Neutrino Cosmology: Lecture II
Neutrino Masses & H_0 Tension

Miguel Escudero Abenza
miguel.escudero@cern.ch

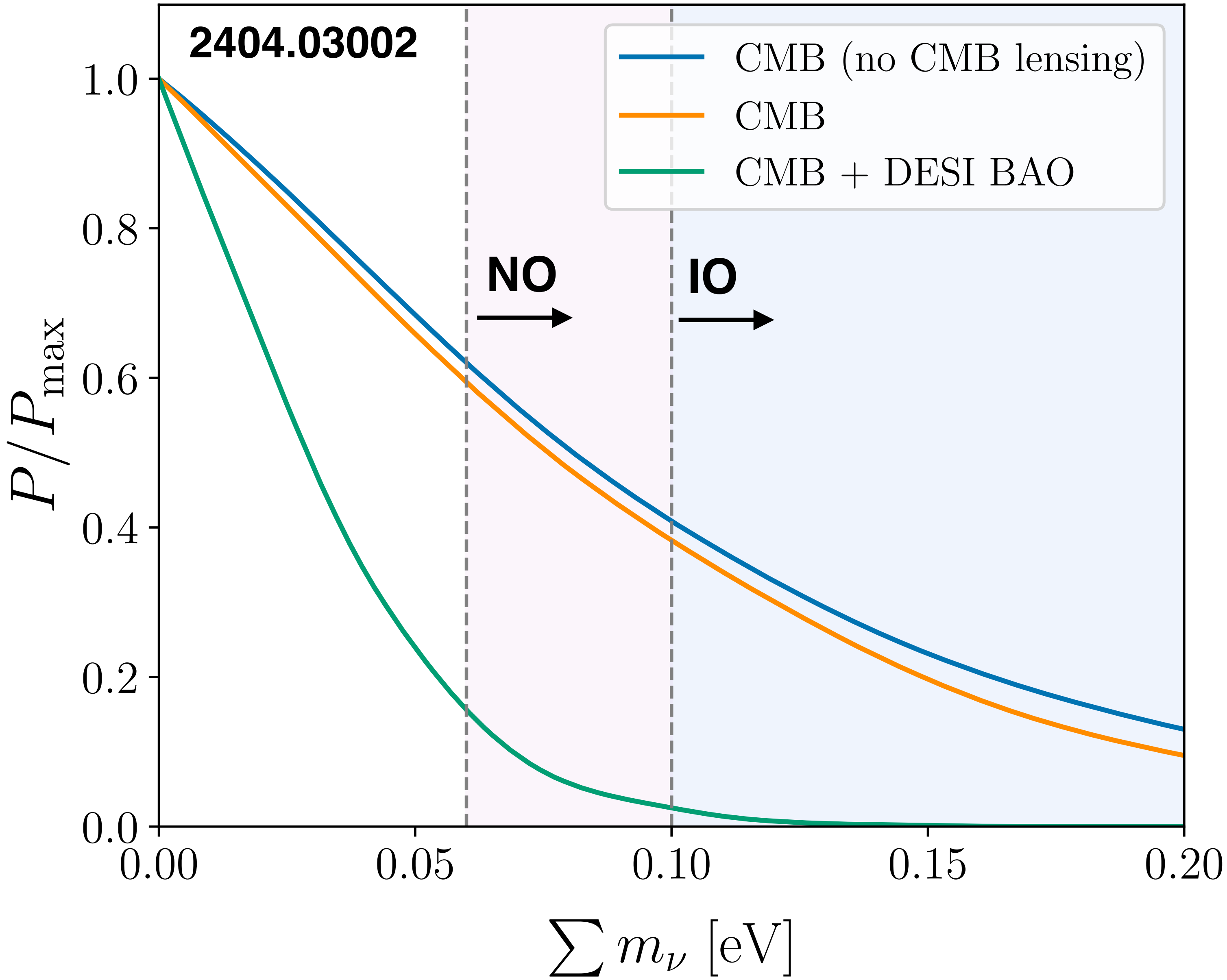
CERN

ISAPP School 2024
Neutrinos and Dark Matter
in the lab and in the Universe
18-09-2024

The Context

On April 2024 the DESI collaboration presented the cosmological results from their 1st year of observations. The results have key implications for the neutrino mass.

$$\sum m_\nu < 0.073\,\mathrm{eV}$$ **(95 % CL, CMB+BAO-DESIY1)**



Outline

Neutrino Masses in Cosmology

Cosmological implications of a neutrino mass

- Physical effects
- Data sets

Cosmological bounds on the neutrino masses

- Dependence upon the data sets
- Dependence upon statistical procedure used
- Cosmological model dependence

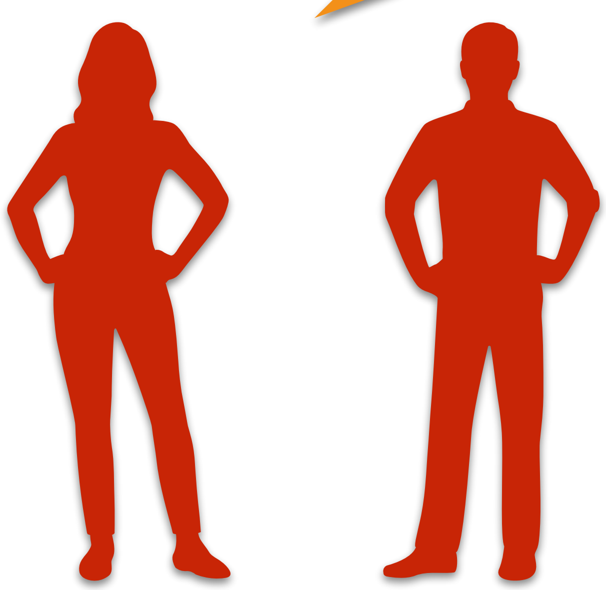
Hubble tension: Status & Implications for m_ν

Set Up

Unlike neutrinos, I do like to interact 😃

The plan is to learn and therefore:

Questions and Comments are most welcome, at any time!!!!



(great thanks to those who asked questions yesterday!)

Key Equations from yesterday

Key things to remember:

- **Neutrinos decouple at a temperature of $T \simeq 2\,\mathrm{MeV}$ and this is the time at which the Cosmic Neutrino Background forms**

- **The Cosmic Neutrino Background is almost a perfect blackbody spectrum with $T_\nu = T_\gamma/1.4$**

- **The average energy of a relativistic particle is $\langle E \rangle \simeq 3T$. A neutrino becomes non-relativistic when $m_\nu \simeq 3T_\nu$ which happens at**

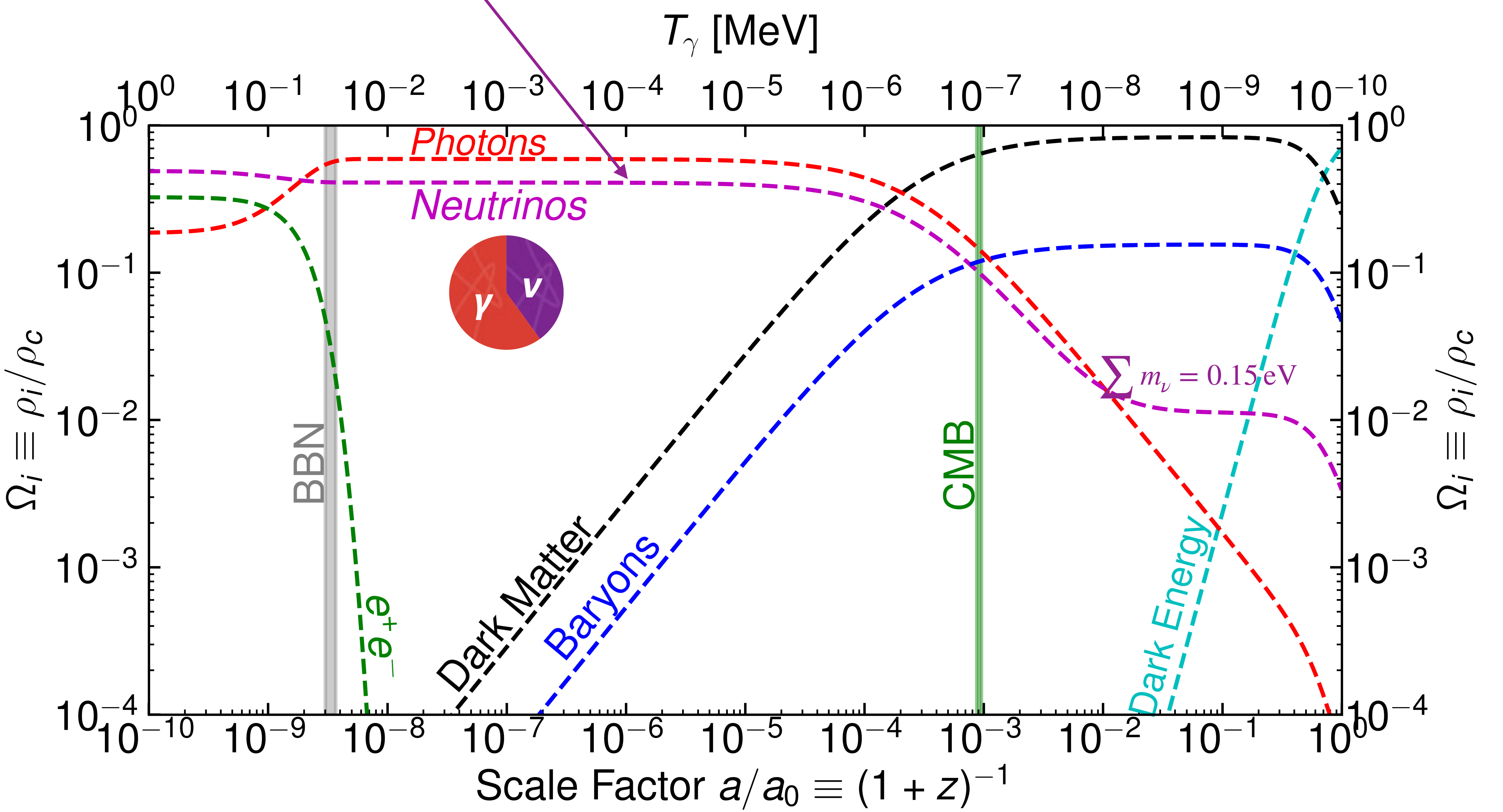
$$z_\nu^{\mathrm{non-rel}} \simeq 200 \frac{m_\nu}{0.1\,\mathrm{eV}}$$

- **Energy density is simply $\rho = \langle E \rangle \times n$, which implies at $T_\nu \ll m_\nu$:**

$$\Omega_\nu h^2 = \frac{\rho_\nu}{\rho_c/h^2} = \sum m_\nu/(93.14\,\mathrm{eV})$$

Neutrino Evolution

Neutrinos are always a relevant species in the Universe's evolution

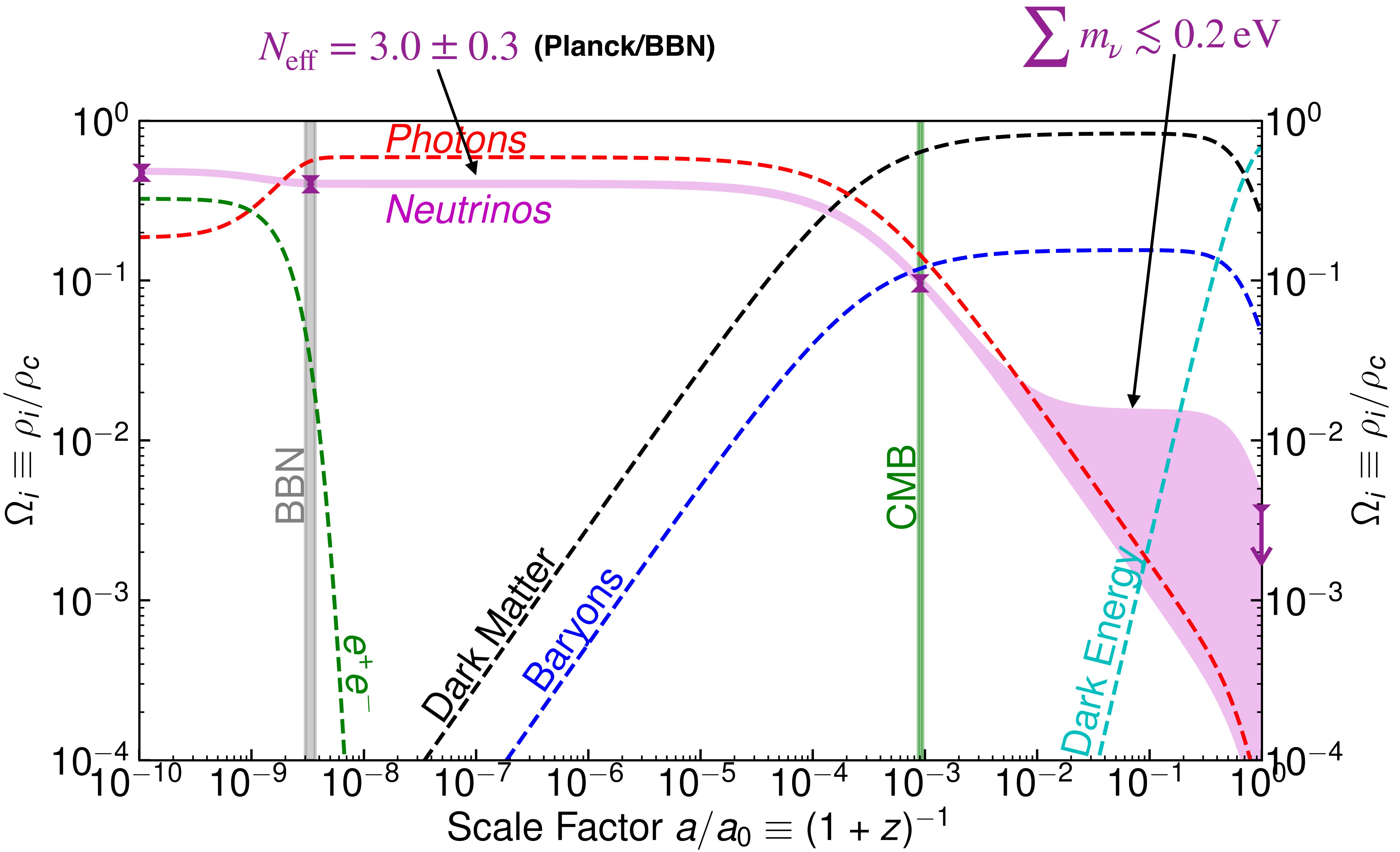


Non-Rel: $z_\nu^{\mathrm{non-rel}} \simeq 200 \frac{m_\nu}{0.1\,\mathrm{eV}}$

Hot DM: $\Omega_\nu h^2 = \sum m_\nu/(93.14\,\mathrm{eV})$

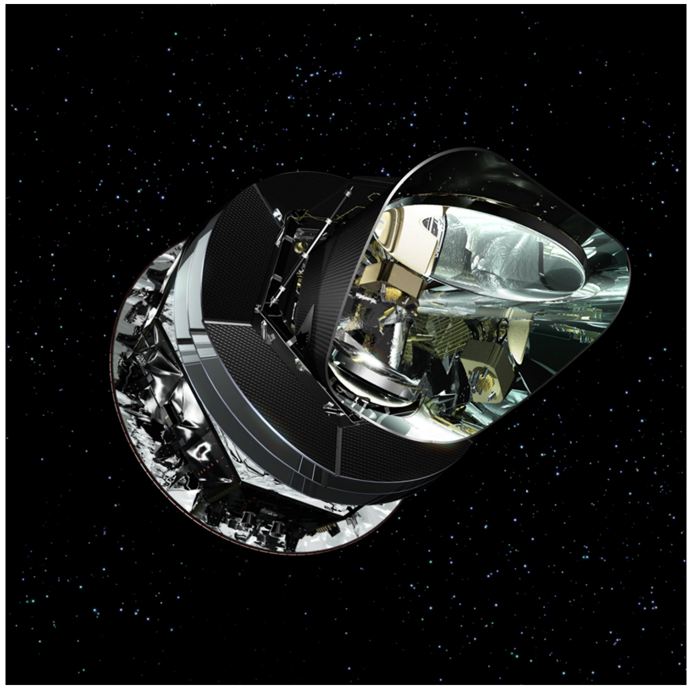
Global Perspective

Current knowledge:

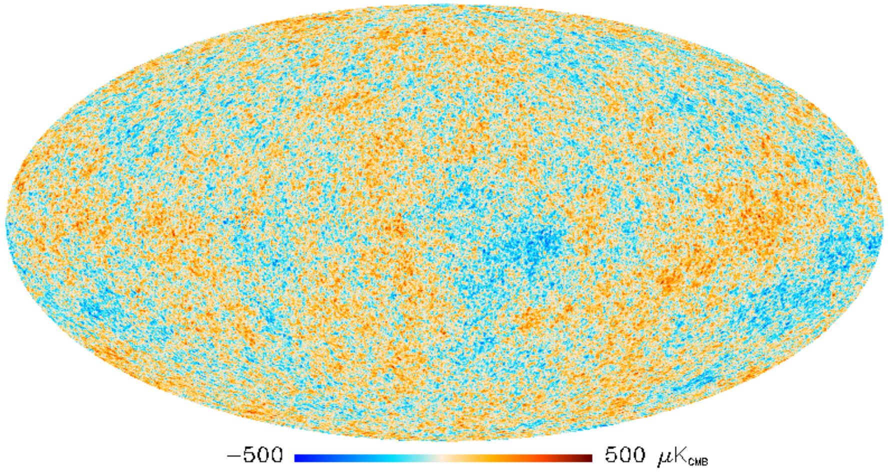


Main players of today

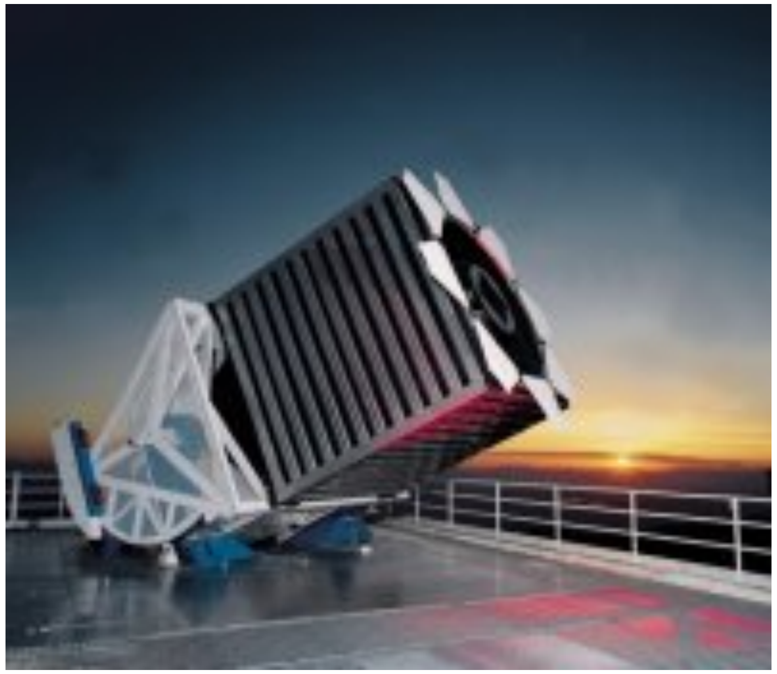
Planck



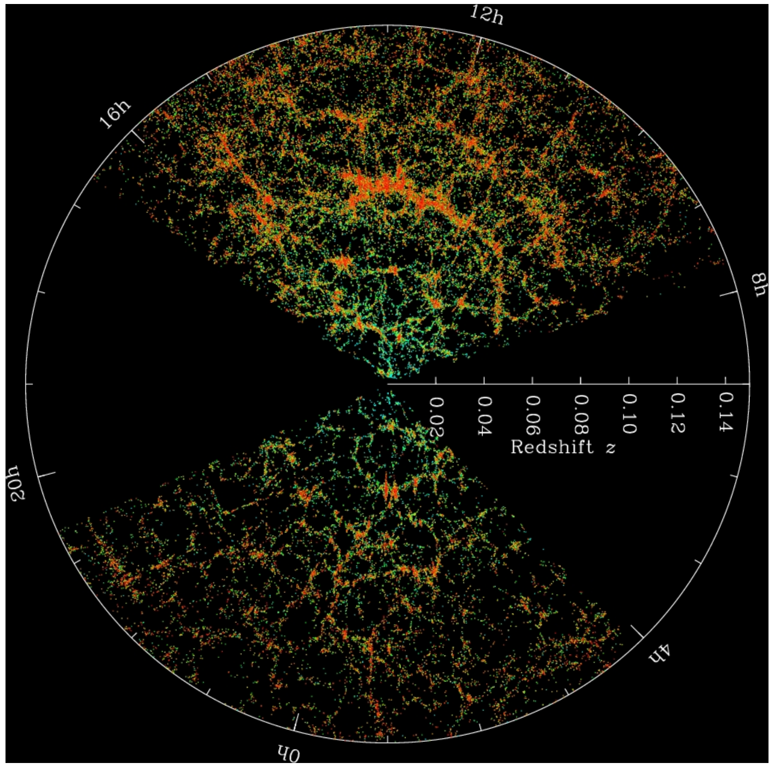
full sky, with
$\Delta T/T \simeq 2 \times 10^{-6}$ **to** $\theta \simeq 0.2^\circ$



