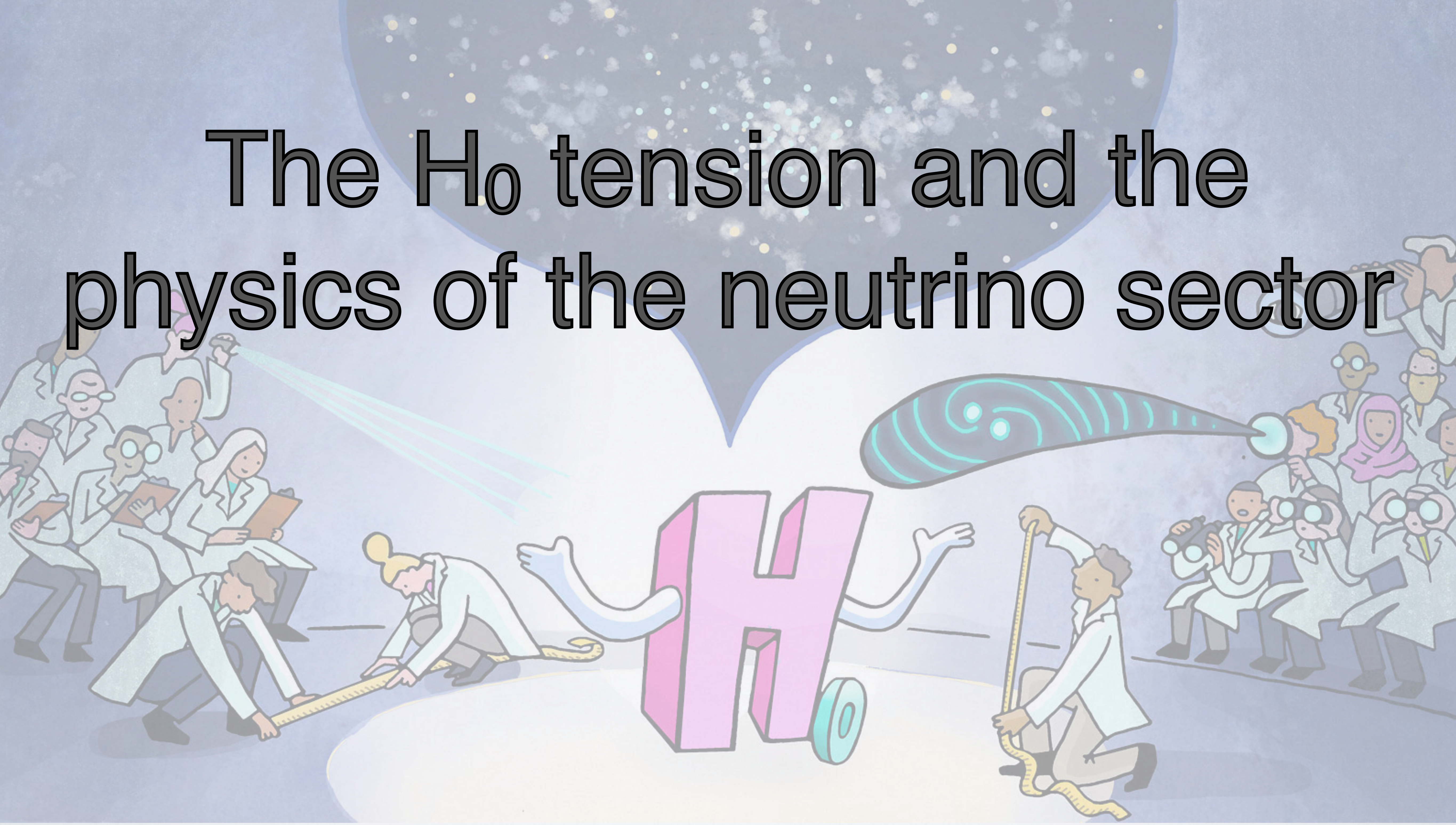
The H_0 tension and the physics of the neutrino sector



Credit: Symmetry Magazine

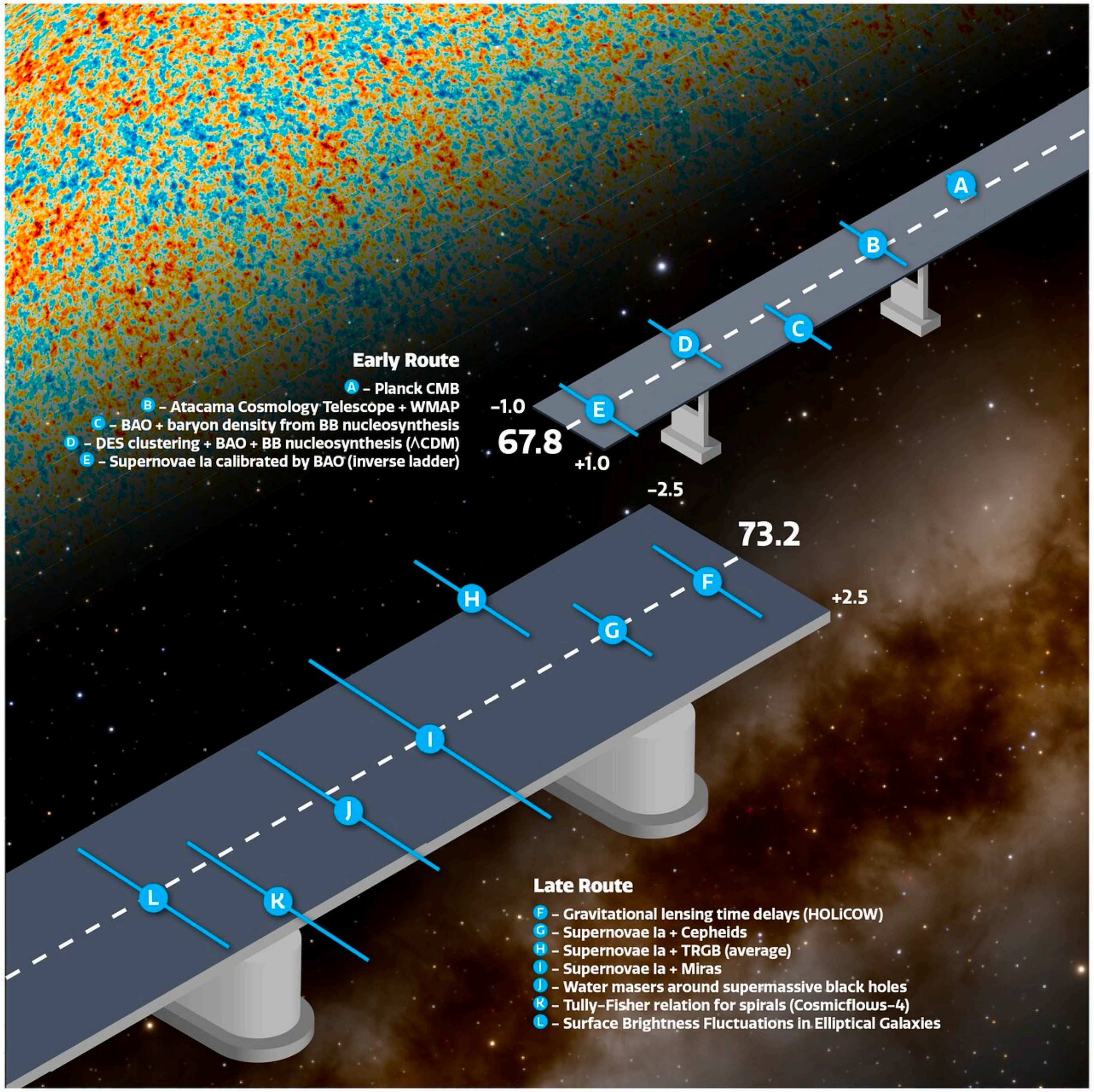
Antonio J. Cuesta

University of Córdoba (Spain)

