COSMO ESPRESSO
Cosmology and Fundamental Physics with ESPRESSO

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BBN: Concordance or New Physics?

Testing the Universality of Physical Laws at the BBN Epoch

Carlos.Martins@astro.up.pt

So, What's Your Point?

The observed acceleration of the universe shows that our theories of cosmology and particle physics are incomplete (or incorrect?)

Our current ΛCDM model is clearly a simple (though convenient) approximation to a more fundamental theory

New physics is out there, waiting to be discovered; astrophysical facilities must search for, identify and characterize this new physics

In what follows I highlight BBN's role in testing the universality of physical laws

Scalars, Because They Are There

We know since 2012 (thanks to the LHC) that fundamental scalar fields are among Nature's building blocks

→ Widely used in cosmology, e.g., inflation, cosmic defects, dynamical dark energy, dynamical fundamental couplings, ...

Cosmological scalar fields will naturally couple to the rest of the model, leading to long-range forces and 'varying constants'

→ *Cf. Dicke 1964, Carroll 1998, Damour & Donoghue 2010, ...*

E.g., electromagnetic sector couplings yield spacetime variations of the fine-structure constant, with multiple testable fingerprints

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Review

The status of varying constants: a review of the physics, searches and implications

C J A P Martins

Centro de Astrofísica da Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal
Instituto de Astrofísica e Ciências do Espaço, CAUP, Rua das Estrelas, 4150-762 Porto, Portugal

E-mail: Carlos.Martins@astro.up.pt

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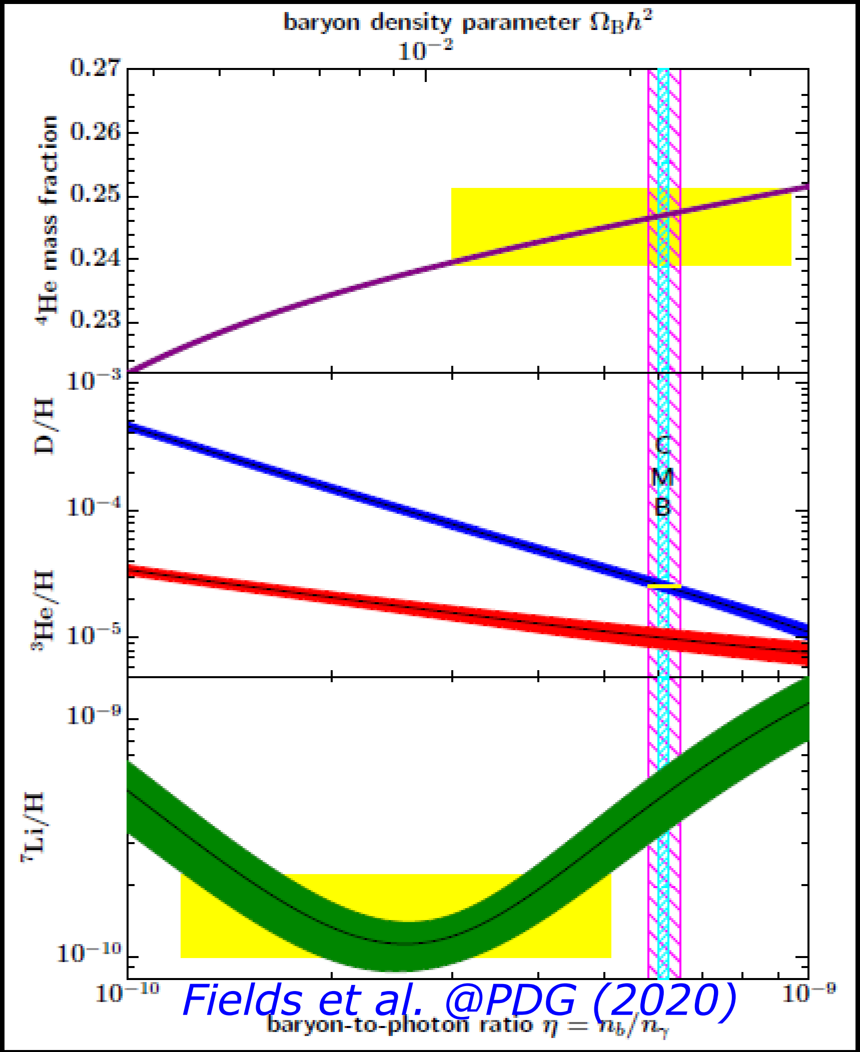
Self-Consistent Perturbative Analysis



BBN is a cornerstone of Hot Big Bang model, limited by the long-standing Li7 problem

→Is there a further D problem? [Pitrou et al. 2020]

If a fiducial theoretical model is chosen and sensitivity coefficients are known, can be studied perturbatively *[Pitrou et al. 2018]*

$$\frac{\Delta Y_i}{Y_i} = \sum_j C_{ij} \frac{\Delta X_j}{X_j}$$

Well-known for neutron lifetime, number of neutrinos and baryon-to-photon ratio, etc. Recently extended for GUT models in Clara & Martins 2020, Martins 2021, +in prep.

Builds upon Muller at al. 2004, Flambaum & Wiringa 2007, Coc et al. 2007, Dent et al. 2007, ...

BBN With GUTs: Early Results

In the published work, fiducial theoretical model is Pitrou et al. 2018, and data is from PDG2018

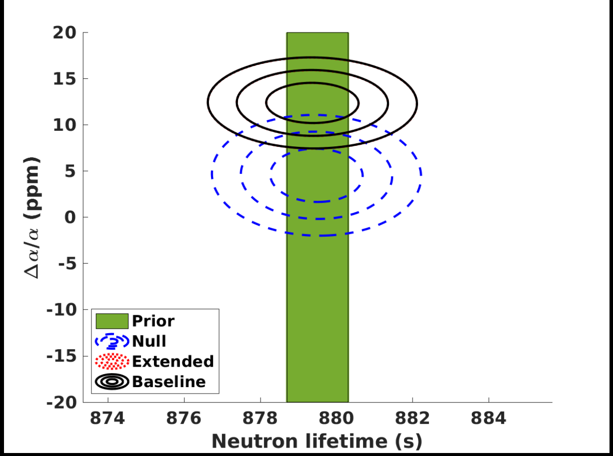
Abundance	Theoretical	Observed
Y_p	0.24709 ± 0.00017	0.245 ± 0.003
$(D/H) \times 10^5$	2.459 ± 0.036	2.545 ± 0.025
$(^3He/H) \times 10^5$	1.074 ± 0.026	1.1 ± 0.2
$(^7Li/H) \times 10^{10}$	5.624 ± 0.245	1.6 ± 0.3

