Gravitational waves from inflation

Sachiko Kuroyanagi (ICRR, U. of Tokyo)

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  - Generation mechanism
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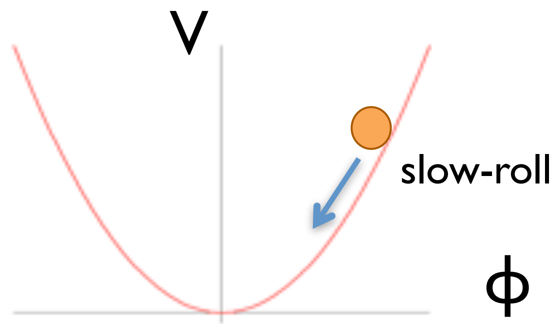
■ Introduction

Inflation: a phase of accelerated expansion of the universe

solves the Horizon/Flatness/Monopole problem

Standard picture of inflation



- driven by a scalar field Φ
- occurs when it slowly rolls down its potential

quantum fluctuations in Φ → scalar perturbations

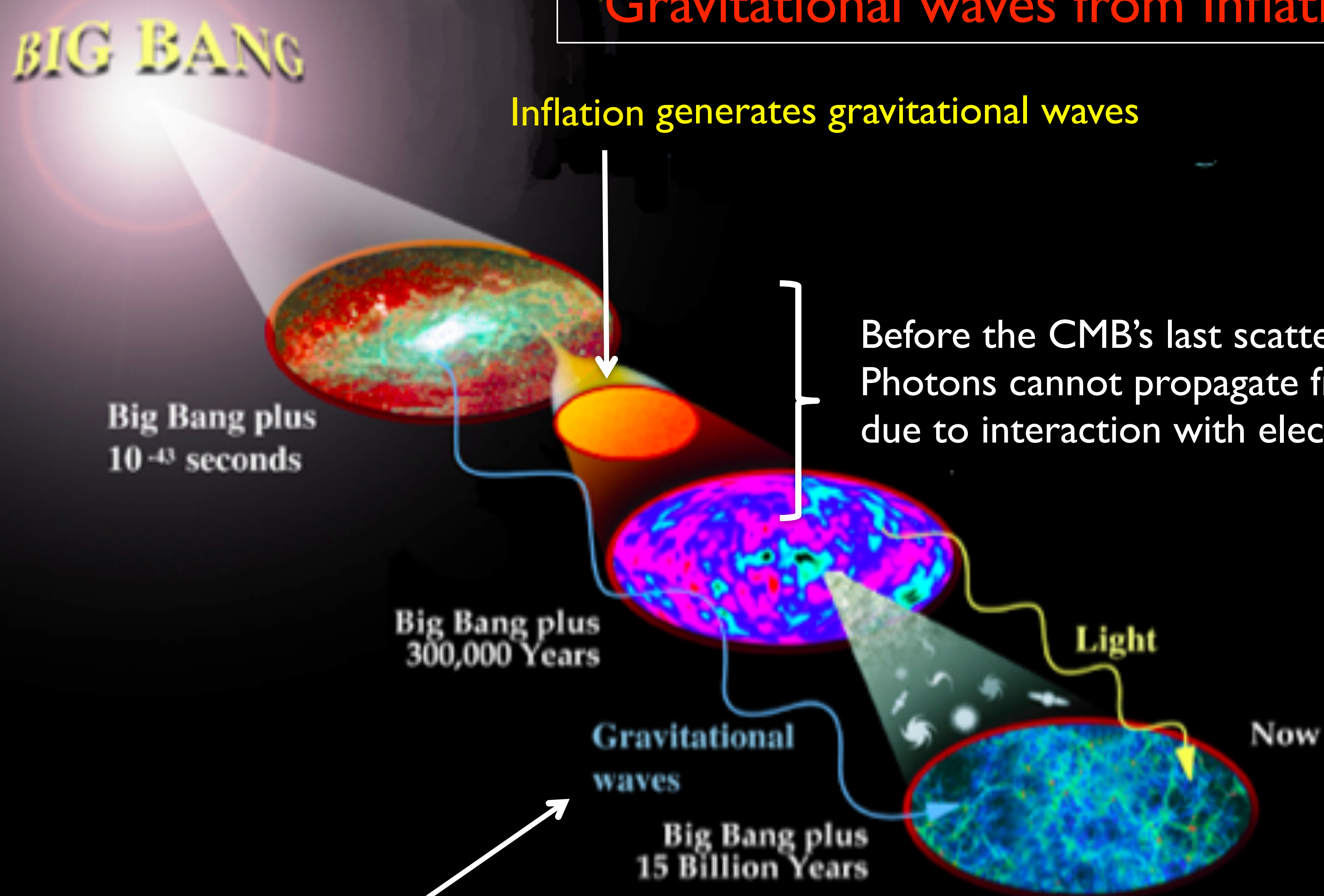
→ origin of the large scale structure

quantum fluctuations in space-time → tensor perturbations

→ exist as a gravitational wave background

Gravitational waves from Inflation

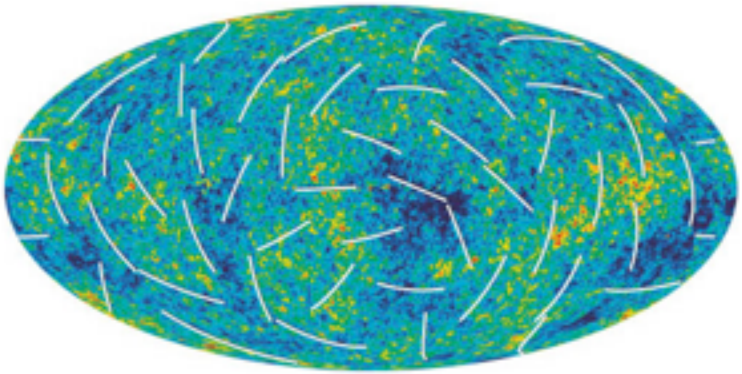
Inflation generates gravitational waves



Before the CMB's last scattering:
Photons cannot propagate freely
due to interaction with electrons

Inflationary GWs propagate freely because
of their weak interactions with matter → Only way to directly observe inflation!

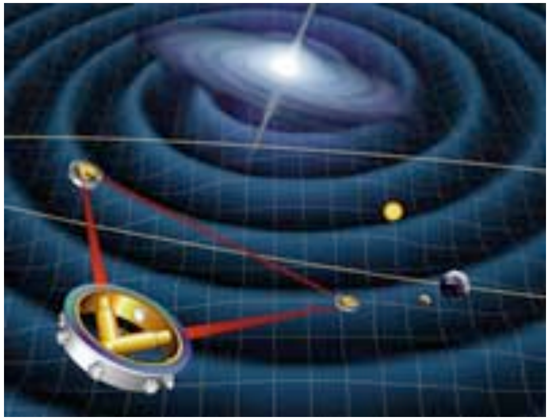
■ Ongoing efforts to detect the gravitational waves from inflation



WMAP Three Year Polarized CMB Sky (http://wmap.gsfc.nasa.gov/)

CMB B-mode polarization

Planck (launched on 2009)
LiteBIRD, CMBpol, COrE (2020?)
Ground-based experiments



LISA image (http://lisa.nasa.gov/)

Direct detection

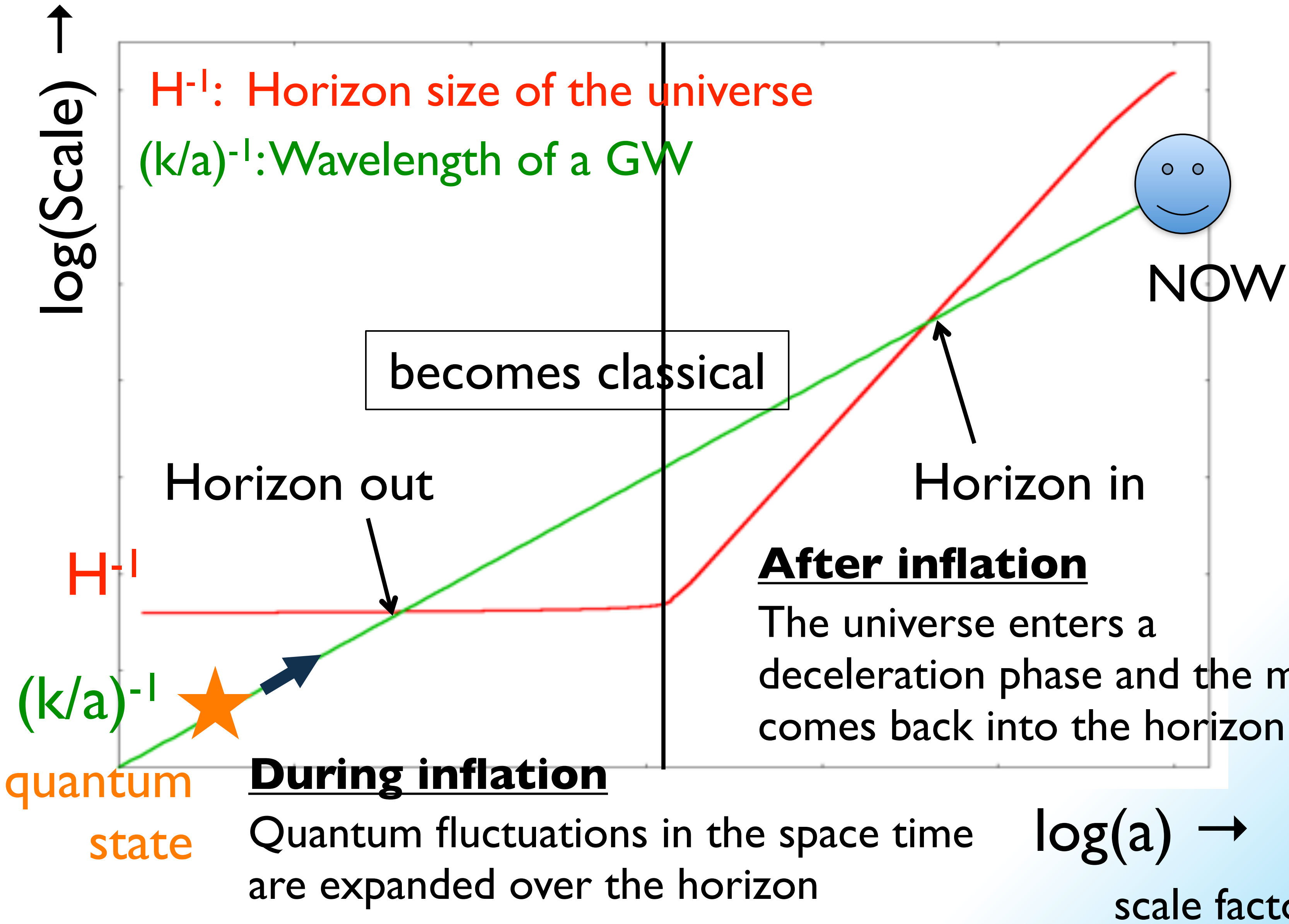
Ground-based experiments
LIGO, LCGT
→sensitivity is not enough

BBO (post LISA, 2025-30???)
DECIGO (2027?)

→ next generation tools to probe inflation!

Basics of the inflationary gravitational wave background

■ Generation mechanism



After inflation

The universe enters a deceleration phase and the mode comes back into the horizon

During inflation

Quantum fluctuations in the space time are expanded over the horizon

■ Propagation equation for GWs

The Einstein equation yields

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2}\nabla^2 h_{ij} = 16\pi G\Pi_{ij}$$

expansion term ($3H\dot{h}_{ij}$)

anisotropic stress term (Π_{ij})

The Robertson-Walker metric

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

Neglecting the anisotropic stress term and Fourier transforming the equation...

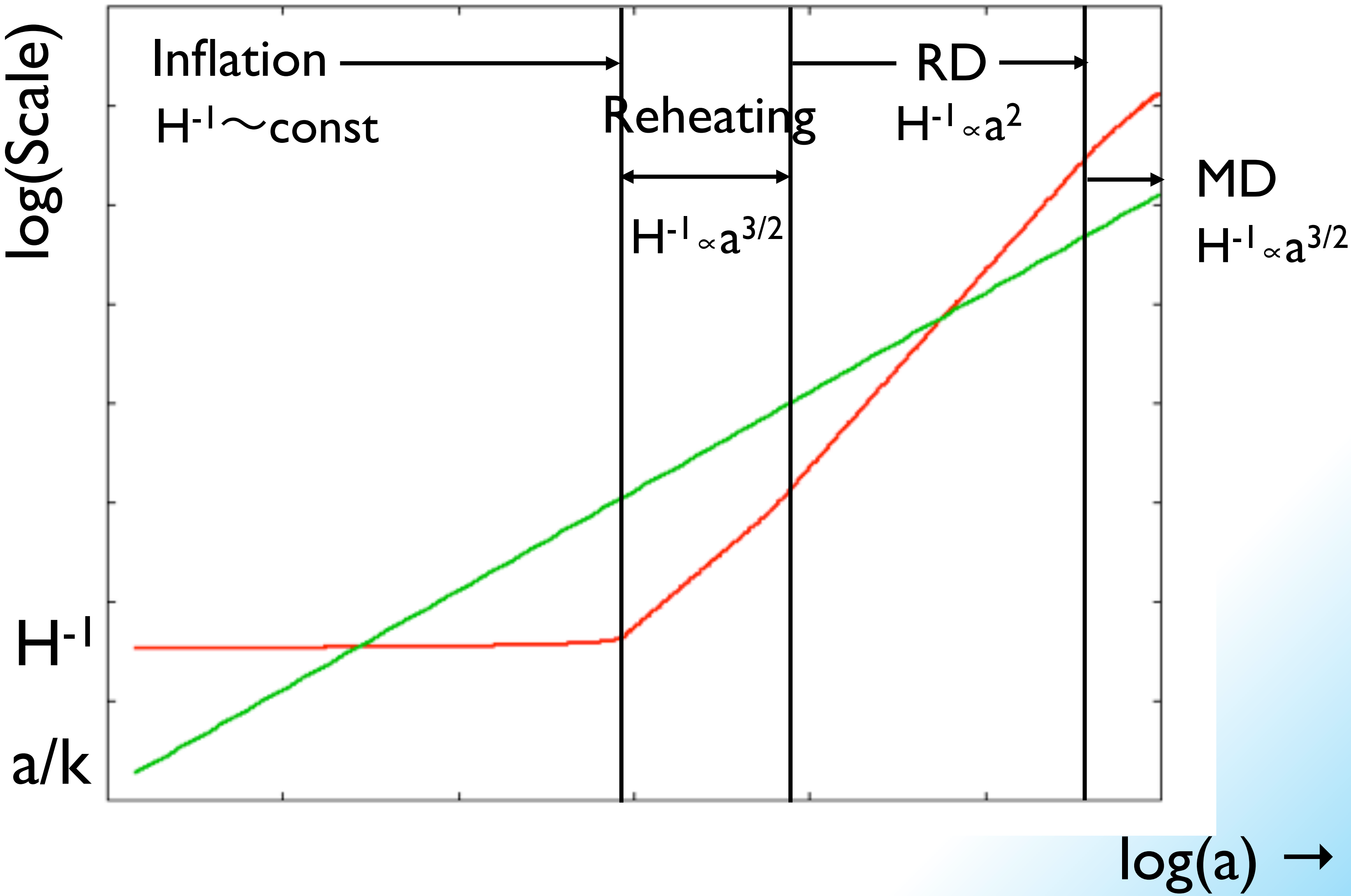
$$\ddot{h}^{\lambda}_{\mathbf{k}} + 3H\dot{h}^{\lambda}_{\mathbf{k}} + \frac{k^2}{a^2}h^{\lambda}_{\mathbf{k}} = 0$$

- Outside the horizon（H>k/a） $h^{\lambda}_{\mathbf{k}} \propto \mathrm{const.}$
- Inside the horizon（H<k/a） $h^{\lambda}_{\mathbf{k}} \propto a^{-1}e^{-ik\tau}.$

→ Hubble expansion rate (H) determines how the GW behaves.

■ Hubble expansion history

↑ In the standard inflation cosmology



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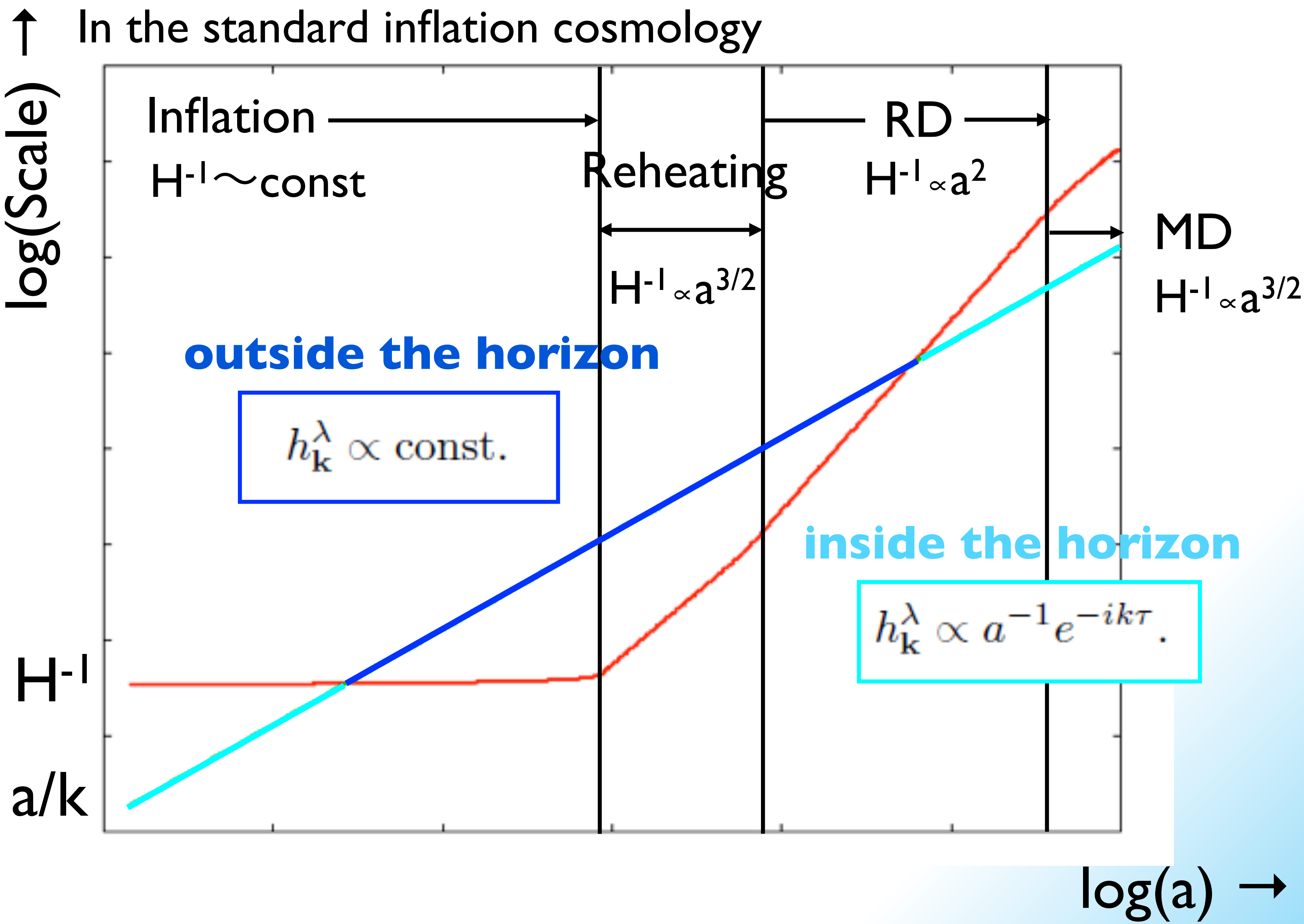

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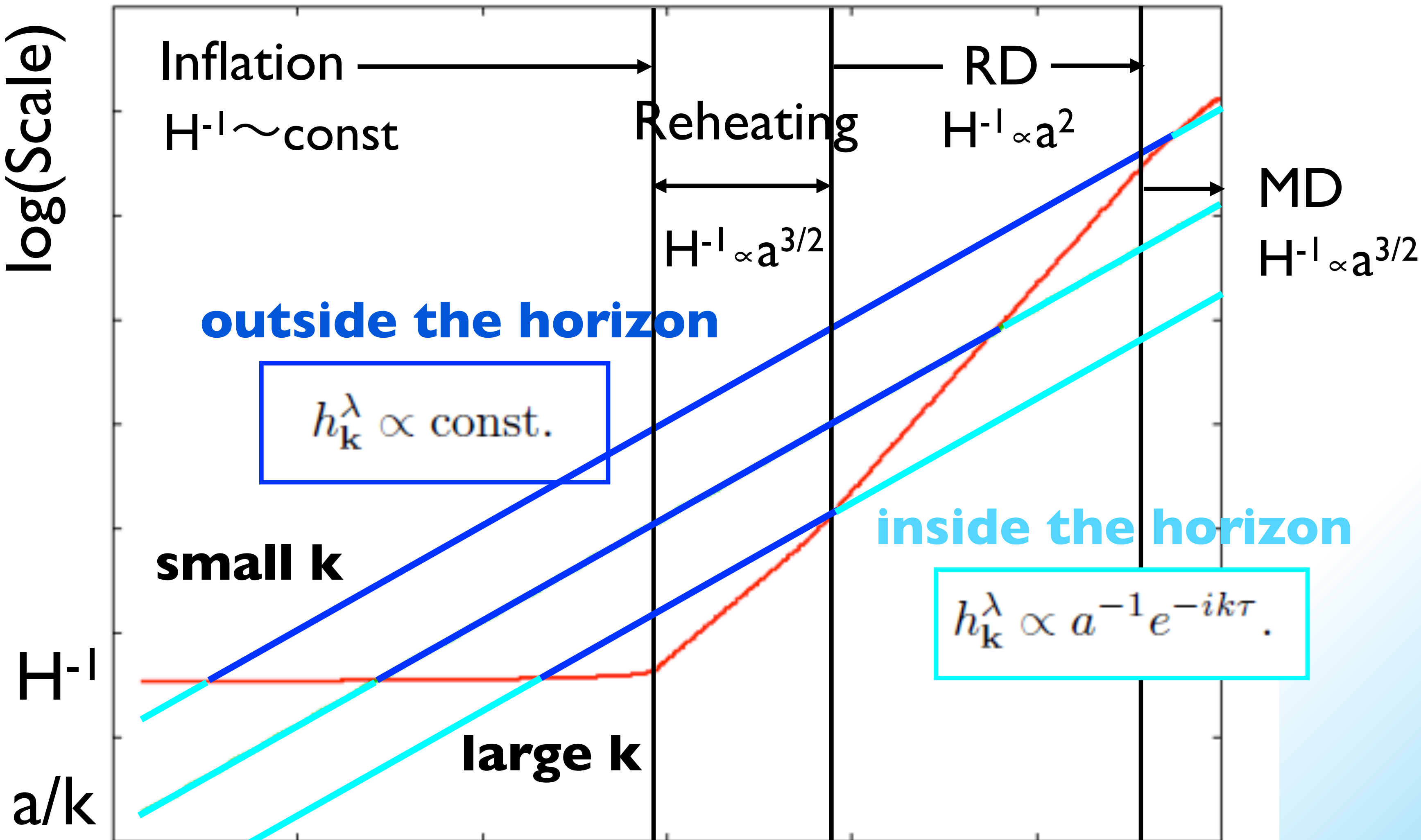


Each mode experiences different evolution

= different amplitude for different frequency

■ Spectrum shape

The spectral energy density $\Omega_{GW} \equiv \frac{1}{\rho_c}\frac{d\rho_{GW}}{d\ln k} = \frac{1}{12}\left(\frac{k}{aH}\right)^2 \frac{k^3}{\pi^2}\sum_\lambda |h_{\mathbf{k}}^\lambda|^2$

