Gravitational waves from a curvaton model with blue spectrum

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OUTLINE

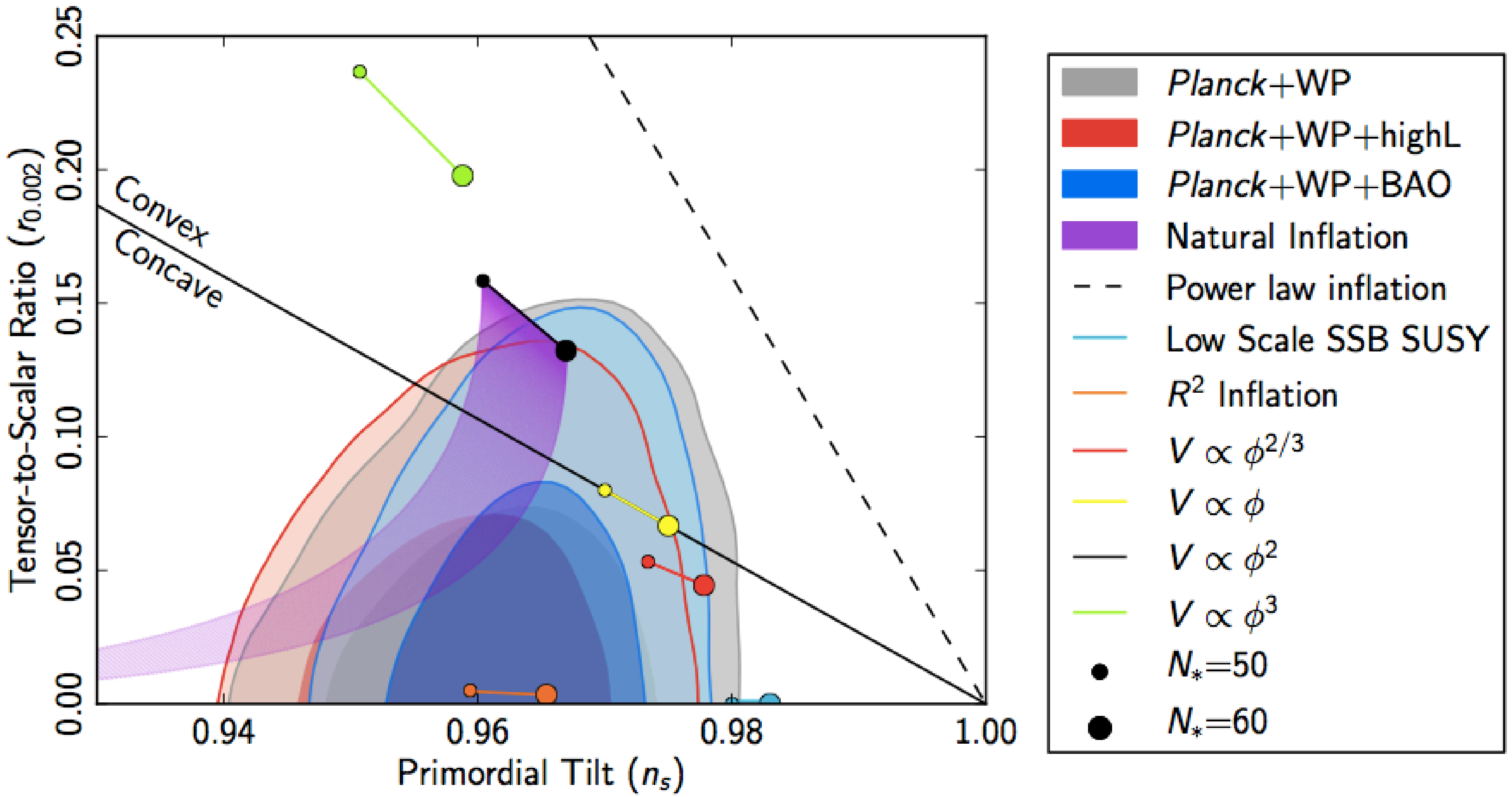
1. Introduction
2. Curvaton model with blue spectrum
3. Scalar-induced gravitational waves
4. Results

I. Introduction

CMB temperature anisotropy probe (Planck, WMAP)

has revealed the large scale primordial curvature perturbations

We can constrain inflation models!



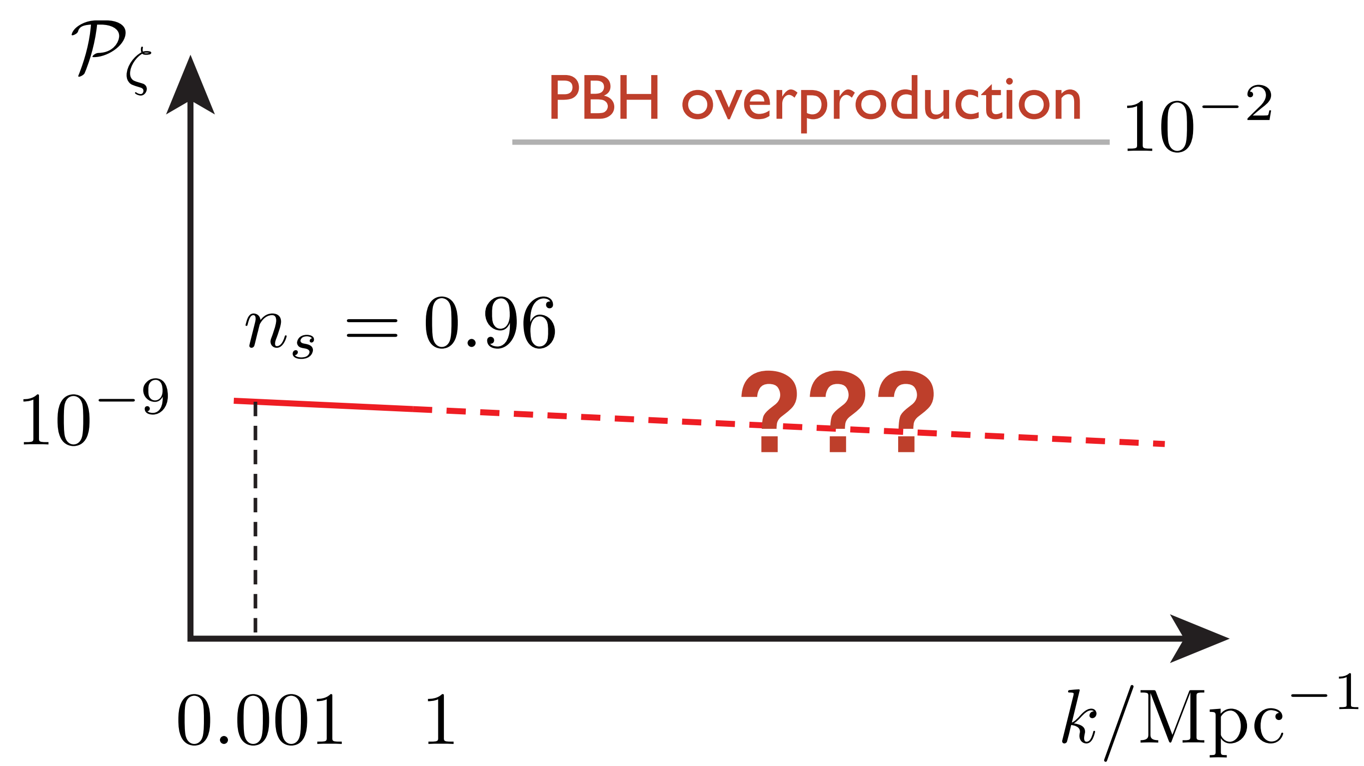
Planck 2013 results. XXII. Constraints on inflation

☺☺ CMB is a powerful tool to see the very early universe! ☺☺

☹ CMB can't tell us the small scale perturbations.

