Big-bang nucleosynthesis:

Its role in cosmology and its problem with lithium

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Possibility of big-bang related research at Phase I SARAF
μWorkshop
Soreq Nuclear Research Center
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The hot big bang model

The universe started out in a hot and dense state

If not an actual spacetime singularity, perhaps an exit from inflation followed by "reheating" to T well above the electroweak scale

Space has been expanding and its contents cooling ever since

Expansion is dictated by general relativity ("cosmological" solutions aren't static)

Cooling is dictated by expansion

Big bang nucleosynthesis (BBN) in context

Baryogenesis left a signature – nonzero baryon density with no antibaryons – but it is just a number

Inflation left density perturbations that so far look like a featureless power law (dramatic developments are possible from CMB)

Most information about cosmology comes from times after BBN:

Propagation of baryon/photon sound waves between matter/radiation equality ($z \sim 3200$) and CMB last scatter ($z \sim 1100$)

Expansion rate since $z \sim 4$ (this year's Nobel Prize)

Spatial distribution of galaxies & their clusters – growth of structure probes the "background" cosmology

Big bang nucleosynthesis (BBN) in context

The new situation is very different from the old “three pillars of cosmology”

An army is now determining the parameters that characterize our universe and its evolution: $\Omega_B h^2$, $\Omega_{\rm CDM} h^2$, Ω_Λ, $\Delta^2_{\mathcal{R}}$, n_s, τ, A_{SZ}, t_0, r, $N_{\rm eff}$, $\ldots$

BBN is no longer the main measure of the mean baryon density $\Omega_B h^2 = 8\pi G \rho_B / 3$

Speculative particle theory has also moved on – BBN used to constrain weird ideas with MeV-scale (energy) or minute-scale (time) consequences

Still, BBN provides the most direct check that the standard cosmology works at those energy/time scales

It is also a source of very precise predictions (0.5% to 10%) from the standard model

Ingredients of modern BBN

1. General relativity

Friedmann-Robertson-Walker metric

$$ds^2 = dt^2 - [R(t)]^2 \left[\frac{dr^2}{1 - kr^2} + r^2 d\Omega^2 \right]$$

describes homogeneous & isotropic universe, sizes scale with $R(t)$

Insertion into Einstein equations gives the expansion rate

$$\left(\frac{R'(t)}{R(t)} \right)^2 = \frac{8\pi G}{3} \rho$$

with $\rho = \rho_B + \rho_\gamma + \rho_\nu + \rho_e + \cdots$

In minimal model, densities are assumed homogeneous (doesn't matter much)

Ingredients of modern BBN

2. Statistical mechanics of Fermi & Bose gases

$$\rho = \frac{g}{8\pi^3}\int \frac{E}{\exp\left[(E-\mu)/kT\right]\pm 1} d^3p$$

Initial conditions are assumed to be equilibrium at a well-defined T

Each species (baryons, photons, electrons, 3 neutrino flavors) evolves at a well-defined temperature

T declines during isentropic expansion, since $\rho_x \propto R^{-4}$ for $m \ll kT$ (γ, ν) and $\rho_x \propto R^{-3}$ for $m \gtrsim kT$

Heat can be exchanged between species – when $e^{\pm}$ annihilate mostly into photons ($T \sim 500$ keV), almost no energy goes to ν

Relativistic species with $E \sim p$ dominate until long after BBN

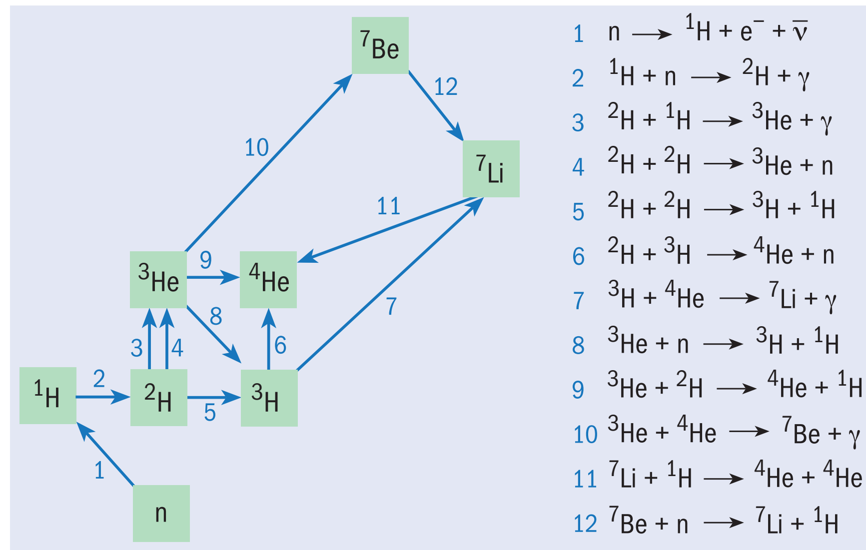
Ingredients of BBN

3. Nuclear cross sections

Abudance evolution proceeds through nuclear collisions

Cross sections are mainly empirical

Only 12 processes matter*



Calculations with huge reaction networks and nuclei to CNO region have been done

Weak $p+l \leftrightarrow n+\bar{l}$ processes are all normalized to neutron lifetime & computed from weak-interaction physics

BBN in three easy steps

At temperatures above $T \sim 10^{10}$ K, the ratio of neutrons to protons is governed by equilibrium enforced by weak interactions:

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

and "crossed" diagrams

Nucleosynthesis starts at $T \sim 10^{10}$ K, when the rates for processes maintaining equilibrium become slower than the universal expansion

