Big Bang Nucleosynthesis simulations for ^{2}H abundance predictions

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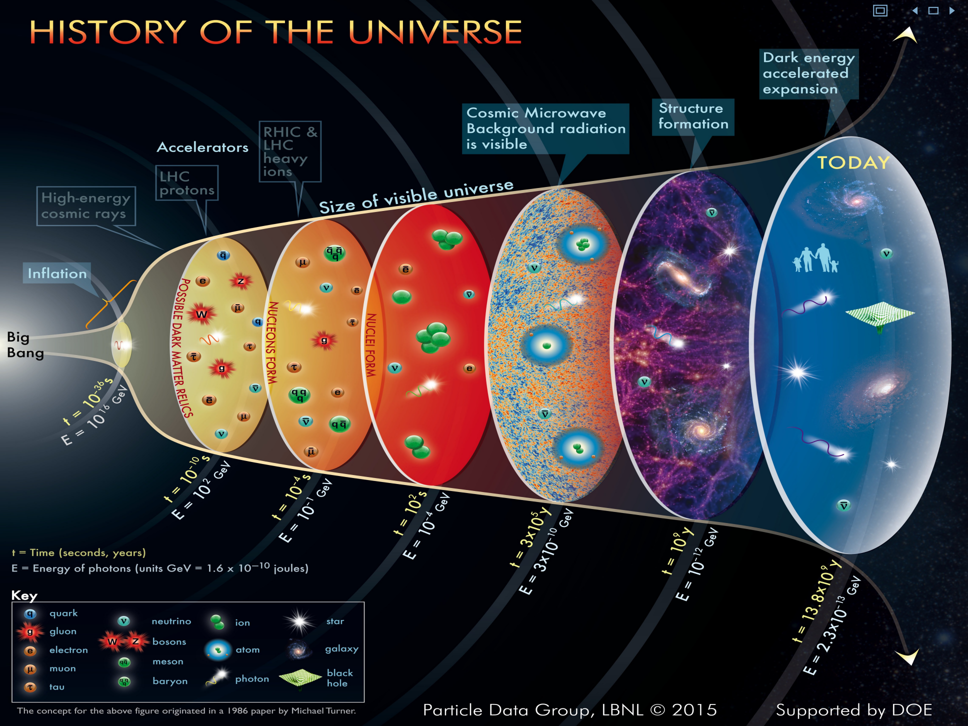
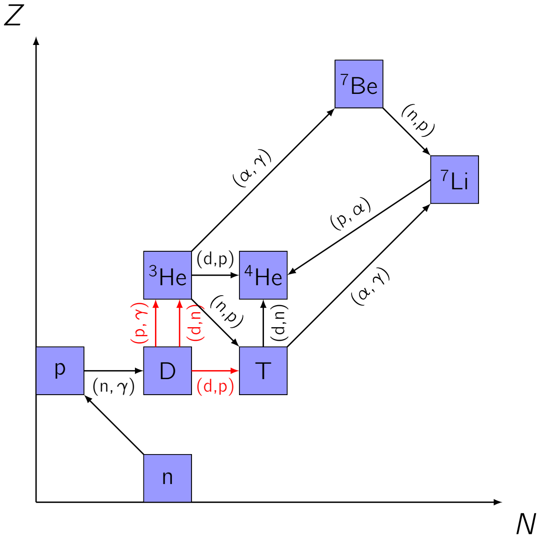
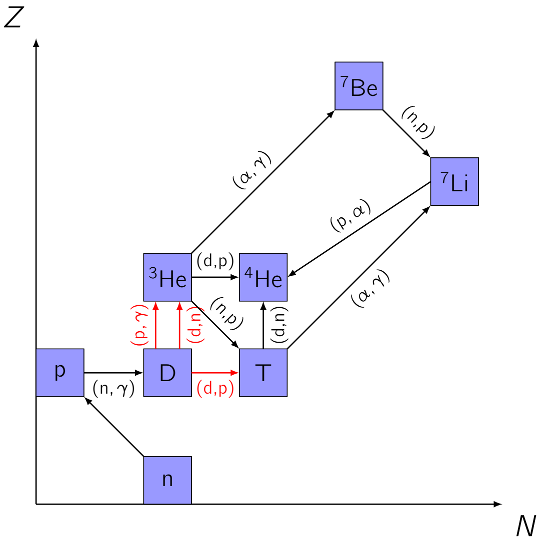

HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE

Big Bang Nucleosynthesis I: Motivation



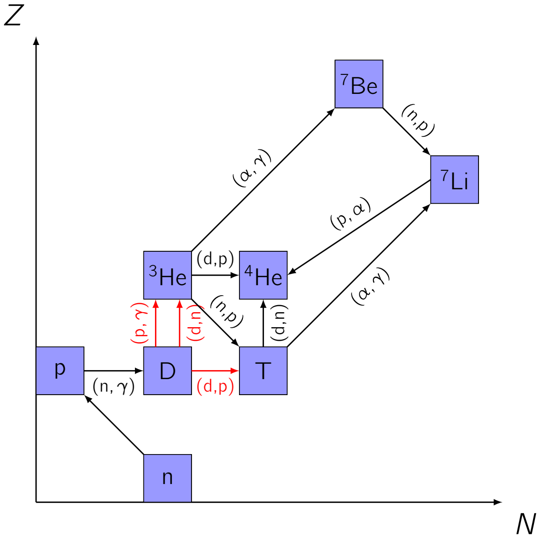
- Interplay of particle-/nuclear physics and general relativity

Big Bang Nucleosynthesis I: Motivation



- Interplay of particle-/nuclear physics and general relativity
- Prediction of light isotope abundances (mainly D,^{4}He and ^{7}Li)