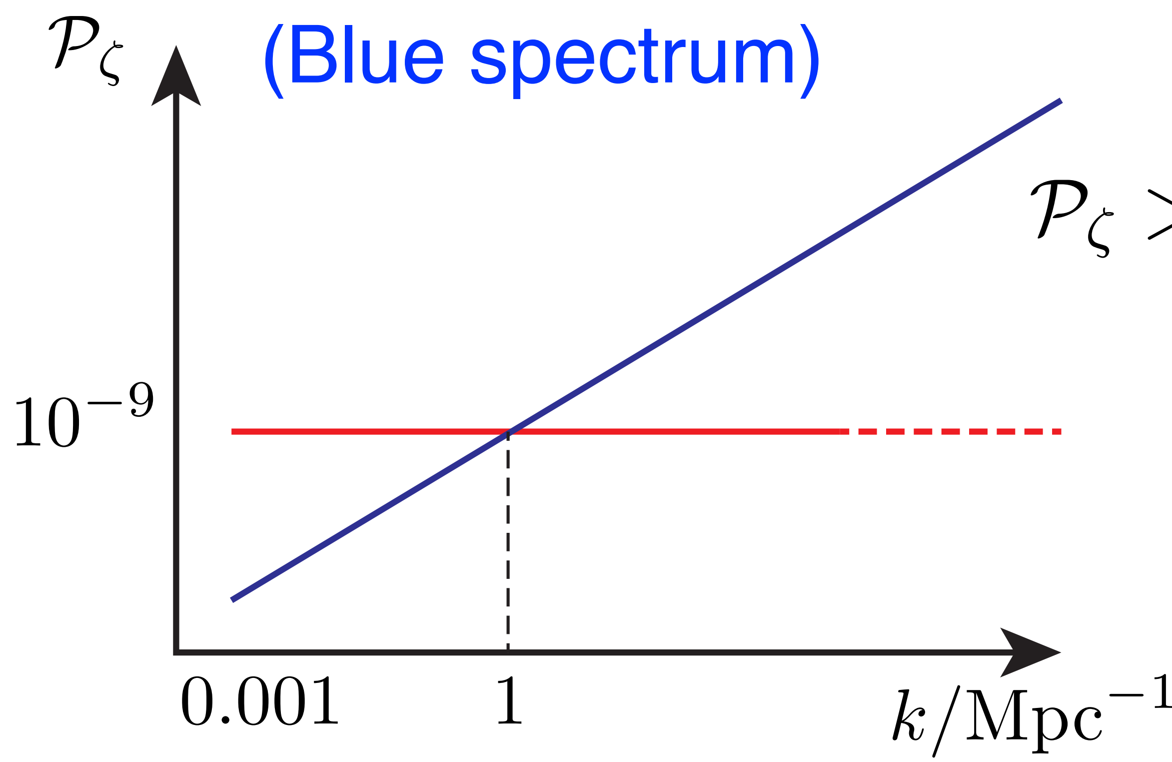
We know only the curvature perturbation on scales $k \lesssim 1\ \mathrm{Mpc}^{-1}$

$\mathcal{P}_\zeta = 2 \times 10^{-9}$ & $n_s = 0.96$ for $k < 1\ \mathrm{Mpc}^{-1}$



✭ Scales: $k > 1\ \mathrm{Mpc}^{-1}$ are free from the observation

It may be ...



$\mathcal{P}_\zeta \gg 10^{-9}$ & $n_s > 1$

for $k > 1\ \mathrm{Mpc}^{-1}$

Why blue spectrum?

High energy physics (SUSY, SUGRA)
predicts many scalar fields in the very early universe

◆ Inflaton ▶▶ drive inflation, primordial adiabatic perturbation
◆ Other scalar fields ▶▶ primordial isocurvature perturbation

Heavy scalar field (ex. Hubble-induced mass in SUGRA)

$H \sim m_\sigma$

✦ Heavy scalar fields predict
large curvature perturbation on small scales

If we can see the small-scale perturbations,
we will get some hints about the high energy physics.

Q. How can we see the small scale perturbations?

Stochastic Gravitational Wave Background (SGWB)

Tensor mode metric perturbation

$$ds^2 = a^2(\eta)\left[-d\eta^2 + (\delta_{ij} + h_{ij})dx^i dx^j\right]$$ with $h^i_i = 0$ & $\partial_i h^i_j = 0$

(trace-free & transverse)

GW observation → small scale perturbations

$10^{11}\ \mathrm{Mpc}^{-1} \lesssim k \lesssim 10^{15}\ \mathrm{Mpc}^{-1}$ (Direct detection)

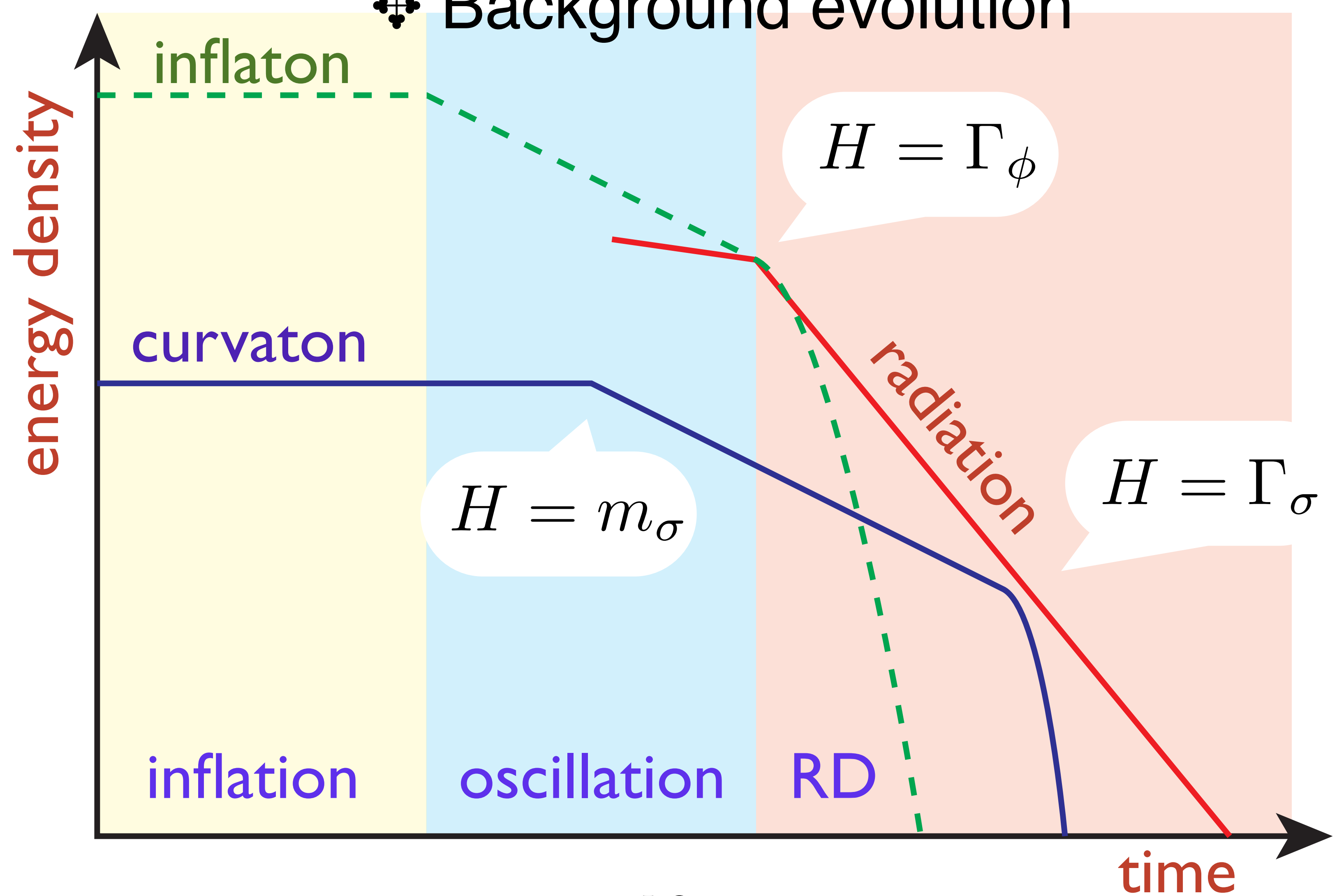
$k \sim 10^{7}\ \mathrm{Mpc}^{-1}$ (Pulsar timing)

