Cosmological Lithium Problem

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Course: Modern Astrophysics

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November 9, 2023

- Introduction
- Big Bang Nucleosynthesis
- Measurement of Primordial Abundances
- Proposed Solutions
- Conclusion

What is Lithium?

1 Introduction

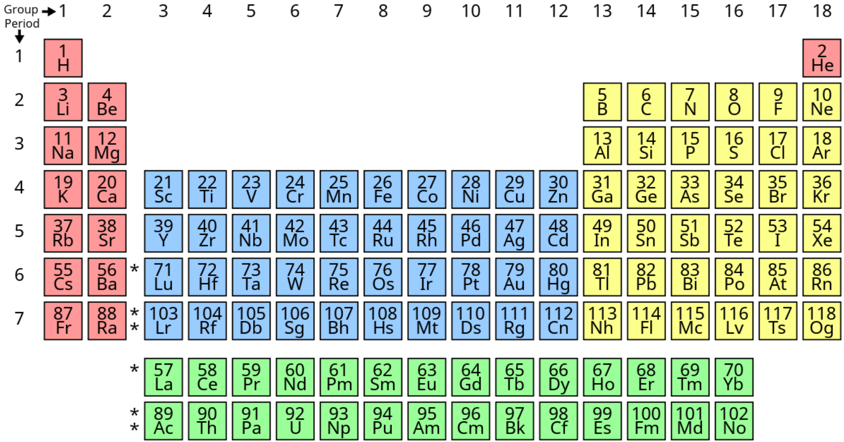

Figure: Periodic Table

The first three minutes

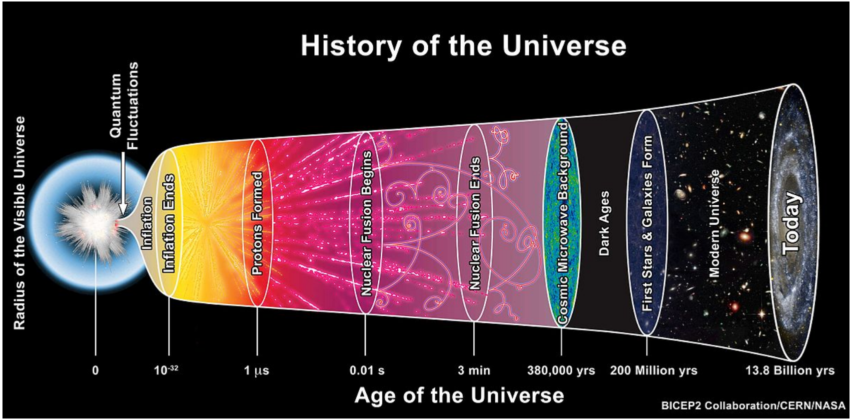

Figure: The evolution of the early universe

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2 Big Bang Nucleosynthesis

Section 2.1

The Evolution of the Early Universe

Theoretical Framework

- Cosmological Principle: The universe is homogeneous and isotropic at a large scale
- General Relativity: Friedmann-Lemaitre-Robertson-Walker metric.
- Standard Model of Particle Physics and Thermodynamics.

$\rightarrow$ In 1940s, G. Gamow developed the $\alpha\beta\gamma$ theory of the early universe.
$\rightarrow$ Big Bang Nucleosynthesis

Observational Cosmology

2 Big Bang Nucleosynthesis

In 1929, Edward Hubble discovered that the galaxies are moving away from us at $v = H_0 d$.

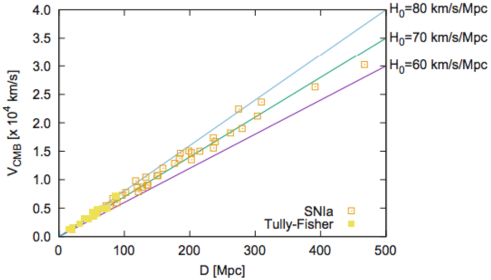

Figure: Hubble diagram for type Ia supernovae and Tully-Fisher relation

In 1965, A. Penzias and R. Wilson discovered the Microwave Background Radiation.

