The Effective Theory of Inflation, Cosmological Observations Contrasted with Quantum Fields in (Quasi)-De Sitter Spacetime

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THE PHYSICS OF DE SITTER SPACETIME

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DM + Λ + Baryons + Radiation

The Standard Cosmological Model $=$ Concordance Model

- Begins by the inflationary era. Slow-Roll inflation explains horizon and flatness.
- Gravity is described by Einstein's General Relativity.
- Particle Physics described by the Standard Model of Particle Physics: $SU(3) \otimes SU(2) \otimes U(1) =$ qcd+electroweak model.
- Dark matter is non-relativistic during the matter dominated era where structure formation happens. DM is outside the SM of particle physics. CDM $\Longrightarrow$ WDM.
- Dark energy described by the cosmological constant Λ.

Standard Model of the Universe: Concordance Model

$ds^2 = dt^2 - a^2(t)\, d\vec{x}^{\,2}$: spatially flat geometry.

The Universe starts by an **INFLATIONARY ERA**.

Inflation = Accelerated Expansion: $\frac{d^2a}{dt^2} > 0$.

During inflation the universe expands by at least sixty or so efolds: $e^{66} \simeq 10^{29}$. Inflation lasts $\simeq 10^{-36}$ sec and ends by $z \sim 10^{27}$ followed by a radiation dominated era.

Matter can be effectively described during inflation by a single Scalar Field $\phi(t, \boldsymbol{x})$: the Inflaton.

Lagrangean: $\mathcal{L} = a^3(t) \left[\frac{\dot{\phi}^2}{2} - \frac{(\nabla\phi)^2}{2\, a^2(t)} - V(\phi) \right]$.

Friedmann eq.: $H^2(t) = \frac{1}{3\, M_{Pl}^2} \left[\frac{\dot{\phi}^2}{2} + V(\phi) \right]$, $H(t) \equiv \dot{a}(t)/a(t)$.

Slow-roll $\Longrightarrow$ quasi-de Sitter space-time.

If $\dot{\phi}^2 \ll V(\phi) \simeq \bar{V} \Longrightarrow a(t) = \bar{a}\, e^{\bar{H}\, t}$, $\bar{H} = \sqrt{\bar{V}}/[\sqrt{3}\, M_{Pl}]$

The Theory of Inflation

We describe inflation as an effective field in the Ginsburg-Landau sense.
D. Boyanovsky, C. Destri, H. J. de Vega, N. G. Sánchez, (review article),
arXiv:0901.0549, Int. J. Mod.Phys. **A 24**, 3669-3864 (2009).
Relevant effective theories in physics:

- Ginsburg-Landau theory of superconductivity. It is an effective theory for Cooper pairs in the microscopic BCS theory of superconductivity.
- The $O(4)$ sigma model for pions, the sigma and photons at energies $\lesssim 1$ GeV. The microscopic theory is QCD: quarks and gluons. $\pi \simeq \bar{q}q$, $\sigma \simeq \bar{q}q$.
- The theory of second order phase transitions à la Landau-Kadanoff-Wilson... (ferromagnetic, antiferromagnetic, liquid-gas, Helium 3 and 4, ...)
- ....

Slow-roll evolution of the Inflaton

During slow-roll the inflaton derivatives are small and the evolution equations can be approximated by:

$$3\,H(t)\,\dot{\phi} + V'(\phi) = 0 \quad , \quad H^2(t) = \frac{V(\phi)}{3M_{Pl}^2}$$

These first order equations can be solved in closed from as:

$$M_{Pl}^2\,N[\phi] = -\int_{\phi}^{\phi_{end}} V(\varphi)\,\frac{d\varphi}{dV}\,d\varphi\,, \quad e^{N[\phi]} = a(\phi_{end})/a(\phi)\,,$$

$N[\phi] =$ the number of e-folds since the field ϕ exits the horizon till the end of inflation. $N \sim 60$.
$\phi_{end} =$ absolute minimum of $V(\phi)$.

Therefore, $\phi^2 =$ scales as $N\ M_{Pl}^2$. We define:

$\chi \equiv \frac{\phi}{\sqrt{N}\ M_{Pl}} =$ is a dimensionless and slow field.

Universal form of the slow-roll inflaton potential:
$V(\phi) = N\ M^4\ w(\chi),\ M =$ energy scale of inflation

SLOW and Dimensionless Variables

$$\chi = \frac{\phi}{\sqrt{N}\; M_{Pl}} \quad , \quad \tau = \frac{m\, t}{\sqrt{N}} \quad , \quad \mathcal{H}(\tau) = \frac{H(t)}{m\,\sqrt{N}} \quad ,$$

$m \equiv \frac{M^2}{M_{Pl}} \quad , \quad |V''(0)| = m^2 =$ inflaton mass, ($|w''(0)| = 1$)

slow inflaton, slow time, slow Hubble.

