Reheating dynamics after inflation

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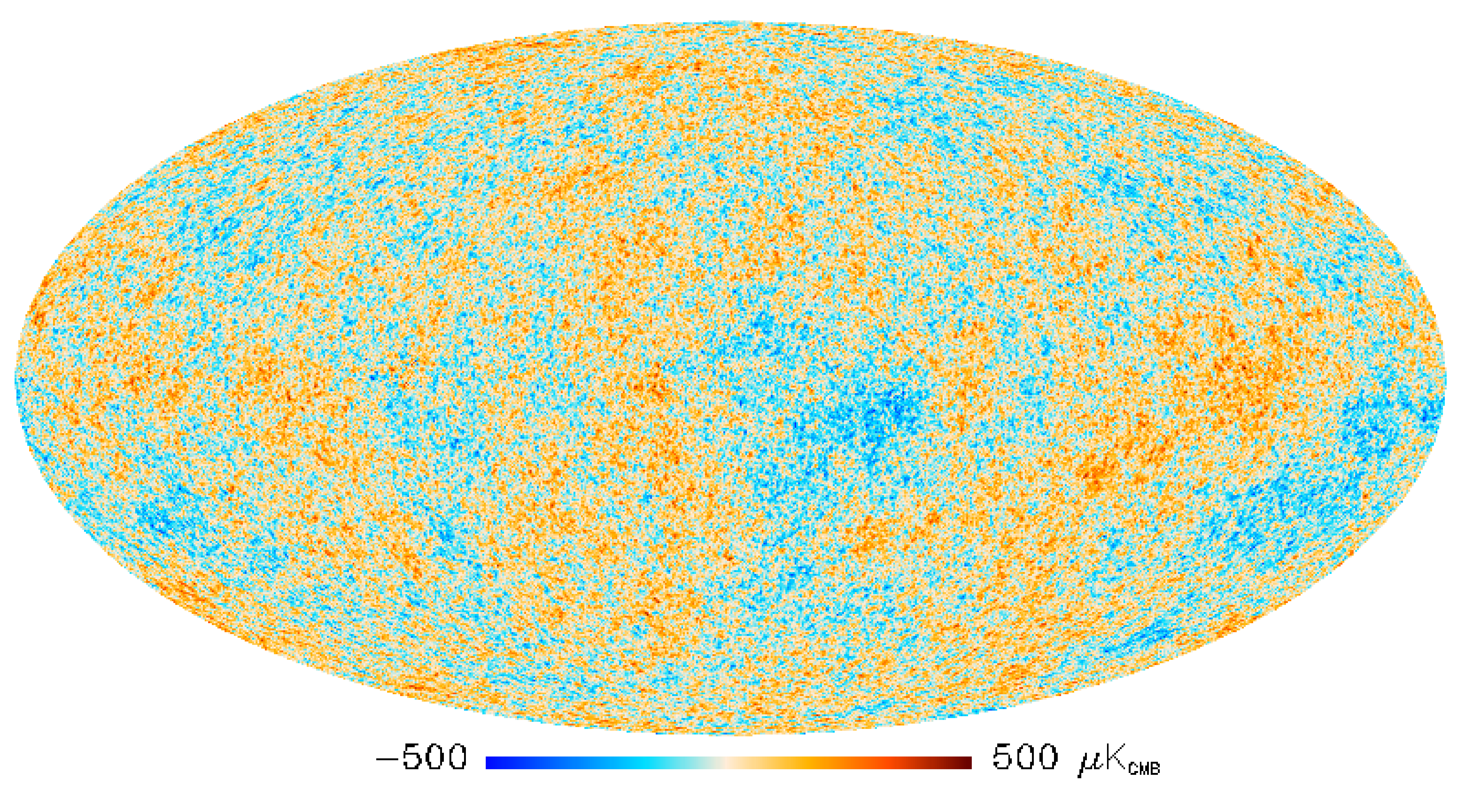
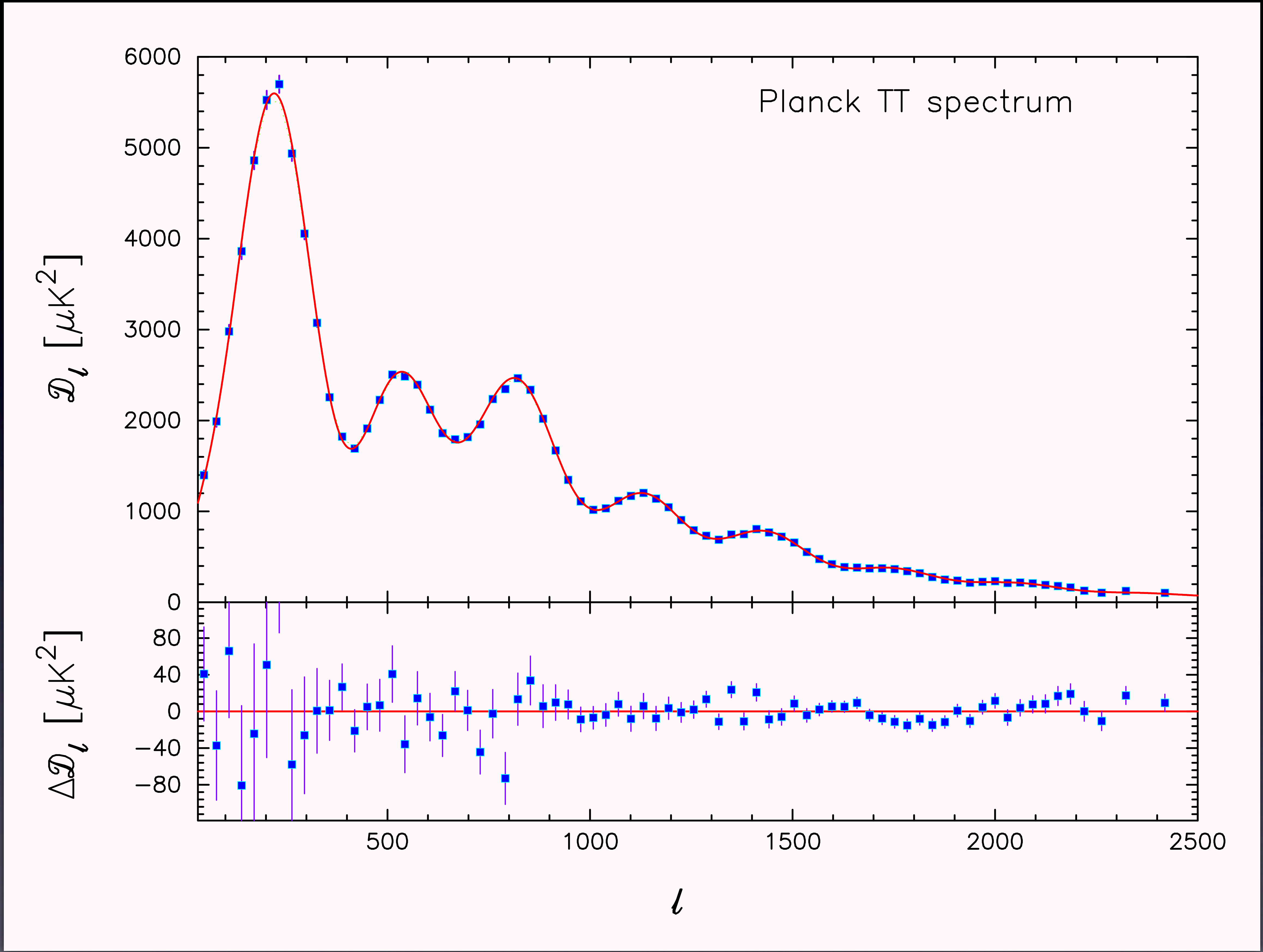
Tohoku Forum for Creativity (2013/10/24)

Contents

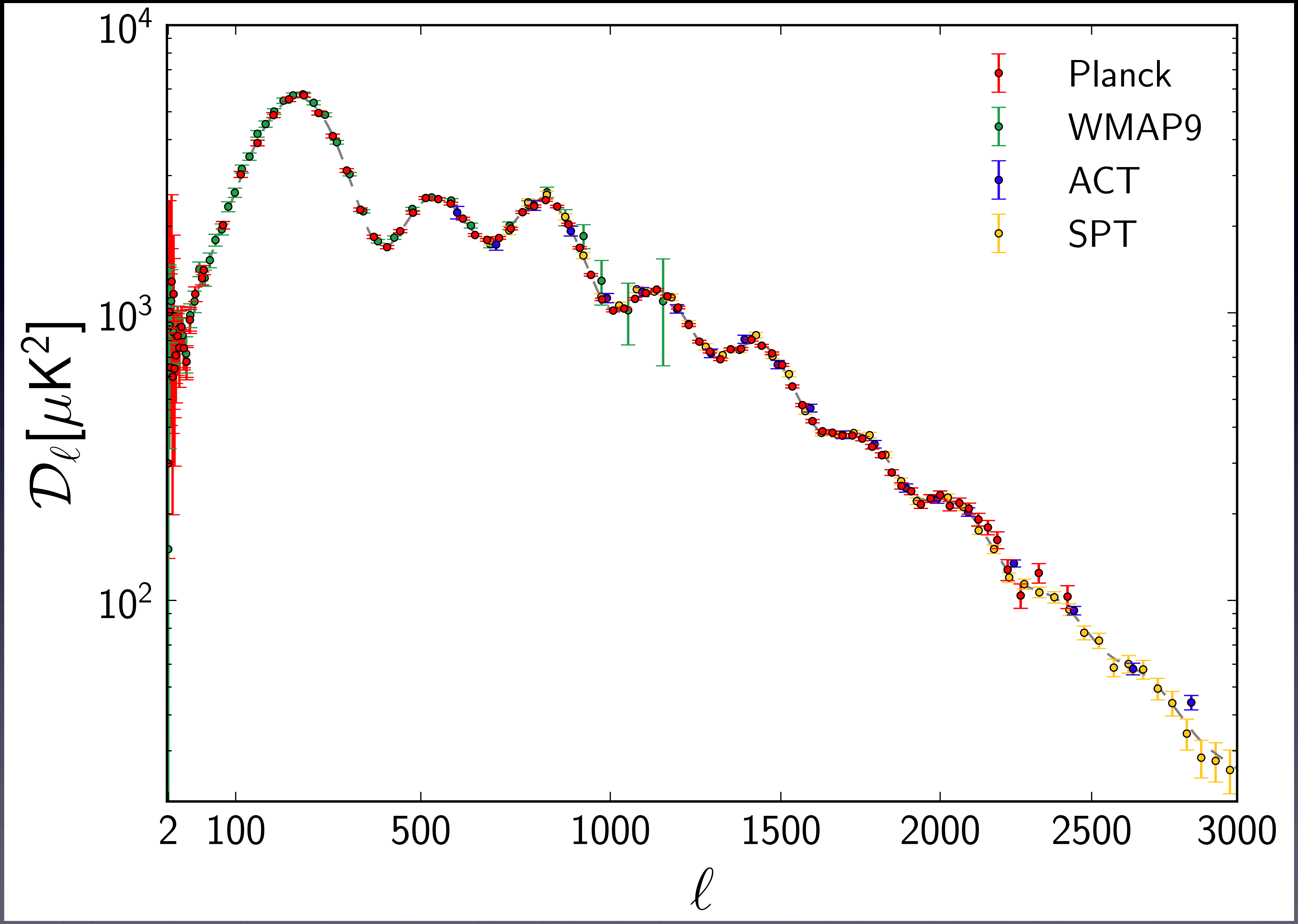
Microwave sky observed by Planck





Planck, 1303.5062

Combined with high-l measurements



Bestfit ΛCDM parameters

	Planck	
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068
τ	0.0925	0.097 ± 0.038
n_s	0.9624	0.9616 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072

