Resolving the Cosmological ^{7}Li Abundance Anomaly via Baryon Emission from Evaporating Primordial Black Holes

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based on joint work with A.D. Dolgov

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Outline

- Big Bang Nucleosynthesis & The ^{7}Li Problem
- (Schwarzschild) black hole evaporation
- Thermalisation of Emitted Baryons
- Possible scenarios:
  - Hot Black Holes ($T \sim 1$ GeV)
  - Cool Black Holes ($T \leq 100$ MeV)
- Conclusions

Big Bang Nucleosynthesis predictions

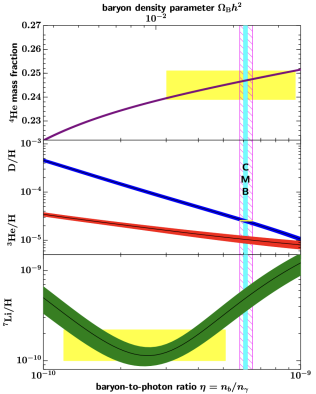


Figure 24.1: The primordial abundances of ^{4}He, D, ^{3}He, and ^{7}Li as predicted by the standard model of Big-Bang nucleosynthesis — the bands show the 95% CL range [50]. Boxes indicate the observed light element abundances. The narrow vertical band indicates the CMB measure of the cosmic baryon density, while the wider band indicates the BBN D+^{3}He concordance range (both at 95% CL).

Figure: Fractions of light elements produced at BBN (PDG, 2024)

Fractions of light elements produced at BBN

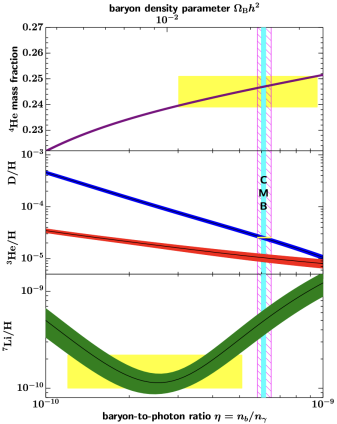


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- The observed abundances of ^{4}He, D, and ^{3}He agree perfectly with theoretical BBN predictions, at the canonical value of the baryon-to-photon ratio $\eta \approx 6 \times 10^{-10}$ found from angular fluctuations of CMBR.

The Lithium-7 problem

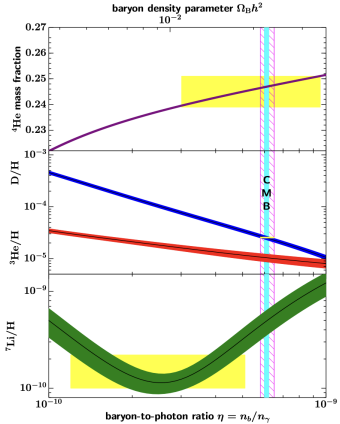


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- Theoretically predicted amount of ^{7}Li at the canonical η exceeds the observed value, $^7\mathrm{Li/H} \approx 1.6 \times 10^{-10}$, approximately by factor 3.

This discrepancy is the well-known primordial lithium problem.

A reduction mechanism

A new mechanism to explain the observed lithium-7 deficit:

- ^{7}Li transformation into ^{8}Li or ^{8}Be by capturing nucleons in the reactions: $^7\mathrm{Li} + n \to {}^8\mathrm{Li} + \gamma$ or $^7\mathrm{Li} + p \to {}^8\mathrm{Be} + \gamma$.
- The produced ^{8}Li or ^{8}Be quickly decay into a pair of ^{4}He.

We assume that the required nucleons are created by the evaporation of Primordial Black Holes (PBH) with properly adjusted parameters.

EA, A.D. Dolgov, *"Possible explanation of primordial ^{7}Li deficit"*,
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(Schwarzschild) black hole evaporation

According to S. Hawking (1974), black hole with mass M_{BH} has the temperature:

$$T_{BH} = \frac{M_{Pl}^2}{8\pi M_{BH}} = 1.05 \cdot 10^3\,\mathrm{GeV}/M_{10}\,, \quad M_{10} = M_{BH}/(10^{10}\mathrm{g})$$

- $M_{Pl} = 2.176 \times 10^{-5}$ g $= 1.22 \times 10^{19}$ GeV is the Planck mass

All particles with masses below T_{BH} are abundantly created in the course of evaporation.

