Big Bang Nucleosynthesis

in a weakly nonideal plasma

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based on
Astron. Astrophys. 650 (2021) A121

in collaboration with
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Hadron Physics (HaPhy) Meeting
November 19, 2021

Contents

1 Introduction

- Standard big bang nucleosynthesis (SBBN)
- Primordial lithium problem
- Non-standard BBN

2 Non-Planckian Radiation

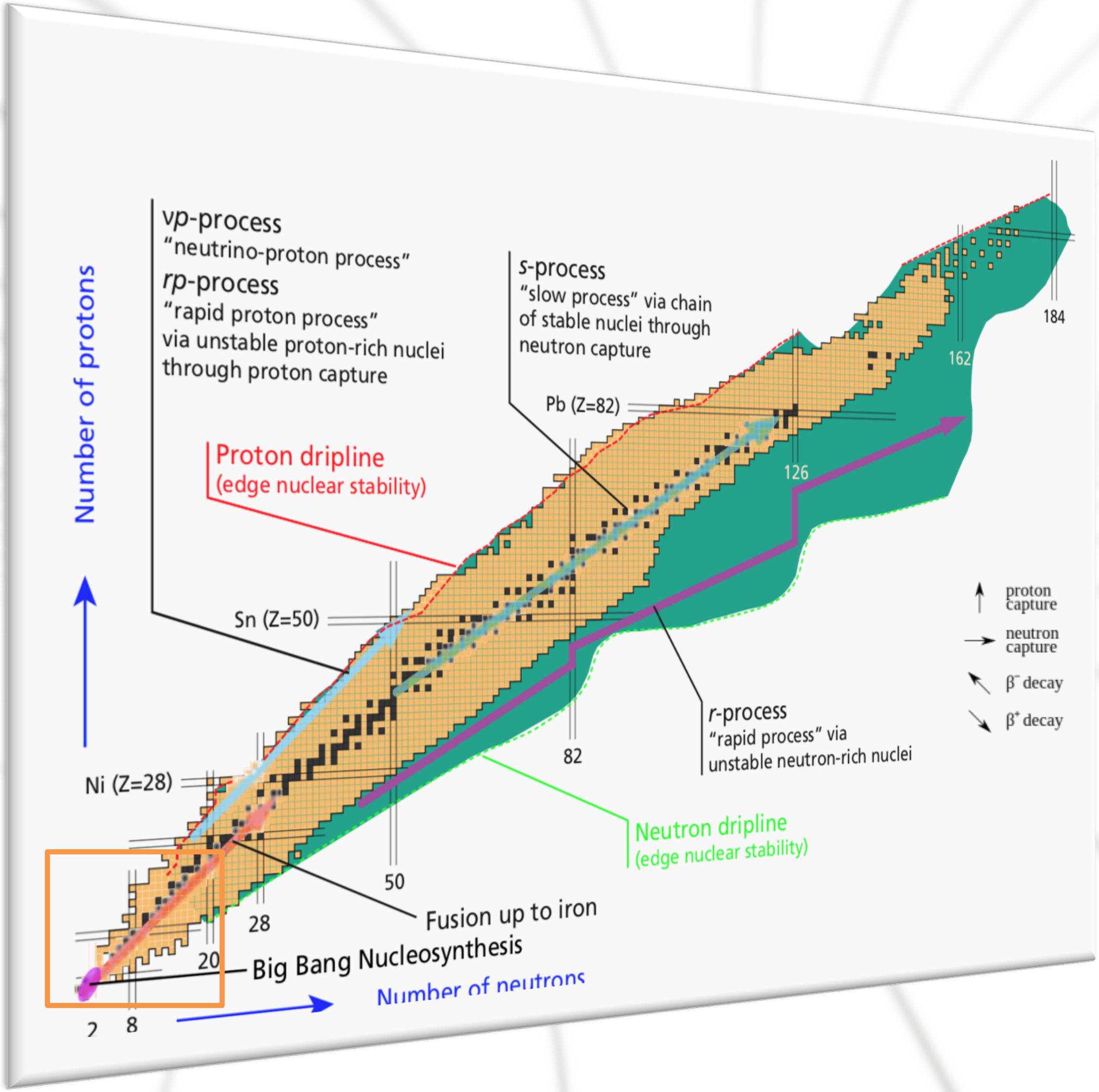
- Numerical solution to the lithium problem
- Photo-disintegration reaction rate
- Expansion rate & freeze-out time

3 Primordial Plasma

- From ideal to weakly non-ideal plasma
- Positron annihilation

4 Summary & Outlook

Origin of elements



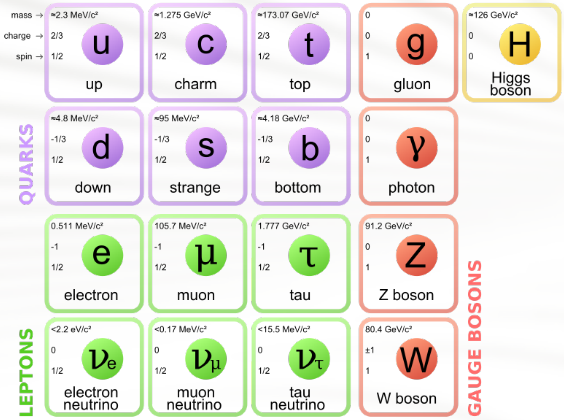
Nucleosynthesis

Big bang nucleosynthesis (BBN)
Stellar nucleosynthesis
Supernova nucleosynthesis
Cosmic ray spallation

