Big Bang Nucleosynthesis

in a weakly nonideal plasma

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in collaboration with

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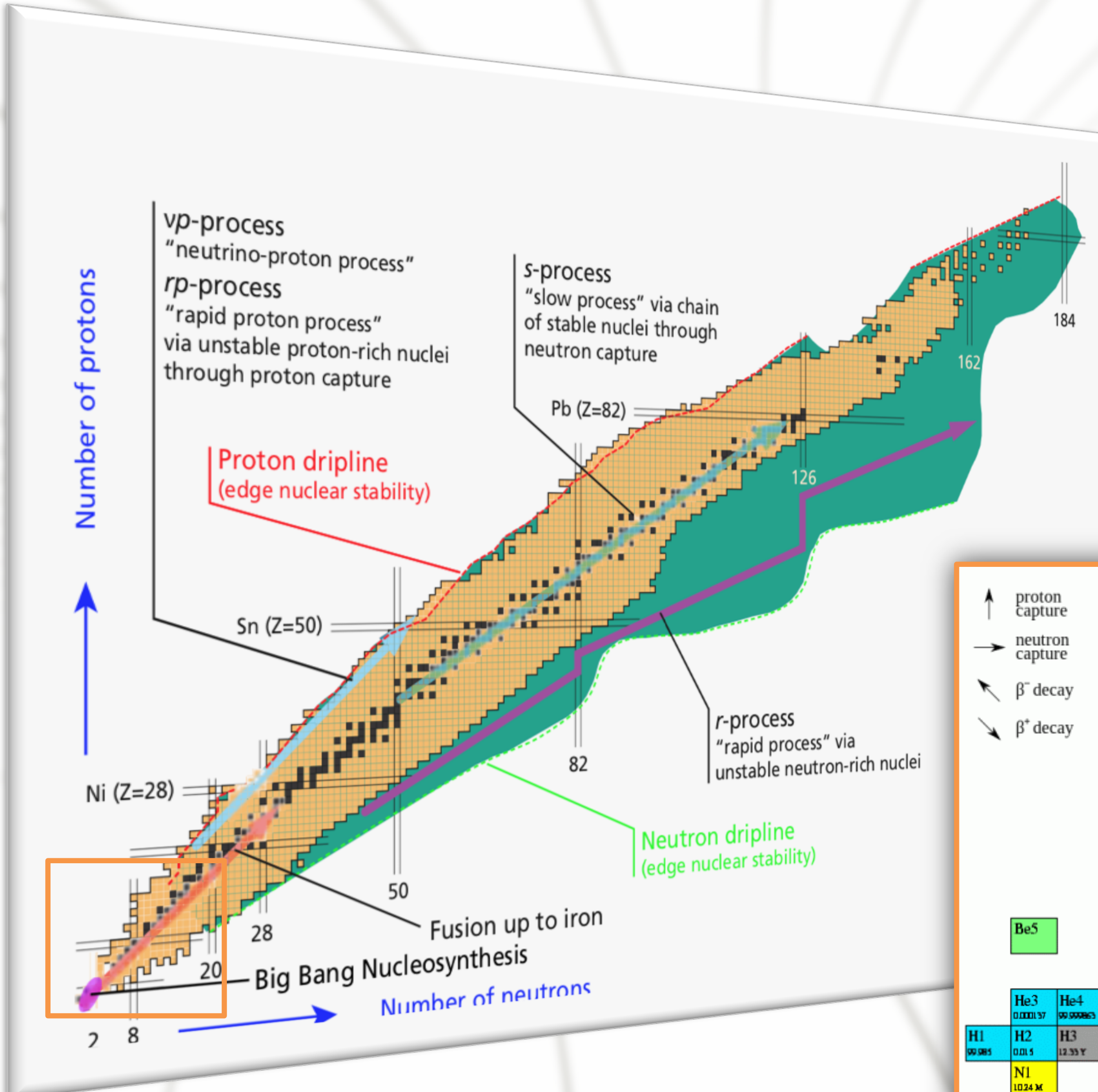
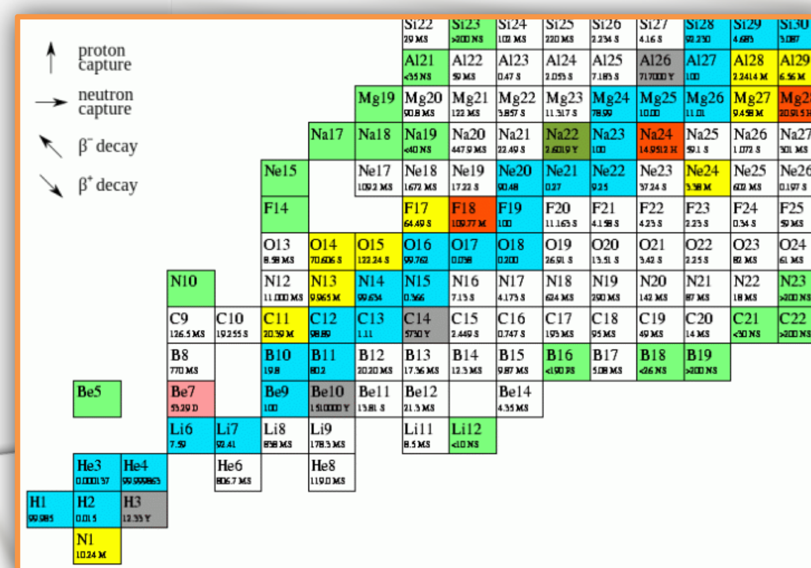
Origin of elements



