Neutrino cosmology

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euclid consortium

15th International Neutrino Summer School
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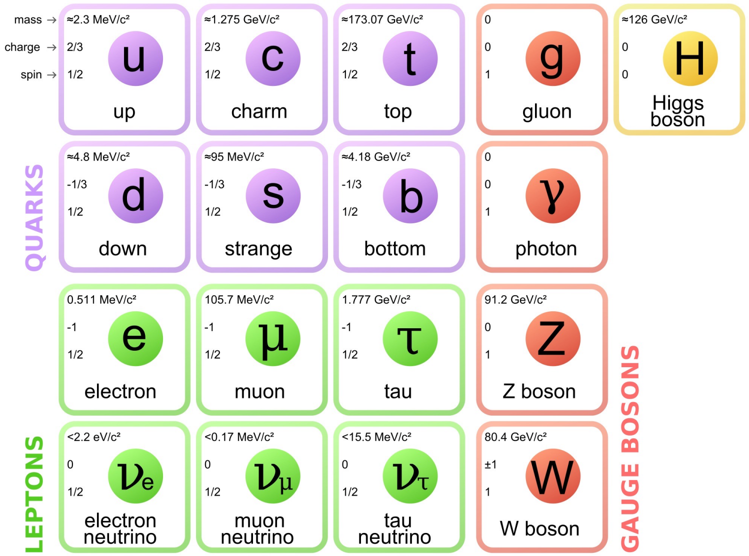
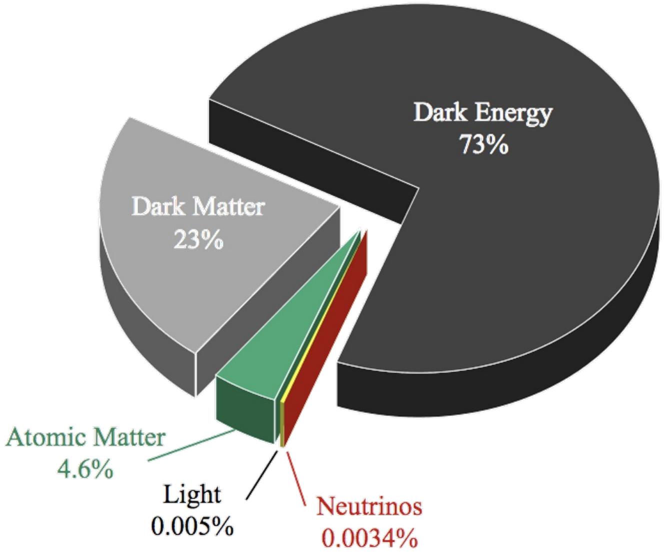
Why neutrino cosmology

Standard Model of particle physics



mass → charge → spin →	$\approx$2.3 MeV/c^2 2/3 1/2 u up	$\approx$1.275 GeV/c^2 2/3 1/2 c charm	$\approx$173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	$\approx$126 GeV/c^2 0 0 H Higgs boson	
QUARKS	$\approx$4.8 MeV/c^2 -1/3 1/2 d down	$\approx$95 MeV/c^2 -1/3 1/2 s strange	$\approx$4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon		
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson		GAUGE BOSONS
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson		

ΛCDM model of cosmology



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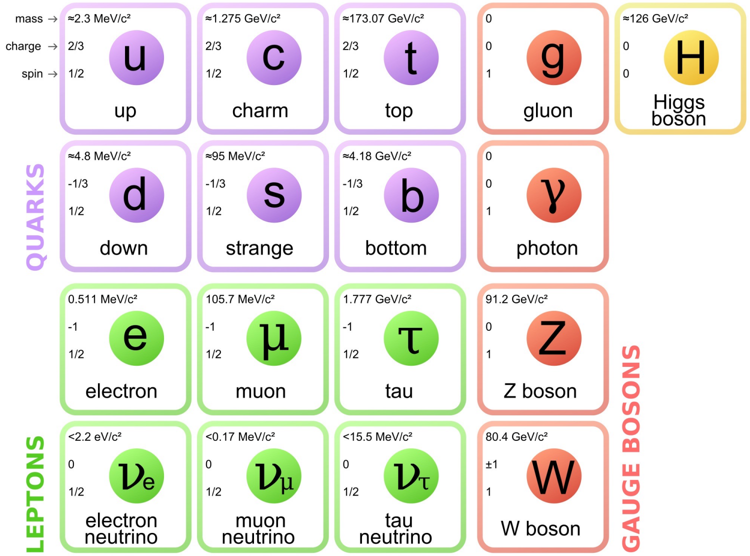

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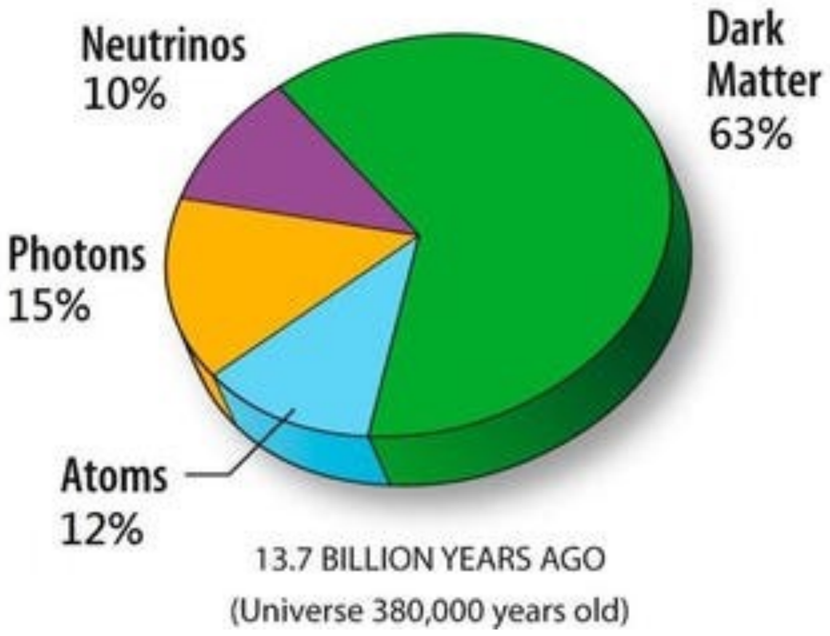

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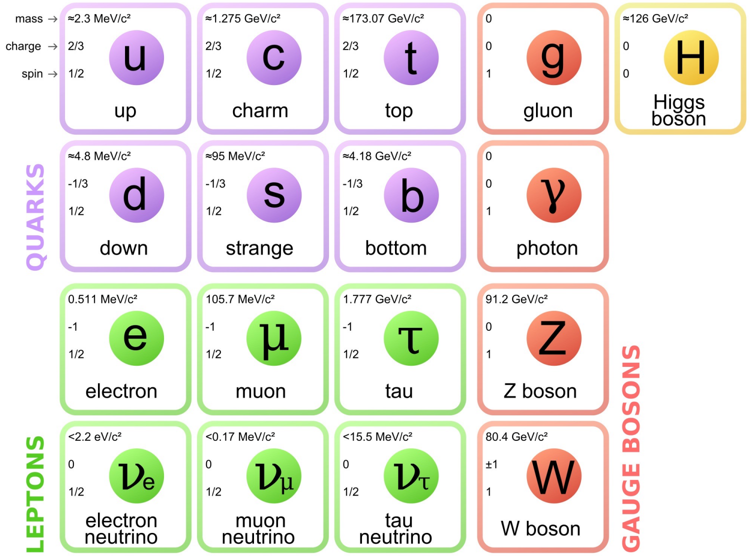

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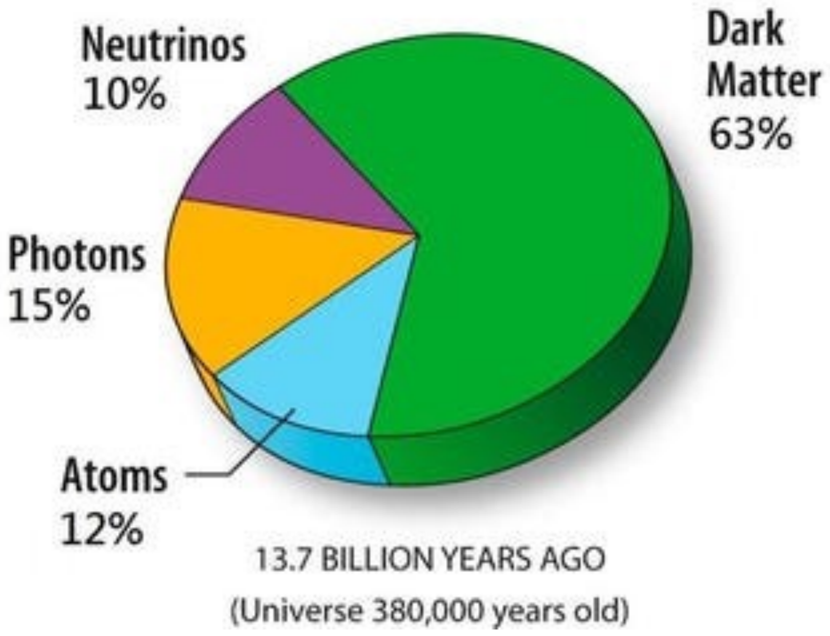

Open questions:

Neutrino masses

Neutrino number

Dark matter

Dark energy

Why neutrino cosmology

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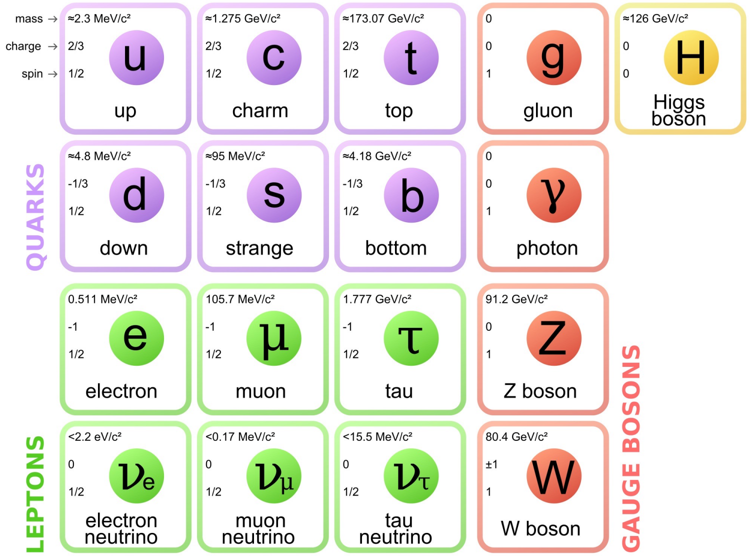

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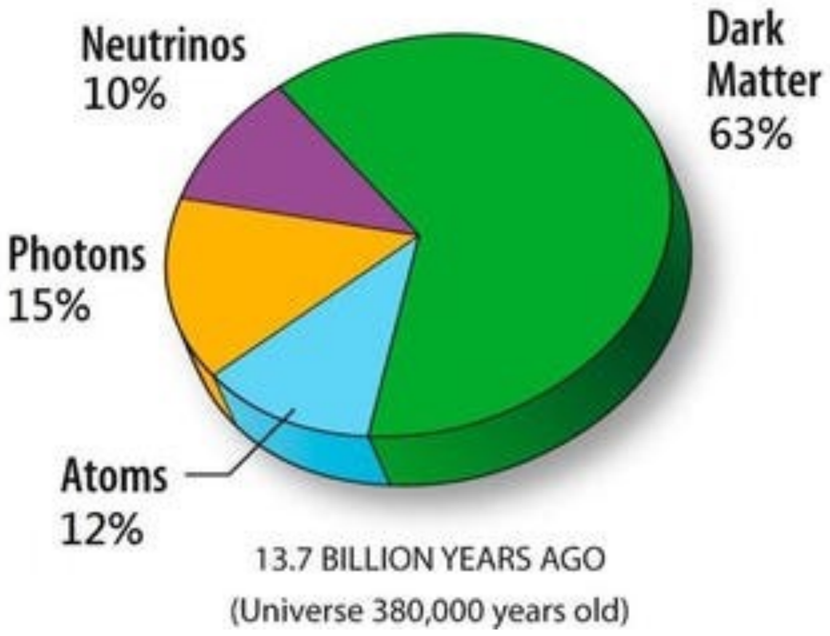

Open questions:

Neutrino masses

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Plan

- A short cosmic history
  Early Universe: A tale of two backgrounds
  - Cosmic Microwave Background (CMB)
  - Cosmic Neutrino Background (CνB)

  Late Universe:
  - Large Scale Structure

- Indirect detection of the CνB: “The number of neutrinos…and other light relics”

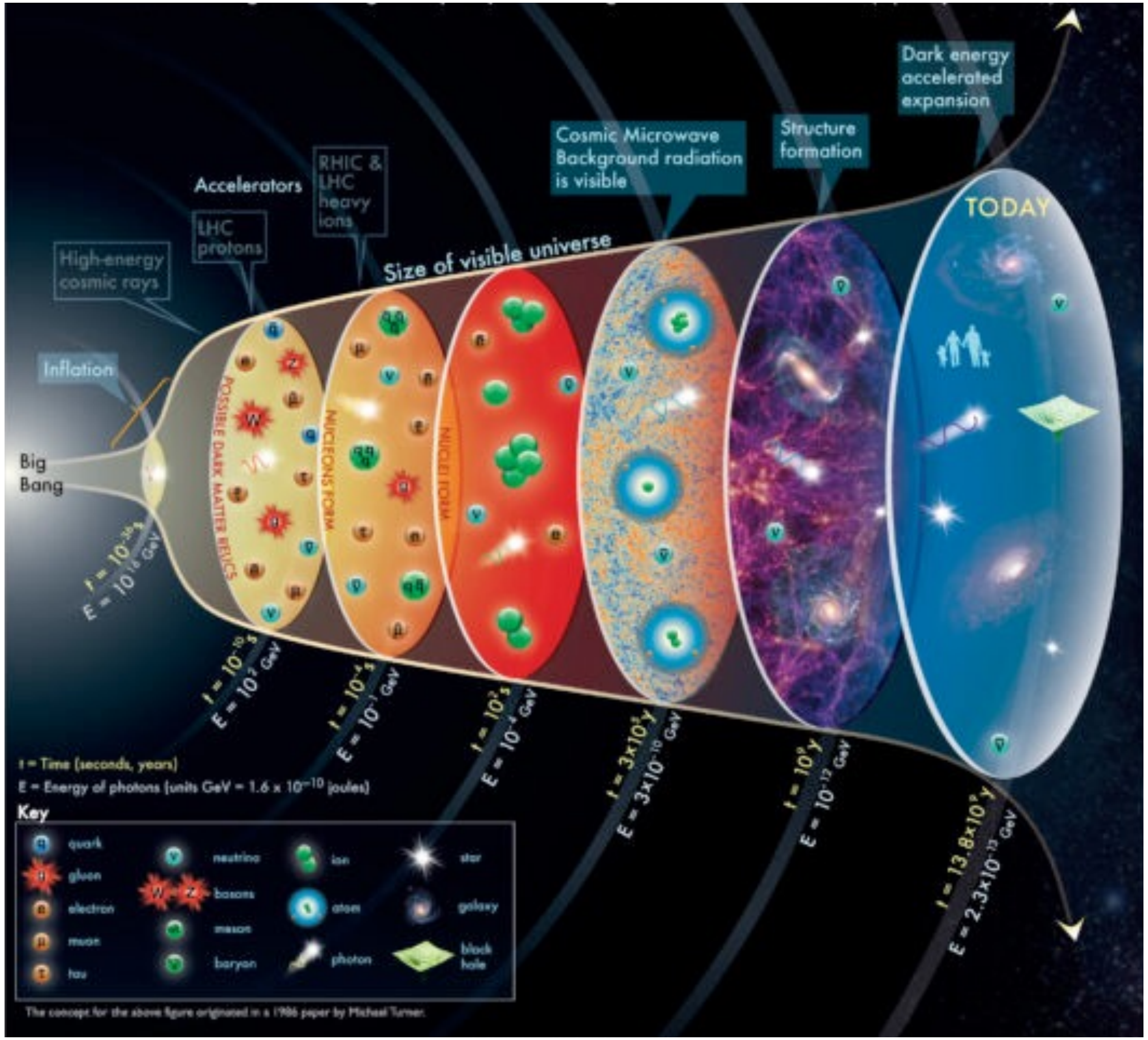
- Detecting the neutrino mass in the CνB

- Non-standard neutrinos
  - The cosmological neutrino mass problem
  - Sterile neutrinos and new interactions

A short cosmic history

The Universe is expanding from a hot dense and homogeneous state.

Particles decouple from the thermal bath when
$\Gamma < H$
leaving behind relics that can survive to present time, and sometimes be detected.



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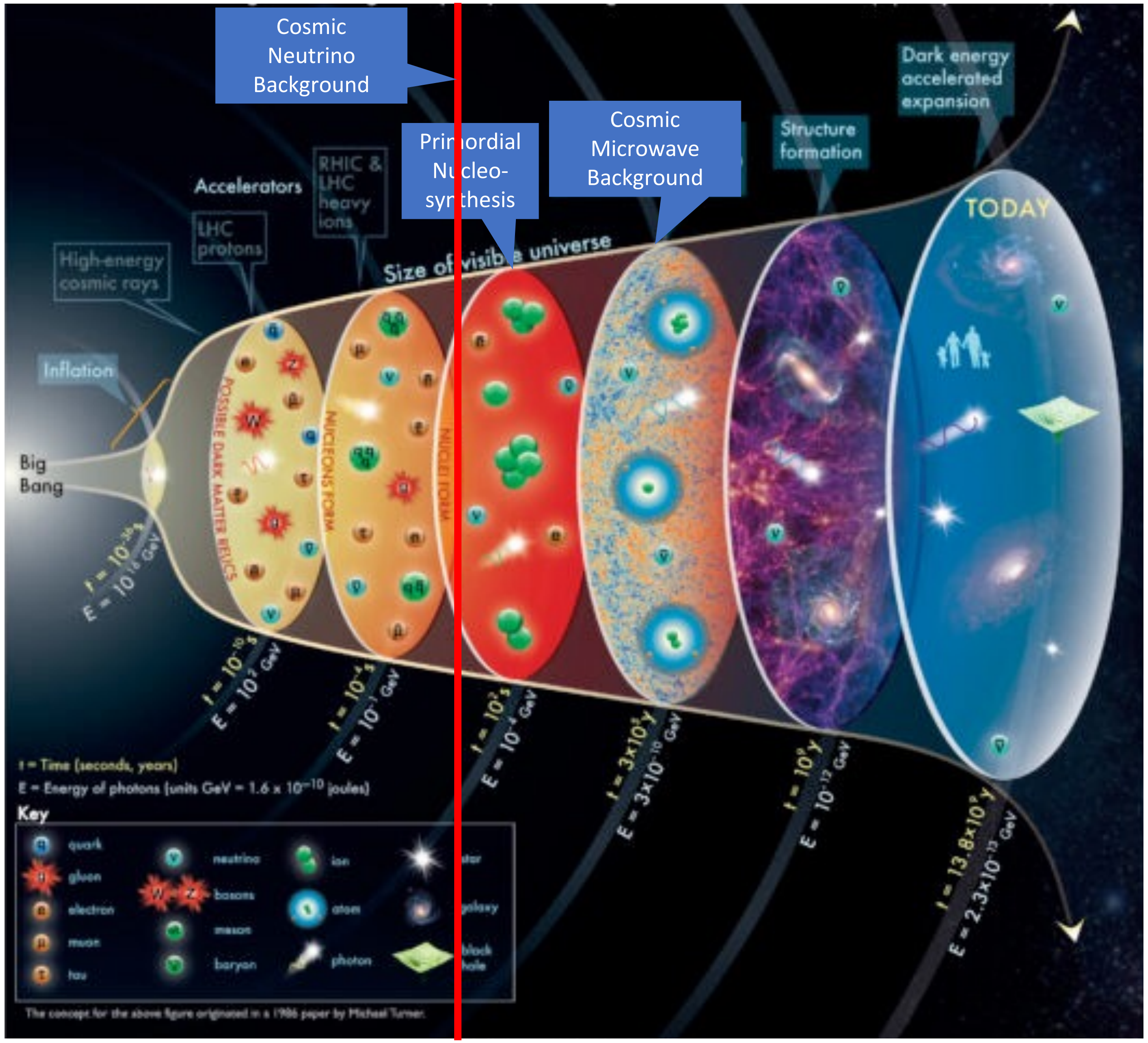

Cosmic Neutrino Background

Primordial Nucleo-synthesis

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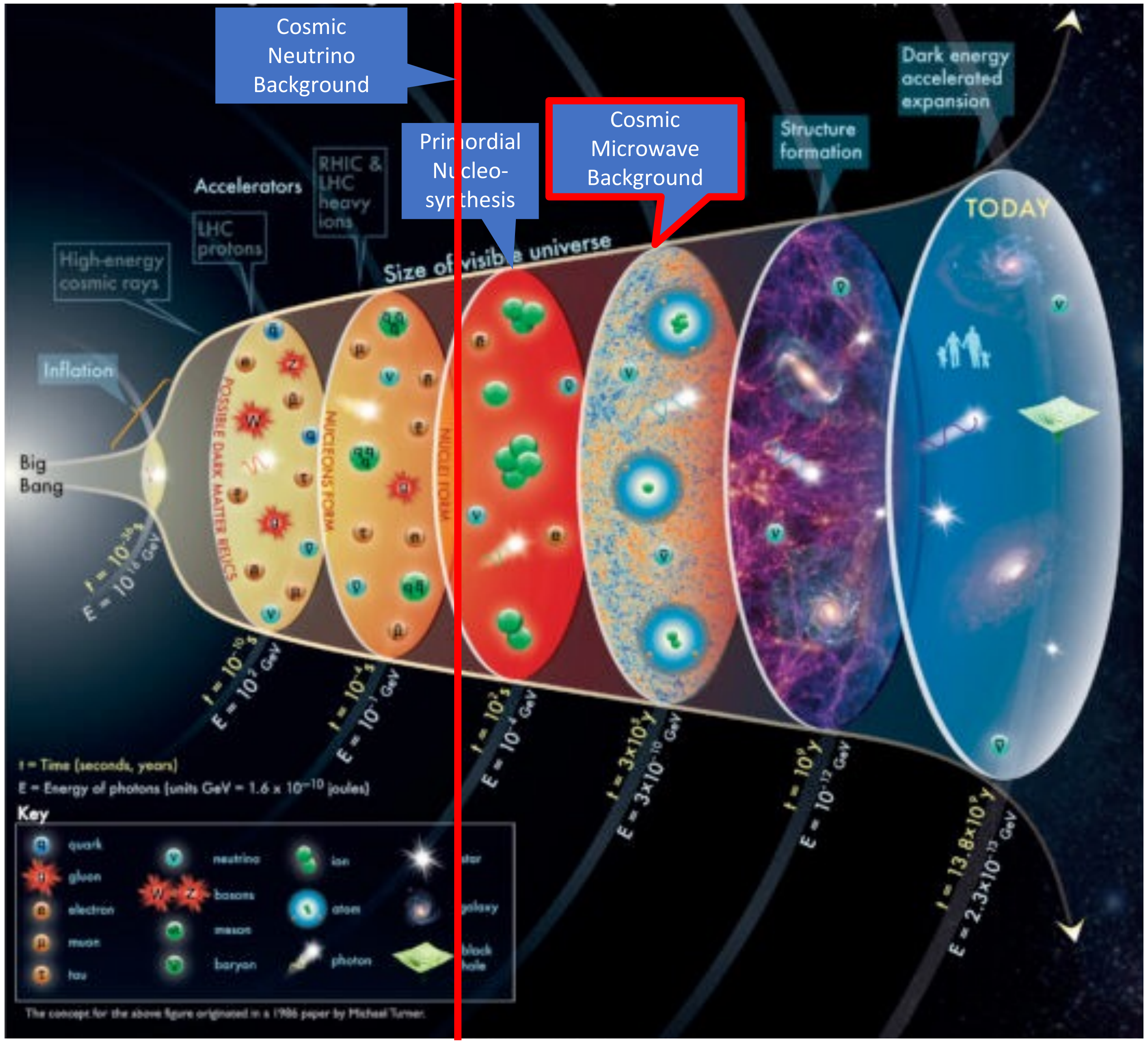


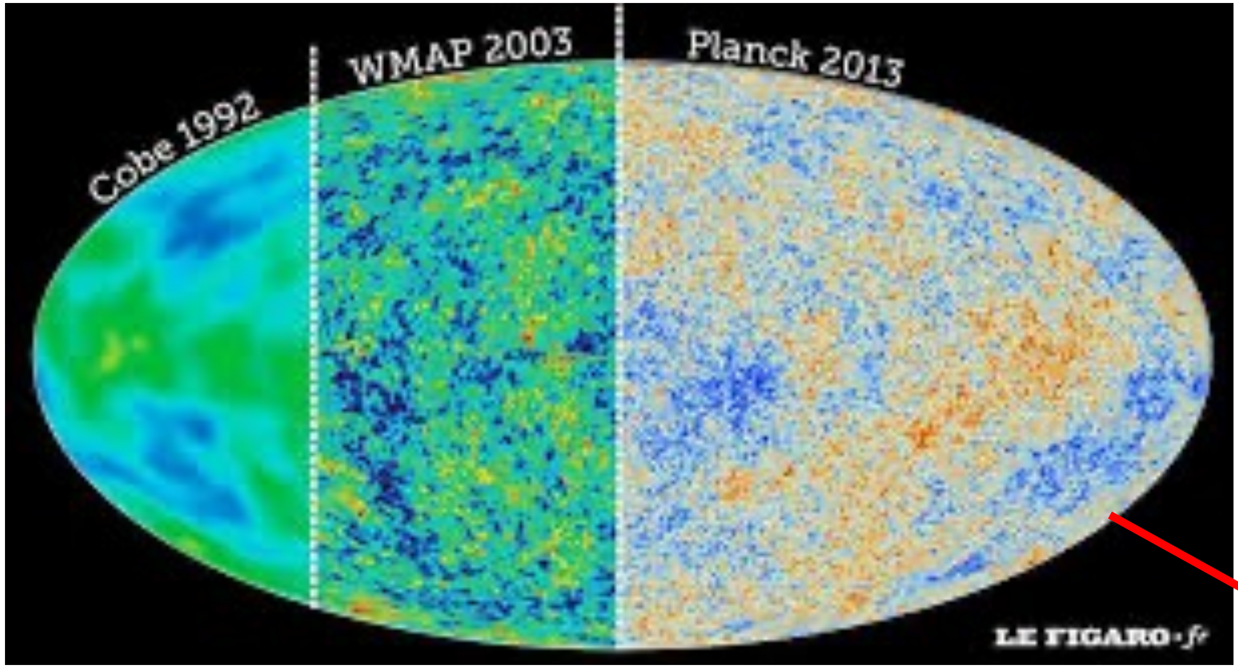
Cosmic Neutrino Background

Primordial Nucleo-synthesis

Cosmic Microwave Background

Cosmic Microwave Background (CMB)

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.

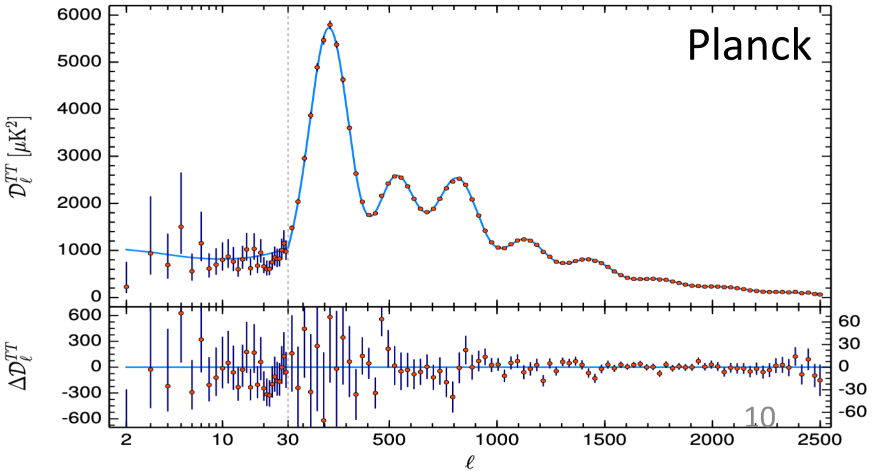


1978 Penzias and Wilson
Discovery of a ~2.7 K background

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

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

$\theta=180°/l$



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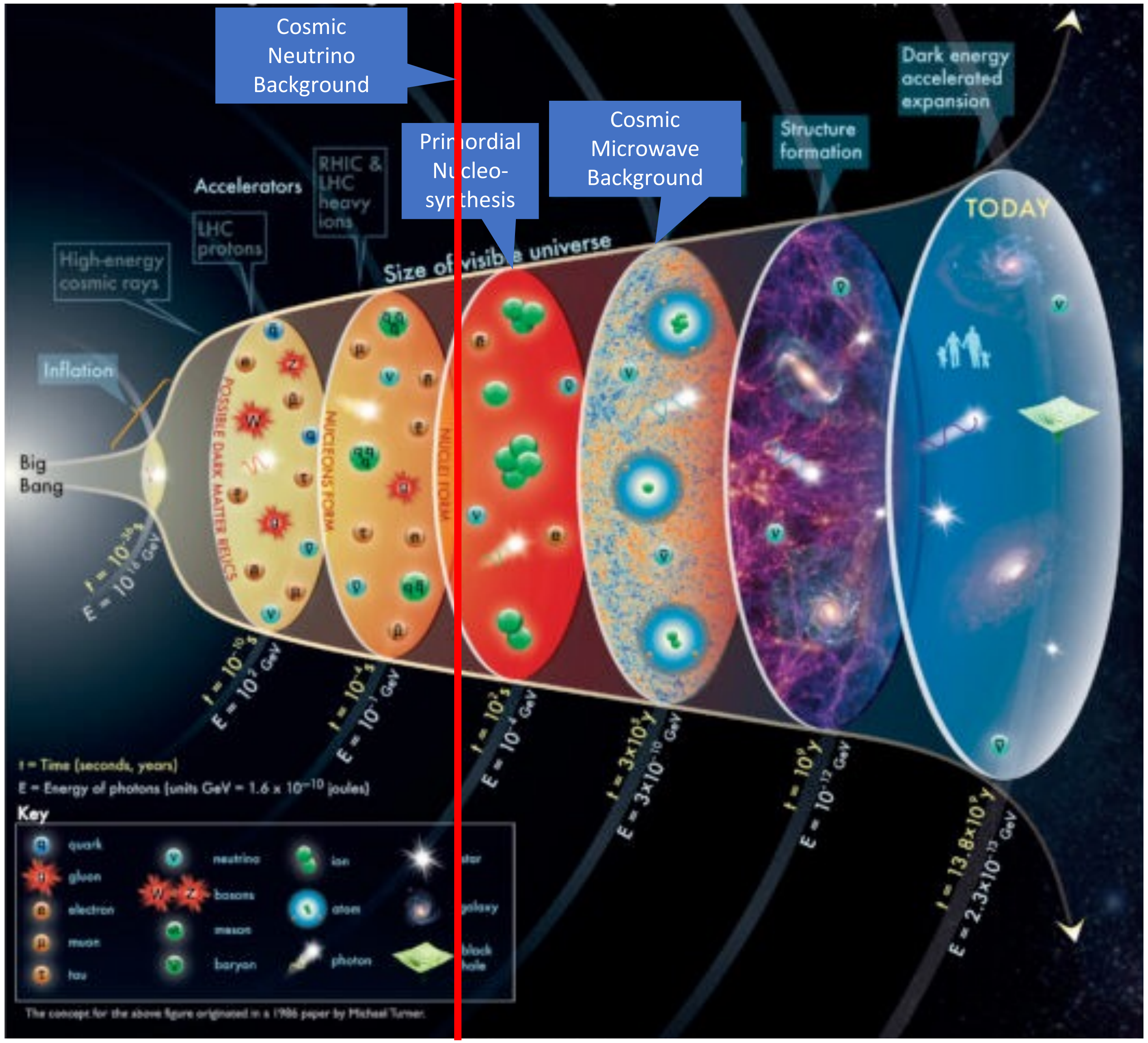

