

AXI-HIGGS COSMOLOGY

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in collaboration with

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(**arXiv:2102.11257** and **arXiv:2105.01631**)

Cosmology from Home

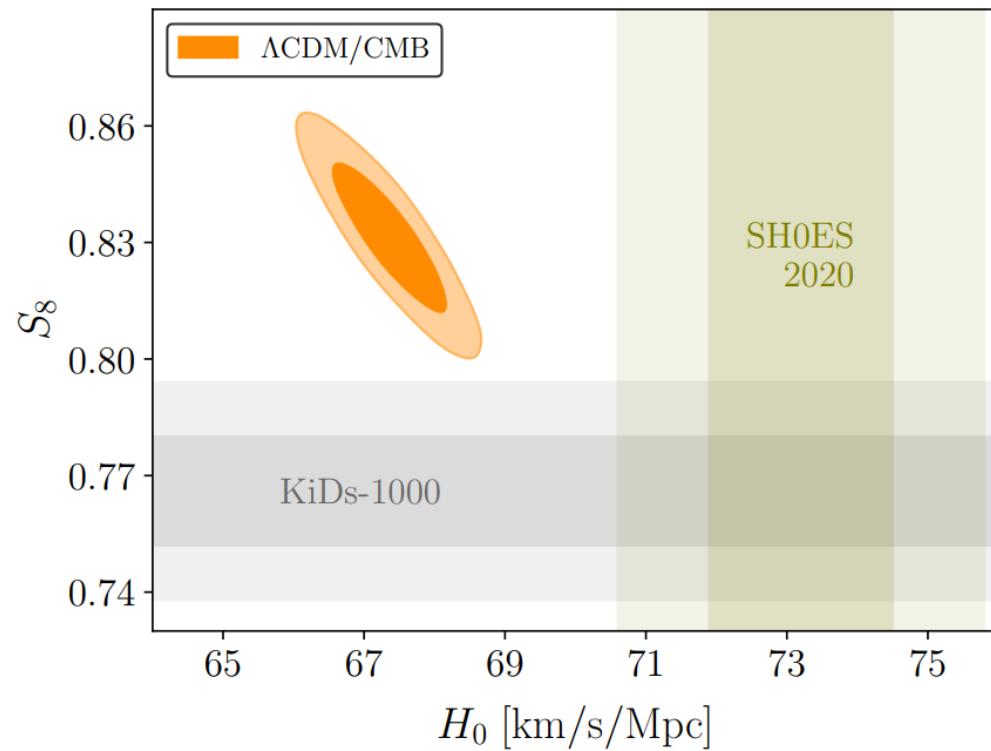
H_0 and S_8 tensions

$$H_{0,\Lambda\text{CDM}} = 67.36 \pm 0.54,$$

$$S_{8,\Lambda\text{CDM}} = 0.832 \pm 0.013,$$

$$H_{0,\text{SH0ES2020}} = 73.2 \pm 1.3$$

$$S_{8,\text{KiDs-1000}} = 0.766 \pm 0.014$$



General strategy:

- Increase H_0 by reducing r_* (or r_d)
- Decrease S_8 by suppressing structure formation

