Linking the lithium problem and the H_0 tension: the gravitational constant at BBN

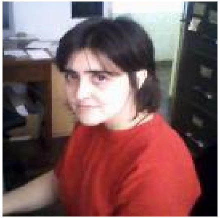
S. Franchino-Viñas

16th. Marcel Grossman meeting, e-Roma, Italia, Luglio 2021

The collaboration

S. Franchino Viñas

ITP, Universität Heidelberg
Dept. of Physics, Universidad Nacional de La Plata

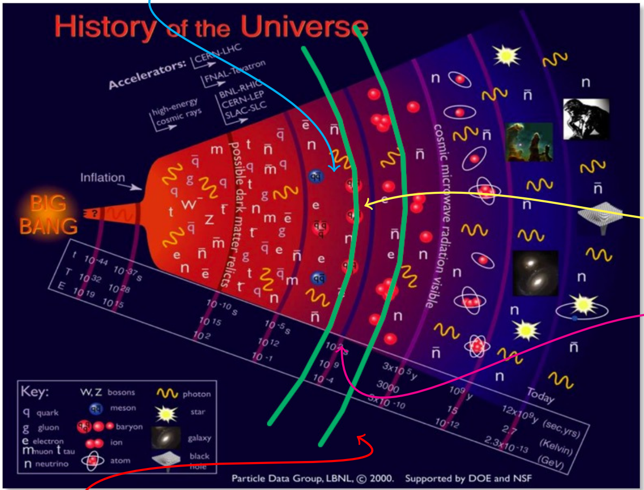


M. Mosquera

Faculty of Astronomy and Geophysics
Universidad Nacional de La Plata

Outline

soup of $e^{\pm}$, protons, neutrons, photons, neutrinos, in equilibrium

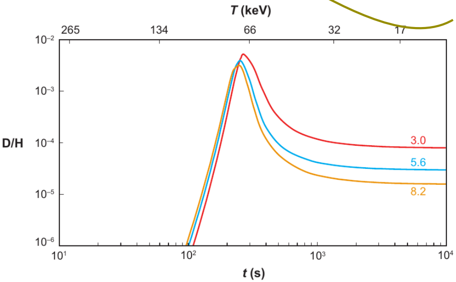


$\sim$ 1 s $\approx$ 0.8 MeV

$\approx \Delta$m(n $\rightarrow$ p + e$^-$ + $\bar{\nu}_e$)

$$\left\{\begin{array}{l} \mathrm{n} + \mathrm{p} \leftrightarrow \mathrm{d} + \gamma, \\ \mathrm{d(p,}\gamma)^3\mathrm{He}, \\ ^3\mathrm{H}(\alpha,\gamma)^7\mathrm{Li}, \\ \qquad\vdots + 100 \end{array}\right.$$

$\sim$ 10 min $\sim$ 30 keV: no more available n and a gap at mass 8



relative abundance of deuterium to hydrogen as a function of time (Steigman 2007)

the abundance depends on the number of baryons:

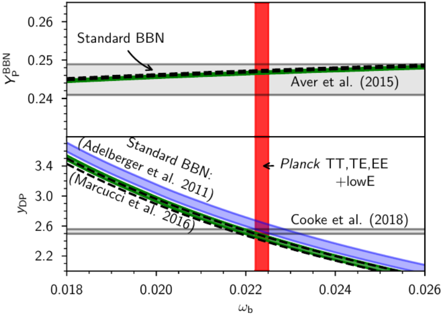
- $\uparrow \omega_{\rm b} \Rightarrow$ D production sets in earlier;
- $\uparrow \omega_{\rm b} \Rightarrow$ lower D/H at the end;

relative abundance of He and D as a function of the baryon density (Planck 2018)

$$\Downarrow$$

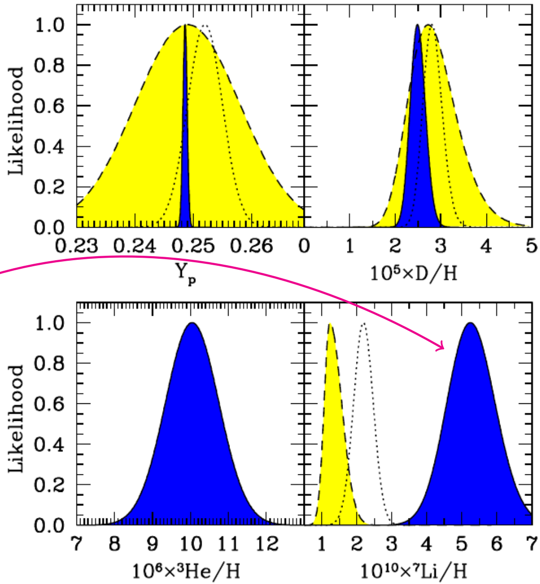
$$\omega_b\Big|_{\rm BBN} = \omega_b\Big|_{\rm CMB}$$

