# Precision cosmology from BBN

Ofelia Pisanti
*Università di Napoli "Federico II" & INFN Napoli*

**mostly based on NAPhysRep:**
**F. Iocco, G. Mangano, G. Miele, O.P., Phys. Rep. 472 (2009) 1**

"Alternative Gravity and Alternative Matter" Workshop
Heraklion, 20-23 May 2015

# What is BBN?

Asking to Google (5 years ago)…

## Answers

From the talk of G. Miele, PASCOS, Valencia, 2010

As first item

- BBN Traditional Christian radio ·
  **Cómo ir al Cielo (*How to go to Heaven*)**

Very evocative!

"Big bang nucleosynthesis" listed by Google at the 4th page

PASCOS 2010, Valencia 4/40

# What is BBN?

And today…

- Technology *über alles*: Raytheon BBN Technologies
- BBN Radio now in 5th position: a more secular world…
- Publishing, business, social networking, game (Bubble Ninja!), finance…
- Physics moved back, from 4th to 5th page!

a less successful BBN?

# A very sensitive precision tool!

- One of the observational pillars of the hot Big Bang.
- One of the first direct probes of the universe history (few seconds after the bang).
- Involves all known interactions: gravitational for the expansion, weak for neutrino and nucleon decoupling, electromagnetic and strong for the nuclear reaction network. So, it is sensitive to a large spectrum of physics.
- Before WMAP: the best way for measuring the baryon fraction (over-constrained theory in its simplest scenario) and $N_{eff}$.

$$\eta_B = \frac{n_B}{n_\gamma} = 273.45 \cdot 10^{-10}\ \Omega_B h^2$$

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

- Today, after Planck, BBN is used as a precision tool (in combination with other cosmological information) to reduce the number of free parameters of SMC AND as a consistency tool for the SMC and SMPP: did you check your model against BBN?

# BBN in few words

About 1 second after the bang, the plasma of γ, $e^-$, ν, n, p (and their antiparticles) reaches a temperature at which weak interactions of ν and N goes out of equilibrium with respect to expansion.

Neutrinos decouple at T~1 MeV and their temperature decreases only due to the effect of the universe expansion, changing with respect to the photon temperature only after the $e^+e^-$ annihilation stage.

n/p ratio (fortunately) freezes out just soon after neutrinos, at $T_D$~0.8 MeV, becoming ~1/7; then, when a sufficient abundance of deuterium forms at $T_{BBN}$~0.1 MeV (not so quickly, the deuterium *bottleneck*) 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).

$$Y_p = \frac{4n_{^4He}}{n_n + n_p} = \frac{4\left(n_n/2\right)}{n_n + n_p} = \frac{2}{1 + n_p/n_n} = 0.25$$

BBN is a simple theory?

# The equations of BBN

Not so simple after all…

$$\frac{\dot{a}}{a} = H = \sqrt{\frac{8\,\pi G_N}{3}\,\rho} \quad ,$$

$$\frac{\dot{n}_B}{n_B} = -\,3\,H \quad ,$$

$$\dot{\rho} = -\,3\,H\,(\rho + P) \quad ,$$

$$\dot{X}_i = \sum_{j,k,l} N_i \left( \Gamma_{kl \to ij} \frac{X_k^{N_k}\,X_l^{N_l}}{N_k!\,N_l!} \; - \; \Gamma_{ij \to kl} \frac{X_i^{N_i}\,X_j^{N_j}}{N_i!\,N_j!} \right) \equiv \Gamma_i \quad ,$$

$$n_B \,\sum_j Z_j\,X_j = n_{e^-} - n_{e^+} \equiv L\left(\frac{m_e}{T}, \phi_e\right) \equiv T^3\,\hat{L}\left(\frac{m_e}{T}, \phi_e\right) \quad ,$$

$$\left(\frac{\partial}{\partial t} - H\,|\mathbf{p}|\frac{\partial}{\partial|\mathbf{p}|}\right) f_{\nu_\alpha}(|\mathbf{p}|, t) = I_{\nu_\alpha}\left[f_{\nu_e}, f_{\bar{\nu}_e}, f_{\nu_x}, f_{\bar{\nu}_x}, f_{e^-}, f_{e^+}\right] \quad ,$$

# The equations of BBN

Not so simple after all…

Weak rates: radiative and finite nucleon mass corr., finite temperature corr., plasma effects

Boltzman equations for a large network of light nuclei abundances (uncertainties from experimental measures and theoretical calculations of reaction rates)

Boltzman equations for neutrino distributions in non-instantaneous decoupling

$$\rho \quad ,$$

$$\frac{\dot{n}_B}{n_B} = -\,3\,H \quad ,$$

$$\dot{\rho} = -\,3\,H\,(\rho + P) \quad ,$$

$$\dot{X}_i = \sum_{j,k,l} N_i \left( \Gamma_{kl \to ij} \frac{X_k^{N_k}\, X_l^{N_l}}{N_k!\, N_l!} - \Gamma_{ij \to kl} \frac{X_i^{N_i}\, X_j^{N_j}}{N_i!} \right.$$

$$n_B \sum_j Z_j\, X_j = n_{e^-} - n_{e^+} \equiv L\left(\frac{m_e}{T}, \phi_e\right) \equiv T$$

$$\left(\frac{\partial}{\partial t} - H\,|\mathbf{p}|\frac{\partial}{\partial |\mathbf{p}|}\right) f_{\nu_\alpha}(|\mathbf{p}|, t) = I_{\nu_\alpha}\left[f_{\nu_e}, f_{\bar{\nu}_e}, f_{\nu_x}, f_{\bar{\nu}_x}, f_{e^-}, f_{e^+}\right] \quad ,$$

# 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. P., JHEP 0009 (2000) 038; P.D. Serpico, et al., JCAP 0412 (2004) 010; O. P., et al., Comp. Phys. Comm. 178 (2008) 956; http://parthenope.na.infn.it

J. MacDonald, D.J. Mullan, Phys. Rev. D 80 (2009) 043507; http://cococubed.asu.edu/code_pages/net_bigbang.shtml

# Neutrinos (fixing the notations)

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, $\mu_\nu$.

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

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

degeneracy parameter, invariant under cosmic expansion

Chemical potentials contribute in increasing the energy density, so increasing the effective number of neutrinos.

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

It is customary to define neutrino asymmetries analogous to the baryon asymmetry.

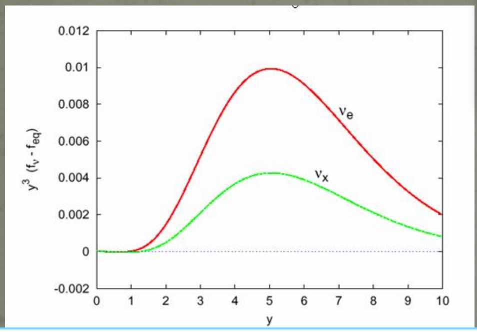
asymmetry parameter, usually considered small, see in two slides

$$\eta_{\nu_i} = \frac{n_{\nu_i} - n_{\bar{\nu}_i}}{n_\gamma} = \frac{1}{12\,\zeta(3)} \left( \frac{T_\nu}{T_\gamma} \right)^3 \left( \pi^2 \xi_i + \xi_i^3 \right)$$

# BBN accuracy (I): neutrinos

In the general picture of BBN, neutrinos enters as part of the radiation of the universe (expansion) and as participants in the weak rates that determine the n/p ratio (initial condition). But, accuracy requires to take into account:

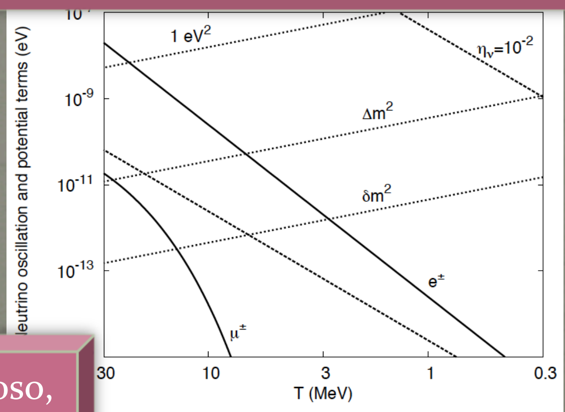
- decoupling of neutrinos is not instantaneous ➔ Boltzman equations
- neutrinos oscillate ➔ proper treatment of matter effect (pag. 144-145 NC)
- neutrinos can be not standard ➔ neutrino lepton numbers change the evolution and the weak rates



