MeV-scale Reheating and Neutrino Thermalization

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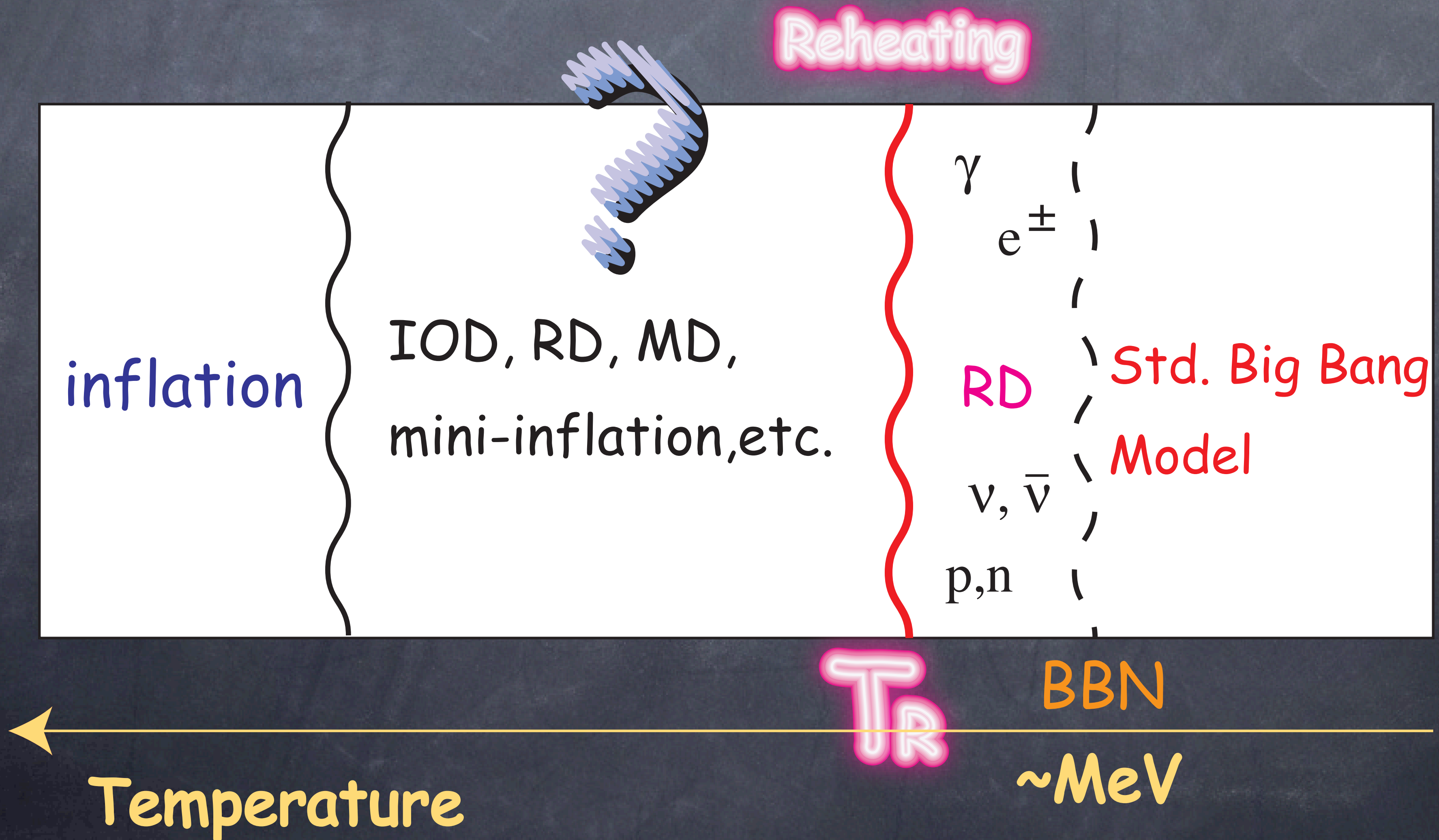
K. Ichikawa, M. Kawasaki, F.T., Phys.Rev. D72(2005)043522

I. Introduction

- What do we know about thermal history of the universe?



Big bang nucleosynthesis

- n-p transformation decouples when

$$\Gamma_{n\leftrightarrow p} = H$$

$$\begin{aligned} n &\leftrightarrow p + e^- + \bar{\nu}_e \\ n + \nu_e &\leftrightarrow p + e^- \\ n + e^+ &\leftrightarrow p + \bar{\nu}_e \end{aligned}$$