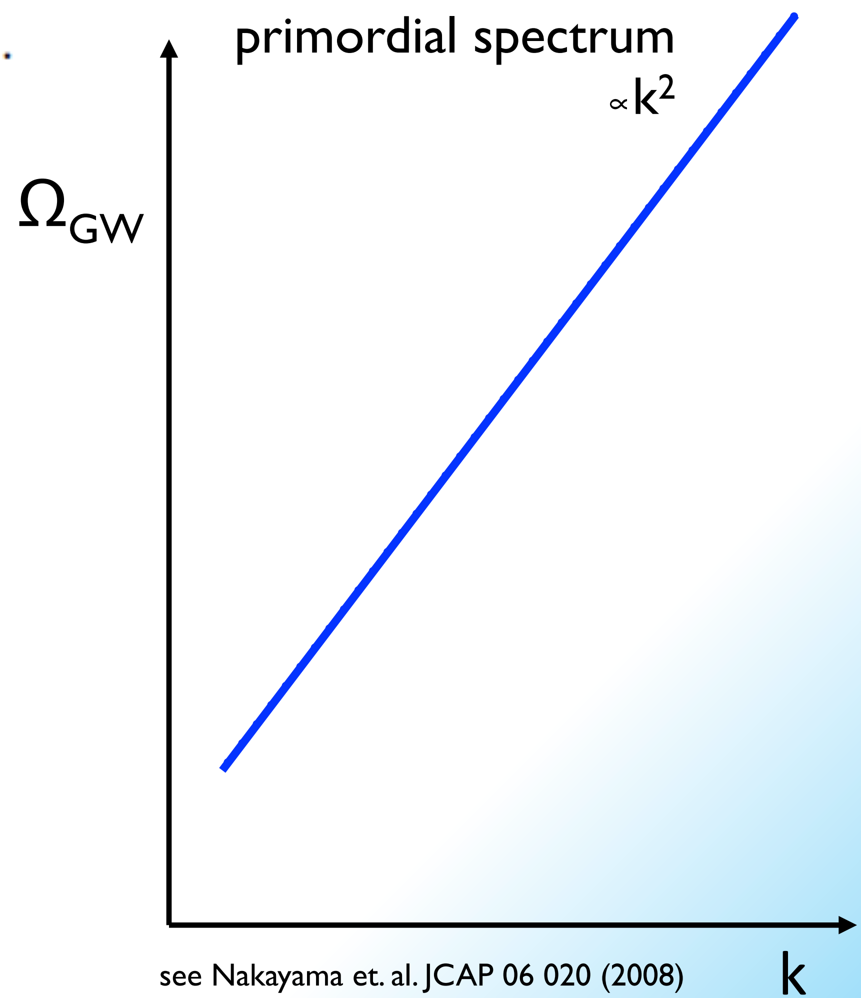
$P_T \propto k^0$

Outside the horizon $h_{\mathbf{k}}^\lambda \propto \text{const.}$

Inside the horizon $h_{\mathbf{k}}^\lambda \propto a^{-1}e^{-ik\tau}.$

Inflation $a \propto \exp(Ht)$

scale invariant spectrum



see Nakayama et. al. JCAP 06 020 (2008)

■ Spectrum shape

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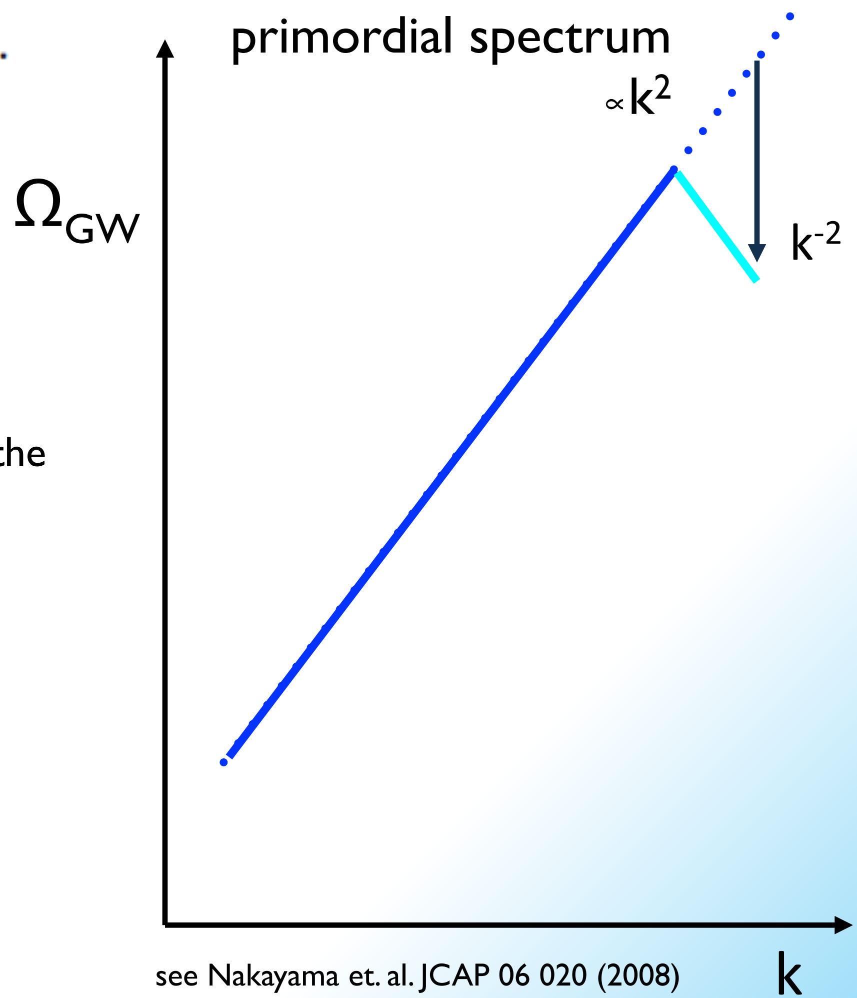
⇩

reheating $a \propto t^{2/3} \longrightarrow k^{-2}$

small scale modes begin to enter the horizon and damp with $\propto a^{-1}$



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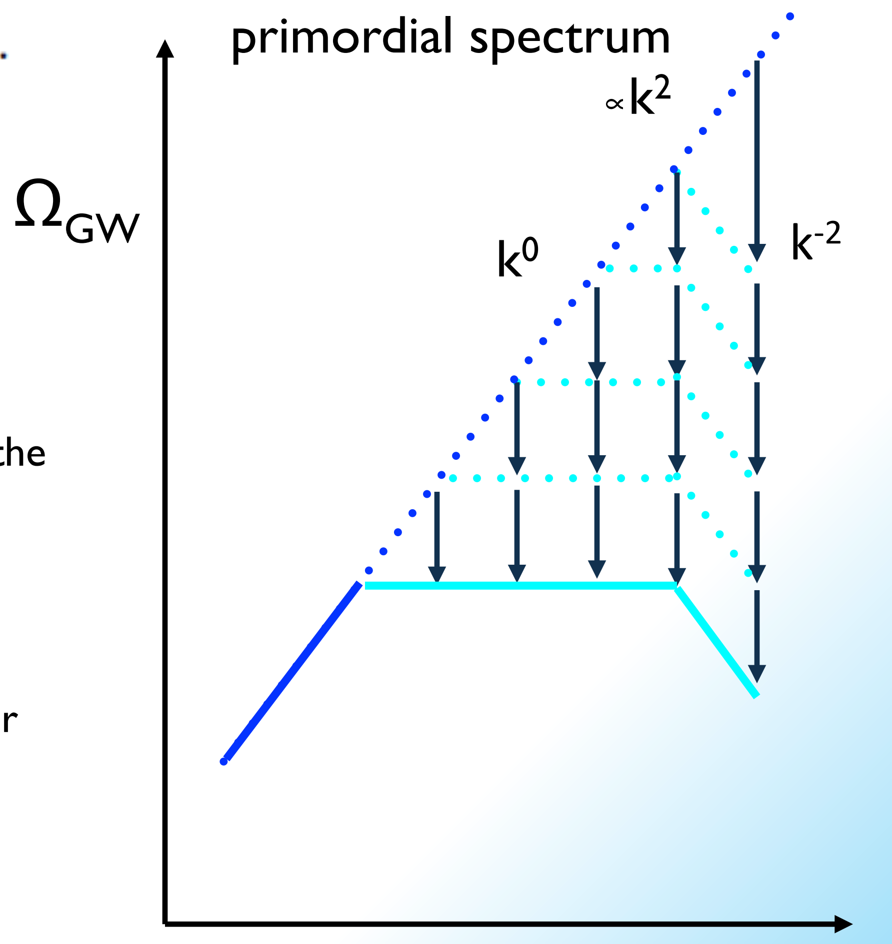
radiation dominant $a \propto t^{1/2} \longrightarrow k^0$

the expansion decelerates so the damping $\propto a^{-1}$ becomes smaller



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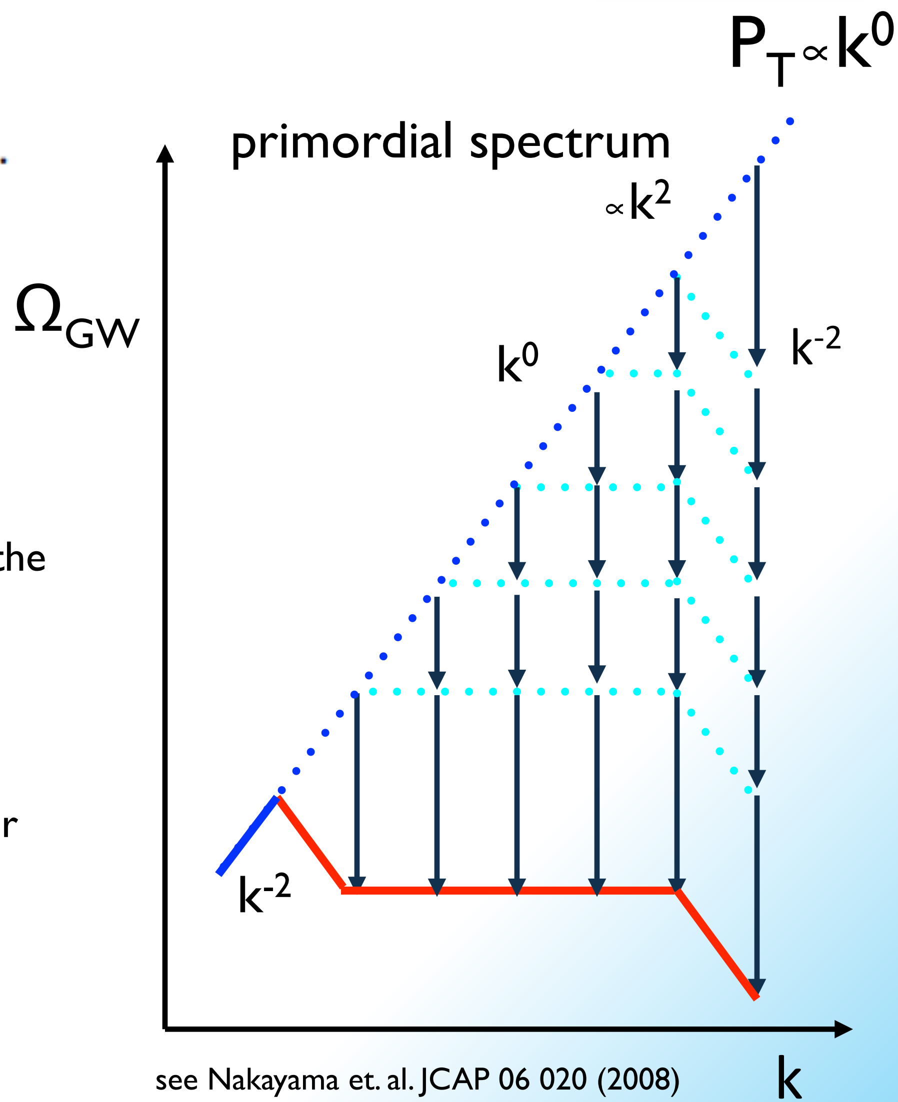
the expansion decelerates so the damping $\propto a^{-1}$ becomes smaller

⇩

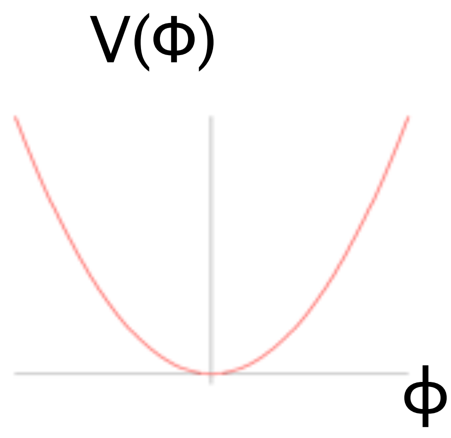
matter dominant $a \propto t^{2/3} \longrightarrow k^{-2}$

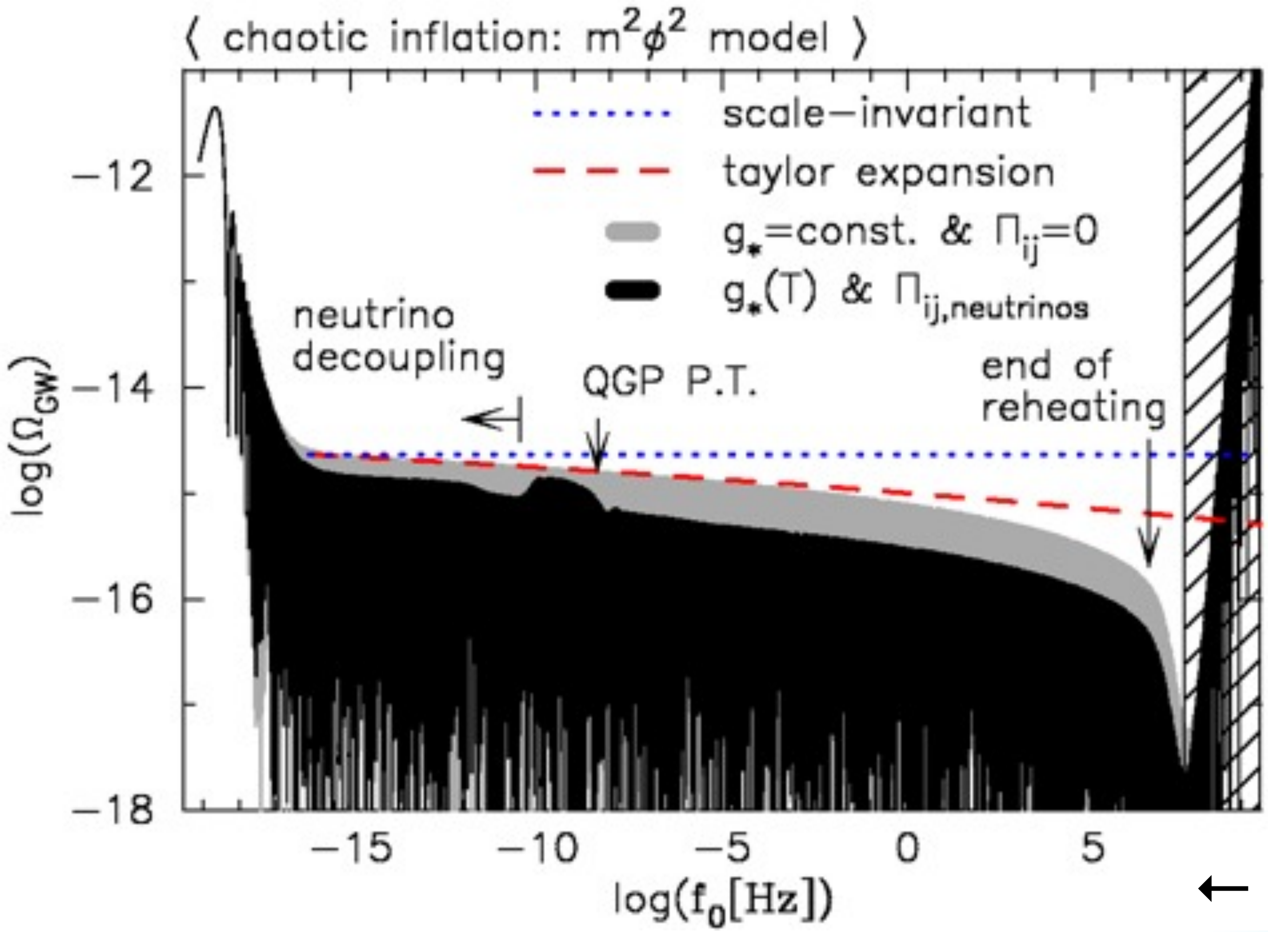


see Nakayama et. al. JCAP 06 020 (2008)

■ Spectrum shape from numerical calculation

Inflation ($m^2\Phi^2$ potential)

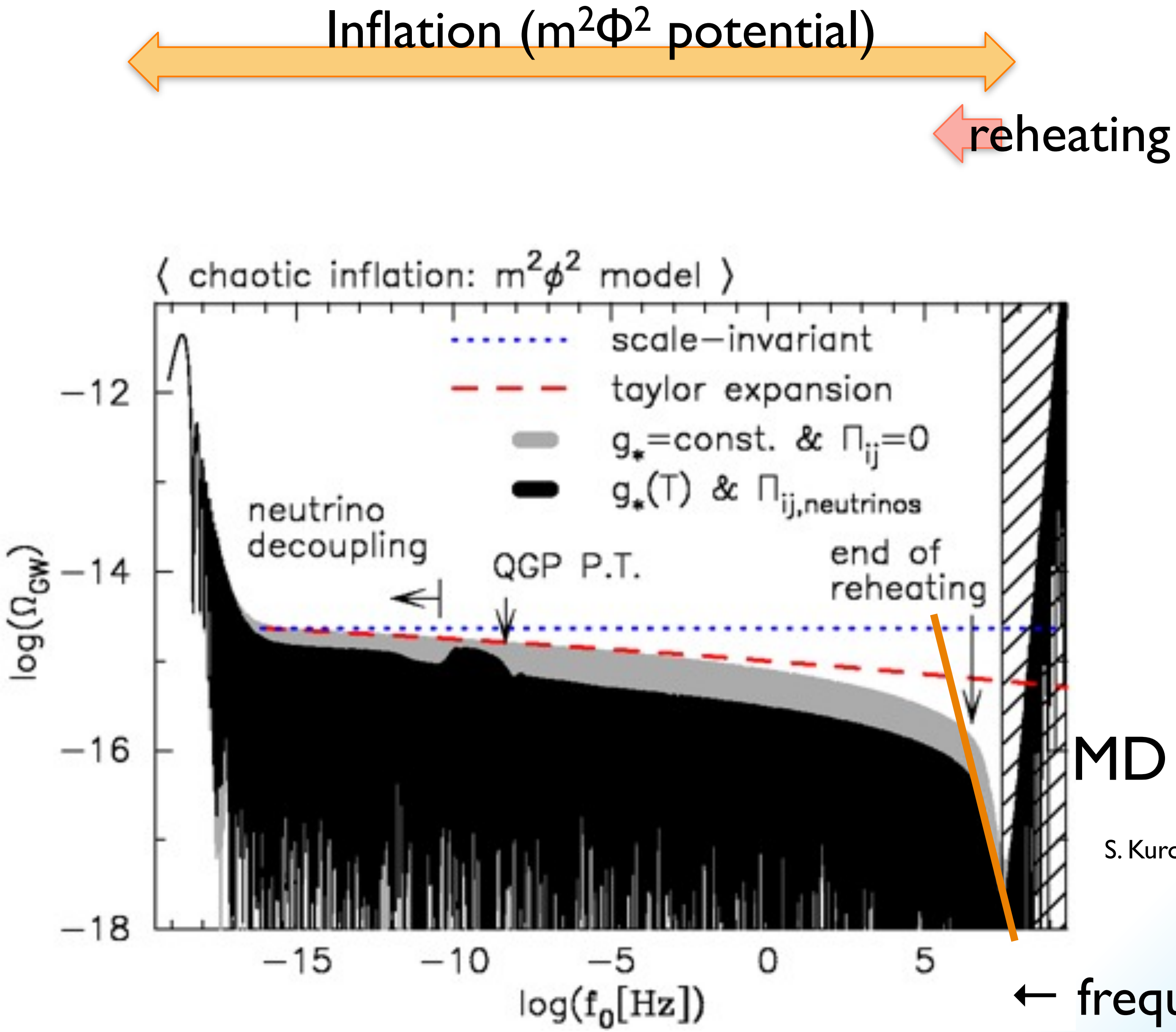


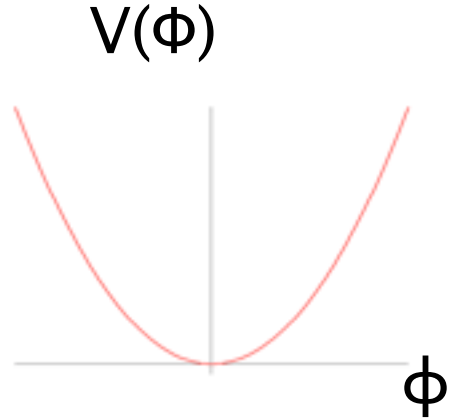


S. Kuroyanagi, T. Chiba and N. Sugiyama, Phys. Rev. D 79, 103501 (2009)

← frequency $f=k/2\pi$

■ Spectrum shape from numerical calculation





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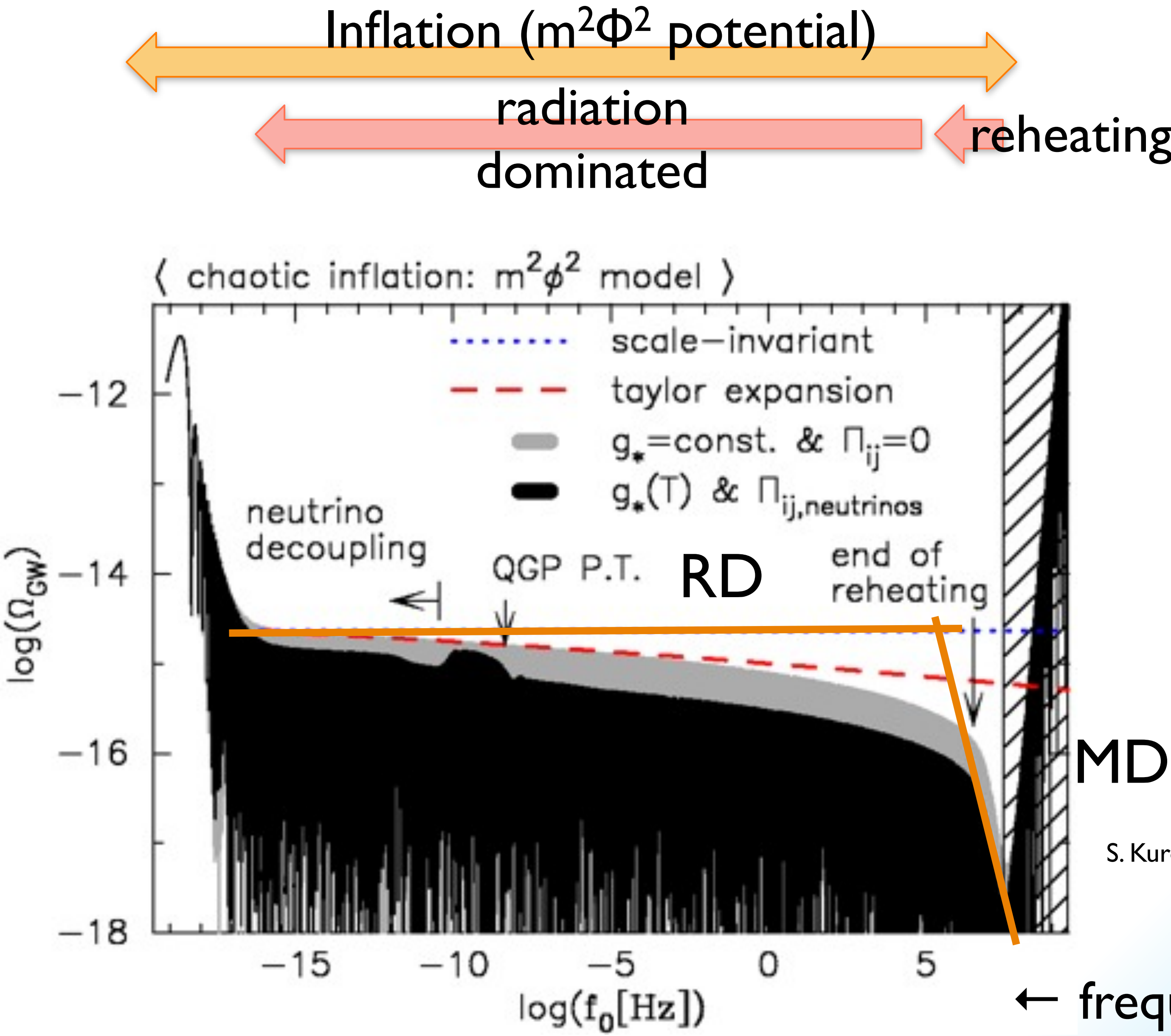

