New Nuclear and Weak Physics in Big Bang Nucleosynthesis

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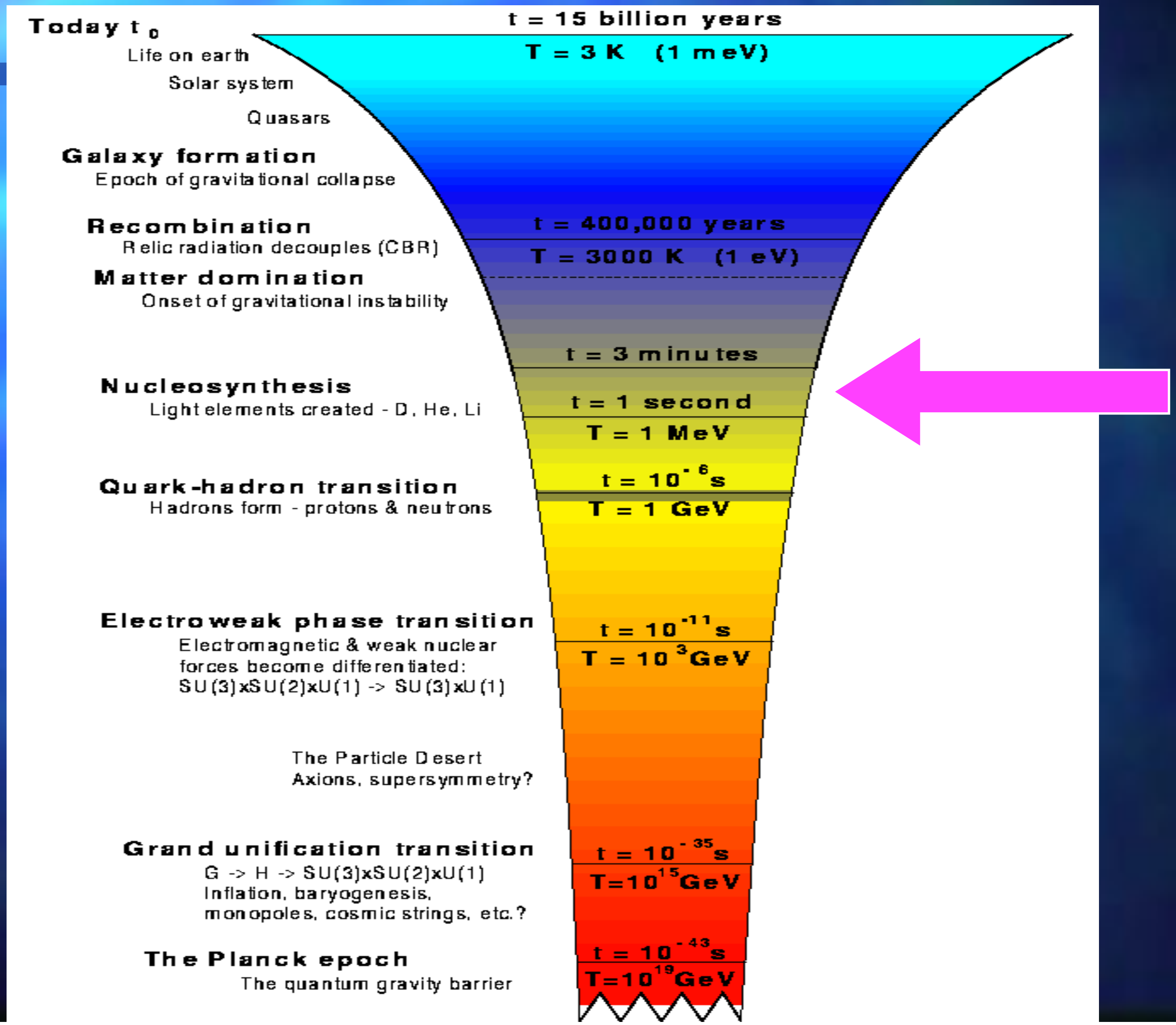
Outline

- Review of BBN
- Current status of BBN predictions & observations
- New nuclear and weak physics
- BBN in light of WMAP-7
- Constraining the heavy sterile neutrino parameter space

BBN is one of our oldest windows into the early universe



Weak Decoupling T ~ 3 MeV

- Neutrinos decouple from the universe.
- Rates for neutrino/antineutrino scattering on electrons and positrons become slow

neutrino scattering rate $\lambda_\nu \sim \left(G_F^2\, T^2\right)\left(T^3\right) = G_F^2\, T^5$

where the Fermi constant is $G_F \approx 1.166 \times 10^{-11}\ \text{MeV}^{-2}$

$$H^2 = \frac{8\pi}{3} G \left(\rho_{\text{total}}\right)$$

- Adiabatically expand

$$T_\nu = T_{decoupling} / a$$

- Retain their thermal Fermi-Dirac Shape (unless another process occurs)

$$T_\nu = (4/11)^{(1/3)} T_\gamma$$

After the neutrinos decouple…

- Continue to interact with the baryons

$$\nu_e + n \rightleftharpoons p + e^-,$$

$$\bar{\nu}_e + p \rightleftharpoons n + e^+,$$

$$n \rightleftharpoons p + e^- + \bar{\nu}_e.$$

- Weak reactions (interconvert neutrons and protons)

Weak Freeze Out

-At T ~ few MeV, rate of these reactions are fast enough that they are in chemical equilibrium so that:

$$\frac{n}{p} \approx e^{(\mu_e - \mu_{\nu_e} - \delta m_{np})/T}$$

-Eventually the universe gets cool enough that the weak rates become slow compared to the expansion rate of the universe

-This is "Weak Freeze Out"

