Seesaw Cosmology

Based on:
NB, C. S. Fong, Ó. Zapata
arXiv:2607.27325 and arXiv:2609.17681

Nicolás BERNAL

جامعة نيويورك أبوظبي
NYU ABU DHABI

Particle Physics in the Early Universe
September 14th-18th, 2026

Standard Reheating

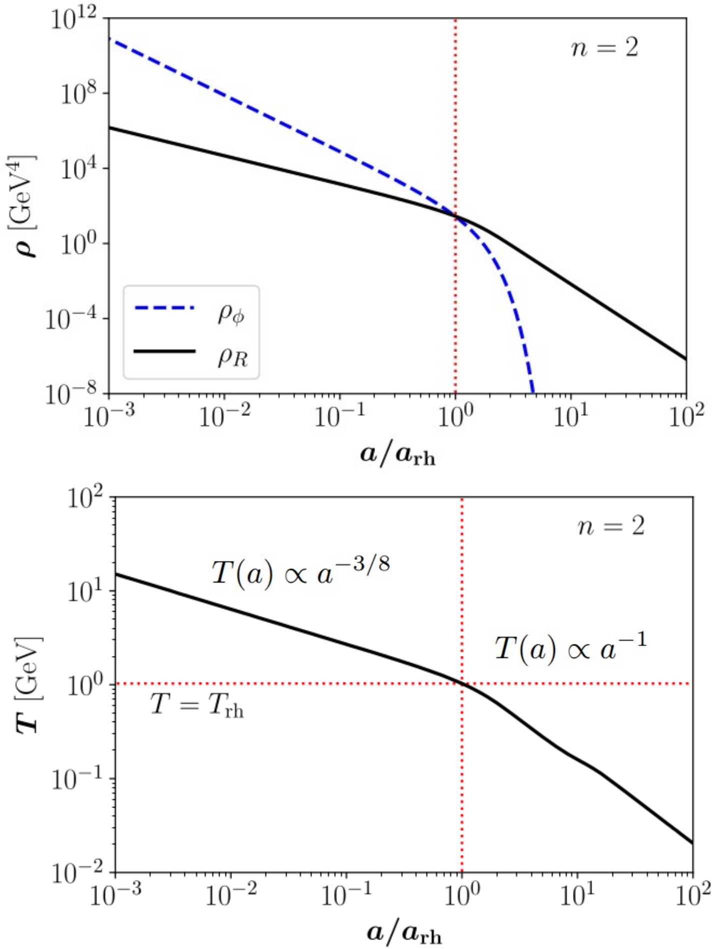
* Singlet scalar inflaton ϕ decays
  or annihilates at rest
  into a pair of SM Higgses: $\phi \to H\, H$

* Only channel available (dim 4)

* Reheating non-instantaneous

* During reheating, nonrelativistic ϕ dominate
  the energy density while decaying:

$$T(a) \propto a^{-3/8}$$



Reheating in Seesaw Cosmology

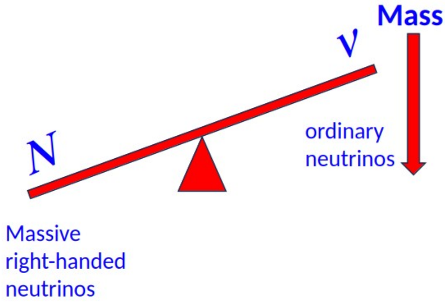
Two-step decay: $\phi \to N\,N$ $\quad$ then $\quad$ $N \to H\,\ell$

* ϕ real CP-even singlet scalar with mass m_ϕ
* N_i SM-singlet fermions with masses M_i
* H Higgs doublet, ℓ lepton doublets

$$-\mathcal{L} \supset \frac{1}{2}\,m_\phi^2\,\phi^2 + \left[\frac{1}{2}\sum_i (M_i + \lambda_i\,\phi)\,N_i\,N_i + \sum_{i,\alpha} y_{i\alpha}\,\epsilon_{ab}\,N_i\,\ell_\alpha^a\,H^b + \mathrm{H.c.}\right]$$

à la type-I seesaw

Type-I Seesaw



$$-\mathcal{L} \supset \frac{1}{2}\, m_\phi^2\, \phi^2 + \left[\frac{1}{2}\sum_i \left(M_i + \lambda_i\, \phi\right) N_i\, N_i + \sum_{i,\alpha} y_{i\alpha}\, \epsilon_{ab}\, N_i\, \ell_\alpha^a\, H^b + \text{H.c.}\right]$$

* Add at least 2 RHNs N_i to generate 2 neutrino masses

$$m_\nu = -v^2\, y^T\, M^{-1}\, y$$

* RHN decay width $\quad \Gamma_{N_i} = \frac{\left(y\, y^\dagger\right)_{ii}\, M_i}{8\pi}$

* for n = 2 RHNs $\quad \Gamma_{N_i} \geq \frac{M_i^2}{8\pi v^2} \begin{cases} \sqrt{\Delta m_{\text{sol}}^2} & \text{for NO,} \\ \sqrt{\left|\Delta m_{\text{atm}}^2\right|} & \text{for IO.} \end{cases}$

$$\Delta m_{\text{sol}}^2 \simeq 7.4 \times 10^{-5}\, \text{eV}^2$$
$$\left|\Delta m_{\text{atm}}^2\right| \simeq 2.5 \times 10^{-3}\, \text{eV}^2$$

* for n = 3 RHNs $\quad \Gamma_{N_i} \geq \frac{M_i^2}{8\pi\, v^2}\, m_0$

Seesaw Cosmology

$\phi \to N\,N \qquad \text{then} \qquad N \to H\,\ell$

* nonrelativistic ϕ decay into relativistic N
* N from relativistic to nonrelativistic
* long-lived N decay into SM

$$\frac{dn_\phi}{dt} + 3\,H\,n_\phi = -\Gamma_\phi\,n_\phi$$

$$\frac{dn_N}{dt} + 3\,H\,n_N = +2\,\Gamma_\phi\,n_\phi - \Gamma_N\,\frac{m_N}{E_N}\,n_N$$

$$\frac{d\rho_R}{dt} + 4\,H\,\rho_R = +\Gamma_N\,\frac{m_N}{E_N}\,E_N\,n_N$$

$$H^2 = \frac{\rho_\phi + \rho_N + \rho_R}{3\,M_P^2}$$

Seesaw Cosmology

$$\frac{dn_\phi}{dt} + 3\,H\,n_\phi = -\Gamma_\phi\,n_\phi$$

$$\frac{dn_N}{dt} + 3\,H\,n_N = +2\,\Gamma_\phi\,n_\phi - \Gamma_N\,\frac{m_N}{E_N}\,n_N$$

$$\frac{d\rho_R}{dt} + 4\,H\,\rho_R = +\Gamma_N\,\frac{m_N}{E_N}\,E_N\,n_N$$

$$H^2 = \frac{\rho_\phi + \rho_N + \rho_R}{3\,M_P^2}$$

Seesaw Cosmology

$$\frac{dn_\phi}{dt} + 3\,H\,n_\phi = -\Gamma_\phi\,n_\phi$$

$$\frac{dn_N}{dt} + 3\,H\,n_N = +2\,\Gamma_\phi\,n_\phi - \gamma_N$$

$$\frac{d\rho_R}{dt} + 4\,H\,\rho_R = +\Gamma_N\,m_N\,n_N$$

$$\gamma_N(a) \equiv \int_{a_I}^{a} da'\,\tilde{\Gamma}_N(a,a')\,\delta n_N(a,a')$$

$$\tilde{\Gamma}_N(a,a') = \frac{m_N}{E_N(a,a')}\,\Gamma_N$$

$$\delta n_N(a,a') = \frac{2\,\Gamma_\phi\,n_\phi(a')}{a'\,H(a')}\left(\frac{a'}{a}\right)^3 \exp\left[-\int_{a'}^{a}\frac{\tilde{\Gamma}_N(a'',a')}{a''\,H(a'')}\,da''\right]$$

Seesaw Cosmology

$$\frac{dn_\phi}{dt} + 3\,H\,n_\phi = -\Gamma_\phi\,n_\phi$$

$$\frac{dn_N}{dt} + 3\,H\,n_N = +2\,\Gamma_\phi\,n_\phi - \gamma_N$$

$$\frac{d\rho_R}{dt} + 4\,H\,\rho_R = +\Gamma_N\,m_N\,n_N$$

System of **coupled integro-differential** equations

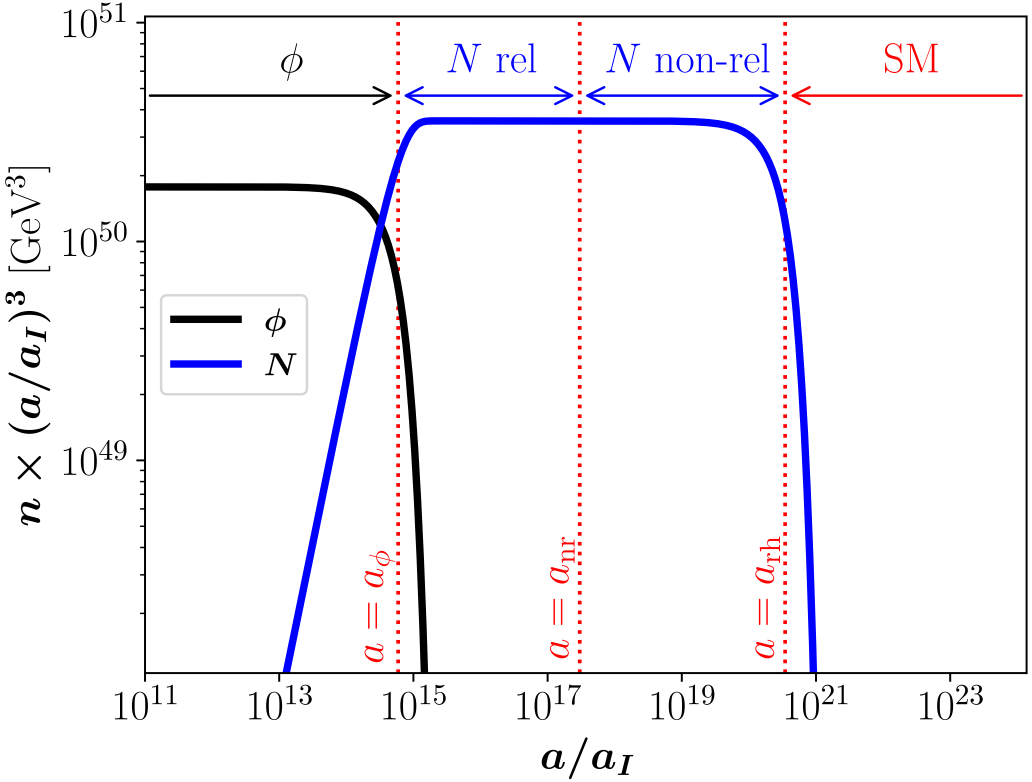
$$\gamma_N(a) \equiv \int_{a_I}^{a} da'\,\tilde{\Gamma}_N(a,a')\,\delta n_N(a,a')$$

$$\tilde{\Gamma}_N(a,a') = \frac{m_N}{E_N(a,a')}\,\Gamma_N$$

$$\delta n_N(a,a') = \frac{2\,\Gamma_\phi\,n_\phi(a')}{a'\,H(a')}\left(\frac{a'}{a}\right)^3 \exp\left[-\int_{a'}^{a}\frac{\tilde{\Gamma}_N(a'',a')}{a''\,H(a'')}\,da''\right]$$