$$\left(\frac{n}{p}\right)_{\rm EQ} = \exp\left(-\frac{Q}{T}\right)$$

$$Q = m_n - m_p = 1.293 \text{MeV}$$

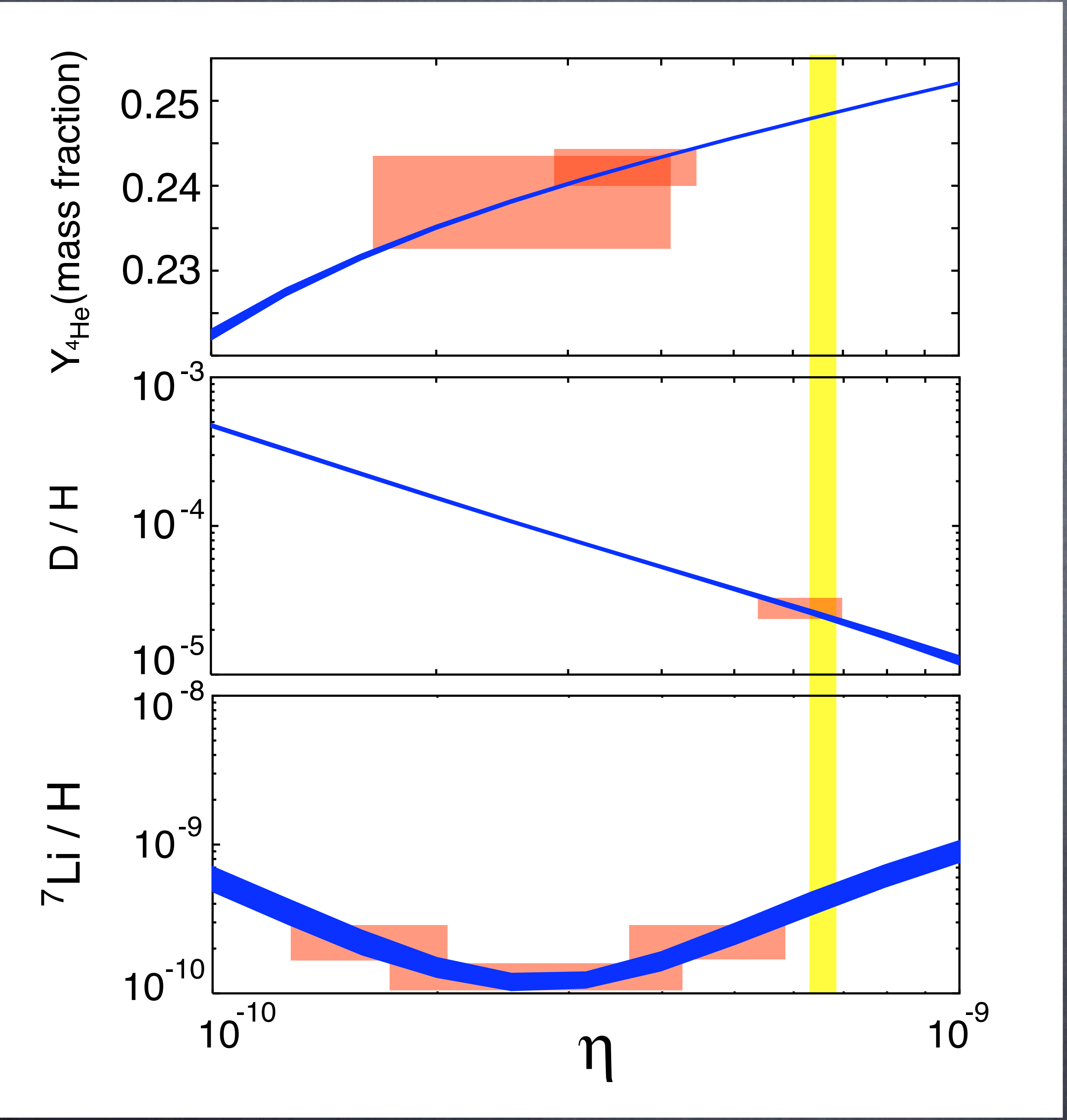
$$T \sim 0.8 \text{MeV}$$

$$2n + 2p \longrightarrow {}^4\text{He}$$

Almost all neutrons are absorbed in ^{4}He !

$$B(^4\text{He}) = 28.3\text{MeV} \gg B(\text{D, T, }^3\text{He})$$

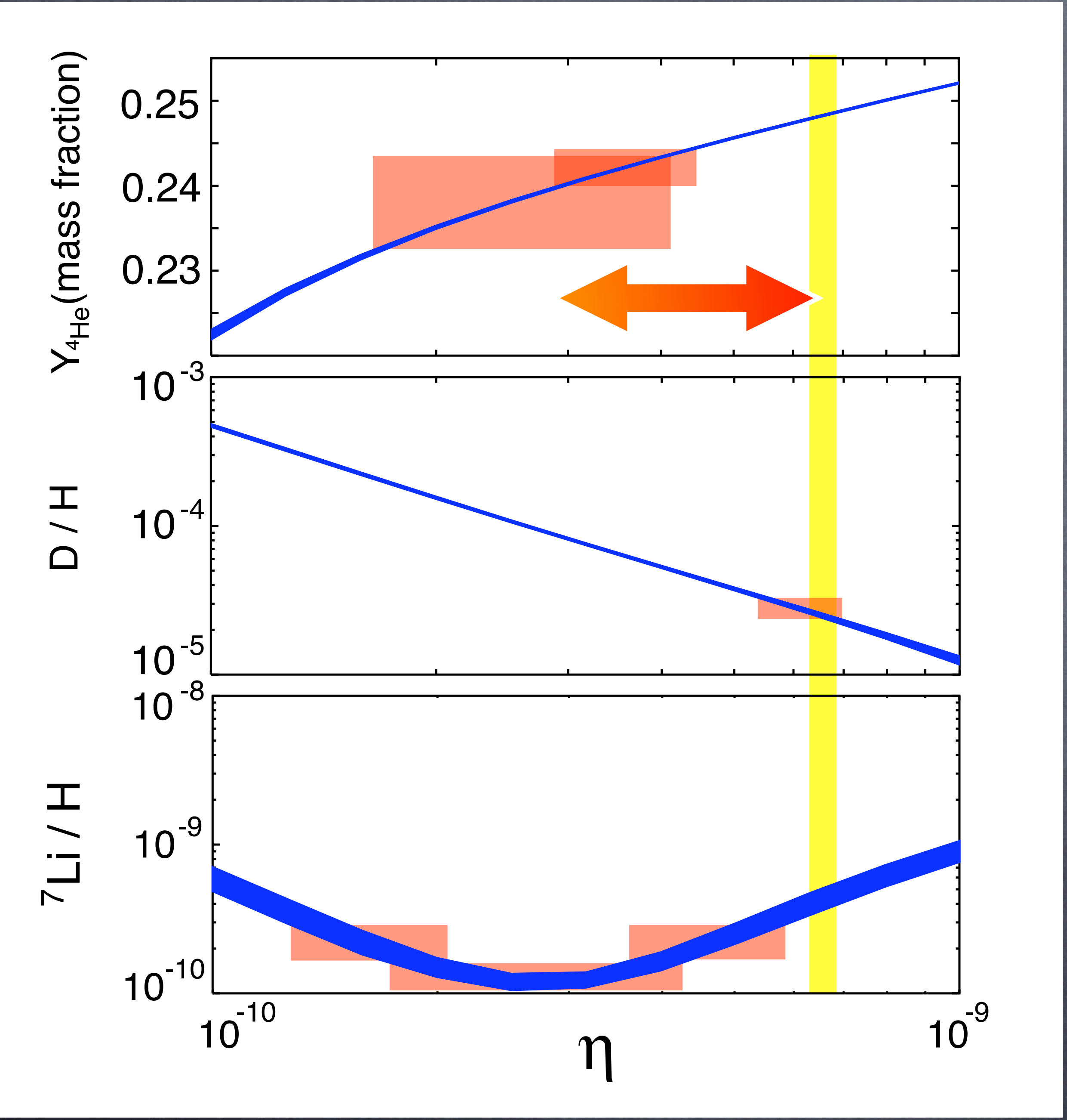
Present status of BBN (th.&obs.)



- sBBN includes only one free parameter:

$$\eta = \frac{n_B}{n_\gamma}$$

Present status of BBN (th.&obs.)