Collaborators: **M. Masip, J.I. Illana (U. Granada), M.E. Gómez (U.Huelva)**

Tensions in Cosmology - Corfu Summer Institute - Sep 10, 2022

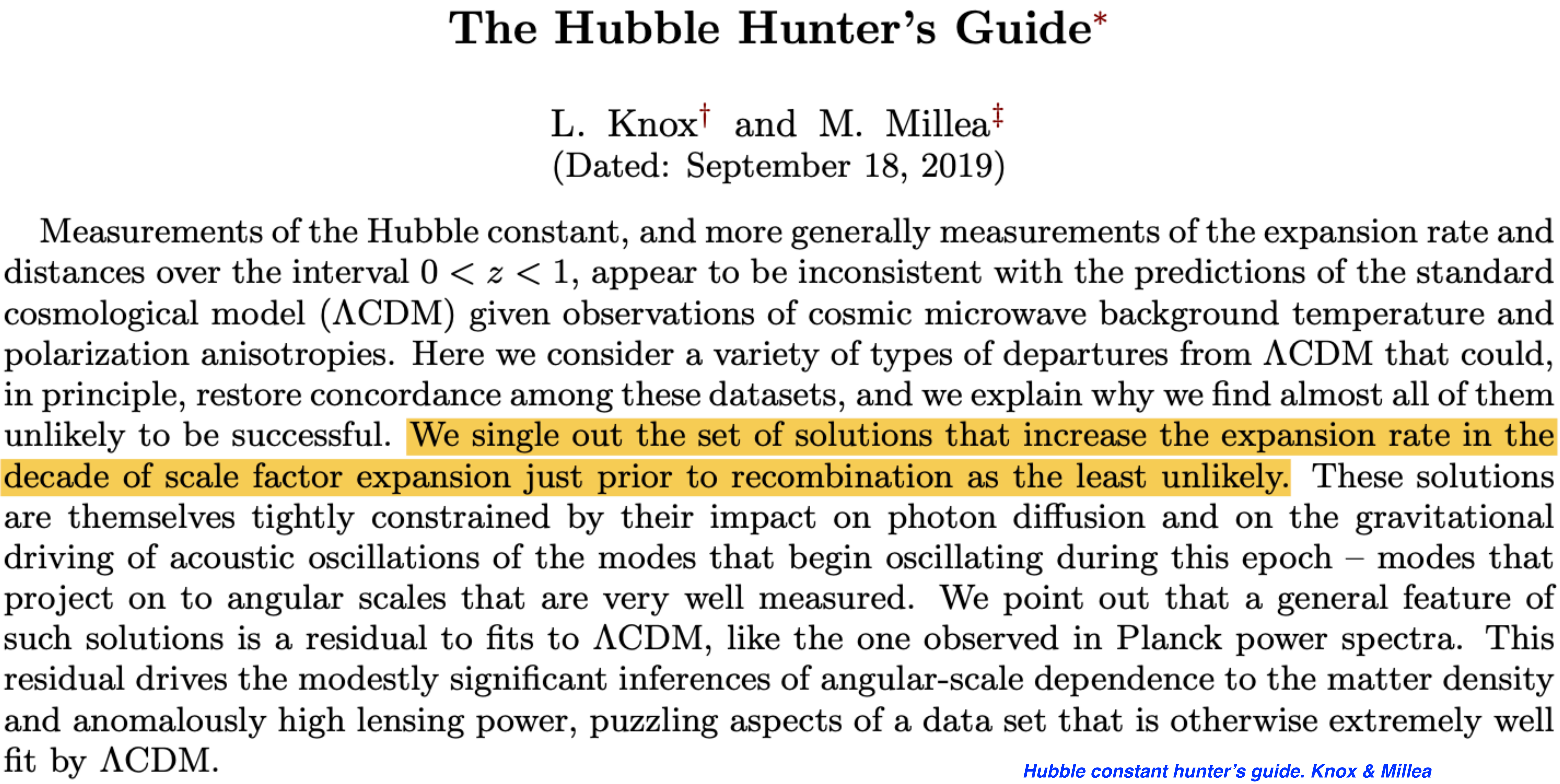
The H_0 tension



Credit: NOIRLab NSF

Where to look?

$$\theta_s = \frac{r_s}{D_A(z_*)} = \left[\int_{z_*}^{\infty} \frac{c_s(z)}{H(z)}\mathrm{d}z\right] \Big/ \left[\int_{0}^{z_*} \frac{c}{H(z)}\mathrm{d}z\right] = \frac{H_0 r_s}{\int_0^{z_*} \frac{c}{E(z)}\mathrm{d}z}$$



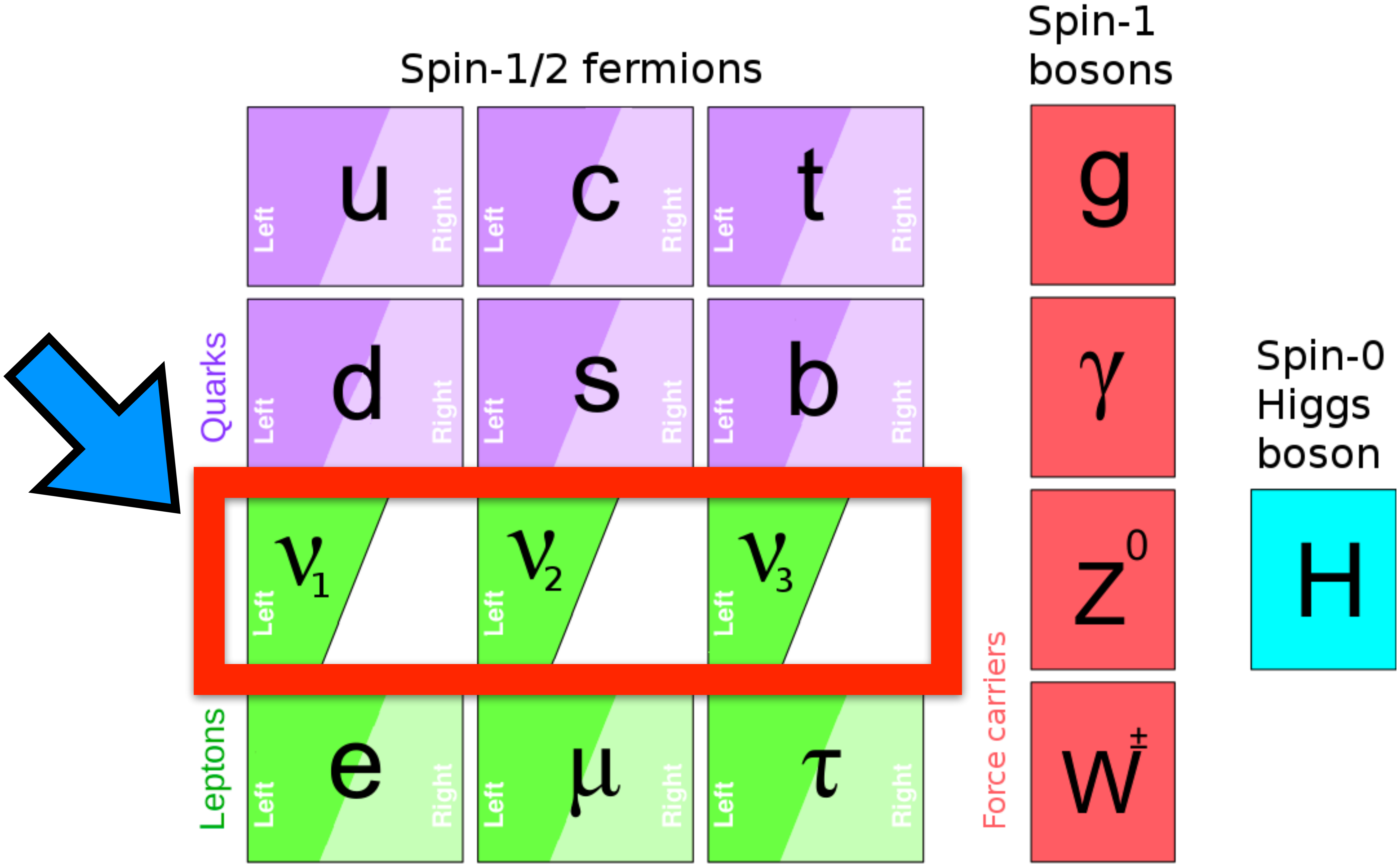
The Hubble Hunter's Guide[*]

L. Knox[†] and M. Millea[‡]
(Dated: September 18, 2019)

Measurements of the Hubble constant, and more generally measurements of the expansion rate and distances over the interval $0 < z < 1$, appear to be inconsistent with the predictions of the standard cosmological model (ΛCDM) given observations of cosmic microwave background temperature and polarization anisotropies. Here we consider a variety of types of departures from ΛCDM that could, in principle, restore concordance among these datasets, and we explain why we find almost all of them unlikely to be successful. We single out the set of solutions that increase the expansion rate in the decade of scale factor expansion just prior to recombination as the least unlikely. These solutions are themselves tightly constrained by their impact on photon diffusion and on the gravitational driving of acoustic oscillations of the modes that begin oscillating during this epoch – modes that project on to angular scales that are very well measured. We point out that a general feature of such solutions is a residual to fits to ΛCDM, like the one observed in Planck power spectra. This residual drives the modestly significant inferences of angular-scale dependence to the matter density and anomalously high lensing power, puzzling aspects of a data set that is otherwise extremely well fit by ΛCDM.

