The many facets of Big Bang Nucleosynthesis

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SUMMARY

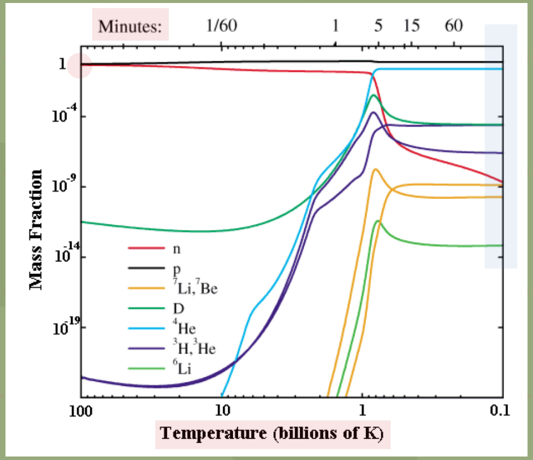
- BBN in brief;
- the quest for precision: data vs theory;
- sensitivities: free parameters and nuclear rates;
- standard BBN;
- non standard scenarios and non standard physics.
- few conclusions

BBN in brief

1. Less than 1 second after the bang, the plasma of γ e^-, ν, n, p (and their antiparticles) is in equilibrium.
2. At T~1 MeV (1 second) neutrinos decouple because their weak interactions go out of equilibrium with respect to expansion.
3. n/p ratio (fortunately) freezes out just soon after neutrinos, at T_D~800 keV; then, when a sufficient abundance of deuterium forms at T_{BBN}~100 keV, the nuclear chain starts: (almost) all neutrons present at this moment go into ^{4}He.

The final result is a universe made by 75% of hydrogen, 25% of ^{4}He (and negligible yields of the other elements up to ^{7}Li).

mass fraction of ^{4}He in a simple equation



$$Y_p = \frac{4\, n_{^4He}}{n_n + n_p} = \frac{4\ n_n/2}{n_n + n_p} = \frac{2}{1 + n_p/n_n} = 0.25$$

BBN in brief

Deuterium formation is crucial for triggering the complicated nuclear reaction chain:

Once D is produced, ^{4}He is rapidly formed, along with small fractions of ^{3}H. ^{3}He, ^{6}Li, ^{7}Li and ^{7}Be.

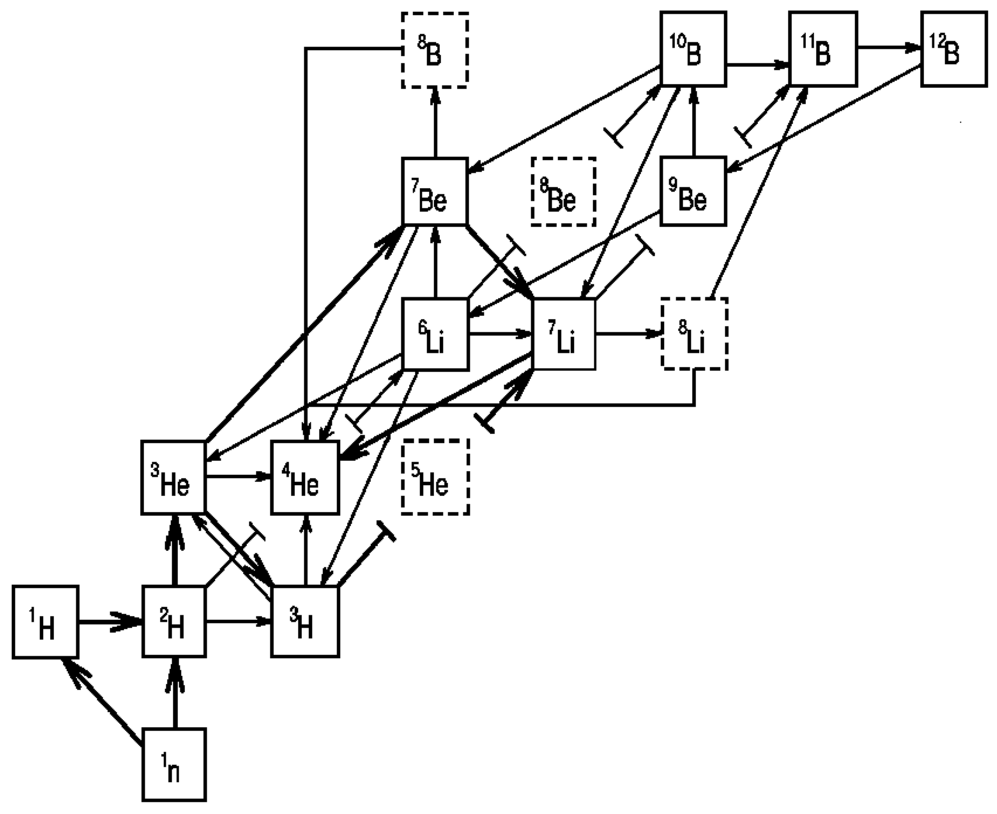
^{7}Be eventually gives ^{7}Li by electron capture:

$$e^- + {}^7\mathrm{Be} \rightarrow \nu_e + {}^7\mathrm{Li}$$

Though both ^{12}C and ^{16}O have larger binding energy than ^{4}He, they are not produced in sensible amounts since:

- i) No tightly bound isotopes with A=5, 8
- ii) Coulomb barrier start to be significant
- iii) Low baryon density suppress triple α processes

(@ 0.1 MeV baryon density is earth atmosphere density at ground level)



BBN in brief

Free parameters, nuclear rates, weak rates
cosmological model

code

Nuclide
abundances

In the standard, minimal model the only free parameter is the baryon to photon number density

Non standard models: extra species, chemical potentials, low energy inflation models, extra dimensions…

$\eta = n_b/n_\gamma = 274\ 10^{-10}\ \Omega_b h^2 \approx 10^{-9}$

BBN in brief

BBN codes

R.V. Wagoner, Astrophys. J. Suppl. 18 (1969) 247; R.V. Wagoner, Astrophys. J. 179 (1973) 343.

L.H. Kawano, 1988. Preprint FERMILAB-Pub-88=34-A; L.H. Kawano, 1992. Preprint FERMILAB-Pub-92=04-A.

R.E. Lopez, M.S. Turner, Phys. Rev. D 59 (1999) 103502.

E. Lisi, S. Sarkar, F.L. Villante, Phys. Rev. D 59 (1999) 123520.

K.A. Olive, G. Steigman, T.P. Walker, Phys. Rep. 333334 (2000) 389.

S. Esposito, G. Mangano, G. Miele, O. Pisanti, JHEP 0009 (2000) 038; P.D. Serpico, et al., JCAP 0412 (2004) 010

…

PArthENoPE: O. Pisanti et al., Comp. Phys. Comm. 178 (2008) 956; Comp. Phys. Comm. 233 (2018) 237

AlterBBN: A. Arbey, Comp. Phys. Comm. 183 (2012) 1822

PRIMAT: C. Pitrou, A. Coc, J.-P. Uzan, E. Vangioni, Phys. Rep. 754 (2018) 1

S. Gariazzo, P.F. de Salas, O. Pisanti, R. Consiglio, *Comput.Phys.Commun.* (2022) 108205, 271

Three public codes, all of them essentially equivalent from the numerical point of view.

The quest for precision: data vs theory

- Accuracy of the BBN codes. Standard physics, theoretical framework well established, but outputs of the nuclear network depend on the determination of several critical reactions. In the past mainly experimental measures (not always in the relevant energy range for BBN, 10÷400 keV in the center of mass), now also theoretical calculations.

→ experimental reaction data and analysis methods

- Accuracy of primordial elements abundances measurement. Indirect observations, since stars have changed the chemical composition of the universe. Strategies are observation in "primordial" systems or careful account for chemical evolution: increasingly precise astrophysical data on D (1%), He measured by different groups with less than 1.5% accuracy but one determination is at 4% distance, the situation is not clear for Li (the value is a factor 2-3 below the BBN prediction, lithium depletion problem).

→ systematics and astrophysical evolution

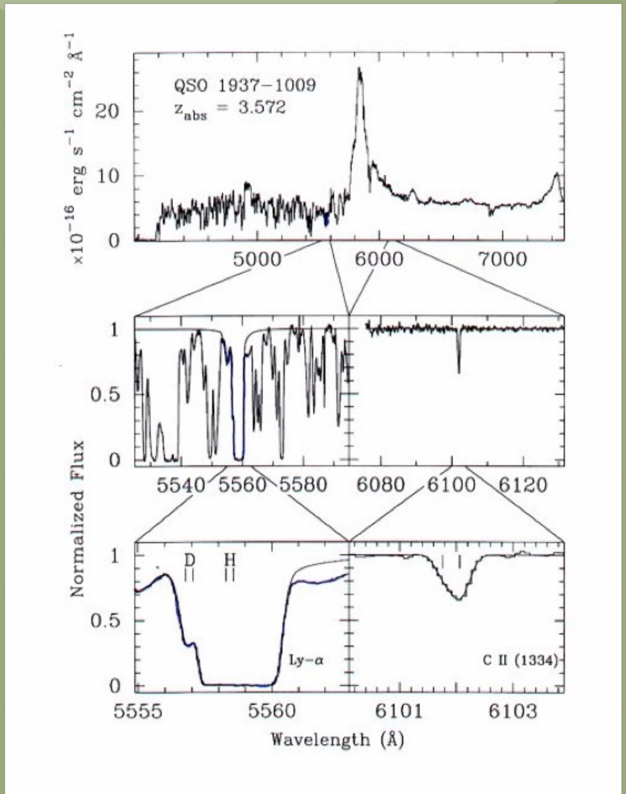
Data

- ^{2}H: it is only destroyed. Observation of Lyman absorption lines by neutral H and D (HI, DI) gas clouds (Damped Lyman-α, DLAs) at red-shift $z \approx 2 - 3$ placed along the line of sight of distant quasar. Few systems, but next generation 30-m class telescopes will increase the number.
- ^{3}He: in stellar interior can be either produced by ^{2}H-burning or destroyed in the hotter regions. It was observed only within Milky Way. Next generation 30-m class telescopes may measure ^{3}He/^{4}He.
- ^{4}He: it is produced inside stars. Observation in ionized gas regions (HeII → HeI recombination lines) in low metallicity environments (BCG or dwarf irregular), with O abundances 0.02 – 0.2 times those in the sun. Then, regression to zero metallicity. Large systematics (1% accuracy at best), but CMB allows interesting measure via ^{4}He effect on acoustic peak tail.
- ^{7}Li: it is produced (BBN and spallation) and destroyed. Observation of absorption lines in spectra of halo stars of POP II. Spite plateau at medium metallicity, but scattered points at low metallicity. The experimental value is a factor 2-3 below the BBN prediction. Attempts at solutions: nuclear rates, stellar depletion, new particles decaying at BBN, axion cooling, variation of fundamental constants. However, a measure from the Small Magellanic Cloud is at BBN level.

Data

^2H

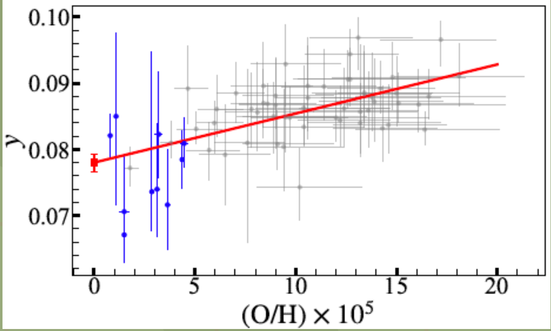
- Determination of D/H at high redshift help ensure that the observed abundance is close to primordial one.
- From a set of five high quality absorbers it was determined $^2H/H=(2.53\pm0.04)\cdot10^{-5}$ (R. Cooke et al., *Astrophys.J.* 781 (2014) 31.
- A measure $^2H/H=(2.45\pm0.28)\cdot10^{-5}$ at z=3.256 remains debated (S. Reimer-Sorensen et al., *MNRAS* 447 (2015) 2925).
- After recent new observations or reanalyses of existing data the new value, with 1.2% uncertainty, is $^2H/H=(2.527\pm0.030)\cdot10^{-5}$ (R. Cooke et al., *Astrophys.J.* 855 (2018) 102).
- The weighted mean of the latest 11 measures gives $^2H/H=(2.55\pm0.03)\cdot10^{-5}$ (B.D. Fields et al., *JCAP* 03 (2020) 010).
- Very promising improvement foreseen in the measure by 30 m class telescopes.

