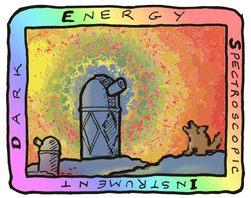

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Cosmological neutrino mass: a frequentist overview

Neutrino mass profile likelihoods in light of the latest DESI data

Domitille Chebat — 17/07/25 — Optimizing the Extraction of Cosmological Information from the Latest Spectroscopic Redshift Surveys

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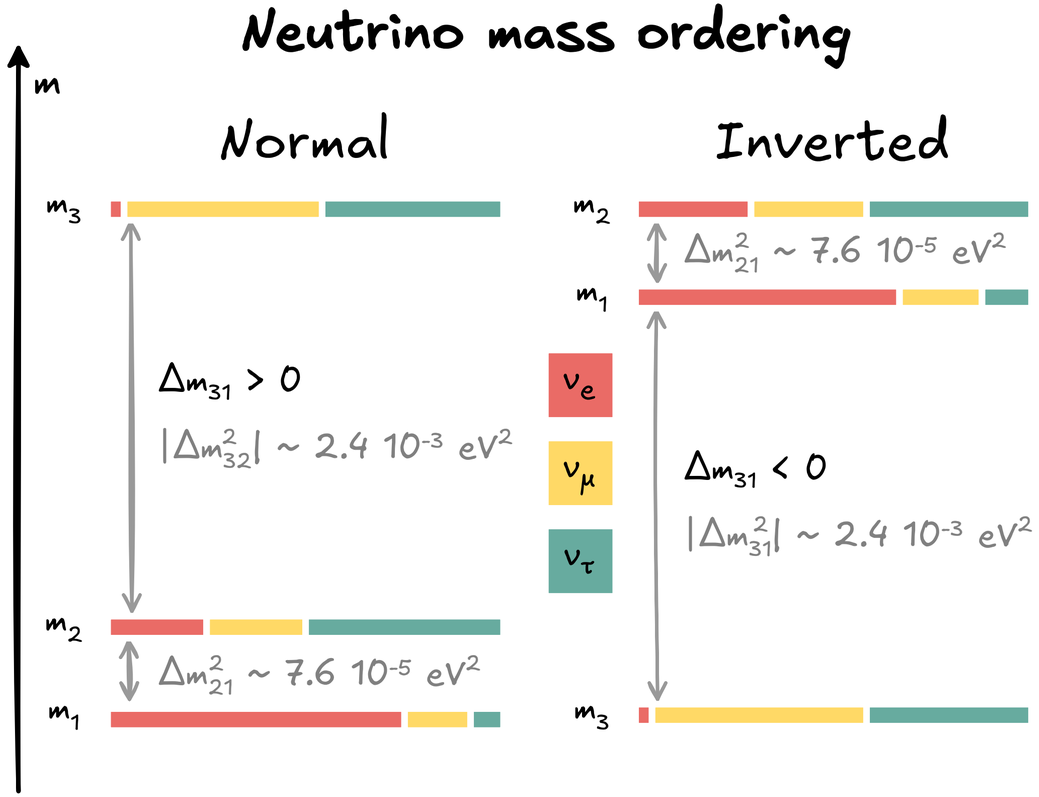
Neutrino mass basics

Neutrinos and neutrino mass

- Electrically neutral, very light
- Three flavors: *e*, μ, τ
- Three mass states: $m_1 < m_2, m_3$
- From flavor oscillations:

$$|\Delta m^2_{32}| \quad >> \quad \Delta m^2_{21}$$



- **Normal** and **inverted** ordering
- Only absolute conclusion: **minimal sum**
  - $\Sigma m_\nu \geq$ 60meV (normal) or $\Sigma m_\nu \geq$ 100meV (inverted)

Neutrino mass basics

Neutrino mass in cosmology

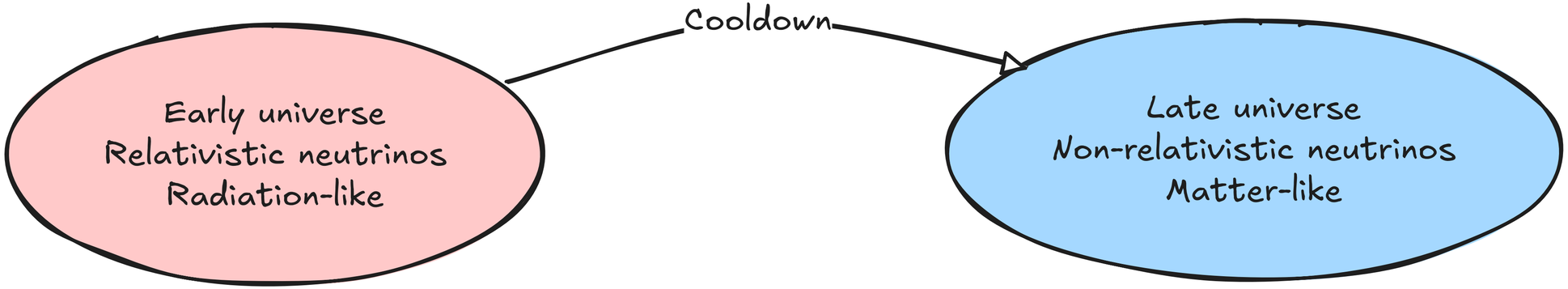
- Cosmological data is not sensitive to flavor, only gravitation
- After the Big Bang, neutrinos are hot and relativistic / **radiation**-like behavior
- They cool down and transition to a non-relativistic behavior
  - affected by gravitation
  - behave (somewhat) like **matter**