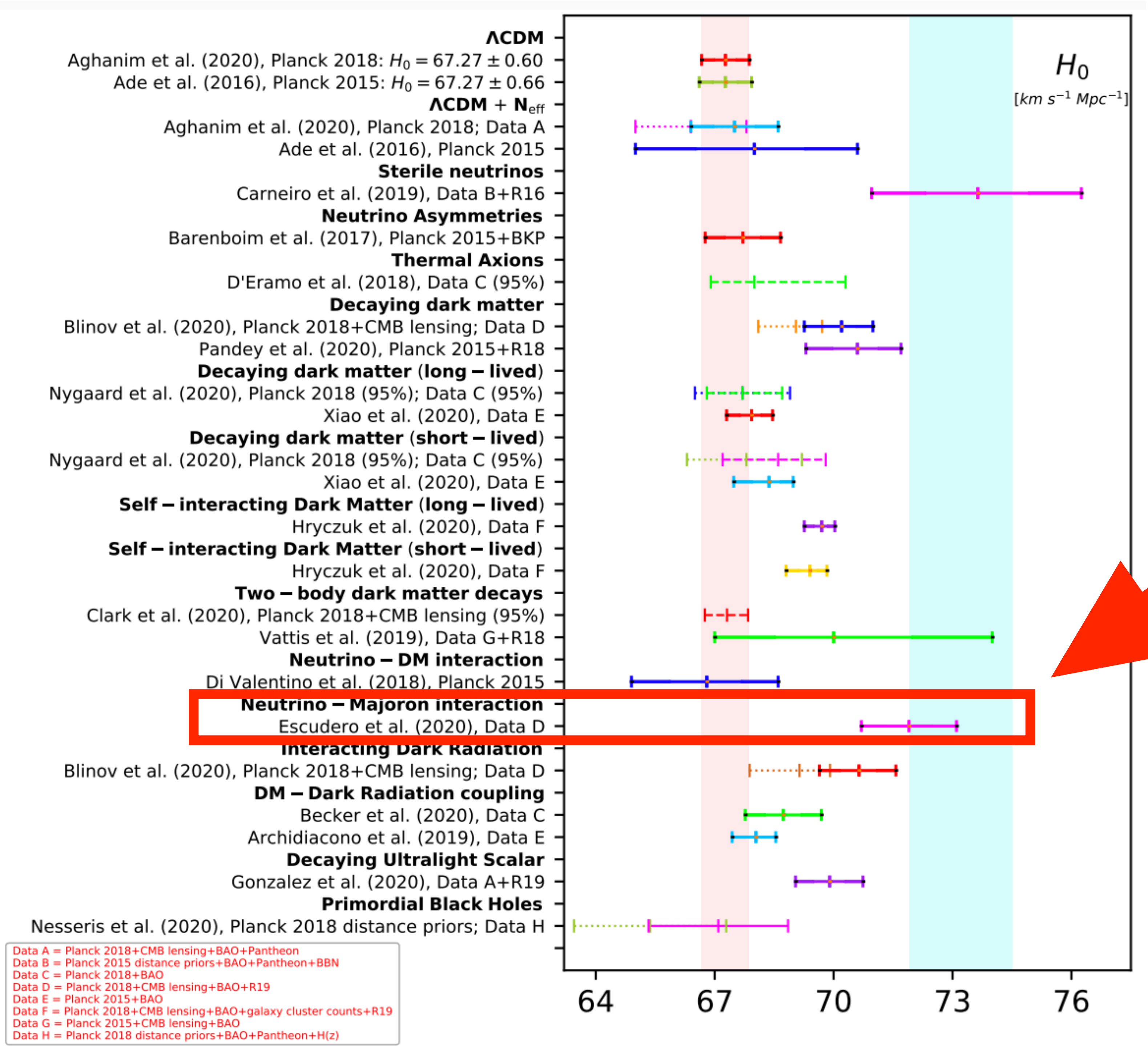
Hubble constant hunter's guide. Knox & Millea
Physical Review D 101.4 (2020) 043533. [arXiv:1908.03663]

Unsolved issues in ***particle physics***



Origin of neutrino masses? Are $\nu = \bar{\nu}$? Baryogenesis via leptogenesis?

A promising proposal to solve the ***H_0*** tension!!

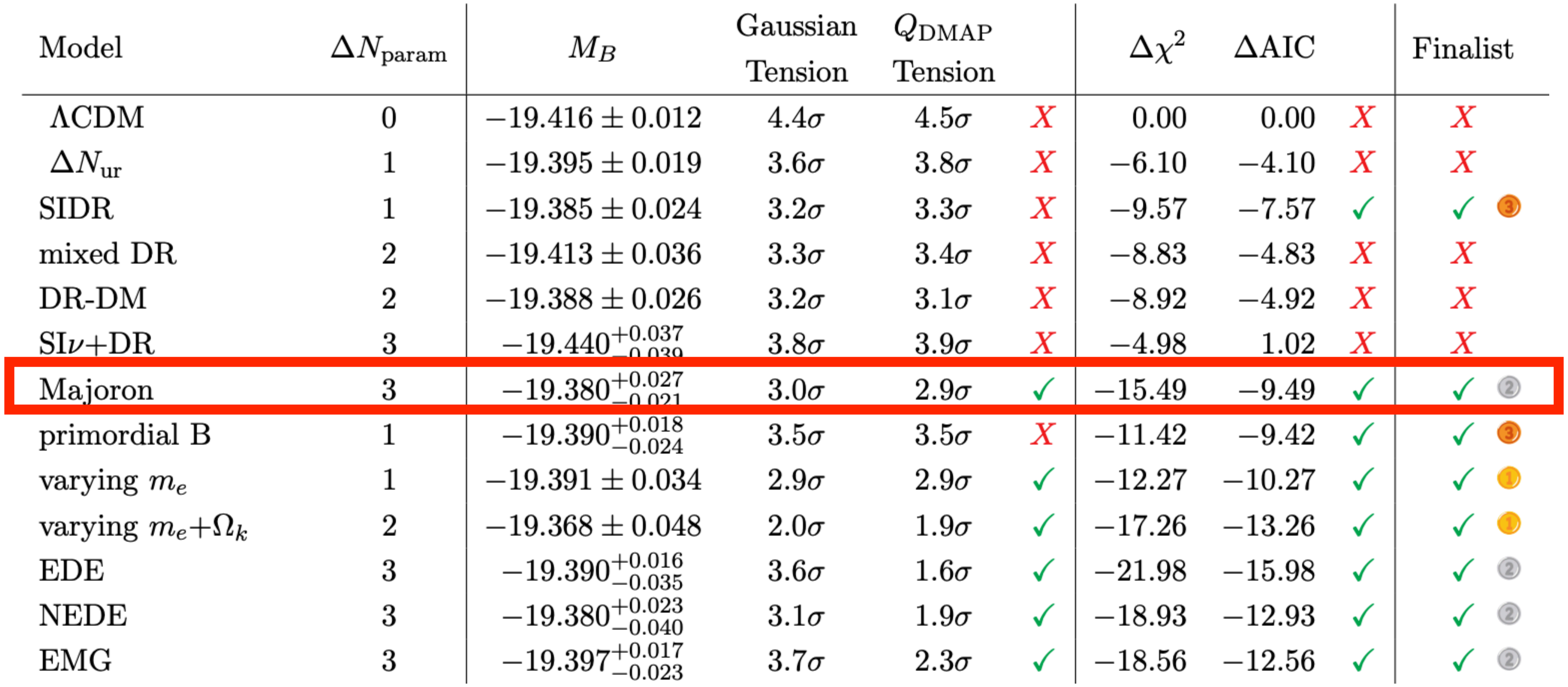


Escudero & Witte majoron

A CMB search for the neutrino mass mechanism and its relation to the Hubble tension. Escudero & Witte. The European Physical Journal C 80.4 (2020): 1-10 [arXiv:1909.04044]

In the Realm of the Hubble tension – a Review of Solutions. Di Valentino et al. Classical and Quantum Gravity 38 (2021) 153001 [arXiv:2103.01183]

A promising proposal to solve the ***H_0*** tension!!



Model	$\Delta N_{\rm param}$	M_B	Gaussian Tension	$Q_{\rm DMAP}$ Tension		$\Delta\chi^2$	ΔAIC		Finalist	
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	✗	0.00	0.00	✗	✗	
$\Delta N_{\rm ur}$	1	-19.395 ± 0.019	3.6σ	3.8σ	✗	-6.10	-4.10	✗	✗	
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	✗	-9.57	-7.57	✓	✓	③
mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	✗	-8.83	-4.83	✗	✗	
DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	✗	-8.92	-4.92	✗	✗	
SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	✗	-4.98	1.02	✗	✗	
Majoron	3	$-19.380^{+0.027}_{-0.021}$	3.0σ	2.9σ	✓	-15.49	-9.49	✓	✓	②
primordial B	1	$-19.390^{+0.018}_{-0.024}$	3.5σ	3.5σ	✗	-11.42	-9.42	✓	✓	③
varying m_e	1	-19.391 ± 0.034	2.9σ	2.9σ	✓	-12.27	-10.27	✓	✓	①
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.9σ	✓	-17.26	-13.26	✓	✓	①
EDE	3	$-19.390^{+0.016}_{-0.035}$	3.6σ	1.6σ	✓	-21.98	-15.98	✓	✓	②
NEDE	3	$-19.380^{+0.023}_{-0.040}$	3.1σ	1.9σ	✓	-18.93	-12.93	✓	✓	②
EMG	3	$-19.397^{+0.017}_{-0.023}$	3.7σ	2.3σ	✓	-18.56	-12.56	✓	✓	②

The H0 Olympics: A fair ranking of proposed models. Schoneberga et al.
Physics Reports 984 (2022) 1-55 [arXiv:2107.10291]

What is a ***majoron***? ϕ

“The majoron is a **pseudo-Goldstone boson** arising from the **spontaneous symmetry breaking** of a **global** U(1) **lepton number symmetry**”

This framework provides a dynamical mechanism to explain:

1) **the small mass of neutrinos** due to the existence of much heavier right-handed neutrinos (see-saw)
2) **lepton number violating processes** (such as baryogenesis)
3) by-product: the appearance of a **light scalar particle** (pseudo-Goldstone boson) which couples to neutrinos

Parameters of the ***majoron*** model

$$m_\phi, \Gamma_{\rm eff}, \Delta N_{\rm eff}$$

Are they actually “free”?