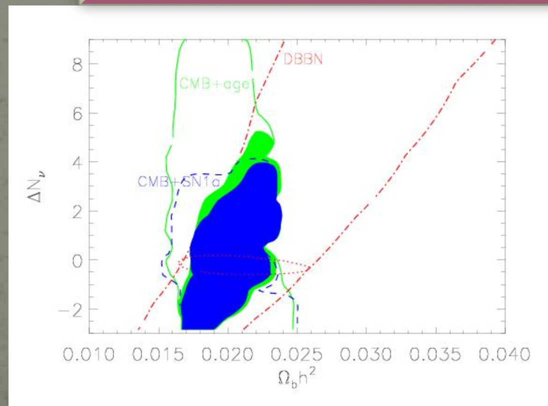

$$f_{\nu_\alpha}(x,y) = \frac{1}{e^{y-\xi_\alpha}+1}\left(1+\delta f_{\nu_\alpha}(x,y)\right)$$

S. Esposito, G. Miele, S. Pastor, M. Peloso, O. P., Nuc. Phys. B 590 (2000) 539

J. Lesgourgues, G. Mangano, G. Miele, S. Pastor, Neutrino Cosmology, Cambridge




S.H. Hansen, G. Mangano, A. Melchiorri, G. Miele, O. P., Phys. Rev. D 65 (2001) 023511



# BBN accuracy (II): weak rates

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

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

S. Esposito, G. Mangano, G. Miele, O. P., Nuc. Phys. B 540 (1999) 3

$\tau_n$(th) = 961 s

$\tau_n$(exp) = 880.3±1.1 s

Corrections to the weak rates:

$\tau_n$(th) = 893.9 s

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

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

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

$$\frac{^2\mathrm{H}}{\mathrm{H}} = 2.53 \times 10^{-5}\, R_3^{-0.55} R_4^{-0.45} R_2^{-0.32} R_1^{-0.20} \left(\frac{\omega_b}{0.02273}\right)^{-1.62} \left(\frac{\tau_n}{\tau_{n,0}}\right)^{0.41}$$

$$\frac{^3\mathrm{He}}{\mathrm{H}} = 1.02 \times 10^{-5}\, R_7^{-0.77} R_2^{0.38} R_4^{-0.25} R_3^{-.20} R_5^{-0.17} R_1^{0.08} \left(\frac{\omega_b}{0.02273}\right)^{-0.59} \left(\frac{\tau_n}{\tau_{n,0}}\right)^{0.15},$$

$$Y_p = 0.2480\, R_3^{0.006} R_4^{0.005} R_1^{0.005} \left(\frac{\omega_b}{0.02273}\right)^{0.39} \left(\frac{\tau_n}{\tau_{n,0}}\right)^{0.72},$$

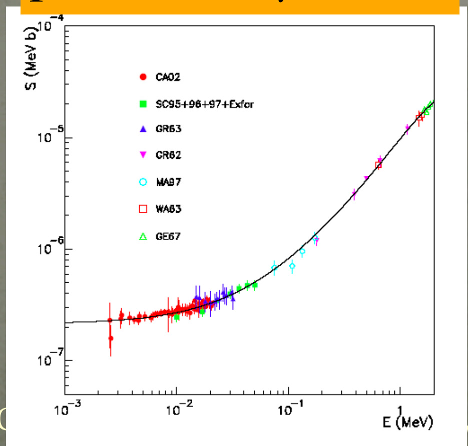
$$\frac{^7\mathrm{Li}}{\mathrm{H}} = 4.7 \times 10^{-10} R_1^{1.34} R_8^{0.96} R_7^{-0.76} R_{10}^{-0.71} R_3^{0.71} R_2^{0.59} R_5^{-0.27} \left(\frac{\omega_b}{0.02273}\right)^{2.12} \left(\frac{\tau_n}{\tau_{n,0}}\right)^{0.44}.$$

# BBN accuracy (III): nuclear network

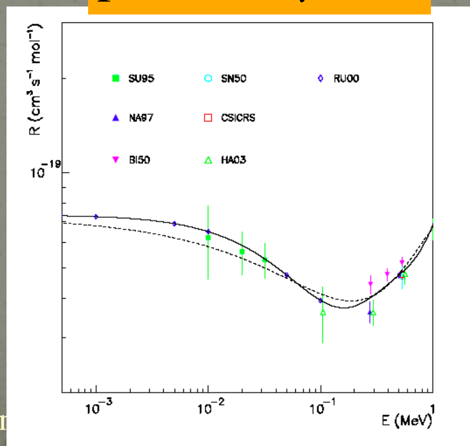
The accuracy of the BBN nuclear network depends on the determination of several critical reactions. While in the past one could count only on experimental measures (not always in the relevant energy range for BBN, 30÷300 keV in the center of mass), recently theoretical calculations, at least for some reaction, become available.

- Dpγ. Major improvement: underground measurement (LUNA experiment).
- pnγ. A very accurate theoretical result using pion-less effective field theory: 0.1% uncertainty on $^{2}H/H$ (G. Rupak, Nucl. Phys. A 678 (2000) 409).
- $^{3}H\alpha\gamma$. Results from the ERNA experiment: but the $^{7}Li$ problem is still there.

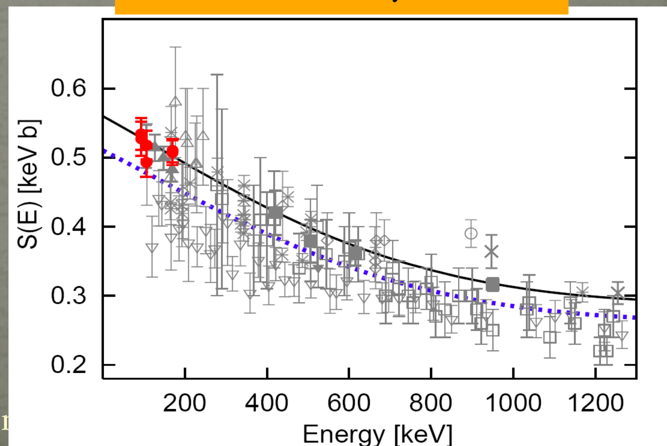
$$p + {}^{2}H \rightarrow \gamma + {}^{3}He$$