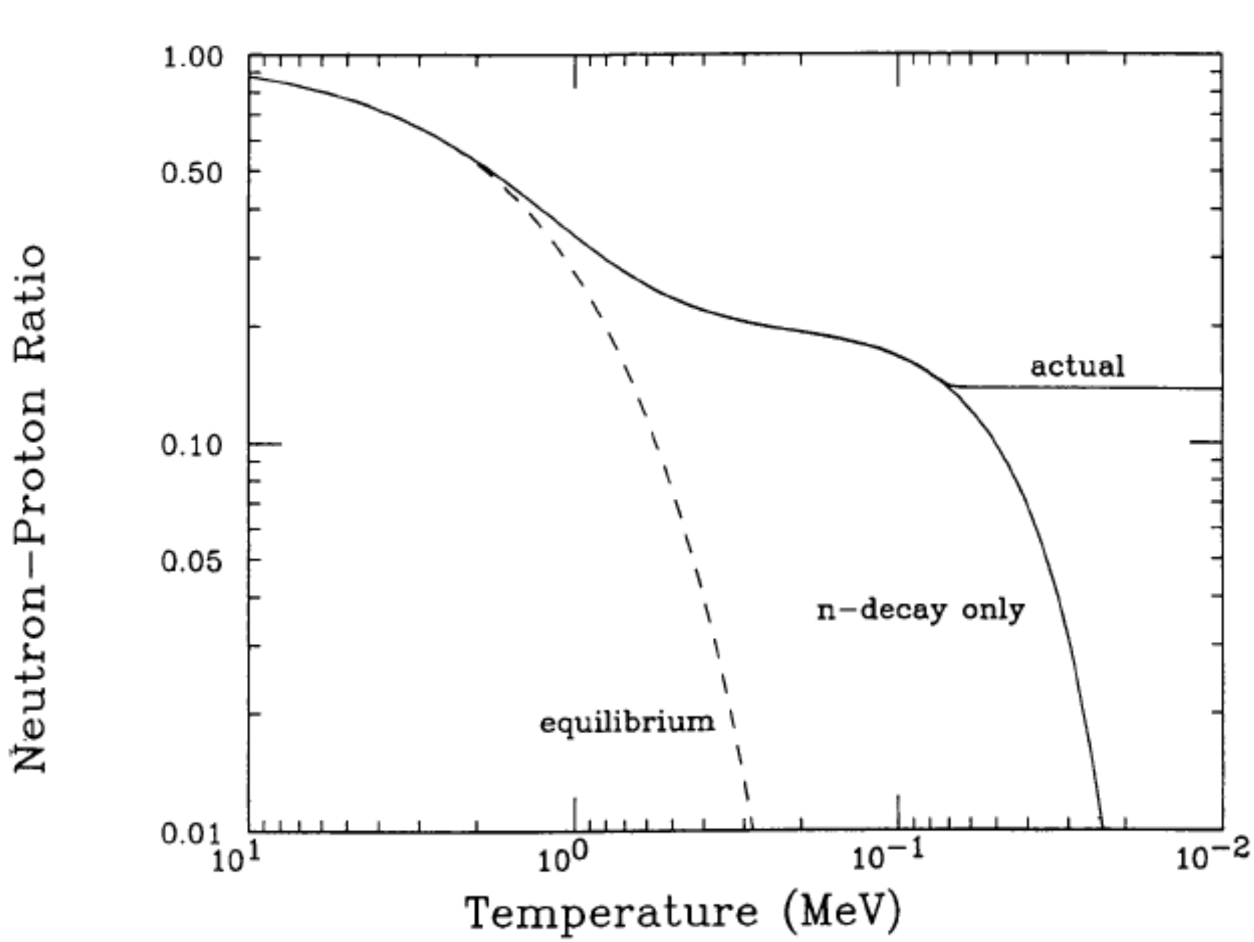
$$\lambda_{\text{weak reactions}} / H \sim (T/0.8\ \text{MeV})^3$$

Weak Freeze Out

$$\nu_e + n \rightleftharpoons p + e^-,$$

$$\bar{\nu}_e + p \rightleftharpoons n + e^+,$$

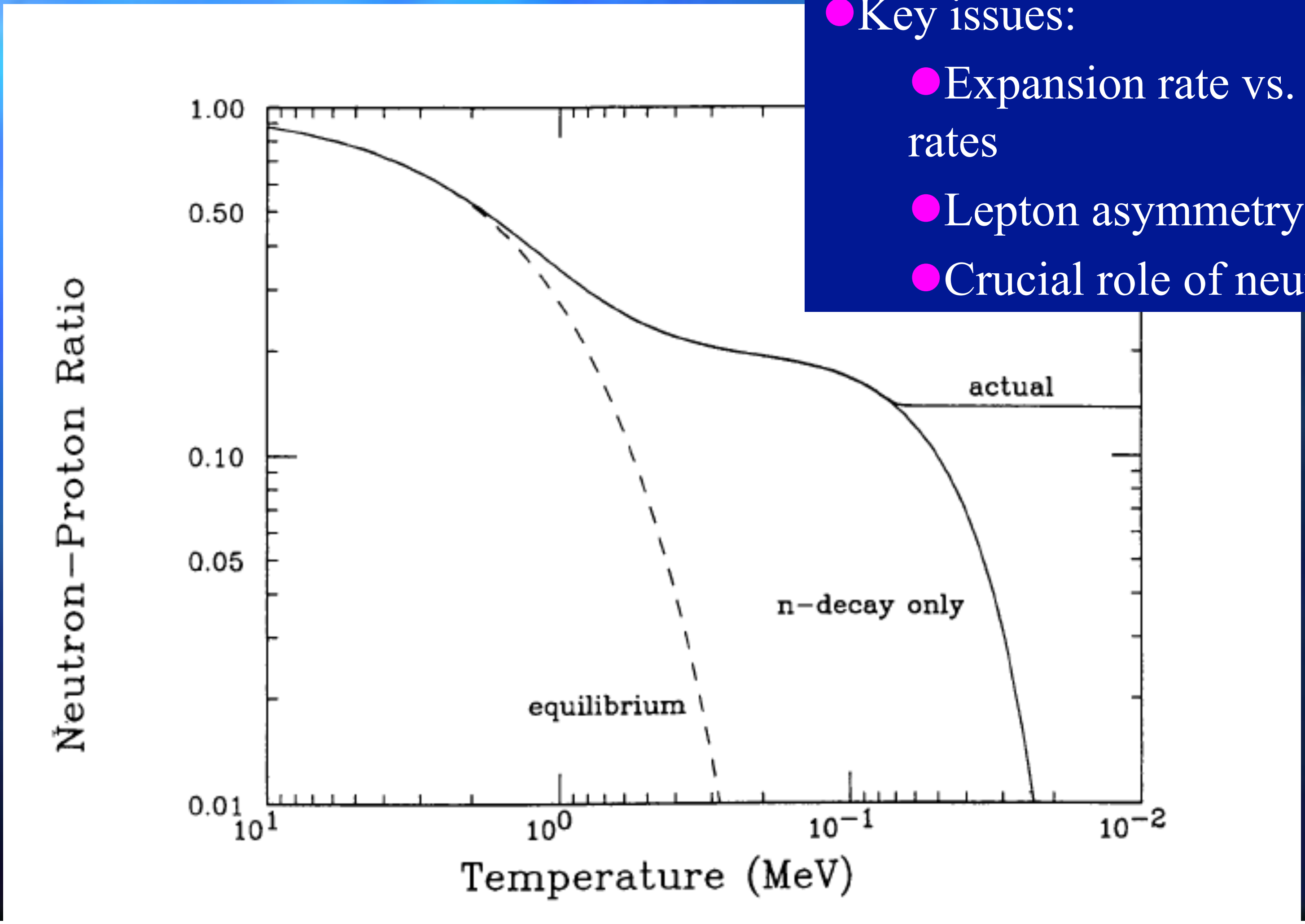
$$n \rightleftharpoons p + e^- + \bar{\nu}_e.$$



