From Reheating to Inflaton Regeneration

Kunio Kaneta

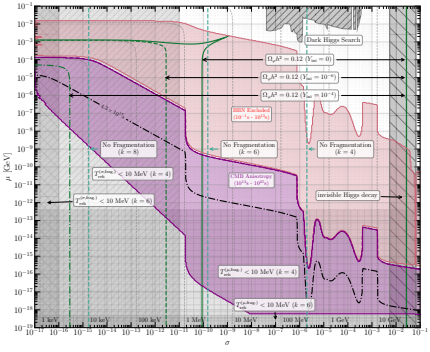
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Photo: South Pole Telescope

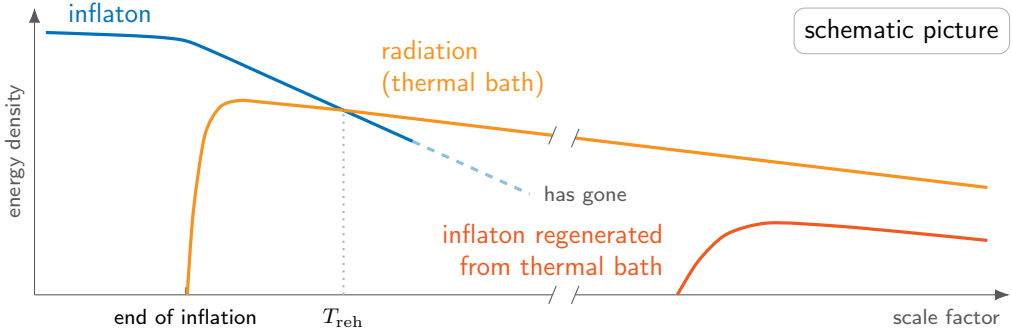
Outline



- Motivation: two way processes
- Inflaton Regeneration in Generic Scalar Case
- The Standard Model Higgs Portal
- Summary

- Motivation: two way processes

Standard lore and other situations



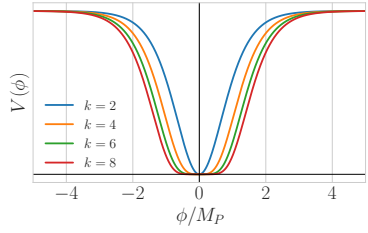
- What we regularly suppose: inflaton drives inflation, reheats the Universe, and then has gone (true in quadratic potential, e.g. Starobinsky model)
- Other situations: after it's gone, inflaton is regenerated from thermal bath
- Why this happens?: inflaton mass can be smaller than the temperature in some class of models, e.g., extended α-attractor type of models

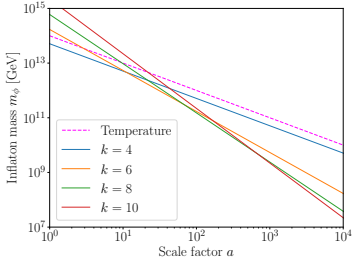
Extended T-model

- An example of inflaton potential:

$$V(\phi) = \lambda M_P^4 \left[\sqrt{6}\tanh\left(\frac{\phi}{\sqrt{6}M_P}\right)\right]^k = \begin{cases} 6^{k/2}\lambda M_P^4 & (\phi \gg M_P) \\ \lambda M_P^4(\phi/M_P)^k & (\phi \ll M_P) \end{cases}$$

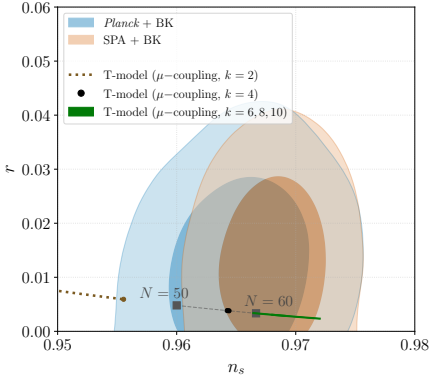
- Effective mass after inflation: $m_\phi^2 = V'' \propto \phi^{k-2}$
- $m_\phi \to 0$ as ϕ relaxes to $\phi = 0$, i.e. $m_\phi < T$ at later times, enabling the production of inflaton particles from thermal bath

