2016/12/06 Rikkyo U seminar

Recent developments in ***open Inflation***

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2016/12/06 Rikkyo U seminar

Recent developments in ***open Inflation***

Inflation with quantum tunneling

Da

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Part 1

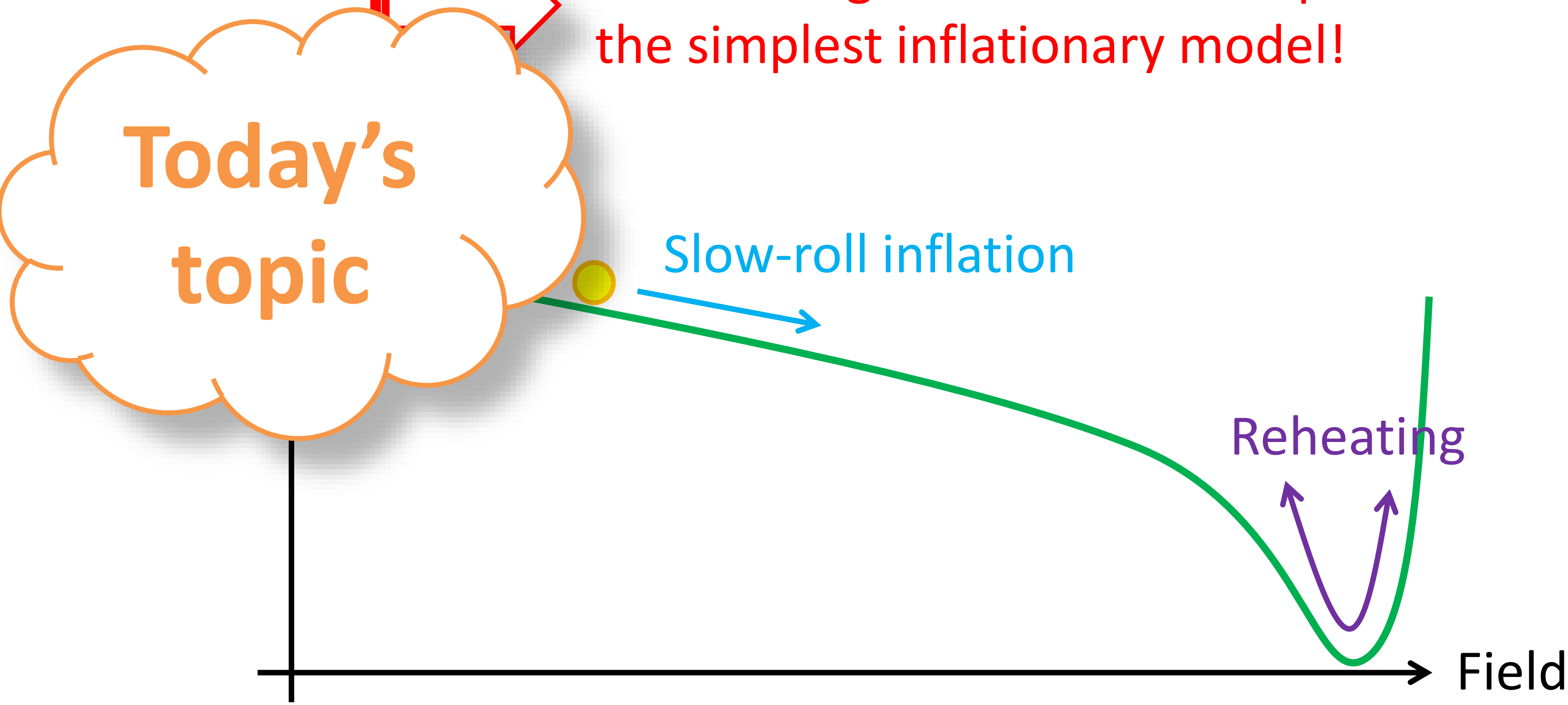
INTRODUCTION

Inflation

- Almost scale invariant spectrum
- Highly Gaussian fluctuations
- Spatially quite flat

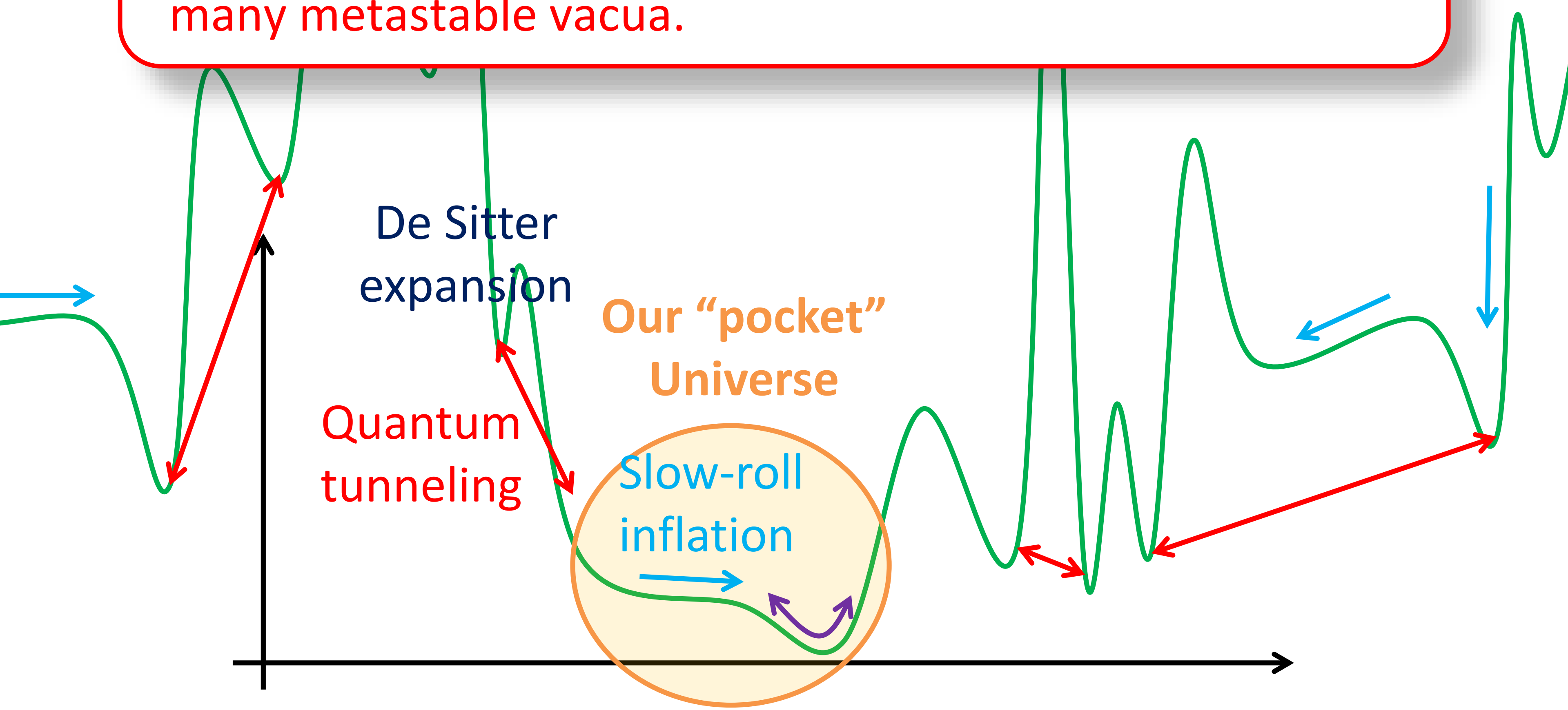
[Planck2015]

⇒ Excellent agreement with the prediction of the simplest inflationary model!

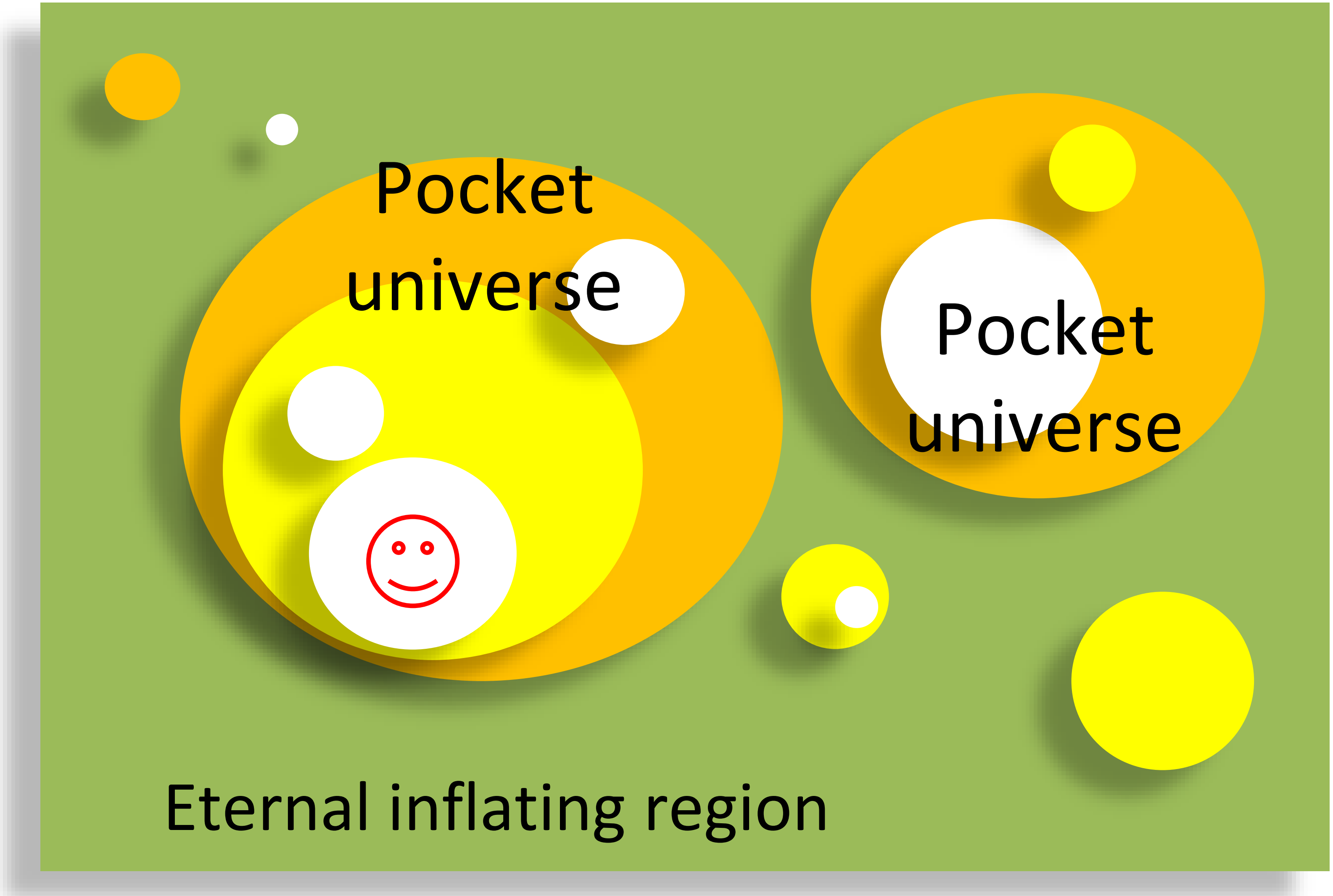


Neighborhood we live in

It is quite possible that our part of the Universe appeared as a result of quantum tunneling after trapped in one of many metastable vacua.



Whole universe



[Bousso+Polchinski (2000), Susskind (2003), Douglas (2003), Kachru+ (2003),…]

String theorists consider…

$O(10^{500})$ metastable dS states with different properties depending on vev of scalar fields, compactifications,…

“String landscape” picture

The inflationary multiverse becomes divided into an exponentially large number of different exponentially large “pocket universes” with different laws of low-energy physics operating in each of them.

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

*Revisit "**Open Inflation**" !*

Plan

1. Introduction (finish)

2. Open inflation

3. Recent developments

    3.1. Effect of rapid-rolling

    3.2. CMB asymmetry

4. Future prospects

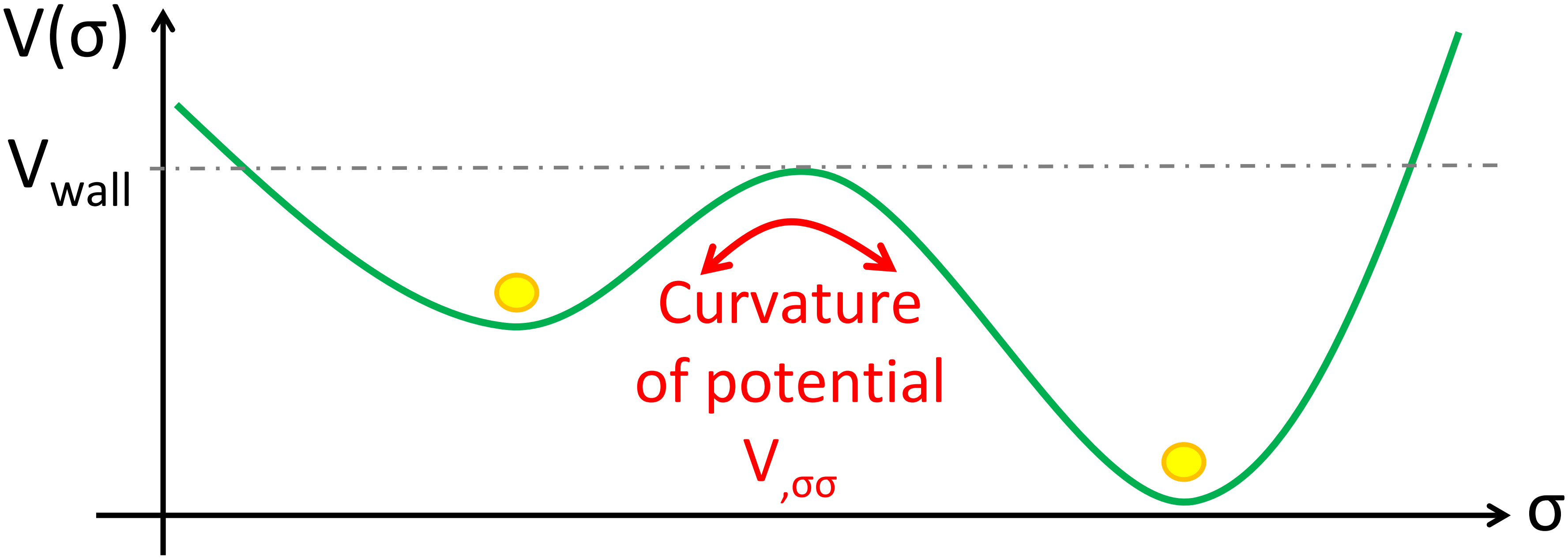
Part 2

OPEN INFLATION –BACKGROUND EVOLUTION–

[Jensen+Steinhardt(1984)]

