Based on the collaboration with Tommy Ohlsson and Shun Zhou: PRD 97 (2018) 075009

Constraining Secret Neutrino Interactions with Big Bang Nucleosynthesis

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Secret interactions among neutrinos can appear in several NP models and motivated by a number of phenomenological considerations

Some examples

- **The Majoron model**

$$-\mathcal{L} = \overline{\ell_{\rm L}} Y_{\rm D} \widetilde{H} N + \frac{1}{2} \overline{N} Y_N \Phi N^c + {\rm h.c.}$$

$$\Phi = \frac{(v+\rho)}{\sqrt{2}} e^{i\theta/v} \Rightarrow \theta\, \overline{\nu_{\rm L}} \gamma_5 \nu_{\rm L}^c$$

- **Neutrinophilic two-Higgs-doublet model (ν2HDM)**

$$-\mathcal{L} = \overline{\ell_{\rm L}} Y_l H E_{\rm R} + \overline{\ell_{\rm L}} Y_\nu \Phi \nu_{\rm R} + {\rm h.c.}$$

$$M_\nu = Y_\nu \langle \Phi \rangle \qquad \langle \Phi \rangle \sim {\rm eV}$$

$$\Downarrow$$

$$\rho \overline{\nu_{\rm L}} \nu_{\rm L}^c$$

Wang, Wang & Yang, EPL, 06
Gariel & Nandi, PLB, 07
Sher & Triola, PRD, 2011

- **Gauged** $L_\mu - L_\tau$

$$-\mathcal{L} = g' Z'_\mu \overline{\ell_{\rm L}^\alpha} \gamma^\mu \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix}_{\alpha\beta} \ell_{\rm L}^\beta \Rightarrow Z'_\mu \overline{\nu_{\rm L}} \gamma^\mu \nu_{\rm L}$$

- **Solving the small-scale structure problem of WIMP CDM**
- **Fuzzy dark matter interacting with neutrinos**
- **Reconcile the tension between cosmology and eV sterile neutrino**

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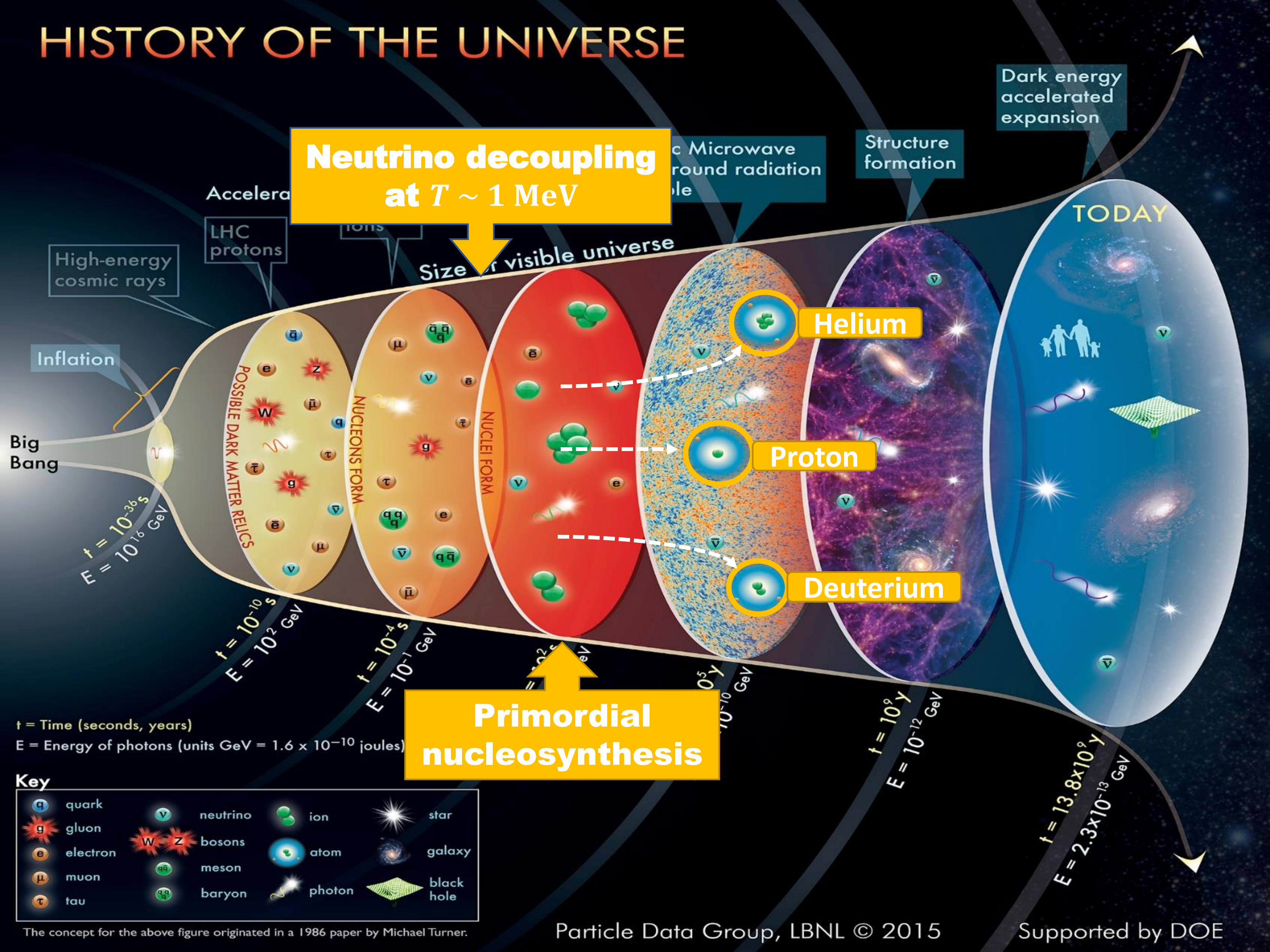
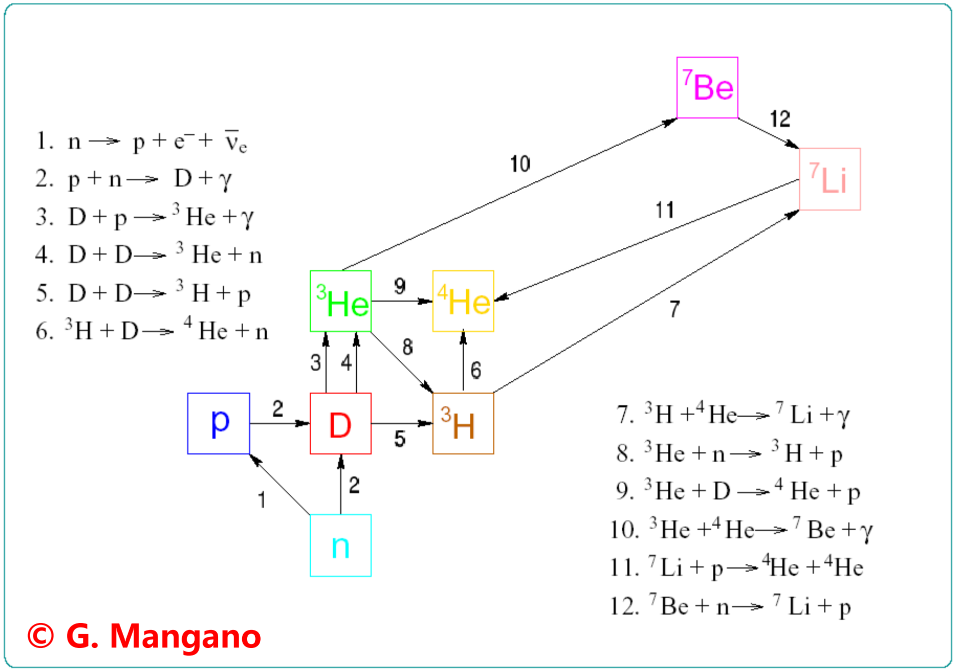
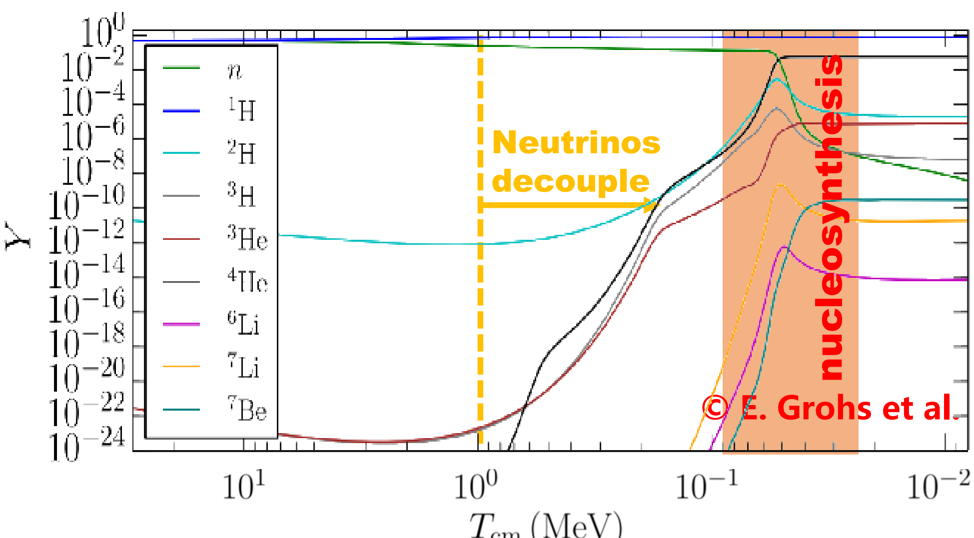


