WORKING PACKAGE 4

Absorption from Primordial Black Holes as source of baryon asymmetry

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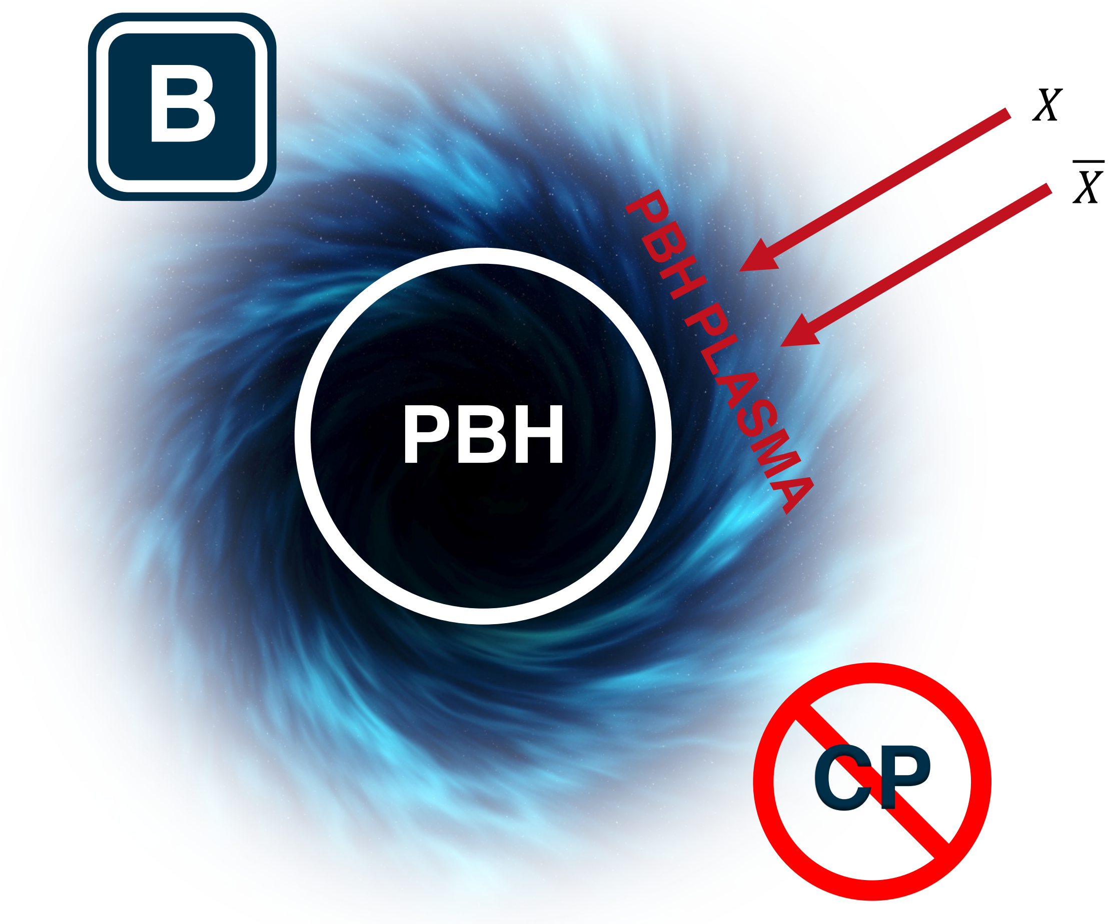
Arxiv: 2106.11980

THE MECHANISM

Arxiv: 2009.04361

Baryon conserving interactions



$$\eta_B = B_X \frac{n_X - n_{\overline{X}}}{s_r}$$

- X and $\overline{X}$ interact with the **plasma**
- Baryon asymmetry is generated by different **absorption** of X and $\overline{X}$ carrying **baryon number** onto PBH.
- PBHs **evaporation** stops the absorption.
- X **decay** transfers the baryon number into the SM sector

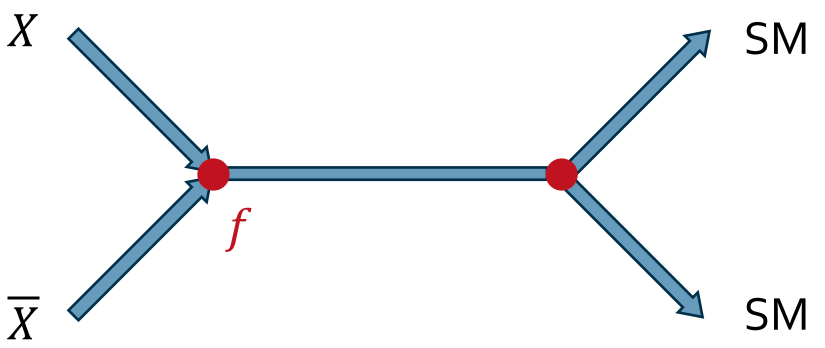
INTRODUCTION

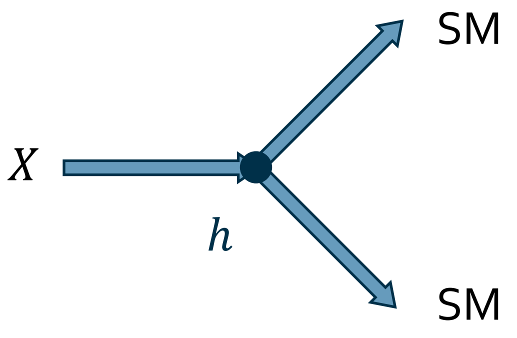
Free parameters:

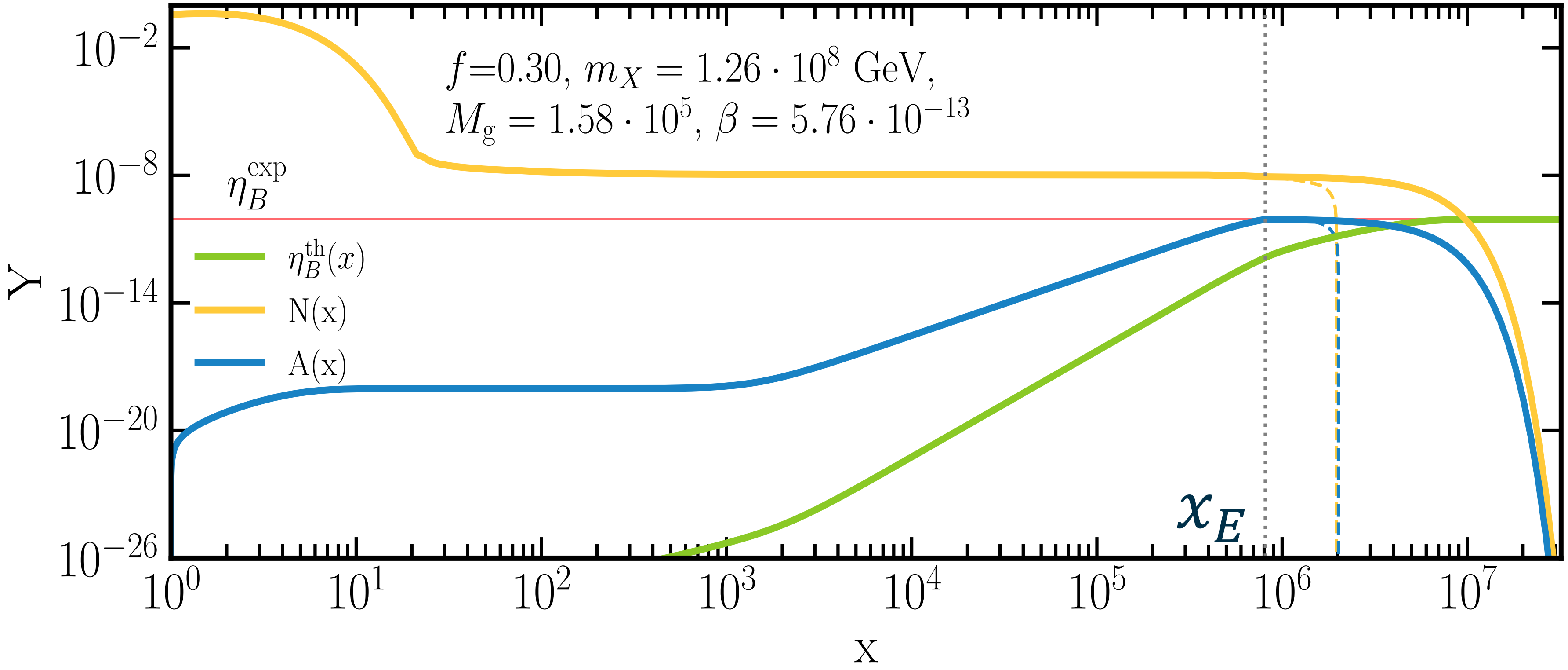
- m_X: X mass;
- M: PBH mass;
- f: Coupling SM-X, ;
- h: Decay coupling;
- $\beta = \frac{\rho_{PBH}}{\rho_R}\Big|_{T_{form}}$

