Probing Beyond-the-Standard-Model Physics with Inflationary Gravitational Waves (IGWs)

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Refs:

Jinno, TM and Nakayama, PLB713 ('12) 129

Jinno, TM and Nakayama, PRD86 ('12) 123502

Jinno, TM and Nakayama, in preparation

PLANCK 2013, '13.05.24

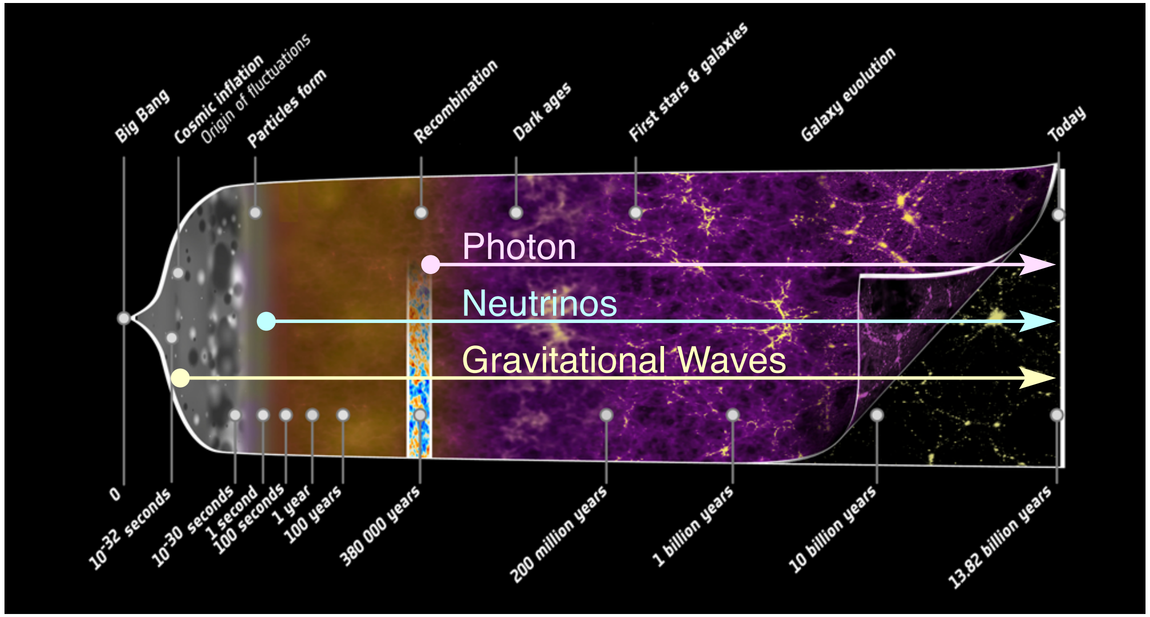
1. Introduction

PLANCK (and other) results strongly support inflation

⇒ What happened between inflation epoch and today?

Today's subject

Use the IGW as a probe of BSM physics which governs the evolution of the early universe



The history of our universe is imprinted in IGWs

$\Rightarrow$ The IGW spectrum is sensitive to the thermal history (and hence to the BSM physics)

$\Rightarrow$ The IGW spectrum may be measured in (far) future by, for e.g., BBO / DECIGO

Outline

1. Introduction
2. Gravitational Waves: Production and Evolution
3. Studying the Early Universe with IGWs
4. Summary

2. IGWs: Production and Evolution

Gravitational wave: Fluctuation of the metric

Metric: $ds^2 = -dt^2 + a^2(t)(\delta_{ij} + 2h_{ij})dx^i dx^j$

Fourier modes:

$$h_{ij}(t, \vec{x}) = \frac{1}{M_{\mathsf{Pl}}} \sum_{\lambda=+,\times} \int \frac{d^3\vec{k}}{(2\pi)^3} \tilde{h}_{\vec{k}}^{(\lambda)}(t) \epsilon_{ij}^{(\lambda)} e^{i\vec{k}\vec{x}}$$

$\epsilon_{ij}^{(\lambda)}$: polarization tensor (transverse & traceless)

Quantum fluctuation generated during inflation

$$\Delta_h^2(k \ll aH) \equiv \frac{k^3}{2\pi^2 V} \times \frac{1}{M_{\mathsf{Pl}}^2} \sum_{\lambda} \left\langle |\tilde{h}_{\vec{k}}^{(\lambda)}|^2 \right\rangle_{\text{inflation}} \simeq \frac{2}{M_{\mathsf{Pl}}^2} \left(\frac{H_{\text{inf}}}{2\pi} \right)^2$$