Big Bang Nucleosynthesis I: Motivation



- Interplay of particle-/nuclear physics and general relativity
- Prediction of light isotope abundances (mainly D,^{4}He and ^{7}Li)
- Tool for probing our understanding of the early universe

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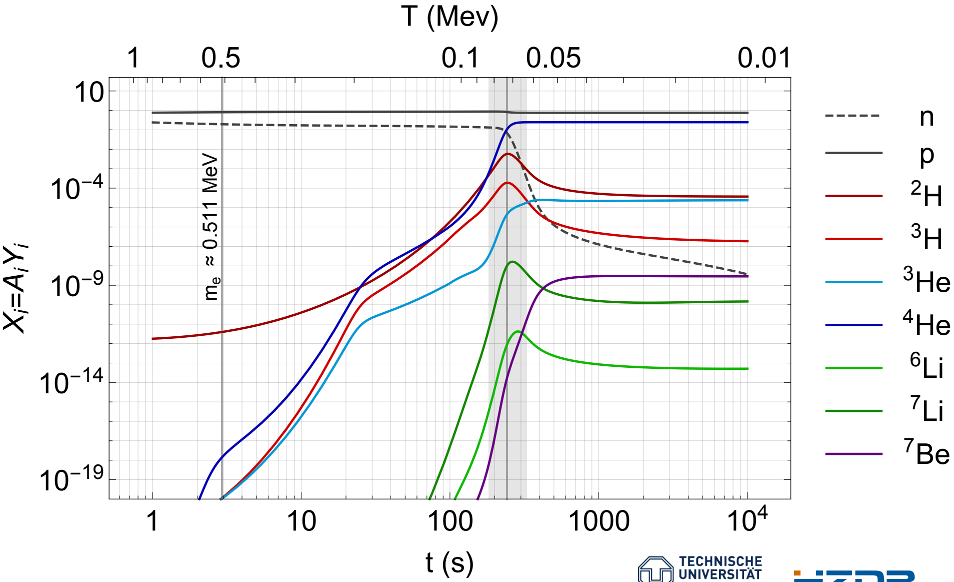
Big Bang Nucleosynthesis I: Motivation



Big Bang Nucleosynthesis II: Cosmology

- Einstein's field equations:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = 8\pi G_{\mathrm{N}} T_{\mu\nu}$$

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- Einstein's field equations:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = 8\pi G_{\mathrm{N}} T_{\mu\nu}$$

- Assumptions:
  - Cosmological principle: spatial homogeneity and isotropy
  - flat space time geometry without spatial curvature
  - radiation dominated cosmos

Big Bang Nucleosynthesis II: Cosmology

- 1st Friedmann Equation:

$$H^2 \equiv \frac{\dot{K}(t)}{K(t)} = \frac{8\pi}{3} G_\mathrm{N} \rho(t)$$

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Big Bang Nucleosynthesis II: Cosmology

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$$\frac{K_0 T_0}{KT} = \mathcal{S}(T)^{1/3} \Rightarrow K(T) = \frac{K_0 T_0}{T \mathcal{S}(T)^{1/3}}$$

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$\longrightarrow$ need to know $\rho(T)$.

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Big Bang Nucleosynthesis II: Cosmology

- Total energy density:

$$\rho = \rho_\nu + \rho_{\text{pl}} + \rho_{\text{b}} + \rho_{\text{cdm}}$$

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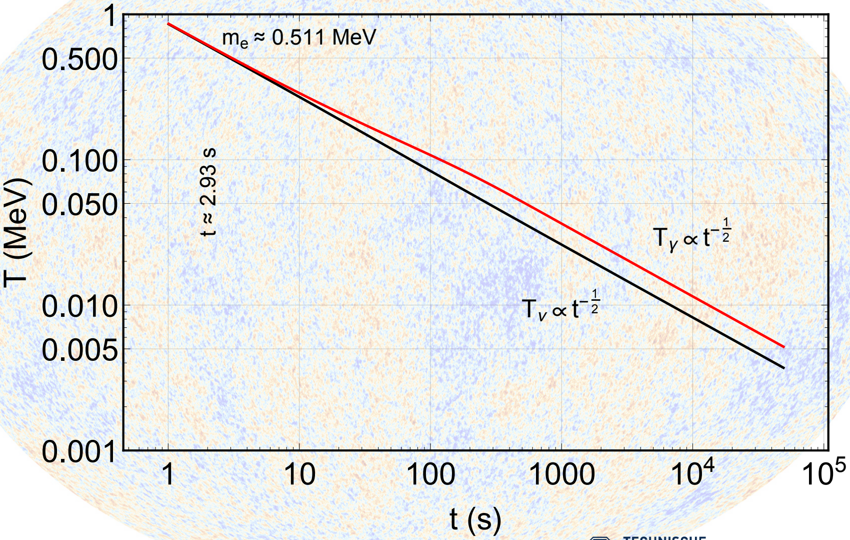
- (cold) Baryon density:

$$\rho_{\mathrm{b}} = n_{\mathrm{b}} m_{\mathrm{b}} = \left(\frac{K_0}{K}\right)^3 \rho_{\mathrm{c}} \Omega_{\mathrm{b}} h^2, \quad \frac{n_{\mathrm{b}} T}{\rho_\gamma} = \frac{\bar{n}_{\mathrm{b}}}{\bar{\rho}_\gamma} \propto \eta \ll 1$$

