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Imprints of Reheating Dynamics on Gravitational Waves from Phase Transitions

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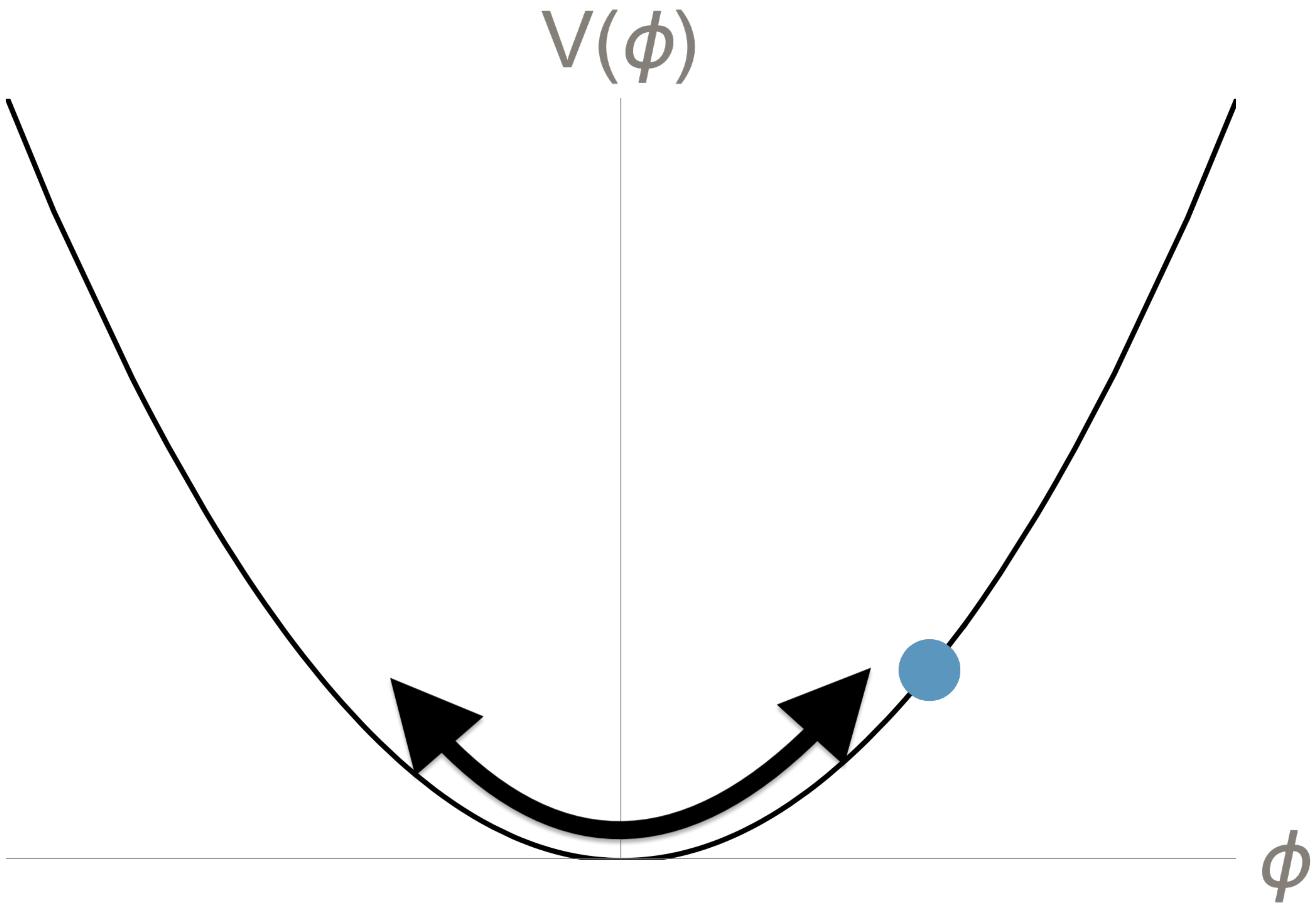
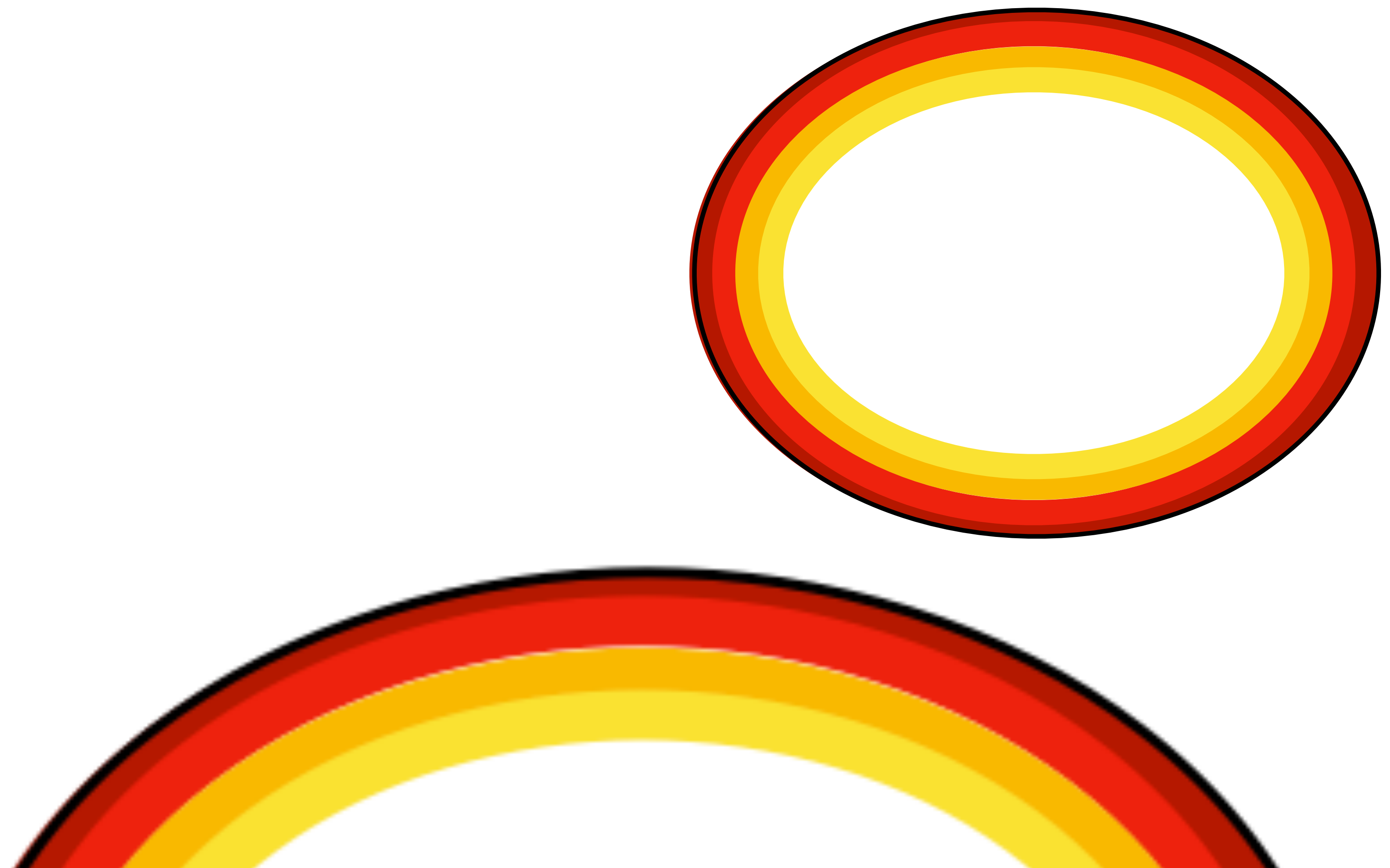