as Cosmological Standard Model dictates

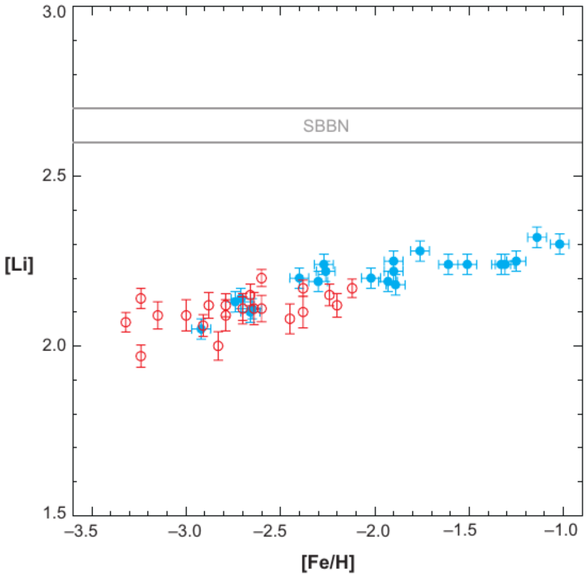


Agreement of numerical computations and observations is impressive!

Not quite so for Li...



(Fields 2012)



(Steigman 2007); [Li]=12+ log(Li/H)

D: only destroyed (small binding energy);

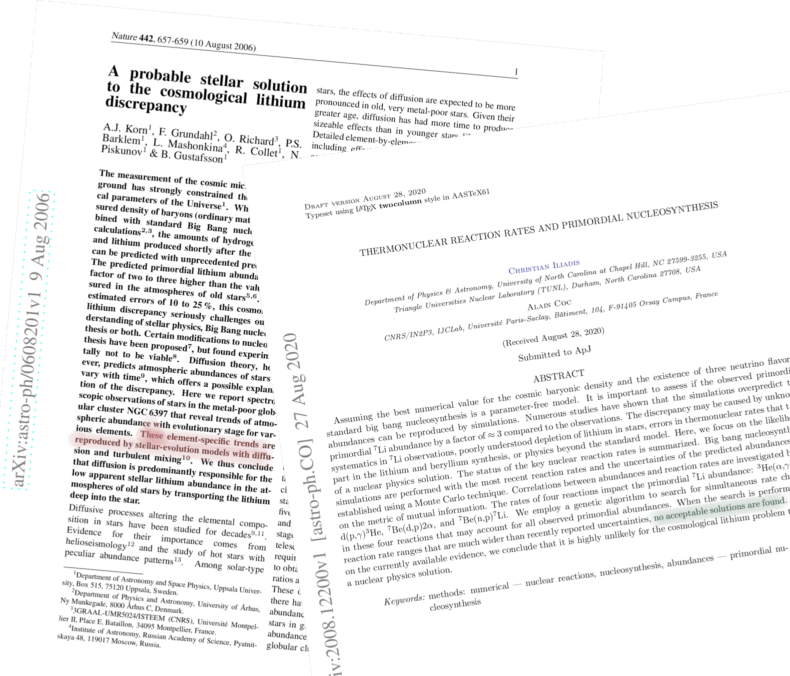
^{4}He: produced in stars by burning hydrogen; keep track of metallicity/look at extragalactic regions;

^{7}Li: more involved. . .

- burned in inner layers of stars;
- may survive in outer layers of coolest stars;
- produced in hotter interiors (super red giants), collisions of cosmic ray nuclei (unfortunately including α-α fusion);

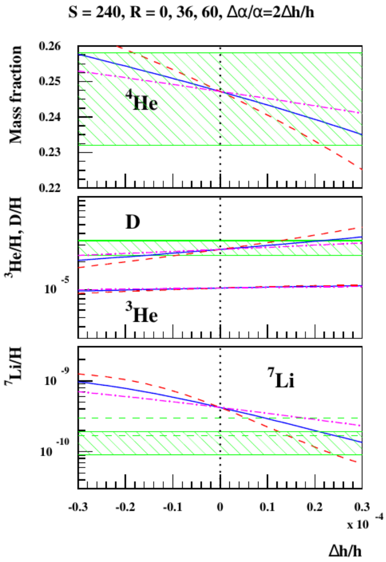
Solutions:

1. modify the astrophysics;
2. check the involved nuclear reactions;
3. invoke Beyond Standard Model physics;



Outline

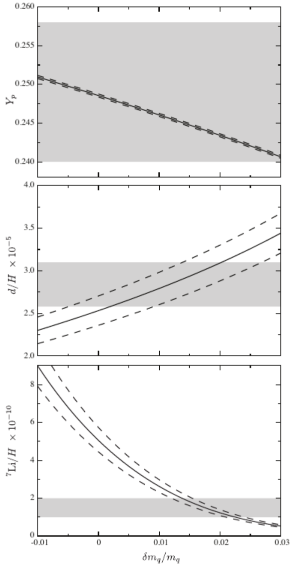
Why should the fundamental constants that we use in our daily physics be the same as those 10^9 years ago?



