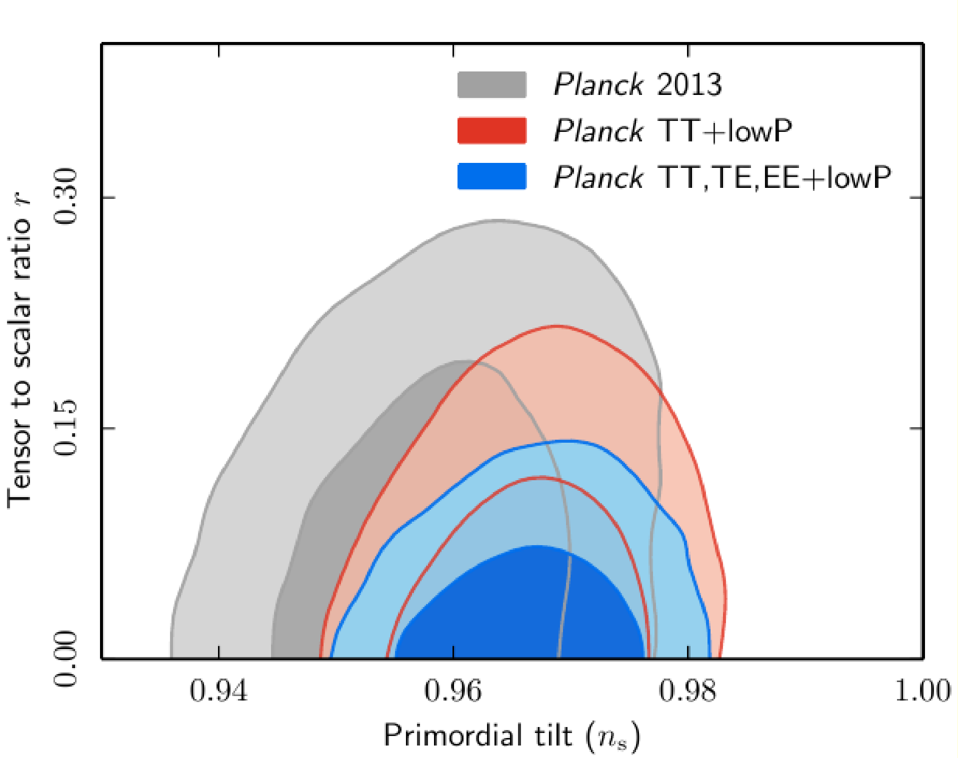


The slope of the primary spectrum in disagreement wit H-Z: n_s=0.96 (WMAP, Planck, different data CMB+extras included)
GW are not “visible”, *r* =0 possible, but *r* > 0 impossible to exclude. Planck: r<0.12 (95%). It corresponds to V*<(1.94*10^{16}GeV)^4

[Ade et al. 2013, arXiv:1303.5082]

(2020: the limits are tighter, *r* < 0.06 or so)

Planck 2015: Inflation



$$
\begin{aligned}
r_{0.002} &< 0.10 \quad (95\,\%\ \mathrm{CL},\ \textit{Planck}\ \mathrm{TT{+}lowP})\,,\\
r_{0.002} &< 0.11 \quad (95\,\%\ \mathrm{CL},\ \textit{Planck}\ \mathrm{TT{+}lowP{+}lensing})\,,\\
r_{0.002} &< 0.11 \quad (95\,\%\ \mathrm{CL},\ \textit{Planck}\ \mathrm{TT{+}lowP{+}BAO})\,,\\
r_{0.002} &< 0.10 \quad (95\,\%\ \mathrm{CL},\ \textit{Planck}\ \mathrm{TT,TE,EE{+}lowP})\,.
\end{aligned}
$$

