New frontiers in neutrino cosmology

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UNIVERSITÀ DEGLI STUDI DI MILANO

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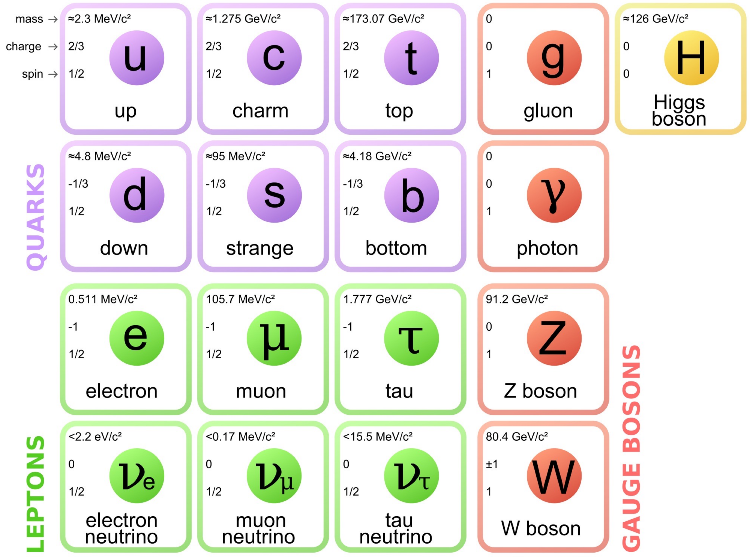
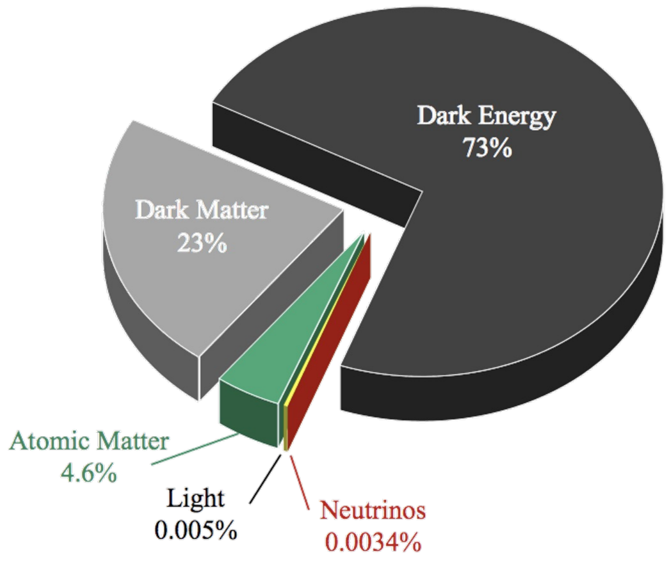
Why neutrino cosmology

Standard Model of particle physics



ΛCDM model of cosmology



Open questions:

Neutrino masses

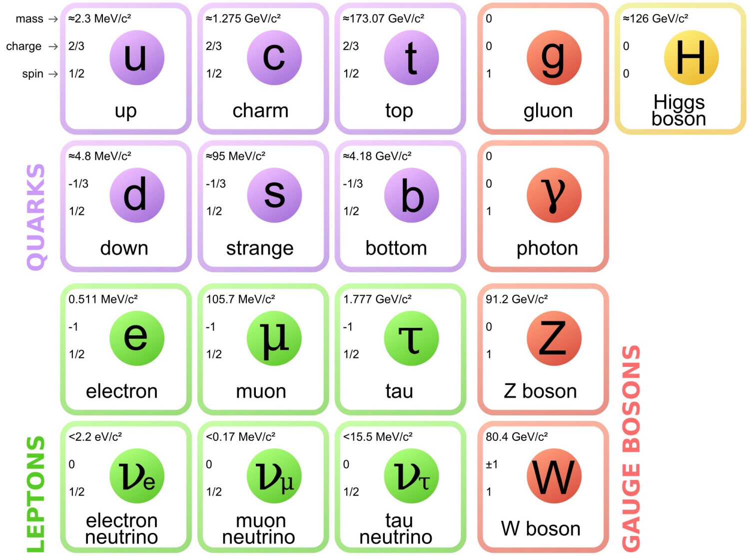
Neutrino number

Dark matter

Dark energy

Why neutrino cosmology

Standard Model of particle physics



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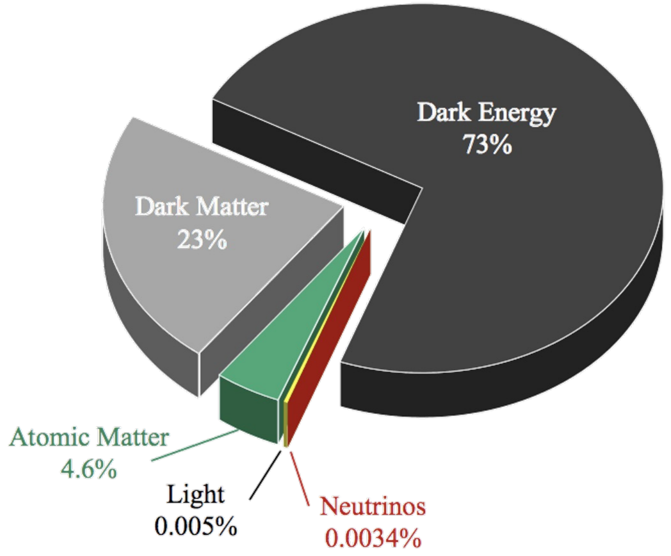

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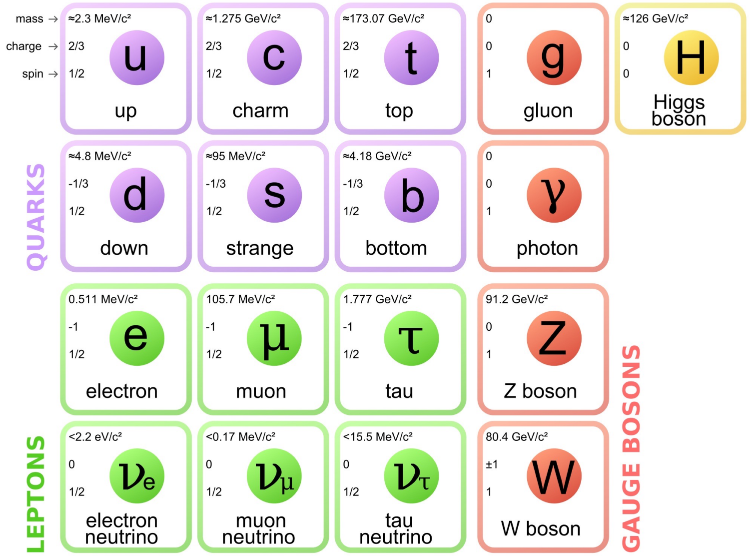

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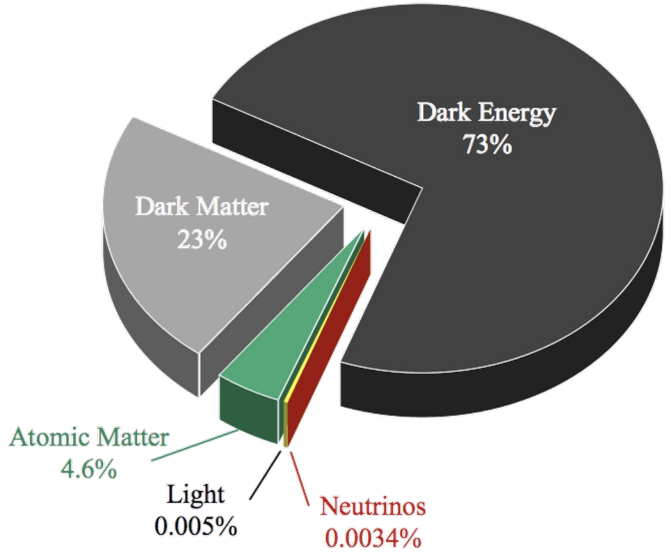


Open questions:

Neutrino masses

H_0 problem

Neutrino number

Dark matter

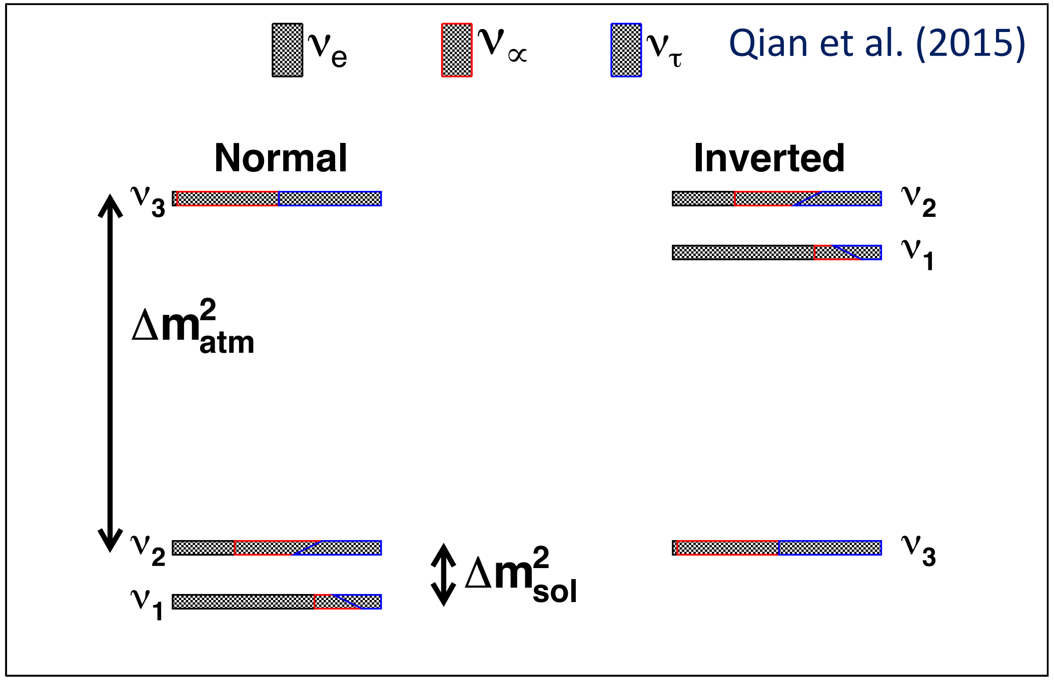
Small scale problem

Dark energy

Neutrinos from the lab

Neutrino oscillations

Neutrino Mass Hierarchy

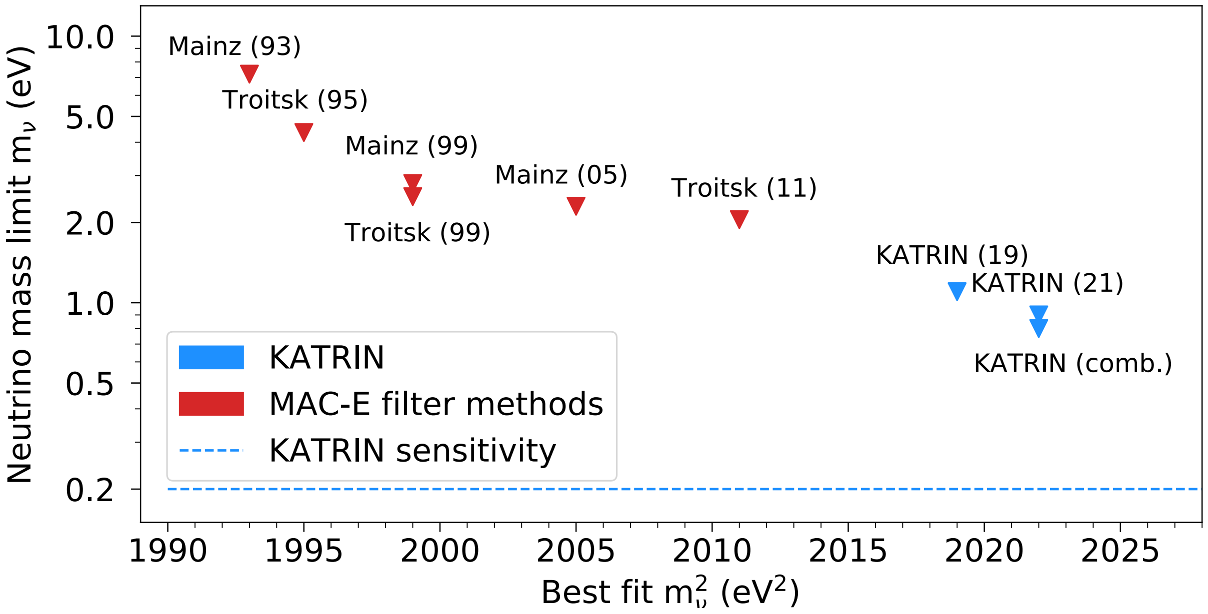


Min. Σm_ν (NH) = 0.058 eV; Min. Σm_ν (IH)= 0.100 eV

The absolute neutrino mass scale is not yet determined by neutrino oscillation data

Neutrino β-decay

(Neutrinoless ββ-decay only if neutrinos are Majorana)



$m_\beta^2 = \Sigma_i |U_{ei}|^2 m_i^2 < 0.8$ eV (90% CL)

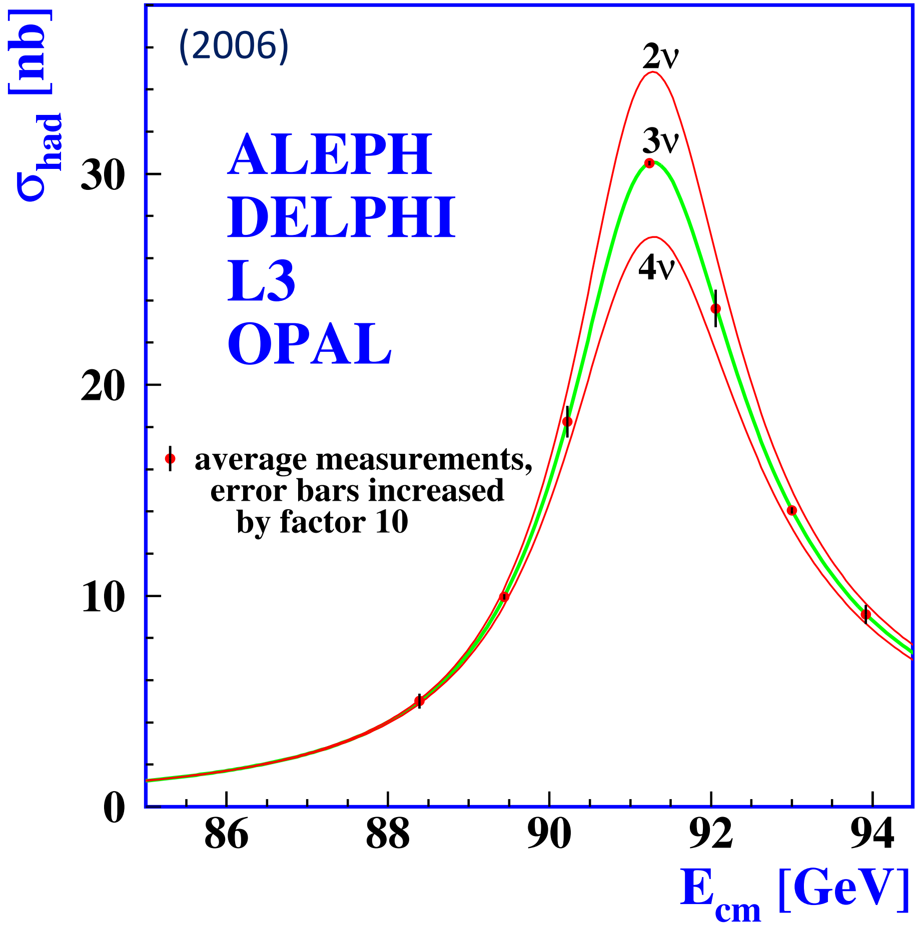
[Aker et al. (2022)]

