Cosmic surveys and the quest for the neutrino mass

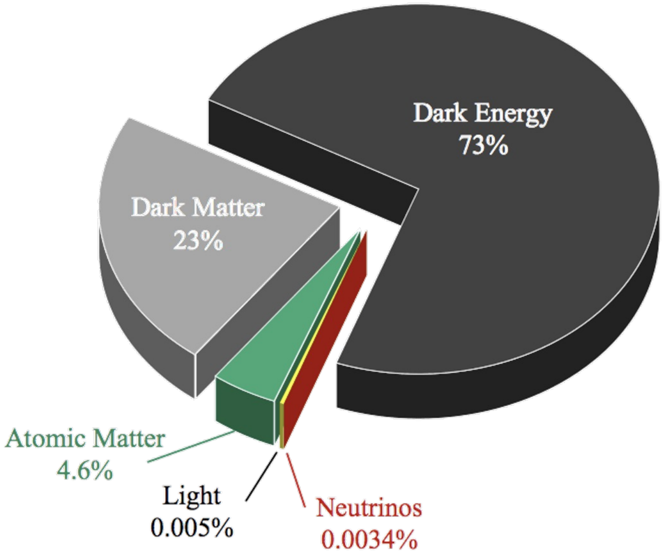
Maria Archidiacono

UNIVERSITÀ DEGLI STUDI DI MILANO

Euclid consortium

IRN Neutrino meeting - IP2I, Lyon, France, June 2025

Why neutrino cosmology



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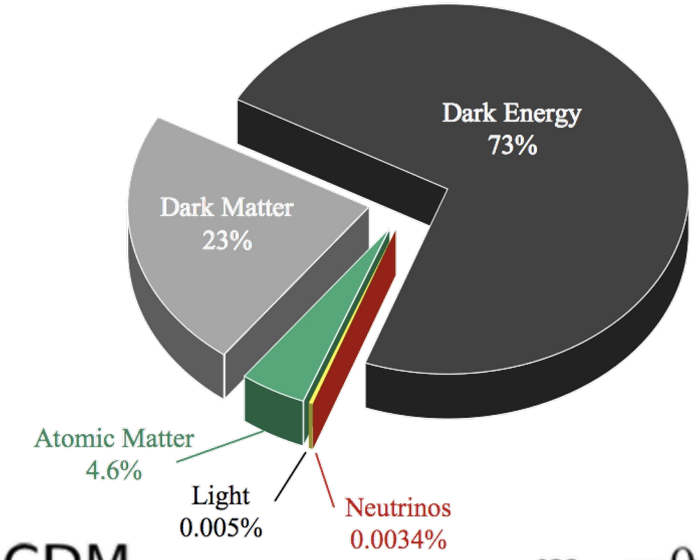
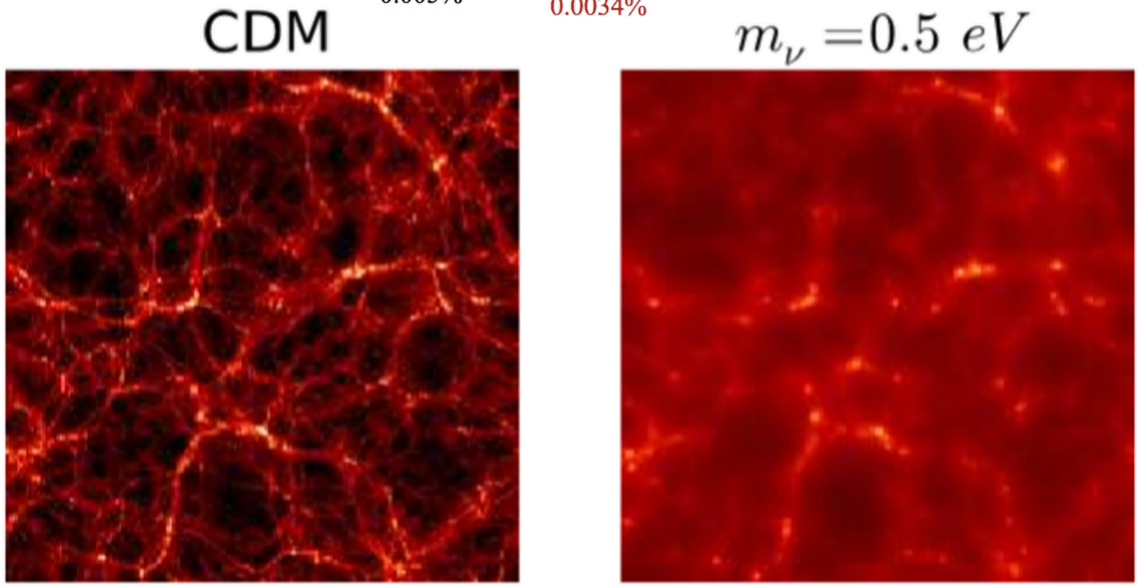


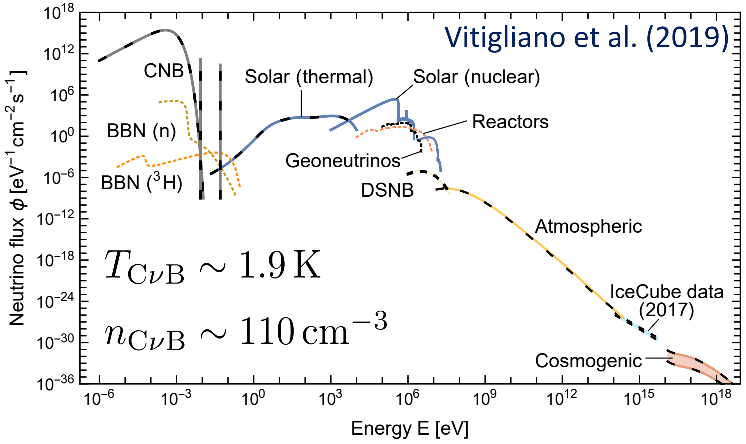


Villaescusa Navarro et al. (2013)

A short cosmic history

A short cosmic history

Cosmic Neutrino Background (T~1MeV)



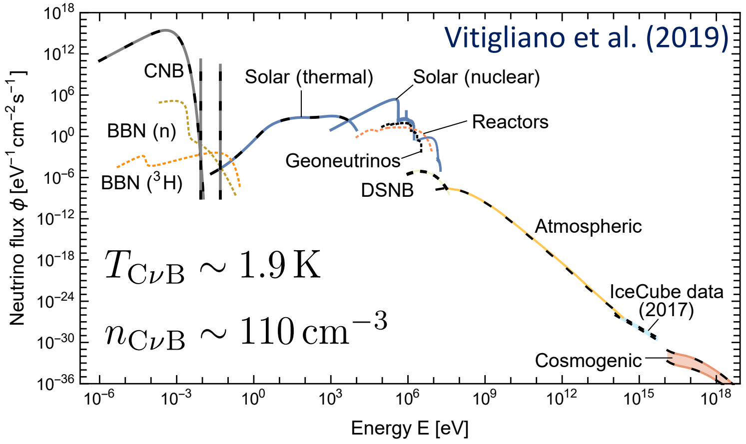
➔ Direct detection not in the near future

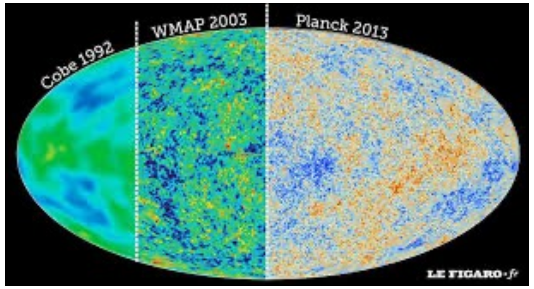
➔ Footprints in cosmological observables

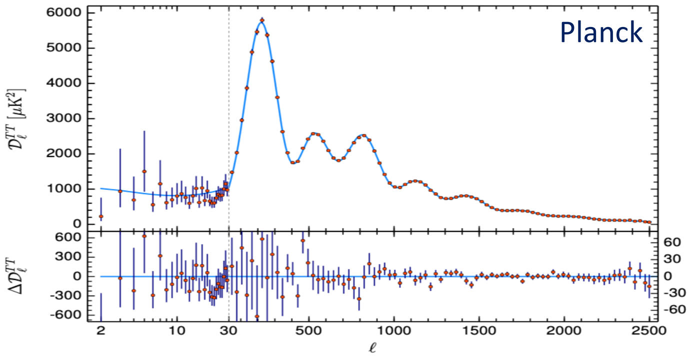
A short cosmic history

Cosmic Neutrino Background (T~1MeV)

Cosmic Microwave Background (T~0.2eV)







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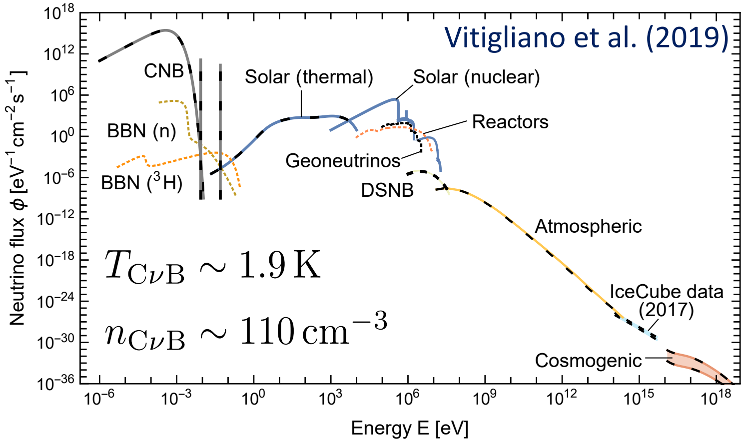

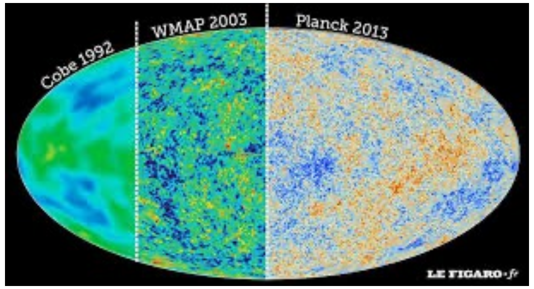

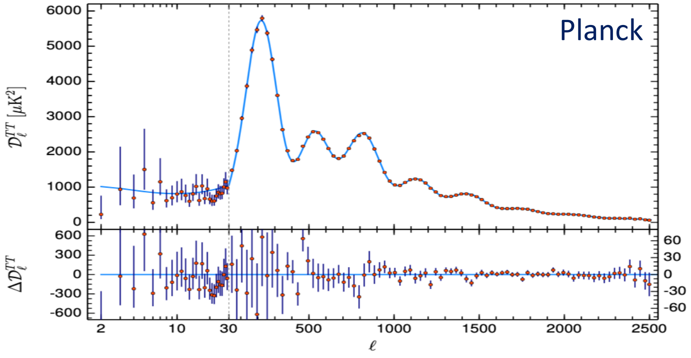

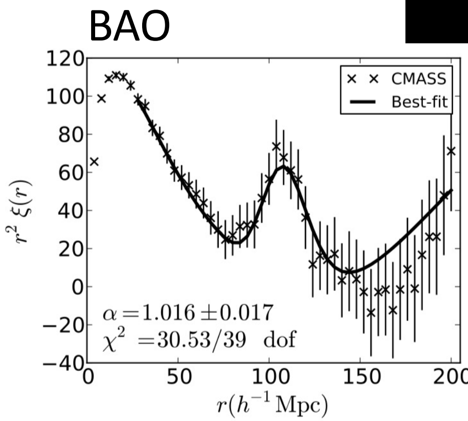

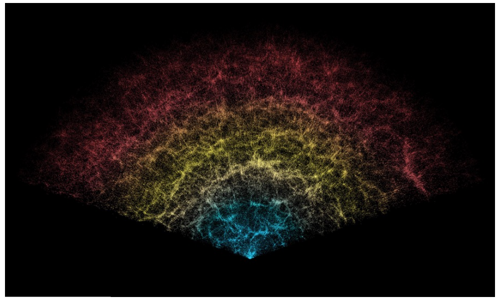

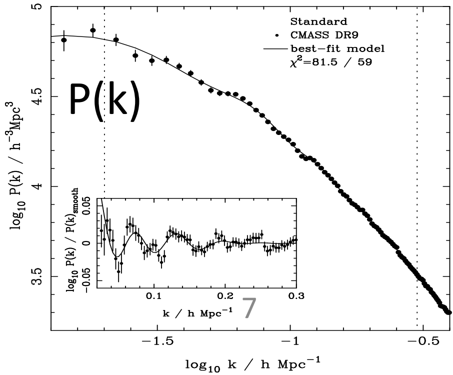

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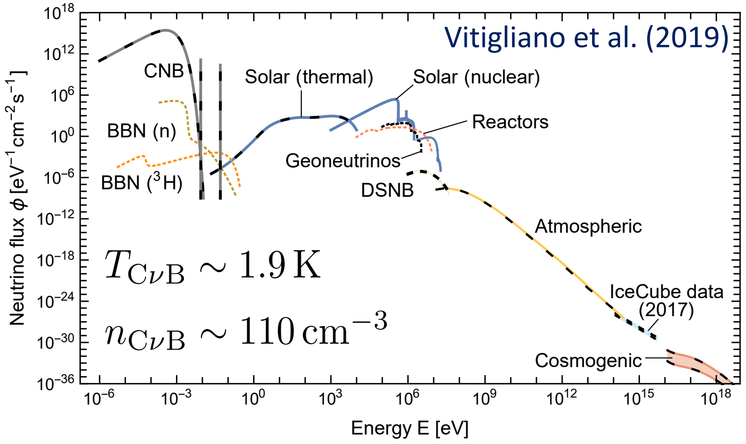

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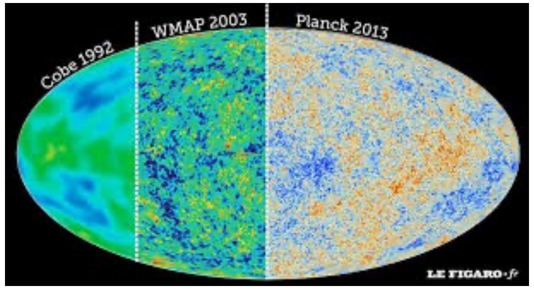
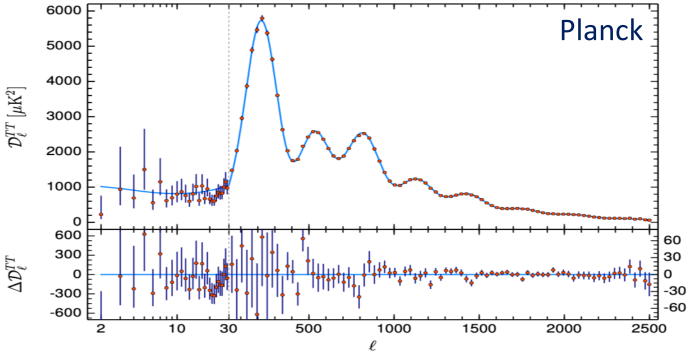
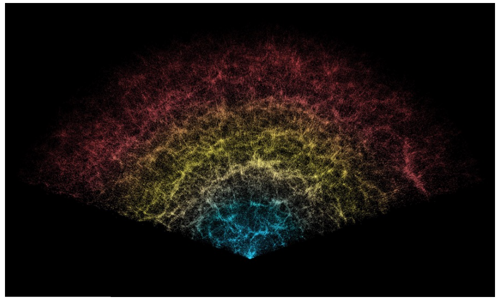
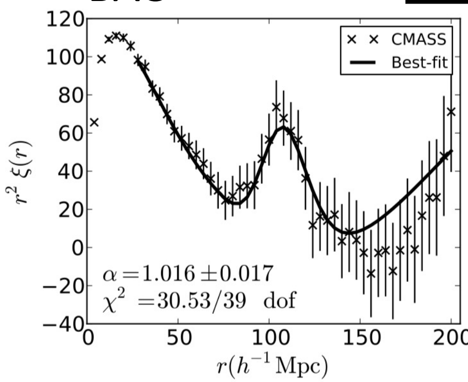
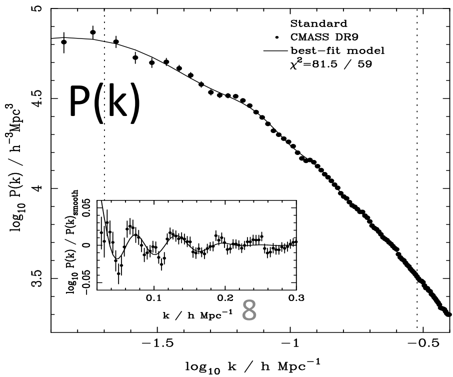




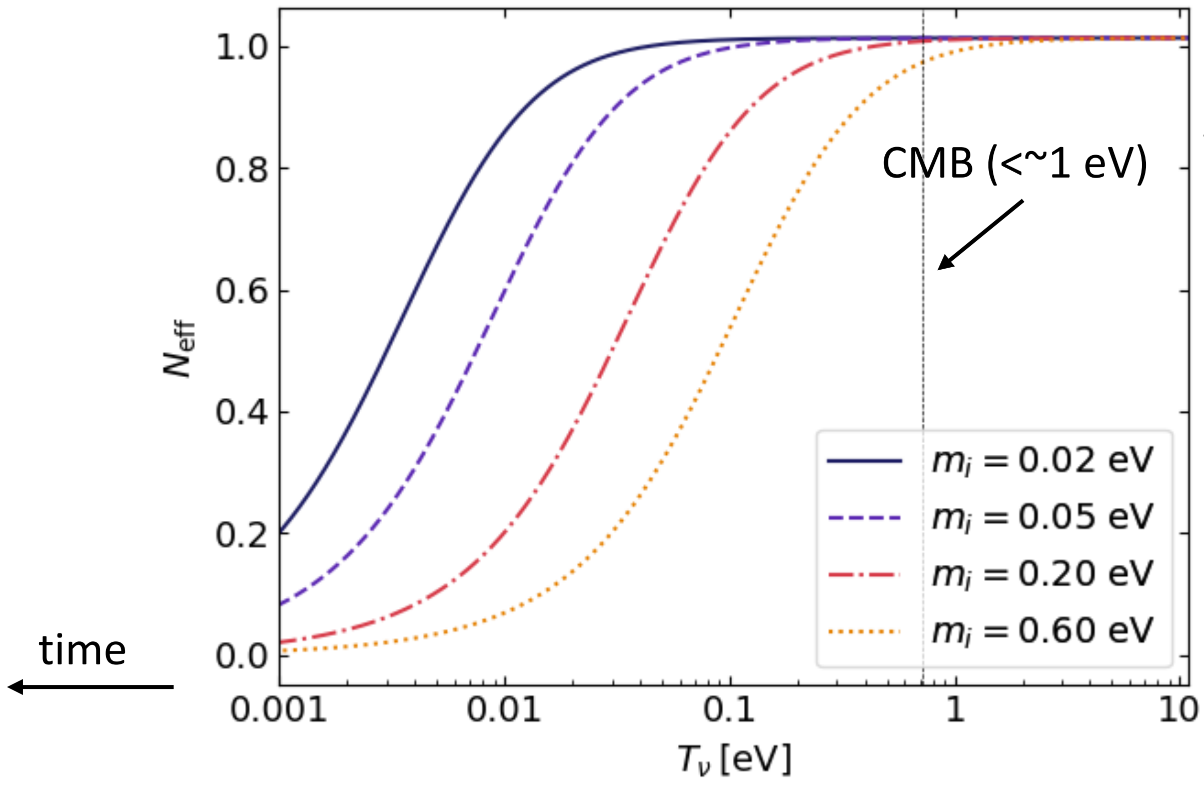


BAO





The duality of the CνB



Early times: neutrinos as **radiation**

$$\rho_{rad} = \rho_\gamma \left[1 + N_{\mathrm{eff}} \frac{7}{8} \left(\frac{4}{11}\right)^{4/3}\right]$$

$$N_{\mathrm{eff}} = \frac{\text{(energy density of neutrinos + BSM light particles)}}{\text{(energy density of one neutrino species)}}$$

