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Kazuyuki Sugimura, JGRG 22(2012)111204

“Non-gaussian bubbles from tunneling in the inflationary era”

RESCEU SYMPOSIUM ON

GENERAL RELATIVITY AND GRAVITATION

JGRG 22

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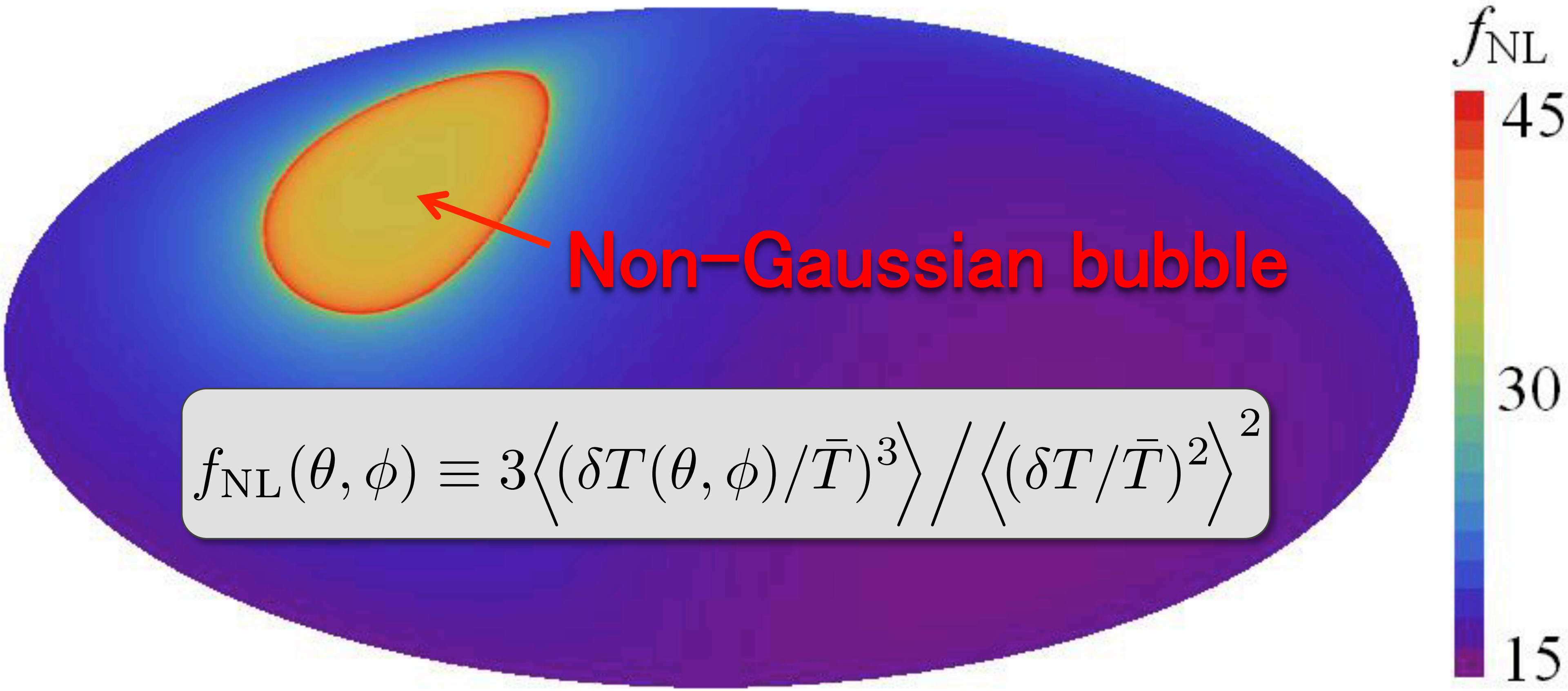
Non-Gaussian bubbles in the sky



$$f_{\rm NL}(\theta,\phi) \equiv 3\left\langle(\delta T(\theta,\phi)/\bar{T})^3\right\rangle \Big/ \left\langle(\delta T/\bar{T})^2\right\rangle^2$$

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YUKAWA INSTITUTE FOR THEORETICAL PHYSICS
Kazuyuki Sugimura (YITP, Kyoto University)
D. Yamauchi and M. Sasaki, (EPL 100 (2012) 29004)

