What cosmology can tell us about neutrinos

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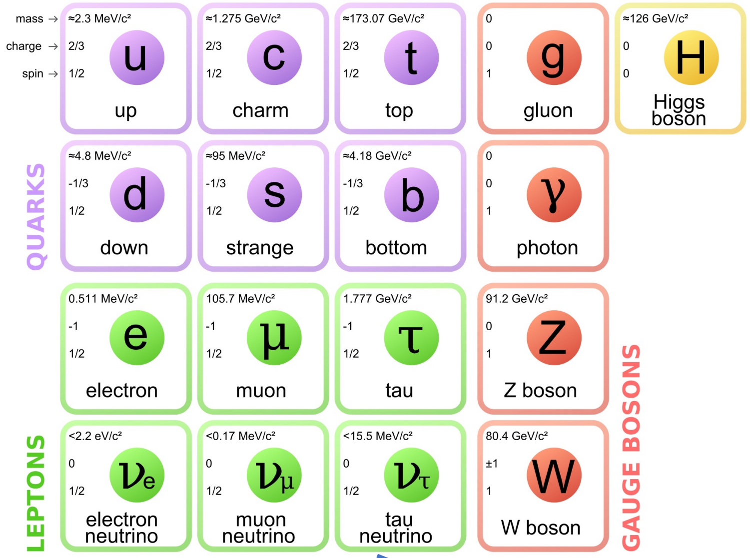
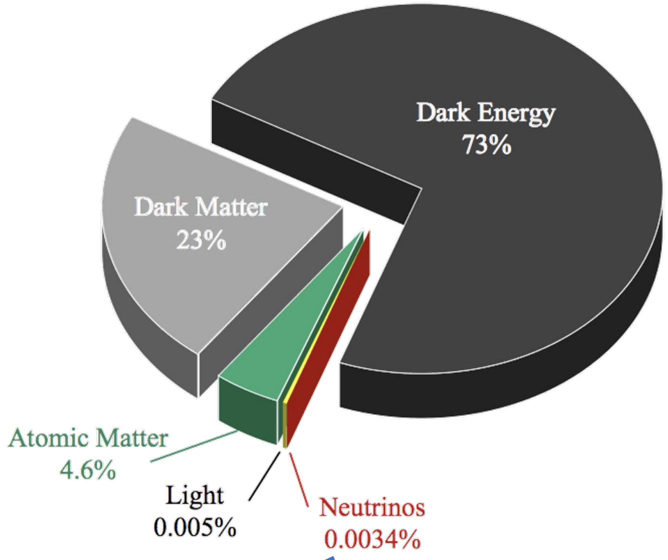
Why neutrino cosmology

Standard Model of particles



ΛCDM model of cosmology



Open question:
Neutrino mass

What cosmology can tell us about neutrinos

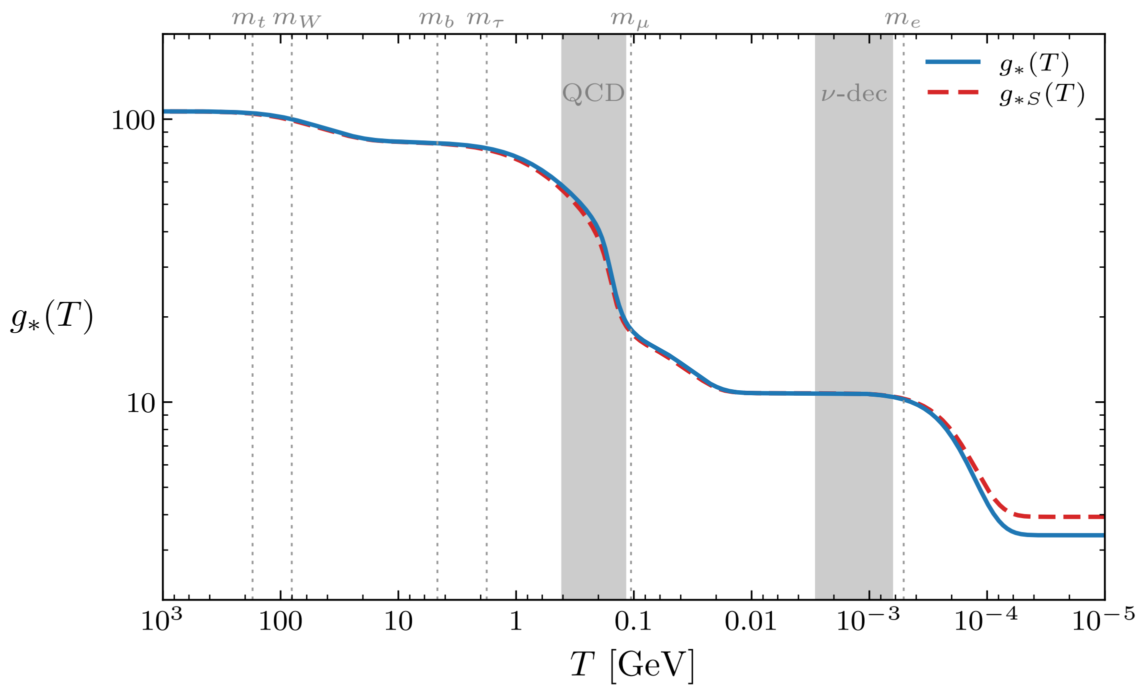
- Neutrino number $N_{eff} = \frac{\text{(energy density of neutrinos + BSM light particles)}}{\text{(energy density of one neutrino species)}}$

  $N_{eff}^{SM} = 3.043 \pm 0.001$ [Mangano et al. 2002, Froustey et al. 2020, Cielo et al. 2023]

- 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]

How cosmology can measure neutrinos



$$\Gamma_{\rm weak} \sim H \text{ at } T \sim 1 \text{ MeV}$$

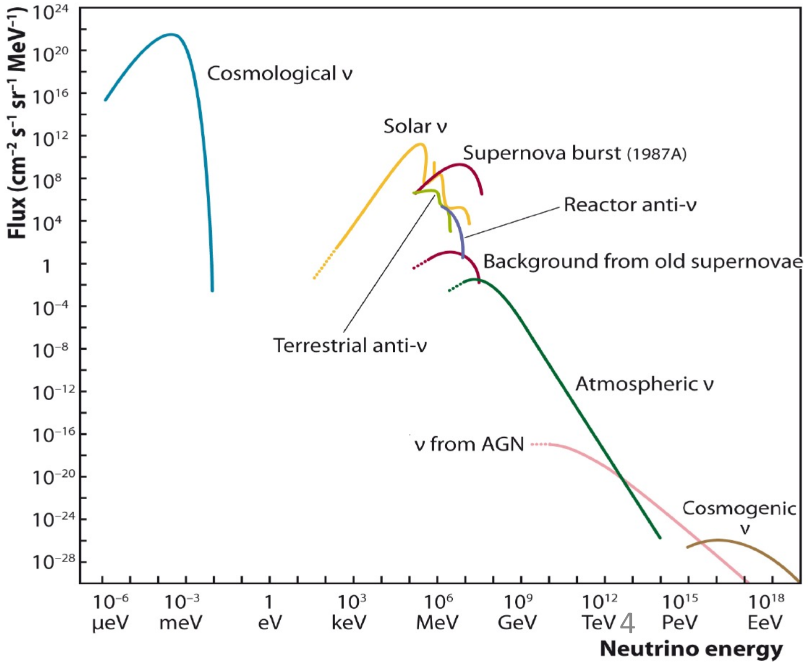
$$T_\nu = T_\gamma \left(\frac{4}{11}\right)^{1/3}$$

Today:

$T_\nu \sim 1.9$ K

$n_\nu \sim 300$ cm^{-3}

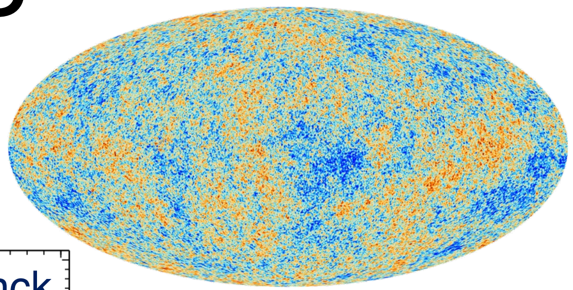
Indirect probes from cosmological observables

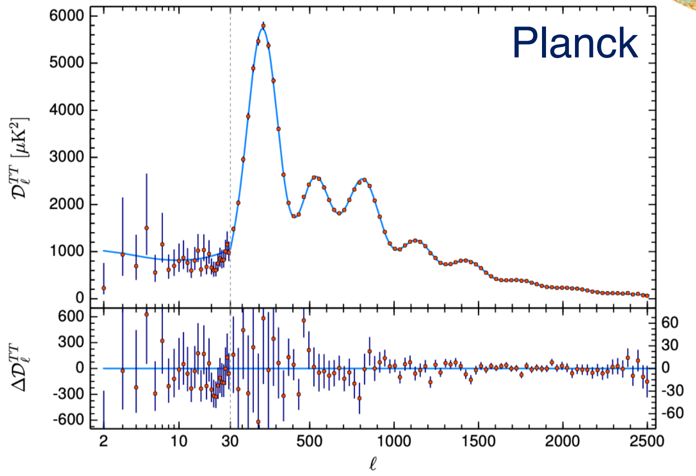


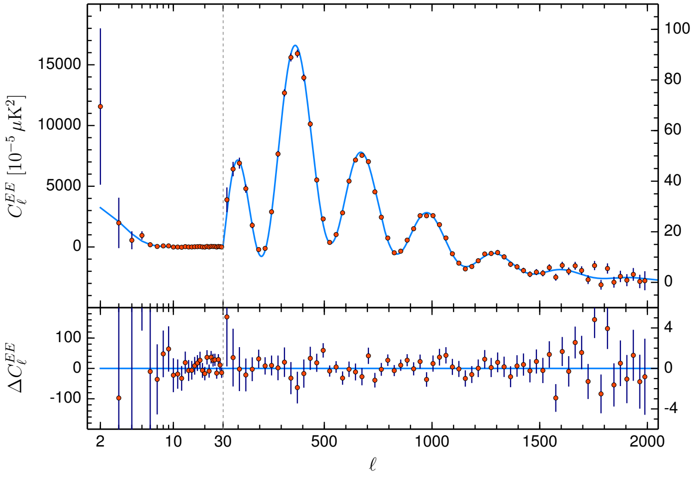
Cosmological observables

Early Universe

CMB (z ~ 1100)

