Effective field theory approach to quasi-single field inflation and effects of heavy fields

Toshifumi Noumi

(Math Phys Lab, RIKEN)

reference:

・JHEP 1306 (2013) 051 [arXiv:1211.1624]
with Masahide Yamaguchi (TIT) and Daisuke Yokoyama (Seoul NU)

・[arXiv:1307.7110] with Masahide Yamaguchi (TIT)

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possible probe of high energy physics

Tos

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spontaneous breaking of time-diffeomorphism

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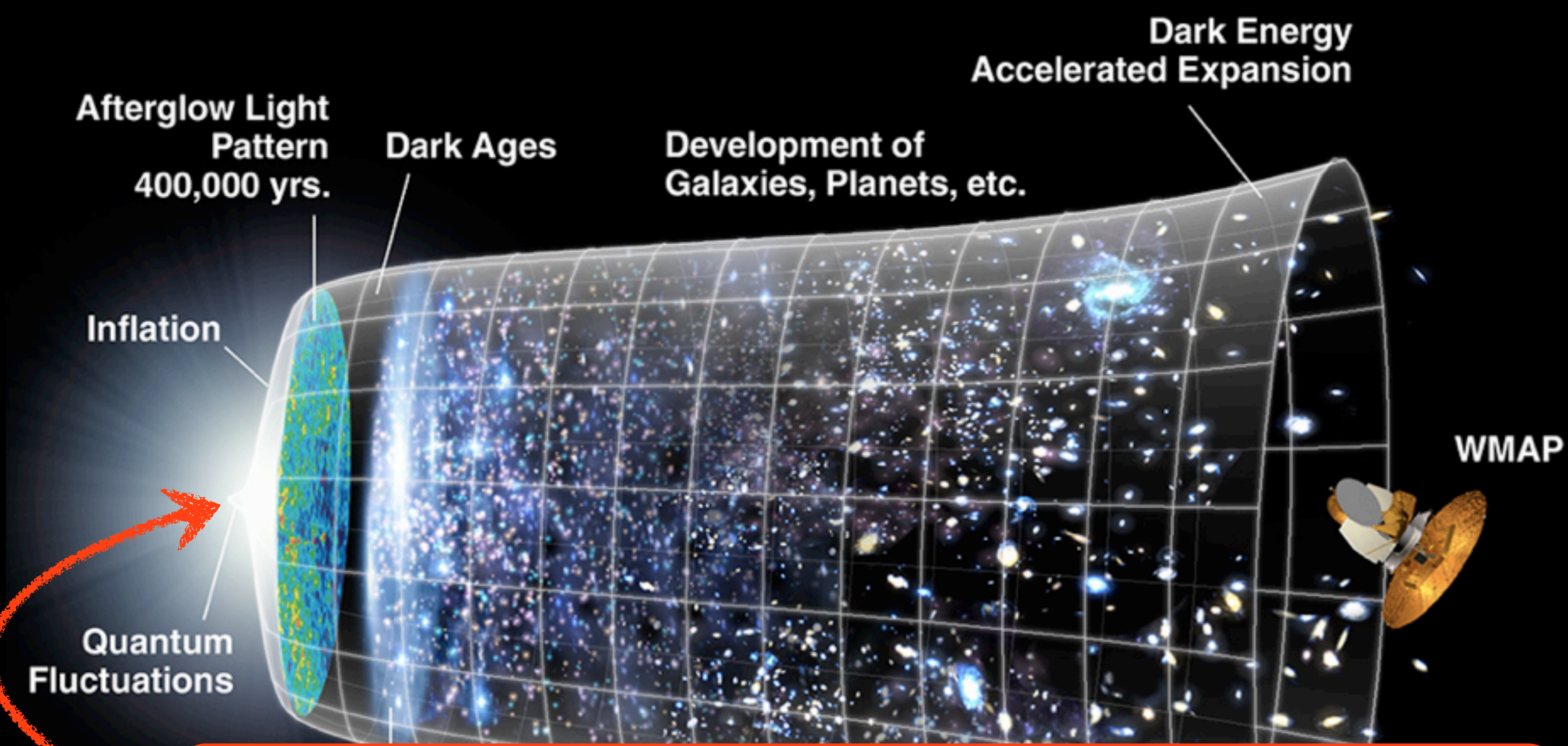
inflation



inflation: accelerated expansion of the Universe

- **explains horizon problem, flatness problem, …**
- **generates primordial curvature fluctuations**

  → seeds of structures of the Universe

single-field slow-roll inflation

- introduce an inflaton field:

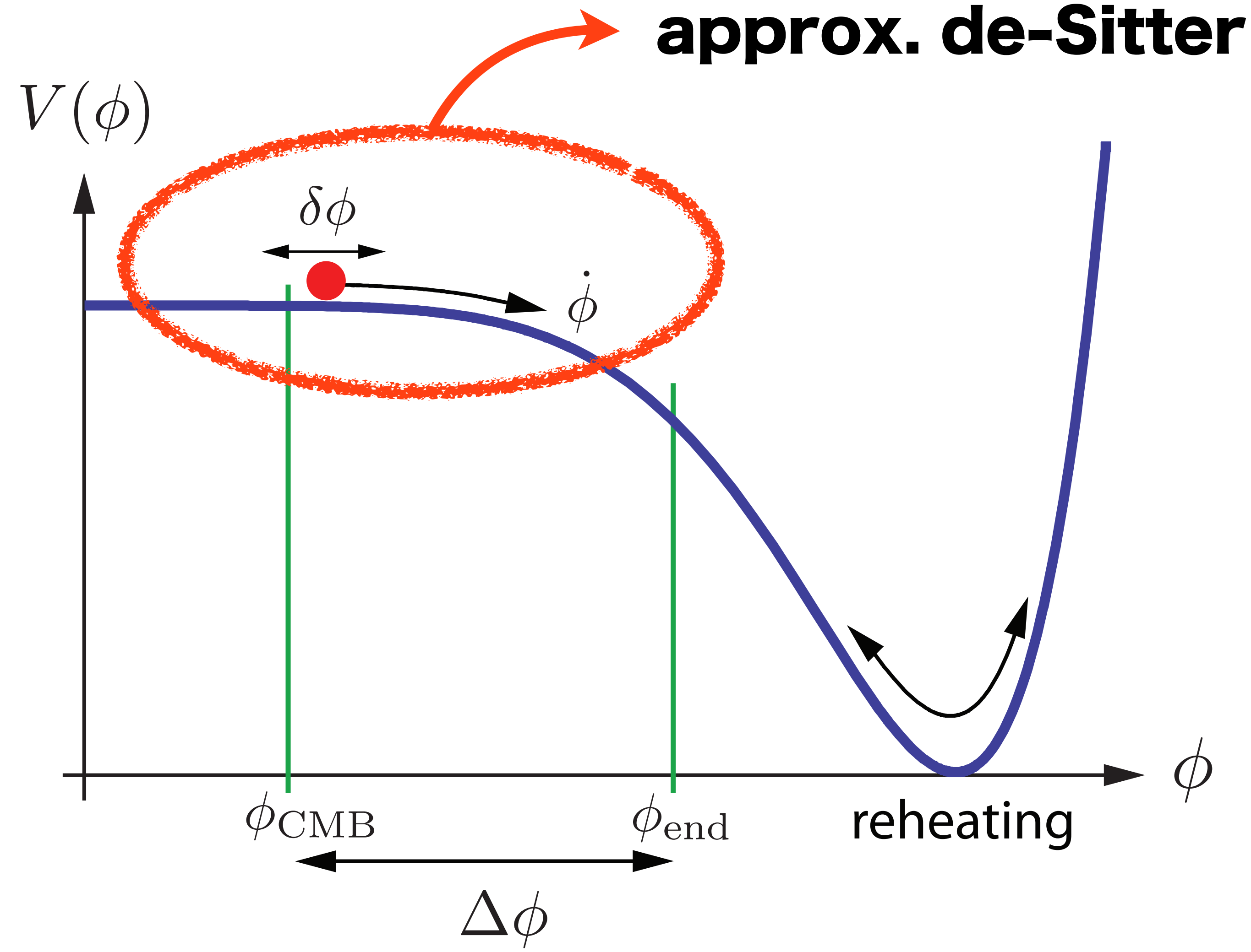
$$\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)$$

- FRW spacetime

$$ds^2 = -dt^2 + a(t)^2 d\vec{x}^2$$

- Hubble parameter: $H(t) = \frac{\dot{a}}{a}$

(horizon problem
observation



$$\longrightarrow \quad \ln\left[\frac{a(t_f)}{a(t_i)}\right] \gtrsim 60 \quad \epsilon = -\frac{\dot{H}}{H^2} \ll 1 \quad \eta = \frac{\dot{\epsilon}}{\epsilon H} \ll 1$$

a lot of models have been proposed and are being killed by experiments!

how to distinguish models?