- To cure the discrepancy, we need
  - large L

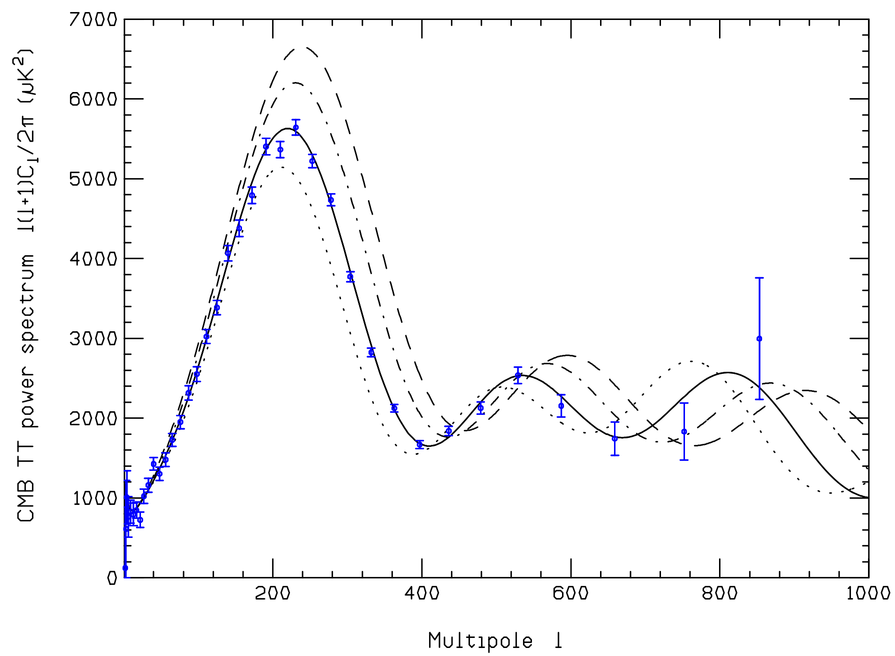
    or
  - $N_\nu < 3$

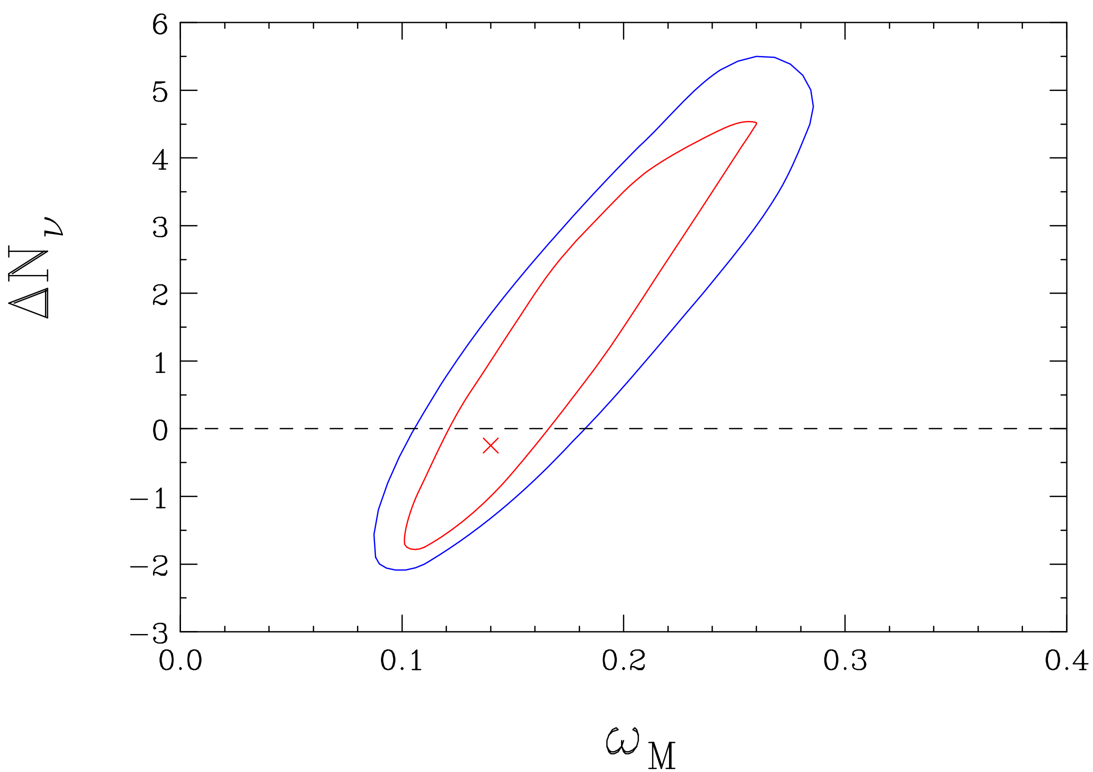
    realized if $T_R = O(\mathrm{MeV})$

$N_\nu \equiv \Sigma\rho_\nu/\rho_{\nu,\mathrm{std.}}$

Cosmic Microwave Background

The form of Cl also depends on ΔN.





$0.9 \leq N \leq 8.3$

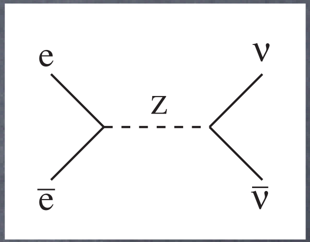
$N_{best\ fit} = 2.75$

from WMAP data

V. Barger et al, PLB 566(2003)8

What if T_{RH} is around MeV?

✓ Neutrinos might not be fully thermalized. [Kawasaki, Kohri, Sugiyama, '99, '00]



➡ The predicted abundances of the light elements (especially ^{4}He) are affected.

It has been widely believed that N_ν ↘ Y_p ↘

What we did:

- We investigated the MeV-scale reheating scenario, taking account of

thermalization processes of neutrinos

+ neutrino oscillations

- ✓ We found that ^{4}He abundance **increases** as N_ν decreases due to flavor mixings!

$$N_\nu \searrow \quad Y_p \nearrow$$

(to be detailed later)

II. Role of neutrinos in BBN

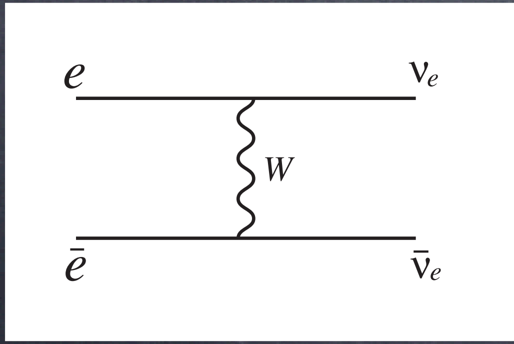
Reheating processes (Setup)

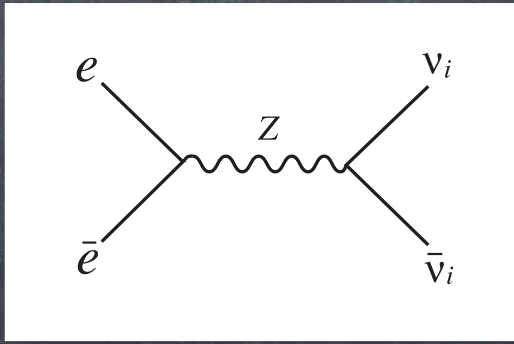
$$\phi \to \gamma,\, e^{\pm}$$

We define the reheating temperature by $\Gamma = 3H(T_R)$

$$\Gamma = 2.03 \left(\frac{T_R}{\text{MeV}}\right)^2 \ \text{sec}^{-1}.$$

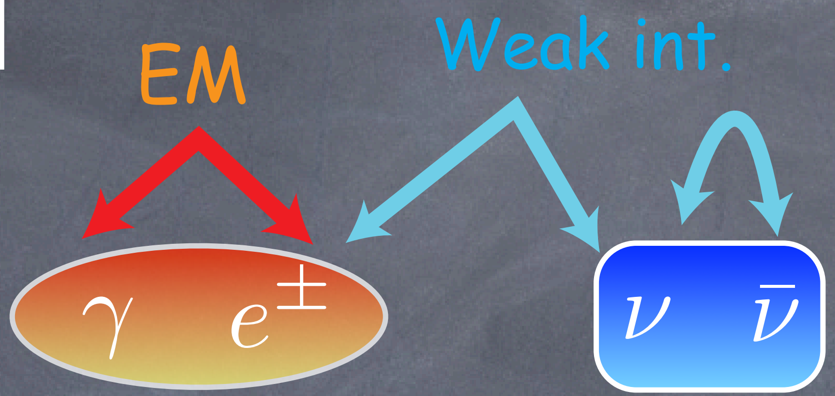
- We assume that neutrinos are exclusively produced via $e^- + e^+ \leftrightarrow \nu + \bar{\nu}$





Decoupling of ν

radiation:



$T < m_\mu$

thermal. eq. via EM int.

decouple @ T = a few MeV

In std. BBC,

$$T_d \sim 5\text{MeV} \quad \text{for} \quad \nu_{\mu,\tau}$$

$$T_d \sim 3\text{MeV} \quad \text{for} \quad \nu_e$$

[Hannestad & Madsen '95]
[Dolgov, Hansen & Semikoz, '97, '99]

ν_e is more likely to be produced at T ~MeV.