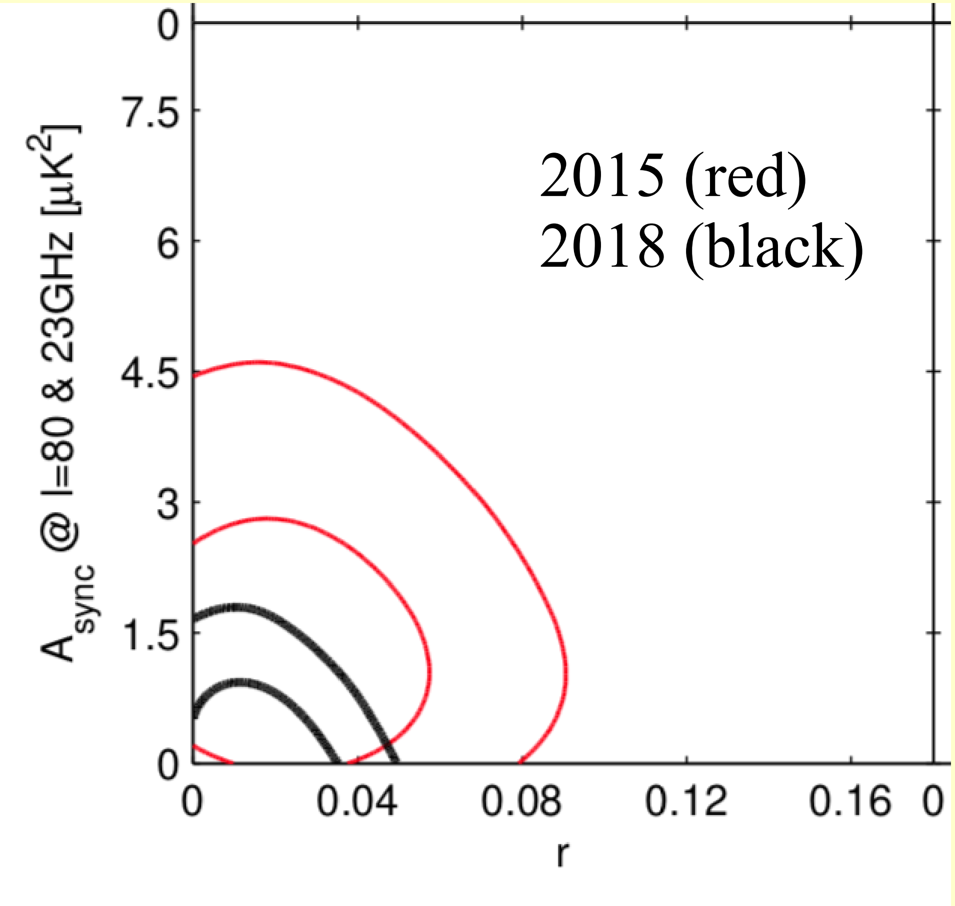
Limits 2015: similar

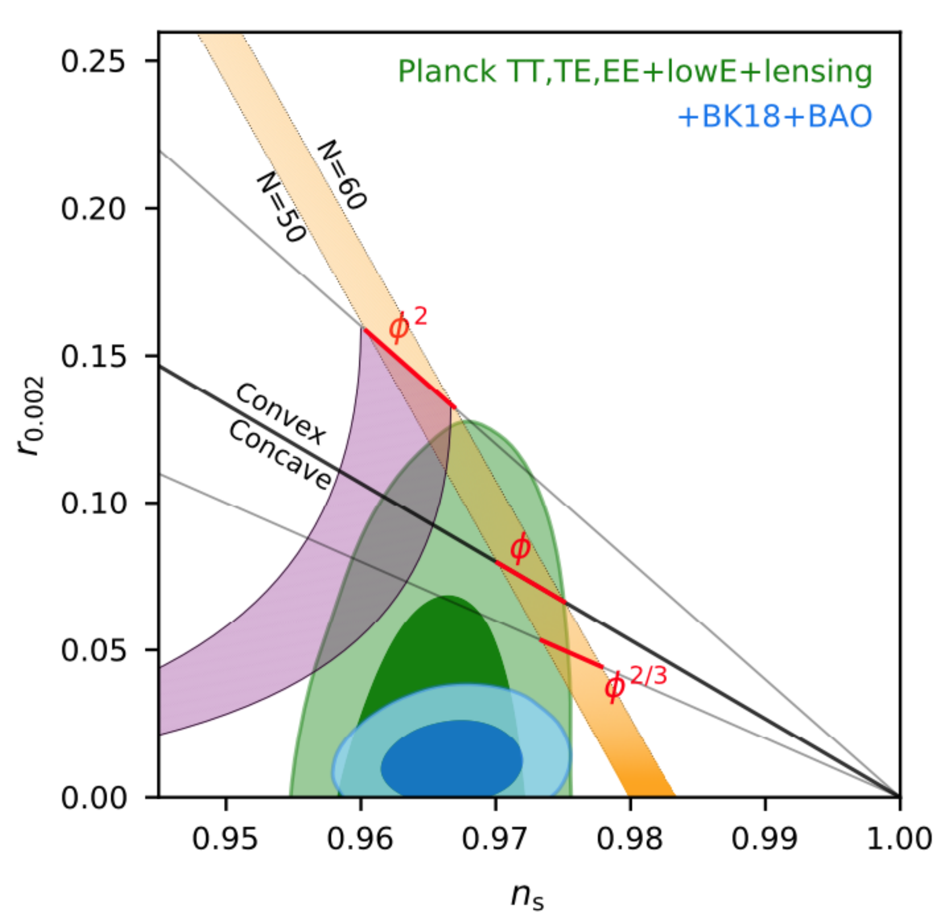
[Ade et al. 2015, arXiv:1502.02114]

