NEUTRINOS AND WEAK INTERACTIONS IN THE EARLY UNIVERSE

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16 Apr 2019

Nuclei as BSM Laboratories – ECT*

OUTLINE

- Big Bang Nucleosynthesis Theory
  - Overview: Physics and Computation
  - Neutron-to-proton ratio
  - Nuclear Freeze-Out
- Primordial-Abundance Observations
  - Helium-4
  - Deuterium and the Cosmic Microwave Background
  - Lithium Isotopes
- Lithium Problem(s)
  - Lithium-6 Status
  - Stellar Solutions to Lithium-7
  - Nuclear Solutions
  - Particle solutions
  - Aside: Coming age of Precision Cosmology
- Summary and Conclusions

EPOCHS OF INTEREST

Equilibrium initial conditions
Nonequilibrium evolution

time ↓ / ↑ Temp

$e^{\pm}(\nu_i,\nu_i)e^{\pm} \sim \nu_j(\nu_i,\nu_i)\nu_j \lesssim H$	(WD)	$T \sim 1\,\mathrm{MeV}$, $t \sim 1\,\mathrm{s}$
$n(\nu_e, e^-)p \lesssim H$	(WFO)	
$e^-(e^+,\gamma)\gamma \lesssim H$	($e^{\pm}$A)	
$n(p,\gamma)d \lesssim H$	(NFO)	$T \sim 100\,\mathrm{keV}$, $t \sim 100\,\mathrm{s}$

Standard BBN - Physics

Definition: Primordial synthesis of ≥ 9 light elements

$$n,\ p,\ d,\ {}^3\mathrm{H},\ {}^3\mathrm{He},\ {}^4\mathrm{He},\ {}^6\mathrm{Li},\ {}^7\mathrm{Li},\ {}^7\mathrm{Be}$$

$$Y_i \equiv n_i/n_b$$

$$Y_\mathrm{P} = 4Y_{^4\mathrm{He}}$$

High Entropy per Baryon in relativistic components

$$s_\mathrm{pl} = \frac{1}{n_b}\frac{\rho + P}{T} \sim 10^9$$

Relativistic species in thermally populated states

Initial equilibrium (10 MeV)

Bosons	Fermions
γ	$e^\pm$
	ν_e, ν_μ, ν_τ
	$\overline{\nu}_e, \overline{\nu}_\mu, \overline{\nu}_\tau$

After weak decoupling (100 keV):

$$\gamma \quad e^\pm \quad (\nu)$$

After $e^\pm$ annihilation (10 keV):

$$\gamma \quad (\nu)$$

Conservation of comoving entropy per baryon

$$\left.\frac{T_\mathrm{cm}}{T}\right|_\mathrm{f.o.} = \left(\frac{4}{11}\right)^{1/3}$$

Standard BBN - Computation

Numerical treatments:

- First complete calculation: Wagoner, Fowler, Hoyle (1967)
- Updated calculation: Smith, Kawano, Malaney (1993)
- Modern codes: PArthENoPE; AlterBBN; PRIMAT

Isotropic and Homogeneous geometry

Evolution of three thermodynamic/cosmological variables:

$$\begin{cases} T & : \text{photon (plasma) temperature} \\ h_v & : \text{ratio of baryon energy density to } T^3 \\ \phi_e & : \text{electron degeneracy parameter} \end{cases}$$

25 Nuclear Reactions:

$$\frac{dY_i}{dt} = \sum_{j,k,l} N_i \left(-\frac{Y_i^{N_i} Y_j^{N_j}}{N_i! N_j!} [ij]_k + \frac{Y_k^{N_k} Y_l^{N_l}}{N_k! N_l!} [kl]_j \right)$$

Neutrinos preserve Fermi-Dirac shape:

$$f(\epsilon) = \frac{1}{e^{\epsilon} + 1} \qquad \epsilon = E_\nu / T_{\rm cm}$$

Neutron to proton rates

$$\nu_e + n \leftrightarrow p + e^-$$
$$e^+ + n \leftrightarrow p + \overline{\nu}_e$$
$$n \leftrightarrow p + \overline{\nu}_e + e^-$$

6 Neutron-to-proton rates set n/p

ν_e capture on neutron, normalized to neutron lifetime

$$\lambda_{\nu_e n \to p e^-} = \frac{G_F^2(1+3g_A^2)}{2\pi^3} \int\limits_0^\infty dE_\nu C(E_\nu + \delta m_{np}) Z(E_\nu + \delta m_{np}, E_\nu)$$
$$\times E_\nu^2 (E_\nu + \delta m_{np}) \sqrt{(E_\nu + \delta m_{np})^2 - m_e^2}$$
$$\times [f_{\nu_e}(E_\nu)][1 - g_{e^-}(E_\nu + \delta m_{np})]$$

$$\frac{1}{\tau_n} = \frac{G_F^2(1+3g_A^2)}{2\pi^3} \int\limits_0^{\delta m_{np} - m_e} dE_\nu C(\delta m_{np} - E_\nu) Z(\delta m_{np} - E_\nu, E_\nu)$$
$$\times E_\nu^2 (\delta m_{np} - E_\nu) \sqrt{(\delta m_{np} - E_\nu)^2 - m_e^2}$$

Neutron to proton ratio – Primordial Helium

Equilibrium:

$$\mu_{\nu_e} + \mu_n = \mu_p + \mu_{e^-}$$

$$n/p = \exp\left[-\frac{\delta m_{np}}{T} + \phi_e - \xi_{\nu_e}\right]$$

Common Approximation at late times after Weak Freeze-Out (WFO):