Axi-Higgs model

- The Higgs VEV is driven by the axion

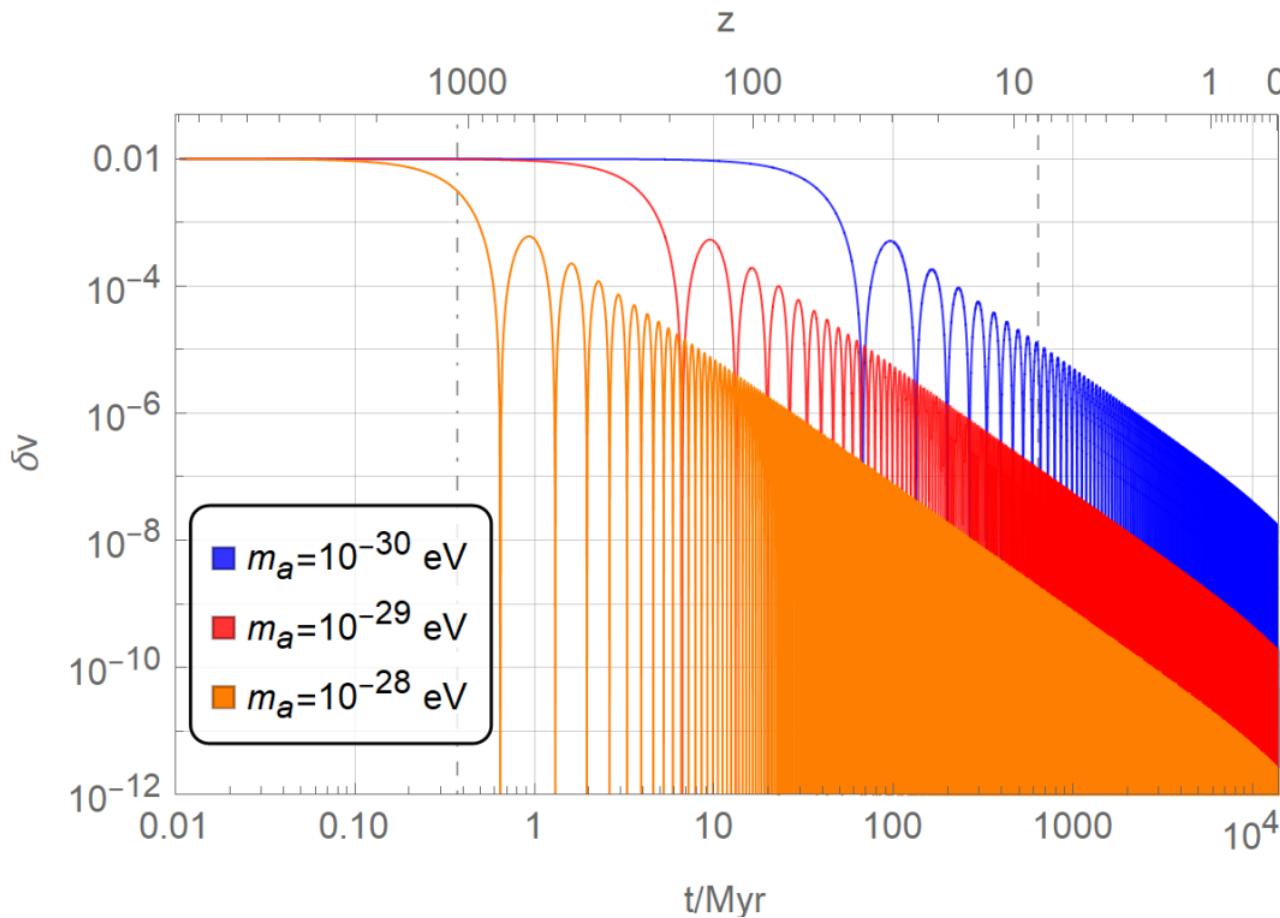
$$\nu = \nu_0(1 + \delta\nu) = 246 \text{ GeV} \left(1 + \frac{Ca^2}{2M_{Pl}^2} \right)$$

- Axion field evolves following misalignment mechanism:

$$\rho_a \propto a_{\text{ini}}^2 \text{ at early times; } \quad \rho_a \propto \omega_a (1+z)^3 \text{ at late times}$$

→ Axi-Higgs introduces extra parameters: $\delta\nu_{\text{ini}}$ and ω_a

Higgs-VEV evolution



Axi-Higgs resembles:

- Λ CDM with higher VEV before recombination
- Λ CDM with axion DM after recombination

Recombination

Higgs VEV increases $\rightarrow m_e$ increases
 \rightarrow electrons recombine faster
 \rightarrow earlier recombination: z_* increases
 \rightarrow sound horizon reduces:

$$r_* = \int_{z_*}^{\infty} \frac{c_s(z)}{H(z)} dz$$

\rightarrow diameter distance reduces to keep:

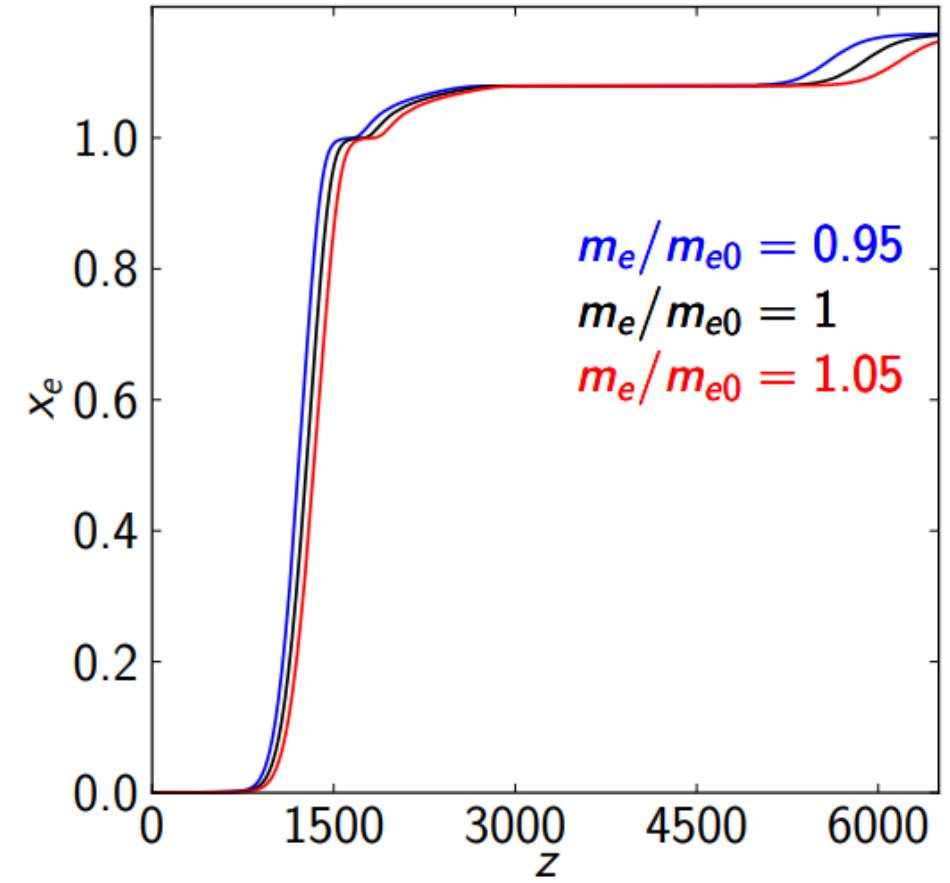
$$\theta_* = \frac{r_*}{D_*} = \text{const}$$

\rightarrow more late-time energy budget is needed:

$$D_* = \int_0^{z_*} \frac{dz}{H(z)} \propto \int_0^{z_*} \frac{dz}{\sqrt{\omega_m(1+z)^3 + \omega_\Lambda}}$$

\rightarrow higher Hubble constant:

$$H_0 \propto \omega_m + \omega_\Lambda$$



arXiv:1406.7482, 1912.03986

Structure formation

Axion is a part of DM:

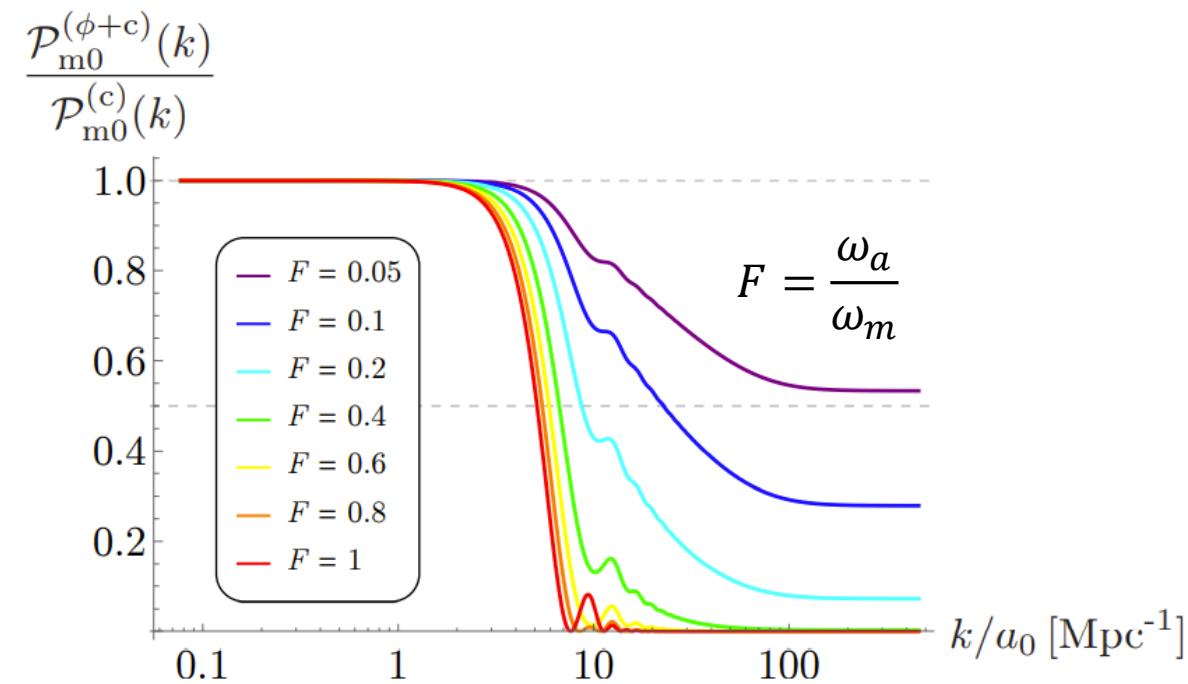
$$\delta_m = \delta_c + \delta_a$$

→ contribute to structure formation:

$$\delta_m^2 \propto P_m(k)$$

→ reduce matter amplitude S_8 :