For the 3 neutrino families of the SM: $N_{\mathrm{eff}}^{SM} = 3.044$

CMB + DESI BAO [DESI Collaboration: Adame et al. (2024)]

$N_{\mathrm{eff}} = 3.10 \pm 0.17$ (95% CL) -> thermalised sterile ν excluded

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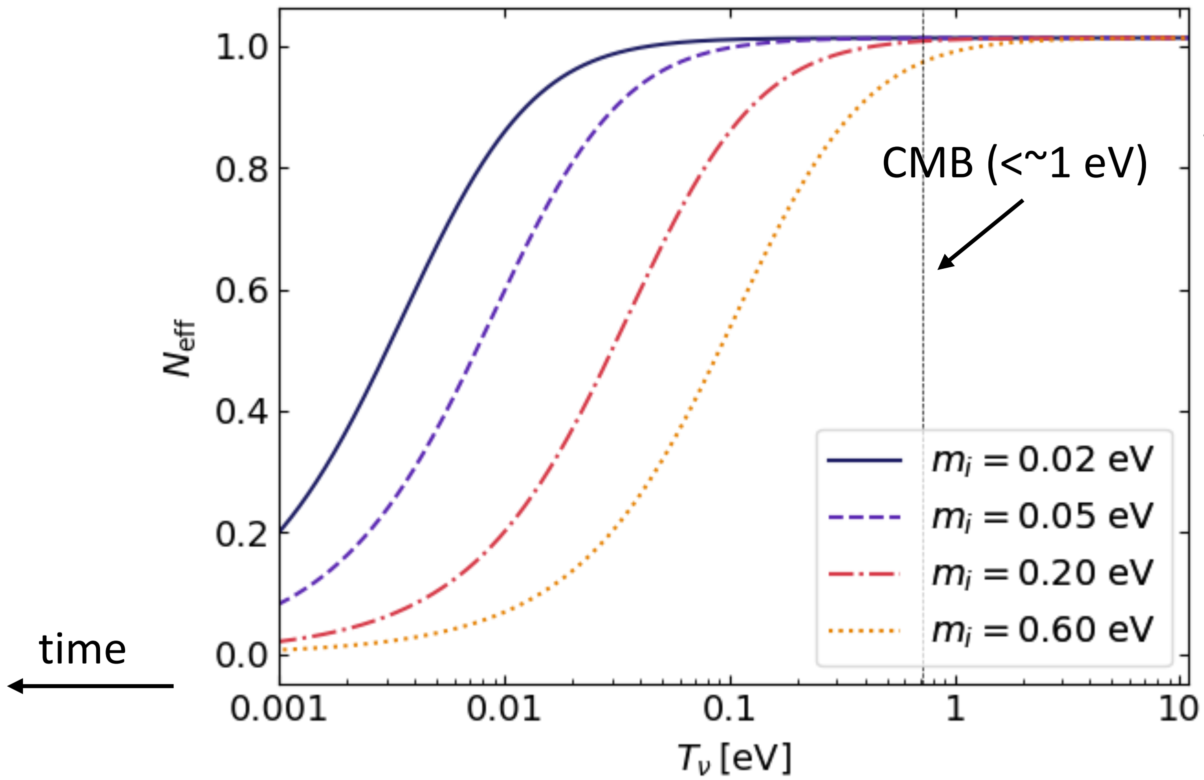

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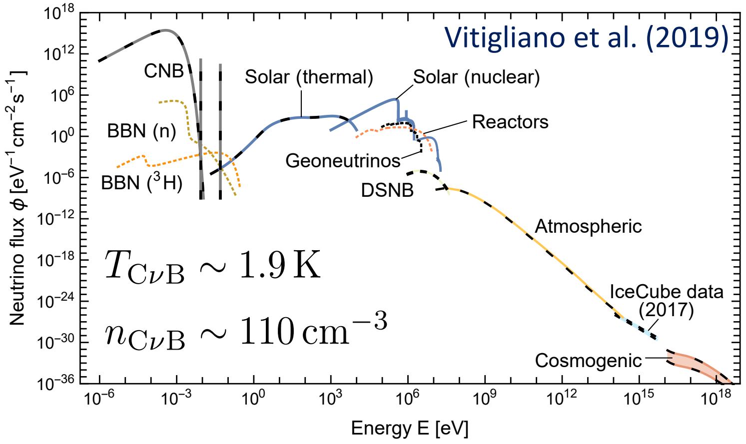
Late times (after CMB formation): neutrinos as **matter** (contributing to dark matter as hot dark matter)

- Hot dark matter energy density → Sum of neutrino mass $\Omega_\nu h^2 = \frac{\sum m_{\nu,i}}{93.12\text{eV}}$ [Mangano et al. (2005), Froustey et al. (2020)], but not individual masses [Archidiacono et al. (2020)].

Detecting the neutrino mass in the CνB

A short cosmic history

Cosmic Neutrino Background (T~1MeV)



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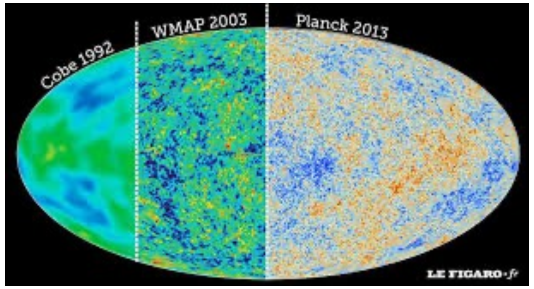
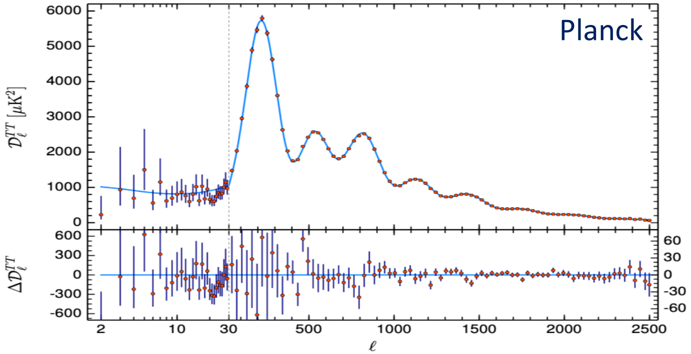
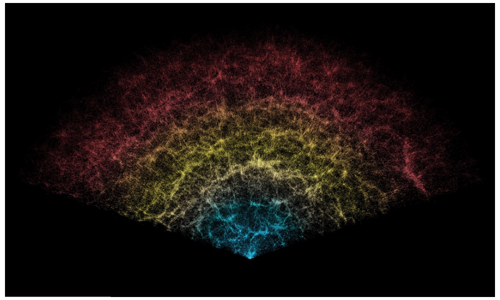




Structure formation (LSS)



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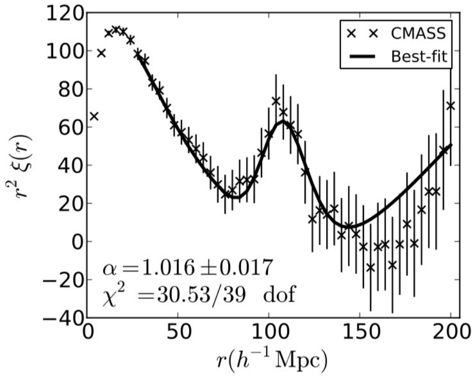
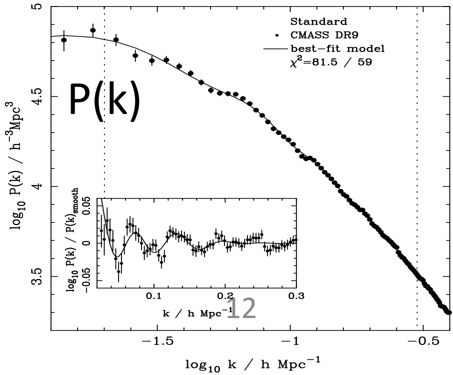
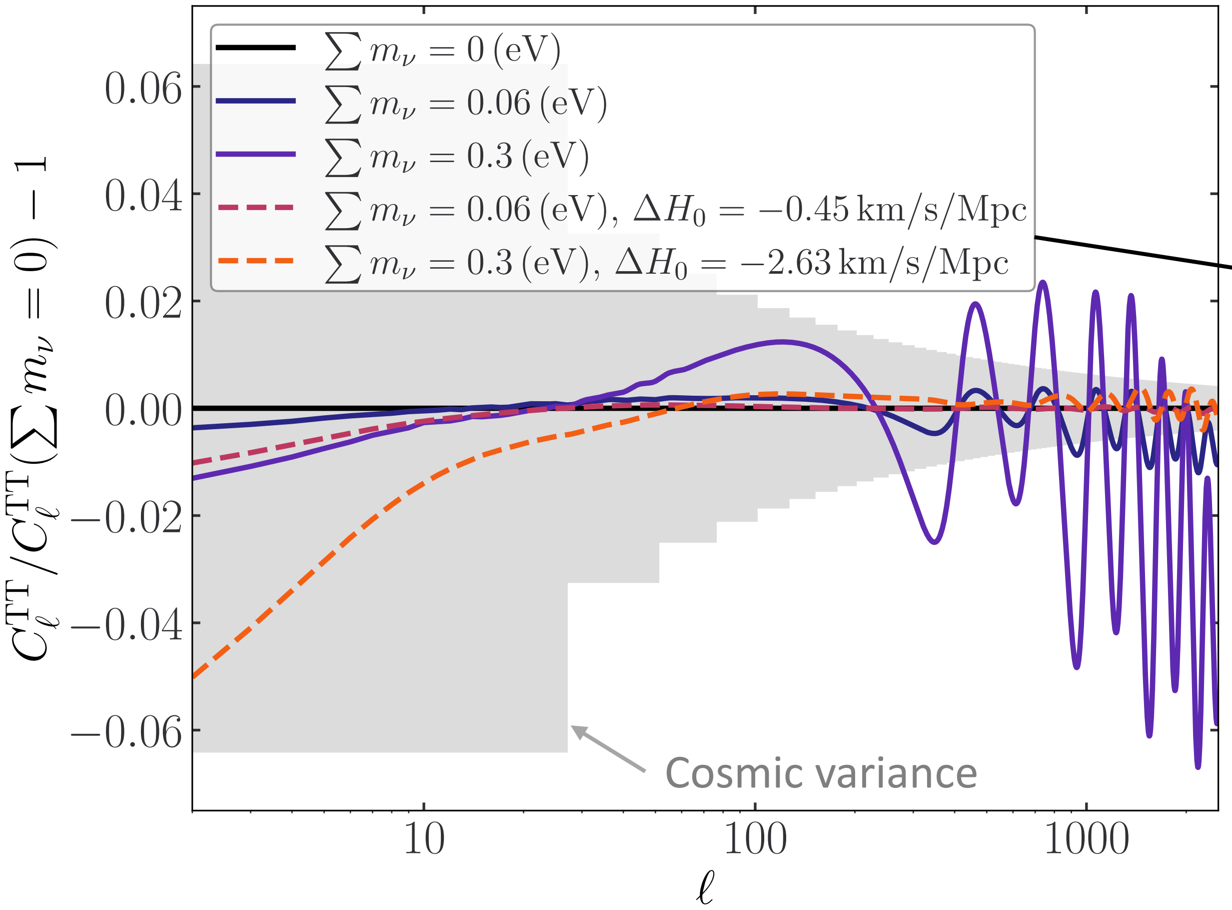


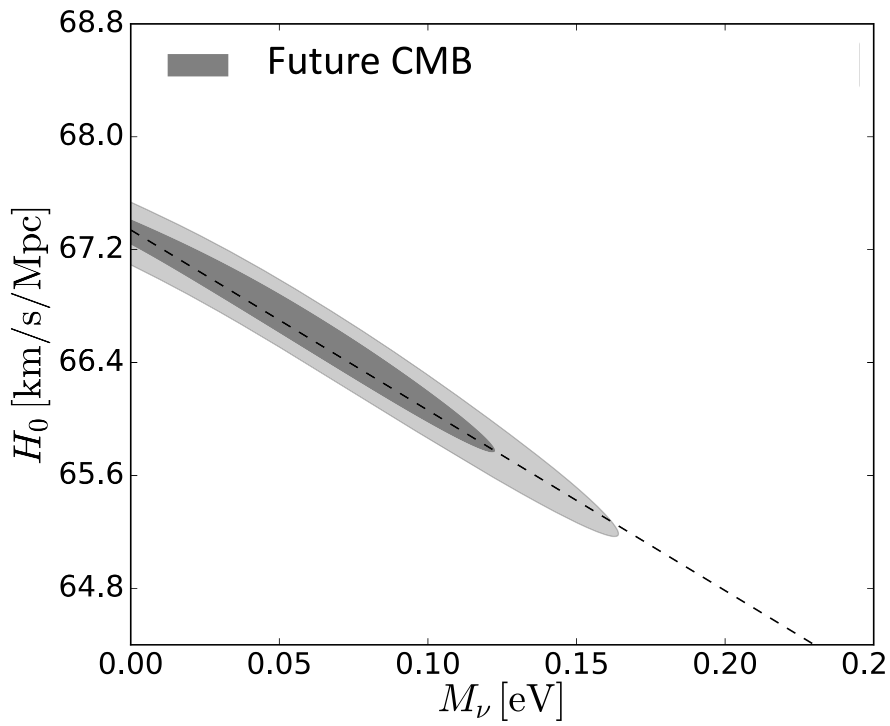


Neutrino mass probes: CMB



- Background effects
- Perturbation effects

Varying the Hubble constant H_0 compensates for the variation of the neutrino mass -> same observable within c.v.



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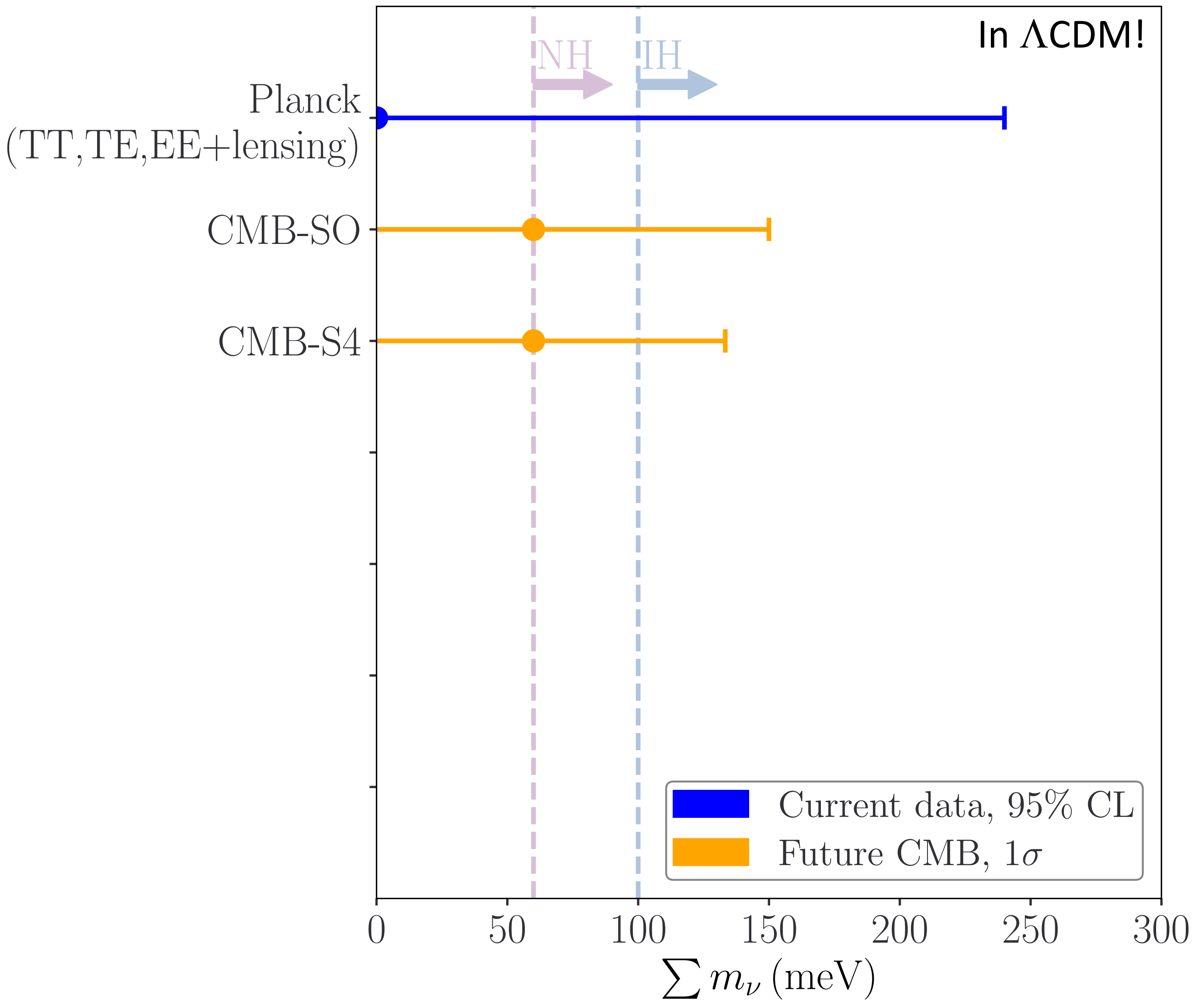

