PArthENoPE reloaded: revising the BBN reaction network

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BBN in few words

Seventhy years after the seminal $\alpha\beta\gamma$ paper (Alpher, Bethe, Gamow, 1948):

- Theoretical (standard) framework well established
- Increasingly precise data on Deuterium, ^{4}He
- Increasingly precise data on nuclear process rates from lab experiments at low energies (10 KeV – MeV)
- Baryon fraction measured very accurately by CMB

COSMOLOGY ASTROPHYSICS ⟺ **FUNDAMENTAL MICROPHYSICS**

BBN 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, Olive, …

BBN in four steps

i)	Initial conditions	$T > 1$ MeV
ii)	n/p ratio freeze out	$T \approx 1$ MeV
iii)	D bottleneck	$T \approx 0.1$ MeV
iv)	nuclear chain	$0.1 \text{ MeV} > T > 0.01$ MeV

- BBN Input (Free Parameters + New Physics?):

- baryon density: $$\Omega_b h^2 = \frac{1 - 0.007125\, Y_p}{273.279} \left(\frac{T_\gamma^0}{2.7255K} \right)^3 \eta_{10}$$ (FP)

- energy density of neutrinos
  1) non instantaneous decoupling effects
  2) neutrino chemical potentials (FP)
  3) non standard neutrino physics (FP)

- extra relativistic d.o.f., exotic physics (NP)

Contribution to the total amount of relativistic degrees of freedom historically described as "effective number of neutrinos"(?):

$$\rho_\nu + \rho_X(?) \equiv \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \left(N_\nu^{eff} + \Delta N_\nu\right)\rho_\gamma$$

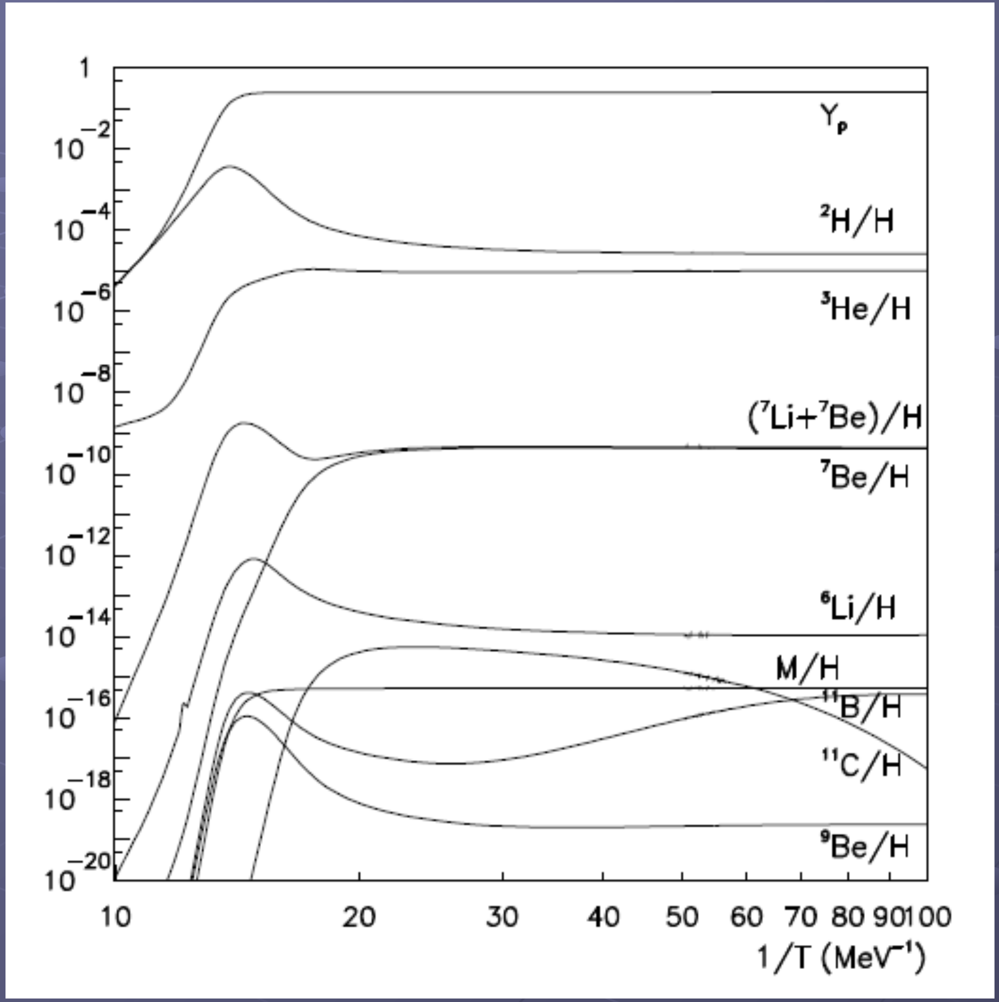
- BBN Output: $\mathbf{X_a}$

Nuclides considered in BBN

Z \ N	0	1	2	3	4	5	6	7	8
0		n							
1	H	^{2}H	^{3}H						
2		^{3}He	^{4}He						
3				^{6}Li	^{7}Li	^{8}Li			
4				^{7}Be		^{9}Be			
5				^{8}B		^{10}B	^{11}B	^{12}B	
6						^{11}C	^{12}C	^{13}C	^{14}C
7						^{12}N	^{13}N	^{14}N	^{15}N
8							^{14}O	^{15}O	^{16}O

BBN accuracy

1. Weak interactions freeze out at T ~1 MeV
2. Deuterium forms via
   p n →D γ
   at T ~ 0.1 MeV
3. Nuclear chain



^{4}He mass fraction (Y_p):
weak rates and n/p freezing + neutrino decoupling

D,^{3}He, ^{7}Li:

nuclear rate network

Solving numerically BBN dynamics

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

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

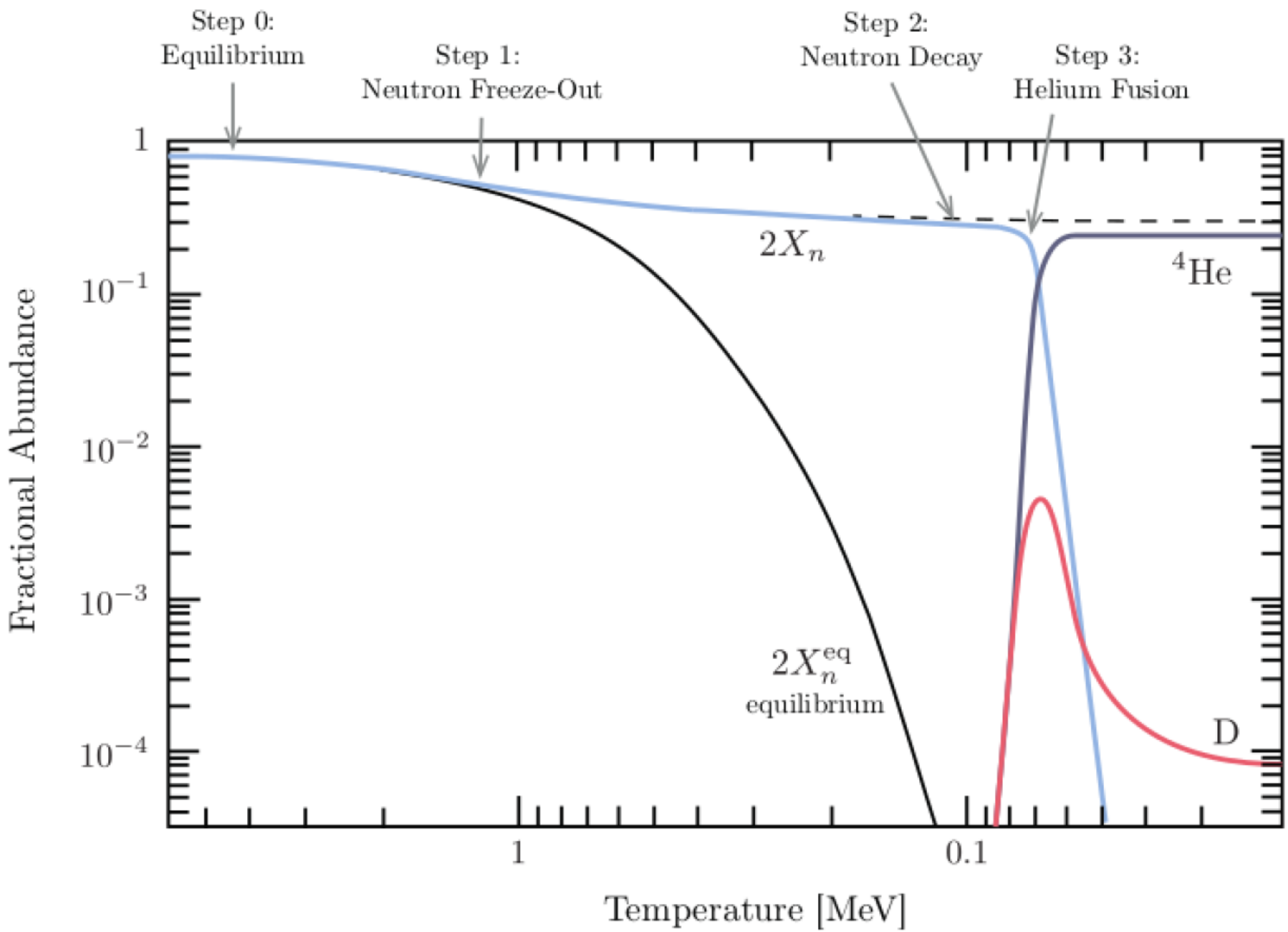
$$\dot{\rho} = -\,3\,H\,(\rho + P) \quad ,$$

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

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

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

Neutrino decoupling and n/p freeze out can be computed independently of nuclear abundances!



Step 0:
Equilibrium
Step 1:
Neutron Freeze-Out
Step 2:
Neutron Decay
Step 3:
Helium Fusion
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Fractional Abundance
$2X_n$
^{4}He
$2X_n^{eq}$
equilibrium
D
1
0.1
Temperature [MeV]

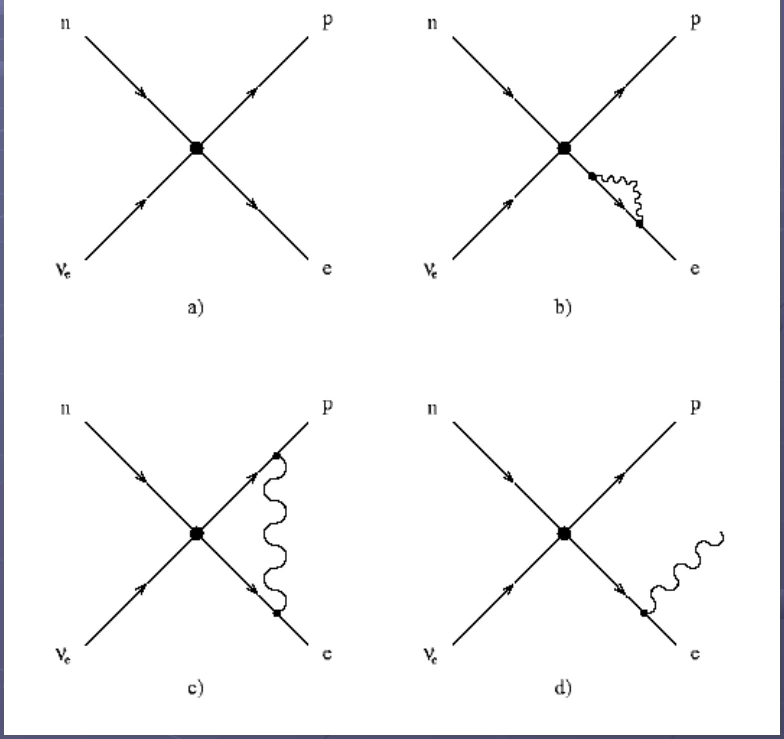
BBN accuracy I

weak rates:

known at 0.1% level:

- Radiative corrections
- Finite nucleon mass
- Thermal effects
- Effects of non-thermal features in neutrino distribution

$$(a)\quad \nu_e + n \rightarrow e^- + p \quad , \qquad (d)\quad \overline{\nu}_e + p \rightarrow e^+ + n$$
$$(b)\quad e^- + p \rightarrow \nu_e + n \quad , \qquad (e)\quad n \rightarrow e^- + \overline{\nu}_e + p$$
$$(c)\quad e^+ + n \rightarrow \overline{\nu}_e + p \quad , \qquad (f)\quad e^- + \overline{\nu}_e + p \rightarrow n$$



Main uncertainty still present:
neutron lifetime
τ_n= 880.2 ± 1.0 sec (PDG 2016)

τ_n=878.5 ± 0.8 sec (Serebrov et al 2005)

^{4}He mass fraction Y_P linearly increases with τ_n: 0.246 - 0.249

S. Esposito et al. PRD58:105023,1998.
S. Esposito et al. NPB540:3-36,1999.
S. Esposito et al. NPB568:421-444,2000.

BBN accuracy II

neutrino decoupling: T ~ MeV

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.945K \rightarrow kT_\nu \approx 1.68 \cdot 10^{-4}\, eV$$

small entropy release to ν's from e^+- e^- annihilation

- momentum dependent distortion in ν distribution
- smaller photon temperature
- change in time-temperature relationship

$$\left(i\partial_t - H p \partial_p\right)\rho = \left[\frac{M^2}{p} - \frac{8\sqrt{2}G_F}{m_W^{\,2}} E, \rho + \ldots\right] + C(\rho)$$

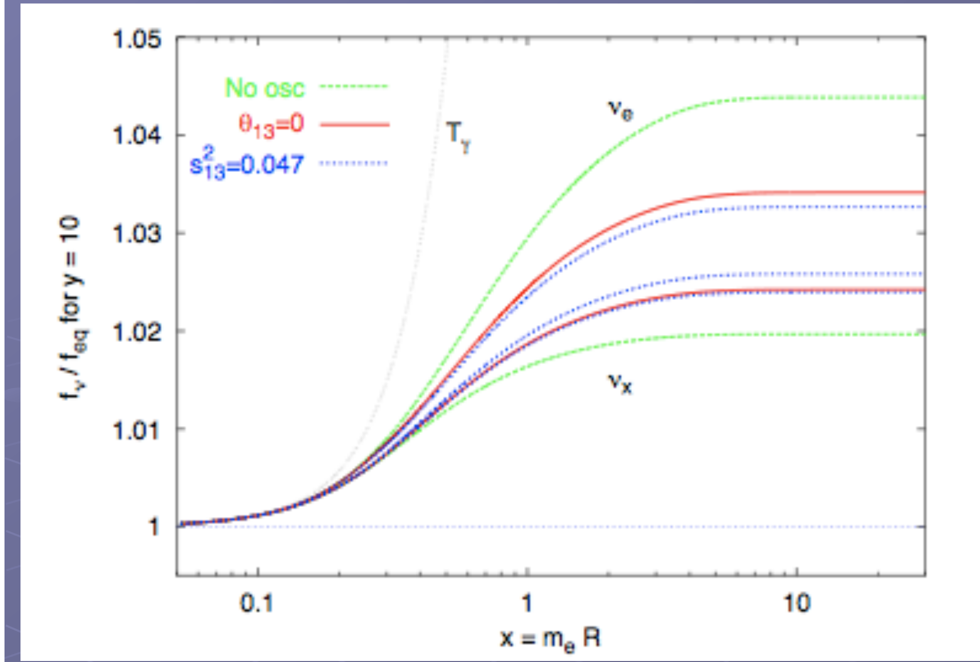
flavour transitions

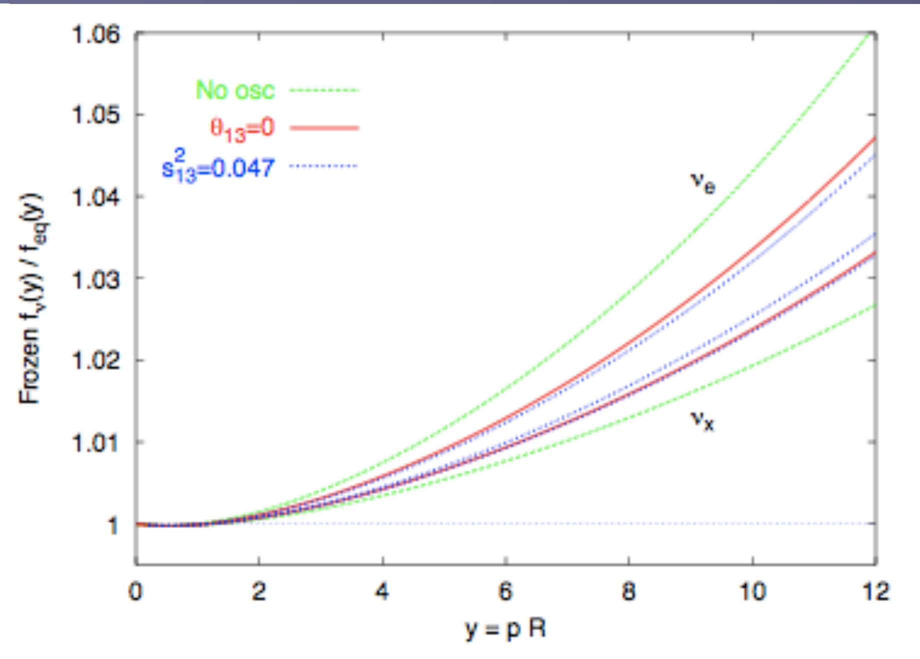
$$\rho(p,t) = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} & \rho_{e\tau} \\ \rho_{\mu e} & \rho_{\mu\mu} & \rho_{\mu\tau} \\ \rho_{\tau e} & \rho_{\tau\mu} & \rho_{\tau\tau} \end{pmatrix}$$

distributions
(F.D. in equilibrium)

A. Dolgov et al. Nucl.Phys.B503: 426-444, 1997.
S. Esposito et al. Nucl.Phys.B590:539-561,2000.
G. Mangano et al. Phys.Lett.B534:8-16,2002.
G. Mangano et al. Nucl.Phys.B729:221-234,2005.
G. Mangano et al. Nucl.Phys.B756:100-116,2006.
G. Mangano et al. JCAP 1103, 035, 2011.
G. Mangano et al. Phys.Lett. B708:1-5,2012.
P. De Salas & S. Pastor JCAP 1607, 051, 2016.

Assuming oscillations but vanishing neutrino chemical potentials





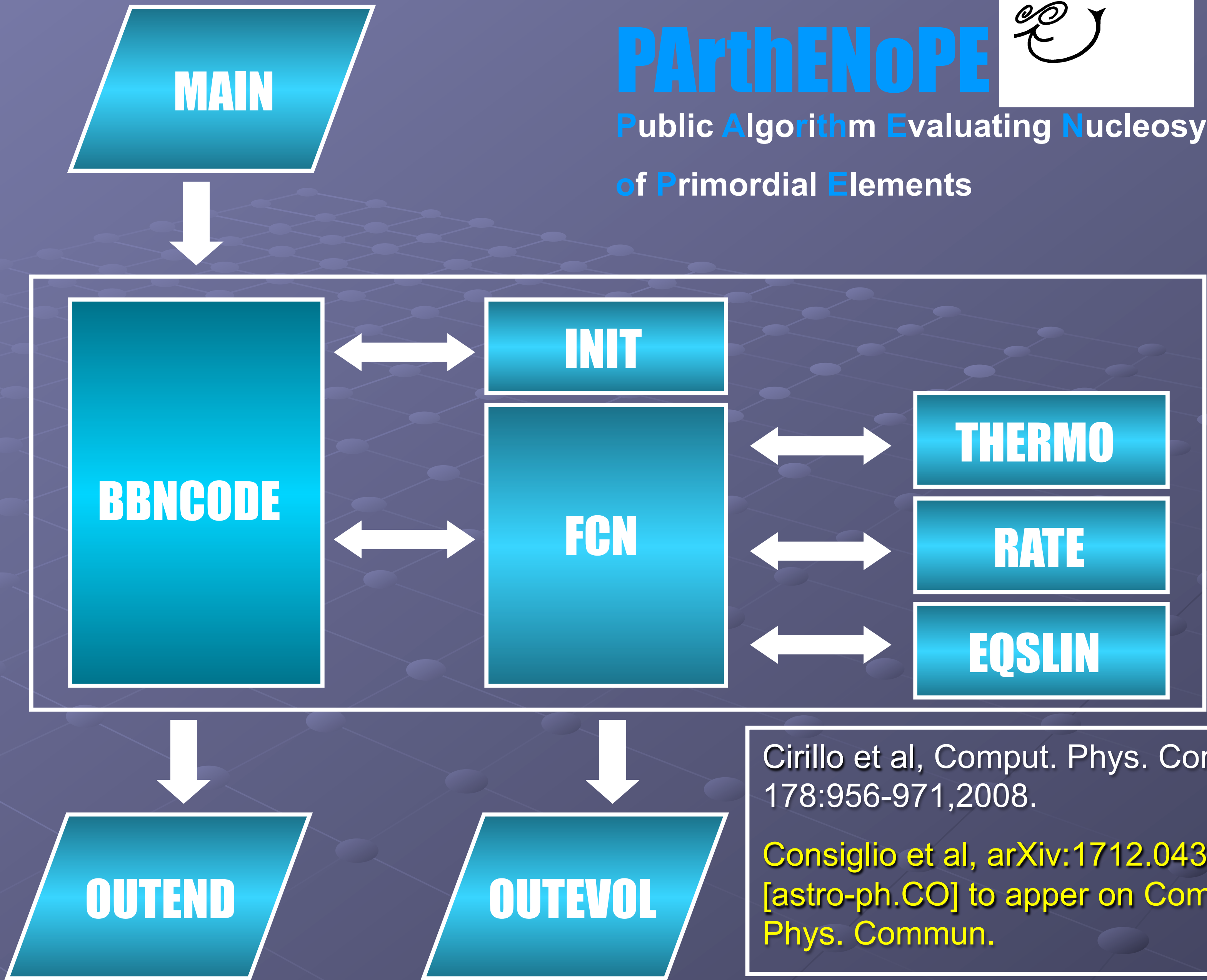
z=T a	$\delta\rho_e$	$\delta\rho_x$	N_ν^{eff}
1.4	0.73%	0.52%	**3.045**

$$N_\nu^{\rm eff} = \left(\frac{z^0}{z^{\rm fin}}\right)^4 \left(3 + \frac{\delta\rho_{\nu_e}}{\rho_\nu^0} + 2\frac{\delta\rho_{\nu_x}}{\rho_\nu^0}\right) \simeq \left(3 - 12\frac{\delta z}{z^0} + \frac{\delta\rho_{\nu_e}}{\rho_\nu^0} + 2\frac{\delta\rho_{\nu_x}}{\rho_\nu^0}\right)$$

Small effect on ^{4}He mass fraction: $\delta Y_p = 2 \times 10^{-4}$

PArthENoPE

Public Algorithm Evaluating Nucleosynthesis of Primordial Elements



Cirillo et al, Comput. Phys. Commun. 178:956-971,2008.

Consiglio et al, arXiv:1712.04378 [astro-ph.CO] to apper on Comput. Phys. Commun.