quantum fluctuations during inflation → sees of structures

※ initial conditions in standard cosmology

dof during inflation

- inflaton ϕ
- metric $g_{\mu\nu}$
- others σ

(ϕ, $g_{\mu\nu}$) → two gauges

two gauges

- spatially flat gauge

  inflaton ϕ and graviton γ_{ij}

- unitary gauge

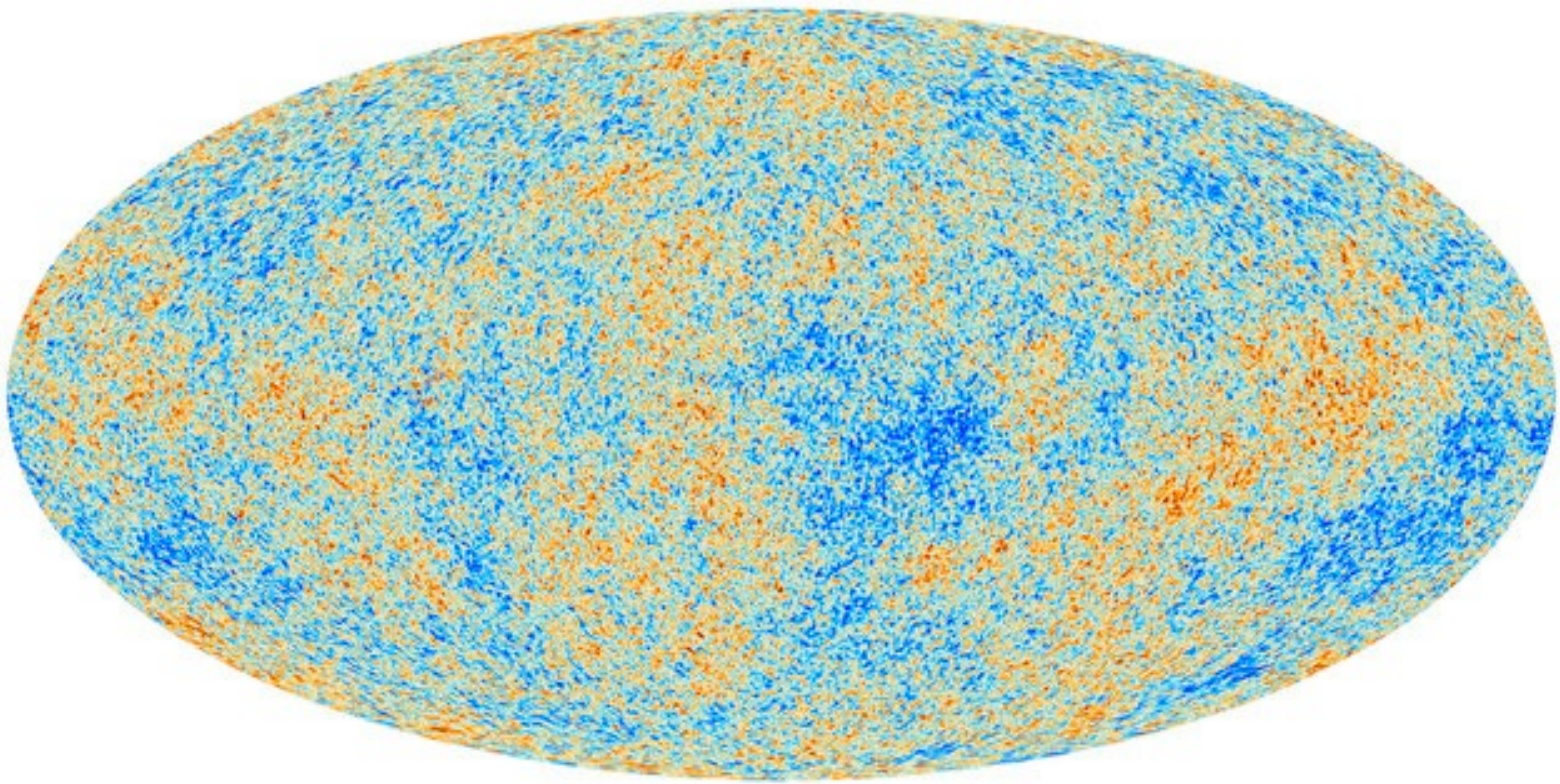
$$ds^2 = -dt^2 + a^2 e^{2\zeta} (e^{\gamma})_{ij} dx^i dx^j$$

  scalar perturbation ζ

  tensor perturbation γ_{ij}

- ζ, γ_{ij} : fluctuation of scale factor
- cosmic expansion cools Universe → CMB temp. fluctuations

CMB as seen by Planck



$$\frac{\delta T}{T} \sim 10^{-5}$$

as a probe of (very) high energy physics?

models based on high energy theory have been also discussed

(ex. supergravity, superstring theory, ...)

one generic feature of such high energy based models:

massive scalar fields other than inflaton

- supergravity: generically $m_{\rm scalar} \sim H$
- extra dimensions: Kaluza-Klein modes
- superstring theory: moduli of compactification

can be used as a probe of high energy physics!?

can affect primordial curvature perturbations!?

when heavy fields become relevant?

suppose that the potential has a massive direction

in addition to the slow-roll direction

if you roll along the bottom of potential...

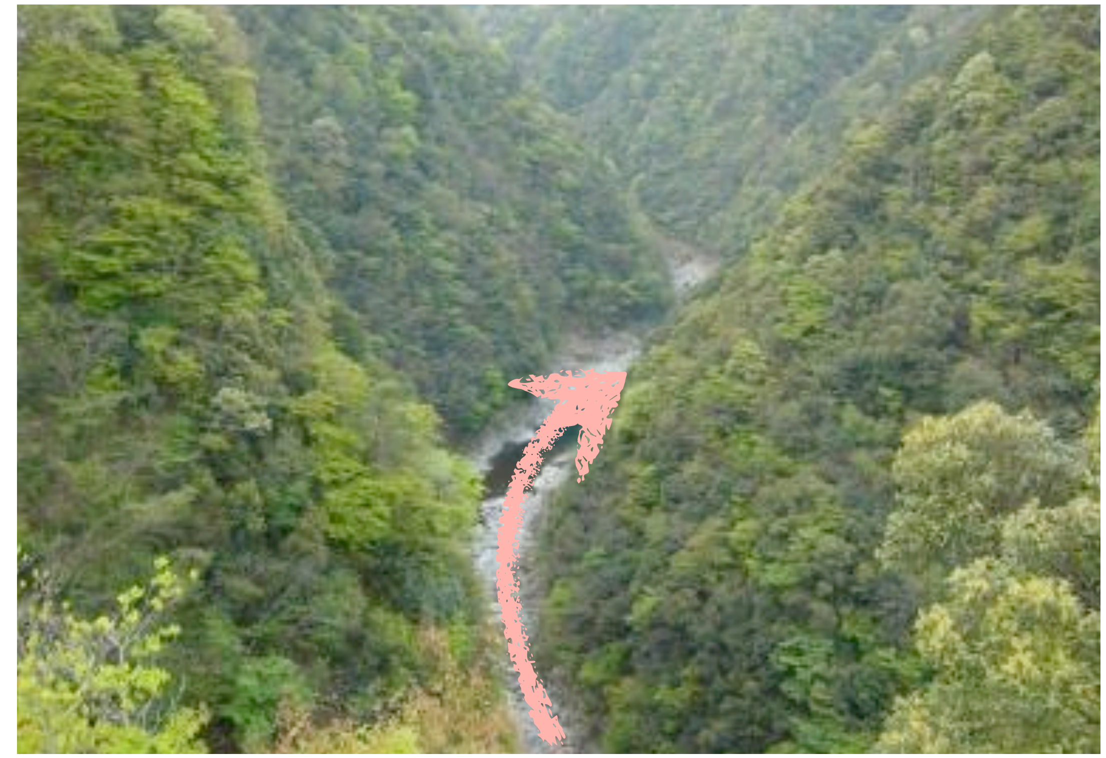
- don’t feel the massive potential
- single field approximation works well

if you roll along the bottom of potential...

- don’t feel the massive potential
- single field approximation works well

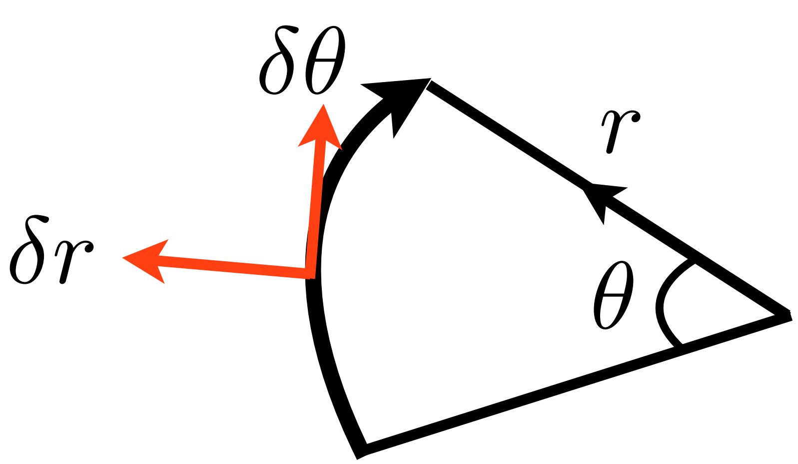
two typical situation you feel massive potential

turn and climb the potential



potential itself is turning

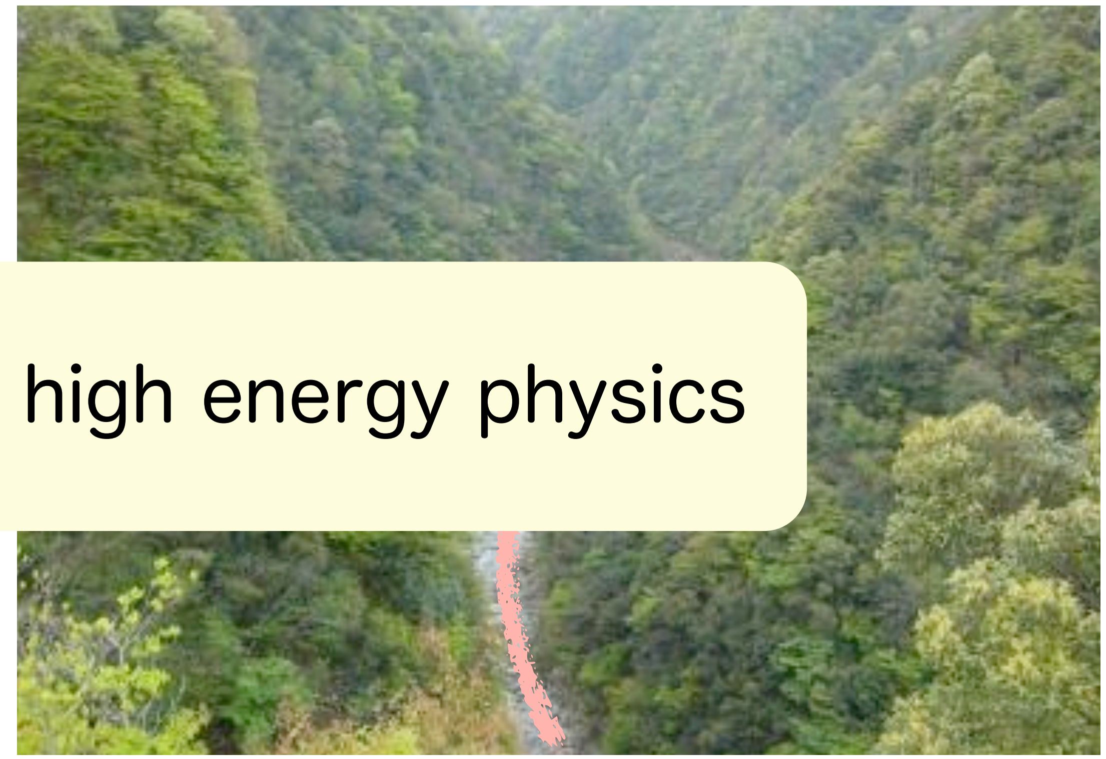
※ in each case, you will feel centrifugal force during the turn