$$n/p(t) = e^{-\delta m_{np}/T_{\rm WFO}} e^{-(t-t_{\rm WFO})/\tau_n}$$

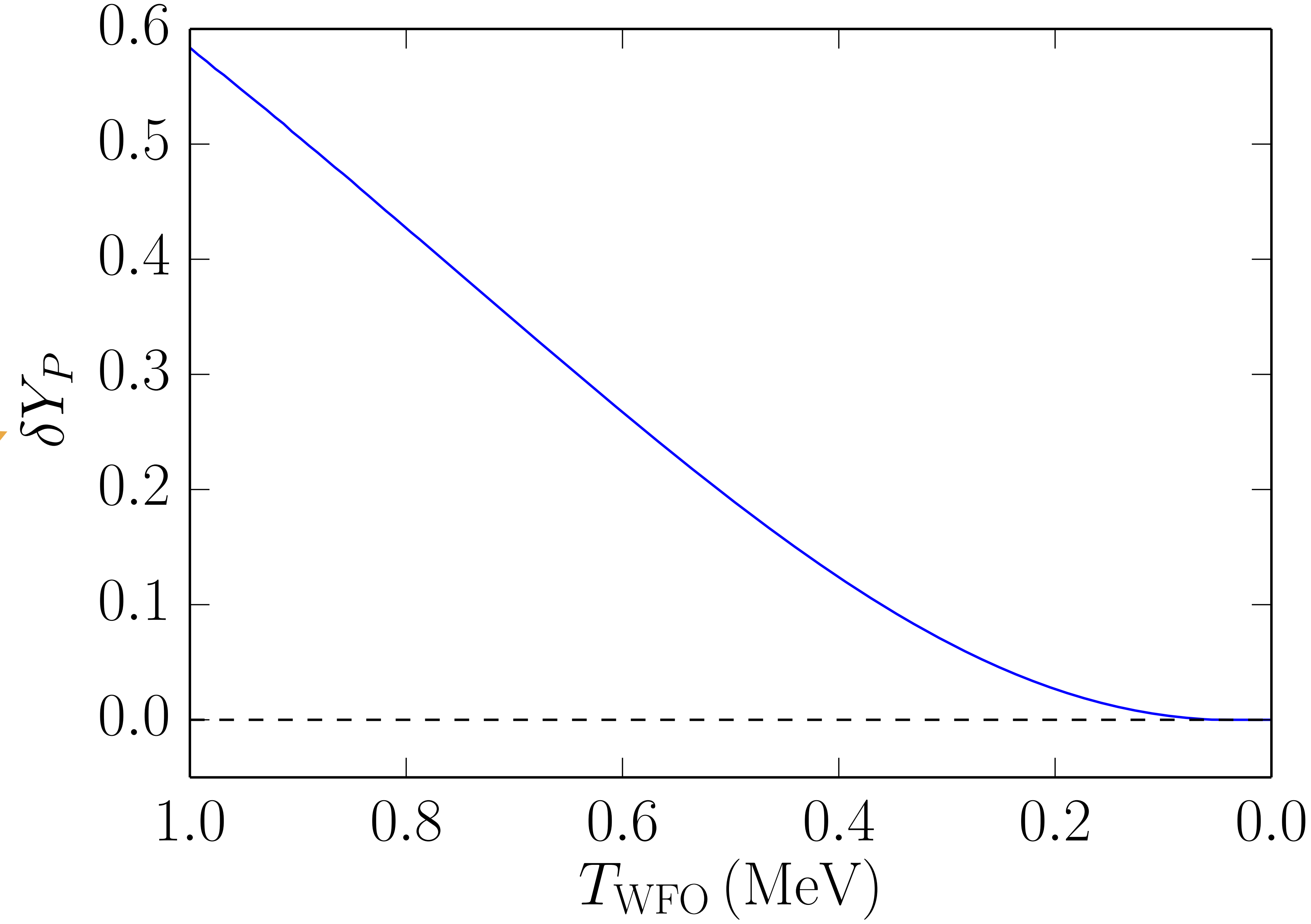
How Accurate is the WFO approximation?