Sensitivity: 200 meV (90% CL)

Neutrinos from the lab

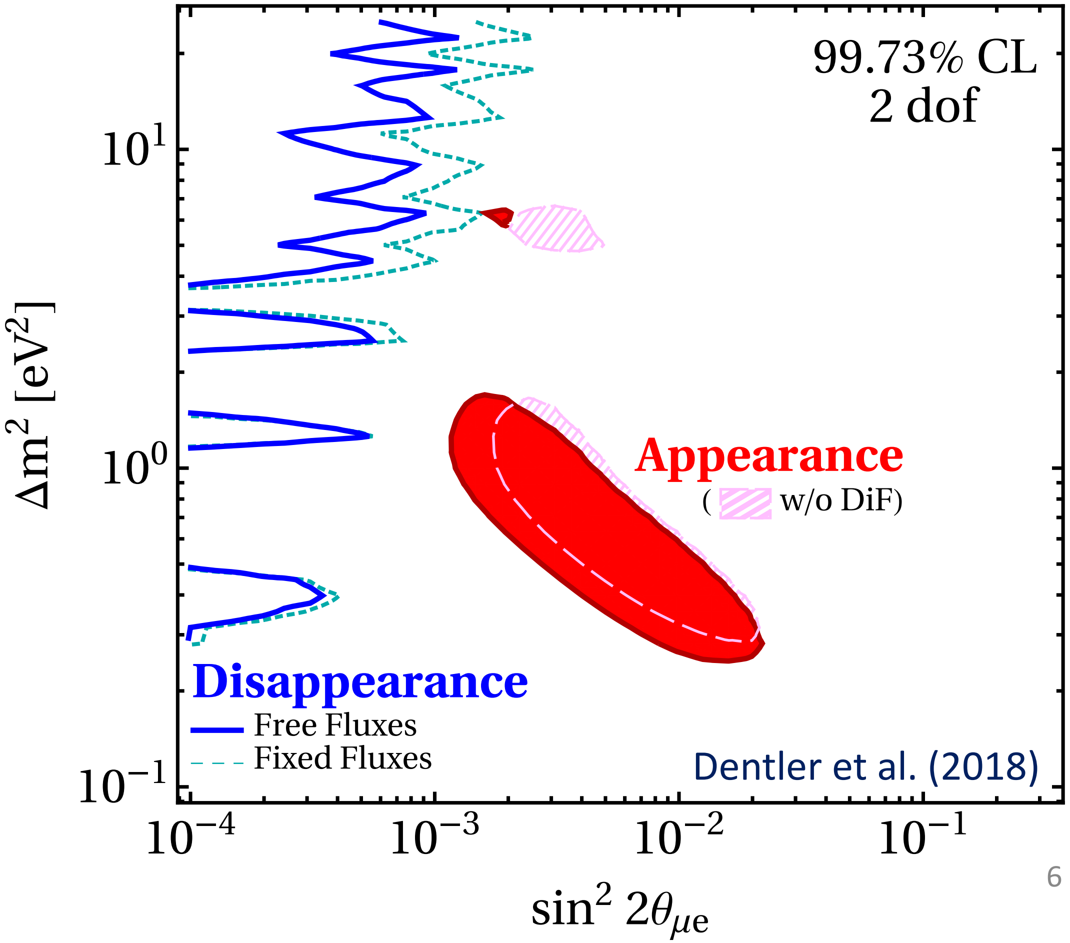
Invisible decay width of the Z-boson

$N_\nu = 2.9840 \pm 0.0082$

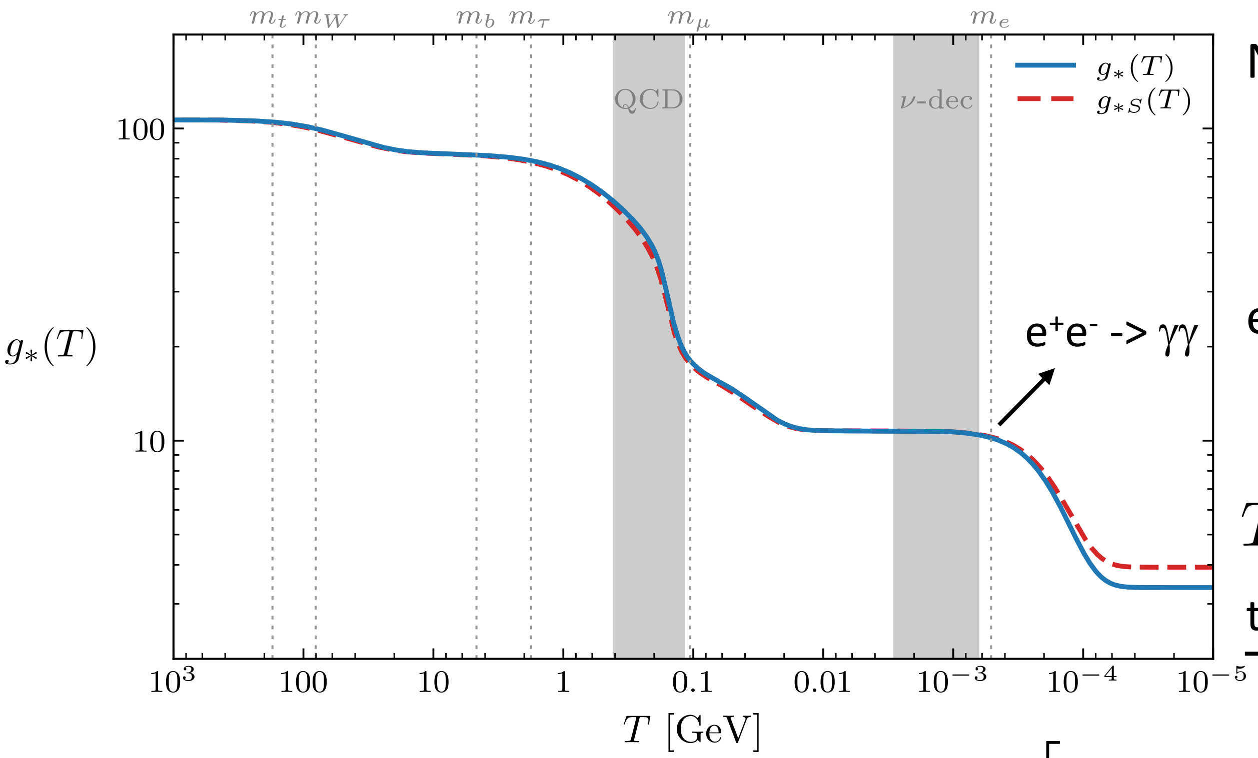


Neutrino oscillation anomalies

Global fit 3(active)+1(sterile)



A short history of cosmic neutrino background



Neutrino decoupling: $\Gamma_{\text{weak}} \sim H$

e^+e^- annihilations: $T_\nu = T_\gamma \left(\frac{4}{11}\right)^{1/3}$

$T_{\nu,0} = 1.9\,\mathrm{K}$

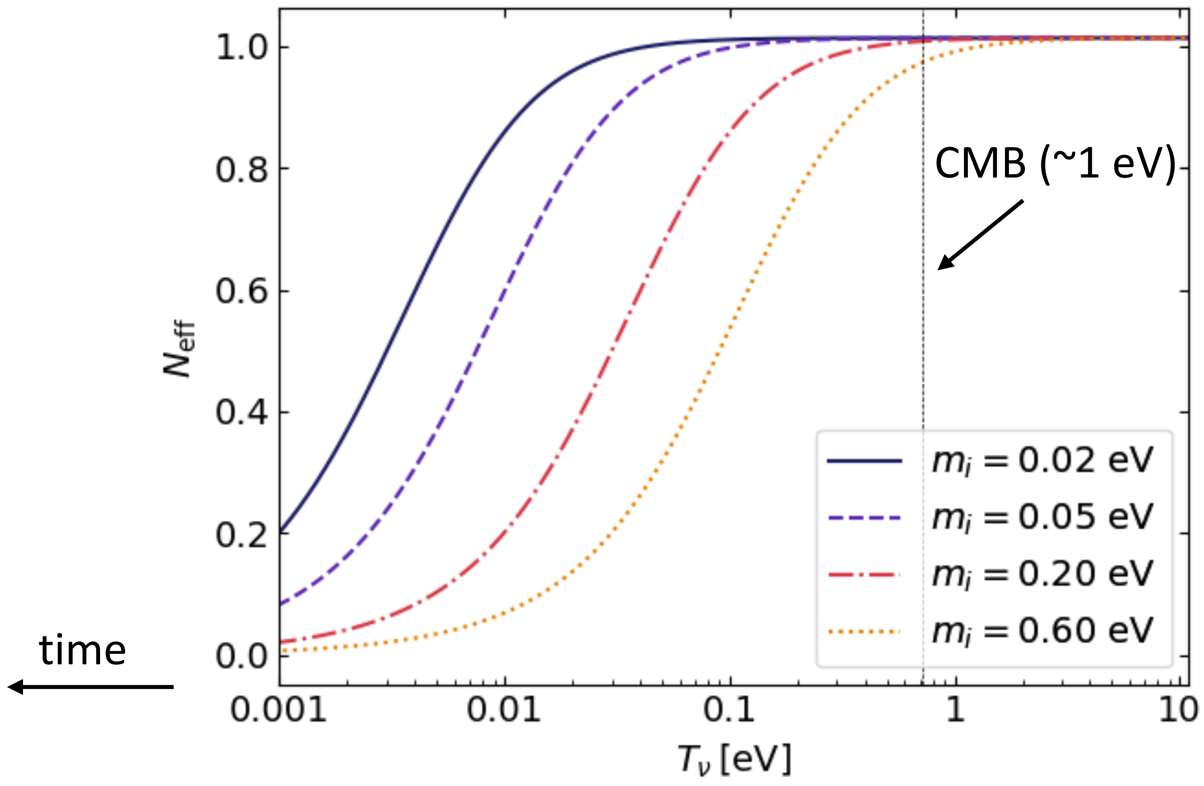
time →

Early times: neutrinos as <u>radiation</u> $\rho_{rad} = \rho_\gamma \left[1 + N_{\text{eff}} \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right]$

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

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

A short history of cosmic neutrino background



Neutrino non-relativistic transition:

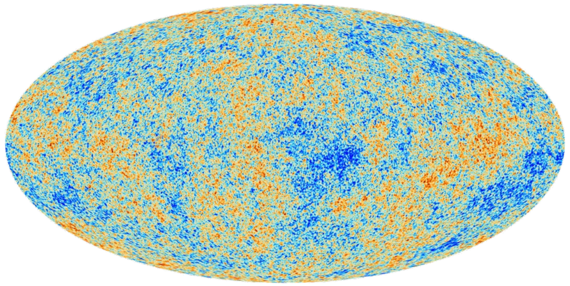
$$z_{\mathrm{nr},i} = \frac{m_{\nu,i}}{0.5\,\mathrm{eV}}$$

Late times: neutrinos as matter

- 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]

Cosmological observables

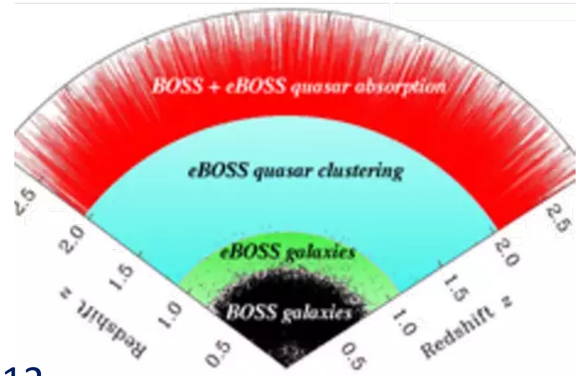


Early Universe

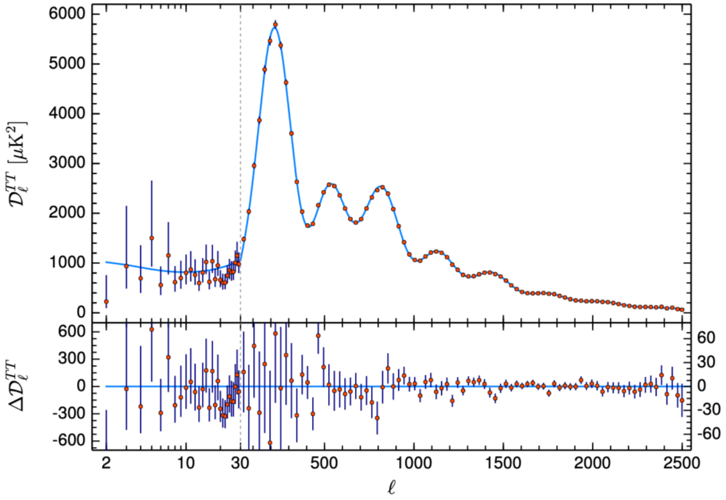
CMB (z=1080)
Temperature,
polarization, (lensing)

Late Universe

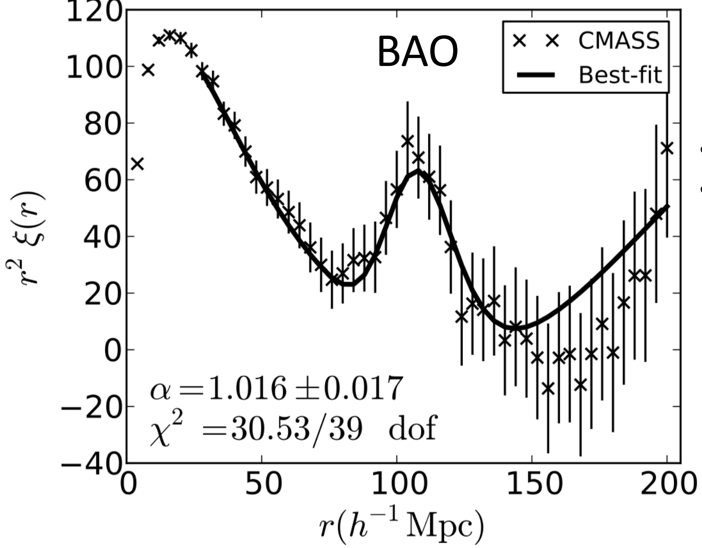
LSS (z<~2-3)
Galaxy positions and
weak lensing