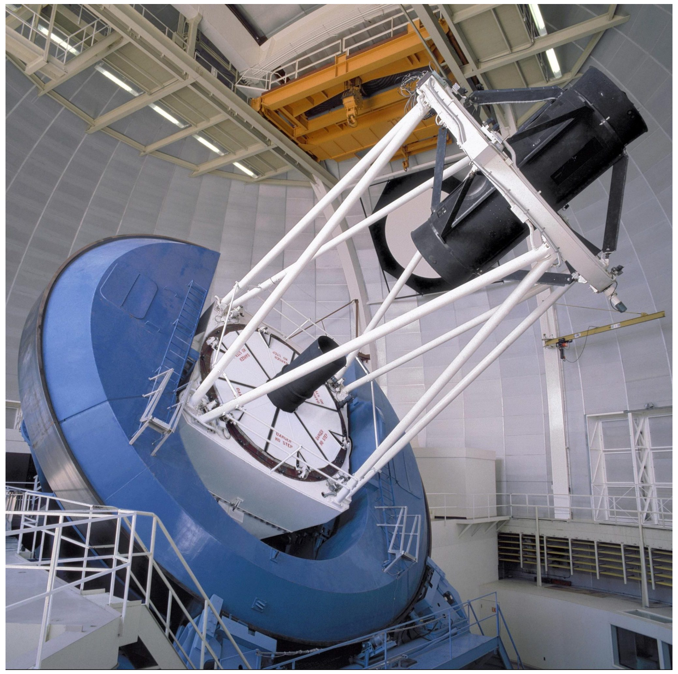
SDSS



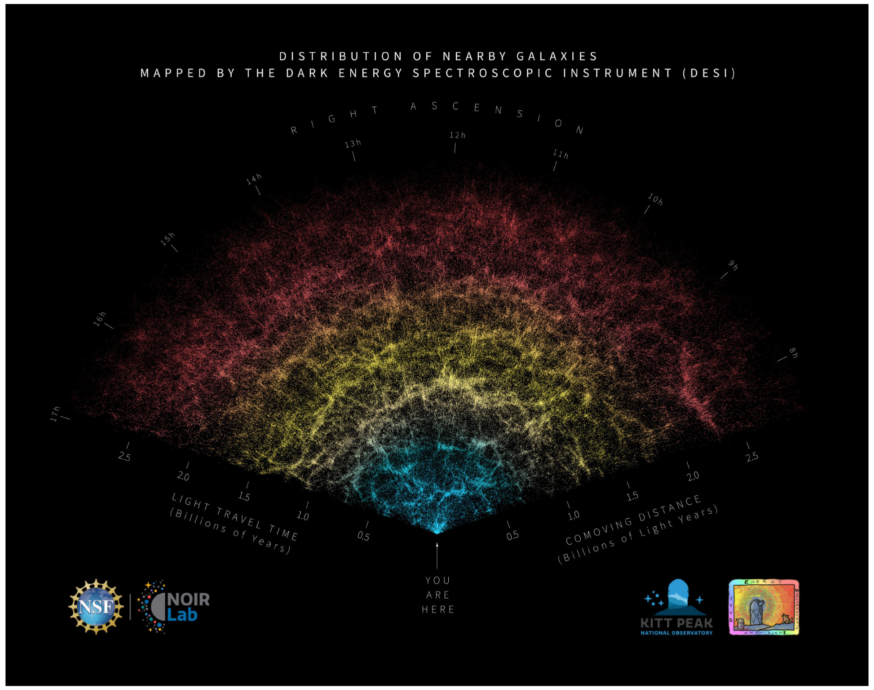
1.5M galaxies



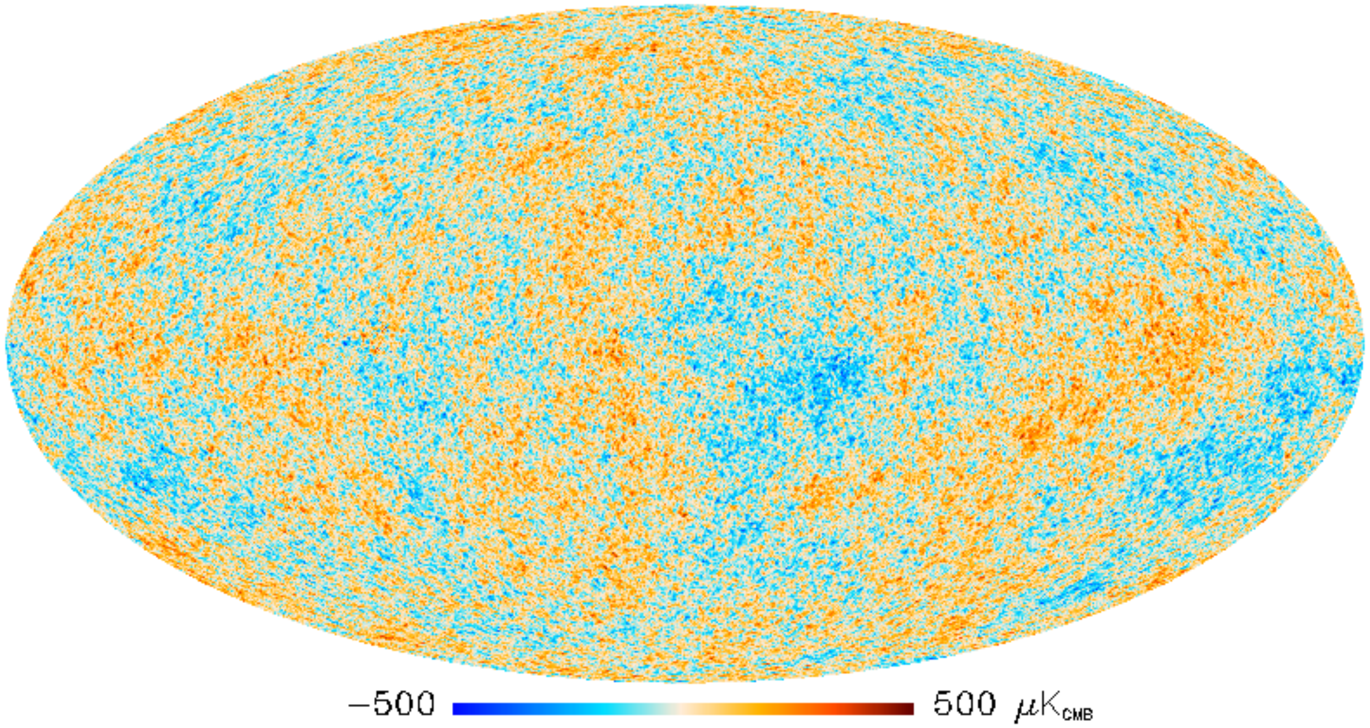
DESI



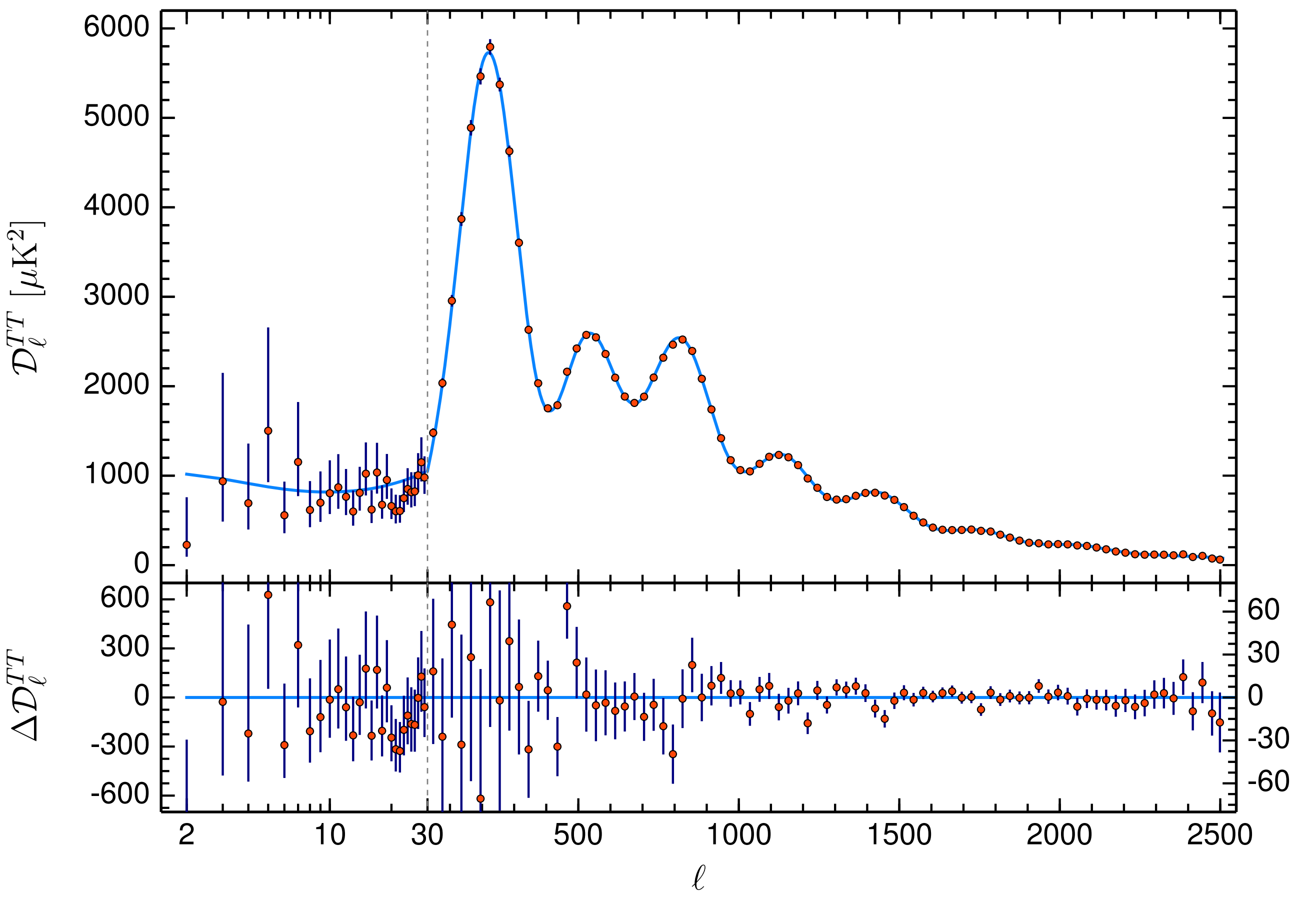
5M galaxies



The Data: CMB

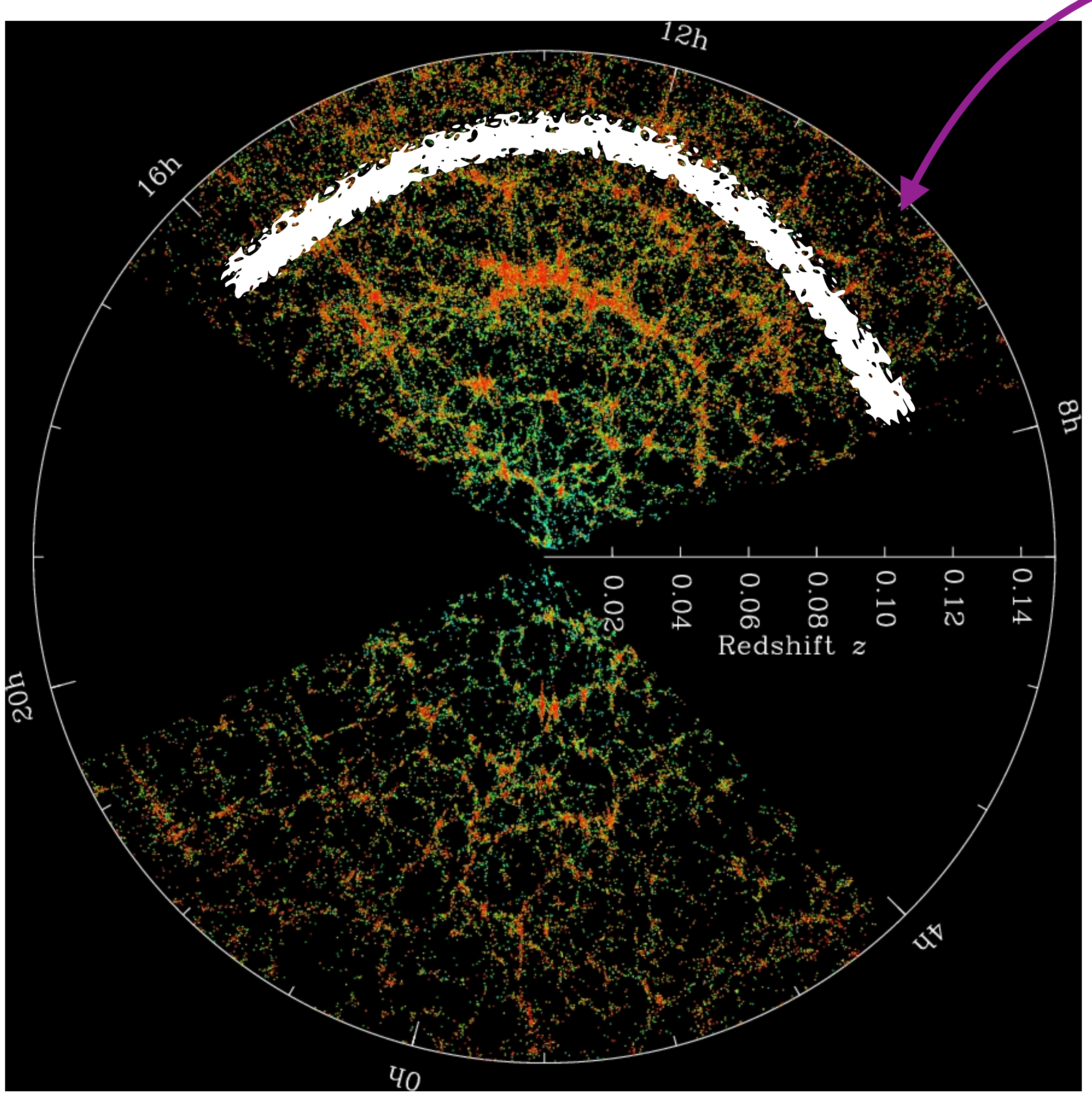


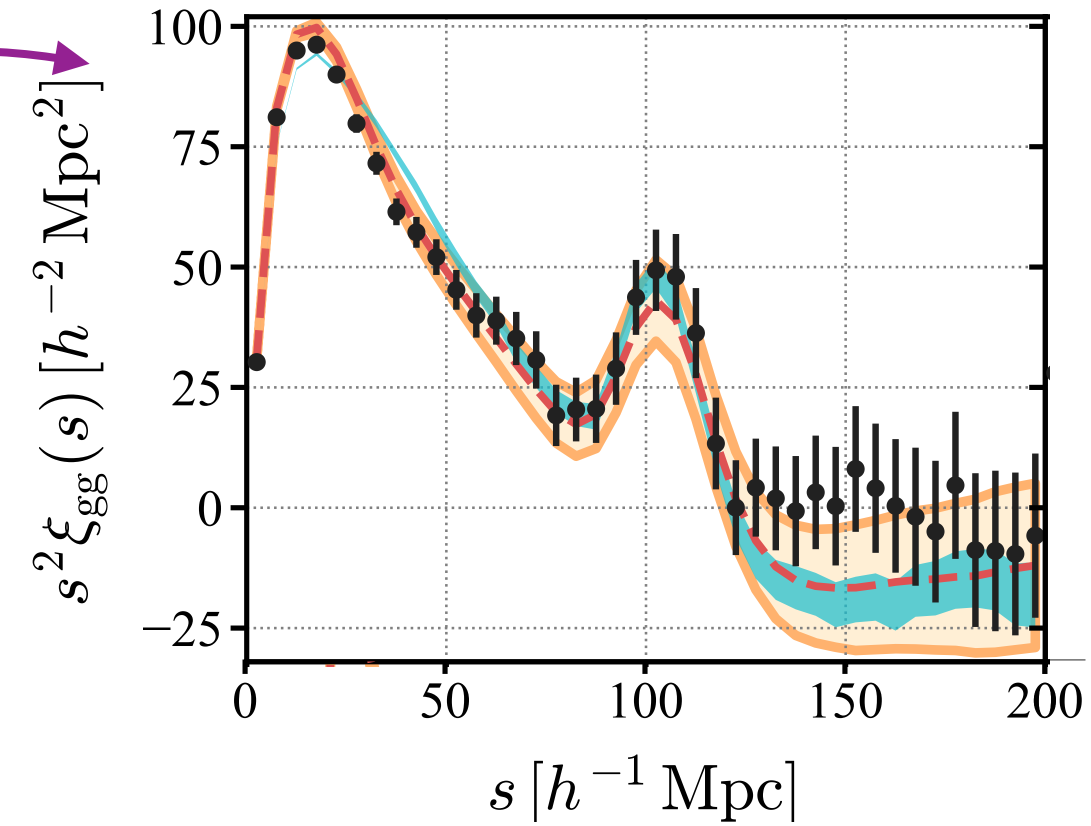
−500
500 μK$_{\rm CMB}$

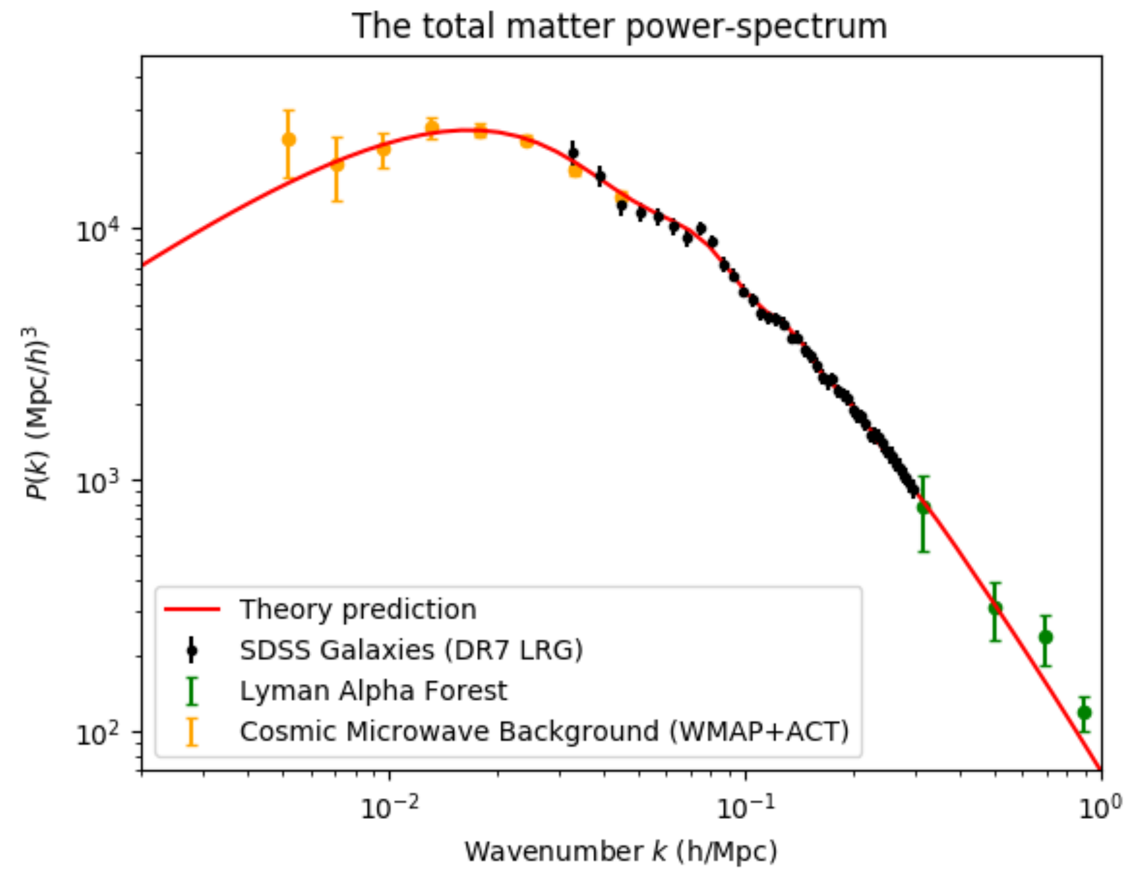


6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}$ [μK^2]
600
300
0
-300
-600
$\Delta\mathcal{D}_\ell^{TT}$
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ

The Data: Galaxy Clustering







Evidence for Cosmic Neutrinos

- **Current constraints**

BBN	$N_{\rm eff}^{\rm BBN} = 2.86 \pm 0.28$	**Pisanti et al. 2011.11537**
Planck+BAO	$N_{\rm eff}^{\rm CMB} = 2.99 \pm 0.17$	**Planck 2018, 1807.06209**

- **Standard Model prediction:** $N_{\rm eff}^{\rm SM} = 3.043(1)$
- **Data is in excellent agreement with the Standard Model prediction**
- **This provides strong (albeit indirect) evidence for the Cosmic Neutrino Background.**

Yesterday! **Today!**

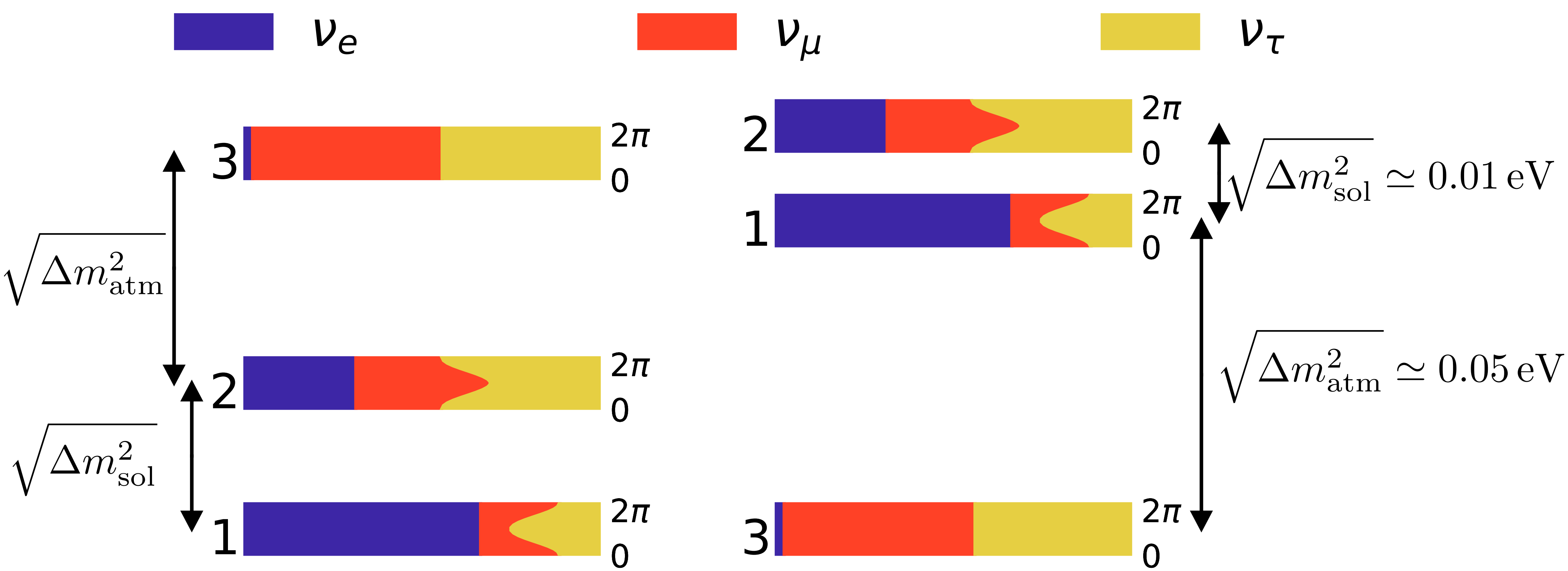
Implications:

1) Stringent constraint on many BSM settings ← Yesterday!

2) We can use cosmological data to test neutrino properties ← Today!