χ and $w(\chi)$ are of order one.

Evolution Equations:

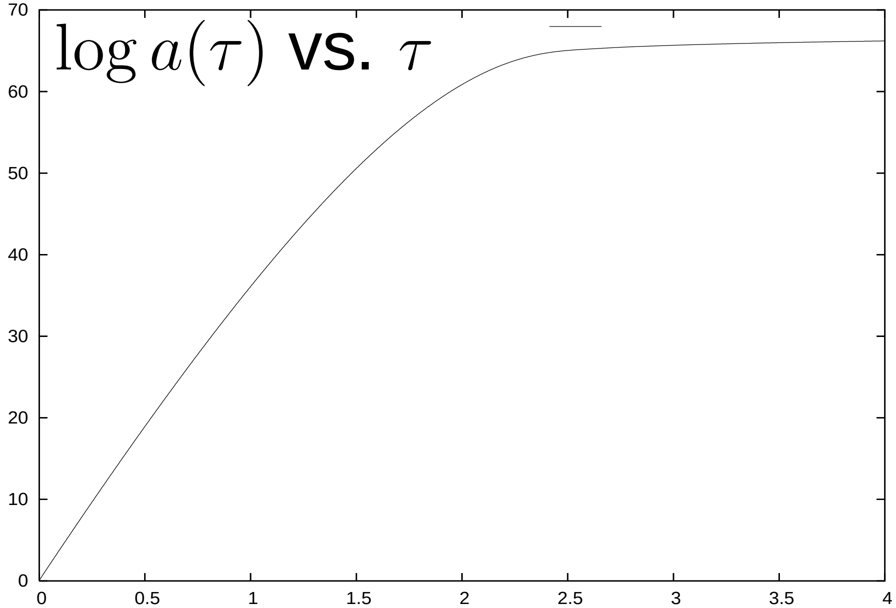
$$\mathcal{H}^2(\tau) = \frac{1}{3}\left[\frac{1}{2\,N}\left(\frac{d\chi}{d\tau}\right)^2 + w(\chi)\right] \quad ,$$

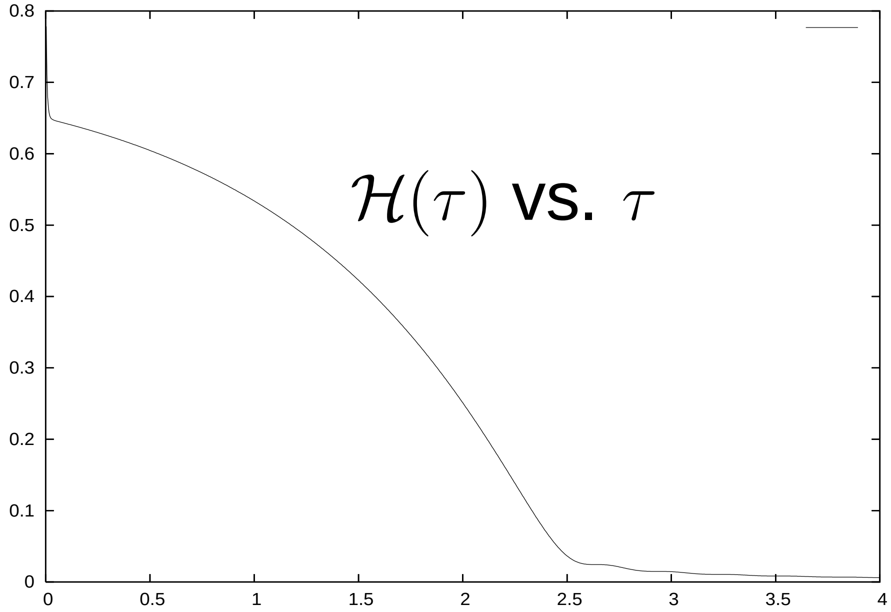
$$\frac{1}{N}\,\frac{d^2\chi}{d\tau^2} + 3\,\mathcal{H}\,\frac{d\chi}{d\tau} + w'(\chi) = 0 \quad .$$

$1/N$ terms: corrections to slow-roll

Higher orders in slow-roll are obtained systematically by expanding the solutions in $1/N$.