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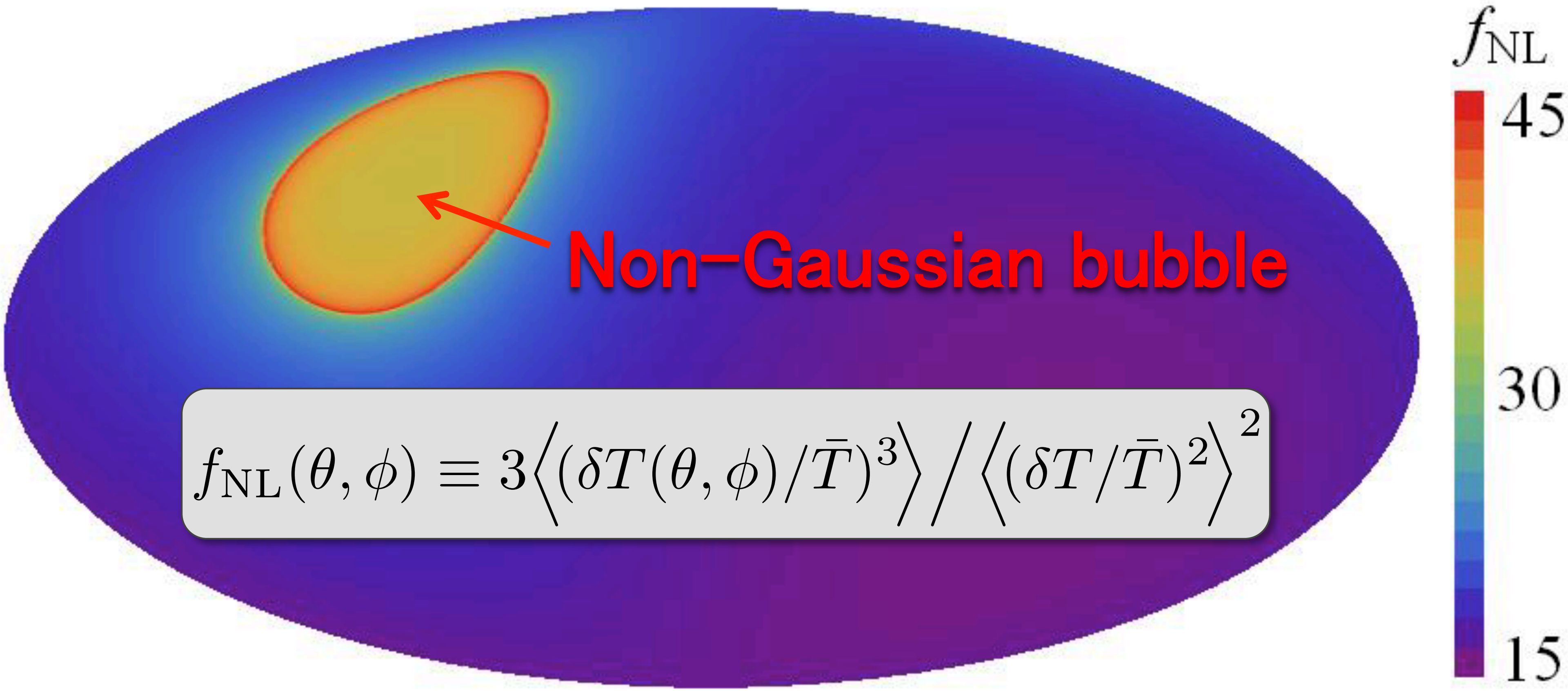

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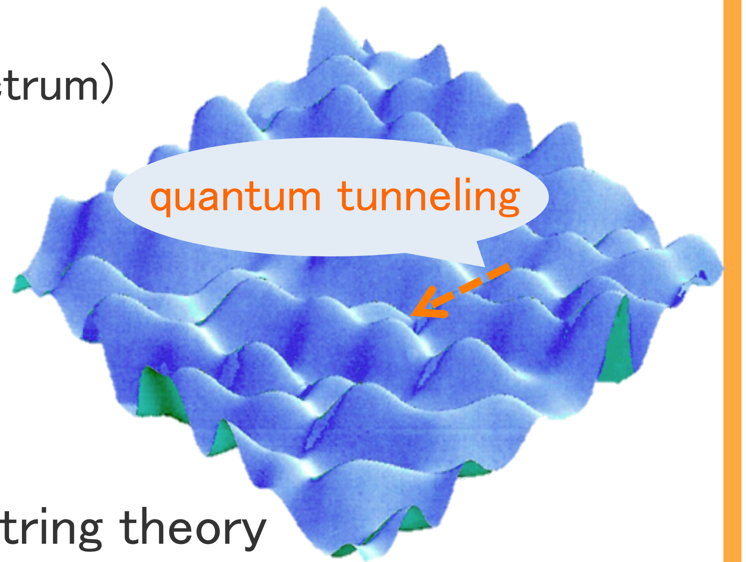
60th celebration of the birthday, congratulations!!