Neutrino Properties

Figure from de Salas et al. 1806.11051



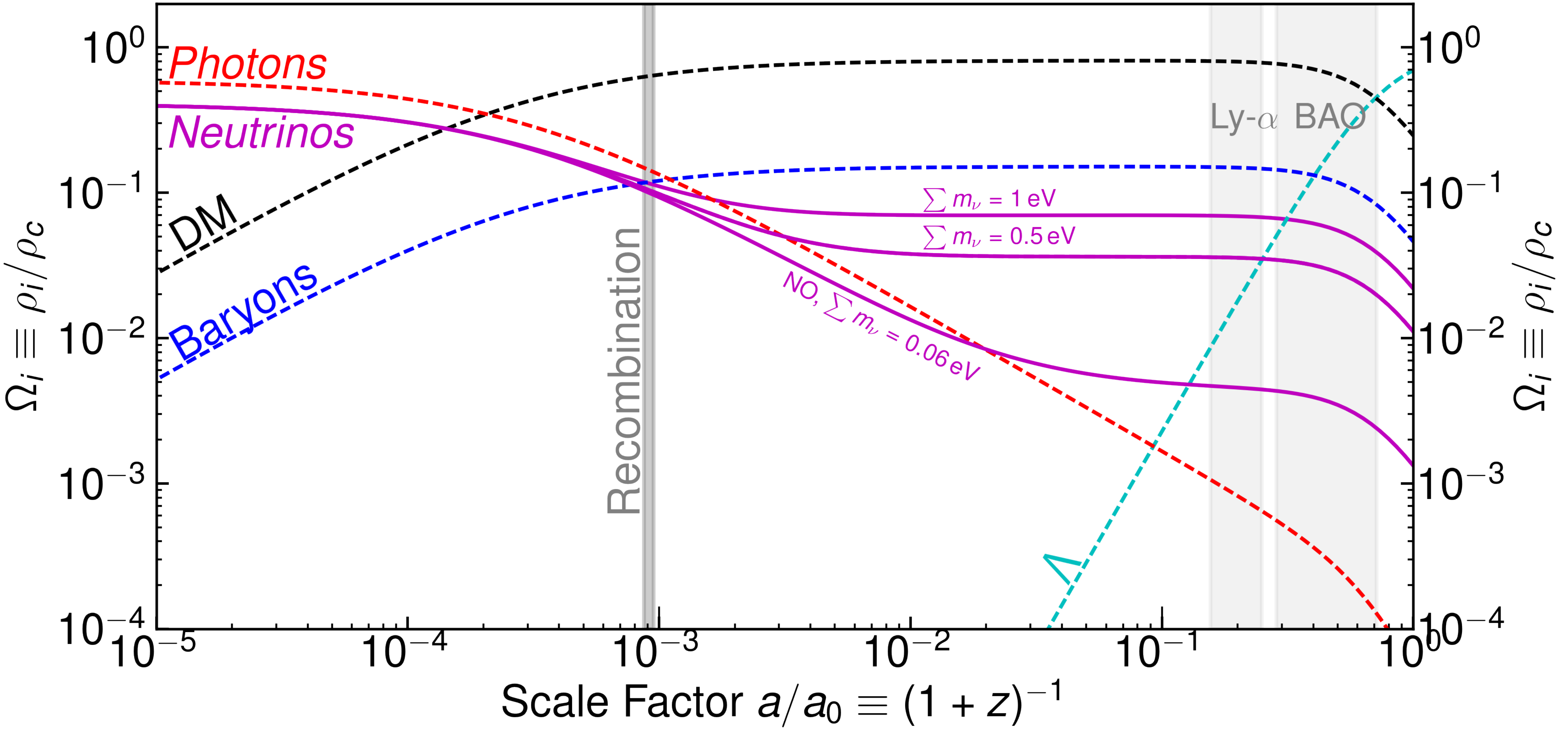
Normal $\sum m_\nu \gtrsim 0.06\,{\rm eV}$

Inverted $\sum m_\nu \gtrsim 0.10\,{\rm eV}$

- **Mass differences and mixings measured with high precision**
- **What is $\delta_{\rm CP}$ and what is the mass ordering?** — Neutrino Oscillations
- **Are Neutrinos Dirac or Majorana particles?** — 0v2β Experiments
- **What is the neutrino mass scale? i.e. Σm_ν? i.e. $m_{\rm lightest}$?** — KATRIN & Cosmology

Neutrino Masses in Cosmology

- **1) Massive neutrinos enhance the expansion history** $H \propto \sqrt{\rho}$



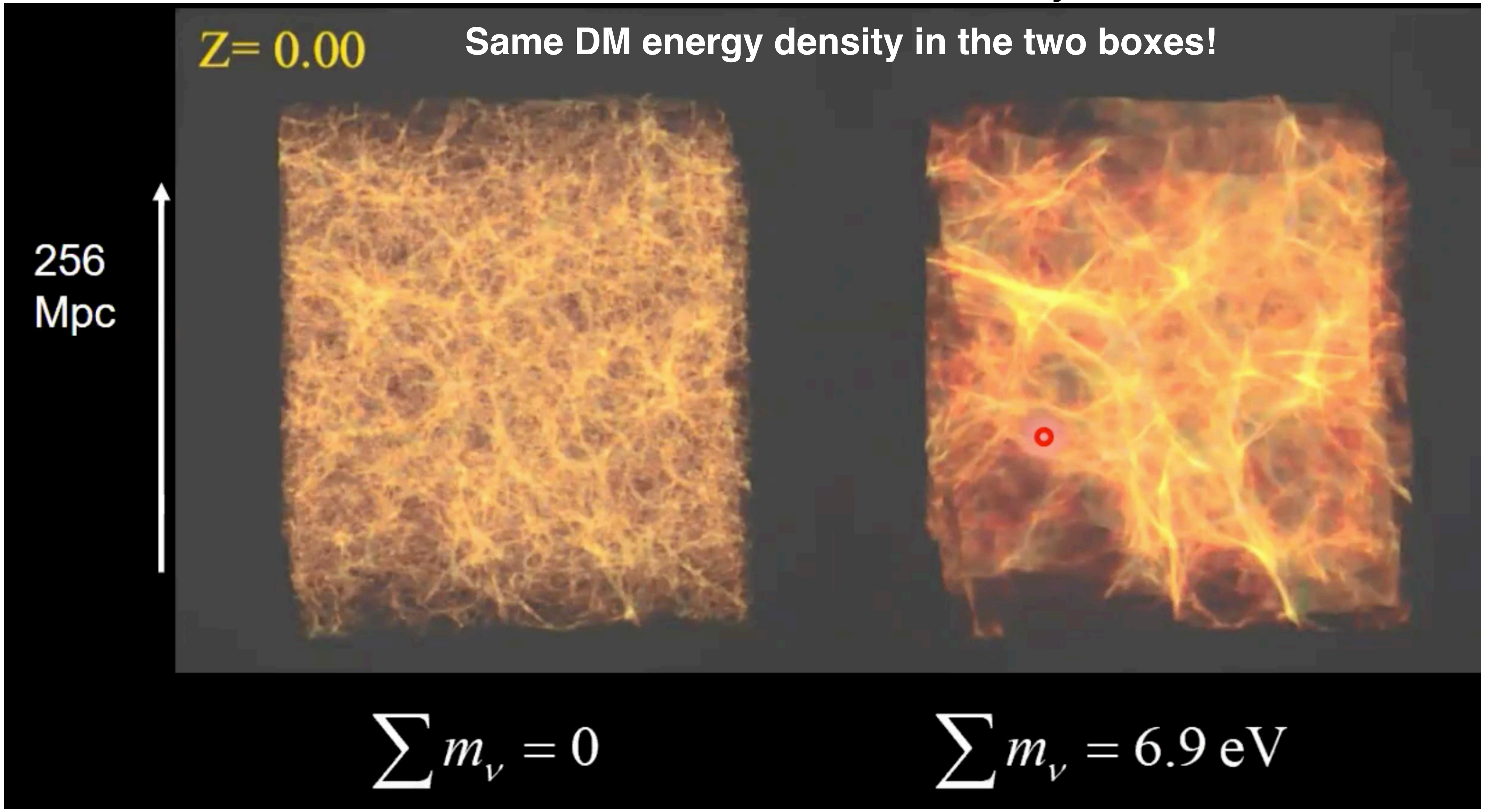
Non-Rel: $z_\nu^{\text{non-rel}} \simeq 200 \dfrac{m_\nu}{0.1\,\text{eV}}$

Hot DM: $\Omega_\nu h^2 = \sum m_\nu/(93.14\,\text{eV})$

Neutrino Masses in Cosmology

- **2) Massive neutrinos suppress the growth of structure**

Taken from a talk by Steen Hannestad Link.



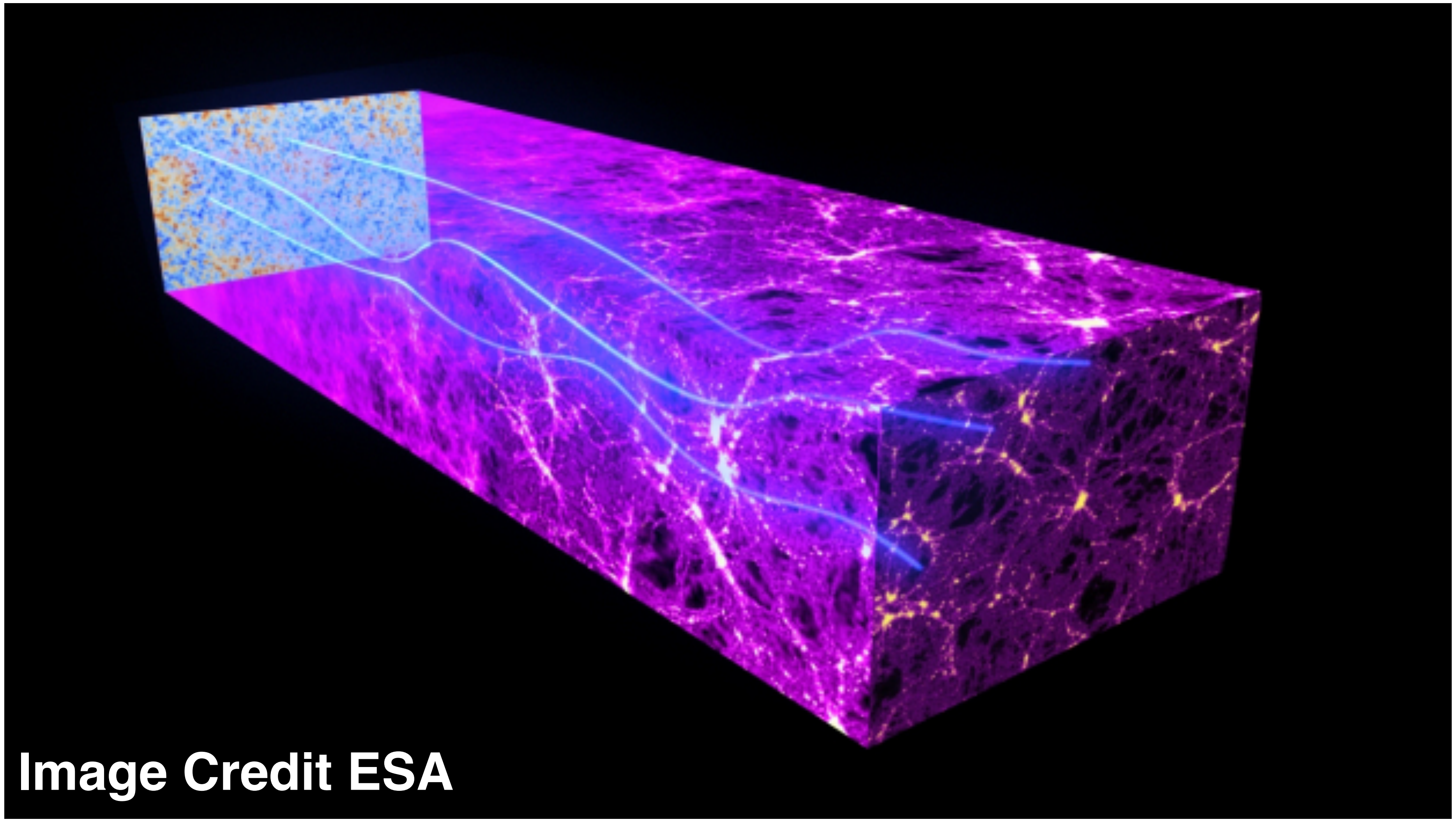
This happens because neutrinos travel very fast and therefore cannot fall in gravitational potentials. The effect of this smoothing is proportional to Ω_ν

Neutrino Masses in Cosmology

Cosmic Microwave Background Anisotropies

Neutrinos of $m_\nu < 0.5\,\mathrm{eV}$ become non-relativistic after recombination. That means that their effect on the anisotropies is somewhat small!

The most relevant impact is through the effect of gravitational lensing:

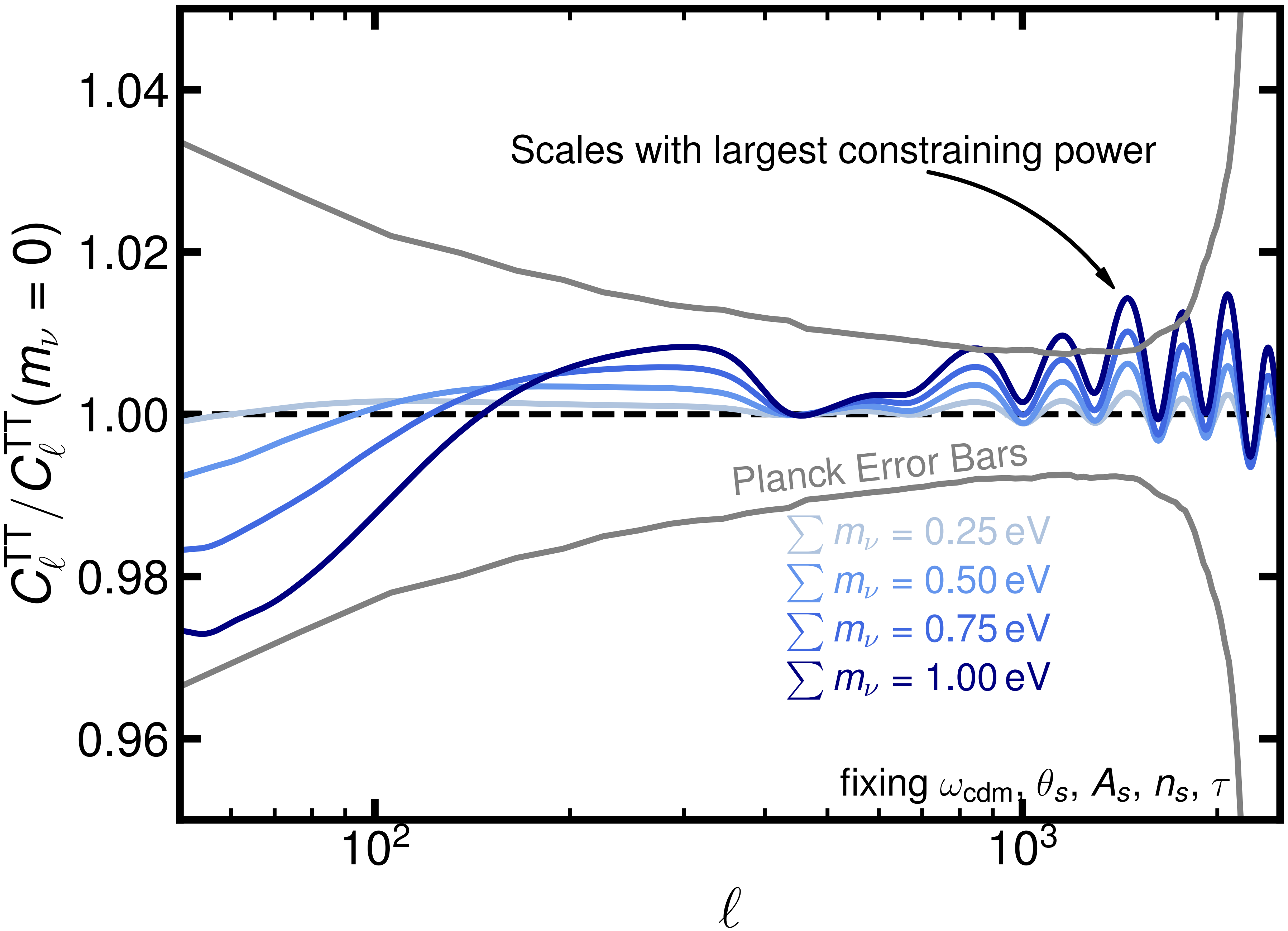


The larger the neutrino mass the less is the CMB light lensed!