$$S_8^2 \propto \int_0^\infty P_m(k) W^2(kR_8) dk$$



arXiv:1410.2896, 1708.00015

Axi-Higgs constraints

$$\omega_b = 0.02329 \pm 0.00022$$

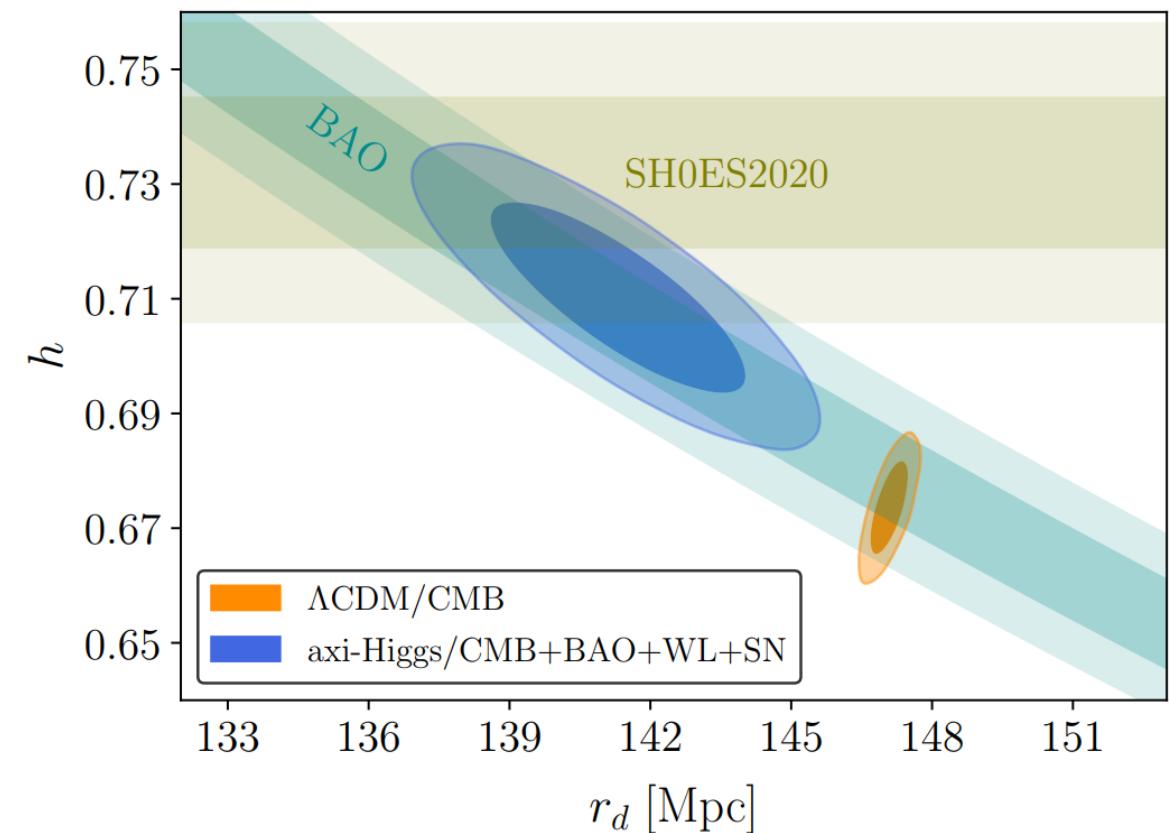
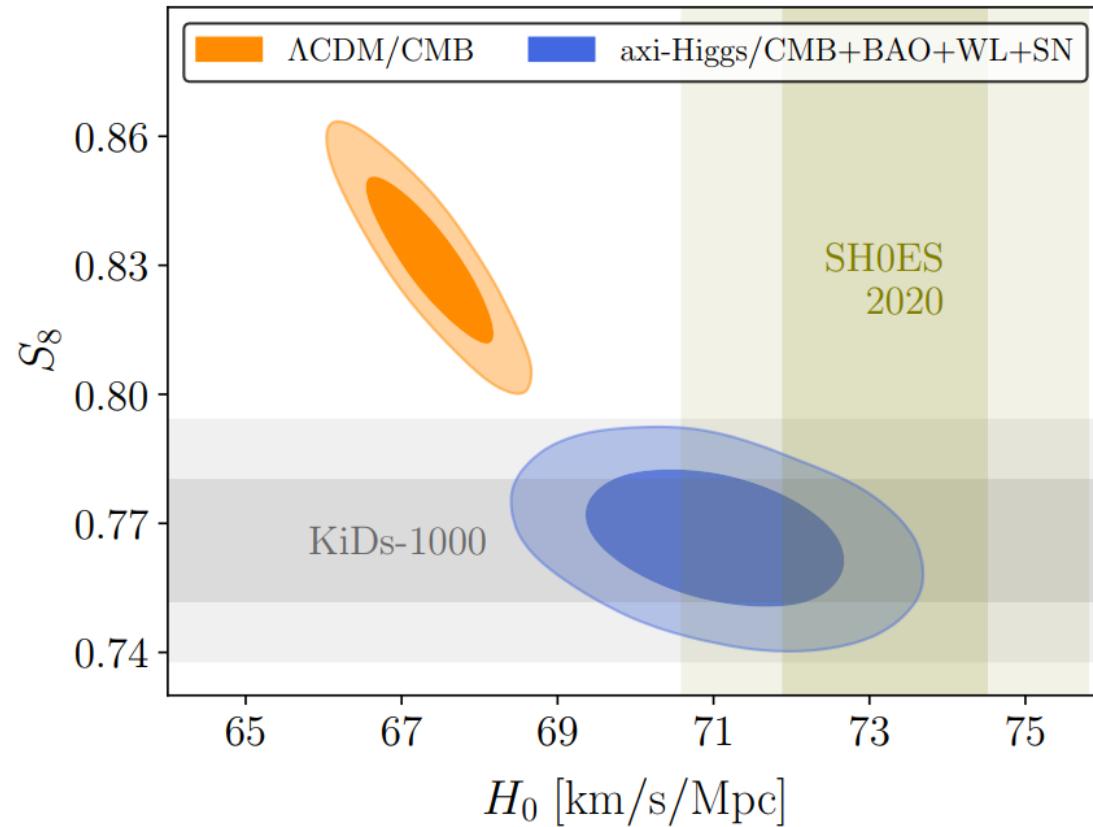
$$\omega_c = 0.1247 \pm 0.0024$$