The energy flux of the emitted radiation is:

$$J \sim T^4 r_g^2, \quad r_g = 2M_{BH}/M_{Pl}^2 \implies \dot{M}_{BH} \sim \left(-M_{BH}^{-2}\right)$$

Correspondingly the mass of BH, created at time moment $t^{(in)}$ evolves as $M_{BH}(t) = M_{BH}^{(in)}\left[(\tau_{BH} - t + t^{(in)})/\tau_{BH}\right]^{1/3}$ with the black hole life-time equal to:

$$\tau_{BH} \approx 3 \times 10^3 N_{eff}^{-1} \frac{M_{BH}^3}{M_{Pl}^4} \implies \tau_{BH} = 160\, M_{10}^3\ \mathrm{sec}$$

$N_{eff} \approx 100$ is the effective number of particle species with masses smaller T_{BH}.

Thermalisation

Baryons produced in the course of BH evaporation quickly lose their energy through interaction with the primeval plasma.

The thermalisation/equilibration time can be estimated as:

$$t_{eq} = 1/\left(\sigma_{tot} v_{cosm} n_{cosm}\right)$$

- σ_{tot} is the total interaction cross-section of baryons with background matter
- v_{cosm} is the relative velocity of the colliding particles in cosmological plasma
- n_{cosm} is the number density of particles in the primeval plasma

In thermal equilibrium:

$$n_{cosm} \approx 0.1\, T_{cosm}^3\, g_*$$

- T_{cosm} is the temperature of the cosmological plasma
- $g_* \sim 10^2$ is the number of particle species
- The numerical coefficient is equal to 0.09 for fermions and 0.12 for bosons.

Hubble cooling time

Equilibrium is established if the characteristic thermalisation time is **shorter** than the Hubble expansion (cooling) time: $\tau_{therm} < \tau_{cosm}$

According to the Friedmann equation, the Hubble parameter, H, is expressed through the cosmological energy density (for $3D$ flat universe):

$$\frac{3H^2 M_{Pl}^2}{8\pi} = \varrho_{cosm}$$

The energy density of cosmological plasma at thermal equilibrium:

$$\varrho_{cosm} = \frac{\pi^2 g_*}{30} T_{cosm}^4$$

Hence the Hubble cooling time as a function of cosmological temperature:

$$\tau_{cosm} \equiv H^{-1} = \left(\frac{90}{8\pi^3 g_*}\right)^{1/2} \frac{M_{Pl}}{T_{cosm}^2} = 0.5\,\mathrm{sec}\,(\mathrm{MeV}/T_{cosm})^2$$

Efficient thermalisation condition: $\tau_{therm} < \tau_{cosm}$

- Baryons created by PBHs typically have energies of the order of the PBH temperature, i.e. about 1 GeV in our cases.
- The energetic baryons are ejected into a low-energy background plasma, which is assumed to have much higher number and energy densities than the baryons created by the evaporating PBH.

These energetic baryons would lose energy during the characteristic thermalisation time:

$$\tau_{therm} = \left(\sigma_{tot} v_{evap} n_{cosm}\right)^{-1}, \quad n_{cosm} \approx 0.1\, T_{cosm}^3\, g_*$$

- v_{evap} is typical velocity of evaporating particles, initially $v_{evap} \sim c$

The condition $\tau_{therm} < \tau_{cosm}$ would be fulfilled when the cross-section satisfies the inequality:

$$\sigma_{tot} v_{evap} > 5 \times 10^{-42} \left(\frac{\mathrm{keV}}{T_{cosm}}\right) \mathrm{cm}^2$$

This is surely true for the case we are interested in.

Thermal equilibrium in cosmology is established **much faster** than the Hubble expansion rate for any reasonable value of the interaction cross-section.

Possible scenario: Hot Black Holes ($T \sim 1 GeV$)

PBH with such temperature could efficiently create baryons and anti-baryons.

- In this case: $M_{BH} \sim 10^{13}$ g, $\tau_{BH} \sim 1.6 \times 10^2 (M_{BH}/10^{10} g)^3 \,\mathrm{sec} \approx 1.6 \times 10^{11}$ sec

At the cosmological time $\tau_{cosm} = \tau_{BH}$ the cosmological plasma temperature was:

$$T_{cosm}(\tau_{BH}) \approx 1.8\,\mathrm{eV}$$

- The hydrogen recombination: $T_{rec} \approx 3100K \approx 0.27$ eV $\ll E_{bind} = 13.6$ eV
- The recombination takes place at $z_{rec} = 1100$ and $t_U^{(rec)} \approx 1.2 \times 10^{13}$ sec.

