On the contribution of ***infrared secular effects*** to primordial fluctuations via ***quantum interference***

Junsei Tokuda (Kyoto Univ.)

collaborator：Takahiro Tanaka (Kyoto Univ. & YITP)

Working in progress.

Refs. : JT and T.Tanaka JCAP02(2018)014

JT and T.Tanaka JCAP11(2018)022

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plan

- 1. Introduction (9 pages.)

  Infrared secular effects, Stochastic picture of inflation

- 2. Body (11 pages.)
  - Discuss the validity of the stochastic picture of inflation.
  - Violation of the stochastic picture up to non-zero quantum coherence during inflation, and its consequences.

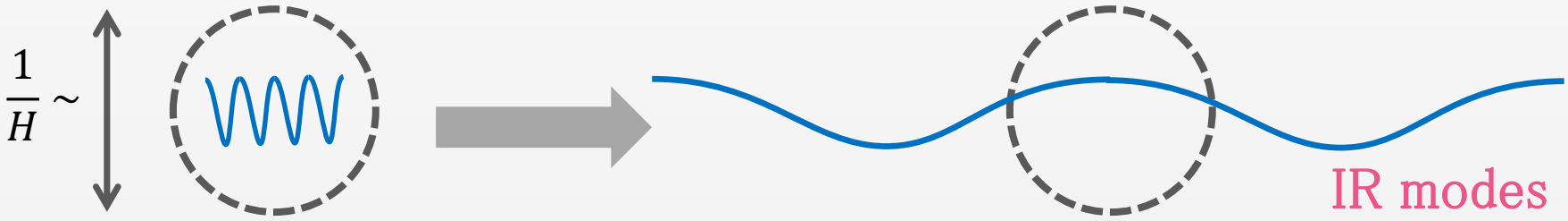
(Working in progress……)

- 3. Summary (1 page.)

Generation of fluctuations

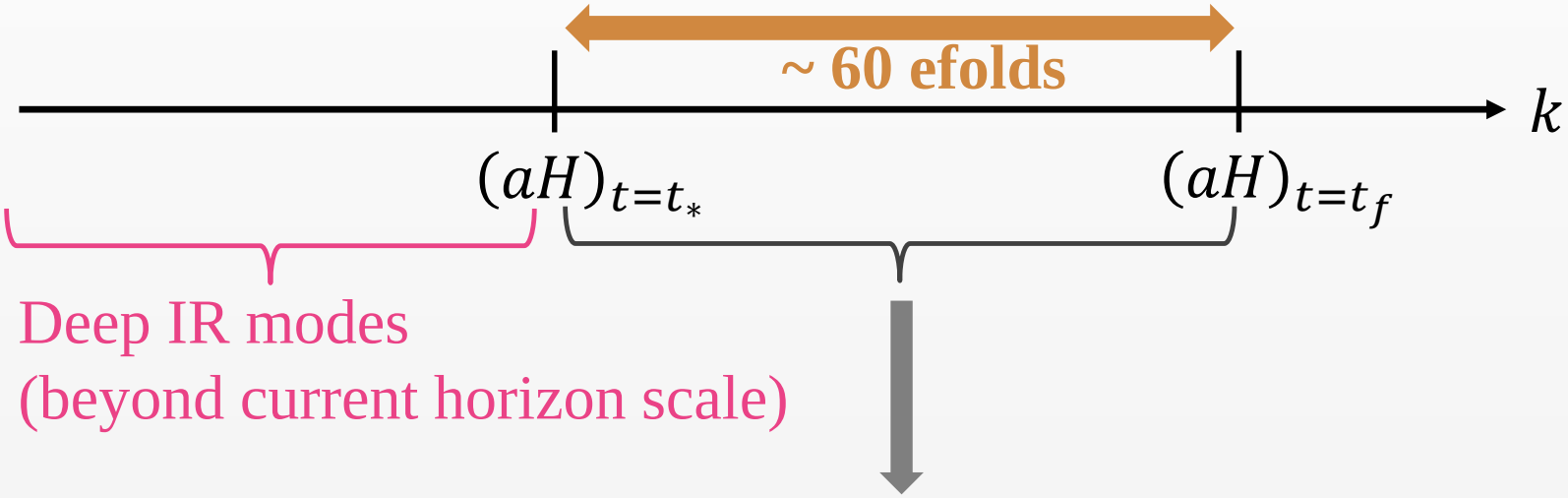
- Microscopic fluctuations → Macroscopic. (IR modes)
  (super-horizon modes)

$$\lambda_{\mathrm{ph}} = \frac{2\pi a(t)}{k} \approx \frac{2\pi e^{Ht}}{k}$$



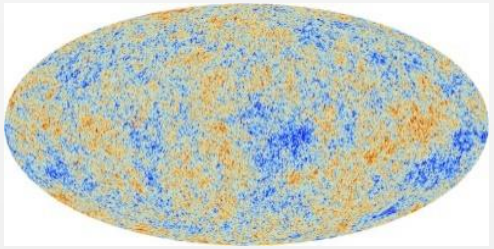
Observables=Quantum fluctuations

- These fluctuations are the seeds of various objects, *e.g.*, galaxies.



