Constraining Majoron from Big-Bang Nucleosynthesis

Sougata Ganguly

Institute for Basic Science
CTPU-PTC

CTPU Joint Tea Time
September 30, 2024

Based on Phys.Rev.D 110 (2024) 1, 015019
S. Chang, **SG**, T.H. Jung, T.S. Park, C.S. Shin

Outline of the talk

- **Introduction to Majoron and Standard BBN (SBBN)**
- **Effect of Majoron on BBN**
- **Summary**

Type-I see-saw: Lepton number violation

$$\mathscr{L} = -y_{ij}\overline{\ell}_{i_L} N_{j_R} \tilde{\Phi} - \frac{M_{ij}}{2} \overline{N}^c_{i_R} N_{j_R} + h.c$$

$$\langle \Phi \rangle \neq 0$$

$$\mathscr{L}_{\text{mass}} = -\frac{1}{2} \begin{pmatrix} \overline{\nu}_L & \overline{N}_R{}^c \end{pmatrix} \begin{pmatrix} 0 & M_D \\ M_D^T & M \end{pmatrix} \begin{pmatrix} \nu_L{}^c \\ N_R \end{pmatrix} + h.c$$

$\frac{yv}{\sqrt{2}}$, Dirac mass term

Majorana mass term
Lepton number is violated by 2 units

Type-I see-saw: Lepton number violation

$$\mathscr{L} = -y_{ij}\overline{\ell}_{i_L} N_{j_R}\tilde{\Phi} - \frac{M_{ij}}{2}\overline{N}^c_{i_R} N_{j_R} + h.c$$

$\langle \Phi \rangle \neq 0$

$$\mathscr{L}_{\text{mass}} = -\frac{1}{2}\left(\overline{\nu}_L \quad \overline{N}_R{}^c\right)\begin{pmatrix} 0 & M_D \\ M_D^T & M \end{pmatrix}\begin{pmatrix} \nu_L{}^c \\ N_R \end{pmatrix} + h.c$$

$\frac{yv}{\sqrt{2}}$, Dirac mass term

Majorana mass term
Lepton number is violated by 2 units

For $M_D \sim 246\,\text{GeV}$, and $M \sim 10^{15}\,\text{GeV}$

$$m_\nu \simeq \frac{M_D^2}{M} \sim 0.1\,\text{eV}$$

Type-I see-saw: Lepton number violation

$$\mathscr{L} = -y_{ij}\overline{\ell}_{iL}N_{j_R}\tilde{\Phi} - \frac{M_{ij}}{2}\overline{N}^c_{i_R}N_{j_R} + h.c$$

$$\langle \Phi \rangle \neq 0$$

$$\mathscr{L}_{\text{mass}} = -\frac{1}{2}\left(\overline{\nu}_L \quad \overline{N}_R{}^c\right)\begin{pmatrix} 0 & M_D \\ M_D^T & M \end{pmatrix}\begin{pmatrix} \nu_L{}^c \\ N_R \end{pmatrix} + h.c$$

$\frac{yv}{\sqrt{2}}$, Dirac mass term

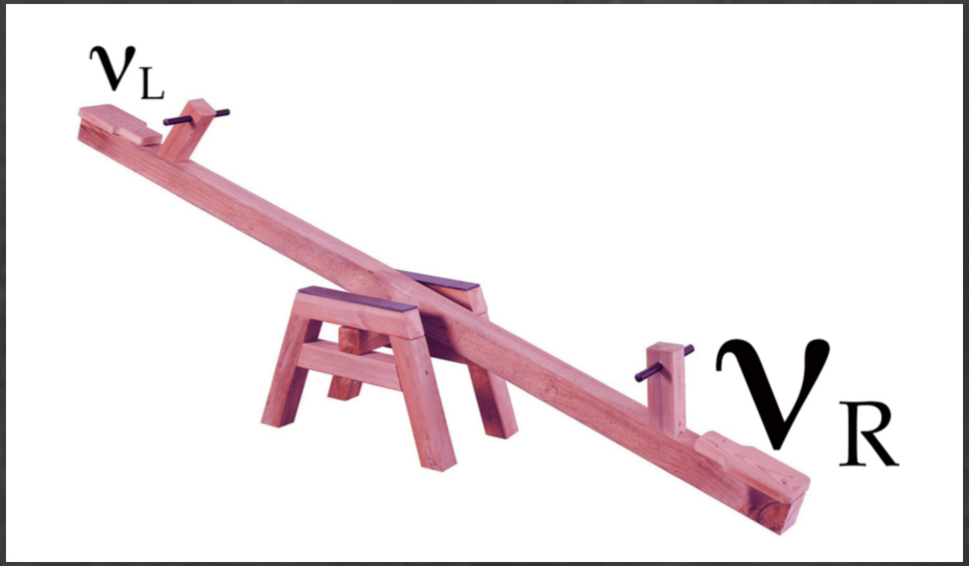
Majorana mass term

Lepton number is violated by 2 units

For $M_D \sim 246\,\text{GeV}$, and $M \sim 10^{15}\,\text{GeV}$

$$m_\nu \simeq \frac{M_D^2}{M} \sim 0.1\,\text{eV}$$

Naturally explains the smallness of ν mass



Type-I see-saw: Lepton number violation

$$\mathscr{L} = -y_{ij}\overline{\ell}_{iL}N_{j_R}\tilde{\Phi} - \frac{M_{ij}}{2}\overline{N}^c_{i_R}N_{j_R} + h.c$$

$\langle\Phi\rangle \neq 0$

$$\mathscr{L}_{\text{mass}} = -\frac{1}{2}\left(\overline{\nu}_L \quad \overline{N}_R{}^c\right)\begin{pmatrix} 0 & M_D \\ M_D^T & M \end{pmatrix}\begin{pmatrix} \nu_L{}^c \\ N_R \end{pmatrix} + h.c$$

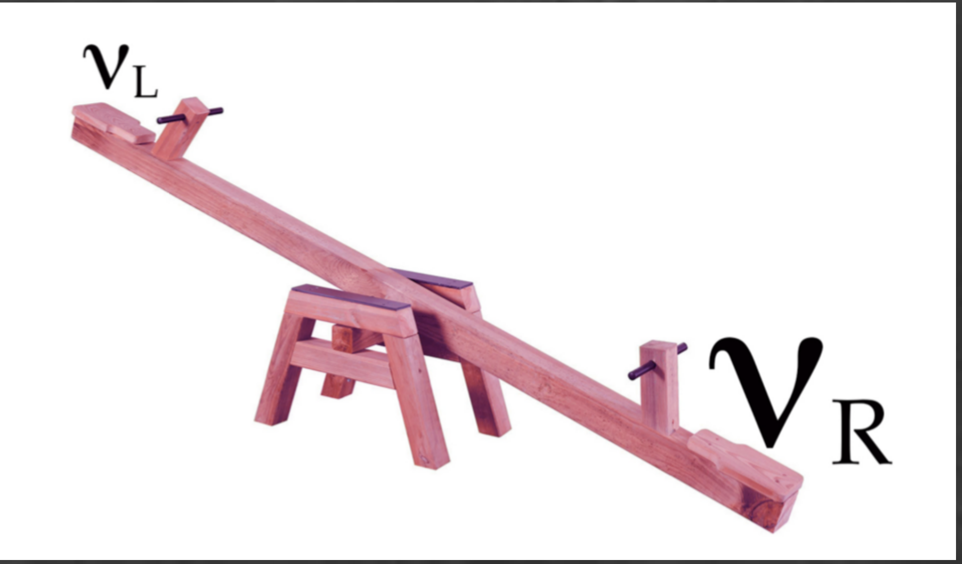
$\frac{yv}{\sqrt{2}}$, Dirac mass term

Majorana mass term
Lepton number is violated by 2 units

For $M_D \sim 246\,\text{GeV}$, and $M \sim 10^{15}\,\text{GeV}$

$$m_\nu \simeq \frac{M_D^2}{M} \sim 0.1\,\text{eV}$$

Naturally explains the smallness of ν mass



But what is the origin of lepton number breaking term???

Lepton number breaking

Lepton number breaking

Consider an SM gauge singlet complex scalar σ with lepton number -2

$$\mathscr{L}_{\text{New}} = i\overline{N}_{i_R}\gamma^\mu\partial_\mu N_{i_R} - \left(\lambda_{ij}\overline{N}_{i_R}{}^c N_{j_R}\sigma + h.c\right) - (y_{ij}\overline{\ell}_{i_L}N_{j_R}\tilde{\Phi} + h.c) + V(\Phi,\sigma)$$

Lepton number breaking

Consider an SM gauge singlet complex scalar σ with lepton number -2

$$\mathscr{L}_{\text{New}} = i\overline{N}_{i_R}\gamma^\mu\partial_\mu N_{i_R} - \left(\lambda_{ij}\overline{N}_{i_R}{}^c N_{j_R}\sigma + h.c\right) - (y_{ij}\overline{\ell}_{i_L}N_{j_R}\tilde{\Phi} + h.c) + V(\Phi,\sigma)$$

$\sigma = \frac{1}{\sqrt{2}}(\phi + f + iJ)$ breaks global $U(1)_L$ symmetry spontaneously

Lepton number breaking

Consider an SM gauge singlet complex scalar σ with lepton number -2

$$\mathscr{L}_{\mathrm{New}} = i\overline{N}_{i_R}\gamma^\mu\partial_\mu N_{i_R} - \left(\lambda_{ij}\overline{N}_{i_R}{}^c N_{j_R}\sigma + h.c\right) - (y_{ij}\overline{\ell}_{i_L}N_{j_R}\tilde{\Phi} + h.c) + V(\Phi,\sigma)$$

$\sigma = \frac{1}{\sqrt{2}}(\phi + f + iJ)$ breaks global $U(1)_L$ symmetry spontaneously

J is a Nambu-Goldstone boson, which is known as Majoron and it can be massive via explicit symmetry breaking terms. We treat the mass of Majoron as a free parameter.

Lepton number breaking

Consider an SM gauge singlet complex scalar σ with lepton number -2

$$\mathscr{L}_{\text{New}} = i\overline{N}_{i_R}\gamma^\mu\partial_\mu N_{i_R} - \left(\lambda_{ij}\overline{N}_{i_R}{}^c N_{j_R}\sigma + h.c\right) - (y_{ij}\overline{\ell}_{i_L}N_{j_R}\tilde{\Phi} + h.c) + V(\Phi,\sigma)$$

$\sigma = \frac{1}{\sqrt{2}}(\phi + f + iJ)$ breaks global $U(1)_L$ symmetry spontaneously

J is a Nambu-Goldstone boson, which is known as **Majoron** and it can be massive via explicit symmetry breaking terms. We treat the mass of Majoron as a free parameter.

Majoron only couples with the SM sector via $\frac{g}{2}J\bar{\nu}_L{}^c\nu_L + \mathrm{H.C}$ where $g \sim \frac{m_\nu}{f}$

Lepton number breaking

Consider an SM gauge singlet complex scalar σ with lepton number -2

$$\mathscr{L}_{\text{New}} = i\overline{N}_{i_R}\gamma^{\mu}\partial_{\mu}N_{i_R} - \left(\lambda_{ij}\overline{N}_{i_R}{}^{c}N_{j_R}\sigma + h.c\right) - (y_{ij}\overline{\ell}_{i_L}N_{j_R}\tilde{\Phi} + h.c) + V(\Phi,\sigma)$$

$\sigma = \frac{1}{\sqrt{2}}(\phi + f + iJ)$ breaks global $U(1)_L$ symmetry spontaneously

J is a Nambu-Goldstone boson, which is known as **Majoron** and it can be massive via explicit symmetry breaking terms. We treat the mass of Majoron as a free parameter.

Majoron only couples with the SM sector via $\frac{g}{2}J\bar{\nu}_L{}^{c}\nu_L + \text{H.C}$ where $g \sim \frac{m_\nu}{f}$

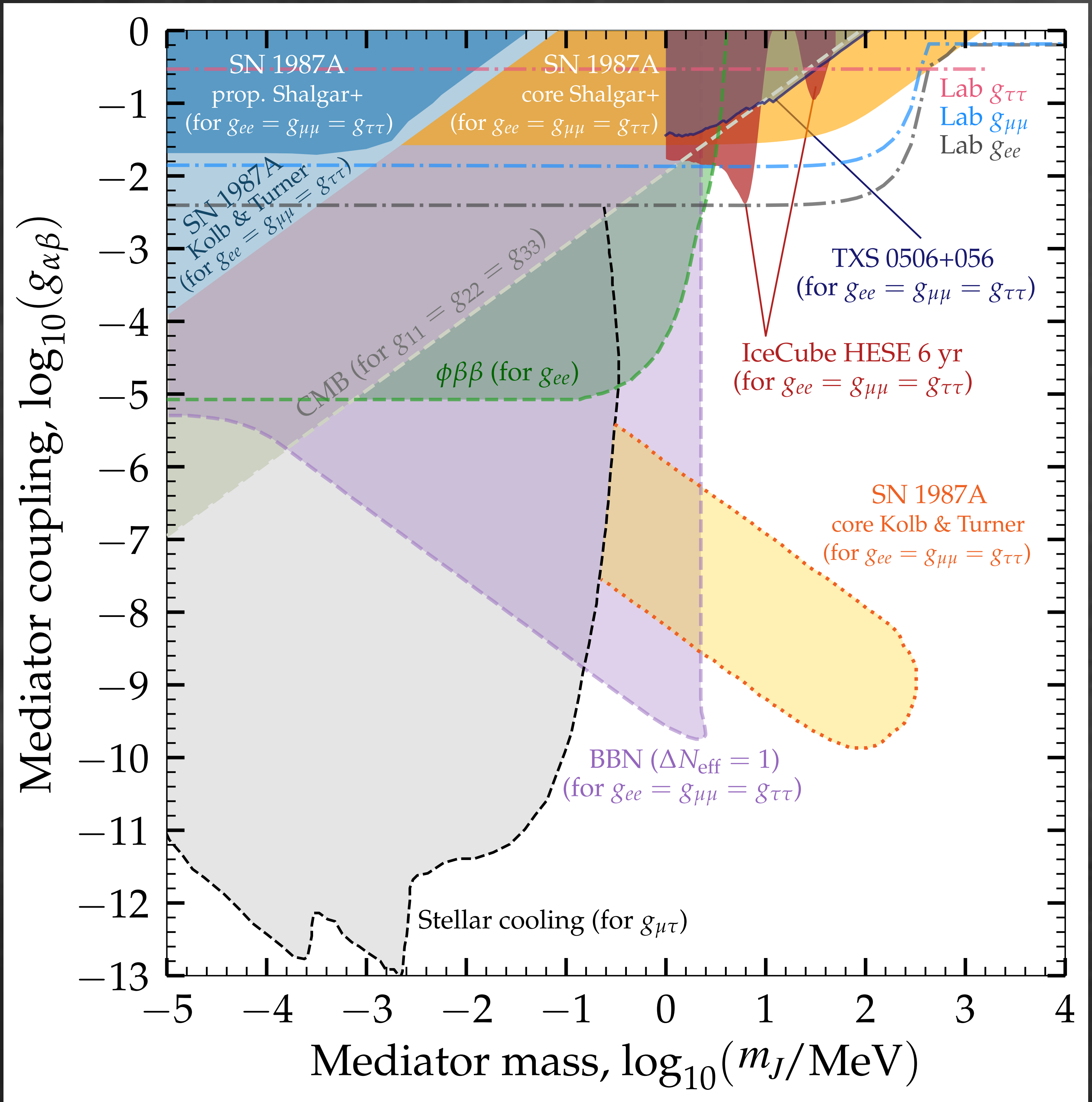
Naturally suppressed coupling with the SM sector

Majoron Phenomenology

m_J

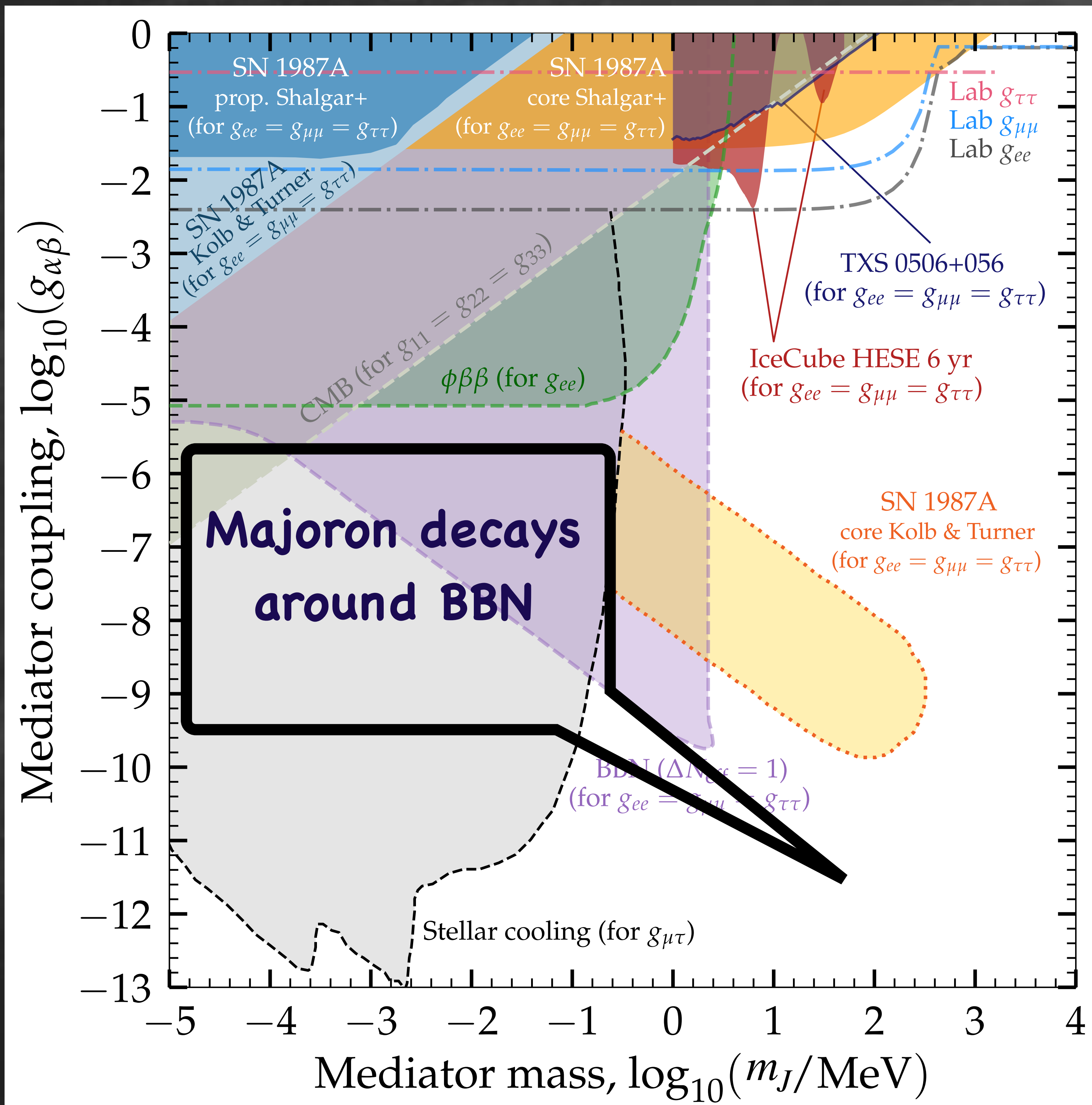
Snowmass 2021, arXiv: 2203.01955

Majoron Phenomenology



Snowmass 2021, arXiv: 2203.01955

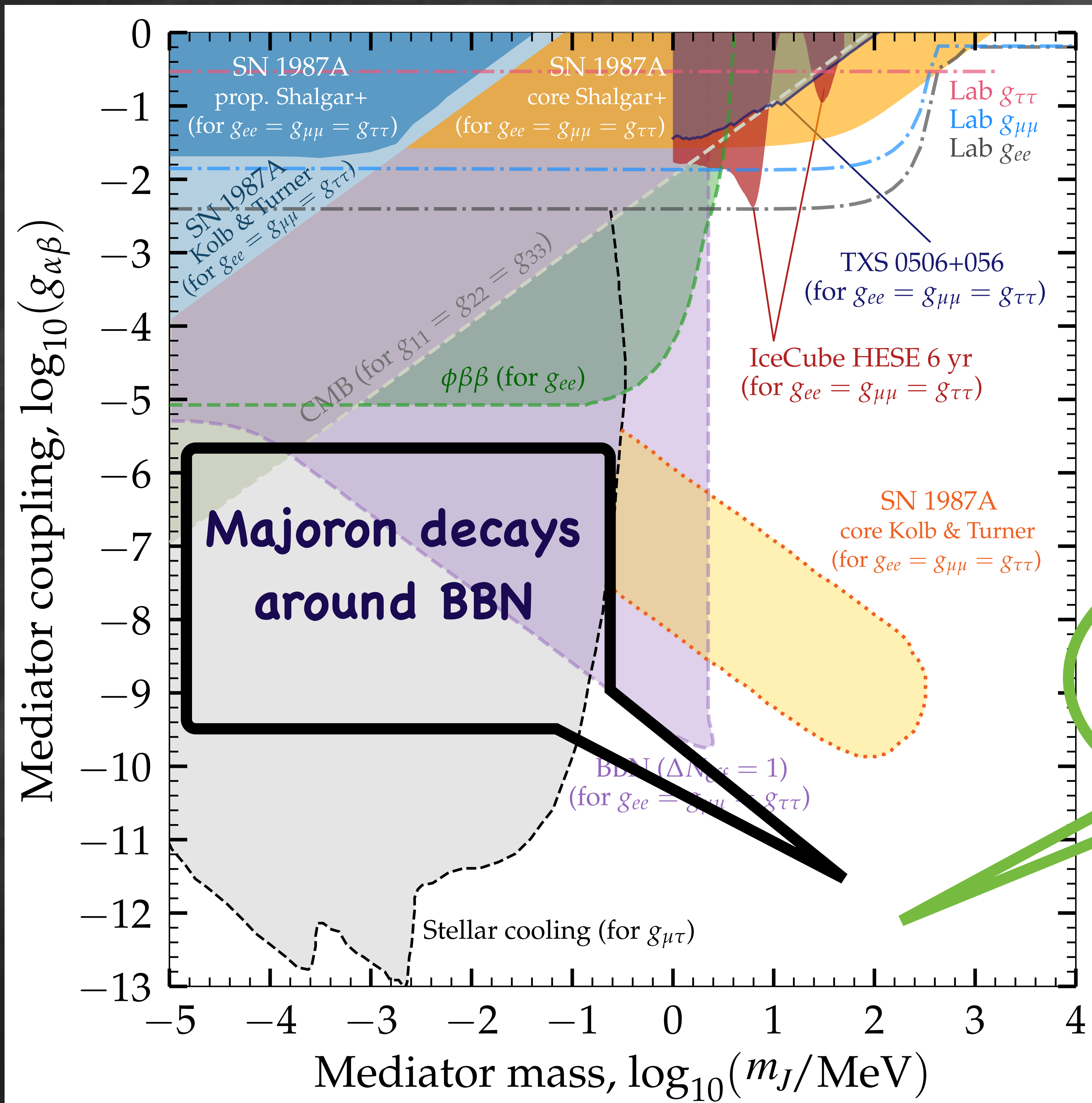
Majoron Phenomenology



$$\mathscr{L} \supset -\frac{ig_{\alpha\beta}}{2}\bar{\nu}_\alpha\gamma_5\nu_\beta J$$

Snowmass 2021, arXiv: 2203.01955

Majoron Phenomenology



$$\mathscr{L} \supset -\frac{i g_{\alpha\beta}}{2} \bar{\nu}_\alpha \gamma_5 \nu_\beta J$$

Can we constrain this region of parameter space from BBN?