HISTORY OF THE UNIVERSE
Neutrino decoupling at $T \sim 1$ MeV
Structure formation
Dark energy accelerated expansion
LHC protons
High-energy cosmic rays
Inflation
Big Bang
Size of visible universe
TODAY
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
Helium
Proton
Deuterium
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 10^{-4}$ s
$E = 10^{-1}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8 \times 10^{9}$ y
$E = 2.3 \times 10^{-13}$ GeV
Primordial nucleosynthesis
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6×10^{-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

Standard Theory of BBN

See Cyburt et al., RMP, 16, for a review





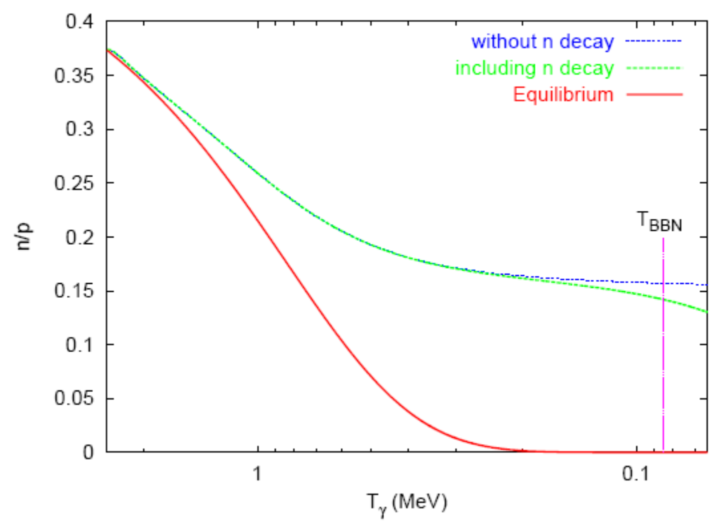
Phase I: 0.8-0.1 MeV n-p reactions

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

n/p freezing and neutron decay

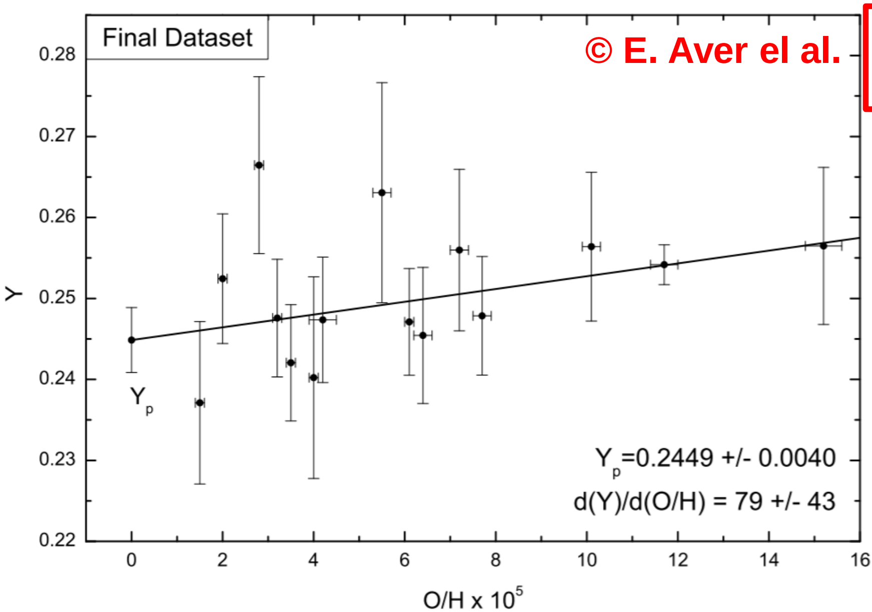
$$n \longleftrightarrow p + e^- + \bar{\nu}_e$$