The neutron/proton ratio freezes out at

$$\frac{n_n}{n_p} = \exp[-(m_n - m_p)/kT] \sim \frac{1}{7}$$

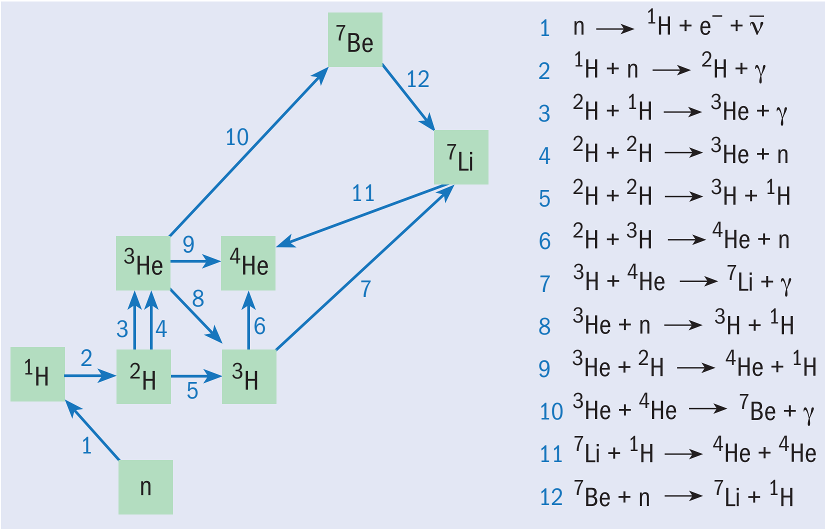
followed by free neutron decay

This is Weak Freezeout

BBN in three easy steps

At the time of weak freezeout, relative amounts of light nuclei are in Nuclear Statistical Equilibrium (NSE)

Almost all nucleons are free, small amounts of D, ^{3}He, ^{3}H, and ^{4}He



Dropping T gradually favors $A = 3$ and 4

At $\sim$ 5 minutes, almost all neutrons are in ^{4}He (large per-particle binding energy)

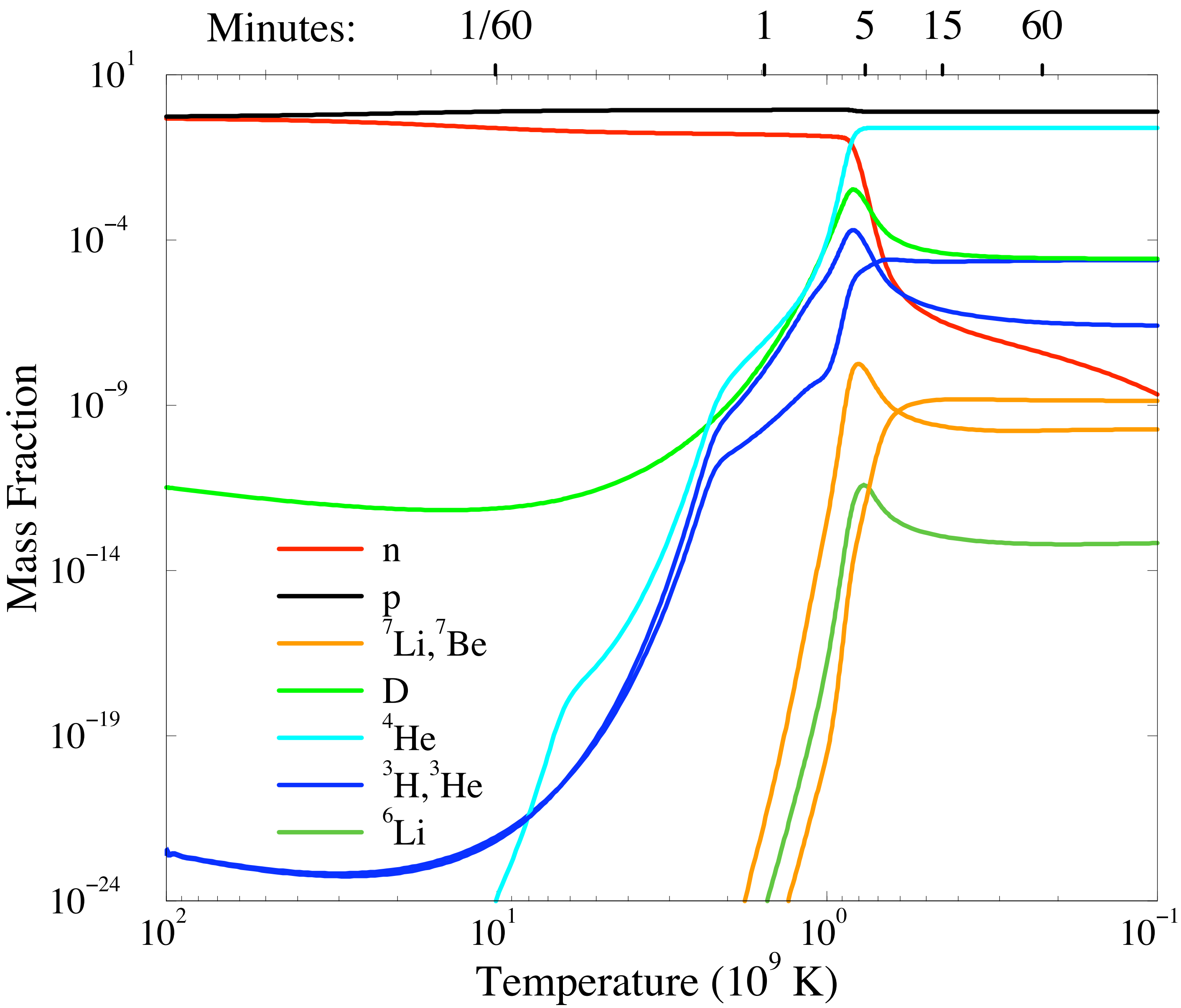
Low ρ and T, Coulomb barriers, disappearance of neutrons, fragility to proton reactions, and lack of stable $A = 5, 8$ nuclei all cause Final Freezeout

BBN in a nutshell

1. Weak Freezeout
   (∼ 1 second)

2. Statistical equilibrium & quasi-equilibrium
   (∼ 1 second
   to 5 minutes)

3. Final Freezeout
   (> 5 minutes)



The “Schramm plot”

Yields depend on one variable, n_B/n_γ (already true for Alpher, Follin, Herman)