Exact Inflaton Dynamics: $w(\chi) = \frac{y}{32}(\chi^2 - \frac{8}{y})^2$





Slow-roll Inflaton Dynamics

Integrating the inflaton evolution eqs. to the order $1/N$:

$$\log \frac{a(t)}{a(0)} = \sqrt{\frac{2\,N}{3\,y}}\; m\,t - \frac{1}{8}\,\frac{\varphi^2(0)}{M_{Pl}^2}\;\left[e^{\sqrt{\frac{2\,y}{3\,N}}\;m\,t} - 1\right]$$

$$H(t) = m\,\sqrt{\frac{2\,N}{3\,y}}\left[1 - \frac{y}{8\,N}\,\frac{\varphi^2(0)}{M_{Pl}^2}\;e^{\sqrt{\frac{2\,y}{3\,N}}\;m\,t}\right]$$

Hubble $H(t)$ slowly decreases during slow-roll.

De Sitter universe plus $1/N$ corrections:

During slow-roll the universe is quasi-De Sitter.

$$H(\text{end slow} - \text{roll}) \simeq H(\text{slow} - \text{roll beginning})/\sqrt{N}$$

$$\sqrt{N} \simeq 8$$

$$m\,t_{end\;slow-roll} = \sqrt{\frac{3\,N}{2\,y}}\;\log\left[\frac{8\,N\,M_{Pl}^2}{y\,\varphi^2(0)}\right]$$

The Slow-roll regime is an attractor

(Belinsky-Grishchuk-Zeldovich-Khalatnikov, 1985)

Primordial Power Spectrum

Adiabatic Scalar Perturbations: $P(k) = |\Delta_{k\;ad}^{(S)}|^2\; k^{n_s-1}$.

To dominant order in slow-roll:

$$|\Delta_{k\;ad}^{(S)}|^2 = \frac{N^2}{12\,\pi^2}\;\left(\frac{M}{M_{Pl}}\right)^4\;\frac{w^3(\chi)}{w'^2(\chi)}\;.$$

Hence, for all slow-roll inflation models:

$$|\Delta_{k\;ad}^{(S)}| \sim \frac{N}{2\,\pi\sqrt{3}}\left(\frac{M}{M_{Pl}}\right)^2$$

The WMAP result: $|\Delta_{k\;ad}^{(S)}| = (0.494 \pm 0.1) \times 10^{-4}$

determines the scale of inflation M (using $N \simeq 60$)

$$\left(\frac{M}{M_{Pl}}\right)^2 = 0.85 \times 10^{-5} \;\longrightarrow\; M = 0.70 \times 10^{16} \text{ GeV}$$

The inflation energy scale turns to be the grand unification energy scale !! We find the scale of inflation without knowing the tensor/scalar ratio r !!

The scale M is independent of the shape of $w(\chi)$.

spectral index n_s, the ratio r and the running of n_s

$r \equiv$ ratio of tensor to scalar fluctuations.
tensor fluctuations = primordial gravitons.

$$n_s - 1 = -\frac{3}{N}\left[\frac{w'(\chi)}{w(\chi)}\right]^2 + \frac{2}{N}\frac{w''(\chi)}{w(\chi)} \quad , \quad r = \frac{8}{N}\left[\frac{w'(\chi)}{w(\chi)}\right]^2$$

$$\frac{dn_s}{d\ln k} = -\frac{2}{N^2}\frac{w'(\chi)\,w'''(\chi)}{w^2(\chi)} - \frac{6}{N^2}\frac{[w'(\chi)]^4}{w^4(\chi)} + \frac{8}{N^2}\frac{[w'(\chi)]^2\,w''(\chi)}{w^3(\chi)} \, ,$$

χ is the inflaton field at horizon exit.

$n_s - 1$ and r are always of order $1/N \sim 0.02$ (model indep.)

Running of n_s of order $1/N^2 \sim 0.0003$ (model independent).

Primordial Non-gaussianity $f_{NL} =$ order $1/N$

D. Boyanovsky, H. J. de Vega, N. G. Sanchez,
Phys. Rev. D 73, 023008 (2006), astro-ph/0507595.

Ginsburg-Landau Approach

Ginsburg-Landau potentials:
polynomials in the field starting by a constant term.

Linear terms can always be eliminated by a constant shift of the inflaton field.

The quadratic term can have a positive or a negative sign:

$$\begin{cases} w''(0) > 0 \to \text{single well potential} \to \text{large field (chaotic) inflation} \\ w''(0) < 0 \to \text{double well potential} \to \text{small field (new) inflation} \end{cases}$$

The inflaton potential must be bounded from below $\Longrightarrow$ highest order term must be even with a positive coefficient.

Renormalizability $\Longrightarrow$ degree of the inflaton potential ≤ 4.

