

Varying Higgs VEV Cosmology and an Axionic Solution

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Based on [2102.11257] and [2105.01631]

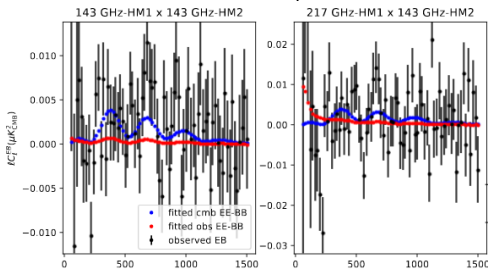
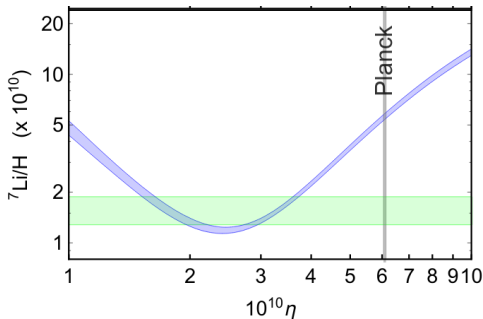
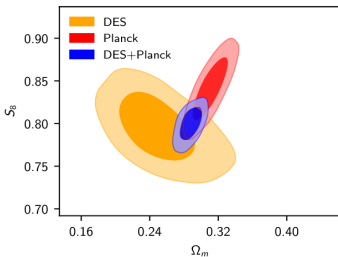
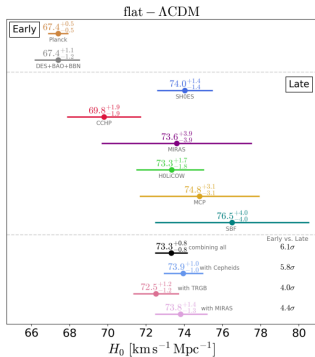
w/ Leo WH Fung, Tao Liu, Hoang Nhan Luu, Yu-Cheng Qiu and S.-H. Henry Tye

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Tension in Λ CDM

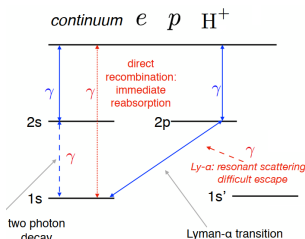
- ▶ From CMB and local measurements: $H_{0,\text{P18}} = 67.36 \pm 0.54$ km/s/Mpc [Aghanim et al., 2020] vs. $H_{0,\text{late}} = 73.3 \pm 0.8$ km/s/Mpc [Verde et al., 2019] from $z \lesssim 2$.
- ▶ From Big Bang Nucleosynthesis (BBN): the abundance ratio ${}^7\text{Li}/\text{H} \times 10^{10}$: 1.6 ± 0.3 (observed) vs. 5.6 ± 0.3 (theoretical) [Zyla et al., 2020, Pitrou et al., 2018, Iliadis and Coc, 2020].
- ▶ The weak lensing measurement of S_8 together with the clustering parameter σ_8 [Troxel et al., 2018] yields a value smaller $S_{8,\text{DES}} = 0.773^{+0.026}_{-0.020}$ than that given by the CMB- Λ CDM value: $S_{8,\text{CMB}} = 0.832 \pm 0.013$.
- ▶ Recently measurement of isotropic cosmic birefringence (ICB) based on the cross-power (parity-violating) C_l^{EB} data in CMB [Minami and Komatsu, 2020], deviate from 0 by $\sim 2.4\sigma$.



[Verde et al., 2019, Pitrou et al., 2018, Handley and Lemos, 2019, Minami and Komatsu, 2020]

Overview: Changing VEV by an Axion

Tension in H_0 can be alleviated if m_e is $\mathcal{O}(1\%)$ heavier when $z \sim 1100$ (recombination) [Ade et al., 2015, Hart and Chluba, 2020]



- ▶ The Bohr radius $\downarrow$ as $m_e \uparrow$
- ▶ Earlier “freeze out” of recombination.
- ▶ During BBN, $m_q \uparrow$ makes ${}^7\text{Li} \downarrow$.

A slowly changing field that moves $v \propto m_e$: the axion.