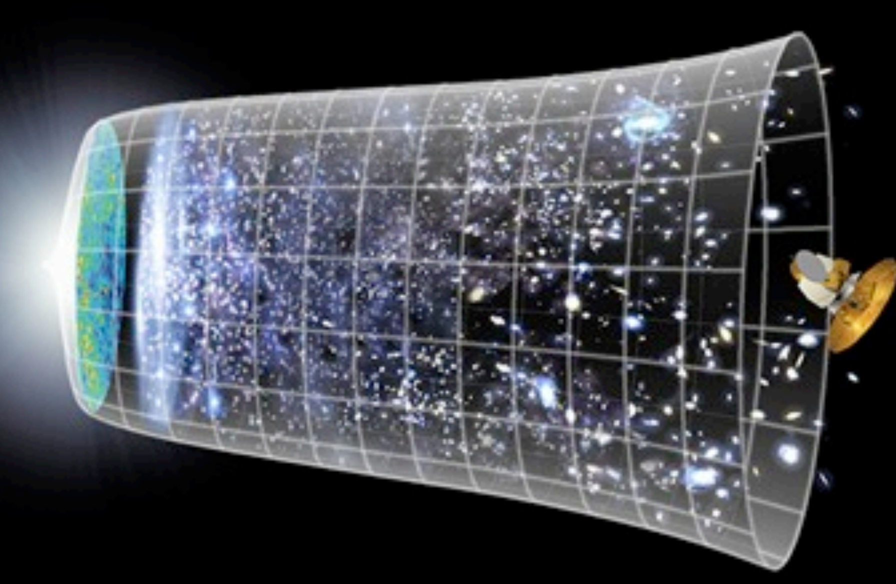
Initial condition of the density perturbation determined by inflation

$$\mathcal{P}_\zeta(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

Inflation

A.Guth (1981), K.Sato (1981)

- Accelerated expansion of the universe driven by a scalar field (inflaton)
- Solve horizon problem and flatness problem
- Quantum fluctuation of the inflaton gives seed of the density perturbation



Perturbations

- Metric Perturbation

$$ds^2 = -\mathcal{N}^2 dt^2 + a^2(t) e^{2\zeta(\vec{x})} (\delta_{ij} + h_{ij}(\vec{x})) dx^i dx^j$$

Scalar perturbation

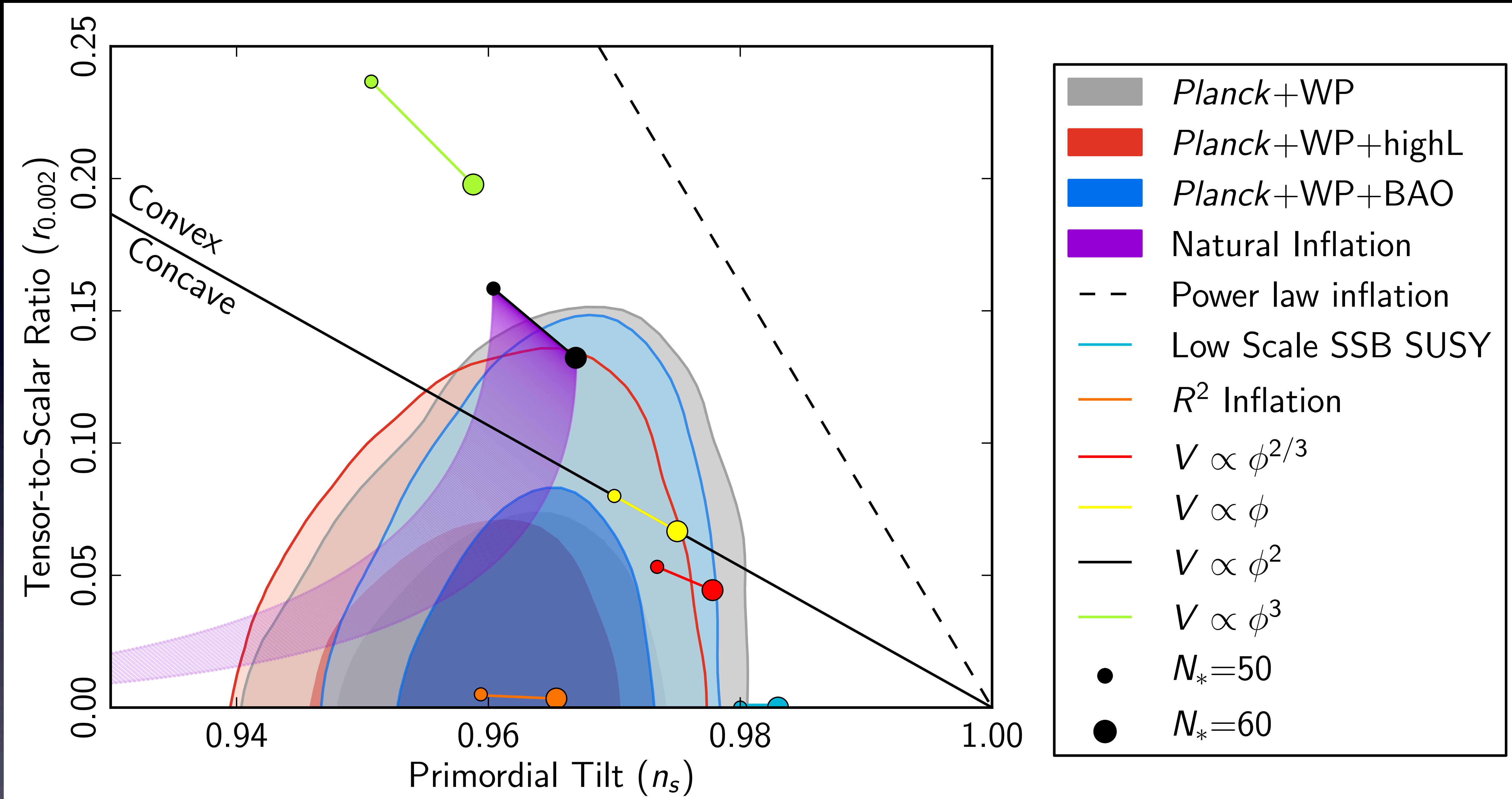
Tensor perturbation (Gravitational wave)

- Power spectrum :

$$\Delta_\zeta^2 = \frac{V_{\rm inf}}{24\pi^2 M_P^4 \epsilon} \left(\frac{k}{k_0}\right)^{n_s - 1} \qquad \Delta_h^2 = \frac{2V_{\rm inf}}{3\pi^2 M_P^4} \left(\frac{k}{k_0}\right)^{n_t}$$

B-mode

$$n_s = 1 - 6\epsilon + 2\eta$$



Planck, 1303.5082

$$n_s = 1 - 6\epsilon + 2\eta \qquad r \equiv \frac{\Delta_h^2}{\Delta_\zeta^2} = 16\epsilon$$

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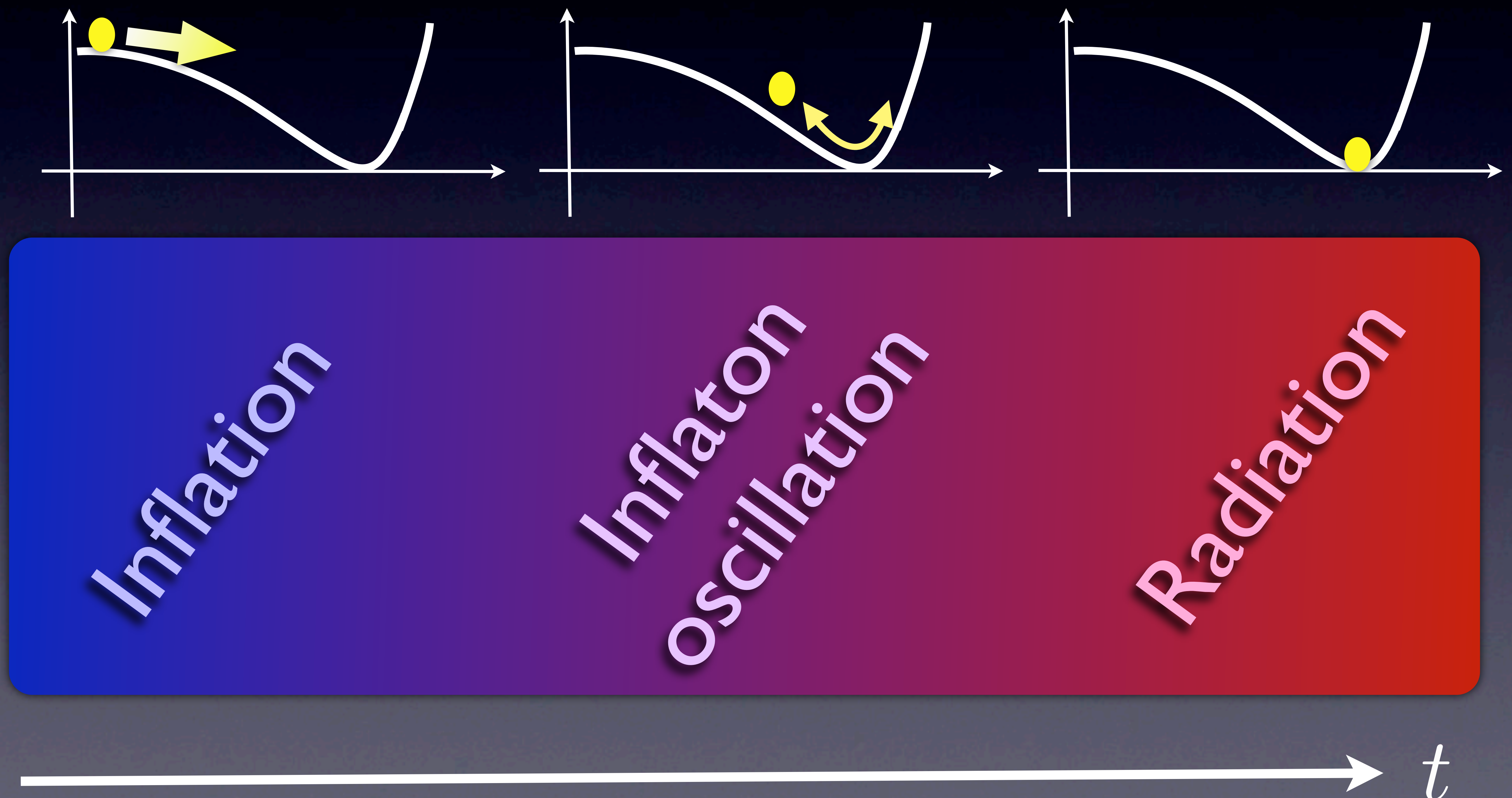
1. Inflation

2. Reheating : perturbative decay

3. Reheating : dissipative effects

Reheating



Importance of reheating

Reheating temperature T_{R} is important since it determines :

- Efficiency of Leptogenesis/Baryogenesis
- Gravitino abundance (Thermal / Nonthermal)
- Abundance of unwanted relics (moduli, axion, axino, ...)
- Precise prediction of spectral index
- etc...