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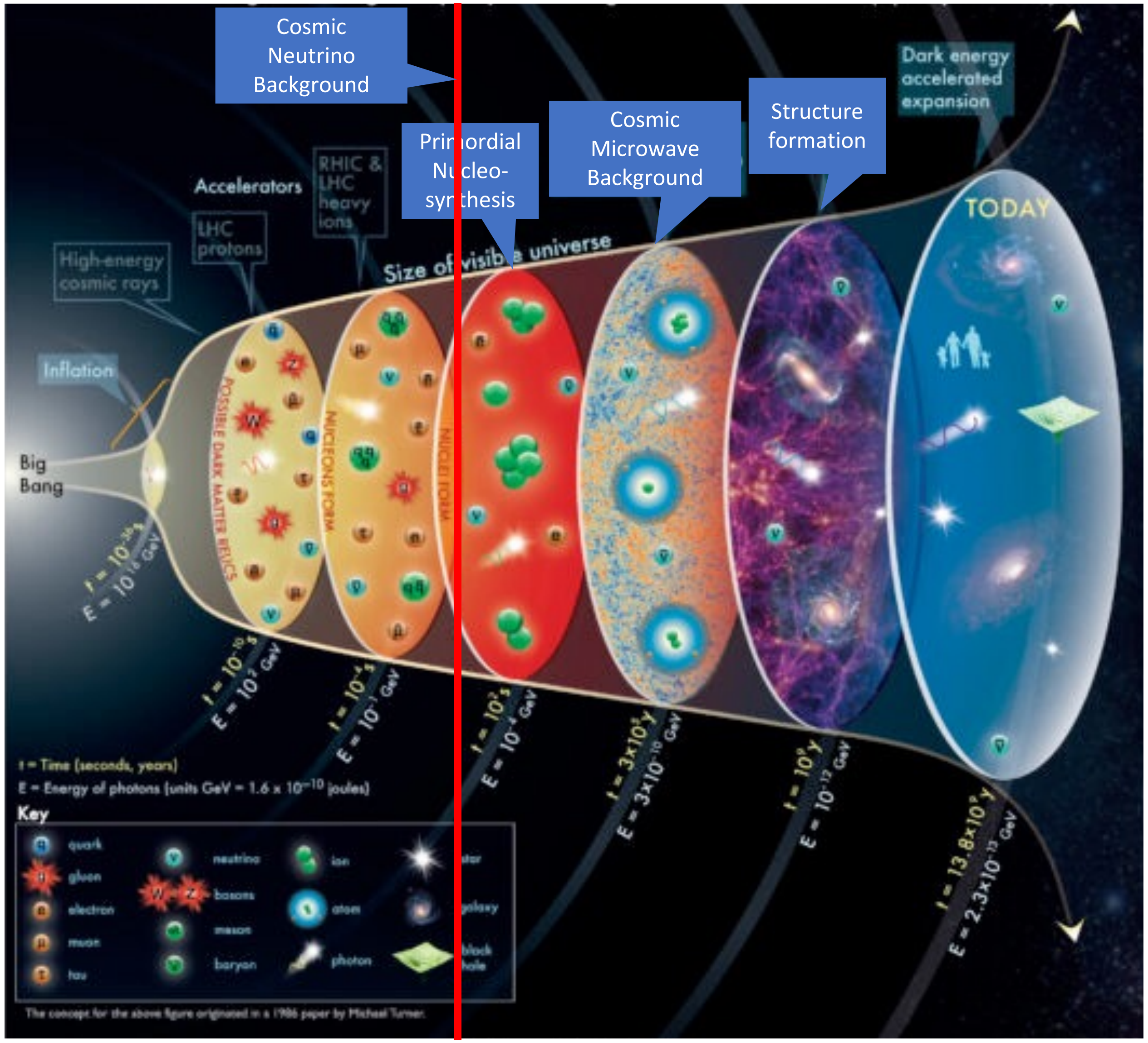


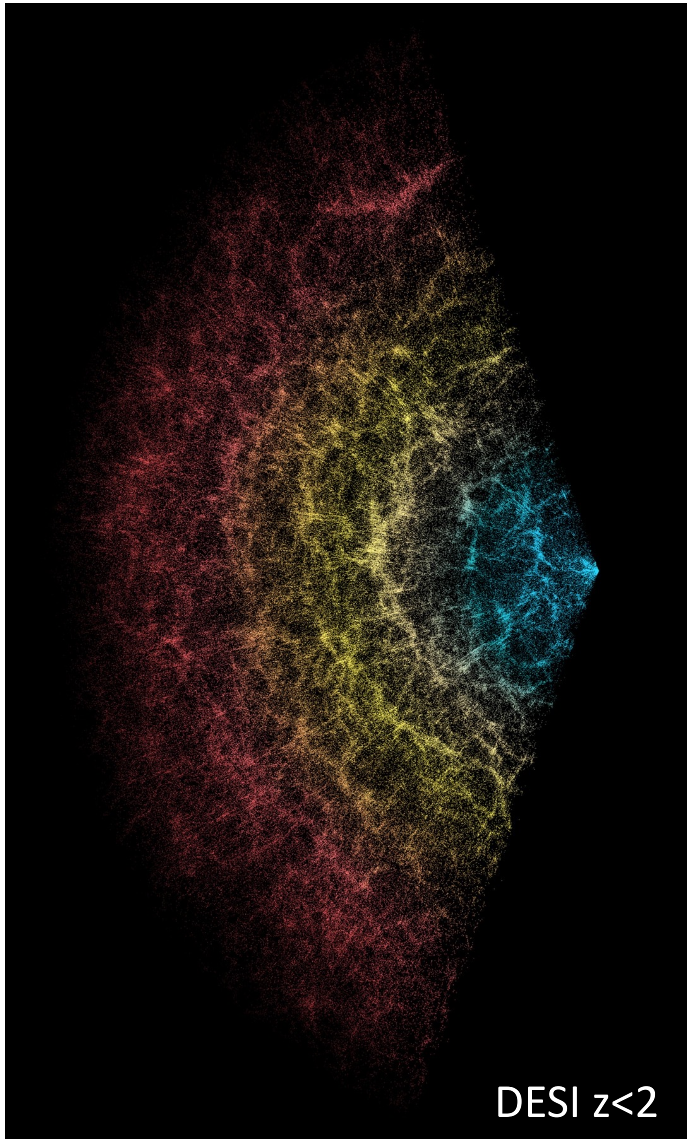
Cosmic Neutrino Background

Primordial Nucleo-synthesis

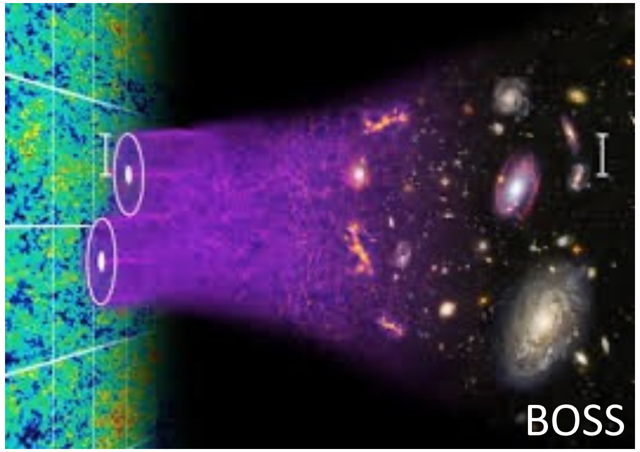
Cosmic Microwave Background

Structure formation

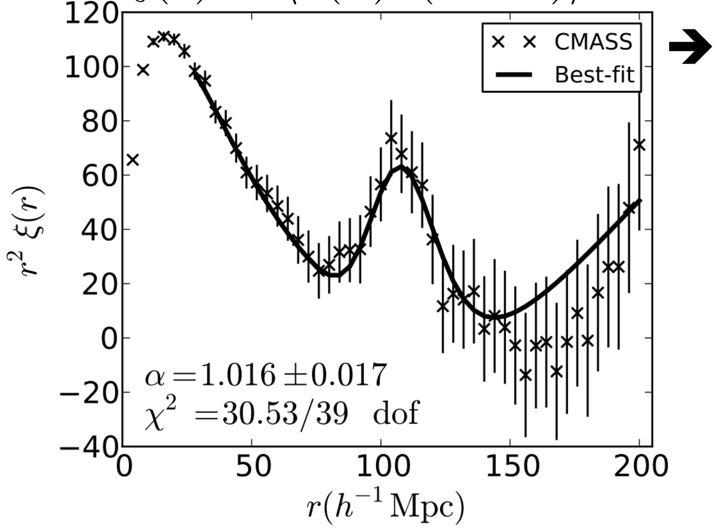
Large scale structure (LSS)



Baryon Acoustic Oscillations (BAO)

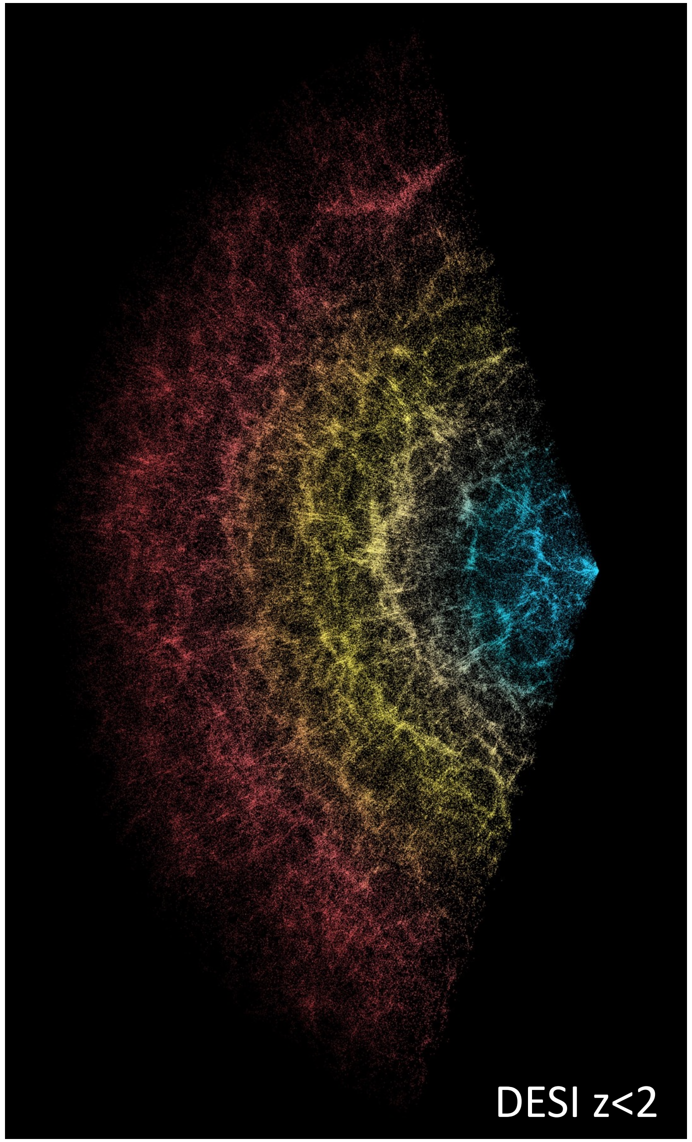


$$\xi(\mathbf{r}) = \langle \delta(\mathbf{x}) \delta(\mathbf{x}+\mathbf{r}) \rangle$$



➔ Expansion history

Large scale structure (LSS)



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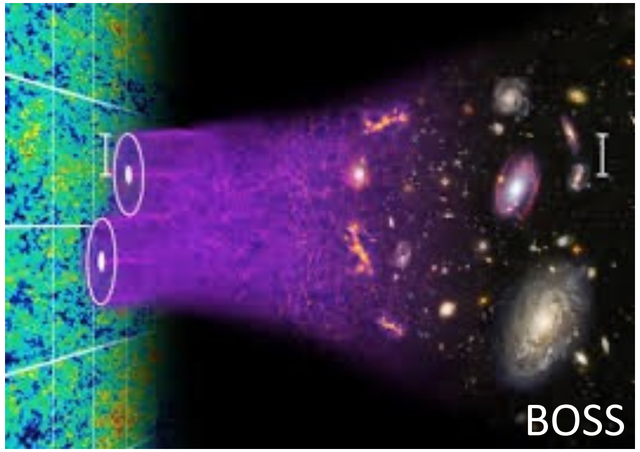

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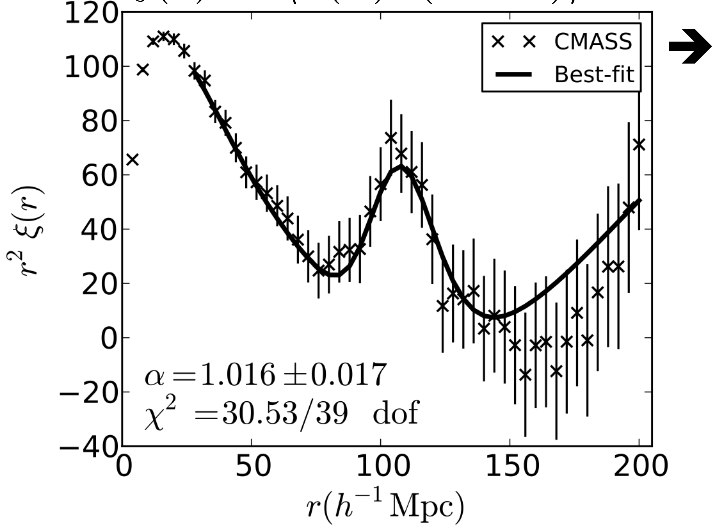
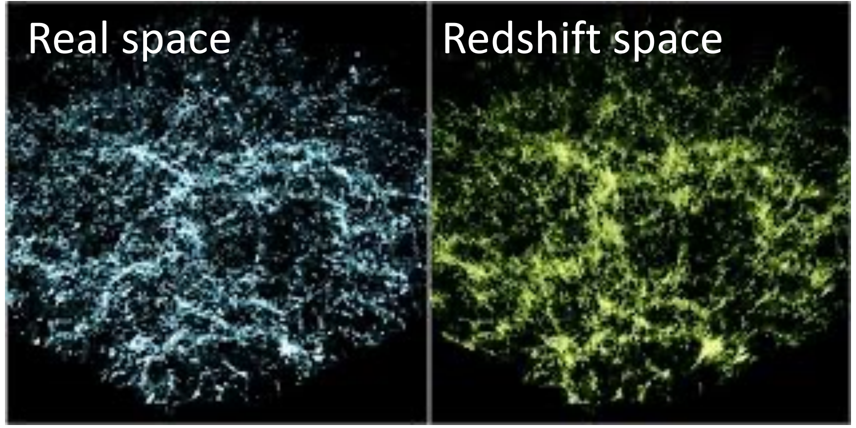


➔ Expansion history

Redshift space distortions



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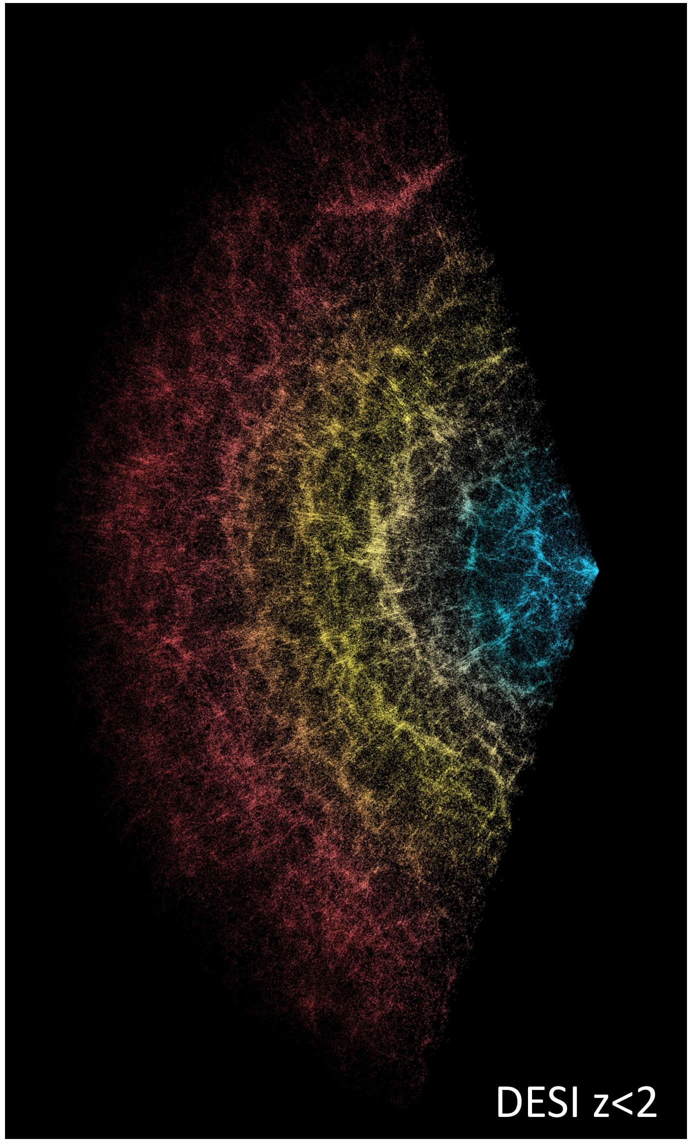

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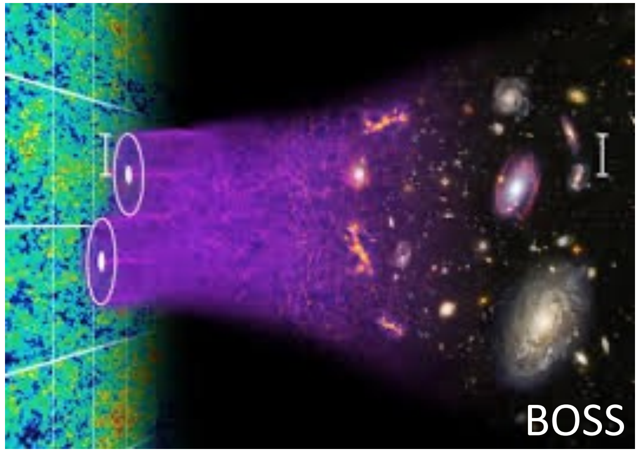
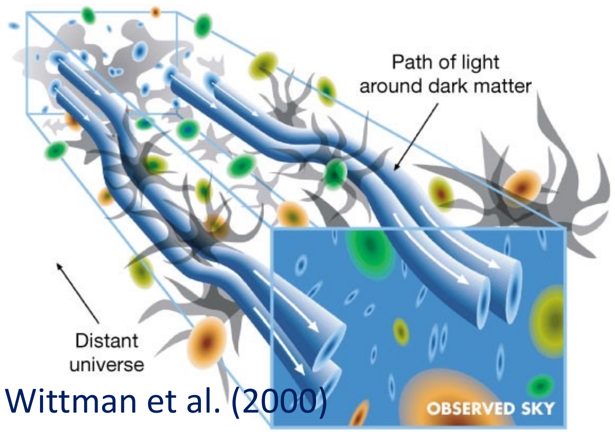
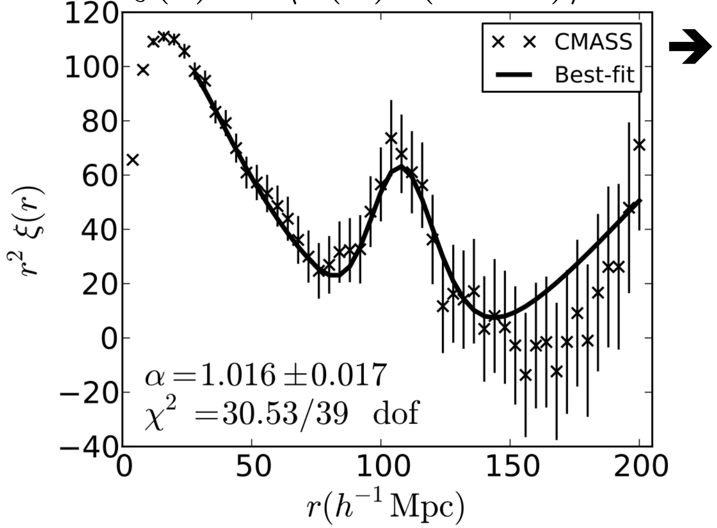


With imaging
Weak gravitational lensing



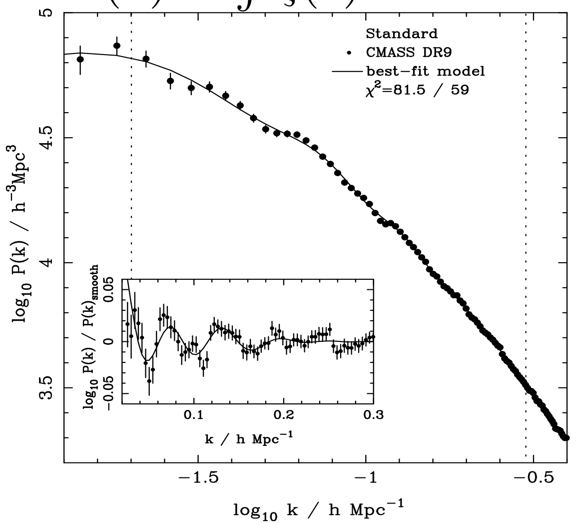
Wittman et al. (2000)

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



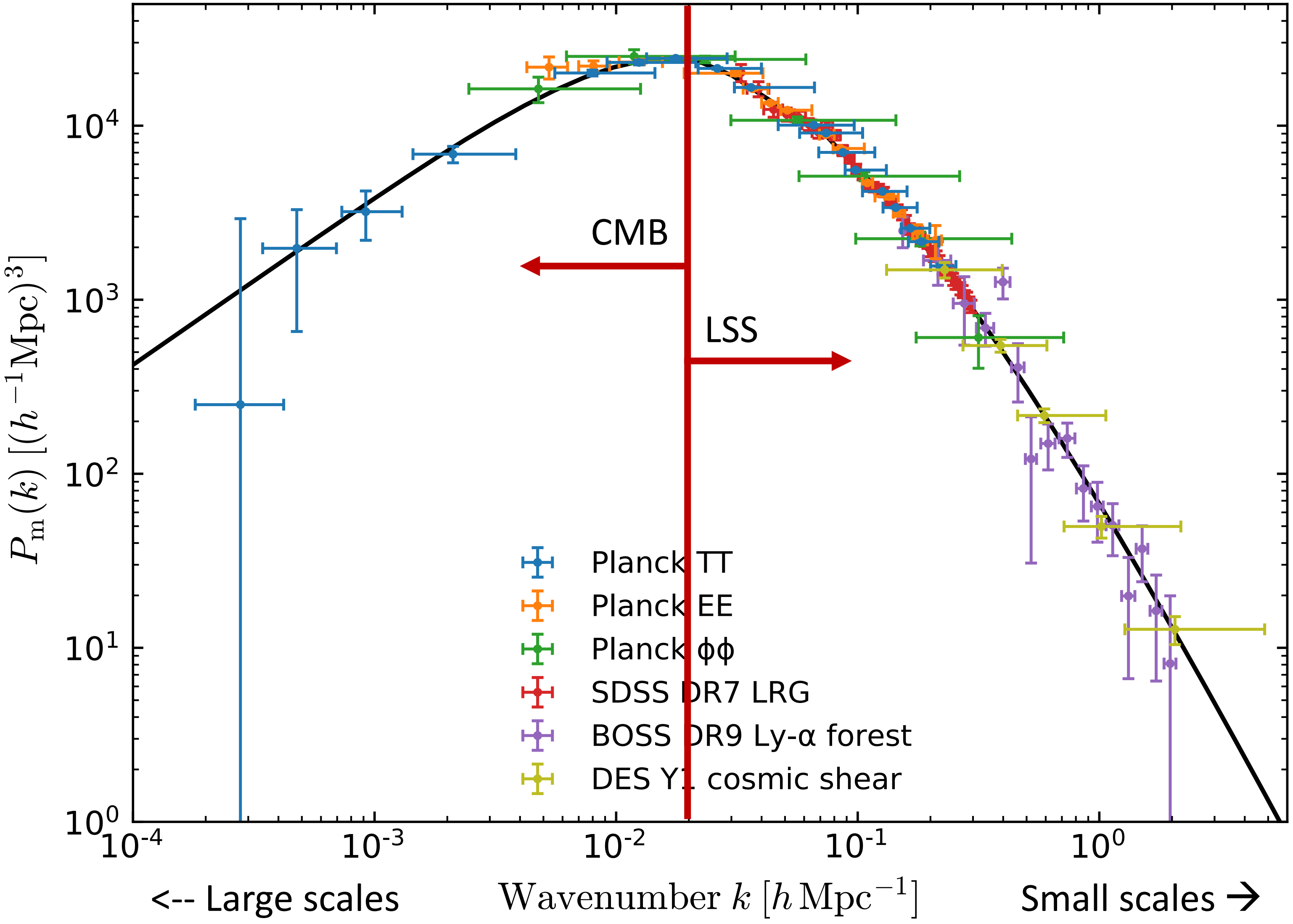
➔ Expansion history

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



➔ Expansion history and growth of structures

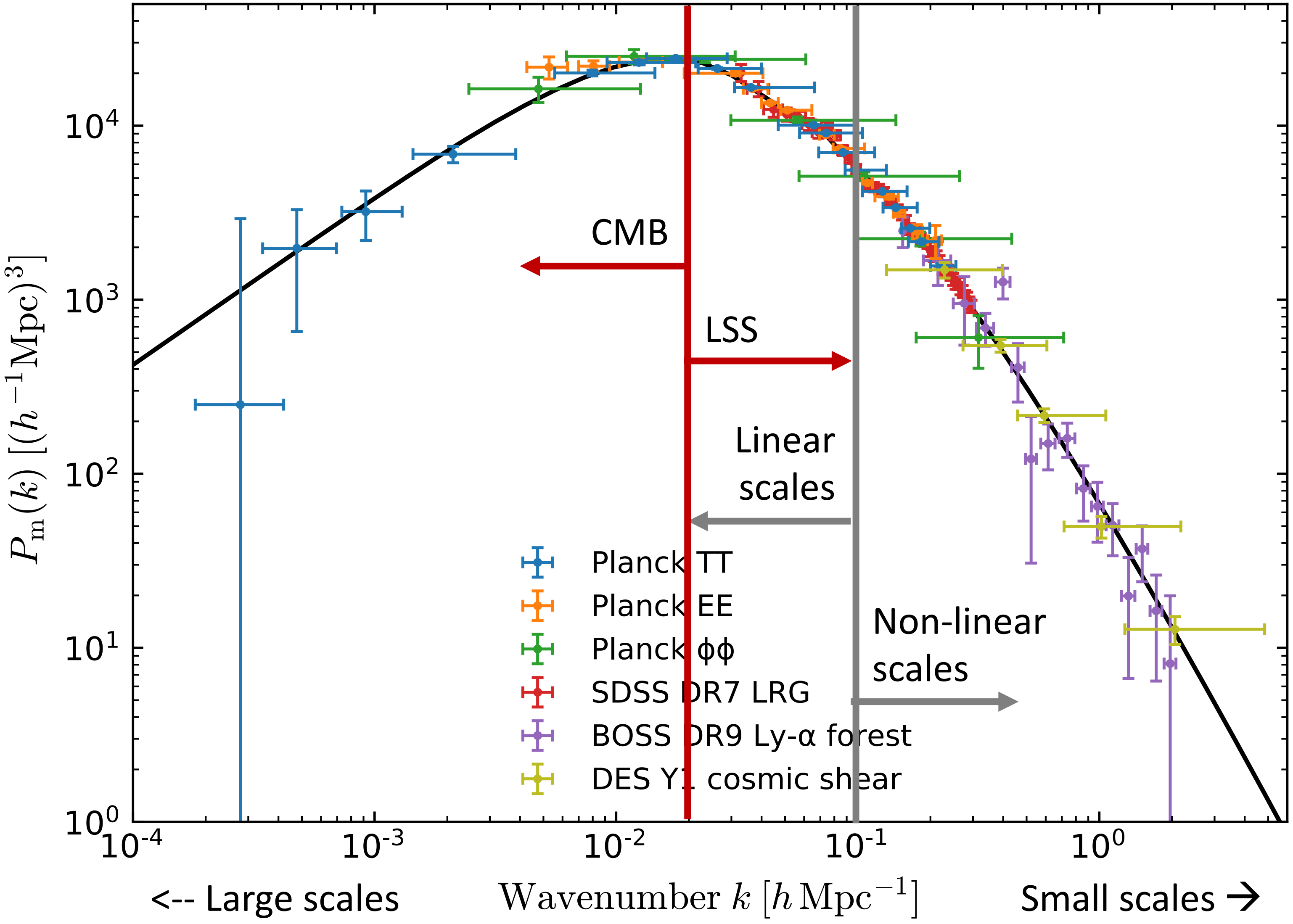
Different observables at different scales



Different observables at different scales

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

CPU time for one model: << 1 sec



<-- Large scales

Small scales →

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

CPU time for one model: ~ khrs-Mhrs

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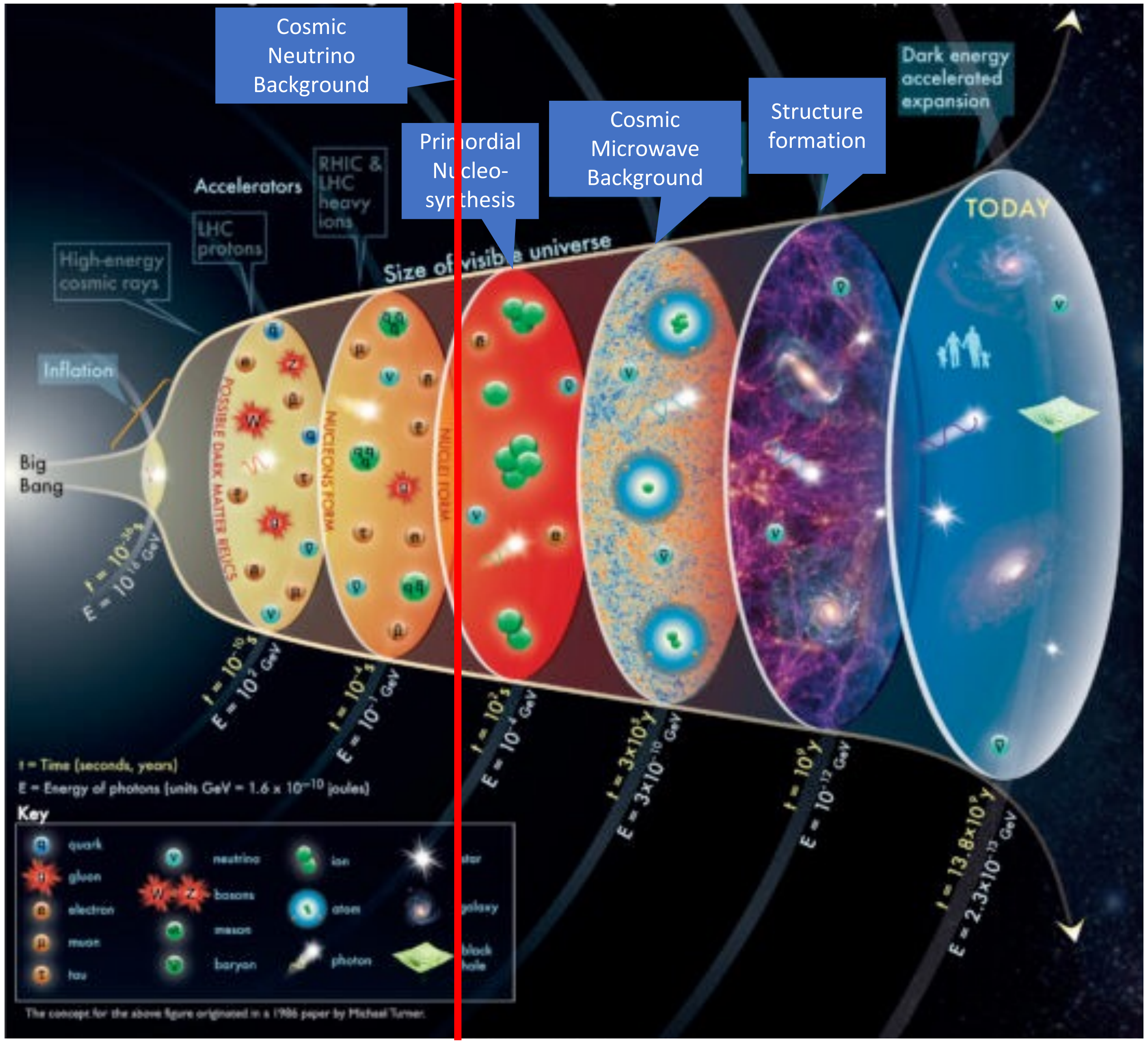

