Title: Observing the Structure of the Landscape by Large and Small Scale Cosmological Probes

Date: Mar 16, 2010 02:00 PM

URL: http://pirsa.org/10030035

Abstract: TBA

Observing the Structure of the Landscape by Large and Small Scale Cosmological Probes

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Based on 1001.5172 [hep-th]. accepted to JCAP
and a work in progress

Perimeter Institute,
March 16th, 2010

Introduction to Chain Inflation

In the original picture of inflation proposed by A. Guth (1981), the universe was trapped in a metastable vacuum. This would lead to a quasi-exponential expansion of the space-time.

However in order to exit from inflationary phase, the nucleation rate from the false minimum to the true one should be substantial. This requirement has clashes with the other one coming from having enough number of e-foldings needed to solve the problems of SBB.

Chain inflation is an incarnation of the old idea of old inflation, where instead of having one vacuum, one has a series of metastable minima. The universe tunnels rapidly through a series of first order phase transitions. During the time spent in any one of these minima, the universe inflates by a fraction of an e-fold.

K. Freese & D. Spolyar (2005)

- At each stage, the phase transition is rapid enough that bubbles of true vacuum intersect one another and percolation is complete.
- Recalling that we have a huge number of vacua in string theory, one may take this approach seriously and try to realize it within stringy agents.

Introduction to Chain Inflation

Danielsson & Chialva (2008), instead of the above sequential approach to chain inflation, assumed that during the course of inflaiton the universe is divided to patches, each in a phase, which is segregated from its neighbors by domain walls. Taking this ensemble approach to chain inflation, they studied the mechanism of generation of density perturbations in chain inflation.

- They also tried to realize chain inflation in the context of flux-compactified string theory, using complex structure moduli as the agents.
- Motivated by these studies, they considered two landscape structures; in one the energy of the vacua changes with the index of vacuum in the ladder as $\epsilon_n = i\, m_f^4$. In the second one the energy is a quadratic function of the vacuum index, $\epsilon_n = i^2 m_f^4/2$. They also established a formalism to calculate the amplitude of density perturbations and spectral index.
- Following their formalism, I will show that these chain inflation models have specific predictions for the CMB which is characterized by the vacuum structure. One can also obtain interesting bounds on the vacua energy gap assuming that thermalization has been successful at each stage.
- Also I will try to further constrain the reheating temperature gap by requiring that the amount of gravity waves generated during chain inflation from Bubble collision do not be large to overclose th universe.

Work in progress

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Outline

- Review of the Previous Results by Danielsson & Chialva
- Chain Inflation: Realization in String Theory
- Matching the models with observations
- Distinguishing Chain inflation from its slow-roll counterparts
- Bound on T_R from GW Production through Bubble Collision
- Conclusion

Chain Inflation: Review of the previous results

- Consider a theory with a potential with many metastable minima at different energies.
- The phase transitions among the various vacua proceed by nucleation of bubbles. The bubbles are filled by the new vacuum at a lower energy, and all the latent heat of the transition is stored within the walls of the bubbles. When bubbles collide the energy of the walls is converted in radiation (massless string states).
- The values for the decay rate per unit physical volume, Γ_n between vacua n and $n-1$such that percolation and large scale thermalization is achieved at every phase transition.
- Decays between two distant vacua are strongly suppressed
- The bubbles are produced with negligible volume and expand at the speed of light.
- The energy of the walls is optimally transferred to radiation in the collision and the thermalization time is very short.
- As time passes, we observe the Universe as filled with the radiation produced from the collisions of the walls of the bubbles of our phase and small patches, distributed in an homogeneous way, composed of the previous phases.