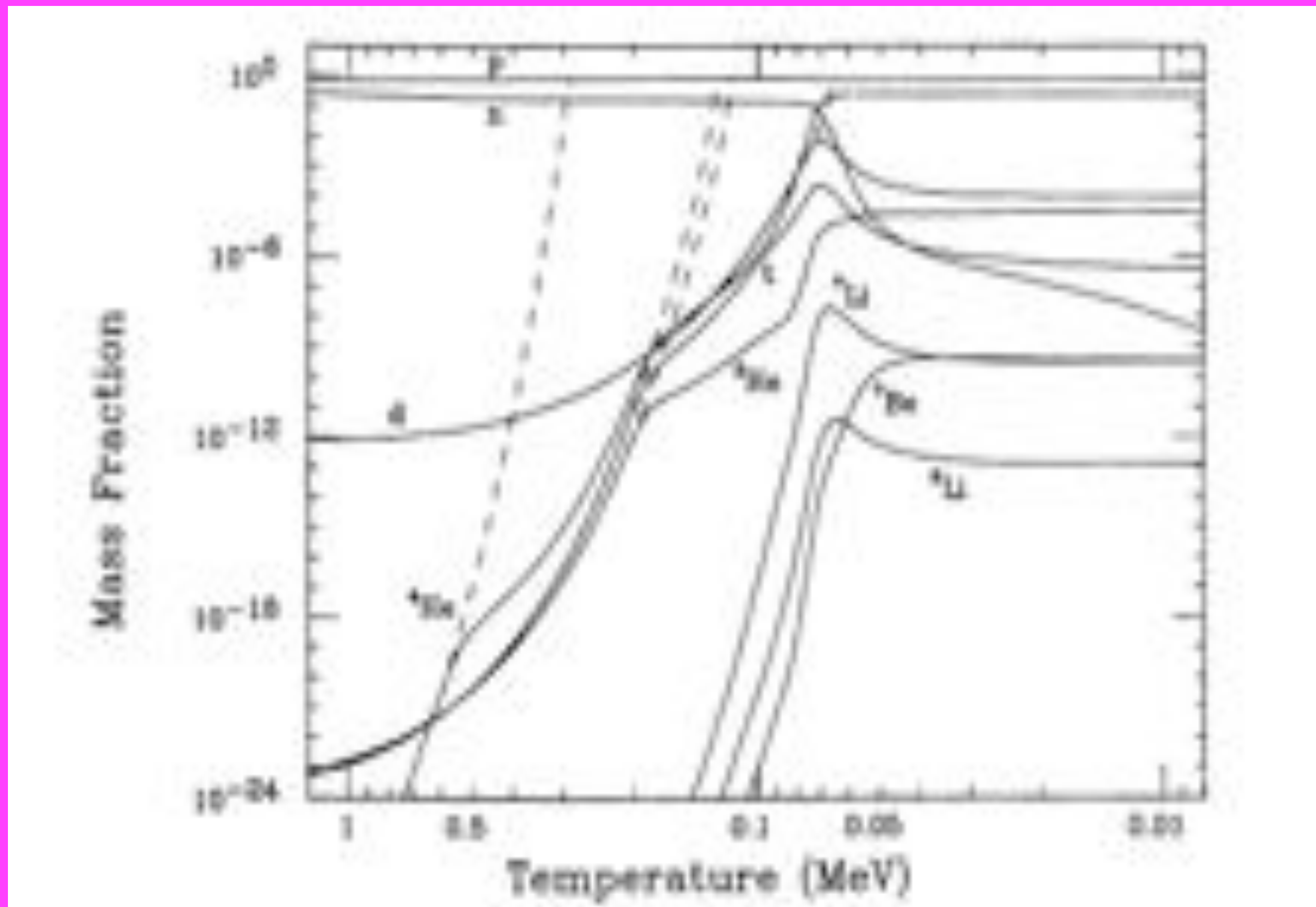
Weak Freeze Out

$\nu_e + n \rightleftharpoons p + e^-,$ $\bar{\nu}_e + p \rightleftharpoons n + e^+,$ $n \rightleftharpoons p + e^- + \bar{\nu}_e.$

- Key issues:
  - Expansion rate vs. weak rates
  - Lepton asymmetry
  - Crucial role of neutrinos

