Non-Gaussianity in a nucleated bubble

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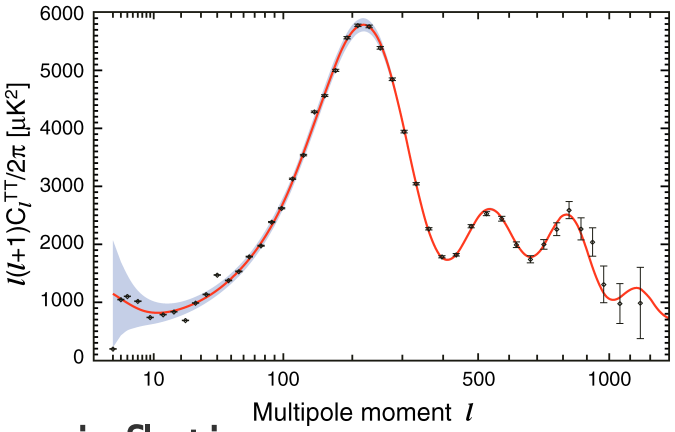
Introductions

Inflation and observation

- Inflation explains beginning of Big Bang
  - Horizon problem
  - Flatness problem
  - Monopole problem

http://lambda.gsfc.nasa.gov



- CMB 2-point correlation agrees astonishingly with the prediction from inflation

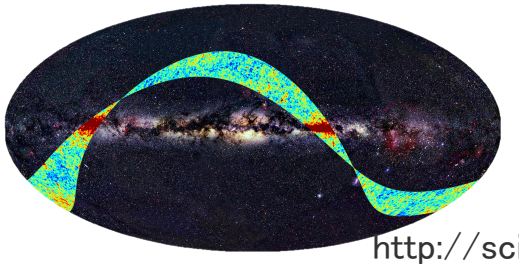
- CMB 3-point correlation is now getting within reach
  - Current status of local type Non-Gaussianity (WMAP7yr)

$$f_{\rm NL} = 32 \pm 42 \quad (95\%\ \text{C.L.})$$

$$\sim 5 \quad \text{Planck data (2013?)}$$

Non-Gaussianity tells us detail of inflation

Planck first light(2009)

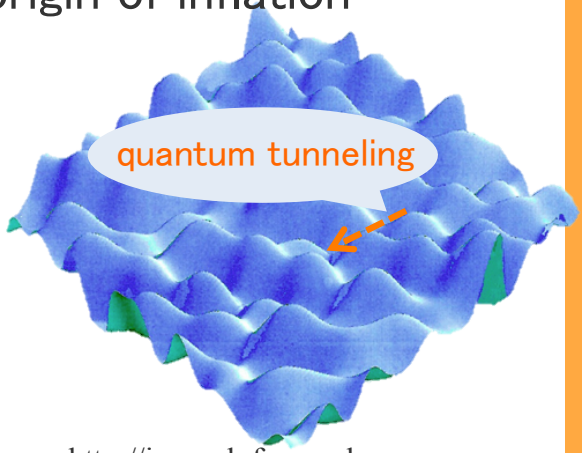


http://sci.esa.int

- simple slow-roll inflation model
  - predict small non-Gaussianity and might be disfavored by Planck
  - thinking beyond slow-roll approximation may become necessary

detail of inflation ⇔ the secret origin of inflation

- inflation in string landscape (Susskind, 2003)
  - possesses more details than simple slow-roll model
    - local potential minima
    - multi-field
  - realization of inflation in string theory
  - attractive candidate explanation for the origin of inflation



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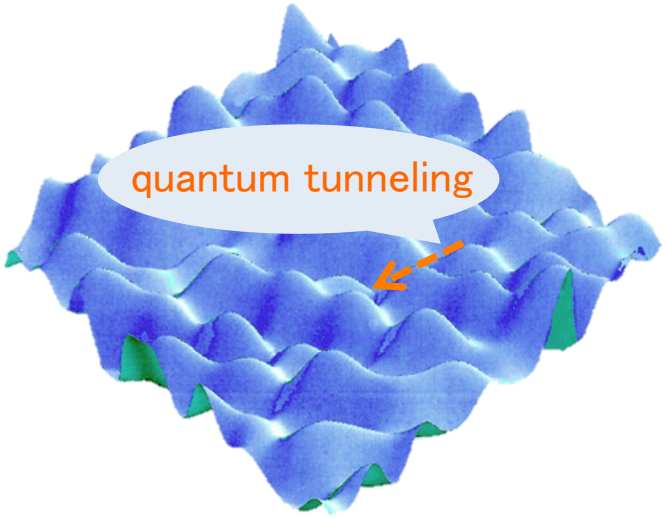
Bubble nucleation in string landscape