conversion interaction from kinetic term :

$$r^2 \partial_\mu \theta \partial^\mu \theta \ni \delta r \, \dot{\delta\theta}$$

two typical situation you feel massive potential



can be a probe of high energy physics

turn and climb the potential

potential itself is turning

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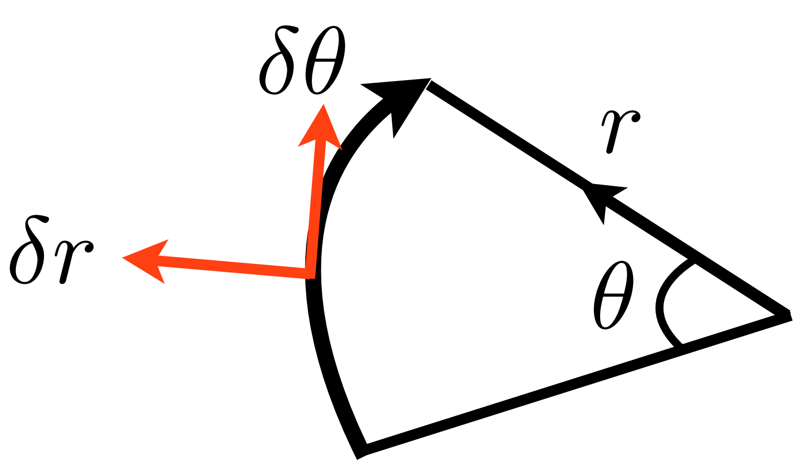


conversion interaction from kinetic term :

$$r^2\partial_\mu\theta\partial^\mu\theta \ni \delta r\,\delta\dot{\theta}$$

signatures from conversion interaction + heavy fields:

quasi-single field inflation [Chen-Wang '09]

- potentially large non-Gaussianities
- intermediate shape between local and equilateral types

effective sound speed from heavy fields [ex. Achucarro et al '11]

- heavy fields can change dispersion relations of light fields

sudden turning trajectory [ex. Gao et al '12]

- a kind of resonances in primordial power spectra

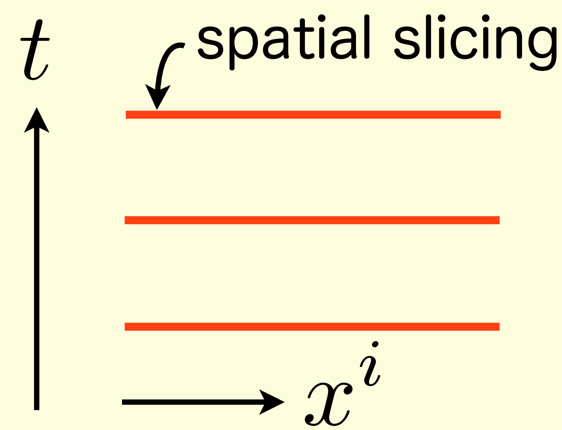
would like to discuss effects of heavy fields + conversion
more systematically and in more general settings
$\rightarrow$ effective field theory (EFT) approach to inflation

General action from EFT approach

EFT approach to inflation [Cheung-Creminelli-Fitzpatrick-Kaplan-Senatore '07]

inflation : approx. de-Sitter expansion → time-dep. scalar curvature $R(t)$

(time-dep. vev of inflaton)



→ spontaneous breakdown of time diffeo

※ unbroken time-dep. spatial diffeo $\delta x^i = \epsilon^i(t, x^i)$

relevant dof + symmetry breaking structure → effective action

※ write down all possible interactions preserving unbroken symmetry!

advantages:

- systematic expansions in perturbations and derivatives
- interactions at different orders are related by symmetry

EFT approach to inflation [Cheung-Creminelli-Fitzpatrick-Kaplan-Senatore '07]

- simplest case (⇔ single field inflation)

relevant dof = metric $g_{\mu\nu}$ only

※ time-diffeo breaking → 2 transverse and 1 longitudinal physical modes

(inflaton is eaten by graviton)

we would like to construct the most general action

- constructed from the metric $g_{\mu\nu}$
- invariant under unbroken time-dependent spatial diffeo
- around given FRW background
  (background field satisfy the eom)

free indices: upper 0's

$$S = \int d^4x\sqrt{-g}\,F(R_{\mu\nu\rho\sigma}, g^{00}, K_{\mu\nu}, \nabla_\mu, t)$$

$K_{\mu\nu}$: extrinsic curvature on constant-time spatial slices

Generic action with heavy fields [Noumi-Yamaguchi-Yokoyama '12]

- in our case...

relevant dof = metric $g_{\mu\nu}$ + additional massive scalar field σ

※ time-diffeo breaking → 2 transverse and 1 longitudinal physical modes

(inflaton is eaten by graviton)

we would like to construct the most general action

- constructed from the metric $g_{\mu\nu}$ and σ
- invariant under unbroken time-dependent spatial diffeo
- around given FRW background (background field satisfy the eom)

$$S = \int d^4x\sqrt{-g}\,F(R_{\mu\nu\rho\sigma}, g^{00}, K_{\mu\nu}, \nabla_\mu, t, \sigma)$$

$K_{\mu\nu}$: extrinsic curvature on constant-time spatial slices

Generic action with heavy fields [Noumi-Yamaguchi-Yokoyama '12]

1. expand the action around a given FRW background

2. introduced the Goldstone boson $\boldsymbol{\pi}$ via Stuckelberg method

   - Goldstone boson π non-linearly realizes time diffeo

$$\pi(x) \to \tilde{\pi}(\tilde{x}) = \pi(x) - \xi^0(x) \quad \text{with} \quad t \to \tilde{t} = t + \xi^0(x)$$

   - $\zeta = -H\pi$ at the linear order

Generic action with heavy fields [Noumi-Yamaguchi-Yokoyama '12]

3. write the action schematically as $S = S_\pi + S_\sigma + S_{\rm mix}$

S_π : no σ (⇔ single field)

S_σ : kinetic term of σ, self-interaction of σ, ...

$S_{\rm mix}$: conversion of π and σ, ...

$$S_\pi \ni \int d^4x\, a^3 \left[-M_{\rm Pl}^2 \dot{H}\left(\dot{\pi}^2 - \frac{(\partial_i \pi)^2}{a^2}\right)\right]$$

$$S_{\rm mix} \ni \int d^4x\, a^3 \left[-2\beta\dot{\pi}\sigma - \beta\left(\dot{\pi}^2 - \frac{(\partial_i \pi)^2}{a^2}\right)\sigma\right]$$

※ nontrivial cubic interaction from conversion : typically, $f_{NL} = \mathcal{O}(1 \sim 10)$

※ interactions at different orders are related by symmetry

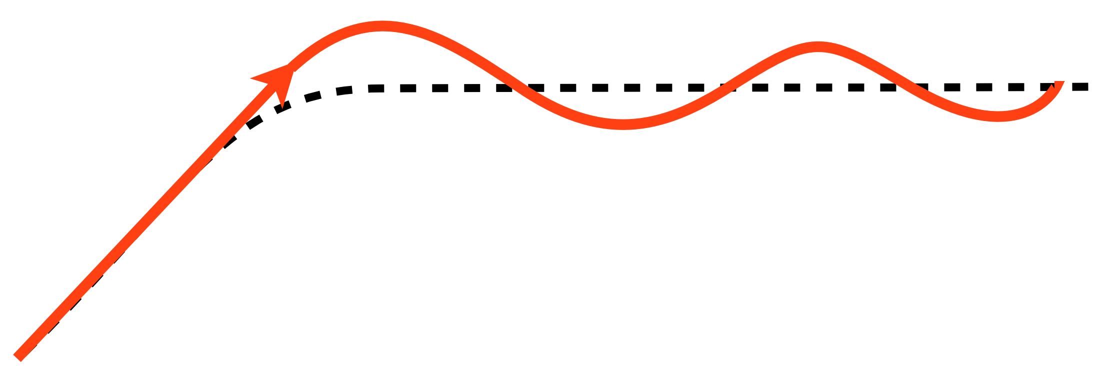
※ model is specified by time-dep. parameters such as $H(t)$ and β

Example: effects of heavy field oscillations

[Noumi-Yamaguchi ’13]

heavy field oscillations can occur in the case of

1. turning potential

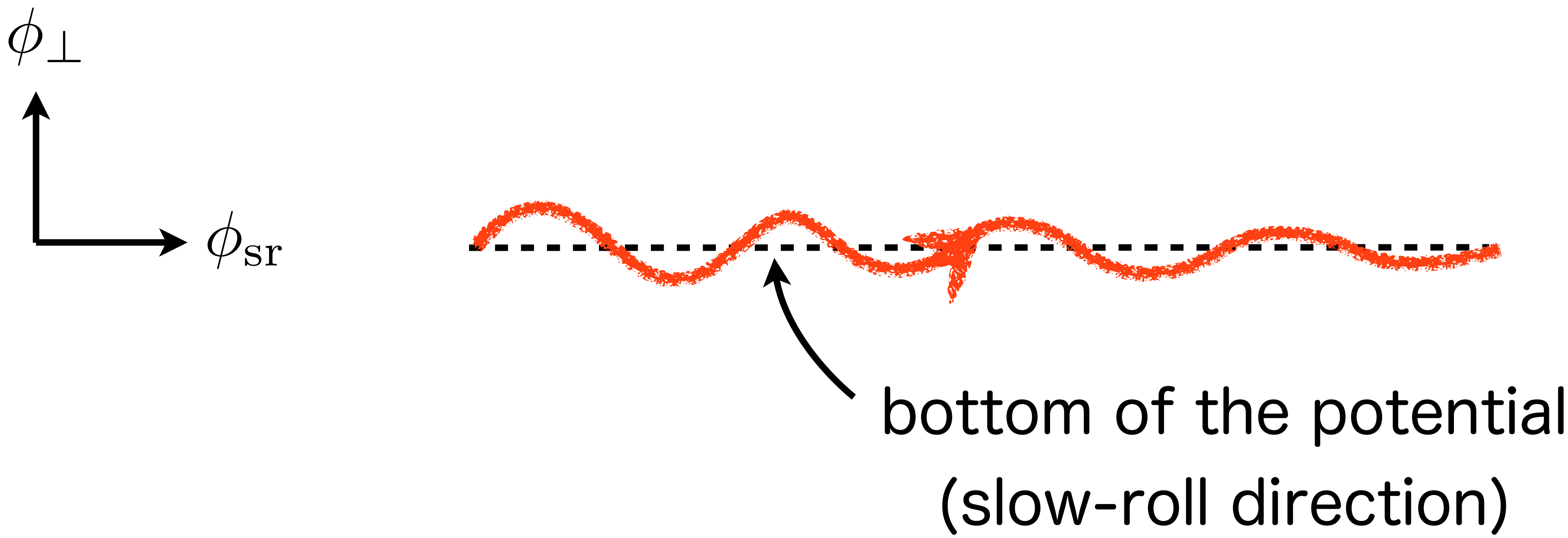


2. phase transition (of massive direction)

two effects of heavy field oscillations:

1. deformations of Hubble parameter
2. conversion interactions

Deformations of Hubble parameter



if background trajectory oscillates...