$$Y_{\rm P} \simeq \left.\frac{2n/p}{1+n/p}\right|_{\rm f.o.}$$

Lepton capture rates set to zero at T_{WFO}

No Pauli blocking in free neutron decay

Helium-4 Deviation from Baseline

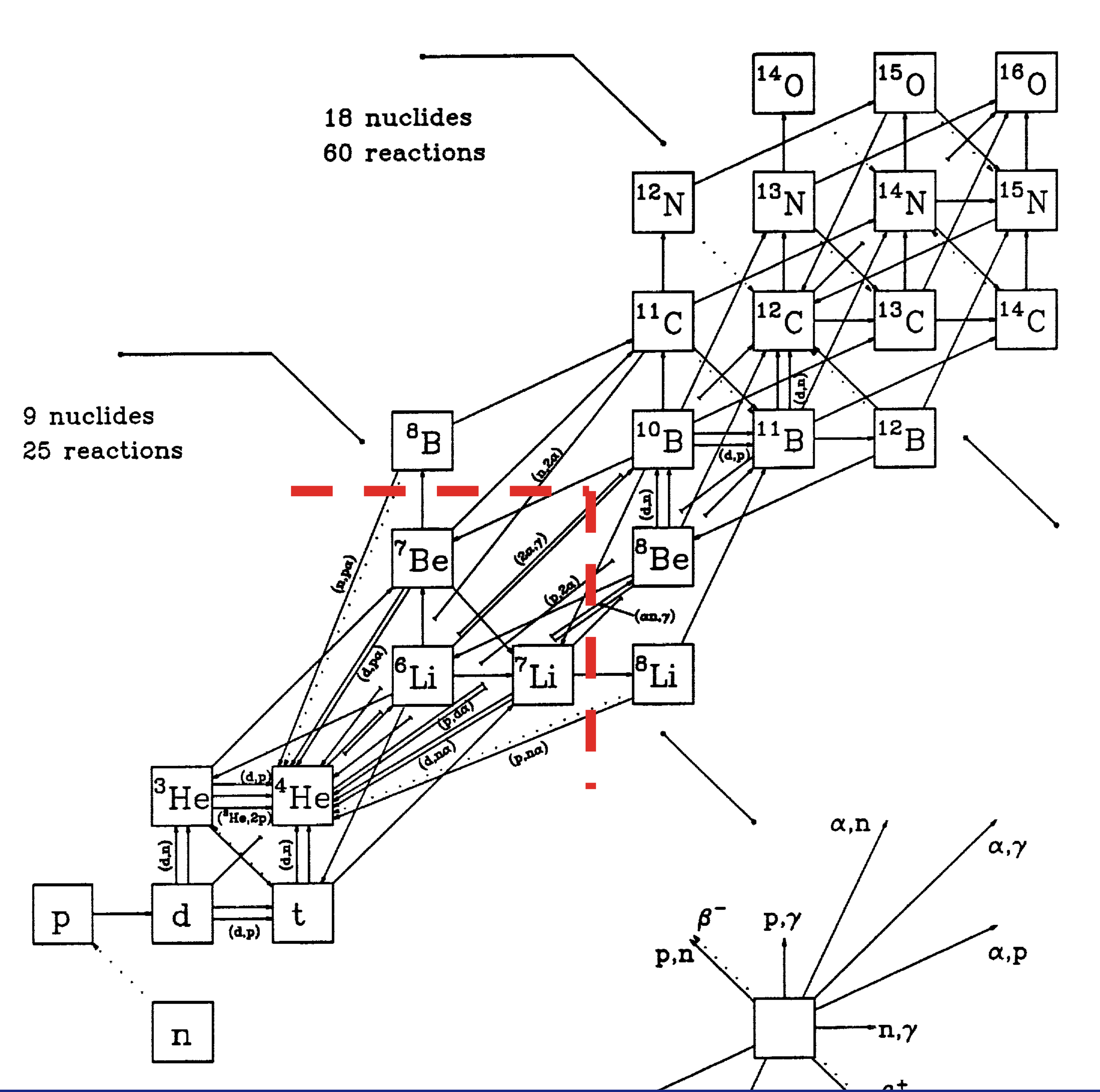


arXiv: 1607.02797

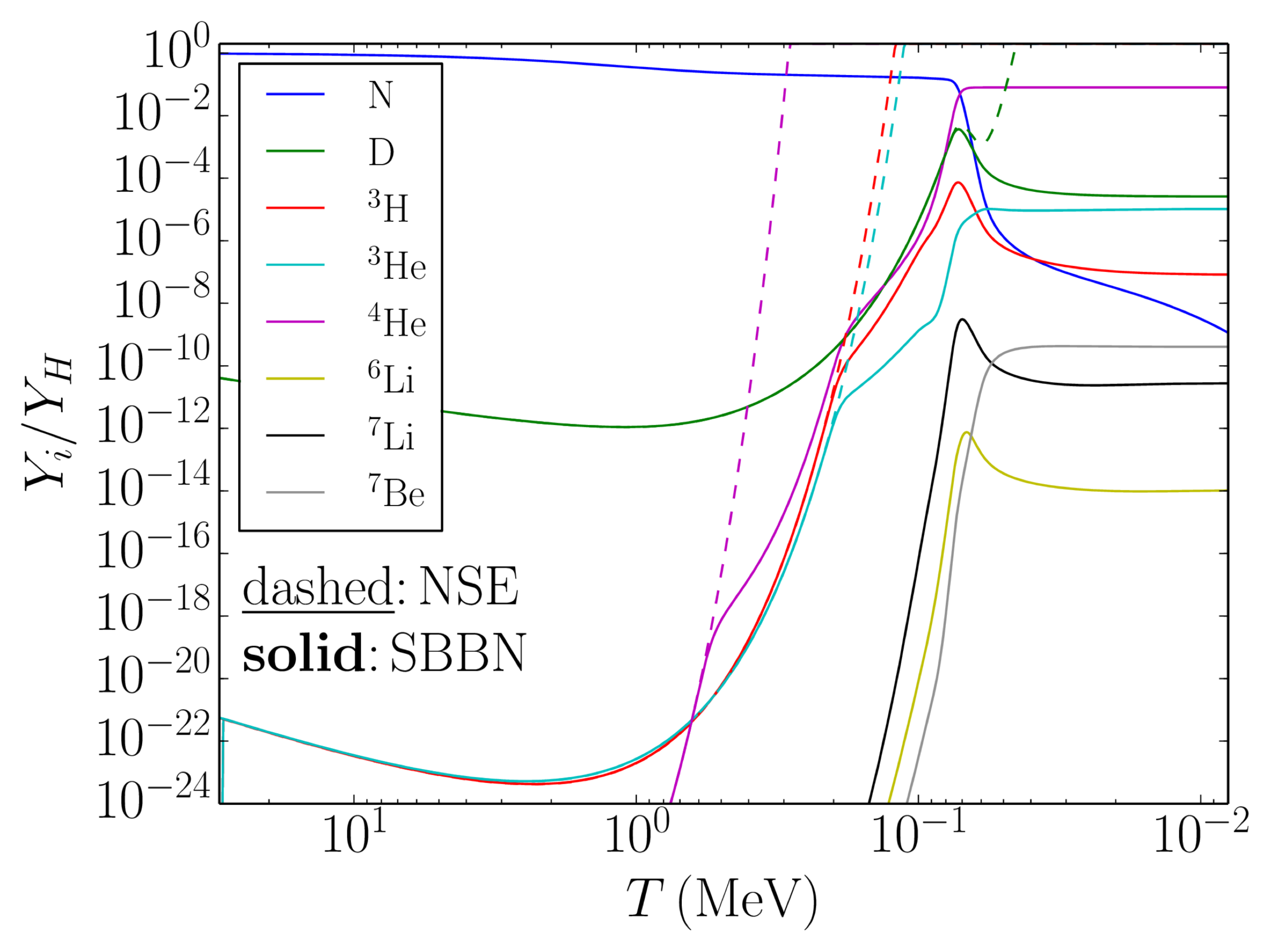
Nuclear Reaction Network

25 strong, electromagnetic, and weak nuclear reactions

Thermally averaged reaction-rate coefficients



Freeze-Out from NSE



Equilibrium initial conditions
Nonequilibrium evolution

$$\omega_b = 0.022$$

$$\eta = 6.08 \times 10^{-10}$$