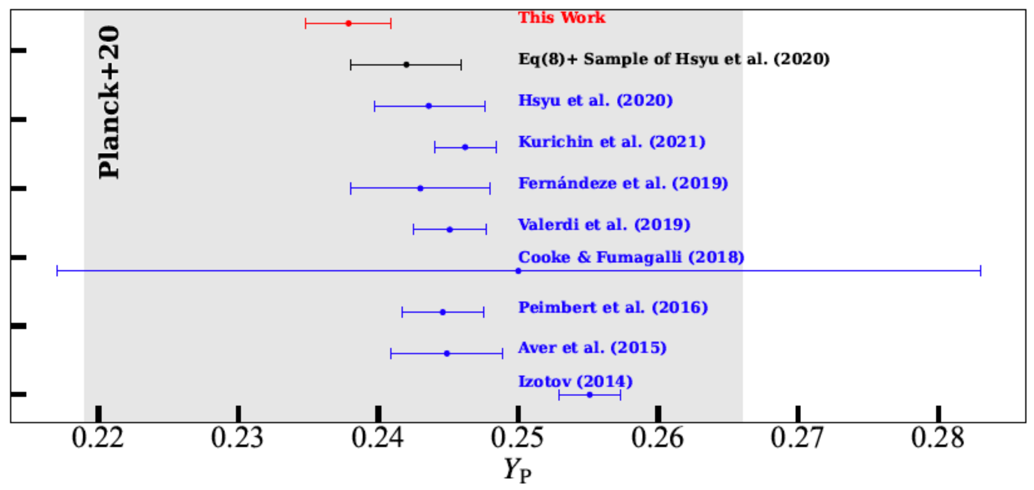


Data

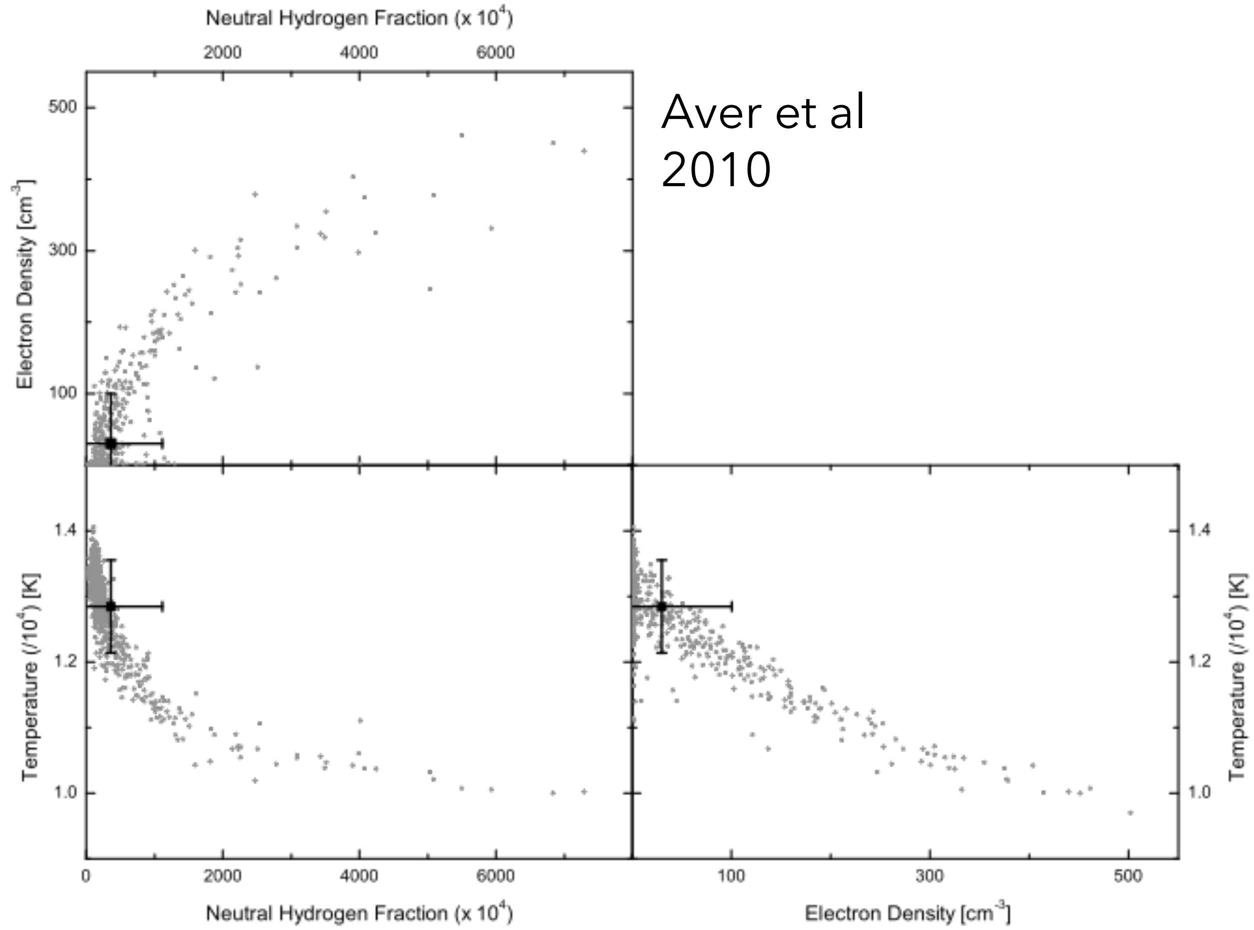
^{4}He

- The theoretical model used for extracting the abundance contains several physical parameters (among which ^{4}He abundance, electron density, optical depth, temperature, neutral H fraction). However, there was a degeneracy between the electron density and the temperature of the gas.
- More recently, the near-infrared (NIR) line HeIλ10830 was included in the analysis, which is key to removing such a degeneracy.
- From the study of 54 galaxies (three of which are Extremely Metal Poor Galaxies, EMPGs, less than 10% of solar metallicity), it results Y_p=0.2436±0.0040 (T. Hsyu et al, *Astrophys.J.* 896 (2020) 77).
- An alternative method consists in studying intergalactic absorption lines in almost primordial clouds between us and a background quasar, from which Y_p=0.250±0.033 (C. Sykes et al, *MNRAS* 492 (2020) 2151). Same authors give Y_p=0.248±0.001 as a weighted average of all recent determinations.
- Adding to the sample 10 EMPGs, a new results was released recently, Y_p=0.2379±0.0030 (A. Matsumoto et al, e-Print: 2203.09617).





Data



Aver et al
2010

Main sources of systematics:

i) interstellar reddening
ii) temperature of clouds
iii) electron density

Possible developments: using more H lines

Theory

Inputs:

nuclear rates (experimental values extrapolated in the relevant energy range)
baryon density (η)
energy density in relativistic degrees of freedom

$$N_\nu \equiv \frac{\rho_\nu}{\frac{7\pi^2}{120}T^4}$$

$$\rho_R = \rho_\gamma\left[1+\frac{7}{8}3.044\left(\frac{4}{11}\right)^{4/3}\right] + \Delta N_{eff}\cdot\rho_\gamma\left[\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right]$$

The present (and future) precision of astrophysical observations of primordial nuclide abundances led to a large effort in improving precision of theoretical predictions for ^{4}He and deuterium (mainly), i.e.

1. Weak rates now computed including radiative corrections
2. More precise data on nuclear cross sections and «ab initio» nuclear theoretical calculations
3. Neutrino evolution including oscillations and obtained solving the full kinetic equations

Theory

Example of the issue: neutron decay. In the Born approximation the thermal averaged rate in the limit of vanishing densities is

$$\tau_n^{-1} = \frac{G_F^2(c_V^2 + 3c_A^2)}{2\pi^3} m_e^5 \int_1^{\Delta/m_e} d\varepsilon\, \varepsilon \left(\varepsilon - \frac{\Delta}{m_e}\right)^2 \left(\varepsilon^2 - 1\right)^{1/2}$$

$\tau_n(\mathrm{th}) = 961$ s

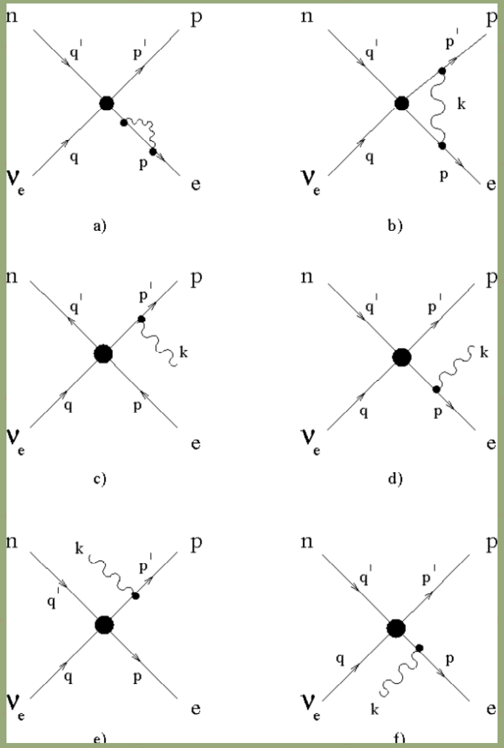
S. Esposito, et al (1999)

$\tau_n(\mathrm{exp}) = 878.4 \pm 0.5$ s

Corrections to the weak rates:

$\tau_n(\mathrm{th}) = 893.9$ s

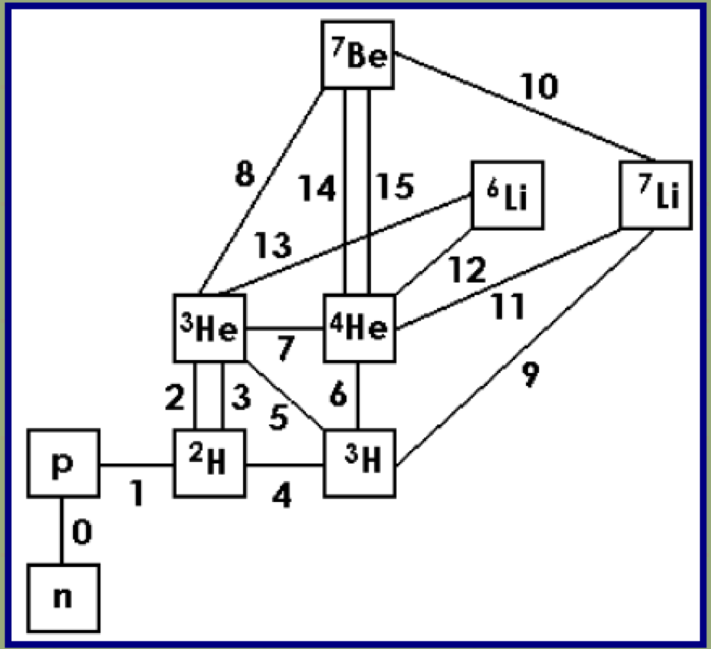
- radiative corrections $O(\alpha)$
- finite nucleon mass corrections $O(T/m_N)$
- plasma effects $(\alpha\, T/m_e)$



Weak rates are the main issue for calculating Y_p, and the main uncertainty is the experimental error in the neutron lifetime.

Theory

In the last decade more precise datas have been obtained on nuclear cross sections in the CM energy range relevant for BBN. Ab initio calculations and LUNA result on dpgamma!



Deuterium synthesis

Symbol	Reaction	Symbol	Reaction
R_0	τ_n	R_8	$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$
R_1	$p(n,\gamma)d$	R_9	$^3\mathrm{H}(\alpha,\gamma)^7\mathrm{Li}$
R_2	$^2\mathrm{H}(p,\gamma)^3\mathrm{He}$	R_{10}	$^7\mathrm{Be}(n,p)^7\mathrm{Li}$
R_3	$^2\mathrm{H}(d,n)^3\mathrm{He}$	R_{11}	$^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$
R_4	$^2\mathrm{H}(d,p)^3\mathrm{H}$	R_{12}	$^4\mathrm{He}(d,\gamma)^6\mathrm{Li}$
R_5	$^3\mathrm{He}(n,p)^3\mathrm{H}$	R_{13}	$^6\mathrm{Li}(p,\alpha)^3\mathrm{He}$
R_6	$^3\mathrm{H}(d,n)^4\mathrm{He}$	R_{14}	$^7\mathrm{Be}(n,\alpha)^4\mathrm{He}$
R_7	$^3\mathrm{He}(d,p)^4\mathrm{He}$	R_{15}	$^7\mathrm{Be}(d,p)2\,^4\mathrm{He}$

before LUNA

Reaction	Rate symbol	$\sigma_{^2\mathrm{H/H}} \times 10^5$
$p(n,\gamma)^2\mathrm{H}$	R_1	± 0.002
$d(p,\gamma)^3\mathrm{He}$	R_2	± 0.062
$d(d,n)^3\mathrm{He}$	R_3	± 0.020
$d(d,p)^3\mathrm{H}$	R_4	± 0.013

0.1%
87%
9%
3.8%

V. Mossa et al, Nature 587 (2020) 7833, 210
L.E. Marcucci et al, *Phys.Rev.Lett.* 116 (2016) 10, 102501
L.E. Marcucci et al, e-Print:2207.01433

Di Valentino et al., Phys. Rev. D90 (2014) no. 2, 023543

Sensitivities: free parameters

Goal. Use BBN as a probe of cosmological model, fundamental physics & as a guideline for nuclear physics experiments

Few examples:

- Nuclear rates fixing deuterium abundance
- Exotic scenario: varying fundamental constants
- Baryon density and dark radiation (after LUNA and recent ^{4}He data)

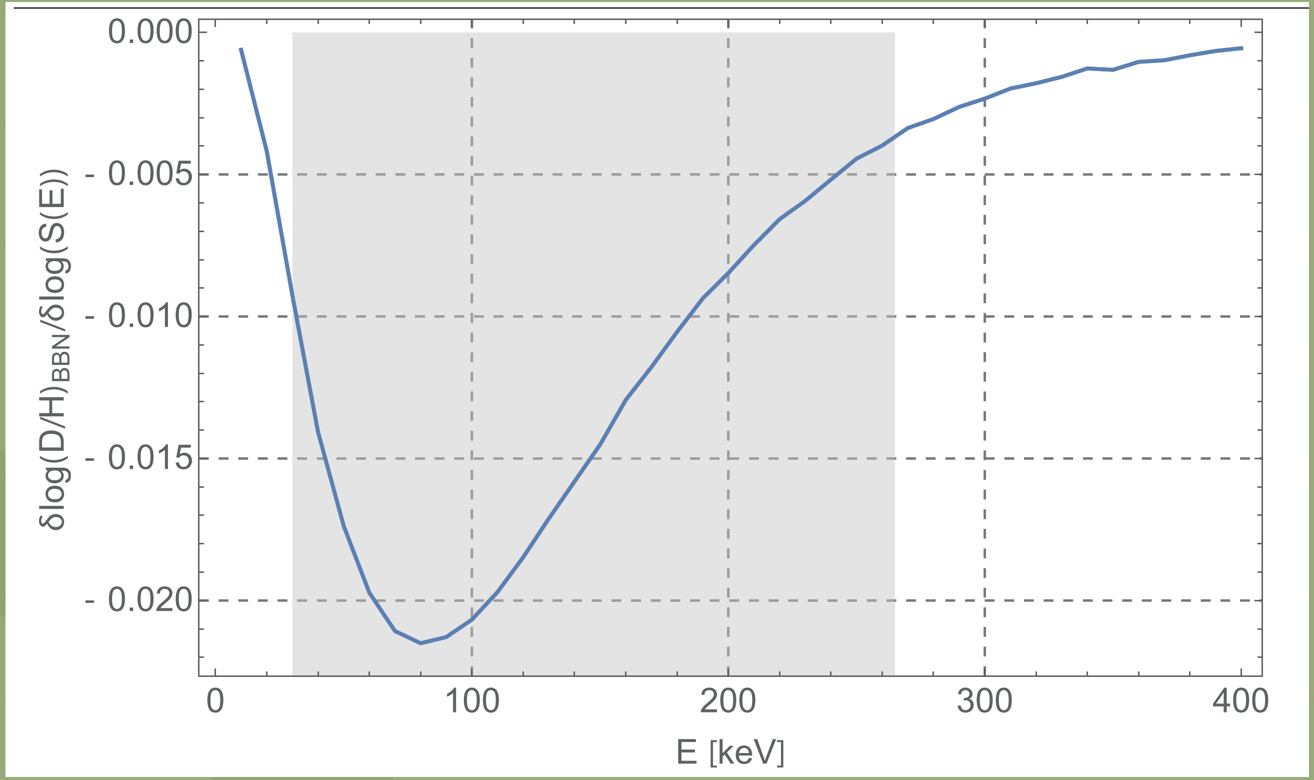
Nuclear rates fixing deuterium abundance

