Stochastic Inflation in Compact Extra Dimensions

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work with J. Martin and J. Yokoyama, Phys. Rev. D82:023515, 2010

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Conclusions

Slow Roll Trajectory vs. Quantum Kicks



typical time interval $\Delta t = 1/H$:

$$\Delta \phi_{
m cl} = -rac{{\sf V}'}{3{\sf H}}\,\Delta {
m t} = -rac{{\sf V}'}{3{\sf H}^2}$$

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$$\Delta \phi_{
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m t} = -rac{{\sf V}'}{3{\sf H}^2}$$

quantum kicks:

$$\Delta \phi_{\rm qu} = \frac{\mathsf{H}}{2\pi}$$

If $\Delta \phi_{\rm qu} \simeq \Delta \phi_{\rm cl}$, classical trajectory receives quantum corrections.

"stochastic inflation"

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Introduction		
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Stochastic Inflation		

Dual Descriptions

separate ϕ into long / short wavelength modes $\phi(\vec{x}, t) = \varphi(t)$ long = smoothed $+ \underbrace{\int \frac{\mathrm{d}^{3}\vec{k}}{(2\pi)^{3/2}} \Theta(k - \sigma aH) \left[\hat{a}_{k} \,\delta \phi_{k}(t) \, e^{-i\vec{k}\cdot\vec{x}} + \mathrm{h.c.}\right]}_{\mathrm{short} = \mathrm{noise}}$

Starobinsky & Yokoyama (1994), Martin & Musso (2006), Kühnel & Schwarz (2008,2009,2010) etc.

scale $\propto 1/\sigma H$

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separate ϕ into long / short wavelength modes $\phi(\vec{x}, t) = \varphi(t)$ long = smoothed $+ \int \frac{d^3\vec{k}}{(2\pi)^{3/2}} \Theta(k - \sigma a H) \left[\hat{a}_k \, \delta \phi_k(t) \, e^{-i\vec{k} \cdot \vec{x}} + \text{h.c.} \right]$ short = noise Starobinsky & Yokoyama (1994), Martin & Musso (2006), Kühnel & Schwarz (2008,2009,2010) etc.

Smoothed field $\underbrace{\varphi(t)}_{\text{long}}$ is a stochastic process w/ gaussian white noise $\underbrace{\xi(t)}_{\text{short}}$.

Langevin:

$$\dot{\varphi} = -\frac{V'}{3H} + \frac{H^{3/2}}{2\pi}\xi(t)$$

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Dual Descriptions

 $\mathcal{O} \triangleleft \mathcal{O} \bigcirc \mathcal{O}$ separate ϕ into long / short wavelength modes 00000 scale $\bigcirc \bigcirc \bigcirc \bigcirc \bigcirc$ $\phi(\vec{x},t) = \varphi(t)$ long = smoothed $\propto 1/\sigma H$ **♦** $+\int \frac{\mathrm{d}^{3}\vec{k}}{(2\pi)^{3/2}} \Theta(k-\sigma aH) \left[\hat{a}_{k} \,\delta\phi_{k}(t) \,e^{-i\vec{k}\cdot\vec{x}} + \mathrm{h.c.}\right]$ short = noise $\varphi(t)$ Starobinsky & Yokoyama (1994), Martin & Musso (2006), Kühnel & Schwarz (2008.2009.2010) etc.

Smoothed field $\varphi(t)$ is a stochastic process w/ gaussian white noise $\xi(t)$. long short

Langevin:

 $\dot{\varphi}$

Fokker Planck:

$$= -\frac{V'}{3H} + \frac{H^{3/2}}{2\pi} \xi(t) \qquad \qquad \frac{\partial P(\varphi,t)}{\partial t} = \frac{\partial}{\partial \varphi} \left\{ \frac{H^{3/2}}{8\pi^2} \frac{\partial}{\partial \varphi} \left[H^{3/2} P(\varphi,t) \right] + \frac{V'}{3H} P(\varphi,t) \right\}$$

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Perturbative Solution (Martin & Musso 2006)

Langevin:

$$\dot{arphi}=-rac{V'}{3H}+rac{H^{3/2}}{2\pi}\,\xi(t)$$

- solve perturbatively: $\varphi(t) = \varphi_{cl}(t) + \delta \varphi_1(t) + \delta \varphi_2(t) + \dots$
- use gaussian properties: $\langle \xi(t) \rangle = 0, \langle \xi(t)\xi(t') \rangle = \delta(t - t')$