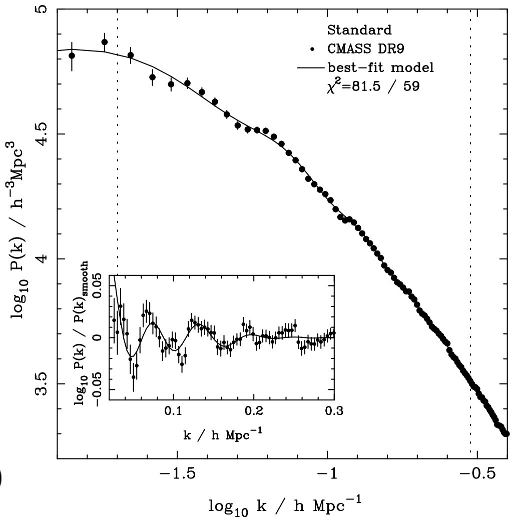


Planck



Anderson et al. 2012



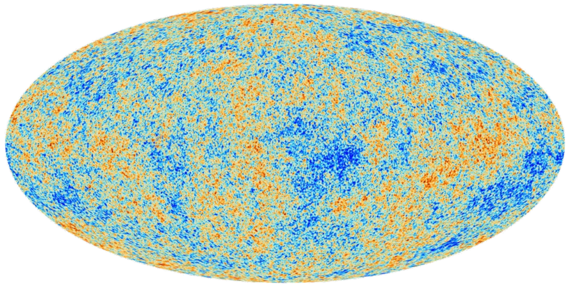


$$\xi(\mathbf{r}) = \langle \delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{r})\rangle \qquad P(k) = \int \xi(\mathbf{r}) e^{i\mathbf{k}\cdot\mathbf{r}} d^3x$$

Cosmological observables

Early Universe

CMB (z=1080)
Temperature,
polarization, (lensing)



Late Universe

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Galaxy positions and
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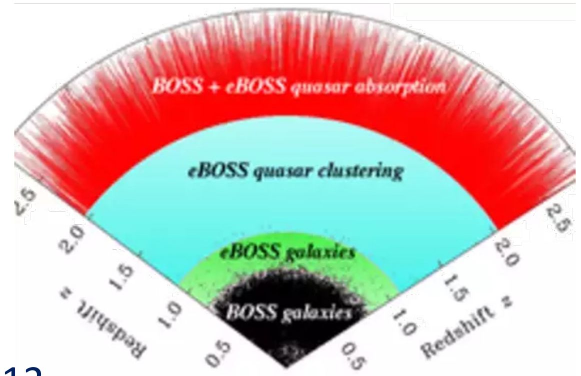
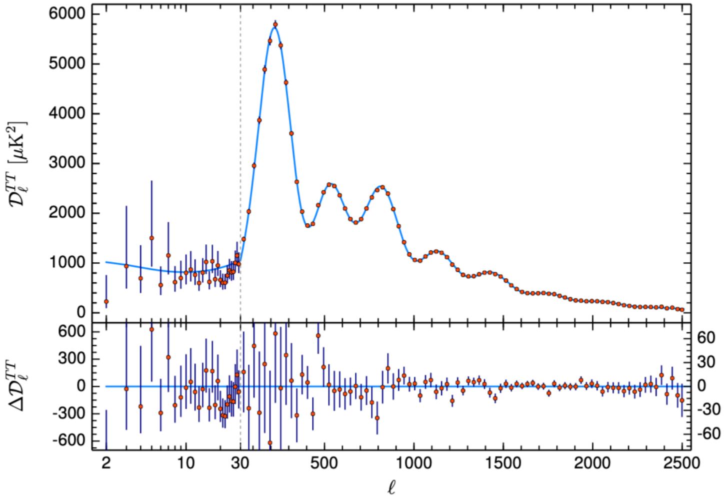


Planck



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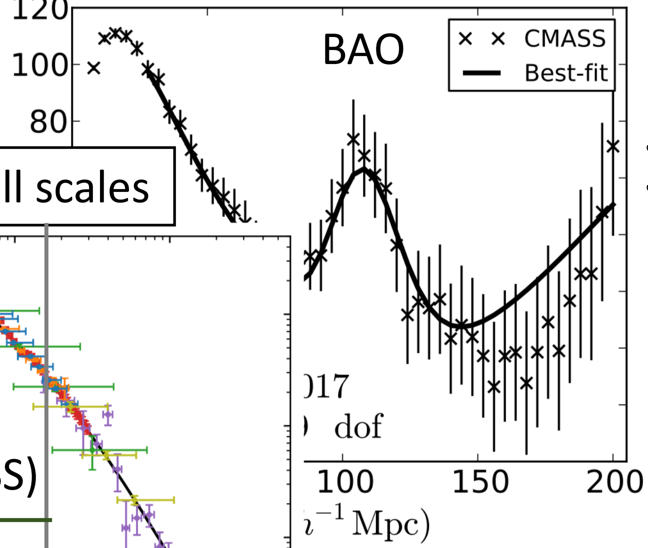
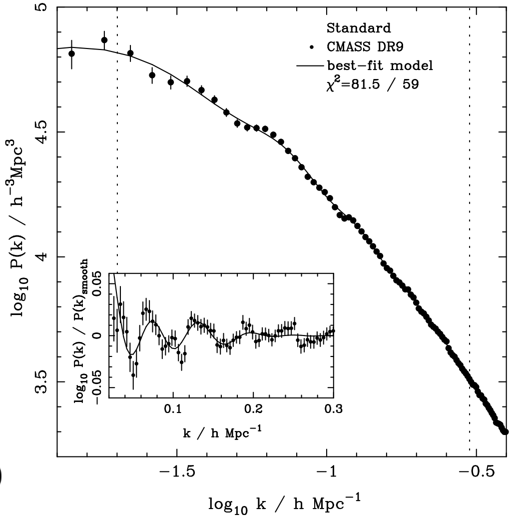
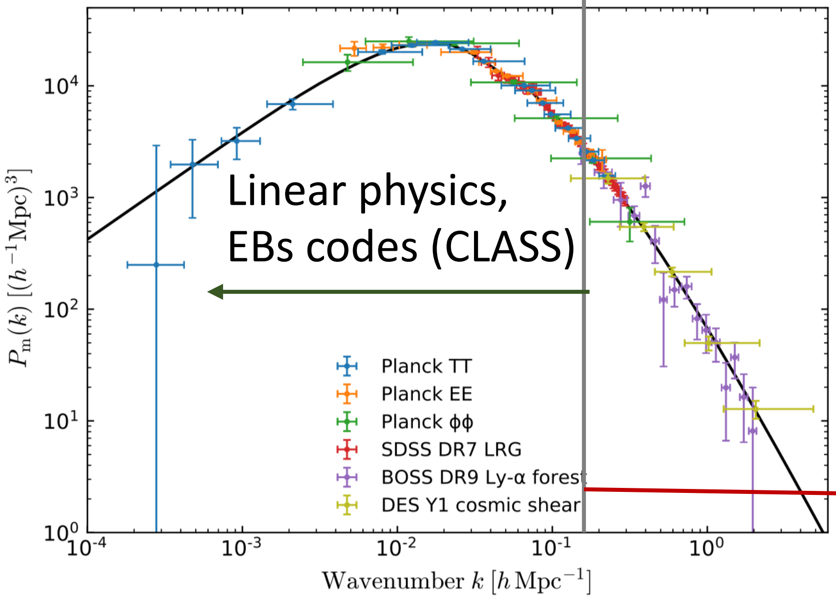




Large scales - small scales



Non-linear processes

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

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

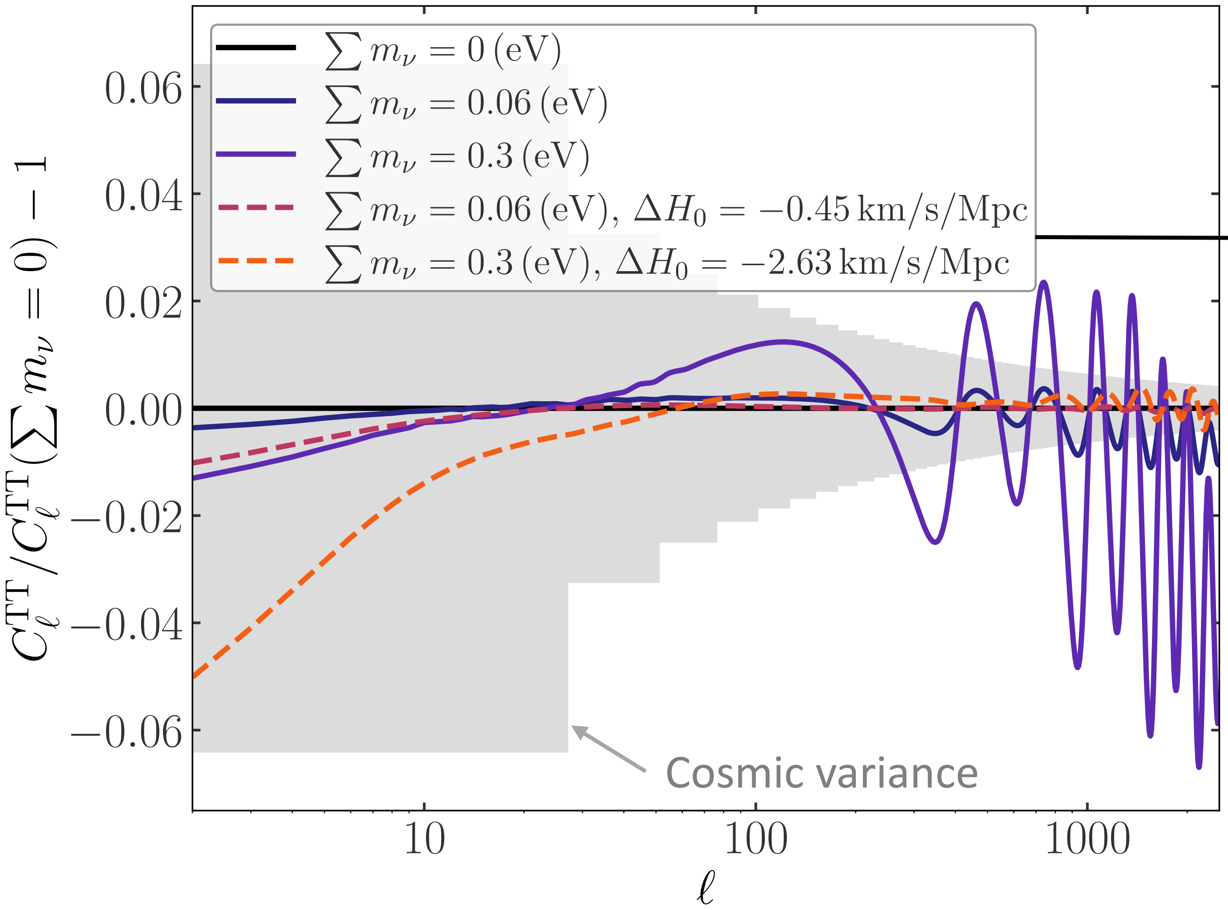
Plan

- Neutrino mass

- Neutrino number and new light particles

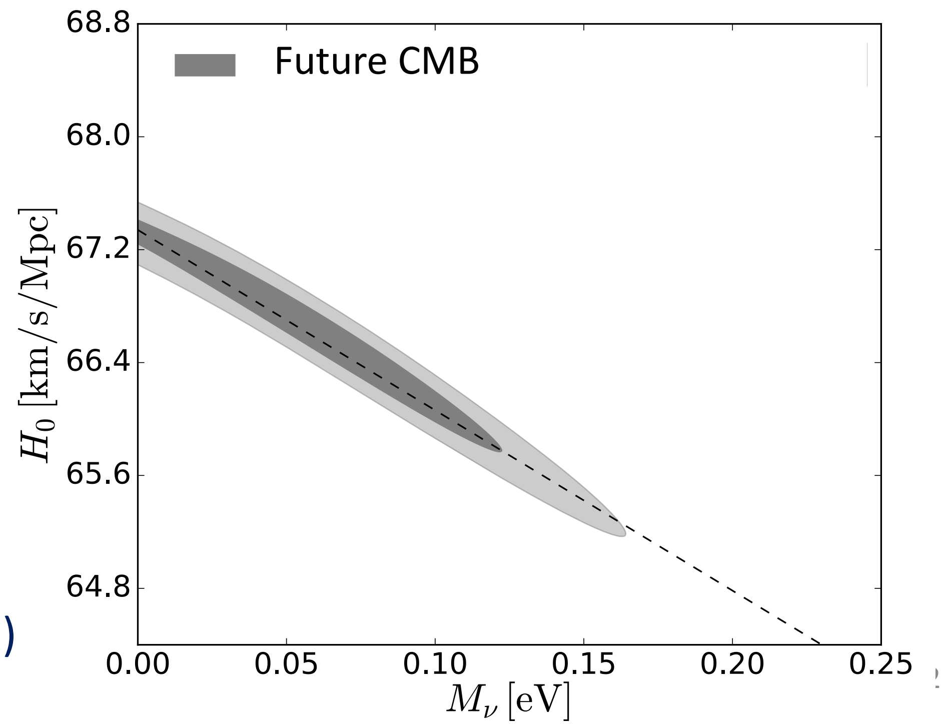
  $N_{eff} = N_{eff}^{SM}(=3.044)+\Delta N_{eff}$

Neutrino mass probes: CMB



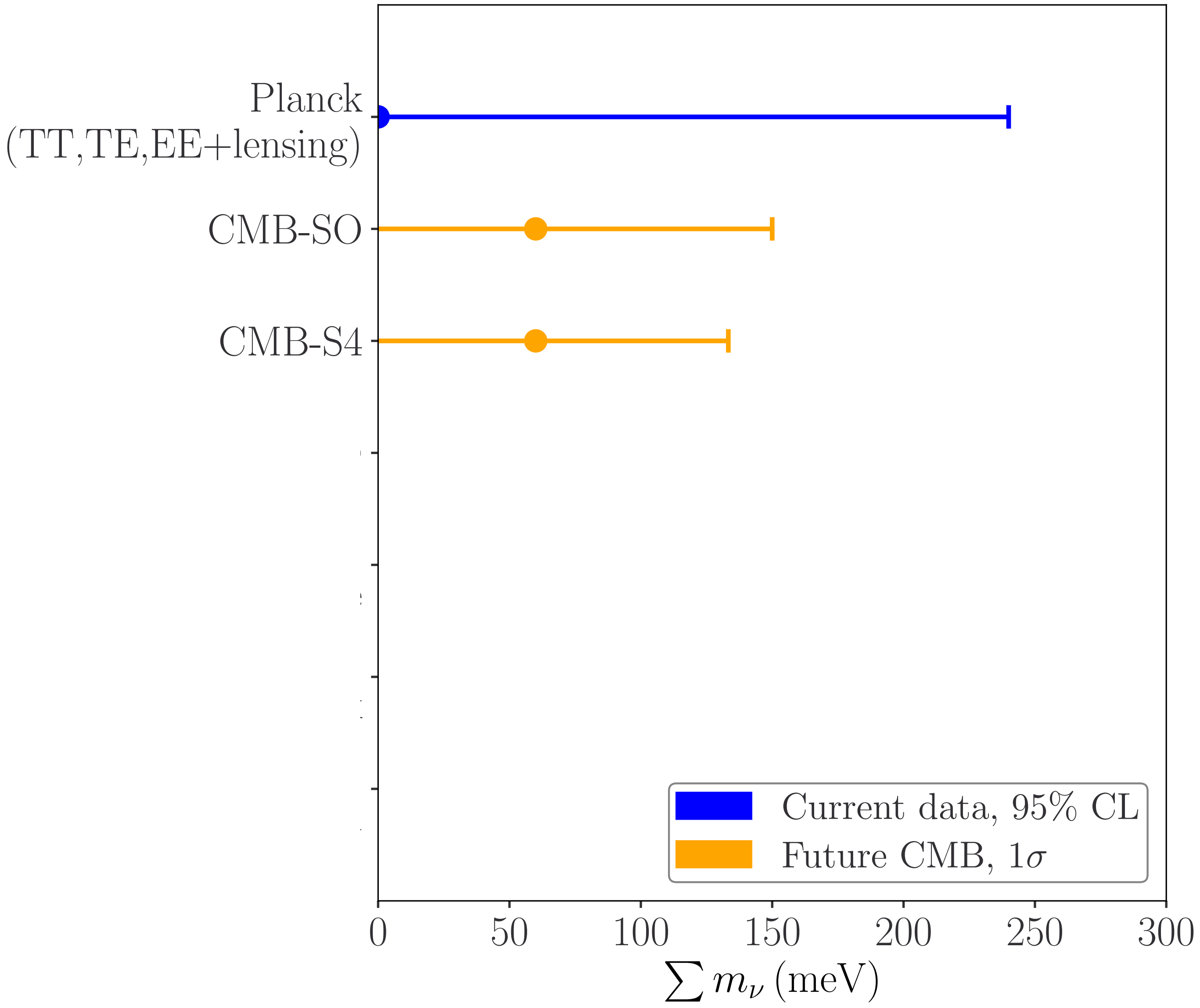
- Background effects
- Perturbation effects