ℹ️ Non-relativistic transition happened between the CMB and now (z~100)

Neutrino mass basics

Neutrino mass in cosmology — the geometrical effect

- Universe expansion: neutrinos go from **radiation** to **matter** contribution



$$\Omega_{\rm m} = \Omega_{\rm b} + \Omega_{\rm c} \qquad \Omega_{\rm m} = \Omega_{\rm b} + \Omega_{\rm c} + \Omega_{\nu}$$

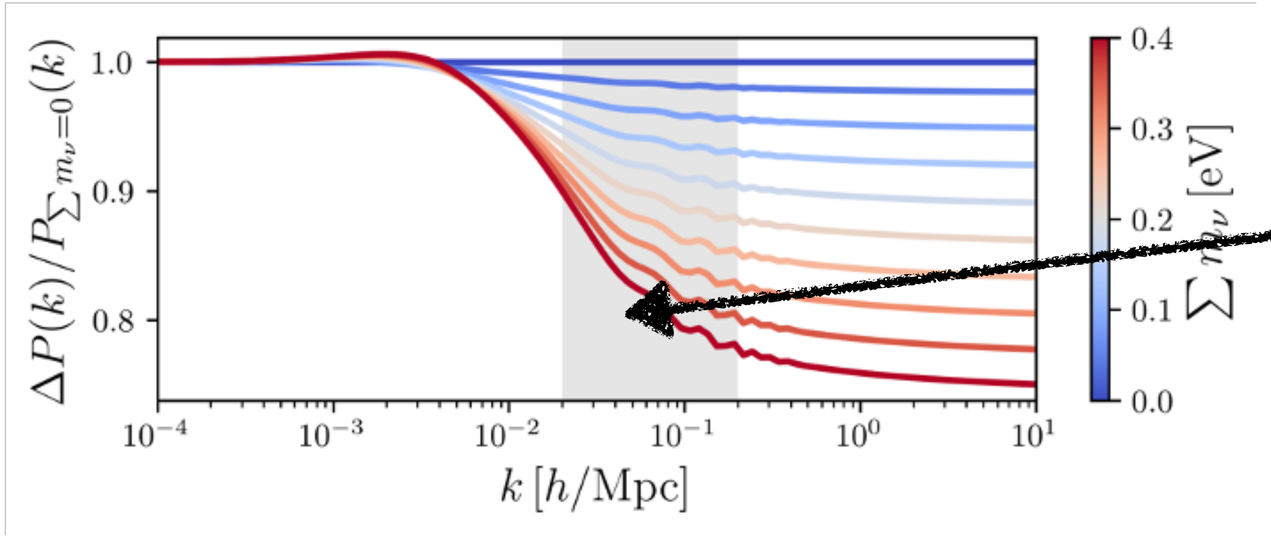
$$H(z) = H_0\sqrt{\Omega_\Lambda + \Omega_{\rm m}(1+z)^3 + \Omega_{\rm r}(1+z)^4}$$

- This affects distance measurements (typically, CMB BAO *vs* DESI BAO)

Neutrino mass basics

Neutrino mass in cosmology — the free-streaming effect

- Neutrinos cluster post non-relativistic transition
- Very warm: non-negligible free-streaming length λ_{fs}
- Clustering inhibited below λ_{fs}: **small-scale power spectrum suppression**



DESI full-shape sensitivity

Credit: Arnaud de Mattia

Methodology

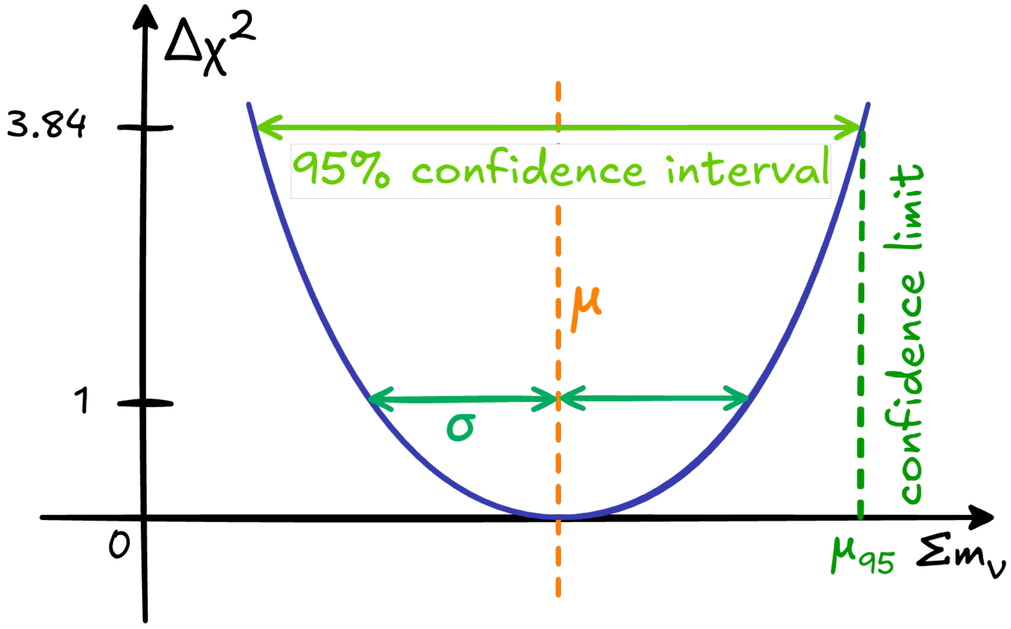
Methodology

Profile likelihoods, confidence intervals (regular case)