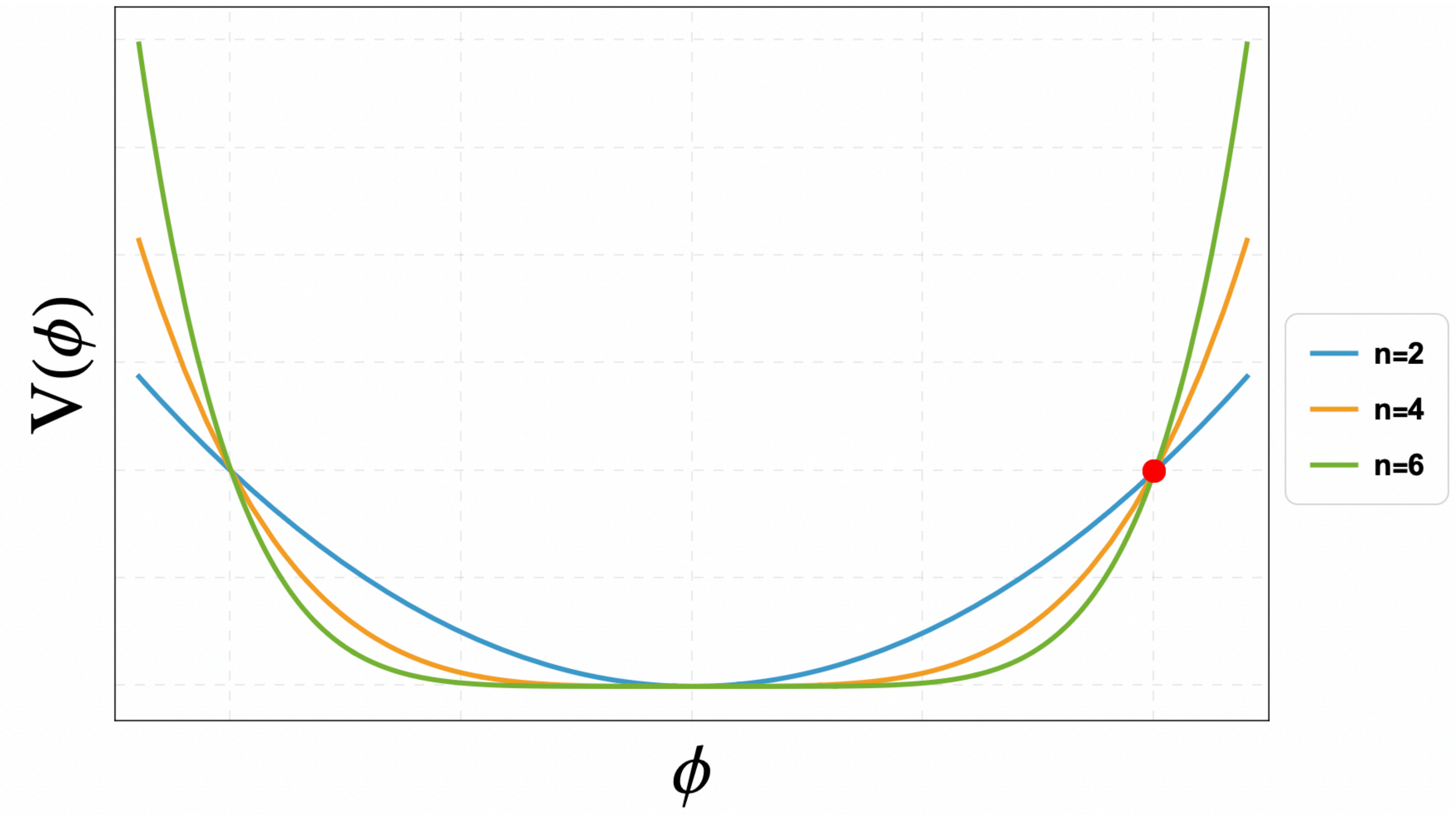
Inflaton Potential

$$V(\phi) = \lambda_\phi \frac{\phi^n}{\Lambda^{n-4}}$$

Canonical example α-attractors:

$$V(\phi) = \lambda_\phi \, M_P^4 \left[\tanh \left(\frac{\phi}{\sqrt{6\,\alpha}\, M_P} \right) \right]^n$$

Kallosh, Linde, Starobisnky' ++



How to reheat?

Perturbatively —> Inflaton decays/scatters to visible sector

$$\mathscr{L}^{\phi}_{\text{int}} \supset -\mu\,\phi\,|\varphi|^2 - y_\psi\,\overline{\Psi}\,\Psi\,\phi \;+ \sigma\,\phi^2\,\left|\varphi\right|^2$$

$$\Gamma_\phi(a) = \begin{cases} \dfrac{\mu_{eff}^2}{8\pi\, m_\phi(a)} & \text{Bosonic} \\ \dfrac{y_{eff}^2}{8\pi}\, m_\phi(a) & \text{Fermionic} \\ \dfrac{\sigma_{eff}^2}{8\pi\, m_\phi(a)^3} & \text{Scattering} \end{cases}$$

We consider each case scenario separately!

Inflaton dynamics

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

Energy $$\rho_\phi \equiv \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

Pressure $$p_\phi \equiv \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

→ Equation of state $$w \equiv \frac{p_\phi}{\rho_\phi} = \frac{n-2}{n+2}$$

Turner,PhysRevD.28.1243

Γ sets the reheating efficiency!