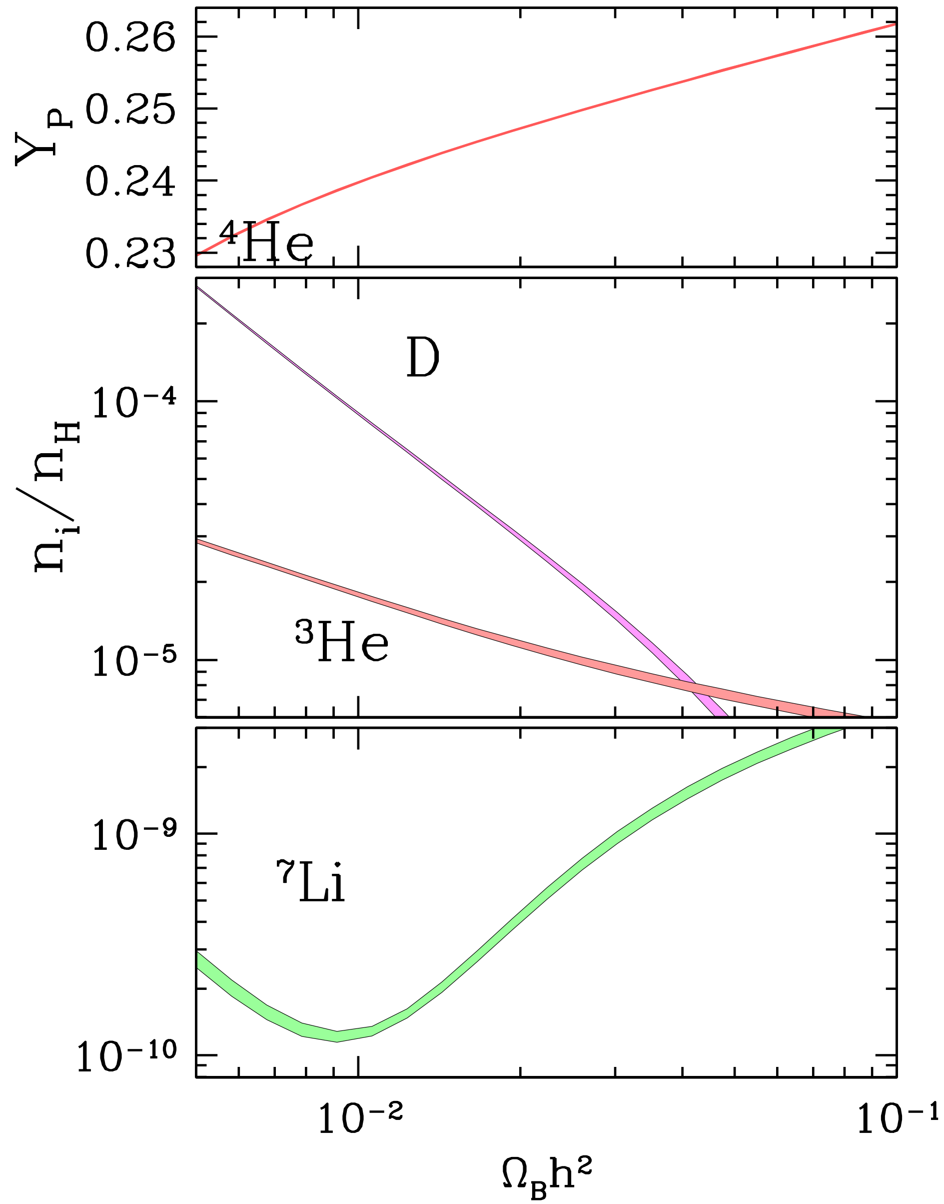
Conventional units are $\Omega_B \equiv \rho_B/\rho_{\text{crit}}$

$\Omega_B h^2 =$
$8\pi G\rho_B/(300 \text{ km s}^{-1} \text{ Mpc}^{-1})$

$h \sim 0.7$ is Hubble’s constant in customary units, so $h^2 \sim 1/2$

Widths of curves reflect nuclear inputs

Need to find matter that has not been processed post-BBN



BBN today

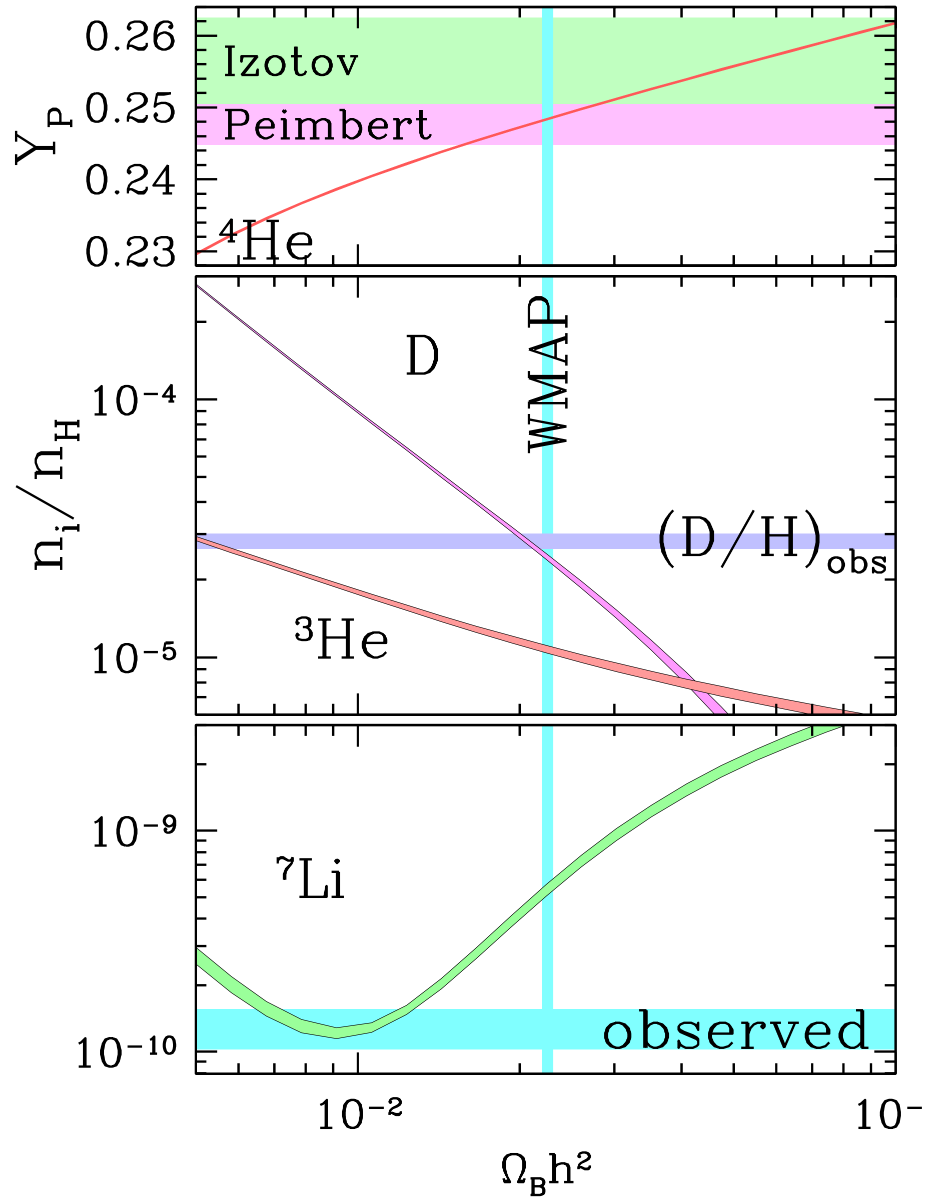
Questions:

Are the primordial abundances consistent with the rest of cosmology?

