# Varying Higgs VEV in Cosmology and an Axionic Solution

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Based on [2102.11257] and [2105.01631]
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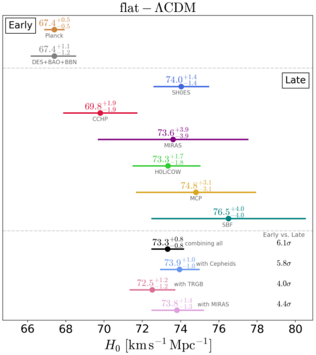
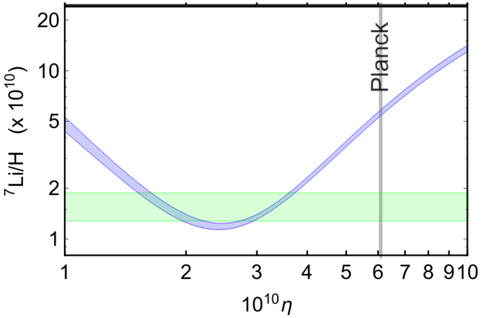
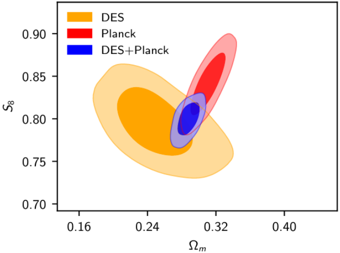
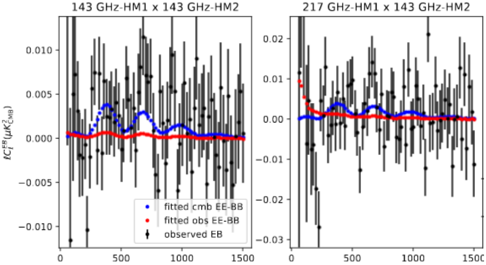
# Tension in $\Lambda$CDM

- From CMB and local measurements: $H_{0,\mathrm{P18}} = 67.36 \pm 0.54$ 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 $^{7}$Li/H$\times 10^{10}$: $1.6 \pm 0.3$ (observed) vs. $5.6 \pm 0.3$ (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 $\sigma_8$ [Troxel et al., 2018] yields a value smaller $S_{8,\text{DES}} = 0.773^{+0.026}_{-0.020}$ than that given by the CMB-$\Lambda$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 $\sim 2.4\sigma$.



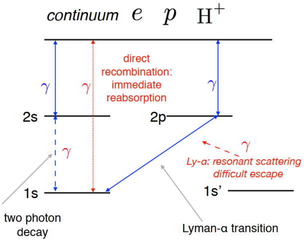




[Verde et al., 2019, Pitrou et al., 2018, Handley and Lemos, 2019, Minami and Komatsu, 2020]

# 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 $^7$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 ($\sigma_8$ tension resolved).
- The $aF^{\mu\nu}\tilde{F}_{\mu\nu}$ coupling leading to non-zero ICB [Fujita et al., 2020]

# CMB: Basic Formula

The angular sound horizon $\theta_* = \dfrac{r_*}{D_*}$ provides sensitivity to $H_0$ :

$$r_* = \int_{z_*}^{\infty} dz \frac{c_s(z)}{H(z)} \propto \int_{z_*}^{\infty} dz \Big/ \sqrt{3\left[1 + \frac{3\omega_b}{4\omega_\gamma(1+z)}\right]\left[\omega_r(1+z)^4 + \omega_m(1+z)^3 + \omega_\Lambda\right]} \quad (1)$$

$$D_* = \int_0^{z_*} dz \frac{1}{H(z)} \propto \int_0^{z_*} dz \Big/ \sqrt{\omega_r(1+z)^4 + \omega_m(1+z)^3 + \omega_\Lambda}\ , \quad (2)$$

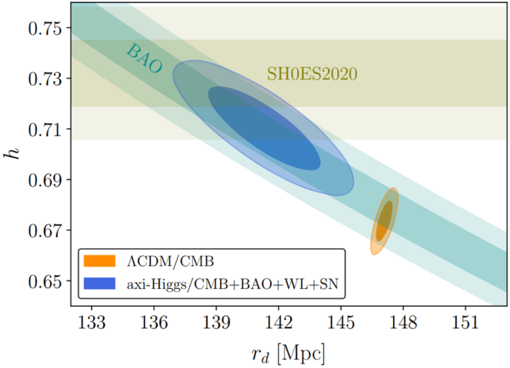
## Earlier recombination $\Rightarrow$ higher $H_0$

- 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. $\Rightarrow \frac{\partial \log(r_*)}{\partial \log(z_*)} \simeq -0.66\ ,\ \frac{\partial \log(D_*)}{\partial \log(z_*)} \sim -10^{-2}$ .
- Larger cosmological constant is possible.