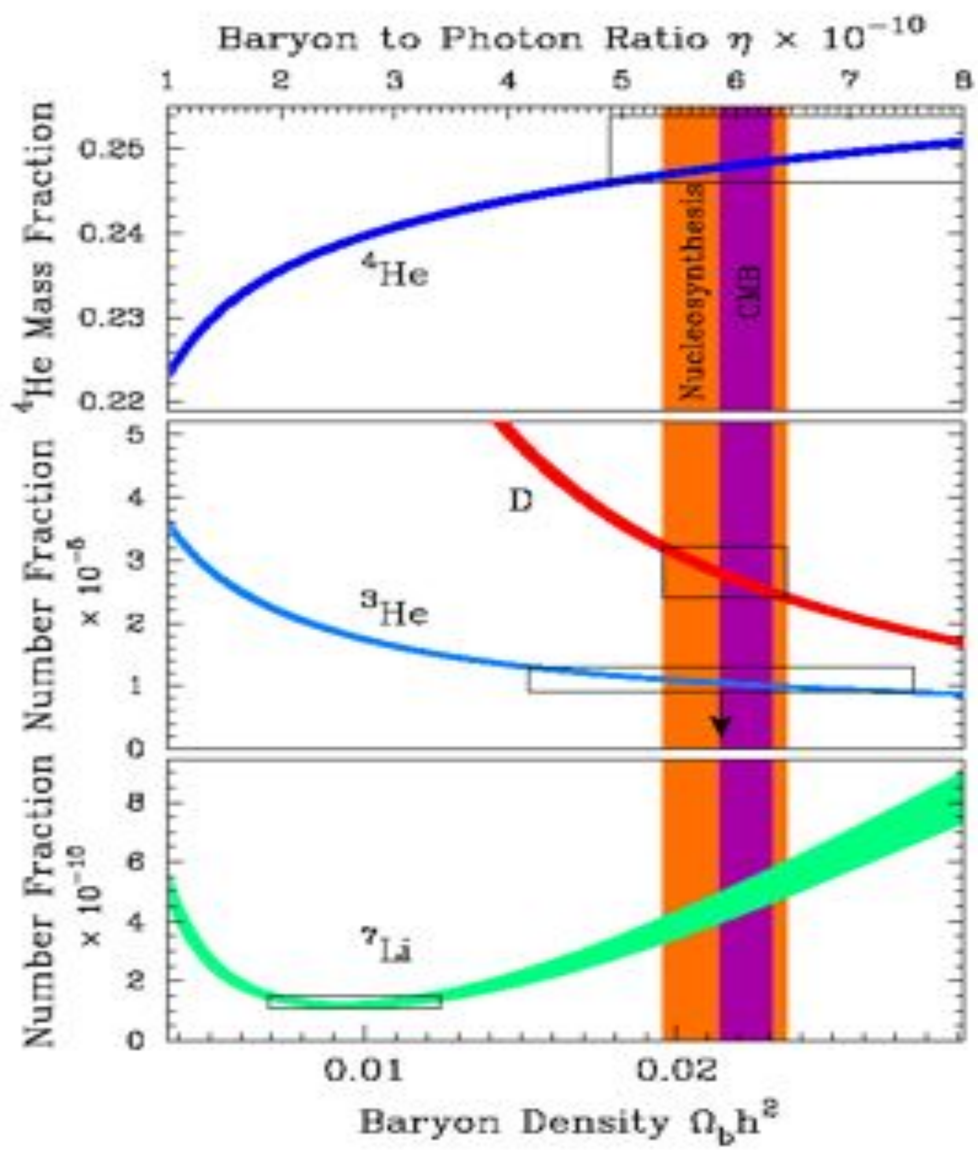


Nucleosynthesis t ~ 1s, T~1 MeV



Entropy--setting temp. scale for nucleosynthesis
--effect on deuterium

Current Status of BBN Comparisons

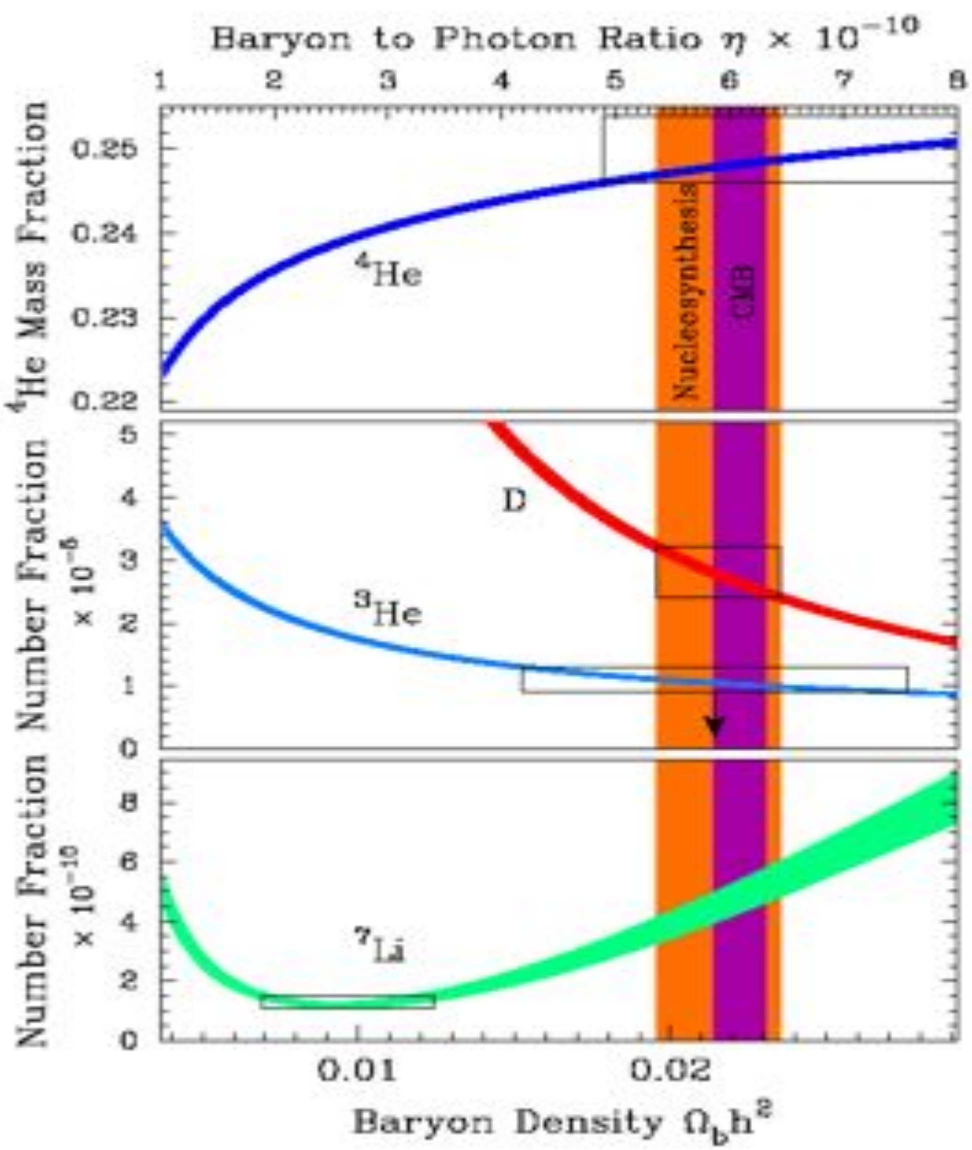


- Element abundance yield prediction as a function of baryon-to-photon ratio:

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma}$$

- Boxes are the observational measurements of the primordial element abundances.

Hints of Unknown Physics



- ^{7}Li?

Factor of 2-3 over-predicted.

(measured by absorption spectra in the surface of old metal poor stars)

Many theories invoked (such as cosmic ray spallation, rotational effects to dilute lithium in the surface, nuclear physics uncertainties)

- ^{6}Li?

New observational evidence (Asplund et al 2006) suggest ~4 orders of magnitude more than prediction

Addressing ^{7}Li and ^{6}Li Issues with Nuclear Physics

- Extend the BBN nuclear reaction network to contain more reactions involving beryllium and lithium isotopes