$$s_{\rm pl} = 5.89 \times 10^9$$

$$\tau_n = 885.1\,\mathrm{s}$$

Theoretical Predictions

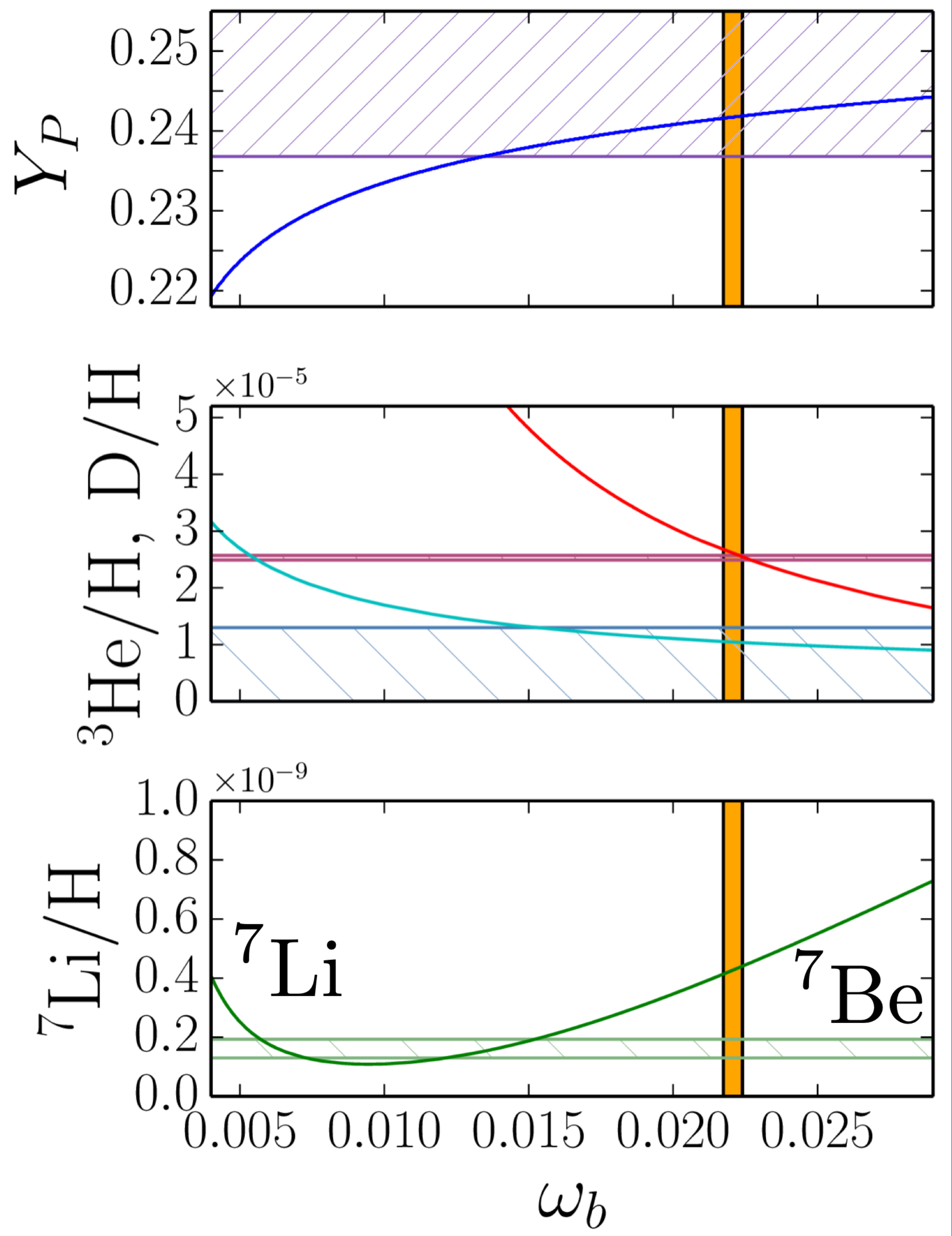
$$Y_{\rm P} = 0.247$$

$$\rm D/H = 2.66 \times 10^{-5}$$

$$\rm ^3He/H = 1.05 \times 10^{-5}$$

$$\rm ^7Li/H = 4.29 \times 10^{-10}$$

$$\rm ^6Li/^7Li = 2.69 \times 10^{-5}$$

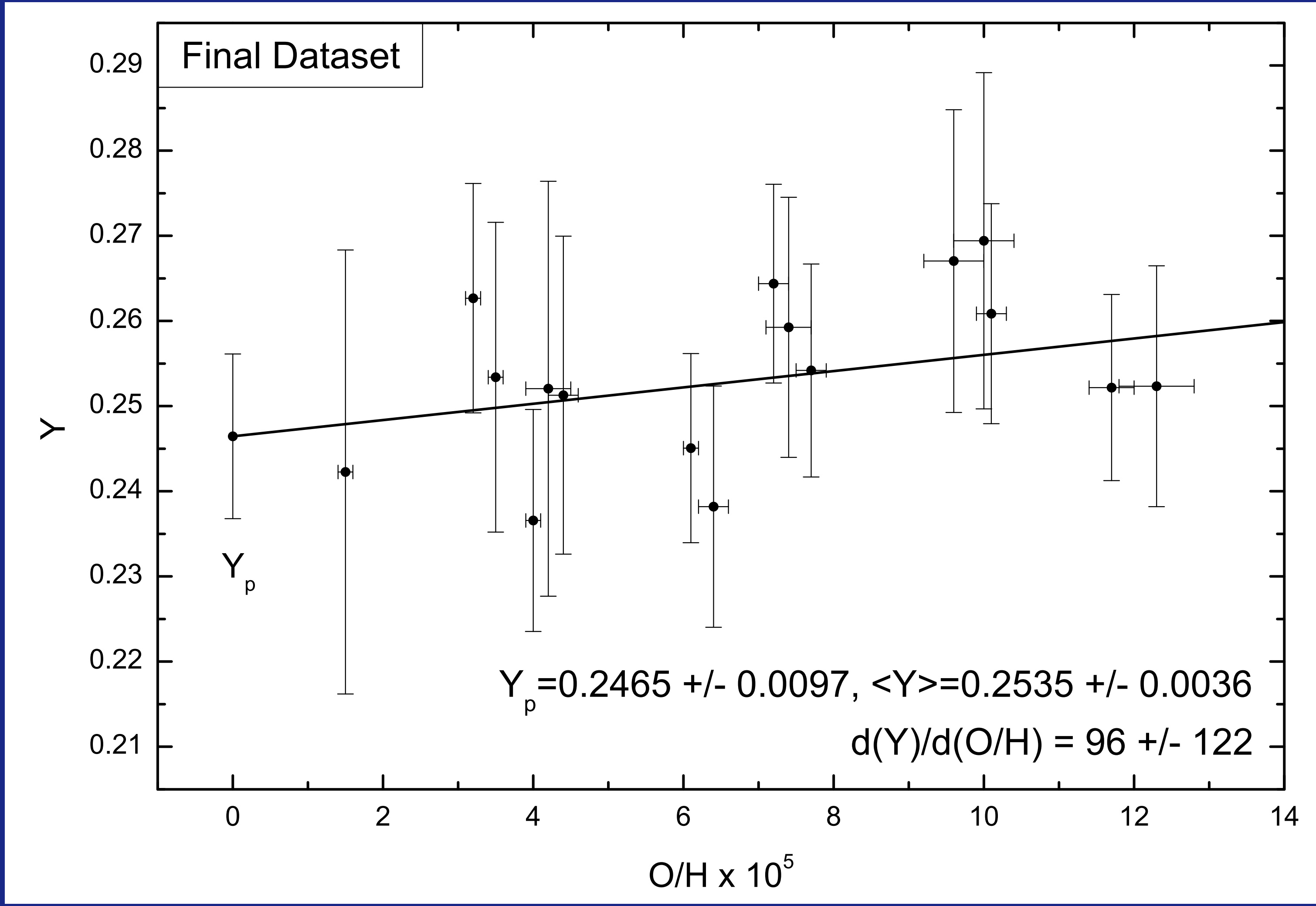


Observations of Primordial Helium

Linear regression of HII regions in metal-poor galaxies

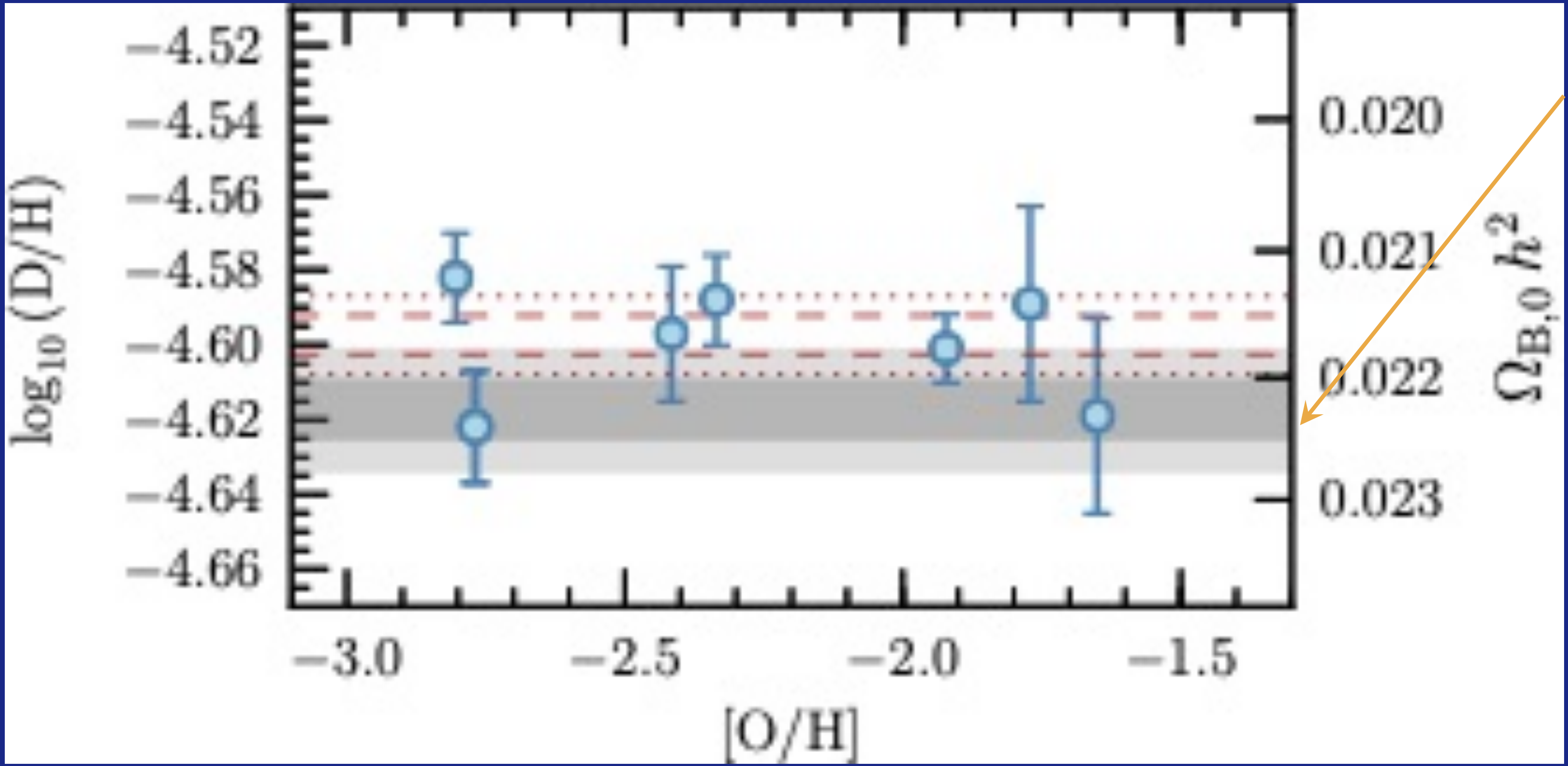
Also see Izotov and Thuan

Competitive CMB measurements forthcoming



Aver et al (2013)