# CMB Preference

The two most important (so far) constraint that we decide to match

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




Relative to Planck18 fit values:

- $H_0 \sim 71 \pm 1$km/s/Mpc when $\delta v \sim 4\%$ .
- $H_0 \sim 69 \pm 1$km/s/Mpc when $\delta v \sim 1\%$ .
- $\omega_c$ also increases.

# Introducing the Axion

# Axion as the Modulator of VEV

The minimal coupling ($\phi$ = Higgs , $a$ = axion):

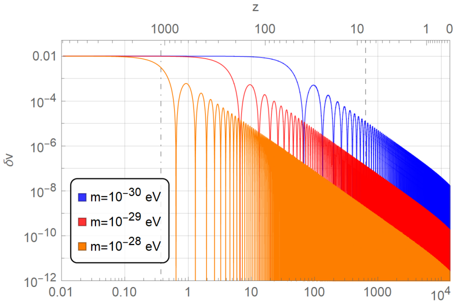
$$V(\phi, a) \sim V_{\rm SM} = \mu^2|\phi|^2 + \frac{\kappa}{4}|\phi|^4 ,$$

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

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

"Misalignment" with $m_a \lesssim 10^{-29}$eV:

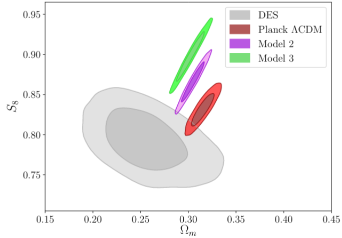
- Higgs always in the bottom.
- $a \rightarrow$ sub-component of DM.
- $x \equiv \rho(\text{axion DM})/\rho(\text{all matter})$.
- $x \sim \mathcal{O}(1\%)$ when $f_a \sim M_{\rm PL}$.

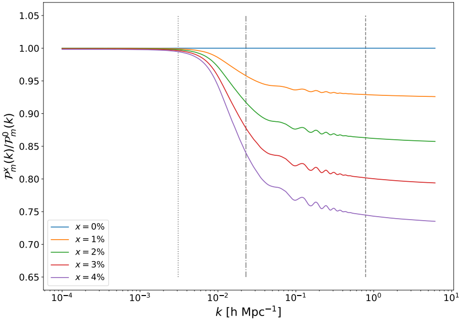


# $\sigma_8/S_8$ Tension Resolved

The dillemma of early recombination solution of $H_0$ tension: more CDM to fit CMB $\Rightarrow$ higher $\sigma_8$ [Jedamzik et al., 2020]

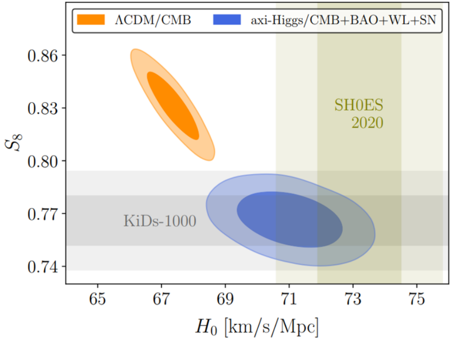
$$\frac{\mathcal{P}_m^x(k)}{\mathcal{P}_m^0(k)} = \left(\frac{k_J(z_{eq})}{k}\right)^{10-2\sqrt{25-24x}} \quad (3)$$



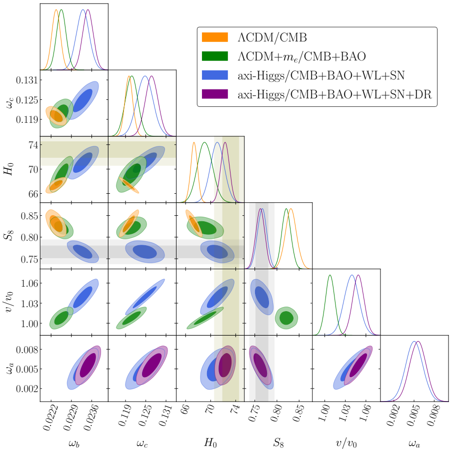




The axion quantum pressure and its potential force suppress the structural formation smaller than the Jeans scale. [Marsh and Ferreira, 2010, Kobayashi et al., 2017].