Two possibilities

M_{Pl}=1 unit

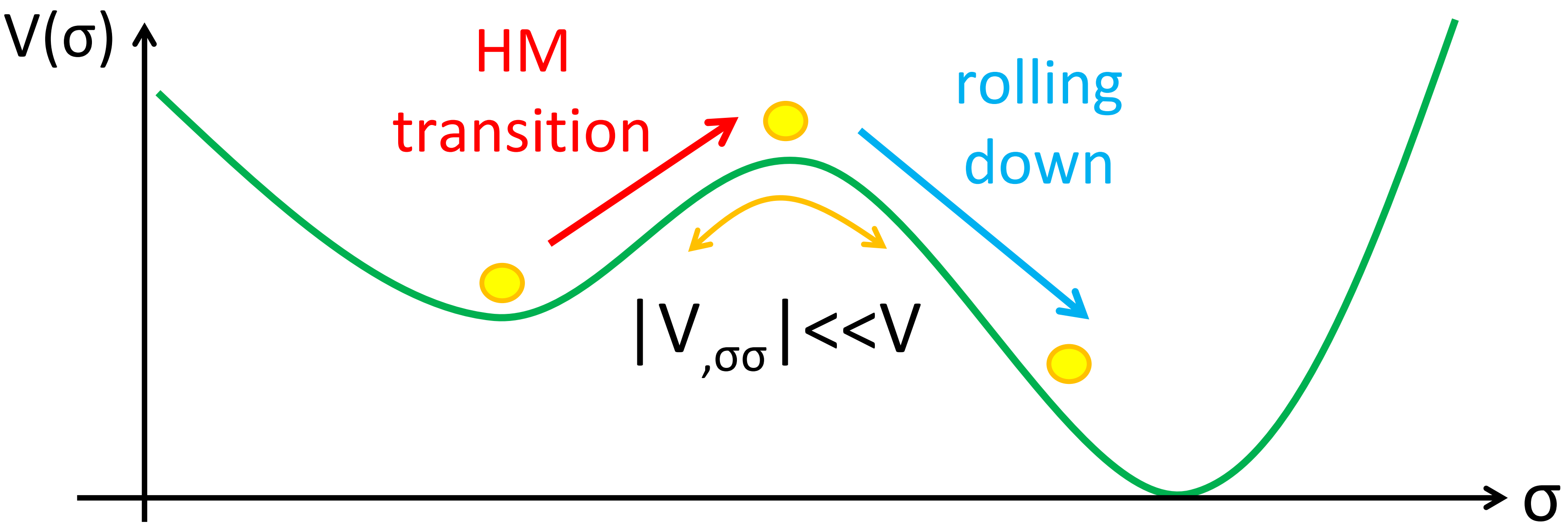


- $|V_{,\sigma\sigma}| \ll V_{\mathrm{wall}} \rightarrow$ Hawking-Moss tunneling
- $|V_{,\sigma\sigma}| \gg V_{\mathrm{wall}} \rightarrow$ Coleman-de Luccia tunneling

[Hawking+Moss(1982)]

Hawking-Moss (HM) tunneling

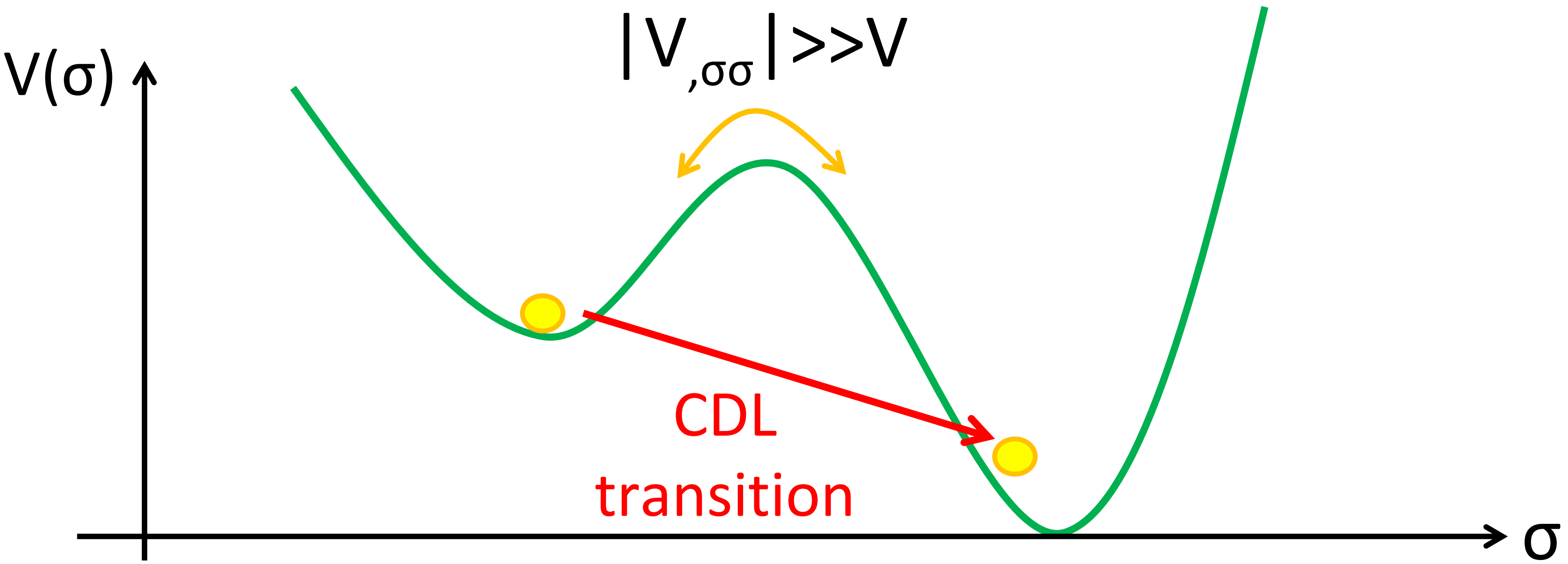
- Tunneling to **a top of the barrier** due to the quantum fluctuations
  - ✓ Too large density perturbations unless e-folds>>60 [Linde(1995)]
    → If the final transition is HM, we can not see any deviation from the standard prediction of slow-roll inflation.



[Coleman+de Luccia(1980)]

Coleman-de Luccia (CDL) tunneling

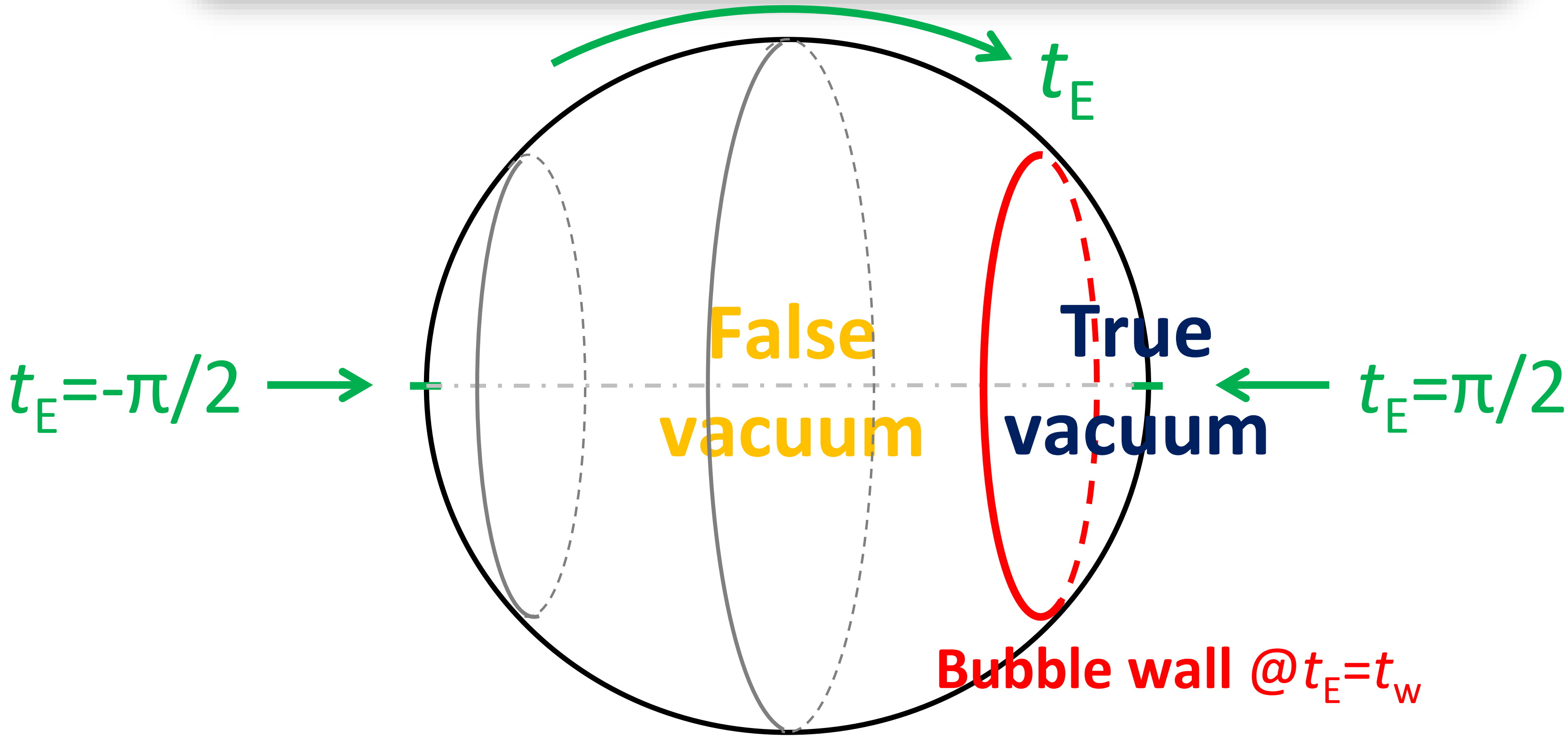
- Tunneling mediated by an ***O*(4)-symmetric solution** of Euclidean Einstein-scalar equations.
  - ✓ Reflecting the symmetry of a tunneling process, the region inside the bubble becomes an ***open*** FLRW universe!



[Coleman+de Luccia(1980)]

O(4) symmetric CDL bounce solution

$$ds^2 = dt_E^2 + \cos^2 t_E \left(dr_E^2 + \sin^2 r_E d\Omega^2\right)$$



✓ Note that an O(4)-sym solution is expected to be most likely to occur (at least in the case of vacuum decay without gravity).

[Coleman+de Luccia(1980)]

Background evolution in CDL

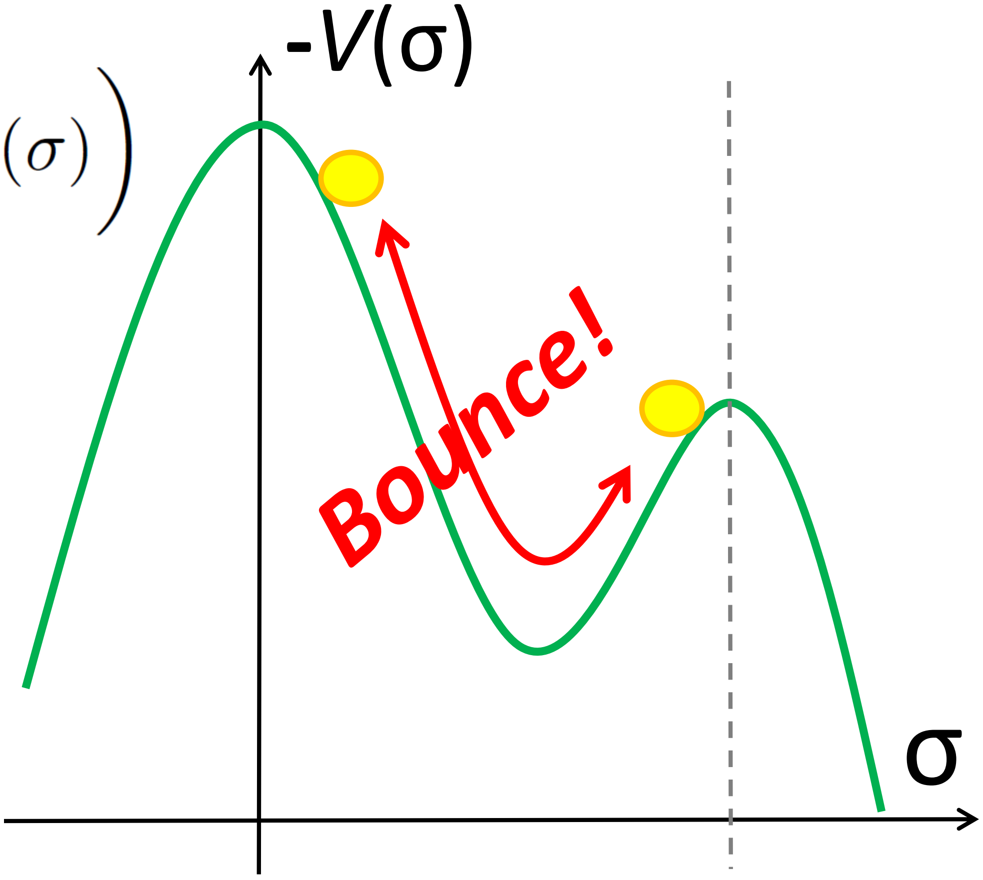
$$ds^2 = dt_E^2 + a^2(t_E)\left(dr_E^2 + \sin^2 r_E d\Omega^2\right)$$

✓ Basic equations

$$\begin{cases} H^2 - \dfrac{1}{a_E^2} = \dfrac{1}{3}\left(\dfrac{1}{2}\dot{\sigma}^2 - V(\sigma)\right) \\ \dot{H} + \dfrac{1}{a_E^2} = -\dfrac{1}{2}\dot{\sigma}^2\,, \\ \ddot{\sigma} + 3H\dot{\sigma} - V' = 0\,. \end{cases}$$