Inflaton decay

- Inflaton must couple to SM sector directly or indirectly for successful reheating

- Inflaton coupling to SM particles, e.g.,
  - Higgs $W = k\phi H_u H_d$
  - Right-handed neutrino $W = y\phi NN$

Inflaton decay rate : $$\Gamma(\phi \to NN) \simeq \frac{y^2}{16\pi} m_\phi$$

$(m_\phi > m_N = y\langle\phi\rangle)$

- $\ddot{\phi} + (3H + \Gamma_\phi)\dot{\phi} + V' = 0$

  decay rate

  $$\rho_r + 4H\rho_r = \Gamma_\phi \rho_\phi$$

  $$H^2 = \frac{1}{3M_P^2}(\rho_\phi + \rho_r)$$

- Reheating is completed at $\Gamma_\phi \sim H$

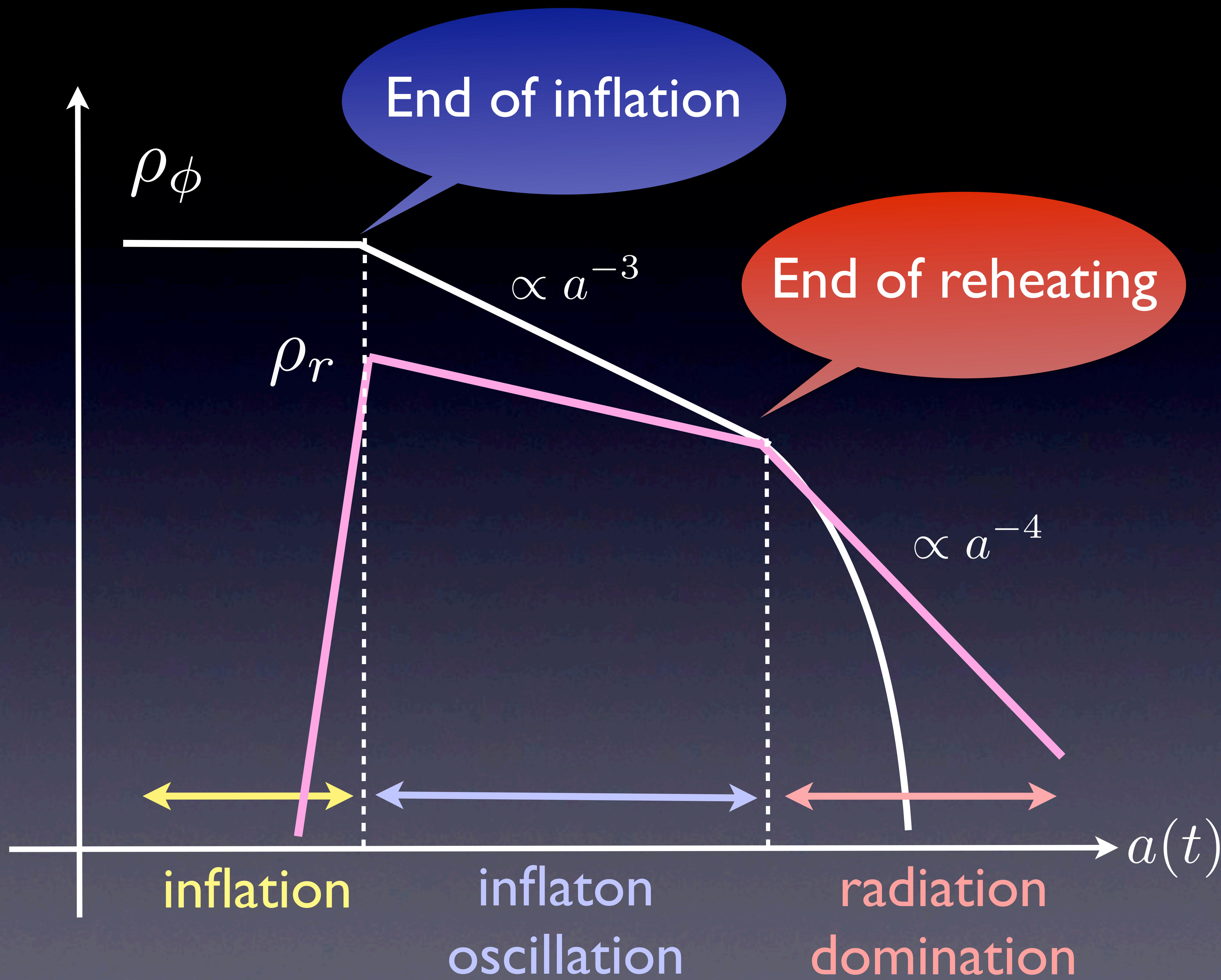
  Reheating temperature : $T_{\rm R} \sim \sqrt{\Gamma_\phi M_P}$

- Radiation before the completion of reheating

  $$\Gamma_\phi \ll H \ : \ \rho_r \sim \rho_\phi \frac{\Gamma_\phi}{H} \sim T_{\rm R}^2 H M_P$$

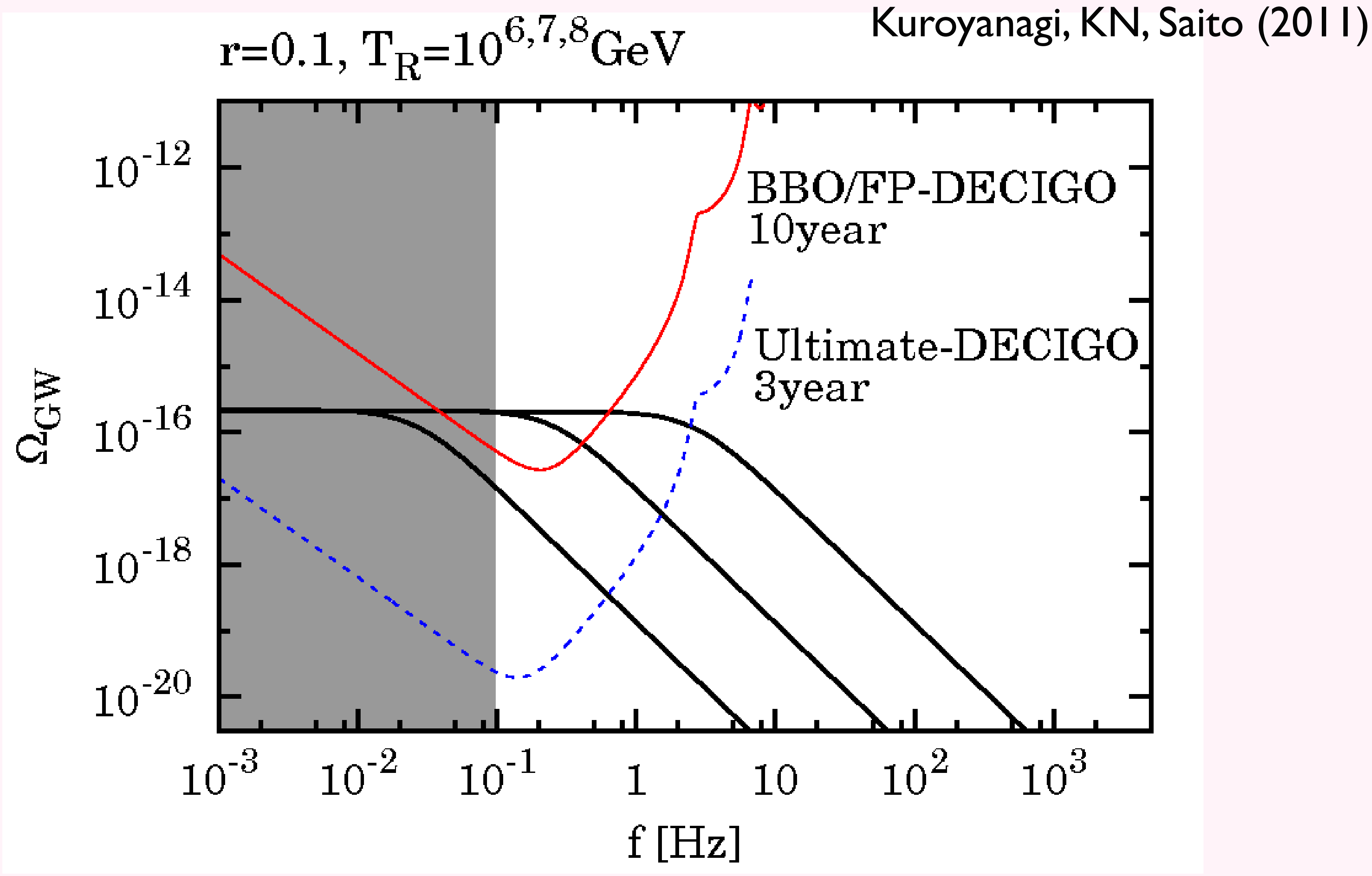
  $$\longrightarrow \quad T \sim (T_{\rm R}^2 H M_P)^{1/4}$$

- $$\begin{cases} T \propto a(t)^{-3/8} & \text{for} \quad T > T_{\rm R} \\ T \propto a(t)^{-1} & \text{for} \quad T < T_{\rm R} \end{cases} \qquad \text{if} \ \rho_\phi \propto a(t)^{-3}$$


End of inflation
End of reheating
ρ_ϕ
ρ_r
$\propto a^{-3}$
$\propto a^{-4}$
$a(t)$
inflation
inflaton oscillation
radiation domination

Thermal history imprinted in inflationary GWs !

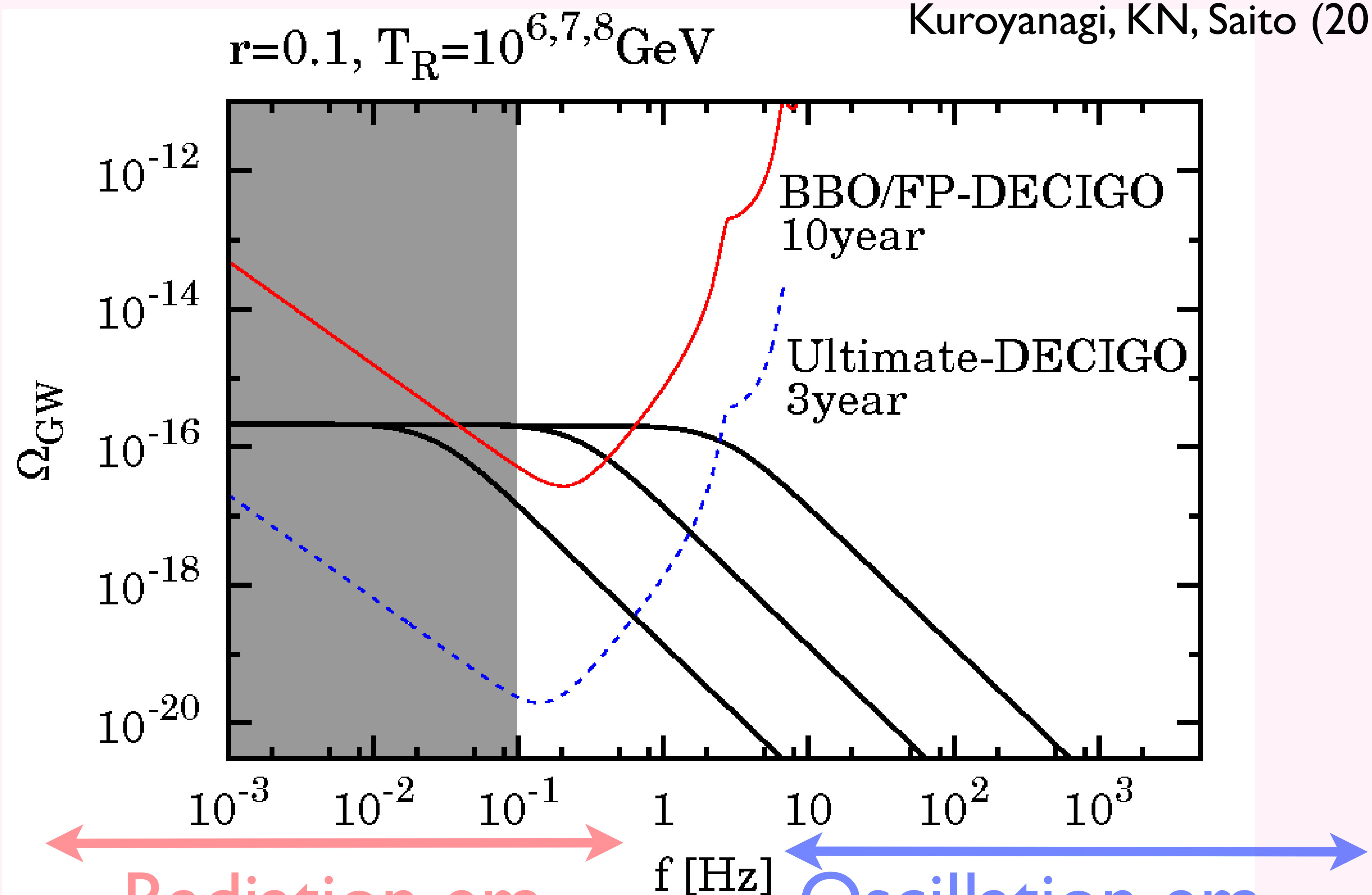
Seto, Yokoyama (2003), Boyle, Steinhardt (2005), KN, Saito, Suwa, Yokoyama (2008)