Standard BBN

Particles & interactions

Standard model of particle physics



Thermal distribution

Boltzmann-Gibbs statistics

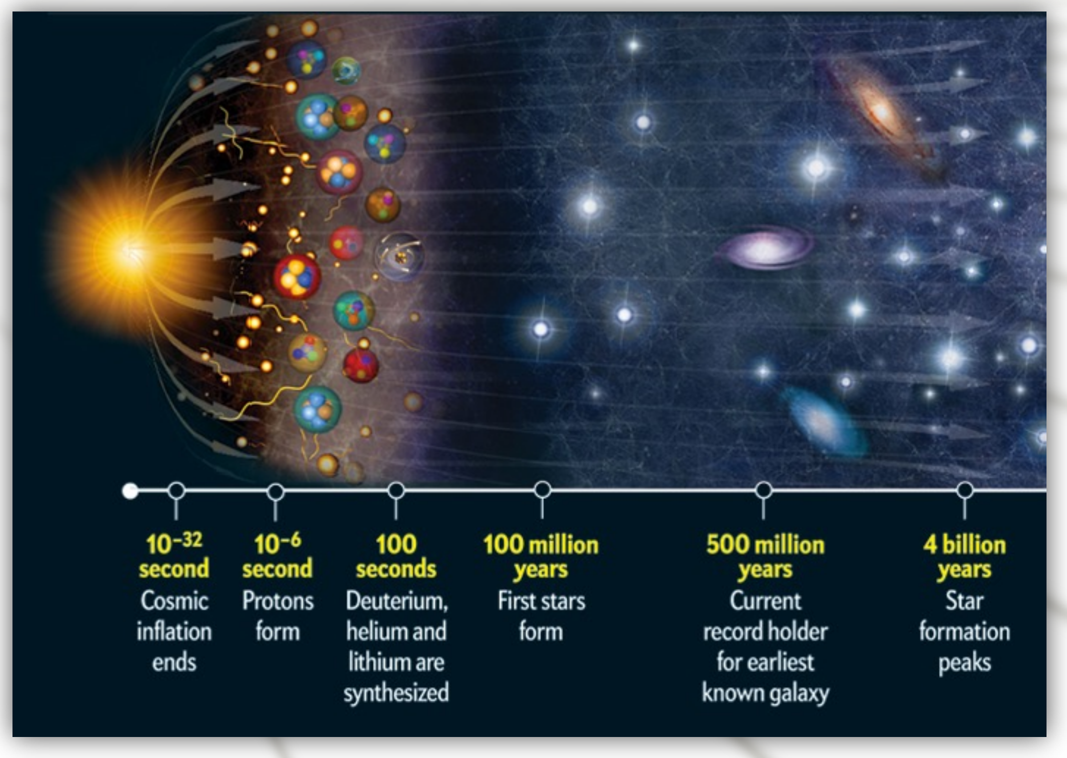
$$f(E) \propto \exp\left(-E/kT\right)$$

Cosmic expansion

General relativity

Homogeneous & isotropic universe

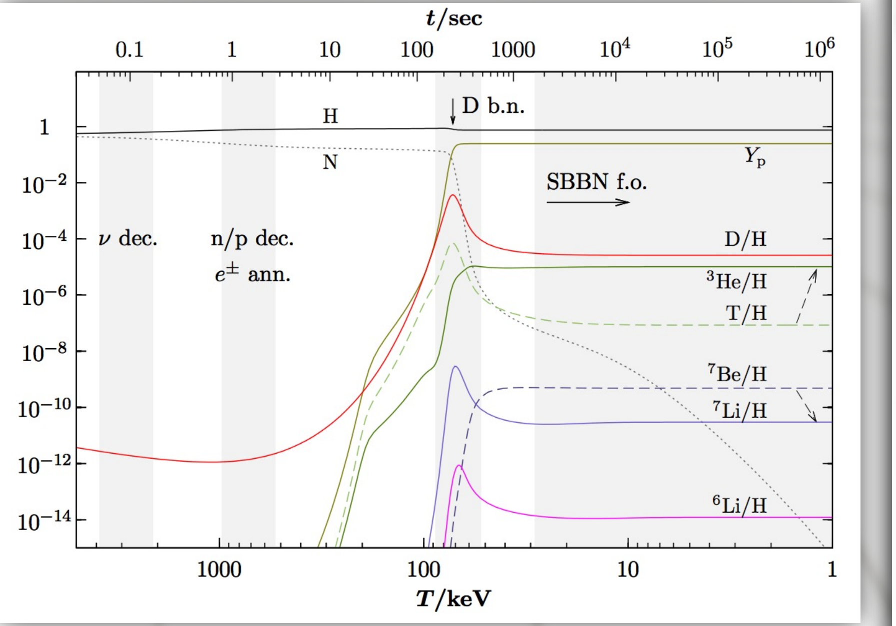
$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

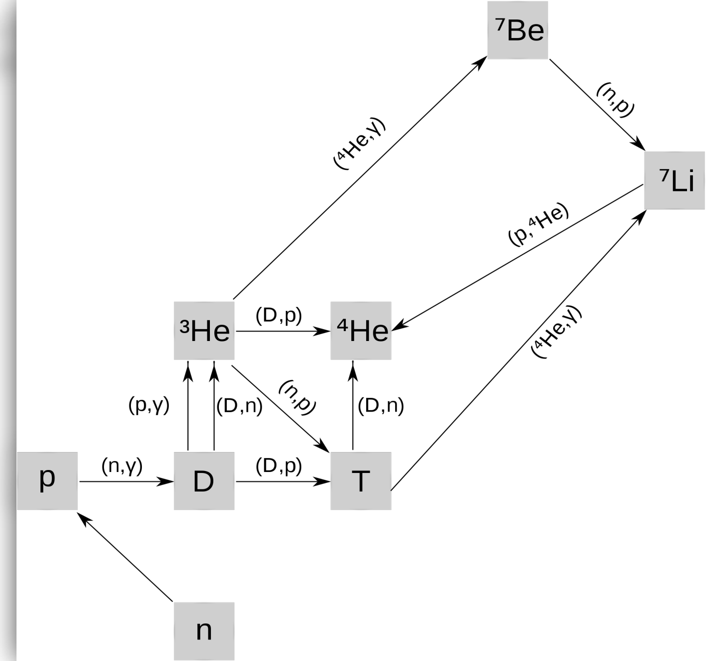


Standard BBN

BBN network calculation

Kawano, FERMILAB-Pub-92/04-A (1992)





Primordial abundances

Standard BBN prediction

Abundances as a function of baryon-to-photon ratio.

Cosmic microwave background (CMB) constraint:

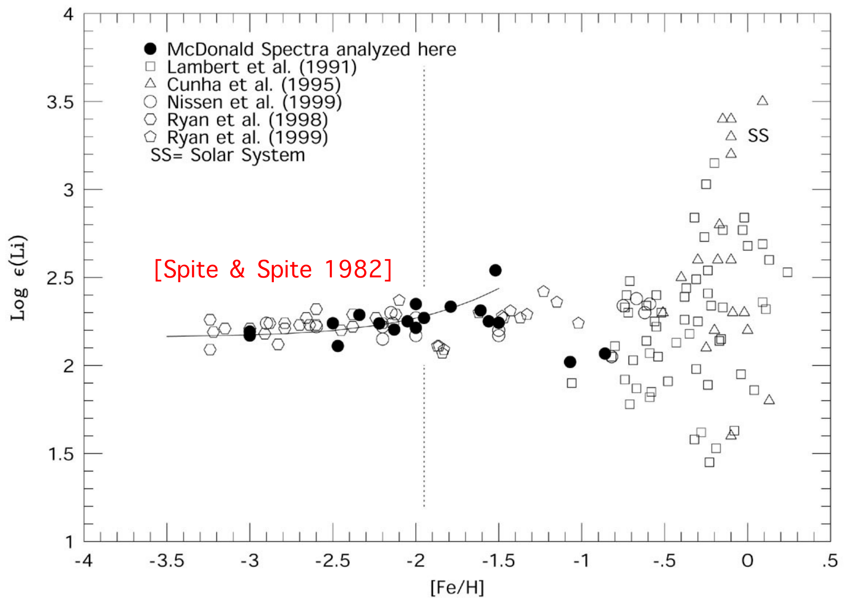
$$\eta = (6.094 \pm 0.063) \times 10^{-10}$$

[Planck collaboration 2016]

