What cosmology can tell us about neutrinos

Maria Archidiacono

UNIVERSITÀ DEGLI STUDI DI MILANO

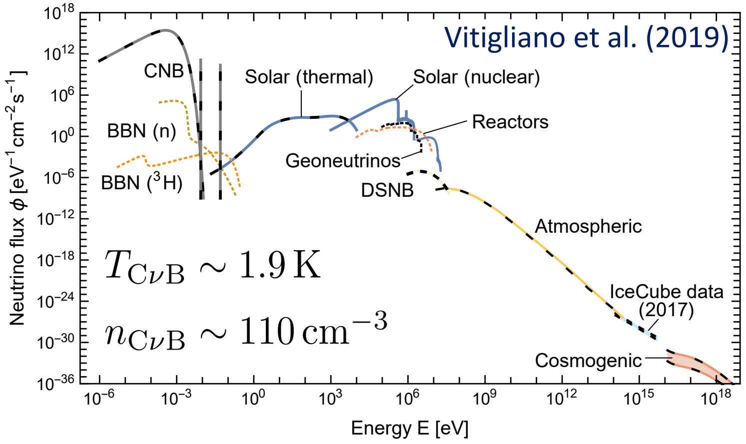
Euclid consortium

XXXI International Conference on Neutrino Physics and Astrophysics
June 16-22, 2024, Milan

A short cosmic history

A short cosmic history

Cosmic Neutrino Background (T~1MeV)



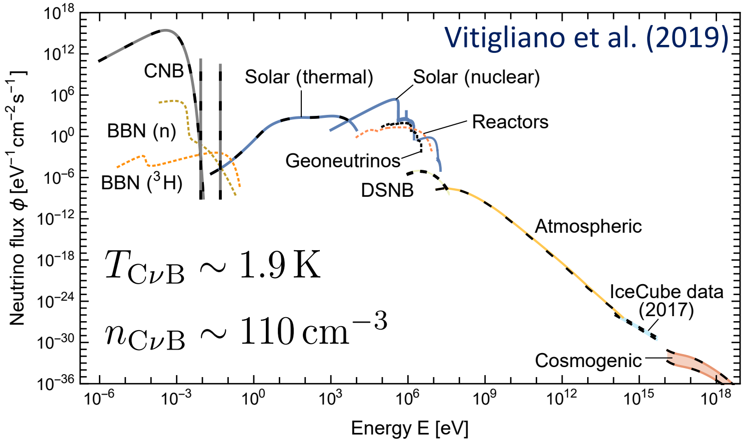
➔ Direct detection not in the near future

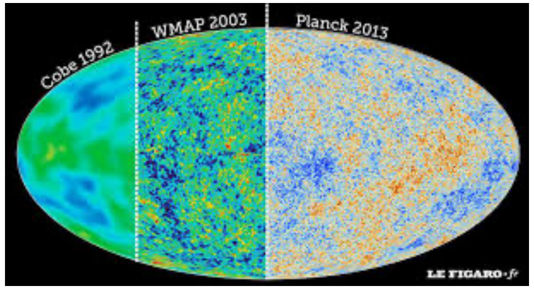
➔ Footprints in cosmological observables

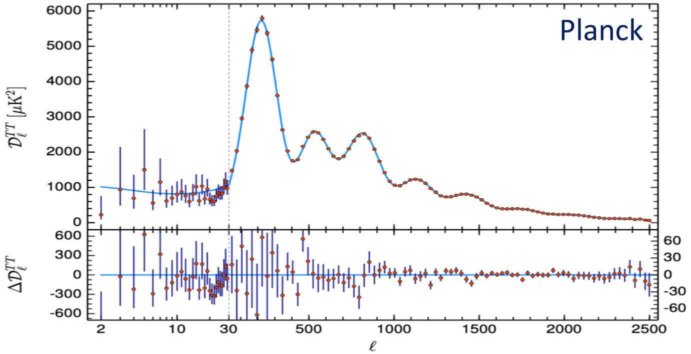
A short cosmic history

Cosmic Neutrino Background (T~1MeV)

Cosmic Microwave Background (T~0.2eV)







➔ Direct detection not in the near future

➔ Footprints in cosmological observables

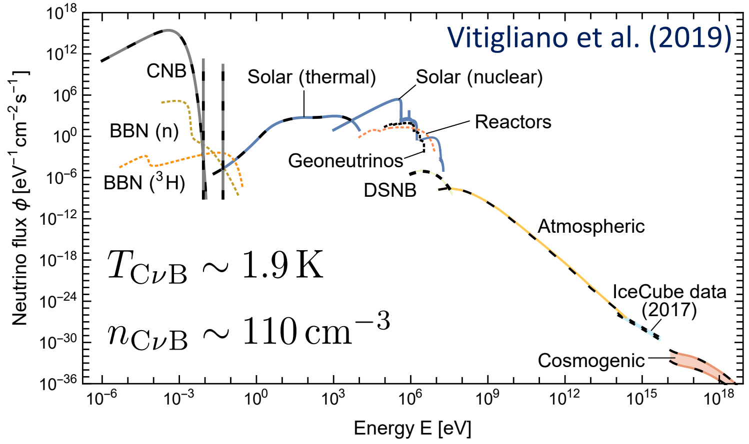
A short cosmic history

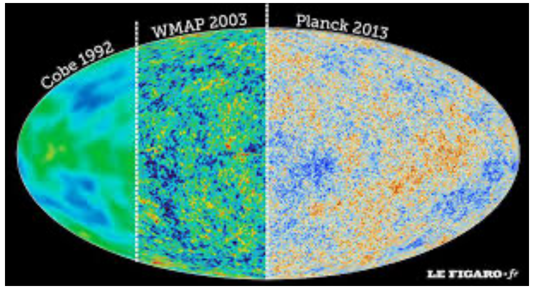
10^{-32} seconds | 1 second | 100 seconds | 380 000 years | 300–500 million years | Billions of years | 13.8 billion years

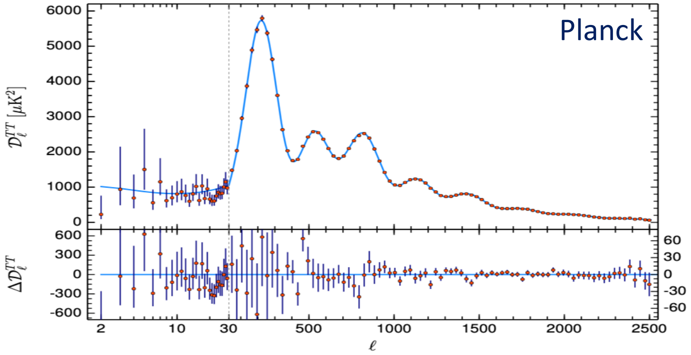
Cosmic Neutrino Background (T~1MeV)

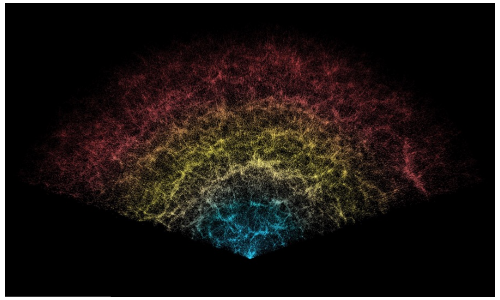
Cosmic Microwave Background (T~0.2eV)

Structure formation (LSS)

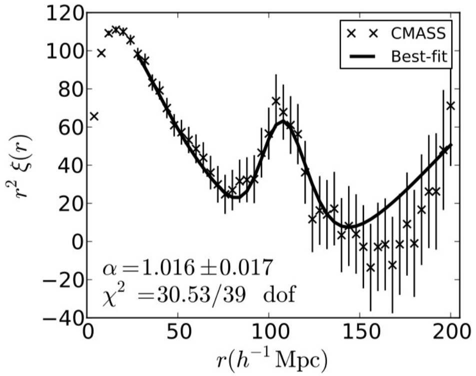


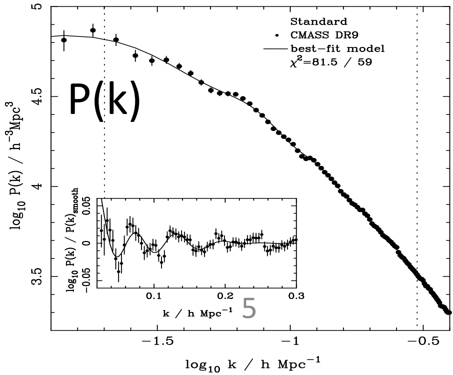






BAO

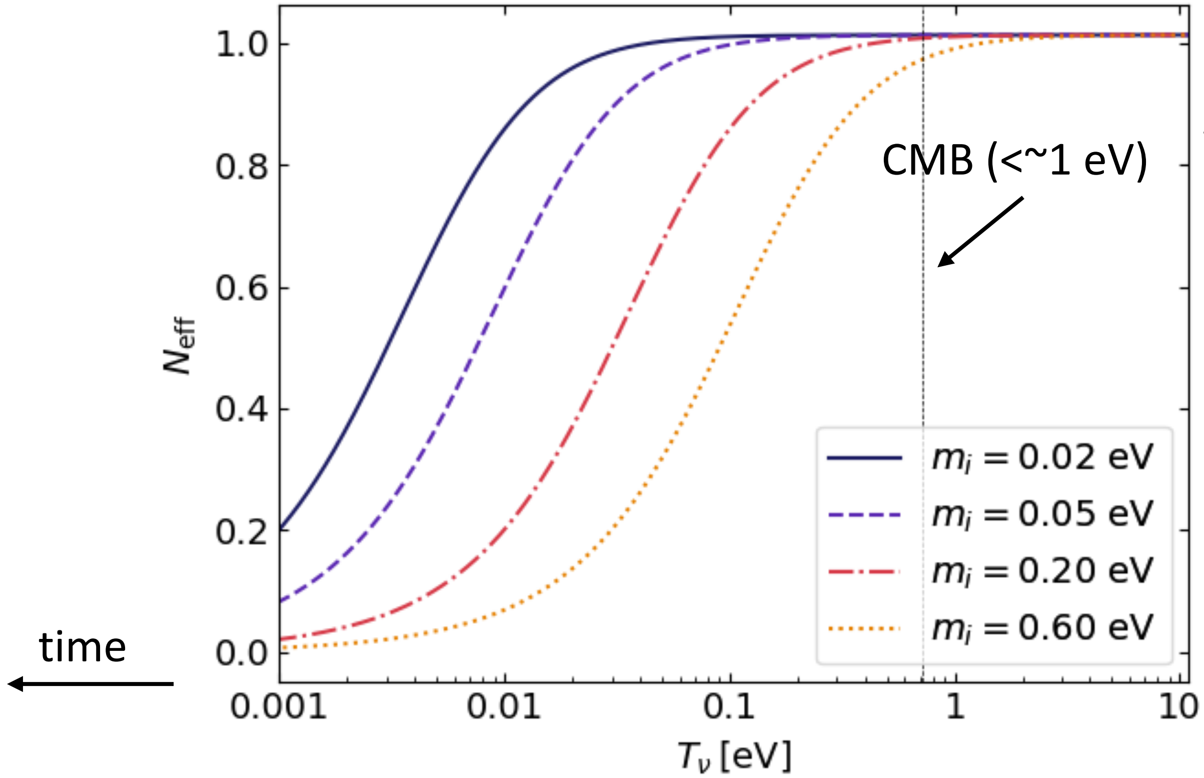




➔ Direct detection not in the near future

➔ Footprints in cosmological observables

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_{eff} = (energy density of neutrinos + BSM light particles) / (energy density of one neutrino species)