$\Rightarrow$ The amplitude of the IGW is proportional to H_{inf}

IGW evolution after inflation

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{1}{M_{\mathrm{Pl}}^2}T_{\mu\nu} \;\Rightarrow\; \ddot{\tilde{h}}_{\vec{k}}^{(\lambda)} + 3H\dot{\tilde{h}}_{\vec{k}}^{(\lambda)} + \frac{k^2}{a^2(t)}\tilde{h}_{\vec{k}}^{(\lambda)} \simeq 0$$

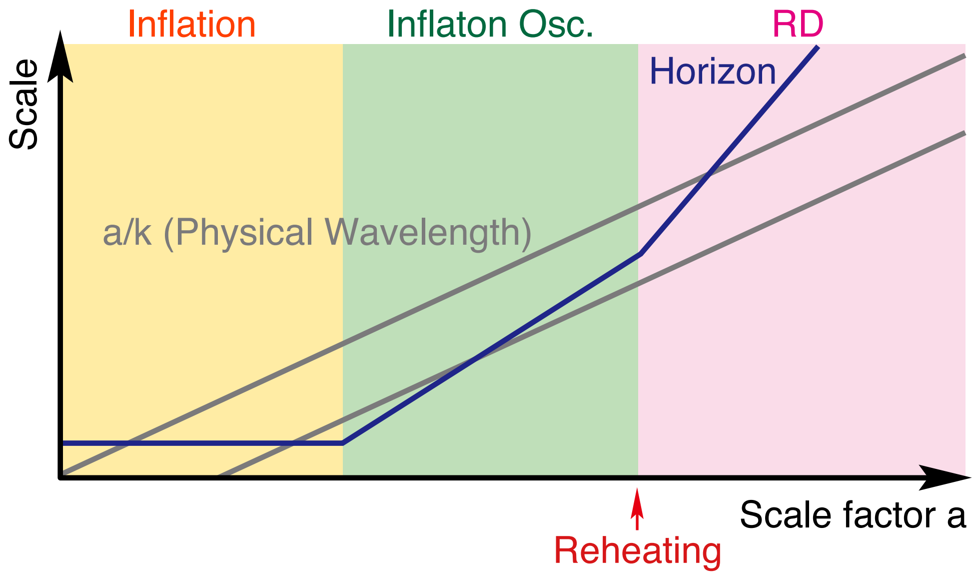
Evolution of IGWs: after inflation

- $k \lesssim aH$: $\tilde{h}_{\vec{k}} \sim$ const.

$$\Rightarrow \frac{d\rho_{\mathrm{GW}}}{d\ln k} \propto a^{-2}$$

- $k \gtrsim aH$: $\langle \tilde{h}_{\vec{k}}^2 \rangle_{\mathrm{osc}} \sim a^{-2}$

$$\Rightarrow \frac{d\rho_{\mathrm{GW}}}{d\ln k} \propto a^{-4}$$



$$\frac{d\rho_{\mathrm{GW}}}{d\ln k} = \frac{k^3}{2\pi^2 V}\sum_{\lambda}\left[\frac{1}{2}\left|\dot{\tilde{h}}_{\vec{k}}^{(\lambda)}\right|^2 + \frac{1}{2}\left(\frac{k}{a}\right)^2\left|\tilde{h}_{\vec{k}}^{(\lambda)}\right|^2\right]$$

Present spectrum of the IGW in the simplest case

[Nakayama, Saito, Suwa & Yokoyama]

$$\Omega_{\mathsf{GW}}(k) \equiv \left[\frac{1}{\rho_{\mathsf{crit}}}\frac{d\rho_{\mathsf{GW}}}{d\ln k}\right]_{\mathsf{NOW}}$$

