Precision constraints on nuclear and neutrino reactions via Big Bang nucleosynthesis

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LA-UR-18-24541

CIPANP Palm Springs
2018 May 29

Outline

- **Motivation -- use BBN* to:**
  - Observations
  - Applied: constrain light nuclear reactions at few percent level
  - Fundamental: constrain neutrino & beyond standard model (BSM) physics

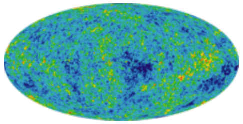
Objective: sub-percent accuracy on light element abundances

- **Overview**
  - BBN
  - Reaction network of light nuclei
  - Neutrino (semi-classical & quantum) kinetic equation energy transport
- **Results**

***BBN = ‘big bang’ or ‘primordial nucleosynthesis’**

The 'Big Five' observations

***Exciting* situation developing** . . . because of the advent of . . .



- comprehensive cosmic microwave background (CMB) observations (CMB-S4)
  - N_{eff} : "effective number" of relativistic species; Y_p : ^{4}He mass fraction (relative to proton); η (Ω_b): baryon-to-photon number fraction; Primordial deuterium abundance $(D/H)_p$; Σm_ν
- 10/30-meter class, adaptive optics, and orbiting observatories
  - e.g., precision determinations of deuterium abundance dark energy/ matter content, structure history etc.
- Laboratory neutrino mass/mixing measurements
  - mini/micro-BooNE, EXO, LBNE

This is setting up an over-determined situation where ***new*** Beyond Standard Model **neutrino physics** may manifest

Motivation (I): light nuclear reactions

- Light nuclear reaction cross sections
  - *Ab initio* many-body approaches to reaction theory
    - GFMC; NCSM; CHSH; RGM; ...
  - Phenomenological approaches
    - Multichannel unitary R-matrix; non-linear constraint

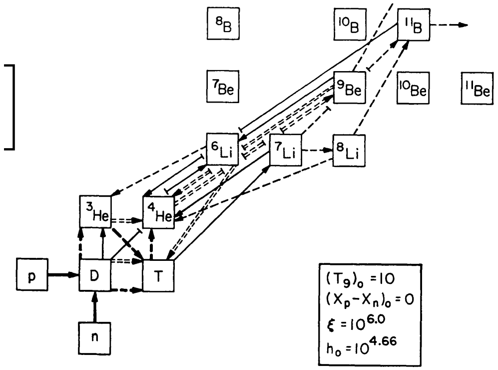
$$T_{fi} - T_{fi}^{\dagger} = 2i \sum_{n} T_{fn}^{\dagger} \rho_n T_{ni}$$

  - Improve current theoretical/phenom. accuracies to ~ few %
    - Recent [*Marcucci etal: PRL116,102501'16*] d(p, γ)^{3}He modifies S-factor by 10%
- Nuclear reaction network

$$\frac{dY_{\alpha_1}}{dt} = \sum_{\alpha_2 \beta} \Big[- n_b \langle v_{\beta\alpha} \sigma_{\beta\alpha} \rangle Y_{\alpha_1} Y_{\alpha_2} + n_b \langle v_{\beta\alpha} \sigma_{\alpha\beta} \rangle Y_{\beta_1} Y_{\beta_2} \Big]$$

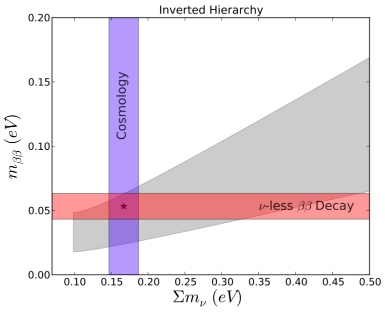
  - determine completeness/accuracy of NRN
  - Verification & validation of

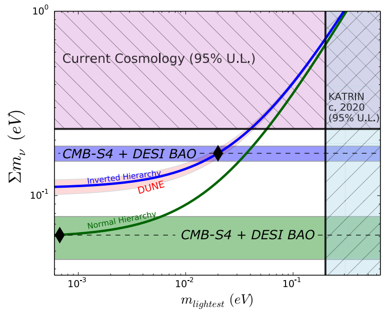
    light nuclear reaction data



Motivation (II): neutrinos, BSM

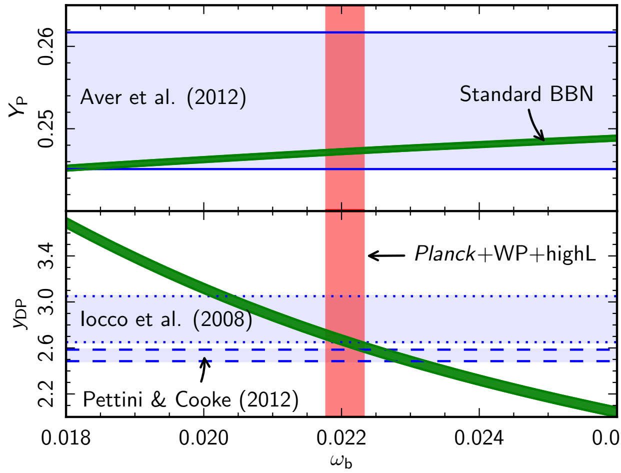
- Neutrino properties from precision cosmology
  - lepton number violation
  - Σm_ν; ***NB:*** dependence on neutrino spectra





