Towards a neutrino mass detection from ongoing and upcoming cosmological surveys

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UNIVERSITÀ DEGLI STUDI DI MILANO

Euclid consortium

Neutrino Frontiers, Focus week, July 1-5, 2024, GGI, Arcetri

A short cosmic history

See lectures by Yvonne Wong

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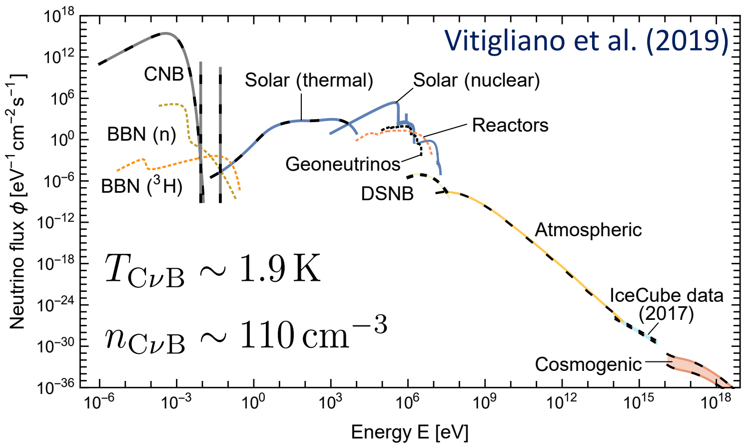
Cosmic Neutrino Background (T~1MeV)



➔ No direct detection yet

➔ Footprints in cosmological observables

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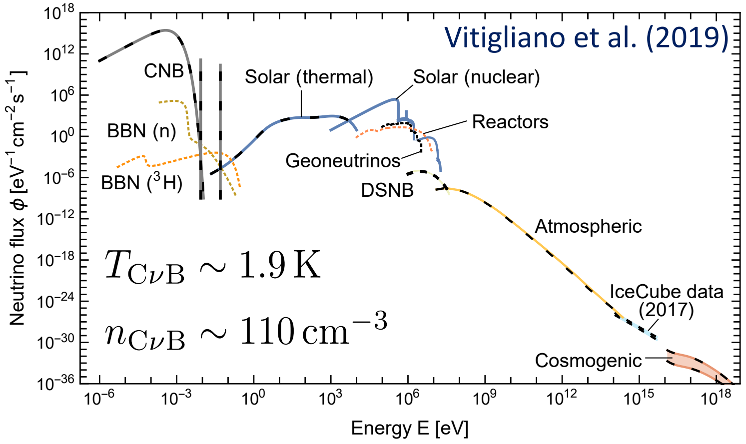
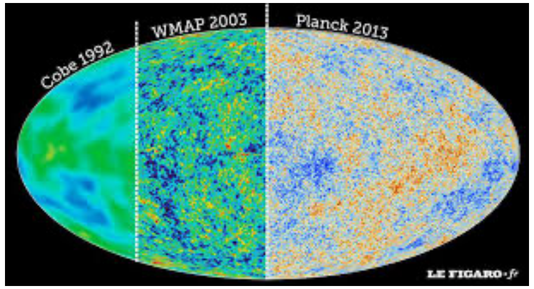
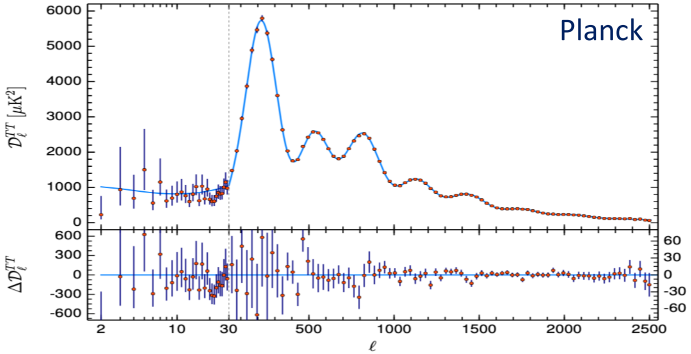
Cosmic Microwave Background (T~0.2eV)



$T_{C\nu B} \sim 1.9\,\mathrm{K}$

$n_{C\nu B} \sim 110\,\mathrm{cm}^{-3}$





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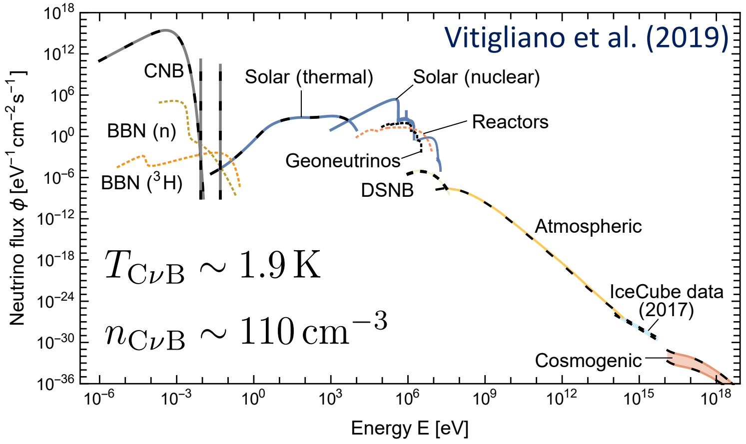
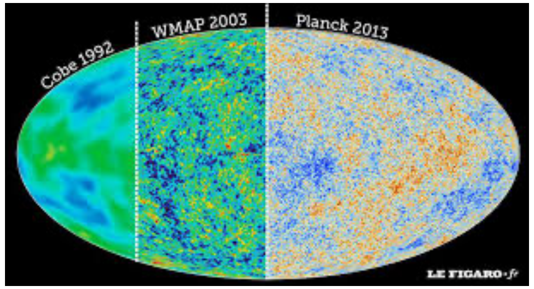
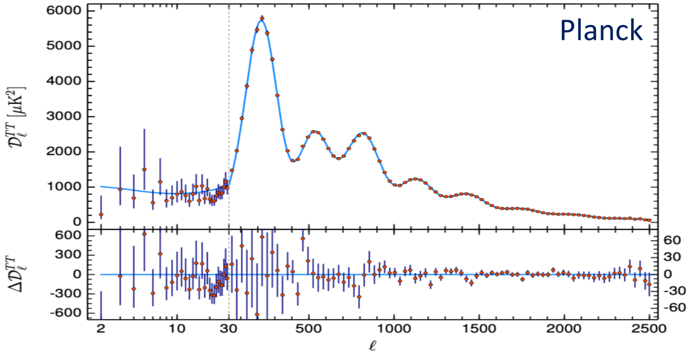
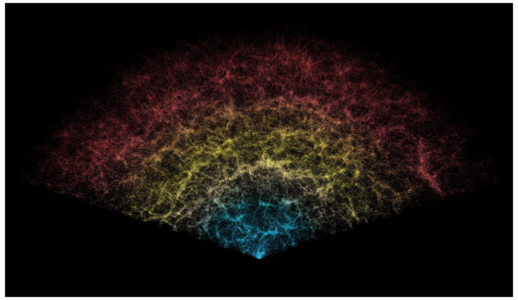
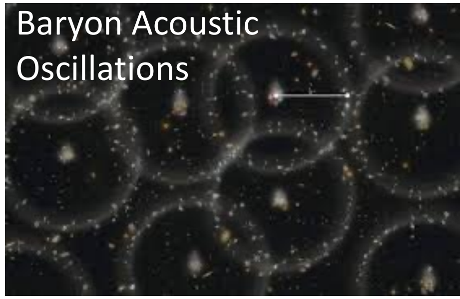




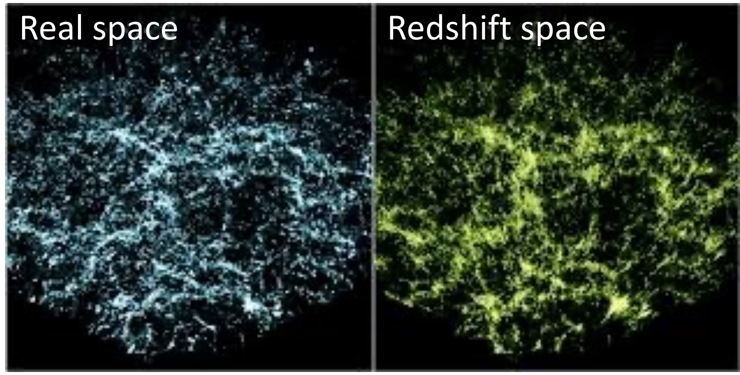


Spectroscopic galaxy survey





Redshift space distortions



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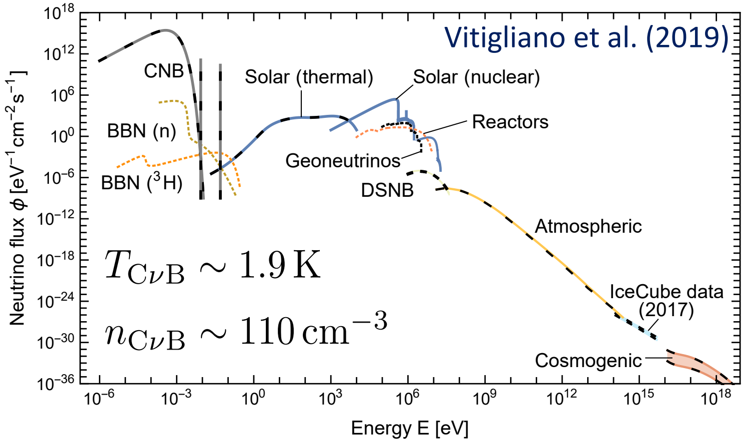
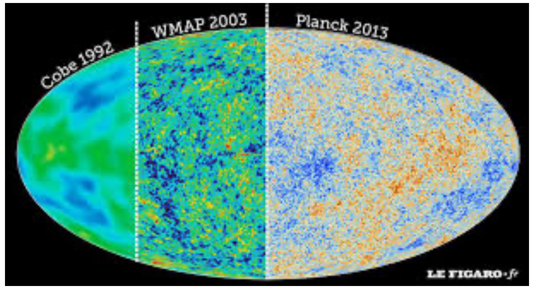
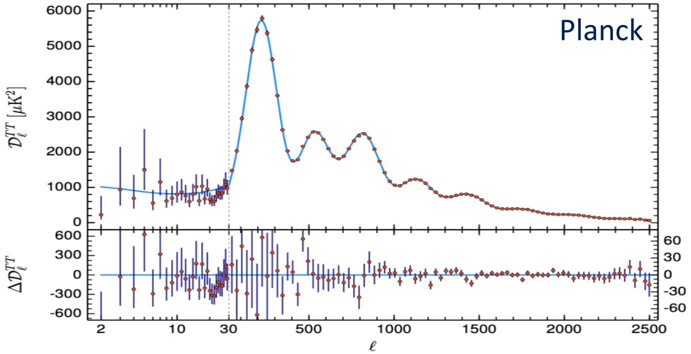
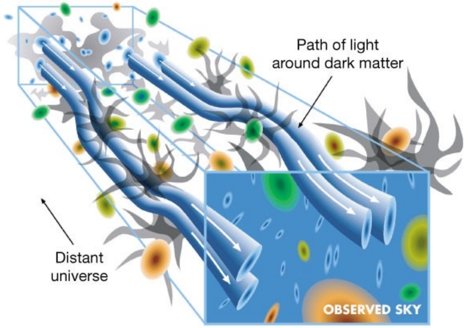






Photometric galaxy survey

Weak gravitational lensing



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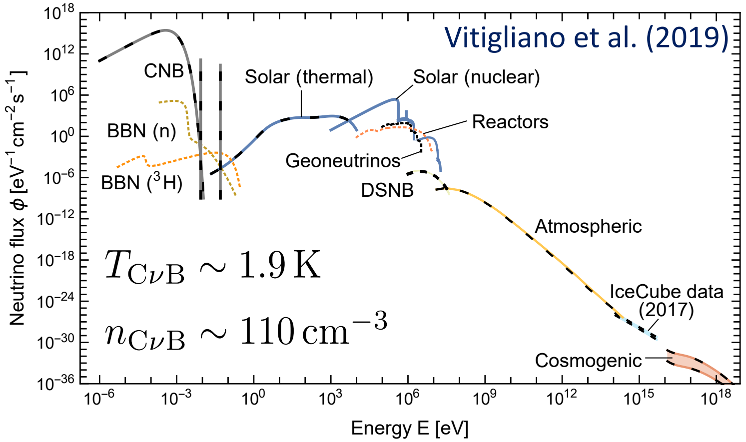

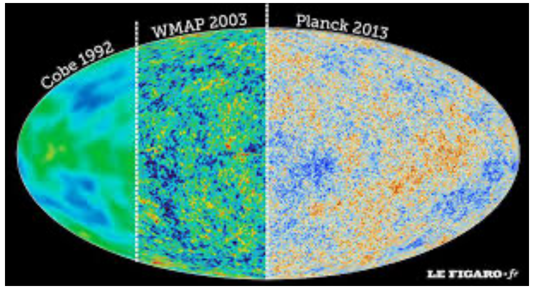

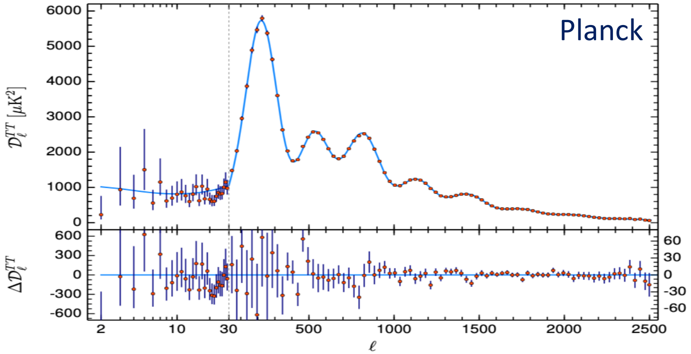

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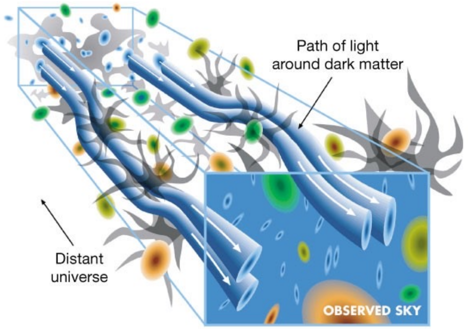
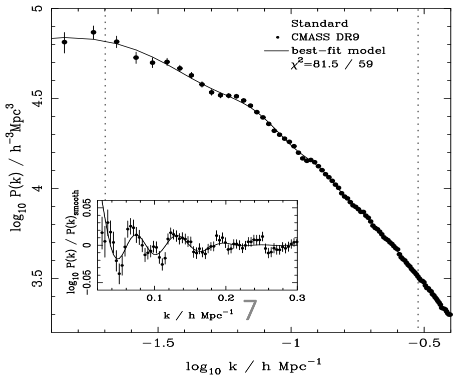