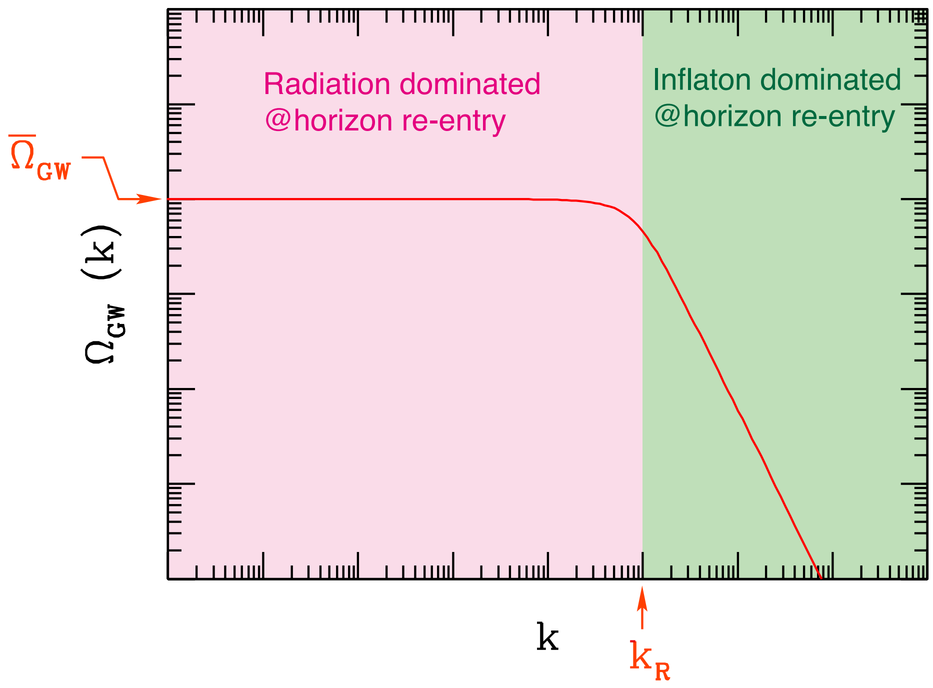
$\Omega_{\mathsf{GW}}(k < k_{\mathsf{R}}) \sim$ const., if nothing happens after the reheating

- $\bar{\Omega}_{\mathsf{GW}} \propto H_{\mathsf{inf}}^2$
- $\bar{\Omega}_{\mathsf{GW}} \simeq 6 \times 10^{-16}\left(\frac{r}{0.1}\right)$