n/p ratio is the key to fix Y_p, sensitive to new physics models



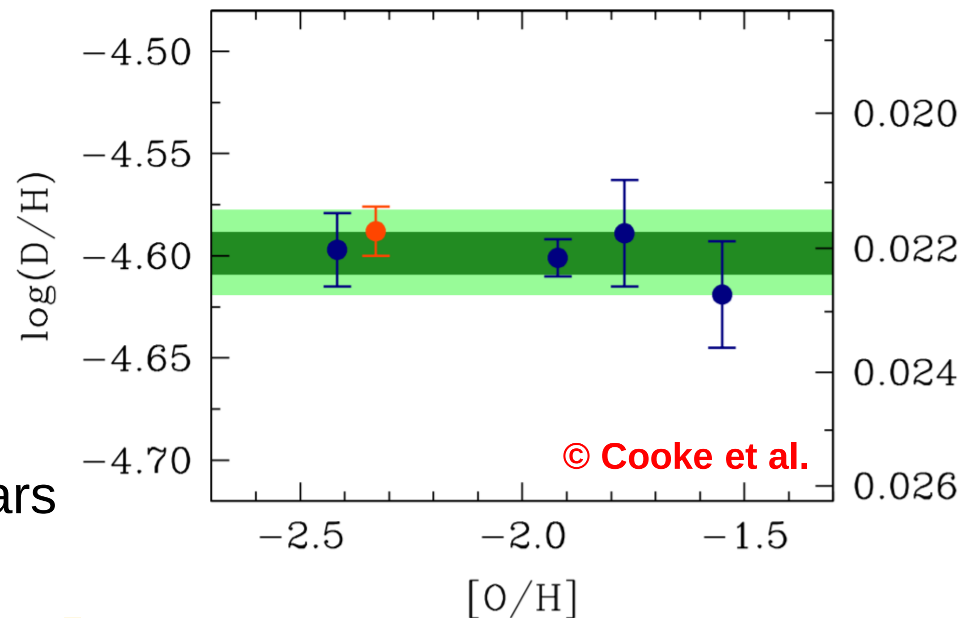
$$\left(\frac{n}{p}\right)_{eq} \simeq \exp\left(-\frac{m_n - m_p}{T_\gamma}\right) = \exp\left(-\frac{1{,}293 \text{ MeV}}{T_\gamma}\right)$$

BBN Observations



Y_p mass fraction of ^4He:

emission lines from the low-metallicity extragalactic H II (ionized H) regions then extrapolate to zero metallicity



Abundance ratio D/H

absorption lines by high-z and low-z Lyα neutral clouds from distant quasars

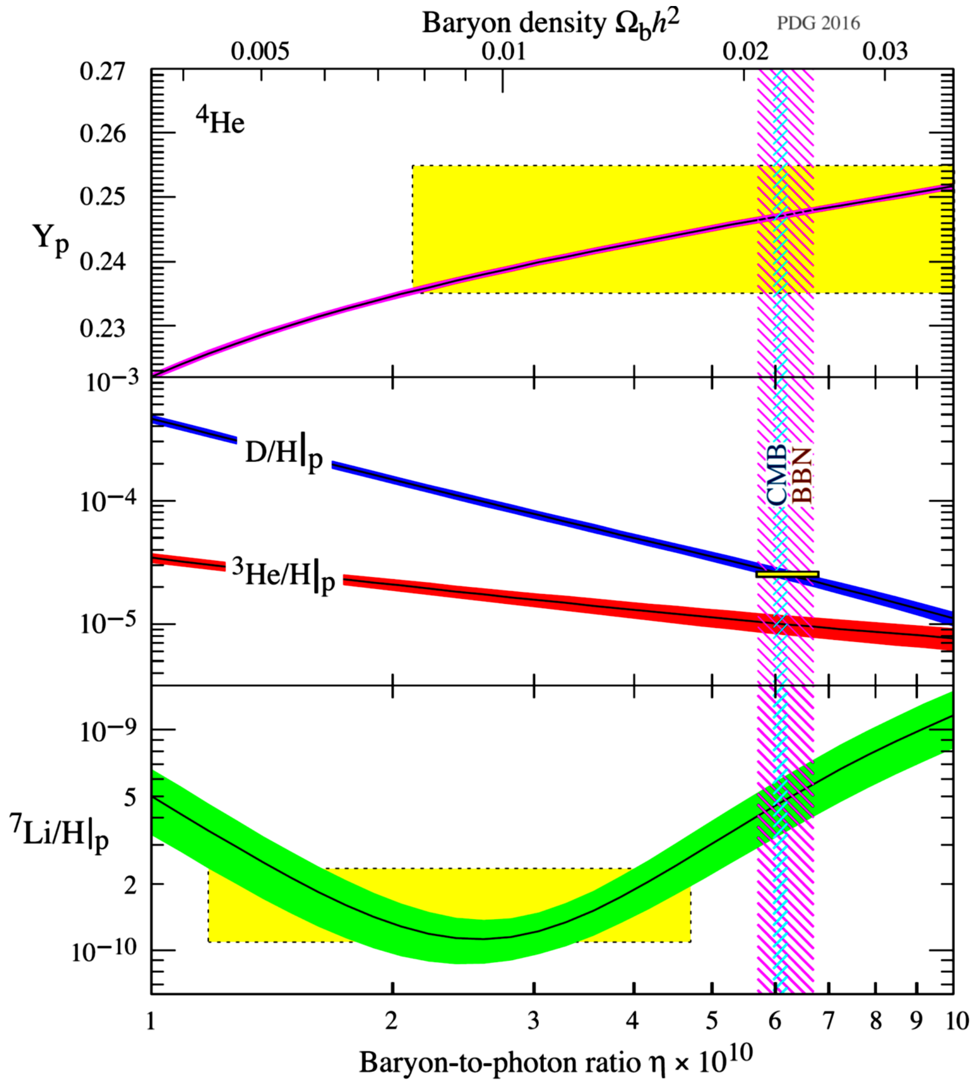
$^3He/H$:

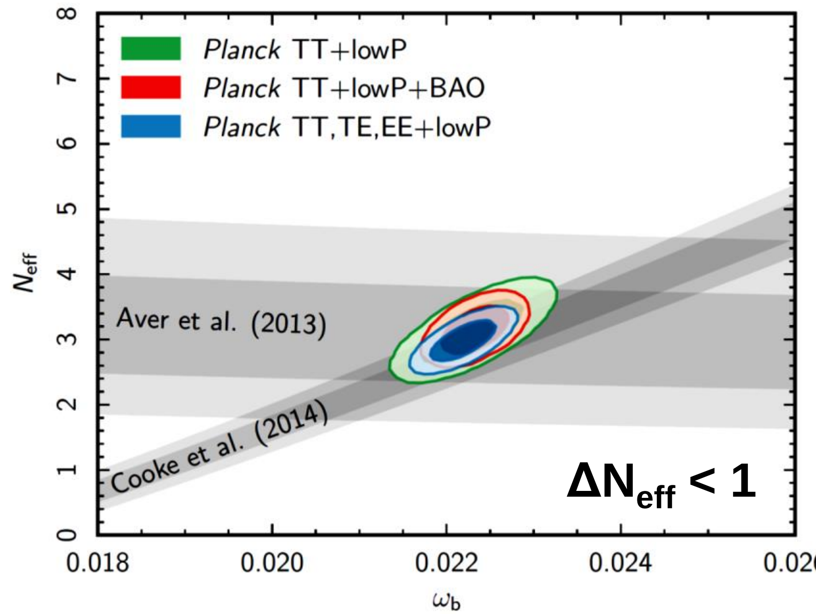
detectable via hyperfine emission line of gas clouds available only within Milky Way.

$^7Li/H$:

emission lines from metal-poor halo stars of Milky Way

Big Bang Nucleosynthesis (BBN) and CMB





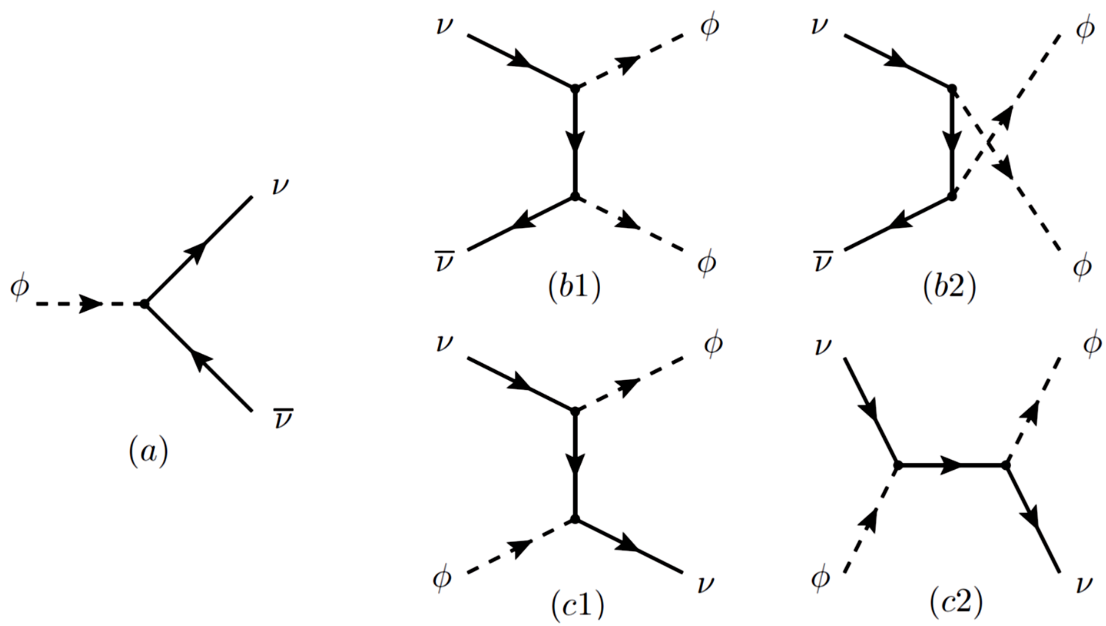
Simple BBN Constraints

Working Example: $$\mathcal{L}_{\rm SNI} = g_\phi^{\alpha\beta}\overline{\nu_{\alpha L}}\nu^{\rm C}_{\beta L}\phi + g_V^{\alpha\beta}\overline{\nu_{\alpha L}}\gamma^\mu\nu_{\beta L}V_\mu + {\rm h.c.}$$

Either scalar or vector boson & flavor-diagonal and universal couplings

Assume no right-handed neutrinos, otherwise more severely constrained

Require $\Delta N_{\rm eff}$ < 1 on the extra radiation at the temperature *T* = 1 MeV



Decays and inverse decays dominate for a relatively large mass

For small masses, the annihilation of neutrino pairs is more efficient

For *m* < 1 MeV, one can just count the relativistic degrees of freedom

$N_{\rm eff} \equiv (\rho_{\rm r} - \rho_\gamma)/(\rho_\nu/3)$

Scalar Boson | **Vector Boson**

Extra Radiation $\Delta N_{\rm eff} = 1/2 \cdot 8/7 \approx 0.57$ $\Delta N_{\rm eff} = 3/2 \cdot 8/7 \approx 1.71$

Simple BBN Constraints

Boltzman Equations

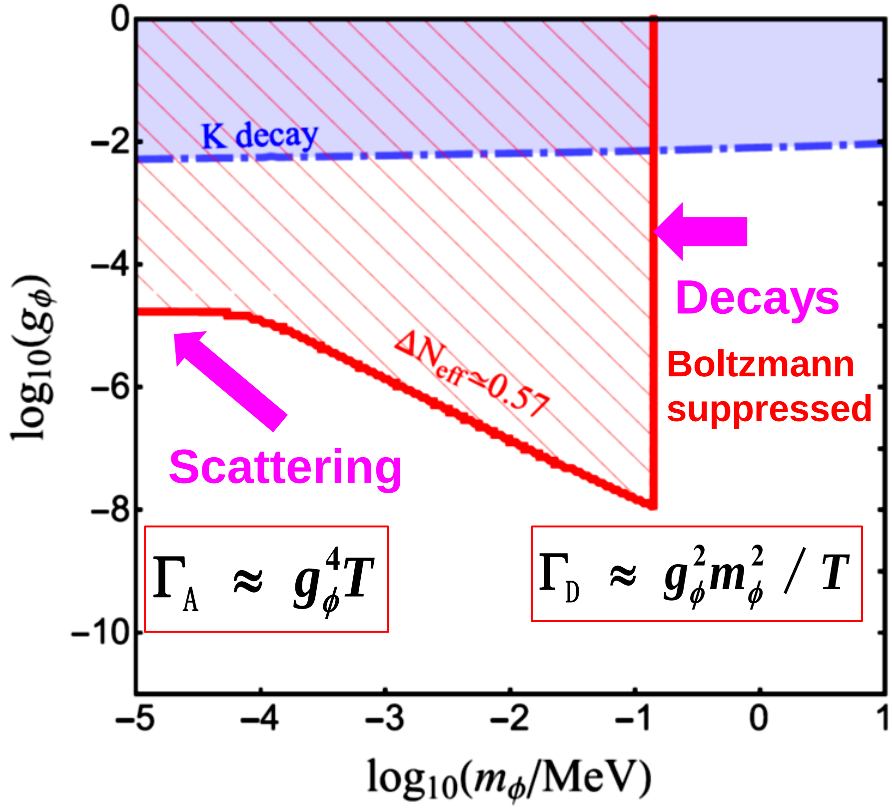
$$\frac{\partial f_i(|\mathbf{p}_i|,t)}{\partial t} - H|\mathbf{p}_i|\frac{\partial f_i(|\mathbf{p}_i|,t)}{\partial|\mathbf{p}_i|} = C^i_{\rm D}(f_\nu, f_{\phi/V}) + C^i_{\rm A}(f_\nu, f_{\phi/V}) + C^i_{\rm E}(f_\nu, f_{\phi/V})$$