Introductions

Motivation

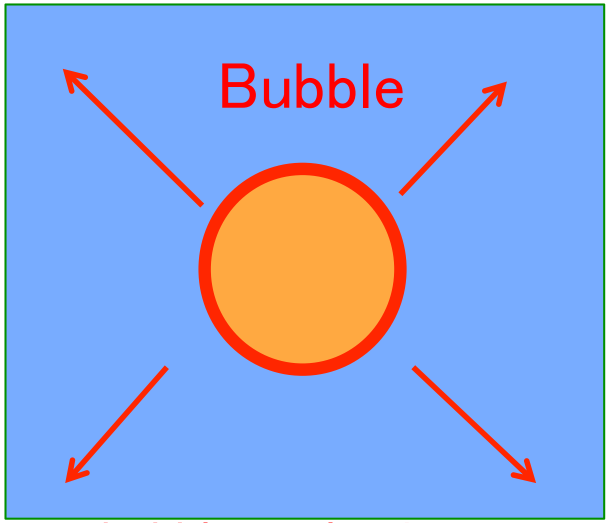
http://journalofcosmology.com



potential for scalar fields

- **Inflation** (flatness, homogeneity, power spectrum)
  - good consistency with observation
  - What is the physical origin of inflation?

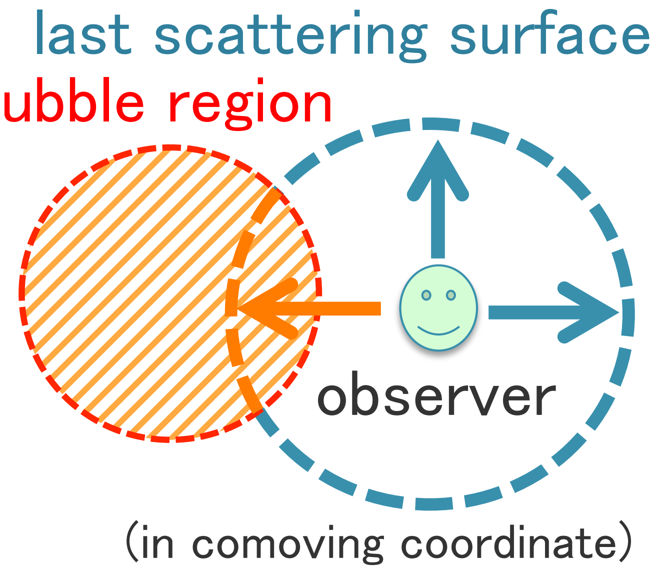
- **String landscape** (Susskind, 2003)
  - attempt to explain the origin of inflation with string theory
  - many scalar fields & local potential minima



bubble nucleation

- **Bubble nucleation** (= quantum tunneling) (= 1^{st} order phase trainsition)
  - tunneling between local minima
  - scalar–field bubble is nucleated during inflation

Bubbles in the sky



- **After inflation**
  - all scalar fields, including bubbles, decay
  - but, signature of bubbles may be seen as some bubble feature in the sky

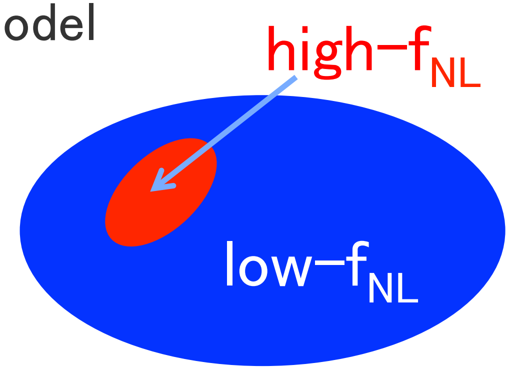
- **Non-Gaussianity f_{NL}** (Komatsu and Spergel, 2001)

$$\phi(x) = \phi_{\rm L}(x) + f_{\rm NL}\left(\phi_{\rm L}^2(x) - \left\langle \phi_{\rm L}^2 \right\rangle\right)$$

(ϕ_L: Gaussian variable)

  - f_{NL} is one way to parameterize deviation from Gaussian statistics
  - small for the simplest inflation model (Maldacena 2002)
  - suitable for detection of deviation from the simplest model

- **Non-Gaussian bubbles**
  - bubble signature may be seen in non-Gaissianity
  - f_{NL} can be different for each CMB sky patch
  - we show how it happens using a toy model