Neutrino Masses in Cosmology

Cosmic Microwave Background Anisotropies

The effect of neutrino masses in the CMB:



$$\sum m_\nu < 0.54\,\mathrm{eV}$$

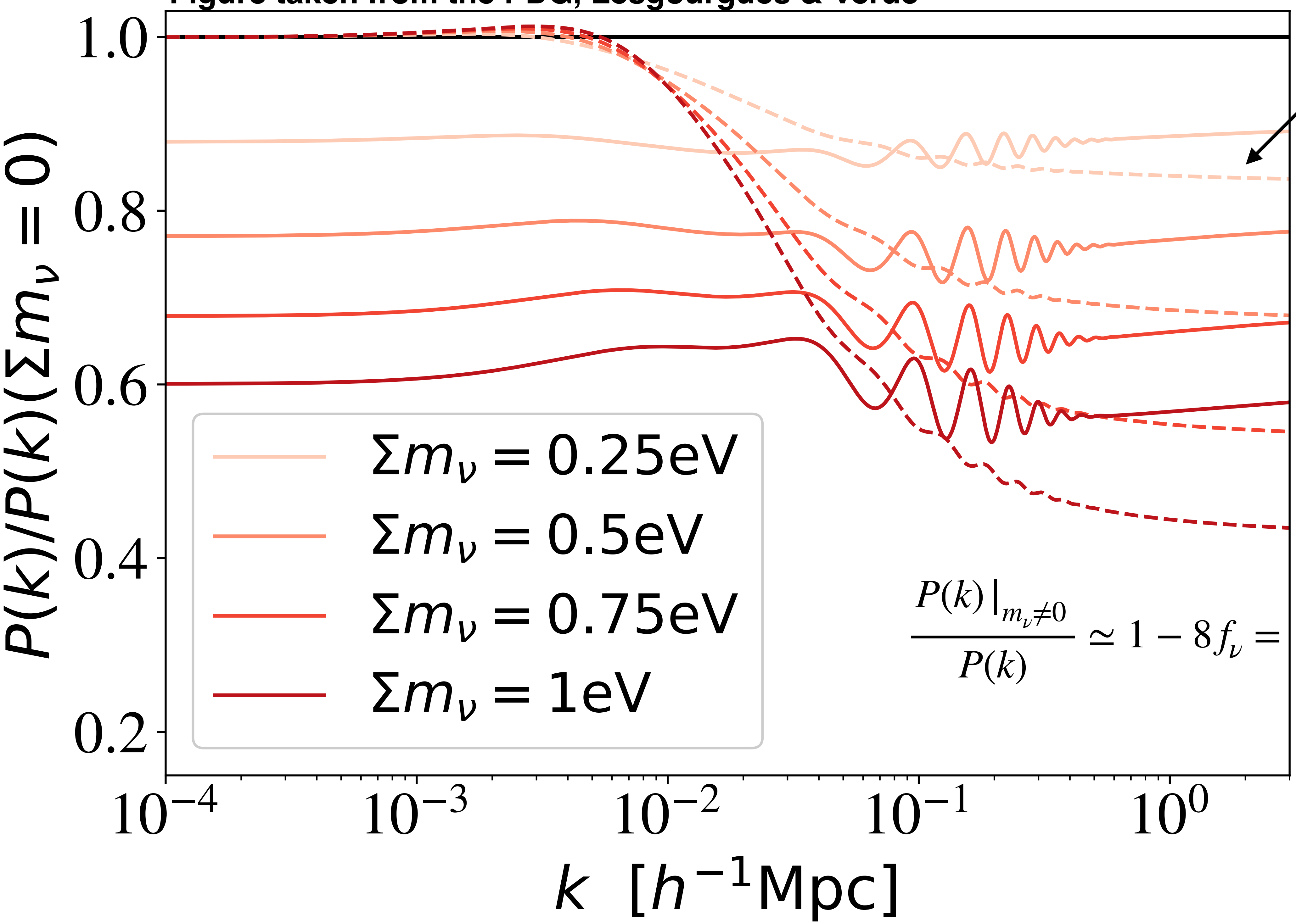
(95 % CL, TT+lowE)

Neutrino Masses in Cosmology

Galaxy Surveys

Suppression from $\Omega_\nu h^2$

Figure taken from the PDG, Lesgourgues & Verde



$$\frac{P(k)\,|_{m_\nu \neq 0}}{P(k)} \simeq 1 - 8 f_\nu = 1 - 8\,\frac{\Omega_\nu}{\Omega_{\rm cdm} + \Omega_b + \Omega_\nu}$$

Neutrino Masses in Cosmology

On the Standard Model of Cosmology:

ΛCDM ≡ Universe currently dominated by a Cosmological Constant and with Cold Dark Matter

Model parametrized by 6 parameters: $\Omega_b h^2 \quad \Omega_{\rm cdm} h^2 \quad A_s \quad n_s \quad \tau_{\rm reio} \quad \theta_s$

Parameter degeneracies with the neutrino mass:

see e.g. Archidiacono et al. [1610.09852]

$\sum m_\nu$ **is strongly correlated with** H_0 **and** Ω_m

because:

1) The amount of lensing is strongly correlated with the dark matter abundance too

2) The angular diameter distance to recombination is also constrained by these two parameters

BAO data can break precisely these degeneracies!

Neutrino Masses from Cosmology

Planck 2018 for ΛCDM (1807.06209)

$$\sum m_\nu < 0.54\,\mathrm{eV}$$ **(95 % CL, TT+lowE)**

$$\sum m_\nu < 0.26\,\mathrm{eV}$$ **(95 % CL, TTTEEE+lowE)**

$$\sum m_\nu < 0.24\,\mathrm{eV}$$ **(95 % CL, TTTEEE+lowE+lensing)**

$$\sum m_\nu < 0.12\,\mathrm{eV}$$ **(95 % CL, TTTEEE+lowE+lensing+BAO-SDSS)**

DESI (2404.03002)

$$\sum m_\nu < 0.073\,\mathrm{eV}$$ **(95 % CL, CMB+BAO-DESIY1)**

To be compared to the KATRIN bound: $\sum m_\nu < 1.5\,\mathrm{eV}$

But also with the minimal possible value!

$$\sum m_\nu \gtrsim 0.06\,\mathrm{eV} \qquad \sum m_\nu \gtrsim 0.10\,\mathrm{eV}$$

Neutrino Masses from Cosmology

$$\sum m_\nu < 0.073\,\mathrm{eV}$$ **(95 % CL CMB+BAO-DESIY1)**

Very robust bounds from linear Cosmology $\Delta T/T \sim 10^{-5}$

What about other non-linear cosmological data?

What about possible systematics in the Planck CMB and BAO data?

What is the dependence upon the assumed statistical procedure?

And, all cosmological bounds are cosmological model dependent

What is the dependence upon the assumed Cosmological Model?

Neutrino Masses from Cosmology

Data beyond Planck within ΛCDM

$\sum m_\nu < 0.26\,\mathrm{eV}$	**Planck**	**Planck 1807.06209**
$\sum m_\nu < 0.12\,\mathrm{eV}$	**Planck+SDSS-BAO**	**Planck 1807.06209**
$\sum m_\nu < 0.073\,\mathrm{eV}$	**CMB+DESI-BAO**	**DESI 2404.03002**
$\sum m_\nu < 0.86\,\mathrm{eV}$	**SDSS P(k)**	**Ivanov et al. 1909.05277**
$\sum m_\nu < 0.16\,\mathrm{eV}$	**Planck+SDSS P(k)**	**Ivanov et al. 1912.08208**
$\sum m_\nu < 0.58\,\mathrm{eV}$	**Lyman-α+H_0prior**	**Palanque-Delabrouille et al. 1911.09073**
$\sum m_\nu < 0.10\,\mathrm{eV}$	**Planck+Lyman-α**	
$\sum m_\nu < 0.048\,\mathrm{eV}$	**Planck+DESI+H_0**	**Jiang et al. 2407.18047**
$\sum m_\nu < 0.081\,\mathrm{eV}$	**Planck+DESI+SN**	**Jiang et al. 2407.18047**

- **Planck+BAO drive current cosmological constraints [compare DESI and SDSS]**
- **Non-linear or mildly non-linear data sets break degeneracies in the fit**
- **The larger H_0 is, the stronger the constraint on $\sum m_\nu$ is** **(However, this comes from combining two data sets in strong tension!)**

Neutrino Masses from Cosmology

Not only the bounds are stringent but there is no sign for a non-zero neutrino mass!

Jiang et al. [2407.18047]

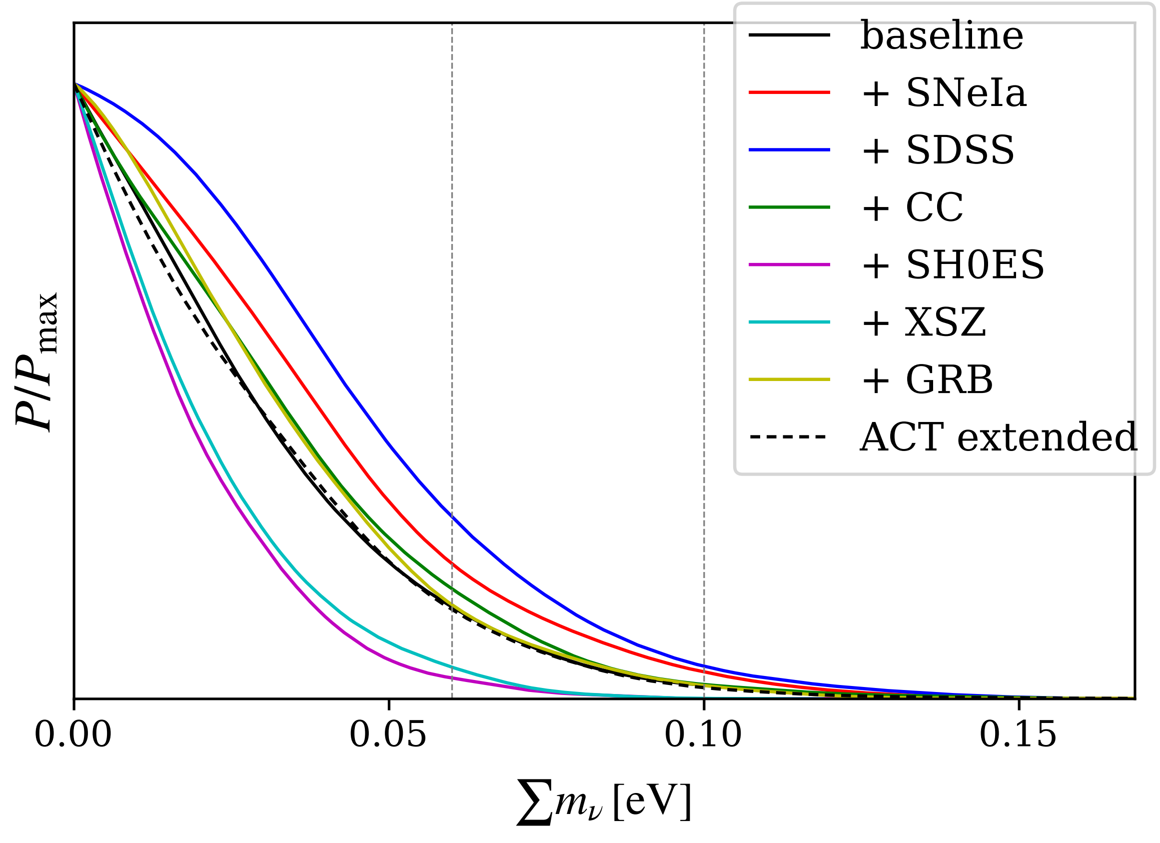
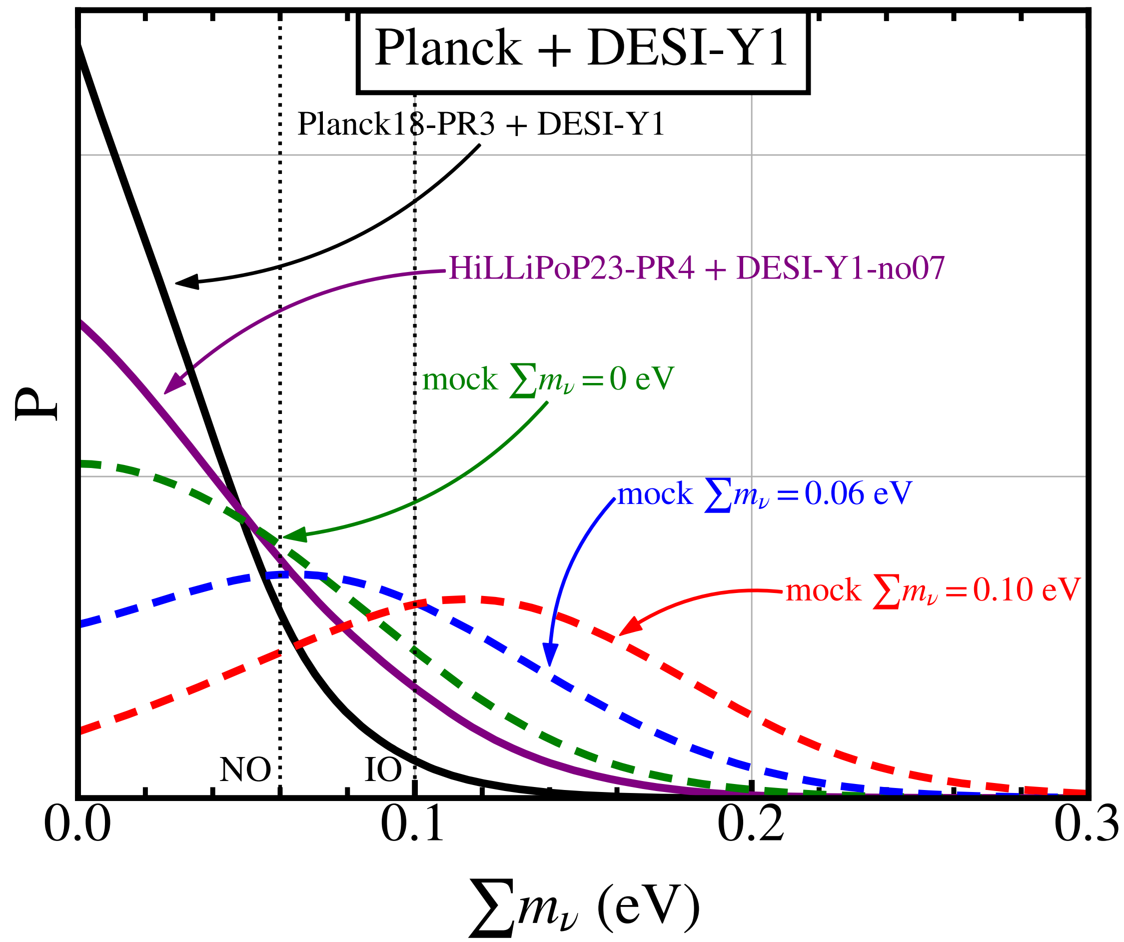


FIG. 1. Posterior distributions for the sum of the neutrino masses $\sum m_\nu$ (in eV) obtained within the 7-parameter ΛCDM+$\sum m_\nu$ model in light of different dataset combinations, as per the color coding.

Naredo-Tuero et al. [2407.13831]



Neutrino Masses from Cosmology

Neutrino masses and the Planck lensing anomaly

There is an anomaly in the Planck 2018 data at high multipoles which could potentially have relevant implications for the neutrino mass constraints

This tension (3σ) is parametrized in terms of the A_L parameter, which is an *unphysical parameter* modifying the amplitude of the lensing spectrum!