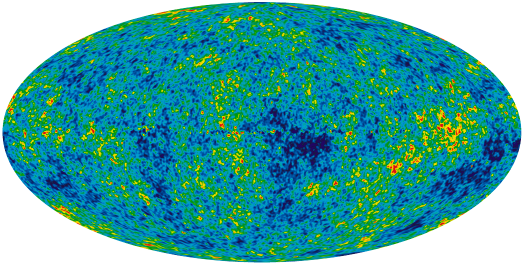

Figure: Cosmic Microwave Background (WMAP)

Friedmann Equation governed the expansion of the universe:

$$\boxed{\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi}{3}\mathrm{G}\rho} \tag{1}$$

where a(t) is the dimensionless cosmic scale factor.

Big Bang Nucleosynthesis occurs in the radiation-dominated epoch ($a < 10^{-5}$), so the energy density has $\rho \propto T^4$, and $a \propto t^{1/2}$, time - temperature equation is expressed as:

$$\boxed{t \approx 1\mathrm{s}\left(\frac{1\mathrm{MeV}}{\mathrm{T}}\right)^2} \tag{2}$$

Section 2.2

Big Bang nucleosynthesis

Baryogenesis & Nucleon Freeze Out

At t $\lesssim$ 1s, thermal equilibrium of nucleons via weak interaction:

$$\nu_e + n \longleftrightarrow p + e^-$$

$$p + \bar{\nu_e} \longleftrightarrow e^+ + n$$

Maxwell-Boltzmann distribution of nucleons:

$$\boxed{\frac{N_n}{N_p} = \left(\frac{m_n}{m_p}\right)^{3/2} \times exp\left(-\frac{(m_n - m_p)c^2}{k_B T}\right)} \tag{3}$$

- Since $(m_n - m_p)c^2 = 1.3\text{MeV}$, the equilibrium at $\text{k}_\text{B}\text{T} \gg 1.3\text{MeV}$ will be of 1 to 1.
- Universe cools to about $\text{k}_\text{B}\text{T} = 0.7\text{MeV}$, weak interaction can't hold the first two reactions in equilibrium any longer, and the ratio $\frac{N_n}{N_p}$ "freezes out" at 1/6.
- Neutrons with a mean life-time of ~881.5 s starts to decay freely.

$$n \rightarrow p + e^- + \bar{\nu_e}$$

$\rightarrow \frac{N_n}{N_p}$ drops to $\sim 1/7$ by the time the nuclear reaction began.

Big Bang nucleosynthesis

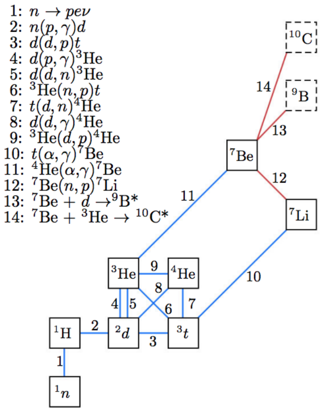

Figure: Simplified BBN nuclear network

Reaction of deuterium

$$p + n \longleftrightarrow d + \gamma$$

$E_{binding} \sim 0.22$ MeV.

- Deuterium is the key element in BBN
- Universe cooled to $k_B T \sim 0.07$ MeV, increasing deuterium abundances $\to$ further reactions
- An excess of photons would shift to the left the reaction $\to$ reduce the production of deuterium

$\to$ The **light element abundances** can be constrain by the **baryon to photons ratio**.

Big Bang nucleosynthesis summary

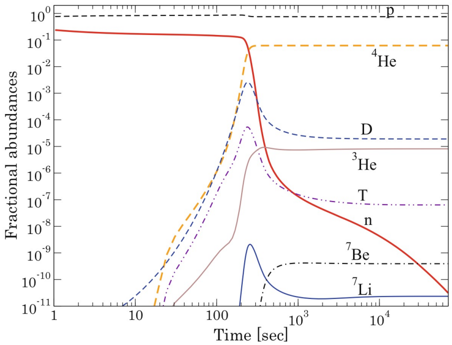

Figure: Evolution of abundance during BBN era for $\eta_{10} = 6.19$

- Predicts the primordial abundances of the light elements like D, ^{3,4}He and $^{6,7}Li$
- Occurs in the radiation-dominated epoch, $\sim$ 1s to $\sim$ 3 min after the big bang.
- Depends on the baryon-to-photon ratio $\eta \equiv \frac{N_b}{N_\theta}$, more conveniently written as: $\eta_{10} \equiv 10^{10}\eta$.
- Can be inferred from observational data in metal-poor objects and CMB.