Varying H_0 to fix θ_s (i.e., the angular size of the sound horizon at recombination)



Archidiacono, Brinckmann, Lesgourgues, Poulin, JCAP (2017)

Neutrino mass constraints: CMB



Fiducial value:

- Σm_{ν} = 58 meV

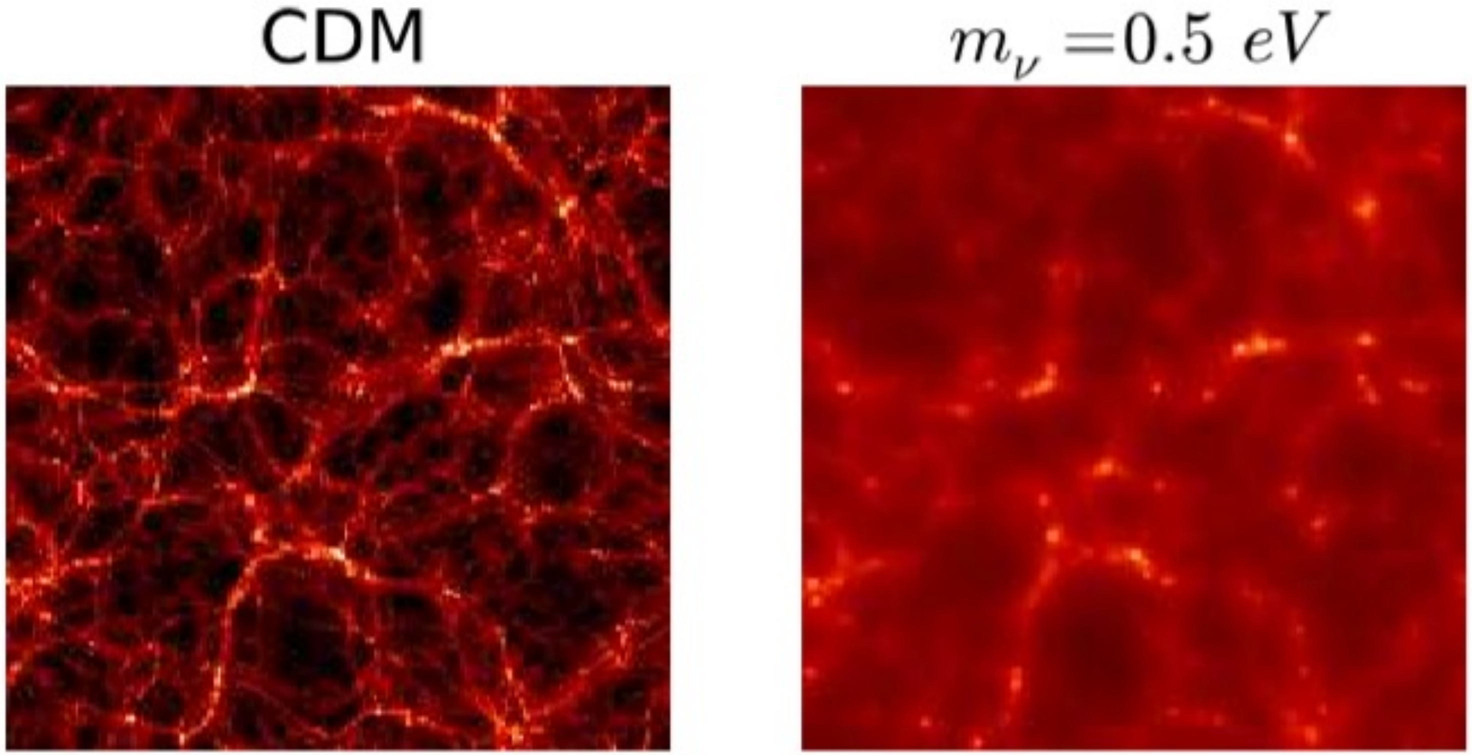
Minimum from neutrino oscillation experiments

CMB alone will not be able to detect the neutrino mass

→ Large Scale Structures

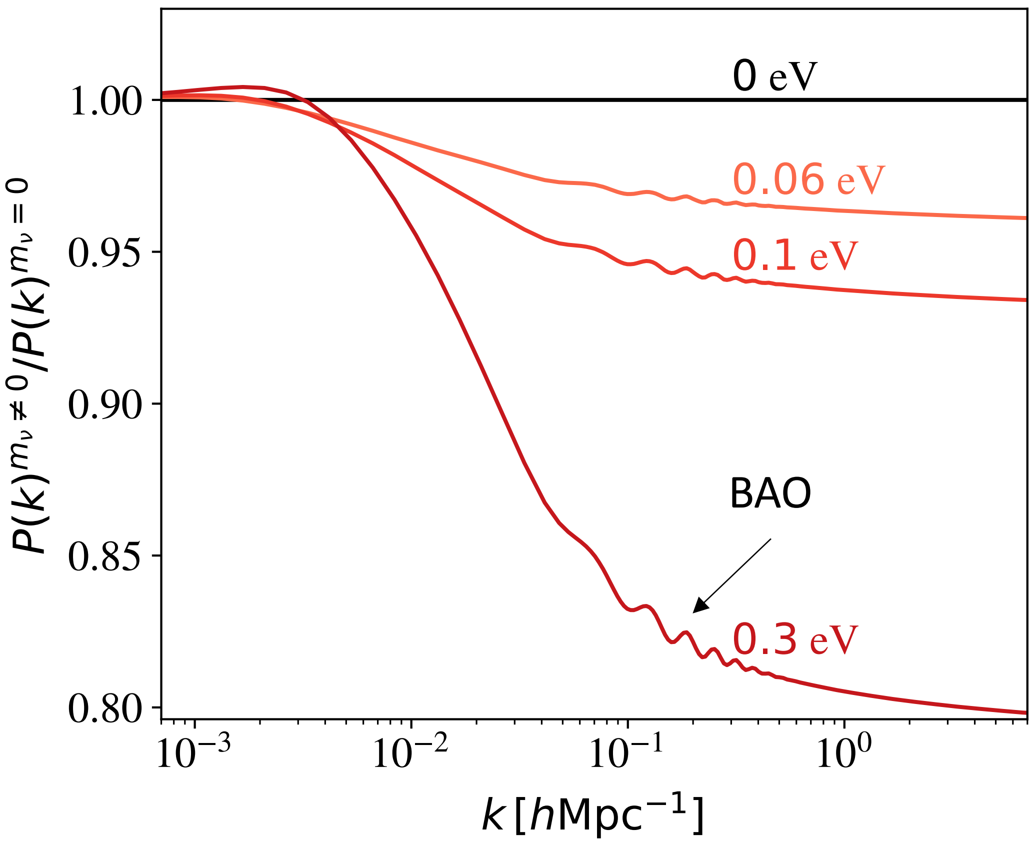
Neutrino mass probes: structure formation

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

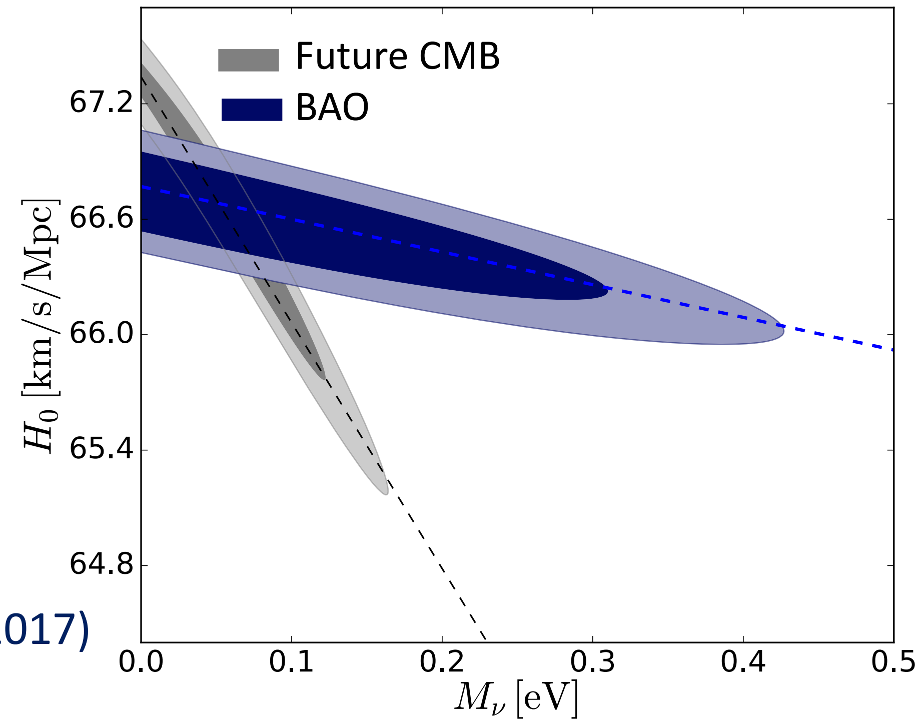


Villaescusa Navarro et al. (2013)

Neutrino mass probes: P(k)

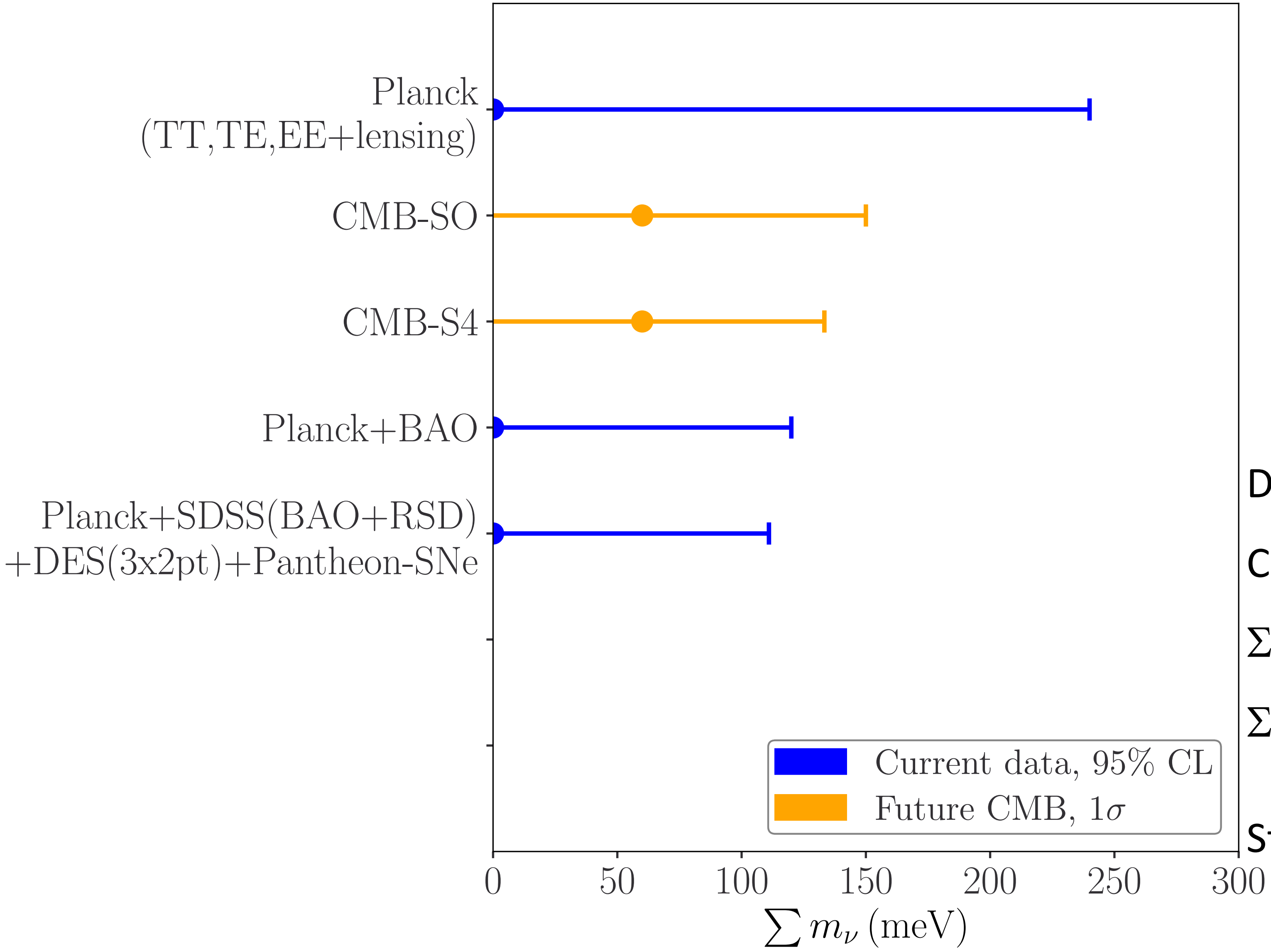


- Massive neutrinos do not cluster
- Massive neutrinos slow down the growth of CDM perturbations
  - Massless neutrino Universe $\delta_{\mathrm{cdm}}^{m_\nu=0} \propto a$
  - Massive neutrino Universe $\delta_{\mathrm{cdm}}^{m_\nu\neq 0} \propto a^{1-\frac{3}{5}\frac{\Omega_\nu}{\Omega_m}}$



Archidiacono, Brinckmann, Lesgourgues, Poulin, JCAP (2017)

Neutrino mass constraints: recent history



DESI Collaboration:

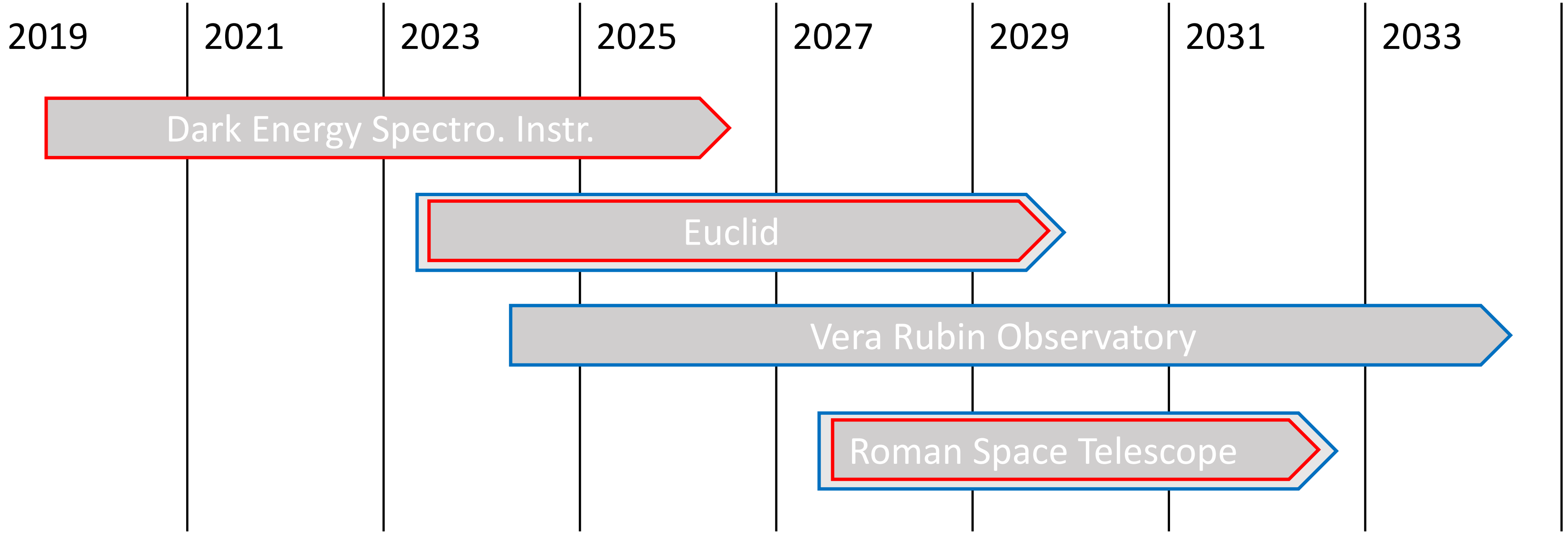
CMB (Planck+ACT) + DESI BAO

Σm_ν < 72 meV, 95% CL, Σm_ν > 0

Σm_ν < 113 meV, 95% CL, Σm_ν > 59 meV

Still no evidence/detection

Stage IV Large Scale Surveys

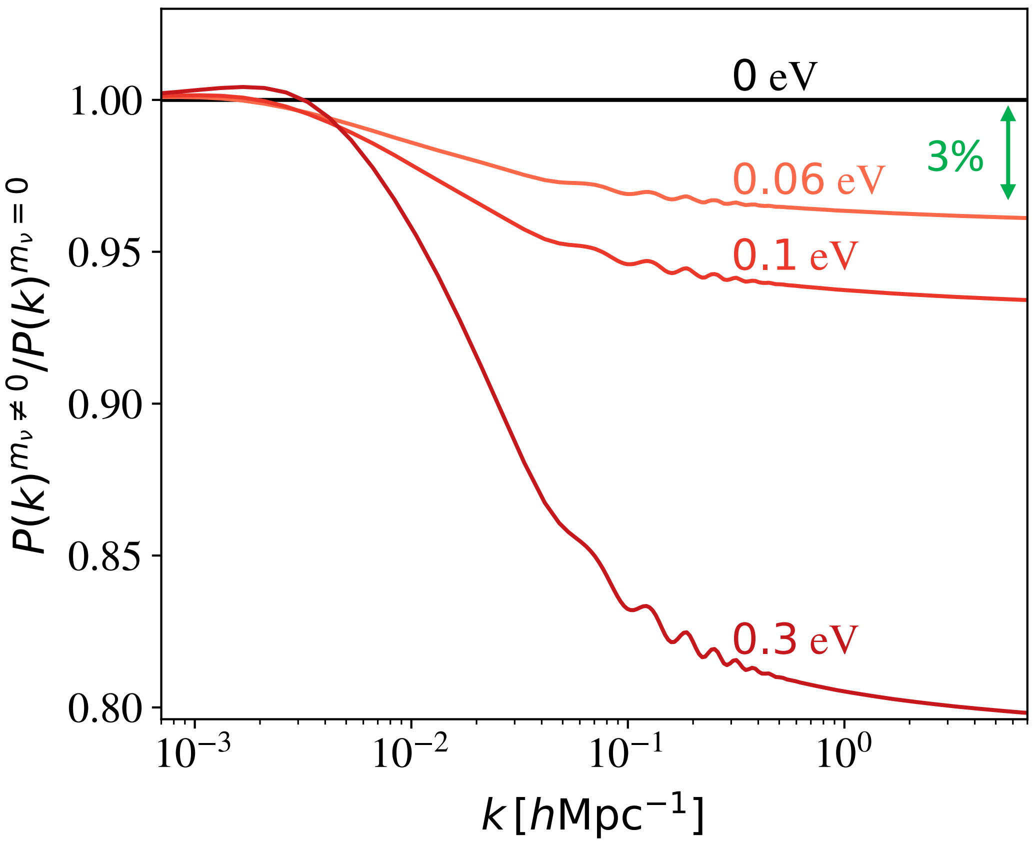


Spectroscopy
Imaging

Euclid in a nutshell

- **ESA** M2 space mission in the framework of the Cosmic Vision program
- Launch **July 1st 2023**. Duration **> 6 years**
- 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** (<u>1% accuracy</u>)

Neutrino mass probes: P(k)



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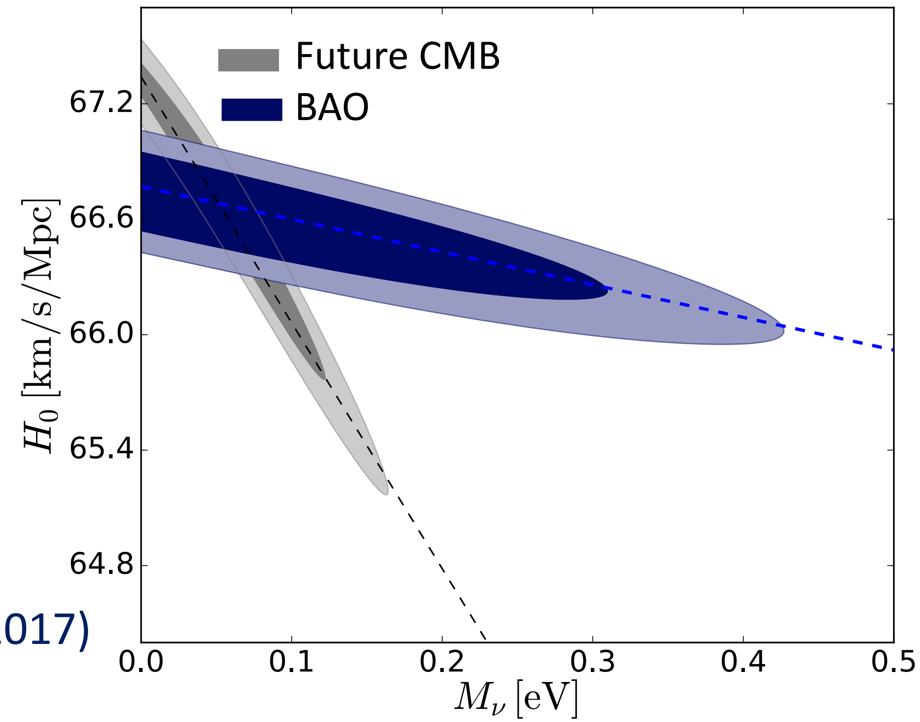


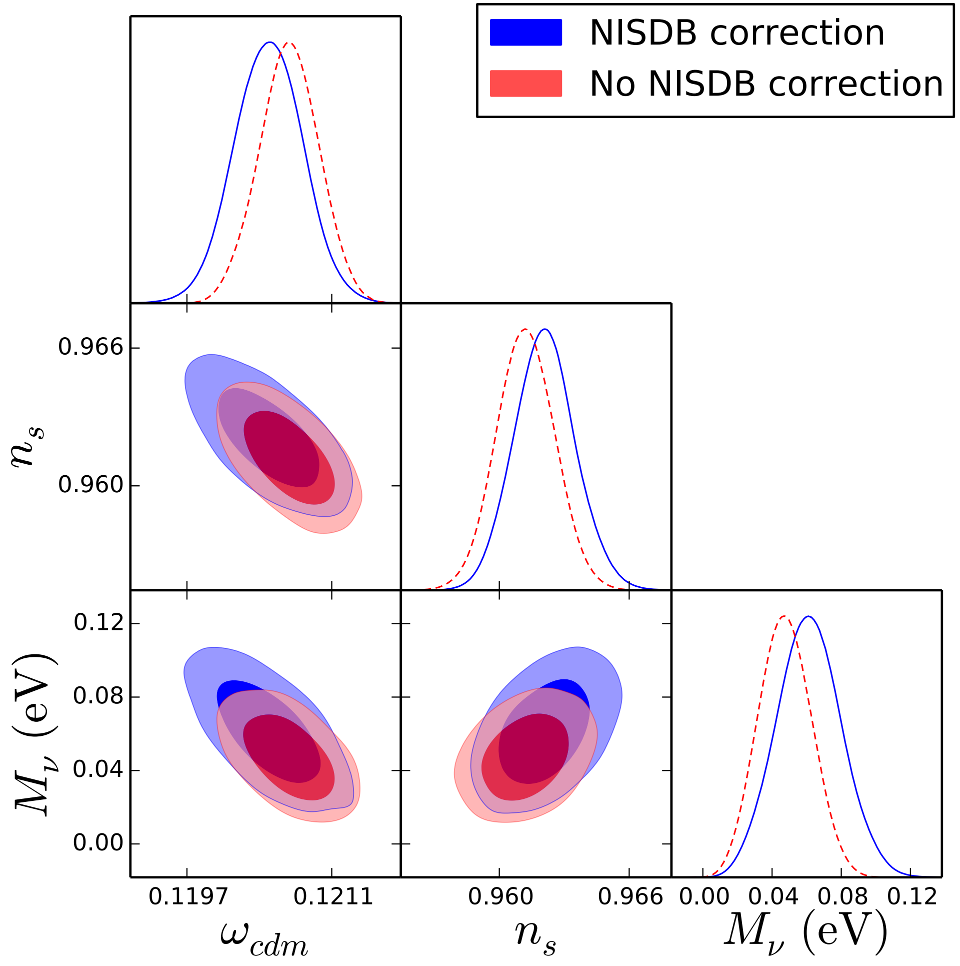
Archidiacono, Brinckmann, Lesgourgues, Poulin, JCAP (2017)

Known unknowns (systematics, etc.)

1. Galaxy bias $P_{galaxy} = b^2 P_{matter}$ [Castorina et al. (2014); Vagnozzi, Brinckmann, Archidiacono, Freese, Gerbino, Lesgourgues, Sprenger, JCAP (2018)]

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

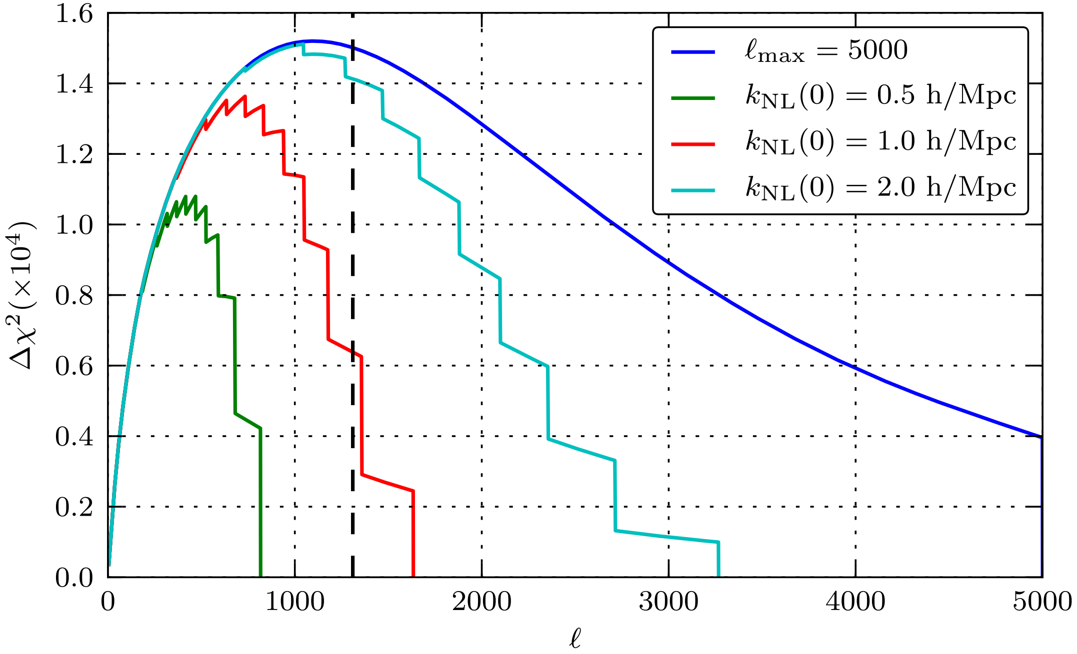
3. Baryonic feedback [Spurio Mancini et al. (2023)]



Vagnozzi, Brinckmann, Archidiacono, Freese, Gerbino, Lesgourgues, Sprenger, JCAP (2018)

Modelling the unknowns

Sprenger, Archidiacono, Brinckmann, Clesse, Lesgourgues, JCAP (2019)



$$k_{nl}(z) \propto k_{nl}(0)(1+z)^{2/(2+n_s)}$$

$$l_{\max}^{zi} = k_{nl}(z) \times \bar{r}_{peak}^{zi}$$

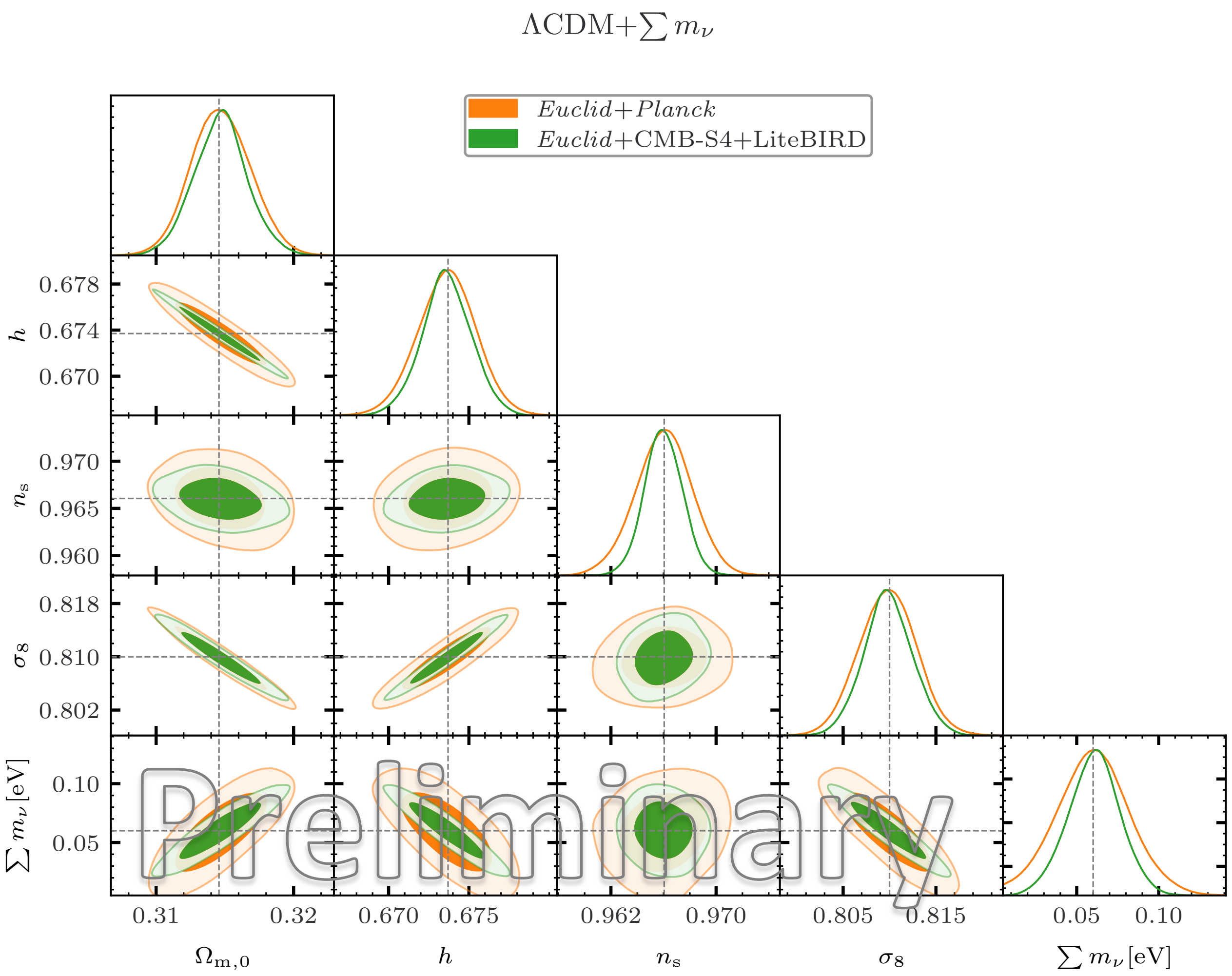
Redshift dependent cut-off in k:
Larger scales start behaving non-linearly later (i.e., at smaller z) with respect to smaller scales.