In PArthENoPE 2.0 the set of BBN equations are transformed in (z = me/T)

$$\frac{d\phi_e}{dz} = \frac{1}{z}\frac{\hat{L}\,\kappa_1 + \left(\hat{\rho}_{e\gamma} + \hat{\mathrm{p}}_{e\gamma B} + \frac{\mathcal{N}(z)}{3}\right)\kappa_2}{\hat{L}\,\frac{\partial\hat{\rho}_e}{\partial\phi_e} - \frac{\partial\hat{L}}{\partial\phi_e}\left(\hat{\rho}_{e\gamma} + \hat{\mathrm{p}}_{e\gamma B} + \frac{\mathcal{N}(z)}{3}\right)} \quad ,$$

$$\frac{dX_i}{dz} = -\frac{\widehat{\Gamma}_i}{3\,z\,\widehat{H}}\,\frac{\kappa_1\,\frac{\partial\hat{L}}{\partial\phi_e} + \kappa_2\,\frac{\partial\hat{\rho}_e}{\partial\phi_e}}{\hat{L}\,\frac{\partial\hat{\rho}_e}{\partial\phi_e} - \frac{\partial\hat{L}}{\partial\phi_e}\left(\hat{\rho}_{e\gamma} + \hat{\mathrm{p}}_{e\gamma B} + \frac{\mathcal{N}(z)}{3}\right)} \quad ,$$

Where for z_{in} = me/10 MeV

$$\hat{L}(z_{\mathrm{in}},\,{\phi_e}^0) = \frac{2\,\zeta(3)}{\pi^2}\,\eta_i\,\sum_i Z_i\,X_i(z_{\mathrm{in}})$$

$$\begin{aligned}
\phi_e(z_{\mathrm{in}}) &= {\phi_e}^0 \quad , \\
X_1(z_{\mathrm{in}}) &\equiv X_n(z_{\mathrm{in}}) = (\exp\{\hat{q}\,z_{\mathrm{in}}\} + 1)^{-1} \quad , \\
X_2(z_{\mathrm{in}}) &\equiv X_p(z_{\mathrm{in}}) = (\exp\{-\hat{q}\,z_{\mathrm{in}}\} + 1)^{-1} \quad , \\
X_3(z_{\mathrm{in}}) &\equiv X_{^2\mathrm{H}}(z_{\mathrm{in}}) = g_{^2\mathrm{H}}\,\frac{4\,\zeta(3)}{\sqrt{\pi}}\left(\frac{m_e}{M_N z_{\mathrm{in}}}\right)^{\frac{3}{2}}\eta_i\,X_p(z_{\mathrm{in}})\,X_n(z_{\mathrm{in}})\,\exp\left\{\hat{B}_{^2\mathrm{H}}\,z_{\mathrm{in}}\right\} \\
X_i(z_{\mathrm{in}}) &= X_{\mathrm{min}} \qquad\qquad i = {}^3\mathrm{H}, \ldots \quad .
\end{aligned}$$

NAG routines substituted by ODEPACK libraries.
A Graphical User Interface added.

PArthENoPE v.2

arXiv:1712.04378 [astro-ph.CO]

PArthENoPE 2.0 allows to treat non-standard physics

- Extra degrees of freedom

$$\rho_X = \frac{7}{8}\frac{\pi^2}{30}\Delta N_{\rm eff} T_X^4 \, ,$$

where T_X=T for T> T_d=2.3MeV and

$$T_X = T \left[\frac{\hat{\rho}_{e\gamma B}(T) + \hat{\rm p}_{e\gamma B}(T)}{\hat{\rho}_{e\gamma B}(T_d) + \hat{\rm p}_{e\gamma B}(T_d)} \right]^{1/3} \, , \quad T < T_d \, .$$

- Chemical potential of the active neutrinos
- Energy density of the cosmological constant

http://parthenope.na.infn.it

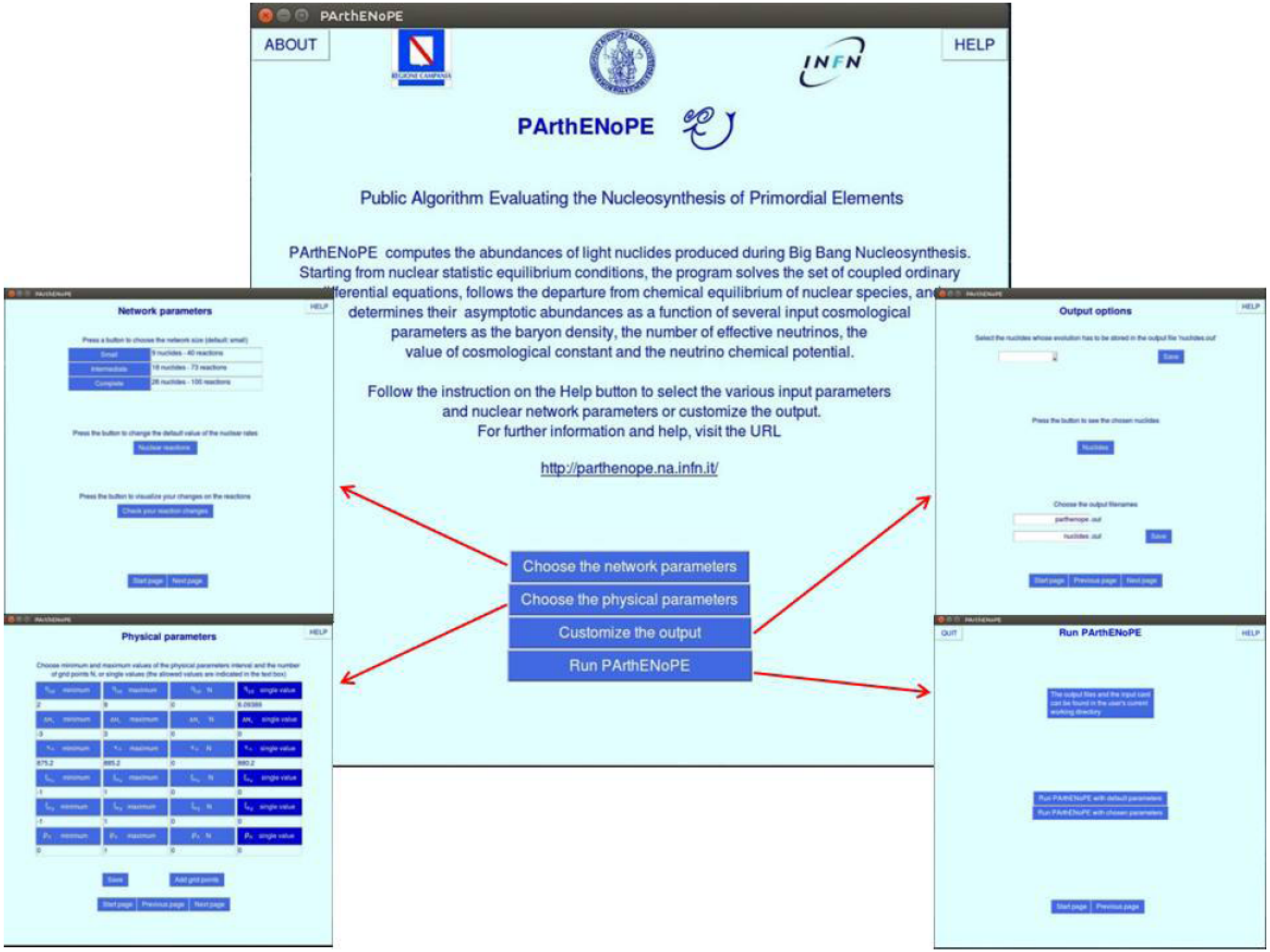


Figure 2: GUI Start page.

The user can run PArthENoPE with whatever set of chosen parameters (the allowed range of

BBN accuracy III – the nuclear chain

Nuclear rates for typical i +j processes enter the BBN set of equations

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

Typically expressed in terms of the so-called astrophysical S-factor, S(E), namely the intrinsic nuclear part of the reaction probability

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

If there is not a theoretical model it has to be fitted by the experimental data sets just covering limited energy ranges and sometimes affected by different normalization errors. Their combination is affected by D'Agostini's bias that requires a way out strategy.

For the reactions involving Deuterium

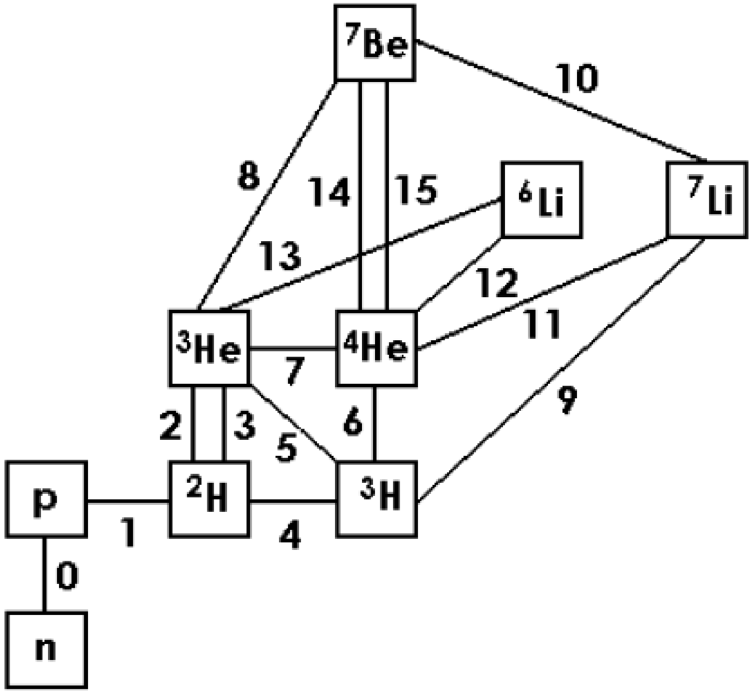
Three approaches:

- Single Dataset Normalization option, SDN, (Coc et al. 2015), inspired by the theoretical expected behaviour
- Average Dataset Normalization option, ADN, (Cyburt et al. 2001) based on S-factor presented in NACRE compilation
- Single Dataset Normalization with Penalty trick option, SDNP, (Serpico et al. 2004) which is a generalization of D'Agostini 1994. Method used in Parthenope 2.0

$$\chi^2(a_l, \omega_k) = \chi^2_{\mathrm{stat}} + \chi^2_{\mathrm{norm}}$$

$$\chi^2_{\mathrm{norm}} = \sum_k \frac{(\omega_k - 1)^2}{\epsilon_k^2}$$

The main reactions for D uncertainty



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}	$^7\mathrm{Be}(d,p)2\,^4\mathrm{He}$

Reaction	$\sigma_{^2H/H} \times 10^5$	$\epsilon(\%)$
$p(n,\gamma)^2H$	± 0.002	0.07%
$d(p,\gamma)^3He$	± 0.007	0.3%
$d(d,n)^3He$	± 0.023	0.9%
$d(d,p)^3H$	± 0.016	0.7%

→ Main contribution to D uncertainty

$^2H\ (p,\gamma)\ ^3He$

It is a fundamental process of ^3He synthesis in many astrophysical contexts like nuclear fusion in stars as part of the p-p chain but also in BBN

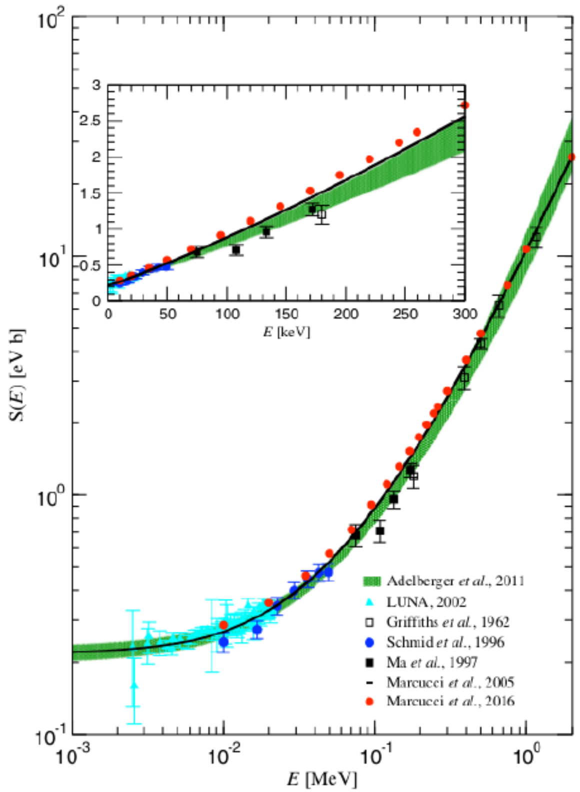


Figure 3.2: The astrophysical S-factor obtained in [60] (red points) plotted with the available experimental data of Refs. [62], [63], [64], [65], the previous calculation of the same authors [61] (solid black line), and the best-fit to the data of Adelberger et al. [56] (green band). The inset shows the relevant BBN energy range.