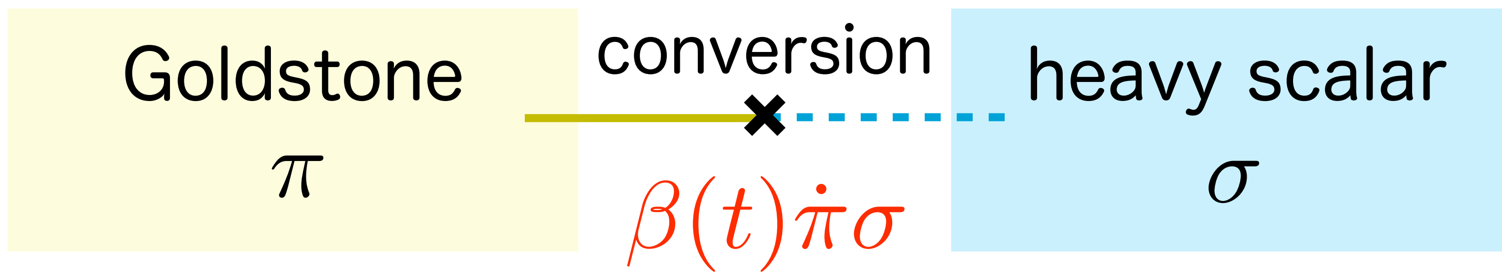
Friedman equation: $-2M_{\rm Pl}^2\dot{H} = \dot{\phi}_{\rm sr}^2 + \dot{\phi}_\perp^2$ ← oscillating

- deformed Hubble parameter $\dot{H} = \dot{H}_{\rm sr} + \delta\dot{H}$ ← oscillating

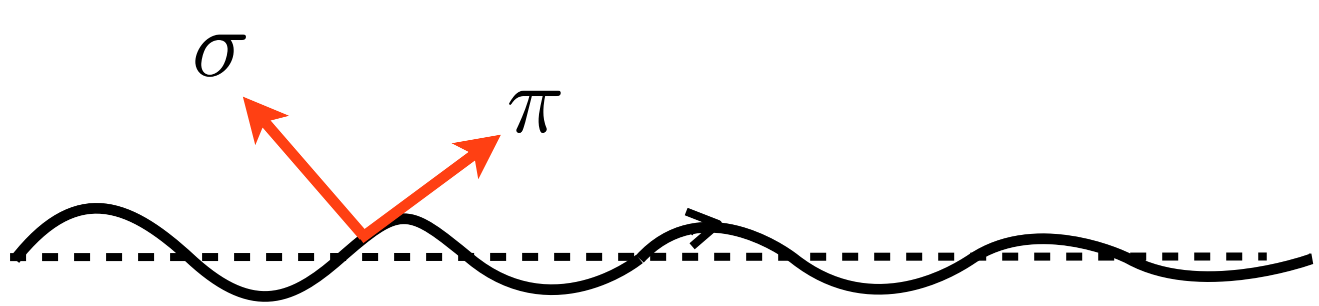
→ π - π interaction $\int dt d^3x\, a^3(-M_{\rm Pl}^2\delta\dot{H})\left[\dot{\pi}^2 - \frac{(\partial_i\pi)^2}{a^2}\right]$

conversion interaction

two dof of scalar perturbations:



- for turning background trajectory...



$\rightarrow$ π - σ conversion appears during the turn

- coupling β oscillates with frequency m

$\rightarrow$ oscillating π - σ interaction: $\int dt d^3x\, a^3 \beta(t)\dot{\pi}\sigma$

two effects of heavy field oscillations:

① Hubble deformation → π - π interaction

$$\int dt d^3x \, a^3 (-M_{\rm Pl}^2 \delta \dot{H}) \left[\dot{\pi}^2 - \frac{(\partial_i \pi)^2}{a^2} \right]$$

② π - σ conversion interaction

$$\int dt d^3x \, a^3 \beta(t) \dot{\pi} \sigma$$

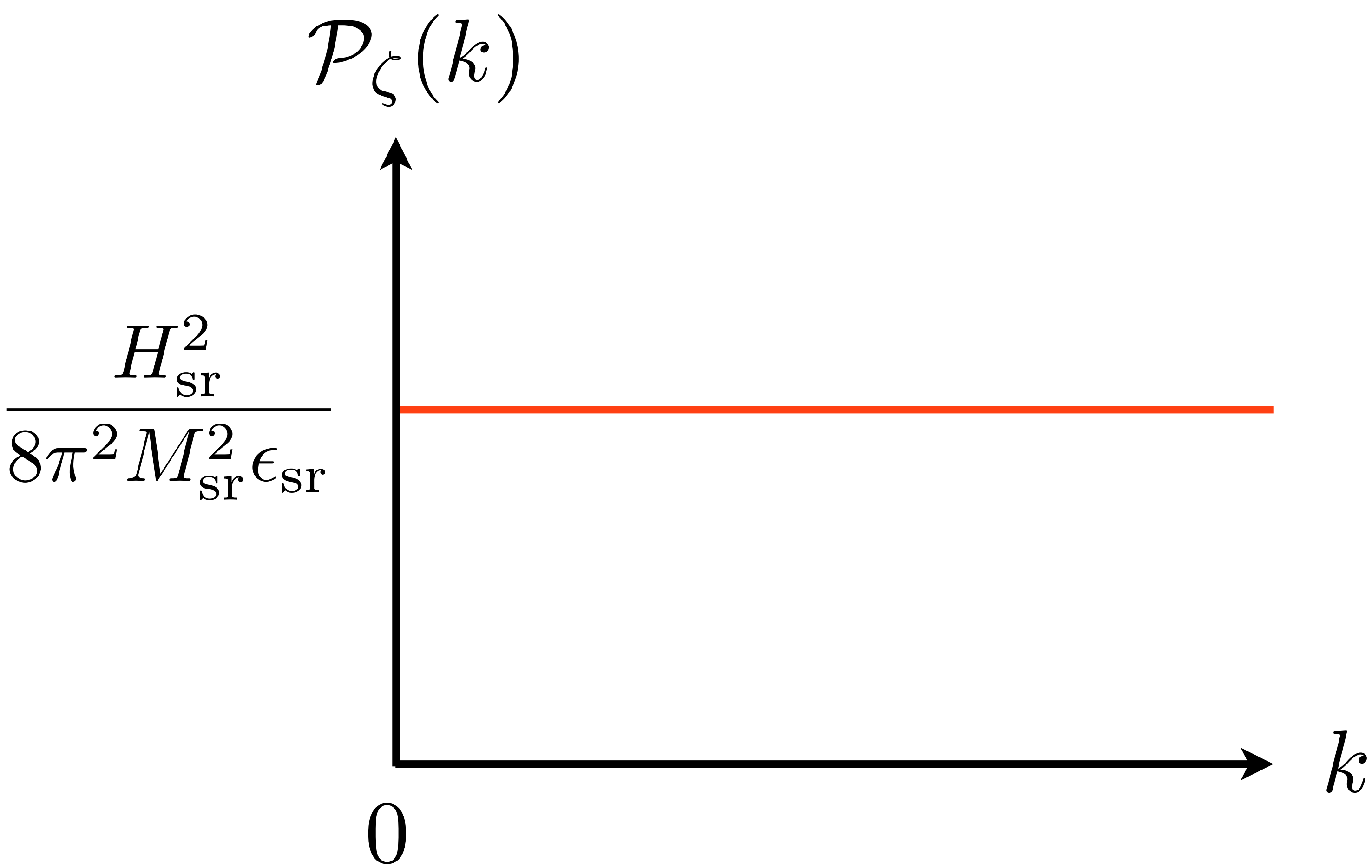
※ $\delta H(t)$ and $\beta(t)$ is oscillating

effects on primordial power spectrum

if there are no oscillations...

single slow-roll $\rightarrow$ almost scale invariant power spectrum

$$\mathcal{P}_\zeta(k) = \frac{H_{\rm sr}^2}{8\pi^2 M_{\rm sr}^2 \epsilon_{\rm sr}}$$



