Anthropic Considerations for Big Bang Nucleosynthesis

International School of Nuclear Physics – Erice 2024

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Motivation

- Fundamental constants: show up in every discipline of science
- We know them to precisions given units of parts per 10^9 [1]

permeability of free space	μ_0	$4\pi \times 10^{-7}$ N A^{-2} = 12.566 370 614 ... $\times 10^{-7}$ N A^{-2}	exact
fine-structure constant	$\alpha = e^2/4\pi\epsilon_0\hbar c$	7.297 352 5664(17)$\times 10^{-3}$ = 1/137.035 999 139(31)†	0.23, 0.23
classical electron radius	$r_e = e^2/4\pi\epsilon_0 m_e c^2$	2.817 940 3227(19)$\times 10^{-15}$ m	0.68
(e^- Compton wavelength)/2π	$\lambda\!\!\!^{-}_e = \hbar/m_e c = r_e \alpha^{-1}$	3.861 592 6764(18)$\times 10^{-13}$ m	0.45
Stefan-Boltzmann constant	$\sigma = \pi^2 k^4/60\hbar^3 c^2$	5.670 367(13)$\times 10^{-8}$ W m^{-2} K^{-4}	2300
Fermi coupling constant**	$G_F/(\hbar c)^3$	1.166 378 7(6)$\times 10^{-5}$ GeV^{-2}	510
weak-mixing angle	$\sin^2\hat{\theta}(M_Z)$ ($\overline{\rm MS}$)	0.231 22(4)††	1.7×10^5
$W^\pm$ boson mass	m_W	80 379(12) GeV/c^2	1.5×10^5

- Some theories predict changes in these constants over cosmological time scales

How fine-tuned is our universe? [2]

- How can we test this? $\Rightarrow$ Laboratory: Big Bang Nucleosynthesis (BBN) [3]

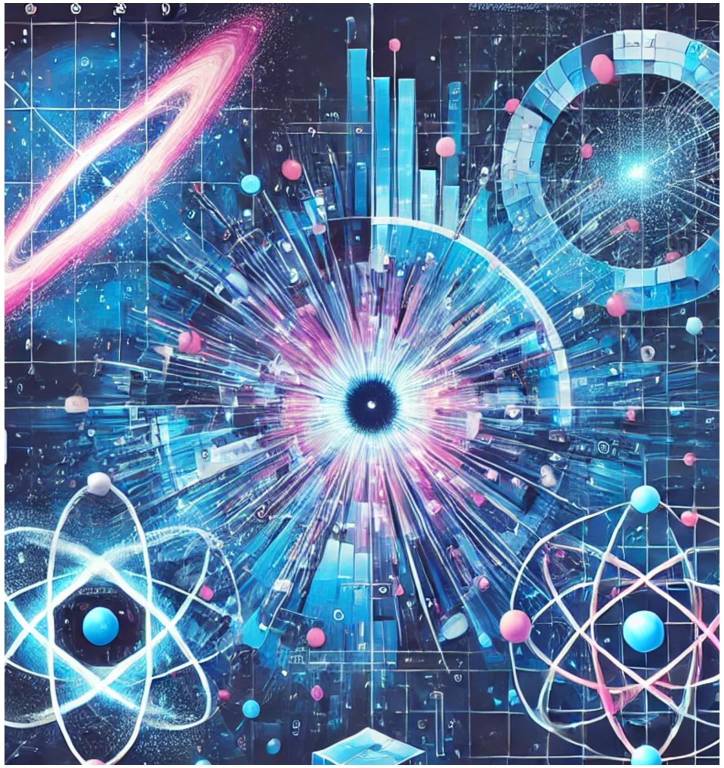
[1] PDG: Workman et al., 2022, [2] Dirac, 1973 and many others, [3] Olive, Steigman, and Walker, 2000; Iocco et al., 2009; Cyburt et al., 2016; Pitrou et al., 2018a

This talk

In this work: studied BBN under variation of

- the electromagnetic coupling constant α [1]
  - ☞ also using results from Halo EFT calculations[2]
- the Higgs vacuum expectation value (VEV) v [3]

Goal: find a bound on these variations through comparing calculations with experimental values for light element abundances



: Source: ChatGPT

[1] Meißner, Metsch, HM 2023; Bergström, Iguri, Rubenstein, 1999; Nollett, Lopez, 2002; Dent,Stern,Wetterich, 2007; Coc et al., 2007;

[2] Meißner, Metsch , HM 2024; Hammer, Ji, Phillips, 2017; [3] Meißner, HM 2024; Burns et al., 2024