Big Bang Nucleosynthesis II: Cosmology



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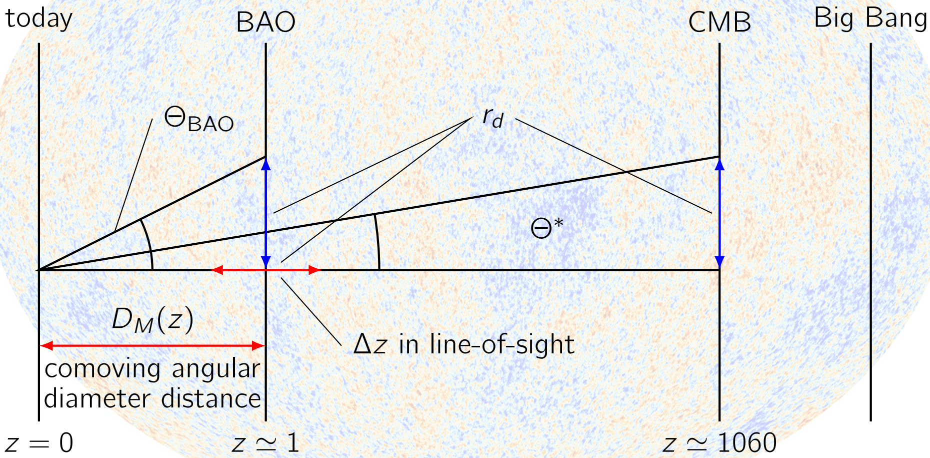
Basics of BAO Cosmology

BAO = Baryon Acoustic Oscillations
(sketch not to scale, adapted from Antony Lewis)



Basics of BAO Cosmology

BAO = Baryon Acoustic Oscillations

- Observables:
  - aperture: $\Theta_{\mathrm{BAO}} = r_d / D_M(z) = r_d / ((1+z)\int_0^z dz'/H(z'))$
  - redshift intervals: $\Delta z = H(z) r_d$

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- Sound horizon of baryon-photon-fluid:

$$r_d = \left(3\left(1 + \frac{3\omega_{\mathrm{b}}}{4\Omega_{\mathrm{r}} h^2}\right)\right)^{-1/2} \int_{z_d}^{\infty} dz \frac{1}{H(z)}$$

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- High redshift Hubble parameter:

$$H(z) \simeq H_0\sqrt{\Omega_{\text{r}}(1+z)^4 + \Omega_{\text{m}}(1+z)^3}$$

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Basics of BAO Cosmology

BAO = Baryon Acoustic Oscillations

- i.e. Lyα BAO measurement (matter dominated universe):

$$\begin{aligned} \Theta_{\text{BAO}} &\simeq \frac{1}{2(1+z)(1-1/\sqrt{1+z})} r_d H_0 \Omega_{\text{m}}^{1/2} \\ \Delta z &\simeq (1+z)^{3/2} r_d H_0 \Omega_{\text{m}}^{1/2} \end{aligned}$$

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.. can be broken by knowing $r_d \longrightarrow \omega_{\mathrm{b}}$: BBN feature

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- $\Omega_{\mathrm{m}} - H_0$ parameter space available

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Big Bang Nucleosynthesis III: Nuclear Physics

- Abundance evolution:

$$\frac{dY_i}{dt} = \sum_{jkl} N_i \left(\Gamma_{kl \to ij} \frac{Y_l^{N_l} Y_k^{N_k}}{N_l! N_k!} - \Gamma_{ij \to kl} \frac{Y_i^{N_i} Y_j^{N_j}}{N_i! N_j!} \right)$$

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- abundances: $Y_i = \frac{n_i}{n_\mathrm{b}}$

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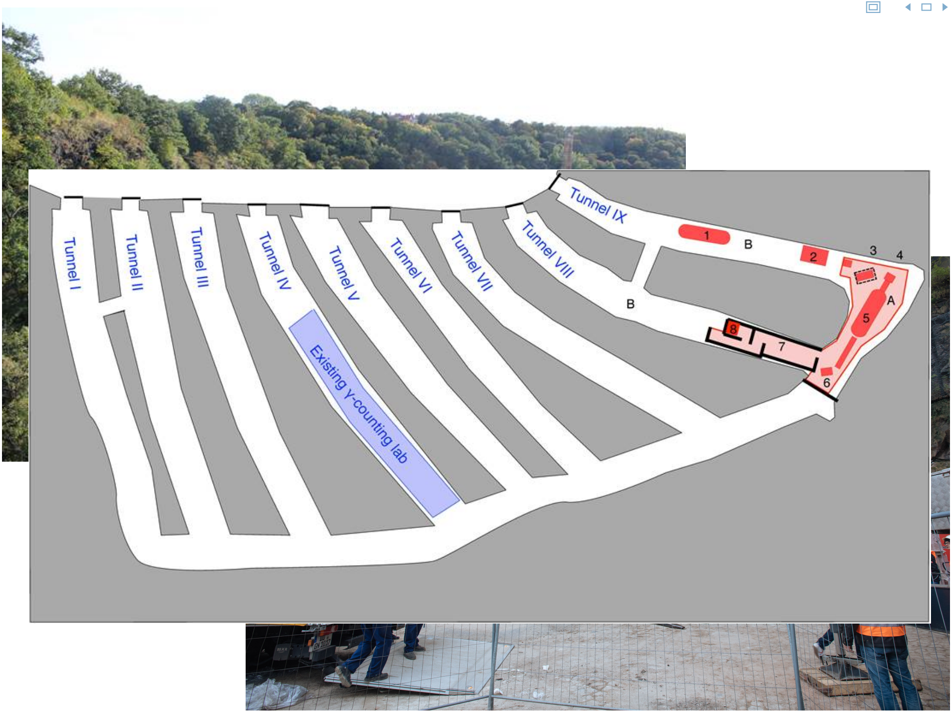
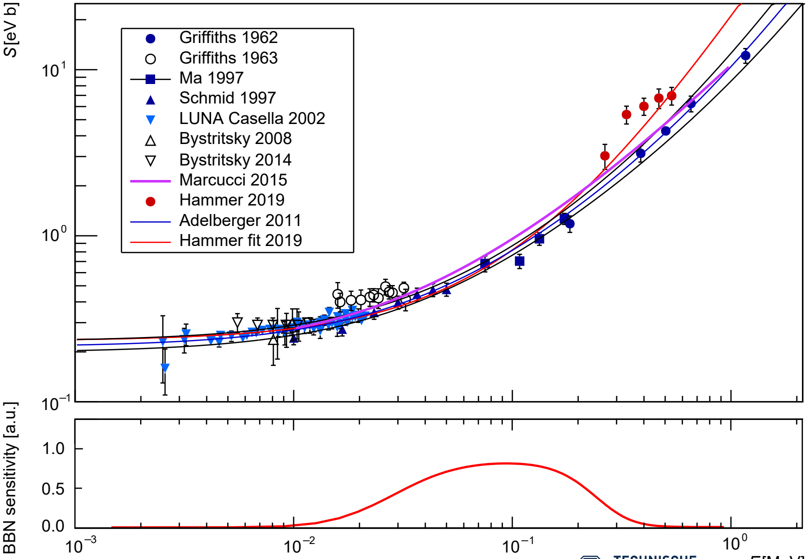
- abundances: $Y_i = \frac{n_i}{n_\mathrm{b}}$
- reaction rates: $\Gamma_{ij} \propto \langle \sigma v \rangle = \sqrt{\frac{8}{T^3 \pi \mu_{ij}}} \int_0^\infty dE E \underbrace{\sigma(E)}_{\text{Felsenkeller}} e^{-\frac{E}{T}}$