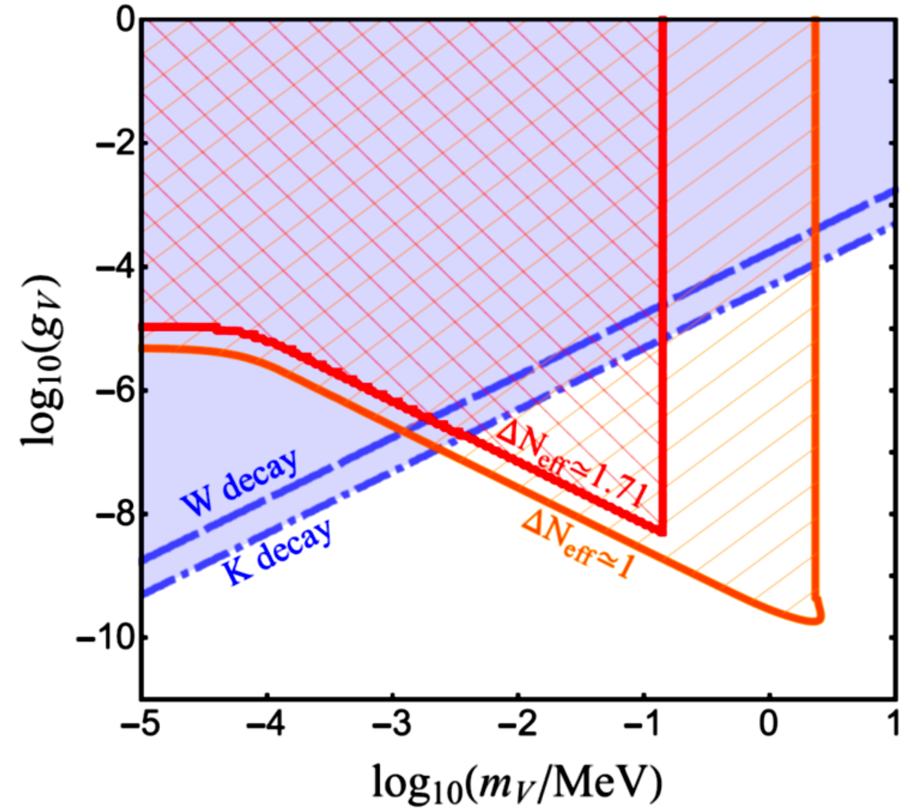
with collision terms

$$C^\phi_{\rm D} = \frac{1}{2E_\phi}\int {\rm d}\tilde{p}_\nu {\rm d}\tilde{p}_{\overline{\nu}}\tilde{\delta}^4(p)\left[f_\nu f_{\overline{\nu}}(1+f_\phi) - f_\phi(1-f_\nu)(1-f_{\overline{\nu}})\right]|\overline{\mathcal{M}}_{\rm D}|^2 ,$$

$$C^\phi_{\rm A} = \frac{1}{2E_\phi}\int {\rm d}\tilde{p}_\nu {\rm d}\tilde{p}_{\overline{\nu}}{\rm d}\tilde{p}'_\phi\tilde{\delta}^4(p)\left[f_\nu f_{\overline{\nu}}(1+f'_\phi)(1+f_\phi) - f_\phi f'_\phi(1-f_\nu)(1-f_{\overline{\nu}})\right]|\overline{\mathcal{M}}_{\rm A}|^2$$

$$C^\phi_{\rm E} = \frac{1}{2E_\phi}\int {\rm d}\tilde{p}_\nu {\rm d}\tilde{p}'_\nu{\rm d}\tilde{p}'_\phi\tilde{\delta}^4(p)\left[f_\nu f'_\phi(1+f_\phi)(1-f'_\nu) - f'_\nu f_\phi(1+f'_\phi)(1-f_\nu)\right]|\overline{\mathcal{M}}_{\rm E}|^2$$