$$N = \frac{Y_X + Y_{\overline{X}}}{2}$$

$$A = Y_X - Y_{\overline{X}}$$



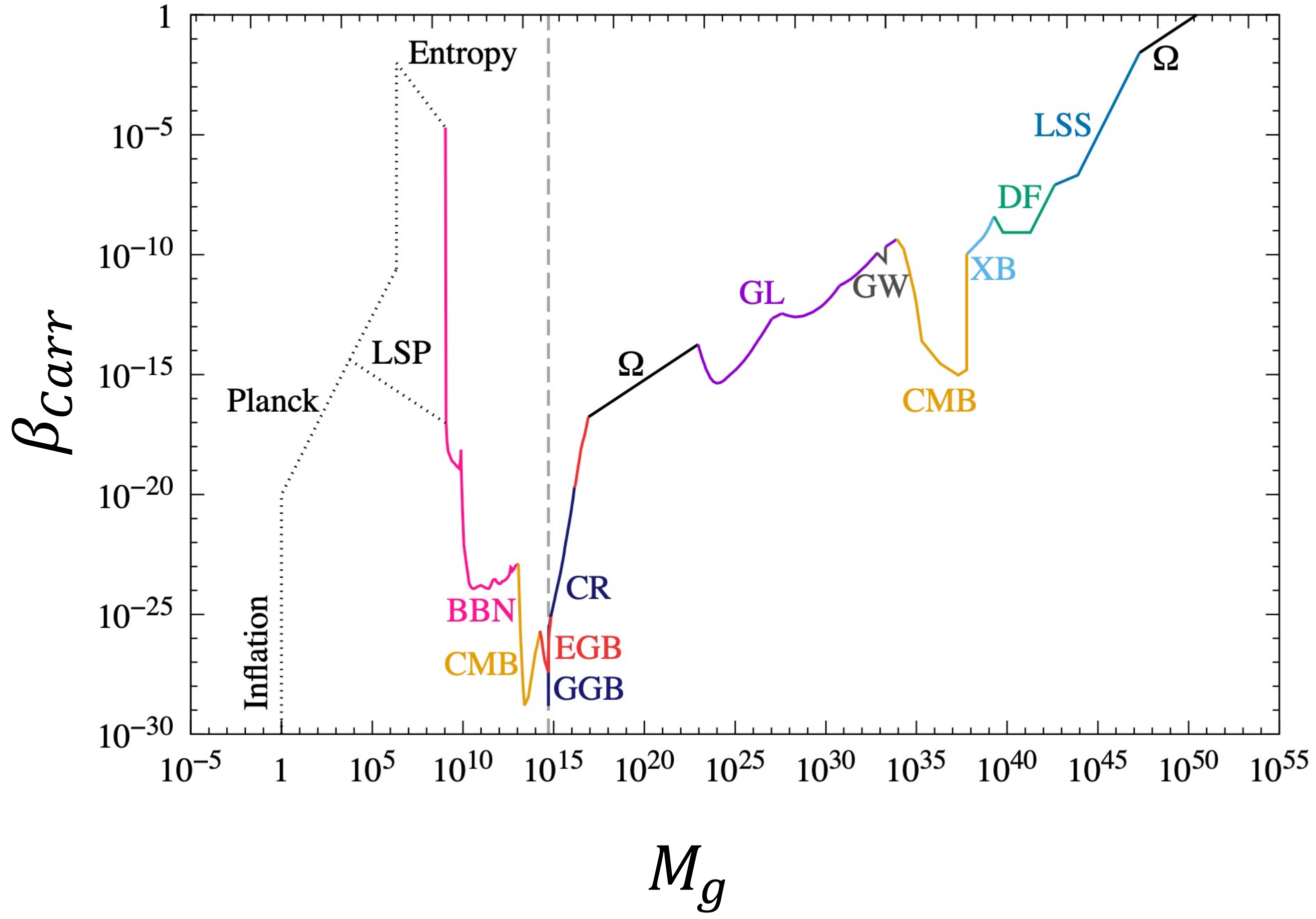




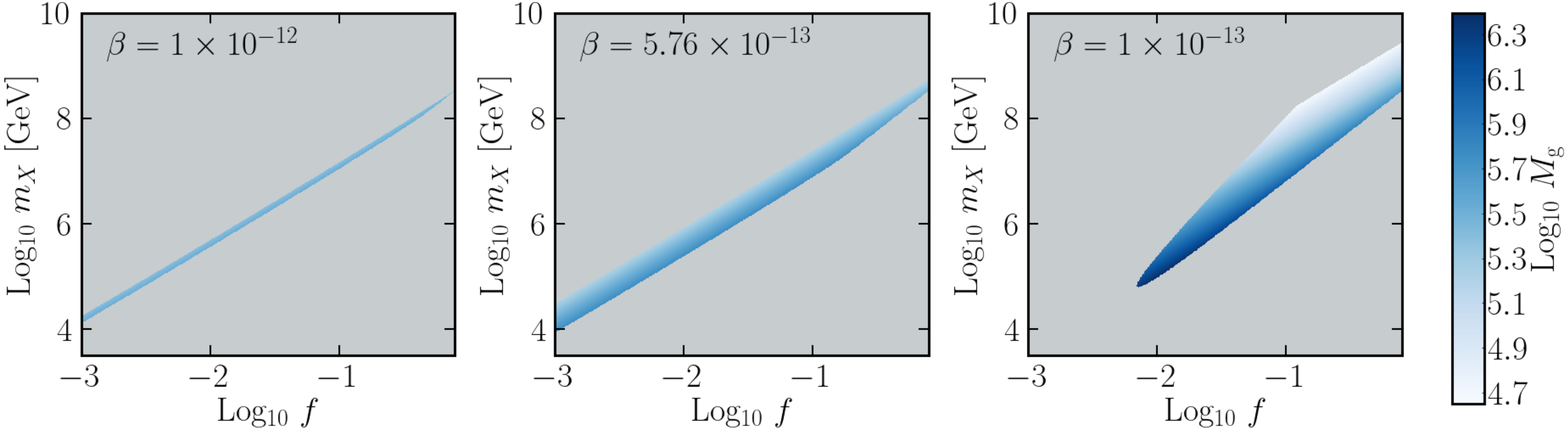
CONSTRAINTS

arXiv:2002.12778

- $\beta < \beta_{Carr}$
- Entropy generated by the X decay $\ll s_R$
- $x_E < x_{dec} < x_{BBN}$
- $h^4 x_{dec}^2 < f^4$
- $\frac{\rho_{PBH}}{\rho_{Rad}} \approx \beta \frac{T_{form}}{T_e} \ll 1$
- $R_{ae} = \frac{\left(\frac{dM}{dt}\right)_{acc}}{\left(\frac{dM}{dt}\right)_{eva}} < 0.1$



RESULTS

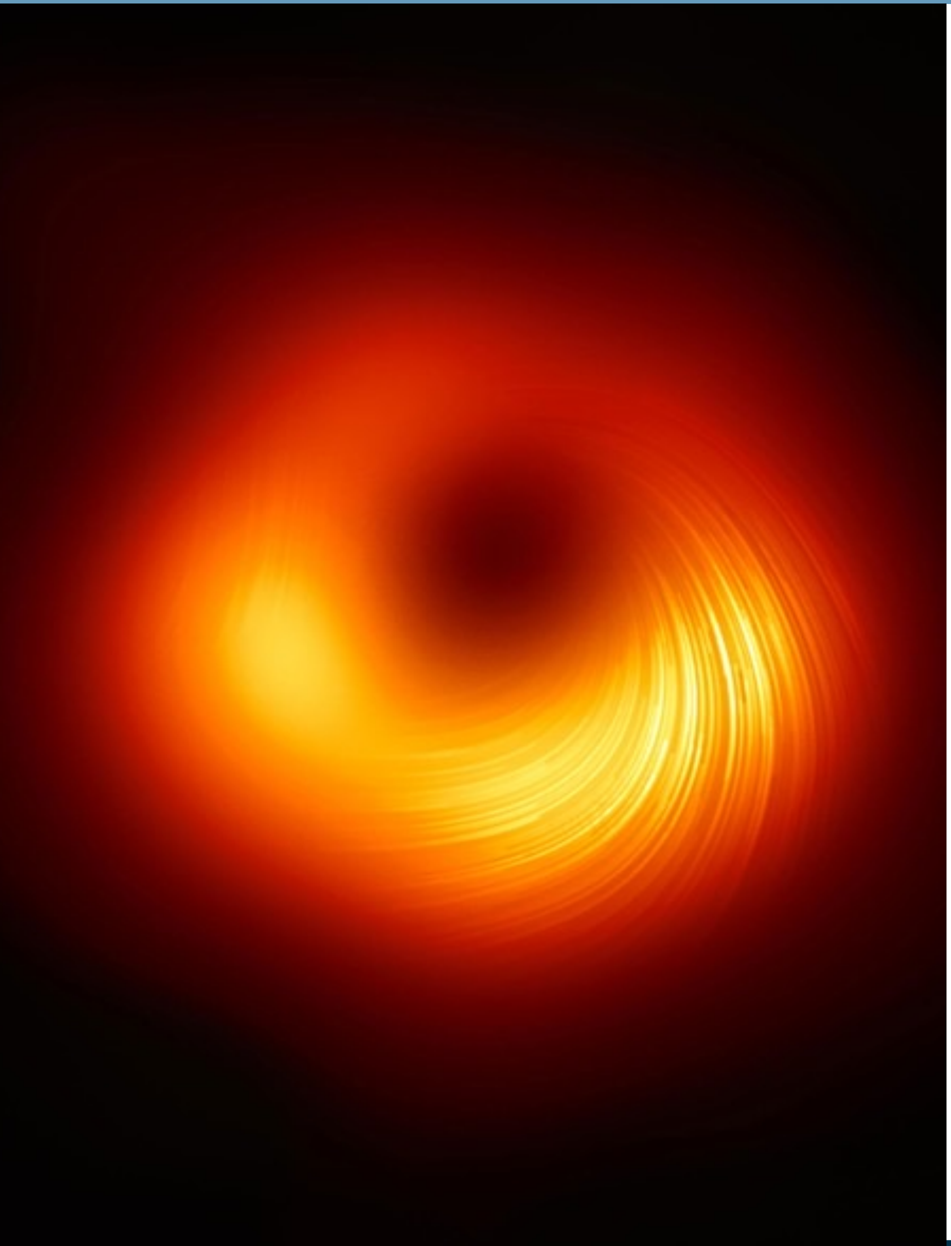


We provide a viable new baryogenesis model based on the Dolgov-Pozdnyakov model by solving the Boltzmann equation

We study the full parameter space of the model

THANK YOU FOR THE ATTENTION

EVOLUTION EQUATIONS



X and $\overline{X}$ evolve according to the interplay between different processes:

- Interaction with the plasma;
- Absorption in the PBHs;
- Decay.

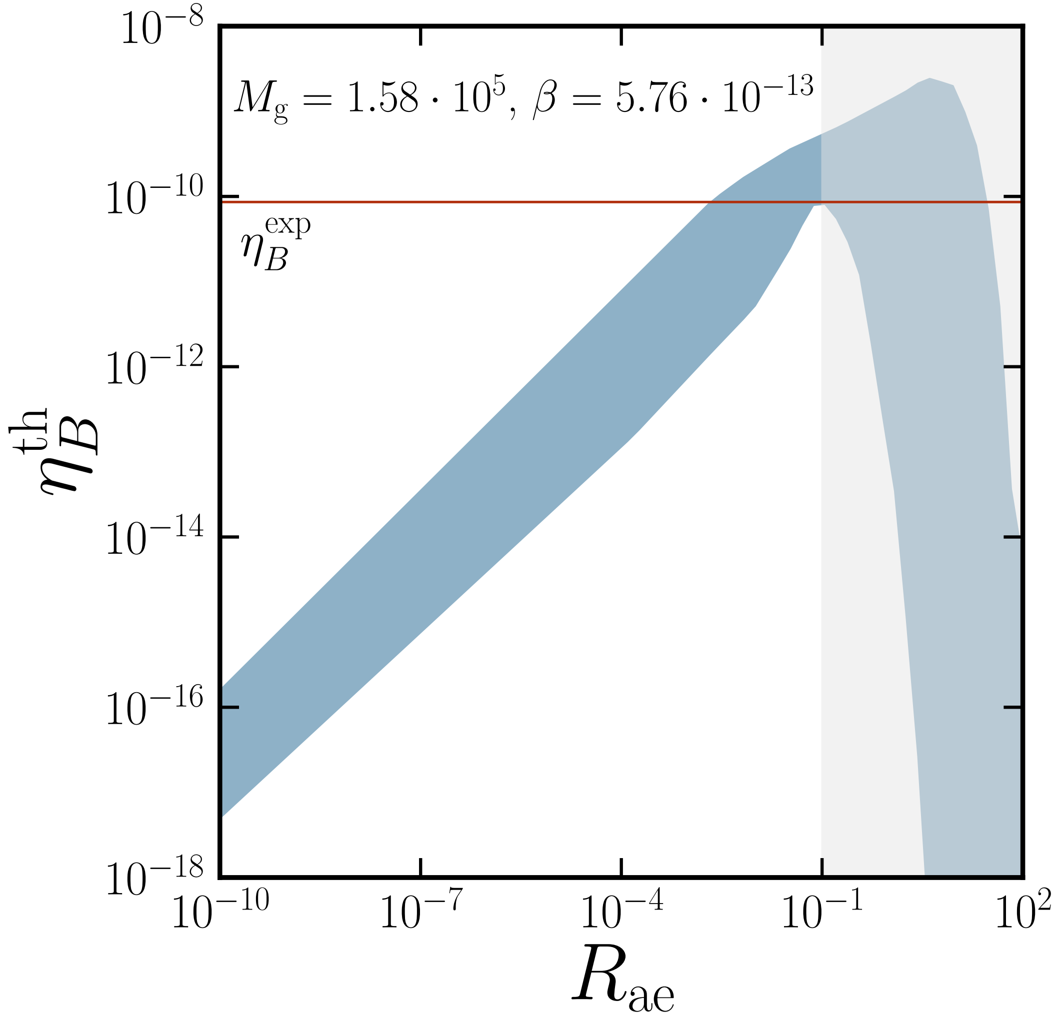
We have five **free parameters**: m_X, M, f, h, β.