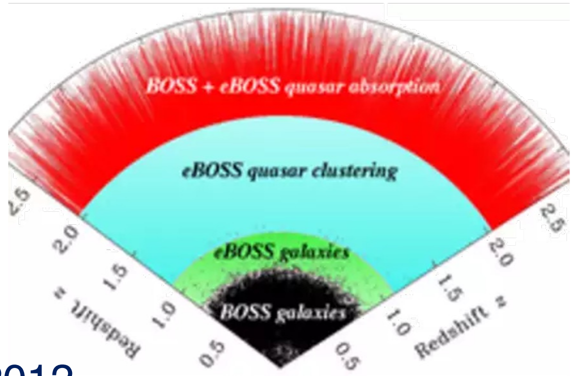




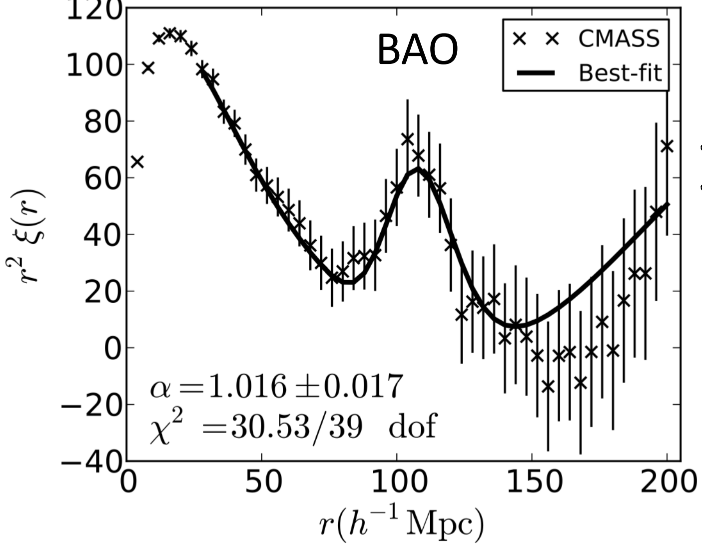


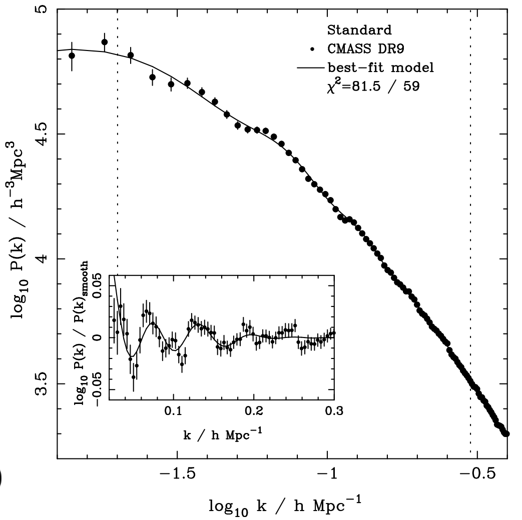
Late Universe

LSS z<~3
Galaxy positions
and weak lensing



Anderson et al. 2012





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

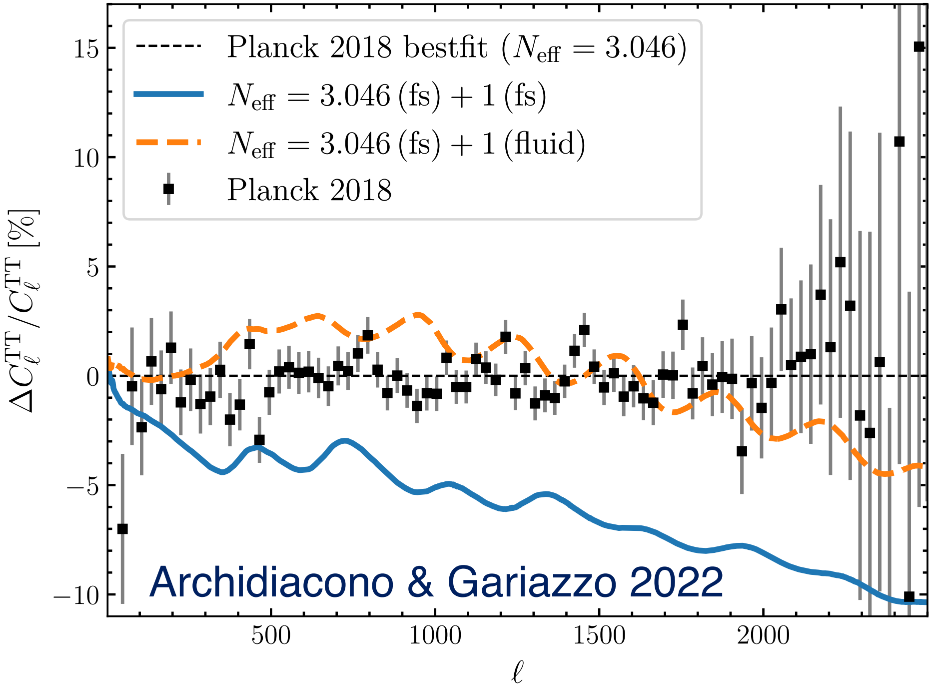
Neutrino non-rel.

$$z_{\mathrm{nr},i} \sim \frac{m_{\nu,i}}{0.5\,\mathrm{meV}}$$

Indirect probes of CνB

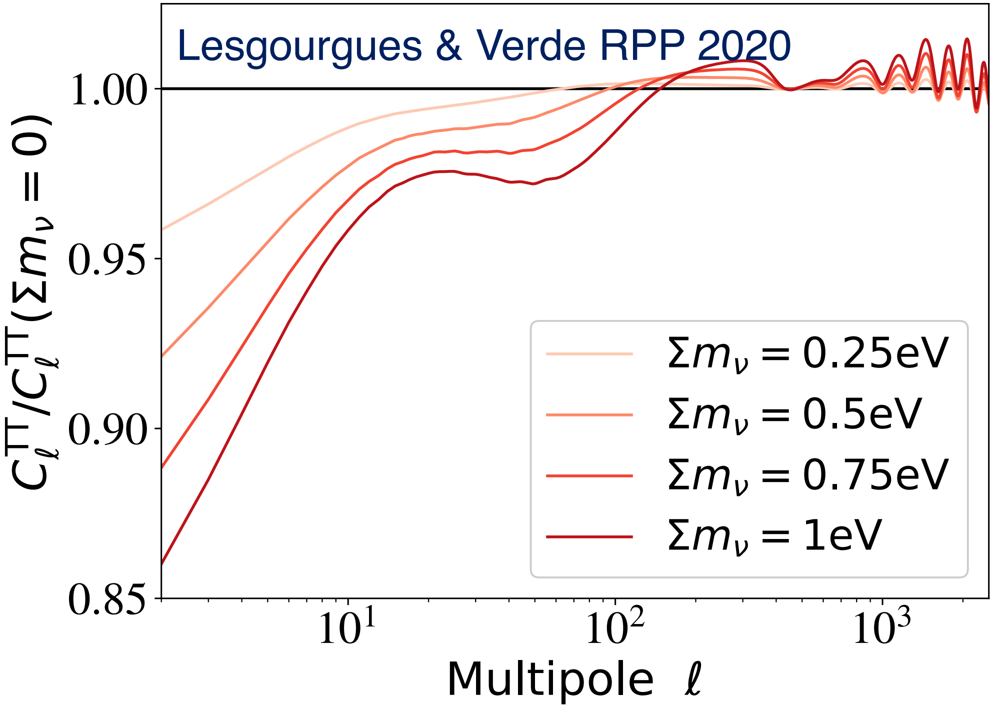
- Impact on CMB [Bashinsky & Seljak 2004, Lesgourgues & Pastor 2006]

N_{eff}



Planck TT,TE,EE + lowE
$N_{eff} = 2.92 \pm 0.36$ (95%cl)
…+BBN $N_{eff} = 2.78 \pm 0.28$ (68%cl) [Pisanti et al. 2021]

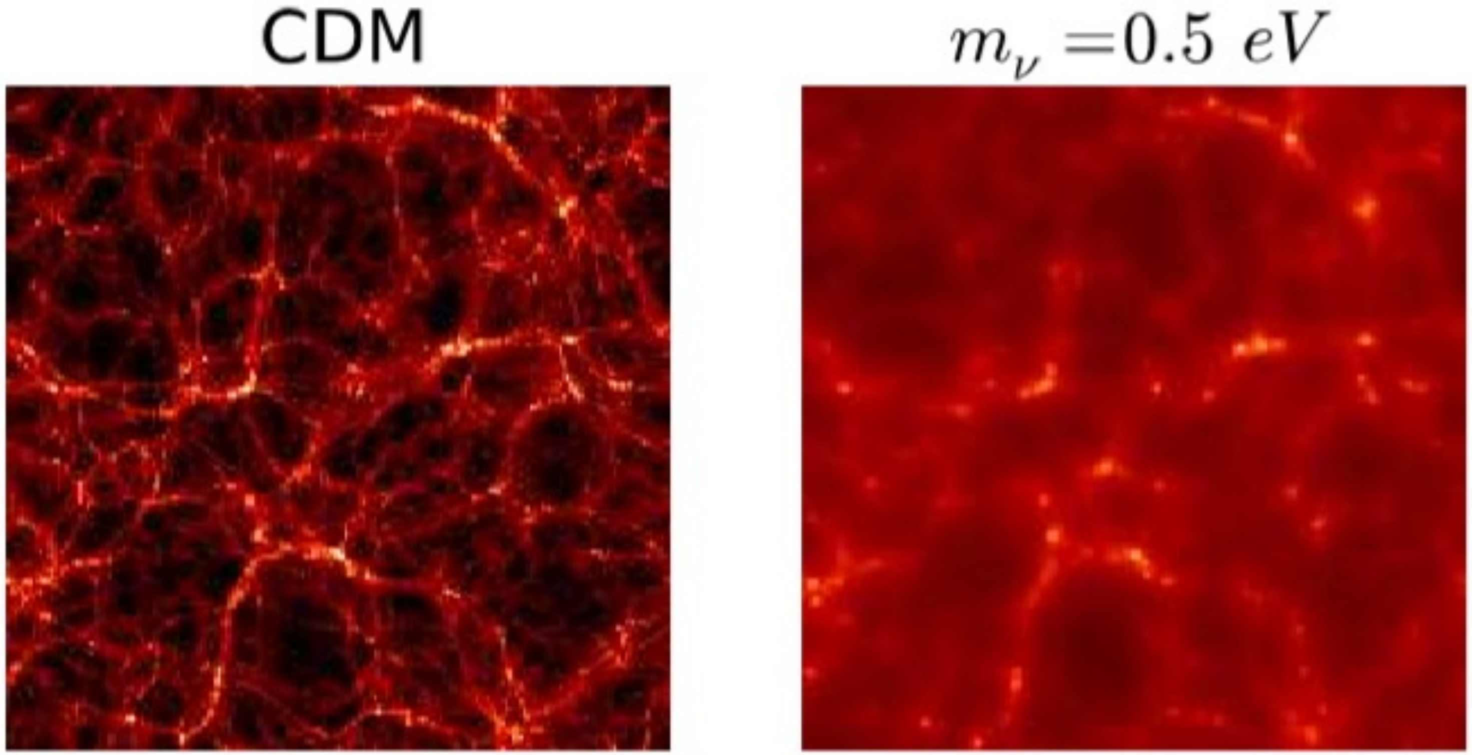
Σm_ν



Planck TT,TE,EE + lowE
$\Sigma m_\nu < 0.26$ eV (95%cl)