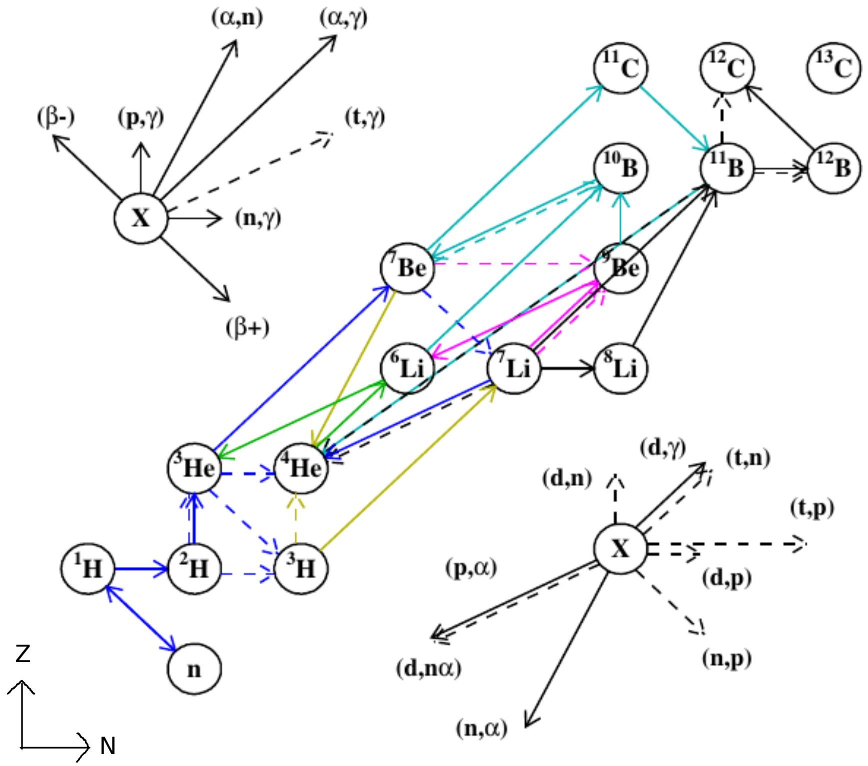
Introducing BBN – Evolution of Abundances

- abundance $Y_i = n_i / n_b$, with n_i density of nucleus i and n_b total baryon density
- Need to solve system of rate equations

$$\dot{Y}_i \supset -Y_i \Gamma_{i\to\dots} + Y_j \Gamma_{j\to i+\dots} + Y_k Y_l \Gamma_{kl\to ij} - Y_i Y_j \Gamma_{ij\to kl}$$

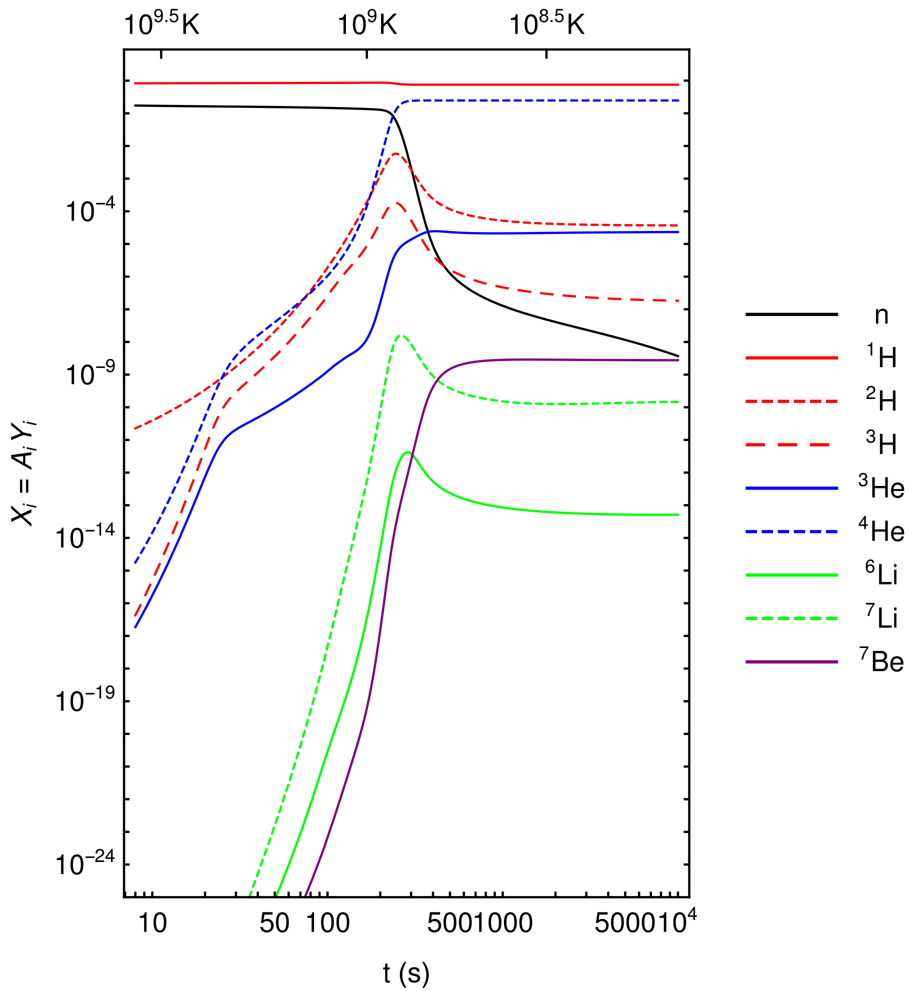
- Used five different codes[1] to get an estimate of systematical errors

[1] PRIMAT : Pitrou et al., 2018b, AlterBBN : Arbey et al., 2020, PArthENoPE : Gariazzo et al., 2022, NUC123 : Kawano, 1992 and PRyMordial : Burns, Tait, and Valli, 2023