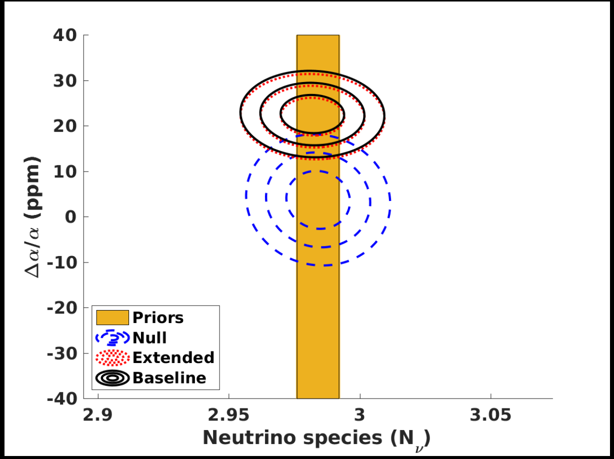
Three fiducial GUT models where all couplings are allowed to vary

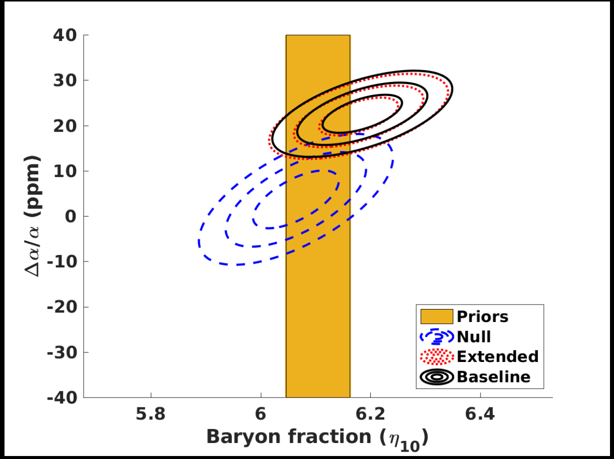
Unification (R & S fixed), cf. Coc et al. 2007
Dilaton (R & S fixed), cf. Nakashima et al. 2010
Clocks (R & S free) cf. Ferreira et al. 2012

$$\frac{\Delta Y_i}{Y_i} = (x_i + y_i S + z_i R)\frac{\Delta\alpha}{\alpha}$$

Examples: τ_n in Unification model, N_ν and η_{10} in Dilaton model







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$$\frac{\Delta Y_i}{Y_i} = (x_i + y_i S + z_i R)\frac{\Delta\alpha}{\alpha}$$

GUTs are a possible solution to the Li7 problem, for values of α at the BBN epoch larger than the local one by O(10) ppm of relative variation

Scenarios	Unification	Dilaton	Clocks
Paper 1 (Baseline)	12.5 ± 2.9	19.9 ± 4.5	$2.2^{+15.6}_{-0.6}$
Paper 1 (Null)	4.6 ± 3.8	5.8 ± 6.5	$1.0^{+7.1}_{-0.9}$
Paper 2 (Baseline)	16.1 ± 3.9	22.6 ± 5.5	$2.5^{+3.5}_{-0.5}$
Paper 2 (Null)	4.6 ± 5.5	3.7 ± 8.4	$0.8^{+1.5}_{-0.6}$

Best-fit values in ppm and $\Delta\chi^2=4$ range, with other parameters marginalized

If Li7 is excluded from the analysis, one obtains competitive limits on α variations (comparable to QSO ones and much stronger than CMB ones)

BBN With GUTs: Latest Results

Caveat: the following results are not yet peer-reviewed

From here onwards the fiducial theoretical model is the one in Pitrou et al. 2020, and the observed abundances from PDG2020

Abundance	Theoretical	Observed
Y_p	0.24721 ± 0.00014	0.245 ± 0.003
$(D/H) \times 10^5$	2.439 ± 0.037	2.547 ± 0.025
$(^3He/H) \times 10^5$	1.039 ± 0.014	1.1 ± 0.2
$(^7Li/H) \times 10^{10}$	5.464 ± 0.220	1.6 ± 0.3

The following priors are used (also cf. PDG2020)