$$H_0 = 71.1 \pm 1.1$$

$$\nu/\nu_0 = 1.039 \pm 0.011$$

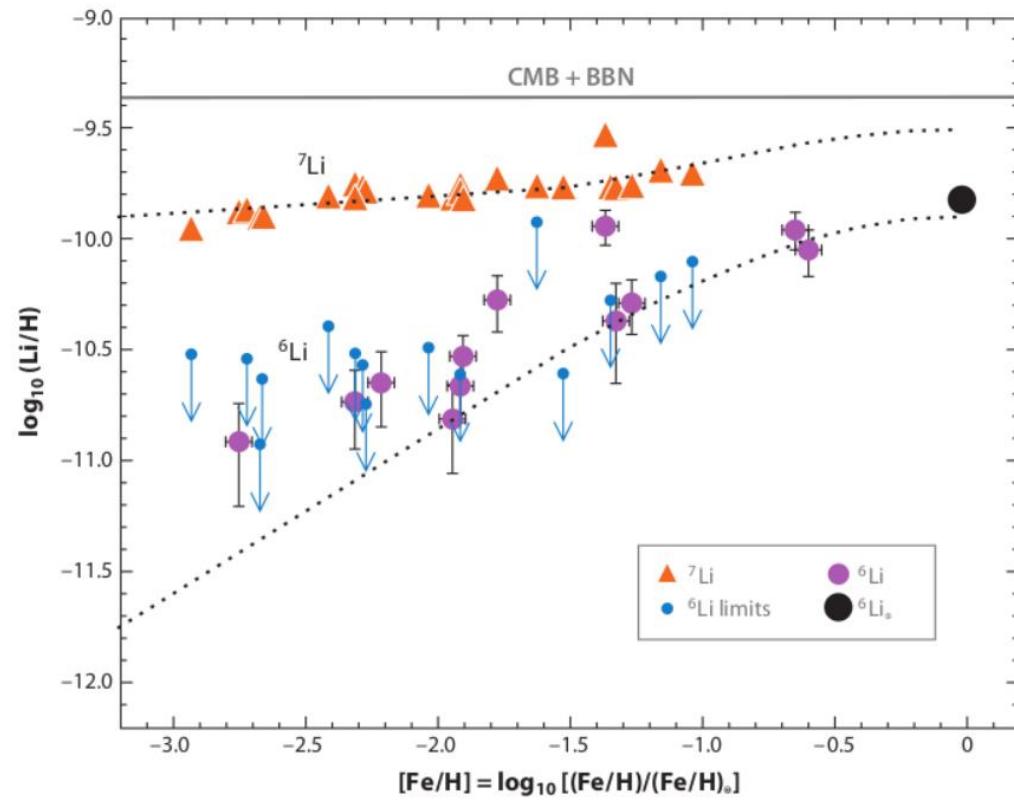
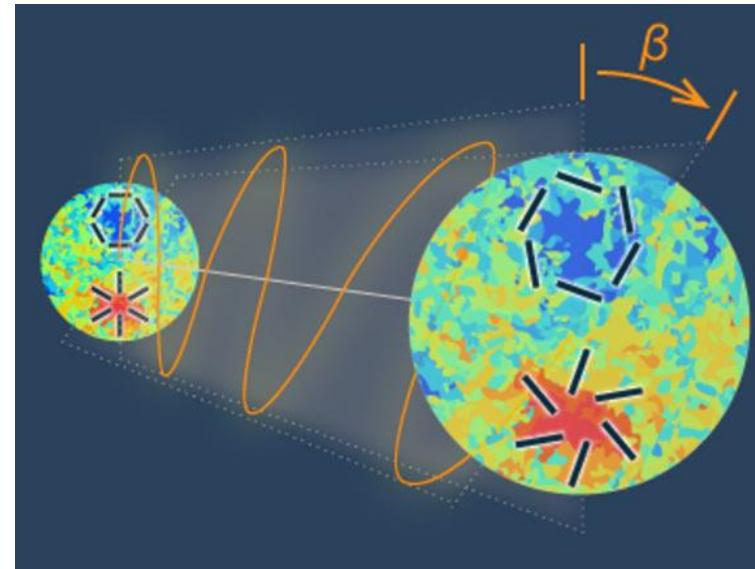
$$\omega_a = 0.0050 \pm 0.0013$$

$$S_8 = 0.766 \pm 0.011$$



Next discussion

- Impact on BBN to resolve well-known Lithium puzzle.
- Explanation for isotropic cosmic birefringence (ICB) signal
- Impact on quasar spectra (QS) and atomic clock (AC) measurements