Indirect probes of CνB

- Impact on structure formation: Free-Streaming $d_{\mathrm{FS},i} \sim 1\,\mathrm{Gpc}\frac{eV}{m_{\nu,i}}$



Indirect probes of CνB

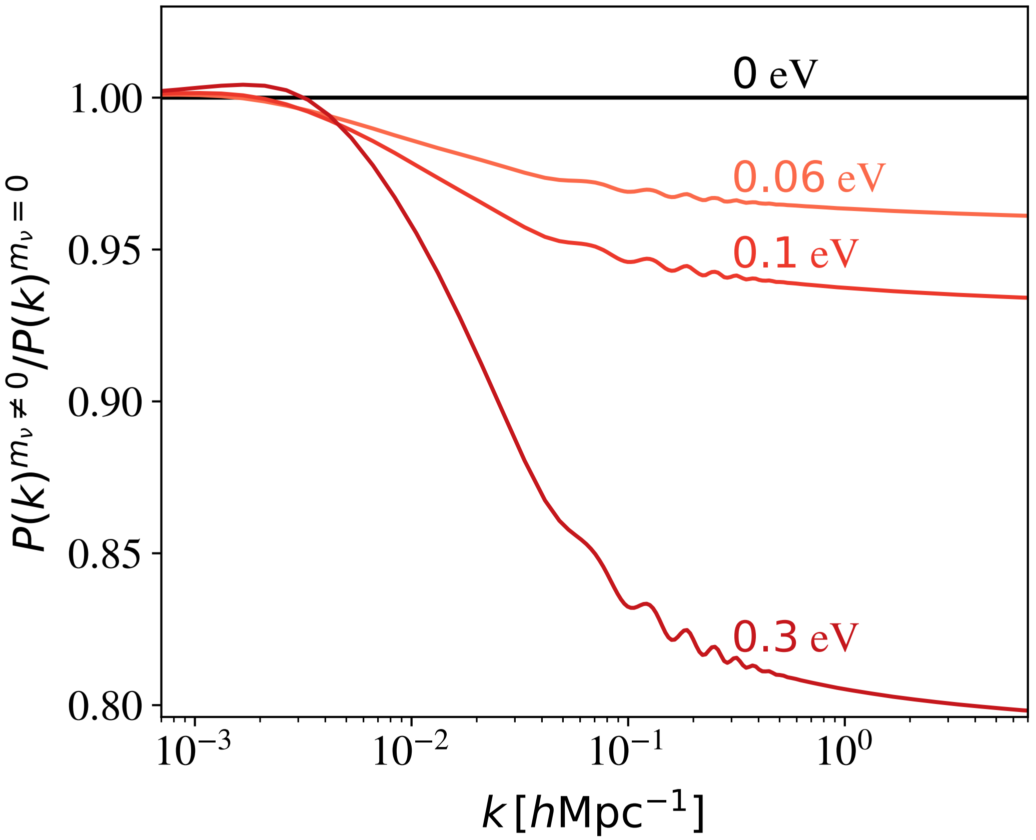
- Impact on power spectrum of matter density fluctuations

$$\delta_{\rm cdm}^{m_\nu=0} \propto a$$

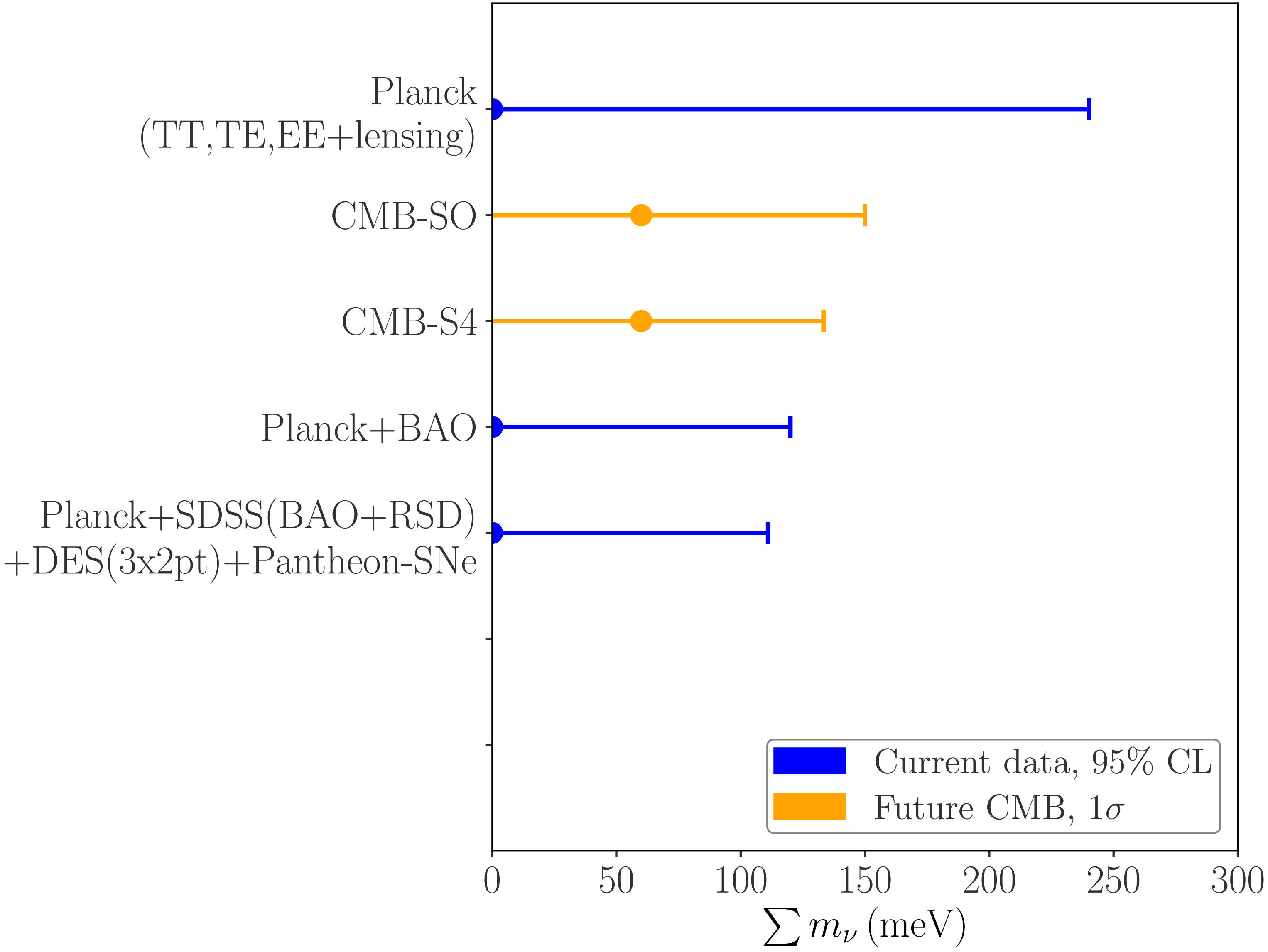
$$\delta_{\rm cdm}^{m_\nu\neq 0} \propto a^{1-\frac{3}{5}\frac{\Omega_\nu}{\Omega_m}}$$

Planck TT,TE,EE + low E + lensing + BAO
$\Sigma m_\nu < 0.12$ eV (95%cl)

Planck TT,TE,EE + low E + lensing + SDSS (BAO+RSD)+Pantheon SN+DES 3x2pt
$\Sigma m_\nu < 0.111$ (95%cl) [Alam et al. 2021]



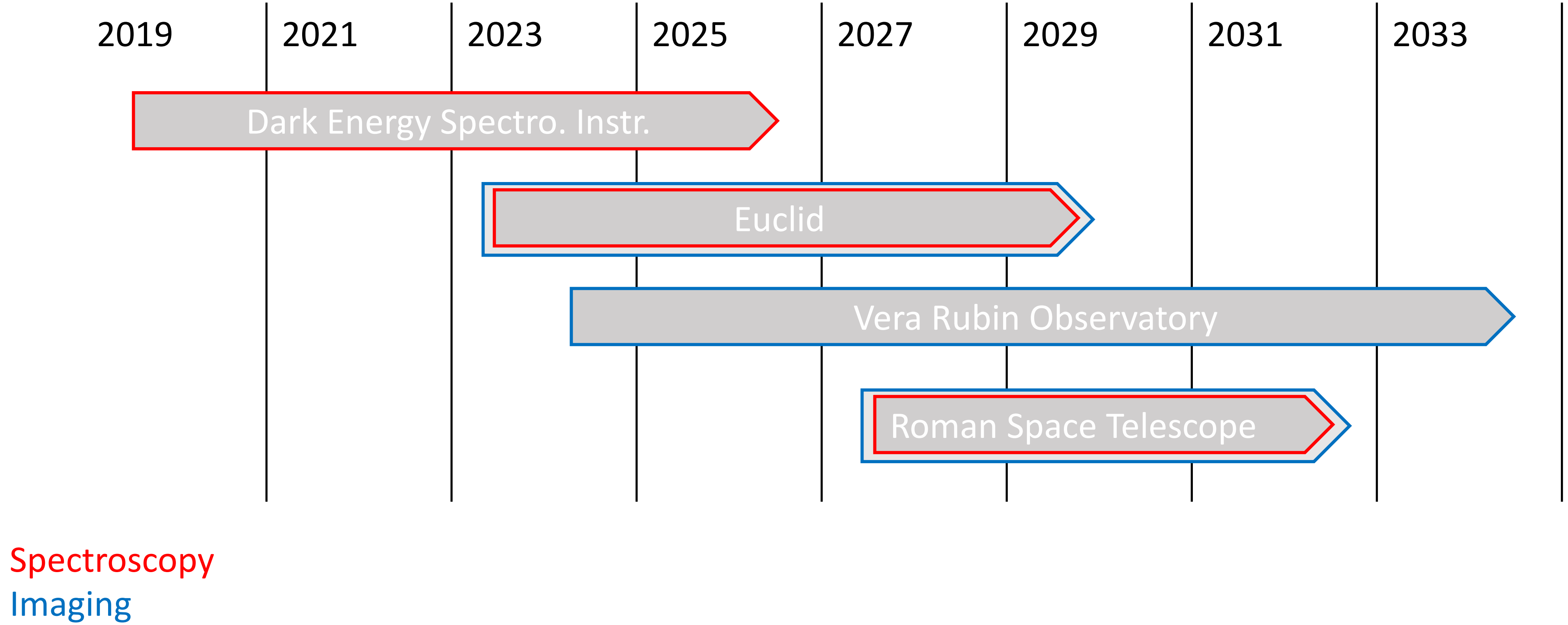
Neutrino mass constraints: recent history