Seesaw Cosmology

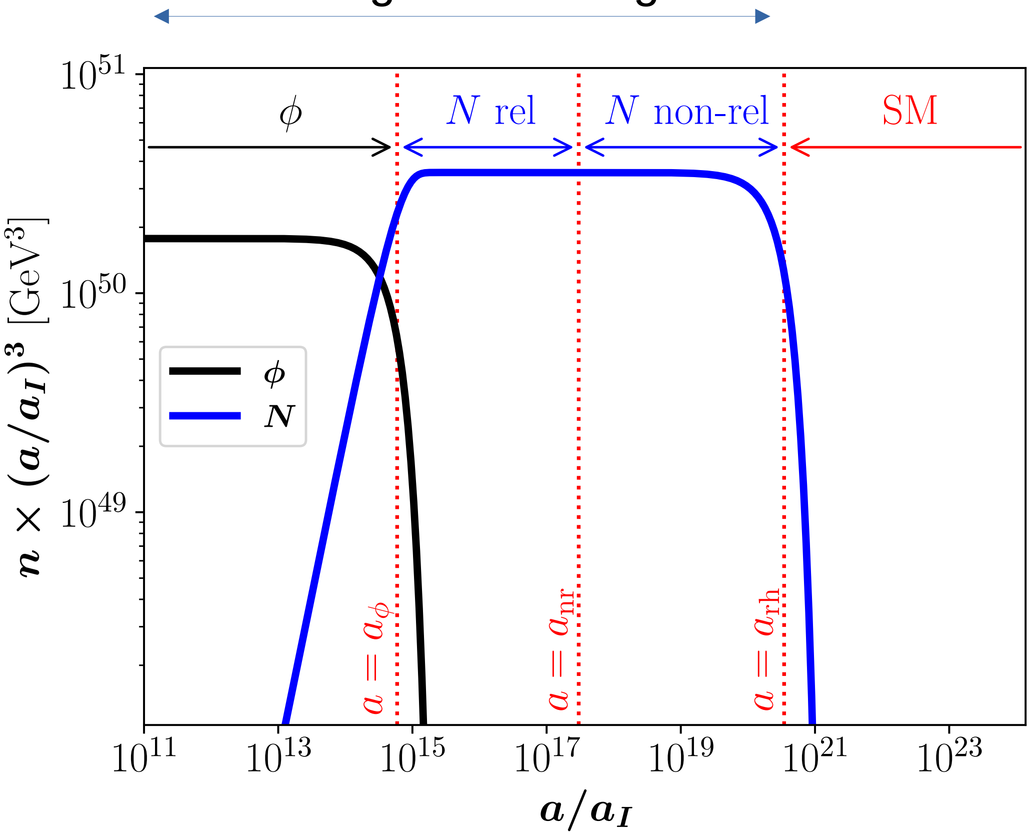
3 stages reheating



$$H_I = m_\phi = 10^{13} \text{ GeV}$$
$$m_N = 10^{10} \text{ GeV}$$
$$\Gamma_\phi = 10^{-9} \text{ GeV}$$
$$\Gamma_N = 10^{-19} \text{ GeV}$$

Seesaw Cosmology

3 stages reheating



$$H_I = m_\phi = 10^{13}\ \text{GeV}$$
$$m_N = 10^{10}\ \text{GeV}$$
$$\Gamma_\phi = 10^{-9}\ \text{GeV}$$
$$\Gamma_N = 10^{-19}\ \text{GeV}$$

Duration of the eras

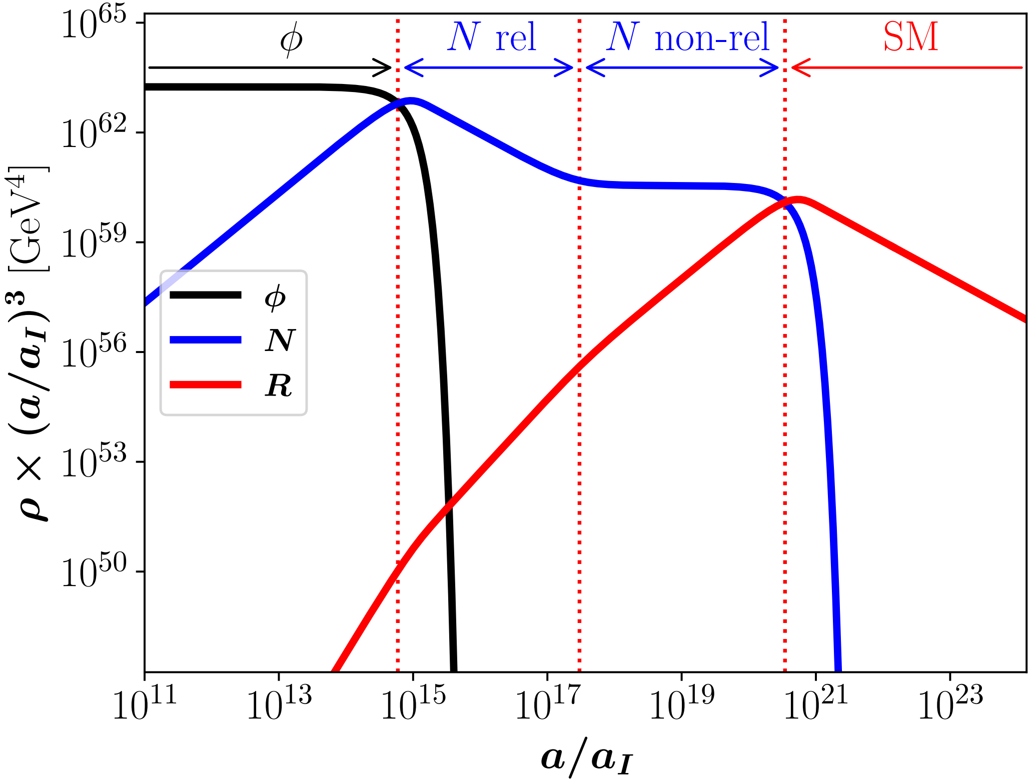
ϕ $$\frac{a_\phi}{a_I} \simeq \left(\frac{5}{2}\frac{H_I}{\Gamma_\phi}\right)^{2/3}$$

N rel $$\frac{a_{\rm nr}}{a_\phi} \simeq \frac{m_\phi}{2\,m_N}\,\beta_N \qquad \beta_N \equiv \left(1 - \frac{4\,m_N^2}{m_\phi^2}\right)^{1/2}$$

N non-rel $$\frac{a_{\rm rh}}{a_{\rm nr}} \simeq \left(\frac{16}{\beta_N^4}\,\frac{m_N^4\,\Gamma_\phi^2}{m_\phi^4\,\Gamma_N^2}\right)^{1/3}$$

Seesaw Cosmology

3 stages reheating



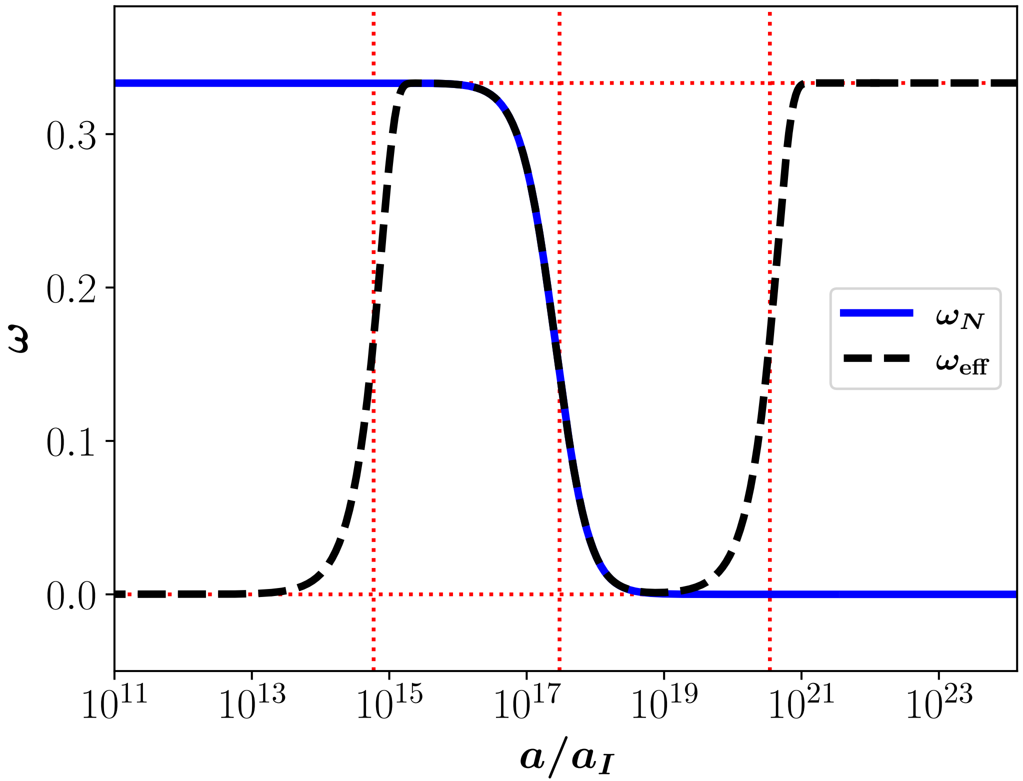
$$H_I = m_\phi = 10^{13}\ \text{GeV}$$
$$m_N = 10^{10}\ \text{GeV}$$
$$\Gamma_\phi = 10^{-9}\ \text{GeV}$$
$$\Gamma_N = 10^{-19}\ \text{GeV}$$