Cosmology no longer has 3 simple pillars

"ΛCDM" or "concordance model" from many data: expansion rate, galaxy distributions, CMB, quasar absorbtion lines, etc.

With 2% precise $\Omega_B h^2$ from CMB, BBN gives very precise predictions



Deviations teach about particle physics, cosmology, stellar evolution, model atmospheres... unfortunately non-independently

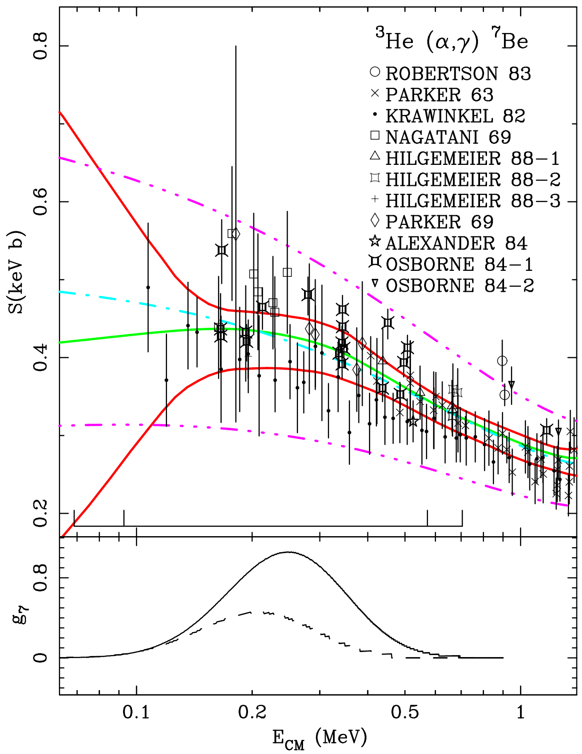
BBN post-WMAP: Precise Li/H predictions

With $\Omega_B h^2$ from the WMAP experiment (CMB), ^{4}He is predicted to 0.5%, D & ^{3}He to $\sim$ 5%

Lithium prediction has improved in the past 10 years – all goes through $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$

Some inconsistency remains, but overall precision went from $\sim$ 10% to 7%

From



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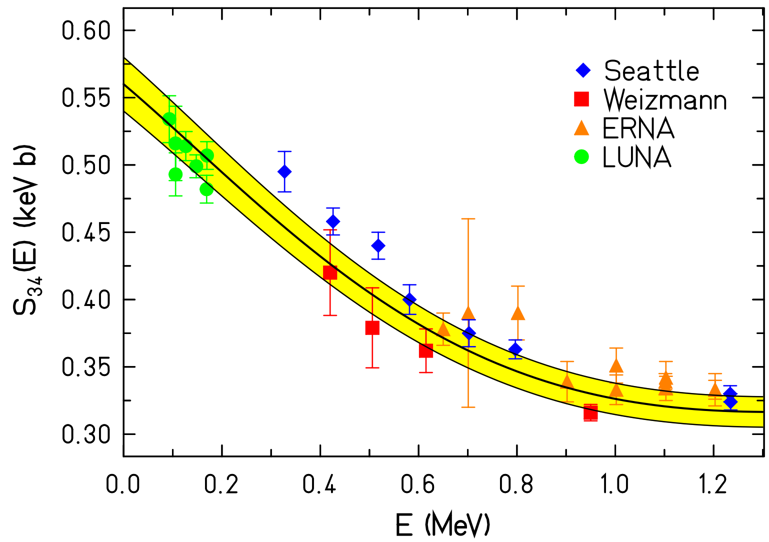


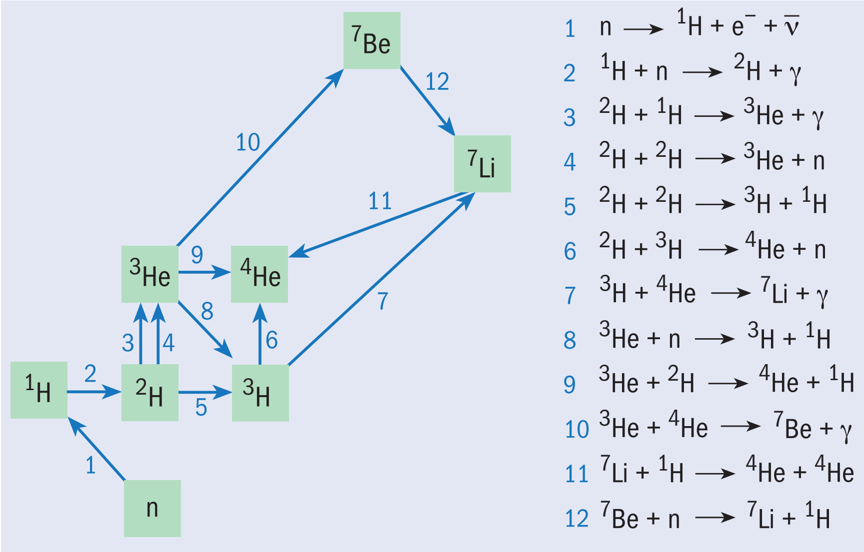
Prediction is $\mathrm{Li/H} = (5.5 \pm 0.6) \times 10^{-10}$, only 2% from $\Omega_B h^2$

BBN post-WMAP: Room for improvement in Li/H

Only one of the 12 known important rates destroys ^{7}Li at $\Omega_B h^2 = 0.0226$