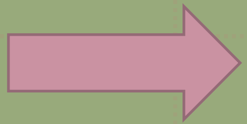
Precise data on D/H ratio (1% accuracy) suggested that one of the main reaction cross section ($d(p,\gamma)\ ^3He$) may be larger than what found by experiments (Adelberger et al 2011)

Di Valentino et al, 2014

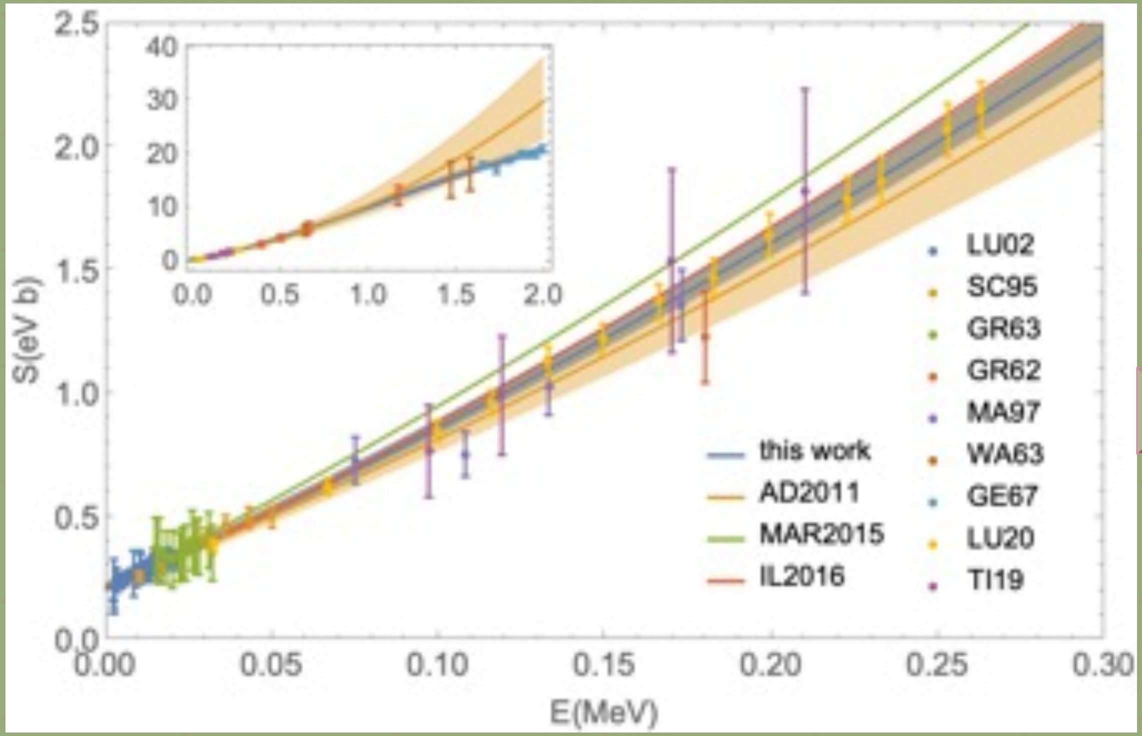
Same from ab initio theoretical calculation   Marcucci et al, 2015

In which energy range to measure the cross section? Sensitivities





LUNA @ LNGS



V. Mossa et al., Nature 587 (2020) 7833, 210

Before LUNA

- previous data were scarce in the BBN range with ~ 9% uncertainty
- phenomenological fit by Adelberger et al. (AD2011, orange line and band)
- *ab initio* theoretical prediction by Marcucci et al. (2005) updated in 2016 (green line), 15% higher than AD2011
- Bayesian analysis by Iliadis et al. (2016, red line)

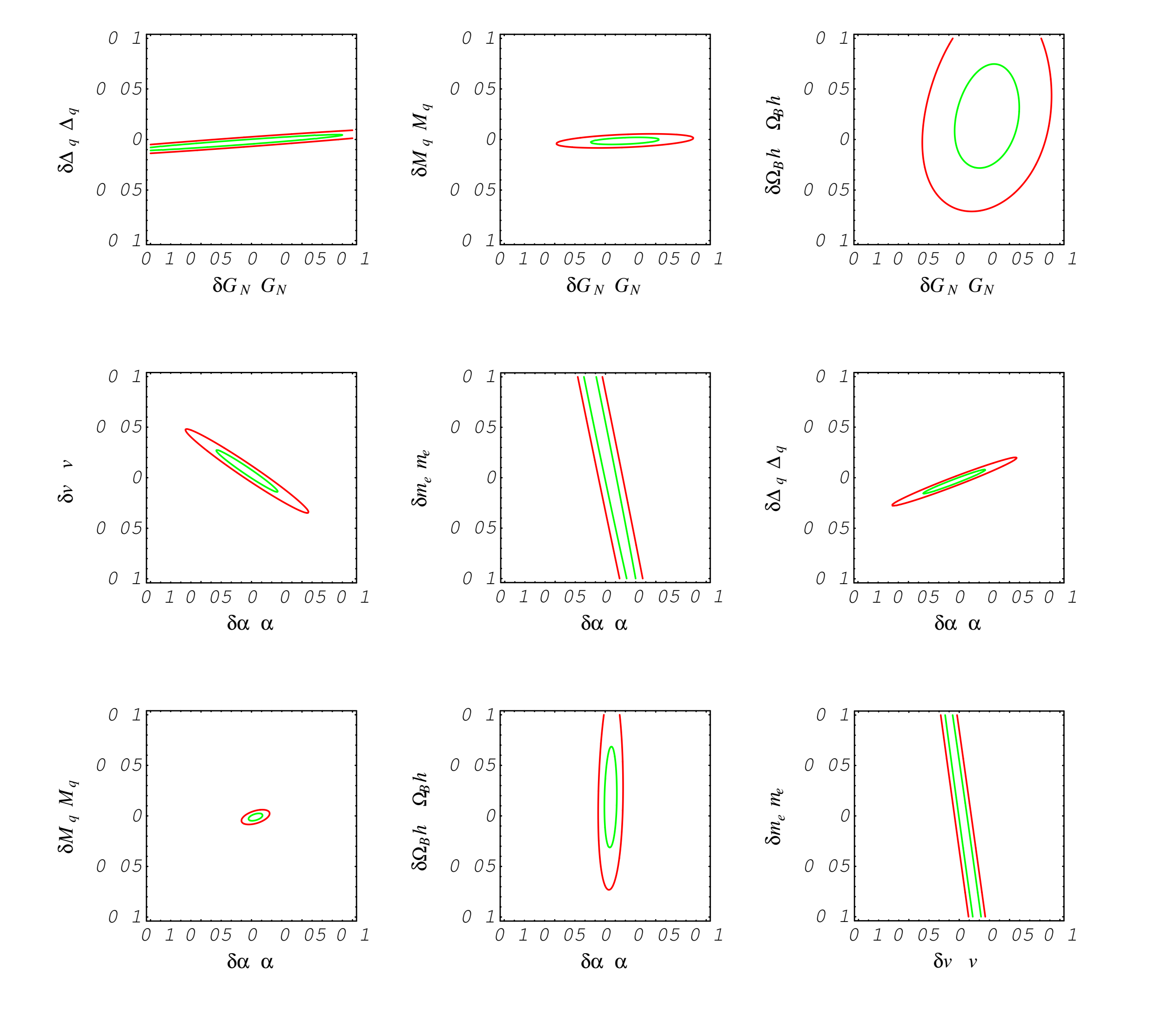
After LUNA

- very precise data (yellow points), $\Delta S/S \leq 2.6\%$, in [30,300] keV E_{cm}
- S-factor global fit (dominated by LUNA data) with 3rd order polynomial, $\chi_{red}^2 = 1.02$ (Nature 2020, blue line and band)

Exotic scenario: varying fundamental constants

Dirac idea: small (or large) values for (adimensional) fundamental constants may be a signal that they are not «constant», and there might be an underlying dynamics.

Sensitivity of BBN



Baryon density and dark radiation (after LUNA and recent ^{4}He data)

A way to estimate sensitivity: run a BBN code (PArthEnoPE) as a function of input parameters and fit nuclei abundances

$$\frac{D}{\mathrm{H}} = 2.51 \times 10^{\;\,5}\, R_{pn\gamma}^{0.20}\, R_{dp\gamma}^{0.31}\, R_{ddn}^{0.51}\, R_{ddp}^{0.42} \left(\frac{\omega_b}{0.02242}\right)^{1.61} \left(\frac{\tau_n}{879.4\,\mathrm{s}}\right)^{0.43} \left(1+\frac{N_{\mathrm{e}}}{3.045}\right)^{0.41},$$

$$Y_p = 0.2469\, R_{pn\gamma}^{0.005}\, R_{dp\gamma}^{0.0002}\, R_{ddn}^{0.006}\, R_{ddp}^{0.005} \left(\frac{\omega_b}{0.02242}\right)^{0.04} \left(\frac{\tau_n}{879.4\,\mathrm{s}}\right)^{0.72} \left(1+\frac{N_{\mathrm{e}}}{3.045}\right)^{0.16}$$

Improving precision...

Non-instantaneous neutrino decoupling

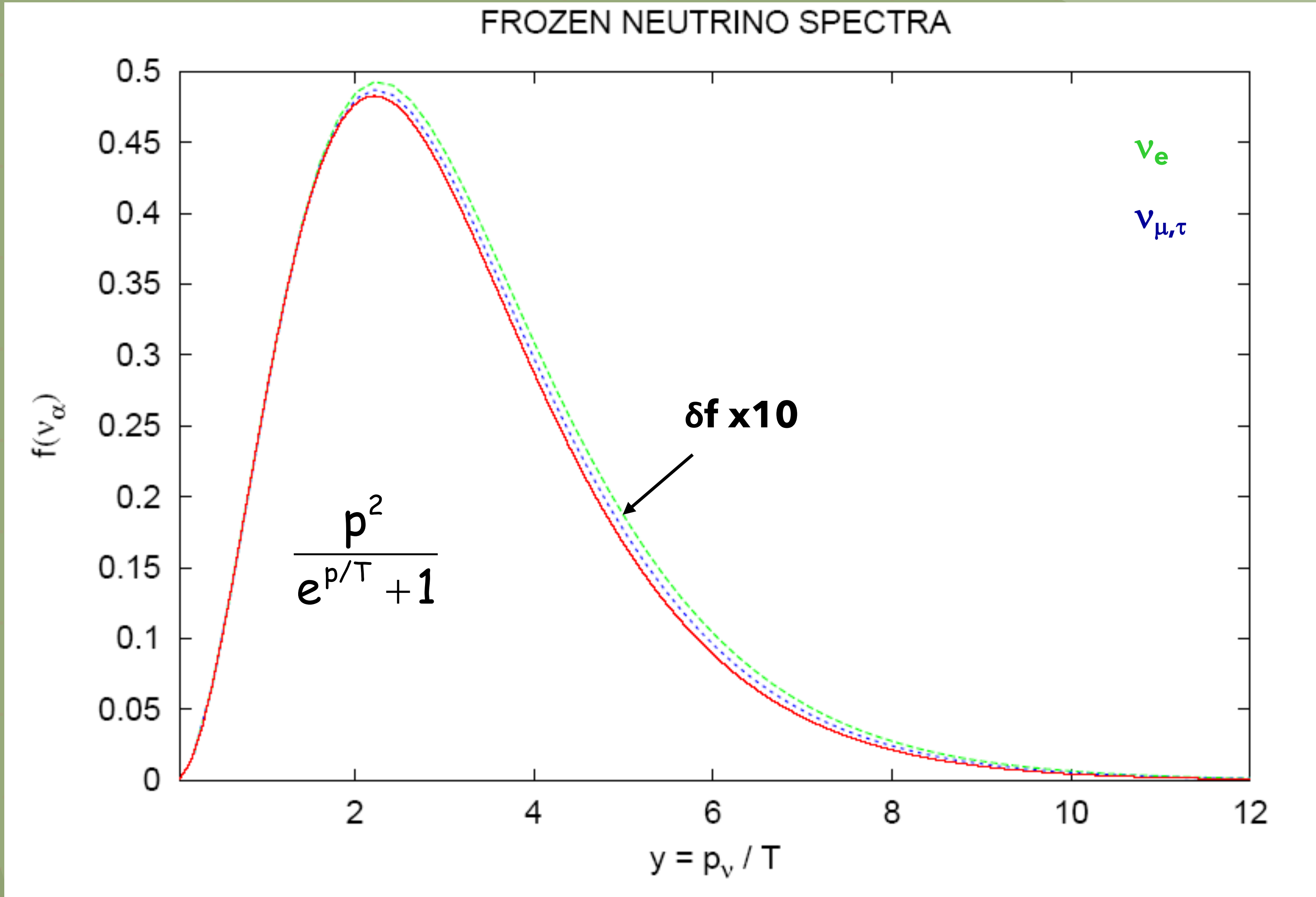
At $T \sim m_e$, e^+e^- pairs annihilate heating photons

$$e^+e^- \to \gamma\gamma$$

But, since $\mathbf{T_{dec}(\nu)}$ is close to $\mathbf{m_e}$, neutrinos share a small part of the entropy release

$$\mathbf{f_\nu = f_{FD}(p, T_\nu)[1+\delta f(p)]}$$

Improving precision



Results

	$T_{fin}^{\gamma} / T_0^{\gamma}$	$\delta\rho_{\nu e}$(%)	$\delta\rho_{\nu\mu}$ (%)	$\delta\rho_{\nu\tau}$(%)	N_{eff}
Instantaneous decoupling	1.40102	0	0	0	3
SM	1.3978	0.94	0.43	0.43	3.046
+3v mixing (θ_{13}=0)	1.3978	0.73	0.52	0.52	3.046
+3v mixing ($\sin^2\theta_{13}$=0.047)	1.3978	0.70	0.56	0.52	3.046

Dolgov, Hansen & Semikoz, 1997
G.M. et al, 2002
G.M. et al, 2005
M. Escudero 2020
De Salas et al. 2021

Using BBN as a tool

- Choose the scenario, that is the parameters of your model: A, B, ….