Duration of the eras

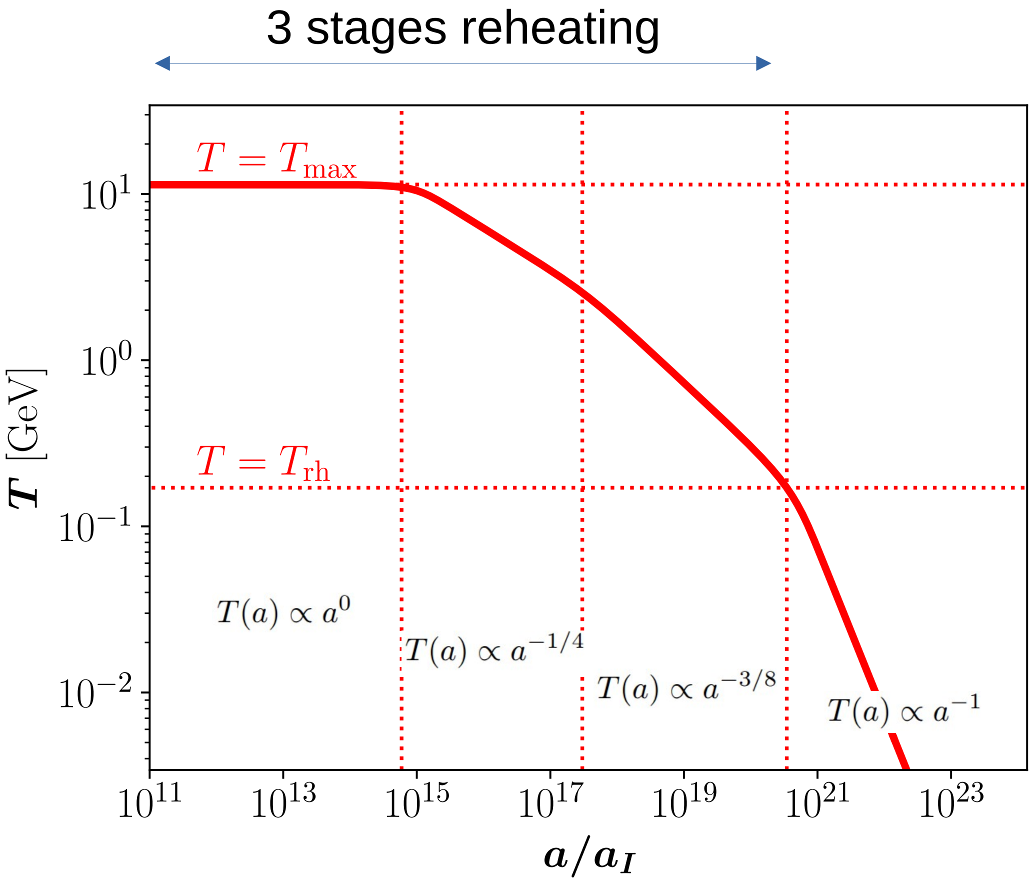
ϕ	$\frac{a_\phi}{a_I} \simeq \left(\frac{5}{2}\frac{H_I}{\Gamma_\phi}\right)^{2/3}$	
N rel	$\frac{a_{\rm nr}}{a_\phi} \simeq \frac{m_\phi}{2\,m_N}\beta_N$	$\beta_N \equiv \left(1 - \frac{4\,m_N^2}{m_\phi^2}\right)^{1/2}$
N non-rel	$\frac{a_{\rm rh}}{a_{\rm nr}} \simeq \left(\frac{16}{\beta_N^4}\frac{m_N^4\,\Gamma_\phi^2}{m_\phi^4\,\Gamma_N^2}\right)^{1/3}$	

Seesaw Cosmology

3 stages reheating



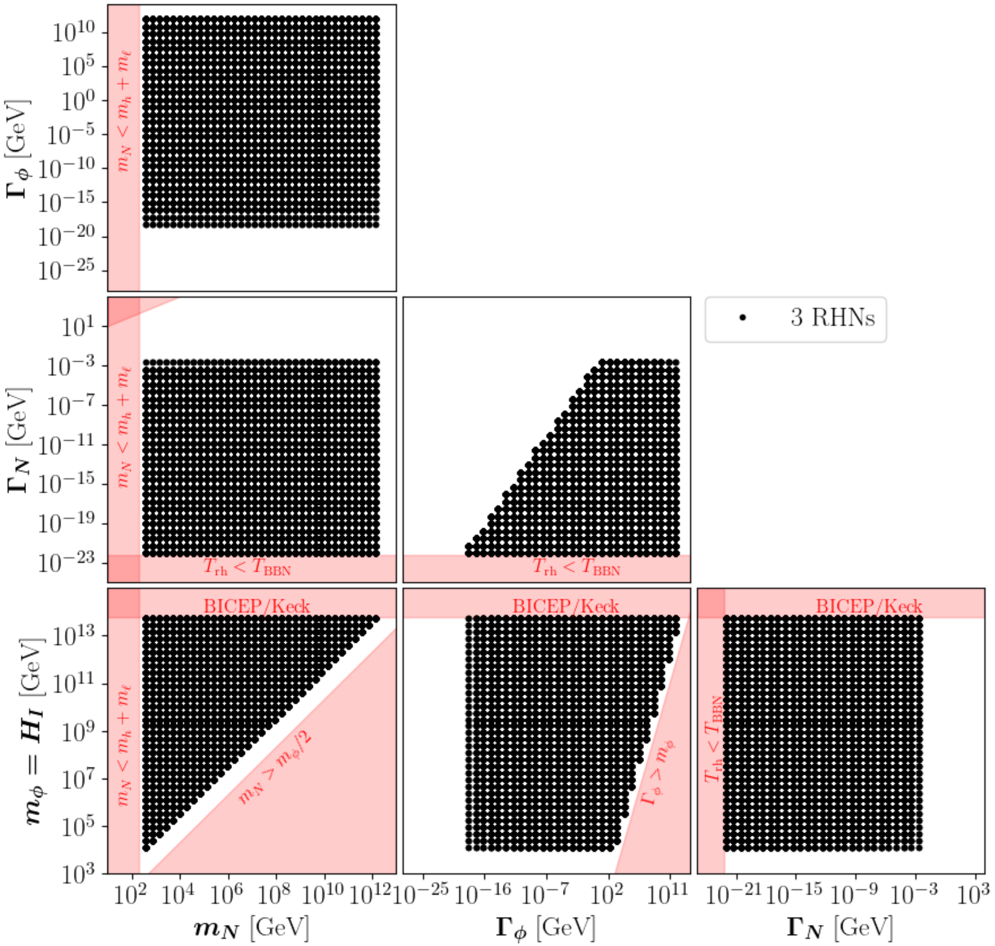
Seesaw Cosmology



$$T_{\rm max}^4 \simeq \frac{30}{\pi^2 g_\star} M_P^2 \, \Gamma_\phi \, \Gamma_N \, \frac{m_N}{m_\phi}$$

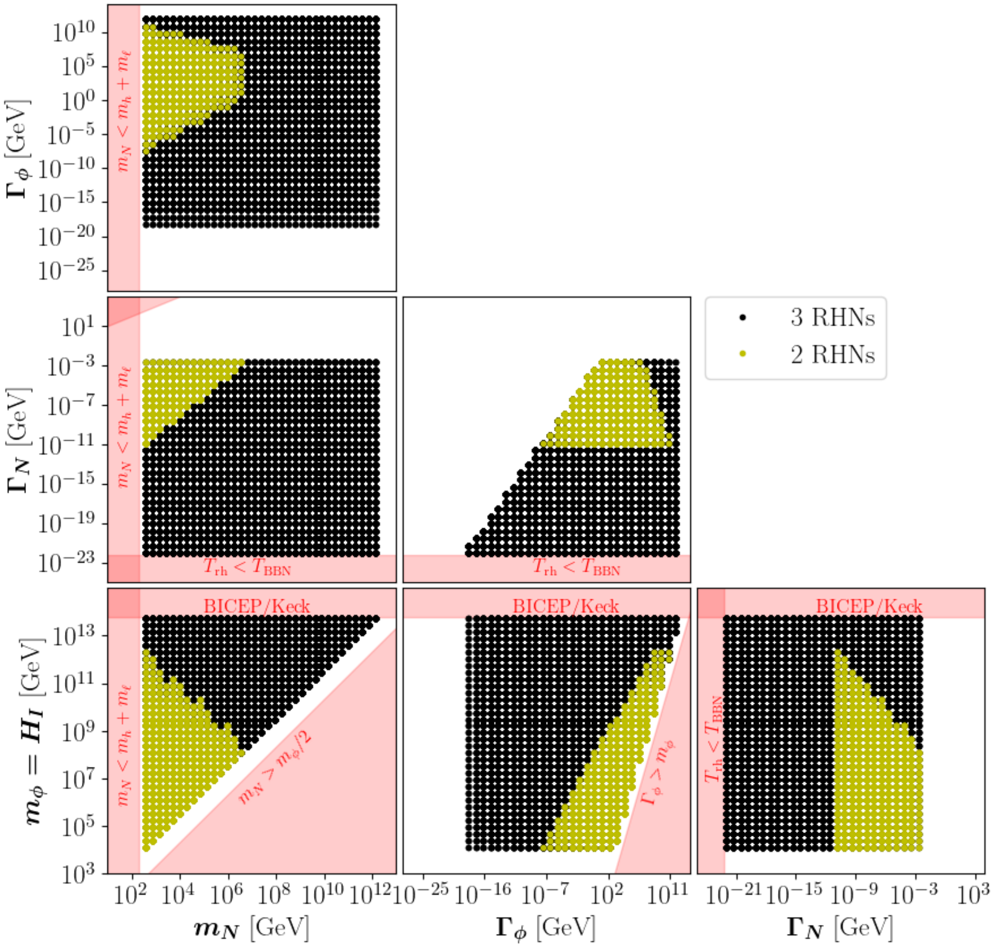
$$T_{\rm rh}^2 \simeq \frac{6}{\pi} \sqrt{\frac{2}{5\, g_\star}} \, M_P \, \Gamma_N$$