Thermal history imprinted in inflationary GWs !

Seto, Yokoyama (2003), Boyle, Steinhardt (2005), KN, Saito, Suwa, Yokoyama (2008)

Kuroyanagi, KN, Saito (2011)



Radiation era

$\Omega_{\rm GW} \propto f^0$

Oscillation era

$\Omega_{\rm GW} \propto f^{-2}$

Contents

1. Inflation

2. Reheating : perturbative decay

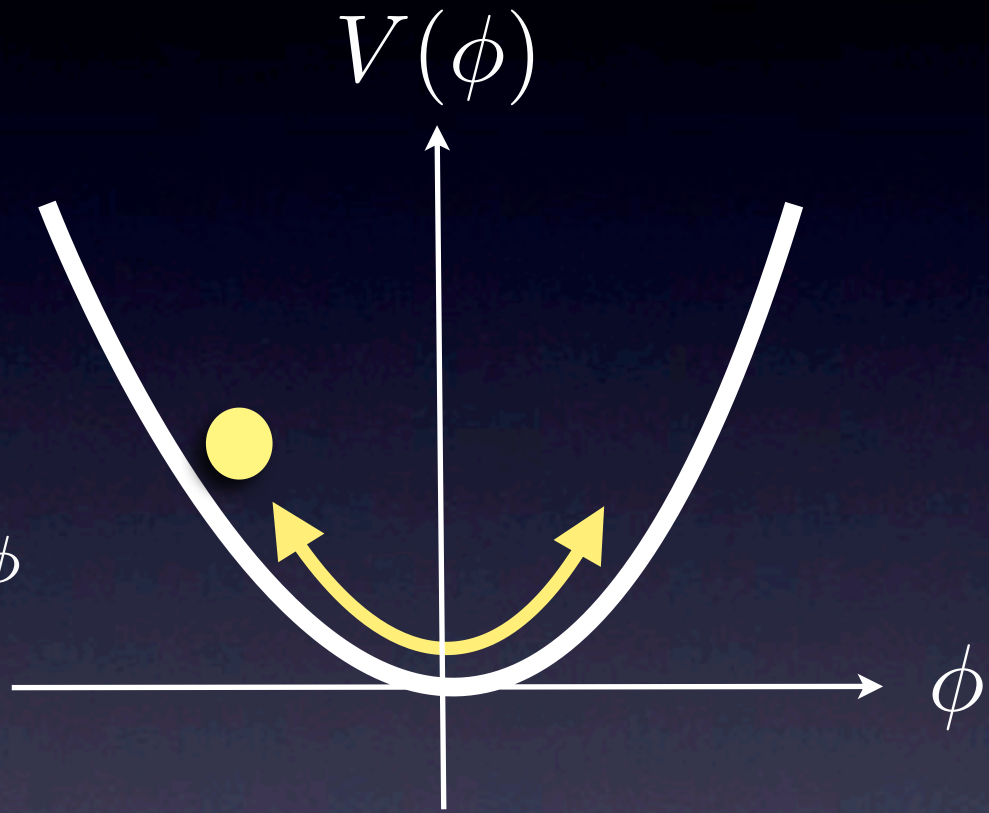
3. Reheating : dissipative effects

K.Mukaida, KN, 1208.3399
K.Mukaida, KN, 1212.4985

Reconsider Reheating

- Example: $\mathcal{L} = \lambda\phi\chi\bar{\chi}$
  - Reheating temperature

    $T_{\rm R} \sim \sqrt{\Gamma_\phi M_P} \quad \Gamma_\phi \sim \lambda^2 m_\phi$



- However, ...
  - χ obtains time-dependent mass $\sim \lambda\phi(t)$
  - χ obtains thermal mass $\sim gT$

What if $m_\chi^{\rm eff} > m_\phi$? Does inflaton decay ?

Alchemical inflation

KN, F.Takahashi, 1206.3191

- $W = S(\mu^2 - \lambda\psi^m - g\phi^n)$ e.g., $\psi^2 = H_u H_d$

  Flat direction: $\mu^2 = \lambda\psi^m + g\phi^n$

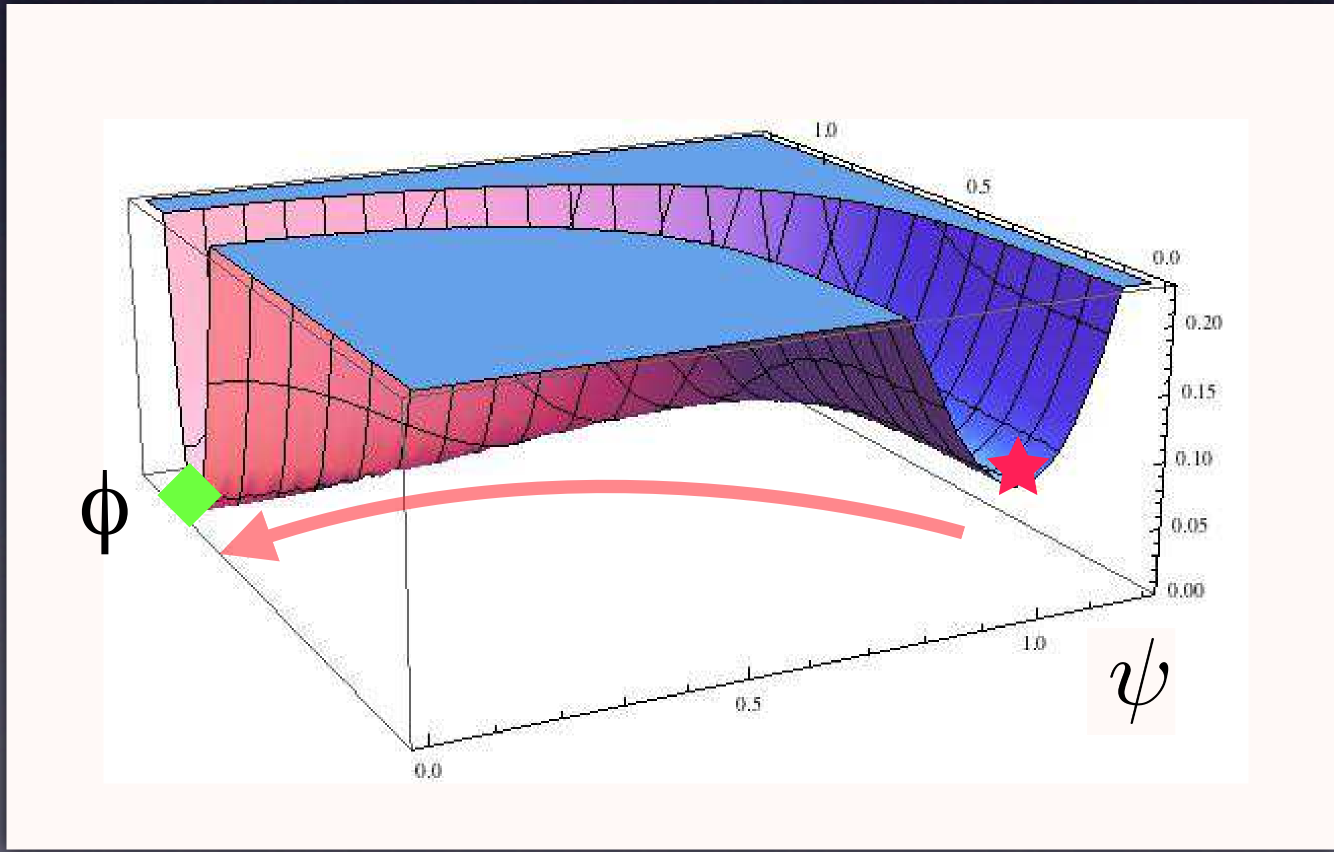
  Lifted by SUSY breaking: $V_{\rm soft} = m_\psi^2|\psi|^2 + m_\phi^2|\phi|^2$

- Around $\phi \sim 0$:

$$V(\phi) \sim \frac{m_\chi^2 \mu^2}{\lambda}\left(1 - \frac{g\phi^n}{\mu^2}\right)$$

$(m = 2)$

New inflation



Alchemical inflation

KN, F.Takahashi, 1206.3191

- After inflation $\psi = 0$ is minimum.

