YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

Korea Institute for Advanced Study

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Non-Gaussian Bubbles in the Sky

- signatures of string landscape from inflation -

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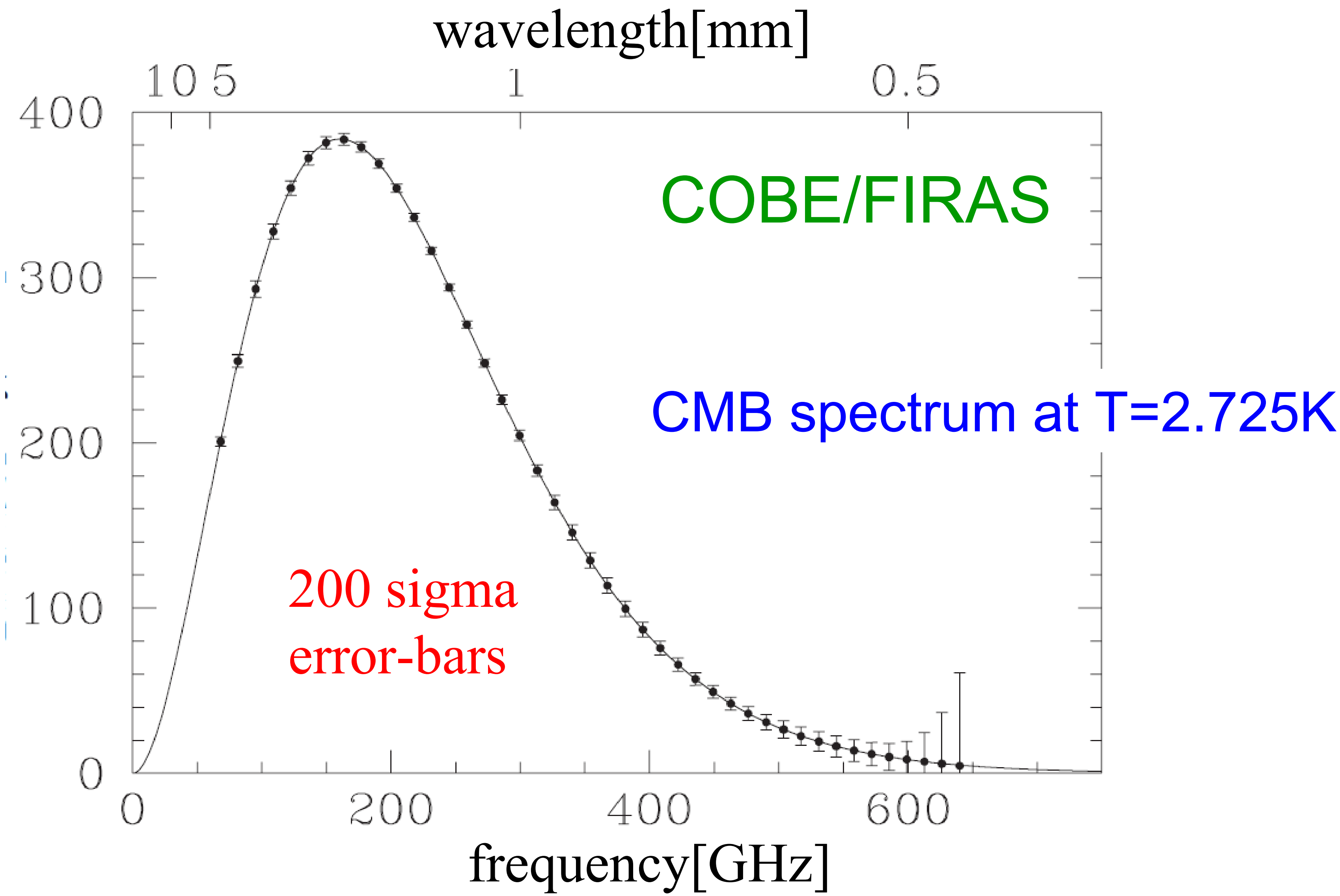
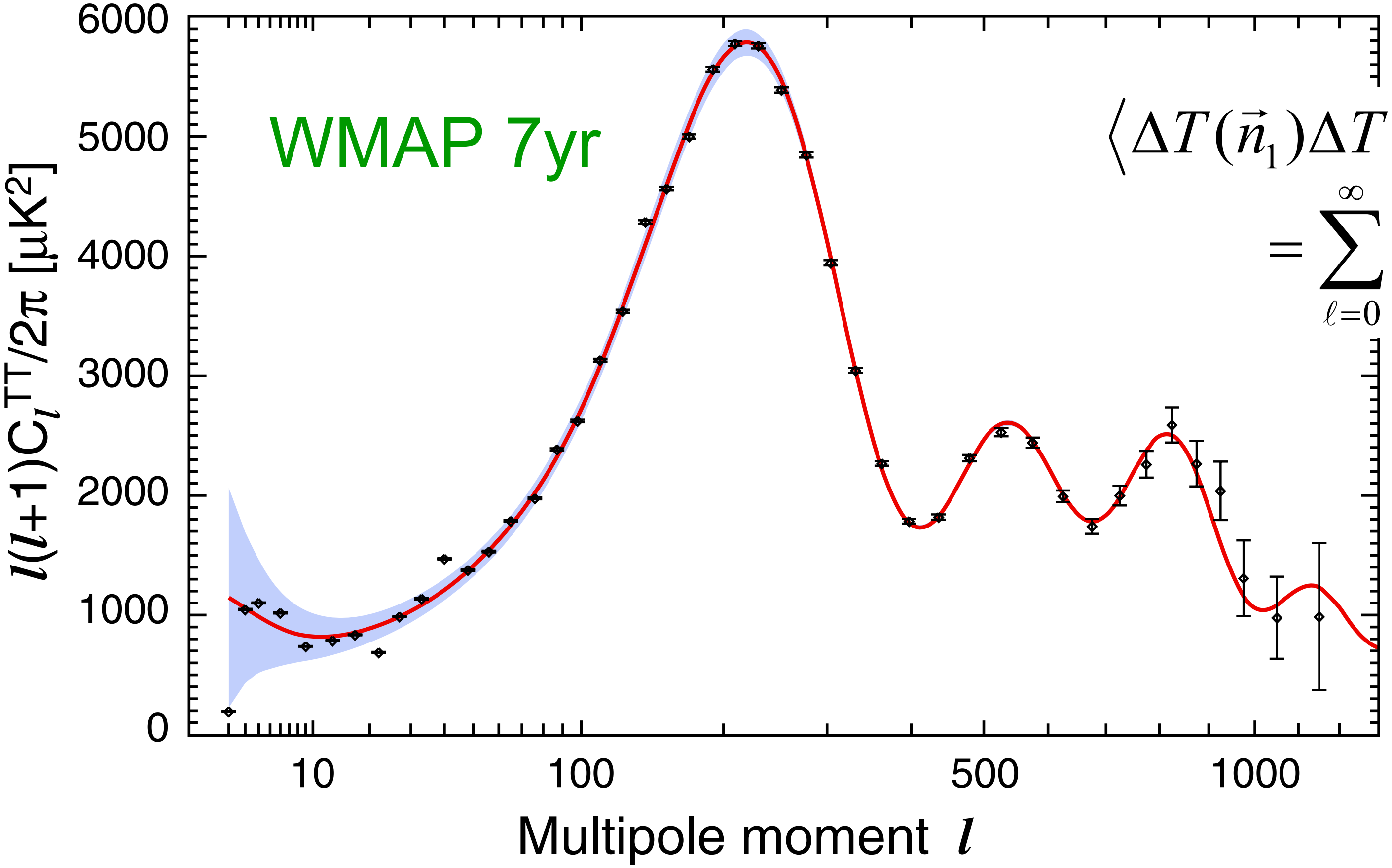
K. Sugimura, D. Yamauchi & MS, EPL 100 (2012) 29004
[arXiv:1208.3937 [astro-ph.CO]]