Observed density perturbations

e.g. large scale fluc. → CMB



ESA, Planck Collaboration (2013)

Naively,

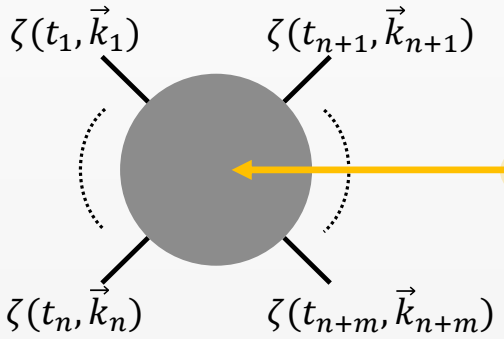
Observables = QFT expectation values of ζ: $< \zeta \cdots \zeta >$

IR secular effects

- $< \zeta \cdots \zeta >$ contains very large loop corrections:

ζ, h_{ij} : metric perturbations

ϕ : isocurvature modes



loops of ζ, h_{ij} and loops of ϕ

Deep IR contribution is divergent or significantly large.

e.g.) interaction vertex which includes an interaction picture field ϕ_{I} without derivative can yield the following loop corrections:

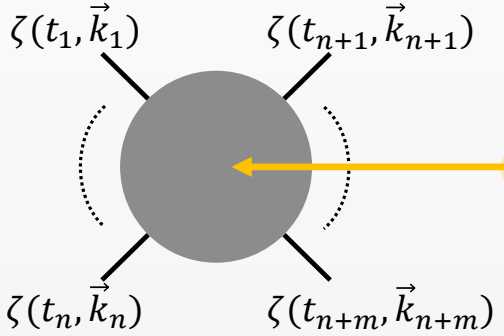
$$< \phi_{\mathrm{I}}^2 > \propto \int_{k_0} \mathrm{d}^3 l \, \frac{1}{l^3} \sim \ln k_0 \to \infty \ (\text{as } k_0 \to 0).$$

IR secular effects: interesting!

- $< \zeta \cdots \zeta >$ contains very large loop corrections:

ζ, h_{ij} : metric perturbations

ϕ : isocurvature modes



loops of $\zeta, h_{\rm ij}$ and loops of ϕ

Deep IR contribution is divergent or significantly large.

- If IR loops affect observables, it would be interesting because

1. IR loops may **modify the current predictions,**
2. the dynamics **before** 60 e-folds may be imprinted on observables!

Be skeptical.

- Large IR loops may signal the inappropriate definition of observables.

  e.g.) QED

  Take into account the soft photon emission/exchange whose energy is below the detector resolution

  ⇓

  Finite scattering amplitudes.

- It seems that we are in the similar situation.
  We should reconsider which quantities are really observables for us.

IR secular effects from isocurvature modes

IR loops affect observables for a local observer ?

- We should reconsider which quantities are really observables for us.

1. loops of ζ, h_{ij} (metric perturbations) T. Tanaka and Y. Urakawa (2009,…)

IR loops of ζ, h_{ij} = *gauge* artifact

2. loops of ϕ (isocurvature modes)

