Seesaw Cosmology

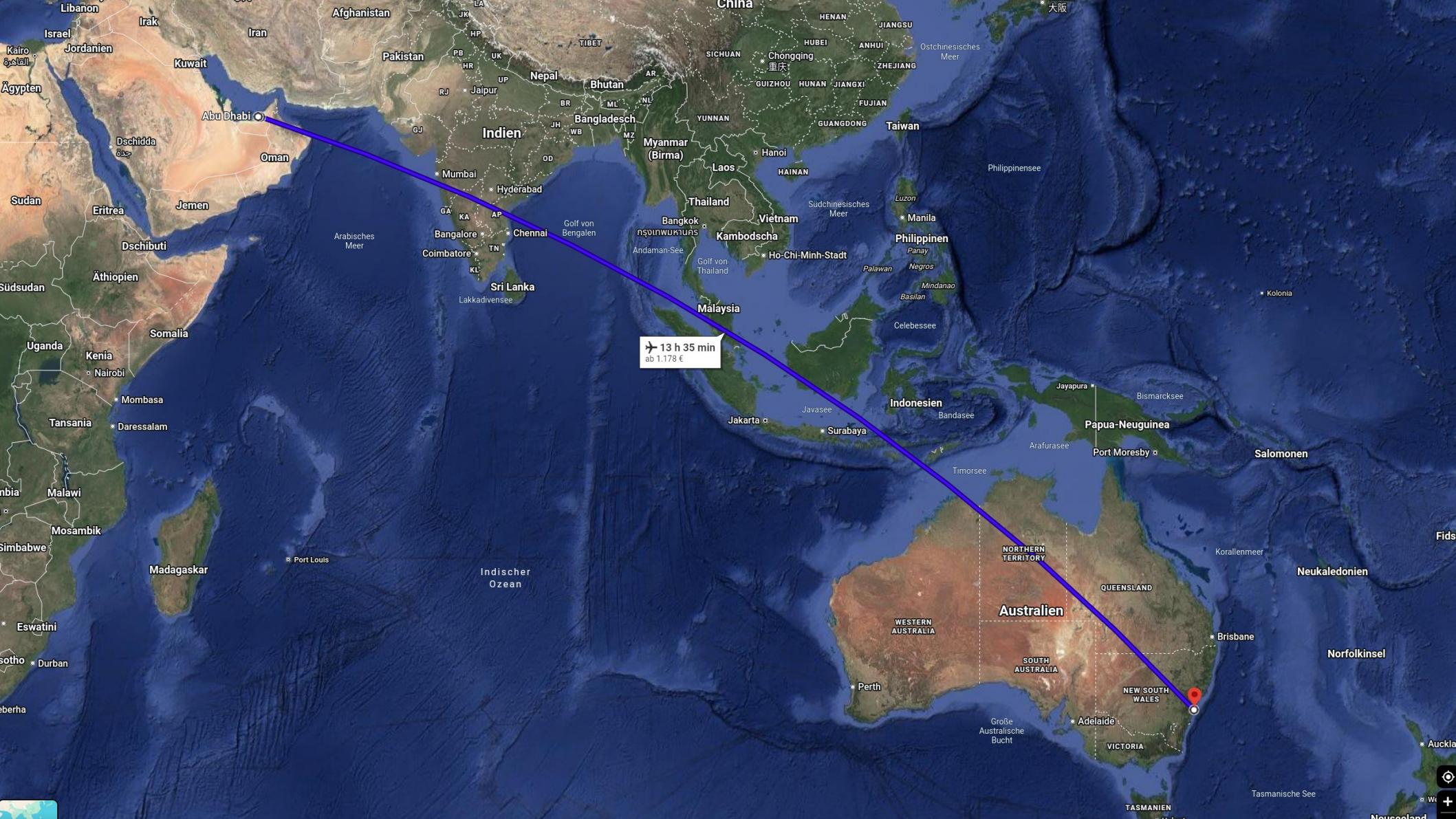
Based on:
NB, C. S. Fong, Ó. Zapata
arXiv:2607.27325 and arXiv:2609.17681

Nicolás BERNAL

جامعة نيويورك أبوظبي

NYU ABU DHABI

Sydney-CPPC zoom seminar
November 5th, 2026 – **6 am**


13 h 35 min
ab 1.178 €
Abu Dhabi
Sydney
Libanon
Israel
Irak
Iran
Afghanistan
Jordanien
Kuwait
Pakistan
Nepal
Bhutan
Bangladesch
Indien
China
Taiwan
Ostchinesisches Meer
Südchinesisches Meer
Philippinensee
Myanmar (Birma)
Laos
Thailand
Vietnam
Kambodscha
Hanoi
Bangkok
Manila
Philippinen
Ho-Chi-Minh-Stadt
Kolonia
Ägypten
Kairo
Dschidda
Oman
Sudan
Eritrea
Jemen
Dschibuti
Äthiopien
Südsudan
Somalia
Uganda
Kenia
Nairobi
Mombasa
Tansania
Daressalam
Malawi
Mosambik
Simbabwe
Madagaskar
Port Louis
Eswatini
Durban
Mumbai
Hyderabad
Bangalore
Chennai
Coimbatore
Sri Lanka
Lakkadivensee
Arabisches Meer
Golf von Bengalen
Andaman-See
Golf von Thailand
Malaysia
Indonesien
Jakarta
Surabaya
Javasee
Bandasee
Celebessee
Timorsee
Arafurasee
Jayapura
Bismarcksee
Papua-Neuguinea
Port Moresby
Salomonen
Neukaledonien
Korallenmeer
Indischer Ozean
Australien
NORTHERN TERRITORY
QUEENSLAND
WESTERN AUSTRALIA
SOUTH AUSTRALIA
NEW SOUTH WALES
VICTORIA
Brisbane
Perth
Adelaide
Große Australische Bucht
Norfolkinsel
Tasmanische See
TASMANIEN

Standard Reheating

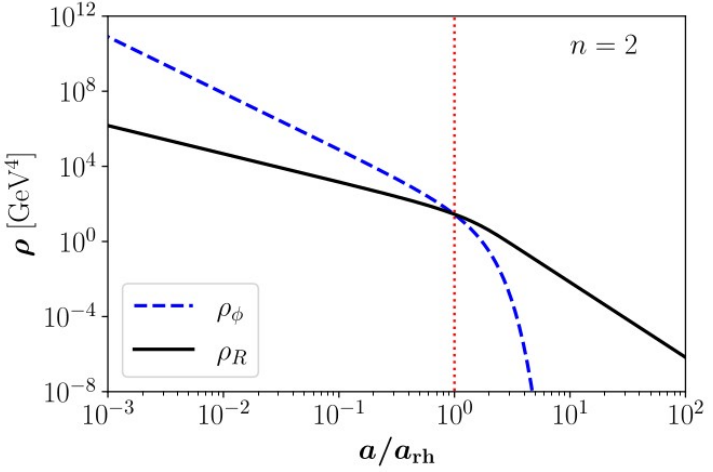
* Singlet scalar inflaton ϕ decays
  or annihilates at rest
  into a pair of SM Higgses: $\phi \to H\,H$

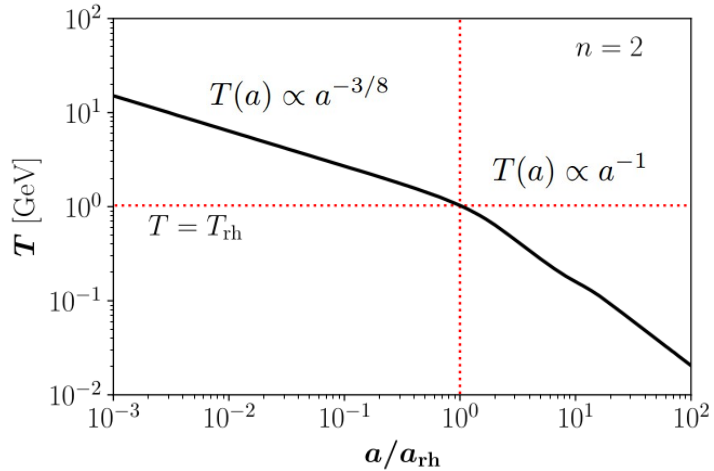
* Only channel available (dim 4)

* 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: $\phi \to N\,N$ then $N \to H\,\ell$

* 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

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

Reheating in Seesaw Cosmology

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

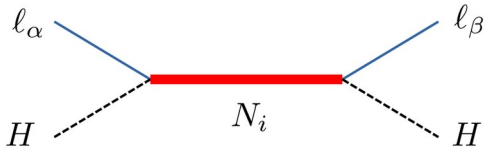
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à la type-I seesaw

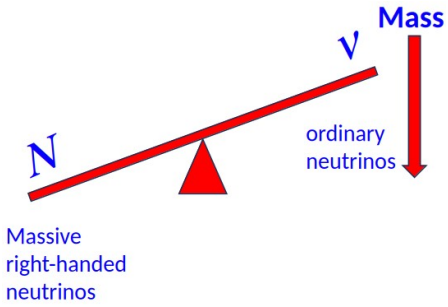
Type-I Seesaw

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



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

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



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

* for n = 2 RHNs

$$\Gamma_{N_i} \geq \frac{M_i^2}{8\pi v^2} \begin{cases} \sqrt{\Delta m^2_{\text{sol}}} & \text{for NO,} \\ \sqrt{\left|\Delta m^2_{\text{atm}}\right|} & \text{for IO.} \end{cases}$$

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

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

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

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

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

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

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

Seesaw Cosmology

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Seesaw Cosmology

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

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

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

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System of **coupled integro-differential** equations