The theory of inflation is an effective theory $\Longrightarrow$ higher degree potentials are acceptable

Stability under the addition of terms of higher order. Otherwise, the description obtained could not be trusted.

Fourth order Ginsburg-Landau inflationary models

$$w(\chi) = w_o \pm \frac{\chi^2}{2} + G_3\, \chi^3 + G_4\, \chi^4 \quad , \quad G_3 = \mathcal{O}(1) = G_4$$

$$V(\phi) = N\, M^4\, w\left(\frac{\phi}{\sqrt{N}\, M_{Pl}}\right) = V_o \pm \frac{m^2}{2}\, \phi^2 + g\, \phi^3 + \lambda\, \phi^4 \, .$$

$$m = \frac{M^2}{M_{Pl}} \quad , \quad g = \frac{m}{\sqrt{N}} \left(\frac{M}{M_{Pl}}\right)^2 G_3 \quad , \quad \lambda = \frac{G_4}{N} \left(\frac{M}{M_{Pl}}\right)^4$$

Notice that

$$\left(\frac{M}{M_{Pl}}\right)^2 \simeq 10^{-5} \quad , \quad \left(\frac{M}{M_{Pl}}\right)^4 \simeq 10^{-10} \quad , \quad N \simeq 60 \, .$$

- Small couplings arise naturally as ratio of two energy scales: inflation and Planck.
- The inflaton is a light particle:
  $m = \frac{M^2}{M_{Pl}} \simeq 0.003\, M \;, \quad m = 2.5 \times 10^{13}$ GeV
  $H \sim \sqrt{N}\, m \simeq 2 \times 10^{14}$ GeV.

MCMC Results for double–well inflaton potential

Bounds: $r > 0.023$ (95% CL) , $r > 0.046$ (68% CL)

Most probable values: $n_s \simeq 0.964$, $r \simeq 0.051$ ⇐measurable!!
The most probable double–well inflaton potential has a moderate nonlinearity with the quartic coupling $y \simeq 1.26 \ldots$.

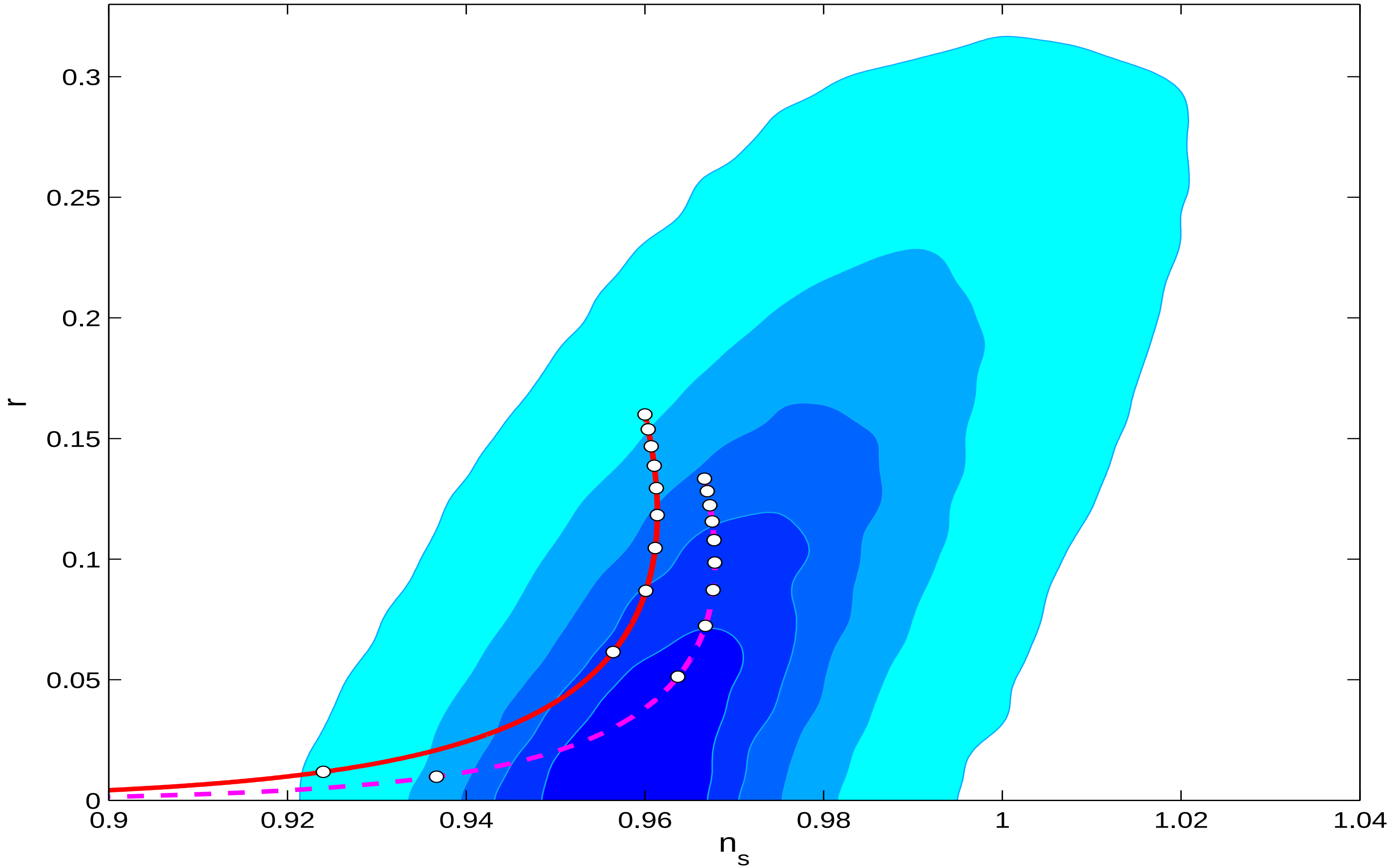
The $\chi \to -\chi$ symmetry is here spontaneously broken since the absolute minimum of the potential is at $\chi \neq 0$