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

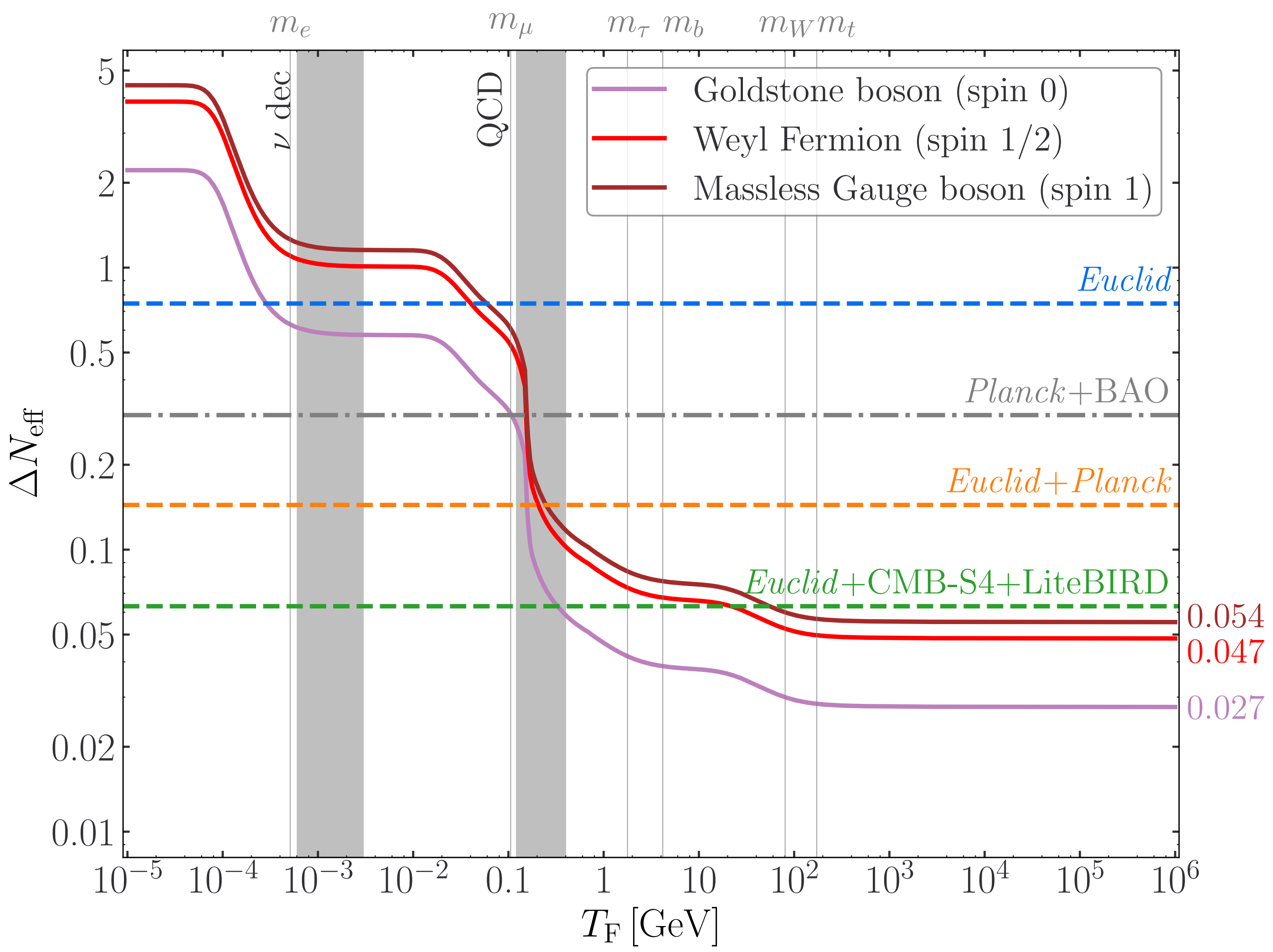
Talk by Stefano Gariazzo

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

N_{eff} = 3.10 ± 0.17 (95% CL)

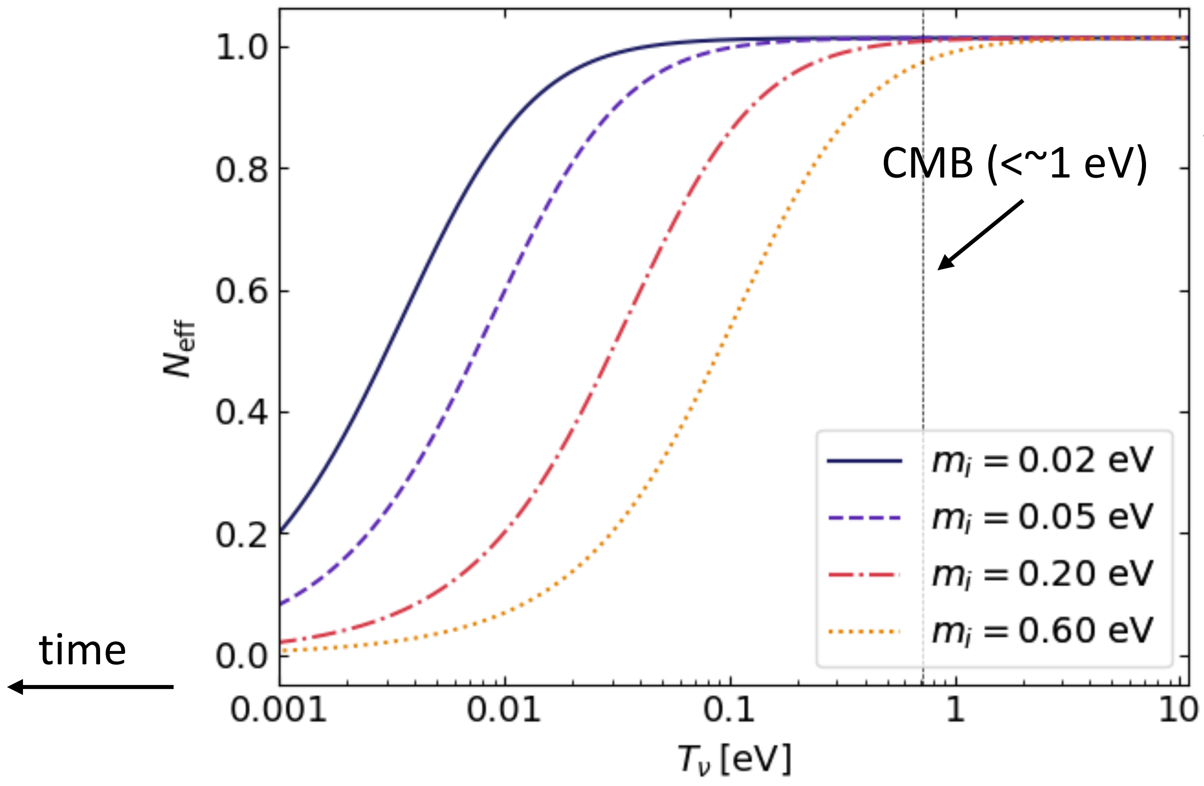
Bounds on new light particles (ΔN_{eff})

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



Euclid Collaboration: Archidiacono et al. (2024)

The duality of the CνB



Early times: neutrinos as **radiation**

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

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

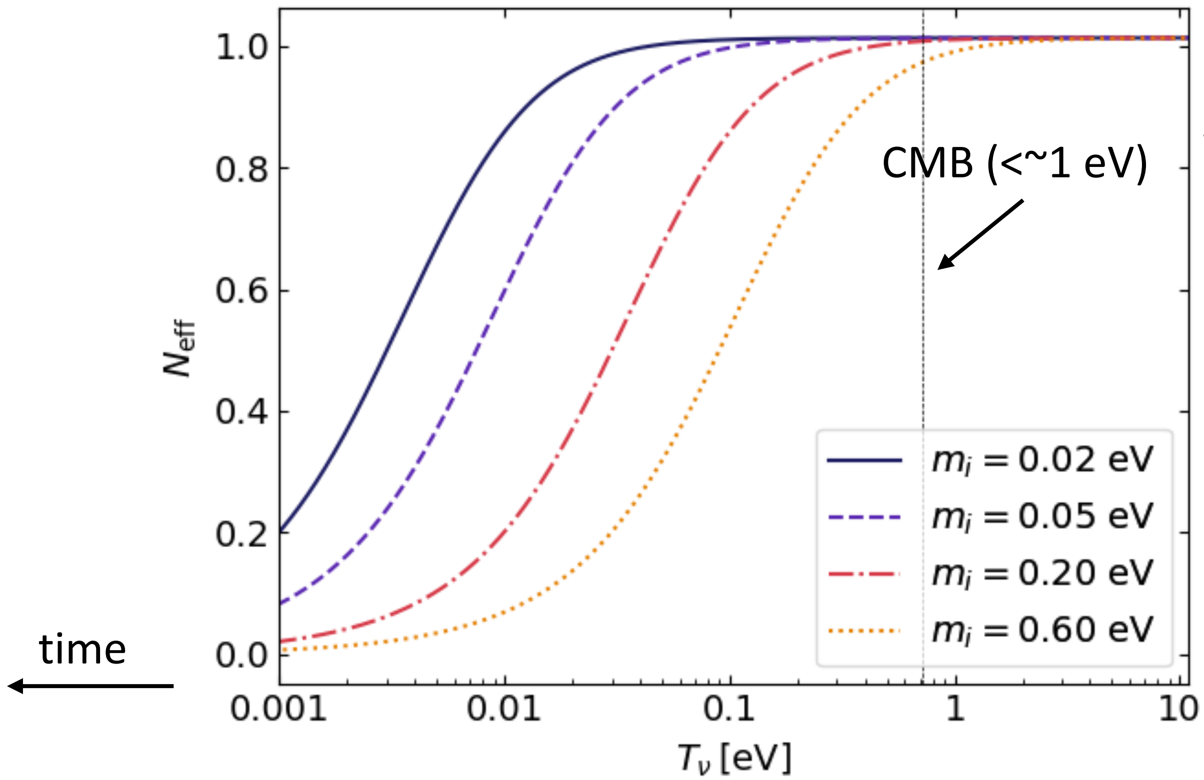
For the 3 neutrino families of the SM: $N_{eff}^{SM} = 3.044$

Talk by Stefano Gariazzo

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

$N_{eff} = 3.10 \pm 0.17$ (95% CL)

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_{eff} = (energy density of neutrinos + BSM light particles) / (energy density of one neutrino species)

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

Talk by Stefano Gariazzo

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

$N_{eff} = 3.10 \pm 0.17$ (95% CL)