Reheating dynamics

Inflaton

$$\frac{d\rho_\phi}{dt} + \frac{6\,n}{2+n} H \rho_\phi = -\frac{2\,n}{2+n} \Gamma_\phi \rho_\phi \,.$$

Radiation

$$\frac{d\rho_R}{dt} + 4\,H \rho_R = +\frac{2\,n}{2+n} \Gamma_\phi \rho_\phi \,.$$

Analytic solution!

$$\rho_\phi(a) \simeq \rho_\phi(a_{rh}) \left(\frac{a_{rh}}{a}\right)^{\frac{6\,n}{2+n}}$$

$$\rho_R(a) \simeq \frac{2\sqrt{3}\,n}{2+n} \frac{M_P}{a^4} \int_{a_I}^{a} \Gamma_\phi(a') \sqrt{\rho_\phi(a')}\, a'^3\, da'$$

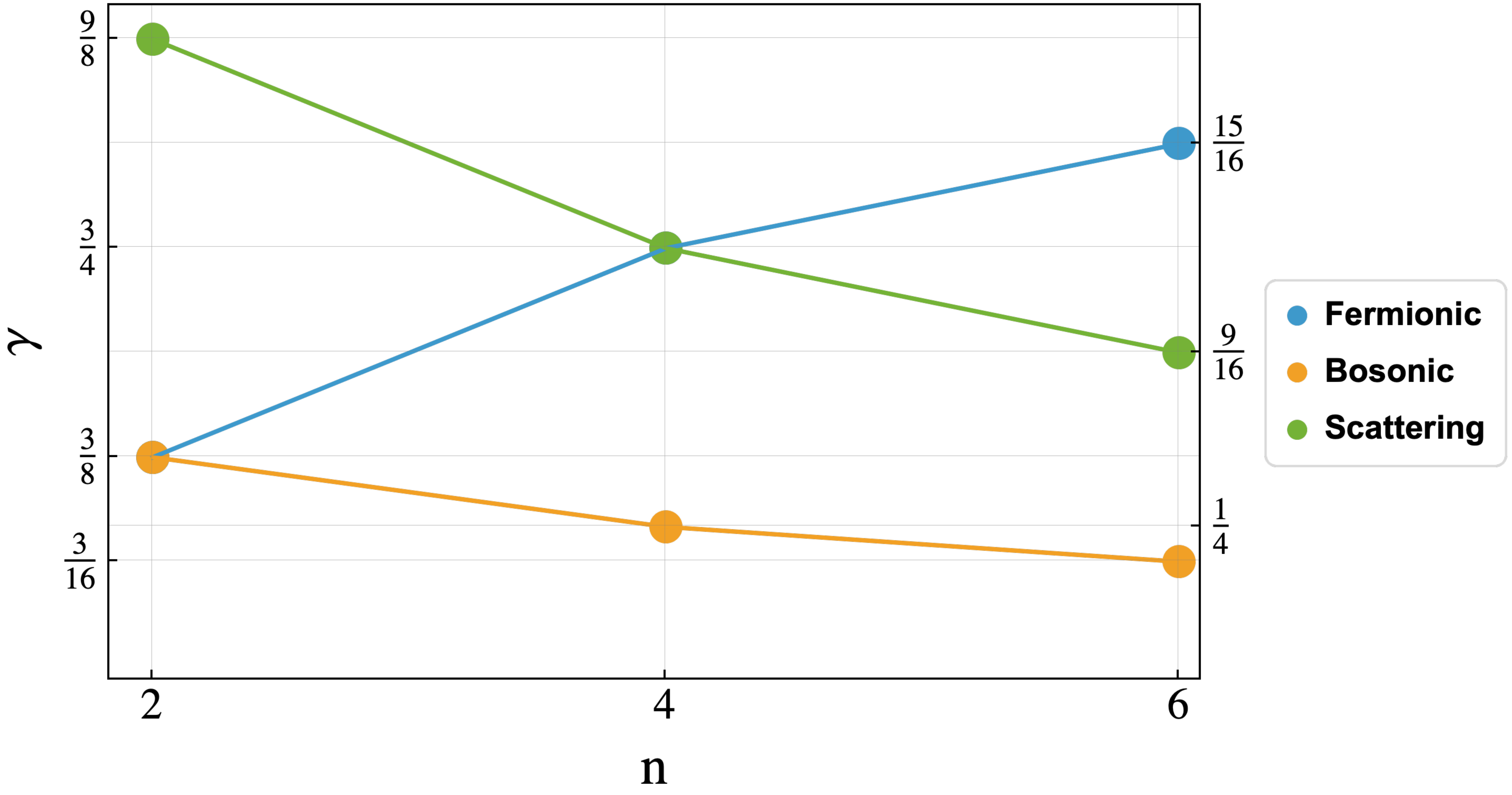
$$\Rightarrow \quad \boxed{T \sim \frac{1}{a^\gamma}}$$

γ depends on decay channel

Background Solution

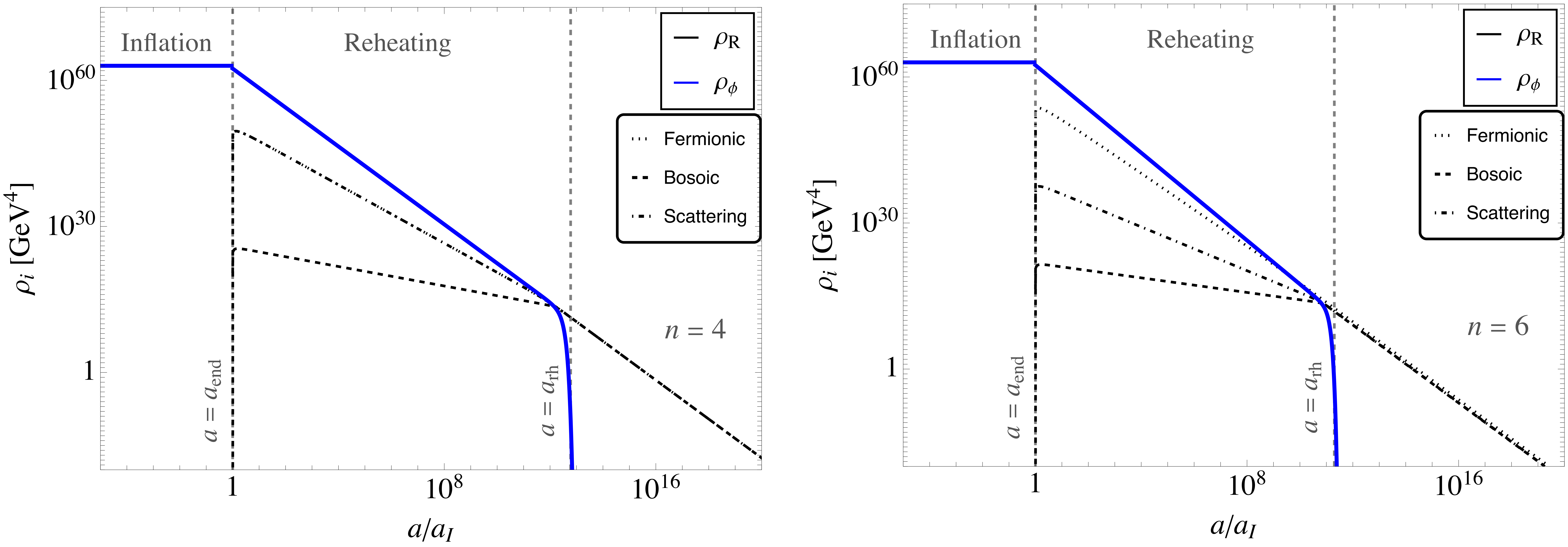
During reheating $T(a) \simeq T_{rh} \left(\frac{a_{rh}}{a} \right)^{\gamma}$