Seesaw Cosmology



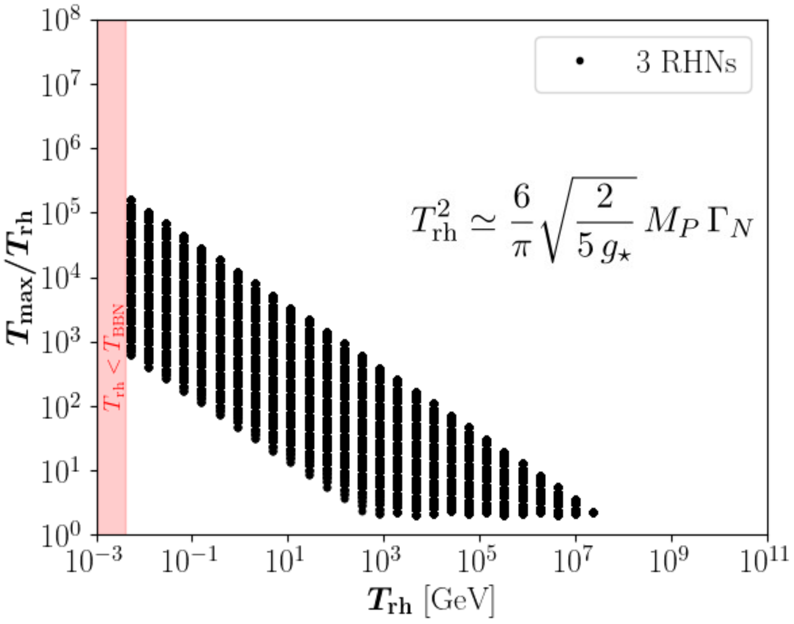
- Kinematics: $m_\phi > 2\,m_N$ and $m_N > m_h + m_\ell$
- BBN: $T_{\rm rh} > T_{\rm BBN} \quad \rightarrow \quad \Gamma_N > f(T_{\rm BBN})$
- BICEP/Keck: $H_I \lesssim 6 \times 10^{13}$ GeV
- Narrow decay widths: $\Gamma_i < m_i$
- $a_\phi/a_I,\ a_{\rm nr}/a_\phi,\ a_{\rm rh}/a_{\rm nr} > 10$
- $n = 3$ RHNs: $\Gamma_N \geq \frac{m_N^2}{8\pi\, v^2}\, m_0$

Seesaw Cosmology



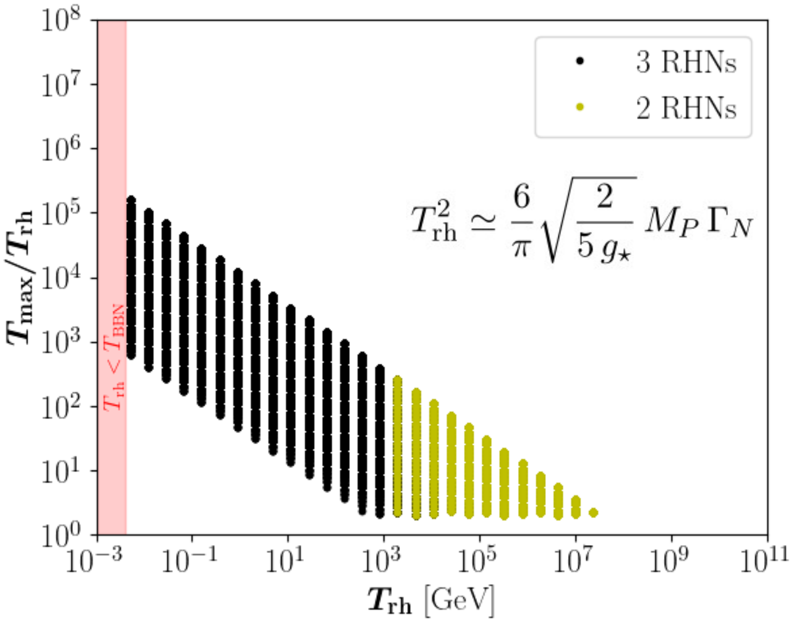
- Kinematics: $m_\phi > 2\,m_N$ and $m_N > m_h + m_\ell$
- BBN: $T_{\rm rh} > T_{\rm BBN}$ $\rightarrow$ $\Gamma_N > f(T_{\rm BBN})$
- BICEP/Keck: $H_I \lesssim 6 \times 10^{13}$ GeV
- Narrow decay widths: $\Gamma_i < m_i$
- $a_\phi/a_I,\ a_{\rm nr}/a_\phi,\ a_{\rm rh}/a_{\rm nr} > 10$
- $n = 3$ RHNs: $\Gamma_N \geq \frac{m_N^2}{8\pi\, v^2}\, m_0$
- $n = 2$ RHNs: $\Gamma_N \geq \frac{m_N^2}{8\pi\, v^2}\, \sqrt{\Delta m^2_{\rm sol}}$ (NO)

Seesaw Cosmology



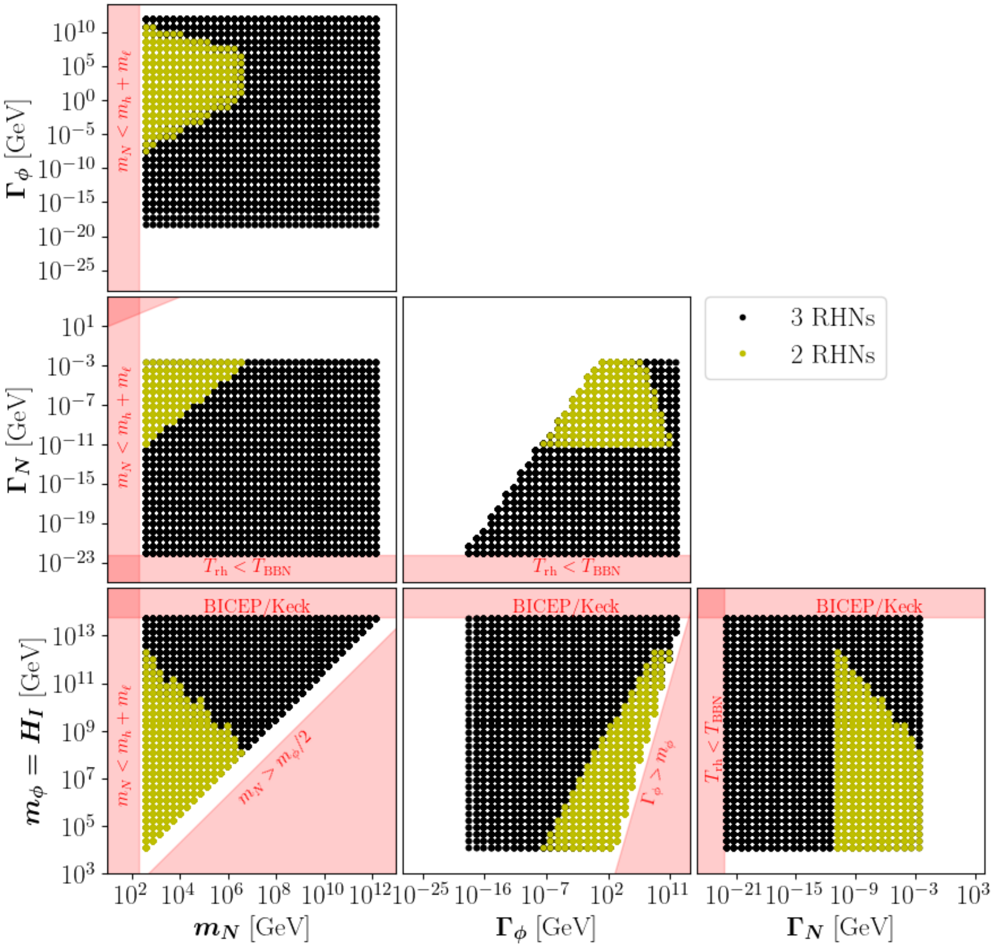
- Kinematics: $m_\phi > 2\,m_N$ and $m_N > m_h + m_\ell$
- BBN: $T_{\rm rh} > T_{\rm BBN} \quad \to \quad \Gamma_N > f(T_{\rm BBN})$
- BICEP/Keck: $H_I \lesssim 6 \times 10^{13}$ GeV
- Narrow decay widths: $\Gamma_i < m_i$
- a_ϕ/a_I, $a_{\rm nr}/a_\phi$, $a_{\rm rh}/a_{\rm nr} > 10$
- $n = 3$ RHNs: $\Gamma_N \geq \frac{m_N^2}{8\pi\, v^2}\, m_0$

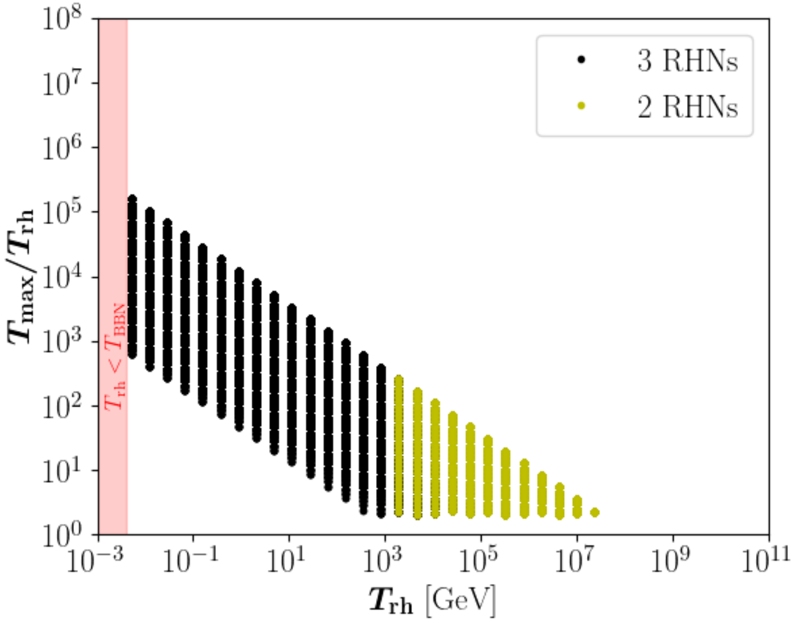
Seesaw Cosmology



- Kinematics: $m_\phi > 2\,m_N$ and $m_N > m_h + m_\ell$
- BBN: $T_{\rm rh} > T_{\rm BBN} \quad \to \quad \Gamma_N > f(T_{\rm BBN})$
- BICEP/Keck: $H_I \lesssim 6 \times 10^{13}$ GeV
- Narrow decay widths: $\Gamma_i < m_i$
- $a_\phi/a_I,\ a_{\rm nr}/a_\phi,\ a_{\rm rh}/a_{\rm nr} > 10$
- $n = 3$ RHNs: $\Gamma_N \geq \frac{m_N^2}{8\pi\,v^2}\,m_0$
- $n = 2$ RHNs: $\Gamma_N \geq \frac{m_N^2}{8\pi\,v^2}\,\sqrt{\Delta m^2_{\rm sol}}$ (NO)