- Profile likelihood: function of $\sum m_\nu$
  - Fix the parameter of interest $\sum m_\nu$
  - Maximize the likelihood with regard to all other parameters

- Gaussian likelihood → χ^2 / parabola
  - σ = data constraining power
  - μ_0 = parabola minimum
- 95% confidence limit at $\Delta\chi^2 = 3.84$

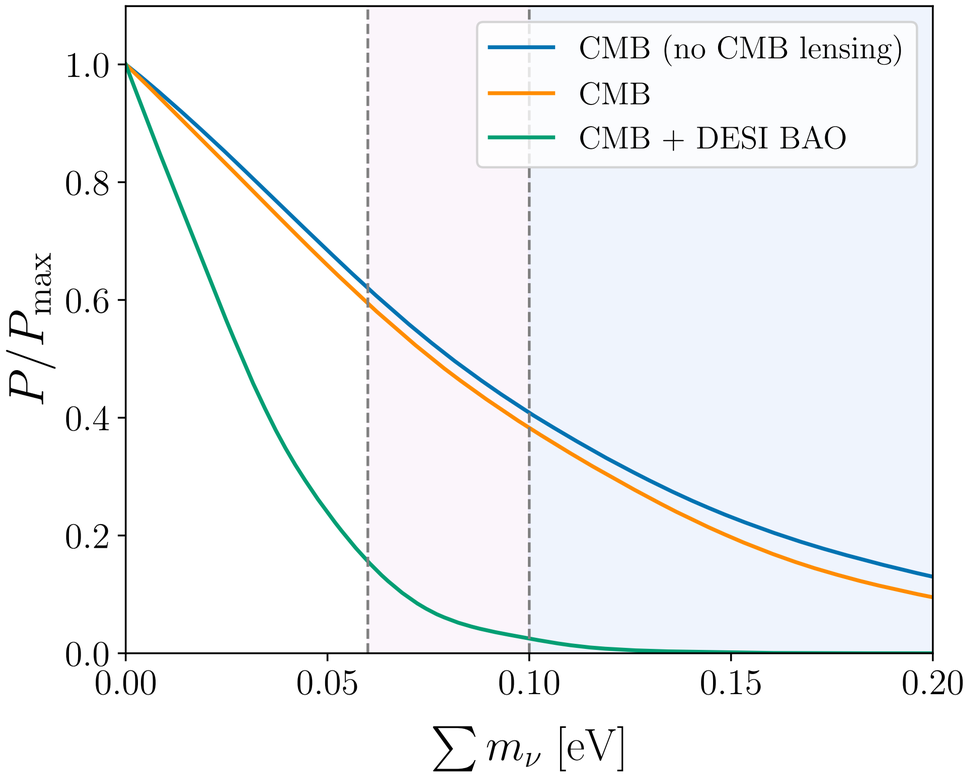
$$\sum m_\nu \mapsto \min_{\mathcal{C},\,\mathcal{N}} -2\log\left(\mathcal{L}\left(\sum m_\nu, \mathcal{C}, \mathcal{N}\right)\right)$$



Methodology

Why profile likelihoods?

- Immunity to prior volume effects (as opposed to Bayesian inference)
  - *eg* for DESI full-shape
- Bayesian neutrino mass inference is cut off by zero limit
- In this situation, profile likelihoods
  - Also provide a 95% CL limit (confidence)
  - Inform on the data's constraining strength



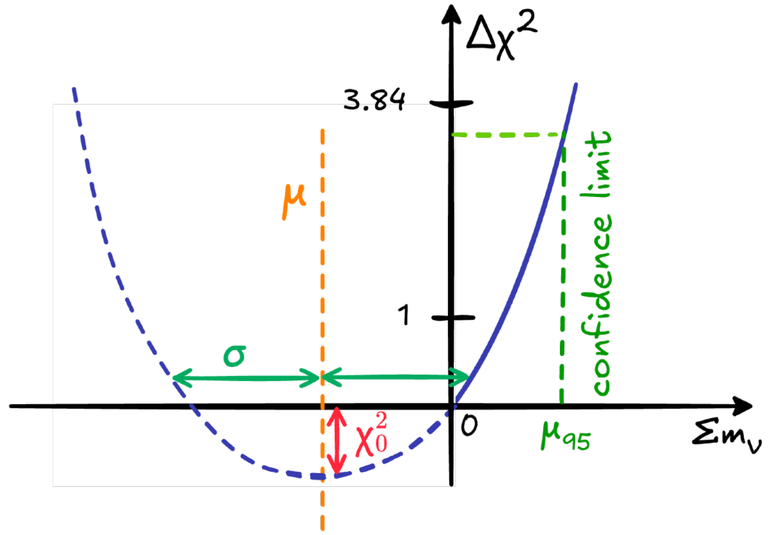
DESI 2024 VI, fig 11: marginalized 1D posterior constraints on Σm_ν