CMB-S4 SB

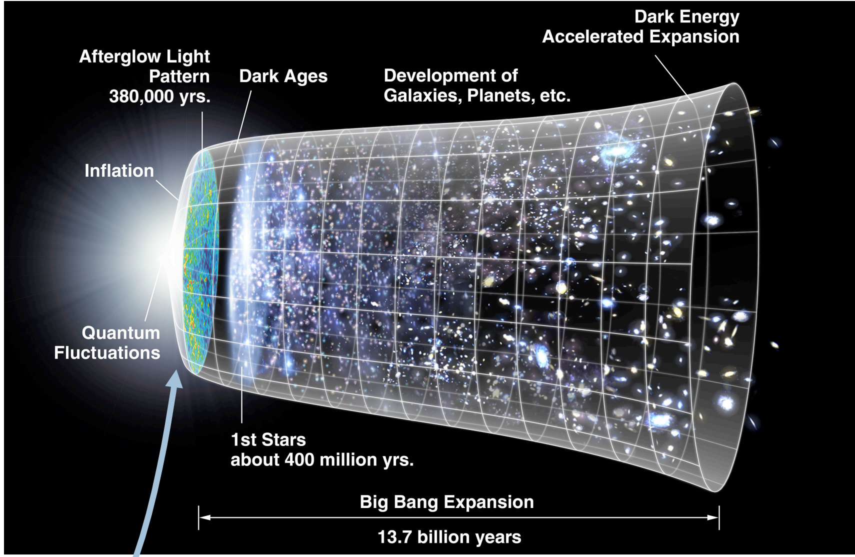
- BSM: Develop ability to test array of scenarios
  - Requires sub-percent precision abundances
  - Sterile neutrinos; heavy particle decay
    - see Friday talk G. Fuller @ NMNM/TSEI: Parallel 8

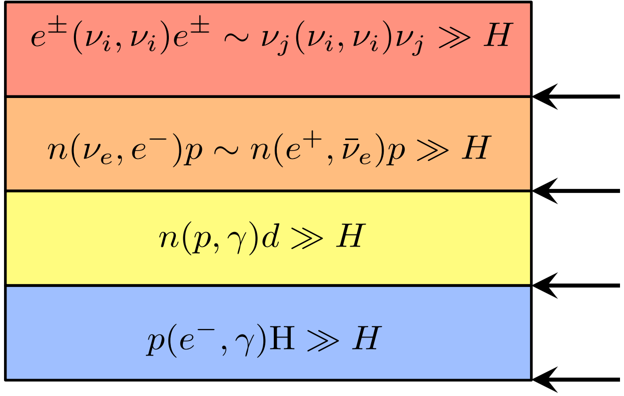


PlanckXVI(2014)

BBN briefly (I)

- Prior to CMB formation
- Expansion driven freeze-outs
  - Hubble rate datum
- Idealization
  - reality: epochs overlap significantly





H : Hubble rate

$e^{\pm}(\nu_i,\nu_i)e^{\pm} \sim \nu_j(\nu_i,\nu_i)\nu_j \gg H$

Weak Decoupling (T~1 MeV)

$n(\nu_e,e^-)p \sim n(e^+,\bar{\nu}_e)p \gg H$

Weak Freeze-Out (T~.7 MeV)

$n(p,\gamma)d \gg H$

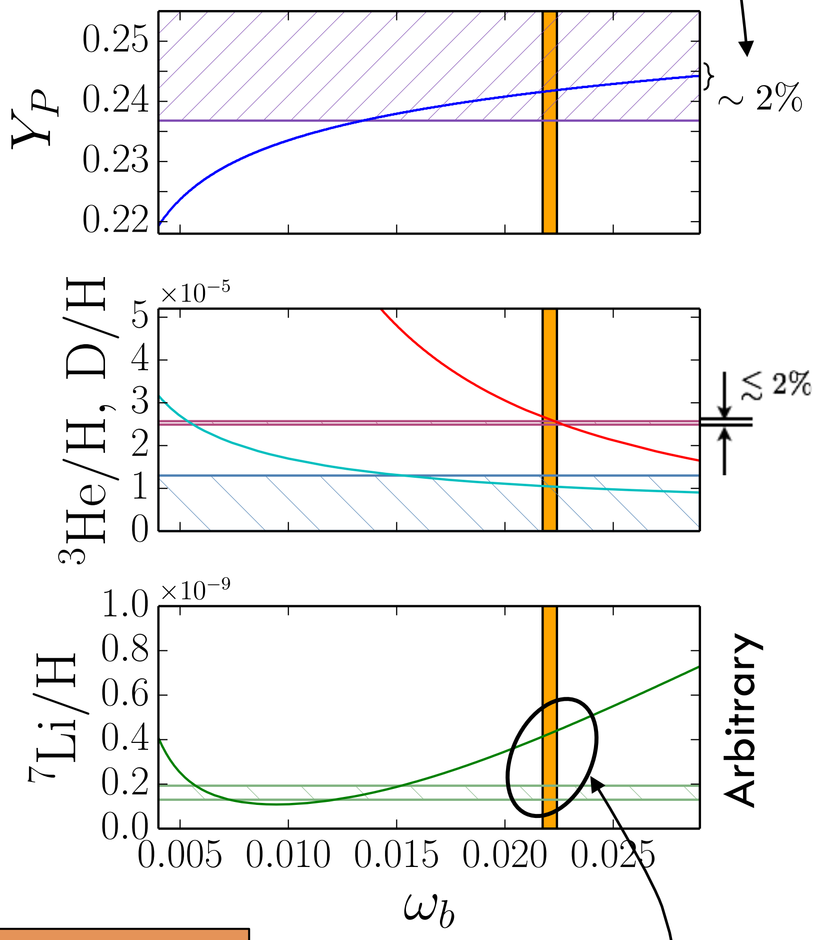
NSE Freeze-Out (T~10's keV)