II. Curvaton model with blue spectrum

❖ Curvaton scenario

1. inflation
2. inflaton coherent oscillation
   - curvaton starts to oscillate at $H = m_\sigma$
3. radiation domination (after inflaton decay)
   - curvaton decays at $H = \Gamma_\sigma$

✣ Background evolution



Curvature perturbation from multi scalar field

【inflaton ⊕ curvaton】

δN formalism: $\zeta = \delta N = N_\phi \delta\phi_* + N_\sigma \delta\sigma_* + \ldots$

There are 2 contributions ☛ inflaton curvaton

Power spectrum of curvature perturbation is defined via

$$\langle \zeta(\mathbf{k},\eta)\zeta(\mathbf{k}',\eta)\rangle = \frac{2\pi^2}{k^3}\mathcal{P}_\zeta(k,\eta)\delta^{(3)}(\mathbf{k}+\mathbf{k}')$$

$\zeta \ni \zeta_{\rm inf},\ \mathcal{S}_\sigma$

$$\mathcal{P}_\zeta(k,\eta) = \mathcal{P}_{\zeta,{\rm inf}}(k) + \mathcal{P}_{\zeta,{\rm curv}}(k)$$

We assume

Inflaton part reproduces CMB results: $\mathcal{P}_\zeta = 2\times 10^{-9}$ & $n_s = 0.96$

⊕

Curvaton part is required to be $\mathcal{P}_{\zeta,{\rm curv}} < \mathcal{P}_{\zeta,{\rm inf}}$ for $k < 1\ {\rm Mpc}^{-1}$

Curvaton part of the power spectrum

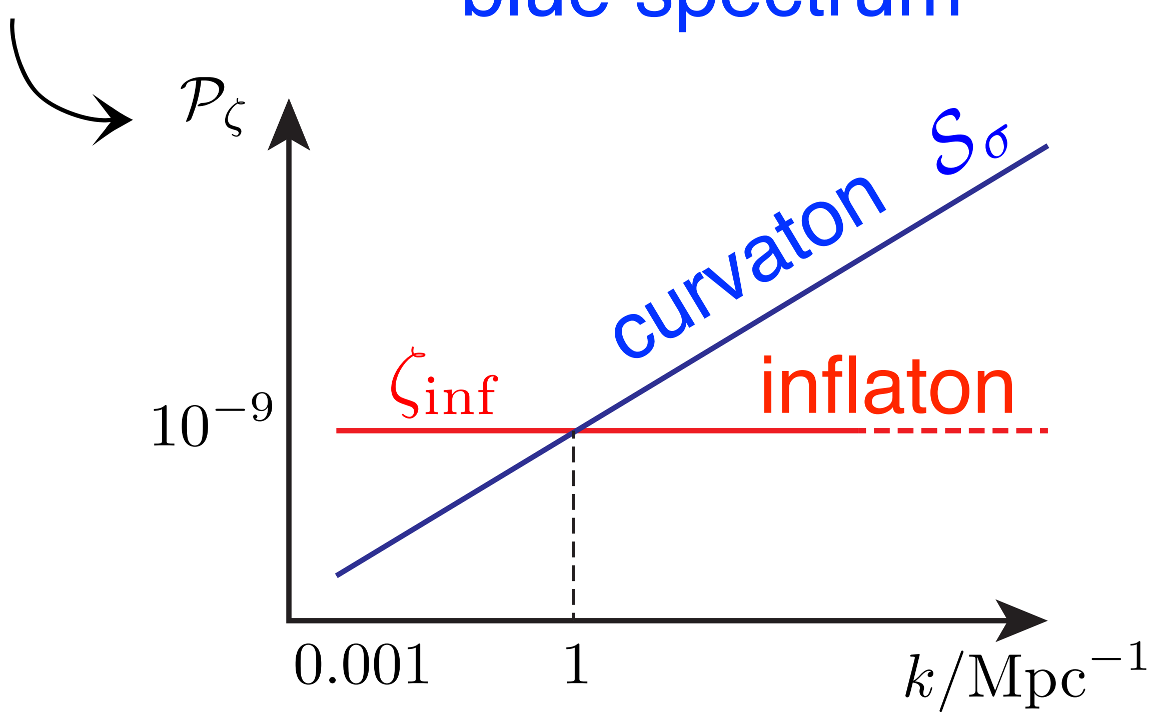
$$\mathcal{P}_{\zeta,\mathrm{curv}}(k) = \mathcal{P}_{\zeta,\mathrm{curv}}(k_c)\left(\frac{k}{k_c}\right)^{n_\sigma - 1}$$

with

$$\mathcal{P}_{\zeta,\mathrm{curv}}(k_c) = \mathcal{P}_{\zeta,\mathrm{inf}} \sim 2\times 10^{-9} \quad \& \quad k_c = 1\ \mathrm{Mpc}^{-1}$$