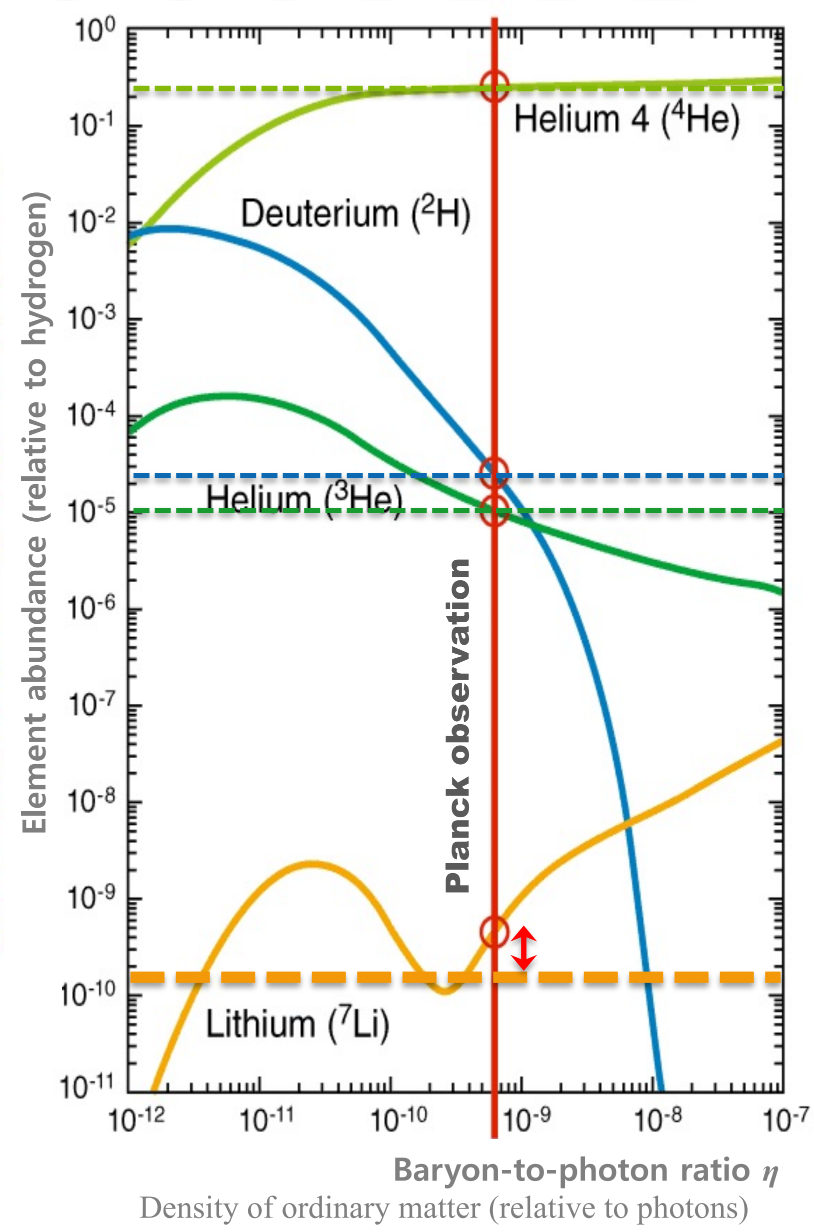
Primordial ^{7}Li problem

Spectra of metal-poor stars

Observed ^{7}Li abundance is smaller than the SBBN prediction.



[Spite & Spite 1982]

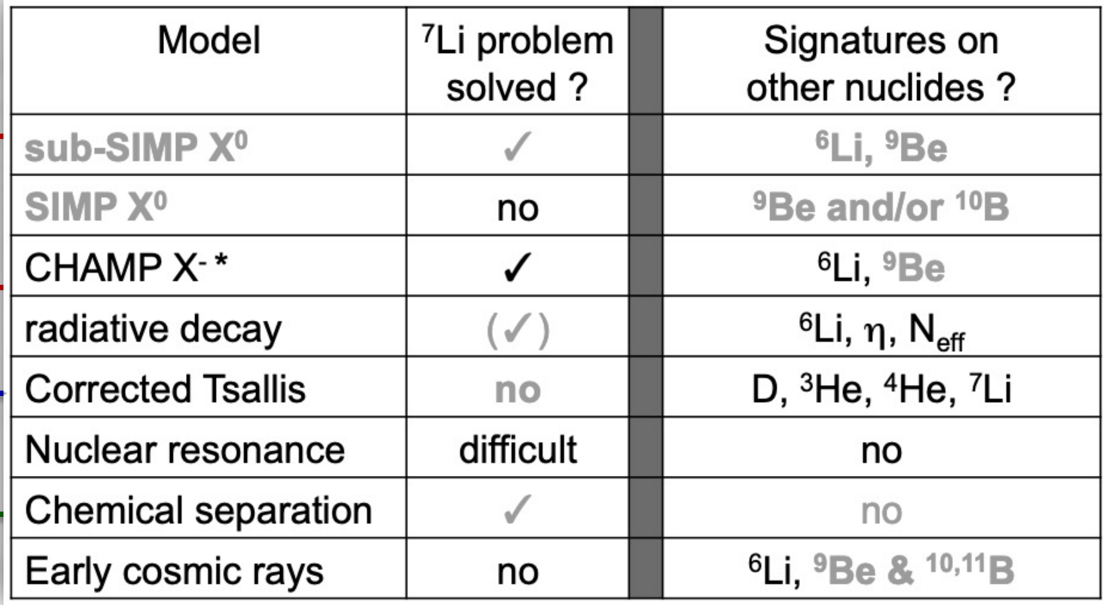


Baryon-to-photon ratio η

Density of ordinary matter (relative to photons)

Non-standard BBN

[Kusakabe's ppt]



Model	^{7}Li problem solved ?	Signatures on other nuclides ?
sub-SIMP X^0	✓	^{6}Li, ^{9}Be
SIMP X^0	no	^{9}Be and/or ^{10}B
CHAMP X^- *	✓	^{6}Li, ^{9}Be
radiative decay	(✓)	^{6}Li, η, N_{eff}
Corrected Tsallis	no	D, ^{3}He, ^{4}He, ^{7}Li
Nuclear resonance	difficult	no
Chemical separation	✓	no
Early cosmic rays	no	^{6}Li, ^{9}Be & ^{10,11}B

Massive particle

Non-Maxwellian velocity distribution

B-field

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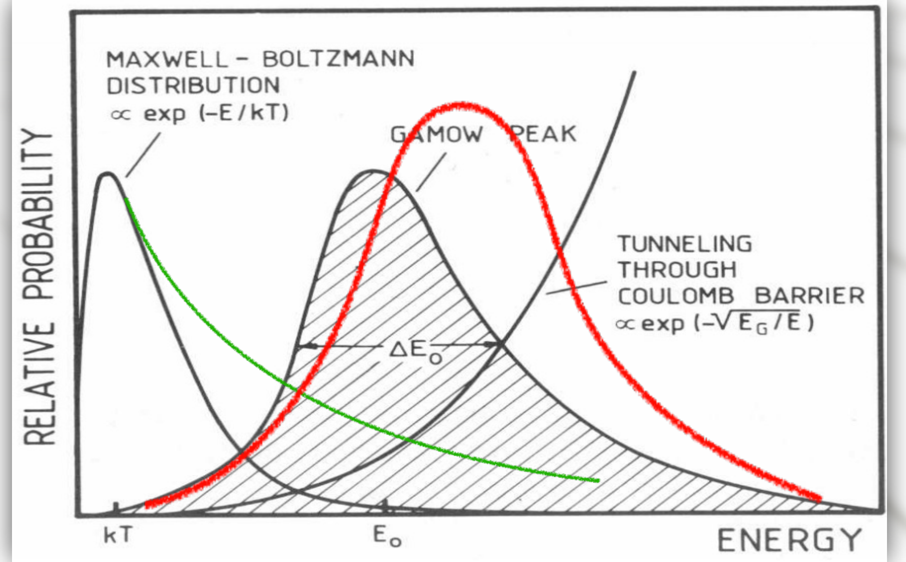
Thermonuclear reaction rate