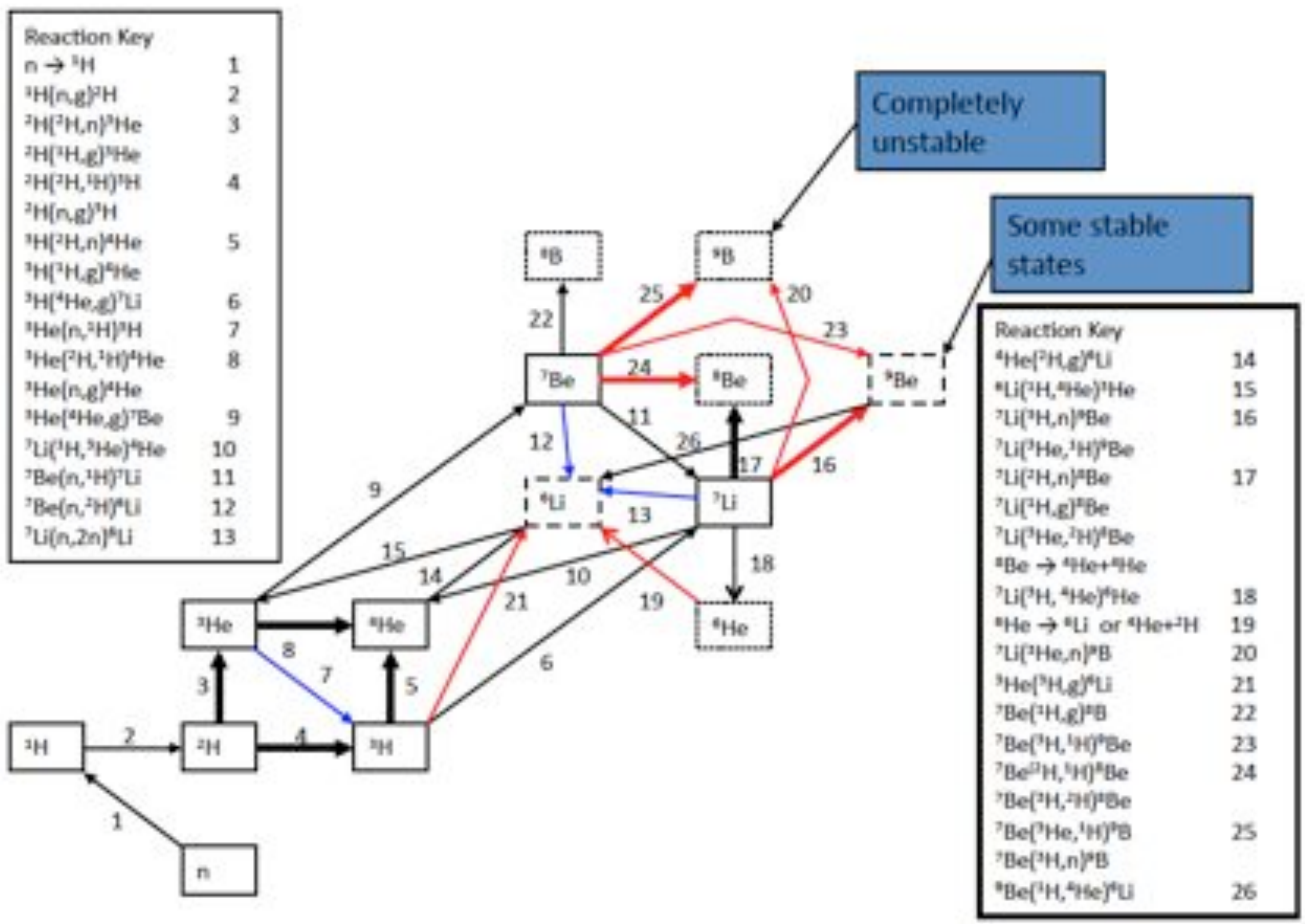


TABLE I:
Reactions Added to the BBN Code

Reaction	Q-value (MeV)	Comment	Effect
^{7}Li(^{3}H,n)^{9}Be(ground state)	10.439	1 (Ref. [40])	none
^{7}Li(^{3}H,n)^{9}Be(excited states)	10.439	1 (Ref. [40])	none
^{7}Li(^{3}He,p)^{9}Be(ground state)	11.202	2 (Ref. [41, 42])	none
^{7}Li(^{3}He,p)^{9}Be(excited states)	11.202	2 (Ref. [41, 42])	none
^{7}Li(^{3}He,n)^{9}B	9.352	9 (Ref. [43])	none
^{7}Li(^{3}He,^{2}H)^{8}Be	17.608	8 (Ref. [44, 45])	none
^{7}Li(^{2}H,n)^{8}Be	15.031	8 (Ref. [44, 45])	none
^{7}Li(^{3}He,^{4}He)^{6}Li(ground state)	13.328	4 (Ref. [46])	none
^{7}Li(^{3}He,^{4}He)^{6}Li(excited states)	13.328	4 (Ref. [46])	none
^{7}Li(^{3}H,^{4}He)^{6}He	9.838	3 (Ref. [47])	none
^{7}Be(^{3}H,^{4}He)^{6}Li(ground state)	14.208	4	small
^{7}Be(^{3}H,^{4}He)^{6}Li(excited states)	14.208	4	small
^{7}Be(^{3}H,p)^{9}Be(ground state)	12.082	6	small
^{7}Be(^{3}H,p)^{9}Be(excited states)	12.082	6	small
^{3}He(^{3}H,γ)^{6}Li(low lying states)	15.795	5 (Ref. [48, 49])	large
^{9}Be(p,α)^{6}Li(ground state)	2.126	Ref. [50]	none
^{7}Be(p,γ)^{8}B	0.137	Ref. [50]	none
^{7}Be(^{2}H,p)^{8}Be	16.674	8 (Ref. [44, 45])	large
^{7}Be(^{3}H,^{4}He)^{6}Li	14.208	4	small
^{7}Be(^{3}H,n)^{9}B	10.232	7	small
^{7}Be(^{3}H,^{2}H)^{8}Be	12.641	8 (Ref. [44, 45])	small
^{7}Be(^{3}He,p)^{9}B	10.995	7	none
^{7}Be(^{2}H,^{3}He)^{6}Li	-0.112	10	none
^{7}Be*(^{2}H,^{3}He)^{6}Li	0.317	10	large
^{7}Be*(^{2}H,p)^{8}Be	17.103	8 (Ref. [44, 45])	large
^{7}Be*(p,γ)^{8}B	0.566	Ref. [50]	large

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^{9}Be(p,α)^{6}Li(ground state)	2.126	Ref. [50]	none
^{7}Be(p,γ)^{8}B	0.137	Ref. [50]	none

New Nuclear Physics for Big Bang Nucleosynthesis

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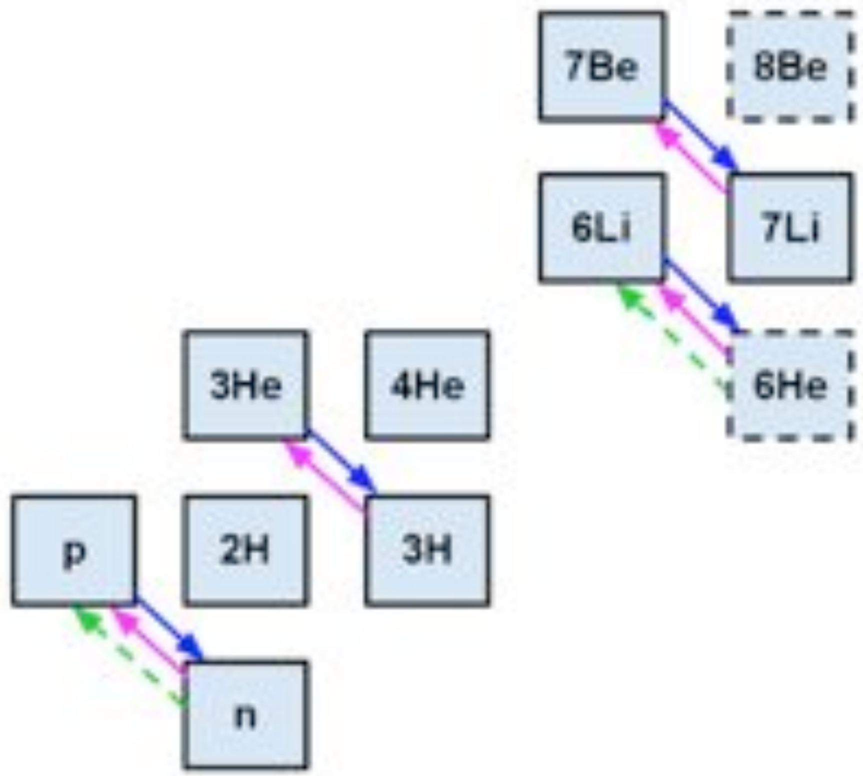
[2] *Department of Physics and Astronomy, Ohio University, Athens, OH 45701*
[3] *Department of Physics, University of California, San Diego, La Jolla, CA 92093-0319*
[4] *Physics Department, Arizona State University, Tempe, AZ 85287-1404*
(Dated: September 1, 2010)