# Constraints with Non-zero Axion DM




⇑ Posterior distribution of $S_8$ vs. $H_0$ in different benchmarks

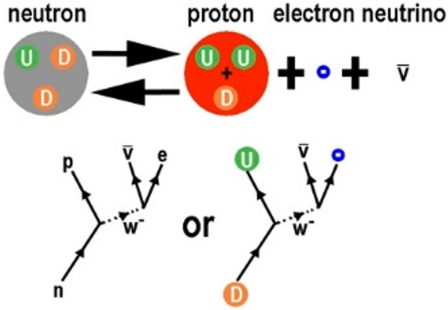



⇒ Posterior in the Axi-Higgs vs. ΛCDM [Aghanim et al., 2020] and $\delta v(m_e)$ only [Hart and Chluba, 2020].

# BBN: An Alternative VEV

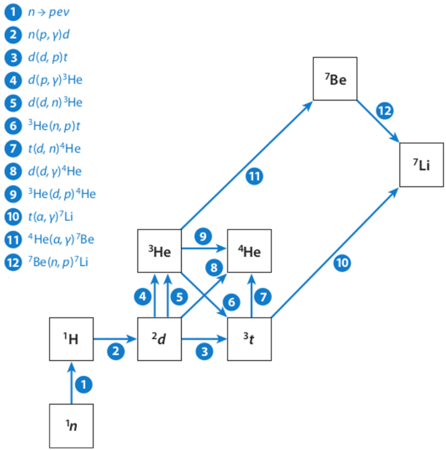
Heuristically, the neutron to proton number ratio $n/p$ can be written as [Hall et al., 2014]:

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

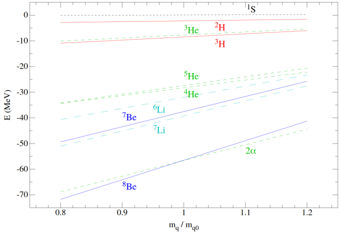


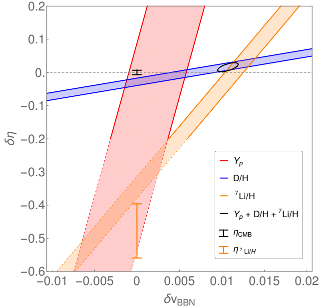
# BBN: Basic Parameters

- Fermi constant $G_F \propto v^{-2}$ that affect weak interactions (neutron decay & $n-p$ conversion).
- 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 $\Delta m_{np} \equiv m_n - m_p$
- Averaged light quark mass $\bar{m}_q \equiv (m_u + m_d)/2 \propto v$: significantly influence the rates of strong/nuclear interactions.



# Compatibility with BBN and $^7$Li Problem




Heavy nuclei more fragile as $m_q \uparrow \Rightarrow m_\pi \uparrow$, $^7$Li production harder.

[Flambaum and Wiringa, 2007]

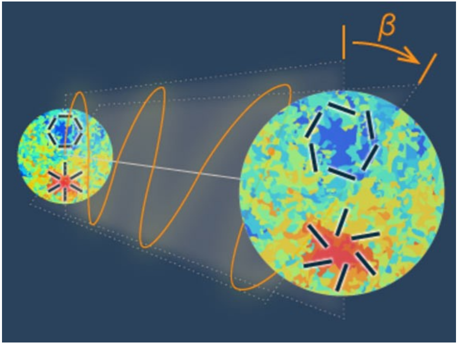
| Y \ X | $m_W$ | $m_e$ | $\Delta m_q$ | $\bar{m}_q$ | $\eta$ |
|---|---|---|---|---|---|
| $Y_p$ | 2.9 | 0.40 | −5.9 | −1.0 | 0.039 |
| D/H | 1.6 | 0.59 | −5.3 | 10 | −1.6 |
| $^7$Li/H | 1.7 | −0.04 | −5.3 | −60 | 2.1 |

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

- $\delta v \equiv (v_{\rm BBN} - v_0)/v_0 \simeq 1\%$
- $\delta\eta \simeq \delta\omega_b \simeq 1 - 3\%$

Overlaps w/ CMB preference!