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Microwave Background Anisotropies as a Cosmic Baryometer

- CMB can measure the cosmic baryon density with high precision

$$\Omega_b = 3.66 \times 10^{-3} \eta_{10} h^{-2} \qquad (4)$$

where $\Omega_b = \dfrac{\rho_b}{\rho_{cr}}$,
$\mathrm{h} = \mathrm{H_0/km.s^{-1}.Mpc^{-1}}$

- The cosmological parameters are determined from the satellites WMAP 9 year and Planck respectively.

$$\Omega_b h^2 = 0.02264 \pm 0.00050$$
$$\Omega_b h^2 = 0.02222 \pm 0.00023$$

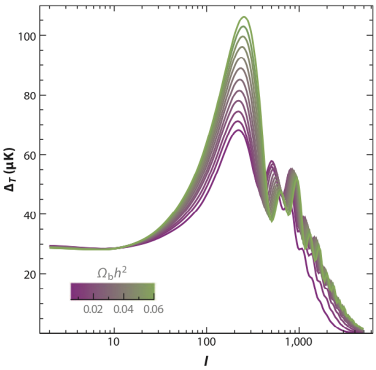

Figure: CMB sensitivity to cosmic baryon content

Light-Element Observations

3 Measurement of Primordial Abundances

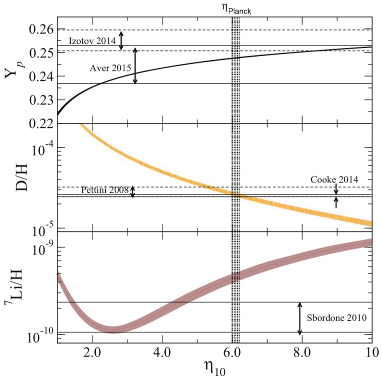

Figure: Abundance of light elements produced in BBN. Upper panel is mass fraction Y of ^{4}He. Line-widths indicate uncertainties in nuclear reaction rates

The primordial abundance is deduced from observations of objects with low metallicity.

- **Helium abundance** Y_p is derived from observations of He I emission lines of low-metallicity blue compact dwarf galaxies:

$$Y_p = 0.2551 \pm 0.0022 \quad \text{(Izotov et al, 2014)}$$
$$Y_p = 0.2449 \pm 0.0040 \quad \text{(Aver et al, 2015)}$$

- **Deuterium Abundance** is derived from D and H absorption lines toward high-redshift quasars due to intervening intergalatic clouds:

$$D/H = (2.82 \pm 0.19) \times 10^{-5} \quad \text{(Pettini et al, 2008)}$$
$$D/H = (2.53 \pm 0.04) \times 10^{-5} \quad \text{(Cooke et al, 2014)}$$

Light-Element Observations

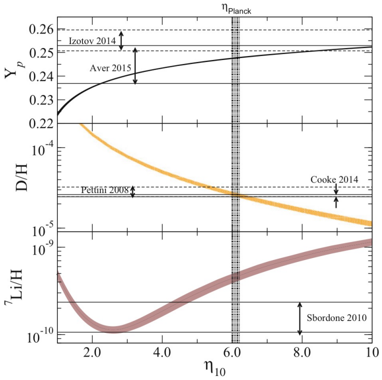

Figure: Abundance of light elements produced in BBN. Line-widths indicate uncertainties in nuclear reaction rates. The vertical shaded region indicates the range $\eta_{10} = 6.07 \pm 0.06$ determined from Planck.

The primordial abundance is deduced from observations of objects with low metallicity

- **Lithium Abundance** is derived from Li I absorption lines in metal-poor dwarf stars.
  - Measurements of Li I λ 6798 $\mathring{A}$ absorption line of 28 dwarfs in the galatic halo (Sbordone et al, 2010):

$$^7Li/H = (1.58 \pm 0.31) \times 10^{-10}$$

  - Taking account of significant depletion or destruction during the lifetime of dwarf stars (Korn et al, 2006):

$$^7Li/H = (2.75 - 4.17) \times 10^{-10}$$

Lithium Observation

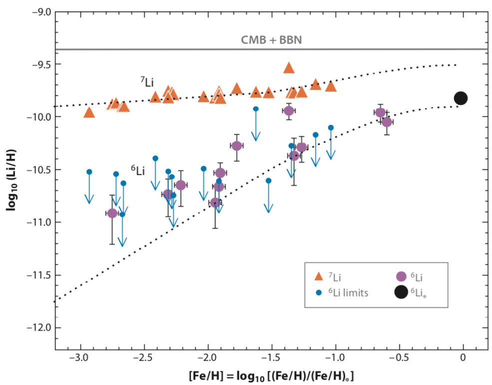

Figure: Lithium abundances in selected metal-poor Galactic halo stars. Asplund M, et al. (2006)