1. Cosmology Today

- Big Bang theory has been firmly established



Strong evidence for Inflation



$$\langle \Delta T(\vec{n}_1)\Delta T(\vec{n}_2)\rangle = \sum_{\ell=0}^{\infty} \frac{2\ell+1}{4\pi} C_\ell P_\ell(\cos\theta).$$

- highly Gaussian fluctuations
- almost scale-invariant spectrum

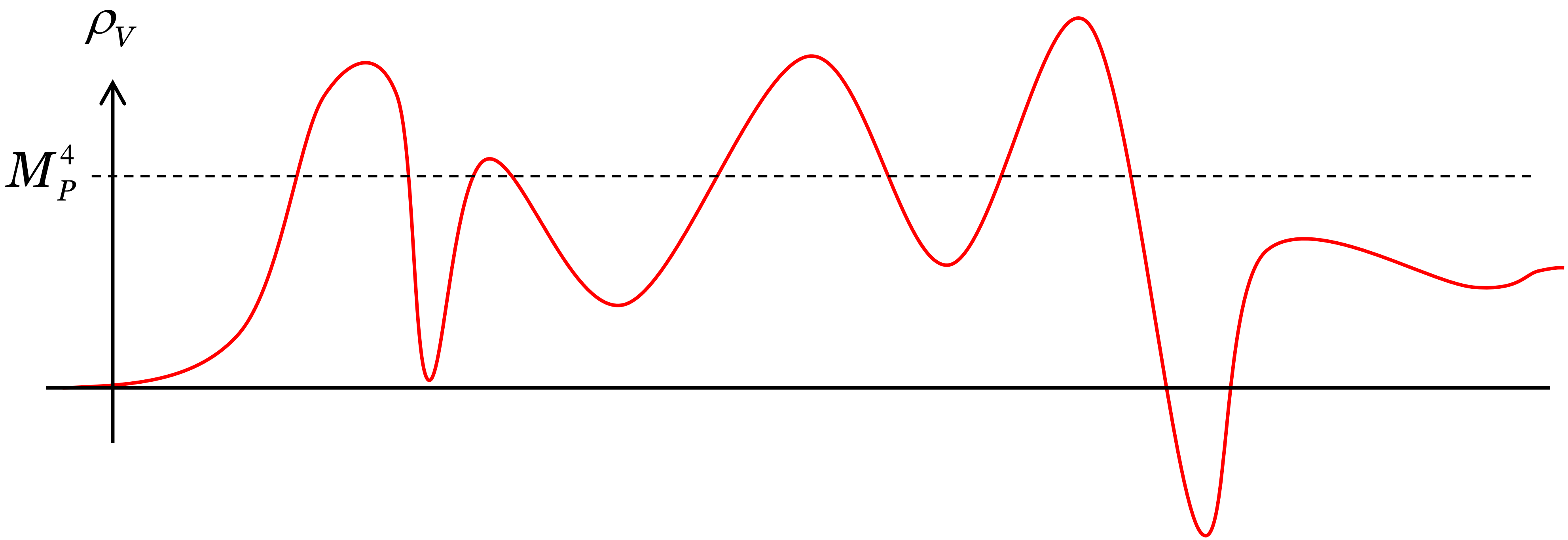
only to be confirmed (by tensor modes?)

What’s next?