$$\gamma = \begin{cases} \gamma_f \equiv \frac{3}{2} \frac{n-1}{n+2} & \text{Fermionic} \\ \gamma_b \equiv \frac{3}{2} \frac{1}{n+2} & \text{Bosonic} \\ \gamma_{b,s} \equiv \frac{9}{2} \frac{1}{n+2} & \text{Scattering} \end{cases}$$



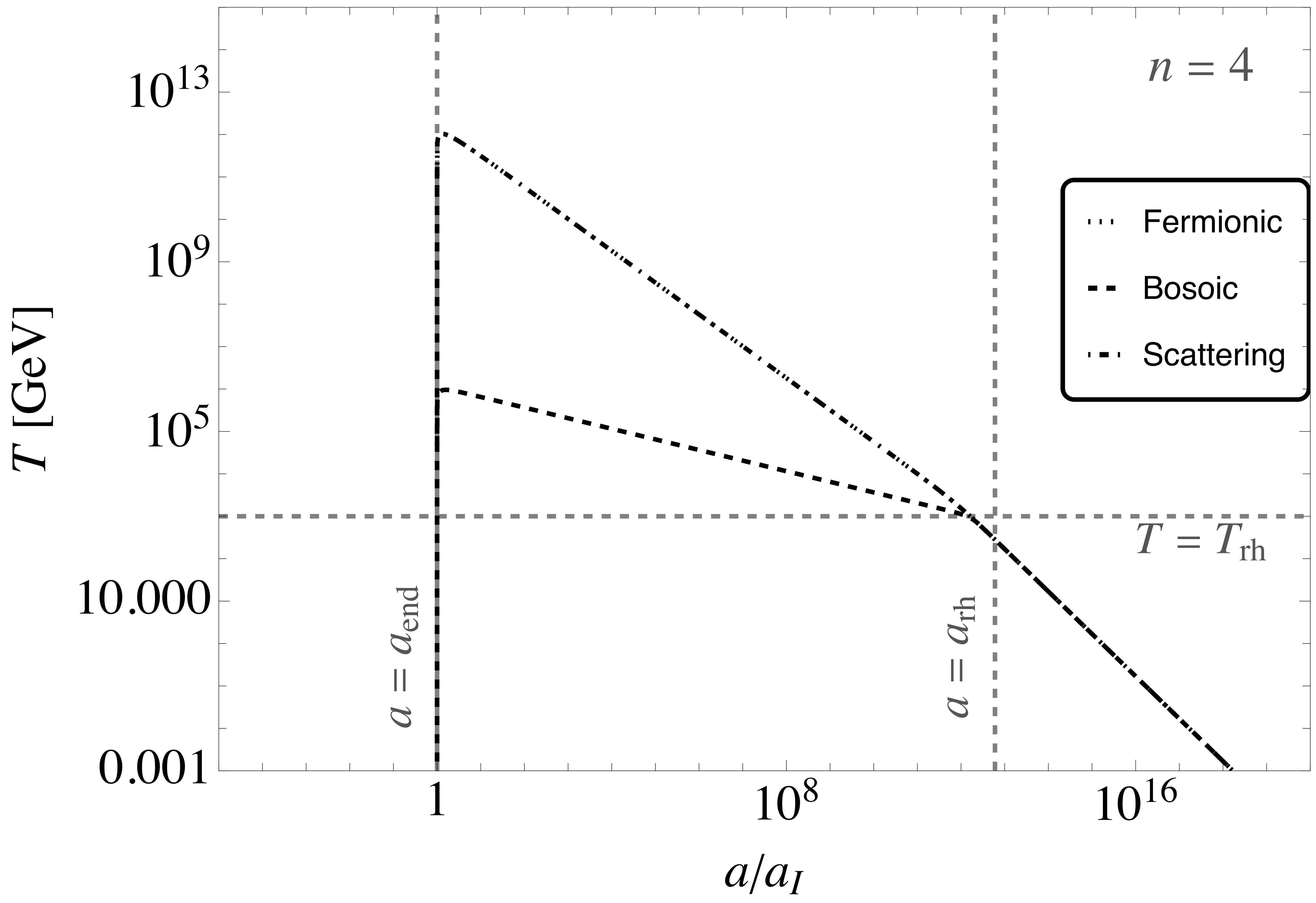
Smaller γ → slower cooling → delayed T_p → suppressed GWs