Axi-Higgs Cosmology

Lingfeng Li (HKUST)

Based on [2102.11257] and [2105.01631]

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

Cosmology from Home

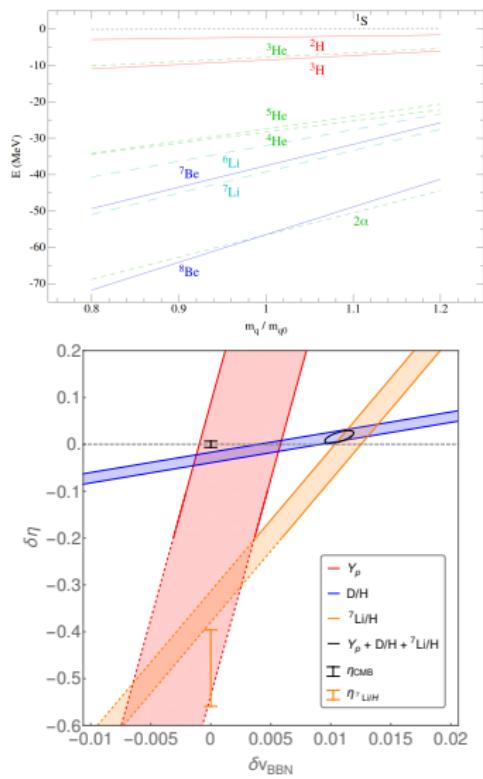
BBN: An Alternative VEV

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 ^7Li Problem



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

X Y	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
$^7\text{Li}/\text{H}$	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]:

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

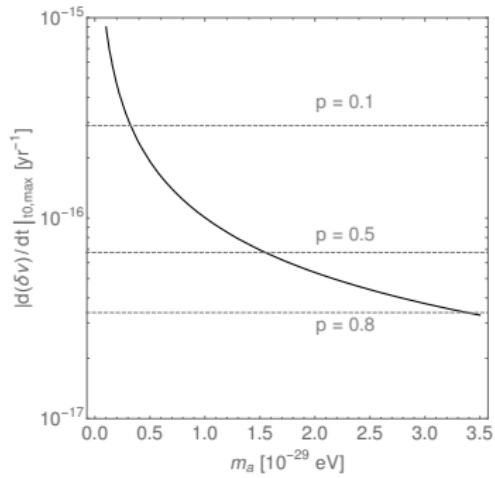
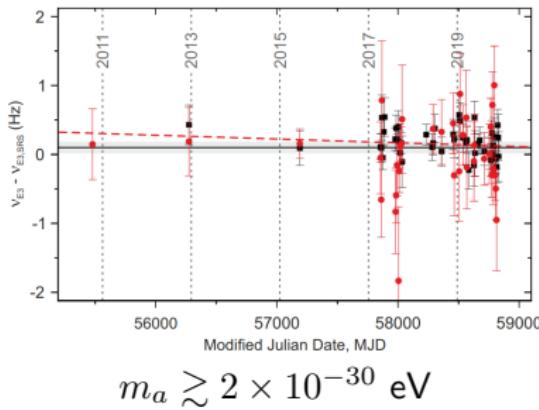
$$\beta \sim -\frac{1}{16\pi^2} \frac{a_{\text{ini}}}{f_a} = 0.35 \pm 0.14(\text{degree}), \quad \Rightarrow \quad \frac{a_{\text{ini}}}{f_a} \simeq 1.0 \pm 0.3 . \quad (2)$$

[Minami and Komatsu, 2020]