Euclid weak lensing only, improvement wrt Planck

$k_{\max}$	$100\omega_b$	$\omega_{\rm cdm}$	θ_s	$\ln(10^{10}A_s)$	n_s	$\tau_{\rm reio}$	M_ν [eV]
0.5 h/Mpc	0.77	0.27	0.97	0.94	0.72	0.96	0.50
1.0 h/Mpc	0.76	0.27	0.94	0.95	0.70	0.98	0.41
2.0 h/Mpc	0.76	0.25	0.97	0.94	0.65	0.97	0.36
$l_{\max} = 5000$	0.74	0.24	0.94	0.94	0.58	0.96	0.30
Planck only	1.00	1.00	1.00	1.00	1.00	1.00	1.00

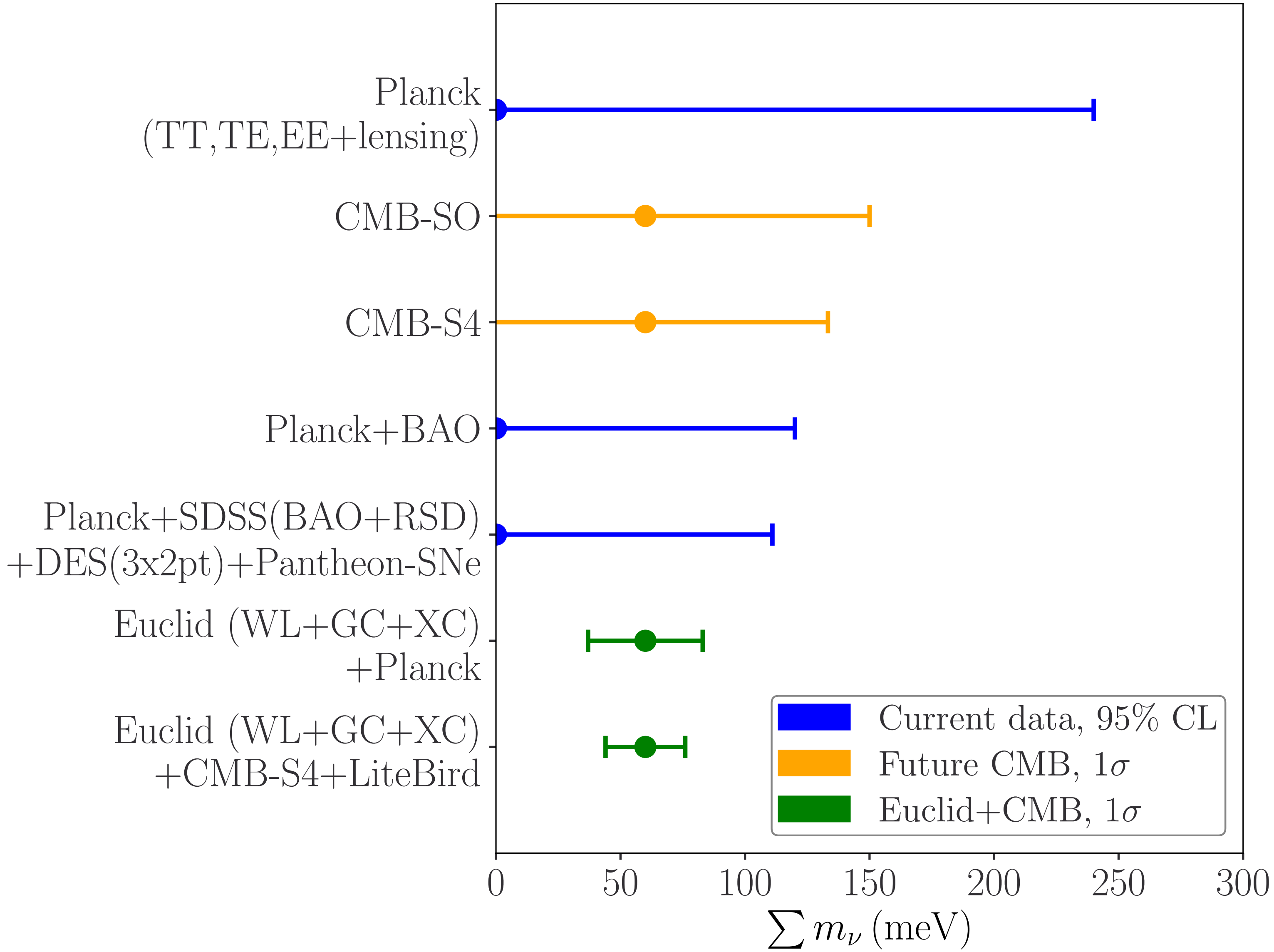
Neutrino mass constraints: the future

Euclid preparation: Sensitivity to neutrino parameters.
Lead authors: Archidiacono & Lesgourgues



Implementation of mock Euclid likelihoods in the MontePython software
[Euclid: Validation of the MontePython forecasting tools, Casas et al. (including Archidiacono), (2023)]

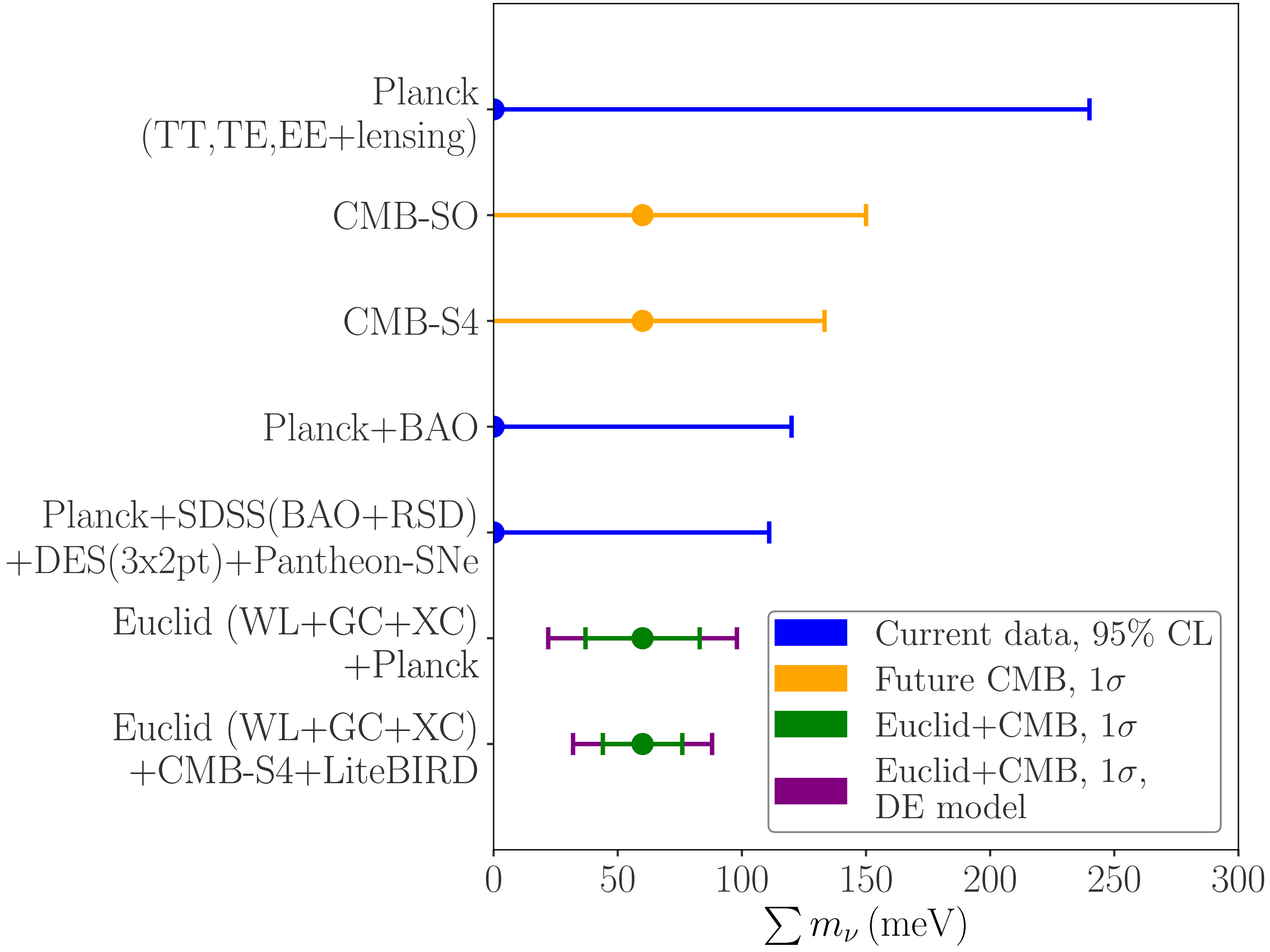
Neutrino mass constraints: the future



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

Euclid+CMB-S4+LiteBird: >3σ

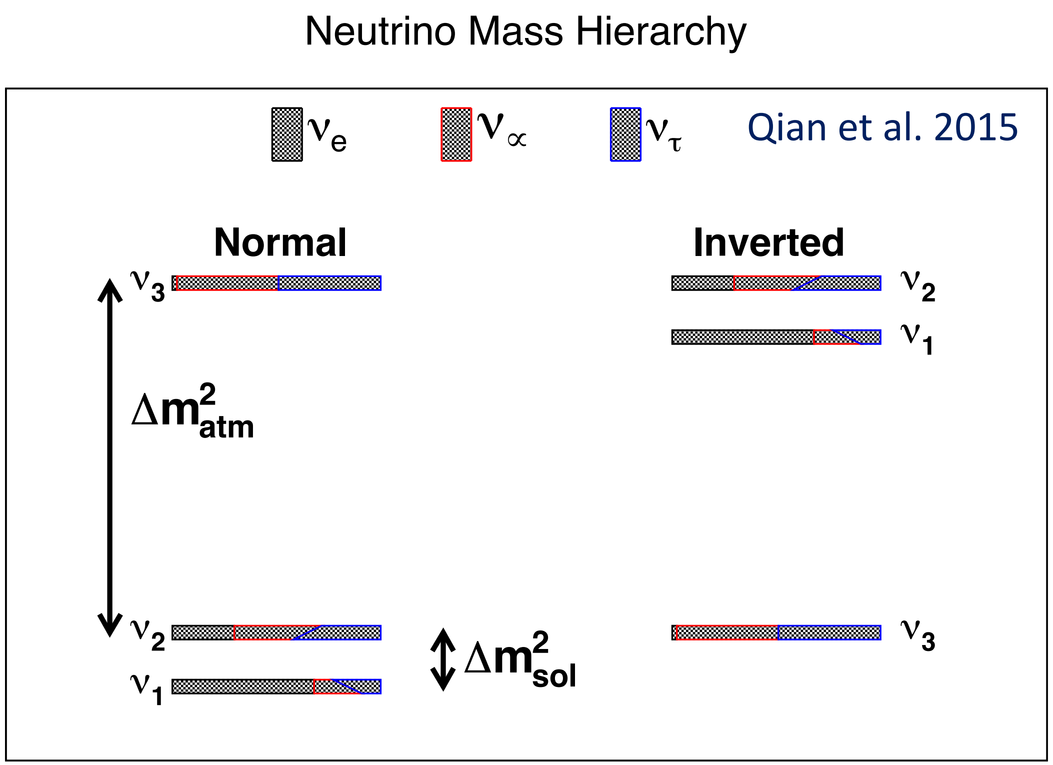
Neutrino mass constraints: the future



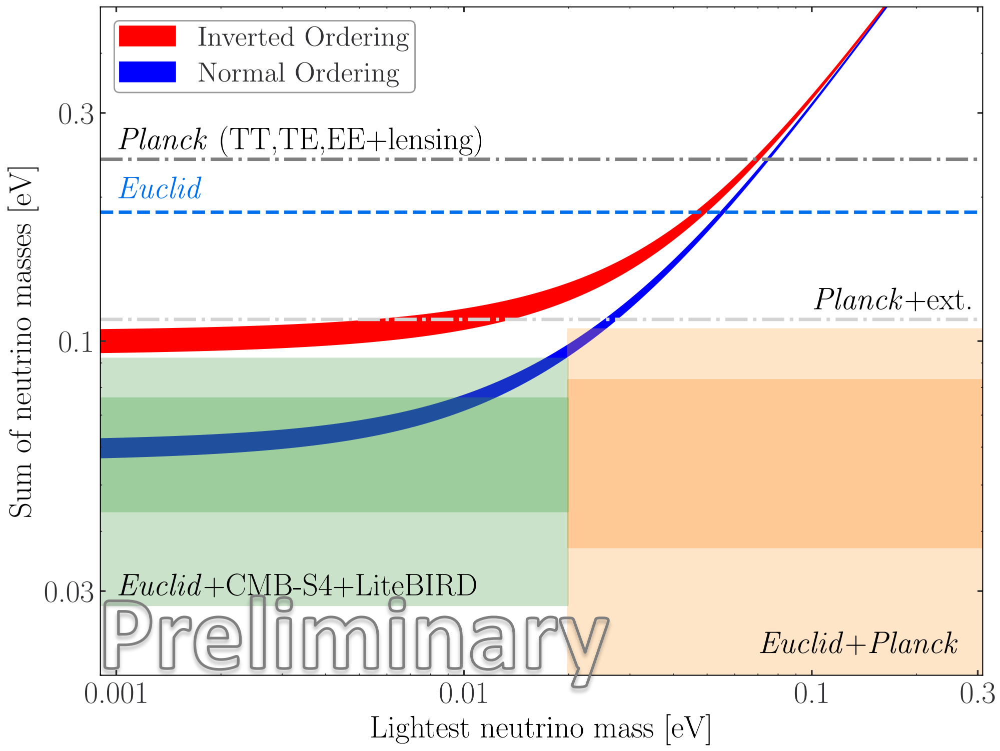
Replacing the cosmological constant with dark energy with a time varying equation of state parameter increases the error by a factor 2.