: Taken from Pitrou et al., 2018a

Introducing BBN – The Timescales



: produced by PRIMAT

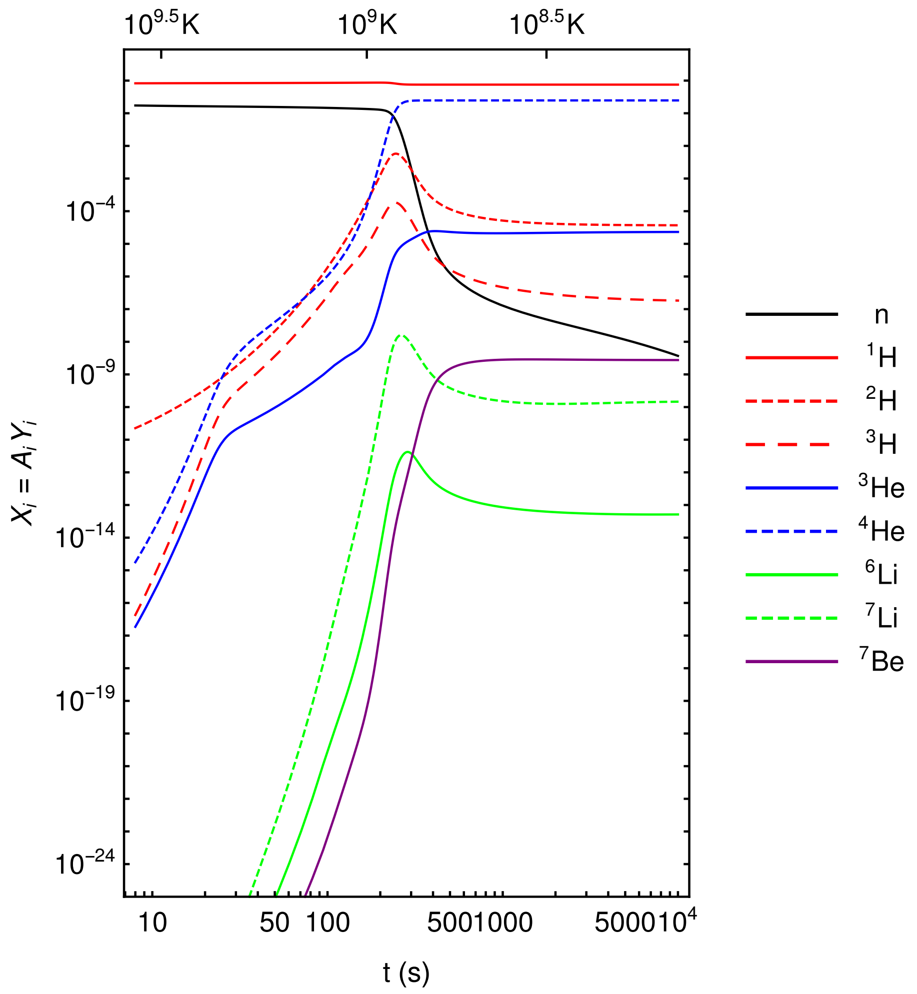
- $t \leq 1\,\mathrm{s}$

  Weak $n \leftrightarrow p$ reactions

  ☞ number density ratio $\frac{n_n}{n_p} = e^{-Q_n/T}$, Q_n: mass difference

  ☞ at 1 s or $T \approx 1\,\mathrm{MeV}$: freeze-out and free neutron decay

Introducing BBN – The Timescales



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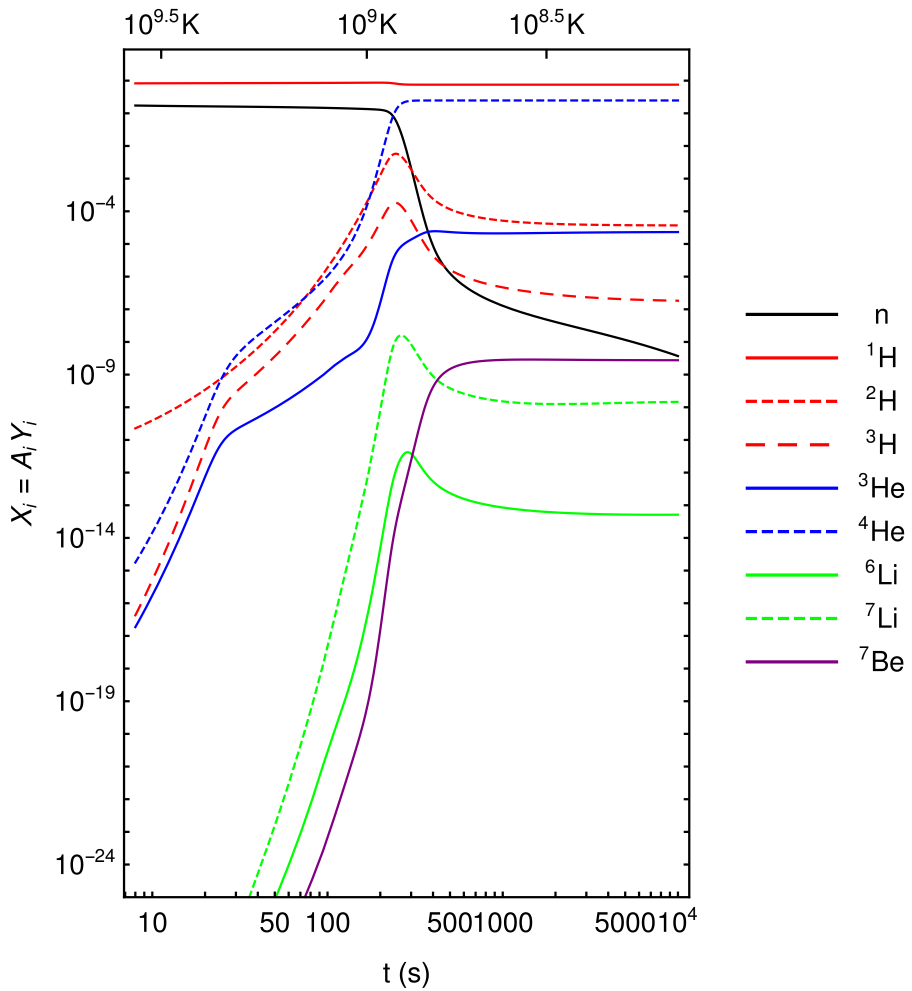
  ☞ at 1 s or $T \approx 1\,\mathrm{MeV}$: freeze-out and free neutron decay