P(k) = Matter power spectrum of density fluctuations



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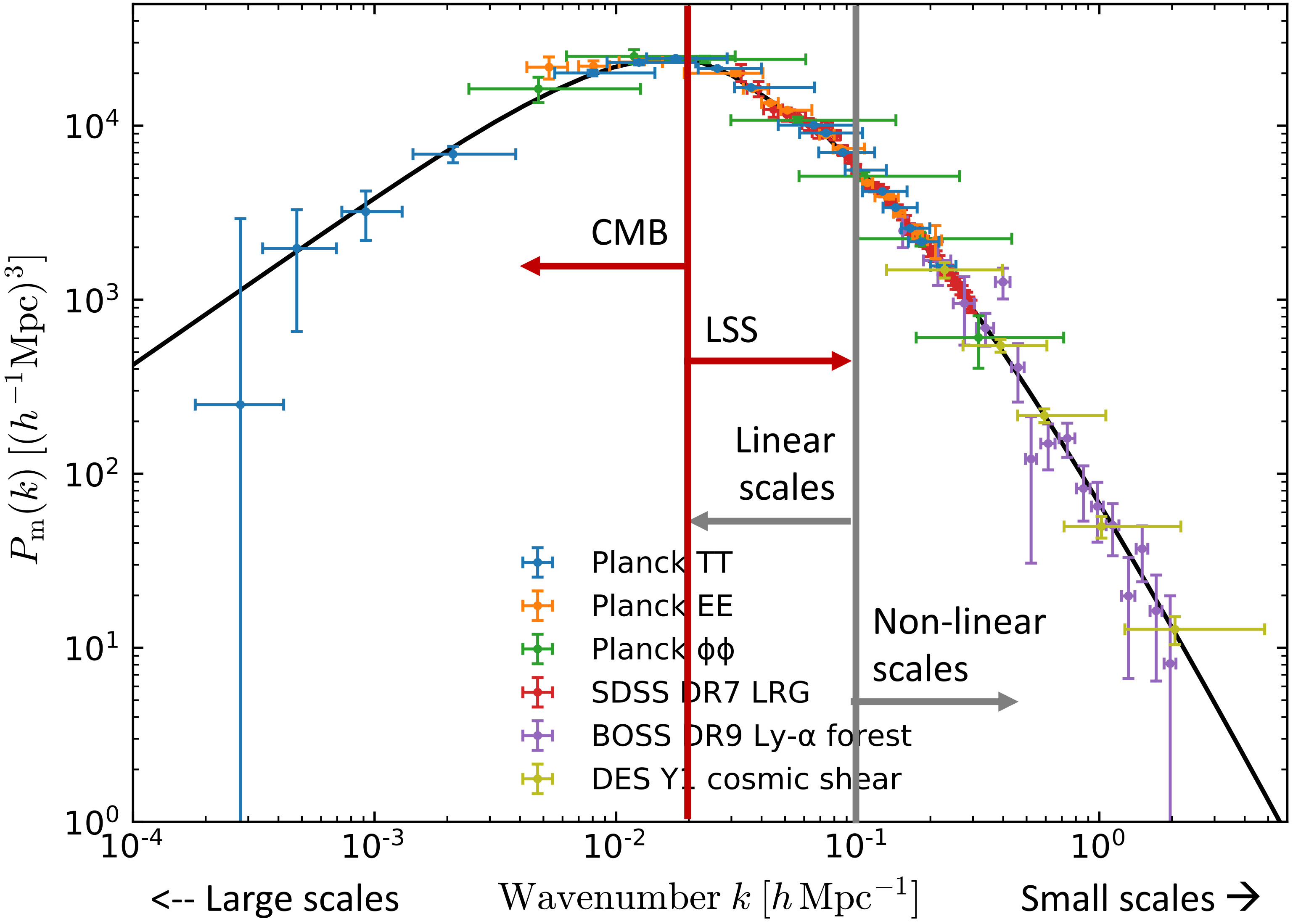
Different observables at different epochs/scales

Linear scales: predictions of observables from Einstein-Boltzmann solvers (CLASS or CAMB)

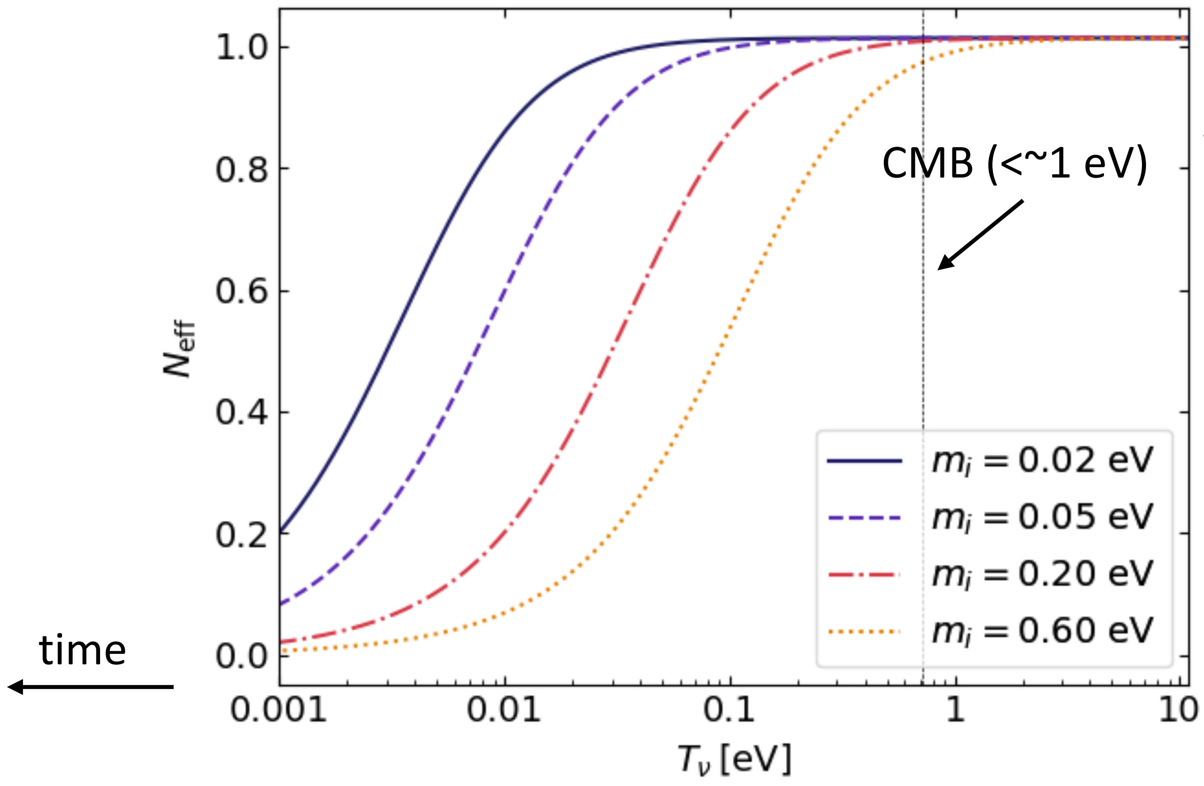
CPU time for one model: << 1 sec



Non-linear scales: predictions of observables from N-body simulations

CPU time for one model: ~ khrs-Mhrs

The duality of the CνB



Early times: neutrinos as **radiation**

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

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

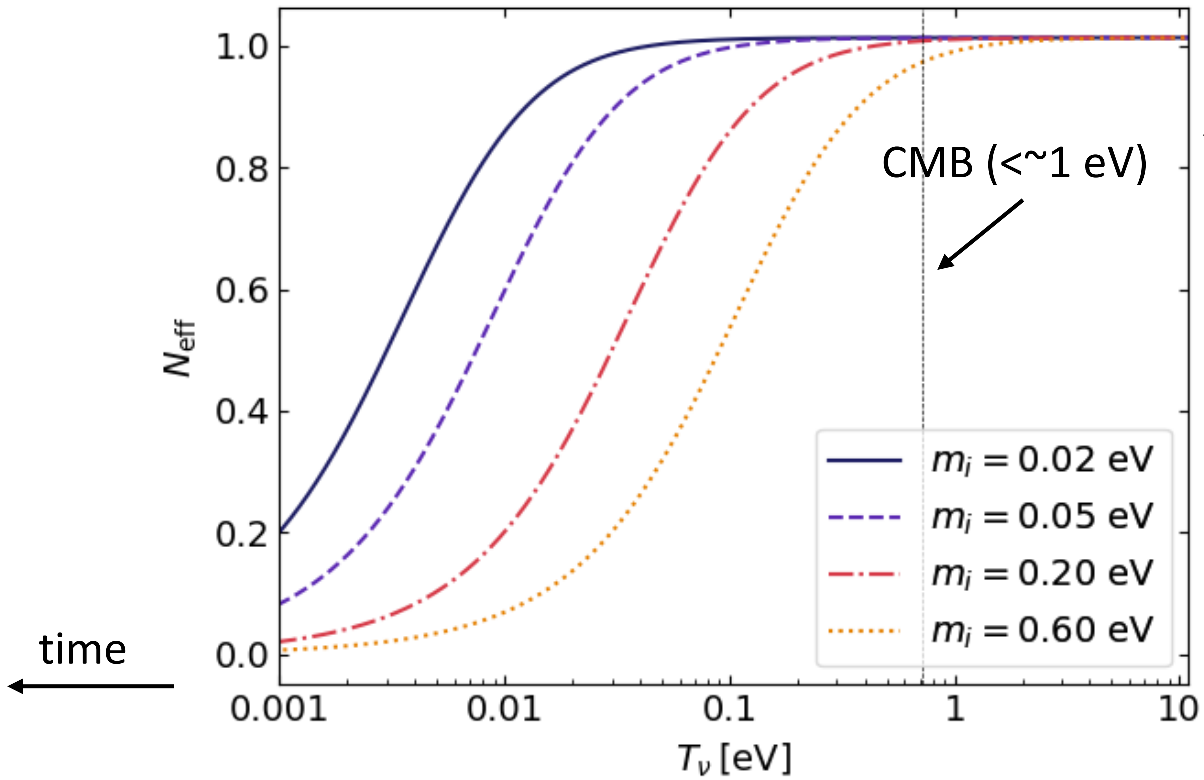
For the 3 neutrino families of the SM: $N_{\rm eff}^{\rm SM} = 3.044$

See talk by Gariazzo, Froustey

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

$N_{\rm eff} = 3.10 \pm 0.17$ (68% CL)

The duality of the CνB



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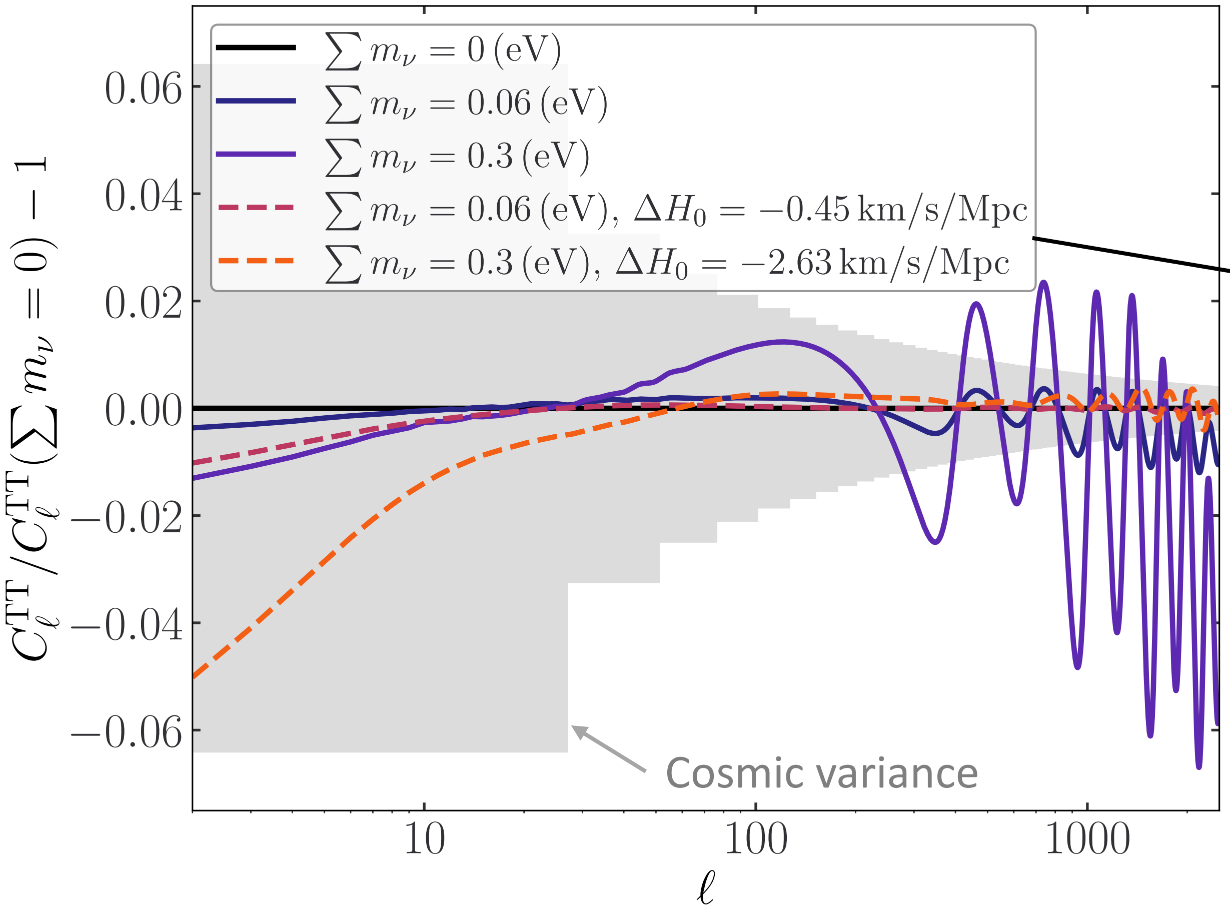
Late times (after CMB formation): neutrinos as **matter** (contributing to dark matter as hot dark matter)