$p(e^-,\gamma)\mathrm{H} \gg H$

Recombination (T~0.2 eV)

BBN briefly (II)

- Early FLRW universe
  - Homogeneous & isotropic
  - Hubble expansion drives out-of-equilibrium dynamics
  - Cooling thermonuclear fusion reactor
    - nuclei bathed in neutrinos/photons
    - produces ^{4}He (Y_P), D, ^{3}He & ^{7}Li
    - NB: out-of-equilibrium
- Status of observation
  - [now] ↦ [planned]
  - $Y_P \sim 5\% \mapsto \sim 1\%$
  - D/H $\sim 2\% \mapsto \lesssim O(1\%)$
  - ^{7}Li $\sim O(50\%) \mapsto O(\text{few }\%)$



Precision effects viz. BURST

^{7}Li problem

BBN briefly (II)

Precision effects viz. BURST

- Early FLRW universe
  - Homogeneous & isotropic
  - Hubble expansion drives out-of-equilibrium dynamics
  - Cooling thermonuclear fusion reactor
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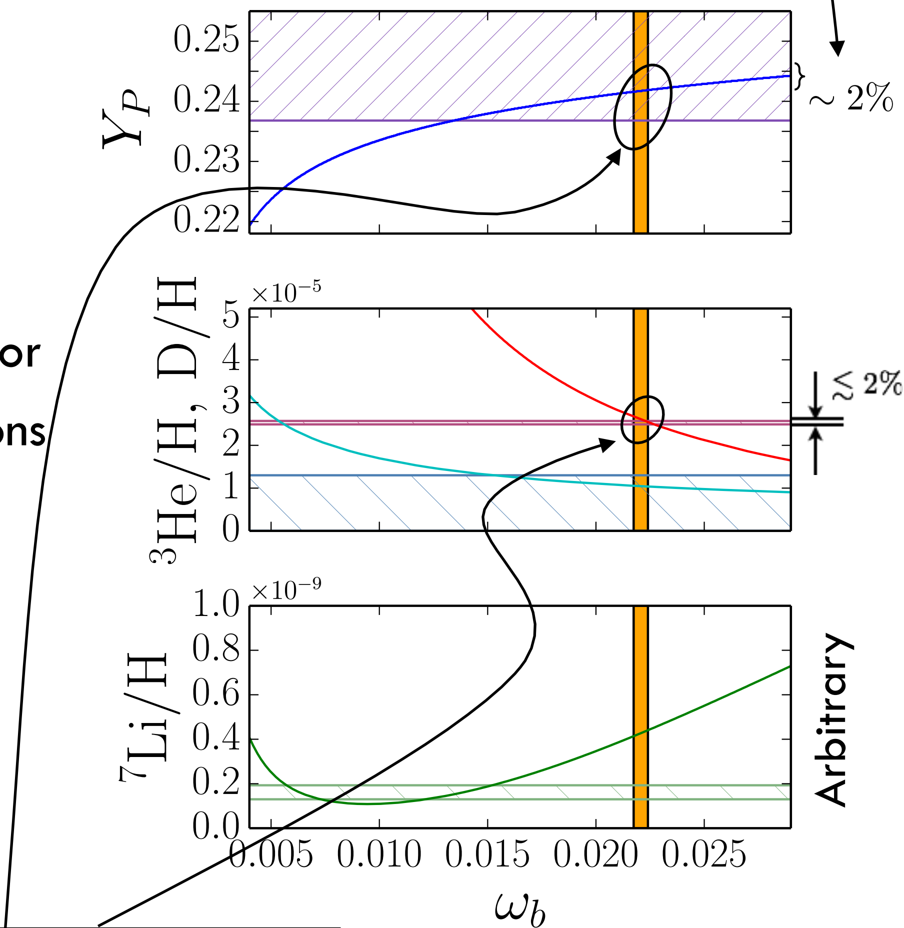