Snowmass 2021, arXiv: 2203.01955

Big-Bang Nucleosynthesis: Formation of light elements

Most abundant light elements are Hydrogen ($\sim 75\%$) and Helium ($\sim 25\%$)

Big-Bang Nucleosynthesis: Formation of light elements

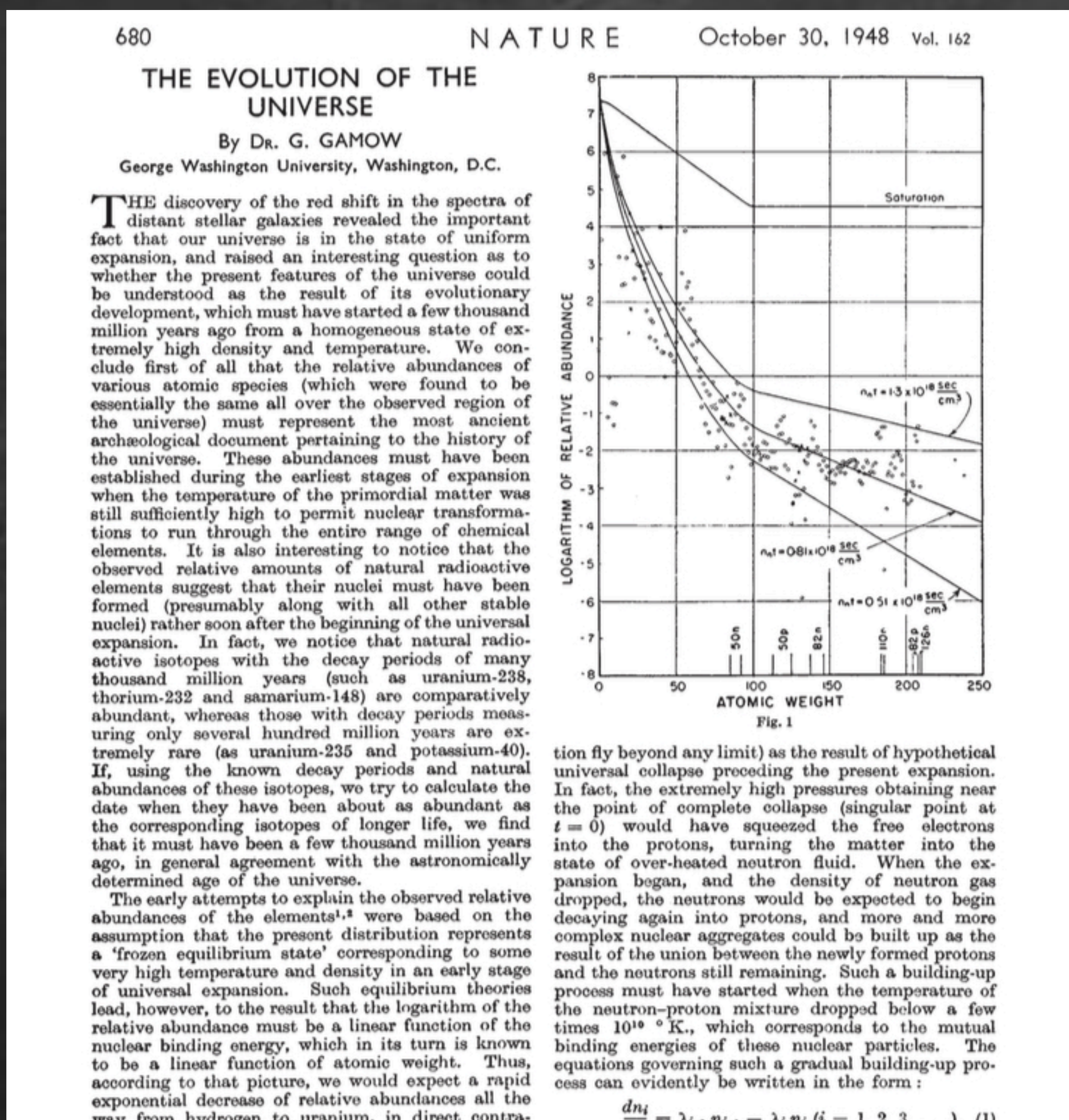
Most abundant light elements are Hydrogen ($\sim 75\%$) and Helium ($\sim 25\%$)

But where did the elements come from?????

Big-Bang Nucleosynthesis: Formation of light elements

Most abundant light elements are Hydrogen ($\sim 75\%$) and Helium ($\sim 25\%$)

But where did the elements come from?????



680 NATURE October 30, 1948 Vol. 162

THE EVOLUTION OF THE UNIVERSE

By Dr. G. GAMOW

George Washington University, Washington, D.C.

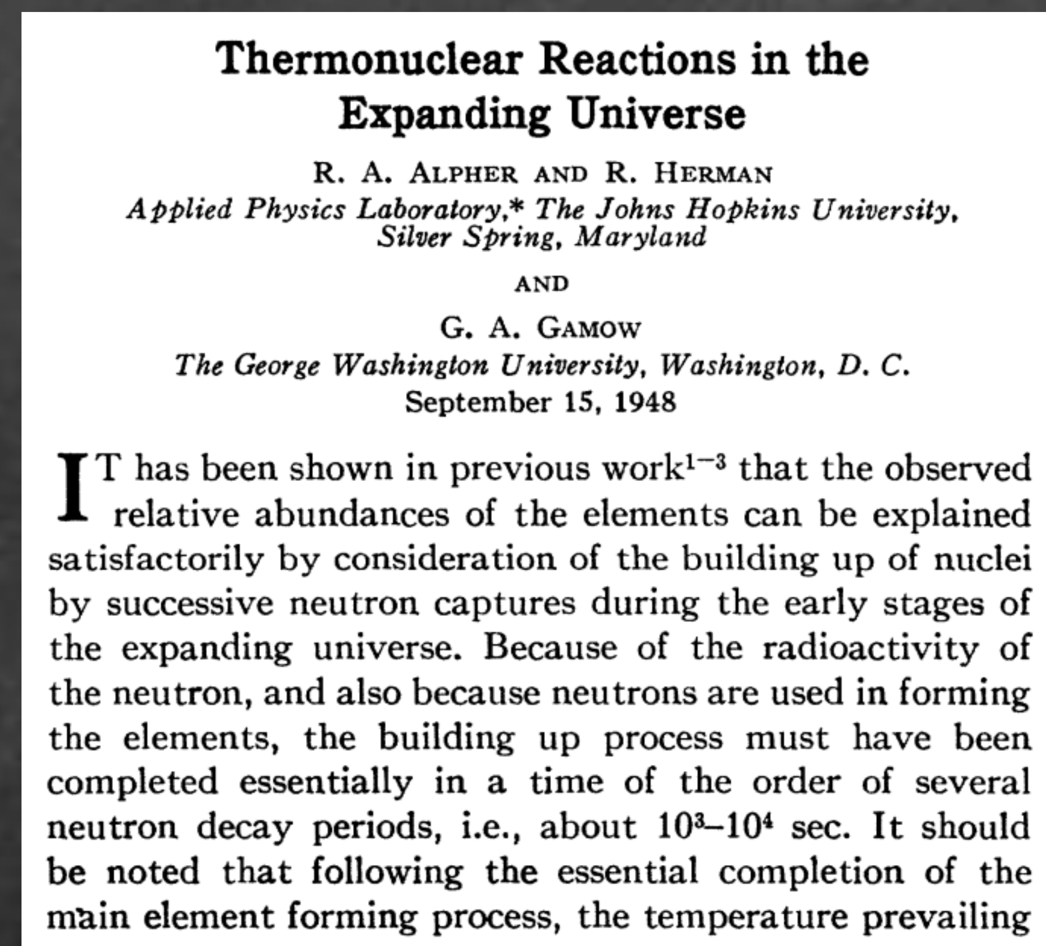
THE discovery of the red shift in the spectra of distant stellar galaxies revealed the important fact that our universe is in the state of uniform expansion, and raised an interesting question as to whether the present features of the universe could be understood as the result of its evolutionary development, which must have started a few thousand million years ago from a homogeneous state of extremely high density and temperature. We conclude first of all that the relative abundances of various atomic species (which were found to be essentially the same all over the observed region of the universe) must represent the most ancient archæological document pertaining to the history of the universe. These abundances must have been established during the earliest stages of expansion when the temperature of the primordial matter was still sufficiently high to permit nuclear transformations to run through the entire range of chemical elements. It is also interesting to notice that the observed relative amounts of natural radioactive elements suggest that their nuclei must have been formed (presumably along with all other stable nuclei) rather soon after the beginning of the universal expansion. In fact, we notice that natural radioactive isotopes with the decay periods of many thousand million years (such as uranium-238, thorium-232 and samarium-148) are comparatively abundant, whereas those with decay periods measuring only several hundred million years are extremely rare (as uranium-235 and potassium-40). If, using the known decay periods and natural abundances of these isotopes, we try to calculate the date when they have been about as abundant as the corresponding isotopes of longer life, we find that it must have been a few thousand million years ago, in general agreement with the astronomically determined age of the universe.

The early attempts to explain the observed relative abundances of the elements[1,2] were based on the assumption that the present distribution represents a 'frozen equilibrium state' corresponding to some very high temperature and density in an early stage of universal expansion. Such equilibrium theories lead, however, to the result that the logarithm of the relative abundance must be a linear function of the nuclear binding energy, which in its turn is known to be a linear function of atomic weight. Thus, according to that picture, we would expect a rapid exponential decrease of relative abundances all the way from hydrogen to uranium, in direct contra-

Fig. 1

tion fly beyond any limit) as the result of hypothetical universal collapse preceding the present expansion. In fact, the extremely high pressures obtaining near the point of complete collapse (singular point at $t = 0$) would have squeezed the free electrons into the protons, turning the matter into the state of over-heated neutron fluid. When the expansion began, and the density of neutron gas dropped, the neutrons would be expected to begin decaying again into protons, and more and more complex nuclear aggregates could be built up as the result of the union between the newly formed protons and the neutrons still remaining. Such a building-up process must have started when the temperature of the neutron–proton mixture dropped below a few times 10^{10} °K., which corresponds to the mutual binding energies of these nuclear particles. The equations governing such a gradual building-up process can evidently be written in the form:

$$\frac{dn_i}{dt} = \lambda_{i-1} n_{i-1} - \lambda_i n_i \; (i = 1, 2, 3, \ldots), \quad (1)$$



Thermonuclear Reactions in the Expanding Universe

R. A. Alpher and R. Herman

Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland*

AND

G. A. Gamow

The George Washington University, Washington, D. C.

September 15, 1948

IT has been shown in previous work[1–3] that the observed relative abundances of the elements can be explained satisfactorily by consideration of the building up of nuclei by successive neutron captures during the early stages of the expanding universe. Because of the radioactivity of the neutron, and also because neutrons are used in forming the elements, the building up process must have been completed essentially in a time of the order of several neutron decay periods, i.e., about 10^3–10^4 sec. It should be noted that following the essential completion of the main element forming process, the temperature prevailing

Assumptions of SBBN

Assumptions of SBBN

Universe is homogeneous and isotropic.

↓

Friedmann equations: $H^2 = \frac{8\pi\rho_{\rm tot}}{3M_{Pl}^2}$ and $\frac{\ddot{a}}{a} = -\frac{4\pi}{3M_{pl}^2}\left(\rho_{\rm tot} + 3p_{\rm tot}\right)$

Assumptions of SBBN

Universe is homogeneous and isotropic.

↓

Friedmann equations: $H^2 = \frac{8\pi\rho_{\rm tot}}{3M_{Pl}^2}$ and $\frac{\ddot{a}}{a} = -\frac{4\pi}{3M_{pl}^2}\left(\rho_{\rm tot} + 3p_{\rm tot}\right)$

Energy density of the Universe is dominated by radiation

↓

$$a \propto t^{1/2}$$

Assumptions of SBBN

Universe is homogeneous and isotropic.

↓

Friedmann equations: $H^2 = \frac{8\pi\rho_{\rm tot}}{3M_{Pl}^2}$ and $\frac{\ddot{a}}{a} = -\frac{4\pi}{3M_{pl}^2}(\rho_{\rm tot} + 3p_{\rm tot})$

Energy density of the Universe is dominated by radiation

↓

$$a \propto t^{1/2}$$

All the nuclear reaction raters are calculated based on the Standard Model

SBBN timescales

Temperature

SBBN timescales

Temperature

$T_i \gg 1.293\,\mathrm{MeV}$ — **BBN starts:** $n_n \simeq n_p = \dfrac{n_b}{2}$

SBBN timescales

Temperature

$0.7\,\mathrm{MeV}$ — n and p freeze-out

$T_i \gg 1.293\,\mathrm{MeV}$ — **BBN starts:** $n_n \simeq n_p = \dfrac{n_b}{2}$