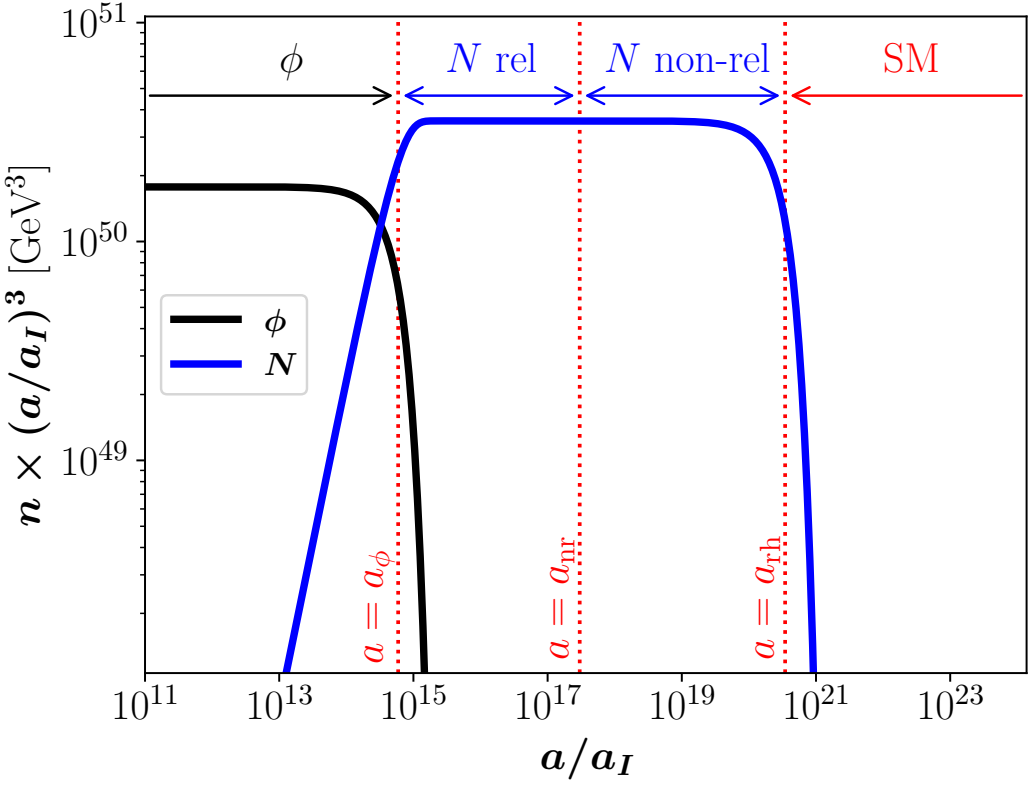
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Seesaw Cosmology

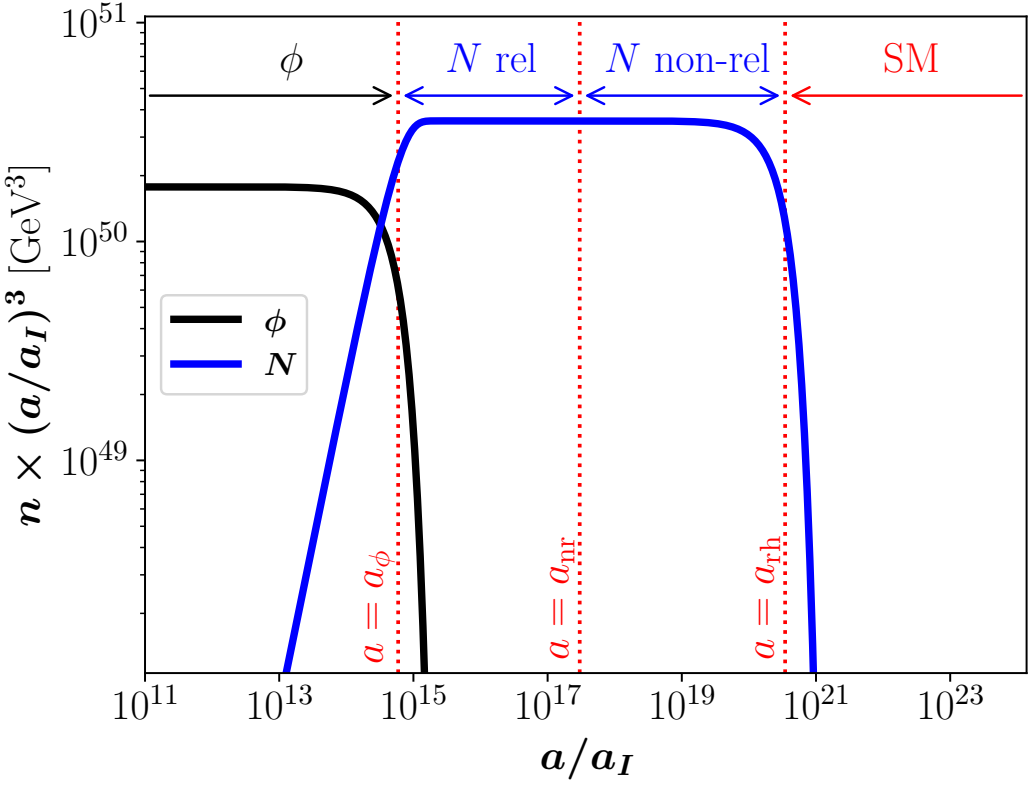
3 stages reheating



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

Seesaw Cosmology

3 stages reheating



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Duration of the eras

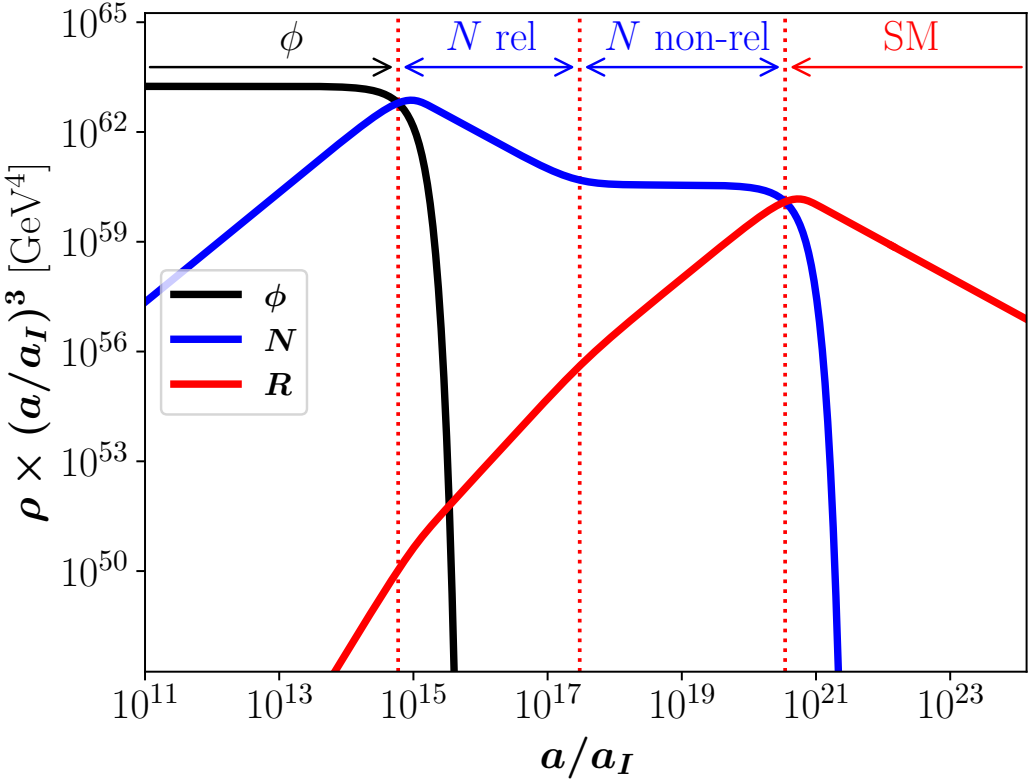
ϕ
$$\frac{a_\phi}{a_I} \simeq \left(\frac{5}{2}\frac{H_I}{\Gamma_\phi}\right)^{2/3}$$

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



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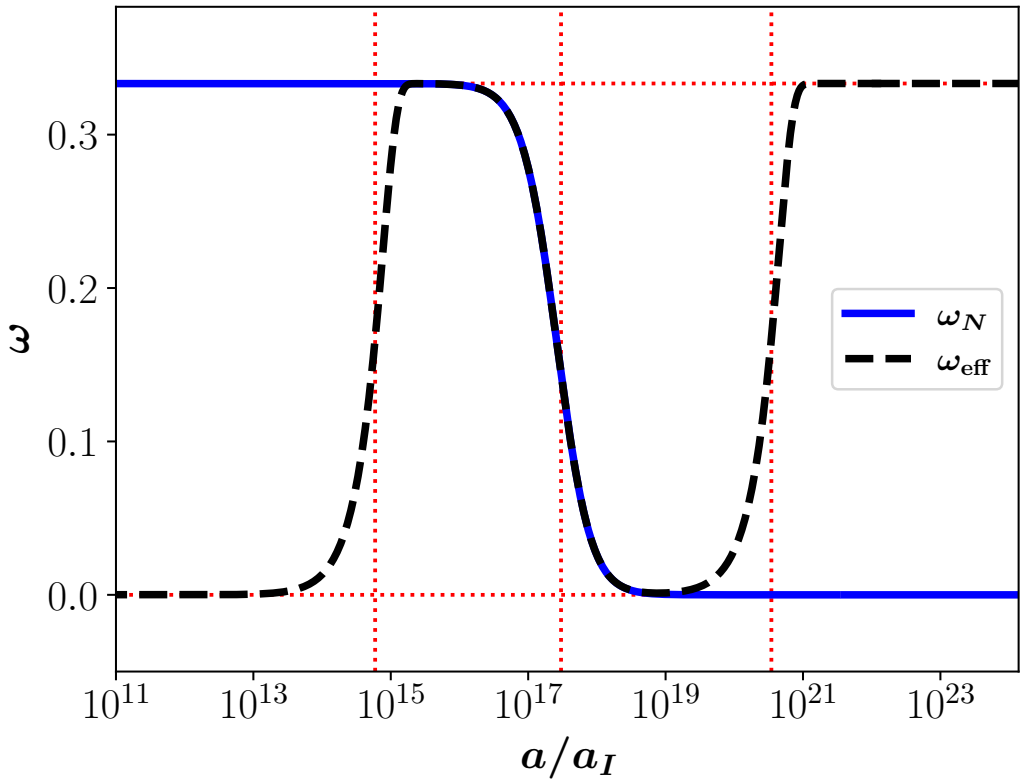
$$\phi \qquad \frac{a_\phi}{a_I} \simeq \left(\frac{5}{2}\frac{H_I}{\Gamma_\phi}\right)^{2/3}$$