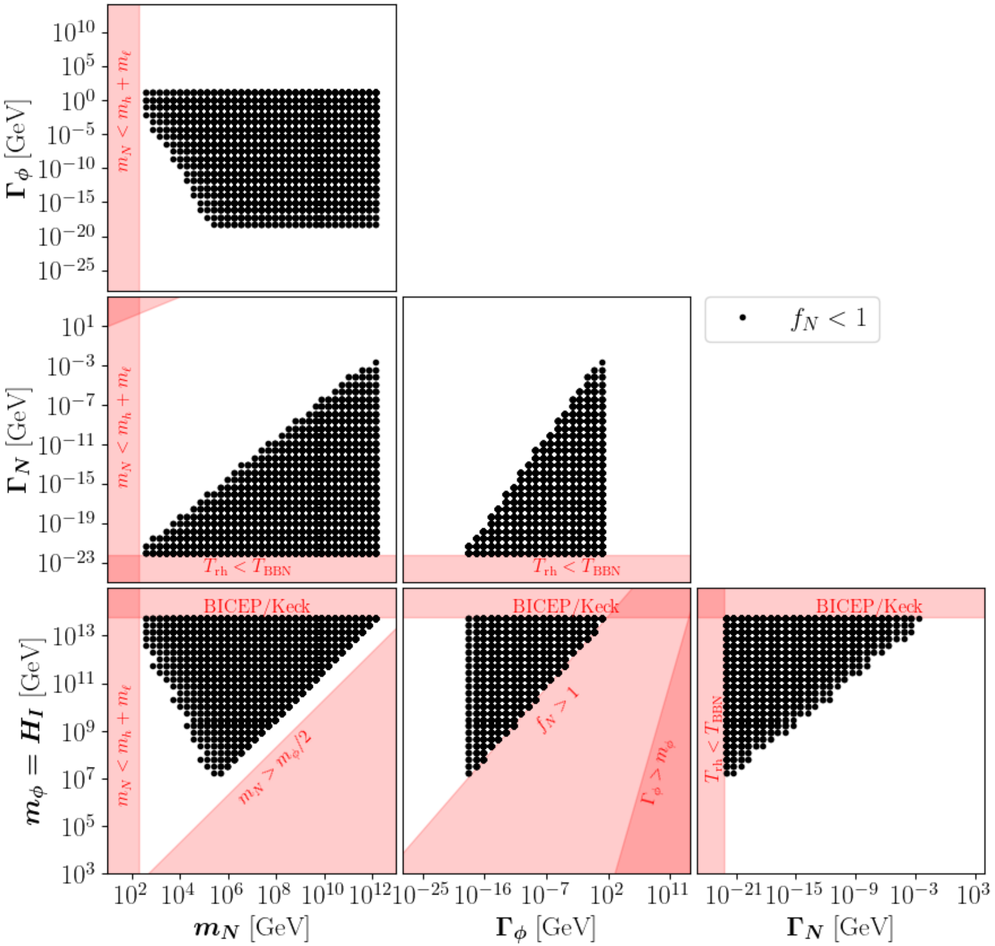
Seesaw Cosmology

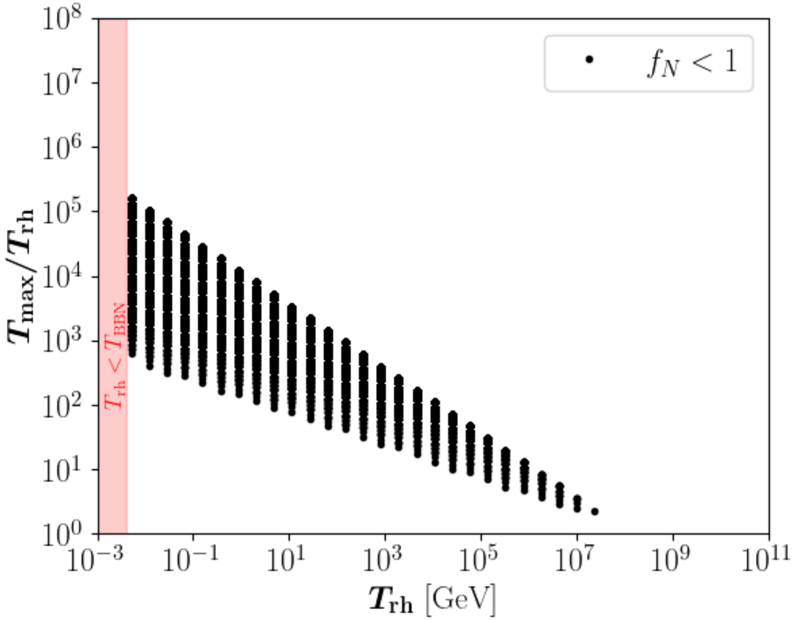




What about the role of quantum statistics?

Seesaw Cosmology





Avoiding saturation
$f_N < 1$

Seesaw Cosmology with Quantum Statistics

* Highly nonrelativistic ϕ inject *monochromatic* N with momentum $p_\star \equiv \frac{m_\phi}{2}\,\beta_N$

* N simply redshifts: no sizable self-interactions to redistribute their momenta

* Strong saturation ($f_N(p_N, a) \simeq 1$) occurs for

$$\Xi(a) \equiv \frac{f_N(p_\star, a)}{1 - f_N(p_\star, a)} \simeq \frac{2\pi^2\,\Gamma_\phi\,n_\phi(a)}{\mathcal{H}(a)\,p_\star^3} \gg 1$$

Seesaw Cosmology with Quantum Statistics

Solve the system at the level of *phase-space* distributions

$$\left[\frac{\partial}{\partial t} - \mathcal{H}\, p_\phi\, \frac{\partial}{\partial p_\phi}\right] f_\phi(p_\phi, t) = -\frac{1}{2\,E_\phi}\,\frac{1}{2!}\int d\Pi_1\, d\Pi_2\, (2\pi)^4\, \delta^{(4)}(p_\phi - p_1 - p_2)\, |\mathcal{M}_{\phi\to NN}|^2$$
$$\times \Big[f_\phi\, [1 - f_N(p_1)]\, [1 - f_N(p_2)] - [1 + f_\phi]\, f_N(p_1)\, f_N(p_2) \Big]$$

$$\left[\frac{\partial}{\partial t} - \mathcal{H}\, p_1\, \frac{\partial}{\partial p_1}\right] f_N(p_1, t) = +\frac{1}{2\,E_1}\int d\Pi_\phi\, d\Pi_2\, (2\pi)^4\, \delta^{(4)}(p_\phi - p_1 - p_2)\, |\mathcal{M}_{\phi\to NN}|^2$$
$$\times \Big[f_\phi\, [1 - f_N(p_1)]\, [1 - f_N(p_2)] - [1 + f_\phi]\, f_N(p_1)\, f_N(p_2) \Big]$$
$$- \Bigg[\frac{1}{2\,E_1} \sum_\alpha \int d\Pi_\ell\, d\Pi_H\, (2\pi)^4\, \delta^{(4)}(p_1 - p_\ell - p_H)\, |\mathcal{M}_{N\to \ell_\alpha H}|^2$$
$$\times \Big[f_N\, [1 - f_\ell]\, [1 + f_H] - [1 - f_N]\, f_\ell\, f_H \Big] + \mathrm{CP} \Bigg]$$

$$\frac{d\rho_R}{dt} + 4\,\mathcal{H}\,\rho_R = +\Gamma_N\, m_N\, n_N$$

Seesaw Cosmology with Quantum Statistics

Solve the system at the level of *phase-space* distributions

$$\left[\frac{\partial}{\partial t} - \mathcal{H}\, p_\phi\, \frac{\partial}{\partial p_\phi}\right] f_\phi(p_\phi, t) = -\frac{1}{2\,E_\phi}\,\frac{1}{2!}\int d\Pi_1\, d\Pi_2\, (2\pi)^4\, \delta^{(4)}(p_\phi - p_1 - p_2)\, |\mathcal{M}_{\phi\to NN}|^2$$
$$\times \Big[f_\phi\,[1 - f_N(p_1)]\,[1 - f_N(p_2)] - [1 + f_\phi]\, f_N(p_1)\, f_N(p_2)\Big]$$

$$\left[\frac{\partial}{\partial t} - \mathcal{H}\, p_1\, \frac{\partial}{\partial p_1}\right] f_N(p_1, t) = +\frac{1}{2\,E_1}\int d\Pi_\phi\, d\Pi_2\, (2\pi)^4\, \delta^{(4)}(p_\phi - p_1 - p_2)\, |\mathcal{M}_{\phi\to NN}|^2$$
$$\times \Big[f_\phi\,[1 - f_N(p_1)]\,[1 - f_N(p_2)] - [1 + f_\phi]\, f_N(p_1)\, f_N(p_2)\Big]$$
$$- \Bigg[\frac{1}{2\,E_1}\sum_\alpha \int d\Pi_\ell\, d\Pi_H\, (2\pi)^4\, \delta^{(4)}(p_1 - p_\ell - p_H)\, |\mathcal{M}_{N\to\ell_\alpha H}|^2$$
$$\times \Big[f_N\,[1 - f_\ell]\,[1 + f_H] - [1 - f_N]\, f_\ell\, f_H\Big] + \mathrm{CP}\Bigg]$$

$$\frac{d\rho_R}{dt} + 4\,\mathcal{H}\,\rho_R = +\Gamma_N\, m_N\, n_N$$

System of **coupled integro-differential** equations

Seesaw Cosmology with Quantum Statistics

Assume ϕ has a highly nonrelativistic *initial* distribution

$$f_\phi(\vec{p}_\phi, t_0) = (2\pi)^3\, n_\phi(t_0)\, \delta(\vec{p}_\phi)$$

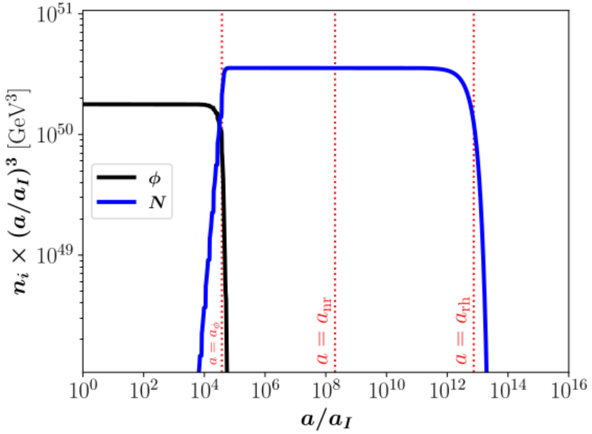
System of **coupled integro-differential** equations