- Run your favourite BBN code and determine the theoretical abundances $X_i(A,B,\ldots)$ with corresponding uncertainties $\sigma_i(A,B,\ldots)$.

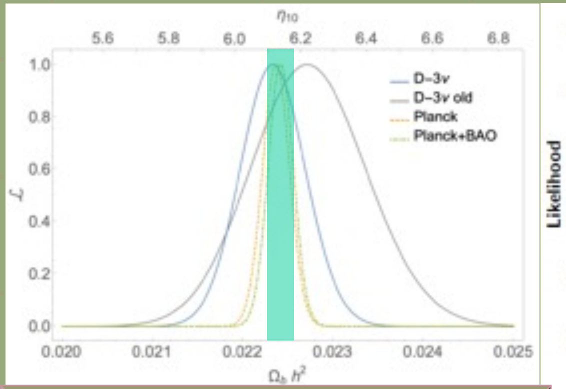
- Construct likelihood functions for your abundances:

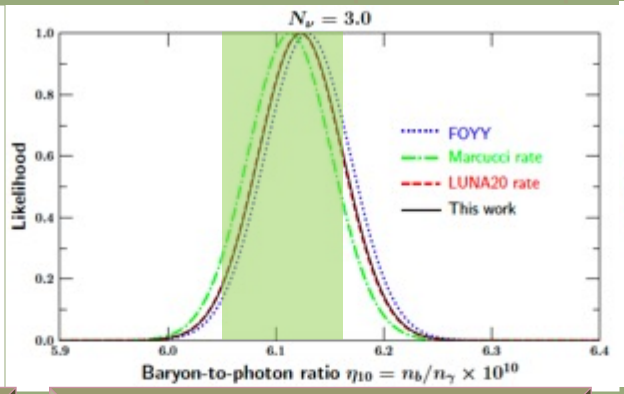
$$L_i(N_{eff},\eta) = \frac{1}{2\pi\sigma_i^{th}(N_{eff},\eta)\sigma_i^{ex}} \int dx \exp\left(-\frac{(x - Y_i^{th}(N_{eff},\eta))^2}{2\sigma_i^{th}(N_{eff},\eta)^2}\right) \exp\left(-\frac{(x - Y_i^{ex})^2}{2\sigma_i^{2x}}\right)$$

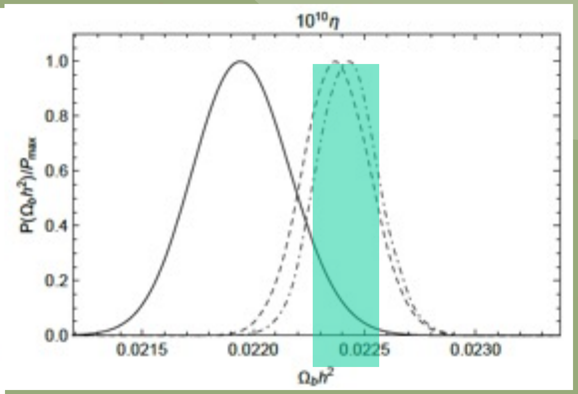
- Determine confidence level contours from the comparison of theoretical and experimental quantities.

Standard BBN

BBN/CMB concordance. Only free parameter is the baryon density





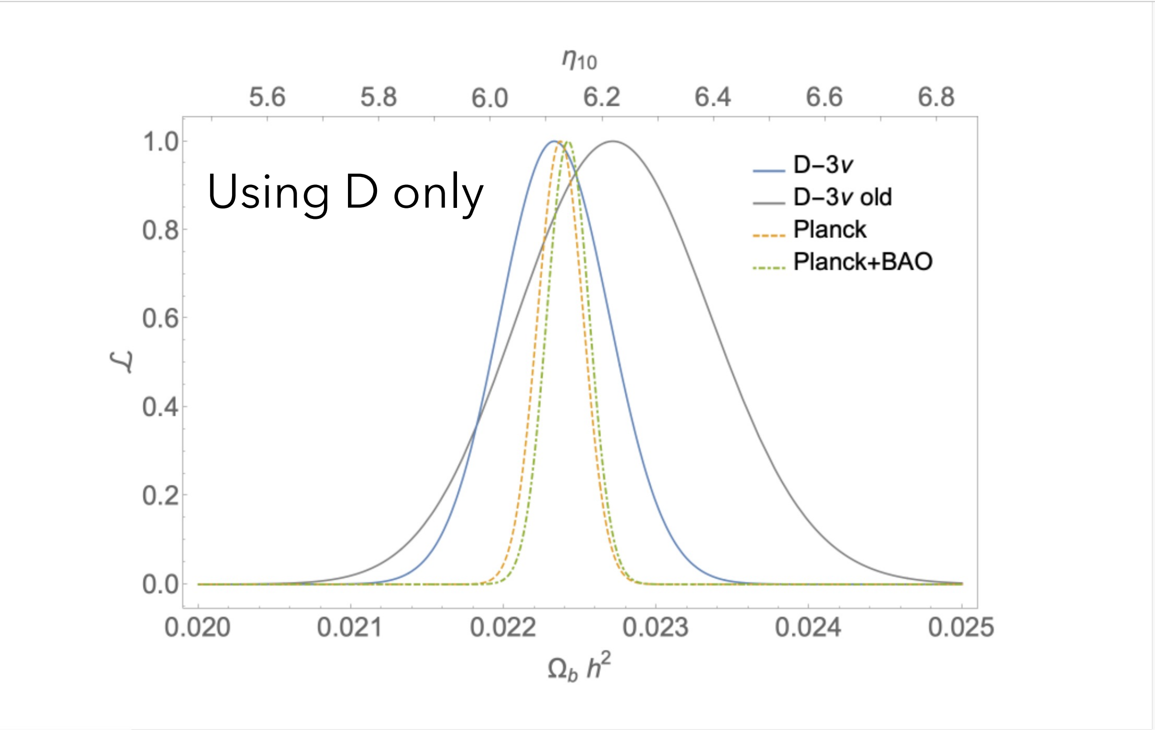


O.Pisanti et al, JCAP 04 (2021) 020

Yeh et al., JCAP 03 (2021) 046

Pitrou et al., MNRAS. 502 (2021) 2, 2474

- A(blue) and B(black) in fair agreement with each other and with Planck (1σ green bands)
- C(solid) shows 1.84σ tension with Planck
- Likelihoods come from:
- A: only D_{BBN}, D/H=2.527±0.030
- B: D_{BBN}+ Y_{pBBN}+CMB, D/H=2.55±0.03, Y_p=0.2453+-0.0034
- C: D_{BBN}+ Y_{pBBN}, D/H=2.527±0.030, Y_p=0.2453+-0.0034
- Planck green bands correspond to:
- A: Planck +$Y_p(\omega_b)$ + lensing + BAO
- B: Planck + lensing
- C: Planck +$Y_p(\omega_b)$ + lensing + BAO



Non standard scenarios

BBN is a powerful «cosmological probe» and can test more exotic scenarios for either the cosmological model or fundamental interactions. In particular when combined with CMB data (Planck)

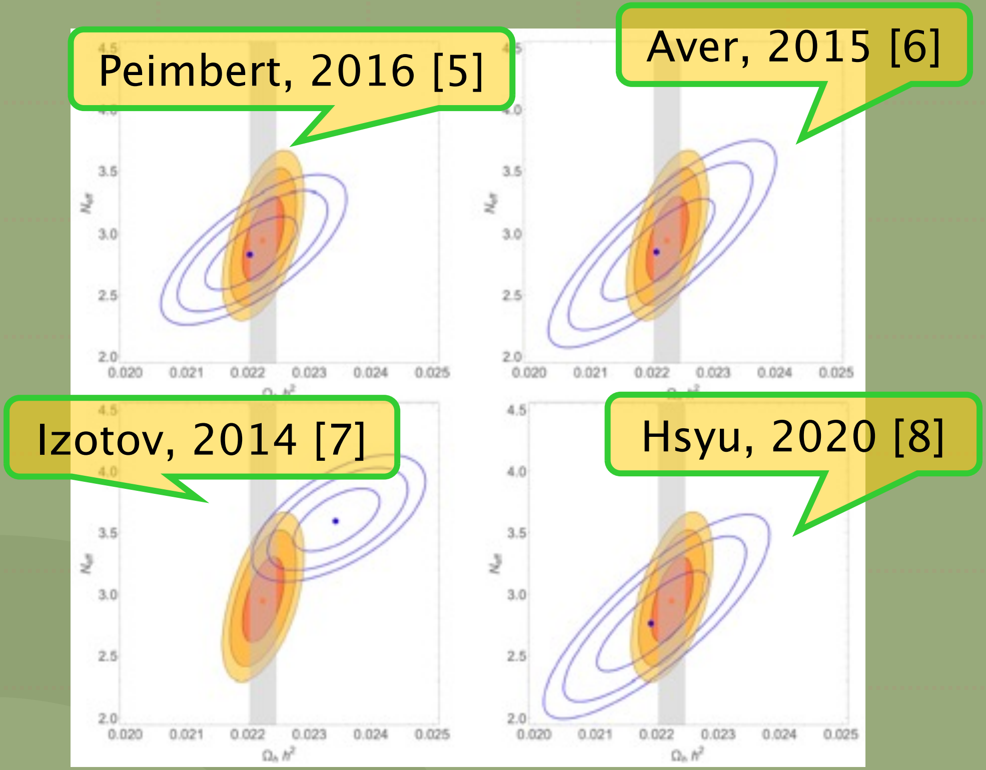
Few examples:

- Non standard neutrino distribution in phase space
- Neutrino chemical potentials, i.e. neutrino-antineutrino (helicity) asymmetry
- Non standard lepton interactions
- Sterile neutrinos, dark radiation
- Decaying massive particles
- Low reheating at the Mev scale
- Massive particles in the MeV range or heavier
- Varying coupling constant
- Extra-dimensions
- …

Non standard scenarios

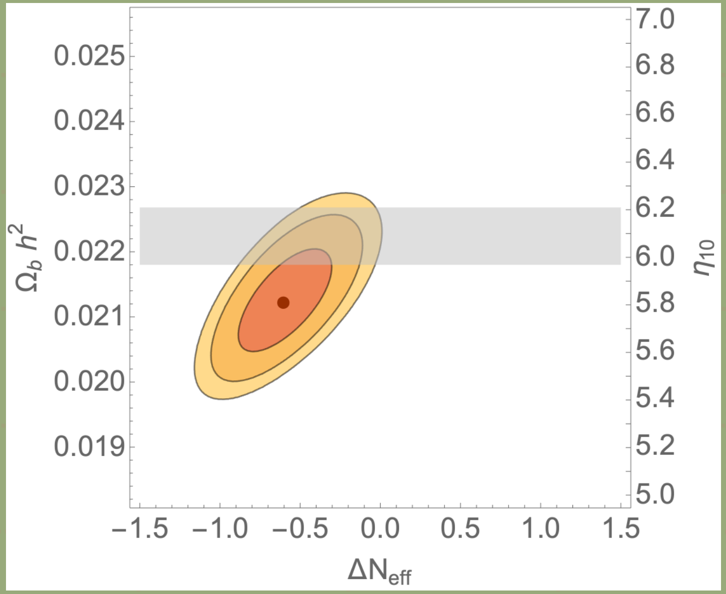
Extra radiation: ΔN_{eff} , degeneracy with $\Omega_b h^2$ when using only D/H

To break the degeneracy the ^{4}He abundance can be used in addition to D/H



	ω_b	$N_{\rm eff}$
Planck	0.02237 ± 0.00015	3.045
Planck+BAO	0.02242 ± 0.00014	3.045
D-3ν	0.02233 ± 0.00036	3.045
D+Planck	0.02224 ± 0.00022	2.95 ± 0.22
BBN [5]	0.0220 ± 0.0005	2.84 ± 0.20
BBN [6]	0.0221 ± 0.0006	2.86 ± 0.28
BBN [7]	0.0234 ± 0.0005	3.60 ± 0.17
BBN [8]	0.0219 ± 0.0006	2.78 ± 0.28

Matsumoto et al, arXiv:2203.09617 (2022)



Non standard scenarios

Degenerate neutrinos?

Until neutrinos are coupled (and after their decoupling, till electron-positron annihilation) they are described by an equilibrium FD distribution, which depends on their chemical potential, μ_ν.