Coc, Nunes, Olive, Uzan, Vangion 2007 (also Coc, Descouvemont, Olive, Uzan, Vangioni 2012,. . .)

GUT: $\Delta v = S\Delta h$, $\Delta\Lambda_{QCD} \sim R\Delta\alpha$

Berengut, Flambaum, Dmitriev 2009 (also Dmitriev, Flambaum, Webb 2004 . . .)



SF, and M. Mosquera (2107.xxxxx):

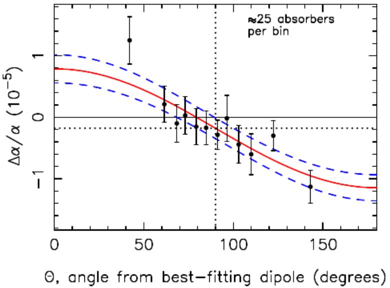
independent variation of G_N and α (and $\langle v \rangle$) at BBN (AlterBBN, Arbey 2018)
$+$ statistical analysis to obtain the best fit of the yields

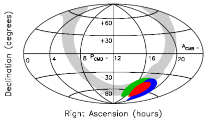
	$\Delta\alpha/\alpha[10^{-2}]$	$\Delta\langle v\rangle/\langle v\rangle[10^{-2}]$	G_{BBN}/G_N	χ^2_{min}
Fit 1	-2.83 ± 0.24	$--$	$1.167^{+0.015}_{-0.016}$	1.95
Fit 2	-3.35 ± 0.45	-1.50 ± 0.20	1.170 ± 0.020	0.70

	$\mathrm{D/H}\,[10^{-5}]$	Y_{P}	$^7\mathrm{Li/H}\,[10^{-10}]$
Fit 1	2.605 ± 0.040	0.2472 ± 0.0016	2.09 ± 0.12
Fit 2	2.545 ± 0.058	0.2561 ± 0.0050	2.03 ± 0.22
Observational weighted mean value	2.541 ± 0.022	0.2542 ± 0.0014	2.01 ± 0.14
Standard computation	2.547 ± 0.050	0.2466 ± 0.0001	4.60 ± 0.32

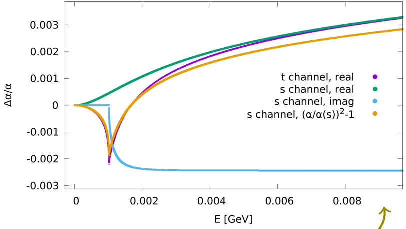
(Observational data from the last decade)

Motivations for a varying α



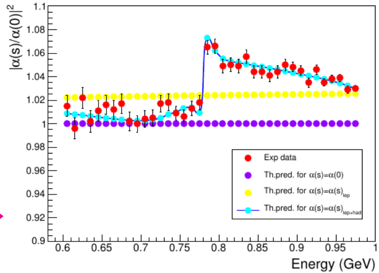


Webb, King, Murphy, Flambaum, Carswell and Bainbridge 2011 (QUASAR absorption spectra from Very Large Telescope and Keck telescope)



SQED program, Jegerlehner 2018;

KLOE-2 Collaboration 2017, $e^+e^- \rightarrow \mu^+\mu^-\gamma$ running coupling constant in QFT



A varying G_N? Motivations from GUTs, but more simply from QFT in curved spaces.

Quantum contributions to the gravitational action! For free fields,

$$\Gamma_{\rm scalar}[g] = \frac{1}{2}\mathrm{Tr_s}\log\left(\Delta + \xi R + m_s^2\right)\,, \tag{1}$$

render the gravity action non-local,

$$\Gamma[g] = \Gamma_{\rm loc}[g] + \frac{m^2}{2(4\pi)^2}\int \mathrm{d}^4x\sqrt{g}\,B(\frac{\Delta}{m^2})R$$
$$+\frac{1}{2(4\pi)^2}\int \mathrm{d}^4x\sqrt{g}\left\{C^{\mu\nu\alpha\beta}\,C_1(\frac{\Delta}{m^2})\,C_{\mu\nu\alpha\beta} + R\,C_2(\frac{\Delta}{m^2})\,R\right\},$$

infinities lead to renormalization/running G_N (SF, Paula-Netto, Shapiro, Zanusso, 2019).