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

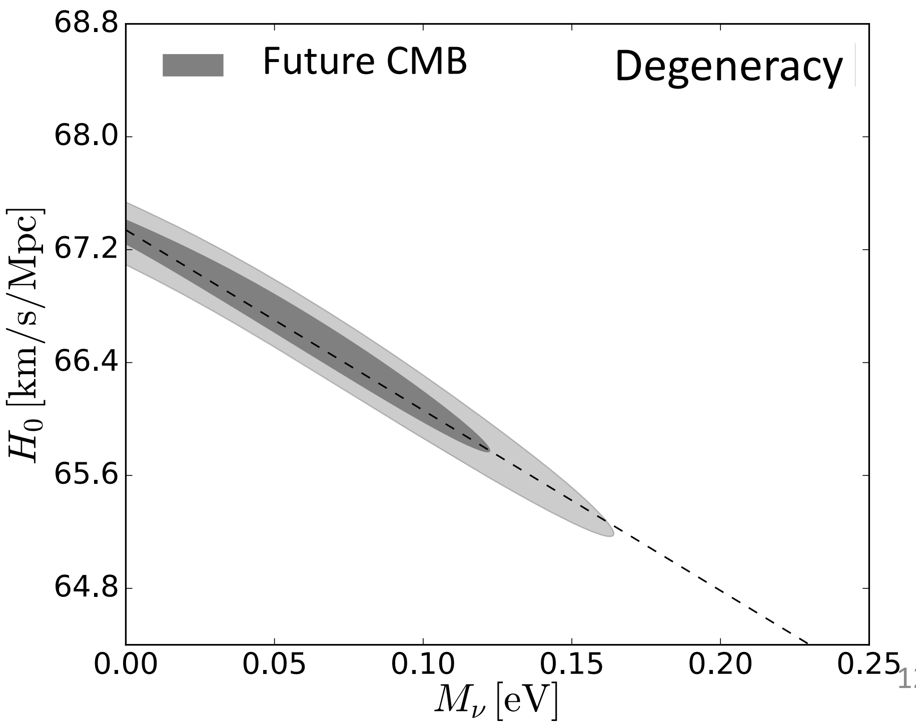
Detecting the neutrino mass in the CνB

Neutrino mass probes: CMB

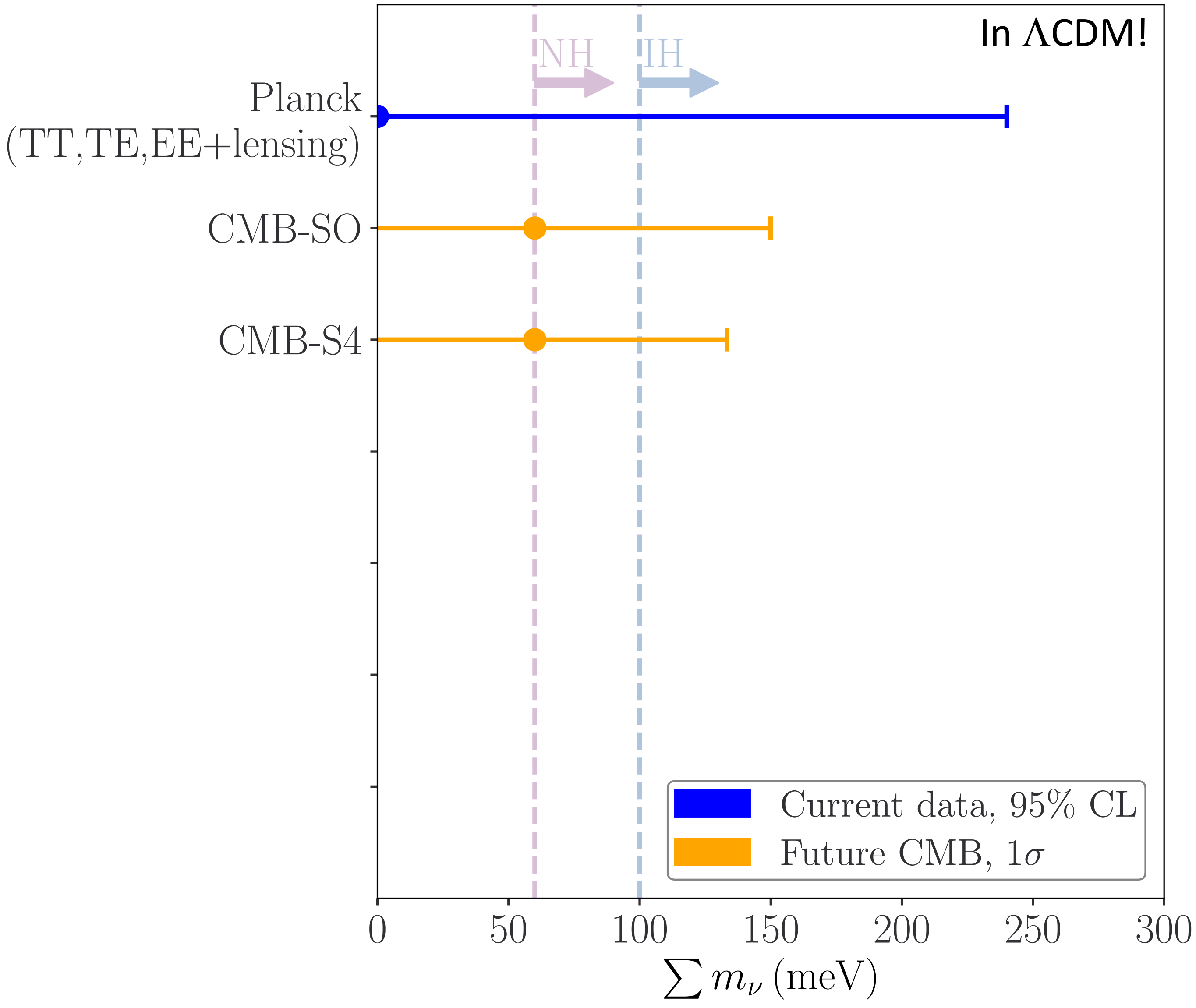


- Background effects
- Perturbation effects

Varying the Hubble constant H_0 compensates for the variation of the neutrino mass.



Neutrino mass constraints: CMB



KATRIN: Σm_ν <~ 1.5 eV

Fiducial value:

- Σm_ν = 58 meV

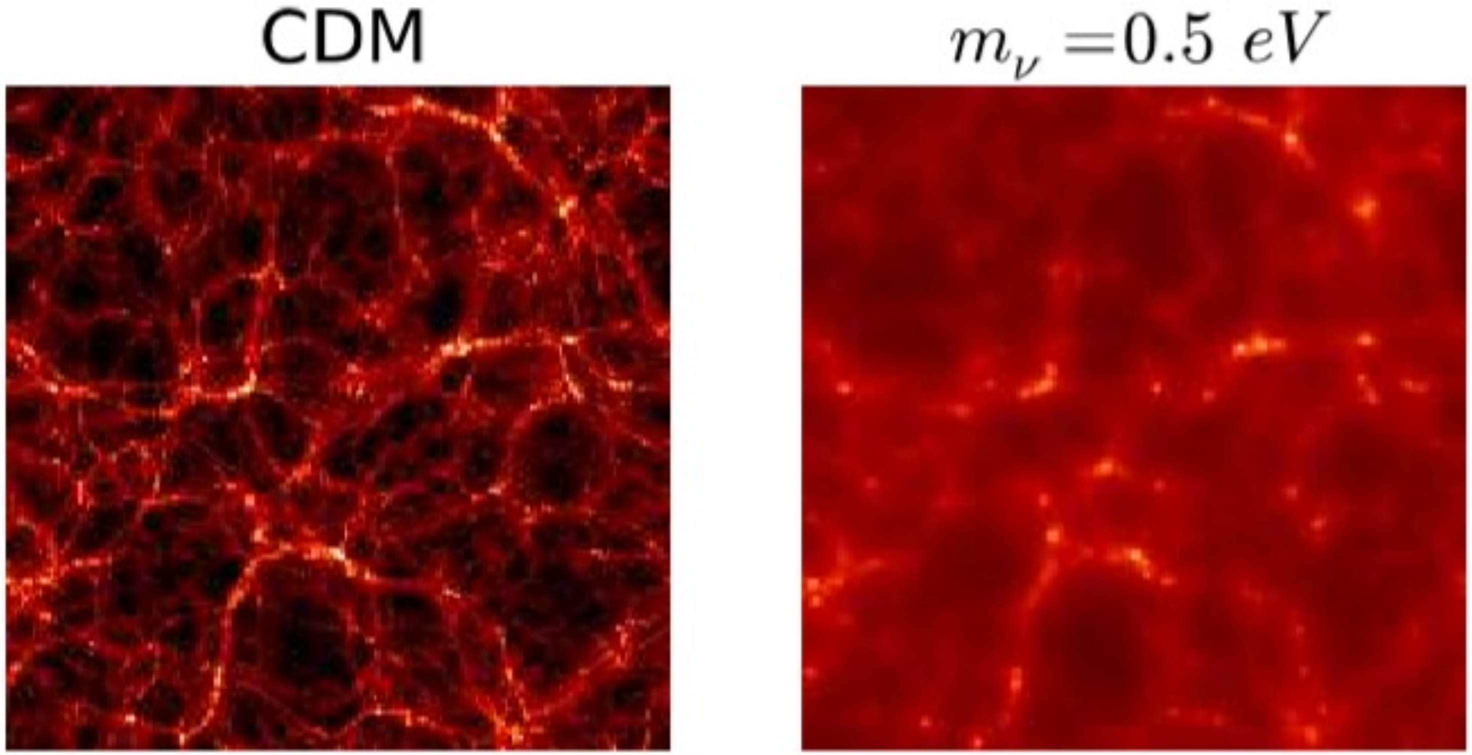
CMB alone will not be able

to detect the neutrino mass

→ Large Scale Structures

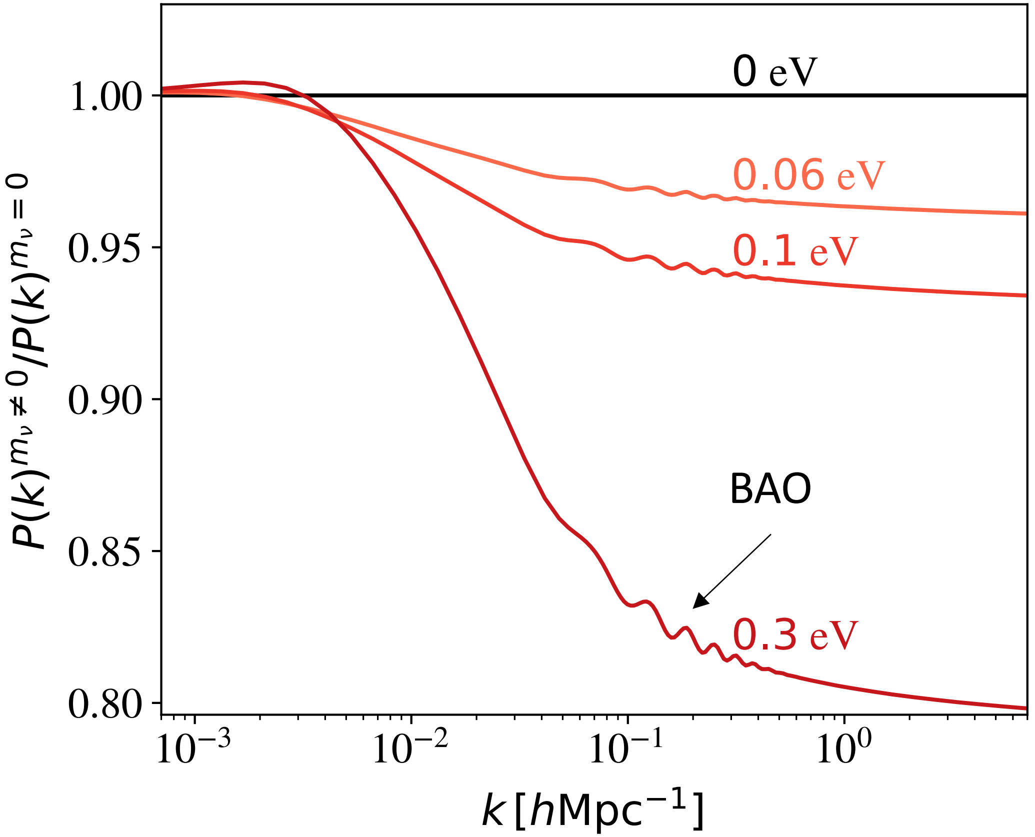
Neutrino mass probes: LSS

After the non-relativistic transition (after CMB formation), neutrino free-stream $d_{\mathrm{FS},i} \sim 1\,\mathrm{Gpc}\frac{eV}{m_{\nu,i}}$



Villaescusa Navarro et al. (2013)