Using a theoretical model to reduce the error.
A recent theoretical model presented in Marcucci et al. (2016) in good agreement with the exp. data.
Important data are coming from LUNA.

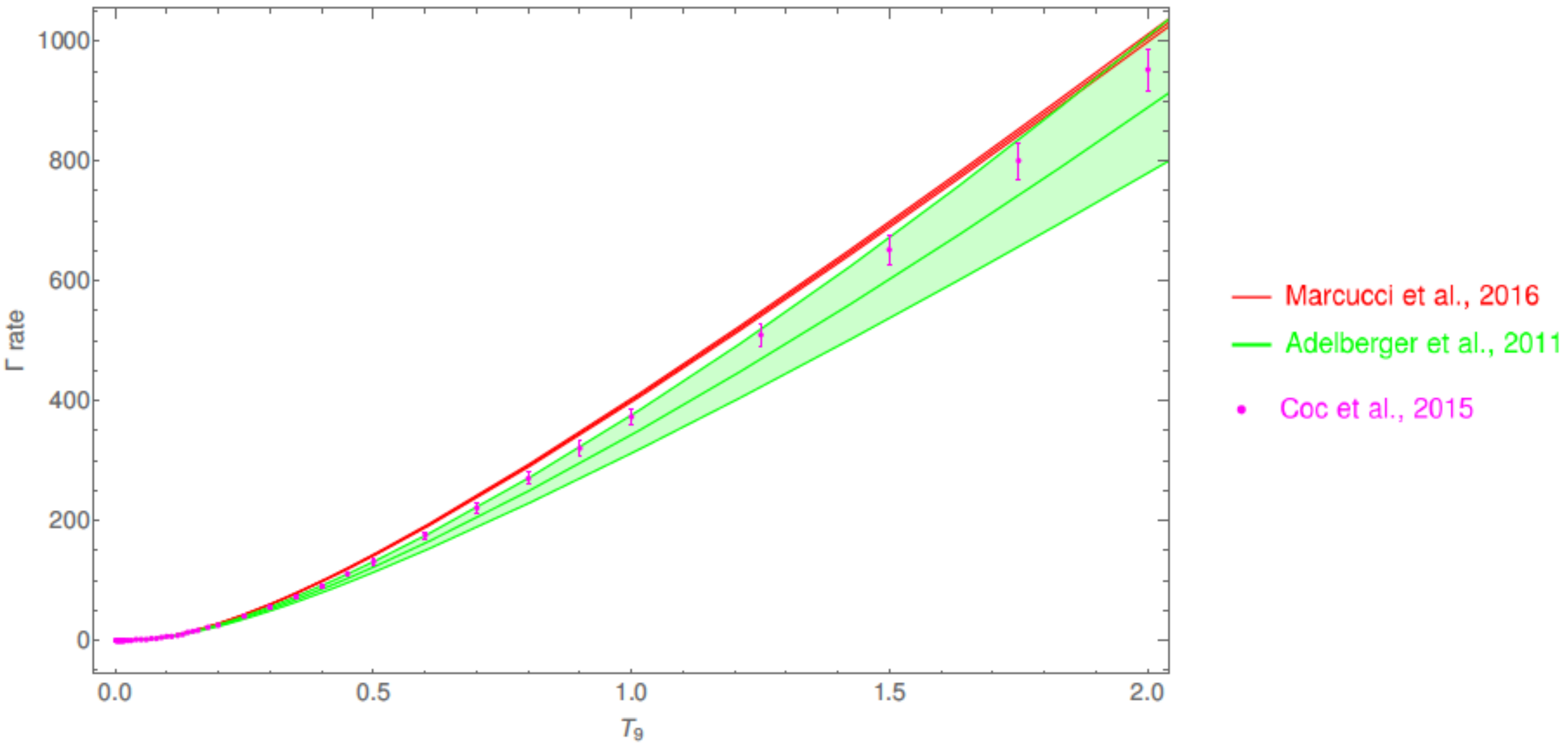
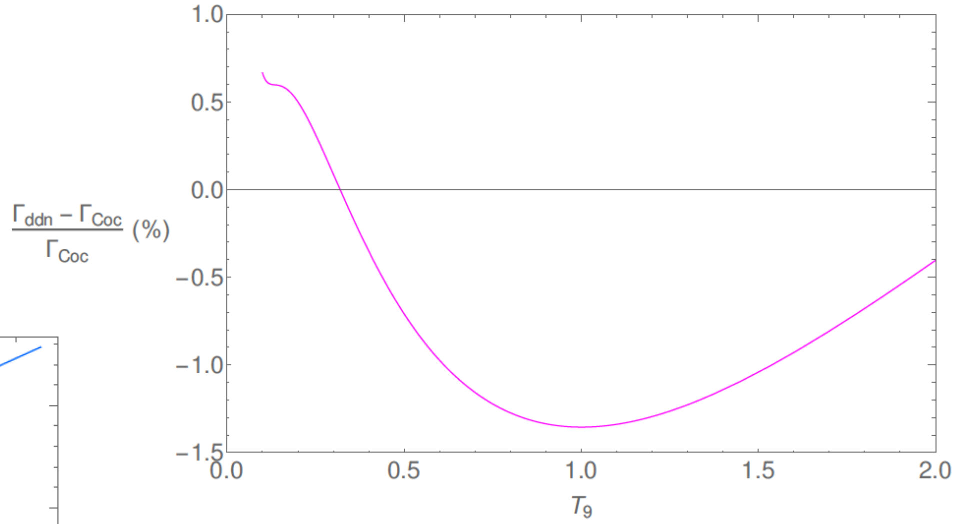
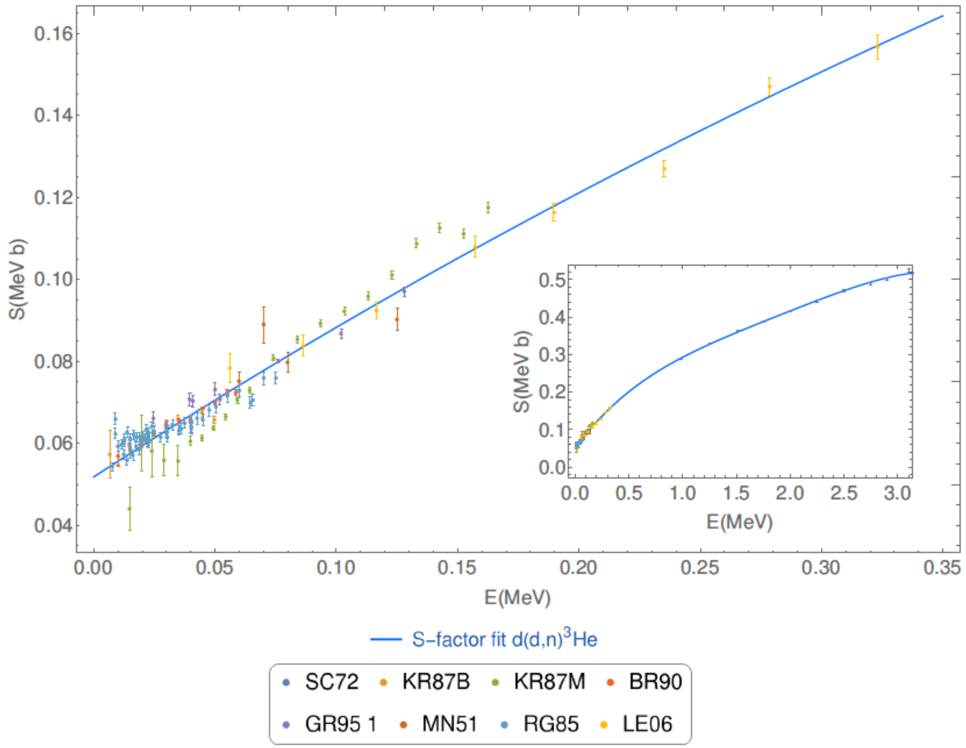


Figure 3.3: Thermal rate of the d(p,γ)^{3}He reaction obtained using: the theoretical model of Marcucci et al., (2016) [60] (red band), the best-fit to the data of Adelberger et al., (2011) [56] (green band) and the SDN method with the theoretical model Marcucci et al., (2005) [61] (magenta points).