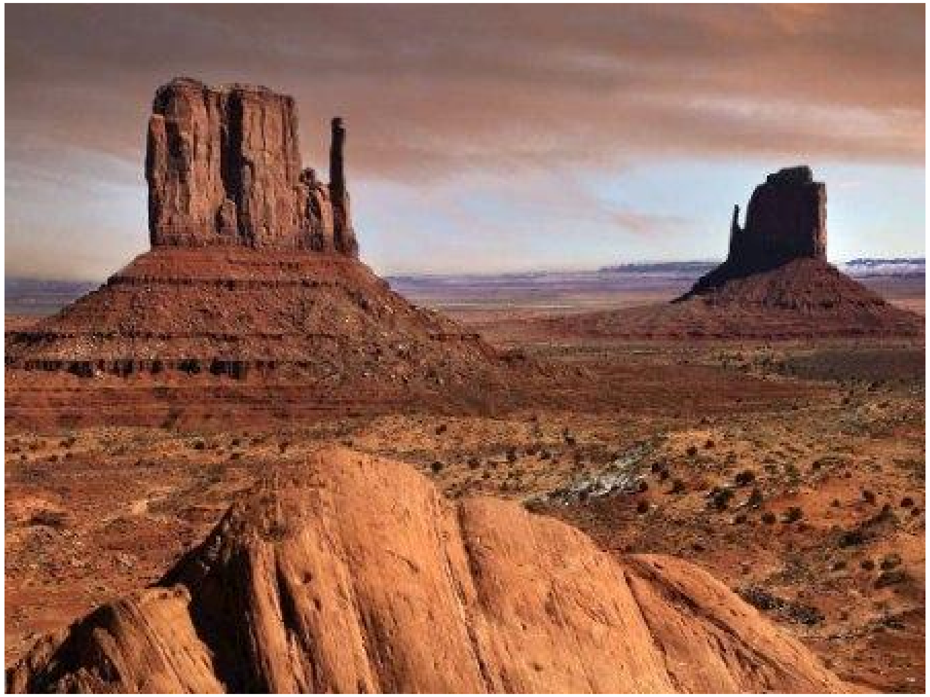
2. String theory landscape

Lerche, Lust & Schellekens ('87), Bousso & Pochinski ('00), Susskind, Douglas, KKLT ('03), ...

- There are ~ 10^{500} vacua in string theory
  - vacuum energy ρ_V may be positive or negative
  - typical energy scale ~ M_P^4
  - some of them have $\rho_V \ll M_P^4$



Is there any way to know what kind of landscape we live in?



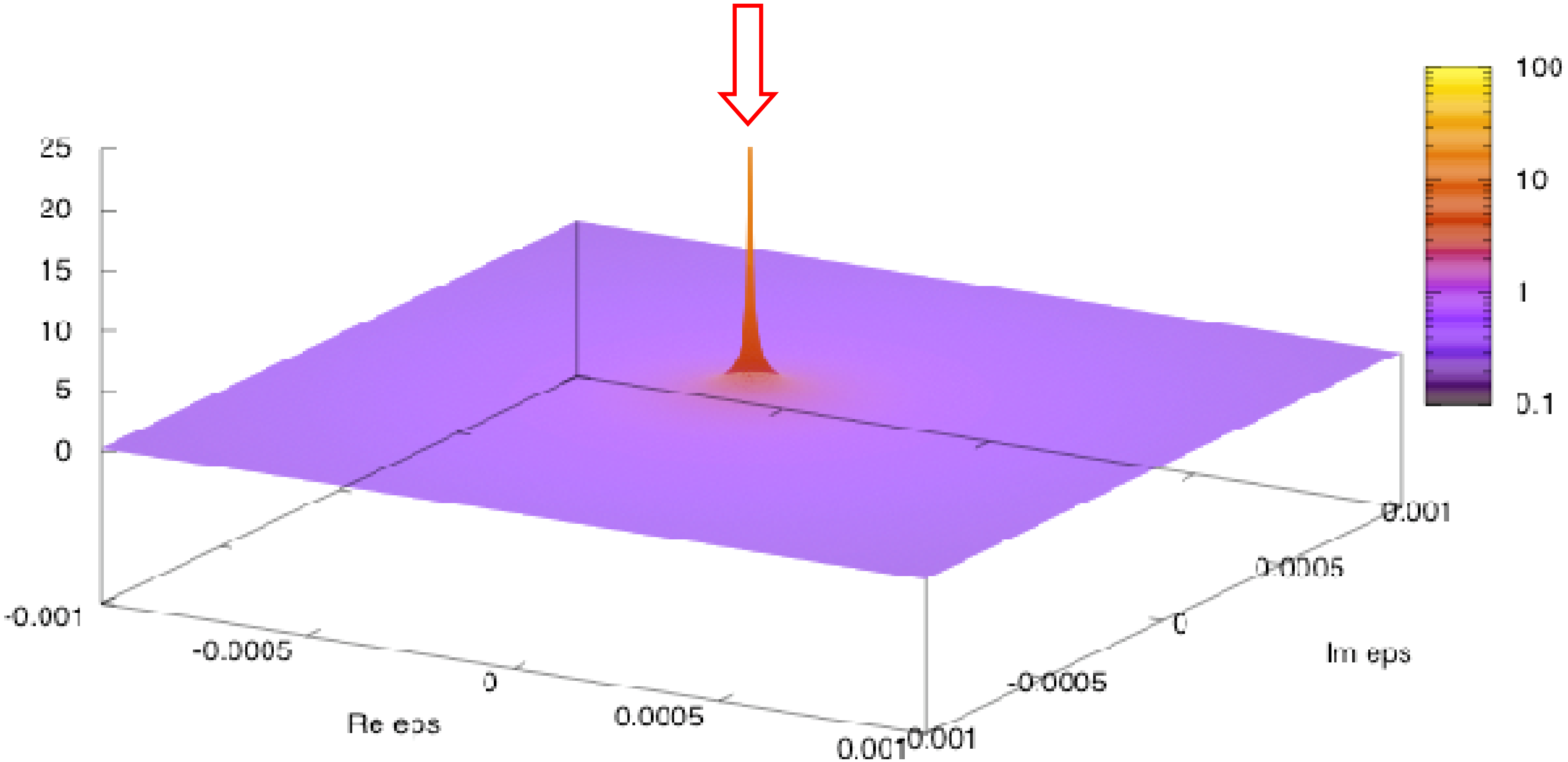
which
?