$$p + n \rightarrow \gamma + D$$

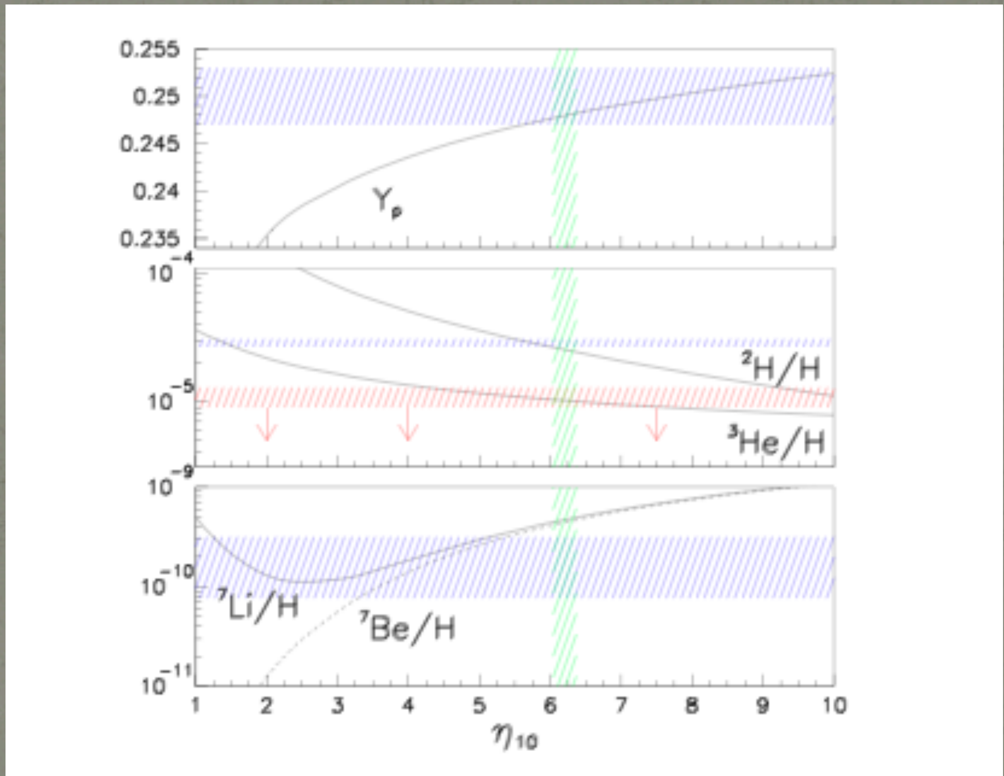



$${}^{3}He + \alpha \rightarrow \gamma + {}^{7}Be$$



# Abundances: how they go

- $\eta_B$: $^2$H and $^7$Li much more sensitive than $^4$He. More baryons imply a larger temperature at deuterium bottleneck and a more efficient burning ➔ less $^2$H and $^3$He and more $^4$He. $^7$Li production dominates for low $\eta_B$, while $^7$Be dominates at high $\eta_B$, leading to the characteristic "lithium dip" versus $\eta_B$in the Schramm plot.



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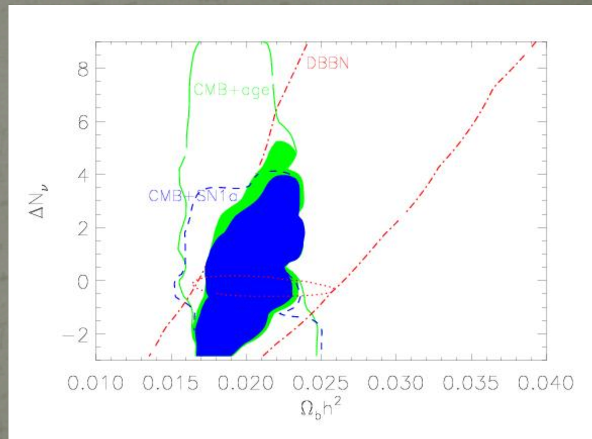
- $N_{eff}$: more relativistic degrees of freedom ➔ a faster expansion. Then an earlier freeze-out of n/p (more $^4He$) and less time available for $^2H$ destruction (more $^2H$).
- $\tau_n$: a decrease in $\Gamma$ ➔ an earlier freeze-out of n/p (more $^4He$) and more neutrons available (more $^2H$).
- $\xi_{\nu i}$: all flavours contribute to $N_{eff}$, giving a faster expansion ➔ more $^4He$. Only $\xi_{\nu e}$ contribute to weak rates (a positive value ➔ more neutrinos ➔ less neutrons ➔ less $^4He$). The degeneracy can be understood in term of the initial condition on the n/p equilibrium value

$$-\frac{Q}{T_D} - \xi_e = const$$

$\xi_e$




$T_D$

# Data (the quest for "primordiality")

- $^2$H: it is only destroyed. Observation of Lyman absorption lines by neutral hydrogen (HI) gas clouds (Quasar Absorption Systems) at red-shift $z \approx 2 - 3$ placed along the line of sight of distant quasar.
- $^3$He: in stellar interior can be either produced by $^2$H-burning or destroyed in the hotter regions. It can be observed via a line accessible only within Milky Way. It is unclear why a correlation with the distance from the center of the galaxy (metallicity) is not observed.
- $^4$He: it is produced inside stars. Observation in ionized gas regions (HeII $\rightarrow$ 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 Planck precision allows interesting measure via $^4$He effect on anisotropy tail.
- $^7$Li: it is produced and destroyed. Observation of absorption lines in spectra of halo stars of POP II. All of them show very similar abundances of $^7$Li (Spite plateau) which should be close to the primordial value. 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.

# $^2$H

- After a period with conflicting high and low measurements of $^2$H, data settled towards a value in reasonably agreement with the BBN prediction using $\eta_B$ from CMB. However, their dispersion was an indication either of an underestimate of systematics or of large effects of the galactic evolution.
- The observation of an absorber at z=3.05 improved the accuracy (from 20% uncertainty to 2% uncertainty) giving $^2H/H=(2.54\pm0.05)\cdot10^{-5}$ (M. Pettini and R. Cooke, Mon. Not. Roy. Astron. Soc. 425 (2012) 2477).
- This, together with another precision observation at z~3.07, triggered a reanalysis of previous data. From a set of five absorbers it was determined

$$\frac{^2H}{H}=\left(2.53\pm0.04\right)\cdot10^{-5}$$

R. Cooke, M. Pettini, R.A. Jorgenson, M.T. Murphy, C.C. Steidel, Ap. J. 781 (2014) 31

- With this determination we get 1.6% uncertainty on $^2$H/H.
- A more recent measure $^2H/H=(2.45\pm0.28)\cdot10^{-5}$ at z=3.256 has a larger uncertainty and its inclusion in the set of previous data does not change the $^2$H determination (S. Reimer-Sorensen et al. Mon. Not. Roy. Astron. Soc. 447 (2015) 2925).

# $^4$He

- The theoretical model used for extracting the abundance contains 8 physical parameters (among which $^4$He abundance, electron density, optical depth, temperature, neutral H fraction). It allows to predict the fluxes of 6 He lines and 3 H lines (relative to Hβ).
- After selection of data (6 He lines available, $\chi^2<4$, anomalous values) 14 objects remain, giving $Y_p=0.2534\pm0.0083$ (linear regression) or $Y_p=0.2574\pm0.0036$ (weighted mean) (E. Aver et al, JCAP 1204 (2012) 004).
- Using new treatment of emissivity, the same type of analysis gives $Y_p=0.2465\pm0.0097$ (linear regression) or $Y_p=0.2535\pm0.0036$ (weighted mean) (E. Aver et al, JCAP 1311 (2013) 017).
- More recently, a new line was included in the analysis, with the characteristic of a different dependence on density and temperature. This reduces the uncertainty (over a factor of 2) and leads to a better defined regression

$$Y_p = 0.2449 \pm 0.0040$$

E. Aver, K.A. Olive, E.D. Skillman, arXiv:1503.08146 [astro-ph.CO]

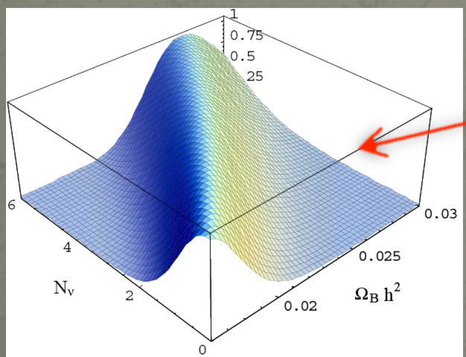
- 1.6% uncertainty, but systematics are underestimated, since most of the available data are not well fit by the model.

# BBN analyses

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

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

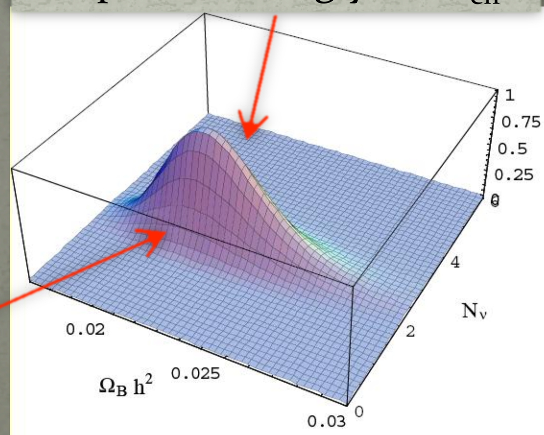
- Determine confidence level contours from the comp… experimental quantities.