- ▶ Introduces a time scale $\gtrsim \mathcal{O}(10^6)$ yrs, $m_a \lesssim 3 \times 10^{-29}$ eV.
- ▶ A light scalar suppresses structure formation (σ_8 tension resolved).
- ▶ The $aF^{\mu\nu}\tilde{F}_{\mu\nu}$ coupling leading to non-zero ICB [Fujita et al., 2020]

CMB: Earlier Recombination

The angular sound horizon $\theta_* = \frac{r_*}{D_*}$
(determines the separation between acoustic peaks)

$$r_* = \int_{z_*}^{\infty} dz \frac{c_s(z)}{H(z)}, \quad D_* = \int_0^{z_*} dz \frac{1}{H(z)}. \quad (1)$$

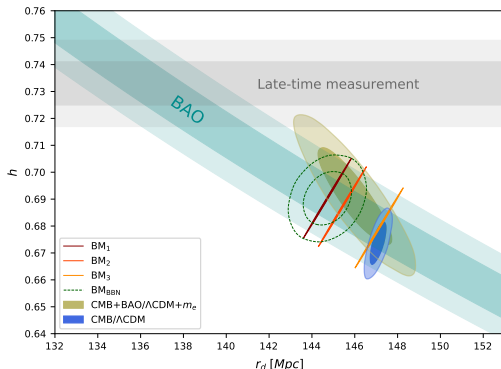
Earlier recombination $\Rightarrow$ higher H_0

- ▶ For r_* , major contribution comes from integration near z_* , earlier z_* reduces r_* .
- ▶ D_* hardly feels the change as it is dominated by late time expansion.
 $\Rightarrow \frac{\partial \log(r_*)}{\partial \log(z_*)} \simeq -0.66$, $\frac{\partial \log(D_*)}{\partial \log(z_*)} \sim -10^{-2}$.
- ▶ Compensated by a larger H_0 (effective when $z \ll z_*$), θ_* fixed.

CMB Preference

The two most important (so far) constraints:

$$(r_d h)_{\text{BAO}} = (99.95 \pm 1.20) \text{ Mpc} , \quad (\theta_*)_{\text{CMB}} = (1.04110 \pm 0.00031) \times 10^{-2} .$$



Relative to Planck18 fit values,
Changing v by (1-4)%:

- ▶ Increased h : $\gtrsim 0.69$
- ▶ ω_c increases by a few%

Axion as the Modulator of VEV

The minimal coupling (ϕ = Higgs , a = axion):

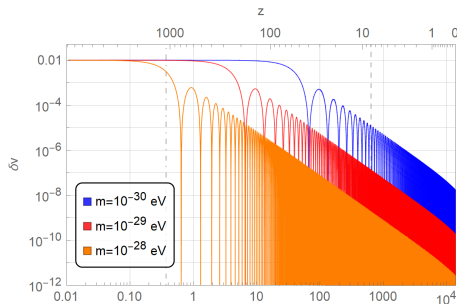
$$V(\phi, a) \sim V_{\text{SM}} = \mu^2 |\phi|^2 + \frac{\kappa}{4} |\phi|^4 ,$$

$$\mu^2 \mapsto \mu^2 (1 + \text{const} \times \frac{a^2}{M_{\text{PL}}^2}) , \quad \kappa \mapsto \kappa (1 + \text{const}' \times \frac{a^2}{M_{\text{PL}}^2}) ,$$

$$W \supset X(m_s^2 G(A) - \kappa K(A) H_u H_d) \rightarrow V_\phi = |m_s^2 G(a) - \kappa K(a) \phi^\dagger \phi|^2 .$$

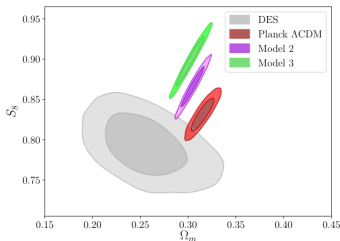
“Misalignment” with $m_a \lesssim 10^{-29} \text{eV}$:

- ▶ Higgs always in the bottom.
- ▶ $a \rightarrow$ sub-component of DM.
- ▶ $x \equiv \rho(\text{axion DM})/\rho(\text{all matter})$.
- ▶ $x \sim \mathcal{O}(1\%)$ when $f_a \sim M_{\text{PL}}$.



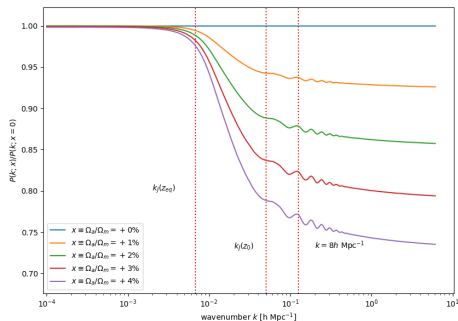
σ_8/S_8 Tension Resolved

The dilemma of early recombination solution of H_0 tension:
more CDM to fit CMB $\Rightarrow$ higher σ_8 [Jedamzik et al., 2020]