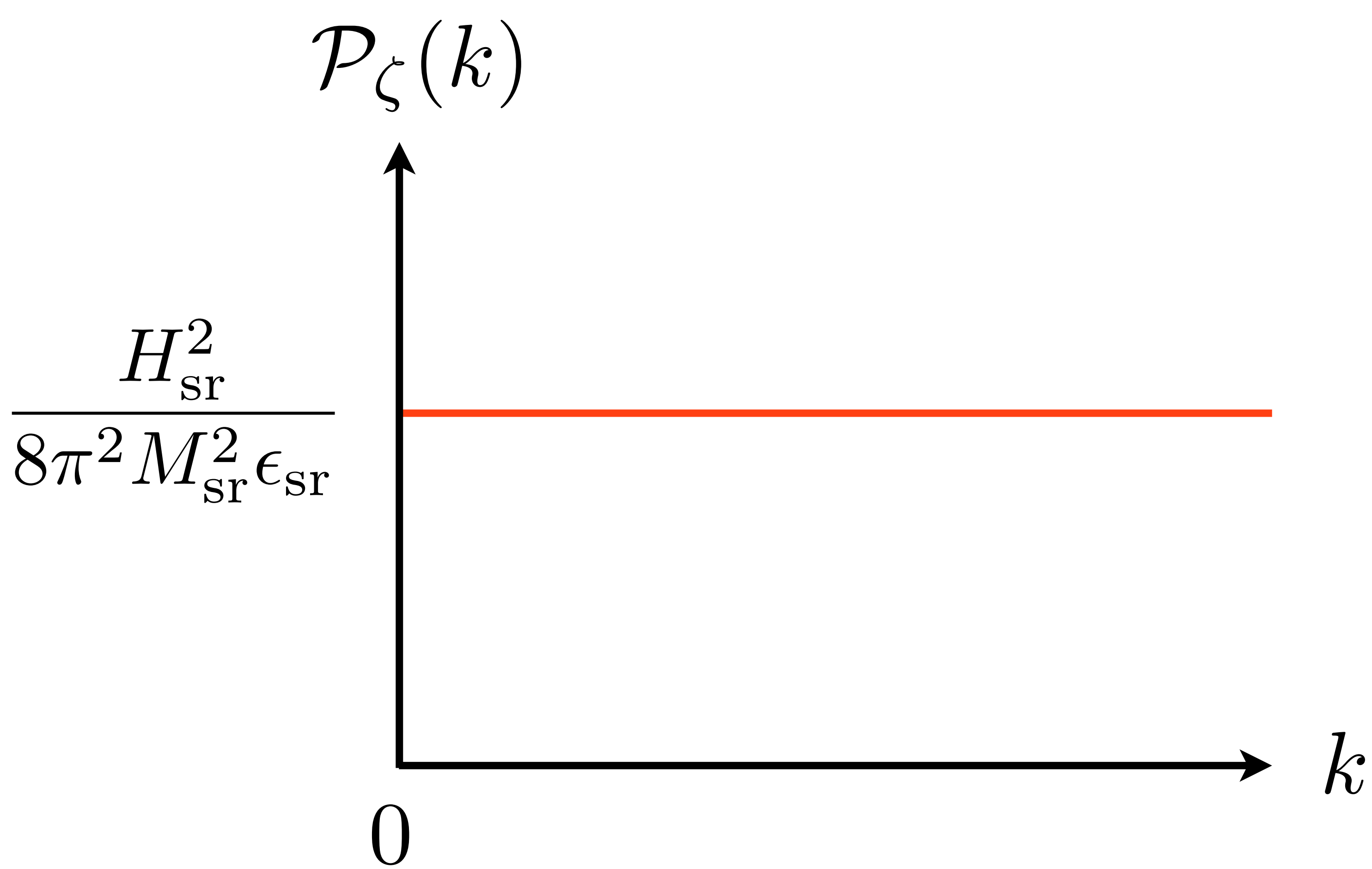
effects on primordial power spectrum

if there are no oscillations...

single slow-roll → almost scale invariant power spectrum

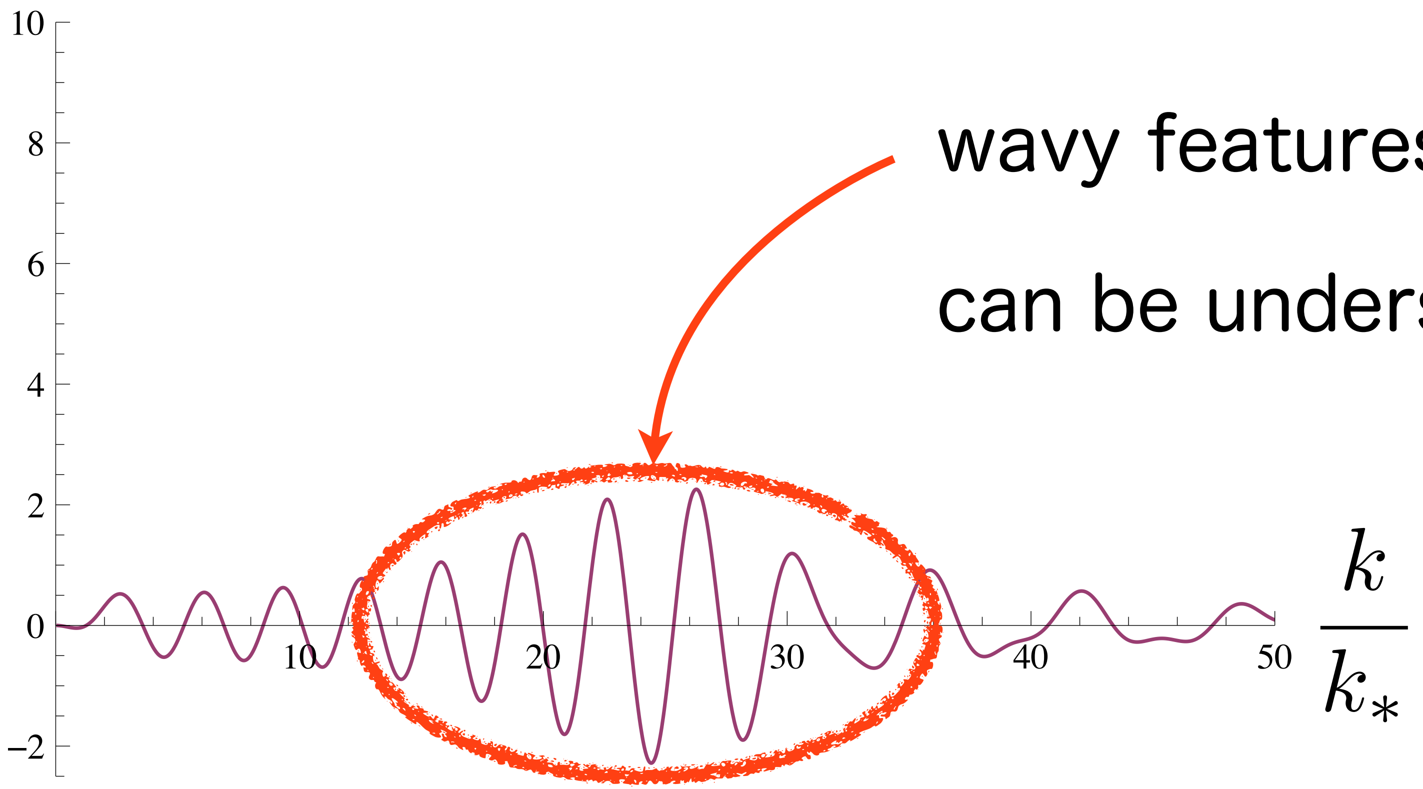
heavy field oscillation → $\mathcal{P}_\zeta(k) = \frac{H_{\rm sr}^2}{8\pi^2 M_{\rm sr}^2 \epsilon_{\rm sr}} (1 + \mathcal{C}_{\delta H} + \mathcal{C}_{\rm conv})$

deviations



effects on primordial power spectrum

$$\frac{\mathcal{C}_{\delta H}(k)}{\alpha^2} \quad \text{for } m = 20H_{\rm sr}$$

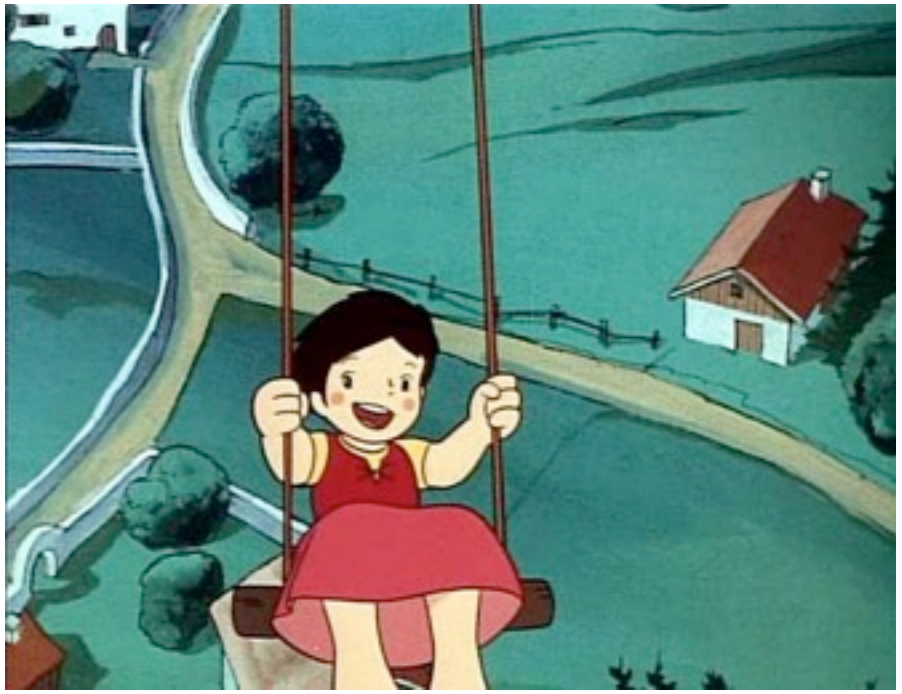


wavy features around $k \sim 20k_*$:

