A fresh look at reheating after inflation

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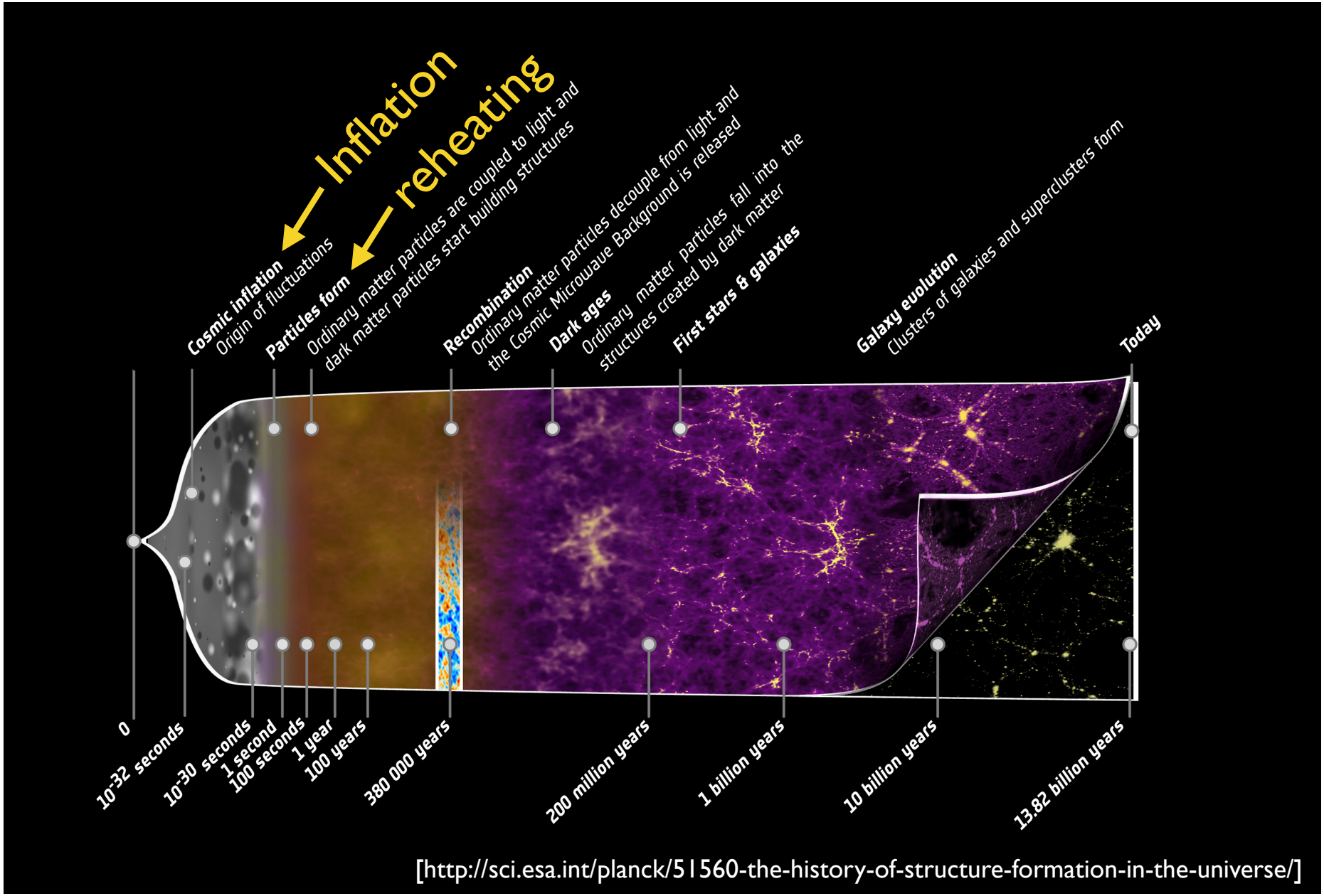
History of the Universe



[http://sci.esa.int/planck/51560-the-history-of-structure-formation-in-the-universe/]