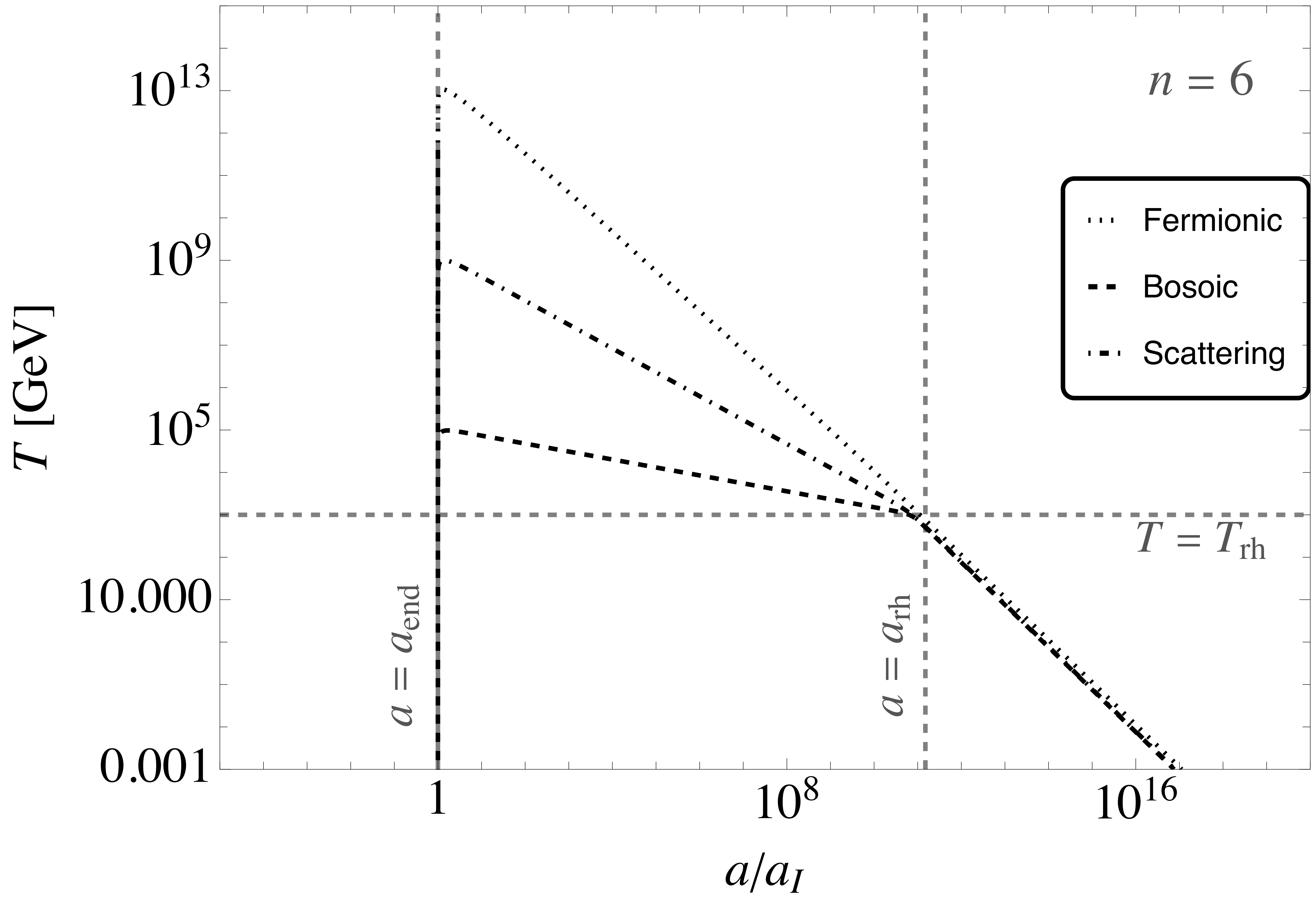
Evolution of energy densities



- Case n=2 there is no difference between bosonic and fermonic decay
- For n=2, Scattering channel does not lead to reheating completion

Temperature Evolution





First-order phase transition in the background

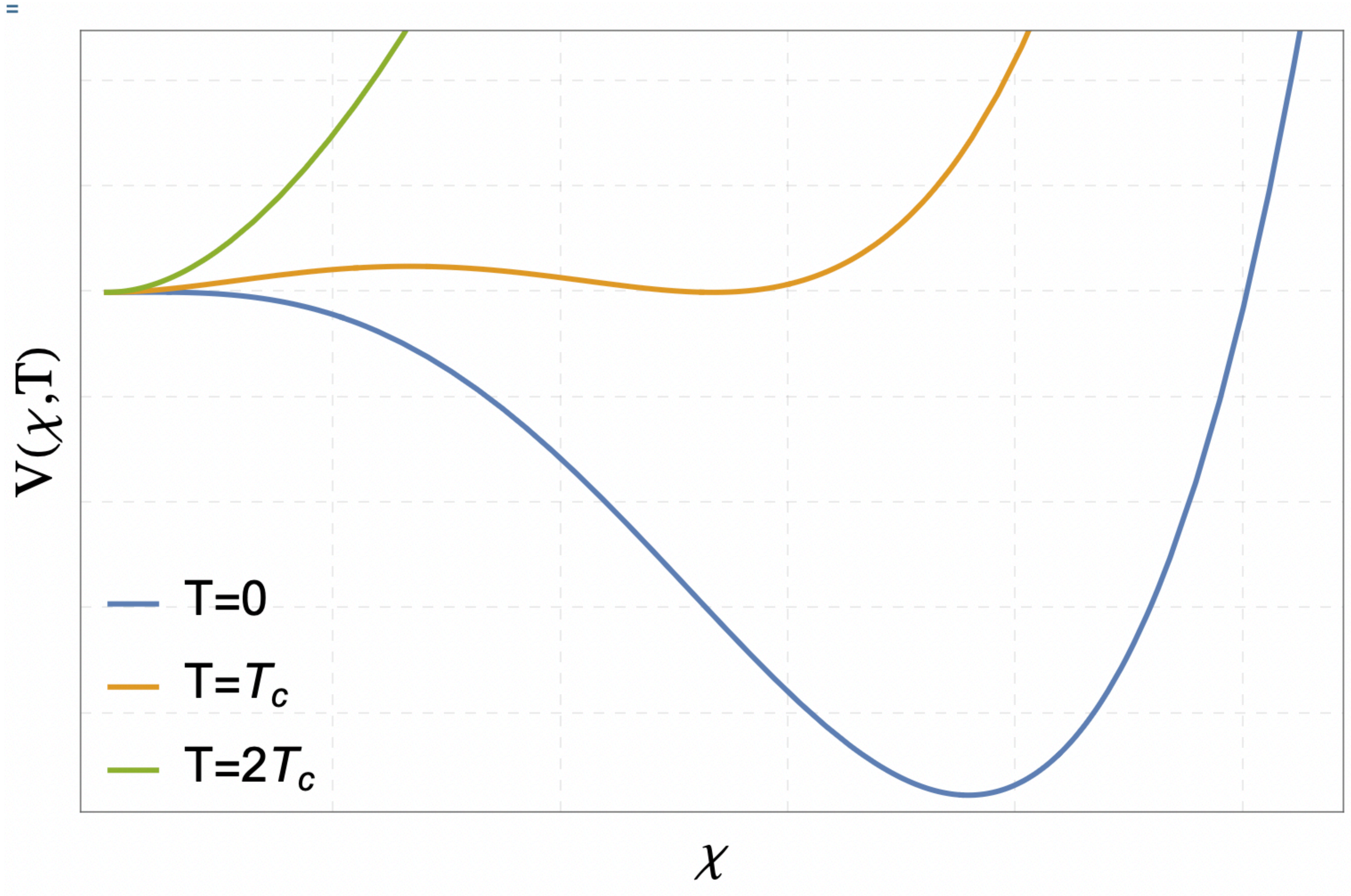
Tree-level barrier toy model

$$V(\chi, T) = \frac{1}{2}(m^2 + b\,T^2)\chi^2 - \frac{1}{3}\eta\chi^3 + \frac{1}{4}\lambda\chi^4$$

- Why a toy model? Phase structure is easily derived analytically!