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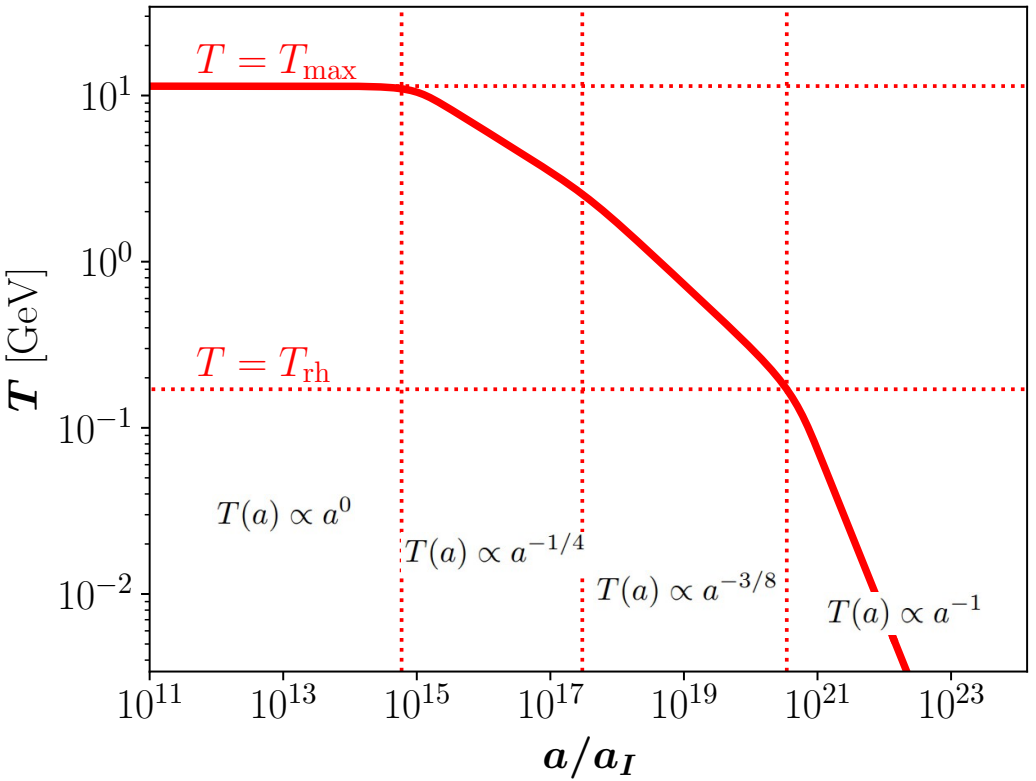
Seesaw Cosmology

3 stages reheating



Seesaw Cosmology

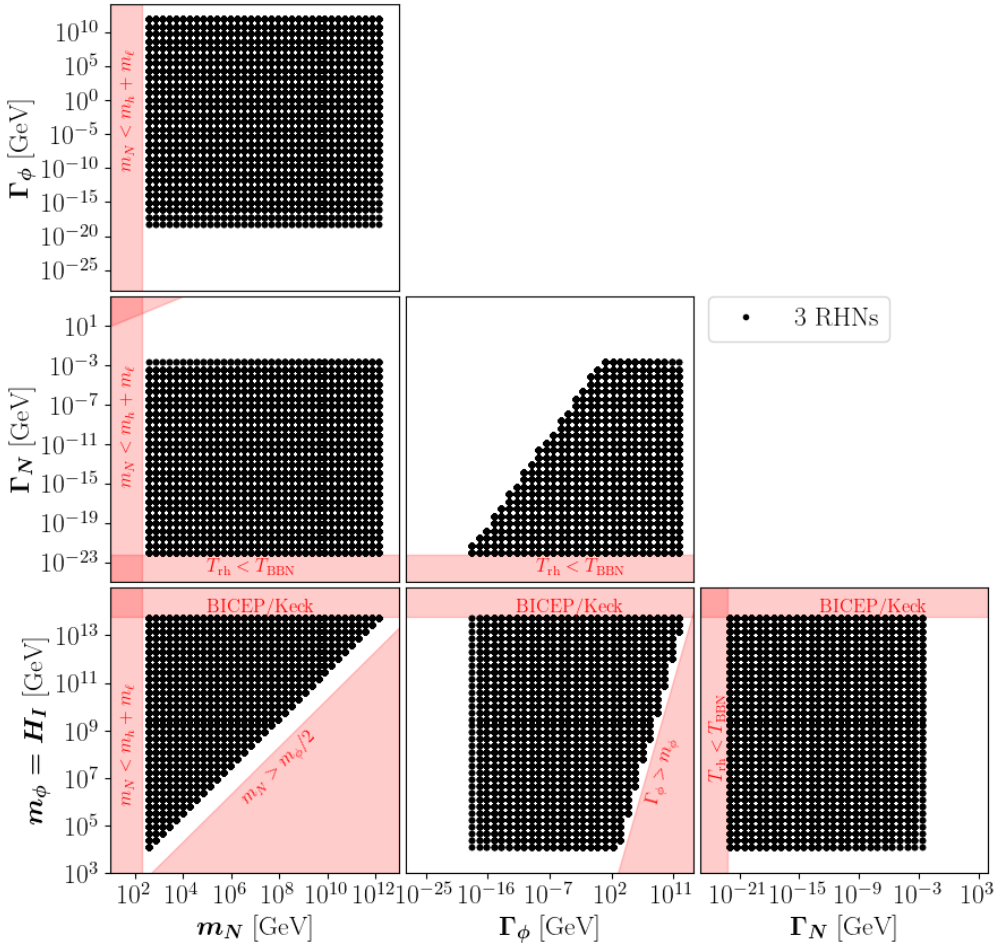
3 stages reheating



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

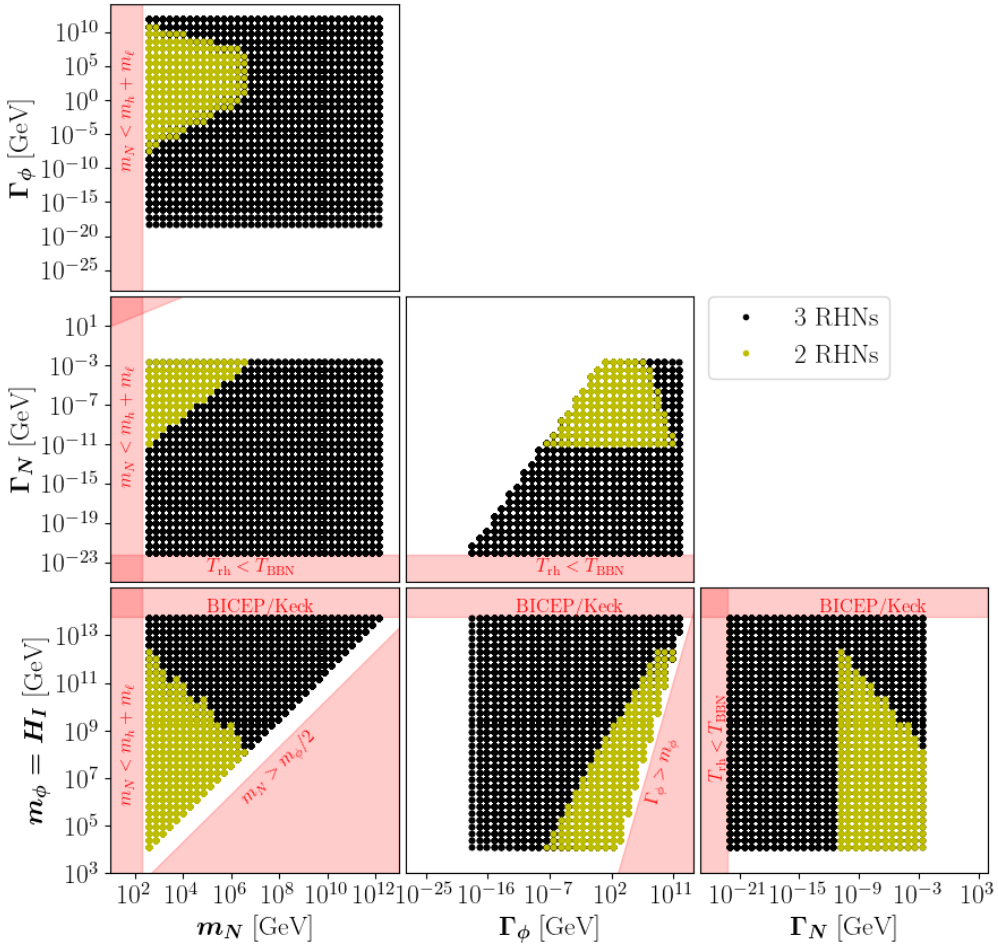
$$T_{\rm rh}^2 \simeq \frac{6}{\pi}\sqrt{\frac{2}{5\, g_\star}}\, M_P\, \Gamma_N$$

Seesaw Cosmology



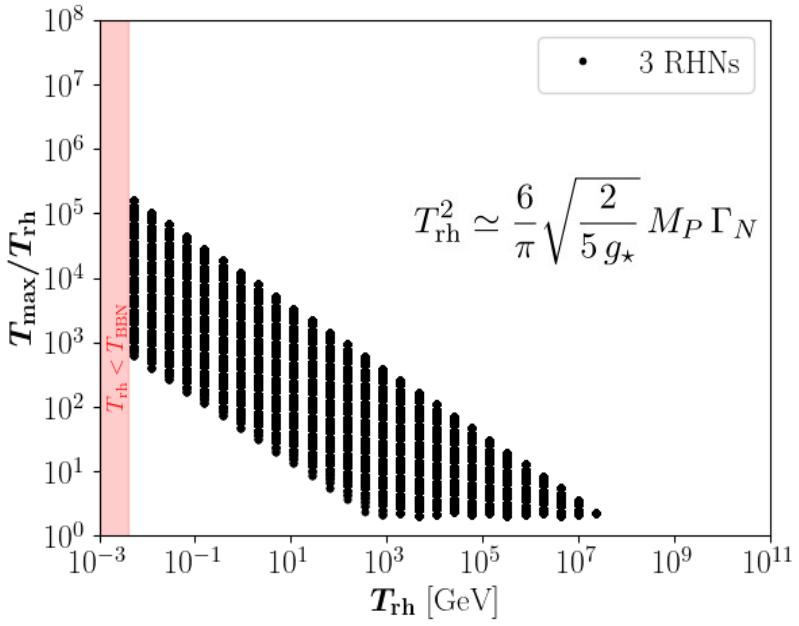
- Kinematics: $m_\phi > 2\, m_N$ and $m_N > m_h + m_\ell$
- BBN: $T_{\rm rh} > T_{\rm BBN} \quad \rightarrow \quad \Gamma_N > f(T_{\rm BBN})$
- BICEP/Keck: $H_I \lesssim 6 \times 10^{13}$ GeV
- Narrow decay widths: $\Gamma_i < m_i$
- $a_\phi/a_I,\ a_{\rm nr}/a_\phi,\ a_{\rm rh}/a_{\rm nr} > 10$
- $n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