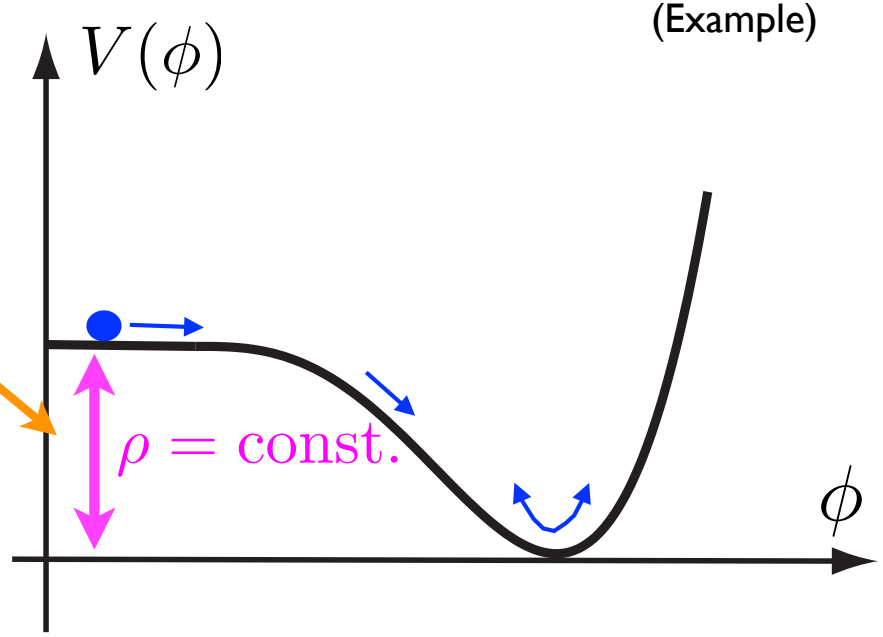
Inflation

- Inflation is considered to be driven by a scalar field, called inflaton field.

The potential energy (vacuum energy) of the inflaton drives inflation.

(Inflation can not only solve the problems in the standard cosmology, but also give the origin of the structure of the Universe.)

(Example)



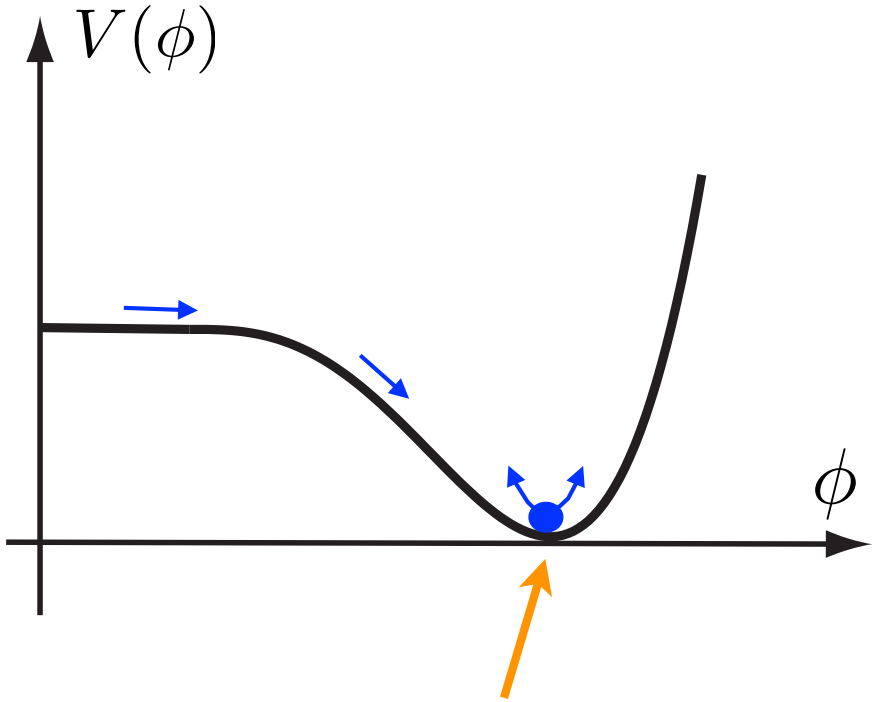
$$\left(\frac{1}{a}\frac{da}{dt}\right)^2 = \frac{1}{3M_{\rm pl}^2}\rho \quad \rightarrow \quad a \propto \exp\left(Ct\right)$$

(accelerated expansion)

Inflation

- Inflation ends when the inflaton rolls down towards the bottom of the potential and begins to oscillate.