$m_\phi \sim \mathrm{eV}$ if we want to modify expansion rate before (but close to) recombination $(T = 0.26\mathrm{eV})$

$\Delta N_{\rm eff} \sim 1$ if we want to reduce the Hubble tension significantly: $H_0 \simeq (67.5 + 6.2\Delta N_{\rm eff})\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$ (e.g. arXiv:1907.07569)

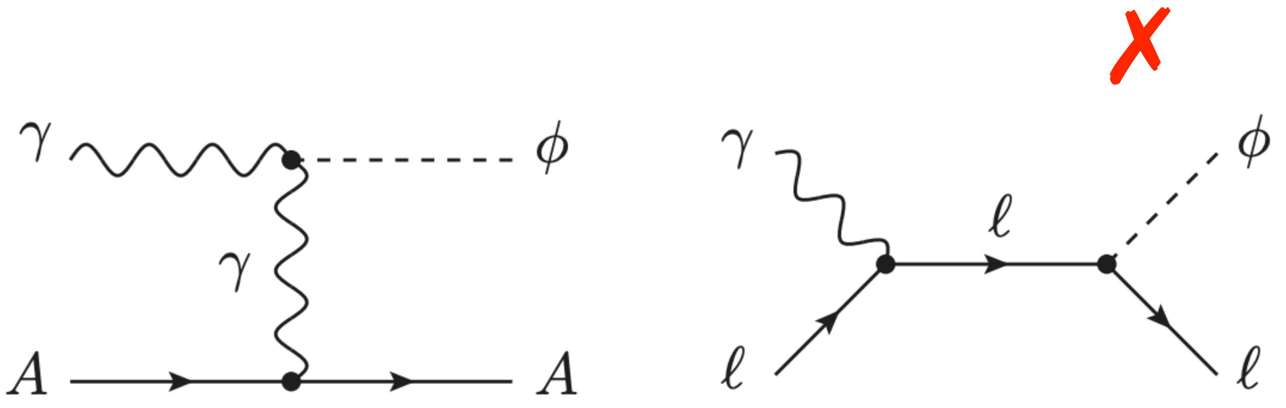
$\Gamma_{\rm eff} \equiv \Gamma/H \gtrsim 1$ if we want the majoron to have thermal equilibrium with the neutrinos (reduce neutrino free streaming)

Antonio J. Cuesta “The H₀ tension and the physics of the neutrino sector” Tensions in Cosmology - Corfu 2022

What if *besides* we make the majoron an ***axion-like particle***?

Cosmology of an Axion-Like Majoron. A.J.Cuesta, J.I. Illana, M. Masip, M. Gómez
Journal of Cosmology and Astroparticle Physics* 04 (2022) 009 *[arXiv:2109.07336]

This can transfer energy from **photons** to this dark radiation, due to resonant production in the primordial magnetic field ($B \lesssim 1\mathrm{nG}$)



$$\gamma \overset{\overrightarrow{B}}{\longleftrightarrow} \phi$$ ✔

Our majoron has tiny couplings to charged leptons. Therefore, the **Primakoff and Compton production of majorons** is very inefficient

However, the presence of a primordial magnetic field can mediate **resonant production of majorons** in the primordial plasma **at a specific temperature**

Bonus effect: since resonant production of majorons made some photons disappear (photons oscillating into majorons), **if this happened *after* BBN**, this would mean that **the actual baryon-to-photon ratio at BBN was smalller** than what is measured at recombination, in a way that is **consistent with the latest BBN deuterium observations.**

What if *besides* we make the majoron an ***axion-like particle***?

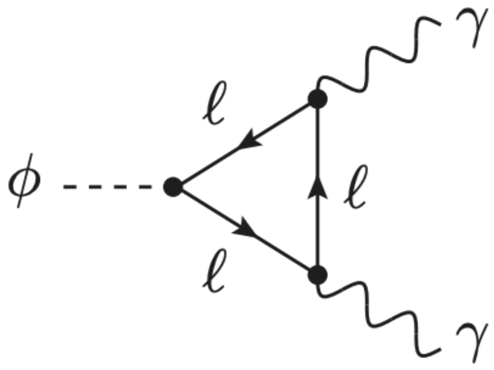
Cosmology of an Axion-Like Majoron. A.J.Cuesta, J.I. Illana, M. Masip, M. Gómez
Journal of Cosmology and Astroparticle Physics **04 (2022) 009 *[arXiv:2109.07336]***

Just before recombination, 3 major things happen:

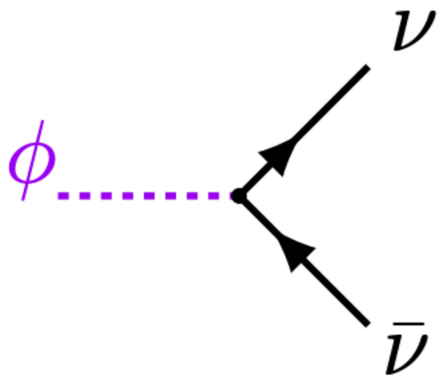
1) the majorons (that evolved as a decoupled species) become in thermal contact with the neutrinos, **damping their free-streaming**

2) Since m_ϕ is similar to the temperature at recombination, These particles will become non-relativistic when $T < m_\phi/3$ losing energy with the expansion **slower than radiation** (e.g. neutrinos)

3) When the temperature is lower than m_ϕ , the reaction $\phi \leftrightarrow \nu\bar{\nu}$ only happens in one direction. making them vanish into **neutrinos (not photons)**