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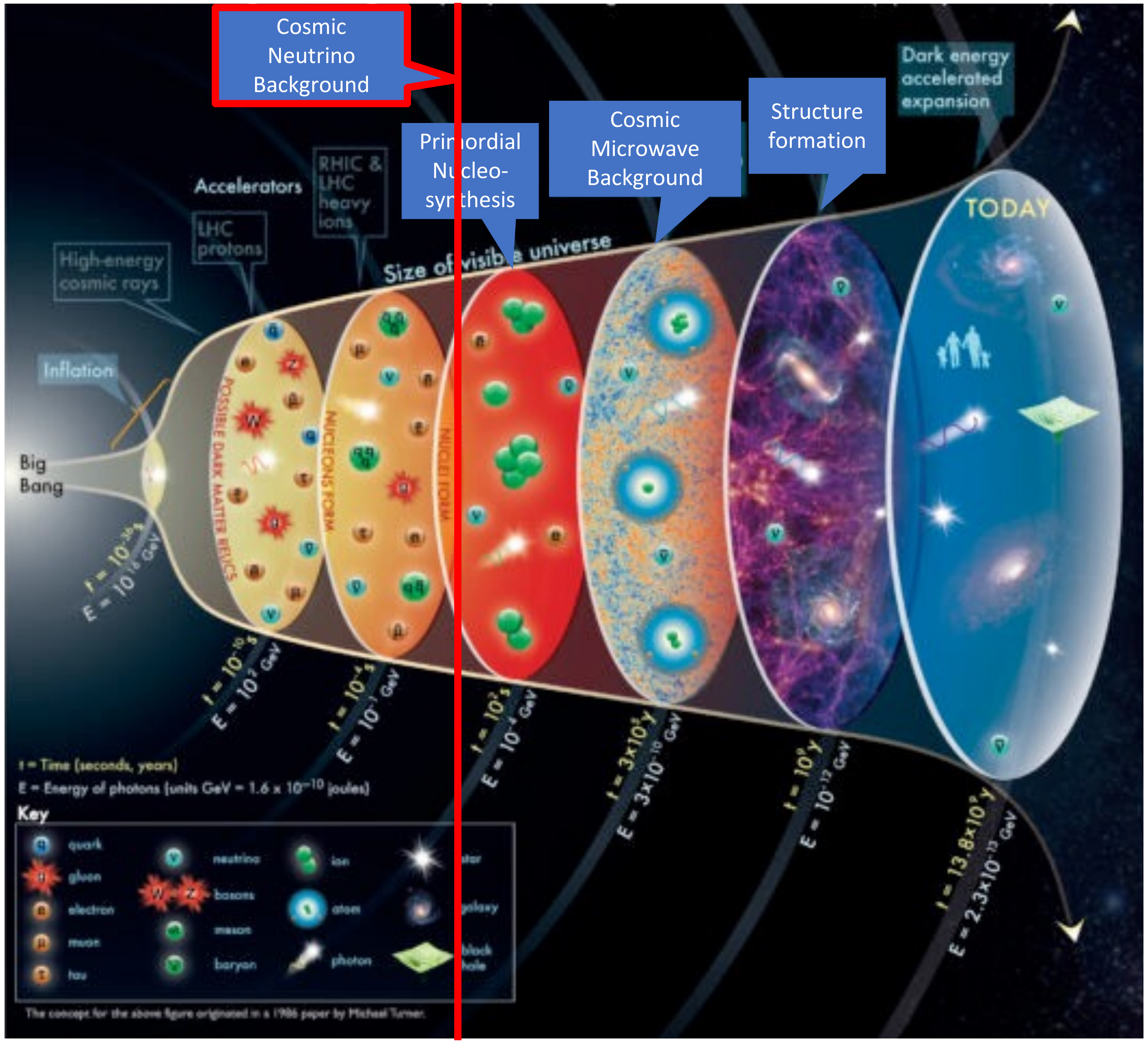

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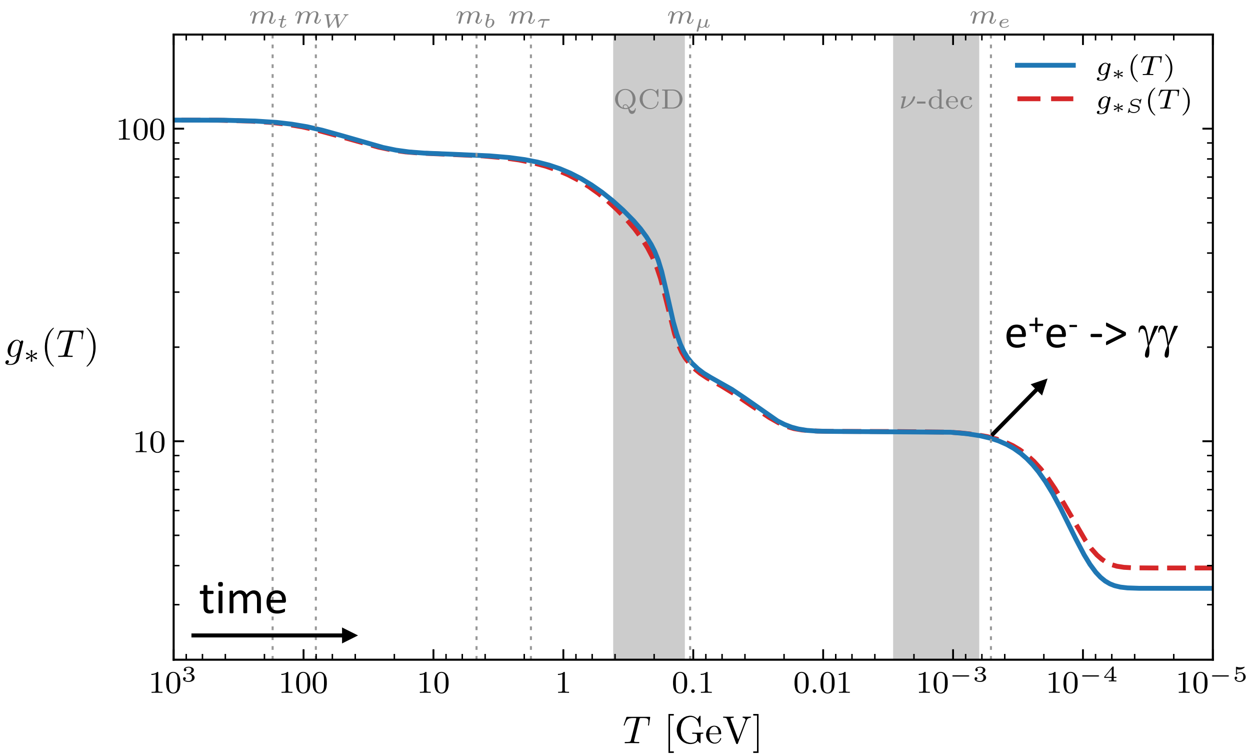
The cosmic neutrino background (CνB)



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

Applying entropy density conservation

$$T_{\mathrm{C}\nu\mathrm{B}} = \left(\frac{4}{11}\right)^{1/3} T_{\gamma,\mathrm{CMB}}$$

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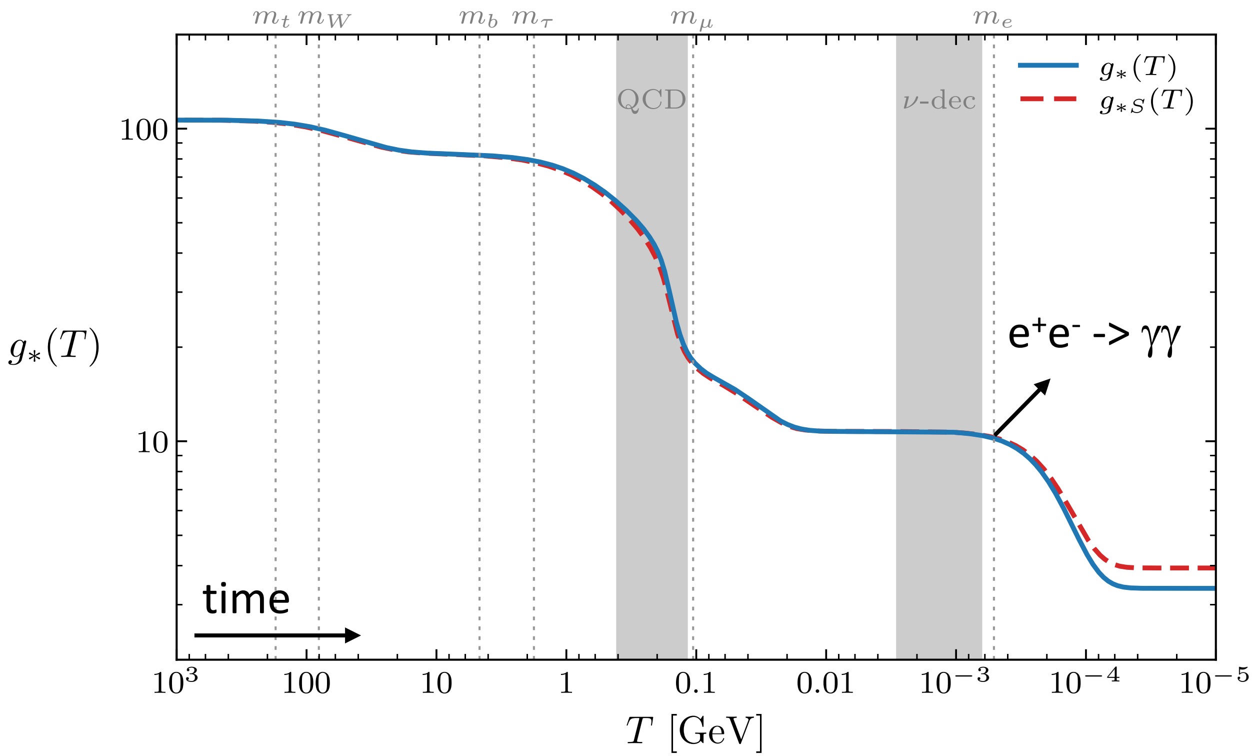

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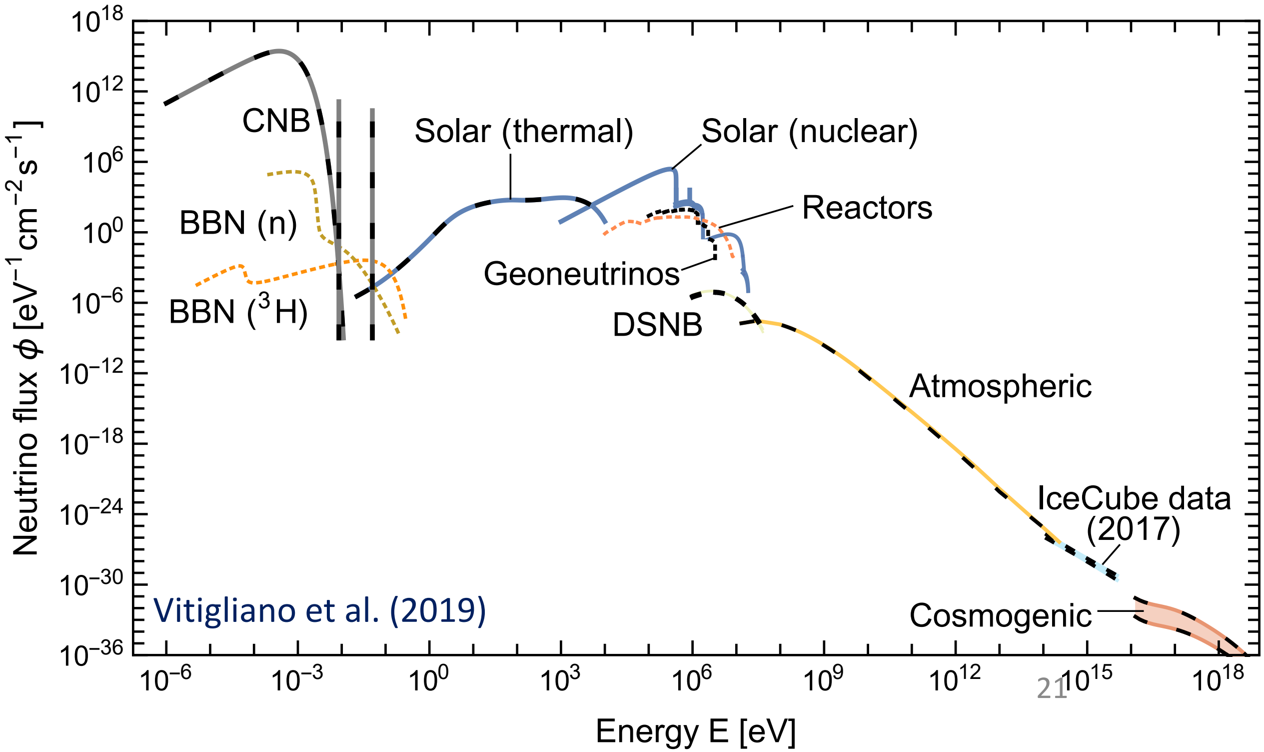
$$T_{\mathrm{C}\nu\mathrm{B}} = \left(\frac{4}{11}\right)^{1/3} T_{\gamma,\mathrm{CMB}}$$

Today:

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

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

- ➔ Direct detection of the CνB not in the near future
- ➔ Footprints of the CνB in CMB and LSS



Vitigliano et al. (2019)

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

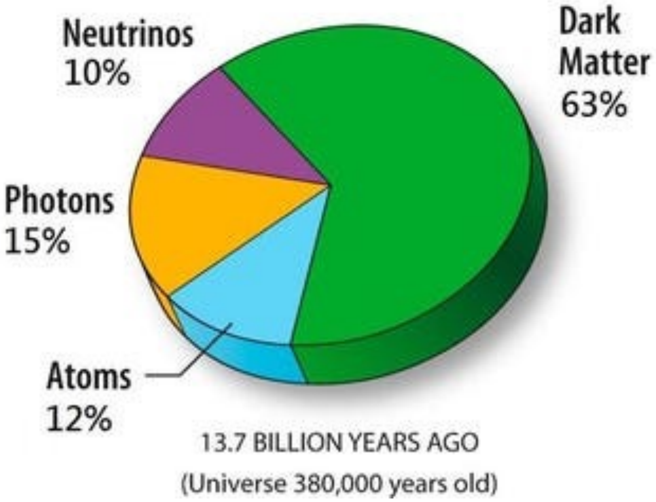
The N_{eff} parameter

The expansion rate of the Universe depends on its ingredients

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

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

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



DR = Dark Radiation, BSM light relics

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

For the 3 neutrino families of the SM

$N_{\mathrm{eff}}^{\mathrm{SM}} = 3.044 \pm 0.001$ [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.

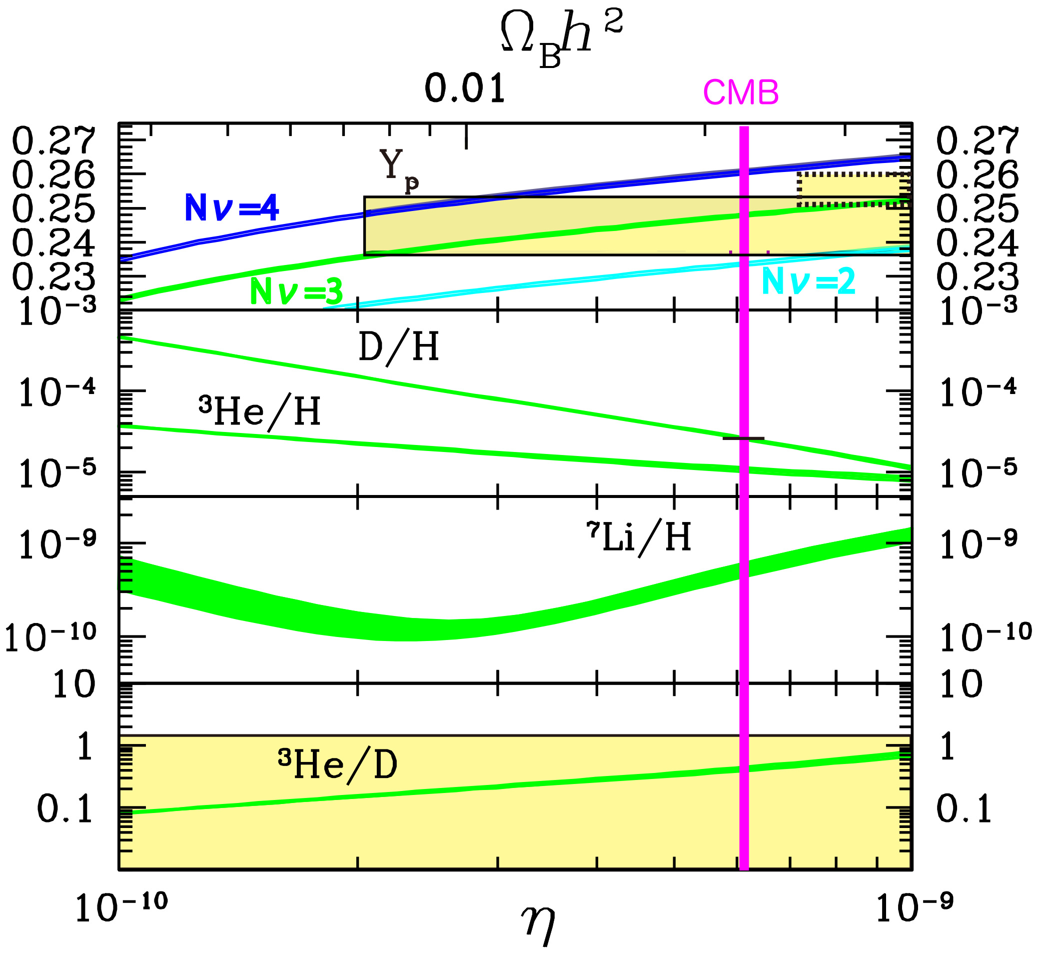
$$H = \Gamma\big|_{T=T_{freeze}} \qquad T_{freeze} \approx 0.6\, g_*^{1/6}\ MeV$$

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

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

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

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



Kawasaki et al. (2018)

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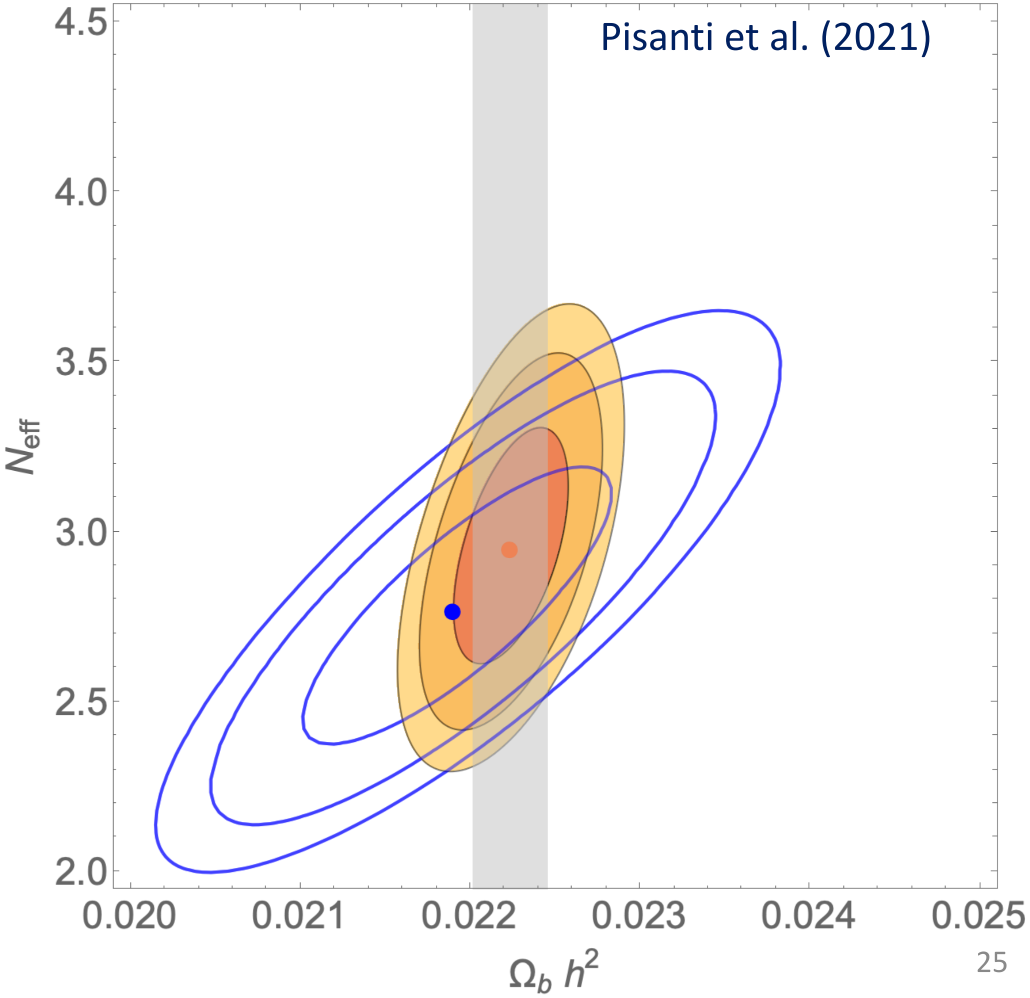
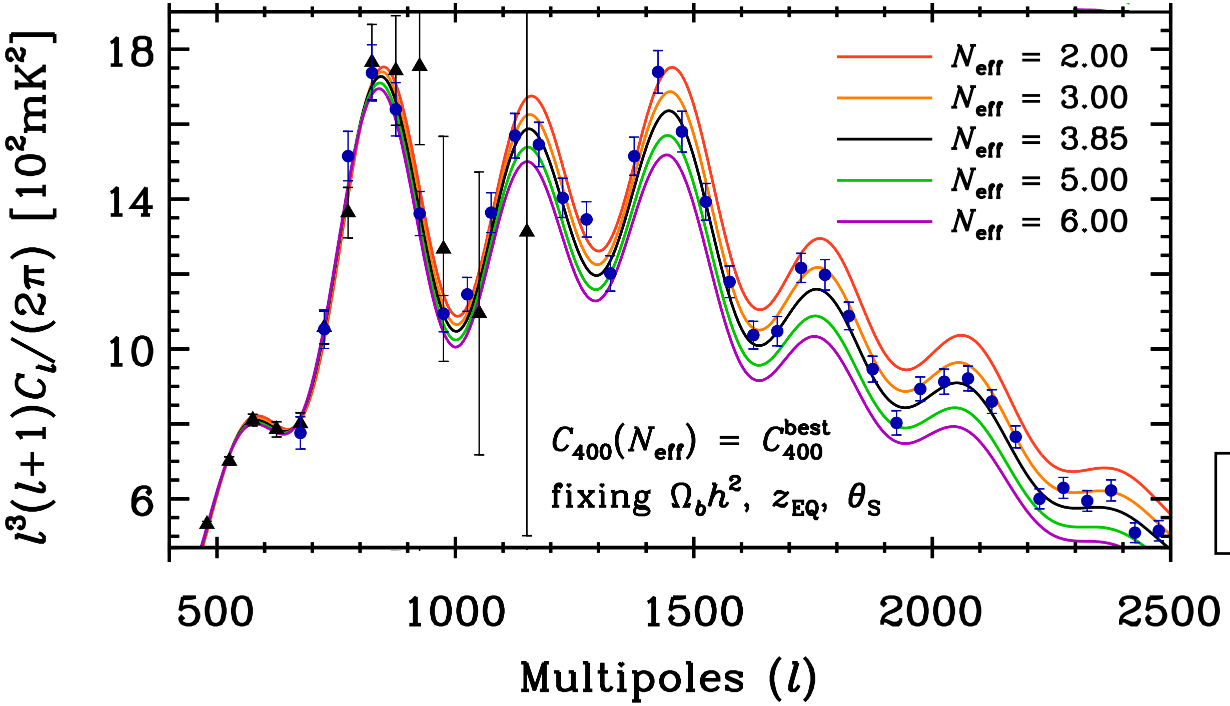
$$\boxed{N_{eff} = 2.78 \pm 0.28\ \ (68\%\ CL)}$$



N_{eff} probes: CMB

Hou et al. (2012)



- Increase of diffusion (Silk) damping al large *l*

$$\theta_{\rm d} \propto \theta_{\rm s}\, H^{0.5}$$

Planck TTTEEE

$N_{\text{eff}} = 2.92 \pm 0.36$ (95% CL)

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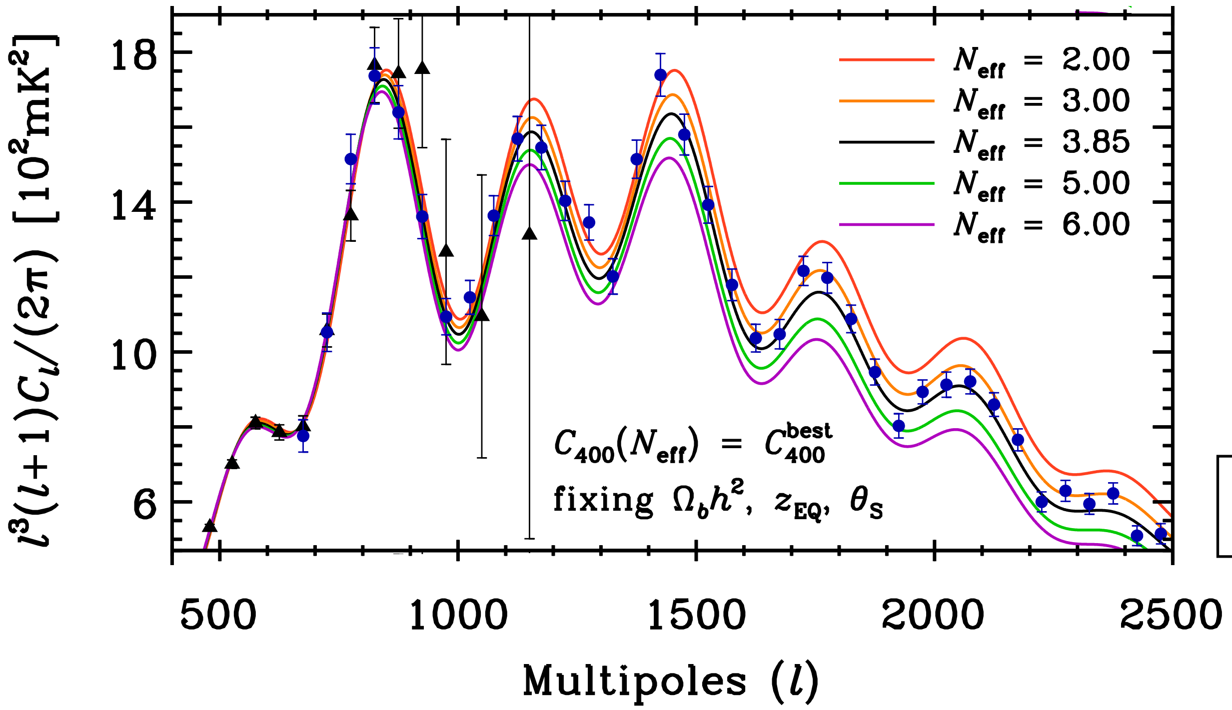

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Planck TTTEEE

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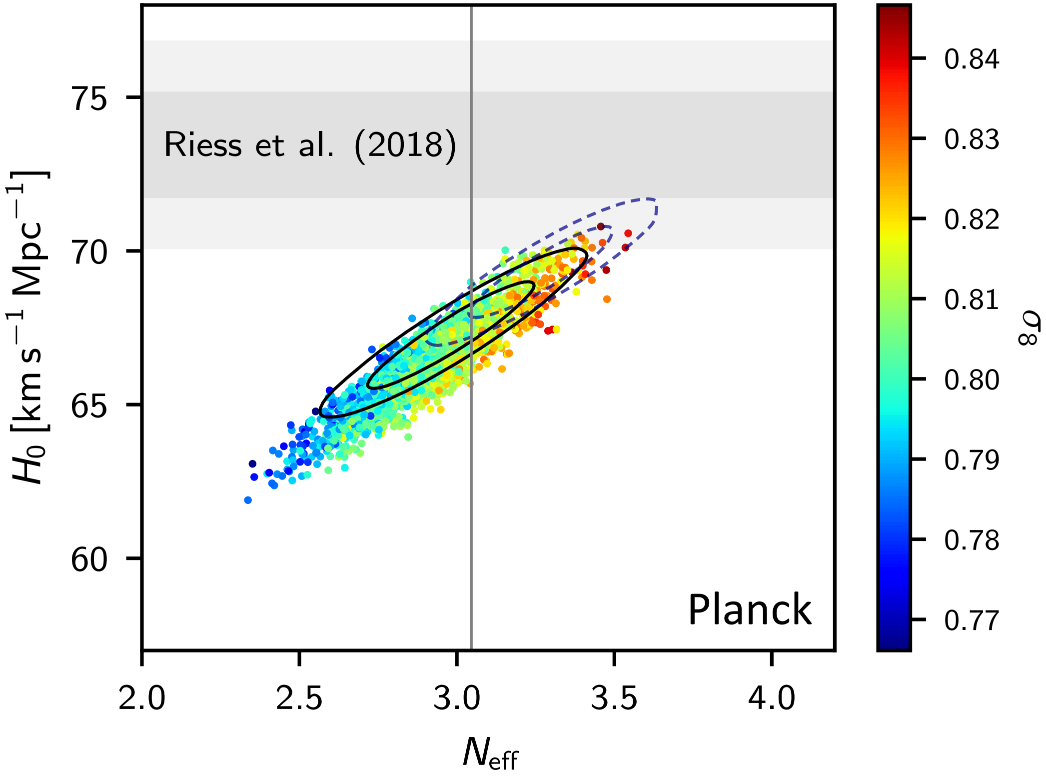
- Phase shift of the CMB acoustic peaks*

* The angular size of the sound horizon at CMB (θ_s) can be adjusted by increasing H_0

N_{eff} probes: CMB



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)]

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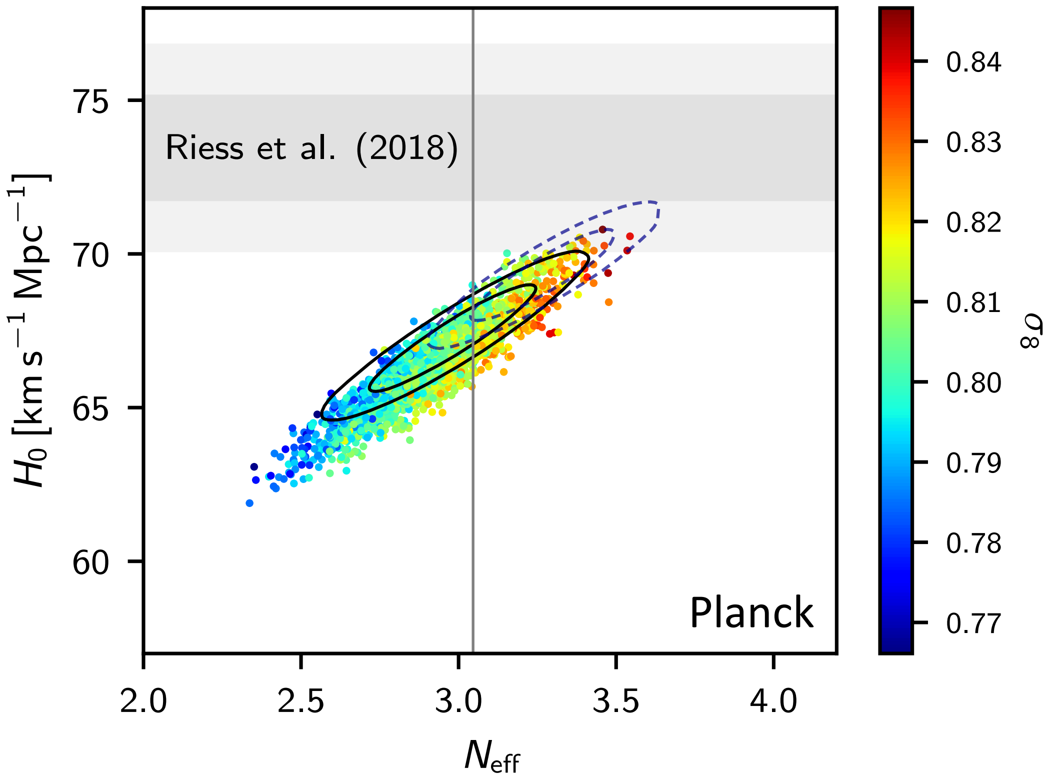