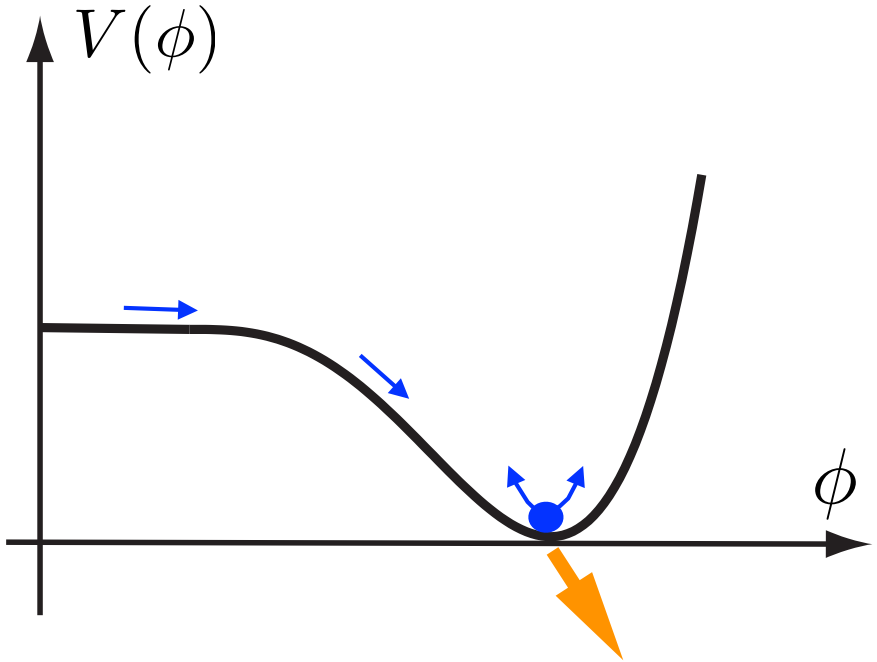
(The end of inflation is usually defined at the epoch when a slow-roll parameter becomes unity.)



Reheating after inflation

- At some point, the inflaton decays into radiation particles and the Universe becomes radiation-dominated.

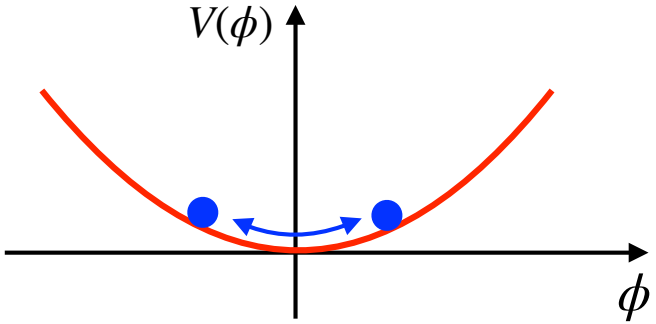
(When the Hubble expansion rate decreases below the decay rate ϕ, the inflaton decays.)



Inflaton decays into radiation particles (reheating)

"Vanilla" reheating scenario

- Usually the bottom of the inflaton potential is assumed as $V = \frac{1}{2} m_\phi^2 \phi^2$



→ The energy density of oscillating inflation scales as $\rho_\phi \propto a^{-3}$

- To realize the hot Universe (radiation-dominated Universe), the inflaton needs to decay via some coupling to other particles:

$$L_{\rm int} \subset \underset{(\phi \to \bar{\psi}\psi)}{y\phi\bar{\psi}\psi}, \qquad \underset{(\phi \to \chi\chi)}{\mu\phi\chi^2}, \qquad \underset{(\phi\phi \to \chi\chi)}{\sigma\phi^2\chi^2}$$

- Once the decay rate of ϕ becomes larger than the Hubble rate, other particles are significantly produced to make RD Univ.

Possible inflaton potential

- In some inflation models, there is no quadratic term (mass term).

example) T-model of inflation: [Kallosh, Linde1306.5220]

$$V(\phi) = \lambda M_{\rm pl}^4 \tanh\left(\frac{\phi}{\sqrt{6}M_{\rm pl}}\right)^n \quad (n = 2k)$$

(This model is consistent with Planck+BK.
NB: A recent ACT result.)

[ACT collaboration 2503.14454]

→ The potential at the bottom can be written as $V(\phi) \propto \phi^n$

- The energy density of oscillating ϕ scales as $\rho_\phi \propto a^{-6n/(n+2)}$

(e.g., $\rho_\phi \propto a^{-4}$ for $n = 4$; $\rho_\phi \propto a^{-9/2}$ for $n = 6$)

- If $n > 4$, ϕ is massless and self-interacting.