The considered black holes evaporated, while the cosmic plasma was still ionized.

The temperature of cosmic plasma during the main part of evaporation period was quite low, so the produced baryons could not destroy existing primordial D, He and Li nuclei, since their binding energies are several MeV. However, the created anti-baryons could be dangerous and might destroy ^{4}He or D.

But: the produced anti-baryons efficiently annihilate with baryons of cosmological background.

The total rate of (anti)baryons production

The fluxes of baryons and antibaryons, created by a single PBH, are the same:

$$J_B = 0.1 g_* f_B T_{BH}^3, \text{ where } T_{BH} = 10^3\,\mathrm{GeV}/M_{10}$$

- $f_B < 1$ is the relative fraction of (anti)baryons with respect to the total radiation emitted by BH.

The total rate of (anti)baryons production, $\dot{n}_B$, emitted from the sphere of the area $A = 4\pi r_g^2$ ($r_g = 2M_{BH}/M_{Pl}^2 \approx 1.5 \cdot 10^{-18} M_{10}$ cm) per unit time, by black holes with the number density n_{BH}:

$$\dot{n}_B + 3Hn_B \approx \dot{n}_B = J_B A\, n_{BH} = [0.1 g_* f_B \cdot (10^3\,\mathrm{GeV}/M_{10})^3 \cdot (4\pi r_g^2)] \cdot n_{BH}$$

- [...] is the rate of baryon or antibaryon production by a single black hole.
- The number densities of baryons and antibaryons created by BH are initially the same

We have neglected here the Hubble friction term because the cosmological expansion is slow in comparison with the characteristic time of the process.

The rate of ^{4}He fission

Inserting numerical values we obtain the total rate of (anti)baryons production:

$$\dot{n}_B \approx (1.8 g_* f_B) M_{10}^{-1} n_{BH}\ GeV.$$

Using the relation 1 GeV $= 1.52 \cdot 10^{24}$ sec^{-1}, we rewrite it in seconds:

$$\dot{n}_B = (2.75 g_* f_B) M_{10}^{-1} 10^{24} n_{BH}\ \mathrm{sec}^{-1}.$$

The number density of (anti)baryons produced via the complete BH evaporation:

$$n_B = n_{\bar{B}} \approx \tau_{BH} \dot{n}_{BH} = (4.4 f_B g_*)\, M_{10}^2 \times 10^{26} n_{BH}$$

- where the value $\tau_{BH} = 160 M_{10}^3$ sec is used.

The rate of ^{4}He fission by anti-baryons is governed by the equation:

$$\dot{n}(^4He) = -\sigma_{fis} v_{He}^{\bar{p}} n_B n(^4He)$$

- $v_{He}^{\bar{p}}$ is the relative velocity of $\bar{p}$ and He nuclei (essentially thermally average proton velocity)

We estimate the fission cross-section based on the geometrical size of the ^4He-nucleus:
$l(^4He) = 1.68 \times 10^{-13}$ cm $\Longrightarrow$ $\sigma_{\mathbf{fis}} = \mathbf{2.8 \times 10^{-26}\ cm^2}$.

Number density of excessive baryons

The temperature of the cosmic plasma at the moment of BH evaporation is $T_{cosm}(\tau_{BH}) \approx 1.8$ eV and the cosmological time at that period:

$$\tau_{cosm} = 0.5\,\mathrm{sec}\,(\mathrm{MeV}/T_{cosm})^2 = 1.54 \cdot 10^{11}\,\mathrm{sec}$$

The relative number of destroyed helium-4 nuclei by anti-baryons during the cosmological time:

$$r_{He} \equiv \frac{\Delta n(^4He)}{n(^4He)} = \sigma_{fis} v^{\bar{p}}_{He} n_B \tau_{cosm} \approx 6 \times 10^{22}\,(f_B g_*) M_{10}^2 n_{BH}\, v^{\bar{p}}_{He}\,\mathrm{cm}^3$$