Seesaw Cosmology



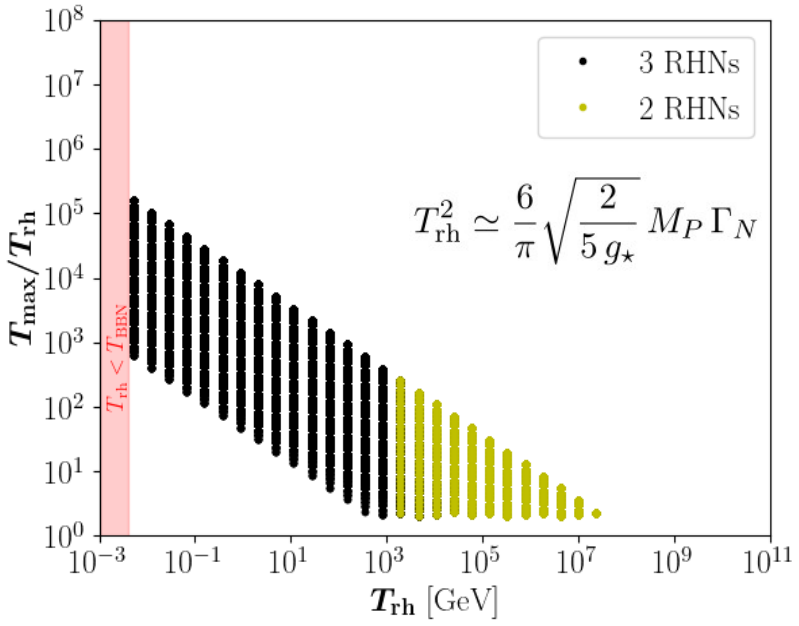
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- $n = 2$ RHNs: $\Gamma_N \geq \frac{m_N^2}{8\pi\, v^2}\, \sqrt{\Delta m^2_{\rm sol}}$ (NO)

Seesaw Cosmology



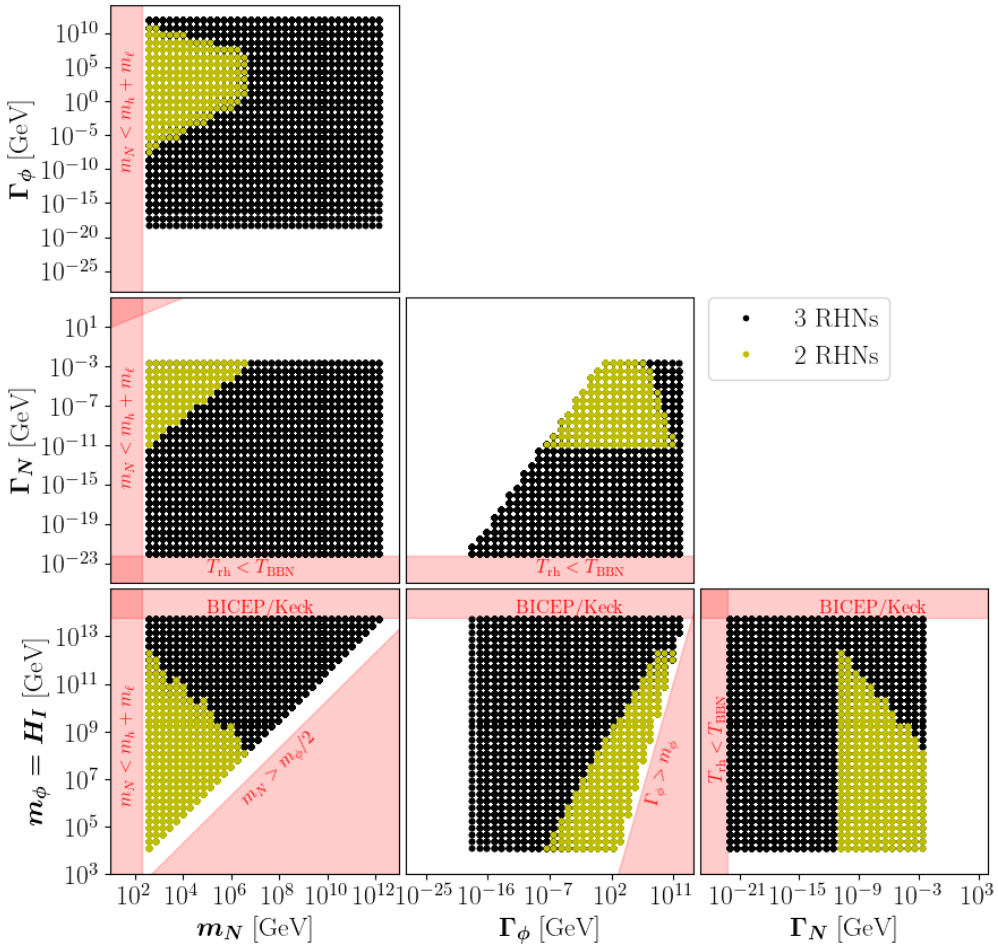
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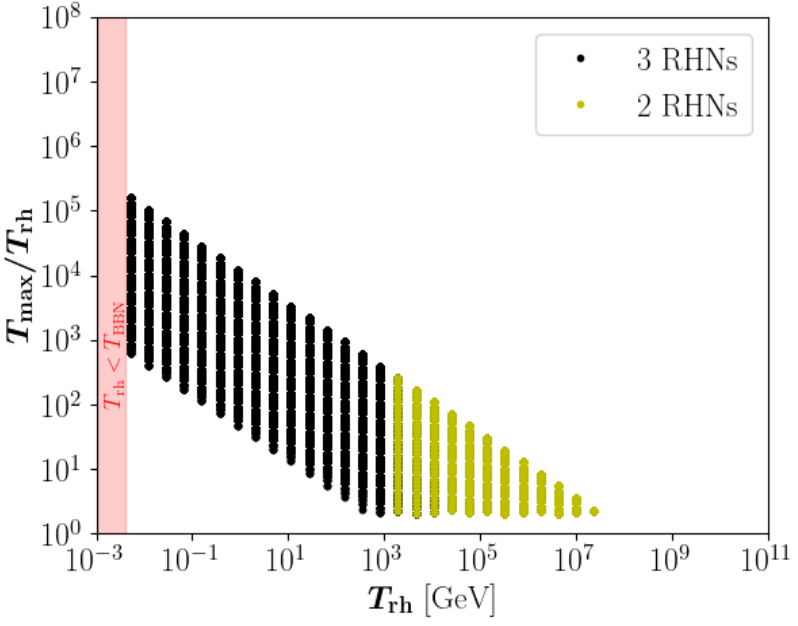
Seesaw Cosmology



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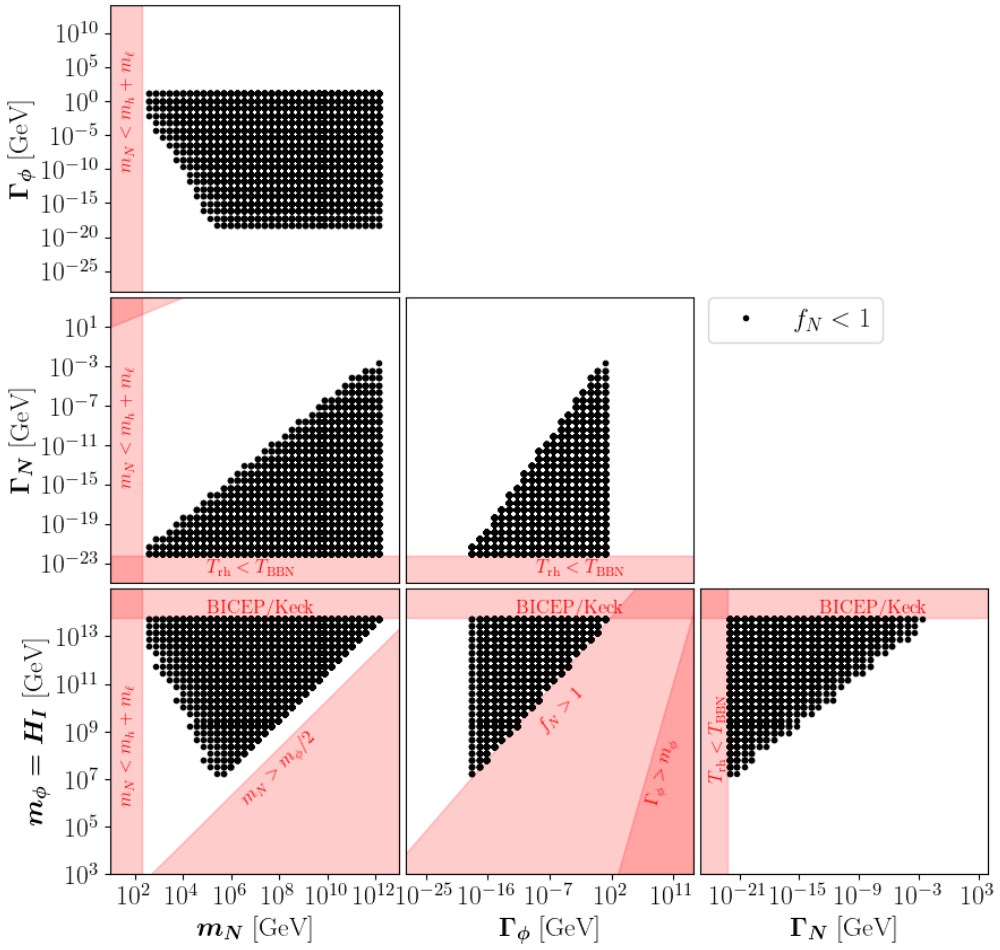
Seesaw Cosmology