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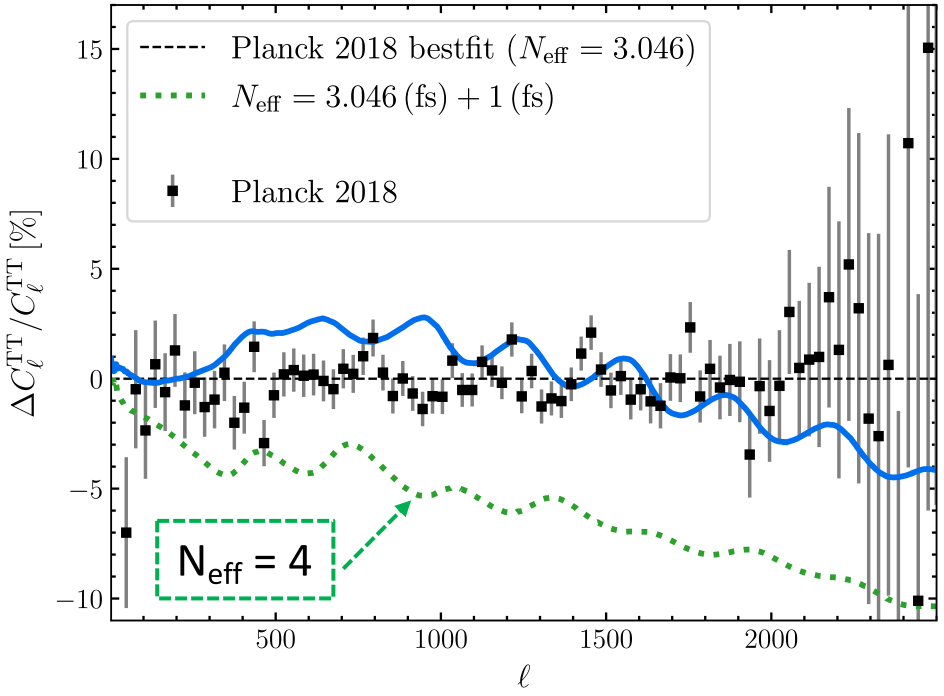
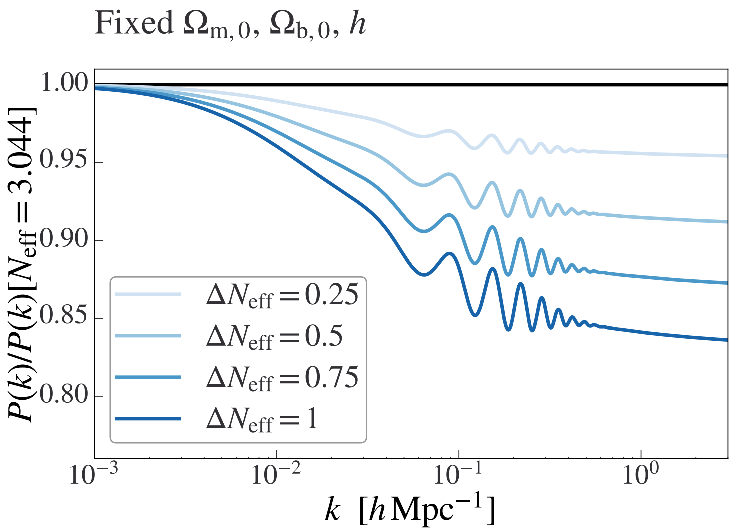
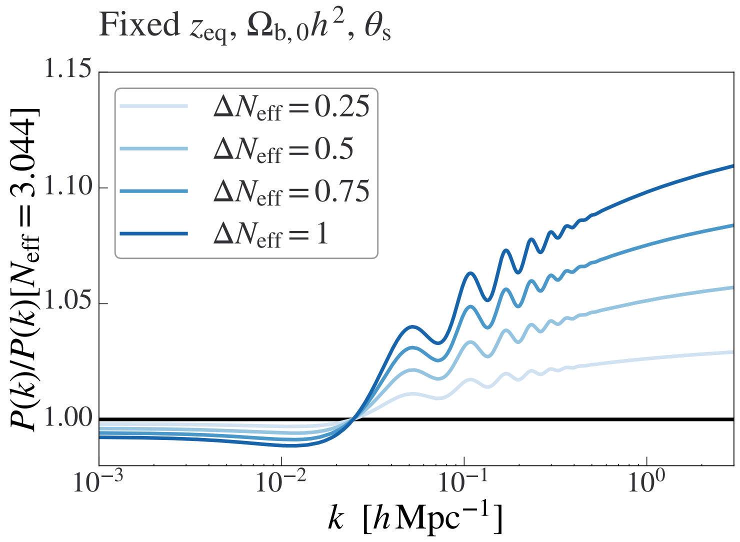
N_{eff} = 4 provides a bad fit of Planck data →



N_{eff} probes: LSS





- Phase shift of the BAO

CMB (Planck + ACT)

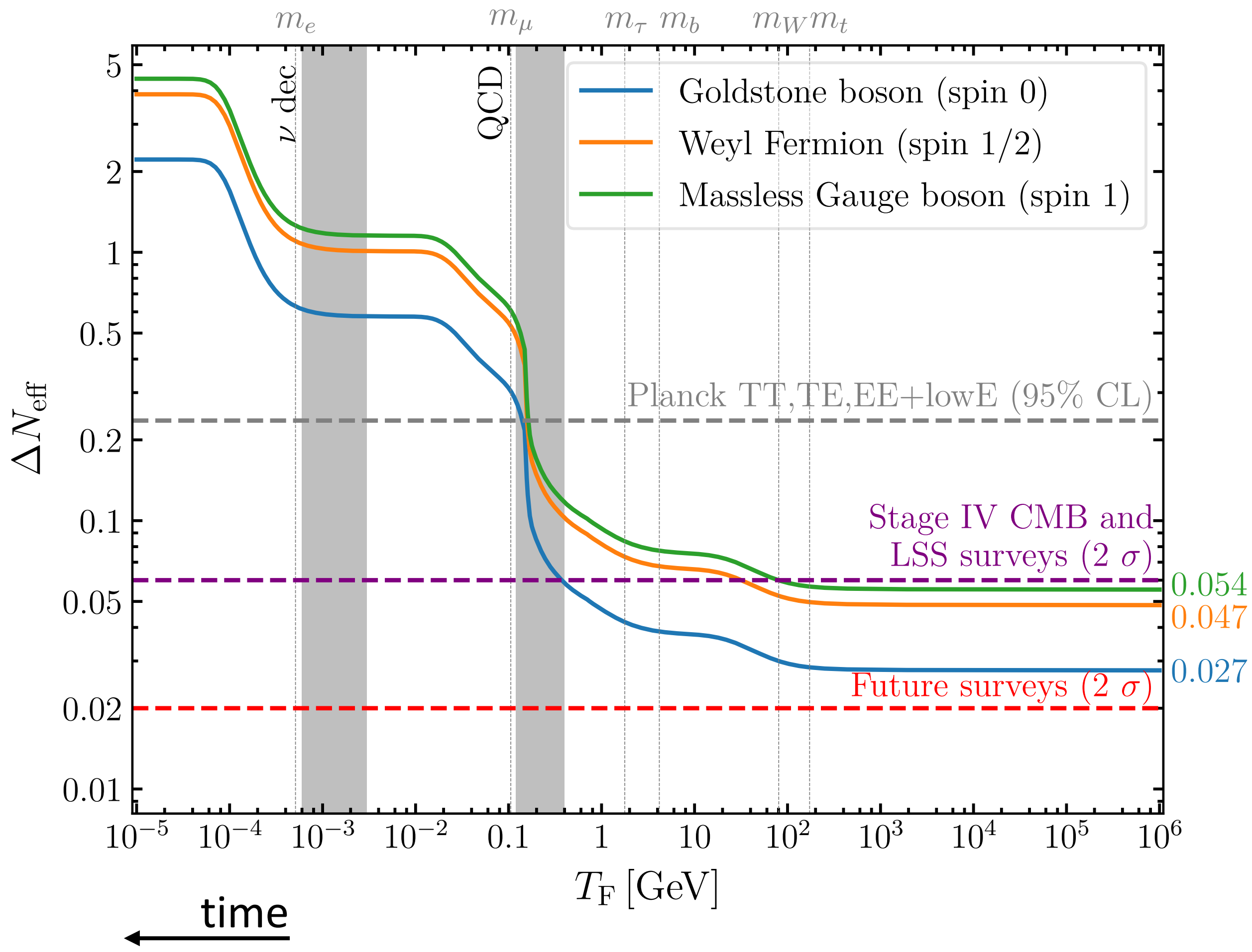
$N_{eff} = 2.98 \pm 0.20$ (95% CL)

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

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

$\Delta N_{\rm eff}$: other light relics (if any)

$$\Delta N_{\rm eff} = \frac{\rho_{\rm DR}}{\rho_\nu} \propto \left(\frac{T_{\rm DR}}{T_\nu}\right)^4$$



N_{eff}: conclusions

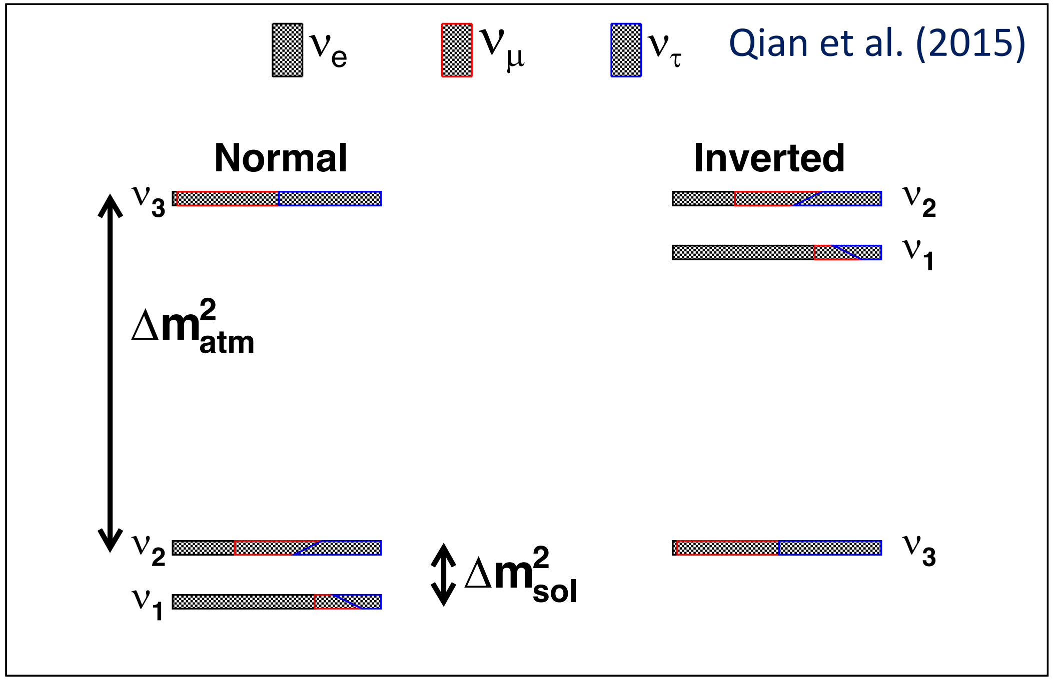
- Cosmology provides an indirect detection of the CνB
- Cosmology at different epochs and at different scales is consistent with Standard Model prediction $N_{eff}^{SM} = 3.044$
- Future CMB and LSS surveys can exclude the existence of new light particles decoupling before the onset of QCD phase transition for any spin.

Detecting the neutrino mass in the CνB

Neutrinos from the lab

Neutrino oscillations

Neutrino Mass Hierarchy



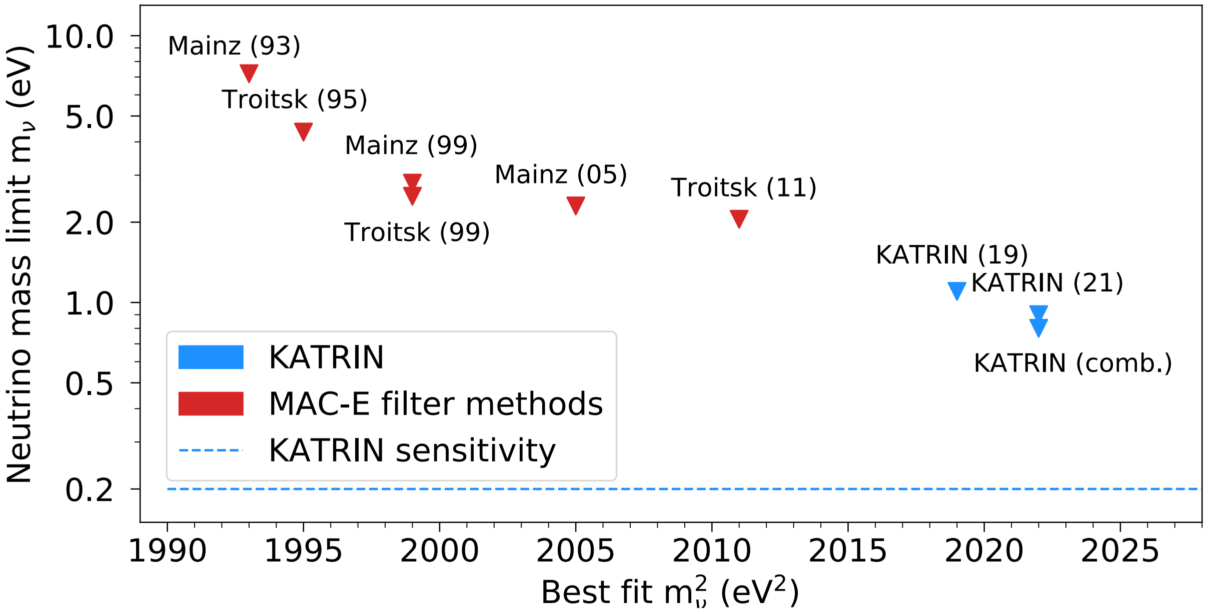
Min. Σm_ν (NH) = 0.058 eV; Min. Σm_ν (IH)= 0.100 eV

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

Lectures by Di Lodovico, Lisi, Maricic, Petcov

Neutrino β-decay

(Neutrinoless ββ-decay only if neutrinos are Majorana)



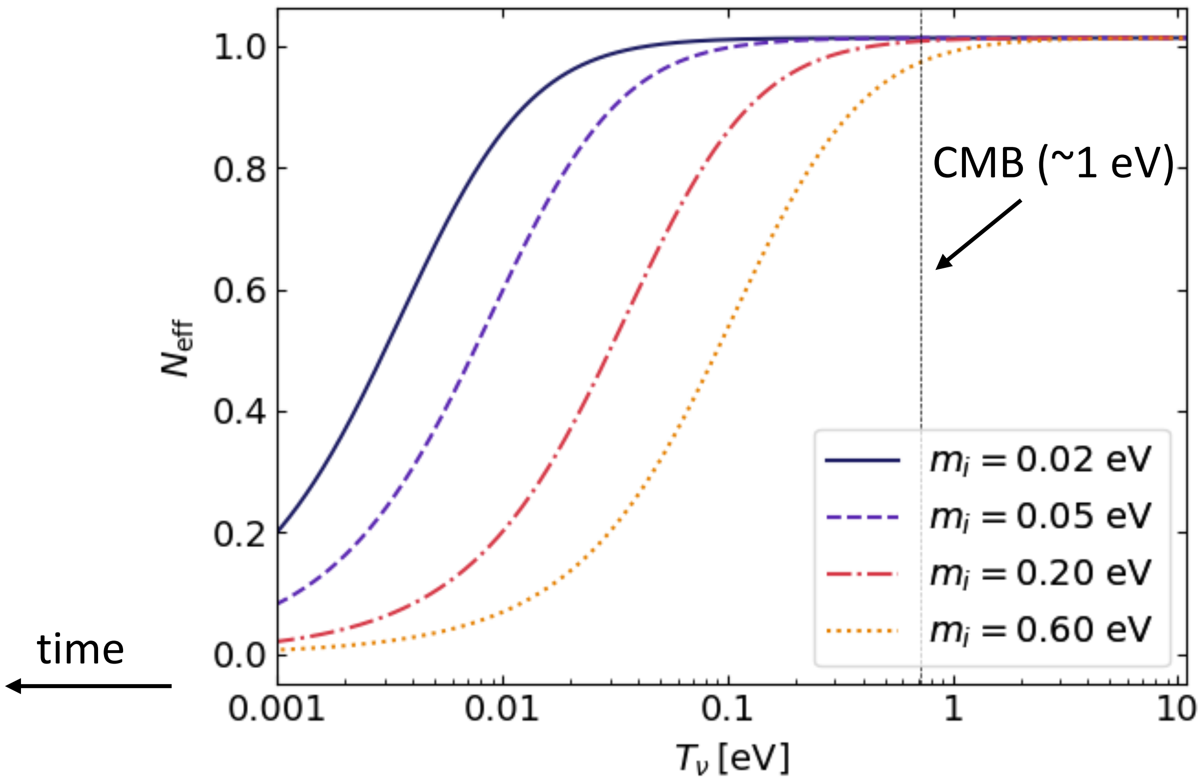
$m_\beta^2 = \Sigma_i |U_{ei}|^2 m_i^2 < 0.8$ eV (90% CL)

[Aker et al. (2022)]

Sensitivity: 200 meV (90% CL)

Colloquium by Kathrin Valerius

The duality of the CνB



Early times: neutrinos as **radiation**

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

Neutrino non-relativistic transition

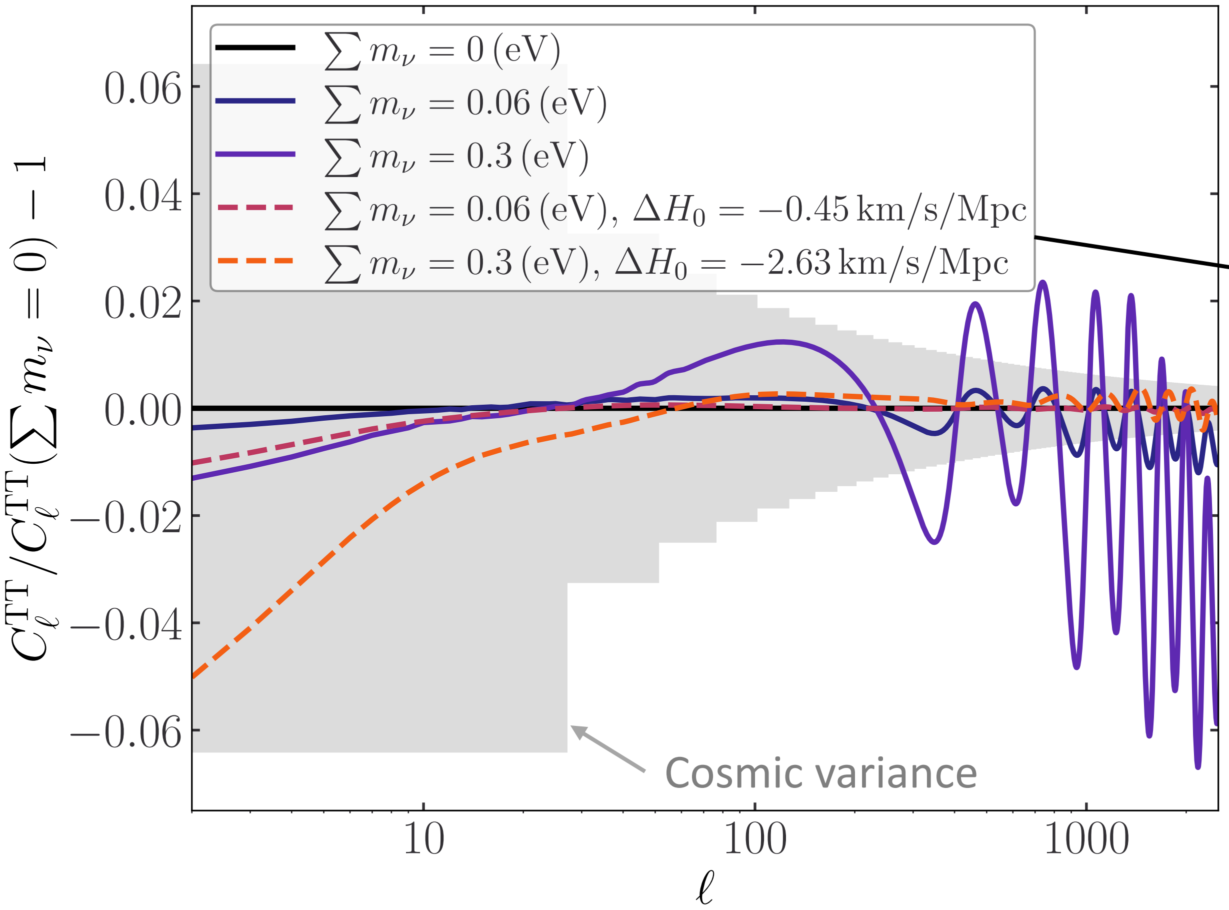
$$z_{{\rm nr},i} = 2 \times 10^3 \left(\frac{m_{\nu,i}}{1\,{\rm eV}}\right)$$

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

- Neutrino mass $\Omega_\nu h^2 = \dfrac{\sum m_{\nu,i}}{93.12{\rm eV}}$ [Mangano et al. 2005, Froustey et al. 2020]

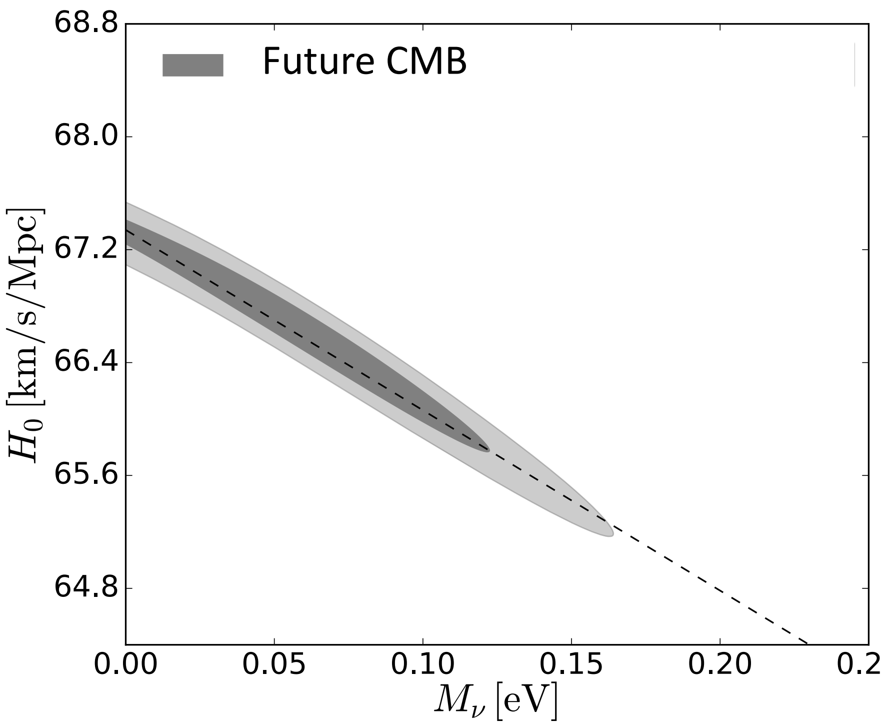
  not individual masses

Neutrino mass probes: CMB

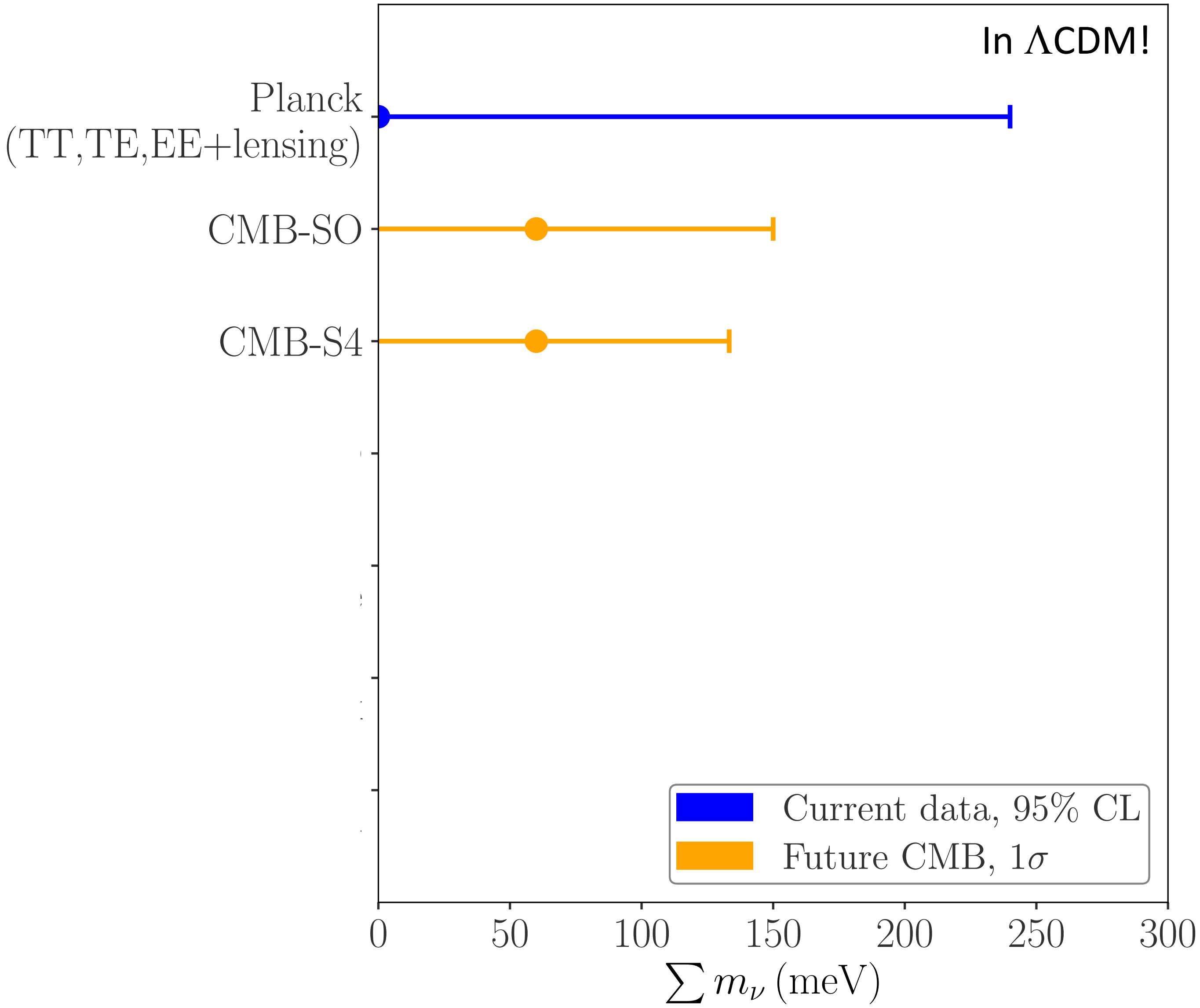


- Background effects
- Perturbation effects

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



Neutrino mass constraints: CMB



KATRIN: Σm_ν <~ 2.7 eV

Fiducial value:

- Σm_ν = 58 meV

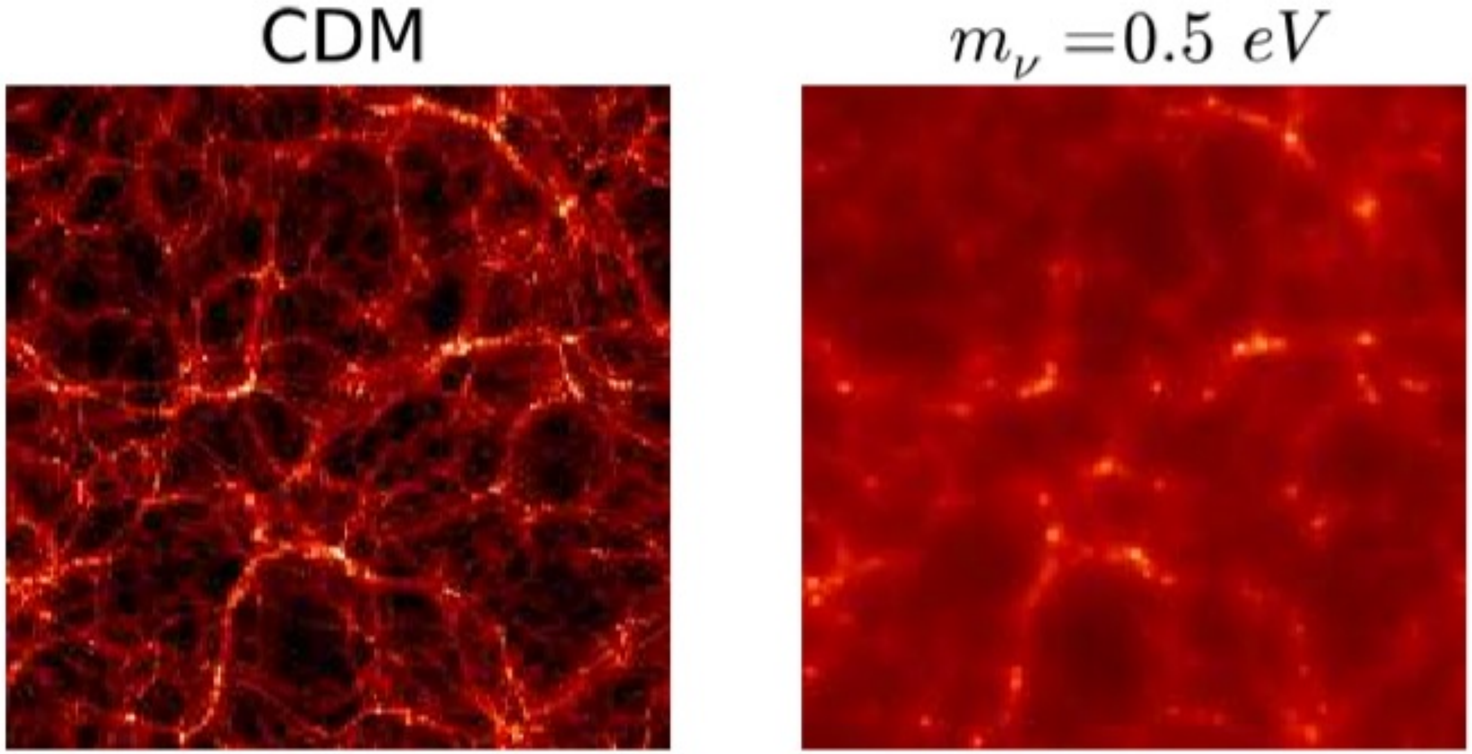
Minimum from neutrino oscillation experiments