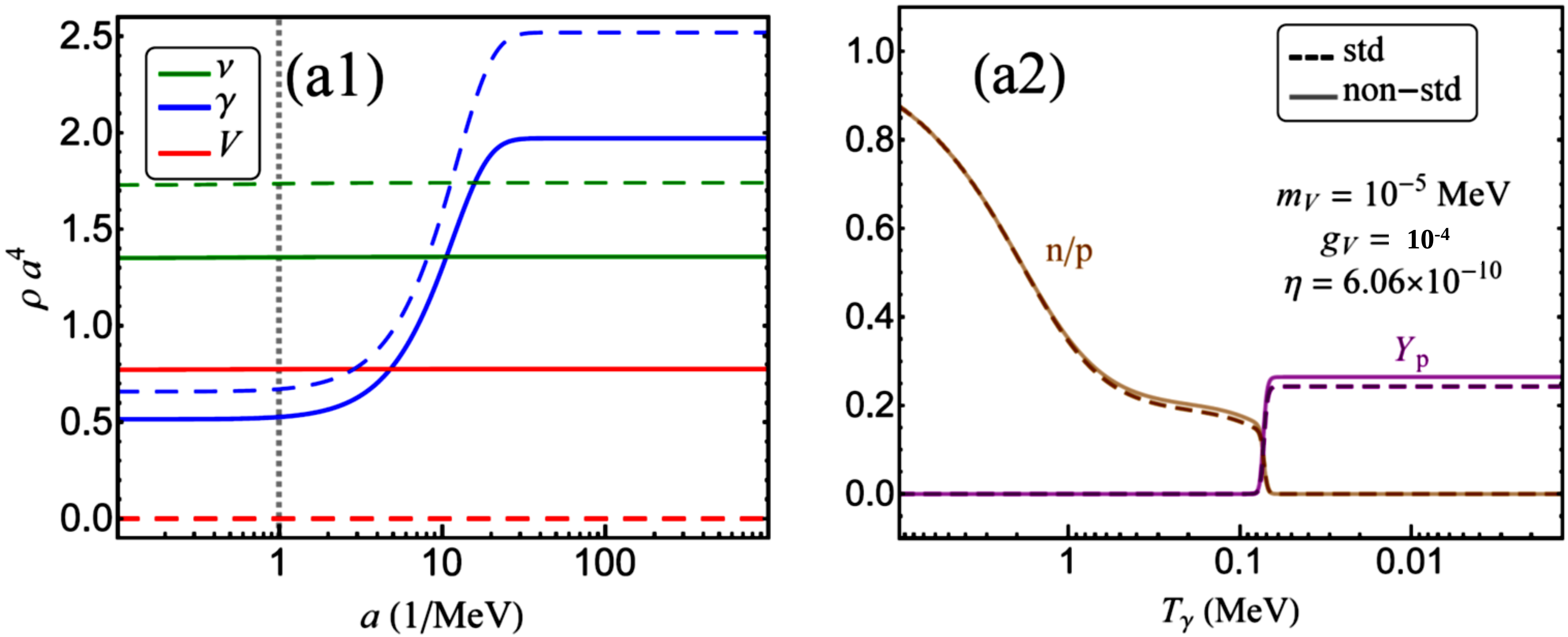
Light Element Abundances

Note: expansion rate dominated by radiation during the whole BBN era

Calculate the energy density of extra radiation by using Boltzmann Eqs

Compute the light element abundances via the public code **AlterBBN**

Case I: reaches thermal equilibrium above T = 10 MeV Arbey, 1106.1363



The vector boson V thermalized far above T = 10 MeV or a = 0.1 MeV^{-1}

Weak interactions for n-p freeze out earlier, so a larger n/p & Y_p by 8.5%

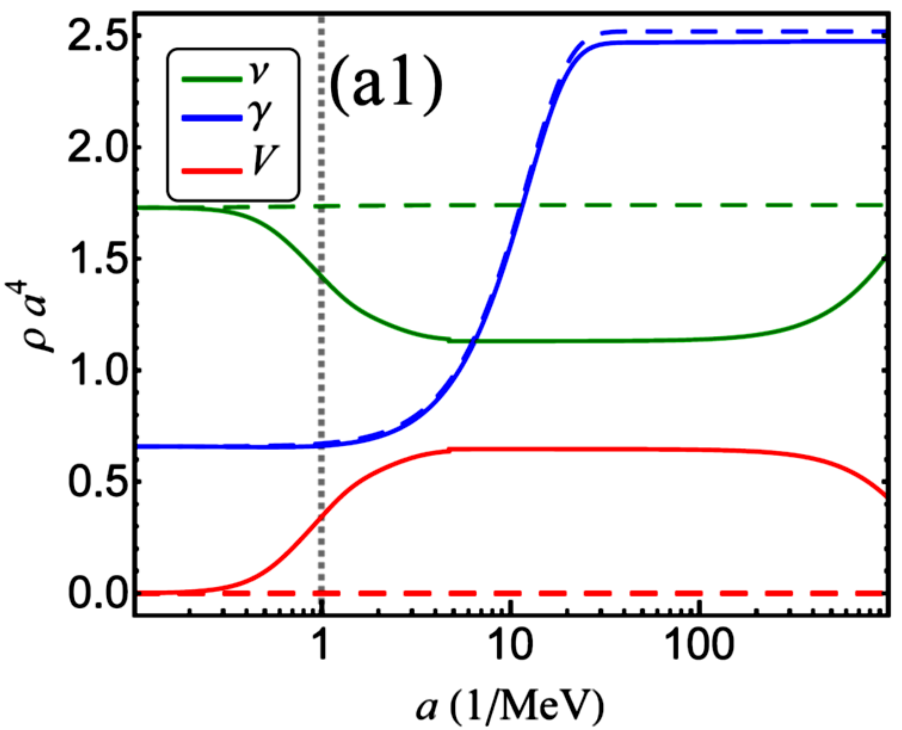
Light Element Abundances

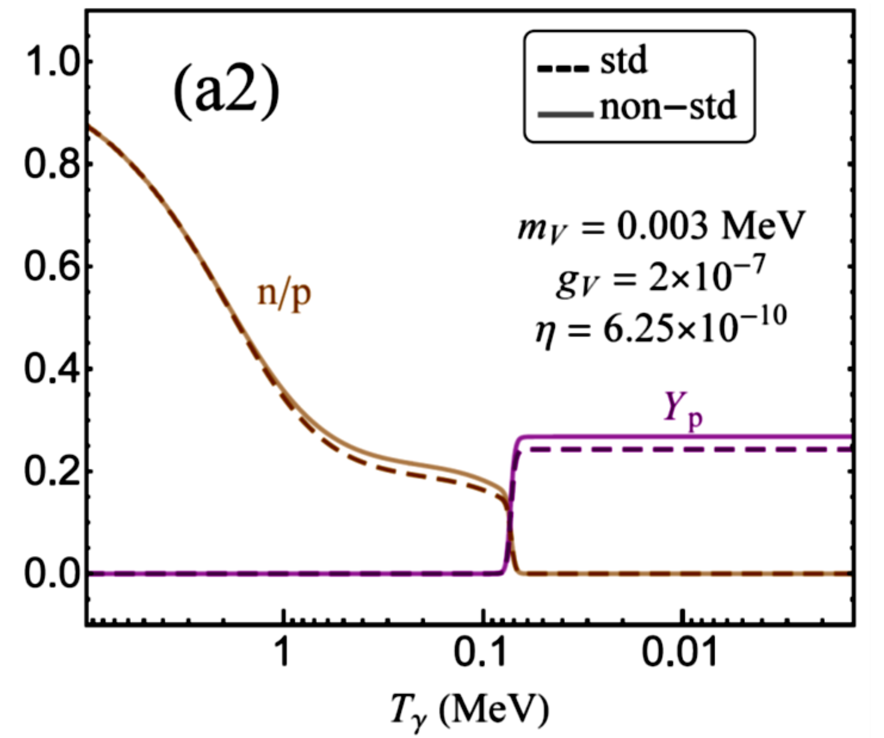
Note: expansion rate dominated by radiation during the whole BBN era