^{4}He & D are potentially more interesting than ^{7}Li

Self-consistent neutrino transport

- “Self-consistent”
  - Previous approaches evolve neutrinos and ‘post-process’ BBN
    - ΔY_P~0.05%: very small; currently unmeasurable
  - Current approach solves neutrino energy transport and BBN ***concurrently***
    - ΔY_P~1%: possibly observable with ELT’s
- Neutrino energy transport in the early universe
  - Solve the neutrino quantum kinetic equations
    - Allow lepton number asymmetry
    - *18:10 [340] Neutrino Flavor Transformation and the Cosmic Lepton Asymmetry JOHNS, Luke [Friday NMNM/TSEI Parallel 8]*
  - Describe e^+/e^-/photon/baryon plasma in terms of equilibrium distributions for all times/temperatures

Neutrino Boltzmann kinetic equation

[PRD93.083522.2016]

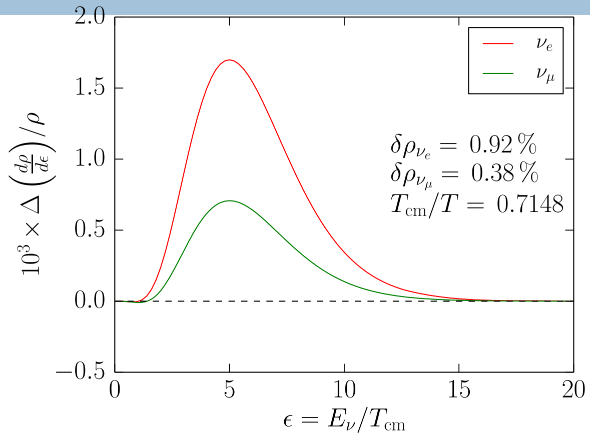
☐ Semi-classical kinetics

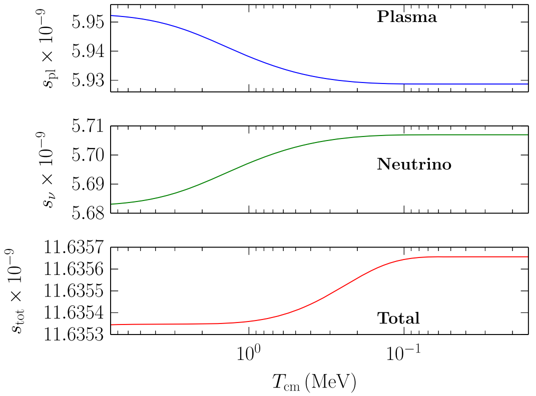
$$\left[\frac{\partial}{\partial t} - H(a)p\frac{\partial}{\partial p}\right] f_{\nu_i}(p,t) = C_{\nu_i}[f_j].$$

$$C^{(r)}_{\nu_1}[f_j] = \frac{1}{2E_1}\int \frac{d^3p_2}{(2\pi)^3 2E_2}\frac{d^3p_3}{(2\pi)^3 2E_3}\frac{d^3p_4}{(2\pi)^3 2E_4} \times (2\pi)^4\delta^{(4)}(P_1+P_2-P_3-P_4)S_r\langle|\mathcal{M}_r|^2\rangle \times F_r(p_1,p_2,p_3,p_4),$$

$$\begin{gathered}
\nu_i + \nu_i \leftrightarrow \nu_i + \nu_i \\
\nu_i + \nu_j \leftrightarrow \nu_i + \nu_j \\
\nu_i + \bar{\nu}_i \leftrightarrow \nu_i + \bar{\nu}_i \\
\nu_i + \bar{\nu}_j \leftrightarrow \nu_i + \bar{\nu}_j \\
\nu_i + \bar{\nu}_i \leftrightarrow \nu_j + \bar{\nu}_j \\
\nu_e + e^- \leftrightarrow e^- + \nu_e \\
\nu_{\mu(\tau)} + e^- \leftrightarrow e^- + \nu_{\mu(\tau)} \\
\nu_e + e^+ \leftrightarrow e^+ + \nu_e \\
\nu_{\mu(\tau)} + e^+ \leftrightarrow e^+ + \nu_{\mu(\tau)} \\
\nu_e + \bar{\nu}_e \leftrightarrow e^- + e^+ \\
\nu_{\mu(\tau)} + \bar{\nu}_{\mu(\tau)} \leftrightarrow e^- + e^+
\end{gathered}$$

- Effects beyond thermodynamic approach:
  - distortion of F-D equil. spectra
  - entropy generation and flow from plasma to neutrinos
  - upscattering of low-energy ν
  - nonlinearties in feedback between ν evolution and BBN
- Deviation from relativistic species' energy





Processes	$T_{\rm cm}/T$	$100 \times \delta\rho_{\nu_e}$	$100 \times \delta\rho_{\nu_\mu}$	$\Delta N_{\rm eff}$
All	0.7148	0.9282	0.3771	0.03397
10, 11	0.7147	0.9383	0.2867	0.03063
1, 2, 10, 11	0.7147	0.9268	0.2963	0.03078
1, 2, 3, 4, 5, 10, 11	0.7147	0.8557	0.3465	0.03136
6, 7, 8, 9	0.7140	0.1853	0.0639	0.00723
1, 2, 6, 7, 8, 9	0.7140	0.1724	0.0778	0.00753
1, 2, 3, 4, 5, 6, 7, 8, 9	0.7140	0.1559	0.0886	0.00763