Let's define $N = \frac{Y_X + Y_{\overline{X}}}{2}$, $A = Y_X - Y_{\overline{X}}$. The **evolution equations** are:

$$\frac{dN}{dx} = -\frac{\lambda}{x^2}\left(N^2 - N_{eq}^2\right) - \alpha x^2 N - \mu x N$$

$$\frac{dA}{dx} = \alpha x^2 (f^2 N - A) - \mu x A$$

$$\frac{d\eta_B}{dx} = \mu x A$$



The **constraints** are:

1. $\beta < \beta_{Carr}$
2. Entropy generated by the X decay negligible
3. $x_E < x_{dec} < x_{BBN}$
4. Annihilation process induced by h is negligible with respect to the one induced by f
5. $\frac{\rho_{PBH}}{\rho_{Rad}} \approx \beta \frac{T_{form}}{T_e} \ll 1$
6. $R_{ae} = \frac{\left(\frac{dM}{dt}\right)_{acc}}{\left(\frac{dM}{dt}\right)_{eva}} < 0.1$

PRIN NAT-NET Meeting
6 July 2021

Probing axion-like particle radiation from primordial black holes

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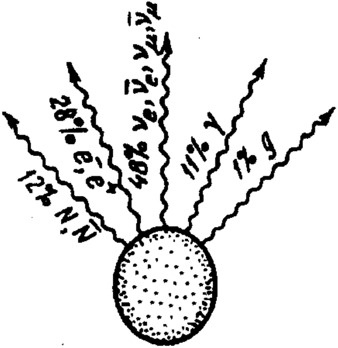
Università degli Studi di Bari "Aldo Moro"

Based on a work in progress in collaboration with A. Mirizzi, D. Montanino and F. Capozzi

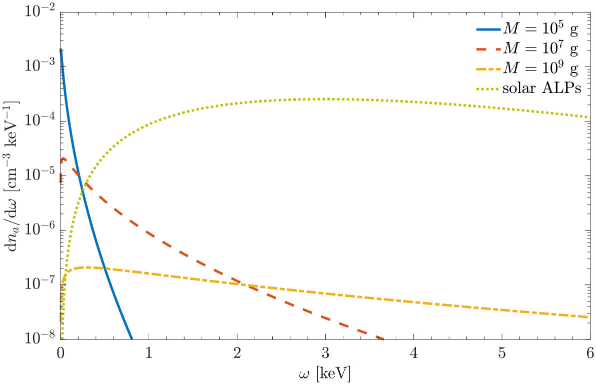
ALPs from primordial black holes

- Primordial black holes formed by collapse of density fluctuations in the Early Universe[1]
- Early matter domination is possible
- Subsequent radiation is produced by Hawking evaporation of PBHs (before BBN)
- Possible non-thermal ALP production mechanism



[1] Zel'dovich and Novikov 1967; Hawking 1971; Carr and Hawking 1974

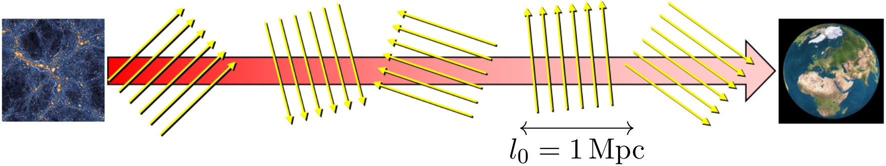
Hawking ALP spectra



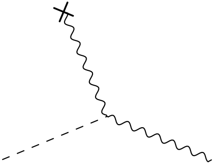
- 1–$10\,\mathrm{keV}$ range: soft X-ray frequencies
- Independent of initial PBH fraction
- Longer tails for high M (monochromatic[2])

[2] Other PBH mass spectra reviewed in Carr et al. 2020 [2002.12778]

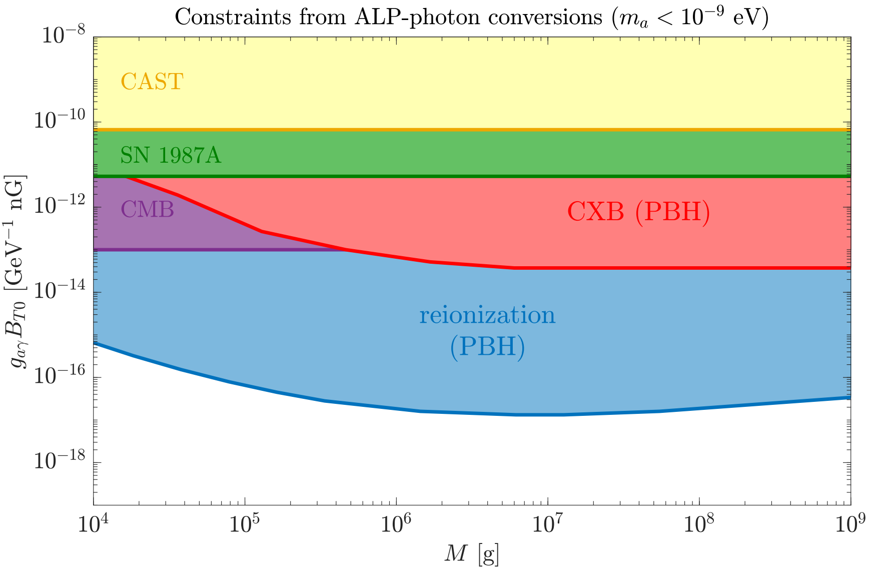
ALP-photon conversions in primordial magnetic fields



- ALP-photon mixing is possible in external magnetic fields thanks to $g_{a\gamma}$ coupling[3]
- Conversions inject high energy photons in the Universe contributing to
  - The present-day X-ray background
  - Reionization of the intergalactic medium (measured by optical depth τ)



[3] Raffelt and Stodolsky 1988



Bounds from CAST [1705.02290], SN 1987A [1410.3747] and CMB [0905.4865]

reported assuming $B_0 = 1\,\mathrm{nG}$

Conclusions

- PBH domination is a very possible occurrence in the Early Universe
- Several observable signatures if PBHs emit axion-like particles
- Also studied: contribution to dark radiation, decay of massive ALPs
- Stringent constraints on ALP-photon mixing in this scenario
- Further developments: include gravitons (e.g. from spinning PBHs) and graviton-photon conversions in the picture

Thank you for your attention!

PRIN meeting

6^{th} July 2021

Thermal axions with multi-eV masses are possible in low-reheating scenarios

Based on
PC, M. Lattanzi, A. Mirizzi and F. Forastieri,
arXiv:2104.03982 [astro-ph.CO]

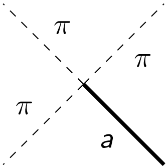
Pierluca Carenza
Bari Univ. & INFN

Thermal axion production

T. Moroi and H. Murayama, Phys. Lett. B **440** (1998), 69-76

L. Di Luzio *et al.*, Phys. Rept. **870** (2020), 1-117

Hadronic axions are produced by pion interactions



$$\mathcal{L}_{a\pi} = \frac{C_{a\pi}}{f_\pi f_a}(\pi^0\pi^+\partial_\mu\pi^- + \pi^0\pi^-\partial_\mu\pi^+ - 2\pi^+\pi^-\partial_\mu\pi^0)\partial^\mu a$$

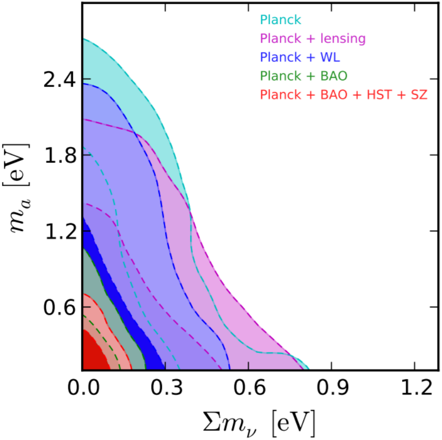
where

- f_a is the Peccei-Quinn scale
- $f_\pi = 92.4\,\text{MeV}$ is the pion decay constant
- $C_{a\pi} = \frac{1-z}{3(1+z)}$, $z = m_u/m_d \simeq 0.48$

The cosmological axion bound

E. Di Valentino *et al.*, Phys. Lett. B **752** (2016), 182-185

Axions are Hot Dark Matter: constraints from $N_{\rm eff} \sim 3.046$ and $\Omega_h h^2 \lesssim 2 \times 10^{-3}$

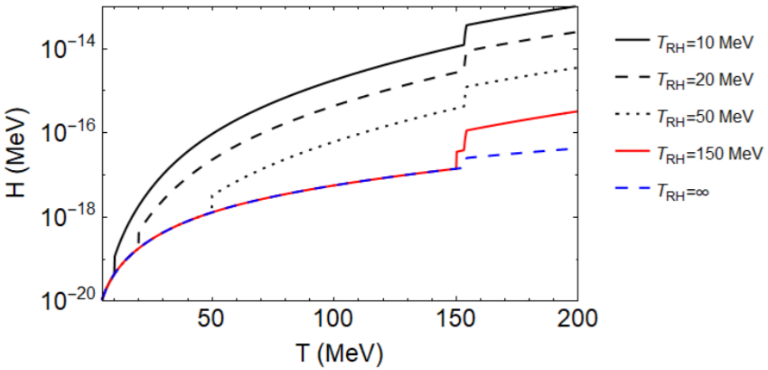


Constraint on the axion mass: $m_a \lesssim 0.53$ eV

Low-reheating cosmologies

D. Grin *et al.*, Phys. Rev. D **77** (2008), 085020

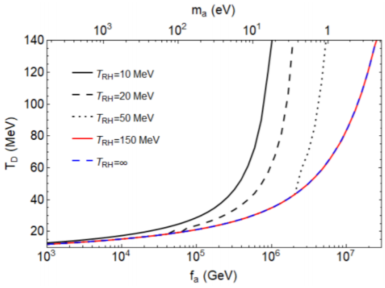
The inflaton decay into Standard Model particles happens at $T_{\rm RH}$



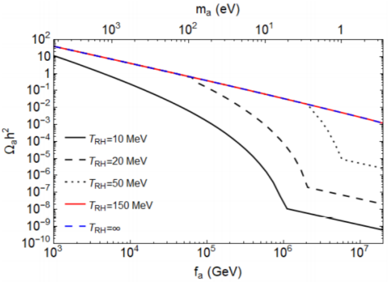
The reheating temperature might be as low as $T_{\rm RH} \sim 5\,\rm MeV$
P. F. de Salas *et al.*, Phys. Rev. D **92** (2015) no.12, 123534

The axion mass bound in LTR cosmologies

The axion relic density is diluted by the faster cosmic expansion



Decoupling temperature vs f_a



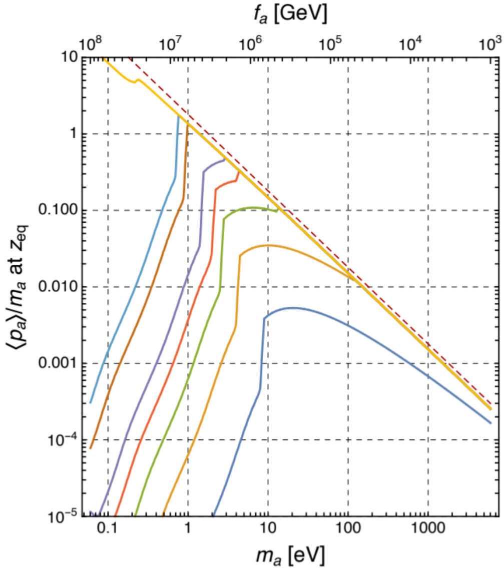
Axion density vs f_a

A recent work questioned the validity of the $\pi\pi \to \pi a$ rate calculation for $T_{\rm D} \gtrsim 60\,$MeV

L. Di Luzio, G. Martinelli and G. Piazza, [arXiv:2101.10330 [hep-ph]].

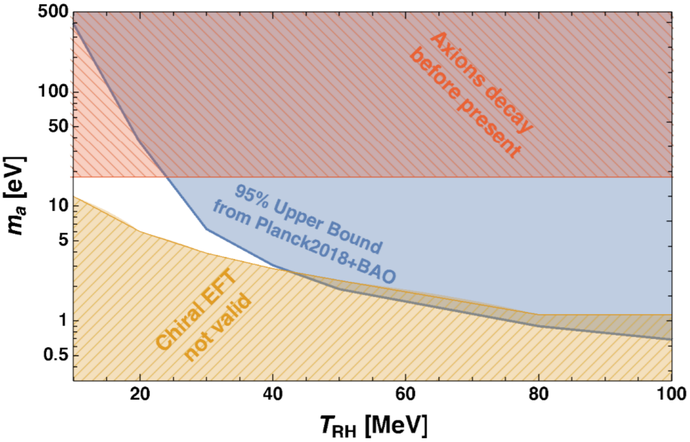
Axion Cold Dark Matter in a LTR scenario

The axion temperature is lowered: axions act as Cold Dark Matter in a LTR scenario



The relaxation of the bound

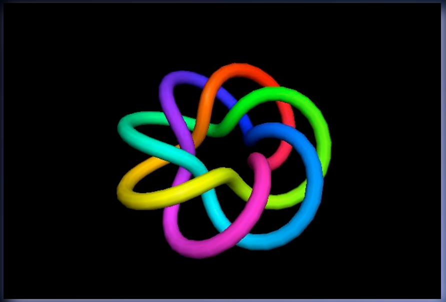
The cosmological axion bound is strongly relaxed in a LTR scenario



Conclusions

- The cosmological axion bound is relaxed in a LTR scenario
- Axions at the eV scale are probed by astrophysics (Supernova axions? Resonant solar conversions?)
- Also many experiments are planned to study this region (AMELIE, CUORE, WIMP-like experiments)

THANKS FOR YOUR ATTENTION!