Calculate the energy density of extra radiation by using Boltzmann Eqs

Compute the light element abundances via the public code **AlterBBN**

Case III: not in thermal equilibrium at T = 1 MeV





The vector boson V not be fully thermalized at T = 1 MeV ($\Delta N_{eff} = 0.5$)

But neutrino temperature is greatly reduced, so a larger n/p & Y_p by 10%

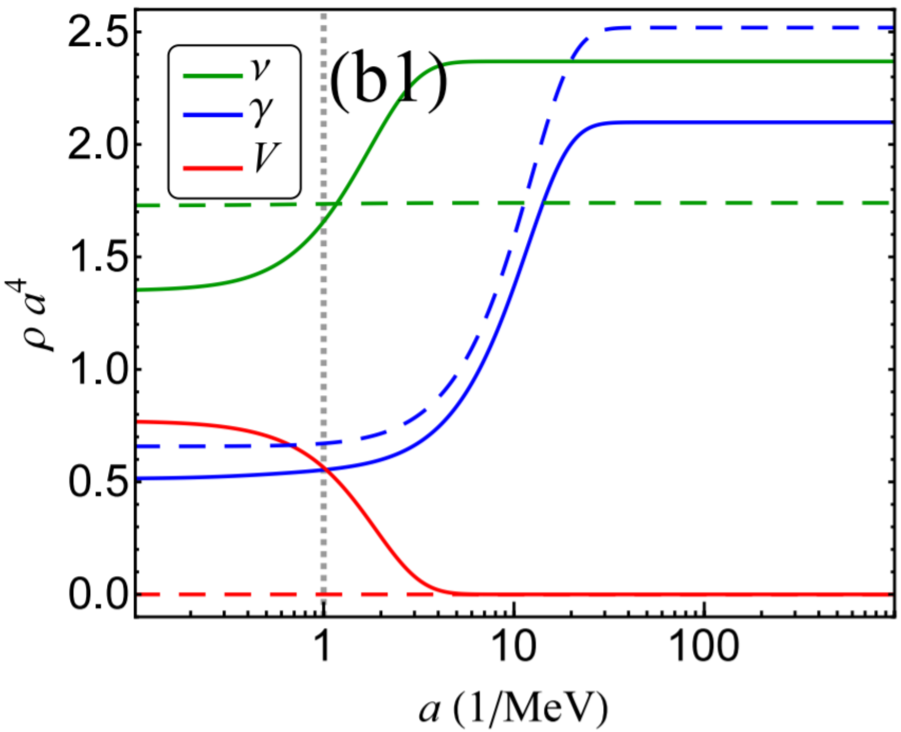
Light Element Abundances

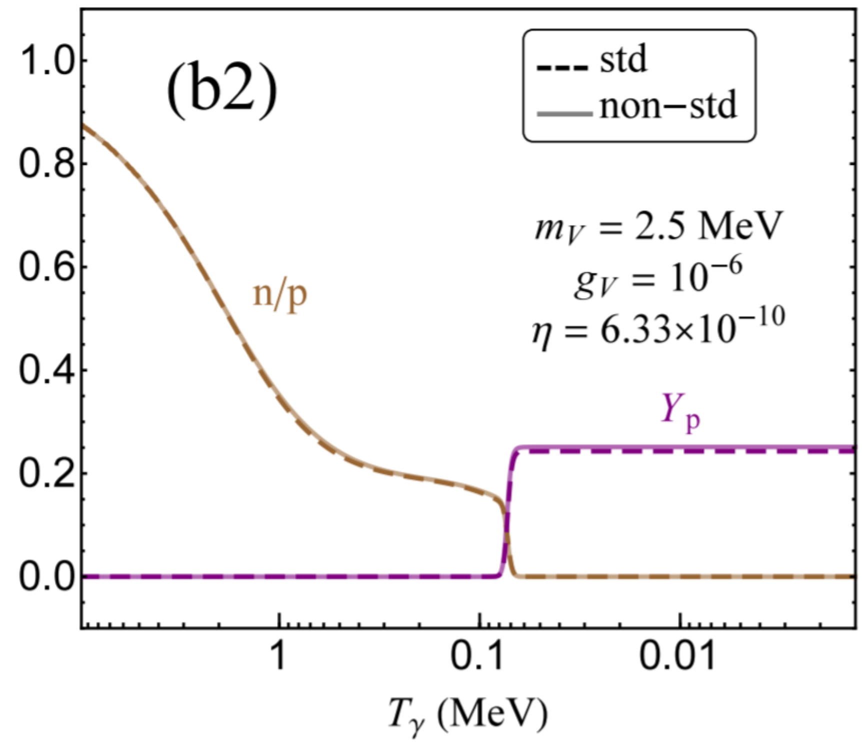
Note: expansion rate dominated by radiation during the whole BBN era

Calculate the energy density of extra radiation by using Boltzmann Eqs

Compute the light element abundances via the public code **AlterBBN**

Case IV: Boltzman suppression after T = 1 MeV





The thermalized *V* transfer entropy to neutrinos after T = 1 MeV (ΔN_{eff} = 1.5)

But neutrino temperature is also enhanced, cancellation happens!