✗



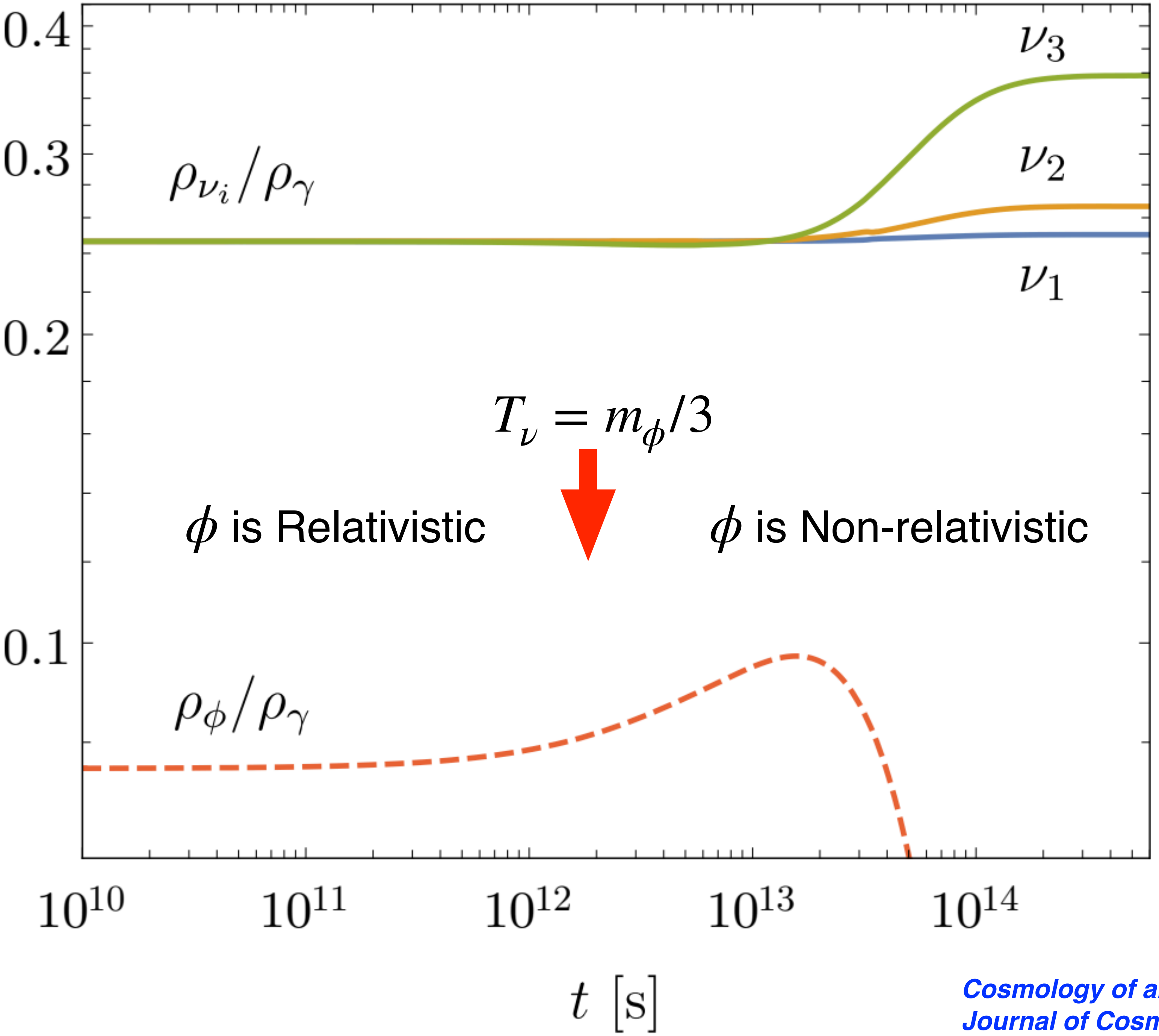
✔

$$\phi \leftrightarrow \nu\bar{\nu}$$

The result is a **net increase in the expansion rate** of the Universe **without spoiling the fit to CMB** observations, thus reducing the Hubble tension.

Precision early universe thermodynamics made simple: Neff and neutrino decoupling in the Standard Model and beyond. Escudero, M. Journal of Cosmology and Astroparticle Physics, 05 (2020) 048. [arXiv:2001.04466]

Energy density evolution (***background***)

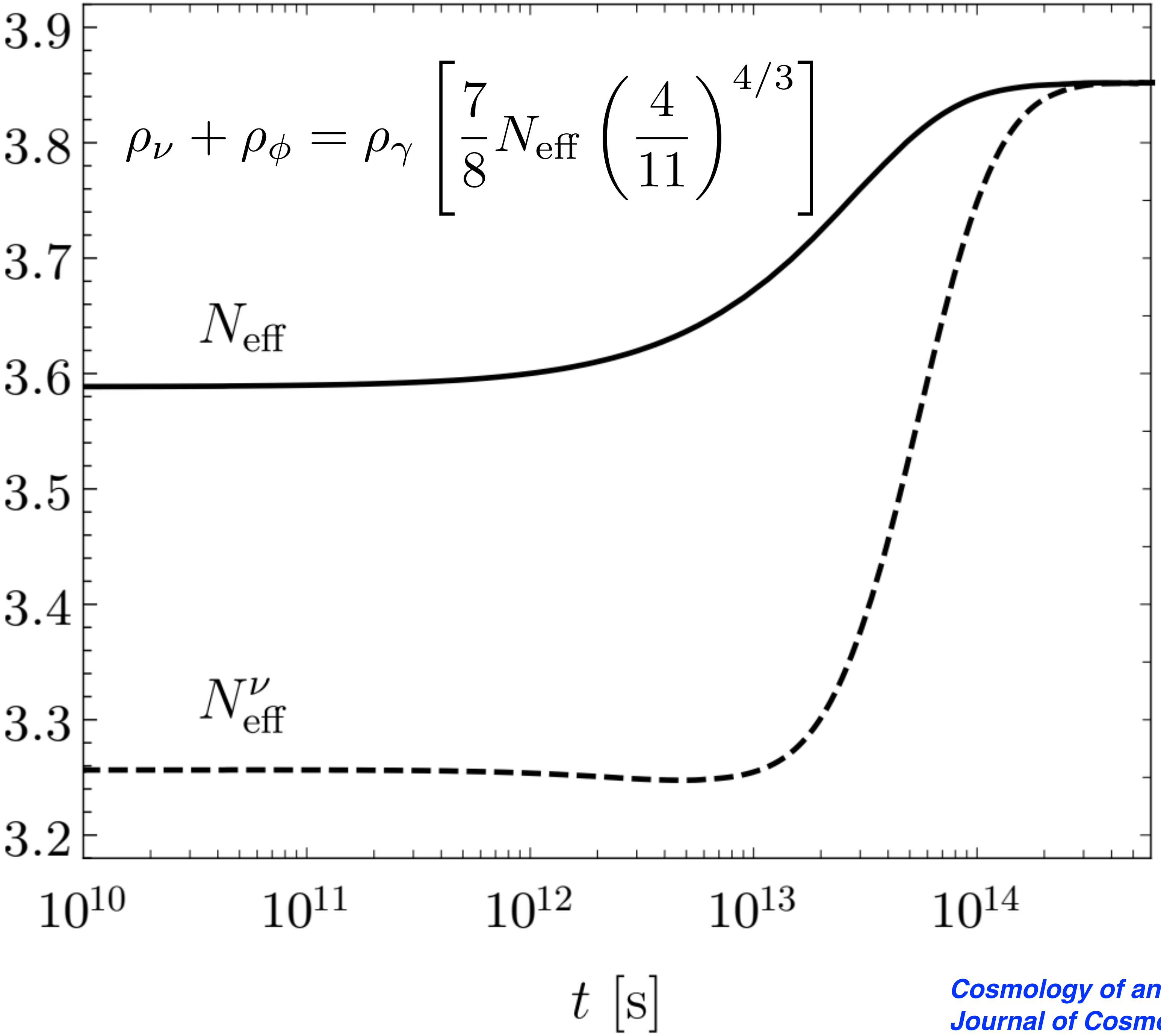


At temperatures $T \lesssim m_\phi$ majorons artificially increase their energy density with respect to photons, because **non-relativistic matter** in an expanding Universe cools down **slower than radiation**.

Shortly after that, majorons **decay into active neutrinos**, injecting energy into the neutrino sector.

Cosmology of an Axion-Like Majoron. A.J.Cuesta, J.I. Illana, M. Masip, M. Gómez
Journal of Cosmology and Astroparticle Physics 04 (2022) 009 [arXiv:2109.07336]

Energy density evolution (***background***)

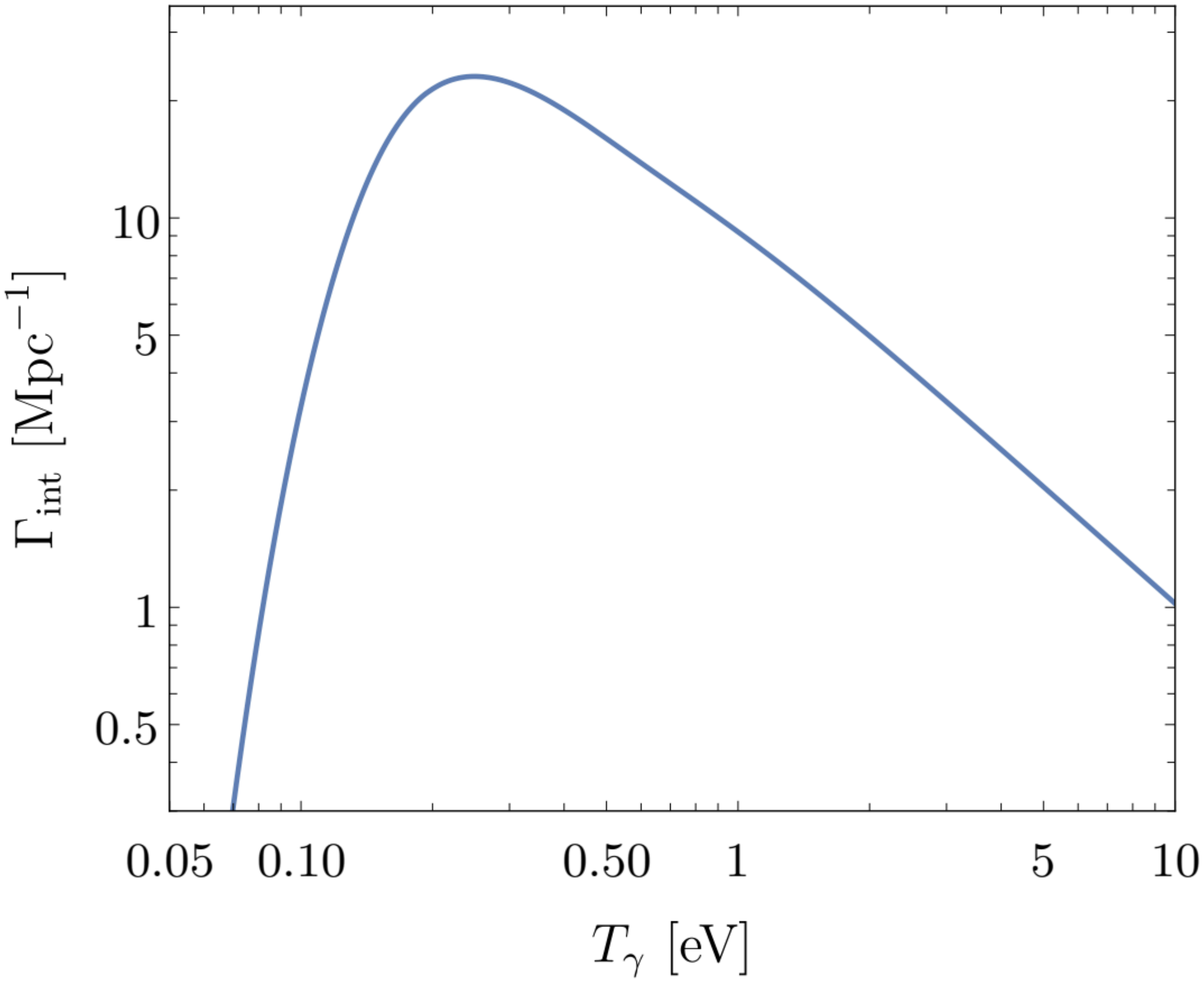


Left: **after BBN, some photons are lost** (into ϕ), therefore $\Delta N^\nu_{\rm eff} \simeq 0.26$ and since $\Delta N^\phi_{\rm eff} \simeq 0.32$ there is a total $\Delta N_{\rm eff} \simeq 0.58$

