Neutrinos in cosmology

Maria Archidiacono

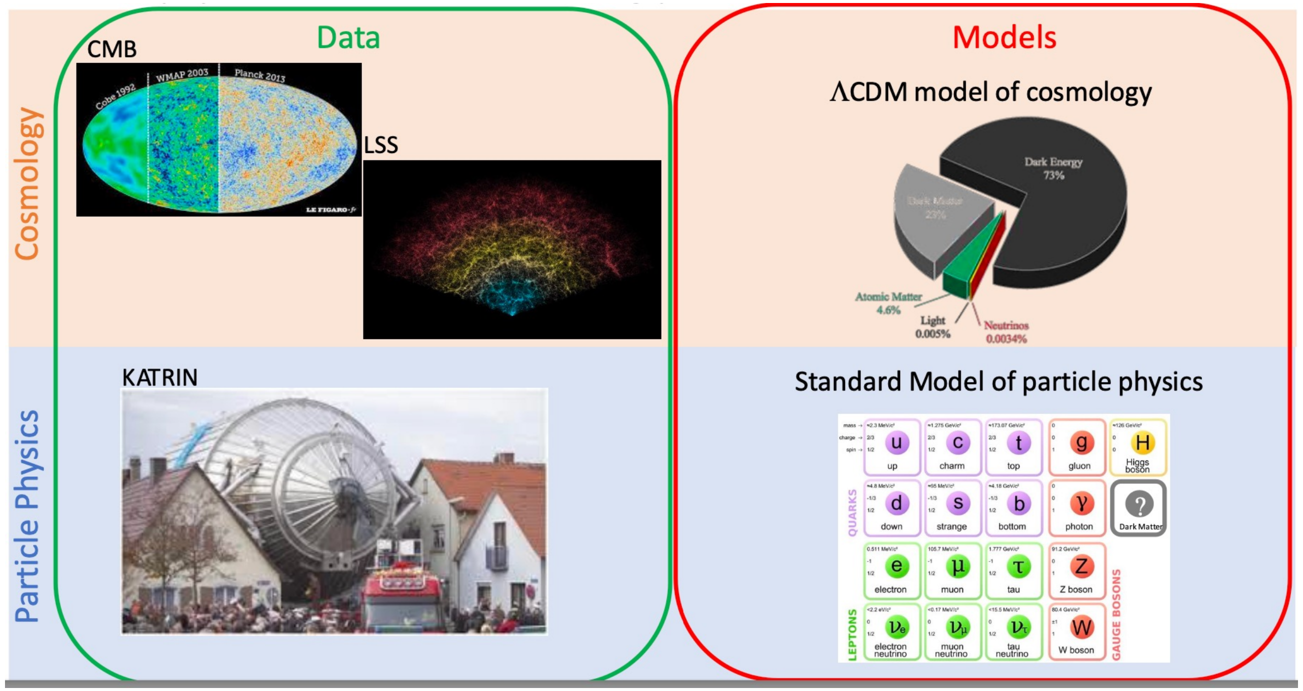
UNIVERSITÀ DEGLI STUDI DI MILANO

Euclid consortium

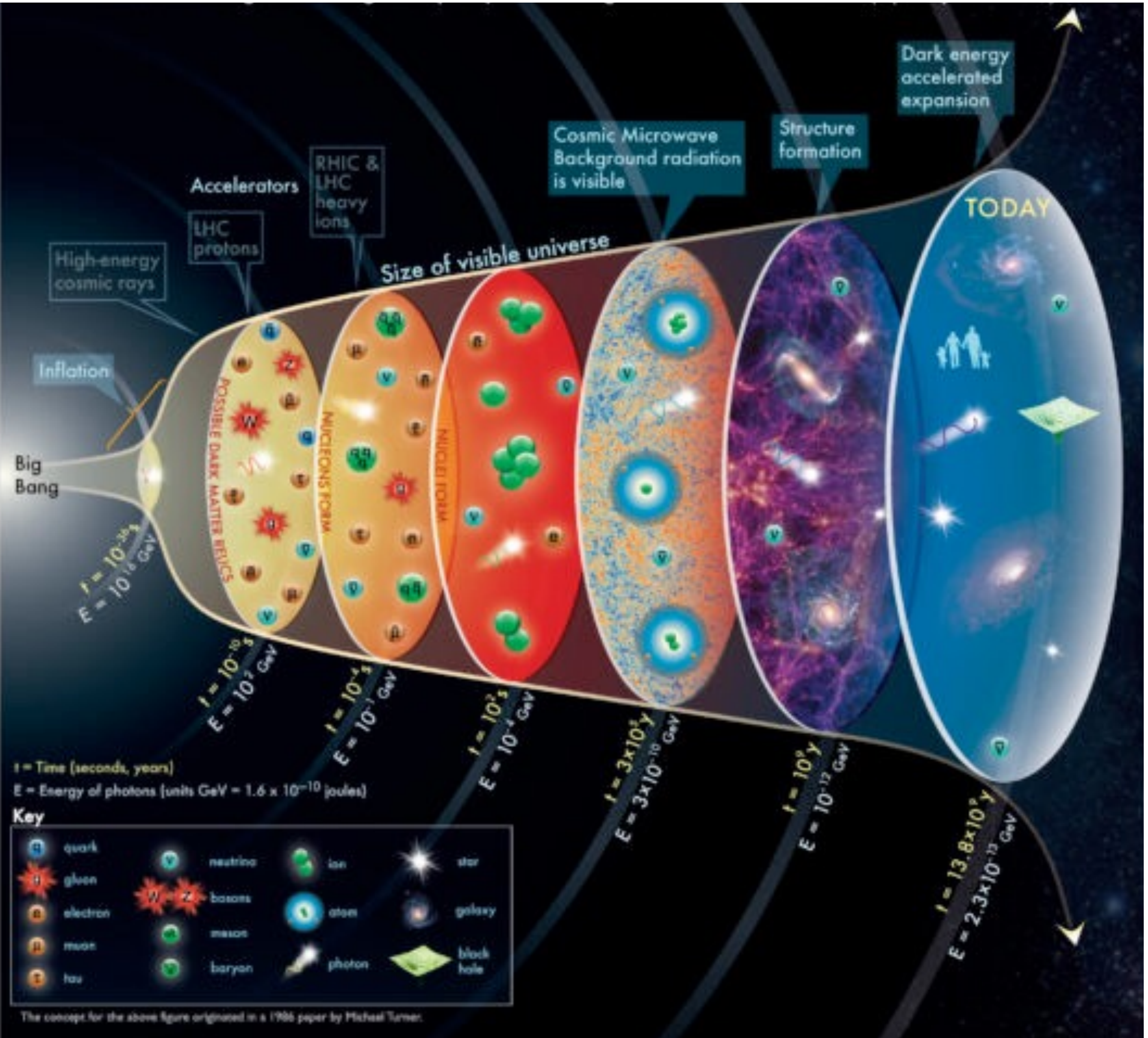
INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS, 47th Course
Neutrinos in Cosmology, in Astro-, Particle- and Nuclear Physics
Erice, Sicily, September 16 - 22 2026

Plan

- A short cosmic history
- Detecting the neutrino mass in the CνB
- The cosmological neutrino mass problem



A short cosmic history



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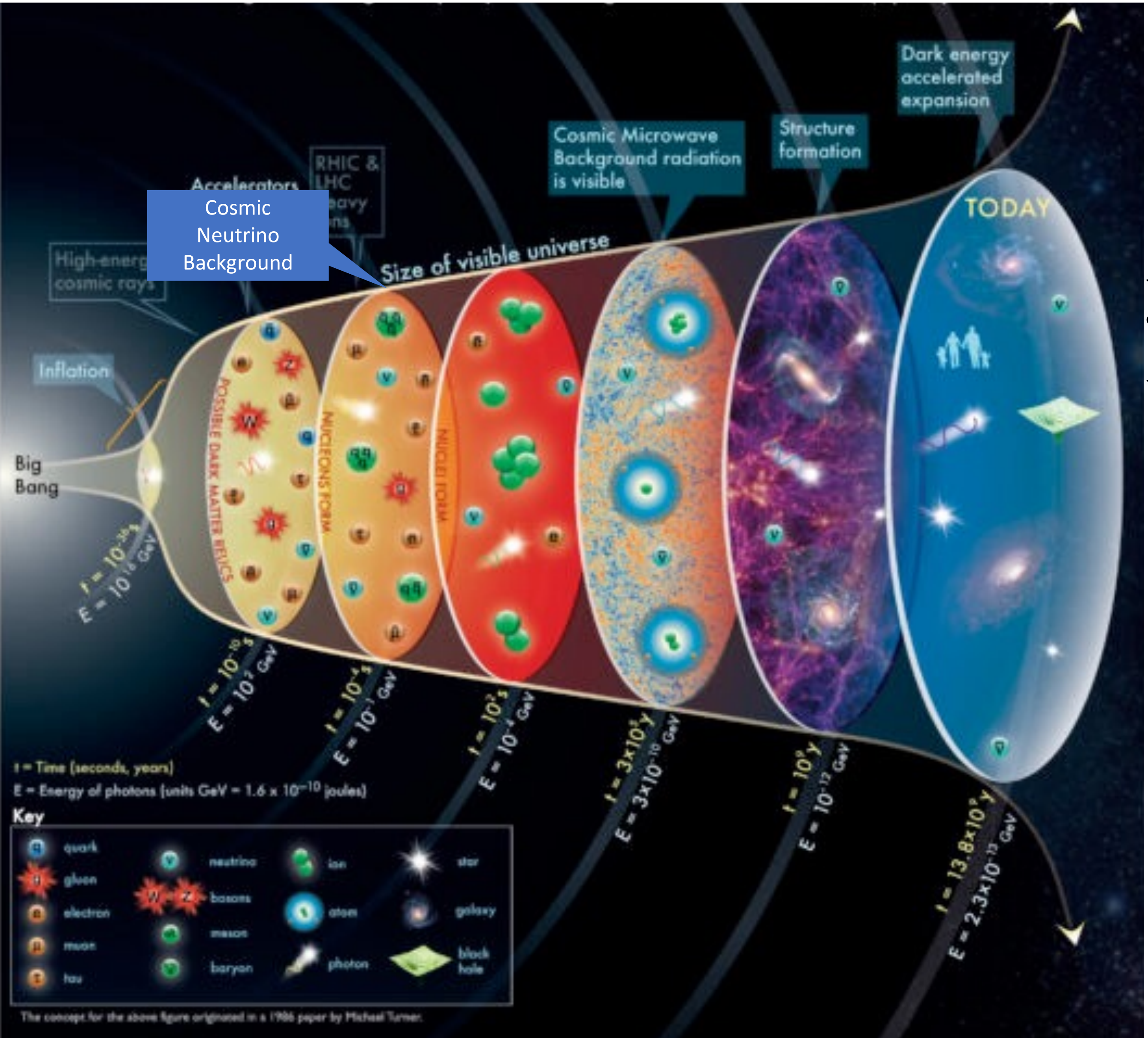
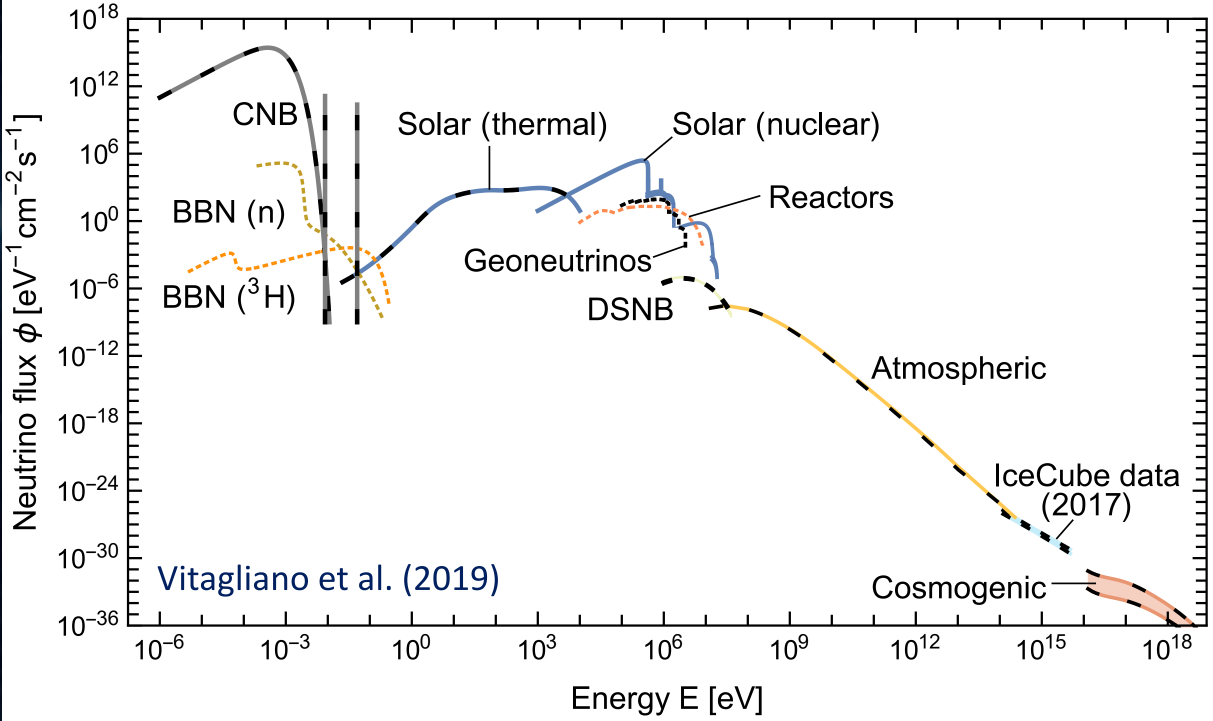


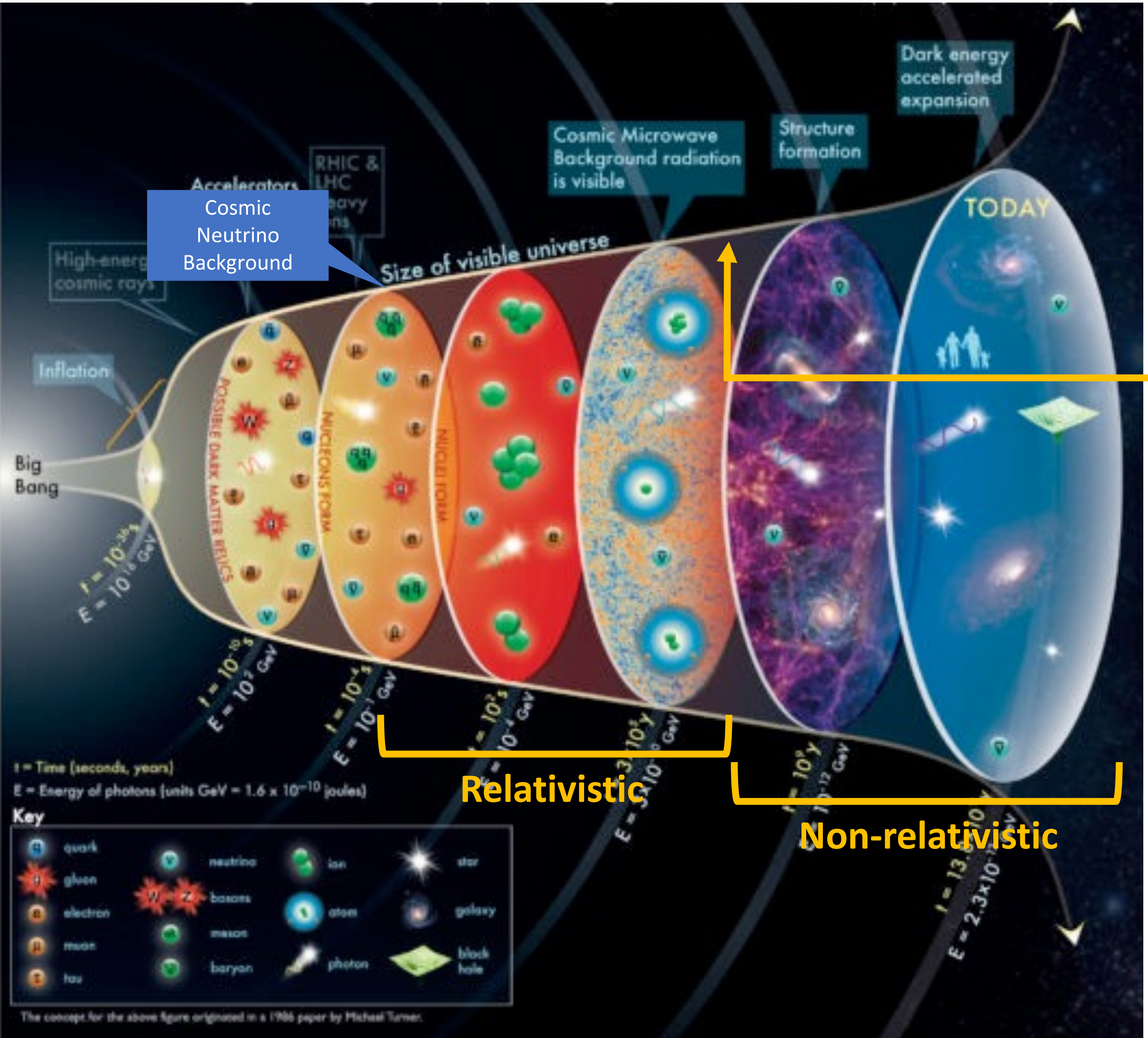
The neutrino background formed 1 sec after the big bang, at T~1 MeV, when the weak interactions become inefficient.