Los Alamos
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EST. 1943

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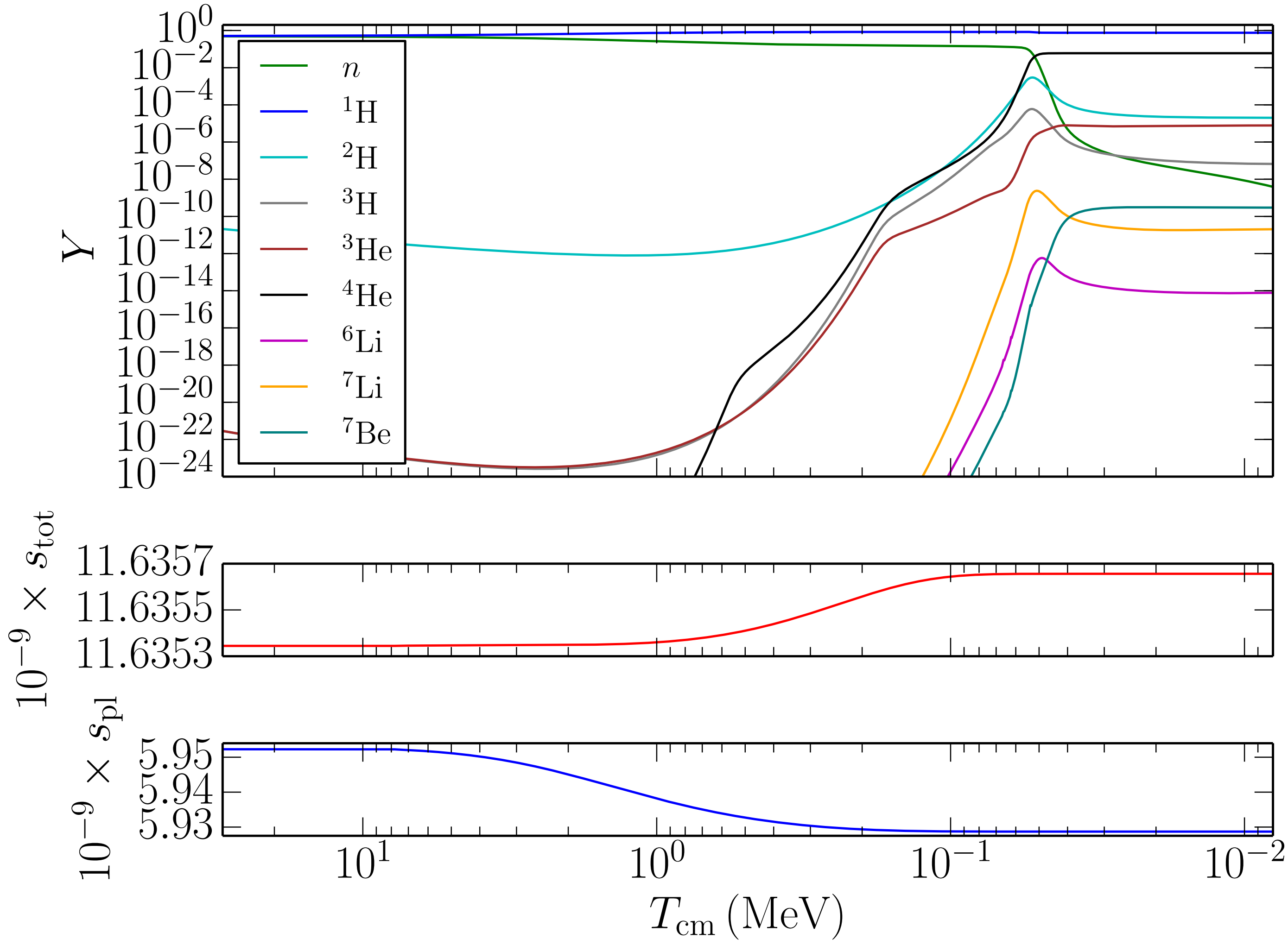
Coupled BBN/ ν kinetics



Boltzmann evolution results (I)

- "Baseline" abundances
  - uncorrected

$$Y_P^{(\mathrm{N})} \equiv X_{^4\mathrm{He}} = 0.2438,$$

$$(\mathrm{D/H})^{(\mathrm{N})} \equiv Y_\mathrm{D}/Y_\mathrm{H} = 2.627 \times 10^{-5},$$

$$(^3\mathrm{He/H})^{(\mathrm{N})} = 1.049 \times 10^{-5},$$

$$(^7\mathrm{Li/H})^{(\mathrm{N})} = 4.277 \times 10^{-10}.$$

  - Coulomb corrected

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

$$Y_P^{(\mathrm{Q})} = 0.2478,$$

$$(\mathrm{D/H})^{(\mathrm{Q})} = 2.650 \times 10^{-5},$$

$$(^3\mathrm{He/H})^{(\mathrm{Q})} = 1.052 \times 10^{-5},$$

$$(^7\mathrm{Li/H})^{(\mathrm{Q})} = 4.317 \times 10^{-10}$$

cf. PARTHENOPE $Y_P \approx 0.2473$ CPC178,956'08

cf. Pitrou *et al.* $Y_P \approx 0.2470$ j.physrep.2018.04.005

Boltzmann evolution results (II)