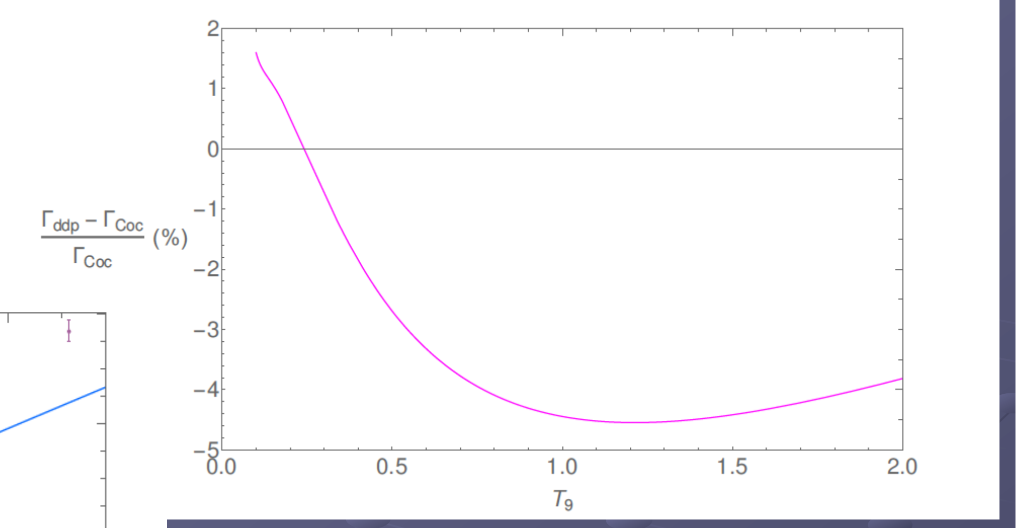
$^2H(d,n)^3He$ SDN vs SDNP

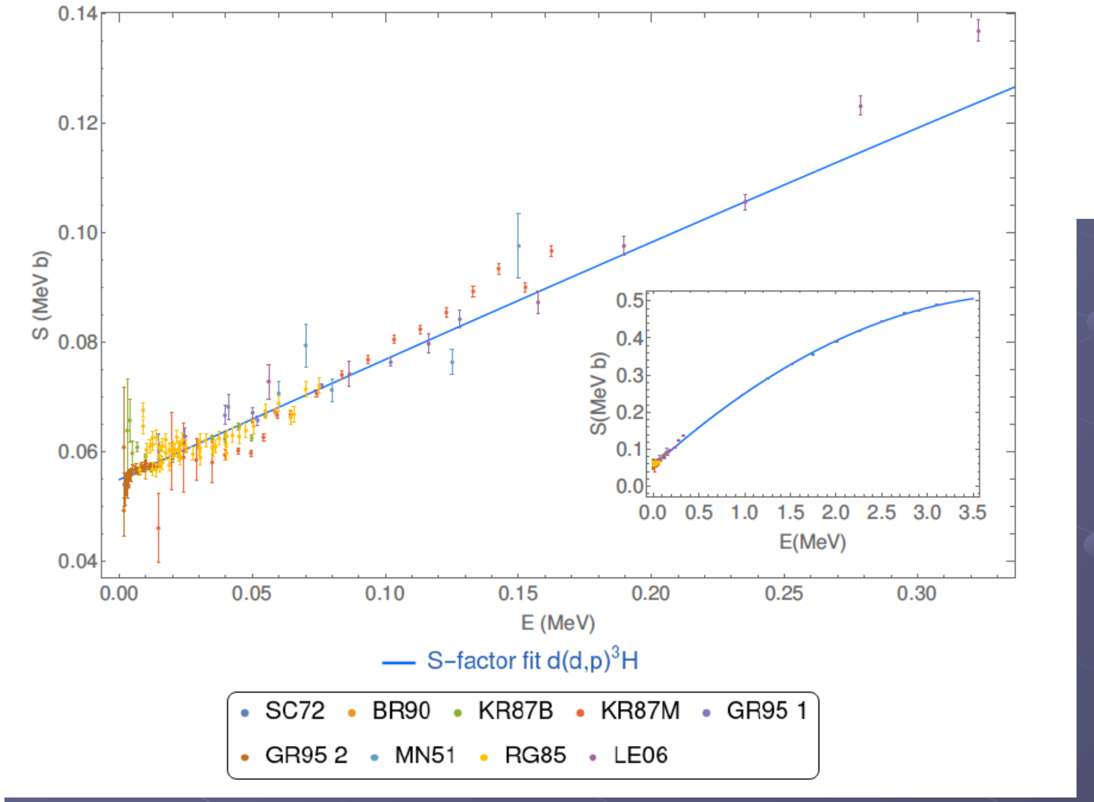




$^2H(d,p)^3H$

SDN vs SDNP

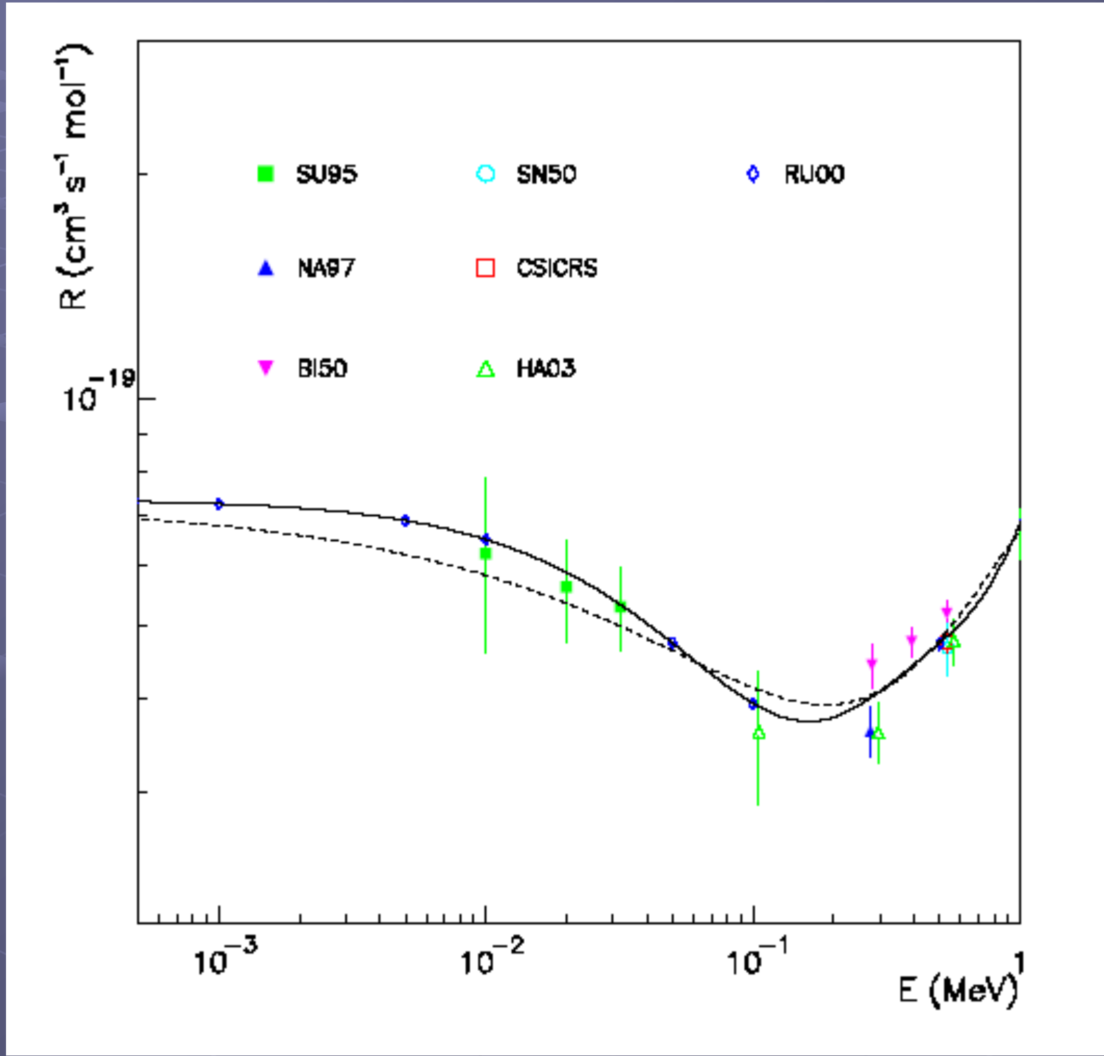




For completeness

p n → D γ

Pionless effective field theory at N^2LO and N^4LO (Rupak)

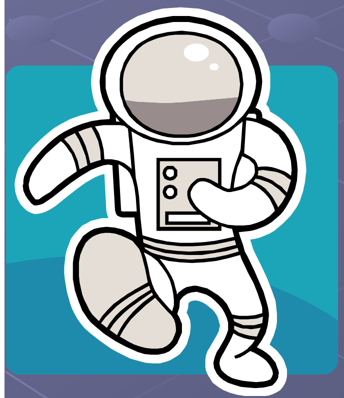


error in 1-2% range

ASTROPHYSICAL OBSERVATIONS

Main problem

We cannot observe directly primordial abundances, since stars have changed the chemical composition of the universe



1) Observations in systems negligibly contaminated by stellar evolution;

2) Carefull account for galactic chemical evolution.

Deuterium (see next talk!)

The astrophysical environments which seem the most appropriate are the hydrogen-rich clouds absorbing the light of background QSO's at high redshifts.

To apply the method one must require:

(i) neutral hydrogen column density in the range $17 < \log[N(H_I)/cm^{-2}] < 21$;

(H_I regions are interstellar cloud made of neutral atomic hydrogen)

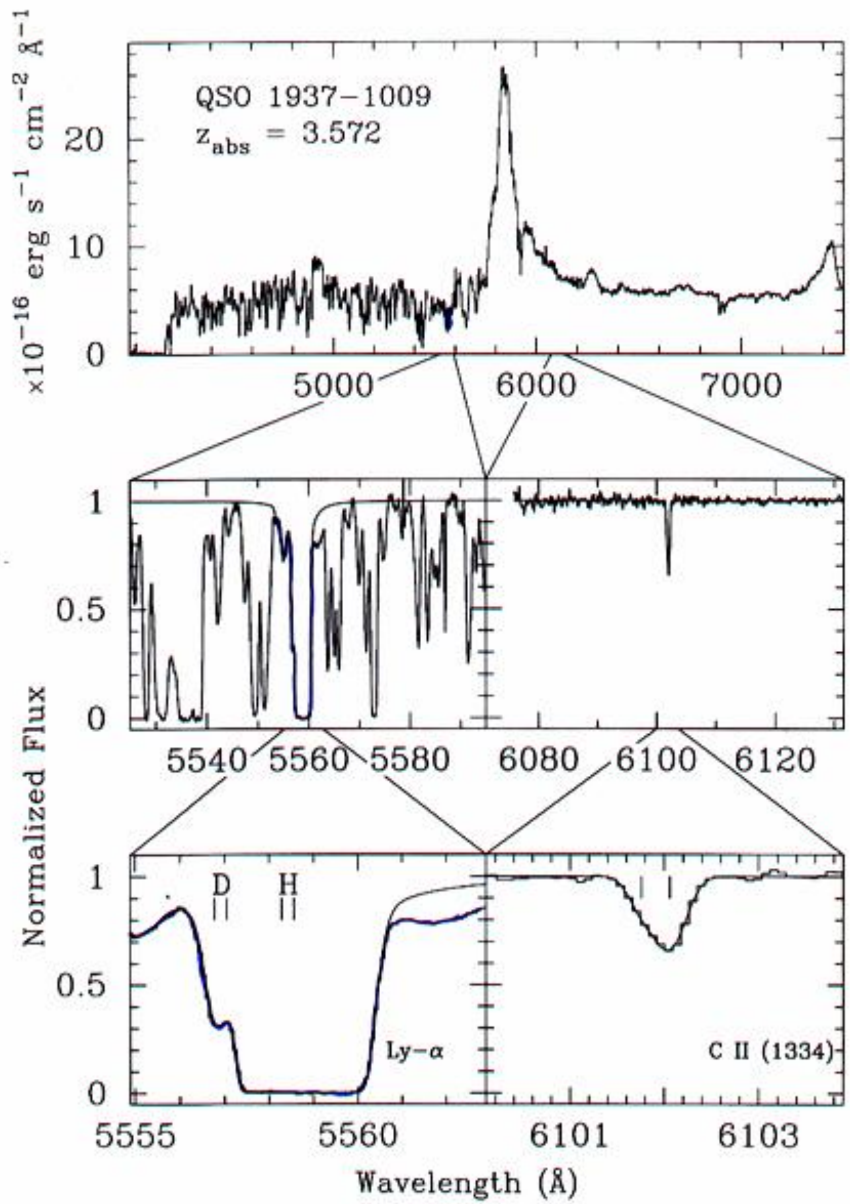
(ii) low metallicity [M/H] to reduce the chances of deuterium astration;

(iii) low internal velocity dispersion of the atoms of the clouds, allowing the isotope shift of only 81.6 km/s to be resolved.

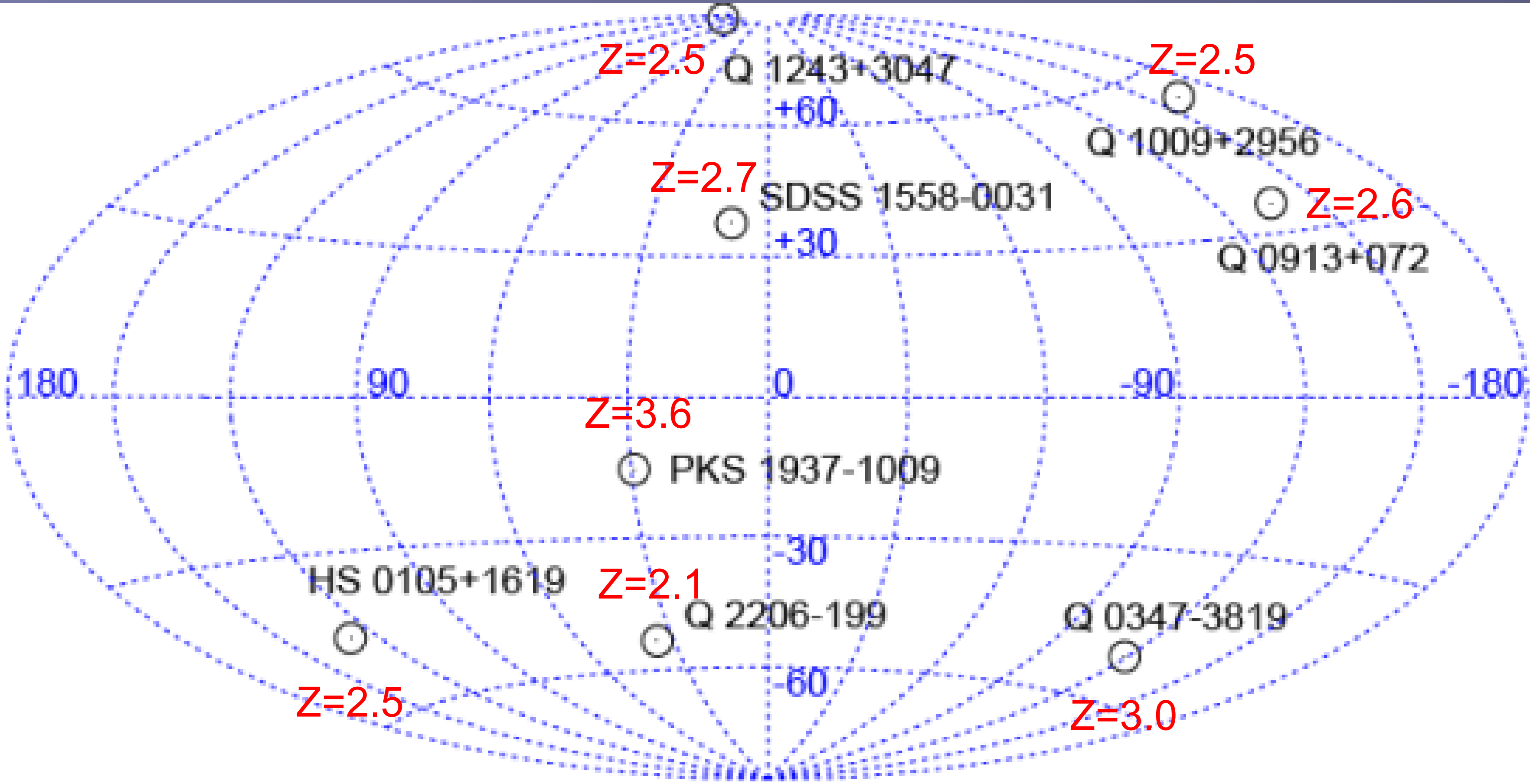
Only a small bunch of QAS's pass the exam!