Actually ^{7}Be is destroyed via $^7\text{Be}(n,p)^7\text{Li}(p,\alpha)^4\text{He}$

That rate is pretty well known & does not dominate the BBN error budget



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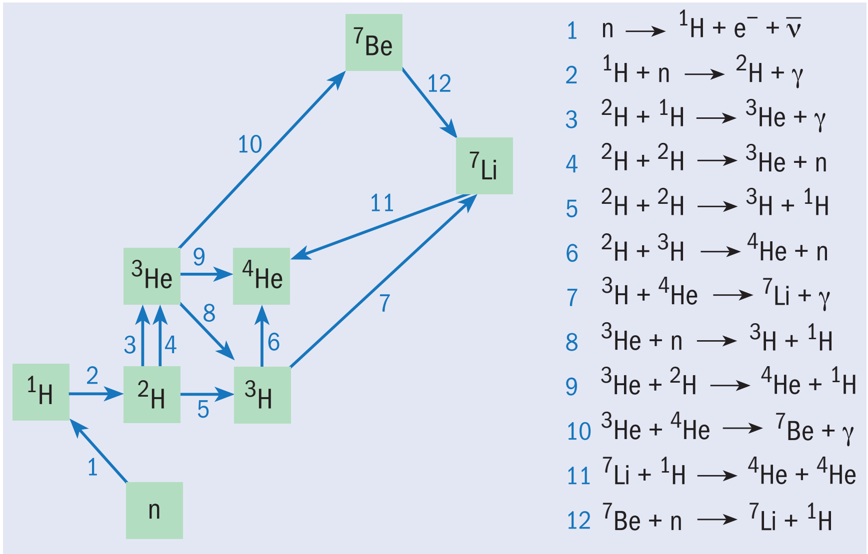


Actually ^{7}Be is destroyed via $^7\mathrm{Be}(n,p)^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$

That rate is pretty well known & does not dominate the BBN error budget

But there is another rate that biases Li/H by 1% & is assigned no error in most studies

We are here to talk about $^7\mathrm{Be}(n,\alpha)^4\mathrm{He}$ and $^7\mathrm{Be}(n,\gamma\alpha)^4\mathrm{He}$

Current rate is p-wave extrapolation of a very old upper limit σ_{th}

Dividends could be large...

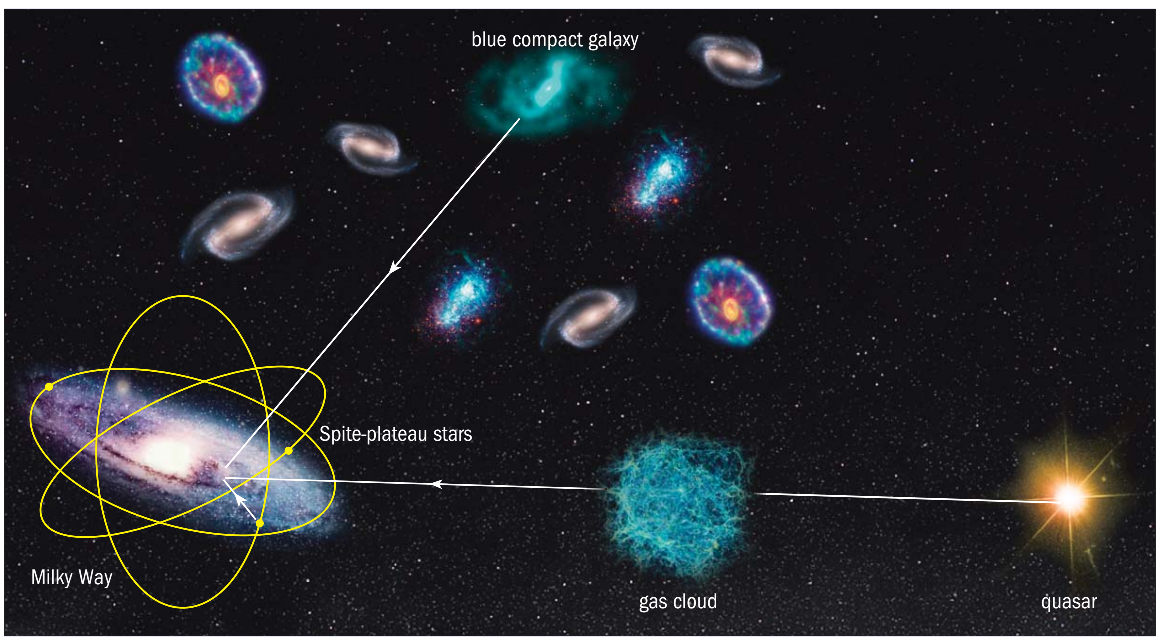
Precise theory meets less-precise measurement

Few places in the universe today preserve the primordial abundances

Stars have made a lot of other stuff (good for us!) & destroyed a lot of ^{2}H

Tests of BBN beyond the ubiquitous $Y \sim 0.25 \pm 0.05$ are difficult

Each nuclide is observed in some different place where matter is primitive & lines can be seen



^{7}Li: A puzzle in the oldest stars

$\mathrm{Li/H} \sim 10^{-10}$ is only observed in stars

Very old stars are needed: $\mathrm{Fe/H} < 0.1$ solar in outer Galaxy

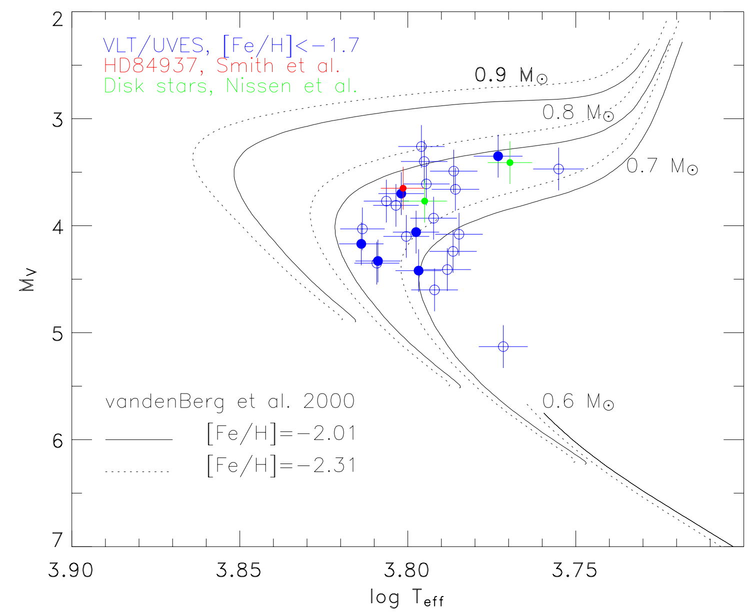
Also stars with unaltered surface abundances