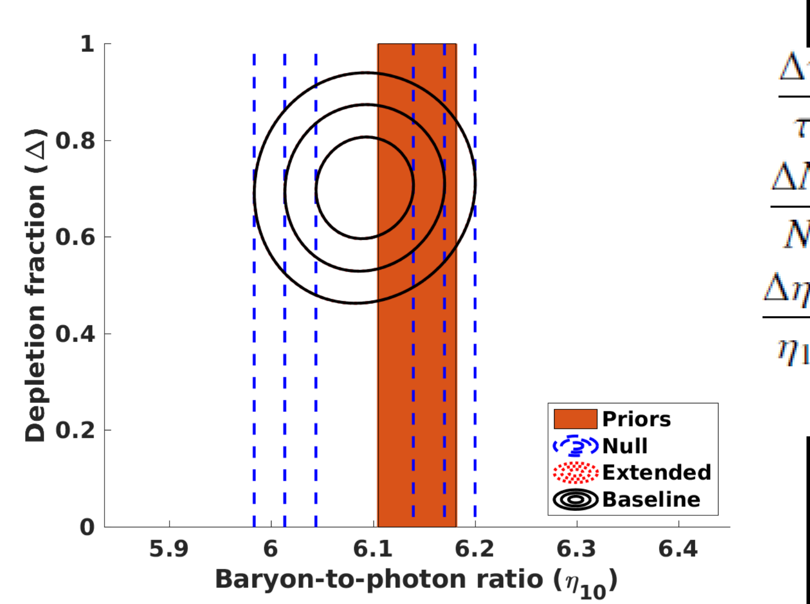
$\tau_n = 879.4 \pm 0.6\, s$

$N_\nu = 2.984 \pm 0.008$

$\eta_{10} = 6.143 \pm 0.038$

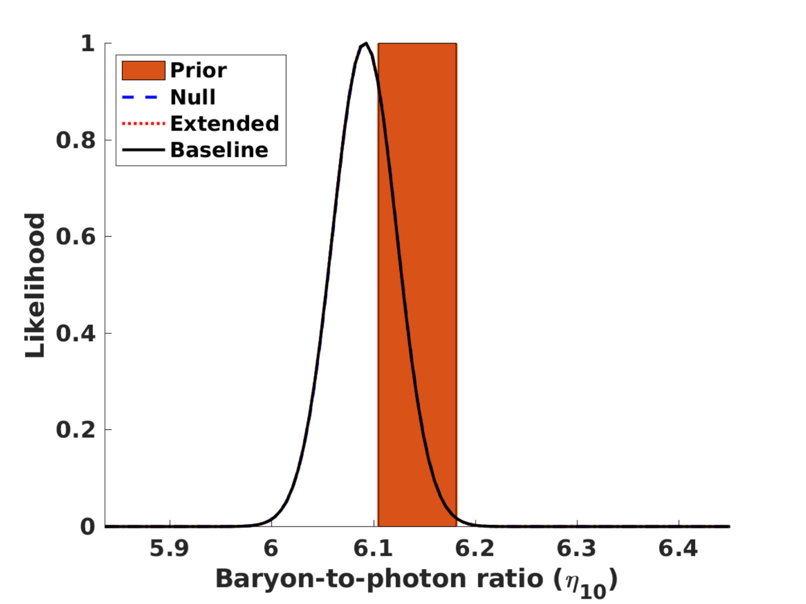
Li7 Depletion in the Standard Model

Phenomenological parametrization $(7Li)_{ast} = (1 - \Delta)(7Li)_{cos}$



$$\frac{\Delta\tau_n}{\tau_n} = 0.0000 \pm 0.0007$$
$$\frac{\Delta N_\nu}{N_\nu} = 0.0004 \pm 0.0022$$
$$\frac{\Delta\eta_{10}}{\eta_{10}} = -0.0082 \pm 0.0050$$
$$\Delta = 0.70 \pm 0.07$$

Best-fit values and $\Delta\chi^2$=1 range, with other parameters marginalized



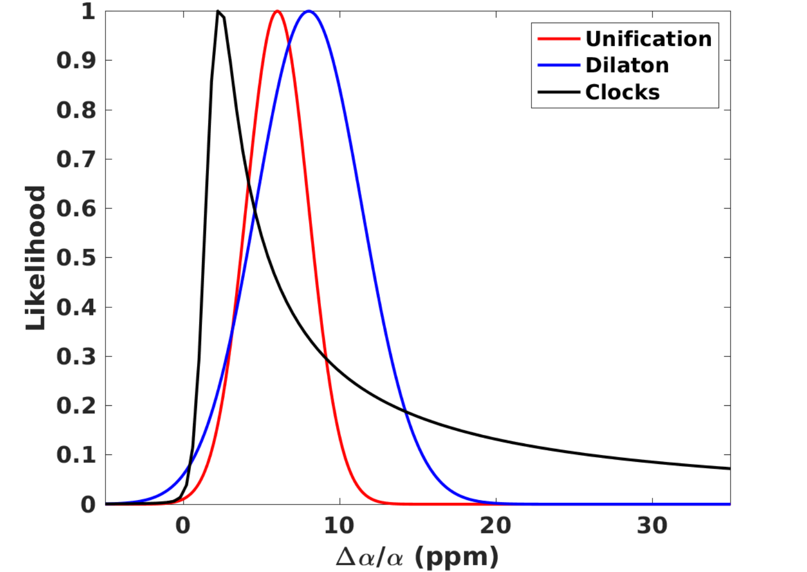
Small discrepancy in preferred values of η_{10} in CMB+BAO and BBN, previously noted by Pitrou et al. 2020 and Yeh et al. 2020

