CMB S4

Challenging ΛCDM: Massive neutrinos, extra neutrinos, and other surprises in cosmology

UH HEP Seminar

Presentation based on manuscripts: [**2412.05451**, 2208.14435 & 2309.11492]

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12/10/2024

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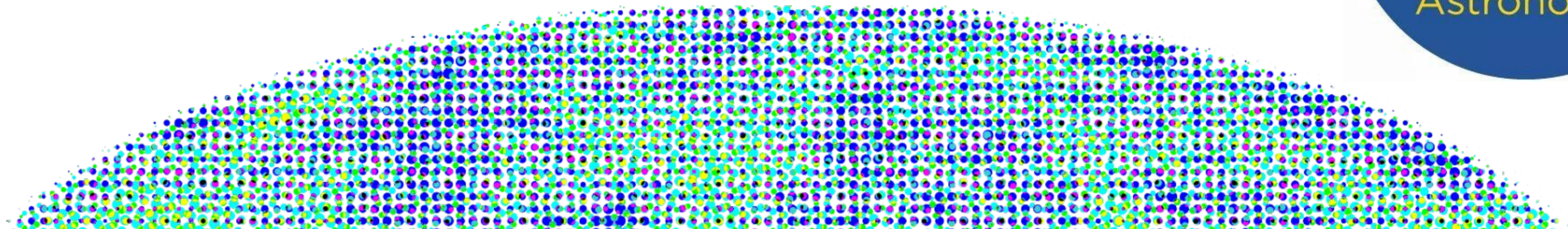


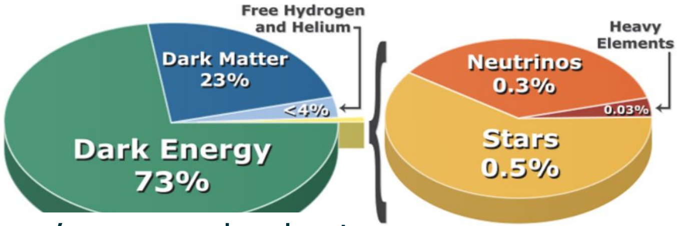
Cosmological observations and Neutrino physics

- Impact of neutrinos in cosmological observables.
- Power of cosmology testing the **ΛCDM** and **Neutrino physics**: Σm_ν and N_{eff}
- Results:
  - 1.- Sum of the neutrino masses
  - 2.- Effective number of light relativistic particles
  - 3.- Cosmological Tensions and beyond Standard Model Scenarios

ΛCDM: detailed description of our Universe

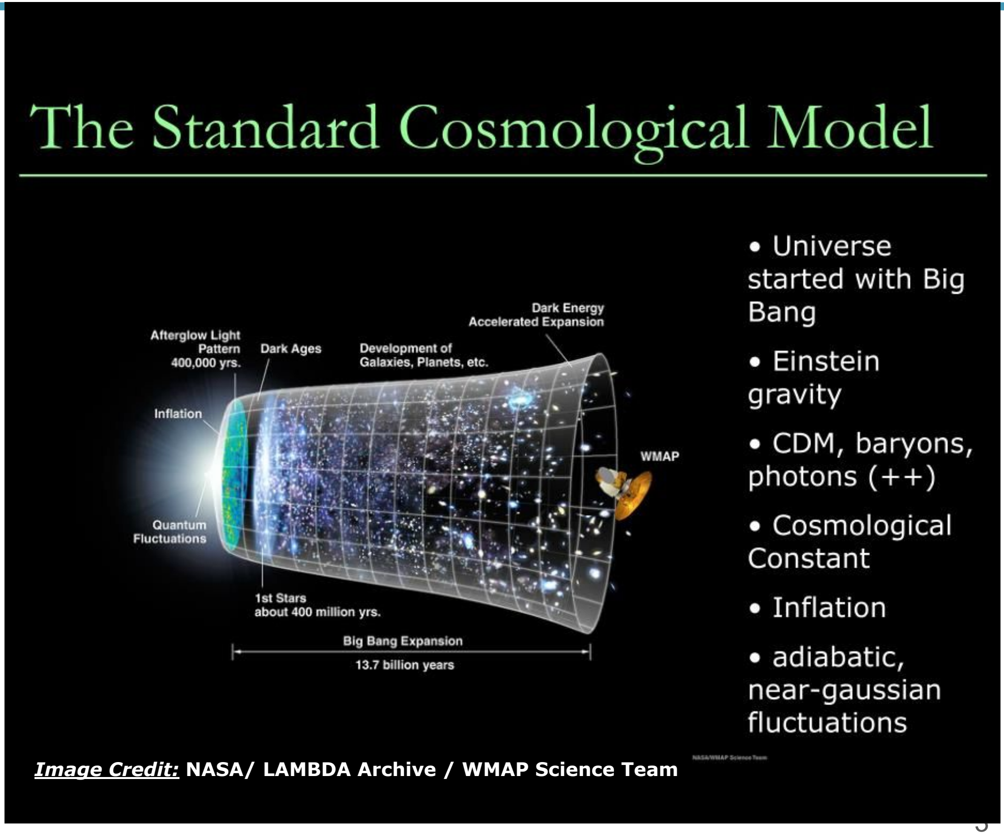
Mathematical model based on three major features:

1. **Inflation:** early accelerated expansion.
2. **Dark matter:** clustering component.
3. **Dark Energy:** (Cosmological cte. Λ).

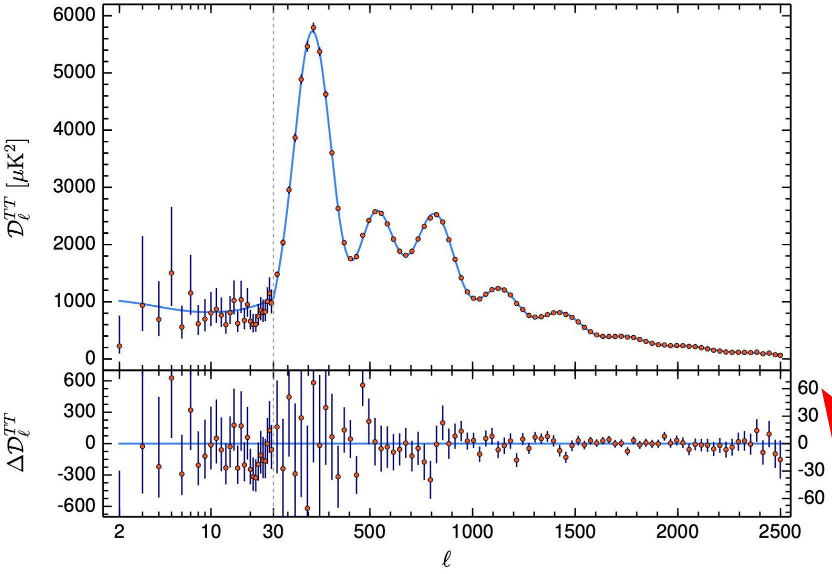


Universe's energy budget

Image credit: The Conversation



ΛCDM: detailed description of our Universe



Planck 2018 Temperature power spectrum
Image credits:2109.01760

ΛCDM consistent with enormous diverse, high-quality observational data (LSS, anisotropy of the CMB, light-element abundances …)

ΛCDM characterized **just 6 parameters:**

1. Baryon density: $\omega_B \equiv \Omega_B h^2$
2. Matter density: $\omega_M \equiv \Omega_M h^2$
3. Spectral index density perturbations: n_S
4. Amplitude of density perturbations: A_S
5. Optical depth to the CMB due to re-ionization: τ
6. Sound horizon at recombination: θ_{MC}

Impressive precision! excellent fit to the CMB anisotropy data

by
l.

ΛCDM: detailed description of our Universe

Testable consequences driven observational cosmology since the 1980s…

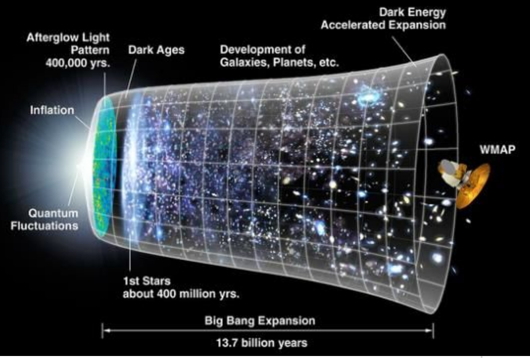
Cosmic Neutrino Background (CνB)

-Indirect evidence support its presence

-BBN, CMB, LSS inconsistent without relativistic neutrino component.

-Cosmology attuned to neutrino properties: mass and density

The Standard Cosmological Model



- Universe started with Big Bang
- Einstein gravity
- CDM, baryons, photons (++)
- Cosmological Constant
- Inflation
- adiabatic, … an

$$\Omega_\nu h^2 = \frac{\sum m_\nu n_\nu}{\rho_{\rm crit}} \simeq \frac{\sum m_\nu}{93.13\, h^2}$$

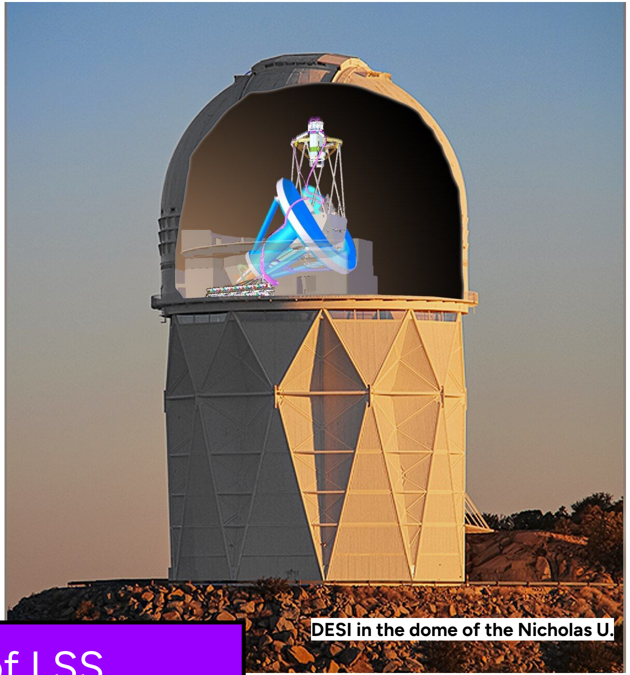
Cosmological implications of Σm_ν

1. ν_s always relevant to Universe's energy density
   ⇨ contribute to H(z). $H \propto \sqrt{\rho}.$

2. ν_s travel ultra relativistically speeds (until temp. drops below m_ν their masses) ⇨
   ⇨ ν_s do NOT cluster at small scales
   ⇨ **suppress amount of structure small scales**.