CMB sky map

Toy Model

Three scalar fields

Name	Role	Energy density/Hierarchy
Inflaton: Ψ	slow-roll inflation	high
Tunneling field: σ	bubble nucelation	middle
Curvaton: ϕ	curvature pert. generation	low

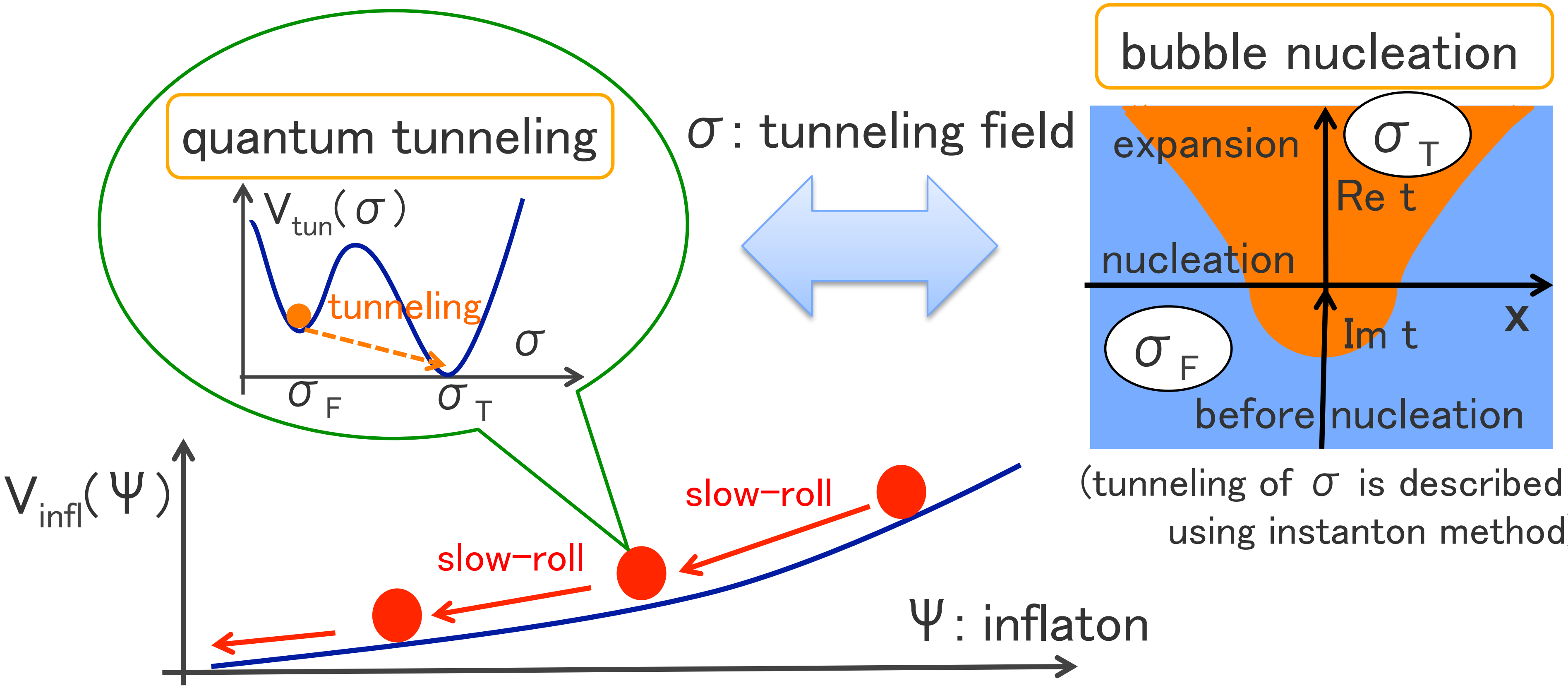
(Lyth, Ungarelli & Wands;
Enqvist & Sloth; Moroi & Takahashi)

no backreaction approximation

(Curvaton scenario: Curvaton affects neither slow-roll inflaiton nor bubble nucleation. But it decays later than inflaton and tunneling field. Then, its energy density becomes relatively higher and it creates curvature pert. when it decays.)