Right: **before recombination majorons decay** when they become **non-relativistic**, contributing another 0.27 to the total $\Delta N_{\rm eff} \simeq 0.85$

Cosmology of an Axion-Like Majoron. A.J.Cuesta, J.I. Illana, M. Masip, M. Gómez
Journal of Cosmology and Astroparticle Physics* 04 (*2022*) 009 *[arXiv:2109.07336]

Interaction rate evolution (***perturbations***)



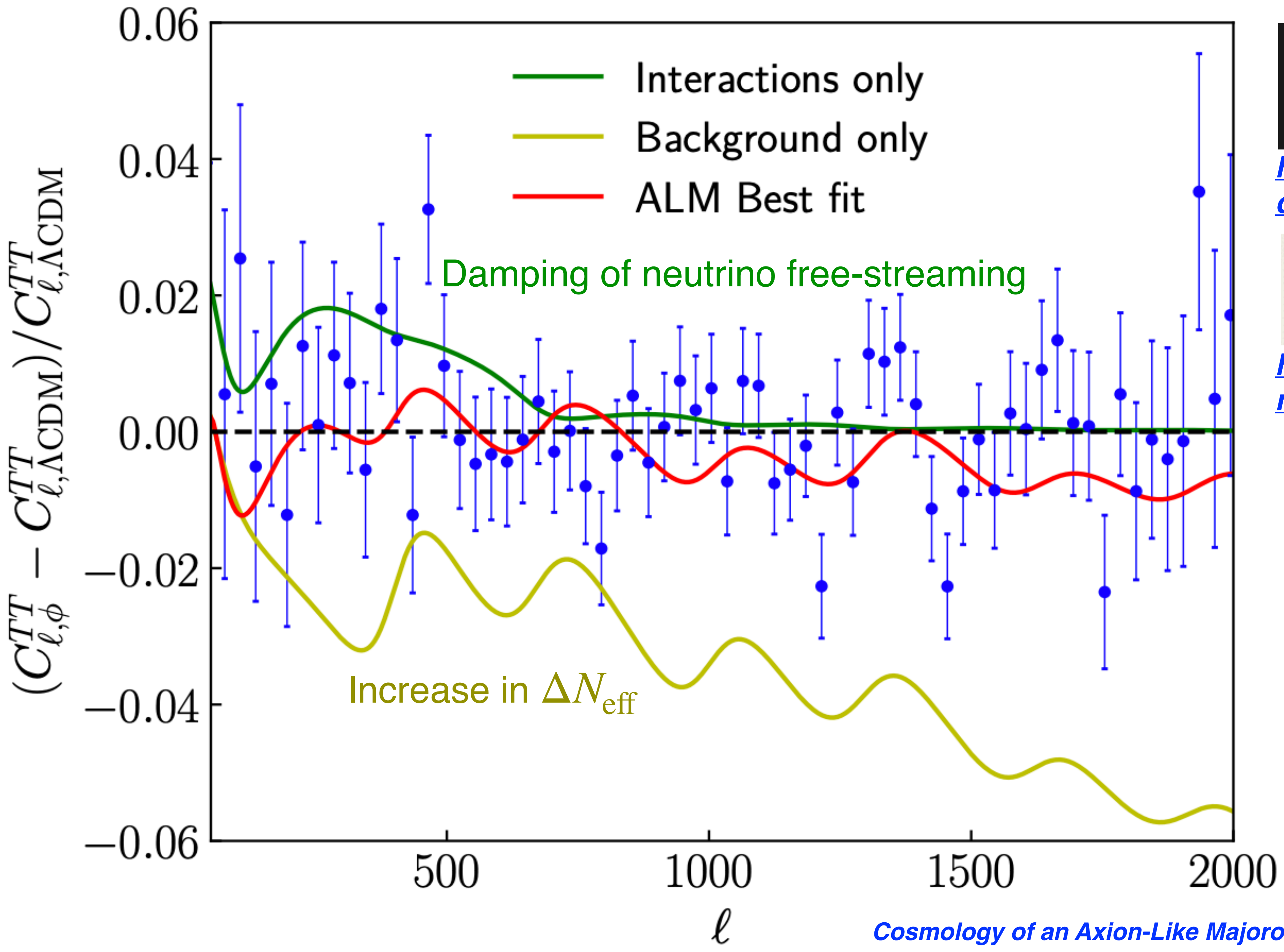
The **majoron–neutrino interaction rate** ($\phi \leftrightarrow \nu\bar{\nu}$) is close (but slightly below) that required for full thermal equilibrium.

These interactions will **damp the number of free streaming neutrinos**, which is necessary to preserve the position of the peaks of the CMB acoustic oscillations.

These interactions are only effective between 10 $m_\phi \geq T_\gamma \geq m_\phi/10$, and given the value of m_ϕ they will only alter CMB multipoles $\ell \leq 1000$ (& galaxy clustering!).

Cosmology of an Axion-Like Majoron. A.J.Cuesta, J.I. Illana, M. Masip, M. Gómez
Journal of Cosmology and Astroparticle Physics 04 (*2022*) 009 *[arXiv:2109.07336]*

MCMC Fit to cosmological data



CLASS

the Cosmic Linear Anisotropy Solving System

[***https://lesgourg.github.io/class_public/class.html***](https://lesgourg.github.io/class_public/class.html)

Monte Python

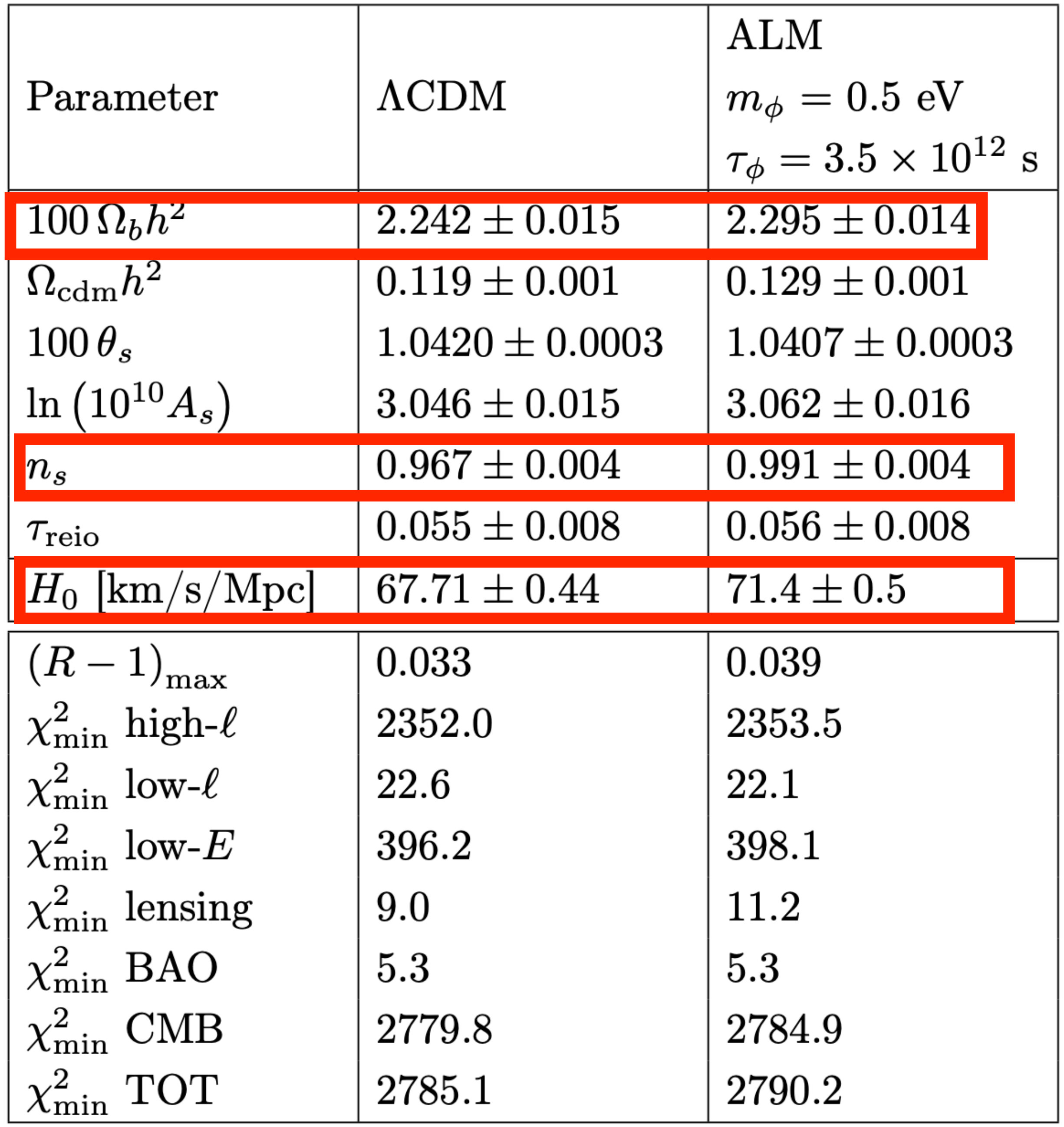
The Monte Carlo code for CLASS in Python