SBBN timescales

Temperature

$0.1\,\text{MeV}$ — Deuterium bottleneck and formation of light elements begins

$0.7\,\text{MeV}$ — n and p freeze-out

$T_i \gg 1.293\,\text{MeV}$ — BBN starts: $n_n \simeq n_p = \dfrac{n_b}{2}$

SBBN timescales

Temperature

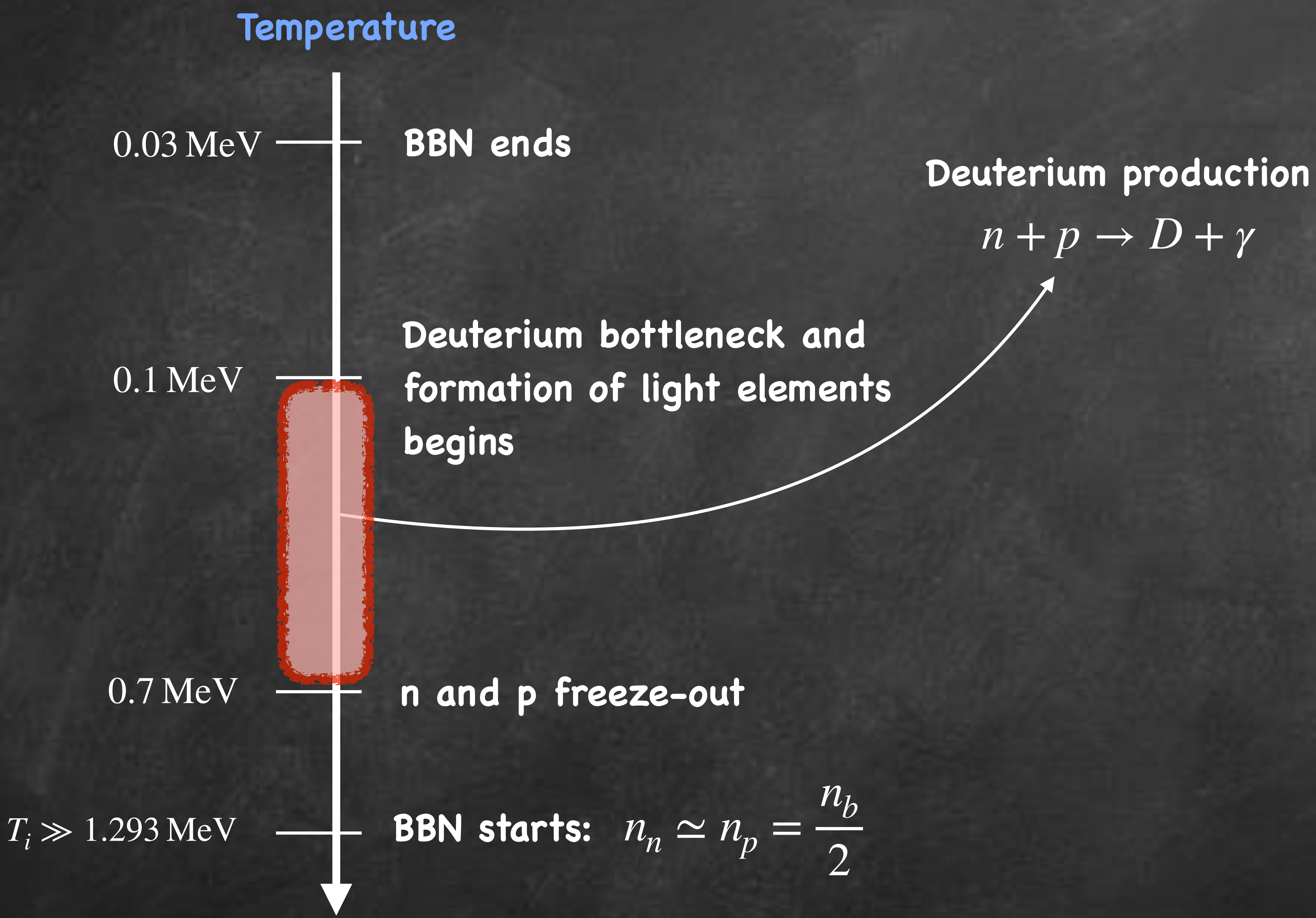
0.03 MeV — BBN ends

0.1 MeV — Deuterium bottleneck and formation of light elements begins

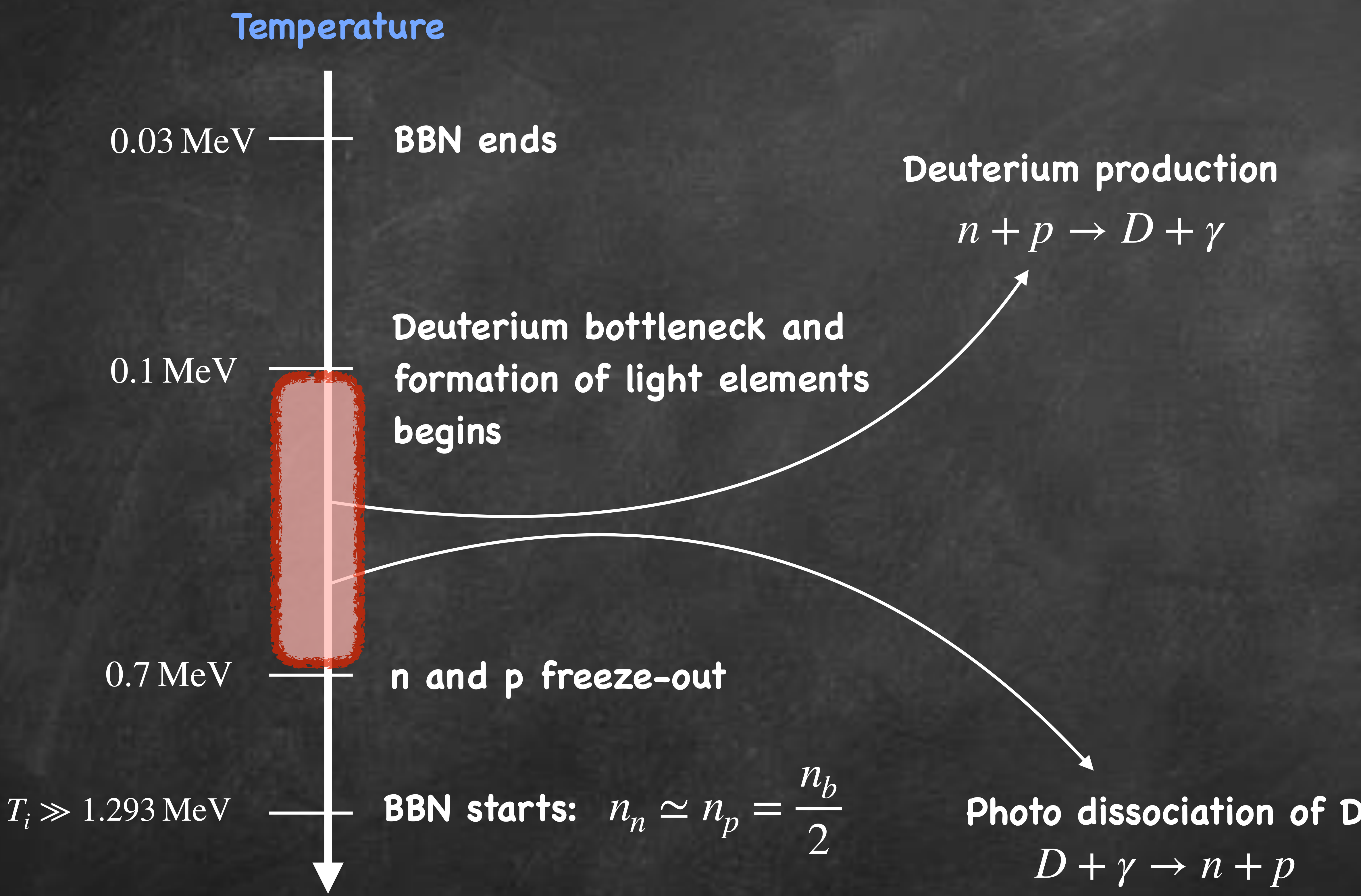
0.7 MeV — n and p freeze-out

$T_i \gg 1.293\,\mathrm{MeV}$ — BBN starts: $n_n \simeq n_p = \dfrac{n_b}{2}$

SBBN timescales

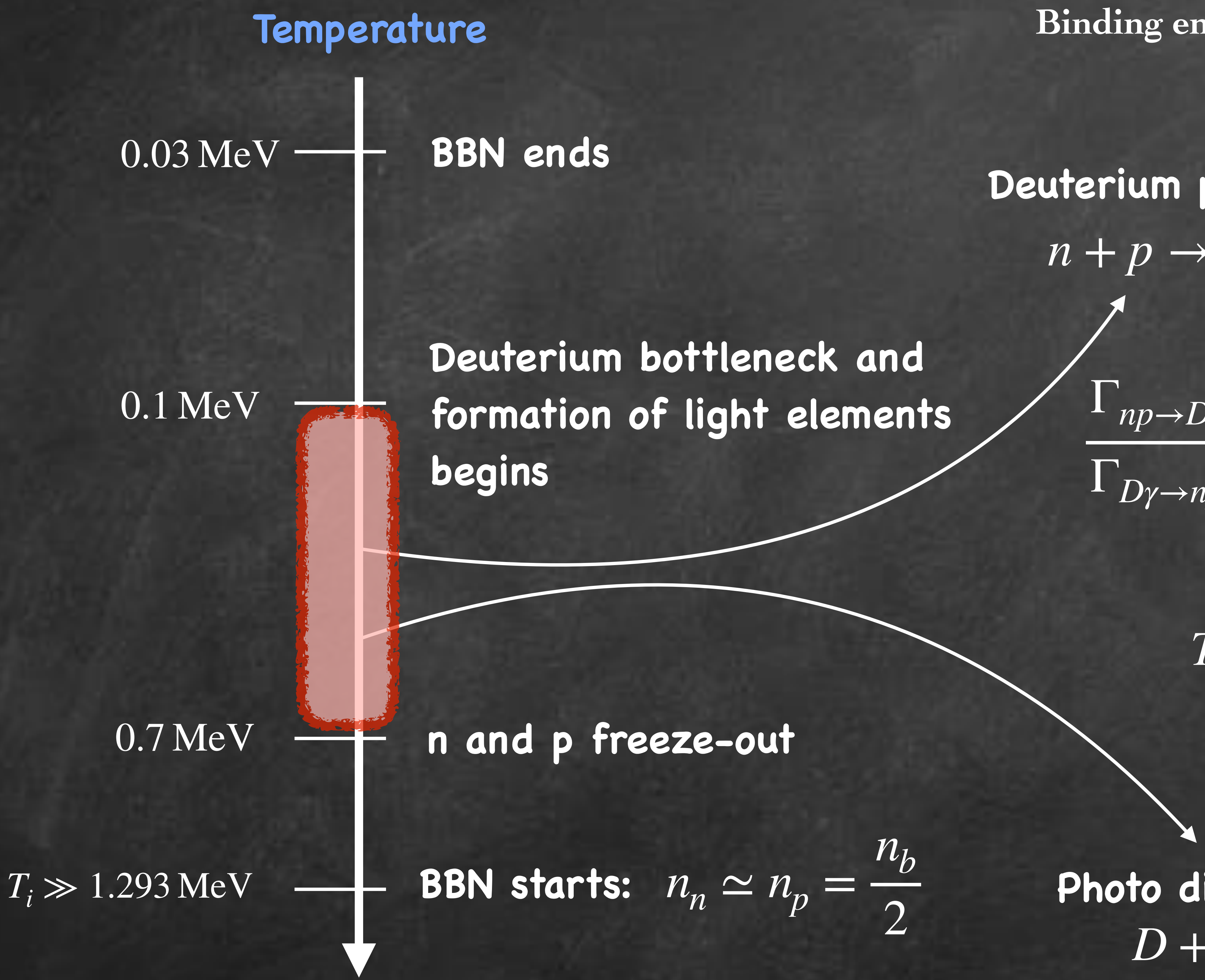


SBBN timescales



SBBN timescales

Binding energy of D $(B_D) \simeq 2.2\,\mathrm{MeV}$



Deuterium production

$$n + p \to D + \gamma$$

$$\frac{\Gamma_{np \to D\gamma}}{\Gamma_{D\gamma \to np}} \simeq 10^{-10} e^{B_D/T} \simeq 1$$

when

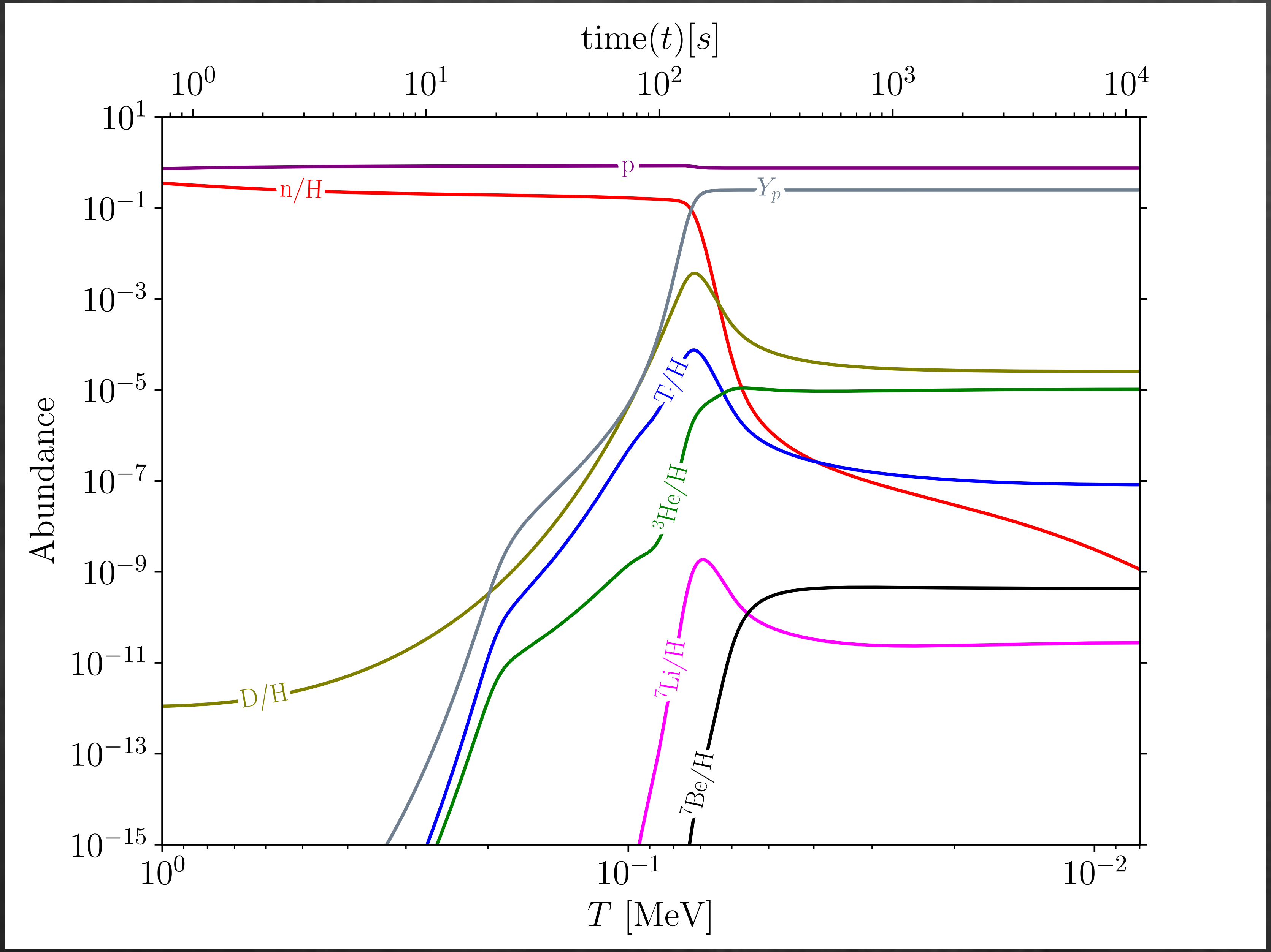
$$T \simeq 0.09\,\mathrm{MeV}$$

Photo dissociation of D

$$D + \gamma \to n + p$$

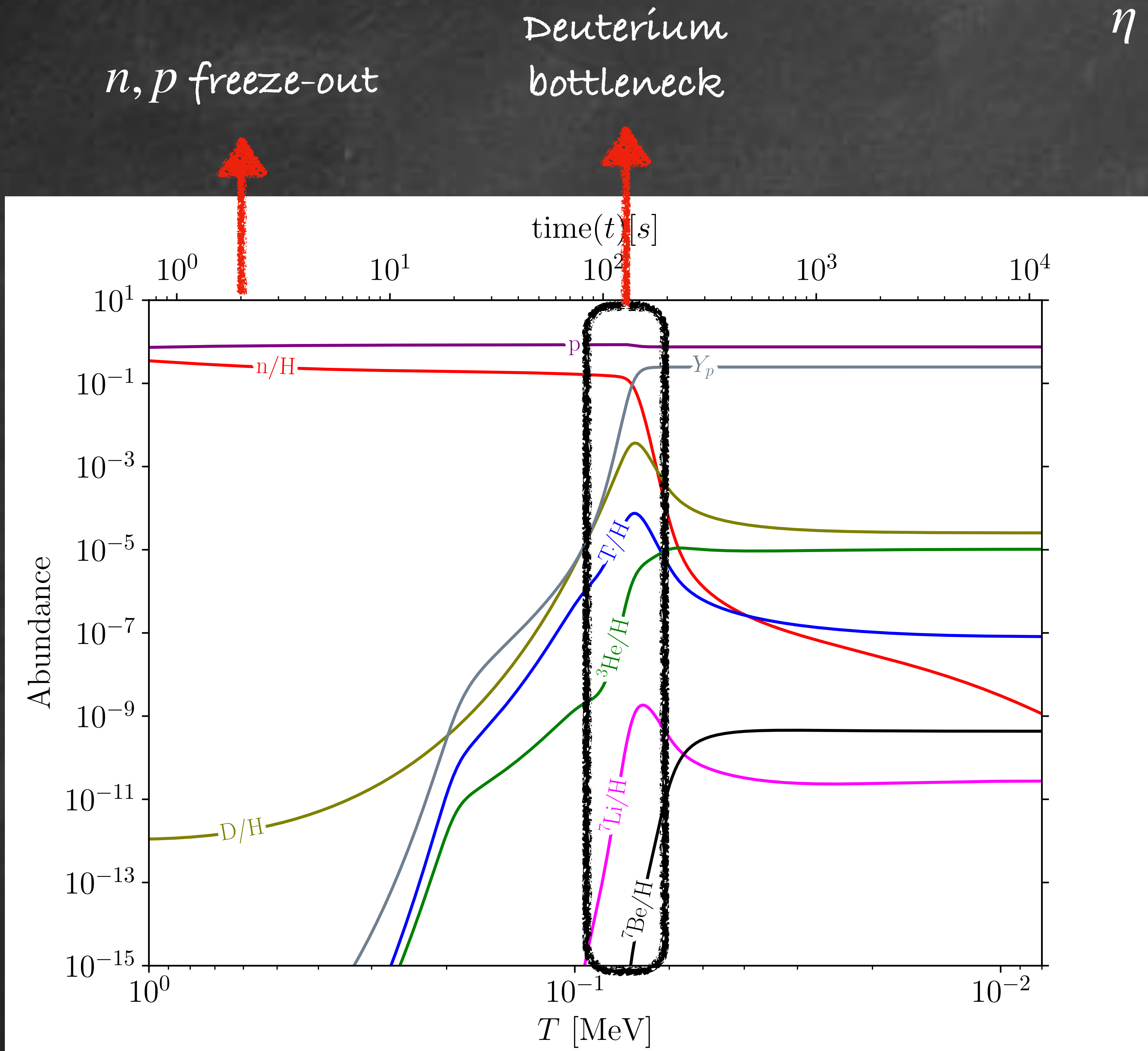
Time Evolution

$$\eta = (6.104 \pm 0.058) \times 10^{-10}$$
$$\tau_n = 879.4 \pm 0.6\, s$$



Time Evolution

$$\eta = (6.104 \pm 0.058) \times 10^{-10}$$
$$\tau_n = 879.4 \pm 0.6\, s$$



Current status

Y_p

SBBN prediction: 0.24691 ± 0.00018

Observation: 0.245 ± 0.003

D/H

SBBN prediction: $(2.57 \pm 0.13) \times 10^{-5}$

Observation: $(25.47 \pm 0.29) \times 10^{-6}$

^{3}He/H

SBBN prediction: $(10.03 \pm 0.90) \times 10^{-6}$

Observation : $< (1.09 \pm 0.18) \times 10^{-5}$

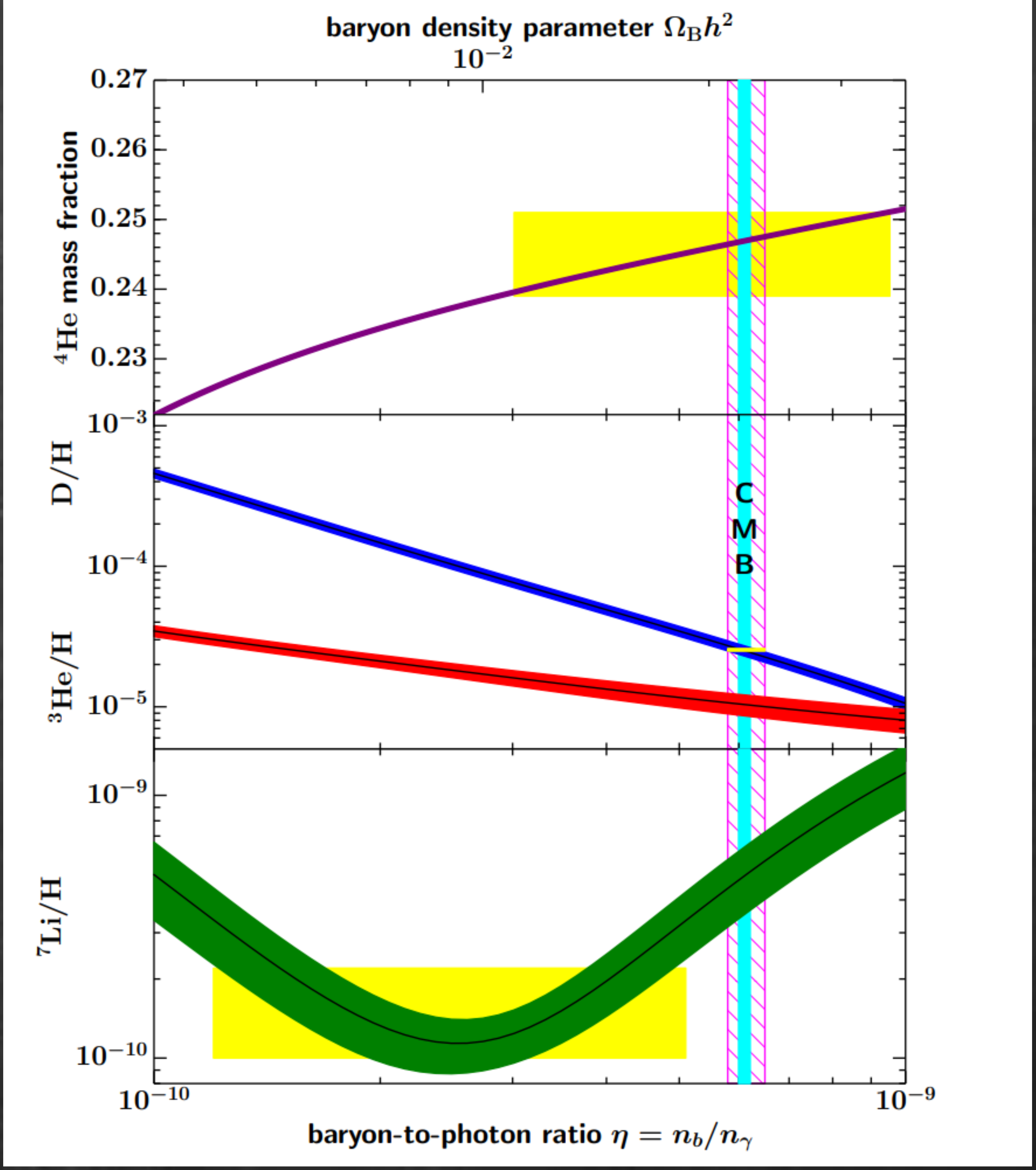
2203.11256

^{7}Li/H

SBBN prediction: $(4.72 \pm 0.72) \times 10^{-10}$

Observation: $(1.6 \pm 0.3) \times 10^{-10}$

Curve width corresponds to the theoretical uncertainty in the nuclear cross sections