Bubble nucleation during slow-roll inflation

- Slow-roll inflation is not affected by bubble nucleation
- Bubble nucleates at one moment of slow roll inflation
  (for simplicity, we consider single nucleation case)



(tunneling of σ is described using instanton method)

Curvaton evolution in the universe with a bubble

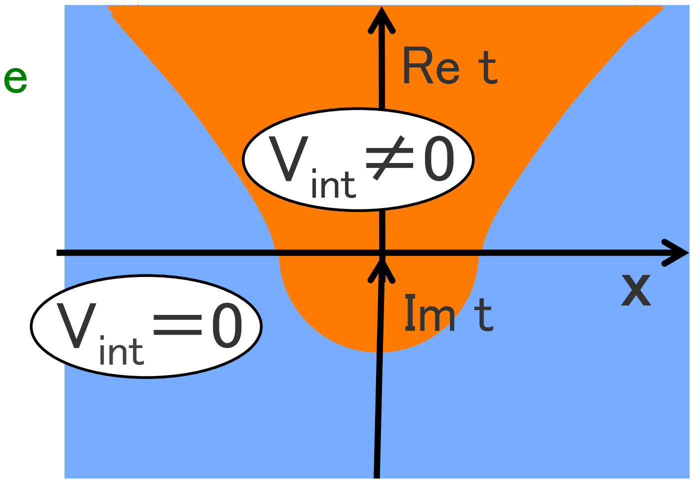
- **Original potential** for curvaton ϕ has interaction with tunneling field

$$V(\phi) = \frac{m^2}{2}\phi^2 + V_{\rm int}(\sigma, \phi)$$

- **Effective potential** for ϕ in the universe with bubble of σ

$$V_{\rm int}^{\rm (eff)}(\phi; x) := V_{\rm int}(\underline{\bar{\sigma}}(x), \phi)$$

substituitng background bubble



- **Non-linear self interaction**

  is assumed to vanish at false vacuum

$$V_{\rm int}(\sigma, \phi) = \lambda(\sigma)\phi^3 \qquad (\lambda(\sigma_{\rm F}) = 0)$$

⇒ Non-Gaussianity is generated only inside bubble

Method

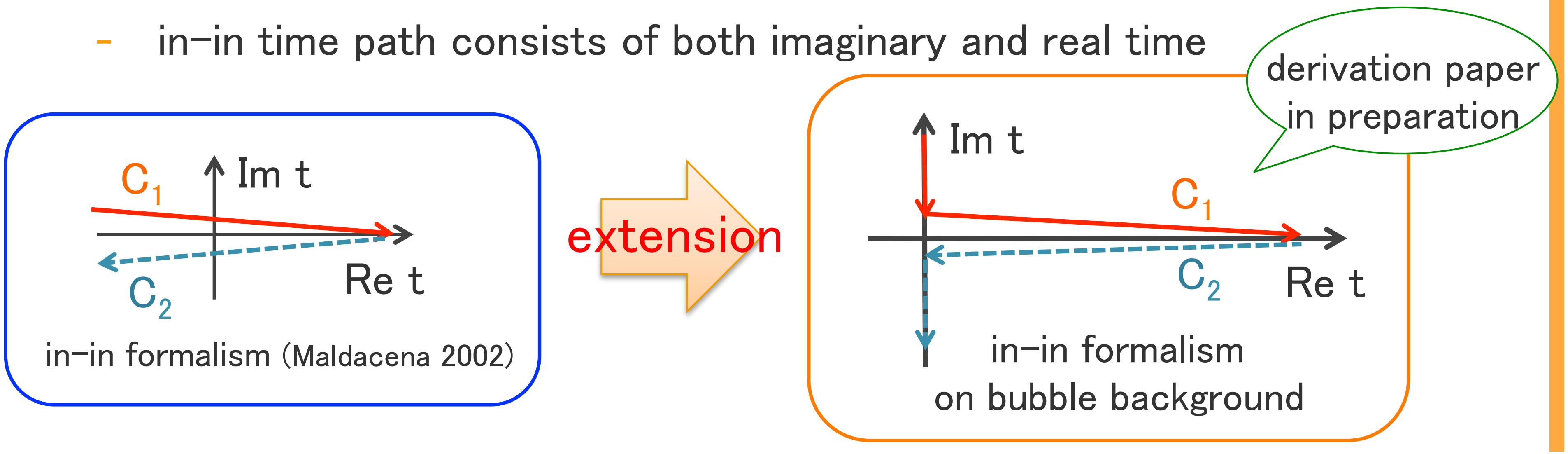
How to calculate 3pt function in the universe with a bubble

- Background bubble of σ is described by CDL instanton
  (Coleman and De Luccia(CDL), 1980)
  - imaginary time evolution describes nucleation process
  - real time evolution describes expansion afterwards

- skewness of ϕ on bubble background

$$\left\langle \phi^3(x) \right\rangle = \left\langle 0 \middle| P\left(\phi^3(x) \exp\left[-\frac{i}{\hbar} \int_{C_1+C_2} dt \int d^3\mathbf{x} \sqrt{-g} V^{(\mathrm{eff})}_{\mathrm{int}}(\phi(x);x) \right] \right) \middle| 0 \right\rangle$$