$$w(\chi) = \frac{y}{32}\left(\chi^2 - \frac{8}{y}\right)^2$$

MCMC analysis calls for $w''(\chi) < 0$ at horizon exit
$\Longrightarrow$ double well potential favoured.

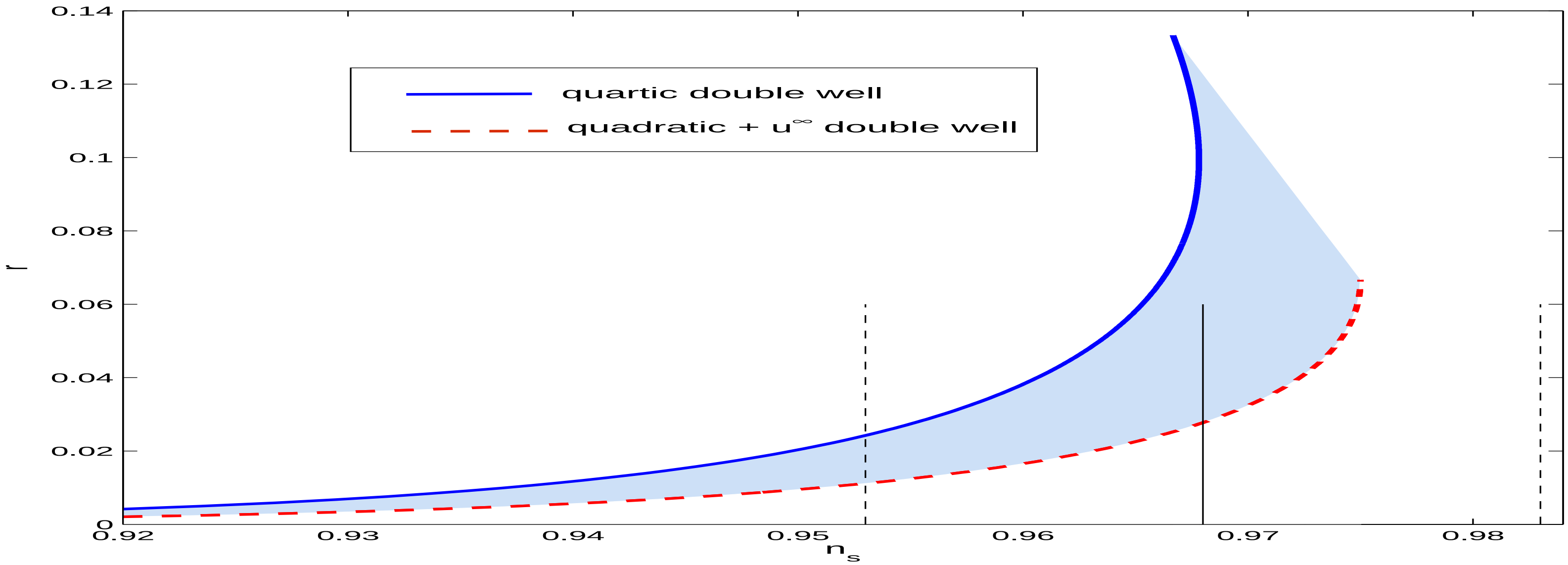
C. Destri, H. J. de Vega, N. Sanchez, MCMC analysis of WMAP data points to broken symmetry inflaton potentials and provides a lower bound on the tensor to scalar ratio, Phys. Rev. D77, 043509 (2008), astro-ph/0703417.