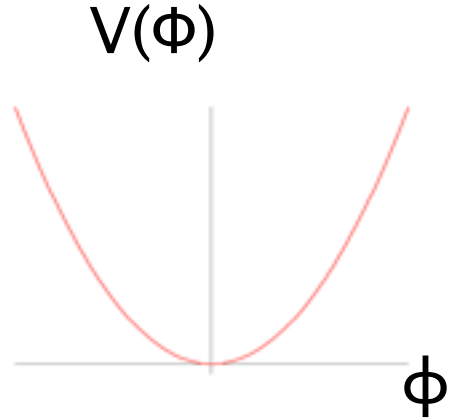

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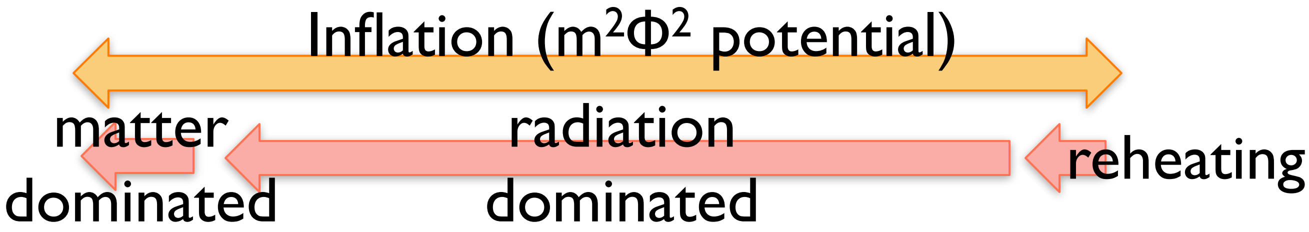

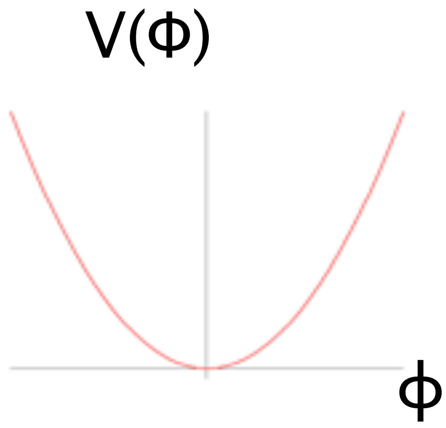

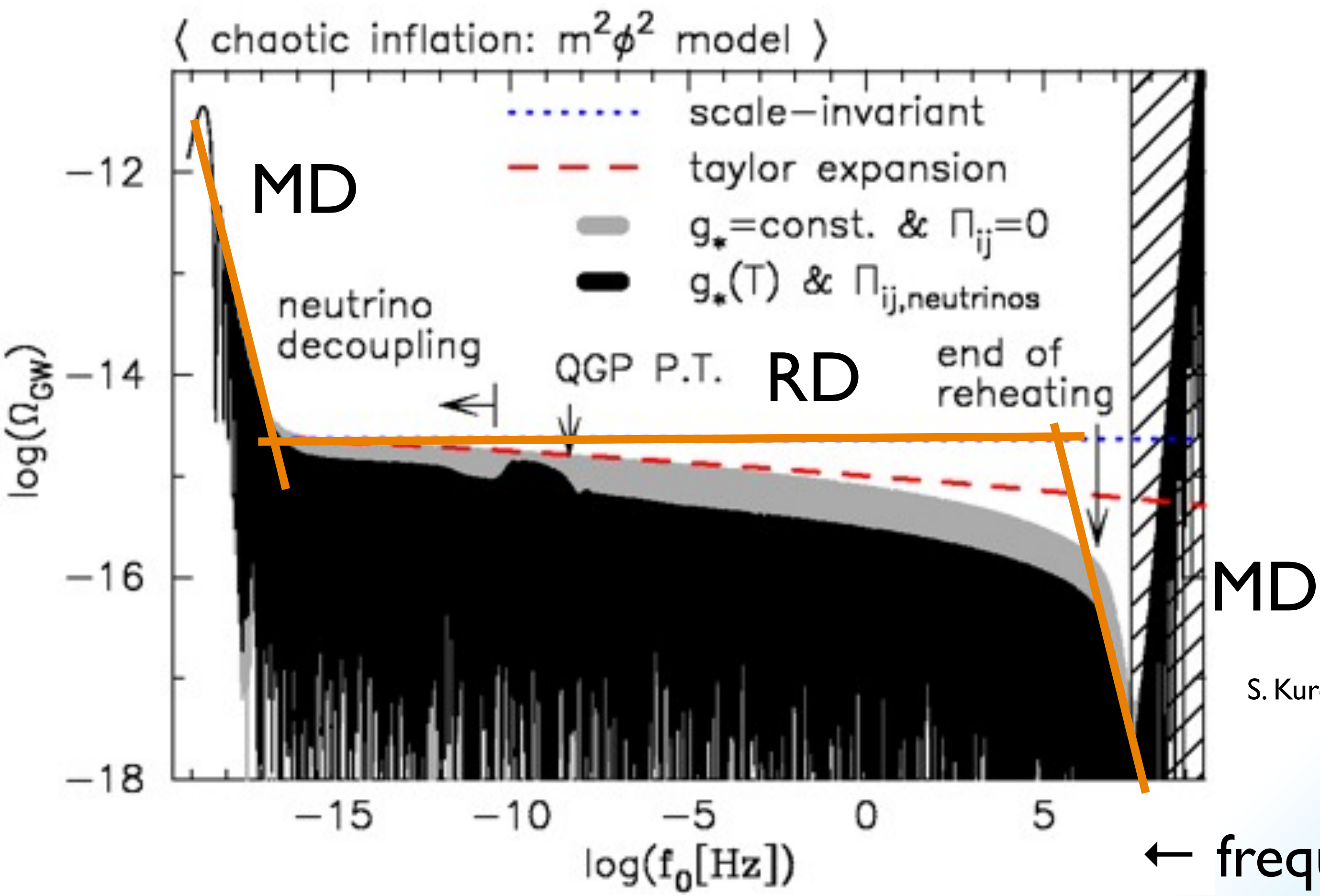

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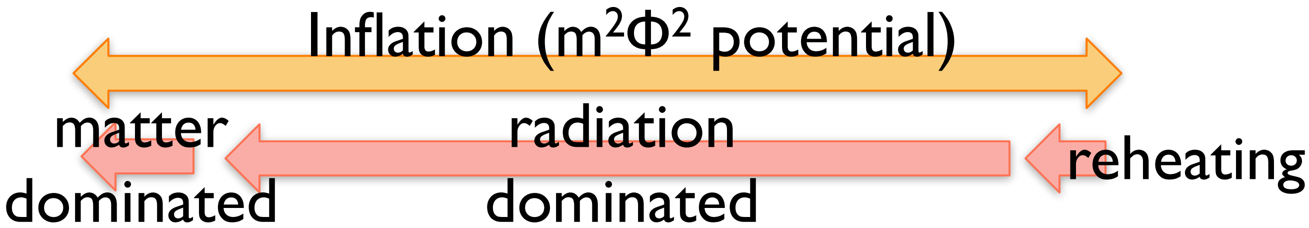

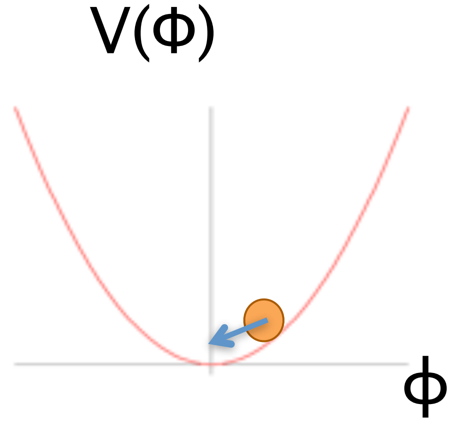

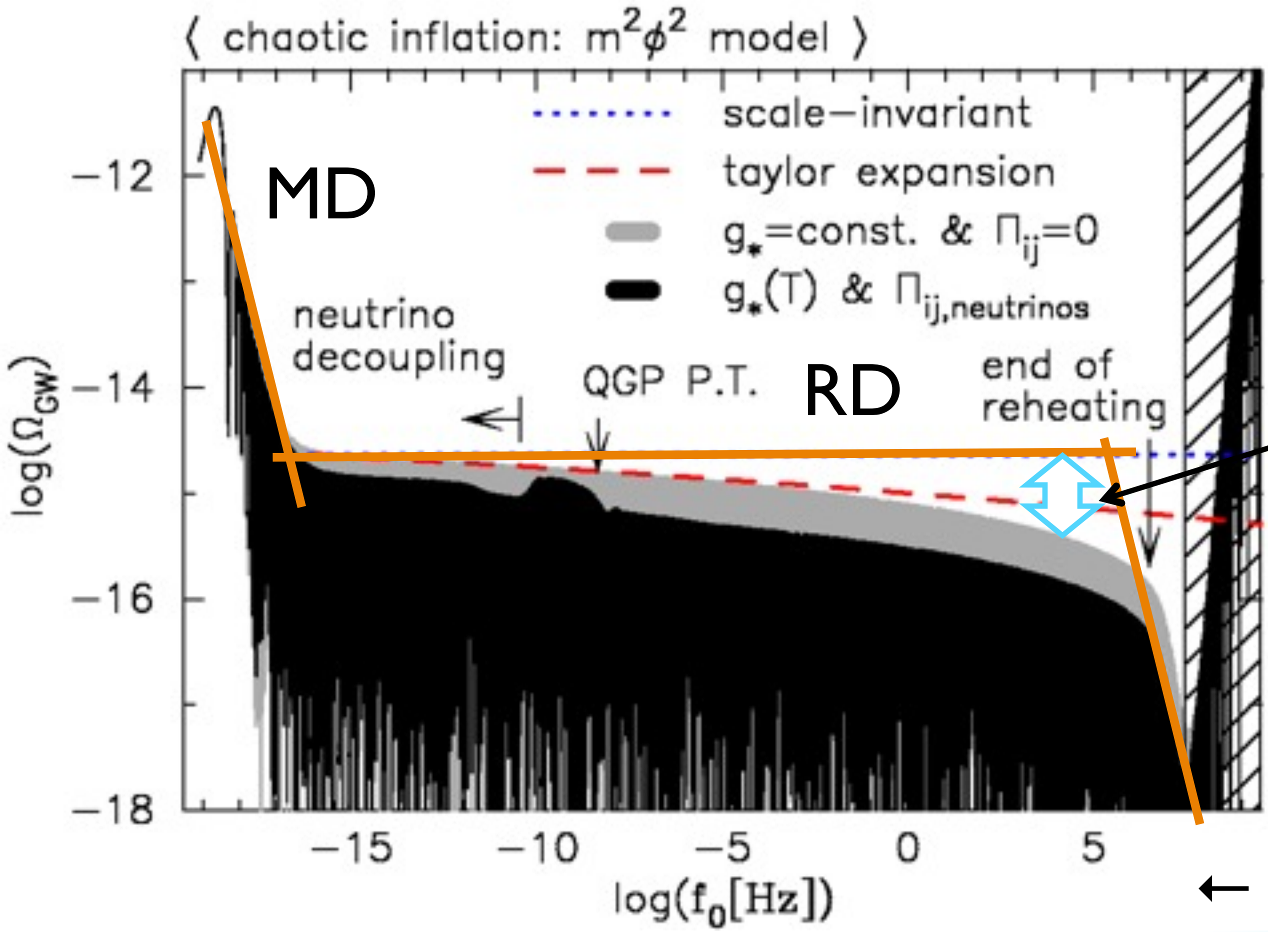

tilt of the spectrum
+
deviation from the slow-roll

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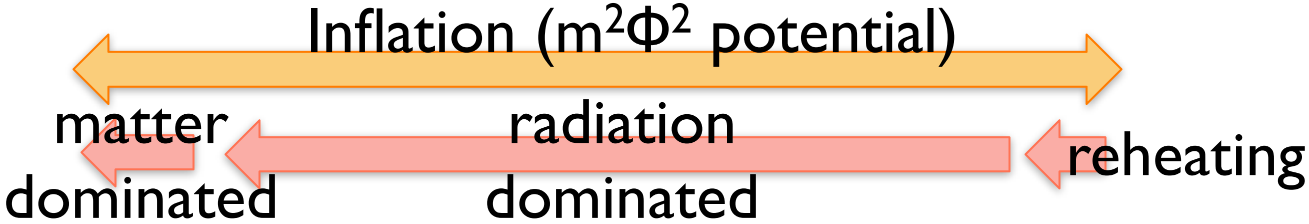

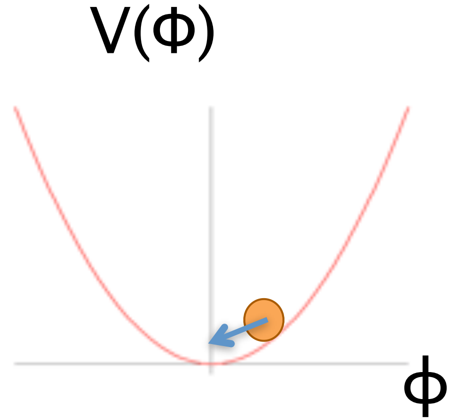

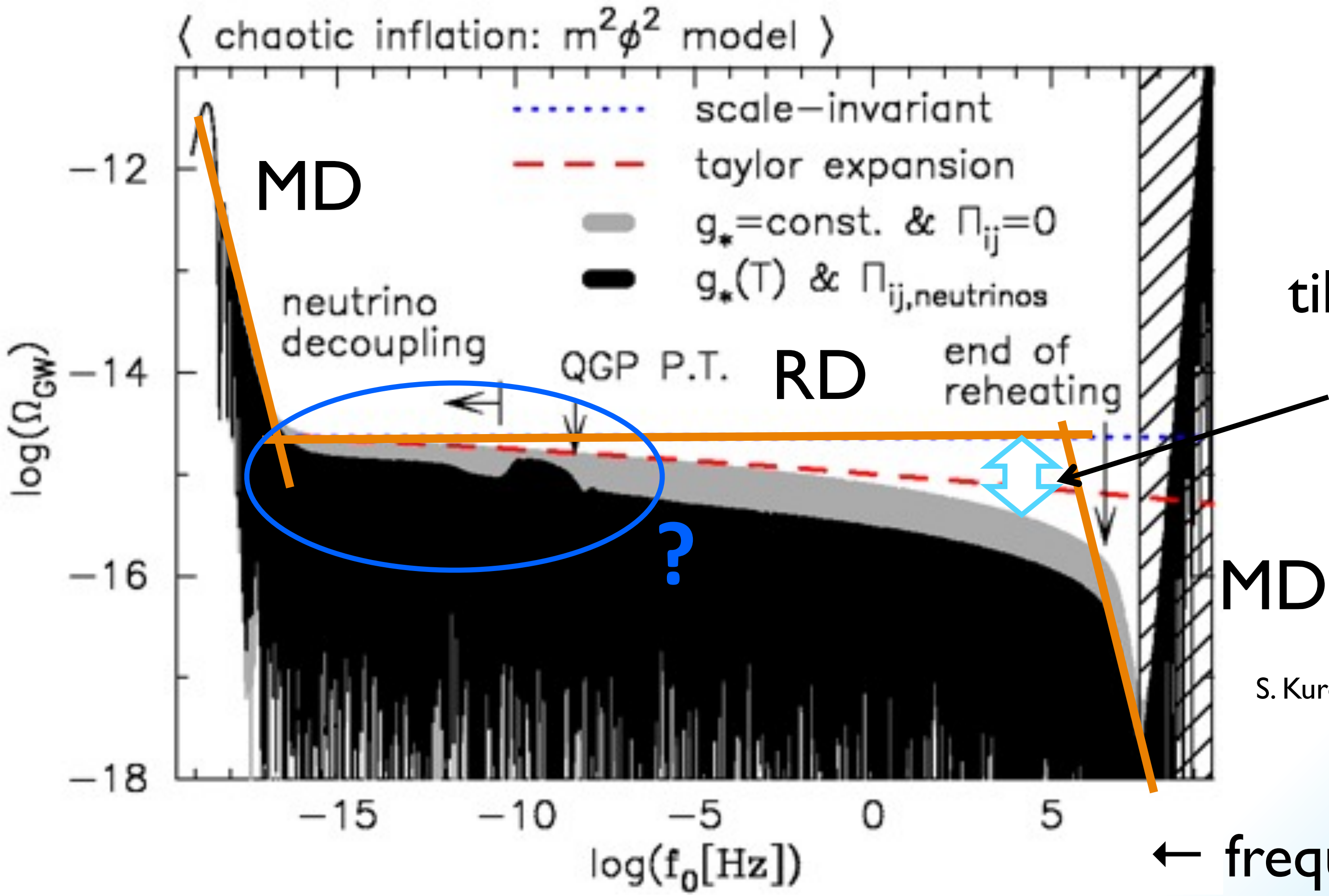

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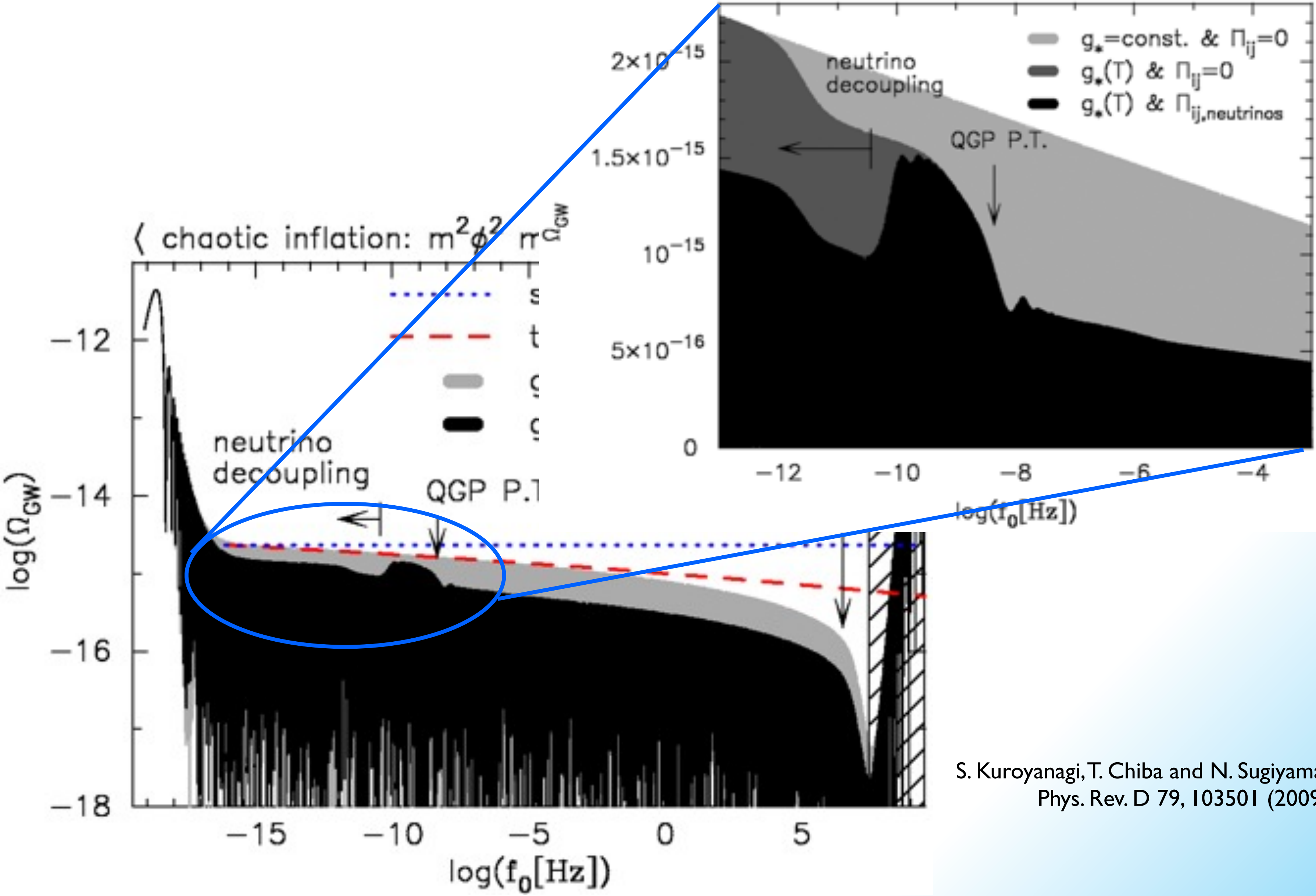

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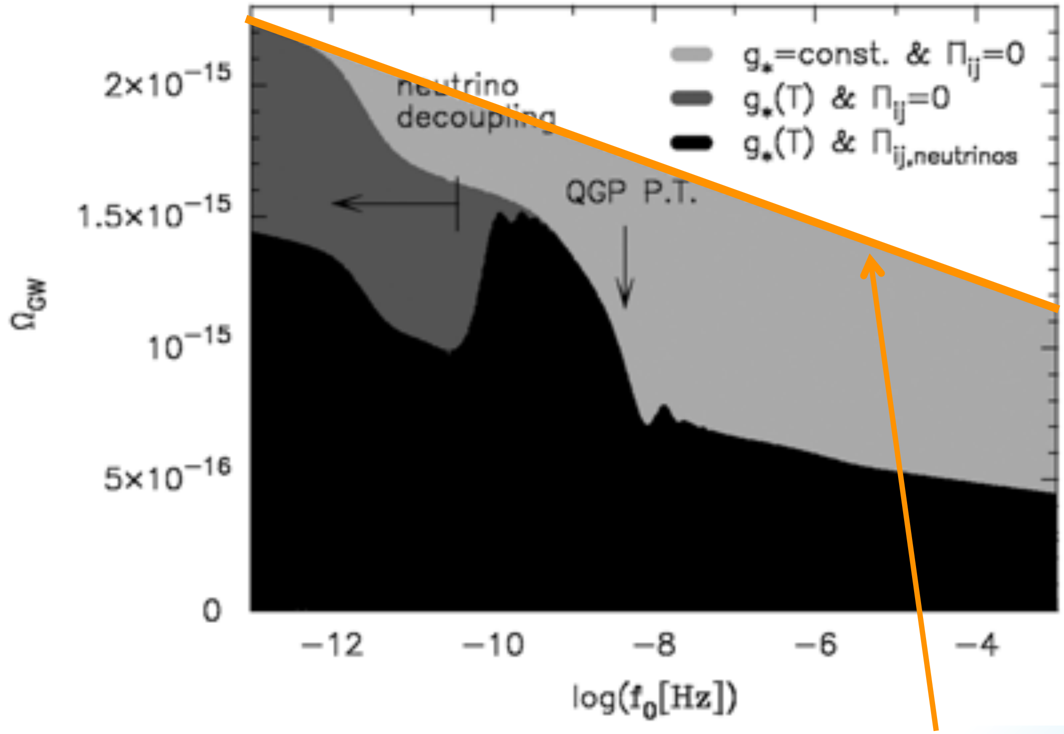
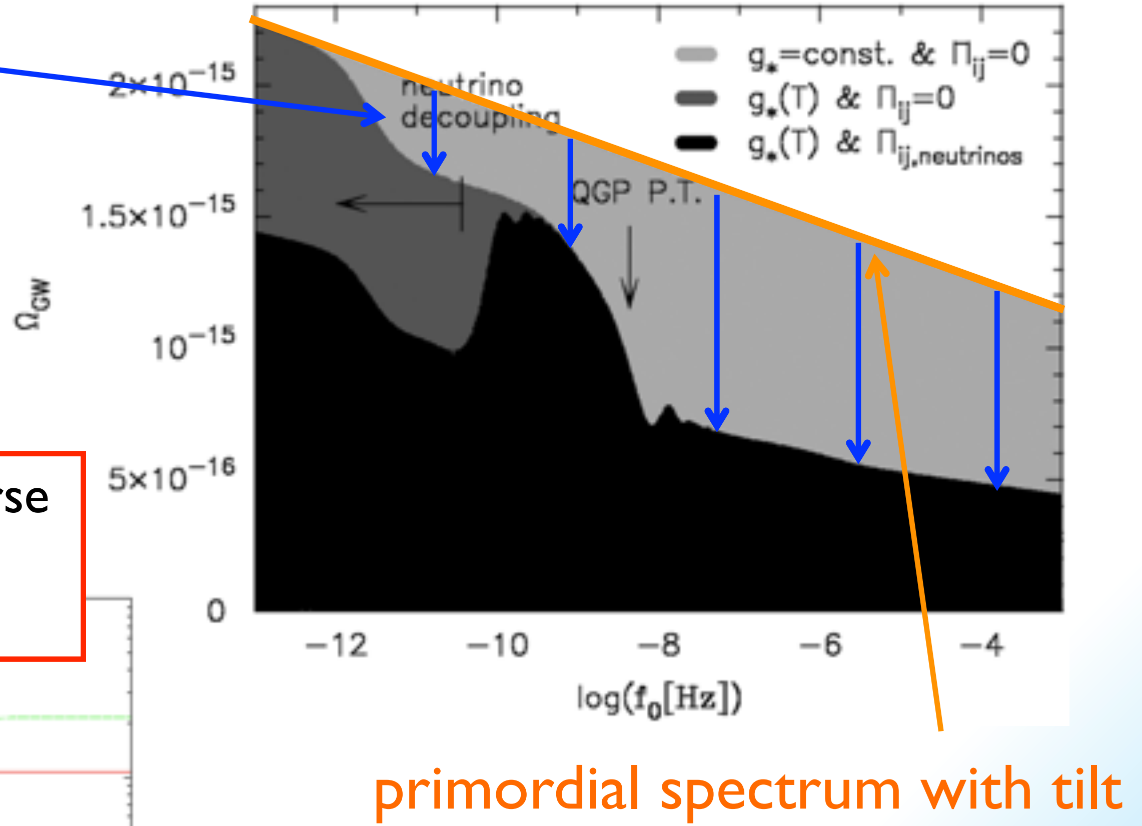


primordial spectrum with tilt

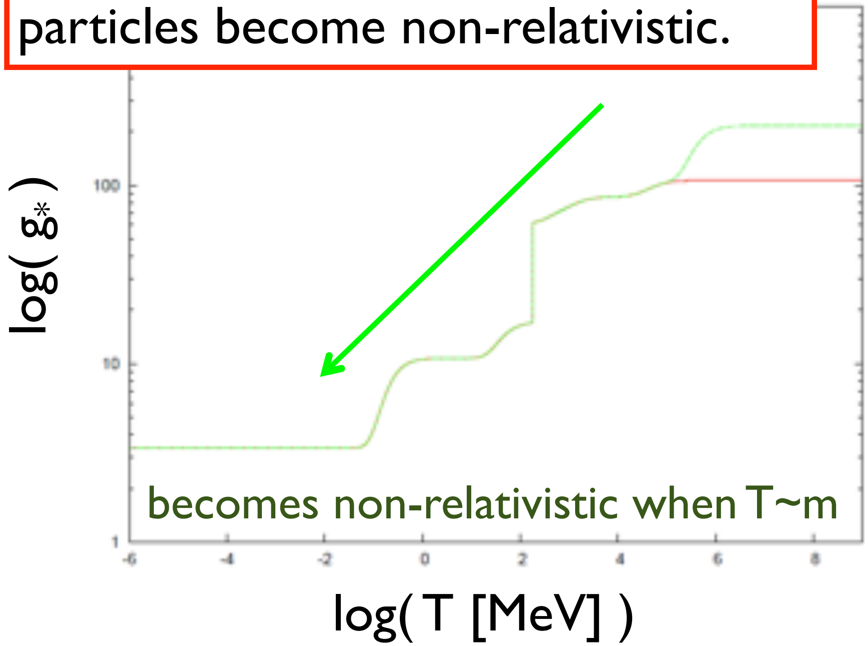
■ Spectrum shape from numerical calculation