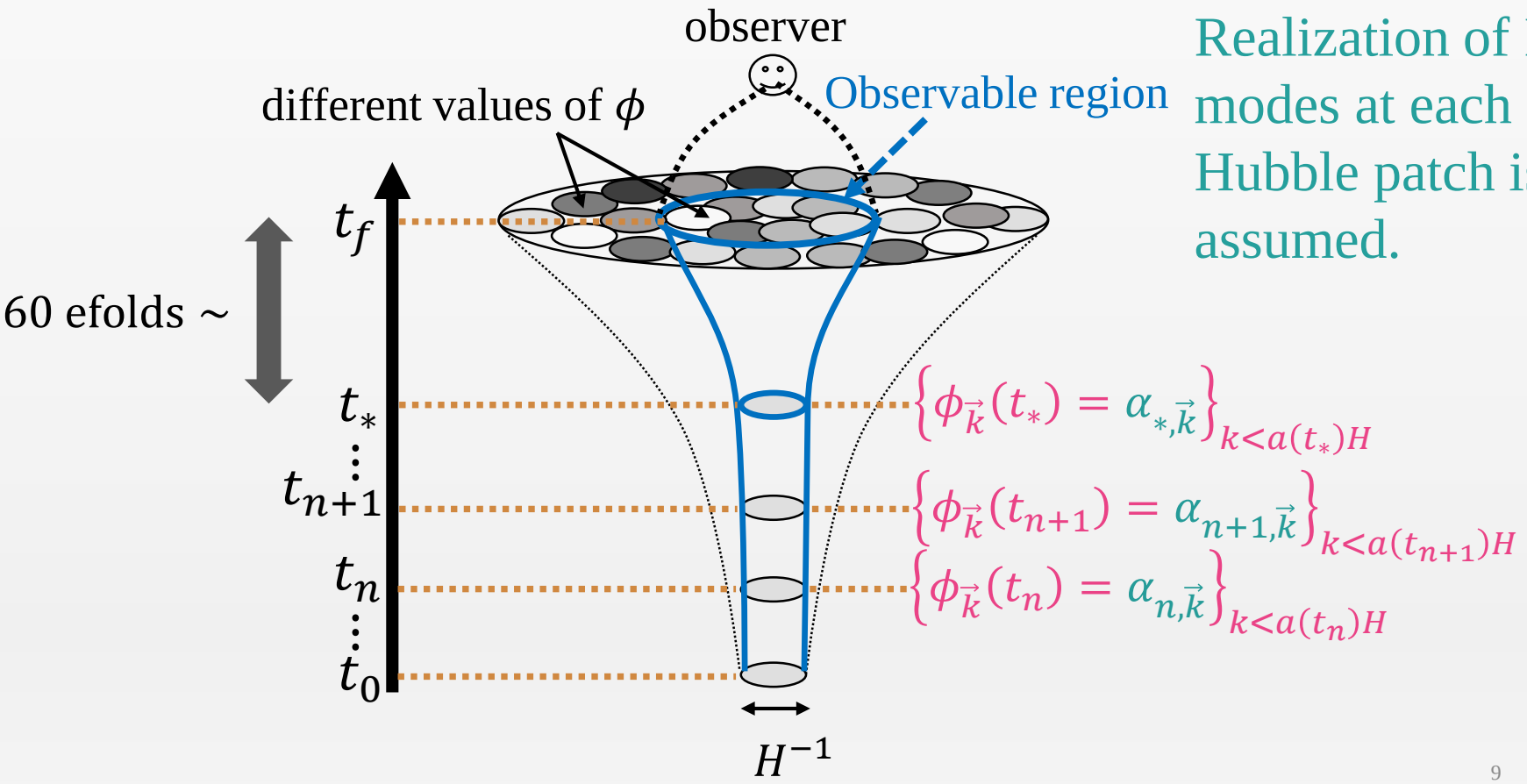
➡ Above discussion does not apply. T. Tanaka and Y. Urakawa (2010, 2011)

- From now on, we concentrate on a light scalar field on inflationary background.

Classical stochastic picture

A. Linde(1986) A. A. Starobinsky (1986)
Y. Nambu and M. Sasaki (1989)

- Fluctuations of deep IR modes $(k < a(t_*)H)$ are completely neglected **by hand.**



Realization of IR modes at each Hubble patch is assumed.