β-decay experiment KATRIN, current constraint:

Σm_ν <~ 1.5 eV

Fiducial value:

- Σm_ν = 58 meV

CMB alone will not be able to detect the neutrino mass

→ Large Scale Structures

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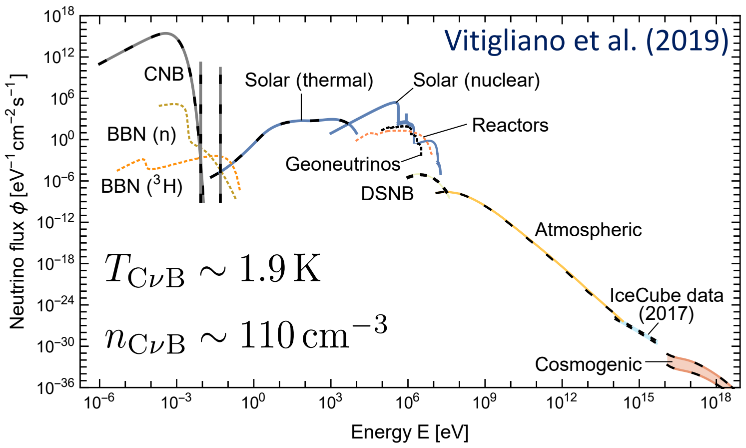

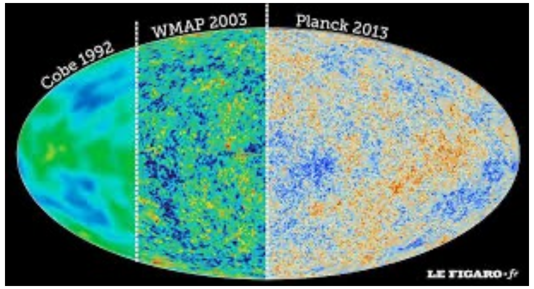

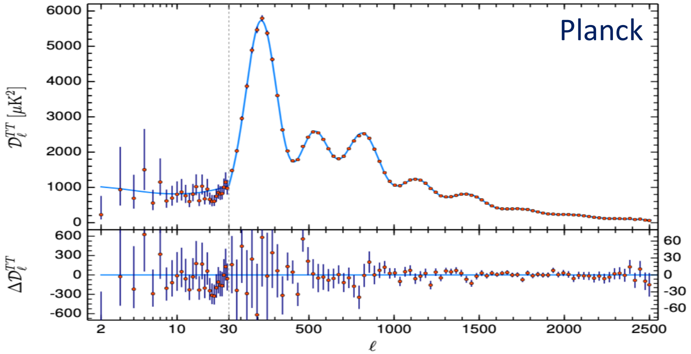

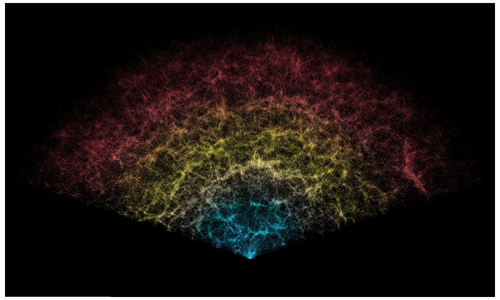

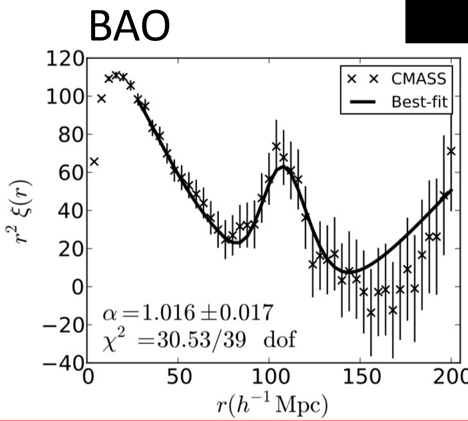

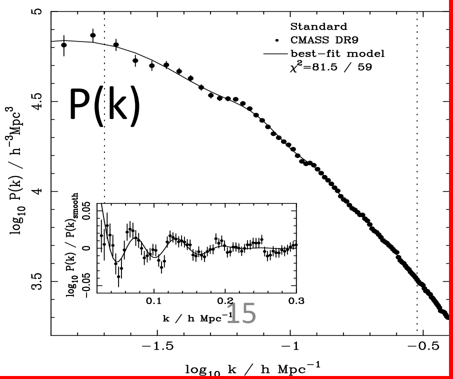

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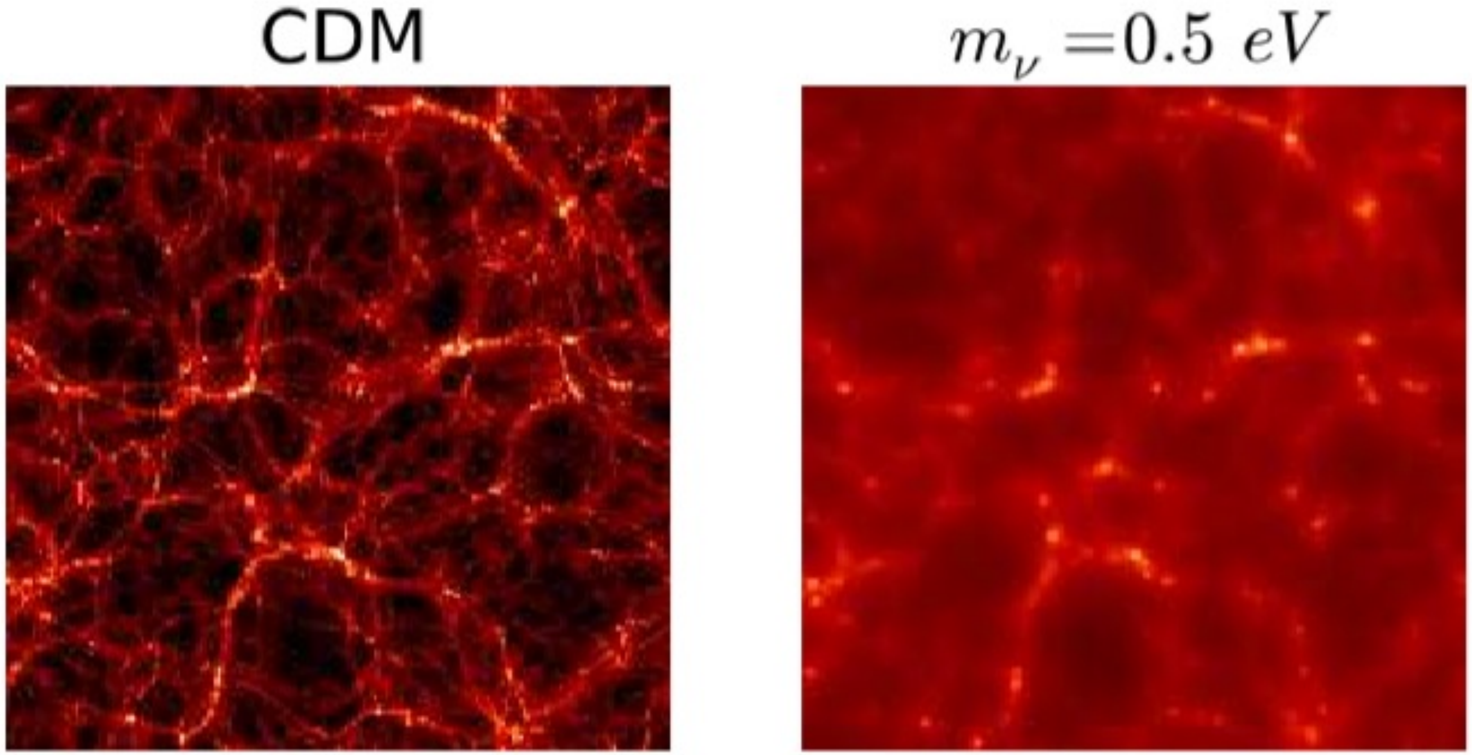
Neutrino mass probes: LSS

- Free-Streaming $d_{\mathrm{FS},i} \sim 1\,\mathrm{Gpc}\frac{eV}{m_{\nu,i}}$



Villaescusa Navarro et al. (2013)

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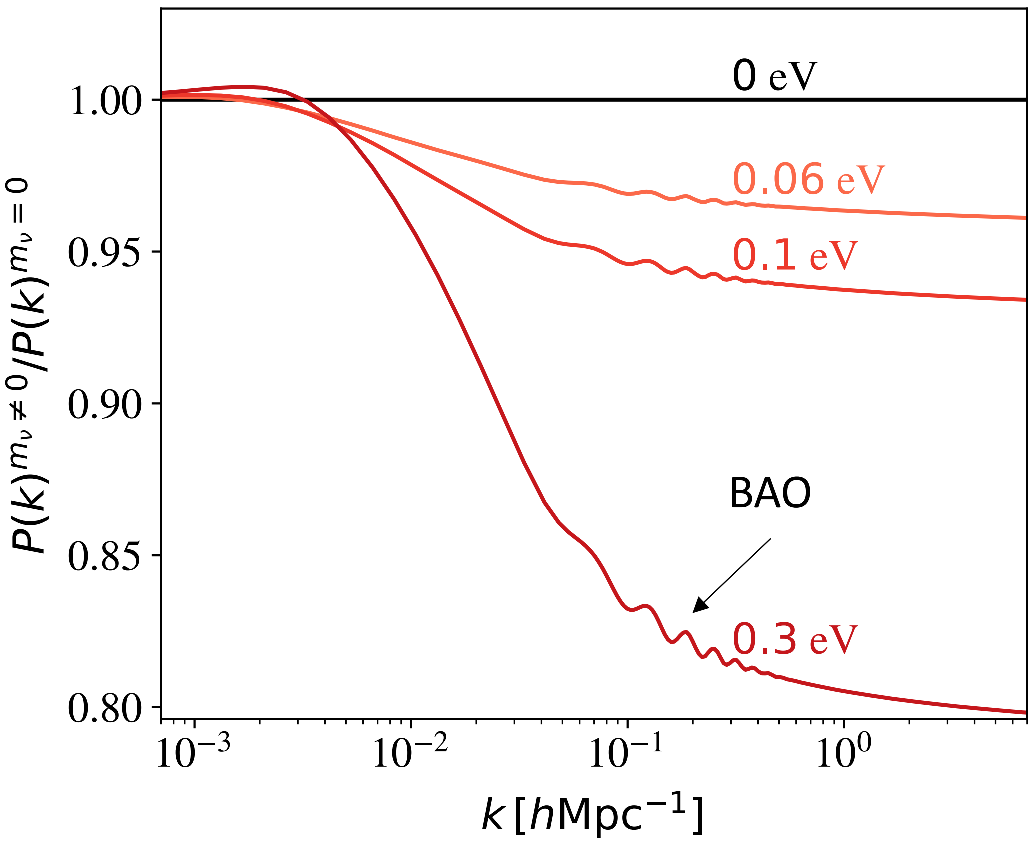

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- Massive neutrinos slow down the growth of CDM perturbations
  - Massless neutrino Universe $\delta_{\rm cdm}^{m_\nu=0} \propto a$
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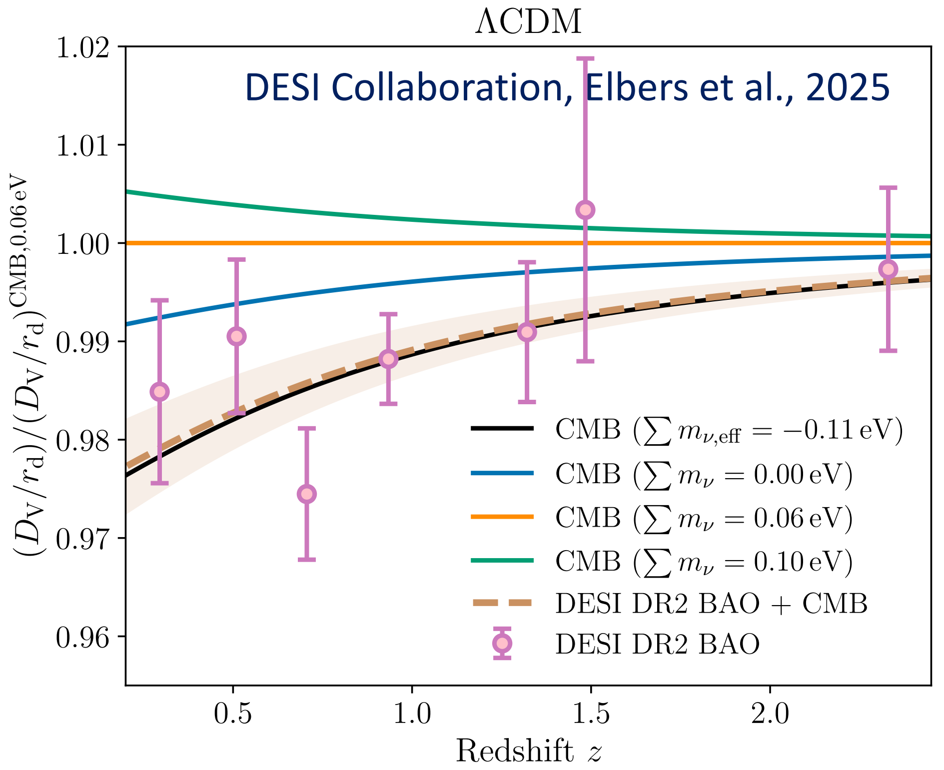

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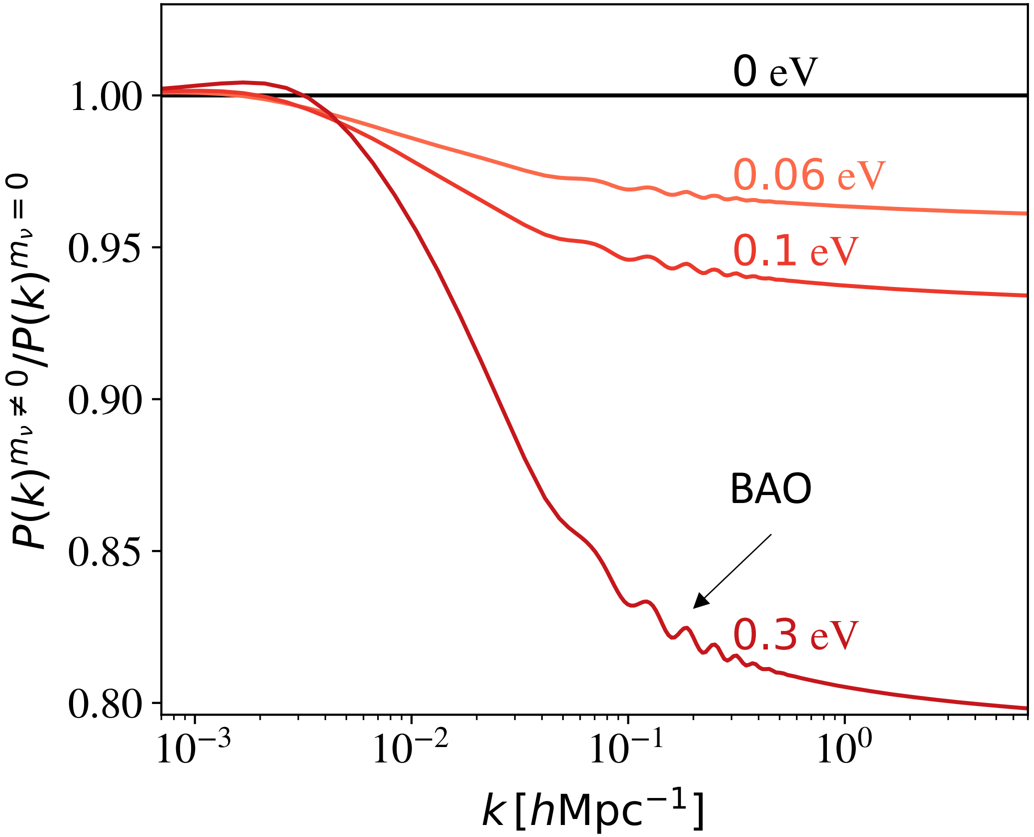