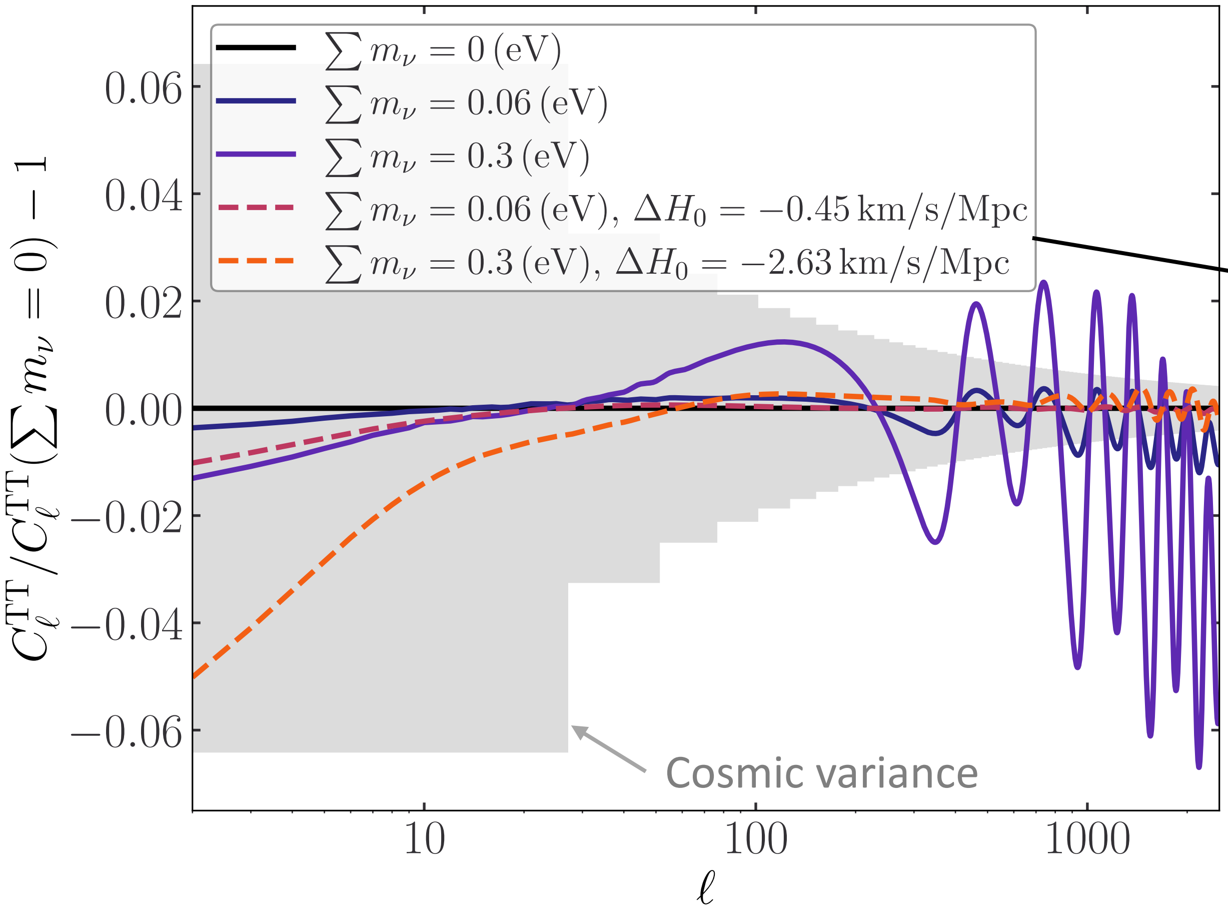
Late times (after CMB formation): neutrinos as **matter** (contributing to dark matter as hot dark matter)

- 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)]

  not individual masses [Archidiacono et al. (2020)]

