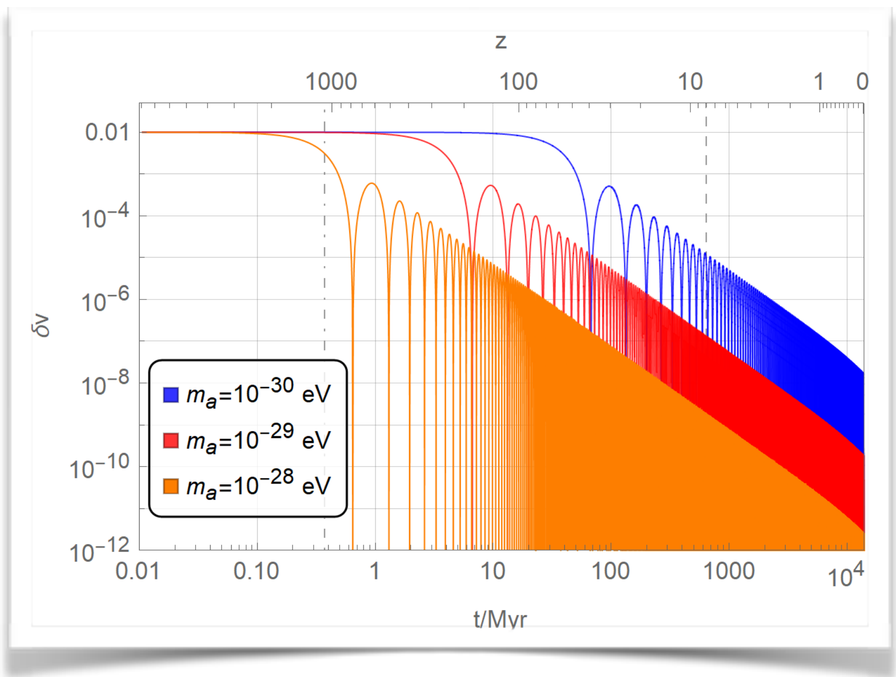
Sydney-CPPC Seminar, Apr. 2021



Axi-Higgs Cosmology

Tao Liu

The Hong Kong University of Science and Technology

Based on arXiv:2102.11257, and ongoing project
in collaboration with Fung, Li, Luu, Qiu and Tye

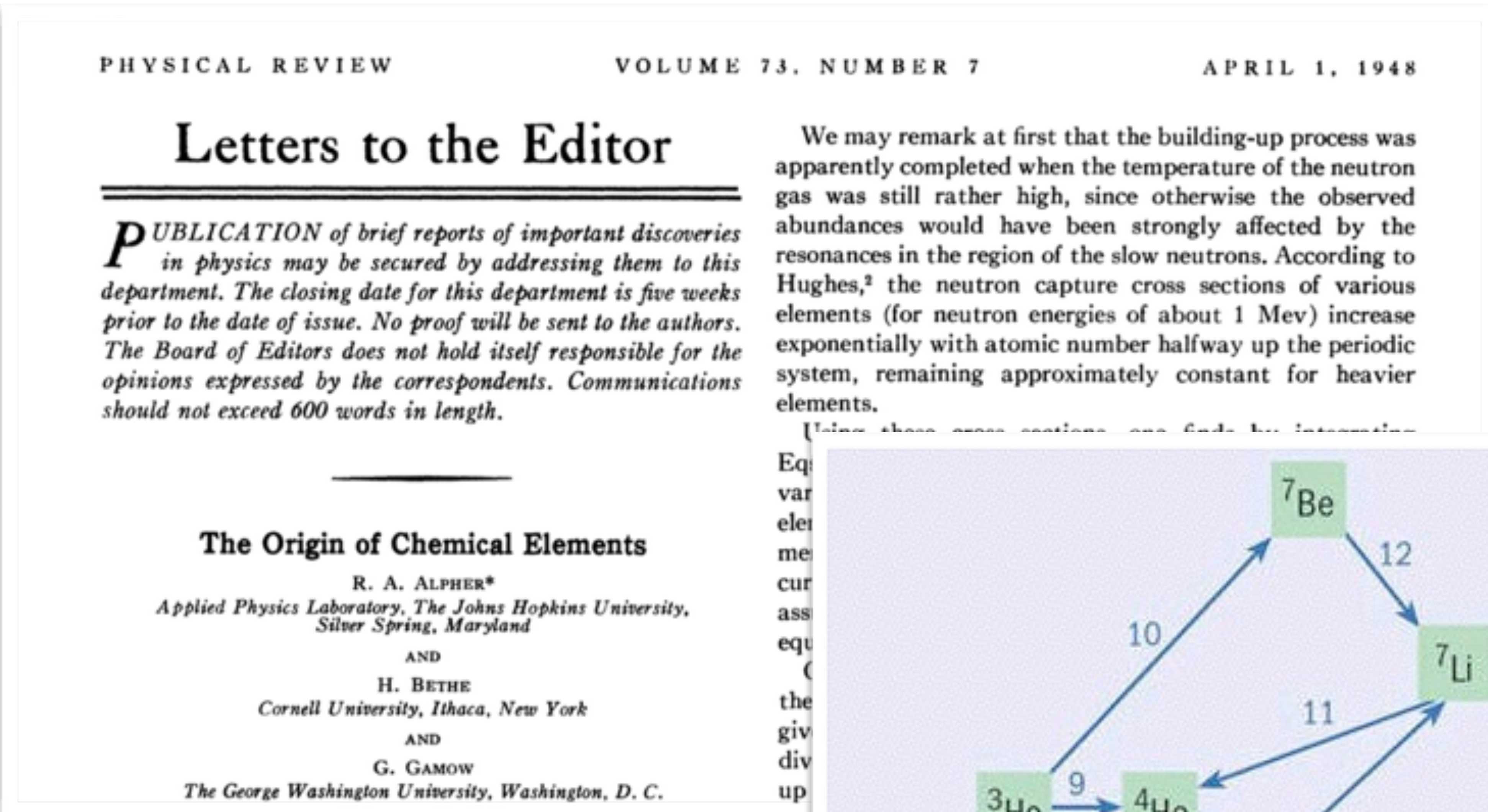
Puzzles from Precision Cosmology

Since half an century before, cosmology has made tremendous progress, moving from a speculative to a precision science. The inflation scenario, big bang nucleosynthesis (BBN), cosmic microwave background (CMB) and structure formation have merged theory and data into a nice picture about our universe. However, a series of puzzles also arise… …

- Li-7 problem
- Hubble tension
- S_8 tension
- Isotropic cosmic birefringence (ICB) anomaly
- … …

Question: is there an underlying theory being responsible for these puzzles or at least some of them?

Big-Bang Nucleosynthesis



PHYSICAL REVIEW VOLUME 73, NUMBER 7 APRIL 1, 1948

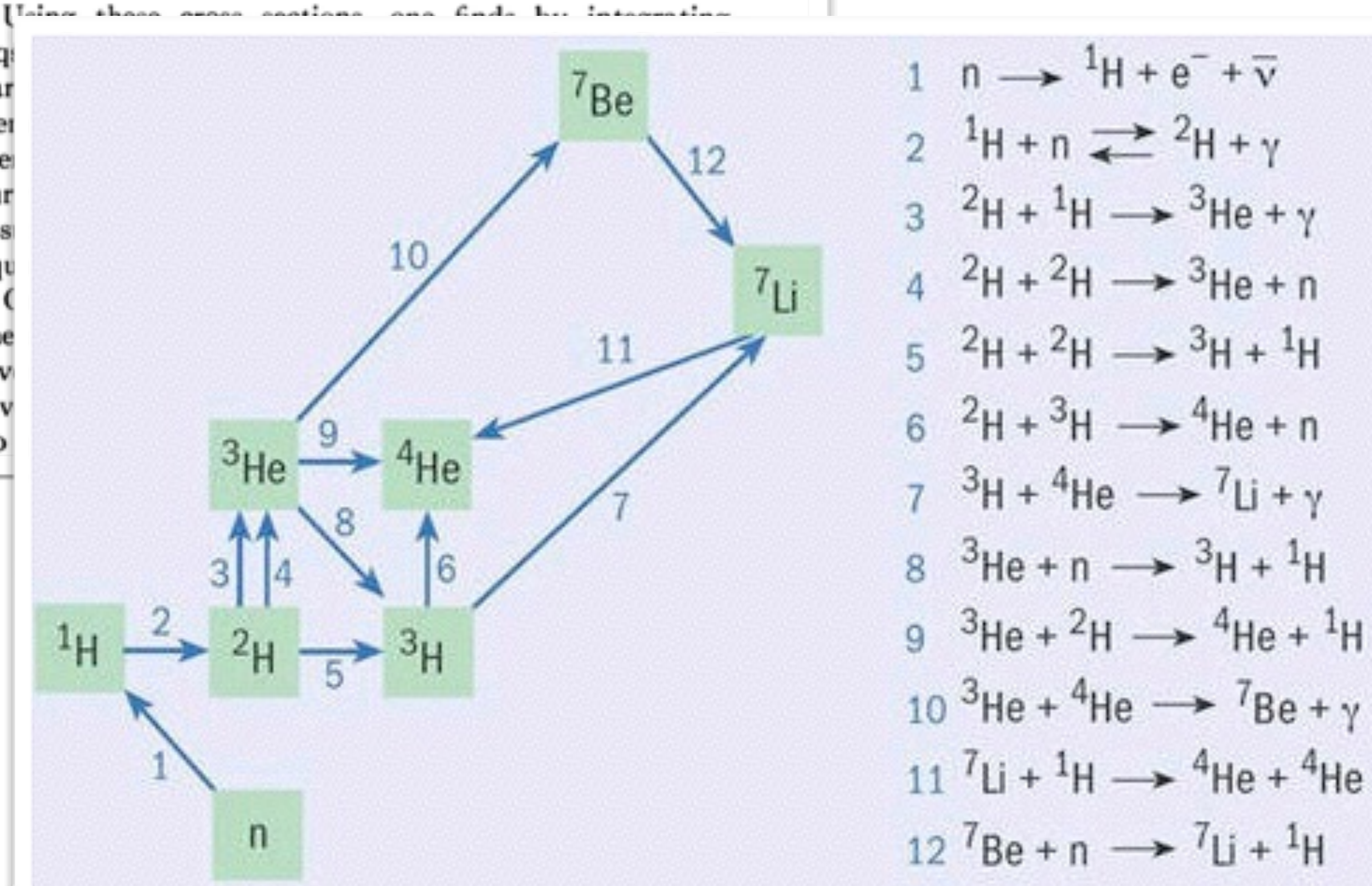
Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

The Origin of Chemical Elements

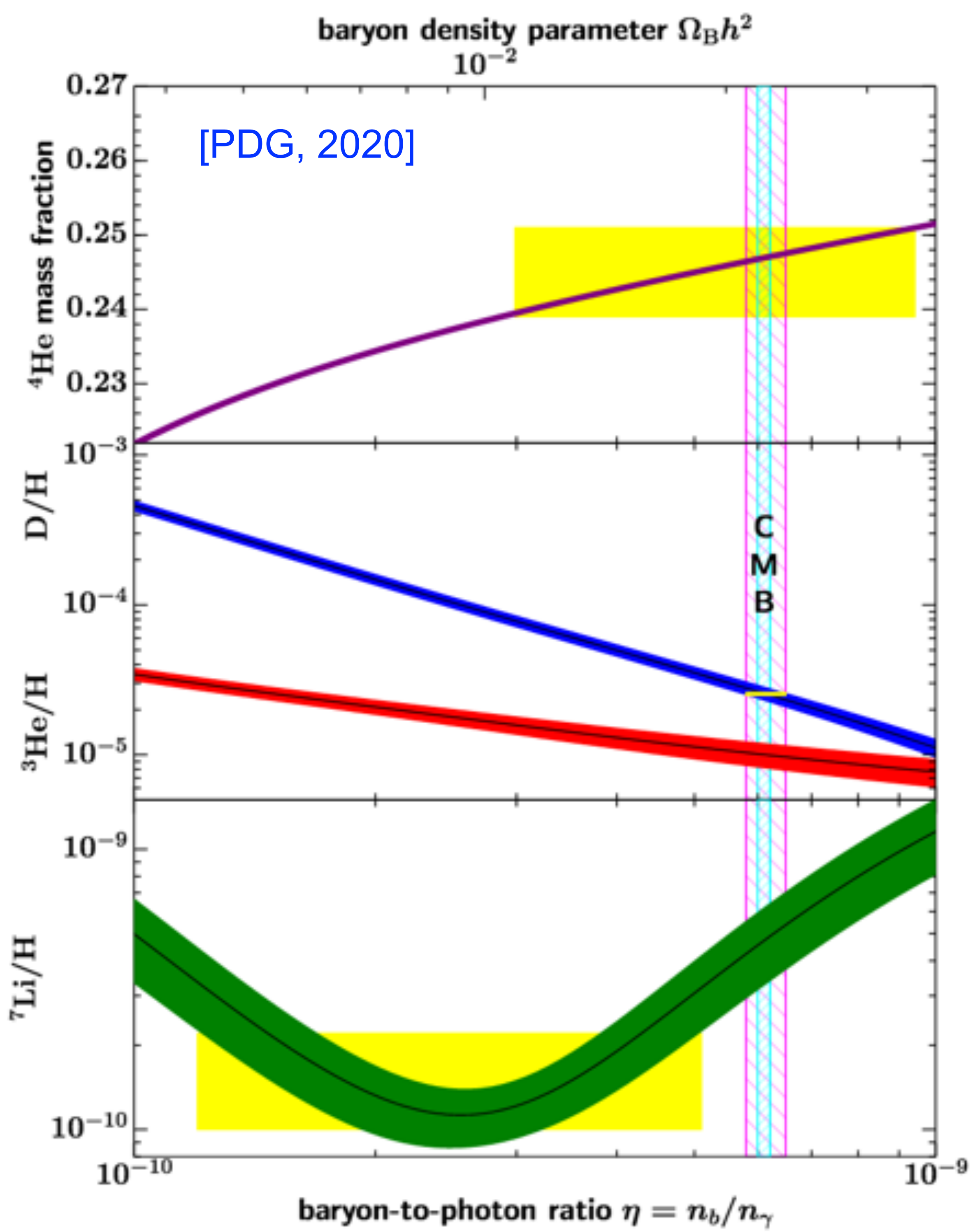
R. A. ALPHER*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland
AND
H. BETHE
Cornell University, Ithaca, New York
AND
G. GAMOW
The George Washington University, Washington, D. C.