Neutrino mass probes: LSS



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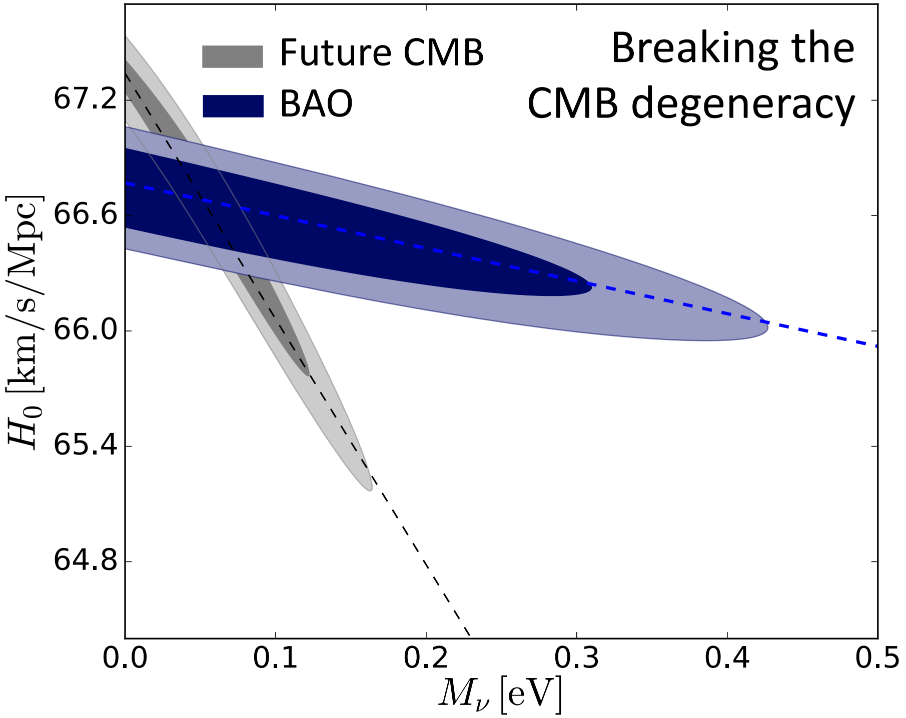
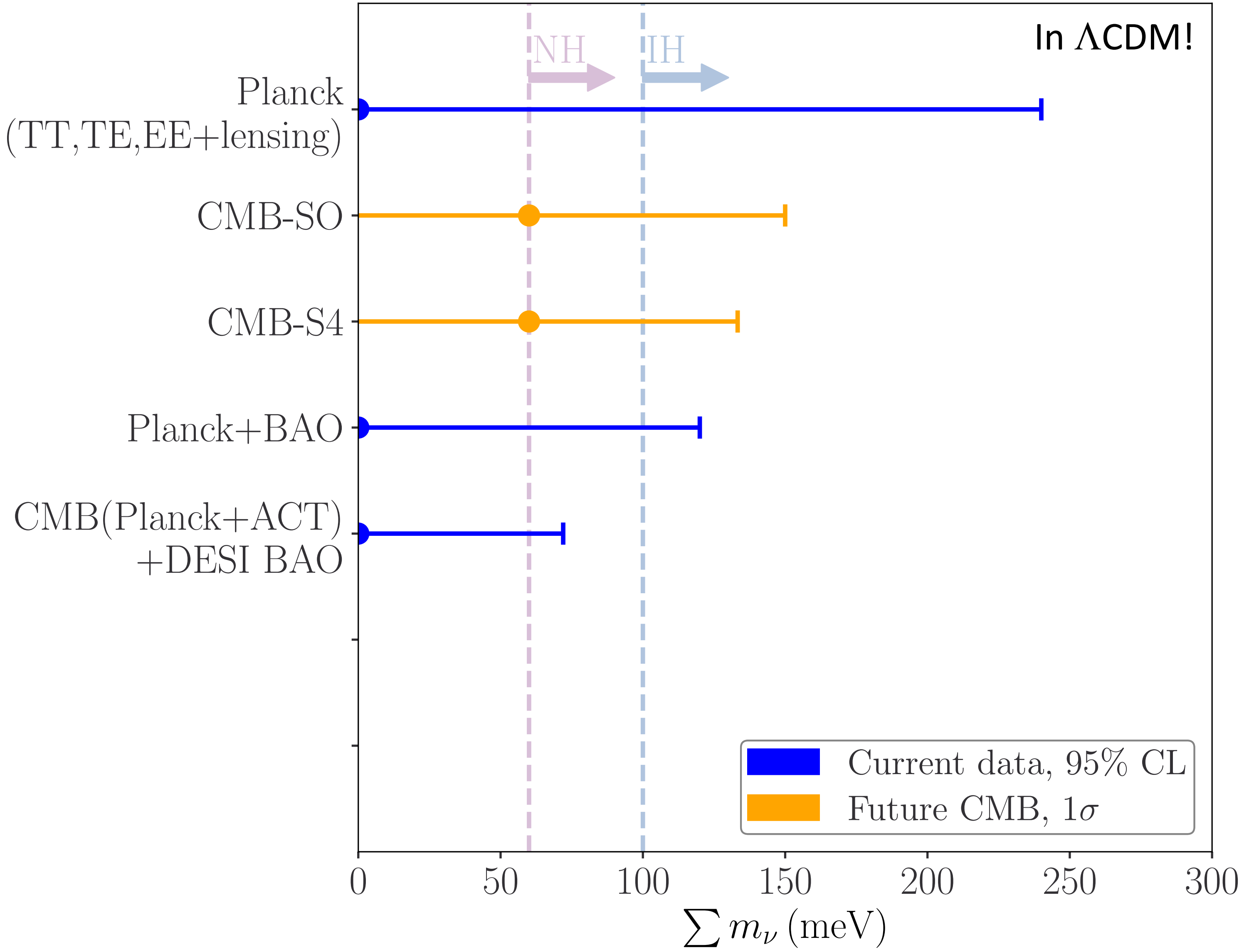
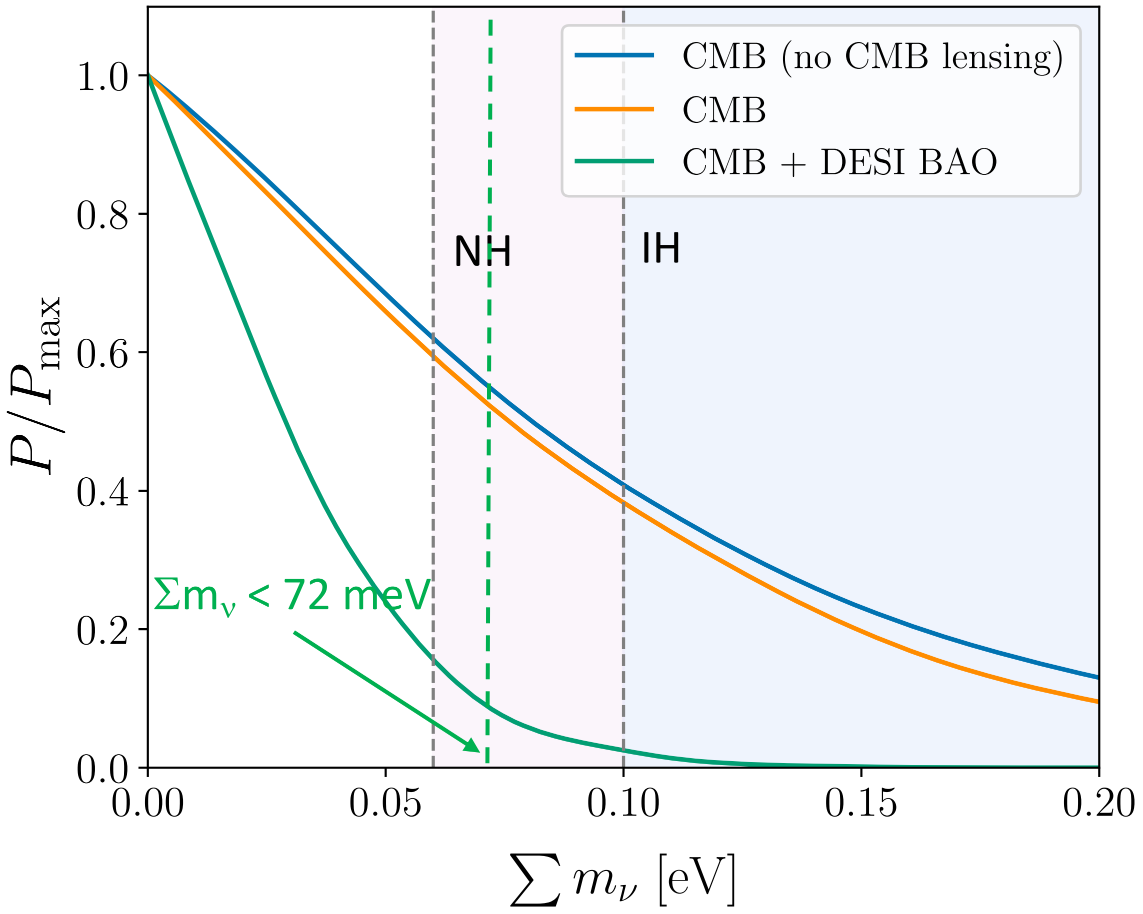


Neutrino mass constraints: CMB+LSS



Neutrino mass constraints: CMB+DESI



DESI Collaboration: Adame et al. (2024)

CMB (Planck+ACT) + DESI BAO: $\Sigma m_\nu < 72$ meV, 95% CL

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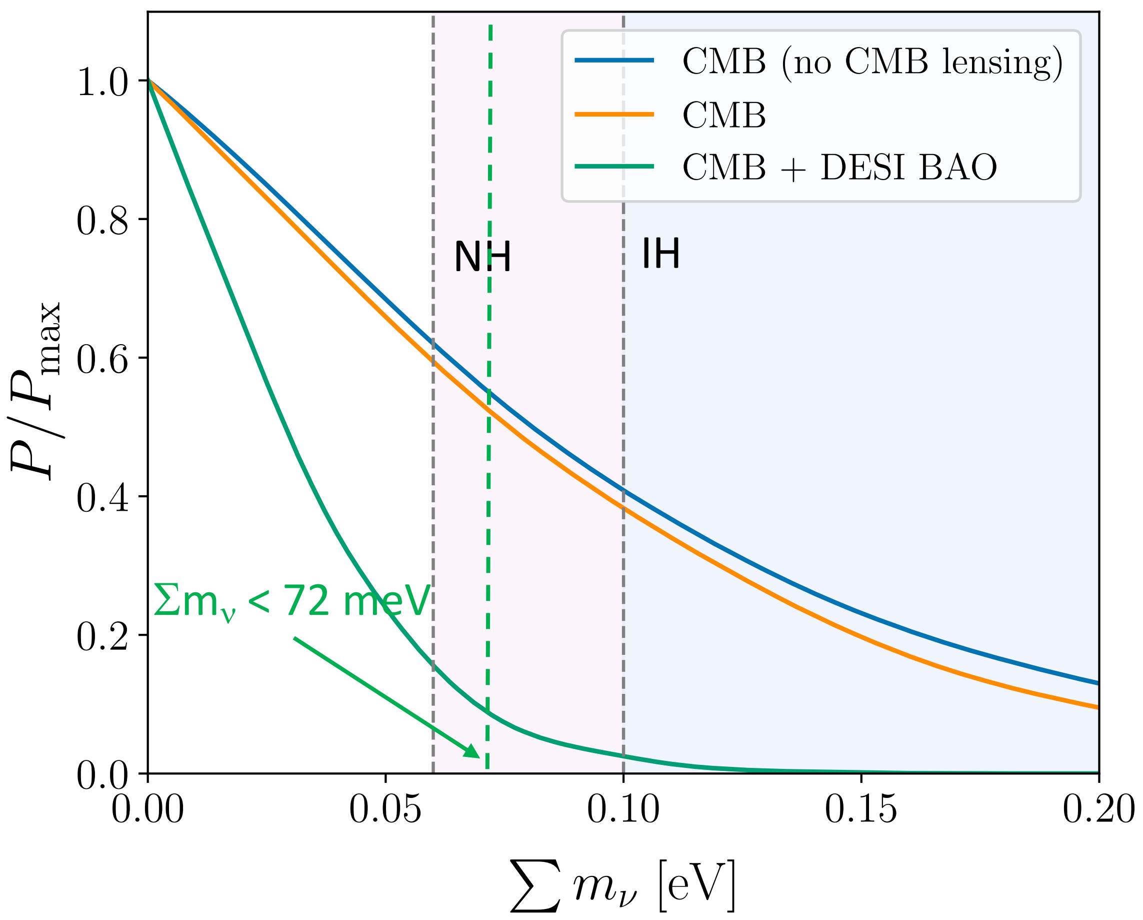

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Prior: $\Sigma m_\nu > 0$

Prior: Σm_ν > 59 meV -> Σm_ν < 113 meV, 95% CL

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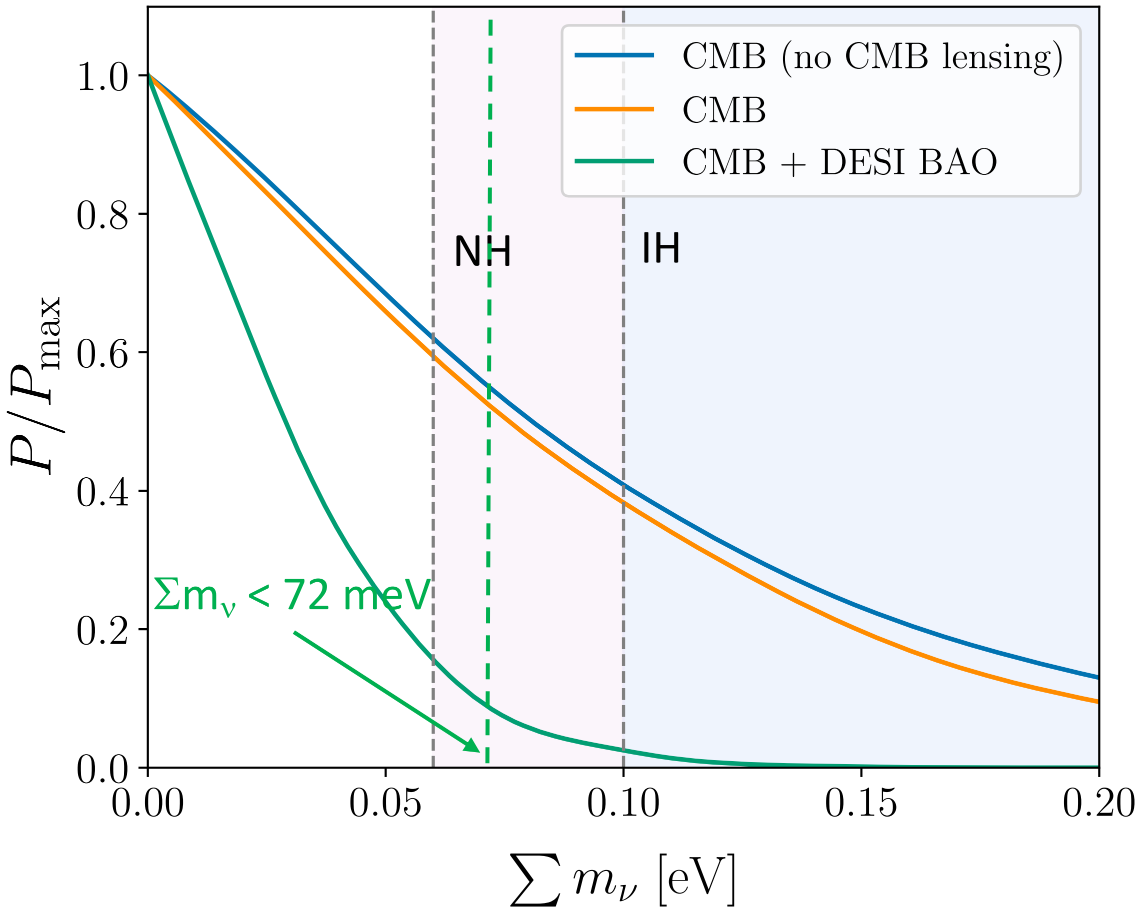