➔Direct detection of the CνB not in the near future

➔Footprints of the CνB in cosmological observables

A short cosmic history



Footprints:

- **Non-relativitic transition**

At early times neutrinos are relativistic. As the Universe expands, their momentum redshifts, and they become non-relativistic when

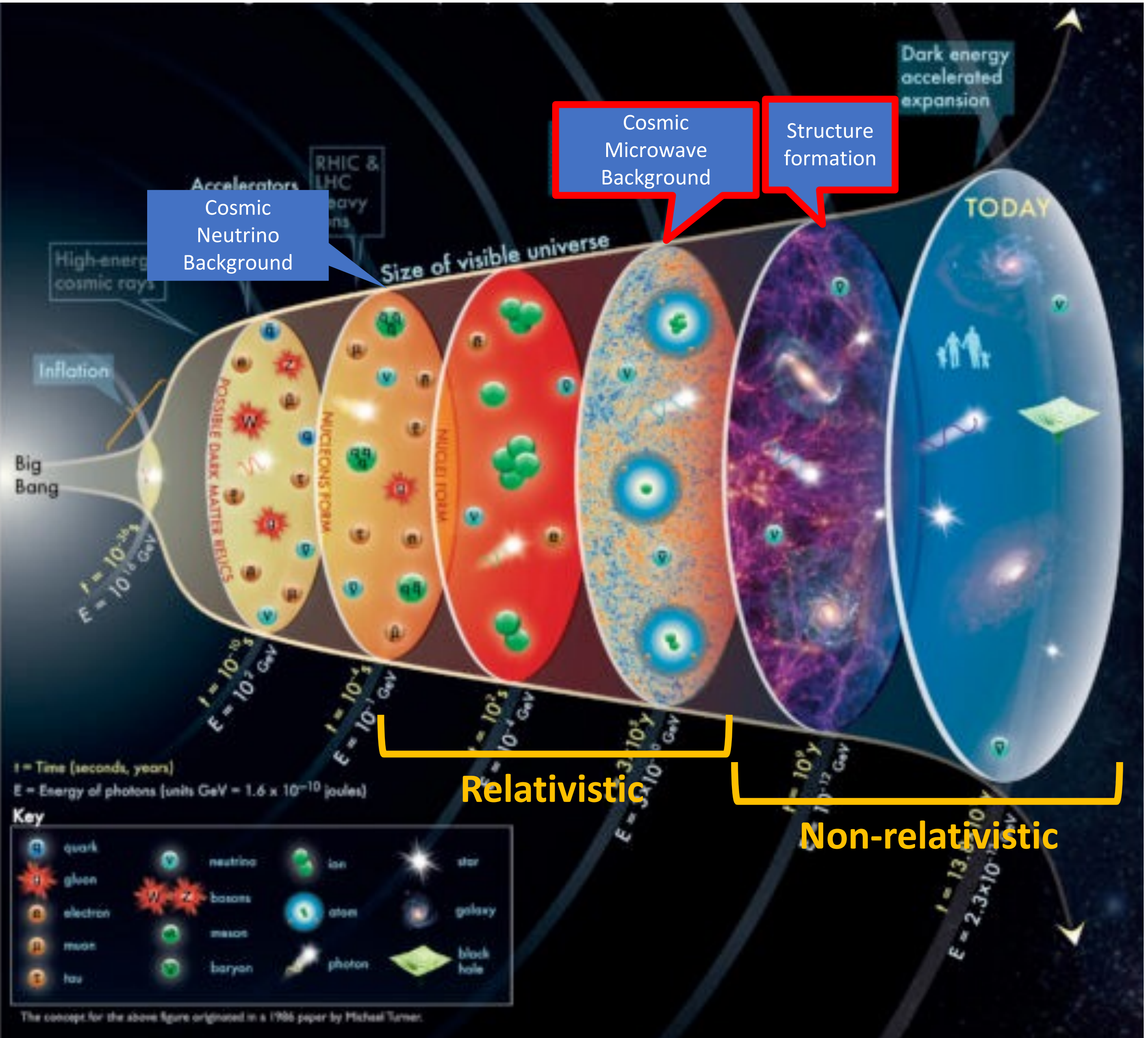
$$z_{\mathrm{nr},i} = 2 \times 10^3 \left(\frac{m_{\nu,i}}{1\,\mathrm{eV}}\right)$$

- **Free-streaming**

Relativistic neutrinos travel essentially at the speed of light. After they become non-relativistic, their thermal velocity remains larger than the escape velocity from gravitational potential wells, thus they cannot be trapped on sufficiently small scales

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

A short cosmic history

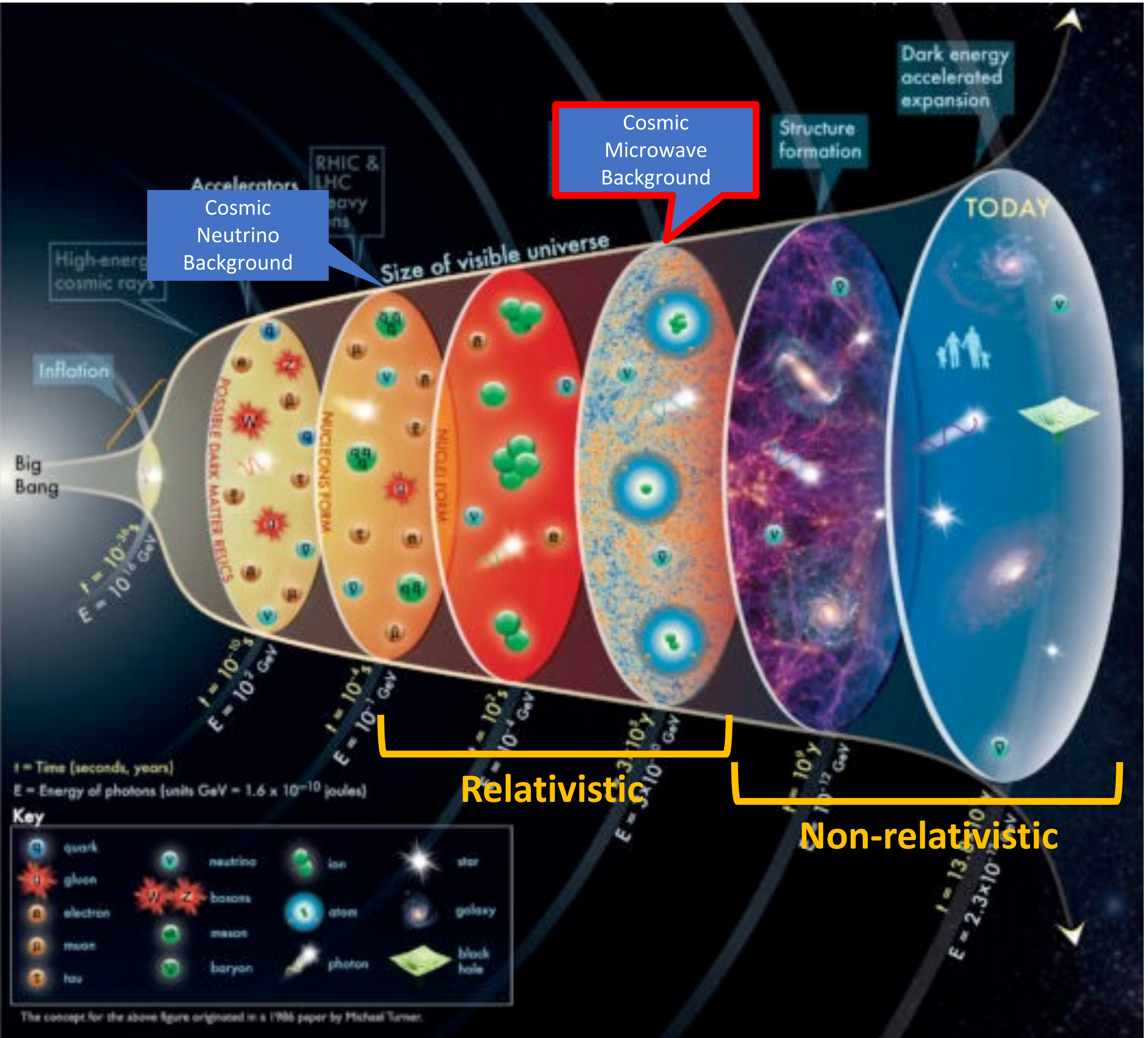


Observables:

- **Cosmic Microwave Background (CMB)**
(neutrinos still relativistic)

- **Large Scale Structure (LSS)**
(neutrinos non-relativistic)

A short cosmic history

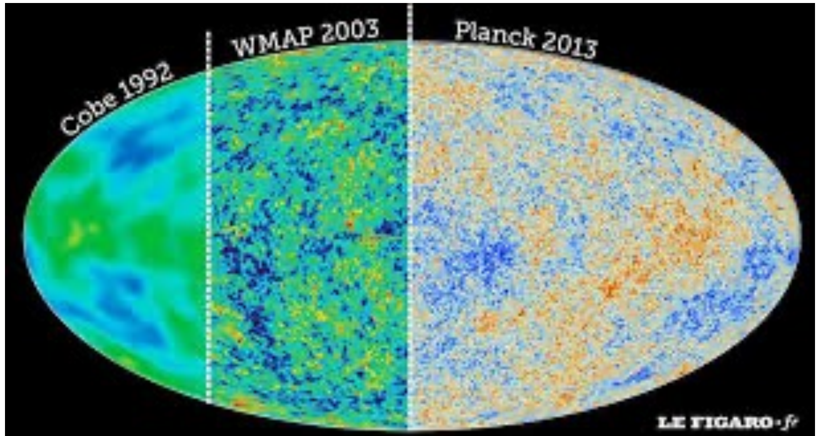


Thermal photon background formed around 300000 years after the big bang (z ~ 1100), when the Universe had a temperature of approximately 0.2 eV (~3000 K). The Universe becomes neutral and transparent to photons.

1978 Penzias and Wilson
Discovery of a ~2.7 K background

2006 Mather and Smooth (COBE)
Measurement of 10^{-5} fluctuations

2019 Peebles
For predicting these fluctuations in 1970 (among other things)



A short cosmic history

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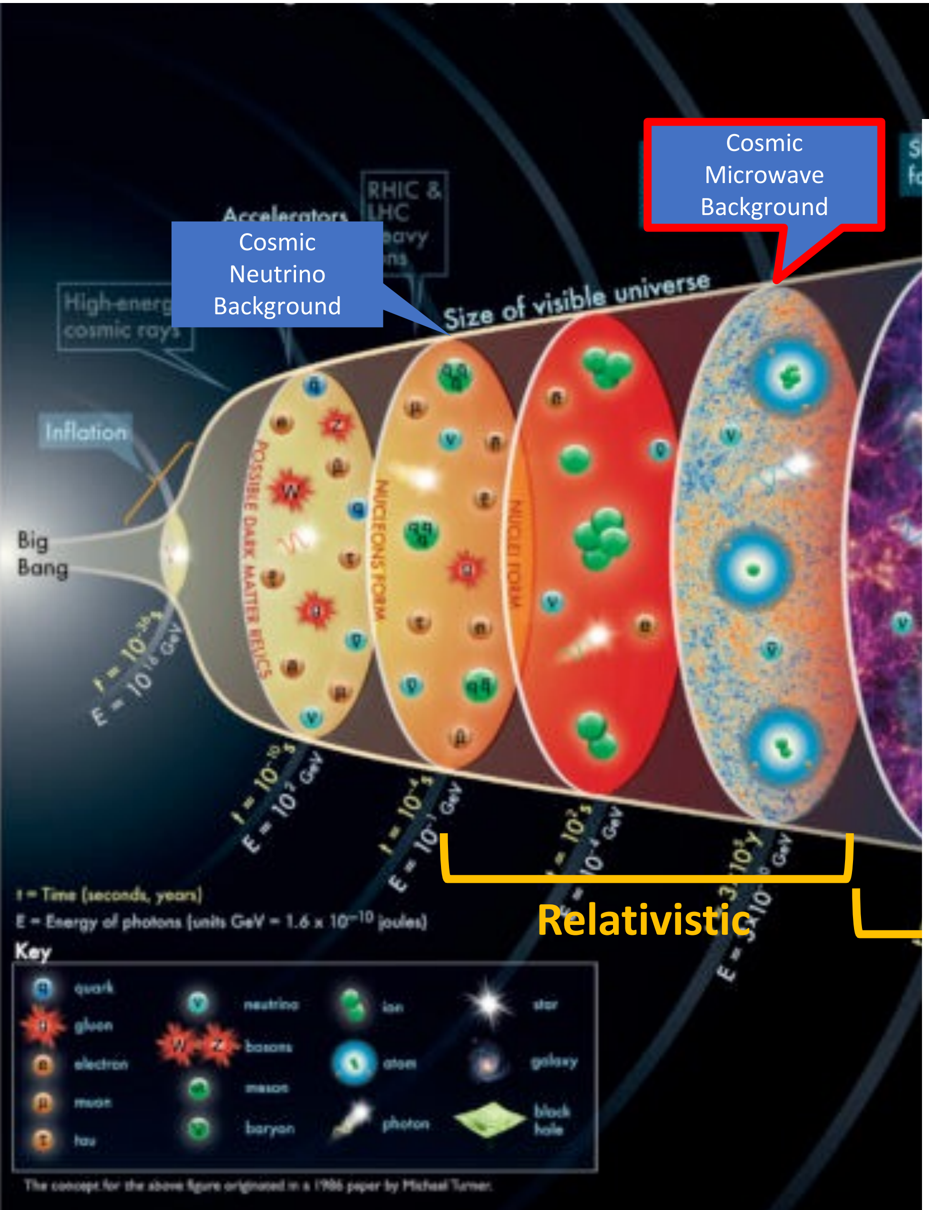

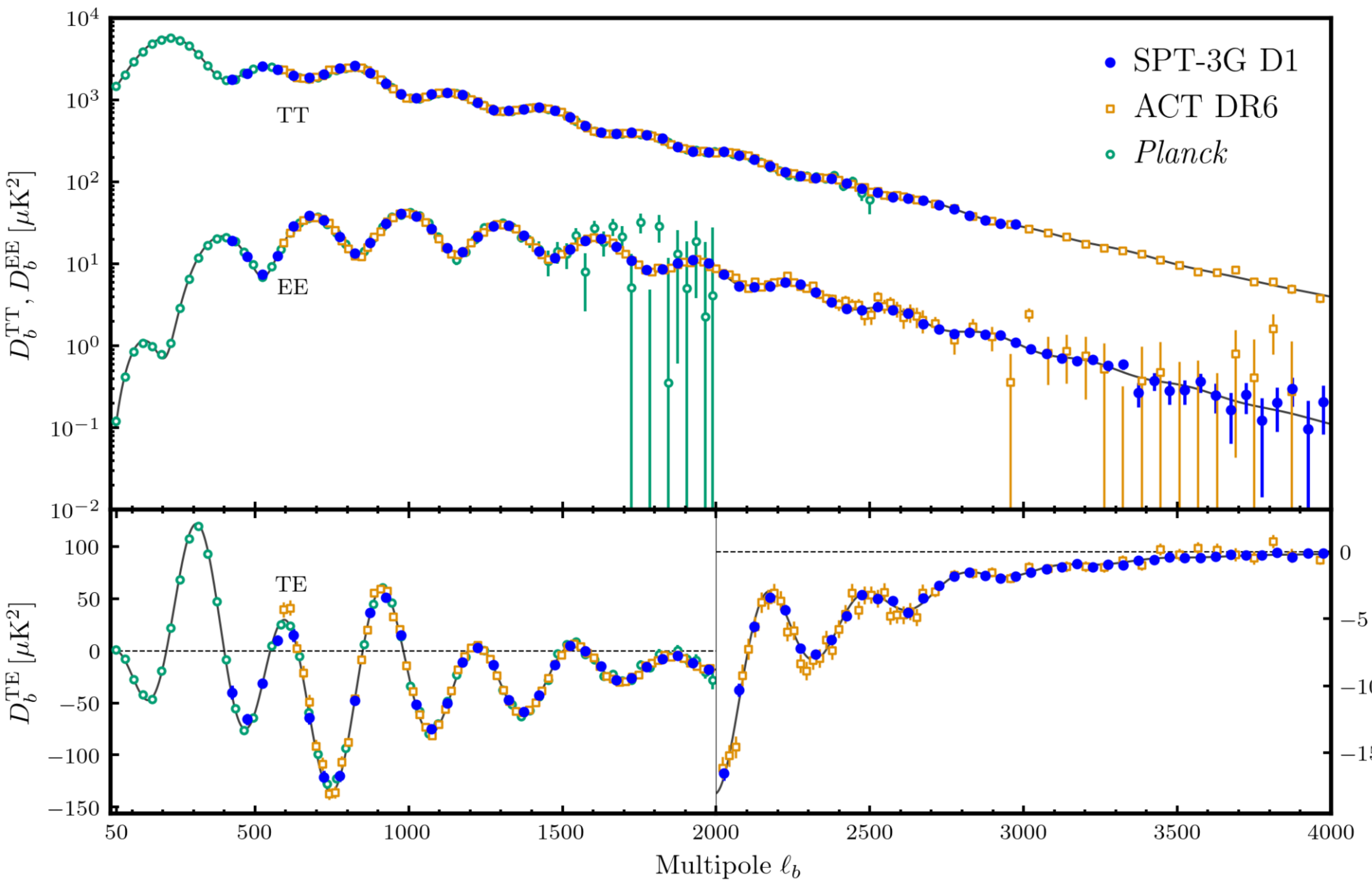

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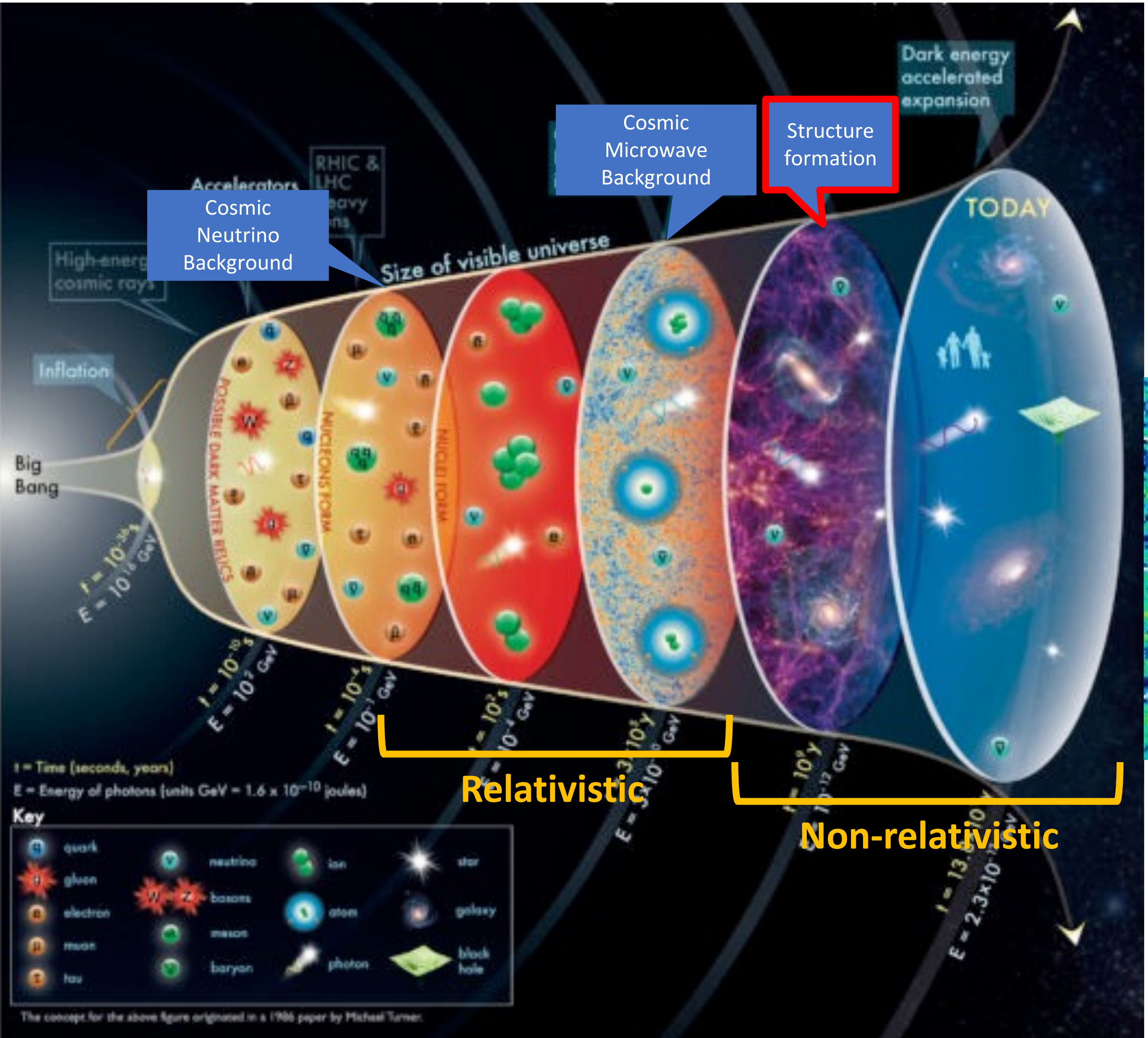
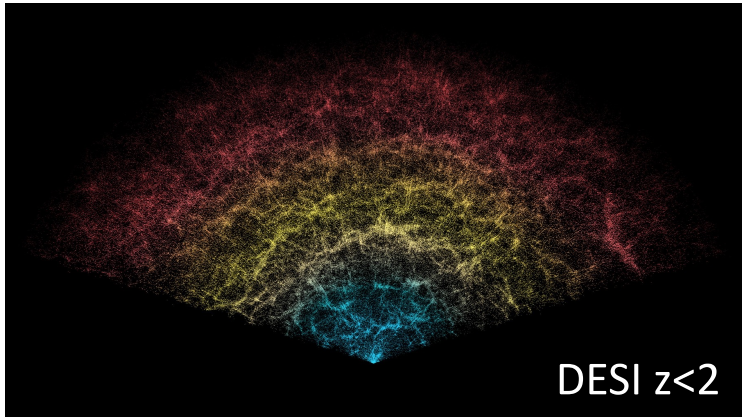
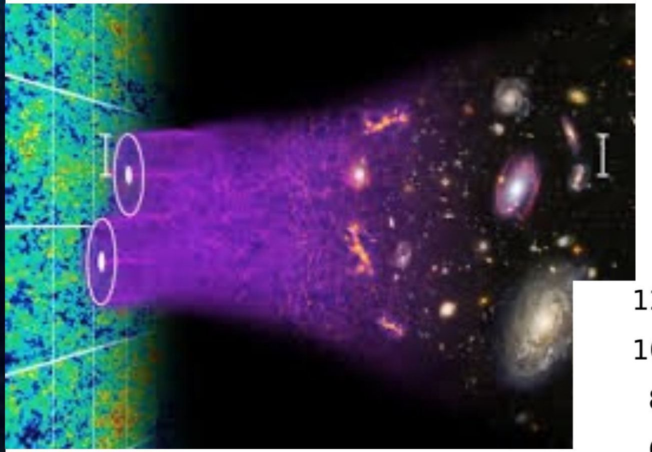