BICEP / *Keck* XIII: Improved Constraints on Primordial Gravitational Waves using *Planck*, WMAP, and BICEP/*Keck* Observations through the 2018 Observing Season

BICEP/*Keck* Collaboration: P. A. R. Ade,[1] Z. Ahmed,[2] M. Amiri,[3] D. Barkats,[4] R. Basu Thakur,[5]

2021PhRvL.127o1301A 2021/10

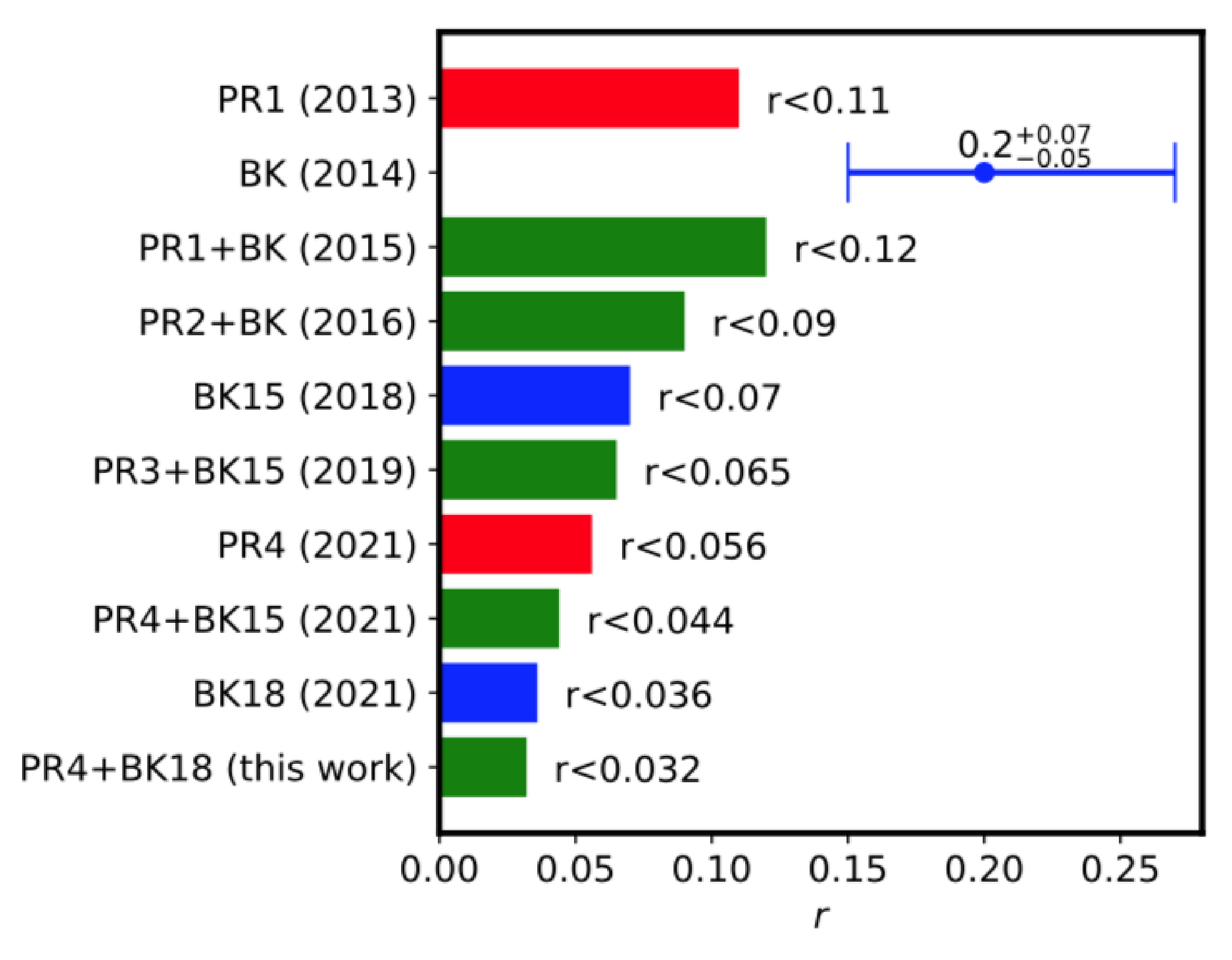




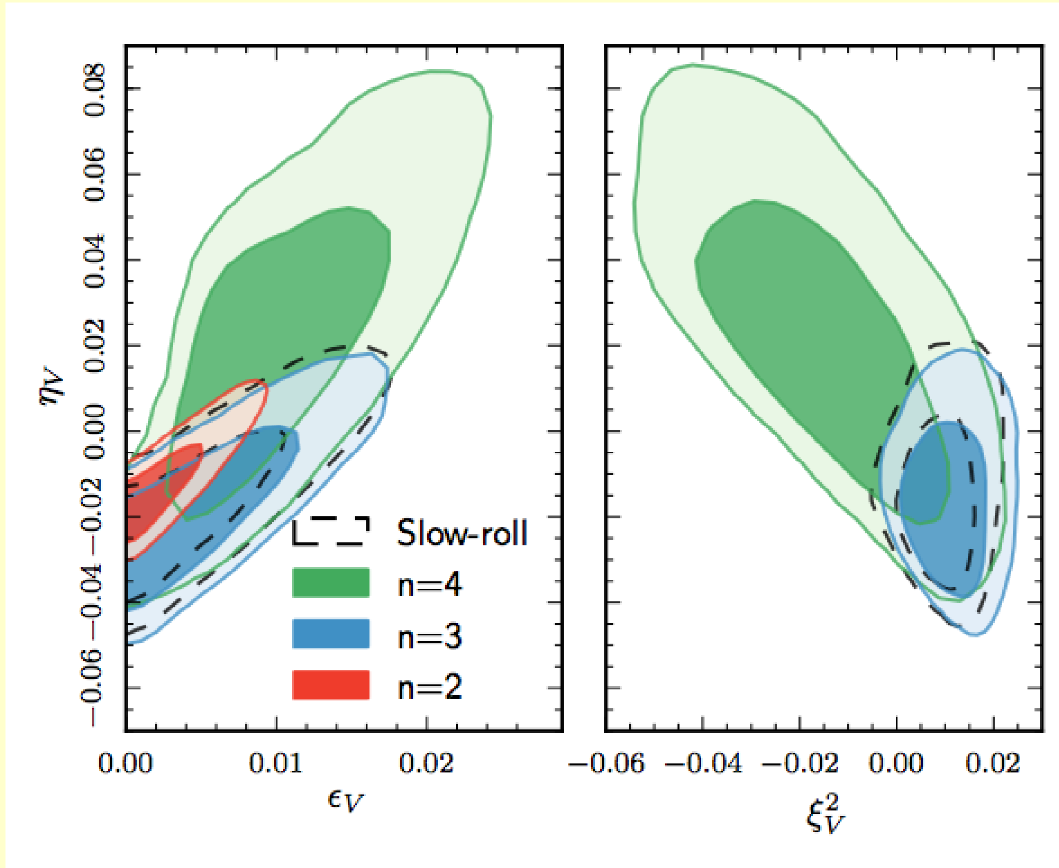
$$r_{0.05} < 0.036 \text{ at } 95\% \text{ confidence}$$