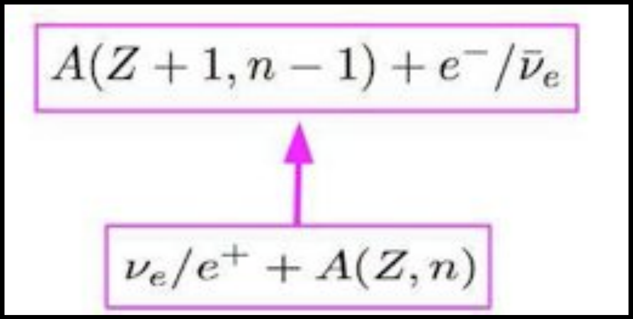
Arxiv:1008.0848

We discuss nuclear reactions which could play a role in Big Bang Nucleosy
of these reactions involve lithium and beryllium isotopes and the rates for
not previously been included in BBN calculations. Few of these reactions are well studied in the laboratory. We also discuss novel effects in these reactions, including thermal population of nuclear

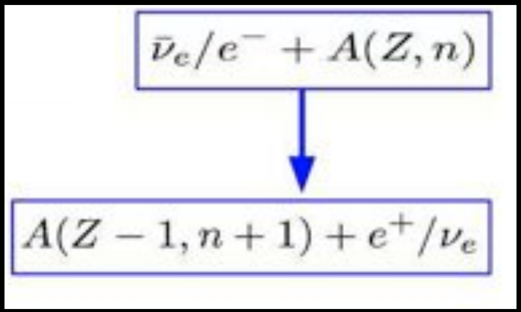
Lepton Capture Reactions



- Green - Beta Decay
- Magenta - electron neutrino and positron capture



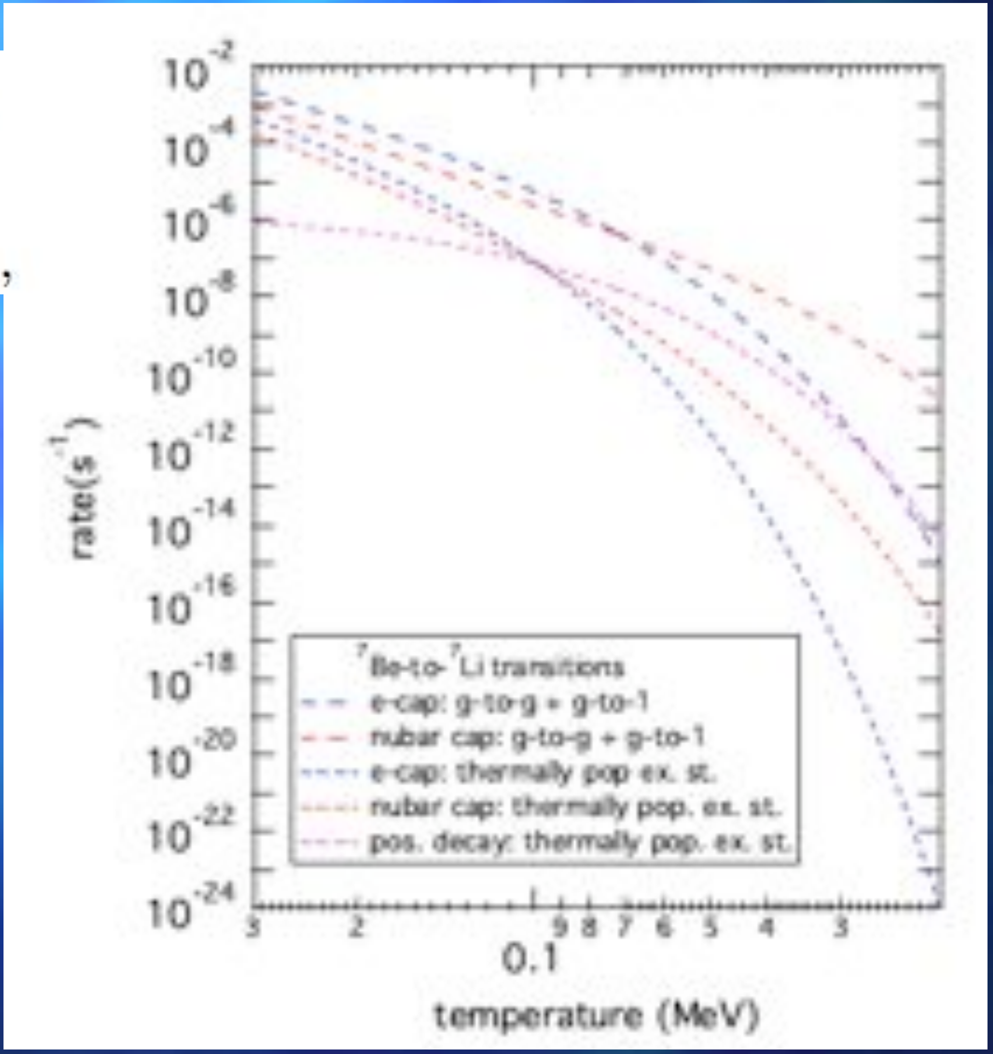
- Blue - electron anti neutrino and electron capture



G. Fuller & C. Smith
Arxiv:1009.0277

Lepton Capture Reactions

$$\bar{\nu}_e + {}^7\mathrm{Be} \rightleftharpoons {}^7\mathrm{Li} + e^+,$$
$$e^- + {}^7\mathrm{Be} \rightleftharpoons {}^7\mathrm{Li} + \nu_e,$$
$${}^7\mathrm{Be}^* \rightarrow {}^7\mathrm{Li} + e^+ + \nu_e,$$