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundances would have been strongly affected by the resonances in the region of the slow neutrons. According to Hughes,[2] the neutron capture cross sections of various elements (for neutron energies of about 1 Mev) increase exponentially with atomic number halfway up the periodic system, remaining approximately constant for heavier elements.



BBN - lays out one of the corner stones of Big-Bang theory

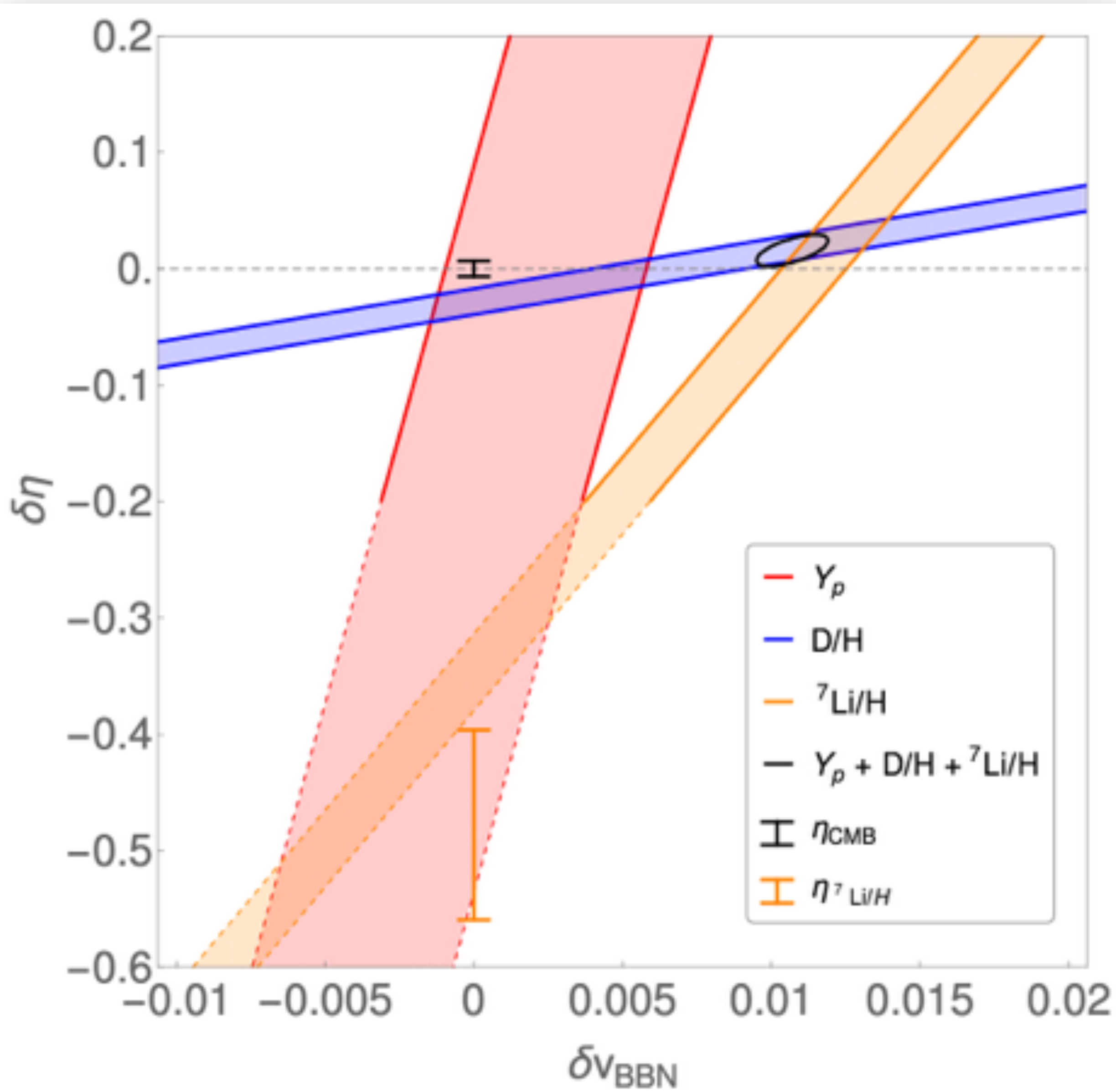
Li-7 Problem



	Prediction [28]	Observation [46]
Y_p	0.2471 ± 0.0002	0.245 ± 0.003
$D/H \times 10^5$	2.459 ± 0.036	2.547 ± 0.025
$^7Li/H \times 10^{10}$	5.62 ± 0.25	1.6 ± 0.3

- Despite its great success in testing He-4 and D/H, while using the CMB eta as input, LCDM fails to predict Li-7 matching with the observation at 8-9 sigma C.L.

One Solution to Li-7 Problem



[B. Li and M.-C. Chu, 2005; T. Dent et. al.; 2007; M.-K. Cheoun et. al., 2011; K. Moroi et. al., 2019]

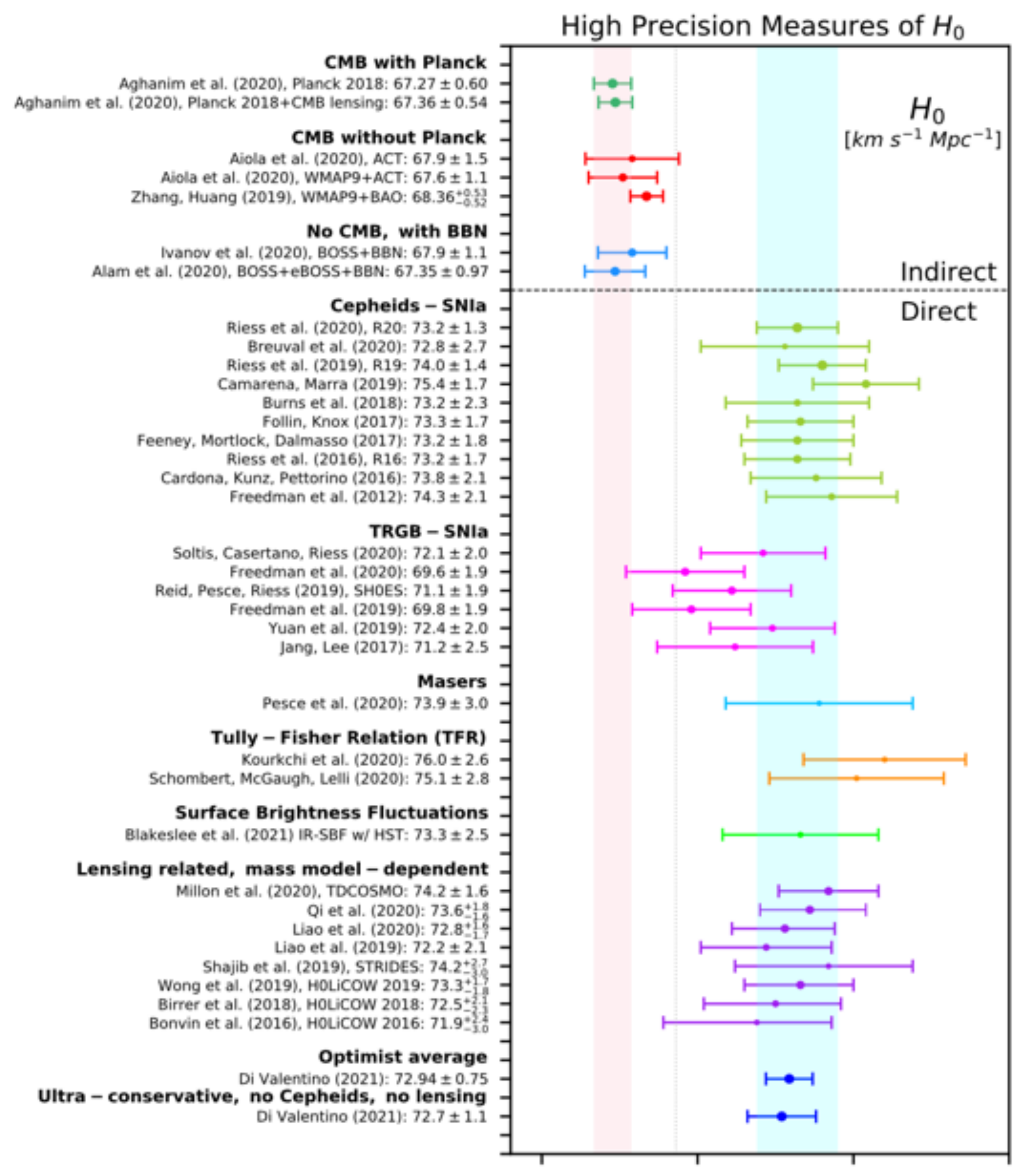
- The solution: varying Higgs VEV during the BBN epoch
- => Modified W-boson mass, mass splitting mp - mn, and pion mass (mediator for nuclear interaction)
- => Modified n-p converting and nucleon interacting rates

$$Y_p(\delta v_{BBN}, \delta\eta) \simeq Y_p(0,0)(1 - 3.6\delta v_{BBN} + 0.039\delta\eta)$$
$$D/H(\delta v_{BBN}, \delta\eta) \simeq D/H(0,0)(1 + 6.9\delta v_{BBN} - 1.6\delta\eta)$$
$$^7Li/H(\delta v_{BBN}, \delta\eta) \simeq {}^7Li/H(0,0)(1 - 64\delta v_{BBN} + 2.1\delta\eta)$$

- => Modified BBN determination for eta (The tension is reduced from 8.8 sgima to 2.5 sigma, according to reduced chi-2)

$$\delta v_{BBN} = (1.1 \pm 0.1)\%, \qquad \delta\eta = (1.7 \pm 1.3)\%$$

Hubble Tension



[E. Di Valentino et. al., 2021]

One Solution to Hubble Tension

- One solution: modified electron mass m_e during recombination epoch [Planck collaboration, 2015]

[L. Hart and J. Chluba, 2019]

Parameter	*Planck* 2018 + varying $\alpha_{EM}(z, p)$	*Planck* 2018 + BAO + varying $\alpha_{EM}(z, p)$	*Planck* 2018 + varying $m_e(z, p)$	*Planck* 2018 + BAO + varying $m_e(z, p)$
$\Omega_b h^2$	0.02233 ± 0.00018	0.02243 ± 0.00016	$0.0197^{+0.0012}_{-0.0015}$	0.02254 ± 0.00019
$\Omega_c h^2$	0.1198 ± 0.0017	0.1201 ± 0.0017	$0.1045^{+0.0074}_{-0.0082}$	0.1209 ± 0.0019
$100\theta_{MC}$	1.0405 ± 0.0049	1.0441 ± 0.0038	0.950 ± 0.046	1.0466 ± 0.0049
τ	0.0545 ± 0.0077	0.0549 ± 0.0076	0.0513 ± 0.0081	0.0544 ± 0.0075
$\ln(10^{10} A_s)$	3.044 ± 0.015	3.043 ± 0.015	3.030 ± 0.018	3.044 ± 0.016
n_s	0.9640 ± 0.0071	0.9622 ± 0.0069	0.9655 ± 0.0064	0.9645 ± 0.0066
$\alpha_{EM}/\alpha_{EM,0}$	0.9997 ± 0.0035	1.0022 ± 0.0027	--	--
$m_e/m_{e,0}$	--	--	$0.878^{+0.057}_{-0.065}$	1.0081 ± 0.0070
p	-0.0011 ± 0.0035	0.0007 ± 0.0031	0.0014 ± 0.0043	-0.0007 ± 0.0043
H_0	67.3 ± 1.4	68.45 ± 0.88	44^{+9}_{-10}	69.1 ± 1.2

- => Reduced cross section of Thomson scattering (inversely prop to the square of m_e) and hence increased z* and decreased sound horizon at rec
- => Unchanged angular sound horizon at rec, despite the increase of the H0 value

Our Methodology

If the variation of m_e during the recombination epoch is caused by a shift (~1%) to Higgs VEV, potentially these these two puzzles can be connected … …

Despite this, we would conduct a semi-analytical study, to understand better how that is achieved in LCDM + m_e

For this purpose, we introduce a LINEAR scheme for the analysis including four parameters to characterize LCDM + m_e: w_b, w_c, h and v. We set their values best-fitting the CMB data in the LCDM model as the reference point ($v = v_0$), and then extract out their deviations from the reference point required for explaining the CMB + BAO data