- The ratio of lithium to hydrogen (Li/H) is nearly independent of the ratio of iron to hydrogen (Fe/H)
- This flat trend is known as the Spite plateau.
- The horizontal band gives the CMB (WMAP) prediction; the gap between this prediction and the plateau illustrates the ^{7}Li problem

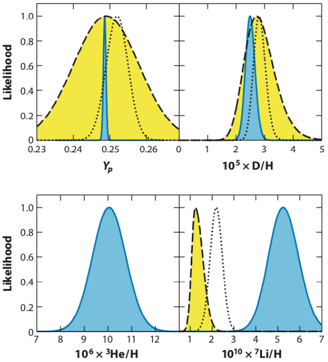

Figure: Comparison of big bang nucleosynthesis (BBN)+ WMAP predictions and observations

- *Blue curves*: the theory likelihoods predicted for standard BBN through the use of the cosmic baryon density determined by WMAP
- *Yellow curves*: the observational likelihoods based on primordial abundances.
- D is in spectacular agreement, ^{4}He is in good agreement.
- With ^{7}Li, the discrepancy is a factor of 4-5 σ.

→ Lithium Problem

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4 Proposed Solutions

Classes of Solutions

Three broad classes of possible solutions:

1. **Astrophysical solutions**: revise the measured primordial lithium abundance.
2. **Nuclear Physics**: alter the reaction flow into and out of mass-7.
3. **Solutions beyond the Standard Model**: invoke new particle physics or nonstandard cosmological physics.

Section 4.1

Astrophysical Solutions

Astrophysical Solutions

Assumptions:

- Validity of standard cosmology and particle physics
- Accurate calculations of mass-7 production in nuclear physics.

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? *What if it's not exactly this way?*

Ionization Correction

The 670.8nm lithium line used in measurements is sensitive to neutral Li^0, but lithium in most stars of interest is mostly singly ionized.

$\rightarrow$ Ionization correction Li^+ / Li^0 must be introduced.

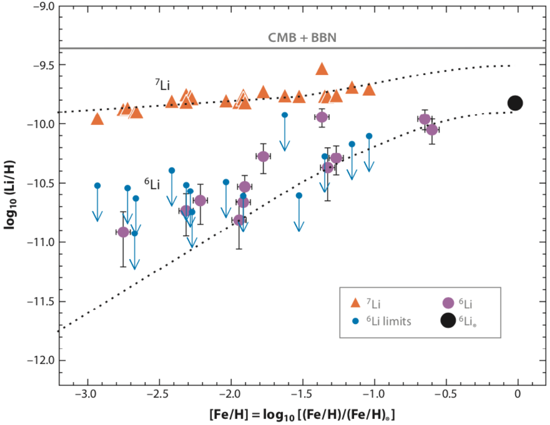
$$\boxed{\frac{n_{i+1}}{n_i} = \frac{2}{n_e}\frac{(2\pi m_e kT)^{3/2}}{h^3}\frac{g_{i+1}}{g_i}e^{-\chi/kT}} \tag{5}$$

$\rightarrow$ **T** $\uparrow$ $\rightarrow$ **Lithium abundances** $\uparrow$ $\rightarrow$ **Closer to predictions!**

In practice, however, it's challenging to accurately determine stellar temperatures...

Lithium destruction in stellar structure and evolution: convection, turbulence, diffusion, etc.