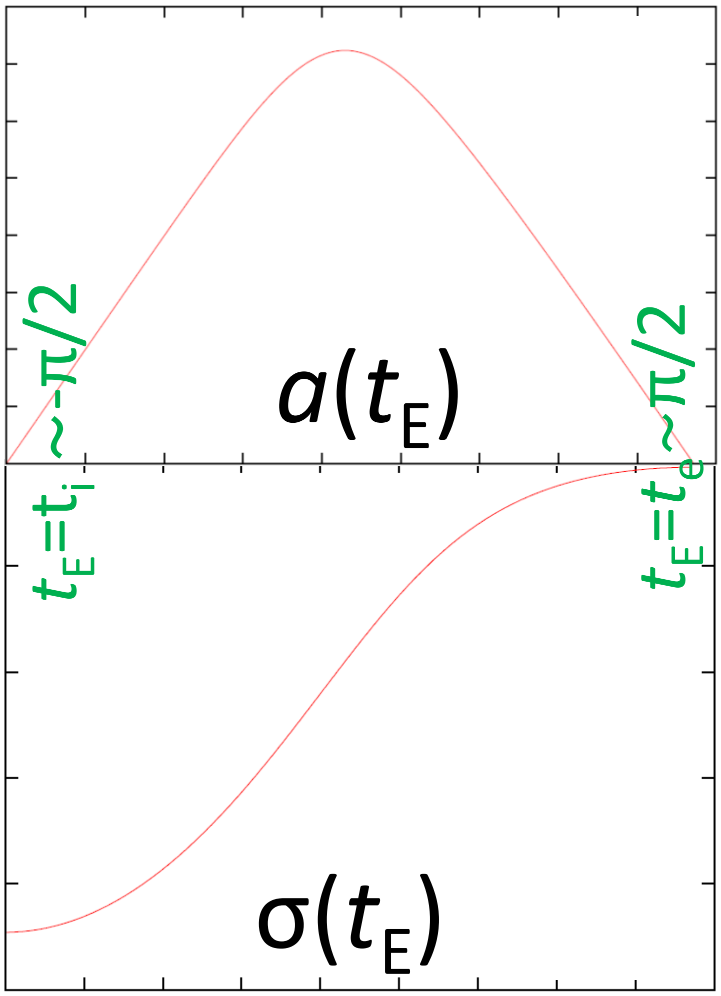
✓ Boundary condition

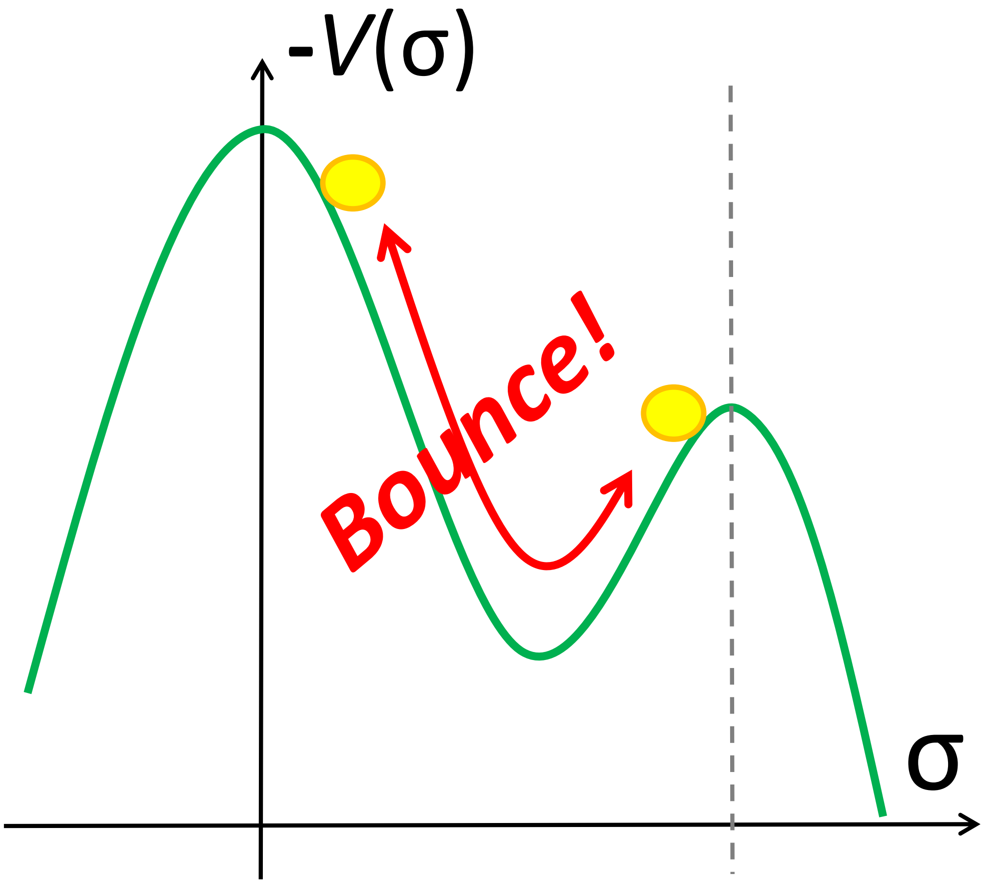
$$\begin{cases} \dot{\sigma}(t_i) = 0\,, \quad \dot{a}(t_i) = 1\,, \\ \dot{\sigma}(t_e) = 0\,, \quad \dot{a}(t_e) = -1\,. \end{cases}$$



[Coleman+de Luccia(1980)]

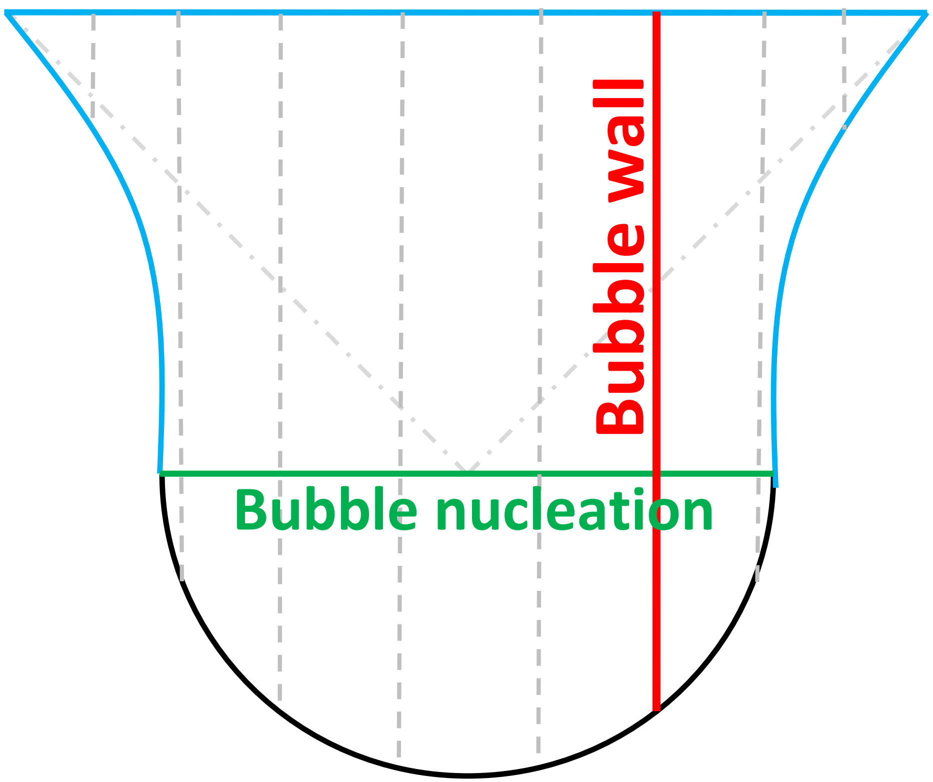
Background evolution in CDL





Geometry after CDL

are obtained by analytic continuation of an CDL solution from Euclidean to Lorentzian:



$$-T^2 + R^2 = 1/H^2$$

Hyperbolic

$$T_E^2 + R^2 = 1/H^2$$

Spherical

[Sasaki+Tanaka+Yamamoto(1994), Bucher+Goldhaver+Turok(1995),...]

$$X^2+Y^2+Z^2+U^2+T_E^2=H^{-2}$$

$T_E=\cos[t_E]\cos[r_E]$

$U=\sin[t_E]$

$Z=\cos[t_E]\sin[r_E]\cos[\theta]$

$X=\cos[t_E]\sin[r_E]\sin[\theta]\cos[\phi]$

$Y=\cos[t_E]\sin[r_E]\sin[\theta]\sin[\phi]$

$T_E \rightarrow i\,T$

$$\begin{cases} t_E = -i\,t_R+\pi/2 = t_C \\ r_E = -i\,r_R = -i\,r_C+\pi/2 \end{cases}$$

$$X^2+Y^2+Z^2+U^2-T^2=H^{-2}$$

$T=\sinh[t_R]\cosh[r_R]$

$U=\cosh[t_R]$

$Z=\sinh[t_R]\sinh[r_R]\cos[\theta]$

$X=\sinh[t_R]\sinh[r_R]\sin[\theta]\cos[\phi]$

$Y=\sinh[t_R]\sinh[r_R]\sin[\theta]\sin[\phi]$

$T=\sinh[r_C]\cos[t_C]$

$U=\sin[t_C]$

$Z=\cosh[r_C]\cos[t_C]\cos[\theta]$

$X=\cosh[r_C]\cos[t_C]\sin[\theta]\cos[\phi]$

$Y=\cosh[r_C]\cos[t_C]\sin[\theta]\sin[\phi]$

Geometry after CDL

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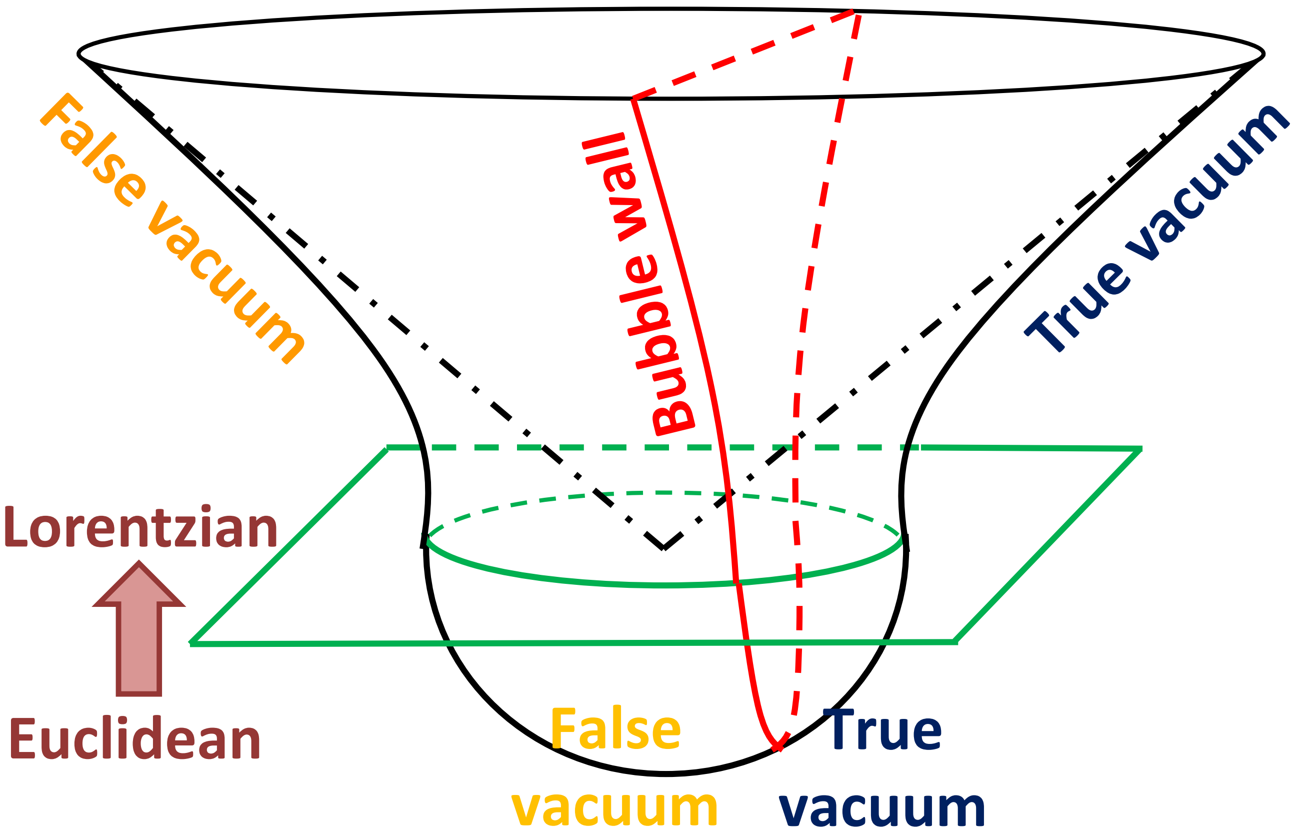
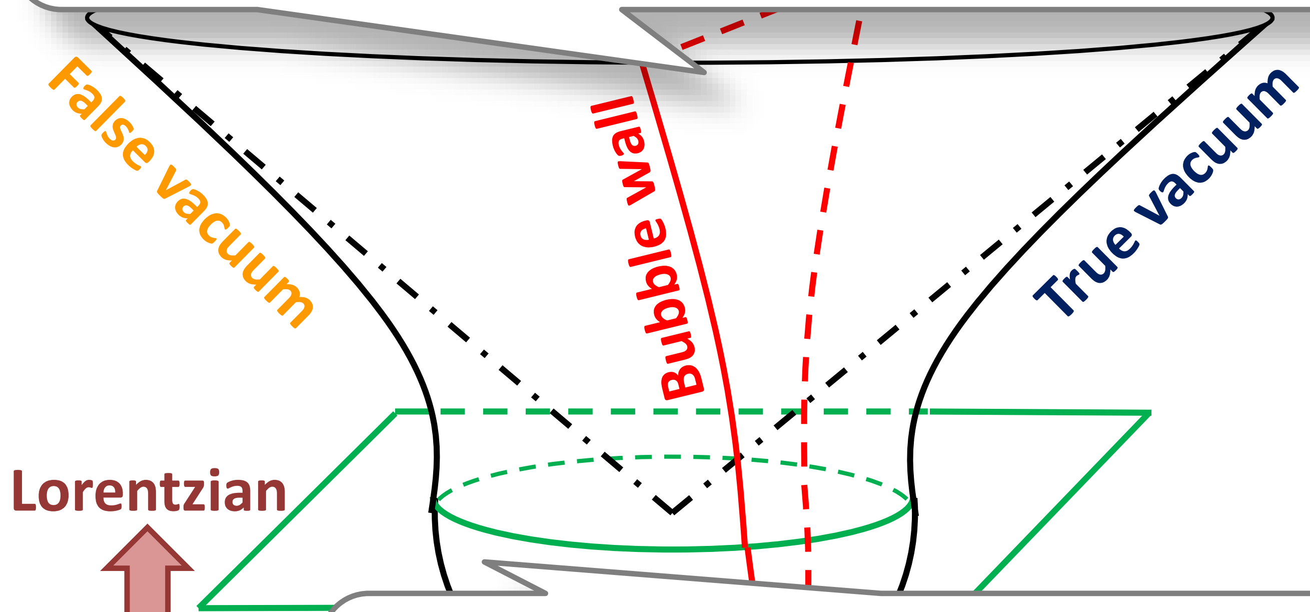