$$R_{12} = N_1 N_2 \langle \sigma v \rangle_{12}$$

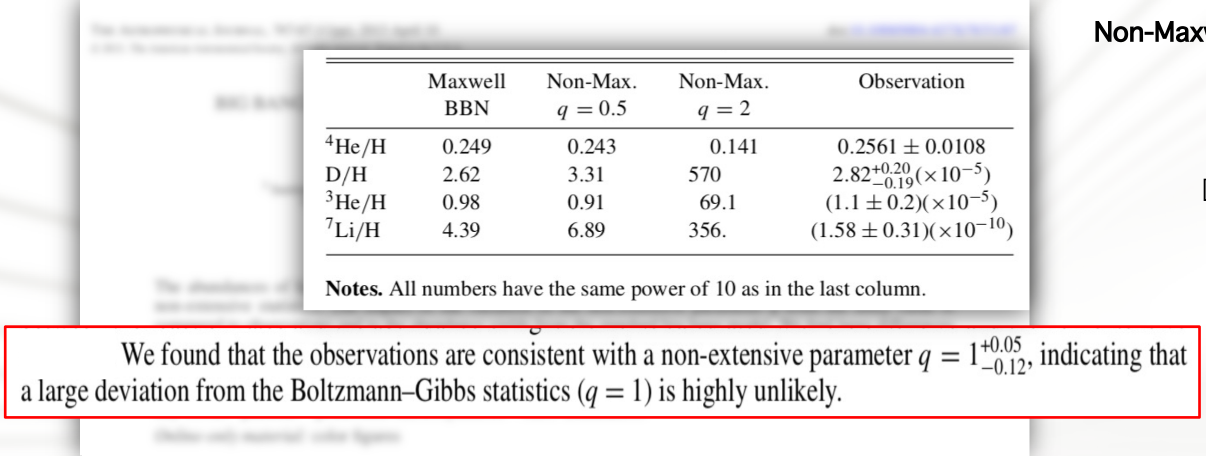
$$\langle \sigma v \rangle_{12} = \int_0^\infty \int_0^\infty \sigma(E)\ |\vec{v}_1 - \vec{v}_2|\ \phi_1(\vec{v}_1)\phi_2(\vec{v}_2)\, d\vec{v}_1 d\vec{v}_2$$

Integration over the relative velocity in CM coordinates

$$\langle \sigma v \rangle_{12} = \left(\frac{8}{\mu\pi}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E)\, E\, \boxed{\exp\left(-\frac{E}{kT}\right)}\, dE$$



Non-Maxwellian distribution



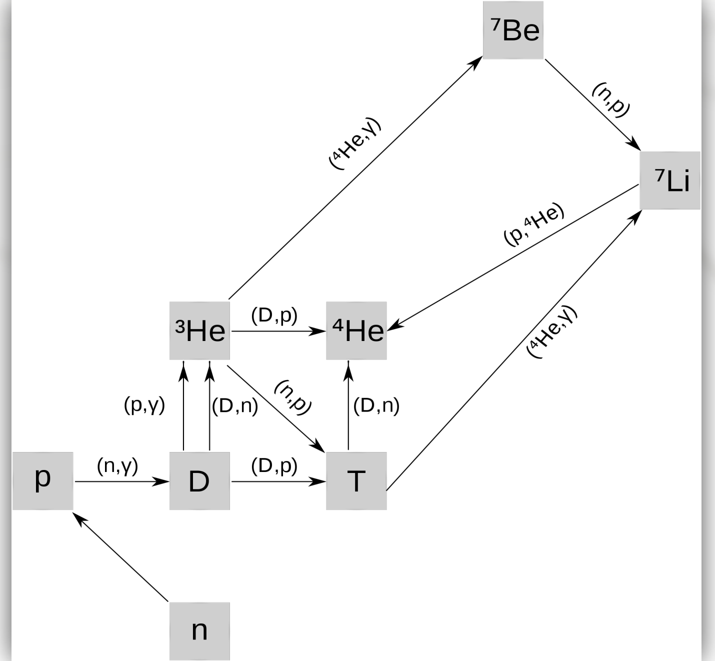
	Maxwell BBN	Non-Max. $q = 0.5$	Non-Max. $q = 2$	Observation
^{4}He/H	0.249	0.243	0.141	0.2561 ± 0.0108
D/H	2.62	3.31	570	$2.82^{+0.20}_{-0.19}(\times 10^{-5})$
^{3}He/H	0.98	0.91	69.1	$(1.1 \pm 0.2)(\times 10^{-5})$
^{7}Li/H	4.39	6.89	356.	$(1.58 \pm 0.31)(\times 10^{-10})$

Notes. All numbers have the same power of 10 as in the last column.

We found that the observations are consistent with a non-extensive parameter $q = 1^{+0.05}_{-0.12}$, indicating that a large deviation from the Boltzmann–Gibbs statistics ($q = 1$) is highly unlikely.

Non-Maxwellian velocity distribution of nuclei

[Bertulani et al., ApJ 767, 67 (2013)]
[Hou et al., ApJ 834, 165 (2017)]
[Kusakabe et al., PRD 99, 043505 (2019)]



Tsallis statistics

$$\frac{dy}{dx} = y \rightarrow y = e^x \rightarrow y = \ln x$$

$$\frac{dy}{dx} = y^q \rightarrow y = (1-(q-1)x)^{\frac{1}{1-q}} \rightarrow y = \frac{x^{1-q}-1}{1-q} \equiv \ln_q x$$

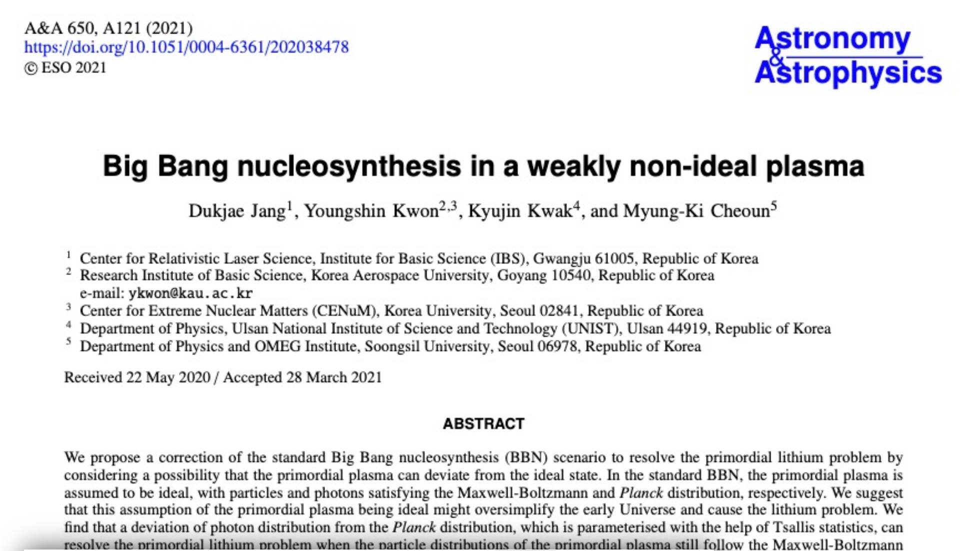
Boltzmann-Gibbs entropy:

$$S_{\mathrm{BG}} = -\sum_{i=1}^{w} p_i \ln p_i = \left\langle \ln \frac{1}{p_i} \right\rangle$$

Non-extensive (Tsallis) entropy:

$$S_q \equiv \left\langle \ln_q \frac{1}{p_i} \right\rangle = \frac{1-\sum p_i^q}{q-1}$$

Non-Planckian distribution



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Astronomy & Astrophysics

Big Bang nucleosynthesis in a weakly non-ideal plasma

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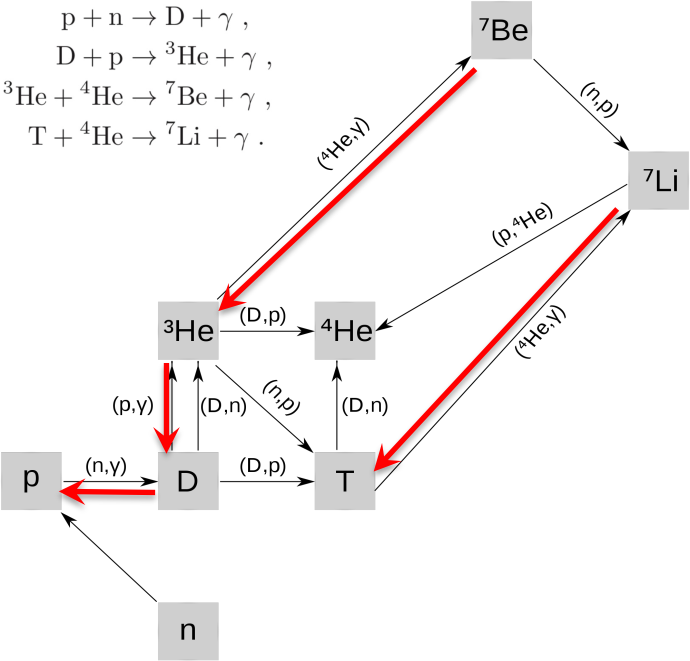
ABSTRACT