Observations of Primordial Deuterium



Planck (2015)

$$10^5 \times \mathrm{D/H} = 2.53 \pm 0.03$$

Cooke et al (2018)

Observations of Helium-3

Bania, Rood, Balser (2002):

$$10^5 \times {}^3\mathrm{He}/\mathrm{H} = 1.1 \pm 0.2$$

Cooke (2015): Proposal to measure ratio ^{3}He/^{4}He in DLAs

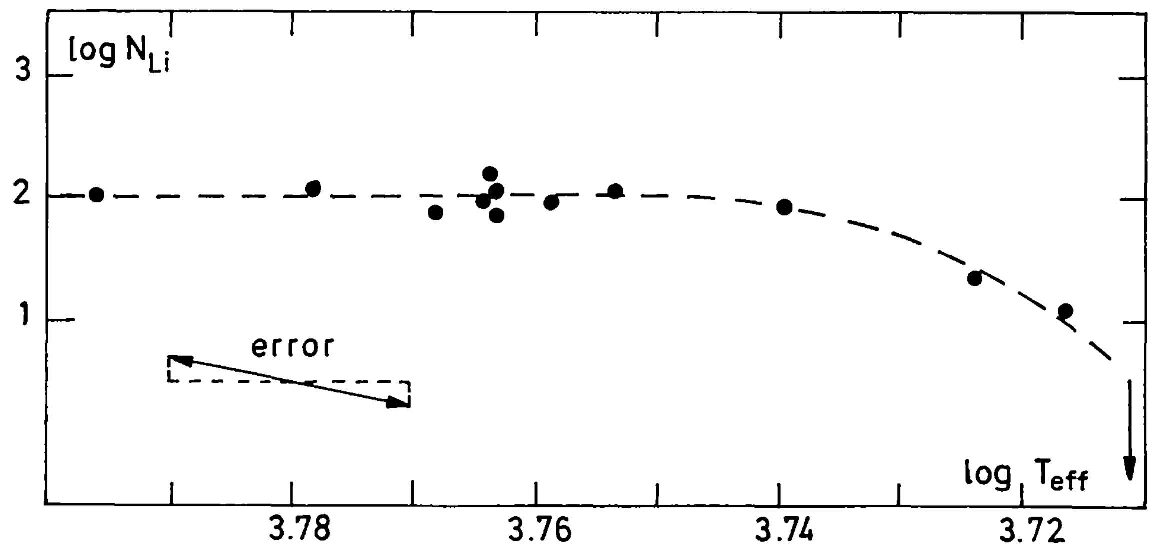
Observations of Lithium

Spite and Spite (1982):

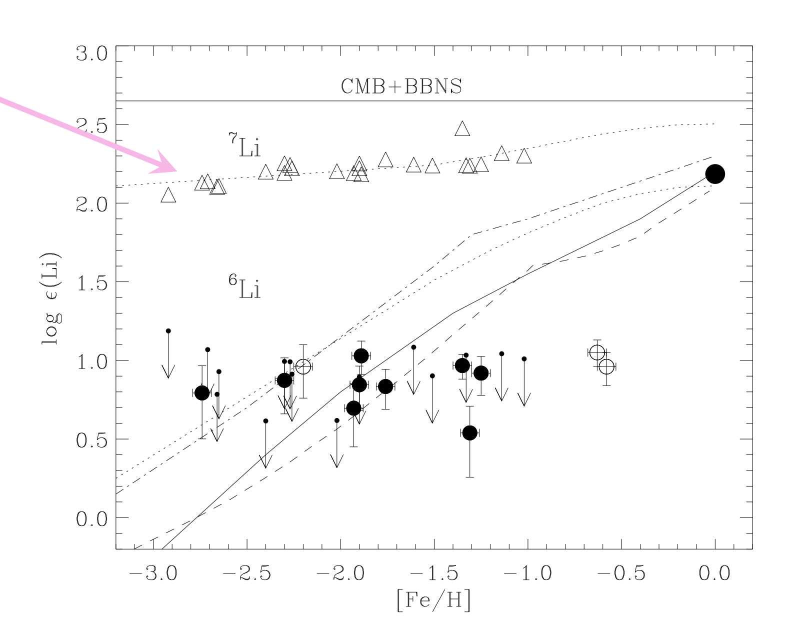
Pop II Halo stars

Abundance vs. Temperature

$$^7\mathrm{Li/H} = 1.12 \times 10^{-10}$$



Slope?



Asplund et al (2006):

Abundance vs. Metallicity

$$\langle ^7\mathrm{Li/H} \rangle = 1.3 \times 10^{-10}$$

$$^6\mathrm{Li}/\,^7\mathrm{Li} = 0.042$$

A Lithium-6 Problem?

Detection of ^{6}Li would create strong tension with SBBN

Asplund et al (2006): Modeled dwarf stars with 1D and 3D Local Thermodynamic Equilibrium (LTE) analyses. Detected blending of 670.8 nm line.

Cayrel et al (2007): NLTE effects important in modeling redward wing of 670.8. Previous detections should be taken as upper limits. Very little affect on ^{7}Li abundance.

Lind et al (2013): More sophisticated 3D NLTE model with Li, Na, and Ca. Reached same conclusions.

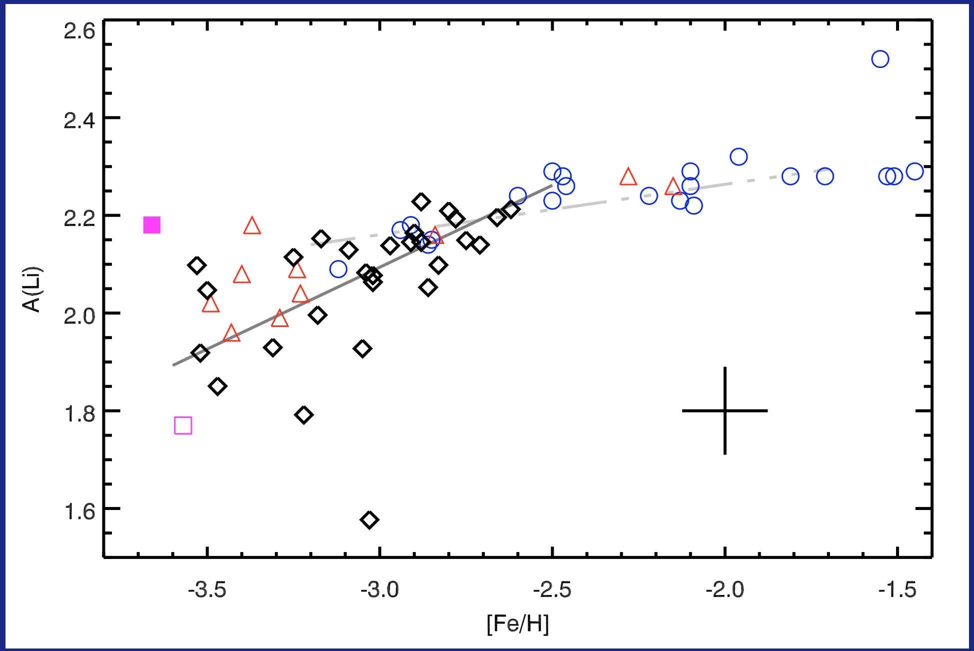
No evidence for ^{6}Li anomaly.