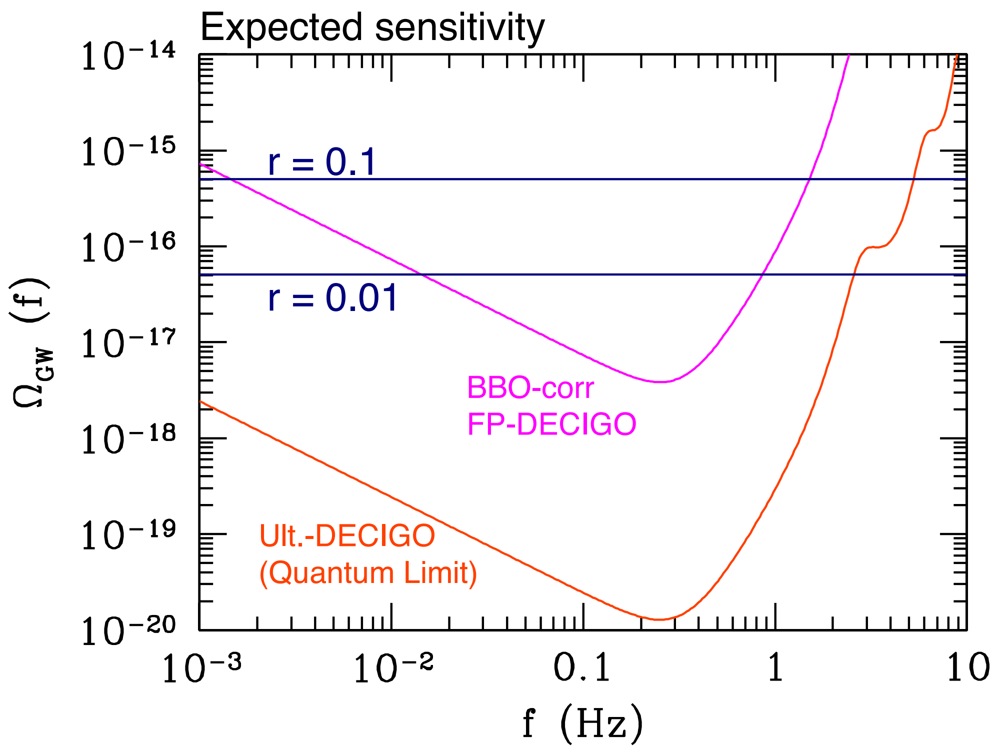
  r: tensor-to-scalar ratio

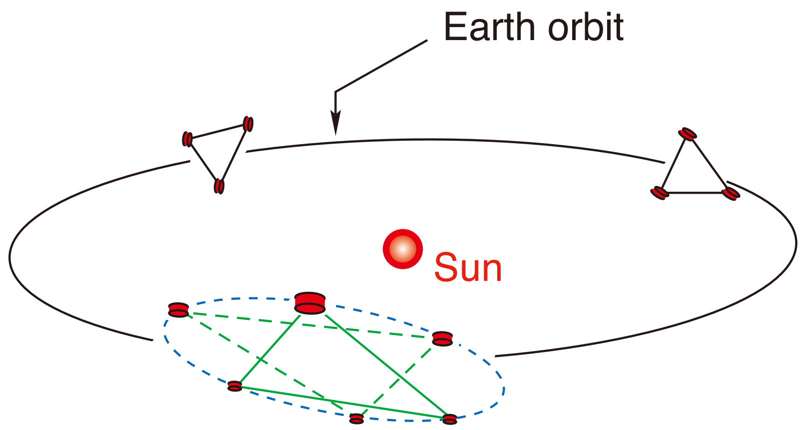
  $r < 0.11$

  [Planck Collaboration]
- k_{R} depends on T_{R}



In future, IGWs may be seen by, for e.g., BBO & DECIGO





[Kudoh, Taruya, Hiramatsu & Himemoto]

- $f = \dfrac{k}{2\pi} \simeq 2.7\ \text{Hz} \times \left(\dfrac{T_{\text{Horizon-In}}}{10^8\ \text{GeV}}\right)$
- $f \lesssim 0.1$ Hz: GWs from white dwarf binaries may dominate

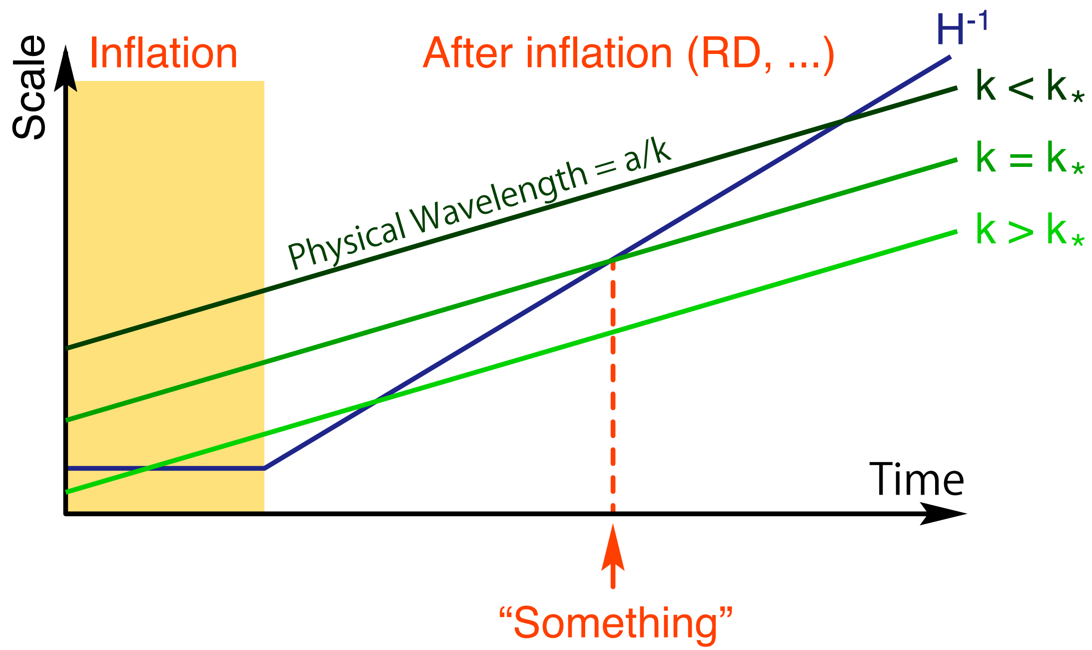
  [Farmer & Phinney]

3. Studying the Early Universe with IGWs

[Jinno, TM & Nakayama]