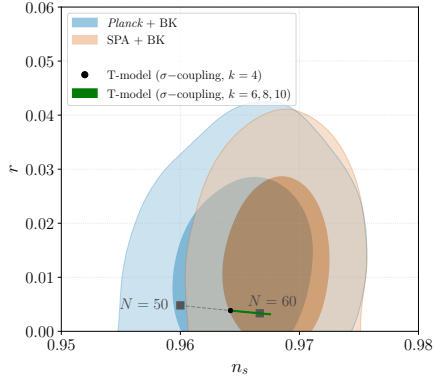




Current status of extended T-model

- Potential coupling λ is fixed by the scalar amplitude: $\lambda \sim \mathcal{O}(10^{-12} - 10^{-14})$
- Planck+BK+ACT+SPT favors $k > 2$

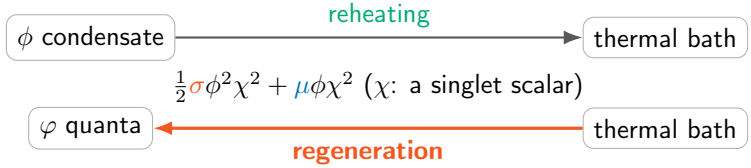




- Inflaton Regeneration in Generic Scalar Case

Scenario of inflaton regeneration

- Inflaton condensate (ϕ) disappears to produce thermal bath (reheating)
- Inflaton particle (φ) appears from thermal bath (regeneration)



Reheating $\longrightarrow$ Radiation Domination $\longrightarrow$ Inflaton Regeneration

$(m_\phi \to 0)$ $(\langle\chi\rangle = 0,\ m_\phi \simeq 0)$ $(\langle\chi\rangle = v,\ m_\phi \neq 0)$

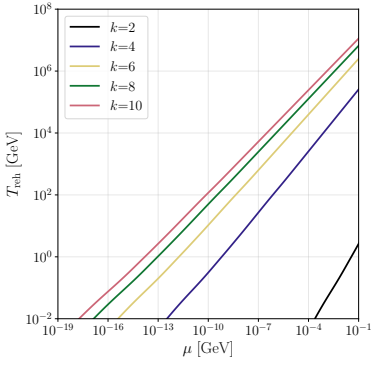
- We suppose χ develops a VEV to give a mass to φ (resembling the SM Higgs)

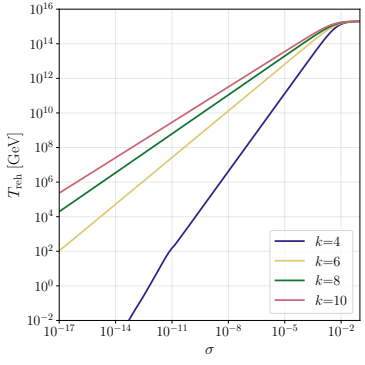
How reheating takes place?

- Portal couplings for reheating:

$$-\mathcal{L}_{\text{int}} = \frac{\sigma}{2}\phi^2\chi^2 + \mu\phi\chi^2 \quad [\sigma : \phi\phi \to \chi\chi \text{ scattering}, \ \mu : \phi \to \chi\chi \text{ decay}]$$

- Large k reheats hotter since $\rho_\phi \propto a^{-6k/(k+2)}$ redshifts faster, so $\rho_R \propto a^{-4}$ catches up sooner



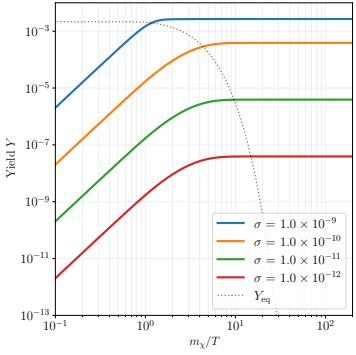


How regeneration proceeds?