Improved limits on the tensor-to-scalar ratio using BICEP and *Planck*

M. Tristram,[1] A. J. Banday,[2] K. M. Górski,[3,4] R. Keskitalo,[5,6] C. R. Lawrence,[3] K. J. Andersen,[7]



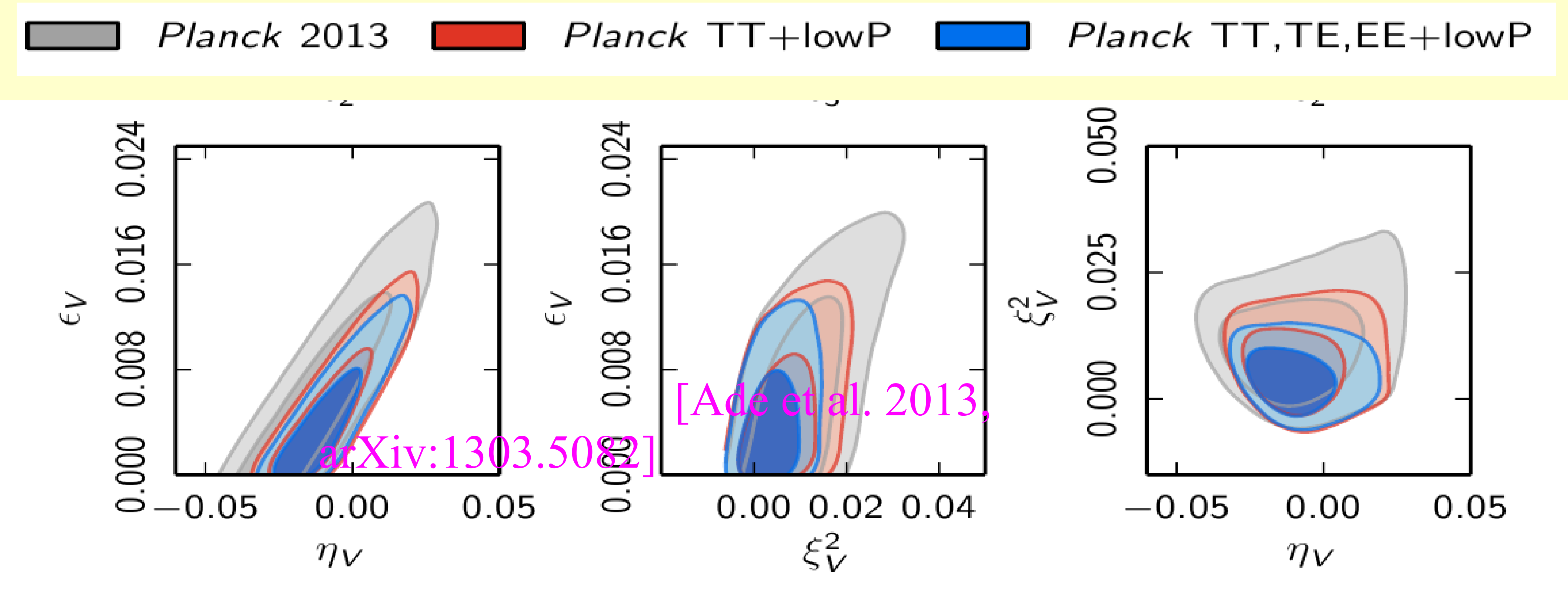
Planck XXII: Inflation



Small inflaton potential parameters. Taylor expansions of the N= 2nd , 3rd , and 4th order are compared. The evolution is calculated numerically. (The visible influence of the 4th order term on the values of 1 -3 order parameters may suggest that the approach is not selfconsistent).

[Ade et al. 2013, arXiv:1303.5082]

Planck 2015: Inflation



[Ade et al. 2013, arXiv:1303.5082]

Limits (2015) on the small parameters of inflaton potential.

[Ade et al. 2015, arXiv:1502.02114]