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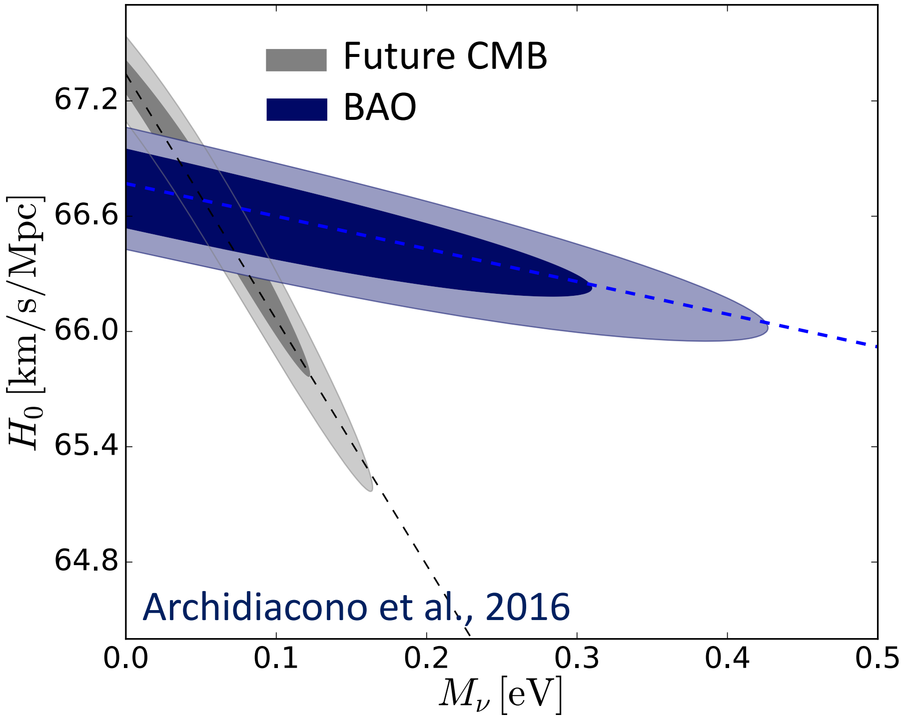
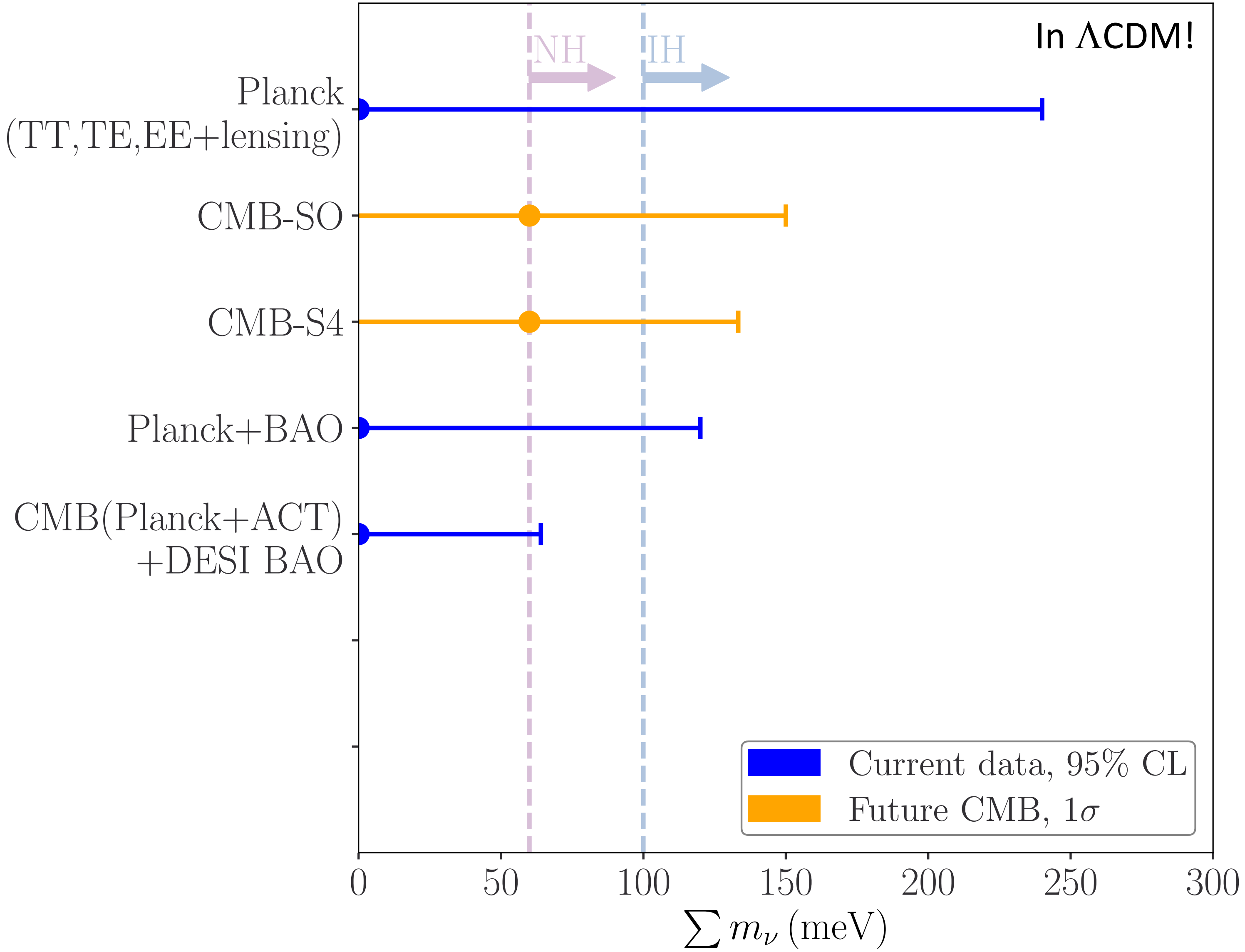
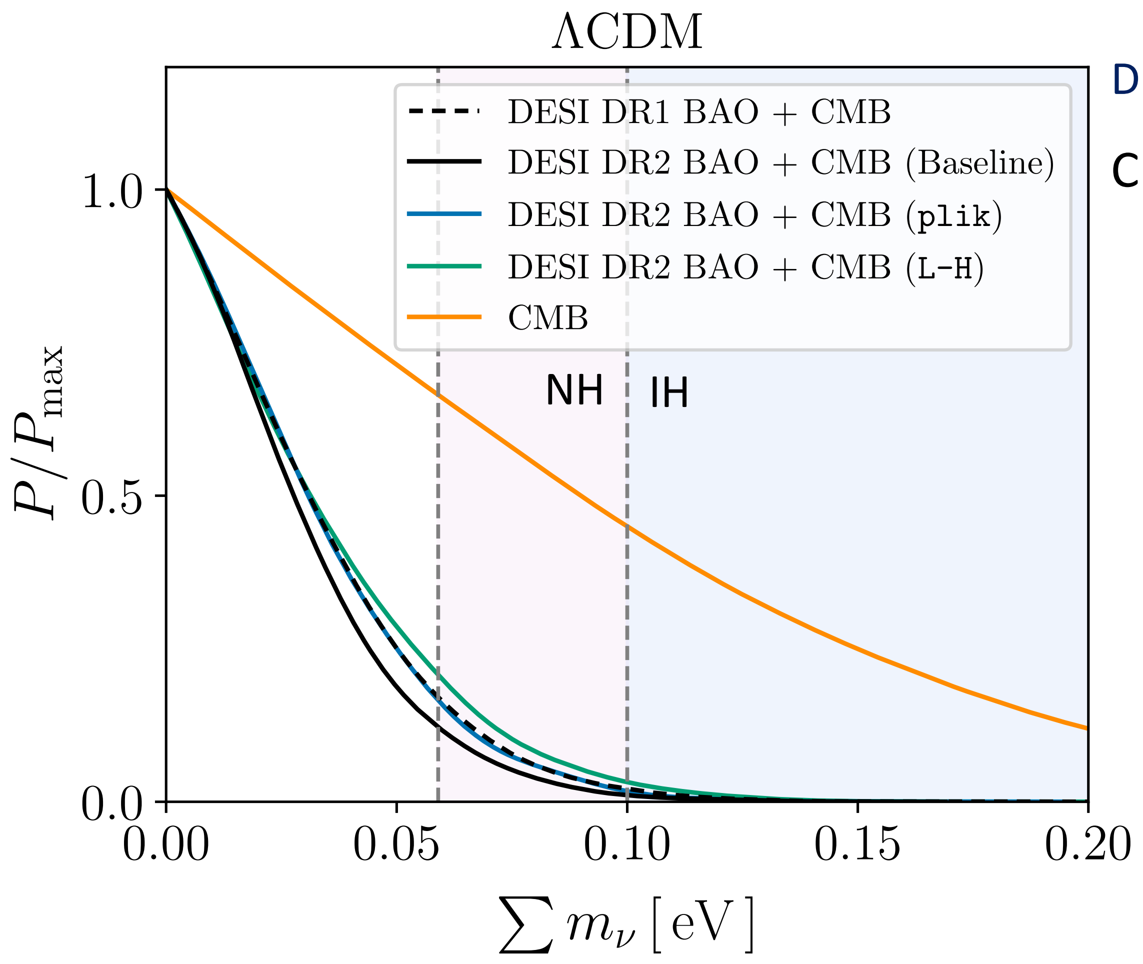


Neutrino mass constraints: CMB+LSS



Neutrino mass constraints: CMB+DESI



DESI Collaboration: Elbers et al. (2025)

CMB (Planck+ACT) + DESI BAO: Σm_ν < 64 meV, 95% CL

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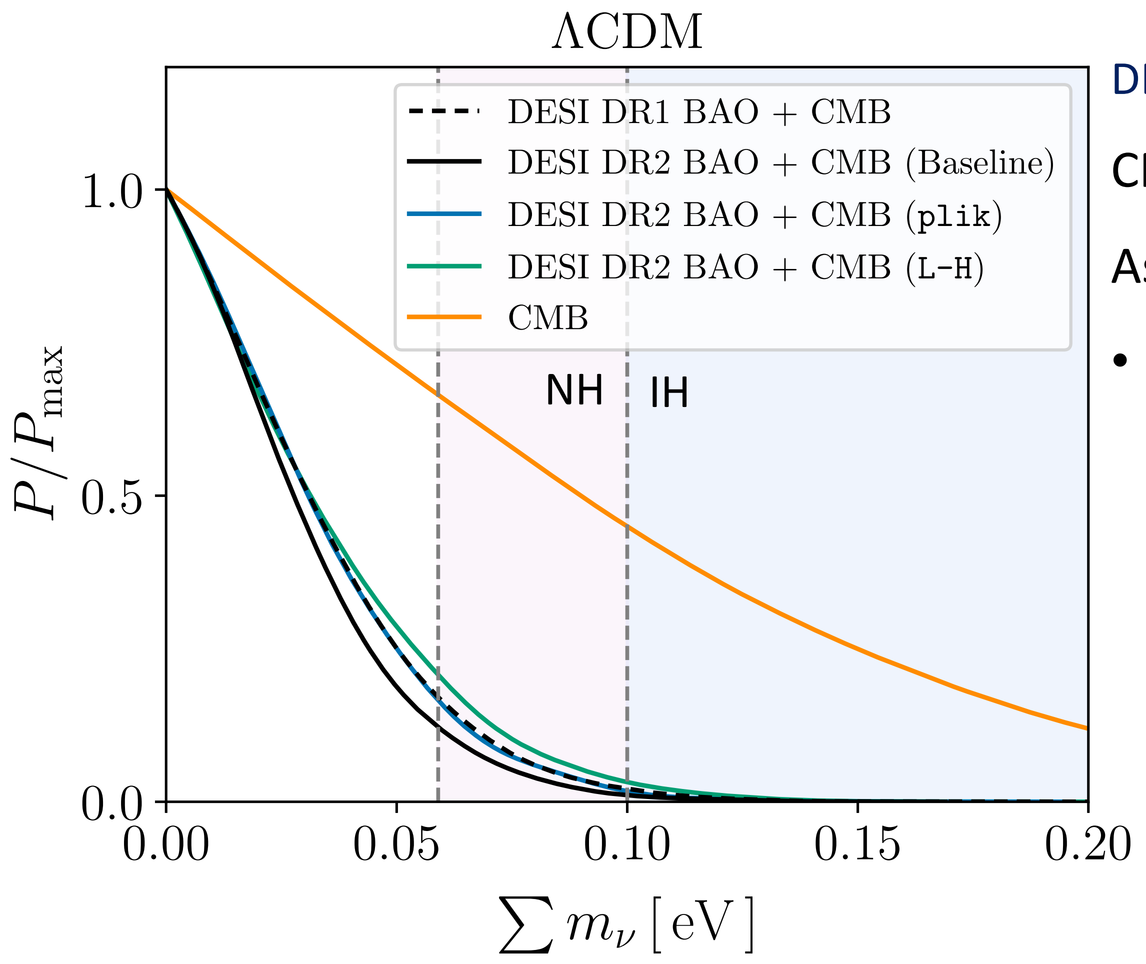

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Assumptions:

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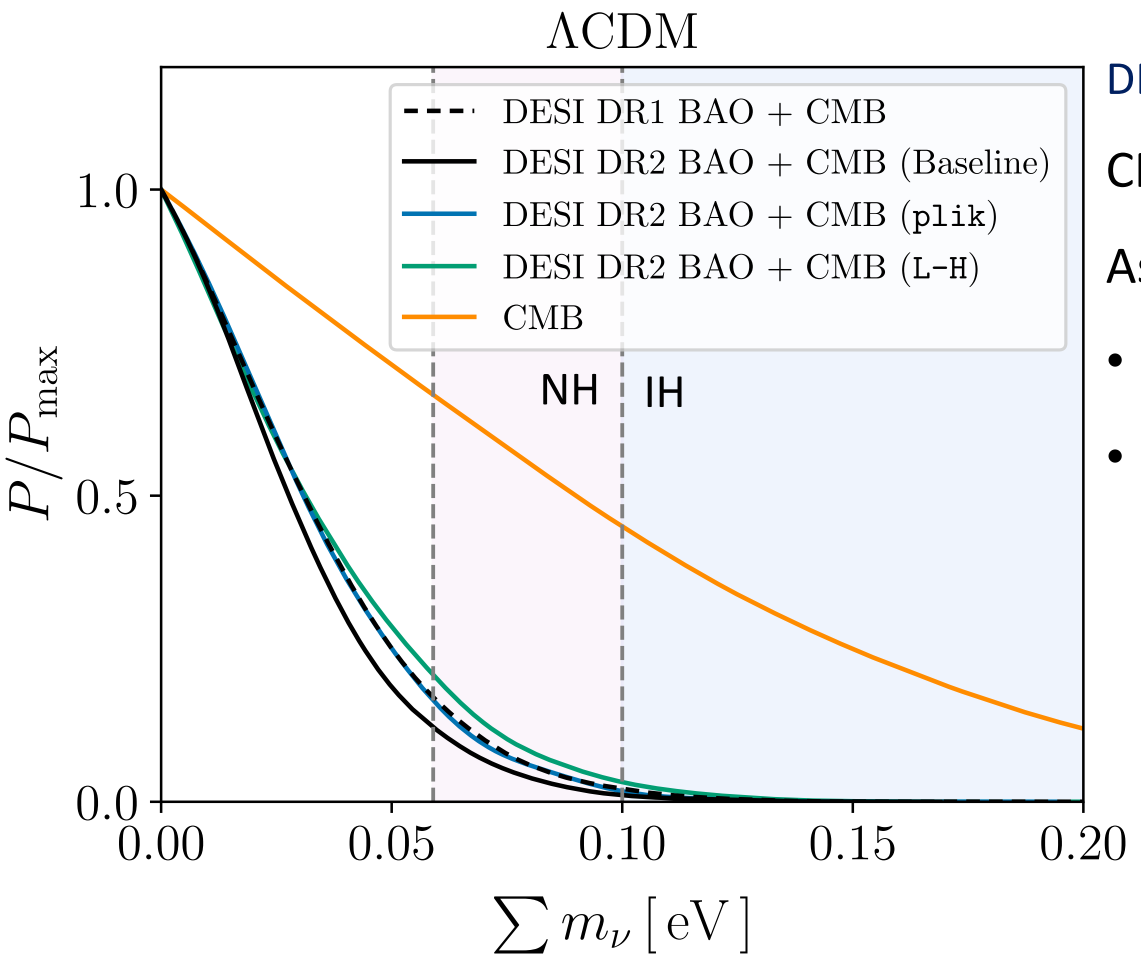

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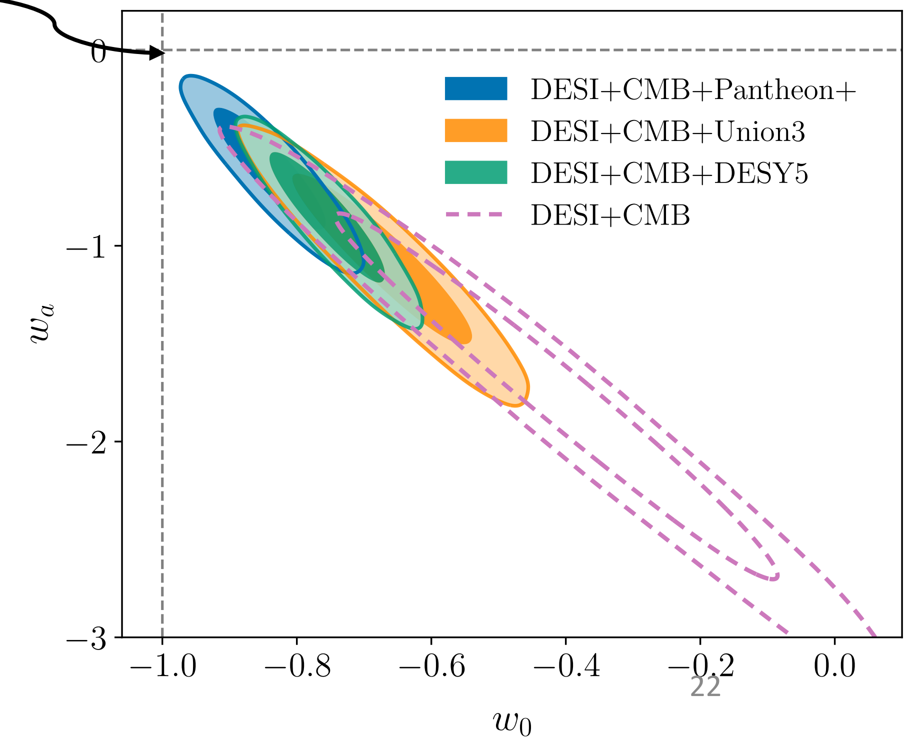

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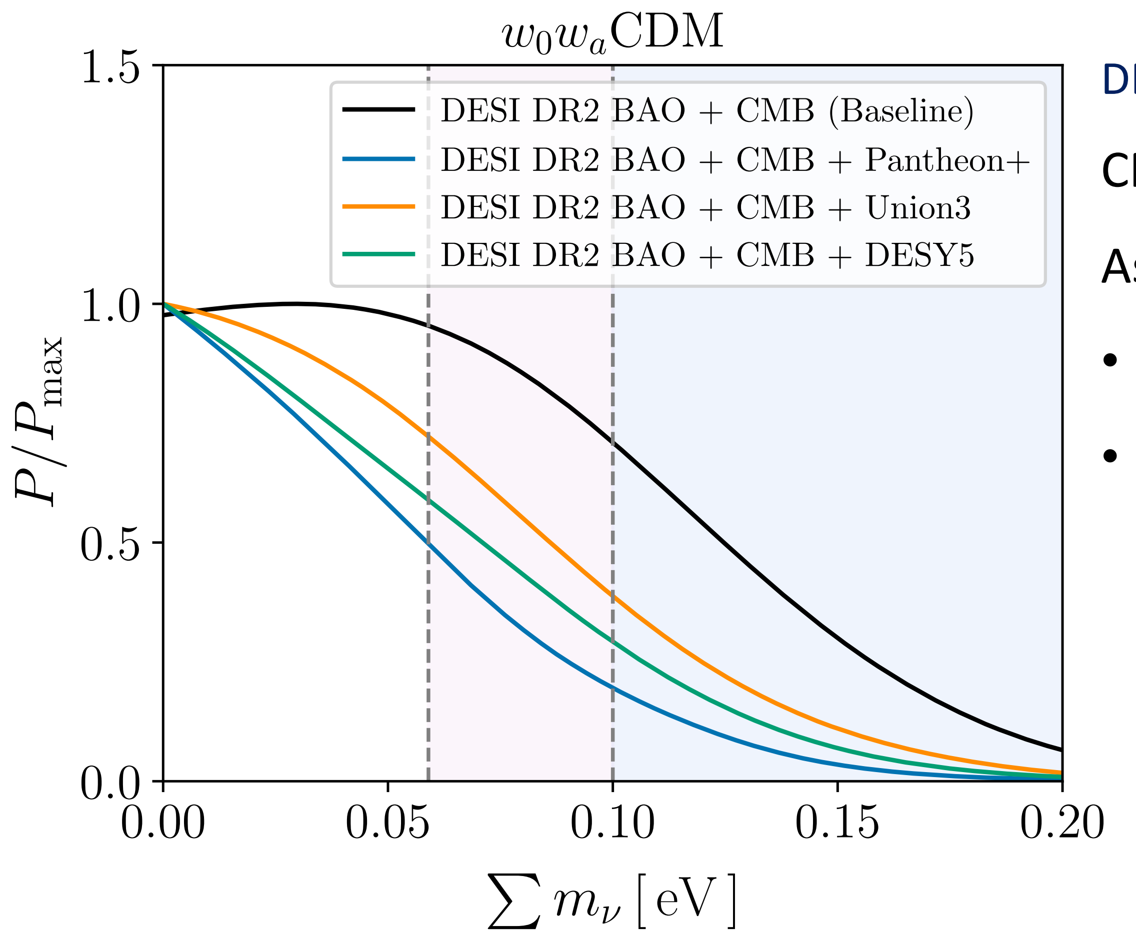