can be understood as resonances

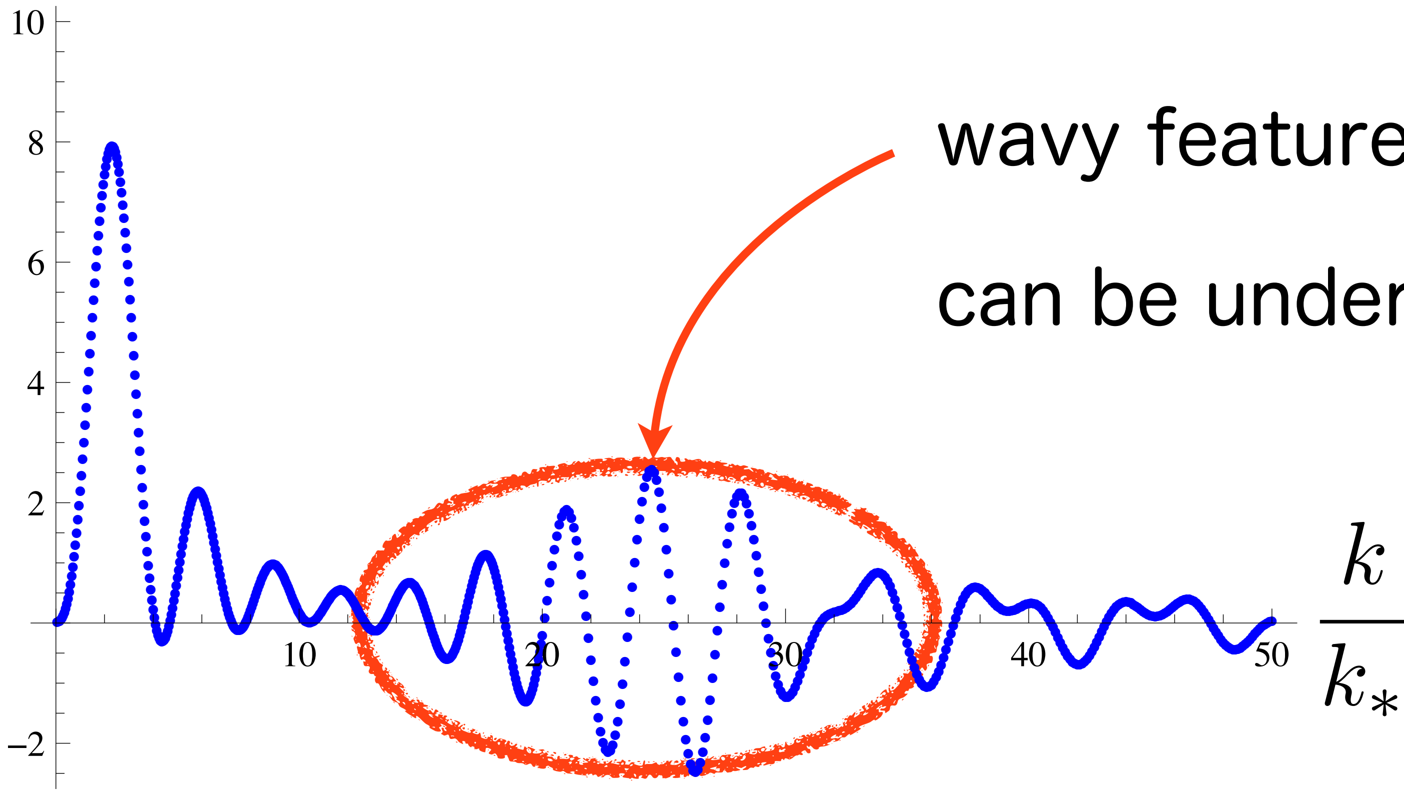
k_*: scale of turning/transition

cf. swing



effects on primordial power spectrum

$\dfrac{\mathcal{C}_{\rm conv}(k)}{\alpha^2}$ for $m = 20H_{\rm sr}$



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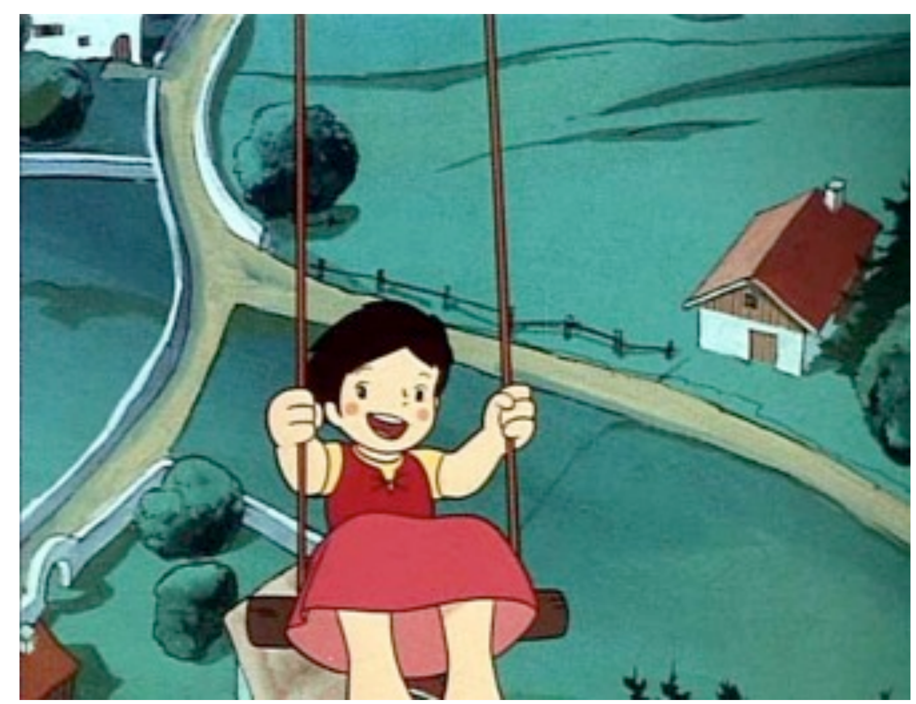
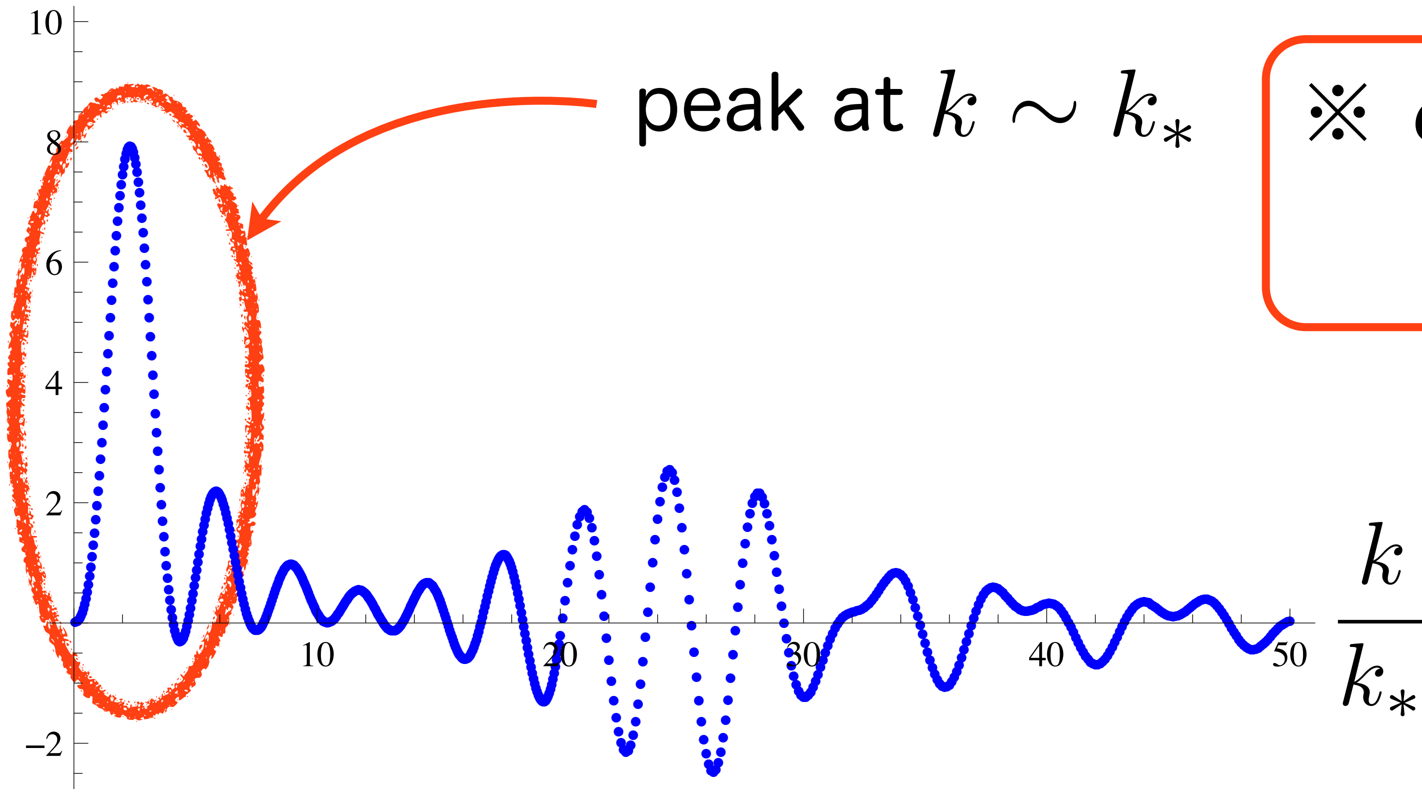