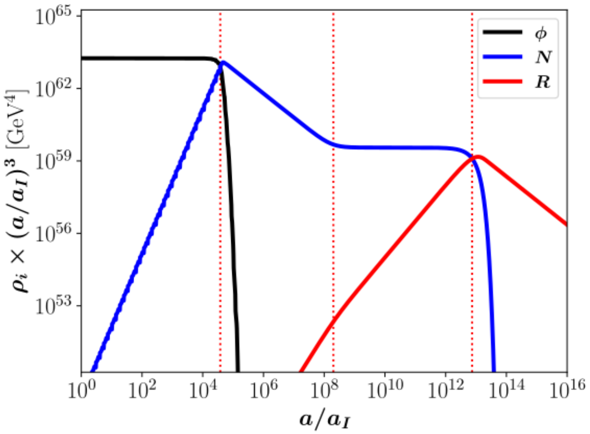
$$\left[\frac{\partial}{\partial t} - \mathcal{H}\, p_\phi\, \frac{\partial}{\partial p_\phi}\right] f_\phi(p_\phi, t) = -\Gamma_\phi\, f_\phi(p_\phi, t)\, [1 - f_N(p_\star, t)]$$

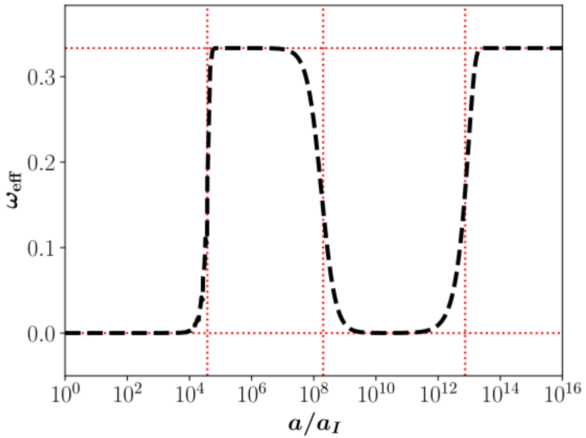
$$\left[\frac{\partial}{\partial t} - \mathcal{H}\, p_N\, \frac{\partial}{\partial p_N}\right] f_N(p_N, t) = \frac{2\pi^2\, \Gamma_\phi\, n_\phi}{p_\star^2}\, \delta(p_N - p_\star)\, [1 - f_N(p_\star, t)] - \frac{\Gamma_N\, m_N}{E_N}\, f_N(p_N, t)$$

$$\frac{d\rho_R}{dt} + 4\, \mathcal{H}\, \rho_R = +\Gamma_N\, m_N\, n_N$$

Seesaw Cosmology with Quantum Statistics



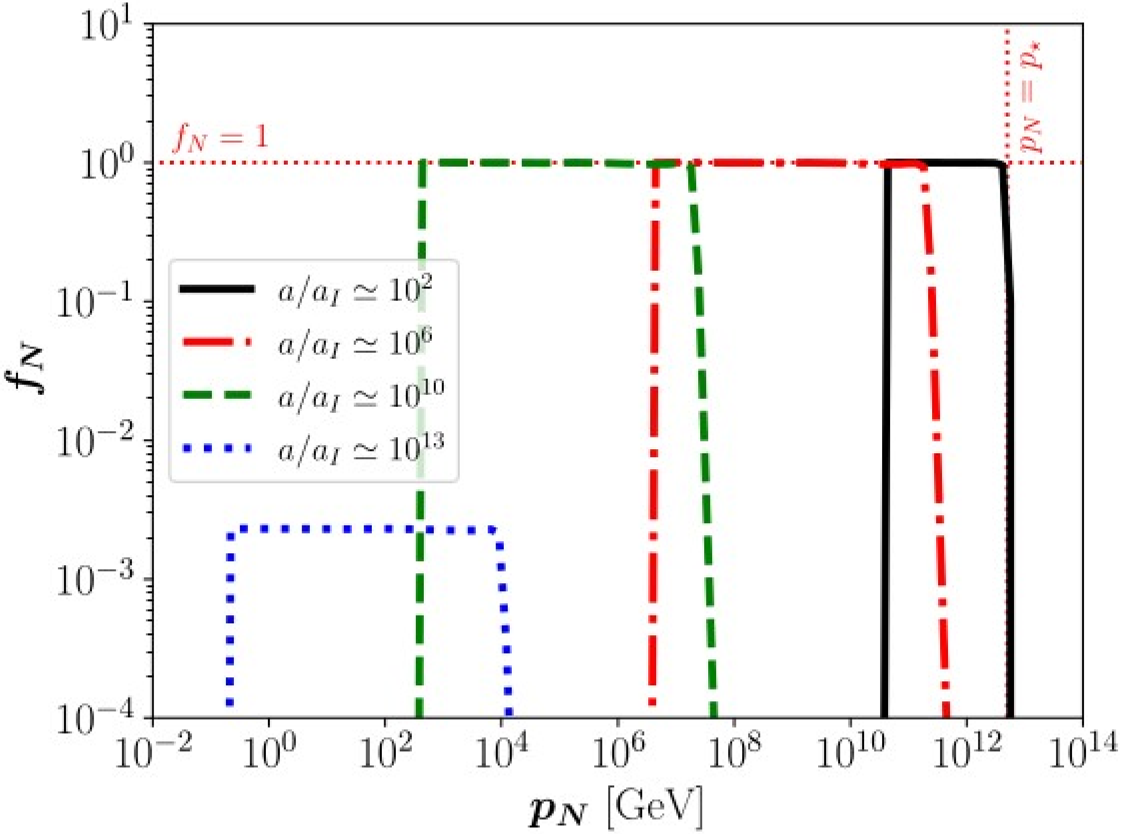




Similar broad phenomenology

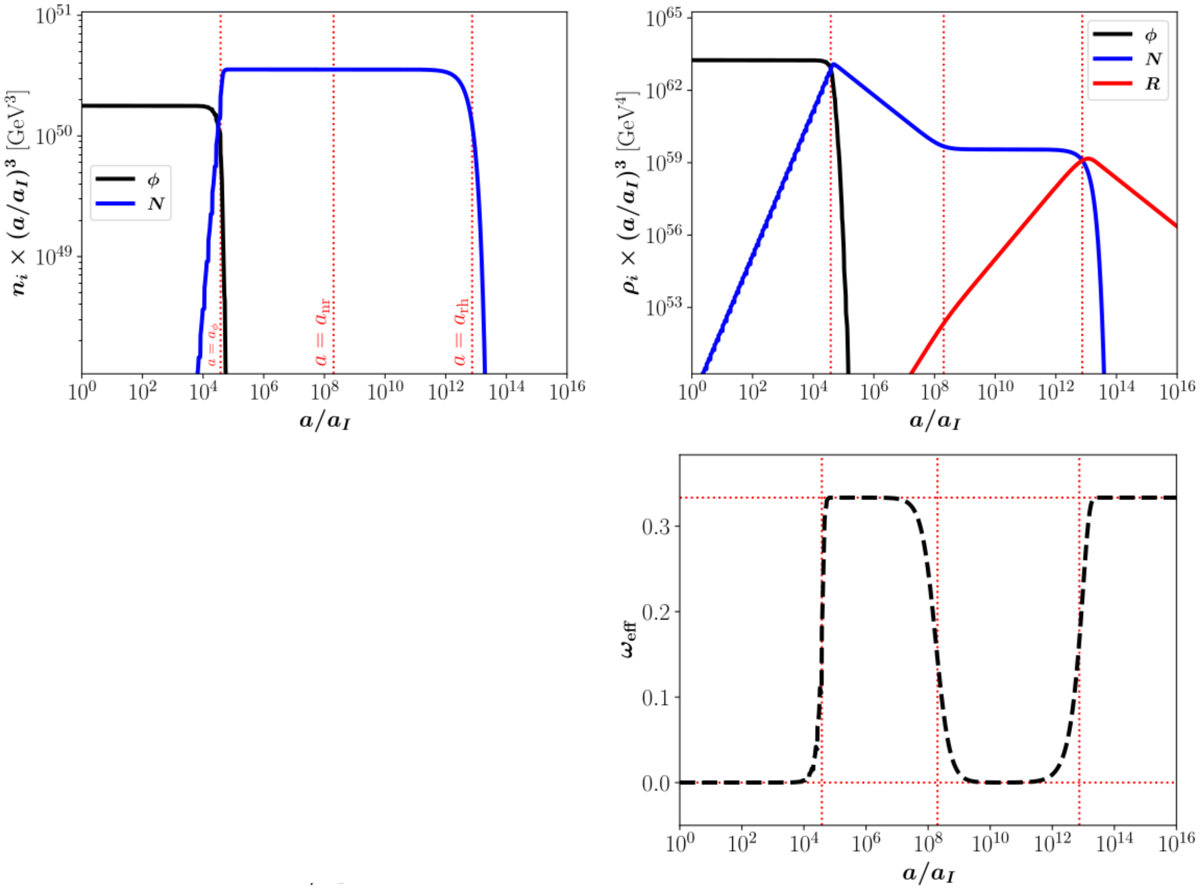
1. nonrelativistic ϕ
2. relativistic N
3. nonrelativistic N
4. SM domination

Seesaw Cosmology with Quantum Statistics



$$H_I = m_\phi = 10^{13}\ \text{GeV}$$
$$m_N = 10^9\ \text{GeV}$$
$$\Gamma_\phi = 10^{11}\ \text{GeV}$$
$$\Gamma_N = 10^{-8}\ \text{GeV}$$