Geometry after CDL

ar
fr

Open-slice of de Sitter [O(3,1) sym]

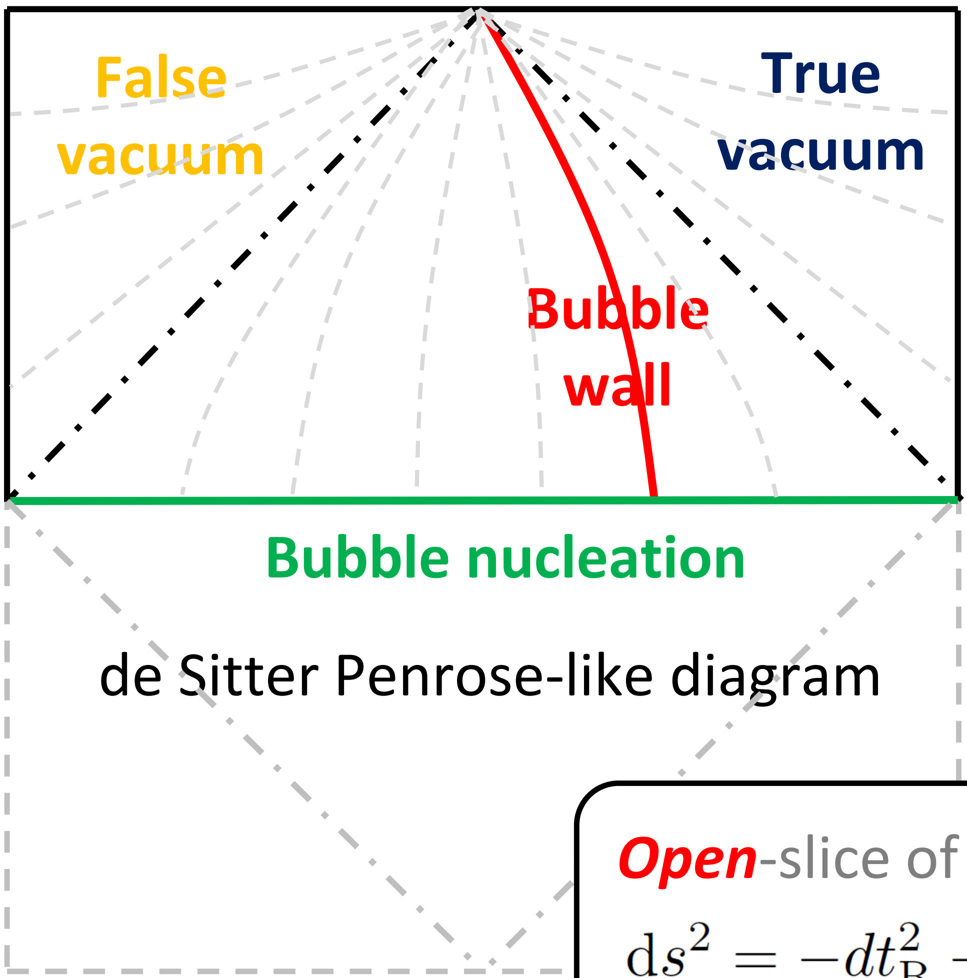
$$ds^2 = -dt_{\rm R}^2 + \sinh^2 t_{\rm R}\left(dr_{\rm R}^2 + \sinh^2 r_{\rm R} d\Omega^2\right)$$

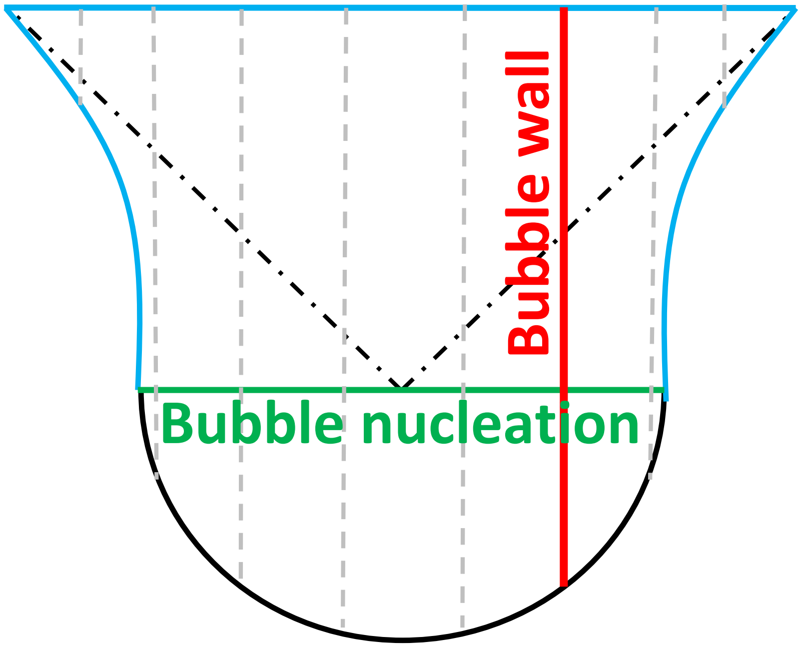


CDL solution [O(4) sym]

$$ds^2 = dt_{\rm E}^2 + \cos^2 t_{\rm E}\left(dr_{\rm E}^2 + \sin^2 r_{\rm E} d\Omega^2\right)$$

Geometry after CDL



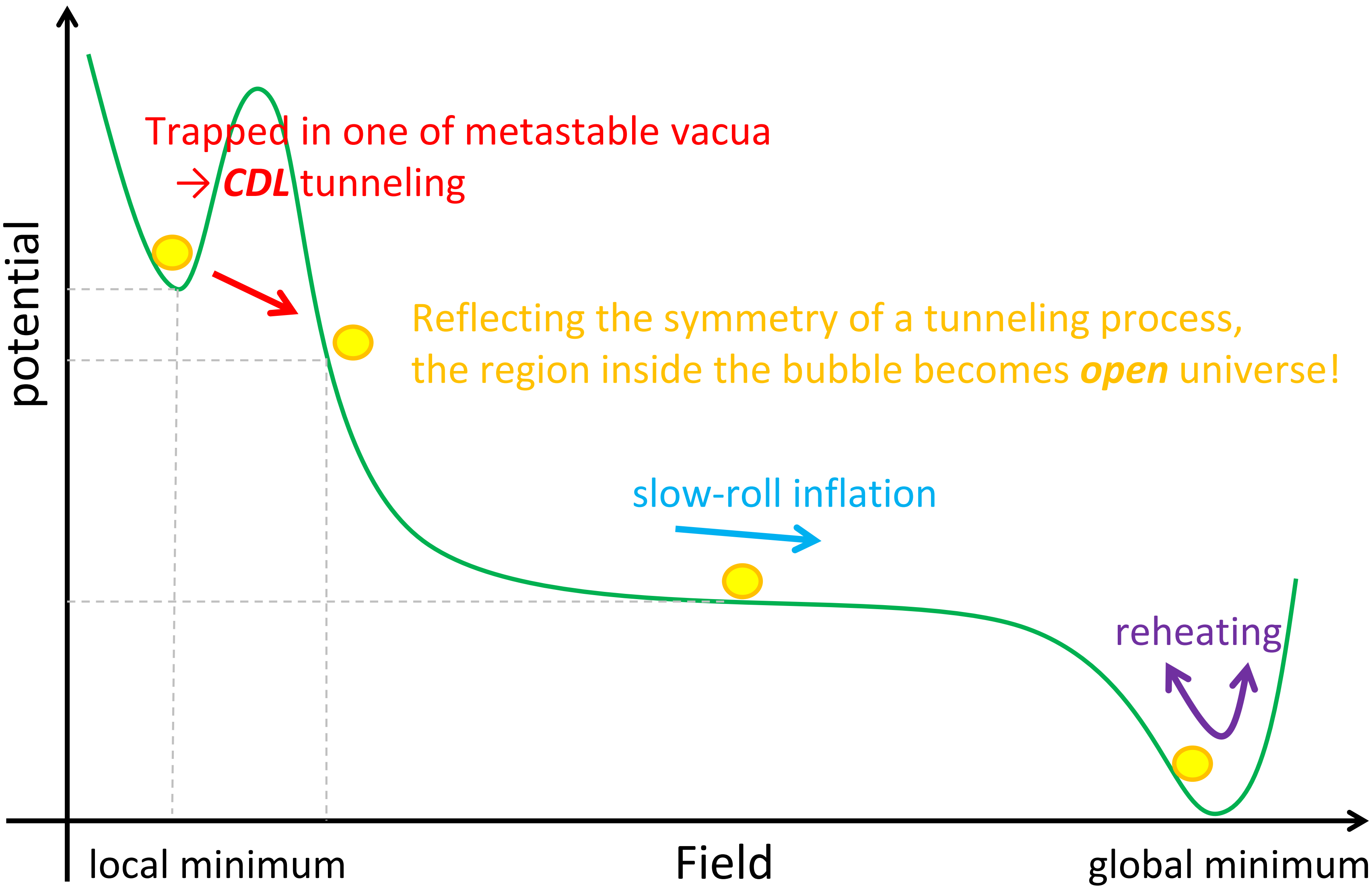


Open-slice of de Sitter [O(3,1) sym]

$$\mathrm{d}s^2 = -dt_\mathrm{R}^2 + \sinh^2 t_\mathrm{R} \left(\mathrm{d}r_\mathrm{R}^2 + \sinh^2 r_\mathrm{R} \mathrm{d}\Omega^2\right)$$

[Gott III (1982), Got III+Statler (1984),Sasaki+Tanaka+Yamamoto+Yokoyama (1993), …]

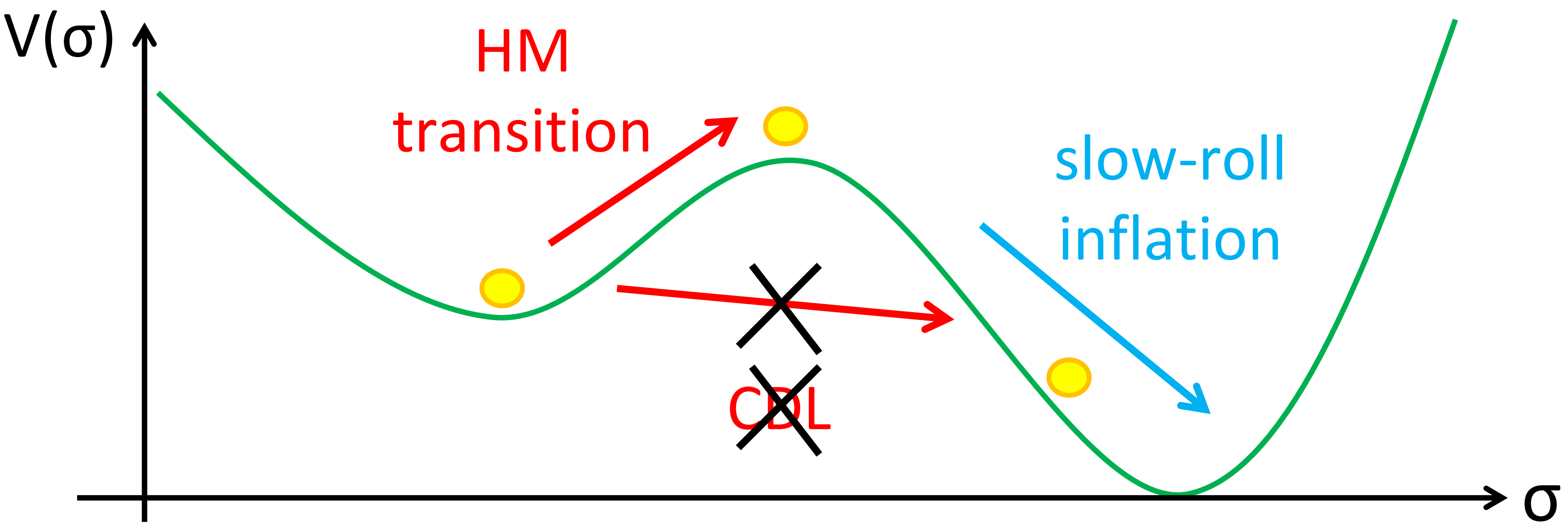
Open Inflation



Ex. 1 : Simplest polynomial potential

$$V(\sigma) = \frac{m^2}{2}\sigma^2 - \frac{\delta}{3}\sigma^3 + \frac{\lambda}{4}\sigma^4$$

- $|V_{,\sigma\sigma}| < 4H^2$: HM tunneling [Linde (1999)]
- The condition for CDL and subsequent slow-roll inflation are not easily satisfied at the same time !