$$v(T) = \frac{\eta + \sqrt{\eta^2 - 4\lambda(m^2 + b\,T^2)}}{2\lambda}$$

$$Tc = \frac{\sqrt{2\eta^2 - 9\lambda m^2}}{3\sqrt{b\,\lambda}}$$



Thermodynamic Parameters

$$T_{\text{max}} > T_c > T_n > T_* \approx T_p > T_{rh}$$

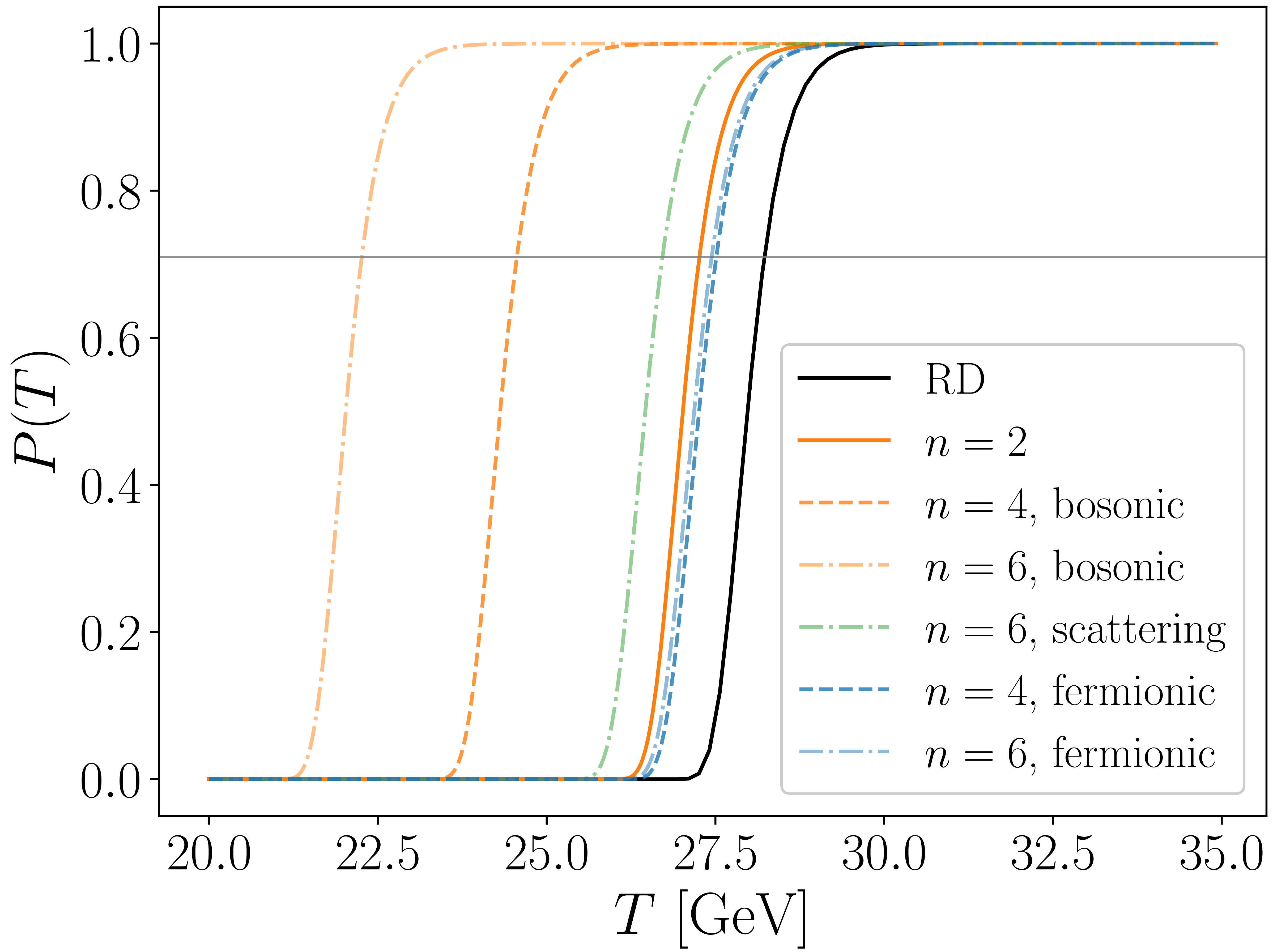
FOPT during reheating!

Bubble Percolation

True Vacuum Fraction

$$I(T) = \frac{4\pi}{3}\int_{T_c}^{T}\frac{dT'}{T'}\frac{\Gamma(T')}{\gamma\, H(T')}a(T')^3 r(T,T')^3$$

- Percolation is defined by the condition $I(T_p) = 0.34$
- $P(T) = e^{-I(T)} = 0.71$
- During reheating, percolation happens at a lower temperature compared to standard radiation domination



Time scale, latent heat & wall velocity

- Inverse time duration, rescaled by γ:

$$\frac{\beta}{H_\star} \equiv \gamma T \frac{d}{dT}\left(\frac{S_3}{T}\right)\Bigg|_{T=T_p}$$

$$\beta \to \tilde{\beta} \equiv \gamma\beta$$

- Latent heat. There are two alphas in the problem!

$$\alpha_R(T) \equiv \frac{\Delta\left(V(T) - T\frac{\partial V}{\partial T}\right)}{\rho_R(T)}$$

RD definition, κ_{sw} uses this

$$\alpha(T) \equiv \frac{\rho_R(T)}{\rho_R(T) + \rho_\phi(T)}\,\alpha_R(T)$$

Our work: inflaton dilution

Prior works (Banik'++25, Abad++'23) miss this!