MCMC Results for the double–well inflaton potential



Solid line for $N = 50$ and dashed line for $N = 60$
White dots: $z = 0.01 + 0.11 * n, \; n = 0, 1, \ldots, 9$,
y increases from the uppermost dot $y = 0, \; z = 1$.

The universal banana region



We find that all $r = r(n_s)$ curves for double–well inflaton potentials in the Ginsburg-Landau spirit fall inside the universal banana region $\mathcal{B}$.

The lower border of $\mathcal{B}$ corresponds to the limiting potential:

$$w(\chi) = \frac{4}{y} - \frac{1}{2}\,\chi^2 \quad \text{for } \chi < \sqrt{\frac{8}{y}} \quad , \quad w(\chi) = +\infty \quad \text{for } \chi > \sqrt{\frac{8}{y}}$$

This gives a lower bound for r for all potentials in the Ginsburg-Landau class: $r > 0.021$ for the current best value of the spectral index $n_s = 0.964$.

Loop Quantum Corrections to Slow-Roll Inflation

$$\phi(\vec{x},t) = \Phi_0(t) + \varphi(\vec{x},t), \quad \Phi_0(t) \equiv < \phi(\vec{x},t) >, \quad < \varphi(\vec{x},t) >= 0$$

$$\varphi(\vec{x},t) = \frac{1}{a(\eta)} \int \frac{d^3k}{(2\,\pi)^3} \left[a_{\vec{k}}\, \chi_k(\eta)\, e^{i\vec{k}\cdot\vec{x}} + \text{h.c.}\right],$$

$a^\dagger_{\vec{k}},\ a_{\vec{k}}$ are creation/annihilation operators,
$\chi_k(\eta)$ are mode functions. $\eta =$ conformal time.
To one loop order the equation of motion for the inflaton is

$$\ddot{\Phi}_0(t) + 3\,H\,\dot{\Phi}_0(t) + V'(\Phi_0) + g(\Phi_0)\,\langle[\varphi(\boldsymbol{x},t)]^2\rangle = 0$$

where $g(\Phi_0) = \frac{1}{2}\,V^{'''}(\Phi_0)$.
The mode functions obey:

$$\chi_k^{''}(\eta) + \left[k^2 + M^2(\Phi_0)\,a^2(\eta) - \frac{a^{''}(\eta)}{a(\eta)}\right]\chi_k(\eta) = 0$$

where $M^2(\Phi_0) = V''(\Phi_0) = 3\,H_0^2\,\eta_V + \mathcal{O}(1/N^2)$

Quantum Corrections to the Friedmann Equation

The mode functions equations for slow-roll become,

$$\chi_k^{''}(\eta) + \left[k^2 - \frac{\nu^2 - \frac{1}{4}}{\eta^2}\right] \chi_k(\eta) = 0 \quad , \quad \nu = \frac{3}{2} + \epsilon_V - \eta_V + \mathcal{O}(1/N^2).$$

The scale factor during slow roll is $a(\eta) = -\frac{1}{H_0 \, \eta \, (1-\epsilon_V)}$.

Slow-roll parameters of order $1/N$:

$$\epsilon_V = \frac{1}{2} \, M_{Pl}^2 \, \left(\frac{V'(\Phi_0)}{V(\Phi_0)}\right)^2 \quad , \quad \eta_V = M_{Pl}^2 \, \frac{V''(\Phi_0)}{V(\Phi_0)}$$

D. Boyanovsky, H. J. de Vega, N. G. Sanchez,

Quantum corrections to slow roll inflation and new scaling of superhorizon fluctuations. Nucl. Phys. B 747, 25 (2006), astro-ph/0503669.

Quantum corrections to the inflaton potential and the power spectra from superhorizon modes and trace anomalies, Phys. Rev. D 72, 103006 (2005), astro-ph/0507596.

Quantum Corrections in slow-roll

Scale invariant case: $\nu = \frac{3}{2}$. $\Delta \equiv \frac{3}{2} - \nu = \eta_V - \epsilon_V$ controls the departure from scale invariance.