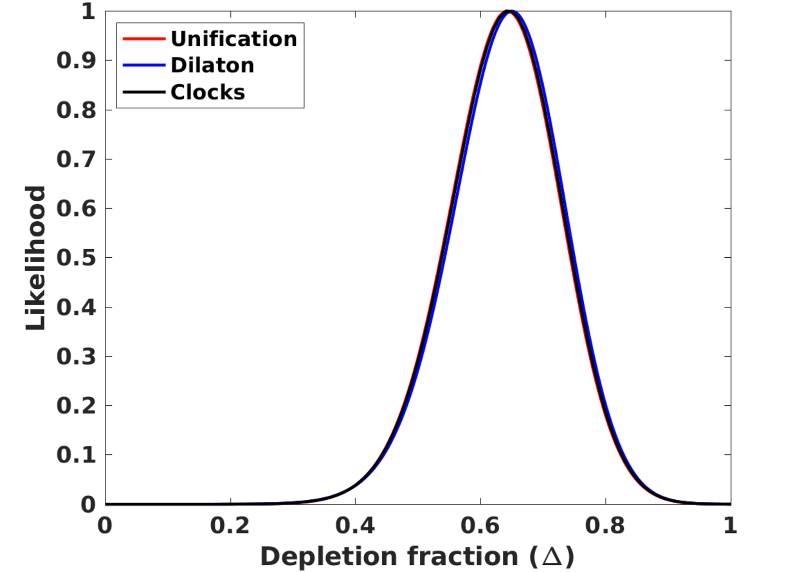
Li7 Depletion in GUTs

Best-fit values and $\Delta\chi^2$=1 range, with other parameters marginalized

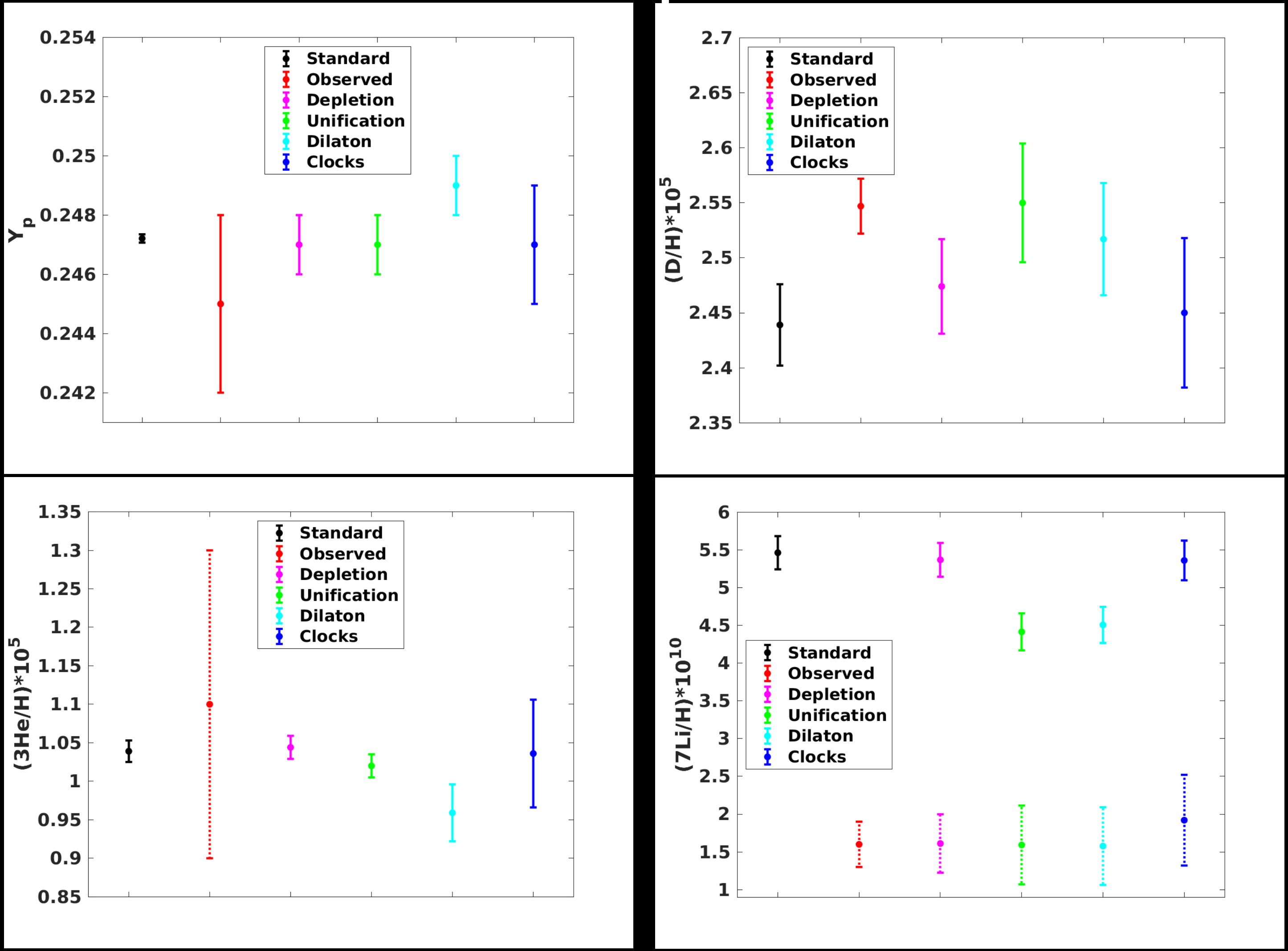
Parameter	Unification	Dilaton	Clocks
$\frac{\Delta\alpha}{\alpha}$ (ppm), Baseline	6.0 ± 2.0	8.0 ± 3.4	$2.2^{+2.4}_{0.8}$
Δ	0.64 ± 0.09	0.65 ± 0.09	0.64 ± 0.09
Y_p	0.247 ± 0.001	0.249 ± 0.001	0.247 ± 0.002
$(D/H) \times 10^5$	2.55 ± 0.05	2.52 ± 0.05	2.45 ± 0.07
$(^3He/H) \times 10^5$	1.02 ± 0.02	0.96 ± 0.04	1.04 ± 0.07
$(^7Li/H) \times 10^{10}$ (Cos)	4.42 ± 0.25	4.51 ± 0.24	5.36 ± 0.26
$(^7Li/H) \times 10^{10}$ (Ast)	1.59 ± 0.52	1.58 ± 0.52	1.92 ± 0.60

Few ppm values of α still mildly preferred in all three models, with reduced astrophysical depletion (by ca. 1σ)