What if $N_\nu < 3$?

$N_\nu \equiv \Sigma\rho_\nu/\rho_{\nu,\mathrm{std.}}$

1. Hubble parameter decreases.

$H \searrow$ $\qquad$ $Y_p \searrow$

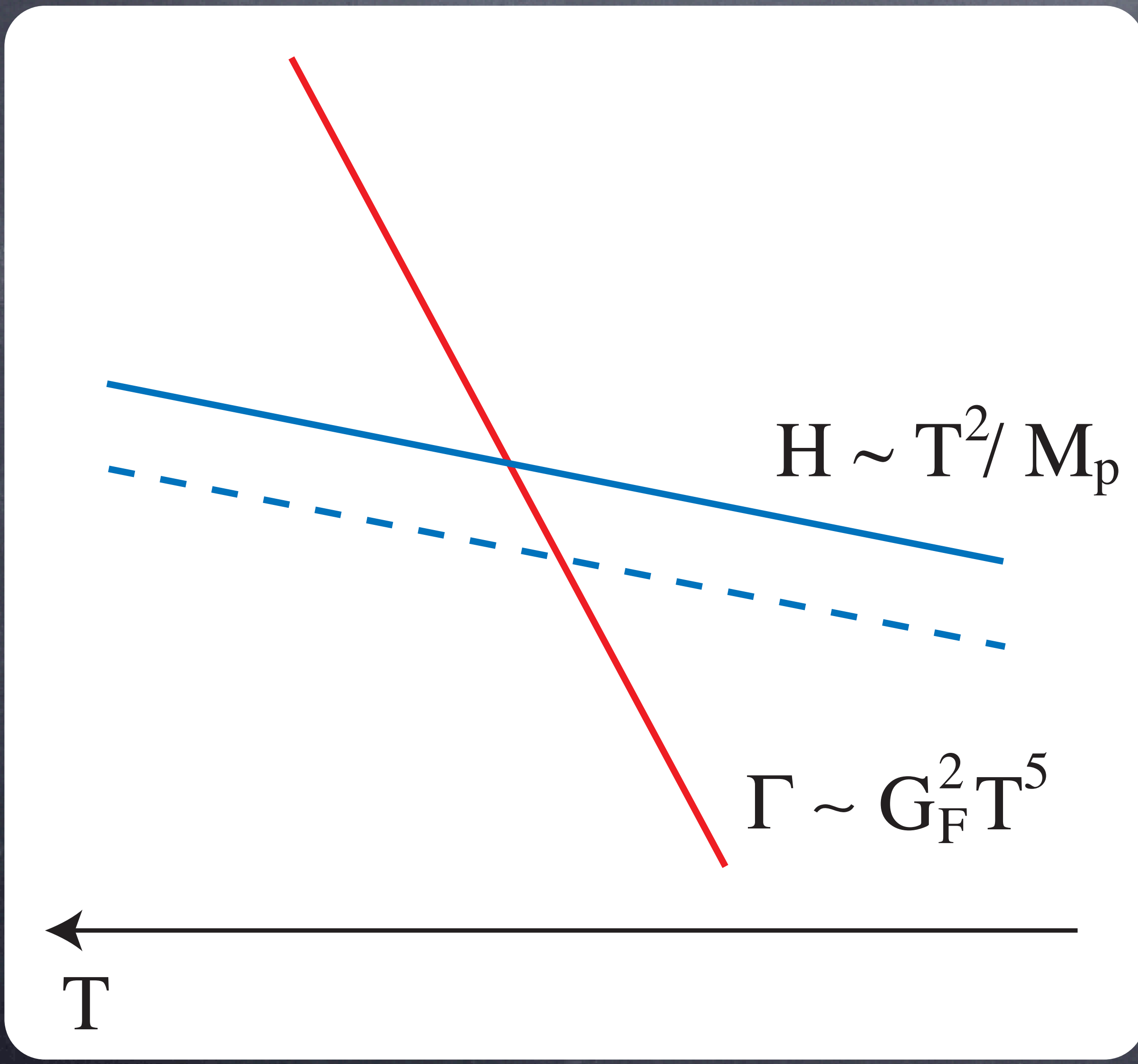
2. The n-p tranf. rate also decreases.

$\Gamma_{n\leftrightarrow p} \searrow$ $\qquad$ $Y_p \nearrow$

3. D bottleneck opens later.

$H(T_D)^{-1} \nearrow$ $\qquad$ $Y_p \searrow$

1. Hubble parameter decreases.



$$\left(\frac{n}{p}\right)_{EQ} = \exp\left(-\frac{Q}{T_*}\right)$$

$$T_* \qquad \left(\frac{n}{p}\right)$$

$$Y_p$$

What if $N_\nu < 3$?