- tunneling of scalar field
  - many local minima in string landscape
  - transition between local minima occurs by quantum tunneling in inflationary era
  - transition occurs locally to keep causality



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⇒ Bubble nucleation

- non-Gaussianity generation by the nucleated bubble
  - non-linear interaction between scalar field and bubble
    - how to calculate?
    - what kind of feature?

Bubble

We will answer these questions using toy model!

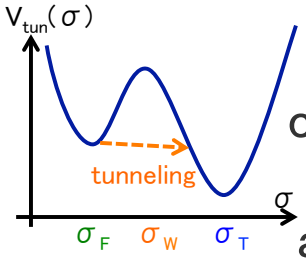
Formulation and sample calculation

of non-Gaussianity from bubble

Toy model (1)

- consider two-field model
  - tunneling field : $\sigma(x)$
  - test field : $\phi(x)$
  - we will calculate 3-point function of $\phi(x)$ under the influence of tunneling field $\sigma(x)$ as background
  - first step towards realistic model ⇒ neglect gravitational effect

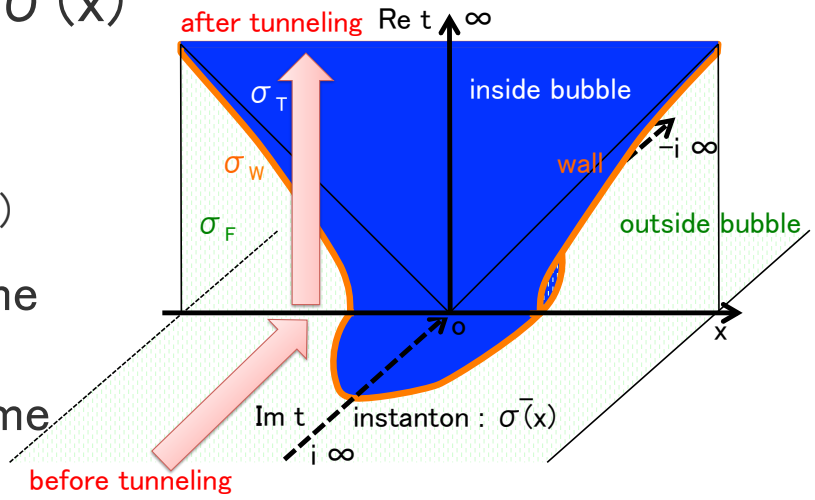
- Background : bubble nucleation of $\sigma(x)$
  - tunneling potential : $V_{tun}(\sigma)$
  - O(4) symmetric instanton : $\bar{\sigma}(x)$ (Coleman 1977)



classical solution in imaginary time

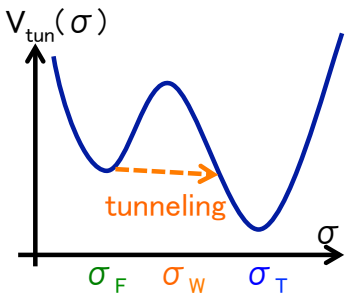
⇓

analytical continuation to real time



(we consider $V_{tun}(\sigma)$ which possesses thin wall instanton)

Toy model(2)



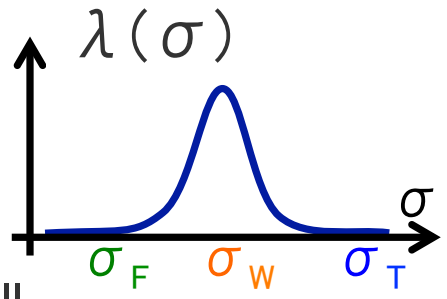
- another test field $\phi(x)$
  - we consider interaction with tunneling field

$$V_{int}(\phi,\sigma) = \lambda(\sigma)\,\phi^3$$

background bubble

$$\lambda(x) = \lambda(\bar{\sigma}(x))$$

$$V_{int}(\phi,x) = \lambda(x)\,\phi^3$$



  - we consider a model with significant 3-pt self coupling only near bubble wall

- Indicator for non-Gaussianity
  - 3-point function of the test field at the same space-time point

$$\langle\phi^3(t_0,\mathbf{x})\rangle \qquad (\langle\phi^3(t_0,\mathbf{x})\rangle = 0 \text{ in free field theory})$$