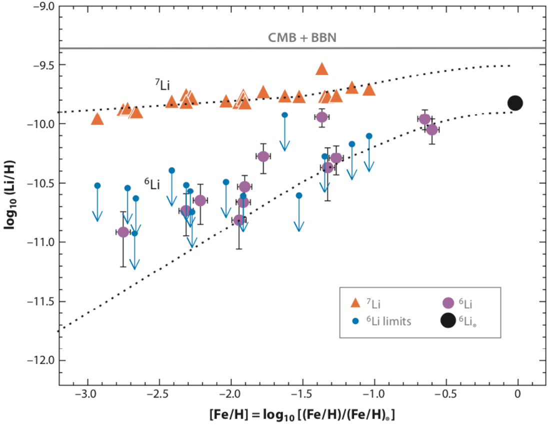
- However, no variations in abundances of different stars in Spite plateau.
- Still, O. Richard et al. (2005): metallicity dependence in the Li abundance → presence of lithium processing on the surface.



Present vs Initial Abundances

Recent works: little variation after destroying lithium abundance by

- O. Richard et al. (2005): turbulence.
- X. Fu et al. (2015): convective overshooting.



Possibility of Astrophysical Solutions?

- Observational status of primordial lithium abundance is uncertain.
- Astrophysical explanations are still possible, although with constraints.
  $\rightarrow$ There might not be an astrophysical solution.
  $\rightarrow$ Exploration of alternative explanations!

Section 4.2

Nuclear Solutions

Assumptions:

- Accurate measurement of primordial lithium.
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? Errors in BBN predictions?

→ Complicated physics due to large nuclear networks

→ There might be *"weak links"* in the standard BBN calculation.

New and Revised Reactions

Possibilities:

- Cross sections of the know important reactions have uncertainties far beyond the quoted errors.
- Cross sections for normally unimportant reactions have been underestimated.
- Incorrect rates of reactions.
- Missing reactions.

1. **Dominant reaction of mass 7 nuclides production:**

$$\boxed{{}^{3}He(\alpha, \gamma)^{7}Be} \tag{6}$$

— Error budget in cross section is small: $\sim 7\%$ (Cyburt RH, Davids B 2008), but absolute cross sections are hard to measure.

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2. Corrections to **weak interaction rates** are too small to impact lithium abundances ($\lesssim 1\%$).

New and Revised Reactions

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New and Revised Reactions

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4. **New reactions?** Boyd et al. (2010) considered a large set of previously neglected reactions - mostly **nonresonant**
   - Allowing extremely large uncertainties in known cross section, most remain unimportant.
   - *Loophole here:* what about **resonances?**

Resonances

Presence of new or poorly measured resonances:

- **(13)** $^{7}\mathrm{Be} + d \to {}^{9}\mathrm{B}^{*}$ (16.71 MeV) could play a more significant role.
- **(14)** $^{7}\mathrm{Be} + t \to {}^{10}\mathrm{B}^{*}$ in present uncertainties could be significant.
- **(15)** $^{7}\mathrm{Be} + {}^{3}\mathrm{He} \to {}^{10}\mathrm{C}^{*}$ could bring cosmic lithium in line with observations if reaction widths are large enough.

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Recent developments:

- S. Hayakawa, et al. (2019), S. Hayakawa, et al. (2019): these resonances help but do not solve the problem.
- C. Iliadis and A. Coc (2020): highly unlikely for the cosmological lithium problem to have a nuclear physics solution.

Section 4.3

Solutions beyond the Standard Model

Cosmological Solutions

The most DRAMATIC class of solutions!

Assumptions:

- Correct measurement of primordial lithium.
- Correct calculations of nuclear physics of BBN.

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$\rightarrow$ Revisit standard BBN calculations: **beyond** Standard Model of particle physics **and/or** standard cosmology!

Dark Matter Decay and SUSY

- Weakly Interacting Massive Particles (WIMPS) - dark matter candidates.
- Probably end points of a decay cascade from heavier particles.
- If decays occur during/after BBN $\rightarrow$ interact with light elements $\rightarrow$ affecting abundances!

- Consider massive particle X ($m_X \gg m_p$) decaying with lifetime τ_X.
- Decay products - high energy nucleons N interact with light elements via fragmentation.

$$N + {}^4\mathrm{He} \rightarrow \begin{cases} 2n + 2p + N \\ d + d + N \\ d + {}^3\mathrm{A} \\ \dots \end{cases} \tag{7}$$

$$n + {}^7\mathrm{Be} \rightarrow p + {}^7\mathrm{Li} \tag{8}$$

Lower Coulomb barrier of ^{7}Li $\rightarrow$ Destruction of mass-7 nuclei $\uparrow$
$\rightarrow$ Predictions closer to observations!