Or at least to know what kind of neighborhood we live in?

ex: distribution function in flux space

Eguchi & Tachikawa, '05

Vacua with enhanced gauge symmetry



may explain the origin of gauge symmetry
in our Universe

Cosmic Landscape

- various vacua realized in the early universe

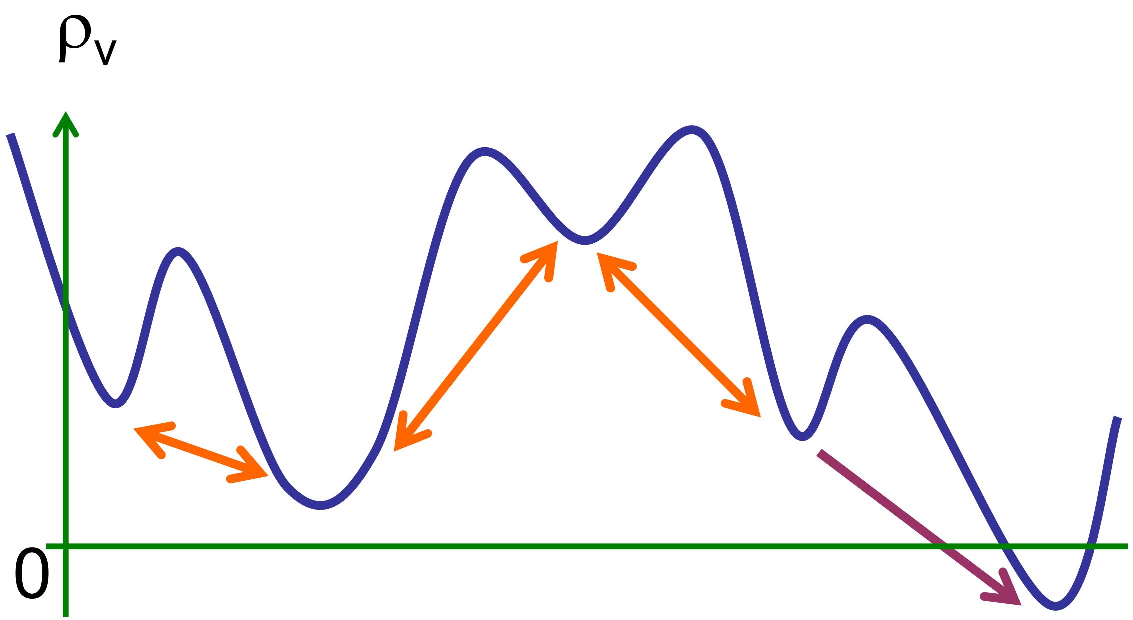
- distribution determined by various factors

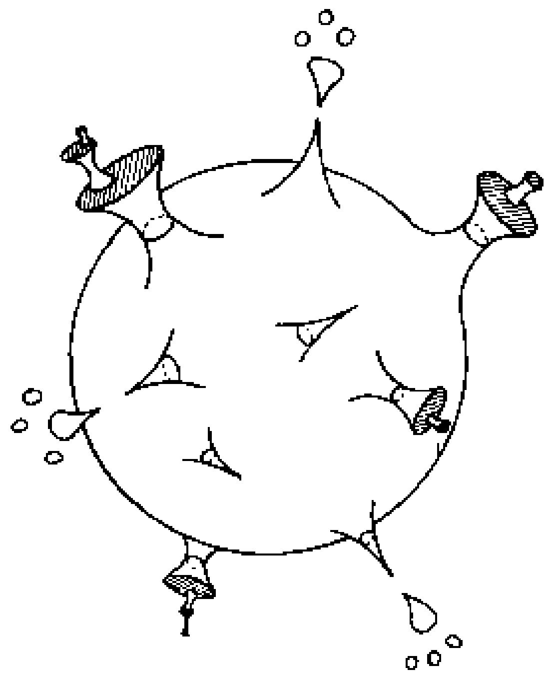
probability measure, density of states,
quantum equilibrium, ...

quantum transitions between various vacua

- Jumping around in the cosmic landscape by quantum tunneling
  - it can go up to a vacuum with larger ρ_v

    (dS space ~ thermal state with $T = H/2\pi$)
  - if it tunnels to a vacuum with negative ρ_v, it collapses within $t \sim M_P/|\rho_v|^{1/2}$.
  - so we may focus on vacua with positive ρ_v: dS vacua





Sato et al. ('81)

➢Anthropic landscape

- Not all of dS vacua are habitable.

"anthropic" landscape   Susskind ('03)

- A universe jumps around in the landscape and settles down to a final vacuum with $\rho_{v,f} \sim M_P^2 H_0^2 \sim (10^{-3}\mathrm{eV})^4$.

$\rho_{v,f}$ must not be larger than this value in order to account for the formation of stars and galaxies.

- Just before it has arrived the current vacuum (=present universe), it must have gone through an era of (slow-roll) inflation and reheating, to create "matter and radiation."

$\rho_{vac} \rightarrow \rho_{matter} \sim T^4$: birth of Hot Bigbang Universe

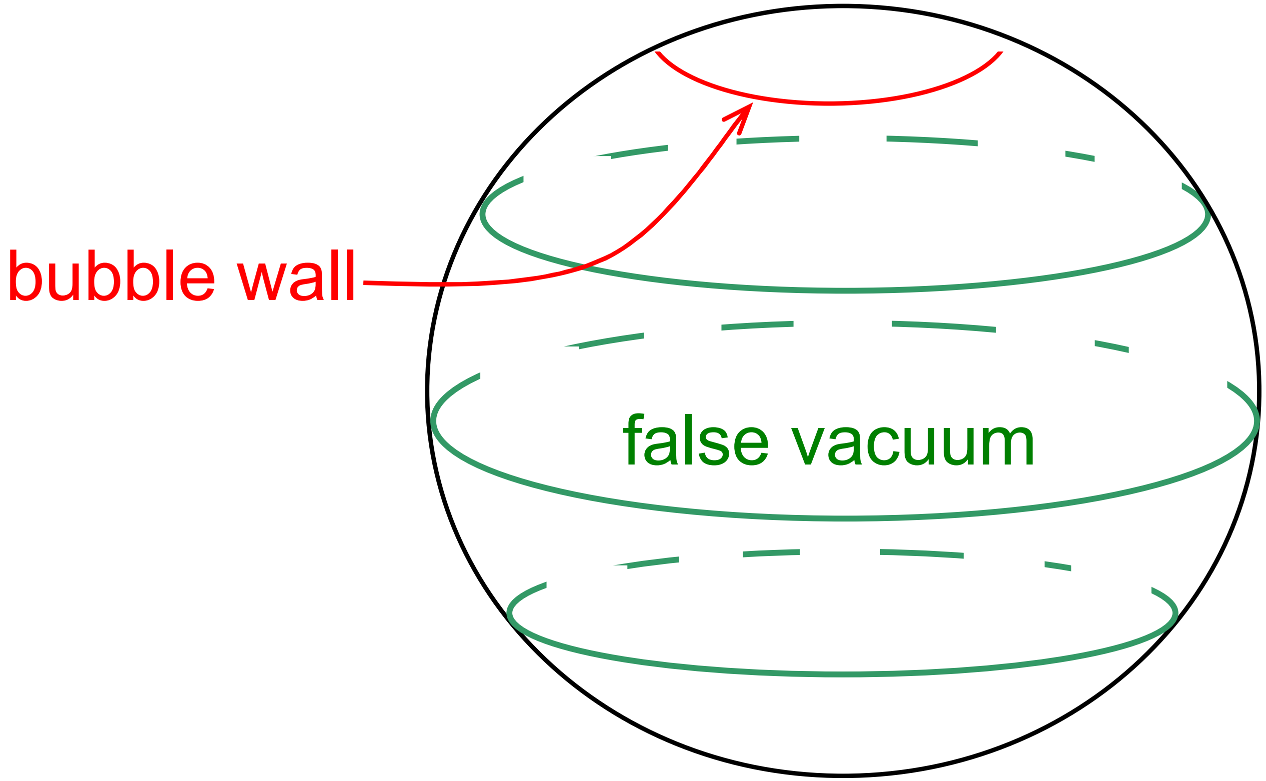
- Most plausible state of the universe before inflation is a dS vacuum with $\rho_V \sim M_P^4$. dS = O(4,1) → O(5) ~ S^4