[***https://github.com/brinckmann/montepython_public***](https://github.com/brinckmann/montepython_public)

Global fit to:
T+P CMB power spectrum (Planck),
CMB lensing (Planck),
BAO data (6dF, SDSS MGS, BOSS)

Cosmology of an Axion-Like Majoron. A.J.Cuesta, J.I. Illana, M. Masip, M. Gómez
Journal of Cosmology and Astroparticle Physics* 04 (*2022*) 009 *[arXiv:2109.07336]

MCMC Fit to cosmological data



Parameter	ΛCDM	ALM $m_\phi = 0.5$ eV $\tau_\phi = 3.5 \times 10^{12}$ s
$100\,\Omega_b h^2$	2.242 ± 0.015	2.295 ± 0.014
$\Omega_{\rm cdm} h^2$	0.119 ± 0.001	0.129 ± 0.001
$100\,\theta_s$	1.0420 ± 0.0003	1.0407 ± 0.0003
$\ln\left(10^{10} A_s\right)$	3.046 ± 0.015	3.062 ± 0.016
n_s	0.967 ± 0.004	0.991 ± 0.004
$\tau_{\rm reio}$	0.055 ± 0.008	0.056 ± 0.008
H_0 [km/s/Mpc]	67.71 ± 0.44	71.4 ± 0.5
$(R-1)_{\rm max}$	0.033	0.039
$\chi^2_{\rm min}$ high-ℓ	2352.0	2353.5
$\chi^2_{\rm min}$ low-ℓ	22.6	22.1
$\chi^2_{\rm min}$ low-E	396.2	398.1
$\chi^2_{\rm min}$ lensing	9.0	11.2
$\chi^2_{\rm min}$ BAO	5.3	5.3
$\chi^2_{\rm min}$ CMB	2779.8	2784.9
$\chi^2_{\rm min}$ TOT	2785.1	2790.2

The result of the global fit results in:

1) An increase in the baryon density (actually in the baryon-to-photon ratio)

2) A increase in the spectral index n_s of the power spectrum (almost Harrison-Zel'dovich)

3) **A larger value of the Hubble constant H_0** consistent with late-Universe measurements, hence reducing the H_0 tension

The χ^2 values are not significantly different to ΛCDM values, so this model provides a similar fit to ΛCDM

Cosmology of an Axion-Like Majoron. A.J.Cuesta, J.I. Illana, M. Masip, M. Gómez
Journal of Cosmology and Astroparticle Physics 04 (*2022*) 009 [*arXiv:2109.07336*]

Conclusions

- **The neutrino sector** has the potential to provide hints to unsolved problems in Cosmology and Particle Physics.

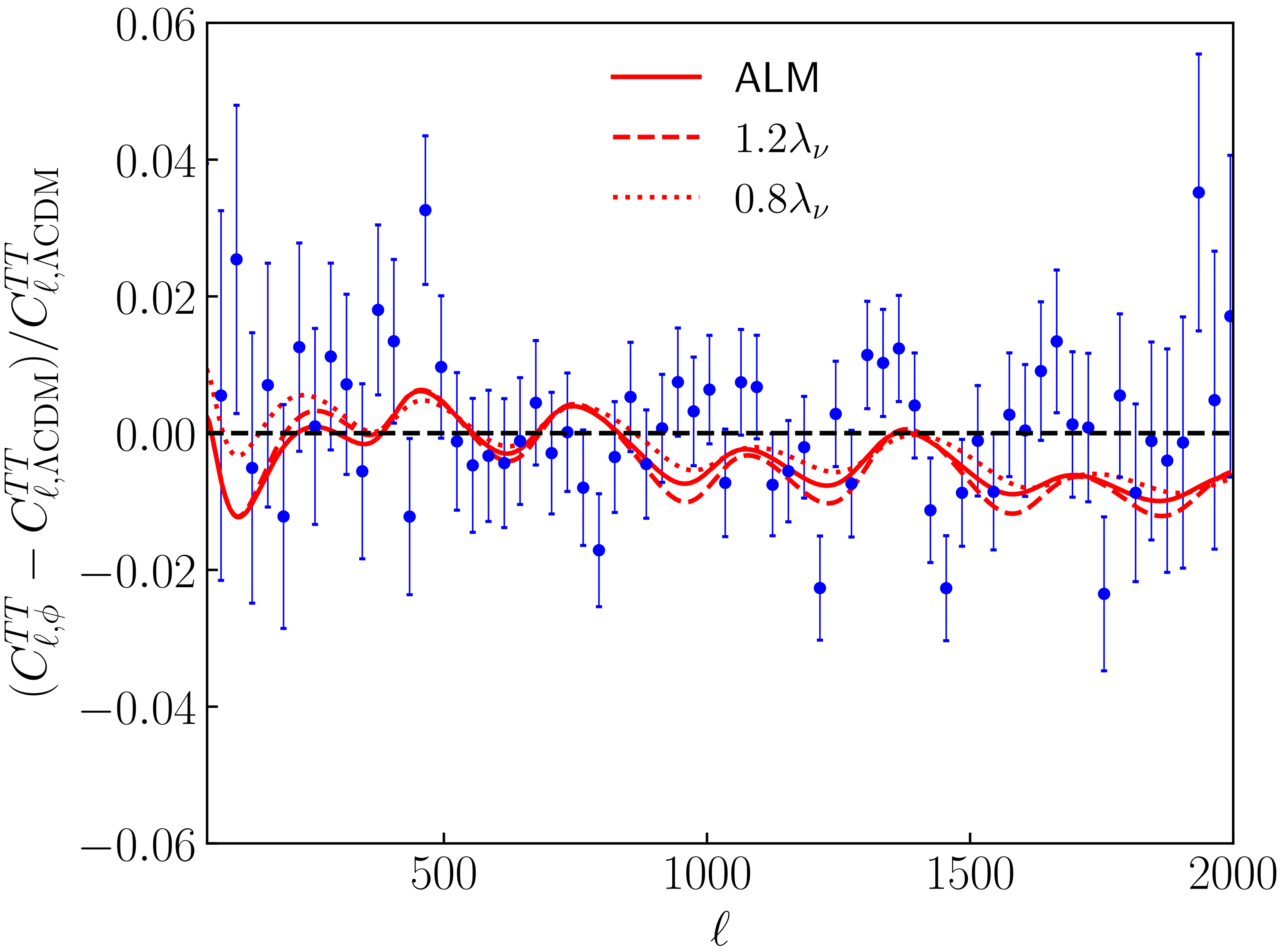
- Extensions to the Standard Model such as the **majoron** can be viable models to explain the origin of neutrino masses, while reducing the H_0 tension.

- An **axion-like majoron** has the advantage that the value of $\Delta N_{\rm eff}$ can be $\simeq 1$, due to photon-to-majoron resonant production, and decay while non-relativistic.

- The majoron parameters can be chosen so that they can **reduce the H_0 tension** without spoiling the fit to CMB or BBN observations.

- A **global fit including CMB and LSS** observables is mandatory in order to better constrain the physics of such extensions.