Dark Matter Decay and SUSY

Production of secondary neutrons:

$$N + {}^4\mathrm{He} \to \begin{cases} 2n + 2p + N \\ d + d + N \\ d + {}^3\mathrm{A} \\ \ldots \end{cases}$$

Mass-7 destruction via ^{7}Be-to-^{7}Li conversion:

$$n + {}^7\mathrm{Be} \to p + {}^7\mathrm{Li}$$

All constraints satisfied except for D/H.

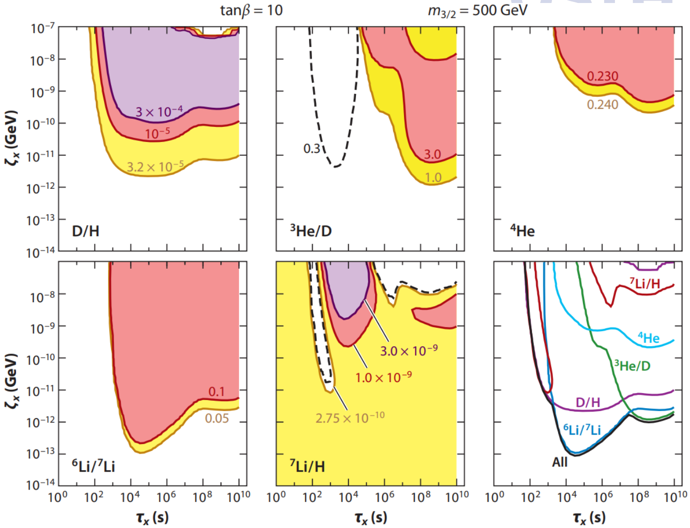

Figure: Abundance contours vs decay lifetime (Cyburt RH et al. 2010)

Supersymmetry: Dark matter candidate - Lightest Supersymmetric Particle (LSP).

- Cyburt RH et al. (2010): Consider present LSP to be decay daughter of spin-3/2 gravitino → Compute likelihood function χ^2
- Interior "islands" - optimal **trade-off between ^{7}Li destruction and deuterium production**.

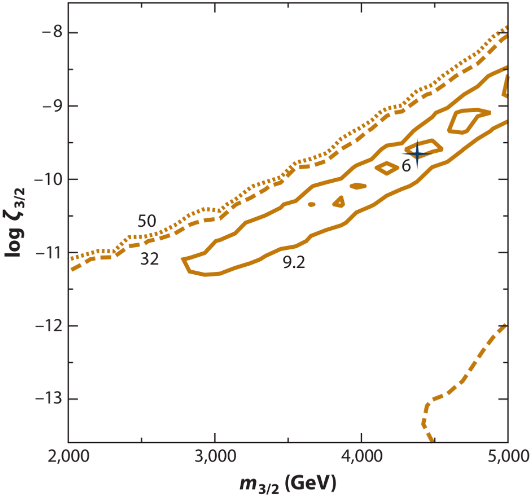

Figure: Contours of χ^2 in the (mass, abundance) plane

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→ Possible solution!

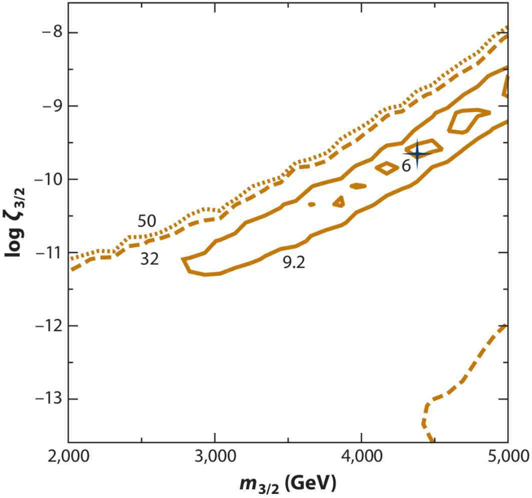

Figure: Contours of χ^2 in the (mass, abundance) plane

Dark Matter Decay and SUSY

Basically, this is **promising area** for further research!

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Although, recent results from the ATLAS experiment (2020) excluded many supersymmetric models...

Changing Fundamental Constants

Observation: variations in fine-structure constant α_{EM} at z ~ 3.