Chain Inflation: Review of the previous results

- The main contributions to the energy density of the universe during chain inflation come from the cosmological constant within each region, ρ^V, and also the energy stored in bubble the walls, $\rho^W(t)$

Collision of the bubble walls will transform this vacuum energy to radiation:

$$\rho(t) = \rho^V(t) + \rho^W(t)$$

$$\rho^V(t) = \sum_{m=0} \epsilon_m p_m(t)$$

$$\rho^W = \sum_{m=1} \Delta\epsilon_m \sum_{n=0}^{m-1} p_n(t)\mathcal{F}_{n,n-1}(t).$$

$$\mathcal{F}_{m,m-1}(t) = \frac{\int_0^t dt' \Gamma_m V^{\text{physical}}(t,t') p_m(t') p_{m,\text{un}}(t,t')}{\int_0^t dt' \Gamma_m V^{\text{physical}}(t,t') p_m(t')}.$$

$$p_{m,\text{un}}(t,t') = \exp\left(-\int_0^t \tilde{\Gamma}_m - \int_0^{t'} \tilde{\Gamma}_m\right)$$

$p_m(t)$: the fraction of volume occupied by the *m*-th vacuum

$\mathcal{F}_{m,m-1}$: the energy weighted fraction stored in uncollided bubble walls of the *m-1* th phase

Γ_m: nucleation rate per unit four volume

$p_{m,\text{un}}(t,t')$: the probability that a wall generated at time *t* is still uncollided at time *t'*

Chain Inflation: Realization in String Theory

In order for chain inflation to be a serious alternative to chaotic inflation, one needs a framework where the required potential arises in a natural way

Larfors, Danielsson & Johansson (07)

- A particularly interesting compactification of string theory is type IIB with fluxes

$$V(z,\tau) = e^K g^{i\bar{i}} D_i W D_{\bar{i}} \bar{W} + e^K g^{\tau\bar{\tau}} D_\tau W D_{\bar{\tau}} \bar{W} - 3e^K |W|^2 .$$

We will focus on the dependence on the complex structure moduli and are therefore mostly interested in the structure of the superpotential. It is obtained from the fluxes as

$$W = F \cdot \Pi - \tau H \cdot \Pi.$$

where $\Pi = (\int_{A_1} \Omega, \int_{B_1} \Omega, \ldots)^T$ with Ω as the holomorphic three form

it is rather easy to find fluxes where the potential has a minimum somewhere in moduli space.

Of particular interest is $F_2 << F_1$ We can then make use of conifold monodromies to generate new minima.

Chain Inflation: Realization in String Theory

Specifically, we need to move in moduli space around the conifold point where the cycle A_1 vanishes.

When we do that we go through a cut and end up on a new sheet. The cycles transform as $B_1 \to B_1 + nA_1$ where *n* is the number of times we go around the conifold. The potential after the transformation can equivalently be evaluated using the old periods but with

$$F_{(3)} \to F_{(3)} + n\,(F_2, 0, 0, \ldots, 0)$$
$$H_{(3)} \to H_{(3)} + n\,(H_2, 0, 0, \ldots, 0)\,.$$

If $F_2 \ll F_1$ we can be reasonably sure that we will find a new minimum near the old one on the next sheet. In this way we can generate an infinite series of minima if the $F_1 \to \infty$ limit of $F_{(3)}$ corresponds to a potential with a minimum. The minima will be positioned along a spiral staircase turning around the conifold point.

- A quadratic behaviour, typically arises when the axiodilaton is stabilized independently of the complex structure moduli.

Chain Inflation: Realization in String Theory

Motivated by these studies of stringy landscape, two models where the energy density in each stage has the following functional forms have been suggested:

$$\epsilon_n = \begin{cases} m_f^4 n & \text{case I} \\ \frac{m_f^4}{2} n^2 & \text{case II} \end{cases} \quad \longrightarrow \quad \rho(t) \sim \begin{cases} m_f^4 n(t) & \text{case I} \\ \frac{m_f^4}{2} n(t)^2 & \text{case II} \end{cases}$$

$$n(t) \equiv N + 1 - \frac{t}{\tau}$$

One can define the equivalent of first slow-roll parameters in these two cases:

$$\varepsilon = \begin{cases} \frac{1}{2n(t)H\tau} & \text{case I} \\ \frac{1}{n(t)H\tau} & \text{case II} \end{cases}$$