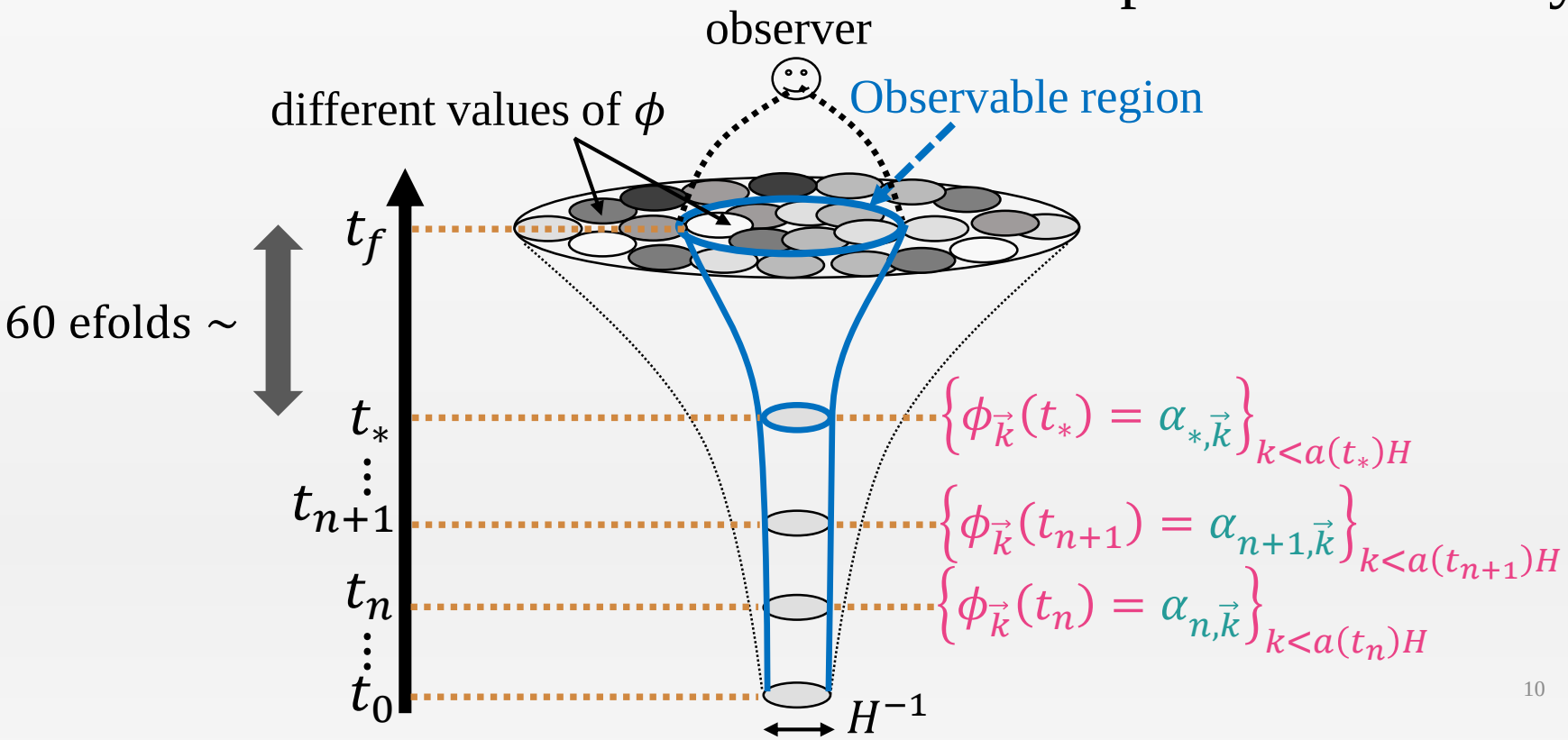
Classical stochastic picture

A. Linde(1986) A. A. Starobinsky (1986)
Y. Nambu and M. Sasaki (1989)

- Fluctuations of deep IR modes $(k < a(t_*)H)$ are completely neglected **by hand.**

$$|\Psi_{\mathrm{stoc}}\rangle = |\Psi\rangle_{\alpha} \neq U(t_f, t_0)|\Psi^0\rangle$$

α specifies some particular history.