- Some unified theories suggest time variations in low-energy physics $\rightarrow$ affecting all SM couplings and particle masses.
- Alternative approach from Coc et al. (2007): changes in nuclear physics parameters $\rightarrow$ Most sensitive parameter is deuteron binding energy B_D. $-0.075 \lesssim \delta B_D/B_D \lesssim -0.04$ can solve lithium problem!

- Proposal: cosmic acceleration due to large-scale density inhomogeneities with varying baryon-to-photon ratio.

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  Regis & Clarkson: observations of ^{7}Li are made locally (low z); D/H and CMB are measured at high z.

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  - Local ^{7}Li <prediction,
  - D/H agrees.
- However, there are lots of contraints and contradictions in observations.

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- Nuclear experiments are focusing on refining the nuclear inputs to BBN. Present facilities are close to testing known or proposed resonances that could impact 7 Be destruction, allowing for a comprehensive understanding of standard BBN.

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5 Conclusion

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- Nuclear experiments are focusing on refining the nuclear inputs to BBN. Present facilities are close to testing known or proposed resonances that could impact 7 Be destruction, allowing for a comprehensive understanding of standard BBN.
- Collider and dark matter experiments, such as the LHC, can either discover supersymmetry and revolutionize particle physics & cosmology, or fails to find supersymmetry and uncovers other surprises. Either way, we would be able to further understand the early universe.

Q&A

Thank you for listening!
Your feedback will be highly appreciated!

A new determination of the primordial He abundance using the He I λ10830 Å emission line: cosmological implications

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ABSTRACT

We present near-infrared (NIR) spectroscopic observations of the high-intensity He I λ10830 Å emission line in 45 low-metallicity H II regions. We combined these NIR data with spectroscopic data in the optical range to derive the primordial He abundance. The use of the He I λ10830 Å line, the intensity of which is very sensitive to the density of the H II region, greatly improves the determination of the physical conditions in the He^+ zone. This results in a considerably tighter Y–O/H linear regression compared to all previous studies. We extracted a final sample of 28 H II regions with Hβ equivalent width EW(Hβ) $\geq$ 150 Å, excitation parameter $O^{2+}/O \geq 0.8$, and with helium mass fraction Y derived with an accuracy better than 3 per cent. With this final sample we derived a primordial ^{4}He mass fraction $Y_p = 0.2551 \pm 0.0022$. The derived value of Y_p is higher than the one predicted by the standard big bang nucleosynthesis model. Using our derived Y_p together with D/H $= (2.53 \pm 0.04) \times 10^{-5}$, and the χ^2 technique, we found that the best agreement between these light element abundances is achieved in a cosmological model with a baryon mass density $\Omega_b h^2 = 0.0240 \pm 0.0017$ (68 per cent confidence level, CL), $\pm$ 0.0028 (95.4 per cent CL), $\pm$ 0.0034 (99 per cent CL) and an effective number of neutrino species $N_{eff} = 3.58 \pm 0.25$ (68 per cent CL), $\pm$ 0.40 (95.4 per cent CL), $\pm$ 0.50 (99 per cent CL). A non-standard value of N_{eff} is preferred at the 99 per cent CL, implying the possible existence of additional types of neutrino species.

Appendix A

The effects of He I λ10830 on helium abundance determinations

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Abstract. Observations of helium and hydrogen emission lines from metal-poor extragalactic H II regions, combined with estimates of metallicity, provide an independent method for determining the primordial helium abundance, Y_p. Traditionally, the emission lines employed are in the visible wavelength range, and the number of suitable lines is limited. Furthermore, when using these lines, large systematic uncertainties in helium abundance determinations arise due to the degeneracy of physical parameters, such as temperature and density. Recently, Izotov, Thuan, & Guseva (2014) have pioneered adding the He I λ10830 infrared emission line in helium abundance determinations. The strong electron density dependence of He I λ10830 makes it ideal for better constraining density, potentially breaking the degeneracy with temperature. We revisit our analysis of the dataset published by Izotov, Thuan, & Stasińska (2007) and incorporate the newly available observations of He I λ10830 by scaling them using the observed-to-theoretical Paschen-gamma ratio. The solutions are better constrained, in particular for electron density, temperature, and the neutral hydrogen fraction, improving the model fit to data, with the result that more spectra now pass screening for quality and reliability, in addition to a standard 95% confidence level cut. Furthermore, the addition of He I λ10830 decreases the uncertainty on the helium abundance for all galaxies, with reductions in the uncertainty ranging from 10–80%. Overall, we find a reduction in the uncertainty on Y_p by over 50%. From a regression to zero metallicity, we determine Y_p = 0.2449 ± 0.0040, consistent with the BBN result, Y_p = 0.2470 ± 0.0002, based on the Planck