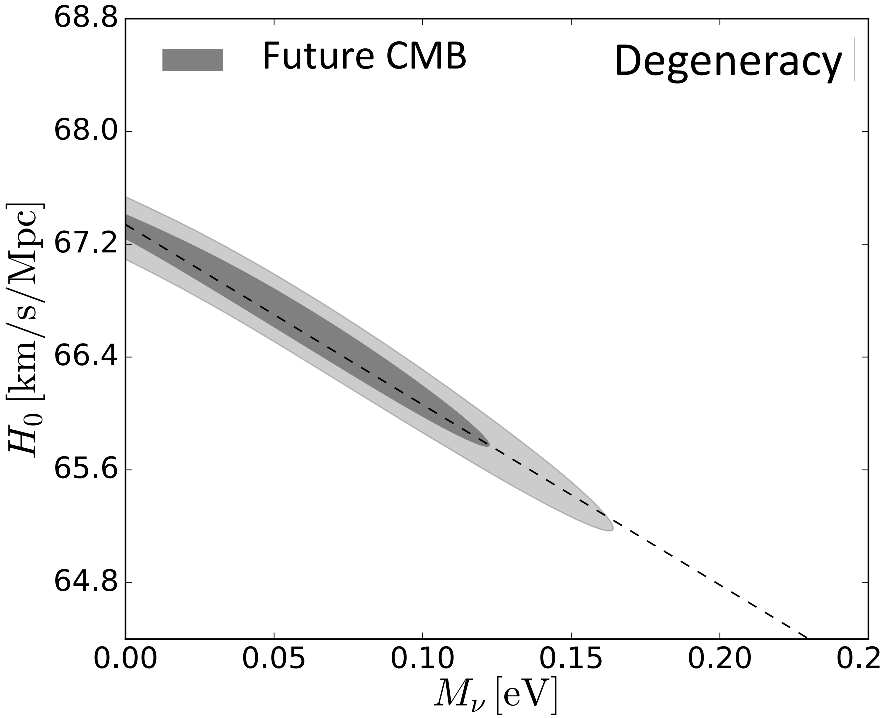
Detecting the neutrino mass in the CνB

Neutrino mass probes: CMB

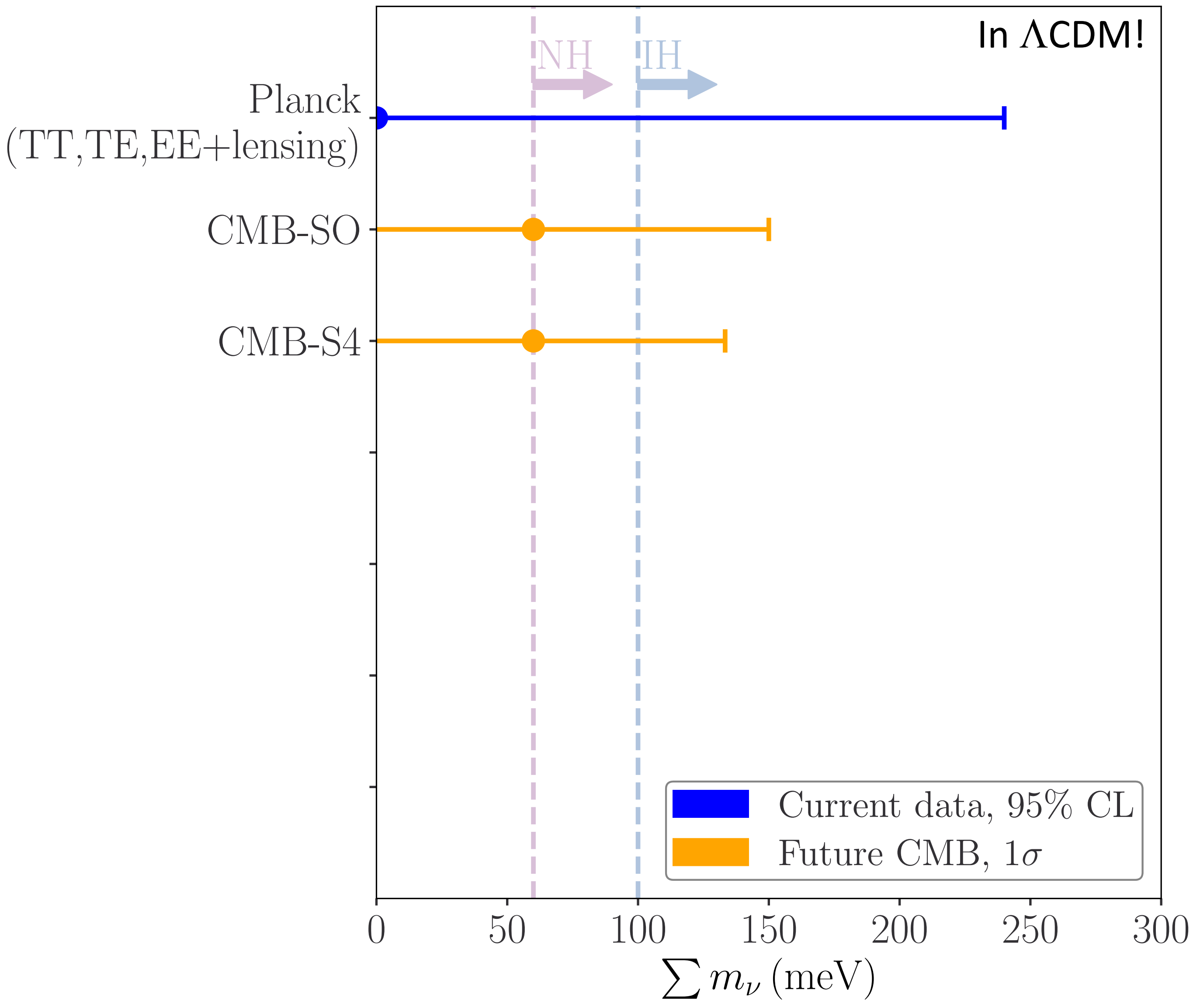


- Background effects
- Perturbation effects

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



Neutrino mass constraints: CMB



KATRIN: Σm_ν <~ 1.5 eV

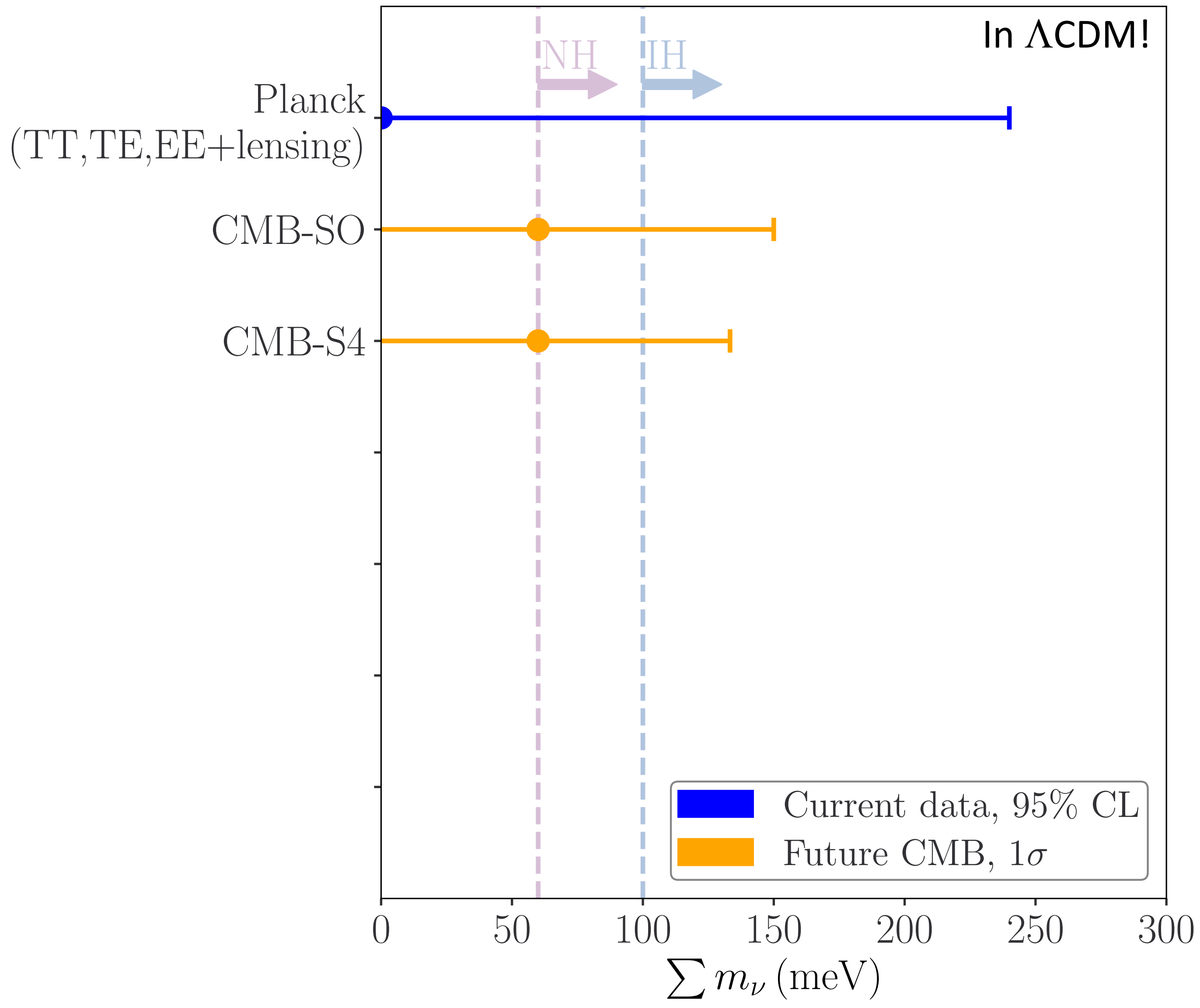
Fiducial value:

- Σm_ν = 58 meV

CMB alone will not be able

to detect the neutrino mass

Neutrino mass constraints: CMB



KATRIN: Σm_ν <~ 1.5 eV

Fiducial value:

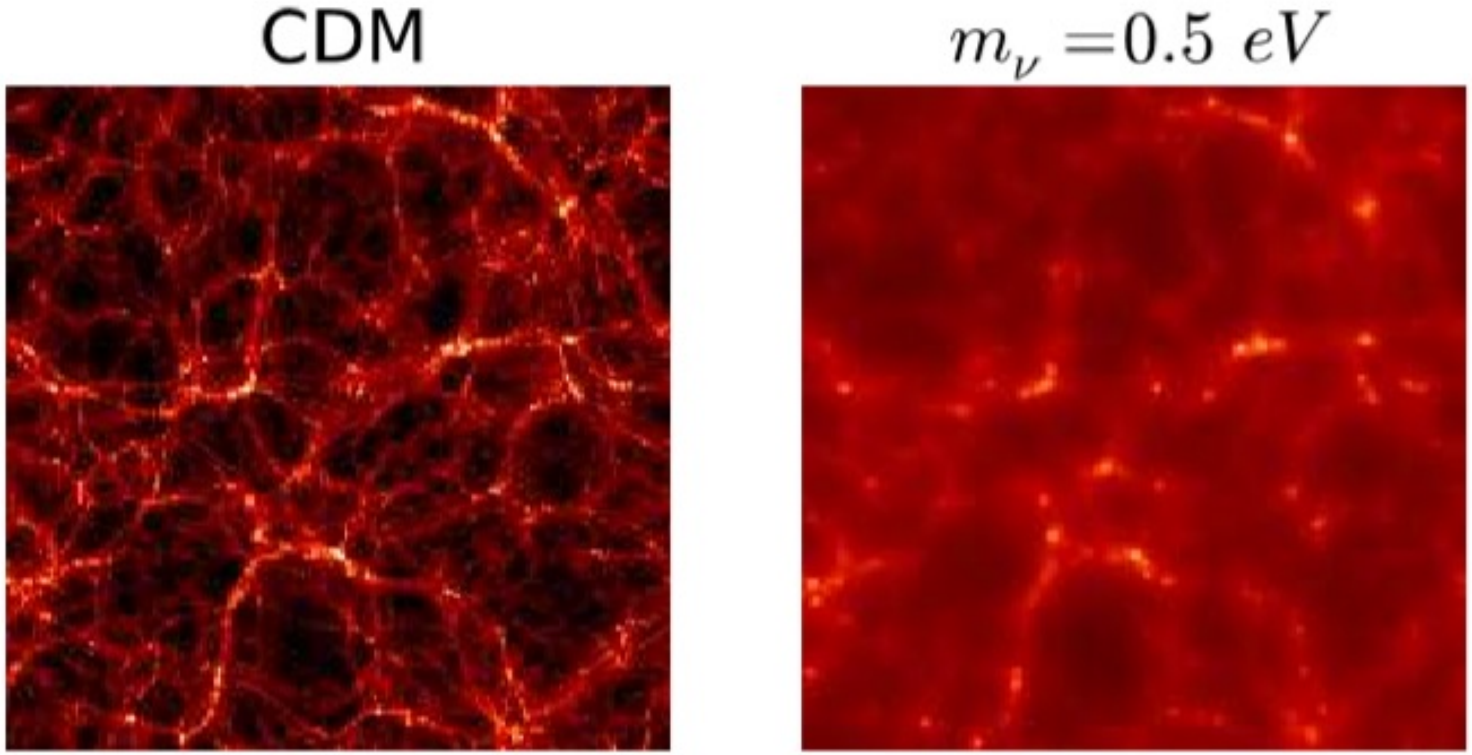
- Σm_ν = 58 meV

CMB alone will not be able to detect the neutrino mass

→ Large Scale Structures

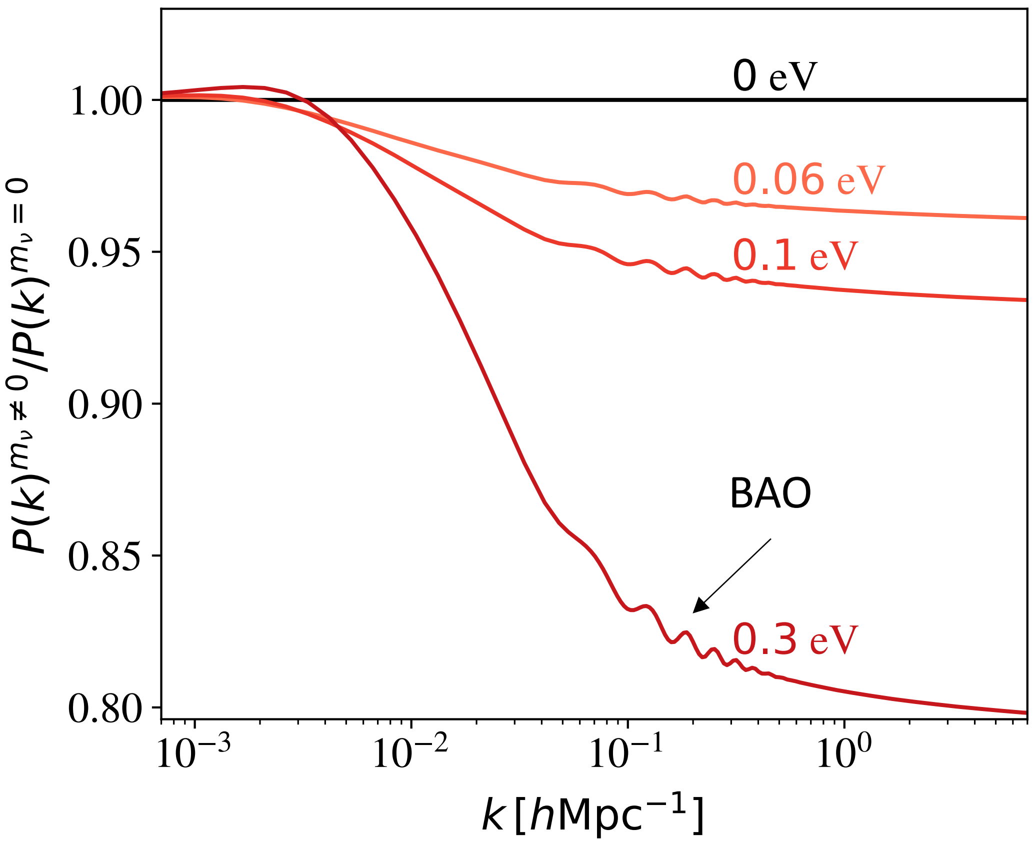
Neutrino mass probes: LSS

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

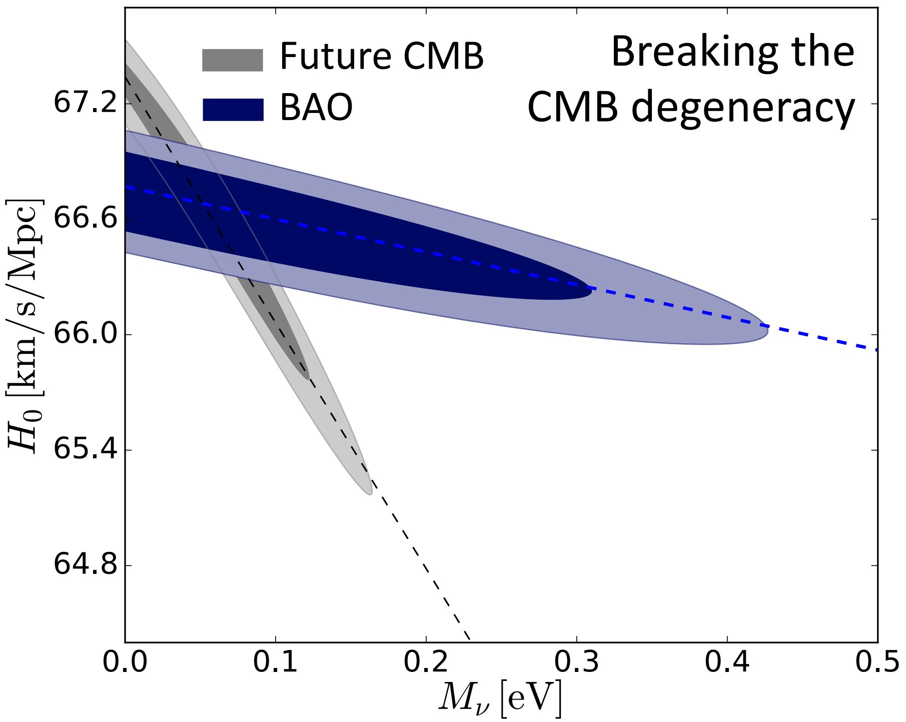


Villaescusa Navarro et al. (2013)