  - extension of in-in formalism to the case with bubble
  - in-in time path consists of both imaginary and real time



From curvaton fluctuation to δT

- How fluctuation evlolves

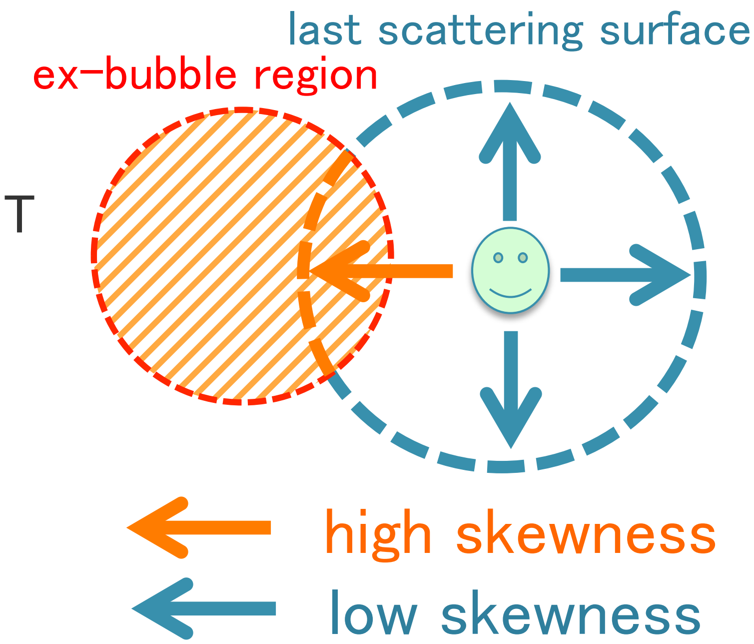
Curvaton mechanism   Sachs–Wolfe effect

$$\phi(x) \Rightarrow \zeta(x) \Rightarrow \delta T(\theta,\varphi)$$

curvaton flucutuation   curvature pert.   CMB anisotropies

- CMB skewness: $\left\langle \delta T^3(\theta,\varphi) \right\rangle$
  - skewness of ϕ becomes skewness of δT
  - observer sees high skewness spot

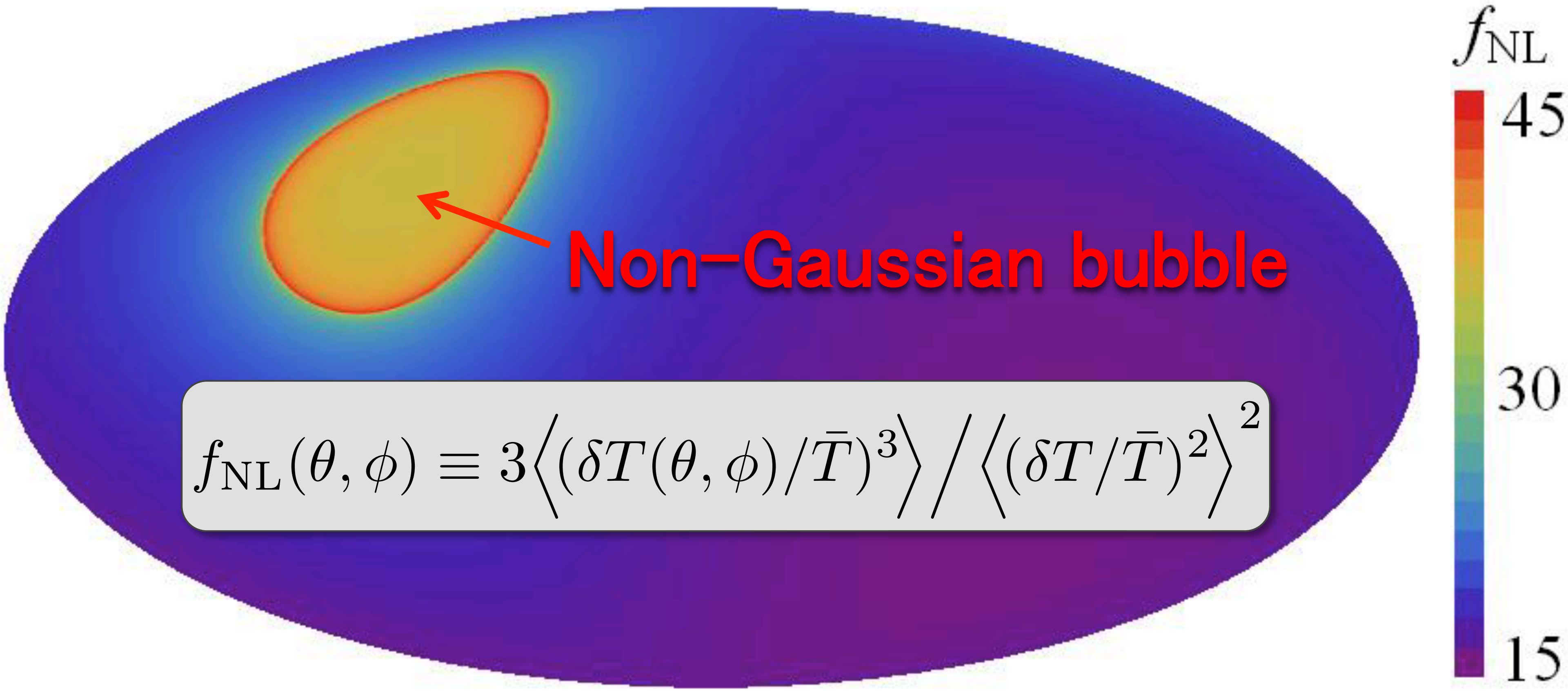
    (= Non–Gaussian bubble)