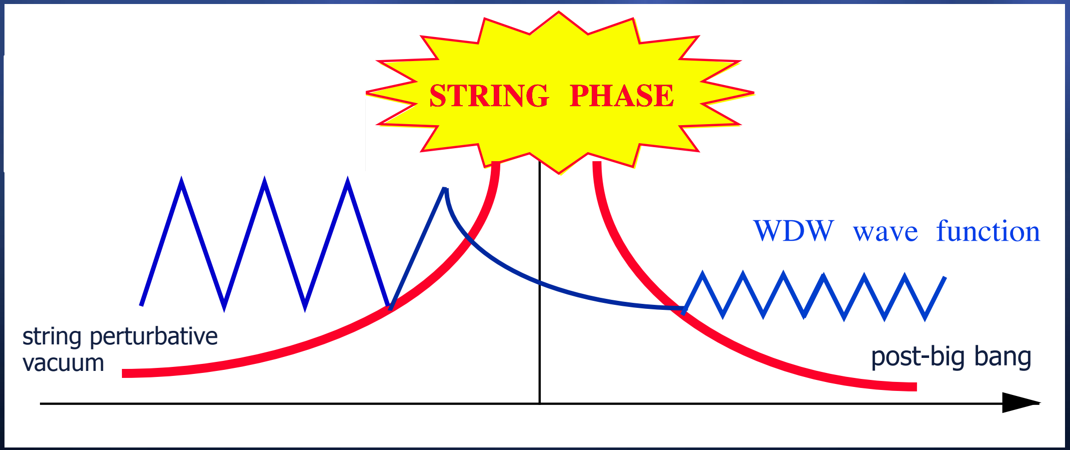
Quantum String Cosmology

M. Gasperini, Universe 7,14 (2021)

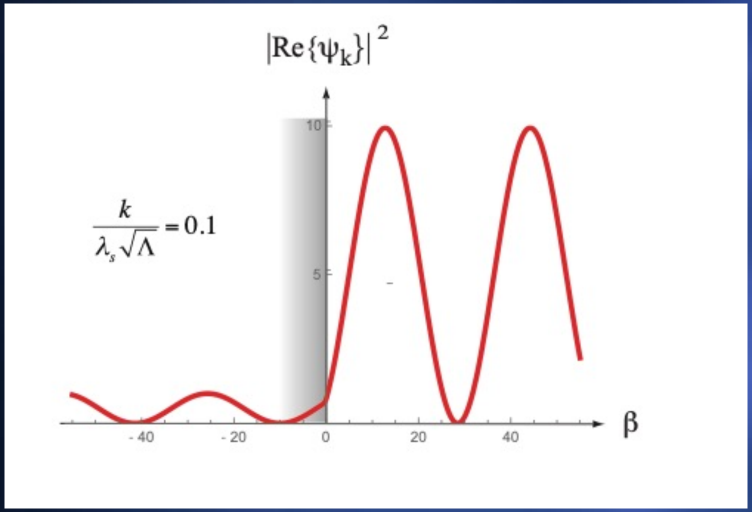
Review su applicazione dell'equaz. di Wheeler-De Witt (WDW) alla cosmologia di stringa:

transizione dal pre- al post-big bang, attraverso regione classicamente proibita, come processo di quantum scattering della WDW wave function. Due possibili scenari:

1) Birth of the Universe as a "tunneling": not from "nothing" but form the string perturbative vacuum

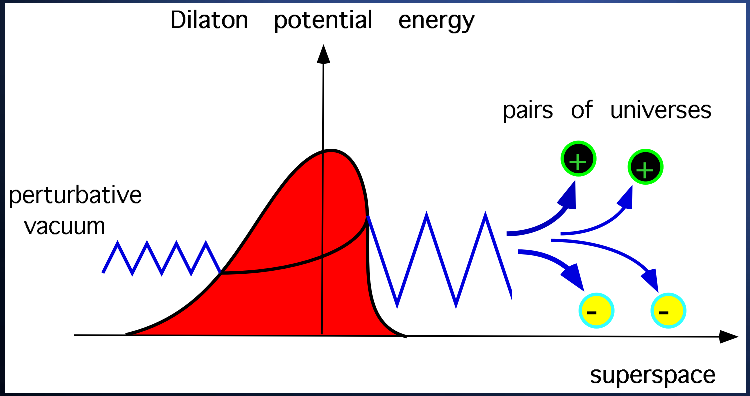


2) Birth of the Universe as "anti-tunneling" form the string perturbative vacuum



"parametric" amplification of the WDW wave function

or,
in the language of "third quantization"



mixing of posive and negative energy modes, ie. production of "pairs of universes" from the vacuum

Comparing the luminosity distance for gravitational waves and electromagnetici signals in a simple model of quadratic gravity

G. Fanizza, G. Franchini, M. Gasperini and L. Tedesco, Gen. Rel. Grav. 52, 111 (2020)

1) La distanza di luminosita' di una sorgente astrofisica dipende dal flusso di energia ricevuto

2) Il flusso di energia ricevuto dipende da come si propaga (e si dissipa) la radiazione emessa

3) Nel modello standard basato sulle equaz. di Einstein I segnali e.m. e GW dentro l'orizzonte hanno la stessa (light cone) propagazione, e forniscono la stessa distanza.

4) Nei modelli di gravita' modificati I segnali e.m. e GW possono avere diversa velocita' (effetto trascurabile) e diversa variazione dell'ampiezza in funzione della distanza percorsa (dovuta a un diverso "friction coefficient" prodotto dalla geometria cosmica)

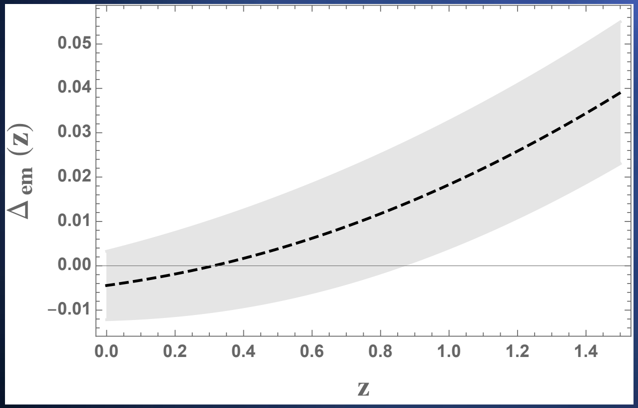
→ tests del modello mediante confronto distanze

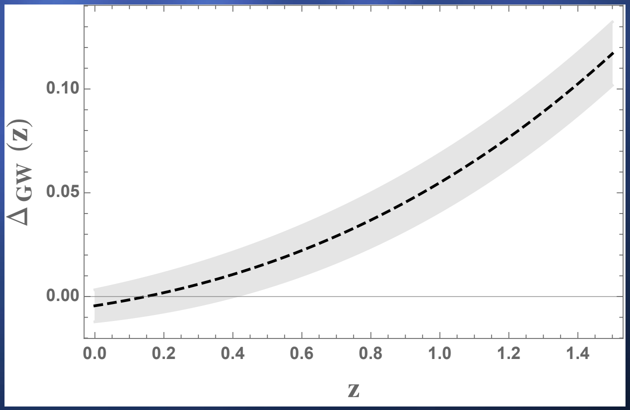
Fittando i dati delle Supernovae (Union 2 data set) con un modello di gravita' quadratica e' possibile stimare (col relativo errore) il friction coefficient

➡ si ottengono cosi' le predizioni del modello considerato per le diverse distanze di luminosita', in funzione del redshift della sorgente

$$\Delta_{em}(z) = (d_L^{em} - d_L^{GR}) / d_L^{GR}$$

$$\Delta_{GW}(z) = (d_L^{GW} - d_L^{GR}) / d_L^{GR}$$





Linearized propagation equation for metri fluctuations in a general (non vacuum) background geometry

G. Fanizza, M. Gasperini, E Pavone and L. Tedesco, JCAP (2021) (in press)

- Espandiamo la metrica attorno al suo valore di background, $g_{\mu\nu} \to g_{\mu\nu} + \delta g_{\mu\nu}$ ed espandiamo l'azione gravitazione di Einstein (inclusa l'interazione con le sorgenti materiali, minimamente accoppiate alla geometria) in serie di Taylor di derivate funzionali rispetto al tensore metrico
- Imponiamo che l'azione sia stazionaria (principio di Hamilton). Al I ordine in $\delta g_{\mu\nu}$ otteniamo le equaz. di Einstein. Al II ordine ordine in $\delta g_{\mu\nu}$ otteniamo la generale equazione del moto per le fluttuazioni $\delta g_{\mu\nu} = h_{\mu\nu}$

$$\nabla^2 h_{\alpha\beta} + 2R_{\mu\alpha\beta\nu}h^{\mu\nu} + Rh_{\alpha\beta} - g_{\alpha\beta}h^{\mu\nu}R_{\mu\nu} - h_\alpha{}^\nu R_{\nu\beta} - h_\beta{}^\nu R_{\nu\alpha} - \\ -\nabla_\beta\nabla_\mu h_\alpha{}^\mu - \nabla_\alpha\nabla_\mu h_\beta{}^\mu + \nabla_\alpha\nabla_\beta h - g_{\alpha\beta}(\nabla^2 h - \nabla_\mu\nabla_\nu h^{\mu\nu}) = -2\lambda_{\rm P}^2\delta^{(1)}T_{\alpha\beta}.$$

equazione valida in qualunque geometria, soluzione delle equazioni di Einstein con sorgenti arbitrarie, e in qualunque dato sistema di cordinate (no gauge choice) per le fluttuazioni tensoriali ⇒ gauge TT ⇒ equaz. si riduce a

$$\nabla^2 h_{\alpha\beta} + 2R_{\mu\alpha\beta\nu}h^{\mu\nu} = \lambda_{\rm P}^2 \left(h_\alpha{}^\nu T_{\nu\beta} + h_\beta{}^\nu T_{\nu\alpha} + \frac{1}{2} g_{\alpha\beta}\, g^{\mu\nu}\delta^{(1)}T_{\mu\nu} - 2\delta^{(1)}T_{\alpha\beta} \right) .$$

Importante notare che le equaz. di propagazione dipende non solo dalla geometria data, ma anche dalla sorgente che la genera

ESEMPIO 1: metrica FLRW, fluido perfetto comovente

$$\ddot{h}_i{}^j + 3H\dot{h}_i{}^j - \frac{\partial^2}{a^2} h_i{}^j = 0$$

ESEMPIO 2: metrica FLRW, fluido comovente con "shear viscosity"

$$\ddot{h}_i{}^j + \left(3H + 2\eta\lambda_{\rm P}^2\right)\dot{h}_i{}^j - \frac{\partial^2}{a^2} h_i{}^j = 0$$

BBN after LUNA

Gianpiero Mangano
Università di Napoli Federico II

Meeting NAT_NET
6 luglio 2021

- Role of BBN in cosmology
- Why measuring a reaction is so important…
- Data & analyses
- The good and the bad
- BBN/CMB concordance

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.
- Cooked with: 1) General Relativity; 2) SMPP with 3 light standard ν; 3) DE and DM not relevant.

$$\rho_{TOT} = \rho_R + \rho_M + \rho_\Lambda$$

- Before Planck: in its simplest scenario an over-constrained theory with a unique parameter, Ω_b → the best way for measuring the baryon fraction. Simple extension with free ΔN_{eff}.

$$\eta_b = \frac{n_b}{n_\gamma} = 273.45 \cdot 10^{-10}\Omega_b h^2$$

$$\rho_R = \rho_\gamma \left[1 + \frac{7}{8} 3.045 \left(\frac{4}{11}\right)^{4/3}\right] + \Delta N_{eff} \cdot \rho_\gamma \left[\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right]$$

- After Planck (pinned down Ω_b), BBN stands as a perfect warning signal of any departure form SMC and SMPP: did you check your model against BBN?

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Article | Published: 11 November 2020

The baryon density of the Universe from an improved rate of deuterium burning

V. Mossa, K. Stöckel, F. Cavanna, F. Ferraro, M. Aliotta, F. Barile, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini, C. G. Bruno, A. Caciolli, T. Chillery, G. F. Ciani, P. Corvisiero, L. Csedreki, T. Davinson, R. Depalo, A. Di Leva, Z. Elekes, E. M. Fiore, A. Formicola, Zs. Fülöp, G. Gervino, A. Guglielmetti, C. Gustavino, G. Gyürky, G. Imbriani, M. Junker, A. Kievsky, I. Kochanek, M. Lugaro, L. E. Marcucci, G. Mangano, P. Marigo, E. Masha, R. Menegazzo, F. R. Pantaleo, V. Paticchio, R. Perrino, D. Piatti, O. Pisanti, P. Prati, L. Schiavulli, O. Straniero, T. Szücs, M. P. Takács, D. Trezzi, M. Viviani & S. Zavatarelli -Show fewer authors

Nature **587**, 210–213(2020) | Cite this article

LUNA measure of D(p,γ)^{3}He cross-section

Cosmological analysis made with BBN code PArthENoPE

Pisanti, O. et al. PArthENoPE: public algorithm evaluating the nucleosynthesis of primordial elements. *Comput. Phys. Commun.* **178**, 956–971 (2008).