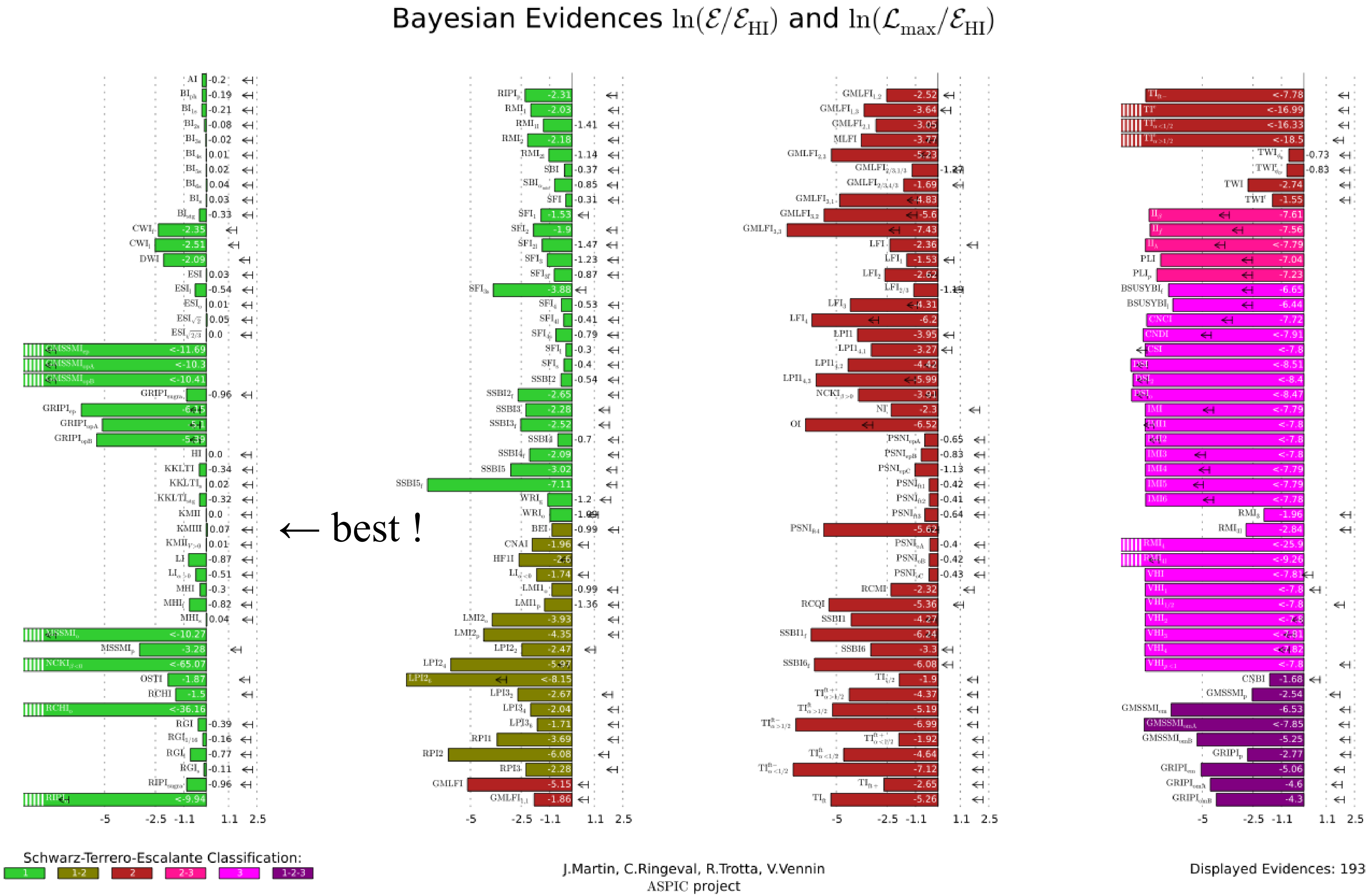


Figure 2. Bayes factors (bars) and absolute upper bound to the Bayes factors (arrows) for the *Encyclopædia Inflationaris* inflationary scenarios, with Higgs inflation as the reference model (see the text for a more accurate description).

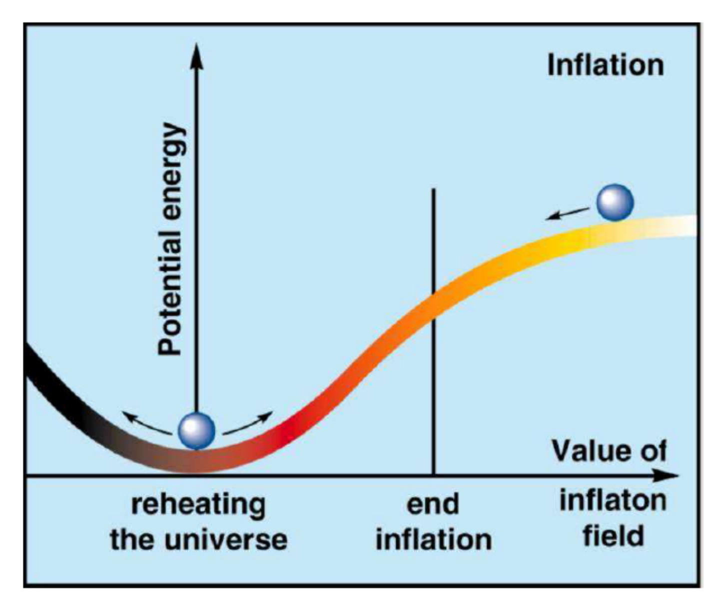
[Martin et al (2013) arXiv:1312.3529]