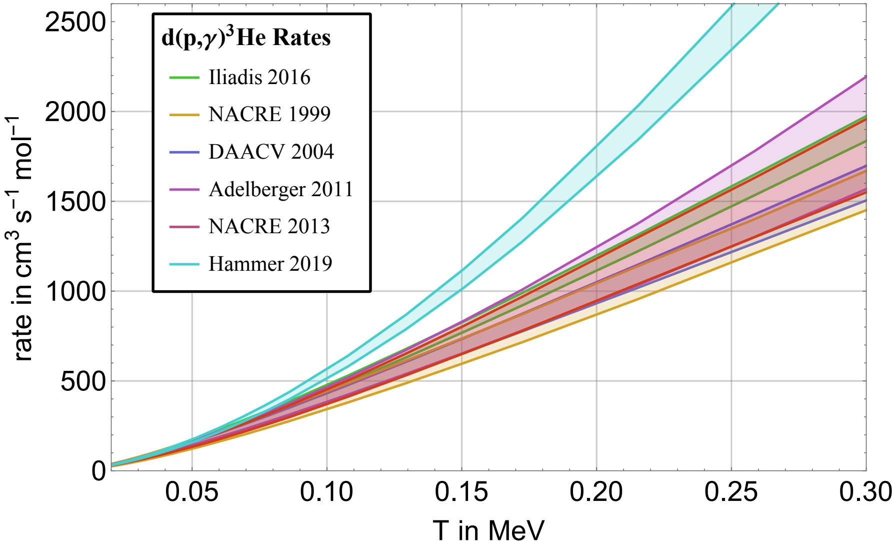


Tunnel I
Tunnel II
Tunnel III
Tunnel IV
Tunnel V
Tunnel VI
Tunnel VII
Tunnel VIII
Tunnel IX
Existing γ-counting lab
1
2
3
4
5
6
7
8
A
B
B

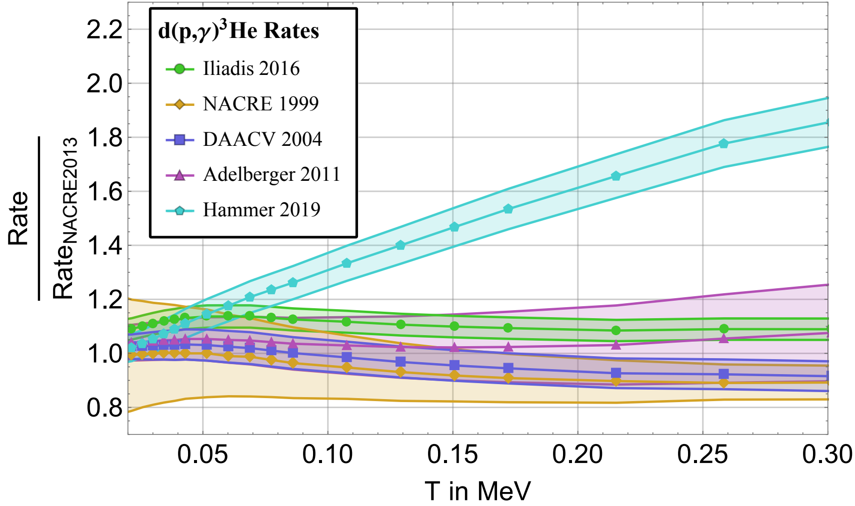
d(p,γ)^{3}He S Factor



d(p,γ)^{3}He Rate Evaluations



$d(p,\gamma)^3He$ Rate Evaluations



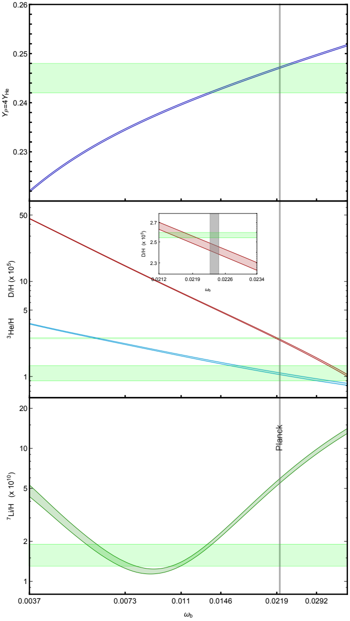
BBN Simulation with PRIMAT[1]: Parameters

[1] C. Pitrou, A. Coc, J.-P. Uzan and E. Vangioni, "Precision big bang nucleosynthesis with improved helium-4 predictions", Physics Reports **754** (2018).