- $t = 1\,\mathrm{min}$

  Deuterium bottleneck: $n + p \to d + \gamma$ efficient

Introducing BBN – The Timescales



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- $t \leq 1\,\mathrm{s}$

  Weak $n \leftrightarrow p$ reactions

  ☞ number density ratio $\frac{n_n}{n_p} = e^{-Q_n/T}$, Q_n: mass difference

  ☞ at 1 s or $T \approx 1\,\mathrm{MeV}$: freeze-out and free neutron decay

- $t = 1\,\mathrm{min}$

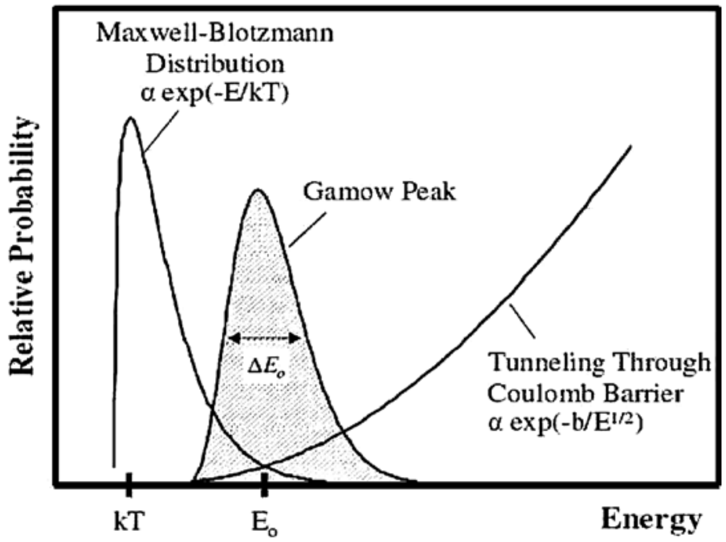
  Deuterium bottleneck: $n + p \to d + \gamma$ efficient

- $t \lesssim 3\,\mathrm{min}$

  Fusion of light elements (up to $^7\mathrm{Be}$)

Variation of α – What to consider

- Nuclear reaction rates: Coulomb barrier $\rightarrow$ energy-dependent penetration factor in cross section[1]
- Radiative capture



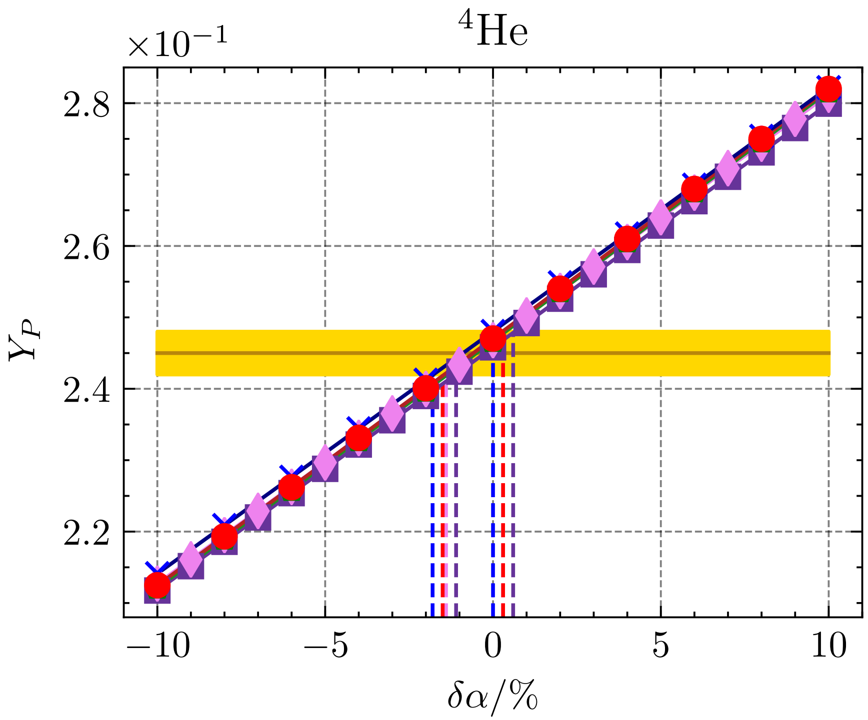
- $n \leftrightarrow p$ and β-decay rates: final (initial) state interactions between charged particles
- Indirect effects: binding energies[2] and Q_n (QED contribution)[3]