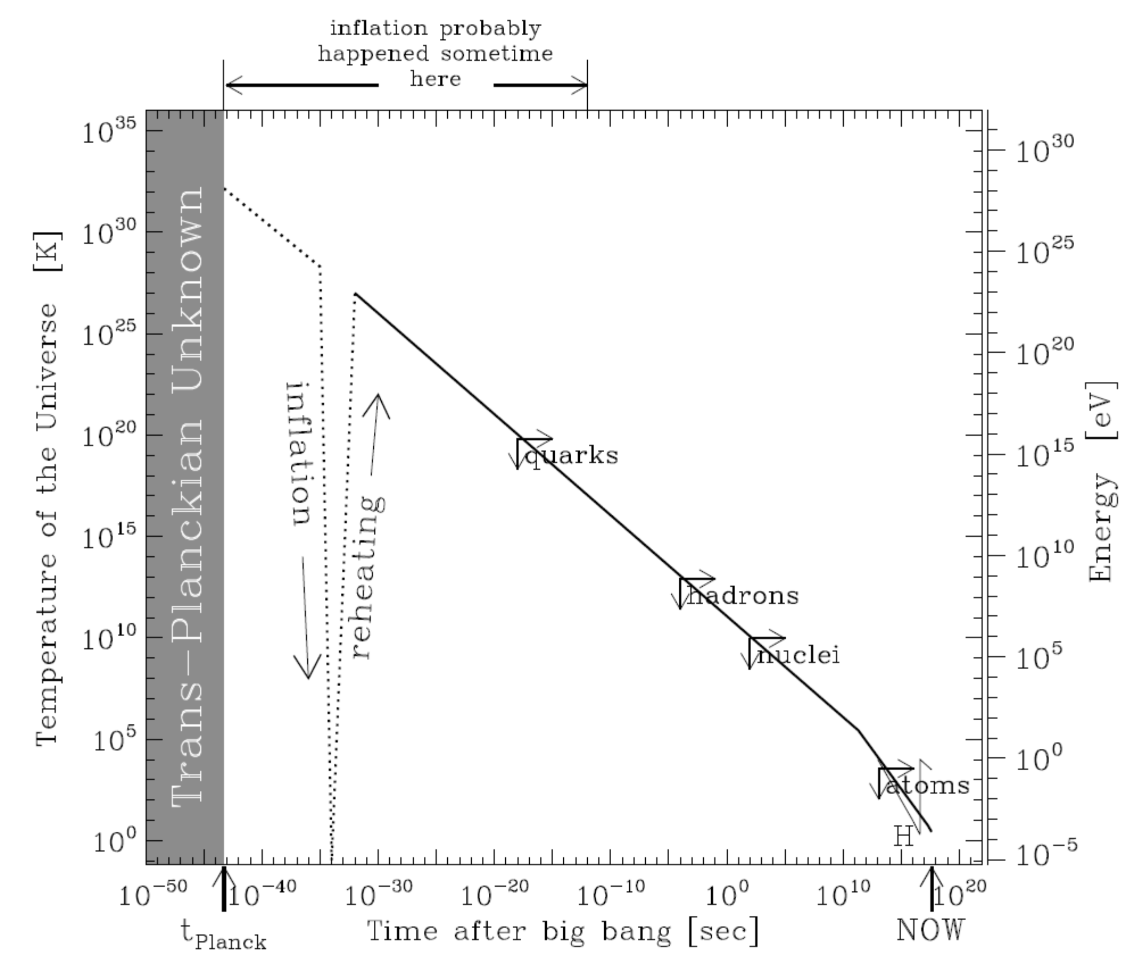
Let us now analyse our results in more detail. Firstly, the answer to the central question of this paper, namely "what is the best model of inflation given the Planck 2013 data?" is KMIII inflation [39–41], whose Bayes factor with respect to Higgs inflation is $\ln B^{\mathrm{KMIII}}_{\mathrm{HI}} = 0.07 > 0$. However, the preference is extremely mild, so much so that it is within the margin of uncertainty of our analysis, and for all practical purposes KMIII inflation has to be regarded as being on the same footing with Higgs inflation, from the point of view of the Planck data.

is an integer. This plot illustrates the power of the Planck data and allows us to summarise our main results: from a large number of models, one is able to single out a relatively small subset corresponding to the "best models". We rule out $\simeq 34\%$ of the models at a strong level of evidence and $\simeq 26\%$ of the models (9% if one includes the complexity) are preferred. All the favoured scenarios belong to the category 1 of the the Schwarz–Terrero-Escalante classification and have a shape consistent with "plateau inflation".

[Martin et al (2013) arXiv:1312.3529]

Phenomenology: after the inflation





•After the inflation when the inflaton field smoothly approaches the global minimum of V, the phase of its oscillations takes place

• All the particles existing before the inflation have been diluted exp(3*69) [(10^30)^3] times

• Inflaton field energy is transformed into new particles filling the Universe anew

Phenomenology: baryogenesis?