- The self-interaction generically leads to the fragmentation of homogeneous condensate of ϕ. [Lozanov, Amin 1608.01213; 1710.06851]

Inflaton fragmentation

- Inflaton acquires quantum fluctuations during the inflationary phase.

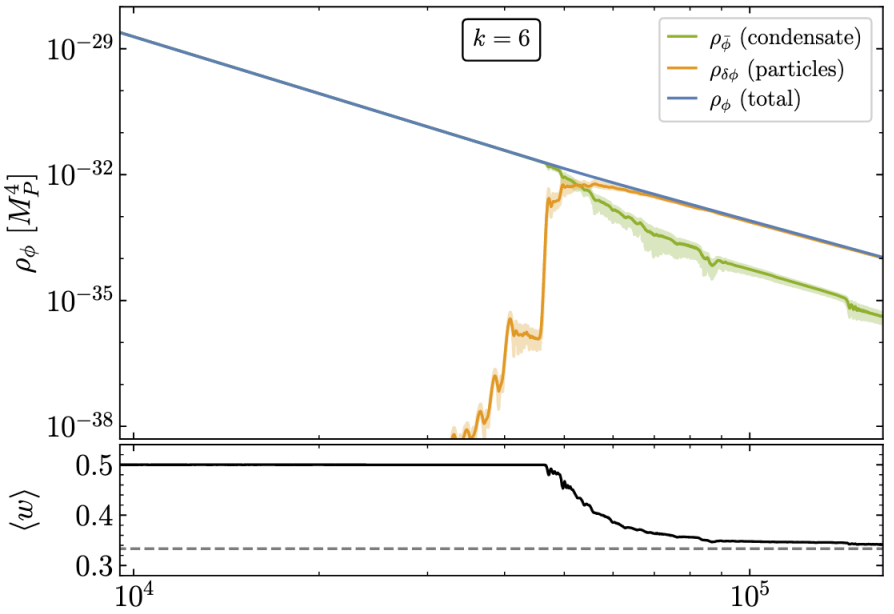
$$\left(\phi(x,t) = \bar{\phi}(t) + \delta\phi(x,t)\right)$$

- Inflaton self-interaction would induce the fragmentation due to the inhomogeneity of ϕ

  ➔ This can be regarded as production of inflaton quanta $\delta\phi$ from homogeneous $\bar{\phi}$: $\bar{\phi}\,\bar{\phi} \to \delta\phi\,\delta\phi$ [Garcia et al., 2308.16231]

- Oscillating (homogeneous) inflaton energy would be transfered to that of the fragmentation.

  ➔ Inflaton (massless) quanta dominates the Universe in late times.



[Garcia et al., 2308.16231]

Inflaton quanta from χ

- Inflaton quanta can also be produced even after the Universe becomes RD from the coupling such as

$$L_{\rm int} \subset y\phi\bar{\psi}\psi\,, \qquad \mu\phi\chi^2\,, \qquad \sigma\phi^2\chi^2$$

For example, we consider the interaction $L_{\rm int} = \sigma\phi^2\chi^2$,

the inflaton quanta can be produced via $\chi\chi \to \delta\phi\,\delta\phi$

- The production of inflaton quanta can be described by

$$\frac{d\rho_{\delta\phi}}{dt} + 4H\rho_{\delta\phi} = R_{\delta\phi}$$ (assuming the inverse production is neglected)

where the production rate is $R_{\delta\phi} \sim \sigma^2 T^5$

➔ The energy density of inflaton quanta becomes significant later times.

Evolution of the inflaton quanta

- During radiation-dominated Universe, $\rho_{\delta\phi}$ scales as $\sim a^{-3}$, which is slower than $\rho_{\rm rad} \propto a^{-4}$

- Effective mass of $\delta\phi$ is given by:

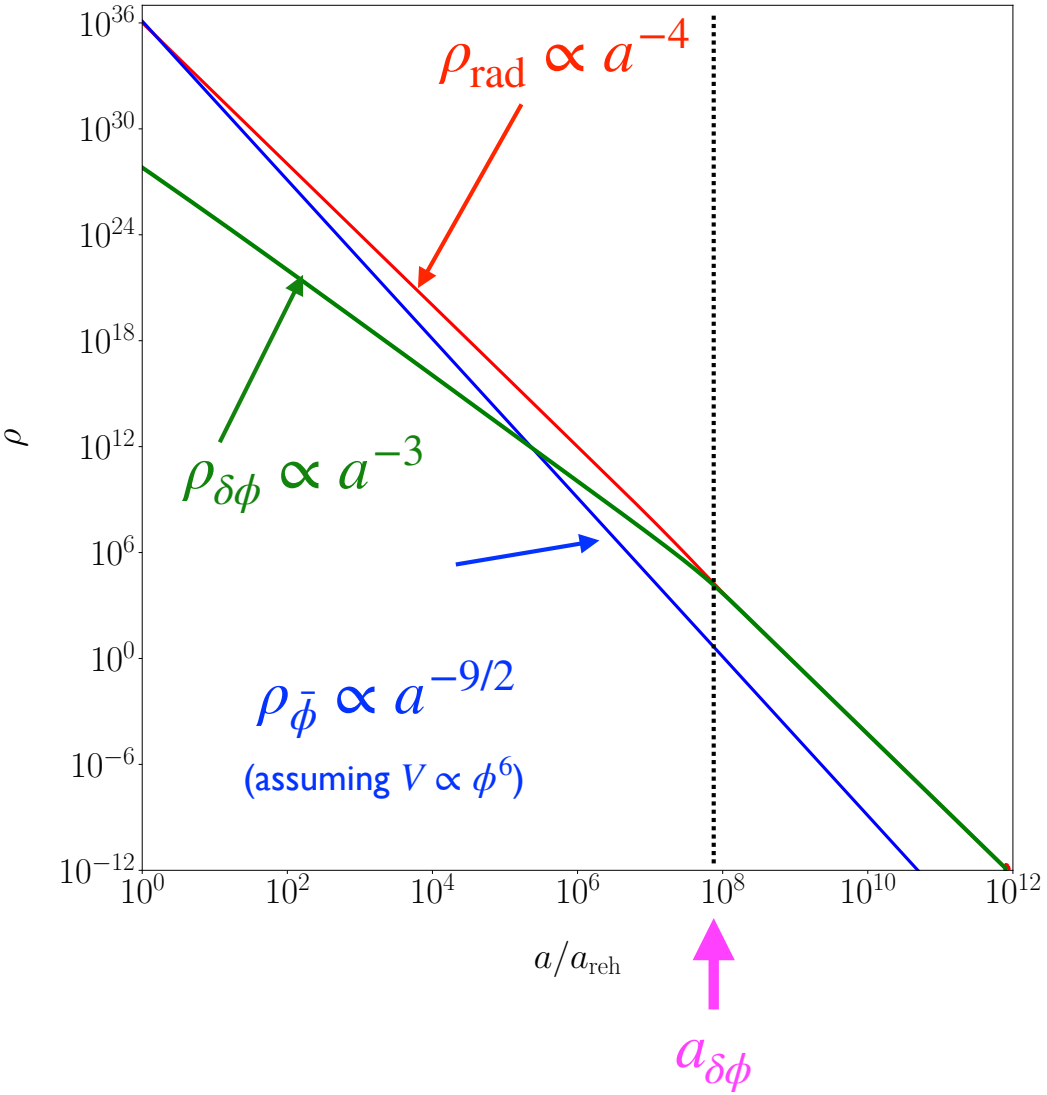
$$(L_{\rm int} = \sigma\phi^2\chi^2)$$

$$m_{\delta\phi} \sim \sqrt{\sigma}\, v$$

(v :VEV of χ)

- If $\rho_{\delta\phi}$ constitutes a sizable fraction in the Universe, it may harm the cosmological scenario.

[Kaneta, TT, Watanabe in prep.]



Constraints on the coupling between χ and ϕ

- Assuming that χ is Higgs particle, the mass of $\delta\phi$ is generated at EWPT:

$$\begin{cases} T > T_{\rm EW}: \ \delta\phi \text{ is massless} \\ T < T_{\rm EW}: \ m_{\delta\phi} = \sqrt{\sigma} \times (246 \text{ GeV}) \end{cases}$$

- Demanding that $\delta\rho_{\delta\phi}/\rho_{\rm tot} < 0.1$, we can obtain the bound on the coupling.

→ We can constrain the reheating model by considering the effects of the inflaton quanta after reheating.