Neutrino mass ordering

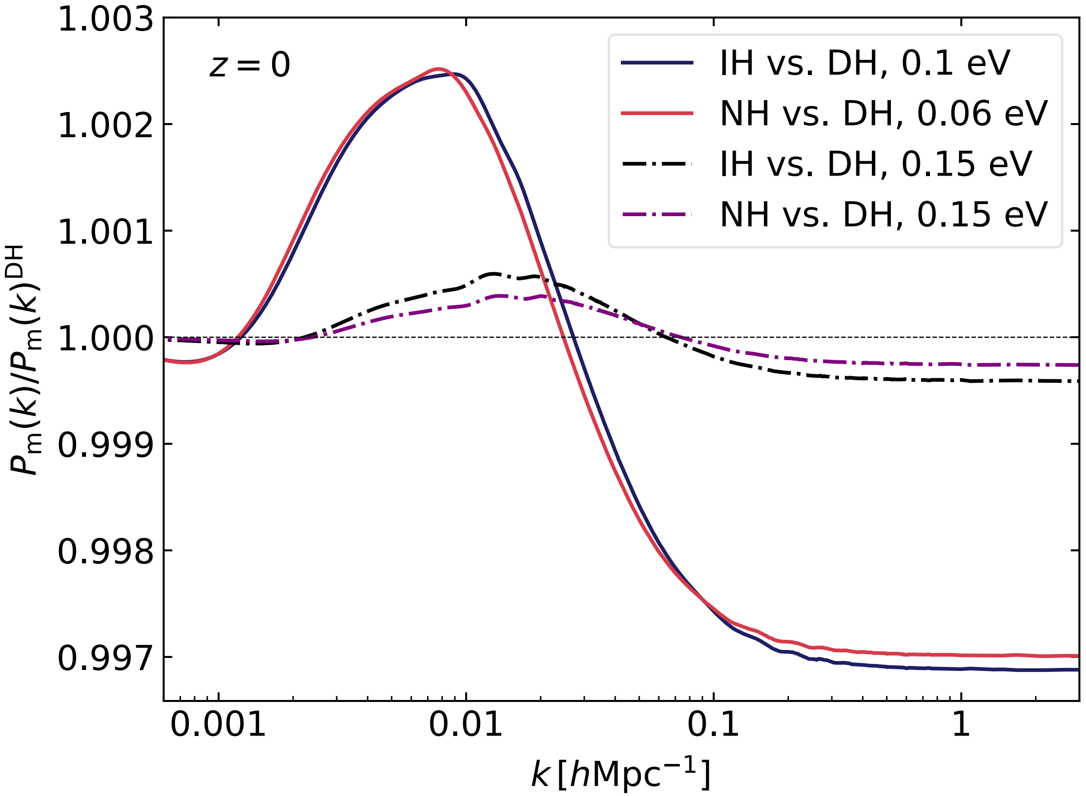
Constraints derived under the assumption $m_1=m_2=m_3$ (degenerate hierarchy, DH)



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



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 is valid, and it is more efficient.

Archidiacono, Hannestad, Lesgourgues, JCAP (2020)

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, 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.

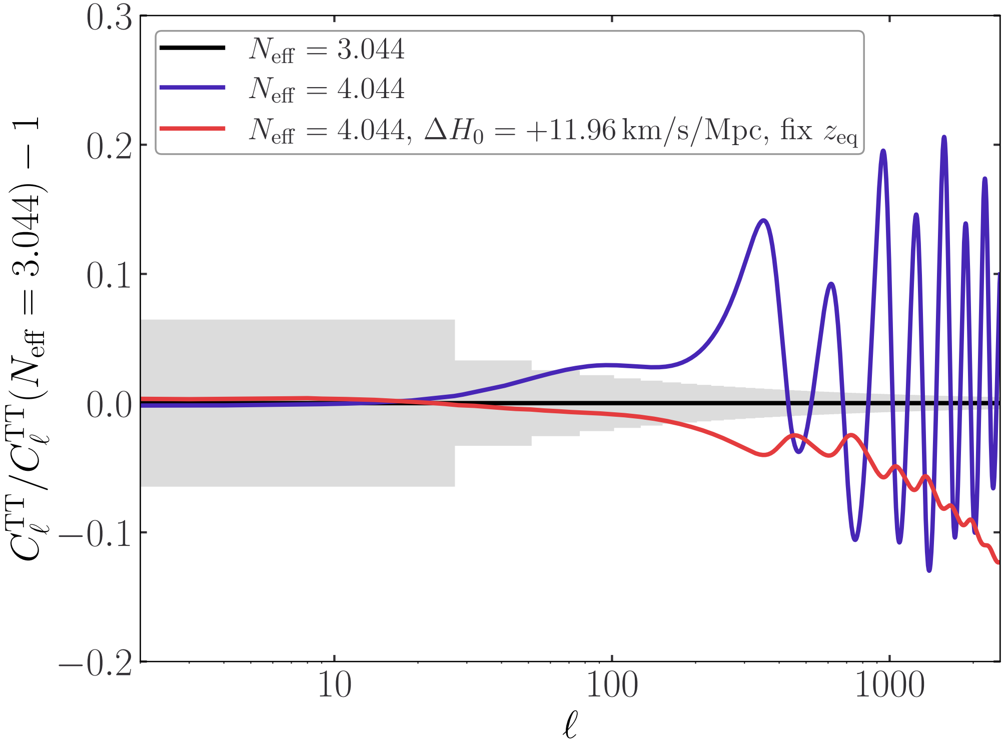
Plan

- Neutrino mass

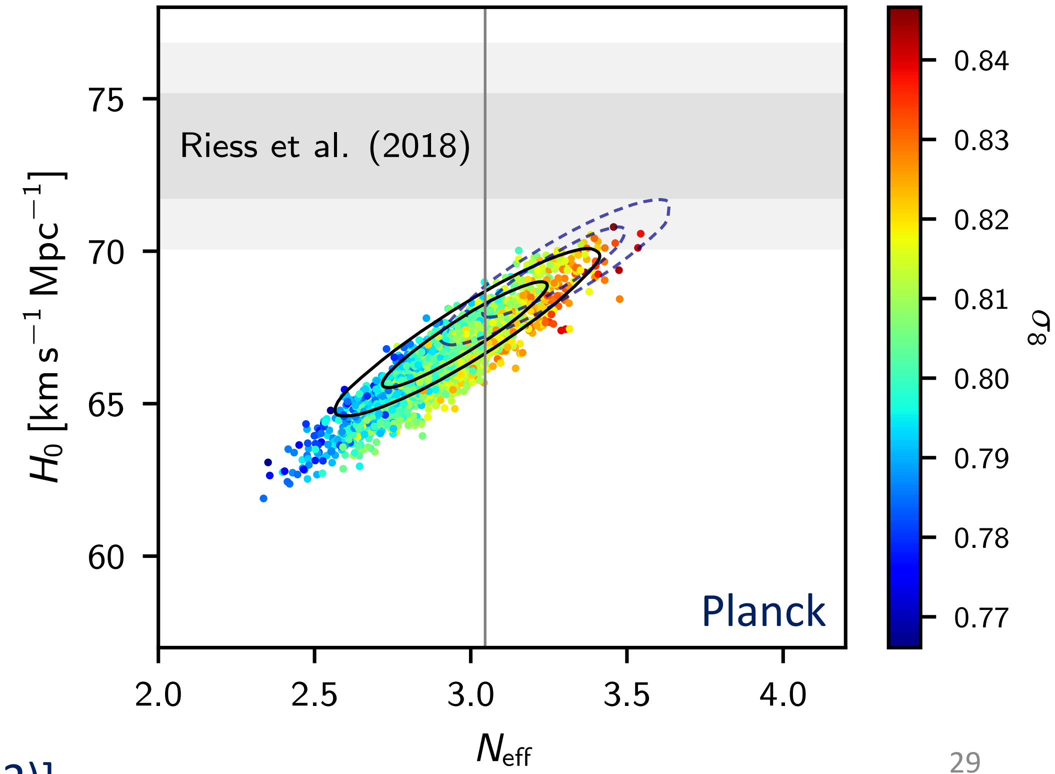
- Neutrino number and new light particles

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

N_{eff} probes: CMB



- Phase shift of the CMB acoustic peaks
- Increase of Silk damping al large *l*



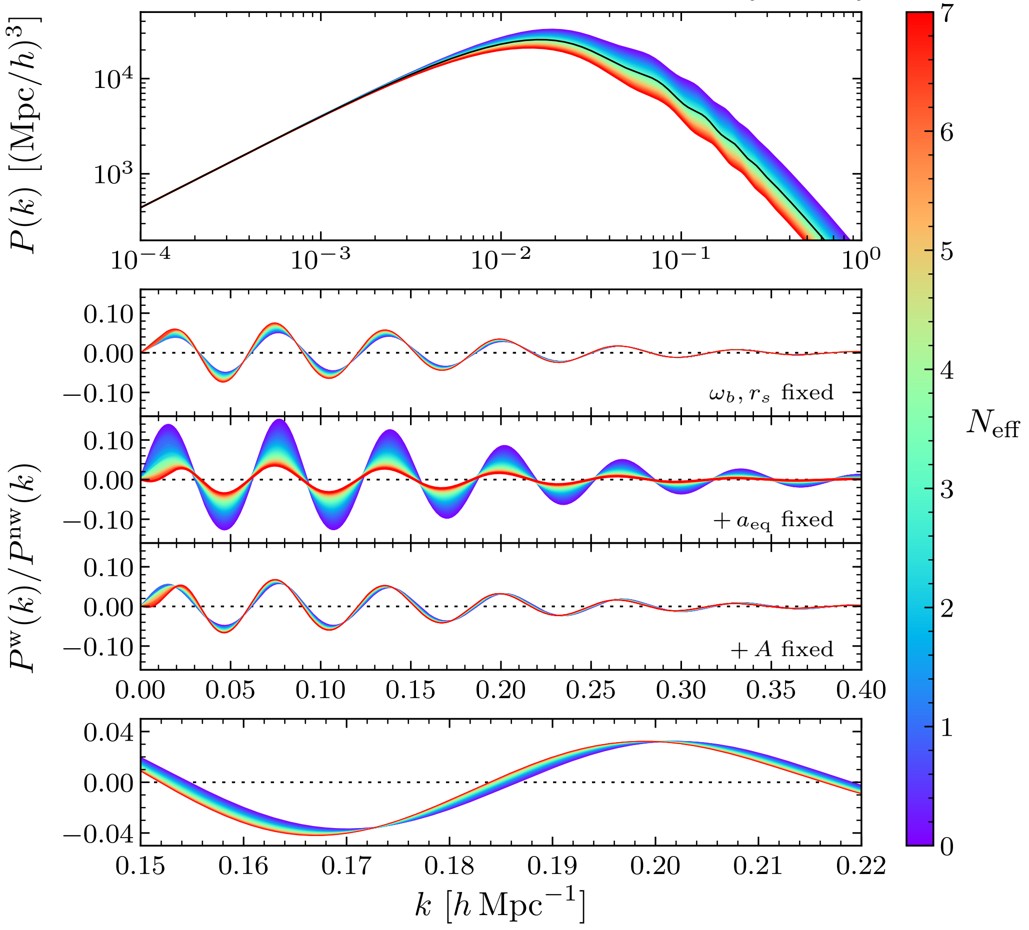
A larger (thermalised) N_{eff} is not a solution to the "H_0 problem":

H_0 = 67.4 ± 0.5 km/s/Mpc (Planck)

H_0= 73.0 ± 1.0 km/s/Mpc (SH0ES) [Riess et al. (2022)]

N_{eff} probes: P(k)

Baumann et al. (2018)



CMB (Planck + ACT)

N_{eff} = 2.98 $\pm$ 0.20 (95% CL)

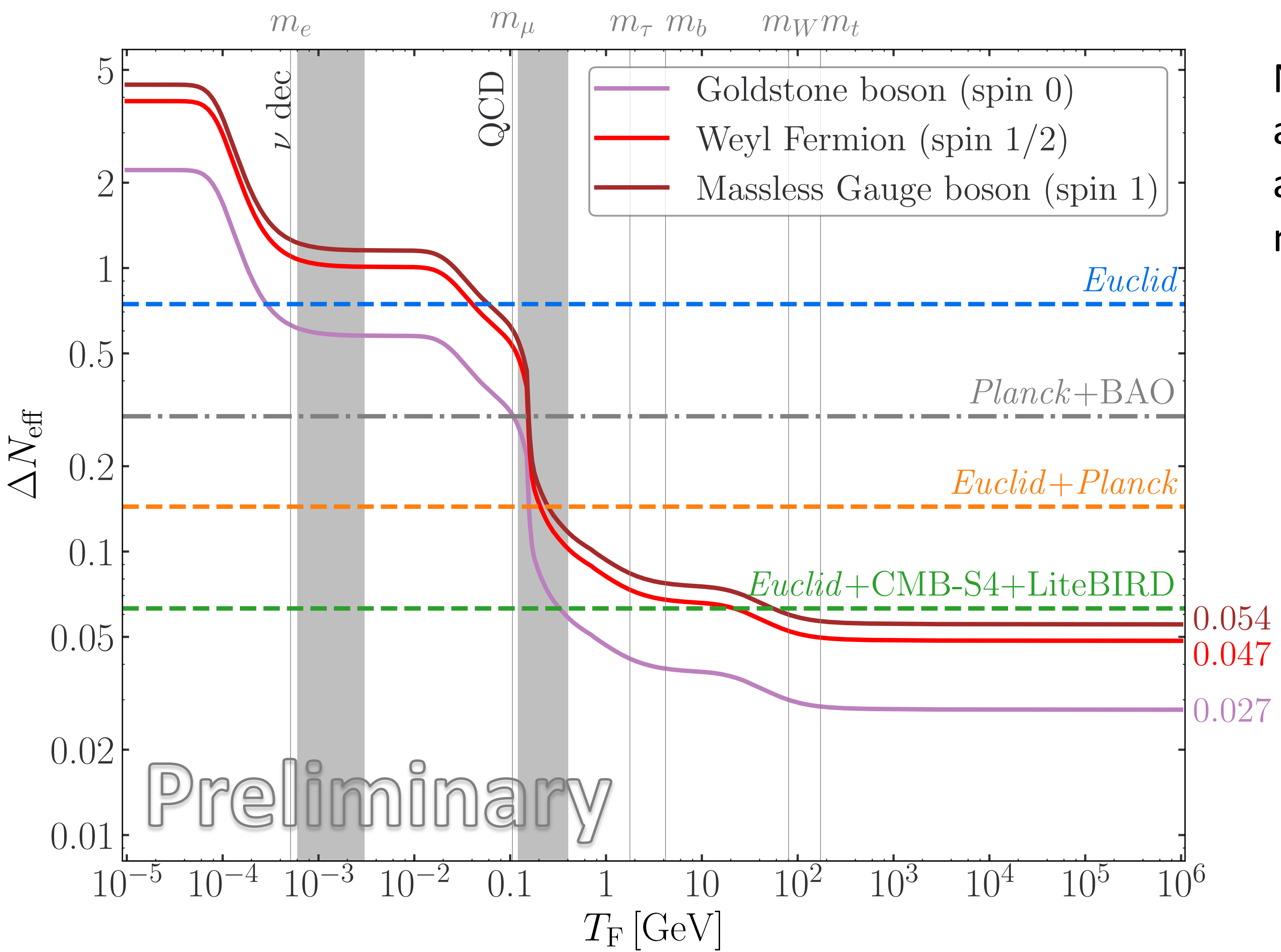
CMB + DESI BAO [DESI Collaboration (2024)]