Chain Inflation: Review of the previous results

We assume the total number of vacua is *N+1* and the nucleation rate per unit time, $\tilde{\Gamma}_m(t) \equiv \Gamma_m V^{\rm physical}(t) = \tilde{\Gamma}$ to be constant over time and independent of *m*, we have to solve the following coupled set of differential equations to find $p_m(t)$:

$$\begin{aligned} \dot{p}_N &= -\tilde{\Gamma} p_N, \\ \dot{p}_{N-1} &= -\tilde{\Gamma} p_{N-1} + \tilde{\Gamma} p_N, \\ &\cdots \\ \dot{p}_0 &= \tilde{\Gamma} p_1. \end{aligned}$$

$$\sum_m p_m(t) = 1.$$

$$p_i(t) = \frac{(\tilde{\Gamma} t)^{N-i}}{(N-i)!} e^{-\tilde{\Gamma} t}.$$

$$\mathcal{F}_{i,i-1} = \frac{p_{i-1}(t)(N-i)!}{(N-i)! - \Gamma(N-i+1,t)}.$$

Cosmological Perturbations in Chain Inflation

- In chain inflation, two kinds of perturbations are generated. On one hand, the quantum fluctuations as in the case of slow-roll, and on the other hand, the statistical fluctuations of bubble nucleation and collision.

- The basic quantity we use to describe the energy density for vacuum and radiation is represented by the fraction of universe occupied by the m−th vacuum

$$\begin{aligned}\dot{p}_m(t) &= -\Gamma_m V^{\text{physical}}(t,t_f)p_m(t) + \Gamma_{m+1} V^{\text{physical}}(t,t_f)p_{m+1}(t)\\ &\equiv -\widetilde{\Gamma}_m(t)p_m(t) + \widetilde{\Gamma}_{m+1}(t)p_{m+1}(t).\end{aligned}$$

The quantity $\widetilde{\Gamma}_m(t)$ represents the average number of bubbles of the m-th vacuum generated at a time t, irrespective of the bubbles generated at previous times. Actual number of such bubbles is therefore distributed according to a Poisson distribution with mean value $\widetilde{\Gamma}_m(t)$. Therefore, a first kind of fluctuation in $p_m(t)$ is due to the statistical fluctuations in this quantity, being equal to $\sqrt{\widetilde{\Gamma}_m(t)}$

- Also the fluctuations of the metric leads to fluctuations in the physical volume, $V^{\text{physical}}(t,t')$ and that in turn will lead to fluctuations in $p_m(t)$

Cosmological Perturbations in Chain Inflation

Danielsson & Chialva (2008) showed that the EOM of curvature perturbations of the comoving hypersurface, $\zeta = z\mathcal{R}$ could be derived from the following action

$$S = \frac{1}{2}\int \left[\zeta'^2 + \frac{1}{3}\zeta(\Delta + \mathcal{H}^2 z)\zeta + \frac{z''}{z}\zeta^2\right] d\eta\, d^3x.$$

$$\zeta'' + \left(\frac{1}{3}k^2 - \frac{1}{3}\mathcal{H}^2 z - \frac{z''}{z}\right)\zeta = 0.$$

$$c_S = \frac{1}{\sqrt{3}}$$

It is due to the fact that the role of kinetic energy is played with radiation whose equation of state parameter is 1/3.