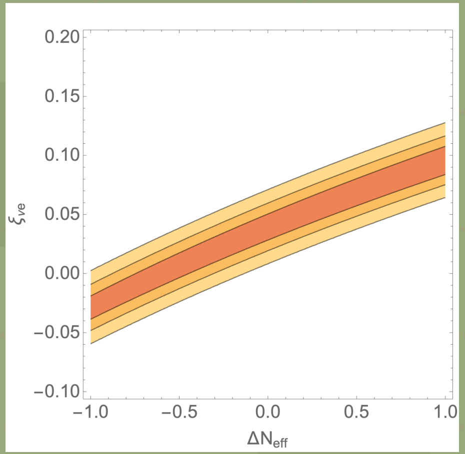
$$f_{eq}(p,T) = \frac{1}{e^{\frac{p-\mu_{\nu_i}}{T}}+1}$$

degeneracy parameter, invariant under cosmic expansion

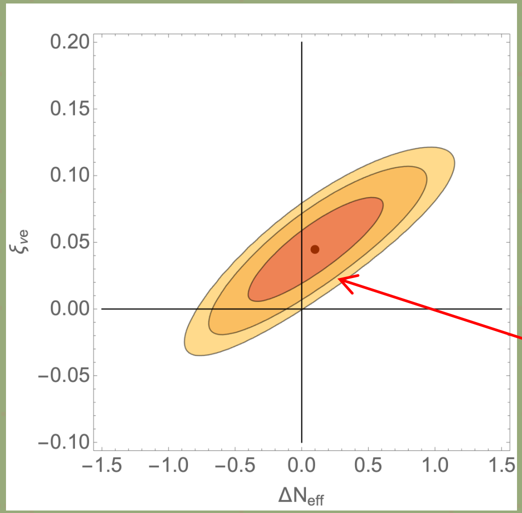
$$\xi_i \equiv \frac{\mu_{\nu_i}}{T}$$

Chemical potentials contribute in increasing the energy density, so increasing the effective number of neutrinos. All flavours contribute to N_{eff}, giving a faster expansion ➔ more ^{4}He; only $\xi_{\nu e}$ contribute to weak rates (a positive value ➔ more neutrinos ➔ less neutrons ➔ less ^{4}He): degeneracy in the $\xi_{\nu e} - \Delta N_{eff}$ plane.

$$\Delta N_{eff}^{(\xi)} = \sum_i \left(\frac{30\xi_i^2}{7\pi^2} + \frac{15\xi_i^4}{7\pi^4} \right)$$



Planck prior



1-σ

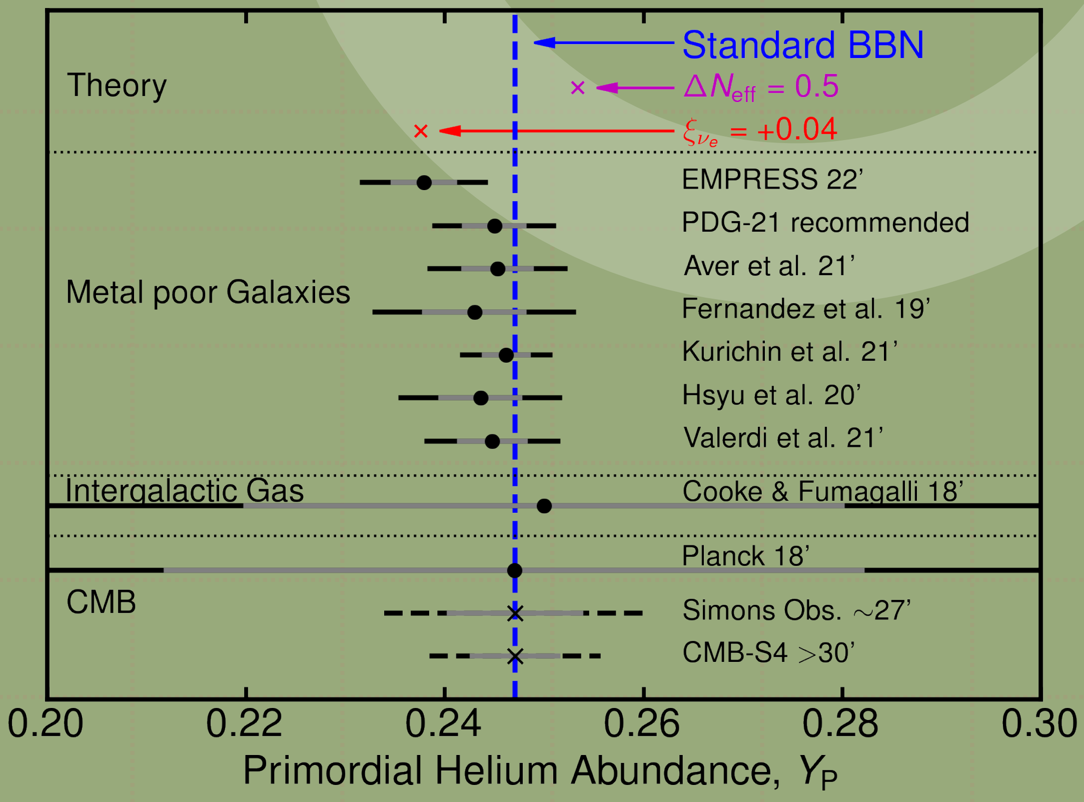
$$\xi_{\nu e} = 0.046 \pm 0.025$$

$$N_{eff} = 3.14 \pm 0.33$$

tension with standard scenario using Matsumoto et al Y_p determination

Non standard scenarios

- M.Escudero et al, 2022



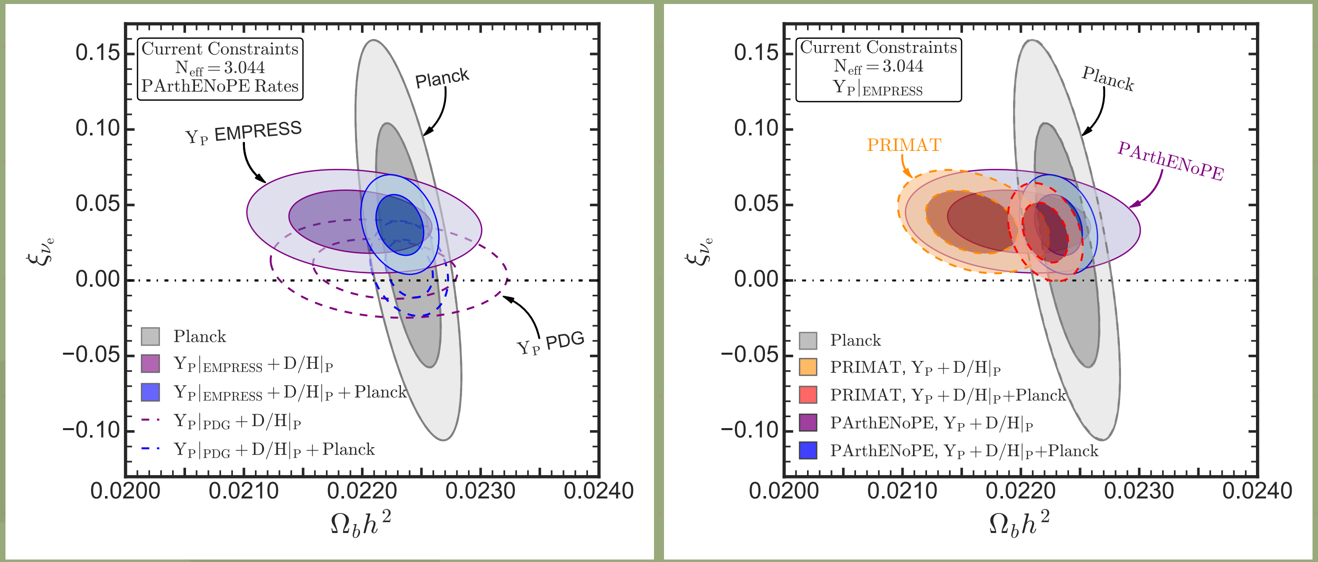


FIG. 2. 1 and 2σ C.L. regions for ξ_{ν_e} and $\Omega_b h^2$ from nucleosynthesis data, CMB data, and their combination for a cosmlogical scenario without dark radiation (*i.e.* assuming $N_{\rm eff} = N_{\rm eff}^{\rm SM} = 3.044$). The left panel compares the favored regions for two determinations of the helium abundance (EMPRESS survey and the PDG-21 recommended value) adopting the PArthENoPE nuclear rates, while the right panel compares the favored regions for two choices of the nuclear reaction rates (PArthENoPE or PRIMAT) adopting the EMPRESS measurement of the helium abundance.

Non standard scenarios

Sterile neutrinos

Hints for sterile neutrino states from
long(short) standing anomalies

LSND, MiniBoone
Reactor anomaly
Gallium anomaly

$m_\nu \approx \mathrm{eV}$, $\sin^2 \theta_{as} \approx 10^{-2}$

With standard assumptions too many sterile neutrinos in the early universe, produced via oscillations, i.e. a larger N_{eff} if oscillations are effective before neutrino decoupling, and distortion of standard neutrino (ν_e) distribution in phase space

Non standard scenarios

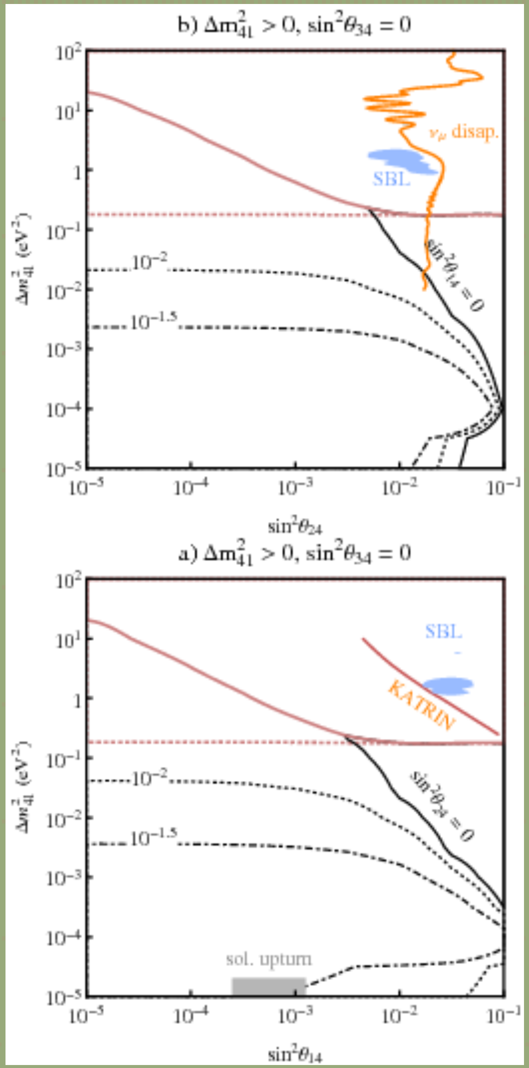
The standard case, after Planck 2013

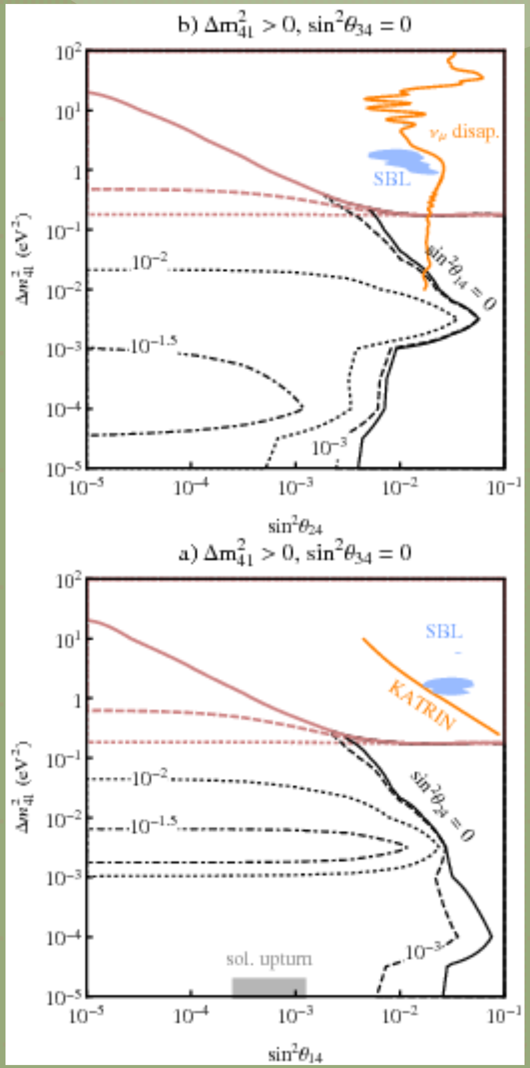
$N_{eff} < 3.30 \pm 0.27$
$m_s < 0.38$ eV

New Planck analysis
even stronger!