As a start, we encode these requirements as variation conditions of two observables

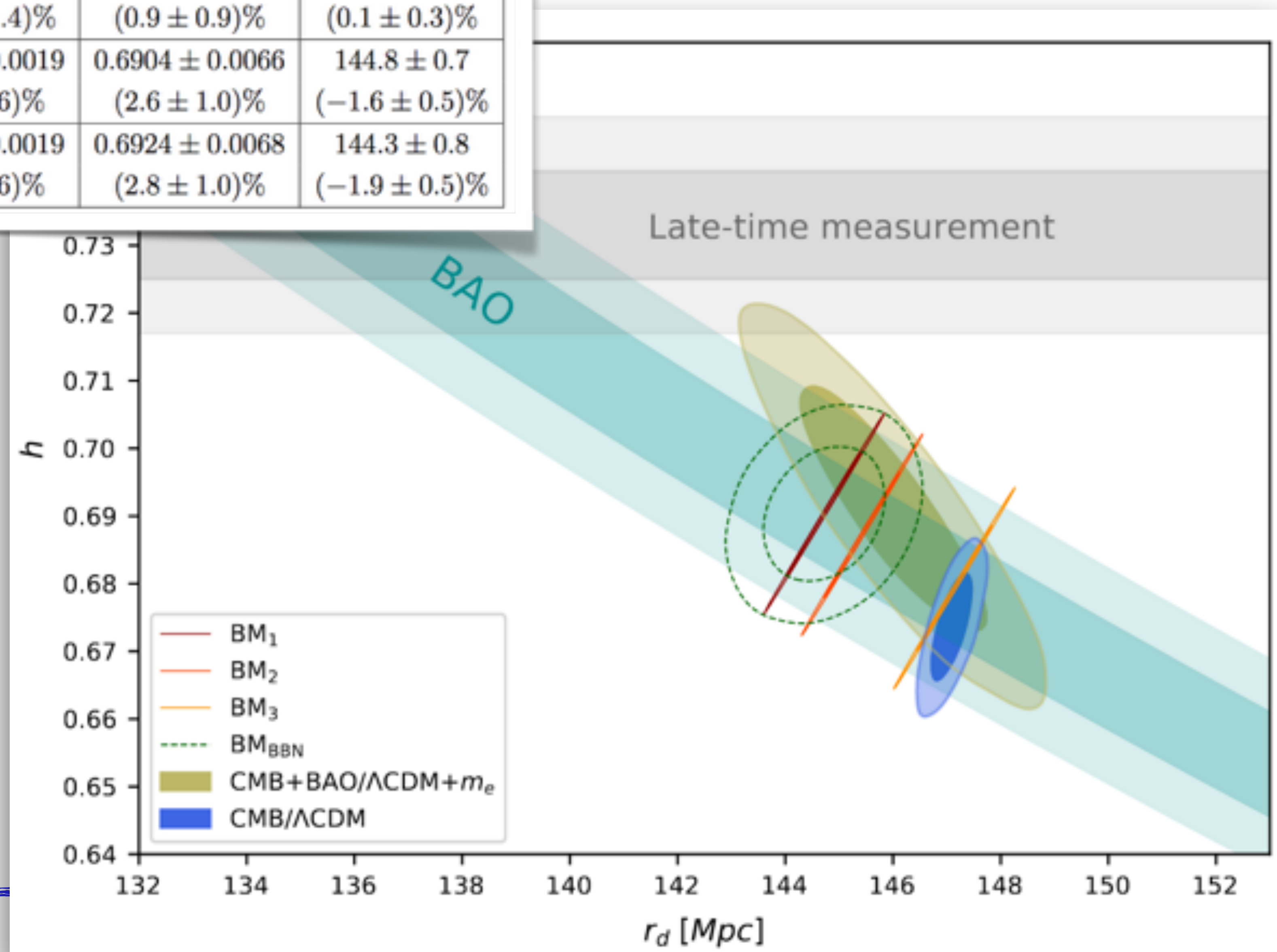
$$\begin{aligned} d\ln r_* - d\ln D_* &= d\ln\theta_* \equiv 0 \\ d\ln r_d + d\ln h &= d\ln(r_d h) \equiv \mathrm{BAO} - \mathrm{CMB(Ref)} \end{aligned}$$

Then the shift to H_0 or h can be solved out in various benchmark models characterized by different values of w_b and v (e.g., the ones favored by BBN)

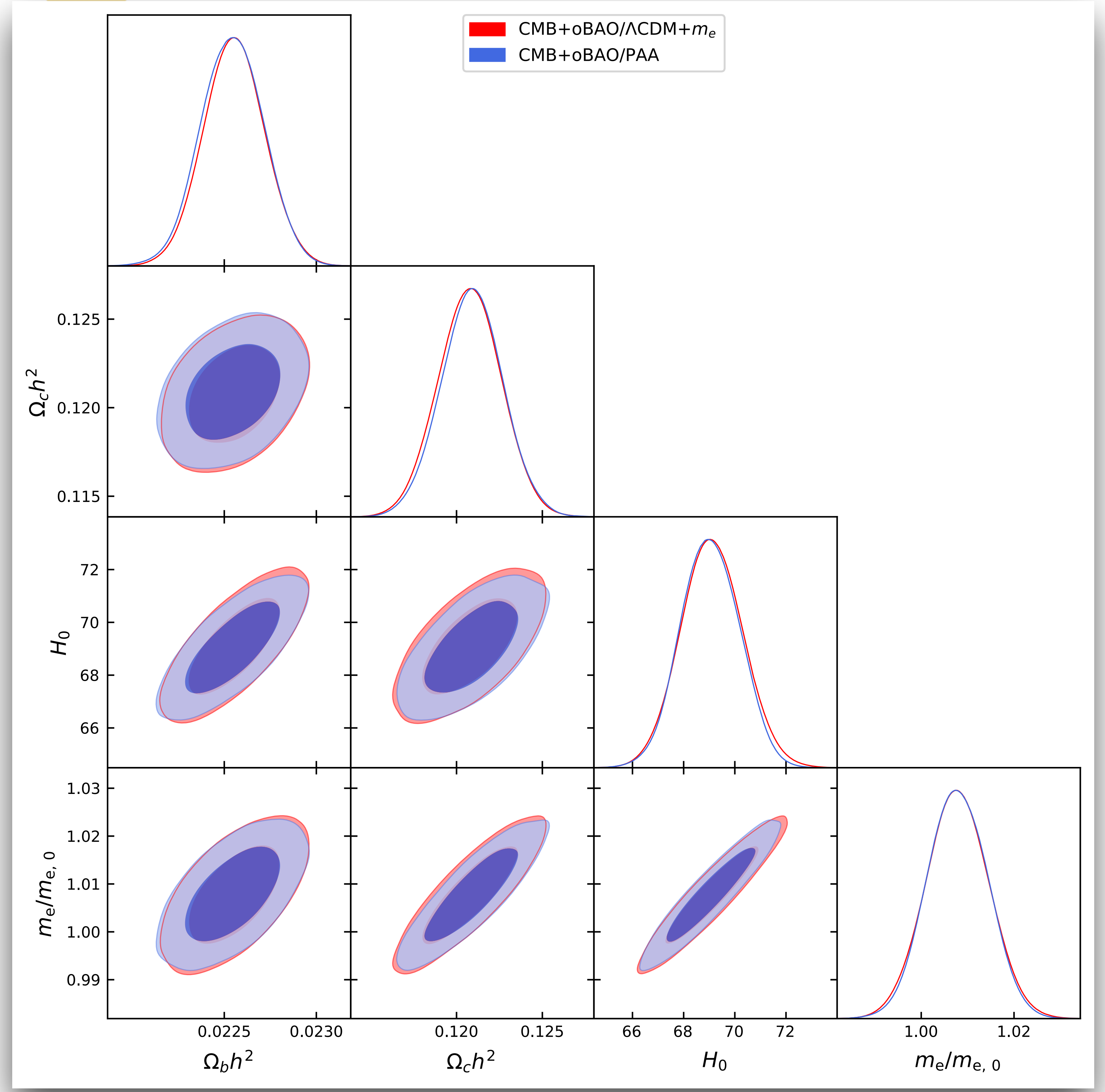
Hubble Tension - Benchmarks

Models	v/v_0	ω_b	ω_c	h	r_d
Ref	1.000	0.02238	0.1201	0.6732	147.07
ΛCDM+m_e +P18+BAO	1.008 ± 0.007 $(0.8 \pm 0.7)\%$	0.02255 ± 0.00017 $(0.8 \pm 0.8)\%$	0.1208 ± 0.0019 $(0.6 \pm 1.6)\%$	0.6910 ± 0.014 $(2.6 \pm 2.1)\%$	146.0 ± 1.3 $(-0.7 \pm 0.9)\%$
BM_1	1.011 1.1%	0.02276 1.7%	0.1236 ± 0.0017 $(2.9 \pm 1.4)\%$	0.6904 ± 0.0061 $(2.6 \pm 0.9)\%$	144.5 ± 0.4 $(-1.8 \pm 0.3)\%$
BM_2	1.010 1.0%	0.02238 0.0%	0.1229 ± 0.0017 $(2.3 \pm 1.4)\%$	0.6872 ± 0.0061 $(2.1 \pm 0.9)\%$	145.4 ± 0.5 $(-1.1 \pm 0.3)\%$
BM_3	1.000 0.0%	0.02260 1.0%	0.1189 ± 0.0017 $(-1.0 \pm 1.4)\%$	0.6793 ± 0.0061 $(0.9 \pm 0.9)\%$	147.1 ± 0.5 $(0.1 \pm 0.3)\%$
$\mathrm{BM}_{\mathrm{BBN}}$	1.011 ± 0.001 $(1.1 \pm 0.1)\%$	0.02276 ± 0.00030 $(1.7 \pm 1.3)\%$	0.1236 ± 0.0019 $(2.9 \pm 1.6)\%$	0.6904 ± 0.0066 $(2.6 \pm 1.0)\%$	144.8 ± 0.7 $(-1.6 \pm 0.5)\%$
$\mathrm{BM}_{\mathrm{BBN(NL)}}$	1.012 ± 0.002 $(1.2 \pm 0.2)\%$	0.02290 ± 0.00031 $(2.3 \pm 1.4)\%$	0.1243 ± 0.0019 $(3.5 \pm 1.6)\%$	0.6924 ± 0.0068 $(2.8 \pm 1.0)\%$	144.3 ± 0.8 $(-1.9 \pm 0.5)\%$

The same trend as that in [L. Hart and J. Chluba, 2019] is observed, as v varies: a positive shift of v results in a smaller r_d and bigger h value.



More Comprehensive Treatment (Preliminary)



CMB scales [W. Hu, 2000]

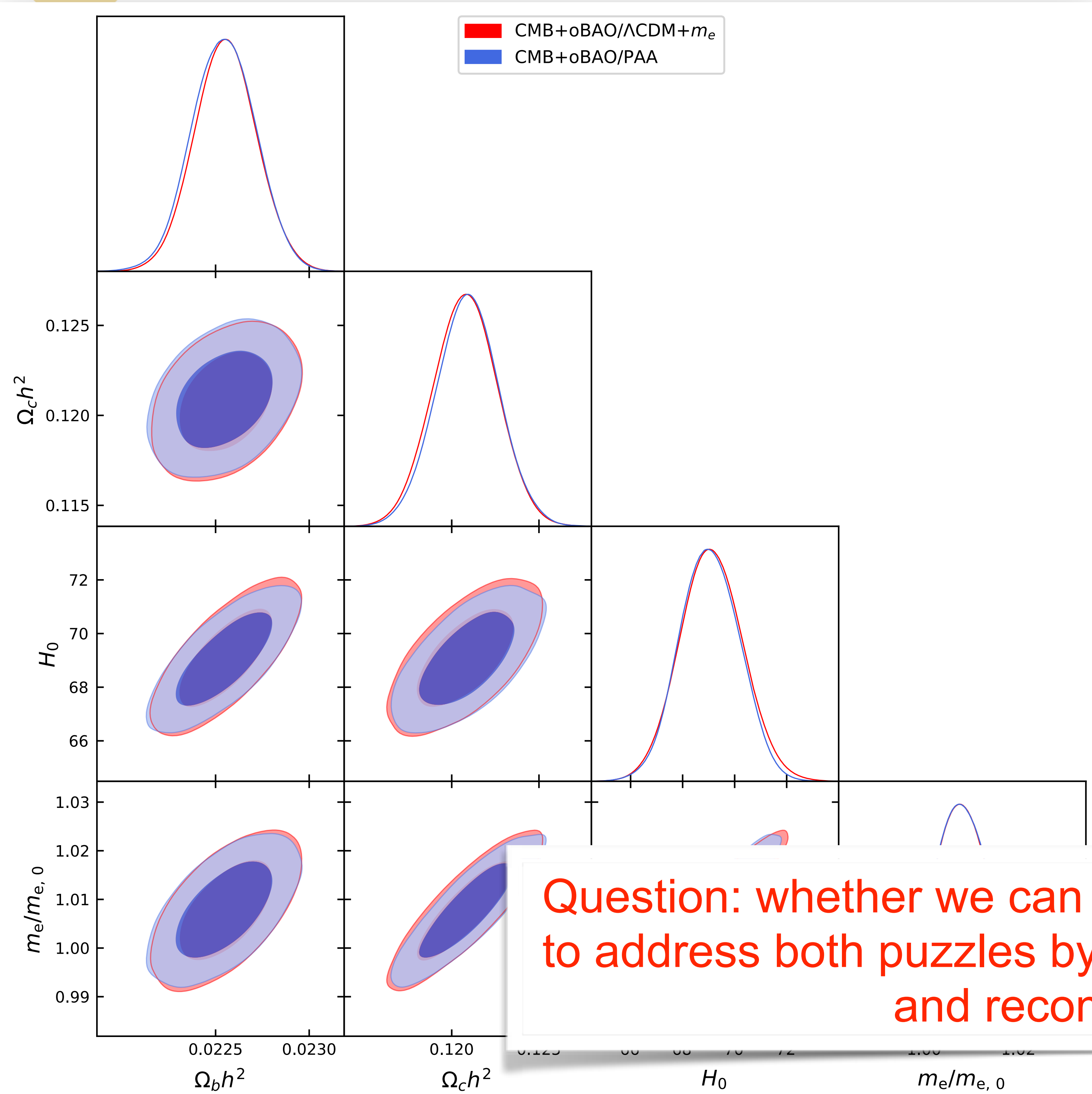
$$\delta l_a = \delta D_* - \delta r_* \,,$$
$$\delta l_{\rm eq} = \delta k_{\rm eq} + \delta D_* \,,$$
$$\delta l_D = \delta k_D + \delta D_* \,,$$