Usable stars define the “Spite plateau” in T_{eff} and Fe/H

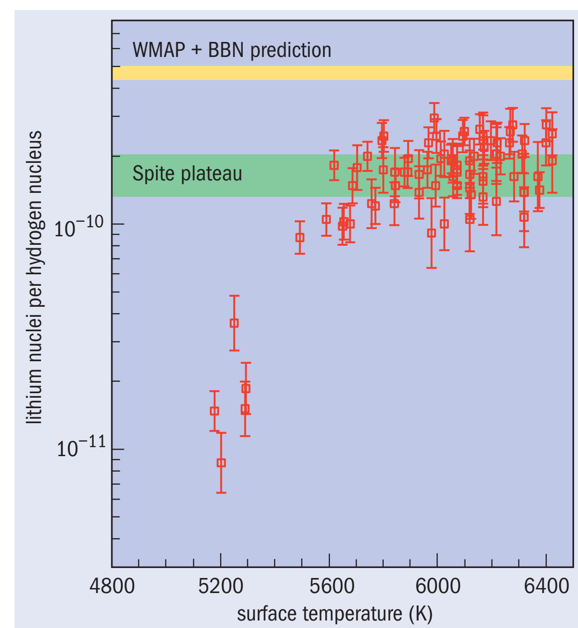
Old but on main sequence today: $M \leq 0.8 M_\odot$

Thin surface convection: largest M possible

Deeper surface convection $\longrightarrow$ ^{7}Li burns via $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$ at 2.5×10^6 K

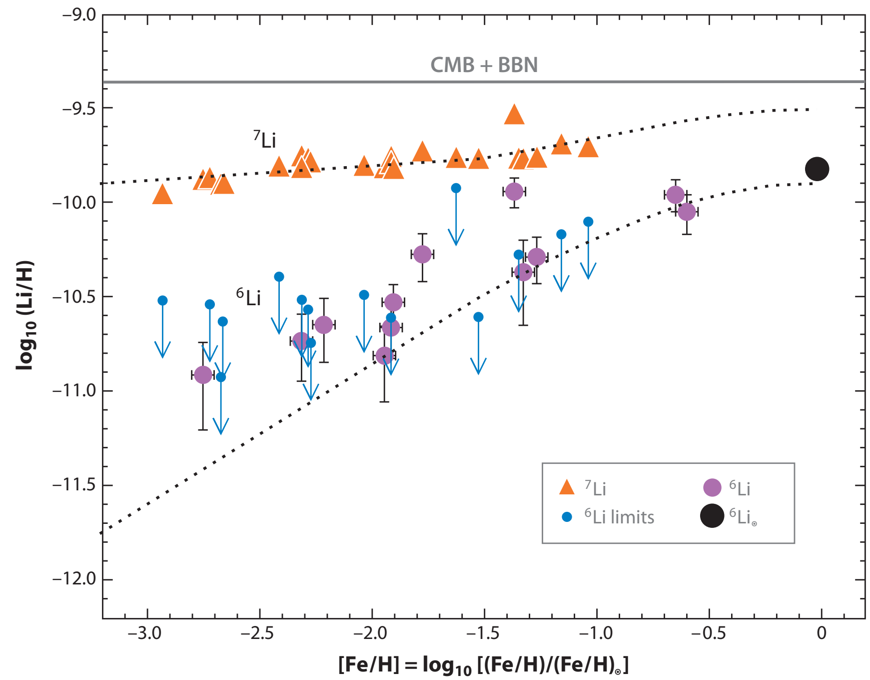


Lambert 2004



^{7}Li: A puzzle in the oldest stars

The same stars show a plateau in
Li/H vs Fe/H as $Fe/H \to 0$



Asplund 2006 via Fields 2011

The interpretation ~ 1980 was that this was
the primordial abundance

Much ink has been spilled over uniformity or
not of the plateau

It is clear from recent years that some very
low-Fe/H stars have much lower Li/H

BBN abundances from these stars requires that 1) the stars formed with primordial
Li/H and 2) surface Li has not been burned

^{7}Li: A puzzle in the oldest stars

Results for the Spite-plateau abundance have been pretty stable over time (post-2007 data missing but similar)

Authors	$A(\mathrm{Li})$	[Fe/H]
Spite & Spite 1982	2.05 ± 0.15	-2.4 to -1.1
Thorburn 1994	2.3 ± 0.2 (95%)	$\lesssim -2.2$
Ryan et al. 2000	$2.09^{+0.19}_{-0.13}$	-3.3 to -2.3
Bonifacio & Molaro 1997	2.238 ± 0.012 stat ± 0.05 sys	-3.4 to -1.5
Charbonnel & Primas 2005	2.214 ± 0.093	-3.5 to -1.5
Boesgaard et al. 2005	2.215 ± 0.110	-3.6 to -1.5
Asplund et a. 2006	2.21 ± 0.07	-3.0 to -1.0
Bonifacio et al. 2007	2.10 ± 0.09	-3.5 to -2.5

$$A(\mathrm{Li}) \equiv \log_{10}(\mathrm{Li}/\mathrm{H}) + 12$$

These works vary some in stellar-atmosphere modelling – add errors at your own risk

Two references claim significant positive slopes for $A(\mathrm{Li})$ vs [Fe/H]