Stellar Solutions to Lithium-7

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

Proposed solutions:

1. Atomic diffusion w/ turbulence
2. Gravity Waves
3. Rotational Mixing
4. Combination….



Sbordone et al (2010):
Spite plateau breakdown for $[\mathrm{Fe}/\mathrm{H}] \lesssim -2.8$; no slope above

Frebel et al (2019): Single star with $[\mathrm{Fe}/\mathrm{H}] < -6.3$ and $A(\mathrm{Li}) = 1.7$

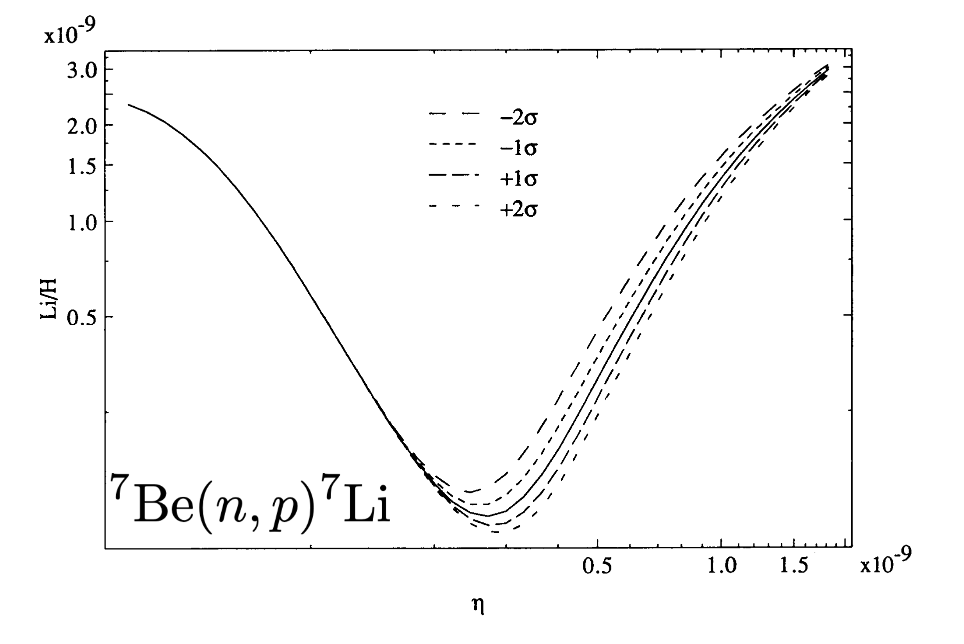
Aguado et al (2019): $[\mathrm{Fe}/\mathrm{H}] < -6.1$ and $A(\mathrm{Li}) = 2.02 \pm 0.08$

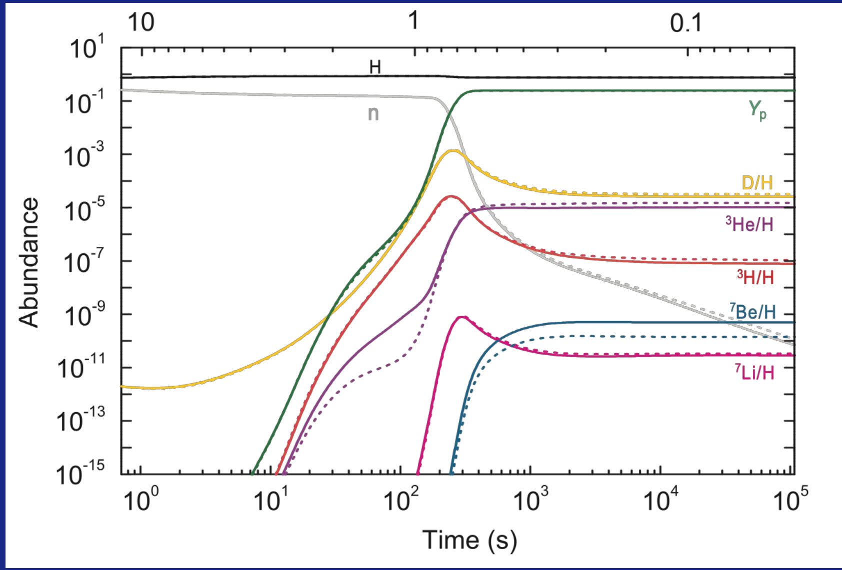
Primordial Nuclear Solutions to Lithium-7

Krauss and Romanelli (1990): MC variation of rxn. cross sections

Civitarese and Mosquera (2013): Put in resonances in ^{7}Li rxn. chain

Hou et al (2017): Tsallis statistics for baryons – reevaluate $\langle \sigma v \rangle$





Particle Solutions to Lithium-7

Coc and Vangioni (2017):

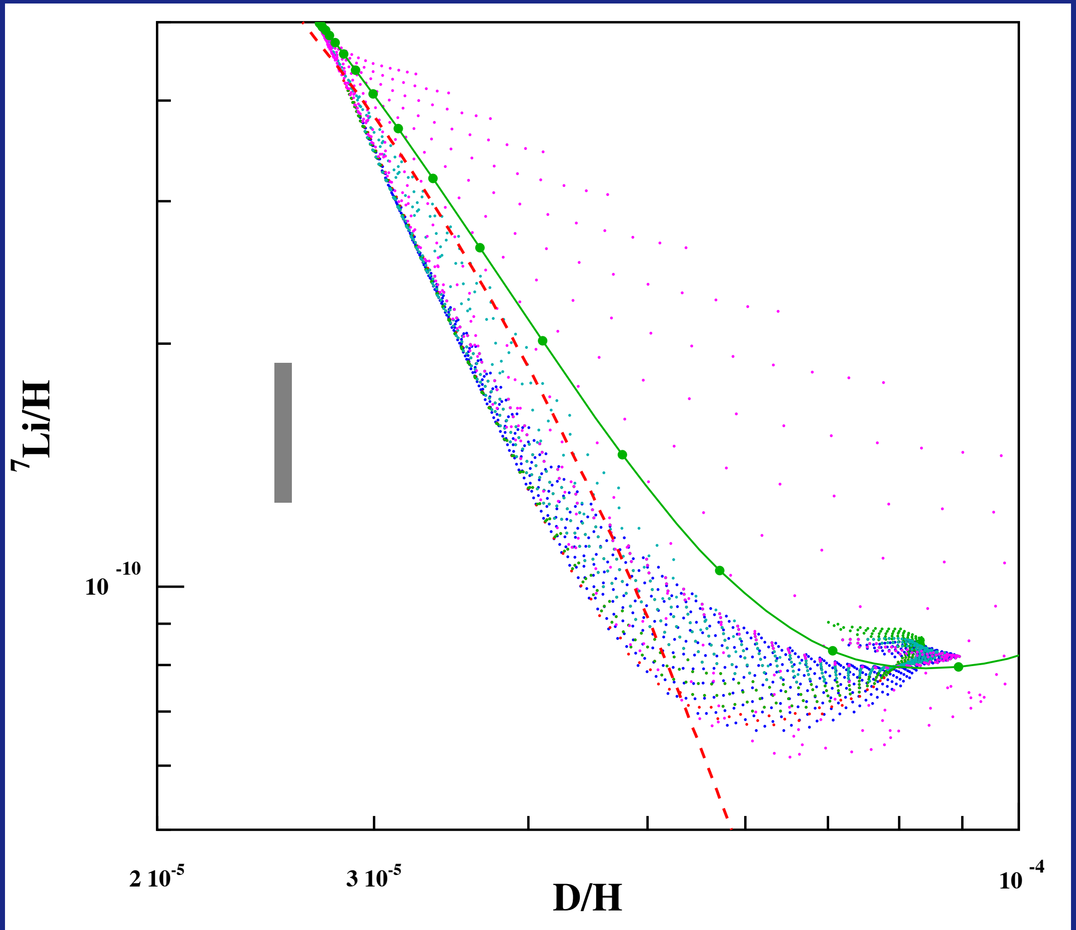
Blue, green, red dots: neutron oscillations