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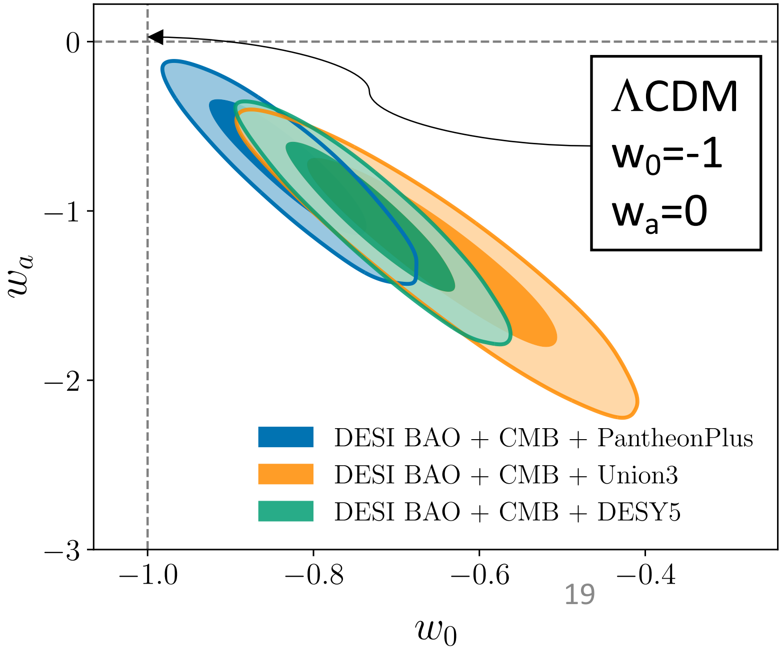
In ΛCDM!

In w0waCDM:

Σm_ν < 195 meV



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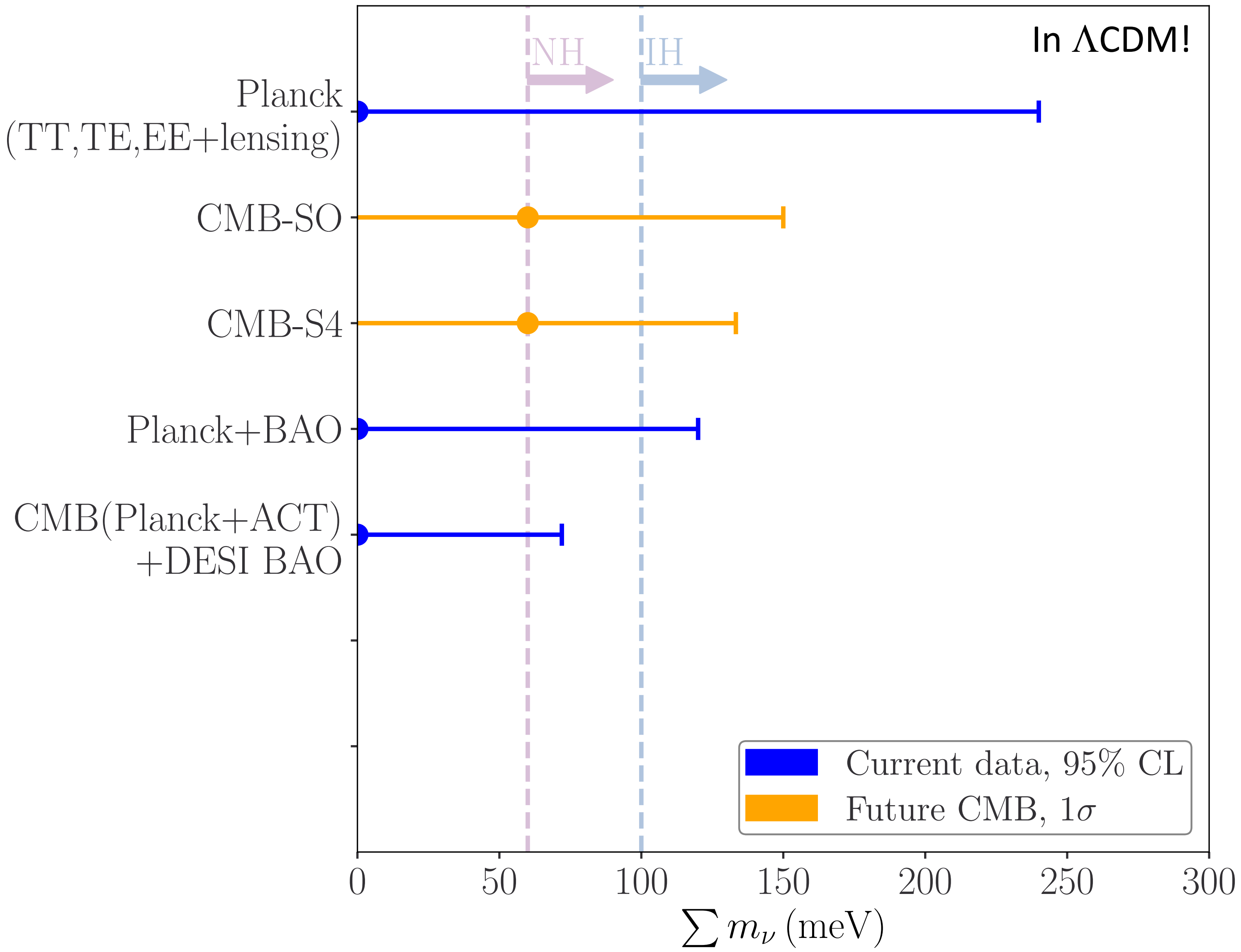


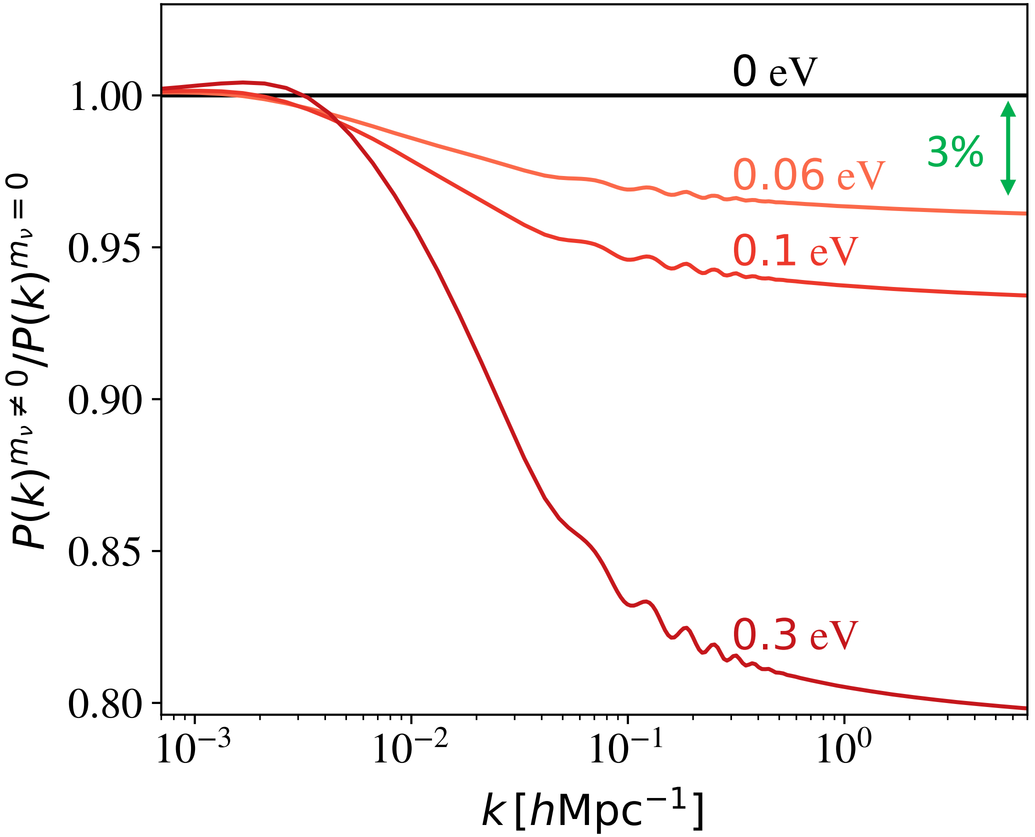
Still no evidence/detection!

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 **30 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 on P(k)

Neutrino mass probes: LSS



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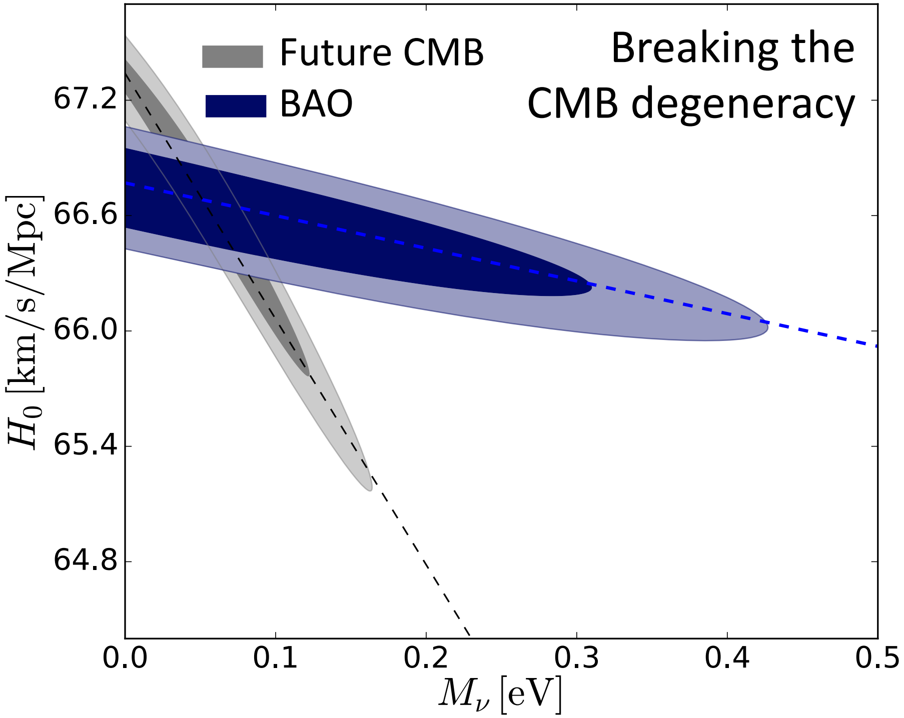

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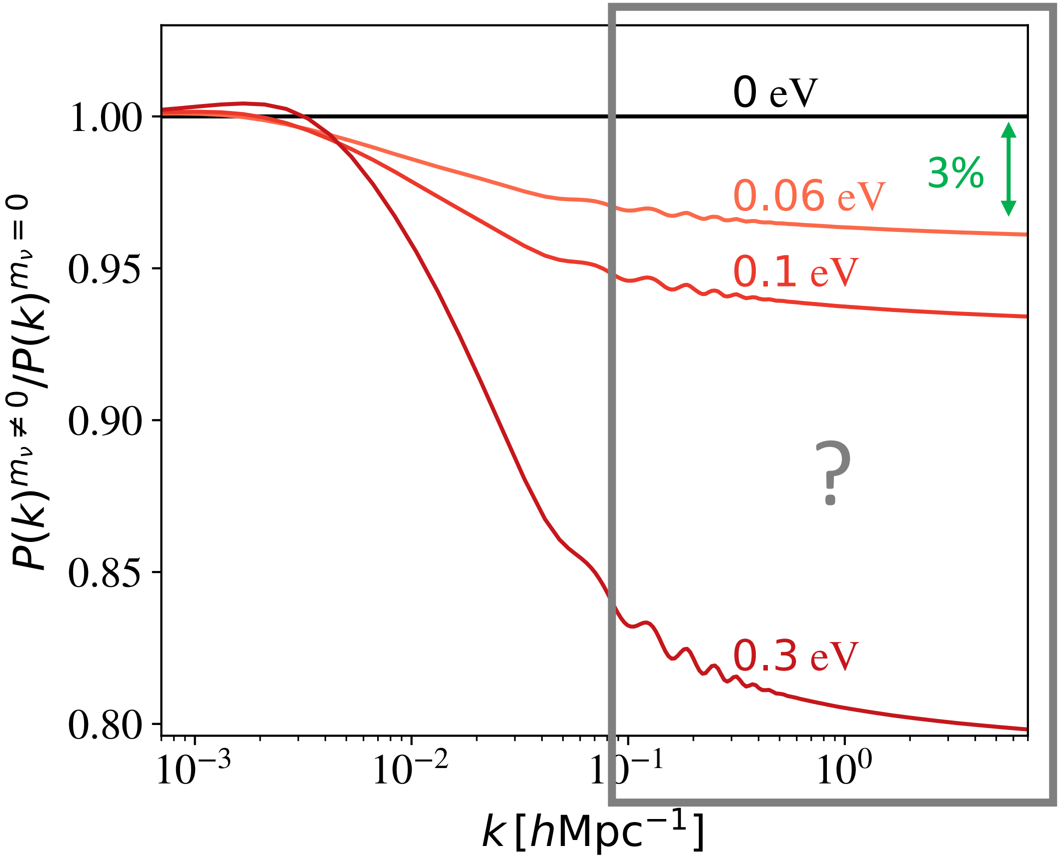