^{7}Li: A puzzle in the oldest stars

From Charbonnel & Primas,

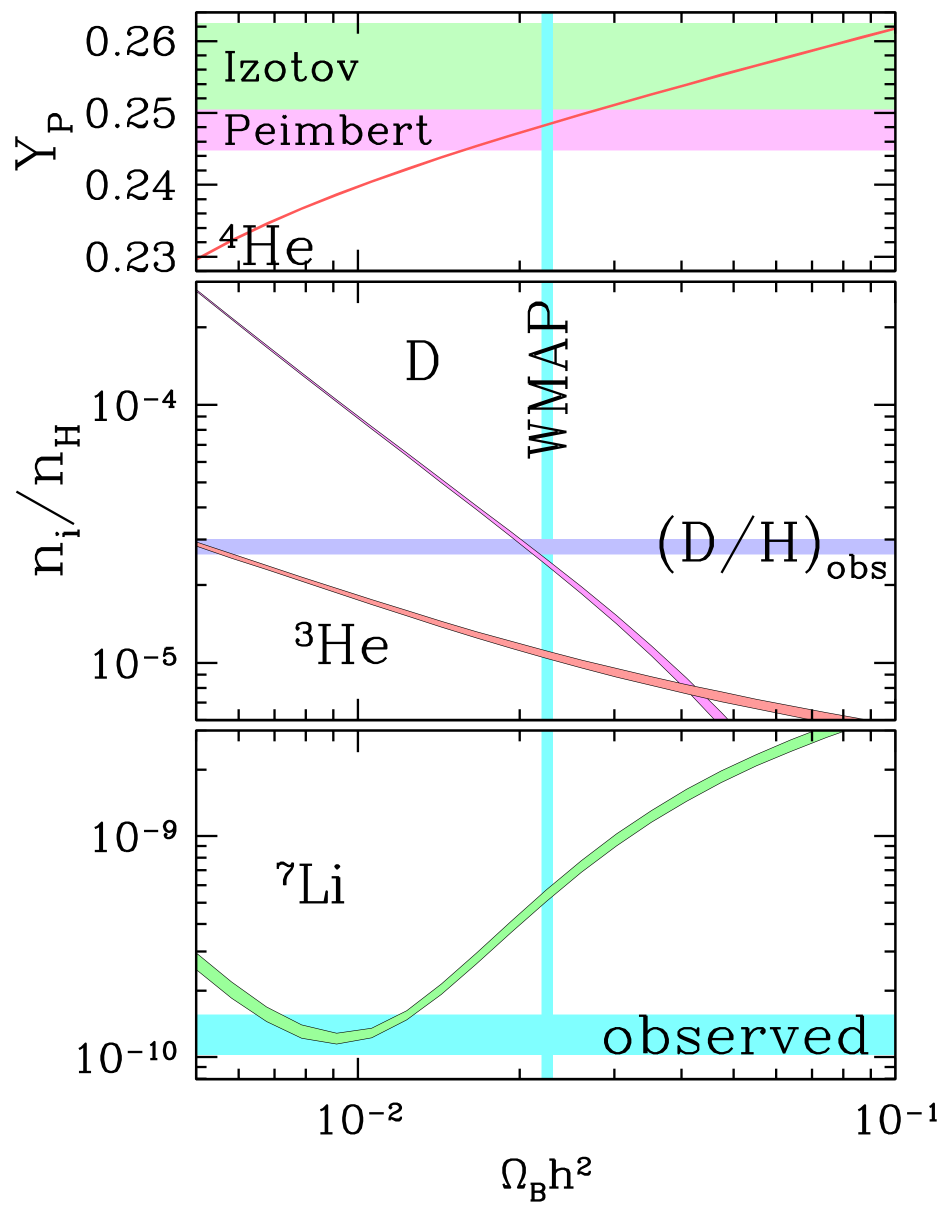
$$\mathrm{Li/H} = (1.6^{+0.4}_{-0.3}) \times 10^{-10}$$

Theory gave $(5.5 \pm 0.6) \times 10^{-10}$

Difference is something like 5σ

(factor of 3.4)

So what gives?



^{7}Li: A puzzle in the oldest stars

Bad nuclear cross sections?

The "canonical" reactions are too well measured to be factor-of-4 wrong

Some people are picking through resonance lists looking for $A = 9, 10, 11$ candidate states (Cyburt & Pospelov, Chakraborty et al.)

Few possibilities exist, not being especially vetted for nuclear physics

$^7\mathrm{Be}(d,p)^8\mathrm{Be}$ has just been completely ruled out by two measurements (one "unintentional")

It is often forgotten that $^7\mathrm{Be}(n,\alpha)^4\mathrm{Be}$ or $^7\mathrm{Be}(n,\gamma\alpha)^4\mathrm{Be}$ have never been measured at BBN energies

It seems unlikely to me that either approaches the rate of $^7\mathrm{Be}(n,p)^7\mathrm{Li}$

On the other hand, the current unfounded rate biases the prediction in some direction (1% different from leaving it out)

Maybe measurement will clear the way for a second partial solution?

^{7}Li: A puzzle in the oldest stars

Bad inference of compositions from stellar atmospheres?

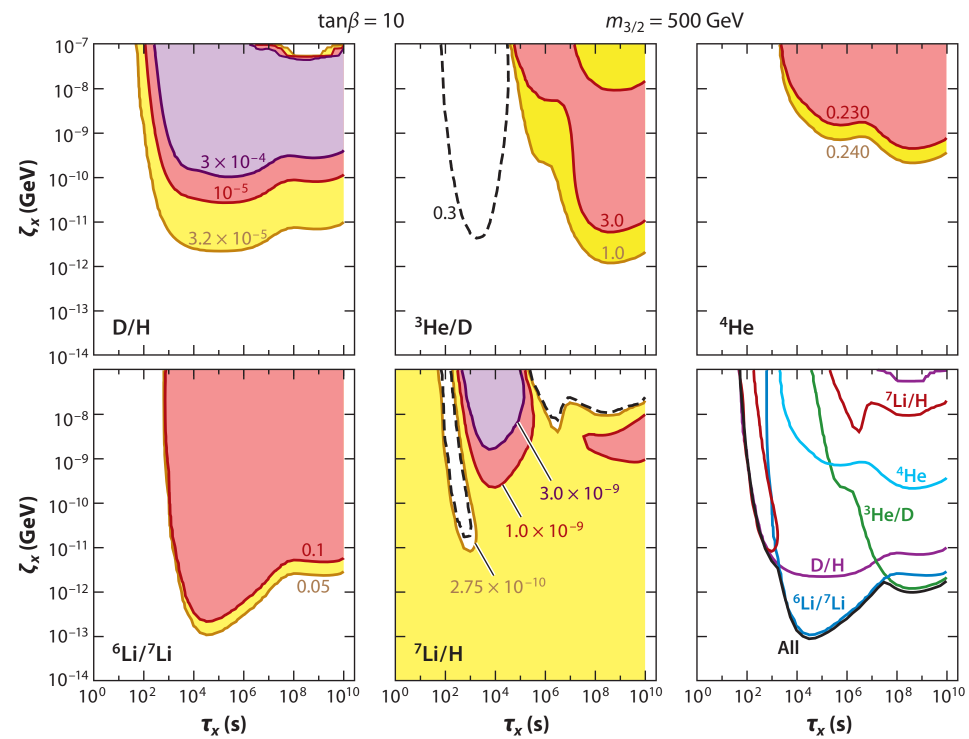
Asplund et al. 2006 found same Li/H from 610 nm Li^+ line as from 670 nm neutral line