However effects suppressed by M_P. Two bypass:

- a phenomenological approach, e.g. Running Vacuum Models (Solà Peracaula+ 2021); running of cosmological constant and G_N so that

$$\rho_{\rm vac}(H) = \frac{3}{8\pi G_N}\left(c_0 + \nu H^2 + \tilde{\nu}\dot{H}\right)\,; \tag{2}$$

- reinterpret the variation of G_N at BBN as extra relativistic degrees of freedom $\Delta N_{\rm eff}$:

$$\frac{\Delta G}{G_N} \approx \frac{7}{43}\Delta N_{\rm eff}\,. \tag{3}$$

Outline

$\Delta N_{\rm eff}$ implies a change in H...

Can we translate our ΔG_N to a ΔH_0?

Consider

- two different universes, one with $N_{\rm eff} = 3$ and another with $N_{\rm eff}$ arbitrary;
- both of them should have the same $r_s H_0$, to avoid disagreements with observations;

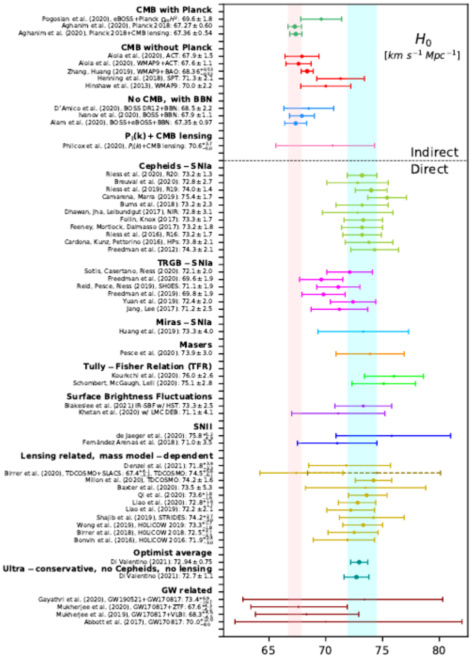
$$\Downarrow$$

$$H_0(N_{\rm eff}) \approx H_0(3)\sqrt{0.595 + 0.135 N_{\rm eff}}\,.$$

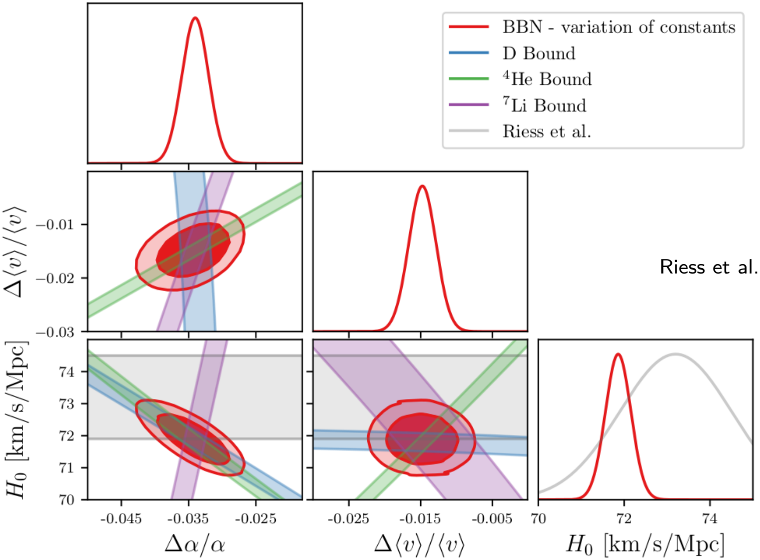
as given by Planck 2018

our result $\Delta N_{\rm eff} \sim 1$

Di Valentino+ 2021

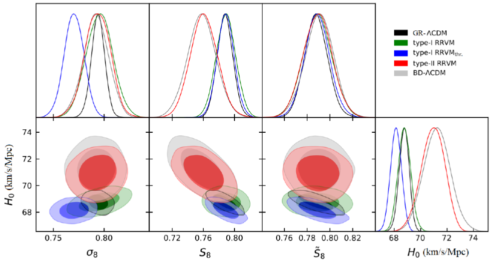


Variation of constants at BBN: SF, M. Mosquera arxiv 2107:xxxxx

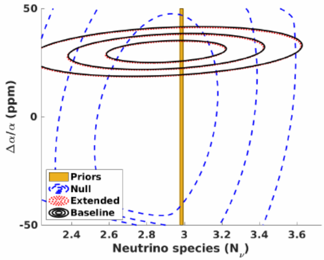


Riess et al.: Cepheids+SNI

Other approaches

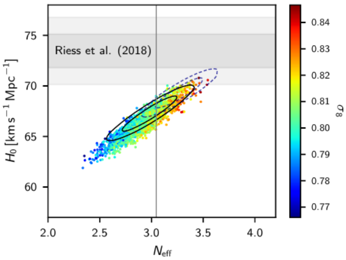


RVM@CMB, Solà+ 2021,
$\Delta G_N/G_N \sim 10\%$



GUT@BBN, Martins 2021

$N_{\mathrm{eff}} \sim 3.00 \pm 0.55$ (95%, TT+lowE), Planck 2018



Outline

- Revisit the lithium problem with the latest observations.
- Joint variation of α, G_N (and $\langle v \rangle$) could provide a solution.
- Well-motivated?