Best-fit GUT+Depletion Models



One-sigma ranges are shown throughout

Astrophysical (i.e., not cosmological) values shown with dotted bars

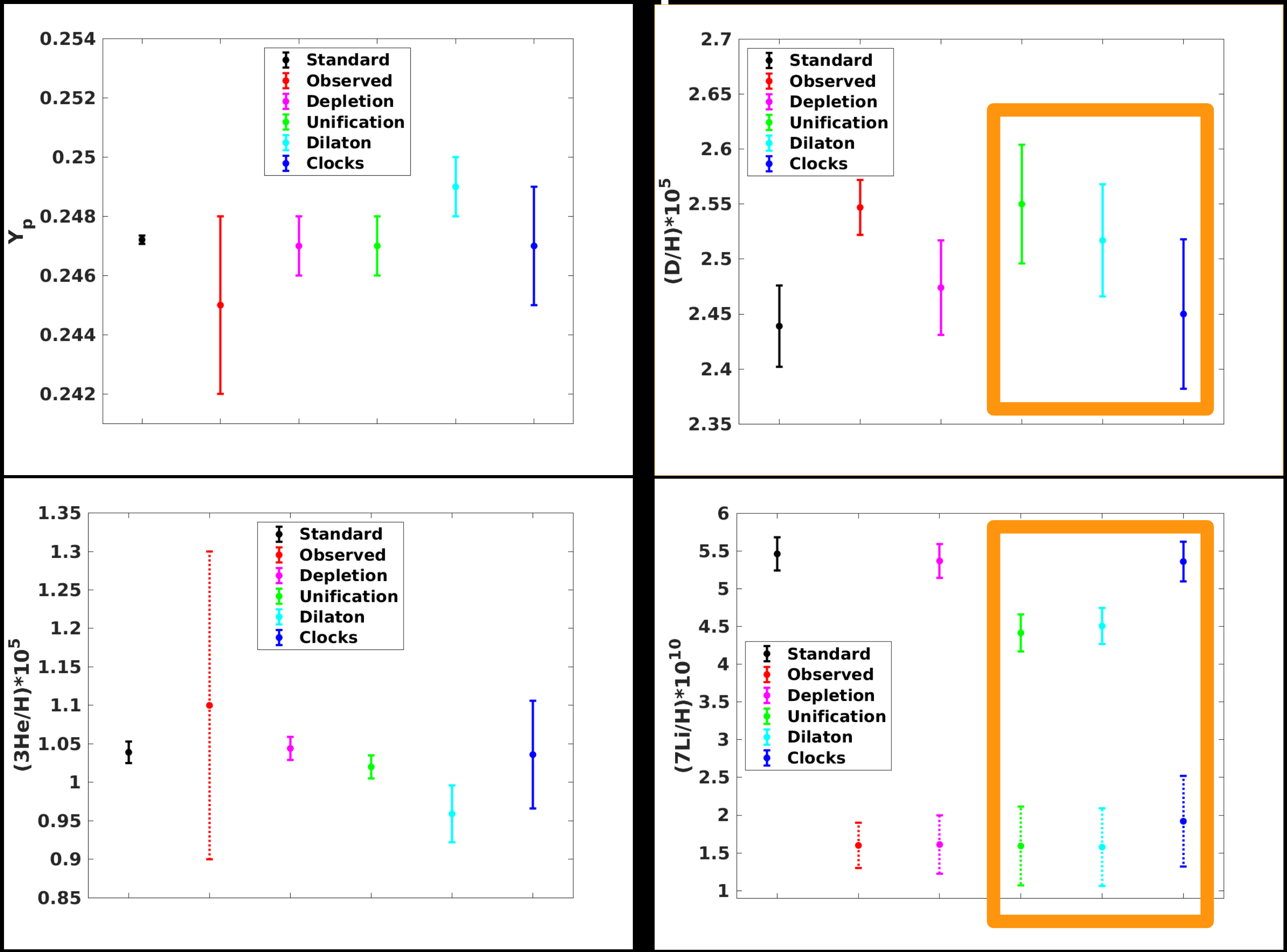
Points to note

→D/Li7 anticorrelation

→He4/He3 anticorrelation

→Different predictions of Unification and Dilaton, testable with better data

Best-fit GUT+Depletion Models



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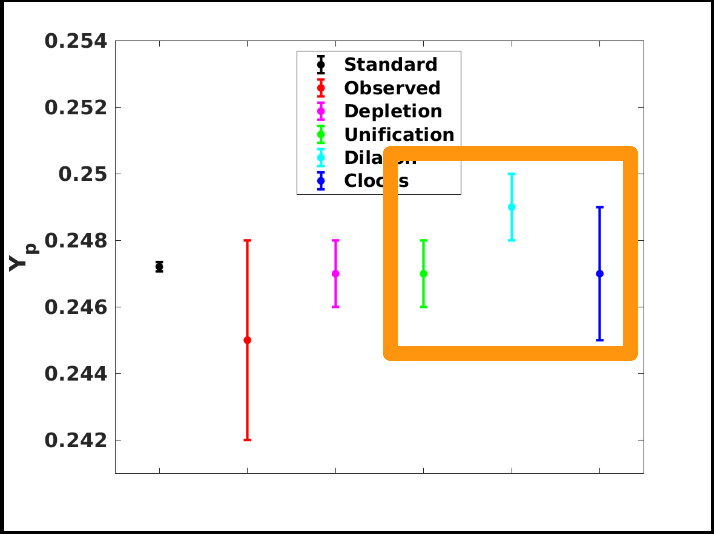

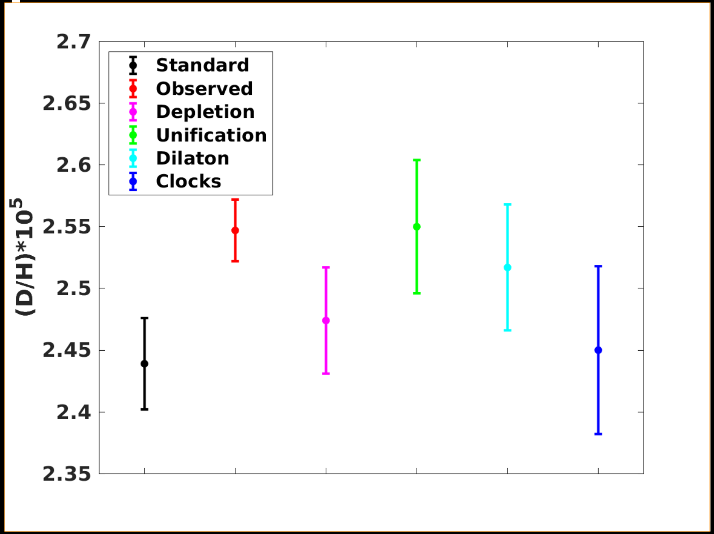

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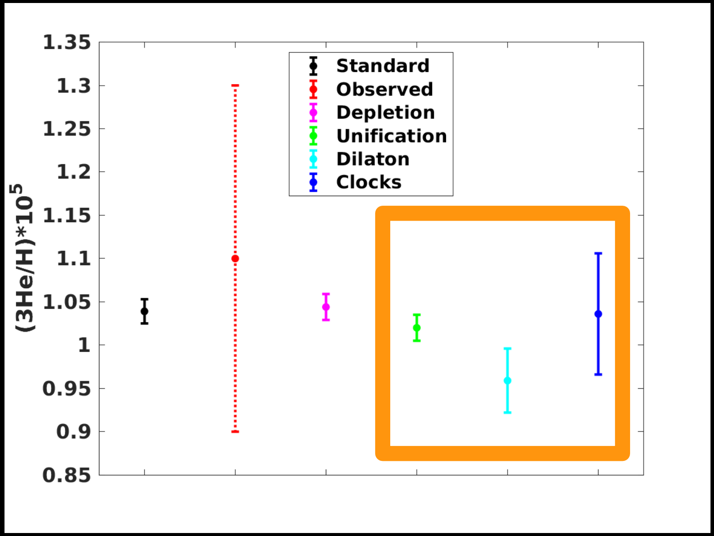