Observation of Lyman absorption lines in gas clouds in QAS's at high redshift ($z \approx 2 - 3$) with low metallicity

$0.01 - 0.001\ (C/H)_{solar}$



The best 8 QAS's in Galactic coordinates



$^2H/H = (2.87^{+0.22}_{-0.21})\ 10^{-5}$ Iocco et al. 2009

$^2H/H = (3.02 \pm 0.23)\ 10^{-5}$ Olive et al. 2012

Recent observations and reanalysis of existing data about D abundance show a plateau as a function of redshift (for z ≥ 2) with a very small scattering for systems with comparable metallicity

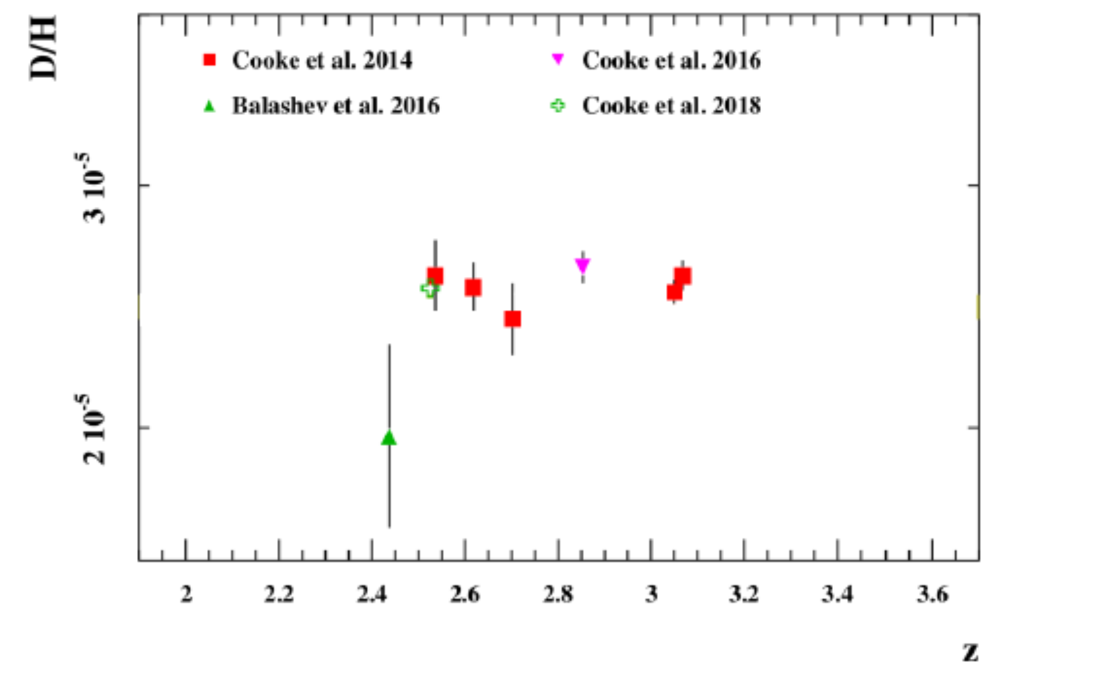


Figure 2.5: Recent D/H observations, as a function of the redshift of the absorber.

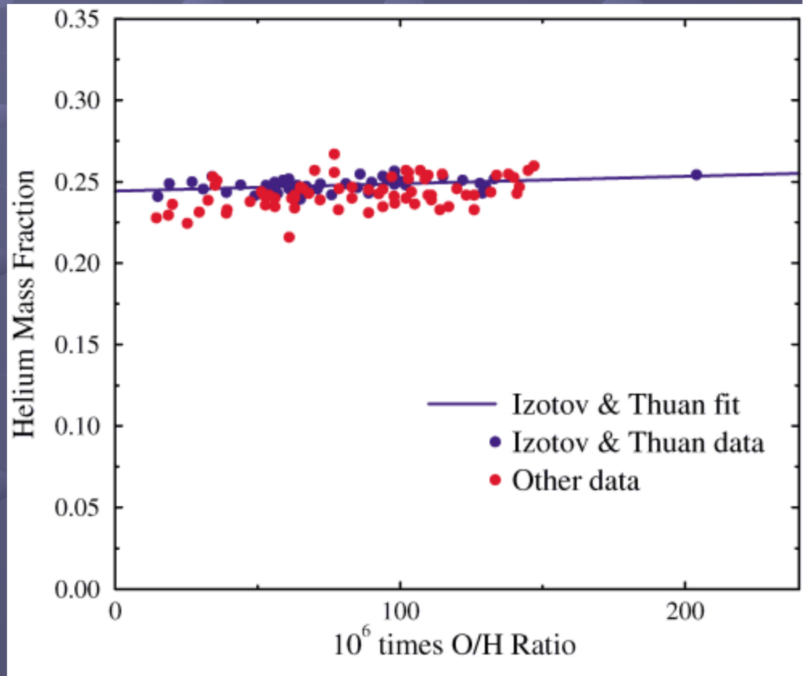
$^2H/H = (2.527 \pm 0.030)\ 10^{-5}$ Cooke et al. 2018

^{4}He

^{4}He evolution can be simply understood in terms of nuclear stellar processes which through successive generations of stars have burned hydrogen into ^{4}He and heavier elements, hence increasing the ^{4}He abundance above its primordial value. Since the history of stellar processing can be tagged by measuring the *metallicity* (Z) of the particular astrophysical environment, the primordial value of ^{4}He mass fraction Y_p can be derived by extrapolating the Y_p-O/H and Y_p - N/H correlations to O/H and N/H

- Observation of ionized gas (HeII HeI recombination lines in H_{II} regions) in Blue Compact Galaxies (BCGs)

  which are the least chemically evolved known galaxies
- Y_P in different galaxies plotted as function of O and N abundances.
- Regression to "zero metallicity"



Different analyses

- Izotov et al. 14 near-infrared spectroscopic observations of the high-intensity HeI atomic emission line with λ=10830 A in 45 low-metallicity HII region; 28 objects selected. They estimate

  $Y_p = 0.2551 \pm 0.0022$

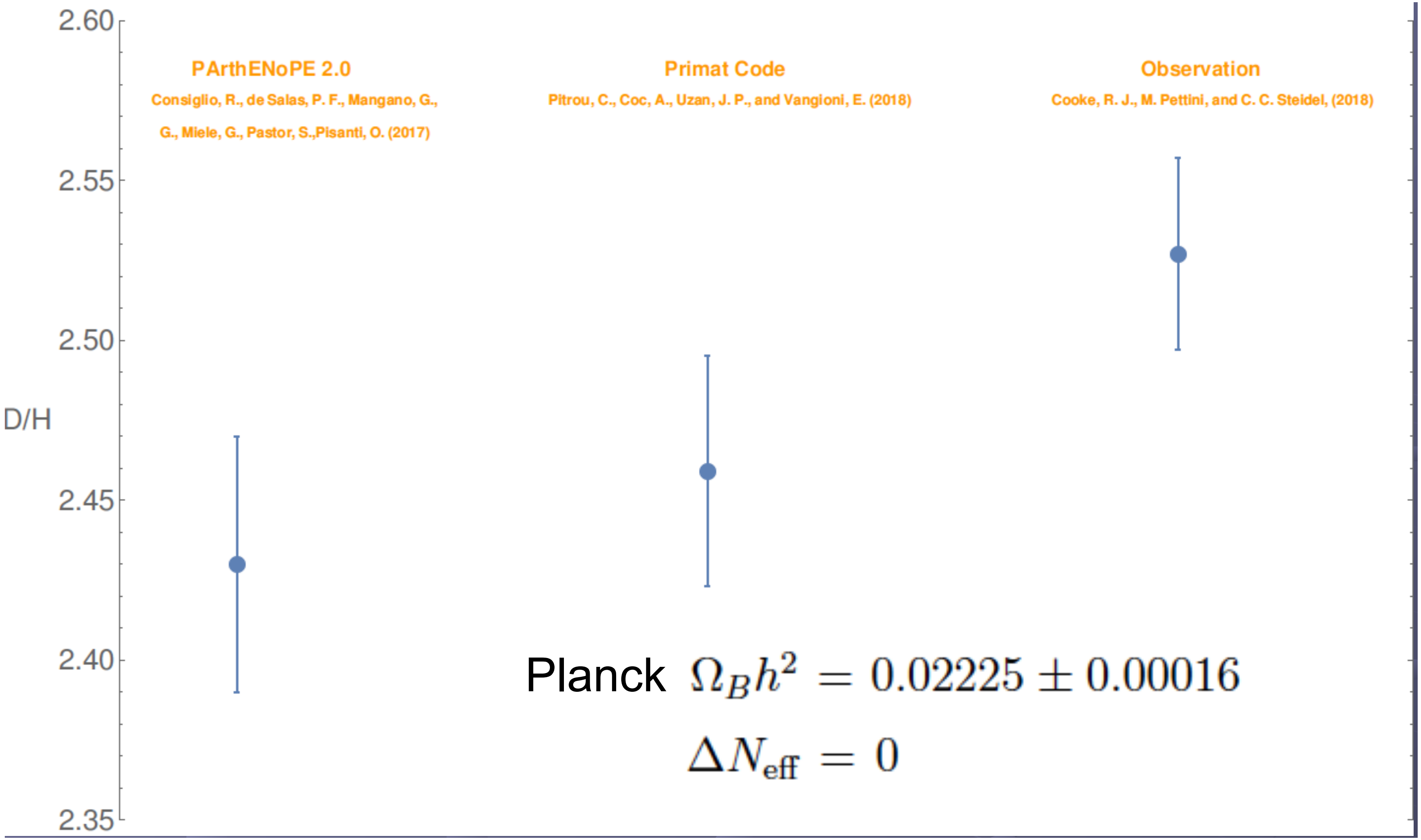
- Aver et al 15 Starting from the same regions but making a stricter selection on data, 16 objects selected