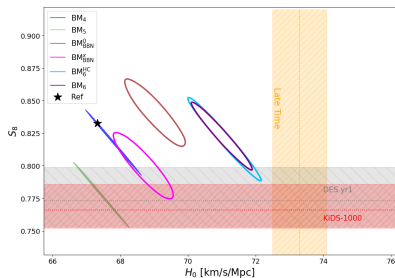


The axion quantum pressure and its potential force suppress the structural formation smaller than the Jeans scale.
[Marsh and Ferreira, 2010, Kobayashi et al., 2017].

$$\frac{\mathcal{P}_m^x(k)}{\mathcal{P}_m^0(k)} = \left(\frac{k_J(z_{\text{eq}})}{k} \right)^{10-2\sqrt{25-24x}} \quad (2)$$

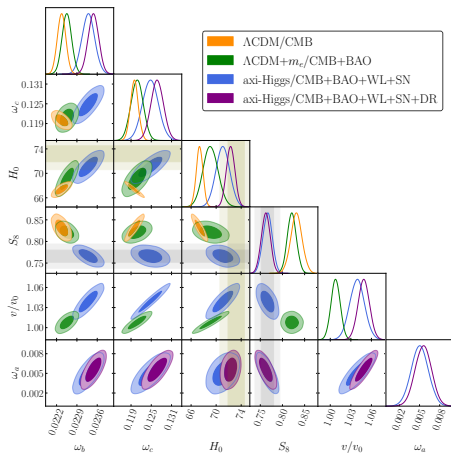


Constraints with Non-zero Axion DM



↑ Posterior distribution of S_8 vs. H_0 in different benchmarks

⇒ Posterior in the **Axi-Higgs** model vs. **Λ CDM** and **changing VEV** but no axion.



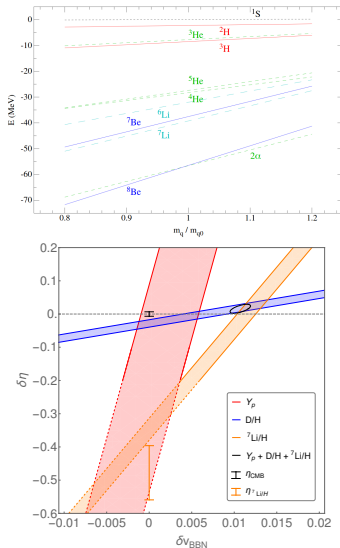
BBN: An Alternative VEV

Heuristically, the neutron to proton number ratio n/p can be written as [Hall et al., 2014]:

$$\frac{n}{p} \sim e^{-\frac{\Delta m_{np}}{T_{np}}} e^{-\frac{t_D}{\tau_n}}$$

- ▶ Fermi constant $G_F \propto v^{-2}$ that affect weak interactions. Larger $m_W \Rightarrow$ earlier $n \leftrightarrow p$ freeze out & longer τ_n .
- ▶ Electron mass $m_e \propto v$. Similar effect.
- ▶ Increasing the isospin-breaking $\Delta m_q \equiv m_d - m_u \propto v$ contributes to larger $\Delta m_{np} \equiv m_n - m_p \Rightarrow$ later $n \leftrightarrow p$ freeze out & shorter τ_n .
- ▶ Averaged light quark mass $\bar{m}_q \equiv (m_u + m_d)/2 \propto v$. The change of $\bar{m}_q$ may significantly influence the rates of strong/nuclear interactions. Essentially changes m_π , **making nuclei unstable**.

Compatibility with BBN and ${}^7\text{Li}$ Problem



Heavy nuclei more fragile as
 $m_q \uparrow \Rightarrow m_\pi \uparrow$, ${}^7\text{Li}$ production harder.
 [Flambaum and Wiringa, 2007]

$Y \backslash X$	m_W	m_e	Δm_q	$\bar{m}_q$	η
Y_p	2.9	0.40	-5.9	-1.0	0.039
D/H	1.6	0.59	-5.3	10	-1.6
${}^7\text{Li}/H$	1.7	-0.04	-5.3	-60	2.1

[Dent et al., 2007, Cheoun et al., 2011,
 Mori and Kusakabe, 2019]

► $\delta v \equiv (v_{\text{BBN}} - v_0)/v_0 \simeq 1\%$

► $\delta\eta \simeq \delta\omega_b \simeq 1 - 3\%$

Overlaps w/ CMB preference!