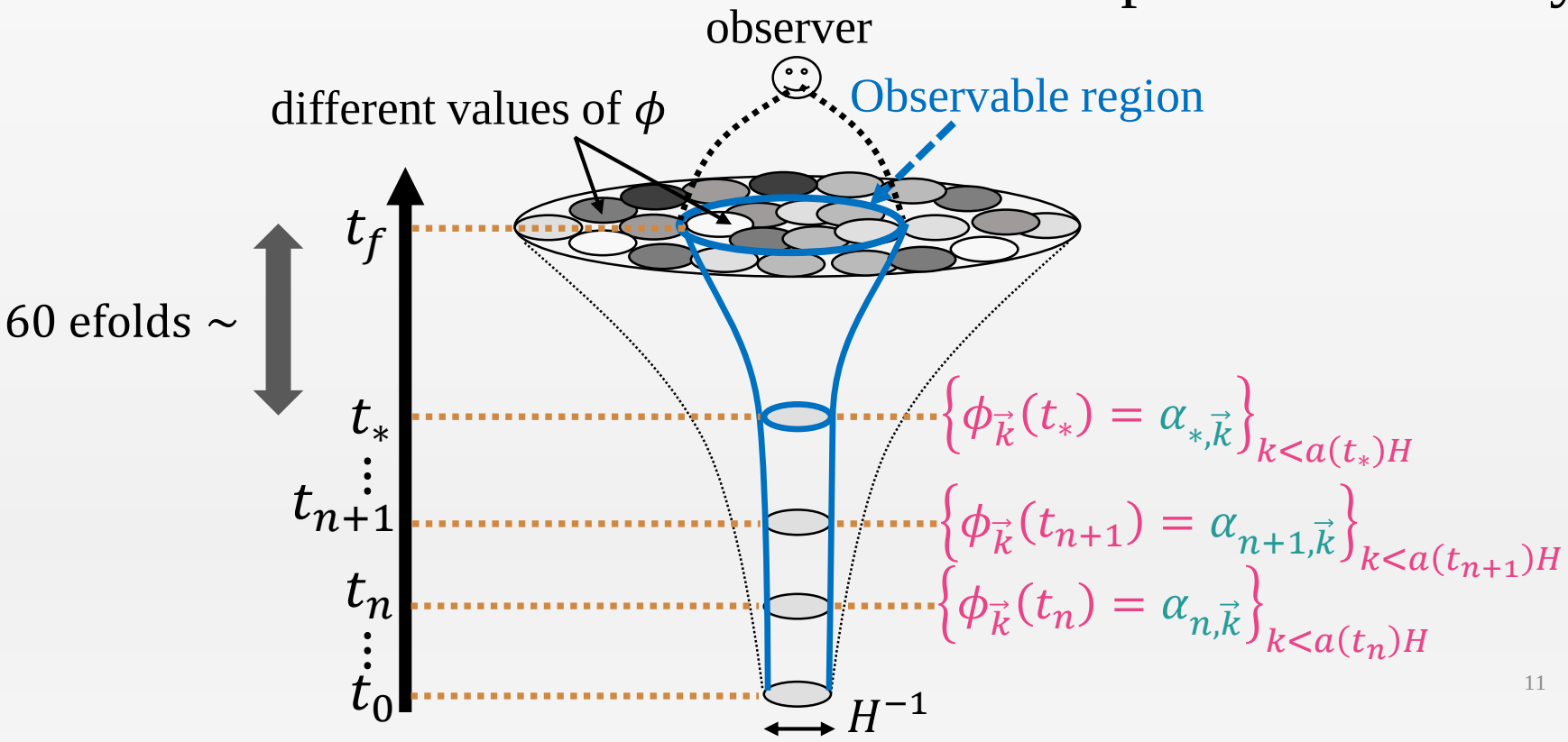
Classical stochastic picture ?

A. Linde(1986) A. A. Starobinsky (1986)
Y. Nambu and M. Sasaki (1989)

- Fluctuations of deep IR modes $(k < a(t_*)H)$ are completely neglected **by hand. Can we justify $|\Psi_{\mathrm{stoc}}\rangle$?**

$$|\Psi_{\mathrm{stoc}}\rangle = |\Psi\rangle_{\alpha} \neq U(t_f, t_0)|\Psi^0\rangle$$

α specifies some particular history.



Importance of the decoherence (1/3)

- Expectation: quantum decoherence may justify the stochastic picture of inflation.
- E.g.) Let us consider the following situation. E. Joos and H. D. Zeh (1985)

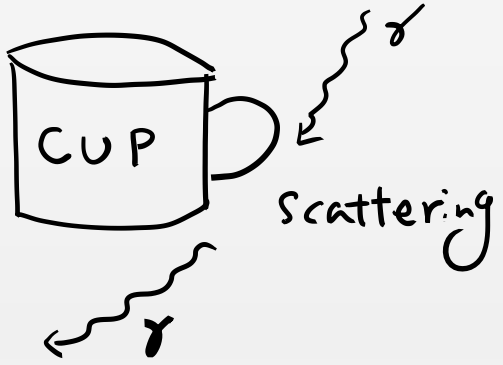
$$\mathcal{H}_{\mathrm{tot}} = \mathcal{S} \otimes \mathcal{E},$$

$$|\Psi^0\rangle = |\Psi^{(S,0)}\rangle_{\mathcal{S}} \otimes |\Psi^{(E,0)}\rangle_{\mathcal{E}} \Rightarrow |\Psi\rangle = \sum_x c(x)|x\rangle_{\mathcal{S}} \otimes |e_x\rangle_{\mathcal{E}}$$

Cup photon

with $\left(|e_{x_1}\rangle_{\mathcal{E}}, |e_{x_2}\rangle_{\mathcal{E}}\right) \propto \delta_{x_1 x_2}$

$$(|X\rangle, |Y\rangle) := \langle X|Y\rangle$$



System is decohered in the basis $\{|x\rangle_{\mathcal{S}}\}$:

$$\rho_{\mathcal{S}} := Tr_{\mathcal{E}}(|\Psi\rangle\langle\Psi|) = \sum_x |c(x)|^2 |x\rangle_{\mathcal{S}\mathcal{S}}\langle x|$$

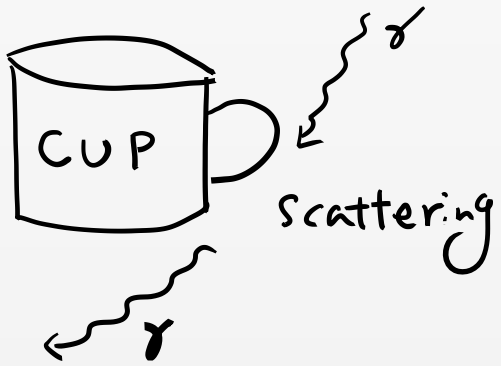
Importance of the decoherence (2/3)

- E.g.) Let us consider the following situation.