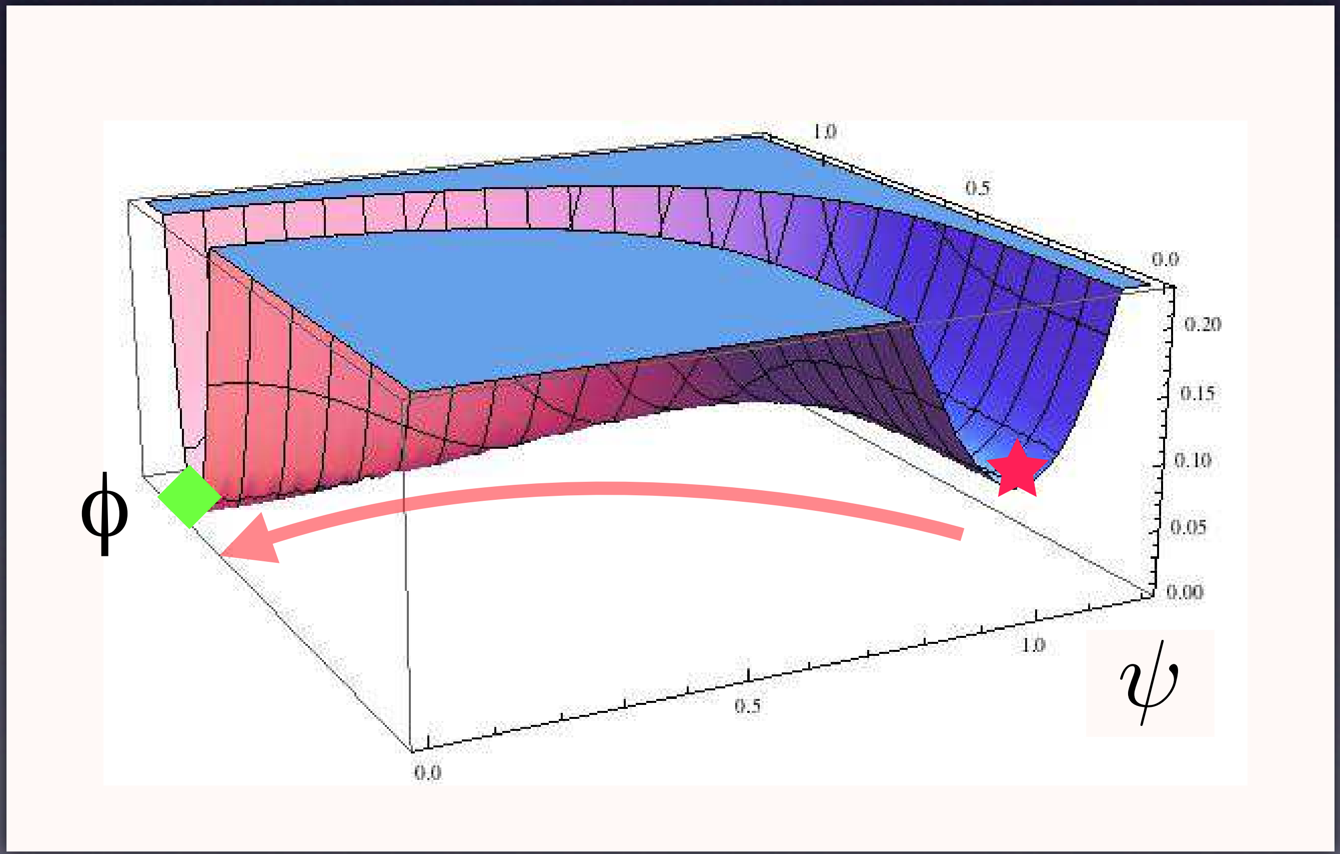
  ⟶ Coherent oscillation around $\psi = 0$

Inflaton automatically turns into Higgs !

- Reheating proceeds via dissipation of Higgs condensate.

$\psi_i \sim 10^{15}\mathrm{GeV}$

$m_\psi \sim 10^{6}\mathrm{GeV}$



Inflation scale

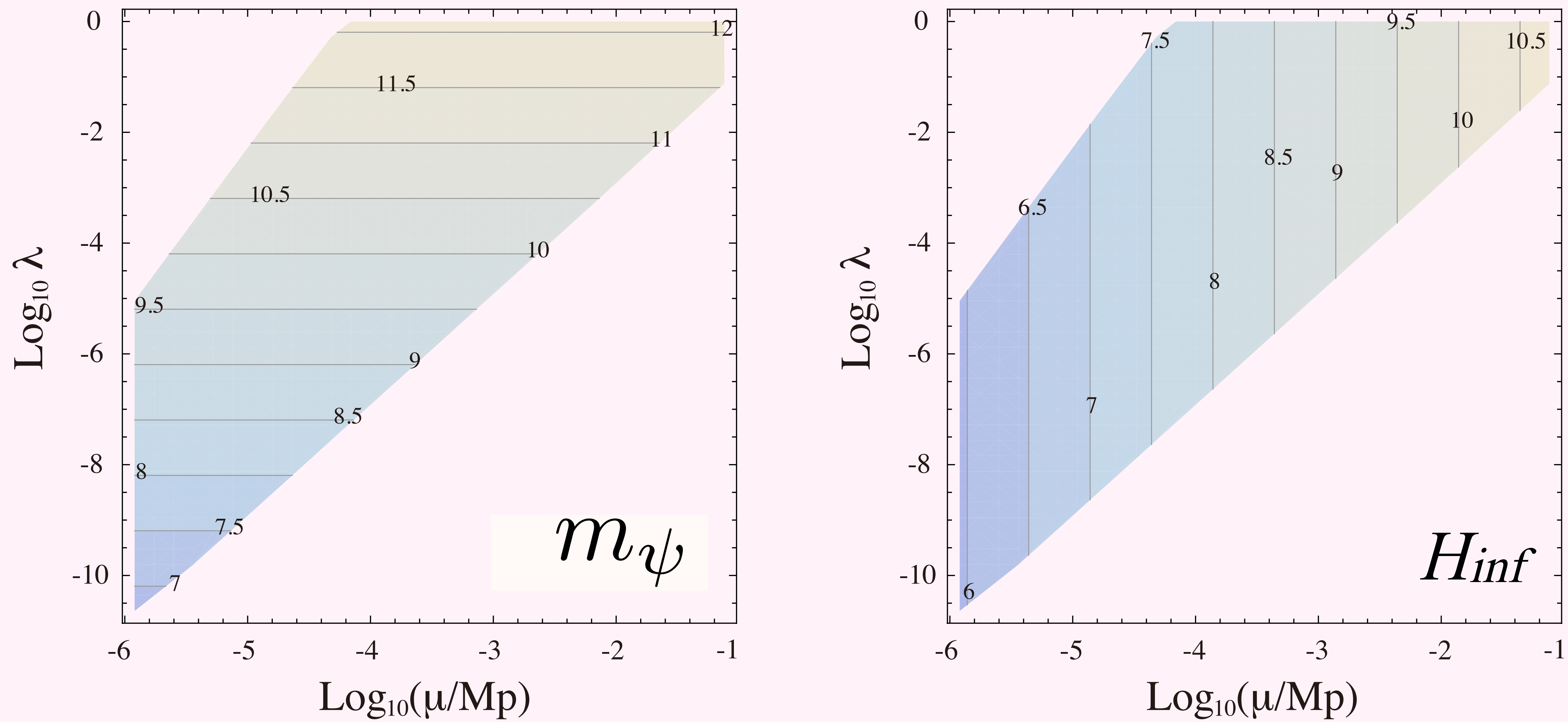


Figure 3: The contours of $\log_{10}[m_\chi/\mathrm{GeV}]$ (left) and $\log_{10}[H_{\mathrm{inf}}/\mathrm{GeV}]$ (right) where we set $g = 1$, $m = 2$, $n = 4$ and $N = 50$.

Alchemical inflation

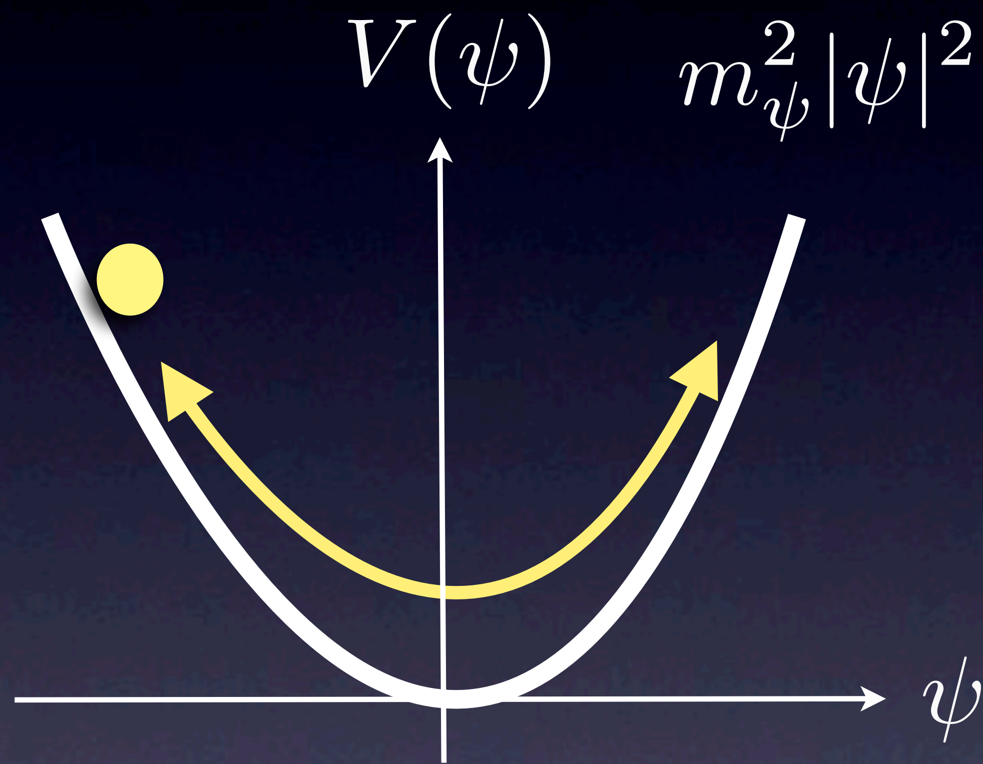
KN, F.Takahashi, 1206.3191

- Reheating proceeds via dissipation of Higgs condensate.

$$\psi_i \sim 10^{15}\mathrm{GeV}$$

$$m_\psi \sim 10^{6}\mathrm{GeV}$$

$$\mathcal{L} \sim y_t \psi Q \bar{t} + \cdots$$



- Standard perturbative calculation does not work.
- The same is true for most Higgs inflation models.

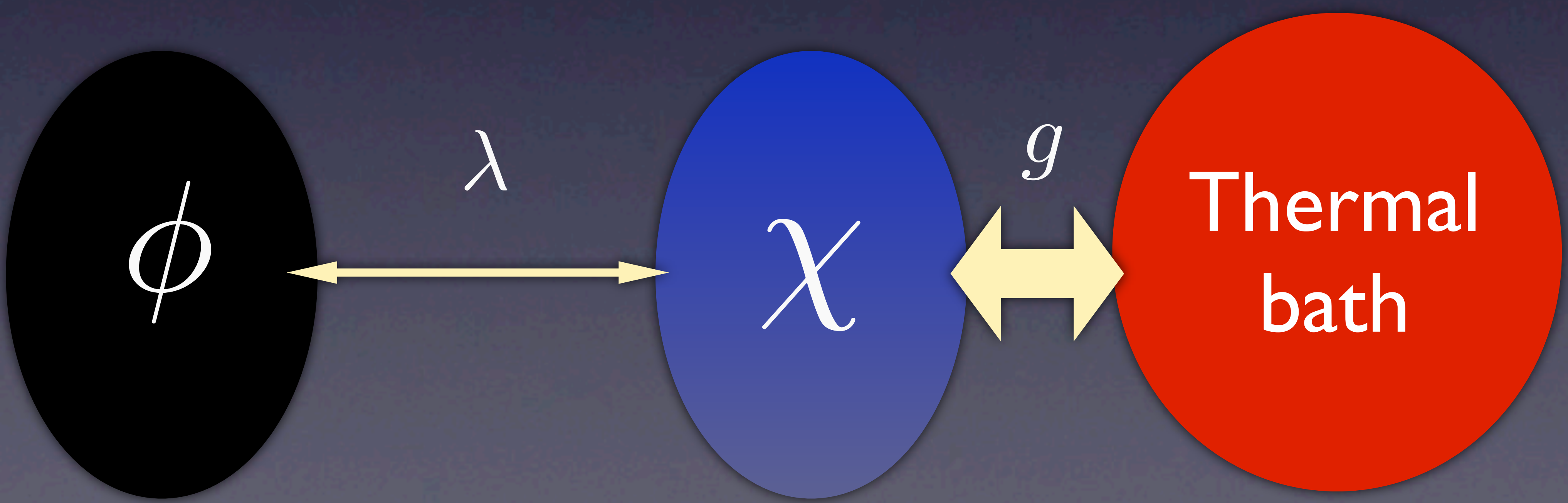
How to deal with reheating ?