Nucleosynthesis

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



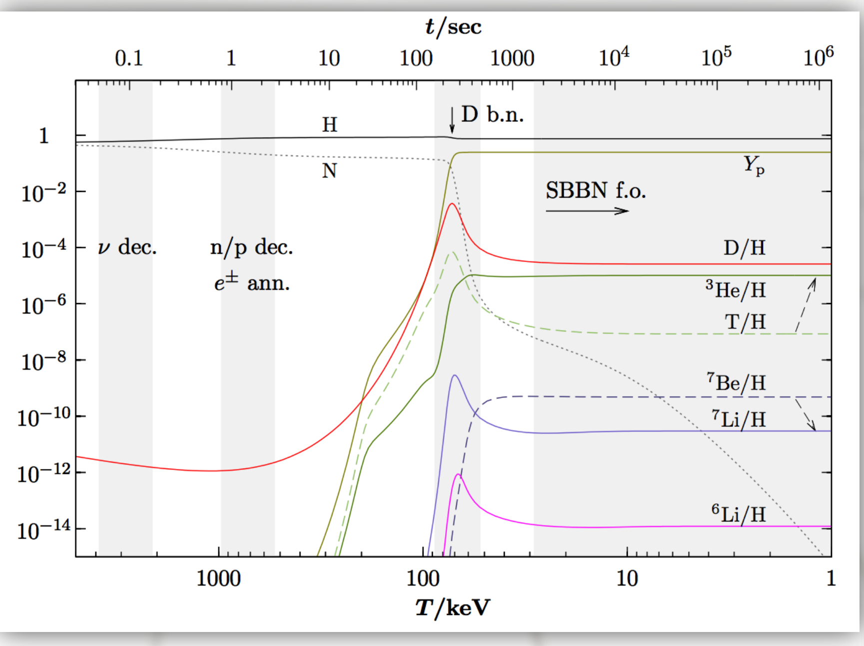
Standard BBN

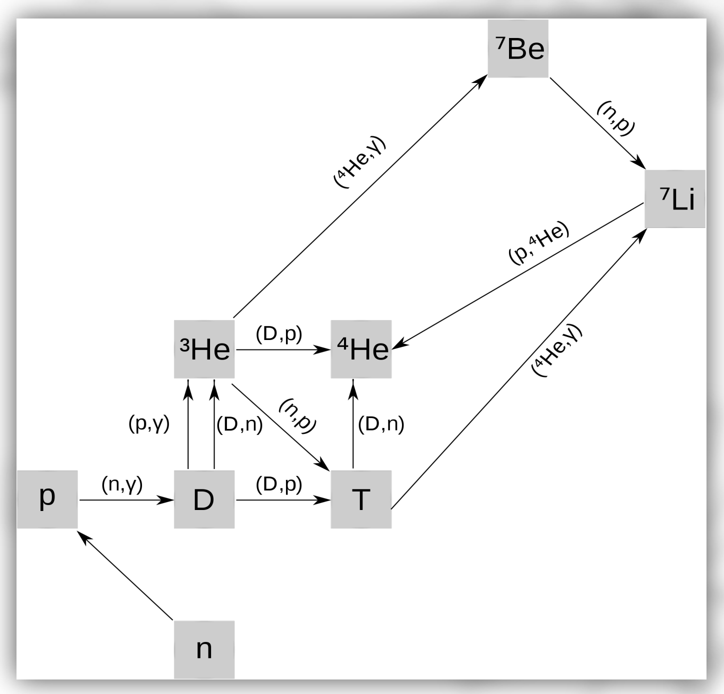
BBN network calculation

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

Two-body nuclear reaction rate: $\sigma(1+2 \to 3+4)$

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





Primordial abundances

Standard BBN prediction

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

Cosmic microwave background (CMB) constraint:

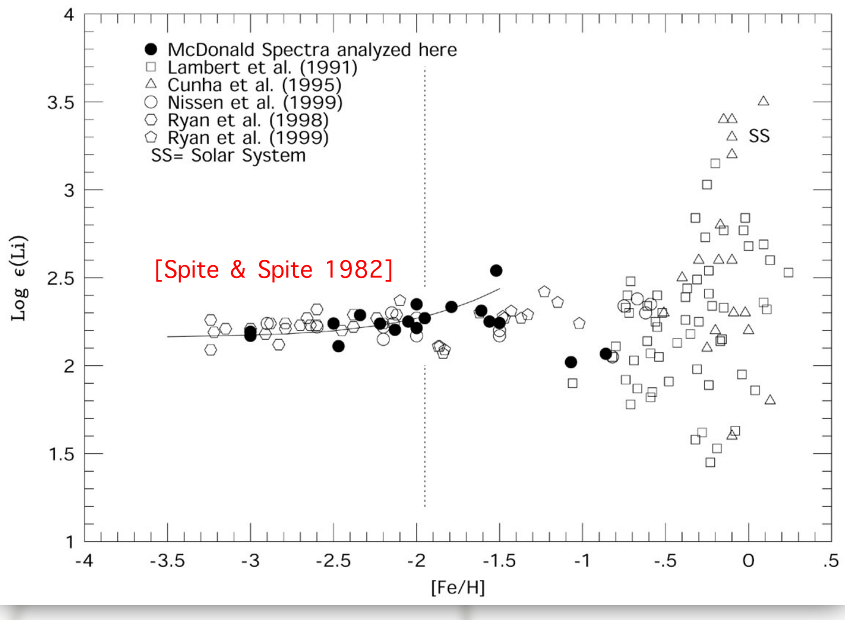
$$\eta = (6.094 \pm 0.063) \times 10^{-10}$$

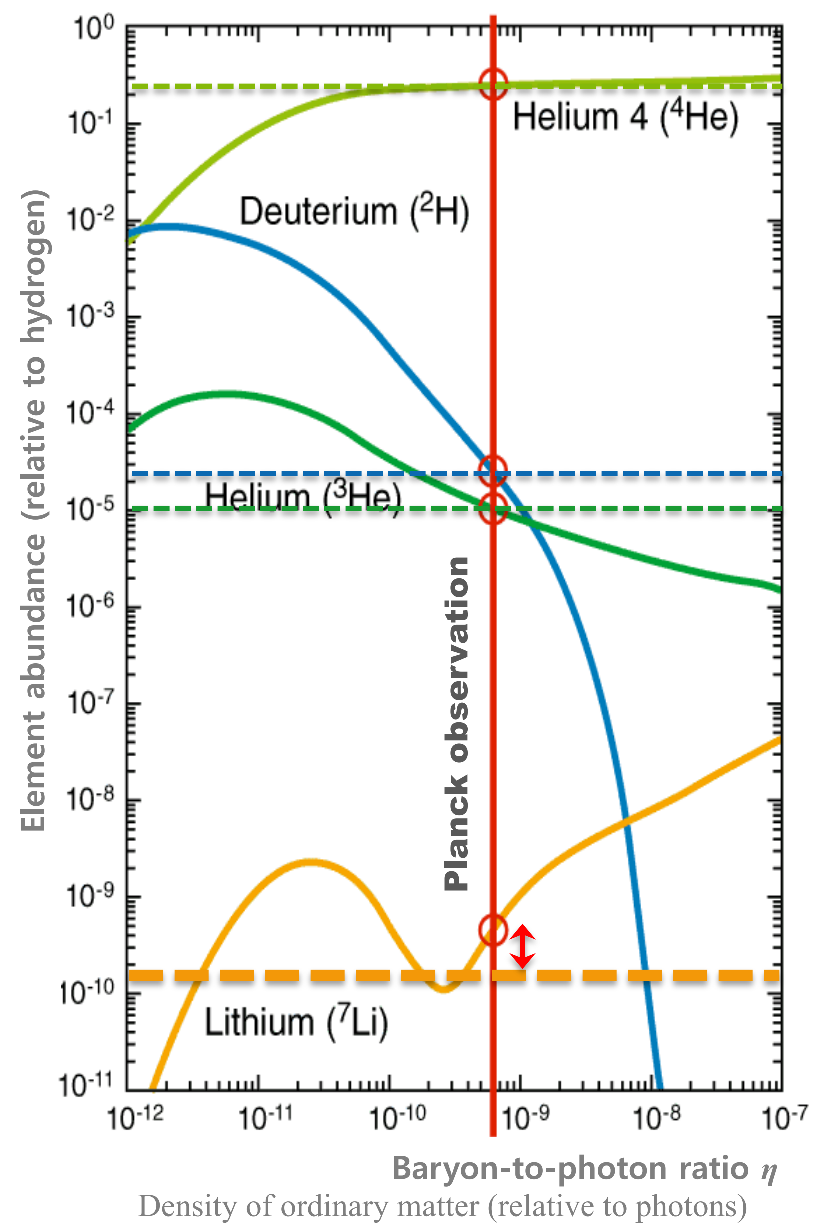
[Planck collaboration 2016]

Primordial ^{7}Li problem

Spectra of metal-poor stars

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





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.

