UNIVERSO PRIMITIVO
10-11th February 2022

BIG BANG NUCLEOSYNTHESIS IN THE *f(R,T)* MODIFIED THEORY OF GRAVITY

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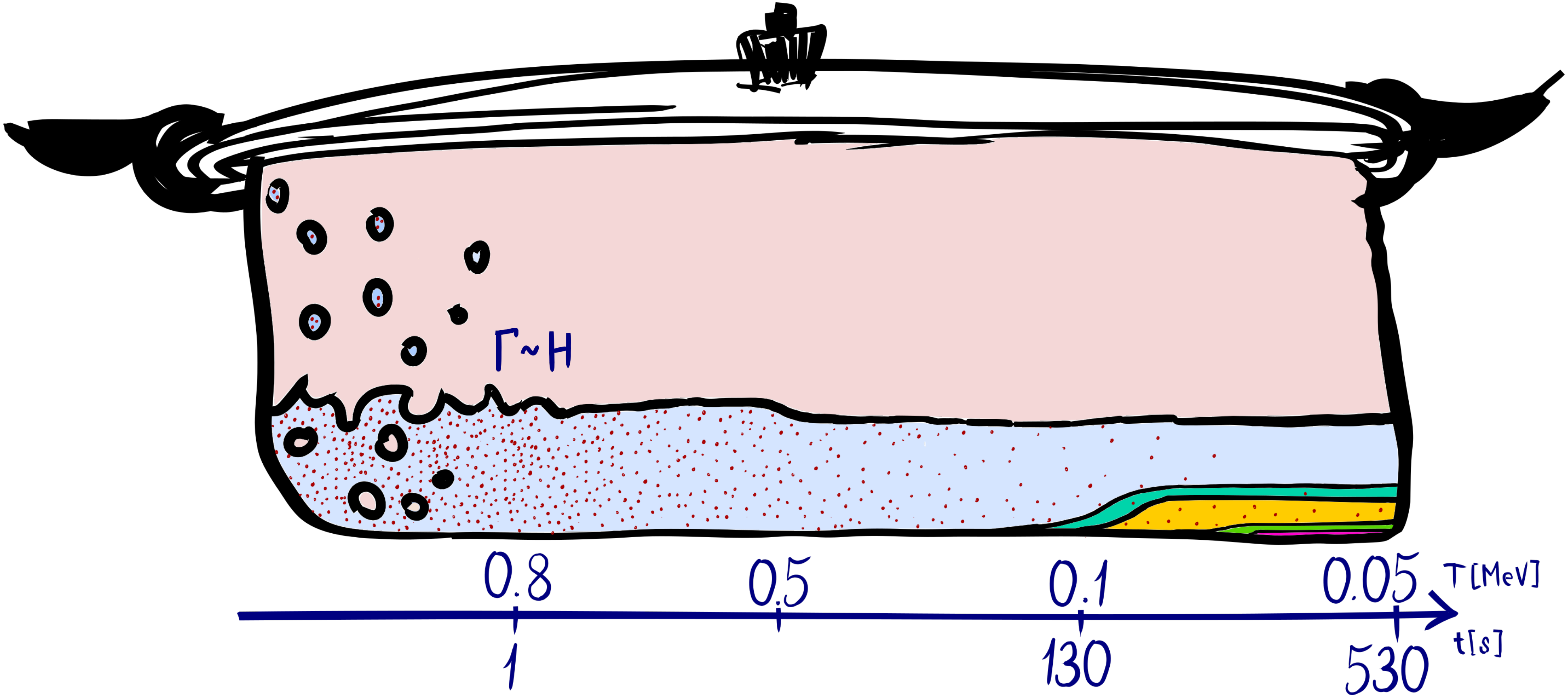
Acknowlegments: UIDB/04434/2020 & UIDP/04434/2020, PTDC/FIS-OUT/29048/2017, PTDC/FIS-AST/0054/2021.