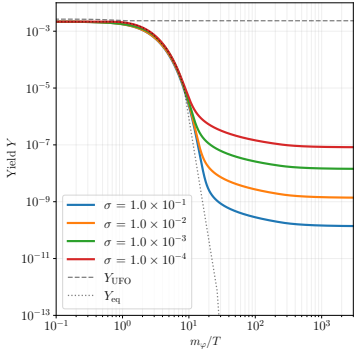
- The same portal coupling puts φ back:

$$\frac{\sigma}{2}\varphi^2\chi^2 + \mu\varphi\chi^2 \xrightarrow{\chi=v+\chi'} \underbrace{\frac{\sigma}{2}v^2\varphi^2}_{\text{a mass for } \varphi} + \underbrace{\sigma v\,\varphi^2\chi'}_{\chi\to\varphi\varphi} + \underbrace{2\mu v\,\varphi\chi'}_{\varphi\chi \text{ mixing}} + \cdots$$

- The mass: $m_\varphi^2 = \sigma v^2 + c\mu^2/16\pi^2$ (tree + CW)
- Production channels: $\chi \to \varphi\varphi$ and $\chi\chi \to \varphi\varphi$
- Freeze-in and freeze-out, $Y = n_\varphi/s$



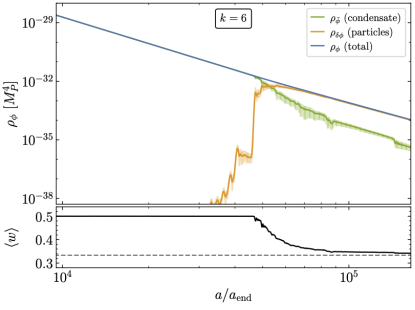
freeze-in



freeze-out

Non-perturbative contribution

- Freeze-in is sensitive to $Y_{\rm ini}$, and inflaton fragmentation may give non-zero $Y^{\rm frag}$



[Garcia, Gross, Mambrini, Olive, Pierre, Yoon, '23]

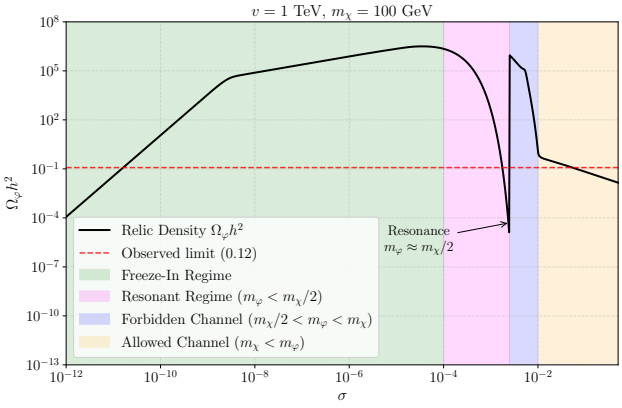
- How fast the fragments go away?

$$Y^{\rm frag} \simeq \begin{cases} \dfrac{1}{1728\, g_*^{1/4} c_s} \left[13 - \left(\dfrac{a}{a_{\rm reh}} \right)^3 \right]^3 & (\mu\text{-decay}) \\ \dfrac{1}{g_*^{1/4} c_s} \left(\dfrac{4}{3 + a/a_{\rm reh}} \right)^3 & (\sigma\text{-scattering}) \end{cases}$$

$$c_s = \frac{2\pi^4}{45\zeta(3)} \simeq 3.6$$

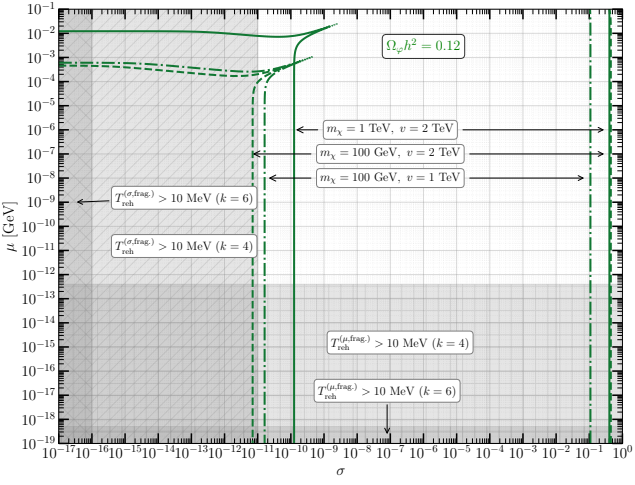
- $Y^{\rm frag}$ becomes negligible when $T_{\rm reh}$ is sufficiently high ($k \geq 6$ is fine, but should be careful for $k = 4$)