BAO scales

$$\delta\alpha_\perp(z_{\rm eff}) = \delta D(z_{\rm eff}) - \delta r_d \,,$$
$$\delta\alpha_\parallel(z_{\rm eff}) = \delta H(z_{\rm eff}) + \delta r_d \,,$$
$$\delta\alpha_V(z_{\rm eff}) = \frac{2}{3}\delta D(z_{\rm eff}) - \frac{1}{3}\delta H(z_{\rm eff}) - \delta r_d$$

The numerical results in [L. Hart and J. Chluba, 2019] are almost perfectly reproduced using this semi-analytical+likelihood method!

More Comprehensive Treatment (Preliminary)



CMB scales [W. Hu, 2003]

$$\delta l_a = \delta D_* - \delta r_* \ ,$$

$$\delta l_{\rm eq} = \delta k_{\rm eq} + \delta D_* \ ,$$

$$\delta l_D = \delta k_D + \delta D_* \ ,$$

BAO scales

$$\delta\alpha_\perp(z_{\rm eff}) = \delta D(z_{\rm eff}) - \delta r_d \ ,$$

$$\delta\alpha_\parallel(z_{\rm eff}) = \delta H(z_{\rm eff}) + \delta r_d \ ,$$

$$\delta\alpha_V(z_{\rm eff}) = \frac{2}{3}\delta D(z_{\rm eff}) - \frac{1}{3}\delta H(z_{\rm eff}) - \delta r_d$$

Question: whether we can find a realization in particle physics to address both puzzles by varying the Higgs VEV in the BBN and recombination epochs?

analytical likelihood method?

Axi-Higgs Model: Our Proposal

A system of axion + Higgs, with the Higgs evolution being driven by the axion field. Effectively, we have

$$V = V_a + V_\phi = V_a(a) + \left| K(a) \left(m_s^2 F(a) - \kappa \phi^\dagger \phi \right) \right|^2$$

$$W = X \left(m_s^2 G(A) - \kappa K(A) H_u H_d \right) + \cdots \to V_\phi = \left| m_s^2 G(a) - \kappa K(a) \phi^\dagger \phi \right|^2$$

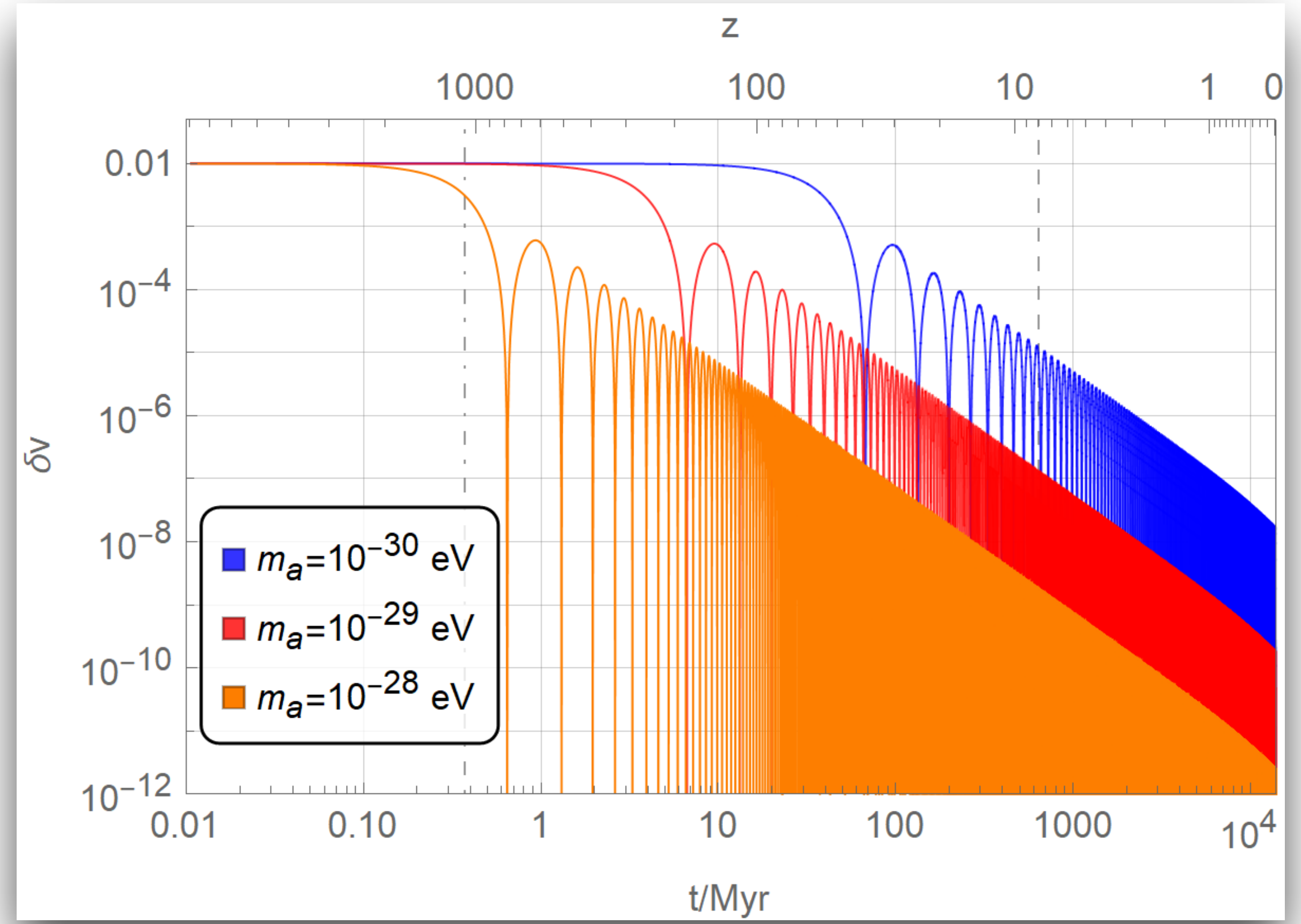
$$\ddot{v} + (3H + \Gamma_\phi)\, \dot{v} - 2\kappa B v = 0$$

During cosmic evolution, any deviation of B(=sqrt(V_phi)) from zero will be stopped by the big Higgs decay width. If that happens, e.g., caused by axion oscillation, the Higgs VEV will be shifted instantly to an axion-driven profile defined by B=0.

$$\langle \phi^\dagger \phi \rangle = \frac{v^2}{2} = \frac{m_s^2}{\kappa} F(a)$$

$$\delta v(t) = F(a(t))^{1/2} - 1 \simeq \frac{C a(t)^2}{2 M_{\rm Pl}^2}$$

Axi-Higgs Model



$$\delta v(t) = F(a(t))^{1/2} - 1 \simeq \frac{Ca(t)^2}{2M_{\rm Pl}^2}$$

The axion evolution is approximately described by physics for a damped harmonic oscillator:

$$\ddot{a} + 3H(t)\dot{a} + \frac{\partial V_a}{\partial a} = 0$$

At early cosmic time, the large H(t) freezes the axion field to an initial value

$$a_{\rm ini} = \left(\frac{2\delta v_{\rm ini} M_{\rm Pl}^2}{C}\right)^{1/2}$$

$$\delta v_{\rm ini} = \delta v_{\rm rec} = \delta v_{\rm BBN}.$$

Once H(t) becomes smaller than m_a, the axion field starts to oscillate around the potential minimal point in an underdamped manner

$$a(t) \simeq \mathcal{A}_m(t) a_{\rm ini} \cos(m_a t)$$

$$\Delta z \simeq 0.83 \left(\frac{1+z}{10}\right)^{2.5} \left(\frac{m_a}{10^{-30}\,\mathrm{eV}}\right)^{-1}$$

Axi-Higgs Model - Axion Mass

- Condition 1: the axion field starts to roll down near or after the recombination => the same $a_{\rm ini}$ throughout the BBN-recombination epoch and hence $a_{\rm rec} = a_{\rm BBN}$ =>

$$m_a \lesssim 3.3 \times 10^{-29}\,\mathrm{eV}$$

- Condition 2: the axion field oscillates with a highly-suppressed amplitude at low redshifts and today. => To satisfy the experimental bounds set by atomic-clock and quasar measurements

Atomic clock (AC)

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

[R. Lange et. al., 2021]

$$m_a > 1.0 \times 10^{-29}\,\mathrm{eV} \quad (68\%\ \mathrm{C.L.})$$

$$m_a > 1.6 \times 10^{-30}\,\mathrm{eV} \quad (95\%\ \mathrm{C.L.})$$

Axi-Higgs Model

In this context, the Li-7 problem and Hubble tension can be simultaneously addressed, with a shift to the Higgs VEV throughout the BBN-recombination epoch.

Moreover, as an ultralight CP-odd bosonic D.O.F., the axion in this model has special properties:

- Big de Broglie wavelength (~100-1000 Mpc, in comparison to the galactic-cluster scale ~1-10 Mpc)
- Coupling with photons

$$\mathcal{L} \sim \frac{1}{32\pi^2}\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Question: will these properties bring detectable impacts on cosmology and astronomy, other than BBN and Hubble?

S_8 (σ_8) Tension

σ_8 is the matter clustering amplitude (root mean square of matter density fluctuations) on the scale of galactic cluster, namely, $R_8 = 8h^{-1}\mathrm{Mpc}$. In the Fourier momentum space, it is given by

$$\sigma_8^2 = \sigma^2(r = R_8) = \int_0^\infty \mathcal{P}_m(k) W^2(kR_8) dk$$

Yet, the effect of σ_8 is inseparable from the growth rate of structure, in the galaxy-clustering observations. The direct observable is instead

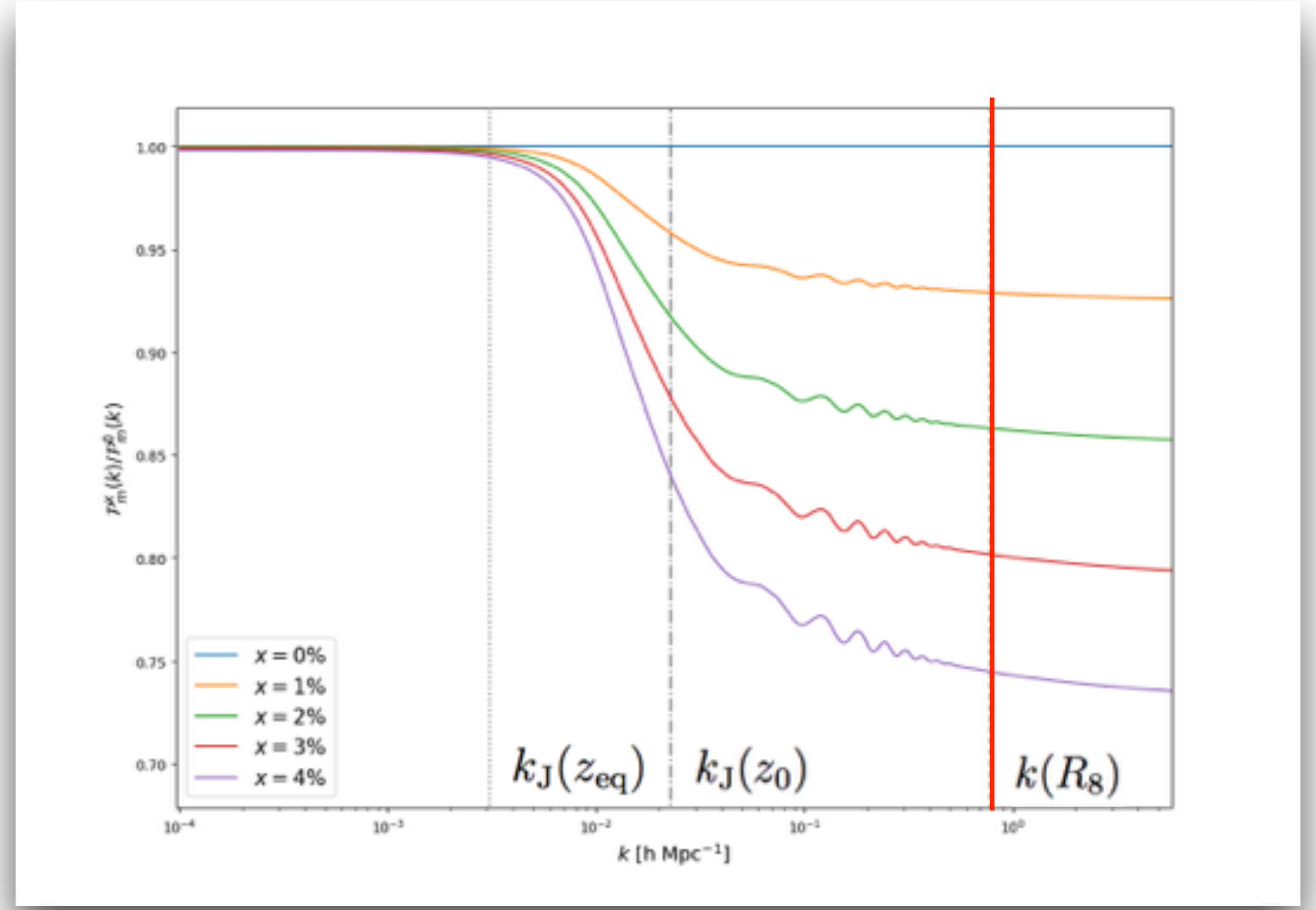
$$S_8 \equiv \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{0.5}$$