$N_\nu \equiv \Sigma\rho_\nu/\rho_{\nu,\mathrm{std.}}$

1. Hubble parameter decreases.

H ↘ Y_p ↘

2. The n-p tranf. rate also decreases.

$\Gamma_{n\leftrightarrow p}$ ↘ Y_p ↗

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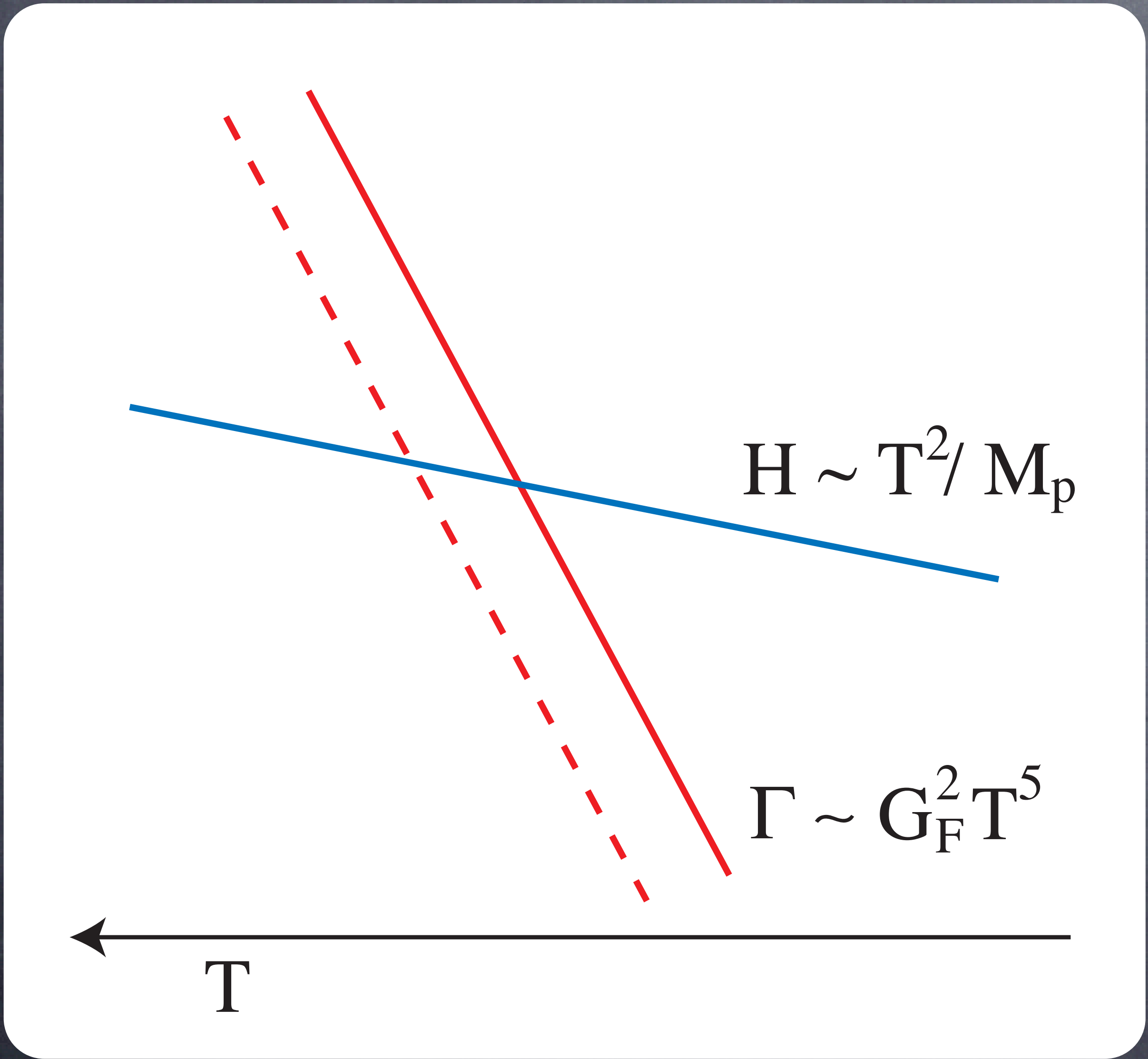


$$n \leftrightarrow p + e^- + \bar{\nu}_e$$
$$n + \nu_e \leftrightarrow p + e^-$$
$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$

$$\left(\frac{n}{p}\right)_{\rm EQ} = \exp\left(-\frac{Q}{T_*}\right)$$

T_* ↑ $\left(\frac{n}{p}\right)$ ↑

⇒ Y_p ↑

What if $N_\nu < 3$?

$N_\nu \equiv \Sigma\rho_\nu/\rho_{\nu,\mathrm{std.}}$

- ✓ Hubble parameter decreases.

  H Y_p

- ✓ The n-p tranf. rate also decreases.

  $\Gamma_{n\leftrightarrow p}$ Y_p

- ✓ D bottleneck opens later.

  $H(T_D)^{-1}$ Y_p

III. Thermalization of Neutrinos

- Density matrices:

$$\left\langle a_j^\dagger(\mathbf{p})\, a_i(\mathbf{p}')\right\rangle = (2\pi)^3\delta^{(3)}(\mathbf{p}-\mathbf{p}')\,[\rho_{\mathbf{p}}]_{ij},$$
$$\left\langle b_i^\dagger(\mathbf{p})\, b_j(\mathbf{p}')\right\rangle = (2\pi)^3\delta^{(3)}(\mathbf{p}-\mathbf{p}')\,[\bar{\rho}_{\mathbf{p}}]_{ij}.$$

$\{i,j\} = \{e,\mu,\tau\}$

- diagonal components: dist. func. of ν_i
- off-diagonal ones: corr. between ν_i and ν_j.

QKEs for density matrix

$$\nu + e^{\pm} \leftrightarrow \nu + e^{\pm}$$
$$\nu + \bar{\nu} \leftrightarrow e^{-} + e^{+}$$

$$Ha\frac{d\rho_p}{da} = -i[\Omega(p), \rho_p] + I_{\rm coll}(p).$$

refractive term [flavor mixings]

collision term [neutrino thermalization]

where

$$\Omega(p) \equiv \Omega_V(p) - \frac{8\sqrt{2}G_F p}{3m_W^2}E$$

$$\Omega_V(p) = \frac{1}{2p}UM^2U^T, \quad M^2 \equiv \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix}, \quad U \equiv \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} \\ -\sin\theta_{12} & \cos\theta_{12} \end{pmatrix}.$$

$$E = \begin{pmatrix} \rho_e + \rho_{\bar{e}} & 0 \\ 0 & 0 \end{pmatrix} = \begin{pmatrix} (7/60)\pi^2T^4 & 0 \\ 0 & 0 \end{pmatrix},$$

Approximate 2 flavor analysis assuming $\theta_{13} \approx 0$

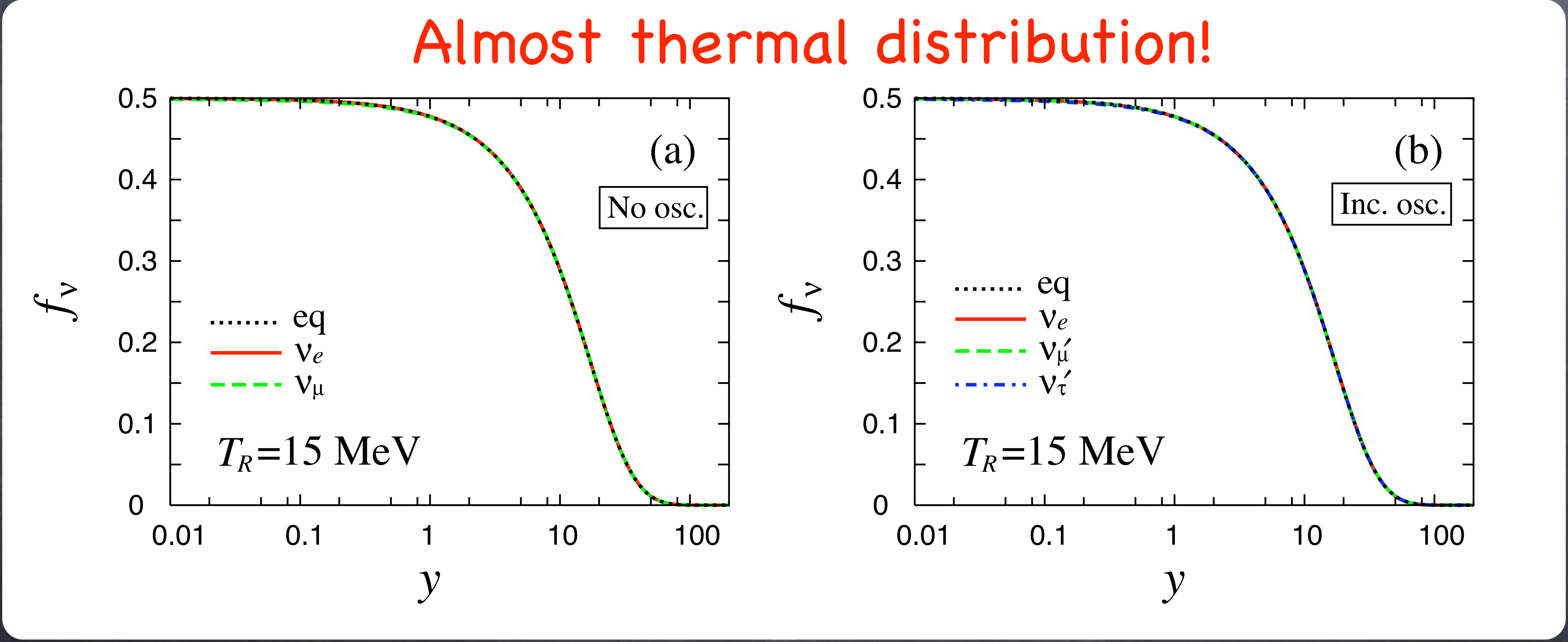
Parameters:

$$\sin^2\theta_{12} = 0.315$$

$$m_2^2 - m_1^2 = 7.3 \times 10^{-5}\mathrm{eV}^2$$

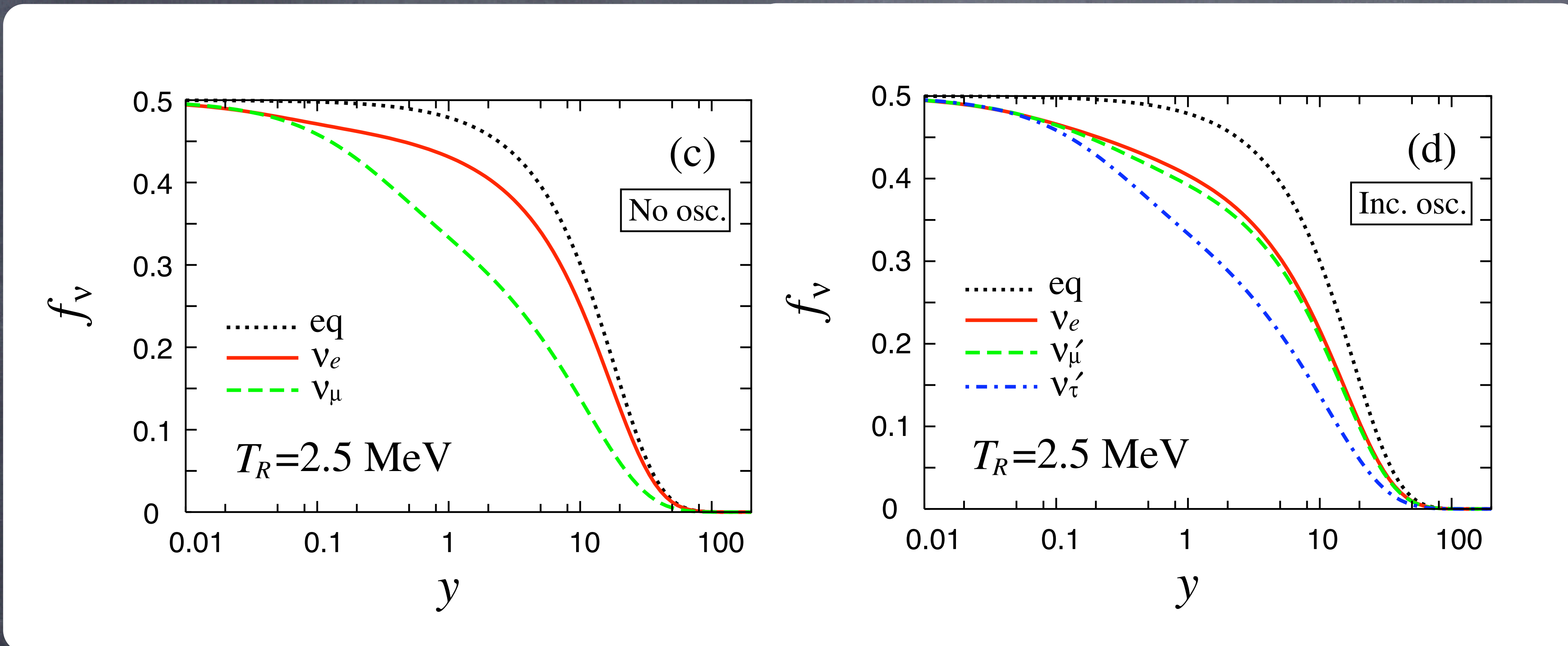
IV. Results & Discussions

- The final dist. functions [T_R=15MeV]



Momentum is normalized as y = ap

The final dist. functions [T_R=2.5MeV]