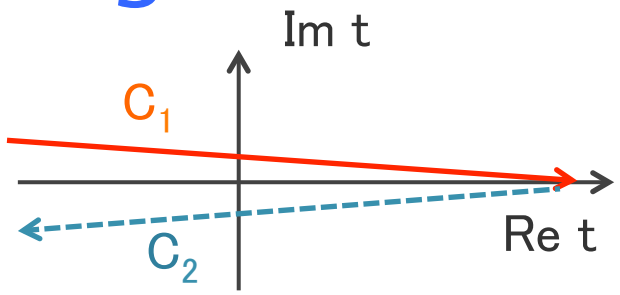
How can we describe QFT on instanton background, or tunneling?

QFT on instanton background

- usual in-in formalism(Mardacena 2002)

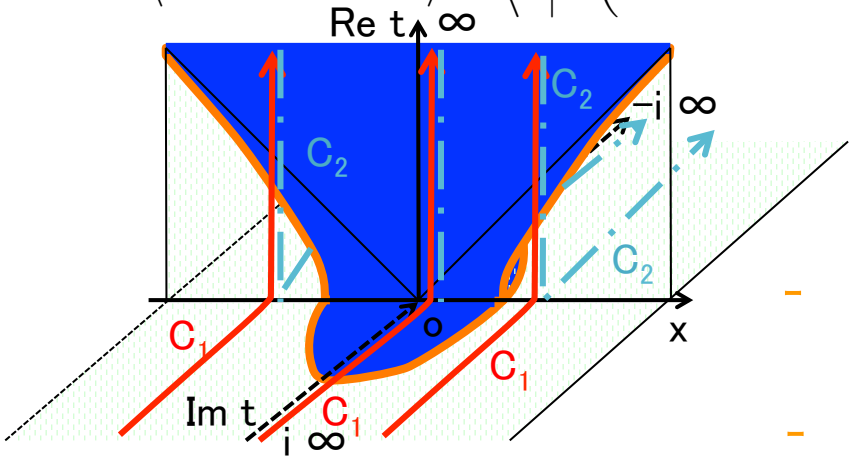
$$\left\langle \phi(x_1)\phi(x_2)\phi(x_3) \right\rangle = \left\langle 0 \left| P\left(\phi(x_1)\phi(x_2)\phi(x_3) \exp\left[-\frac{i}{\hbar} \int_{C_1+C_2} dt H_I[\phi(x)] \right] \right) \right| 0 \right\rangle$$

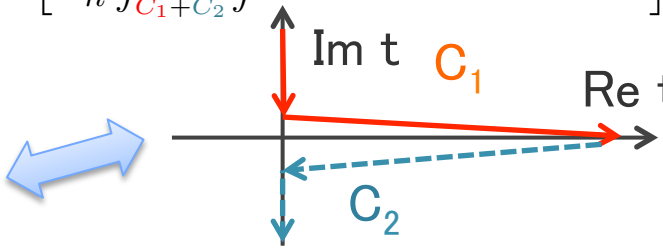
  - integration of H_I along in-in time path



- In-in formalism on instanton background (preliminary)

$$\left\langle \phi(x_1)\phi(x_2)\phi(x_3) \right\rangle = \left\langle 0 \left| P\left(\phi(x_1)\phi(x_2)\phi(x_3) \exp\left[-\frac{i}{\hbar} \int_{C_1+C_2} dt \int d^3\mathbf{x}\sqrt{-g} V_{\rm int}(\bar{\sigma}(x), \phi(x)) \right] \right) \right| 0 \right\rangle$$





  - in-in time path including imaginary time → interactions during tunneling
  - V_{int} depends on background bubble