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$$\begin{split} \left\langle \delta \varphi_{1}^{2} \right\rangle &= \frac{\kappa}{2} \left(\frac{H'}{2\pi} \right)^{2} \int_{\varphi_{\mathrm{cl}}}^{\phi_{\mathrm{in}}} \mathrm{d}\phi \, \left(\frac{H}{H'} \right)^{3} \\ \left\langle \delta \varphi_{2} \right\rangle &= \frac{H''}{2H'} \left\langle \delta \varphi_{1}^{2} \right\rangle \\ &+ \frac{H'}{4\pi m_{\mathrm{Pl}}^{2}} \left[\left(\frac{H^{3}}{H'^{2}} \right)_{\phi_{\mathrm{in}}} - \left(\frac{H^{3}}{H'^{2}} \right)_{\varphi_{\mathrm{cl}}} \right] \end{split}$$

Fokker Planck:

probability to find field value φ at time t in single domain

• use $\langle \delta \varphi_1^2 \rangle$ and $\langle \delta \varphi_2 \rangle$ to determine $P(\varphi, t)$ in the gaussian approximation

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$$\begin{split} \left\langle \delta \varphi_1^2 \right\rangle &= \frac{\kappa}{2} \left(\frac{H'}{2\pi} \right)^2 \int_{\varphi_{\rm cl}}^{\phi_{\rm in}} \mathrm{d}\phi \, \left(\frac{H}{H'} \right)^3 \\ \left\langle \delta \varphi_2 \right\rangle &= \frac{H''}{2H'} \left\langle \delta \varphi_1^2 \right\rangle \\ &+ \frac{H'}{4\pi m_{\rm Pl}^2} \left[\left(\frac{H^3}{H'^2} \right)_{\phi_{\rm in}} - \left(\frac{H^3}{H'^2} \right)_{\varphi_{\rm cl}} \right] \end{split}$$

Fokker Planck:

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• use $\langle \delta \varphi_1^2 \rangle$ and $\langle \delta \varphi_2 \rangle$ to determine $P(\varphi, t)$ in the gaussian approximation

$$\mathsf{P}(arphi,\mathsf{t}) = rac{1}{\sqrt{2\pi \left\langle \delta arphi_1^2
ight
angle}} \, \exp\left[-rac{(arphi - \left\langle arphi
ight
angle)^2}{2 \left\langle \delta arphi_1^2
ight
angle}
ight]$$

where
$$\langle \varphi \rangle \equiv \varphi_{\rm cl} + \langle \delta \varphi_2 \rangle$$

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Example

chaotic inflation with $V(arphi)=rac{m^2}{2}\,arphi^2$, large $\phi_{
m in}/m_{
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Modified Kinetics		

k-Inflation

two ways to drive inflation:



flat potential
$$\mathcal{L} = rac{\dot{arphi}^2}{2} - V(arphi)$$

modified kinetic term $\mathcal{L} = P(X, \varphi)$ where $X = -\frac{g^{\mu\nu}}{2}\partial_{\mu}\varphi\partial_{\nu}\varphi$

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Armendariz-Picon, Damour and Mukhanov (1999) Garriga and Mukhanov (1999)

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lodified Kinetics

k-Inflation from String Theory: Dirac Born Infeld (DBI)

effective 4d DBI inflaton action:

$$S = -\int d^{4}x \sqrt{-g} \left[V(\varphi) - T(\varphi) + T(\varphi) \sqrt{1 + \frac{1}{T(\varphi)} g^{\mu\nu} \partial_{\mu} \varphi \partial_{\nu} \varphi} \right]$$



 $V(\varphi)$: potential $T(\varphi)$: warped brane tension

"speed limit": $\gamma(\dot{\varphi}, \varphi) = \frac{1}{\sqrt{1 - \dot{\varphi}^2 / \mathsf{T}(\varphi)}}$ two free functions of 10d background geometry

 $\gamma \approx$ 1: standard regime $\gamma \gg$ 1: "ultrarelativistic" DBI regime

Silverstein and Tong (2003) Alishahiha, Silverstein and Tong (2004)

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Solutions and Probability Distribution Functions