(Planck XIII 2015-2018)

$N_{eff} = 3.04 \pm 0.22$
$m_s < 0.38$ eV





Non standard scenarios

Lepton asymmetry suppresses sterile production (or might enhance it through a MSW resonance) via a matter potential term

$H_\nu = \sqrt{2}\, G_F\, \eta_\nu$

This renders the equation of motion non linear

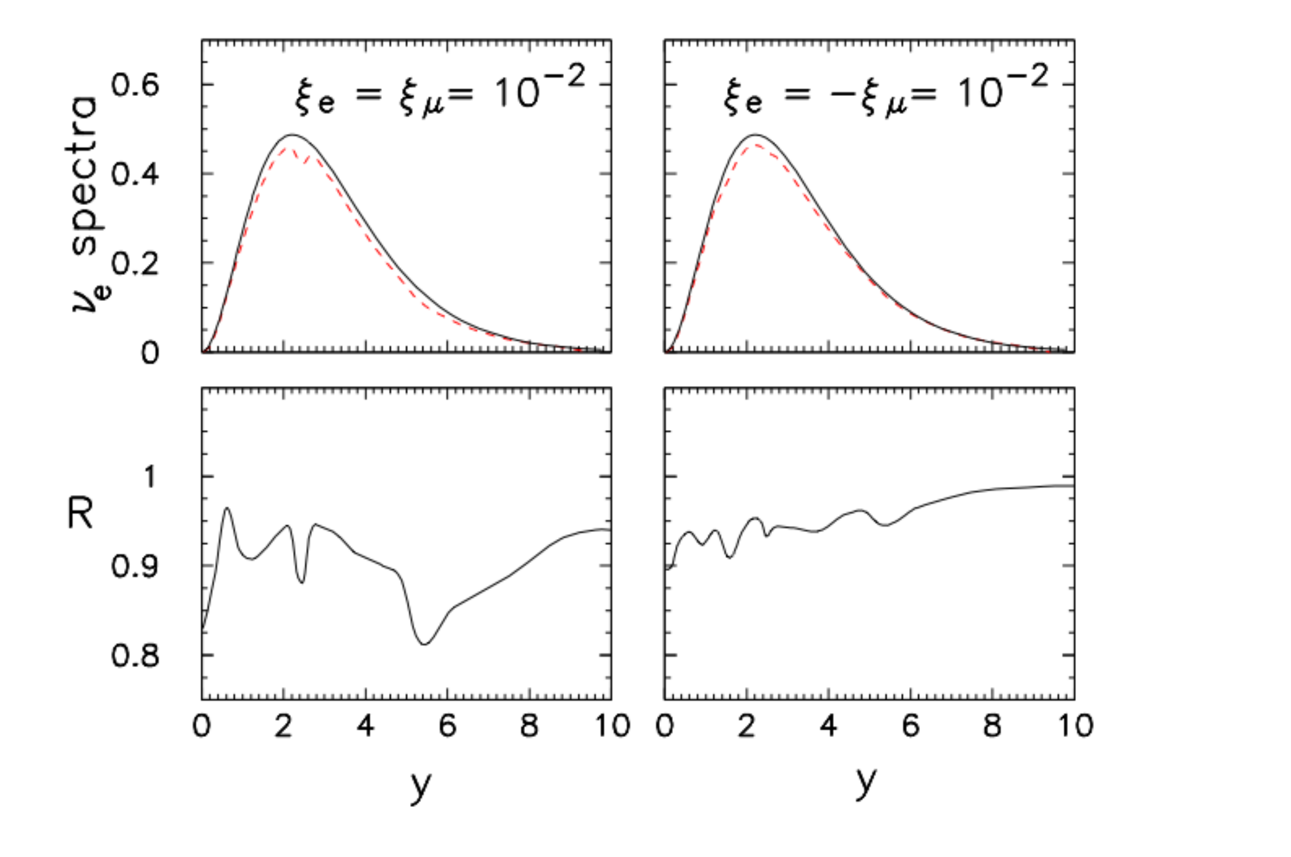
Usual approximation: mean momentum <p> = 3.15 T and 1+1 neutrinos

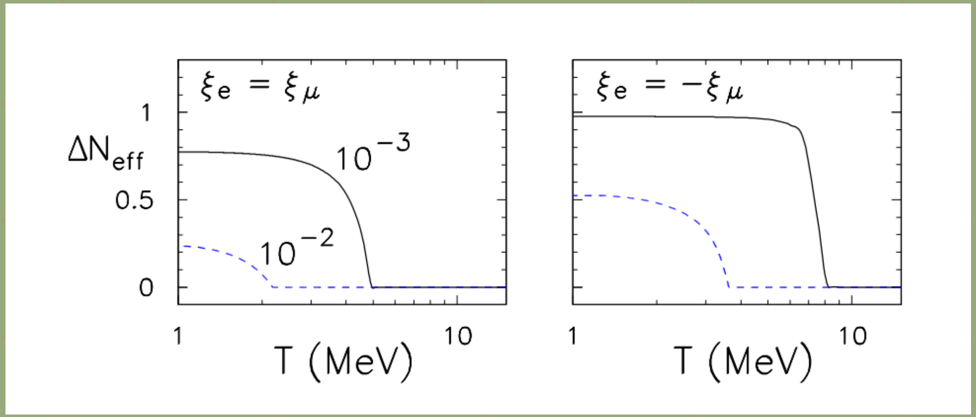
Unsatisfactory, for several reasons:

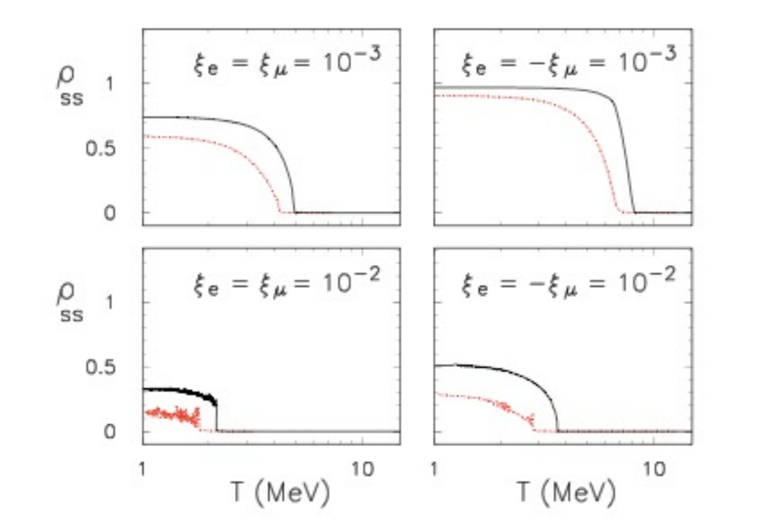
- Oscillation is a mode dependent effect, and thus sterile production can start at different times and results into a different yield
- Oscillations may deform electron neutrino spectrum, and this in turn can change BBN prediction
- In 1+1 scenarios no “repopulation” and interplay of the active neutrinos via standard mixing

Non standard scenarios

N.Saviano et al, 2013







y=p a

multi- momentum

average momentum

Few conclusions

- BBN, alone or combined with other cosmological probes (CMB, LSS,…) can constrain exotic physics beyond the Standard Model
- Presently, up to some claims of a 2 sigma level tension, the standard picture is consistent
- New astrophysical precise data are expected in the next years or so, maybe urging theorist to further improve the precision of the BBN prediction as well as nuclear rate determinations

Back up slides

BBN in brief

History

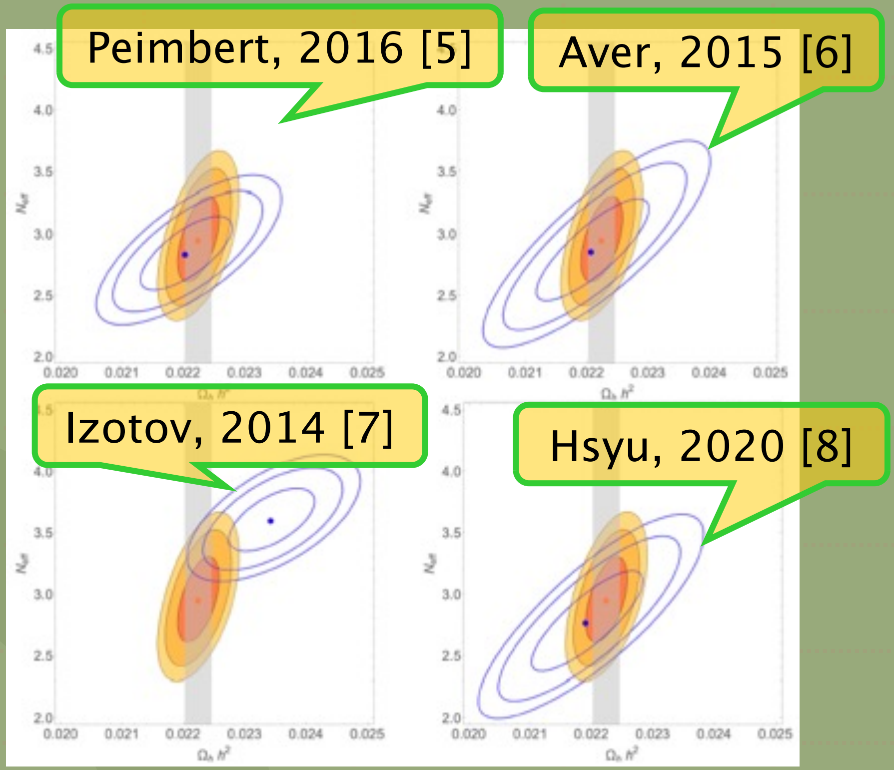
- 1946 Gamow: nuclear reactions in the early universe might explain the abundances of elements.
- Fermi and Turkevich: lack of stable nuclei with mass 5 and 8 prevents significant production of nuclei more massive than ^7Li.
- 1964 Peebles, Hoyle and Tayler: $Y_P \approx 0.25$.
- 1967 Wagoner, Fowler and Hoyle: first detailed calculation of light nuclei abundances.
- ……..Schramm, Turner, Steigman,….and many others

Non standard scenarios

Dark radiation

BBN and CMB indirect probes of non-standard cosmological models. In particular, BBN is strongly sensitive to the Hubble parameter. Since at BBN epoch $\rho \simeq \rho_R$ a possible departure from the standard scenario can show up in N_{eff}.

To break the degeneracy an abundance orthogonal to D (^{4}He, blue contours) or an independent constraining information (CMB, orange contours).



- Different Y_p estimates result in compatibility or tension of BBN with the Planck measure of the baryon density and amount of radiation -> systematics in the astrophysical measurement of Y_p can play a major role.

	ω_b	$N_{\rm eff}$
Planck	0.02237 ± 0.00015	3.045
Planck+BAO	0.02242 ± 0.00014	3.045
D-3ν	0.02233 ± 0.00036	3.045
D+Planck	0.02224 ± 0.00022	2.95 ± 0.22
BBN [5]	0.0220 ± 0.0005	2.84 ± 0.20
BBN [6]	0.0221 ± 0.0006	2.86 ± 0.28
BBN [7]	0.0234 ± 0.0005	3.60 ± 0.17
BBN [8]	0.0219 ± 0.0006	2.78 ± 0.28

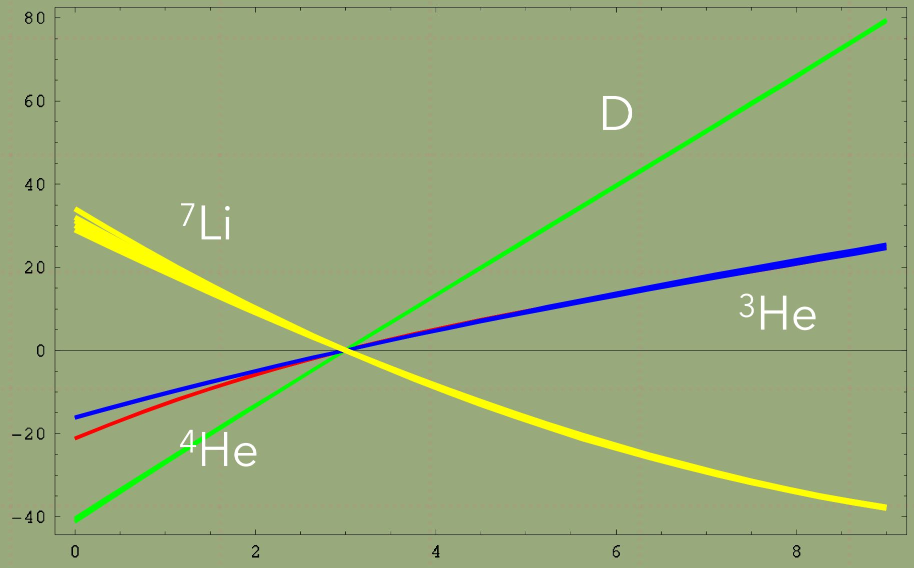
Again improving precision…

$$\rho_R = \rho_\gamma + \rho_\nu + \rho_x = \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N^{eff}{}_\nu\right)\rho_\gamma$$

They couple to gravity and contribute to expansion

Faster expansion $\rightarrow$ earlier weak process freeze-out

$\rightarrow$ more neutrons per protons



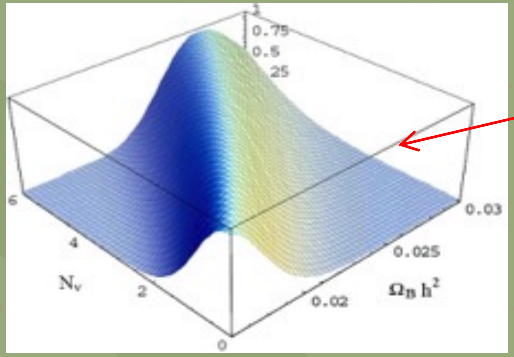
Bounds on extra light particles or exotic neutrino features

Using BBN as a tool

- Choose the scenario, that is the parameters of your model: A, B, ….
- Run your favourite BBN code and determine the theoretical abundances X_i(A,B,…) with corresponding uncertainties σ_i(A,B,…).
- Construct likelihood functions for your abundances:

$$L_i(N_{eff},\eta) = \frac{1}{2\pi\sigma_i^{th}(N_{eff},\eta)\sigma_i^{ex}} \int dx \exp\left(-\frac{(x - Y_i^{th}(N_{eff},\eta))^2}{2\sigma_i^{th}(N_{eff},\eta)^2}\right) \exp\left(-\frac{(x - Y_i^{ex})^2}{2\sigma_i^{ex\,2}}\right)$$

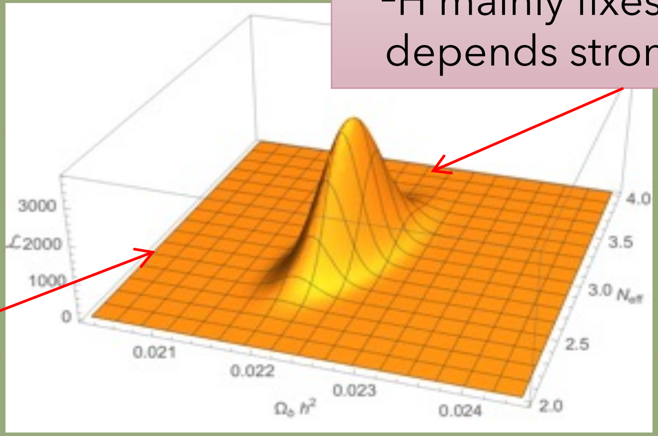
- Determine confidence level contours from the comparison of theoretical and experimental quantities.