$$\& \quad n_\sigma > 1$$

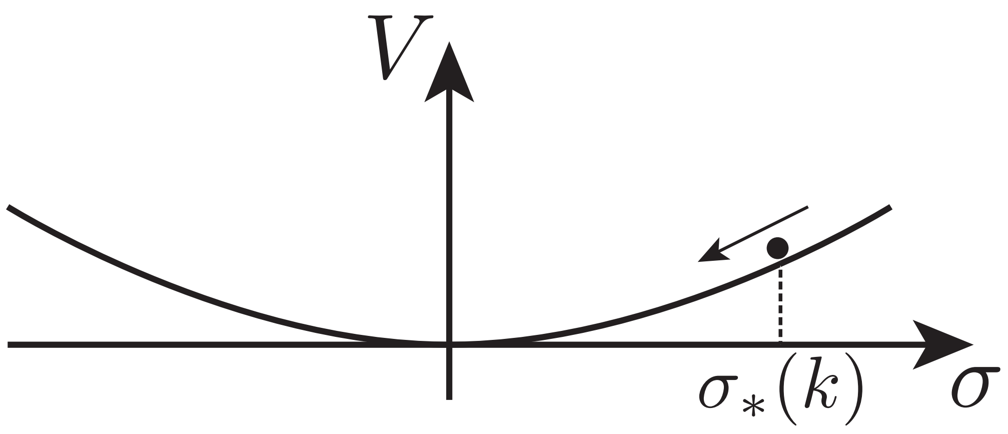
blue spectrum

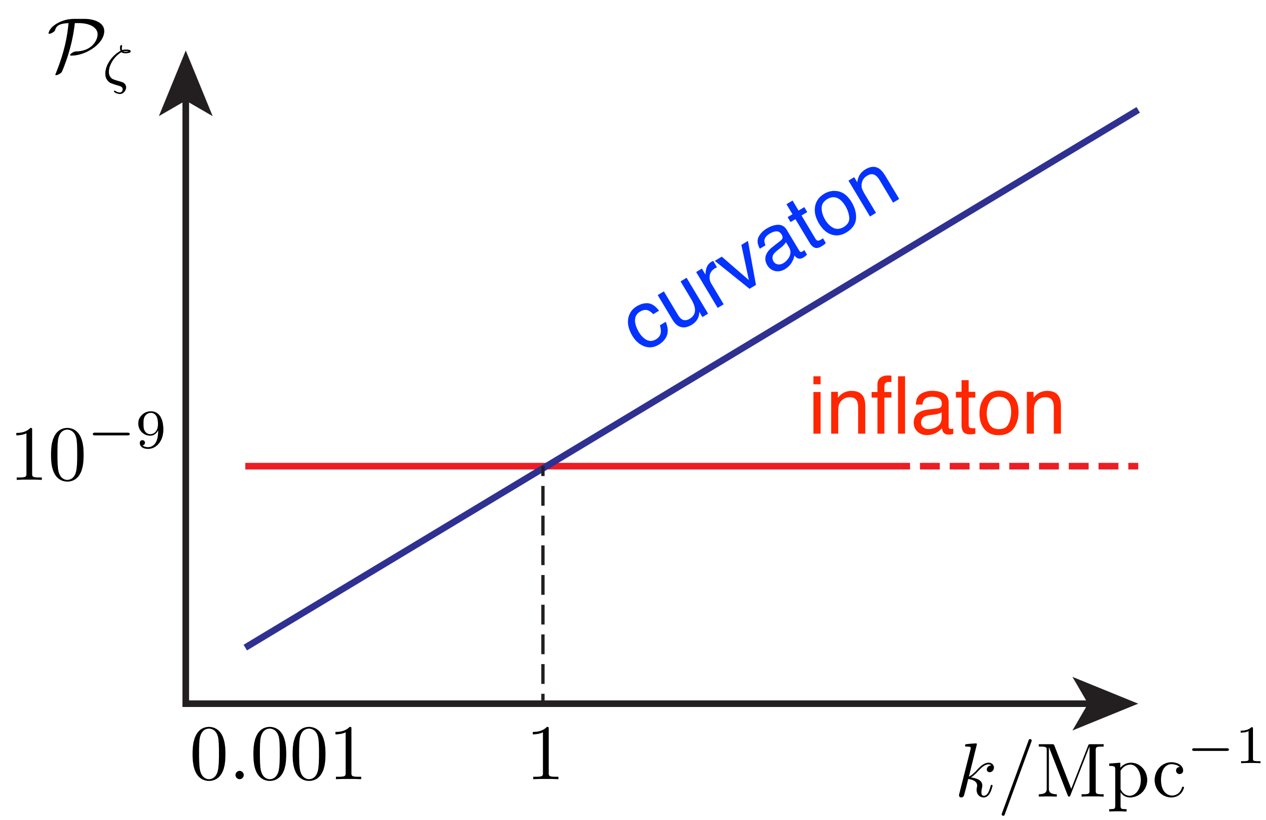


✣ Models

1. Quadratic curvaton model

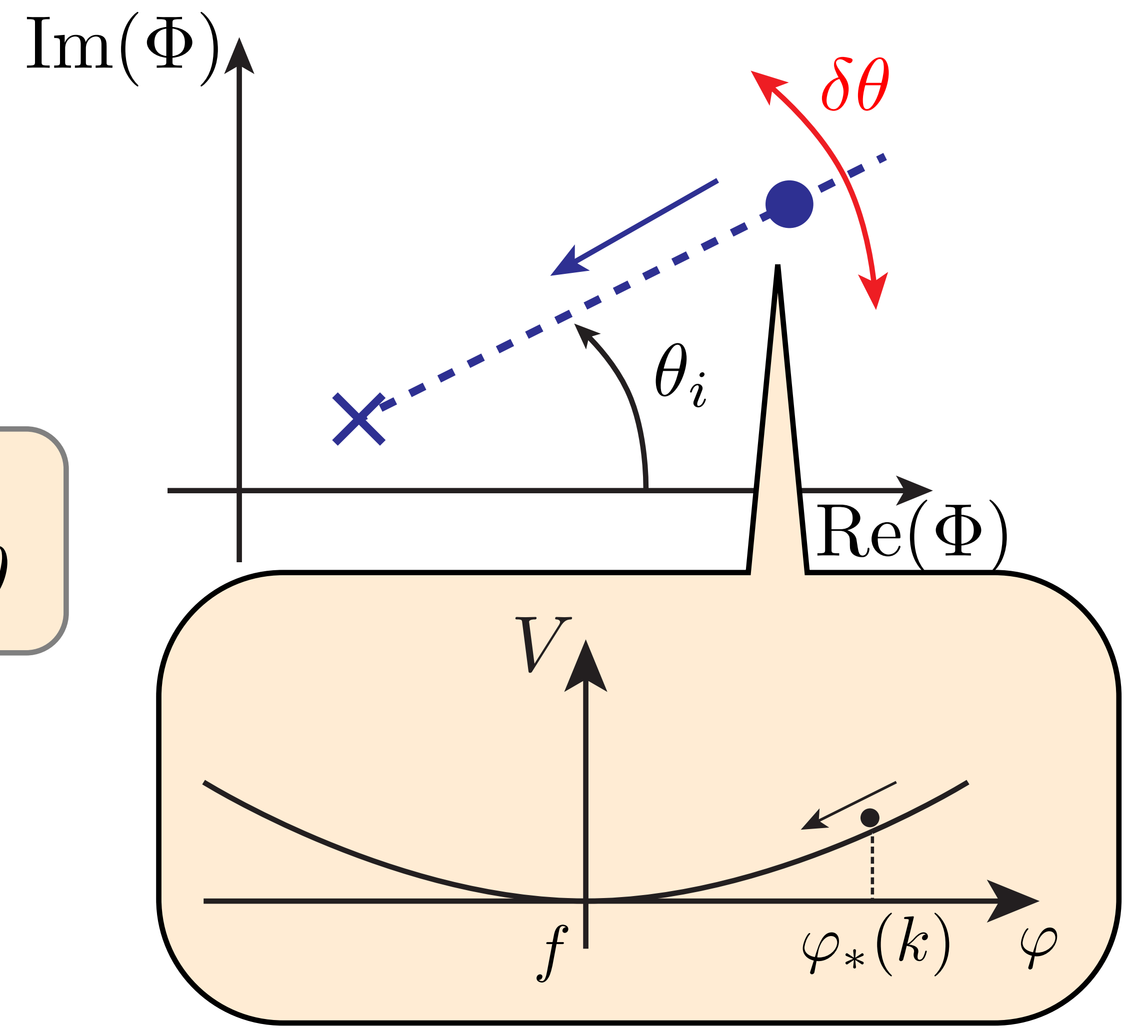
$$V(\sigma) = \frac{1}{2} m_\sigma^2 \sigma^2 \quad \Rightarrow \quad n_\sigma \simeq 1 + \frac{2m_\sigma^2}{3H_{\rm inf}^2}$$





2. Axion-like curvaton model

[Kasuya & Kawasaki, 0904.3800]



Complex scalar field: $\Phi = \varphi e^{i\theta}/\sqrt{2}$

Curvaton lives in the phase component of the scalar field: $\sigma = f\theta$

Potential of the curvaton:

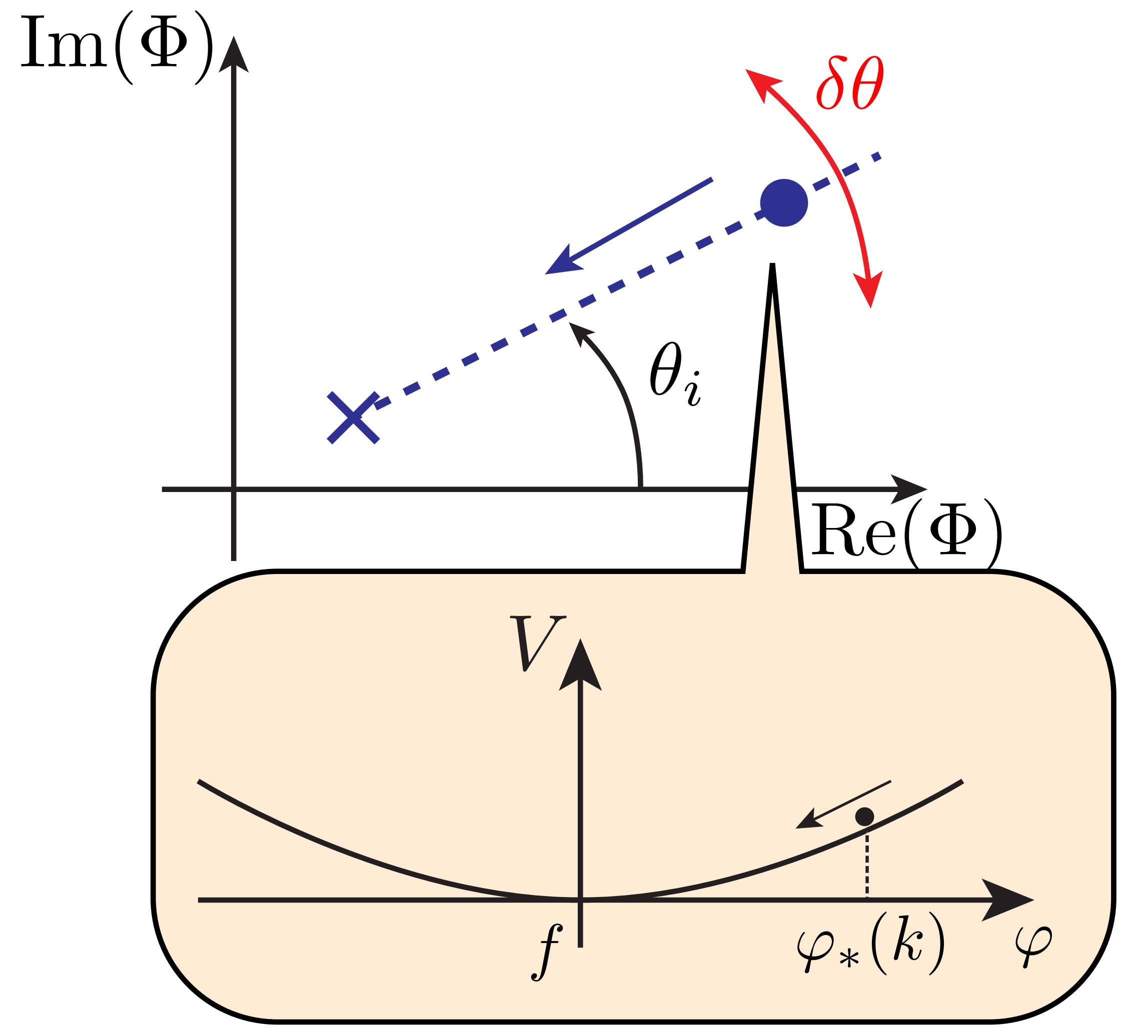
$$V(\sigma) = \Lambda^4\left[1 - \cos\left(\frac{\sigma}{f}\right)\right] \simeq \frac{1}{2}m_\sigma^2\sigma^2$$

↳ $m_\sigma \ll H_{\rm inf}$ ▶▶ θ is unchanged during inflation

Potential of radial component: $V(\varphi) = \frac{1}{2}cH_{\rm inf}^2(\varphi - f)^2$

$m_\varphi \sim H_{\rm inf}$ ▶▶ φ rolls down the potential somewhat rapidly.

Fluctuations



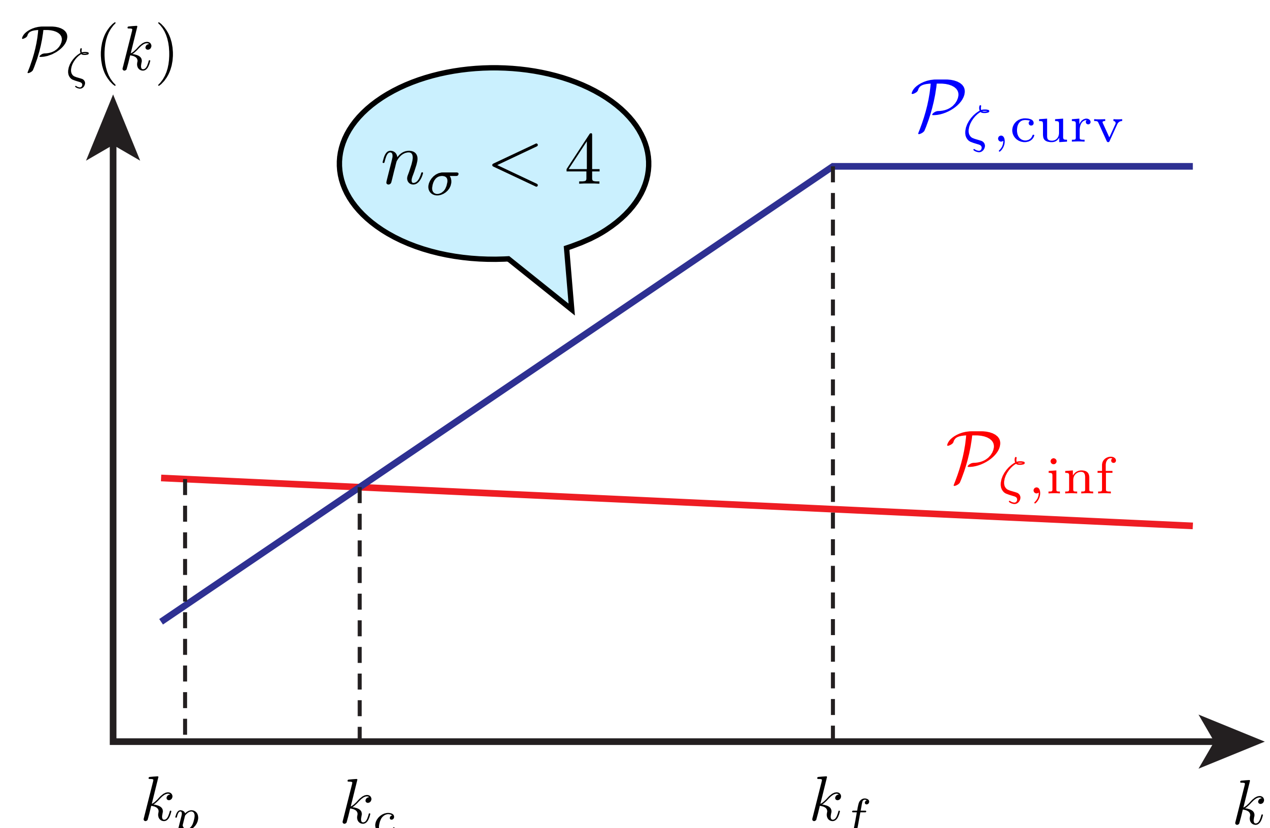
$\delta\theta/\theta$ is fixed at the value of horizon exit during inflation

$$\hookrightarrow \quad \frac{\delta\sigma_*}{\sigma_*} = \frac{\delta\theta_*}{\theta_i} = \frac{H_{\mathrm{inf}}}{2\pi\varphi_*\theta_i}$$

fluctuation of the curvaton on superhorizon scale

$\varphi_* = \varphi_*(k)$ is the value when the scale k exit the horizon

$$\mathcal{P}_{\zeta,\mathrm{curv}} \propto \varphi_*^{-2}$$



III. Scalar-induced gravitational waves

Our setup

❊ Perturbed metric (scalar & tensor modes)

$$ds^2 = a^2(\eta)\left[-(1+2\Phi)d\eta^2 + \left[(1-2\Psi)\delta_{ij} + \frac{1}{2}h_{ij}\right]dx^i dx^j\right]$$

h_{ij} : tensor mode ➤ stochastic background of GW

❊ Energy-momentum tensor (curvaton part)

$$T_{\mu\nu} = \partial_\mu \sigma \partial_\nu \sigma - g_{\mu\nu}\left(\frac{1}{2}g^{\alpha\beta}\partial_\alpha \sigma \partial_\beta \sigma + V(\sigma)\right)$$

Einstein equation: $G_{\mu\nu} = 8\pi G T_{\mu\nu}$

source term

Evolution for SGWB: $h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = -4\hat{\mathcal{T}}^{lm}_{ij}\mathcal{S}_{lm}$

$\mathcal{H} = a'/a$, $\hat{\mathcal{T}}^{lm}_{ij}$: projection tensor into TT tensor

★ source term is zero at 1st order (No late-time GW production!)