Damping due to the changes in effective number of degrees of freedom g_*

$$\rho(T) = \frac{\pi^2}{30} g_*(T) T^4,$$
$$s(T) = \frac{2\pi^2}{45} g_{*s}(T) T^3$$



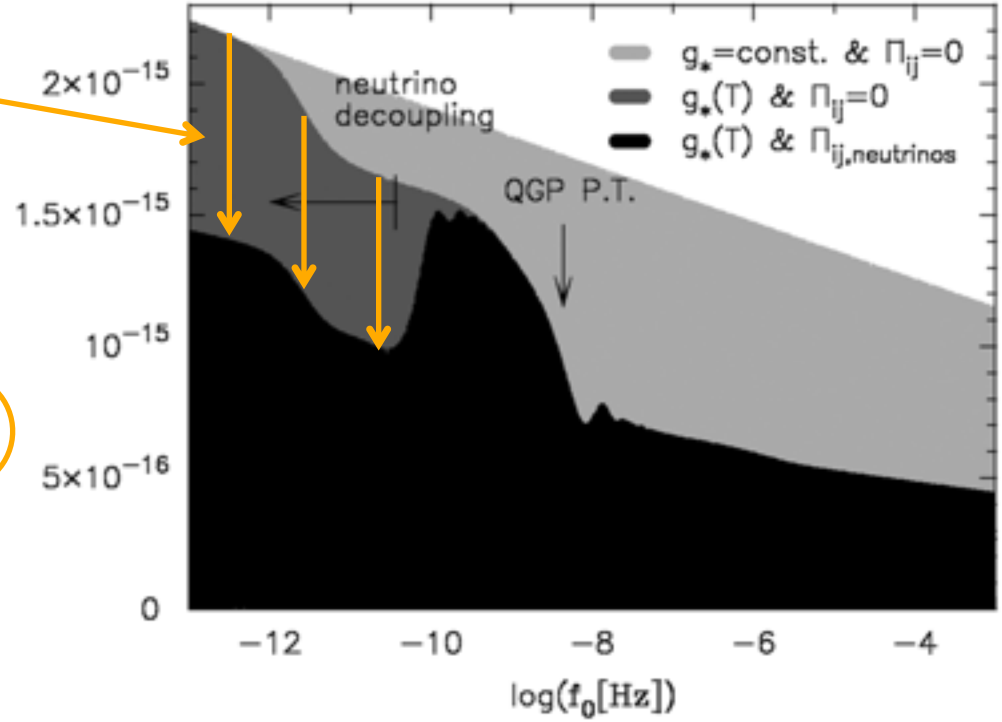
As the temperature of the universe decreases, relativistic matter particles become non-relativistic.



temperature decreases
→ contribution to ρ and s decreases
→ step-like changes in H
→ step shape in Ω_{GW}

■ Spectrum shape from numerical calculation

Damping due to the neutrino anisotropic stress

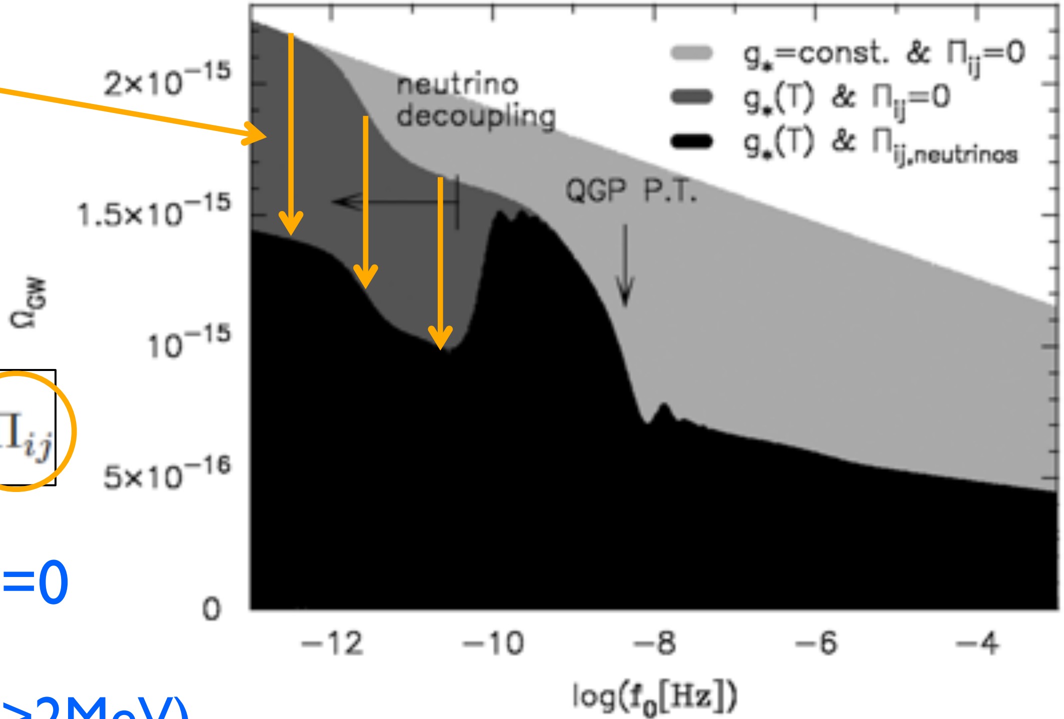


$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2}\nabla^2 h_{ij} = 16\pi G\Pi_{ij}$$

anisotropic stress term

■ Spectrum shape from numerical calculation

Damping due to the
neutrino anisotropic stress



$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2}\nabla^2 h_{ij} = 16\pi G\Pi_{ij}$$

anisotropic stress term =0

Before neutrino decoupling (T>2MeV)

Anisotropic stress is suppressed by the coupling with matter ($e^{\pm}$)

■ Spectrum shape from numerical calculation

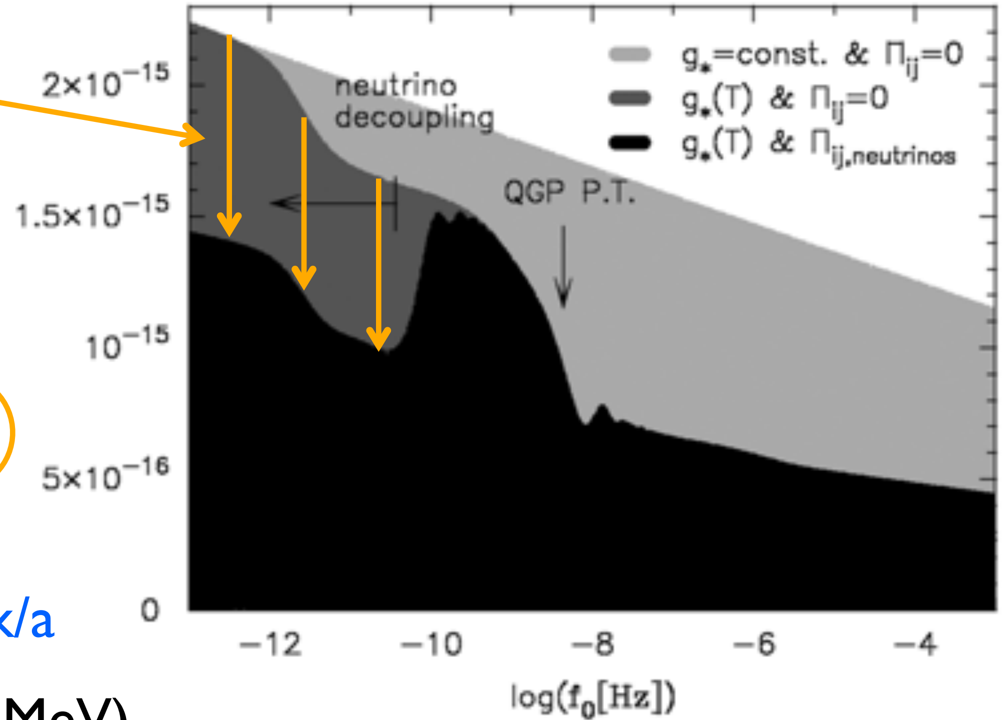
Damping due to the neutrino anisotropic stress

initially =0

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2}\nabla^2 h_{ij} = 16\pi G\Pi_{ij}$$

gives energy

→ Damping only when H~k/a



<u>Before neutrino decoupling (T>2MeV)</u>

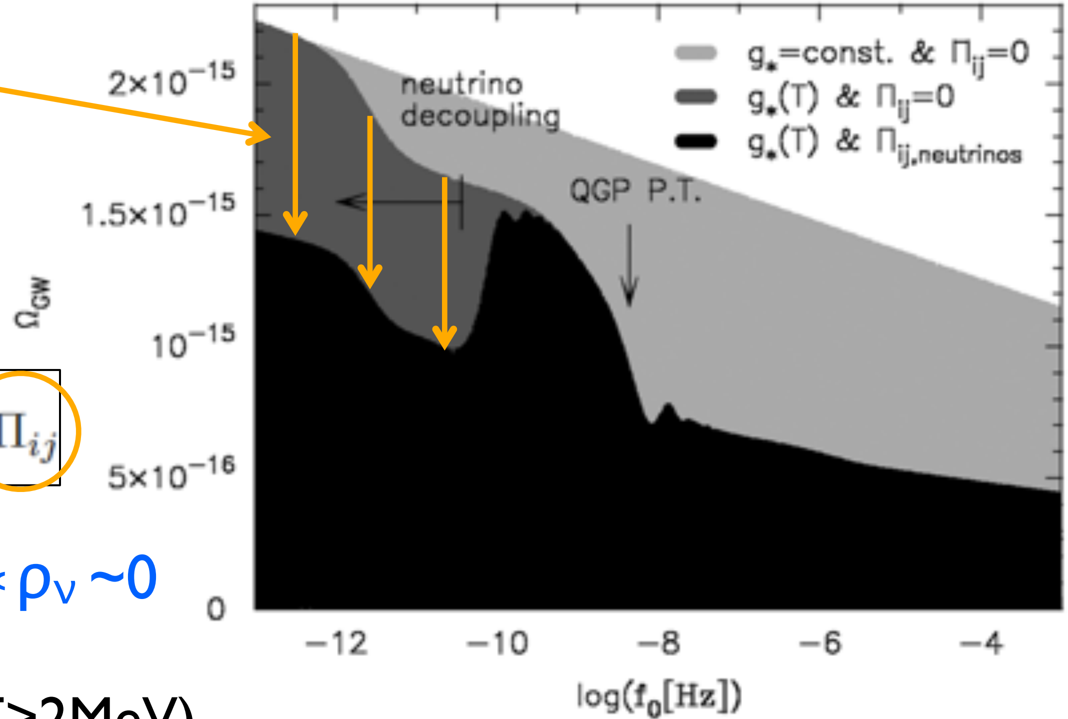
Anisotropic stress is suppressed by the coupling with matter ($e^{\pm}$)

<u>After neutrino decoupling (T<2MeV)</u>

Neutrino anisotropic stress affects GWs as a viscosity when they enter the horizon

■ Spectrum shape from numerical calculation

Damping due to the
neutrino anisotropic stress



$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2}\nabla^2 h_{ij} = 16\pi G\Pi_{ij}$$

anisotropic stress term $\propto \rho_\nu \sim 0$

Before neutrino decoupling (T>2MeV)

Anisotropic stress is suppressed by the coupling with matter ($e^{\pm}$)

After neutrino decoupling (T<2MeV)

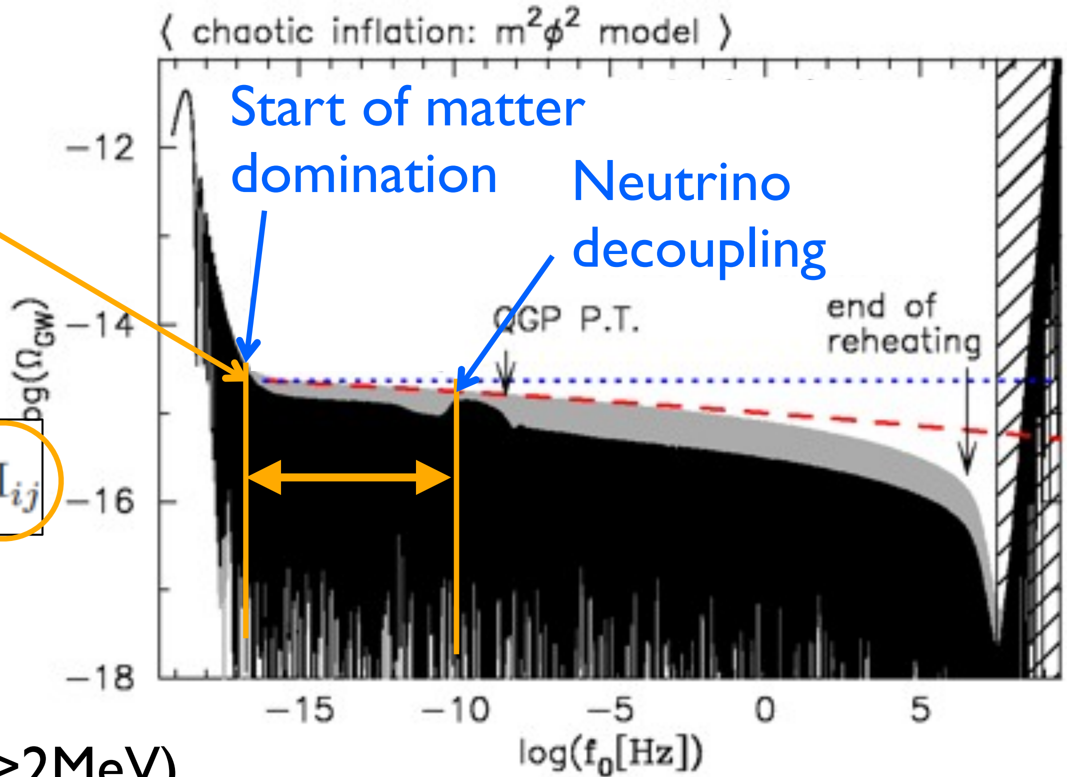
Neutrino anisotropic stress affects GWs as a viscosity when they enter the horizon

After the Universe becomes matter-dominated

The energy density of radiation becomes negligible

■ Spectrum shape from numerical calculation

Damping due to the neutrino anisotropic stress



$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2}\nabla^2 h_{ij} = 16\pi G\Pi_{ij}$$

anisotropic stress term

<u>Before neutrino decoupling (T>2MeV)</u>

Anisotropic stress is suppressed by the coupling with matter ($e^{\pm}$)

<u>After neutrino decoupling (T<2MeV)</u>

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<u>After the Universe becomes matter-dominated</u>

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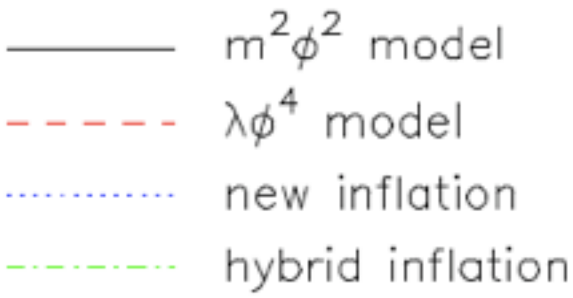
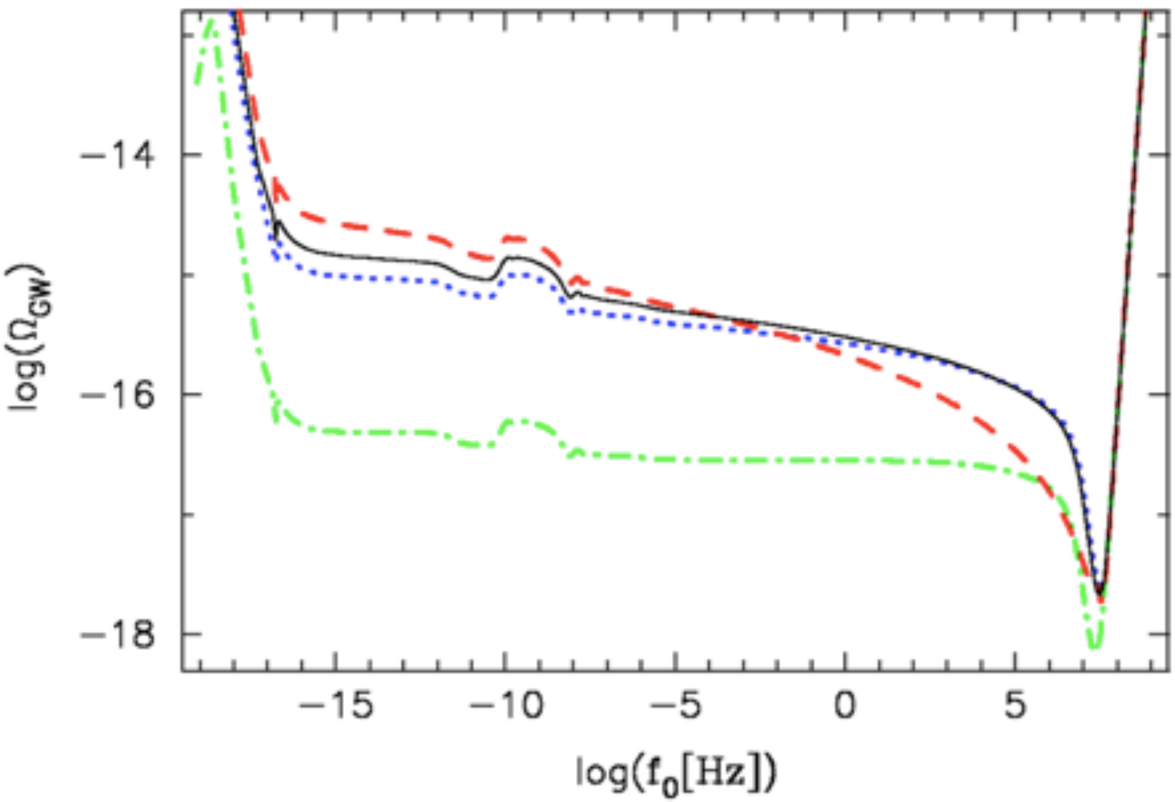
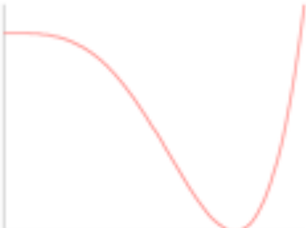
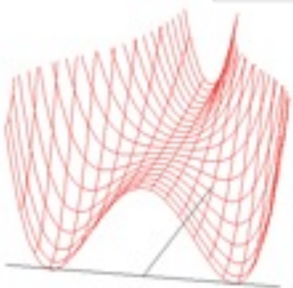
■ Other inflation models









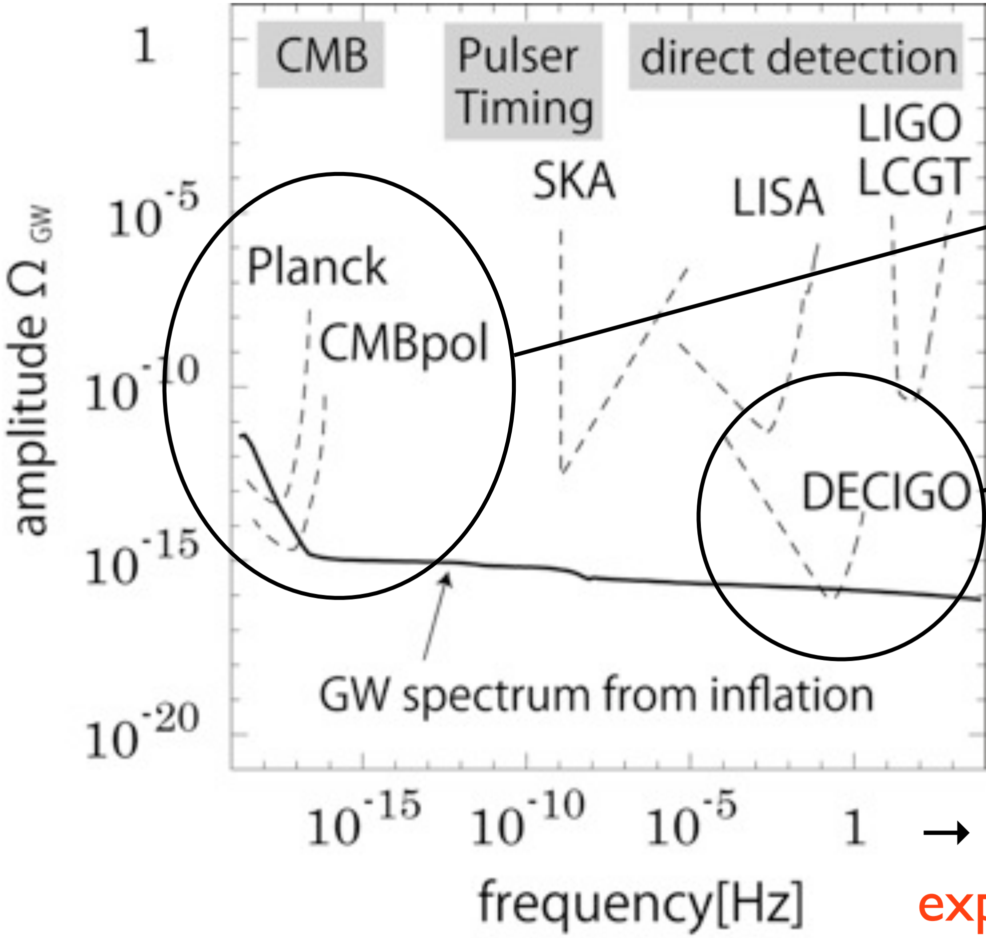
→ Differences in the amplitude and the tilt

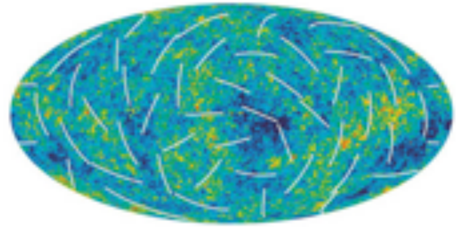
→ can be used to specify inflation model

Observational aspects of the inflationary gravitational wave background

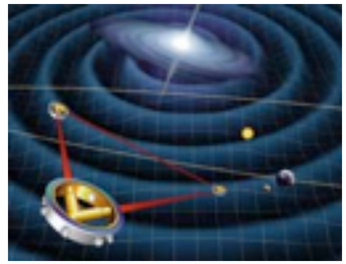
■ Ongoing efforts to detect the GWB

Sensitivity curves of future gravitational wave experiments
& spectrum of the gravitational wave background





CMB B-mode polarization



Direct detection

→ looking at two different frequencies.
expected to provide independent information from each other.