CMB alone will not be able to detect the neutrino mass

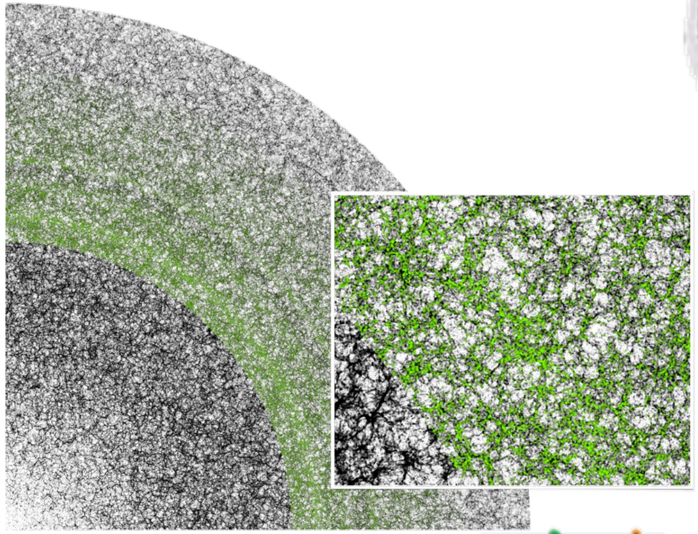
→ S4 Large Scale Structures

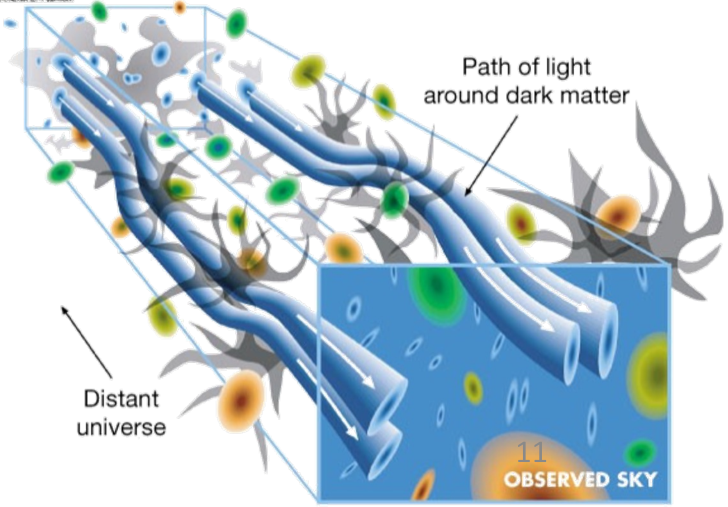
Stage IV Large Scale Surveys



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 (**15.000 deg^2**) and deep survey (40 deg^2 in 3 different fields)
- Measurements of over **1 billion images** and more than **10 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)





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Planck TT,TE,EE + low E + lensing + BAO
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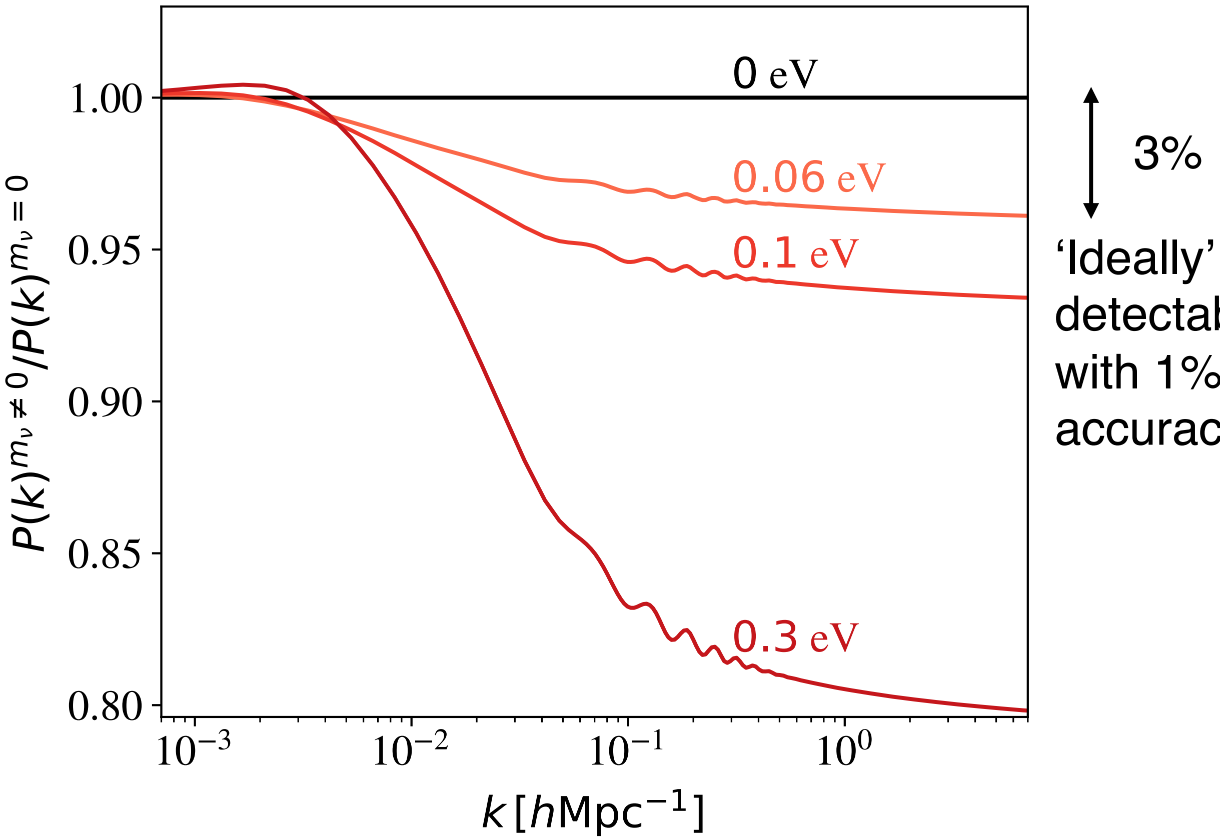


'Ideally' detectable with 1% accuracy

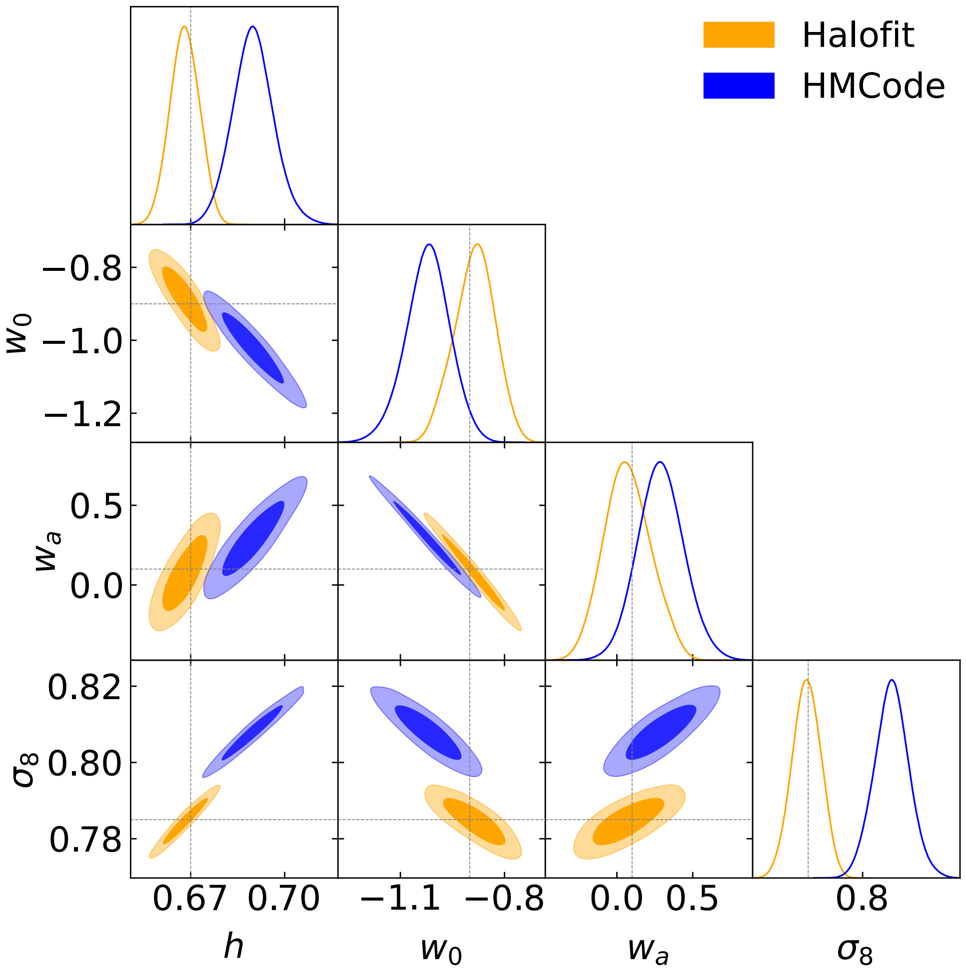
Known unknowns (systematics, etc.)