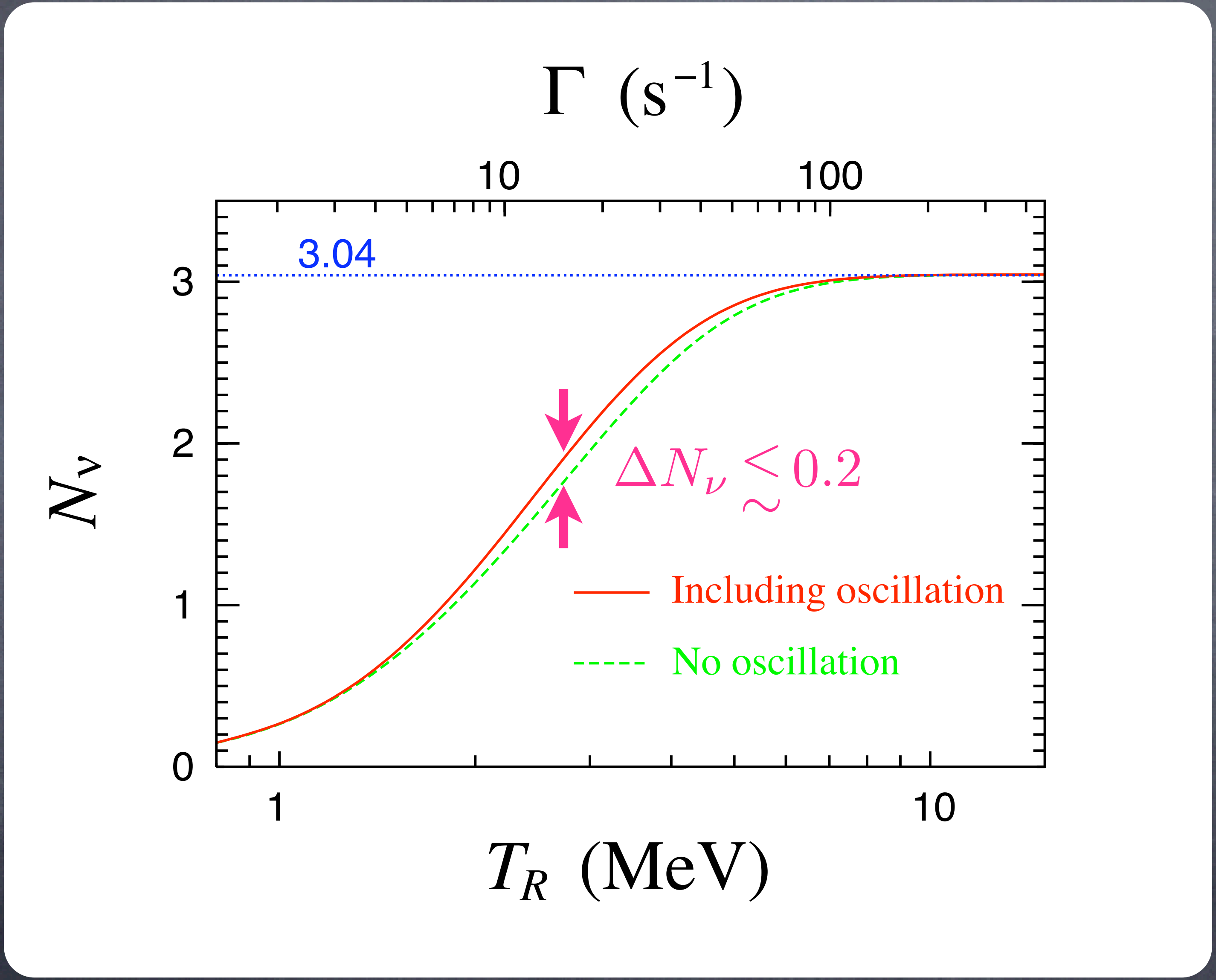


$$f_{\nu_e} > f_{\nu'_\mu} = f_{\nu'_\tau}$$

$$f_{\nu_e} \sim f_{\nu'_\mu} > f_{\nu'_\tau}$$

Due to flavor mixings, $f_{\nu'_\mu}$ ↑ f_{ν_e} ↓ $\Gamma_{n\leftrightarrow p}$ ↓

Effective number of neutrinos



N_ν (i.e. H) does not change much!

Two competing effects:

(1) Slowing down of the expansion rate

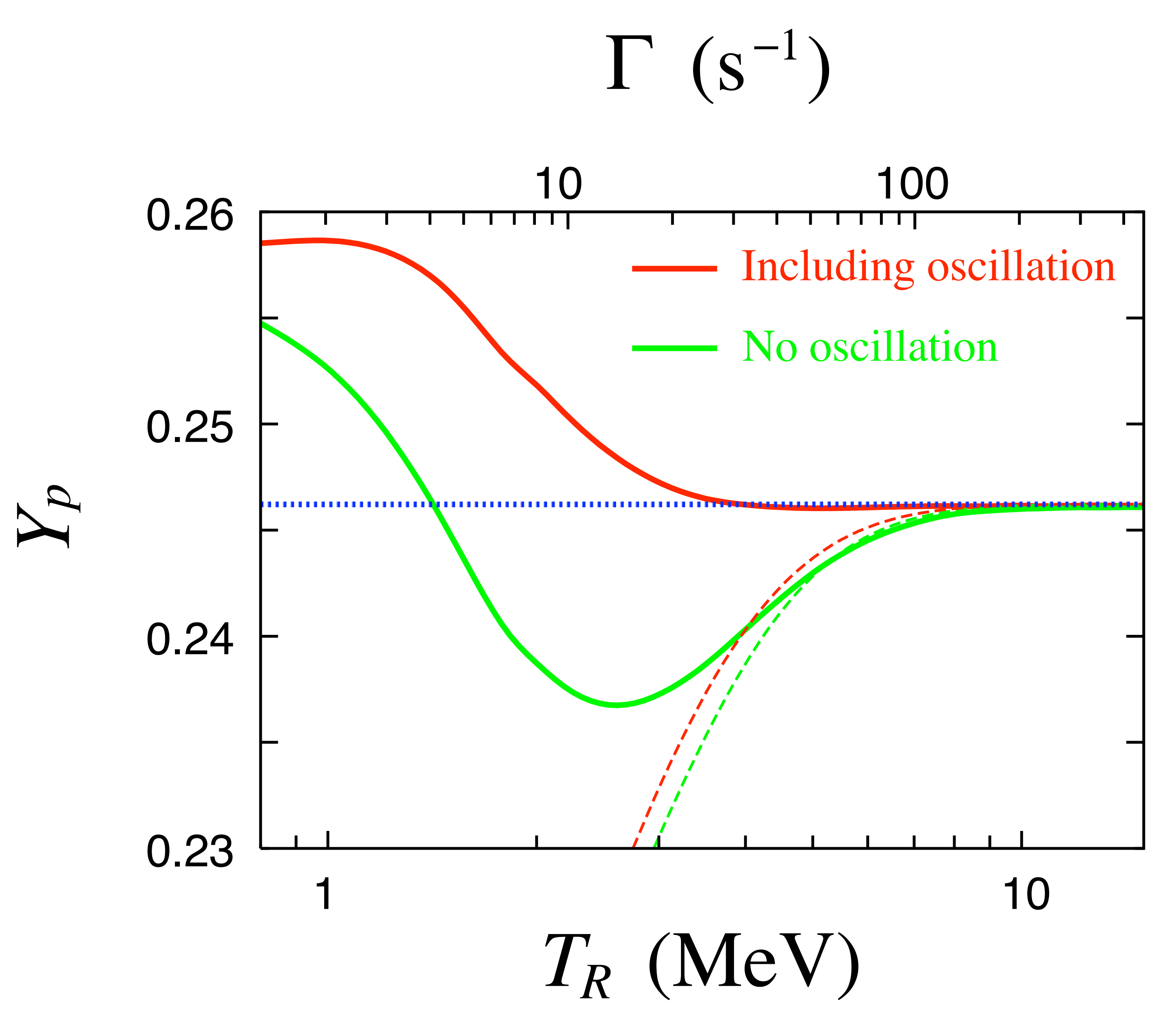
H ↓ Y_p ↓

(2) Decrease in $\Gamma_{n\leftrightarrow p}$

$\Gamma_{n\leftrightarrow p}$ ↓ Y_p ↑

Taking into consideration the neutrino oscillations, the effect (2) becomes more important!

^{4}He abundance Y_p and T_R



V. Conclusion

- We have investigated the MeV-scale reheating scenario, paying particular attention to neutrino oscillations.