We propose a correction of the standard Big Bang nucleosynthesis (BBN) scenario to resolve the primordial lithium problem by considering a possibility that the primordial plasma can deviate from the ideal state. In the standard BBN, the primordial plasma is assumed to be ideal, with particles and photons satisfying the Maxwell-Boltzmann and *Planck* distribution, respectively. We suggest that this assumption of the primordial plasma being ideal might oversimplify the early Universe and cause the lithium problem. We find that a deviation of photon distribution from the *Planck* distribution, which is parameterised with the help of Tsallis statistics, can resolve the primordial lithium problem when the particle distributions of the primordial plasma still follow the Maxwell-Boltzmann

and its effects on the cosmic



$$
\begin{aligned}
\mathrm{p} + \mathrm{n} &\to \mathrm{D} + \gamma \ , \\
\mathrm{D} + \mathrm{p} &\to {}^3\mathrm{He} + \gamma \ , \\
{}^3\mathrm{He} + {}^4\mathrm{He} &\to {}^7\mathrm{Be} + \gamma \ , \\
\mathrm{T} + {}^4\mathrm{He} &\to {}^7\mathrm{Li} + \gamma \ .
\end{aligned}
$$

Simple ansatz for **non-Planckian photon distribution**

$$f_q = \frac{1}{\left[1 - (1-q)\frac{E}{kT}\right]^{\frac{1}{q-1}} - 1}$$

For $q \to 1$, the Planck distribution is recovered.

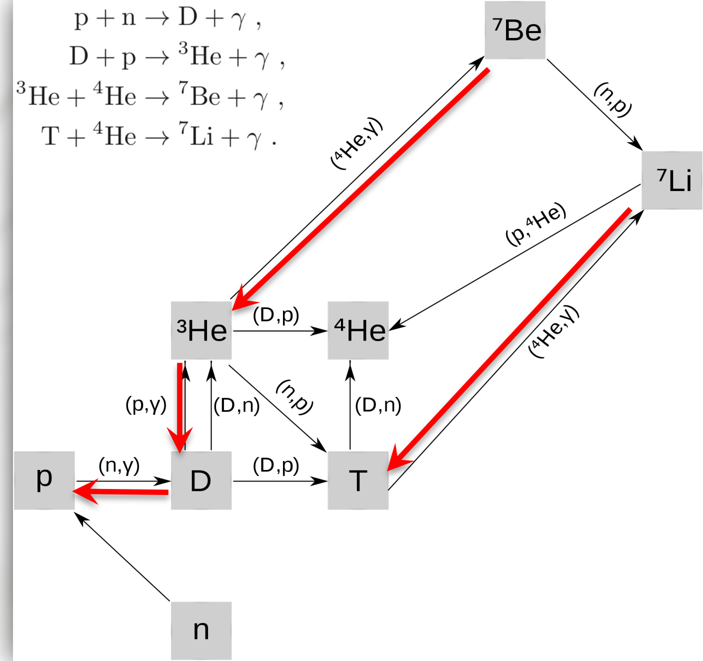
$$\lim_{q \to 1} f_q = \frac{1}{e^{\frac{E}{kT}} - 1}$$

$$q(T) = \theta(T - T_{\mathrm{tr}}) + \theta(T_{\mathrm{tr}} - T)\, q'$$

$$q' = 1.027 \text{ and } T_{\mathrm{tr}} = 4 \times 10^8\ \mathrm{K}$$

	SBBN	This work	Observation
Y_{p}	0.2474	0.2474	0.2446 ± 0.0029
D/H (10^{-5})	2.493	2.525	2.527 ± 0.03
^{3}He/H (10^{-5})	1.092	0.9253	$\leq 1.1 \pm 0.2$
^{7}Li/H (10^{-10})	5.030	1.677	1.58 ± 0.31

Photo-disintegration reaction



$$\mathrm{p} + \mathrm{n} \to \mathrm{D} + \gamma\,,$$
$$\mathrm{D} + \mathrm{p} \to {}^3\mathrm{He} + \gamma\,,$$
$${}^3\mathrm{He} + {}^4\mathrm{He} \to {}^7\mathrm{Be} + \gamma\,,$$
$$\mathrm{T} + {}^4\mathrm{He} \to {}^7\mathrm{Li} + \gamma\,.$$

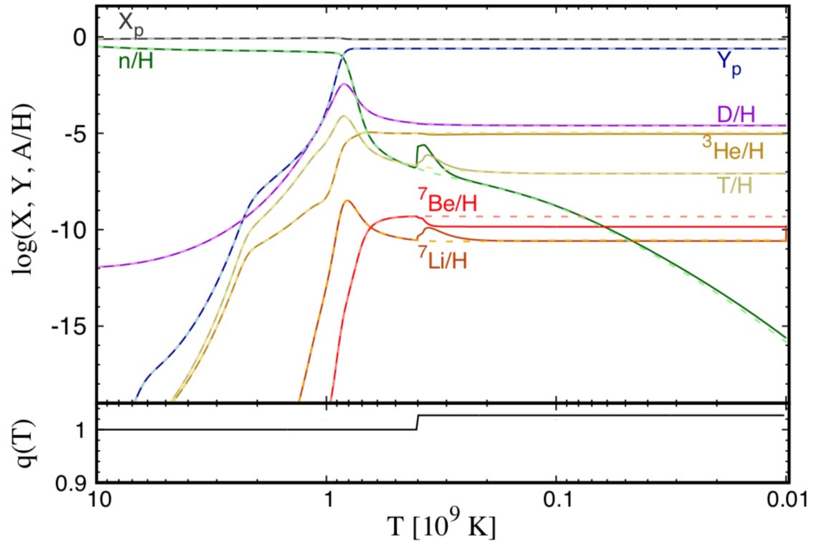
Reaction rate

For a reaction in the form of $3 + \gamma \to 1 + 2$

$$N_\gamma \langle \sigma c \rangle_{3\gamma} = \frac{m_{12}}{\pi^2 \hbar^3} \frac{g_1 g_2}{g_3 (1 + \delta_{12})}$$
$$\times \int_0^\infty \sigma_{12}(E)\, E \, \frac{1}{\left[1 - (1-q)\frac{E+Q}{kT}\right]^{\frac{1}{q-1}} - 1} \, dE$$

using a detailed balance relation between the forward and reverse cross sections.

$$\sigma_{3\gamma}(E_\gamma) = \frac{g_1 g_2}{g_3 (1 + \delta_{12})} \frac{m_{12}\, c^2 E}{E_\gamma^2} \sigma_{12}(E)$$



Photon number density

$$N_\gamma = \frac{1}{\pi^2 \hbar^3 c^3} \int_0^\infty \frac{E_\gamma^2}{\left[1 - (1-q)\frac{E_\gamma}{kT}\right]^{\frac{1}{q-1}} - 1} \, dE_\gamma$$

Photon energy density

Photon energy density

$$\rho_\gamma = \frac{(kT)^4}{(\hbar c)^3}\,\frac{\pi^2}{15}\,\frac{1}{(4-3q)(3-2q)(2-q)}\,.$$