CMB alone will not be able to detect the neutrino mass

→ Large Scale Structures

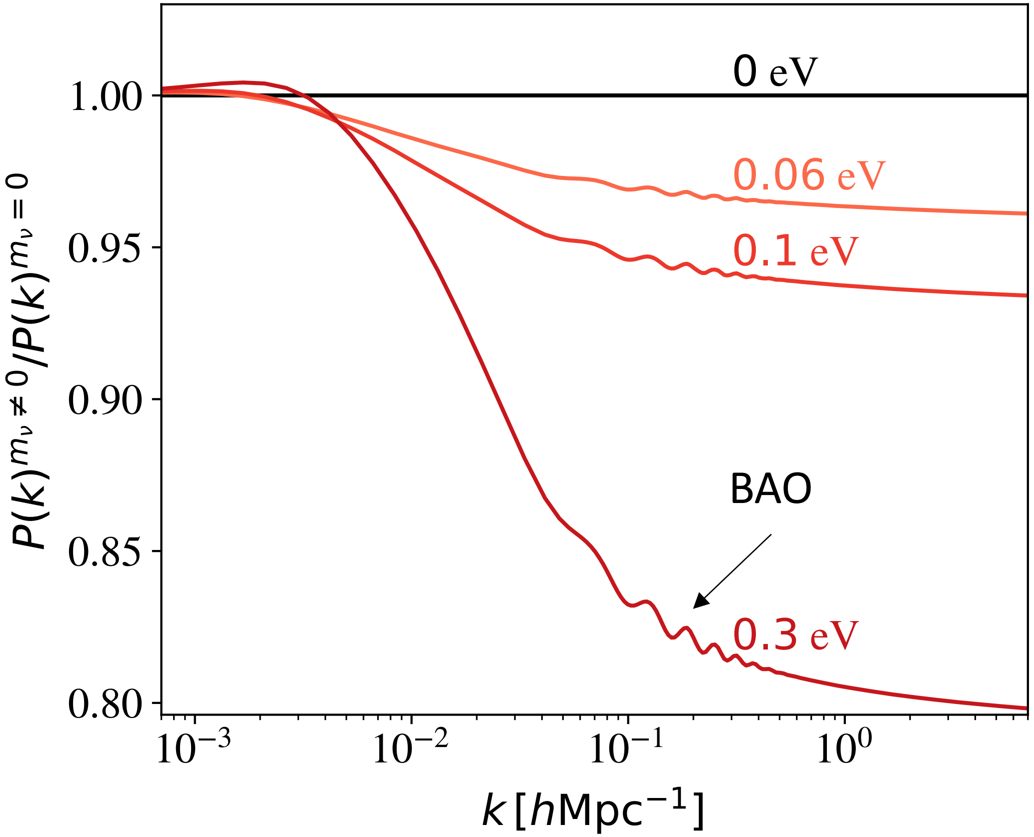
Neutrino mass probes: LSS

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



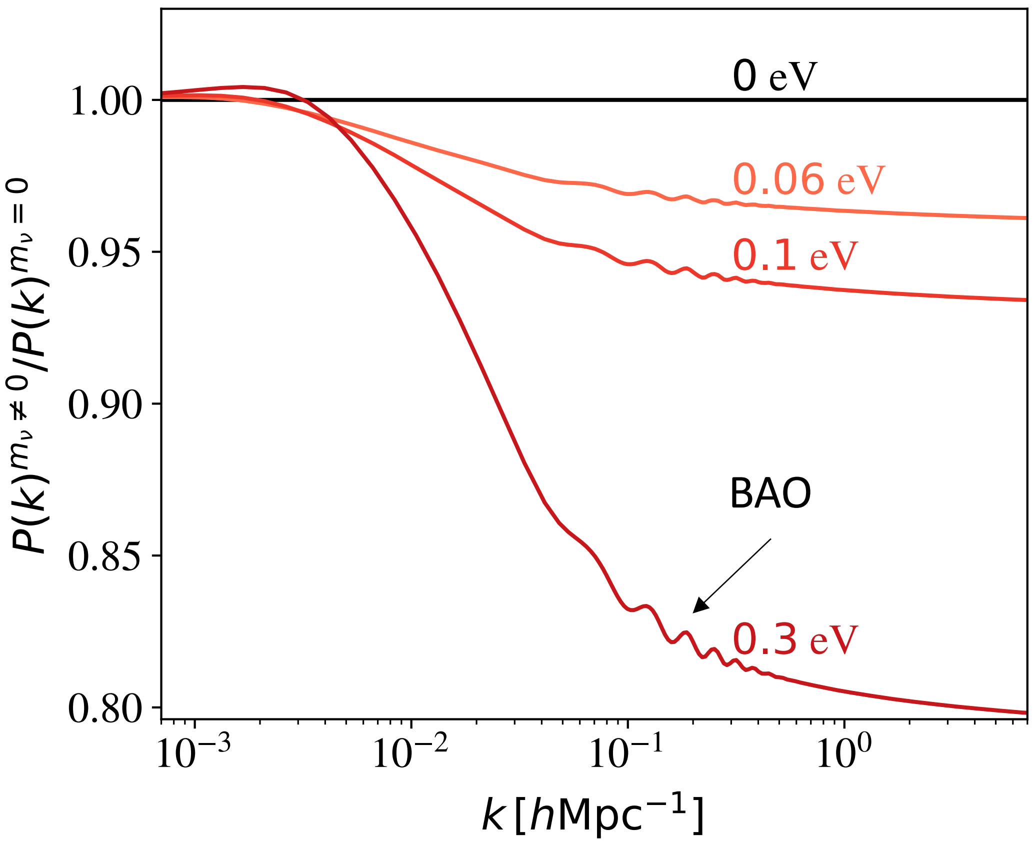
Villaescusa Navarro et al. (2013)

Neutrino mass probes: LSS



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

Neutrino mass probes: LSS



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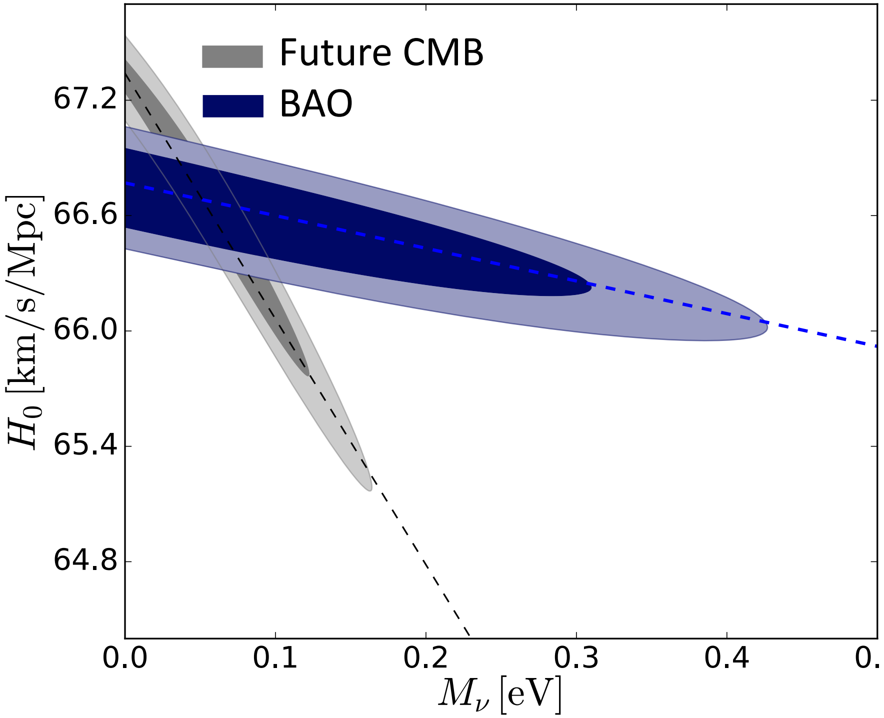
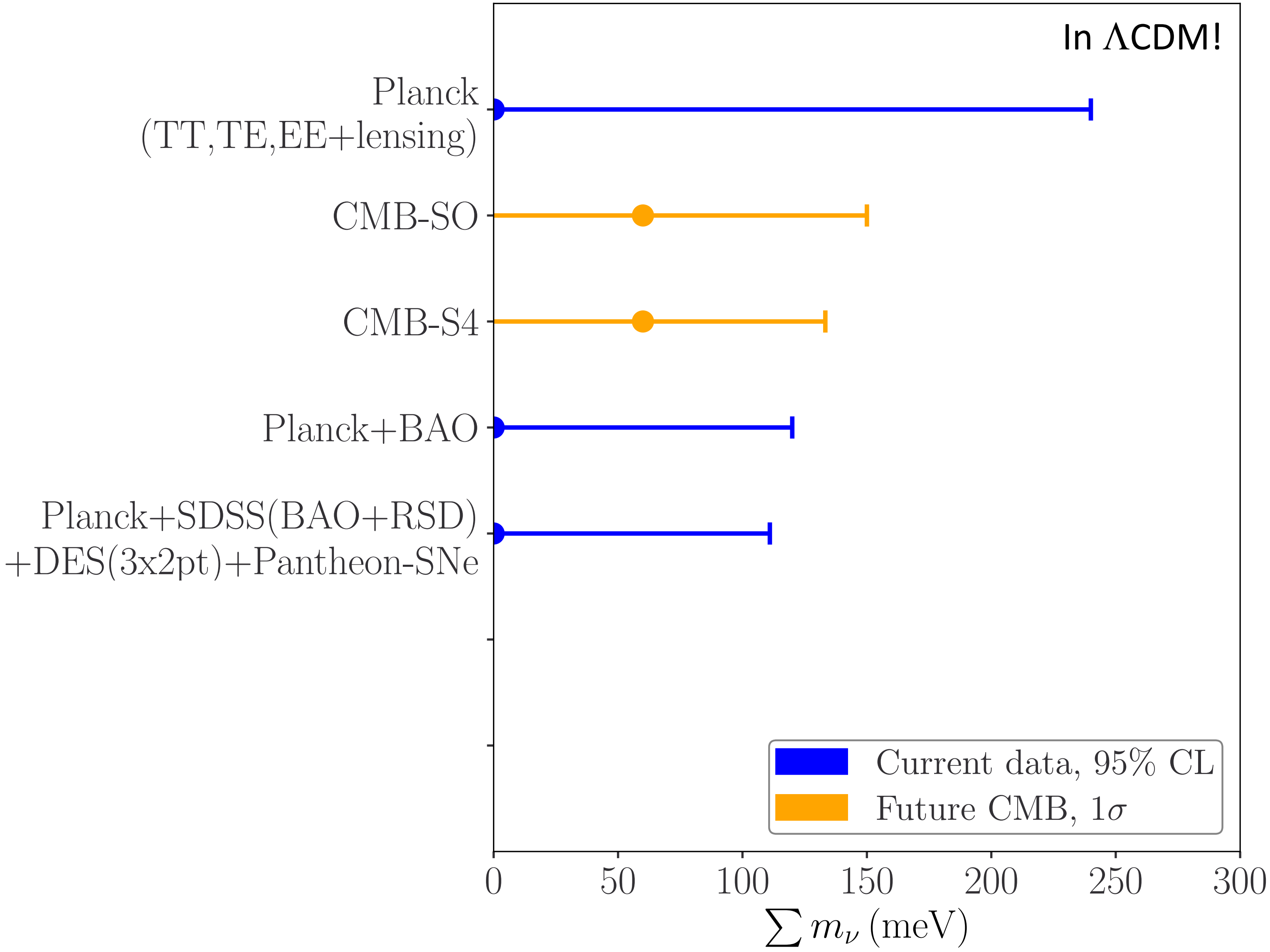
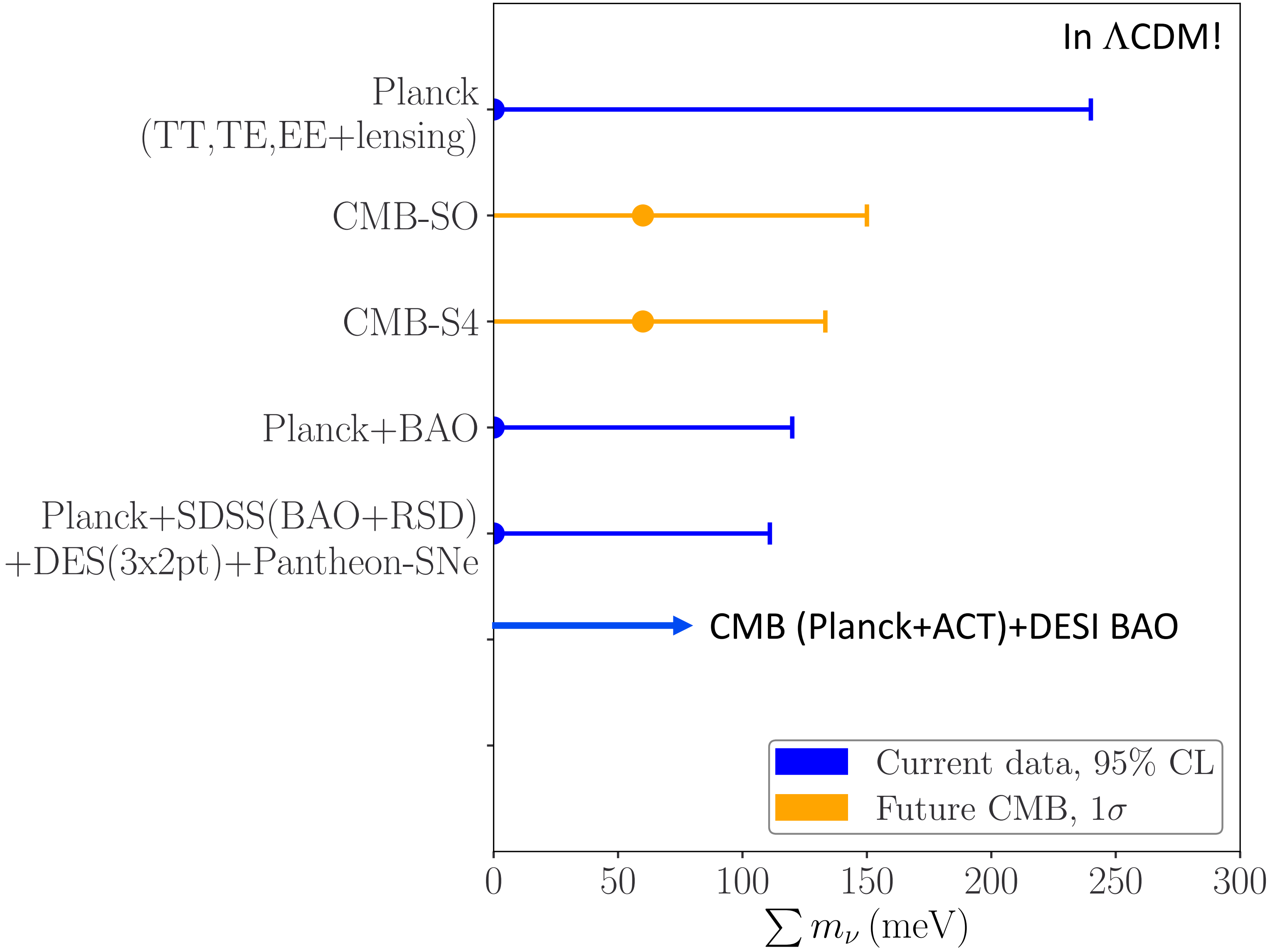


Neutrino mass constraints: LSS



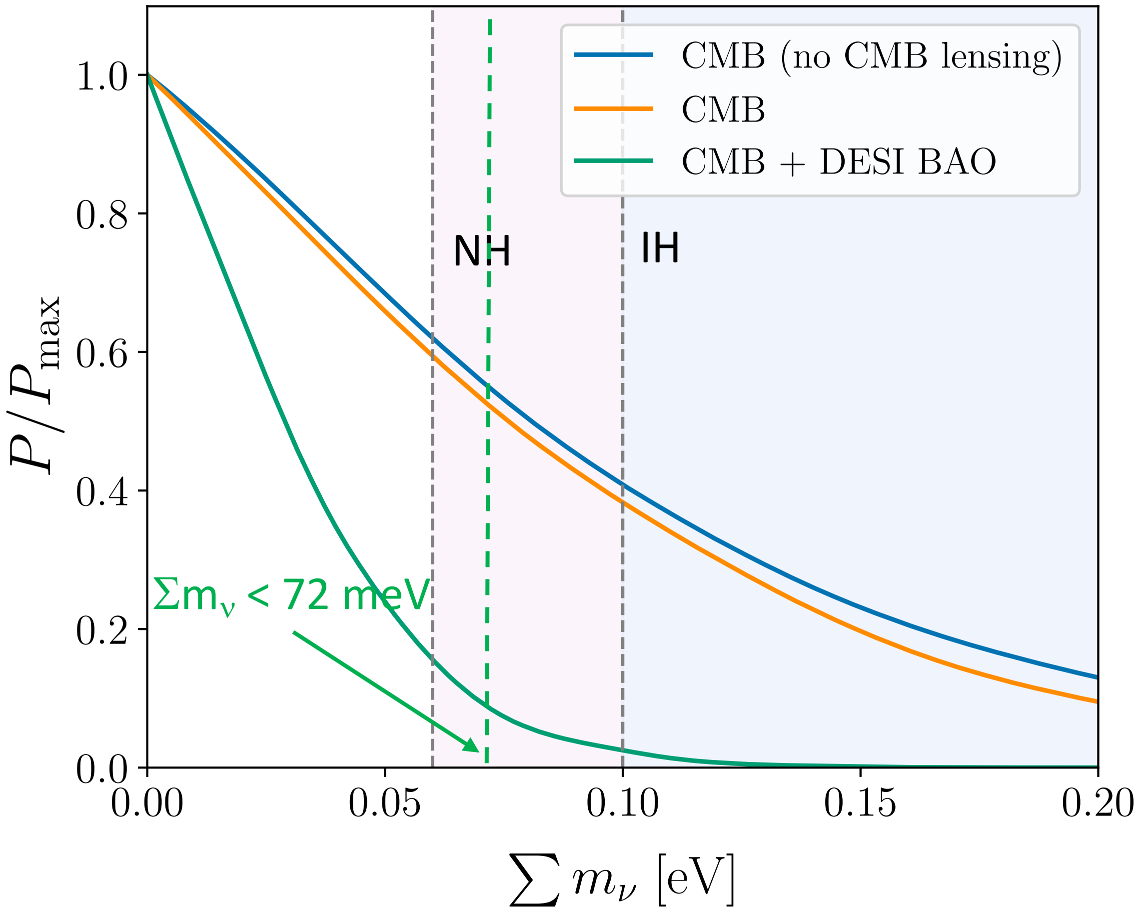
Neutrino mass constraints: LSS



In ΛCDM!

CMB (Planck+ACT)+DESI BAO

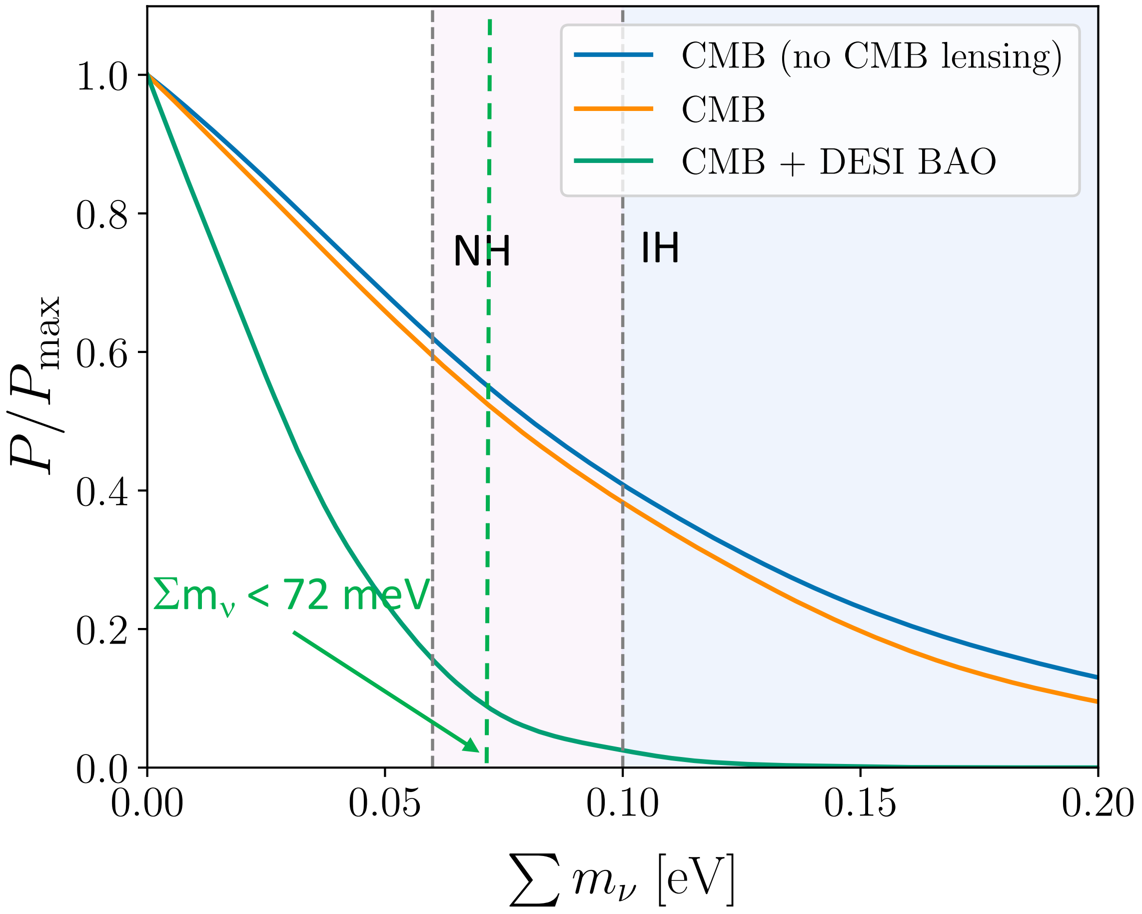
Neutrino mass constraints: DESI



DESI Collaboration: Adame et al. (2024)

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

Neutrino mass constraints: DESI



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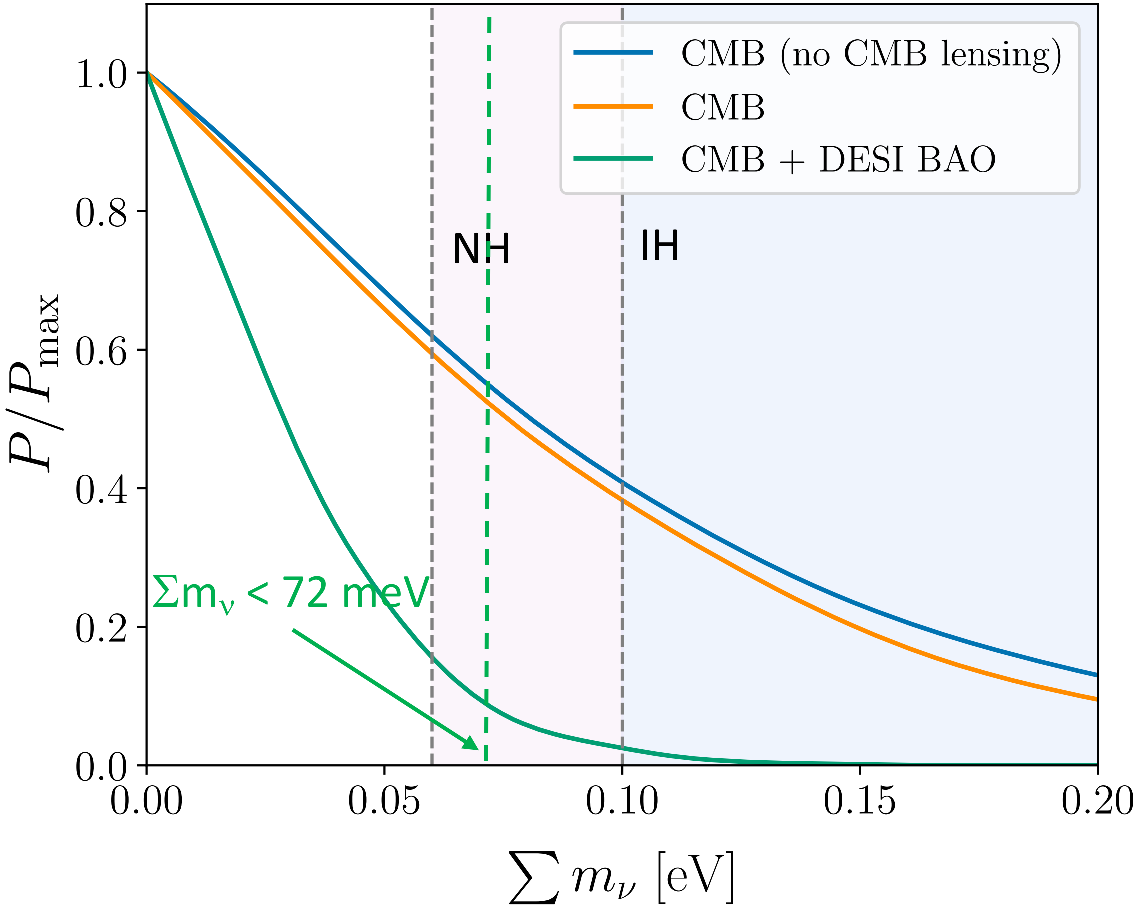
CMB (Planck+ACT) + DESI BAO: $\Sigma m_\nu < 72$ meV, 95% CL

Prior: $\Sigma m_\nu > 0$

Prior: $\Sigma m_\nu > 59$ meV -> $\Sigma m_\nu < 113$ meV, 95% CL

Neutrino mass constraints: DESI



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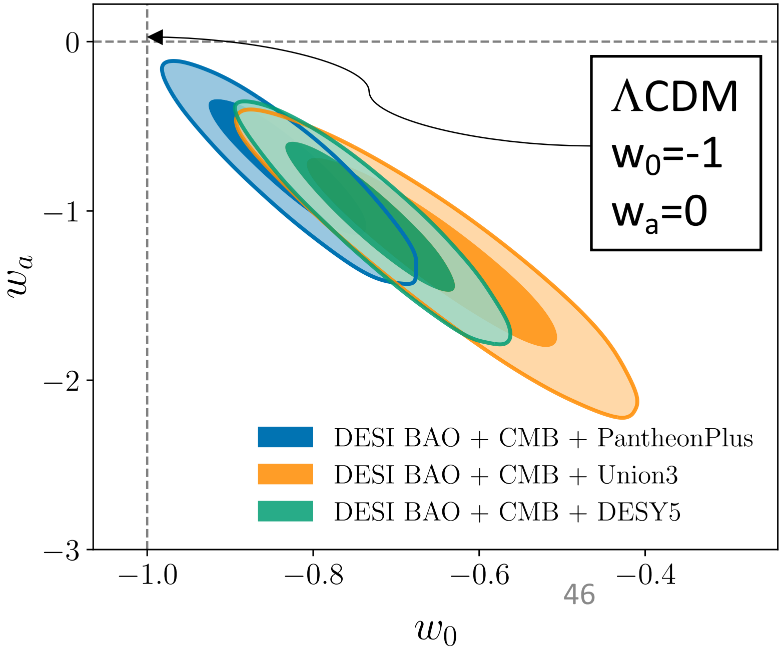
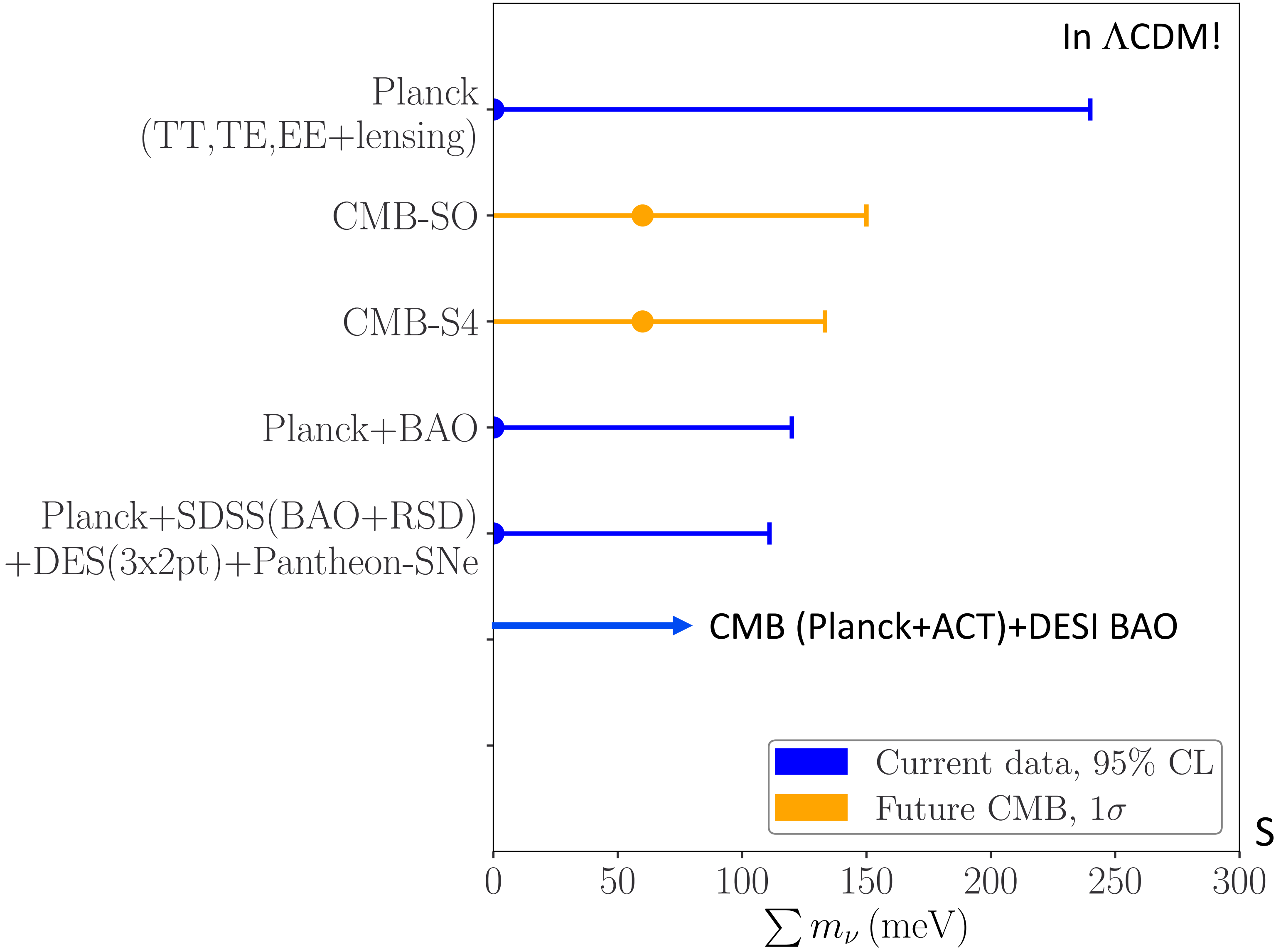
In ΛCDM!

In w0waCDM:

$\Sigma m_\nu < 195$ meV

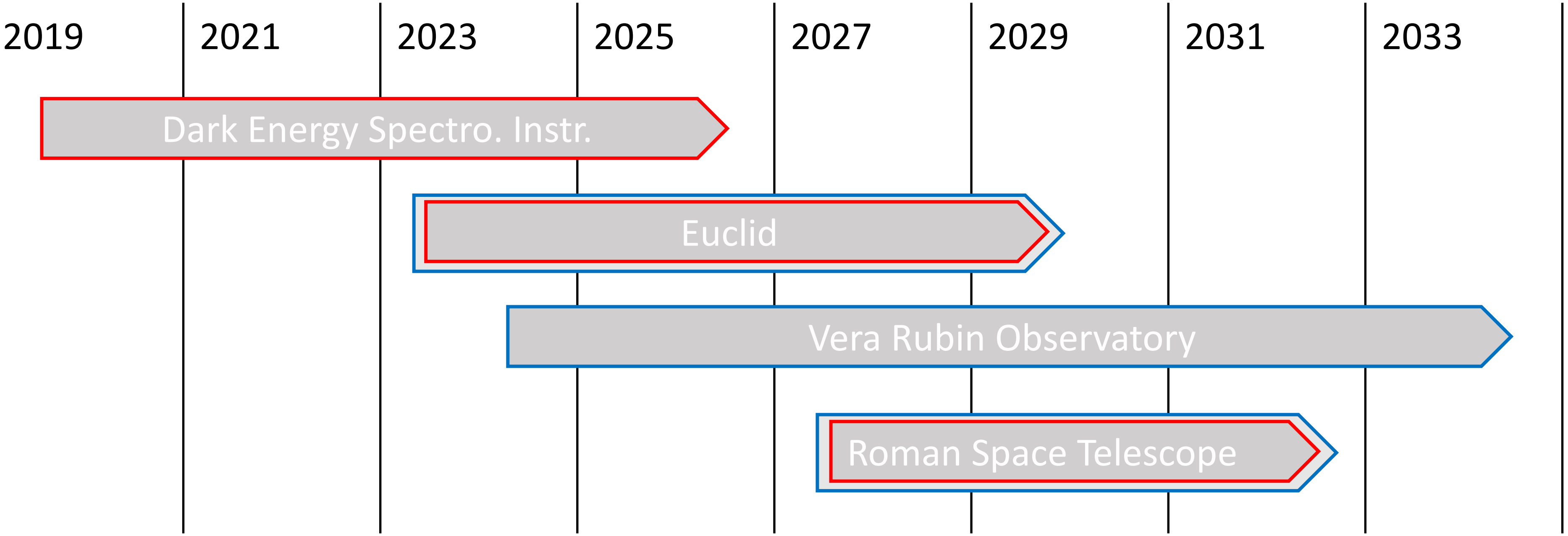


Neutrino mass constraints: LSS



Still no evidence/detection!