- $N_\nu = 3$
  - $N_{\mathrm{eff},0} \approx 3.045$ (standard model value)
- $\alpha_{\mathrm{FS}} = \frac{e^2}{4\pi}$
- $\tau_n = (879.4 \pm 0.6)\,\mathrm{s}$ (PDG 2019)
- $\omega_\mathrm{b} \equiv \Omega_\mathrm{b} h^2 = 0.02237 \pm 0.00018$
- $N_\mathrm{eff} = 2.98 \pm 0.17$

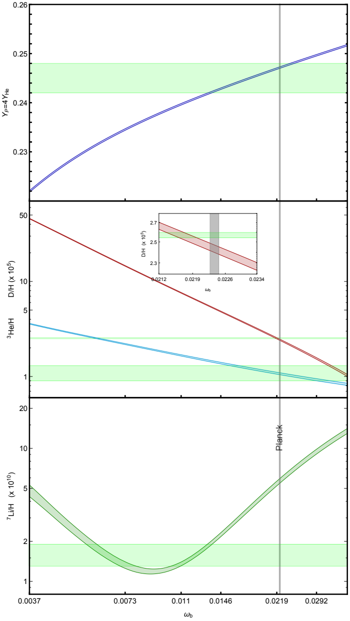
  Planck 2018 TT,TE,EE+lowE+BAO+lensing data

Big Bang Nucleosynthesis IV: Concordance Plot



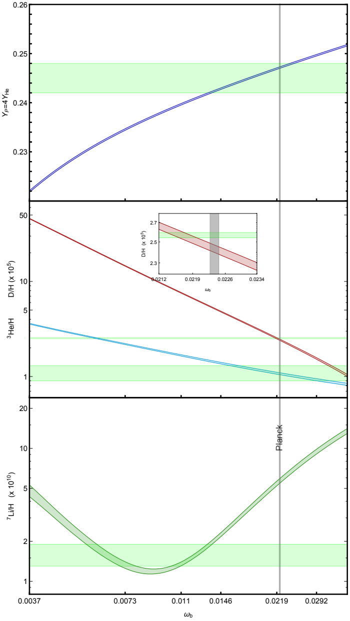
- BBN+CMB+primordial abundances

Big Bang Nucleosynthesis IV: Concordance Plot



- BBN+CMB+primordial abundances
- PDG 2018 recommended astronomical values:

Big Bang Nucleosynthesis IV: Concordance Plot



- BBN+CMB+primordial abundances
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  - ^{4}He mass fraction: $Y_\mathrm{p} = (0.245 \pm 0.003)$

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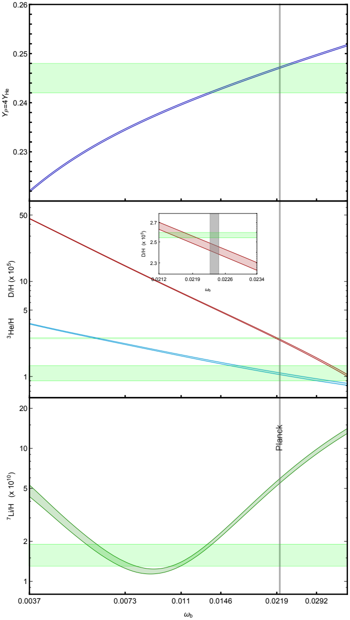
Big Bang Nucleosynthesis IV: Concordance Plot



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  - $\frac{\mathrm{D}}{\mathrm{H}} = (2.569 \pm 0.027) \times 10^{-5}$

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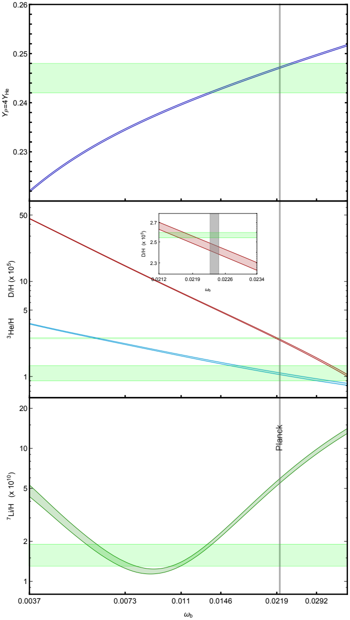

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  - ^{4}He mass fraction: $Y_p = (0.245 \pm 0.003)$
  - $\frac{D}{H} = (2.569 \pm 0.027) \times 10^{-5}$
  - $\frac{^7Li}{H} = (1.6 \pm 0.3) \times 10^{-10}$