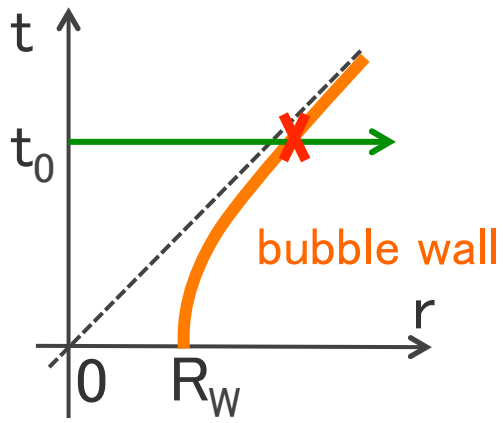
- We have derived this formulation in Quantum Mech.
  - solving tunneling wave function (in free theory cf. Yamamoto 1993)

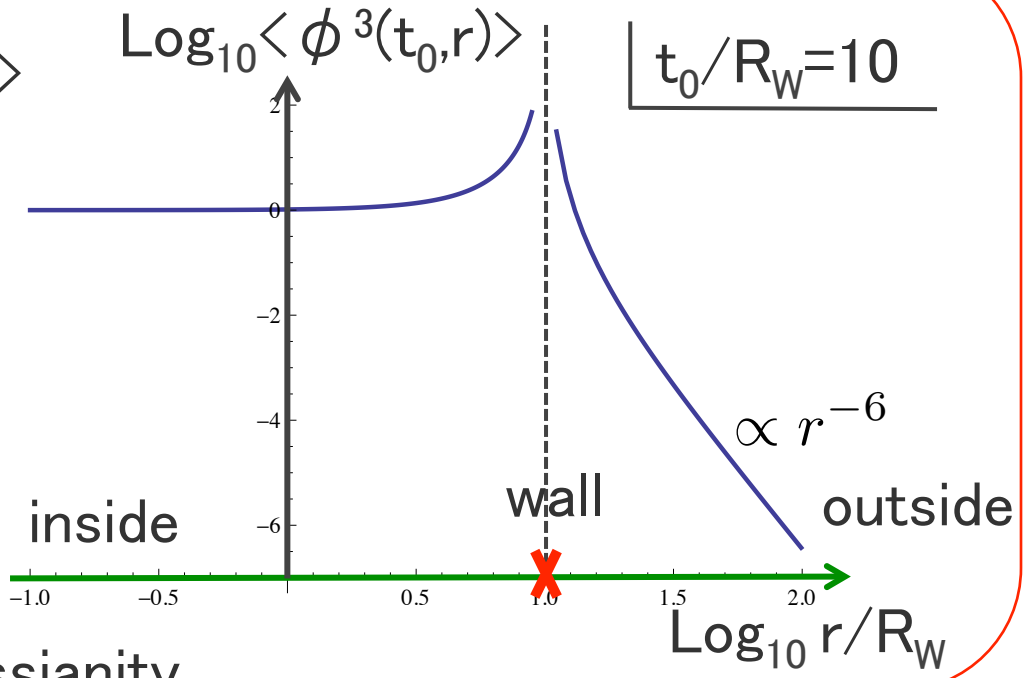
    derivation in QFT is now in progress!!

Result (preliminary)

($\langle \phi^3(t_0,x) \rangle = 0$ in free field theory)

- 3-point function $\langle \phi^3(t_0,r) \rangle$
  - along $t=t_0$ surface





- inhomogeneity in non-Gaussianity
  - asymptotic dependence
    - far outside the bubble $\langle \phi^3 \rangle \propto r^{-6}$
    - near the bubble wall $\langle \phi^3 \rangle \to \infty$
    - around the center of the bubble $\langle \phi^3 \rangle \to \mathrm{const.}$

(due to thin-wall approximation)

This is the first calculation of non-Gaussian correlation on O(4)-symmetric instanton background!!

Conclusions and future works

Conclusions

- We have studied non-Gaussianity when a bubble is nucleated by quantum tunneling of scalar field
- Non-linear interactions with a bubble during and after its nucleation generate non-Gaussianity
- 3-point function of test scalar field on instanton background was calculated in a toy model using in-in formalism through imaginary time
- Calculated non-Gaussianity has radial dependence

Future works

- Calculation of observable in realistic model
  - including gravitational effect
  - inflationary background
  - open inflation
- Derivation of in-in formalism through imaginary time in Quantum Field Theory
  - Only Quantum Mech. case has been derived
- Special analysis in observation
  - analysis targeting inhomogeneous Non-Gaussianity has been left untouched
  - we may find a trace of bubble nucleation in inflationary era, and it might be an outcome of string landscape