✶ Source term for GW ▶ 2nd order perturbations

(scalar)×(scalar) can be a source term for GW

2 kind of source terms

◆ GWs from scalar metric perturbations (lhs of Einstein eq.)

$$\mathcal{S}_{ij}^{\Phi} = -2\partial_i\Phi\partial_j\Phi - \mathcal{H}^{-2}\partial_i(\Phi' + \mathcal{H}\Phi)\partial_j(\Phi' + \mathcal{H}\Phi)$$

◆ GWs from energy-momentum tensor (rhs)

$$\mathcal{S}_{ij}^{\rm kin} = M_P^{-2}\partial_i\delta\sigma\partial_j\delta\sigma$$

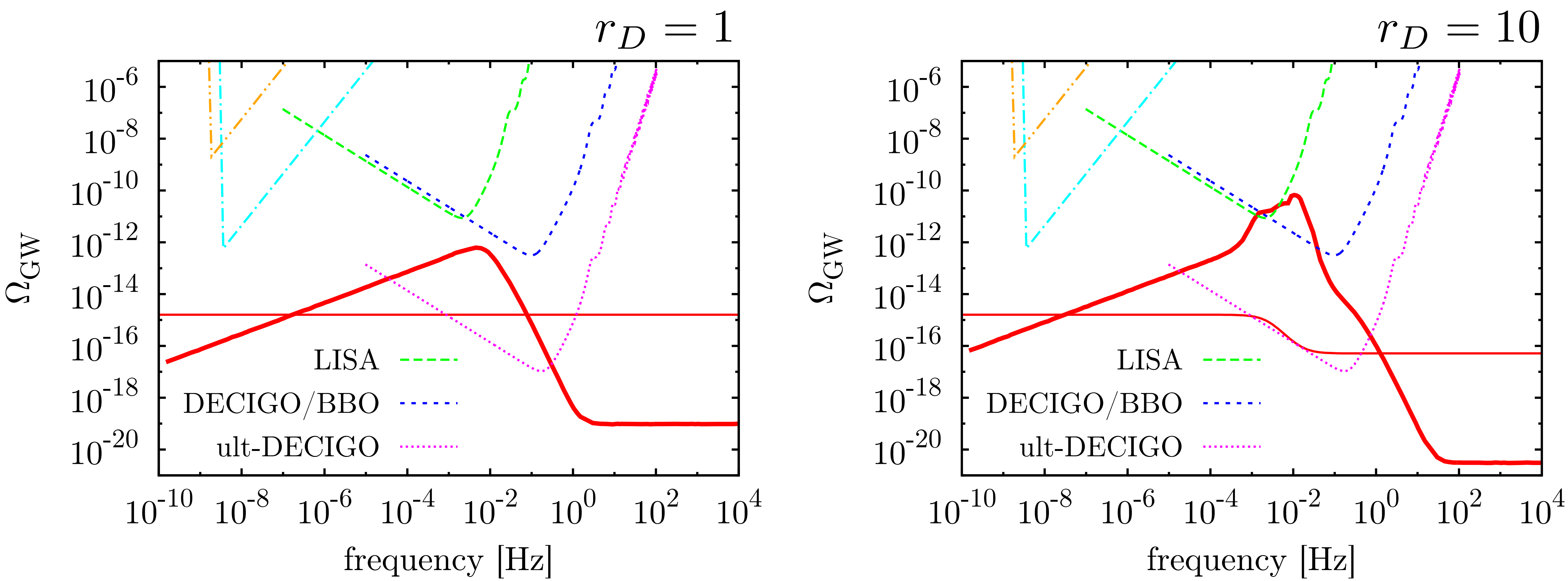
"anisotropic stress"

We have calculated the energy spectrum of GW in blue-tilted curvaton model!

IV. Result

(1) Quadratic curvaton model

$H_{\rm inf} = 3 \times 10^{-5} M_P, n_\sigma = 1.3$ $\quad r_D = \rho_\sigma / \rho_r$ at decay



☞ Spectrum has a peak corresponding to the curvaton decay!

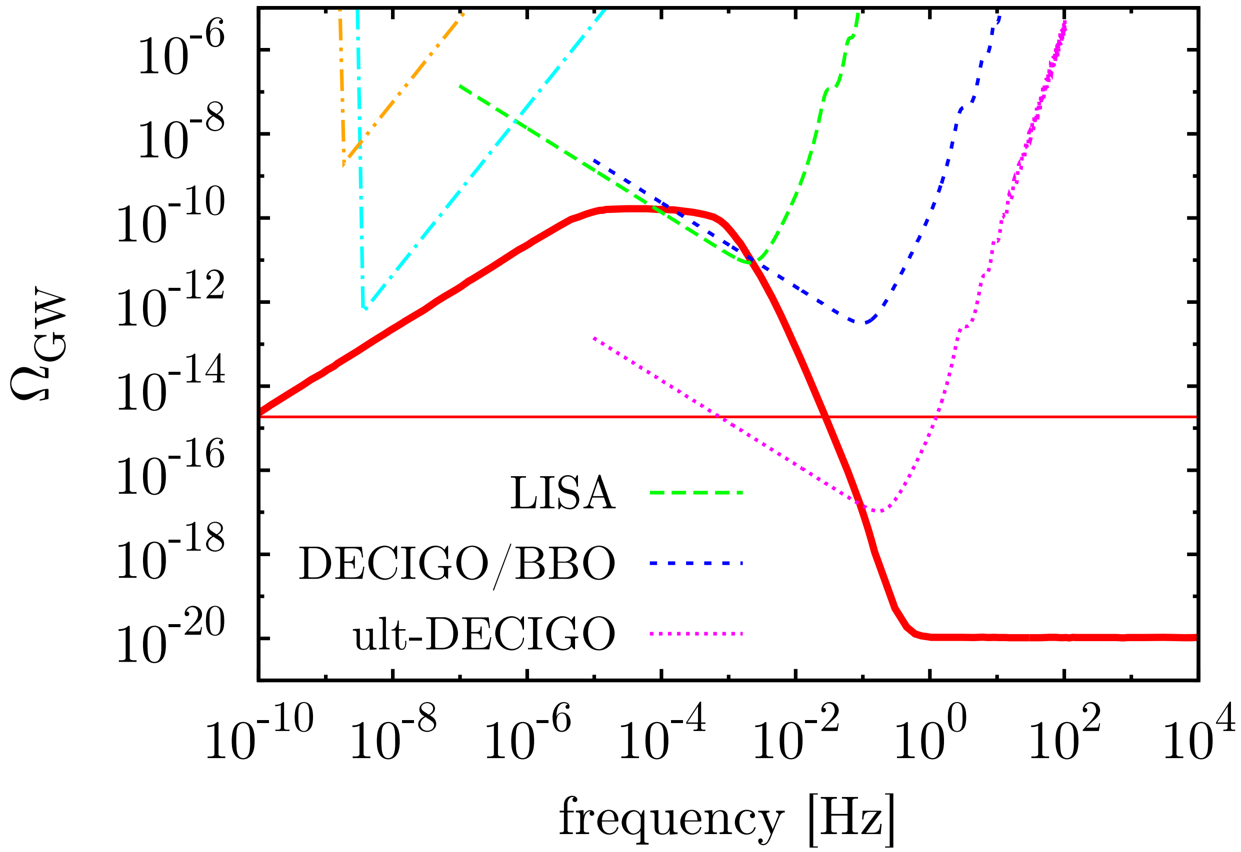
☞ Signal is detectable by future observation!

☞ We can distinguish whether r_D < 1 or not.