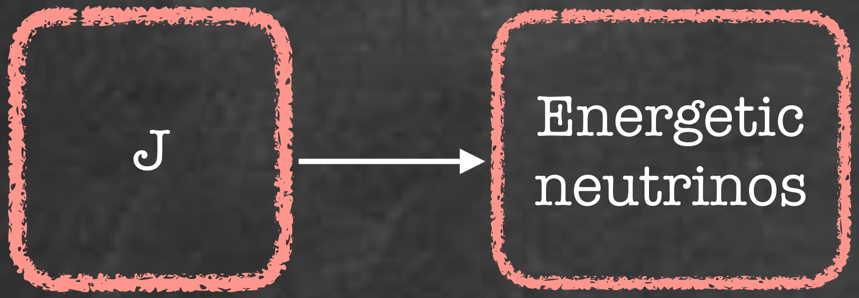


1912.01132, PDG 2022

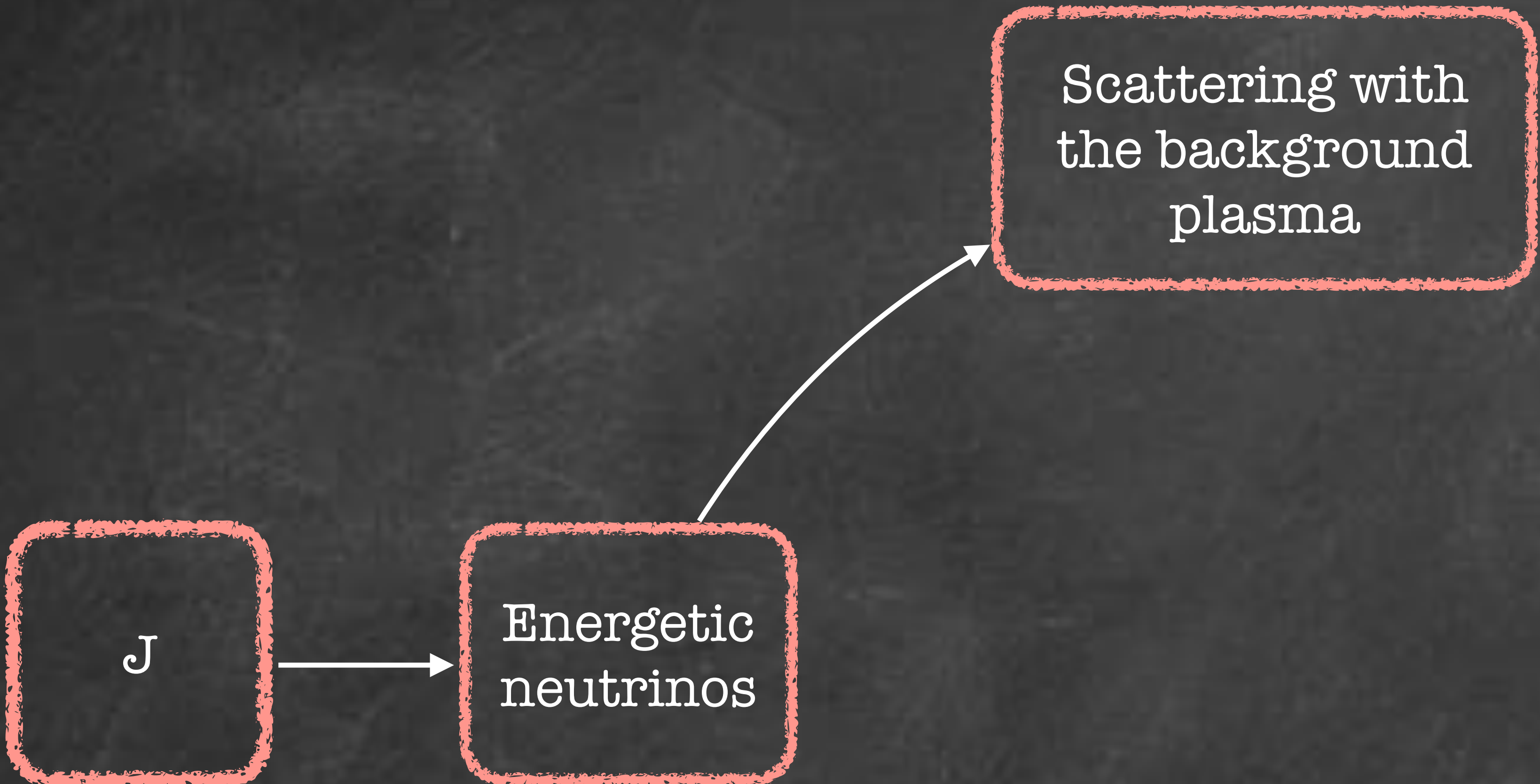
Neutrino injection from Majoron

Neutrino injection from Majoron

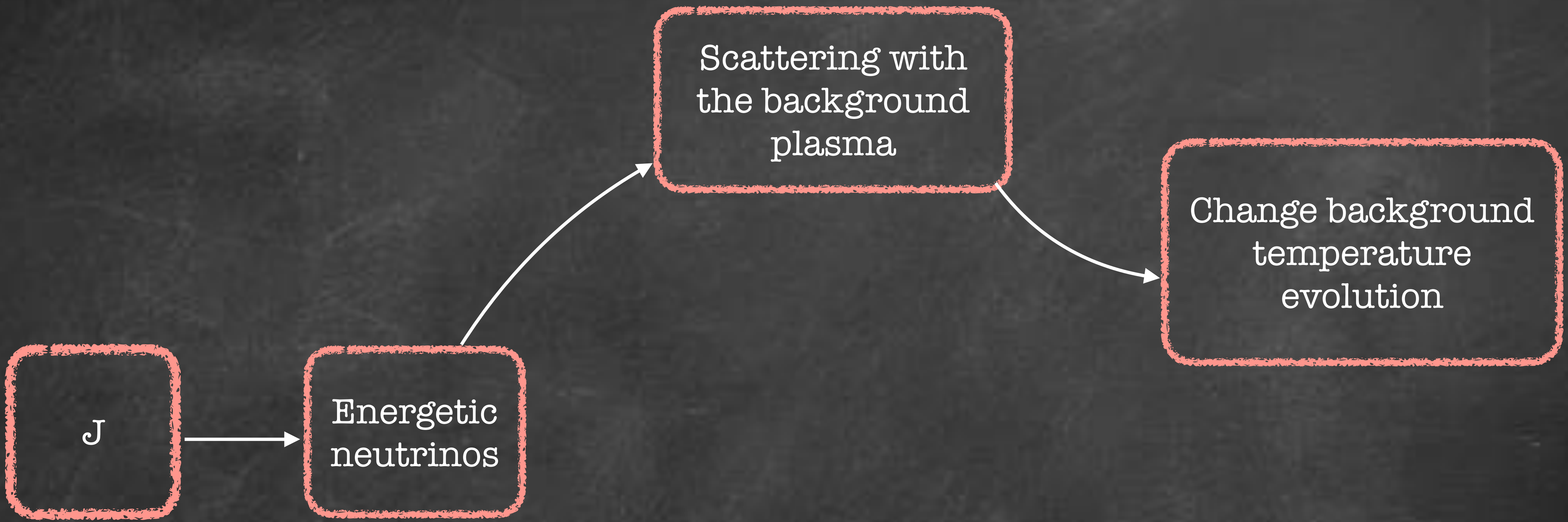
Neutrino injection from Majoron



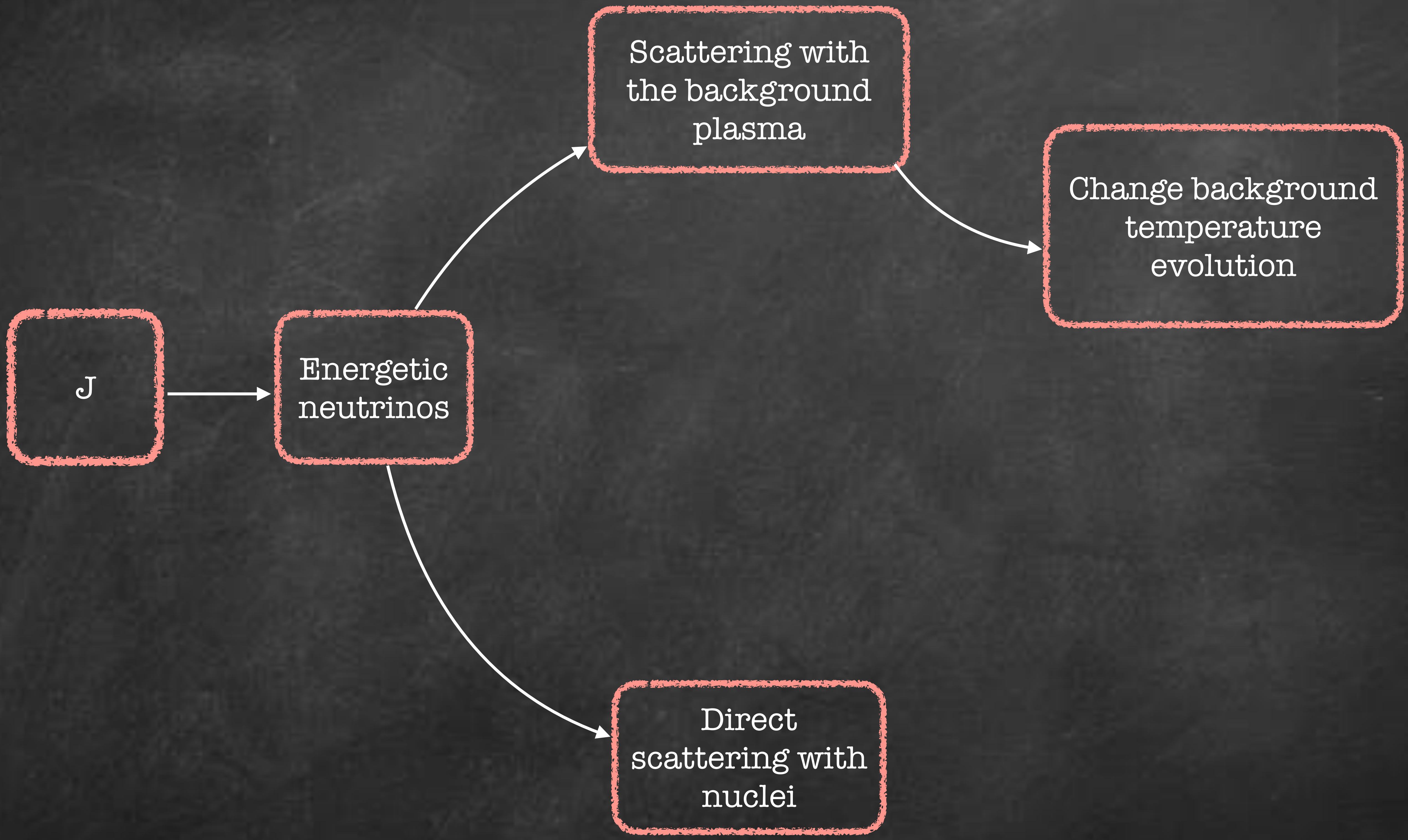
Neutrino injection from Majoron



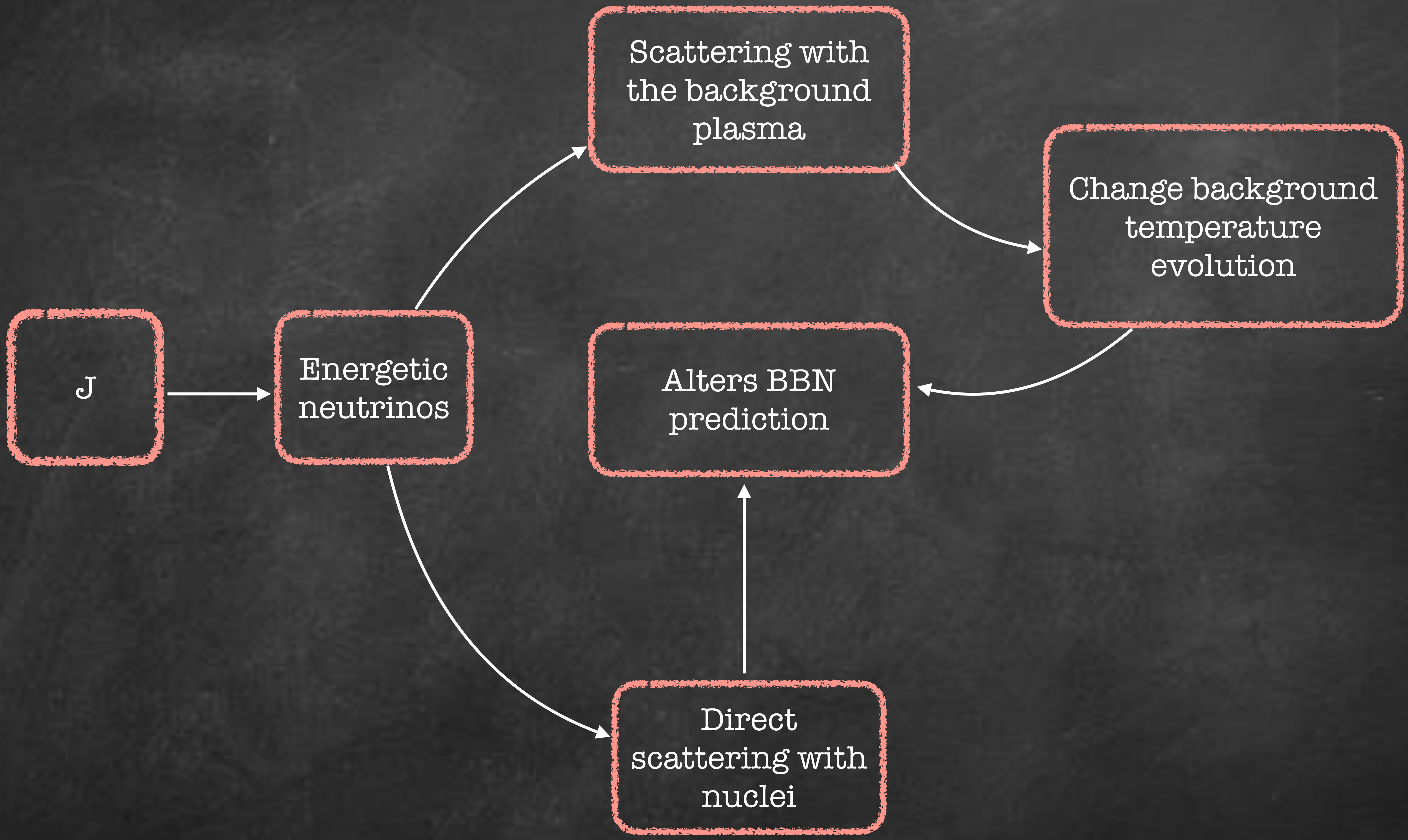
Neutrino injection from Majoron



Neutrino injection from Majoron



Neutrino injection from Majoron



Framework

Framework

- Interaction of SM neutrinos with Majoron is governed by $\mathscr{L} = -\frac{ig}{2}\overline{\nu}_i\gamma_5\nu_i J$

Framework

- Interaction of SM neutrinos with Majoron is governed by $\mathscr{L} = -\dfrac{ig}{2}\overline{\nu_i}\gamma_5\nu_i J$
- We treat the Majoron abundance $\left(Y_J^{(0)} \equiv \dfrac{n_J}{s}\right)$ at the onset of BBN as a free parameter

Framework

- Interaction of SM neutrinos with Majoron is governed by $\mathscr{L} = -\frac{ig}{2}\overline{\nu_i}\gamma_5\nu_i J$
- We treat the Majoron abundance $\left(Y_J^{(0)} \equiv \frac{n_J}{s}\right)$ at the onset of BBN as a free parameter
- Majoron couplings with SM-neutrinos are flavor universal

Framework

- Interaction of SM neutrinos with Majoron is governed by $\mathscr{L} = -\frac{ig}{2}\overline{\nu_i}\gamma_5\nu_i J$
- We treat the Majoron abundance $\left(Y_J^{(0)} \equiv \frac{n_J}{s}\right)$ at the onset of BBN as a free parameter
- Majoron couplings with SM-neutrinos are flavor universal
- Three free-parameters: $Y_J^{(0)}, m_J, \tau_J$ where τ_J is the lifetime of Majoron

Framework

- Interaction of SM neutrinos with Majoron is governed by $\mathscr{L} = -\frac{ig}{2}\overline{\nu_i}\gamma_5\nu_i J$
- We treat the Majoron abundance $\left(Y_J^{(0)} \equiv \frac{n_J}{s}\right)$ at the onset of BBN as a free parameter
- Majoron couplings with SM-neutrinos are flavor universal
- Three free-parameters: $Y_J^{(0)}, m_J, \tau_J$ where τ_J is the lifetime of Majoron
- Our analysis is restricted between $1\,\mathrm{MeV} \leq m_J \leq 10\,\mathrm{GeV}$

Framework

- Interaction of SM neutrinos with Majoron is governed by $\mathscr{L} = -\frac{ig}{2}\overline{\nu_i}\gamma_5\nu_i J$
- We treat the Majoron abundance $\left(Y_J^{(0)} \equiv \frac{n_J}{s}\right)$ at the onset of BBN as a free parameter
- Majoron couplings with SM-neutrinos are flavor universal
- Three free-parameters: $Y_J^{(0)}, m_J, \tau_J$ where τ_J is the lifetime of Majoron
- Our analysis is restricted between $1\,\mathrm{MeV} \leq m_J \leq 10\,\mathrm{GeV}$

  * for $m_J \leq 1\,\mathrm{MeV}$, injected neutrinos from Majoron decay cannot affect the BBN processes

Framework

- Interaction of SM neutrinos with Majoron is governed by $\mathscr{L} = -\frac{ig}{2}\overline{\nu}_i\gamma_5\nu_i J$
- We treat the Majoron abundance $\left(Y_J^{(0)} \equiv \frac{n_J}{s}\right)$ at the onset of BBN as a free parameter
- Majoron couplings with SM-neutrinos are flavor universal
- Three free-parameters: $Y_J^{(0)}, m_J, \tau_J$ where τ_J is the lifetime of Majoron
- Our analysis is restricted between $1\,\mathrm{MeV} \leq m_J \leq 10\,\mathrm{GeV}$
  - * for $m_J \leq 1\,\mathrm{MeV}$, injected neutrinos from Majoron decay cannot affect the BBN processes
  - * for $m_J \geq 10\,\mathrm{GeV}$, muons and pions can be produced from the scattering of ν_{nt} with background plasma. We avoid such complexity by restricting our analysis up to $m_J = 10\,\mathrm{GeV}$

Treatment of non-thermal neutrinos

Treatment of non-thermal neutrinos

- We separate the momentum distribution function of ν by $f_{\nu_{\rm bg}} + f_{\nu_{\rm nt}}$

Treatment of non-thermal neutrinos

- We separate the momentum distribution function of ν by $f_{\nu_{\rm bg}} + f_{\nu_{\rm nt}}$

- Highly energetic non-thermal neutrino reduces its energy and merges into the background plasma by a single scattering

Treatment of non-thermal neutrinos

- We separate the momentum distribution function of ν by $f_{\nu_{\rm bg}} + f_{\nu_{\rm nt}}$

- Highly energetic non-thermal neutrino reduces its energy and merges into the background plasma by a single scattering

$$\frac{\partial f_{\nu_{\rm nt}}}{\partial t} - Hp\frac{\partial f_{\nu_{\rm nt}}}{\partial p} = \left[J \to \nu_{\rm nt}\nu_{\rm nt}\right] - [\text{Scattering between } \nu_{\rm nt} \text{ and } (\nu_{\rm bg}, e)]$$

Less number of neutrinos in the intermediate energy range with respect to the actual scenario.

Treatment of non-thermal neutrinos

- We separate the momentum distribution function of ν by $f_{\nu_{\rm bg}} + f_{\nu_{\rm nt}}$

- Highly energetic non-thermal neutrino reduces its energy and merges into the background plasma by a single scattering

$$\frac{\partial f_{\nu_{\rm nt}}}{\partial t} - Hp\frac{\partial f_{\nu_{\rm nt}}}{\partial p} = \left[J \to \nu_{\rm nt}\nu_{\rm nt}\right] - \text{[Scattering between } \nu_{\rm nt} \text{ and } (\nu_{\rm bg}, e)\text{]}$$

Less number of neutrinos in the intermediate energy range with respect to the actual scenario.

However it gives correct momentum-distribution at high-energy limit which is relevant for the $\nu_{\rm nt}$-nuclei scattering since these cross sections are proportional to the energy of $\nu_{\rm nt}$

Effect of Majoron on BBN

Effect of Majoron on BBN

- Injected neutrinos ($\nu_{\rm nt}$) enhance $p \to n$ conversion and as a result, the abundance of n will increase. $\nu_{\rm nt}$ also scatters with other light elements.

Effect of Majoron on BBN

- **Injected neutrinos ($\nu_{\rm nt}$) enhance $p \to n$ conversion and as a result, the abundance of n will increase. $\nu_{\rm nt}$ also scatters with other light elements.**

$$\frac{dX_A}{dt} = \Gamma_{\rm SBBN} + \sum_B \left(X_B\,\delta\Gamma_{B\to A} - X_A\,\delta\Gamma_{A\to B}\right)$$

$$\delta\Gamma_{A\to B} = \frac{1}{2\pi^2}\int_0^{m_J/2} dE_{\nu_{\rm nt}} f_{\nu_{\rm nt}} E_{\nu_{\rm nt}}^2 \sigma_{\nu_{\rm nt}A\to B}$$

$$X_A = \frac{n_A}{n_b}$$

Effect of Majoron on BBN

- Injected neutrinos ($\nu_{\rm nt}$) enhance $p \to n$ conversion and as a result, the abundance of n will increase. $\nu_{\rm nt}$ also scatters with other light elements.
- Injected neutrinos can heat-up the background neutrinos and it will change the equilibrium value of n/p ratio as well as the neutron freeze-out temperature.

$$\frac{dX_A}{dt} = \Gamma_{\rm SBBN} + \sum_B \left(X_B\, \delta\Gamma_{B\to A} - X_A\, \delta\Gamma_{A\to B} \right)$$

$$\delta\Gamma_{A\to B} = \frac{1}{2\pi^2} \int_0^{m_J/2} dE_{\nu_{\rm nt}} f_{\nu_{\rm nt}} E_{\nu_{\rm nt}}^2 \sigma_{\nu_{\rm nt} A\to B}$$

$$X_A = \frac{n_A}{n_b}$$

Effect of Majoron on BBN

- Injected neutrinos ($\nu_{\rm nt}$) enhance $p \to n$ conversion and as a result, the abundance of n will increase. $\nu_{\rm nt}$ also scatters with other light elements.
- Injected neutrinos can heat-up the background neutrinos and it will change the equilibrium value of n/p ratio as well as the neutron freeze-out temperature.

$$\frac{dX_A}{dt} = \Gamma_{\rm SBBN} + \sum_B \left(X_B\,\delta\Gamma_{B\to A} - X_A\,\delta\Gamma_{A\to B}\right)$$

$$\delta\Gamma_{A\to B} = \frac{1}{2\pi^2}\int_0^{m_J/2} dE_{\nu_{\rm nt}} f_{\nu_{\rm nt}} E^2_{\nu_{\rm nt}} \sigma_{\nu_{\rm nt}A\to B}$$

$$+\left(\Gamma'_{A\to B} - \Gamma^{\rm SBBN}_{A\to B}\right)$$

↓

Non-zero only for $n \to p$ conversion

$$X_A = \frac{n_A}{n_b}$$

Effect of Majoron on BBN

- Injected neutrinos ($\nu_{\rm nt}$) enhance $p \to n$ conversion and as a result, the abundance of n will increase. $\nu_{\rm nt}$ also scatters with other light elements.
- Injected neutrinos can heat-up the background neutrinos and it will change the equilibrium value of n/p ratio as well as the neutron freeze-out temperature.
- Modify the Hubble parameter

$$\frac{dX_A}{dt} = \Gamma_{\rm SBBN} + \sum_B \left(X_B\, \delta\Gamma_{B\to A} - X_A\, \delta\Gamma_{A\to B}\right)$$

$$\delta\Gamma_{A\to B} = \frac{1}{2\pi^2}\int_0^{m_J/2} dE_{\nu_{\rm nt}} f_{\nu_{\rm nt}} E_{\nu_{\rm nt}}^2 \sigma_{\nu_{\rm nt} A\to B}$$