S_8 (σ_8) tension: a ~2-3 sigma discrepancy between the inferred S_8 value from the CMB data assuming the LCDM model and its value obtained from direct measurements in the late-time universe, in particular, DES and KiDS-1000

$$S_{8,\mathrm{CMB}} = 0.832 \pm 0.013$$

$$S_{8,\mathrm{DES}} = 0.773^{+0.026}_{-0.020} \,, \qquad S_{8,\mathrm{KiDS-1000}} = 0.766^{+0.020}_{-0.014}$$

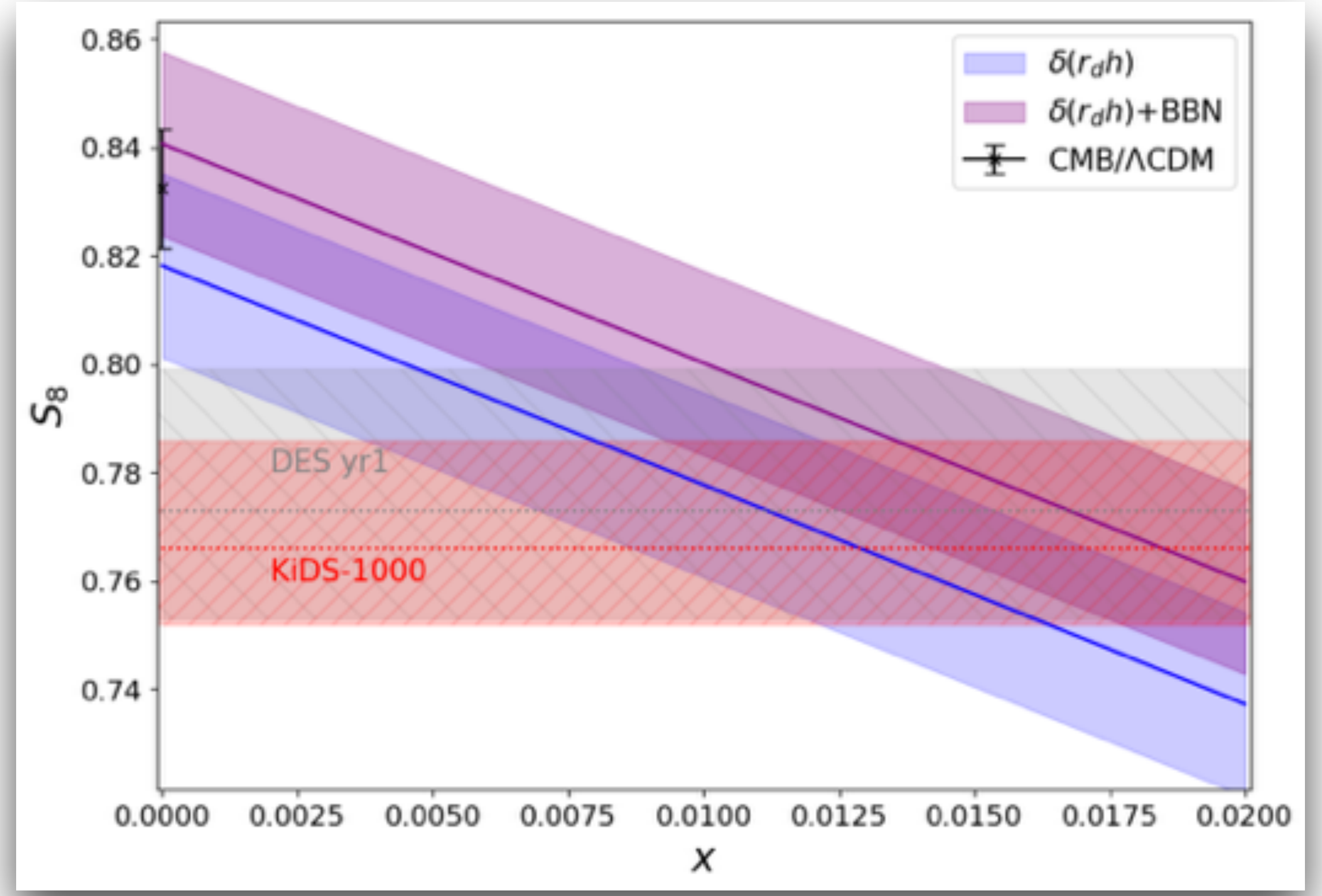
S_8 (σ_8) Tension



``Axi-Higgs'' opportunity: its axion is wavy, and hence can suppress the formation of structure in the universe scale-dependently. Here the suppression scale is determined by its mass m_a, while the suppression strength is determined by its matter density ($x = \omega_a / \omega_m$)

$$k_J(z) = \frac{\sqrt{m_a H(z)}}{(1+z)} \qquad a_{ini} \simeq 3.7 \times 10^{17}\,\mathrm{GeV} \left(\frac{x}{0.01}\right)^{1/2}$$

S_8 (σ_8) Tension



- Applying the linear analysis again with the extra parameter x and constraint $\delta S_8 = 0.5\delta\Omega_m + \delta\sigma_8$ we find (using **AxionCAMB**)

$$H_0 \simeq H_{0,\mathrm{P18}} \left(1.01 \pm 0.01 + 1.37\delta v_{\mathrm{rec}} - 0.52x\right)$$

$$S_8 \simeq S_{8,\mathrm{P18}} \left(0.98 \pm 0.02 + 2.62\delta v_{\mathrm{rec}} - 4.86x\right)$$

- By turning on x, the S_8 tension with the late-time measurements gets alleviated

Cosmic Birefringence

PHYSICAL REVIEW D VOLUME 43, NUMBER 12 15 JUNE 1991

ARTICLES

Einstein equivalence principle and the polarization of radio galaxies

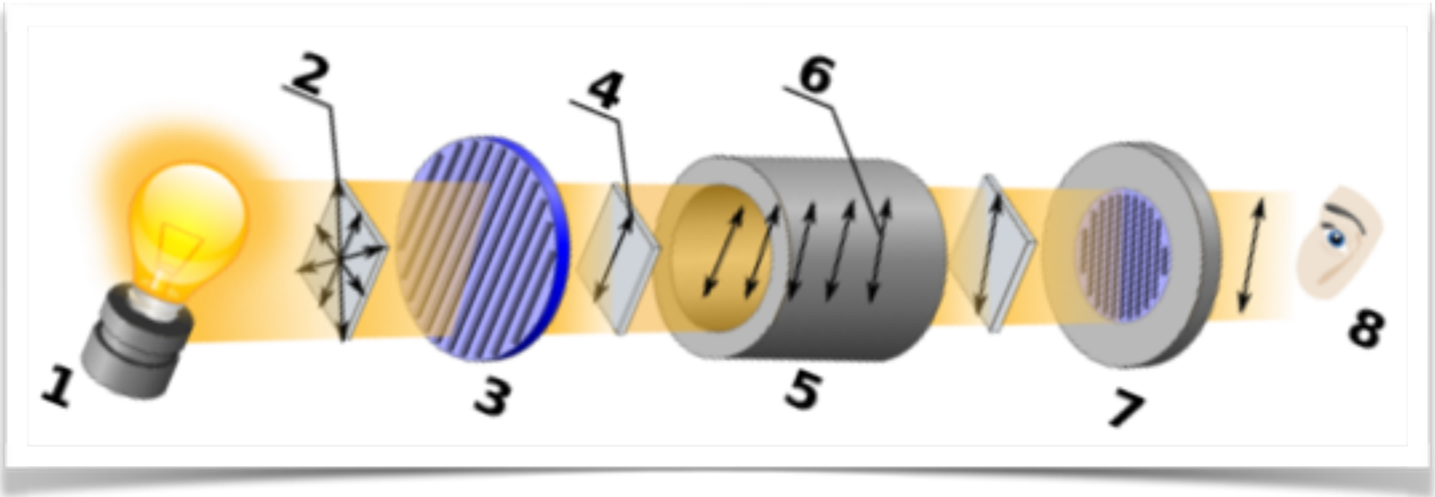
Sean M. Carroll and George B. Field
Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138
(Received 26 December 1990)

Cosmic Birefringence

$$L \sim -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2}m_a^2 a^2 + \frac{g}{2} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

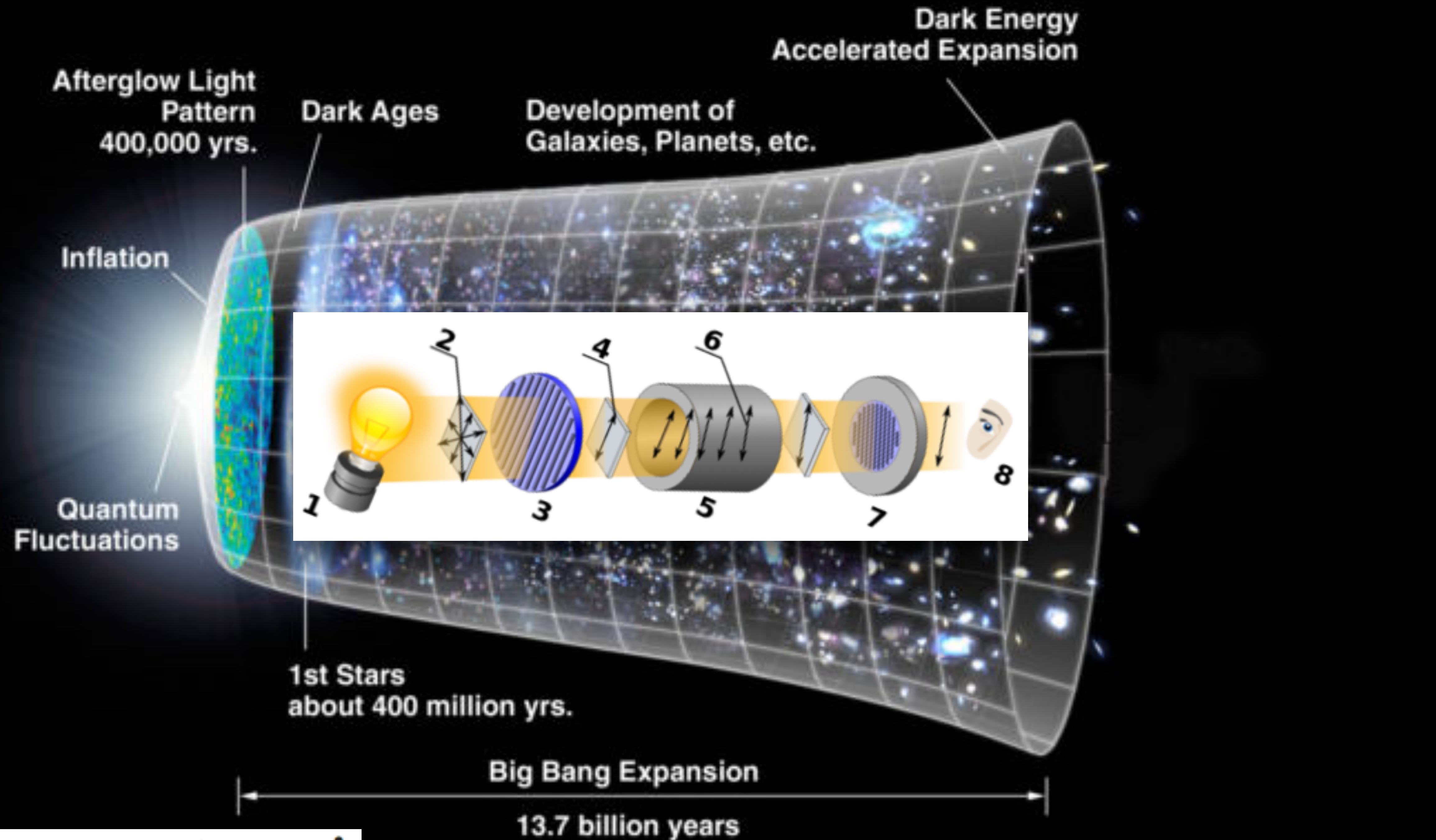
$$\begin{pmatrix} \partial_t^2 + k^2 + m_a^2 & 0 & 0 \\ 0 & \partial_t^2 + k^2 + \eta(t)k & 0 \\ 0 & 0 & \partial_t^2 + k^2 - \eta(t)k \end{pmatrix} \begin{pmatrix} i\hat{a} \\ f_+ \\ f_- \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$$