Melendez & Ramirez made everyone unhappy with a different T_{eff} scale, only got $\Delta A(\text{Li}) = 0.15$ (need 0.54)

Breakup by decay cascade from $\tau \sim 1$ yr massive particle?

Doesn't seem to work with D – also destroyed but possibly restored by ^{4}He breakup

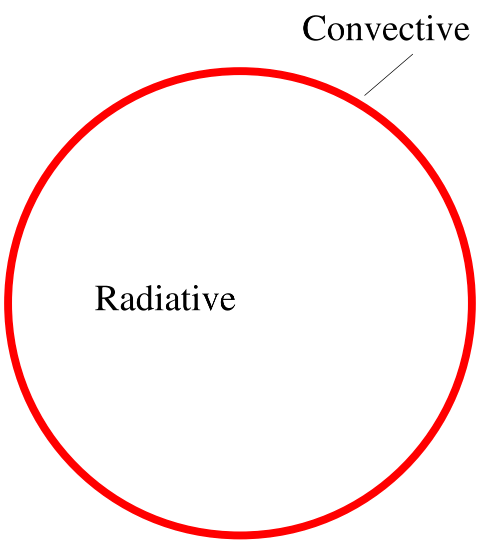
Model shown here doesn't find a balance



Fields 2011

^{7}Li: A puzzle in the oldest stars

Disappearance below the surface layers?



Plateau stars were chosen for convective envelope too thin to reach 2.5×10^6 K at the bottom

But diffusion into underlying radiative layers is possible & does happen – question is how fast

^{7}Li: A puzzle in the oldest stars

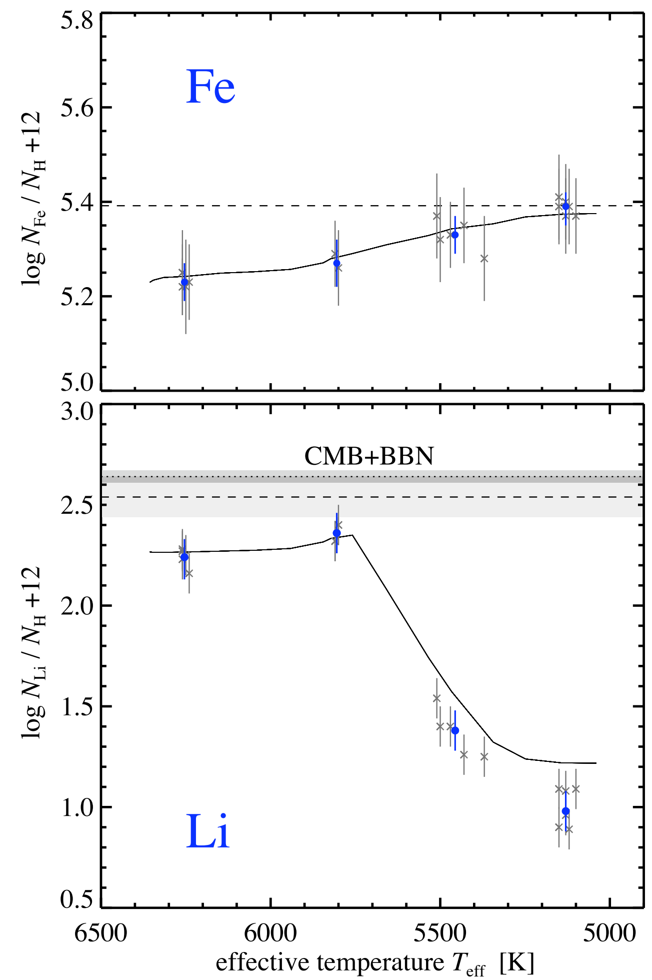
Korn et al., Charbonnel & Primas, Lind et al. all see signs of mixing

Evolution off main sequence onto giant branch "dredges up" material

Pockets of Li & other elements get exposed to surface

Models are fairly crude & not matched exactly but maybe point the way

There is some dispute as to how much of the effect is an artifact of stellar-atmosphere models



Korn et al. 2006

Mucciarelli et al. 2011 argue that amount of dredge-up dilution is known, so minimum Li/H tells you original amount

BBN and the lithium problem

Big bang nucleosynthesis remains an important part of the standard “concordance cosmology” – checks that it applies back to ~ 1 s after the Beginning

BBN makes very specific predictions about the initial composition of the universe

Making the predictions as precise as possible (to % or below) is a worthwhile enterprise

The lithium prediction is an obvious mismatch to what is observed in metal-poor stars

The field of solutions is wide open – all proposed solutions have problems

Lithium will teach us something important about one or more of the fields that intersects in BBN

BONUS MATERIAL

The ten most interesting things that ever happened (chronological order)

0. Singularity?

1. Inflation – "false vacuum" causes rapid expansion, creates density perturbations

2. Long ($\log(t/1\ \mathrm{s}) \ll -1$) succession of equilibria at $T > 1$ TeV

3. Baryogenesis – slightly more matter than antimatter

4. Nucleosynthesis – n/p ratio frozen, light nuclei assembled
   (1 s to 10 min., $z \sim 10^{11}$ to 10^{9}, $T = 1$ MeV to 10 keV)

5. Matter/radiation equality – expansion rate changes, density perturbations grow ($z \sim 3200$)

6. Matter & radiation decouple – neutral atoms, cosmic background radiation released ($z \sim 1100$)

7. Dark ages – slow cooling

8. The first stars ($z \sim 20$?)

9. Assembly of galaxies, clusters, "large scale structure" ($z \sim 3$)

10. Humans ($z \equiv 0$)