Absence of ***fine-tuning***

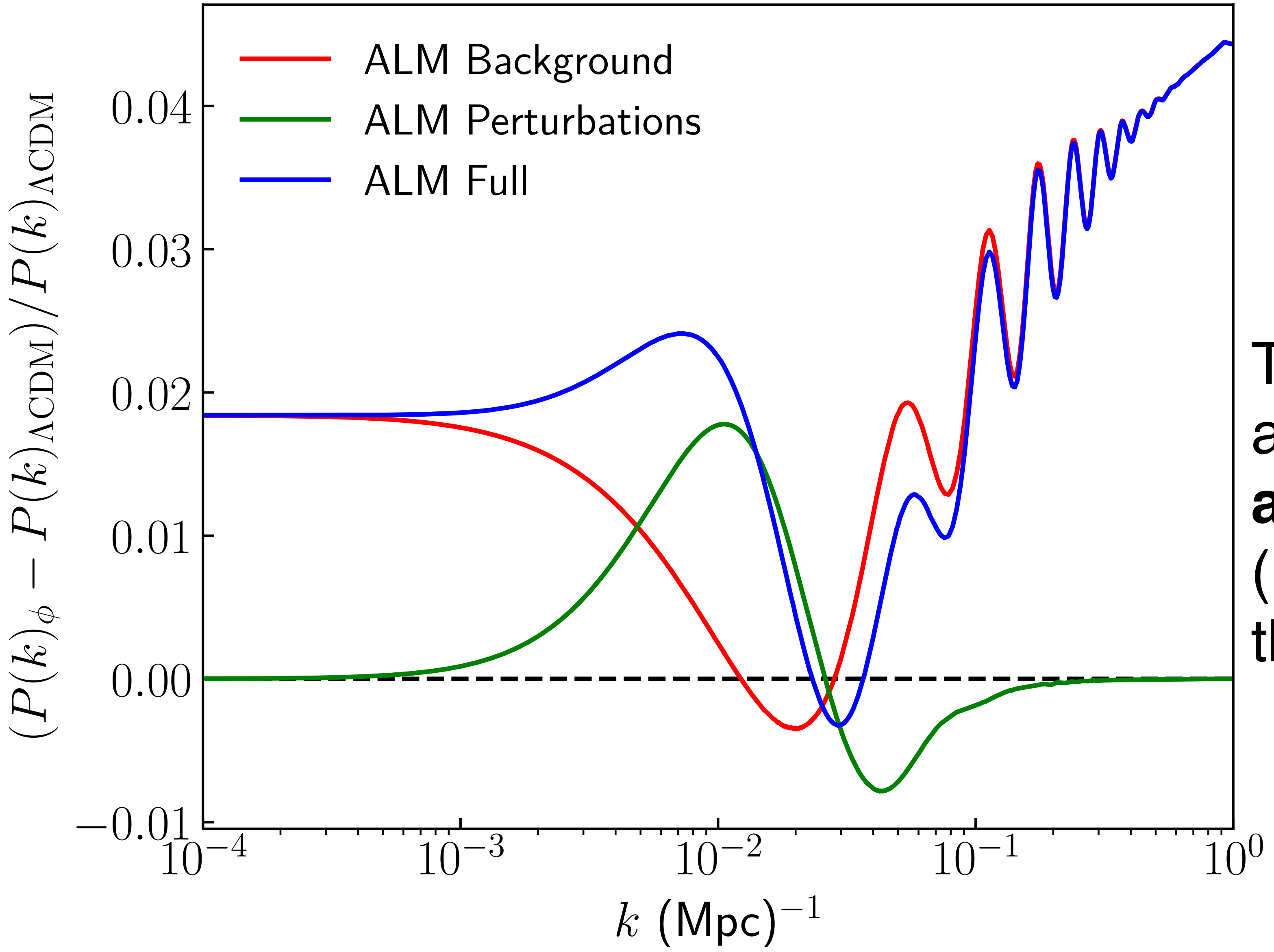


A 20% difference in the neutrino-majoron coupling does not significantly change the χ2 values or the H_0 prediction.

Hence the model prediction is robust against fine-tuning.

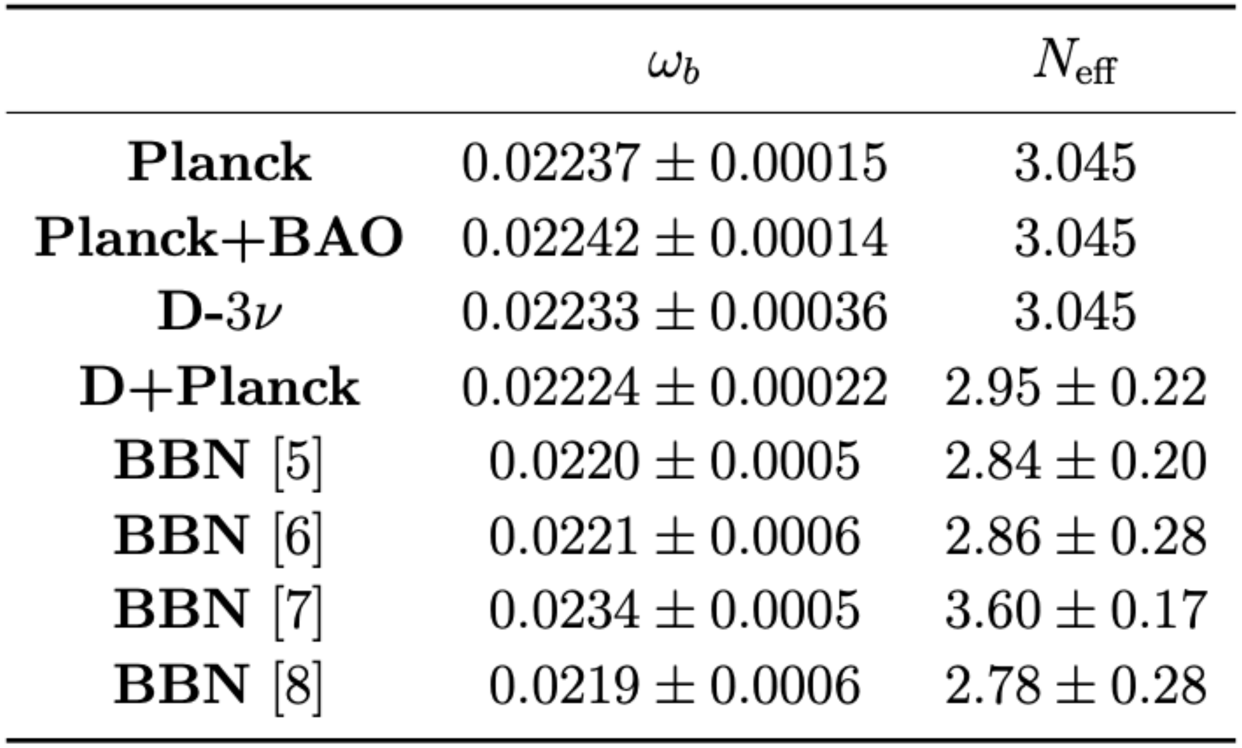
Cosmology of an Axion-Like Majoron. A.J.Cuesta, J.I. Illana, M. Masip, M. Gómez
Journal of Cosmology and Astroparticle Physics 04 (*2022*) 009 *[arXiv:2109.07336]*

Effect on the ***matter power spectrum***



The signature of ALM appears
at mildly non-linear scales
at the level of 2%
(Partially degenerate with
the signature of neutrino masses)

Implications on ***Big Bang Nucleosynthesis***



	ω_b	$N_{\rm eff}$
Planck	0.02237 ± 0.00015	3.045
Planck+BAO	0.02242 ± 0.00014	3.045
D-3ν	0.02233 ± 0.00036	3.045
D+Planck	0.02224 ± 0.00022	2.95 ± 0.22
BBN [5]	0.0220 ± 0.0005	2.84 ± 0.20
BBN [6]	0.0221 ± 0.0006	2.86 ± 0.28
BBN [7]	0.0234 ± 0.0005	3.60 ± 0.17
BBN [8]	0.0219 ± 0.0006	2.78 ± 0.28

Primordial Deuterium after LUNA: concordances and error budget
Pisanti et al. JCAP 04 (2021) 020 [arXiv:2011.11537]

The inferred baryon abundance is larger than in LCDM. Naively, this means a larger baryon-to-photon ratio than in LCDM.

However, after BBN some photons disappeared into majorons, so **we need to undo this effect** to calculate the actual baryon-to-photon ratio at BBN

-> **"effective"** $\Omega_b h^2$ **at BBN** in our model:
$\Omega_b h^2$ = **0.02187 ± 0.00014**

which is a better fit to the low values obtained from deuterium primordial abundances.

Cosmological ***evolution***

SM particles
+ heavy v’s
+ majoron
in thermal
equilibrium

T=500GeV

Decay of
heavy v’s

majoron
decouples
(freeze-out)

$\Delta N_{\rm eff} = 0.026$

T=1MeV

Light v’s
decouple

e+e-
annihilation

$\Delta N_{\rm eff} = 0.070$

T=26 keV

BBN ends

Resonant
production
of majorons
in B field

$\Delta N_{\rm eff} = 0.58$

T=0.5 eV

Recombination

Thermal contact
Between ϕ and ν_3

Majoron decays
into neutrinos

$\Delta N_{\rm eff} = 0.85$