■ Constraints on inflationary parameters

<u>In CMB observations</u>

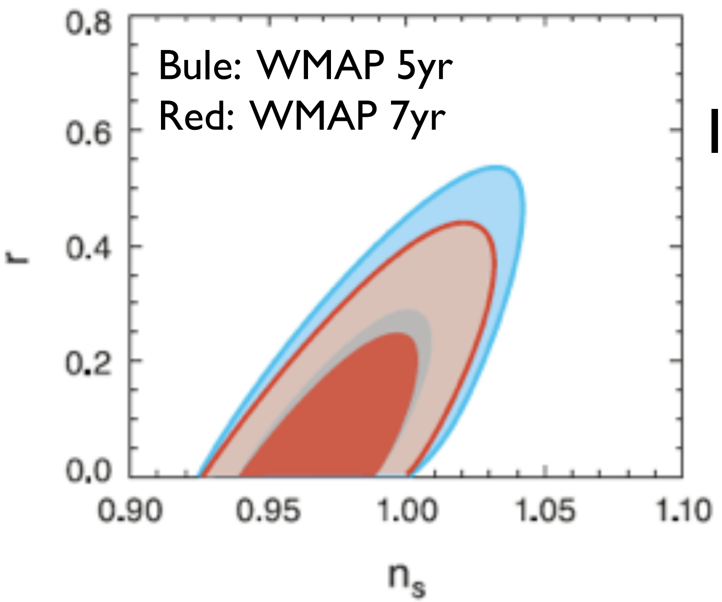
Slow-roll parameters $\epsilon \equiv \frac{m_{Pl}^2}{16\pi}\left(\frac{V'}{V}\right)^2 \quad \eta \equiv \frac{m_{Pl}^2}{8\pi}\frac{V''}{V}$

common parametrization of inflation

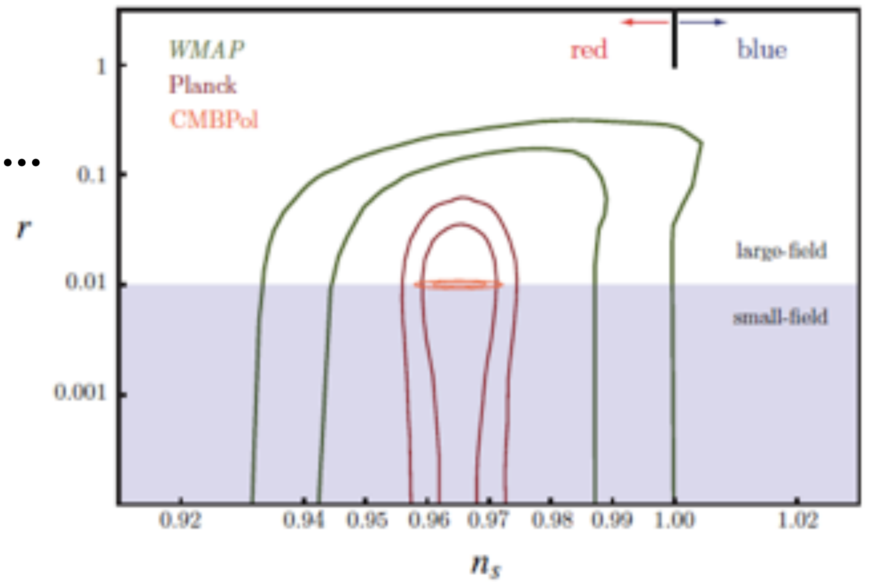
→ related to observational values

tilt of the scalar spectrum $n_S - 1 \simeq -6\epsilon - 2\eta$

tensor-to-scalar ratio $r \simeq 16\epsilon$



In future...



WMAP 7yr constraint: E. Komatsu, et al. APJ Suppl. 192, 18 (2011)

D. Baumann et al., arXiv:0811.3919 [astro-ph]

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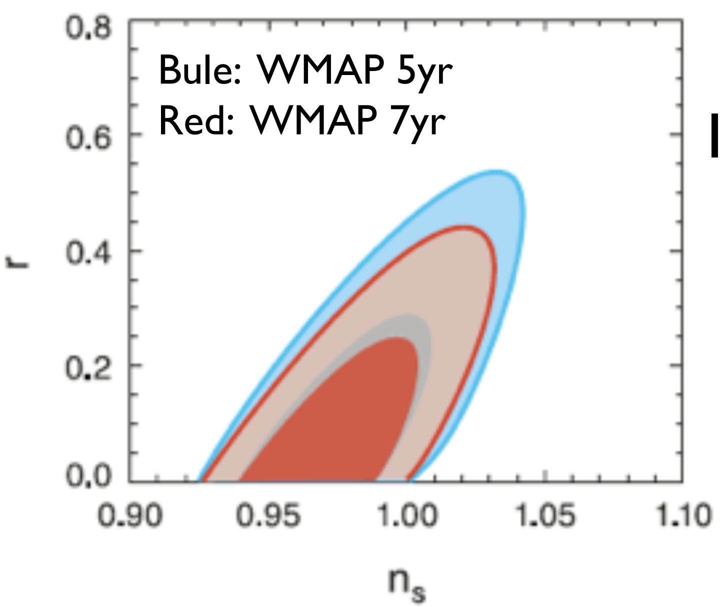
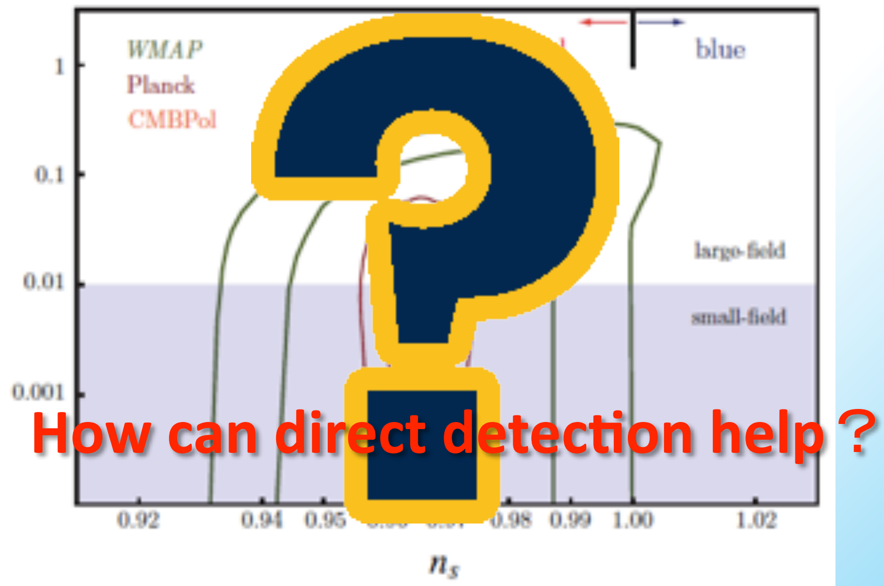
tilt of the scalar spectrum $n_S - 1 \simeq -6\epsilon - 2\eta$

tensor-to-scalar ratio $r \simeq 16\epsilon$



WMAP 7yr constraint: E. Komatsu, et al. APJ Suppl. 192, 18 (2011)

In future...



D. Baumann et al., arXiv:0811.3919 [astro-ph]

■ Constraints from direct detection

In slow-roll parametrization...

primordial spectrum transfer function

includes all effects after inflation

$$\Omega_{\rm GW} = \frac{1}{12}\left(\frac{k}{H_0}\right)^2 \mathcal{P}_T(k) T_T^2(k)$$

Parametrizing the scale dependence in the form of the Taylor expansion around the CMB scale $k_\star$

$$\mathcal{P}_T(k) = \mathcal{P}_{T\star} \exp\left[n_{T\star} \ln\frac{k}{k_\star} + \frac{1}{2!}\alpha_{T\star} \ln^2\frac{k}{k_\star} + \cdots \right]$$

normalization at the CMB scale

$$\mathcal{P}_T = r\mathcal{P}_S$$

spectral index

$$n_T \simeq -2\epsilon$$

running

$$\alpha_T \simeq 4\epsilon\eta - 8\epsilon^2$$

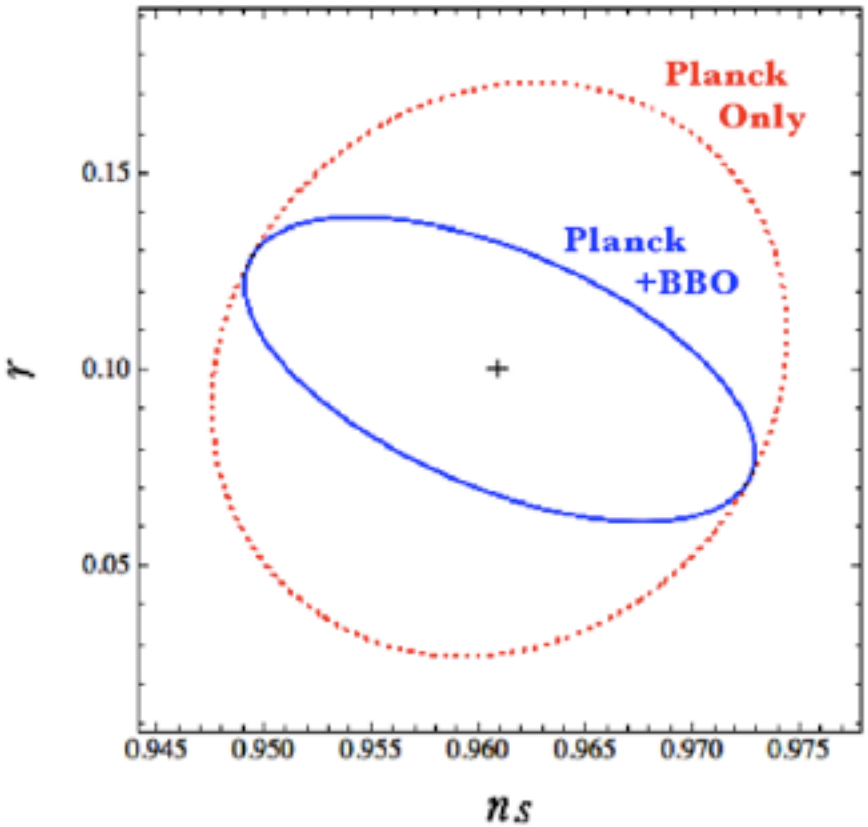
→ can be related to the parameters for CMB

$$n_S - 1 \simeq -6\epsilon - 2\eta$$

$$r \simeq 16\epsilon$$

■ Constraints from direct detection

r_{fid}=0.1, SNR=18.2



10 year observation

Direct detection mainly tightens the constraint on tensor-to-scalar ratio (r)

■ Testing the consistency relation

tensor-to-scalar ratio: $r \simeq 16\epsilon$

tilt of the tensor spectrum: $n_T \simeq -2\epsilon$

Consistency relation: $r = -8n_T$

→ **test of the inflation theory**

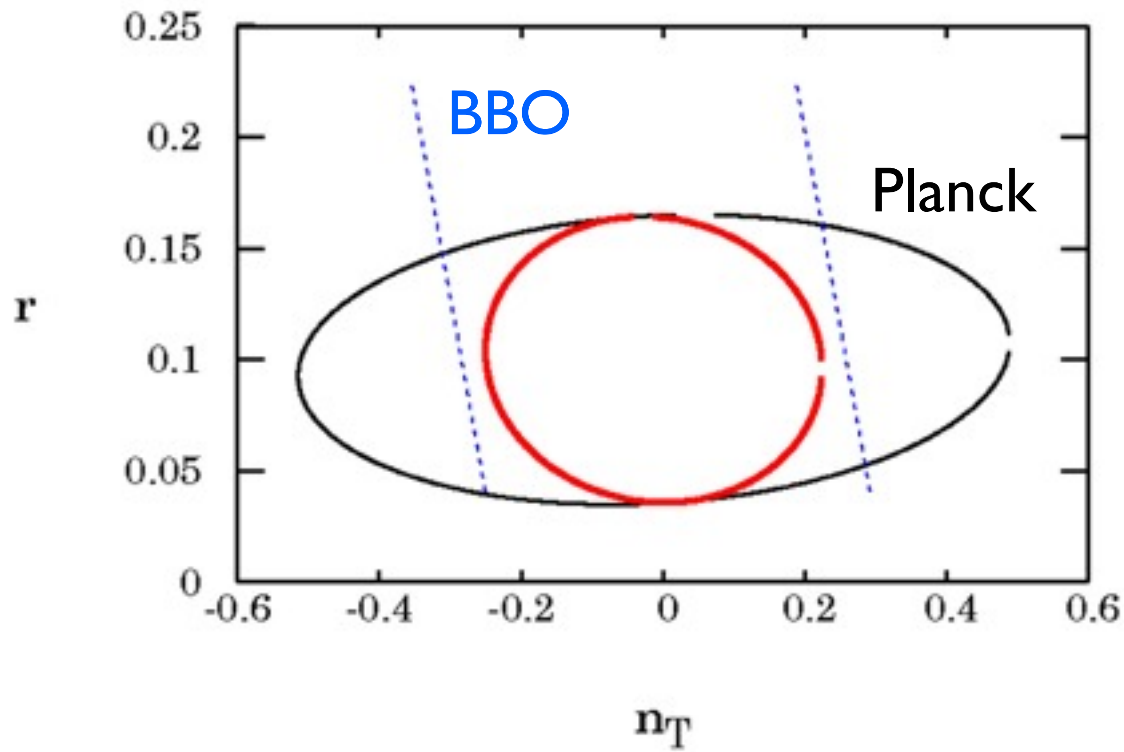
■ Testing the consistency relation

tensor-to-scalar ratio: $r \simeq 16\epsilon$

tilt of the tensor spectrum: $n_T \simeq -2\epsilon$

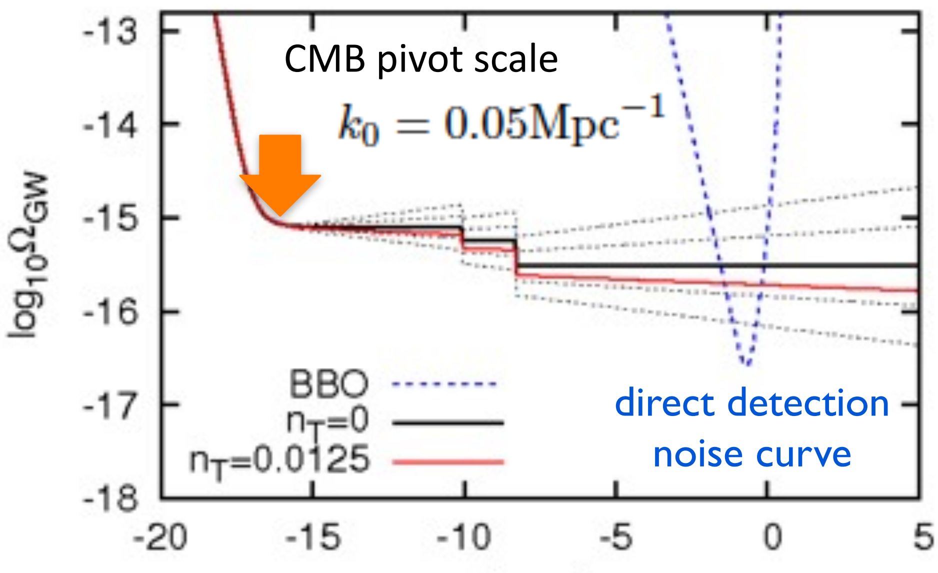
Consistency relation: $r = -8n_T$

→ **test of the inflation theory**



$$\mathcal{R} = -\frac{r}{8n_T} = 1.0 \pm 7.6$$

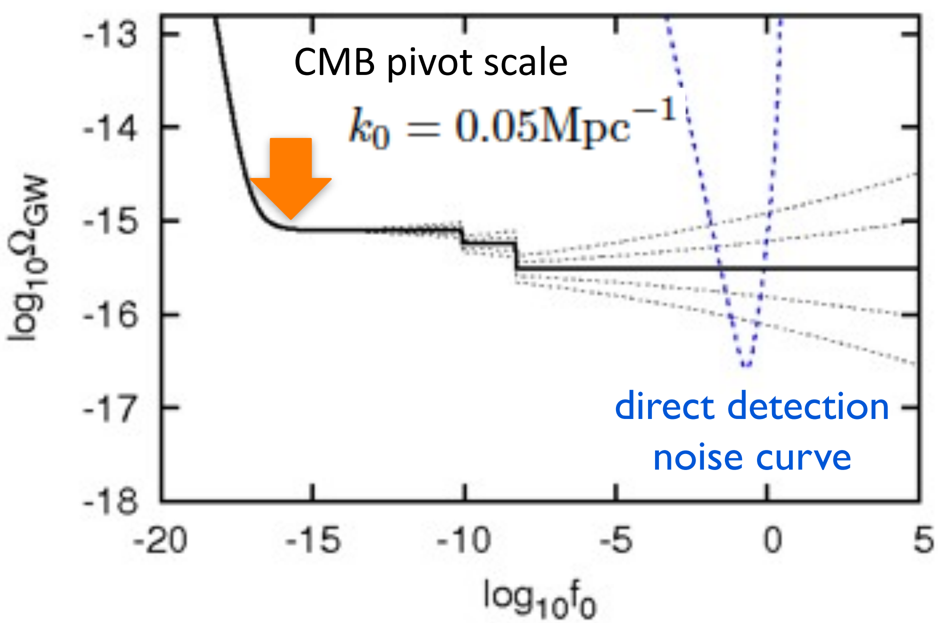
■ Testing the consistency relation



$$\mathcal{P}_{T\star} \exp\left[n_{T\star} \ln \frac{k}{k_\star} + \frac{1}{2!}\alpha_{T\star} \ln^2 \frac{k}{k_\star} + \cdots \right]$$

running

Changing n_T...
($n_T=\pm0.2, \pm0.4, -r/8$)



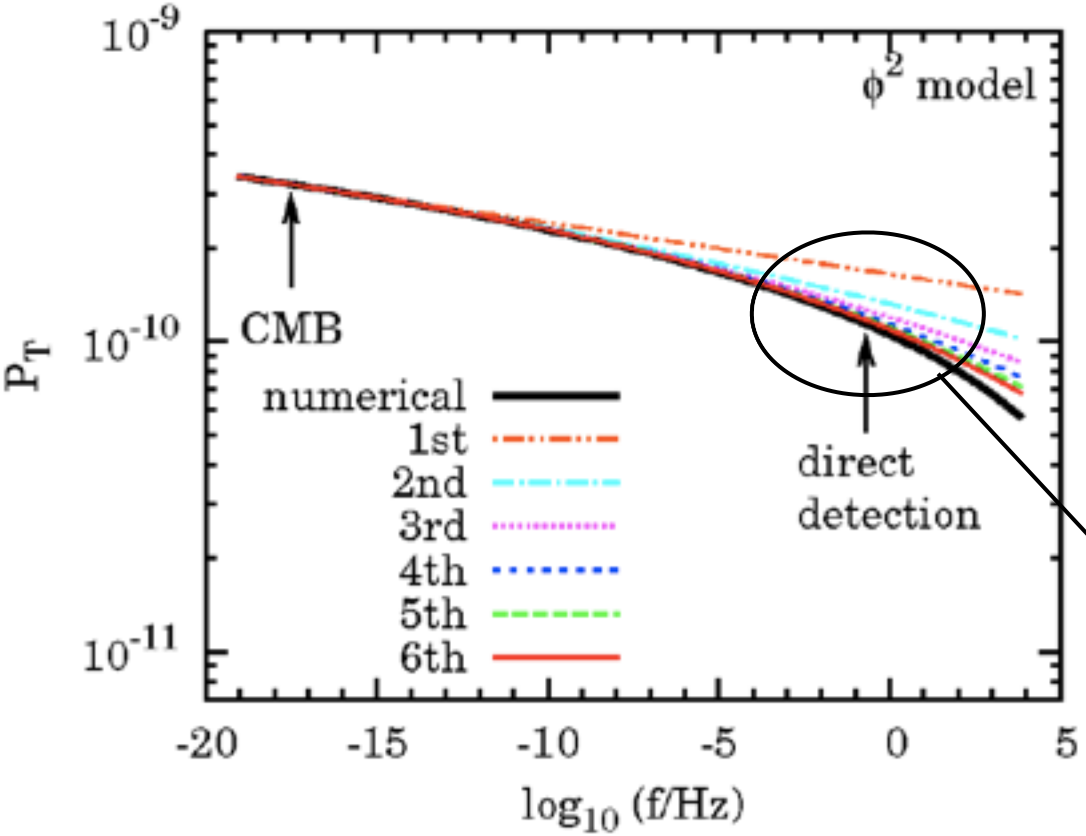
Changing α_T...
($\alpha_T=\pm0.001, \pm0.002$)

→ strong degeneracy between n_T and α_T

■ Note on the slow-roll expression

Effect of higher order terms

$$\mathcal{P}_T(k) = \mathcal{P}_{T\star} \exp\left[n_{T\star} \ln\frac{k}{k_\star} + \frac{1}{2!}\alpha_{T\star}\ln^2\frac{k}{k_\star} + \frac{1}{3!}\beta_{T\star}\ln^3\frac{k}{k_\star} + \frac{1}{4!}\gamma_{T\star}\ln^4\frac{k}{k_\star} + \frac{1}{5!}\delta_{T\star}\ln^5\frac{k}{k_\star} + \frac{1}{6!}\theta_{T\star}\ln^6\frac{k}{k_\star} + \cdots \right]$$



overestimation of the spectrum amplitude!

■ Note on the slow-roll expression

Effect of higher order terms

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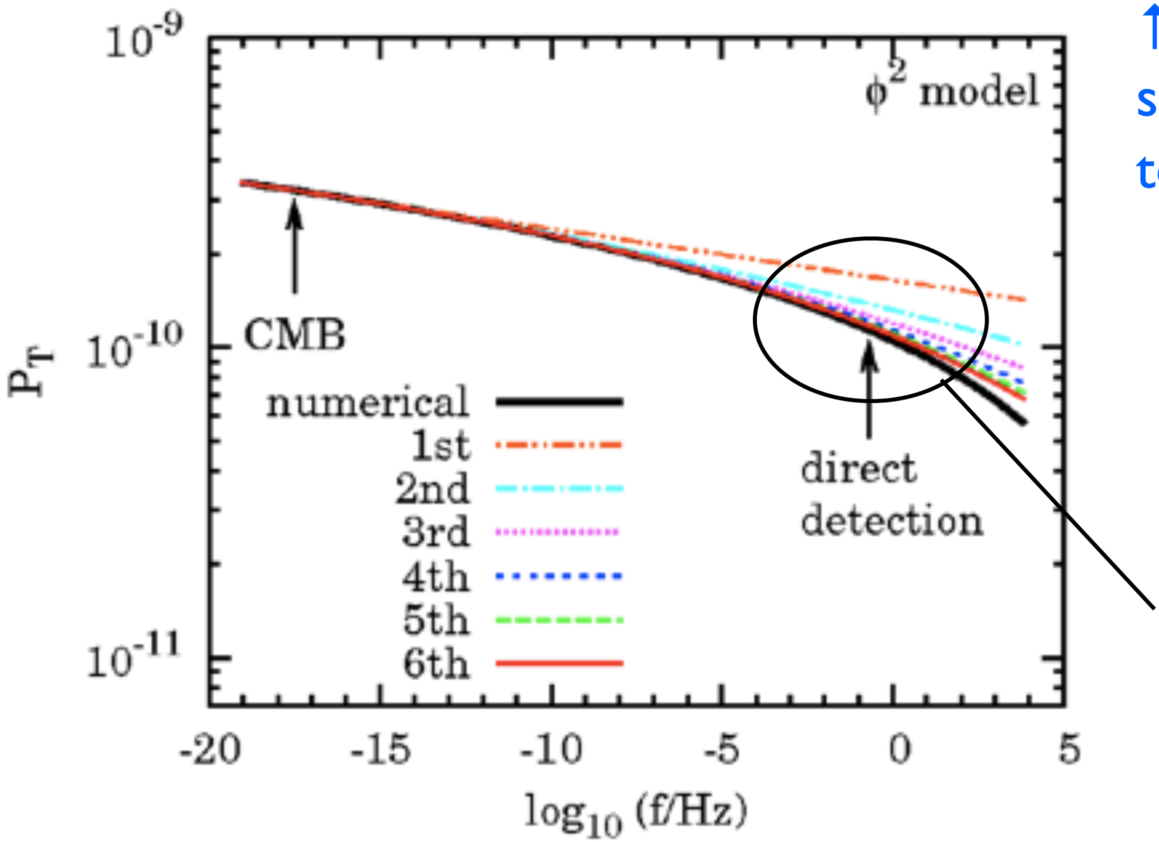
↑ coefficient parameters suppress the higher order terms with $O(\varepsilon^n)$



overestimation of the spectrum amplitude!