In presence of $N_{eff}$, $^2H$ alone is not sufficient in breaking the degeneracy…

… while the combined $^2H$-$^4He$ likelihood can do the work

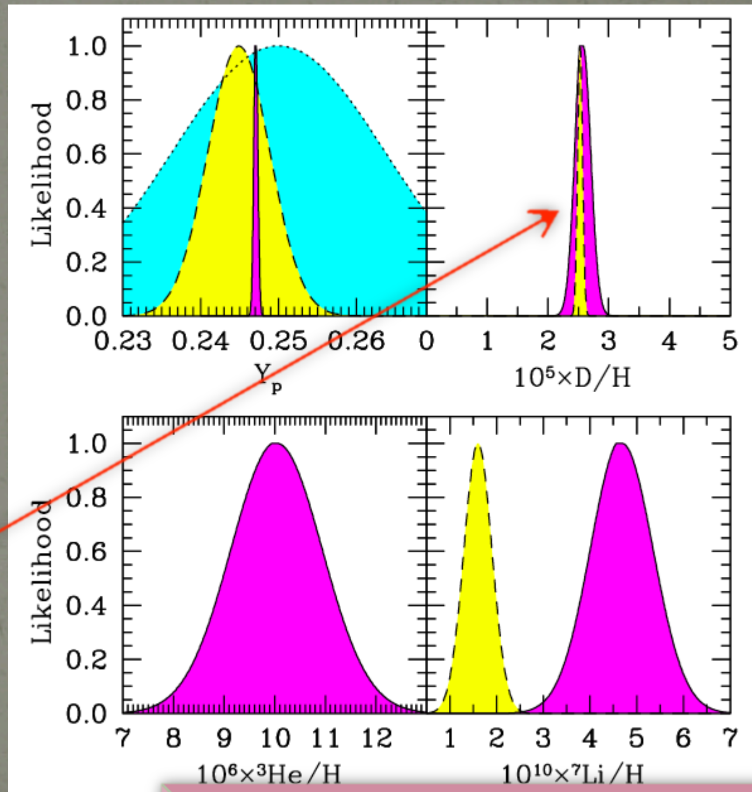
$^2H$ mainly fixes $\Omega_B h^2$, $^4He$ depends strongly on $N_{eff}$



# BBN plus CMB analysis (I)

Since the first results from WMAP experiment, CMB gave a more precise determination of $^2H$ with respect to BBN. Moreover, at present, measurements of the CMB damping tail at small angular scales (high l) probe both $\mathbf{Y_p}$ and $\mathbf{N_{eff}}$.

- $N_\nu=3$ ($N_{eff}=3.046$)
- $^2H$ and $^4He$ BBN+CMB likelihoods (purple) perfectly consistent with observational ones (yellow)
- $^3He$ experimental measure missing
- $^7Li$ likelihoods disjoint
- CMB-only prediction for $Y_p$ (cyan) least precise, but consistent with the other
- the deuterium result shows a spectacular agreement among physics from z~3 (QSO), z~1000 (CMB), and z~$10^{10}$ (BBN)!




R.H. Cyburt, B.D. Fields, K.A. Olive, T. Yeh, arXiv:1505.01076 [astro-ph]

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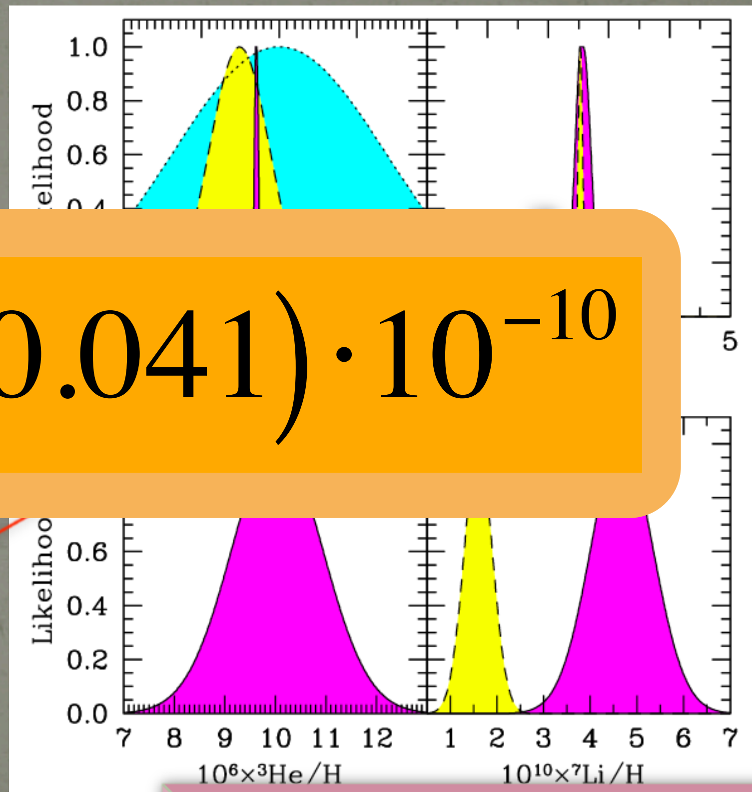
- $^3H$
- $^7L$
- CI
  least precise, but consistent with the other
- the deuterium result shows a spectacular agreement among physics from z~3 (QSO), z~1000 (CMB), and z~$10^{10}$ (BBN)!

$$\eta_B = (6.101 \pm 0.041)\cdot 10^{-10}$$

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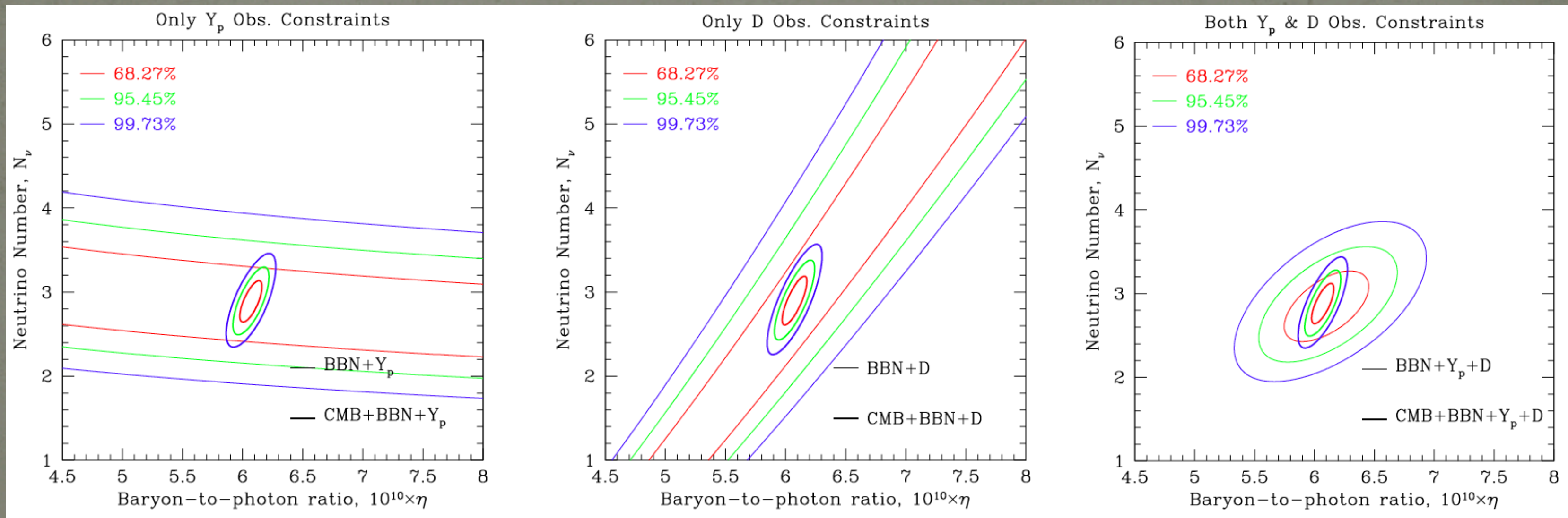
# BBN plus CMB analysis (II)

In the first two panels only one abundance is used (then narrowed by CMB), in the third both abundances.