Stage IV Large Scale Surveys

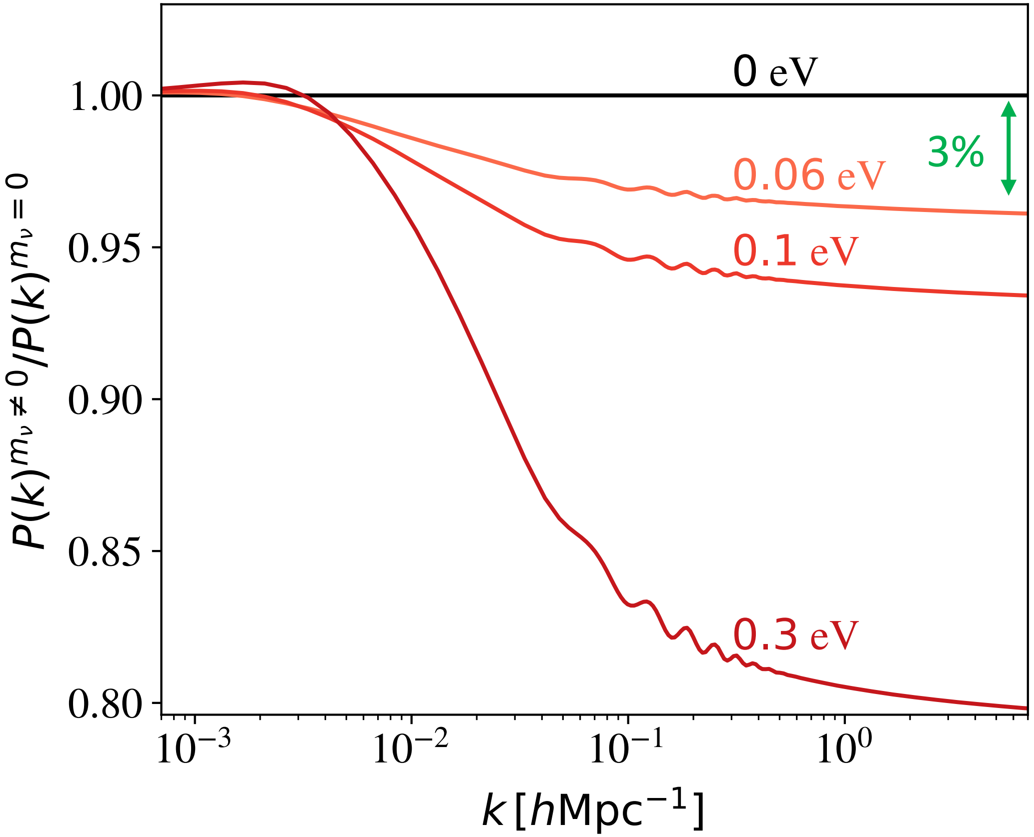


Spectroscopy
Imaging

Euclid in a nutshell

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

Neutrino mass probes: LSS



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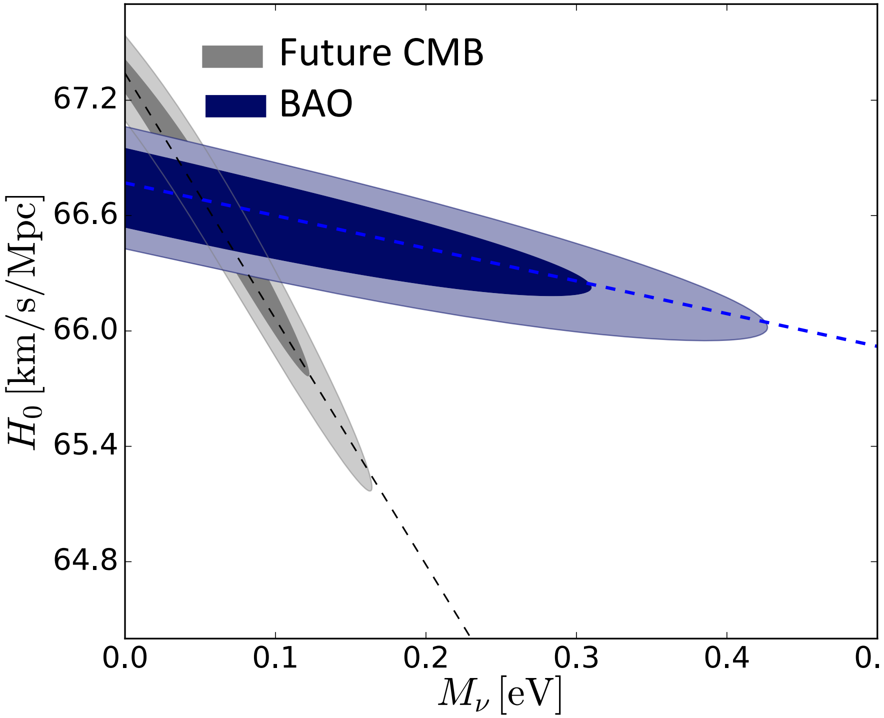
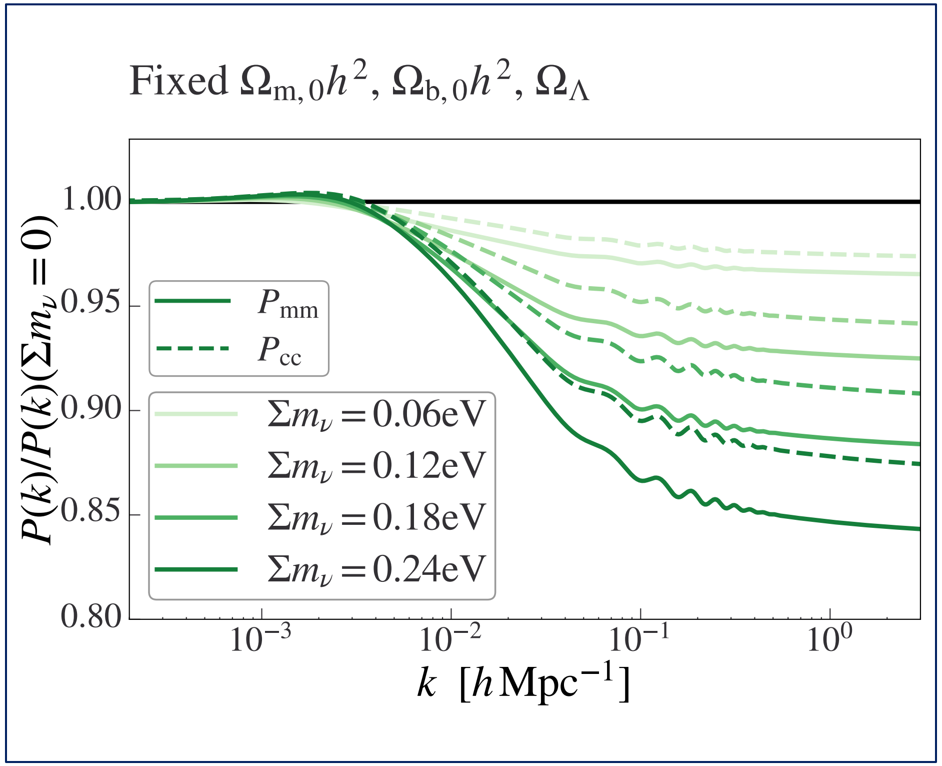


Known unknowns (systematics, etc.)

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



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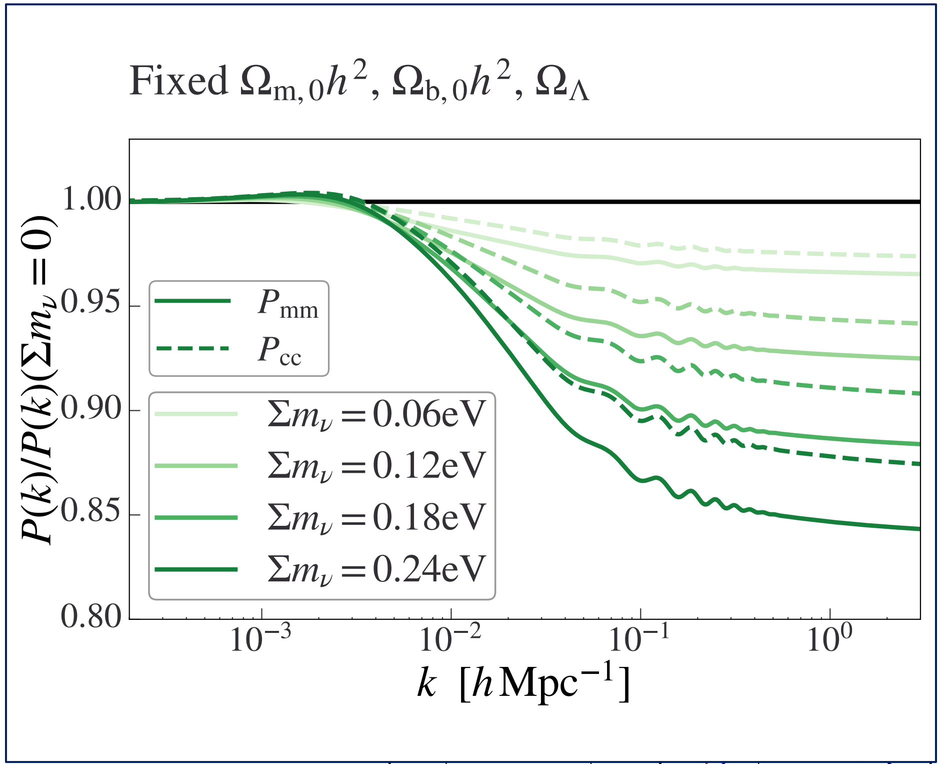
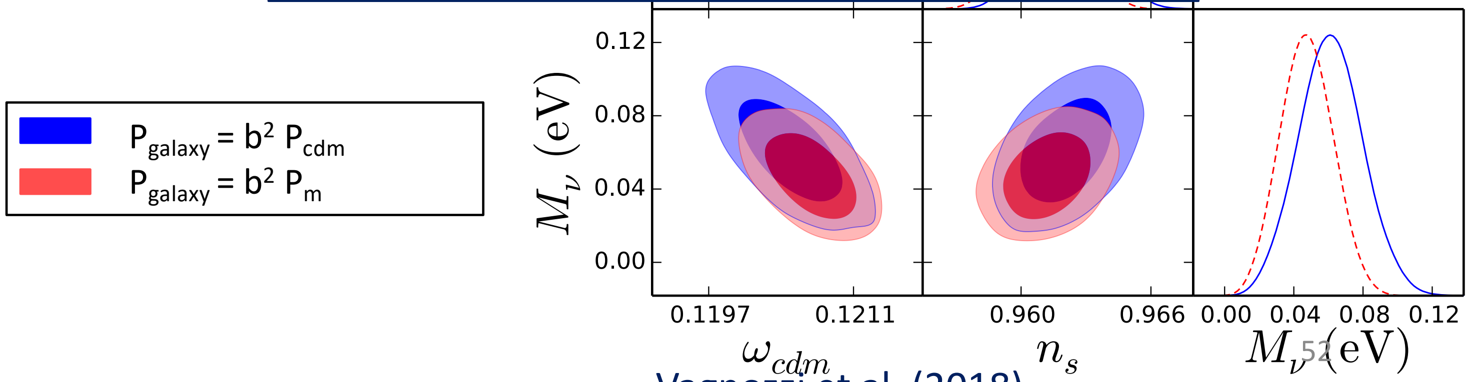


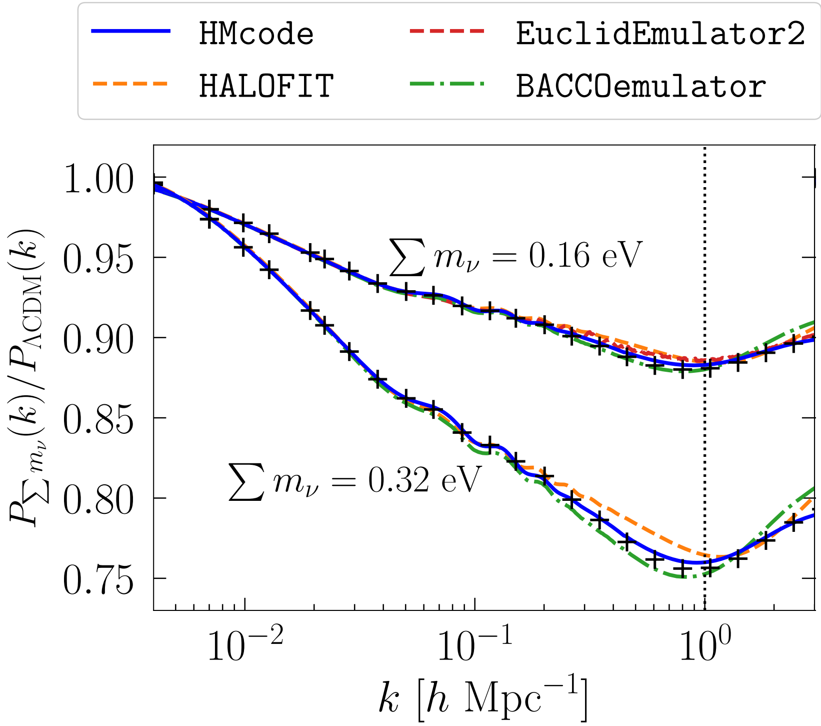


Vagnozzi et al. (2018)

Known unknowns (systematics, etc.)

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); Euclid Collaboration: Archidiacono et al. (2024)]



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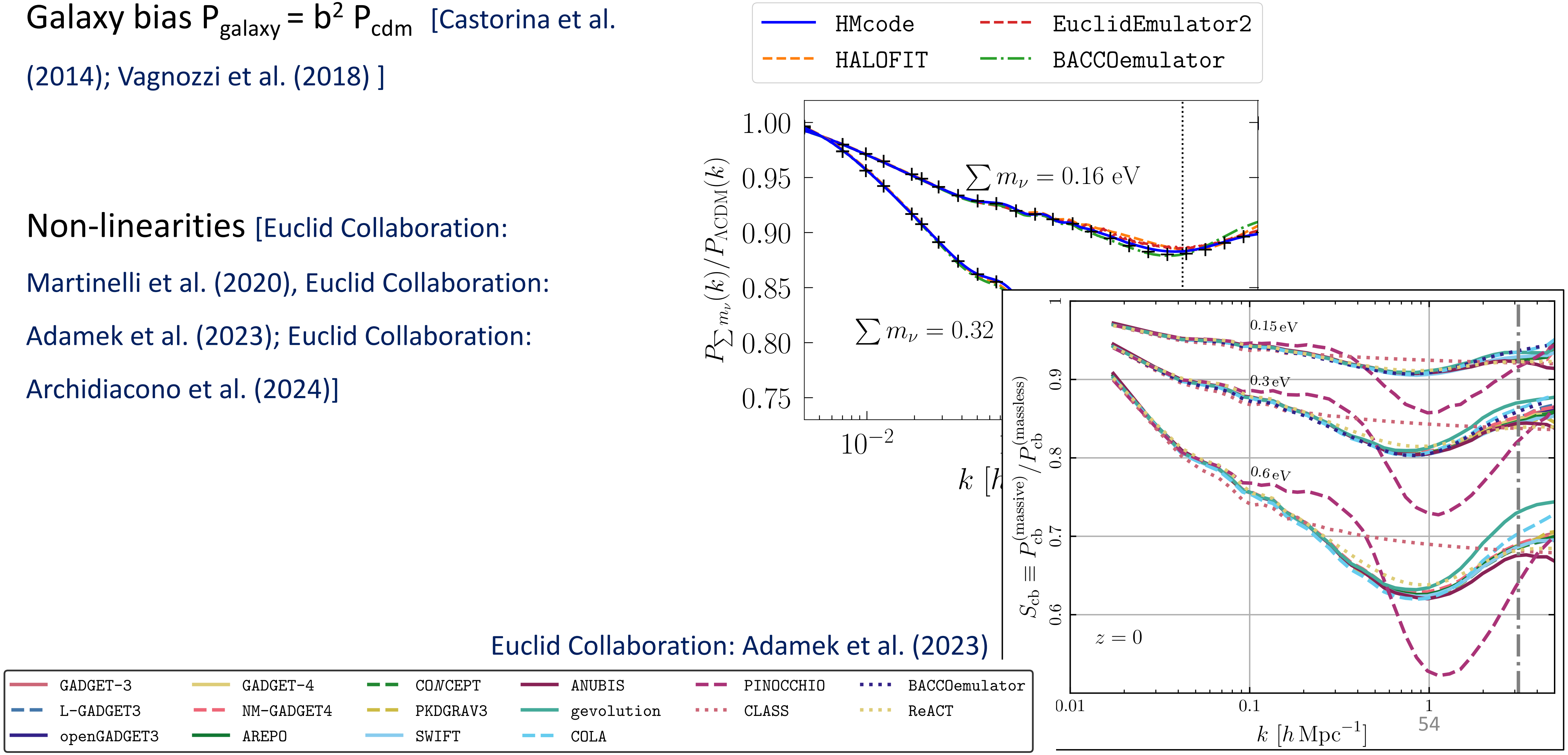
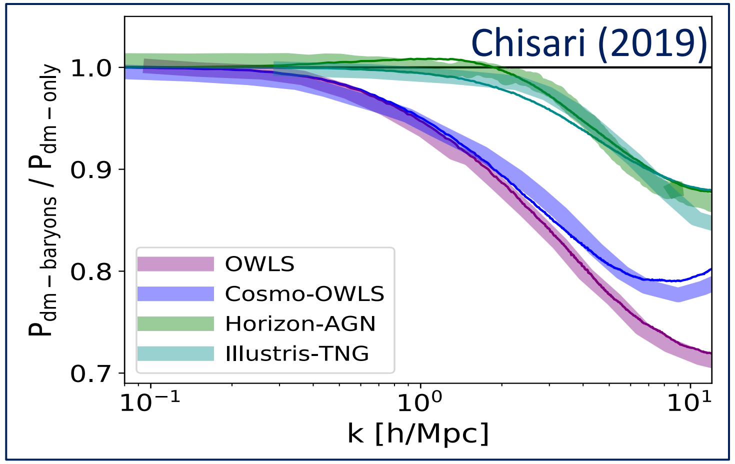


Euclid Collaboration: Adamek et al. (2023)

Known unknowns (systematics, etc.)



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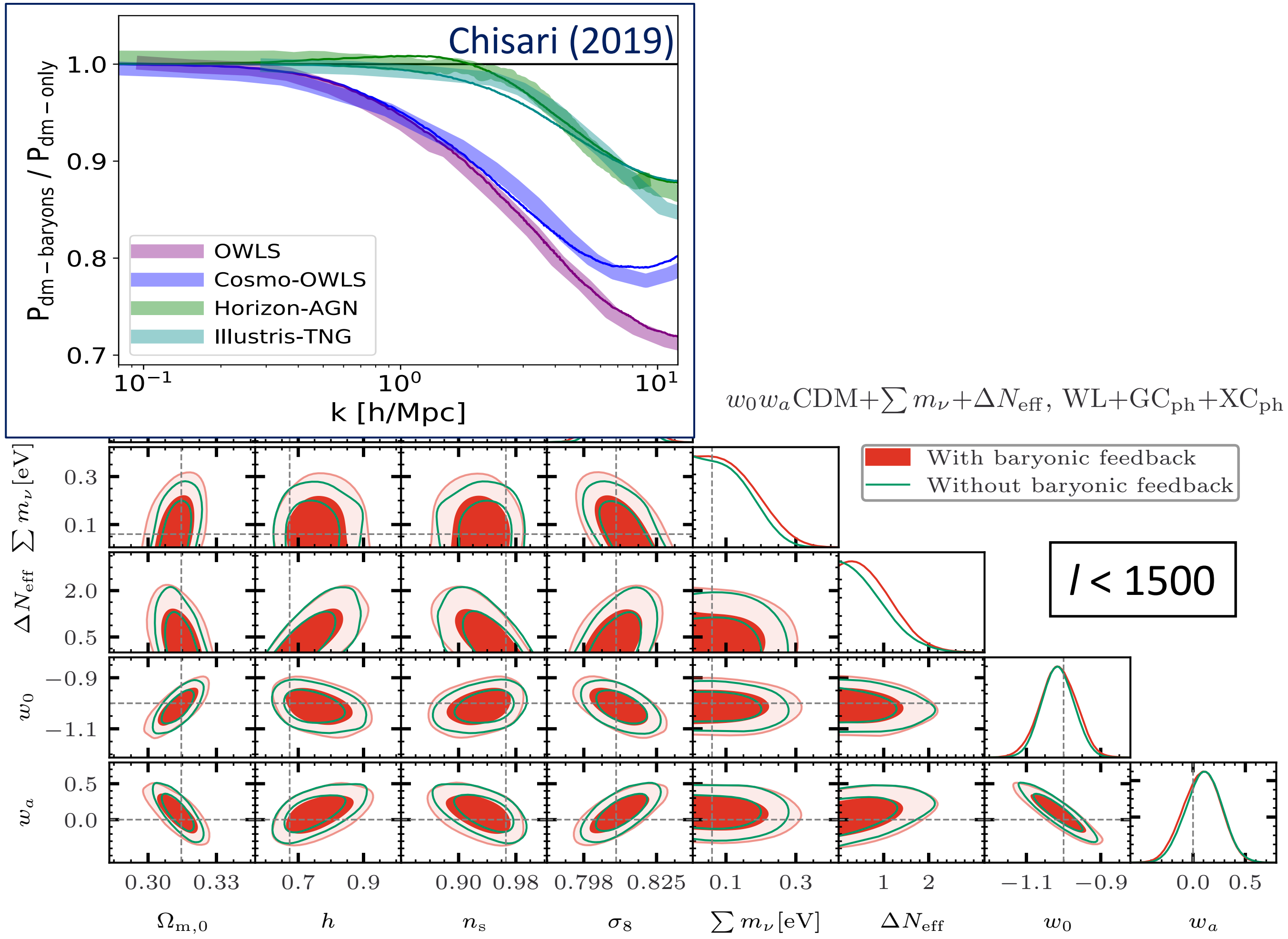
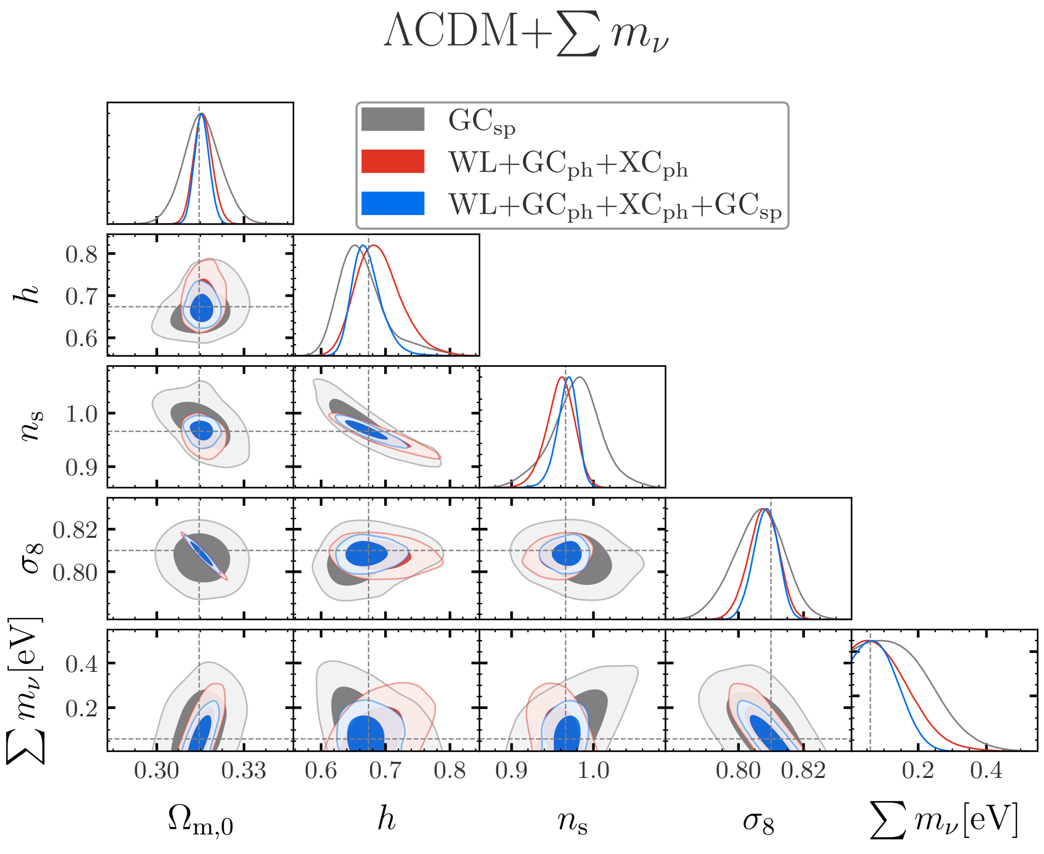
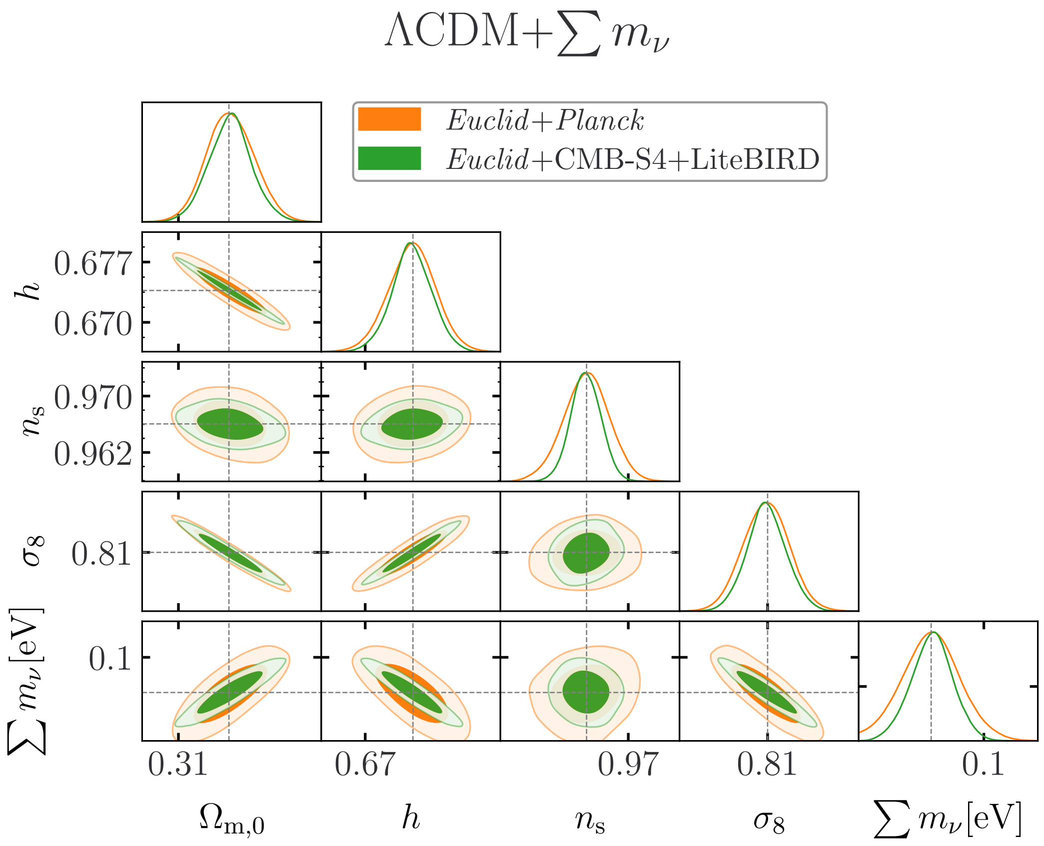


Neutrino mass constraints: the future

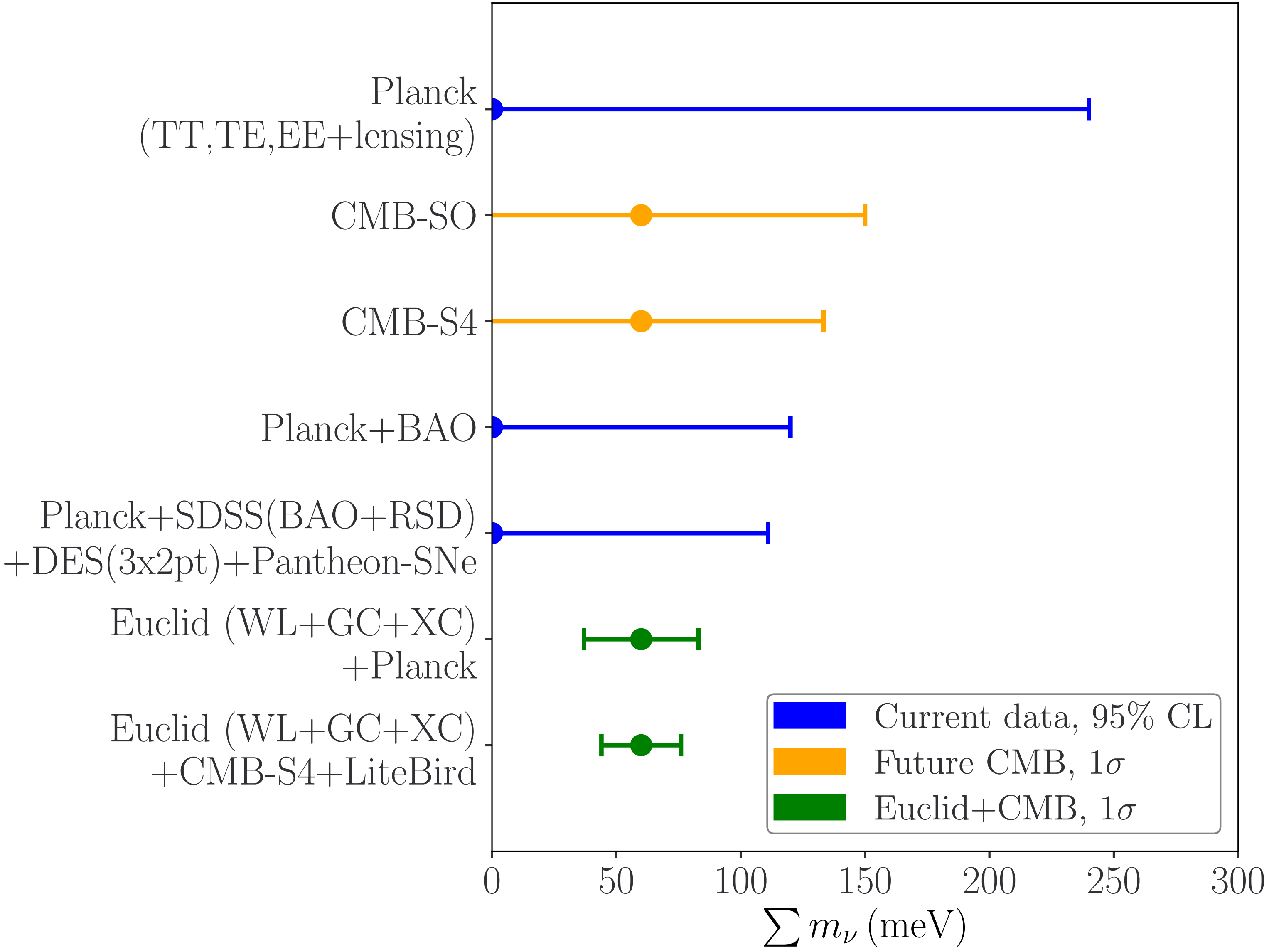
Euclid preparation: Sensitivity to neutrino parameters.
Euclid Collaboration: Archidiacono et al., arXiv:2405.13495