Importantly, the Planck collaboration claims that the most likely origin of this tension is a statistical fluctuation:

1807.06209

***Planck* 2018 results. VI. Cosmological parameters**

If the $A_L > 1$ preference is simply a statistical excursion (perhaps the most likely explanation), this indicates that there are random features in the spectrum that are pulling some parameters unusually far from expected values.[30] There are several

In addition, more recent analyses of the Planck data do point in that direction:

see Rosenberg, Gratton & Efstathiou 2205.10869

The lower noise of the NPIPE maps leads to tighter parameter constraints, with a ~10% improvement in most ΛCDM parameters in TTTEEE due primarily to improvements in polarization. For ΛCDM extensions we find that, relative to PR3, NPIPE polarization shrinks the error bars on Ω_K and A_L from EE by 40% and 25% respectively, and by 15% and 8% in TTTEEE. That these smaller error bars are accompanied by shifts toward the ΛCDM values continues the trend observed in EG21 of decreasing the Ω_K and A_L tensions as more data is used, as would be expected if these pulls were due to a statistical fluctuation. Overall, we conclude that NPIPE, despite

see Tristan et al 2309.10034

With *Planck* PR4, we find results even more compatible with unity compared to previous releases. Indeed for TTTEEE, we now obtain

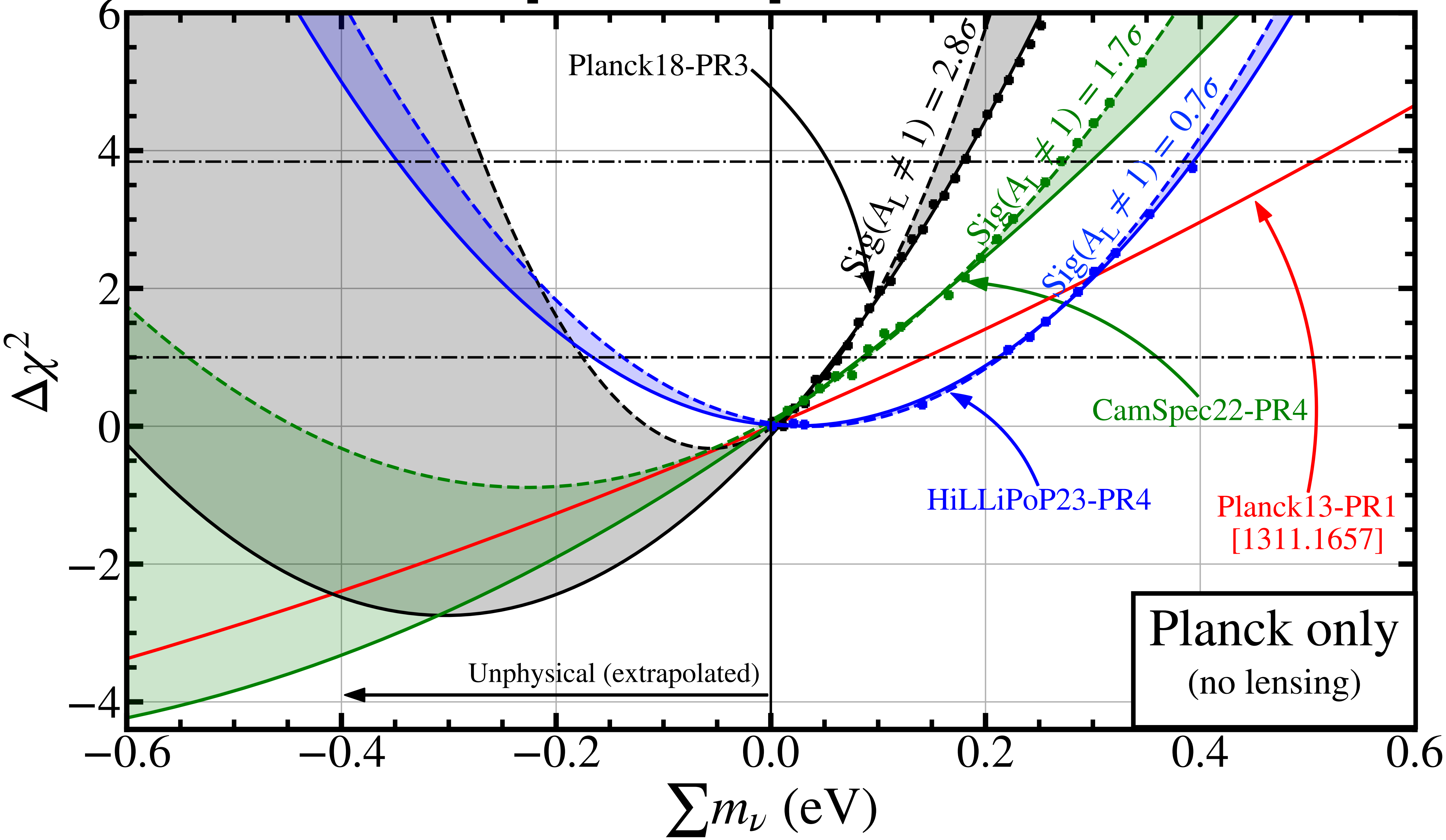
$$A_L = 1.039 \pm 0.052, \quad (35)$$

which is compatible with the ΛCDM expectation (at the $0.7\,\sigma$ level). As shown in Table 6, while the results for EE and TE

Neutrino masses and the Planck lensing anomaly

The neutrino mass bound weakens in Planck implementations not featuring the lensing anomaly

Naredo-Tuero et al. [2407.13831]

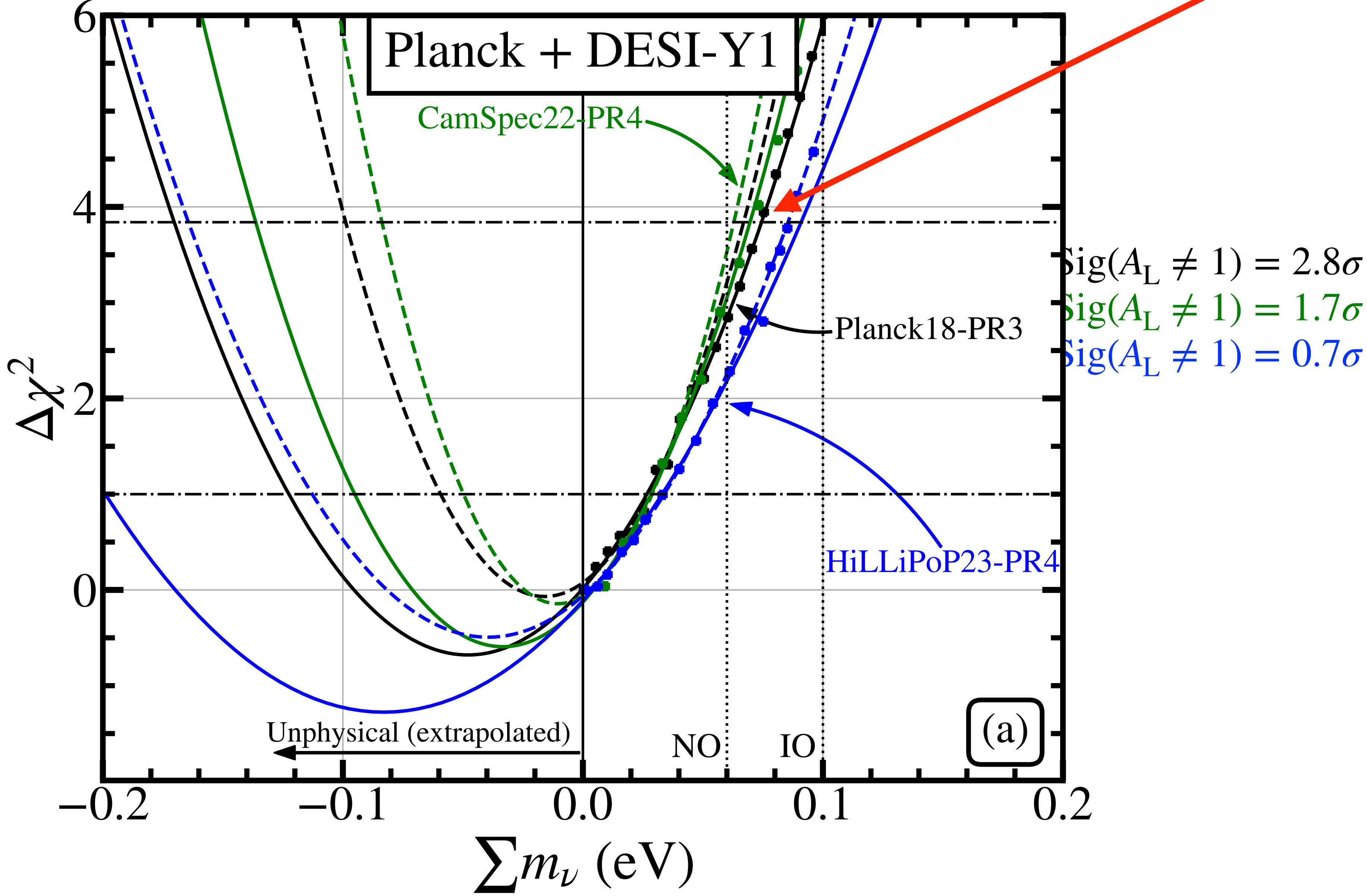


Neutrino Masses from Cosmology

Neutrino masses and the Planck lensing anomaly

The shift is not so significant when adding BAO data but still can vary within 30%!

Naredo-Tuero et al. [2407.13831]

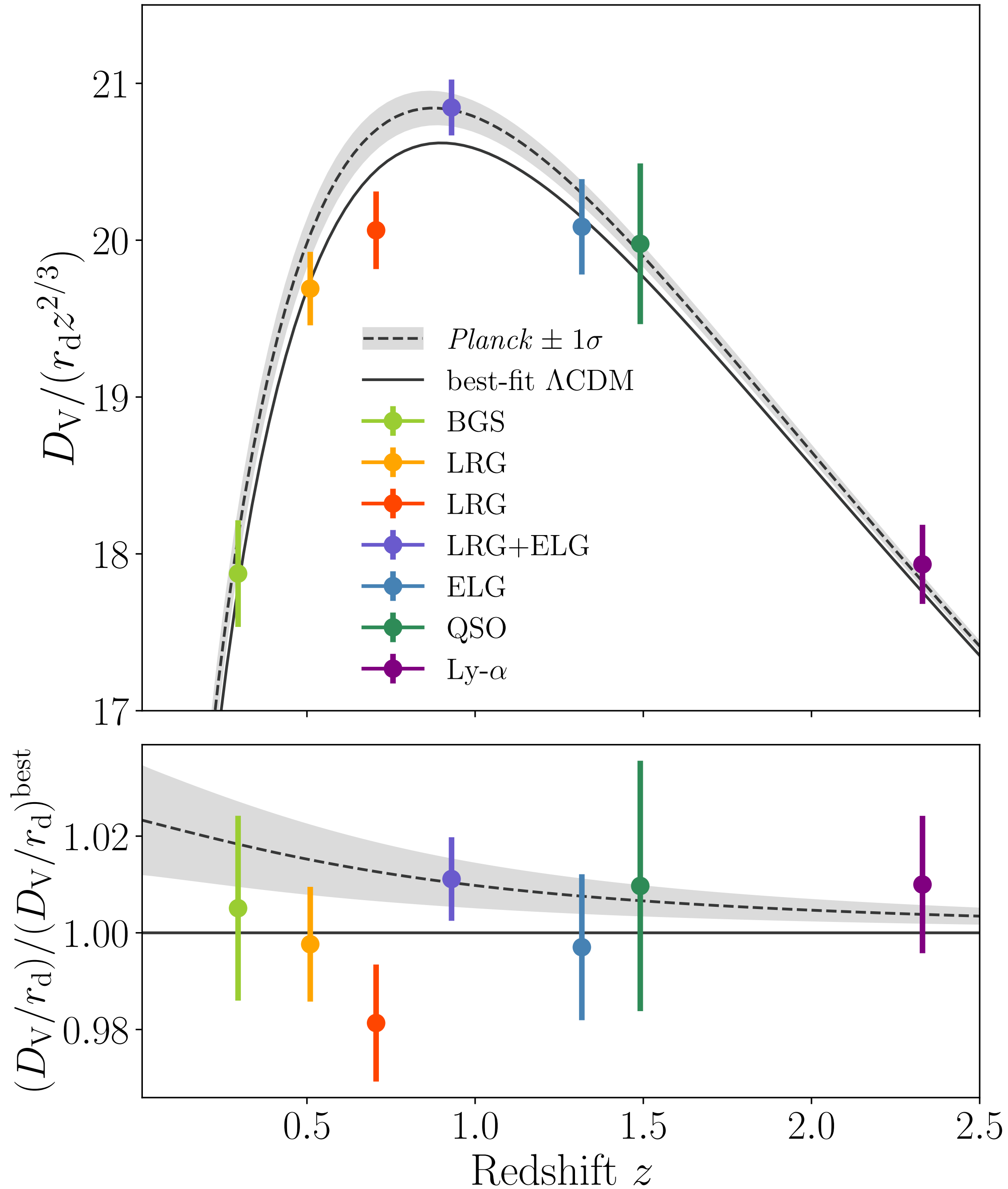


Neutrino Masses from Cosmology

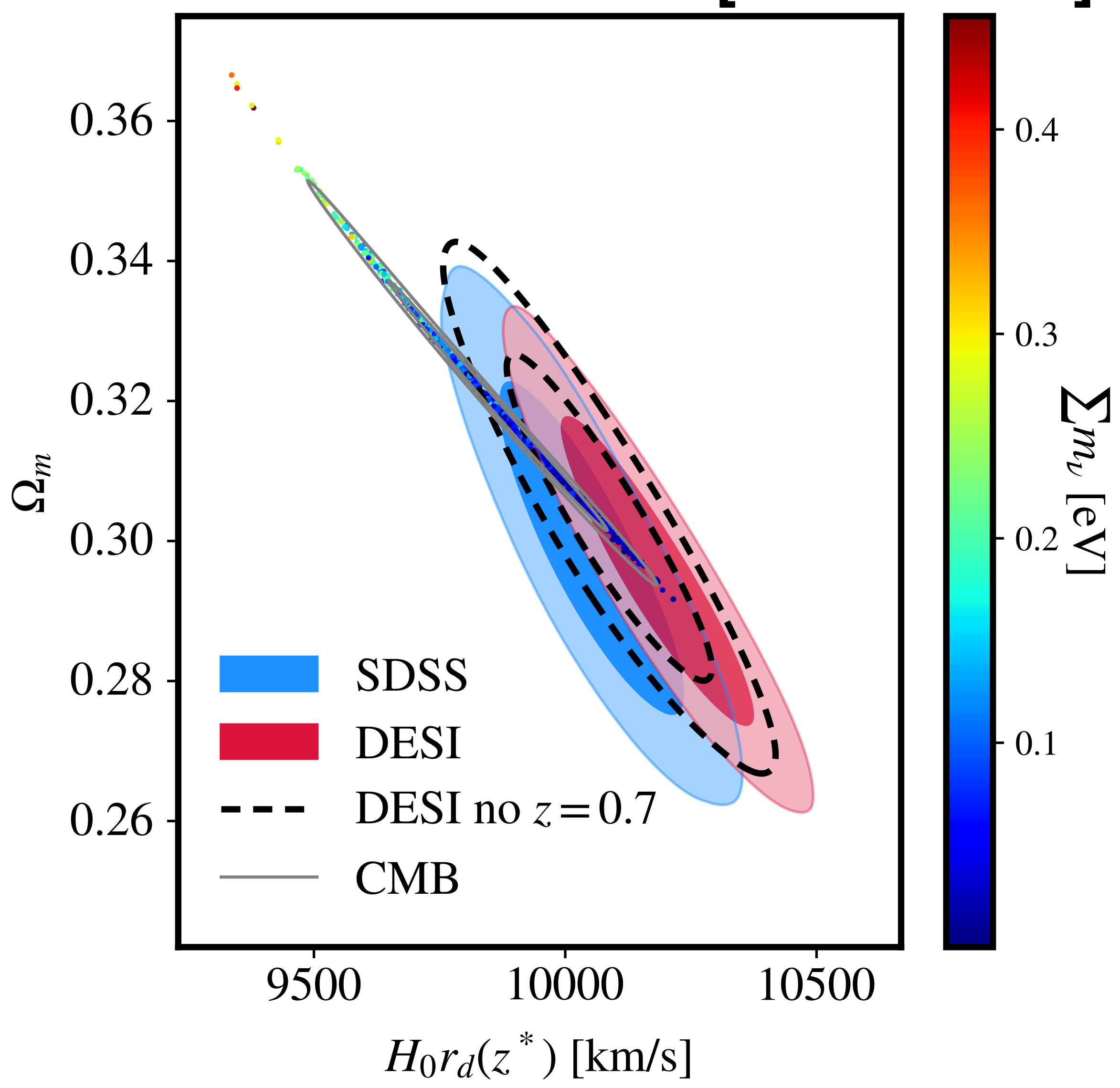
Neutrino masses and DESI BAO data

DESI BAO data is overall in 2σ tension with Planck predictions

DESI [2404.03002]



Naredo-Tuero et al. [2407.13831]



The bound is relaxed by ~30% if the z=0.7 bin is not used in the analysis

Neutrino Masses from Cosmology

Neutrino masses and statistical procedure use

Cosmological analyses are typically performed using Bayesian statistics. That means one needs to impose a prior for all the parameters including the neutrino mass Σm_ν. This adds some level of arbitrariness in the resulting bound.