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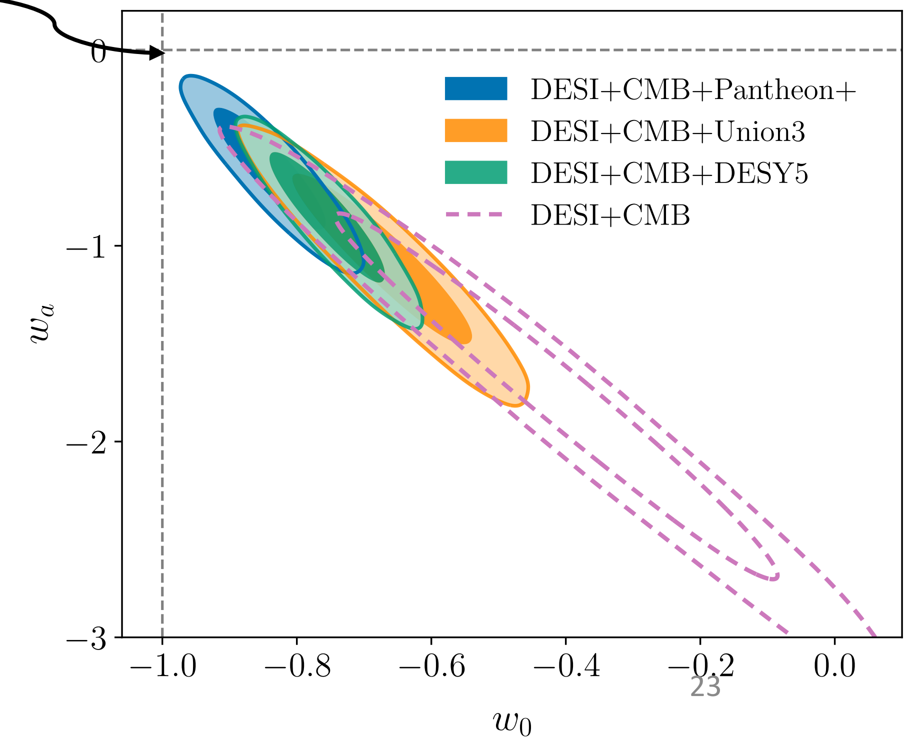
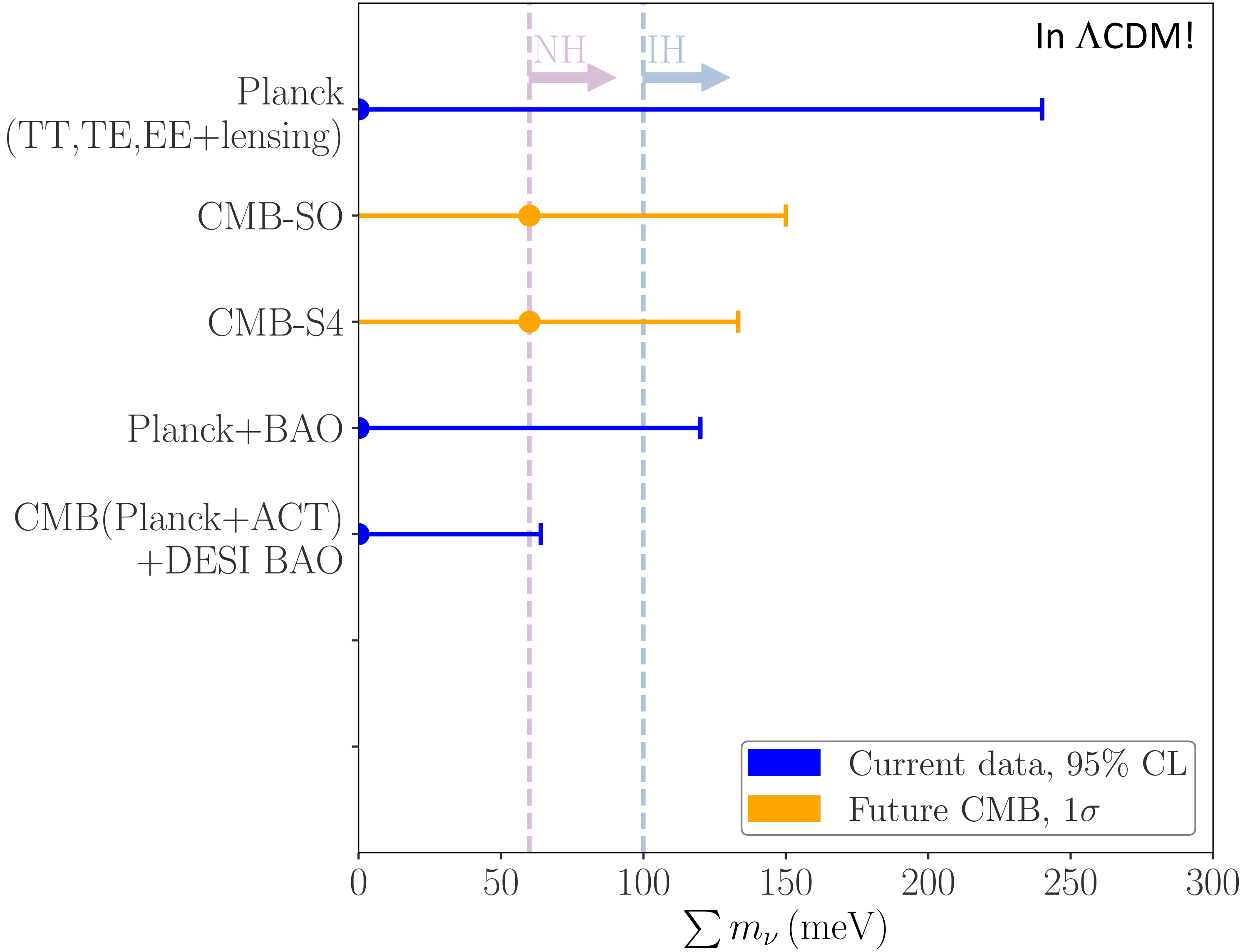


In w0waCDM (Prior: $\Sigma m_\nu > 0$):
CMB (Planck+ACT) + DESI BAO: Σm_ν < 0.16 eV, 95% CL

Neutrino mass constraints: CMB+LSS

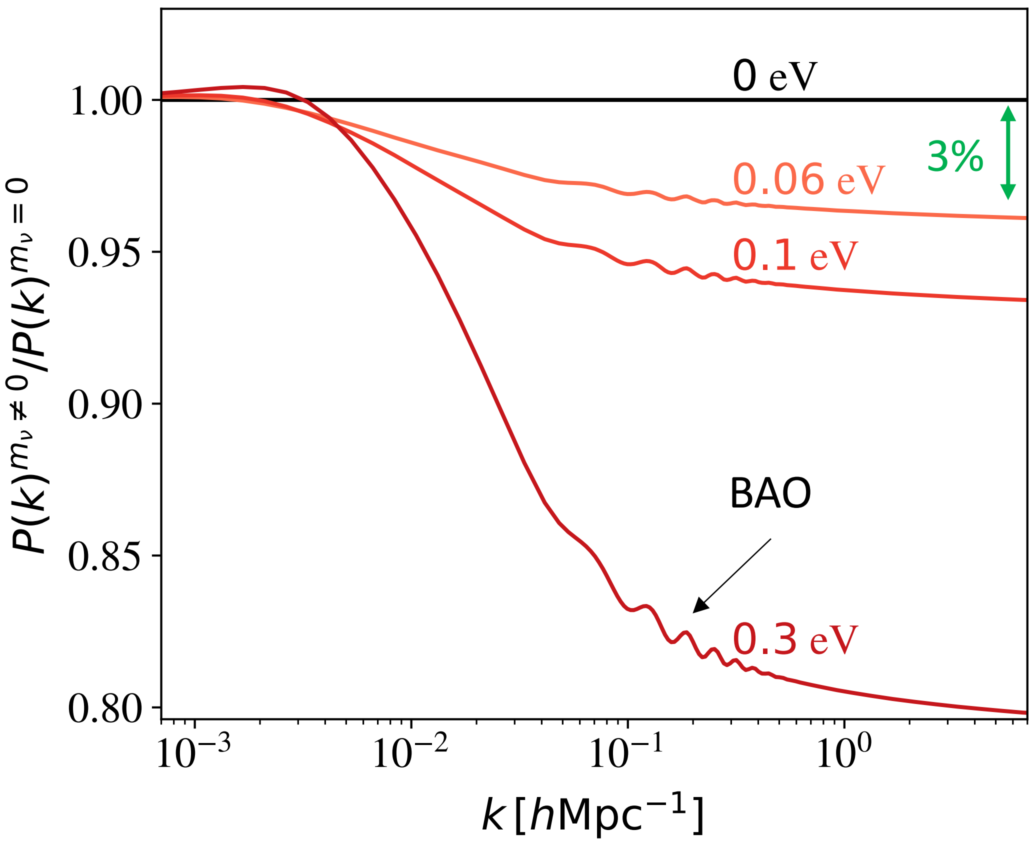


Still no evidence/detection!

Euclid in a nutshell

- **ESA** M2 space mission in the framework of the Cosmic Vision program
- Launch **July 1st 2023**. Duration **> 6 years**
- 1.2m telescope with two instruments: Visible Imager (**VIS**) and Near Infrared Spectrometer and Photometer (**NISP**)
- Wide survey (**14.000 deg^2**) and deep survey (40 deg^2 in 3 different fields)
- Measurements of over **1 billion images** and more than **20 millions spectra** of galaxies out to z>2
- Main scientific objectives: **Dark Energy**, **Dark Matter**, and **General Relativity**
- Primary probes: **Galaxy Clustering** and **Weak Lensing** (1% accuracy)

Neutrino mass probes: LSS



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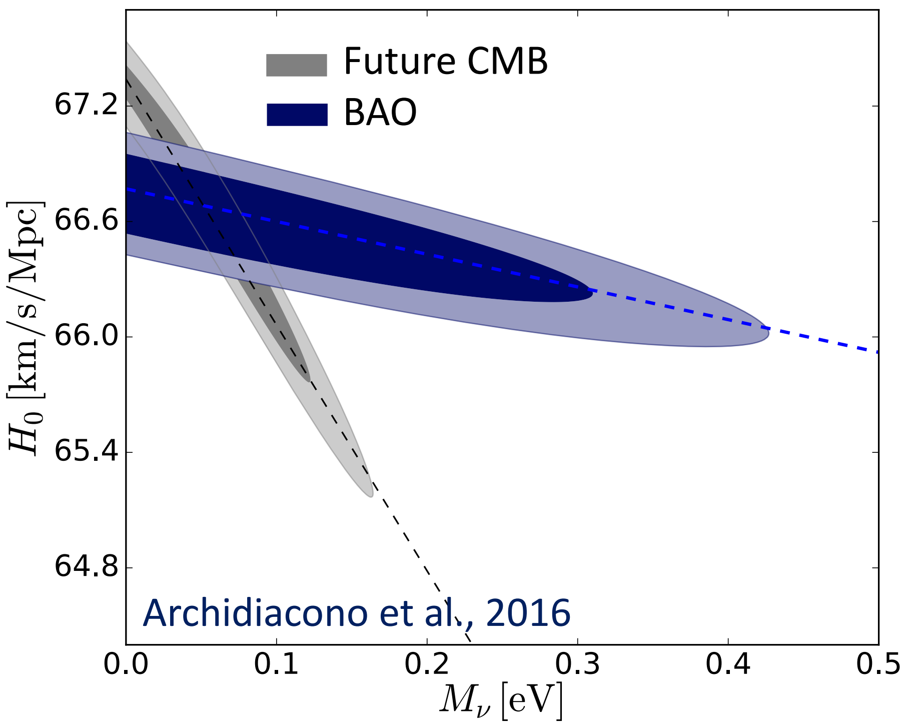

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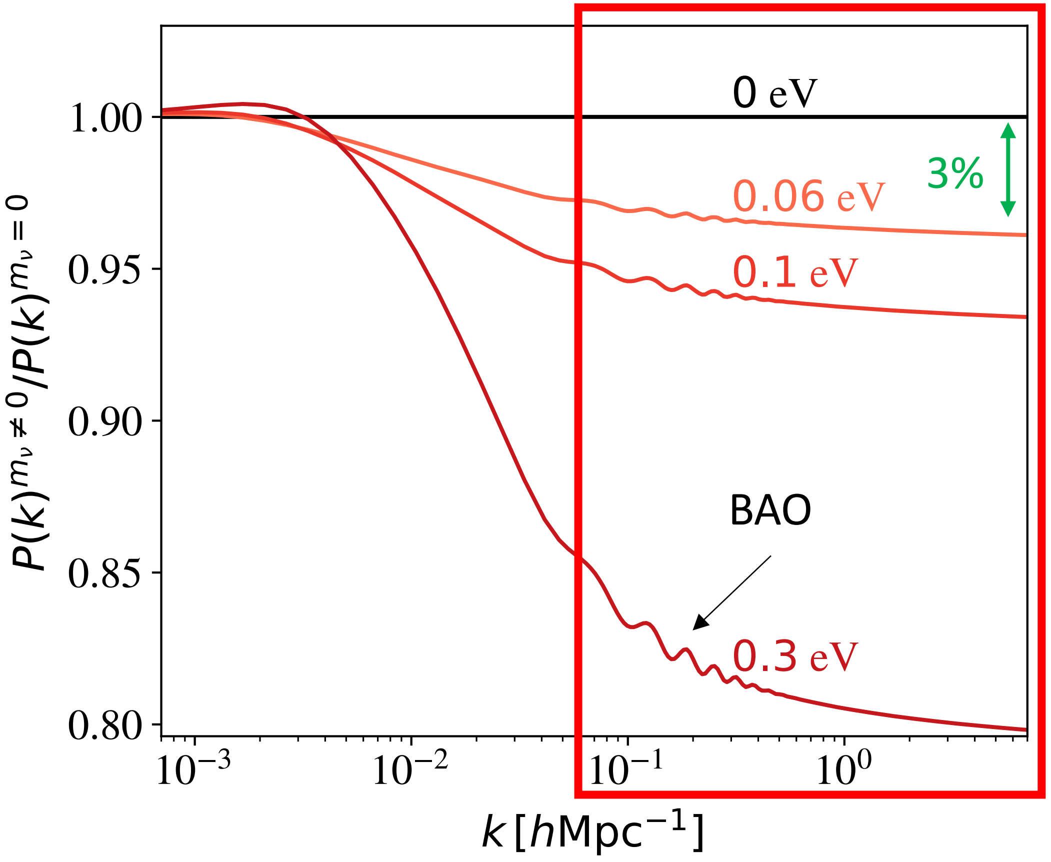

The precision of the theoretical model does not match the accuracy of the observational data.