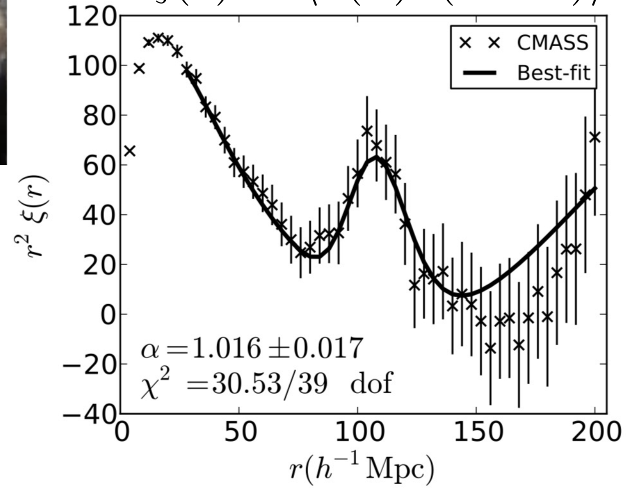




Baryon Acoustic Oscillations (BAO)

➔ Expansion history

$$\xi(\mathbf{r}) = \langle \delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{r}) \rangle$$



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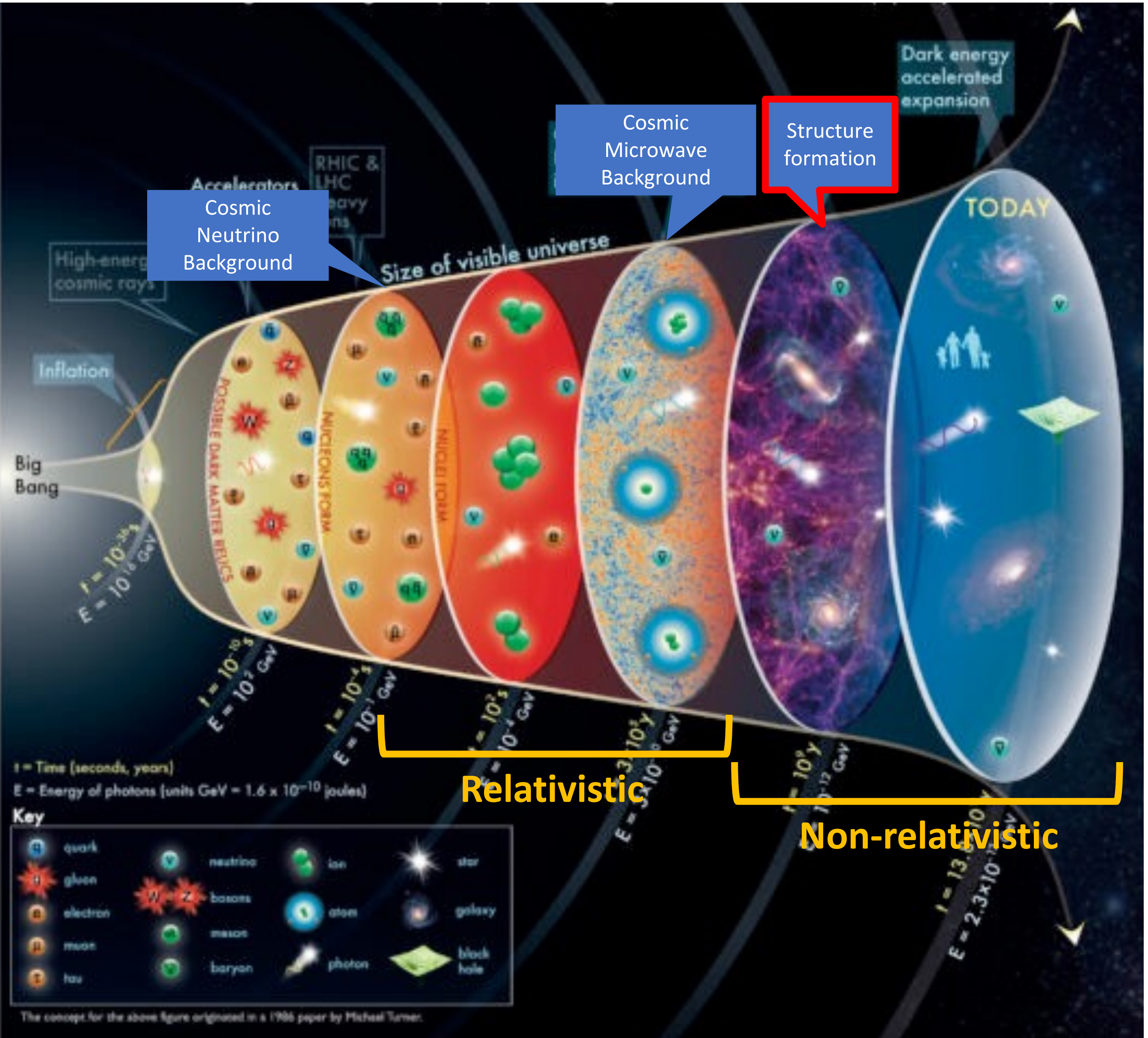
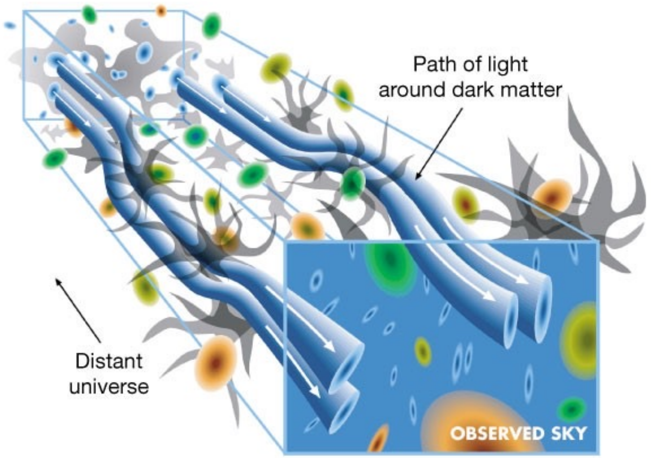
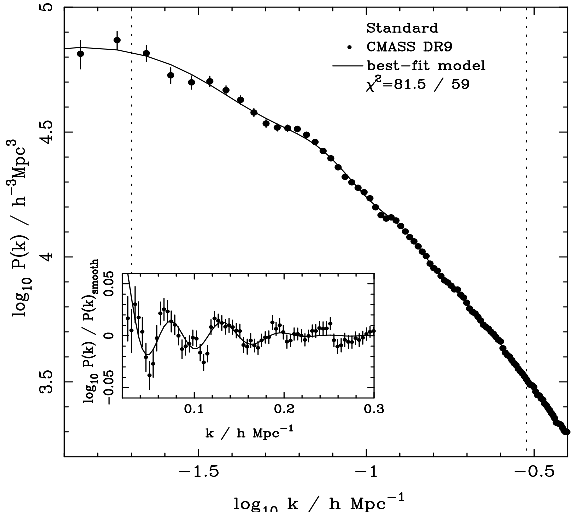


Weak gravitational lensing



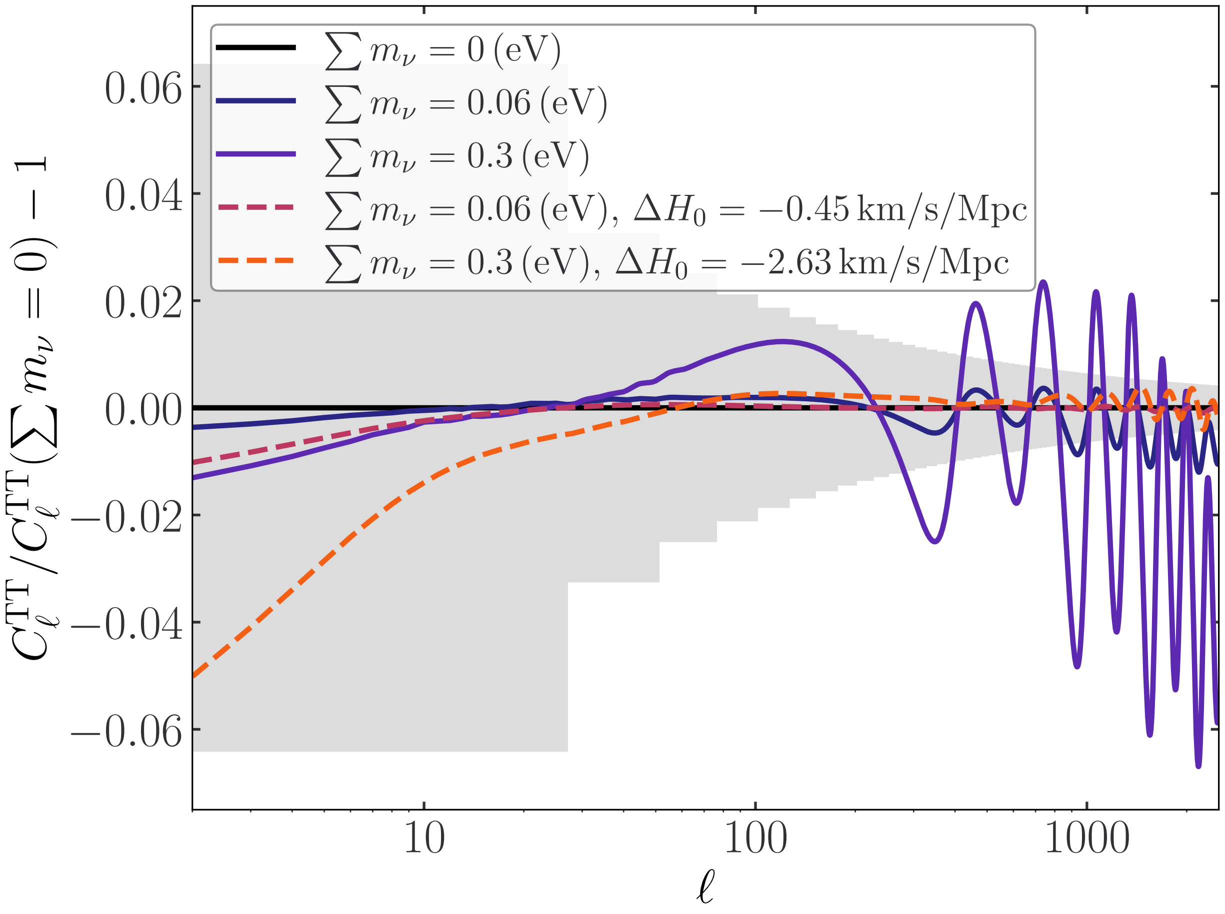
$$P(k) = \int \xi(\mathbf{r}) e^{i\mathbf{k}\cdot\mathbf{r}} d^3x$$



➔ Expansion history and growth of structures

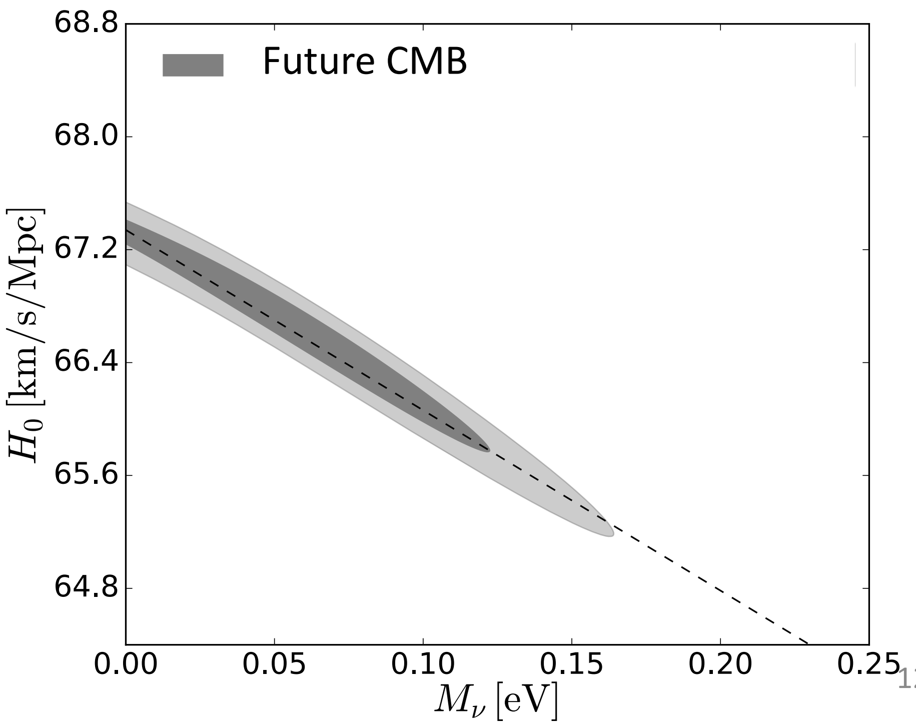
Detecting the neutrino mass in the CνB

Detecting the neutrino mass in the CMB



m_i < 0.6 eV still relativistic at CMB production

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



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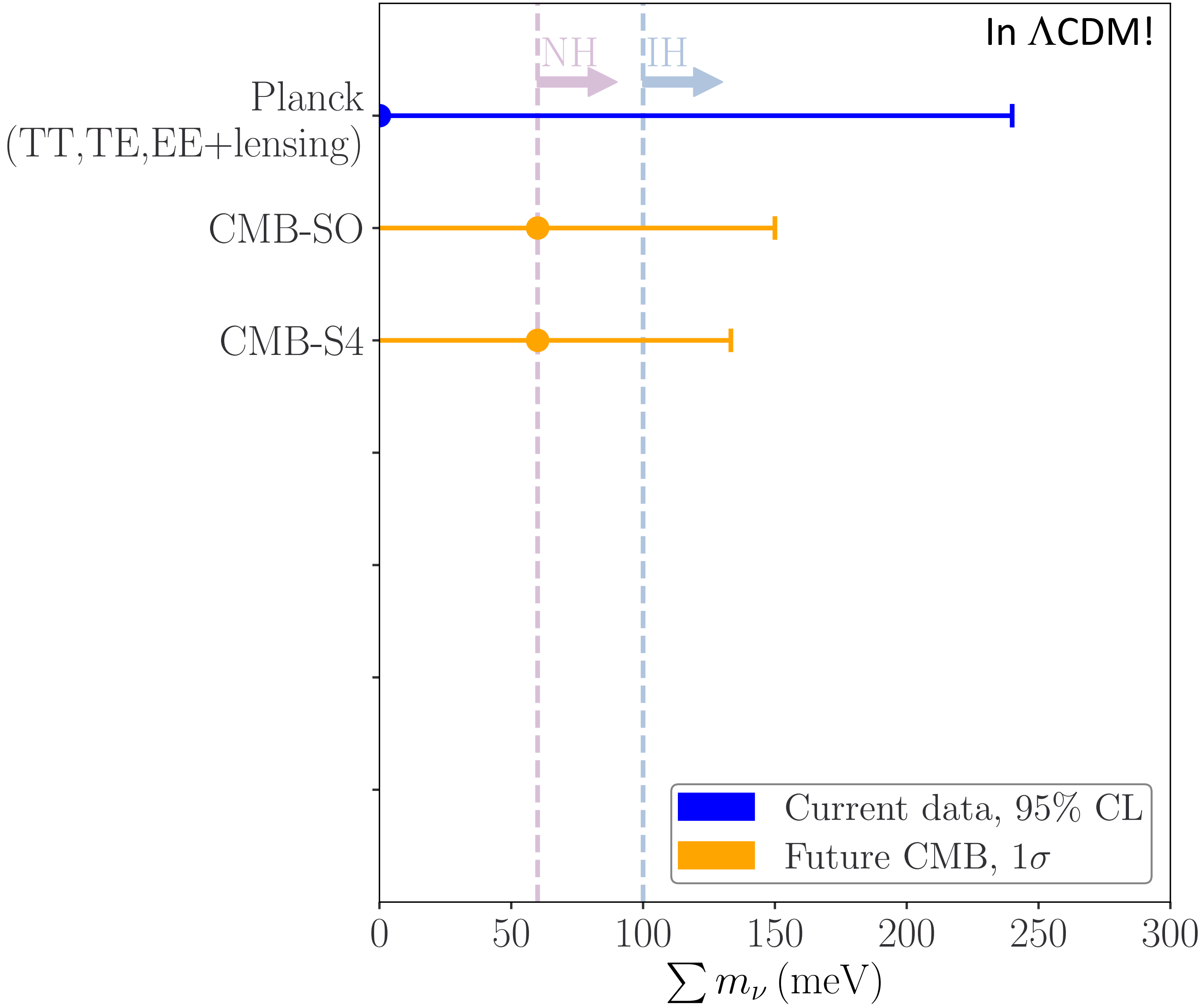


β-decay experiment KATRIN, current constraint:

Σm_ν <~ 1.3 eV

Fiducial value:

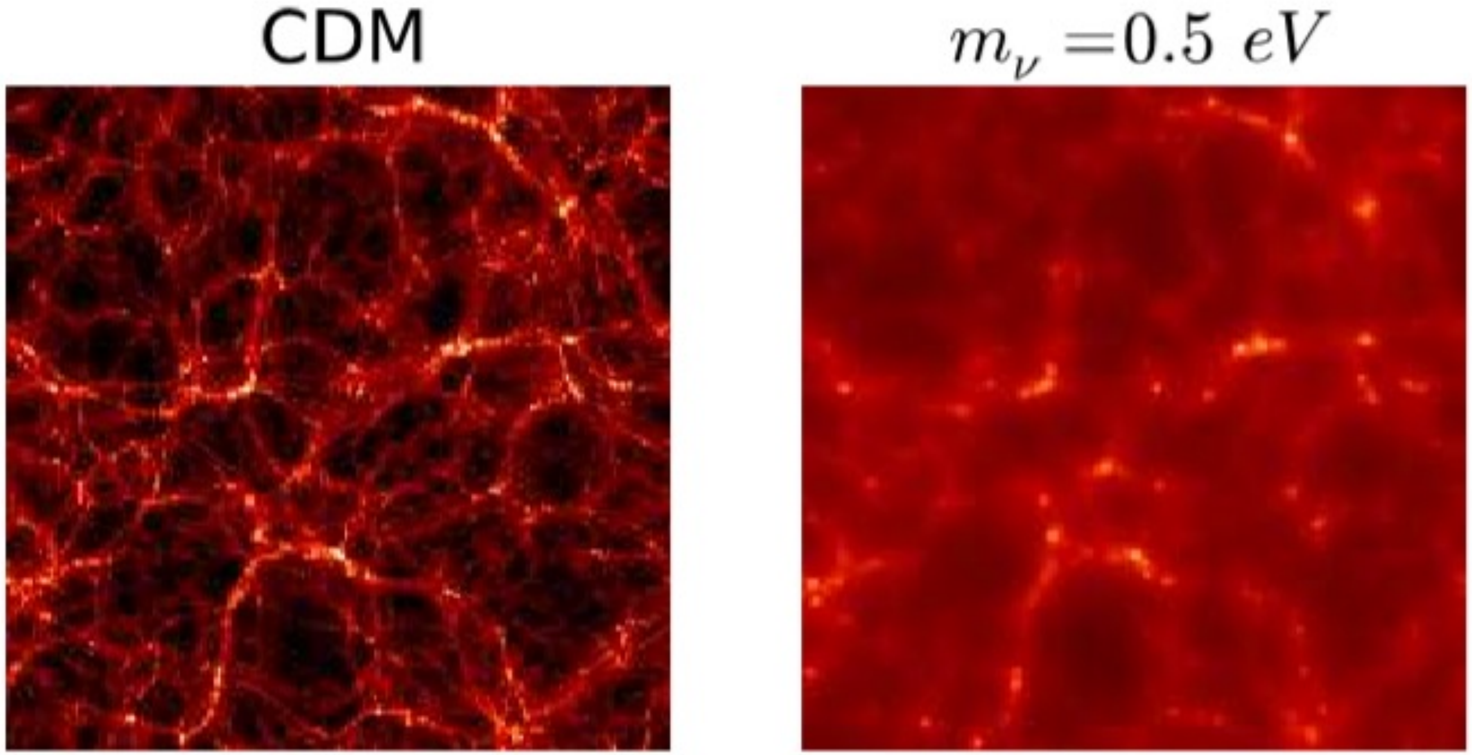
- Σm_ν = 58 meV

CMB alone will not be able to detect the neutrino mass

→ Large Scale Structures

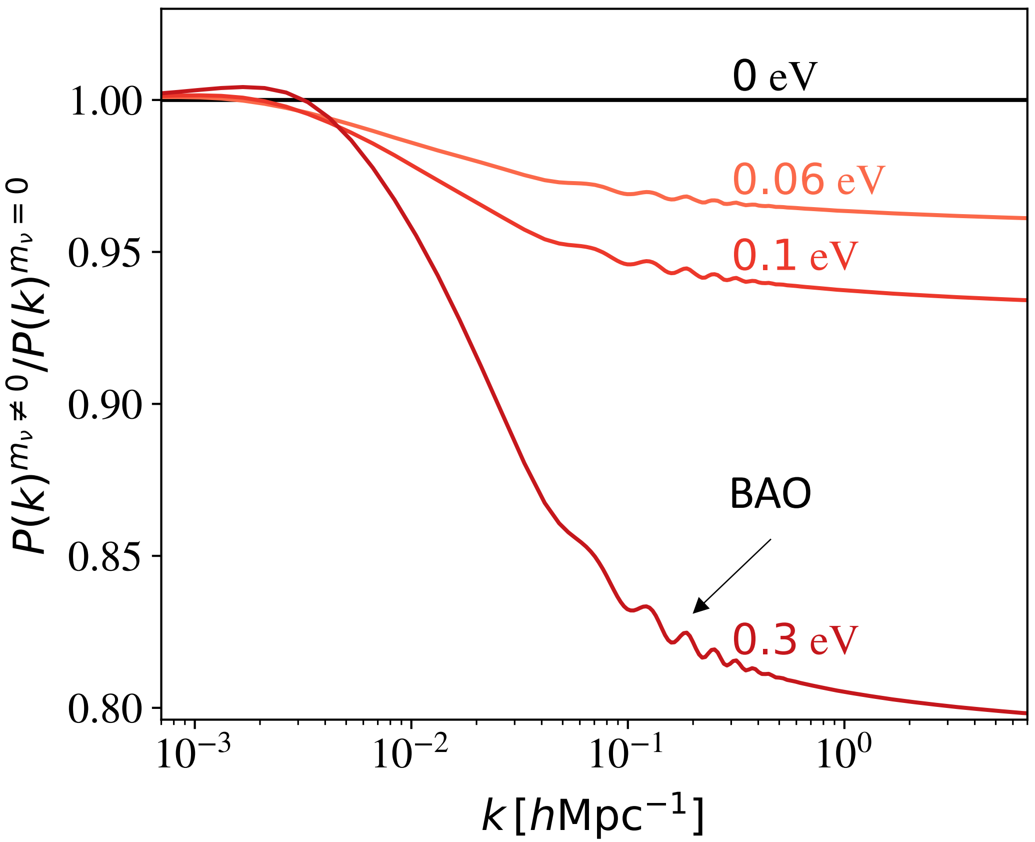
Detecting the neutrino mass with LSS

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



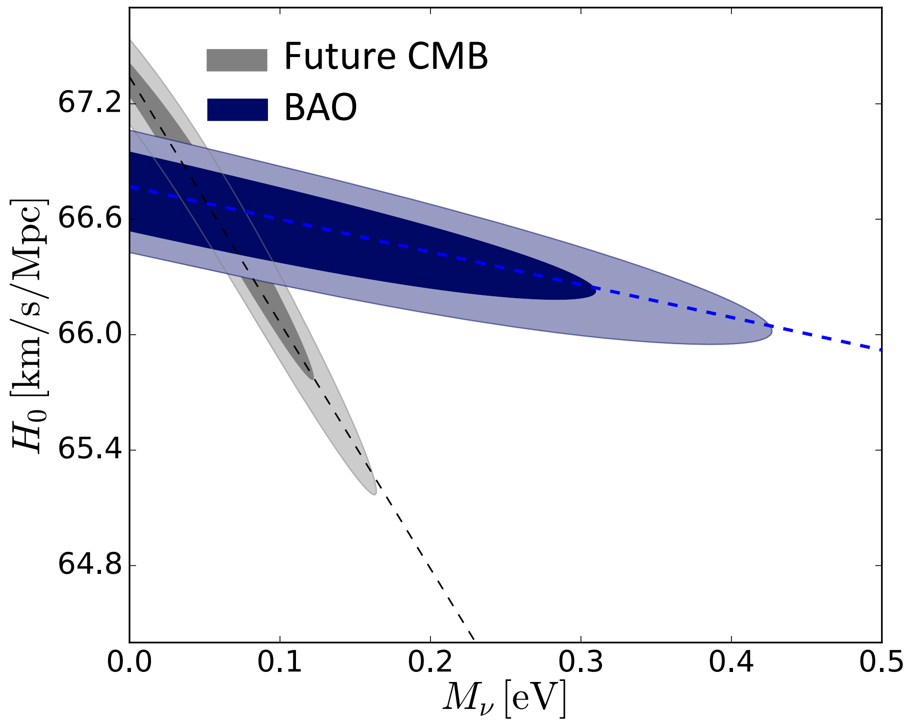
Villaescusa Navarro et al. (2013)

Detecting the neutrino mass with LSS

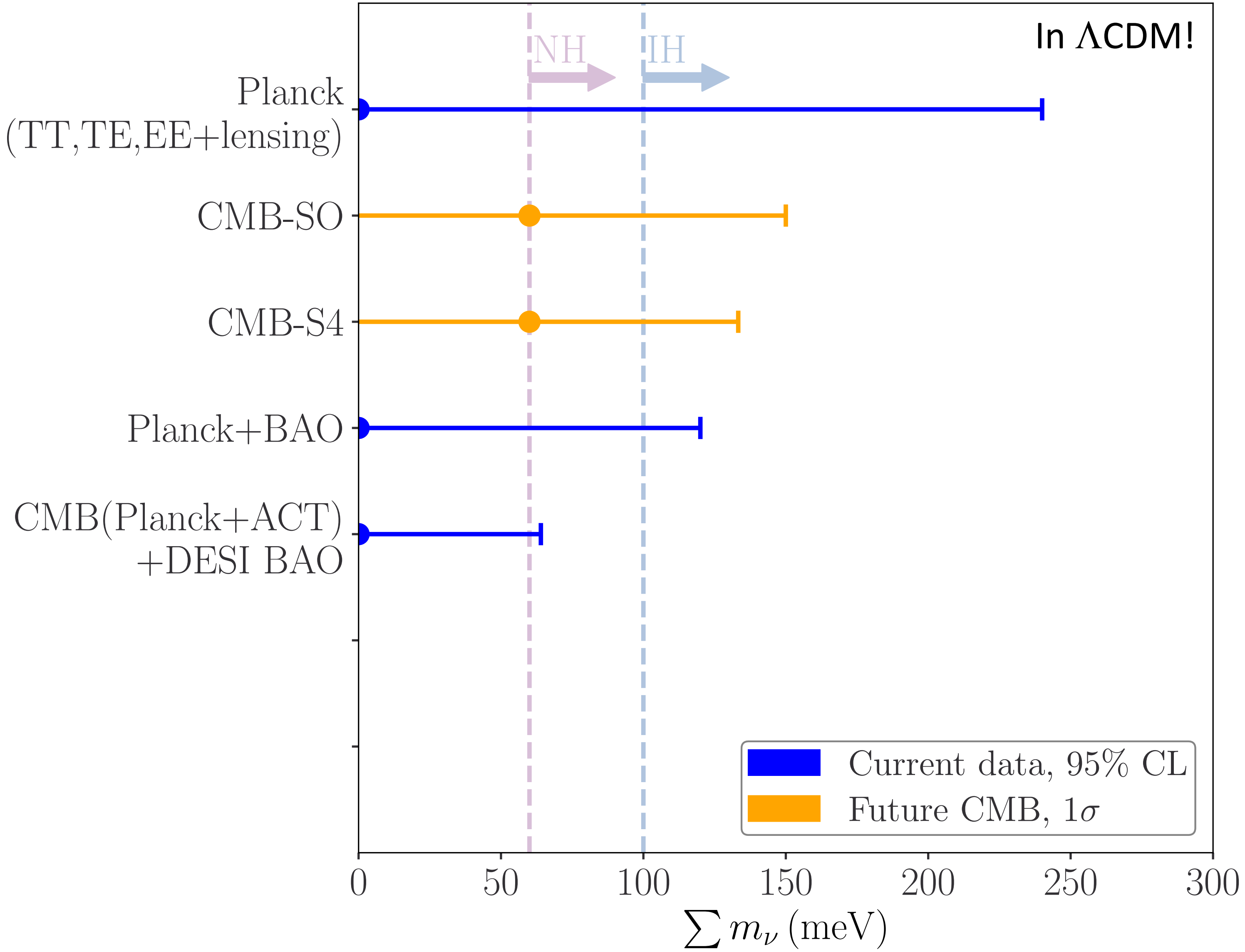


<-- Large scales Small scales →

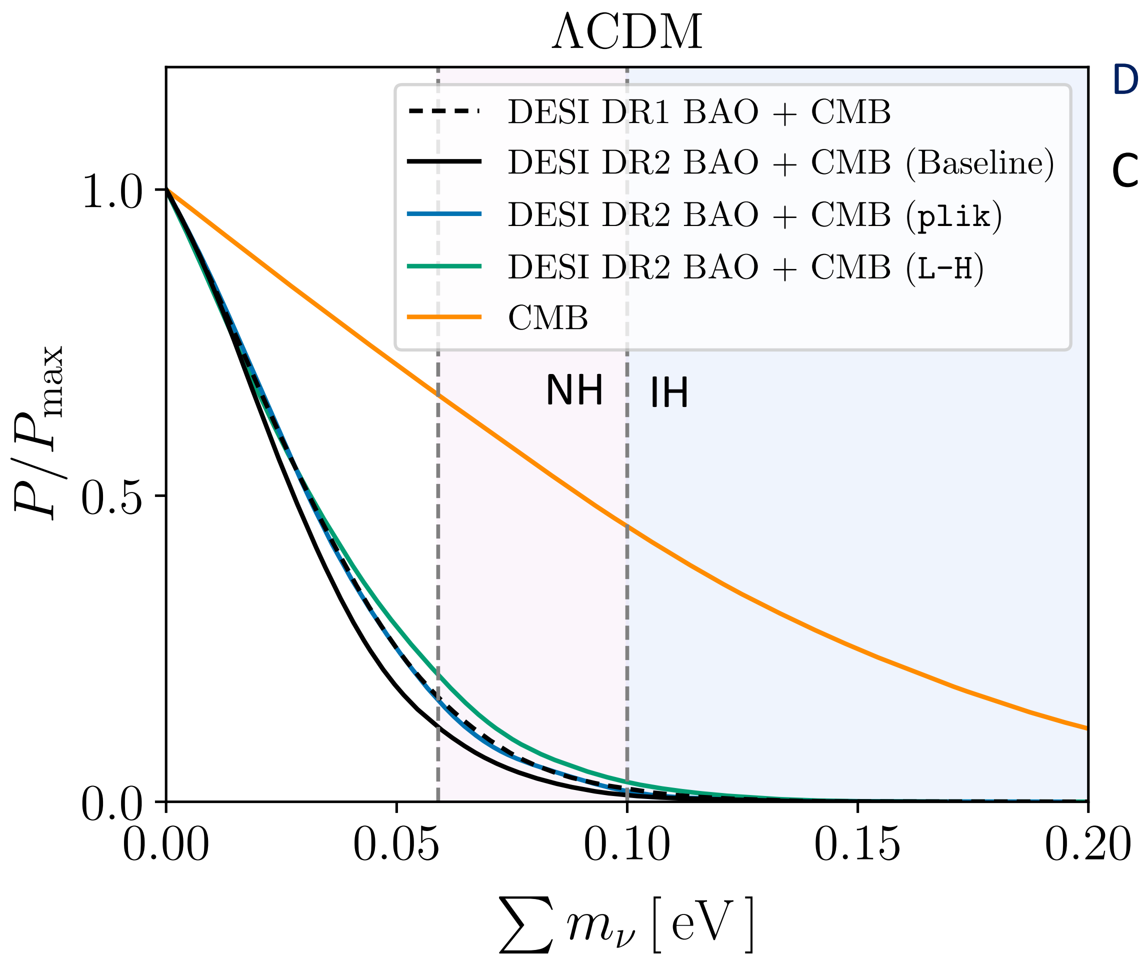
- Massive neutrinos do not cluster
- Massive neutrinos slow down the growth of CDM perturbations
  - Massless neutrino Universe $\delta_{\rm cdm}^{m_\nu=0} \propto a$
  - Massive neutrino Universe $\delta_{\rm cdm}^{m_\nu\neq0} \propto a^{1-\frac{3}{5}\frac{\Omega_\nu}{\Omega_m}}$



Where we stand: 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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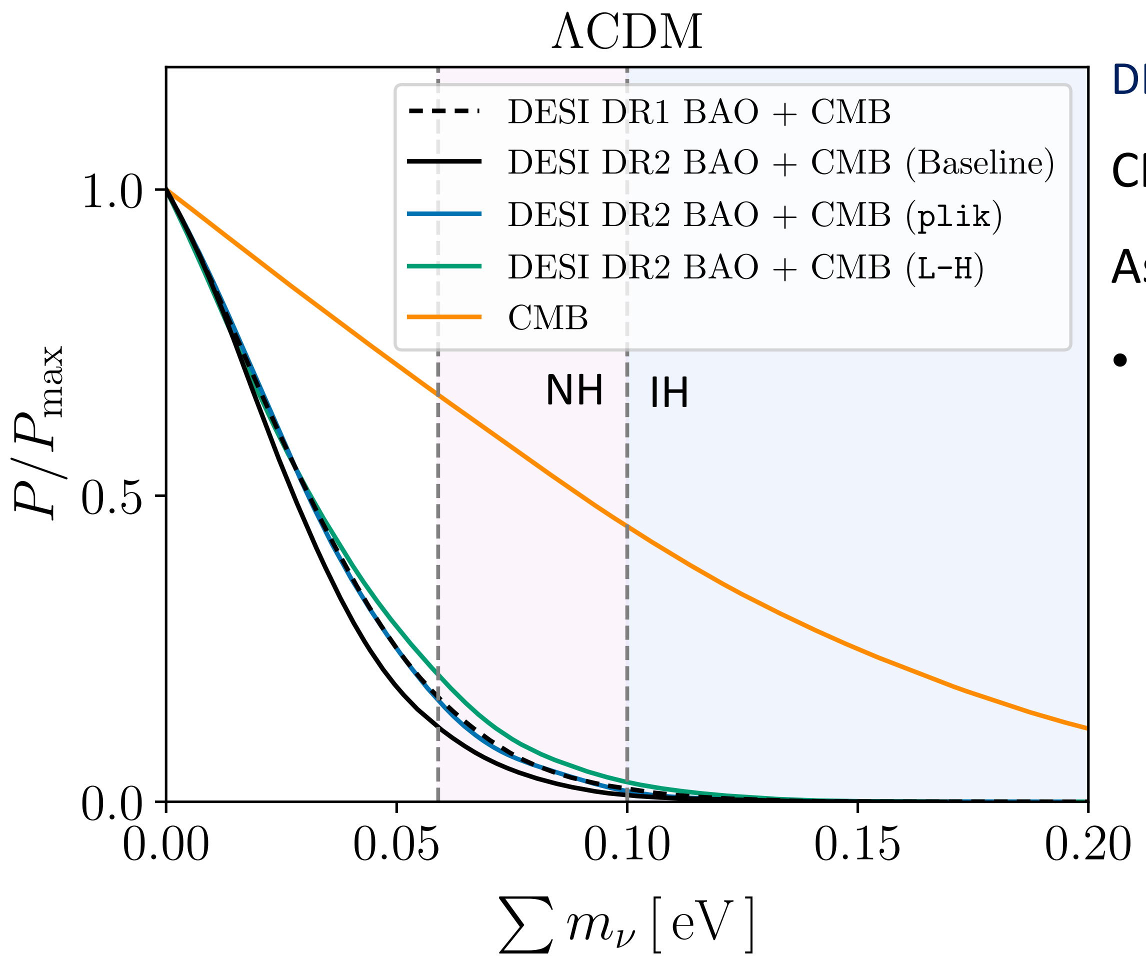

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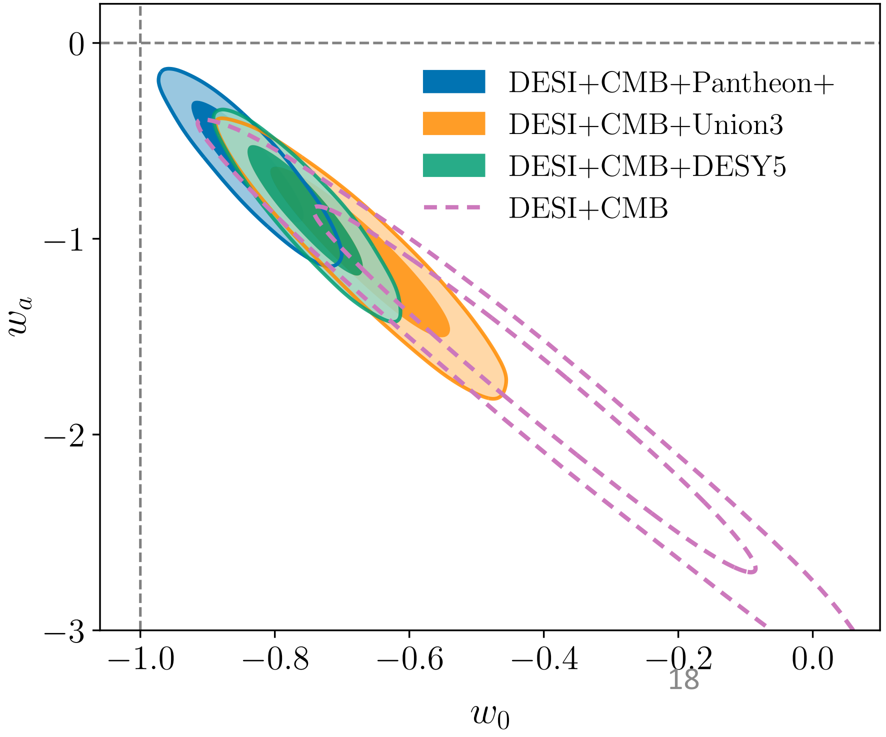
Assumptions:

- In ΛCDM, but CMB+DESI prefer w0waCDM



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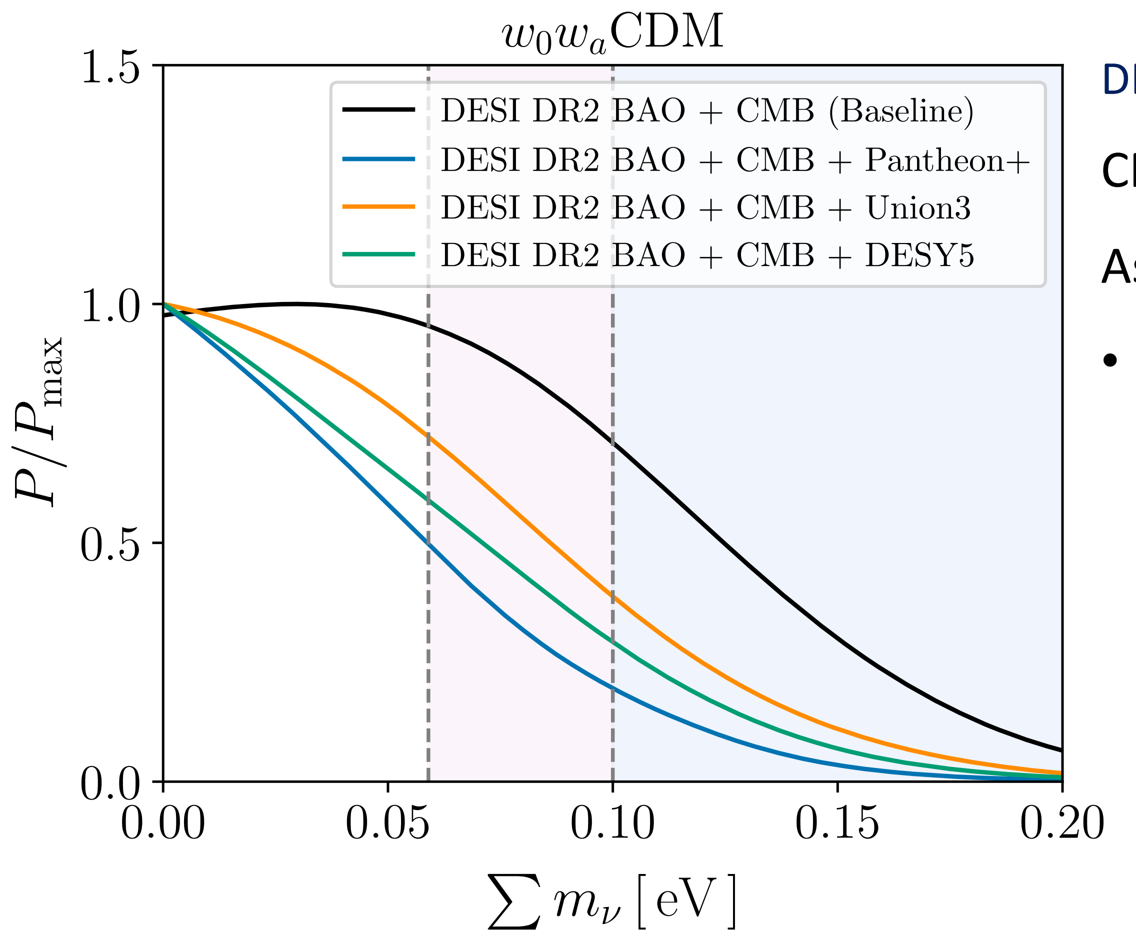

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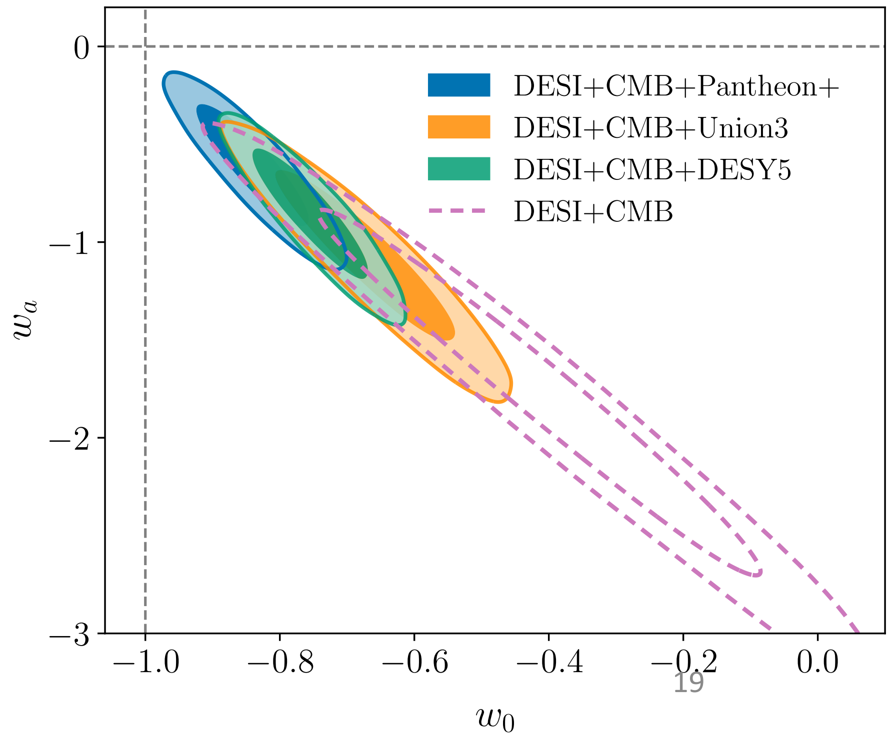
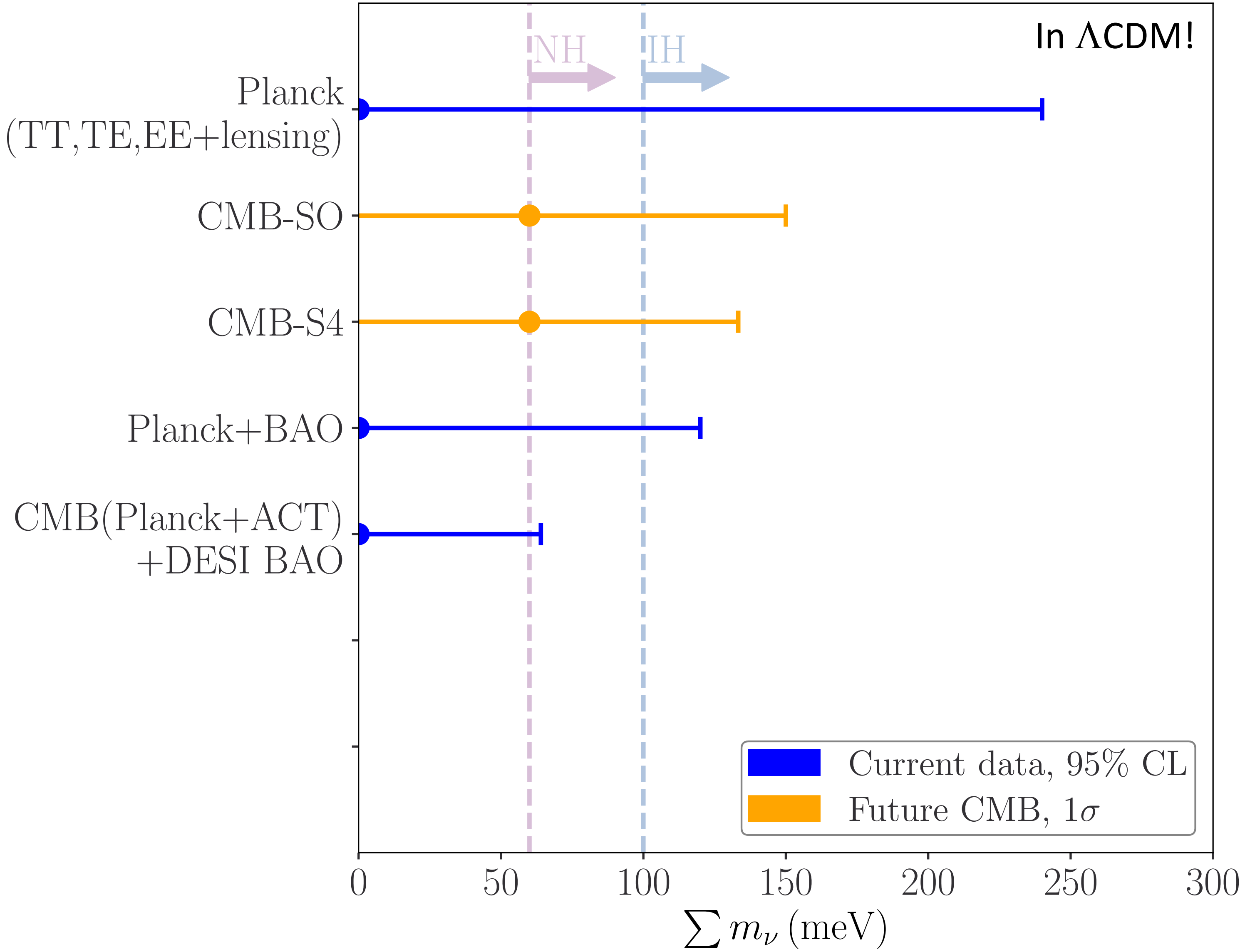


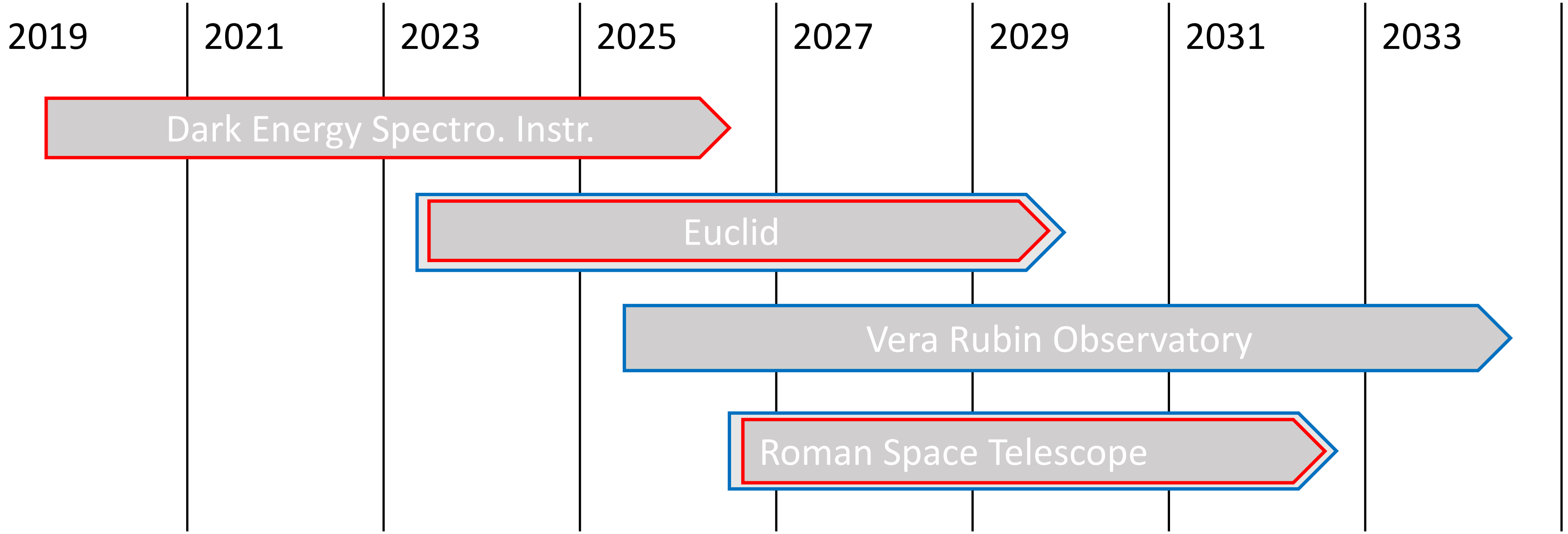
In w0waCDM:
CMB (Planck+ACT) + DESI BAO: Σm_ν < 0.16 eV, 95% CL

Where we stand: CMB+LSS



Still no evidence/detection!

Stage IV Large Scale Surveys

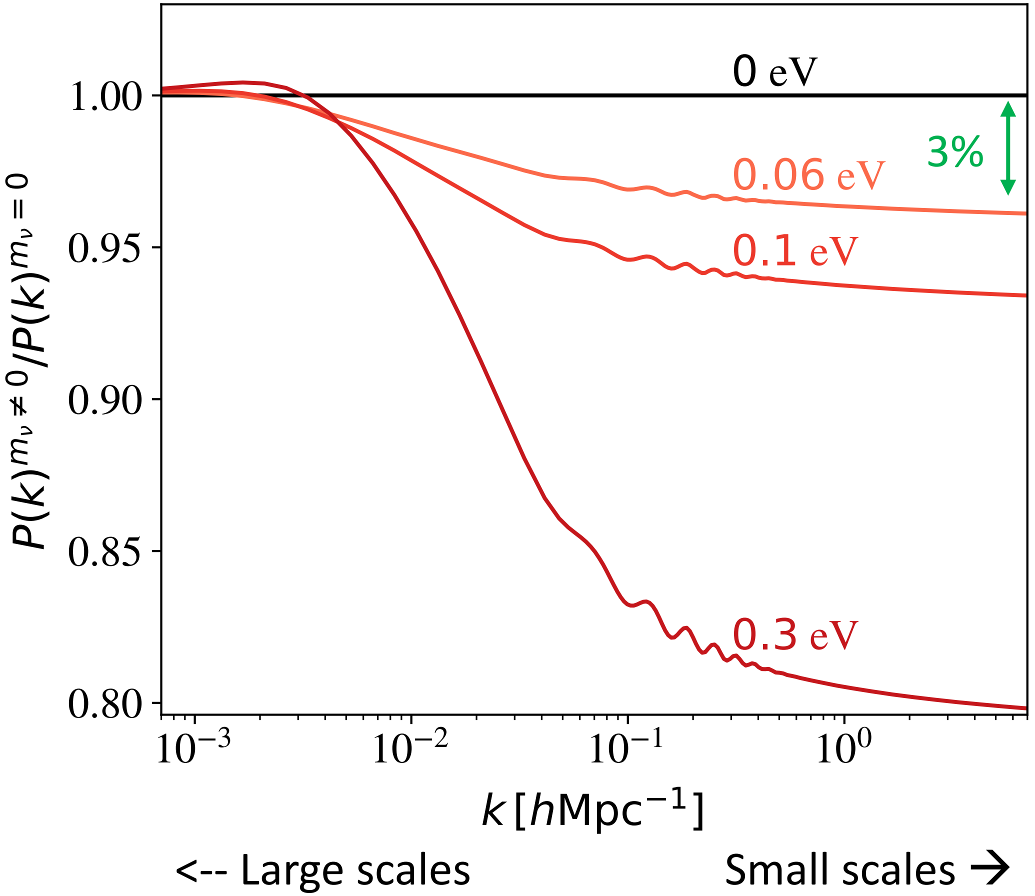


Spectroscopy
Imaging

Euclid in a nutshell

- **ESA** M2 space mission in the framework of the Cosmic Vision program
- Launch **July 1st 2023**. Duration **> 6 years**
- **DR1 November 2026 & Mid 2027!**
- 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</u>)

Detecting the neutrino mass with LSS



We will have accurate data, but we still do not have an equally accurate theory

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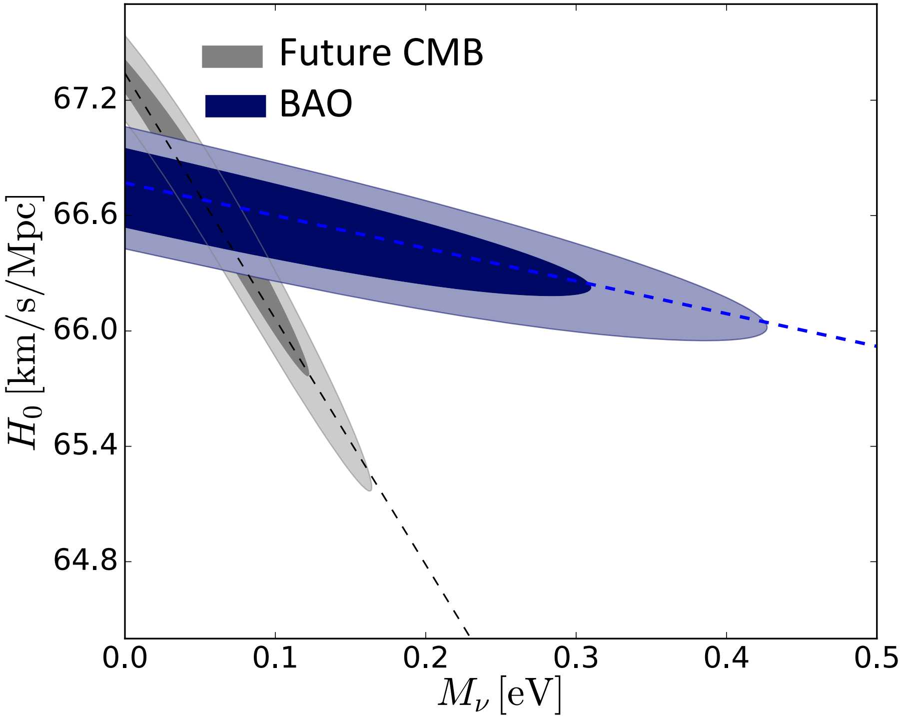

Known unknowns (systematics, etc.)

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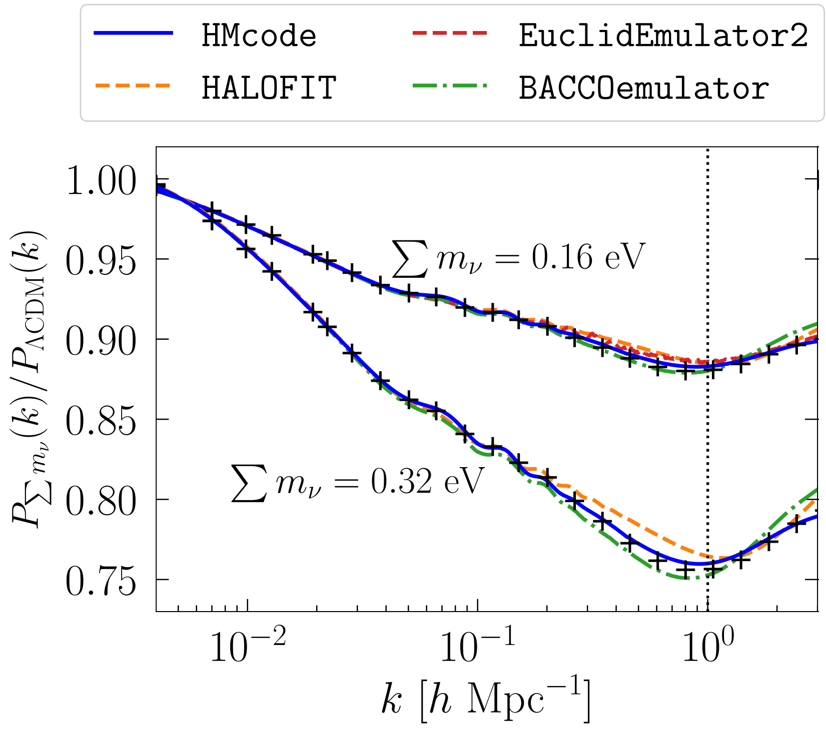

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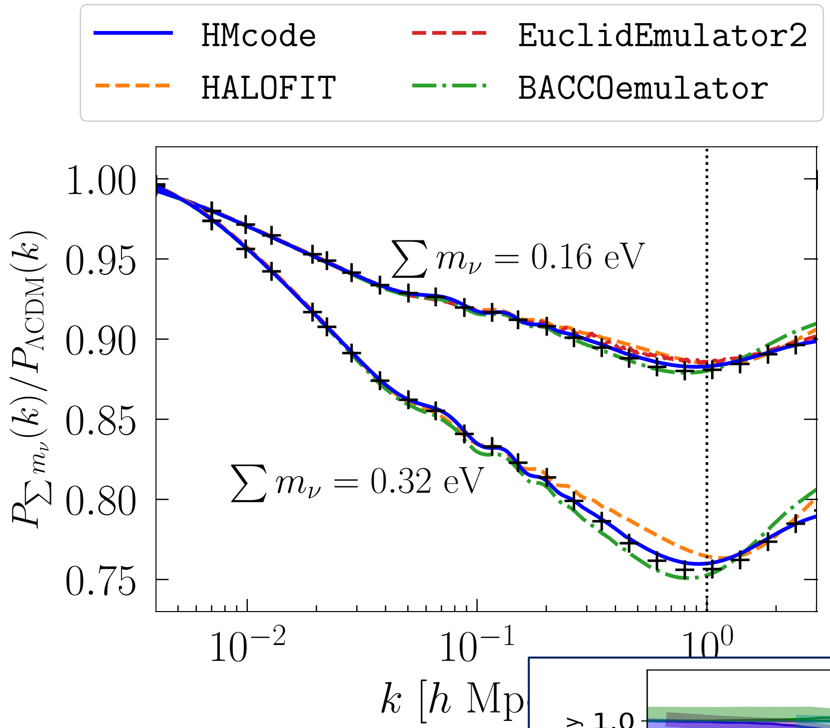
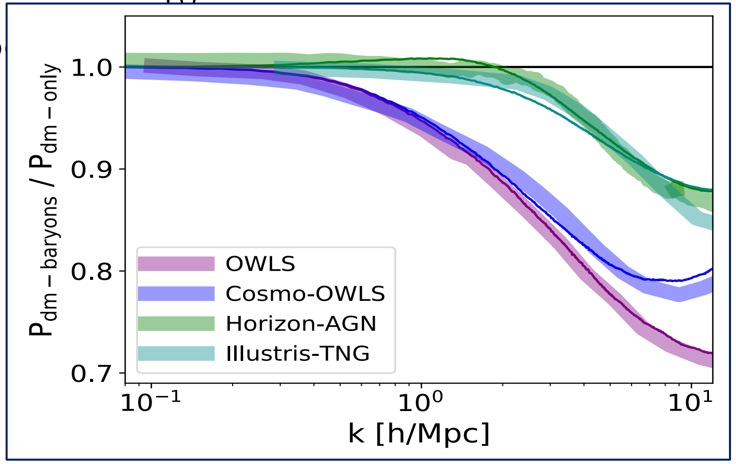
3. Baryonic feedback [Chisari (2019); Euclid Collaboration: Martinelli et al. (2020); Spurio Mancini et al. (2023); Euclid Collaboration: Archidiacono et al. (2024)]