Explicit solutions in slow-roll:

$\chi_k(\eta) = \frac{1}{2} \sqrt{-\pi\eta} \, i^{\nu+\frac{1}{2}} \, H^{(1)}_\nu(-k\eta)$, $\quad H^{(1)}_\nu(z) =$ Hankel function

Quantum fluctuations: $\langle[\varphi(\boldsymbol{x},t)]^2\rangle = \frac{1}{a^2(\eta)} \int \frac{d^3k}{(2\pi)^3} \, |\chi_k(\eta)|^2$

$$\frac{1}{2}\langle[\varphi(\boldsymbol{x},t)]^2\rangle = \left(\frac{H_0}{4\,\pi}\right)^2 \left[{\Lambda_p}^2 + \ln \Lambda_p^2 + \frac{1}{\Delta} + 2\,\gamma - 4 + \mathcal{O}(\Delta)\right]$$

UV cutoff $\Lambda_p = \text{physical cutoff}/H$, $\quad \frac{1}{\Delta} =$ infrared pole.

$\left\langle \dot{\varphi}^2 \right\rangle \quad , \quad \left\langle (\nabla\varphi)^2 \right\rangle$ are infrared finite

Quantum Corrections to the Inflaton Potential

Upon UV renormalization the Friedmann equation results

$$H^2 = \frac{1}{3\,M_{Pl}^2}\left[\frac{1}{2}\,\dot{\Phi_0}^2 + V_R(\Phi_0) + \left(\frac{H_0}{4\,\pi}\right)^2 \frac{V_R^{''}(\Phi_0)}{\Delta} + \mathcal{O}\left(\frac{1}{N}\right)\right]$$

Quantum corrections are proportional to $\left(\frac{H}{M_{Pl}}\right)^2 \sim 10^{-9}$!!

The Friedmann equation gives for the effective potential:

$$V_{eff}(\Phi_0) = V_R(\Phi_0) + \left(\frac{H_0}{4\,\pi}\right)^2 \frac{V_R^{''}(\Phi_0)}{\Delta}$$

$$V_{eff}(\Phi_0) = V_R(\Phi_0)\left[1 + \left(\frac{H_0}{4\,\pi\,M_{Pl}}\right)^2 \frac{\eta_V}{\eta_V - \epsilon_V}\right]$$

in terms of slow-roll parameters

Very DIFFERENT from the one-loop effective potential in Minkowski space-time:

$$V_{eff}(\Phi_0) = V_R(\Phi_0) + \frac{[V_R^{''}(\Phi_0)]^2}{64\,\pi^2} \ln \frac{V_R^{''}(\Phi_0)}{M^2}$$

Quantum Fluctuations:

Scalar Curvature, Tensor, Fermion, Light Scalar.

All these quantum fluctuations contribute to the inflaton potential and to the primordial power spectra.

In de Sitter space-time: $< T_{\mu\nu} >= \frac{1}{4}\, g_{\mu\nu} \;\; < T^{\alpha}_{\alpha} >$

Hence, $V_{eff} = V_R + < T^0_0 >= V_R + \frac{1}{4} < T^{\alpha}_{\alpha} >$

Sub-horizon (Ultraviolet) contributions appear through the trace anomaly and only depend on the spin of the particle.

Superhorizon (Infrared) contributions are of the order N^0 and can be expressed in terms of the slow-roll parameters.

$$V_{eff}(\Phi_0) = V(\Phi_0)\left[1 + \frac{H_0^2}{3\,(4\pi)^2\, M_{Pl}^2}\left(\frac{\eta_v - 4\,\epsilon_v}{\eta_v - 3\,\epsilon_v} + \frac{3\,\eta_\sigma}{\eta_\sigma - \epsilon_v} + \mathcal{T}\right)\right]$$

$\mathcal{T} = \mathcal{T}_\Phi + \mathcal{T}_s + \mathcal{T}_t + \mathcal{T}_F = -\frac{2903}{20}$ is the total trace anomaly.

$\mathcal{T}_\Phi = \mathcal{T}_s = -\frac{29}{30},\;\; \mathcal{T}_t = -\frac{717}{5},\;\; \mathcal{T}_F = \frac{11}{60}$

$\longrightarrow$ the graviton (t) dominates.

Corrections to the Primordial Scalar and Tensor Power

$$|\Delta^{(S)}_{k,eff}|^2 = |\Delta^{(S)}_{k}|^2 \{1+$$

$$+\frac{2}{3}\left(\frac{H_0}{4\,\pi\,M_{Pl}}\right)^2\left[1+\frac{\frac{3}{8}\,r\,(n_s-1)+2\,\frac{dn_s}{d\ln k}}{(n_s-1)^2}+\frac{2903}{40}\right]\right\}$$

$$|\Delta^{(T)}_{k,eff}|^2 = |\Delta^{(T)}_{k}|^2\left\{1-\frac{1}{3}\left(\frac{H_0}{4\,\pi\,M_{Pl}}\right)^2\left[-1+\frac{1}{8}\,\frac{r}{n_s-1}+\frac{2903}{20}\right]\right\}.$$

The anomaly contribution $-\frac{2903}{20} = -145.15$ DOMINATES as long as the number of fermions less than 783.