   The suppression is energy density dependent.

$$\Omega_\nu h^2 = \frac{\sum m_\nu n_\nu}{\rho_{\rm crit}} \simeq \frac{\sum m_\nu}{93.13\ h^2}$$



DESI in the dome of the Nicholas U. Mayall 4-meter Telescope at the Kitt Peak National Observatory. Image credit: Wikipedia

Observations of LSS (DESI, Euclid,...) excellent to search for Σm_ν

Cosmological imprints of ν_s: Σm_ν

How is Planck CMB sensitive to Σm_ν?

1. CMB LENSING EFFECT (dependent A_s & Ω_m)
   ν_s at relativistic speeds →
   suppression matter power spectrum →
   reduction lensing CMB γ from the last scattering surface until today →
   sharper peaks CMB power spectrum.

2. Σm_ν impacts angular diameter distance to last-scattering surface + ν_s contribute

$$H \propto \sqrt{\rho}.$$

⇑ Σm_ν ⟺ ⇑ Ω_m ⟺ ⇓ H_0

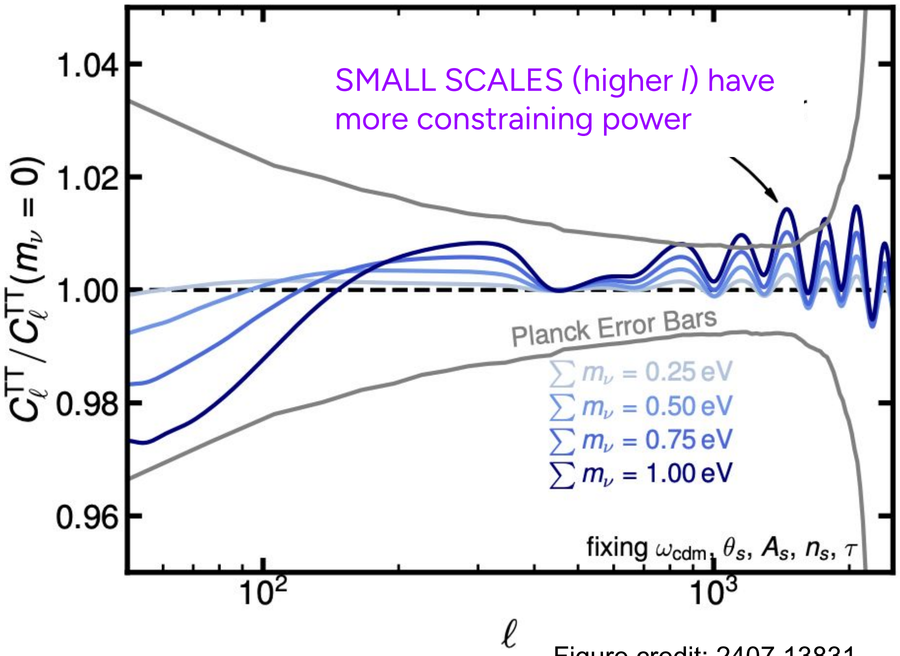


Figure credit: 2407.13831

Late-time expansion history probes (SNe and BAO) to break geometrical degeneracy

Summary: Cosmological imprints of Σm_ν

Key points to make inferences on $\boldsymbol{\Sigma m_\nu}$ from <u>cosmological observations</u>:

1. Understanding CMB lensing on small angular scales,
2. Control over the amplitude of primordial matter power spectrum A_s and ω_m.
3. Accurate probe of expansion history at late-times (include late-time probes to constrain Ω_m).

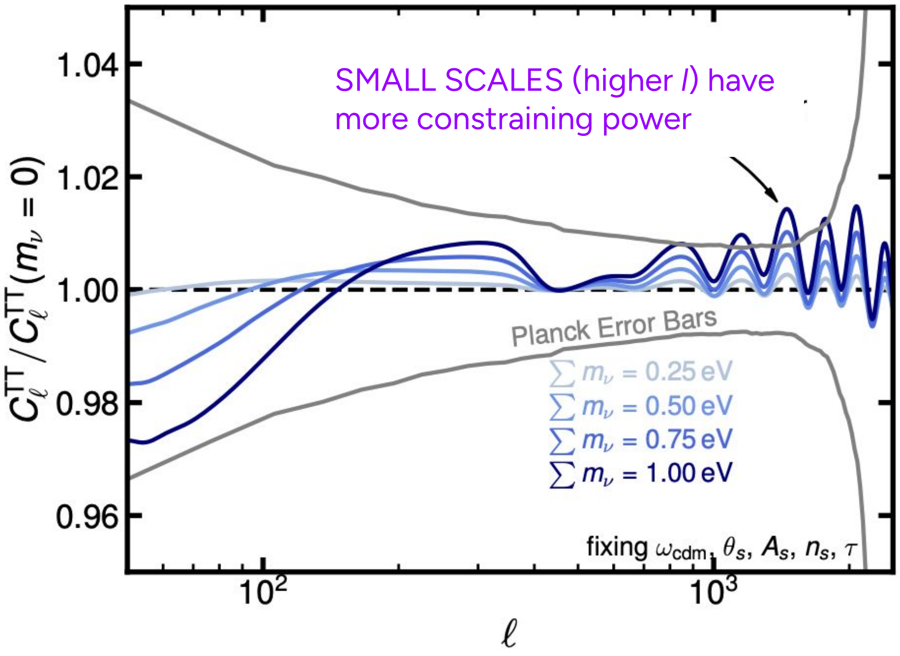


Figure credit: 2407.13831

What is the value of the neutrino mass?

IMAGE CREDIT: https://phys.org/news/2018-06-katrin-neutrino-mass.html

- The absolute neutrino mass scale probed using β-decay:

  KATRIN best bound upper limit on effective neutrino mass

  $\Sigma m_\nu < 1.5$ eV [95% CL] [arXiv:2406.13516]

- Cosmology can constrain neutrino mass > 20 times better today already!*

  $\Lambda\text{CDM}+\sum m_\nu$

  DESI+CMB

  [arxiv 2404.03002]

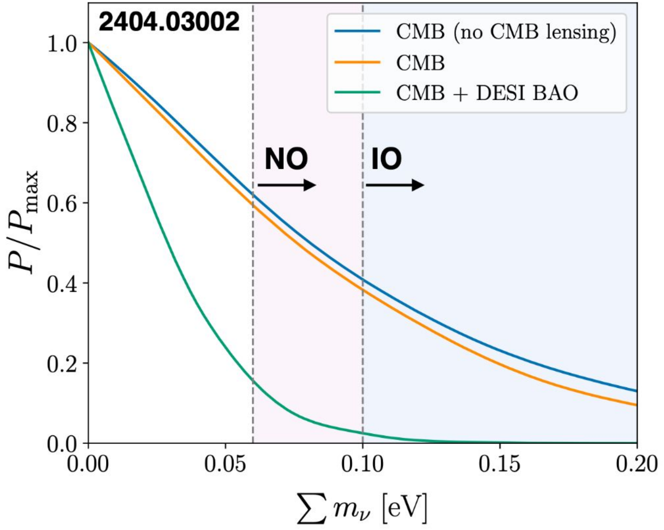
  $$\sum m_\nu < 0.072\,\text{eV} \quad [95\%\ \text{CL}]$$

*model dependent

What is the value of the neutrino mass?

April 2024 DESI DR1 cosmological results with key implications for Σm_ν

$$\sum m_\nu < 0.073\,\text{eV}$$ **(95 % CL, CMB+BAO-DESIY1)**



vs.

Latest lab. Limit KATRIN:

[2406.13516]:

$$\sum m_\nu < 1.5\,\text{eV}$$ **(95 % CL)**

& bound from Planck + SDSS

Planck+SDSS [1807.06209]

$$\sum m_\nu < 0.12\,\text{eV}$$ **(95 % CL)**

Sum of the neutrino masses and Cosmology

From experimental point, cosmology can NOT be described by $\sum m_\nu = 0$,
$\sum m_\nu$ at least 58 meV from oscillation experiments, i.e.: Super-Kamiokande, SNO, KamLAND).

NO 0.58eV

IO 0.1 eV

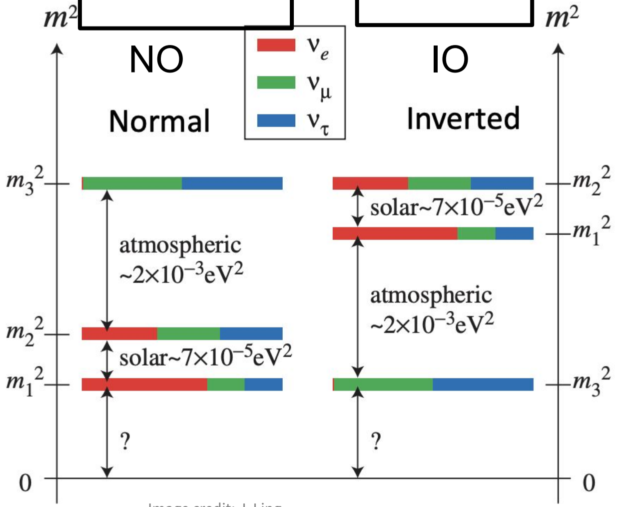


Image credit: J. Ling

- We found employing most robust data sets, statistical validations, theory accuracy :

P18+CMB lensing+DESI(BAO)	**σ**
Preference $\sum m_\nu = 0$ over NO	1.36
Preference NO over IO	1.47

H.García Escudero and K. Abazajian Dec. 2024 (2412.05451)

-Other CMB analysis don't significantly change results (arxiv: 1610.02743)

Upcoming cosmological surveys expected 2-3 **σ** sensitive to $\sum m_\nu$ in the minimal mass scenario.