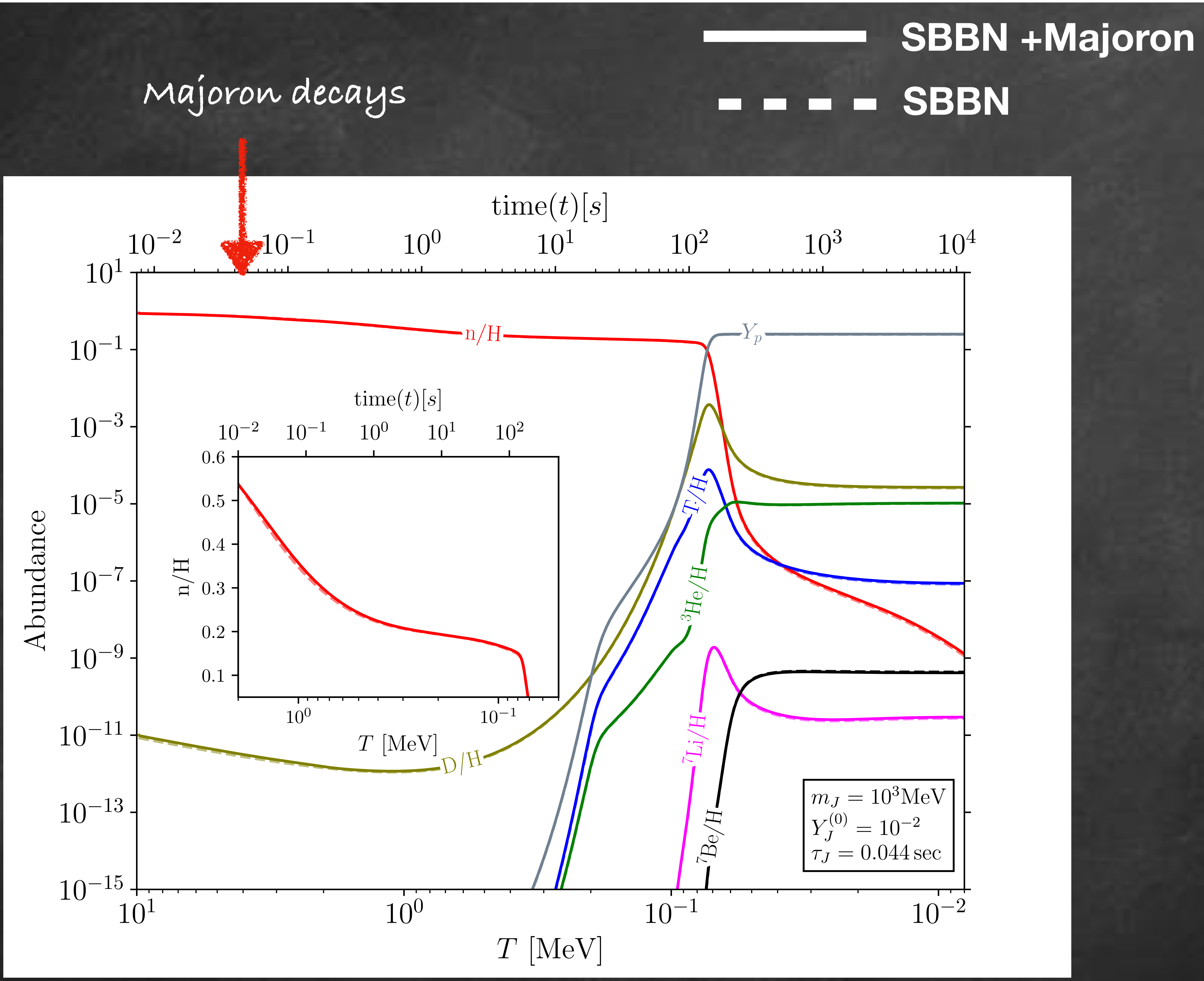
$$+\left(\Gamma'_{A\to B} - \Gamma^{\rm SBBN}_{A\to B}\right)$$

↓

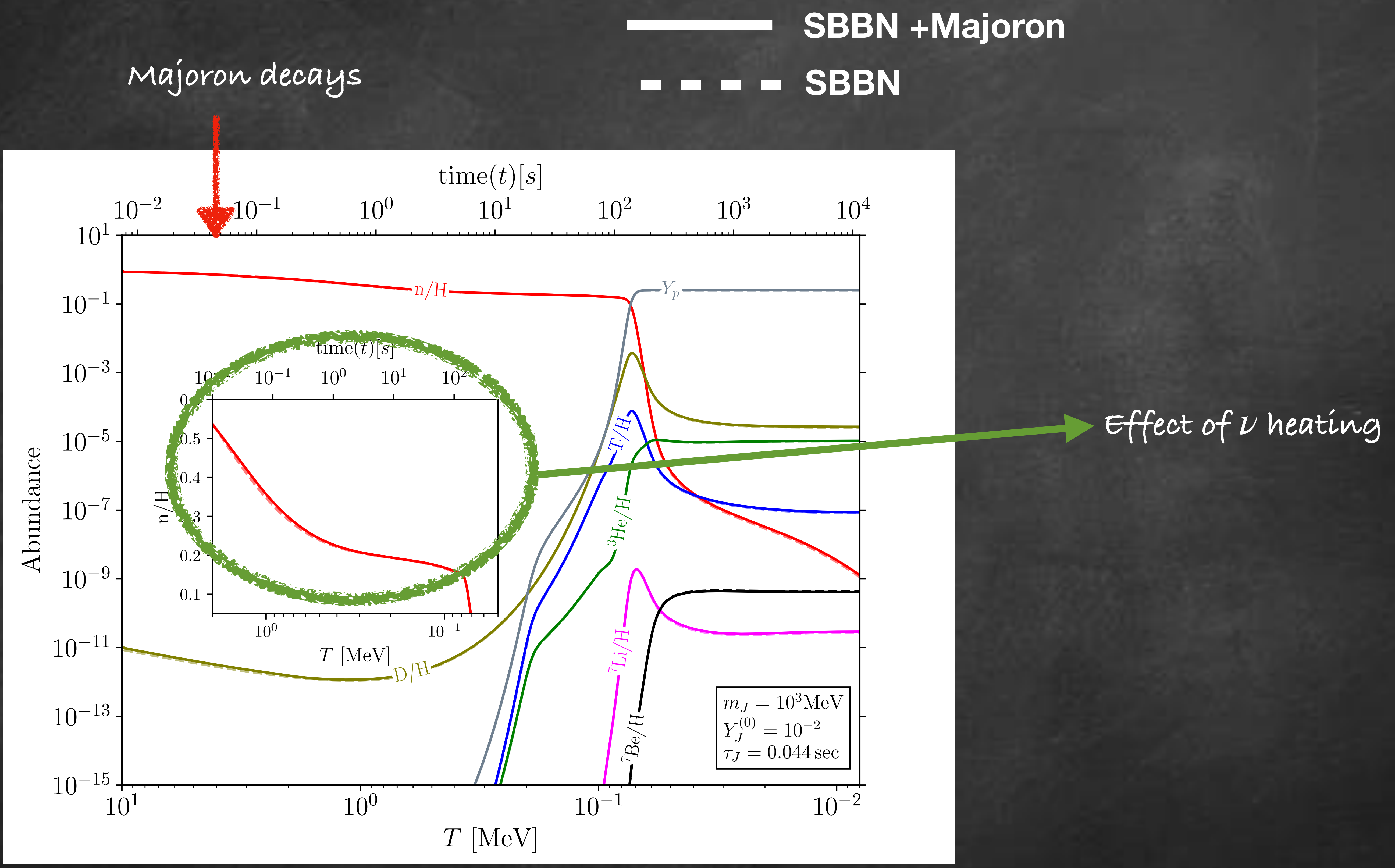
Non-zero only for $n \to p$ conversion

$$X_A = \frac{n_A}{n_b}$$

Evolution in presence of Majoron

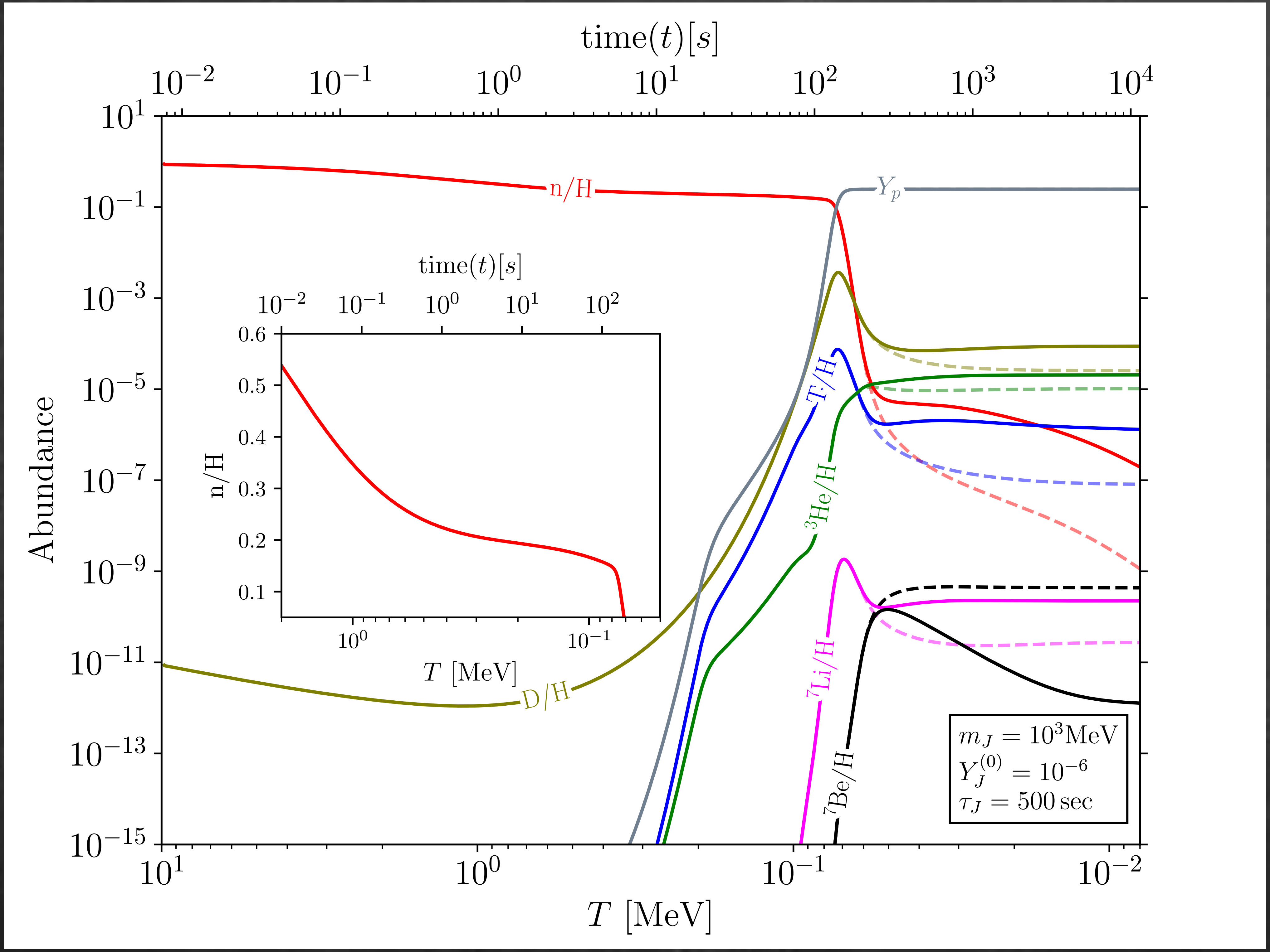


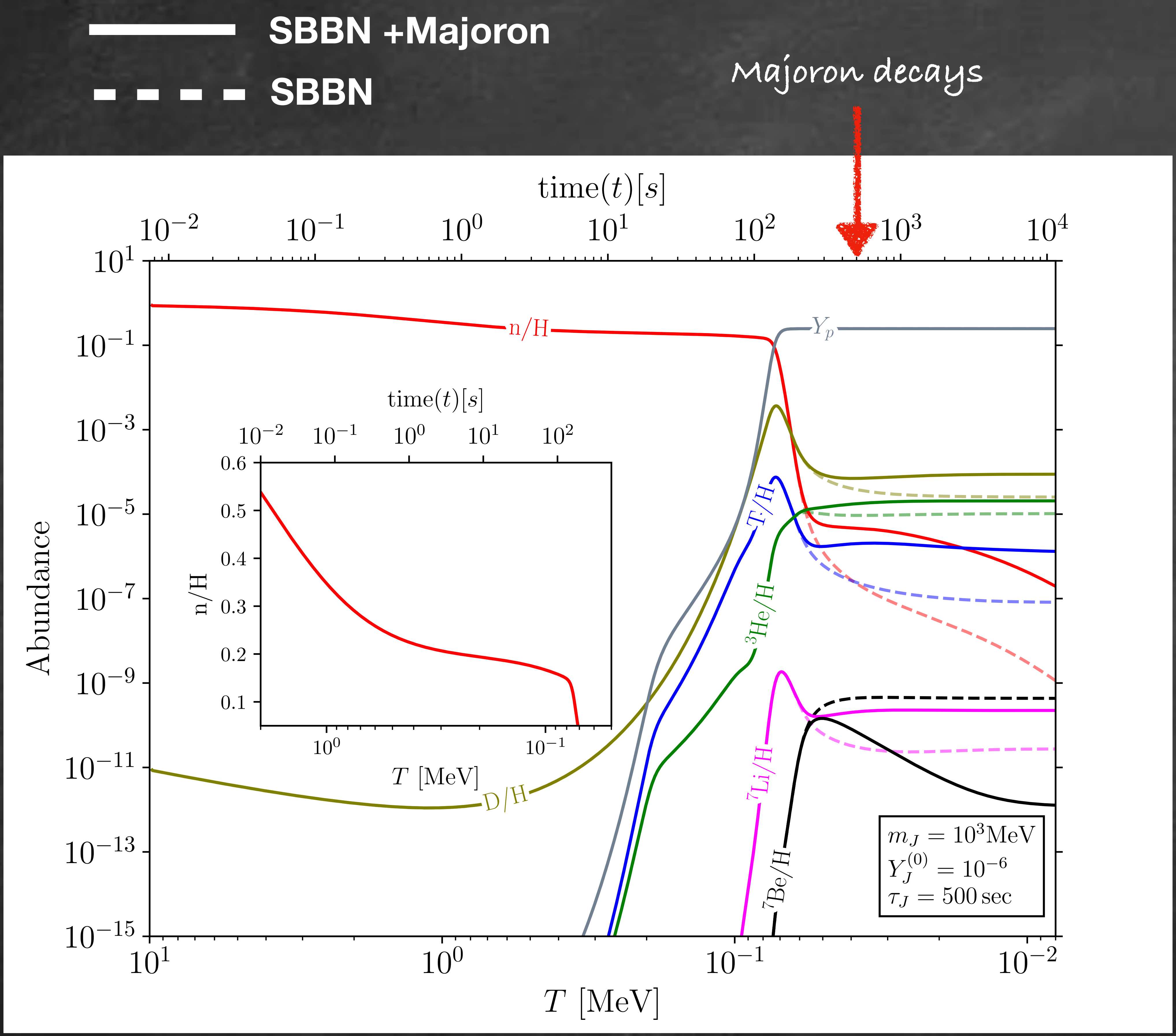
Evolution in presence of Majoron



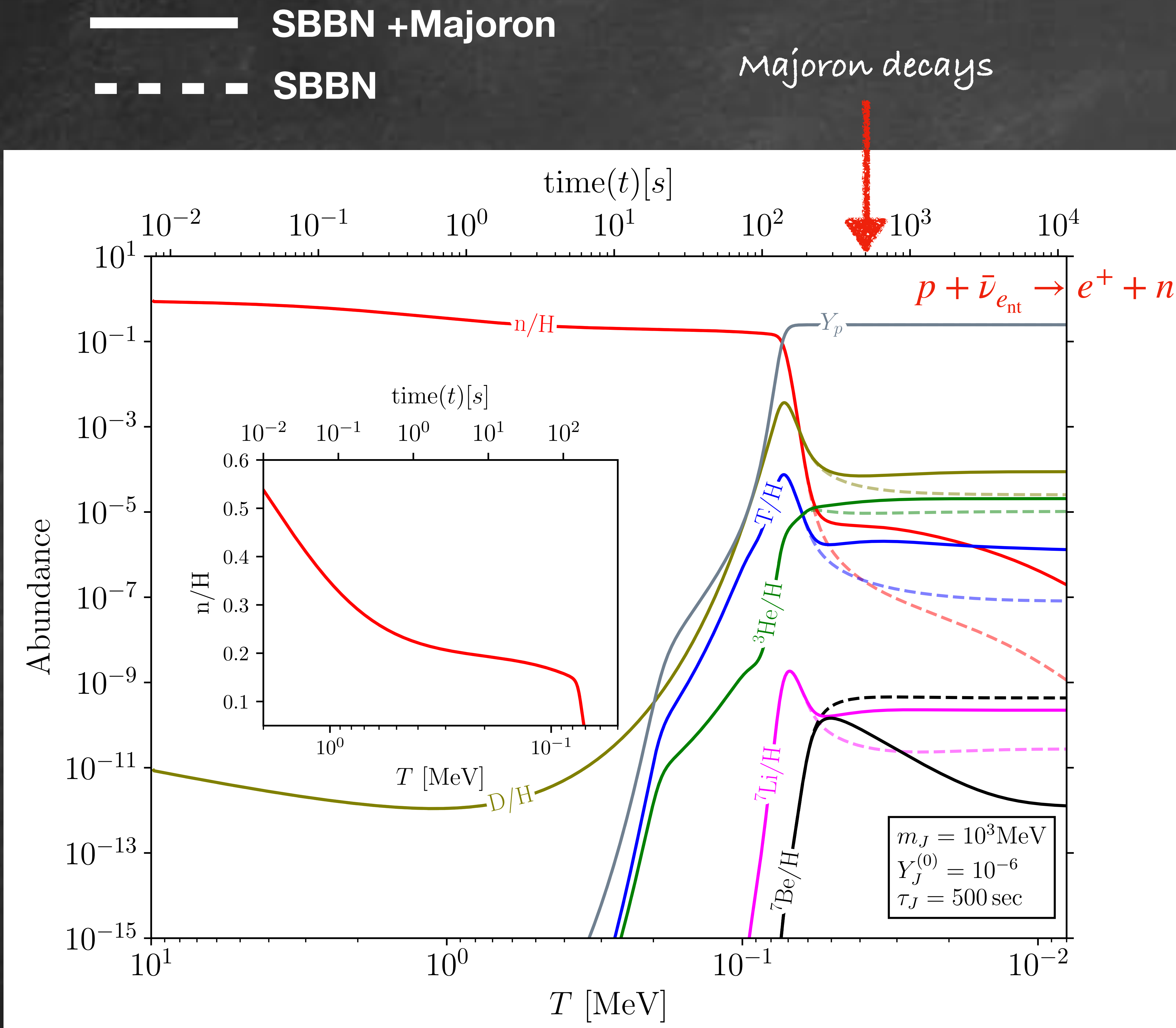
SBBN +Majoron

SBBN





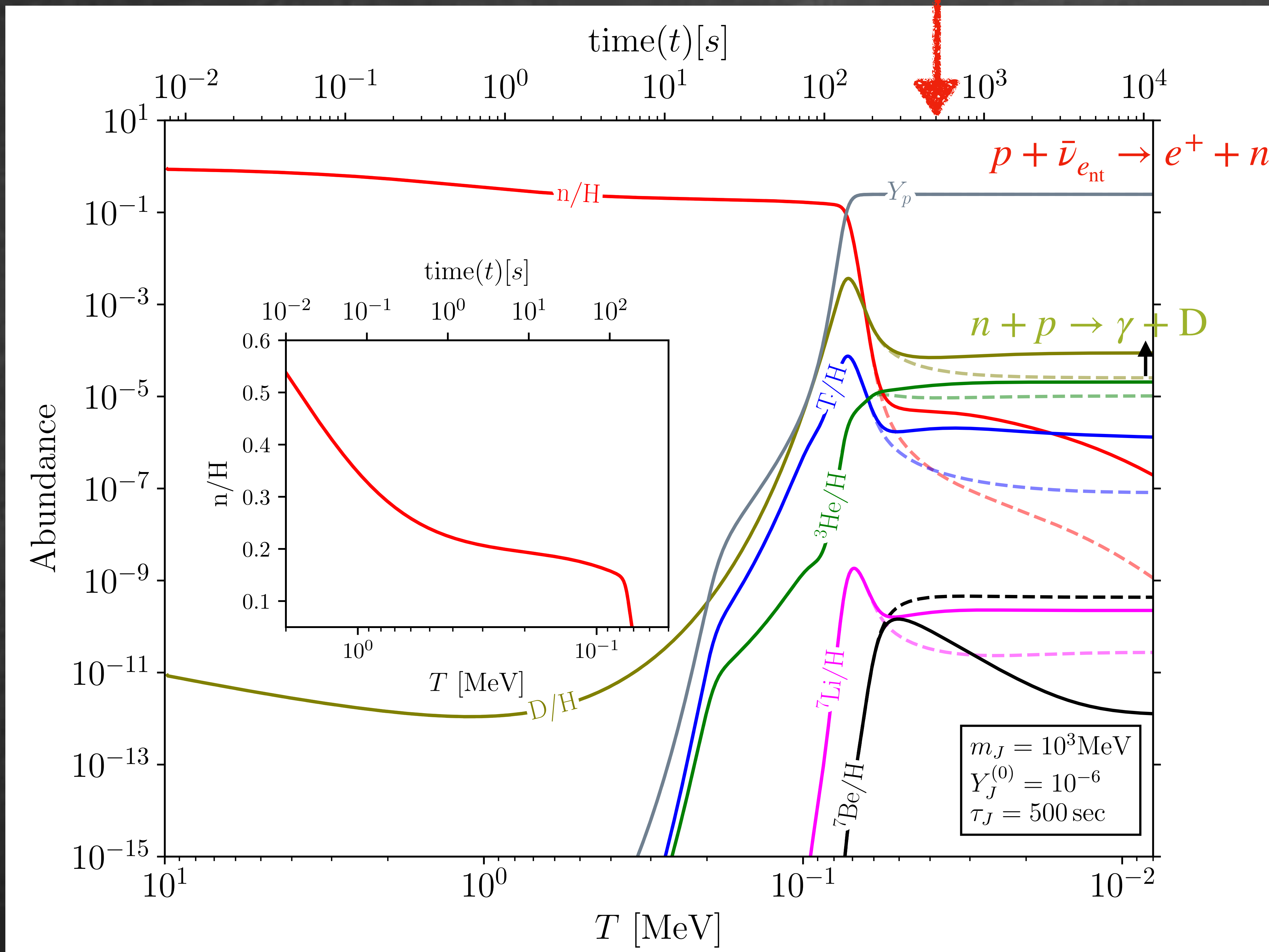
SBBN +Majoron
SBBN
Majoron decays
time(t)[s]
Abundance
n/H
Y_p
D/H
T/H
^{3}He/H
^{7}Li/H
^{7}Be/H
T [MeV]
$m_J = 10^3$MeV
$Y_J^{(0)} = 10^{-6}$
$\tau_J = 500$ sec