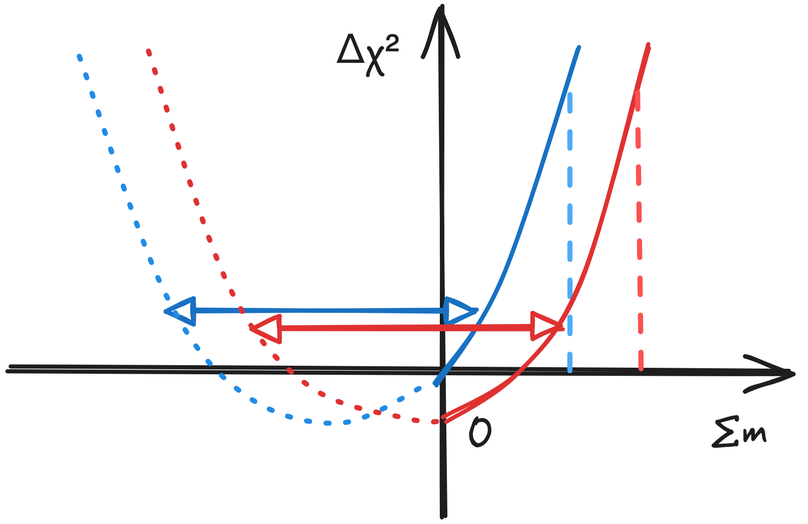
Methodology

How to deal with interrupted profiles

- Profile is cut off: still fit a parabola
- Feldman & Cousins 1998:
  - Confidence limit, accounts for $\mu_0 < 0$
  - Often close to $\Delta\chi^2 = 3.84$
- Isolate *constraining power* from *upper limit* despite cut-off
- Intuitive visual comparison

Planck 2013 XVI, *Naredo-Tuedo+ 2024*, *Herold+ 2025*





Neutrino mass basics

Data combinations

Geometrical effect

Compare early-time ($z << z_{NR}$) and late-time ($z >> z_{NR}$) **distance** measurements

- Relativistic neutrinos: CMB
- Non-relativistic neutrinos: DESI

- CMB: Planck, ACT
- BAO: DESI DR1/DR2 BAO

Free-streaming effect

Compare late-time **matter power spectrum** to primordial tilt and amplitude

- Primordial: CMB, Lya-inferred
- Late-time: DESI FS, CMB lensing

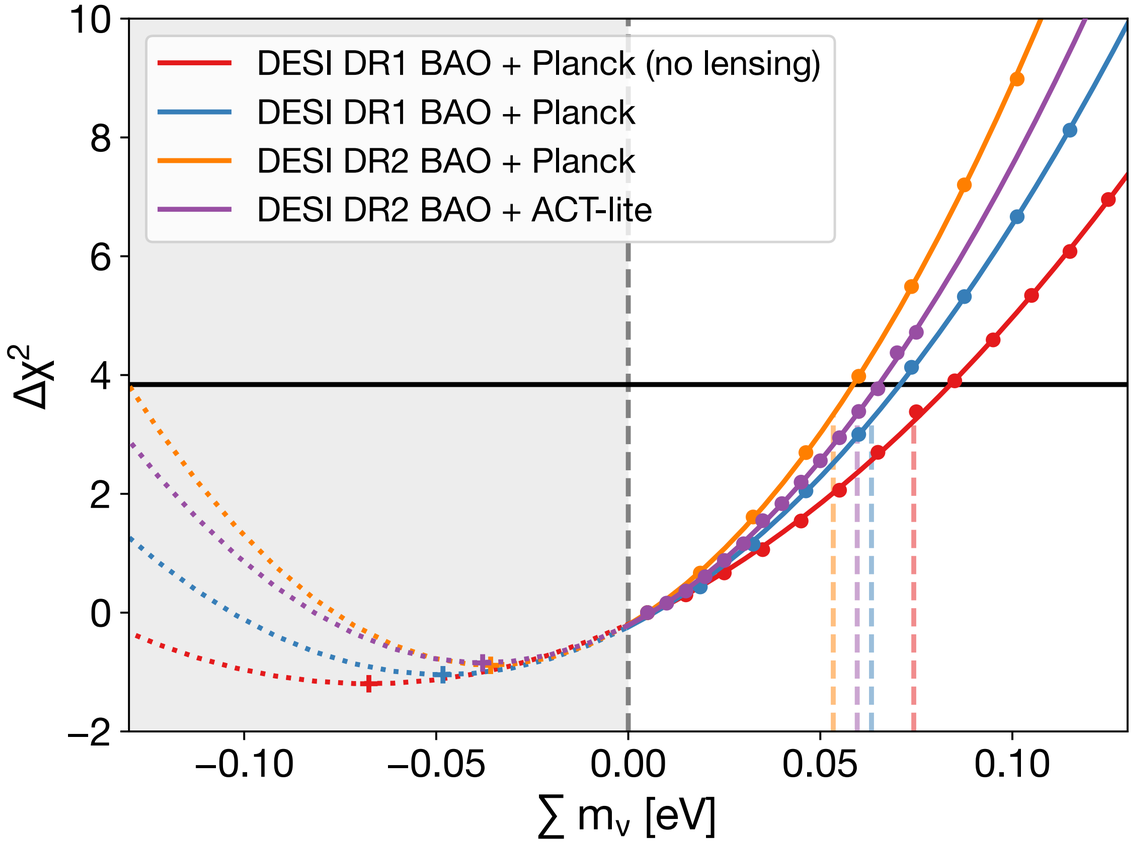
- CMB shape: Planck
- Lya: SDSS DR14 P1D
- CMB lensing: ACT DR6
- FS: DESI DR1 FS