Cosmological analyses are typically performed using Bayesian statistics.

Naredo-Tuero et al. [2407.13831]

$$\sum m_\nu < 0.084\,\mathrm{eV} \quad [\mathrm{Bayesian}]\,, \tag{5a}$$
$$\sum m_\nu < 0.074\,\mathrm{eV} \quad [\mathrm{Bounded-Likelihood}]\,, \tag{5b}$$
$$\sum m_\nu < 0.071\,\mathrm{eV} \quad [\mathrm{Feldman-Cousins}]\,. \tag{5c}$$

$\Sigma m_\nu \in [0 - 3\,\mathrm{eV}]$

$$\sum m_\nu < 0.121\,\mathrm{eV} \quad [\mathrm{NO-Bayesian}]\,, \tag{6a}$$
$$\sum m_\nu < 0.106\,\mathrm{eV} \quad [\mathrm{NO-Bounded-Likelihood}]\,, \tag{6b}$$
$$\sum m_\nu < 0.096\,\mathrm{eV} \quad [\mathrm{NO-Feldman-Cousins}]\,, \tag{6c}$$

$\Sigma m_\nu \in [0.06 - 3\,\mathrm{eV}]$

$$\sum m_\nu < 0.152\,\mathrm{eV} \quad [\mathrm{IO-Bayesian}]\,, \tag{7a}$$
$$\sum m_\nu < 0.138\,\mathrm{eV} \quad [\mathrm{IO-Bounded-Likelihood}]\,, \tag{7b}$$
$$\sum m_\nu < 0.127\,\mathrm{eV} \quad [\mathrm{IO-Feldman-Cousins}]\,. \tag{7c}$$

$\Sigma m_\nu \in [0.1 - 3\,\mathrm{eV}]$

Overall good agreement between the two (10%). Although they address different questions!

Neutrino Masses from Cosmology

Cosmological Model Dependence

Planck+SDSS and 3 degenerate neutrinos

$\sum m_\nu < 0.12\,\mathrm{eV}$	**Standard Case** Planck 1807.06209	ΛCDM+m_ν
$\sum m_\nu < 0.25\,\mathrm{eV}$	**Dark Energy dynamics** Choudhury & Hannestad 19'	CDM+m_ν+ω_a+ω
$\sum m_\nu < 0.15\,\mathrm{eV}$	**Varying Curvature** Choudhury & Hannestad 19'	ΛCDM+m_ν+Ω_k
$\sum m_\nu < 0.13\,\mathrm{eV}$	**Varying N_{eff}** Planck 1807.06209	ΛCDM+m_ν+N_{eff}
$\sum m_\nu < 0.17\,\mathrm{eV}$	**Varying N_{eff}+ω+α_s+m_ν** di Valentino et al. 1908.01391	CDM+m_ν+N_{eff}+ω+α_s+m_ν

- **Constraints are robust upon standard modifications of ΛCDM**

Neutrino Masses from Cosmology

Cosmological Model Dependence

Non-standard Neutrino Cosmologies:

Invisible Neutrino Decay

$$\nu_i \to \nu_j \phi$$

$$\sum m_\nu \lesssim 0.2\,\mathrm{eV}$$

Oldengott et al. 2203.09075 & 2011.01502
Escudero & Fairbairn 1907.05425

$$\nu_i \to \nu_4 \phi$$

at least: $\sum m_\nu \lesssim 0.42\,\mathrm{eV}$

Abellán, Poulin et al. 1909.05275, 2112.13862
Escudero, López-Pavón, Rius & Sandner 2007.04994

Time Dependent Neutrino Masses

Late phase transition

$$\sum m_\nu < 1.4\,\mathrm{eV}$$

Dvali & Funcke 1602.03191
Lorenz et al. 1811.01991 & 2102.13618

Ultralight scalar field screening

$$\sum m_\nu < 3\,\mathrm{eV}$$

Esteban & Salvadó 2101.05804
Wetterich et al. 1009.2461

Non-standard Neutrino Populations

$$T_\nu < T_\nu^{\mathrm{SM}} + \mathrm{DR}$$

$$\sum m_\nu < 3\,\mathrm{eV}$$

Farzan & Hannestad 1510.02201
Escudero, Schwetz & Terol-Calvo 2211.01729

$$\langle p_\nu \rangle > 3.15\, T_\nu^{\mathrm{SM}}$$

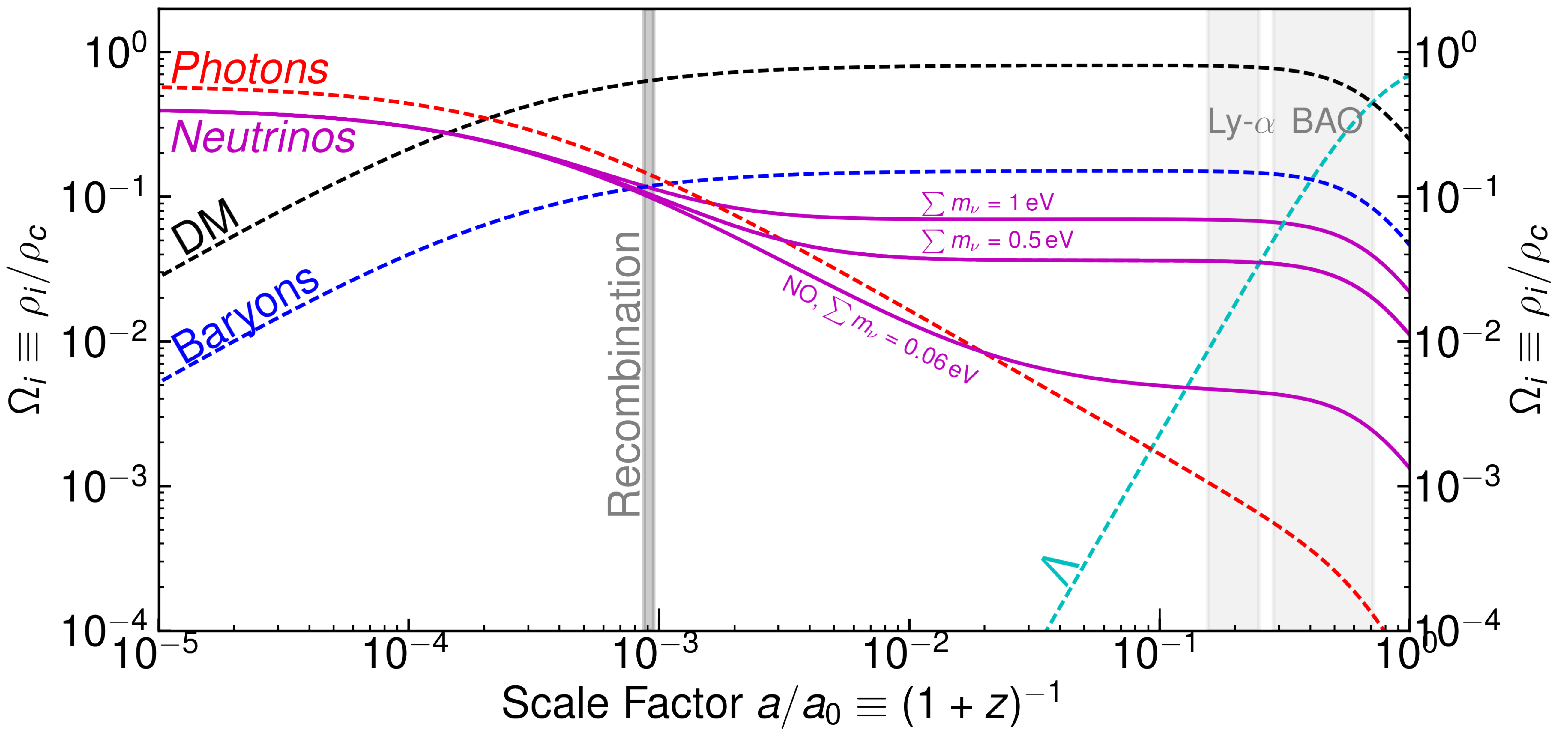
$$\sum m_\nu < 3\,\mathrm{eV}$$

Oldengott et al. 1901.04352
Alvey, Escudero & Sabti 2111.12726

- **Bounds can be significantly relaxed in some extensions of ΛCDM. They require modifications to the neutrino sector.**

But Why? and How?

Neutrino Masses from Cosmology



CMB peaks fix:

$$\theta_s \equiv r_s/D_M(z_\star)$$

$$r_s = \int_{z_\star}^{\infty} \frac{c_s}{H(z')}\, dz'$$

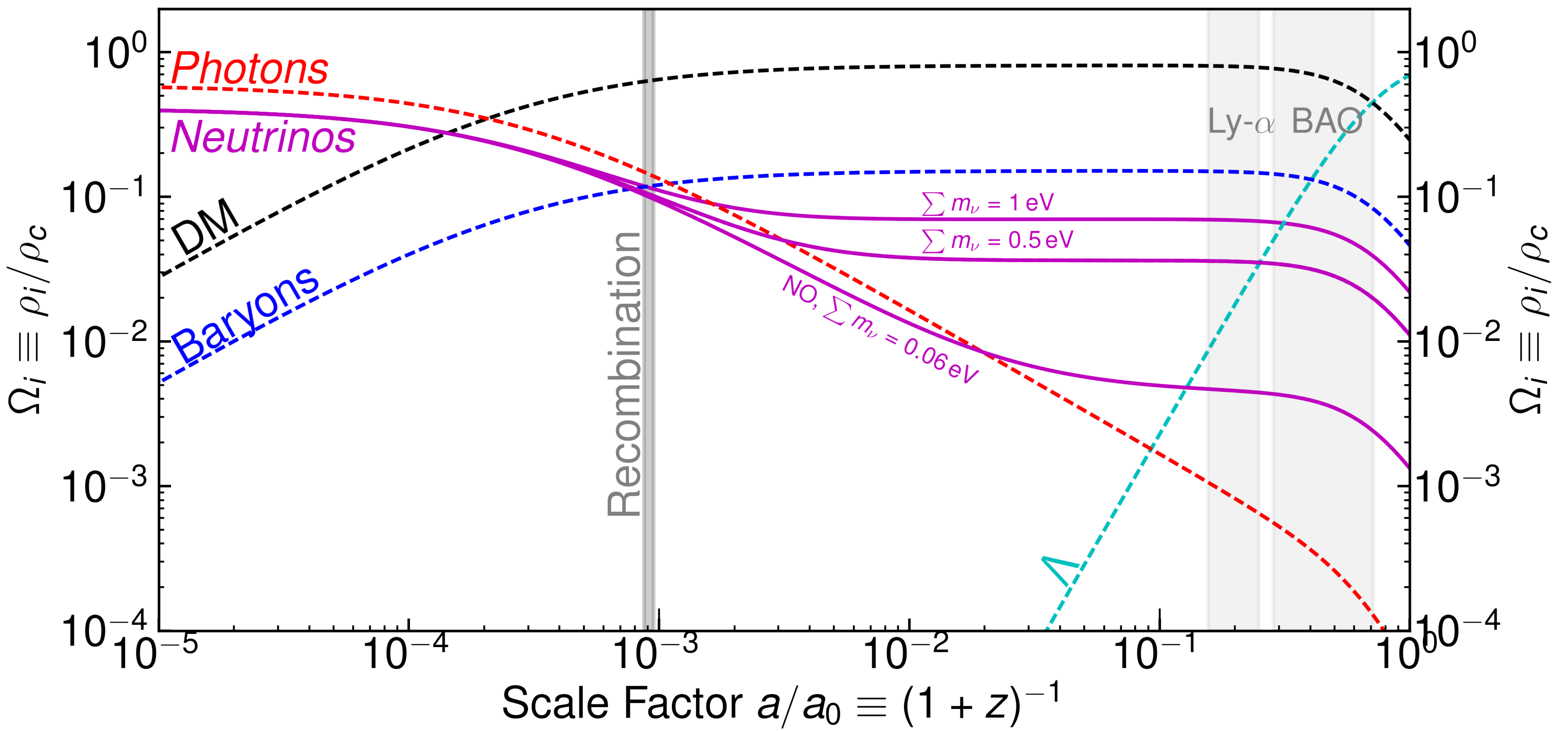
Comoving sound horizon (Early Universe)

$$D_M(z) = \int_0^z \frac{1}{H(z')}\, dz'$$

Comoving angular diameter distance (Late Universe)

Massive neutrinos → $H(z')$

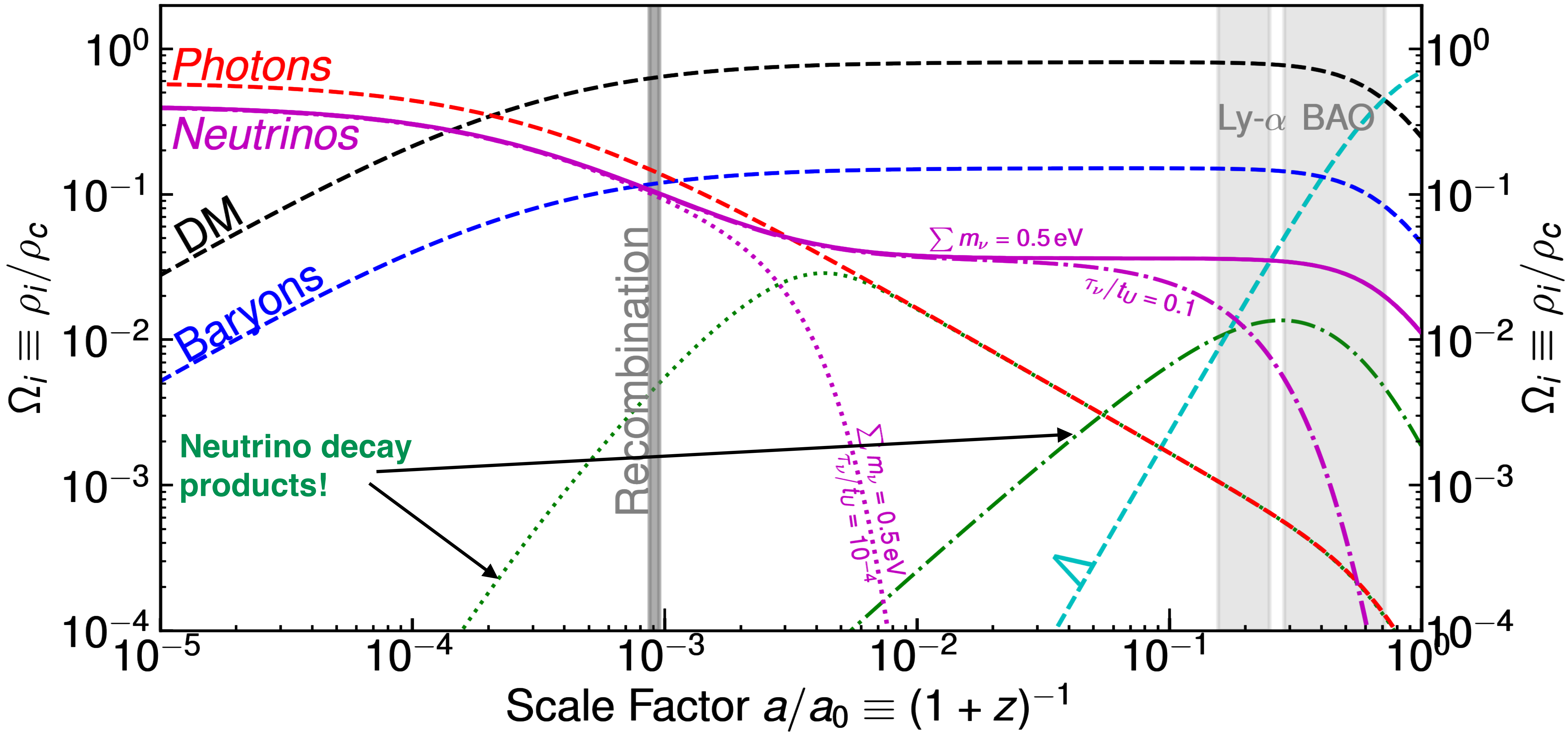
Neutrino Masses from Cosmology



Not only a background effect:

Massive neutrinos also affect CMB lensing $\propto \; \Omega_\nu$

Neutrino Decays



Neutrinos decaying with $\tau_\nu \lesssim t_U/10$ do not impact $D_M(z_{CMB})$

Effect of induced neutrino Lensing is substantially reduced

Unstable Neutrinos can relax the bounds on Σm_ν!