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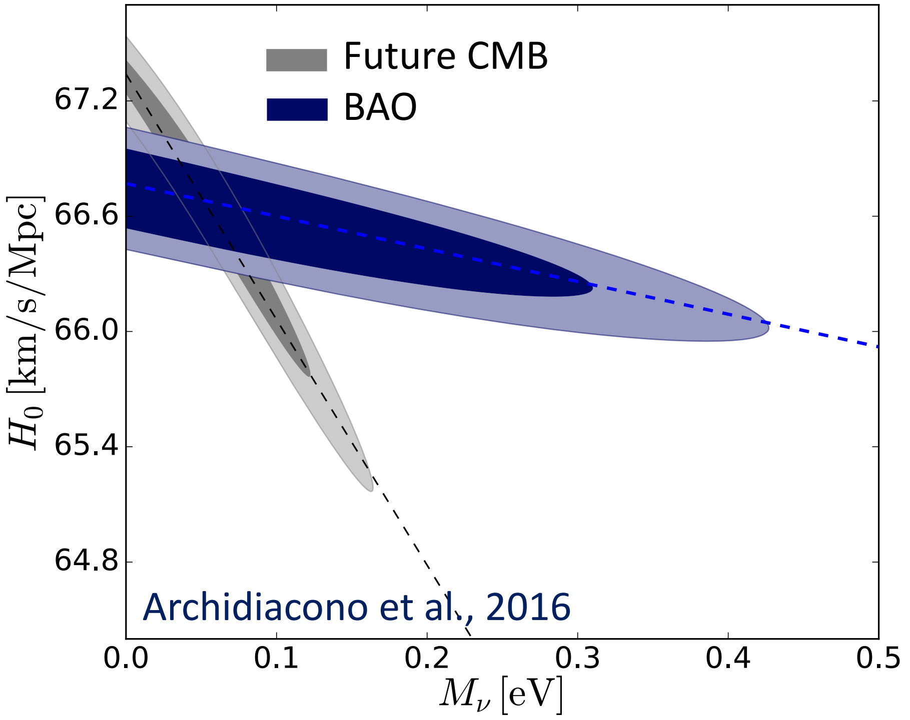
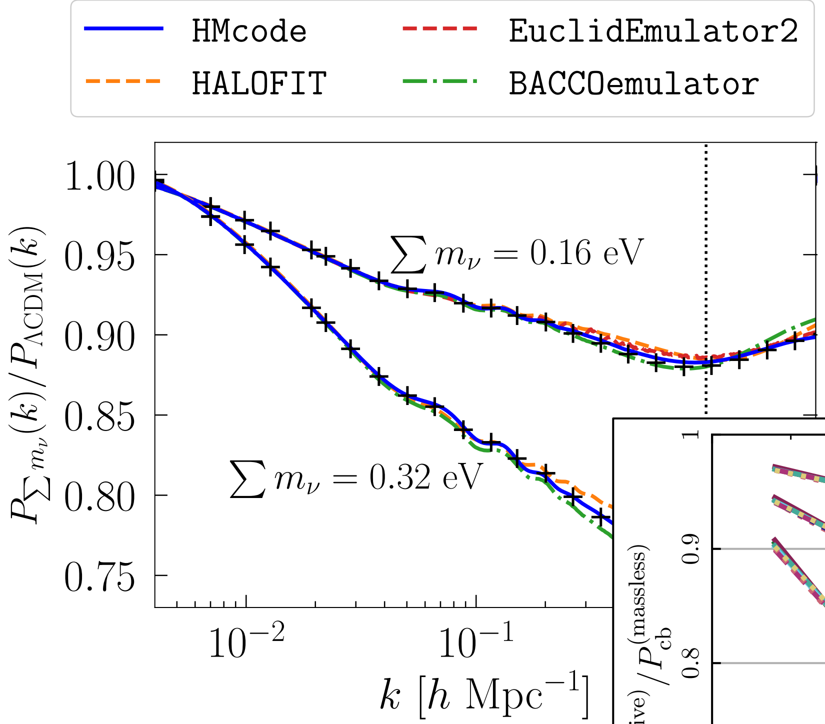
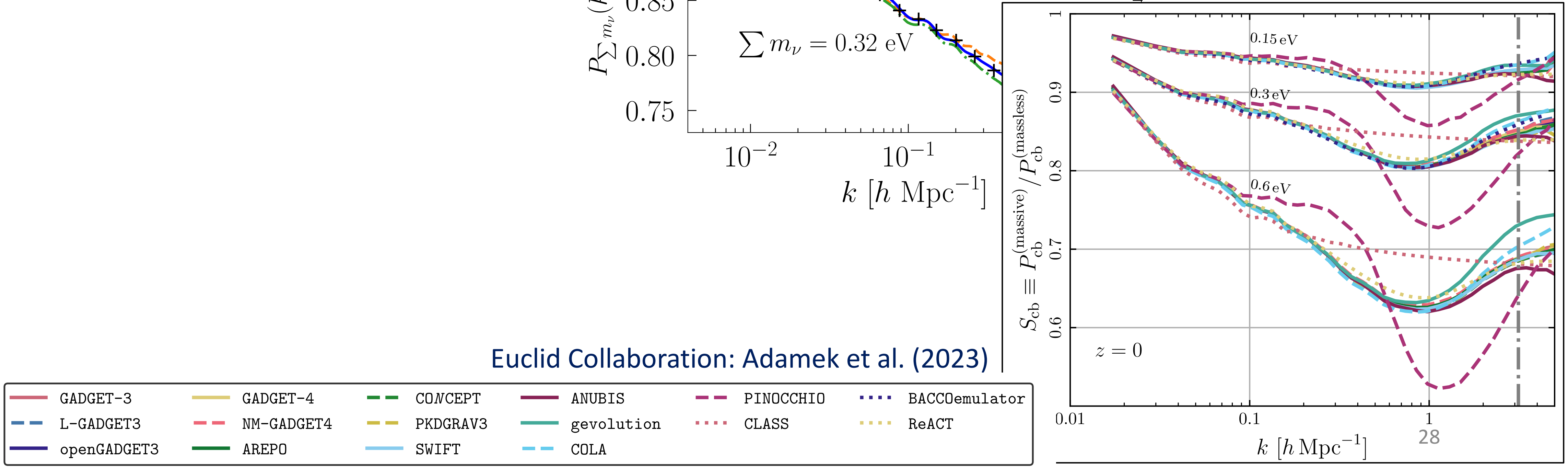


Known unknowns (systematics, etc.)

1. Non-linearities [Euclid Collaboration: Martinelli et al. (2020), Euclid Collaboration: Adamek et al. (2023)]

Euclid Collaboration: Archidiacono et al. (2024)





Euclid Collaboration: Adamek et al. (2023)

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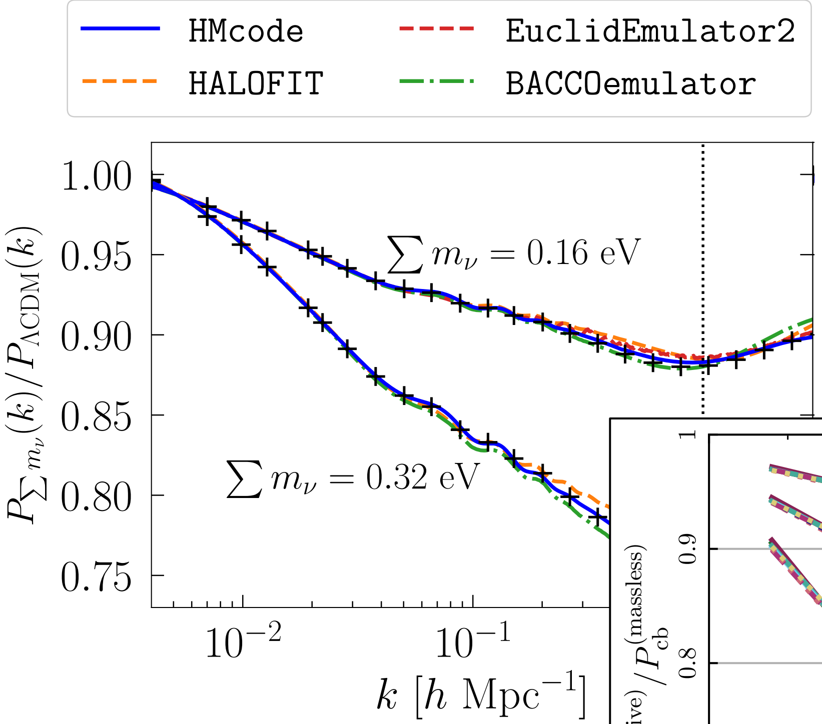
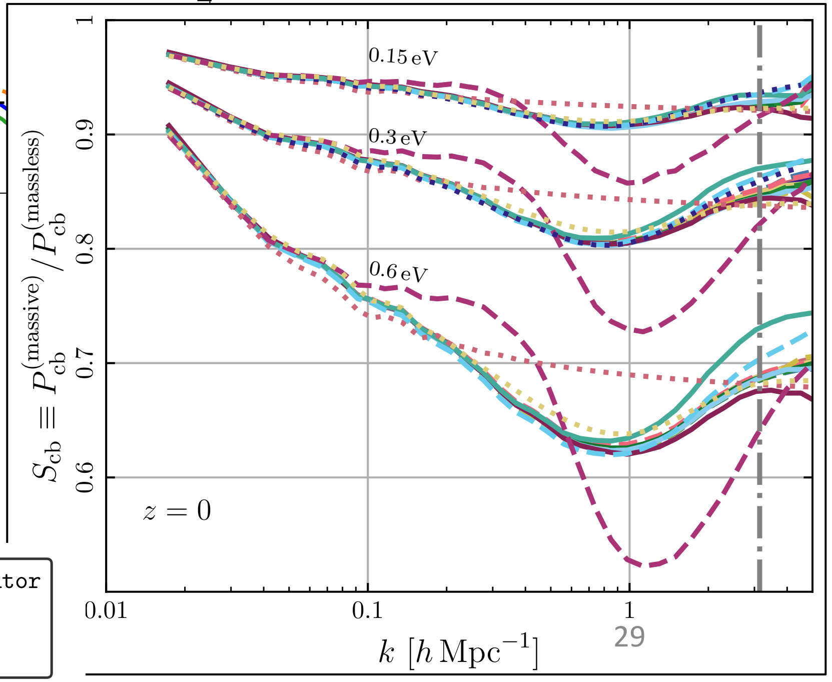
2. Galaxy bias $P_{galaxy} = b^2 P_{cdm}$ [Castorina et al. (2014); Vagnozzi et al. (2018)]

3. Baryonic feedback [Chisari (2019); Euclid Collaboration: Martinelli et al. (2020); Spurio Mancini et al. (2023)]

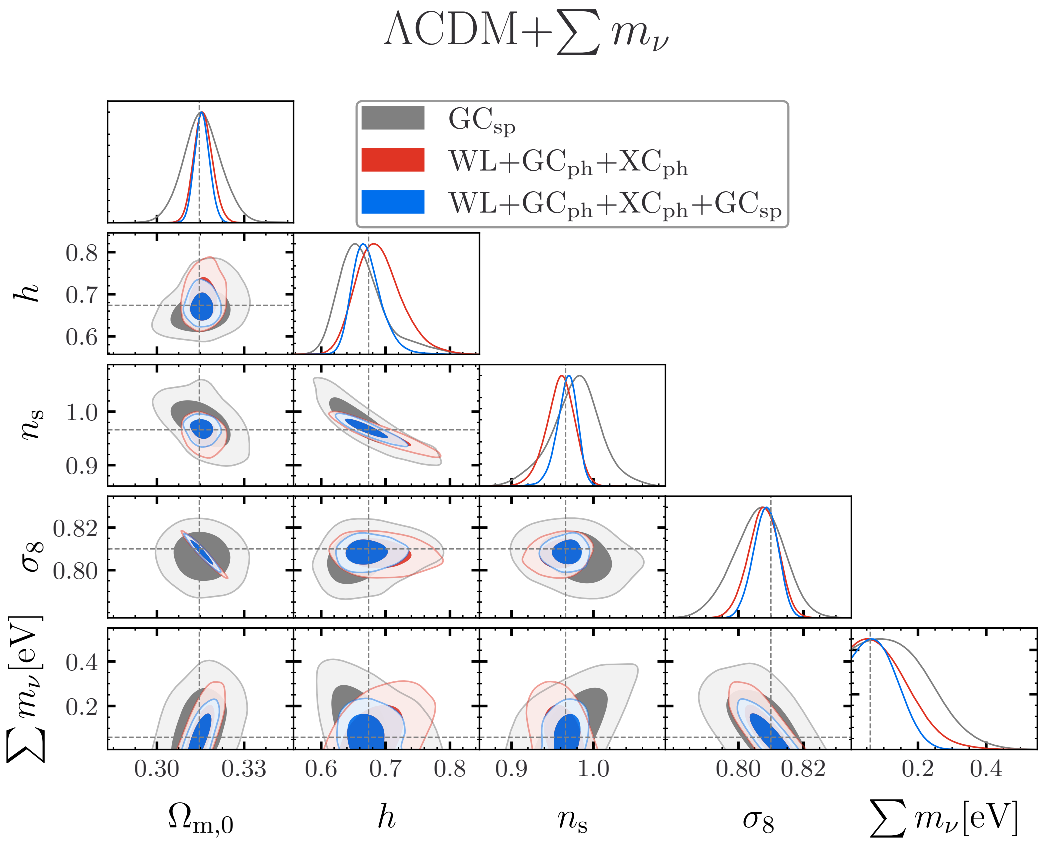
Euclid Collaboration: Archidiacono et al. (2024)

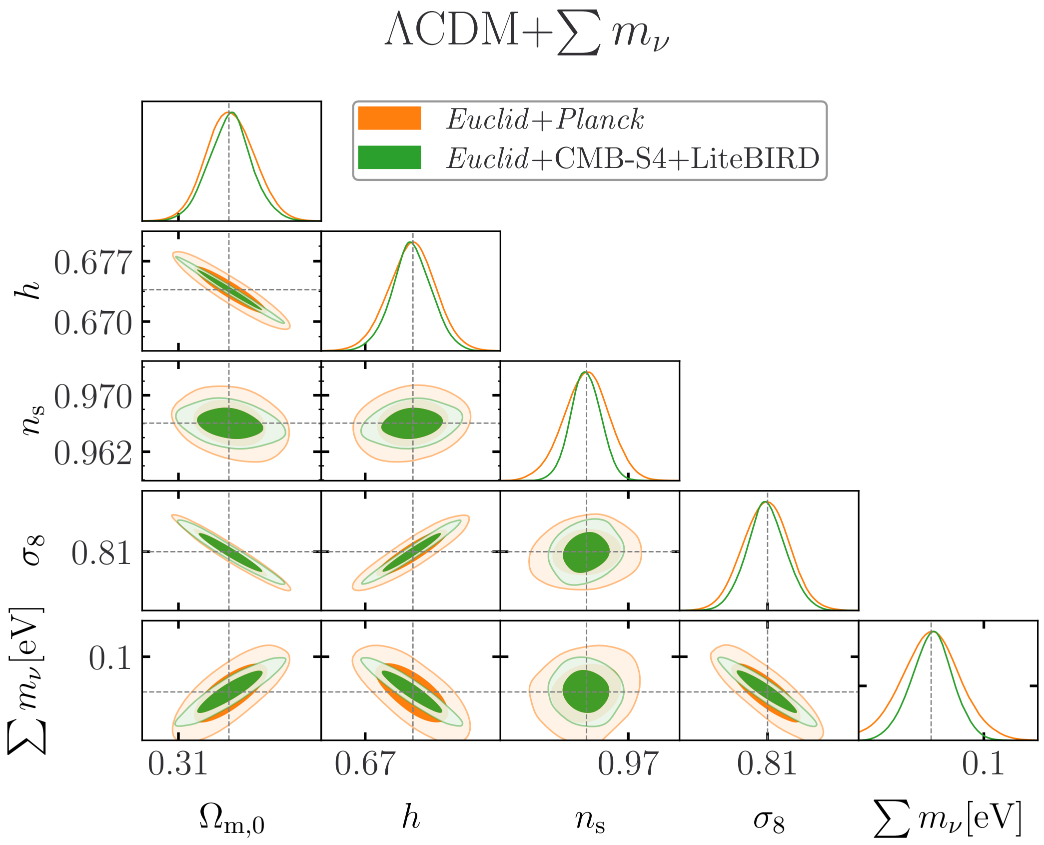




Euclid Collaboration: Adamek et al. (2023)

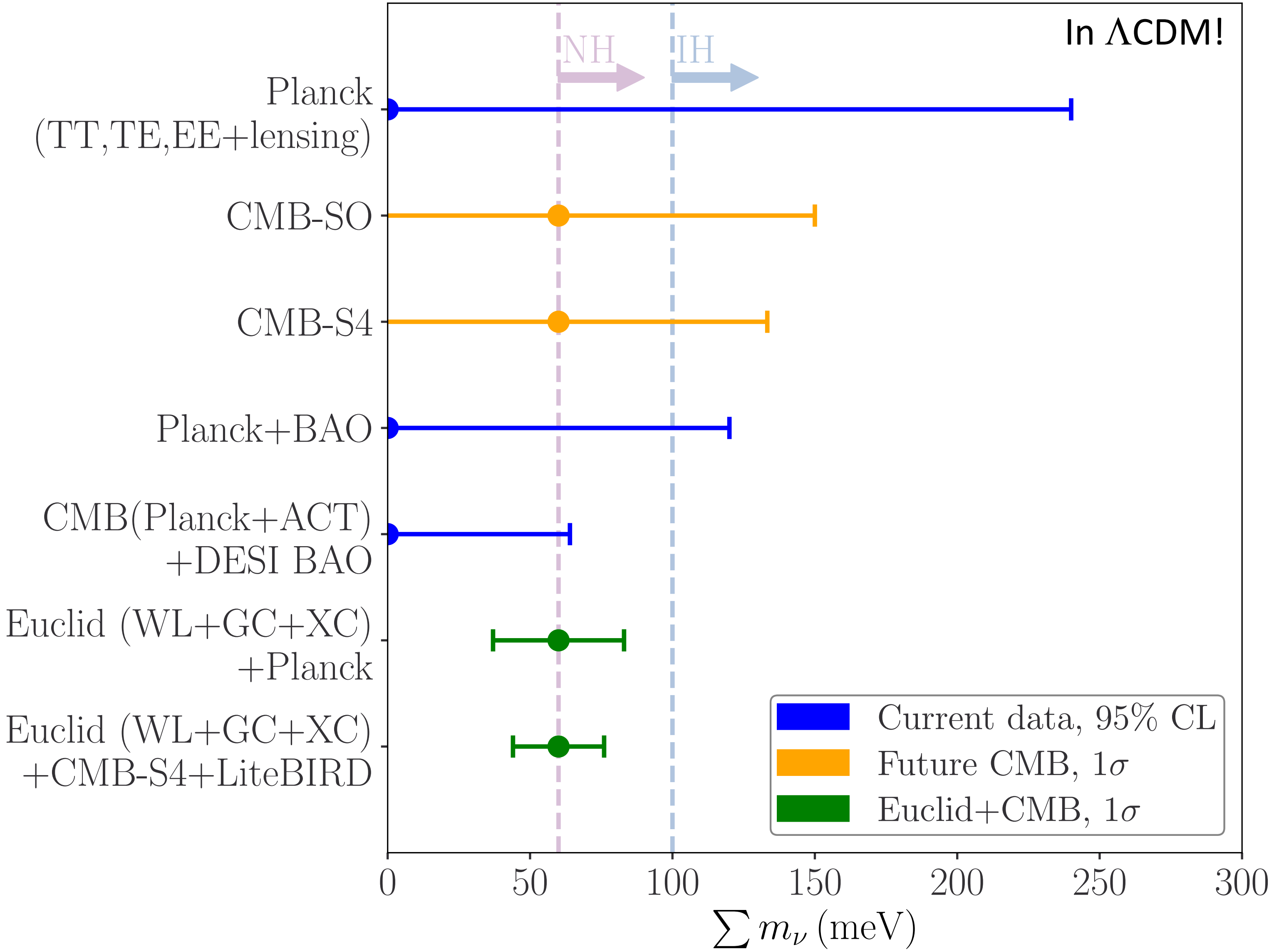
Neutrino mass constraints: the future





Euclid Collaboration: Archidiacono et al. (2024)