■ Note on the slow-roll expression

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$$\mathcal{P}_T(k) = \mathcal{P}_{T\star} \exp\left[n_{T\star} \ln\frac{k}{k_\star} + \frac{1}{2!}\alpha_{T\star}\ln^2\frac{k}{k_\star} + \frac{1}{3!}\beta_{T\star}\ln^3\frac{k}{k_\star} + \frac{1}{4!}\gamma_{T\star}\ln^4\frac{k}{k_\star} + \frac{1}{5!}\delta_{T\star}\ln^5\frac{k}{k_\star} + \frac{1}{6!}\theta_{T\star}\ln^6\frac{k}{k_\star} + \cdots \right]$$

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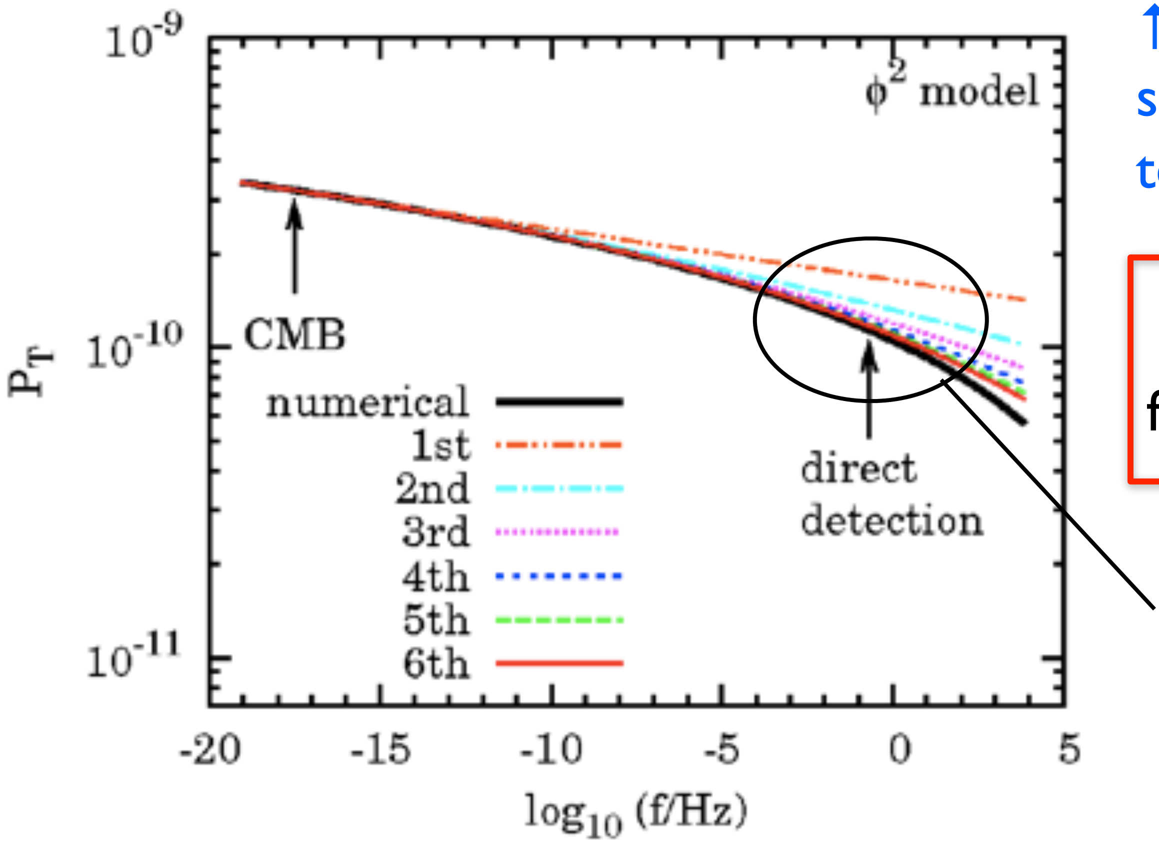


But $\ln(k_{0.2\mathrm{Hz}}/k_\star) \simeq 38.7$

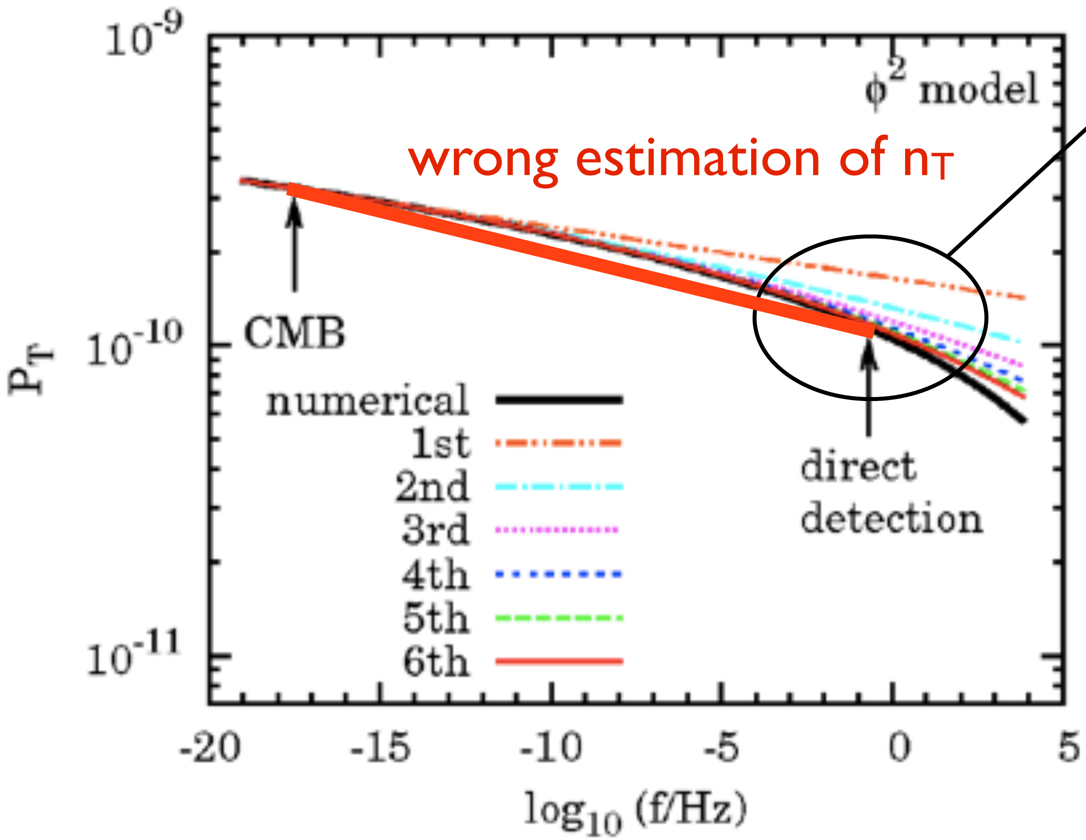
for the direct detection scale

overestimation of the spectrum amplitude!

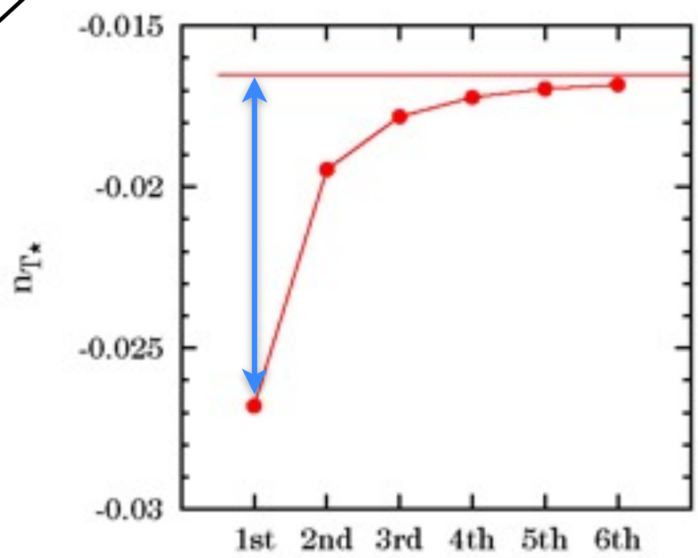
■ Note on the slow-roll expression

Effect of higher order terms

$$\mathcal{P}_T(k) = \mathcal{P}_{T\star} \exp\left[n_{T\star} \ln\frac{k}{k_\star} + \cancel{\frac{1}{2!}\alpha_{T\star}\ln^2\frac{k}{k_\star}} + \cancel{\frac{1}{3!}\beta_{T\star}\ln^3\frac{k}{k_\star}} + \cancel{\frac{1}{4!}\gamma_{T\star}\ln^4\frac{k}{k_\star}} + \cancel{\frac{1}{5!}\delta_{T\star}\ln^5\frac{k}{k_\star}} + \cancel{\frac{1}{6!}\theta_{T\star}\ln^6\frac{k}{k_\star}} + \cdots \right]$$



affects parameter estimation



There still some deviation even if we include the second order

■ Note on the slow-roll expression

Effect of higher order terms

$$\mathcal{P}_T(k) = \mathcal{P}_{T\star} \exp\left[n_{T\star} \ln\frac{k}{k_\star} + \frac{1}{2!}\alpha_{T\star}\ln^2\frac{k}{k_\star} + \frac{1}{3!}\beta_{T\star}\ln^3\frac{k}{k_\star} + \frac{1}{4!}\gamma_{T\star}\ln^4\frac{k}{k_\star} + \frac{1}{5!}\delta_{T\star}\ln^5\frac{k}{k_\star} + \frac{1}{6!}\theta_{T\star}\ln^6\frac{k}{k_\star} + \cdots \right]$$

coefficient parameters of higher order terms ∝ $O(\varepsilon^n)$

large slow-roll parameter → large overestimation

= large tensor to scalar ratio $r \simeq 16\epsilon$

→ more important in case where inflationary gravitational waves are detectable by experiments

→ numerical approach is better?

→ **Need to know the inflation model**

■ Constraints on specific inflation model

Suppose that future observations support the chaotic inflation

Chaotic inflation (Φ^2 potential)

$$V(\phi) = \frac{1}{2}m^2\phi^2$$

2 model parameters

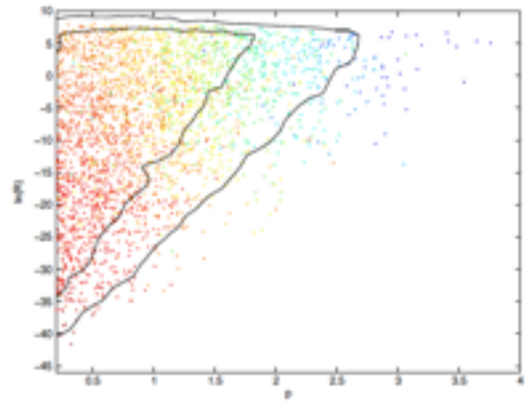
m: mass of the scalar field

N: e-folding number

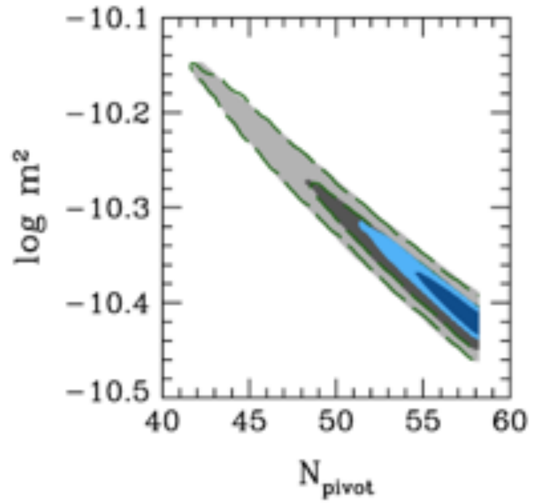
constraint on N?

connecting to Reheating temperature?

Some constraints from WMAP

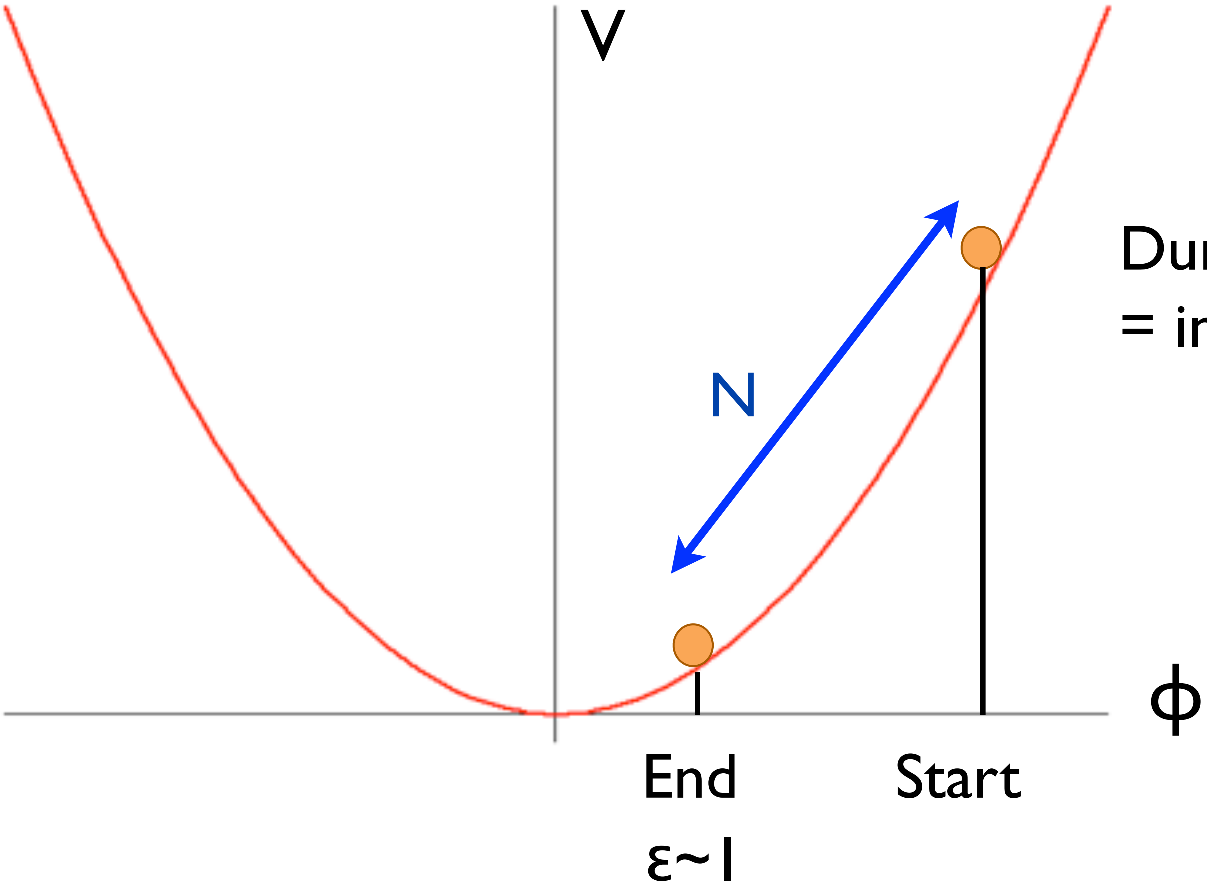


Martin and Ringeval, PRD 83, 043505 (2011)



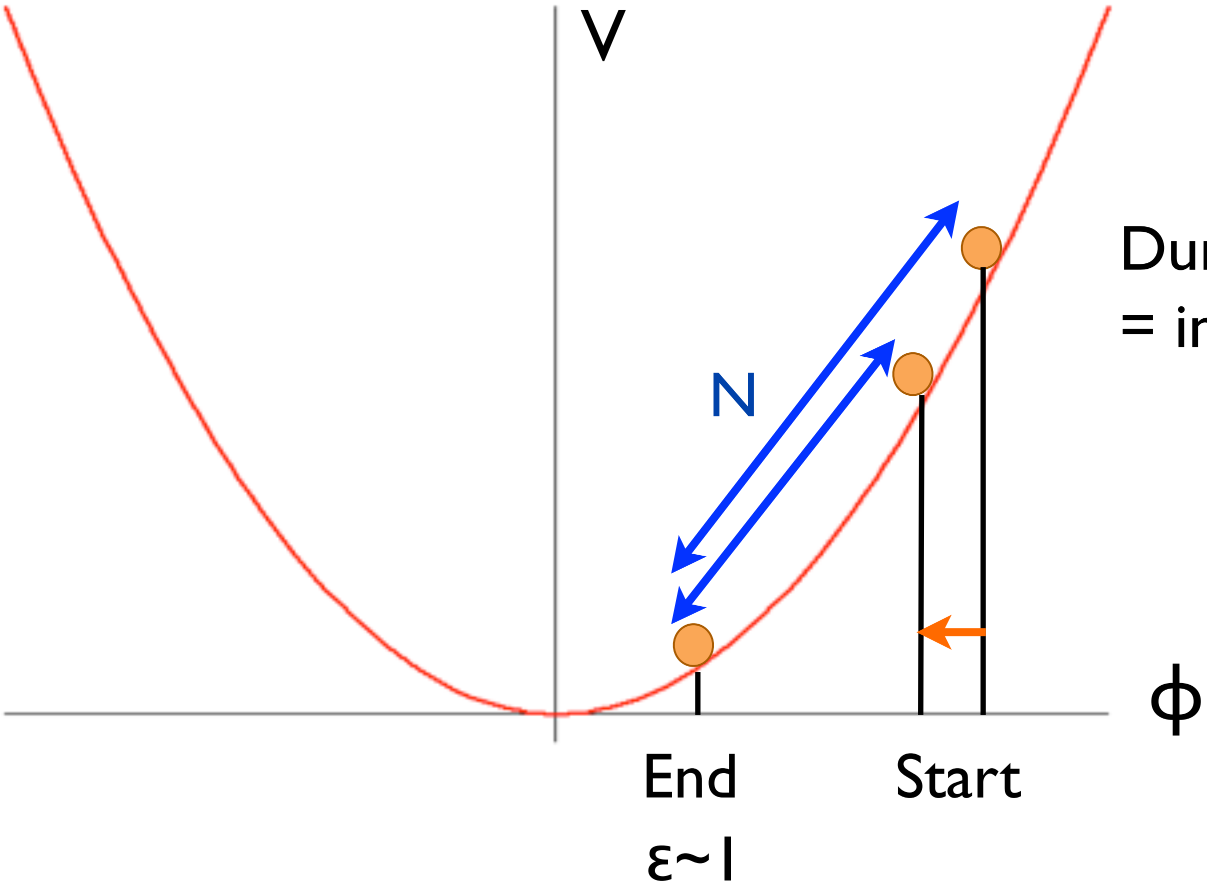
Mortonson et al. PRD 83, 043505 (2011)

■ Constraint on length of inflation



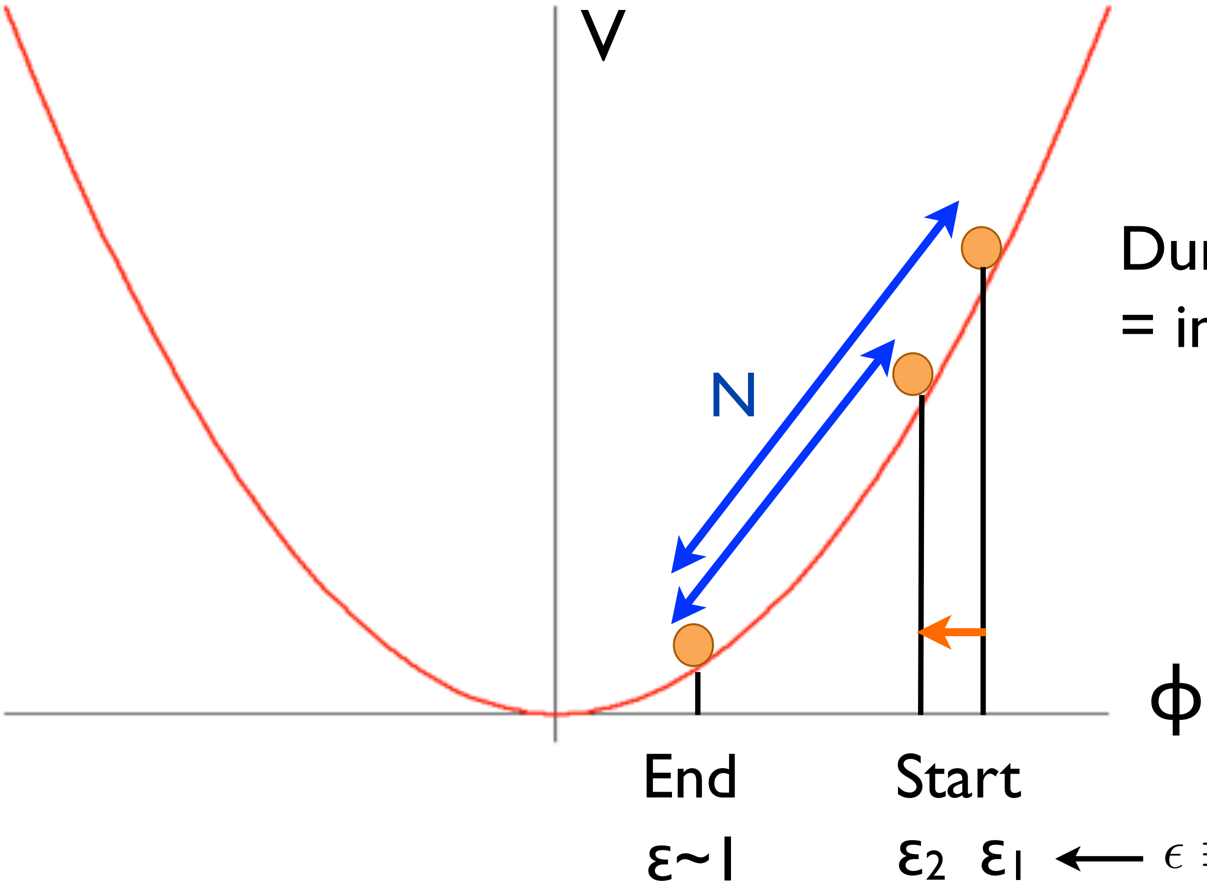
Duration of inflation
= initial value of Φ