(2) Axion-like curvaton model

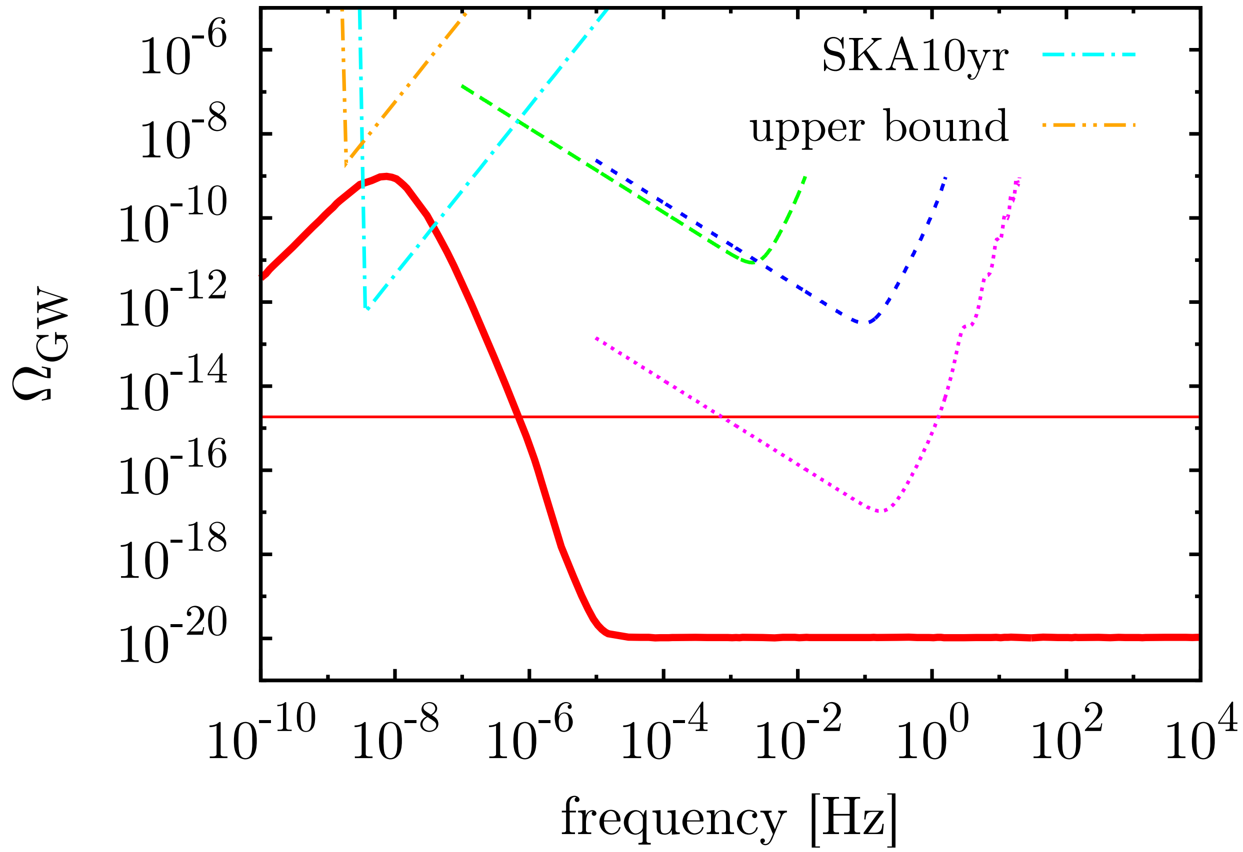
$$H_{\rm inf} = 3 \times 10^{-5} M_P, \ r_D = 1$$

$$n_\sigma = 1.5, \ k_f = 10^{10} \ {\rm Mpc}^{-1}$$



$$f \simeq 2 \times 10^{14} \ {\rm GeV}, \ \ m_\sigma \simeq 3 \times 10^{10} \ {\rm GeV}$$

$$n_\sigma = 1.8, \ k_f = 10^{7} \ {\rm Mpc}^{-1}$$



$$f \simeq 4 \times 10^{13} \ {\rm GeV}, \ \ m_\sigma \simeq 9 \times 10^{3} \ {\rm GeV}$$

- ☛ Characteristic shape (there is a plateau)
- ☛ Signal is detectable by pulsar timing obs.

Summary

Motivation

Heavy scalar fields existing at the inflationary epoch (curvaton) can generate the large curvature perturbation on small scales

▶ Can we detect their imprints by observation?

What we did

We have calculated the amount of GW sourced by the scalar perturbations

(quadratic curvaton model & axion-like curvaton model)

Results

Detectable GW is predicted

- curvaton decay epoch
- curvaton domination

Conclusions:

We can see the imprints of curvaton scenario

or constrain the heavy scalar fields during inflation by GW obs.

❖ Curvaton scenario

1. inflation
2. inflaton coherent oscillation
   - curvaton starts to oscillate at $H = m_\sigma$
3. radiation domination (after inflaton decay)
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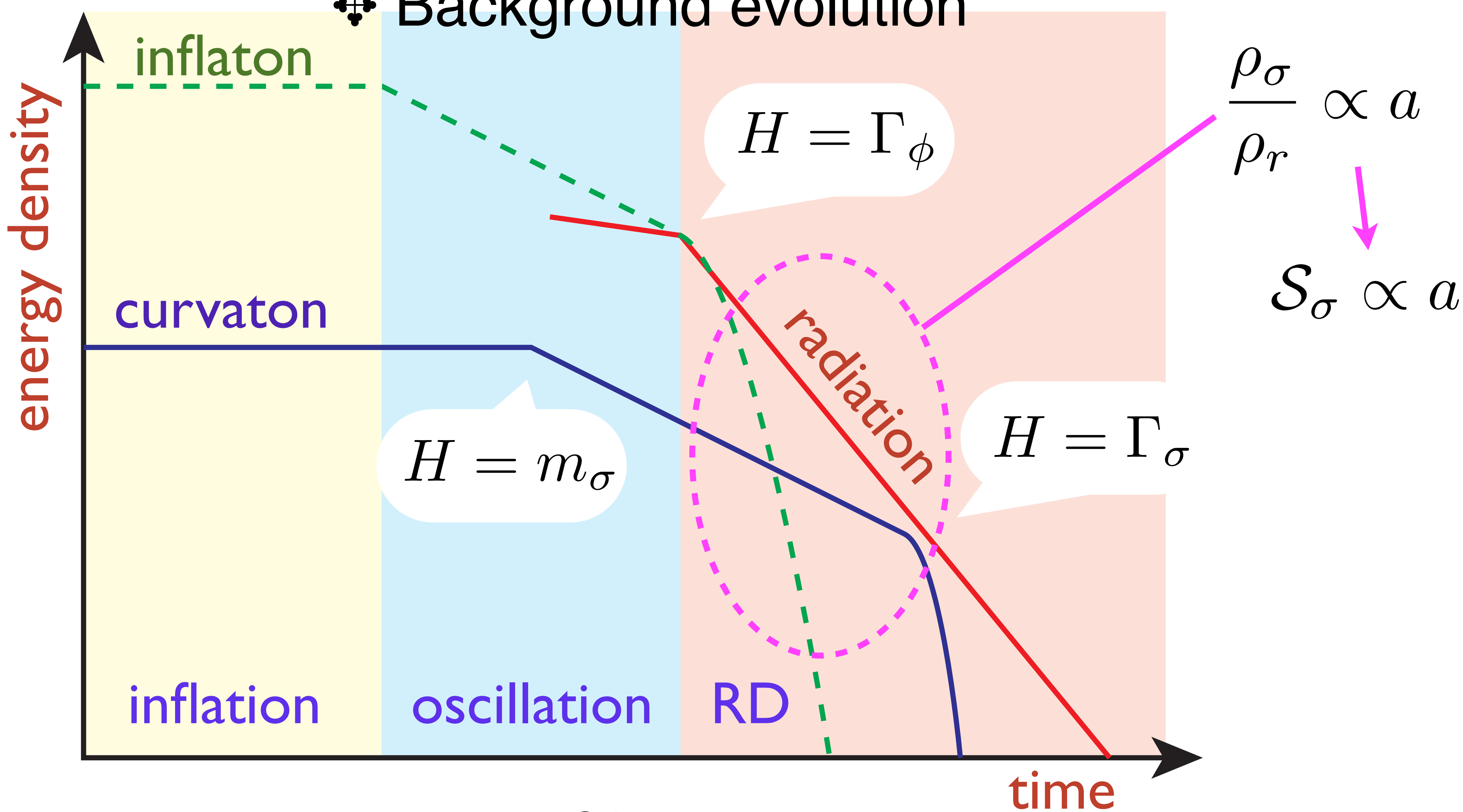
✣ Background evolution



What can we observe?