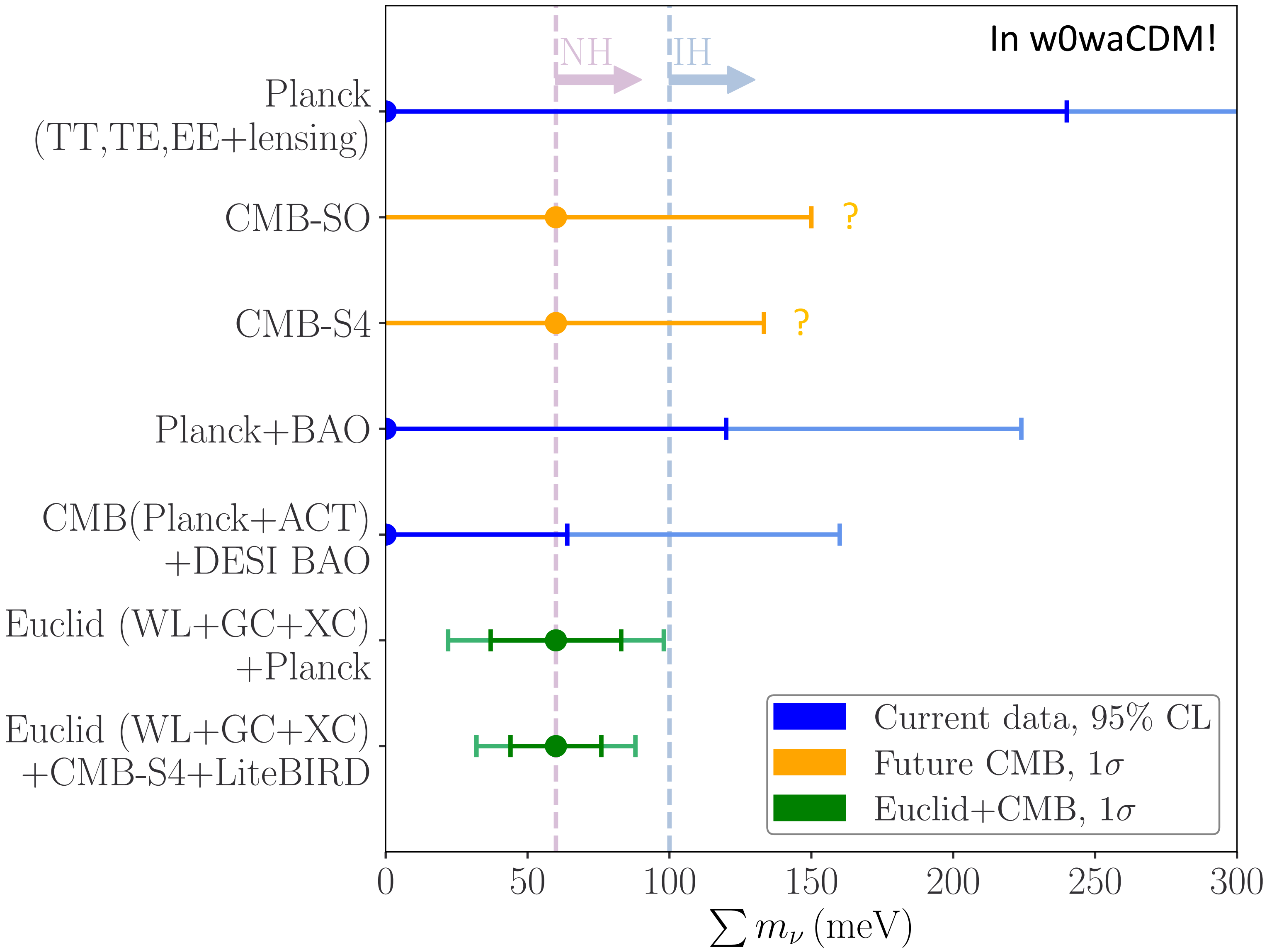
Neutrino mass constraints: the future



Euclid+Planck: >2σ evidence of a non-zero neutrino mass sum

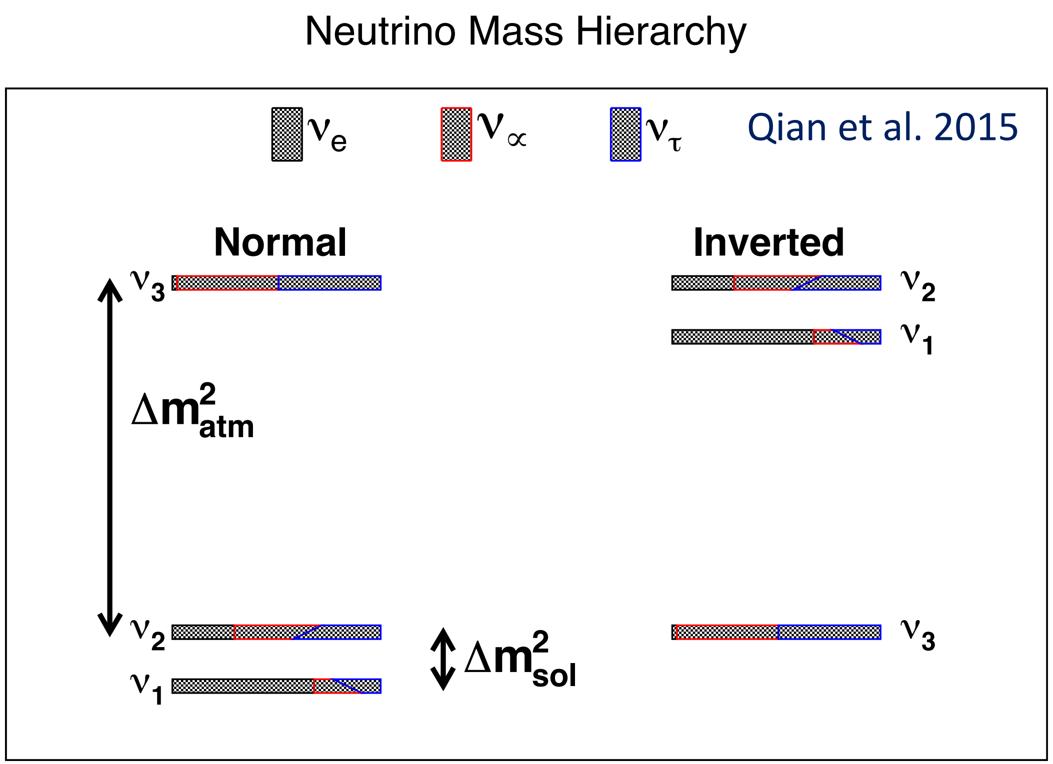
Euclid+CMB-S4+LiteBIRD: >3σ

Neutrino mass constraints: the future



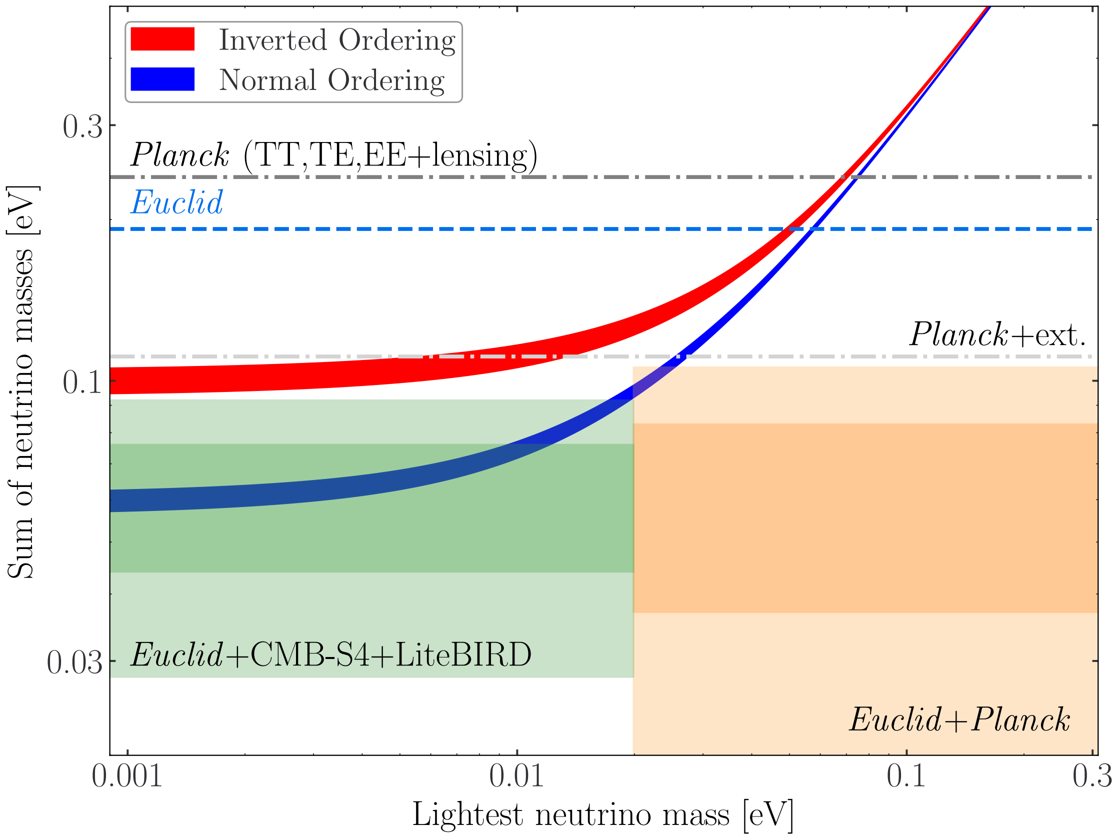
Replacing the cosmological constant with dark energy with a time varying equation of state parameter increases the error by a factor 2.

Neutrino mass ordering



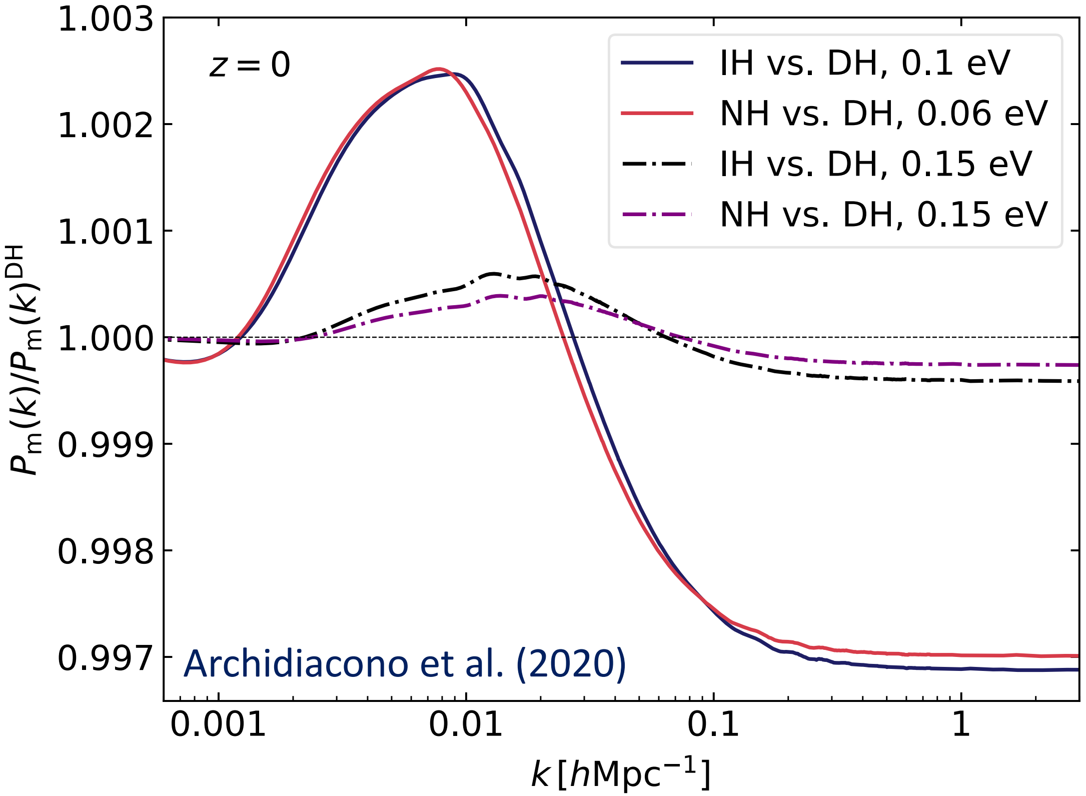
Min. Σm_ν (NH) = 0.058 eV; Min. Σm_ν (IH)= 0.100 eV

Euclid Collaboration: Archidiacono et al. (2024)



Input fiducial value of the forecast Σm_ν = 60 meV

Neutrino mass ordering



The effect induced by the neutrino mass ordering on the cosmological observables is below the sensitivity of current and planned cosmological surveys.

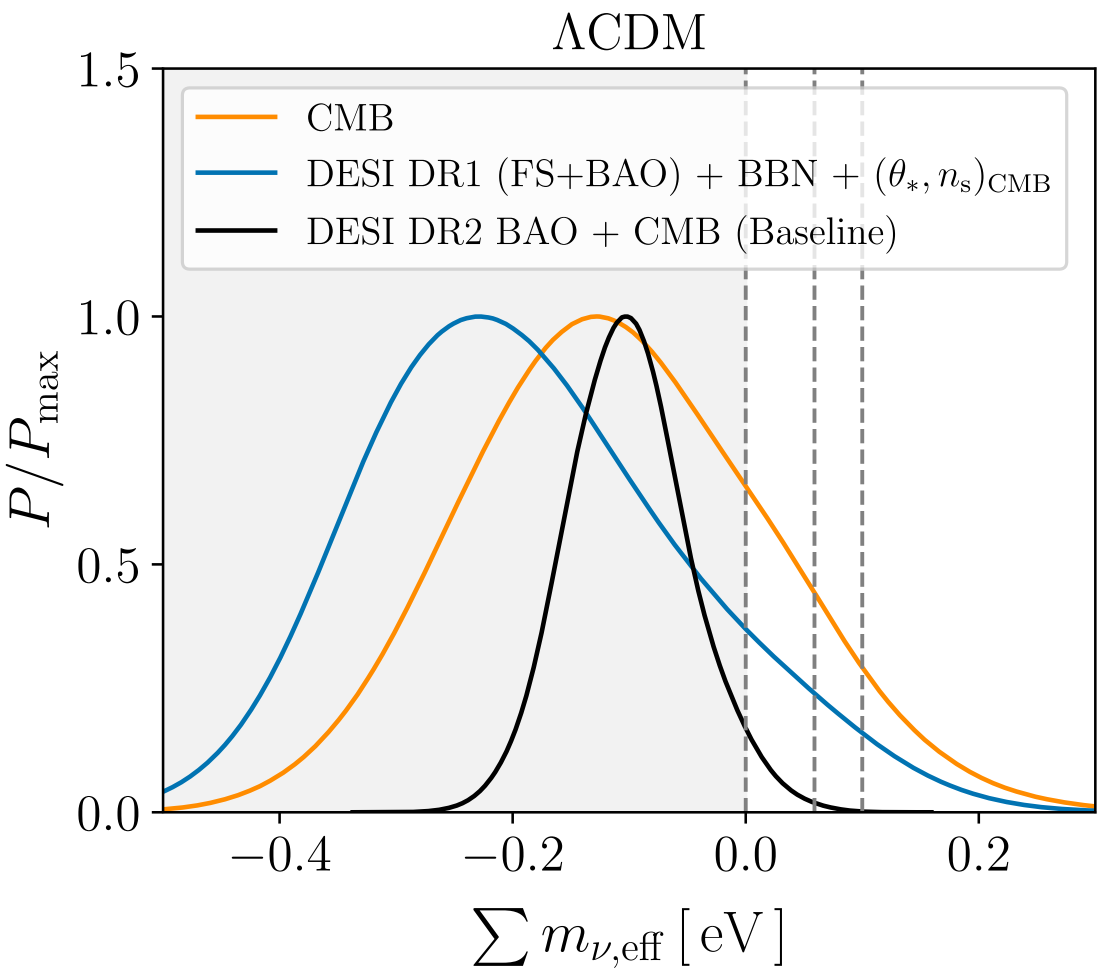
The degenerate hierarchy (DH, $m_1=m_2=m_3$) approximation will still be valid, and it is more efficient.

See also Gariazzo et al. (2022)

Neutrino mass: conclusions

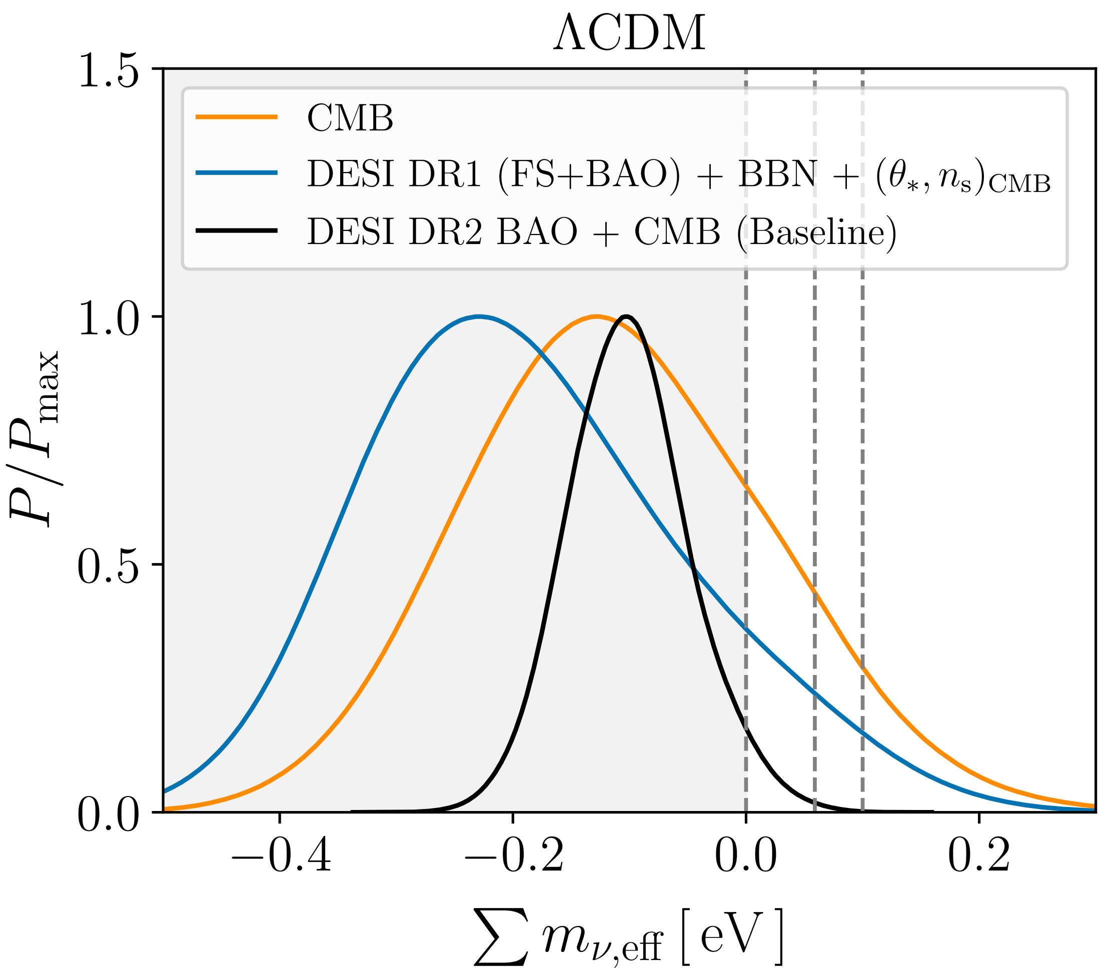
- Euclid in combination with upcoming CMB surveys can achieve a 4σ detection of Σm_ν even if Σm_ν = 0.058 eV (i.e., min. NH)
- Cosmology is not directly sensitive to the neutrino mass ordering, like DUNE or JUNO, however if Σm_ν = 0.058 eV, then future cosmological constraints can exclude IH at about 2σ
- Cosmology is more sensitive than current and planned β-decay experiments. Caveat: cosmology is model dependent, and it requires that systematic effects are under control. Complementarity: cosmology is not sensitive to the Dirac/Majorana nature, mixing angles.
- What if there is a tension between the Cosmos and the Lab?