The scalar curvature fluctuations $|\Delta^{(S)}_{k}|^2$ are ENHANCED and the tensor fluctuations $|\Delta^{(T)}_{k}|^2$ REDUCED.

However, $\left(\frac{H}{M_{Pl}}\right)^2 \sim 10^{-9}$.

D. Boyanovsky, H. J. de Vega, N. G. Sanchez, Phys. Rev. D 72, 103006 (2005), astro-ph/0507596.

The Energy Scale of Inflation

Grand Unification Idea (GUT)

- Renormalization group running of electromagnetic, weak and strong couplings shows that they all meet at $E_{GUT} \simeq 2 \times 10^{16}$ GeV
- Neutrino masses are explained by the see-saw mechanism: $m_\nu \sim \frac{M^2_{\rm Fermi}}{M_R}$ with $M_R \sim 10^{16}$ GeV.
- Inflation energy scale: $M \simeq 10^{16}$ GeV.

Conclusion: the GUT energy scale appears in at least three independent ways.

Moreover, moduli potentials: $V_{moduli} = M^4_{\rm SUSY} \; v\left(\frac{\phi}{M_{Pl}}\right)$

ressemble inflation potentials provided $M_{\rm SUSY} \sim 10^{16}$GeV.
First observation of SUSY in nature??

De Sitter Geometry and Scale Invariance

The De Sitter metric is scale invariant:

$$ds^2 = \frac{1}{(H\ \eta)^2}\left[(d\eta)^2 - (d\vec{x})^2\right] \quad , \quad \eta = \text{conformal time.}$$

But inflation only lasts for N efolds !

Corrections to scale invariance:

$|n_s - 1|$ as well as the ratio r are of order $\sim 1/N$,
The Harrison-Zeldovich point $n_s = 1$ and $r = 0$ corresponds to a critical point.

It is a gaussian fixed point around which the inflation model hovers in the renormalization group (RG) sense with an almost scale invariant spectrum during the slow roll stage.

The quartic coupling:

$$\lambda = \frac{G_4}{N}\ \left(\frac{M}{M_{Pl}}\right)^4 \quad , \quad N = \log\frac{a(\text{inflation end})}{a(\text{horizon exit})}$$

runs like in four dimensional RG in flat euclidean space.

Summary and Conclusions

- We formulate inflation as an effective field theory in the Ginsburg-Landau spirit and obtain $M \sim M_{GUT} \sim 10^{16}$ GeV as inflation energy scale.
- This effective theory is consistent because: $H \ll M \ll M_{Pl}$. Inflaton mass turns to be small: $m \sim H/\sqrt{N}$. Infrared regime !!
- The slow-roll approximation is a $1/N$ expansion, $N \sim 60$. For all slow-roll models $n_s - 1$ and r are $\sim 1/N$. Running: $dn_s/d\ln k \sim 1/N^2$.
- MCMC analysis of WMAP+LSS data plus this theory input indicates a spontaneously symmetry breaking inflaton potential: $w(\chi) = \frac{y}{32}\left(\chi^2 - \frac{8}{y}\right)^2$, $y \simeq 1.26$.
- Lower Bound: $r > 0.023$ (95% CL). Most probable values: $r \simeq 0.051(\Leftarrow$ measurable !!) $n_s \simeq 0.964$.

Summary and Conclusions 2

- Primordial Non-gaussianity $f_{NL} =$ order $1/N$. Too small to be detected.
- Quantum (loop) corrections in the effective theory are of the order $(H/M_{Pl})^2 \sim 10^{-8}$. Same order of magnitude as loop graviton corrections.

Preinflationary and inflationary fast-roll eras and their signatures in the low CMB multipoles,
C. Destri, H. J. de Vega, N. G. Sanchez, arXiv:0912.2994, Phys. Rev. **D 81**, 063520 (2010).

Higher order terms in the inflaton potential and the lower bound on the tensor to scalar ratio r.
C. Destri, H. J. de Vega, N. G. Sanchez, arXiv:0906.4102, Annals of Physics, **326**, 578 (2011).

The Universe is our ultimate physics laboratory

THANK YOU VERY MUCH

FOR YOUR ATTENTION!!