Upper limits Σm_ν inferred from cosmology

Using broad suite of 9 combinations of datasets:

-3 separate CMB analysis

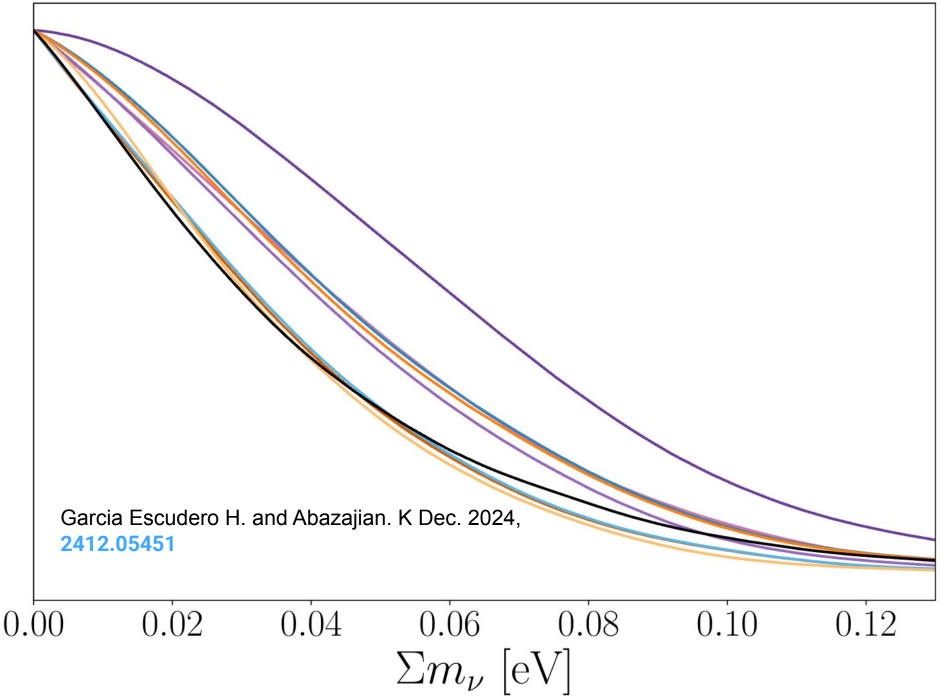
-3 three separate SNe survey data

+CMB Lensing (PR4 + ACT DR6)

+DESI BAO DR1

derive constraints on the Σm_ν

Datasets			
CMB Planck	CMB Lensing	BAO	SNe
P18 CamSpec P20	Lensing PR4 + ACT DR6	DESI DR1	PP U3 DES Y5

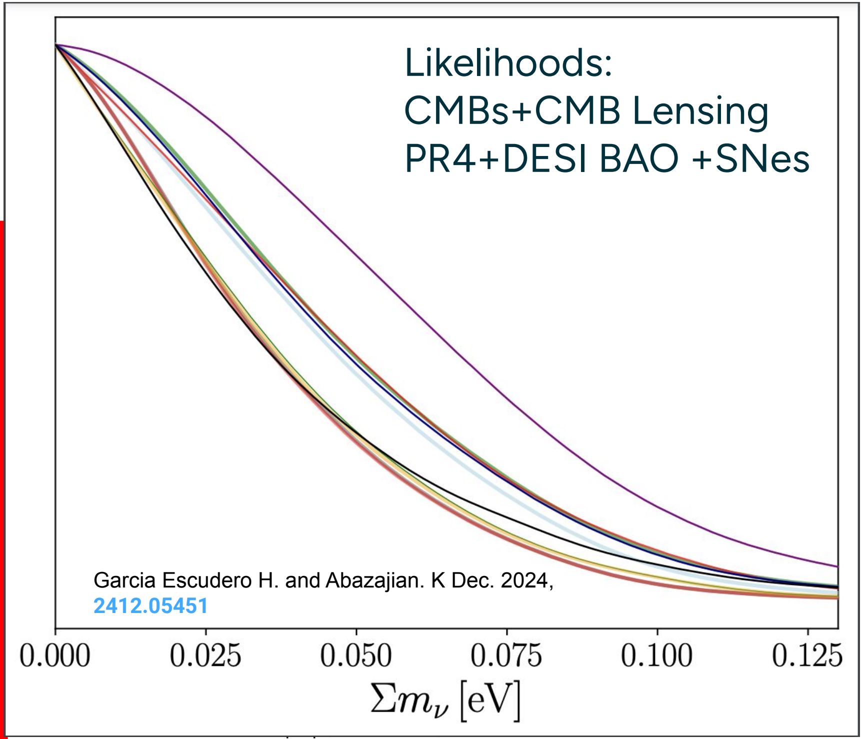


Negative neutrino mass anomaly

$\Sigma m_\nu < 76.9$ meV to
$\Sigma m_\nu < 108$ meV (95%CL)

3 clusters:
-Stringent Σm_ν bound (4 curves)
-Moderate Σm_ν bound (4 curves)
-Relaxed Σm_ν bound (1 curve)

We find P20 PR4 with DES Y5 provide the **most relaxed bound** on neutrino mass only at the ≅1.1 σ vs. NO (58 meV)

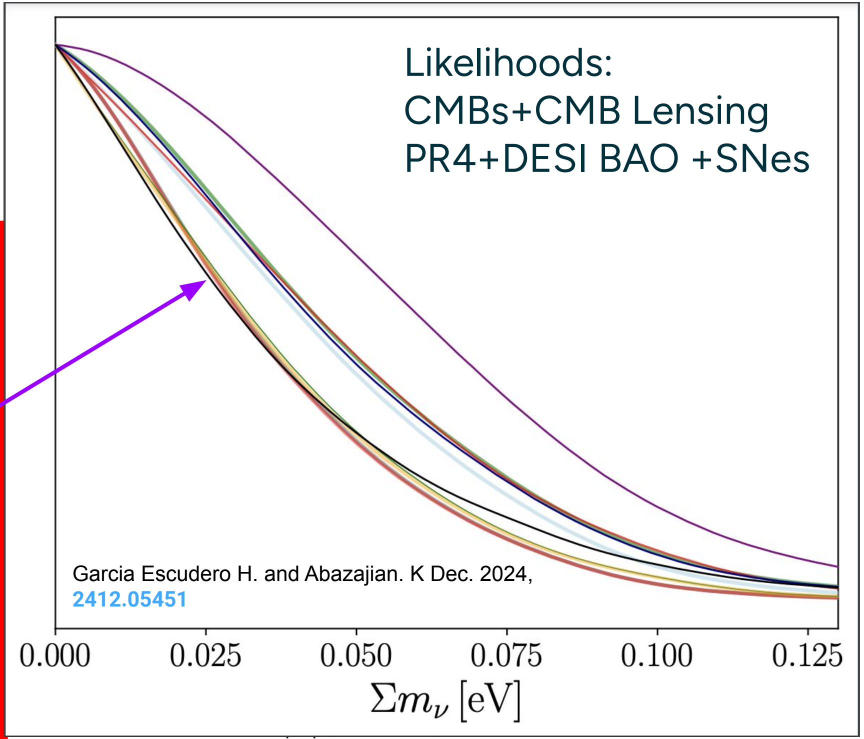


Negative neutrino mass anomaly

$\Sigma m_\nu < 76.9$ meV to
$\Sigma m_\nu < 108$ meV (95%CL)

3 clusters:
-**Most stringent Σm_ν bound**

P18/CamSpec and U3/PP combinations



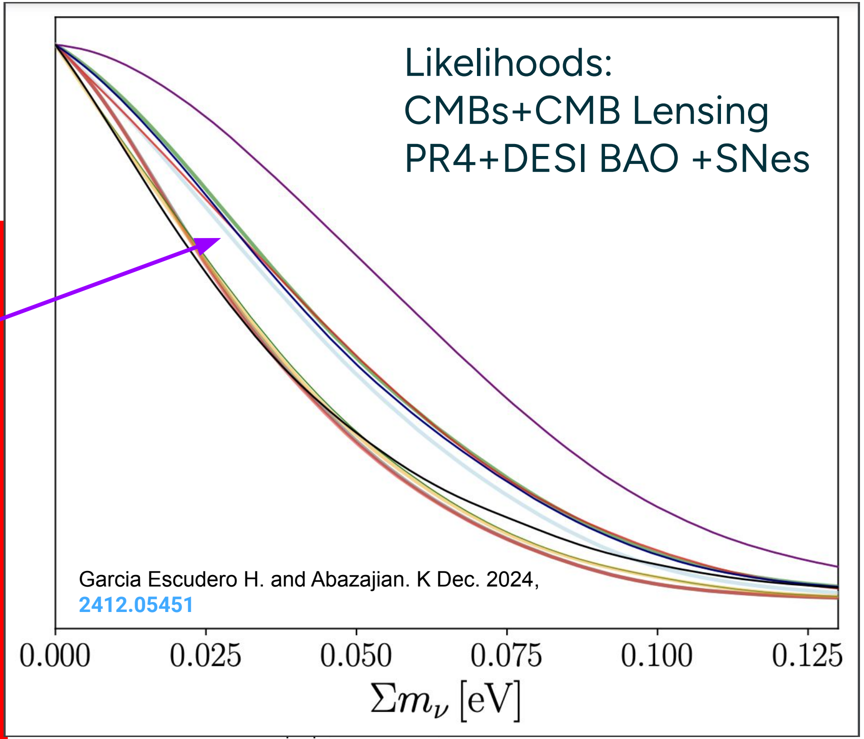
Negative neutrino mass anomaly

Σm_ν<76.9 meV to
Σm_ν<108 meV (95%CL)

3 clusters:

-**Moderate Σm_ν bound**

P18/CamSpec + DES Y5
&
P20 + U3/PP



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$\Sigma m_\nu < 76.9$ meV to
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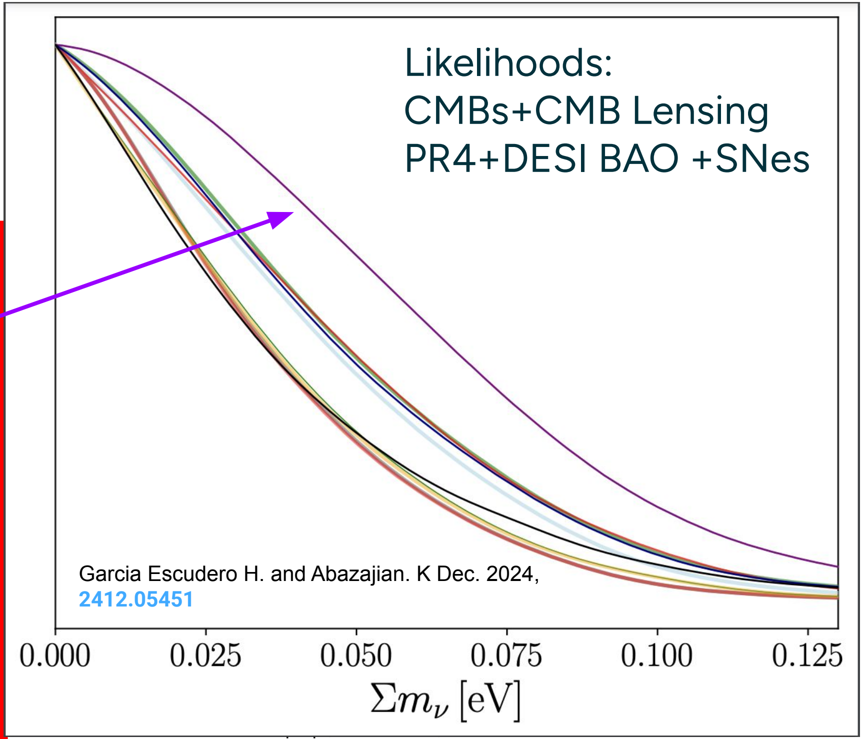


Negative neutrino mass anomaly

$$\Sigma m_\nu(\text{P18, DESI, \& PP}) < 82.1\,\text{meV}\,,$$
$$\Sigma m_\nu(\text{P18, DESI, \& U3}) < 82.1\,\text{meV}\,,$$
$$\Sigma m_\nu(\text{P18, DESI, \& DESY5}) < 98.0\,\text{meV}\,,$$
$$\Sigma m_\nu(\text{CamSpec, DESI, \& PP}) < 76.9\,\text{meV}\,,$$
$$\Sigma m_\nu(\text{CamSpec, DESI, \& U3}) < 77.0\,\text{meV}\,,$$
$$\Sigma m_\nu(\text{CamSpec, DESI, \& DES Y5}) < 86.6\,\text{meV}\,,$$
$$\Sigma m_\nu(\text{P20, DESI, \& PP}) < 94.1\,\text{meV}\,,$$
$$\Sigma m_\nu(\text{P20, DESI, \& U3}) < 93.8\,\text{meV}\,,$$
$$\Sigma m_\nu(\text{P20, DESI, \& DESY5}) < 108\,\text{meV}\,,$$

c and P20 PR4:

ffects.