Two main effects :

1. Preheating

2. Thermal dissipation

- Simple (but realistic) model : $\mathcal{L} = \lambda \phi \chi \bar{\chi}$



Preheating

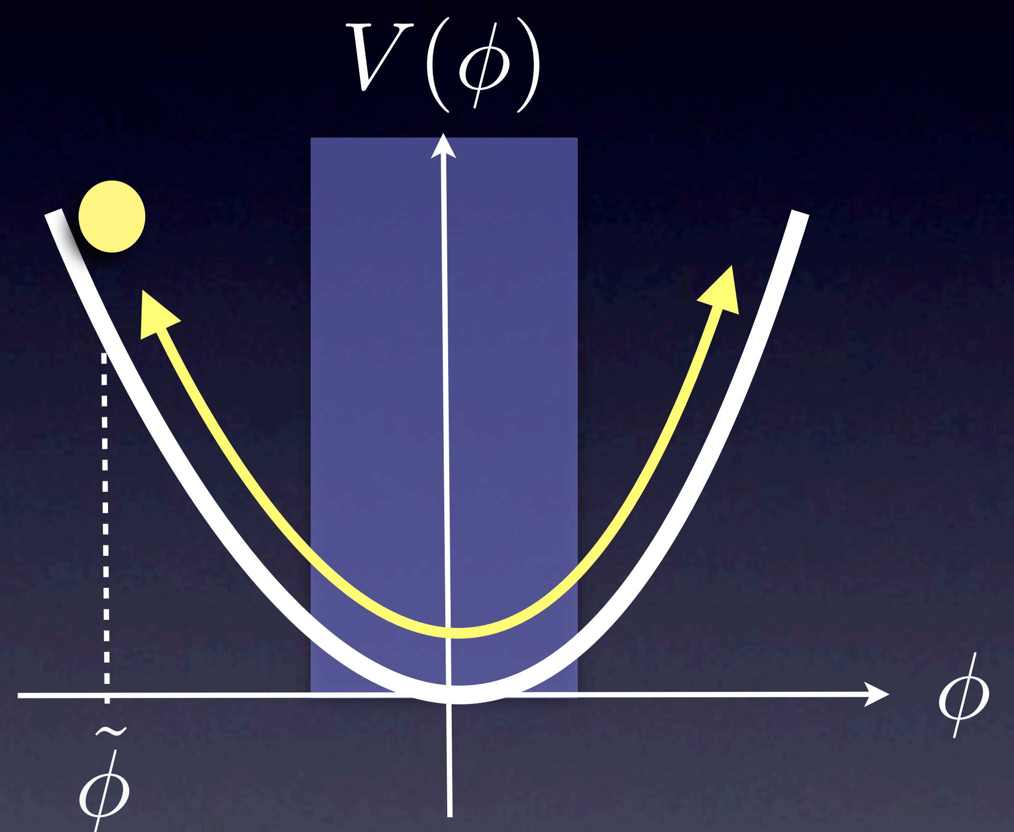
Kofman, Linde, Starobinsky (1997)

- Example: $\mathcal{L} = \lambda\phi\chi\bar{\chi}$

$$m_\chi^{\text{eff}} = \lambda\phi(t)$$

Vacuum for χ is non-adiabatic

if $|\dot{\omega}_\chi/\omega_\chi^2| > 1$



$$\omega_\chi = \sqrt{k^2 + \lambda^2\phi(t)^2 + g^2T^2}$$

Thermal mass

$$\longrightarrow \lambda\tilde{\phi} > \max\left[m_\phi, \frac{g^2T^2}{m_\phi}\right]$$

$$k < k_* = \sqrt{\lambda m_\phi \tilde{\phi}}$$

Preheating

Kofman, Linde, Starobinsky (1997)

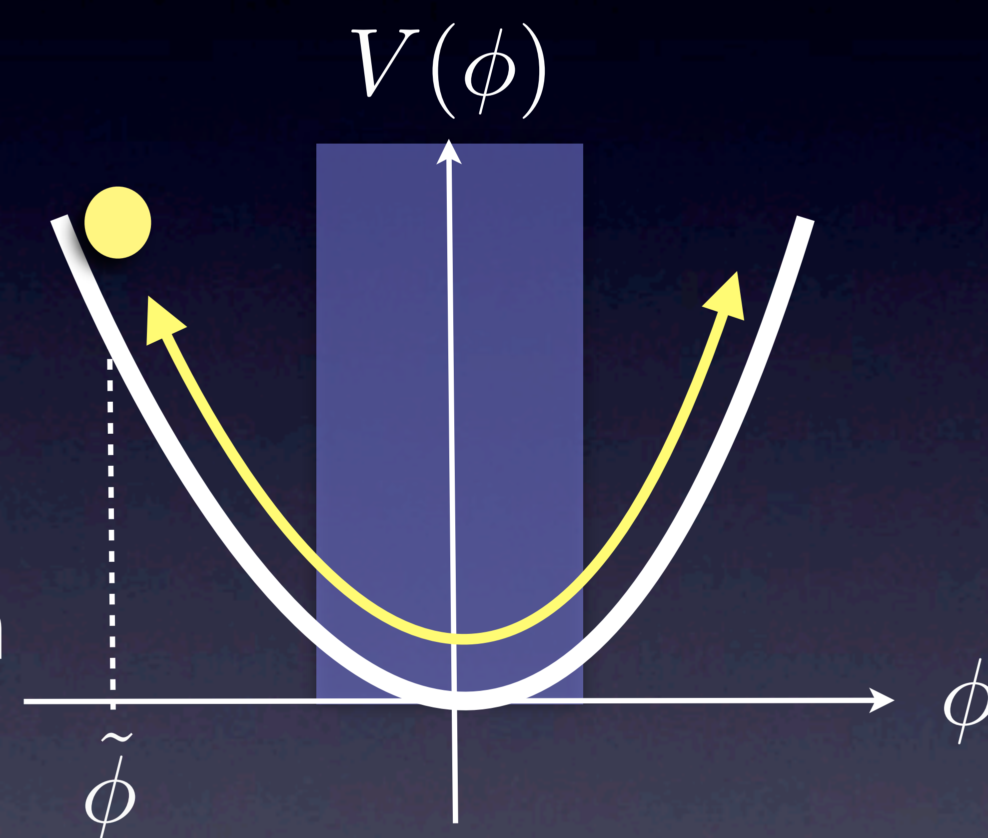
- Number density of χ after production

$$n_\chi \sim k_*^3 \sim (\lambda m_\phi \tilde{\phi})^{3/2}$$

- Produced χ particles decay via gauge/yukawa interaction

$\longrightarrow$ Instant preheating

Felder, Kofman, Linde (1999)



- Effective dissipation rate of ϕ :

$$\Gamma_\phi \sim \frac{\lambda^2 m_\phi}{4\pi^4 g}$$

K.Mukaida, KN (2012)

Thermal effects

- For high-temperature $gT > m_\phi$

  $\longrightarrow$ Thermal blocking $\phi \not\to \chi\bar{\chi}$

- Instead, thermal dissipation comes in.

  - $\lambda\phi \ll T$ χ thermal bath

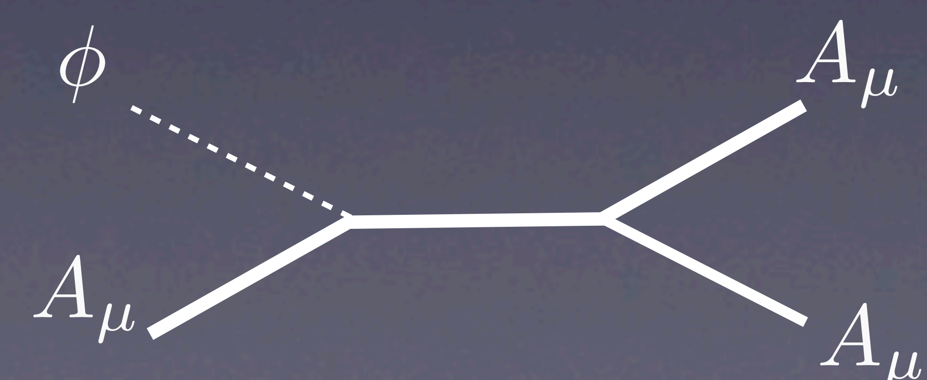
    $$\Gamma_\phi \sim \lambda^2 \alpha T$$

J.Yokoyama (2005), Drewes (2008,2013), Bastelo-Gil, Berera, Ramos (2010)

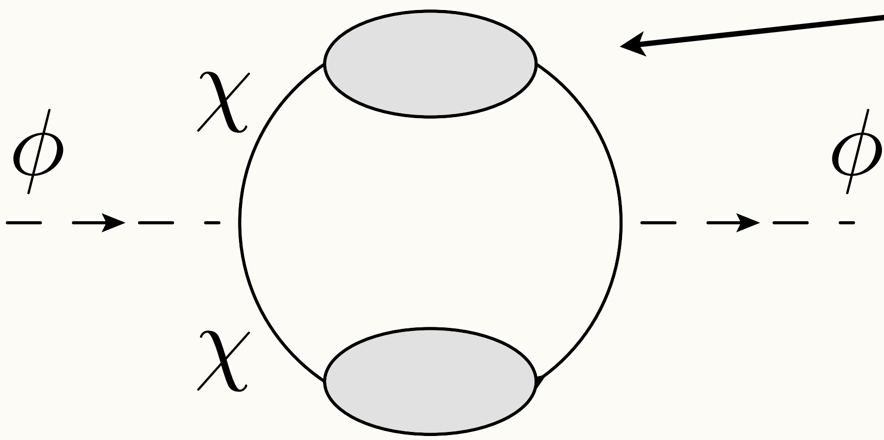
  - $\lambda\phi \gg T$ χ decouples.

    $$\Gamma_\phi \sim \frac{\alpha^2 T^3}{\phi^2}$$

Bodecker (2006), Laine (2008)