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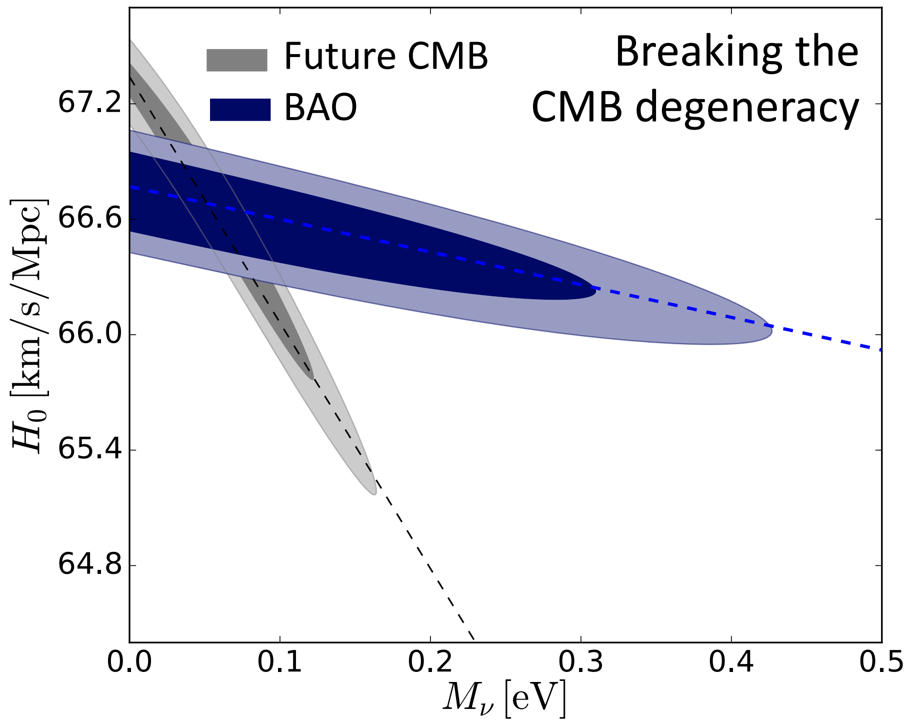

Known unknowns (systematics, etc.)

The 1% challenge on the theoretical prediction

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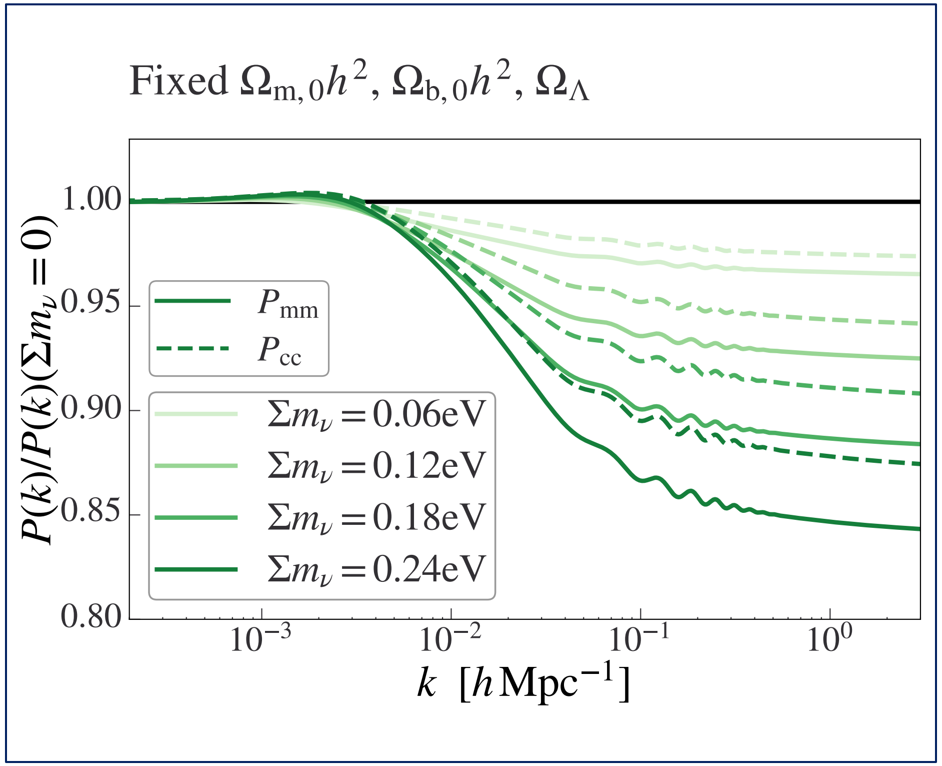

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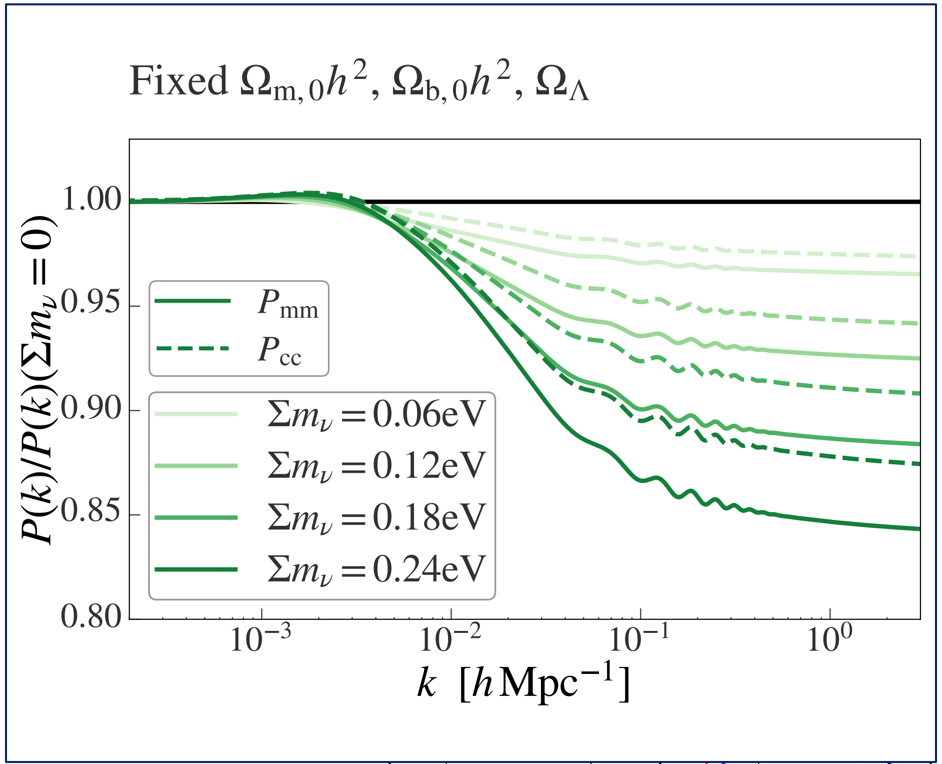

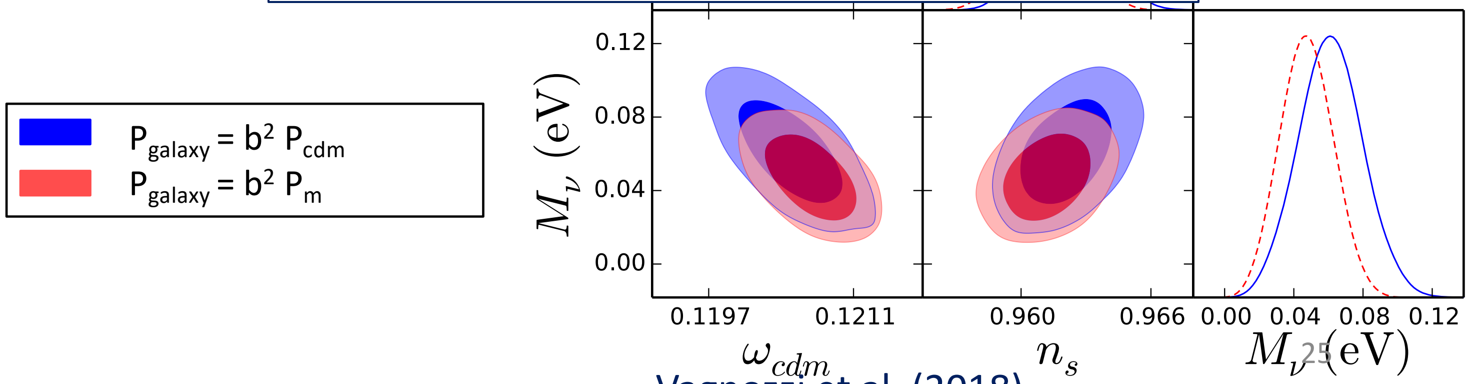

Vagnozzi et al. (2018)

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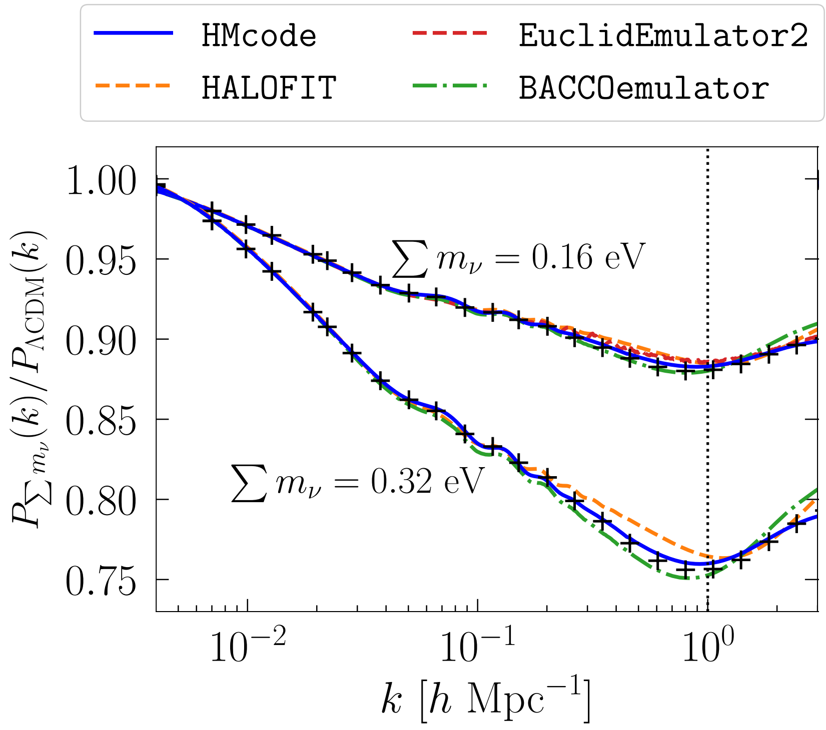

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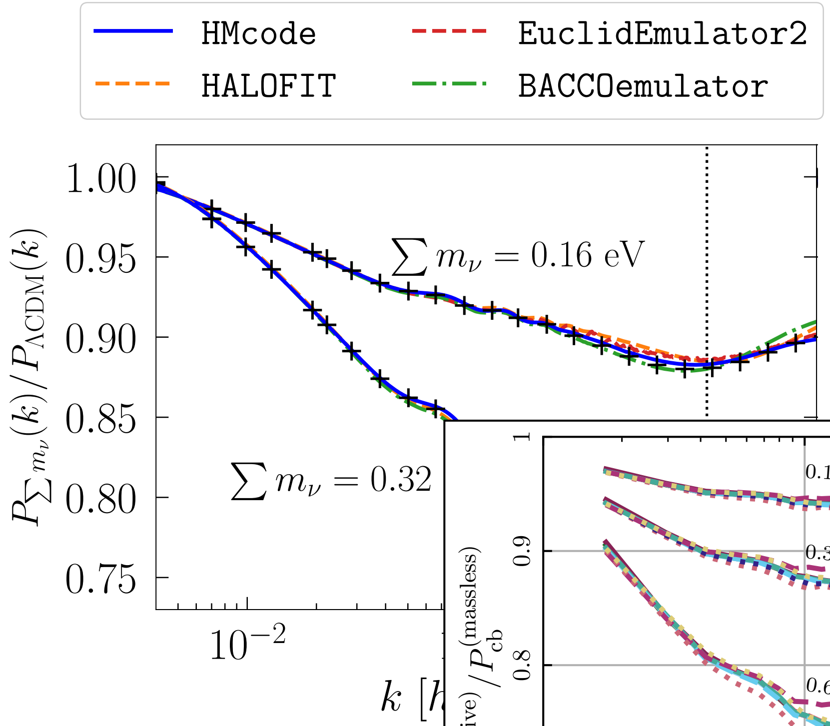

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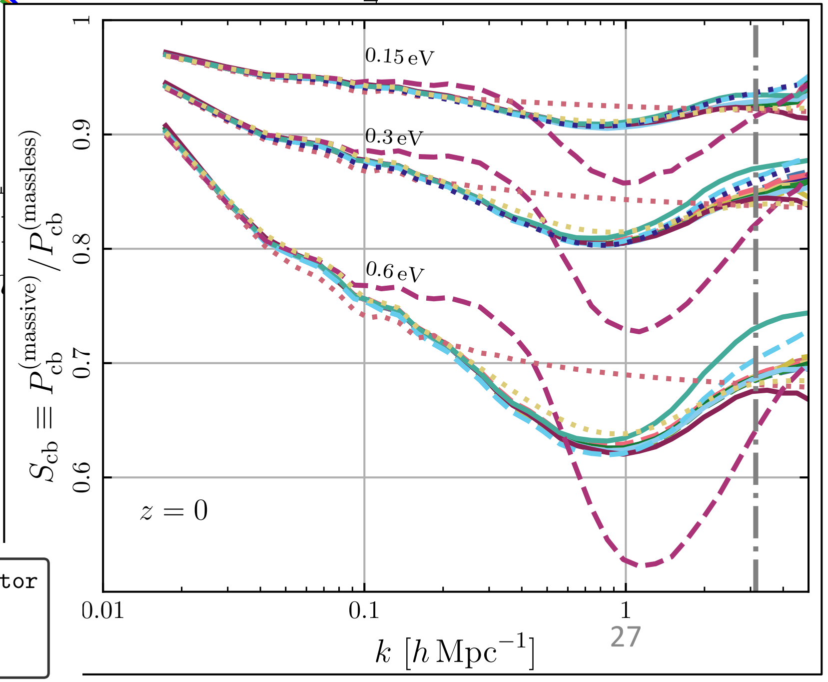