Note: MCMC forecast





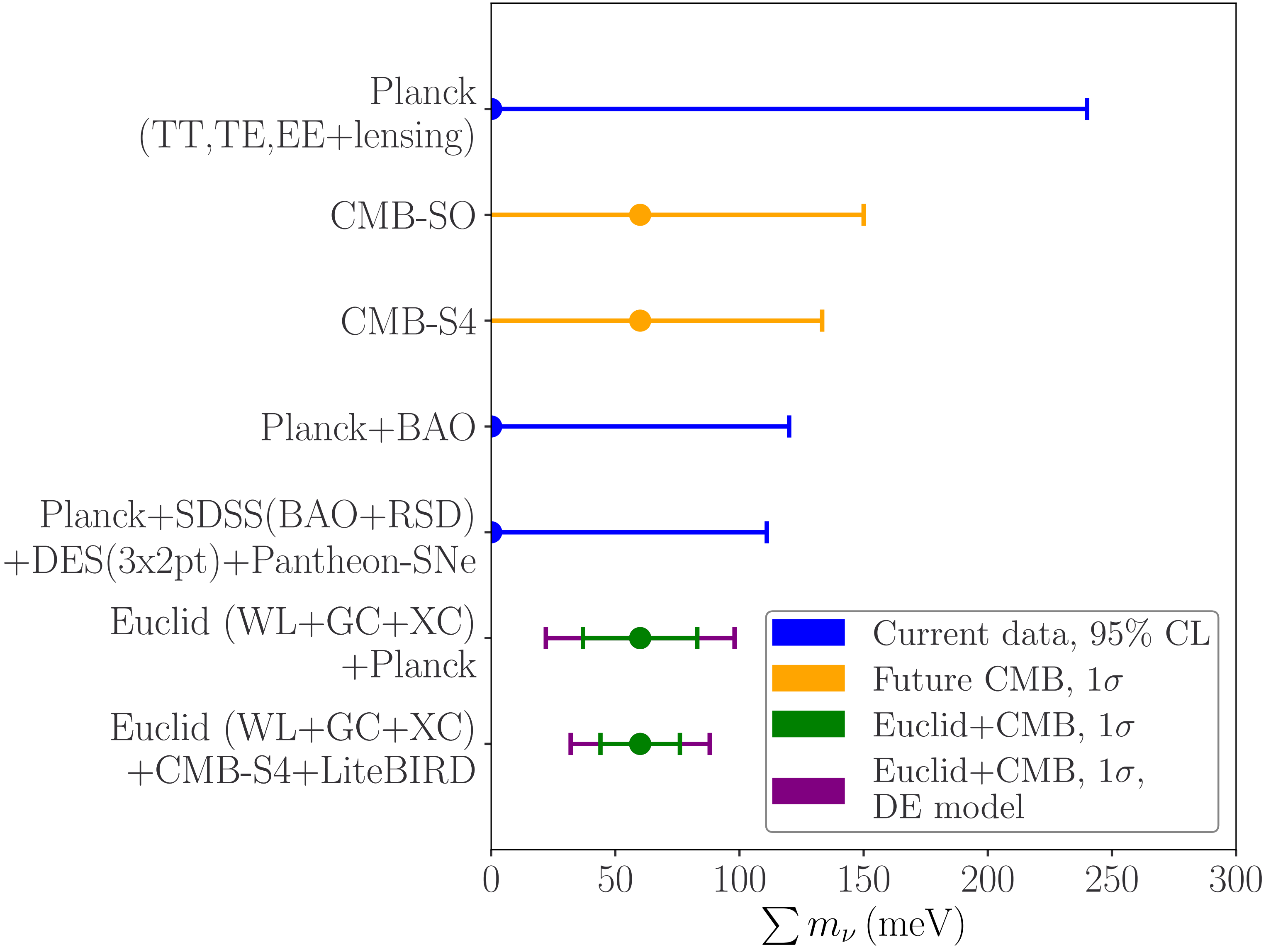
Neutrino mass constraints: the future



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

Euclid+CMB-S4+LiteBird: >3σ

Neutrino mass constraints: the future

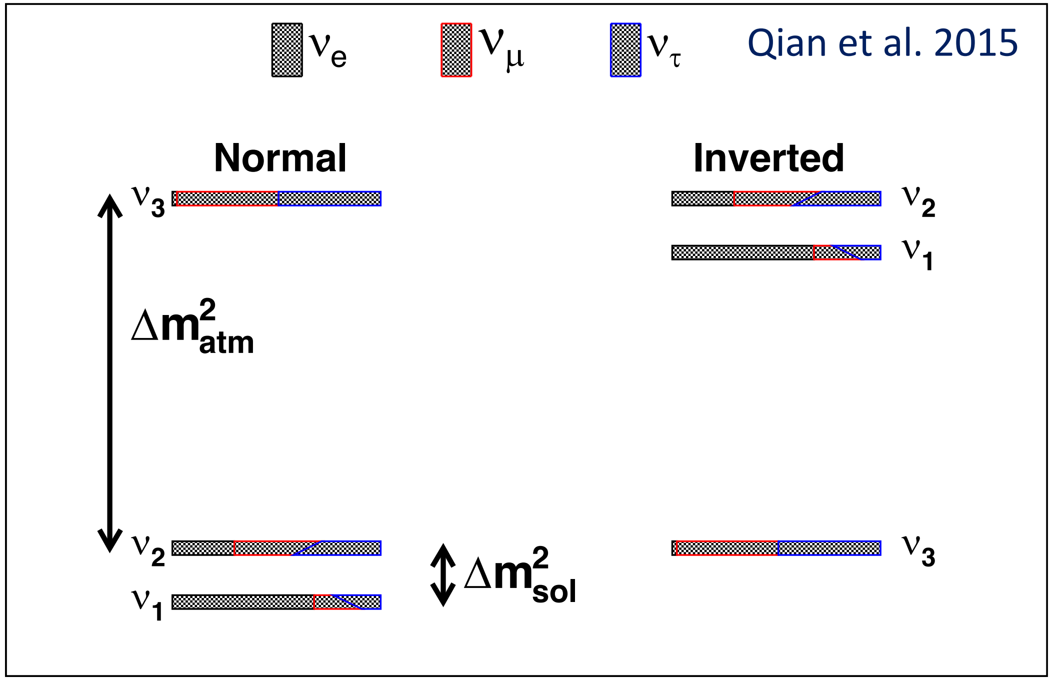


Replacing the cosmological constant with dark energy with a time varying equation of state parameter increases the error by a factor 2.

Neutrino mass ordering

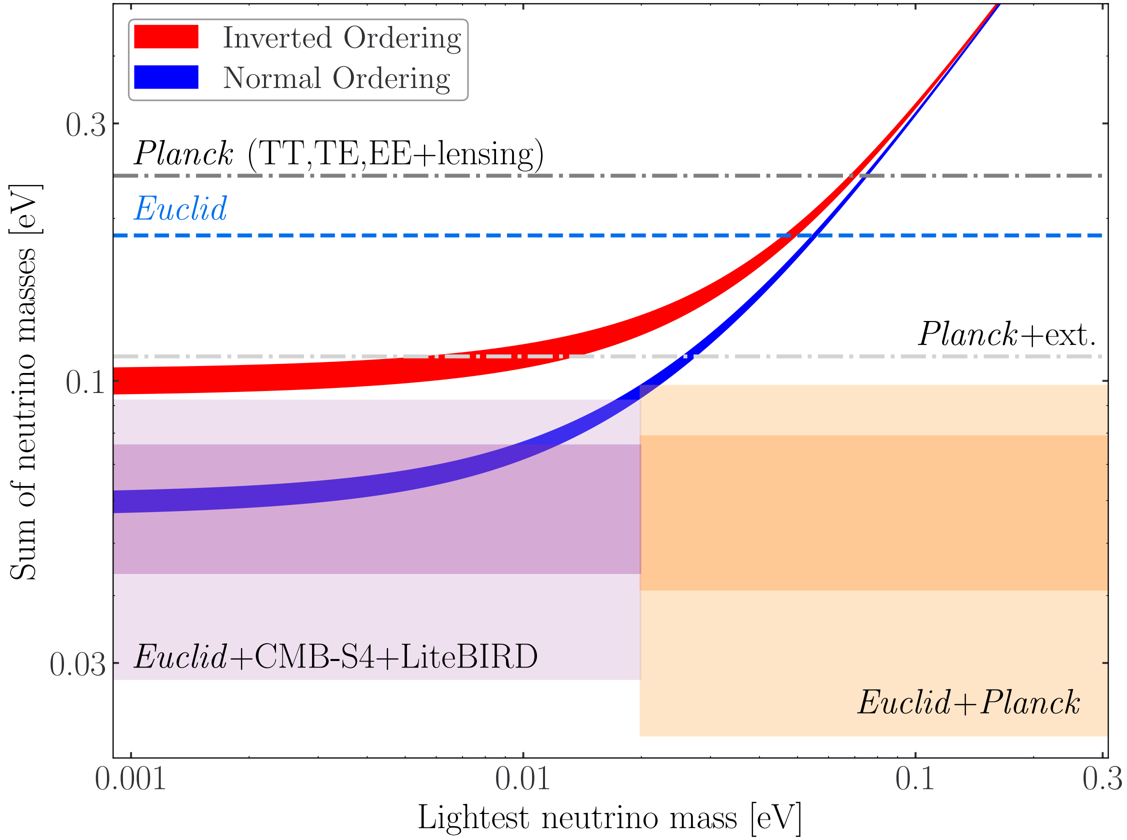
Constraints derived under the assumption $m_1=m_2=m_3$ (degenerate hierarchy, DH)

Neutrino Mass Hierarchy



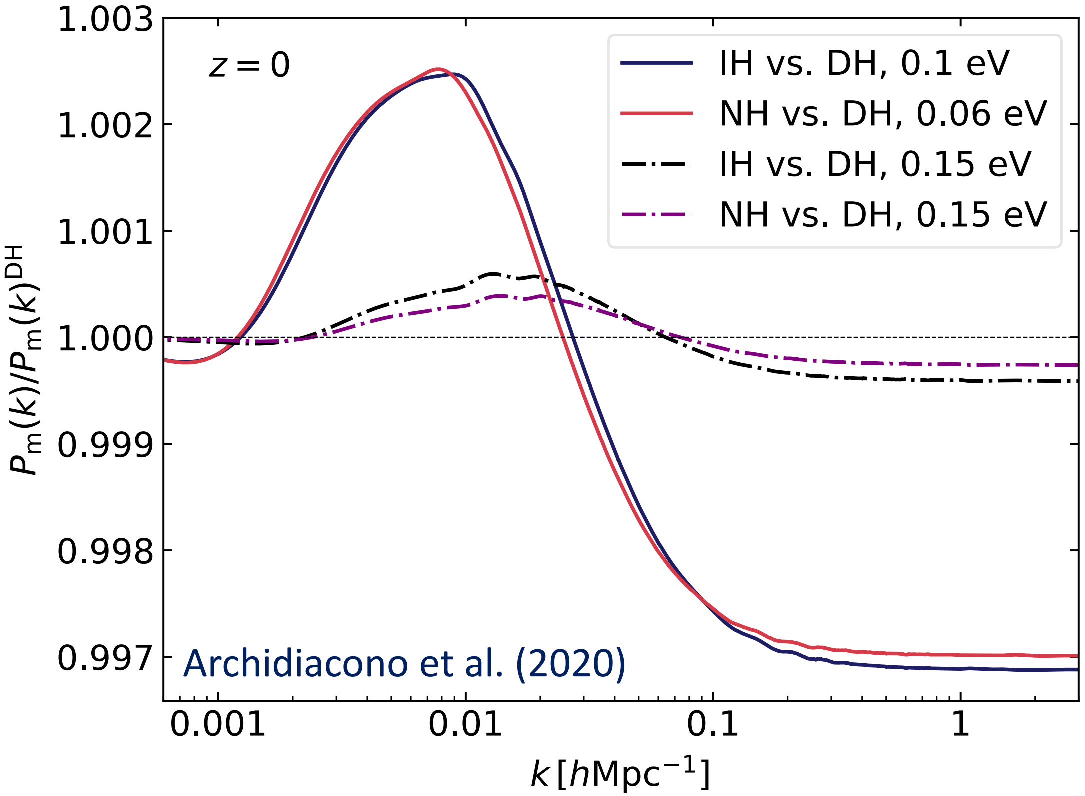
Min. Σm_ν (NH) = 0.058 eV; Min. Σm_ν (IH)= 0.100 eV

Euclid Collaboration: Archidiacono et al. (2024)



Input fiducial value of the forecast Σm_ν = 60 meV

Neutrino mass ordering



Archidiacono et al. (2020)

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.

See also Gariazzo et al. (2022)

Neutrino mass: conclusions

- Euclid in combination with upcoming CMB surveys can achieve a 5σ 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.
- What if there is a tension between the Cosmos and the Lab?

Non-standard neutrinos – part 1
The cosmological neutrino mass problem

The cosmological neutrino mass problem

What if KATRIN (or Project 8) measures a neutrino mass in disagreement with cosmological bounds?

What if the cosmological bounds cross the minimum value allowed by oscillations?

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

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Yes…

1. Beyond ΛCDM (replacing Λ with w0wa dark energy)

The cosmological neutrino mass problem

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Yes…

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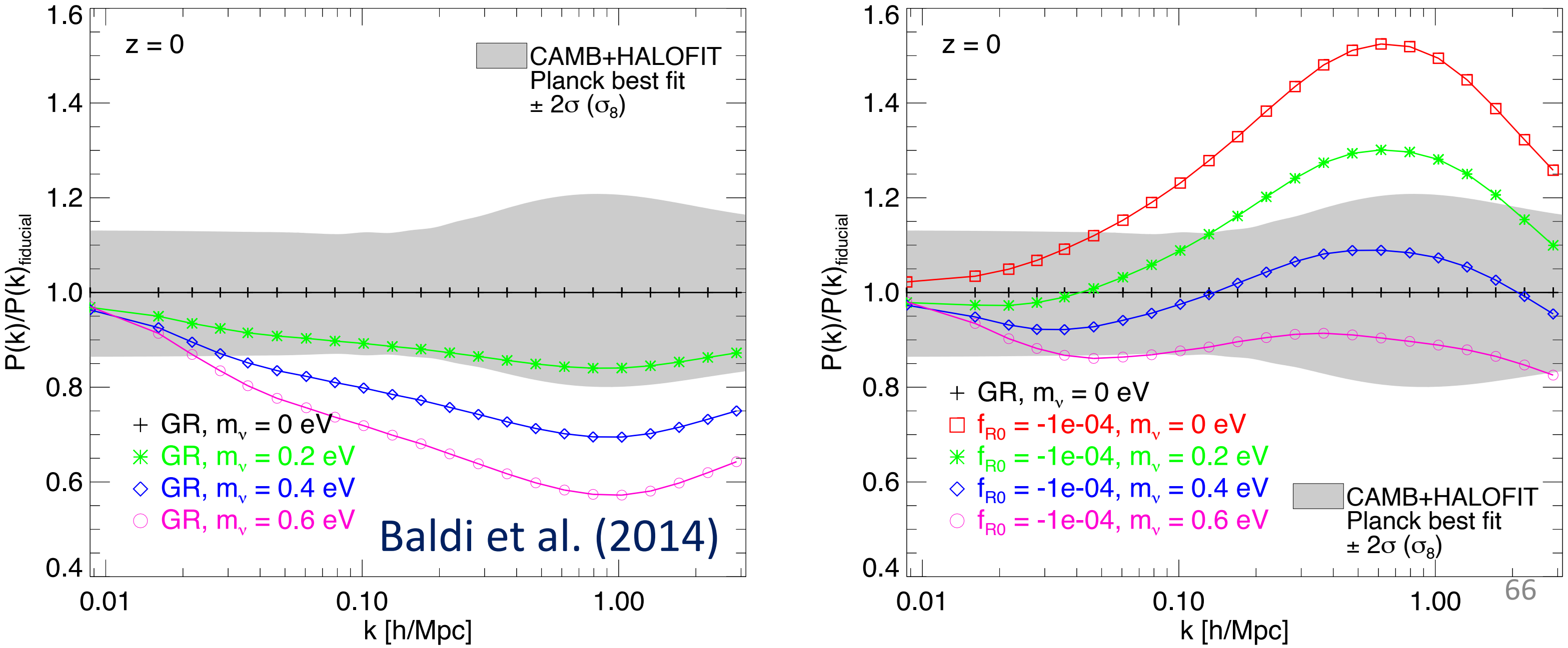
2. Beyond GR



Baldi et al. (2014)

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Yes…

1. Beyond ΛCDM (replacing Λ with w0wa dark energy)
2. Beyond GR
3. Beyond SM
    - Neutrino spectral distortions (from new interactions) [Alvey et al. (2022)] $\Sigma m_\nu < 3$ eV
    - Mass varying neutrinos (late time mass generation) [Lorenz et al. (2021)] $\Sigma m_\nu < 1.5$ eV
    - Invisible neutrino decay into BSM particles [Barenboim et al. (2021)] $\Sigma m_\nu < 0.2$ eV

The cosmological neutrino mass problem

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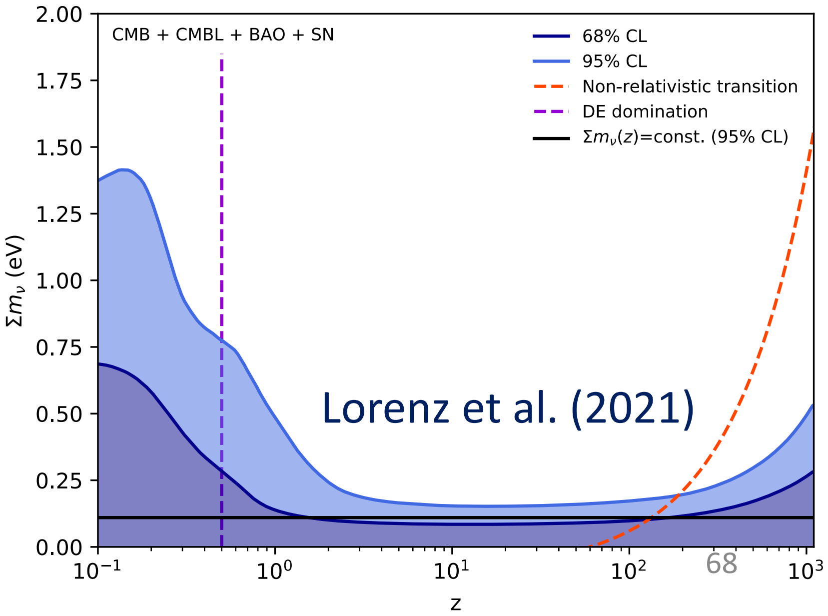
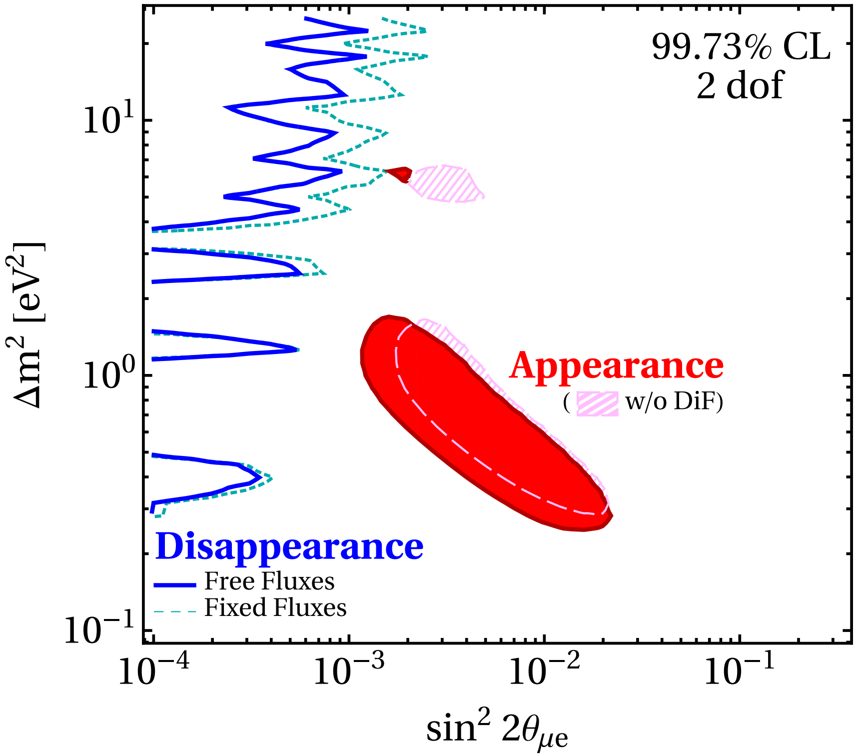


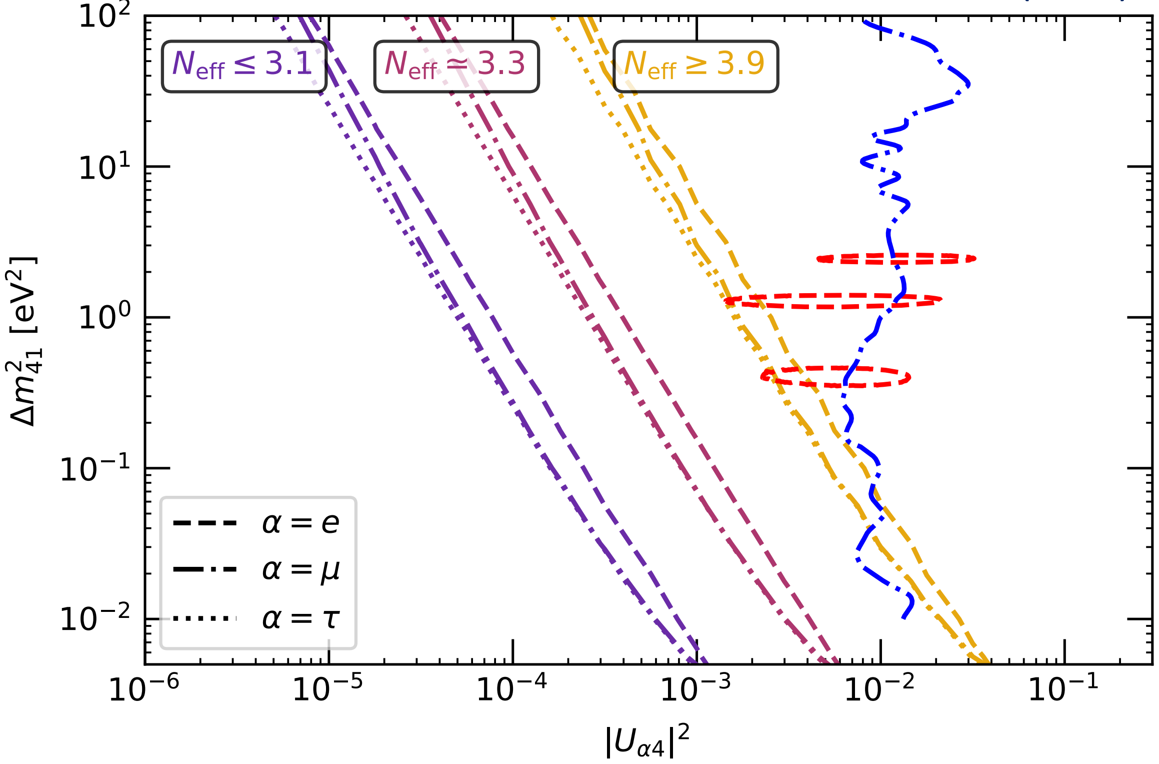
Lorenz et al. (2021)

Non-standard neutrinos – part 2
Sterile neutrinos and new interactions

Light sterile neutrinos



Dentler et al. (2018)



Gariazzo et al. (2019)

Sterile neutrinos in cosmology are facing two problems:

- They are too many: $N_{\rm eff} \sim 4$, while current bounds are $N_{\rm eff} = 2.92 \pm 0.36$ (95% CL)
- They are too massive: $\Sigma m_\nu \sim 1$ eV, while current bounds are $\Sigma m_\nu < 0.1$-0.2 eV

Partial thermalization

$$N_{\text{eff}} = \frac{\rho_\nu^{\text{rel}}}{\rho_{\nu,m=0}^{\text{th}}}$$

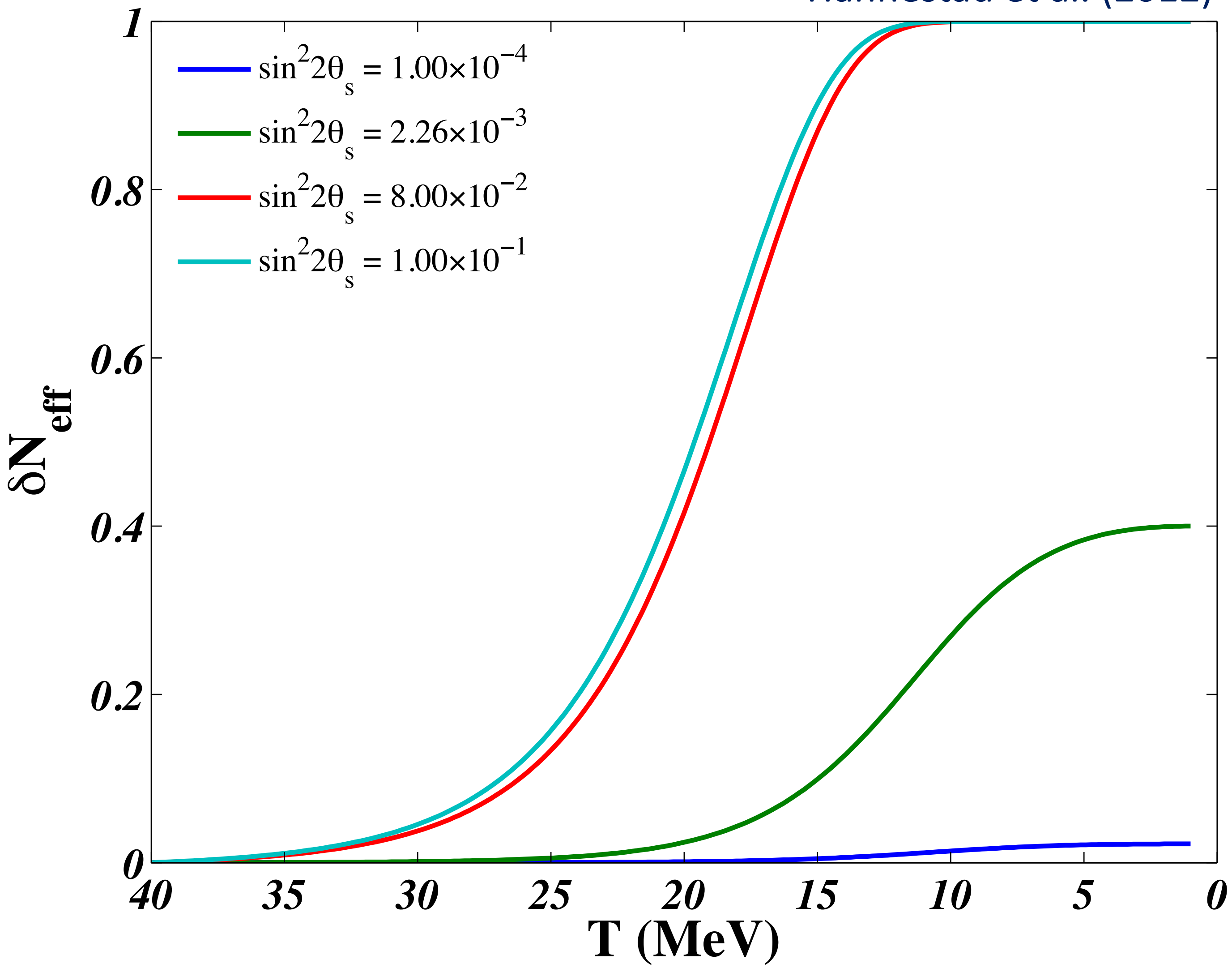
$$\rho_\nu = \frac{g}{2\pi^2} \int dp E p^2 f_\nu(p)$$

$$f_\nu^{\text{th}}(p) = \frac{1}{1+\exp(E/T)}$$

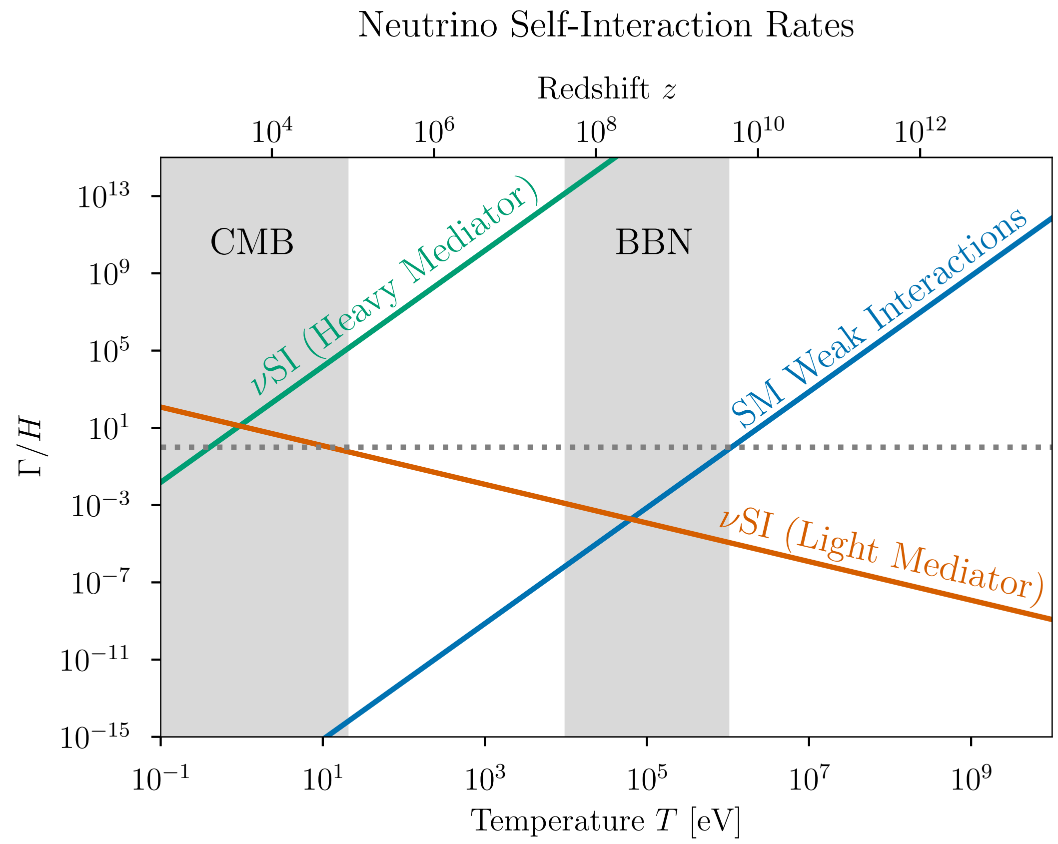
$$\sin^2 2\theta_m = \frac{\sin^2 2\theta_0}{\left(\cos 2\theta_0 + \frac{2E}{\Delta m^2} \underset{\downarrow}{V_s}\right)^2 + \sin^2 2\theta_0}$$

Additional matter-like potential

Hannestad et al. (2012)

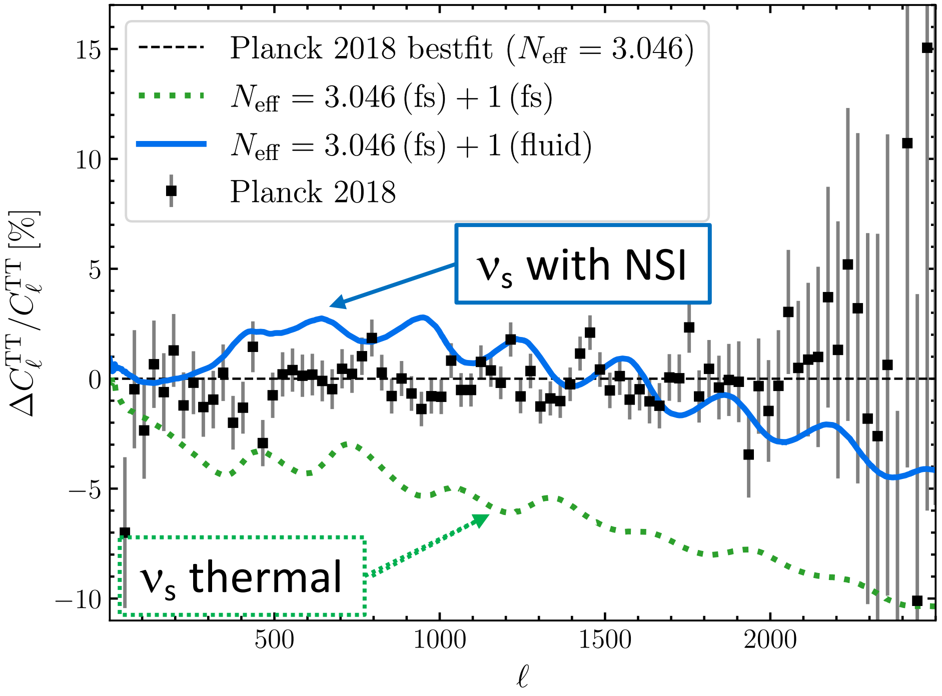


New interactions



Berryman et al. (2023)