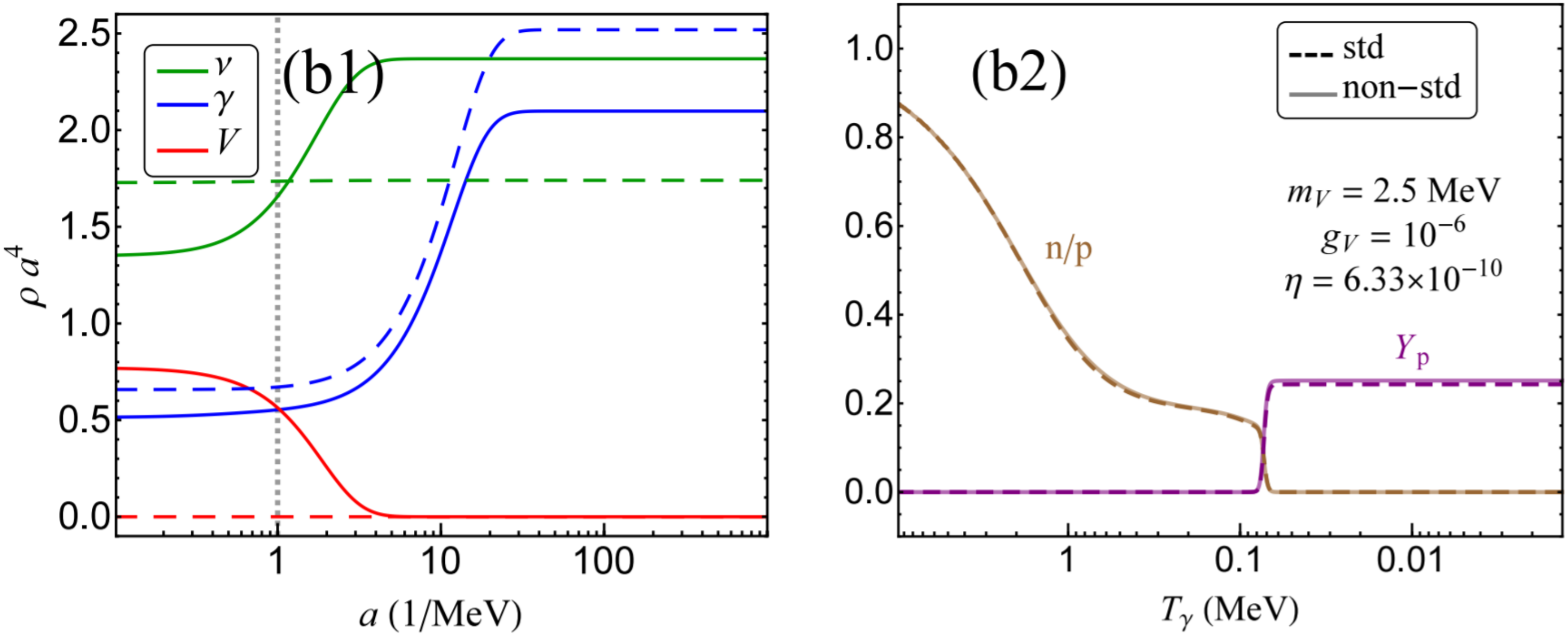
Light Element Abundances

Note: expansion rate dominated by radiation during the whole BBN era

Calculate the energy density of extra radiation by using Boltzmann Eqs

Compute the light element abundances via the public code **AlterBBN**

Case IV: Boltzman suppression after T = 1 MeV



The thermalized *V* transfer entropy to neutrinos after T = 1 MeV ($\Delta N_{eff} = 1.5$)

But neutrino temperature is also enhanced, solving the lithium-7 problem ?

Final Constraints

Constructing the chi-square function (i, j = D, ^{4}He):

Fiorentini, PRD, 98

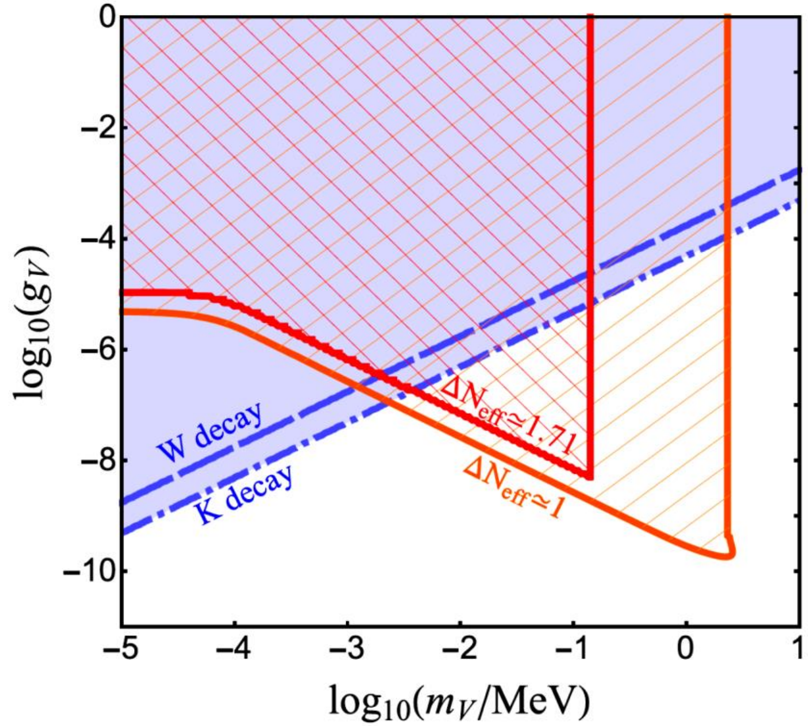
$$\chi^2 = \sum_{i,j} (Y_i^{\rm th} - Y_i^{\rm ex})[S_{ij}]^{-1}(Y_j^{\rm th} - Y_j^{\rm ex})$$

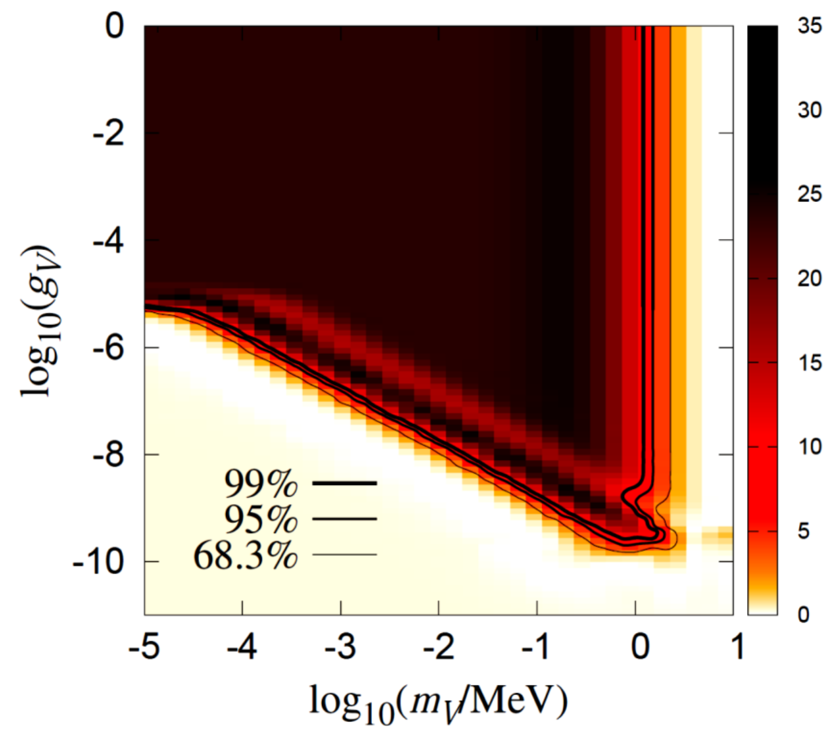
$$Y_{\rm p} = 0.2449 \pm 0.0040$$ → **1.60%**

$$\mathrm{D/H}|_{\rm p} = (2.53 \pm 0.04) \times 10^{-5}$$

Theoretical errors from reaction rates included

Scan over the parameters (η, m_V, g_V) to minimize the chi-square function





Thanks for your attention