effects on primordial power spectrum

$$\frac{\mathcal{C}_{\rm conv}(k)}{\alpha^2} \text{ for } m = 20 H_{\rm sr}$$

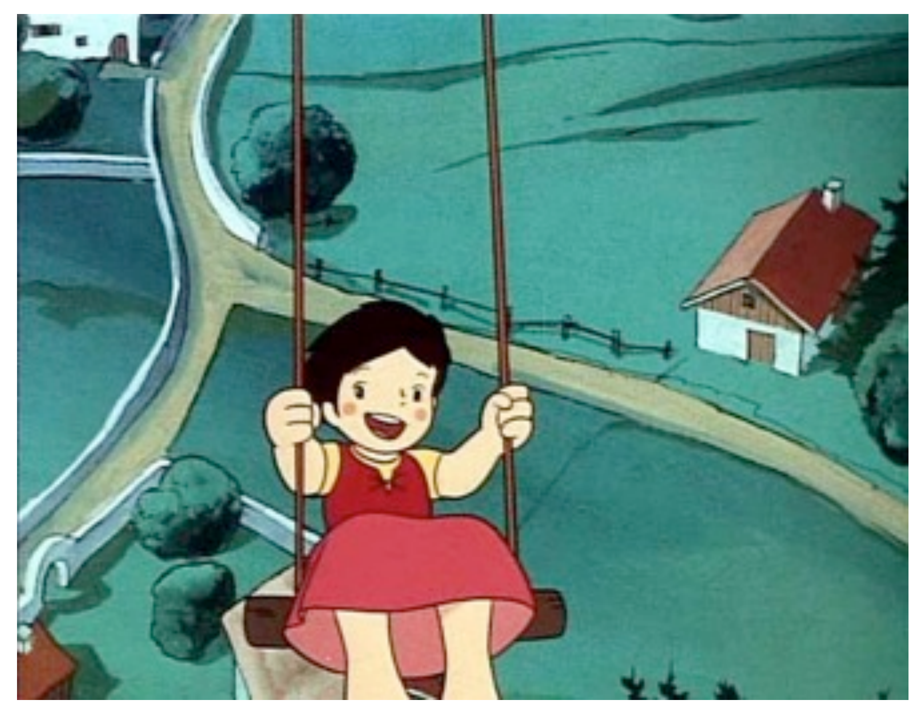


※ σ oscillates with frequency m

→ a kind of resonance

k_*: scale of turning/transition

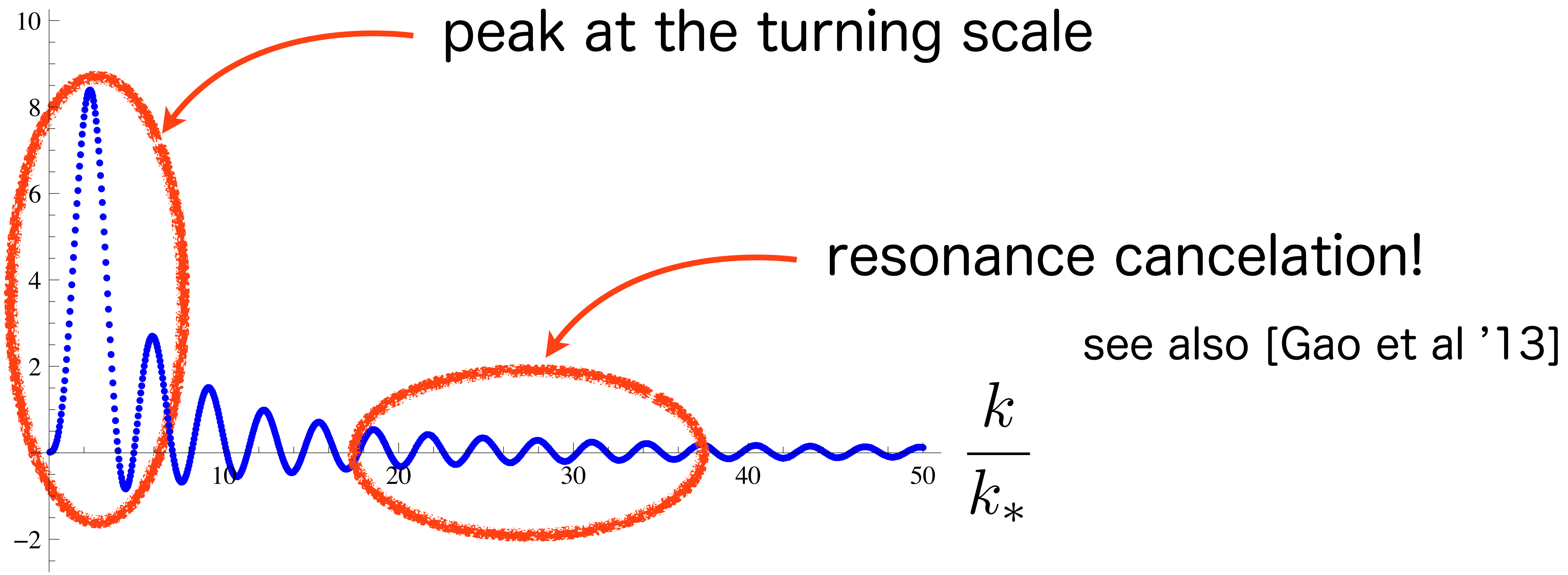
cf. swing



in particular,

when inflaton and heavy scalar have canonical kinetic terms,

- power spectrum $\mathcal{C}_{\delta H}(k) + \mathcal{C}_{\mathrm{conv}}(k)$



- bispectra (non-Gaussianities) are also evaluated

Summary and future direction

summary

conversion + heavy scalar via EFT approach

- general action as expansions in derivatives and perturbations
- interactions at different orders are related by symmetry

example: heavy field oscillations

- peak feature and resonance feature
- resonance cancellation for canonical kinetic terms

future direction

tensor correlations from EFT (in progress)

EFT approach to bottom-up holography

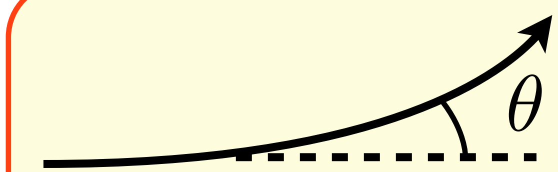
- non-conformal, non-relativistic,...

detectability of heavy field oscillations

resonance cancellation

effects on primordial power spectrum

why resonances cancel each other out?



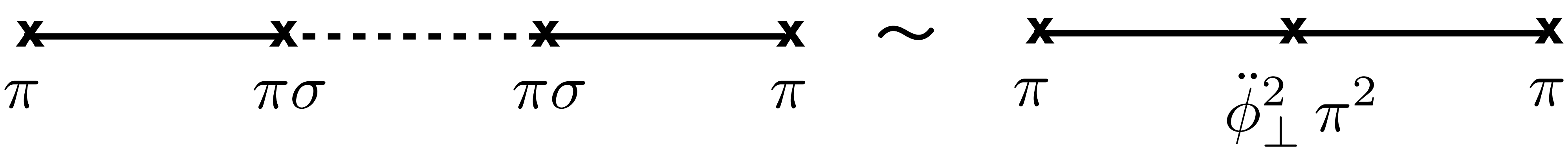
$\theta \simeq \frac{\dot{\phi}_\perp}{\dot{\phi}_{\rm sr}}$

- Hubble deformation effects $M_{\rm Pl}^2 \delta \dot{H} \pi^2 \sim \dot{\phi}_\perp^2 \pi^2$

  ※ $\delta \dot{H}$ originates from velocity $\dot{\phi}_\perp$

- conversion interactions $\beta \dot{\pi} \sigma \sim \ddot{\phi}_\perp \pi \sigma$

  ※ conversion originates from angular velocity $\frac{\ddot{\phi}_\perp}{\dot{\phi}_{\rm sr}}$

$\rightarrow$ 

- couplings of the two interactions have opposite phases

  $\dot{\phi}_\perp^2 \sim \cos^2 mt \ \rightarrow \ \ddot{\phi}_\perp^2 \sim \sin^2 mt$

  $\rightarrow$ negative correlation between the two resonances

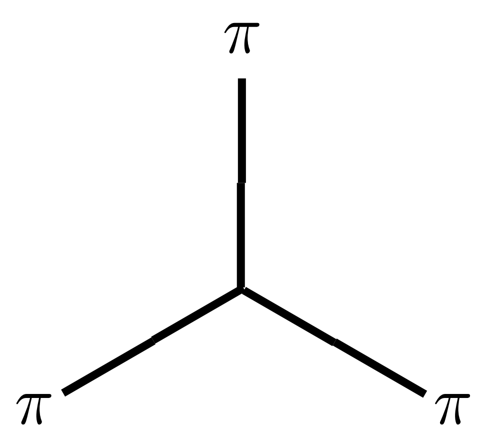
  $\cos^2 mt + \sin^2 mt = 1$: no oscillations $\rightarrow$ no resonances

primordial bispectrum

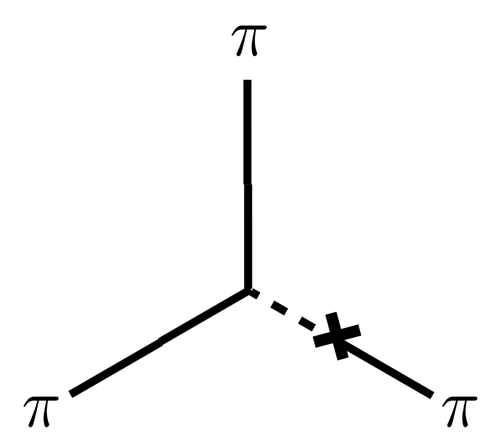
primordial bispectra

scalar three-point functions:

$$\langle \pi_{\mathbf{k_1}} \pi_{\mathbf{k_2}} \pi_{\mathbf{k_3}} \rangle$$

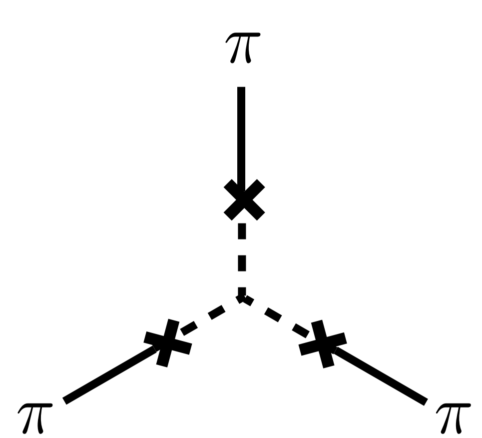
$=$ 

Hubble deformation

$+$ 

conversion

$\mathcal{O}(\alpha^2)$

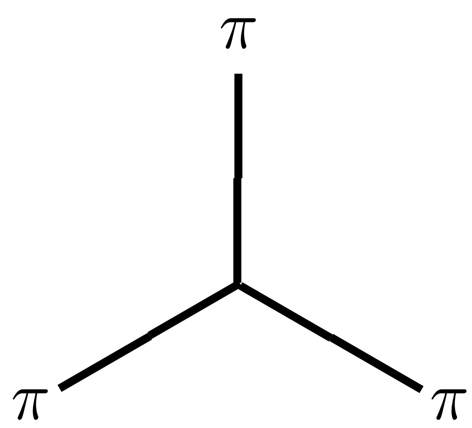
$+$ 

conversion

$\mathcal{O}(\tilde{\lambda}\alpha^2)$ ($\tilde{\lambda} \sim \sigma$ cubic interaction)