BBN in a nutshell

(or in a pressure cooker)



[see also Sandro Moreira's talk tomorrow]

Modified Hubble expansion

$$\xi = \frac{H'}{H_{SBBN}}$$

$$Y_p = (0.2381 \pm 0.0006) + 0.0016\,[\eta_{10} + 100\,(\xi - 1)] + 0.0002\,(\tau_n - 881.5)$$

$$\mathrm{D/H} = 2.60\,(1 \pm 0.06)\left[\frac{6}{\eta_{10} - 6\,(\xi - 1)}\right]^{1.6} \times 10^{-5}$$

$$^{7}\mathrm{Li/H} = 4.82\,(1 \pm 0.10)\left[\frac{\eta_{10} - 3\,(\xi - 1)}{6}\right]^{2} \times 10^{-10}$$

[Kneller & Steigman astro-ph/0406320; Steigman 0712.1100; Steigman 1208.0032]

Modified Hubble expansion

$$\xi = \frac{H'}{H_{SBBN}}$$

Table 1. Summary of primordial abundance of elements inferred from observations [5] and the corresponding theoretical predictions (Eqs. (9)–(11) based on Ref. [42]), using $\eta_{10} = 6.104 \pm 0.058$ from CMB (with no BBN correction) [5], and the recent measurement $\tau_n = 877.75 \pm 0.50$ s [39]. Constraints on a modified Hubble parameter as given by ξ are obtained by equating observations with predictions.

	$Y_\mathbf{p}$	$\mathbf{D/H} \times 10^5$	$^7\mathbf{Li/H} \times 10^{10}$
Observations	0.245 ± 0.003	(2.547 ± 0.025)	(1.6 ± 0.3)
Predictions	$(0.2471 \pm 0.0006) + 0.1600\,(\xi - 1)$	$\frac{(2.60\pm0.16)}{[(1.017\pm0.010)-(\xi-1)]^{1.6}}$	$(4.82 \pm 0.48)\left[(1.017 \pm 0.010) - \frac{(\xi-1)}{2}\right]^2$
ξ	0.987 ± 0.019	1.00 ± 0.19	1.9 ± 0.3

[5] PDG Review – Sec. 24 'Big Bang Nucleosynthesis' (2021 update)
[39] F. M. Gonzalez et al. [UCNτ] 2106.10375
[42] Kneller & Steigman astro-ph/0406320; Steigman 0712.1100 & 1208.0032

[Lithium problem: see also Bruno Carrazedo's talk tomorrow]

Modified Hubble expansion

$$\xi = \frac{H'}{H_{SBBN}}$$

$$106\,(\xi - 1) = \frac{Y_{\rm p} - (0.2374 \pm 0.0006)}{0.0016} - 6\left[\frac{(2.60 \pm 0.16) \times 10^{-5}}{(\mathrm{D/H})}\right]^{1/1.6}$$

[Kneller & Steigman astro-ph/0406320; Steigman 0712.1100; Steigman 1208.0032]

[Particle Data Group Review – Sec. 24 ‘Big Bang Nucleosynthesis’ (2021 update)]

[Bhattacharjee et al. 2004.04684]

$$\xi = 0.99 \pm 0.05$$

$$\Delta N_\nu = 43\left(\xi^2 - 1\right)/7 = -0.15^{+0.63}_{-0.60}$$

$$G'/G_N = \xi^2 = 0.98 \pm 0.10$$

Modified Gravity

Modified Gravity

$$\mathcal{L}_g \propto R$$

curvature scalar

Modified Gravity

$$\mathcal{L}_g \propto R \longrightarrow \mathcal{L}_g \propto f(R)$$

curvature scalar

$f(R,T)$ gravity

$\mathcal{L}_g \propto R \longrightarrow \mathcal{L}_g \propto f(R) \longrightarrow \mathcal{L}_g \propto f(R,T)$

curvature scalar

trace stress-energy

[Harko+ 1104.2669]

$$S = \frac{1}{2\kappa^2}\int f(R,T)\sqrt{-g}d^4x + \int \mathcal{L}_m\sqrt{-g}d^4x$$