- Effect of transport mechanisms

Processes	Y_P	δY_P	$10^5 \times \mathrm{D/H}$	$\delta(\mathrm{D/H})$	$10^5 \times {}^3\mathrm{He/H}$	$\delta({}^3\mathrm{He/H})$	$10^{10} \times {}^7\mathrm{Li/H}$	$\delta({}^7\mathrm{Li/H})$
None	0.2438	0	2.627	0	1.049	0	4.277	0
All	0.2440	4.636×10^{-4}	2.636	3.686×10^{-3}	1.050	1.209×10^{-3}	4.260	-3.916×10^{-3}
10, 11	0.2439	2.124×10^{-4}	2.635	3.202×10^{-3}	1.050	1.048×10^{-3}	4.262	-3.650×10^{-3}
1, 2, 10, 11	0.2439	1.515×10^{-4}	2.635	3.155×10^{-3}	1.050	1.032×10^{-3}	4.261	-3.672×10^{-3}
1, 2, 3, 4, 5, 10, 11	0.2439	2.415×10^{-4}	2.635	3.148×10^{-3}	1.050	1.029×10^{-3}	4.262	-3.543×10^{-3}
6, 7, 8, 9	0.2440	6.730×10^{-4}	2.629	1.002×10^{-3}	1.049	3.348×10^{-4}	4.276	-3.536×10^{-4}
1, 2, 6, 7, 8, 9	0.2440	5.455×10^{-4}	2.629	9.034×10^{-4}	1.049	3.001×10^{-4}	4.275	-3.972×10^{-4}
1, 2, 3, 4, 5, 6, 7, 8, 9	0.2440	5.533×10^{-4}	2.629	8.981×10^{-4}	1.049	2.981×10^{-4}	4.276	-3.797×10^{-4}

1 $\nu_i + \nu_i \leftrightarrow \nu_i + \nu_i$

2 $\nu_i + \nu_j \leftrightarrow \nu_i + \nu_j$

3 $\nu_i + \bar{\nu}_i \leftrightarrow \nu_i + \bar{\nu}_i$

4 $\nu_i + \bar{\nu}_j \leftrightarrow \nu_i + \bar{\nu}_j$

5 $\nu_i + \bar{\nu}_i \leftrightarrow \nu_j + \bar{\nu}_j$

6 $\nu_e + e^- \leftrightarrow e^- + \nu_e$

7 $\nu_{\mu(\tau)} + e^- \leftrightarrow e^- + \nu_{\mu(\tau)}$

8 $\nu_e + e^+ \leftrightarrow e^+ + \nu_e$

9 $\nu_{\mu(\tau)} + e^+ \leftrightarrow e^+ + \nu_{\mu(\tau)}$

10 $\nu_e + \bar{\nu}_e \leftrightarrow e^- + e^+$

11 $\nu_{\mu(\tau)} + \bar{\nu}_{\mu(\tau)} \leftrightarrow e^- + e^+$

Boltzmann evolution results (II)

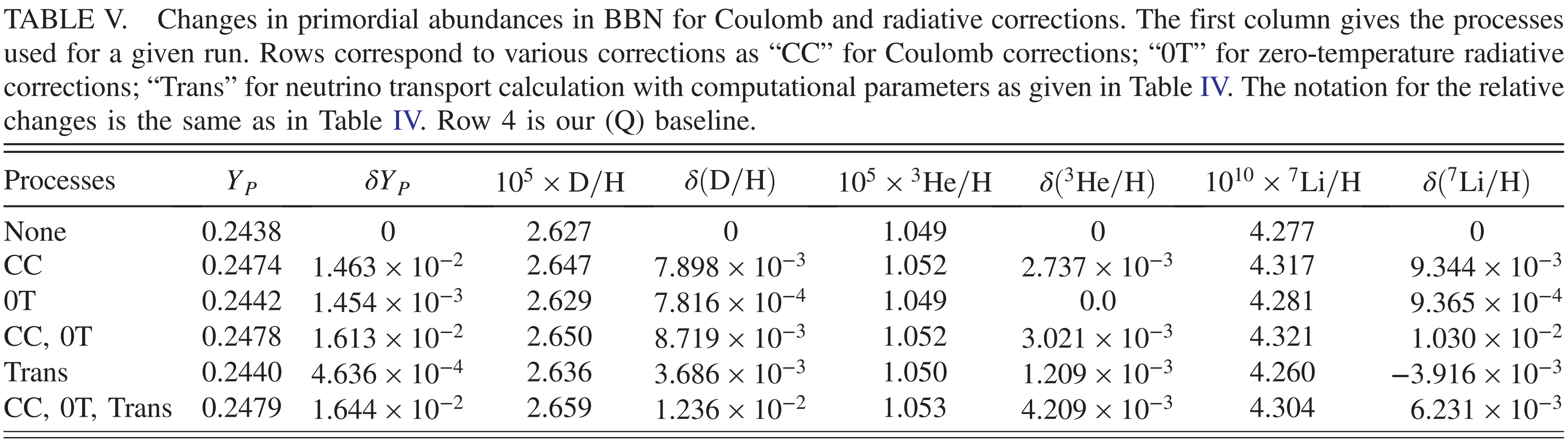


TABLE V. Changes in primordial abundances in BBN for Coulomb and radiative corrections. The first column gives the processes used for a given run. Rows correspond to various corrections as "CC" for Coulomb corrections; "0T" for zero-temperature radiative corrections; "Trans" for neutrino transport calculation with computational parameters as given in Table IV. The notation for the relative changes is the same as in Table IV. Row 4 is our (Q) baseline.