Parity-violating interaction => Different dispersion relations for left- and right-circular polarized photons => Oscillating (linear) polarization angle



$$\Delta\phi = g\int_{t_i}^{t_f} \partial_t a(x,t) = g\int_{t_i}^{t_f} \partial_t [a_0(x,t)\cos(m_a t + \theta(x,t))]$$

Parity-Violating Imprints in CMB



$$\beta = \frac{1}{2} g_{\phi\gamma} \int_{t_{\rm LSS}}^{t_0} dt \dot{\phi}$$

$$C_\ell^{EB,o} = \frac{1}{2}\sin(4\beta)(C_\ell^{EE} - C_\ell^{BB})$$

[Lue, Wang, Kamionkowski, PRL(1999)]

ICB Anomaly

Featured in Physics | Editors' Suggestion

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New Extraction of the Cosmic Birefringence from the Planck 2018 Polarization Data

Yuto Minami and Eiichiro Komatsu

Phys. Rev. Lett. **125**, 221301 – Published 23 November 2020

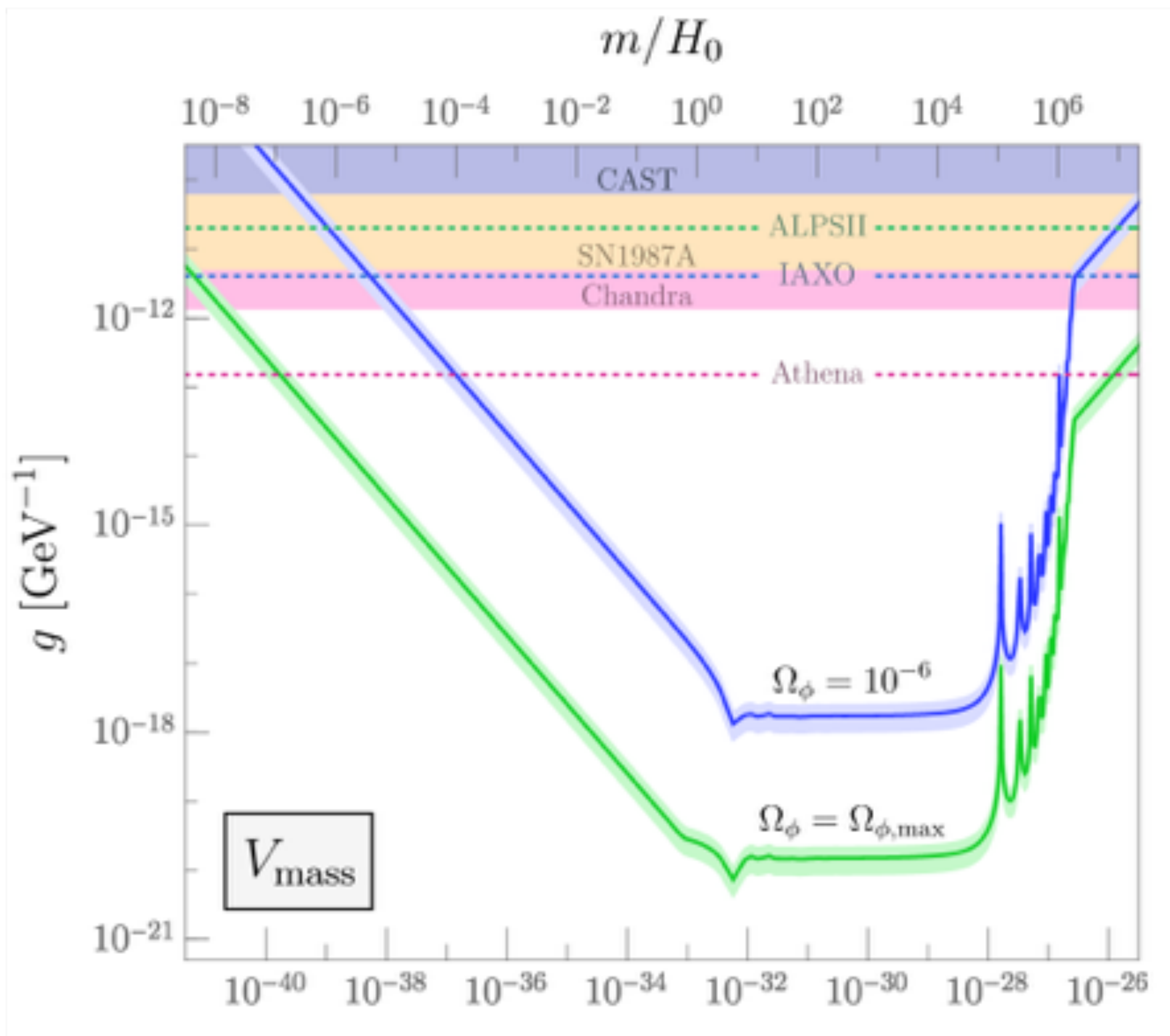
Physics See synopsis: Hints of Cosmic Birefringence?

Article | References | Citing Articles (2) | PDF | HTML | Export Citation

ABSTRACT

We search for evidence of parity-violating physics in the Planck 2018 polarization data and report on a new measurement of the cosmic birefringence angle β. The previous measurements are limited by the systematic uncertainty in the absolute polarization angles of the Planck detectors. We mitigate this systematic uncertainty completely by simultaneously determining β and the angle miscalibration using the observed cross-correlation of the E- and B-mode polarization of the cosmic microwave background and the Galactic foreground emission. We show that the systematic errors are effectively mitigated and achieve a factor-of-2 smaller uncertainty than the previous measurement, finding $\beta = 0.35 \pm 0.14$ deg (68% C.L.), which excludes $\beta = 0$ at 99.2% C.L. This corresponds to the statistical significance of 2.4σ.

Axion Interpretation



[T. Fujita et. al., 2020]

Most-favored axion mass:

$$H_0(\sim 10^{-32}\mathrm{eV}) < m_a < H_{\mathrm{rec}}(\sim 10^{-28}\mathrm{eV})$$

$$\beta \sim -\frac{1}{16\pi^2}\frac{a_{\mathrm{ini}}}{f_a}, \quad \Rightarrow \quad \frac{a_{\mathrm{ini}}}{f_a} \simeq 1.0 \pm 0.3$$

=> Great opportunity for ``axi-Higgs'': the``vanilla'' region of m_a in this model falls into this range

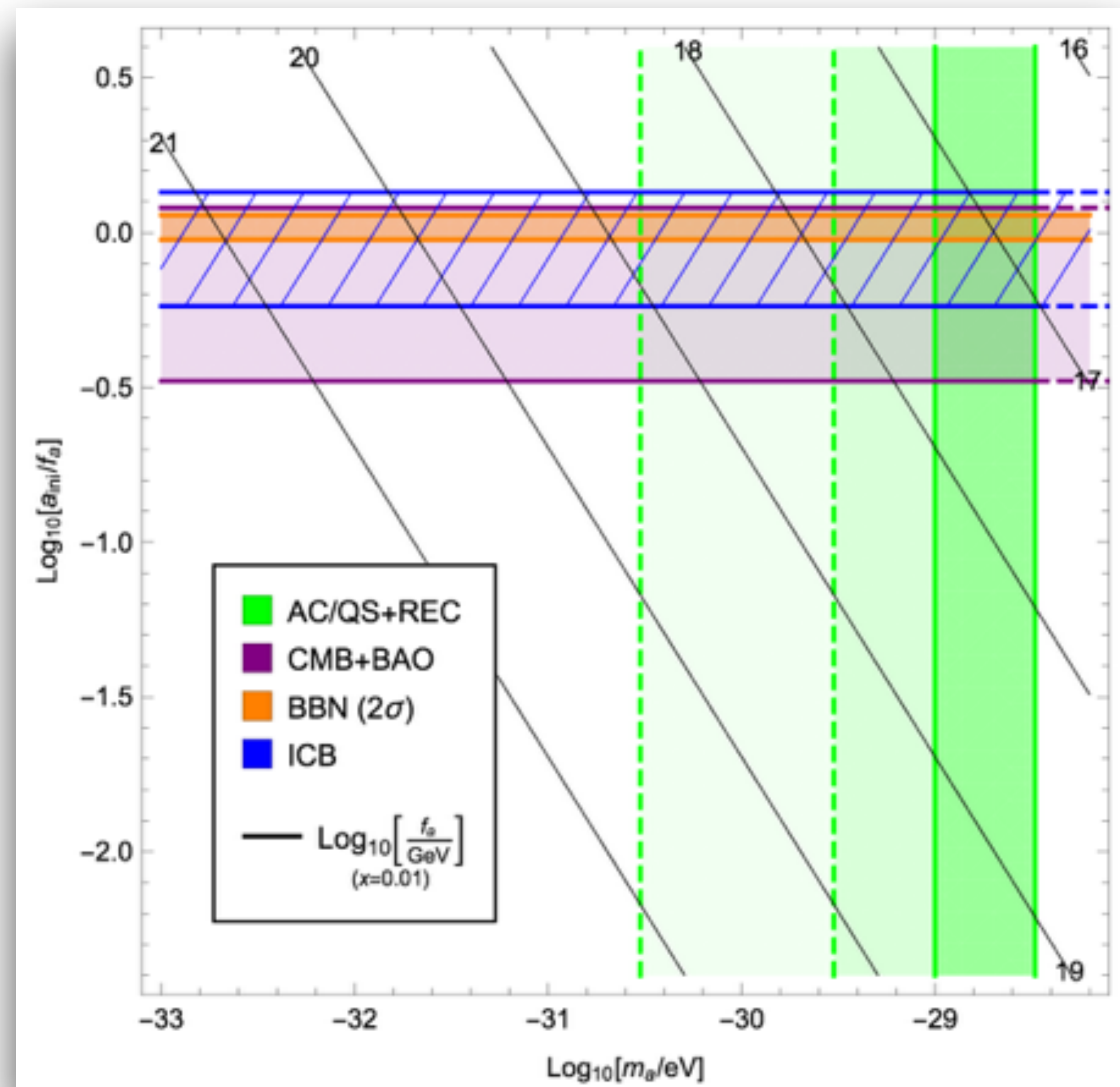
Overall Picture on the Axi-Higgs Cosmology

``Axi-Higgs" - a four-parameter system

$$m_a,\ \delta v_{\rm ini} = C'\left(\frac{a_{\rm ini}}{f_a}\right)^2 \ \text{or}\ C',\ \frac{a_{\rm ini}}{f_a}\ \text{and}\ f_a$$

- m_a: constrained by the requirement of the late-time oscillation and the bounds from the AC/QS measurements
- $\delta v_{\rm ini}$: constrained for addressing Li-7 problem and Hubble tension
- $a_{\rm ini}/f_a$: constrained for explaining ICB anomaly
- f_a: the x value required for addressing S_8 tension determines $a_{\rm ini}$ and hence f_a

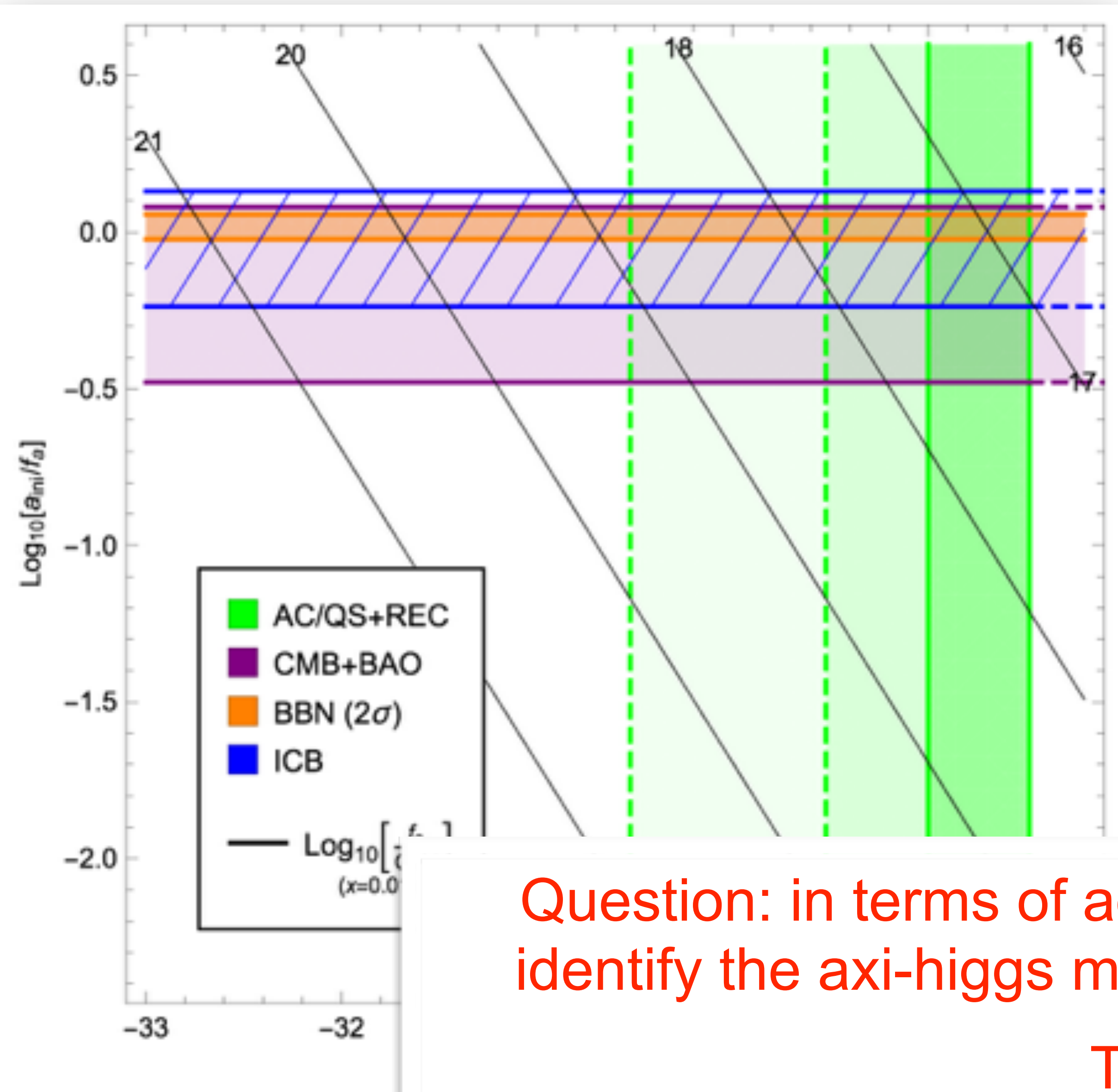
Overall Picture on the Axi-Higgs Cosmology