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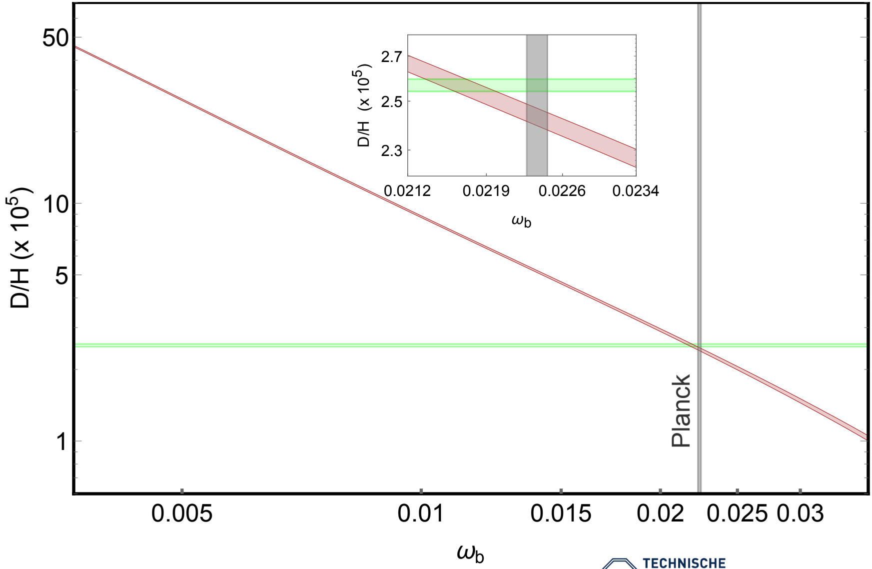
Concordance Plot: D/H



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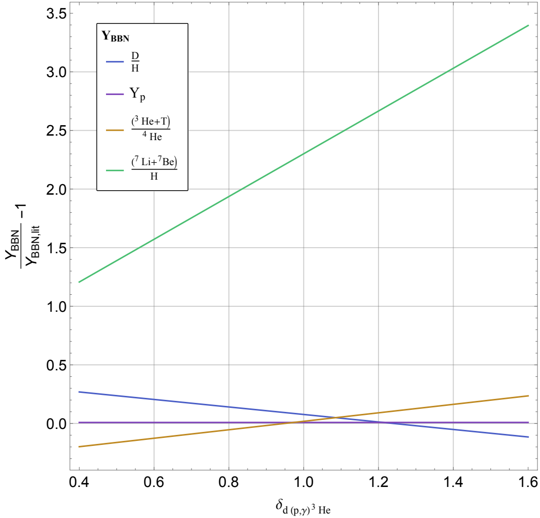
Rate Variations: $d(p,\gamma)^3He$



- $\delta_{d(p,\gamma)^3He}$: global rate factor
- Assumption: linear dependency

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Rate Variations: Overview

- Abundance sensitivity: $\frac{\Delta Y_i}{Y_{i,\mathrm{lit}}} / \frac{\Delta\langle\sigma v\rangle}{\langle\sigma v\rangle}$

Reaction	D/H	Y_p	^{7}Li/H
d(p,γ)^{3}He	-0.32	0	1.82
d(d,n)^{3}He	-0.64	0	2.26
d(d,p)t	-0.50	0	0.16
t(d,n)α	0	0	-0.09
t(α,γ)^{7}Li	0	0	0.08
^{3}He(n,p)t	0.03	0	-0.93
^{3}He(d,p)α	-0.02	0	-2.73
^{3}He(α,γ)^{7}Be	0	0	3.15
^{7}Li(p,α)α	0	0	-0.22
^{7}Be(n,p)^{7}Li	0	0	-2.49

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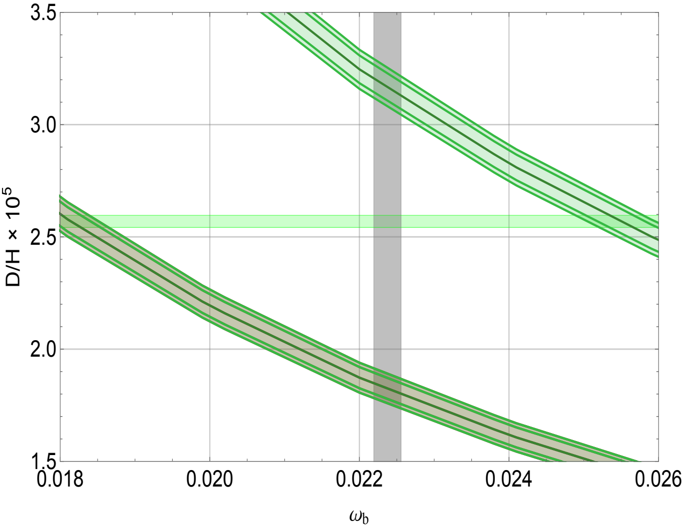
Parameter Variations: Overview

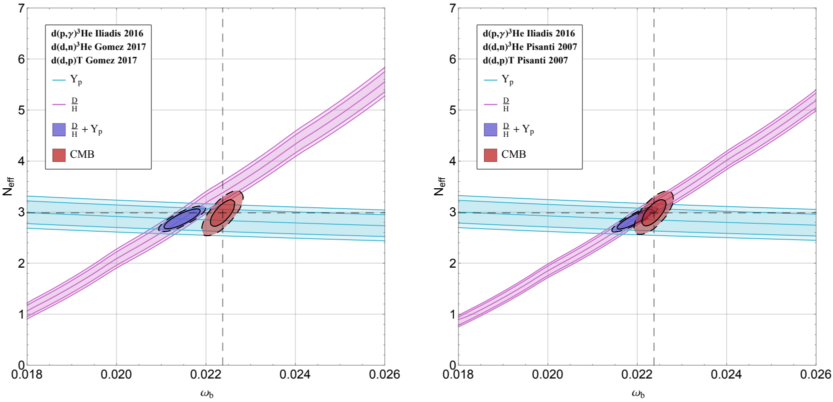
- Abundance sensitivity: $\frac{\Delta Y_i}{Y_{i,\mathrm{lit}}} / \frac{\Delta P}{P_{\mathrm{lit}}}$

Parameter	D/H	Y_p	$^3He/^4He$	$^7Li/H$
ω_b	-1.776	0.039	-0.650	7.090
N_{eff}	0.411	0.170	-0.090	-0.985
τ_n	0.401	0.727	-0.829	1.516
α_{FS}	-0.011	0	0.008	0.085