false vacuum decay via O(4) symmetric (CDL) instanton

Coleman & De Luccia ('80)

O(4) → O(3,1)

inside bubble is an open universe



$$\tau^2 + \vec{x}^2 = R^2$$

$$\Downarrow$$

$$-t^2 + \vec{x}^2 = R^2$$

Creation of open universe

ds vacuum :O(4,1)

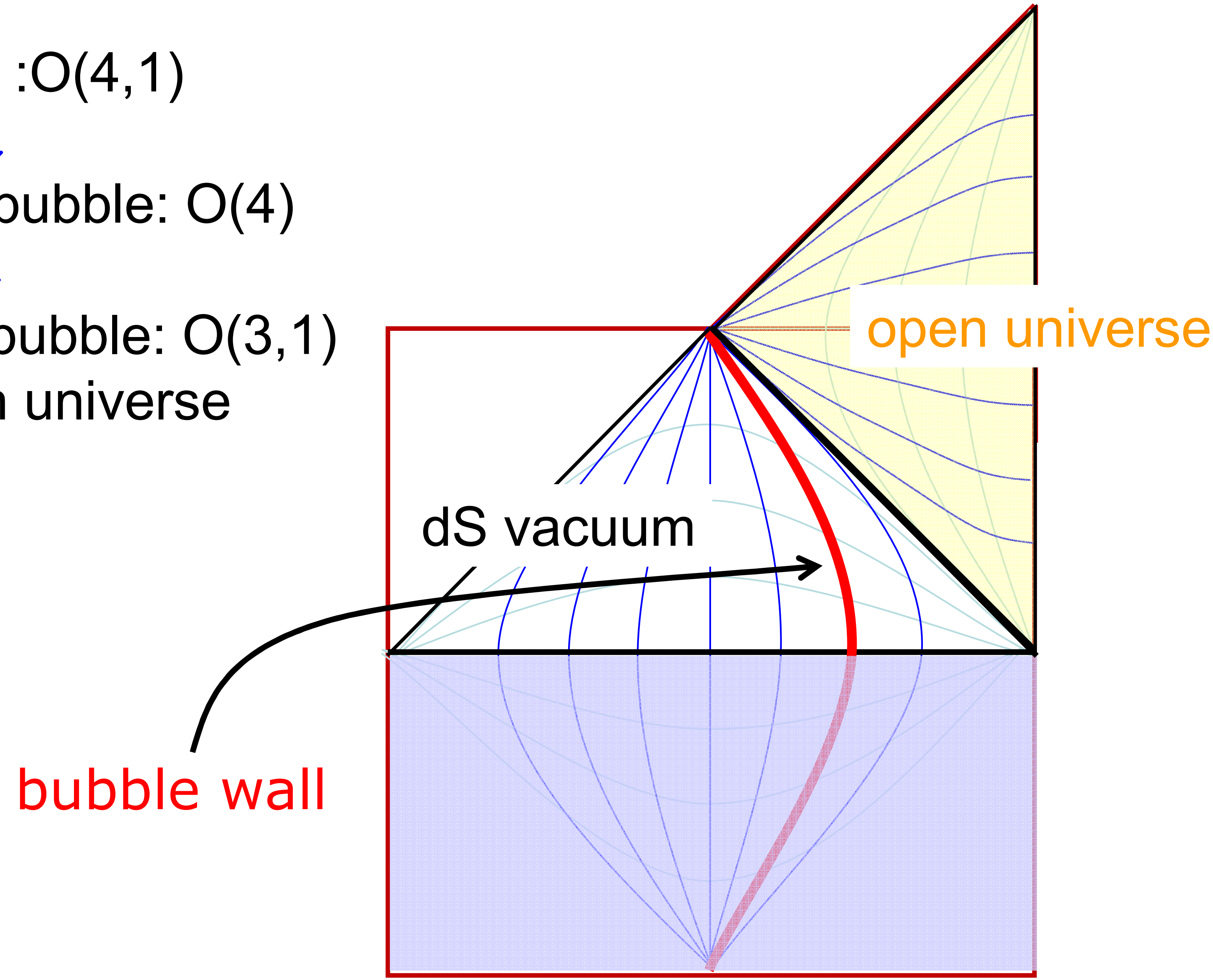
⇩

Euclidean bubble: O(4)