  $Y_p = 0.2449 \pm 0.0040$

- Peimbert et al 16, present a new ^{4}He mass fraction determination, yielding

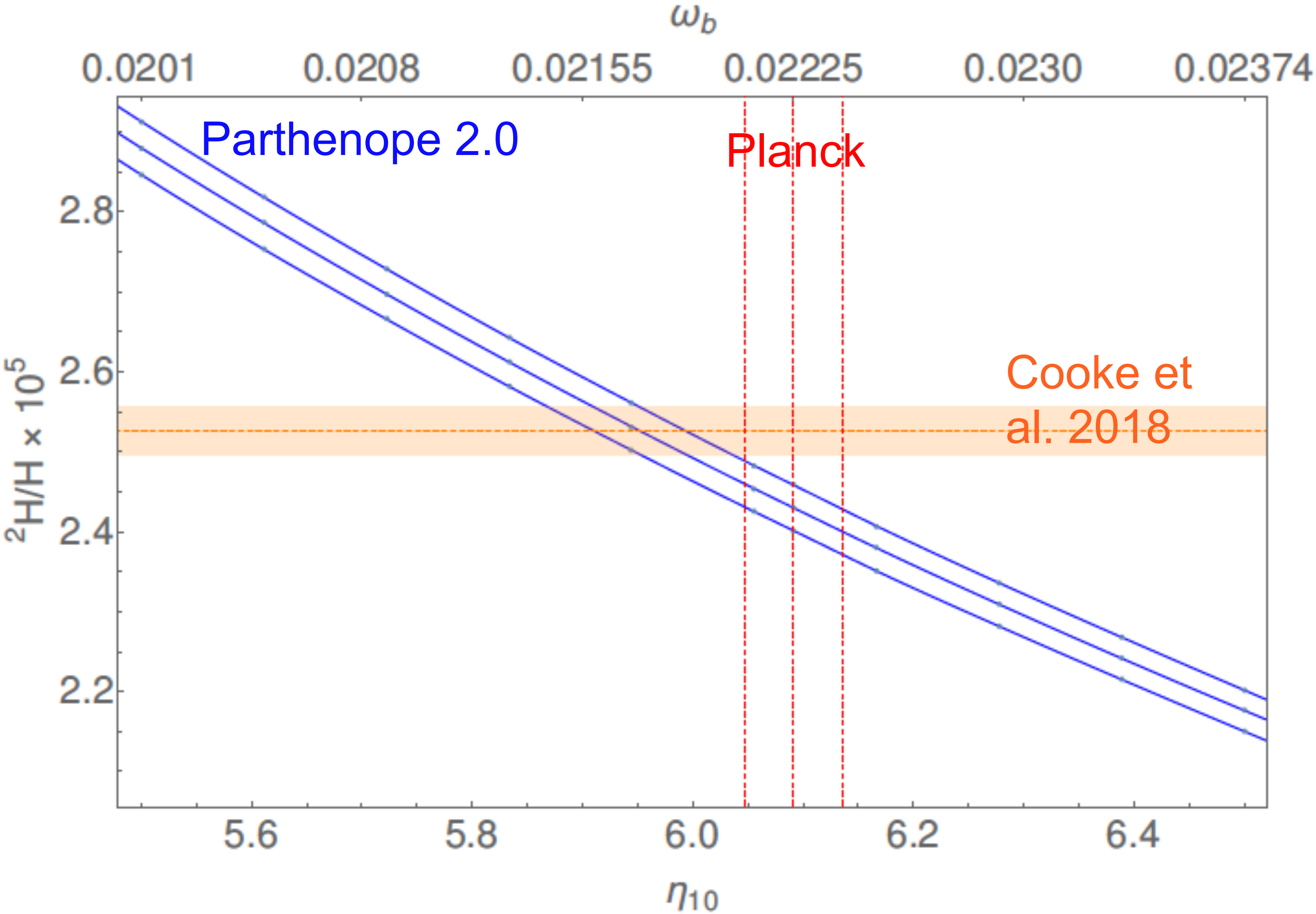
  $Y_p = 0.2446 \pm 0.0029$.

Observations vs predictions

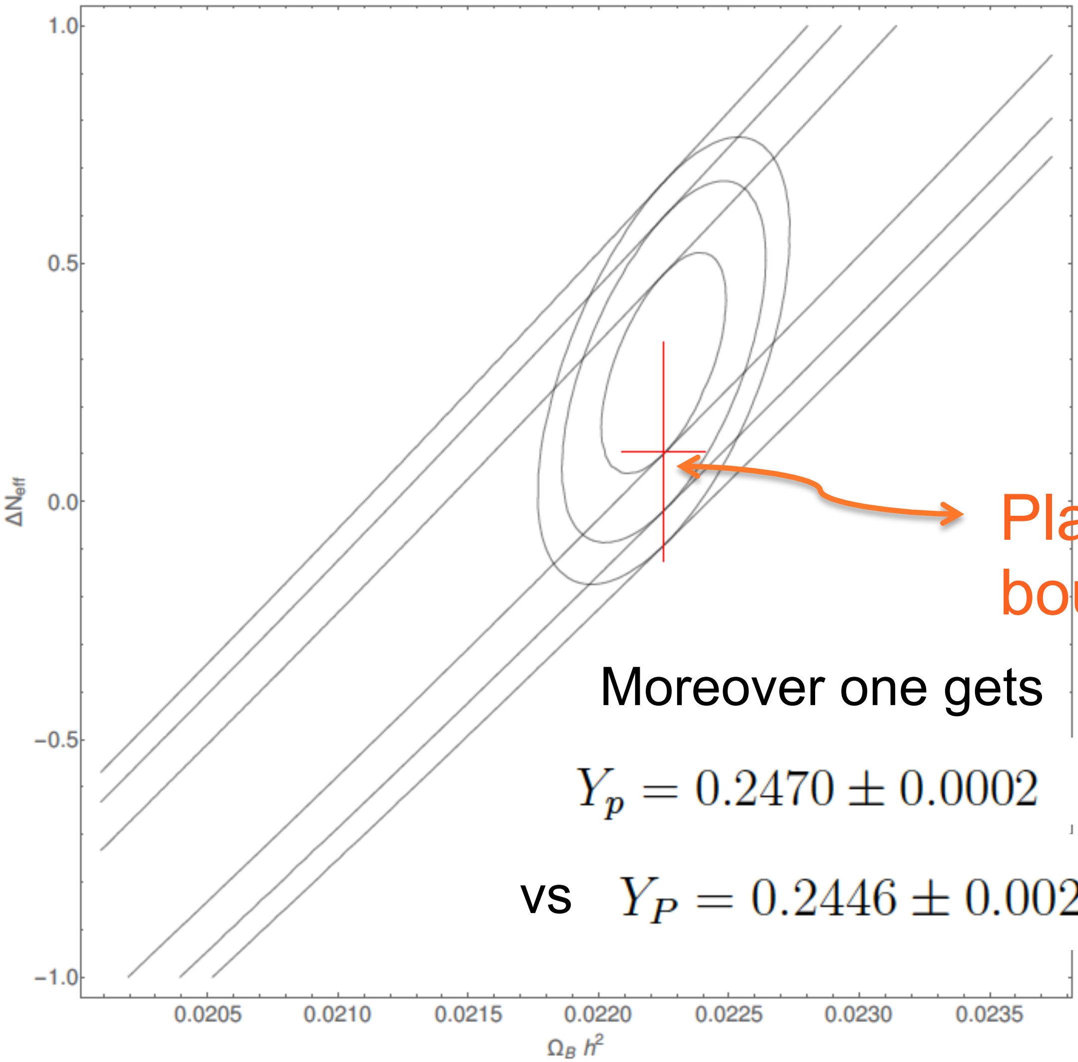


	Our result	Coc et al., (2015) [49]	PRIMAT [75]	Cyburt et al., (2016) [74]	Cooke et al. (2018) [20]
^{2}H/H $\times 10^5$	2.43 ± 0.04	2.45 ± 0.05	2.459 ± 0.036	2.58 ± 0.13	2.527 ± 0.030

Mazzella et al. Work in progress


ω_b
0.0201
0.0208
0.02155
0.02225
0.0230
0.02374
Parthenope 2.0
Planck
Cooke et al. 2018
^{2}H/H × 10^5
2.8
2.6
2.4
2.2
5.6
5.8
6.0
6.2
6.4
η_{10}

Likelihood
ω_B - D



Moreover one gets

$$Y_p = 0.2470 \pm 0.0002 \quad (68\% \text{ C.L.})$$

vs $Y_P = 0.2446 \pm 0.0029$

Figure 3.17: Contours at 68%, 95% and 99% C.L. of the likelihood function for deuterium (open bands) and of the likelihood with a prior on Planck result in the plane $(\omega_B, \Delta N_{\rm eff})$. The red cross corresponds to the values as indicated by Planck Collaboration.

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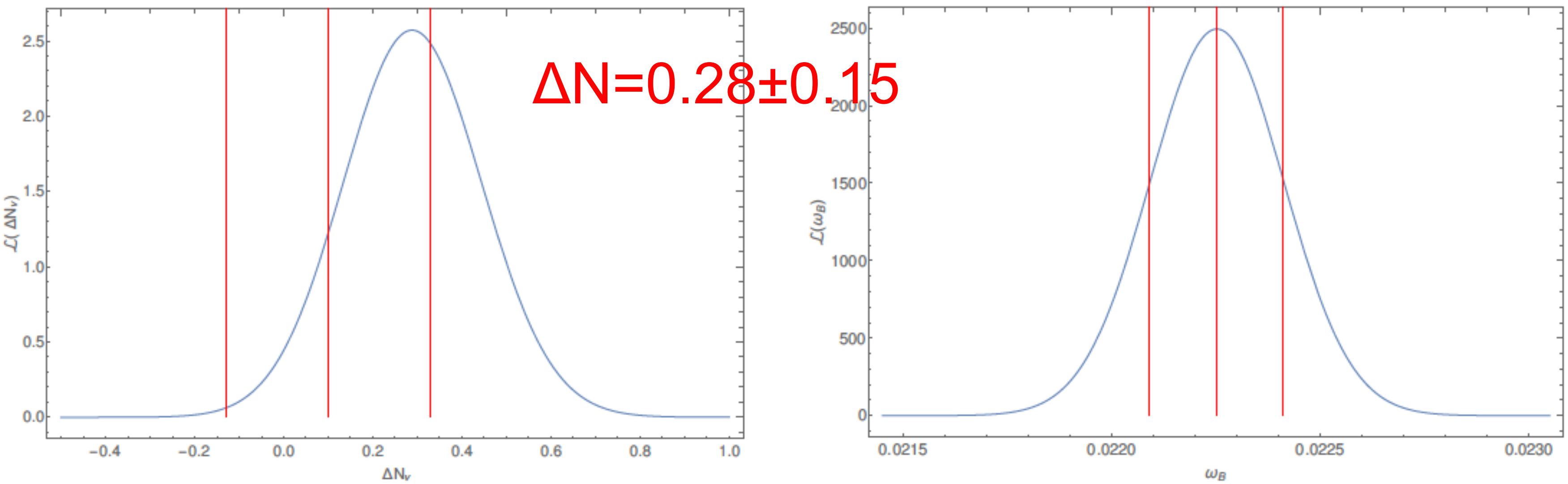

Figure 3.18: Marginalized likelihood functions for $^2H/H$ over ω_B (left panel) and over $\Delta N_{\rm eff}$ (right panel).The red lines representing the central value and the 1-σ error of Planck results.