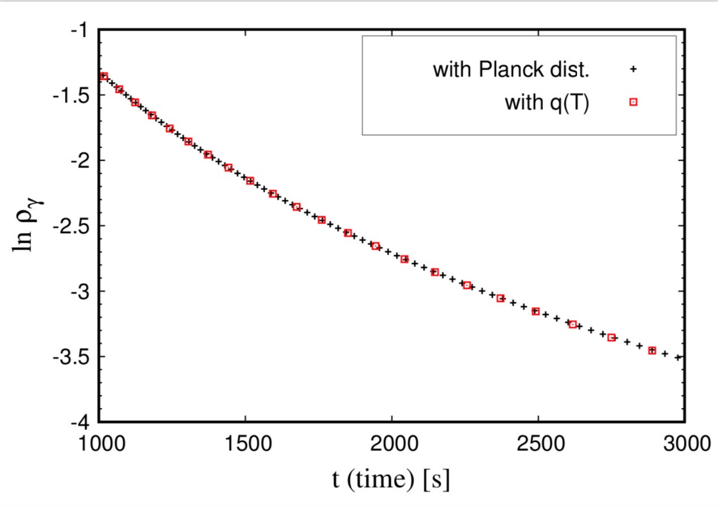
The condition for the energy conservation at the moment of transition

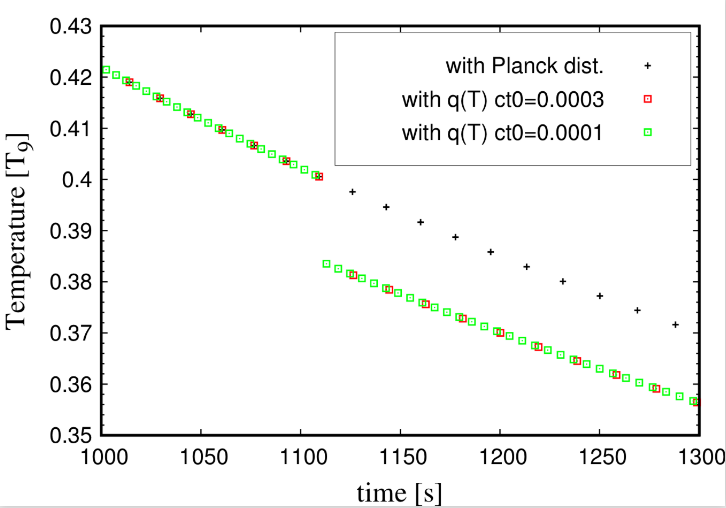
$$\rho_{\gamma\,(q=1)} = \rho_{\gamma\,(q>1)}$$

leads to the sudden temperature drop.

Freeze-out time

The temperature drop advances the freeze-out time of the light elements.

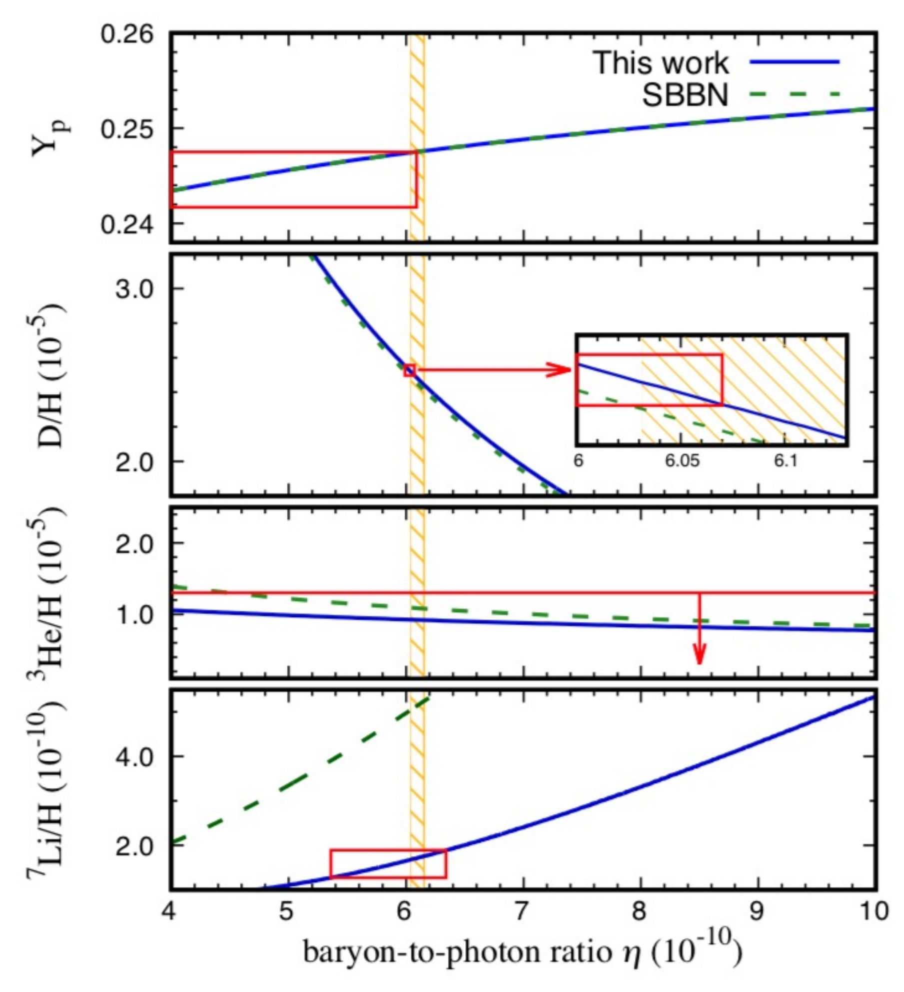




Primordial abundance

Baryon-to-photon ratio

Together with the CMB constraint,
we are able to narrow down the possible range of it
to $6.031 < \eta \times 10^{10} < 6.070$