- Sacharow conditions (1967):
  - Baryon number B violation.
  - C-symmetry and CP-symmetry violation.
  - Interactions out of thermal equilibrium.
- Condition 2 is experimentally confirmed
- Condition 1 does not contradict the standard model. (BUT: it is not implied by the standard model)
- Condition 3 might have been fulfilled after the inflation, when particles were created
- **How to verify possible scenarios? No idea**

Collider Signals of Baryogenesis and Dark Matter from B Mesons: A Roadmap to Discovery

Gonzalo Alonso-Álvarez,[1,2,*] Gilly Elor,[3,†] and Miguel Escudero[4,‡]

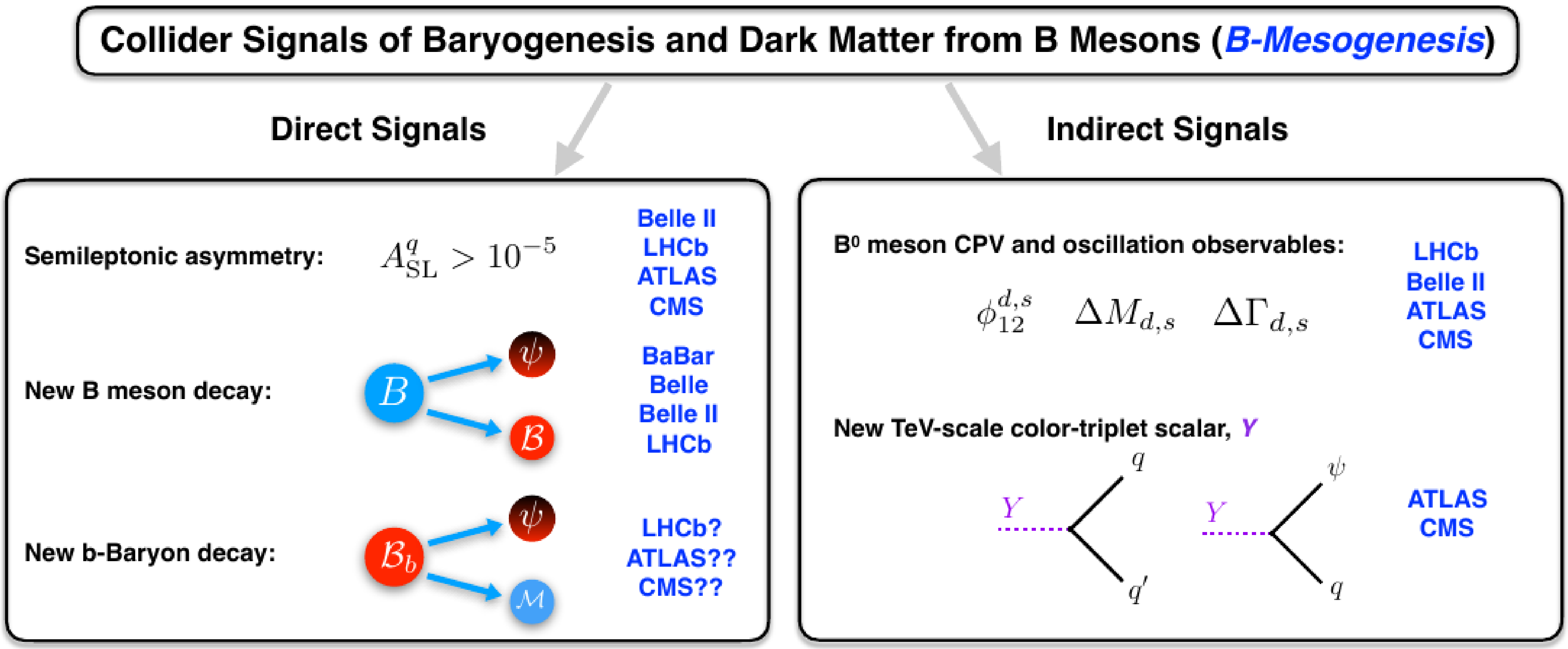


FIG. 1. Summary of the collider implications of baryogenesis and dark matter from B mesons [1], i.e. *B-Mesogenesis*. The distinctive signals of the mechanism are: *i)* the requirement that at least one of the semileptonic (CP) asymmetries in B^0_q decays is $A^q_{\rm SL} > 10^{-5}$, *ii)* that both neutral and charged B mesons decay into a dark sector antibaryon (appearing as missing energy in the detector), a visible baryon, and any number of light mesos with $\text{Br}(B \to \psi\,\mathcal{B}\,\mathcal{M}) > 10^{-4}$, *iii)* that b-flavored baryons should decay into light mesons and missing energy at a rate $\text{Br}(\mathcal{B}_b \to \psi\,\mathcal{M}) > 10^{-4}$. In addition, we include as indirect signals the various oscillation observables in the $B^0_q - \bar{B}^0_q$ system as they are linked to $A^q_{\rm SL}$, and the presence of a new TeV-scale color-triplet scalar Y that is needed to trigger the $B \to \psi\,\mathcal{B}\,\mathcal{M}$ decay. We also highlight the existing experiments that can probe each corresponding signal.