Observational Limits: Atomic Clocks

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

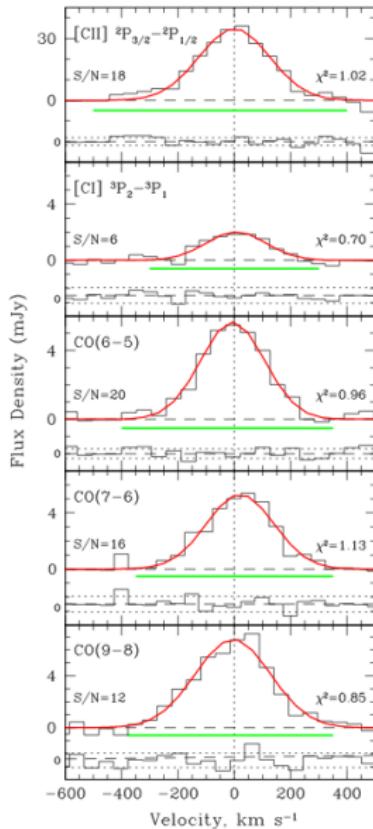
$$\frac{d(\delta v)}{dt} \Big|_{t_0} \simeq \frac{d(\delta \mu)}{dt} \Big|_{t_0} = \\ - (0.08 \pm 0.36) \times 10^{-16} \text{ yr}^{-1}$$



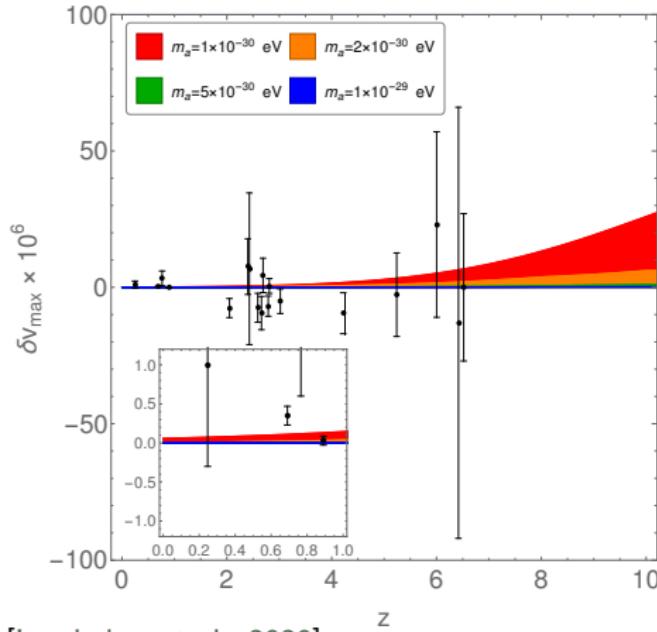
$\mathcal{O}(10^{-18}) \text{ yr}^{-1}$ precision is needed \Rightarrow future improvements of atomic (nuclear) clocks.

Discovery potential within 1-2 decades.

Direct Detection: Molecular Spectral Lines

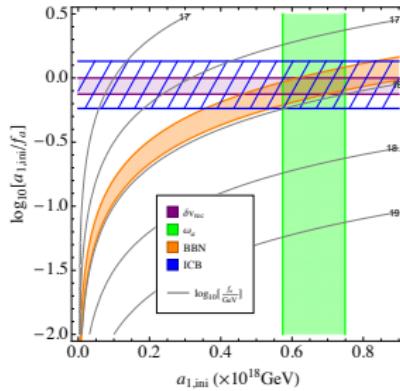
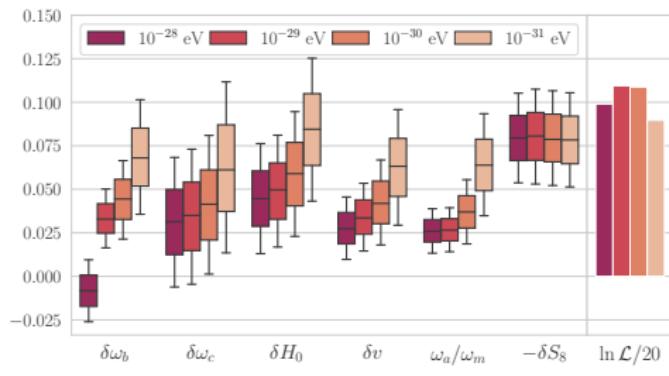


The richness of molecular spectra (electronic, vibrational or rotational, etc.) helps break the degeneracy of the line shift caused by the Higgs VEV variation δv and the redshift z [Safronova et al., 2018]:



[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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