Due to interaction of radiation and vacuum energy.

$$\Delta_{\mathcal{R}}^2 \equiv \frac{k^3 P_{\mathcal{R}}(k)}{2\pi^2} = \frac{H^2}{\pi m_{\rm P}^2 \frac{\varepsilon}{\sqrt{3}}}.$$

Recall that for slow-roll inflation, it is

$$\Delta_R^2 = \frac{H^2}{\pi\, m_P^2\, \varepsilon}$$

$$n_s \equiv 1 + \frac{d\ln \Delta_{\mathcal{R}}^2}{d\ln k} = \begin{cases} 1 - \frac{17}{3}\varepsilon & \text{case I} \\ 1 - \frac{14}{3}\varepsilon & \text{case II} \end{cases}$$

Matching the Models with Observation

Latest WMAP experiment have measured the amplitude of scalar perturbations and its corresponding spectral index to be

$$\Delta^2_{\mathcal{R}} = (2.441 \pm 0.096) \times 10^{-9} \qquad n_s = 0.963 \pm 0.012$$

To match the models with observation, we have to impose these constraints 60 e-foldings before the end of inflation. As in the slow-roll case, the end of inflation is designated $\varepsilon = 1$.

We focus on the case $\epsilon = \mathrm{nm}_f^4$ where $H(t) = \frac{m_f^2}{m_{\mathrm{P}}}\left(\frac{8\pi}{3}\right)^{1/2}\sqrt{N + 1 - \frac{t}{\tau}}$

$$\varepsilon = 1 \Longrightarrow t_f = (N+1)\tau - \left(\frac{3\tau m_{\mathrm{P}}^2}{32\pi m_f^4}\right)^{1/3}.$$

$$N_e(t_i, t_f) = \int_{t_i}^{t_f} H\, dt = 60 \Longrightarrow t_{60} = (N+1)\tau - \left(\frac{98283\ \tau m_{\mathrm{P}}^2}{32\pi m_f^4}\right)^{1/3}.$$

$$\Delta^2_{\mathcal{R}} = 2.441 \times 10^{-9} \Longrightarrow \tau \simeq 6.2669 \times 10^{18}\frac{m_f^4}{m_{\mathrm{P}}^5}.$$

In order to produce the right amount of perturbations at horizon scale, nucleation rate should be

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Matching the Models with Observation

$$N_e \geq 60 \longrightarrow N_{\min} = \frac{2.9198 \times 10^{-12} m_{\mathrm{P}}^4}{m_f^4} - 1. \xrightarrow{N_{\min} > 1} m_f \leq 1.1 \times 10^{-3}\, m_{\mathrm{P}}$$

Therefore, it is not possible to lower the energy scale of inflation by arbitrarily lowering the energy of the gap.

$$H(t_{60}) = 4.9458 \times 10^{-6}\, m_{\mathrm{P}} \longrightarrow r_{60} \equiv \left. \frac{\Delta_T^2}{\Delta_R^2} \right|_{t_{60}} = 0.05773$$

$$n_s(t_{60}) = 1 - \frac{17}{3}\varepsilon(t_{60}) = 0.96869$$

CMBPOl should be able to see the signature at large scales.

Independent of m_f !! Within 2σ level of WMAP results.

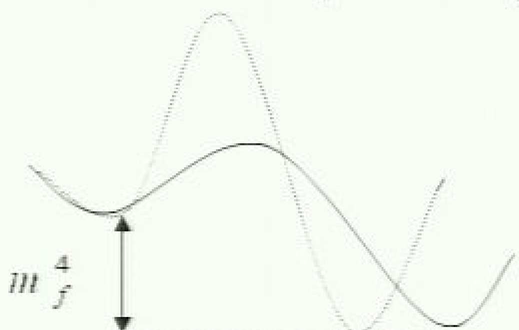
This is different but very close to the prediction of a linear potential, $V(\phi) = \kappa\phi$ For such a linear potential, the scalar spectral index at large scales is 0.975103. This difference is due to interaction of vacuum and radiation components of energy density, which is the characteristic of chain inflation. In principle a very precise measurement of the CMB at large scales should be able to differentiate between the slow-roll linear potential and its chain inflation counterpart.