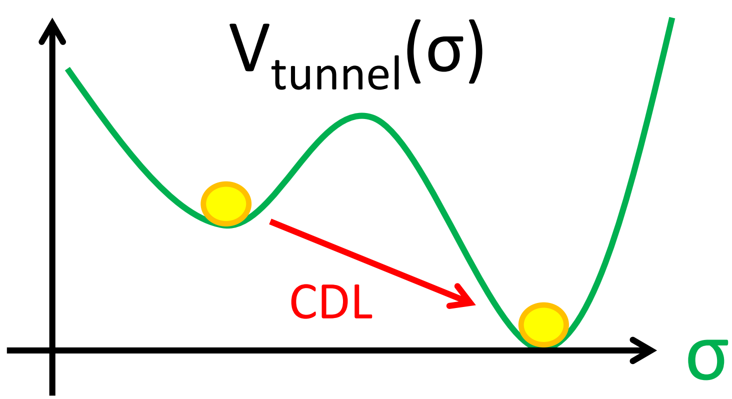
[Linde+Linde+Mezhlumian (1995)]

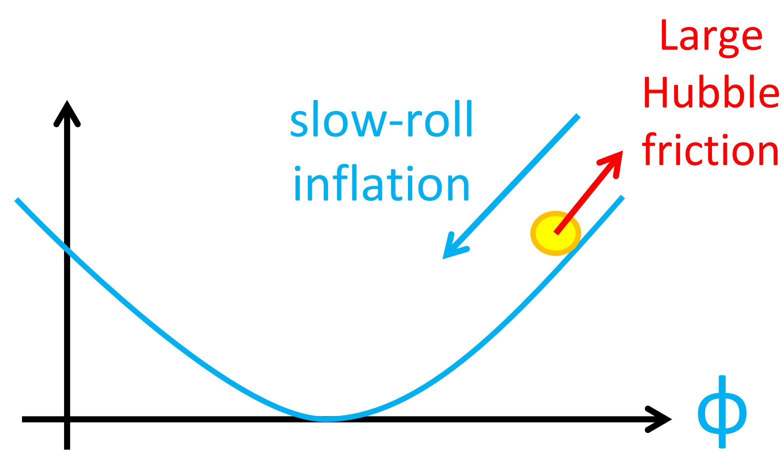
Ex. 2 : Simple two-field model

- Naturally/easily realized in the landscape
  - σ : heavy field → false vacuum decay
  - ϕ : light field → starts rolling after FV decay

$$V(\sigma,\phi) = V_{tunnel}(\sigma)+m^2\phi^2/2$$

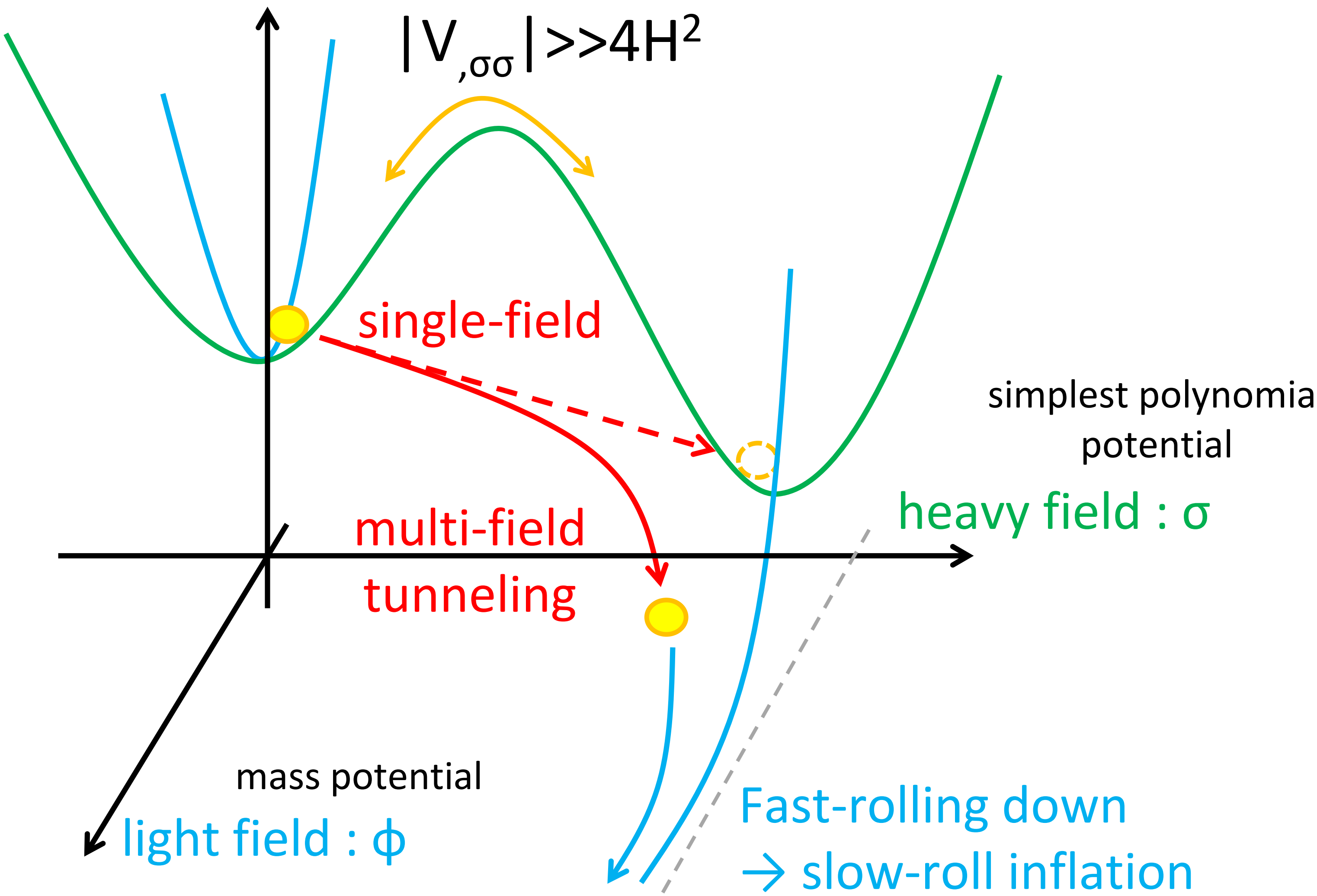
✓ Too large perturbations from supercurvature mode of ϕ unless e-folds>>60 [Sasaki+Tanaka(1996)]





[Sugimura+**DY**+Sasaki, 1110.4773]

Ex. 3 : Multi-field tunneling and inflation



[Sugimura+**DY**+Sasaki, 1110.4773]

Ex. 3 : Tunneling rate ~exp(-*B*)

Mass of light-field ϕ at TV

multi-CDL **effective single-CDL** **HM** **(multi) - (single)**

$m_\phi[m_{\rm pl}]$	$\Delta\sigma[m_{\rm pl}]$	$\Delta\phi[m_{\rm pl}]$	B	B_0	$B_{\rm HM}$	$\Delta B = B - B_0$
10^{-6}	1.91	2.20×10^{-10}	12109.11	12109.11	12679.69	$\lvert\Delta B\rvert < 0.01$
10^{-4}	1.91	2.20×10^{-6}	12108.10	12108.10	12678.65	$\lvert\Delta B\rvert < 0.01$
10^{-3}	1.91	2.19×10^{-4}	12008.71	12008.71	12576.67	$\lvert\Delta B\rvert < 0.01$
5×10^{-3}	1.90	5.34×10^{-3}	9975.05	9975.07	10484.43	-0.02
10^{-2}	1.87	1.97×10^{-2}	6322.66	6322.85	6691.28	-0.19
2×10^{-2}	1.73	6.00×10^{-2}	2188.07	2189.41	2305.67	-1.35
3×10^{-2}	1.38	8.73×10^{-2}	849.20	852.07	868.55	-2.87
4×10^{-2}	0.49	4.58×10^{-2}	372.15	376.39	372.28	-4.25

Multi-field dynamics tends to increase the tunneling-rate (?).

Part 2

OPEN INFLATION –FLUCTUATIONS–

Quantization

Step 1

We need to find the reduced action that contains only the physical degree of freedom.

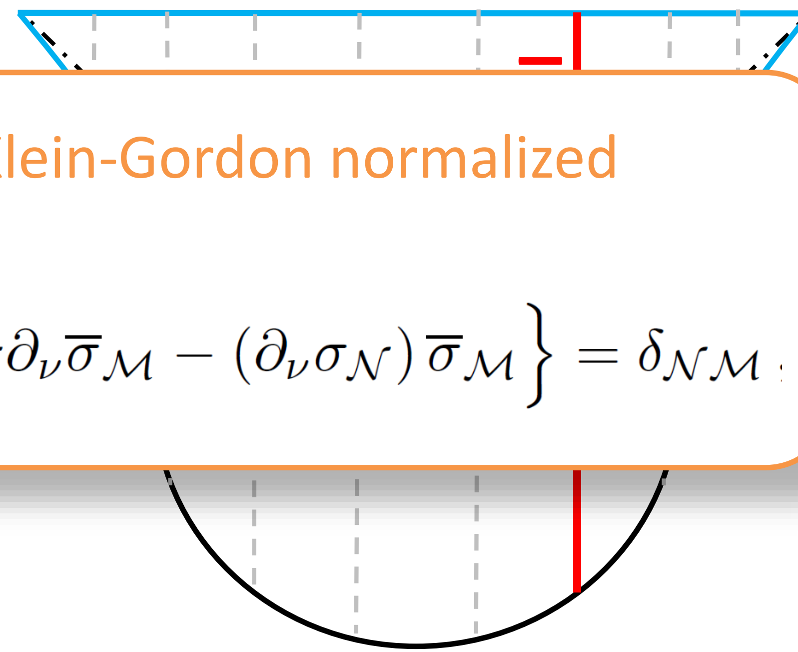
Ex) Simple scalar field

$$S = \int \mathrm{d}^4 x \sqrt{-g} \left(-\frac{1}{2} g^{\mu\nu} \partial_\mu \sigma \partial_\nu \sigma - \frac{1}{2} m^2(\eta)\, \sigma^2 \right)$$

Quantization

Step 2

We need to find ***a complete set of functions*** which obey the field equation and which ***are regular on the lower hemisphere***.



A set of all modes which can be Klein-Gordon normalized on a ***Cauchy surface***

$$(\sigma_{\mathcal{N}}, \sigma_{\mathcal{M}})_{\mathrm{KG}} = -i \int_{\Sigma} \mathrm{d}\Sigma_{\mu}\, g^{\mu\nu} \left\{ \sigma_{\mathcal{N}} \partial_{\nu} \overline{\sigma}_{\mathcal{M}} - (\partial_{\nu} \sigma_{\mathcal{N}})\, \overline{\sigma}_{\mathcal{M}} \right\} = \delta_{\mathcal{N}\mathcal{M}} \,;$$

Quantization

Step 3

We promote the physical degree of freedom to operator and expand it by mode functions $\{\sigma_N, \overline{\sigma_N}\}$ as

$$\widehat{\sigma} = \sum_{\mathcal{N}} \left[\widehat{a}_{\mathcal{N}} \sigma_{\mathcal{N}} + \widehat{a}^{\dagger}_{\mathcal{N}} \overline{\sigma}_{\mathcal{N}} \right]$$

$$[\hat{a}_{\mathcal{N}}, \hat{a}^{\dagger}_{\mathcal{M}}] = \delta_{\mathcal{N}\mathcal{M}}$$

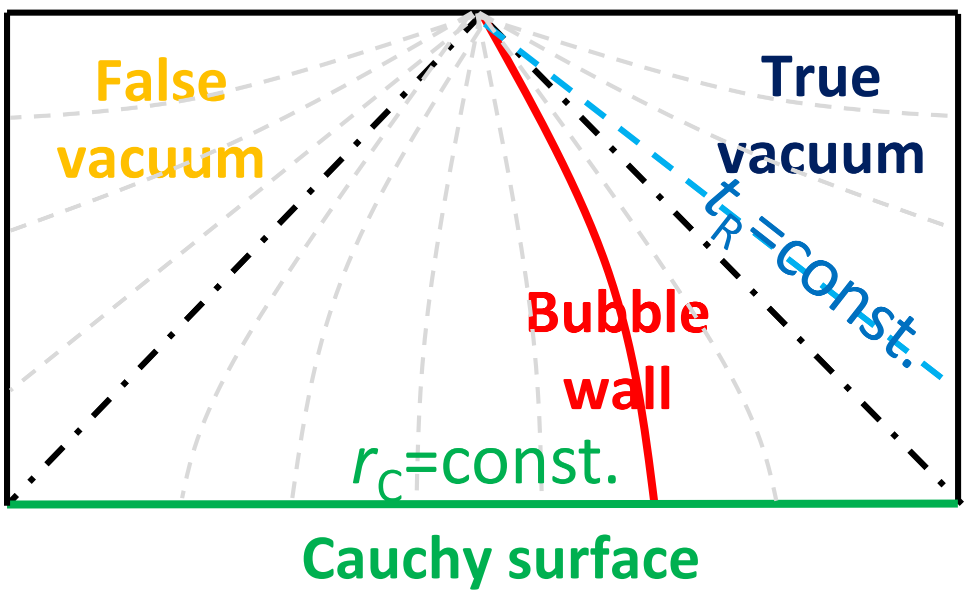
⇨ Mode function σ_N plays the role of positive frequency functions!

[For massive U(1) field, **DY**+Fujita+Mukohyama, 1402.2784]

Difficulty in quantization

The surfaces which respect the maximal sym. (t_R=const.)
are not the Cauchy surface of the whole spacetime.

⇒ We need to work in the center region (r_C=const.), where the background configuration is spatially inhomogenous.



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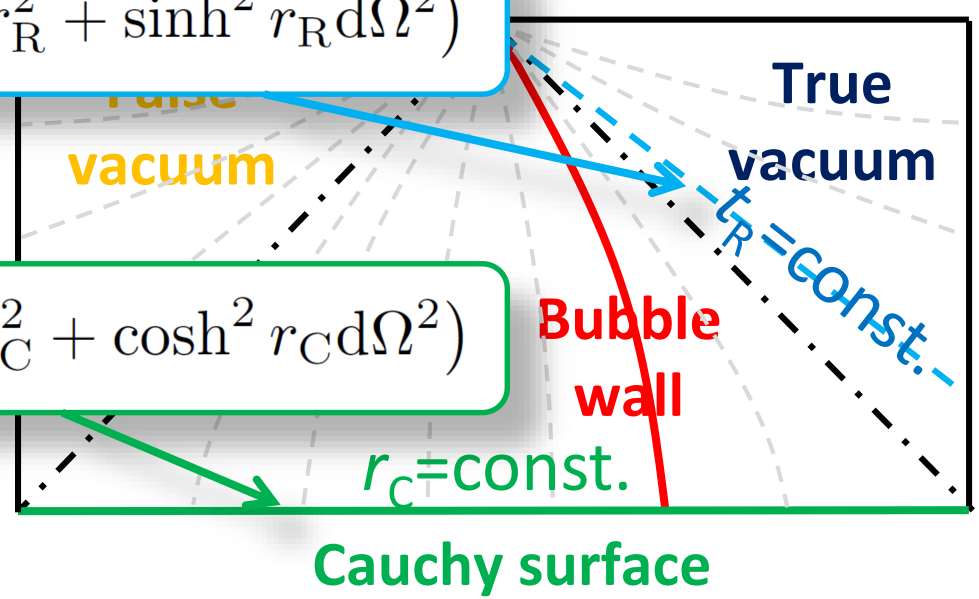
Difficulty in quantization

The surfaces which respect the maximal sym. (t_R=const.) are not the Cauchy surface of the whole spacetime.