$\rightarrow$ $\Delta\alpha$: sign of $\Delta\alpha$ seems OK.
If running: should be one order of magnitude smaller.
Consider runnings in each single reaction?

$\rightarrow$ ΔG_N: interpretation in terms of $\Delta N_{\text{eff}} \sim 1$.
related to H_0! Lithium as Hubblemeter?
sterile neutrino?
interactions to avoid σ_8 constraints?

$$\Gamma_{\mathrm{fermion}}[g] = -\mathrm{Tr}_{\mathrm{f}} \log \left(\not{D} + m_{\mathrm{f}} \right) , \tag{4}$$

$$\Gamma_{\mathrm{proca}}[g] = \frac{1}{2} \mathrm{Tr}_{\mathrm{v}} \log \left(\delta_\mu^\nu \nabla + \nabla_\mu \nabla^\nu + R_\mu{}^\nu + \delta_\mu^\nu m_{\mathrm{v}}^2 \right) , \tag{5}$$

$$\frac{B(z)}{z} = -\frac{4Y}{15a^4} + \frac{Y}{9a^2} - \frac{1}{45a^2} + \frac{4}{675} + \left(\xi - \frac{1}{6} \right) \left(-\frac{4Y}{3a^2} - \frac{1}{a^2} + \frac{5}{36} \right) , \tag{6}$$

and the relevant R divergent term is

$$\Gamma_{\mathrm{loc}}[g] \sim \frac{1}{2(4\pi)^2} \int \mathrm{d}^4 x \sqrt{g} \left\{ -2m^2 \left(\xi - \frac{1}{6} \right) \frac{1}{\bar{\epsilon}} R \right\} \tag{7}$$

In order to renormalize we have to introduce a counterterm or Pauli-Villar's fields. Let's just consider that some counterterm δ_{ct} is introduced at the level of the action for the graviton. In that case

$$\begin{aligned} S_{\mathrm{ren}}[g] &= \frac{m^2}{2(4\pi)^2} \int \mathrm{d}^4 x \sqrt{g} \, \left(-2 \left(\xi - \frac{1}{6} \right) \frac{1}{\bar{\epsilon}} + B(z) + \delta_{ct} \right) R \\ &= \int \mathrm{d}^4 x \sqrt{g} \, b_1(z) R \end{aligned} \tag{8}$$

If we fix $b_1(\mu_0^2) = b_1^{(0)} = (16\pi G_0)^{-1} = \frac{M_p^2}{2}$, with $G_0 = 6,7\,10^{-33} \hbar c^5 \mathrm{MeV}^{-2}$ the DPG measured value of Newton's constant measured at an energy scale μ_0, or the Planck mass $M_p \sim 2.4\,10^{15}\mathrm{MeV}$, then

$$\delta_{ct} = 2 \left(\xi - \frac{1}{6} \right) \frac{1}{\bar{\epsilon}} - B(\mu_0^2) + \frac{2(4\pi)^2}{16\pi m^2 G_0} \tag{9}$$

This fixes b_1 to be

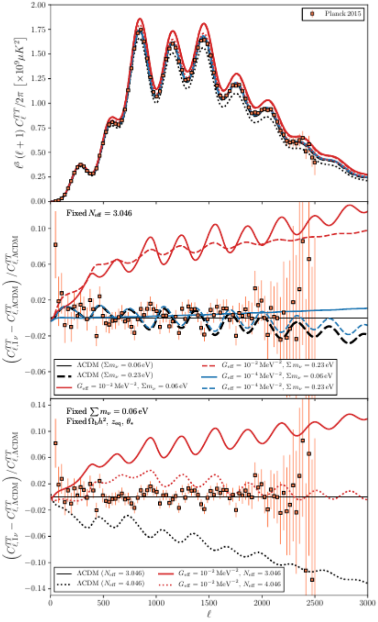
$$b_1(z) = \left[\frac{m^2}{2(4\pi)^2}\left(B(z) - B(\mu_0^2)\right) + \frac{1}{16\pi G_0}\right] \tag{10}$$

and the associated beta function would be

$$\beta_{b_1} \overset{notquiteright}{=} -\frac{m^2}{2(4\pi)^2}\frac{\mu_0\partial}{\partial_{\mu_0}}B(\mu_0^2) \tag{11}$$