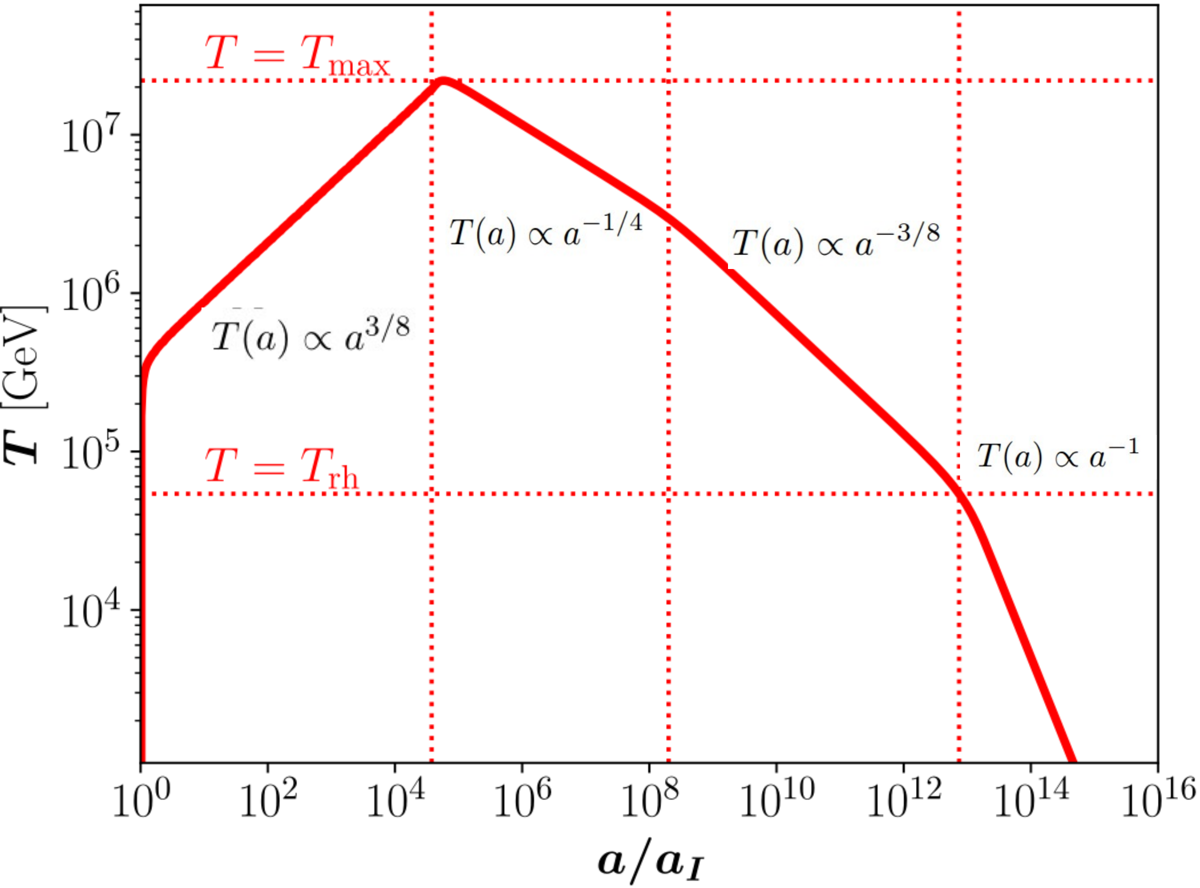
Seesaw Cosmology with Quantum Statistics



Similar broad phenomenology

1. nonrelativistic ϕ
2. relativistic N
3. nonrelativistic N
4. SM domination

Seesaw Cosmology with Quantum Statistics

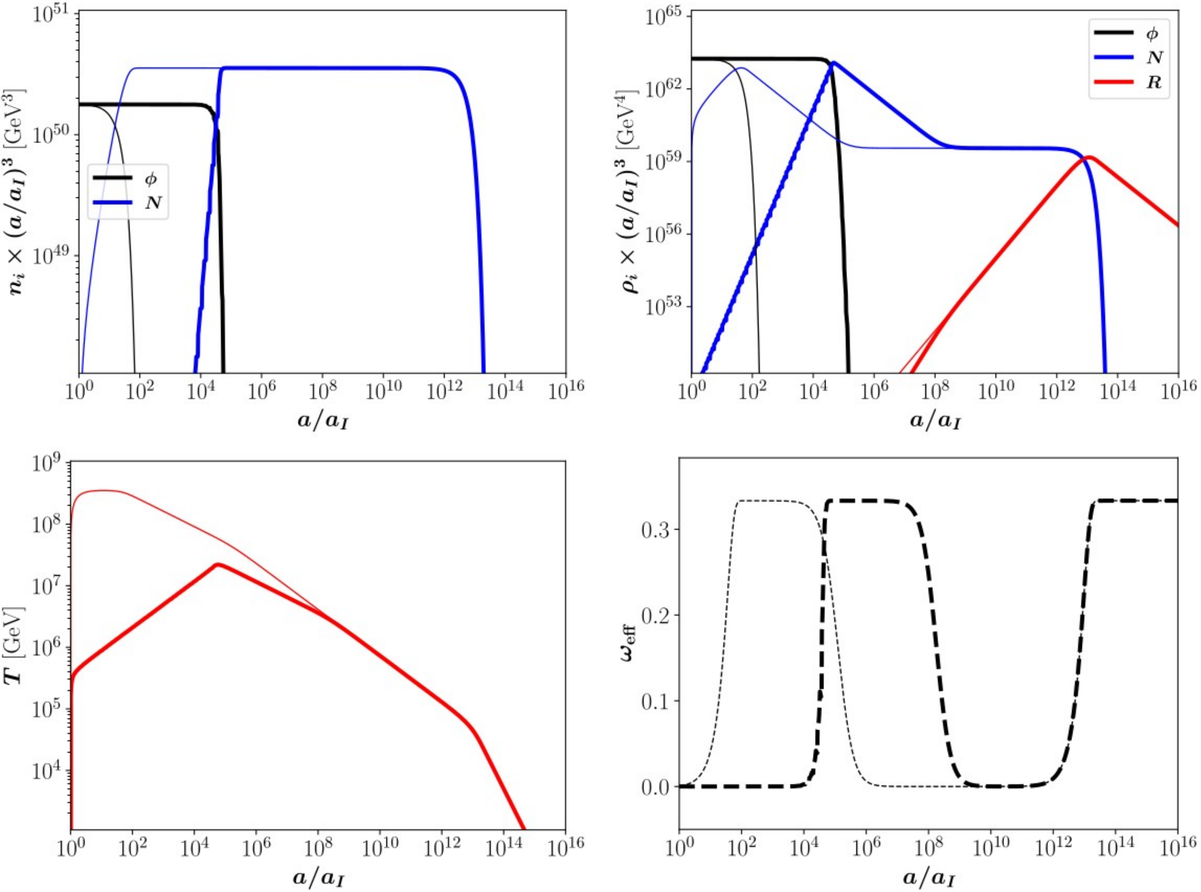


$$T_{\max}^4 \simeq \frac{60\,\beta_N}{11\sqrt{3}\,\pi^3\,g_\star} M_P\,\Gamma_N\,m_N\,m_\phi$$

$$T_{\rm rh}^2 \simeq \frac{6}{\pi}\sqrt{\frac{2}{5\,g_\star}}\,M_P\,\Gamma_N$$

→ ϕ decay is blocked
→ less N created
→ less SM produced
→ No plateau: $T(a) \propto a^{3/8}$

Seesaw Cosmology with Quantum Statistics

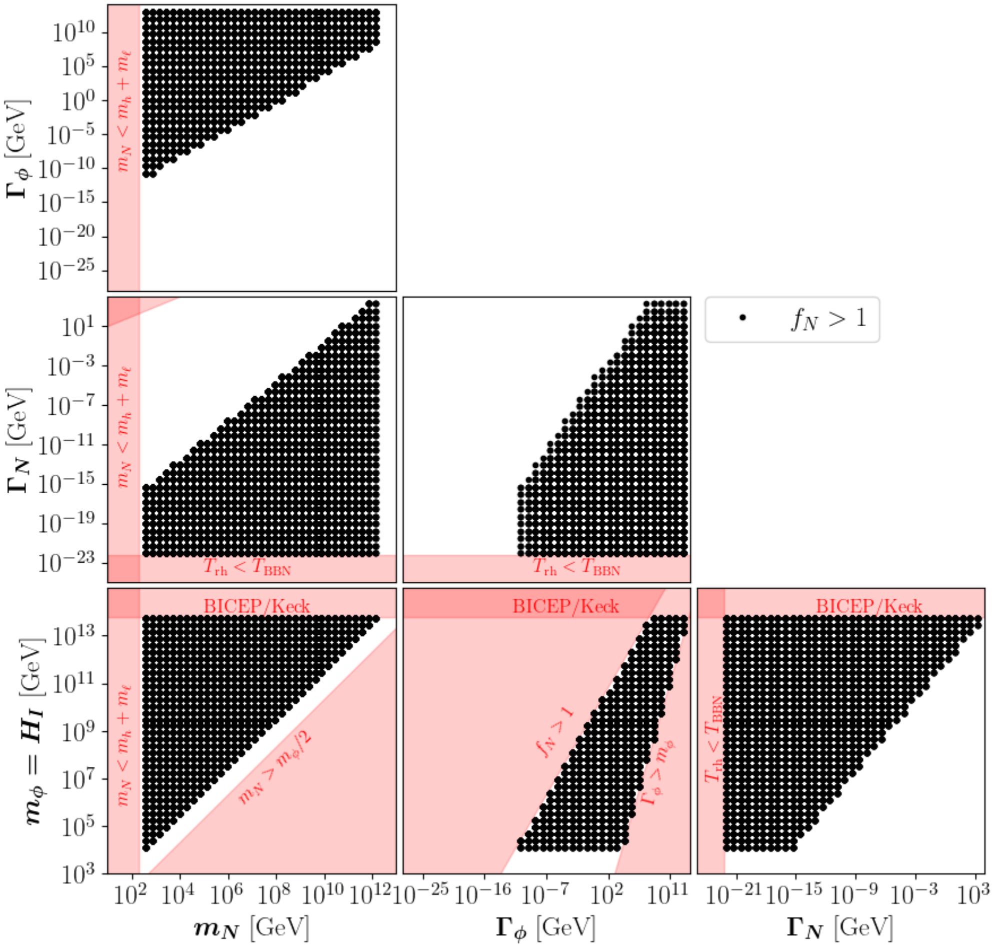


1. nonrelativistic ϕ **longer**
2. relativistic N unchanged
3. nonrelativistic N **shorter**
4. SM domination