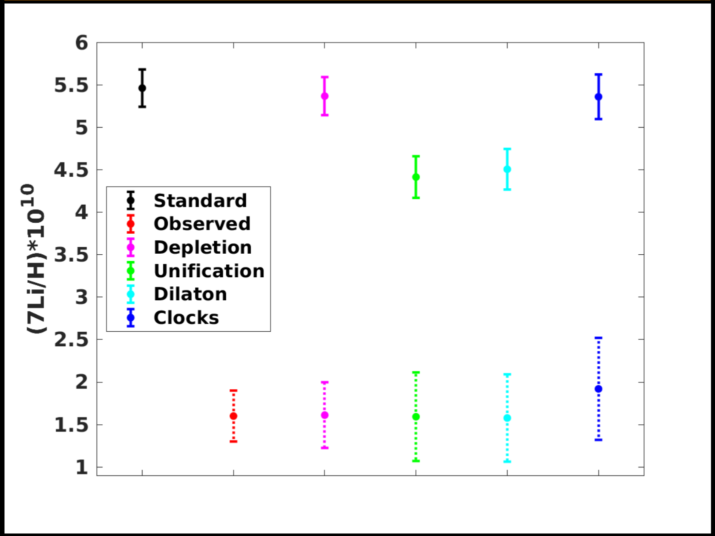

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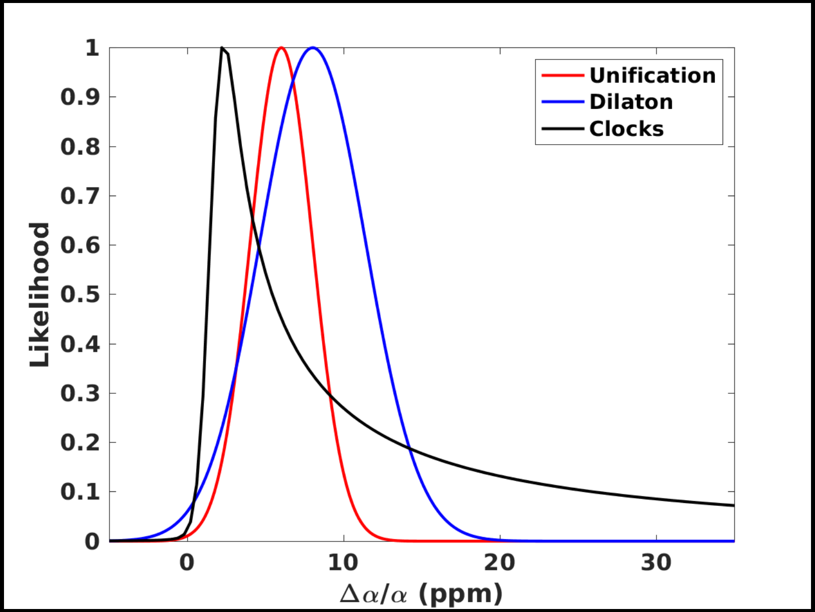
→Different predictions of Unification and Dilaton, testable with better data

What Drives the α Value?



Parameter	Unification	Dilaton	Clocks
$\frac{\Delta\alpha}{\alpha}$ (ppm), Baseline	6.0 ± 2.0	8.0 ± 3.4	$2.2^{+2.4}_{0.8}$
Δ	0.64 ± 0.09	0.65 ± 0.09	0.64 ± 0.09
Y_p	0.247 ± 0.001	0.249 ± 0.001	0.247 ± 0.002
$(D/H) \times 10^5$	2.55 ± 0.05	2.52 ± 0.05	2.45 ± 0.07
$(^3He/H) \times 10^5$	1.02 ± 0.02	0.96 ± 0.04	1.04 ± 0.07
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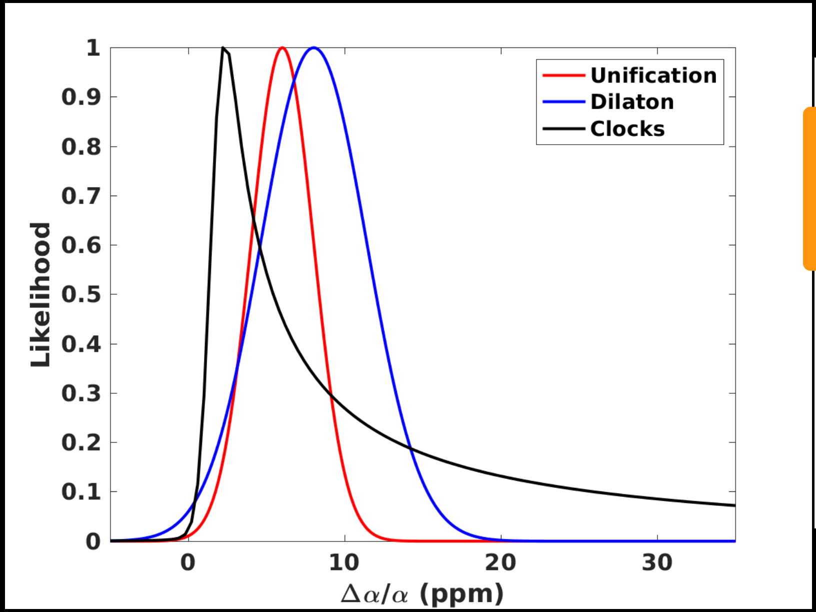
Best-fit values and $\Delta\chi^2$=1 range, with other parameters marginalized

What are the roles of each of the abundances in these constraints?

What Drives the α Value?