  $\mathcal{H}_{\text{tot}} = \mathcal{S} \otimes \mathcal{E}$,

  $|\Psi^0\rangle = |\Psi^{(S,0)}\rangle_{\mathcal{S}} \otimes |\Psi^{(E,0)}\rangle_{\mathcal{E}}$ ⟹ $|\Psi\rangle = \sum_x c(x)|x\rangle_{\mathcal{S}} \otimes |e_x\rangle_{\mathcal{E}}$

  with $\left(|e_{x_1}\rangle_{\mathcal{E}}, |e_{x_2}\rangle_{\mathcal{E}}\right) \propto \delta_{x_1 x_2}$



- Orthogonality $\left(|e_{x_1}\rangle_{\mathcal{E}}, |e_{x_2}\rangle_{\mathcal{E}}\right) \propto \delta_{x_1 x_2}$

  ⟹ It is possible to distinguish $|e_x\rangle_{\mathcal{E}}$ from $|e_y\rangle_{\mathcal{E}}$ when $x \neq y$.

- Suppose that an observer observed the photon state $|e_\alpha\rangle_{\mathcal{E}}$.

  Then, $|\Psi_{obs}\rangle \propto c(\alpha)|\alpha\rangle_{\mathcal{S}} \otimes |e_\alpha\rangle_{\mathcal{E}}$. There is a cup at $x = \alpha$.

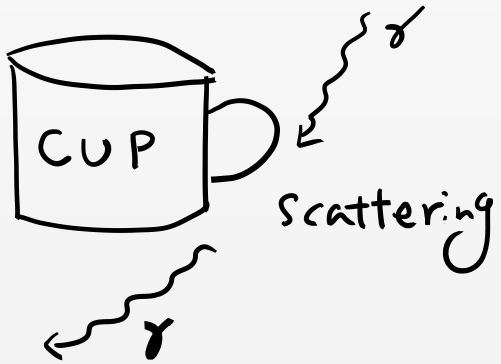
Importance of the decoherence (3/3)

- E.g.) Let us consider the following situation.

$$\mathcal{H}_{\mathrm{tot}} = \mathcal{S} \otimes \mathcal{E},$$

$$|\Psi^0\rangle = |\Psi^{(S,0)}\rangle_{\mathcal{S}} \otimes |\Psi^{(E,0)}\rangle_{\mathcal{E}} \Rightarrow |\Psi\rangle = \sum_x c(x)|x\rangle_{\mathcal{S}} \otimes |e_x\rangle_{\mathcal{E}}$$

with $\left(|e_{x_1}\rangle_{\mathcal{E}}, |e_{x_2}\rangle_{\mathcal{E}}\right) \propto \delta_{x_1 x_2}$



- Key point: orthogonality $\left(|e_{x_1}\rangle_{\mathcal{E}}, |e_{x_2}\rangle_{\mathcal{E}}\right) \propto \delta_{x_1 x_2}$.

  Observer can obtain the information (record) of the system quantum state $|x\rangle_{\mathcal{S}} \in \mathcal{S}$, by monitoring the environment thanks to the orthogonality.

Application to the stochastic picture of inflation?

- Let us consider the possible application of the previous discussion to the stochastic picture of inflation.

- We will investigate whether the information of the history $\boldsymbol{\alpha}$ is recorded in the environment $\boldsymbol{\mathcal{E}}$ which is accessible by an observer:

$$|\Psi^0\rangle = |VAC\rangle \rightarrow |\Psi(t_f)\rangle = \sum_{\boldsymbol{\alpha}} |\Psi\rangle_{\boldsymbol{\alpha}}$$

$$|\Psi\rangle_{\boldsymbol{\alpha}} = |\alpha\rangle_{\mathcal{S}} |z_{\boldsymbol{\alpha}}\rangle_{\mathcal{E}}$$

$\boldsymbol{\alpha}$ specifies some particular history.

- More specifically, we will investigate the orthogonality

$$\left(|z_{\boldsymbol{\beta}}\rangle_{\mathcal{E}}\ , |z_{\boldsymbol{\alpha}}\rangle_{\mathcal{E}}\right) \approx \delta_{\boldsymbol{\alpha\beta}} \quad ?????$$

Application to the stochastic picture of inflation?