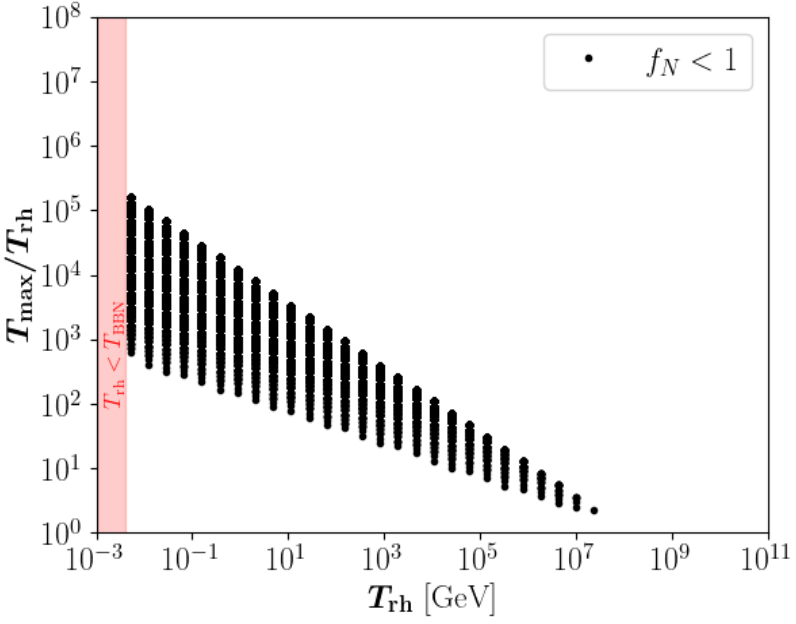




What about the role of **quantum statistics?**

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

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

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

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

Seesaw Cosmology with Quantum Statistics

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

System of **coupled integro-differential** equations

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

Seesaw Cosmology with Quantum Statistics

Assume ϕ has a highly nonrelativistic *initial* distribution

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

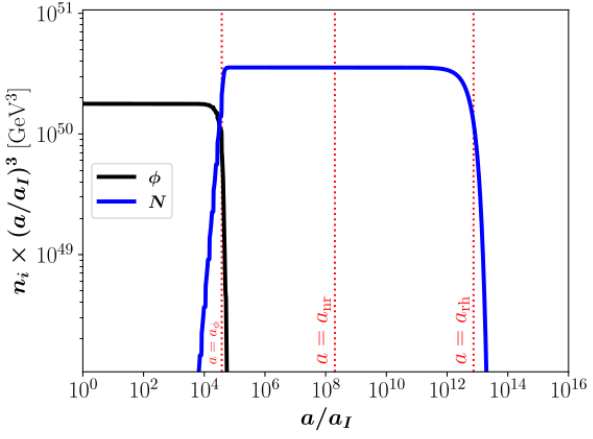
System of **coupled integro-differential** equations

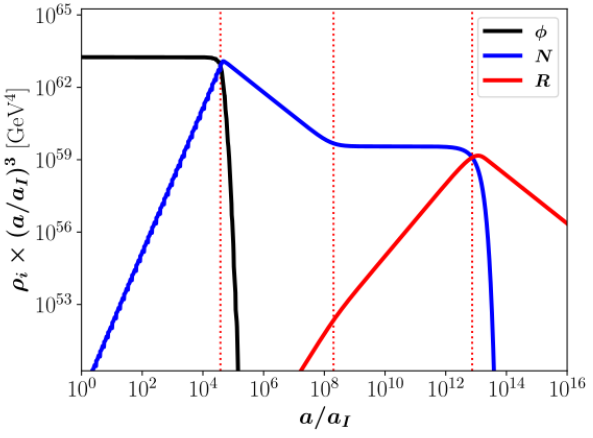
$$\left[\frac{\partial}{\partial t} - \mathcal{H}\, p_\phi \, \frac{\partial}{\partial p_\phi}\right] f_\phi(p_\phi, t) = -\Gamma_\phi \, f_\phi(p_\phi, t) \, [1 - f_N(p_\star, t)]$$

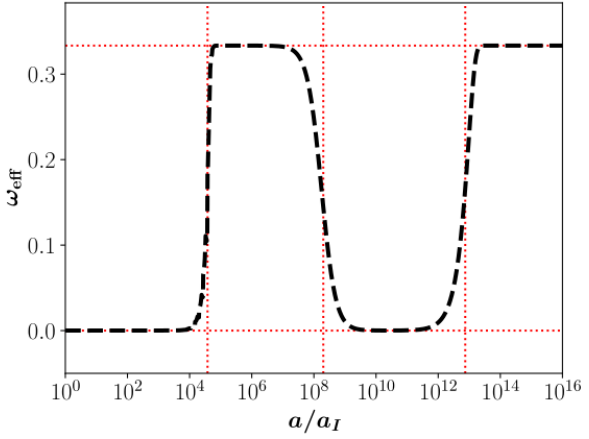
$$\left[\frac{\partial}{\partial t} - \mathcal{H}\, p_N \, \frac{\partial}{\partial p_N}\right] f_N(p_N, t) = \frac{2\pi^2 \, \Gamma_\phi \, n_\phi}{p_\star^2} \, \delta(p_N - p_\star) \, [1 - f_N(p_\star, t)] - \frac{\Gamma_N \, m_N}{E_N} \, f_N(p_N, t)$$

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

Seesaw Cosmology with Quantum Statistics

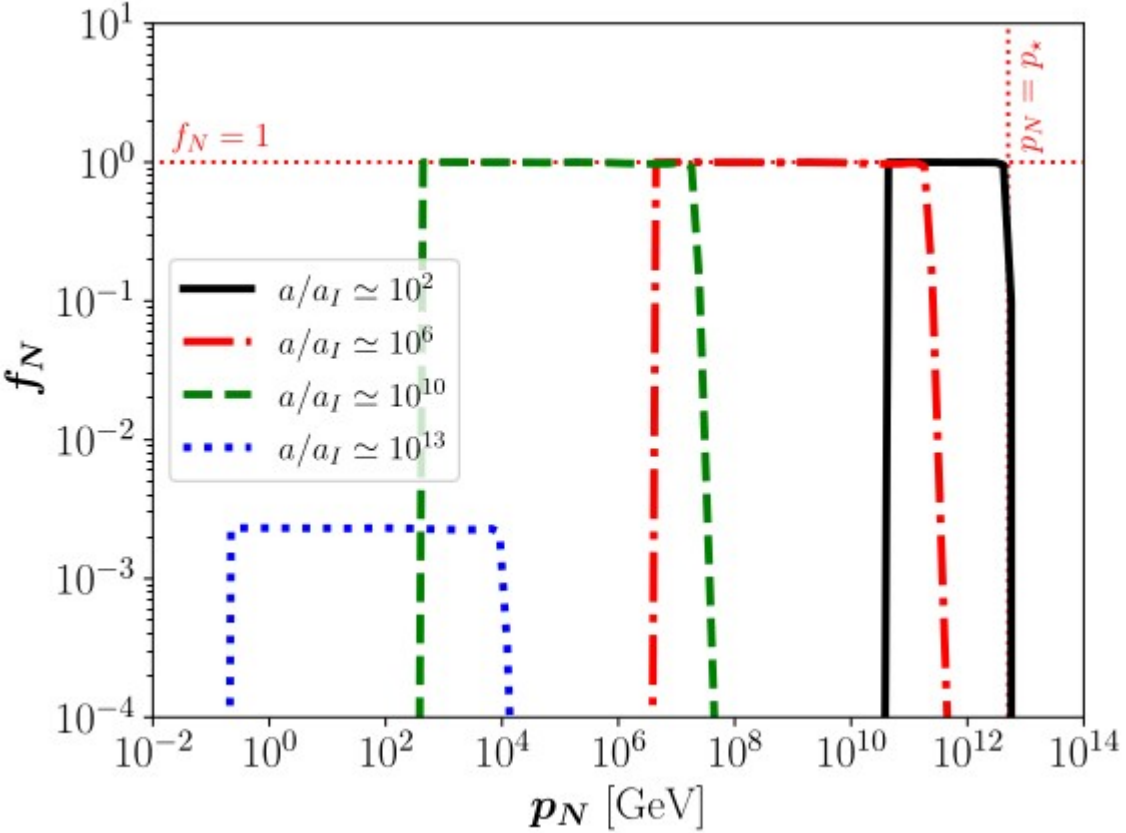






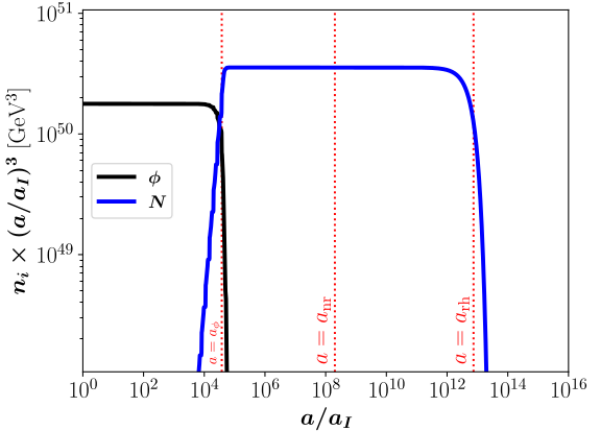
Similar broad phenomenology
1. nonrelativistic ϕ
2. relativistic N
3. nonrelativistic N
4. SM domination