⇒ We need to work in the center region (r_C=const.), where the background configuration is spatially inhomogenous.

$$ds^2 = -dt_R^2 + \sinh^2 t_R \left(dr_R^2 + \sinh^2 r_R d\Omega^2\right)$$

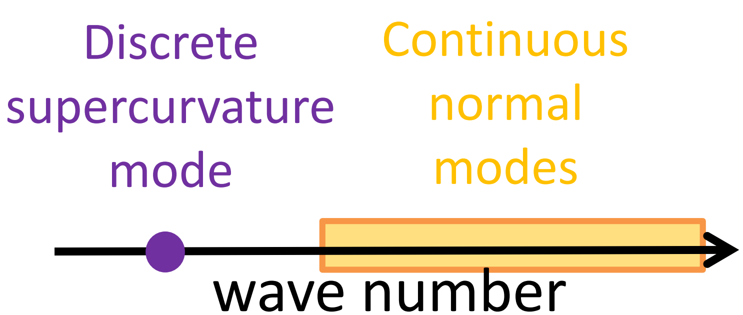
$$ds^2 = dt_C^2 + \cos^2 t_C \left(-dr_C^2 + \cosh^2 r_C d\Omega^2\right)$$

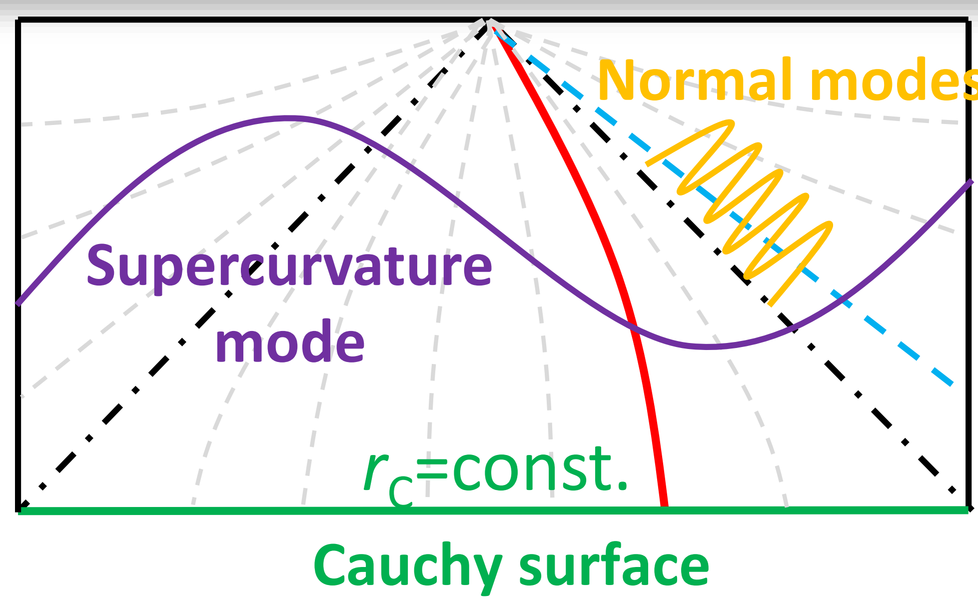


(Discrete) supercurvature mode

There could appear a set of modes which have finite KG norms on Cauchy surfaces, but which ***cannot be quantized on the open chart*** because of the divergent KG norms on the open chart.

$$(\sigma_{\mathcal{N}},\sigma_{\mathcal{M}})_{\mathrm{KG}} = -i\int_{-\infty}^{\infty} \mathrm{d}\eta_{\mathrm{C}} \int \mathrm{d}\Omega\, a^2(\eta_{\mathrm{C}}) \Big\{ \sigma_{\mathcal{N}}\partial_{r_{\mathrm{C}}}\overline{\sigma}_{\mathcal{M}} - (\partial_{r_{\mathrm{C}}}\sigma_{\mathcal{N}})\overline{\sigma}_{\mathcal{M}} \Big\} = \delta_{\mathcal{N}\mathcal{M}}$$





(Discrete) supercurvature mode

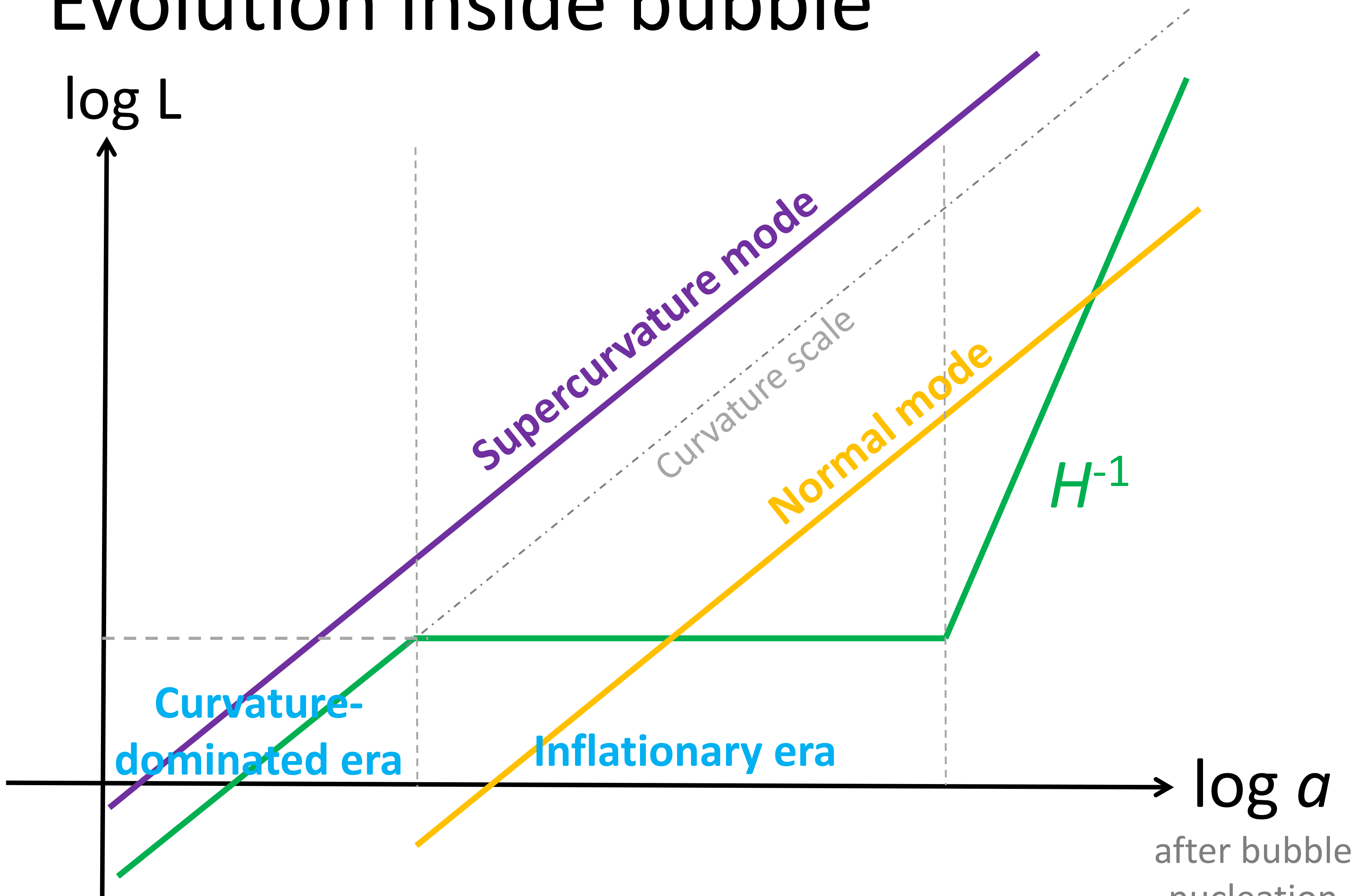
There could appear a set of modes which have finite KG norms on Cauchy surfaces, but which ***cannot be quantized on the open chart*** because of the divergent KG norms on the open chart.

- Canonical scalar field ⟶ × (for $m > 3H/2$) / ○ (for $m \leqq 3H/2$)
  [Sasaki+Tanaka+Yamamoto (1995)]

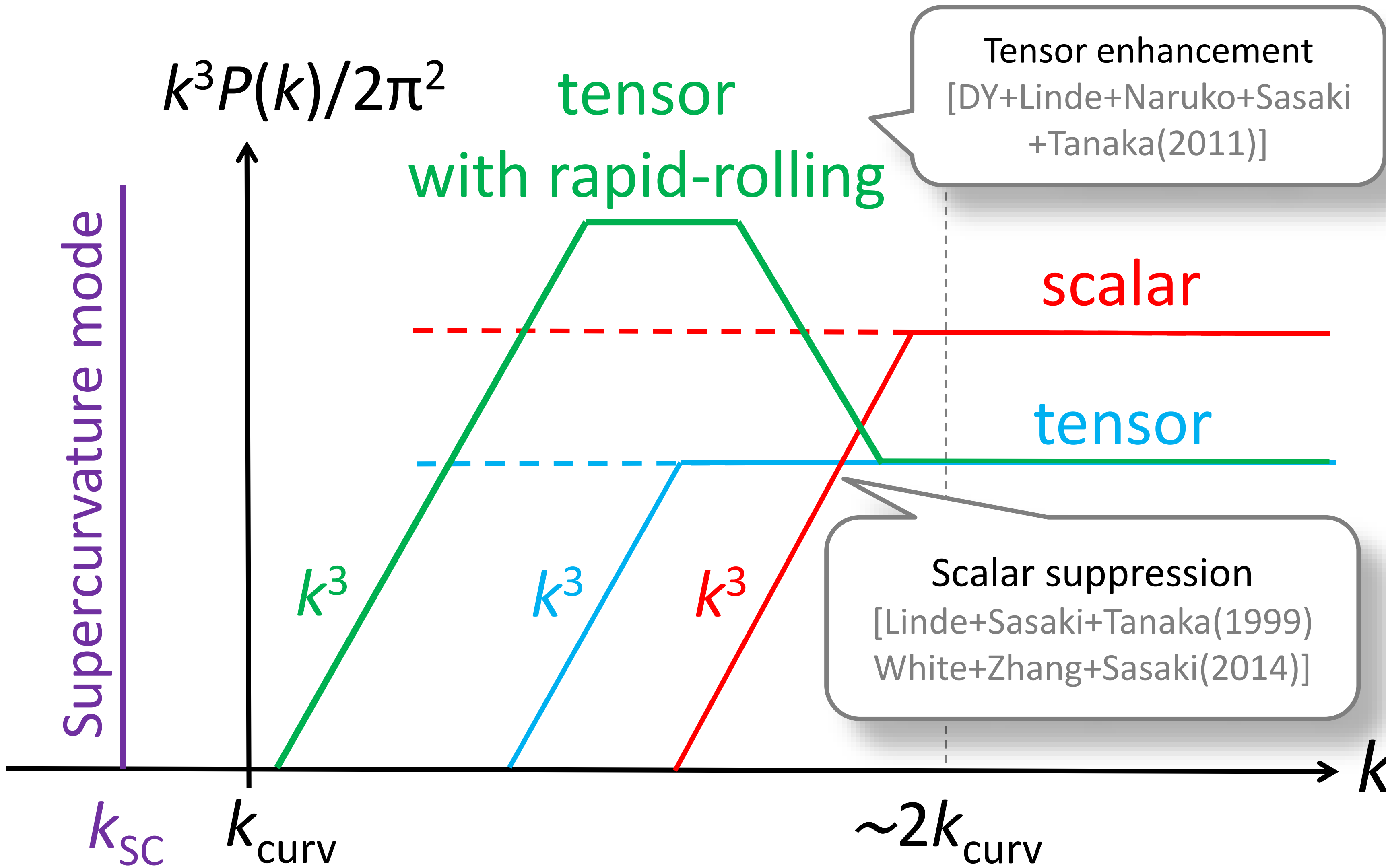
  $k_{SC}{}^2 \simeq (2m^2/3H^2)\, k_{curv}{}^2$

- Tensor perturbations ⟶ ×
  [Tanaka+Sasaki (1997)]
- U(1) gauge field ⟶ ×
  [**DY**+Fujita+Mukohyama, 1402.2784]
- Metric pert.+scalar field ⟶ ? (model-depend)
  [Garriga+Montes+Sasaki+Tanaka(1999)]

Evolution inside bubble



Power spectrum for scalar/tensor



(若干の適当さを含みます)