Cosmological analysis made in collaboration with O. Pisanti

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V. Mossa,
Broggini,
Di Leva, Z.
Gyürky, G.
Masha, R.
Straniero,

Nature 58

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Primordial Deuterium after LUNA: concordances and error budget

Ofelia Pisanti, Gianpiero Mangano, Gennaro Miele, and Pierpaolo Mazzella

Dipartimento di Fisica E. Pancini, Università di Napoli Federico II, and INFN, Sezione di Napoli, Via Cintia, I-80126 Napoli, Italy

Abstract.

The accurate evaluation of the nuclear reaction rates and corresponding uncertainties is an essential requisite for a precise determination of light nuclide primordial abundances. The recent measurement of the $D(p,\gamma)^3He$ radiative capture cross section by the LUNA collaboration, with its order 3% error, represents an important step in improving the theoretical prediction for Deuterium produced in the early universe. In view of this recent result, we present in this paper a full analysis of its abundance, which includes a new critical study of the impact of the other two main processes for Deuterium burning, namely the deuteron-deuteron transfer reactions, $D(d,p)^3H$ and $D(d,n)^3He$. In particular, emphasis is given to the statistical method of analysis of experimental data, to a quantitative study of the theoretical uncertainties, and a comparison with similar studies presented in the recent literature. We then discuss the impact of our study on the concordance of the primordial nucleosynthesis stage with the Planck experiment results on the baryon density $\Omega_b h^2$ and the effective number of neutrino parameter $N_{\rm eff}$, as function of the assumed value of the ^{4}He mass fraction Y_p. While after the LUNA results, the value of Deuterium is quite precisely fixed, and points to a value of the baryon density in excellent agreement with the Planck result, a combined analysis also including Helium leads to two possible scenarios with different predictions for $\Omega_b h^2$ and $N_{\rm eff}$. We argue that new experimental results on the systematics and the determination of Y_p would be of great importance in assessing the overall concordance of the standard cosmological model.

Complete analysis reported in a companion paper: 2011.11537 [astro-ph.CO]

ed in the first few minutes of the Universe through a
ns known as Big Bang nucleosynthesis (BBN)[1,2]. Among the
ring BBN[1,2], deuterium is an excellent indicator of
ecause its abundance is highly sensitive to the primordial
ends on the number of neutrino species permeating the
ronomical observations of primordial deuterium
rcent accuracy[3], theoretical predictions[4–6] based on BBN
rtainties on the cross-section of the deuterium burning
show that our improved cross-sections of this reaction
baryon density at the 1.6 percent level, in excellent
lysis of the cosmic microwave background[7]. Improved
ined by exploiting the negligible cosmic-ray background
boratory for Underground Nuclear Astrophysics (LUNA)
lel Gran Sasso (Italy)[8,9]. We bombarded a high-purity
an intense proton beam from the LUNA 400-kilovolt
he γ-rays from the nuclear reaction under study with a
ector. Our experimental results settle the most uncertain
N calculations and substantially improve the reliability of
es to probe the physics of the early Universe.

LUNA measure of $D(p,\gamma)^3He$ cross-section

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The baryon improved r

V. Mossa, K. Stöckel, F.
Broggini, C. G. Bruno, A
Di Leva, Z. Elekes, E. M.
Gyürky, G. Imbriani, M.
Masha, R. Menegazzo,
Straniero, T. Szücs, M. P

Nature **587**, 210–213(2

1610 Accesses | 97 A

2011.11320 [astro-ph.CO]

Deuterium: a new bone of contention for cosmology?

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24 November 2020

-ph.CO] 23 Nov 2020

ABSTRACT

Recent measurements of the $D(p,\gamma)^3He$ nuclear reaction cross-section and of the neutron lifetime, along with the reevaluation of the cosmological baryon abundance from cosmic microwave background (CMB) analysis, call for an update of abundance predictions for light elements produced during the big-bang nucleosynthesis (BBN). While considered as a pillar of the hot big-bang model in its early days, BBN constraining power mostly rests on deuterium abundance. We point out a new $\simeq 1.8\sigma$-tension on the baryonic density, or equivalently on the D/H abundance, between the value inferred on one hand from the analysis of the primordial abundances of light elements and, on the other hand, from the combination of CMB and baryonic oscillation data. This draws the attention on this sector of the theory and gives us the opportunity to reevaluate the status of BBN in the context of precision cosmology. Finally, this paper presents an upgrade of the BBN code PRIMAT.

Key words: primordial nucleosynthesis, baryon abundance, deuterium

Universe through a
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LUNA 400-kilovolt
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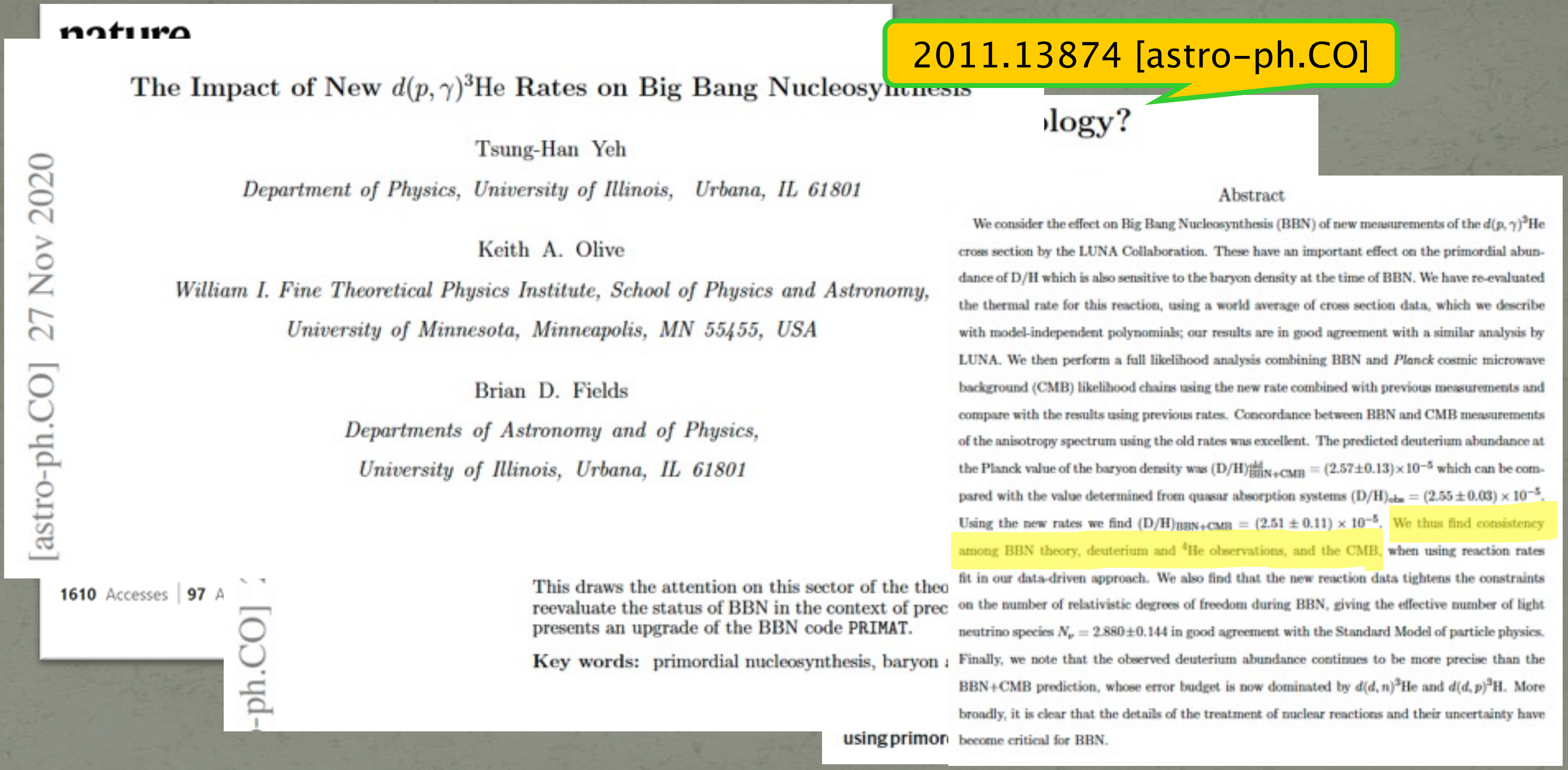
using primordial abundances to probe the physics of the early Universe.

LUNA measure of $D(p,\gamma)^3He$ cross-section

Starting from the end…



nature

The Impact of New $d(p,\gamma)^3$He Rates on Big Bang Nucleosynthesis

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[astro-ph.CO] 27 Nov 2020

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…logy?

This draws the attention on this sector of the theo… reevaluate the status of BBN in the context of prec… presents an upgrade of the BBN code PRIMAT.

Key words: primordial nucleosynthesis, baryon …

using primor…

Abstract

We consider the effect on Big Bang Nucleosynthesis (BBN) of new measurements of the $d(p,\gamma)^3$He cross section by the LUNA Collaboration. These have an important effect on the primordial abundance of D/H which is also sensitive to the baryon density at the time of BBN. We have re-evaluated the thermal rate for this reaction, using a world average of cross section data, which we describe with model-independent polynomials; our results are in good agreement with a similar analysis by LUNA. We then perform a full likelihood analysis combining BBN and *Planck* cosmic microwave background (CMB) likelihood chains using the new rate combined with previous measurements and compare with the results using previous rates. Concordance between BBN and CMB measurements of the anisotropy spectrum using the old rates was excellent. The predicted deuterium abundance at the Planck value of the baryon density was $(D/H)^{old}_{BBN+CMB} = (2.57 \pm 0.13) \times 10^{-5}$ which can be compared with the value determined from quasar absorption systems $(D/H)_{obs} = (2.55 \pm 0.03) \times 10^{-5}$. Using the new rates we find $(D/H)_{BBN+CMB} = (2.51 \pm 0.11) \times 10^{-5}$. We thus find consistency among BBN theory, deuterium and ^{4}He observations, and the CMB, when using reaction rates fit in our data-driven approach. We also find that the new reaction data tightens the constraints on the number of relativistic degrees of freedom during BBN, giving the effective number of light neutrino species $N_\nu = 2.880 \pm 0.144$ in good agreement with the Standard Model of particle physics. Finally, we note that the observed deuterium abundance continues to be more precise than the BBN+CMB prediction, whose error budget is now dominated by $d(d,n)^3$He and $d(d,p)^3$H. More broadly, it is clear that the details of the treatment of nuclear reactions and their uncertainty have become critical for BBN.

LUNA measure of $D(p,\gamma)^3$He cross-section

Precision tool or not?