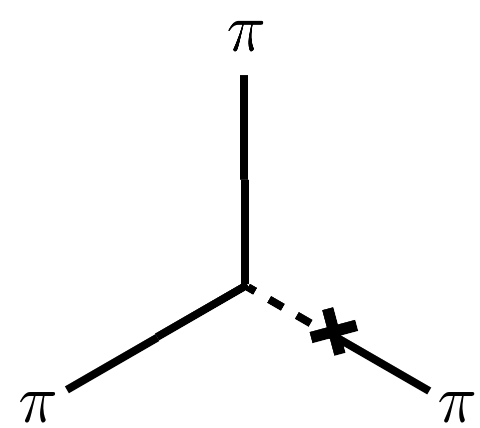
primordial bispectra

※ shape function: $S(k_1, k_2, k_3) \sim \frac{(3\text{-pt})}{(2\text{-pt})^2}$



Hubble deformation

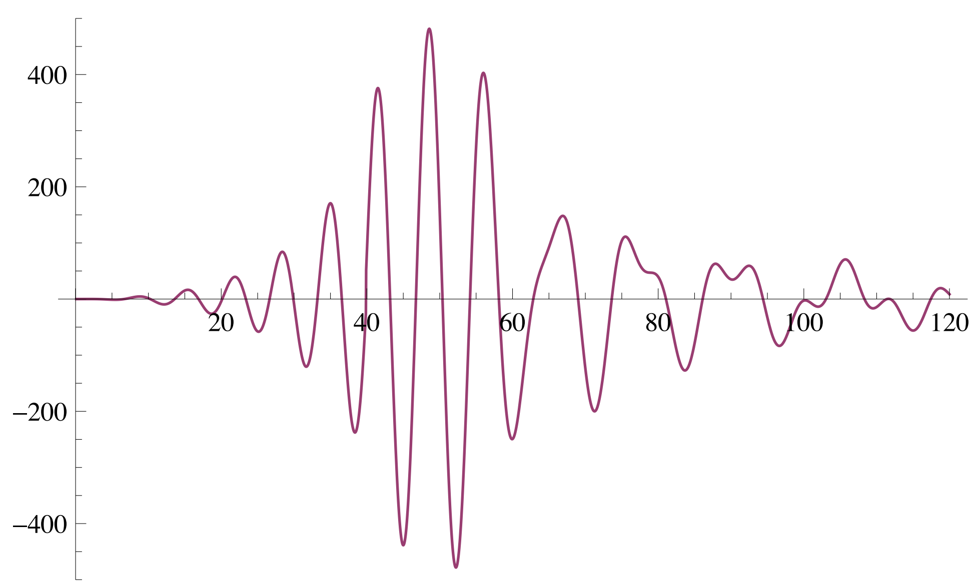
+

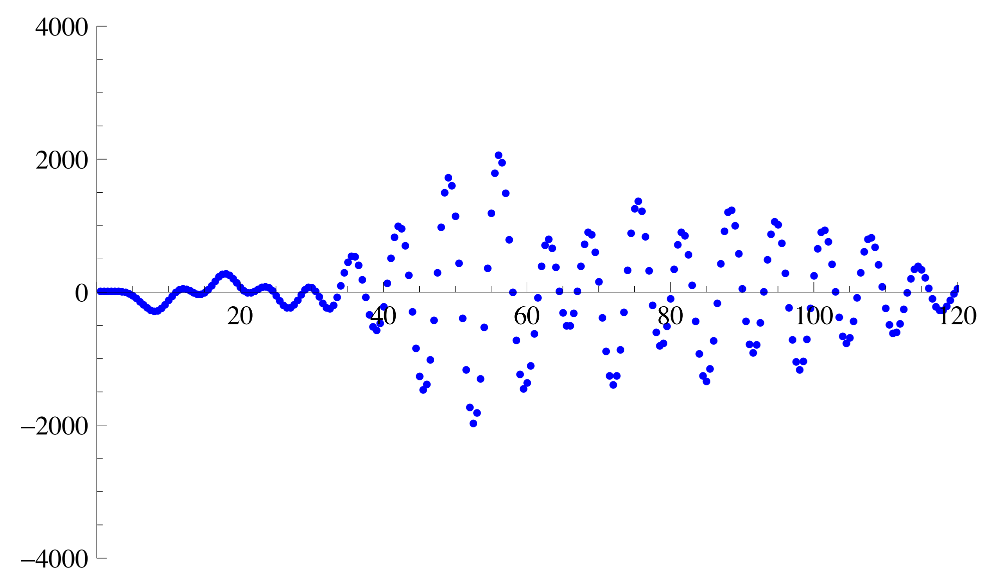


conversion

$\mathcal{O}(\alpha^2)$

scale-dependence for equilateral configurations $k_1 = k_2 = k_3$



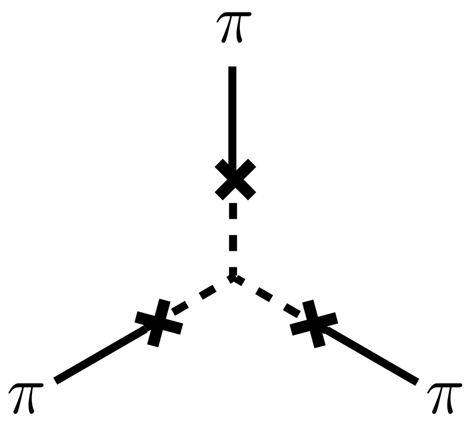


$\frac{\sum_i k_i}{k_*}$

- resonances at the mass scale
- not so large non-Gaussianities $f_{NL} \sim \alpha^2 \left(\frac{m}{H_{\rm sr}}\right)^{5/2} \times \mathcal{O}(1)$

primordial bispectra

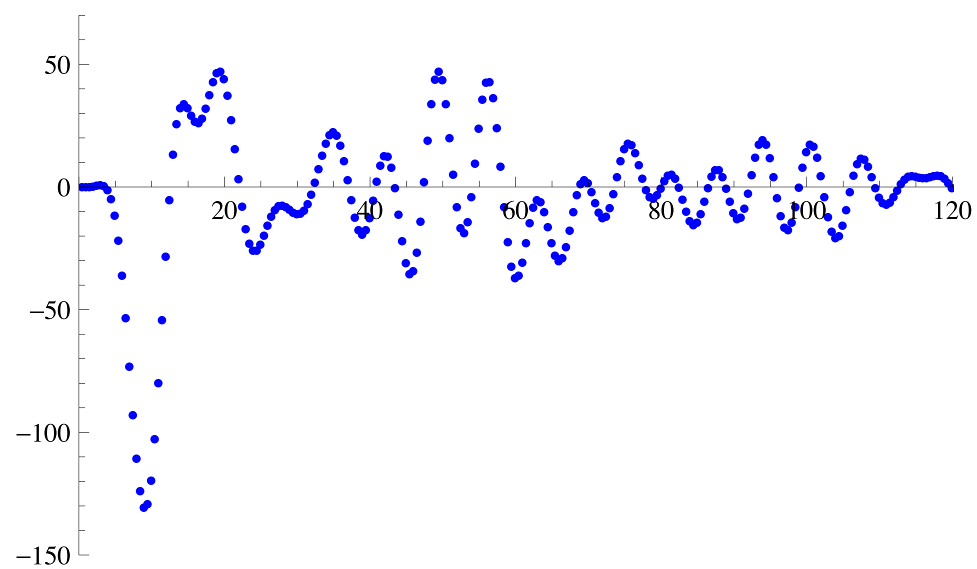
※ shape function: $S(k_1, k_2, k_3) \sim \frac{(3\text{-pt})}{(2\text{-pt})^2}$



conversion

$$\mathcal{O}(\tilde{\lambda}\alpha^2)$$

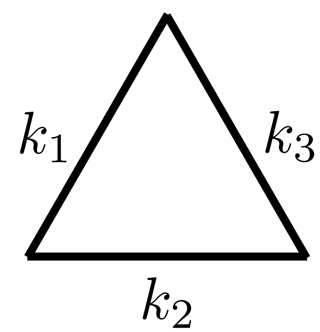
scale-dependence for equilateral configurations $k_1 = k_2 = k_3$



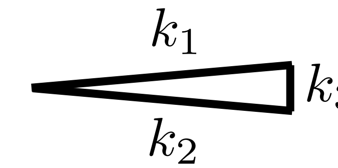
$$\frac{\sum_i k_i}{k_*}$$

- peak at the turning scale
- not so large non-Gaussianities $f_{NL} \sim \tilde{\lambda}\alpha^2 \left(\frac{m}{H_{\rm sr}}\right)^3 \times \mathcal{O}(0.1)$

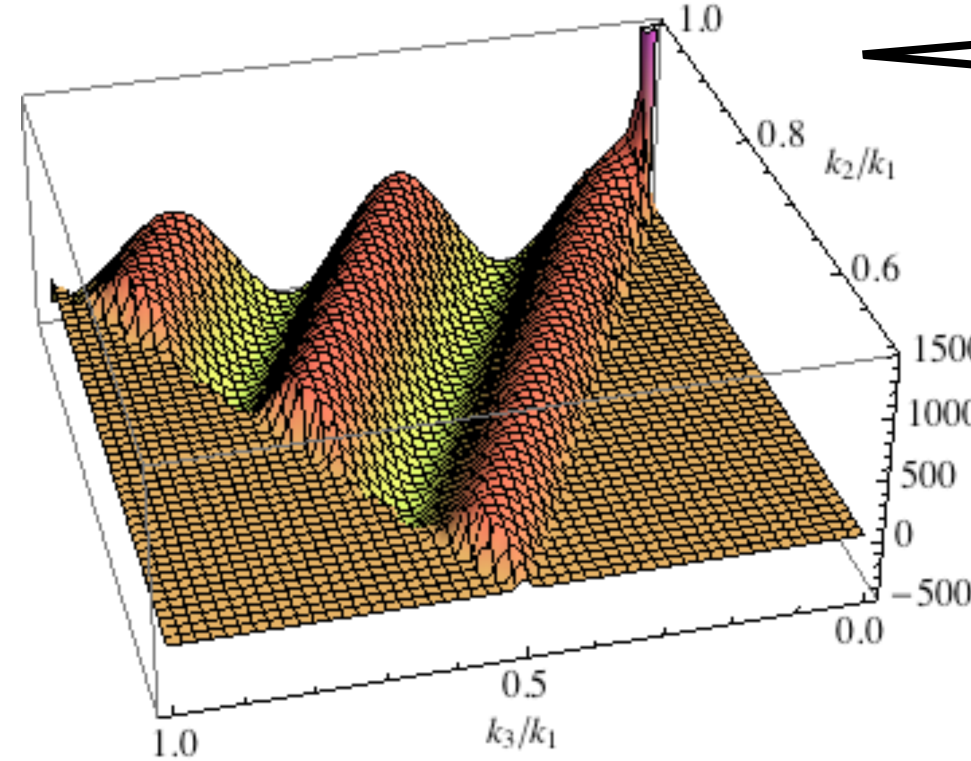
equilateral



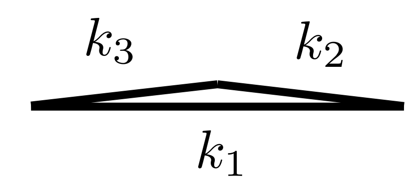
squeezed



shape around resonances



folded



shape around the peak