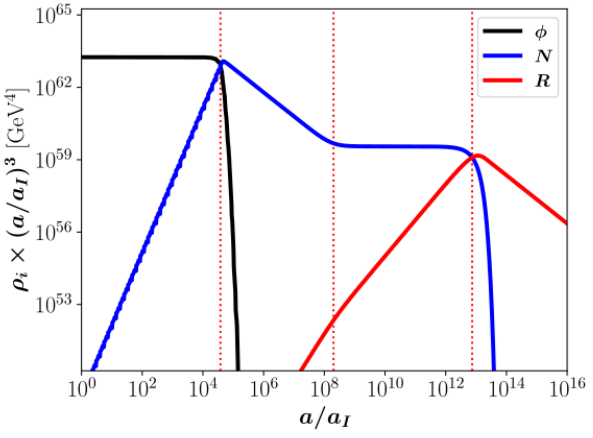
Seesaw Cosmology with Quantum Statistics

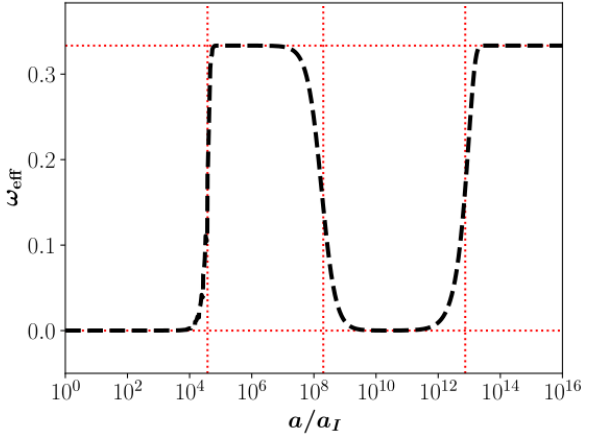


$$H_I = m_\phi = 10^{13}\ \text{GeV}$$
$$m_N = 10^9\ \text{GeV}$$
$$\Gamma_\phi = 10^{11}\ \text{GeV}$$
$$\Gamma_N = 10^{-8}\ \text{GeV}$$

Seesaw Cosmology with Quantum Statistics

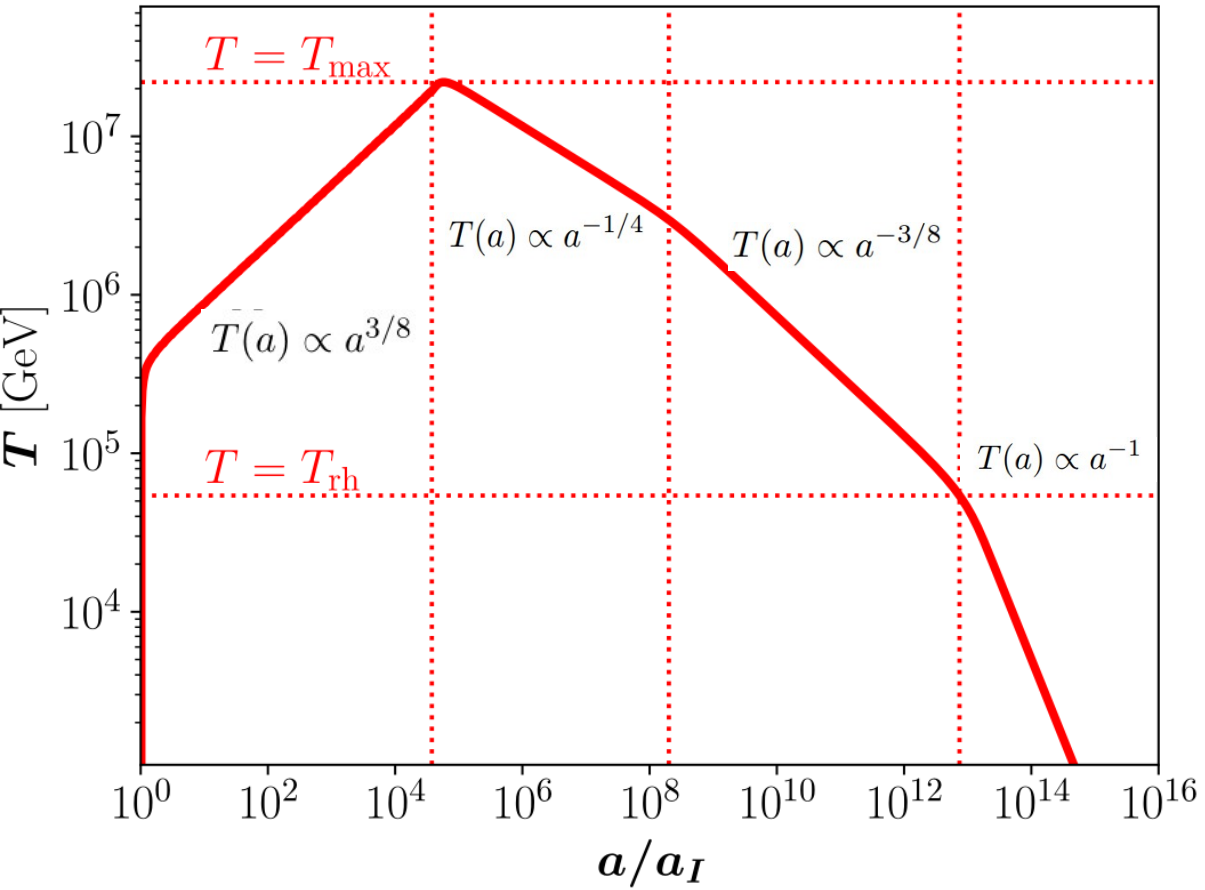






Similar broad phenomenology
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Seesaw Cosmology with Quantum Statistics

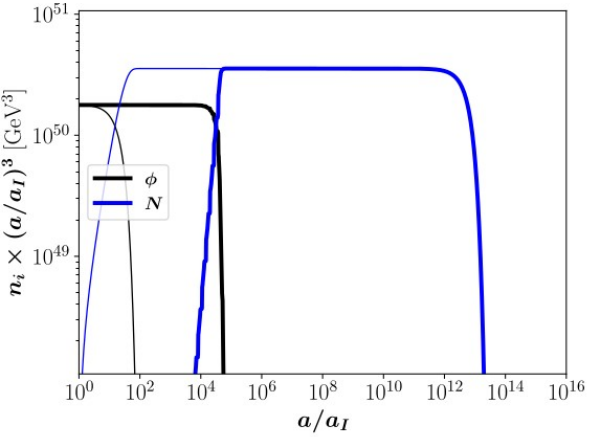


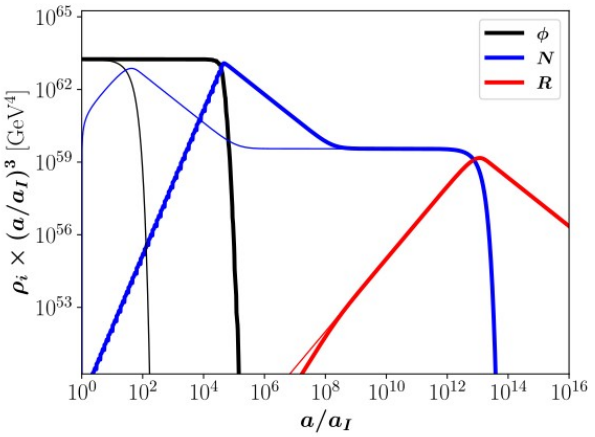
$$T_{\rm max}^4 \simeq \frac{60\,\beta_N}{11\sqrt{3}\,\pi^3\,g_\star}\,M_P\,\Gamma_N\,m_N\,m_\phi$$

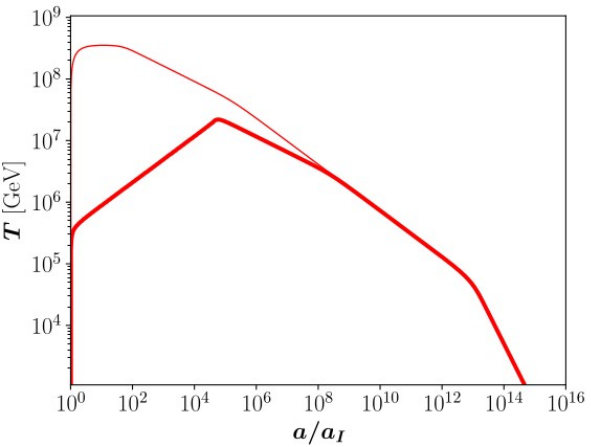
$$T_{\rm rh}^2 \simeq \frac{6}{\pi}\sqrt{\frac{2}{5\,g_\star}}\,M_P\,\Gamma_N$$

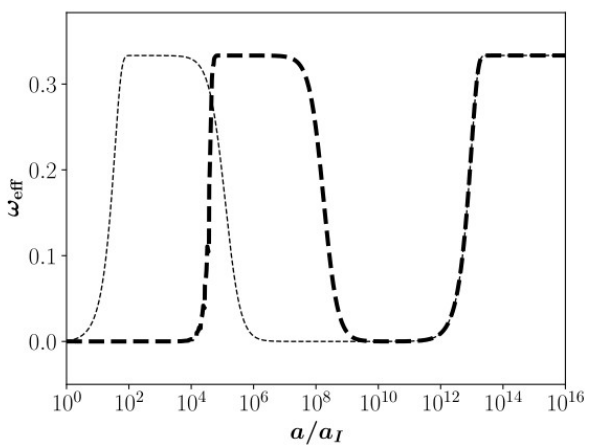
→ ϕ decay is blocked
→ less N created
→ less SM produced
→ No plateau: $T(a) \propto a^{3/8}$