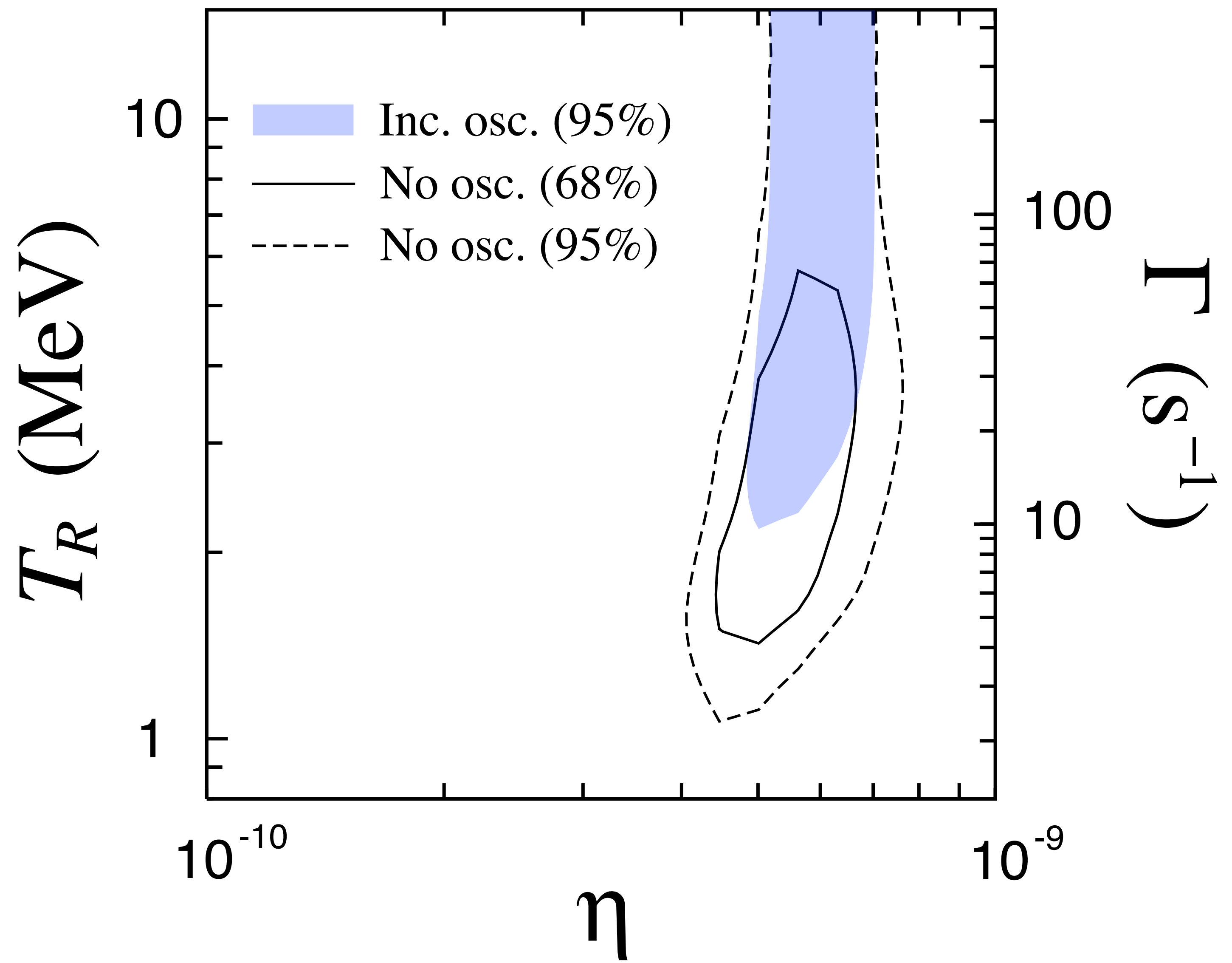
- In contrast to the widespread picture,

$$N_\nu \searrow \quad Y_p \nearrow$$

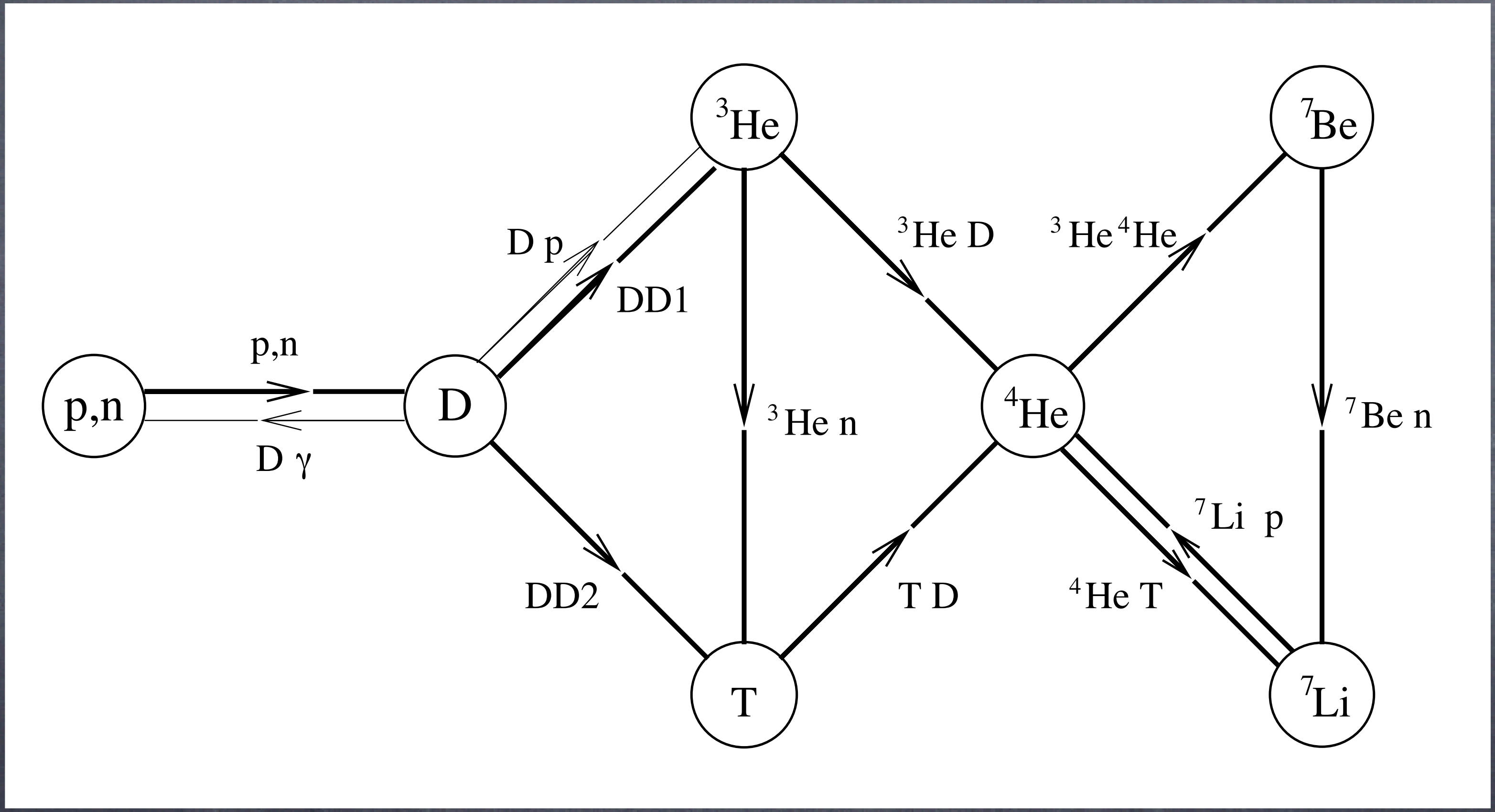
while T_R decreases.

- $T_R \gtrsim 2\,\mathrm{MeV}$ and $N_\nu \gtrsim 1.2$ was obtained.

χ^2 contour plots using data of D and ^{4}He



Important reactions in BBN



V. Mukhanov, astro-ph/0303073