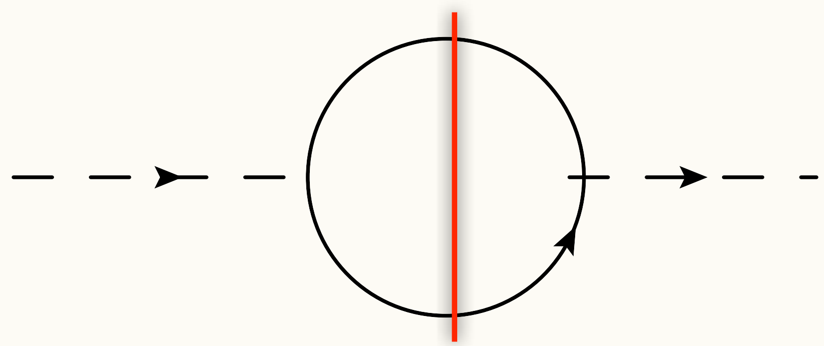


Schematic picture

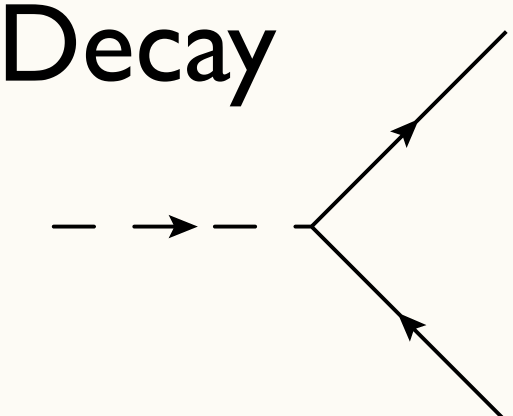


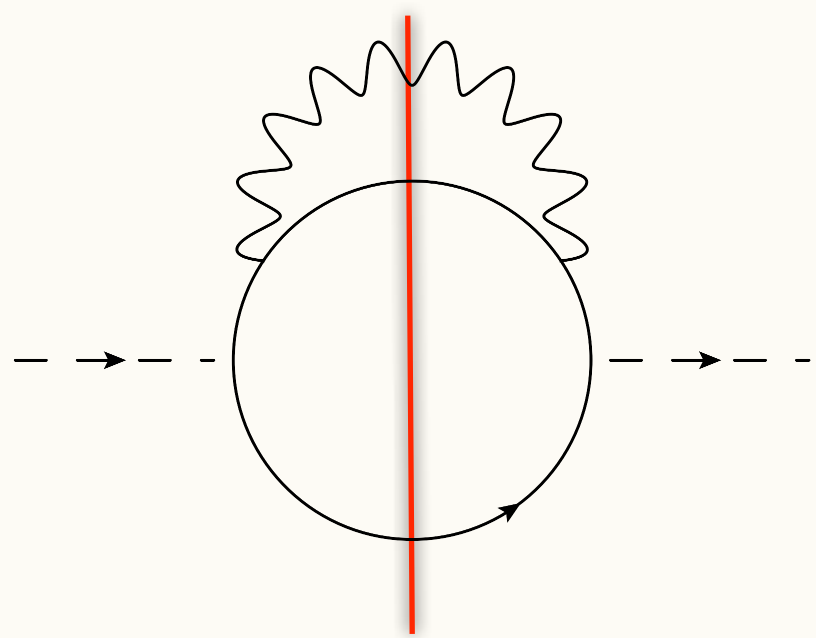
"Quasi-particle"

Dissipation rate : $\Gamma_\phi \sim \left.\frac{\mathrm{Im}\Pi(\omega)}{\omega}\right|_{\omega=m_\phi}$