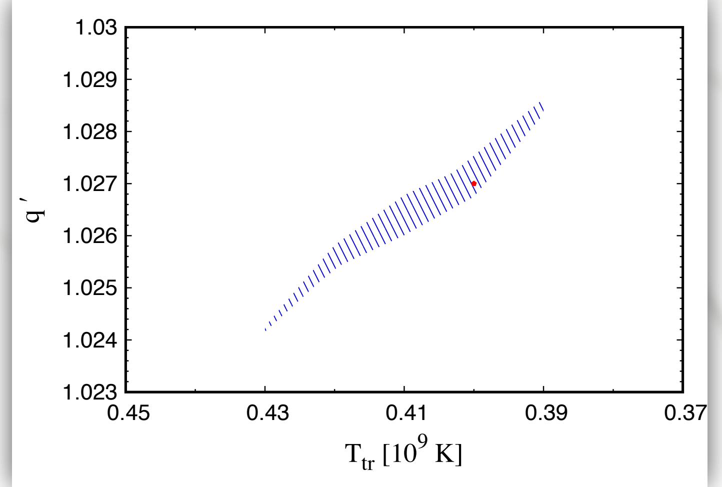
Cosmic Microwave Background

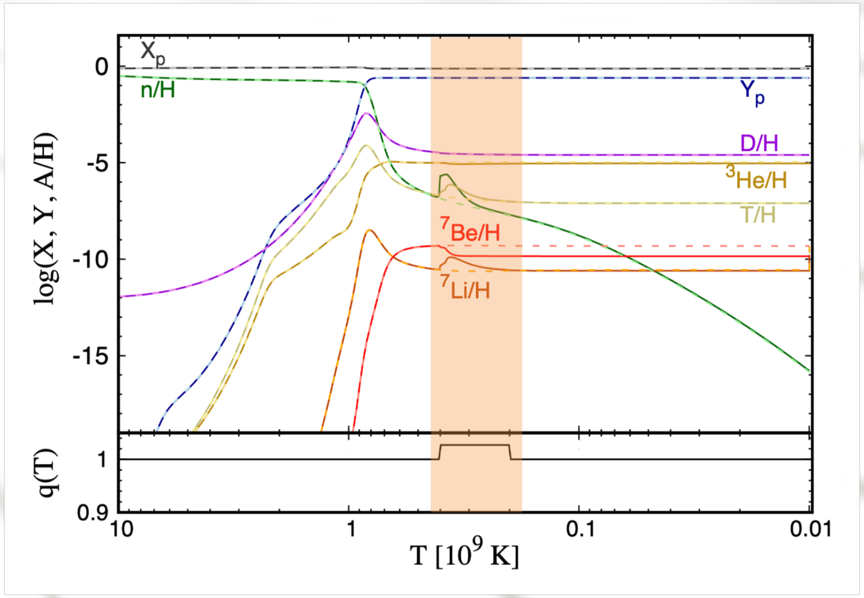
Restoration to blackbody

$$q' = 1.027 \quad \text{at } T_{\rm tr} = 4 \times 10^{8}\,\text{K}$$

$$q = 1 \quad \text{at } T_{\rm re} = 2 \times 10^{8}\,\text{K}$$

	w/o res	w/ res	Observation
$Y_{\rm p}$	0.2474	0.2474	0.2446 ± 0.0029
D/H (10^{-5})	2.525	2.503	2.527 ± 0.03
^{3}He/H (10^{-5})	0.9253	0.9322	$\lesssim 1.1 \pm 0.2$
^{7}Li/H (10^{-10})	1.677	1.664	1.58 ± 0.31





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Standard BBN

Adiabatic process

No heat flux into the Universe

Thermal plasma

Thermal equilibrium

Cosmic expansion rate < Thermonuclear reaction rate

Ideal plasma

Plasma constituents as ideal gases

No collisional effect

Primordial plasma

Plasma parameter

Ratio of mean potential energy and thermal kinetic energy

$$\Gamma = n_e^{1/3}\frac{e^2}{kT}$$

Ideal plasma: $\Gamma \ll 1$

Primordial plasma in SBBN is ideal due to rapidly decreasing electron density.

Non-ideal plasma: $\Gamma \gtrsim 1$

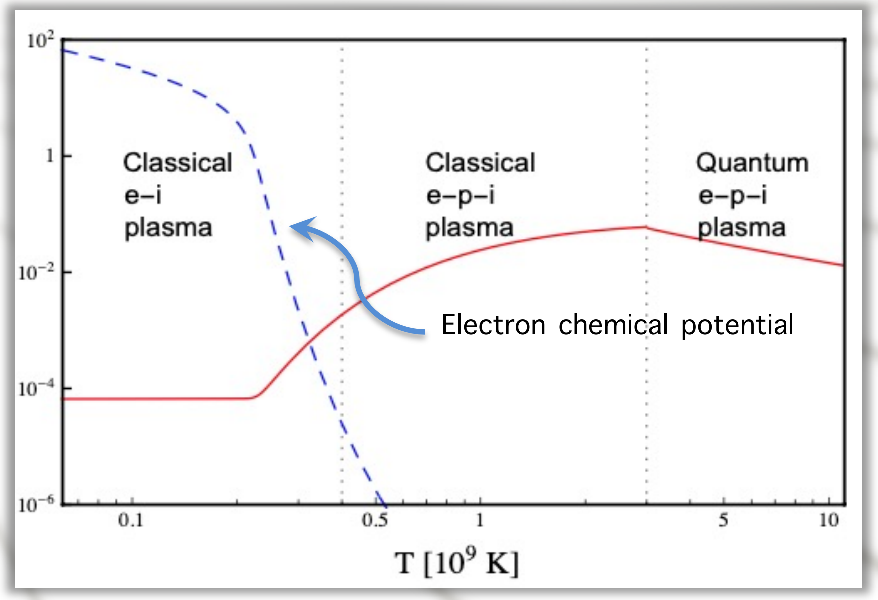
Degenerate electrons

Quantum plasma

$$\Gamma = n_e^{1/3}\frac{e^2}{\varepsilon_F} \propto n_e^{-1/3}$$

$$kT_F \equiv \varepsilon_F = \frac{\hbar^2}{2m}(3\pi^2)^{2/3} n_e^{2/3}$$

Primordial plasma could be (weakly) non-ideal at low temperature (T < 10^8 K).