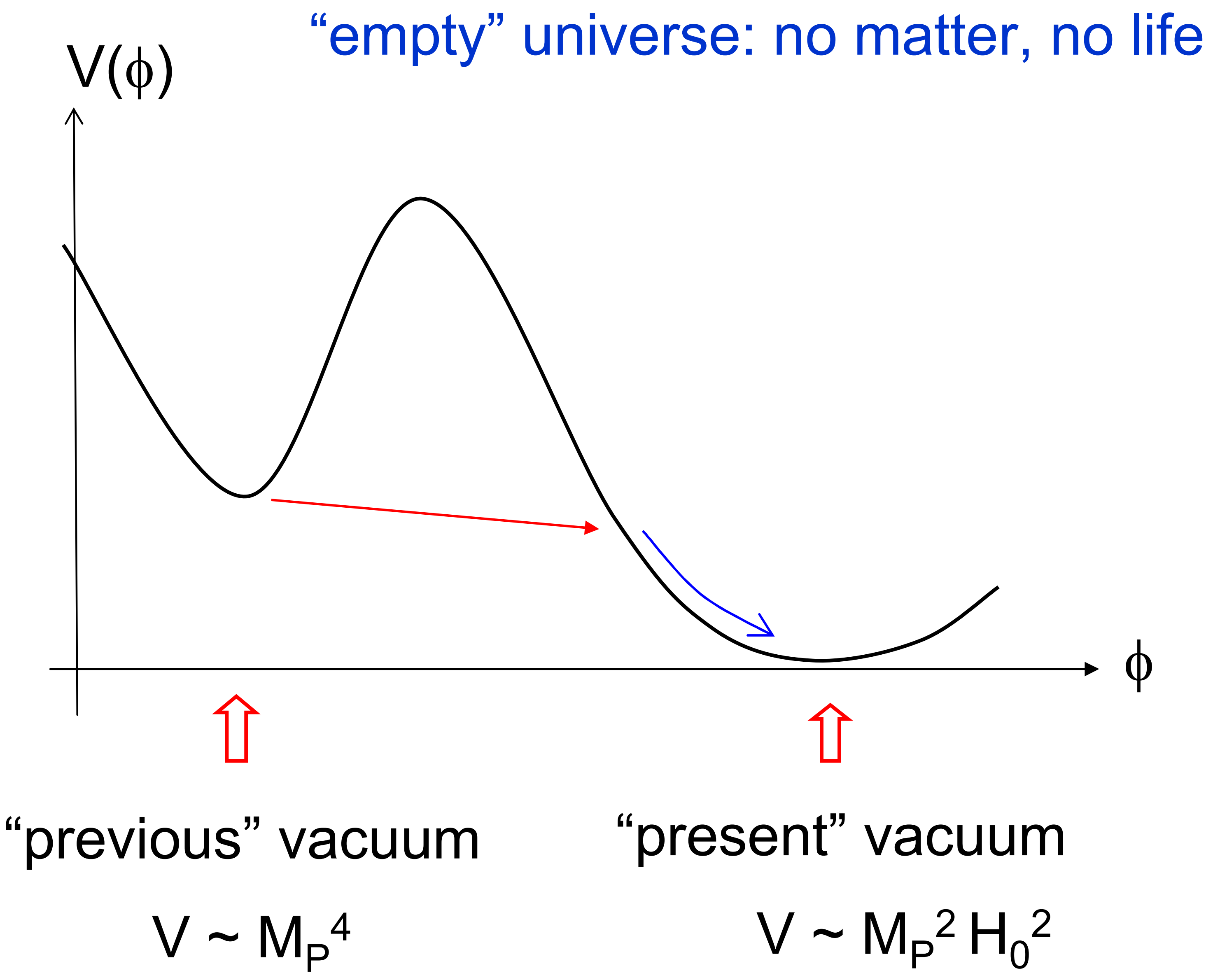
⇩

nucleated bubble: O(3,1)

=open universe



- Natural outcome would be a universe with $\Omega_0 << 1$.



- Anthropic principle suggests that # of e-folds of inflation inside the bubble ($N=H\Delta t$) should be ~ 50 – 60 : just enough to make the universe habitable.

Garriga, Tanaka & Vilenkin ('98), Freivogel et al. ('04)

- Observational data excluded open universe with $\Omega_0 <1$!

- Nevertheless, the universe may be slightly open:

$$1-\Omega_0 = 10^{-2} \sim 10^{-3}$$

may be tested by PLANCK+BAO+...

Colombo et al. ('09)

➢ two possibilities

1. inflation after tunneling was short enough (N~60)

$$1-\Omega_0 = 10^{-2} \sim 10^{-3}$$ “open universe”

⇨ signatures in large angle CMB anisotropies

Yamauchi, Linde, Naruko, Tanaka & MS (2011)

2. inflation after tunneling was long enough (N>>60)

$$1-\Omega_0 \ll 1$$ “flat universe”