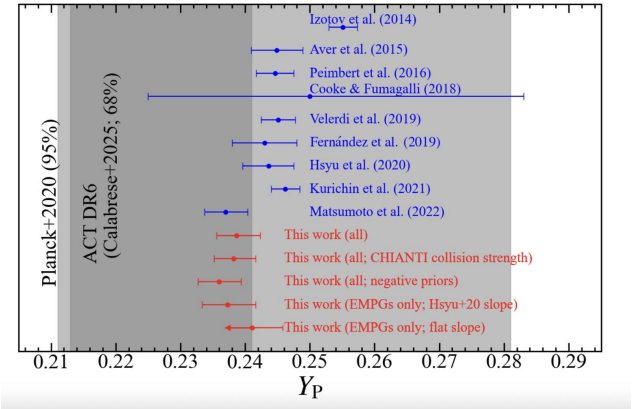
Demanding uncertainty in determination of ^4He density at the level of 10%, i.e. $r_{He} < 0.1$, we obtain:

$$n_{BH} \lesssim \frac{2 \cdot 10^{-24}\,\mathrm{cm}^{-3}}{(f_B g_*)\, v^{\bar{p}}_{He}\, M_{10}^2}$$

Consequently, the upper limit on the number density of excessive (anti)baryons:

$$n_B = 4.4 \times 10^{26}\,(f_B g_*)\, M_{10}^2 n_{BH} \lesssim \frac{10^3}{v^{\bar{p}}_{He}}\,\mathrm{cm}^{-3}$$

Primordial Helium Abundance



H. Yanagisawa et al., "EMPRESS. XV. A New Determination of the Primordial Helium Abundance Suggesting a Moderately Low $Y_{\rm P}$ Value," [arXiv:2506.24050 [astro-ph.GA]]: the Y_P-value is lower than most of the previous estimates by one standard deviation.

About Deuterium

The cross-section of D-destruction is approximately the same as for ^{4}He:

$$\sigma_{fis} \approx 100\, fm^2 \approx 10^{-24} cm^2$$

We expect similar variation of relative deuterium number density as for r_{He}:

$$r_D \equiv \frac{\Delta n(D)}{n(D)} = \sigma_{fis} v_D^{\bar{p}} n_B \tau_{cosm} \approx 6 \times 10^{22} (f_B g_*) M_{10}^2 n_{BH}\, v_D^{\bar{p}}\, \mathrm{cm}^3$$

- $v_D^{\bar{p}}$ is the relative velocity of antiproton and deuterium

Observational data on primordial D-abundances were obtained by different groups. The relative variation of deuterium number densities exceeds 10%.

The account of the interaction of antibaryons with deuterium does not change restriction on the BH number density derived from the observations of ^{4}He.

Elimination of the Evaporated Antibaryons

The evaporated antibaryons could efficiently annihilate with cosmic background baryons.

The number density of the cosmological background baryons is much larger than the density of the evaporated antibaryons:

$$n_B^{cosm} = \eta n_\gamma = 1.44 \cdot 10^{-10} T_{cosm}^3$$

The rate of annihilation of evaporated antibaryons with cosmological baryons is:

$$\dot{n}_{\bar{B}} = -\sigma_{ann} v_{B\bar{B}} n_{\bar{B}} n_B^{cosm}$$

- $\sigma_{ann} v_{B\bar{B}} \approx 2 \cdot 10^{-26} \mathrm{cm}^2$ (the Compton wavelength of a pion squared)

The asymptotic value of the antibaryon suppression factor achieved during cosmological time τ_{cosm} is:

$$r_{\bar{B}} = \frac{n_{\bar{B}}(\tau_{cosm})}{n_{\bar{B}}(t_{in})} = \exp\left(-\sigma_{ann} v_{B\bar{B}} n_B^{cosm} \tau_{cosm}\right) \approx e^{-10}$$

Antibaryons emitted by evaporating PBHs practically disappear and **do not have a destructive impact** on the primordial ^{4}He and D abundances.

Is the remaining baryon density sufficient to destroy ^{7}Li down to the observed value?

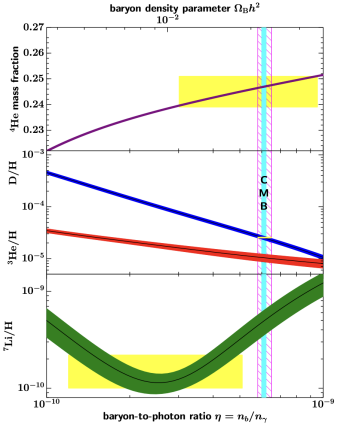
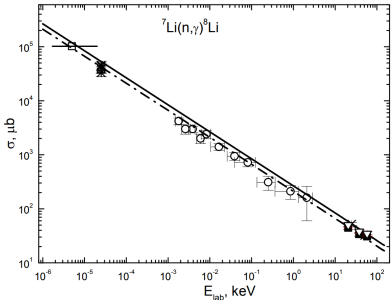