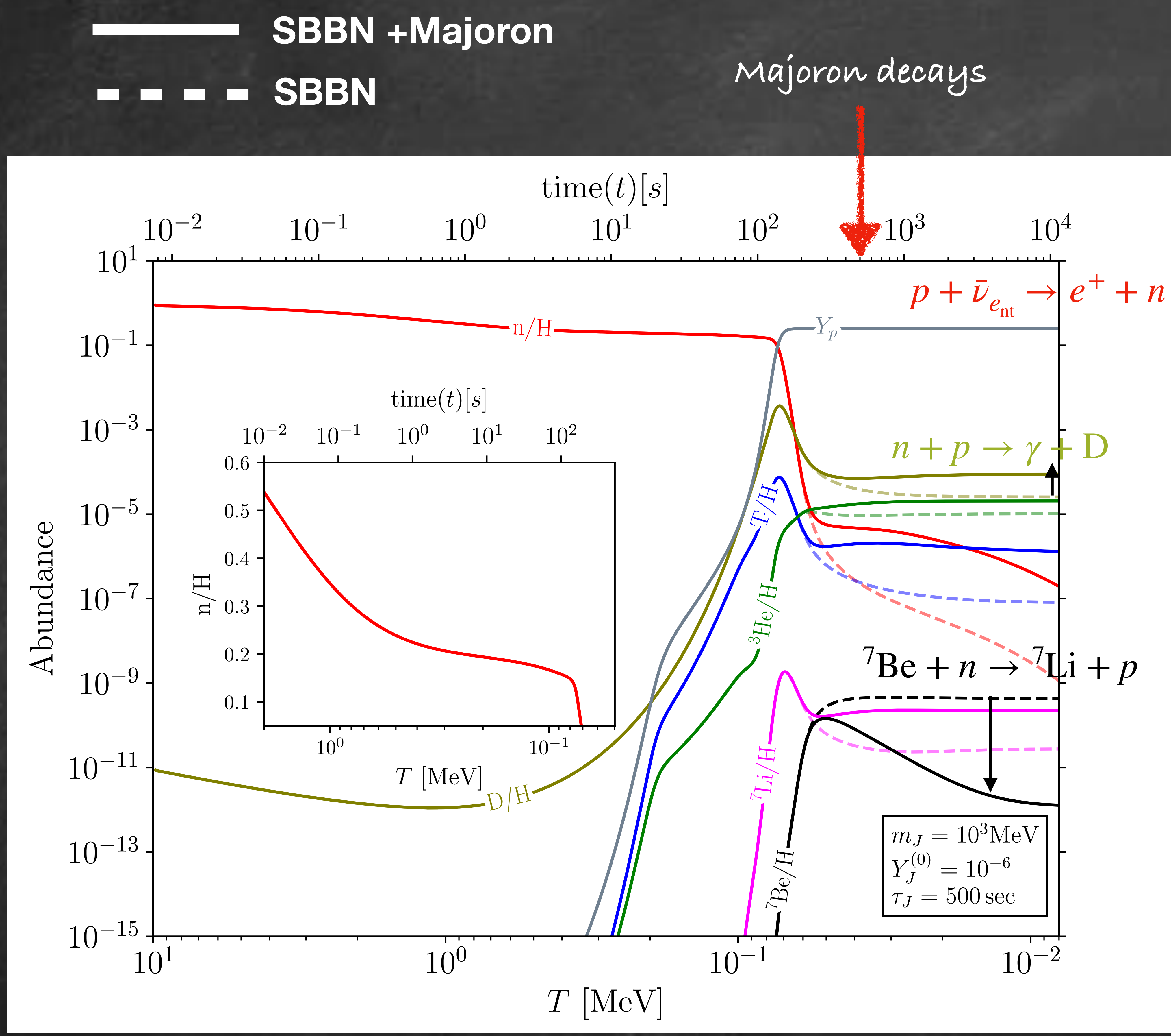

SBBN +Majoron
SBBN
Majoron decays
time(t)[s]
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4}
$p + \bar{\nu}_{e_{nt}} \rightarrow e^+ + n$
Abundance
10^{1} 10^{-1} 10^{-3} 10^{-5} 10^{-7} 10^{-9} 10^{-11} 10^{-13} 10^{-15}
n/H
Y_p
D/H
T/H
^{3}He/H
^{7}Li/H
^{7}Be/H
T [MeV]
10^{1} 10^{0} 10^{-1} 10^{-2}
$m_J = 10^3$MeV
$Y_J^{(0)} = 10^{-6}$
$\tau_J = 500$ sec
n/H
0.6 0.5 0.4 0.3 0.2 0.1

SBBN +Majoron

SBBN

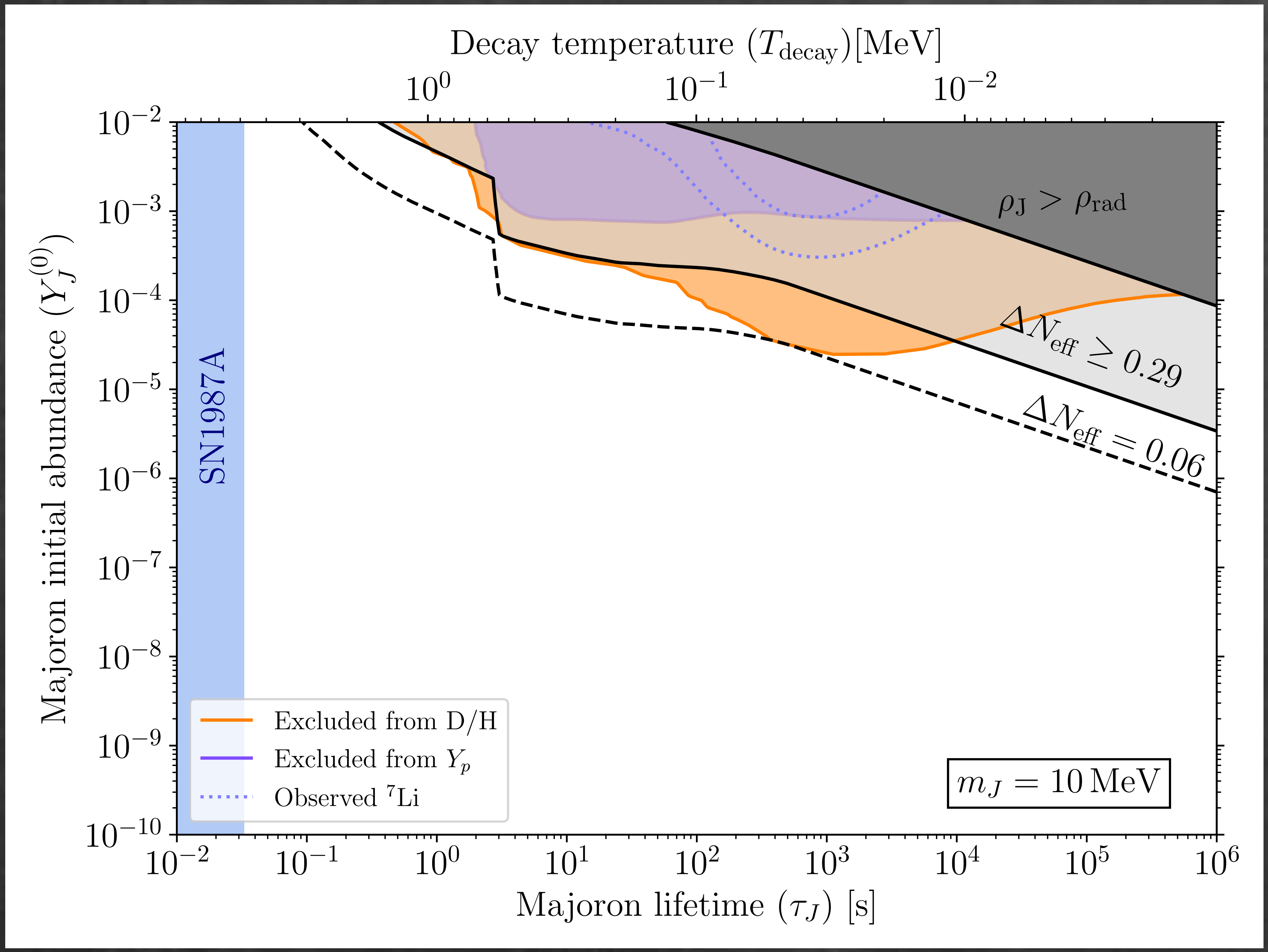
Majoron decays




SBBN +Majoron
SBBN
Majoron decays
time(t)[s]
$p + \bar{\nu}_{e_{nt}} \to e^+ + n$
$n + p \to \gamma + D$
$^7Be + n \to {}^7Li + p$
n/H
Y_p
T/H
$^3He/H$
$^7Li/H$
$^7Be/H$
D/H
Abundance
T [MeV]
$m_J = 10^3 MeV$
$Y_J^{(0)} = 10^{-6}$
$\tau_J = 500$ sec

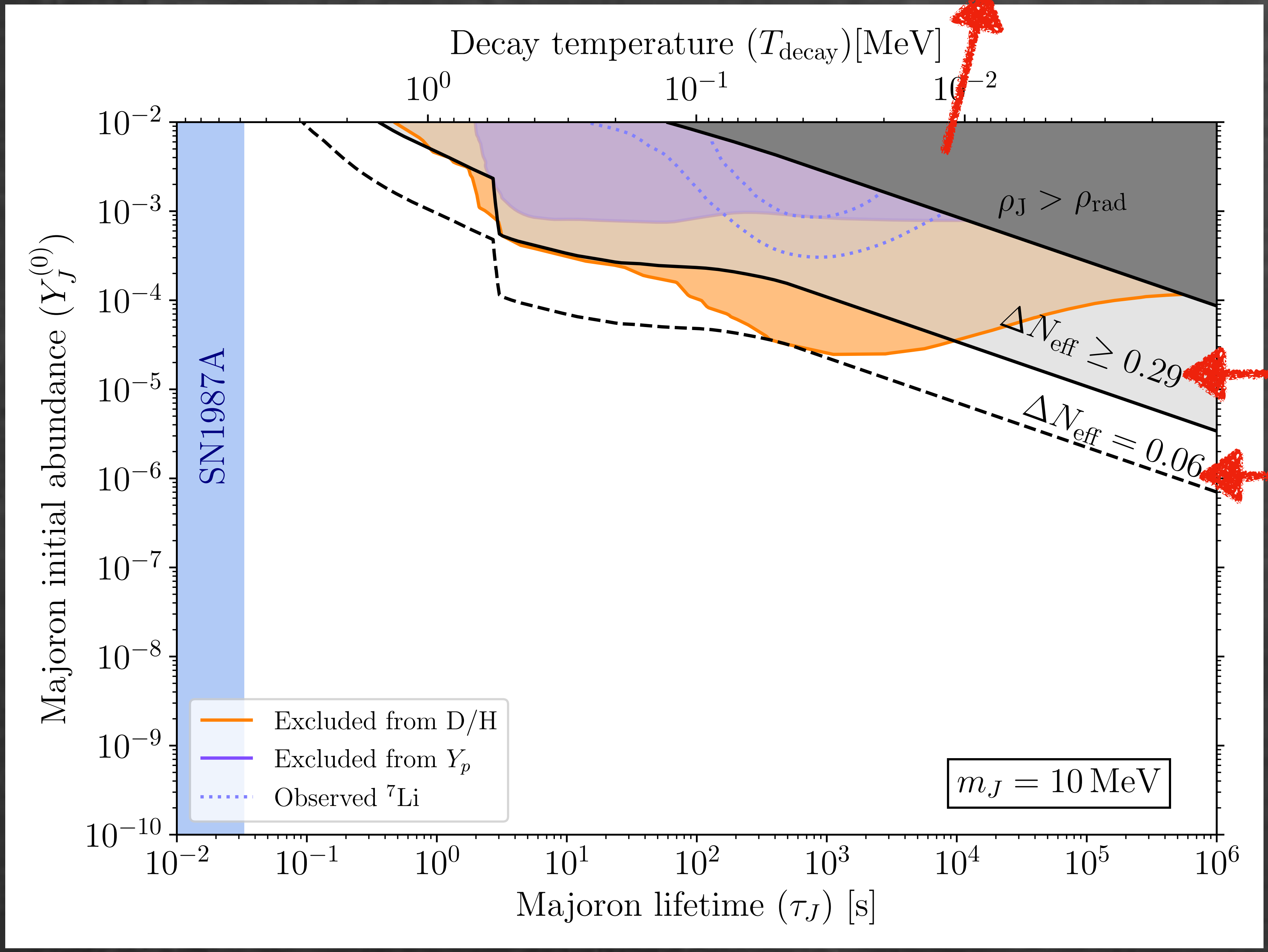
Majoron parameter space in $\tau_J - Y_J^{(0)}$ plane