⇨ signatures from bubble collisions

today’s topic

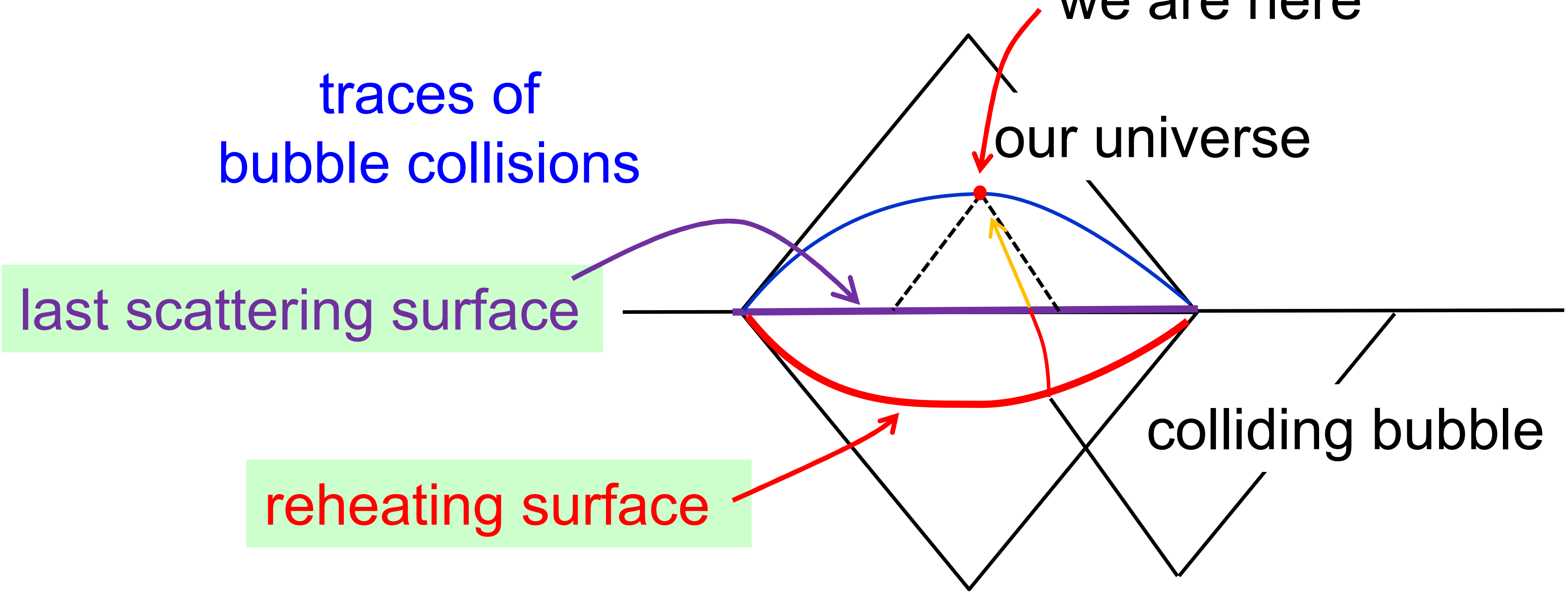
3. Non-Gaussianity from bubble collisions

If inflation inside the bubble lasted long enough

no trace of previous false vacuum

any other signatures?

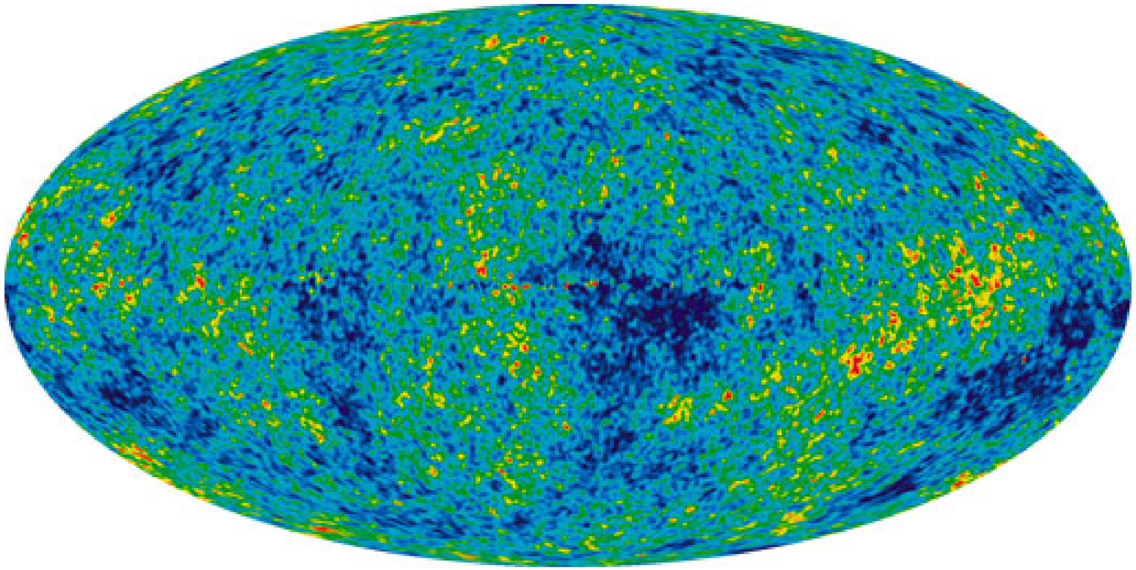
traces of
bubble collisions



➢ simple model

• no (spherically symmetric) bubble seen in the CMB map

⇎ negligible effect on curvature perturbation (~Newton potential) at leading order



bubbles may be seen as “localized” non-Gaussianty

$$\Phi(x) = \Phi_{Gauss}(x) + \underbrace{f_{NL}(x)}_{\text{space-dependent}}\Phi^2_{Gauss}(x) + \ldots$$

- such a model is possible in the curvaton scenario

Lyth & Wands '01, Moroi & Takahashi '01,...

inflaton χ: responsible for inflationary expansion
curvaton ϕ: responsible for curvature perturbation
instanton σ: responsible for quantum tunneling

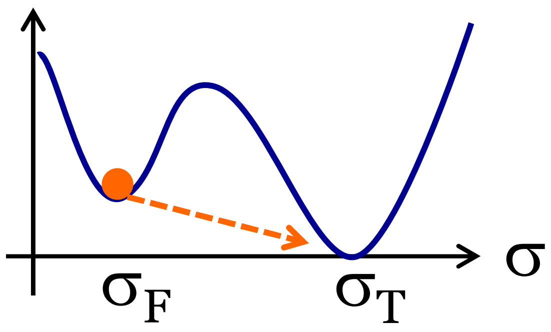
$$V(\phi,\sigma)=\frac{1}{2}m_\phi^2\phi^2+V_{\mathrm{tunnel}}(\sigma)+V_{\mathrm{int}}(\sigma,\phi)$$

- ignore fluctuations of σ as well as of χ for simplicity

curvature perturbation: $\Phi \propto \dfrac{\delta\phi}{\phi}$

$\delta\phi$ may be Non-Gaussian if $V_{\mathrm{int}}(\sigma,\phi) \neq 0$

tunneling field: σ



curvaton: ϕ

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

$$V_{\rm int}(\sigma,\phi) \begin{cases} = 0 & \sigma = \sigma_{\rm F} \\ \neq 0 & \text{otherwise} \end{cases}$$