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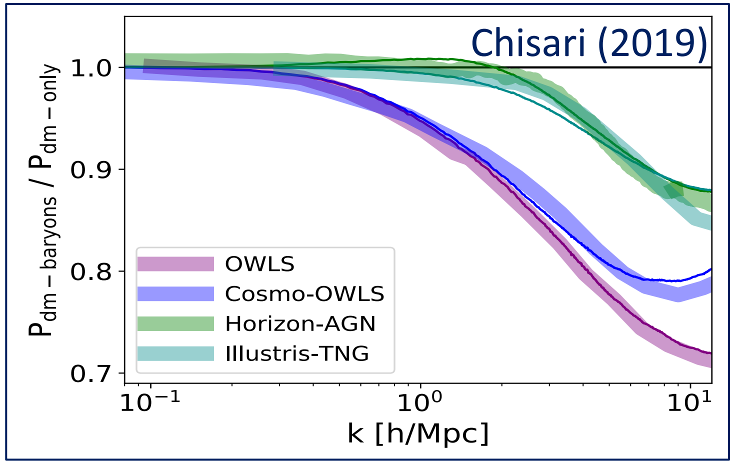

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3. Baryonic feedback [Chisari (2019); Euclid Collaboration: Martinelli et al. (2020); Spurio Mancini et al. (2023); Euclid Collaboration: Archidiacono et al. (2024)]

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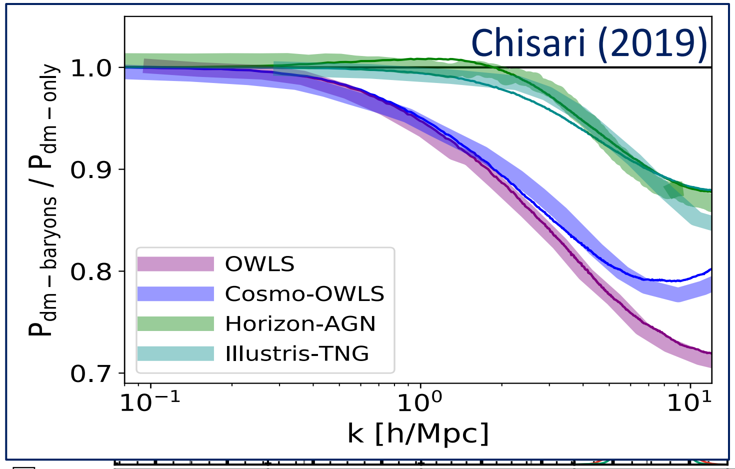
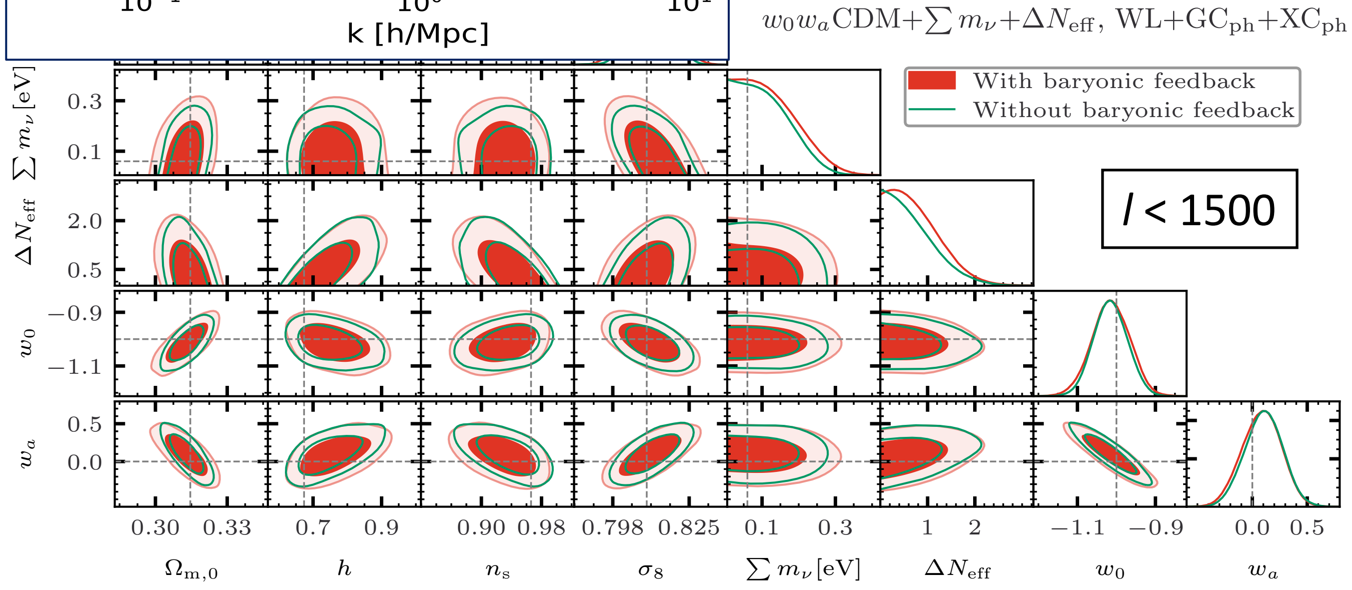
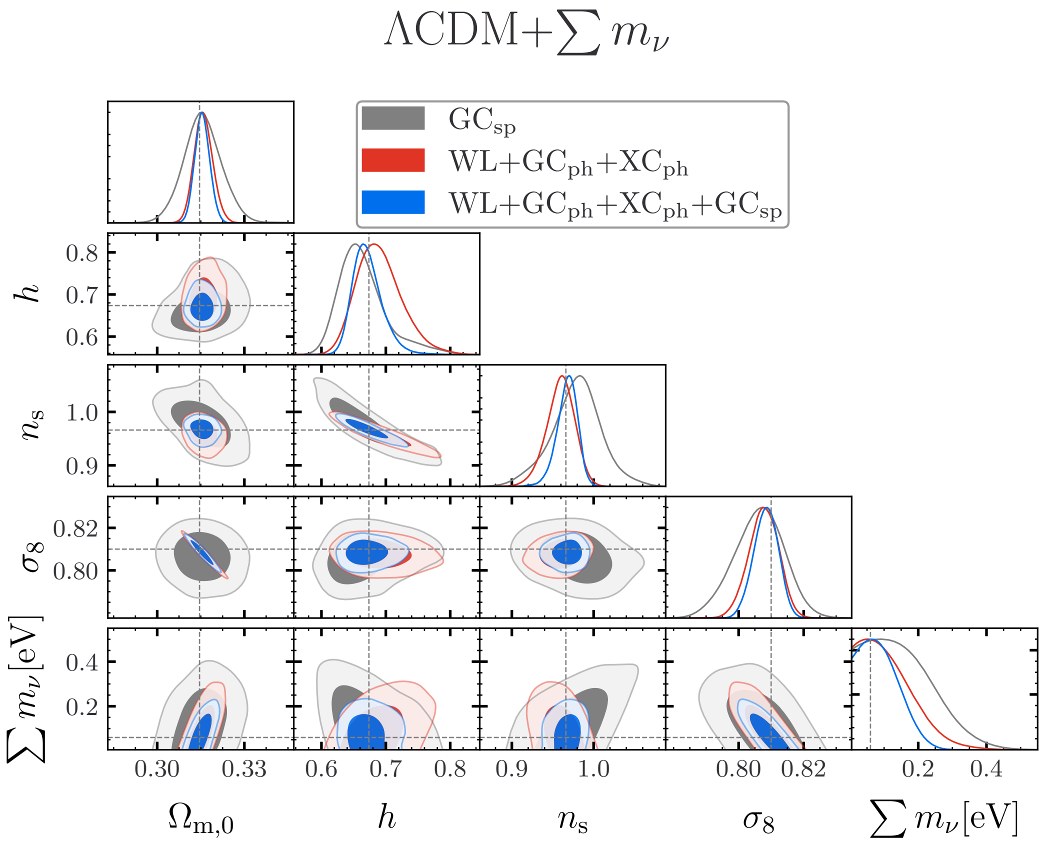
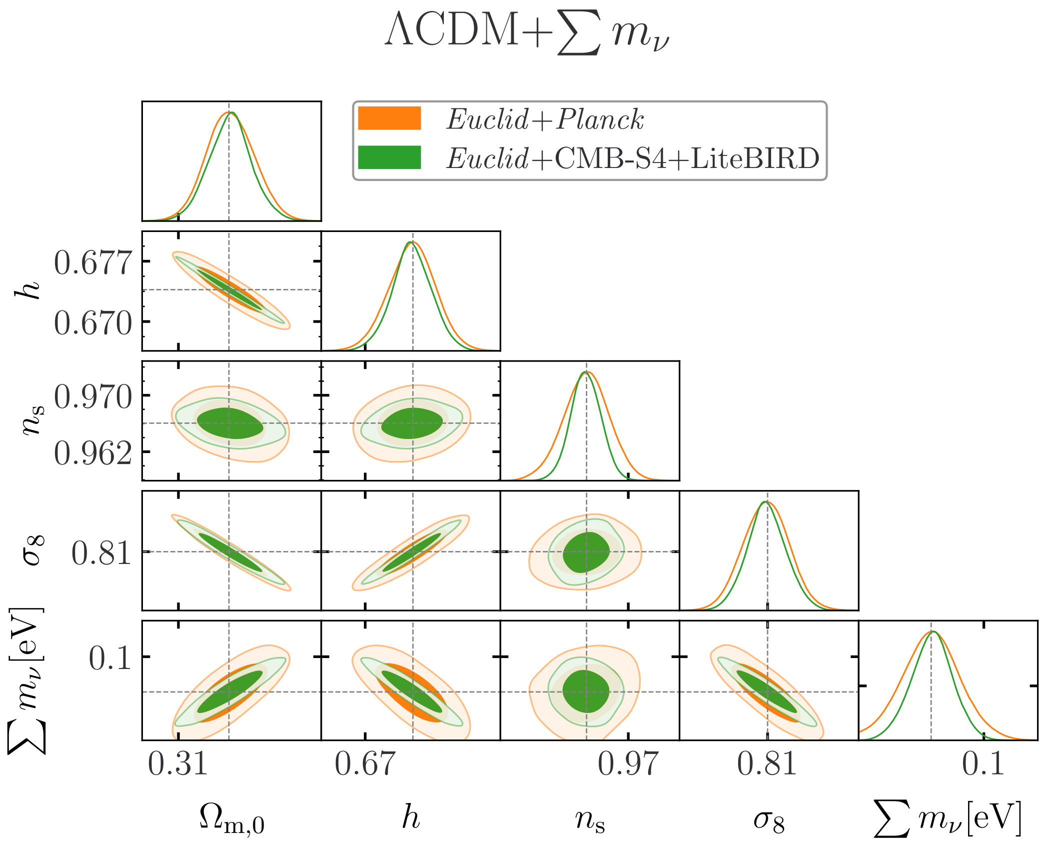




Euclid Collaboration: Archidiacono et al. (2024)