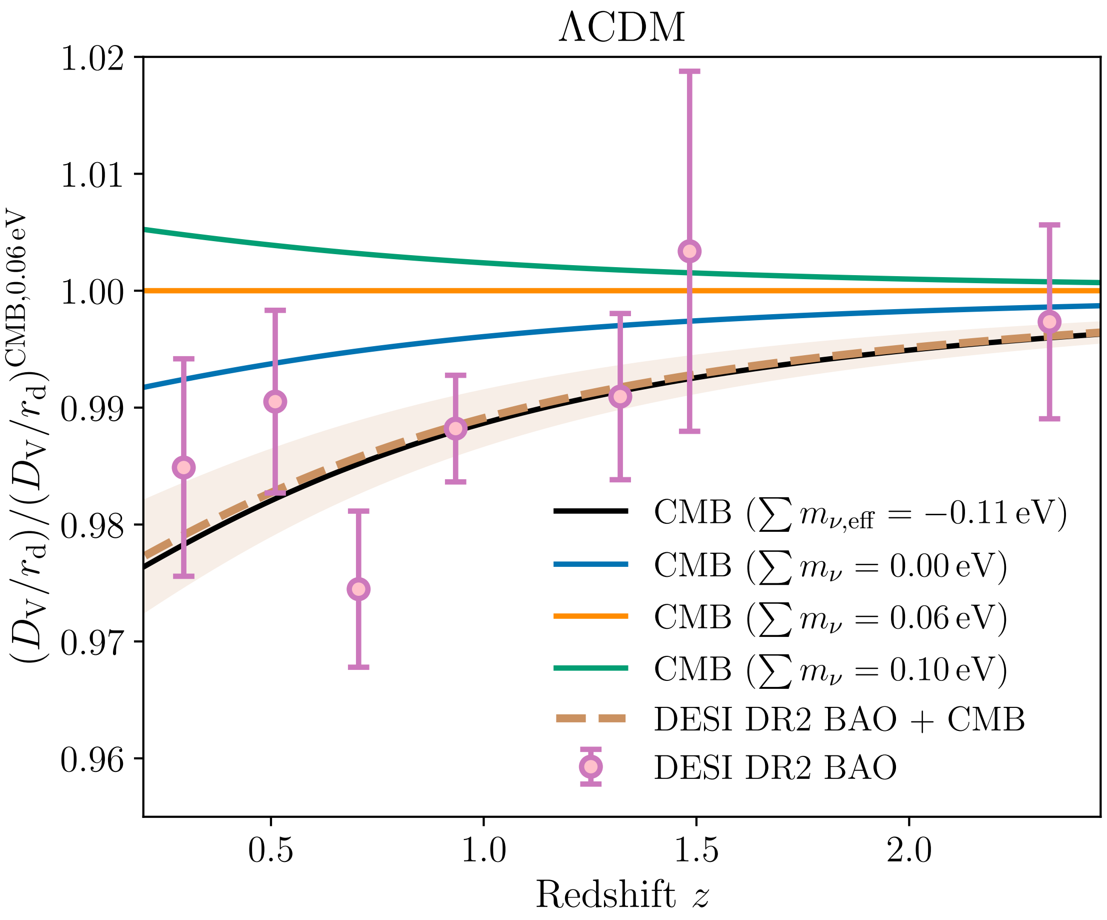
The cosmological neutrino mass problem



DESI Collaboration, Elbers et al., 2025

The cosmological neutrino mass problem





DESI Collaboration, Elbers et al., 2025

The cosmological neutrino mass problem

What if KATRIN (or Project 8) measures a neutrino mass in disagreement with cosmological bounds?

What if the cosmological bounds cross the minimum value allowed by oscillations?

➔ How robust are the cosmological constraints on the neutrino mass? Can they be evaded?

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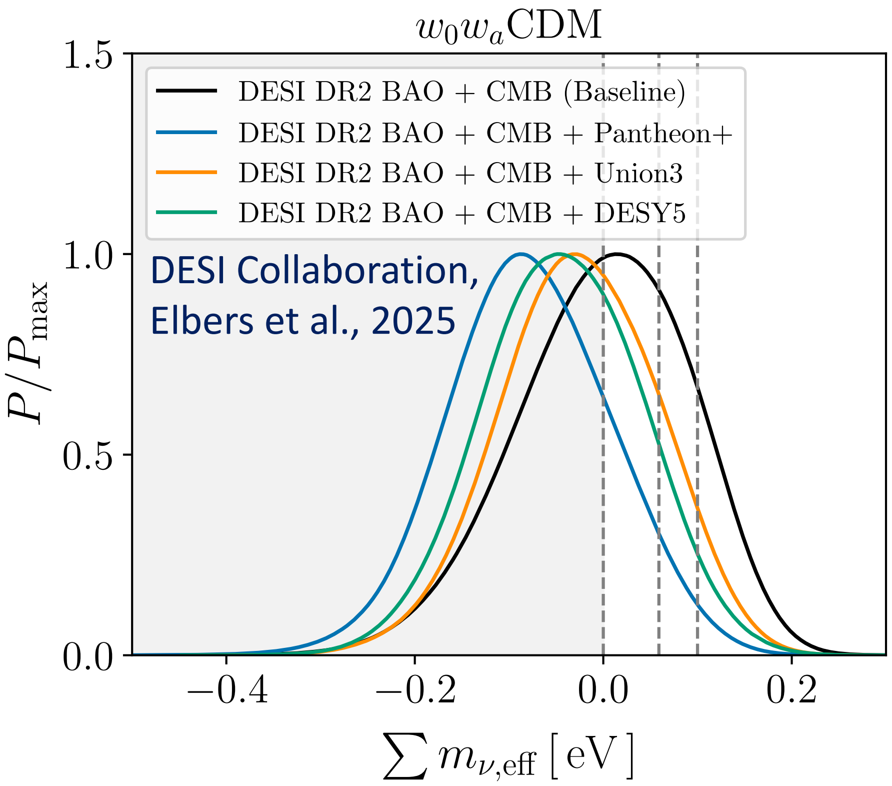
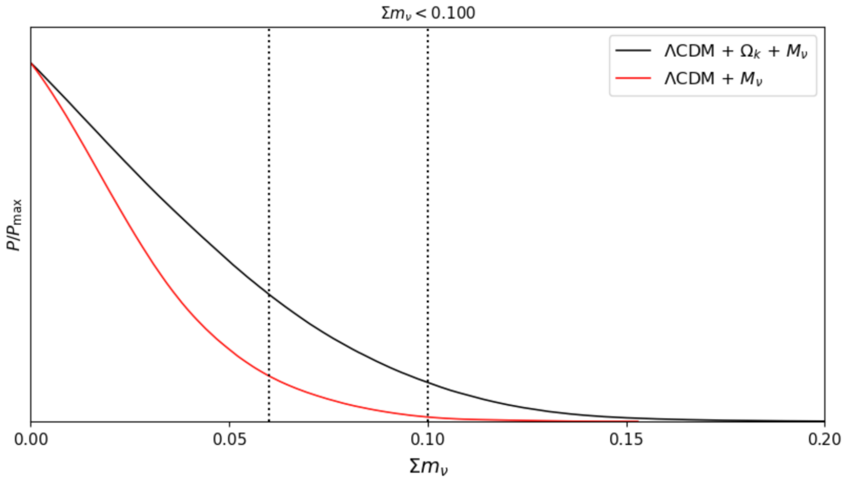


DESI Collaboration, Elbers et al., 2025

Shi-Fan Chen & Zaldarriaga, 2025



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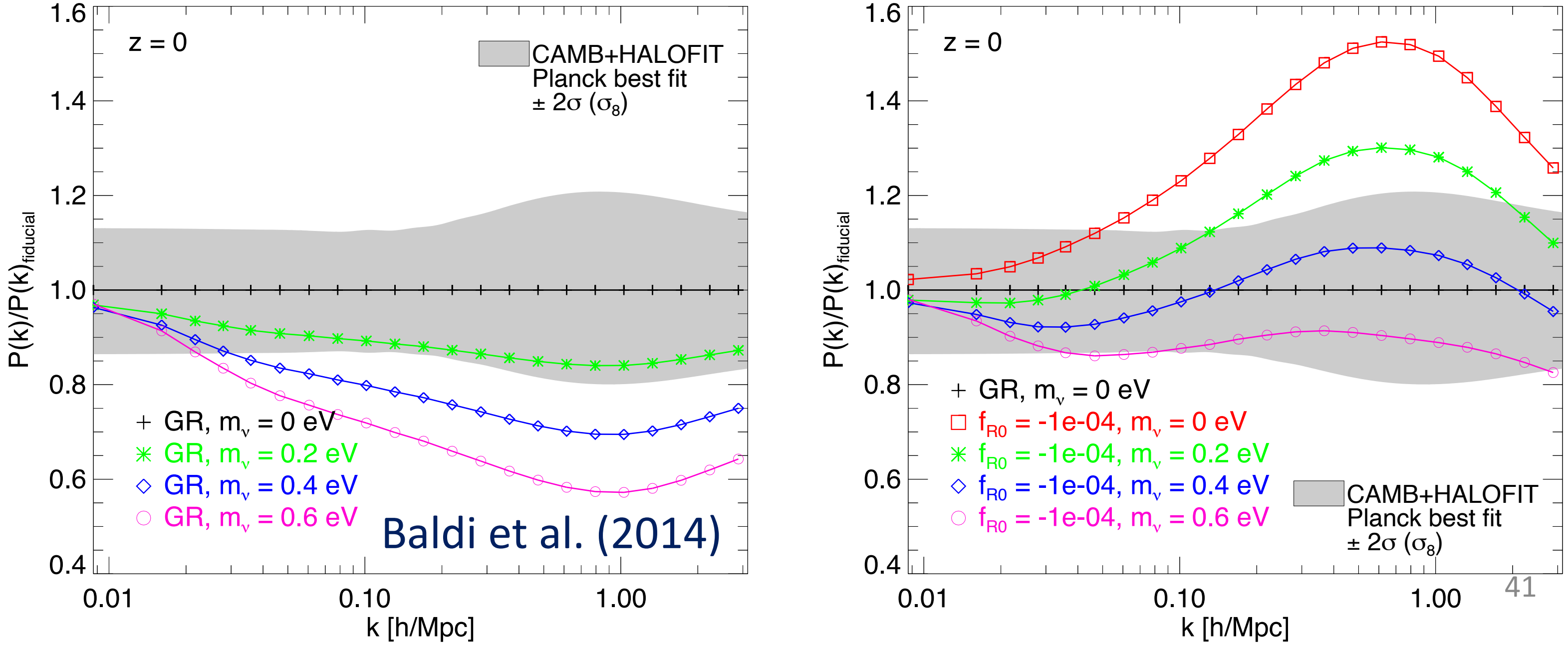

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    - Neutrino spectral distortions (from new interactions) [Alvey et al. (2022)] $\Sigma m_\nu < 3$ eV
    - Mass varying neutrinos (late time mass generation) [Lorenz et al. (2021)] $\Sigma m_\nu < 1.5$ eV
    - Invisible neutrino decay into BSM particles [Barenboim et al. (2021)] $\Sigma m_\nu < 0.2$ eV

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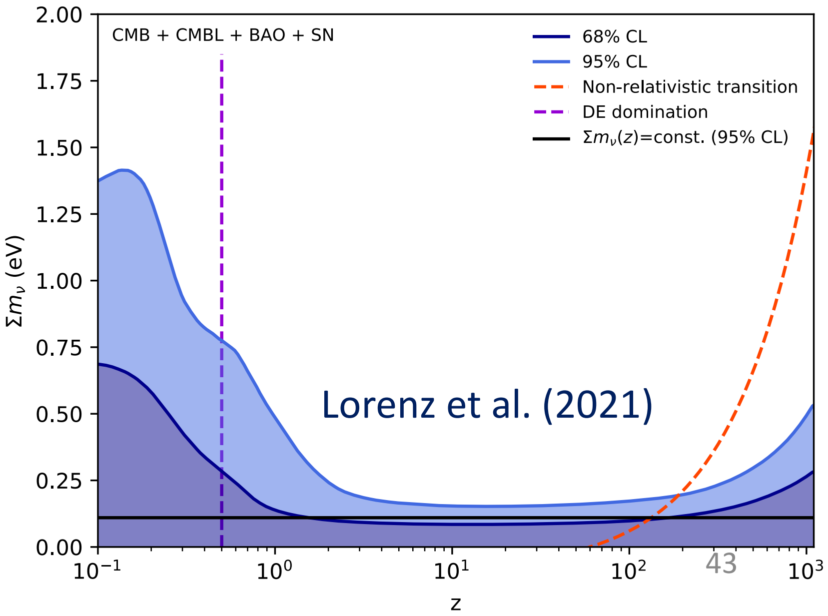


Conclusions

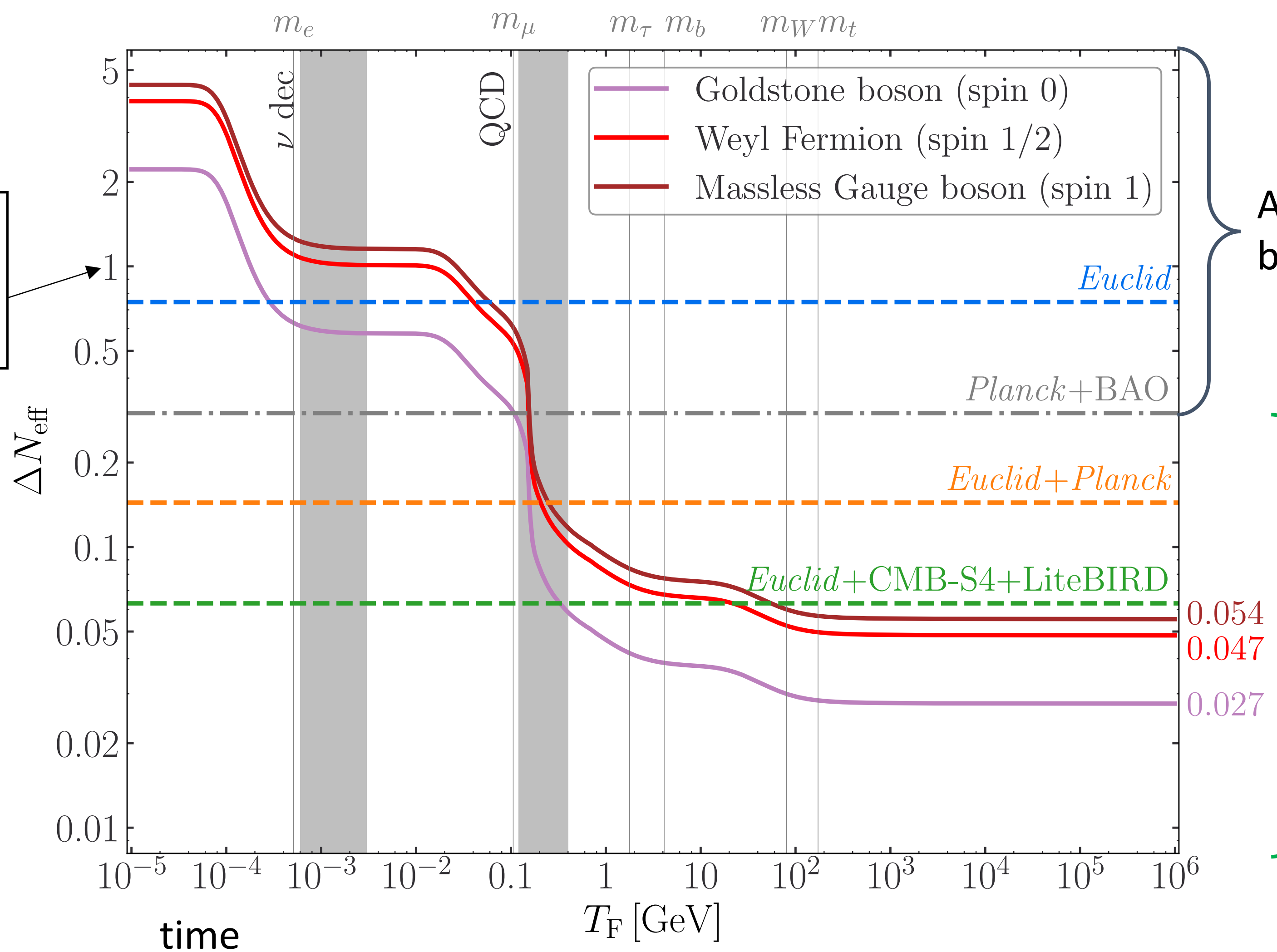
- Neutrino mass: The scenario of no detection, or a tension with ground-based experiments, would require to rethink the cosmological paradigm and/or neutrino physics.

Backup

Bounds on new light particles (ΔN_{eff})

$N_{eff} = N_{eff}^{SM}(=3.044) + \Delta N_{eff}$

Thermalised "sterile" neutrinos already excluded



Already excluded by current limits

Still possible... Probed by future CMB and LSS surveys

time ←

Euclid Collaboration: Archidiacono et al. (2024)