- $Y_p$ fixes $N_{eff}$, while $^2$H depends on both (but more sensitive to $\eta_B$)
- in the first two cases, CMB needed for closing the contours, in the third one it improves the determination

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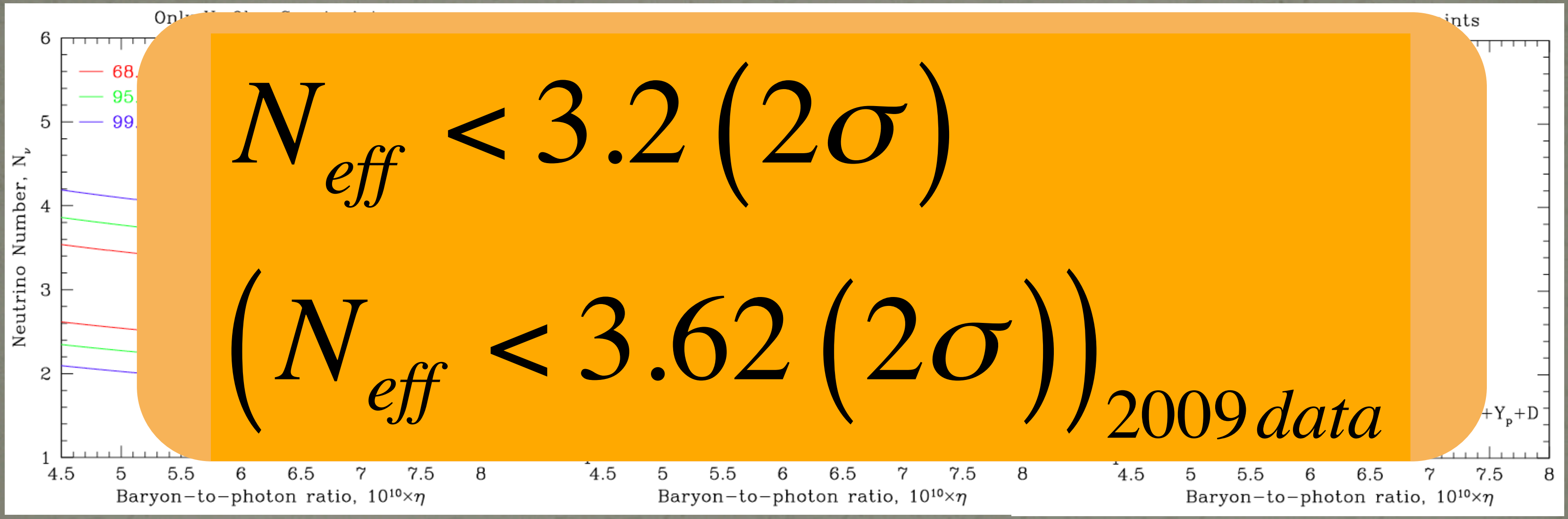



$$N_{eff} < 3.2\,(2\sigma)$$

$$\left(N_{eff} < 3.62\,(2\sigma)\right)_{2009\,data}$$

R.H. Cyburt, B.D. Fields, K.A. Olive, T. Yeh, arXiv:1505.01076 [astro-ph]

# Beyond the SMC

Non standard cosmological models typically “live” in very early epochs, shrouded by the optical depth of pre-recombination plasma. Then, they can be explored only indirectly, by the two best quantitative models we have of the early universe: BBN and CMB.

- BBN it is strongly sensitive to the expansion rate, given by the value of the Hubble parameter. At this regard, two physical quantities have to be under control: the number of degrees of freedom in the radiation density ($N_{eff}$) and the Planck mass ($G_N$) which, as a general feature of alternative cosmological models, emerges as an effective scale at low energy.
- $^2$H, $^3$He and $^7$Li are sensitive to the expansion rate AFTER the $e^+e^-$ annihilation stage, while $^4$He depends ALSO on the expansion rate before this stage (n/p ratio freeze-out).
- One needs to include in the analysis at least two different abundances, in order to break the degeneracy between $\eta_B$ and a possible not standard expansion. In particular, since $^2$H, $^3$He and $^7$Li are most sensitive to $\eta_B$, $^4$He provides the best way to measure departure from the standard expansion rate.

# Brane cosmology and BBN

A mean to reconcile the mismatch between the PP and G scales: the 4-dim standard space (where ordinary matter is confined) is a submanifold embedded in a higher-dimensional spacetime, and the extra dimensions are compactified. A variation with a non-compactified extra dimension was proposed by RS: the ordinary space (the brane) is embedded in a 5-dim AdS space, where gravity propagates (the bulk).

These type of models give two additional terms in the Friedmann equation

$$\Delta\left(H^2\right) = \frac{\rho^2}{36\, M_5^6} + \frac{C}{a^4}$$

"Dark radiation". The coefficient C can be either > or < 0

5-dim Planck mass

For C=0, one gets a slower expansion rate than the standard one, $a \sim t^{1/(3+3w)}$ instead of $a \sim t^{2/(3+3w)}$. We put the classical constraint $\Gamma \sim H$.

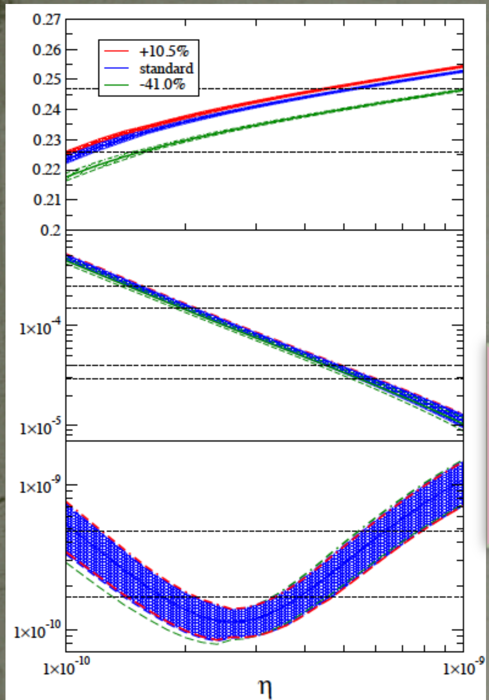
$$\left(\frac{n}{p}\right)_{T_{BBN}} = \exp\left[-\frac{Q}{7.5MeV}\left(\frac{M_5}{TeV}\right)^3\right] e^{-\frac{\Delta t}{\tau_n}}$$