- Assume weak detonations —> $v_w \approx 1$

Imprints on Stochastic Gravitational Wave background

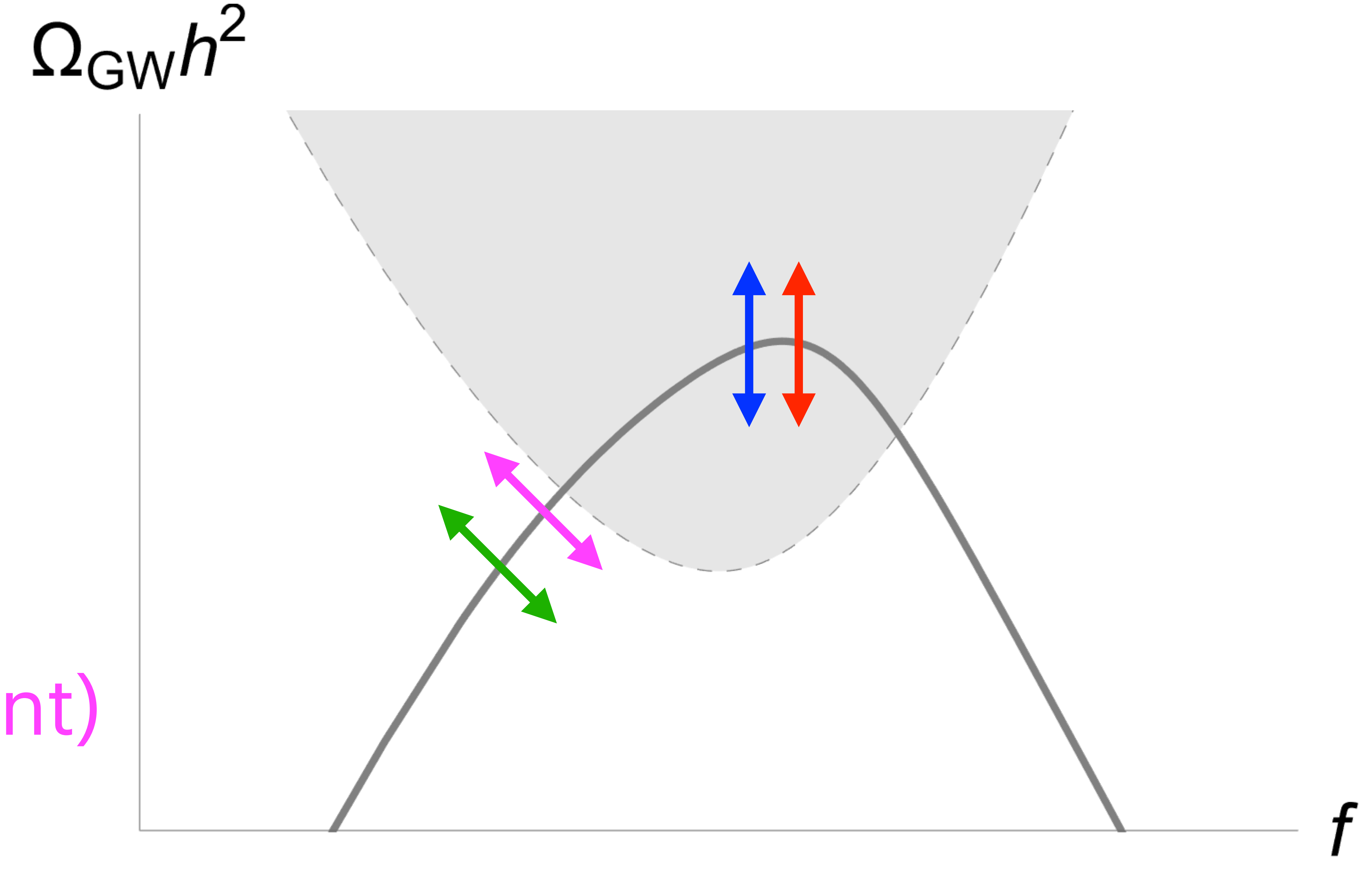
Amplitude

$$\Omega_{GW,0} \propto \left(\kappa_{sw}(\alpha_R)\frac{\alpha}{1+\alpha}\right)^2 \left(\frac{\tilde{\beta}}{H_*}\right)^{-1} \left(\frac{T_*}{T_{rh}}\right)^{\frac{2(n-4)}{\gamma(n+2)}}$$

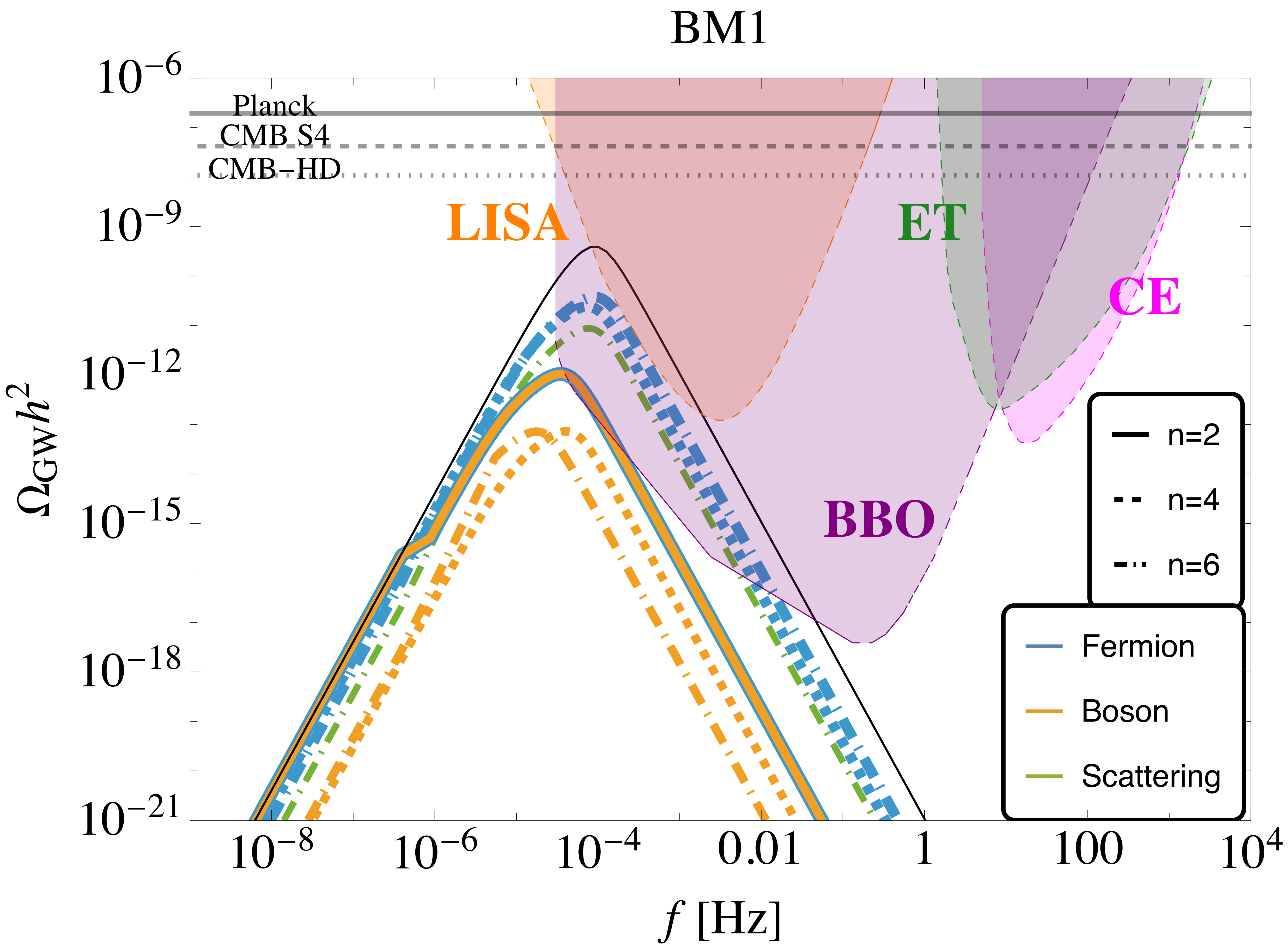
Frequency

$$f_0 \propto T_{rh}\left(\frac{\tilde{\beta}}{H_*}\right)\left(\frac{T_*}{T_{rh}}\right)^{\frac{2n-2}{\gamma(n+2)}}$$