If "something" happens after reheating, $\Omega_{\rm GW}(k)$ is deformed

- Cosmic phase transition
- Domination by extra matter
- $\cdots$



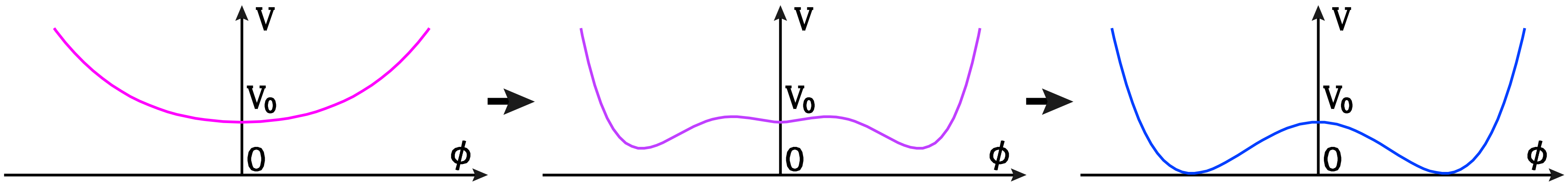
$\Rightarrow$ $\Omega_{\rm GW}(k)$ at $k \sim k_*$ is deformed

Case 1: Phase transition

Example: Peccei-Quinn symmetry breaking

Potential with thermal effects:

$$V(\phi) = \frac{g}{24}(\phi^2 - v_\phi^2)^2 + \frac{h}{24}T^2\phi^2$$



$$\langle\phi\rangle \simeq \begin{cases} 0 & : T > T_c \\ v_\phi & : T < T_c \end{cases}$$

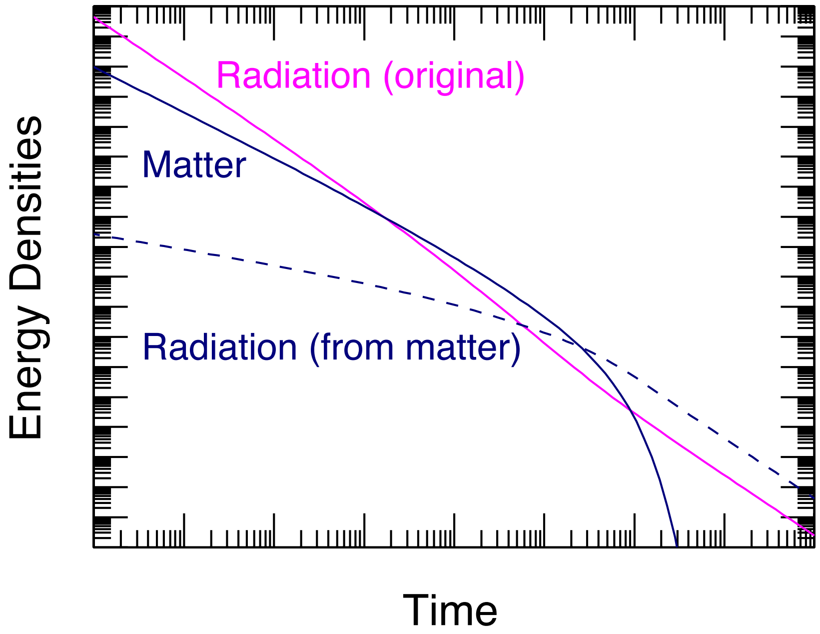
⇒ The universe may be once dominated by the potential energy of ϕ (like thermal inflation)

[Lyth & Stewart]