1. Galaxy bias $P_{galaxy} = b^2 P_{matter} + N$ [Castorina et al. 2014, Vagnozzi, Brinckmann, MA et al. 2018]

2. Non-linearities [Euclid Collaboration: Martinelli, Tutusaus, MA et al. 2020; Euclid Collaboration: Knabenhans et al. 2020]

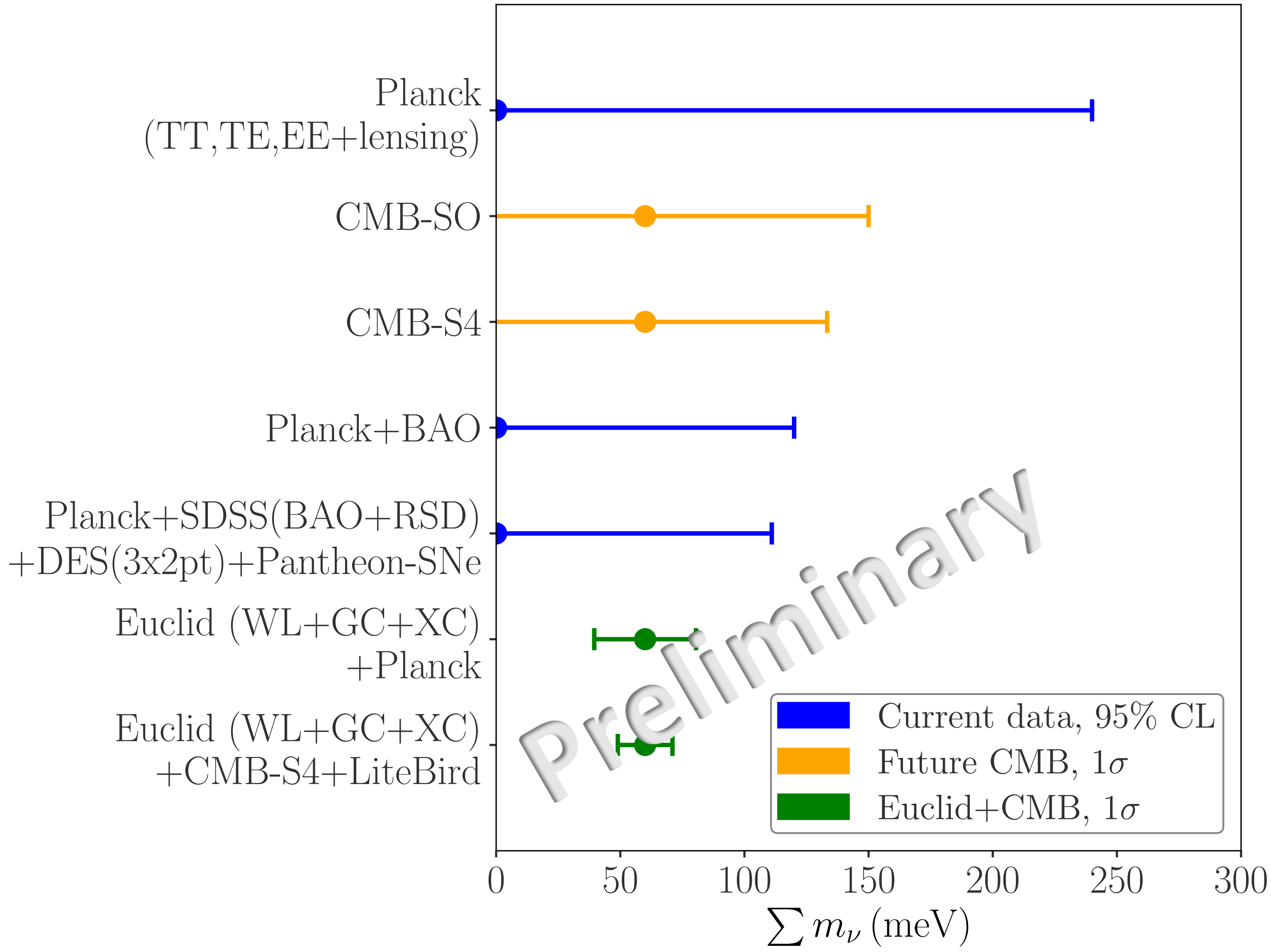
3. Baryonic feedback [Chisari 2019]

Planck+Euclid WL, $\ell_{max} = 5000$



Euclid Collaboration: Martinelli, Tutusaus, Archidiacono et al. 2020

Neutrino mass constraints: the future

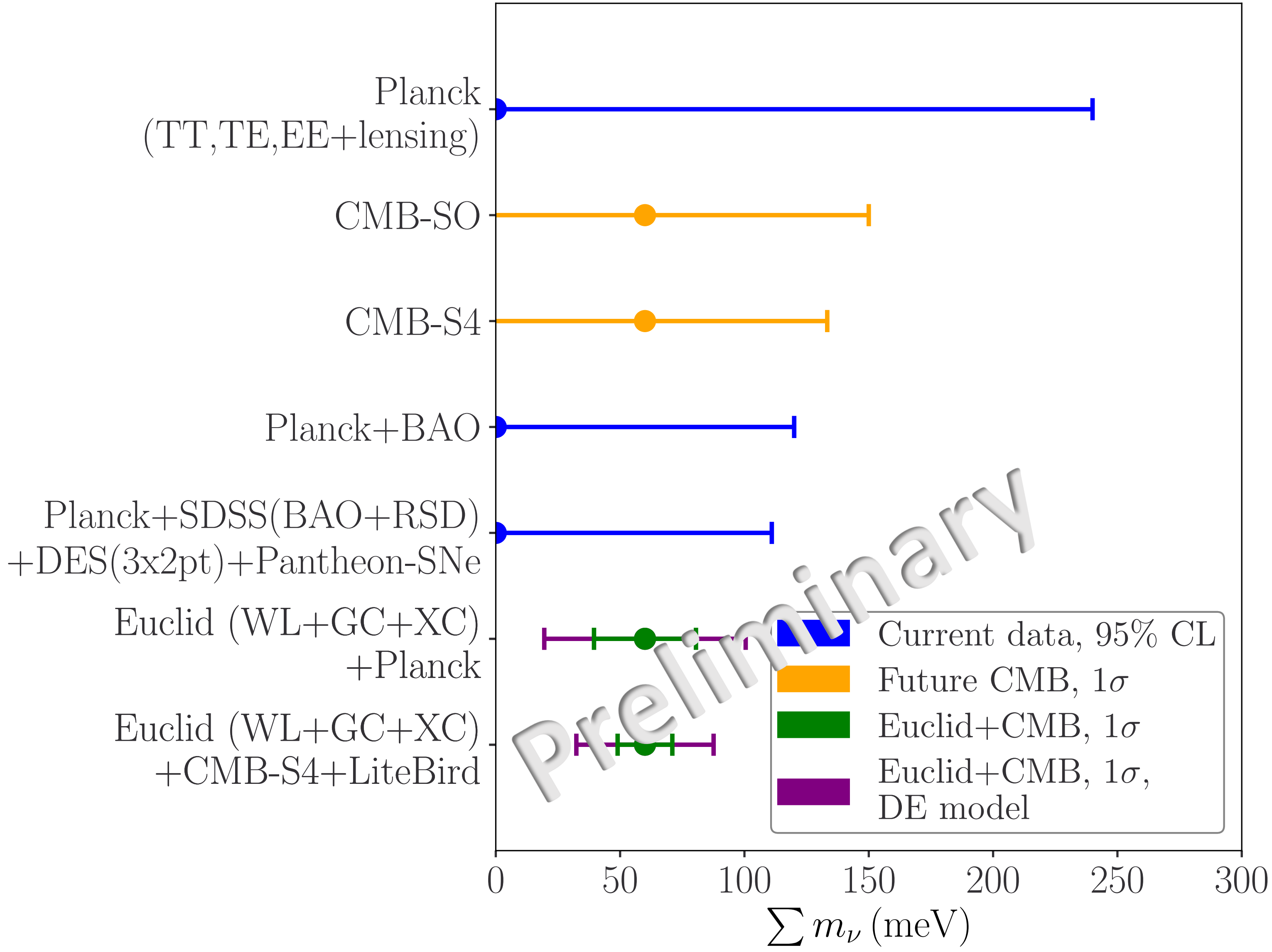


Euclid preparation: Sensitivity to neutrino parameters.
Project leads: Archidiacono & Lesgourgues

Planck + Euclid: 3σ evidence of a non-zero neutrino mass sum

CMB-S4 + Euclid: 5σ

Neutrino mass constraints: the future



Euclid preparation: Sensitivity to neutrino parameters.
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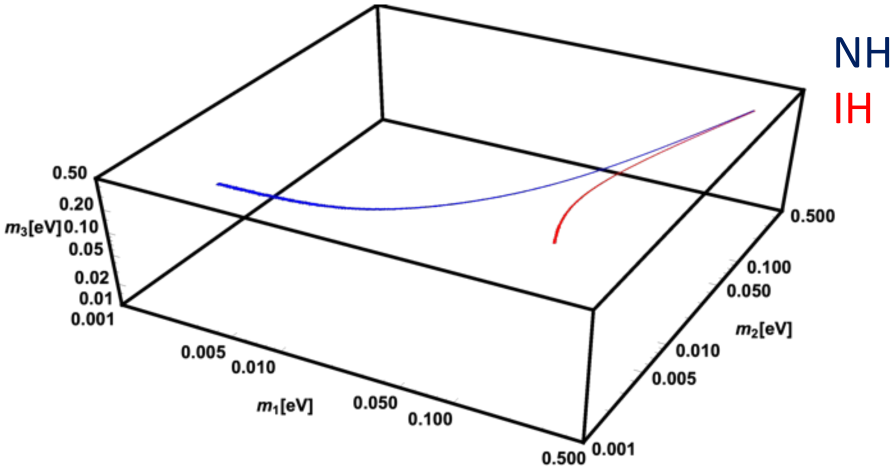
Replacing the cosmological constant with dark energy with a time varying equation of state parameter increases the error by a factor 2

Hierarchy?