Parameter	Unification	Dilaton	Clocks
$\frac{\Delta\alpha}{\alpha}$ (ppm), Null	5.8 ± 2.0	7.3 ± 3.3	$2.2^{+2.4}_{0.8}$
$\frac{\Delta\alpha}{\alpha}$ (ppm), Baseline	6.0 ± 2.0	8.0 ± 3.4	$2.2^{+2.4}_{0.8}$
Δ	0.64 ± 0.09	0.65 ± 0.09	0.64 ± 0.09
Y_p	0.247 ± 0.001	0.249 ± 0.001	0.247 ± 0.002
$(D/H) \times 10^5$	2.55 ± 0.05	2.52 ± 0.05	2.45 ± 0.07
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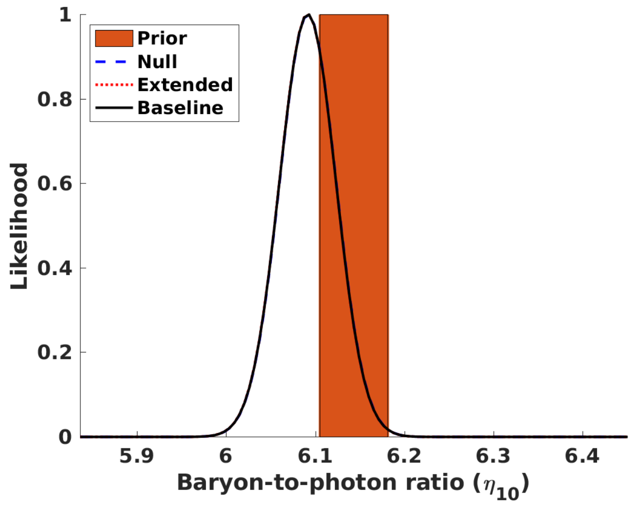
Best-fit values and $\Delta\chi^2$=1 range, with other parameters marginalized

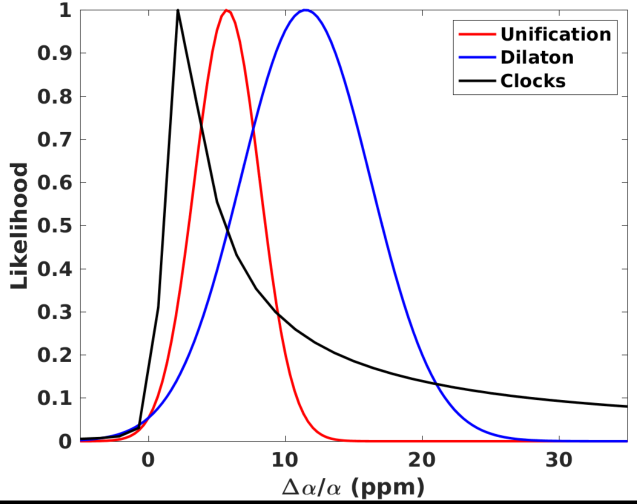
The preference for a $(\Delta\alpha/\alpha)>0$ is <u>not</u> due to the Lithium7 problem

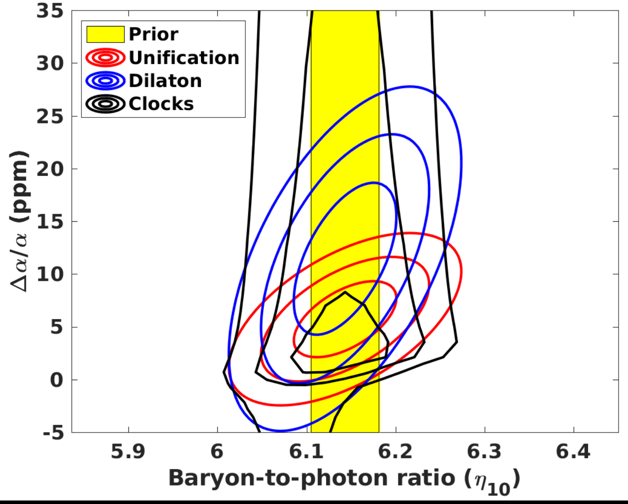
The Deuterium Discrepancy

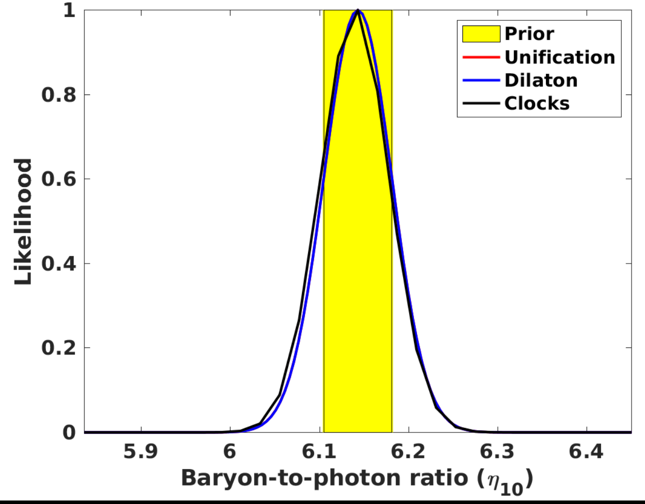
A few ppm α variation solves D discrepancy (i.e., the different CMB and BBN values for η_{10}), given their positive correlation