Result and Conclusion

Result

- calculated non-Gaussian bubble in the CMB sky



$$f_{\rm NL}(\theta,\phi) \equiv 3\left\langle(\delta T(\theta,\phi)/\bar{T})^3\right\rangle \Big/ \left\langle(\delta T/\bar{T})^2\right\rangle^2$$

cf. PLANCK's expected precision(2013 March)
(for homogeneous non-Gaussianity) $|\Delta f_{\rm NL}| \sim \mathcal{O}(5)$

Conclusions

non-Gaussian bubble

- We have shown that a bubble-shaped high-skewness spot in CMB anisotropies may be generated if a bubble is nucleated during inflationary era by using a toy model.

- Usual analysis using statistically homogeneous templates will miss non-Gaussian bubbles even if they exist. However, you may find them by making special analysis targeting them.
(future work)

- If you find non-Gaussian bubbles in near-future observations, it might be the first observational signature of string theory!

Appendix

Model parameters

- Thin-wall instanton

$$\bar{\sigma}(\chi) = \begin{cases} \sigma_{\rm T} & \text{for} \quad 0 \leqslant \chi < HR_{\rm W}, \\ \sigma_{\rm F} & \text{for} \quad HR_{\rm W} < \chi \leqslant \pi \end{cases}$$

(O(4) symmetric instanton depends only on coordinate χ)

- Effective Lagrangian for $\phi = \phi_0 + \delta\phi$

$$\mathcal{L}_I = -\sqrt{-g}\,\lambda H \underline{\delta\left(\chi - HR_{\rm W}\right)}\,\delta\phi^3$$

effective coupling const.

$V_{\rm int}$ is assumed to be large only around bubble wall

- Model parameters for the example

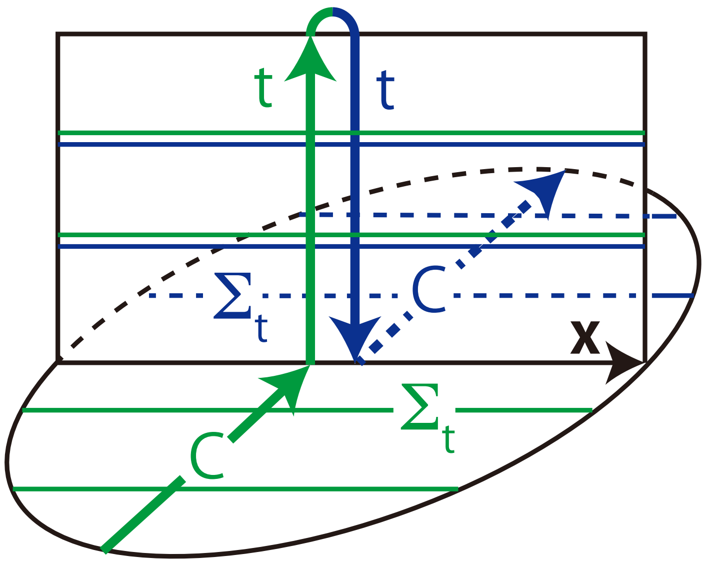
$$H/\phi_0 = 0.001 \;\; \lambda = 0.005, \quad m/H = 0.3, \quad HR_{\rm W} = 0.2\pi$$
$$r_\phi = 0.1, \; |\boldsymbol{x}_0| = r_* = 2, \; Ht_{\rm e} = 50$$