For free N_{eff}, ^{2}H alone is not sufficient in breaking the degeneracy…

… and you need to add another observable (e.g. ^{4}He) or a prior (e.g. Ω_b Planck)

^{2}H mainly fixes $\Omega_B h^2$, ^{4}He depends strongly on N_{eff}



Neutrino distributions matters

Neutrino properties and evolution influences BBN predictions:

- They enter weak rates (ν_e)
- They contribute to the total energy density in the universe i.e. the expansion rate H

unstable ν's: Ω_{tot}, LSS, CMB, e^+ flux

ν oscillations and magnetic moments: BBN

non-thermal effects: CMB, LSS,…

$$f_\alpha(k,t) = e^{-\Gamma_\alpha(t)t} \frac{\Sigma_\beta P_{\alpha\beta}(\mu,B,\theta,m,t)}{\exp(\sqrt{k^2+m_\alpha^{\ 2}}/T(t)-\xi_\alpha)+1} + \delta_\alpha(k,t)$$

# of species: BBN, CMB, …

ν mass: Ω_{tot}, LSS,UHECR

ν chemical potential: BBN, LSS

Non standard scenarios

Low reheating scenarios: universe energy density is dominated by a scalar field decaying into standard particles in the MeV energy range (E is the e^+ - e^- energy density

$$\frac{d\rho_\phi}{dt} = -\Gamma_\phi \rho_\phi - 3H\rho_\phi$$

$$\frac{d\varrho_{\mathbf{p}}}{dt} = -\mathrm{i}\,[\Omega_{\mathbf{p}}, \varrho_{\mathbf{p}}] + C(\varrho_{\mathbf{p}})$$

$$\Omega_{\mathbf{p}} = \frac{\mathrm{M}^2}{2p} - \frac{8\sqrt{2}\,G_{\mathrm{F}}p}{3m_{\mathrm{W}}^2}\,\mathrm{E}\,.$$

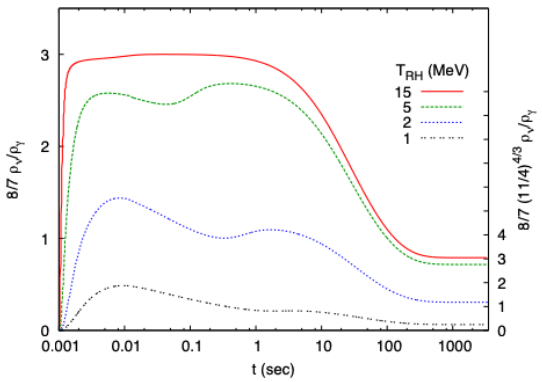


FIG. 1: Time evolution of the ratio of energy densities of neutrinos and photons, normalized in such a way that it corresponds to $N_{\rm eff}$ before (left) and after (right) $e^{\pm}$ annihilations. Four cases with different values of the reheating temperature are shown.

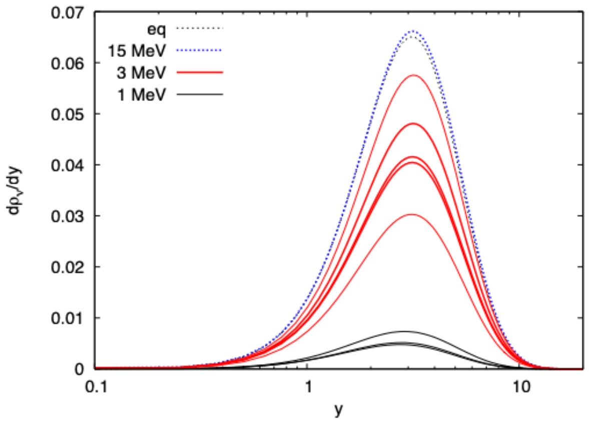


FIG. 2: Final differential spectra of neutrino energies as a function of the comoving momentum for three values of the reheating temperature, compared to an equilibrium spectrum (thin dotted black line). The three thick solid lines for $T_{\rm RH} = 3$ (middle red lines) and 1 MeV (lower black lines) correspond, from larger to smaller values, to ν_e, ν_μ and ν_τ, respectively. For $T_{\rm RH} = 3$ MeV we also include the case without flavor oscillations (thin red lines, upper for ν_e and lower for $\nu_{\mu,\tau}$).

Non standard scenarios

Depending on the reheating temperature (roughly the time of decay of the scalar field) there is a distortion of neutrino distribution and their abundance

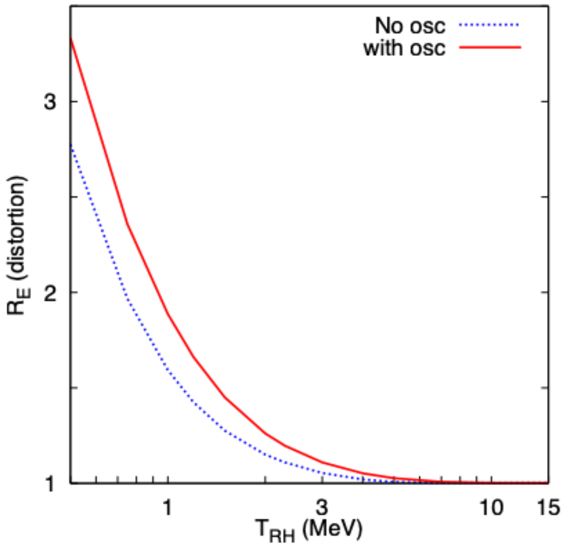


FIG. 3: Distortion of the electron neutrino spectrum parameterized with R_E (defined in the text) as a function of the reheating temperature. A value $R_E > 1$ indicates a significant spectral distortion with respect to equilibrium. Solid curve is for oscillating neutrinos, while dotted is for the no oscillation case and is reported for comparison.

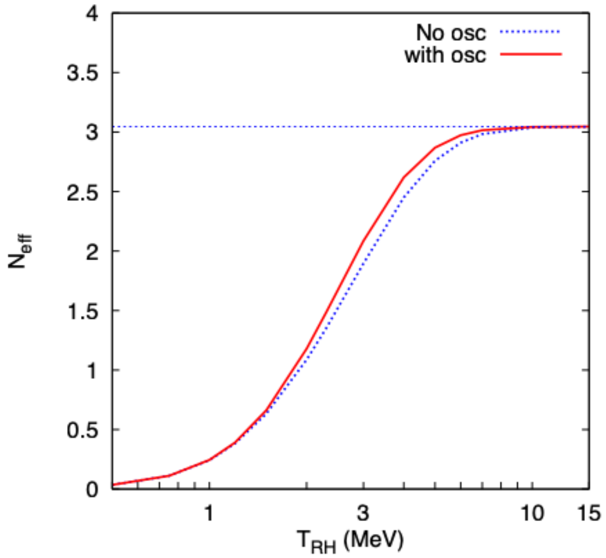


FIG. 4: Final contribution of neutrinos to the radiation energy density in terms of $N_{\rm eff}$, as a function of the reheating temperature. The horizontal line indicates the standard value, $N_{\rm eff} = 3.046$.

Non standard scenarios

…which leads to potentially large changes in both ^{4}He and deuterium abundances

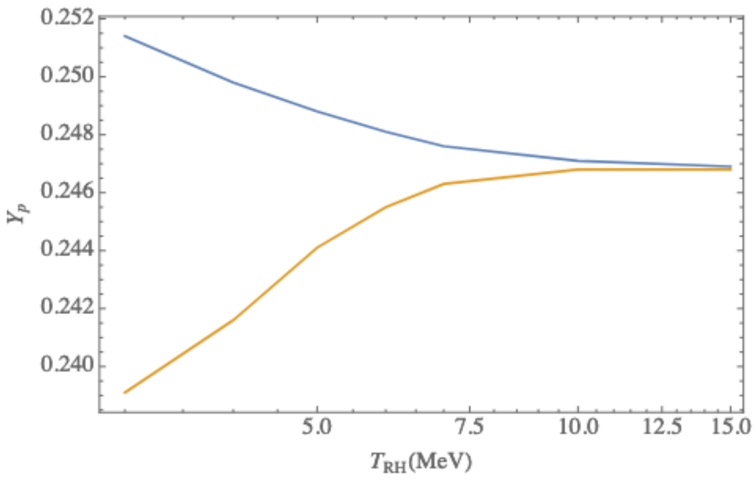


FIG. 6: Values of the primordial helium yield, Y_p, for different values of T_{RH}, taking into account neutrino oscillations (upper blue line) and in absence of the oscillations (lower yellow line).

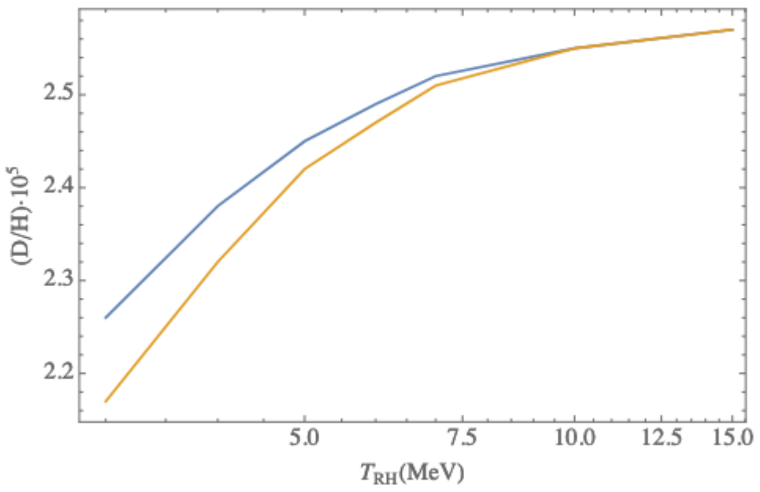


FIG. 7: Values of the deuterium to hydrogen ratio D/H, as a function of T_{RH}, with and without neutrino oscillations (upper blue and lower yellow lines, respectively).

P.F. de Salas et al 2015

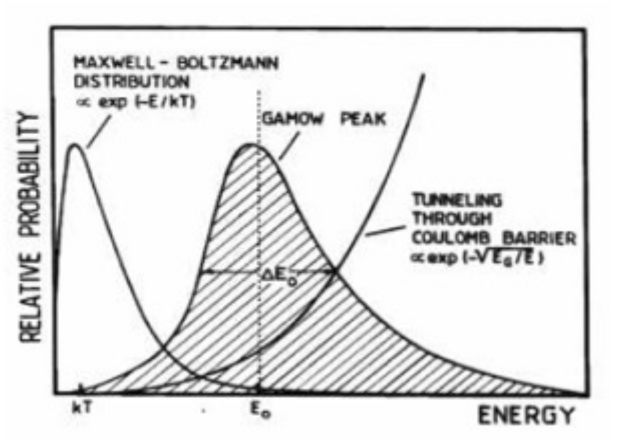
Improving precision

Nuclear cross sections

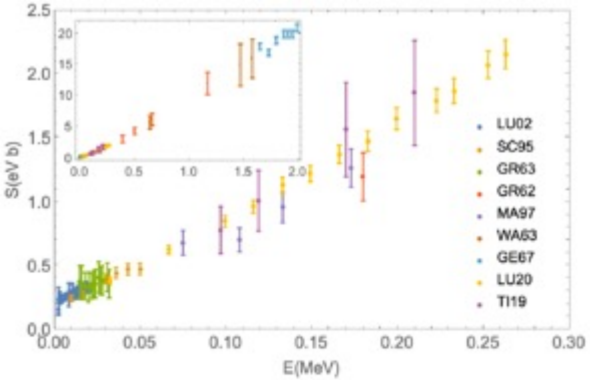
The S-factor is the intrinsic nuclear part of the reaction probability for charged particle induced reactions and is fitted from data (problem: datasets cover limited energy ranges and have different normalization errors, in some cases not even estimated).

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi \mu_{ab}}} T^{-3/2} \int_0^\infty \mathrm{d}E\, E\, \sigma(E)\, \mathrm{e}^{-E/T}$$

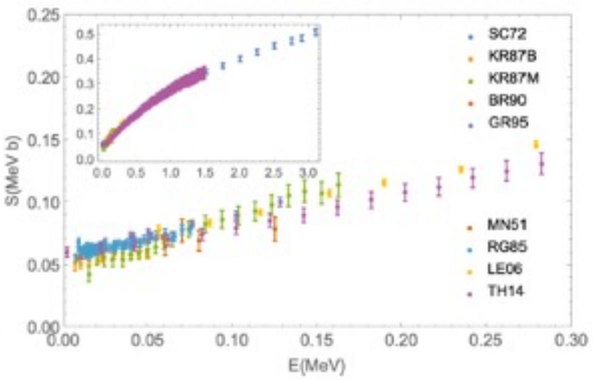
$$S(E) = \sigma(E) E\, e^{\sqrt{E_G/E}}$$



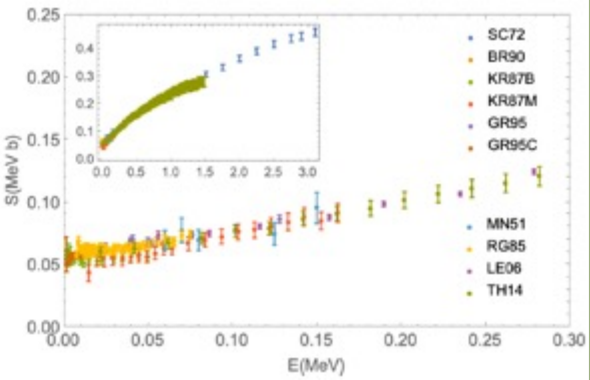
dpγ



ddn



ddp



Improving precision

Rate uncertainties

O.Pisanti et al, JCAP 04 (2021) 020

	$10^5\sigma_i$	$\sigma_i(\%)$
d(p,γ) ^3He	0.014	11
d(d,n) ^3He	0.035	69
d(d,p) ^3H	0.019	20

Yeh et al., JCAP 03 (2021) 046

12%
61%
27%

Reaction i	$10^5\ \sigma_i$(D/H)	$10^5\ \sigma_{\mathrm{omit}\ i}$(D/H)
$d(p,\gamma)^3$He	0.036	0.097
$d(d,n)^3$He	0.081	0.065
$d(d,p)t$	0.054	0.089
^{3}He$(d,p)^4$He	0.002	0.103
$p(n,\gamma)d$	0.002	0.103
^{3}He$(n,p)t$	0.002	0.103
all	0.103	–

Improving precision…

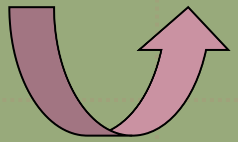
BBN and Neutrino Asymmetry: a leptometer

Large neutrino chemical potentials are not forbidden. They affect BBN!