$T_{\rm max}$ **decreased**
$T_{\rm rh}$ unchanged

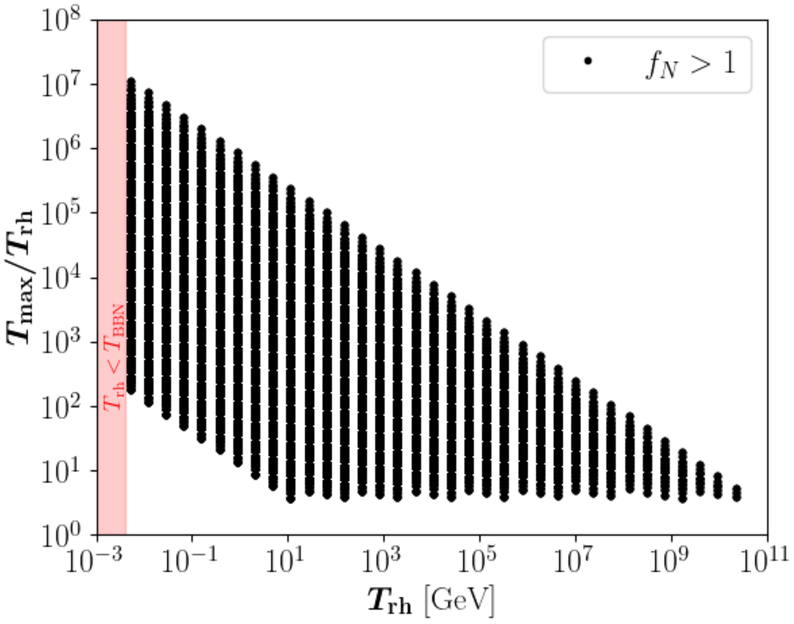
T plateau → $T(a) \propto a^{3/8}$

Seesaw cosmology



- Kinematics: $m_\phi > 2\,m_N$ and $m_N > m_h + m_\ell$
- BBN: $T_{\rm rh} > T_{\rm BBN} \quad \rightarrow \quad \Gamma_N > f(T_{\rm BBN})$
- BICEP/Keck: $H_I \lesssim 6 \times 10^{13}$ GeV
- Narrow decay widths: $\Gamma_i < m_i$
- $a_\phi/a_I,\ a_{\rm nr}/a_\phi,\ a_{\rm rh}/a_{\rm nr} > 10$
- $n = 3$ RHNs: $\Gamma_N \geq \frac{m_N^2}{8\pi\, v^2}\, m_0$
- $n = 2$ RHNs: $\Gamma_N \geq \frac{m_N^2}{8\pi\, v^2}\sqrt{\Delta m^2_{\rm sol}}$ (NO)
- Full Pauli saturation: $f_N > 1$

Seesaw cosmology



- Kinematics: $m_\phi > 2\, m_N \quad \text{and} \quad m_N > m_h + m_\ell$
- BBN: $T_{\rm rh} > T_{\rm BBN} \quad \rightarrow \quad \Gamma_N > f(T_{\rm BBN})$
- BICEP/Keck: $H_I \lesssim 6 \times 10^{13}$ GeV
- Narrow decay widths: $\Gamma_i < m_i$
- a_ϕ/a_I, $a_{\rm nr}/a_\phi$, $a_{\rm rh}/a_{\rm nr} > 10$
- $n = 3$ RHNs: $\Gamma_N \geq \frac{m_N^2}{8\pi\, v^2}\, m_0$
- $n = 2$ RHNs: $\Gamma_N \geq \frac{m_N^2}{8\pi\, v^2} \sqrt{\Delta m^2_{\rm sol}}$ (NO)
- Full Pauli saturation: $f_N > 1$

Seesaw Cosmology with Quantum Statistics

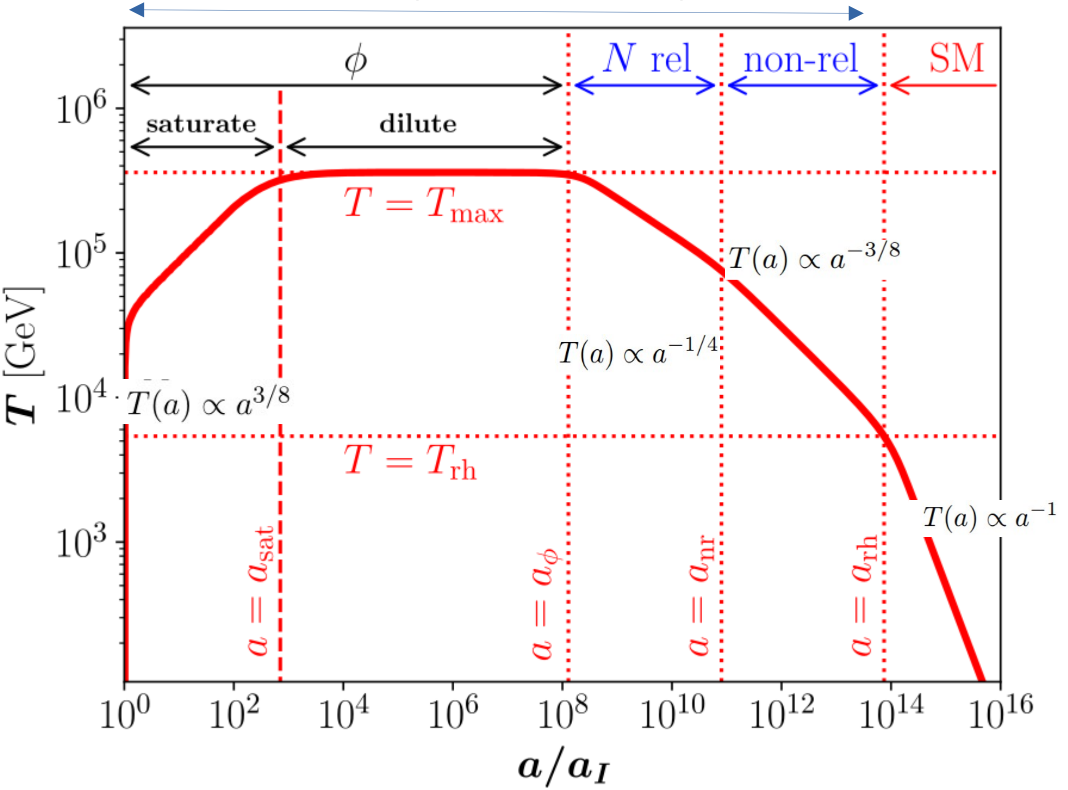
$\mathcal{H}_I = m_\phi = 10^{12}$ GeV

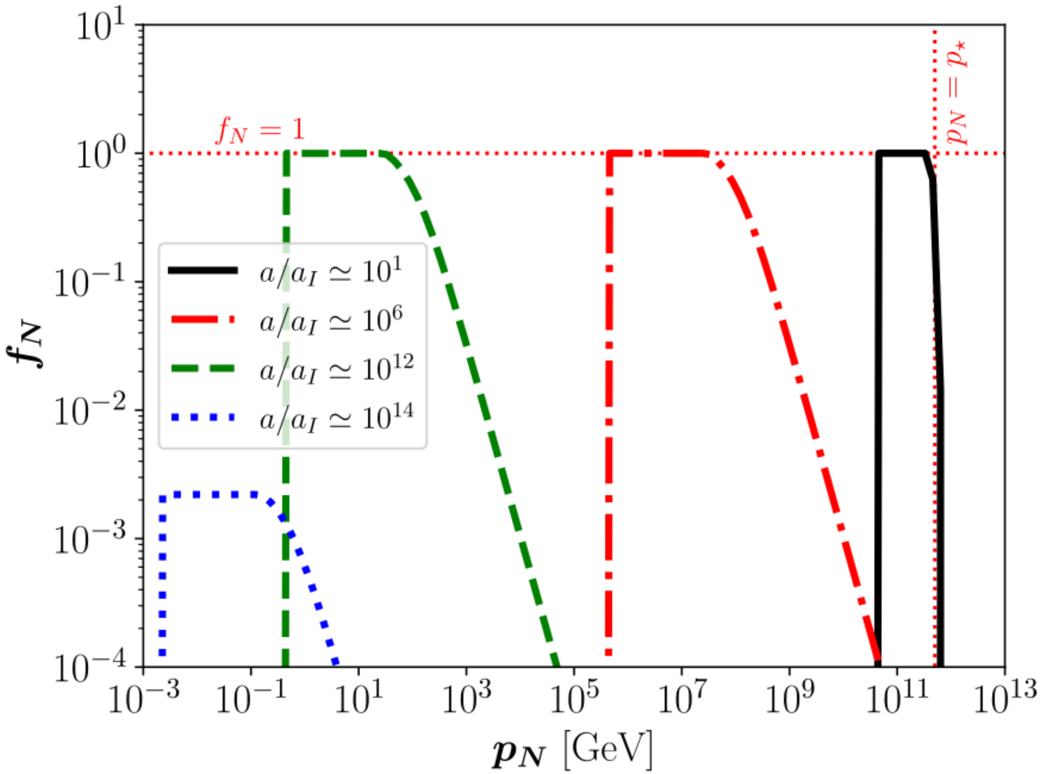
$m_N = 10^9$ GeV

$\Gamma_\phi = 1$ GeV

$\Gamma_N = 10^{-10}$ GeV

4 stages reheating





Seesaw Cosmology Conclusions

Two-step decay: $\phi \to N\, N$ then $N \to H\, \ell$

* Cosmic reheating solved at the level of phase-space distributions
* $\phi \to N\, N$ decays with Pauli blocking
* $N\, N \to \phi$ inverse decays with Bose enhancement
* fully numerical analysis + analytical estimates

	Cosmic reheating				**SM domination**
	ϕ		N		
	saturate	dilute	relativistic	nonrel	
$\boldsymbol{\omega_{\text{eff}}}$	0	0	1/3	0	1/3
$\boldsymbol{T(a)}$	$a^{+3/8}$	a^0	$a^{-1/4}$	$a^{-3/8}$	a^{-1}

* neutrino masses through type-I seesaw
* Phenomenology: Dark matter, leptogenesis, PGWs...

¡Muchas gracias!