Case 2: Temporary matter domination

- Scalar condensations (like saxion in SUSY PQ model)
- Other exotic particles

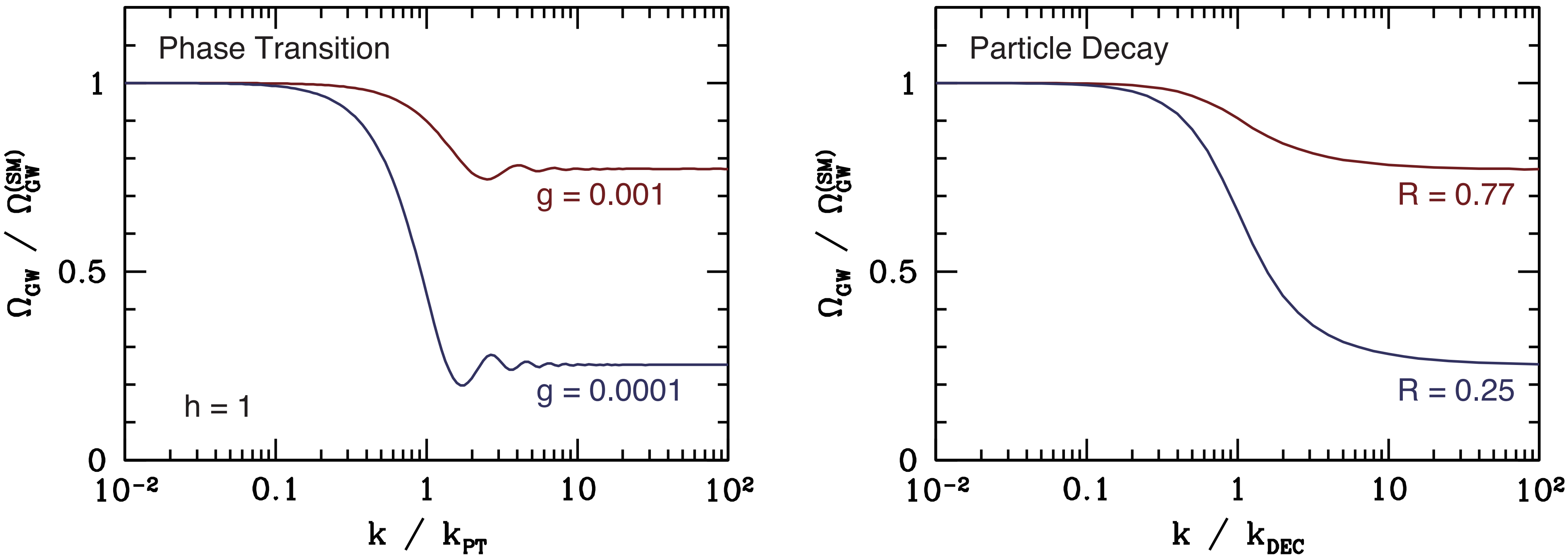
A scalar field once dominates the universe, then decays



- $\rho_{\mathrm{rad}} \propto a^{-4}$
- $\rho_{\mathrm{matter}} \propto a^{-3}$

IGW spectrum for two cases:

[Jinno, TM & Nakayama]

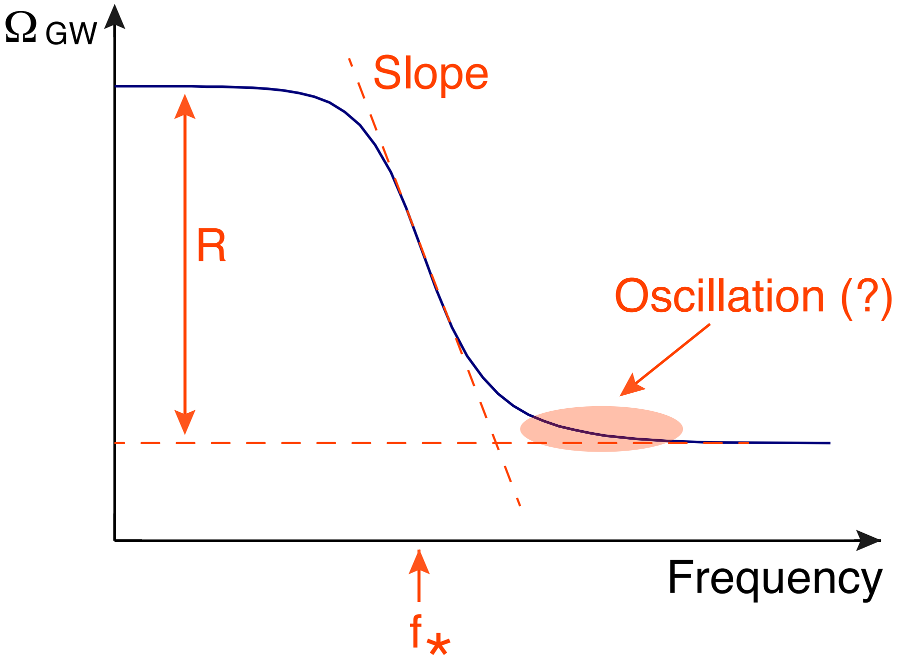


Important parameter:

$$R \equiv \left.\frac{\Omega_{\mathrm{GW}}(k)}{\Omega_{\mathrm{GW}}^{(\mathrm{SM})}(k)}\right|_{k \gg k_{\mathrm{PT}}} = \frac{\rho_{\mathrm{rad}}^{(\mathrm{orig})}}{\rho_{\mathrm{rad}}^{(\mathrm{orig})} + \rho_{\mathrm{rad}}^{(\mathrm{extra})}}$$