From Planck ΔN = 0.1 ± 0.3 (more conservative) or 0.0 ± 0.2 (more restrictive)

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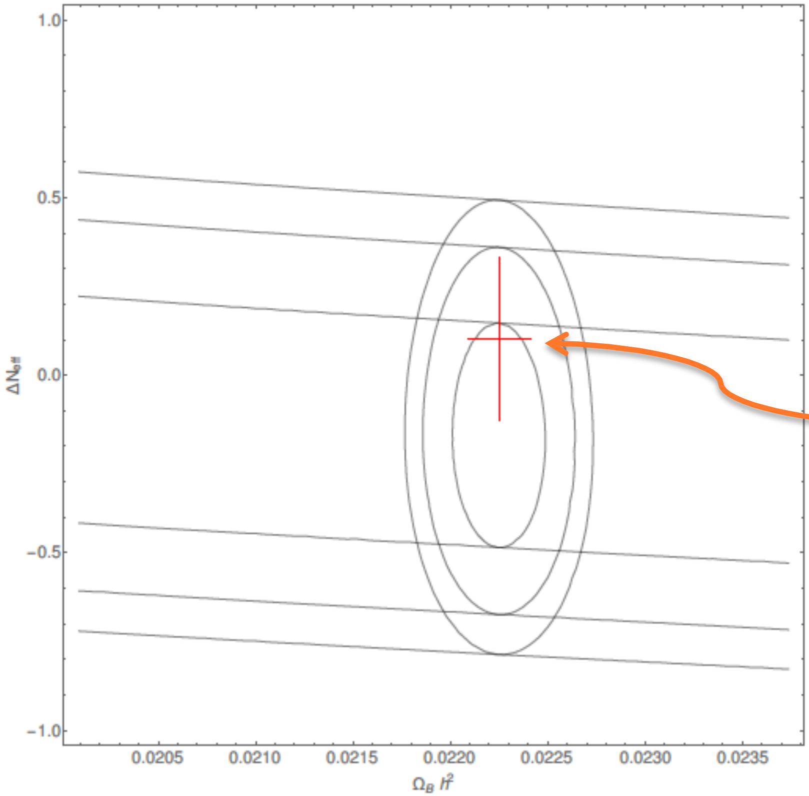
Likelihood

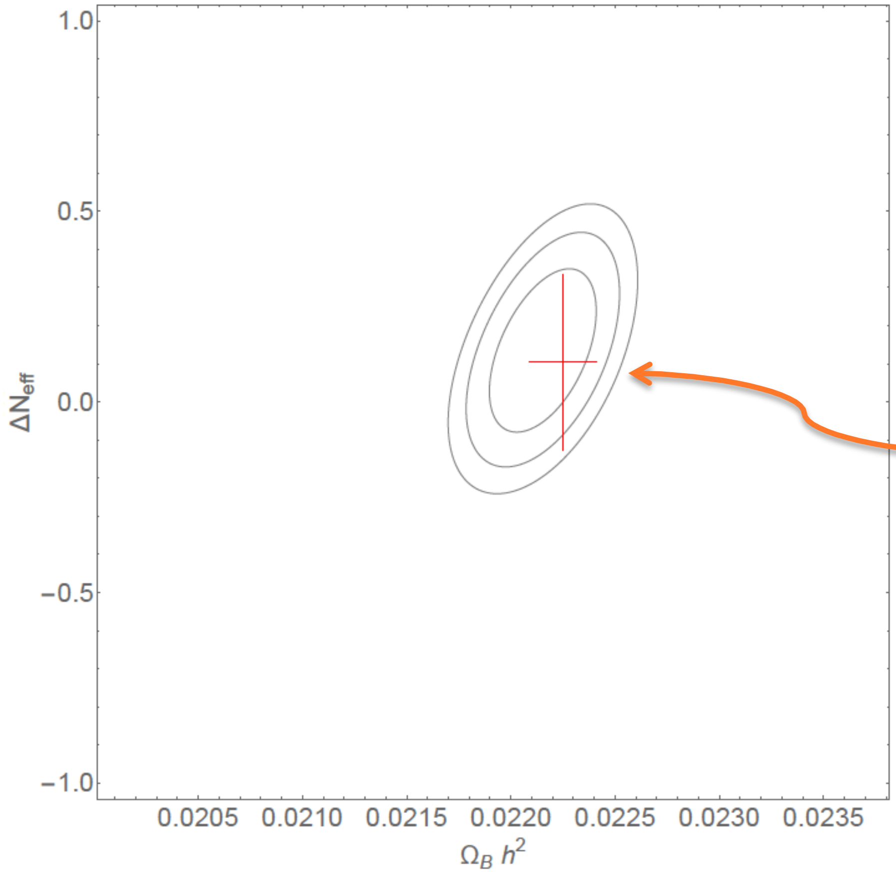
ω_B - ^4He



Planck bounds

Figure 3.19: Contours at 68%, 95% and 99% C.L. of the likelihood function for ^{4}He (open bands) and of the likelihood with a prior on Planck result in the plane $(\omega_B, \Delta N_{\rm eff})$. The red cross corresponds to the standard values as indicated by Planck Collaboration.

Likelihood
ω_B - ^{4}He - D



Planck
bounds

Figure 3.20: Contours at 68%, 95% and 99% C.L. of the combined likelihood function for ^{2}H, ^{4}He and the prior on Planck result in the plane $(\omega_B, \Delta N_{\rm eff})$. The red cross corresponds to the standard values as indicated by Planck Collaboration.

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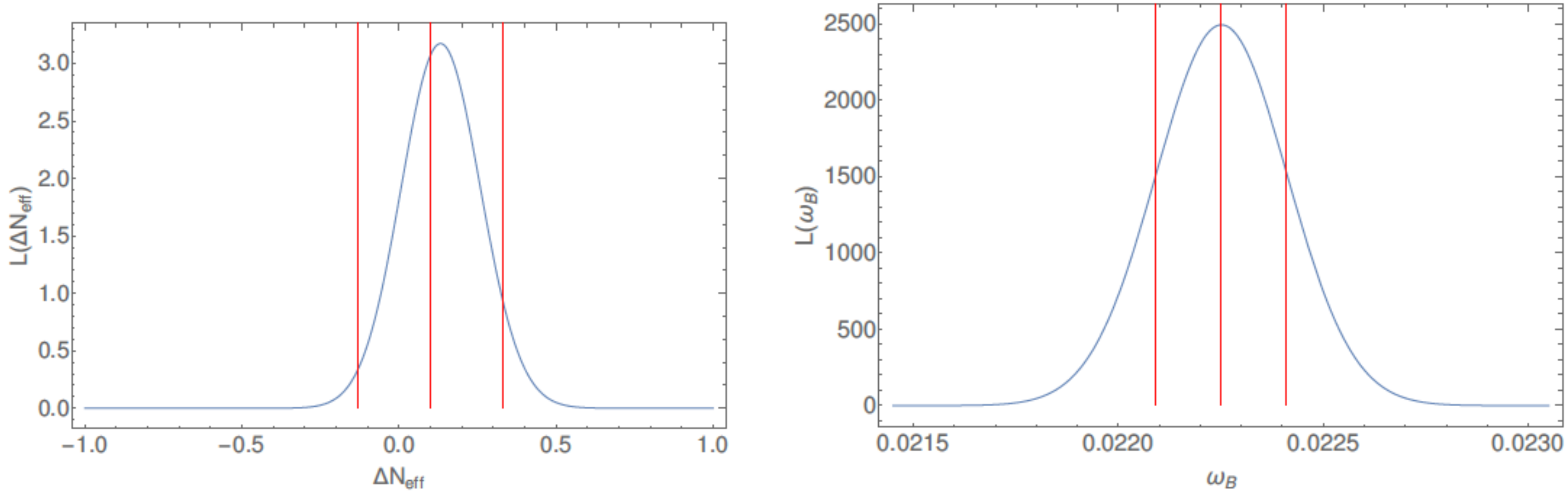

Figure 3.21: Marginalized combined likelihood function for ^{2}H, ^{4}He and the prior on Planck result over ω_B (left panel) and over ΔN_{eff} (right panel).The red lines representing the central value and the 1-σ error of Planck results.

$$N_{\text{eff}} = 3.18 \pm 0.13 \text{ at } 68\% \text{ C.L.}$$

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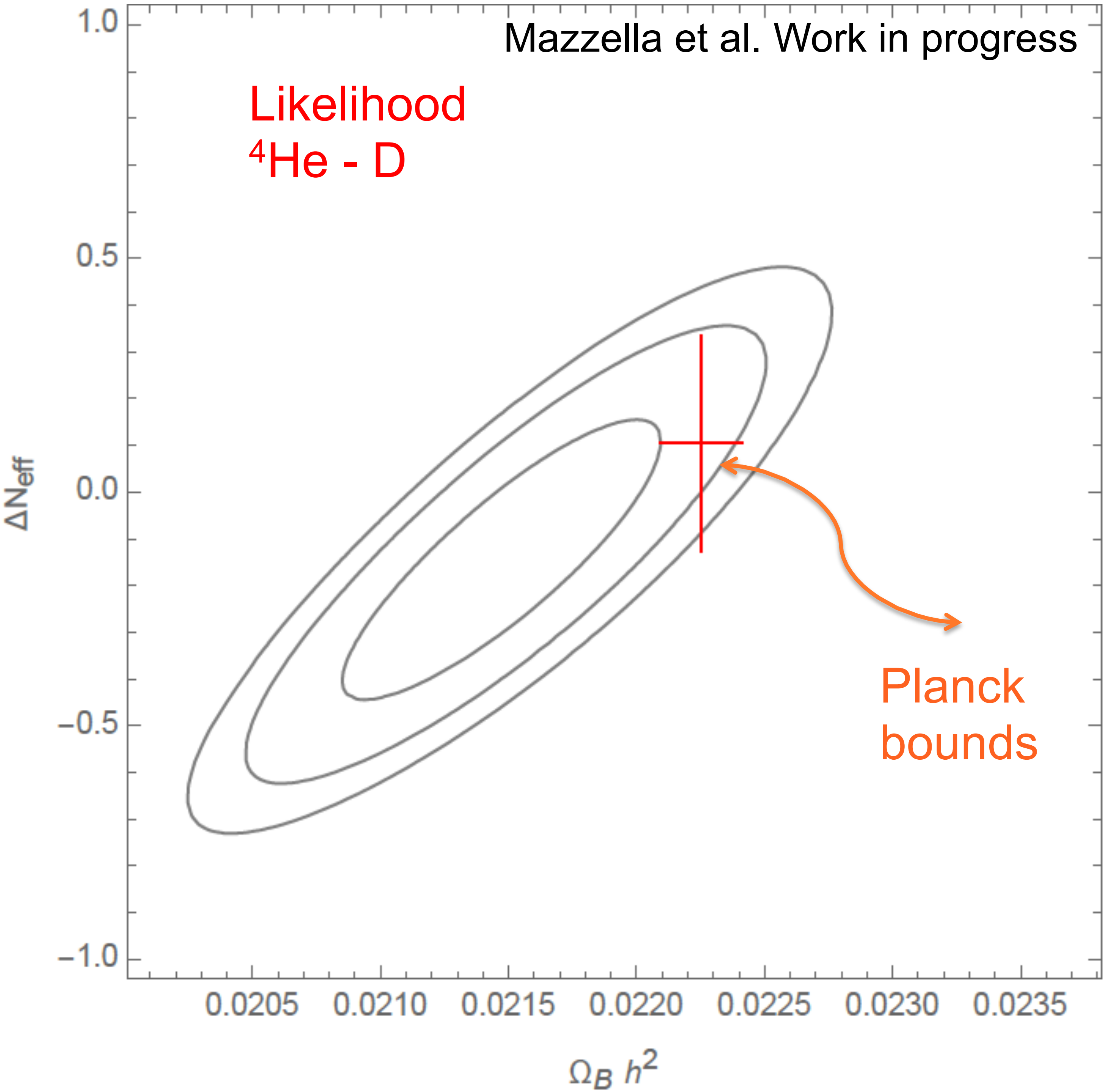
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Likelihood
^{4}He - D
Planck
bounds
1.0
0.5
0.0
−0.5
−1.0
ΔN_{eff}
0.0205
0.0210
0.0215
0.0220
0.0225
0.0230
0.0235
$\Omega_B\ h^2$

Conclusions

•A new version of PArthENoPE 2.0 has just been released. No more NAG routines, it has a GUI and a revised version of few nuclear reactions mainly fixing Deuterium abundance.

• Using the available precise determination of primordial D we bound (once again) the effective number of neutrinos N_ν.

•This quantity, in case of no extra d.o.f., depends upon the chemical potential and the temperature characterizing the three active neutrino distributions,as well as by their possible non-thermal features.

•The likelihood analysis of D and ^{4}He with the Planck ω_B prior provides a fully compatible estimate of N_ν with the analogous results obtained from CMB