Processes	Y_P	δY_P	$10^5 \times \mathrm{D/H}$	$\delta(\mathrm{D/H})$	$10^5 \times {}^3\mathrm{He/H}$	$\delta({}^3\mathrm{He/H})$	$10^{10} \times {}^7\mathrm{Li/H}$	$\delta({}^7\mathrm{Li/H})$
None	0.2438	0	2.627	0	1.049	0	4.277	0
CC	0.2474	1.463×10^{-2}	2.647	7.898×10^{-3}	1.052	2.737×10^{-3}	4.317	9.344×10^{-3}
0T	0.2442	1.454×10^{-3}	2.629	7.816×10^{-4}	1.049	0.0	4.281	9.365×10^{-4}
CC, 0T	0.2478	1.613×10^{-2}	2.650	8.719×10^{-3}	1.052	3.021×10^{-3}	4.321	1.030×10^{-2}
Trans	0.2440	4.636×10^{-4}	2.636	3.686×10^{-3}	1.050	1.209×10^{-3}	4.260	-3.916×10^{-3}
CC, 0T, Trans	0.2479	1.644×10^{-2}	2.659	1.236×10^{-2}	1.053	4.209×10^{-3}	4.304	6.231×10^{-3}

$$\boxed{\begin{aligned}\delta Y_P &= +1.64\% \\ \delta(D/H) &= +1.24\%\end{aligned}}$$

- "All": all antineutrinos/neutrinos on charged leptons and n & p
- Non-linear dependence on included processes
- Perhaps observable with next-generation instruments

Neutrino quantum kinetic equations (QKE)

PHYSICAL REVIEW D **89,** 105004 (2014)
Vlasenko-Fuller-Cirigliano

$$i d_t f(p,t) = \left[\Omega(p) + \sqrt{2} G_F \left(L + \tilde{L}\right) - \frac{8\sqrt{2} G_F p}{3 m_W^2} \left(E + \cos^2\theta_W \tilde{E}\right), f(p,t)\right] + iC[p,f]$$

$$i d_t \bar{f}(p,t) = \left[-\Omega(p) + \sqrt{2} G_F \left(L + \tilde{L}\right) + \frac{8\sqrt{2} G_F p}{3 m_W^2} \left(E + \cos^2\theta_W \tilde{E}\right), \bar{f}(p,t)\right] + i\bar{C}[p,\bar{f}]$$

$$L_{\alpha\beta} = 2\,\delta_{\alpha\beta} \int d_3q \left(g_\alpha(q) - \bar{g}_\alpha(q)\right) \qquad E_{\alpha\beta} = 2\,\delta_{\alpha\beta} \int d_3q\, E_\alpha \left(1 - \frac{m_\alpha^2}{4\,E_\alpha^2}\right) \left(g_\alpha(E_\alpha) + \bar{g}_\alpha(E_\alpha)\right)$$

$$\tilde{L} = \int d_3q \left(f(q,t) - \bar{f}(q,t)\right) \qquad \tilde{E} = \int d_3q\, q \left(f(q,t) + \bar{f}(q,t)\right)$$

$$\Omega(p) = \sqrt{p^2 + M^2} \simeq p + \frac{M^2}{2p} + \cdots$$

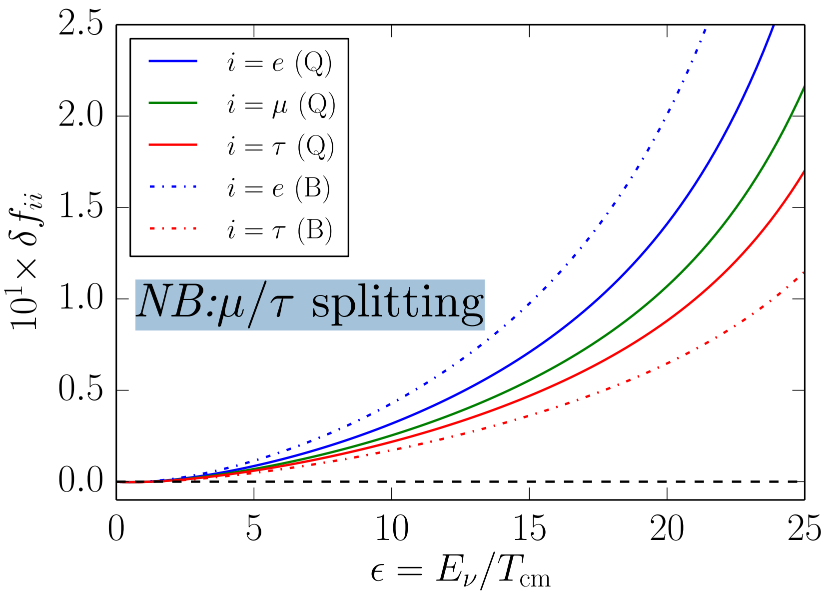
$$M^2 = U_{PMNS}\ M_d^2\ U_{PMNS}^\dagger \qquad M_d^2 = diag(m_1^2, m_2^2, m_3^2)$$