- Accessibility of a local observer at the end of inflation

  ➡ We choose

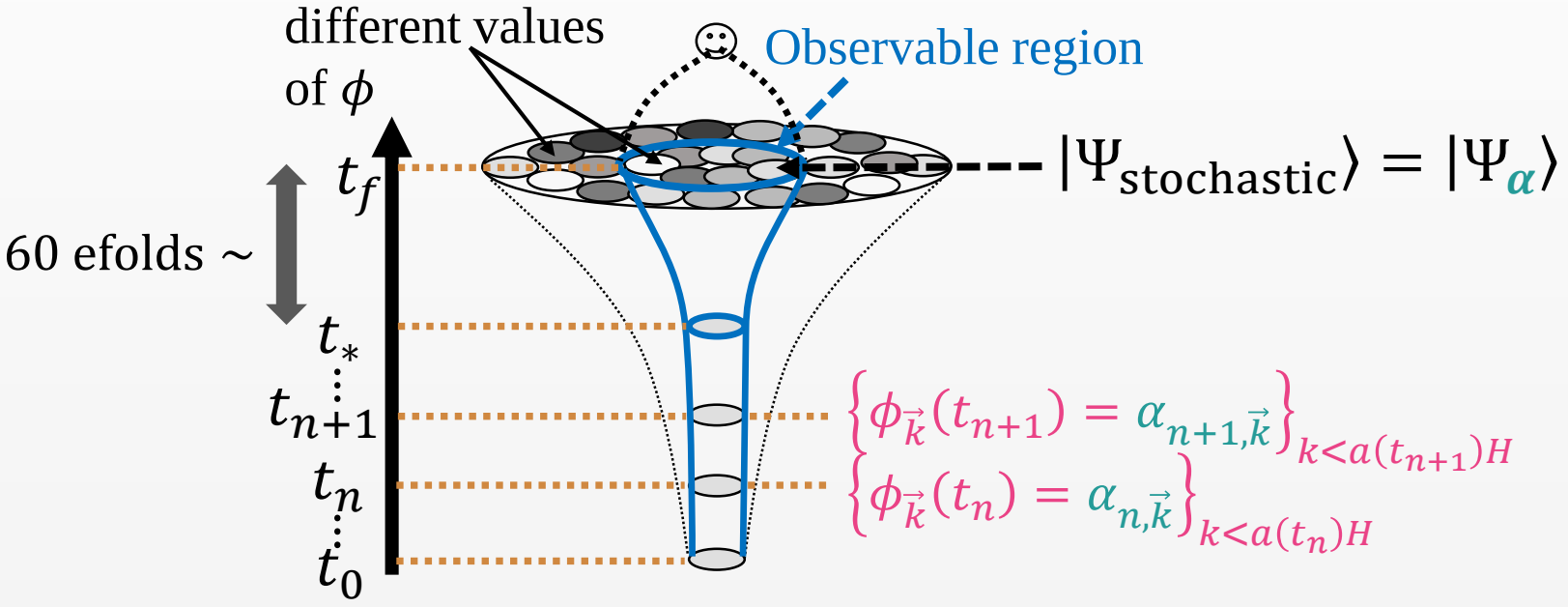
  $$\mathcal{E} = \bigotimes_{k \geq a(t_f)H} \mathcal{H}_{\vec{k}}$$: UV modes at the end of inflation.

  ※ $\mathcal{E}$ contains the UV modes which live outside the observed scale, although we will not care for a while (in this talk).

- We assume that we can monitor the states $\{|z_\alpha\rangle_\mathcal{E}\} \in \mathcal{E}$ somehow.
- From now on, we will

1. define $|\Psi\rangle_\alpha$ and obtain an explicit expression for $|z_\alpha\rangle_\mathcal{E}$
2. confirm that $\left(|z_\beta\rangle_\mathcal{E}, |z_\alpha\rangle_\mathcal{E}\right) \approx \delta_{\alpha\beta}$, by using the path integral.