Matching the Models with Observation

The overall shape of the potential in the chain inflation model could be far from shallowly linear. This is in contrast with the slow-roll model which should be quite shallow to sustain inflation and produce the right amount of perturbations, $\kappa \simeq 1.69 \times 10^{-13} M_{\rm P}^3.$

The only requirements in the chain inflation model, are having a sufficient number of minima to get 60 e-folds of inflation and having the right nucleation rate at each step. The second requirement could be achieved even with a potential whose overall shape is far from flat.

Even though the nucleation time has been fixed in terms of the energy gap it does not mean that the overall shape of the potential (ignoring the wiggles) is fixed.



same nucleation rate between two minima → **Overall shape of the potential which realizes chain inflation could be far from flat**

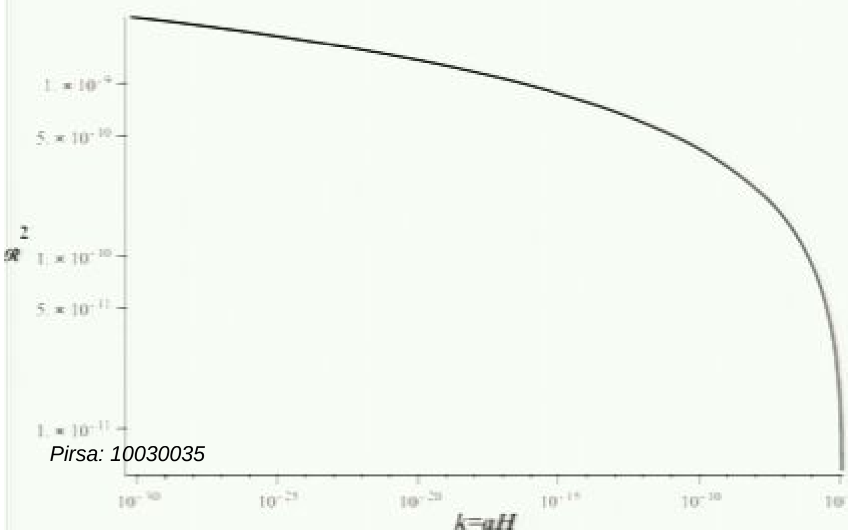
Matching the Models with Observation

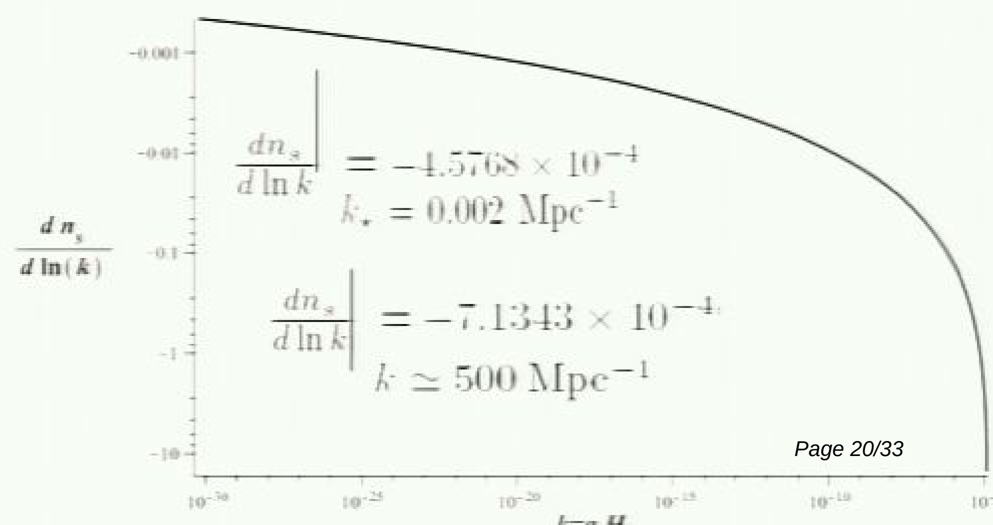
Requiring thermalization $\bar{\Gamma} > 3H$ at each step puts a much more stringent constraint on the energy gap.