$D/H(\omega_b, N_{eff})$



Two Parameter Variations: $N_{\text{eff}}(\omega_b)$



- dpg: Iliadis 2016
- ddn: Gomez 2017 / Pisanti 2007
- ddp: Gomez 2017 / Pisanti 2007

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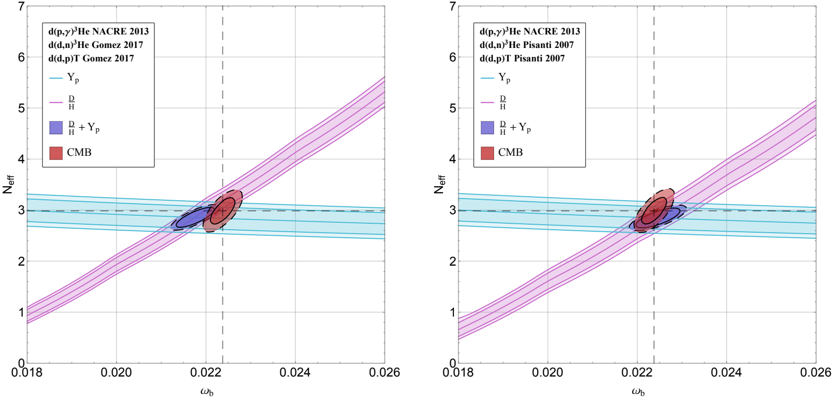
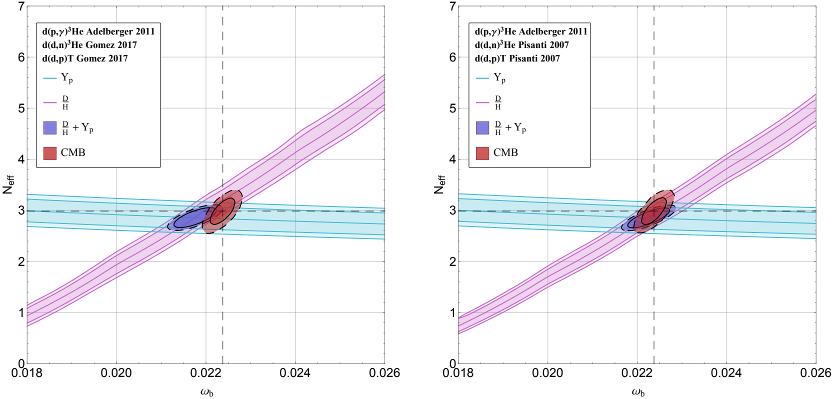


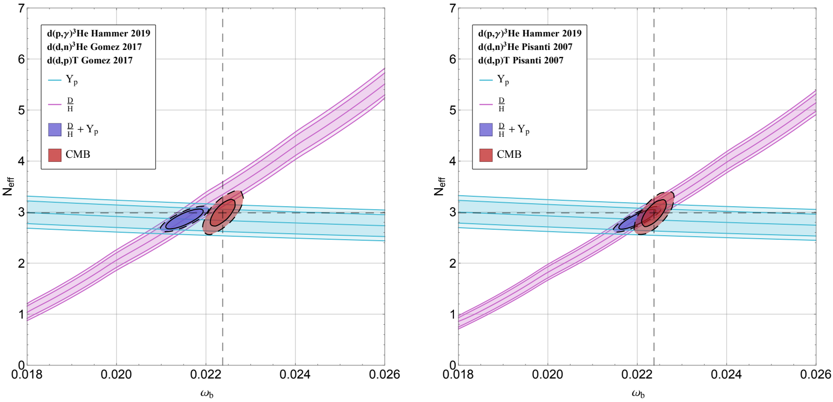
- dpg: NACRE 2013
- ddn: Gomez 2017 / Pisanti 2007
- ddp: Gomez 2017 / Pisanti 2007

Two Parameter Variations: $N_{\mathrm{eff}}(\omega_b)$



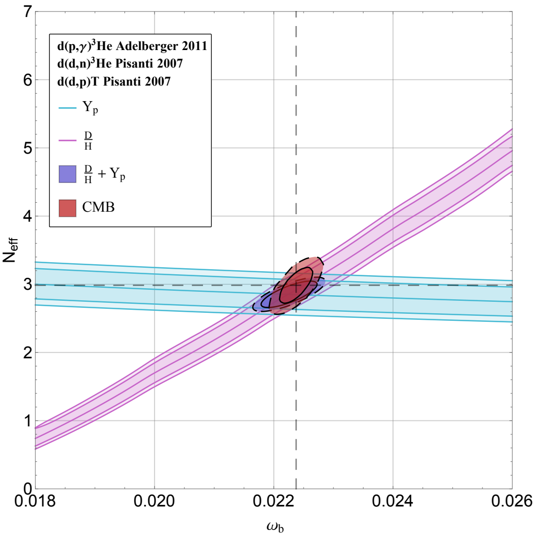
- dpg: Adelberger 2011
- ddn: Gomez 2017 / Pisanti 2007
- ddp: Gomez 2017 / Pisanti 2007

Two Parameter Variations: $N_{\mathrm{eff}}(\omega_{\mathrm{b}})$



- dpg: Hammer 2019
- ddn: Gomez 2017 / Pisanti 2007
- ddp: Gomez 2017 / Pisanti 2007

Two Parameter Variations: $N_{\mathrm{eff}}(\omega_b) \longrightarrow G_N$



Based on Adelberger 2011 + Pisanti 2007:

- $\omega_b = 0.0223 \pm 0.0003$
- $N_{\mathrm{eff}} = 2.85 \pm 0.19$
- $\frac{G_N}{G_{N,0}} = 0.97 \pm 0.03$