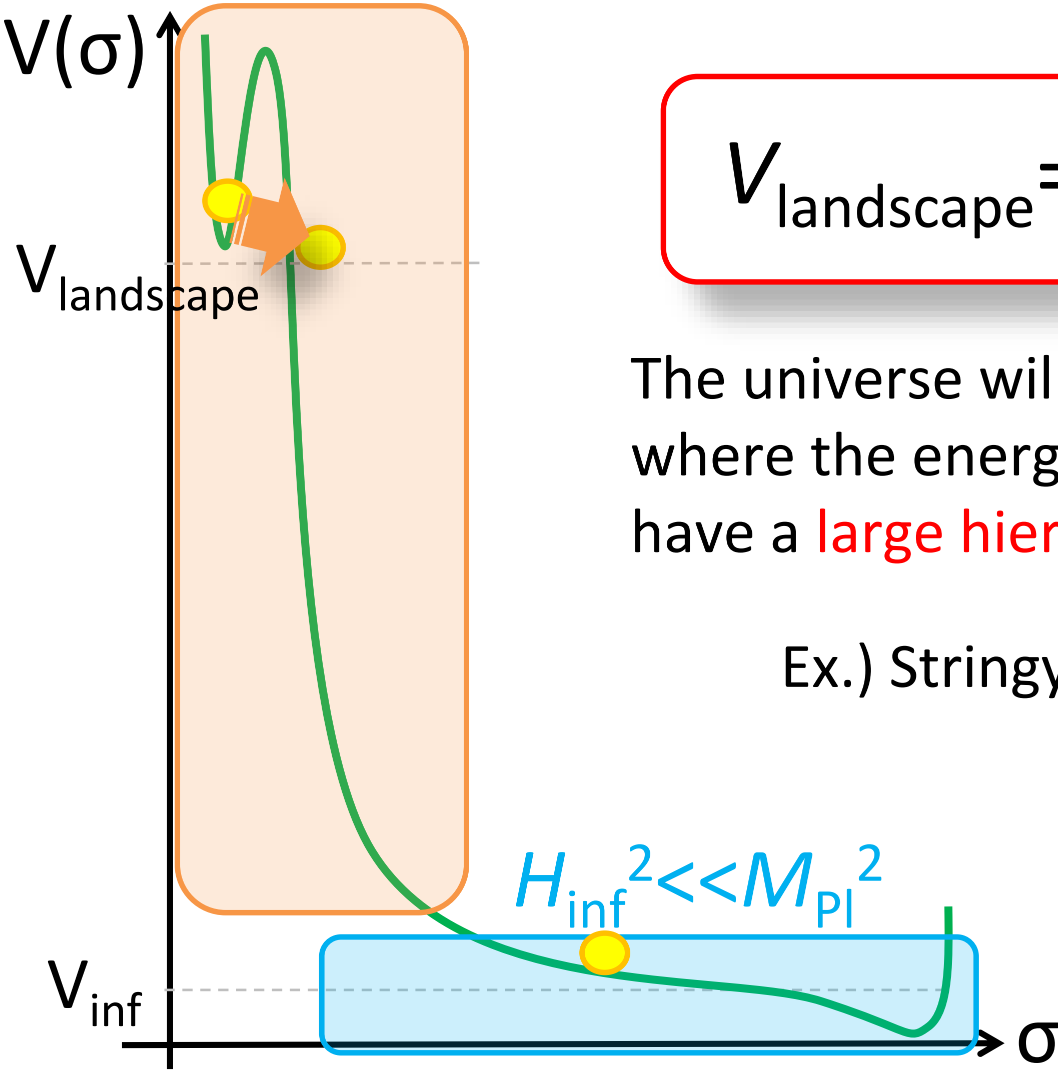
Part 3

RECENT DEVELOPMENTS 1
—SIGNALS FROM STRINGY INFLATION—

Classification for open inflation

Inflation driver $(m<H)$	**Tunneling driver $(m>H)$**	**Curvature pert. ζ**	**Supercurvature mode?**	**note**
σ	σ	σ	$\sigma \to$ ○/×	・Linde(1998) ・Linde+Sasaki+Tanaka(1999) ・Garriga+Montes+Sasaki +Tanaka(1999) ・**DY**+(2011)
σ	ρ	σ	$\sigma \to$ ○	・Linde+Mezhlumian(1995) ・Sasaki+Tanaka(1996) [・tunneling sol : Sugimura+**DY**+Sasaki(2011)]
φ	ρ	σ	$\sigma \to$ ○	
φ	ρ	χ	$\sigma \to$ ○	・Kanno+Sasaki+Tanaka(2013) ・Brnes+Domenech+Sasaki +Takahashi(2016) [・Sugimura+**DY**+Sasaki(2012)]

Requirements for a single-field stringy model



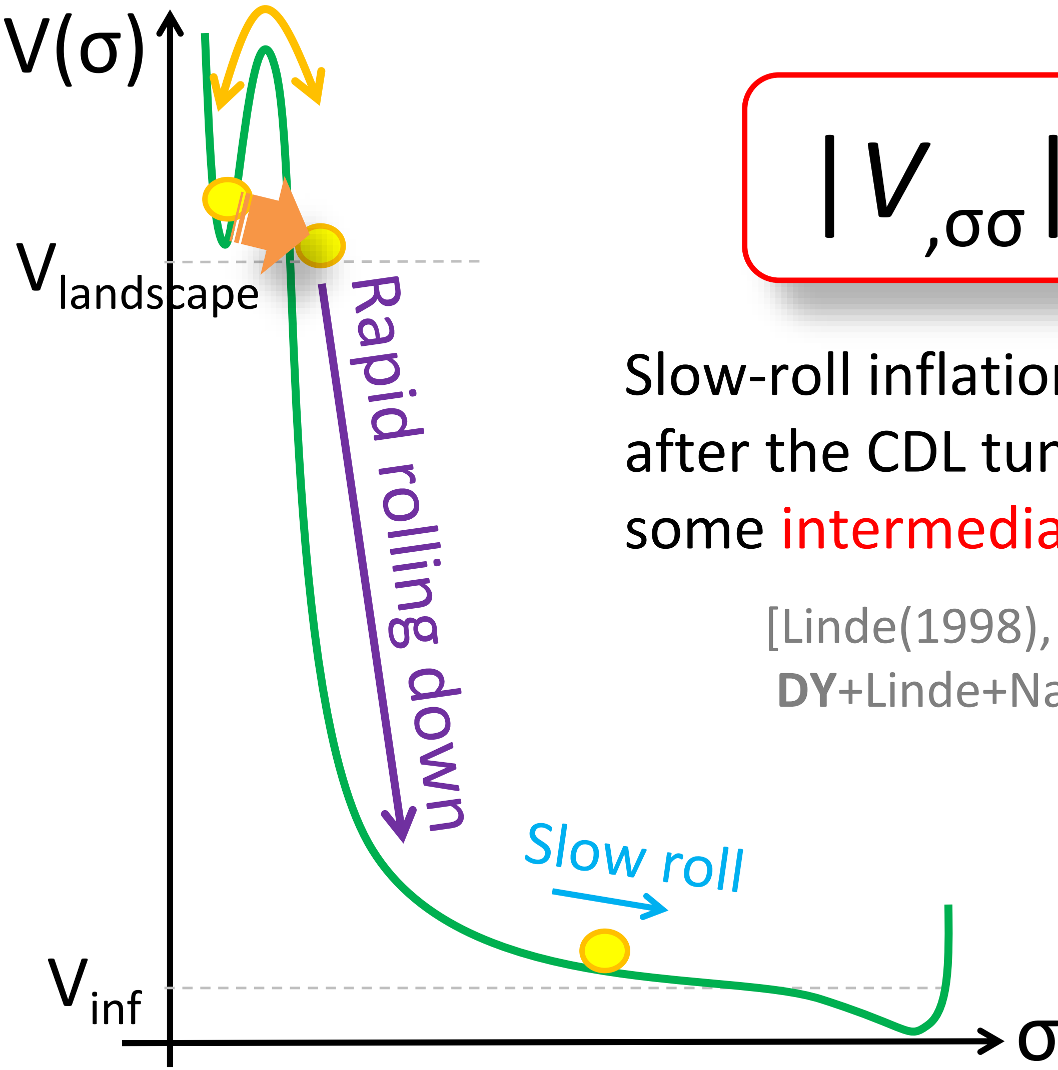
$$V_{\rm landscape} = O(M_{\rm pl}^4) >> V_{\rm inf}$$

The universe will most likely tunnel to a point where the energy scale is still very high and have a large hierarchy between energy scales.

Ex.) Stringy inflation $V_{\rm inf} = O(10^{-30} M_{\rm Pl}^4)$

[Kallosh+Linde(2014)]

Requirements for a single-field stringy model



$$|V_{,\sigma\sigma}| \gg V/M_{Pl}^2$$

Slow-roll inflation does not start immediately after the CDL tunneling, and there must be some intermediate stage of rapid rolling down.

[Linde(1998), Linde+Sasaki+Tanaka(1999), **DY**+Linde+Naruko+Sasaki+Tanaka, 1105.2674]

Tensor-type perturbations

may not be suppressed at all !

$$\langle |h|^2 \rangle \approx \frac{2}{M_{\rm pl}^2} \left(\frac{H}{2\pi} \right)^2$$

Memory of false vacuum may remain in the perturbations on the curvature scale!

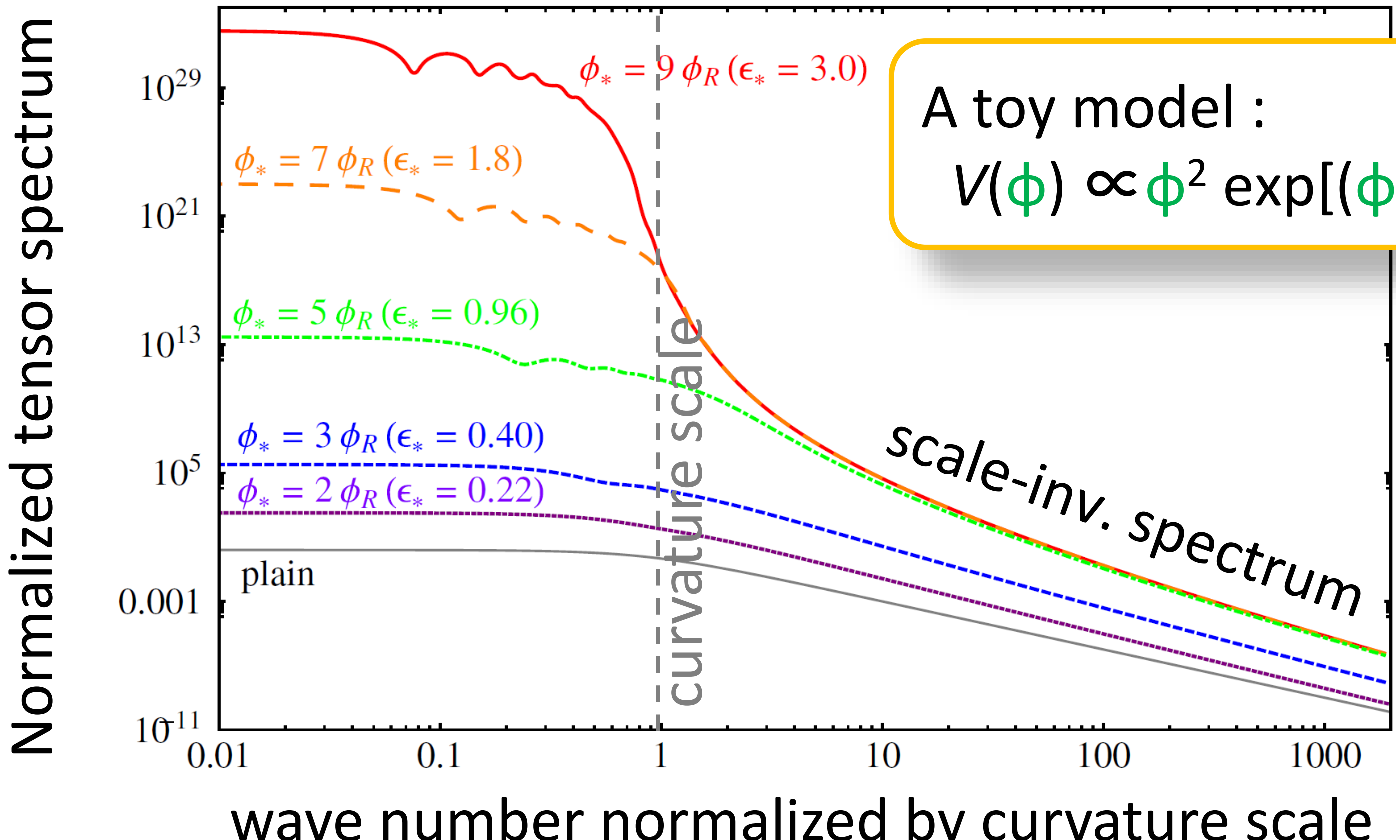
✓ Note : Scalar perturbations may be suppressed by the velocity during RAPID ROLL phase…

$$\langle |\mathcal{R}^2| \rangle \approx \left(\frac{H^2}{2\pi \dot{\phi}} \right)^2$$

[DY+Linde+Naruko+Sasaki+Tanaka,1105.2674]

Primordial tensor spectrum

Keeps the memory of the high energy density in large angular scales, and can be strongly red-tilted.



A toy model :
$V(\phi) \propto \phi^2 \exp[(\phi^2-\phi_R^2)/\phi_R^2]$

Primordial tensor spectrum

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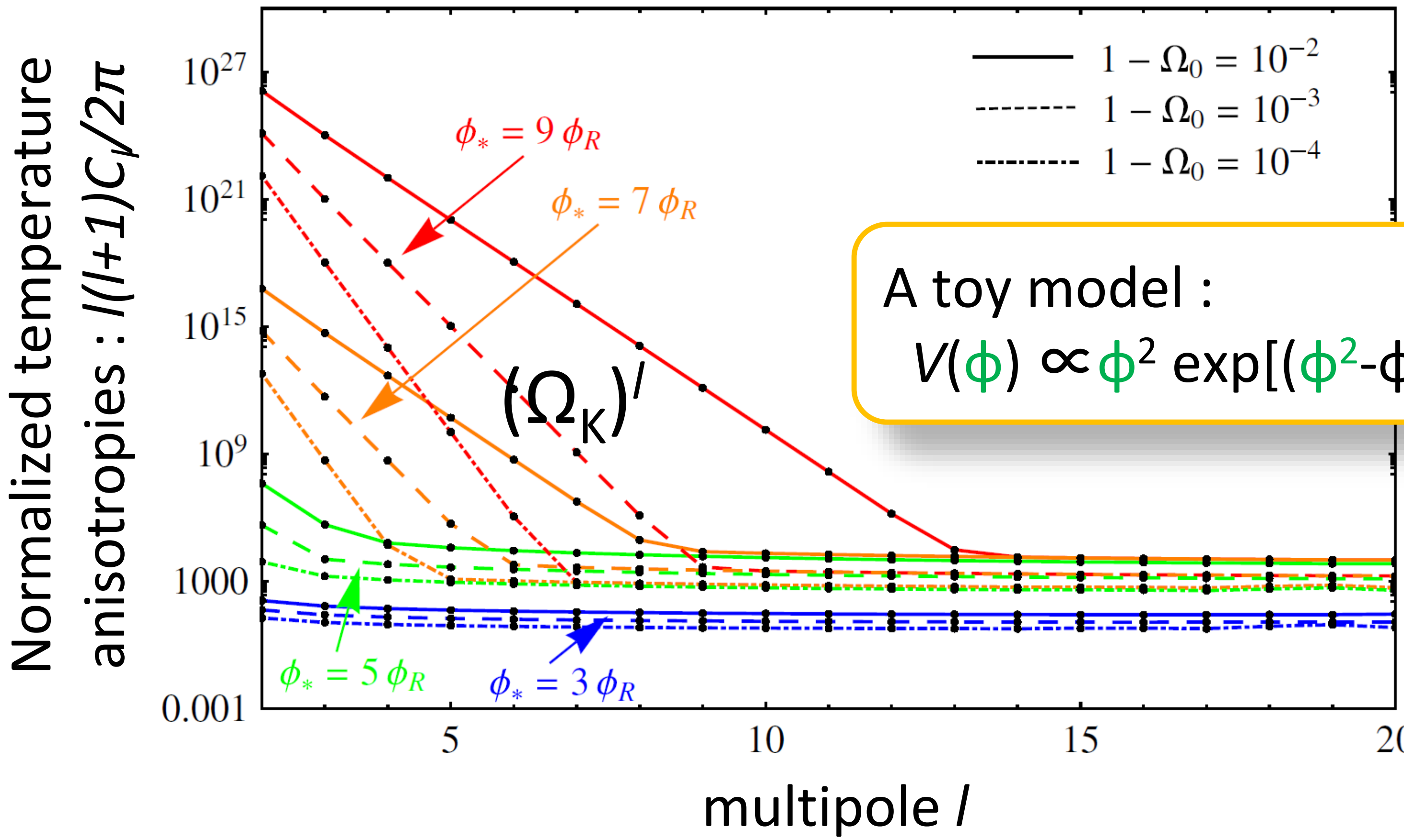