Requirement:

- When $\delta\phi$ has not been thermalized at the epoch of the matter-radiation equality:

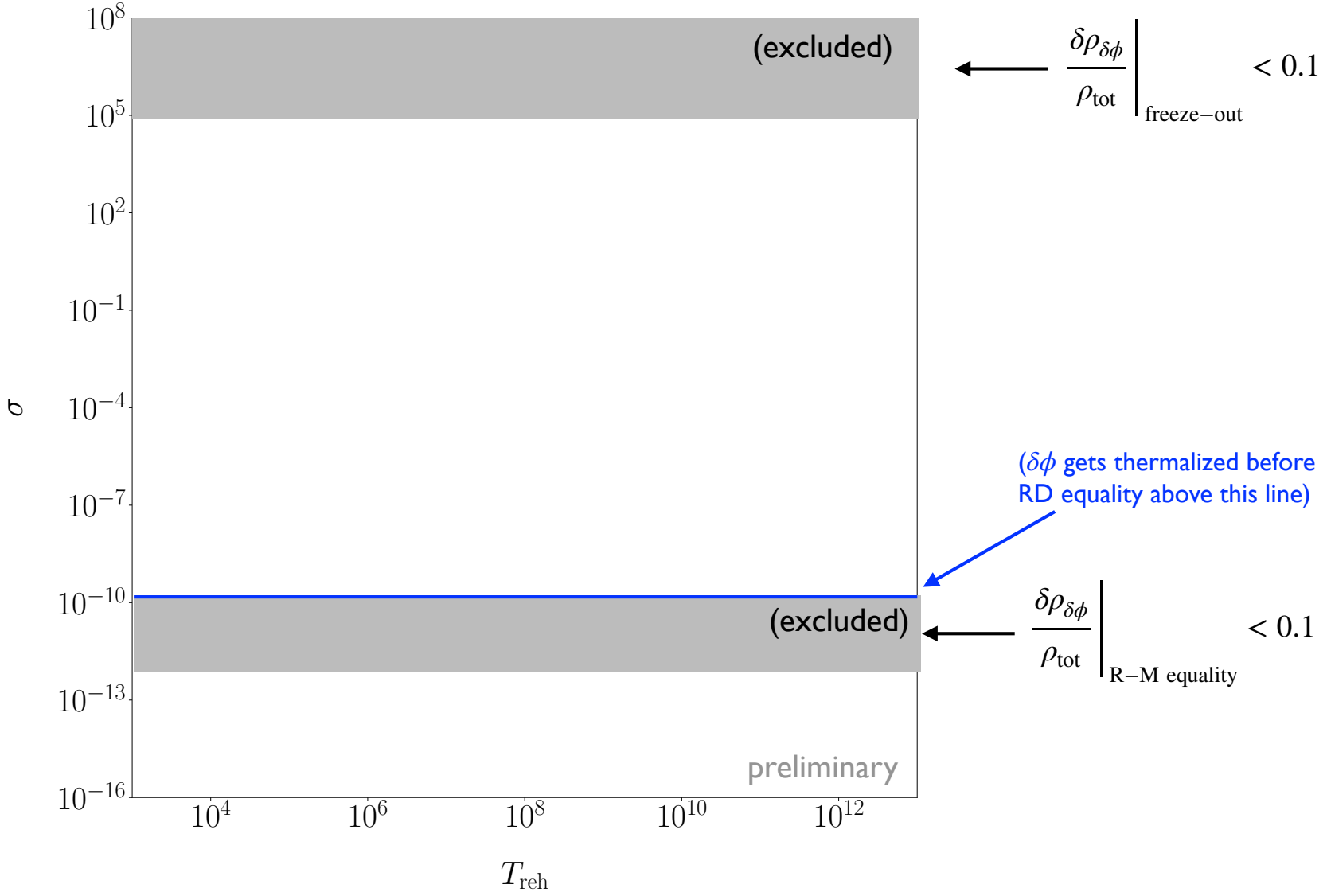
$$\left.\frac{\delta\rho_{\delta\phi}}{\rho_{\rm tot}}\right|_{\rm R-M\ equality} < 0.1$$

- When $\delta\phi$ has been thermalized before the matter-radiation equality:

$$\left.\frac{\delta\rho_{\delta\phi}}{\rho_{\rm tot}}\right|_{\rm freeze-out} < 0.1$$

Constraints on the coupling between χ and ϕ

[Kaneta, TT, Watanabe in prep.]