- Sound wave efficiency (plasma hydro)
- Energy density ratio
- Transition duration (<—>radius)
- Redshift: Background expansion (n-dependent)



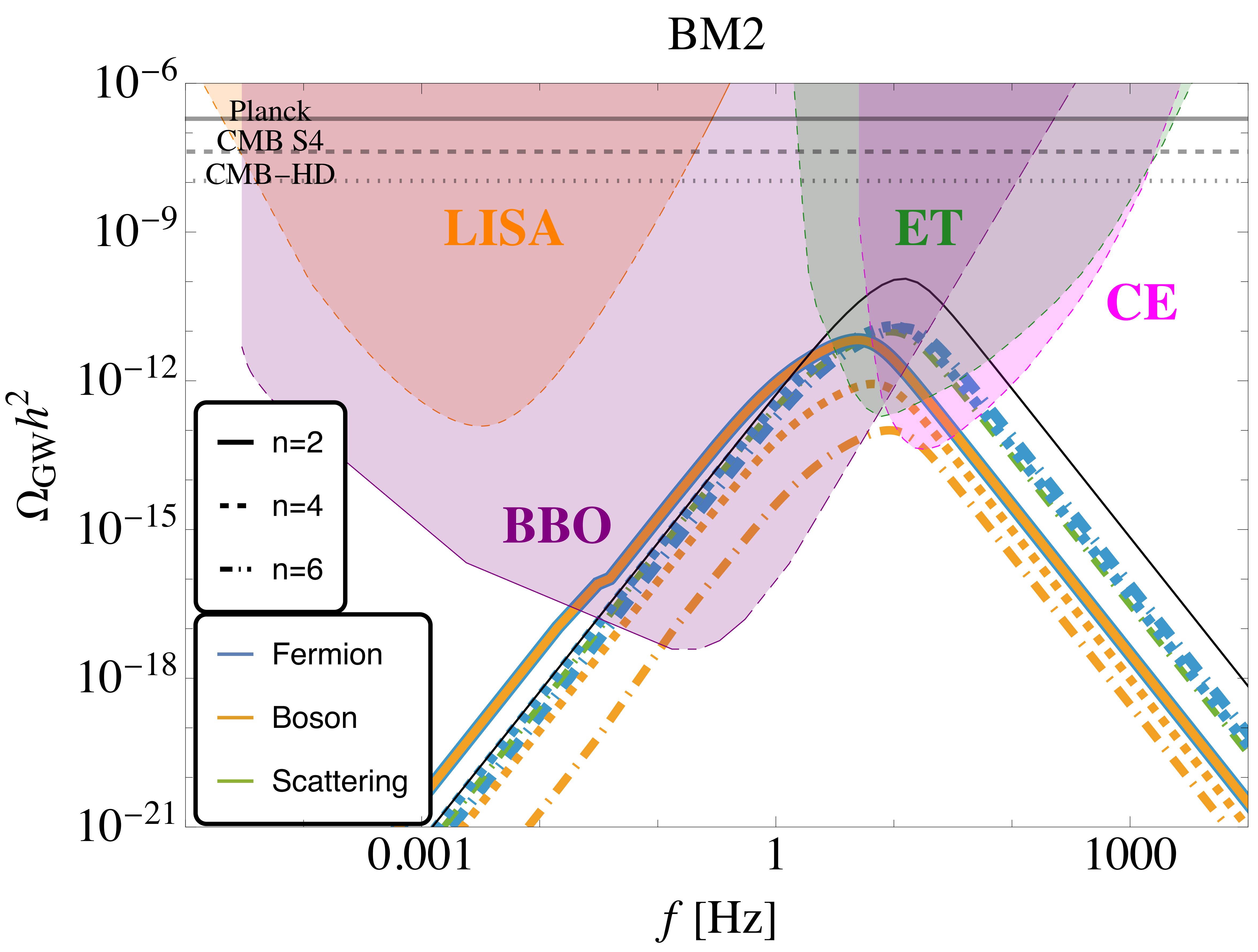
Spectrum Today



Type	n	γ	T_p (GeV)	$\alpha_R(T_p)$	$\alpha(T_p)$	$\tilde{\beta}/H_\star$
RD	–	1	28.23	0.4674	–	62.36
Bosonic decay	2	3/8	27.26	0.5340	0.02447	19.97
	4	1/4	24.56	0.7988	0.001077	7.179
	6	3/16	22.26	1.169	0.0002180	1.611
Bosonic scattering	6	9/16	26.72	0.5773	0.02869	27.10
Fermionic decay	2	3/8	27.26	0.5340	0.02447	19.97
	4	3/4	27.51	0.5156	0.1148	41.71
	6	15/16	27.44	0.5206	0.1605	51.52

Spectrum Today

Type	n	γ	T_p (GeV)	$\alpha_R(T_p)$	$\alpha(T_p)$	$\tilde{\beta}/H_\star$
RD	–	1	1.338×10^6	0.7334	–	165.7
Bosonic decay	2	3/8	1.350×10^6	0.7069	0.1063	63.30
	4	1/4	1.328×10^6	0.7569	0.01263	40.78
	6	3/16	1.305×10^6	0.8107	0.001976	29.55
Bosonic scattering	6	9/16	1.339×10^6	0.7314	0.1138	93.33
Fermionic decay	2	3/8	1.350×10^6	0.7069	0.1063	63.30
	4	3/4	1.343×10^6	0.7235	0.2442	125.1
	6	15/16	1.339×10^6	0.7325	0.2900	155.4



Summary

1. Reheating fundamentally modifies FOPT dynamics
   - γ<1 rescales $\tilde{\beta}$=$\gamma\,\beta$ → delayed nucleation/percolation
   - Fermionic reheating: faster signals (higher γ)
   - Bosonic reheating: suppressed signals (lower γ, slower bubble growth)
2. $\alpha \neq \alpha_R$ during inflaton domination, $\alpha \ll \alpha_R$ (inflaton dilution)
   - Signal suppressed compared to RD

Thank you!

Potential Parameters

Benchmarks	m^2 [GeV^2]	b	η	λ	$T_{\rm rh}$ [GeV]
BM1	10	0.01	1.01	0.002	15
BM2	1000	10^{-8}	1	10^{-9}	10^6

Nucleation Temperature

$$N(t_n) = \int_{t_c}^{t_n} dt \frac{\Gamma(t)}{H(t)^3} = 1 \quad \Rightarrow \quad \int_{T_n}^{T_c} \frac{dT}{T} \frac{\Gamma(T)}{H(T)^4} = \gamma$$

- Reheating delays bubble nucleation compared to radiation domination