Seesaw Cosmology with Quantum Statistics









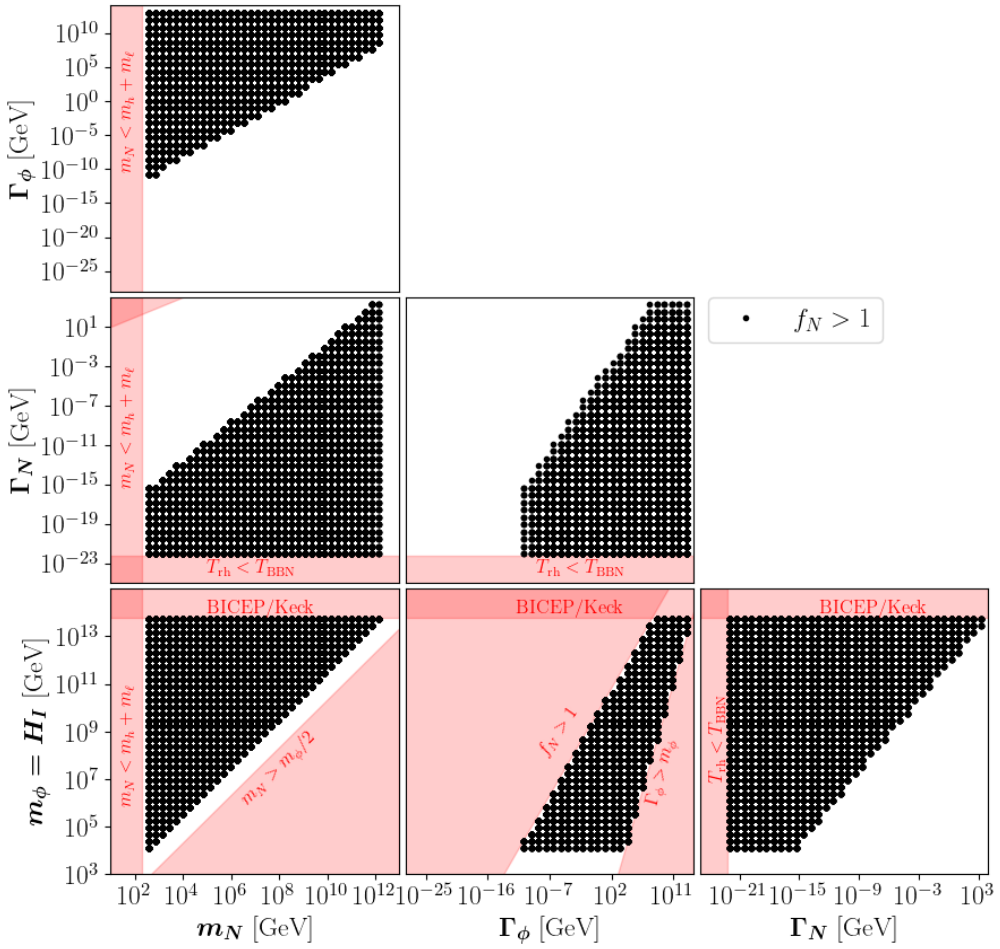
1. nonrelativistic ϕ **longer**
2. relativistic N unchanged
3. nonrelativistic N **shorter**
4. SM domination

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

$T_{\rm rh}$ unchanged

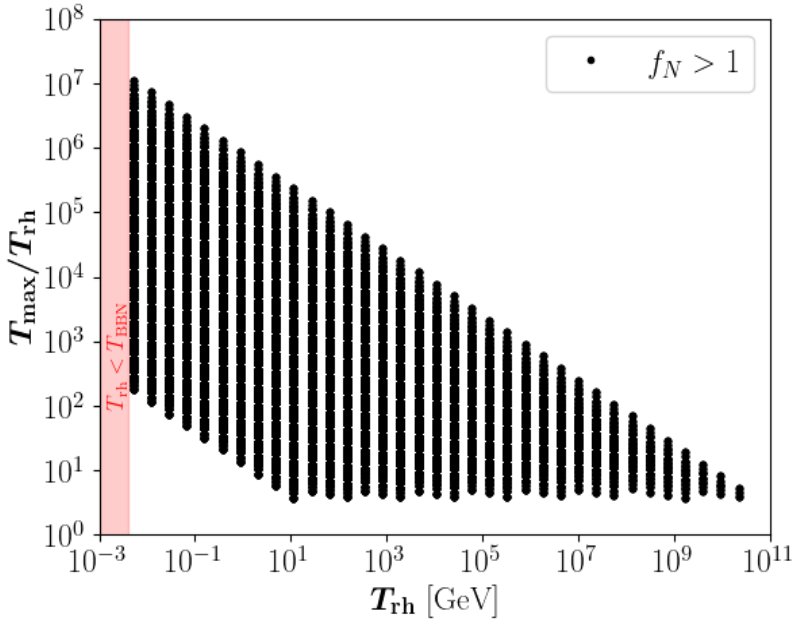
T plateau → $T(a) \propto a^{3/8}$

Seesaw cosmology



- Kinematics: $m_\phi > 2\,m_N \quad$ 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: $f_N = 1$

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Seesaw Cosmology with Quantum Statistics

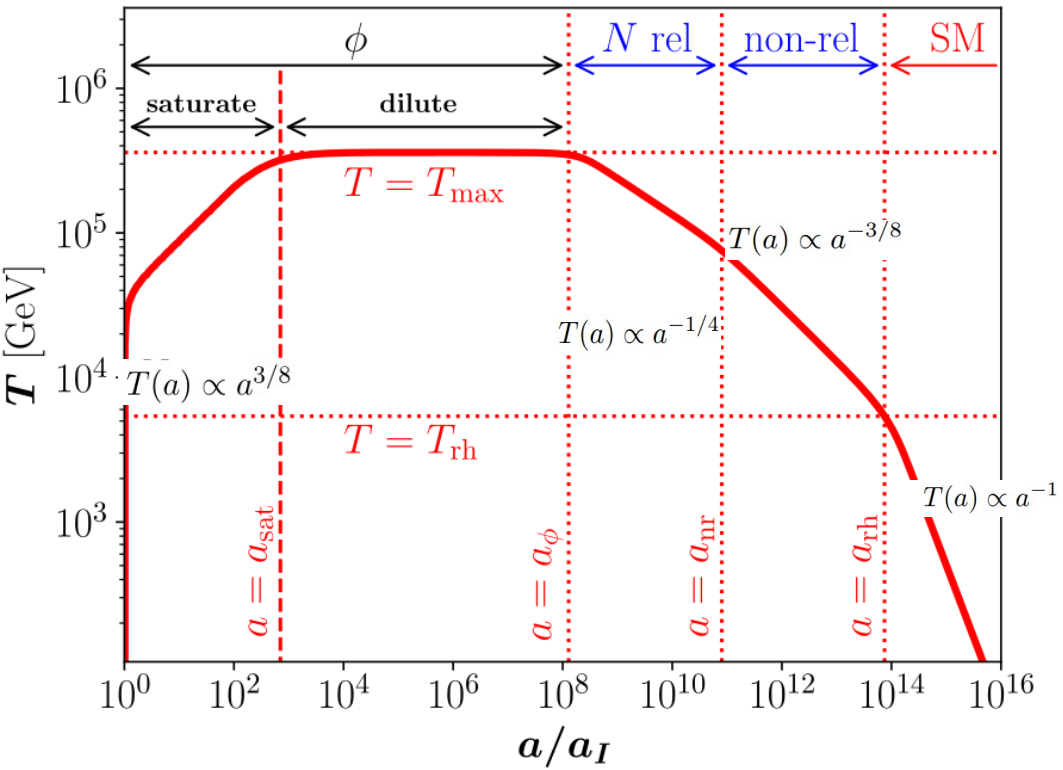
$\mathcal{H}_I = m_\phi = 10^{12}$ GeV

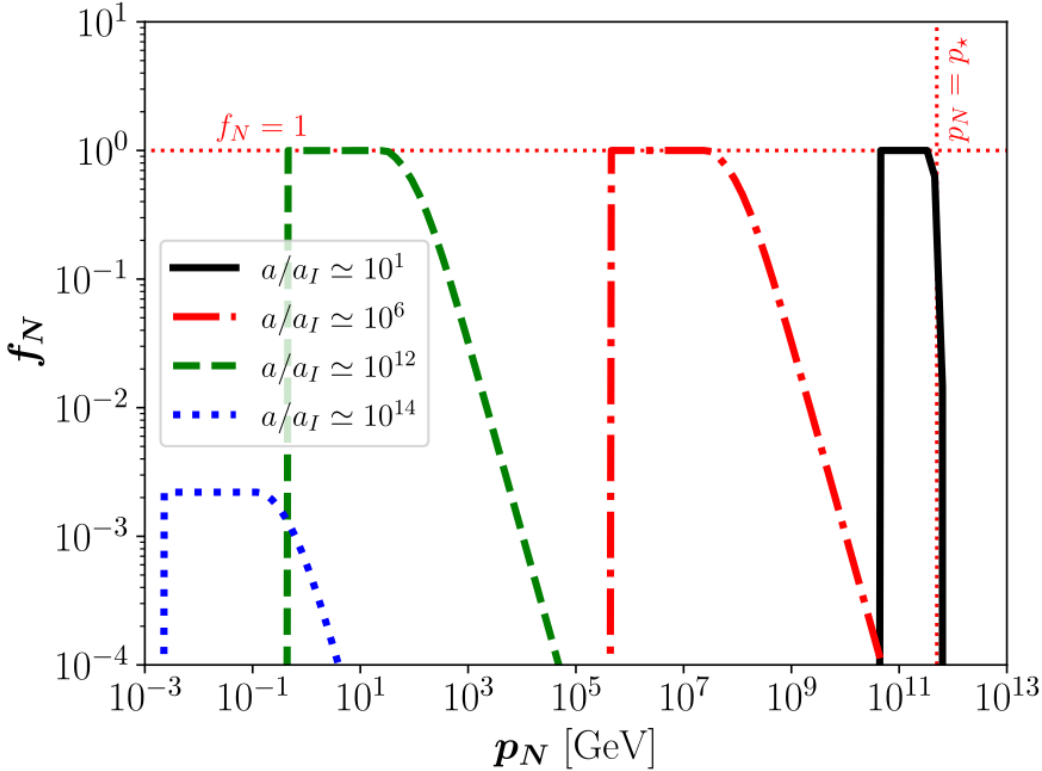
$m_N = 10^9$ GeV

$\Gamma_\phi = 1$ GeV

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

4 stages reheating





Dark matter
in Seesaw Cosmology

Nicolás BERNAL @ NYUAD

UV freeze-in dark matter

- DM could have been produced *nonthermally* from the SM plasma → freeze-in DM

- Out-of-equilibrium reactions require suppressed interaction rates

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UV freeze-in dark matter

DM abundance today

$$m_\chi\, Y_0 = \frac{\Omega h^2\, \rho_c}{s(T_0)\, h^2} \simeq 4.7 \times 10^{-10}\ \text{GeV}$$