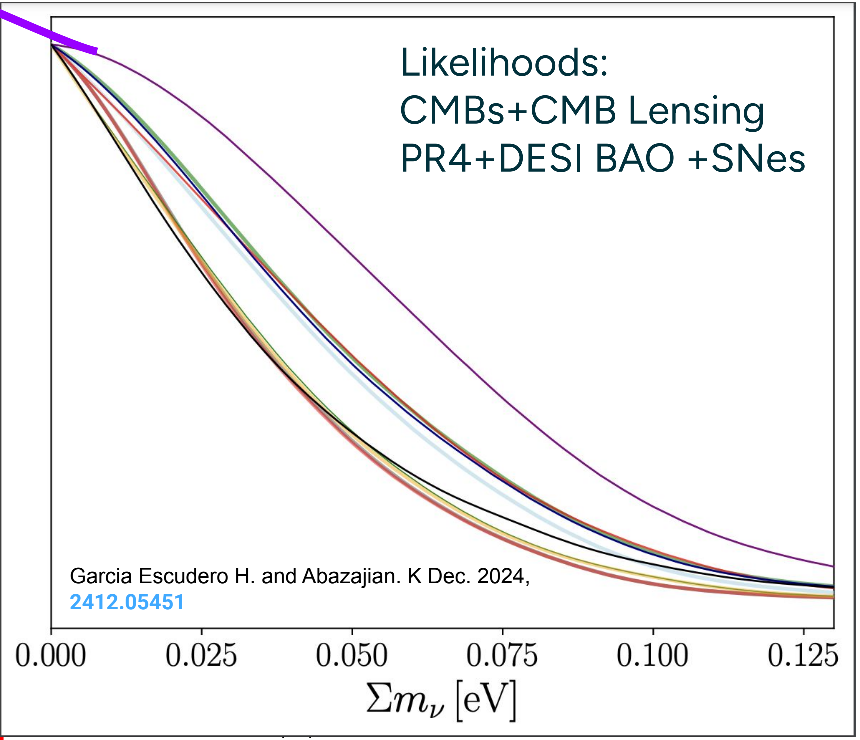
vs. $A_{lens}>1$

Spec), 0.75σ (P20)

3 SNe samples:

PantheonPlus, Union 3 and DESY5

We find P20 PR4 with DES Y5 provide the **most relaxed bound** on neutrino mass only at the ≅1.1 σ vs. NO (58 meV)

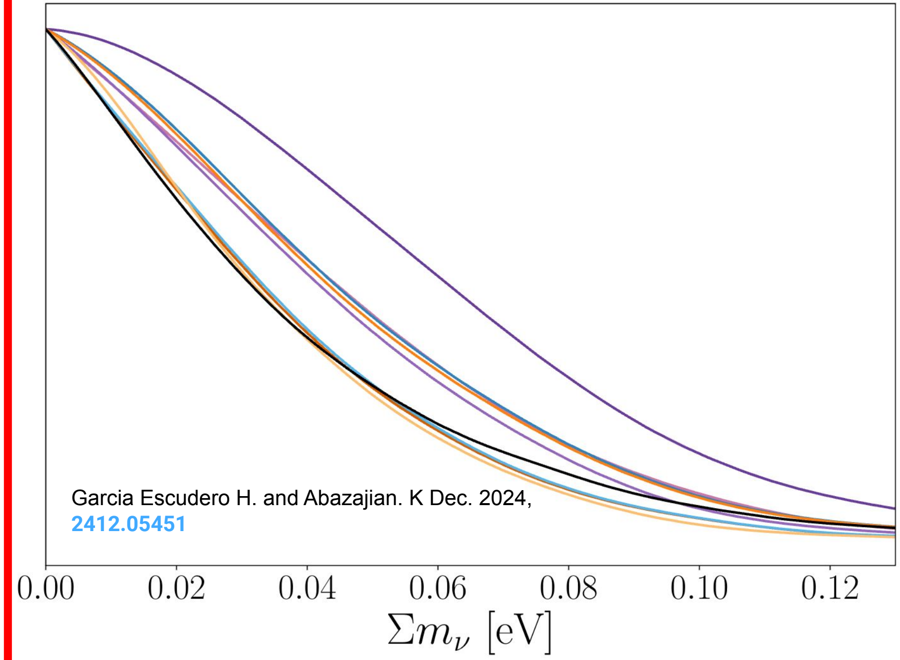


Relaxation upper limits Σm_ν

- **CMB:P20 least lensing anomaly (A_{lens} closer to 1)**
  - More statistical power.
  - Better handle systematic effects.
  - A_{lens} anomaly: $A_{lens,LCDM} = 1$ vs. $A_{lens} > 1$
    2.8 σ (P18) vs. 0.75σ (P20)

- SNe survey data: **DESY5 highest Ω_m** (different Ω_m: Pantheon+, Union 3 & DESY5)

$\Uparrow \Sigma m_\nu \Rightarrow \Uparrow \Omega_m \Rightarrow \Downarrow H_0$



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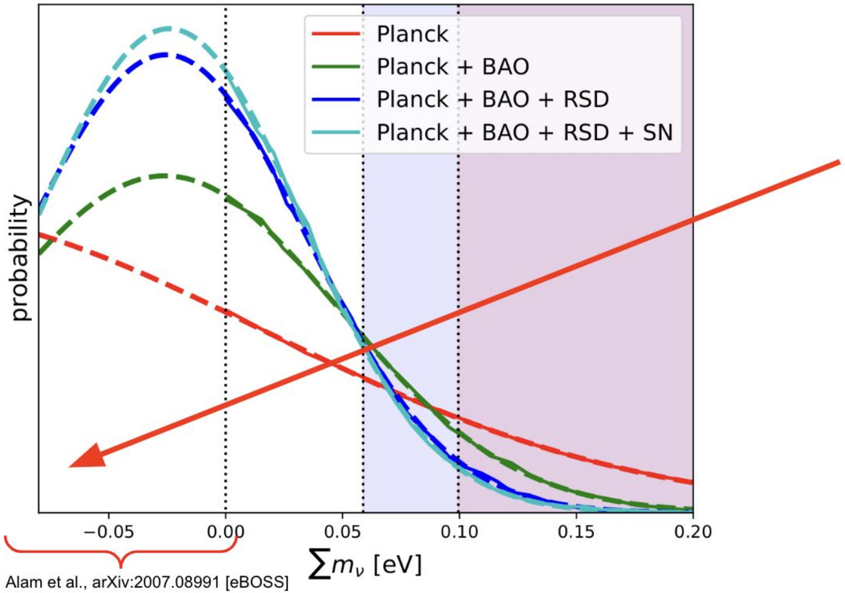
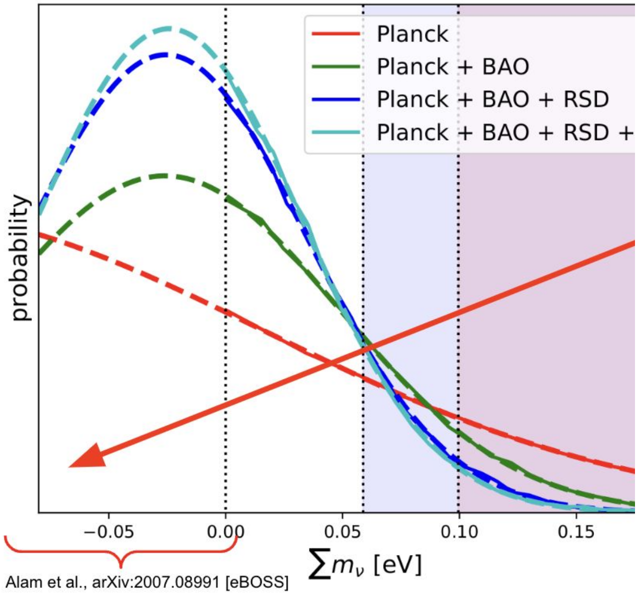
Negative neutrino mass anomaly



Alam et al., arXiv:2007.08991 [eBOSS]

Where is the stringency preference of negative Σm_ν coming from?

Negative neutrino mass anomaly



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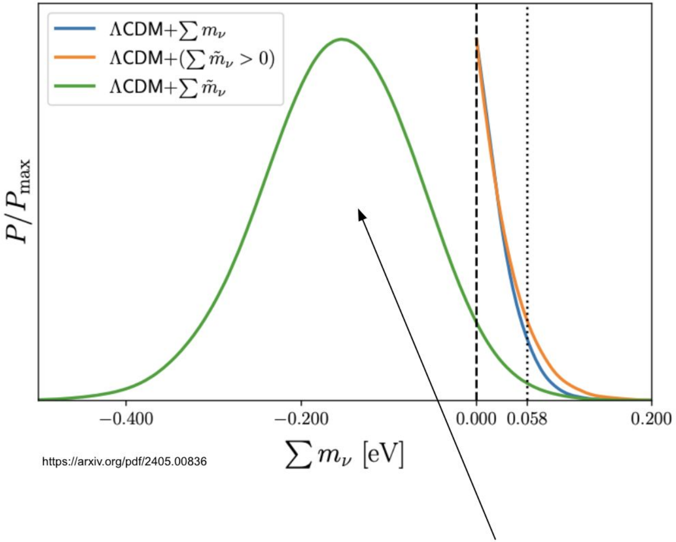