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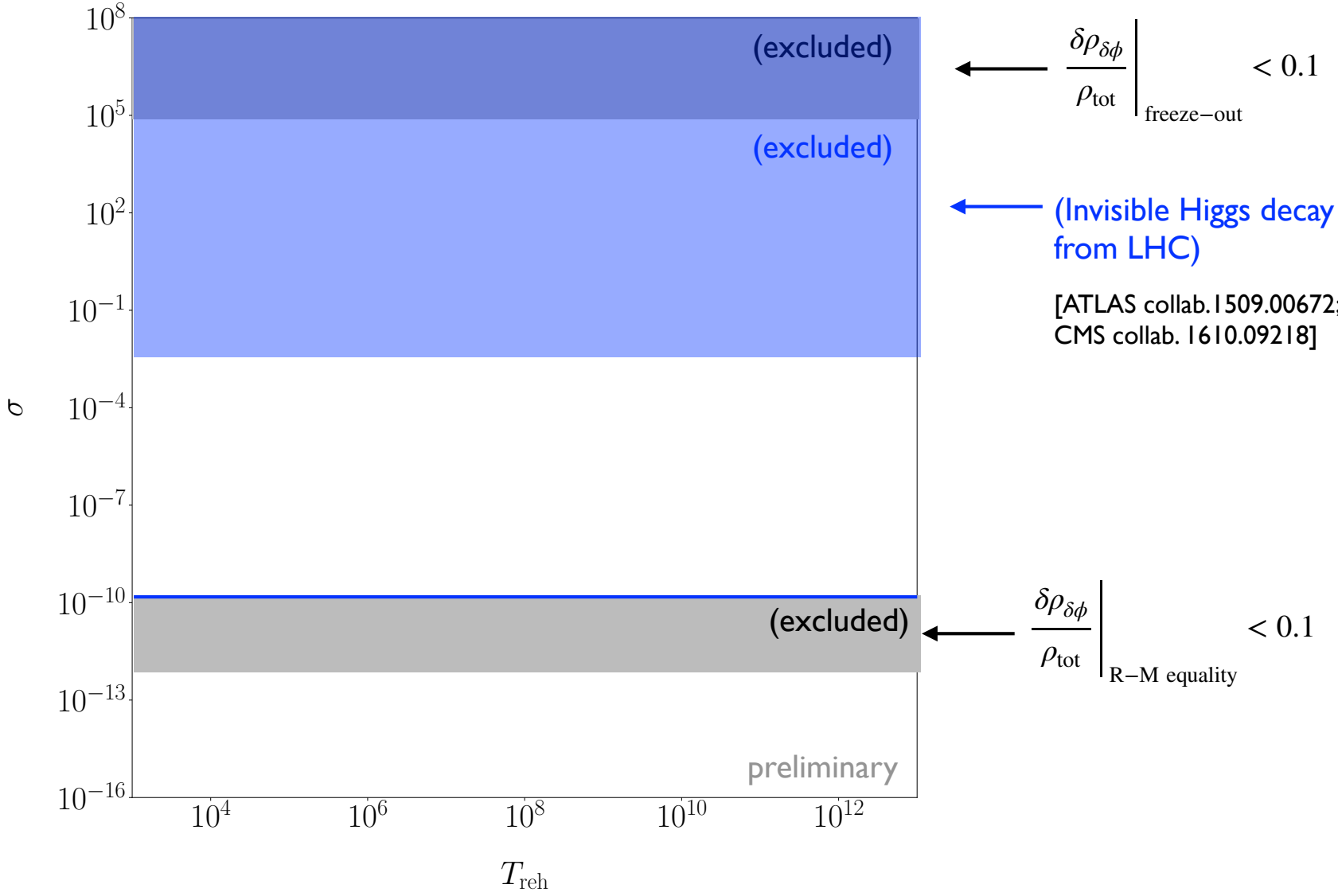

Summary

- Scenarios of the reheating after inflation usually depend on models and are in general considered to be difficult to probe.

- However, when the inflaton potential is non-quadratic (only self-interaction), the generation of the inflaton quanta can significantly affect the evolution of the Universe, through which we can constrain the reheating model.

- If Higgs is coupled to the inflaton (and the inflaton only has a self-interaction), some collider constraints may also be relevant.

- A flesh look at the reheating scenario would give more insight into the physics of the early Universe.