Scalar-tensor f(R,T) gravity

[Rosa 2103.11698]

- Define two scalar fields & potential

$$\varphi \equiv \frac{\partial f}{\partial R} \qquad \psi \equiv \frac{\partial f}{\partial T} \qquad V(\varphi,\psi) \equiv -f(R,T) + \varphi R + \psi T$$

$$S = \frac{1}{2\kappa^2}\int \left[\varphi R + \psi T - V(\varphi,\psi)\right]\sqrt{-g}\,d^4x + \int \mathcal{L}_m \sqrt{-g}\,d^4x$$

Modified Einstein equations

$$G_{\mu\nu} = 8\pi G_N T_{\mu\nu}$$

Modified Einstein equations

$$\varphi G_{\mu\nu} = 8\pi G_N T_{\mu\nu} - \left[\psi\left(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T + \Theta_{\mu\nu}\right) + (g_{\mu\nu}\Box - \nabla_\mu\nabla_\nu)\varphi + \frac{1}{2}g_{\mu\nu}V\right]$$

$$\varphi \equiv \frac{\partial f}{\partial R} \qquad \psi \equiv \frac{\partial f}{\partial T} \qquad \Theta_{\mu\nu} \equiv g^{\rho\sigma}\frac{\delta T_{\rho\sigma}}{\delta g^{\mu\nu}} \qquad \Box \equiv \nabla^\sigma\nabla_\sigma$$

Modified Friedmann equation

- FLRW metric
- Perfect fluid

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

Modified Friedmann equation

- FLRW metric
- Perfect fluid

[Gonçalves et al. 2112.02541]

$$H^2 = \frac{1}{\varphi}\left[\frac{8\pi G_N}{3}\rho - H\dot{\varphi} + \frac{\psi}{2}\left(\rho - \frac{1}{3}P\right) + \frac{1}{6}V\right] - \frac{k}{a^2}$$

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$$H^2 \simeq \frac{1}{\varphi}\left(\frac{8\pi G_N}{3} + \frac{4}{9}\psi\right)\rho_r$$

Modified Friedmann equation

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$\psi = 0$

e.g. $f(R,T) = R + A\,R$

$\varphi = 1$

e.g. $f(R,T) = R + BT$

$\varphi = 1.0 \pm 0.1$

$\psi = 8\pi G_N(-0.015 \pm 0.074)$

$f(R,T) = R + CRT$

Conclusion

- No clear sign of non-standard BBN/gravity

$$\xi = 0.99 \pm 0.05$$

- Constraints of f(R,T) gravity

$$\varphi = 1.0 \pm 0.1 \qquad \psi = 8\pi G_N(-0.015 \pm 0.074)$$

- Unresolved lithium problem
- Further analysis?

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Thank you!

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Field Equations:

$$\varphi R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} \left(\varphi R + \psi T - V\right) - \left(\nabla_\mu \nabla_\nu - g_{\mu\nu} \Box\right)\varphi = \kappa^2 T_{\mu\nu} - \psi\left(T_{\mu\nu} + \Theta_{\mu\nu}\right)$$

Variation of the action w.r.t. φ and ψ:

$$V_\varphi = R$$

$$V_\psi = T$$

$$f(R,T) = R + \mathcal{A}R^{\alpha} + \mathcal{B}T^{\beta} + \mathcal{C}R^{\gamma}T^{\delta}$$

$$\varphi = 1 + \alpha\mathcal{A}R^{\alpha-1} + \gamma\mathcal{C}R^{\gamma-1}T^{\delta}$$

$$\psi = \beta\mathcal{B}T^{\beta-1} + \delta\mathcal{C}R^{\gamma}T^{\delta-1}$$

$$V = (\alpha-1)\,\mathcal{A}R^{\alpha} + (\beta-1)\,\mathcal{B}T^{\beta} + (\gamma+\delta-1)\,\mathcal{C}R^{\gamma}T^{\delta}$$