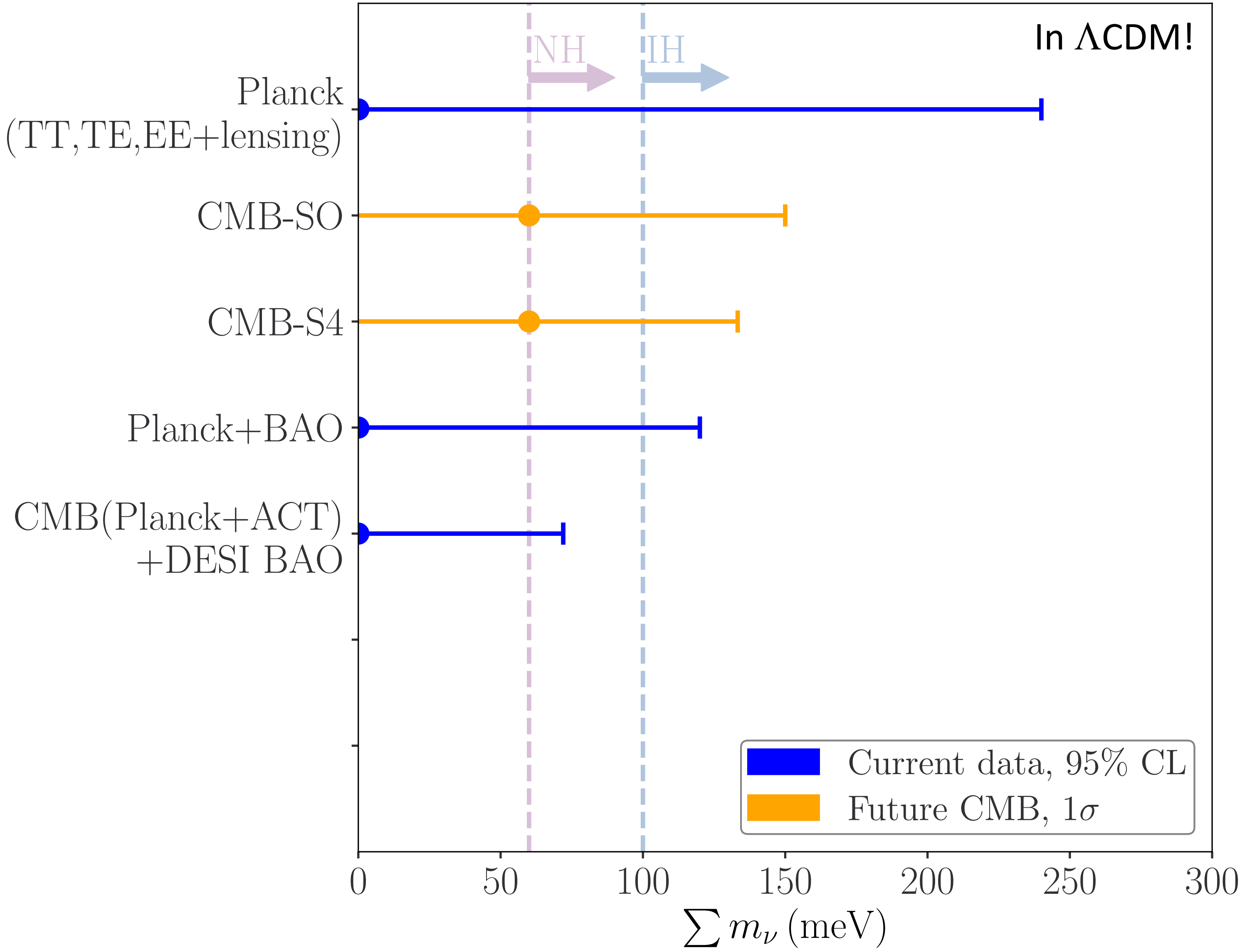
Neutrino mass probes: LSS



- Massive neutrinos do not cluster
- Massive neutrinos slow down the growth of CDM perturbations
  - Massless neutrino Universe $\delta_{\rm cdm}^{m_\nu=0} \propto a$
  - Massive neutrino Universe $\delta_{\rm cdm}^{m_\nu\neq0} \propto a^{1-\frac{3}{5}\frac{\Omega_\nu}{\Omega_m}}$



Neutrino mass constraints: CMB+LSS

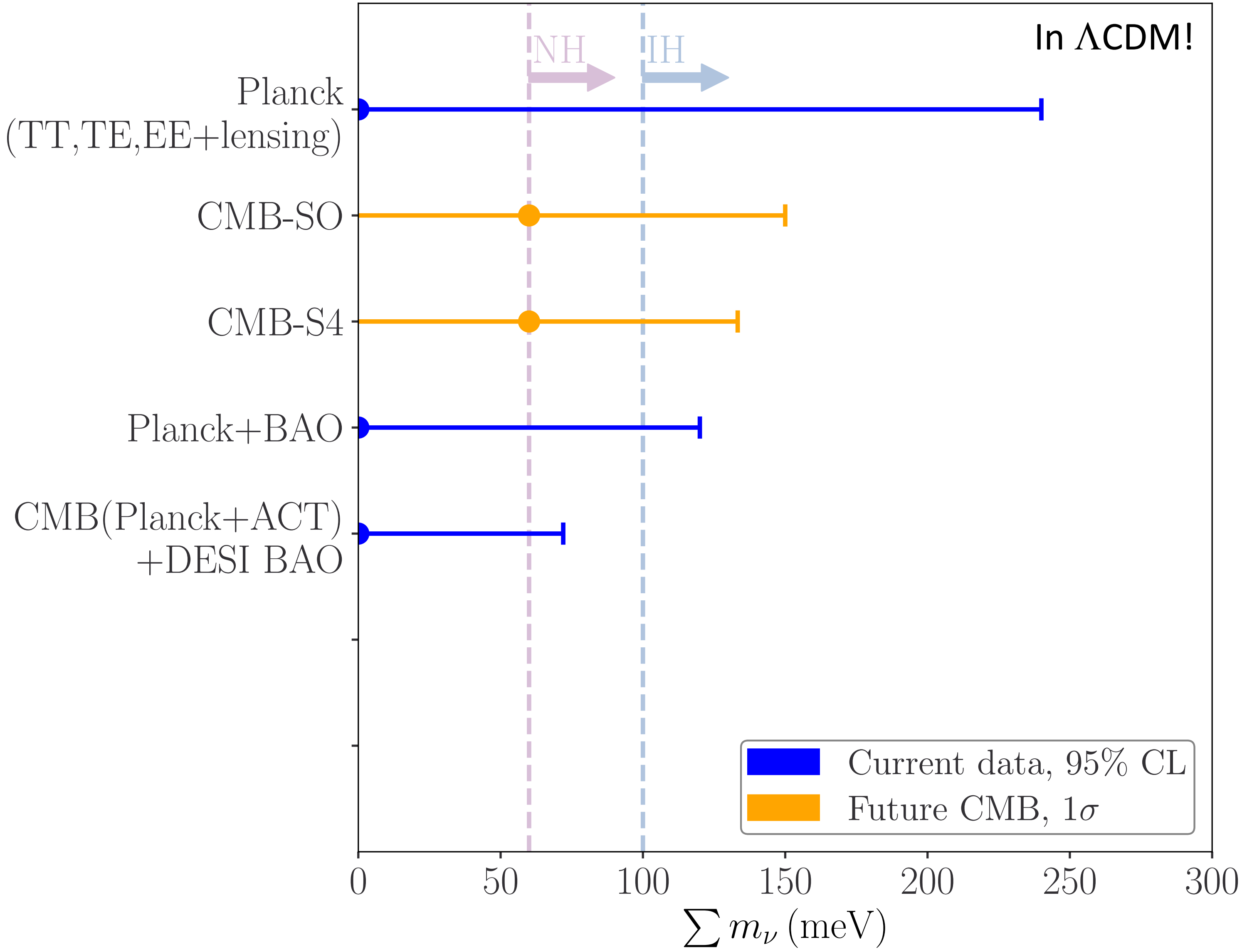


Σm_ν < 72 meV, 95% CL

[DESI Collaboration (2024)]

Talk by Willem Elbers

Neutrino mass constraints: CMB+LSS



Σm_ν < 72 meV, 95% CL
[DESI Collaboration (2024)]
Talk by Willem Elbers

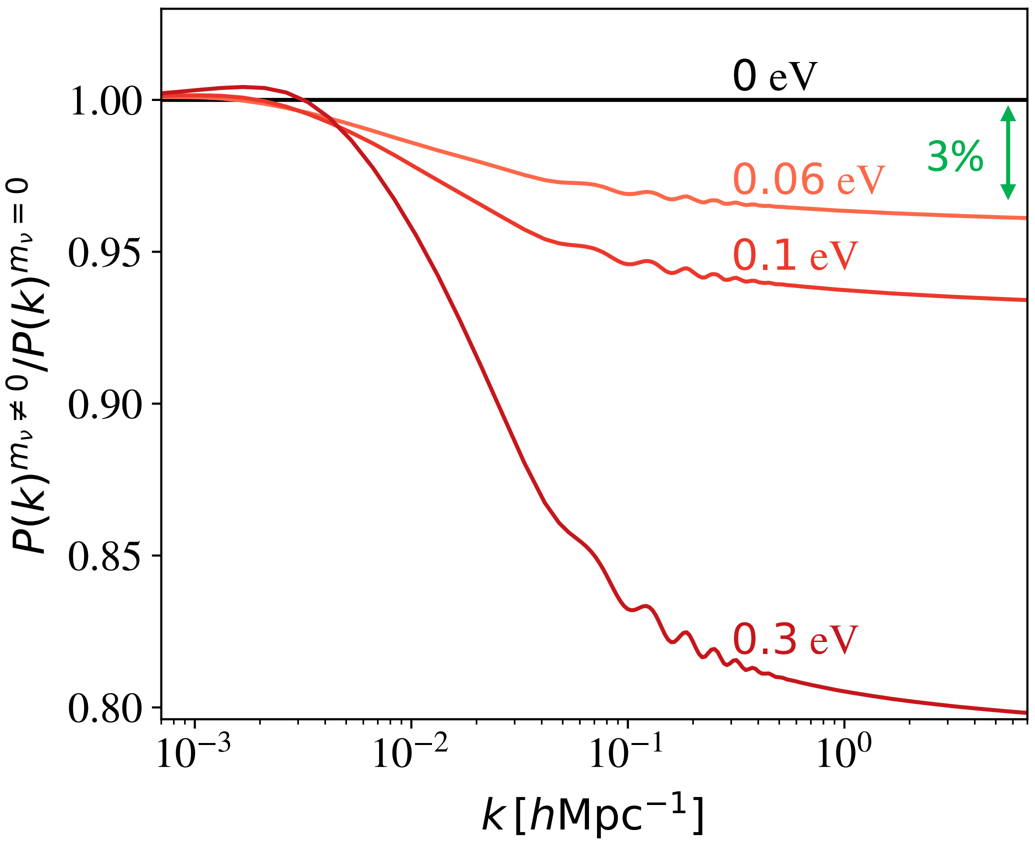
Still no evidence/detection!