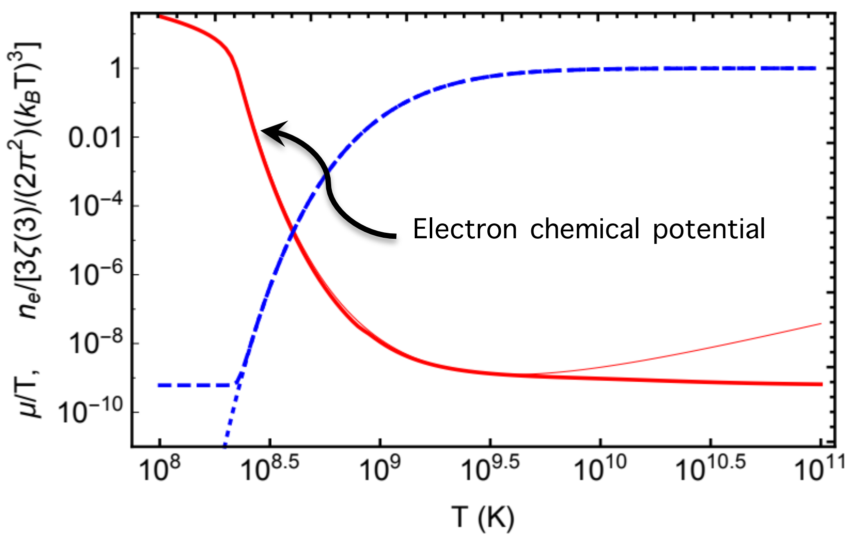
Non-ideal plasma: $\Gamma \gtrsim 1$

Degenerate electrons — Quantum plasma

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

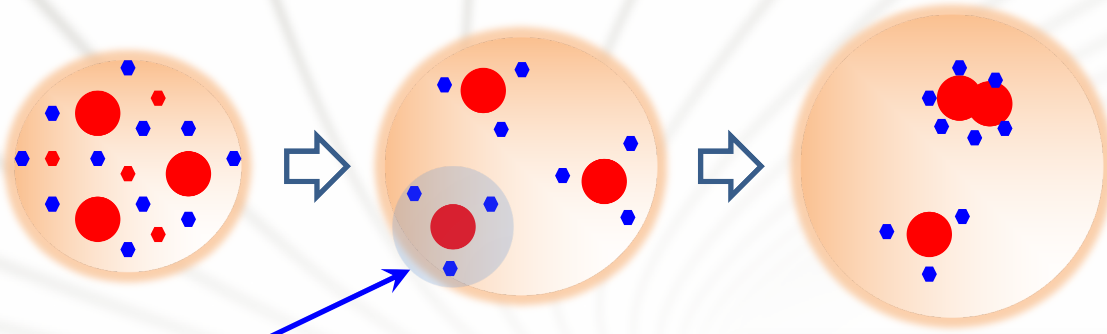
$$kT_F \equiv \varepsilon_F = \frac{\hbar^2}{2m}(3\pi^2)^{2/3} n_e^{2/3}$$

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



[Pitrou et al., Phys.Rept. (2018)]

Primordial plasma



Debye shielding:

Locally dense electrons – Large chemical potential

Plasma oscillation

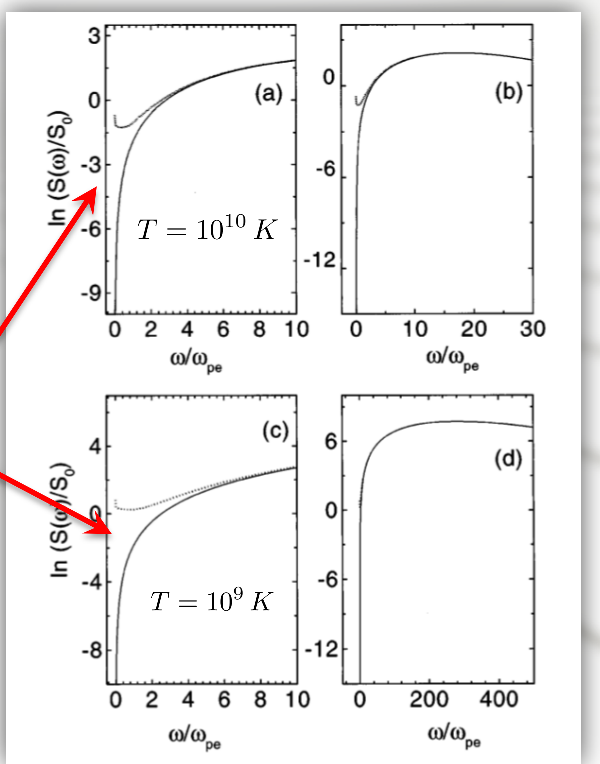
Collective motion of electrons

Dispersion relation:

$$\omega^2 = \omega_p^2 + k^2 c^2$$

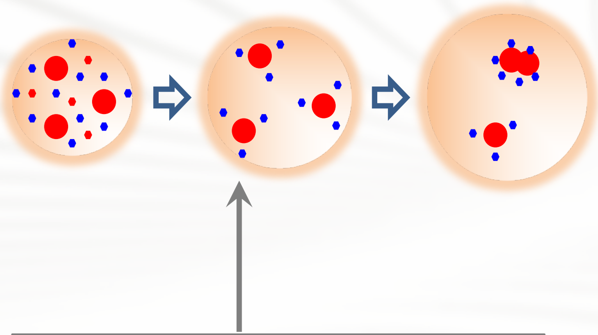
Distortion at low frequencies due to the non-ideality.

[Opher & Opher, PRL (1997)]

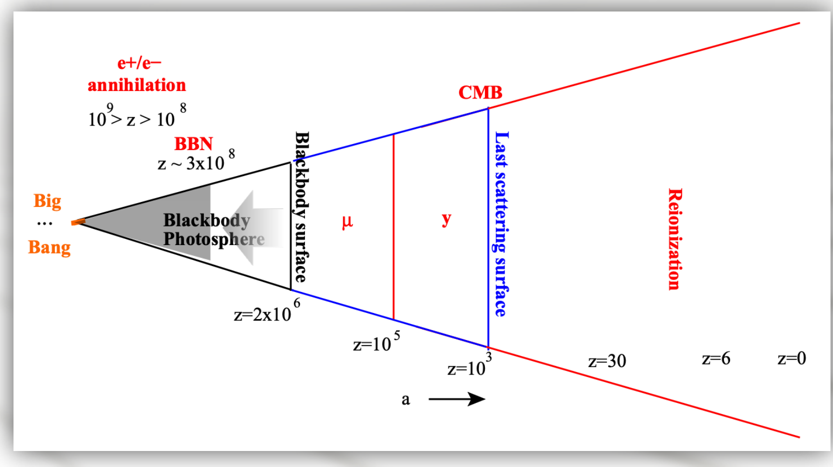


Deviation of EM spectrum from blackbody

Primordial plasma



Optically thinner than in ideal plasma



Non-Planckian distribution

Big bang nucleosynthesis in a weakly non-ideal plasma

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[2]Research Institute of Basic Science, Korea Aerospace University, Goyang 10540, Republic of Korea
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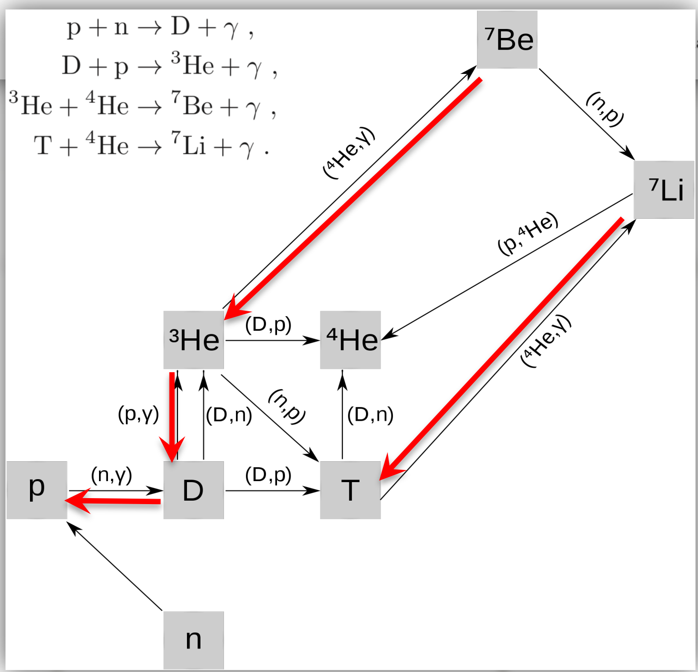
[4]School of Natural Science, Ulsan National Institute of Science and Technology (UNIST), Ulsan 44919, Republic of Korea

We propose a correction of 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, 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 deviation of photon distribution from the Planck distribution, which is parameterized 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 distribution. We discuss how the primordial plasma can be weakly non-ideal in this specific fashion and its effects on the cosmic evolution.