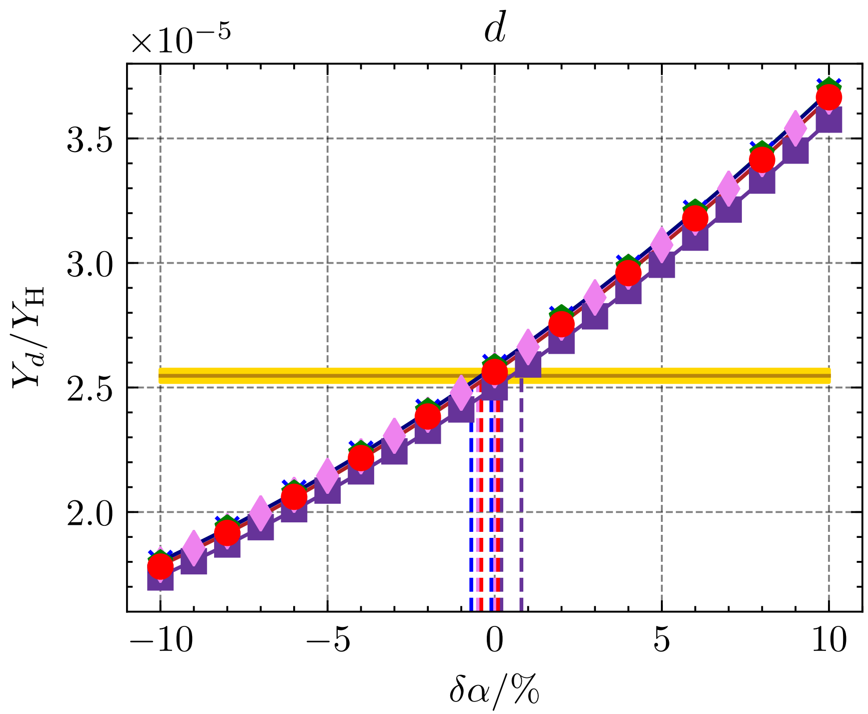
$$\Delta Q_n = Q_n^{\mathrm{QED}} \cdot \delta\alpha = -0.58(16)\,\mathrm{MeV} \cdot \delta\alpha$$

[1] Blatt and Weisskopf, 1979; [2] Elhatisari et al., 2024; [3] Gasser, Leutwyler, and Rusetsky, 2021

Experimental constraints

- PDG[1]: reliable measurements for $^4\mathrm{He}$, d and $^7\mathrm{Li}$ (But: Lithium problem[2])





- 5 codes give similar results
- Only α-variation of $|\delta\alpha| < 1.8\%$ is consistent with experiment

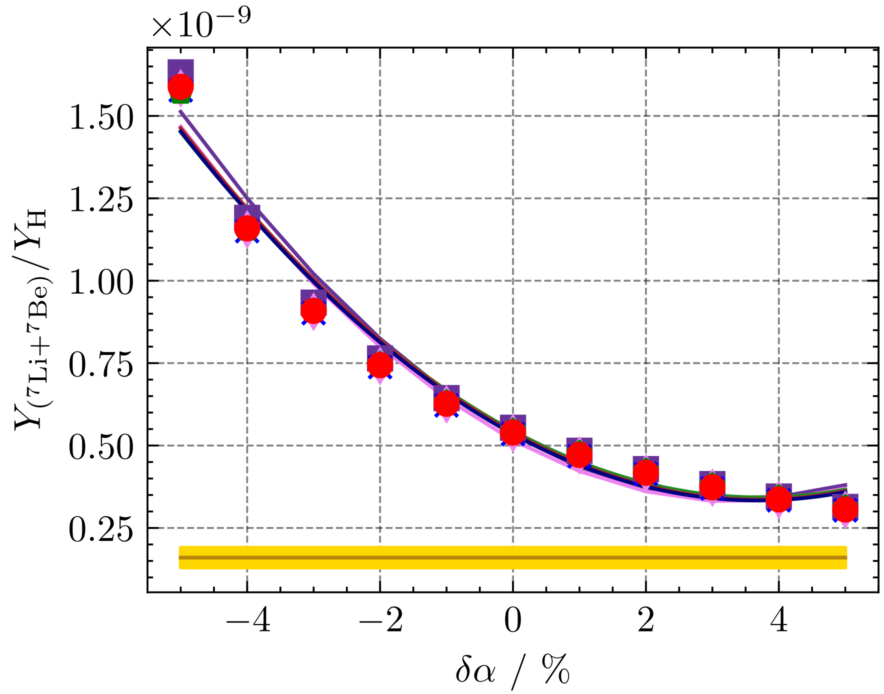
[1] Workman et al., 2022; [2] Fields, 2011