Light blue dots: resonant annihilations

Pink dots: particle decay

Green line: nonresonant annihilations

Red line: qualitative explanation



Other Solutions to Lithium-7

Partial List:

1. Primordial Magnetic Fields (1806.01454)
2. Neutrino secret interactions (1712.04792)
3. Long-lived Negatively Charged Massive Particles (1706.03142)
4. Decays of Axion-like particles (1501.04097)
5. Gravitino decays (1303.0574)
6. Neutral Fermion Decays (1303.2291)
7. Metastable charged sparticles (1209.1347)
8. Hadronic Decays (astro-ph/0408426)

Note: Extra radn. energy density and/or ν degeneracy not viable

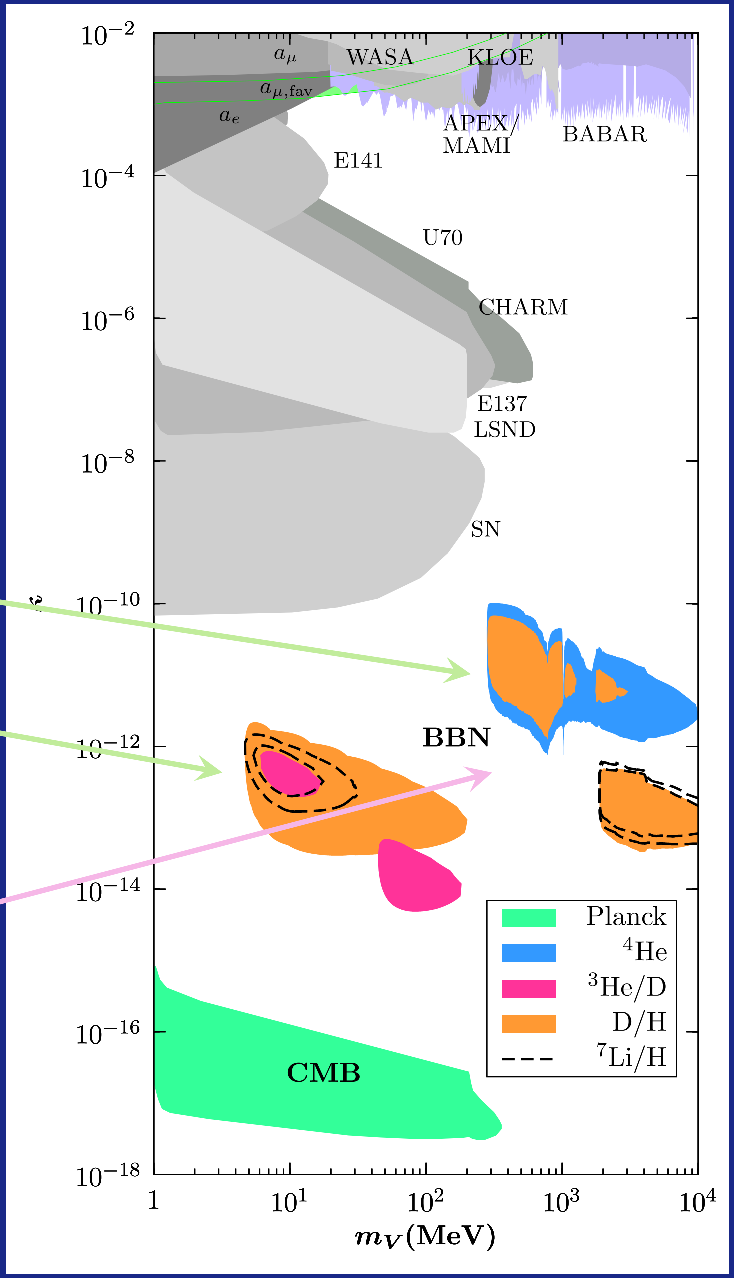
Dark Photons

Fradette et al (2014):
Dark photon decay during and after BBN

n to p interconversion

enhanced photodissociation

entropy dilution (in progress)



Proton Transmutation

Vasquez et al (2012):
Sensitivity study late-time neutron injection by transmuting protons