Results I: geometrical effect *mainly*

Results I: geometrical effect

DESI BAO + CMB

- 🔴 → 🔵 : Add CMB lensing
  σ and μ improve
- 🔵 → 🟠 : update BAO to DR2
  σ and μ improve
- 🟠 → 🟣 : Compare Planck / ACT DR6
  σ relaxes, no other change
- Upper limit changes are consistent with constraining powers
- Upper limits comparable to Bayesian



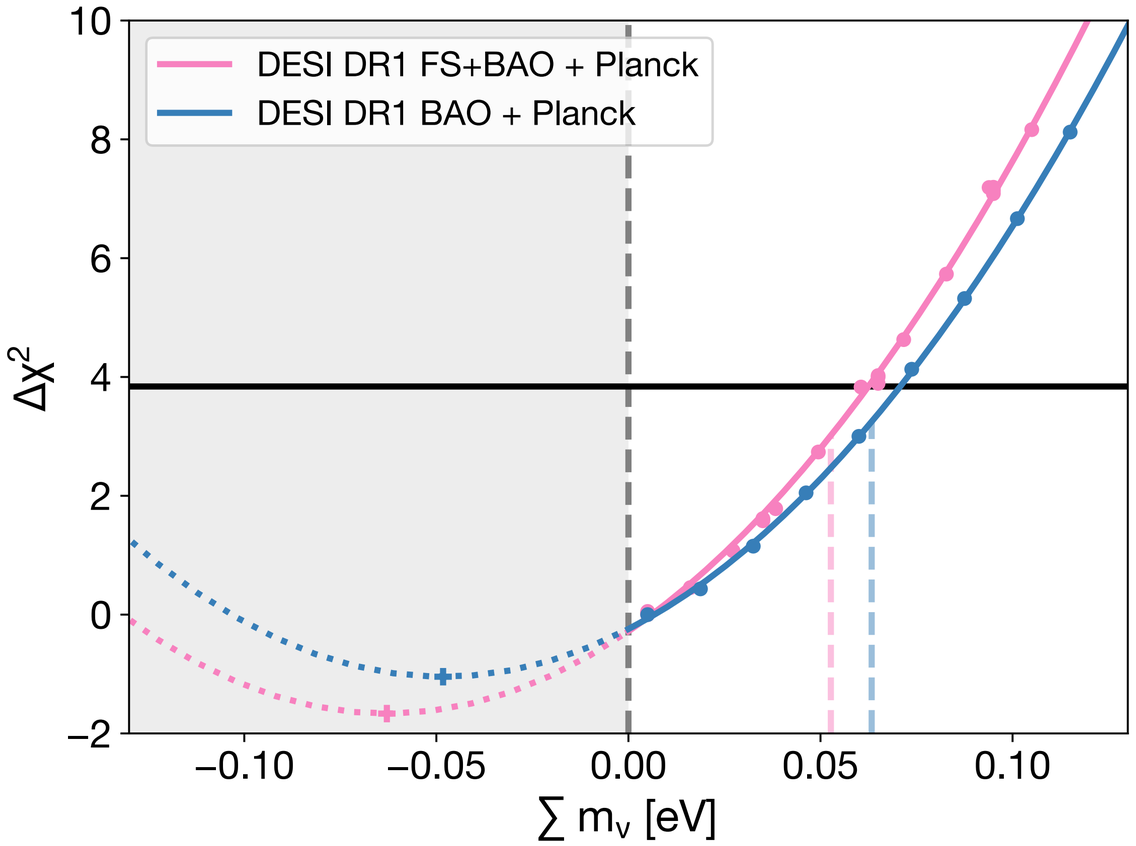
Results I: geometrical effect (mainly)

Adding DESI full-shape

- At first sight, constraint “improves” (upper limit goes down)
- But almost entirely due to a **shift**

Likelihoods	σ	μ_0	95% CL
BAO + Planck	54	-48	63
FS+BAO + Planck	53	-63	53

- FS not competitive against geometry
- Upper limit shift consistent with Bayesian