Halo Effective Field Theory (EFT)

Biggest source of uncertainty: reaction rates and cross sections

$\Rightarrow$ Need theoretical predictions

- So far: only pionless EFT for $n + p \rightarrow d + \gamma$ [1]
- Now: include Halo EFT[2] rates for
  - $n + {}^7\mathrm{Li} \rightarrow {}^8\mathrm{Li} + \gamma$ [3]
  - $p + {}^7\mathrm{Be} \rightarrow {}^8\mathrm{B} + \gamma$ [4]
  - ${}^3\mathrm{H} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Li} + \gamma$ and ${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$ [5]



: Meißner, Metsch, HM 2024: in print (EPJA)

[1] Rupak, 2000; [2] review: Hammer, Ji, Phillips, 2017; [3] Fernando, Higa, Rupak 2012; Higa, Premarathna, Rupak, 2021; [4] Higa, Premarathna, Rupak, 2022;

[5] Higa, Rupak, Vaghani, 2018; Premarathna, Rupak, 2020

${}^7\mathrm{Li} + {}^7\mathrm{Be}$ abundance diverges?

Higgs VEV Variation – What to consider

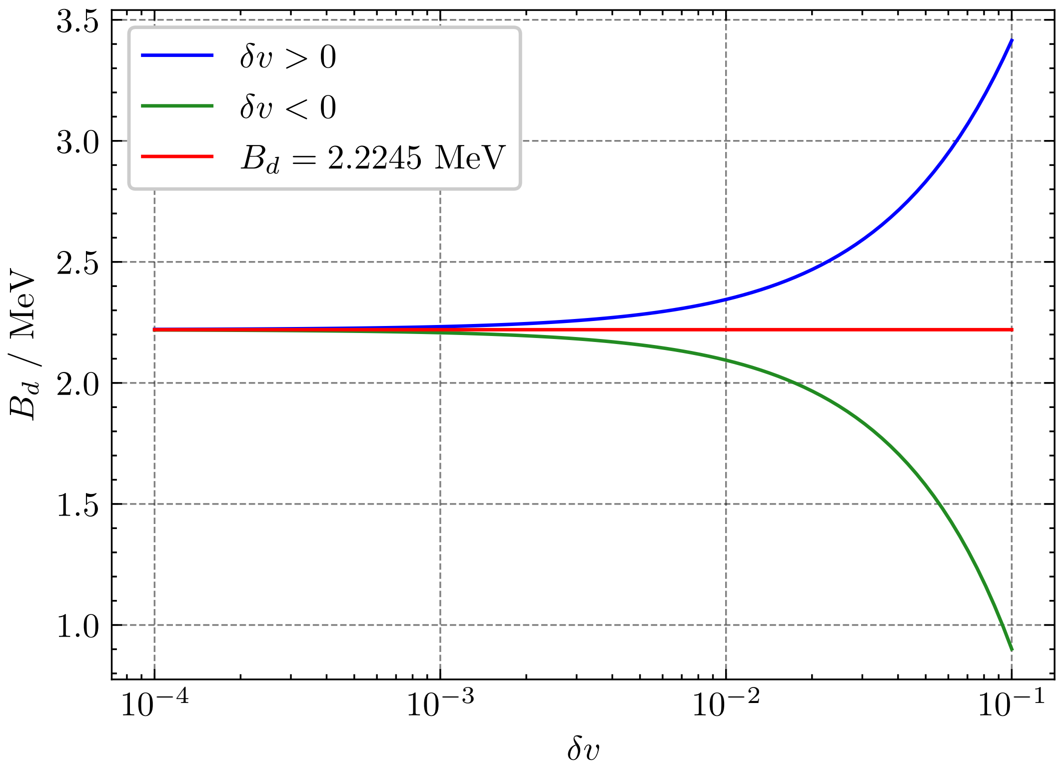
- QCD scale $\Lambda_{\mathrm{QCD}} \propto (1 + \delta v)^{0.25}$[1]
- Fermi constant $G_F \propto (1 + \delta v)^{-2}$
- Change of electron and quark masses $\Rightarrow M_\pi$ through Gell-Mann-Oakes-Renner relation

→ Q_n (QCD part)[2]

→ Deuteron binding energy (right)

→ nucleon mass and axial-vector coupling (from Lattice QCD or ChPT)