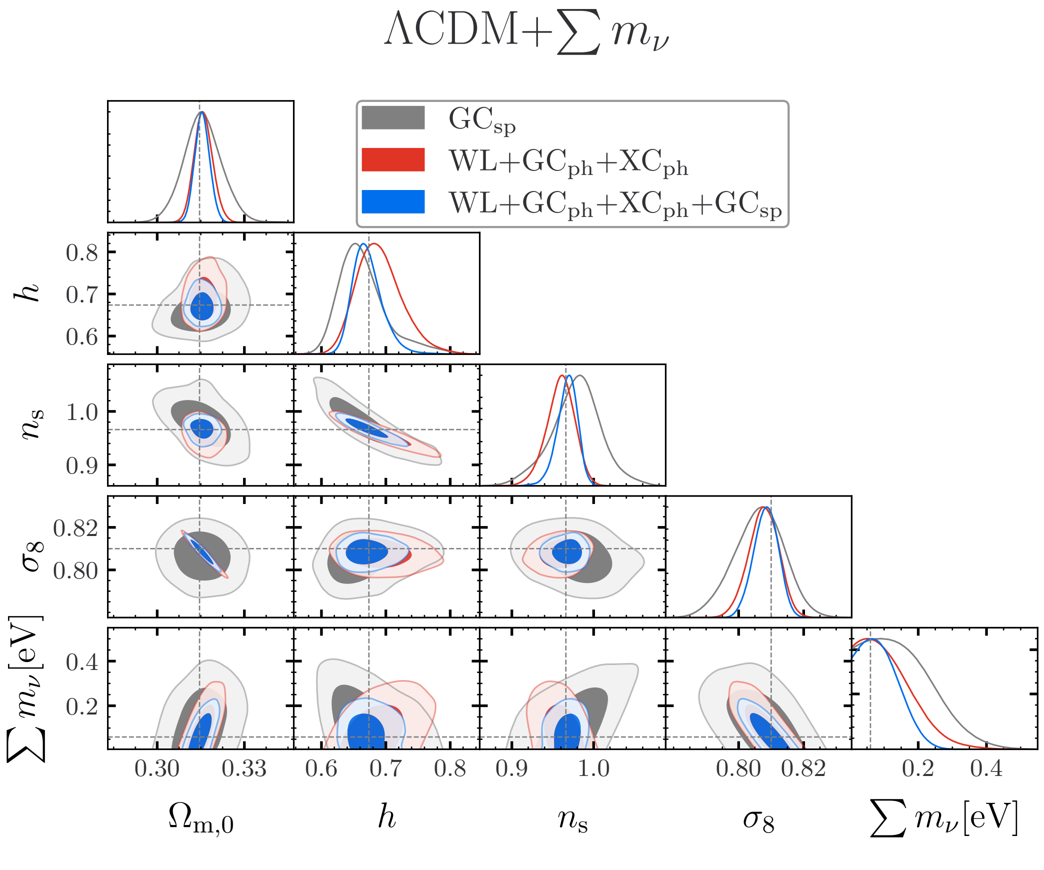


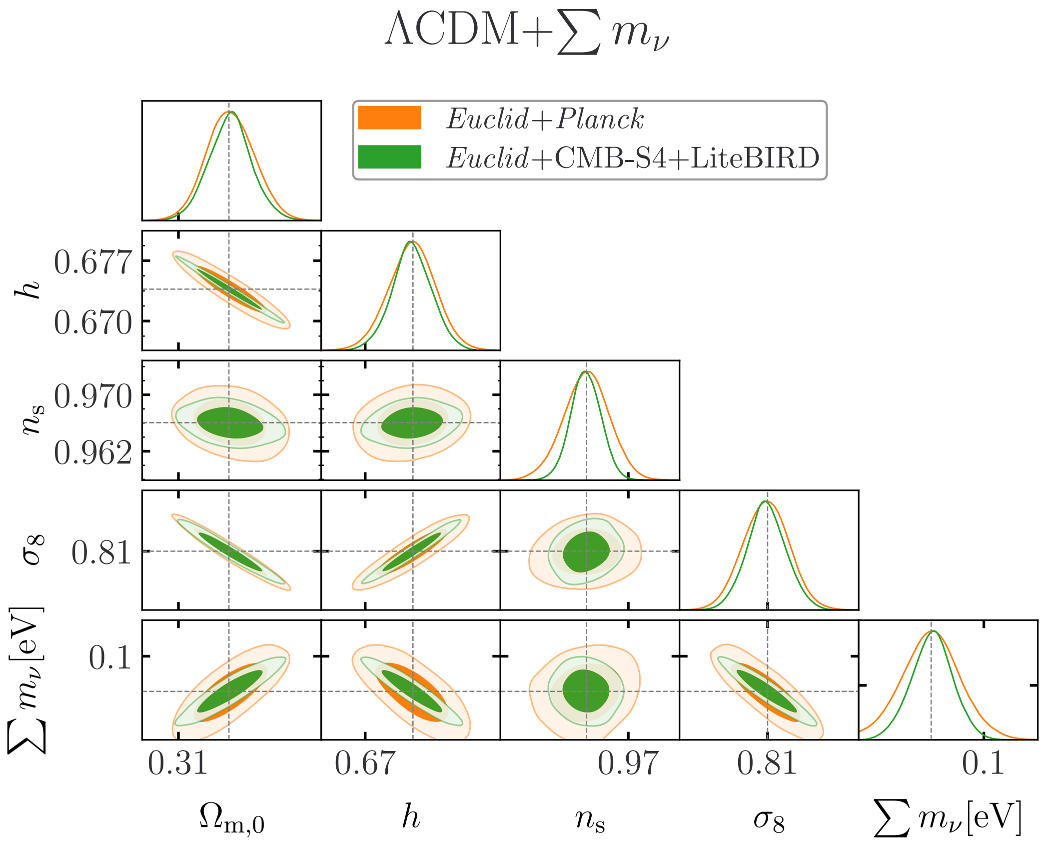
Chisari (2019)



Neutrino mass constraints: the future

Euclid preparation: Sensitivity to neutrino parameters.
Euclid Collaboration: Archidiacono et al. (2025)





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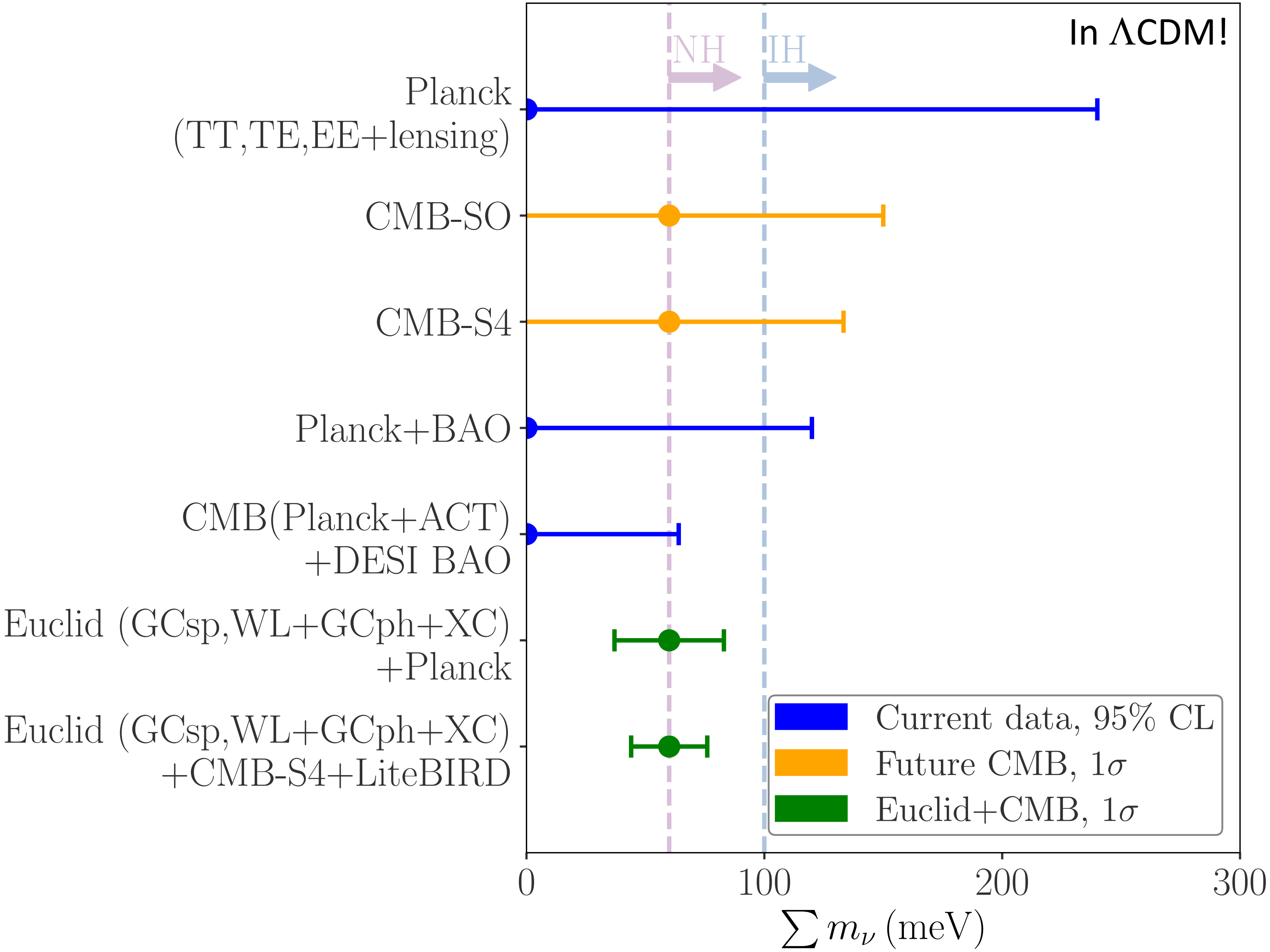
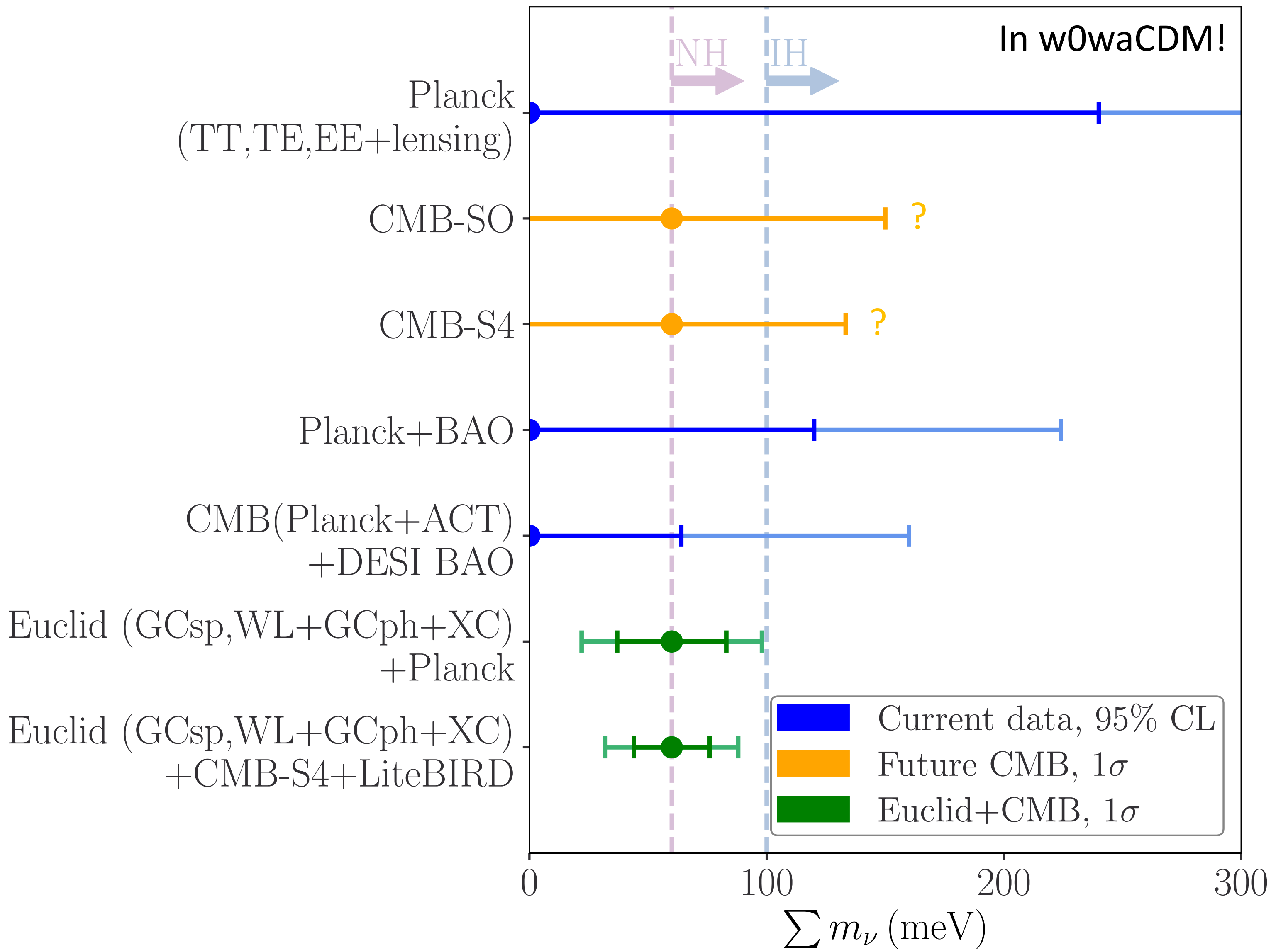


Euclid+Planck: >2σ evidence of a non-zero neutrino mass sum

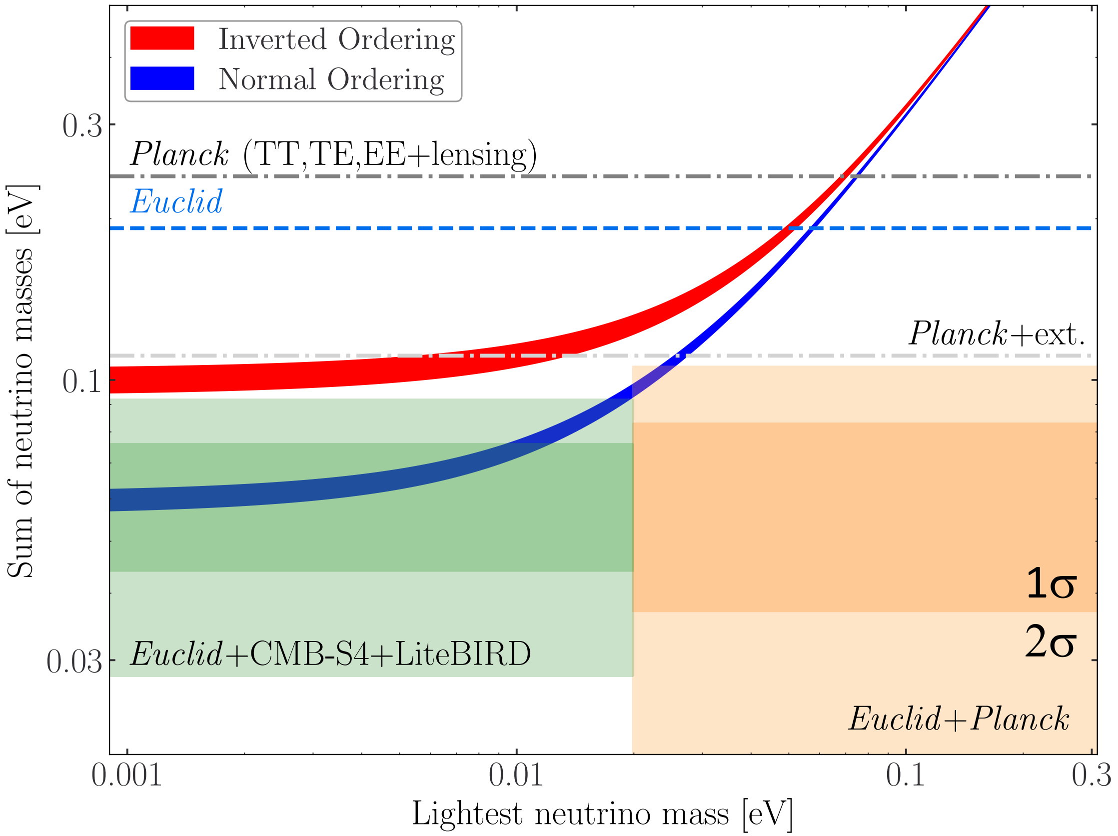
Euclid+CMB-S4+LiteBird: >3σ

Neutrino mass constraints: the future

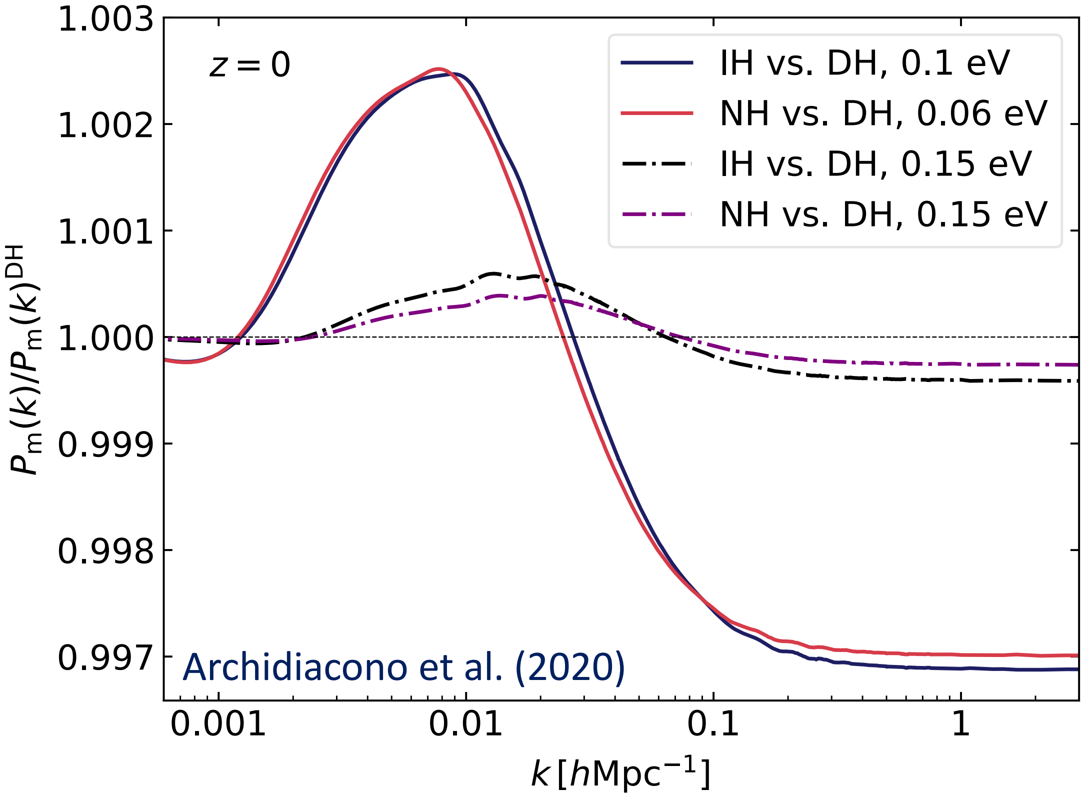


Replacing the cosmological constant with dark energy with a time varying equation of state parameter increases the error by a factor 2.