Information in the IGW spectrum

- $f_* \Rightarrow$ Temperature of "something"
- $R \Rightarrow$ Energy injection
- $d\Omega_{\rm GW}/d\ln k \Rightarrow$ Time scale of the event



- $f_* \simeq 2.7 \text{ Hz} \times \left(\frac{T_*}{10^8 \text{ GeV}} \right)$
- $R = \frac{\rho_{\rm rad}^{\rm (orig)}}{\rho_{\rm rad}^{\rm (orig)} + \rho_{\rm rad}^{\rm (extra)}}$

Case 3: Production of "dark radiation (DR)"

DR: Relativistic particle with large free-streaming length

- Candidates of dark radiation: NG bosons, like axion, $\cdots$

  $\Rightarrow$ They can be produced in association with phase transition, for example

  $\Rightarrow$ They may decay, or may be diluted afterwards

- Non-vanishing anisotropy inertia shows up

  $$\Rightarrow \ddot{\tilde{h}}_{\vec{k}}^{(\lambda)} + 3H\dot{\tilde{h}}_{\vec{k}}^{(\lambda)} + \frac{k^2}{a^2(t)}\tilde{h}_{\vec{k}}^{(\lambda)} = \frac{1}{M_{\rm Pl}^2} \times \text{(anisotropic inertia)}$$

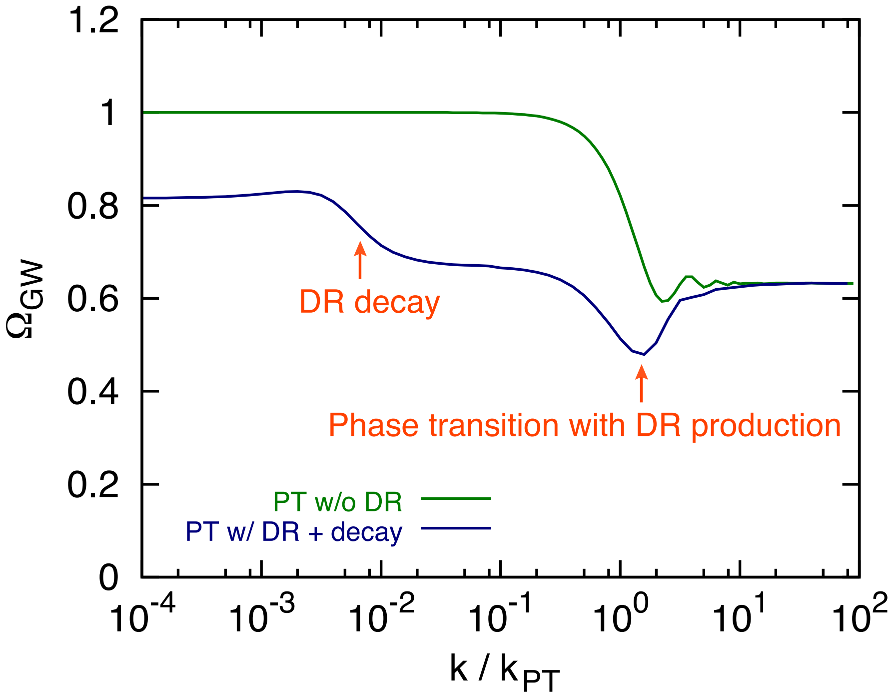
With DR, the IGW spectrum shows characteristic feature

[Weinberg]