Assuming inflation started at Planckian epoch → $m_f < 2.6069 \times 10^{-5}\ m_{\rm P}.$

$m_f < 3.2203 \times 10^{-4}\ m_{\rm P}.$

On the other hand, if one assumes that number of vacua has been right enough to get 60 e-folds, this constraint weakens to





Matching the Models with Observation

B. $\epsilon_t = \frac{t^2}{2} \mathrm{m}_f^4$

$$H(t) = \frac{m_f^2}{m_{\mathrm{P}}} \left(\frac{4\pi}{3} \right)^{1/2} \left(N + 1 - \frac{t}{\tau} \right).$$

Imposing the constraint on the amplitude of density perturbations 60 e-folds before the end of inflation yields:

$$\tau \simeq 6.7679 \times 10^{12} \frac{m_f^2}{m_{\mathrm{P}}^3}.$$

- The scalar spectral index at the today Hubble scale turn out to be independent of m_f again

$$n_s = 0.9614.$$

- Running is still small:

$$\left. \frac{dn_s}{d \ln k} \right|_{k = k_{60}} = -6.83 \times 10^{-4} \qquad \left. \frac{dn_s}{d \ln k} \right|_{k = k_\alpha} = -6.83 \times 10^{-4}$$

Thermalization condition leads to the following bound on the gap mass scale, if inflation has started from Planckian epochs:

$$m_f < 6.5396 \times 10^{-7} \, m_{\mathrm{P}}.$$

Matching the Models with Observation

- One may wonder how general the relation between the value of the scalar spectral index and the vacuum structure is. One may consider the vacua structure with general power-law dependence,

$$\epsilon_i = \frac{m_f^4}{c!} i^c .$$

The relation between the scalar spectral index and the first slow-roll parameter is

$$n_s = 1 - \left(\frac{11}{3} + \frac{2}{c} \right) \varepsilon(t)$$

Following the same approach to data-matching, one finds:

$$n_s = \frac{2(177 + 86c)}{3(120 + 61c)}$$

WMAP seven year results for the scalar spectral index shows that $c > 5$ is ruled out with 68% C.L.

Distinguishing Chain inflation from its slow-roll counterpart

- Due to interaction of radiation with vacuum energy, the scalar spectral index in the chain inflation models will be a little bit different from the slow-roll one.
- The break-down of coarse-graining approach at the scale where bubbles nucleate could lead to oscillations in the spectrum with the amplitude of $\frac{H}{\Lambda}$ where $\Lambda \sim 1/r_b$

Danielsson & Chialva (2008)

- Violation of consistency relation between tensor and scalar spectra:

$$r \equiv \frac{\Delta_T^2}{\Delta_R^2} = -8n_T$$

Stewart & Lyth (1993)

$$\Delta_{\mathcal{R}}^2 \equiv \frac{k^3 P_{\mathcal{R}}(k)}{2\pi^2} = \frac{H^2}{8\pi^2 \frac{\epsilon}{\sqrt{3}}} \longrightarrow r \equiv \frac{\Delta_T^2}{\Delta_R^2} = -\frac{8n_T}{\sqrt{3}}$$

The extra factor of $\sqrt{3}$ in the denominator of the R.H.S. of corresponds to fewer gravity waves at large scale. This smaller amount of gravity waves at large scales, in principle, could make the detection of its scale dependence harder. However one should notice that for a given value of r bigger than 0.01, which is detectable by balloon-borne experiments, the corresponding value of tensor spectral index will be larger by a factor of $\sqrt{3}$ for chain inflation models which makes the detection of scale-dependence easier.