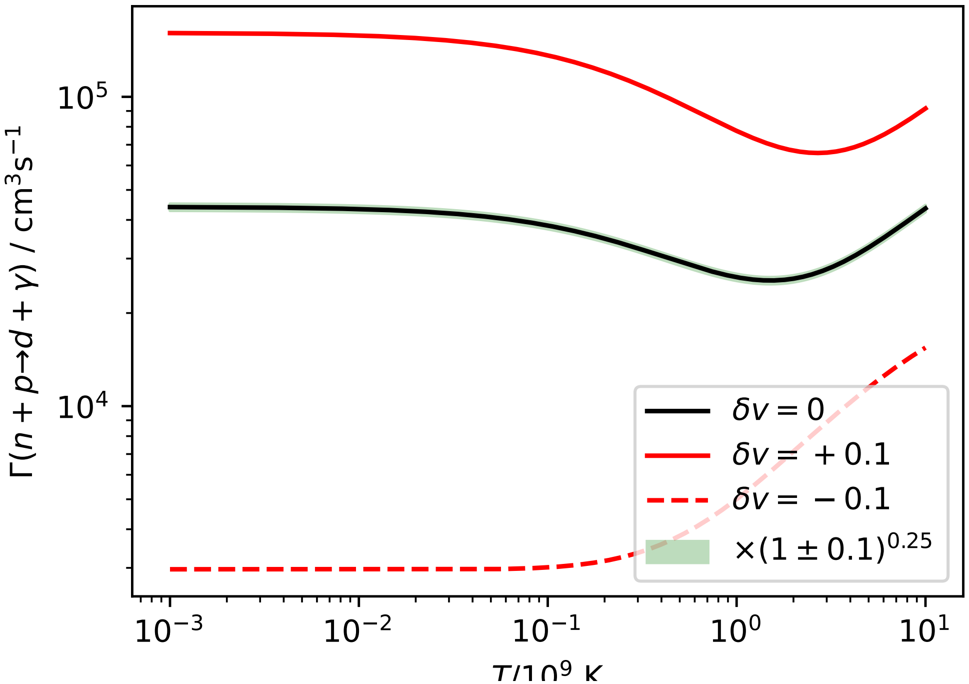
→ nucleon-nucleon scattering parameters (low energy theorems)[3]



[1] Burns et al., 2024, [2] Gasser, Leutwyler, and Rusetsky, 2021, [3] Baru et al., 2015, 2016

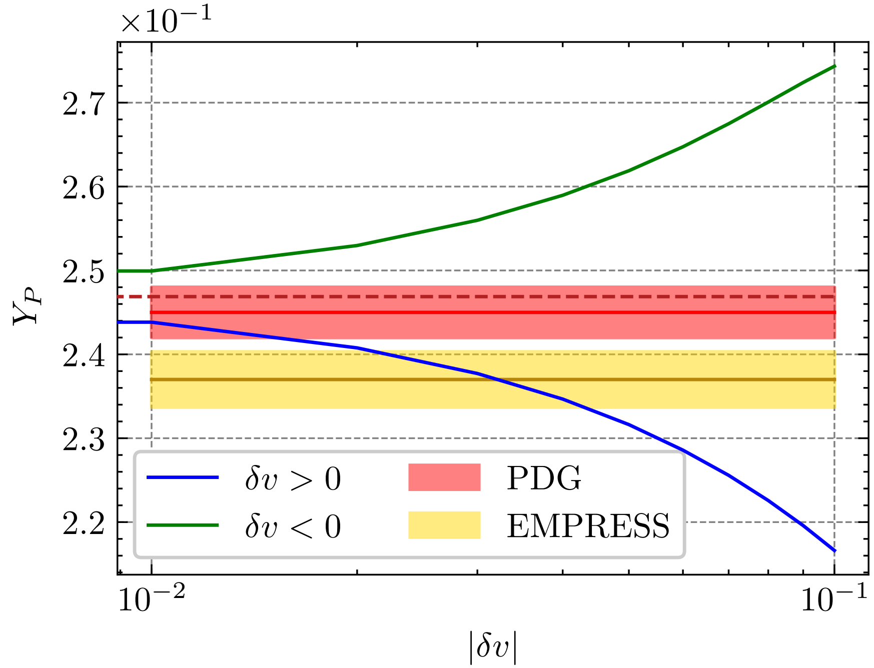
$n + p \to d + \gamma$

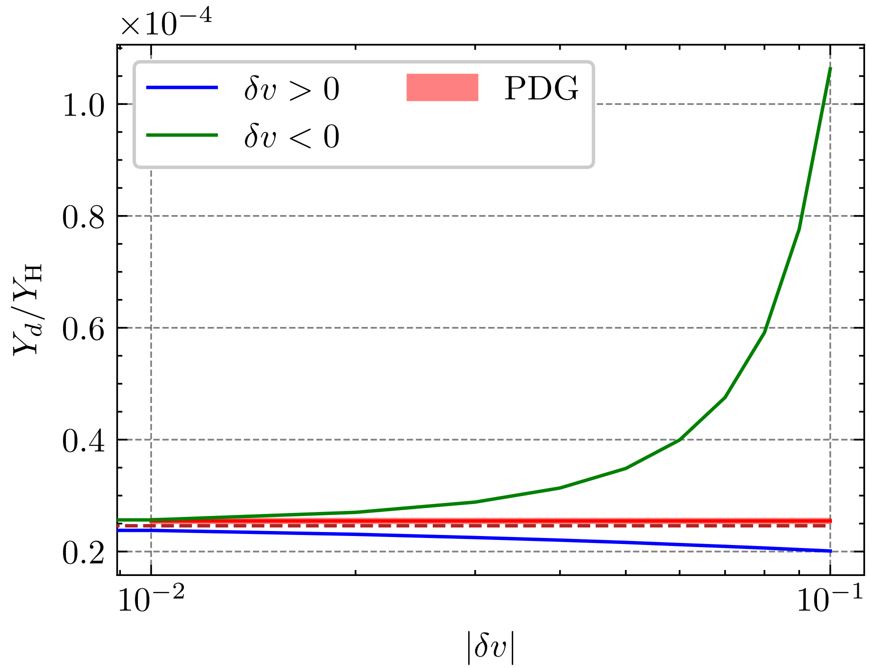
- $n + p \to d + \gamma$ rate[1] depends heavily on
  - deuteron binding energy
  - nucleon mass
  - nucleon-nucleon scattering parameters
- v-dependence much stronger than expected from $(1 + \delta v)^{0.25}$ [2]