Quantum states of the stochastic picture of inflation



Projection on IR modes Unitary time evolution

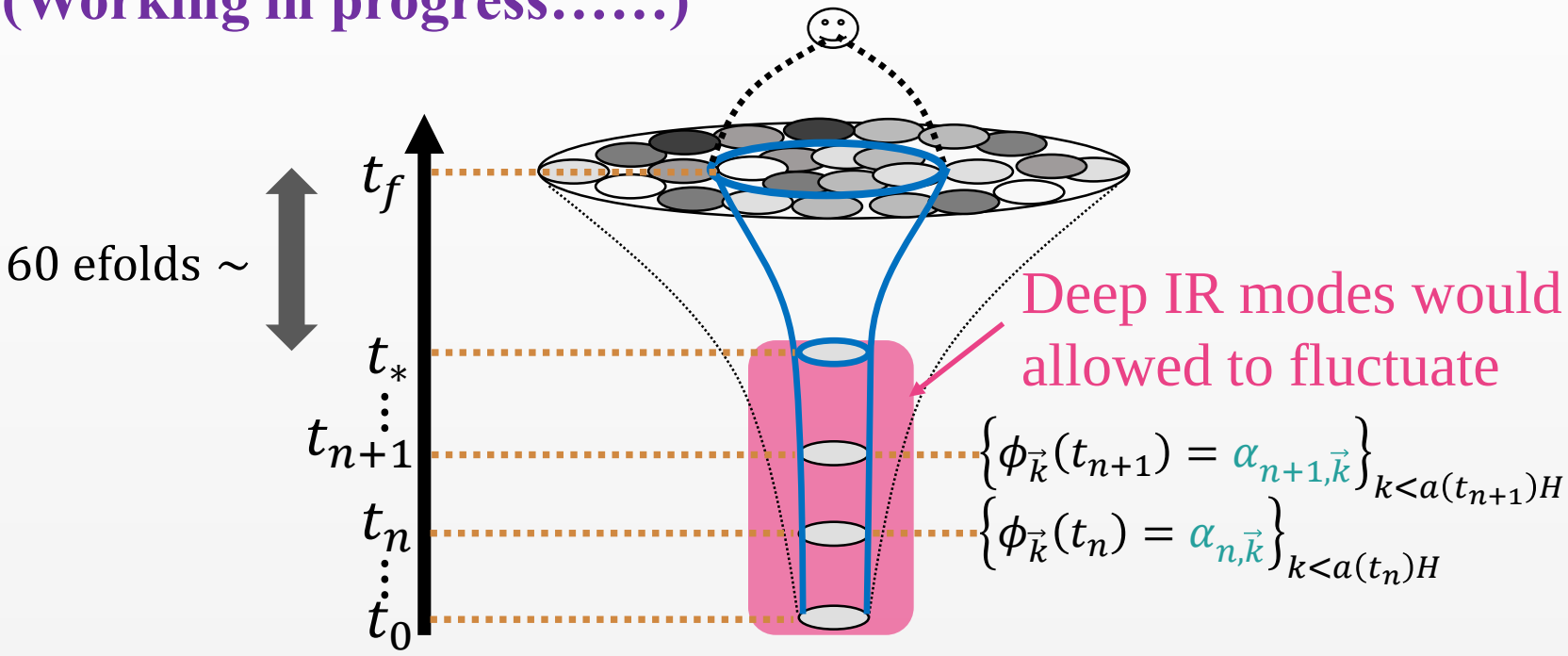
$$|\Psi_{\alpha}\rangle := \hat{C}_{\alpha}|\Psi^0\rangle,\ \hat{C}_{\boldsymbol{\alpha}} := \hat{P}_{\alpha_f} U_{f,f-1} \hat{P}_{\alpha_{f-1}} \cdots U_{21} \hat{P}_{\alpha_1} U_{10}$$

$$\hat{P}_{\alpha_n} := \left(\bigotimes_{k<a(t_n)H} \left|\phi_{\vec{k}} = \alpha_{n,\vec{k}}\right\rangle\left\langle\phi_{\vec{k}} = \alpha_{n,\vec{k}}\right| \right) \bigotimes_{k\geq a(t_n)H} I_{\vec{k}}$$

with $\hat{\phi}_{\vec{k}} \left|\phi_{\vec{k}} = \alpha_{n,\vec{k}}\right\rangle = \alpha_{n,\vec{k}} \left|\phi_{\vec{k}} = \alpha_{n,\vec{k}}\right\rangle$

Deep IR flucuations may affect primordial fluctuations??

(Working in progress……)



- The allowed amplitudes of deep IR modes $(k < a(t_*)H)$ fluctuations will be suppressed by $\left(\frac{a(t_*)}{a(t)}\right)^3$ for $t > t_*$.
- Only primordial fluctuations with mode $k \approx a(t_*)H$ might be affected by the fluctuations of super-Hubble modes (of isocurvature) via quantum interference. **(Working in progress…..)**

Summary

Motivation

Large IR secular effects from isocurvature modes are really observable effects??

Method

Investigate the validity of the stochastic picture of inflation.

Conclusions

1. Stochastic picture might appear only approximately, and would be violated up to the non-zero quantum coherence.
2. Deep IR fluctuations of isocurvature modes **might be able to contribute** to primordial perturbations.

On-going

Qualitative estimation of the contribution of IR secular effects, etc.

IR secular effects might allow us to observe the quantum interference during inflation!