$$m_a,\ \delta v_{\rm ini} = C'\left(\frac{a_{\rm ini}}{f_a}\right)^2 \ \text{or}\ C',\ \frac{a_{\rm ini}}{f_a}\ \text{and}\ f_a$$

- ma is favored to be ~10^{-29} eV (68% C.L.) and ~10^{-29}-10^{-30} eV (95% C.L), the mass region favored for addressing the ICB anomaly
- With C' ~ 0.01, addressing Li-7 problem, Hubble tension, and ICB anomaly all favor a_{ini}/f_a ~ 1.0
- With the a_{ini} value (x~0.01) suggested for mitigating the S_8 (σ_8) tension, f_a is determined to be ~10^{17}-10^{18} GeV, which one is temped to identify with Planck scale

Overall Picture on the Axi-Higgs Cosmology



$$m_a,\ \delta v_{\rm ini} = C'\left(\frac{a_{\rm ini}}{f_a}\right)^2 \text{ or } C',\ \frac{a_{\rm ini}}{f_a} \text{ and } f_a$$

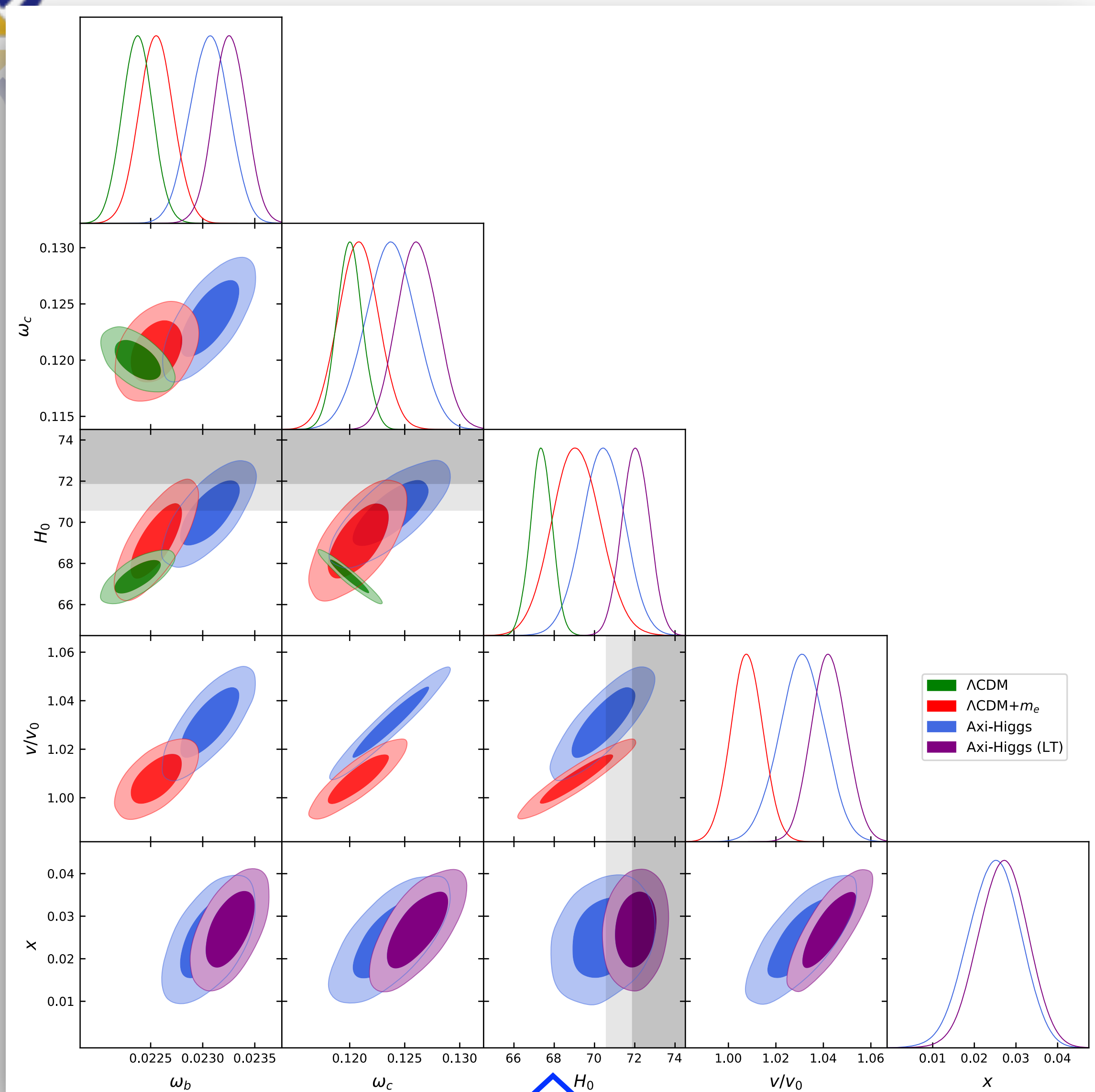
- ma is favored to be ~10^{-29} eV (68% C.L.) and ~10^{-29}-10^{-30} eV (95% C.L), the mass region favored for addressing the ICB anomaly
- With C' ~ 0.01, addressing Li-7 problem, Hubble tension, and ICB anomaly all favor a_{ini}/f_a ~ 1.0
- With the a_{ini} value (x~0.01) suggested for

scale

Question: in terms of addressing the Hubble tension, should we identify the axi-higgs model as Hart & Chiluba (or LCDM + me)?

The answer is ``No''

H&C VS. Axi-Higgs (Preliminary)



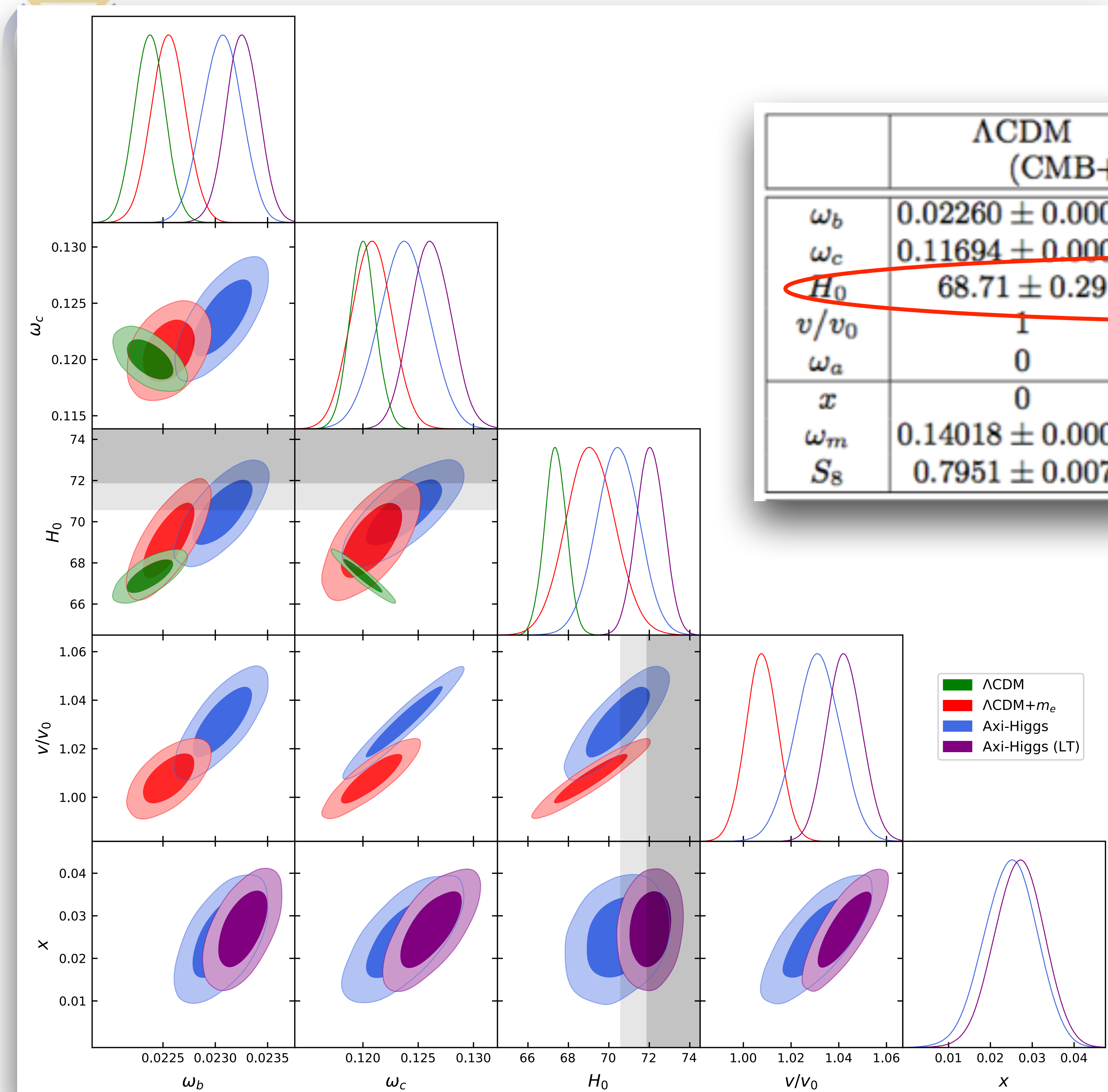
H &. C		Axi-Higgs
LCDM + m_e (one extra DOF)	VS.	LCDM + v, w_a (two extra DOFs; m_a is pre-fixed)

Different from the axion as fuzzy DM (~10^(-22) eV), the axi-Higgs axion does not roll down until after recombination, so its gravitational impacts for the CMB before that are more like dark energy, instead of matter

	$\delta\omega_b$	$\delta\omega_c$	δh	δv	$\delta\omega_a$
δl_a	0.0551	−0.1204	−0.1934	0.6837	−2.7368
$\delta l_{\rm eq}$	0.0944	0.5082	−0.1936	0.0153	−2.7574
δl_D	0.2476	−0.0964	−0.1934	0.4551	−2.6578
$\delta\alpha_V(0.106)$	0.1634	+ 0.1873	−0.9334	+ 0.6161	−0.1999
$\delta\alpha_V(0.15)$	0.1613	+ 0.1759	−0.9062	+ 0.6161	−0.2946
$\delta\alpha_\perp(0.698)$	0.1465	0.0967	−0.7175	0.6161	−0.9536
$\delta\alpha_\parallel(0.698)$	0.1255	−0.0162	−0.4483	0.6161	−1.8942
$\delta\alpha_V(0.845)$	0.1354	0.0369	−0.5747	0.6161	−1.4521
$\delta\alpha_\perp(1.48)$	0.1329	0.0236	−0.5431	0.6161	−1.5622
$\delta\alpha_\parallel(1.48)$	0.1047	−0.1279	−0.1817	0.6161	−2.8242
$\delta\alpha_\perp(2.334)$	0.1254	−0.0165	−0.4475	0.6161	−1.8958
$\delta\alpha_\parallel(2.334)$	0.0968	−0.1702	−0.0807	0.6161	−3.1732
S_8	−0.1012	1.0539	−0.7688	~ 0	−18.973

According to Friedmann eq. $H_0^2 \propto \sum \omega_i$, $w_{b,c}$ tend to increase faster as H_0 increases, such that the variation equations fail in the LCDM. In the axi-higgs Universe, however, these impacts (especially, on eq of $\delta l_{\rm eq}$) tend to be cancelled by that of w_a (``+'' ($w_{b,c}$) vs ``-'' (w_a)) => Axi-Higgs H_0 is bigger than the H &. C prediction!