Power spectrum of h ☞ $\langle h_{\mathbf{k}}(\eta) h_{\mathbf{p}}(\eta) \rangle \equiv \frac{2\pi^2}{k^3} \delta^3(\mathbf{k}+\mathbf{p}) \mathcal{P}_h(k,\eta)$

$$\rho_{\rm GW}(\eta) = \frac{1}{32\pi G a^2} \langle h'_{ij} h'_{ij} \rangle = \frac{k^2}{16\pi G a^2} \int d\ln k \, \mathcal{P}_h(k,\eta)$$

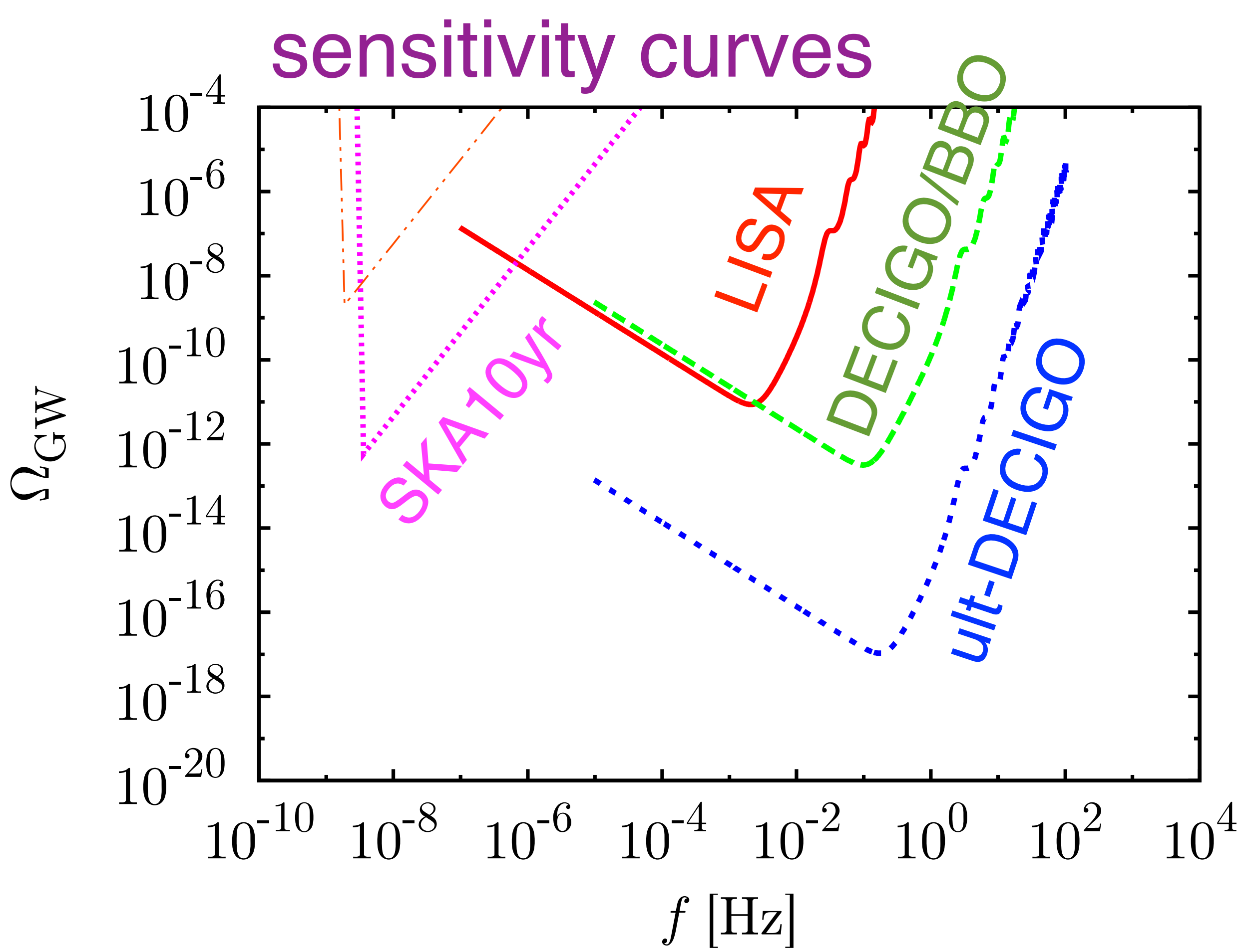
$$\blacktriangleright \quad \Omega_{\rm GW}(k,\eta) = \frac{1}{\rho_{\rm cr}(\eta)} \frac{d\rho_{\rm GW}(\eta)}{d\ln k} = \frac{k^2}{6\mathcal{H}^2(\eta)} \mathcal{P}_h(k,\eta)$$

Energy spectrum today :

$$\Omega_{\rm GW}(k) = \frac{k^2 \Omega_\gamma}{6\mathcal{H}^2(\eta_\star)} \mathcal{P}_h(k,\eta_\star)$$

$$\Omega_\gamma \simeq 4.8 \times 10^{-5}$$

(density parameter of radiation)



✻ GW from curvaton : contribution from EM tensor

Approximated formula : $\Omega_{\rm GW} \sim 10^{-19} \frac{\Gamma}{r_D^2 m_\sigma} \left(\frac{\mathcal{P}_\zeta}{2 \times 10^{-9}} \right)^2$

$\left(r_D = \frac{\rho_\sigma}{\rho_r} \right.$ at decay $\left. \right)$ Bartolo, Matarrese, Riotto & Vaihkonen (2007)

$$\Omega_{\rm GW} \sim 10^{-25} \left(\frac{4}{4 + 3r_D} \right)^4 \left(\frac{\sigma_{\rm osc}}{\sigma(k)} \right)^4 \left(\frac{H_{\rm inf}}{10^{14}\ {\rm GeV}} \right)^4$$

➢ negligible contribution !

$r \lesssim 0.1$ or $H_{\rm inf} \lesssim 10^{14}$ GeV

cf. $\mathcal{S}_{ij}^{\rm kin} = M_P^{-2} \partial_i \delta\sigma \partial_j \delta\sigma \sim k^2 \left(\frac{H_{\rm inf}}{M_P} \right)^2$

✻ GW from curvaton : contribution from curvature

(i) Approximated formula : $\Omega_{\rm GW} \sim 10^{19} \left(\frac{\mathcal{P}_{\zeta,{\rm curv}}(k)}{\mathcal{P}_\zeta(k_c)} \right)^2$

Ananda, Clarkson & Wands (2007),
Baumann, Steinheardt, Takahashi & Ichiki (2007)

(ii) GW is emitted at the horizon reentering

because Φ decays after horizon reentering (RD)

(iii) Peaked spectrum at k_dec

↖ the mode reentering the horizon at the curvaton decay

$k_{\rm dom} \sim 1/\eta_{\rm dom}$ or $k_{\rm NL} \sim \mathcal{P}^{-1/4}_{\zeta,{\rm curv}}(k_{\rm dec})/\eta_{\rm dec}$ for $r_D > 1$

➤ the mode reentering the horizon at curvaton domination
or the mode becoming nonlinear at decay

✻ GW from curvaton : contribution from curvature

(i) Approximated formula : $\Omega_{\rm GW} \sim 10^{-19} \left(\frac{\mathcal{P}_{\zeta,{\rm curv}}(k)}{\mathcal{P}_{\zeta}(k_c)} \right)^2$

Ananda, Clarkson & Wands (2007),
Baumann, Steinheardt, Takahashi & Ichiki (2007)

(ii) GW is emitted at the horizon reentering

because Φ decays after horizon reentering (RD)

(In MD universe, Φ doesn't decay even after horizon reentering
& GWs are continuously emitted)

(iii) Peaked spectrum at k_dec

↑

the mode reentering the horizon at the curvaton decay

because $\mathcal{S}_\sigma \propto a$ before curvaton decay