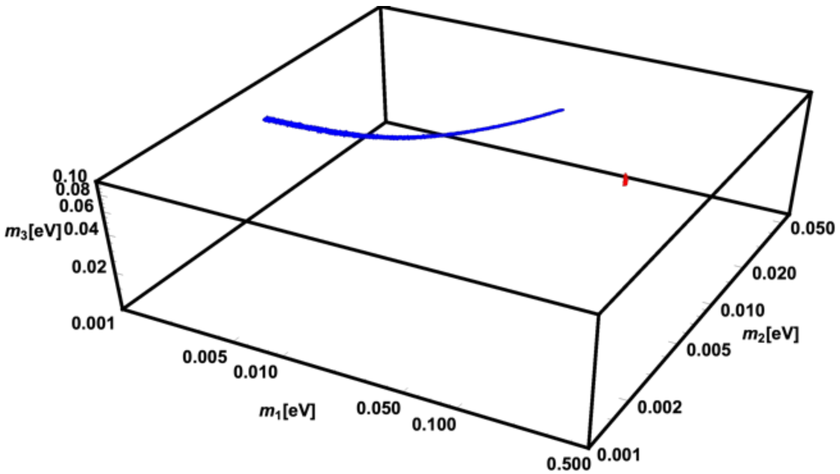
The debate over the hierarchy

«Decisive evidence for the normal hierarchy» Jimenez et al. 2022

Neutrino oscillation data

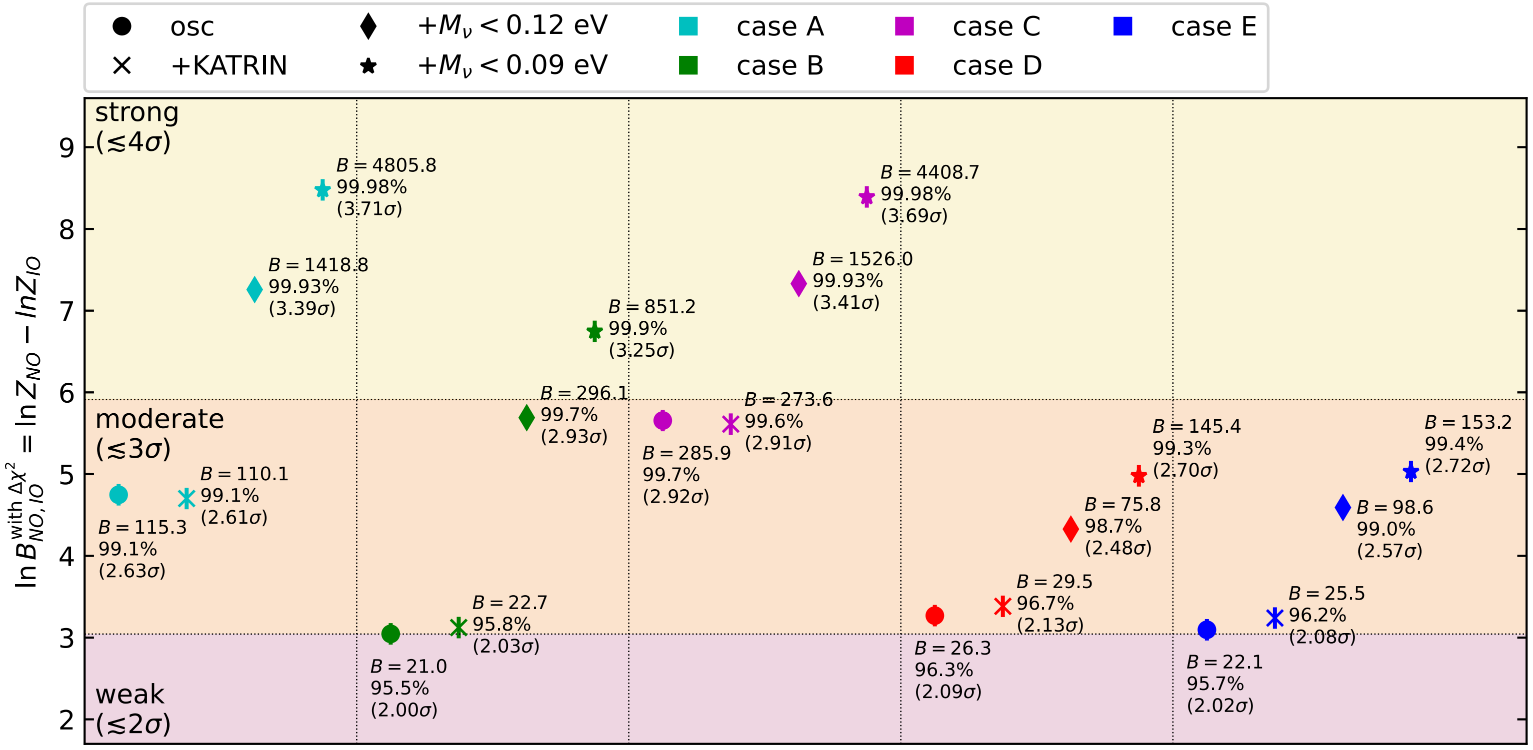


+ Cosmological bound on Σm_ν



The debate over the hierarchy

«Moderate evidence, mostly driven by neutrino oscillation data» Gariazzo et al. 2022 (see also Hergt et al. 2021)

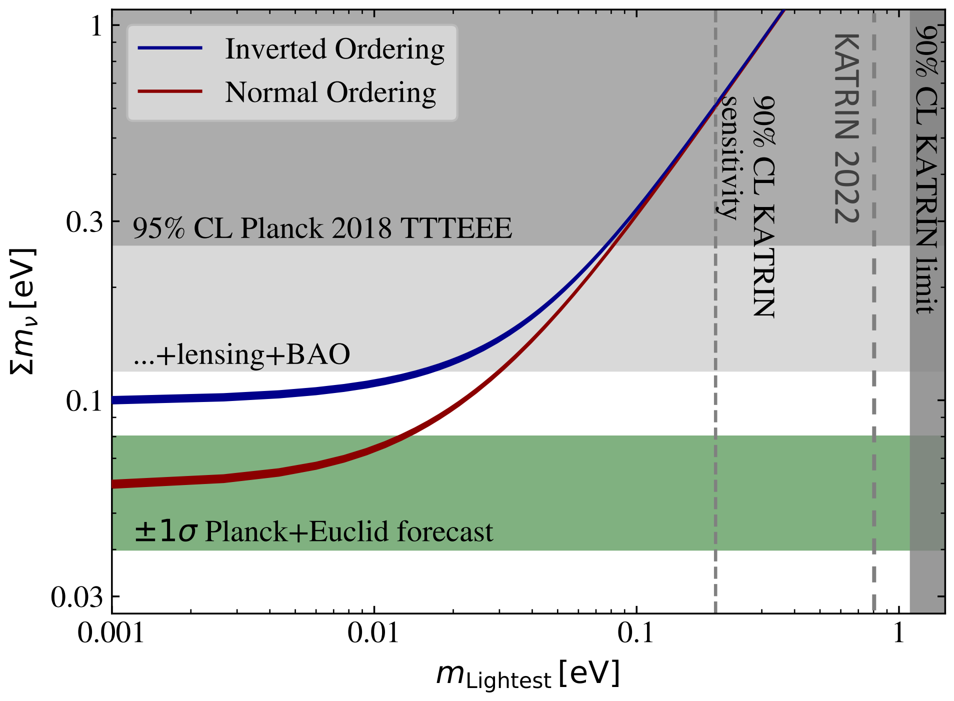


<u>case A</u> is based on Jimenez et al.: a Gaussian prior on the logarithm of the three neutrino mass eigenstates

"The significance of the preference in favor of NO changes significantly when we consider different parameterizations."

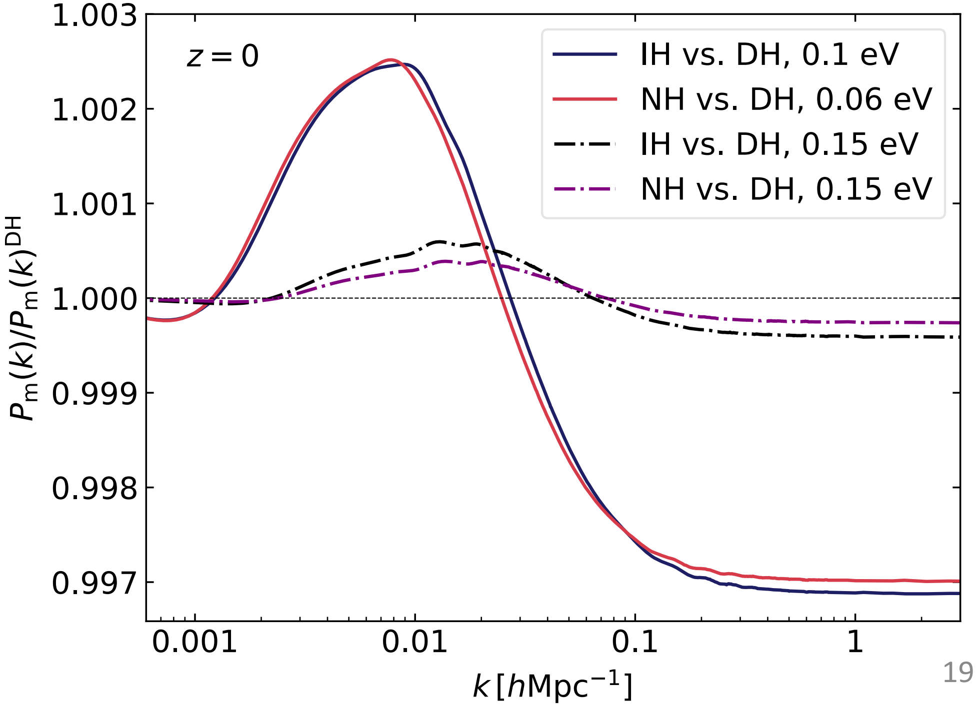
For a different approach, Long et al. 2018, and Heavens & Sellentin 2018

The debate over the hierarchy



Future (current?) cosmological data can potentially disfavour IH

Archidiacono et al. 2020



Cosmology is not sensitive to individual masses

Conclusions

- Current cosmological bounds $\Sigma m_\nu < 0.111$ (95%cl)
- Future LSS and CMB surveys can provide a 3 to 5σ evidence for a non-zero neutrino mass sum
- Caveat:
  - Systematic effects
  - Model dependence

Conclusions

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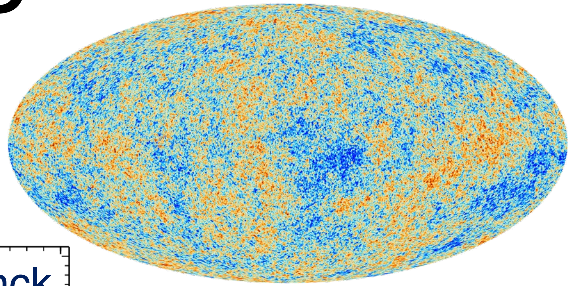
Stay tuned for Euclid results!