■ Constraint on length of inflation



Duration of inflation
= initial value of ϕ

■ Constraint on length of inflation



Duration of inflation
= initial value of Φ

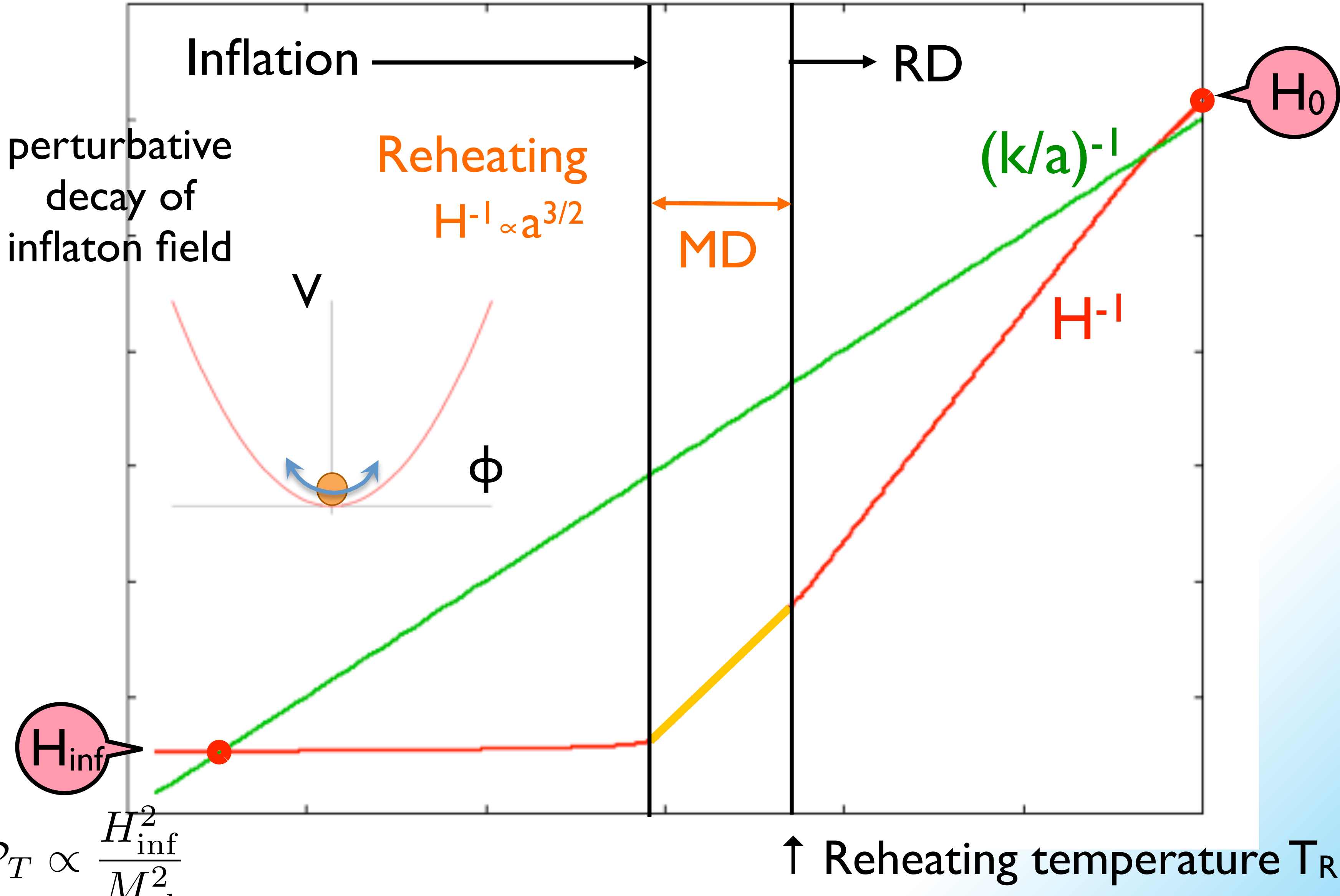
$\longleftarrow \epsilon \equiv \frac{M_{\rm pl}^2}{2}\left(\frac{V'(\phi)}{V(\phi)}\right)^2$

Shift of initial Φ slightly changes the value of slow-roll parameters

→ can correspond to observables

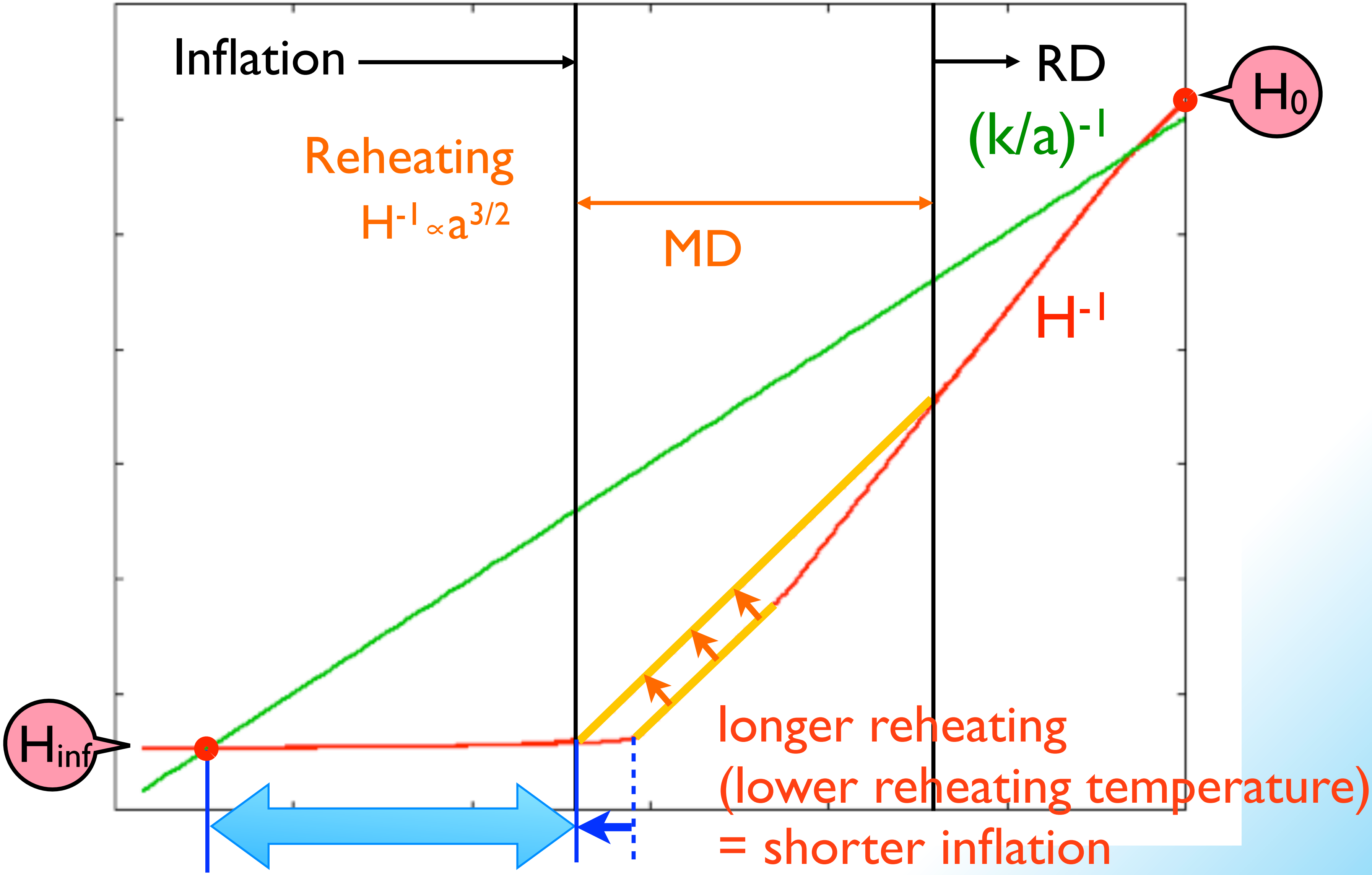
→ depends on inflation model

■ Relation with reheating temperature



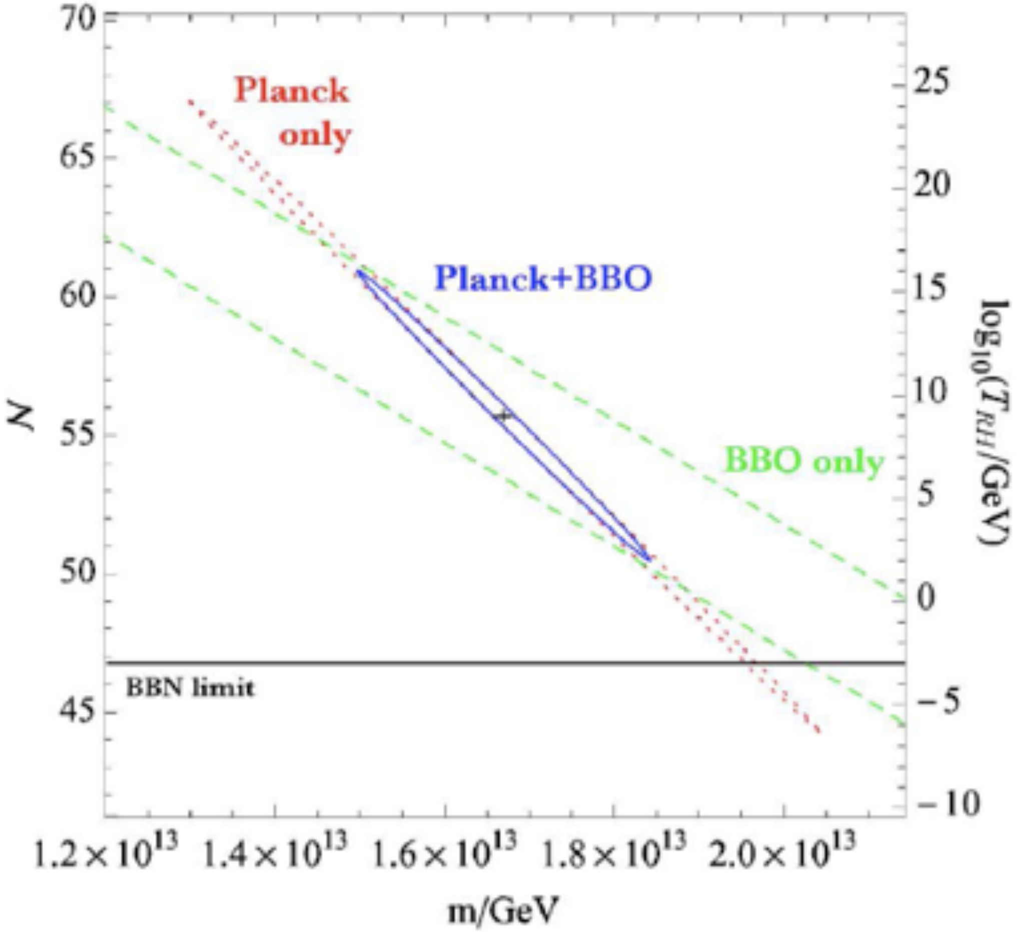
$$\mathcal{P}_T \propto \frac{H_{\rm inf}^2}{M_{\rm pl}^2}$$

■ Relation with reheating temperature



■ Constraint from direct detection

Direct detection may give N
with accuracy of ±5（2σ）



S. Kuroyanagi et. al, Phys. Rev. D 81, 083524 (2011)

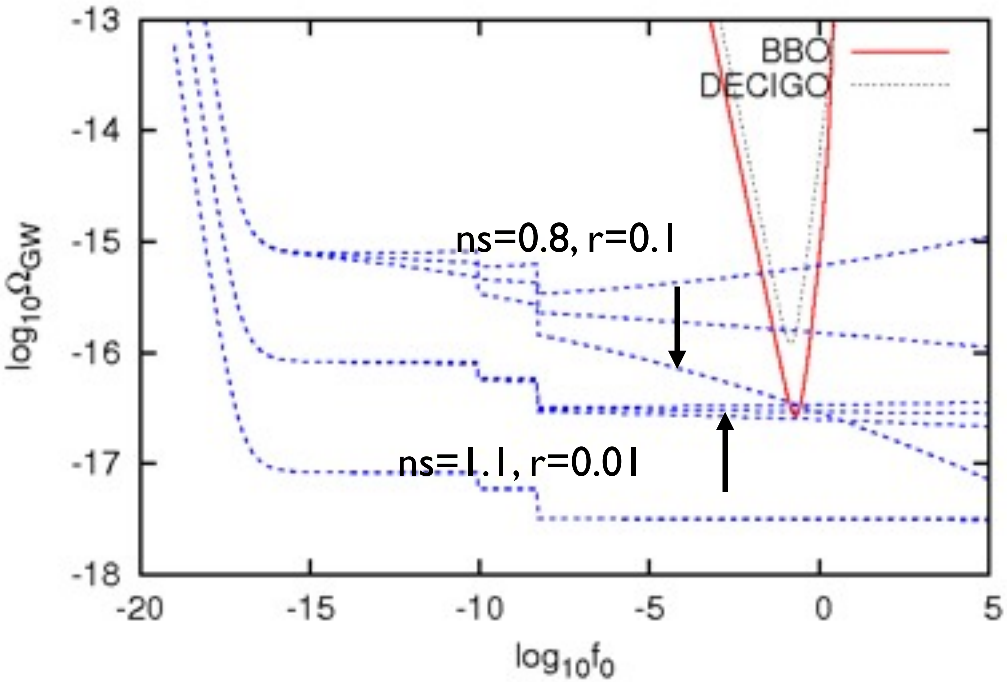
■ Parameter degeneracy

Direct detection detects GWs with a very narrow bandwidth

→ has sensitivity only to the amplitude of the spectrum at 0.1–1Hz

→ cannot distinguish models which gives the same amplitude

→ **Direction of the degeneracy**



←

r=0.1 n_s=1.1

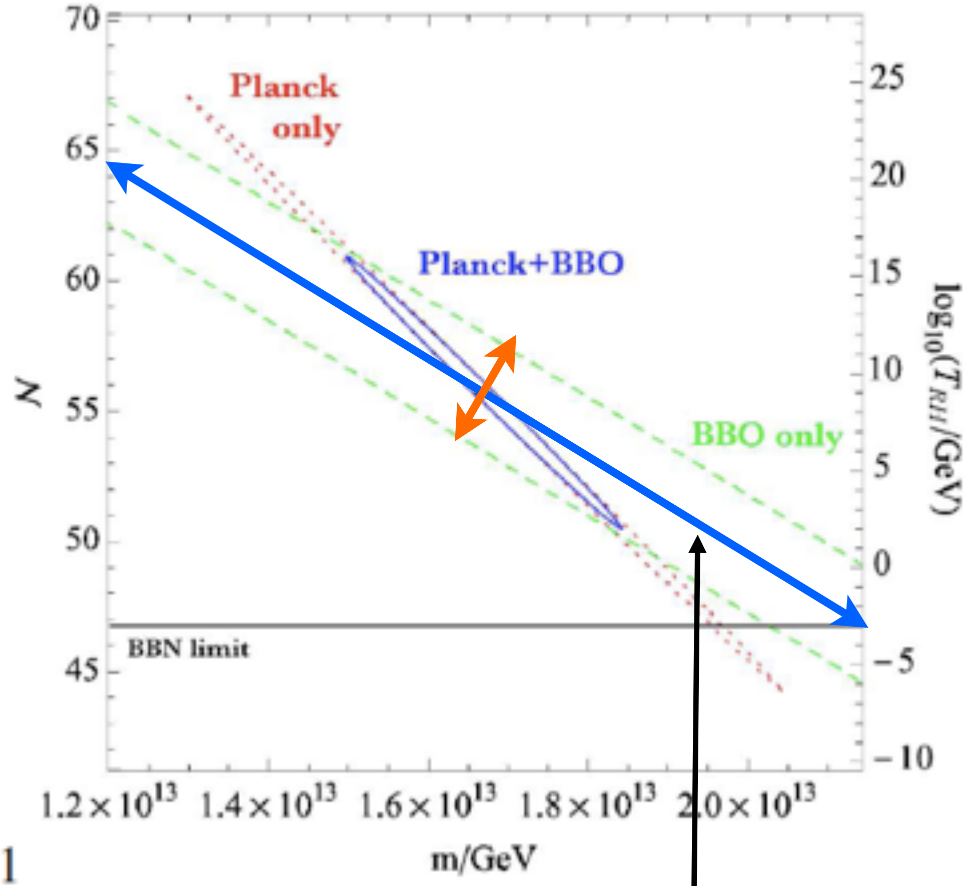
r=0.01 n_s=0.963

r=0.001 n_s=0.8

■ Parameter degeneracy

Direction of the degeneracy
= Direction along which the model gives the same amplitude

Width of the constraint
= Parameter range which the model predicts the similar amplitude



For Φ^2 potential...

$$\Omega_{\rm GW} \propto H(k)^2 \propto V(k)$$
$$= m^2\phi(k)^2/2$$

$$\phi(k)^2 = 2\mathcal{N}(k) + 1$$

$$= m^2[2\mathcal{N}(k) + 1] = \text{const.}$$

N(k)~16.4 for direct detection

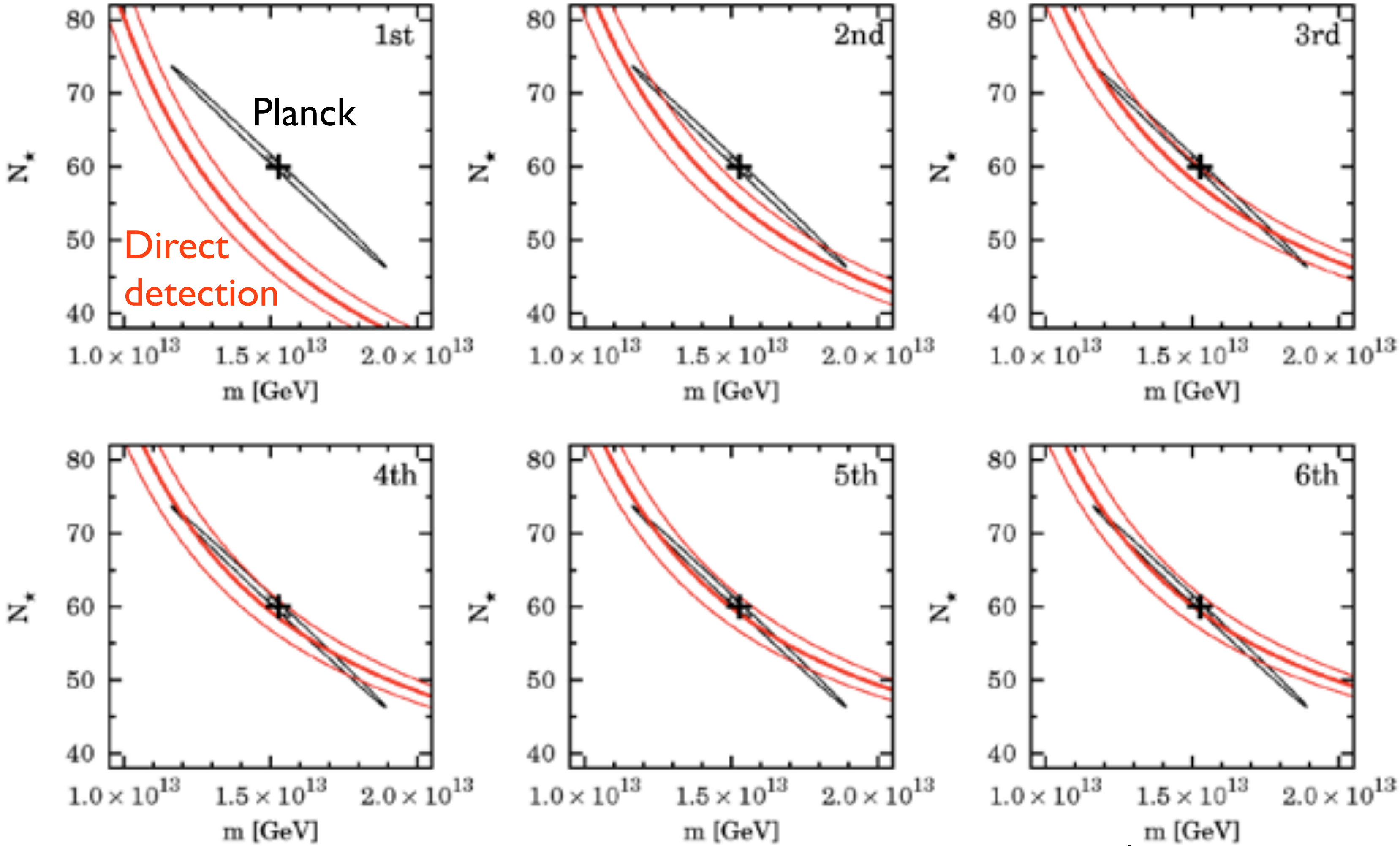
⇨ $$\Delta m/m + \Delta\mathcal{N}/[2\mathcal{N}(k) + 1] = 0$$

■ Effect of higher order terms

$$\mathcal{P}_T(k) = \mathcal{P}_{T\star} \exp\left[n_{T\star} \ln\frac{k}{k_\star} + \frac{1}{2!}\alpha_{T\star} \ln^2\frac{k}{k_\star} + \frac{1}{3!}\beta_{T\star} \ln^3\frac{k}{k_\star} + \frac{1}{4!}\gamma_{T\star} \ln^4\frac{k}{k_\star} + \frac{1}{5!}\delta_{T\star} \ln^5\frac{k}{k_\star} + \frac{1}{6!}\theta_{T\star} \ln^6\frac{k}{k_\star} + \cdots \right]$$

Wrong parameter constraints!