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- The essential process is: $^7\mathrm{Li} + n \rightarrow {}^8\mathrm{Li} + \gamma$
- The cross-section: $\sigma(Li^7) \approx 2 \cdot 10^{-25}\mathrm{cm}^2$
- The produced ^{8}Li quickly decays into two ^{4}He nuclei

The fraction of the destroyed ^{7}Li

The number density of ^{7}Li evolves according to the equation:

$$\dot{n}(^7Li) = -v^n_{Li}\sigma(Li^7)n(^7Li)n_B$$

- $n(^7Li)$ is the number density of ^{7}Li.
- v^n_{Li} is the relative centre of mass velocity of the neutron and Li nuclei (close to thermal neutron velocity)

The fraction of the destroyed ^{7}Li during cosmological time:

$$r_{Li} = \frac{n_{Li}(\tau_{cosm})}{n_{Li}(t_{in})} = \exp\left(-\frac{v^n_{Li}}{v^{\bar{p}}_{He}}\,\sigma(^7Li)n_B\tau_{cosm}\right) \equiv e^{-K}.$$

With numerical values: $\sigma(^7Li) \approx 2\cdot 10^{-25}\mathrm{cm}^2$, $\tau_{cosm} = 1.54\cdot 10^{11}$ sec, and n_B we find K:

$$K = 2\cdot 10^{-25}cm^2 \times 10^3\,\mathrm{cm}^{-3} \times 1.54\cdot 10^{11} \times 3\cdot 10^{10}\mathrm{cm} \times \frac{v^n_{Li}}{v^{\bar{p}}_{He}} \approx \frac{v^n_{Li}}{v^{\bar{p}}_{He}} \approx 1$$

Therefore the ^{7}Li abundance is suppressed by the factor $1/e \approx 0.37$.

With a reasonable choice of the parameters the density of ^{7}Li can be reduced to the observed value.

Cool Black Holes: $T_{BH} \leq$100 MeV. Baryons are not created

The only stable particles that can be produced by such black holes:

- electrons, positrons (in equal amount, if BH is electrically neutral)
- photons, neutrinos

As follows from:

$$T_{BH} = \frac{M_{Pl}^2}{8\pi M_{BH}} \leq 100\,\mathrm{MeV}$$

The black hole mass should be:

$$M_{BH} \approx 10^{14}\mathrm{g}\left(\frac{100\mathrm{MeV}}{T_{BH}}\right)$$

Its life-time would be longer than:

$$\tau_{BH} = 1.6 \cdot 10^{14}\mathrm{sec}\left(\frac{100\,MeV}{T_{BH}}\right)^2 \gtrsim 1.6 \cdot 10^{14}\mathrm{sec}$$

The photon energy immediately after their production from the BH evaporation were close to the T_{BH}. However, the photons could be thermalised due to their scattering on the cold background electrons.

Photon thermalisation

The temperature of the cosmological plasma at τ_{BH} would be below the value:

$$T_{cosm}(\tau_{BH}) \lesssim 0.06\,\mathrm{eV}\left(\frac{T_{BH}}{100\,MeV}\right)$$

This temperature is noticeably smaller than the hydrogen recombination temperature, $T_{rec} \approx 0.27$ eV, that took place at the redshift $z_{rec} = 1100$.

The energetic gamma quanta interacting with neutral atoms would lead to plasma reionisation at redshifts $z_{reion} \lesssim 20$, adding possibly noticeable contribution to the canonical sources of reionisation.

Another potentially observable effect could be a distortion of the CMB spectrum at low frequencies.

Photon thermalisation by scattering on electrons would diminish their energy below ^{4}He binding energy, so they would not destroy ^{4}He nuclei, but they could diminish the number densities of Li and Be down to the observed values.

Conclusions

It is shown:

- A population of evaporating PBH may successfully solve the problem of the too low observed value of lithium number density at the canonical magnitude of the cosmological baryon density.
- There are two possibilities of "hot" and "cool" black holes.
- In the first case excessive lithium is destroyed by nucleons through the reactions $^{7}\mathbf{Li}+n \rightarrow ^{8}\mathbf{Li} +\gamma$ **or** $^{7}\mathbf{Li} +p \rightarrow ^{8}\mathbf{Be}+\gamma$**.**
- Subsequently both ^{8}Li and ^{8}Be quickly decay into a pair of ^{4}He nuclei.
- In the second case the depletion of ^{7}Li could be driven by photons.
- The considered mechanisms may lead to distortion of the CMB angular fluctuations at low frequencies and to make contribution to reionization of the universe.

THE END

THANK YOU FOR ATTENTION