Isotropic Cosmic Birefringence

If the axion has a coupling with the EM gauge field as

$$\frac{1}{32\pi^2} \frac{a}{f_a} F \tilde{F} ,$$

the initial phase of axion breaks parity and rotate the linearly polarized CMB [Harari and Sikivie, 1992]:

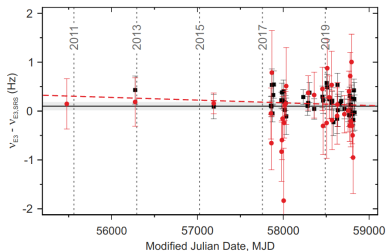
$$\beta = \frac{1}{16\pi^2 f_a} \int_{t_{\text{ini}}}^{t_0} dt \dot{a} = \frac{1}{16\pi^2 f_a} \left[a(t_0) - a(t_{\text{ini}}) \right] . \quad (3)$$

$$\beta \sim -\frac{1}{16\pi^2} \frac{a_{\text{ini}}}{f_a} = 0.35 \pm 0.14(\text{degree}), \quad \Rightarrow \quad \frac{a_{\text{ini}}}{f_a} \simeq 1.0 \pm 0.3 . \quad (4)$$

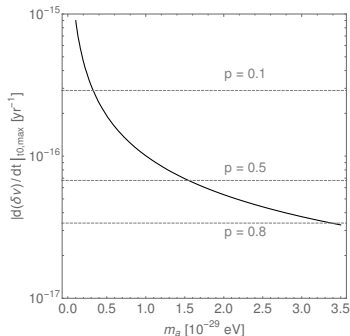
Observational Limits: Atomic Clocks

$d(\delta v)/dt$ limit from atomic clocks [Lange et al., 2021]:

$$\left. \frac{d(\delta v)}{dt} \right|_{t_0} \simeq \left. \frac{d(\delta \mu)}{dt} \right|_{t_0} = (0.08 \pm 0.36) \times 10^{-16} \text{ yr}^{-1}$$



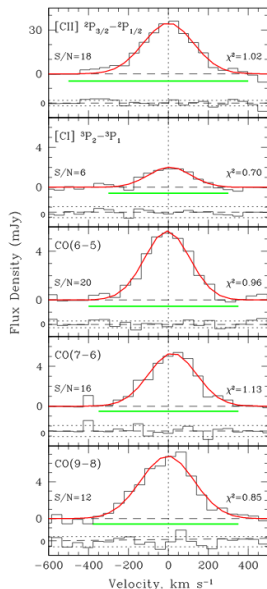
$$m_a \gtrsim 2 \times 10^{-30} \text{ eV}$$



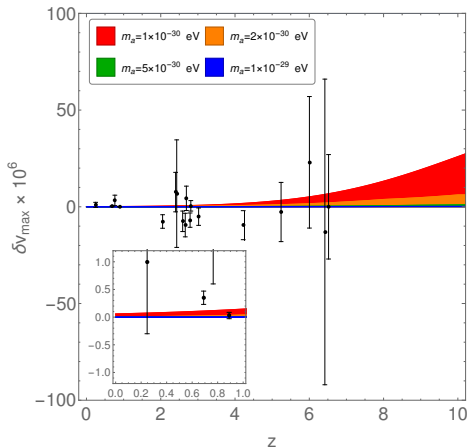
$\mathcal{O}(10^{-18}) \text{ yr}^{-1}$ precision is needed $\Rightarrow$ future improvements of atomic (nuclear) clocks.

Discovery potential within 1-2 decades.

Direct Detection: Molecular Spectral Lines

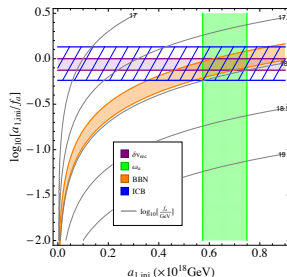
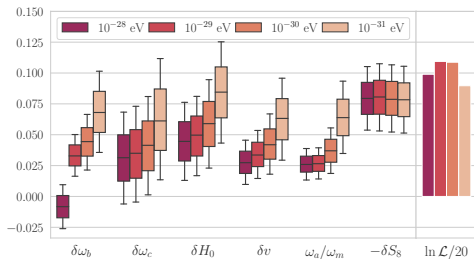


The richness of molecular spectra (electronic, vibrational or rotational, etc.) helps break the degeneracy of the line shift caused by the Higgs VEV variation δv and the redshift z [Safronova et al., 2018]:



[Levshakov et al., 2020].

Summary



- A higher Higgs VEV when $z \gtrsim 1100$:
 - Earlier recombination, larger H_0 .
 - Compatible with BBN (and ${}^7\text{Li}$)!
- An axionic solution:
 - Alleviate tension in σ_8/S_8 , even with more DM.
 - Naturally explaining the non-zero ICB.
 - Great accessibility by different observations.

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