S. Kuroyanagi and T. Takahashi, arXiv:1106.3437[astro-ph]

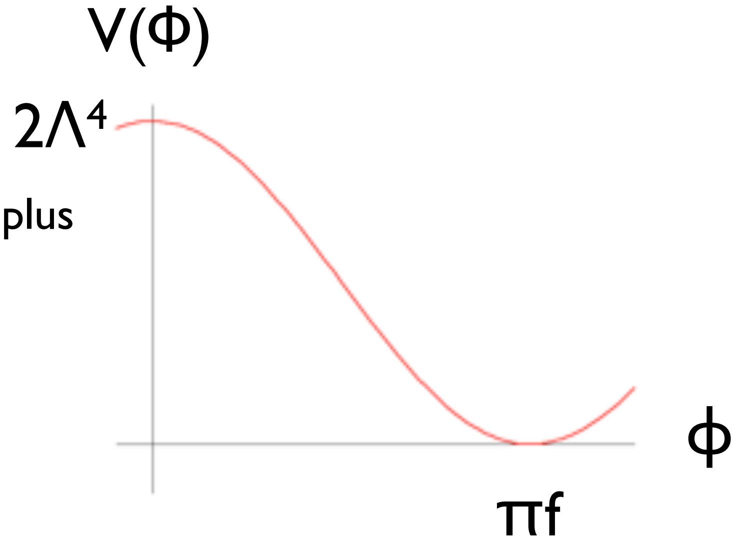


Red lines: Experimental errors in measuring Ω_{GW} (2σ, DECIGO/BBO)

■ Natural inflation model

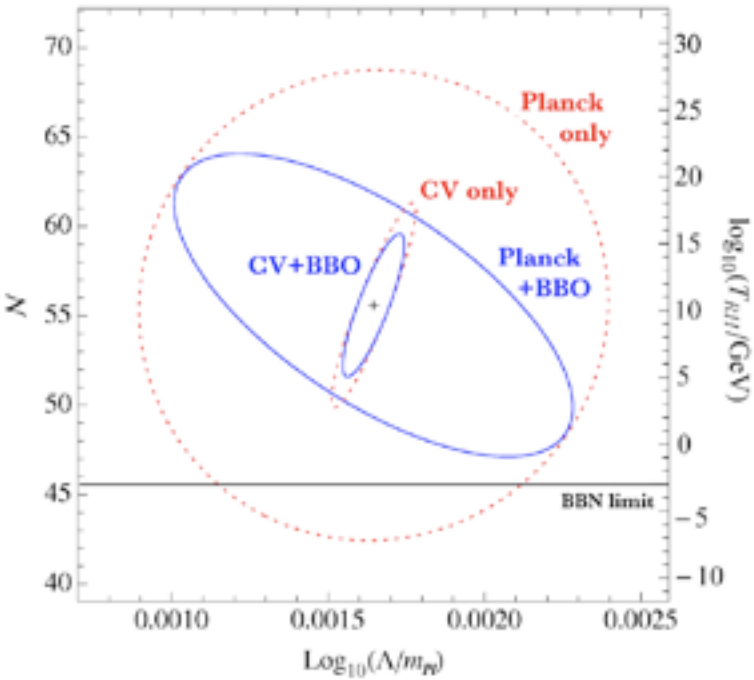
$$V(\phi) = \Lambda^4[1 \pm \cos(N\phi/f)].$$

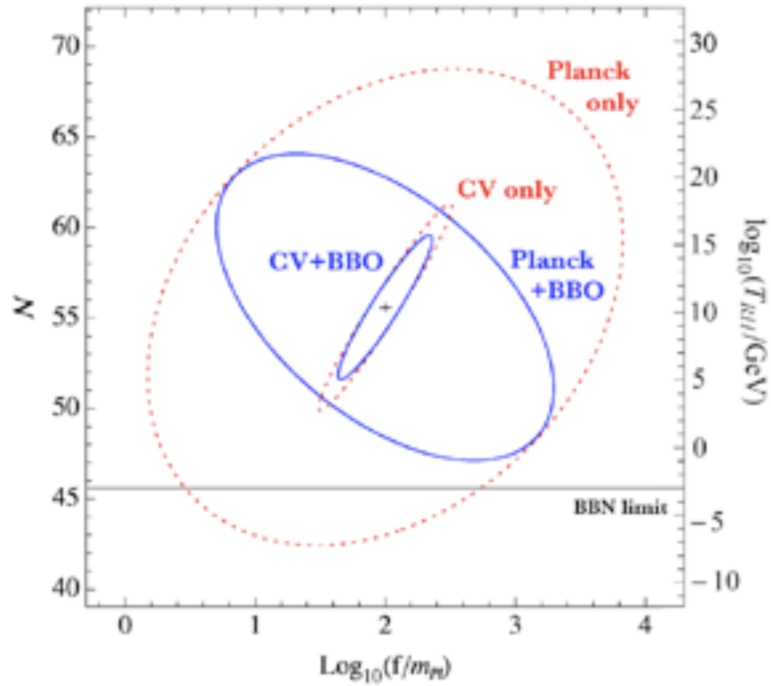
± is taken to be plus
N=1 is assumed



3 model parameters

Λ: height of the potential
f: position of the bottom
N: e-folding number

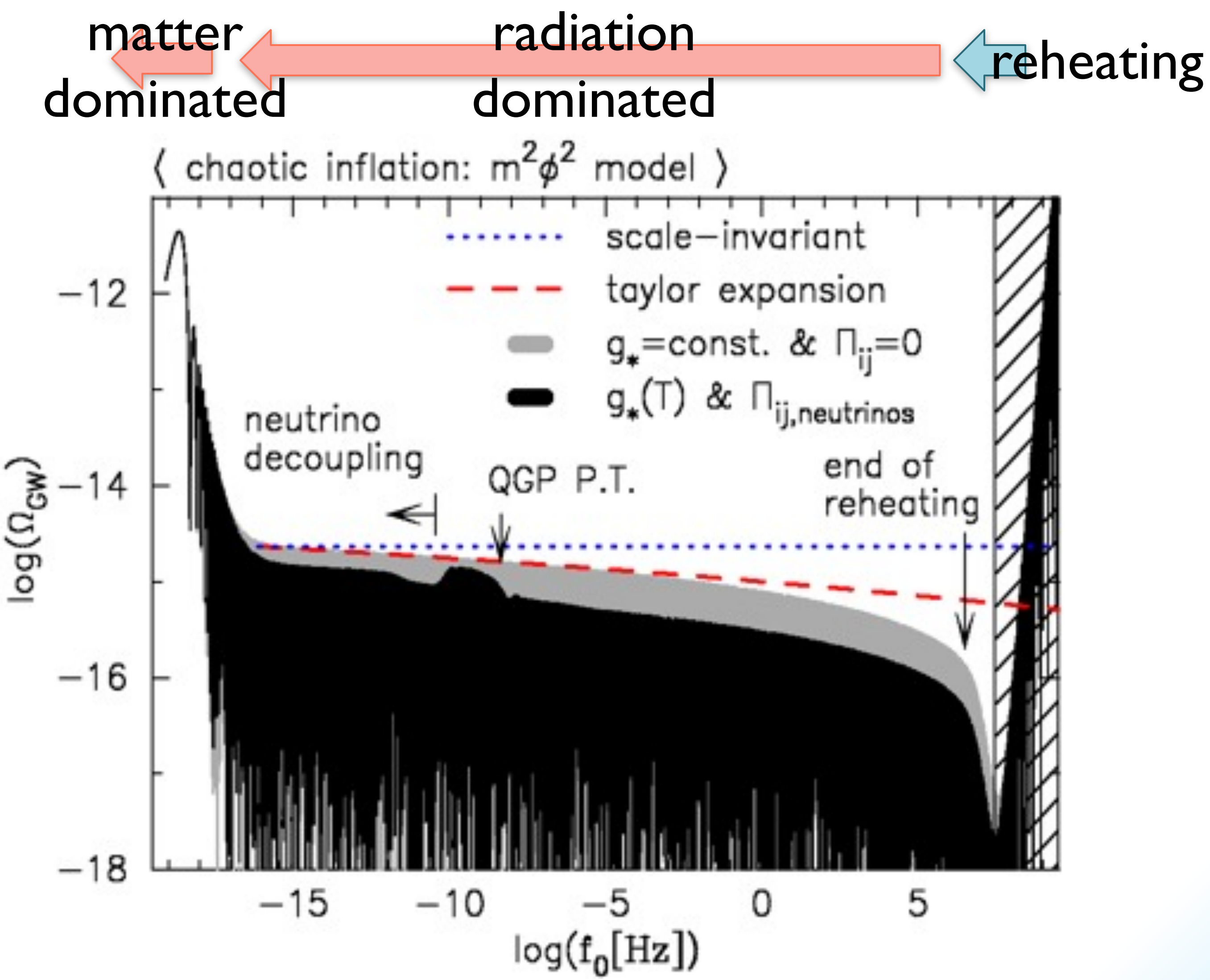




Direct detection has power to improve the constraint from next-generation CMB experiments!

■ Another probe of reheating

Matter dominated phase during reheating induces "dip" in the spectrum



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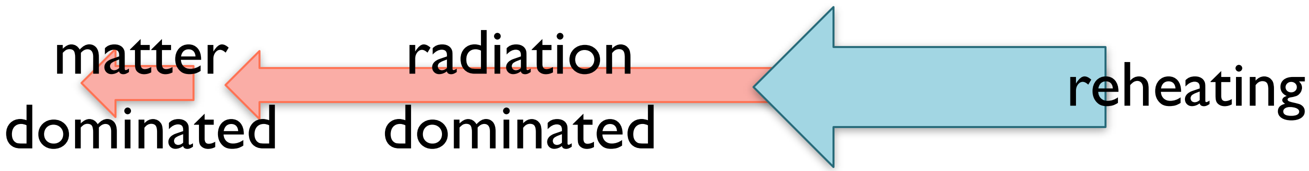
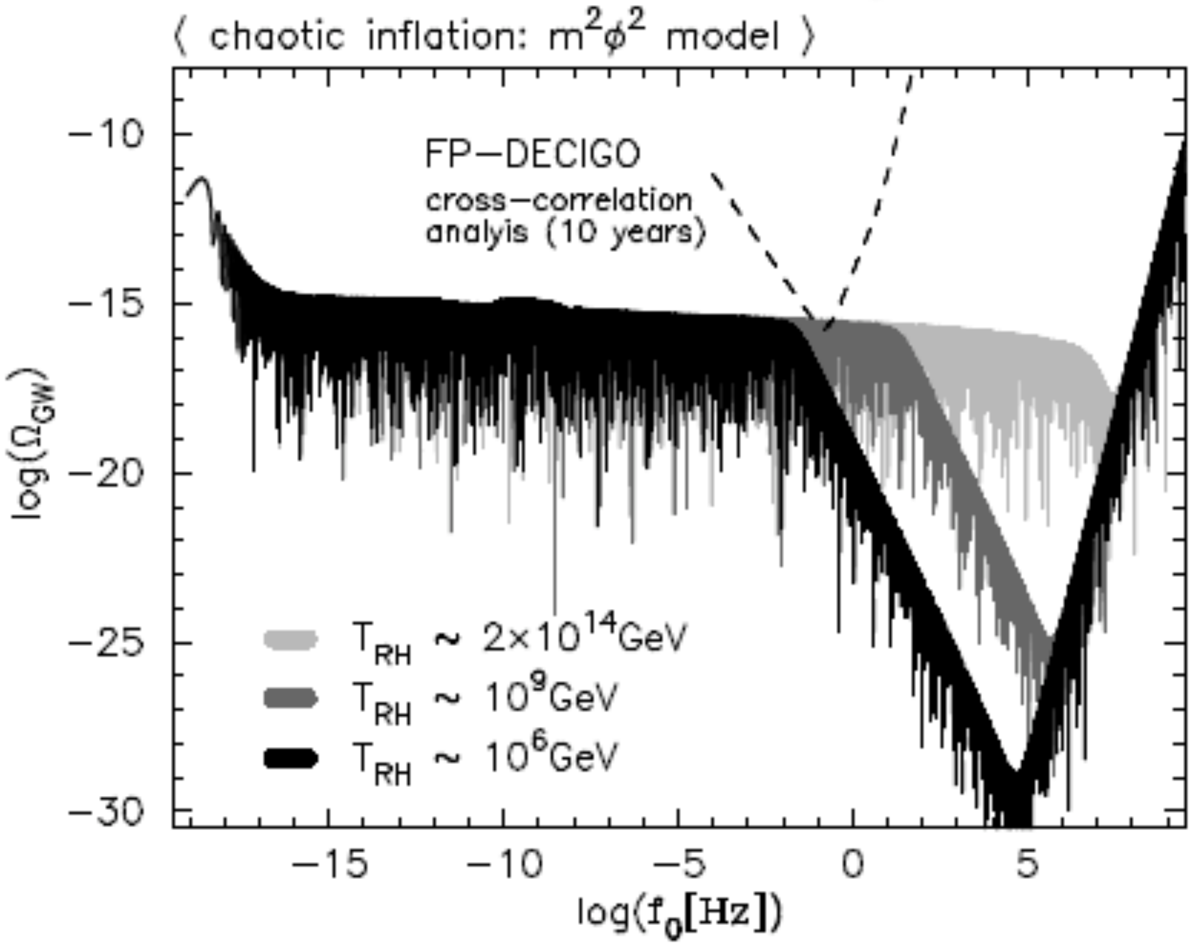
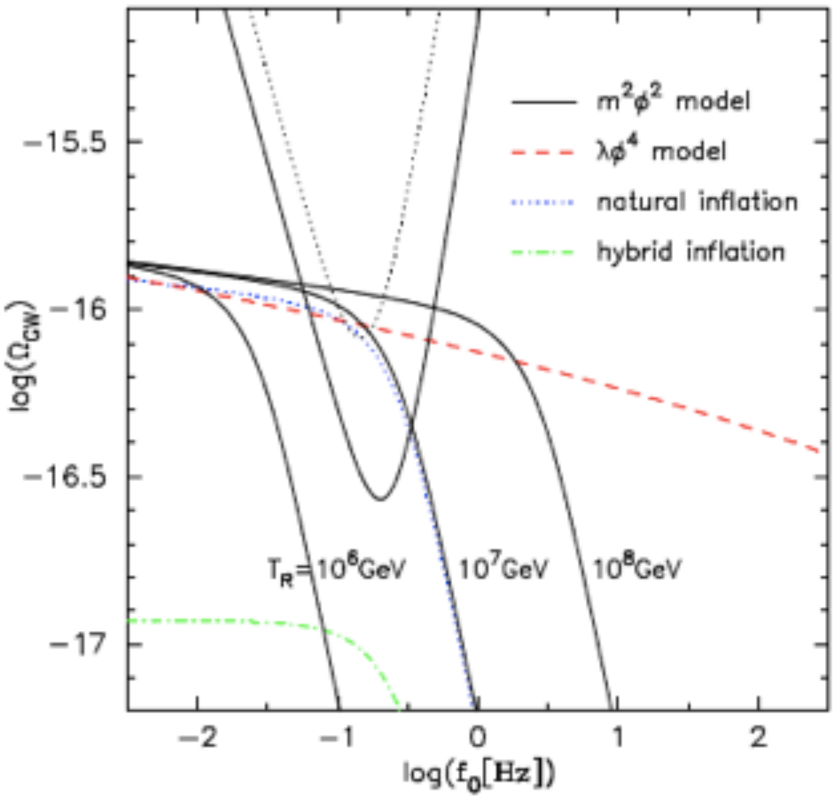




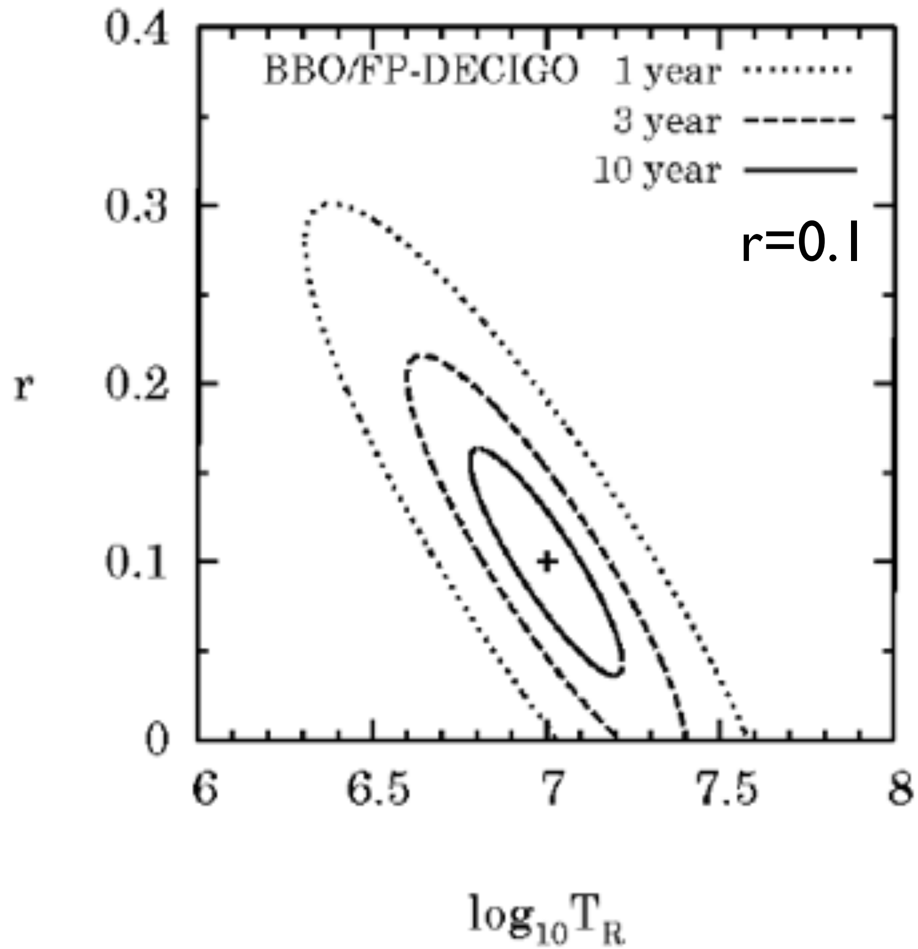
→ The edge comes in the target frequency of DECIGO/BBO

■ Constraint on reheating temperature

If the reheating temperature is ~10^7GeV, it may be possible to detect the signature of reheating (could be only evidence of reheating!) and give a constraint on the reheating temperature.

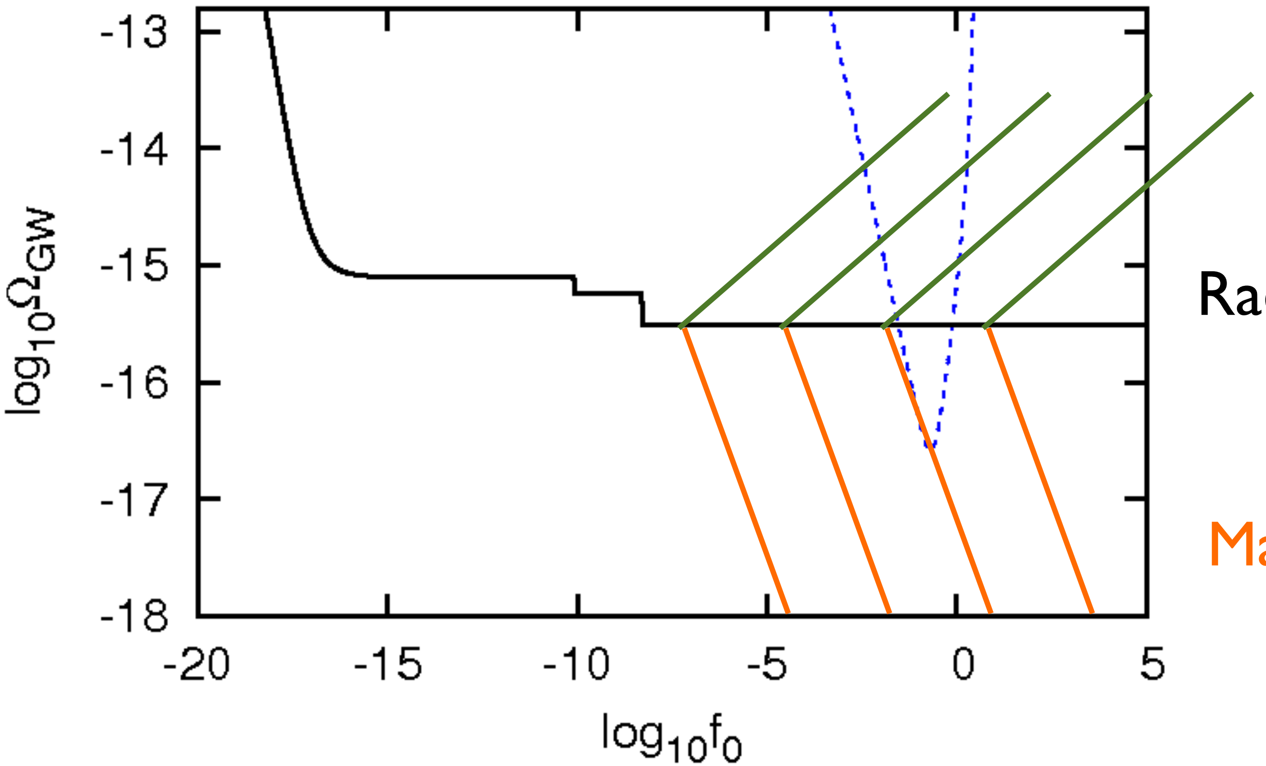


↑ position of the edge depends on reheating temperature



■ Constraint on the equation of state

Gravitational wave background traces the Hubble expansion history of the early universe.



Kination dominant: k^1

w=1

Radiation dominant: k^0

w=1/3

Matter dominant: k^{-2}

w=0

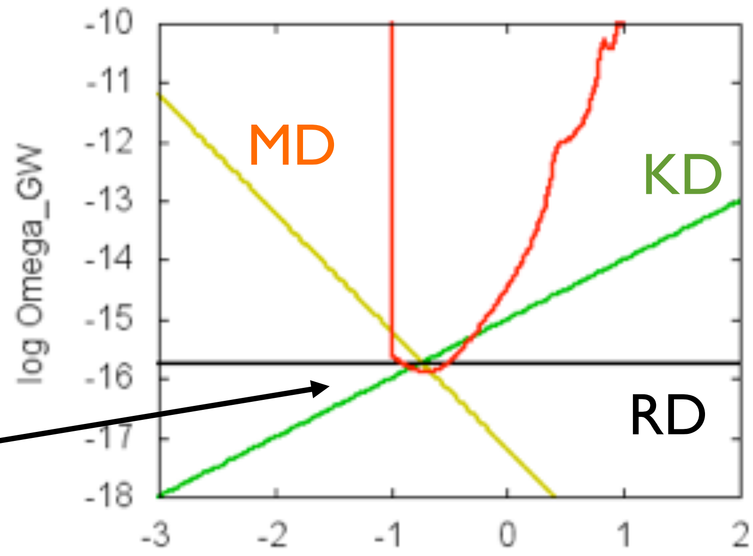
Equation state of the universe: $p = w\rho$

$$H \propto a^{-3(1+\omega)}$$

$$\Omega_{\rm GW} \propto k^{\frac{2(3\omega-1)}{3\omega+1}}$$

■ Constraint on the equation of state

We can get a constraint on ω by measuring the tilt of the spectrum in the sensitivity curve

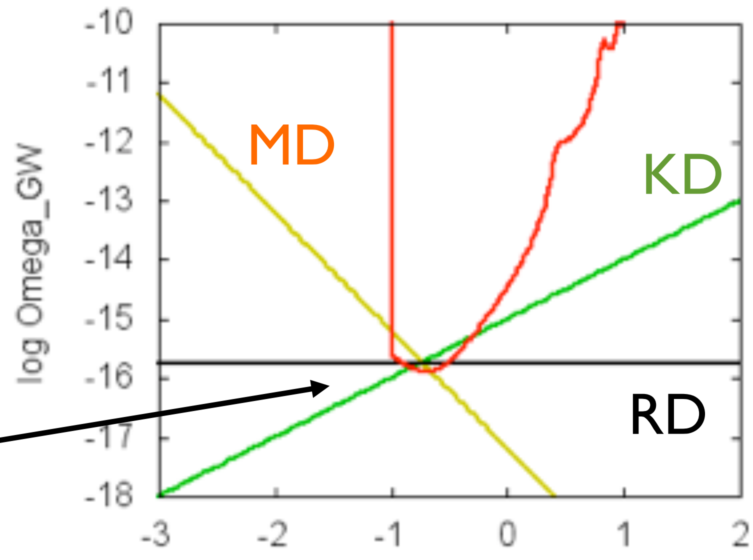


normalization: r=0.1 in the case of the flat spectrum (RD)

w w w

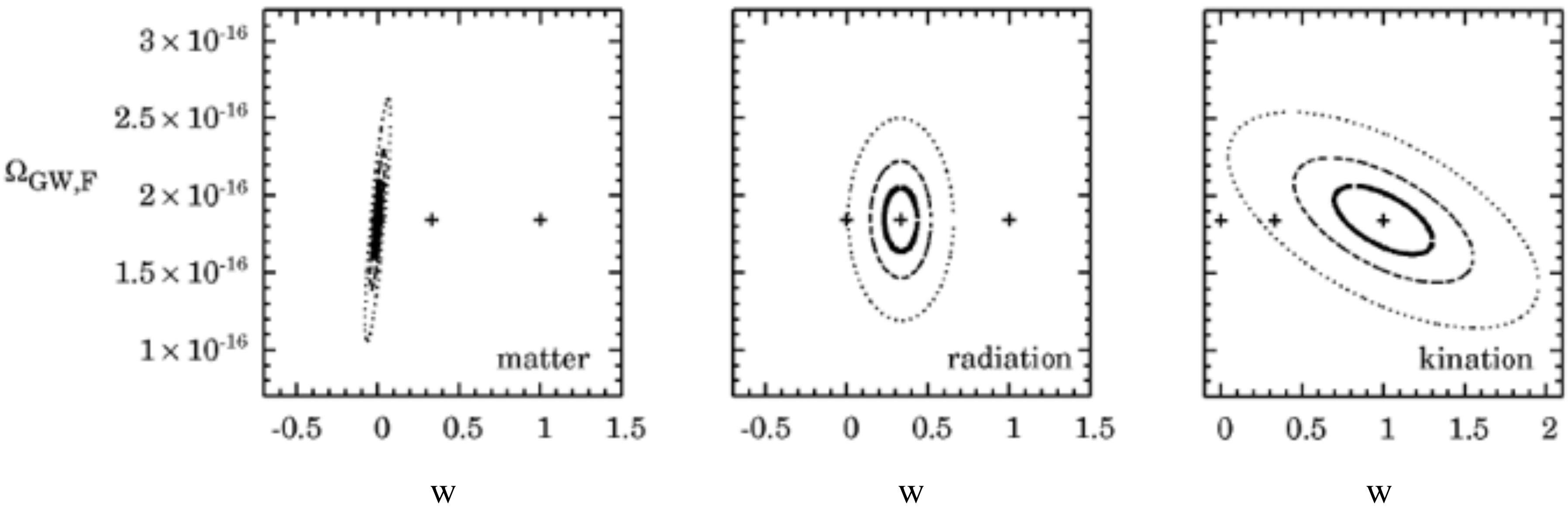
■ Constraint on the equation of state

We can get a constraint on ω by measuring the tilt of the spectrum in the sensitivity curve



normalization: r=0.1 in the case of the flat spectrum (RD)

Matter dominant: k^{-2} Radiation dominant: k^0 Kination dominant: k^1



■ Summary

Gravitational waves generated during inflation have potential to be a powerful observational tool to probe the early universe.

- If detected, they surely provide generous information about inflation.
- Combination of CMB and direct detection helps to constrain inflationary parameters more.
- May give some implication about reheating.
- Also about the equation state of the universe.
- We should note that the common analytic expression for the spectrum (= the Taylor expansion in terms of log(k)) may give poor estimation of the amplitude of the spectrum, and it causes wrong parameter estimation.