Majoron parameter space in $\tau_J - Y_J^{(0)}$ plane



Majoron parameter space in $\tau_J - Y_J^{(0)}$ plane

Majoron dominates the Universe

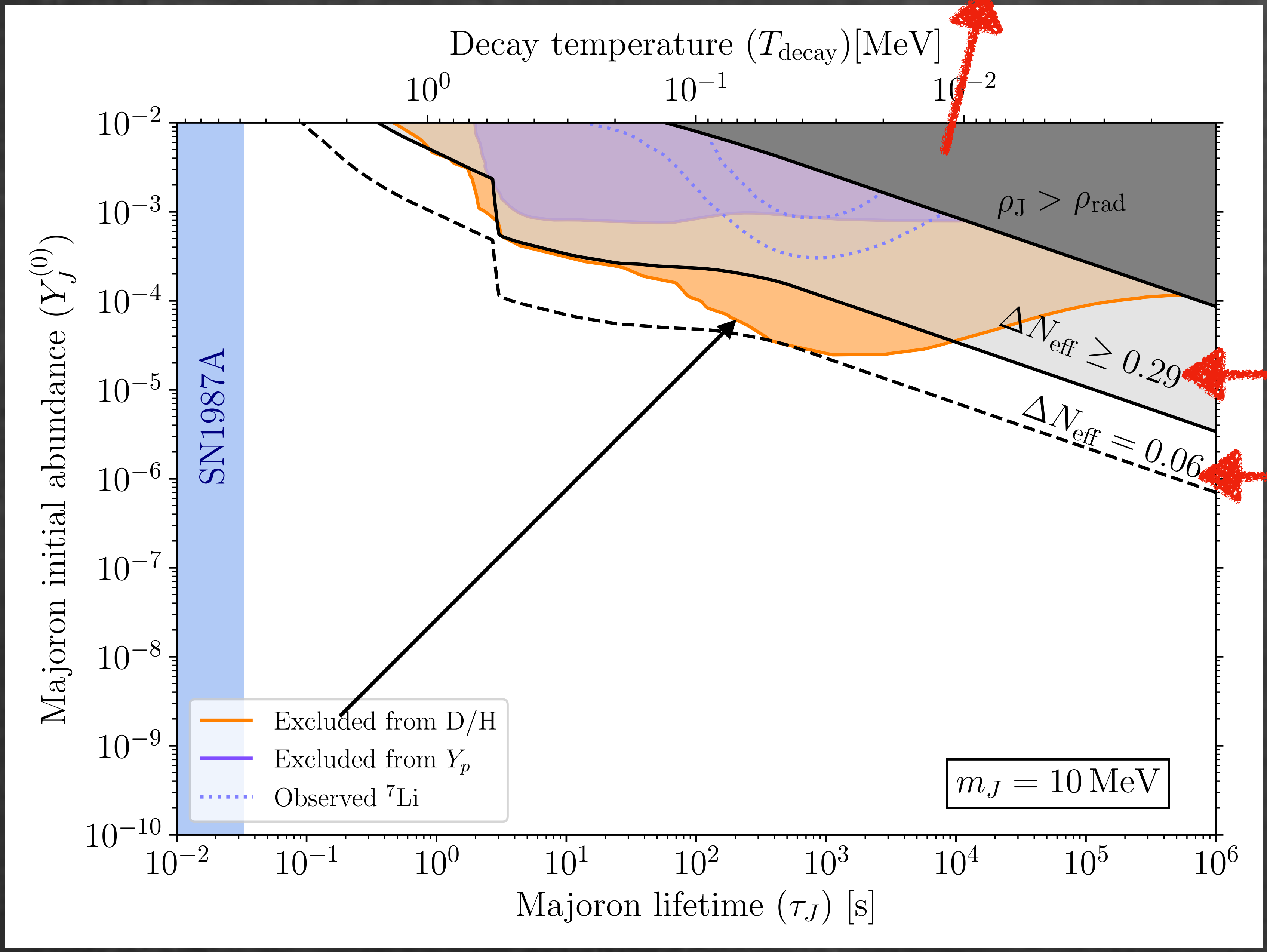


$\Delta N_{\rm eff}$ from CMB

$\Delta N_{\rm eff}$ from CMB-S4

Majoron parameter space in $\tau_J - Y_J^{(0)}$ plane

Majoron dominates the Universe

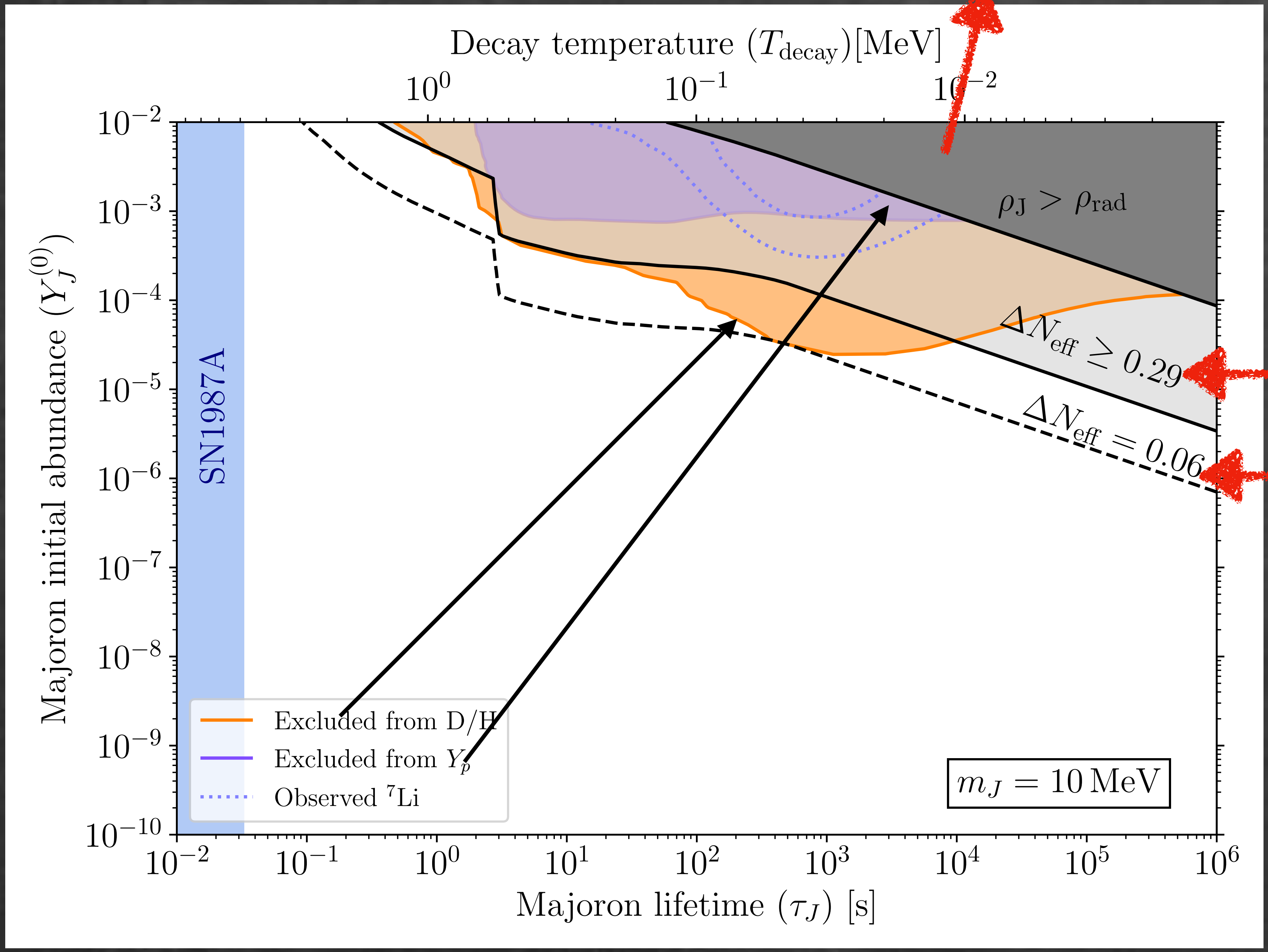


$\Delta N_{\rm eff}$ from CMB

$\Delta N_{\rm eff}$ from CMB-S4

Majoron parameter space in $\tau_J - Y_J^{(0)}$ plane

Majoron dominates the Universe

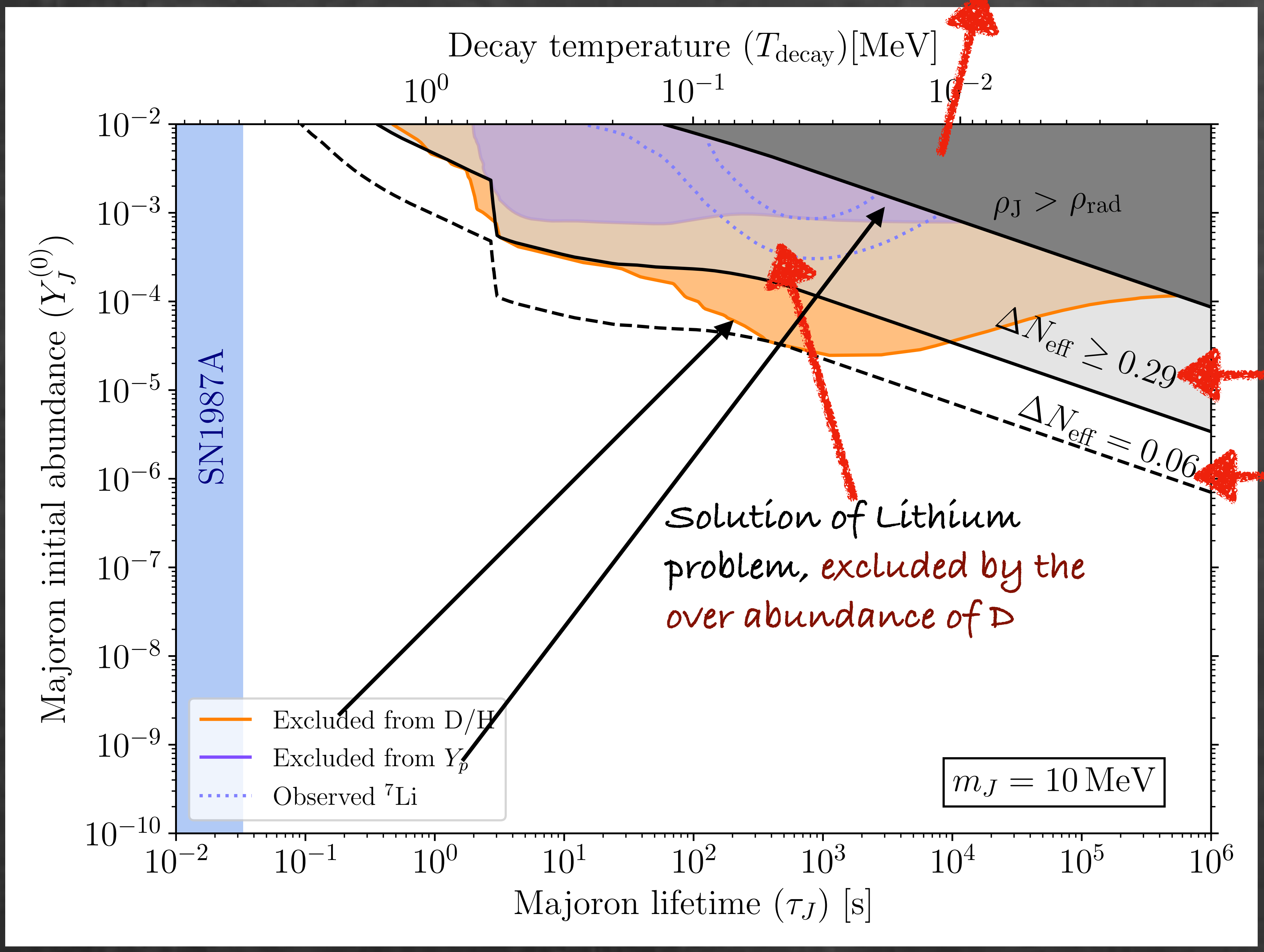


$\Delta N_{\rm eff}$ from CMB

$\Delta N_{\rm eff}$ from CMB-S4

Majoron parameter space in $\tau_J - Y_J^{(0)}$ plane

Majoron dominates the Universe

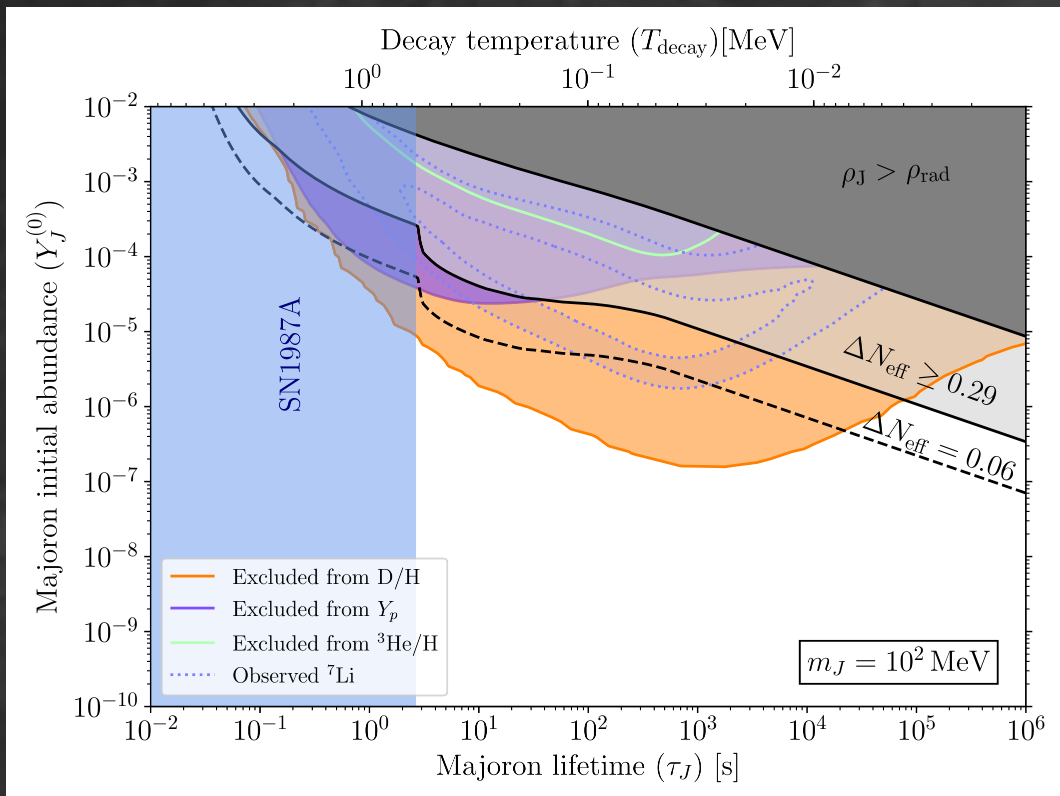


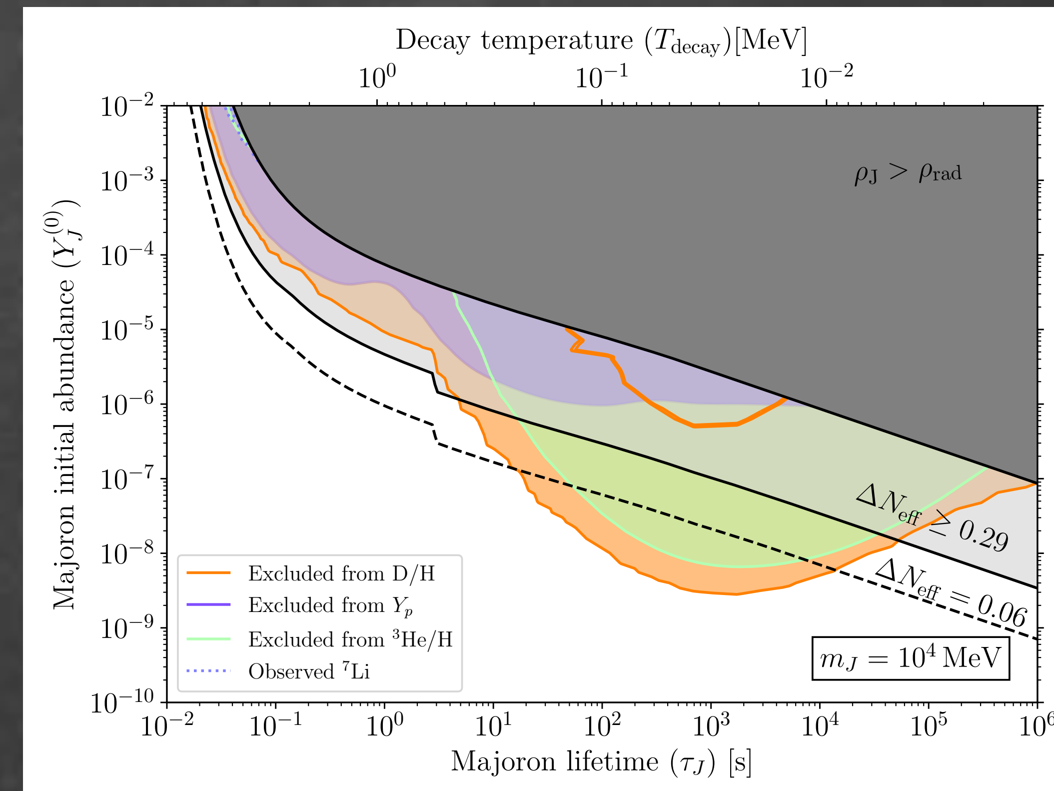
$\Delta N_{\rm eff}$ from CMB

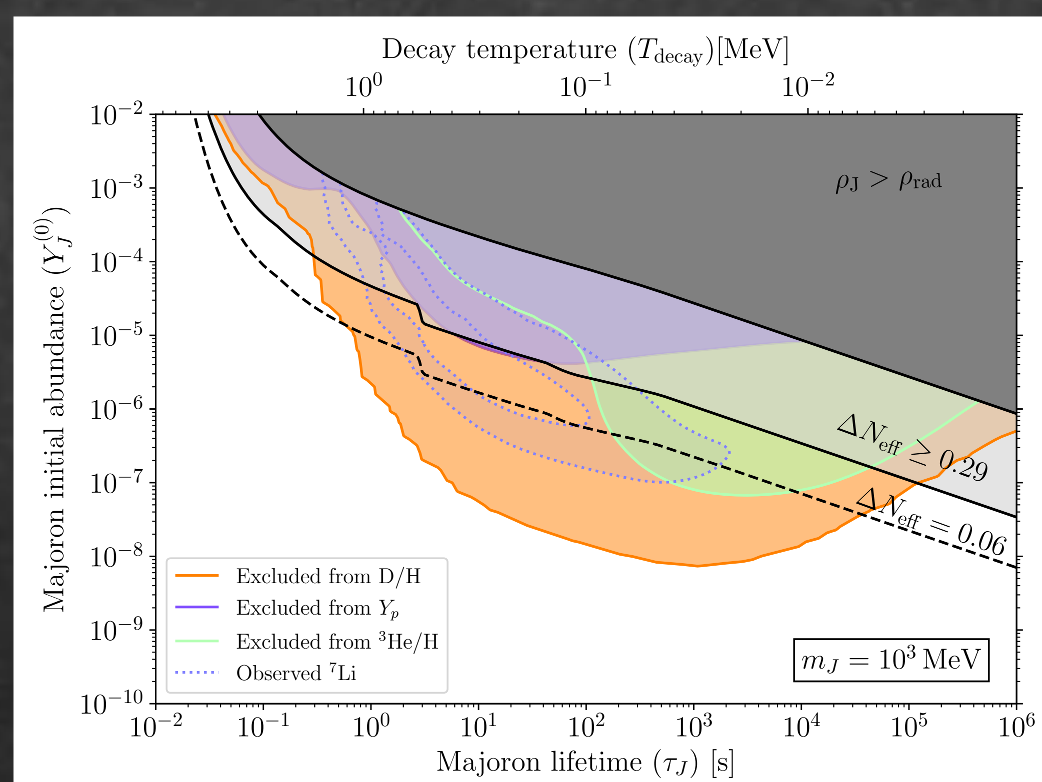
$\Delta N_{\rm eff}$ from CMB-S4

Majoron parameter space in $\tau_J - Y_J^{(0)}$ plane

Majoron parameter space in $\tau_J - Y_J^{(0)}$ plane

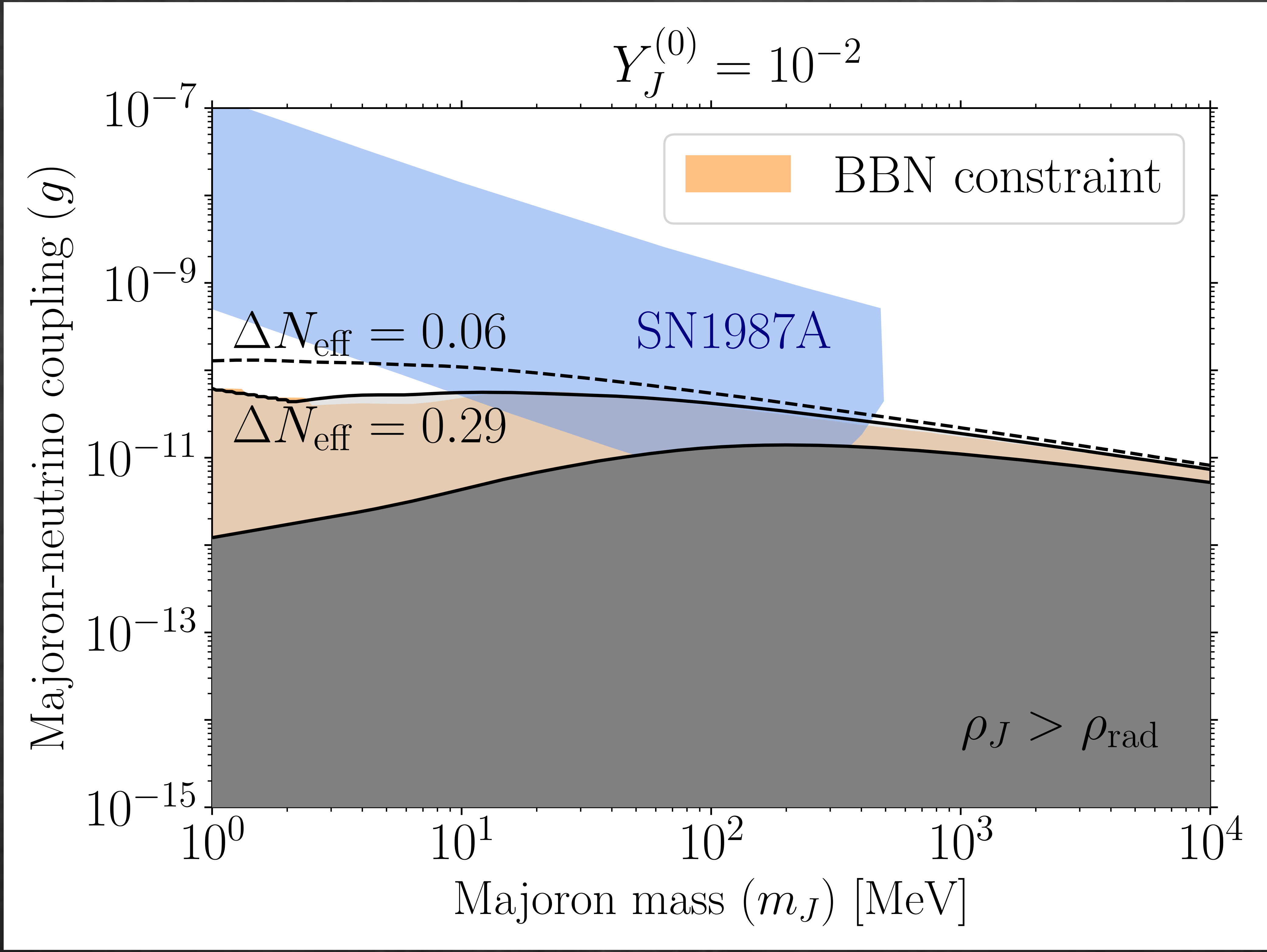






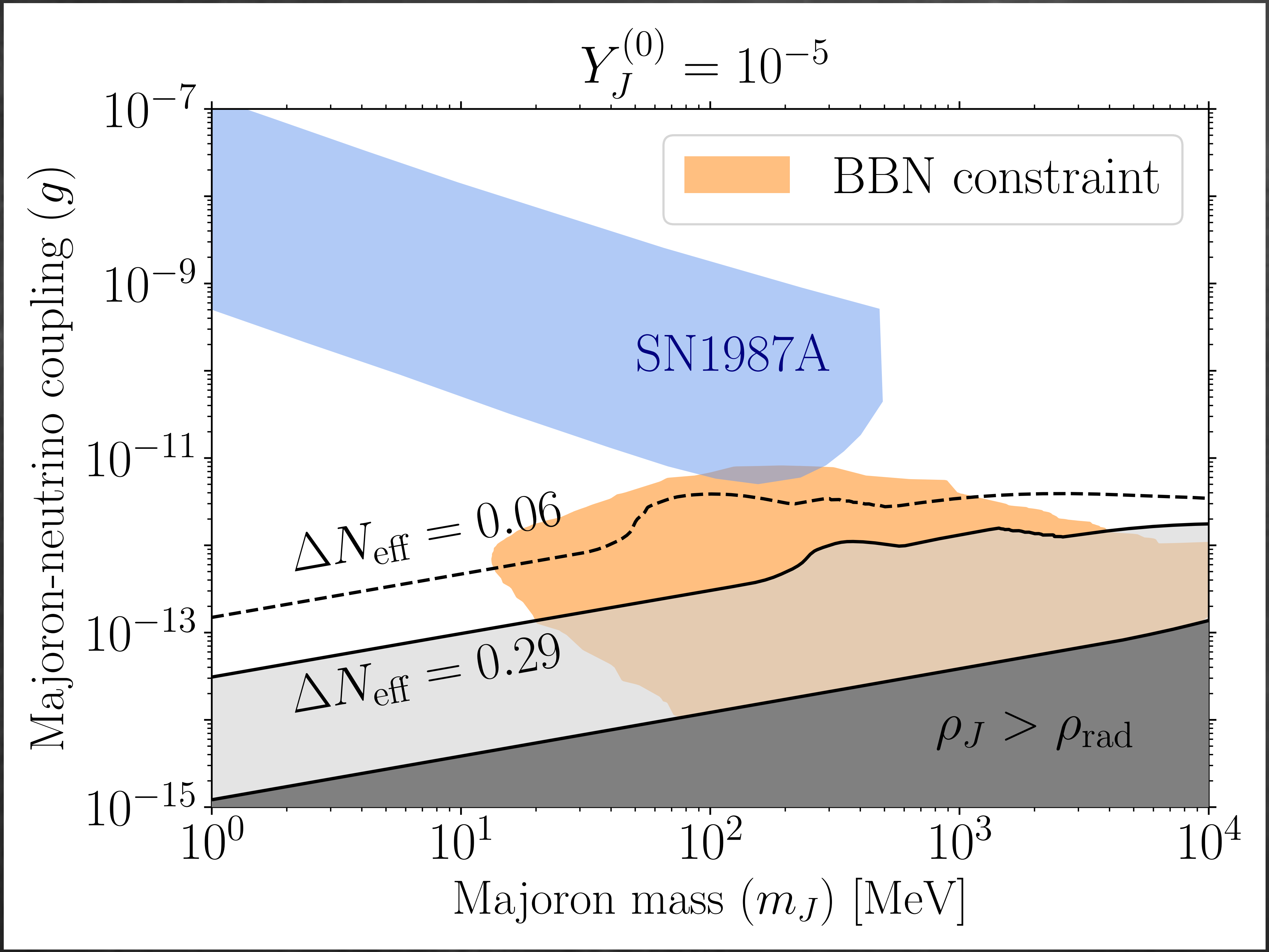
Majoron parameter space in $m_J - g$ plane