$M_5 \sim 8$ TeV and a too large compactification radius

# How much of dark?

On the other side, for large M5, the dark radiation parameter C can be constrained by $N_{eff}$:

$$C = \frac{8\pi G_N}{3}\Delta N_{eff}\,\rho_{\nu 0}\,a^4$$

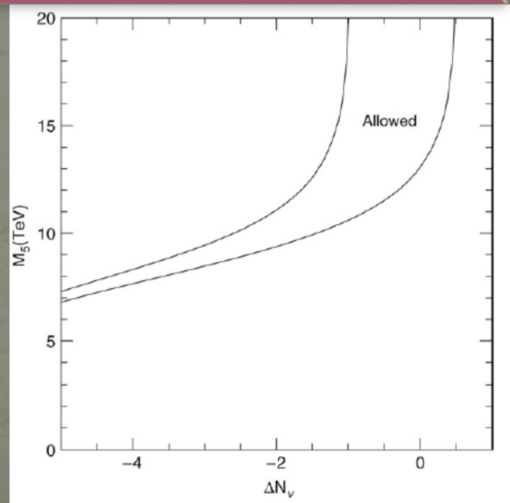



K. Ichiki, M. Yahiro, T. Kajino, M. Orito, G.J. Matthews, Phys. Rev. D 66 (2002) 043521

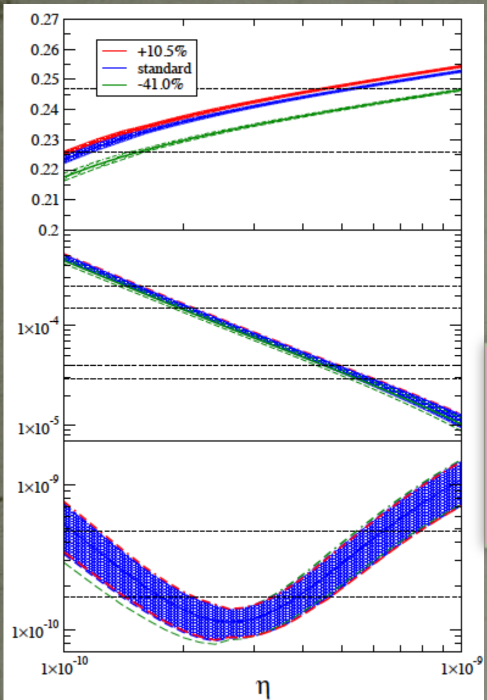
0% (blue), +10.5% (red), -41% (green) dark radiation

$$-1.23 \le \rho_{DR}/\rho_\gamma \le 0.11$$

J.D. Bratt, A.C. Gault, R.J. Sherrer, T.P. Walker, Phys. Lett. B 546 (2002) 19




A small value of M5 ($\rho^2$ term not negligible) can be compensated by a large and negative C ($\Delta N_{eff}$): one can derive a degeneracy of the form $a/M_5^6+\Delta N_{eff}$=const. The band becomes the standard constraint on $\Delta N_{eff}$ for large $M_5$.

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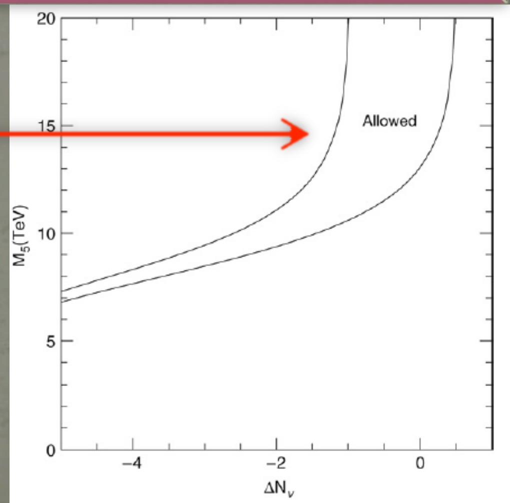
$-1.23 \leq \rho$ ... $/ \rho$ ... $\leq 0.11$

$$M_5(C=0) > 13\, TeV$$

$$-1.0 < \Delta N_{eff} < 0.5$$

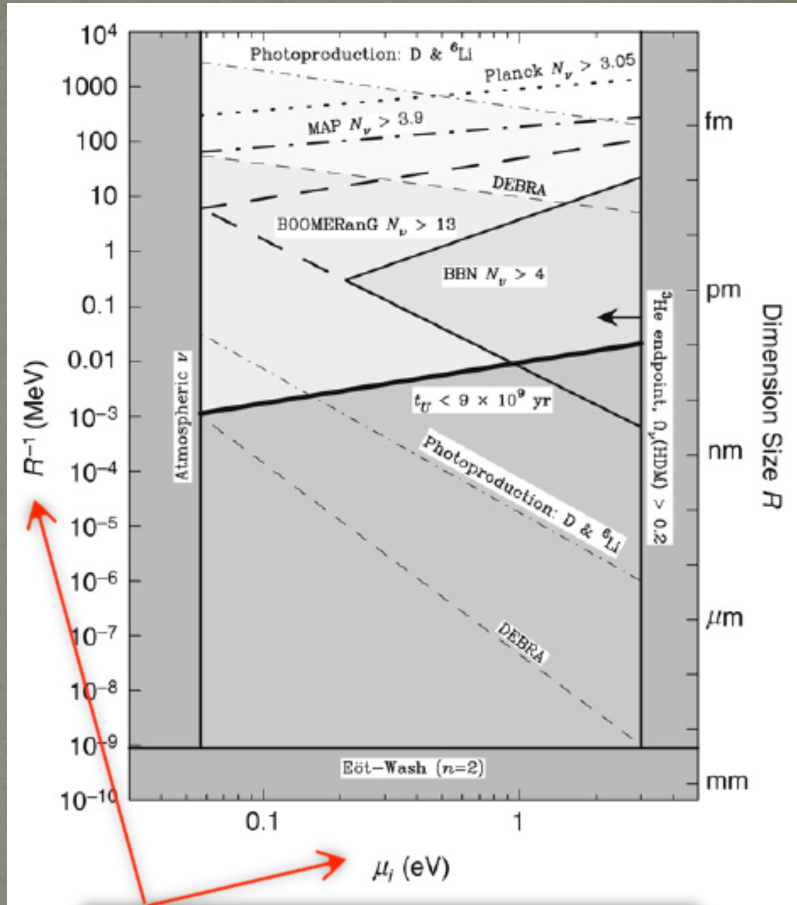
A smal ... n be compe ... e can derive a ... . The band b ... eff for large $M_5$.



# Bulk neutrinos

Neutrino masses through the see-saw mechanism require a scale $10^{11}$-$10^{12}$ GeV, much larger than the extra dimension scale. Solutions have been proposed based on SM-singlet neutrinos in the bulk coupled with lepton doublet on the brane via Yukawa couplings. The resulting infinite tower of sterile neutrinos mixes with active ones, thus contributing to the total radiation content parameterized by $N_{eff}$ and giving observable results on BBN prediction.

K.N. Abazajian, G.M. Fuller, M. Patel, Phys. Rev. Lett. 90 (2003) 061301




R is the radius of the largest extra dimension, $\mu_i$ the mass of a light Dirac neutrino.

# Variation of fundamental constants

The fundamental constants of physics may be indeed variable parameters characterizing the particular state of the universe (Dirac, 1937). For example, theories with extra dimensions such as Kaluza Klein or string theories, naturally predict that 4-dim constants may vary (in time and space), since they represent effective values in the low energy limit, and are sensitive to the size and structures of extra dimensions.

- Lot of physical constants entering the BBN physics: too many free parameters result in a lack of predictive power.
- No unique theoretical framework for an unambiguous determination of their evolution.
- Due to dependence on system of units and measurement technique, only meaningful to consider dimensionless quantities, given by the ratio between two independent and homogeneous constants, like $\Lambda_{QCD}/m_q$.

Two typical strategies:

1. only one or a few free fundamental constants to be fixed in the analysis
2. a specific theoretical model (for example GUTs) which gives constraints among constants, so reducing the free ones

# Varying $G_N$

A variation of $G_N$ has an effect on $H \propto \sqrt{G_N}$, changing n/p ratio and the efficiency of $^2H$ burning. This is seen, as usual, as a change in $N_{eff}$.