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UV freeze-in production

$$\frac{dn_\chi}{dt} + 3\, H\, n_\chi = \gamma_\chi$$

$$\gamma_\chi(T) = \frac{T^p}{\Lambda^{p-4}} \qquad p = 2\,(D-2) \geq 6$$

UV freeze-in dark matter

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Cosmology

Final DM abundance

$$Y_0 = \frac{135}{2\pi^3\, g_{\star s}(T_{\rm rh})} \sqrt{\frac{10}{g_\star(T_{\rm rh})}}\, \frac{M_P\, T_{\rm rh}^{p-5}}{\Lambda^{p-4}}\, \frac{\mathcal{I}(a_I, a_0)}{\mathcal{F}}$$

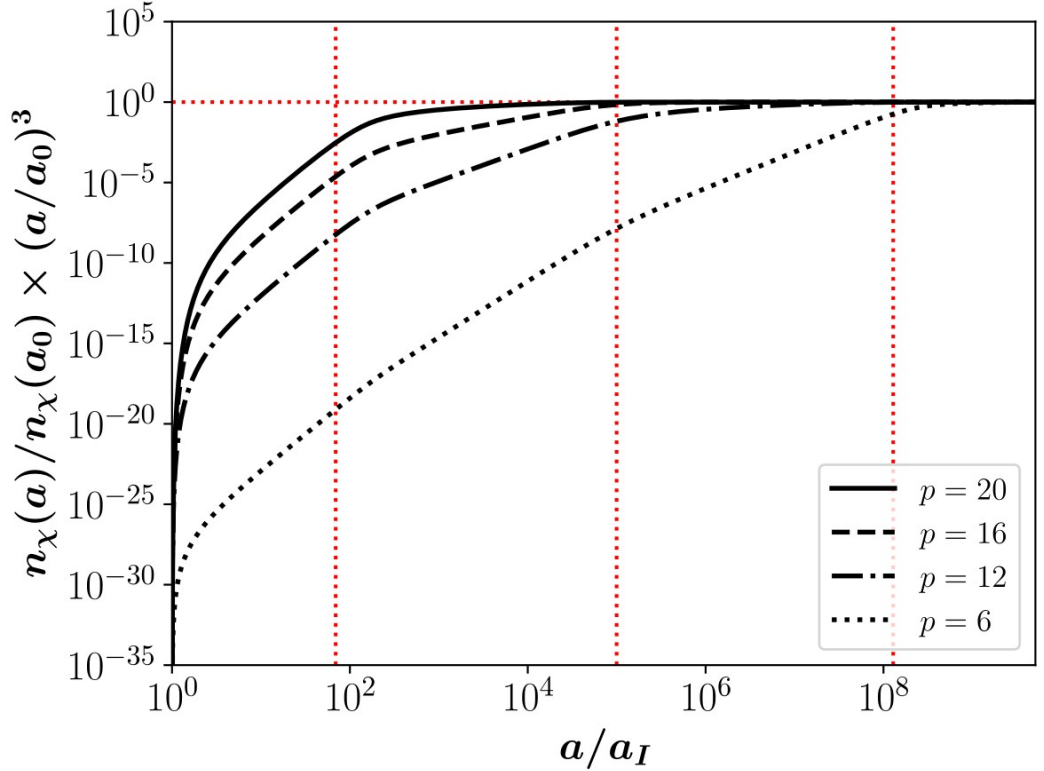
UV freeze-in dark matter

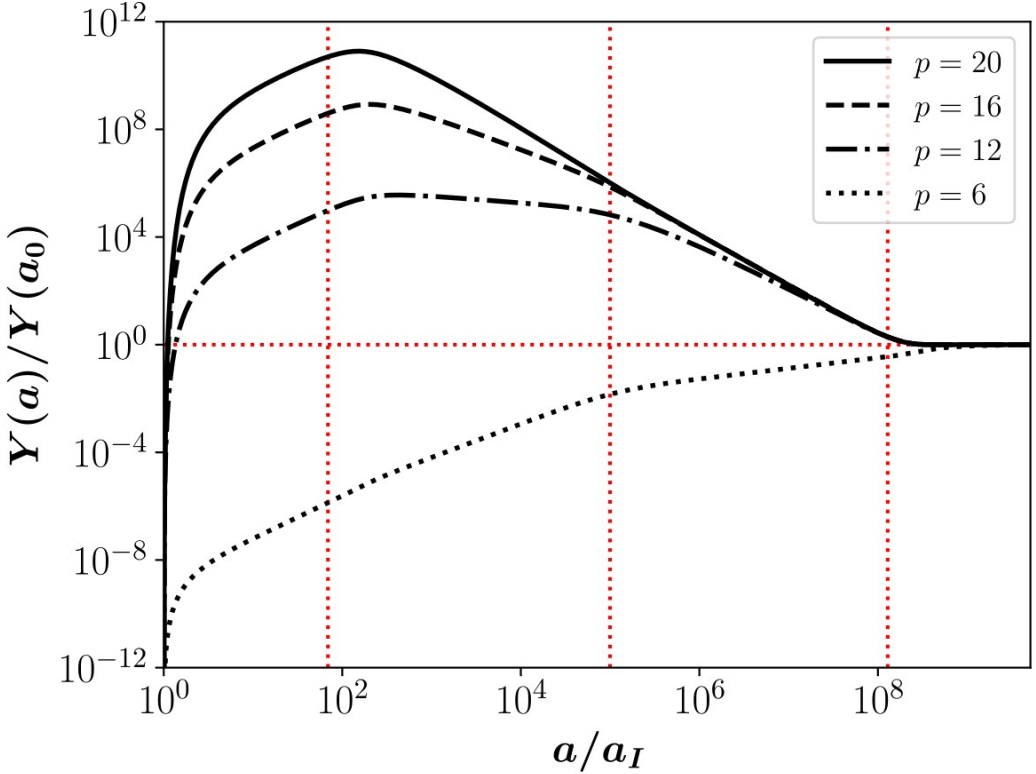
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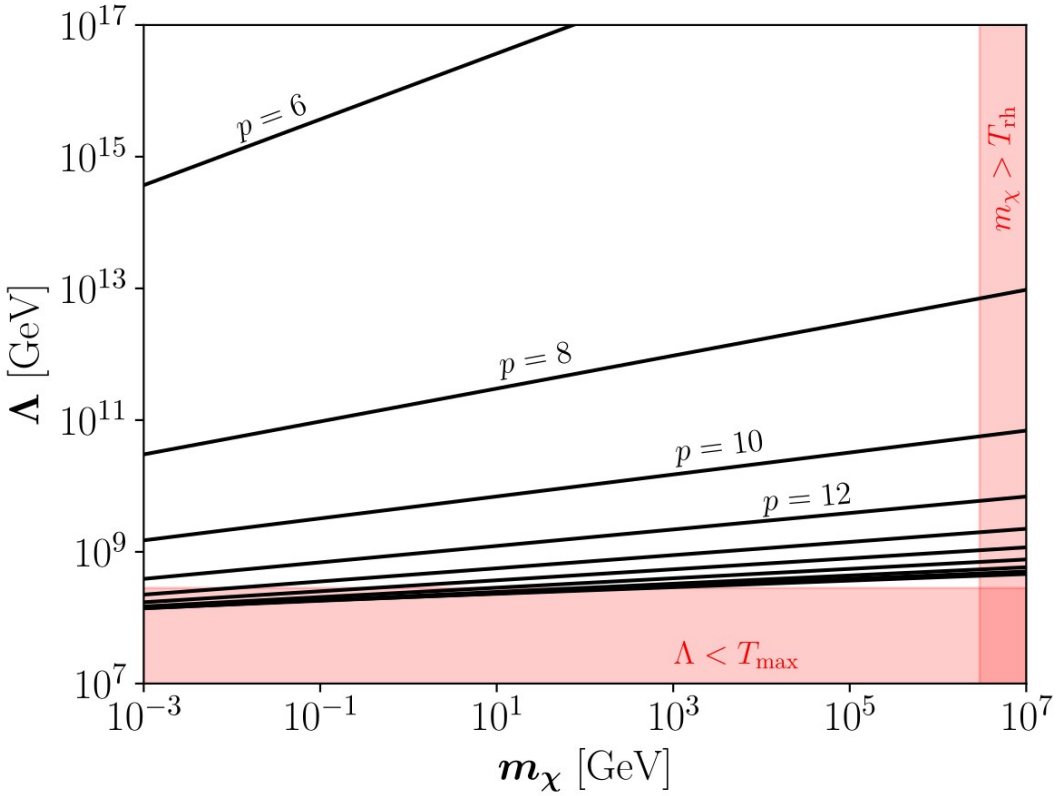
Dimension	p	$\mathcal{I}(a_I,a_0)/\mathcal{F}$
$5 \leq D \leq 7$	$6 \leq p \leq 10$	$\frac{1}{p-5} + \frac{8}{3(12-p)}$
$D = 8$	$p = 12$	$\frac{1}{p-5} + \frac{4}{20-p} + \ln(R_1)$
$9 \leq D \leq 11$	$14 \leq p \leq 18$	$\frac{1}{p-5} + \left[\frac{8}{3(p-12)} + \frac{4}{20-p} + \frac{2}{9}\, R_2^{-\frac{20-p}{4}}\right] R_1^{\frac{3(p-12)}{8}}$
$D = 12$	$p = 20$	$\frac{1}{p-5} + R_1^3\, \ln(R_2) + \left[\frac{8}{3(p-12)} + \frac{2}{9}\right] R_1^{\frac{3(p-12)}{8}}$
$D \geq 13$	$p \geq 22$	$\frac{1}{p-5} + \left[\frac{8}{3(p-12)} + \left(\frac{2}{9} + \frac{4}{p-20}\right) R_2^{\frac{p-20}{4}}\right] R_1^{\frac{3(p-12)}{8}}$

UV freeze-in dark matter





UV freeze-in dark matter



Seesaw Cosmology Conclusions

Two-step decay: $\phi \to N\,N \qquad \text{then} \qquad N \to H\,\ell$

* 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	
$\omega_{\rm eff}$	0	0	1/3	0	1/3
$T(a)$	$a^{+3/8}$	a^{0}	$a^{-1/4}$	$a^{-3/8}$	a^{-1}

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



Thank you!