Posterior of $\sum m_\nu$ (eV) inferred from Planck + ACT Lensing + DESI

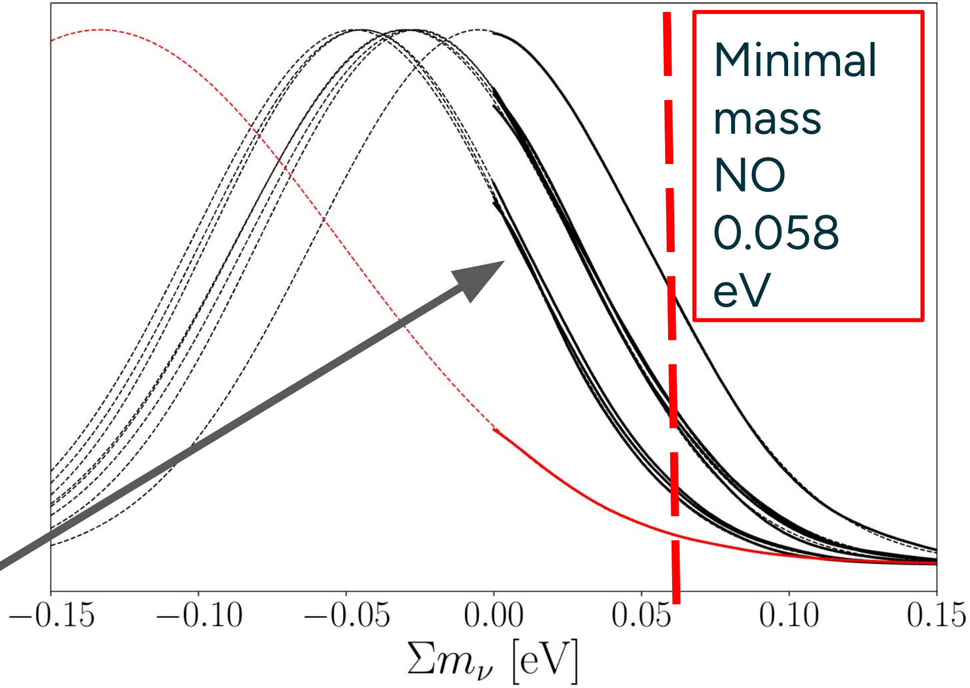
$$\sum m_\nu = -160 \pm 90 \text{ meV} \; (68\%)$$

NEGATIVE NEUTRINO MASS ANOMALY

Fit of Gaussian functions to the posterior distributions to recover the **μ** & **σ** for each combination:

Datasets			
CMB Planck	CMB Lensing	BAO	SNe
P18 CamSpec P20	Lensing PR4 + ACT DR6	DESI DR1	PP U3 DES Y5

All range below 2σ level vs. NO 0.058 eV



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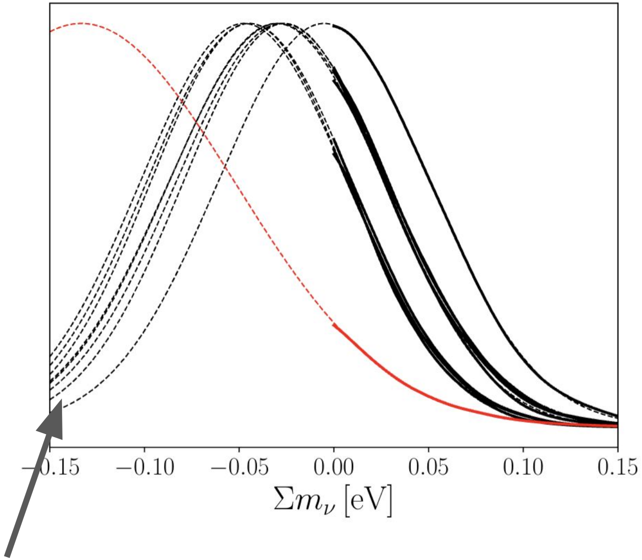
Negative neutrino mass anomaly

- Possible origin of “negative” neutrino mass bounds:
  - CMB lensing excess arxiV: HGE in prep., 2407.07878, 2407.13831
  - Late time expansion history (Ω_m) arxiV: HGE in prep., 2404.03002

  $\Uparrow \Sigma m_\nu \;\Rightarrow\; \Uparrow \Omega_m \;\Rightarrow\; \Downarrow H_0$

- Unphysical negative masses weak tension at <~ 2σ but worth exploring.

- Future CMB, BAO data study this discrepancy.



Black dashed curves represent the Gaussian fits

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Effective Number of Neutrino Species, N_{eff}

- Total cosmological number density of neutrinos

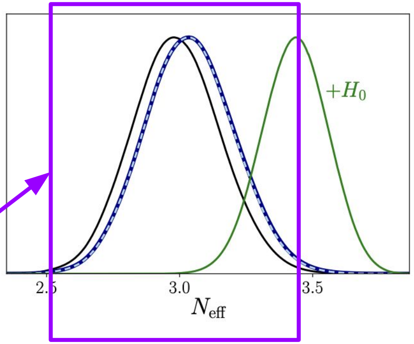
$$n_\nu = N_{\rm eff}\left(\frac{3}{4}\right)\left(\frac{4}{11}\right)n_\gamma,$$

- $N_{eff} = 3$ ⇨ neutrinos instantaneously decoupled from the primordial plasma.

- Neutrino properties early universe → $N_{eff} = 3.044$

arxiv 2005.07047

Upcoming cosmological survey 2-3 **σ** sensitivity N_{eff} can find:



arxiV 1807.06209

N_{eff} consistent with 3.044 →

- Confirmation of standard cosmology
- Precise understanding thermal conditions universe.

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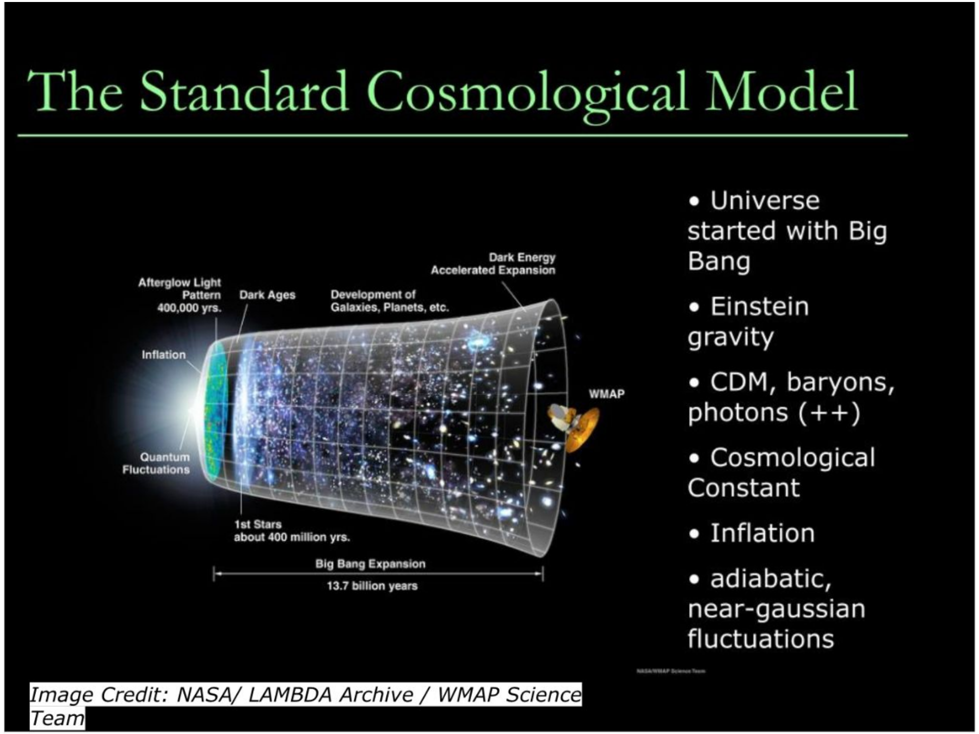
Signature of new physics?!



ΛCDM provides a great fit to most cosmological data, but …

a few significant statistically <u>tensions</u> arise

Cosmological Tensions: Hubble or H_0 tension

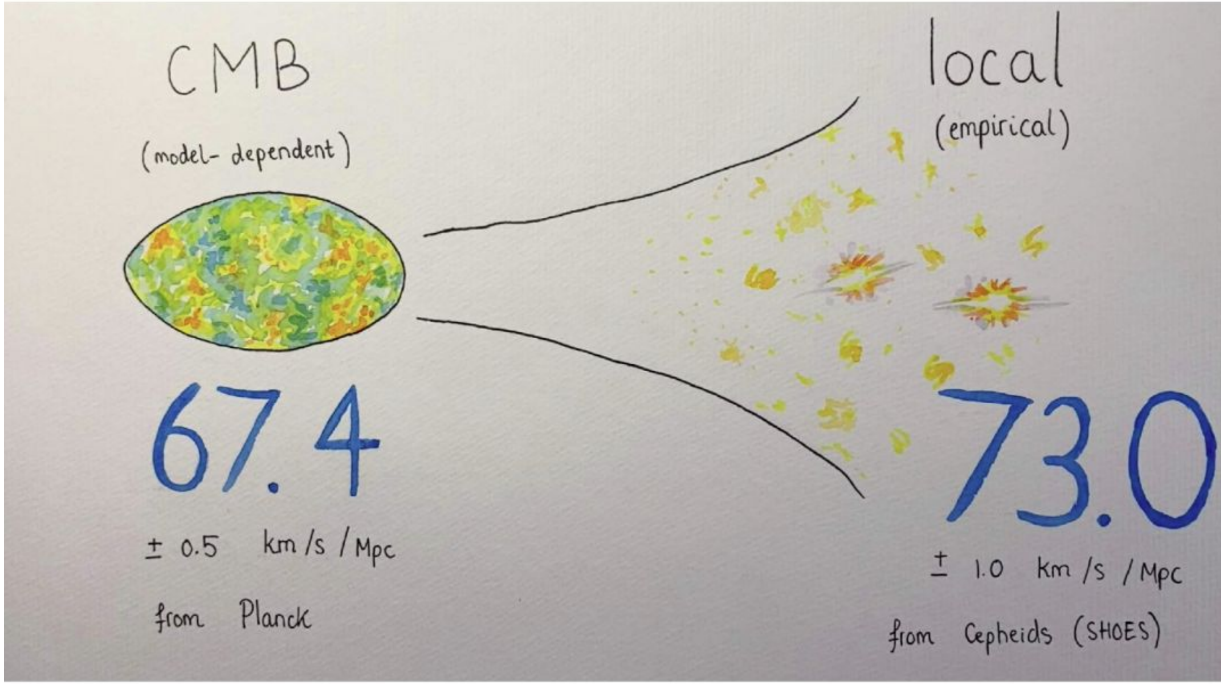


Image credit: Nikki Aradnese

We include last H_0 value from SHOES collaboration:

$$H_0 = 73.04 \pm 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

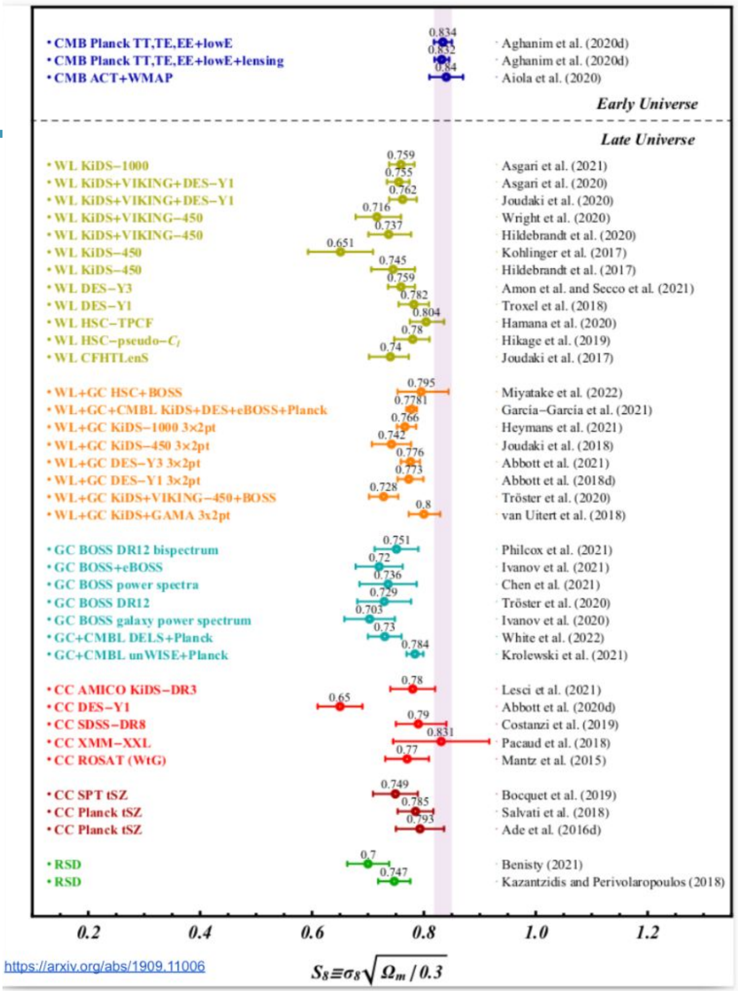
2112.04510

Cosmological Tensions: S_8

S_8 tension:

$$S_8 = \sigma_8 \sqrt{\frac{\Omega_m}{0.3}}$$

- σ_8 measures the amplitude or rate of growth of structure.
- Mismatch between:
  - $\uparrow S_8$ CMB+ΛCDM ($S_8 = 0.832 \pm 0.013$)
  - $\downarrow S_8$ low redshift probes:
    - Weak gravitational lensing (DES)
    - X-Ray Clusters
    - SZ Clusters



https://arxiv.org/abs/1909.11006

Cosmological Tensions: S_8

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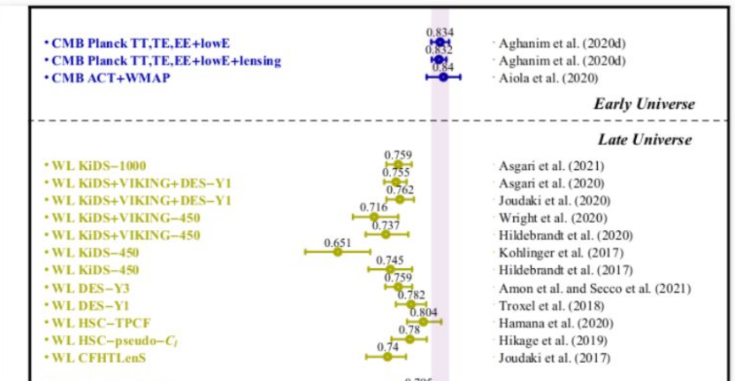
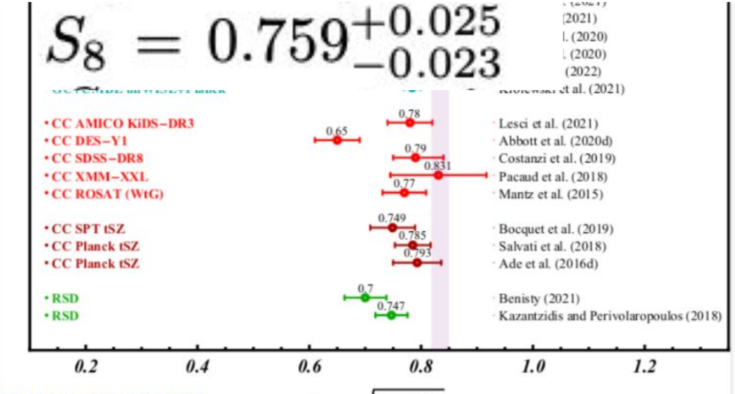


We include S_8 value from Dark Energy Survey Year 3



https://arxiv.org/abs/1909.11006

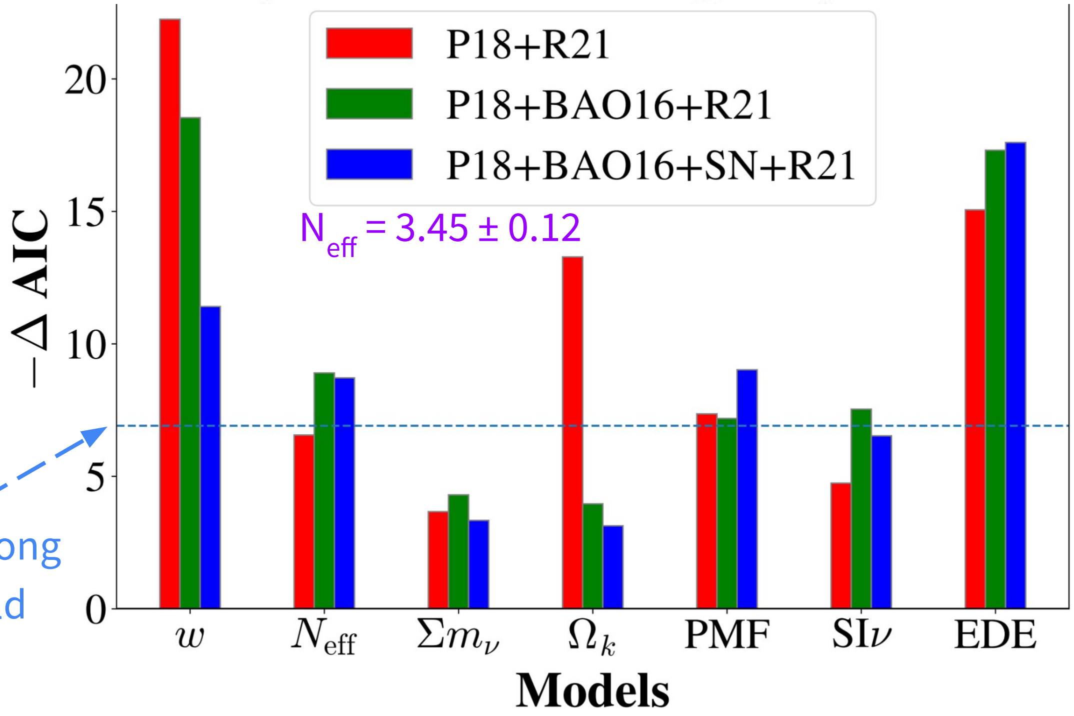
N_{eff} significantly different from 3.044 = **signature of new physics!**

Exploration alleviation cosmological tensions

-4 "winners": EDE, ωCDM,PMF & N_{eff}

-N_{eff} is a preferred model comparable with other exiting candidates

$$\Delta \mathrm{AIC} \equiv -2(\ln \mathcal{L}_{\mathcal{M}} - \ln \mathcal{L}_{\Lambda\mathrm{CDM}}) + 2(N_{\mathcal{M}} - N_{\Lambda\mathrm{CDM}})$$



-6.91 Strong Threshold

arxiv 2208.14435

N_{eff} significantly different from 3.044 = **signature of new physics!**

Exploration alleviation cosmological tensions

-Extra N_{eff} reduces r_s

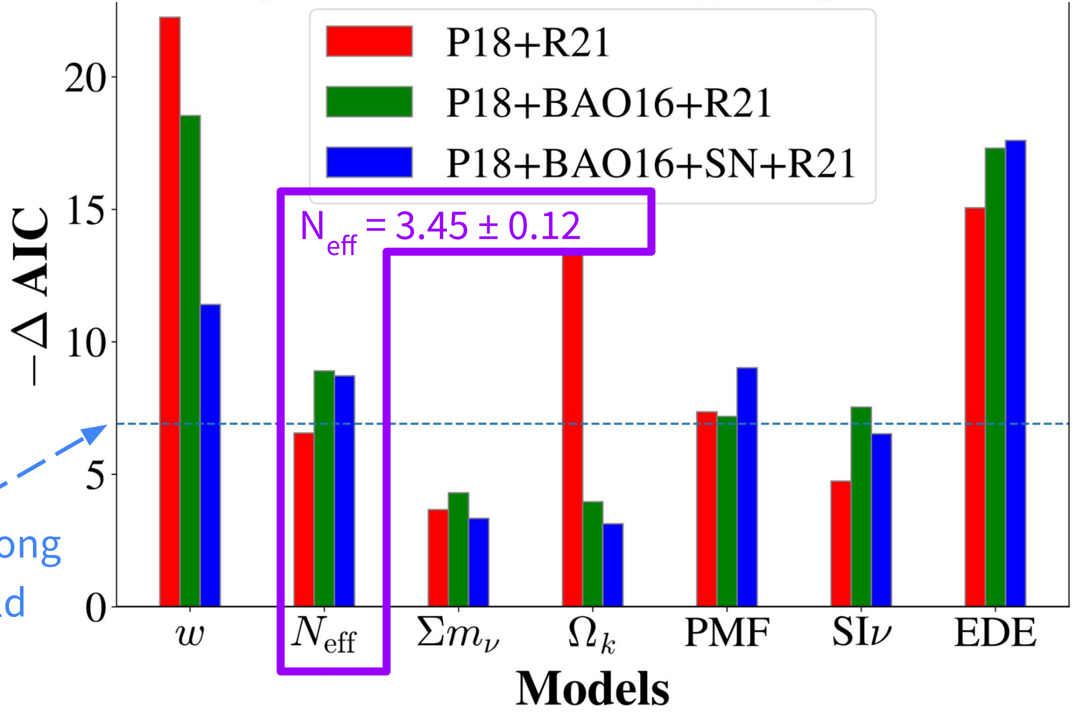
$$r_s = \frac{1}{H_{rec}} \int_0^{t_{rec}} \frac{c_s(t)\, dt / t_{rec}}{[\rho(t)/\rho(t_{rec})]^{1/2}}$$

-Smaller r_s increases H_0

$$H_0 = H_{rec} \frac{\int_{t_{rec}}^{t_0} \frac{c\, dt/t_0}{[\rho(t)/\rho_0]^{1/2}}}{\int_0^{t_{rec}} \frac{c_s(t)\, dt/t_{rec}}{[\rho(t)/\rho(t_{rec})]^{1/2}}}$$