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

…

PArthENoPE: O. P. 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

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

BBN accuracy: understanding the problem

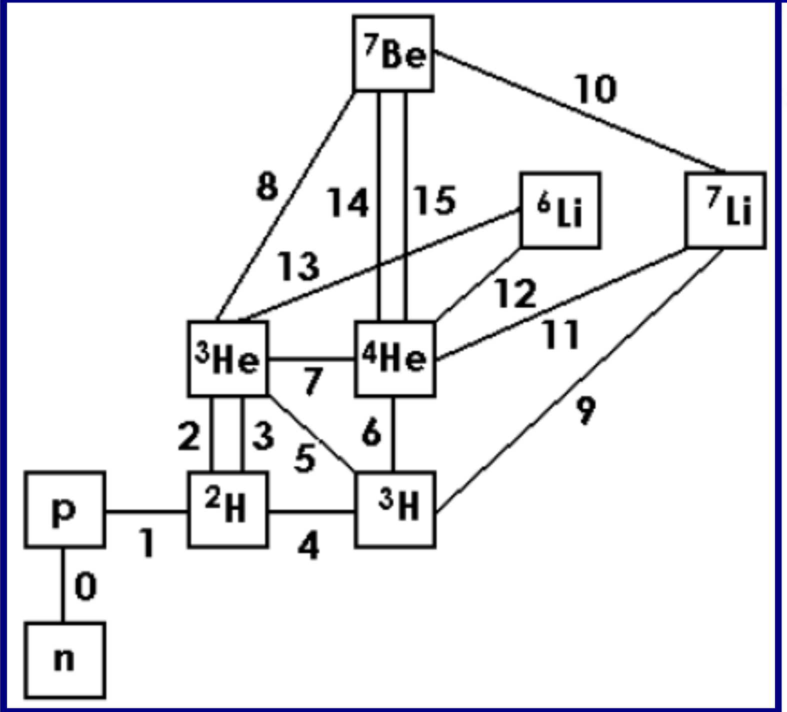
- Accuracy of the BBN codes. Standard physics, theoretical framework well established, but outputs of the nuclear network depend on the determination of several critical reactions. In the past mainly experimental measures (not always in the relevant energy range for BBN, 10÷400 keV in the center of mass),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

→ experimental 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

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

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%

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

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

before LUNA

0.1%
87%
9%
3.8%

after LUNA

	$\sigma_D^{(i)} \cdot 10^5$	$\delta\sigma_i^2/\sigma_{\mathrm{tot}}^2$ (%)
$R_{pn\gamma}$	0.002	0.3
$R_{dp\gamma}$	0.027	58.5
R_{ddn}	0.018	26.9
R_{ddp}	0.013	14.2

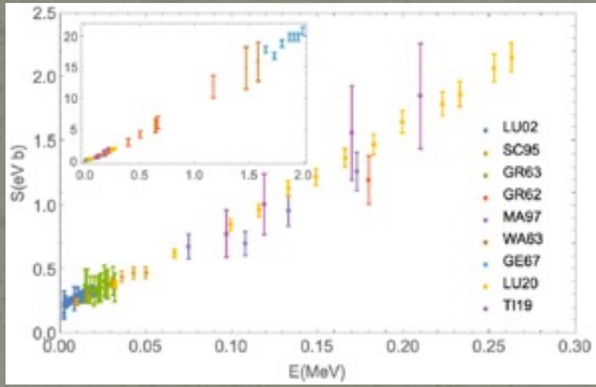
Nuclear cross sections and their analysis

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).

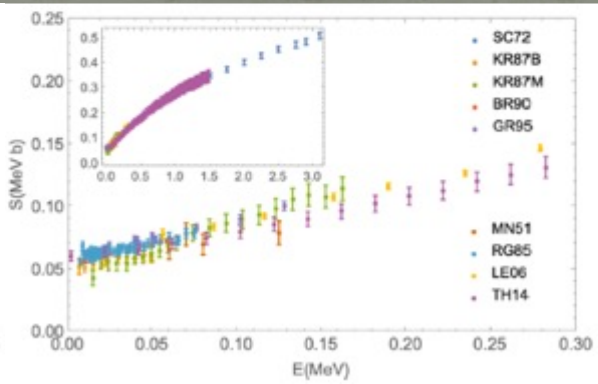
$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi \mu_{ab}}} T^{-3/2} \int_0^\infty \mathrm{d}E\, E\, \sigma(E)\, \mathrm{e}^{-E/T}$$

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

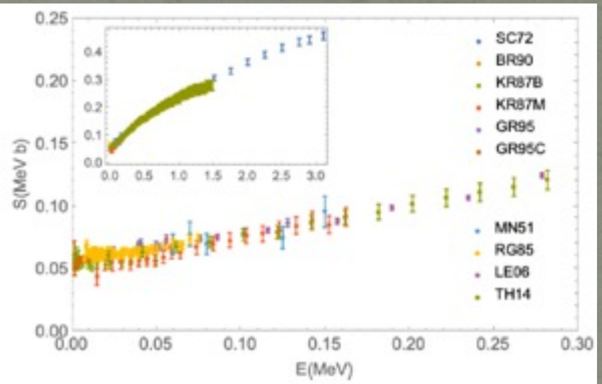
dpγ



ddn

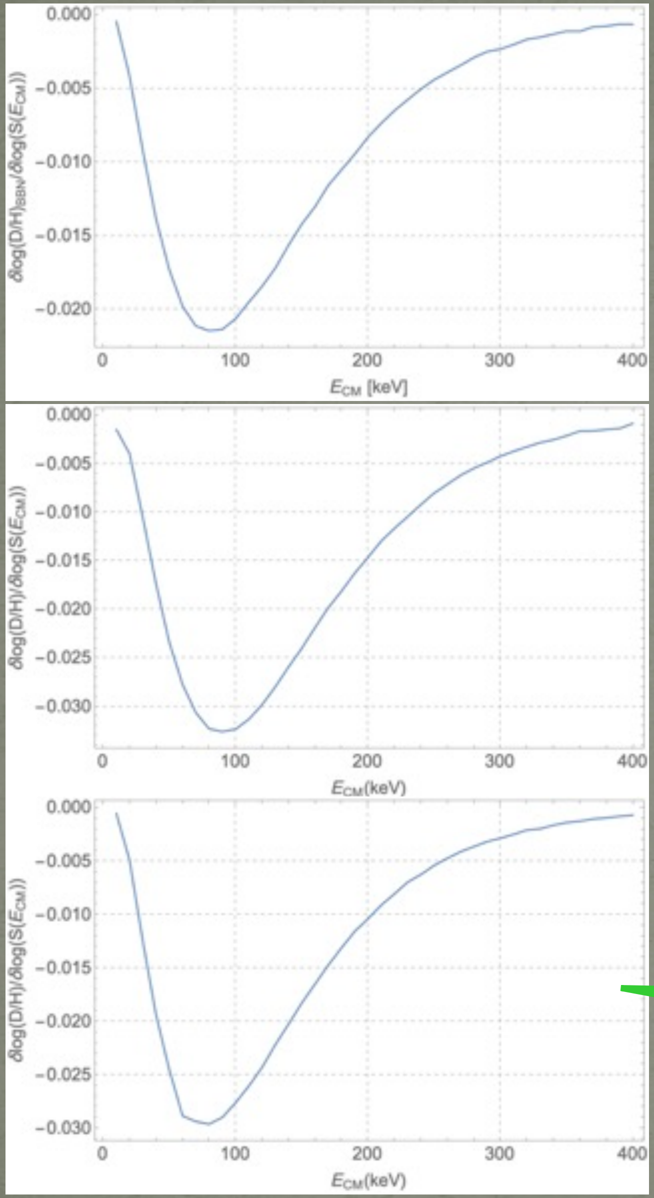


ddp



Analyses differ for: data selection criteria and/or methods of analysis (R-matrix for resonances, empirical or nuclear theory inspired form for smooth S-factors, χ^2, Bayesian, Monte Carlo, ...)

Rate sensitivities



We change the S-factor of δS at a given energy E_{cm} and observe the corresponding variation in the deuterium yield δ(D/H).

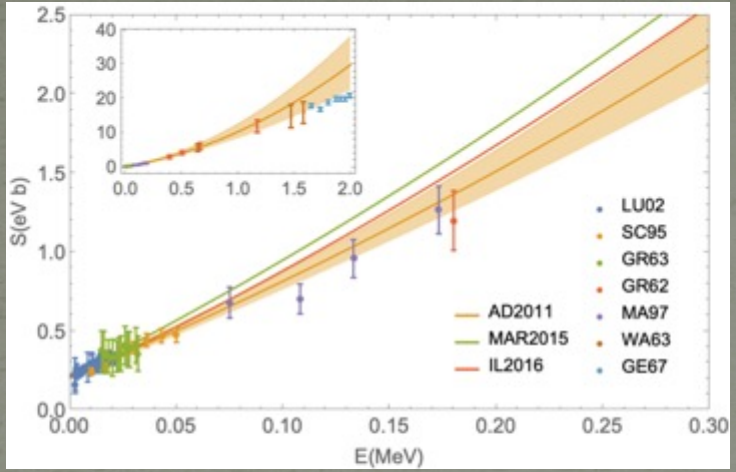
The sensitivity defined as (Fiorentini et al. 1998, Nollett and Burles 2000)

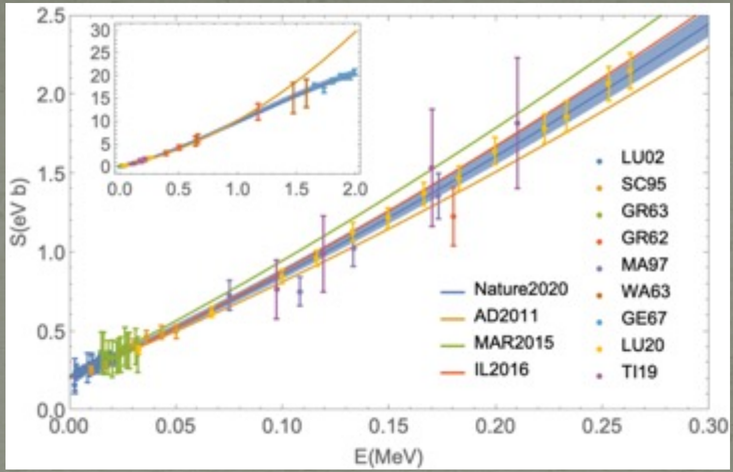
$$\sigma(E_{CM}) = \frac{\delta(D/H)/(D/H)}{\delta S(E_{CM})/S(E_{CM})}$$

For the three deuterium reactions the BBN relevant range is ~ 20-300 keV.

2011.11537 [astro-ph.CO]

Illustrative case I: a precise measure





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 (more details from Gianluca)

- 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)

Deuterium results

Astrophysical determination (Cooke et al 2018)

$$\frac{D}{H} = (2.527 \pm 0.030)10^{-5}$$

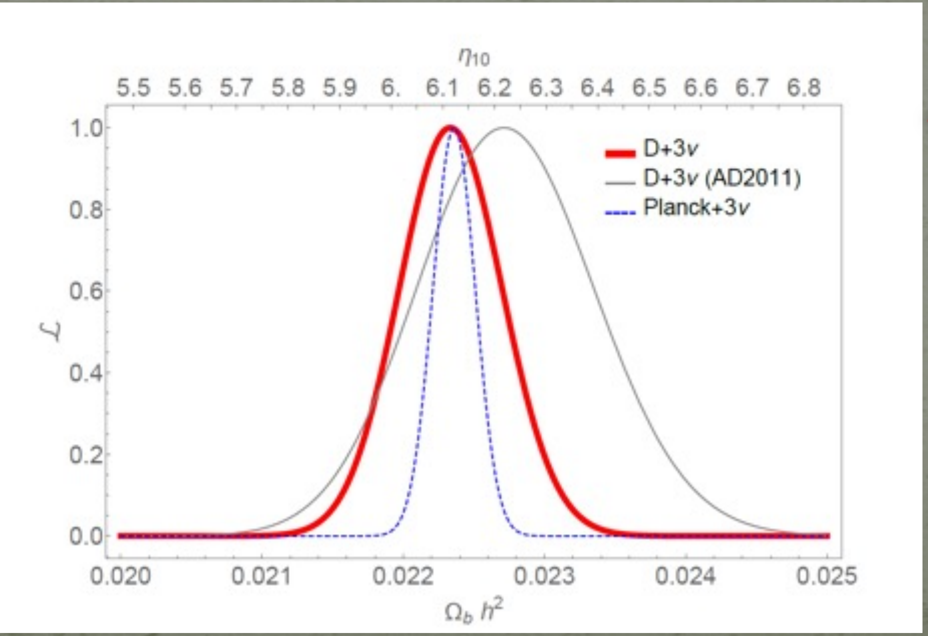
$R_{dp\gamma}$	PArthENoPE2 1	Pitrou *et al.* (2018) [3]	Cyburt *et al.* (2016) [26]
this work	2.54 ± 0.07		
MAR2005 [37]	2.52 ± 0.07	2.459 ± 0.036	
AD2011 [17]	2.58 ± 0.07		2.579
MAR2015 [11]	2.45 ± 0.07		

BBN analyses

- 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:

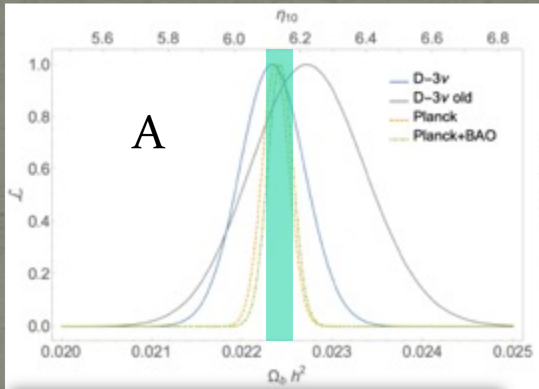
$$L_i(N_{eff},\eta) = \frac{1}{2\pi\sigma_i^{th}(N_{eff},\eta)\sigma_i^{ex}} \int dx \exp\left(-\frac{(x-Y_i^{th}(N_{eff},\eta))^2}{2\sigma_i^{th}(N_{eff},\eta)^2}\right)\exp\left(-\frac{(x-Y_i^{ex})^2}{2\sigma_i^{2x}}\right)$$