Predictions (Preliminary) on the Axi-Higgs H0



	ΛCDM	Axi-Higgs	ΛCDM	Axi-Higgs
	(CMB+nBAO+WL)		(CMB+nBAO+WL+LT)	
ω_b	0.02260 ± 0.00012	0.02306 ± 0.00019	0.02271 ± 0.00012	0.02326 ± 0.00016
ω_c	0.11694 ± 0.00063	0.1237 ± 0.0023	0.11613 ± 0.00060	0.1261 ± 0.0018
H_0	68.71 ± 0.29	70.4 ± 1.1	69.15 ± 0.27	72.05 ± 0.68
v/v_0	1	1.0309 ± 0.0095	1	1.0424 ± 0.0073
ω_a	0	0.0038 ± 0.0010	0	0.00416 ± 0.00097
x	0	0.0248 ± 0.0062	0	0.0269 ± 0.0059
ω_m	0.14018 ± 0.00062	0.1512 ± 0.0032	0.13947 ± 0.00060	0.1542 ± 0.0027
S_8	0.7951 ± 0.0073	0.767 ± 0.010	0.7846 ± 0.0068	0.762 ± 0.010

CMB + BAO + WL(S8)

H_0 = 70.4 km/s/Mpc

CMB + BAO + WL(S8)
+ Late-time H0

H_0 = 72.05 km/s/Mpc

Summary on ``Axi-Higgs''

- One system: an axion coupled with the Higgs field, with the evolution of the Higgs VEV being driven by the axion field.
- Two accidentals:
  - the impacts of δv on BBN and CMB are mostly in W-boson (quark) mass and electron mass, respectively. But, they are intimately linked in the SM of particle physics, where the particle masses are proportional to the Higgs VEV.
  - A priori, only δv matters for addressing the Li-7 problem and Hubble tension. But, the drive of an axion allows us to connect them with solving the S_8 (σ_8) tension and the ICB anomaly.
- High predictivity. The four parameters to characterize this model are all well-determined, by addressing the said cosmic puzzles
- Great accessibility. It should be tested seriously in the near-future AC and QS measurements.

Thank you!

UGC 大學教育資助委員會 University Grants Committee

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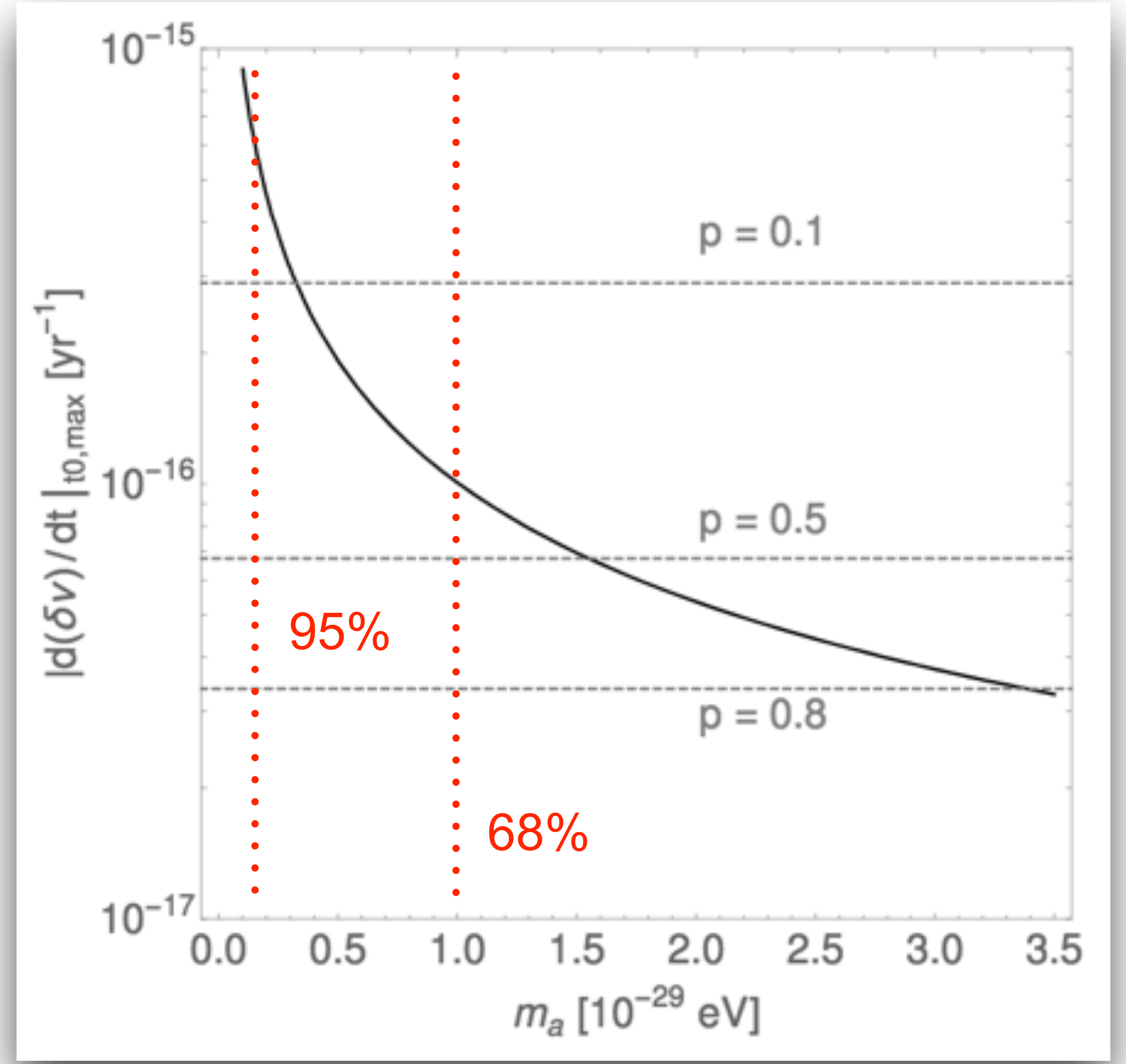
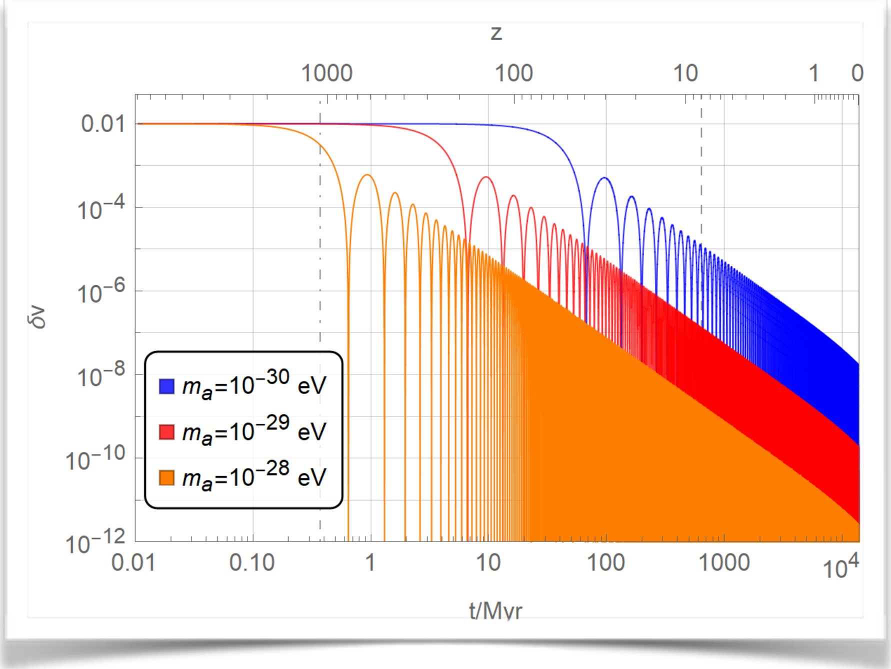
Testing ``Axi-Higgs'' - AC

AC: atomic frequency relies on the mass ratio me/mp
=> test the drift rate of Higgs VEV





$$\left.\frac{d(\delta v)}{dt}\right|_{t_0,\max} \simeq 1.0\times 10^{-15}\left(\frac{m_a}{10^{-30}\,\mathrm{eV}}\right)^{-1}\mathrm{yr}^{-1}$$

The next-generation AC technology may improve the sensitivity to a level

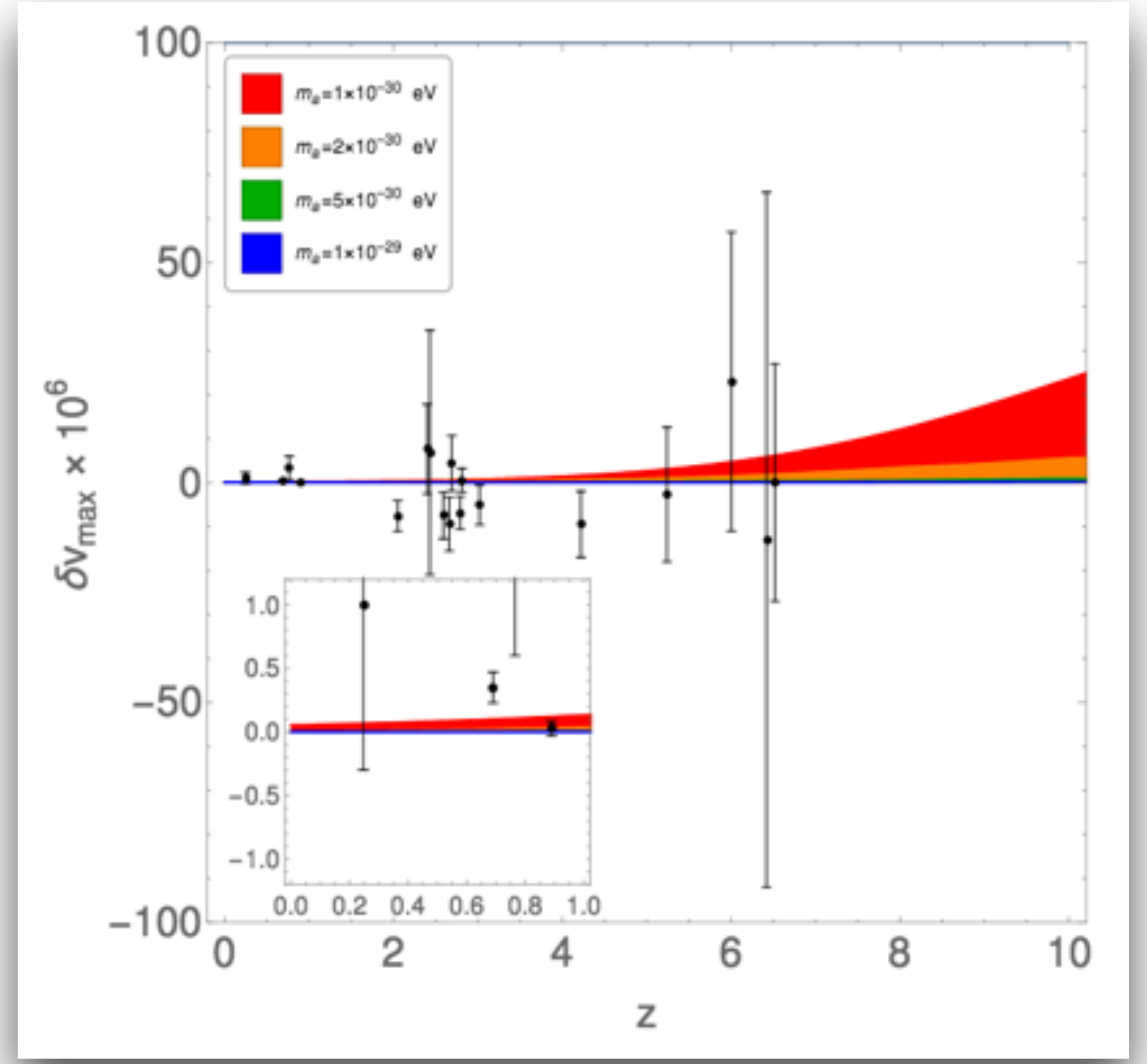
$$\sim \mathcal{O}(10^{-18})\mathrm{yr}^{-1}$$

Testing ``Axi-Higgs'' - QS

QS: the energy levels of electronic, vibrational, and rotational modes of molecules rely on the mass ratio mu=me/mp in different manners:

$$E_{\rm el} \propto \mu^0 \,, \quad E_{\rm vib} \propto \mu^{-0.5} \,, \quad E_{\rm rot} \propto \mu^{-1}$$

=> test the oscillation magnitude of Higgs VEV directly using the molecular absorption spectra of each quasar



$$\delta v_{\rm max} \simeq 1.7 \times 10^{-5} \left(\frac{\delta v_{\rm rec}}{0.01}\right) \left(\frac{1+z}{10}\right)^3 \left(\frac{m_a}{10^{-30}\,{\rm eV}}\right)^{-2}$$

- The combination of eighteen QSs collected in [S. A. Levshakov et. al., 2020] yields a constraint weaker than the AC one at 95% C.L., namely

$$m_a > 5.1 \times 10^{-31} {\rm eV}$$

- Could be well-tested in infrared and radio astronomy, with essentially improved precisions: TMT, JWST, FAST, SKA, etc., and in particular by correlating the data of the QSs at different redshifts (recall the application of PTA for detecting stochastic GWs)