Relic abundance of φ: four distinct regimes



- Freeze-in: $\Omega_\varphi h^2 \propto \sigma$
- Resonant ($m_\varphi < m_\chi/2$): $\chi \leftrightarrow \varphi\varphi$ dominates; sharp dip at $m_\varphi \simeq m_\chi/2$
- Forbidden channel ($m_\chi/2 < m_\varphi < m_\chi$): $\varphi\varphi \to \chi\chi$ is Boltzmann-suppressed
- Allowed / Freeze-out ($m_\chi < m_\varphi$): $\Omega_\varphi h^2 \propto \sigma^{-1}$
- Excluded above the observed $\Omega h^2 = 0.12 \Rightarrow$ upper (or lower) bound on σ

Constraint map for generic scalar case

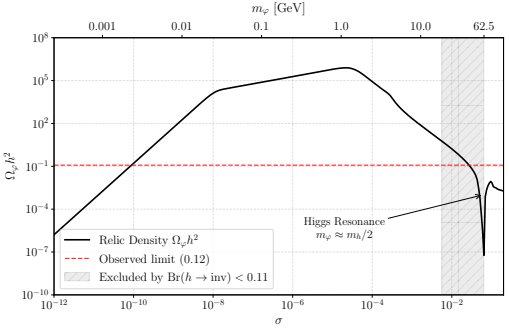


- Between the freeze-in and freeze-out branches: overproduction of $\varphi \Rightarrow$ excluded
- Requiring successful BBN ($T_{\rm reh} > 10$ MeV, incl. fragmentation) carves out the gray region [Garcia, Gross, Mambrini, Olive, Pierre, Yoon, '23]
- Remember this shape: with $\chi = H$ the same structure comes back with more stringent constraint

- The Standard Model Higgs Portal

What is different from the generic scalar case?

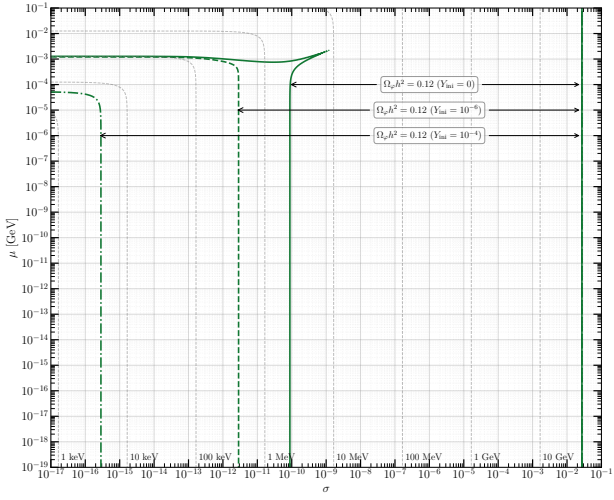
	generic singlet	$\chi = H$
VEV (v)	free	246 GeV
Mass (m_χ)	free	125 GeV
Fate of φ	stable	unstable



Relic abundance ($\mu = 0$)

- Everything but σ and μ is now a measured number
- Mixing with the Higgs makes φ unstable
- Production channels: $h \to \varphi\varphi, hh/W^+W^-/ZZ/f\bar{f} \to \varphi\varphi$

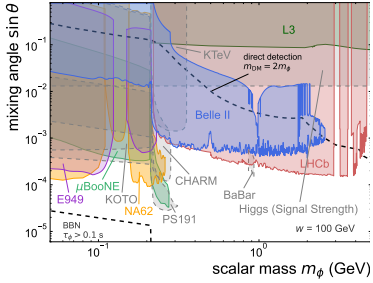
Relic contours in (σ, μ) planes



- Inflaton mass $m_\varphi \simeq \sqrt{\sigma}\, v$ with $v = 246$ GeV
- Green: φ is all of the dark matter. Freeze-in at $\sigma \simeq 10^{-10}$, freeze-out at 2×10^{-2}
- $Y_{\rm ini} = 0,\ 10^{-6},\ 10^{-4}$: a non-zero initial abundance needs less regeneration. Fragmentation gives $Y_{\rm ini} \simeq 0$, $Y_{\rm ini} \neq 0$ parametrizes UV leftovers
- Computed with φ stable