There is one subtle point: the form factor associated to a_3 and b_1 is the same. In order to disentangle this, the first proposal is

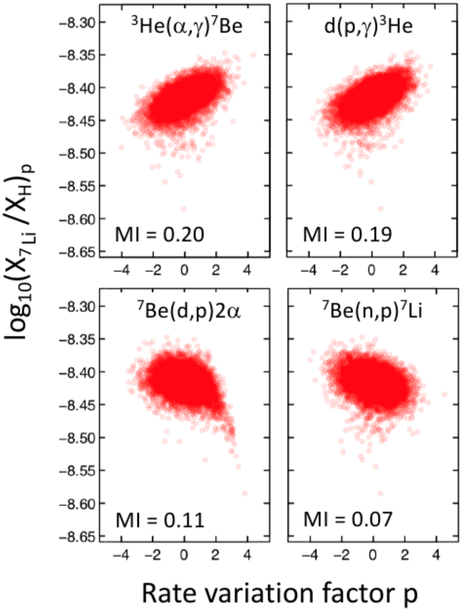
$$\beta_{a_3} \ = \ -\frac{1}{(4\pi)^2}\, z\,\partial_z\left[\frac{B(z) - B(0)}{z}\right], \qquad \beta_{b_1} \ = \ \frac{m^2}{(4\pi)^2}\, z\,\partial_z\Big[B(z) - B_\infty(z)\Big]. \tag{12}$$



Kreisch+ 2019

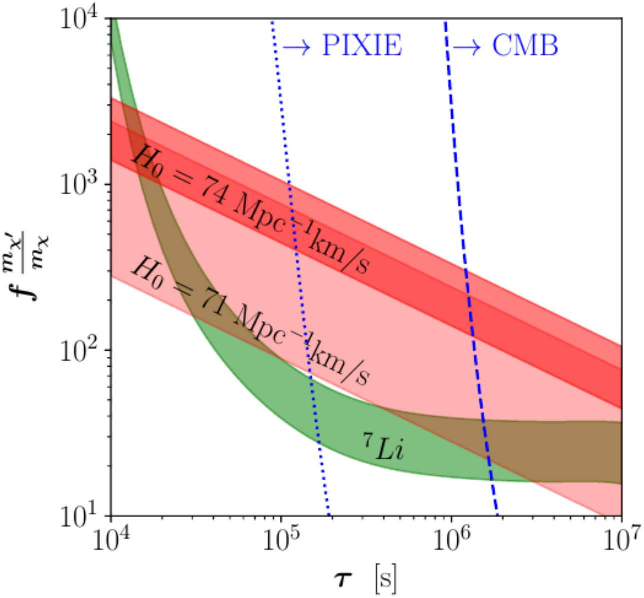
Self-interaction counterbalances the excess of damping caused by an additional neutrino

Mutual information: the system develops new minima but for larger $|p|$



Iliadis, Coc 2020

Light dark matter: decay process
$\chi' \to \chi + \gamma$



Alcaniz, Bernal, Masiero, Queiroz 2020

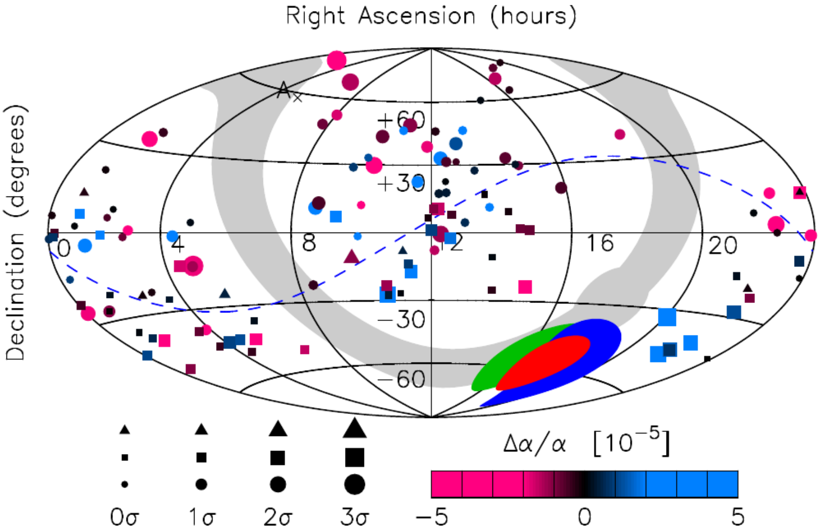
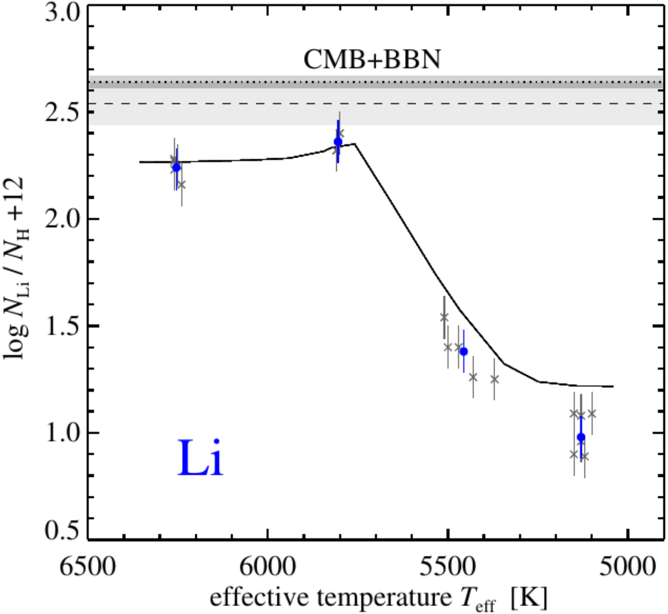