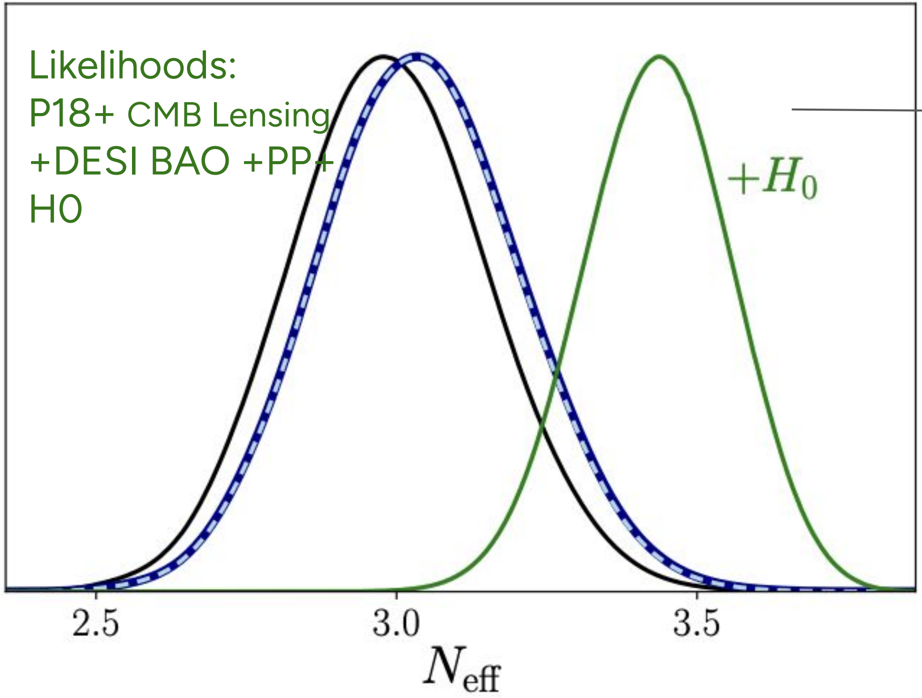
-6.91 Strong Threshold

$$\Delta \text{AIC} \equiv -2(\ln \mathcal{L}_{\mathcal{M}} - \ln \mathcal{L}_{\Lambda\text{CDM}}) + 2(N_{\mathcal{M}} - N_{\Lambda\text{CDM}})$$



arxiv 2208.14435

N_{eff} significantly different from 3.044 = signature of new physics!



N_{eff} = 3.45 (CMB+BAO+SN PP +H_0)

Updating the calculations with DESI BAO DR1 and Pantheon + SNe sample

N_{eff} is a preferred model:

ΔAIC = -10.9

Short baseline anomalies and Sterile neutrinos

- N_{eff} higher than 3.044 = new physics =?? hidden neutrino sector!
- Short baseline neutrino oscillations results (Super-Kamiokande, LSND, MiniBooNE) and Gallium anomaly (i,e.: SAGE, GALLEX, BEST), hint richer neutrino sector.
- More than 3 active neutrinos with one (or more) sterile flavors.

TOTALLY THERMALIZED STERILE NEUTRINOS N_{eff} = 4.044; $m_{\nu,ster}$ = free

$$\Delta N_{\rm eff} = \left[\frac{7}{8}\frac{\pi^2}{15}T_\nu^4\right]^{-1}\frac{1}{\pi^2}\int dp\, p^3\, f_s(p), \qquad \omega_s \equiv \Omega_s h^2 = \frac{m_s^{\rm eff}}{94.1{\rm eV}} = \frac{h^2 m_s^{\rm ph}}{\pi^2 \rho_c}\int dp\, p^2\, f_s(p),$$

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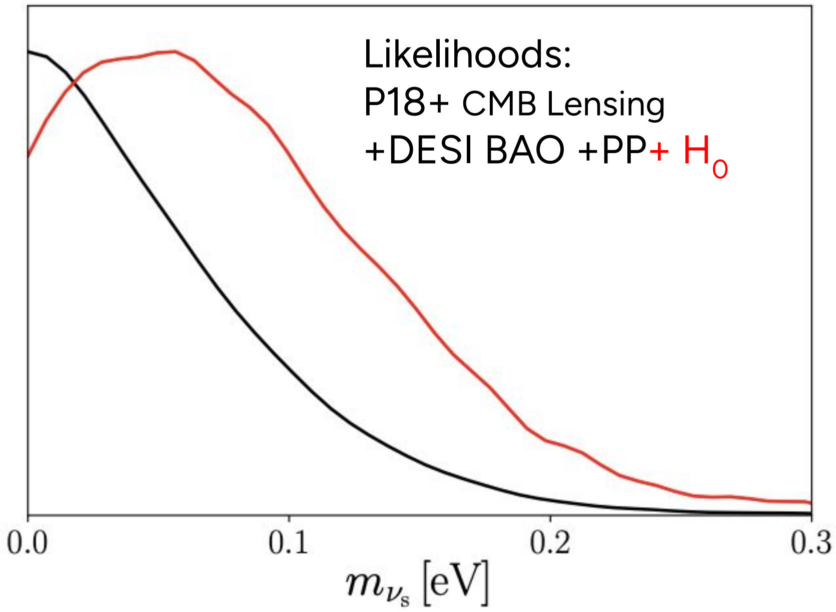
Totally thermalized Sterile Neutrinos

- Strongly disfavored using P18+ CMB Lensing +DESI BAO +PP vs. ΛCDM.

  ΔAIC > 20

- When +H_0 ⇨ ΔAIC =4.5

- A fully thermalized eV scale short baseline sterile neutrino is as consistent with H_0 tension as ΛCDM



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Short baseline anomalies and Sterile neutrinos

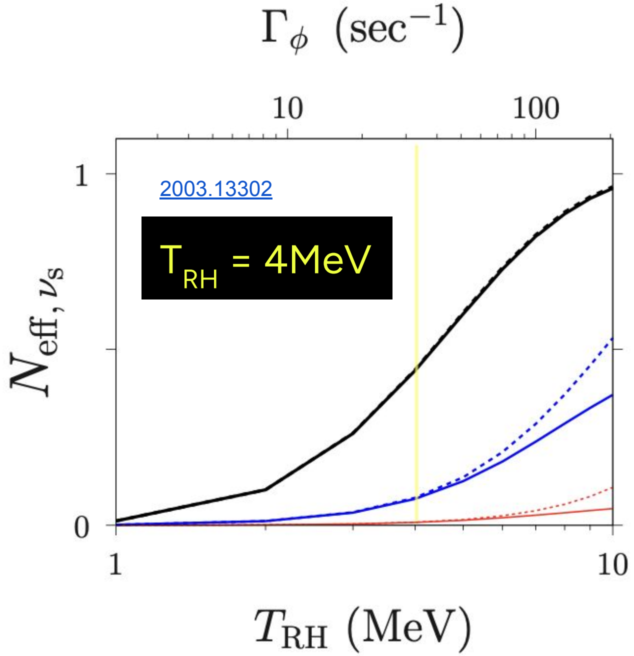
Partially THERMALIZED STERILE NEUTRINOS
3 thermalization cases for 0.1 eV and 1 eV

1.- N_{eff} = 3.49; $m_{\nu,ster}$ = 0.1 eV and 1 eV

2.- N_{eff} = 3.12; $m_{\nu,ster}$ = 0.1 eV and 1 eV

3.- N_{eff} = 3.05; $m_{\nu,ster}$ = 0.1 eV and 1 eV

Results adding H_0
-0.1 eV: ΔAIC=-11.0, -3.7, -2.1
-1eV: ΔAIC=25.9, 0.8, 1.1



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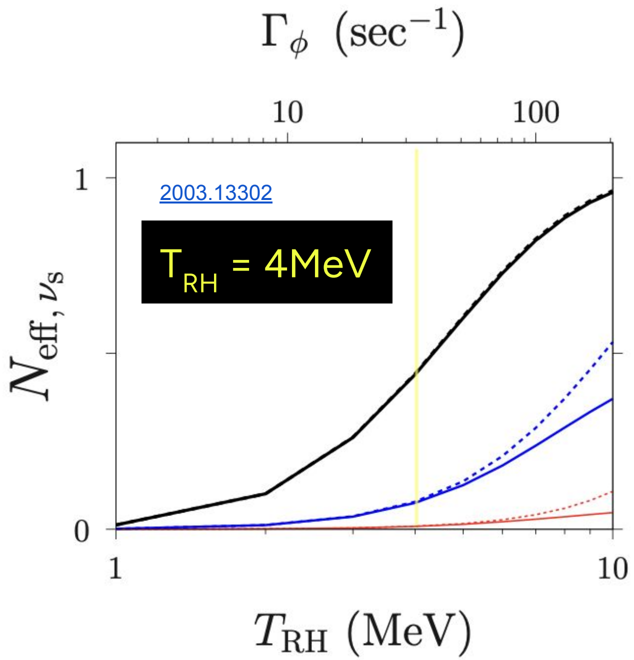
Short baseline anomalies and Sterile neutrinos

Partially THERMALIZED STERILE NEUTRINOS :

- 0.1 eV partially thermalized sterile neutrinos studied are preferentially fit to data alleviating Hubble tension better than ΛCDM.
- Model with 0.1 eV part. Therm. ster. neutrino with N_{eff} 3.39 is strongly preferred over ΛCDM by its AIC as well as Δ□^{2}>3σ.
- Preference due to correlation N_{eff}-Σm_ν in BAO; both can increase without altering BAO



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11-parameter model: ΛCDM + ω_0/ω_a + Ω_k + Σm_ν+N_{eff}

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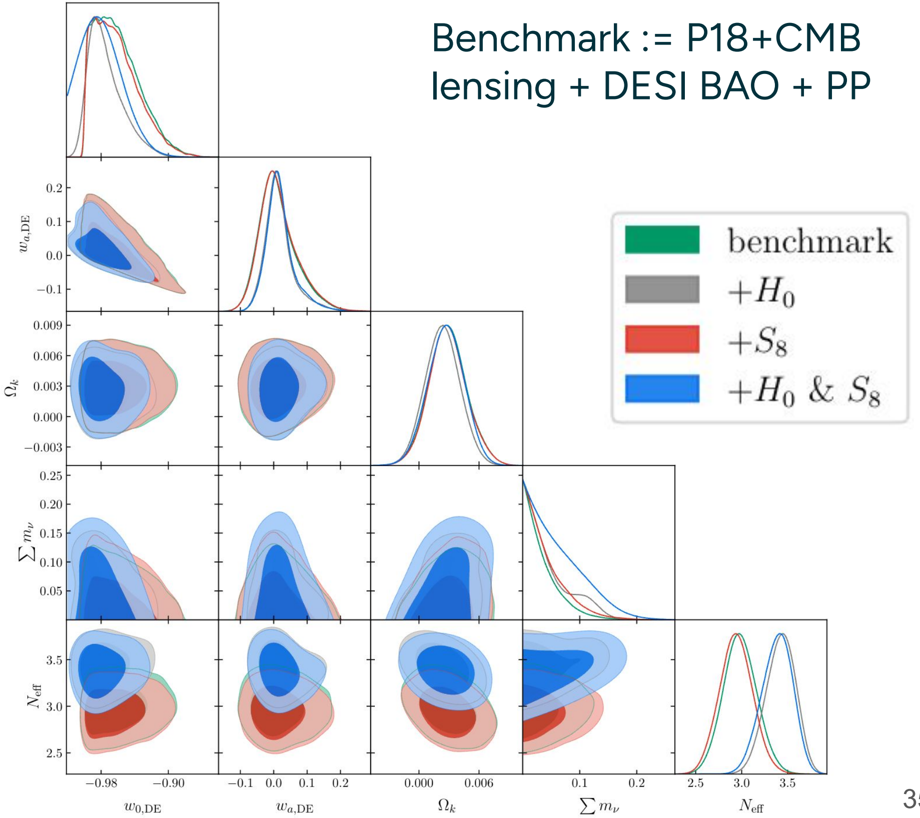
- Simple parameterizations don't often work.
- Test a significantly relaxed model
- Consistency with ΛCDM except:

-w_0 more positive than Λ over 3σ
-less than 2σ away from flat

Parameters	Benchmark
$\Omega_b h^2$	0.02236 ± 0.00022
$\Omega_c h^2$	0.1184 ± 0.0028
$\log(10^{10} A_s)$	3.053 ± 0.016
n_s	0.9639 ± 0.0084
τ_{reio}	$0.0586^{+0.0069}_{-0.0077}$
$100\theta_{MC}$	1.04107 ± 0.00043
Σm_ν (95% CL)	$< 97.0\,\mathrm{meV}$
N_{eff}	2.98 ± 0.18
Ω_k	0.0029 ± 0.0019
w_0	$-0.961^{+0.012}_{-0.037}$
w_a	$0.013^{+0.039}_{-0.066}$

Benchmark := P18+CMB lensing + DESI BAO + PP



11-parameter model: ΛCDM + ω_0/ω_a + Ω_k + Σm_ν+N_{eff}

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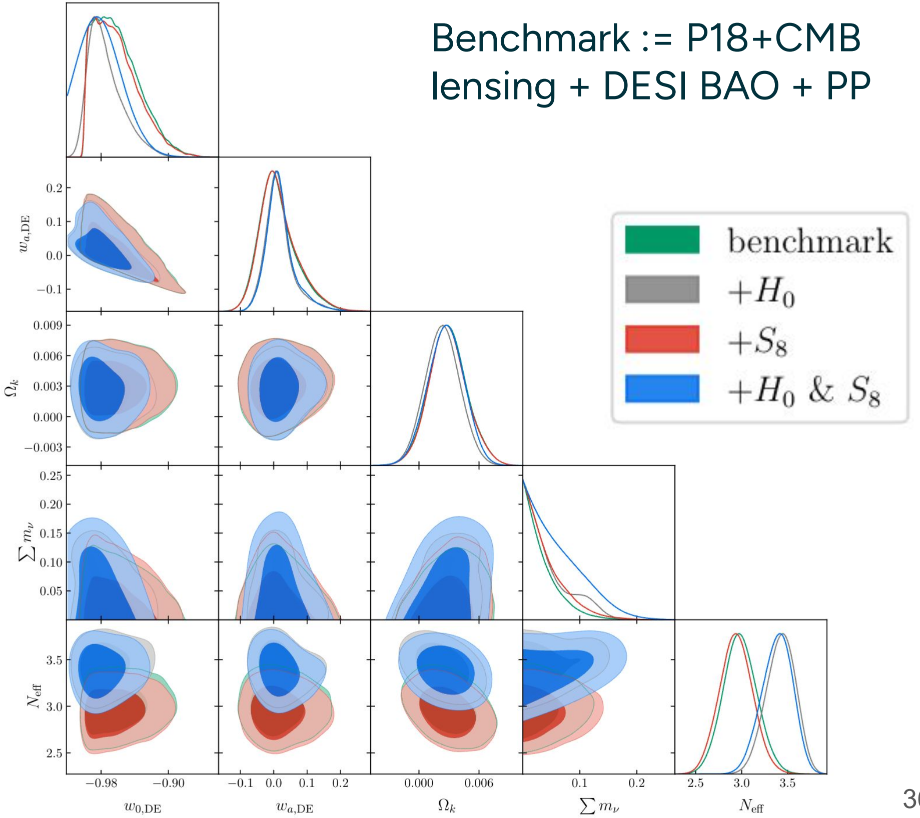
w_a	$0.013^{+0.039}_{-0.066}$

No preference for nontrivial w_a due to shifts in other cosmological parameters

Benchmark := P18+CMB lensing + DESI BAO + PP



11-parameter model: ΛCDM + ω_0/ω_a + Ω_k + Σm_ν+N_{eff}

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Adding tension datasets:

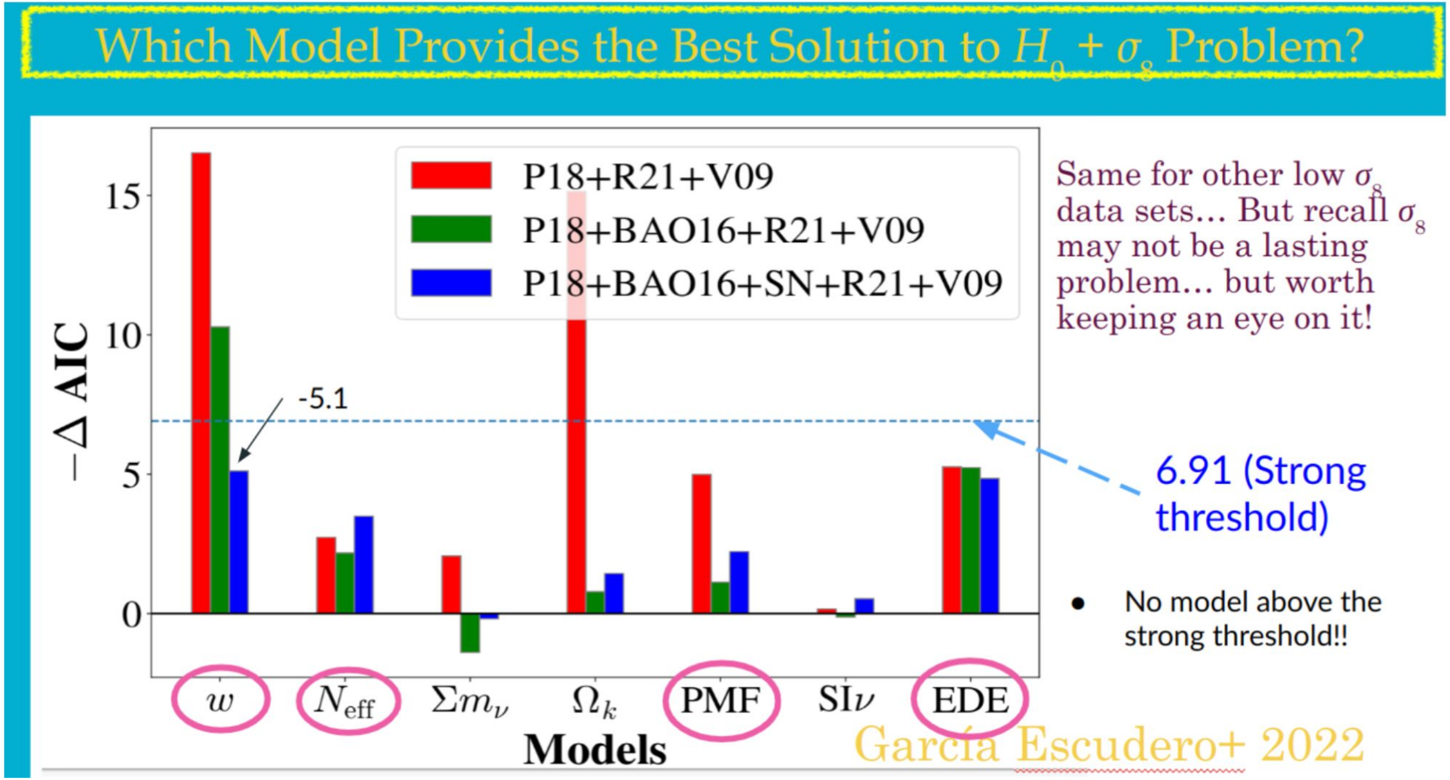
Benchmark := P18+CMB lensing + DESI BAO + PP

Parameters	Benchmark	+ H_0 Post.	+ S_8 Post.	+ H_0 & S_8 Post.
$\Omega_b h^2$	0.02247 ± 0.00013	$0.02274^{+0.00017}_{-0.00020}$	0.02237 ± 0.00022	$0.02273^{+0.00018}_{-0.00021}$
$\Omega_c h^2$	0.1185 ± 0.0083	$0.1251^{+0.0028}_{-0.0025}$	0.11756 ± 0.0027	$0.1241^{+0.0029}_{-0.0025}$
$\log(10^{10} A_s)$	3.049 ± 0.013	3.073 ± 0.018	3.049 ± 0.016	3.072 ± 0.015
n_s	0.9683 ± 0.0036	$0.9808^{+0.0076}_{-0.0069}$	0.9636 ± 0.0084	$0.9804^{+0.0076}_{-0.0068}$
τ_{reio}	0.0586 ± 0.0071	0.0616 ± 0.0089	0.0581 ± 0.0074	$0.0619^{+0.0074}_{-0.0060}$
$100\theta_{MC}$	1.04108 ± 0.00029	1.04044 ± 0.00036	1.04119 ± 0.00043	$1.04048^{+0.0038}_{-0.0043}$
Σm_ν (95% CL)	< 82.1 meV	< 125 meV	< 112 meV	< 130 meV
N_{eff}		3.43 ± 0.15	2.94 ± 0.18	$3.39^{+0.18}_{-0.13}$
Ω_k		0.0023 ± 0.0017	$0.0029^{+0.0017}_{-0.0020}$	0.0027 ± 0.0017
w_0		$-0.975^{+0.012}_{-0.024}$	$-0.962^{+0.012}_{-0.036}$	$-0.978^{+0.018}_{-0.031}$
w_a		$0.016^{+0.027}_{-0.045}$	$0.015^{+0.039}_{-0.060}$	$0.019^{+0.028}_{-0.043}$

-Increase N_{eff}

-Relaxation Σm_ν bound

No model does better than ΛCDM solving $H_0 + S_8$ simultaneously



- No model above the strong threshold!!

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Conclusions and future work

- No model does better than ΛCDM in fitting cosmological data while solving cosmological tensions but…

- Include new cosmological data and reevaluate promising candidate models.

- Study and develop new candidate models further developing winner models:

  1.- New dynamical dark energy models

  2.- Primordial magnetic fields (include full magnetohydrodynamics (MHD) simulations)

  3.-Models providing extra N_{eff}: LRTs, exotic neutrino sector, …

Conclusions and future work

- Cosmological observations are a **very powerful tool** for high precision determination neutrino cosmological parameters.

- Combined cosmological probes (CMB-S4 + BAO) **revolutionize understanding** of **neutrino physics**:

  1.- Test standard cosmological model predictions.
  2.- Shred light to existing cosmological anomalies.
  3.- Test new physics.

- Upcoming observational results next decade critical understanding Universe!

Thank you for attention!
Questions?

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