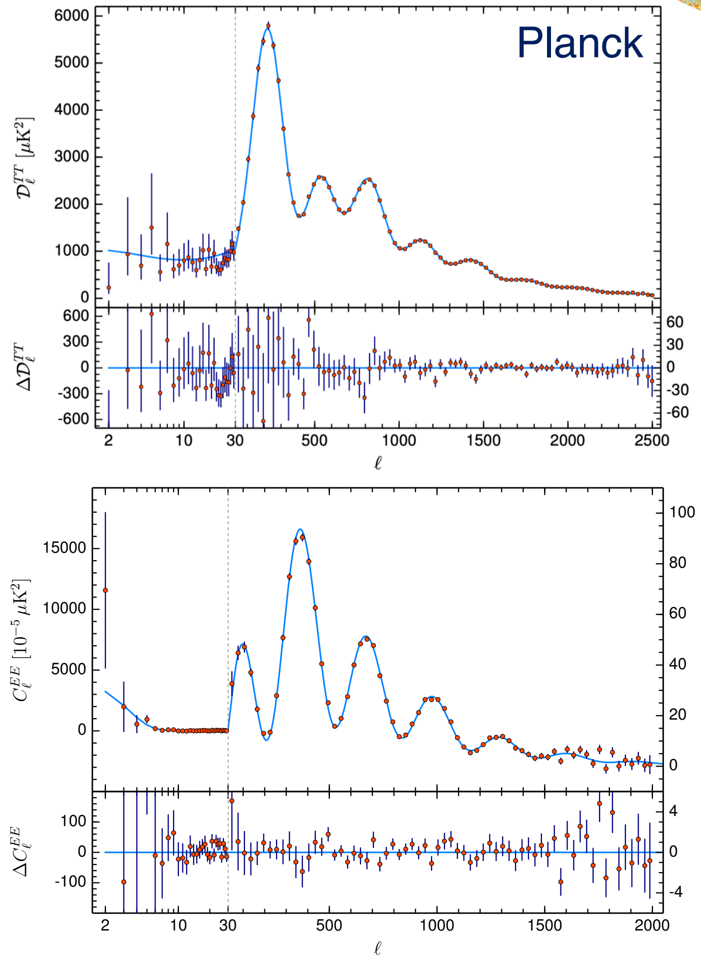
Backup

Cosmological observables



Early Universe

CMB (z ~ 1100)



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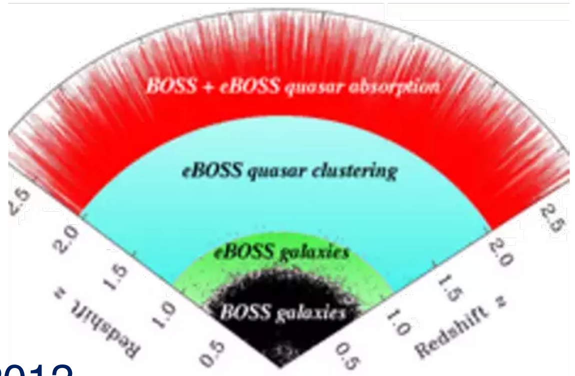
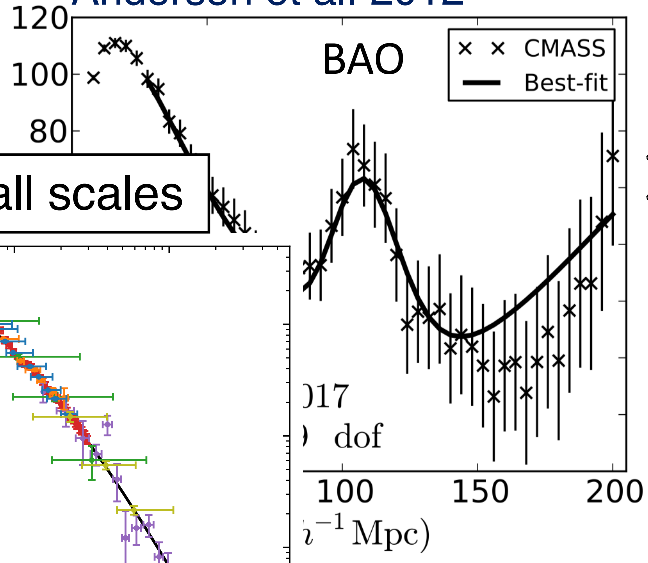
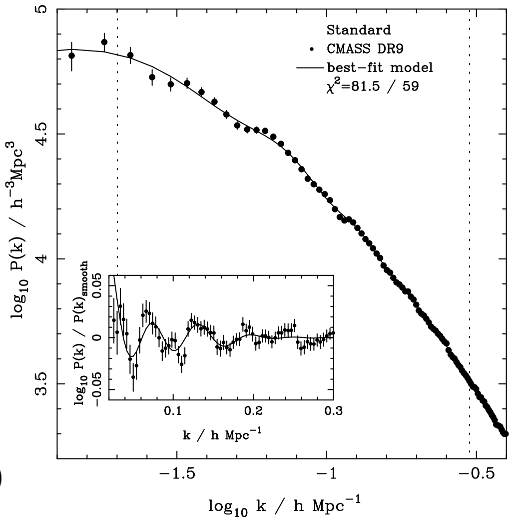
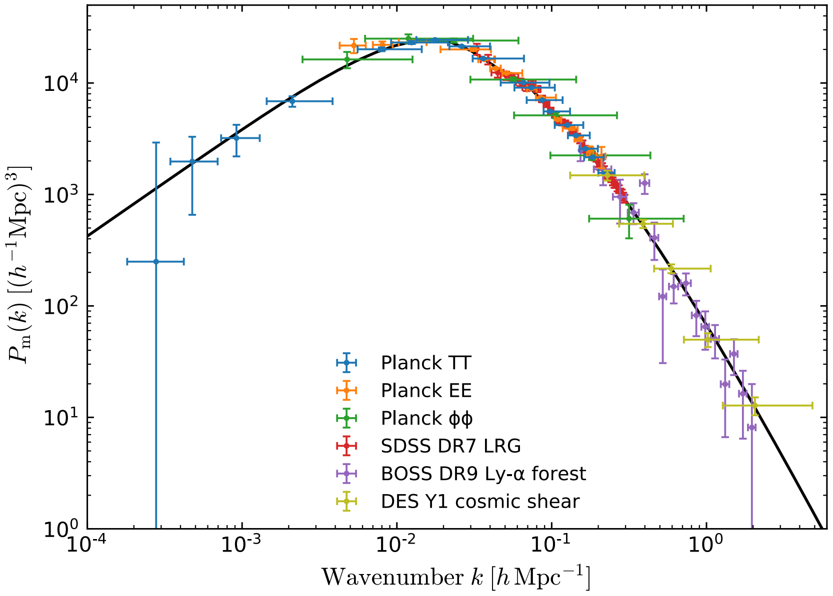


Anderson et al. 2012





Large scales - small scales



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

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Neutrino non-rel.

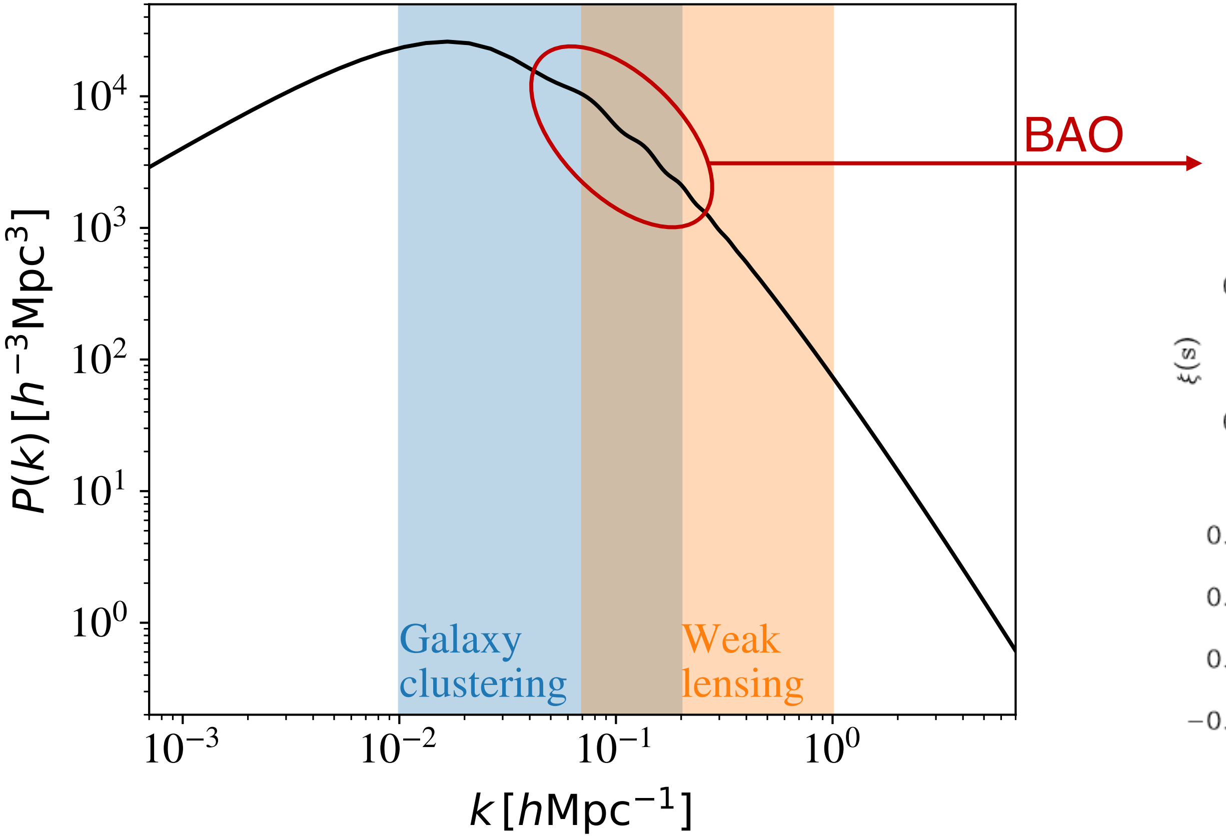
$$z_{\mathrm{nr},i} \sim \frac{m_{\nu,i}}{0.5\,\mathrm{meV}}$$

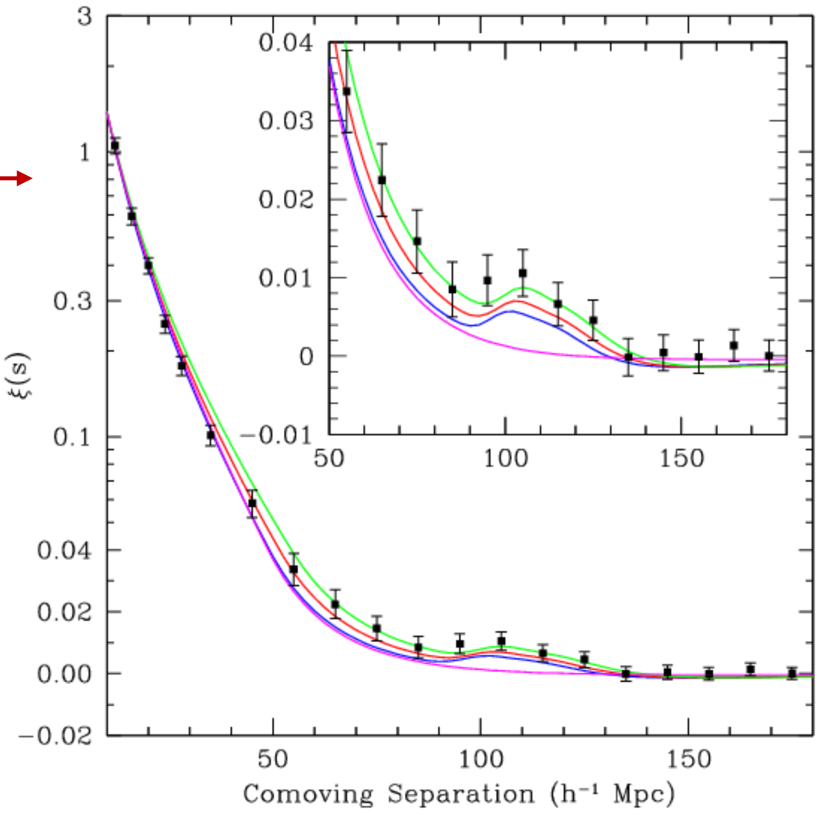
Reconstructing the matter power spectrum