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

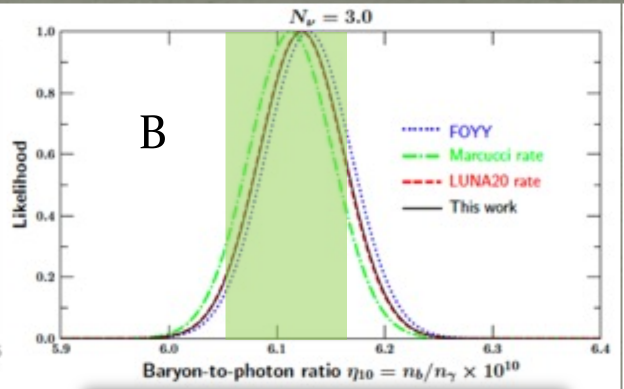


For N_{eff}=3.045, ^{2}H alone is an efficient baryometer

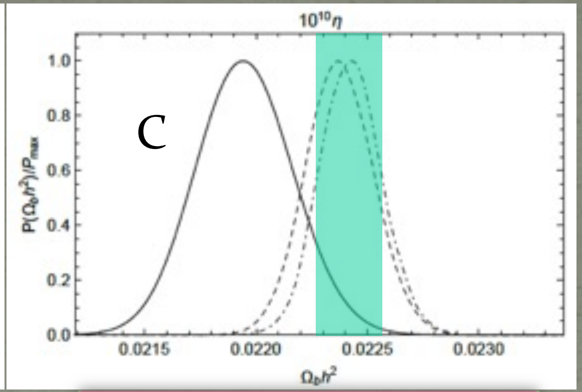
Standard BBN/CMB



Mossa et al , Nature 2020



Yeh et al., 2011.13874



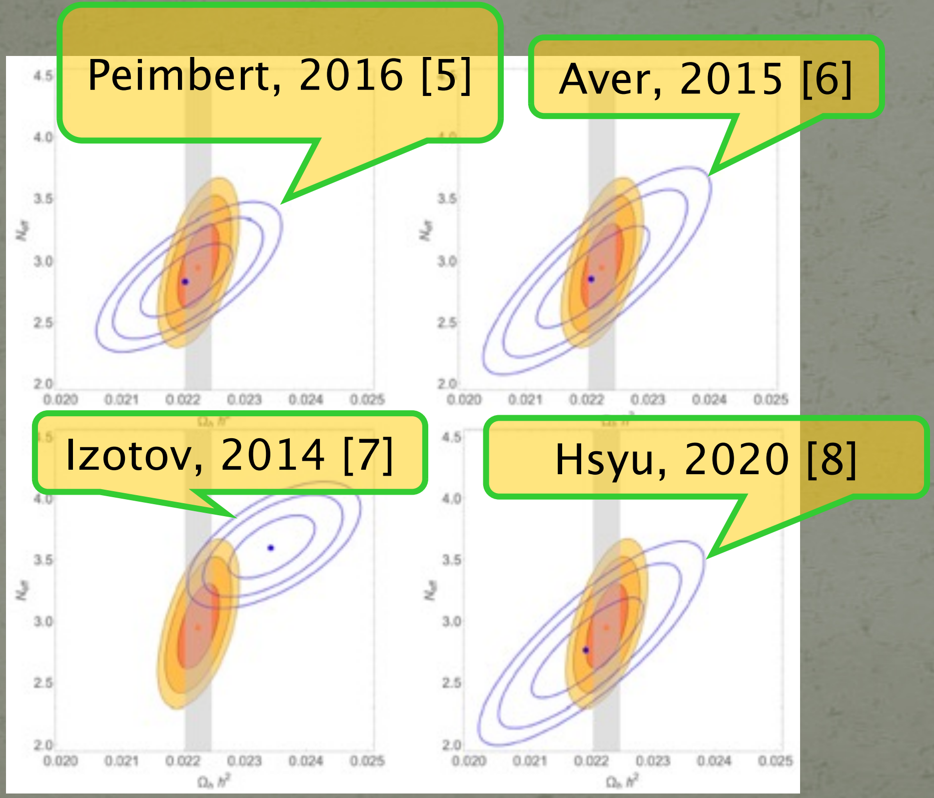
Pitrou et al., 2011.11320

- 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
- Note that the Planck green bands correspond to:
  - A: Planck +$Y_p(\omega_b)$ + lensing + BAO
  - B: Planck + lensing
  - C: Planck +$Y_p(\omega_b)$ + lensing + BAO
- Note that the 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

Non-standard BBN/CMB with N_{eff}

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_{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

Conclusions

Underground measurements of nuclear cross sections are important for many astrophysical and cosmological purposes (solar model, BBN…).

The new precise LUNA result on the dpg astrophysical factor is crucial in assessing the overall concordance of the standard cosmological model and the error budget on primordial deuterium.

Thanks to this measurement the theoretical error on D/H is now approaching the corresponding astrophysical measurement uncertainty.

The baryon density is extremely sensitive to D/H and its result is in excellent agreement with the Planck result (yet there are claims of a slight tension at the level of 2 sigma Pitrou et al 2020).

Possible extra relativistic species in the early universe both at BBN (Deuterium) and CMB formation (Planck) are severely constraint.

New measurements of dd cross section and improvements of ^{4}He abundance !!

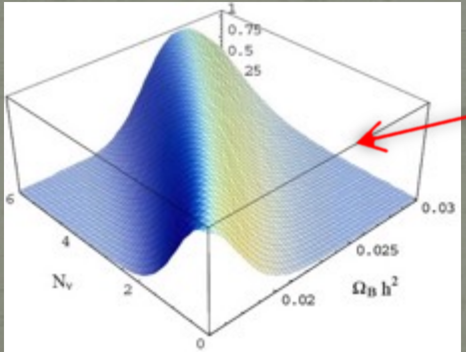
Extra slides

BBN analyses

- 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:

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

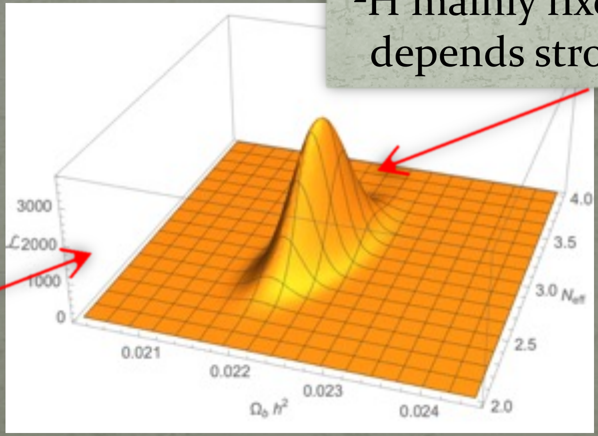
- Determine confidence level contours from the comparison of theoretical and experimental quantities.



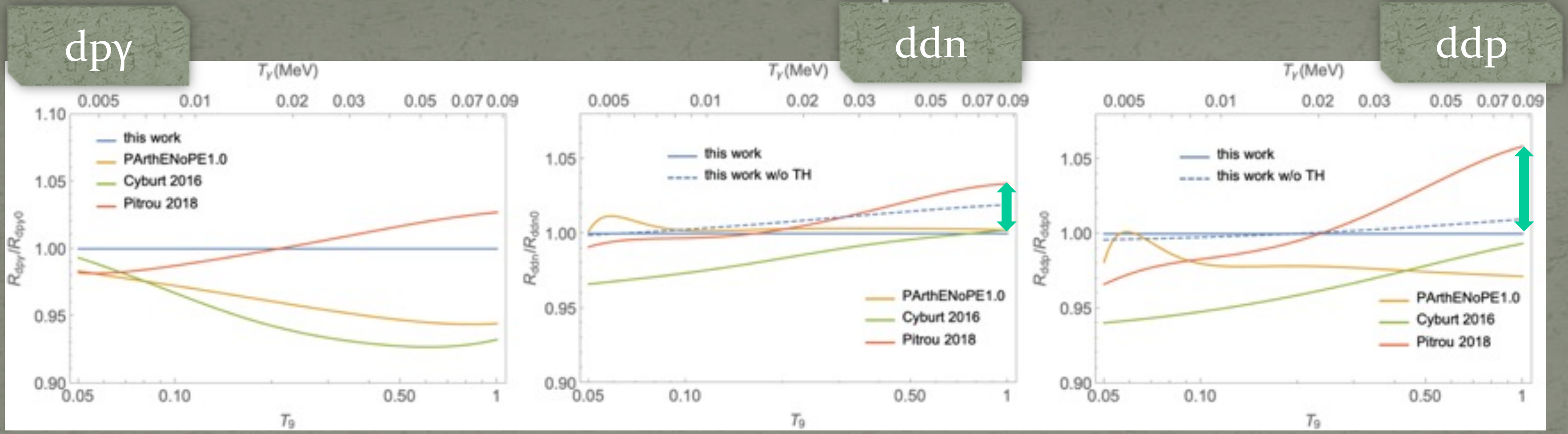
For free N_{eff}, ^{2}H alone is not sufficient in breaking the degeneracy…

… 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}



Rate comparison



Summary

- dpγ: present agreement among different groups [3% difference with previous Pitrou et al. 2018 (Iliadis et al. 2016), 7% with the old dpγ determination of Cyburt et al. 2016 and PArthENoPE1.0 (Adelberger et al. 2011)]
- ddn: 3% difference with Pitrou et al. 2018, much less with Cyburt et al. 2016
- ddp: 6% difference with Pitrou et al. 2018, much less with Cyburt et al. 2016
- DD TH data (Tumino et al, 2014) not relevant: a maximum 2% difference with or w/o TH (compare blue solid and dashed lines)

S-factor

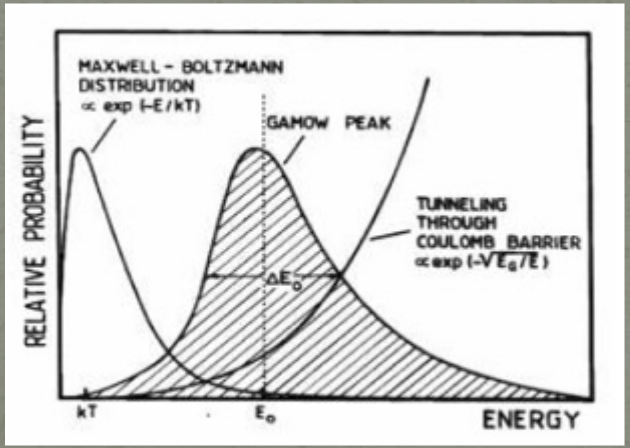
The probability for a thermonuclear reaction to occur in the primordial universe depends mainly on two factors: the velocity distribution of the nuclei in the plasma, given by a Maxwell-Boltzmann distribution, and the nuclear reaction cross section containing the tunneling probability through the Coulomb barrier:

$$\langle \sigma v \rangle = \frac{\sqrt{8/(\pi m)}}{(kT)^{3/2}} \int_0^\infty E\,\sigma(E)\,e^{-E/kT}\,dE,$$

For non-resonant reactions, it can be factorized into a part with the strongly energy-dependent tunneling probability through the Coulomb barrier (the Gamow factor) and a part representing the weakly energy-dependent properties of the nuclear interior (the astrophysical S-factor)

$$\langle \sigma v \rangle_{nr} = \frac{\sqrt{8/(\pi m)}}{(kT)^{3/2}} \int_0^\infty S(E) e^{-2\pi\eta - E/kT}\,dE,$$

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



Analysis methods

- Serpico2004/Pisanti2020: standard chi-squared plus a penalty factor that does not allow ω_k-1 to be greater than the quoted normalization, ε_k:

$$\chi^2(a_l, \omega_k) = \sum_{i_k} \frac{(S_{th}(E_{i_k}, a_l) - \omega_k S_{i_k})^2}{\omega_k^2 \sigma_{i_k}^2} + \sum_k \frac{(\omega_k - 1)^2}{\epsilon_k^2}$$

- Coc2015/Cyburt2016: energy dependence from nuclear physics + normalization from chi-squared:

$$\chi^2(\alpha_k) = \sum_{i_k} \frac{[S_{i_k} - \alpha_k S_{th}(E_{i_k})]^2}{\sigma_{i_k}^2} \qquad \chi^2(\alpha) = \sum_k \sum_{i_k} \frac{[S_{i_k} - \alpha S_{th}(E_{i_k})]^2}{\sigma_{i_k}^2}$$