Neutrino mass ordering



Indirect hints for NH,
only if the true neutrino mass is close to 0.58 eV



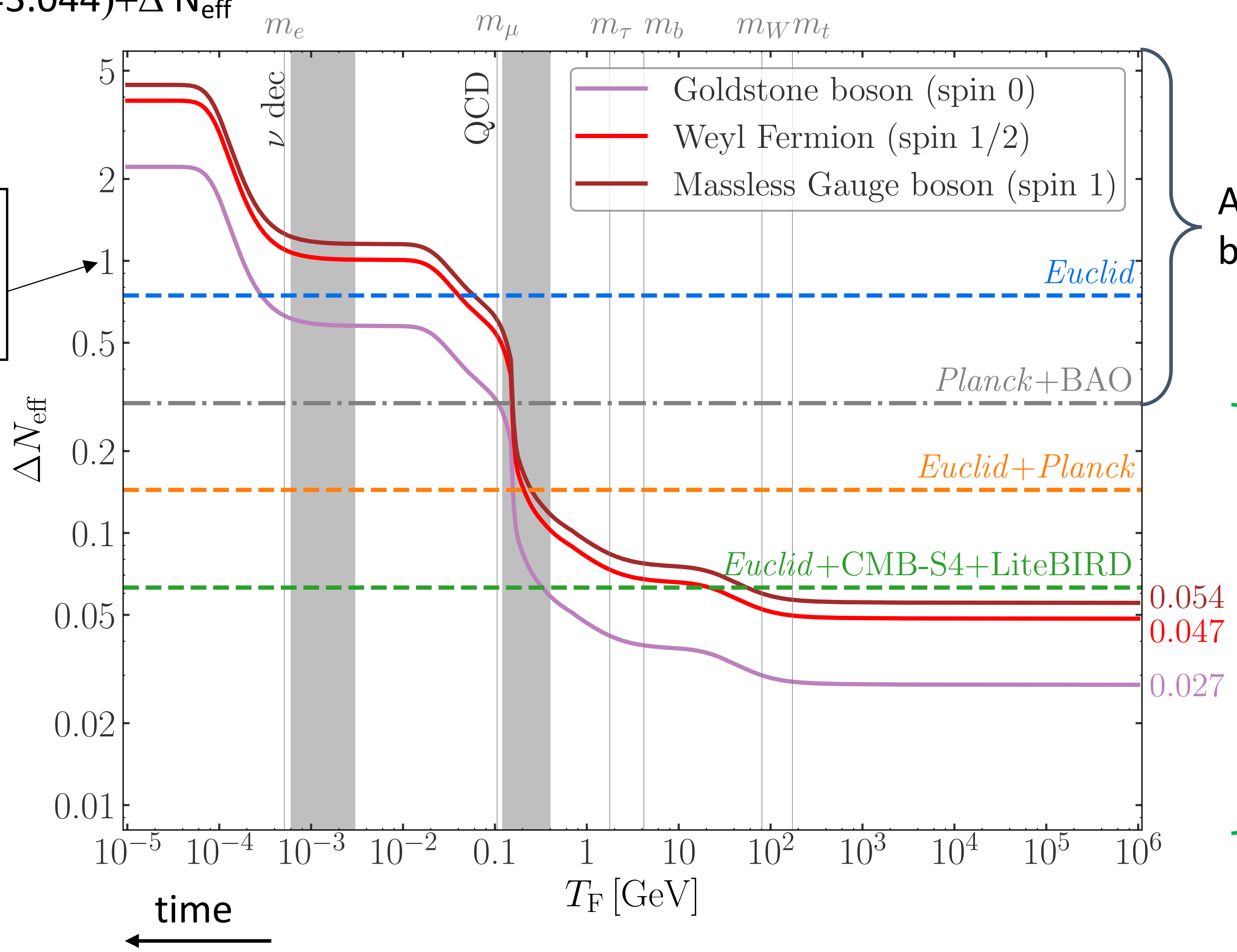
The effect induced by the neutrino mass ordering on the cosmological observables is below the sensitivity of current and planned cosmological surveys.

The DH assumption is valid, and it is more efficient.

Number of neutrinos and neutrino-like particles

Any BSM particle thermalised with the SM in the early Universe, relativistic at decoupling, potentially non-relativistic today $N_{eff} = N_{eff}^{SM}(=3.044)+\Delta N_{eff}$

Thermalised "sterile" neutrinos already excluded

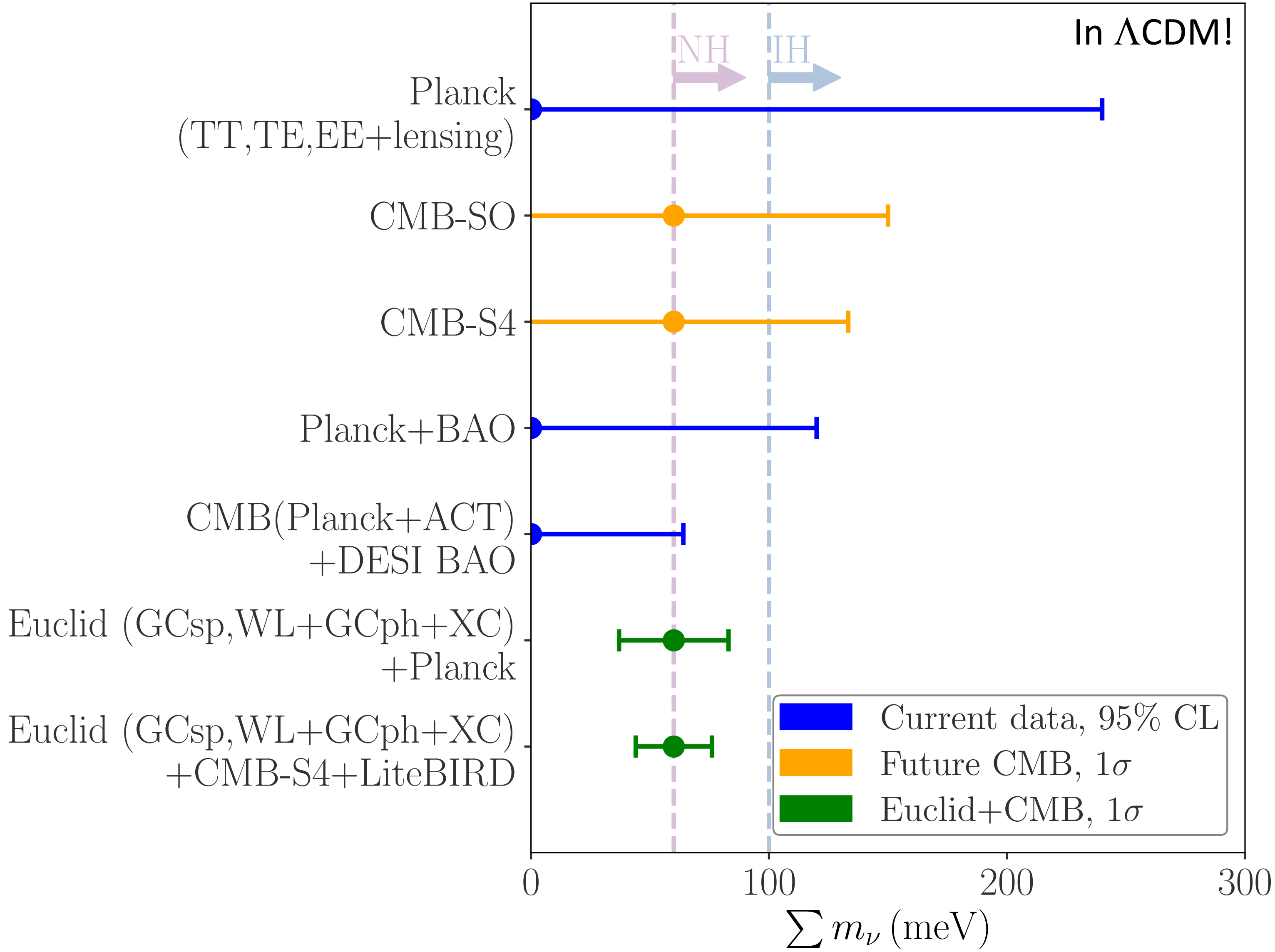


Already excluded by current limits

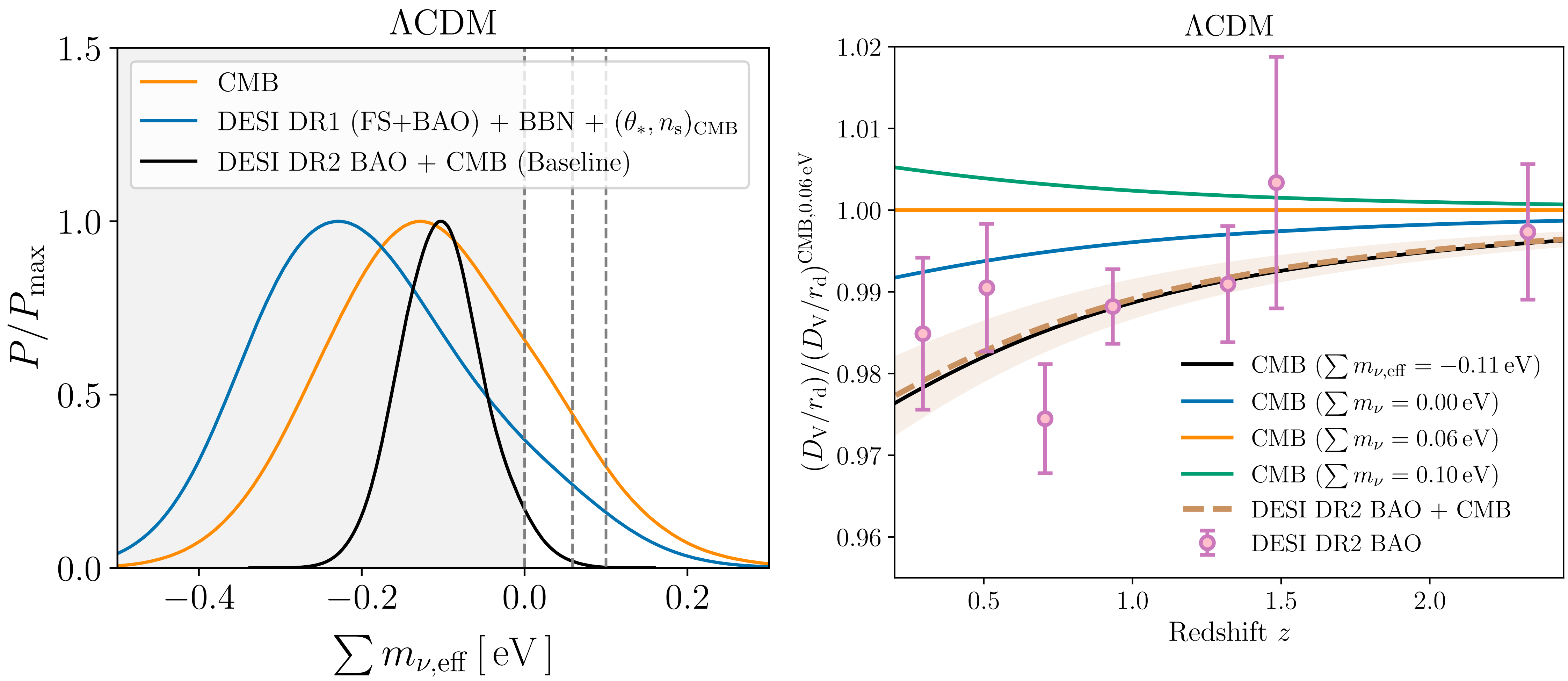
Still possible... Probed by future CMB and LSS surveys

The cosmological neutrino mass problem

Neutrino mass: How low we can go?



The cosmological neutrino mass problem



DESI Collaboration, Elbers et al., 2025

The cosmological neutrino mass problem

What if the cosmological bounds cross the minimum value allowed by oscillations or even the minimal physically meaningful value?

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

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Yes…

1. Beyond ΛCDM
2. Beyond GR
3. Beyond SM

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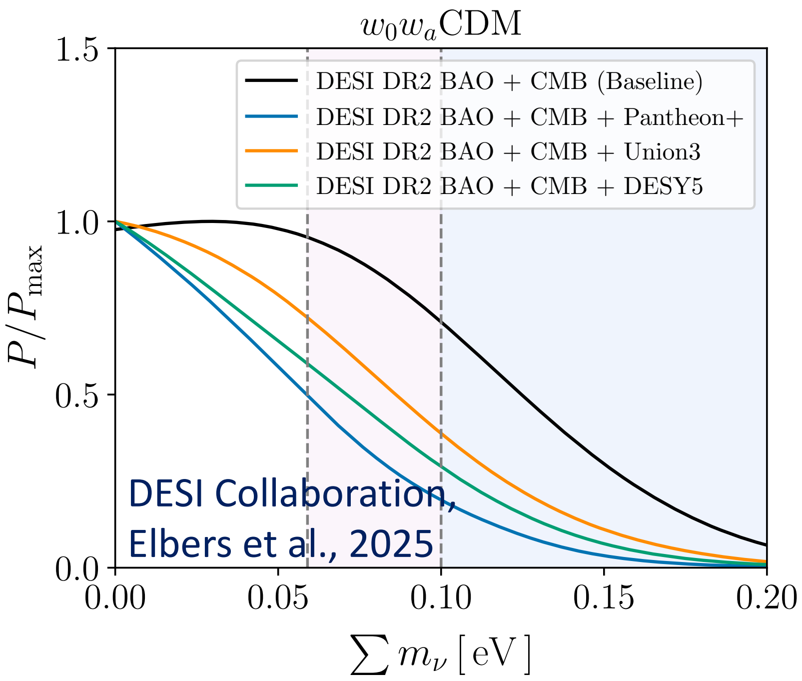
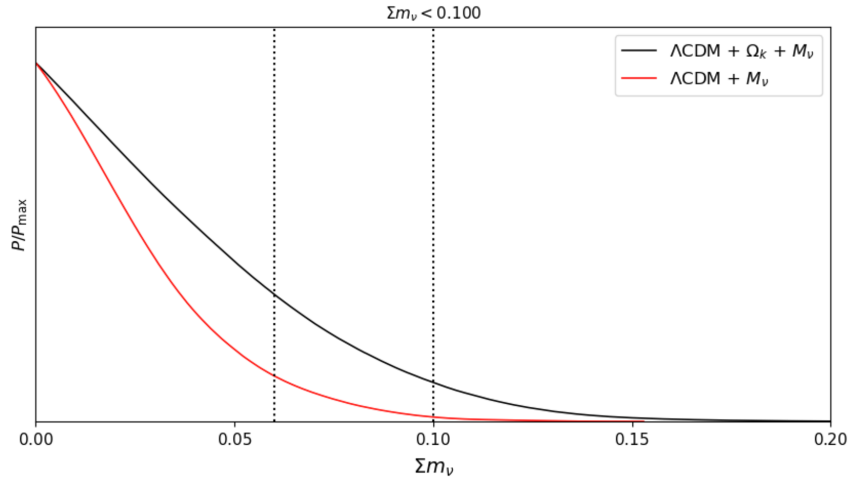


DESI Collaboration, Elbers et al., 2025

Shi-Fan Chen & Zaldarriaga, 2025



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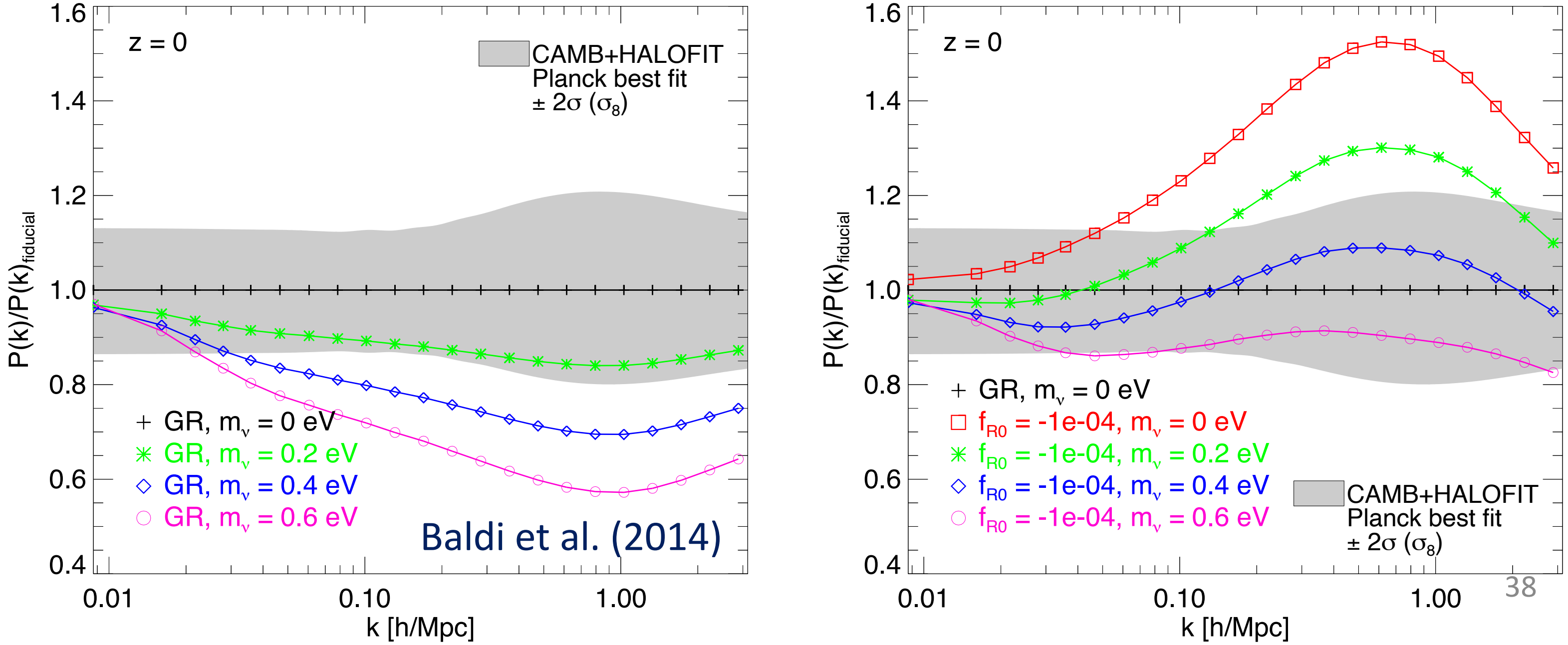

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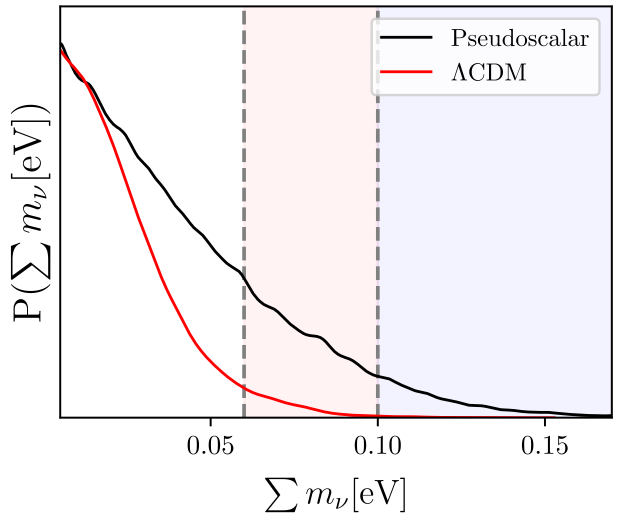
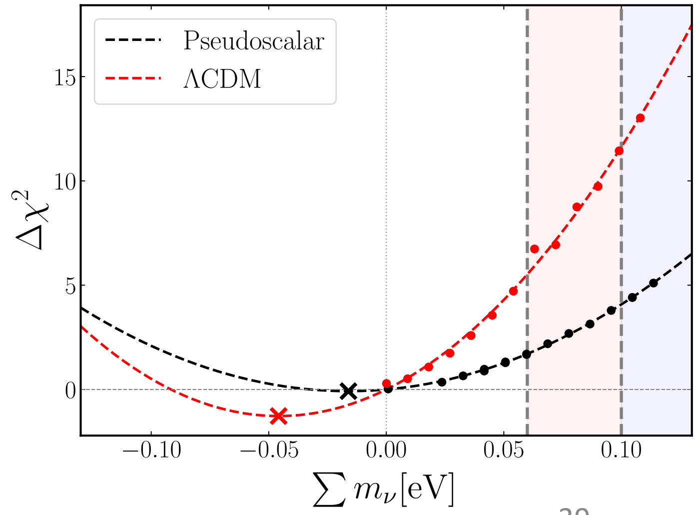
Sharma, Archidiacono, Lesgourgues (2026)





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

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

Cosmology is a remarkably powerful laboratory for neutrino physics, but its constraints are model-dependent and affected by astrophysical and observational systematics. The complementarity with terrestrial neutrino experiments is therefore key to a robust determination of neutrino properties.