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Deuterium abundance in the most metal-poor damped Lyman alpha system: converging on $\Omega_{b,0}h^2$

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ABSTRACT

The most metal-poor damped Lyα system known to date, at $z_{abs} = 2.61843$ in the spectrum of the QSO Q0913+072, with an oxygen abundance of only $\sim$1/250 of the solar value, shows six well-resolved D I Lyman series transitions in high-quality echelle spectra recently obtained with the European Southern Observatory (ESO) VLT. We deduce a value of the deuterium abundance $\log(D/H) = -4.56 \pm 0.04$ which is in good agreement with four out of the six most reliable previous determinations of this ratio in QSO absorbers. We find plausible reasons why in the other two cases the 1σ errors may have been underestimated by about a factor of two. The addition of this latest data point does not significantly change the mean value of the primordial abundance of deuterium, suggesting that we are now converging to a reliable measure of this quantity. We conclude that $\langle \log(D/H)_p \rangle = -4.55 \pm 0.03$ and $\Omega_{b,0}h^2(BBN) = 0.0213 \pm 0.0010$ (68 per cent confidence limits). Including the latter as a prior in the analysis of the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) five-year data leads to a revised best-fitting value of the power-law index of primordial fluctuations $n_s = 0.956 \pm 0.013$ (1σ) and $n_s < 0.990$ with 99 per cent confidence. Considering together the constraints provided by *WMAP 5*, $(D/H)_p$, baryon oscillations in the galaxy distribution, and distances to Type Ia supernovae, we arrive at the current best estimates $\Omega_{b,0}h^2 = 0.0224 \pm 0.0005$ and $n_s = 0.959 \pm 0.013$.

PRECISION MEASURES OF THE PRIMORDIAL ABUNDANCE OF DEUTERIUM*

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ABSTRACT

We report the discovery of deuterium absorption in the very metal-poor ([Fe/H] $= -2.88$) damped Lyα system at $z_{\rm abs} = 3.06726$ toward the QSO SDSS J1358+6522. On the basis of 13 resolved D I absorption lines and the damping wings of the H I Lyα transition, we have obtained a new, precise measure of the primordial abundance of deuterium. Furthermore, to bolster the present statistics of precision D/H measures, we have reanalyzed all of the known deuterium absorption-line systems that satisfy a set of strict criteria. We have adopted a blind analysis strategy (to remove human bias) and developed a software package that is specifically designed for precision D/H abundance measurements. For this reanalyzed sample of systems, we obtain a weighted mean of $({\rm D/H})_{\rm p} = (2.53 \pm 0.04) \times 10^{-5}$, corresponding to a universal baryon density $100\,\Omega_{\rm b,0}\,h^2 = 2.202 \pm 0.046$ for the standard model of big bang nucleosynthesis (BBN). By combining our measure of $({\rm D/H})_{\rm p}$ with observations of the cosmic microwave background (CMB), we derive the effective number of light fermion species, $N_{\rm eff} = 3.28 \pm 0.28$. We therefore rule out the existence of an additional (sterile) neutrino (i.e., $N_{\rm eff} = 4.046$) at 99.3% confidence (2.7σ), provided that the values of $N_{\rm eff}$ and of the baryon-to-photon ratio (η_{10}) did not change between BBN and recombination. We also place a strong bound on the neutrino degeneracy parameter, independent of the ^{4}He primordial mass fraction, $Y_{\rm P}$: $\xi_{\rm D} = +0.05 \pm 0.13$ based only on the CMB+$({\rm D/H})_{\rm p}$ observations. Combining this value of $\xi_{\rm D}$ with the current best literature measure of $Y_{\rm P}$, we find a 2σ upper bound on the neutrino degeneracy parameter, $|\xi| \leqslant +0.062$.

Key words: cosmology: observations – primordial nucleosynthesis – quasars: absorption lines

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