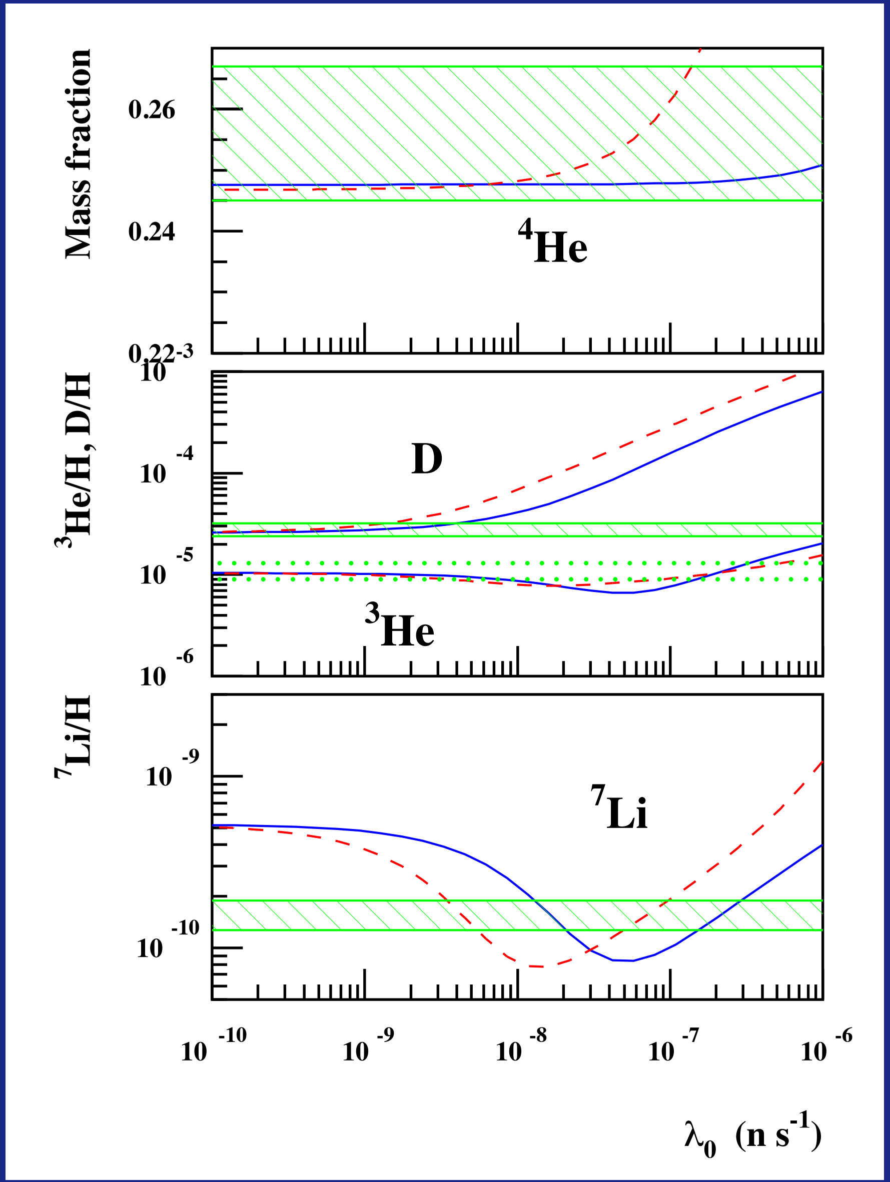
$$p \rightarrow n$$

Solid-blue lines

$$\lambda = \lambda_0 e^{-t/\tau_p}$$

Red-dashed lines

$$\lambda = \lambda_0 \left(\frac{T}{T_c}\right)^3$$



Heavy Sterile Neutrino Decay

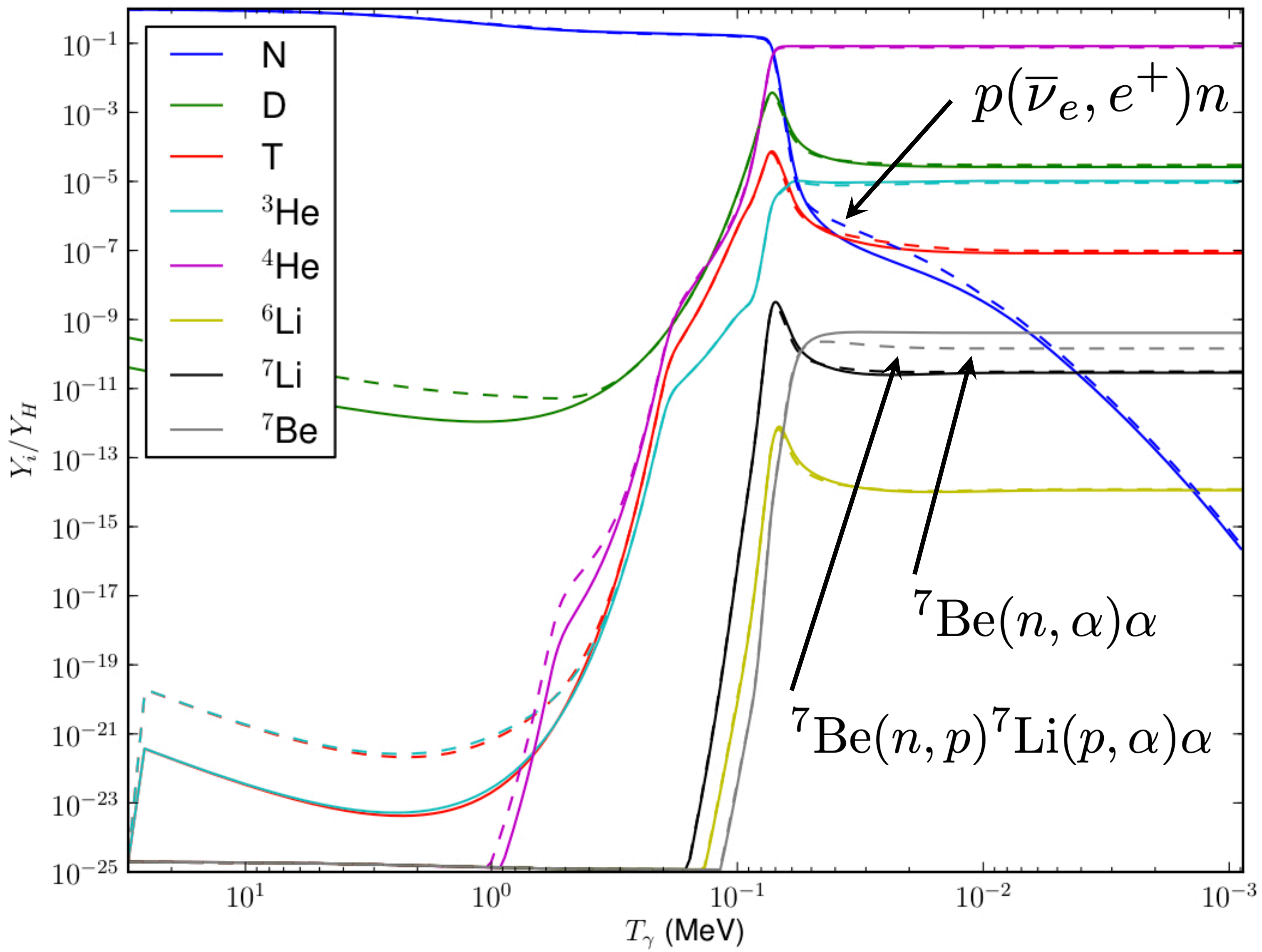
Sterile neutrino decays into mesons and leptons

Dashed Lines:

$$m_s = 300\,\mathrm{MeV}$$

$$\tau_s = 4.0\,\mathrm{s}$$

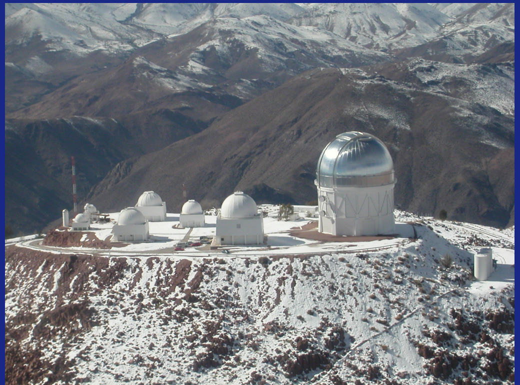
$$N_{\mathrm{eff}} \sim 2.5$$



THE COMING ERA OF PRECISION COSMOLOGY

I. CMB Stage-IV and others
   A. Simons Observatory - Atacama Desert, Chile
   B. South Pole Observatory - South Pole
   C. Other CMB experiments - CLASS and QUIET

II. Thirty-meter class telescopes
   A. EELT and GMT - Atacama
   B. TMT – Mauna Kea, Hawaii



III. Surveys
   A. DES - Cerro Tololo, Chile
   B. DESI - Kitt Peak, AZ
   C. LSST – Cerro Pachón, Chile

Summary and Conclusions

1. Standard BBN theoretically well-understood
2. Observations
   a) D/H excellent agreement with CMB
   b) Potential to measure Y_P to same precision as D/H
3. Lithium is a problem
   a) No evidence for stellar solutions
   b) Primordial solutions must preserve D/H
4. Precision Cosmology next decade

Observations will drive the Theory!

Helium vs. Neutron lifetime