ΛCDM Planck 2018:

- $\omega_b = 0.02237 \pm 0.00018$
- $N_{\mathrm{eff}} = 2.98 \pm 0.17$
- $\frac{G_N}{G_{N,0}} = 0.996 \pm 0.027$

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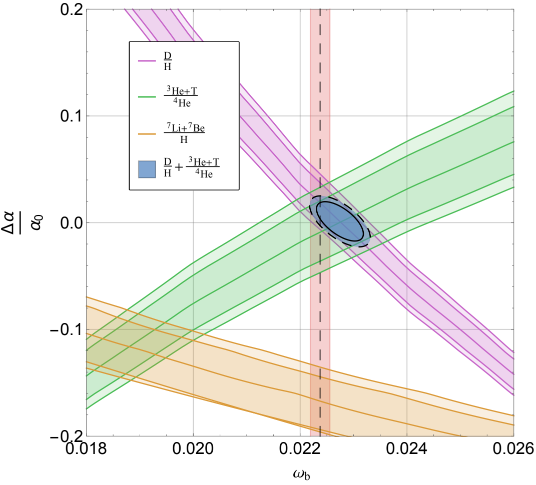
Two Parameter Variations: $\alpha_{FS}(\omega_b)$

Cooke 2015: primordial $\frac{^3He+T}{^4He} = (1.23 \pm 0.02) \times 10^{-4}$



Following Nollett et al. 2002;
Influence on Q value and coulomb barrier of reaction

Based on NACRE 2013 + Pisanti 2007:

$Y_p + \frac{^3He+T}{^4He}$:

- $\omega_b = 0.0227 \pm 0.00034$
- $\frac{\Delta\alpha}{\alpha_0} = (0.001 \pm 0.023)$

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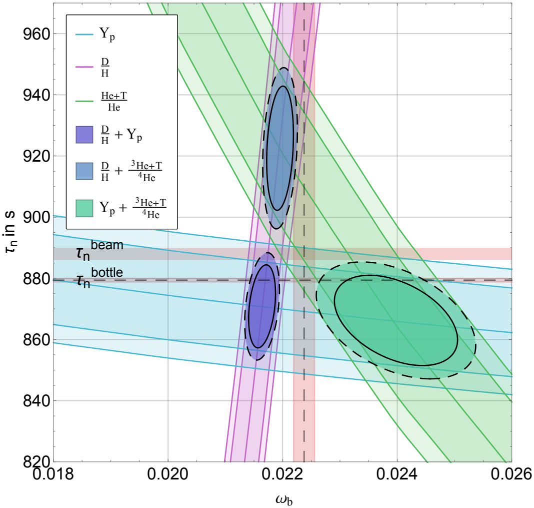
Two Parameter Variations: $\tau_n(\omega_\mathbf{b})$



Y_p+D/H:

- $\omega_b = 0.02164 \pm 0.00022$
- $\tau_n = (870.8 \pm 13.6)$ s

D/H+$\frac{^3He+T}{^4He}$:

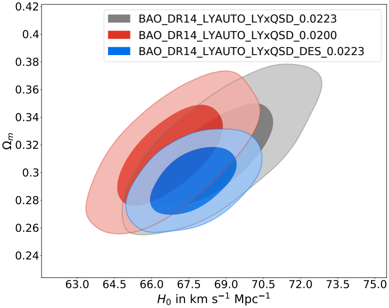
- $\omega_b = 0.02195 \pm 0.00023$
- $\tau_n = (922.5 \pm 20.3)$ s

$Y_p + \frac{^3He+T}{^4He}$:

- $\omega_b = 0.024 \pm 0.001$
- $\tau_n = (866.2 \pm 14.8)$ s

BBN + BAO Constraints on H_0

CosmoMC evaluation of Galaxy + Lyα BAO data with BBN ω_b gaussian prior (following Addison et al. 2018):



$\omega_b = 0.0200 \pm 0.0005$:

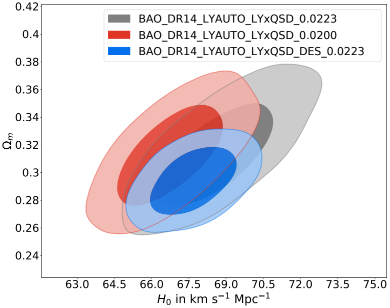
- $\Omega_m = 0.314 \pm 0.024$
- $H_0 = 66.8 \pm 1.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

$\omega_b = 0.0223 \pm 0.0005$:

- $\Omega_m = 0.314 \pm 0.025$
- $H_0 = 68.6 \pm 1.6\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

BBN + BAO Constraints on H_0

CosmoMC evaluation of Galaxy + Lyα BAO and DES 1Y data with BBN ω_b gaussian prior (following Addison et al. 2018):



$\omega_b = 0.0223 \pm 0.0005$:

- $\Omega_m = 0.294 \pm 0.016$
- $H_0 = 67.7 \pm 1.1\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

Riess et al. 2019:

$H_0 = 74.03 \pm 1.42\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

ΛCDM Planck 2018:

$H_0 = 67.4 \pm 0.5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

Conclusion

- Good agreement between BBN and CMB for Adelberger 2011 d(p,γ)^{3}He and Pisanti 2007 d(d,n)^{3}He and d(d,p)t
- α_{FS} seems to be unaltered in BBN era, however $\frac{^3\text{He}+\text{T}}{^4\text{He}}$ abundance is unconventional
- τ_n is not well constrained by BBN
- Constraint on H_0 from BAO+BBN in good agreement with ΛCDM Planck 2018 but 3.5σ tension to Riess et al. 2019 using inverse distance ladder
- New insights on the d(p,γ)^{3}He S-factor from LUNA (Klaus Stöckel et al.) will follow!