$\Rightarrow$ Suppression of low frequency mode of the IGW spectrum

Example 1: Phase transition with DR production

1. Phase transition, which produces DR
2. Decay of (some fraction of) "DR"



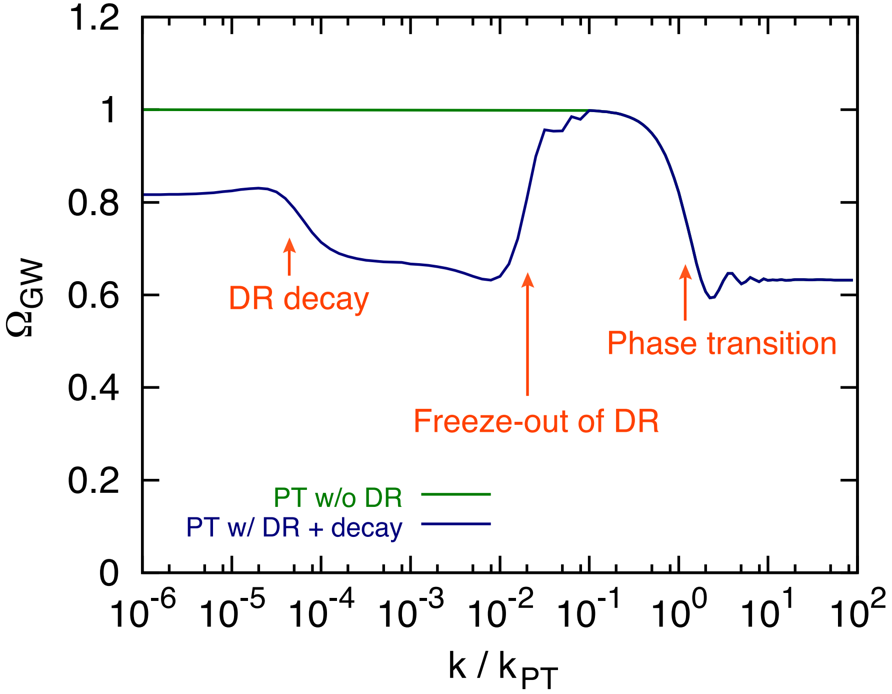
Energy fraction of DR

$33\ \%$ before decay

$13\ \%$ after decay; $\Delta N_{\rm eff} = 0.5$

Example 2: Freeze-out of DR

1. Phase transition, which produces dark-sector particles
2. Particles in the dark sector freeze-out



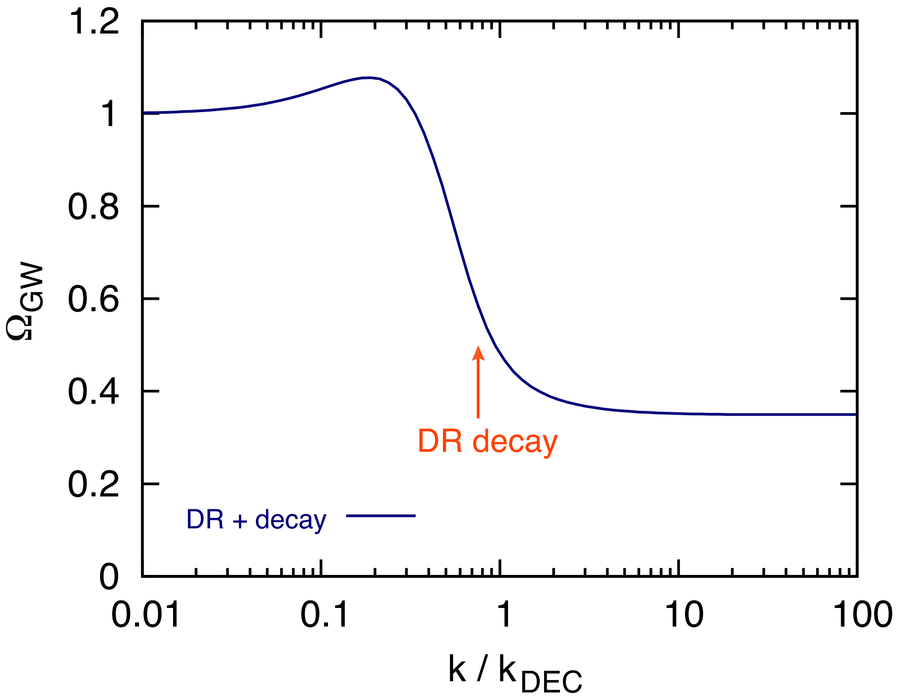
Energy fraction of DR

$33\ \%$ before decay

$13\ \%$ after decay; $\Delta N_{\rm eff} = 0.5$

Example 3: DR domination in the early epoch

1. Universe was once dominated by DR
2. DR decays and reheats the SM sector



Energy fraction of DR

$100\ \%$ before decay

$0\ \%$ after decay

4. Summary

The IGW spectrum contains information about early epoch

- Cosmic phase transition
- Temporary matter domination
- Production of dark-radiation-like fluid
- $\cdots$

Possible progresses in near future:

- Discovery of CMB B-mode signal (PLANCK / CMB interferometric observations)
- Detection of GW by ground-based experiments (Advanced LIGO / KAGRA) to establish the technology
- If these are done, we should better consider satellite-based experiment to detect IGW