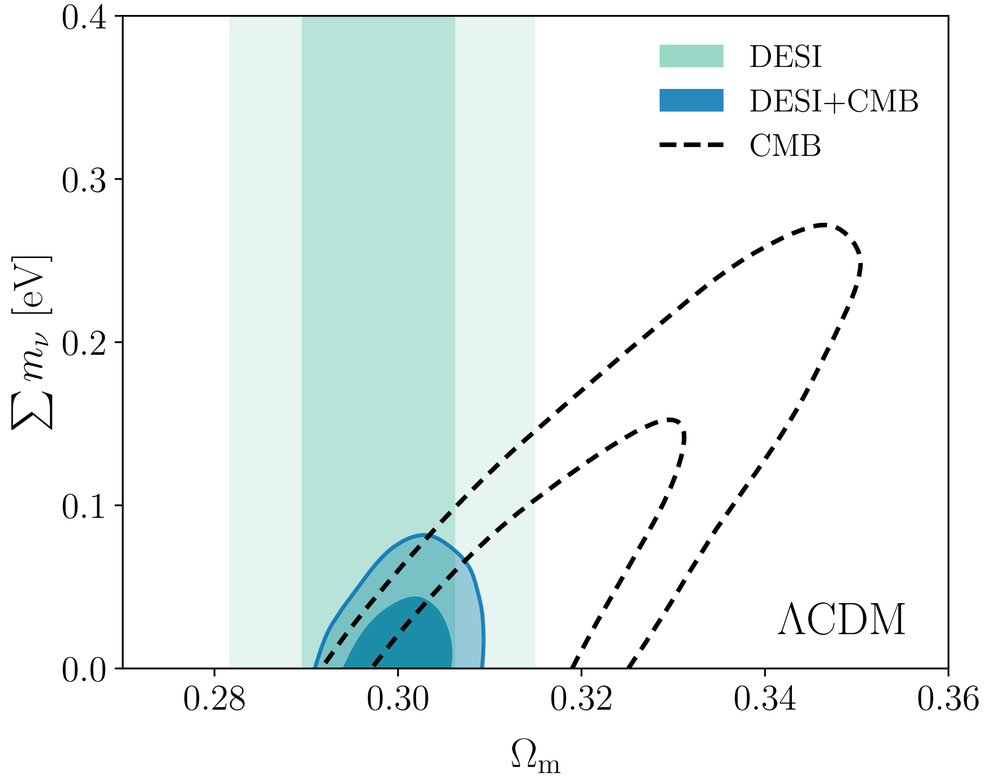


Interlude: but why are the limits so low?

Interlude: but why are the limits so low?

Oscillations, geometry and Ω_m

- "Low" = below the oscillations-set normal ordering minimum ~ 60 meV
- Can be pinned on the combination of
  1. Ω_m - Σm_ν degeneracy in the CMB
  2. DESI preference for Ω_m < CMB one
- Can be relaxed by changing the expansion history (w_0w_aCDM), changing Ω_m (optical depth)…