DBI Langevin Equation and Perturbative Solution

$$\dot{arphi}=-rac{V'}{3H\gamma}+rac{H^{3/2}}{2\pi}\,\xi(t)$$

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• ansatz as before $arphi(t)=arphi_{
m cl}(t)+\deltaarphi_1(t)+\deltaarphi_2(t)+\ldots$, gives

$$\begin{split} \left\langle \delta \varphi_{1}^{2} \right\rangle &= \frac{\kappa}{2} \left(\frac{H'}{2\pi\gamma} \right)^{2} \int_{\varphi_{\rm cl}}^{\phi_{\rm in}} \mathrm{d}\phi \, \left(\frac{H\gamma}{H'} \right)^{3} \\ \left\langle \delta \varphi_{2} \right\rangle &= \frac{(H'/\gamma)'}{2(H'/\gamma)} \left\langle \delta \varphi_{1}^{2} \right\rangle + \frac{H'/\gamma}{4\pi m_{\rm Pl}^{2}} \left[\left(\frac{\gamma^{2}H^{3}}{H'^{2}} \right)_{\phi_{\rm in}} - \left(\frac{\gamma^{2}H^{3}}{H'^{2}} \right)_{\varphi_{\rm cl}} \right] \end{split}$$

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• use these to calculate

$$P(\varphi, t) = rac{1}{\sqrt{2\pi \langle \delta arphi_1^2
angle}} \exp \left[-rac{(arphi - \langle arphi
angle)^2}{2 \langle \delta arphi_1^2
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ight]$$

with $\langle \varphi \rangle = \varphi_{\rm cl} + \langle \delta \varphi_2 \rangle$

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Chaotic Klobanov Strasslar Inflation		

Example. . . and a Problem

$$egin{array}{rcl} V(arphi) &=& V_0 + rac{m^2}{2} \, arphi^2 \ T(arphi) &=& rac{arphi^4}{\lambda} \end{array}$$

param's:

$$m, \alpha = \frac{96\pi^2}{\kappa \lambda m^2}, \ \beta = \frac{V_0}{m^2 m_{\rm Pl}^2}$$

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Character Marken and Character Inflation		

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$$\langle \delta\varphi_1^2 \rangle \simeq \frac{16}{15\sqrt{2}} \left(\frac{m}{m_{\rm Pl}}\right)^2 \frac{\beta^{3/2}}{\alpha^{1/2}} \frac{m_{\rm Pl}^2}{\varphi_{\rm cl}}$$

$$\langle \delta\varphi_2 \rangle \simeq -\frac{4}{15\sqrt{2}} \left(\frac{m}{m_{\rm Pl}}\right)^2 \frac{\beta^{3/2}}{\alpha^{1/2}} \frac{m_{\rm Pl}^2}{\varphi_{\rm cl}}$$

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Recall: $\langle \varphi \rangle = \varphi_{\rm cl} + \langle \delta\varphi_2 \rangle$

$$\langle \varphi \rangle$$
 can become negative!

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Chaotic Klebanov Strassler Inflation

Example. . . and a Problem

$$V(\varphi) = V_0 + rac{m^2}{2} \varphi^2$$

 $T(\varphi) = rac{\varphi^4}{\lambda}$

param's: $m, \alpha = \frac{96\pi^2}{\kappa\lambda m^2}, \beta = \frac{V_0}{m^2 m_{\rm Pl}^2}$ $\langle \delta\varphi_1^2 \rangle \simeq \frac{16}{15\sqrt{2}} \left(\frac{m}{m_{\rm Pl}}\right)^2 \frac{\beta^{3/2}}{\alpha^{1/2}} \frac{m_{\rm Pl}^3}{\varphi_{\rm cl}}$ $\langle \delta\varphi_2 \rangle \simeq -\frac{4}{15\sqrt{2}} \left(\frac{m}{m_{\rm Pl}}\right)^2 \frac{\beta^{3/2}}{\alpha^{1/2}} \frac{m_{\rm Pl}^3}{\varphi_{\rm cl}}$ Recall: $\langle \varphi \rangle = \varphi_{\rm cl} + \langle \delta\varphi_2 \rangle$

 $\langle \varphi
angle$ can become negative!

But in brane inflation, ϕ has a geometric interpretation...



Klebanov & Strassler (2000) Kachru et al. ("KKLMMT", 2003)

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Chaotic Klebanov Strassler Inflation

Example. . . and a Problem

$$V(\varphi) = V_0 + \frac{m^2}{2} \varphi^2$$
$$T(\varphi) = \frac{\varphi^4}{\lambda}$$

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 $\langle \varphi
angle$ can become negative!