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.

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

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

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

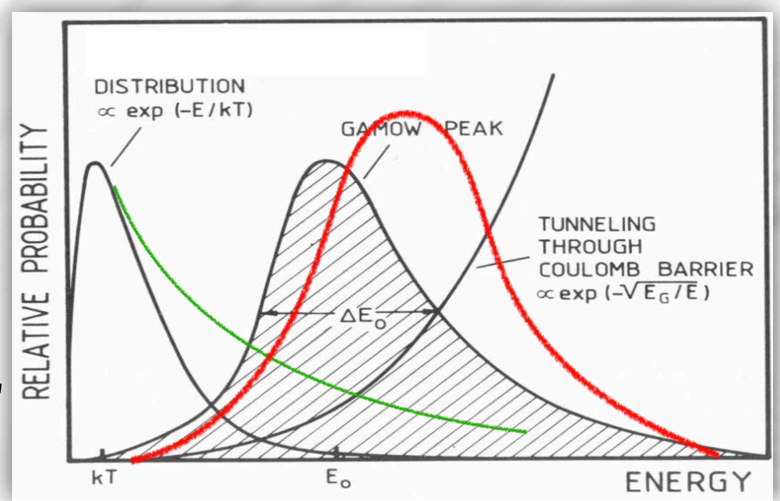
	SBBN	This work	Observation
Y_p	0.2474	0.2474	0.2446 ± 0.0029
D/H (10^{-5})	2.493	2.525	2.527 ± 0.03
^{3}He/H (10^{-5})	1.092	0.9253	$\leq 1.1 \pm 0.2$
^{7}Li/H (10^{-10})	5.030	1.677	1.58 ± 0.31

Photo-disintegration reaction

Reaction rate

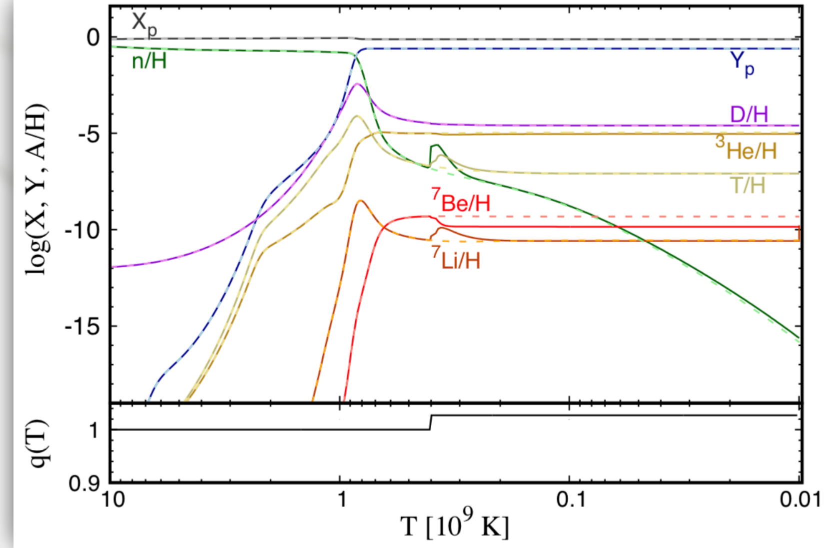
For a reaction in the form of $3 + \gamma \to 1 + 2$

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



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

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

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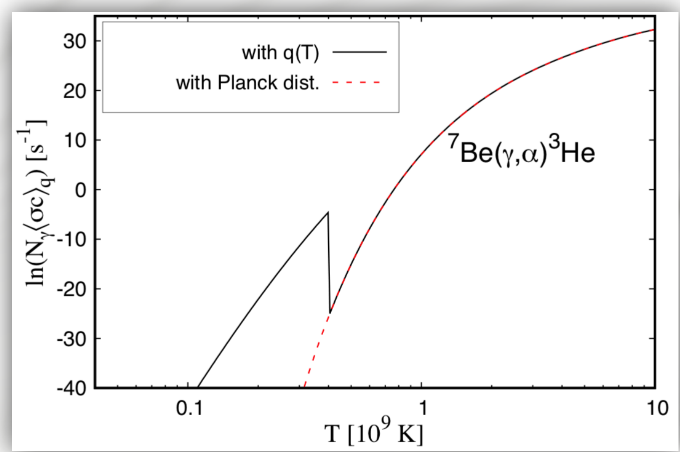