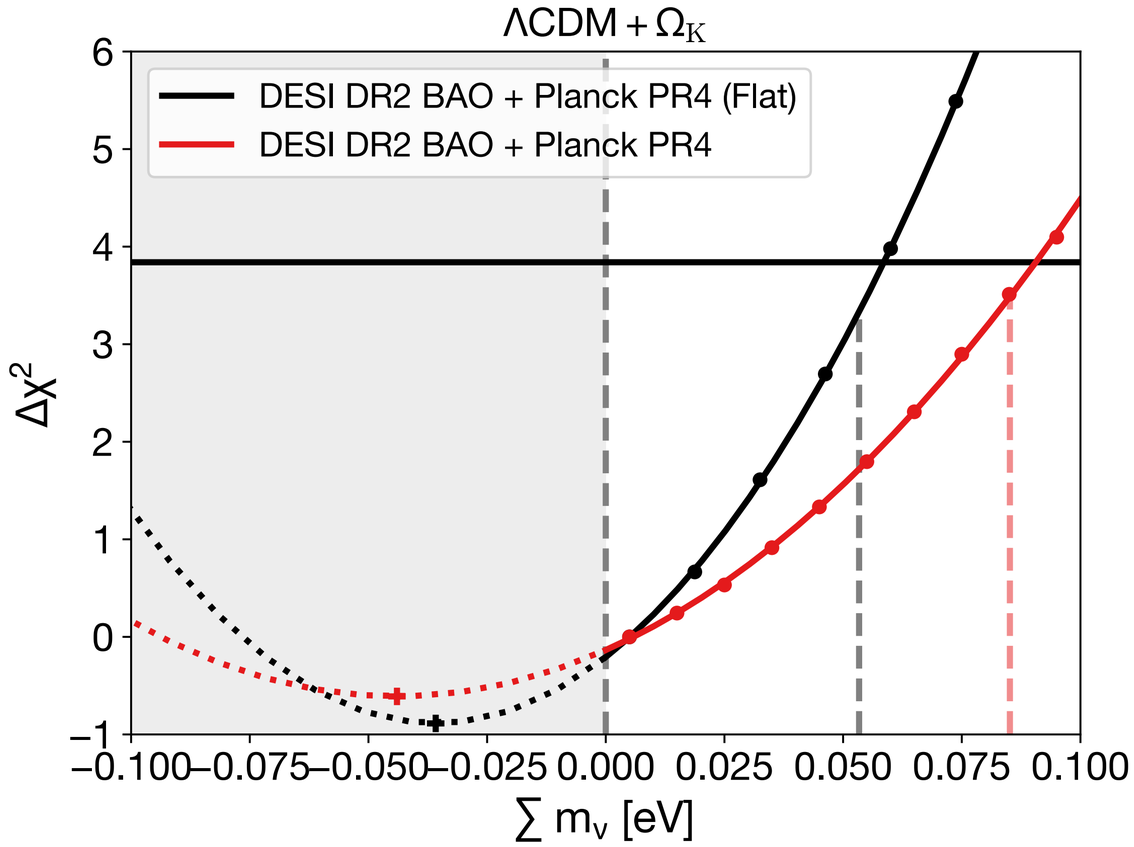


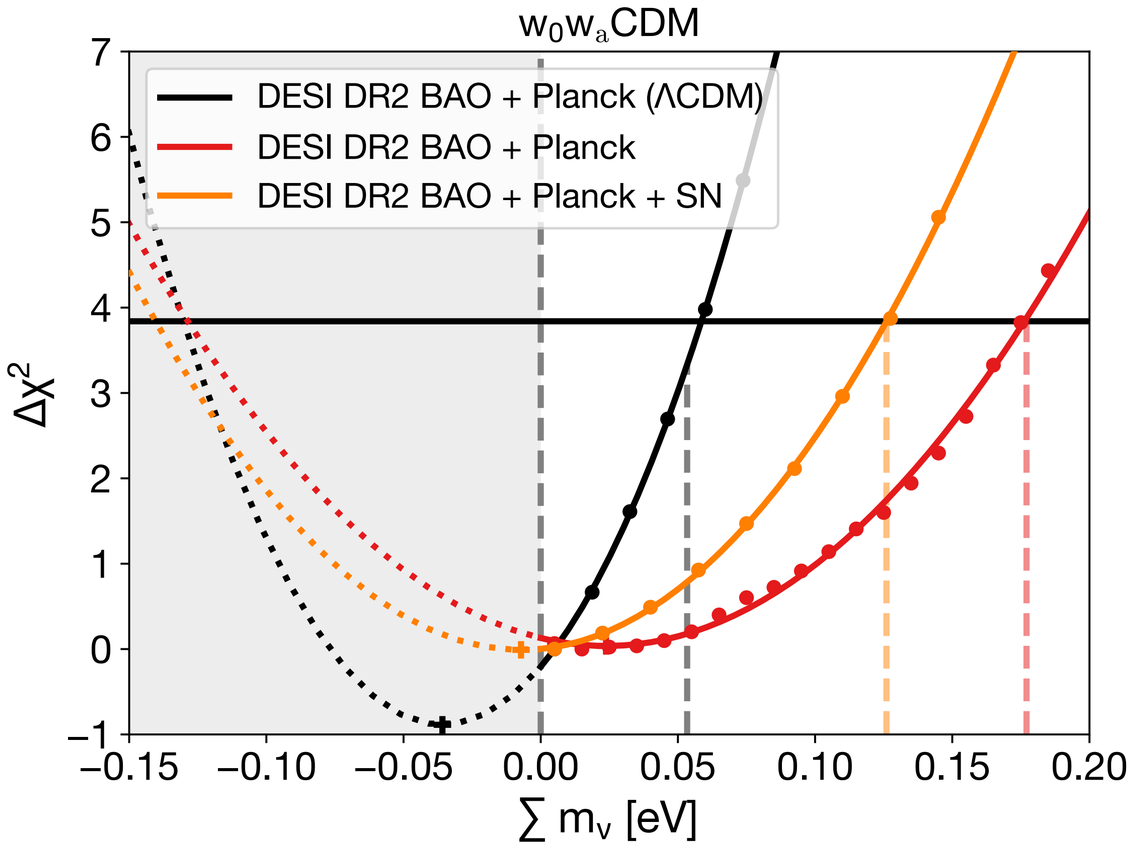
DESI DR2 Results II (2025) — fig. 16

Sailer+ 2025, *Jhaveri+ 2025*

Interlude: but why are the limits so low?