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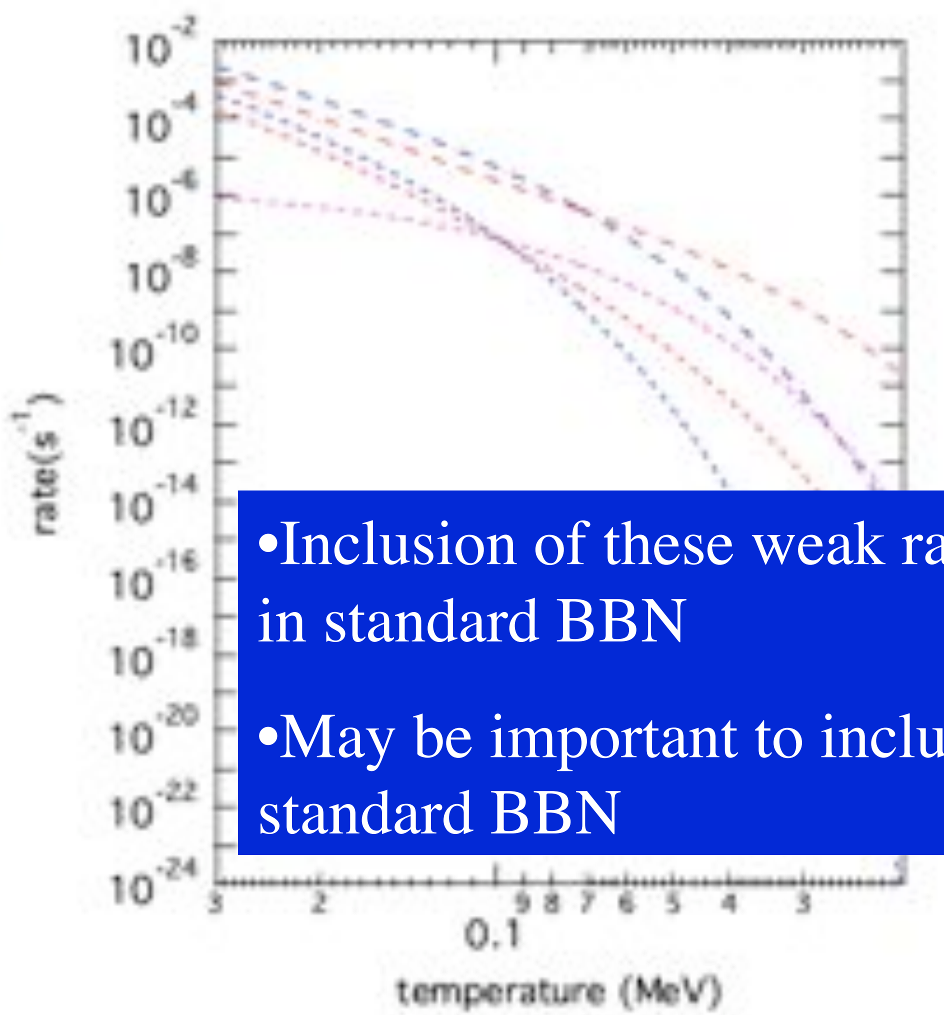
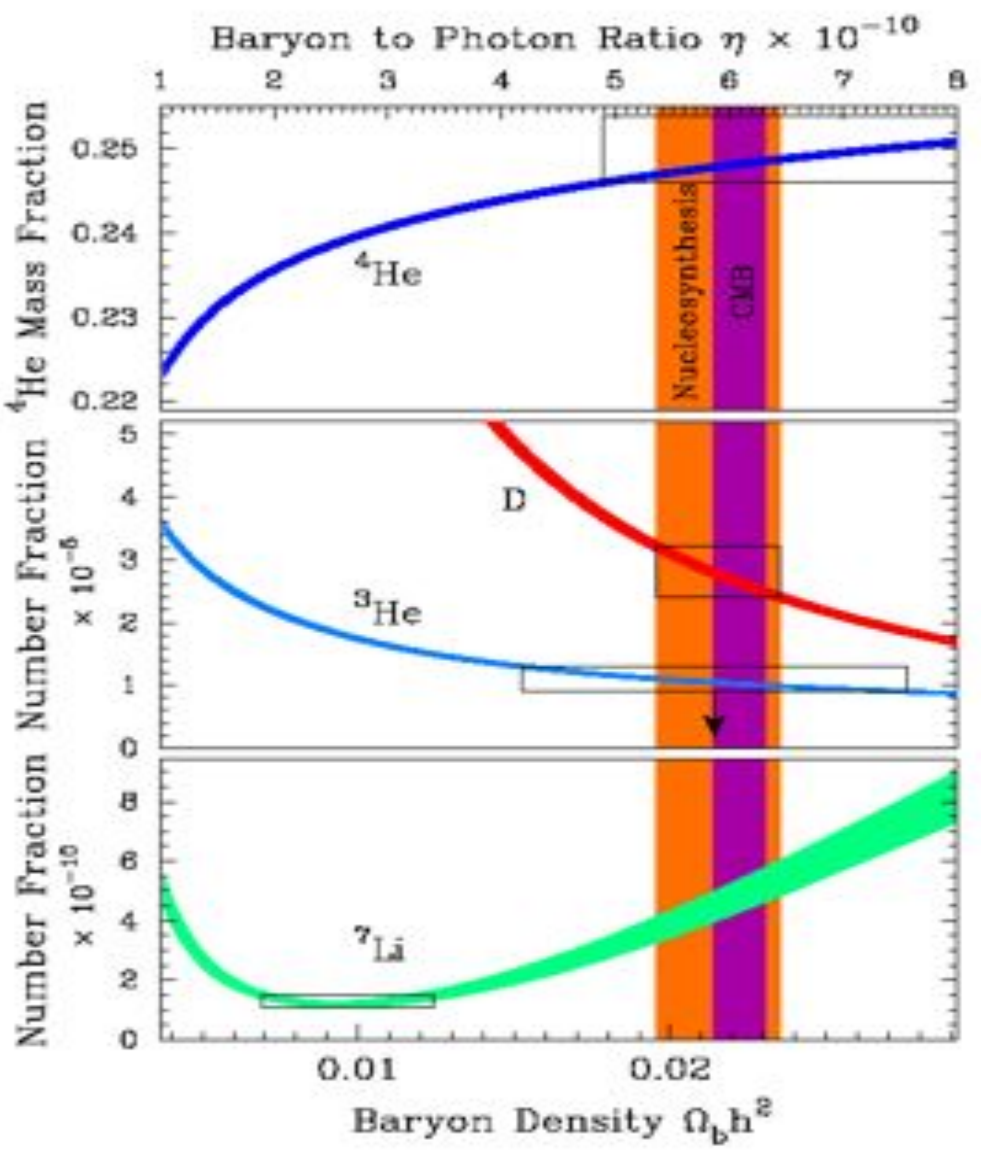


- Inclusion of these weak rates do little in standard BBN
- May be important to include for non-standard BBN

G. Fuller & C. Smith
Arxiv:1009.0277

Hints of Unknown Physics



^{4}He

Two new interesting new observations:

WMAP -7

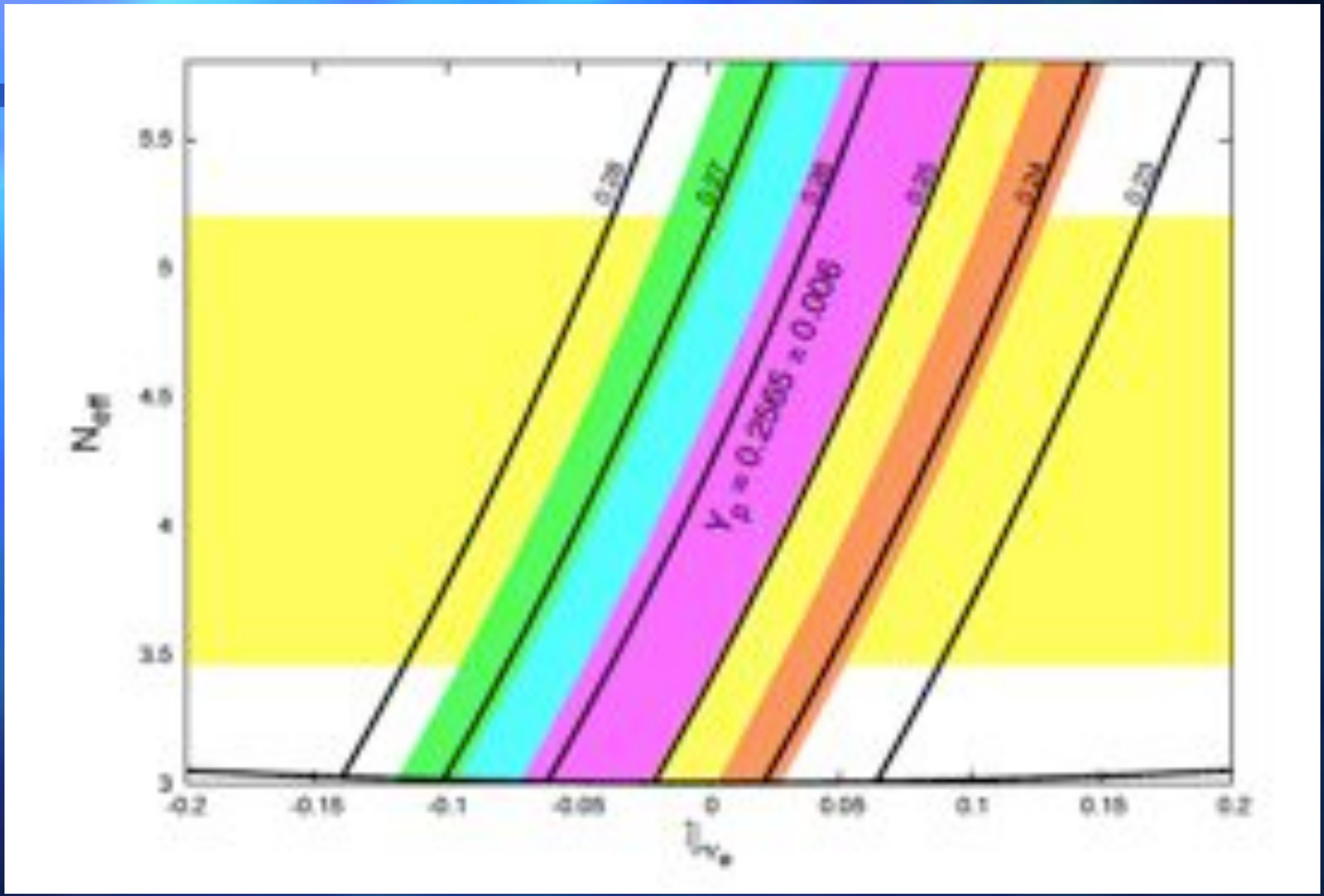
-higher measurement of relativistic energy density

$$N_{\rm eff} = 4.34^{+0.86}_{-0.88}\ (68\%\ \mathrm{CL}),$$

Izotov & Thuan 2010

$$Y_p = 0.2565 \pm 0.0010(\mathrm{stat.}) \pm 0.0050(\mathrm{syst.})$$

Helium considerations



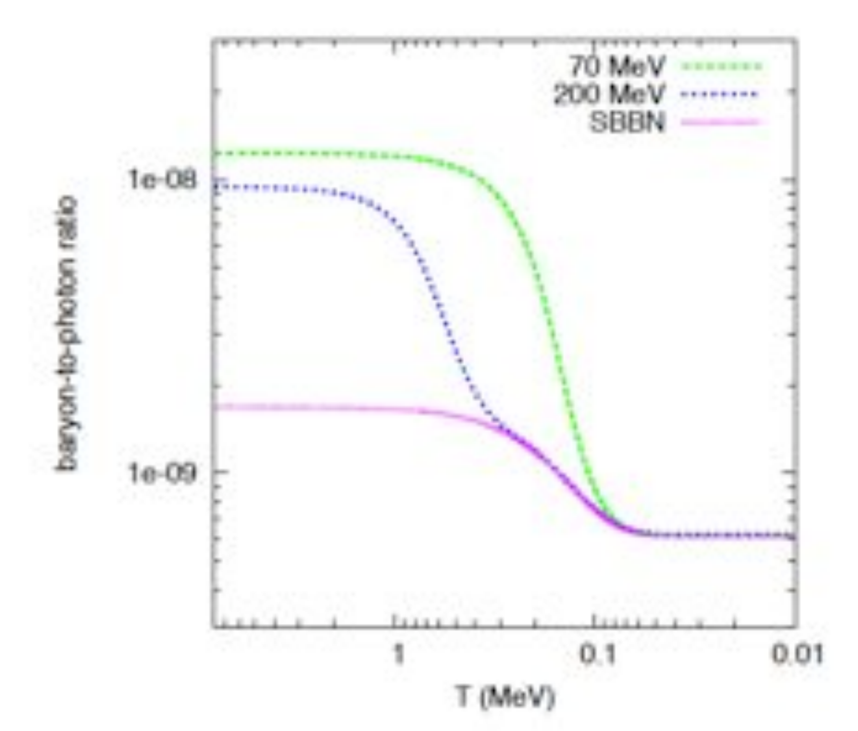
L. Krauss, C. Lunardini, C. Smith (in preparation)

Constraining ~10-100 MeV Sterile Neutrino Parameter Space

- It's not obvious what this will do
- A fully populated state would decouple from the universe around T ~ 1 GeV
- Start out relativistic, go non-relativistic by BBN times
- Significant non-relativistic contribution to energy density (H ~ T^3 instead of H ~ T^4)
- High energy decay products (photons energize the plasma and add entropy, neutrinos could distort neutrino distribution functions)

$$\nu_s \longrightarrow \pi^0 + \nu_{e,\mu,\tau}$$

$$\gamma + \gamma$$



G. Fuller, C. Kishimoto, C. Smith (in preparation)

The end.