[1] Rupak, 2000; [2] Burns et al., 2024

Experimental constraints





: PDG: Workman et al., 2022 ; EMPRESS: Matsumoto et al., 2022

- found more stringent 2σ-bound from deuterium abundance:

$$-0.5\% \leq \delta v \leq -0.1\%$$

To summarize...

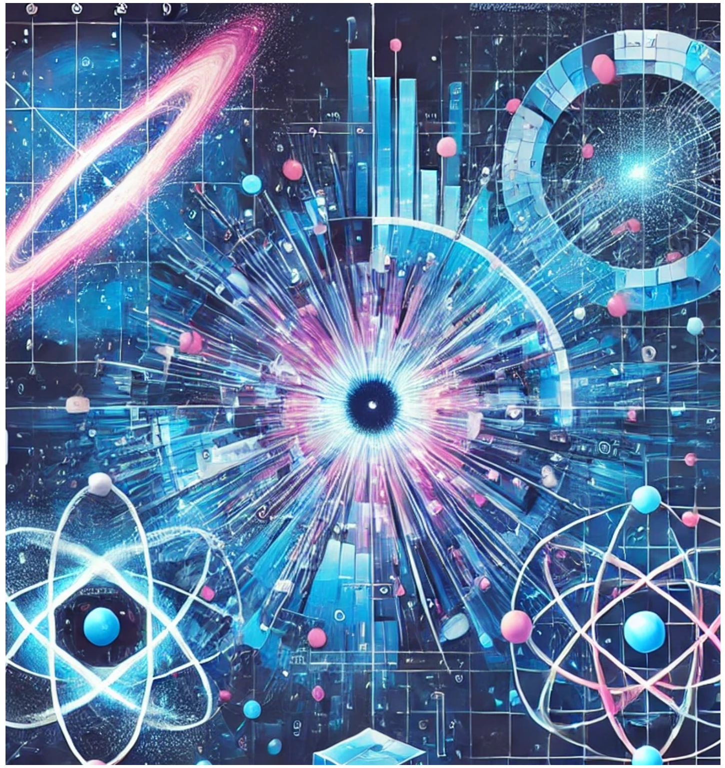
- simulated Big Bang Nucleosynthesis with 5 different codes as laboratory
- considered variation of fundamental physical constants and found
  - for the fine-structure constant (1σ)

$$|\delta\alpha| < 1.8\%$$

  - for the Higgs VEV (2σ)

$$-0.5\% \leq \delta v \leq -0.1\%$$

to be consistent with measurements
- Now: How fine-tuned is our universe?



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Outlook

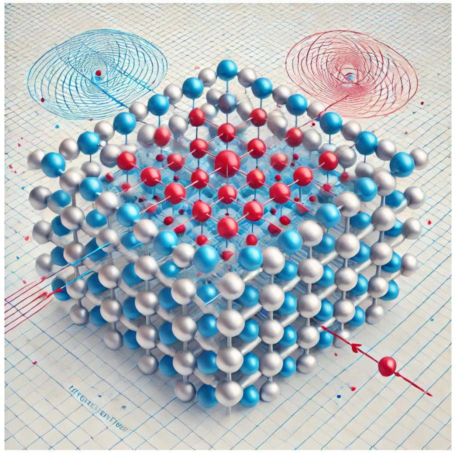
- Combined analysis of α- and v- or α- and quark mass variations
- Quantitative and detailed error estimations
- Main source of uncertainty: reaction cross sections and rates

$\Rightarrow$ need more theoretical predictions

✔ Halo EFT

☞ new: Nuclear Lattice Effective Field Theory → Dean Lee's talk

- → contributions to nuclear binding energies (already used for α-variation)
- → *ab initio* calculation of scattering parameters and rates: deuteron-deuteron reactions in the making
- → can directly vary fundamental parameters: no need for approximation



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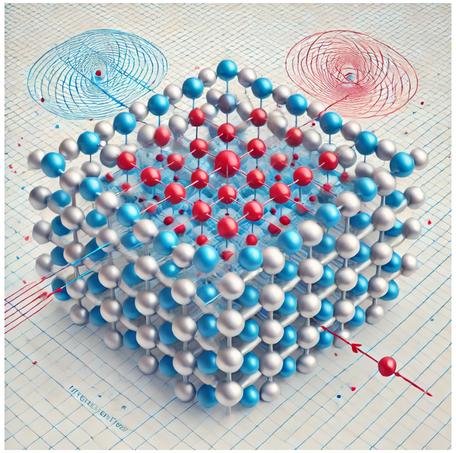

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Thank you for your attention!