Distinguishing Chain inflation from its slow-roll counterpart

Lensing of the *E* mode by density perturbations along lines of sight from the last scattering surface limits the detectibility of *B* modes at $r_{\lim} = 2.6 \times 10^{-4}$. Knox & Song (2006)

Large departures from the single-field consistency relation can be seen if $r \gtrsim 10^{-3}$

Knox and Song (2003) also argue that if a non-zero value for $n_T + r/8$ in the region $r < 0.166$ is observed, one can confidently exclude the single-field slow-roll inflation as the modifications from loop corrections to the consistency relation is quite small in this region.

• All viable chain inflation models, with *c>5*, predict the violation of the consistency relation in the range *r* bigger than *0.05*, but smaller than *0.166*. Therefore distinguishing chain inflation from slow-roll models should be observationally possible in this range.

Bound on T_R from Bubble Collision GW Production

• Chain inflation proceeds through a series of first order phase transitions, which can release gravitational waves (GW).

• The spectrum of gravity waves (GWs) from multibubble collisions at a single phase transition (PT) with energy difference ϵ between false and true vacua has been worked out numerically:

$$I(f) \equiv E_{GW}(f)/\epsilon = \begin{cases} I_{\max}\left(\frac{f}{f_{\max}}\right)^{2.8} & f \leq f_{\max} \\ I_{\max}\left(\frac{f}{f_{\max}}\right)^{-1.8} & f \geq f_{\max}. \end{cases}$$

Kosowsky & Turner (1992)

The peak of the spectrum is at

$$f_{\max} = \frac{0.2}{\tau} \qquad I_{\max} \equiv \frac{E_{\rm GW}}{\epsilon}(f_{\max}) \approx 6\times 10^{-2}\times (H\tau)^2$$

$$f_0 \simeq \frac{3\times 10^{-10}}{\chi}\left(\frac{g_*}{100}\right)^{1/6}\left(\frac{T_*}{1\ \mathrm{GeV}}\right).$$

$$\chi = H\tau$$

$$\Omega_0(f_0)h^2 \equiv \frac{1}{2\pi\rho_c}\frac{dE_{\rm GW}}{d\ln f}(f_0) \simeq 10^{-6}\chi^2\left(\frac{100}{g_*}\right)^{1/3}.$$

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- The break-down of coarse-graining approach at the scale where bubbles nucleate could lead to oscillations in the spectrum with the amplitude of $\frac{H}{\Lambda}$ where $\Lambda \sim 1/r_b$ — Danielsson & Chialva (2008)
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- The break-down of coarse-graining approach at the scale where bubbles nucleate could lead to oscillations in the spectrum with the amplitude of $\frac{H}{\Lambda}$ where $\Lambda \sim 1/r_b$

Danielsson & Chialva (2008)

- Violation of consistency relation between tensor and scalar spectra:

$$r \equiv \frac{\Delta_T^2}{\Delta_R^2} = -8n_T$$

Stewart & Lyth (1993)

$$\Delta_{\mathcal{R}}^2 \equiv \frac{k^3 P_{\mathcal{R}}(k)}{2\pi^2} = \frac{H^2}{8\pi^2 \frac{\epsilon}{\sqrt{3}}} \longrightarrow r \equiv \frac{\Delta_T^2}{\Delta_R^2} = -\frac{8n_T}{\sqrt{3}}$$

The extra factor of $\sqrt{3}$ in the denominator of the R.H.S. of corresponds to fewer gravity waves at large scale. This smaller amount of gravity waves at large scales, in principle, could make the detection of its scale dependence harder. However one should notice that for a given value of r bigger than 0.01, which is detectable by balloon-borne experiments, the corresponding value of tensor spectral index will be larger by a factor of $\sqrt{3}$ for chain inflation models which makes the detection of scale-dependence easier.