# Isotropic Cosmic Birefringence



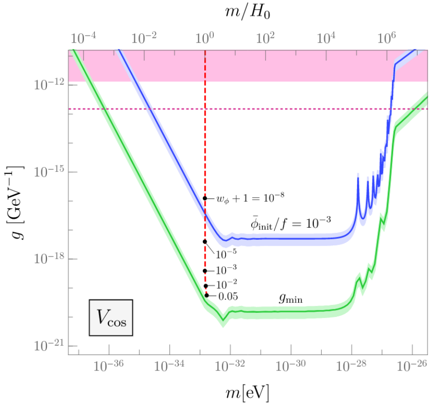

If the axion has a coupling with the EM gauge field as

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

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

$$\beta = \frac{1}{16\pi^2 f_a}\int_{t_{\rm ini}}^{t_0} dt\ \dot{a} = \frac{1}{16\pi^2 f_a}\Big[a(t_0) - a(t_{\rm ini})\Big]\ . \qquad (4)$$

# Isotropic Cosmic Birefringence (II)

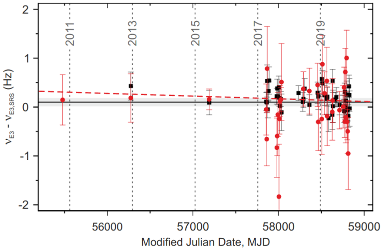



$$\beta \sim -\frac{1}{16\pi^2}\frac{a_{\rm ini}}{f_a} = 0.35 \pm 0.14(\text{degree}), \quad \Rightarrow \quad \frac{a_{\rm ini}}{f_a} \simeq 1.0 \pm 0.3\ . \quad (5)$$

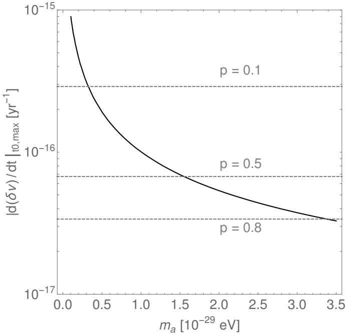
# Observational Limits: Atomic Clocks

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

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



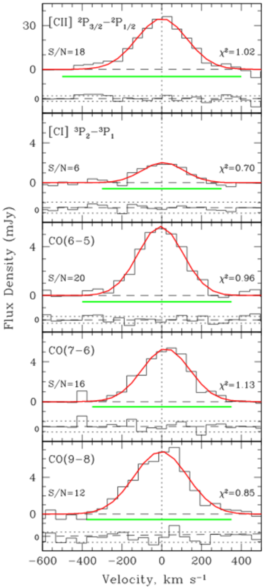

$$m_a \gtrsim 2 \times 10^{-30}\ \text{eV}$$



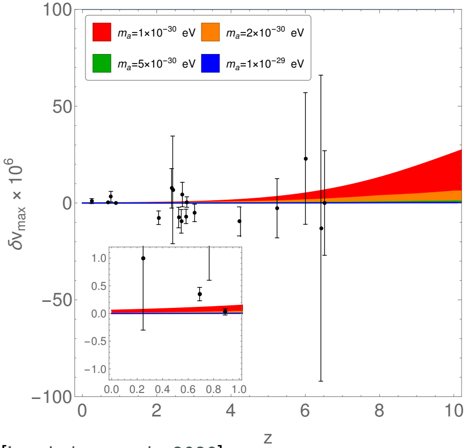

$\mathcal{O}(10^{-18})$ yr$^{-1}$ precision is needed $\Rightarrow$ future improvements of atomic (nuclear) clocks.

Discovery potential within 1-2 decades.

# Direct Detection: Molecular Spectral Lines

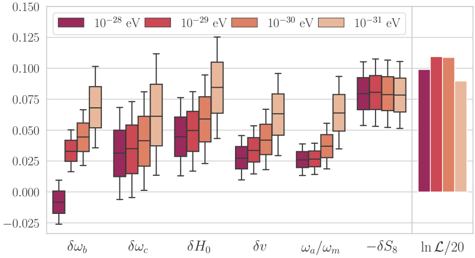


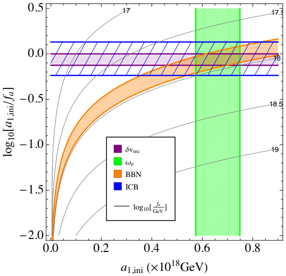

The richness of molecular spectra (electronic, vibrational or rotational, etc.) helps break the degeneracy of the line shift caused by the Higgs VEV variation $\delta v$ and the redshift $z$ [Safronova et al., 2018]:




[Levshakov et al., 2020].

# Summary




- A higher Higgs VEV when $z \gtrsim 1100$:
  - Earlier recombination, larger $H_0$.
  - Compatible with BBN (and $^7$Li)!
- An axionic solution:
  - Alleviate tension in $\sigma_8/S_8$, even with more DM.
  - Naturally explaining the non-zero ICB.
  - Great accessibility by different observations.

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