1) chemical potentials contribute to N_ν (if no extra d.o.f.)

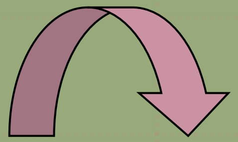
$$N_\nu = 3 + \sum_i \left(\frac{30\xi_i^2}{7\pi^2} + \frac{15\xi_i^4}{7\pi^4} \right) + \ldots.$$

$$\xi_i \equiv \frac{\mu_{\nu_i}}{T}$$



Y_P

2) a positive electron neutrino chemical potential $\boldsymbol{\nu_e}$ (more neutrinos than antineutrinos) favour n->p with respect to p ->n processes.



Y_P

3) Neutrino oscillations mix the three standard active neutrino flavors. We can take all of them equal.

Improving precision…

As the Universe expands, particle densities are diluted and temperature falls. Weak interactions become ineffective to keep neutrinos in good thermal contact with the e.m. plasma

Rough, but quite accurate estimate of the decoupling temperature

Rate of weak processes ~ Hubble expansion rate

$$\Gamma_w \approx \sigma_w |\mathrm{v}| n \,,\ H^2 = \frac{8\pi\rho_R}{3M_p^2} \rightarrow \ G_F^2 T^5 \approx \sqrt{\frac{8\pi\rho_R}{3M_p^2}} \ \rightarrow \ T_{dec}^{\nu} \approx 1\ MeV$$

Since ν_e have both CC and NC interactions with $e^{\pm}$

$T_{dec}(\nu_e)$ ~ 2 MeV

$T_{dec}(\nu_{\mu,\tau})$ ~ 3 MeV

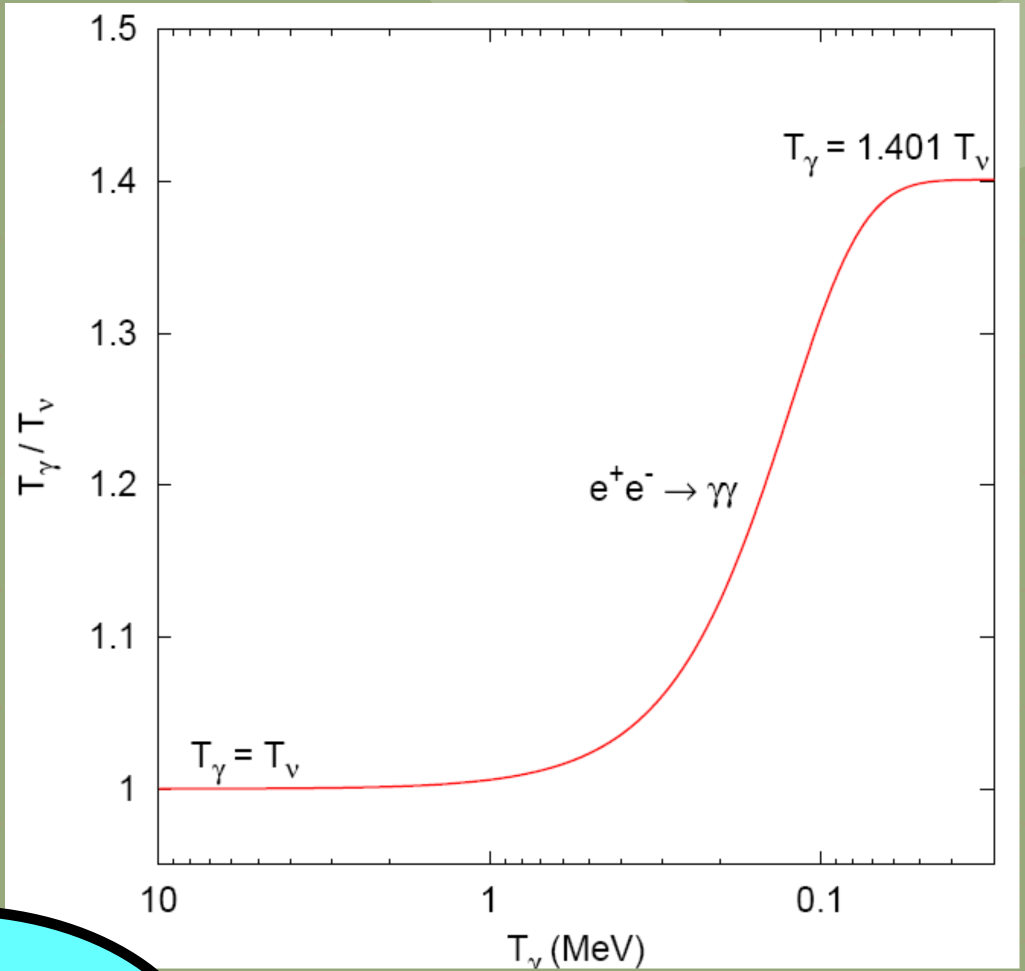
Improving precision...

At $T \sim m_e$, electron-positron pairs annihilate

$$e^+e^- \rightarrow \gamma\gamma$$

heating photons but not the decoupled neutrinos (entropy conservation)

$$\frac{T_\gamma}{T_\nu} = \left(\frac{11}{4}\right)^{1/3}$$



$$f_\nu(p,T) = \frac{1}{e^{p/T_\nu}+1}$$

Improving precision..

Momentum-dependent Boltzmann equation

$$\left(\frac{d}{dt} - Hp\frac{d}{dp_1}\right) f_\nu(p_1,t) = I_{coll}(p_1,t)$$

Statistical Factor

$$\frac{1}{2E_1}\int \prod_{i=2}^{4}\left(\frac{d^3p_i}{(2\pi)^3 2E_i}\right)(2\pi)^4\delta^4(P_1+P_2-P_3-P_4)\,|M|^2\,F$$

9-dim Phase Space

ΣP_i conservation

Process

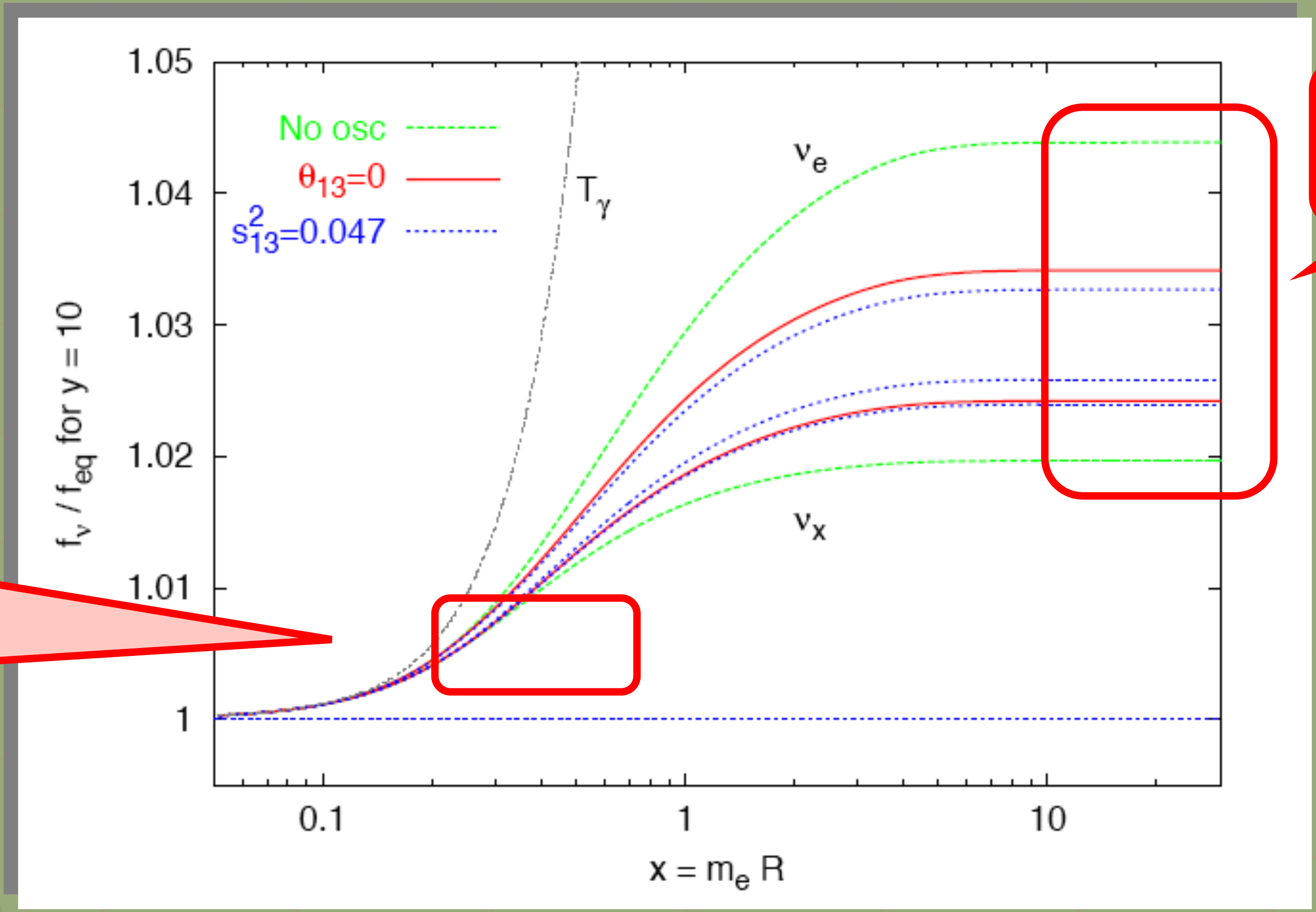
$$F = f_3 f_4[1+f_1][1-f_2] - f_1 f_2[1+f_3][1-f_4]$$

+ evolution of total energy density:

$$\frac{d\rho_R}{dt} = -3H(\rho_R + P_R)$$

Improving precision…

Effects of flavour neutrino oscillations on the spectral distortions

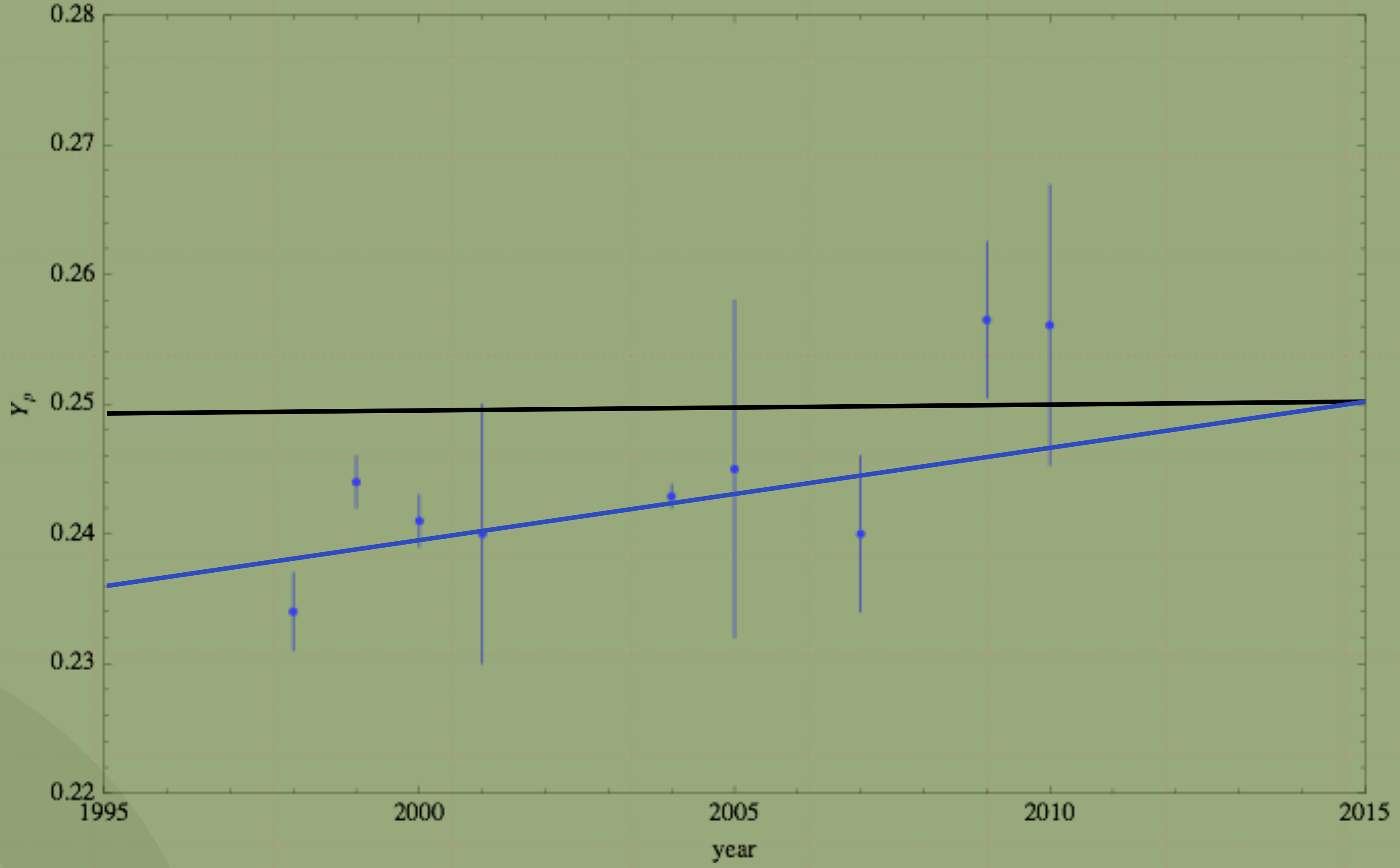


The variation is larger for ν_e

Around T~1 MeV the oscillations start to modify the distortion

Data

^{4}He "evolution"



Improving precision...

Evolution of f_ν for a particular momentum p=10T