But in brane inflation, ϕ has a geometric interpretation...



... and therefore limited field range!

	Geometric Consistency	
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Restricted Field Range		

"Out of Space"?

Problem: w/ stochastic corrections, probability of $\langle \varphi \rangle < \phi_0$ is $\neq 0$!



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Restricted Field Range		

Problem: w/ stochastic corrections, probability of $\langle \varphi \rangle < \phi_0$ is $\neq 0$!



Solution: install absorbing wall(s) in field space and calculate resulting P

'Out of Space"?

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Adapted Probability Distribution Function

Boundary Conditions by Method of Images

$$\mathsf{P}(\varphi = \phi_0) = \mathsf{P}(\varphi = \phi_{\mathrm{uv}}) = 0$$



using $\phi_{\rm mean} \equiv \phi_{\rm cl} + \langle \delta \phi_2 \rangle = \langle \varphi \rangle_{\rm w/o \ walls}$:

$$P_{\mathrm{walls}}(\varphi) = P(\varphi - \phi_{\mathrm{mean}}) - P(\varphi - 2\phi_{\mathrm{uv}} + \phi_{\mathrm{mean}}) - P(\varphi - 2\phi_{0} + \phi_{\mathrm{mean}})$$

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Boundary Conditions (2)

$$\mathsf{P}(\varphi = \phi_0) = \mathsf{P}(\varphi = \phi_{\mathrm{uv}}) = 0$$



using $\phi_{\text{mean}} \equiv \phi_{\text{cl}} + \langle \delta \phi_2 \rangle = \langle \varphi \rangle_{\text{w/o walls}}$: $P_{\text{walls}}(\varphi) = P(\varphi - \phi_{\text{mean}}) - P(\varphi - 2\phi_{\text{uv}} + \phi_{\text{mean}}) - P(\varphi - 2\phi_0 + \phi_{\text{mean}})$ $+ P(\varphi - 2\phi_{\text{uv}} - \phi_{\text{mean}} + 2\phi_0) + P(\varphi - 2\phi_0 - \phi_{\text{mean}} + 2\phi_{\text{uv}})$

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Boundary Conditions (3)

$$\mathsf{P}(\varphi = \phi_0) = \mathsf{P}(\varphi = \phi_{\mathrm{uv}}) = 0$$



This process is repeated ad infinitum: $P_{\text{walls}(\varphi)} = \frac{1}{\sqrt{2\pi \langle \delta \varphi_1^2 \rangle}} \times$

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Mean Field Value between Absorbing Walls

Now use P_{walls} to calculate new $\langle \varphi \rangle = \frac{1}{N} \int_{\phi_0}^{\phi_{\text{uv}}} \mathrm{d}\psi P_{\text{walls}}(\psi, t) \psi$:

$$\int_{\phi_0}^{\phi_{\rm uv}} \mathrm{d}\psi \, P_{\rm walls}(\psi, t) \, \psi = \sum_{n=1}^{\infty} \frac{2}{n\pi} \, \exp\left[-\frac{n^2 \pi^2 \left\langle \delta \varphi_1^2 \right\rangle}{2(\phi_{\rm uv} - \phi_0)^2}\right] \\ \times \sin\left[\frac{n\pi(\phi_0 - \phi_{\rm mean})}{\phi_{\rm uv} - \phi_0}\right] \left[\phi_{\rm uv} \cos(n\pi) - \phi_0\right]$$

Oscillating behaviour!

Note:

 $P_{\rm walls}$ not normalized b/c of absorbing boundary conditions.

Need to calculate $N = \int_{\phi_0}^{\phi_{\rm uv}} \mathrm{d}\psi P_{\rm walls}(\psi, t)$ to find $\langle \varphi \rangle$.

applies to any stochastic inflaton between two absorbing walls

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Example... and Problem Solved

$$lpha = 38, eta = 3.7, m \simeq 2 imes 10^{-7}, \phi_{
m in} = 10^{-3} m_{
m Pl}$$



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Example. . . and Problem Solved



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Example... and Problem Solved



		Conclusions
Conclusions	:	

- In stochastic inflation, the smoothed field φ obeys a Langevin equation. This equation can be solved perturbatively in the noise.
- We generalized this approach to string-inspired DBI models.

But:

The stringy inflaton has a geometric interpretation. Must be respected even by quantum corrections!

- Install walls in field space to find correct PDF's.
- This may affect the behaviour of the inflaton significantly!