(parameters are chosen so that curvaton doesn't affect power spectrum, which is assumed to be generated by inflaton's fluctuation)

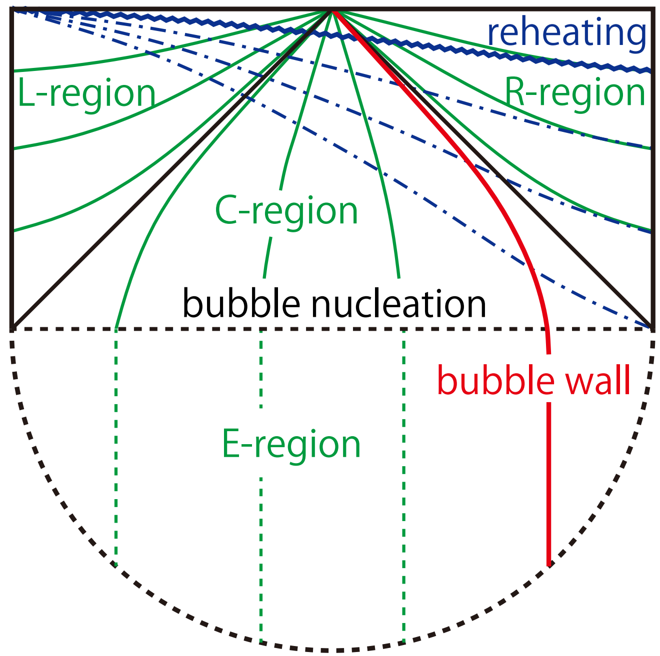
- Parameter dependence of $f_{\rm NL}$ at the center of bubble

$$f_{\rm NL}^{\rm (cen)} \approx \frac{3\times 10^{-4}\,\lambda\, r_\phi^3\, \sin^3(HR_{\rm W})}{A_\zeta^4\, \exp\left(\left(\frac{m}{H}\right)^2 Ht_{\rm e}\right)} \left(\frac{H}{m}\right)^6 \left(\frac{H}{\phi_0}\right)^3.$$

Graphical description of in–in formalism with bubble



in–in time path for
in–in formalism with bubble



Penrose–like diagram of the
bubble nucleating universe

- N–point function

$$\left\langle \delta\phi(x_1)\delta\phi(x_2)\cdots\delta\phi(x_N) \right\rangle = \frac{\left\langle 0 \left| P\delta\phi(x_1)\delta\phi(x_2)\cdots\delta\phi(x_N)e^{i\int_{C\times\Sigma_t} dtd^3\mathbf{x}\mathcal{L}_I} \right| 0 \right\rangle}{\left\langle 0 \left| Pe^{i\int_{C\times\Sigma_t} dtd^3\mathbf{x}\mathcal{L}_I} \right| 0 \right\rangle}$$

curvaton mechanism and $\langle\delta\phi^3\rangle$ to f_{NL}

(Lyth, Ungarelli & Wands; Enqvist & Sloth; Moroi & Takahashi)

- **Curvature pert. at the decay of curvaton**

(conserves outside horizon after that)

$$\zeta = (1 - r_\phi)\zeta_r + r_\phi \zeta_\phi$$

- curvature pert. from curvaton

$$\zeta_\phi = \frac{1}{3}\left.\frac{\delta\rho_\phi}{\rho_\phi}\right|_{t_e} = \frac{1}{3}\left(2\frac{\delta\phi}{\phi_0} + \cancel{\frac{\delta\phi^2}{\phi_0^2}}\right)\Bigg|_{t_e}$$

inflation end

subdominant

- curvature pert. from inflaton
  - ratio of curvaton contribution

- **Sachs-Wolfe effect**

$$(\delta T/T)(\hat{\boldsymbol{n}}) = (1/5)\,\zeta(\boldsymbol{x}_0 + r_*\hat{\boldsymbol{n}}, t_*)$$

- **f_{NL} as a function of $\langle\delta\phi^3\rangle$**

$$f_{\rm NL}(\mathbf{n}) \equiv 3\Big\langle(\delta T(\mathbf{n})/\bar{T})^3\Big\rangle \Big/ \Big\langle(\delta T/\bar{T})^2\Big\rangle^2$$

$$\approx \frac{40 r_\phi^3}{81\langle\zeta^2\rangle^2}\,\frac{\langle\delta\phi^3(|\boldsymbol{x}_0 + r_*\hat{\boldsymbol{n}}|, t_e)\rangle}{\phi_0^3}$$

$\langle\zeta^2\rangle = A_\zeta^2 \equiv 6.25\times 10^{-10}$ (obs.)