New interactions: CMB

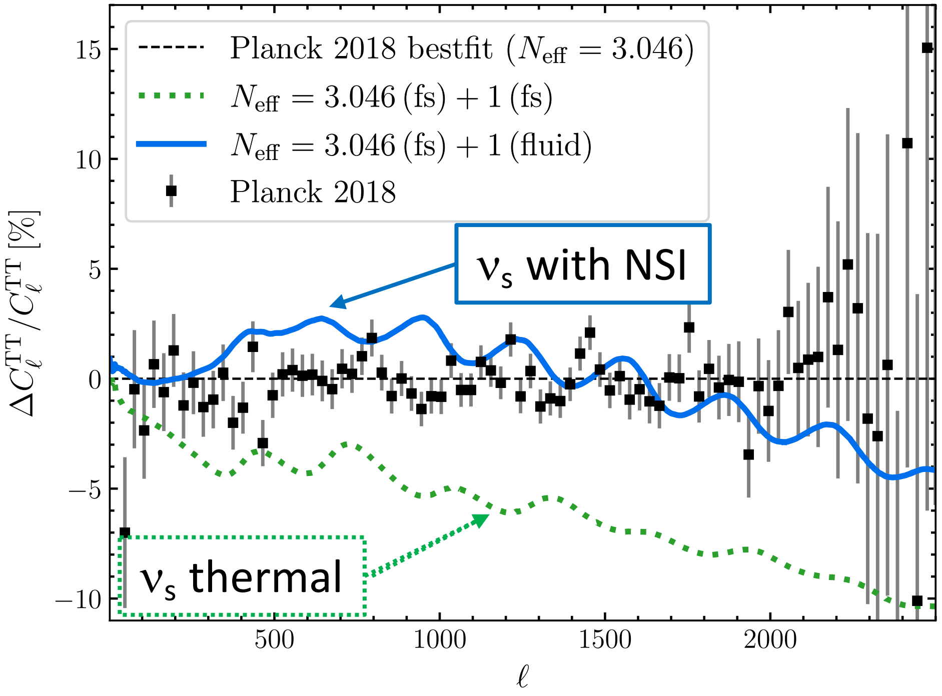


ν_s with NSI

ν_s thermal

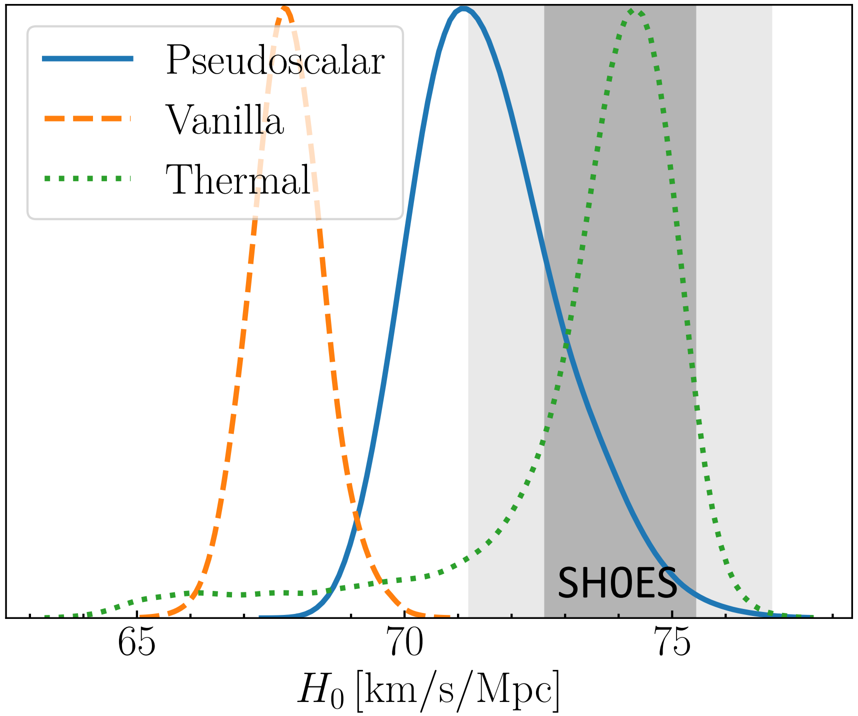
See also Kreisch et al. (2019)

New interactions: CMB

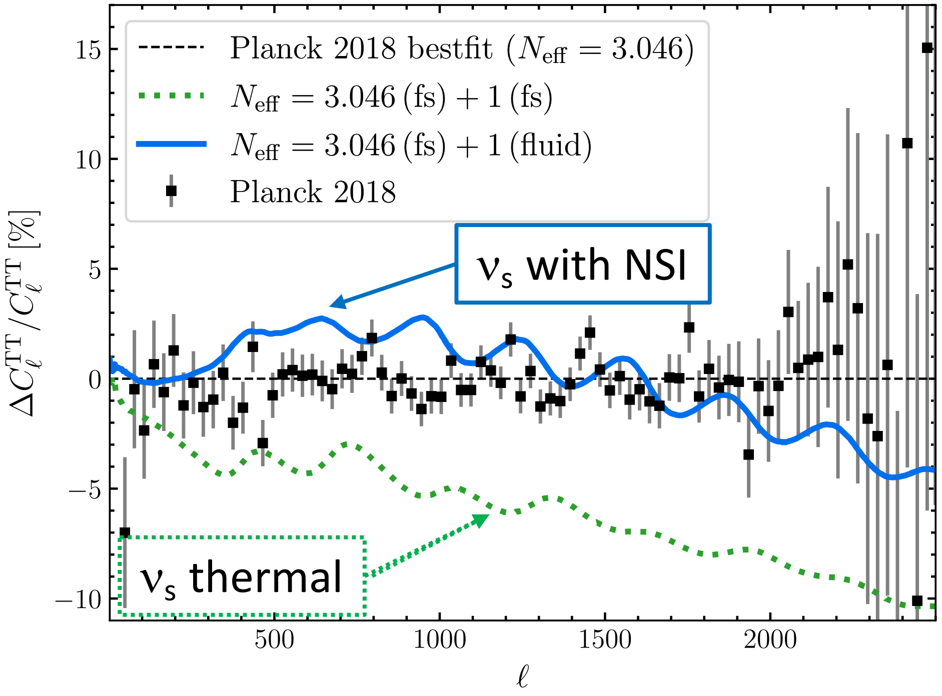


See also Kreisch et al. (2019)

Archidiacono et al. (2021)



New interactions: CMB



See also Kreisch et al. (2019)

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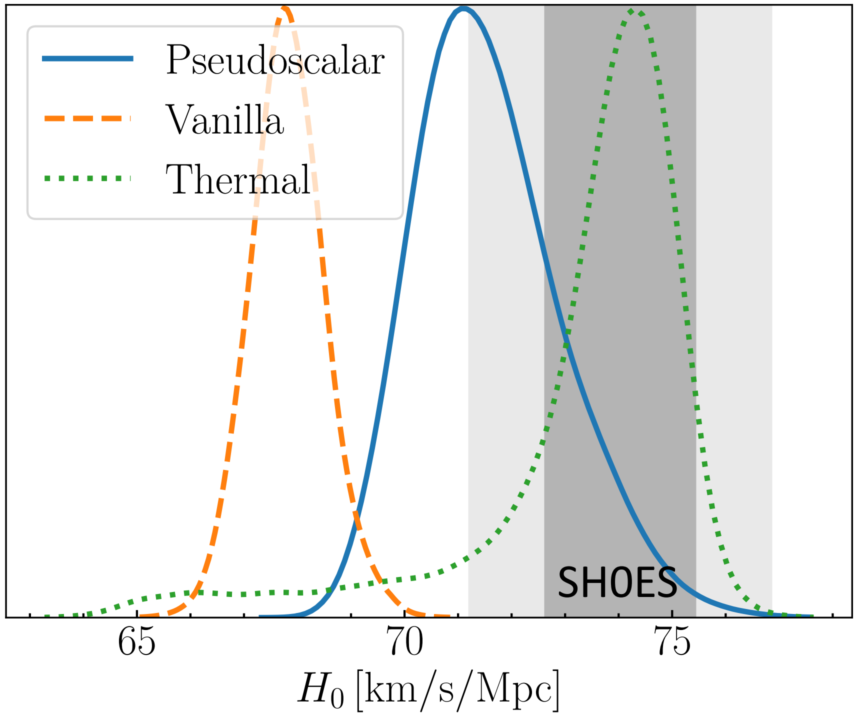
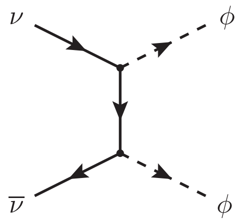


Sterile neutrinos with self-interactions provide:

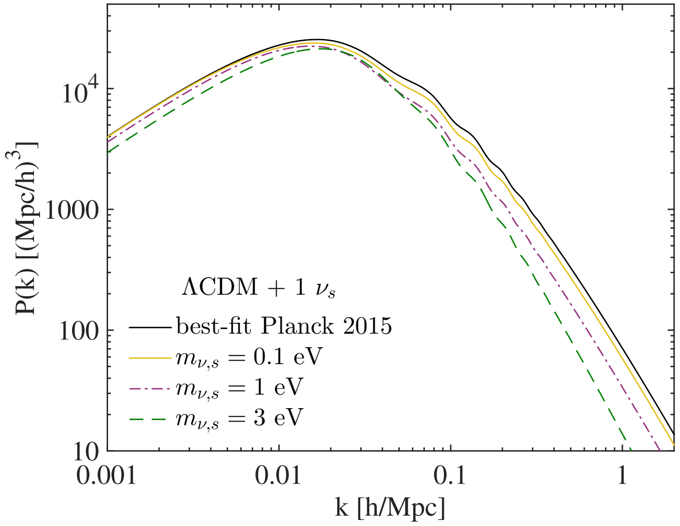
- a good fit to Planck CMB data
  - ✓ Sterile neutrinos are not too many anymore
- a solution to the Hubble constant problem

New interactions: LSS

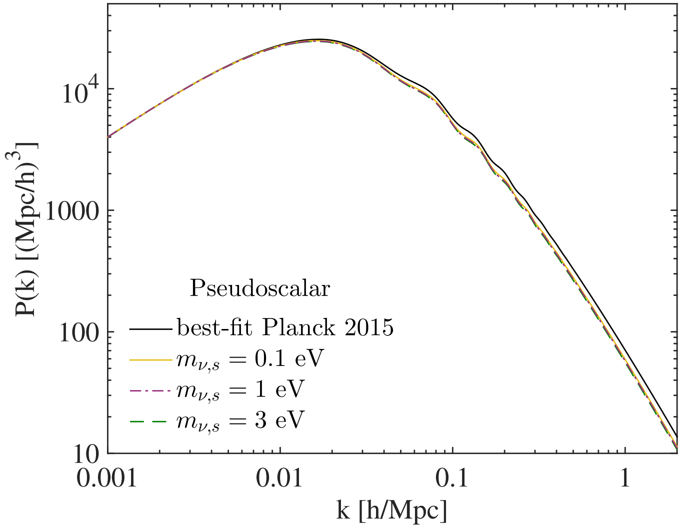


Sterile neutrinos disappear from the cosmic neutrino background.

Without NSI



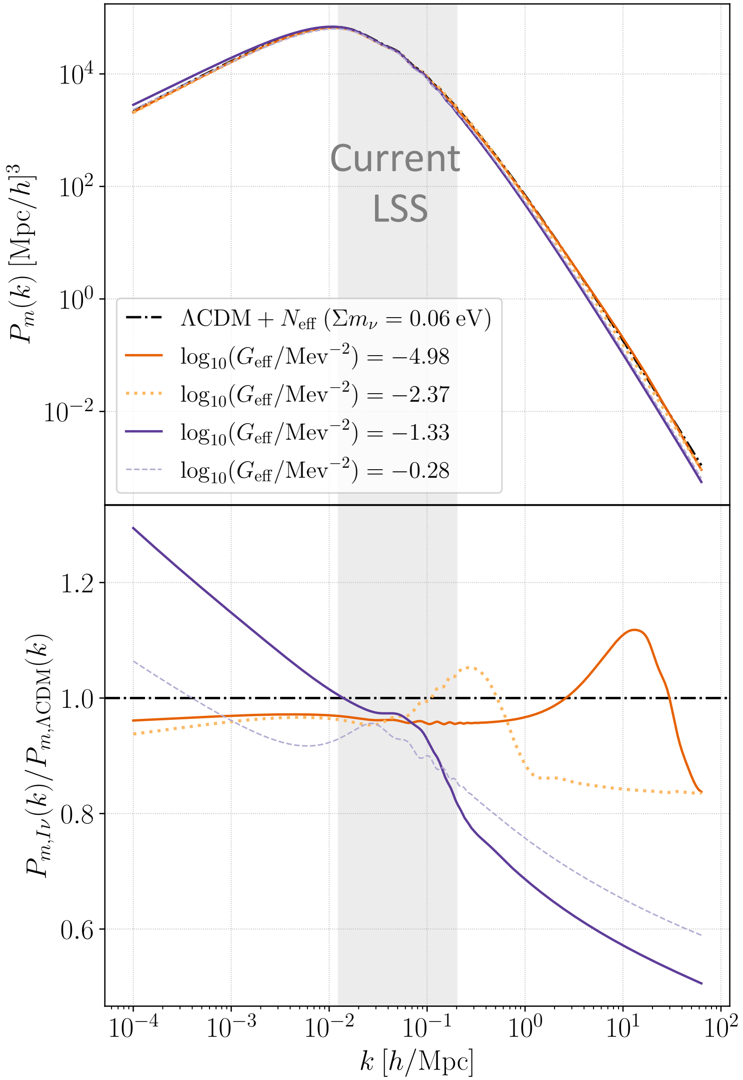
With NSI



✓ Sterile neutrinos are not too massive anymore

New interactions: LSS

Camarena et al. (2023)

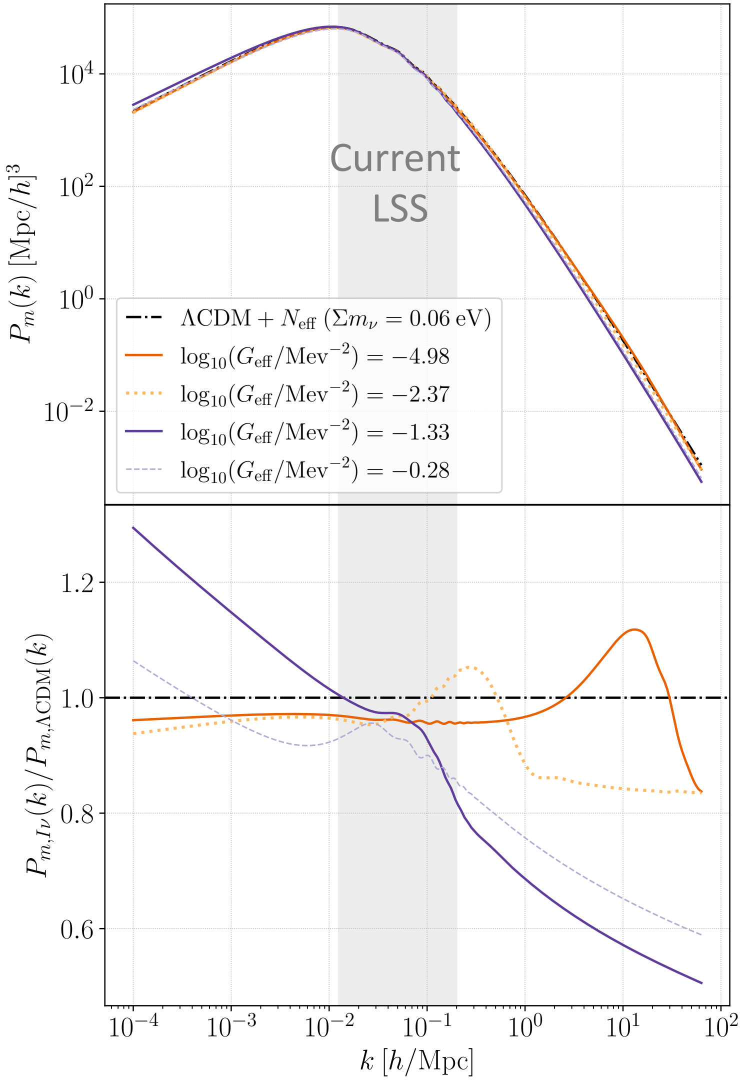


Mild preference for non-vanishing νSI

Stage IV LSS surveys will extend the range where we can test νSI

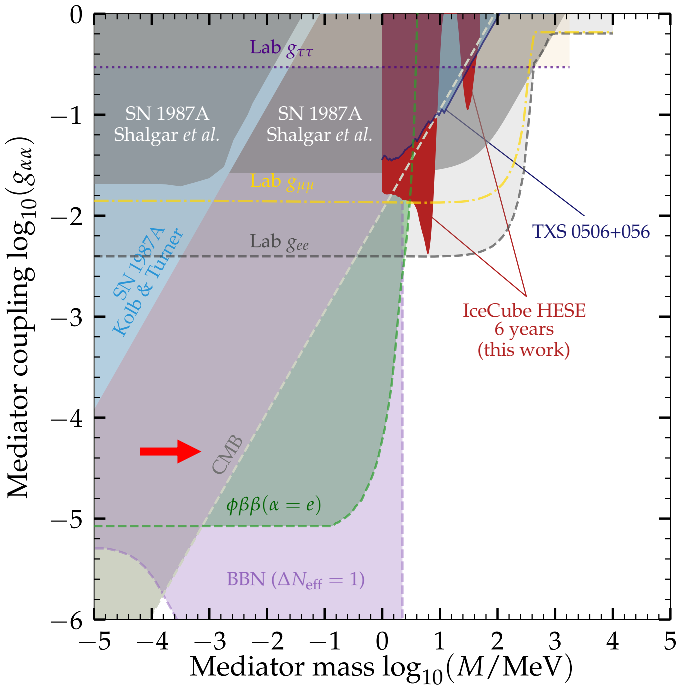
New interactions: LSS

Camarena et al. (2023)



Mild preference for non-vanishing νSI

Stage IV LSS surveys will extend the range where we can test νSI



Astrophysical and laboratory limits might already exclude this model.

Lectures by Coloma, Mirizzi, Sala, Spurio

Bustamante et al. (2020)

Non-standard neutrinos: conclusions

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

Non-standard neutrinos: conclusions

- Neutrino mass: The scenario of no detection, or a tension with ground-based experiments, would require to rethink the cosmological paradigm and/or neutrino physics.
- 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.
- Non-standard interactions can be extended to active neutrinos, but external constraints might rule out their existence.

Useful references

- Textbook
  - J. Lesgourgues, G. Mangano, G. Miele and S. Pastor, *Neutrino Cosmology*
- Reviews
  - A. D. Dolgov, *Neutrinos in cosmology*, Phys. Rept. **370** (2002) 333 [hep-ph/0202122]
  - S. Bashinsky and U. Seljak, *Neutrino perturbations in CMB anisotropy and matter clustering*, Phys. Rev. D **69** (2004) 083002 [astro-ph/0310198]
  - J. Lesgourgues and S. Pastor, *Massive neutrinos and cosmology*, Phys. Rept. **429** (2006) 307 [astro-ph/0603494]

Backup

Neutrino flavour evolution

$$\rho(p,t) = \begin{pmatrix} \rho_{aa} & \rho_{as} \\ \rho_{sa} & \rho_{ss} \end{pmatrix} = \frac{f_0(p)}{2}\left[P_0(p,t) + \bar{\sigma} \times \bar{P}(p,t)\right];$$

$$\frac{d\bar{P}}{dt} = \bar{V} \times \bar{P} - D\bar{P}_T + \frac{R}{f_0}\hat{z}$$

$$\bar{V} = \bar{V}_{vacuum} + \bar{V}_{medium} + \bar{V}_s$$

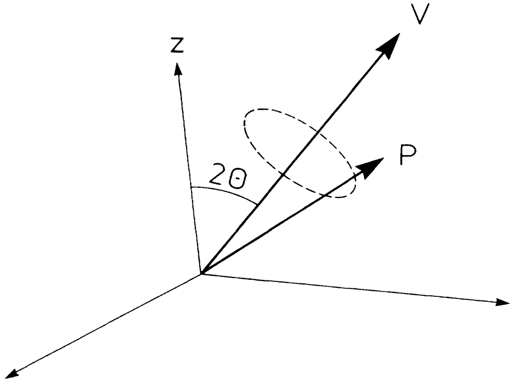
$$V_{vaccum} = \frac{\Delta m^2}{2p}$$

$$V_{medium} \propto \frac{G_F}{M_z^2} n_a p T^4$$

$$D = \frac{1}{2}\Gamma$$ damping

$$R = \Gamma\left(f_0 - \frac{f_0}{2}(P_0 + P_z)\right)$$ repopulation

$$\Gamma_a \propto G_F^2 p T^4$$



Stodolsky PRD (1987)

$$V_s(p_s) = \frac{g_s^2}{8\pi^2 p_s}\int p\,dp(f_\phi + f_s) \sim 10^{-1} g_s^2 T_s$$

$$\Gamma_s = \frac{g_s^4}{4\pi T_s^2} n_s$$

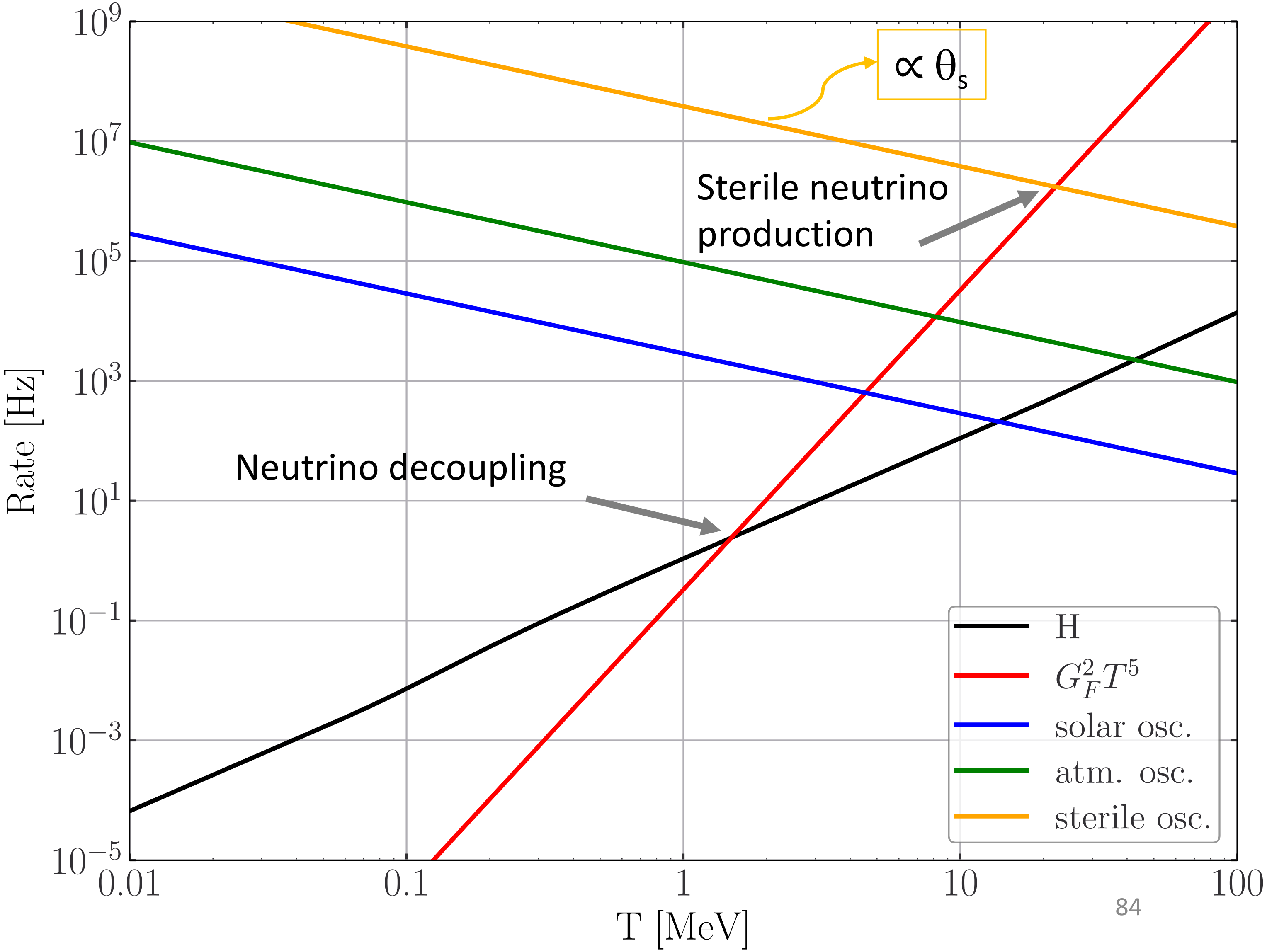
Babu PLB (1992)

Partial thermalization

$$N_{\text{eff}} = \frac{\rho_\nu^{\text{rel}}}{\rho_{\nu,m=0}^{\text{th}}}$$

$$\rho_\nu = \frac{g}{2\pi^2}\int dp E p^2 f_\nu(p)$$

$$f_\nu^{\text{th}}(p) = \frac{1}{1+\exp(E/T)}$$



Light sterile neutrinos with NSI

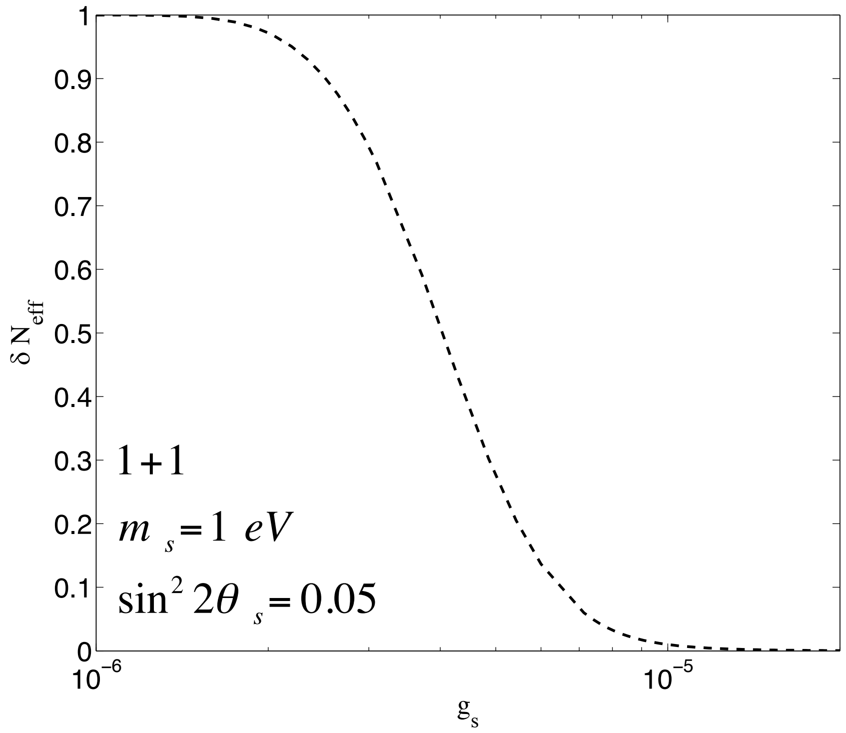
Early time phenomenology

The sterile neutrino is coupled to a new light pseudoscalar ($m_\phi << 1\text{eV}$):

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

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}



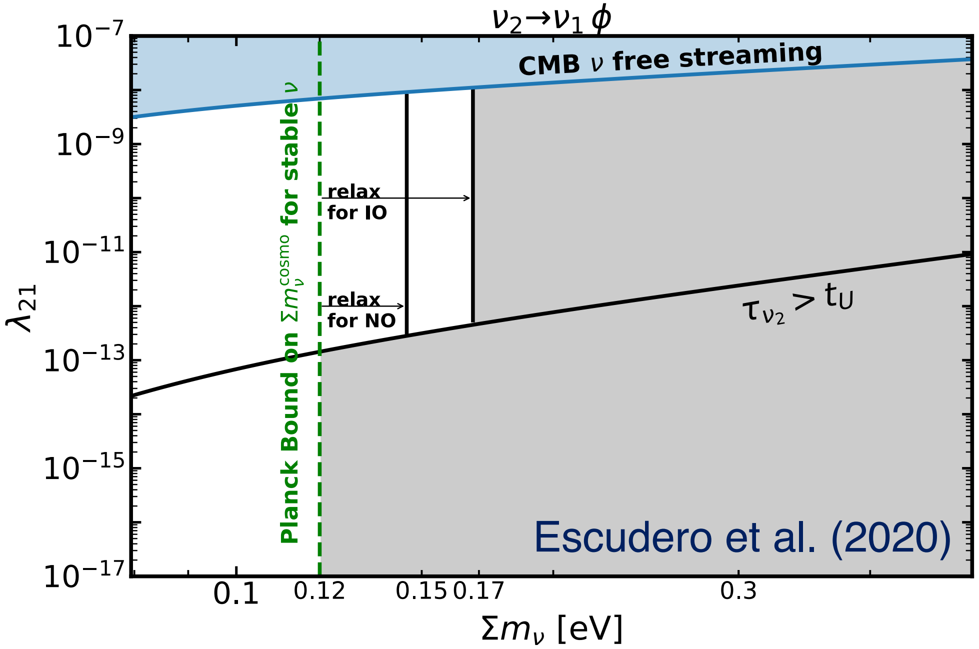
~~Sterile neutrinos are too many and too massive for cosmology~~

BBN bounds

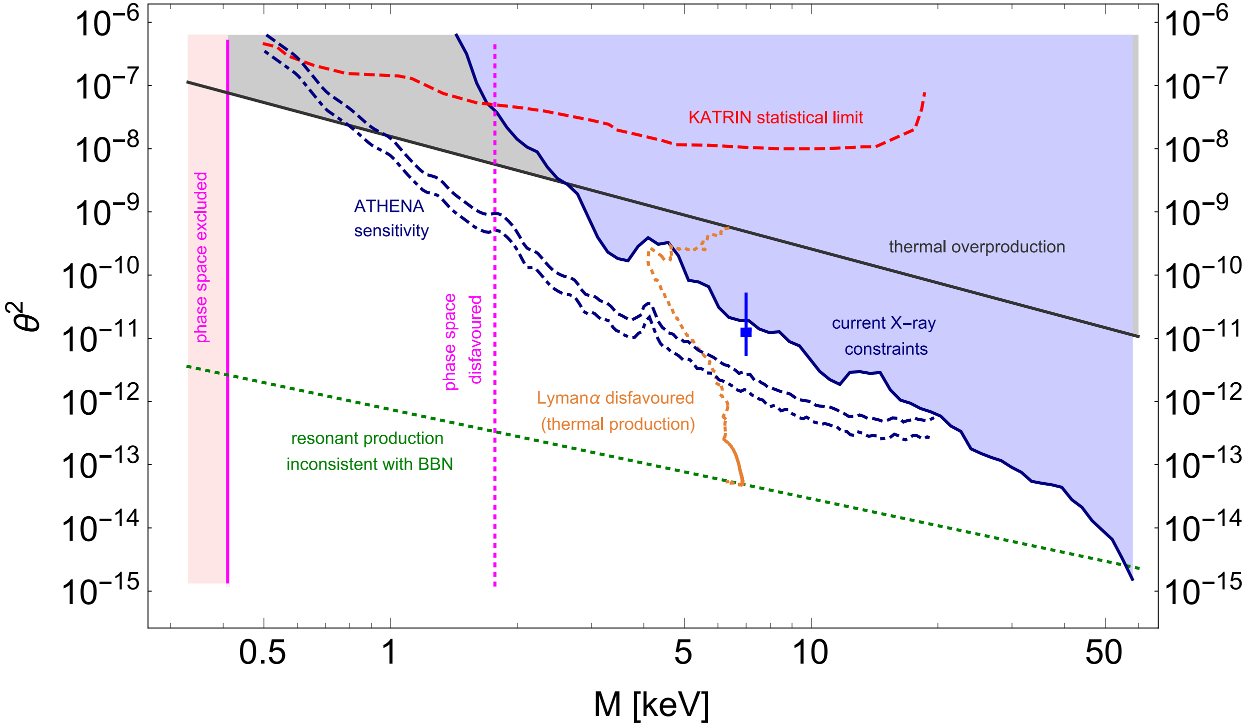
Neutrino mass problem

Cosmological data are more and more pointing towards $\Sigma m_\nu < 0.06$ eV.

- Extended particle physics models (beyond SM)
  - Invisible neutrino decay into BSM particles, e.g. lighter (sterile) neutrinos plus a massless (pseudo)scalar particle [Barenboim et al. 2021, Escudero et al. 2020]



KeV sterile neutrinos (WDM)



Boyarsky et al. (2019)