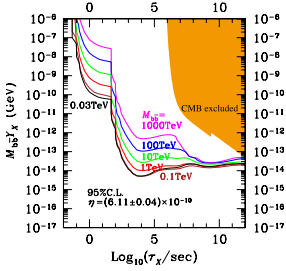
Constraints from colliders, BBN, and CMB

Colliders



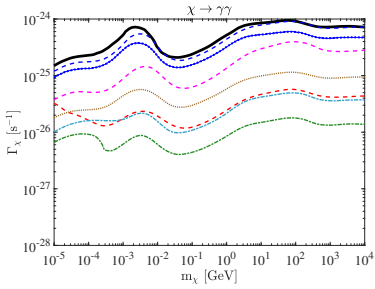
[Ferber, Grohsjean, Kahlhoefer, '23]

BBN



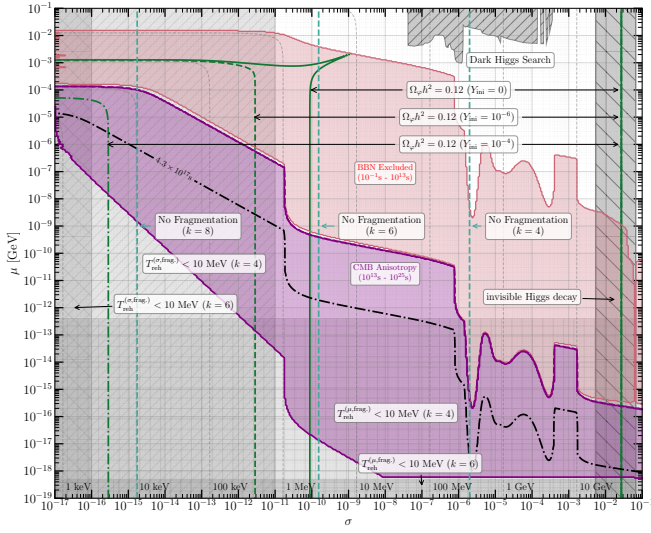
[Kawasaki, Kohri, Moroi, Takaesu, '17]

CMB



[Cang, Gao, Ma, '20]

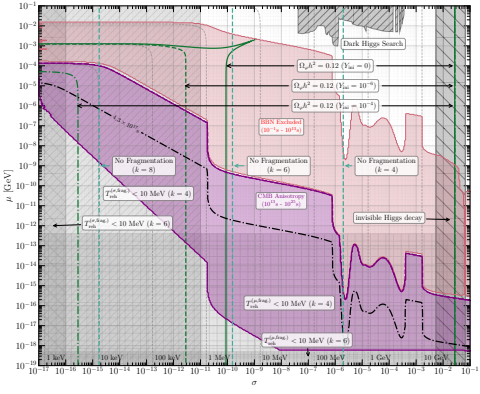
Constraint map for Higgs portal case



- **Hatched**: Dark Higgs Search, invisible Higgs decay
- Red: BBN energy injection. Purple: CMB anisotropy.
- Gray: BBN bound on reheating ($T_{\rm reh} > 10$ MeV)
- Survival region:
  - large μ $\Rightarrow$ unstable φ
  - large σ $\Rightarrow$ high $T_{\rm reh}$

- Summary

Summary



- $V(\phi) \sim \phi^k$ $(k \geq 4)$: $m_\phi(a) \to 0$, opening φ production from the thermal bath
- Portal couplings (σ, μ): reheat the Universe, and then regenerate φ afterwards
- Stable φ: matches the observed abundance on the freeze-in and freeze-out branches, and overproduces in between
- With $\chi = H$: unstable φ, constrained by BBN, CMB, and colliders. White region survives, at large μ (short lifetime) and large σ (high $T_{\rm reh}$)

Thank you!