FIG. 5. Supplementary figure. Same all-sky illustration as in Fig. 1 showing the combined Keck and VLT $\Delta\alpha/\alpha$ measurements. Squares are VLT points. Circles are Keck points. Triangles are quasars observed at both Keck and VLT. Symbol size indicates deviation of $\Delta\alpha/\alpha$ from zero, i.e. $\Delta\alpha/\alpha = A\cos\Theta$. The blue dashed line shows the equatorial region. The grey shaded area shows the Galactic plane with the Galactic centre indicated as a bulge. More and larger blue squares are seen closer to the α-pole (red filled area) and more and larger red circles are seen closer to the α-antipole.

Webb, Flambaum+ 2011

With depletion



Korn+ 2006

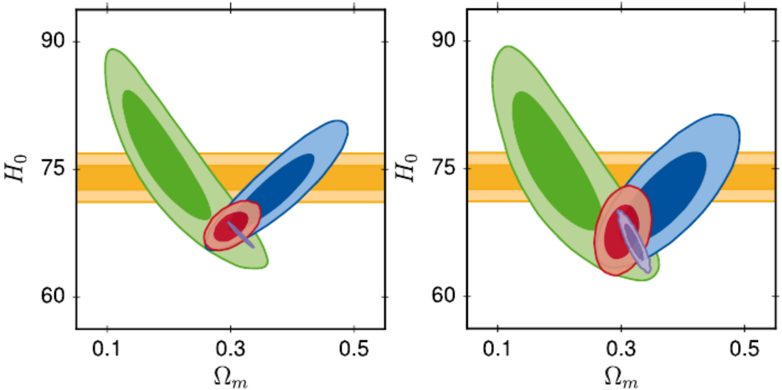
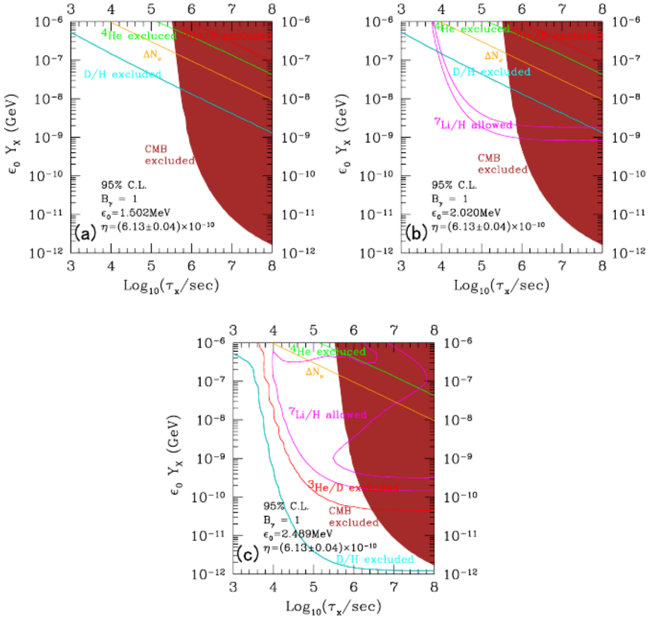


Figure 2: 68% and 95% confidence levels on Ω_m and H_0 with various data sets: BAO+BBN for galaxy BAO (blue), Lyman-α BAO (green), and combined (red). Additionally displayed is the Riess et al 2019 measurement (orange), and the Planck 2018 measurement (purple). **Left:** Minimal ΛCDM model. **Right:** The ΛCDM model extended with N_{eff} .