Euclid in a nutshell

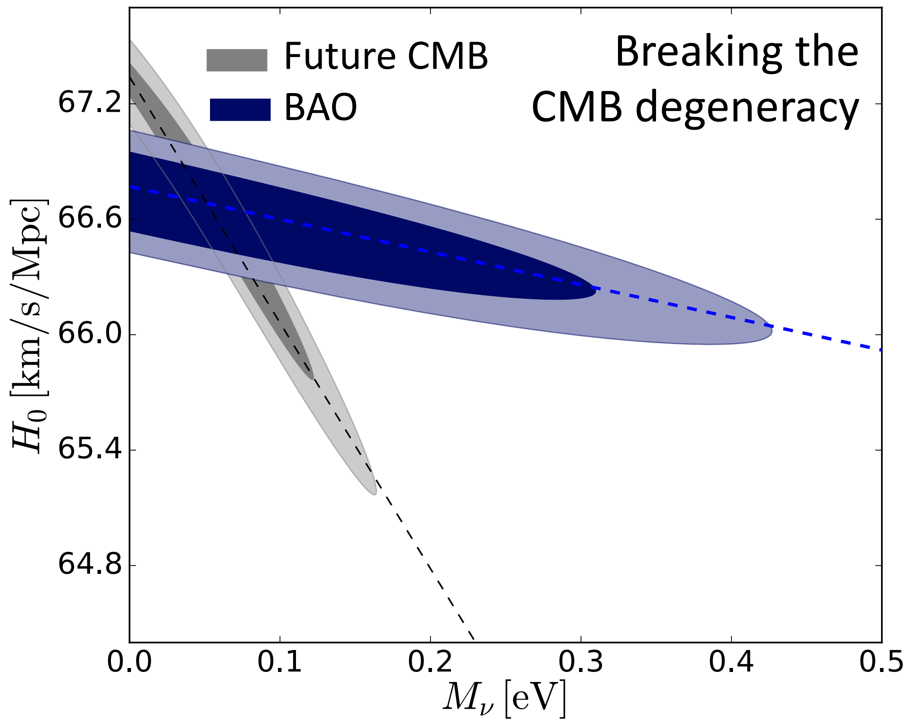
- **ESA** M2 space mission in the framework of the Cosmic Vision program
- Launch **July 1st 2023**. Duration **> 6 years**
- 1.2m telescope with two instruments: Visible Imager (**VIS**) and Near Infrared Spectrometer and Photometer (**NISP**)
- Wide survey (**14.000 deg^2**) and deep survey (40 deg^2 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**

→<u>1% accuracy on P(k)</u>

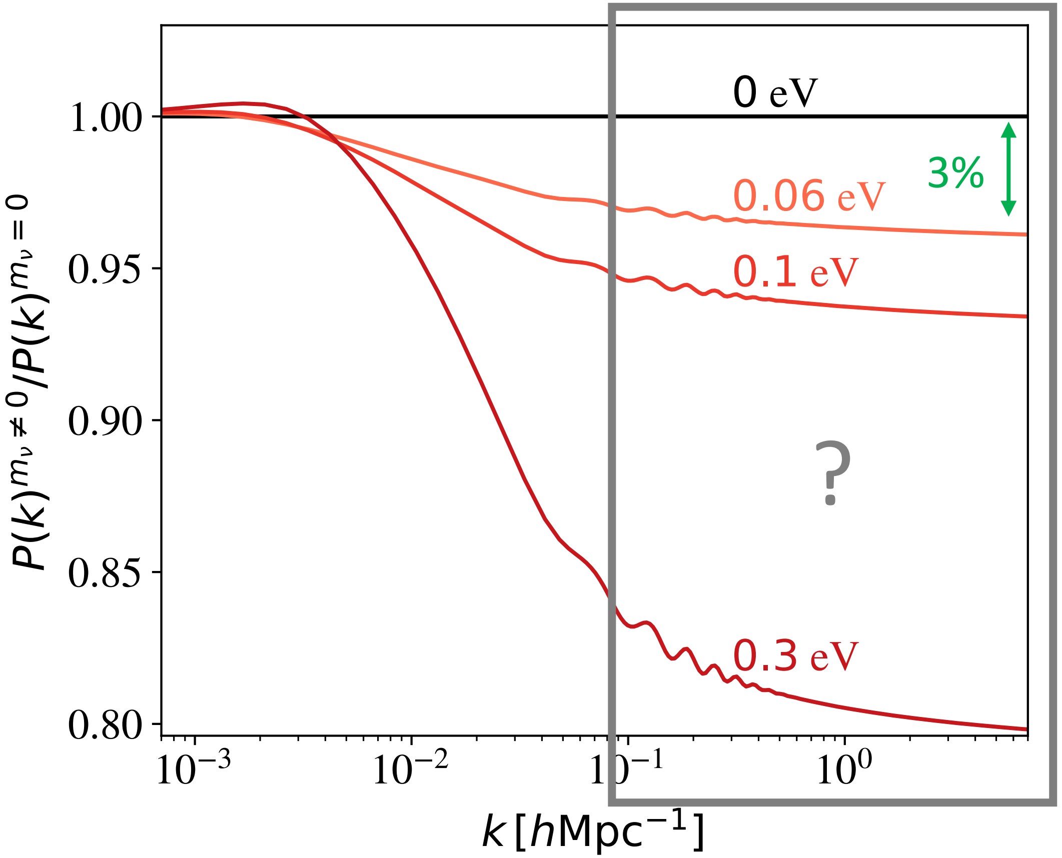
Neutrino mass probes: LSS



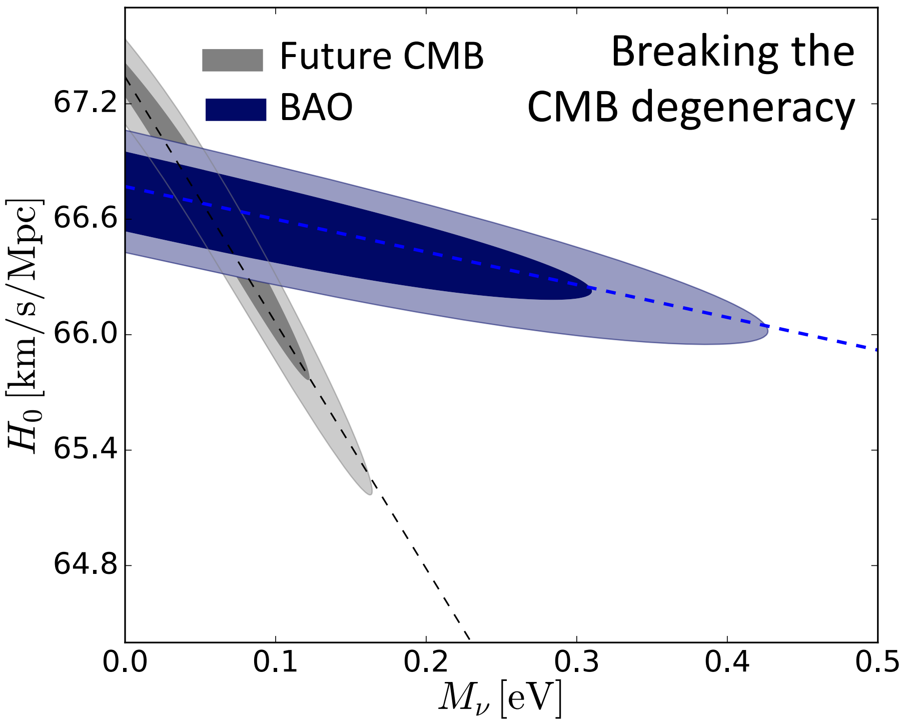
- Massive neutrinos do not cluster
- Massive neutrinos slow down the growth of CDM perturbations
  - Massless neutrino Universe $\delta_{\rm cdm}^{m_\nu=0} \propto a$
  - Massive neutrino Universe $\delta_{\rm cdm}^{m_\nu\neq0} \propto a^{1-\frac{3}{5}\frac{\Omega_\nu}{\Omega_m}}$



Neutrino mass probes: LSS



- Massive neutrinos do not cluster
- Massive neutrinos slow down the growth of CDM perturbations
  - Massless neutrino Universe $\delta_{\mathrm{cdm}}^{m_\nu=0} \propto a$
  - Massive neutrino Universe $\delta_{\mathrm{cdm}}^{m_\nu\neq0} \propto a^{1-\frac{3}{5}\frac{\Omega_\nu}{\Omega_m}}$



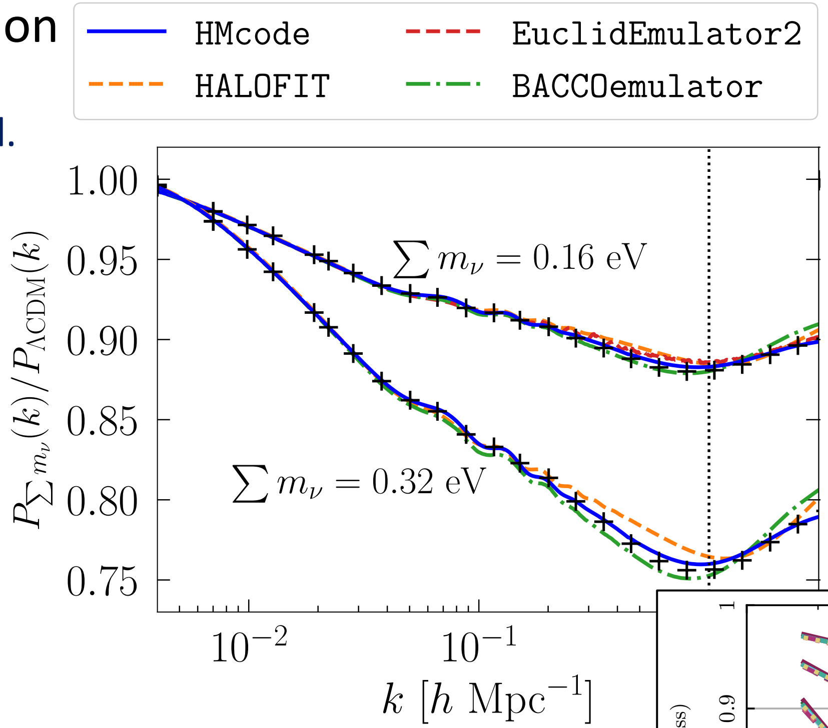
Known unknowns (systematics, etc.)