Distinguishing Chain inflation from its slow-roll counterpart

Lensing of the *E* mode by density perturbations along lines of sight from the last scattering surface limits the detectibility of *B* modes at $r_{\rm lim} = 2.6 \times 10^{-4}$ Knox & Song (2006)

Large departures from the single-field consistency relation can be seen if $r \gtrsim 10^{-3}$

Knox and Song (2003) also argue that if a non-zero value for $n_T + r/8$ in the region $r < 0.166$ is observed, one can confidently exclude the single-field slow-roll inflation as the modifications from loop corrections to the consistency relation is quite small in this region.

- All viable chain inflation models, with *c>5*, predict the violation of the consistency relation in the range *r* bigger than *0.05*, but smaller than *0.166*. Therefore distinguishing chain inflation from slow-roll models should be observationally possible in this range.

Bound on T_R from Bubble Collision GW Production

• Chain inflation proceeds through a series of first order phase transitions, which can release gravitational waves (GW).

• The spectrum of gravity waves (GWs) from multibubble collisions at a single phase transition (PT) with energy difference ϵ between false and true vacua has been worked out numerically:

$$I(f) \equiv E_{GW}(f)/\epsilon = \begin{cases} I_{\max}\left(\frac{f}{f_{\max}}\right)^{2.8} & f \leq f_{\max} \\ I_{\max}\left(\frac{f}{f_{\max}}\right)^{-1.8} & f \geq f_{\max}. \end{cases}$$

Kosowsky & Turner (1992)

The peak of the spectrum is at

$$f_{\max} = \frac{0.2}{\tau} \qquad I_{\max} \equiv \frac{E_{\rm GW}}{\epsilon}(f_{\max}) \approx 6\times 10^{-2}\times (H\tau)^2$$

$$f_0 \simeq \frac{3\times 10^{-10}}{\chi}\left(\frac{g_*}{100}\right)^{1/6}\left(\frac{T_*}{1\ \mathrm{GeV}}\right).$$

$$\chi = H\tau$$

$$\Omega_0(f_0)h^2 \equiv \frac{1}{2\pi\rho_c}\frac{dE_{\rm GW}}{d\ln f}(f_0) \simeq 10^{-6}\chi^2\left(\frac{100}{g_*}\right)^{1/3}.$$

Bound on T_R from Bubble Collision GW Production

- During chian inflation the energy density of gravity waves generated during the early phases, is redshifted exponentially. Therefore the main contribution is coming from the last phase transition. For the chain inflation with linear vacuum structure one obtains:

$$\Omega h^2(f_{max}) = \frac{4.89 \times 10^{16} \; m_f^{12}}{m_P^8 T_R^4}$$

$$f_{max} = \frac{3.805 \times 10^{-9} \; m_P^5}{m_f^4 T_R} \text{Hz}$$

Recalling that for chain inflation with linear structure $m_f < 2.6069 \times 10^{-5} \; m_{\rm P}$. and demanding that the amount of gravity waves produced do not overclose the universe, $\Omega h^2(f_{max}) < 1$ one obtains

$$2.63 \times 10^{-10} \; m_P < T_R$$

For the chain inflation with quadratic structure, one obtains

$$5.24 \times 10^{-12} \; m_P < T_R$$

Conclusion

Knowing that the realization of slow-roll inflation within string theory is quite a difficult task, and noting that metastable vacua are abundant within the string theory landscape, chain inflation might seem a promising alternative approach to realize inflation within string theory.

- Chain inflation, depending on the structure of underlying landscape, has specific predictions for the value of spectral index. Precise measurements of spectral index at large CMB scales can distinguish between these models. In particular future CMB measurements can determine n_s with $\sigma(n_s) = 0.0024$
- Chain inflation can be distinguished from its slow-roll counterparts through the violation of consistency relation and superimposed oscillations.

Seventeen years ago, Copeland et. al. (1993) was argued that with the knowledge of tensor and scalar perturbations, one is in principle able to reconstruct the inflationary potential. Since then various attempts were done to reconstruct the inflationary potential using the data. one may similarly hope that probing the scalar and tensor perturbations at large scales can help us confine the global structure of stringy vacua.