Neutrino mass constraints: the future





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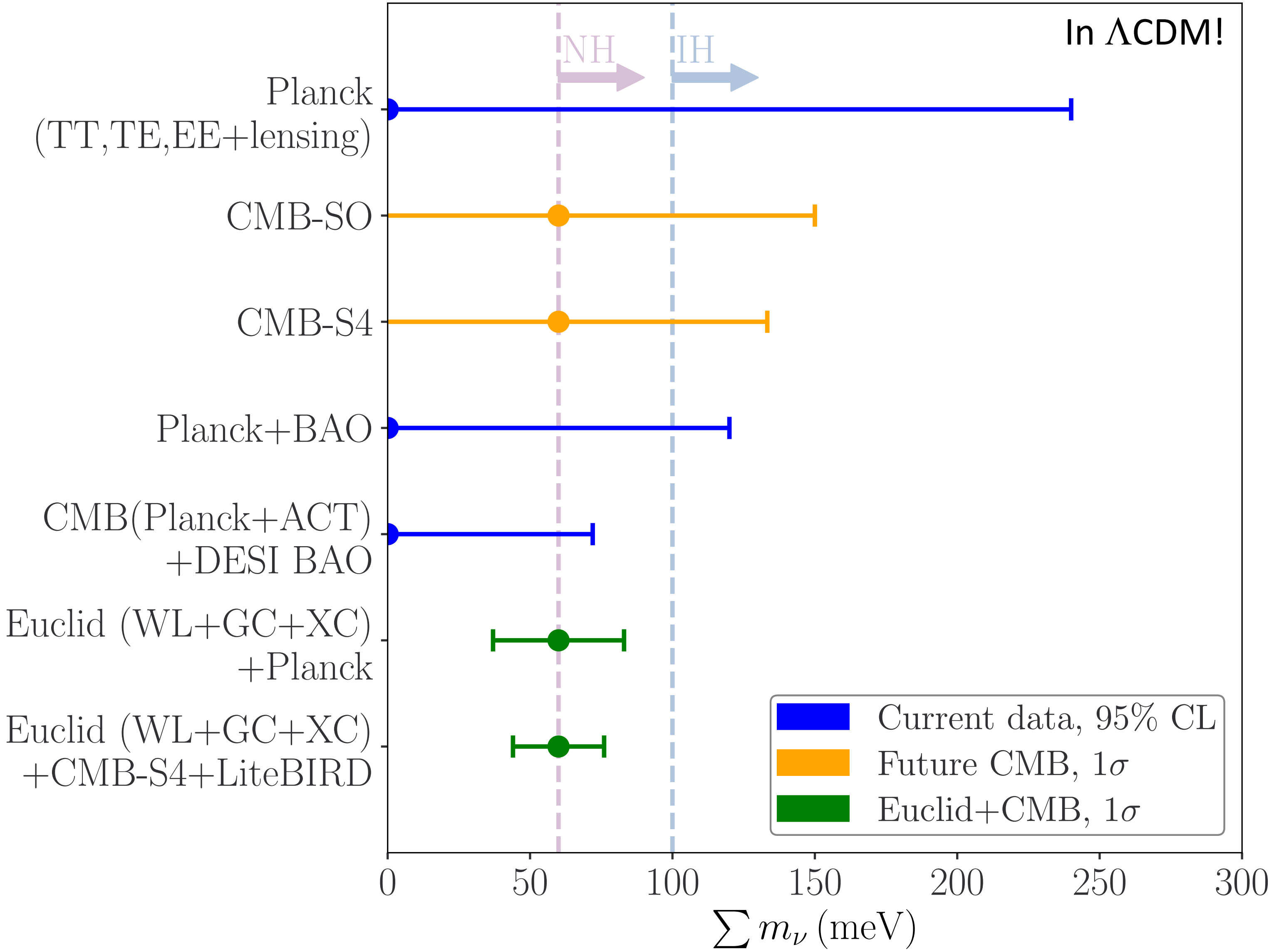
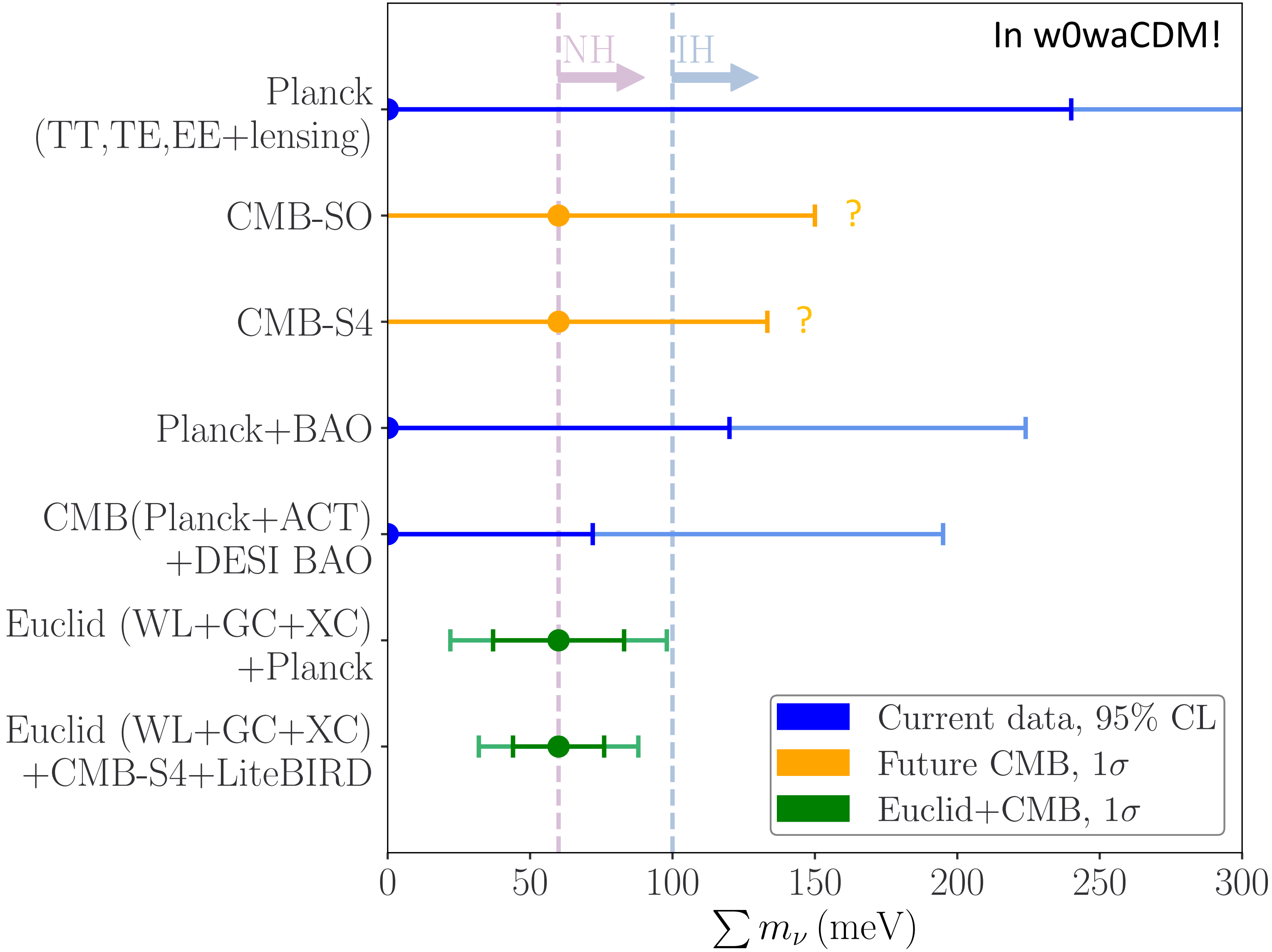


Euclid+Planck: >2σ evidence of a non-zero neutrino mass sum

Euclid+CMB-S4+LiteBIRD: >3σ

Neutrino mass constraints: the future

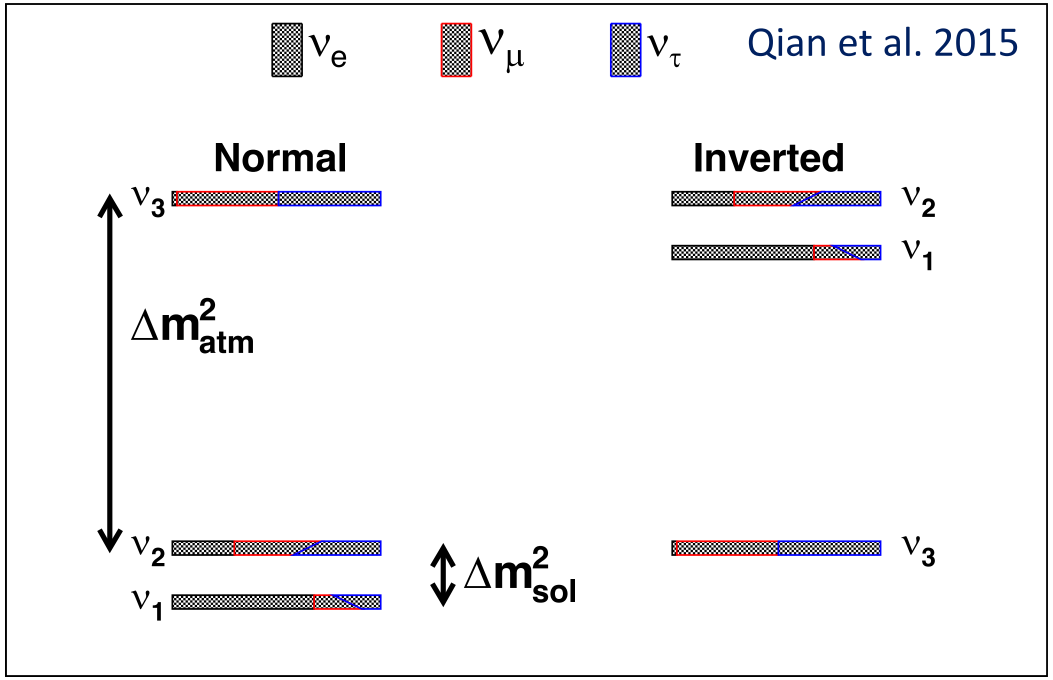


Replacing the cosmological constant with dark energy with a time varying equation of state parameter increases the error by a factor 2.

Neutrino mass ordering

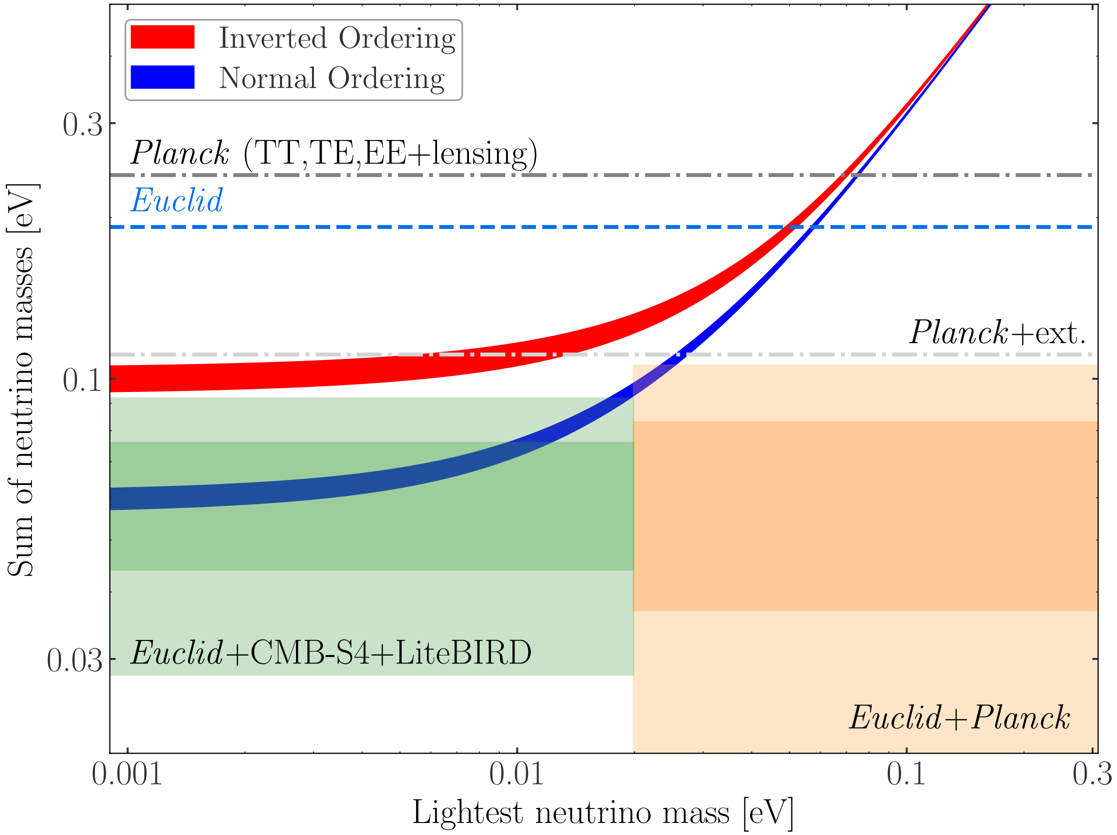
Constraints derived under the assumption $m_1=m_2=m_3$ (degenerate hierarchy, DH)

Neutrino Mass Hierarchy



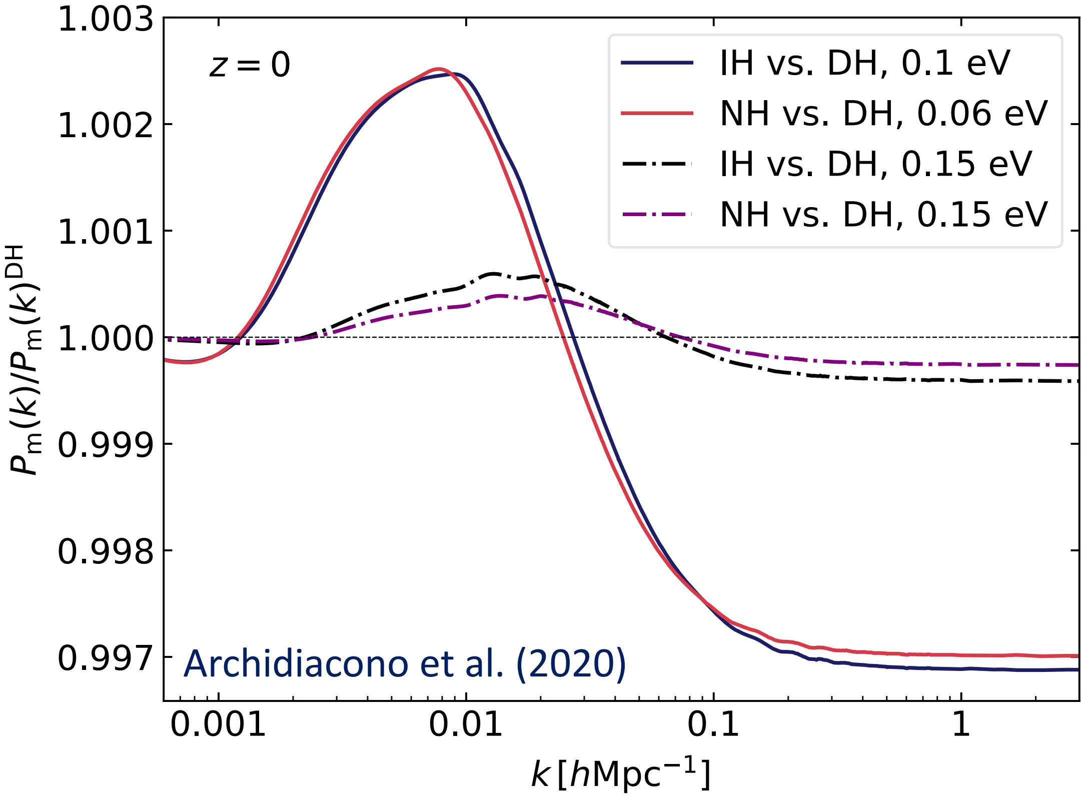
Min. Σm_ν (NH) = 0.058 eV; Min. Σm_ν (IH)= 0.100 eV

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 DH assumption (m_1=m_2=m_3) is valid, and it is more efficient.

See also Gariazzo et al. (2022)

Take home message

- Euclid in combination with upcoming CMB surveys can achieve a 4σ detection of Σm_ν , even if Σm_ν = 0.058 eV
- Cosmology is not directly sensitive to the neutrino mass ordering, like ground-based experiments, 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.
- Open question: What if there is a tension between the Cosmos and the Lab?

Stay tuned