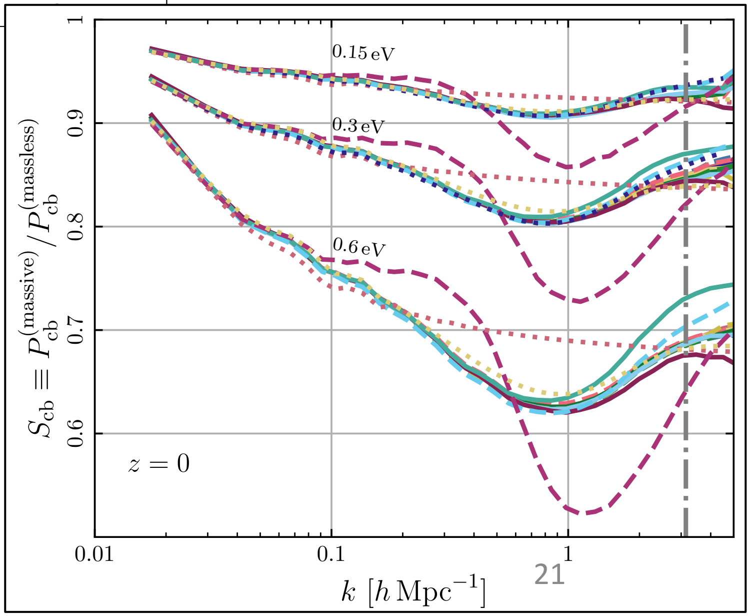
The 1% challenge on the theoretical prediction

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

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

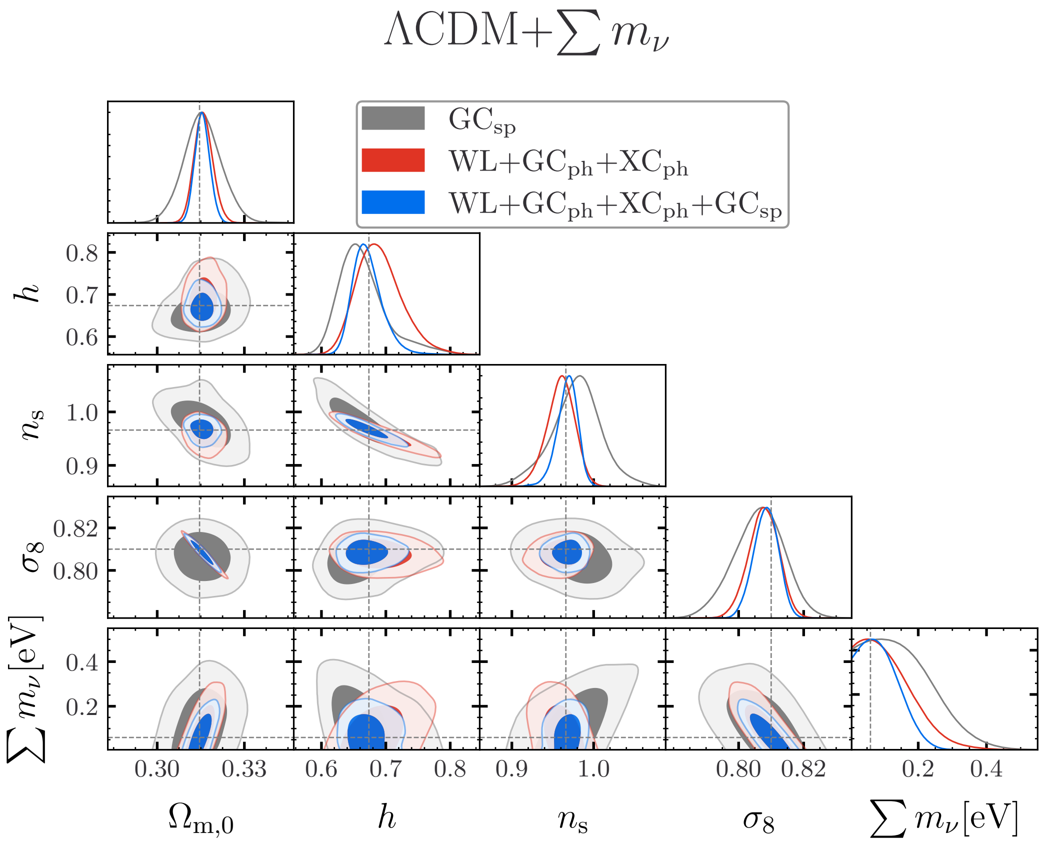
3. Baryonic feedback [Chisari (2019); Euclid Collaboration: Martinelli et al. (2020); Spurio Mancini et al. (2023)]

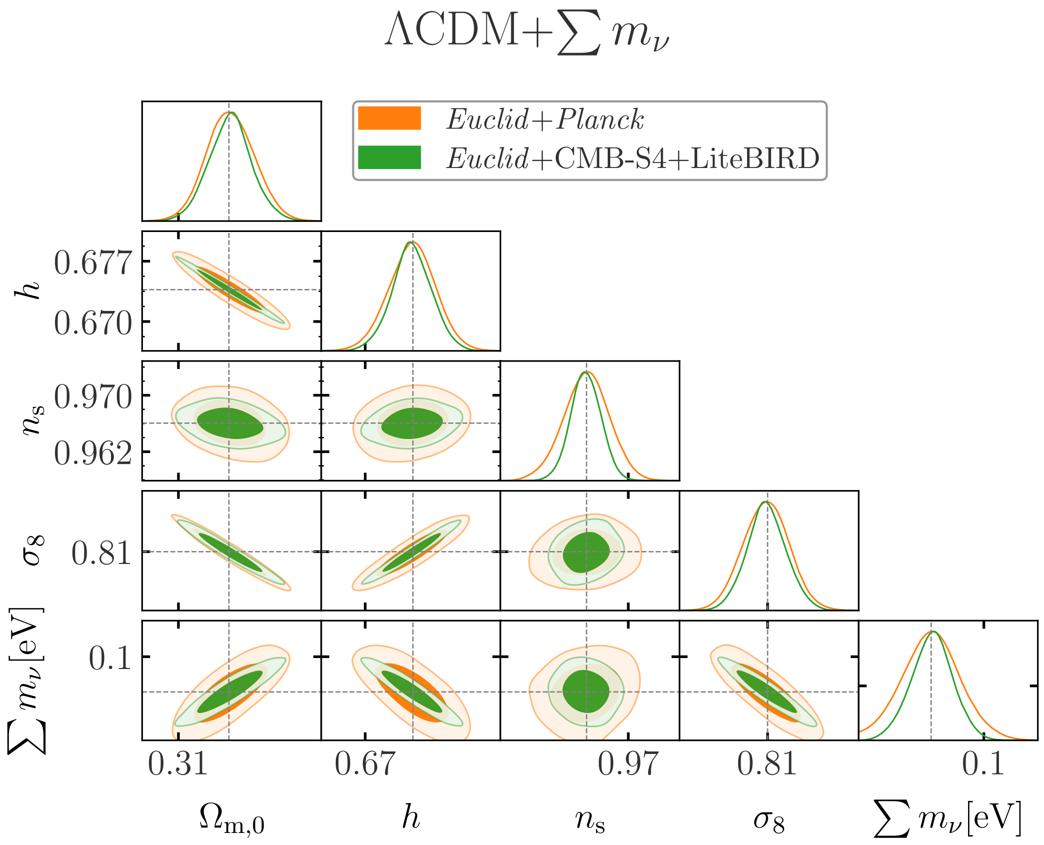




Euclid Collaboration: Adamek et al. (2023)

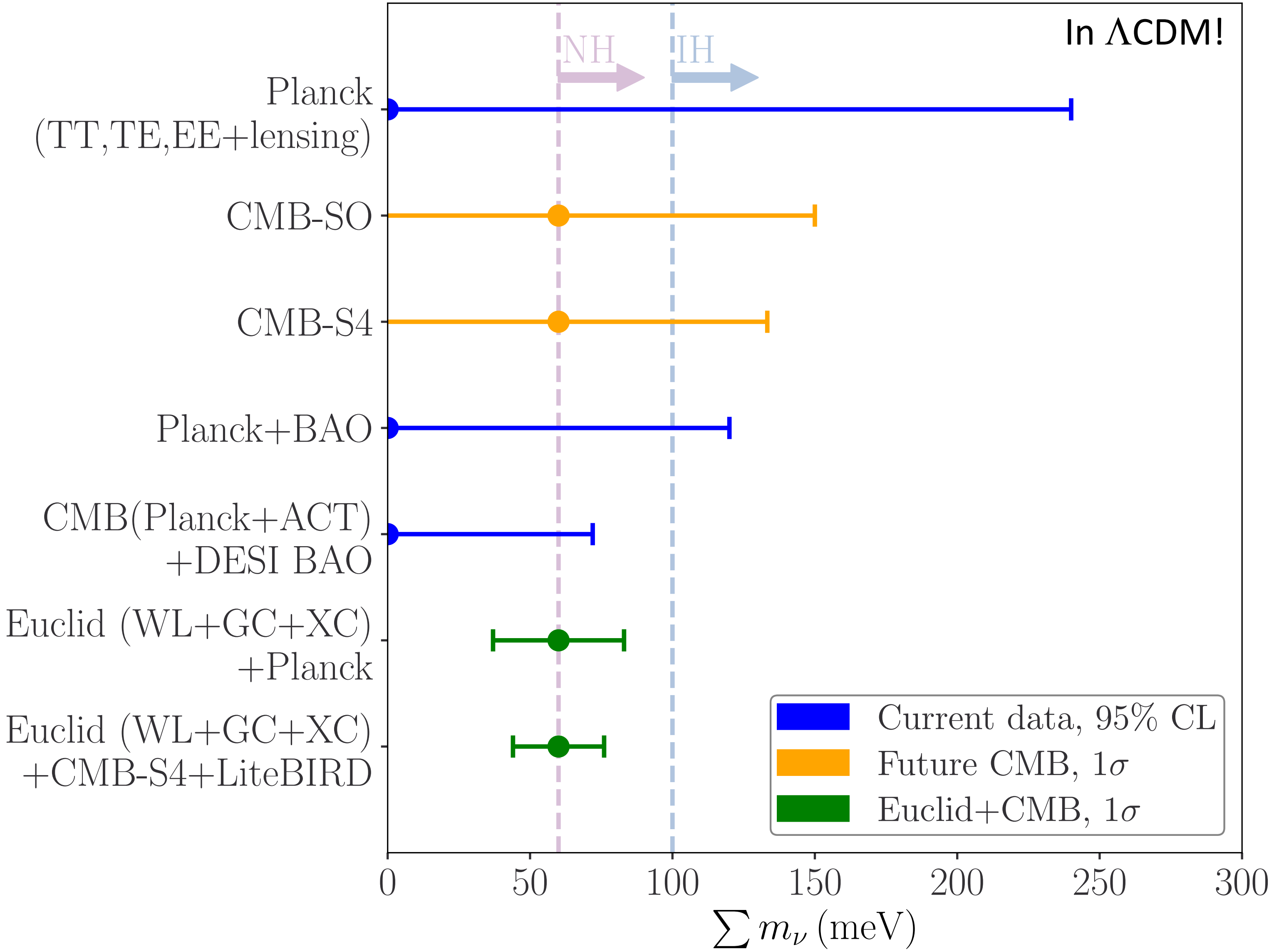
Neutrino mass constraints: the future





Euclid Collaboration: Archidiacono et al. (2024)