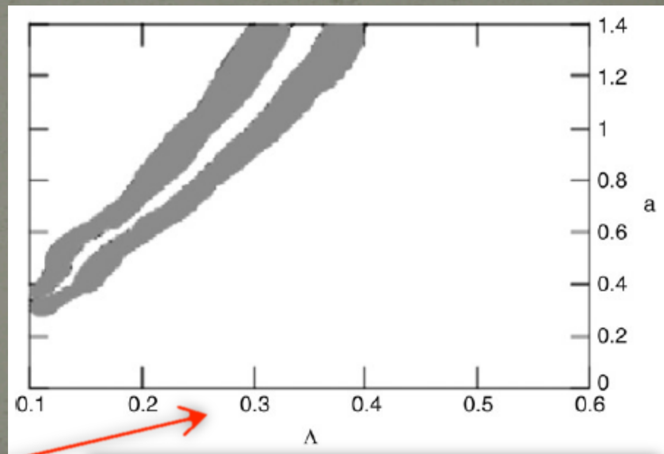
$$H^2 = \frac{8\pi G_N}{3}\rho$$

$$\rho_0 = \frac{\pi^2}{30}\left(2 + \frac{7}{8}4 + \frac{7}{8}2N_{eff}\right)T^4$$

$$\delta G_N \rho_0 = G_N \delta\rho_{N_{eff}}$$

$$\frac{\delta G_N}{G_N} = \frac{7/4\,\Delta N_{eff}}{g_*} = \frac{7}{43}\Delta N_{eff}$$

- An effective $G_N$ is possible in scalar-tensor theories of gravity
- For scalar-tensor theories of gravity, BBN constraints depend strongly on the details of the model
- Particular choices of the scalar field potential could solve the lithium problem, yet leading to values of the deuterium and helium abundances compatible with experimental data




$V(\phi) = \Lambda^2\phi^4$ and a is a parameter in the Einstein action

J. Larena, J.M. Alimi, A. Serna, Astrophys. J. 658 (2007) 1

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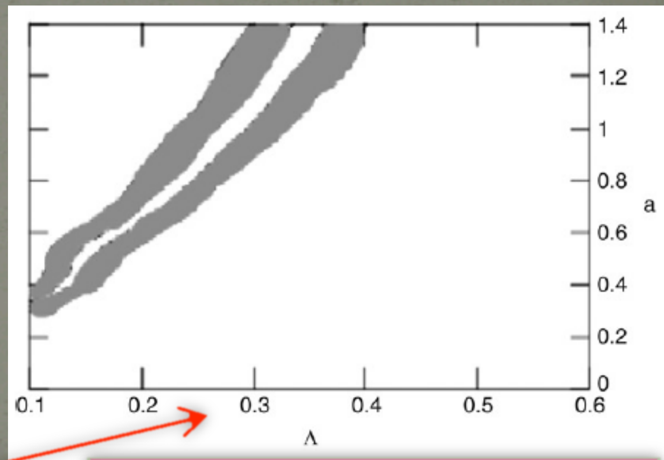
$$Y_p = 0.2484\left(\frac{G_{eff}}{G_N}\right)^{0.35}$$

$$D/H = 2.75\left(\frac{G_{eff}}{G_N}\right)^{0.95} 10^{-5}$$

$$^3He/H = 8.65\left(\frac{G_{eff}}{G_N}\right)^{0.34} 10^{-6}$$

$$^7Li/H = 3.82\left(\frac{G_{eff}}{G_N}\right)^{-0.72} 10^{-10}$$

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# Varying Λ

The observed accelerated expansion of the universe can be explained by a cosmological constant. But there are "old" problems:

- the value of Λ is extremely small with respect to expectations
- (just) today $\Omega_M$ and $\Omega_\Lambda$ are ~ equal

Attempts for alleviating these problems are based on th changing $\Omega_\Lambda$ due to a scalar field Q (quintessence, k-ess lar cases, one has attractor-like solutions of the field equatio

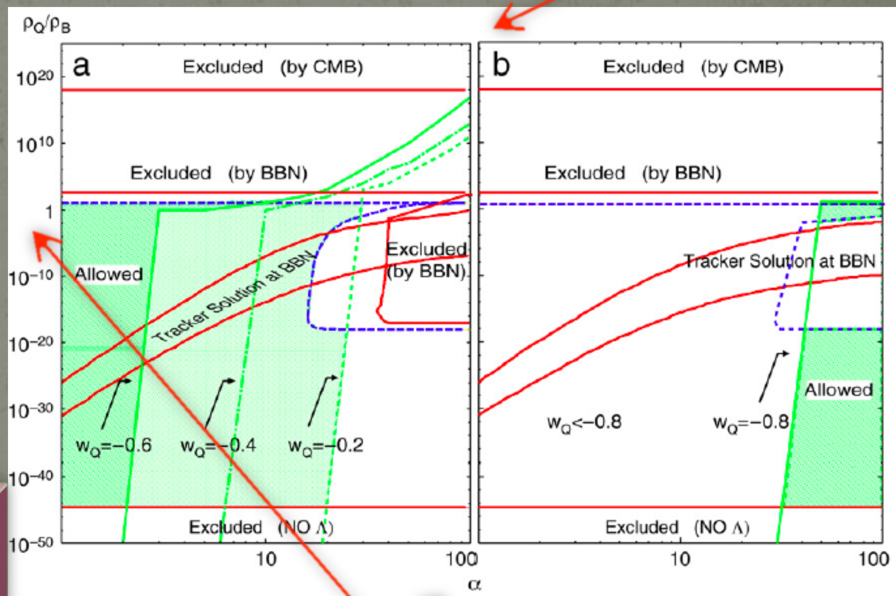
left: inverse power law
right: SUGRA

If the energy density of Q is non-negligible during the radiation dominated period, these models can be constrained by BBN.

NAPhysRep

$$\Omega_Q\big|_{T_D} \leq \left(\frac{\delta\rho_{N_{eff}}}{\rho}\right)_{T_D} = \frac{7/4\,\Delta N_{eff}}{g_* + 7/4\,\Delta N_{eff}} \leq 0.09(2\sigma)$$

M. Yahiro, G.J. Mathews, K. Ichiki, T. Kajino, M. Orito, Phys. Rev. D 65 (2002) 063502




α = exponent of Q,
$\rho_Q/\rho_B$ = ratio between en. den.

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Attempts for alleviating these problems are based on the idea of a dynamically changing $\Omega_\Lambda$ due to a scalar field Q (quintessence, k-essence, etc.): in particular cases, one has attractor-like solutions of the field equations (tracker solutions).

If the energy density of Q is non-negligible during the radiation dominated period, these models can be constrained by BBN.

G. Leon, Y. Leyva, J. Socorro, Phys. Lett. B 732 (2014) 285

NAPhysRep

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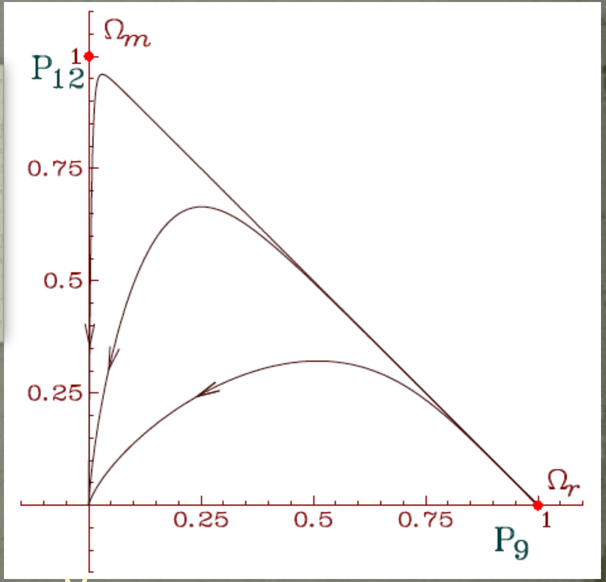
A canonical quintessence scalar field and a phantom scalar field.




But, we don't have BBN constraints if the universe is dominated by a phantom field (quintom model).

# Making the difference with $e^+e^-$

Example: a X particle that contributes to the energy density like a neutrino, $T_X=T_\nu$. Then, the contribution of this species to $\rho_R$ is, after $e^+e^-$ disappearance, diluted by the heating of the photons.