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

Consistent with N_{eff}^{SM} = 3.044

Bounds on new light particles (ΔN_{eff})

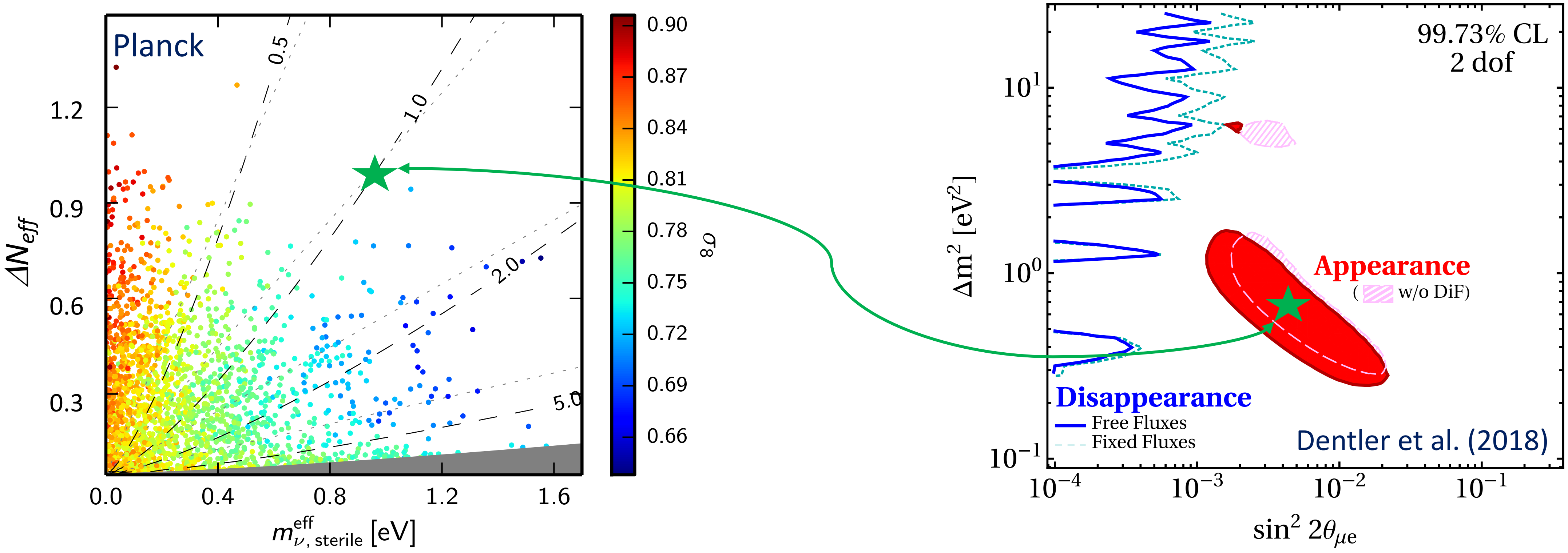
Euclid preparation: Sensitivity to neutrino parameters.
Lead authors: Archidiacono & Lesgourgues



Note: Here the additional particles are assumed to be massless.

Bounds on new light particles (ΔN_{eff}, m_{eff})

The case of light sterile neutrinos



Planck TT,TE,EE+lensing+BAO:

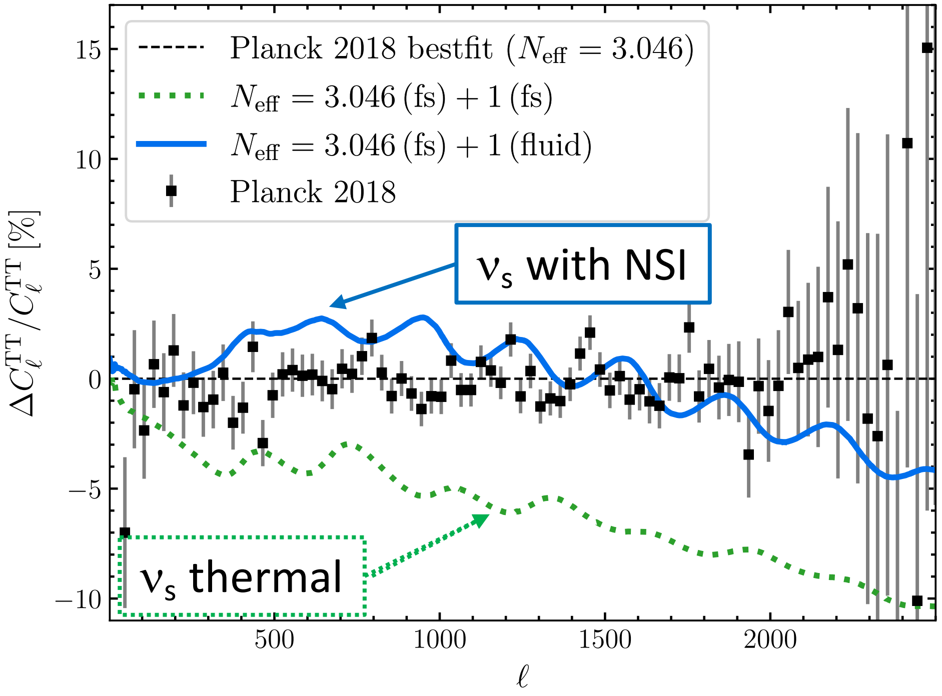
ΔN_{eff} < 0.30 (95% CL)

$m_{sterile}$ < 0.65 eV (95% CL)

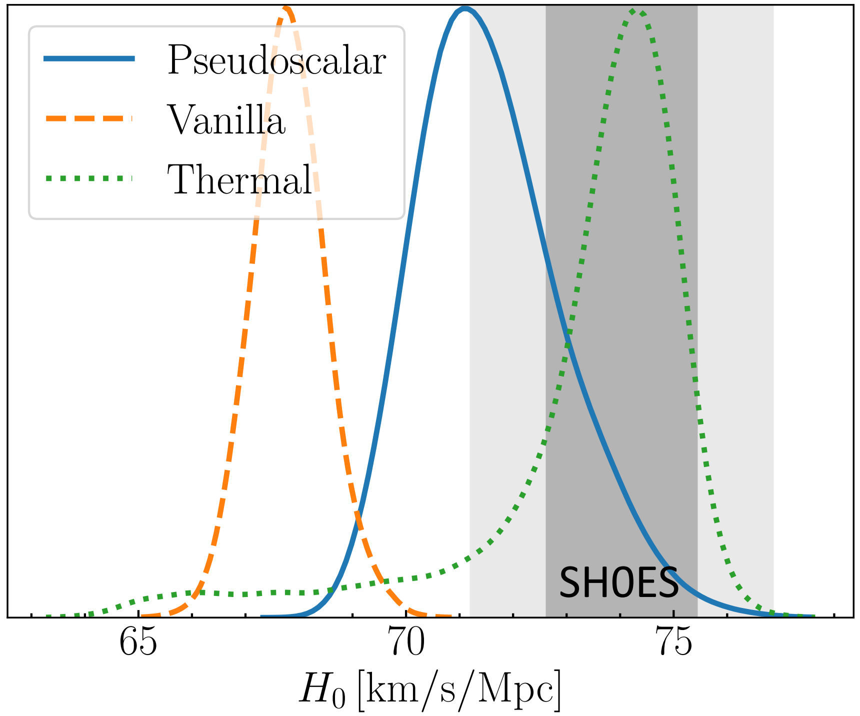
Global fit of neutrino oscillation anomalies

Light sterile neutrinos with self-interations

Archidiacono & Gariazzo, Universe (2022)



Archidiacono, Gariazzo, Giunti, Hannestad, Tram, JCAP (2021)

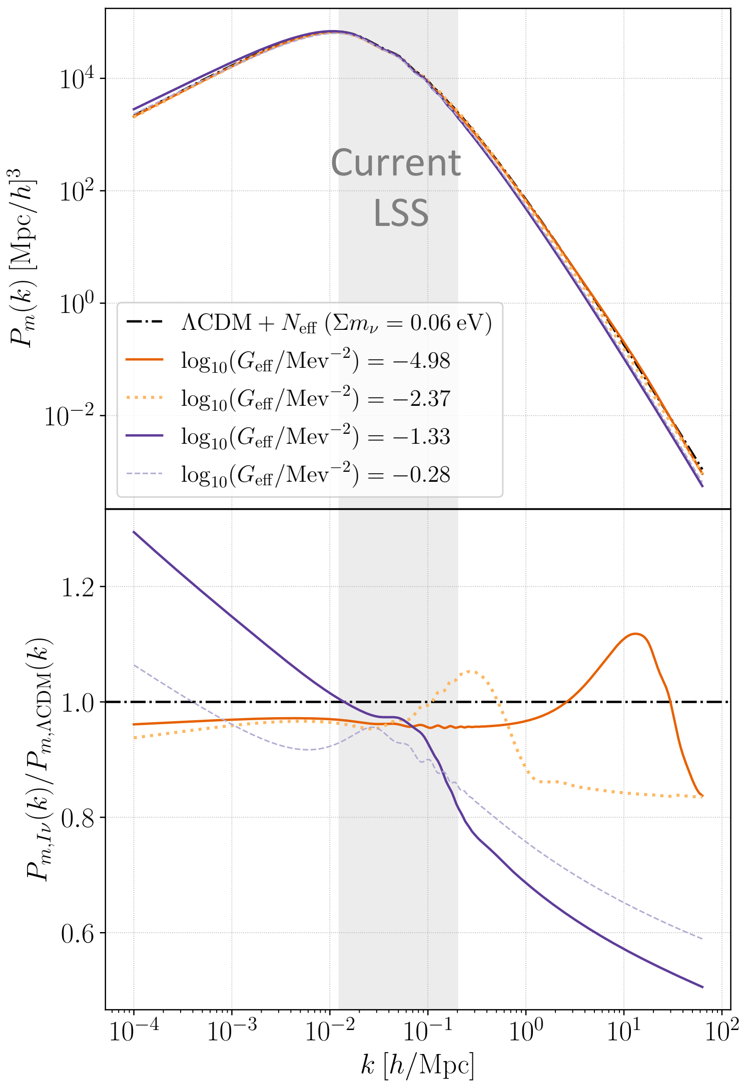


Sterile neutrinos with self-interactions provide:

- a good fit to Planck CMB data
- a solution to the Hubble constant problem

Outlook: constraining νSI with Euclid

Camarena et al. (2023)

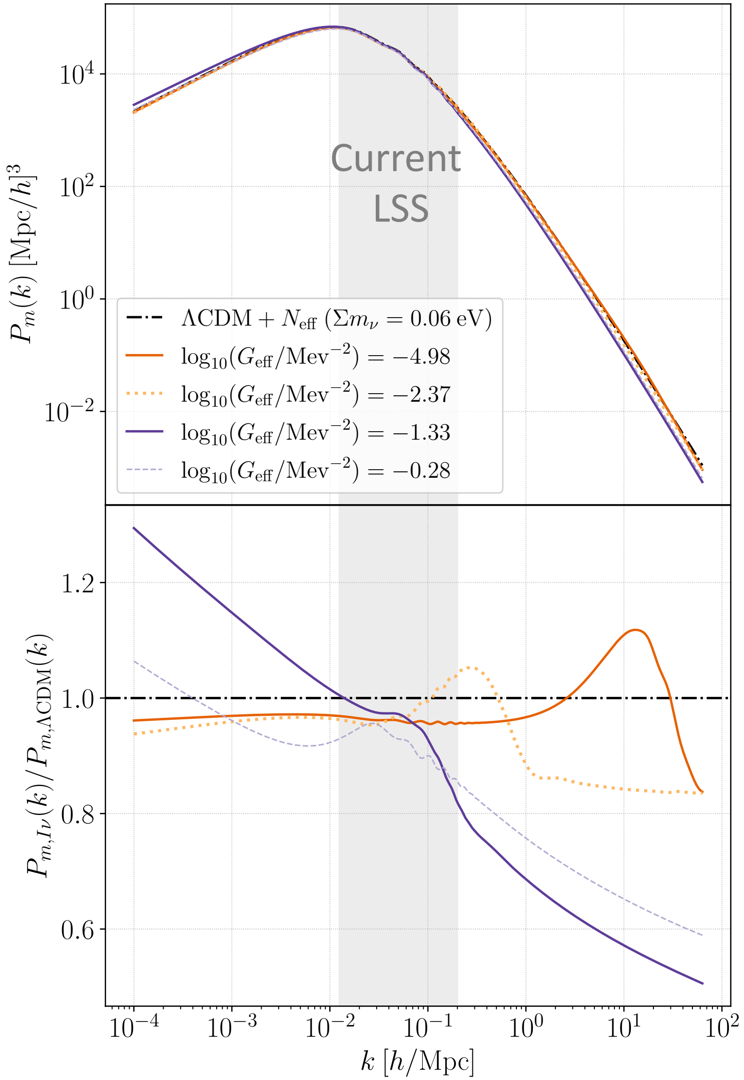


Mild preference for non-vanishing νSI

Euclid will extend the range where we can test νSI

Outlook: constraining νSI with Euclid

Camarena et al. (2023)



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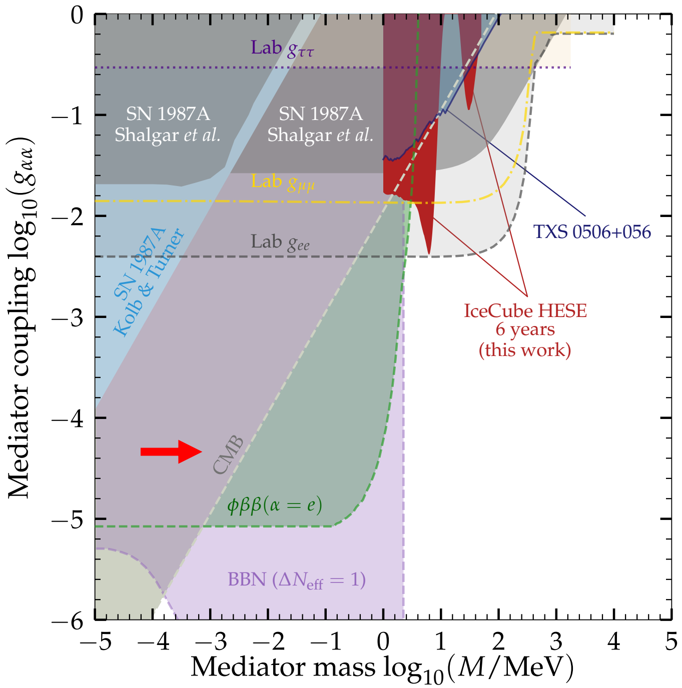

Astrophysical and laboratory limits might already exclude this model.

Bustamante et al. (2020)

Neutrino number and new light particles: conclusions

- Euclid in combination with future CMB surveys can exclude the existence of new light particles decoupling after the onset of QCD phase transition for any spin.

- Light sterile neutrinos, as hinted at by neutrino oscillation anomalies, are already excluded by Planck with high statistical significance. New neutrino self-interactions provide an elegant way to accommodate light sterile neutrinos in cosmology and to solve the H_0 problem.

- Neutrino non-standard interactions: constraints from the lab and from astrophysics might exclude their existence