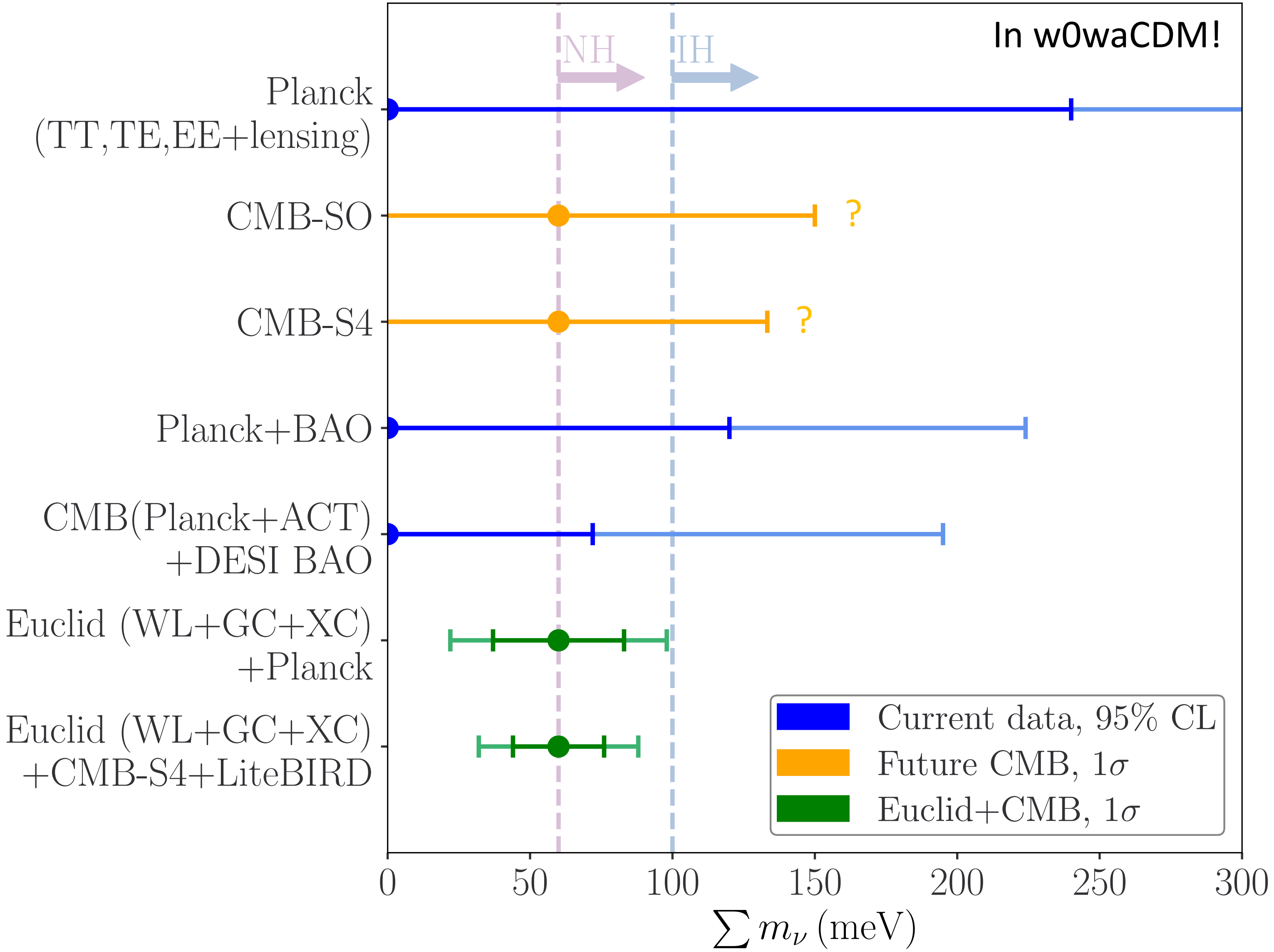
Neutrino mass constraints: the future



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

Euclid+CMB-S4+LiteBIRD: >3σ

Neutrino mass constraints: the future

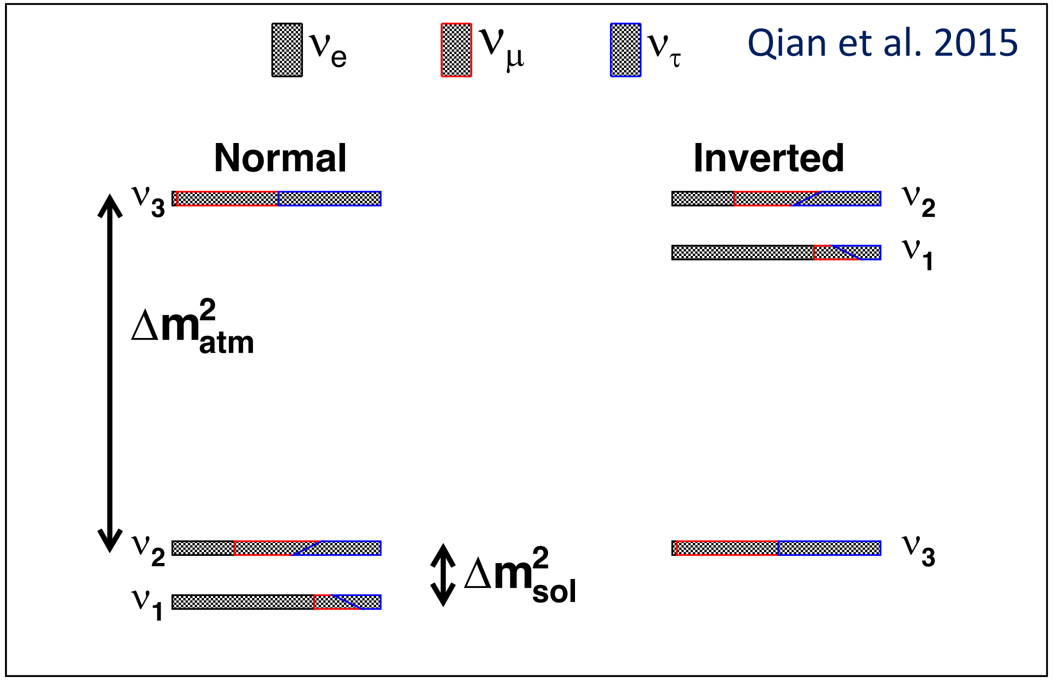


Replacing the cosmological constant with dark energy with a time varying equation of state parameter increases the error by a factor 2.

Neutrino mass ordering

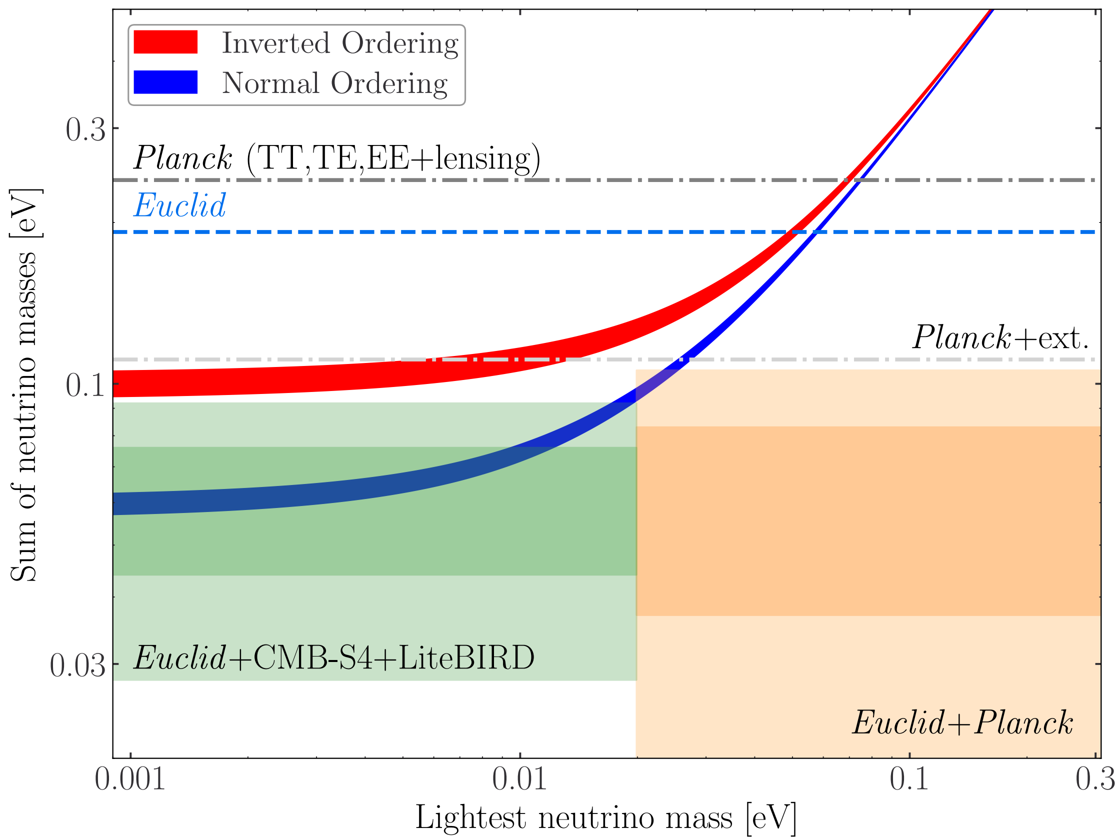
Constraints derived under the assumption $m_1=m_2=m_3$ (degenerate hierarchy, DH)

Neutrino Mass Hierarchy



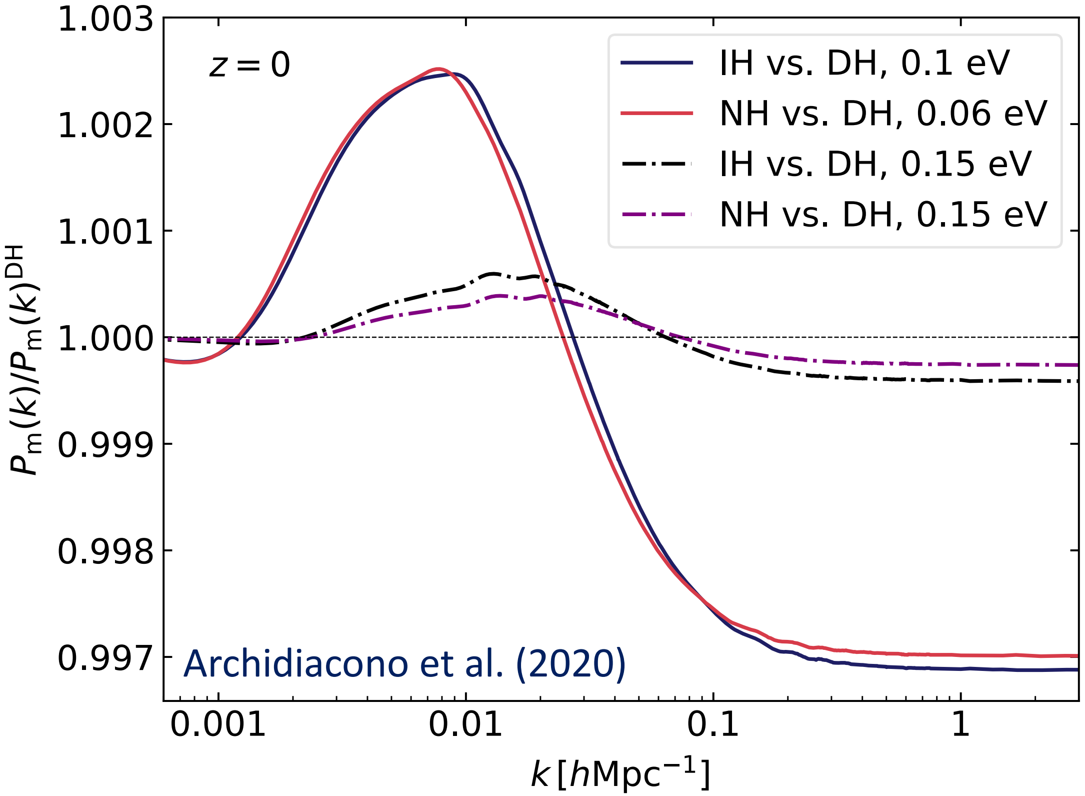
Min. Σm_ν (NH) = 0.058 eV; Min. Σm_ν (IH)= 0.100 eV

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 $\Sigma m_\nu = 0.058$ eV
- Cosmology is not directly sensitive to the neutrino mass ordering, like ground-based experiments, however, if $\Sigma m_\nu = 0.058$ 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?

  See talk by Stefano Gariazzo

Stay tuned