Majoron parameter space in $m_J - g$ plane



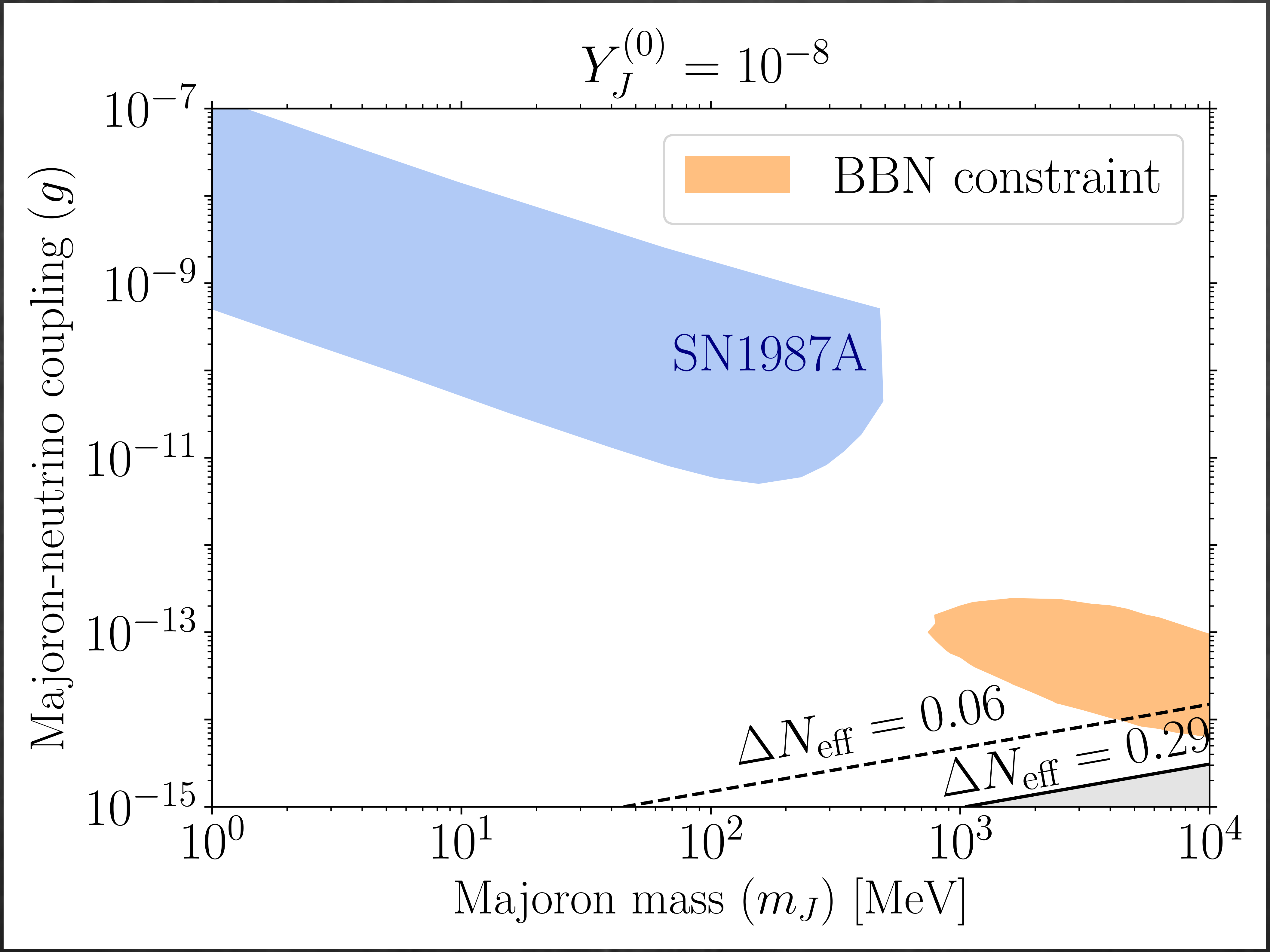
Majoron parameter space in $m_J - g$ plane

Majoron parameter space in $m_J - g$ plane



Majoron parameter space in $m_J - g$ plane

Majoron parameter space in $m_J - g$ plane



Summary

Summary

Our framework:

$$\mathscr{L} = -\frac{ig}{2}\overline{\nu}_i\gamma_5\nu_i J$$

Assumption: Majoron coupling with the neutrinos are flavor universal

We consider

$$1\,\mathrm{MeV} \leq m_J \leq 10\,\mathrm{GeV}$$

Summary

Our framework:

$$\mathscr{L} = -\frac{ig}{2}\overline{\nu}_i\gamma_5\nu_i J$$

Assumption: Majoron coupling with the neutrinos are flavor universal

We consider

$$1\,\mathrm{MeV} \leq m_J \leq 10\,\mathrm{GeV}$$

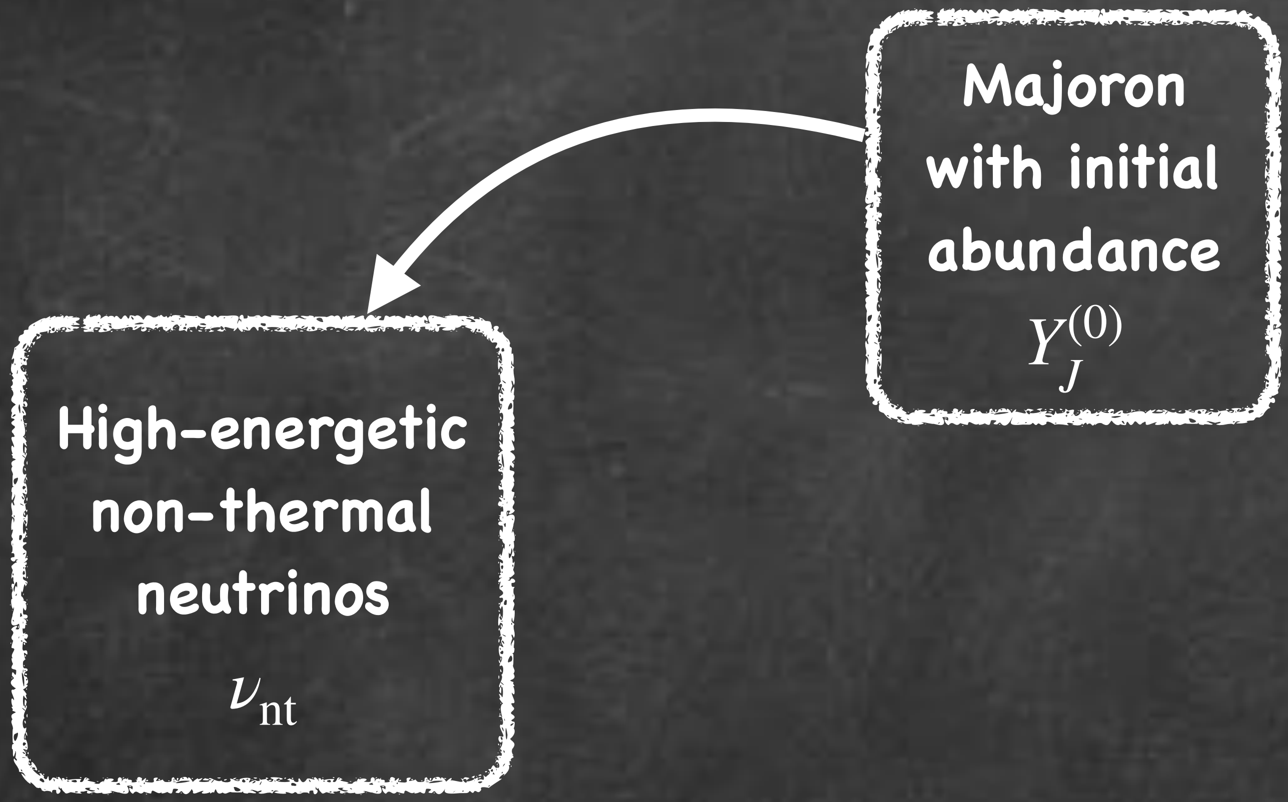
Majoron with initial abundance $Y_J^{(0)}$

Summary

Our framework:
$\mathscr{L} = -\frac{ig}{2}\overline{\nu}_i \gamma_5 \nu_i J$

Assumption: Majoron coupling with the neutrinos are flavor universal

We consider
$1\,\mathrm{MeV} \leq m_J \leq 10\,\mathrm{GeV}$



Summary

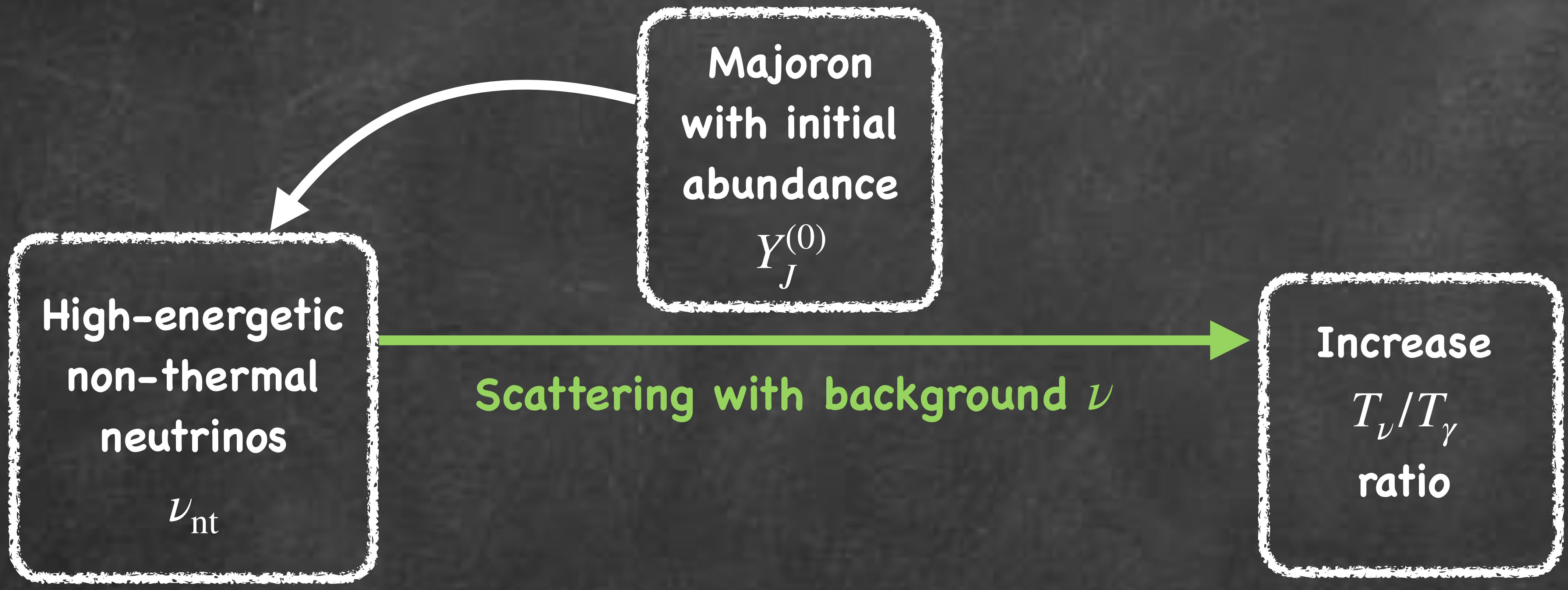
Our framework:

$\mathscr{L} = -\frac{ig}{2}\overline{\nu_i}\gamma_5\nu_i J$

Assumption: Majoron coupling with the neutrinos are flavor universal

We consider

$1\,\mathrm{MeV} \leq m_J \leq 10\,\mathrm{GeV}$



Summary

Our framework:

$$\mathscr{L} = -\frac{ig}{2}\overline{\nu_i}\gamma_5\nu_i J$$

Assumption: Majoron coupling with the neutrinos are flavor universal

We consider

$$1\,\mathrm{MeV} \leq m_J \leq 10\,\mathrm{GeV}$$

Majoron with initial abundance $Y_J^{(0)}$

High-energetic non-thermal neutrinos $\nu_{\rm nt}$

Scattering with background ν

Increase T_ν/T_γ ratio

$t_{np}^{\rm FO} > \tau_J$

increase in $t_{np}^{\rm FO}$ and $n/p_{\rm eq}$

Summary

Our framework:
$$\mathscr{L} = -\frac{ig}{2}\overline{\nu_i}\gamma_5\nu_i J$$

Assumption: Majoron coupling with the neutrinos are flavor universal

We consider
$$1\,\mathrm{MeV} \le m_J \le 10\,\mathrm{GeV}$$

Majoron with initial abundance $Y_J^{(0)}$

High-energetic non-thermal neutrinos $\nu_{\rm nt}$

Scattering with background ν

Increase T_ν/T_γ ratio

$t_{np}^{\rm FO} > \tau_J$

increase in $t_{np}^{\rm FO}$ and $n/p_{\rm eq}$

Light element abundance increases

Summary

Our framework:
$\mathscr{L} = -\frac{ig}{2}\overline{\nu_i}\gamma_5\nu_i J$

Assumption: Majoron coupling with the neutrinos are flavor universal

We consider
$1\,\mathrm{MeV} \leq m_J \leq 10\,\mathrm{GeV}$

Majoron with initial abundance $Y_J^{(0)}$

High-energetic non-thermal neutrinos ν_{nt}

Scattering with background ν

Increase T_ν / T_γ ratio

$t_{np}^{\mathrm{FO}} > \tau_J$

increase in t_{np}^{FO} and n/p_{eq}

Light element abundance increases

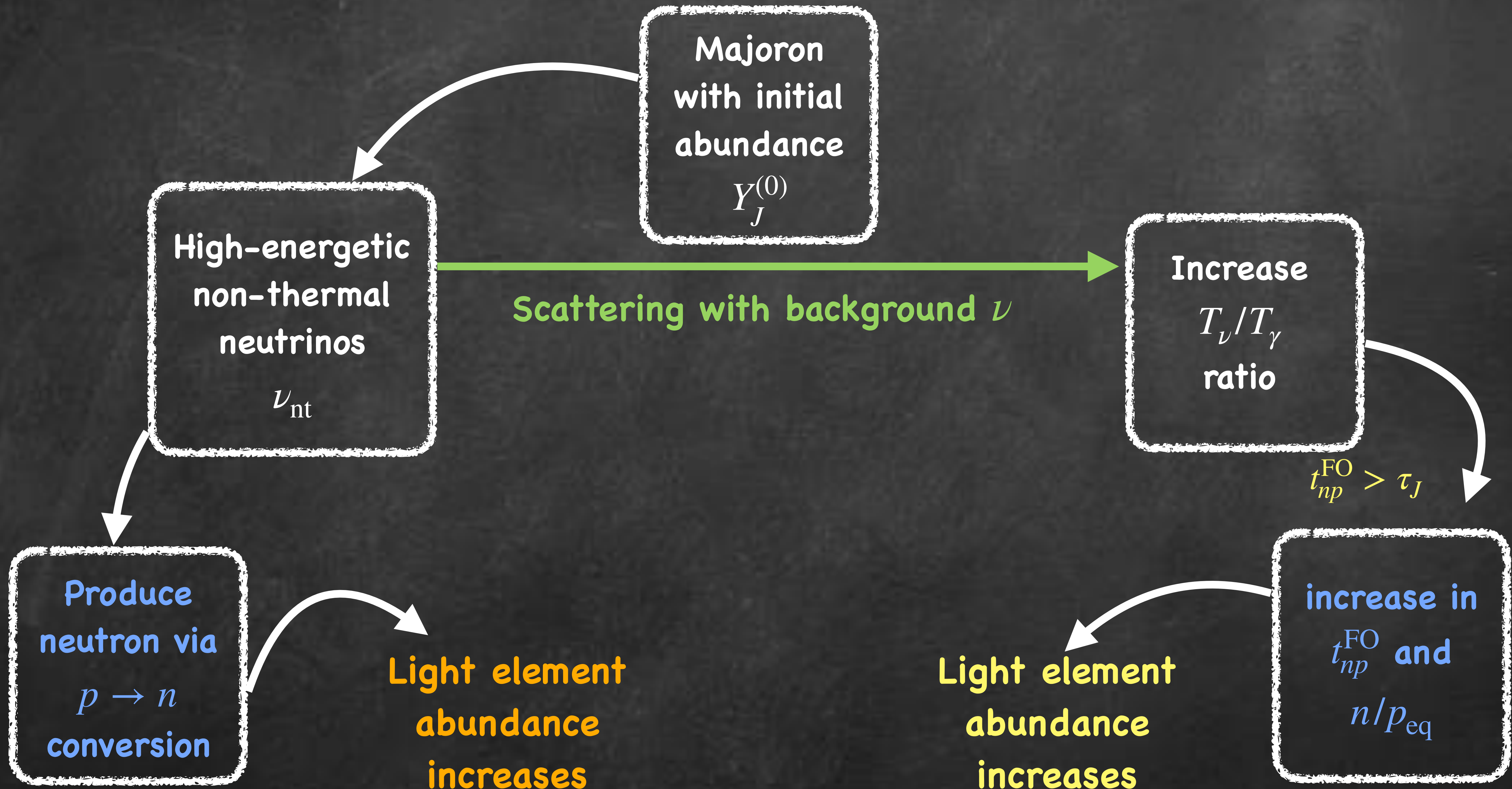
Produce neutron via $p \to n$ conversion

Summary

Our framework:
$\mathscr{L} = -\frac{ig}{2}\overline{\nu_i}\gamma_5\nu_i J$

Assumption: Majoron coupling with the neutrinos are flavor universal

We consider
$1\,\mathrm{MeV} \leq m_J \leq 10\,\mathrm{GeV}$

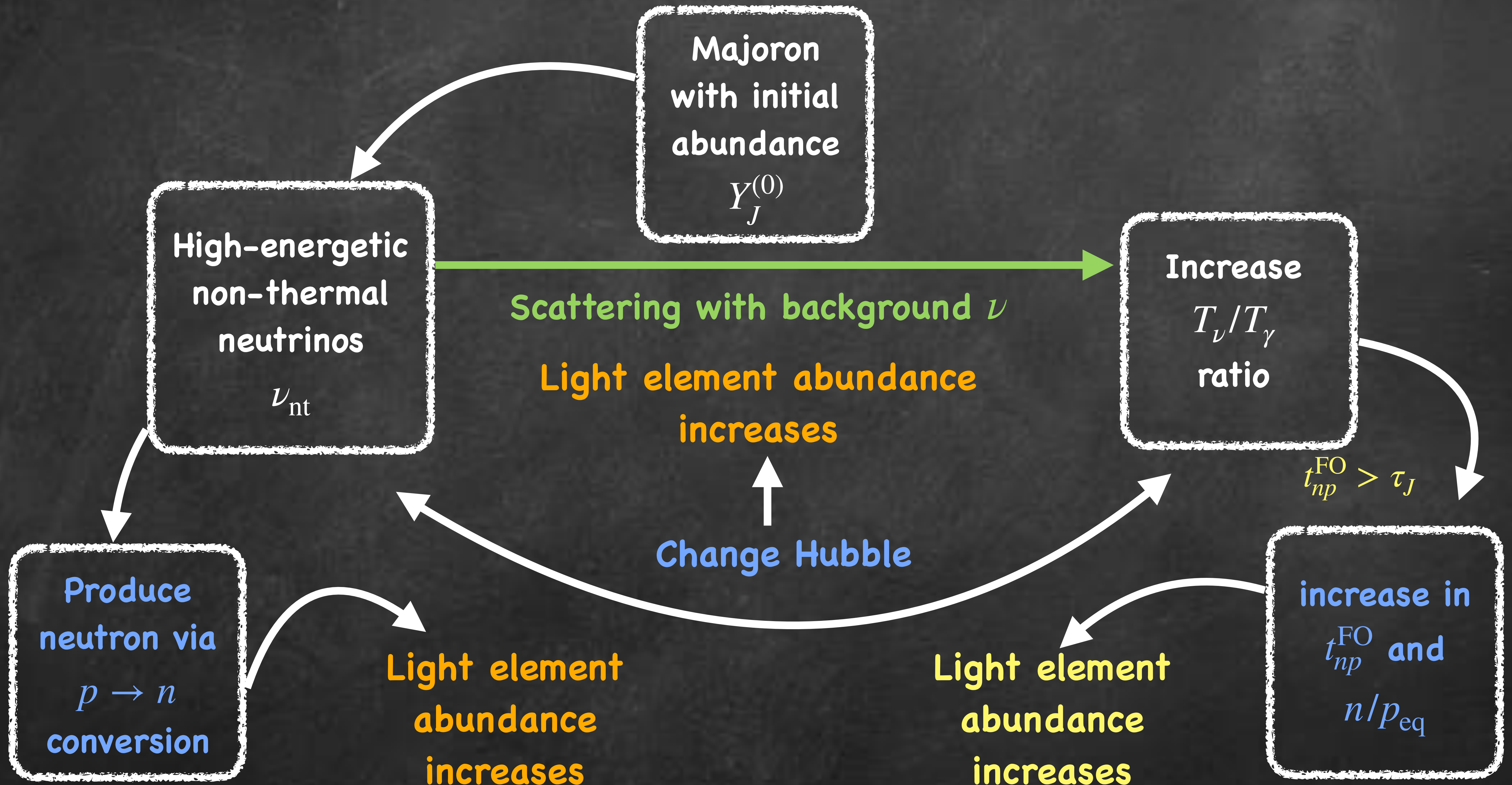


Summary

Our framework:
$$\mathscr{L} = -\frac{ig}{2}\overline{\nu}_i\gamma_5\nu_i J$$

Assumption: Majoron coupling with the neutrinos are flavor universal

We consider
$$1\,\mathrm{MeV} \le m_J \le 10\,\mathrm{GeV}$$



Continue…

In the Majoron mass range between 1MeV to 10 GeV, we show in a model independent manner that non-thermally produced Majoron can have significant effect on the BBN and a significant region of Majoron parameter space can be excluded by BBN.

For Majoron abundance $Y_J^{(0)} = 10^{-2}$, BBN constraint is comparable to the ΔN_{eff} constraint. However, for $Y_J^{(0)} = 10^{-5}$, BBN constraint is stronger than ΔN_{eff} constraint.

Continue..

In the Majoron mass range between 1MeV to 10 GeV, we show in a model independent manner that non-thermally produced Majoron can have significant effect on the BBN and a significant region of Majoron parameter space can be excluded by BBN.

For Majoron abundance $Y_J^{(0)} = 10^{-2}$, BBN constraint is comparable to the $\Delta N_{\rm eff}$ constraint. However, for $Y_J^{(0)} = 10^{-5}$, BBN constraint is stronger than $\Delta N_{\rm eff}$ constraint.

Thank You for your attention !!!!!!