Schöneberg+ 2019

The tension between CMB and late measurements can be rephrased as a tension between BBN and late measurements



Decaying $X \to \gamma\gamma$

Kawasaki+ 2021

Main reactions

1: $n \to p\,e\,\nu$
2: $n(p,\gamma)d$
3: $d(d,p)t$
4: $d(p,\gamma)^3\mathrm{He}$
5: $d(d,n)^3\mathrm{He}$
6: $^3\mathrm{He}(n,p)t$
7: $t(d,n)^4\mathrm{He}$
8: $d(d,\gamma)^4\mathrm{He}$
9: $^3\mathrm{He}(d,p)^4\mathrm{He}$
10: $t(\alpha,\gamma)^7\mathrm{Li}$
11: $^4\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$
12: $^7\mathrm{Be}(n,p)^7\mathrm{Li}$
13: $^7\mathrm{Be} + d \to {}^9\mathrm{B}^*$
14: $^7\mathrm{Be} + {}^3\mathrm{He} \to {}^{10}\mathrm{C}^*$

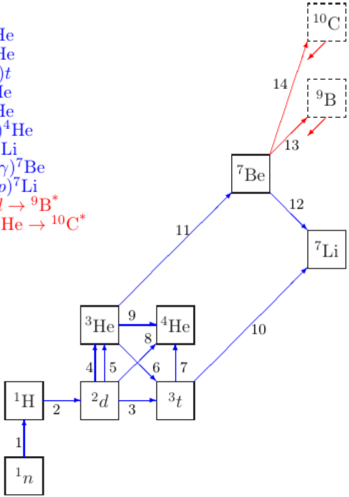
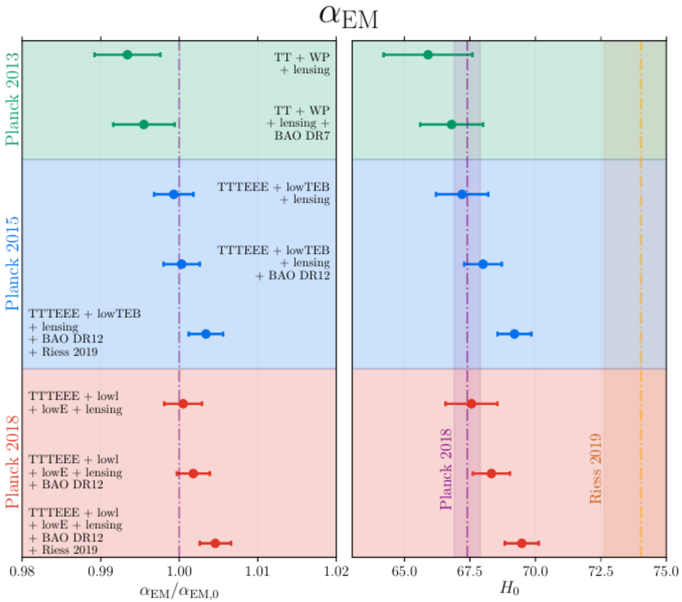


Figure 1: Simplified BBN nuclear network: 12 normally important reactions shown in blue, and proposed/tested new reactions in red.

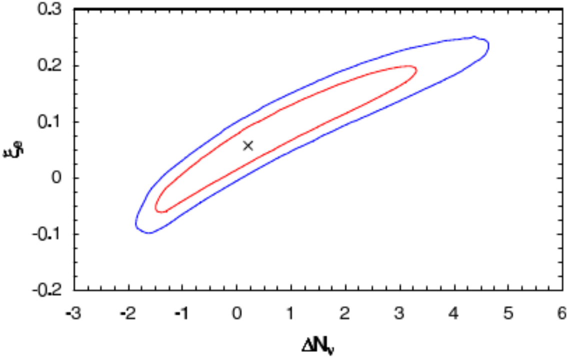
Fields 2012



Hart and Chluba 2020

Best CMB fit of varying α

Degeneracy parameters $\xi = \mu/T$ can hide the $\Delta N_{\rm eff}$



Steigman+ 2003

Variant	Y_p	D/H	^{3}He/H	^{7}Li/H	^{6}Li/H
η (6.1×10^{-10})	0.039	-1.598	-0.585	2.113	-1.512
N_ν (3.0)	0.163	0.395	0.140	-0.284	0.603
G_N	0.354	0.948	0.335	-0.727	1.400
n-decay	0.729	0.409	0.145	0.429	1.372
p(n,γ)d	0.005	-0.194	0.088	1.339	-0.189
^{3}He(n,p)t	0.000	0.023	-0.170	-0.267	0.023
^{7}Be(n,p)^{7}Li	0.000	0.000	0.000	-0.705	0.000
d(p,γ)^{3}He	0.000	-0.312	0.375	0.589	-0.311
d(d,γ)^{4}He	0.000	0.000	0.000	0.000	0.000
^{7}Li(p,α)^{4}He	0.000	0.000	0.000	-0.056	0.000
d(α,γ)^{6}Li	0.000	0.000	0.000	0.000	1.000

Sensitivities of the yields on several variations