This helps with the Li7 problem, reducing the astrophysical depletion required







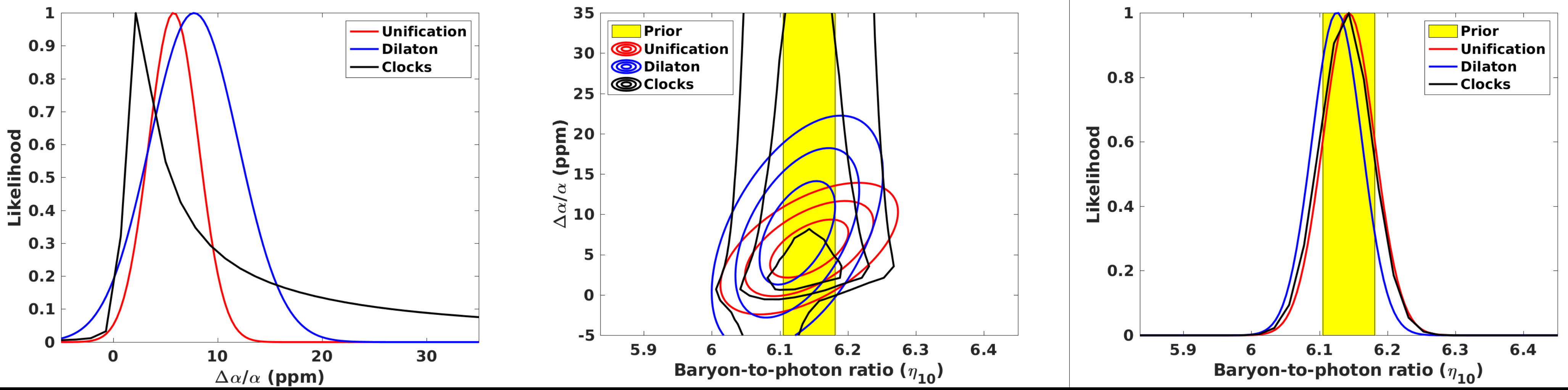


Does Helium4 Matter?

Data	Parameters	Unification	Dilaton	Clocks
D only	Fixed	5.8 ± 2.0	10.9 ± 3.8	$2.3^{+2.1}_{-0.8}$
D only	Marginalized	5.7 ± 2.7	11.3 ± 4.8	$2.1^{+2.9}_{-0.9}$
D + He4	Fixed	5.8 ± 2.0	7.7 ± 3.4	$2.2^{+2.4}_{-0.8}$
D + He4	Marginalized	5.7 ± 2.7	7.7 ± 4.3	$2.1^{+2.7}_{-0.9}$

Best-fit values and $\Delta\chi^2$=1 range, with other parameters marginalized

Not much with the current data, but do note that the answer is model-dependent



A Wish List

Improving observed abundances of Deuterium and Helium4 by factor of 2-3 → stringent test of these models (and α variation)

Closing the loop: a cosmological measurement of the Helium3 abundance → key consistency test of the underlying physics

Improved understanding of the possible astrophysical depletion mechanisms of Lithium7 (cf. work in progress with M.Deal)

So, What's Your Point?

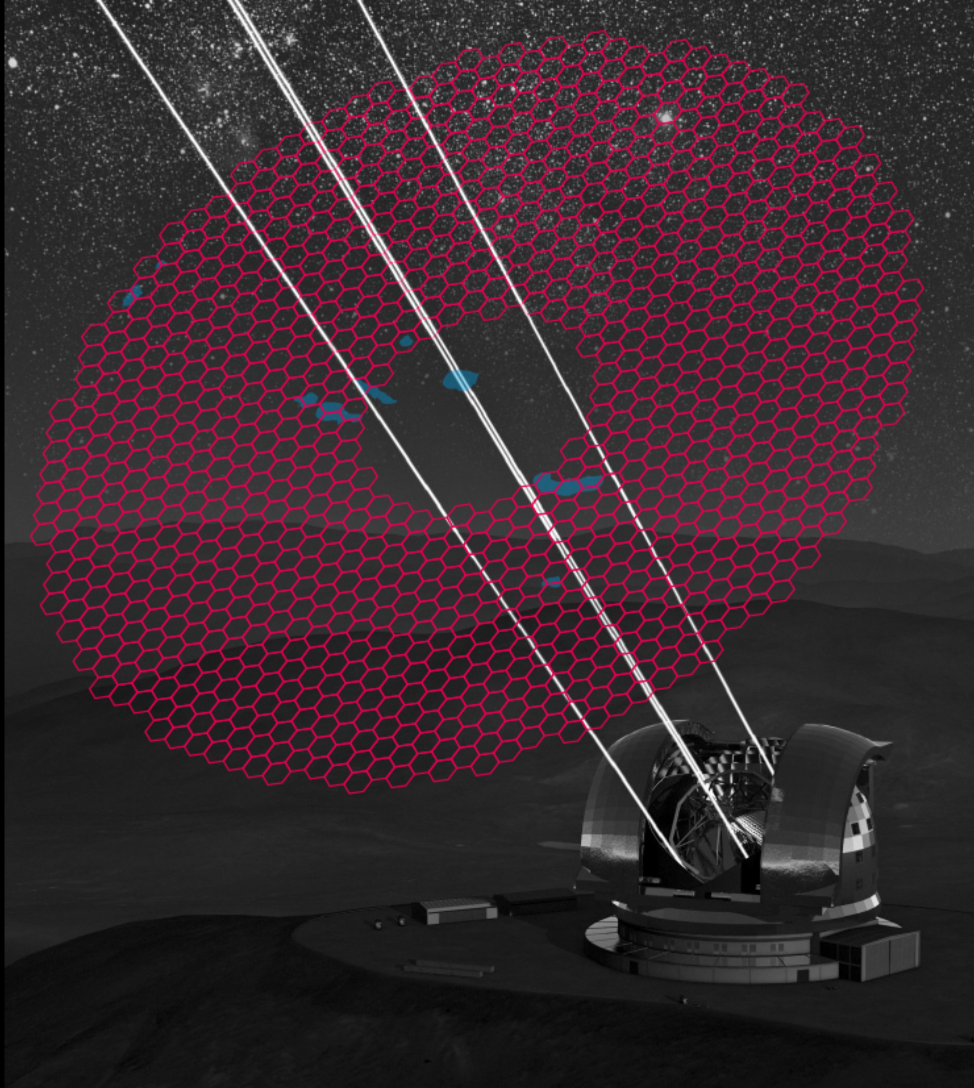
BBN is a very sensitive probe of new physics

The currently available BBN data shows a mild (2-3 standard deviations) preference for $(\Delta\alpha/\alpha)>0$, at the parts per million level

→ *Such variations would be consistent with all other existing α constraints*

Future data (e.g., from the ELT) will enable stringent tests of fundamental physics paradigms

For ESO: Beware critical requirement of efficient blue wavelength coverage (also essential for other fundamental physics tests)



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A hands-on school to prepare the next generation of astrophysicists for the quest for the new physics responsible for the dark universe, in the context of the ELT and forthcoming space facilities.

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