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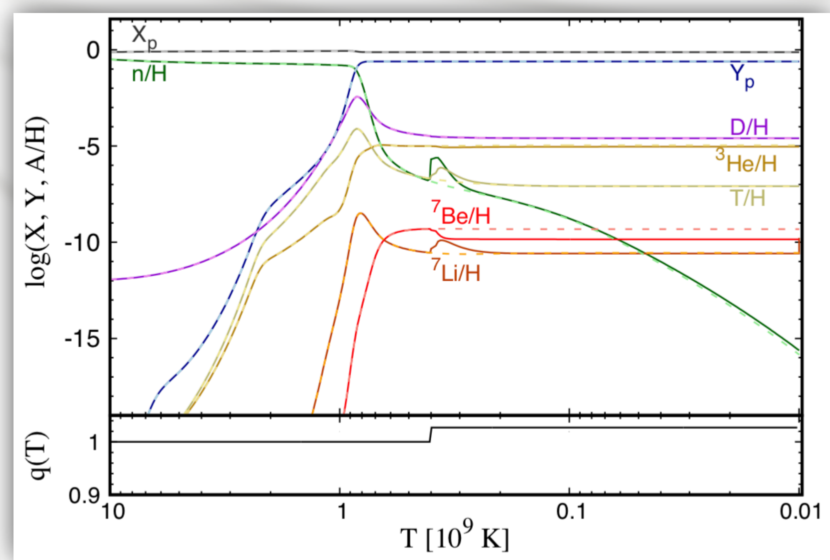

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Photon energy density

Photon energy density

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

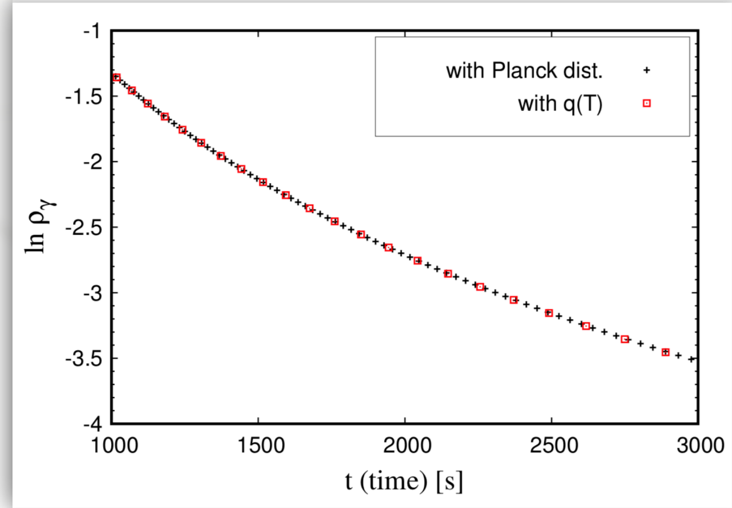
The condition for the energy conservation at the moment of transition

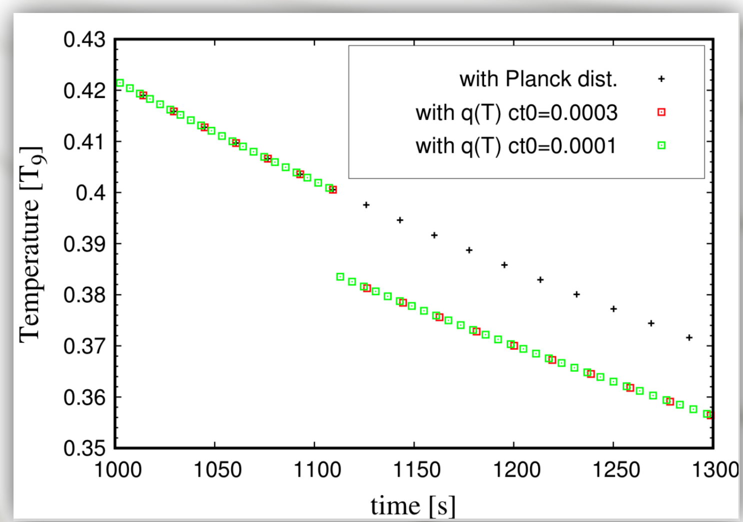
$$\rho_{\gamma\,(q=1)} = \rho_{\gamma\,(q>1)}$$

leads to the sudden temperature drop.