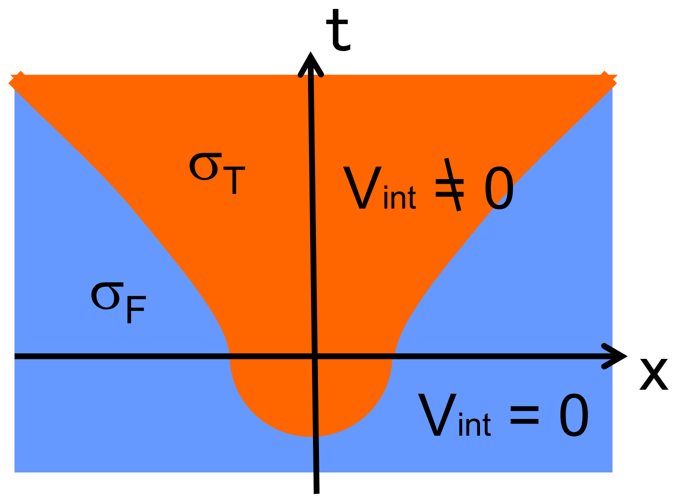
effect of σ = spacetime dependent potential $V^{\rm eff}(\phi)$

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

$V_{\rm int}$ nonlinear in ϕ will induce "localized" non-Gaussianity

$$\Downarrow \quad e.g., \quad V_{\rm int} = \lambda(\sigma)\phi^3$$

non-Gaussian bubble in CMB map

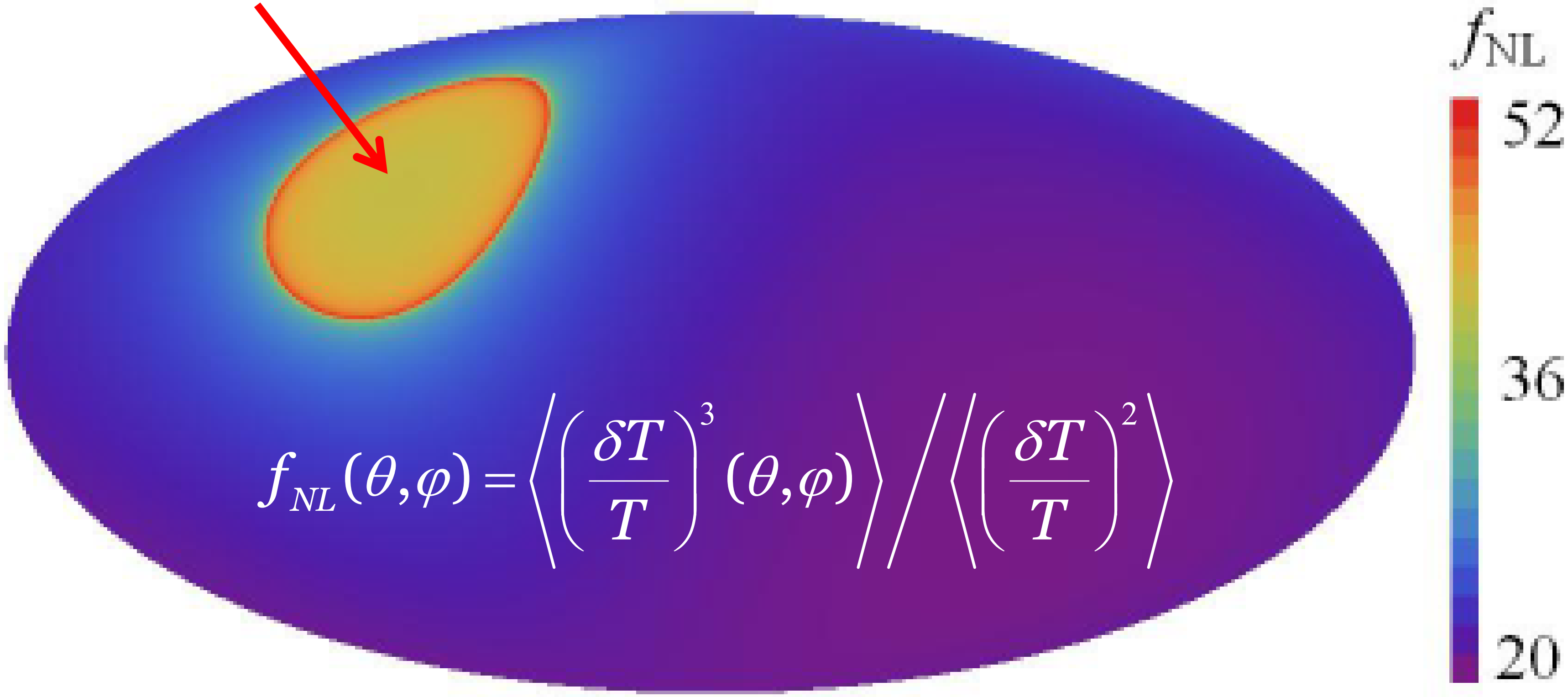


CDL instanton σ(x)

example

$$V^{eff}(\phi) = \frac{1}{2} m_\phi^2 \phi^2 + \lambda \delta(r - r_{wall}) \phi^3; \quad \frac{m_\phi^2}{H^2} = 0.01,\ \lambda = 0.02,\ H r_{wall} = 0.2\pi$$

non−Gaussian bubble in the CMB sky



detection of a spherically symmetric “localized” non-Gaussianity will be the first observational signature of string theory!

4. Summary

- If inflation inside the bubble is short ($N \sim 60$):

"open universe"

$1-\Omega_0 \sim 10^{-2} - 10^{-3}$: string landscape + anthropic argument

⇨ signatures in large angle CMB anisotropies

constrains the string landscape around us.

Yamauchi, Linde, Naruko, Tanaka & MS,
"*Open inflation in the landscape*"
PRD84, 043513 (2011) [arXiv:1105.2674 [hep-th]].

- If inflation lasted long enough (N>>60)

"flat universe"

no signature in the properties of the vacuum...

Nevertheless, we may see other vacuum bubbles colliding with our universe

⇨ non-Gaussian bubbles in the sky!

may be detected in the near future (eg by PLANCK)

will bring us invaluable information about the physics of the early universe, if not string landscape!