A toy model :
$V(\phi) \propto \phi^2 \exp[(\phi^2-\phi_R^2)/\phi_R^2]$

Part 4

ASYMMETRY FROM OPEN INFLATION

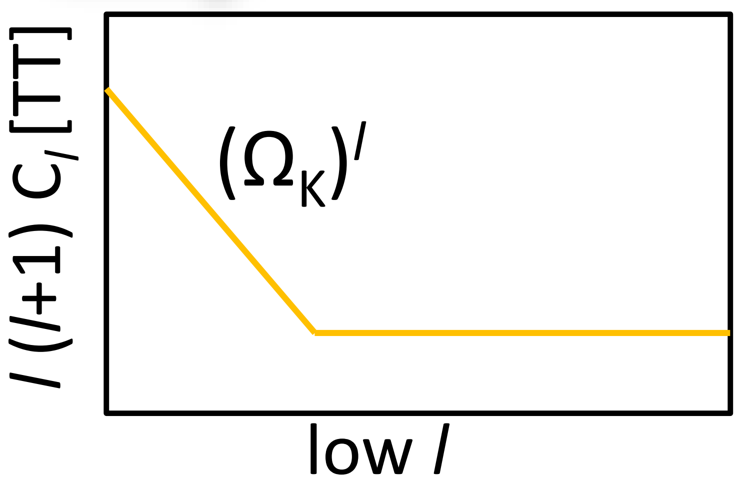
[Zarei+**DY**+Hirouzjahi+Ohta+Naruko+Yamaguchi, work in progress]

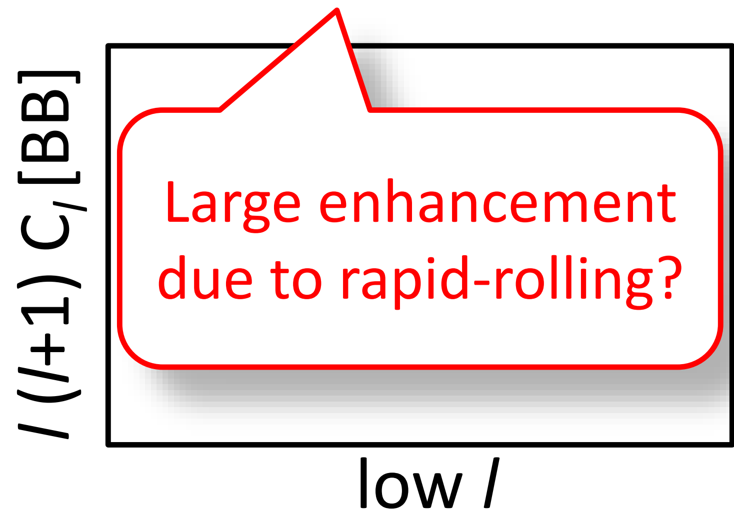
Polarizations from open inflation

- Spatially openness : $\Omega_K=10^{-2}$-10^{-4}
- A complete set of mode functions
  - ✓ (Continuous) normal modes
  - ✓ (Discrete) supercurvature modes

} implement in CAMB code

⇒ CMB temperature + ***polarizations***





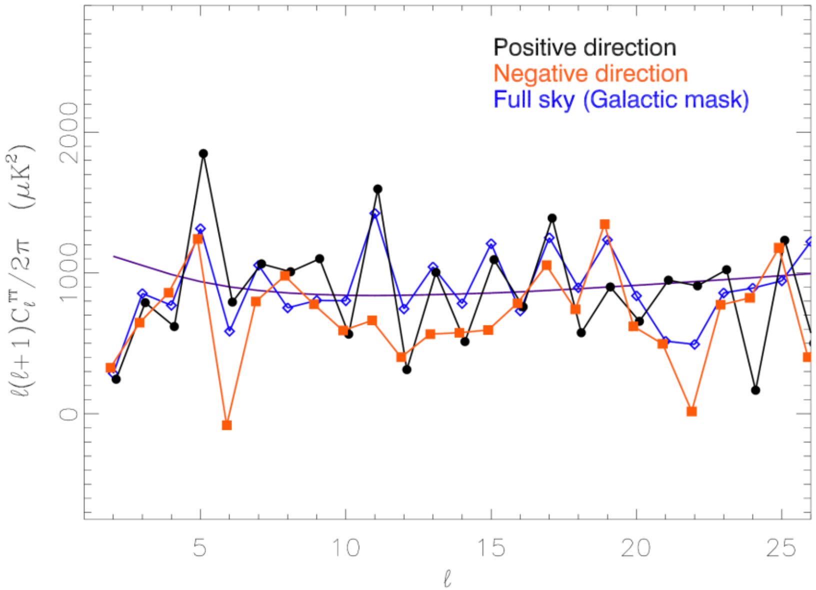
[Planck23 (2013)]

CMB anomalies

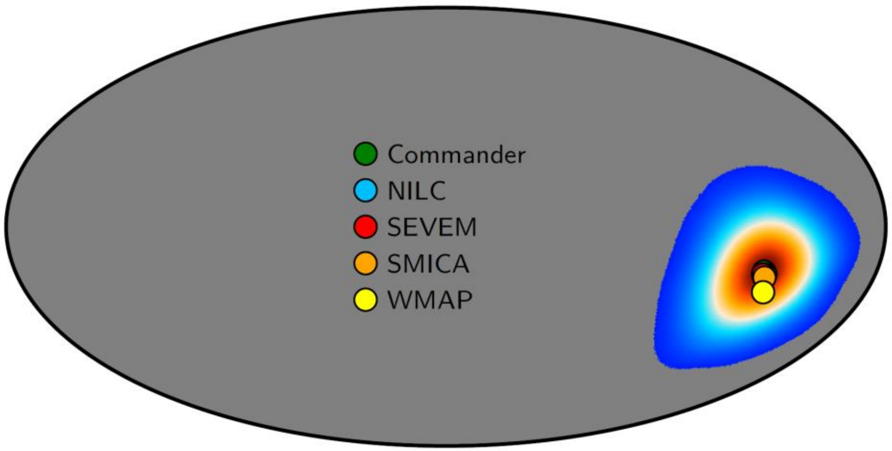
$$\Delta T(\boldsymbol{n}) = (1 + A\,\boldsymbol{p}\cdot\boldsymbol{n})\,\Delta T_{\rm iso}(\boldsymbol{n})$$

$$A = 0.07 \pm 0.02$$

Power asymmetry



Dipole modulation



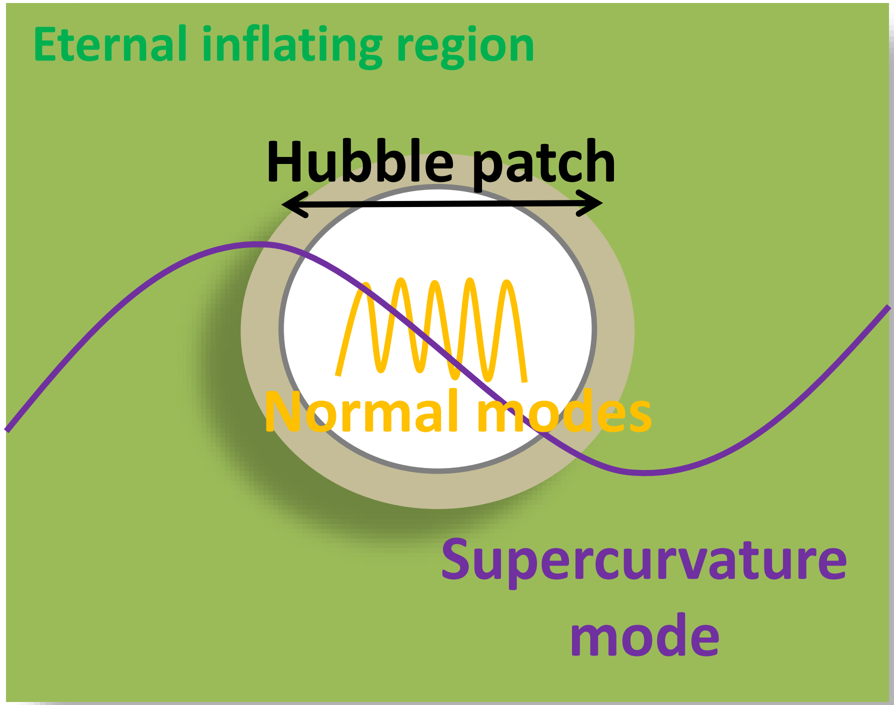
[**DY**+Zarei+Hirouzjahi+Ohta+Naruko+Yamaguchi, work in progress]

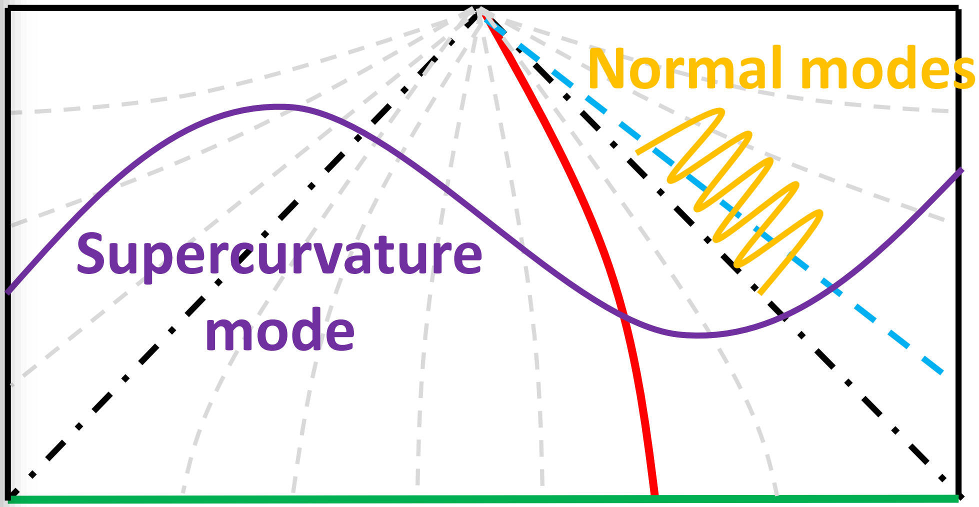
Modulation due to supercurvature

[see also Kanno+Sasaki+Tanaka(2013), Bernes+Domenech+Sasaki+Takahashi(2016)]

We will treat the **supercurvature mode** as a ***nonstochastic quantity*** and we can only observe one realization in our Hubble patch.

⇨ **The modulation of the continuous spectrum**





[DY+Zarei+Hirouzjahi+Ohta+Naruko+Yamaguchi, work in progress]

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⇒ **The modulation of the continuous spectrum**

⇓

$$\mathcal{R}_{\rm c}(\boldsymbol{x}) = \mathcal{N}\Big|_{\sigma_{\rm bg}} - \mathcal{N}\Big|_{\sigma_{\rm bg}+\boxed{\Delta\sigma(\boldsymbol{x})}} - \mathcal{N}_\sigma\Big|_{\sigma_{\rm bg}+\boxed{\Delta\sigma(\boldsymbol{x})}}\delta\sigma(\boldsymbol{x}) - \frac{1}{2}\mathcal{N}_{\sigma\sigma}\Big|_{\sigma_{\rm bg}+\boxed{\Delta\sigma(\boldsymbol{x})}}\delta\sigma^2(\boldsymbol{x}) + \cdots$$

Spatial modulation due to SC mode!

⇒

- Power asymmetry : $A = \Delta P_R / 2P_R$
- Quadrupole : a_{20}

[**DY**+Zarei+Hirouzjahi+Ohta+Naruko+Yamaguchi, work in progress]

Modulation due to supercurvature

[see also Kanno+Sasaki+Tanaka(2013), Bernes+Domenech+Sasaki+Takahashi(2016)]

We will treat the **supercurvature mode** as a ***nonstochastic quantity*** and we can only observe one realization in our Hubble patch.

⇒ **The modulation of the continuous spectrum**

Hemispherical power asymmetry!

[DY+Zarei+Hirouzjahi+Ohta+Naruko+Yamaguchi, work in progress]

Modulation due to supercurvature

[see also Kanno+Sasaki+Tanaka(2013), Bernes+Domenech+Sasaki+Takahashi(2016)]

We will treat the **supercurvature mode** as a ***nonstochastic quantity*** and we can only observe one realization in our Hubble patch.

Question...

- ✓ Does the supercurvature mode with the large amplitude really exist in the realistic open inflationary scenario?

Future prospects

➢ Multifield tunneling and supercurvature mode

✓ Background solution [Sugimura+**DY**+Sasaki (2011)]

✓ Quantization including the effect of the metric perturbations should be taken into account.

✓ would rescue the simplest two field model [Tanaka+Sasaki(1996)]

$$L=(M_{pl}^2/2)R-G_{ab}(\boldsymbol{\varphi})d\varphi^a\cdot d\varphi^b/2-V(\boldsymbol{\varphi})$$

⇨ **supercurvature modes?**

Future prospects

- Higher-order correlations

  - ✓ Bispectrum from scalar ***normal*** modes in exact dS
[Sugimura+Komatsu (2013)]

$$B_\zeta^{\text{subcurv}} \simeq B_\zeta^{\text{usual}} + B_\zeta^{\text{NBD}} \quad \text{(squeezed limit, subcurvature limit)}$$

$$\begin{cases} B_\zeta^{\text{usual}} \rightarrow (1-n_s) P_\zeta(k_{\text{long}}) P_\zeta(k_{\text{short}}) \\ B_\zeta^{\text{NBD}} \rightarrow (k_{\text{short}}/k_{\text{long}}) \exp(-\pi\, k_{\text{short}})\, P_\zeta(k_{\text{long}}) P_\zeta(k_{\text{short}}) \end{cases}$$

enhancement suppression

  - ✓ Extension to the dynamical background is needed.
  - ✓ Contributions from **supercurvature modes@k~$k_{\text{superlong}}$**?

Summary

We are already testing the model of inflation in the context of cosmic/string landscape !