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

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

$$\xi(\mathbf{r}) = \int P(k) e^{-i\mathbf{k}\cdot\mathbf{r}} \frac{d^3k}{(2\pi)^3}$$



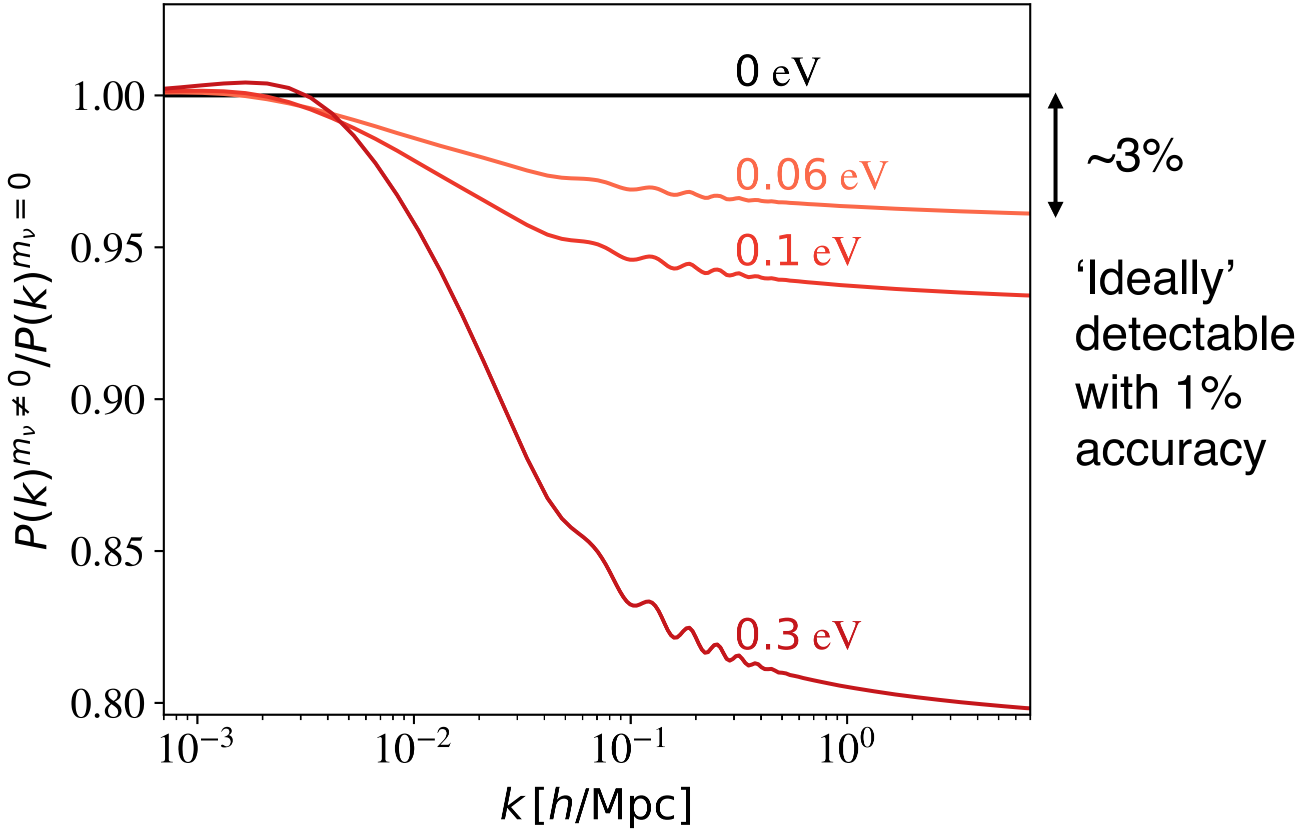


The neutrino mass challange

In a massless neutrino Universe $\delta_{\rm cdm} \propto a$

In a massive neutrino Universe $\delta_{\rm cdm} \propto a^{1-\frac{3}{5}\frac{\Omega_\nu}{\Omega_m}}$

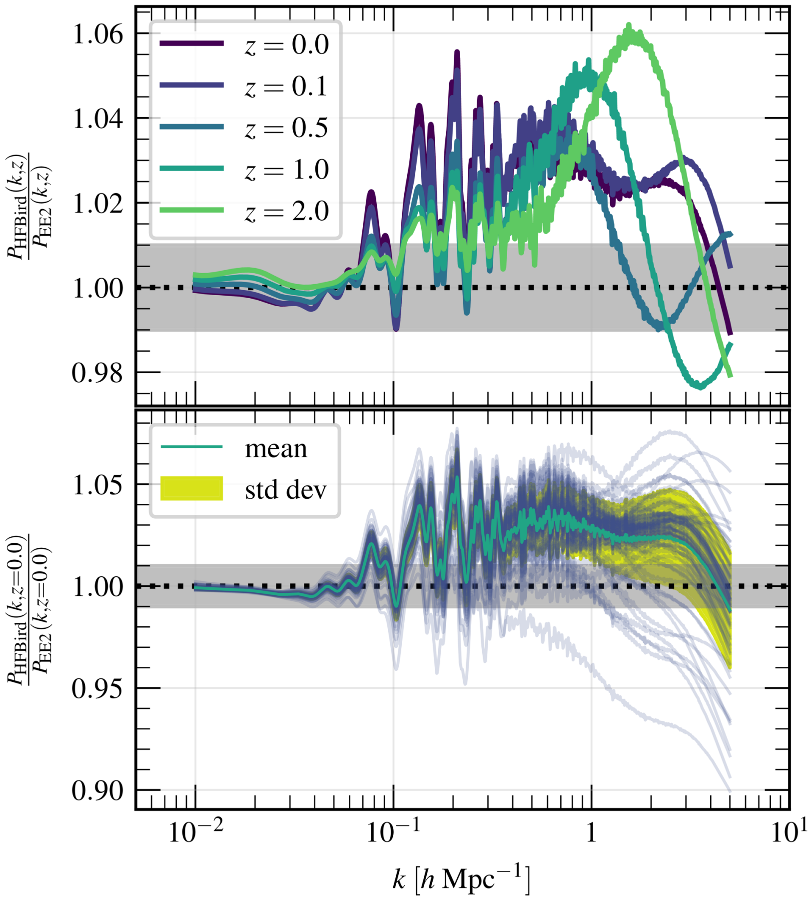
$$\Omega_\nu = \frac{\sum m_\nu}{93.14}$$



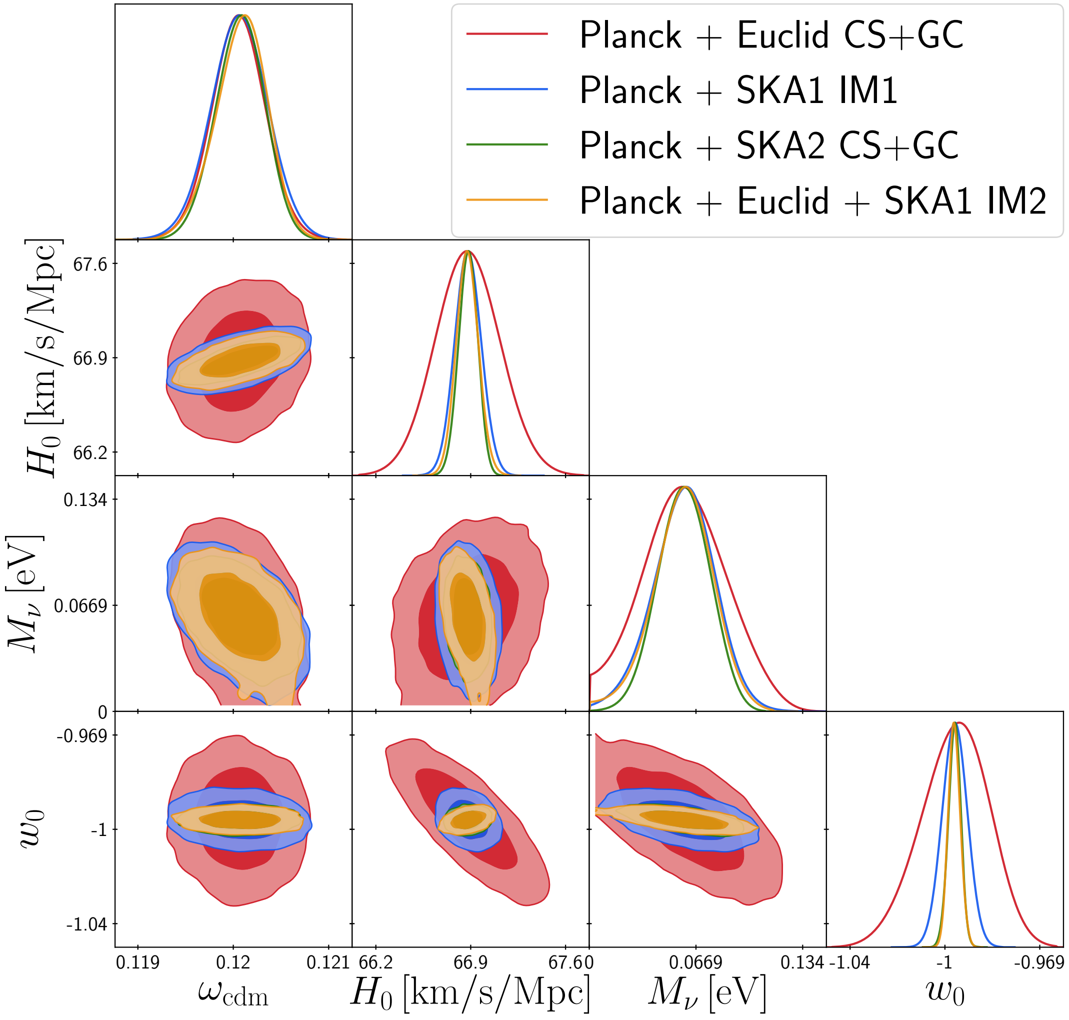
Challanges:

2. Non-linearities: δ ~ 1

Euclid Collaboration. Knabenhans+ 2020



Degeneracies and model dependence



Sprenger, MA et al. 2018

Current bounds and future constraints are model dependent, i.e. they can be relaxed in extended models (beyond ΛCDM)

Higher order statistics can break degeneracies in extended models [Chudaykin et al. 2019, Hahn et al. 2020, Ajani et al. 2020]