Freeze-out time

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





Cosmic Microwave Background

Restoration to blackbody

$$q' = 1.027 \quad \text{at } T_{\rm tr} = 4 \times 10^8\,\text{K}$$
$$q = 1 \quad \text{at } T_{\rm re} = 2 \times 10^8\,\text{K}$$

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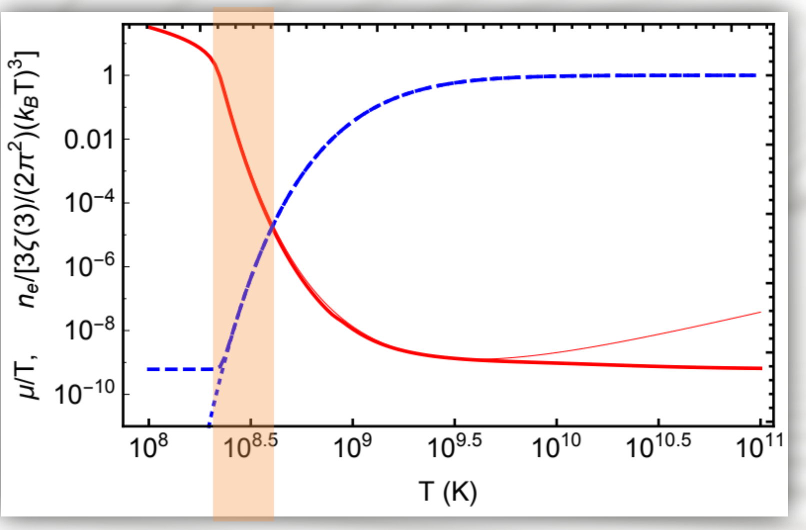

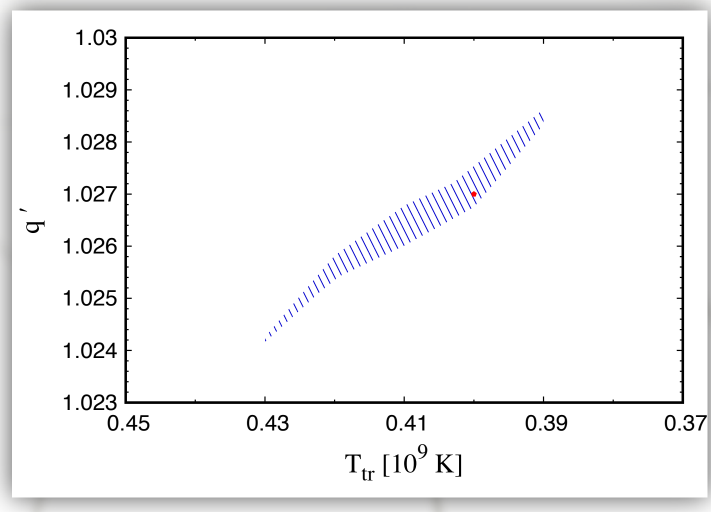

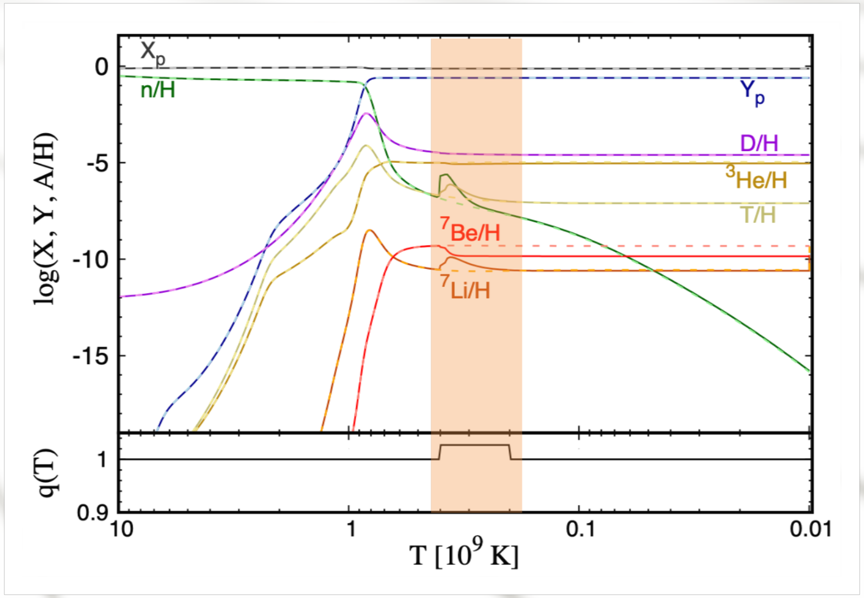

Summary

Primordial lithium problem

Discrepancy between the observation and the prediction of ^{7}Li abundance.

Idea

Large electron chemical potential due to the positron annihilation.
Possibility of nonideal BBN plasma.

Possible solution

Non-Planckian distribution of photons

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Working on

Solving the Boltzmann equation for photon

$$E\frac{\partial f}{\partial t} - \frac{\dot a}{a}|\mathbf{p}^2|\frac{\partial f}{\partial E} = \mathbf{C}[f]$$

THANK YOU for your attention