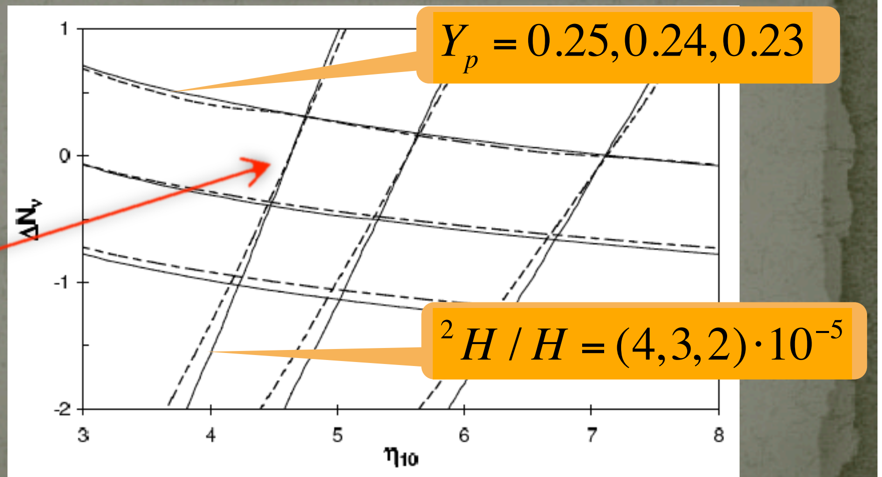
$$\rho_X^{before} = \frac{7}{8}\Delta N_{eff}\frac{\pi^2}{15}T_\nu^2 = \frac{7}{8}\Delta N_{eff}\rho_\gamma \qquad \rho_X^{after} = \frac{7}{8}\Delta N_{eff}\frac{\pi^2}{15}T_\nu^2 = \frac{7}{8}\Delta N_{eff}\left(\frac{4}{11}\right)^{4/3}\rho_\gamma$$

Comparison of this scenario with two "similar" models: a non-minimally coupled quintessence and a non-minimal coupling of a scalar field with the Ricci scalar.

The usual solutions in these scenarios have the characteristic that $\Omega_Q$ is larger in RD (independently on $e^+e^-$).

Isoabundance contours for $^2H$ (vertical) and $^4He$ (horizontal).

J.P. Kneller, G. Steigman, Phys. Rev. D 67 (2003) 063501



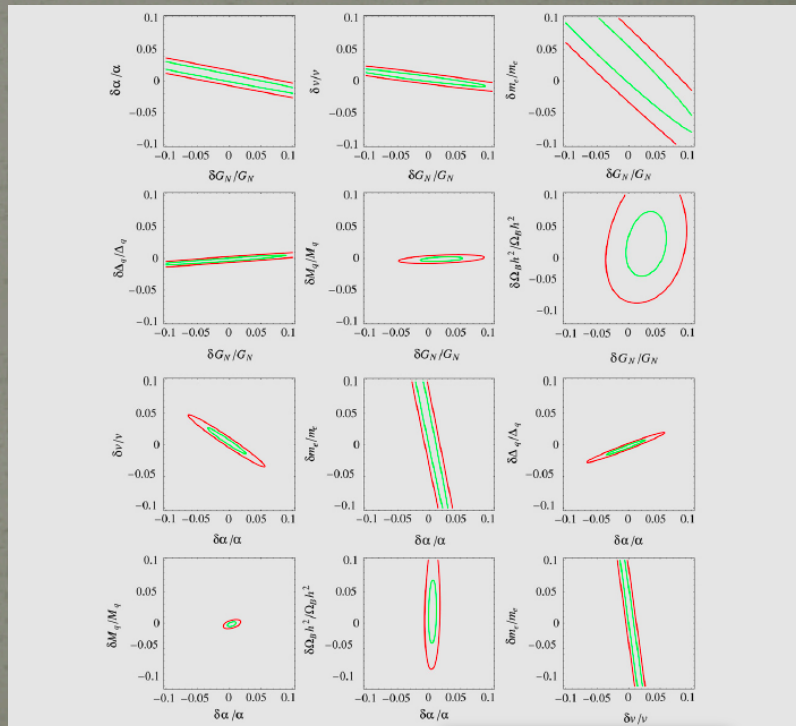
# Varying a lot…

Typical analyses assume that all but a single constant are held fixed. But it is quite natural that several couplings or fundamental scales would be time-dependent. Then, when using BBN to constrain such a scenario several degeneracies emerge.

- Identify the fundamental parameters which influence BBN
- Use a perturbative approach, in the neighborhood of their standard values
- Construct the response matrix R

$$R_{ik} = \frac{\varphi_k}{X_i} \frac{\partial X_i}{\partial \varphi_k}$$

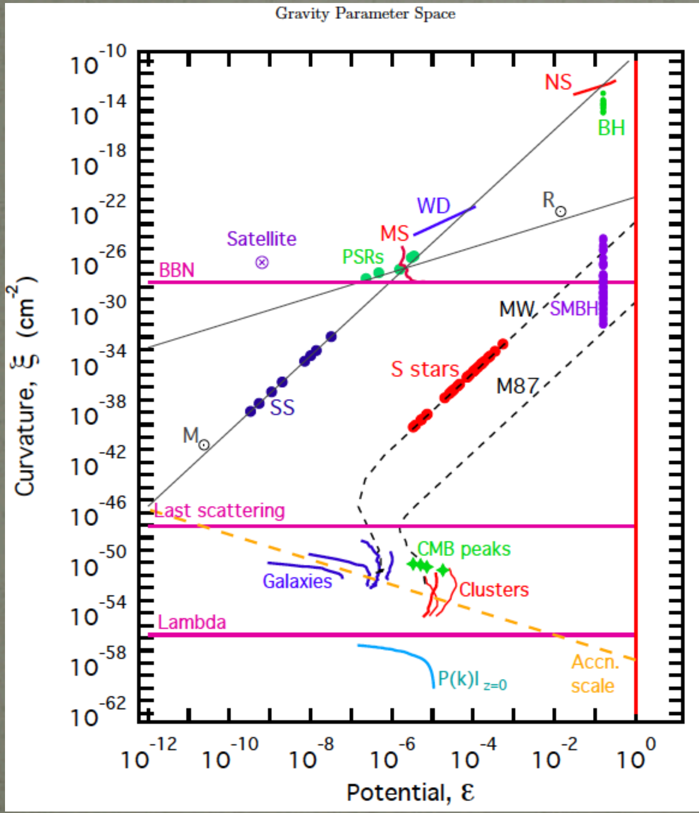
- Construct the $\chi^2$ function by using the experimental data
- Notice the strong correlation of $G_N$ with $\alpha_{em}$, $m_e$ and $\nu$ (Higgs vacuum expectation value).



NAPhysRep

# Tests of gravity on all scales

A classification of astrophysical and cosmological systems in a "gravitational" parameter space. Two gravitational quantifiers: the Kretschmann scalar and the Newtonian gravitational potential. BBN is concerned only with the first one, since it is not possible to assign a ε scale to an unperturbed background.




$$\xi = \left(R^{\alpha\beta\gamma\delta}R_{\alpha\beta\gamma\delta}\right)^{1/2}$$

T. Baker, D. Psaltis, C. Skordis, Astrophys. J. 802 (2015) 63

In particular, for cosmology one distinguishes between a piece coming from cosmological perturbations and a background contribution, $\xi^{\mathrm{cosmo}}$.

$$\xi^{\cos mo} = \frac{\sqrt{12}}{a^2}\left(\dot{H}^2 + H^4\right)^{1/2}$$

Systems that are usually considered complementary in testing relativity can be probing the same set of potentials and curvature.

# Conclusions

- BBN theory quite accurate, at % level (or better)
- Nuclear physics dominates the error budget in $^{2}$H BBN prediction ➔ strong motivation for future measurements of reaction rates.
- More high quality data on $^{4}$He ➔ decreasing uncertainty on $Y_p$ and improved systematics
- $^{7}$Li still puzzling
- New updates from Planck ➔ increased accuracy in the BBN+CMB analyses
- "Alternative" scenarios are probed by BBN mainly through the speed of expansion (new particles, a change in the value of $G_N$, ...) ➔ variation in $N_{eff}$. Conclusion: if your "alternative" model does not change the expansion at the BBN time it is almost safe.
- A different view of what is complementary in testing gravity: in any case, BBN is there!

# "Alternative Gravity and Alternative Matter" Workshop

ITCP - Department of Physics
Heraklion, Crete 20-23 May 2015

# Thank you!