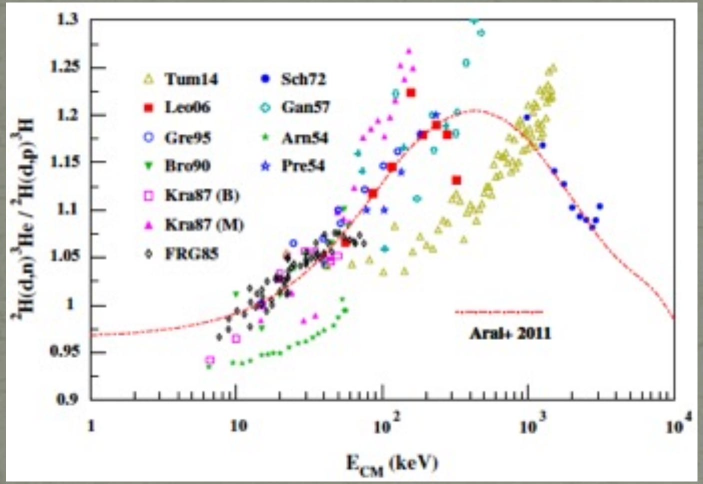
Same definition of the overall scaling factor multiplying the astrophysical S-factor:

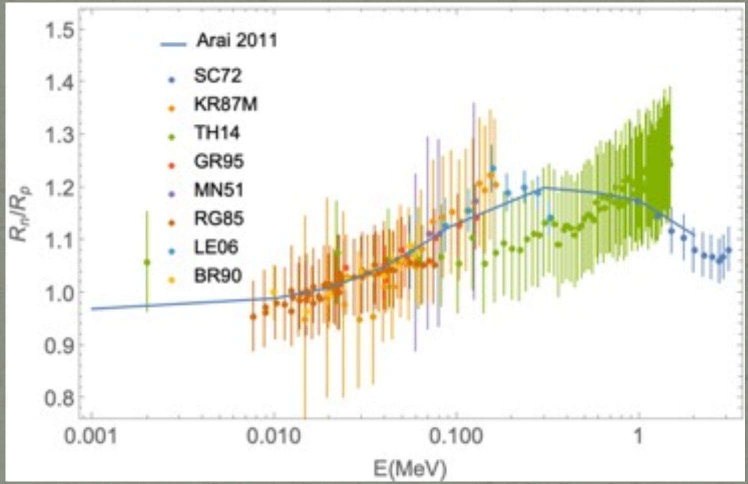
$$\overline{\alpha} = \sum_k \frac{\widehat{\alpha}_k}{\sigma_{\widehat{\alpha}_k}^2} \left(\sum_k \frac{1}{\sigma_{\widehat{\alpha}_k}^2} \right)^{-1} = \frac{\sum_k \sum_{i_k} S_{i_k} S_{th}(E_{i_k})/\sigma_{i_k}^2}{\sum_k \sum_{i_k} S_{th}^2(E_{i_k})/\sigma_{i_k}^2}$$

Trojan Horse DD data

Strict selection on data applied by some authors, excluding all experiments with not quoted/too large systematic uncertainty, for example TH data on DD.

Check: the ratio between ddn and ddp rates should be independent of the nuclear matrix elements. So, deviations may indicate normalization errors. Then, it has been used for discriminating among data sets.





However, data within experimental and fit uncertainties are not inconsistent with theoretical *ab initio* calculation (Arai, Aoyama, Suzuki, Descouvemont, Baye, 2011, not sure about theoretical uncertainty…).

Rate uncertainties

2011.11537 [astro-ph.CO]

	$\sigma_D^{(i)} \cdot 10^5$	$\delta\sigma_i^2/\sigma_{tot}^2$ (%)	$(\sigma_D^{(i)})_{old} \cdot 10^5$	$(\delta\sigma_i^2/\sigma_{tot}^2)_{old}$ (%)
$R_{pn\gamma}$	0.002	0.3	0.002	0.1
$R_{dp\gamma}$	0.027	58.5	0.062	87.0
R_{ddn}	0.018	26.9	0.020	9.1
R_{ddp}	0.013	14.2	0.013	3.8

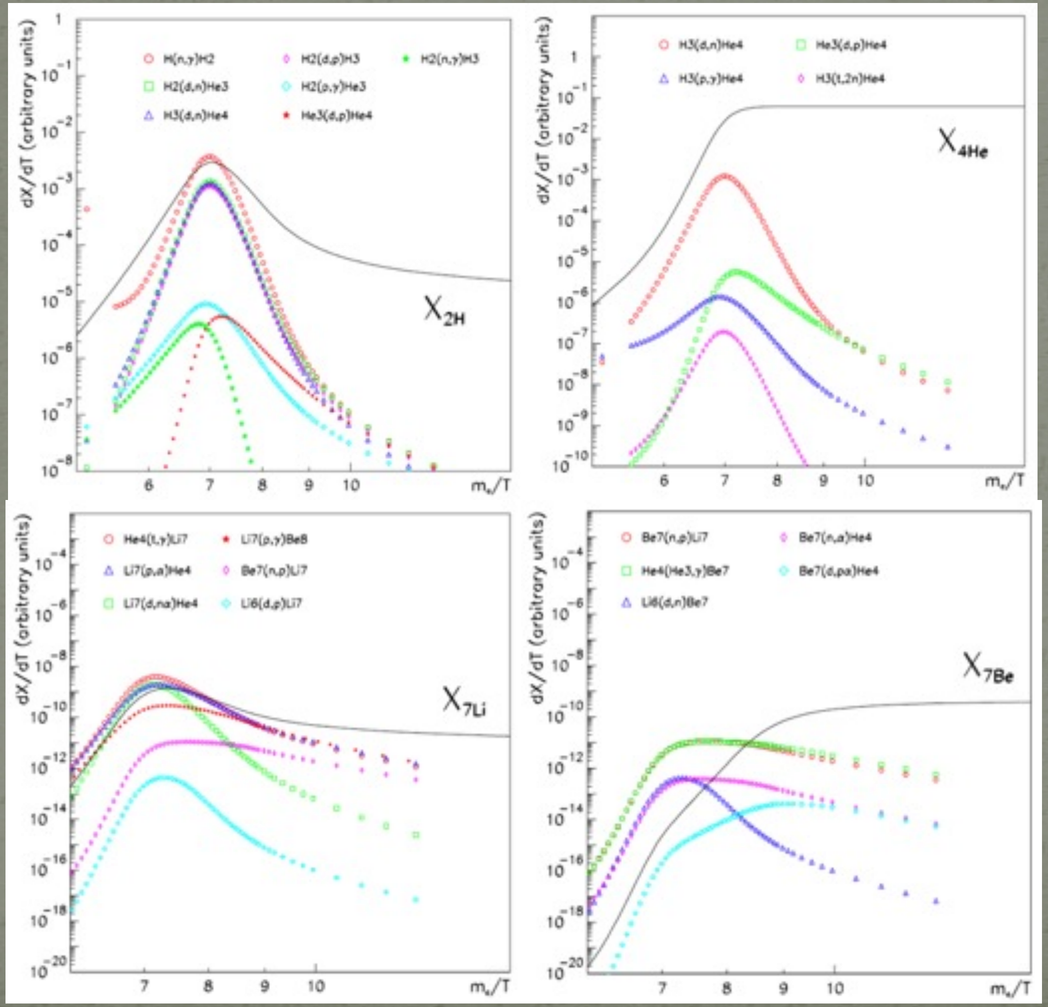
12%
61%
27%

Reaction i	$10^5\ \sigma_i$(D/H)	$10^5\ \sigma_{omit\ i}$(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	–

2011.13874 [astro-ph.CO]

Leading processes (absolutely not exhaustive)

Qualitative understanding of the role of nuclear reactions through its contribution to the right hand side of the Boltzmann equation for a given nuclide.



D

- pnγ, ddn, ddp, dpγ, tdn

4He

- tdn, ^{3}Hedp

Li7

- ^{4}Hetγ, ^{7}Lipα, ^{7}Lipγ, 7Lidnα, ^{7}Benp

7Be

- ^{3}Heαγ, ^{7}Benp, ^{7}Benα

theory

fine

recent

to consider

Data (the quest for "primordiality")

- ^{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 allow 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.

^{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 η_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 $^2H/H=(2.53\pm0.04)\cdot10^{-5}$ (R. Cooke et al., Ap. 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. Mon. Not. Roy. Astron. Soc. 447 (2015) 2925).
- After recent new observations or reanalyses of existing data the new recommended value, with 1.2% uncertainty, is

$$\frac{^2H}{H} = (2.527 \pm 0.030) \cdot 10^{-5}$$

R. Cooke, M. Pettini, C.C. Steidel, Ap. J. 855 (2018) 102

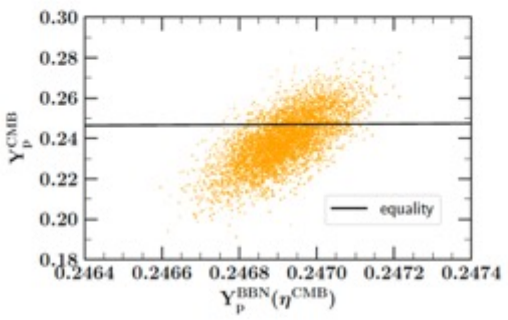
^{4}He

- 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 reduced the uncertainty (over a factor of 2) and led to a better defined regression, with $Y_p=0.2449\pm0.0040$ (E. Aver et al, JCAP 7 (2015) 011), updated in (1.4% uncertainty)

$$Y_p = 0.2453 \pm 0.0034$$

E. Aver et al., arXiv:2010.04180 (2020)

- Promising measurement from the damping tail of the CMB acoustic peak, for the moment not competitive with astrophysical measure.



BBN accuracy: weak rates

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

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

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

$\tau_n(th) = 961$ s

$\tau_n(exp) = 879.4 \pm 0.6$ s

$\tau_n(th) = 893.9$ s

Corrections to the weak rates:

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

$$\nu_e + n \leftrightarrow e^- + p$$

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

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

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.

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

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

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

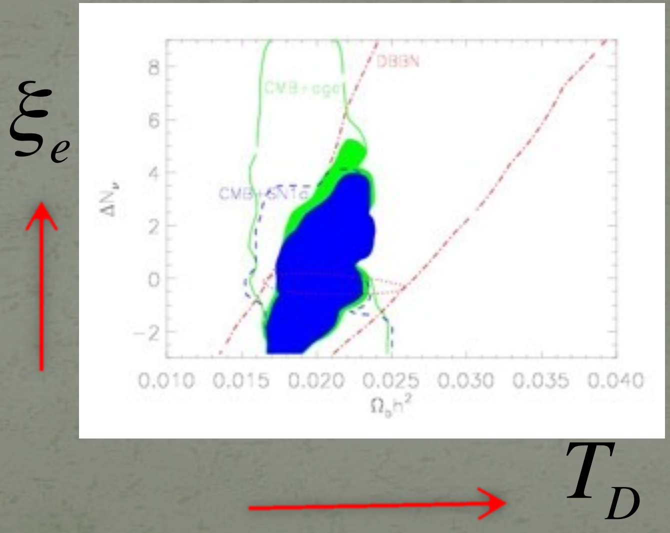
$$\frac{^7\mathrm{Li}}{\mathrm{H}} = 4.7 \times 10^{-10} R_1^{1.34} R_8^{0.96} R_7^{-0.76} R_{10}^{-0.71} R_3^{0.71} R_2^{0.59} R_5^{-0.27} \left(\frac{\omega_b}{0.02273}\right)^{2.12} \left(\frac{\tau_n}{\tau_{n,0}}\right)^{0.44}.$$

BBN outputs: how they go

- η_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 η_B, while ^{7}Be dominates at high η_B, leading to the characteristic "lithium dip" versus η_B in the Schramm plot.
- N_{eff}: more relativistic degrees of freedom ➔ a faster expansion. Then an earlier freeze-out of n/p (more ^{4}He) and less time available for ^{2}H destruction (more ^{2}H).
- τ_n: a decrease in Γ ➔ an earlier freeze-out of n/p (more ^{4}He) and more neutrons available (more ^{2}H).

- $\xi_{\nu i}$: 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). The degeneracy can be understood in term of the initial condition on the n/p equilibrium value

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



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, μ_ν.

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

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

degeneracy parameter, invariant under cosmic expansion

Chemical potentials contribute in increa-sing 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

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