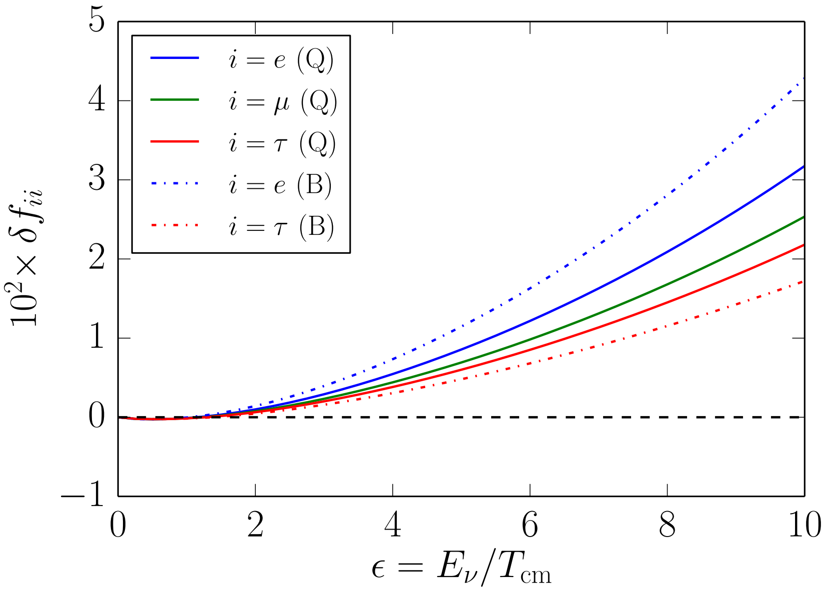
- Non-eq. FT:
  - Wigner transform ν 2-pt function $G^{\alpha\dot{\alpha}}_{\nu,IJ}(x,y) = \langle \hat{\mathrm{T}}_P(\psi^\alpha_I(x)\psi^{\dagger\dot{\alpha}}_J(y))\rangle$
  - Derivative/loop expansion (x,k); small: $\frac{\partial_x, M, \Sigma}{E} = O(\epsilon)$ $\frac{\Pi_\rho, \Pi_F}{E} = O(\epsilon^2)$
  - Assume homogeneity & isotropy
  - Resulting terms: vacuum, lepton asymmteric (L) and symmetric (E) “coherent”/”self”, collision
  - Folklore: “coherent: collective; collision: incoherent” --- STAY TUNED.

Neutrino non-equilibrium results

Employing the time- and momentum-dependent co-rotating frame transformation largely decouples the ultra-high frequency neutrino vacuum oscillations.

$$\tilde{f}(p,t) = e^{-it\Omega(p,t)} f(p,t) e^{+it\Omega(p,t)}$$





- (Q)QKE, ν scatt+vacuum osc.
- (B)Boltzmann, full
- T ~ 0.5 MeV
- **flavor not equilibrated**

Conclusion/Outlook

- Include full standard model/quantum theory:
  - Non-equilibrium field theoretic ***neutrino quantum kinetics***
  - Flavor oscillations: we've shown for the first time that in the self-consistent approach the neutrino flavors have not 'equilibrated' as BBN is starting
  - Test nuclear reactions & BSM scenarios that may affect BBN
- Time/momentum dependent co-rotating frame improves straightforward method by factor of 20 computing time
  - convergence properties undergoing testing
- Related work
  - testing the validity of the assumption of homogeneity and isotropy in the early universe
    - neutrino flavor oscillations can (do?) affect this
    - *S. Shalgar [Friday, NMNM / TSEI: Parallel 8 — Neutrinos and Symmetries (16:10-18:30)]*

Follow-on material

Collaboration

- University
  - G. Fuller (UCSD), L. Johns (UCSD)
  - C. Kishimoto (USD)
- LANL
  - D. Blaschke, V. Cirigliano, E. Grohs, S. Shalgar, M. Paris

Selected recent publications:

[1] Vincenzo Cirigliano, Mark W. Paris, and Shashank Shalgar. Effect of collisions on neutrino flavor inhomogeneity in a dense neutrino gas. *Physics Letters B*, 774:258 – 267, 2017.

[2] Shashank Shalgar. Multi-angle calculation of the matter-neutrino resonance near an accretion disk. *Journal of Cosmology and Astroparticle Physics*, 2018(02):010, 2018.

[3] E. Grohs, George M. Fuller, C. T. Kishimoto, and Mark W. Paris. Lepton asymmetry, neutrino spectral distortions, and big bang nucleosynthesis. *Phys. Rev.*, D95(6):063503, 2017.

[4] E. Grohs and George M. Fuller. Insights into neutrino decoupling gleaned from considerations of the role of electron mass. *Nuclear Physics B*, 923:222 – 244, 2017.