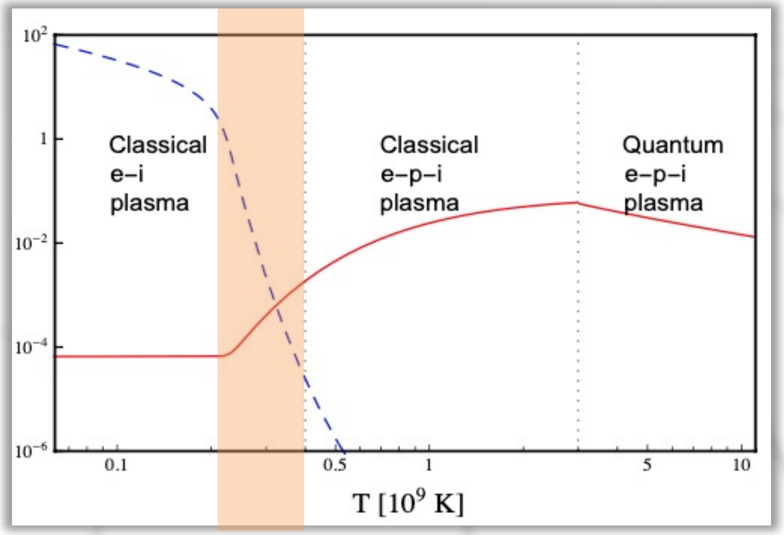


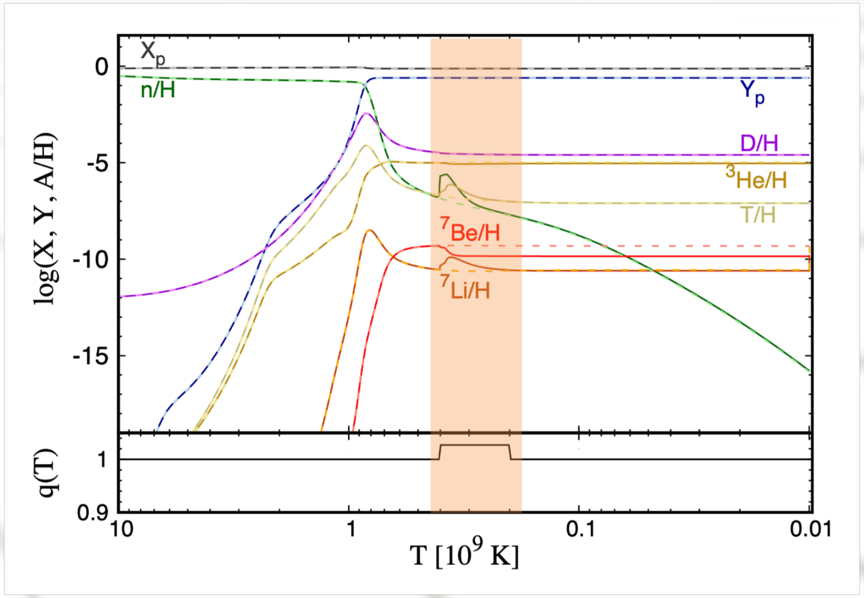
Primordial plasma

What happened

positron annihilation

radiation dominated era to matter dominated era



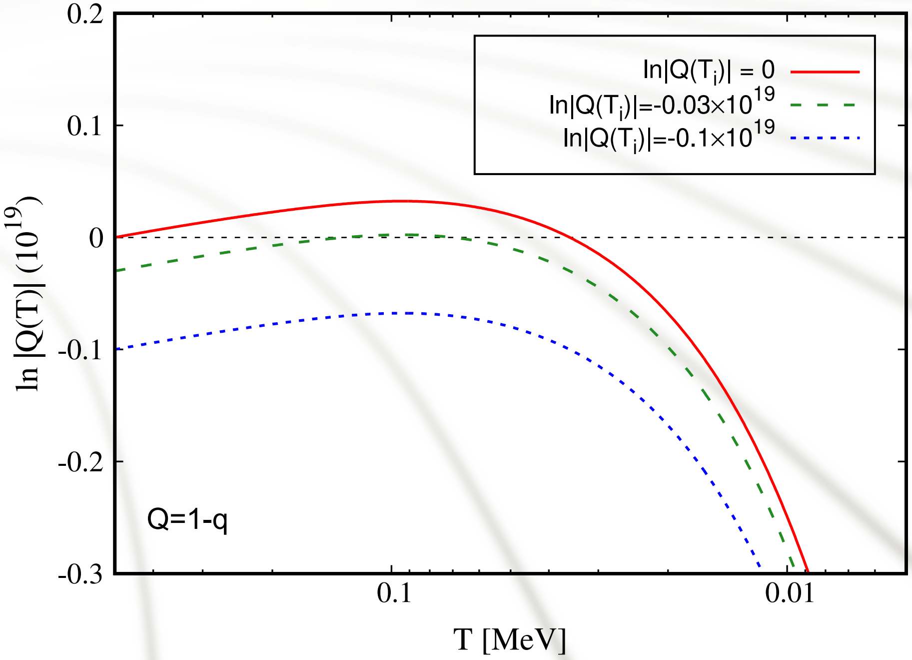


Boltzmann eqn.

$$\frac{\partial f}{\partial t} - \frac{\dot{R}}{R} E \frac{\partial f}{\partial E} = \frac{1}{E} \boxed{C[f]}$$

Collision term
including positron annihilation

$$\frac{dY_1}{dT} = -F \frac{d}{dT}\left[Q(T)T^3/s(T)\right] = -F\left[\frac{Q'(T)T^3}{s(T)} + Q(T)\frac{d}{dT}\left(\frac{T^3}{s(T)}\right)\right]$$



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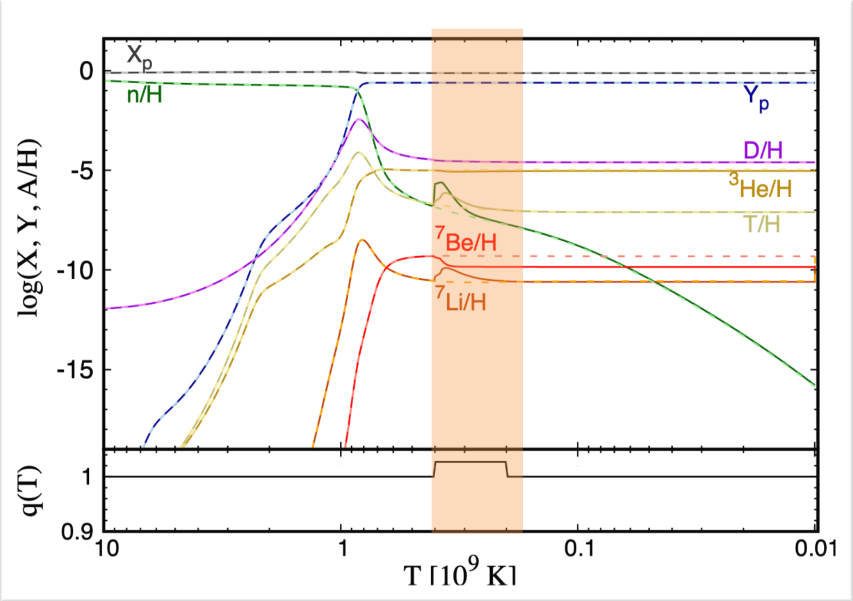
New BBN scenario



Primordial BBN plasma

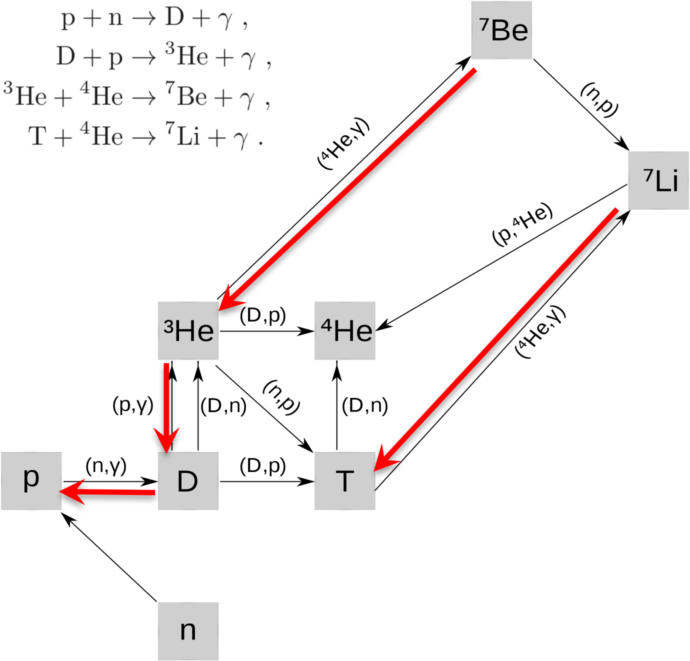
Transition from ideal to weakly non-ideal plasma

⇩

Distortion of photon distribution

⇩

Change of photo-disintegration reaction rate



$$p + n \to D + \gamma \ ,$$
$$D + p \to {}^3\mathrm{He} + \gamma \ ,$$
$${}^3\mathrm{He} + {}^4\mathrm{He} \to {}^7\mathrm{Be} + \gamma \ ,$$
$$T + {}^4\mathrm{He} \to {}^7\mathrm{Li} + \gamma \ .$$

Cosmic expansion

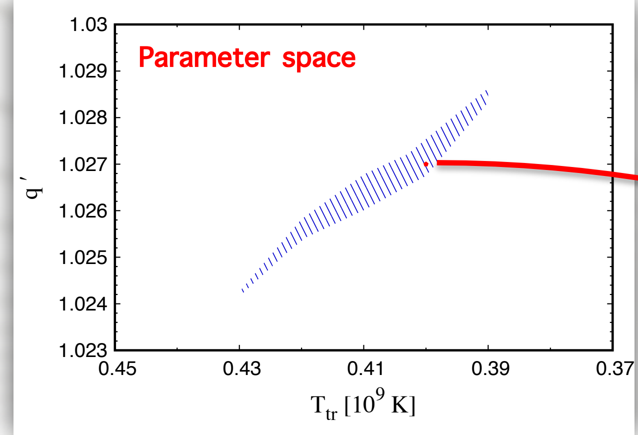
Change of photon energy & number density

⇩

Expansion rate will be also affected.

Solution to the ^{7}Li problem

[Jang *et al.*, arXiv:1812.09472]



Primordial abundances

Deuterium abundance is improved because the change in photon energy density makes the freeze-out time earlier.

Y_p (^{4}He mass fraction) doesn't differ from the SBBN because it's already decoupled at $T > T_{tr}$

$$q' = 1.027 \text{ and } T_{tr} = 4 \times 10^8 \text{ K}$$

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^{7}Li/H (10^{-10})	5.030	1.677	1.58 ± 0.31

^{3}He abundance is obtained safely below the observational upper limit.

Enhanced photo-disintegration processes play a crucial role in reducing the lithium abundance.

THANK YOU for your attention