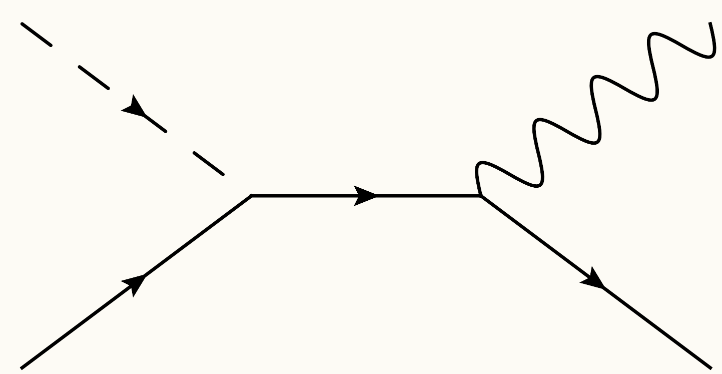


Decay



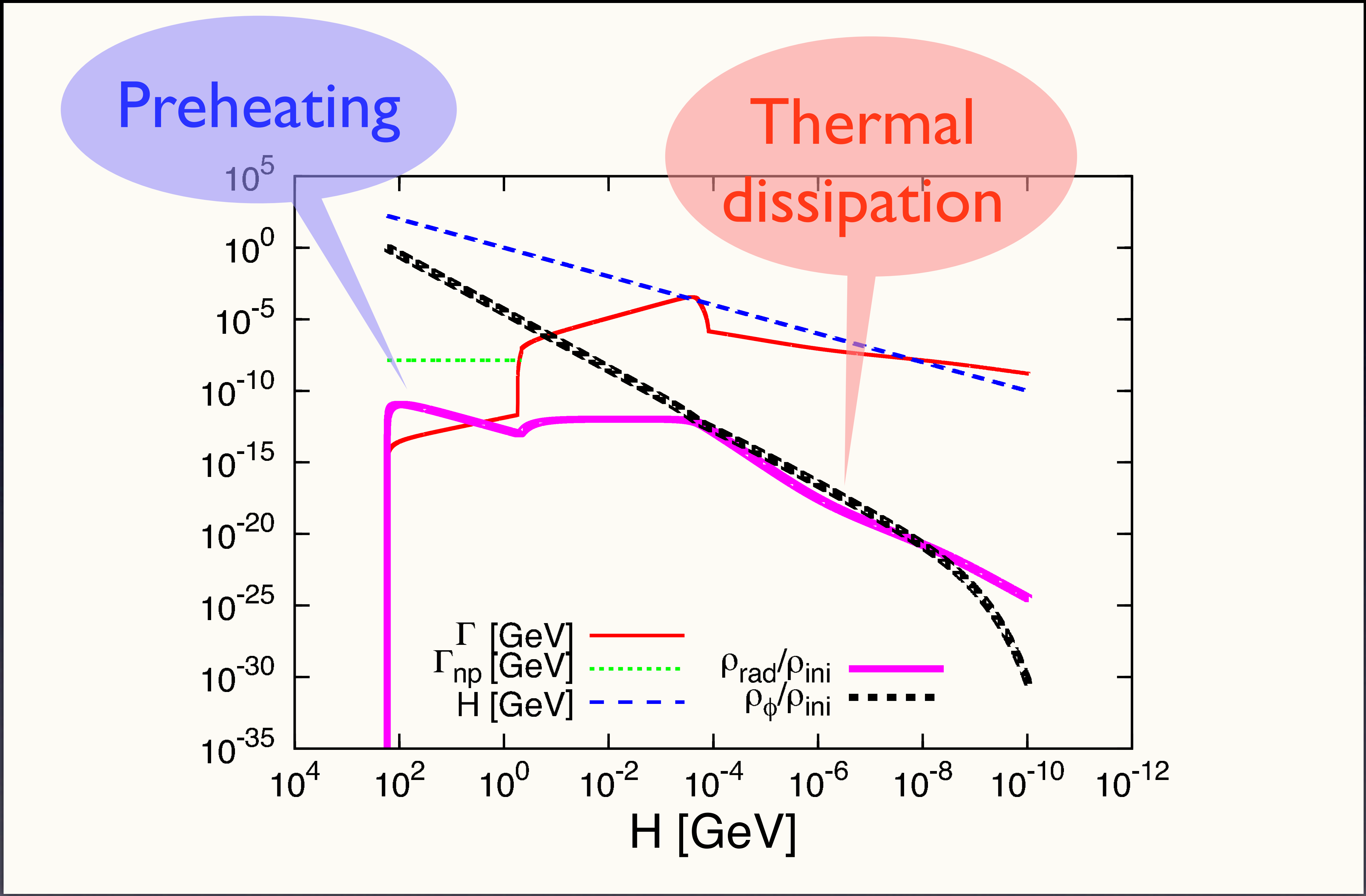


Scatter



Numerical results

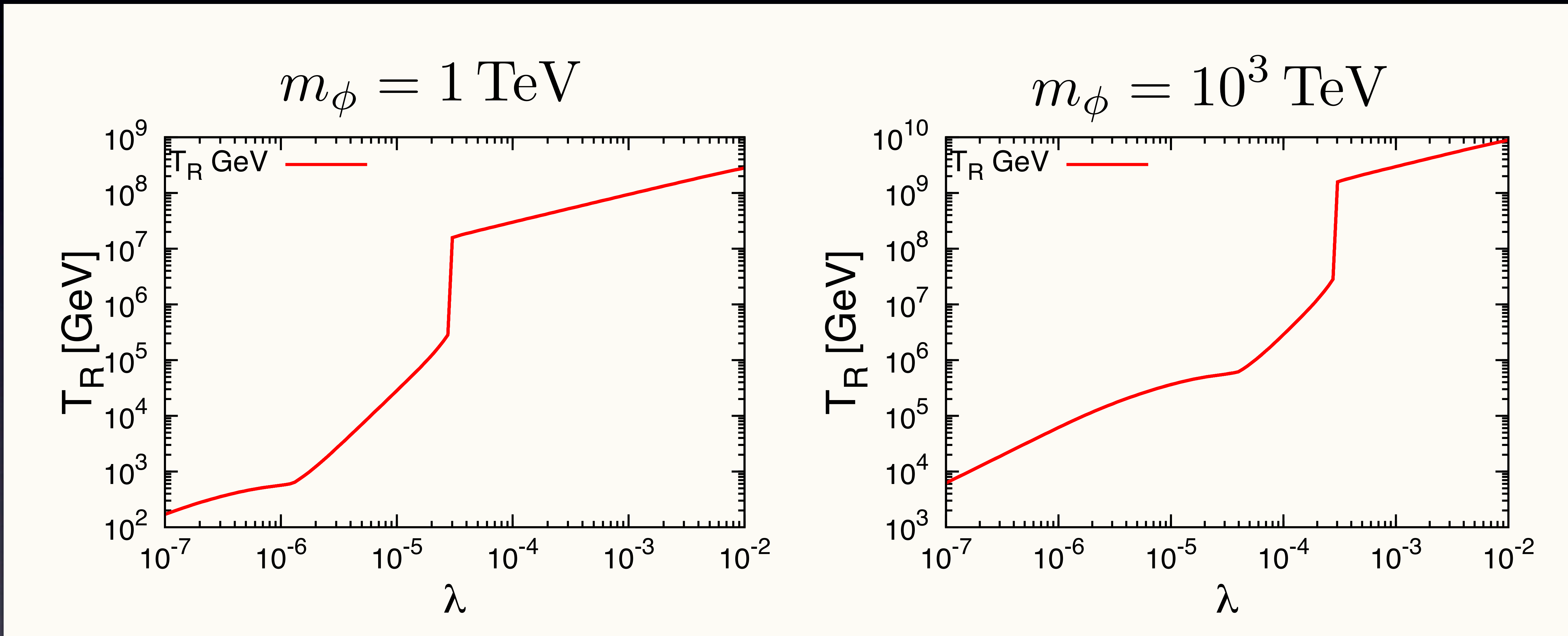
K.Mukaida, KN, 1212.4985



$$(m_\phi, \lambda, \phi_i) = (1\mathrm{TeV}, 10^{-5}, 10^{18}\mathrm{GeV})$$

Reheating temperature

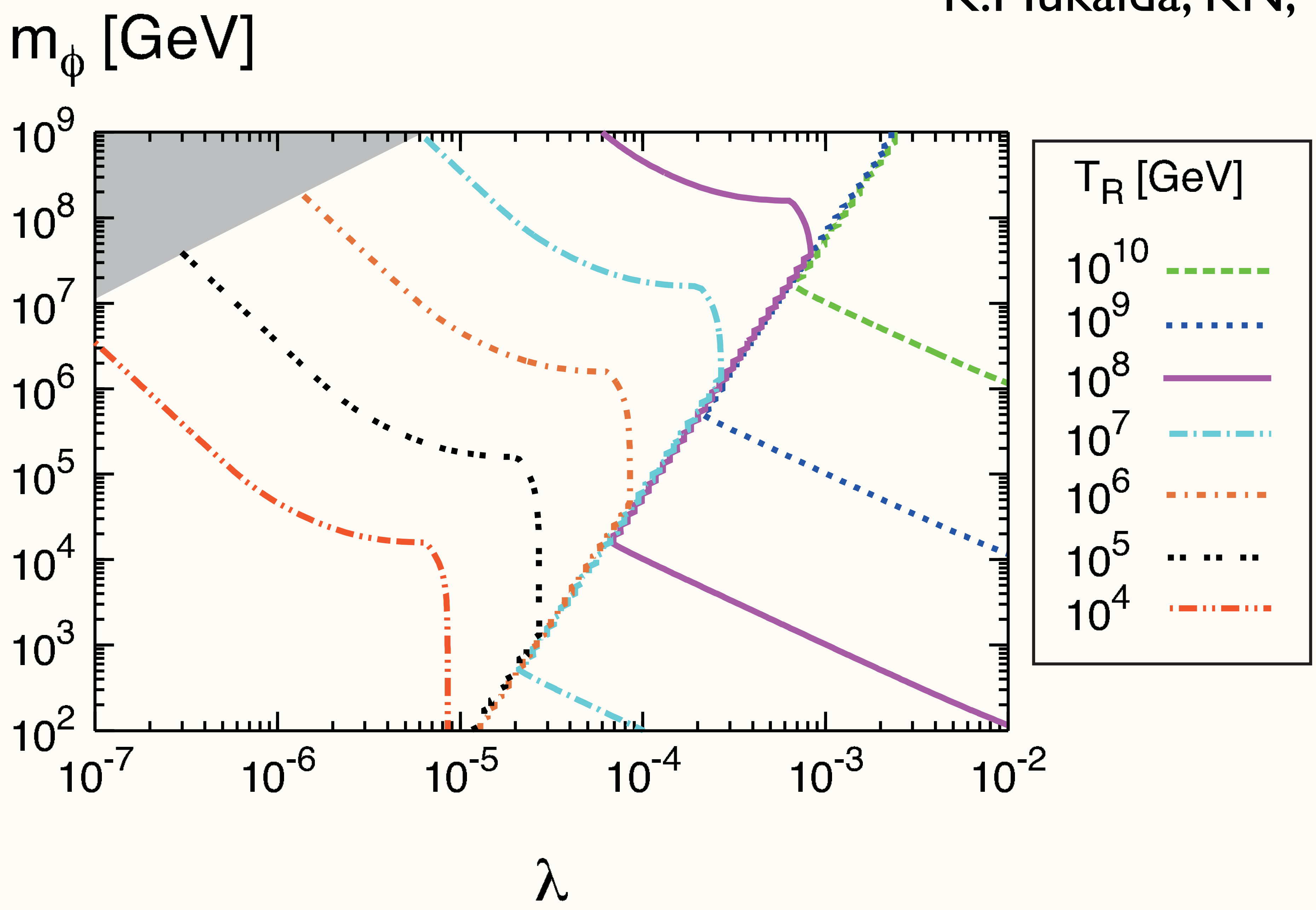
K.Mukaida, KN, 1212.4985



Reheating temperature can be much higher than the inflaton mass.

Reheating temperature

K.Mukaida, KN, 1212.4985



Reheating temperature

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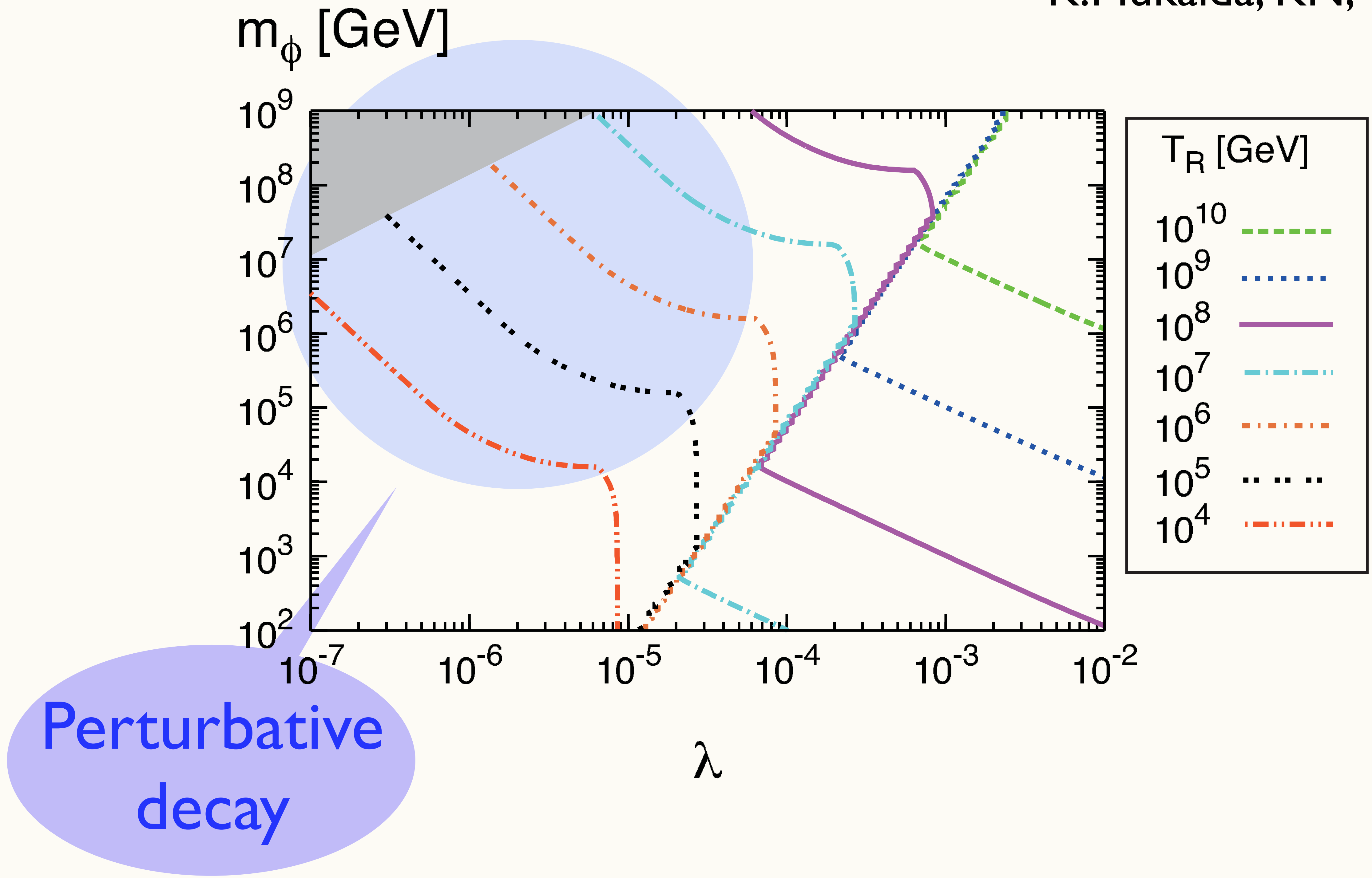

Reheating temperature

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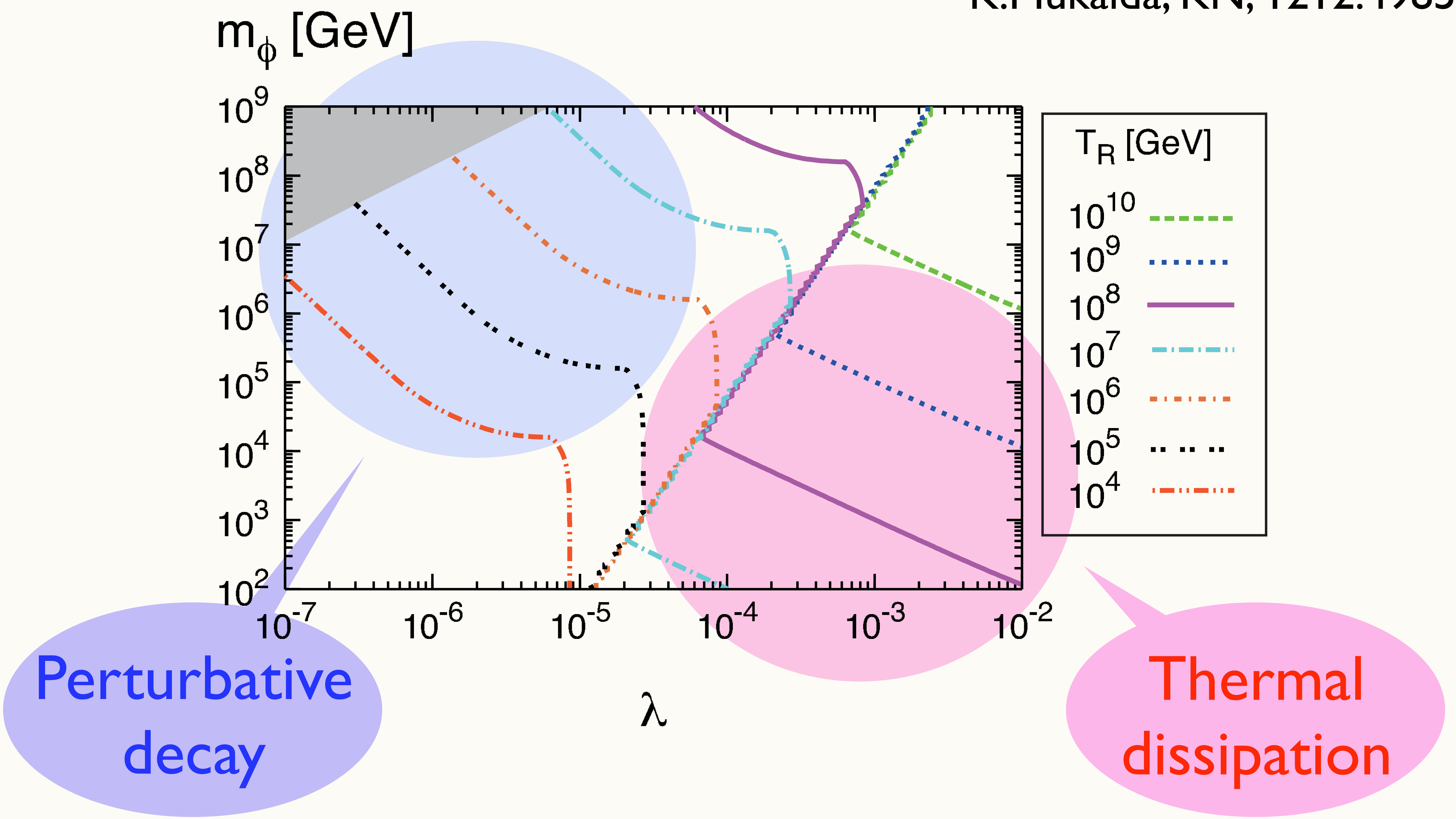

Summary

- The reheating process may be significantly altered by thermal effects.
- Most significant for low-mass inflaton and large coupling constants.
  (e.g., Higgs inflation and its variants)
- Thermal effects are important also for :
  Saxion, Curvaton, Affleck-Dine, ...

See also : T.Moroi, K.Mukaida, KN, M.Takimoto, 1304.6597
K.Mukaida, KN, M.Takimoto, 1308.4394