Backup

The cosmological neutrino mass problem

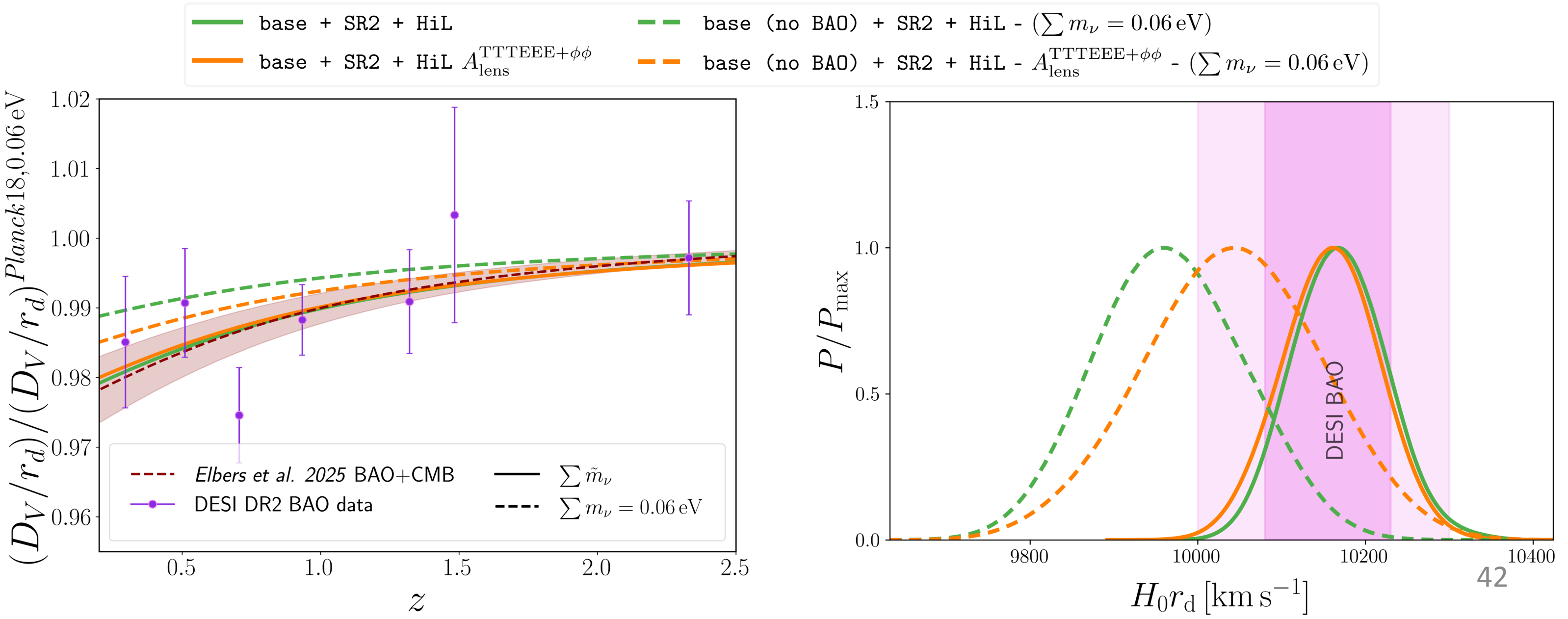
What if the cosmological bounds cross the minimum value allowed by oscillations or even the minimal physically meaningful value?

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

Yes…

1. Beyond ΛCDM
2. Beyond GR
3. Beyond SM
4. “Tensions”

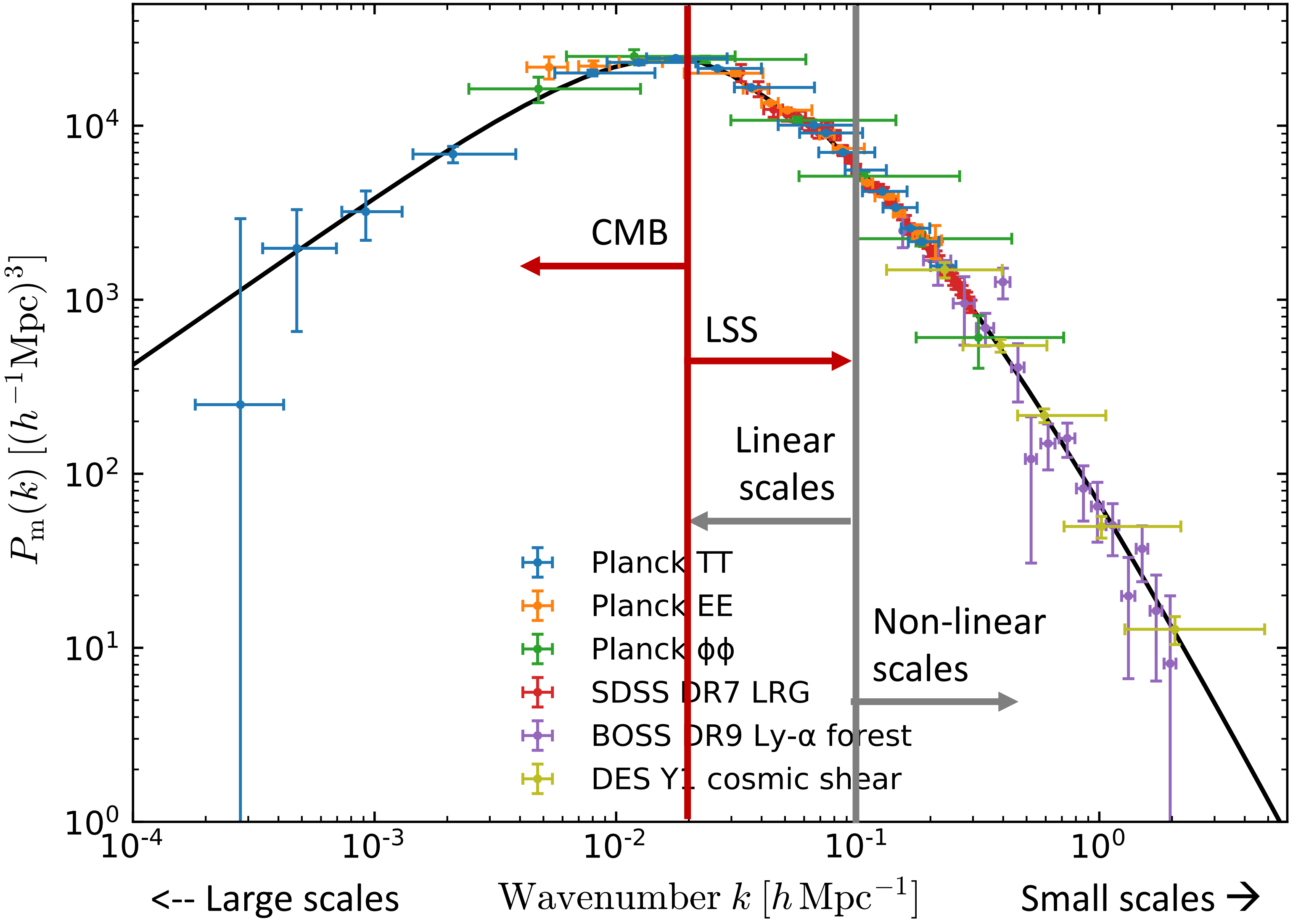
Cozzumbo, Atzori Corona, Murgia, Archidiacono, Cadeddu (2025)



… and at different 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

Indirect detection of the CνB
The number of neutrinos
…and other light relics

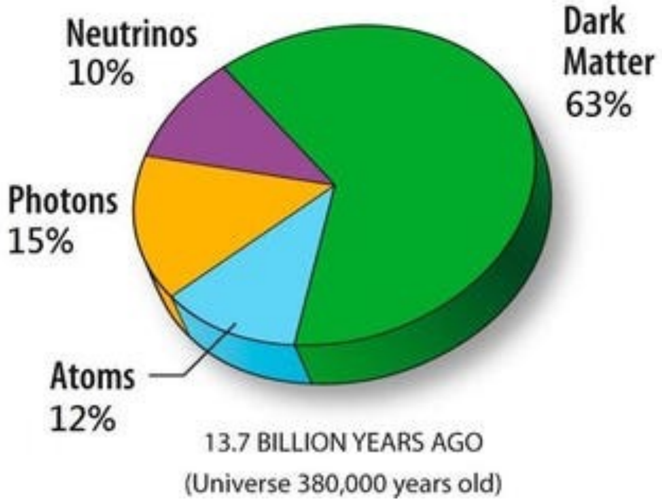
The N_{eff} parameter

The expansion rate of the Universe depends on its ingredients

$$H^2(a(t)) = H_0^2\left(\Omega_{\rm rad}a^{-4} + \Omega_{\rm m}a^{-3} + \Omega_\Lambda\right)$$

$$\Omega_i = \frac{\rho_{i,0}}{\rho_{\rm crit}}$$

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



DR = Dark Radiation, BSM light relics

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

For the 3 neutrino families of the SM

$N_{eff}^{SM} = 3.044 \pm 0.001$ [Mangano et al. (2002), Froustey et al. (2020), Bennett et al. (2021), Drewes et al. (2024)]

N_{eff} probes: BBN

Shortly after neutrino decoupling the weak interactions that kept neutrons and protons in statistical equilibrium freeze out.

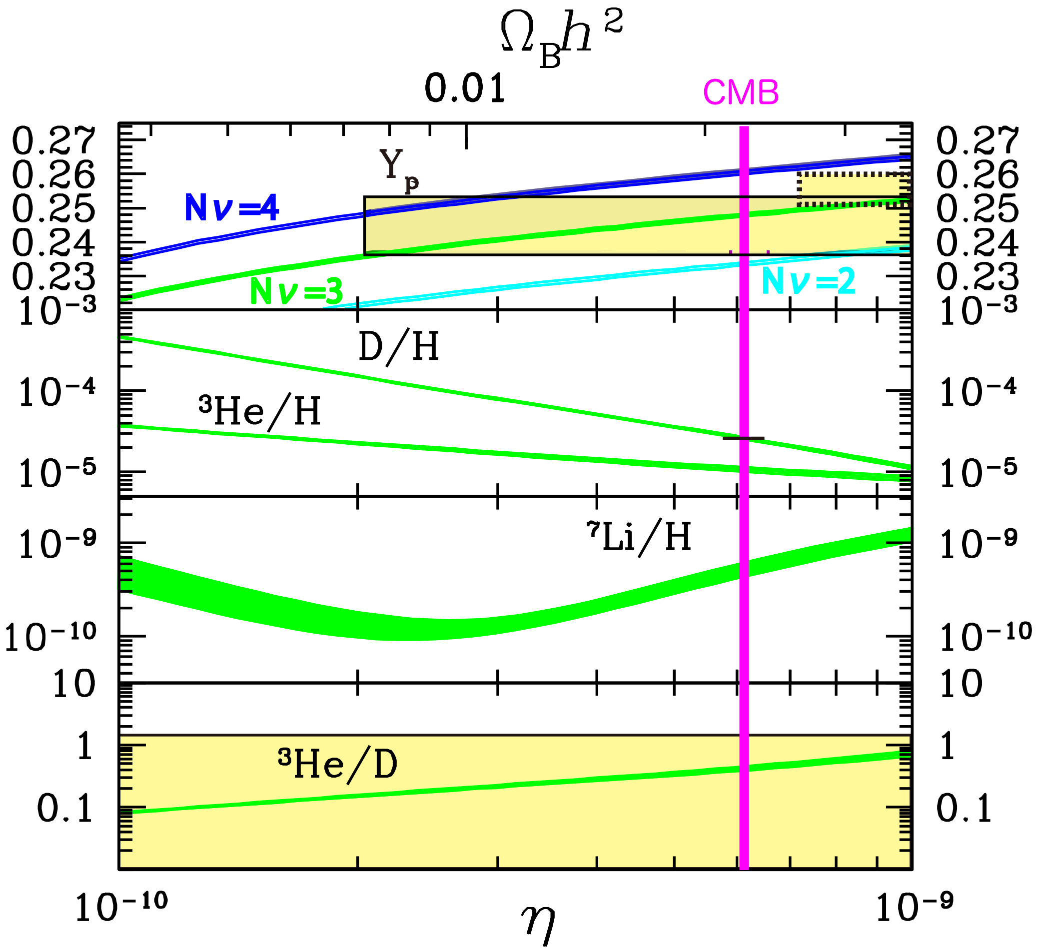
$$H = \Gamma\big|_{T=T_{freeze}} \qquad T_{freeze} \approx 0.6 g_*^{1/6}\ MeV$$

$$\left.\frac{n_n}{n_p}\right|_{T=T_{freeze}} \approx \exp\left(-\frac{(m_n - m_p)}{T_{freeze}}\right) \approx \frac{1}{6}$$

$$Y_P \approx \left.\frac{2n_n/n_p}{1+n_n/n_p}\right|_{T\approx 0.2\,MeV} \propto f(g_*, \Omega_b h^2)$$

$$g_* \to g_* + \frac{7}{4}\Delta N_{eff}$$

$$\left|Y_P^{theo} - Y_P^{obs}\right|_{\Omega_b} \to \Delta N_{eff}\big|_{\Omega_b}$$



Kawasaki et al. (2018)

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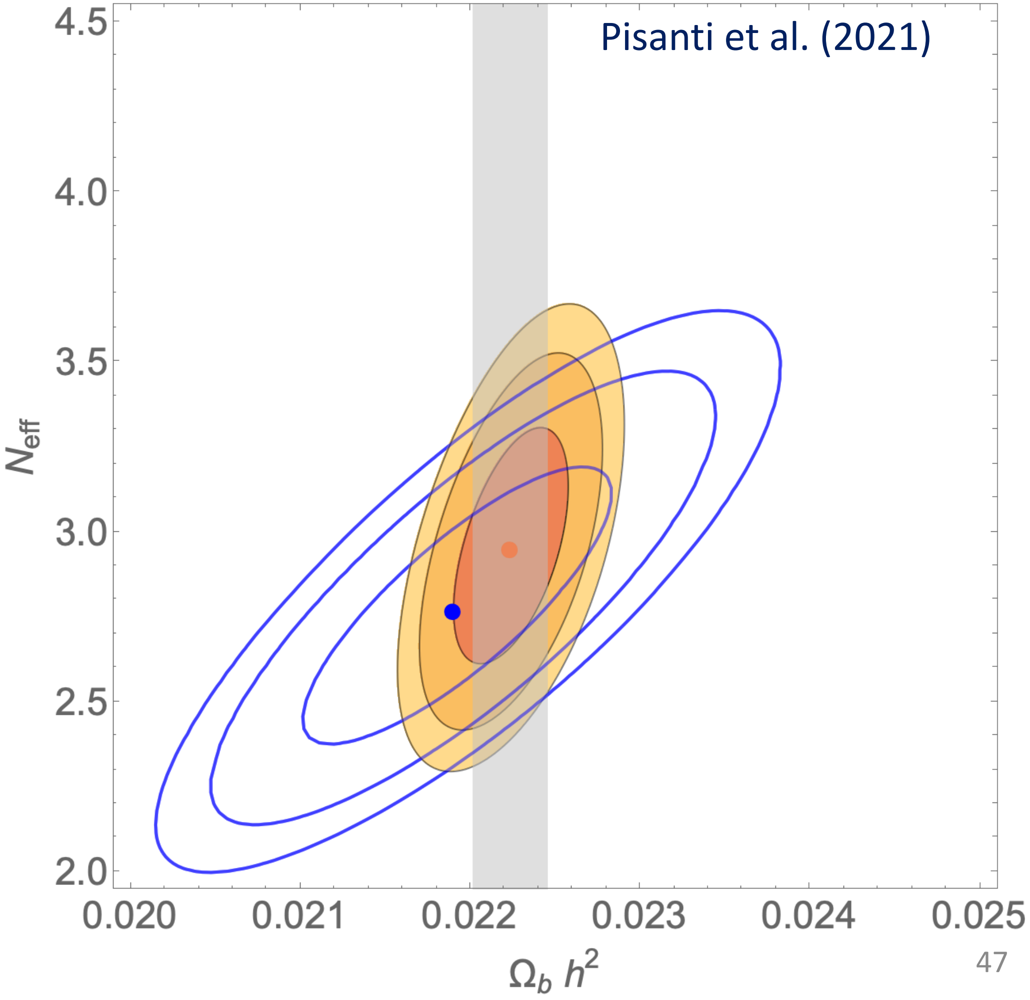


$N_{eff} = 2.78 \pm 0.28$ (68% CL)

Light sterile neutrinos with NSI

Early time phenomenology

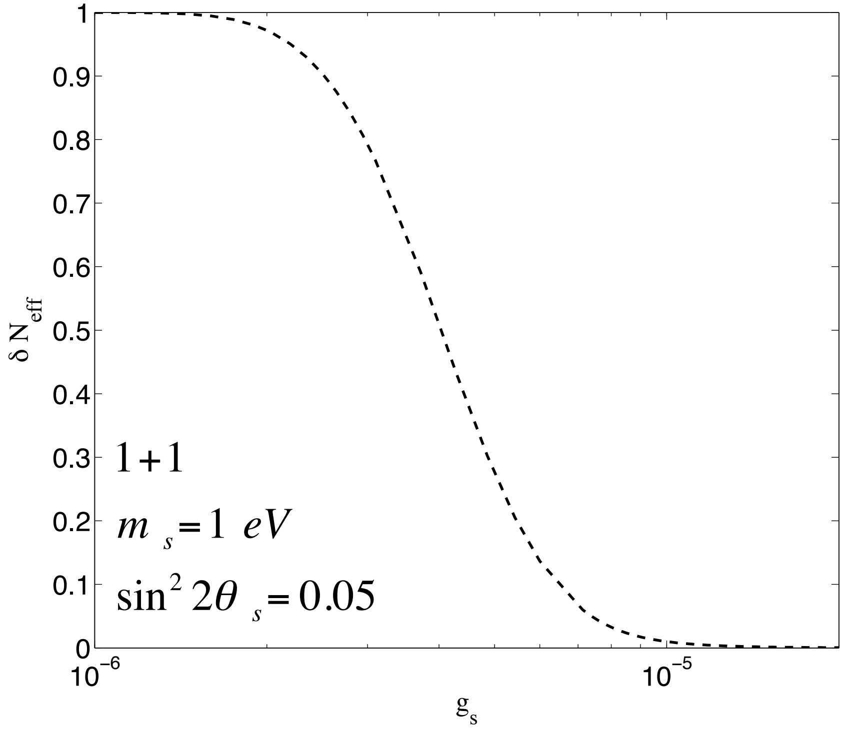
The sterile neutrino is coupled to a new light pseudoscalar (m_ϕ << 1eV):

$$L_{int} \sim g_s \, \phi \, \nu^{-1}_s \, \gamma_5 \, \nu_s$$

If the dimensionless coupling is larger than $g_s \sim 10^{-6}$, the production of sterile neutrinos is delayed until the time of active neutrino decoupling.

One additional sterile neutrino is consistent with the cosmological bounds on N_{eff}

Archidiacono, Hannestad, Hansen, Tram, PRD (2014)



Sterile neutrinos are too many and too massive for cosmology

BBN bounds