… and some solutions: ΛCDM extensions



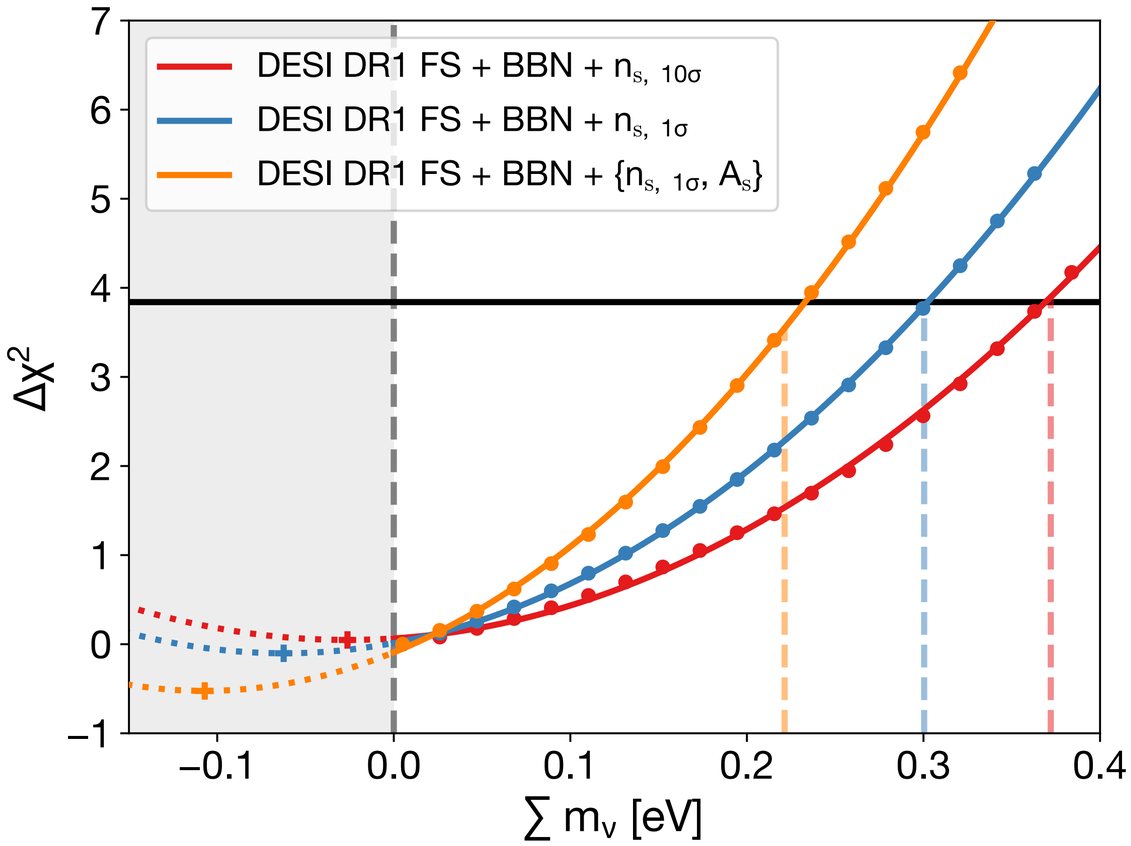


Results II: free-streaming effect

Results II: free-streaming effect

DESI full-shape + CMB spectral index

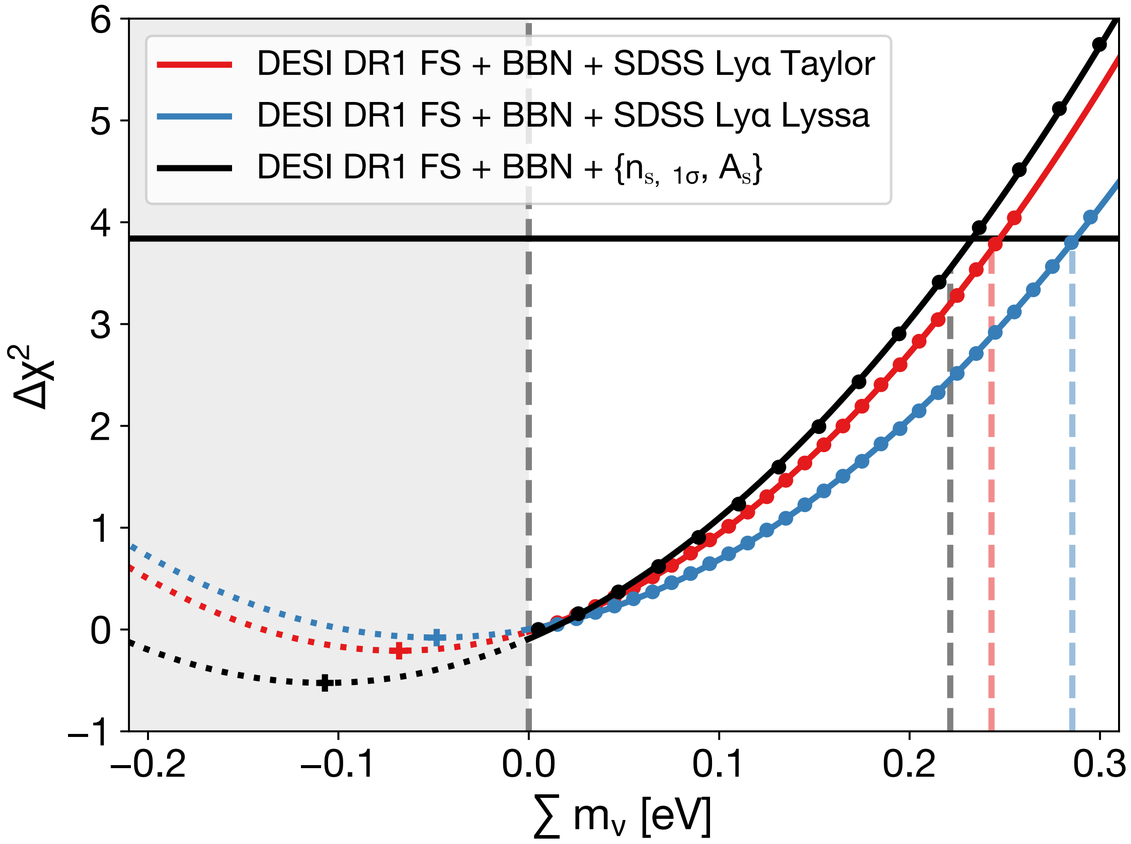
- Compressed primordial shape information from the CMB
- ● → ● → ● : more / more stringent information on primordial shape
- Very relaxed compared to geometrical constraints
- No peak in the positive sector
- Oscillation minima largely included at 95% CL



Results II: free-streaming effect

DESI full-shape + eBOSS Lyman-α P1D

- Compressed Lyα P1D shape, “translates” to primordial shape
- ● / ● : different methods and simulations of eBOSS quasars P1D (*Palanque+ 2020*, *Walther+ 2025*)
- Successful CMB-less constraint!
- Comparable to CMB shape priors
- No peak in positive sector, but oscillation minima included at 95%



Conclusion

Summary and perspectives

2507.12401

- Complementary to Bayesian inference
  - Impervious to prior volume effects (full-shape…)
  - Distinguish *constraining power* σ from *upper limit* at first glance

Paper is out now!
More data combinations
Non-degenerate masses
Lightest neutrino mass…

- Costly procedure, even just in 1D
  - High number of calls
  - More and more expensive

} emulation & autodifferentiation