Neutrino Masses from Cosmology

Cosmological Model Dependence

Non-standard Neutrino Cosmologies:

Invisible Neutrino Decay

$\nu_i \to \nu_j \phi$

$$\sum m_\nu < 0.2\,\mathrm{eV}$$

Oldengott et al. 2203.09075 & 2011.01502
Escudero & Fairbairn 1907.05425

$\nu_i \to \nu_4 \phi$

at least: $\sum m_\nu \lesssim 0.42\,\mathrm{eV}$

Abellán, Poulin et al. 1909.05275, 2112.13862
Escudero, López-Pavón, Rius & Sandner 2007.04994

Time Dependent Neutrino Masses

Late phase transition

$$\sum m_\nu < 1.4\,\mathrm{eV}$$

Dvali & Funcke 1602.03191
Lorenz et al. 1811.01991 & 2102.13618

Ultralight scalar field screening

$$\sum m_\nu < 3\,\mathrm{eV}$$

Esteban & Salvadó 2101.05804
Esteban, Mena & Salvadó 2202.04656

Non-standard Neutrino Populations

$T_\nu < T_\nu^{\mathrm{SM}}$

$$\sum m_\nu < 3\,\mathrm{eV}$$

Farzan & Hannestad 1510.02201
Renk et al. 2009.03286

$\langle p_\nu \rangle > 3.15\, T_\nu^{\mathrm{SM}}$

$$\sum m_\nu < 3\,\mathrm{eV}$$

Oldengott et al. 1901.04352
Alvey, Escudero & Sabti 2111.14870

Take Away Message:

Cosmology can only constrain $\Omega_\nu(z)$ and not directly m_ν

All these models reduce $\Omega_\nu(z)$ with respect to the one in ΛCDM and are in excellent agreement with all known cosmological data

Neutrino Masses from Cosmology

Current cosmological neutrino mass bounds are dominated by Planck in combination with BAO data

Very robust bounds from linear Cosmology $\Delta T/T \sim 10^{-5}$

DESI first year data release has yielded key results:

DESI (2404.03002) $\sum m_\nu < 0.073\,\mathrm{eV}$ **(95 % CL, CMB+BAO-DESIY1)**

What about possible systematics in the Planck or other data?

New Planck likelihood implementations can lead to a 30% relaxation of the bound

The DESI outliers at $z = 0.7$ pull significantly the bound (30%). It would be interesting to see if the trend continues in the data

What is the dependence upon the assumed statistical procedure?

The frequentisist limits agree within 10% with the Bayesian approach using flat priors. This means that the likelihoods seem rather Gaussian.

What is the dependence upon the assumed Cosmological Model?

Bounds are rather robust upon standard modifications of ΛCDM

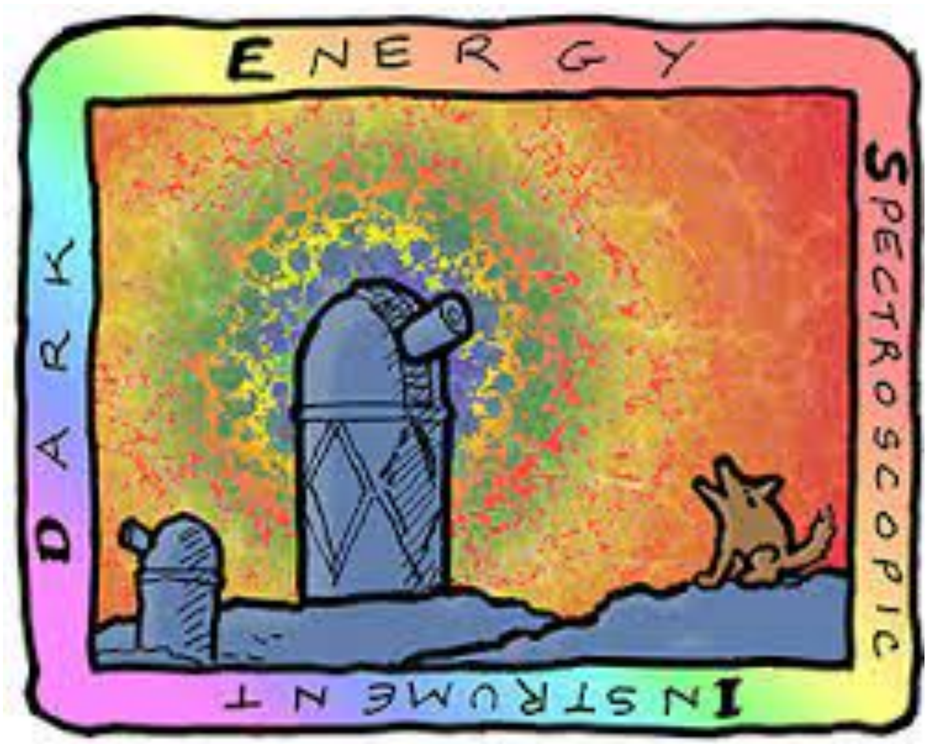
Bounds can however be relaxed in non-standard neutrino cosmologies

These models are exotic, but if we do not detect m_ν they may become a reality

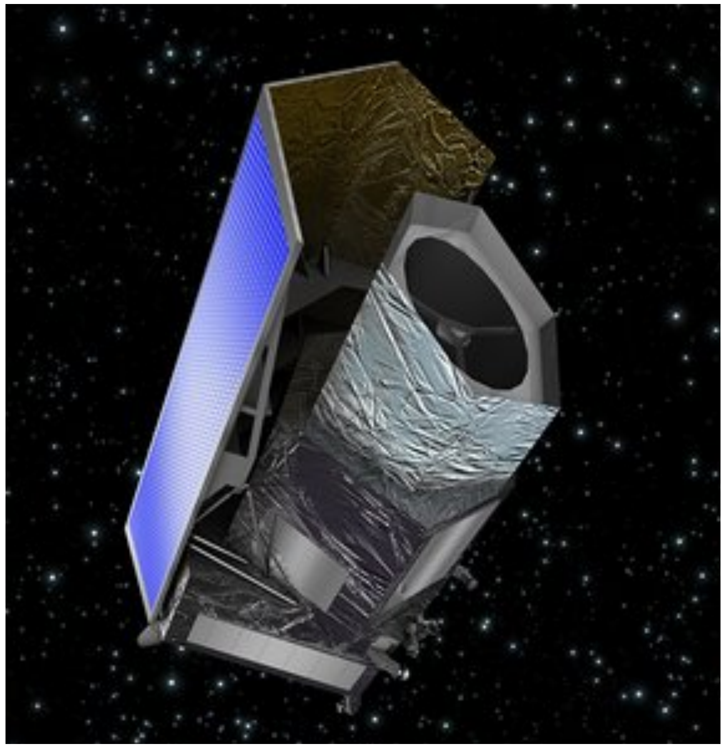
Outlook I: Neutrino Masses

The next generation of galaxy surveys in combination with CMB data are expected to measure the neutrino mass if the Universe is governed by a ΛCDM cosmology

DESI 1611.00036



EUCLID 1110.3193

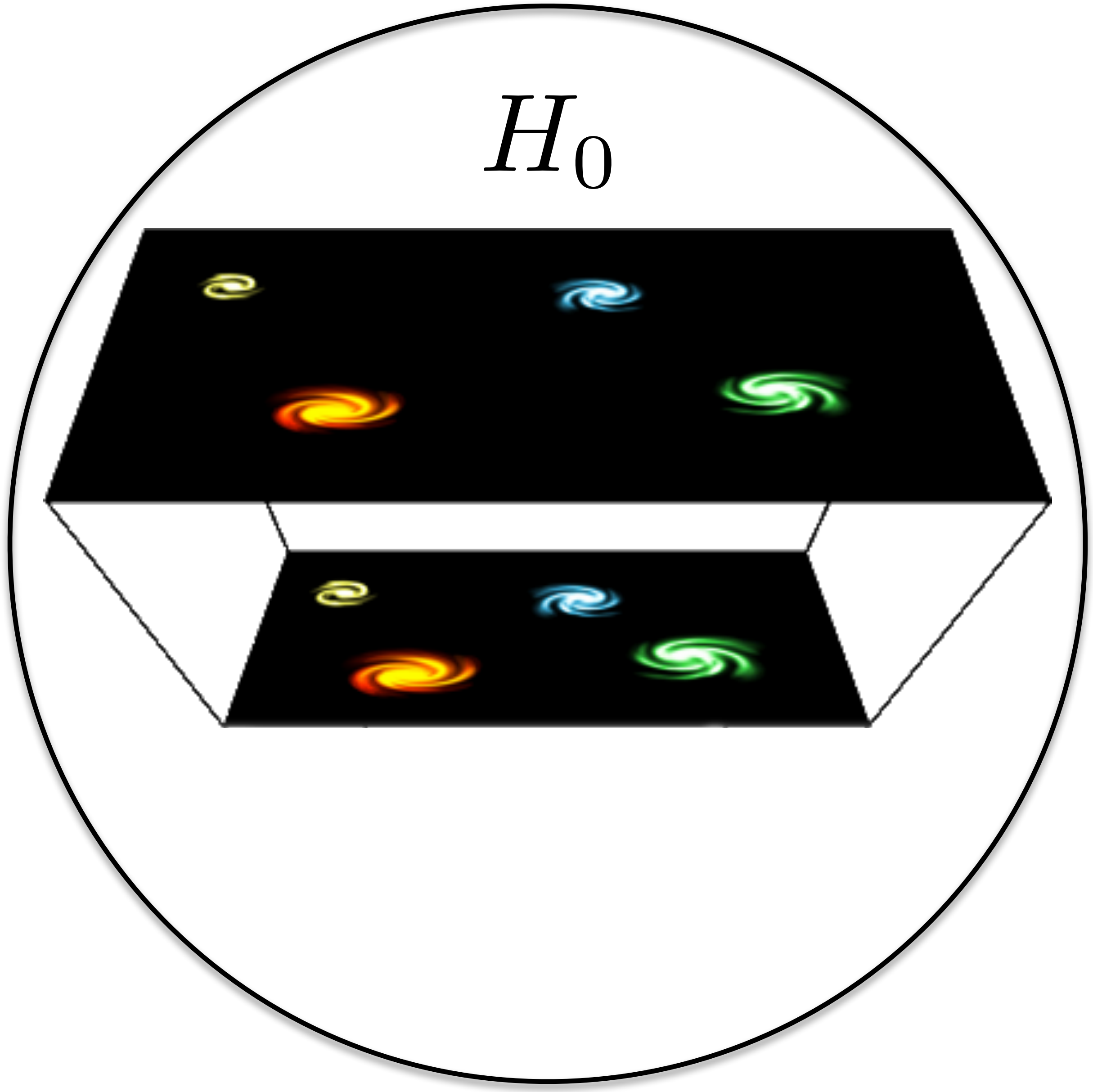


Why? DESI: 30M galaxies and EUCLID: 50M galaxies, but SDSS 1.5M galaxies

We expect the next results from DESI in less than one year! The full power of these data sets will come in the next 4-5 years! $\sigma(\sum m_\nu) = 0.02\,\mathrm{eV}$

In parallel, the KATRIN experiment is taking data and should reach a sensitivity of $m_{\bar{\nu}_e} \lesssim 0.2\,\mathrm{eV}$ **at 90% CL in ~ 3-4 years.**

The Hubble Tension



Local Measurements

Riess *et al.* 2112.04510

$$H_0 = 73.04 \pm 1.04\,\mathrm{km/s/Mpc}$$

ΛCDM Prediction

Planck 2018 1807.06209

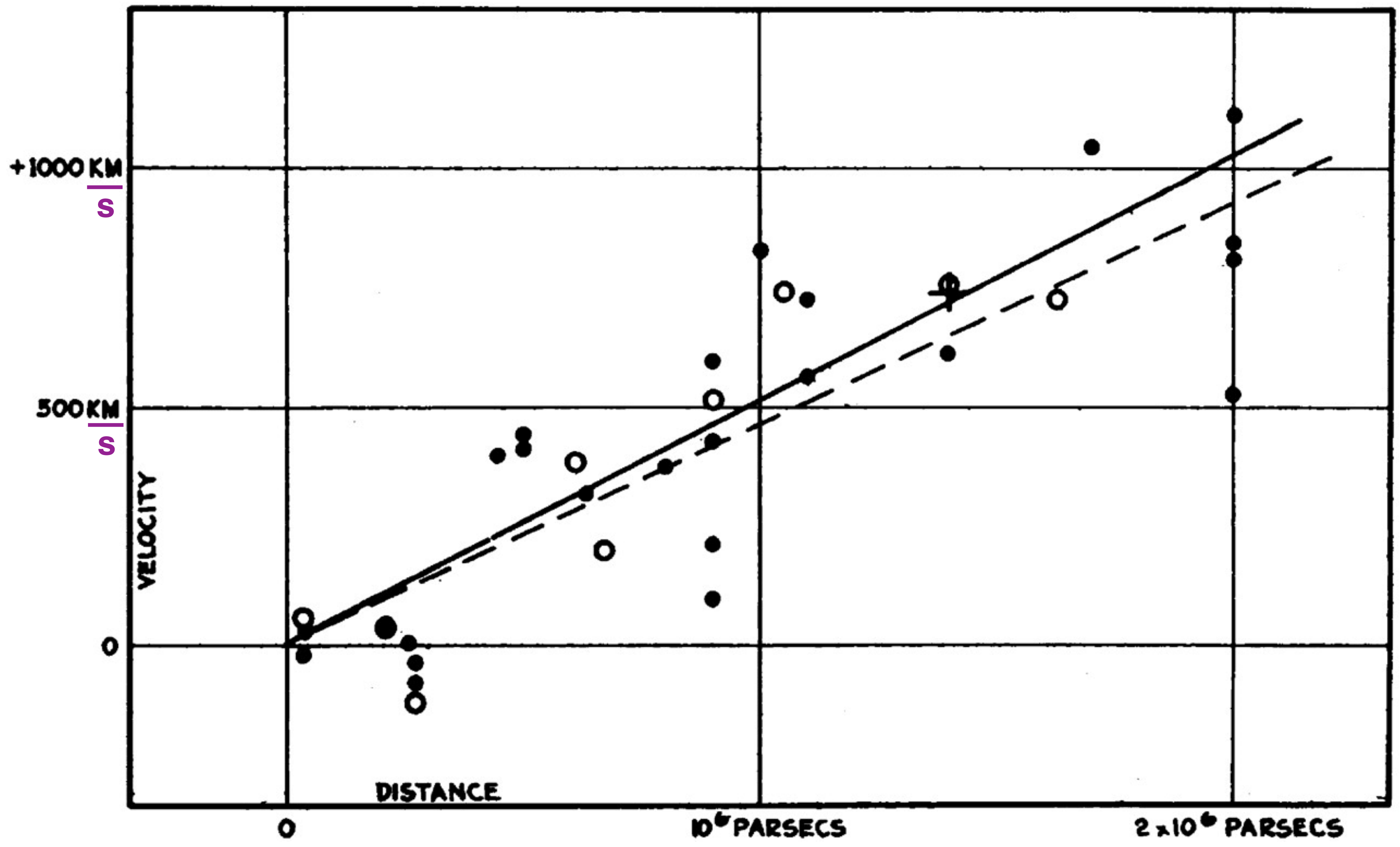
$$H_0 = 67.4 \pm 0.5\,\mathrm{km/s/Mpc}$$

5σ tension within ΛCDM!

The Hubble Law

The Universe is expanding!

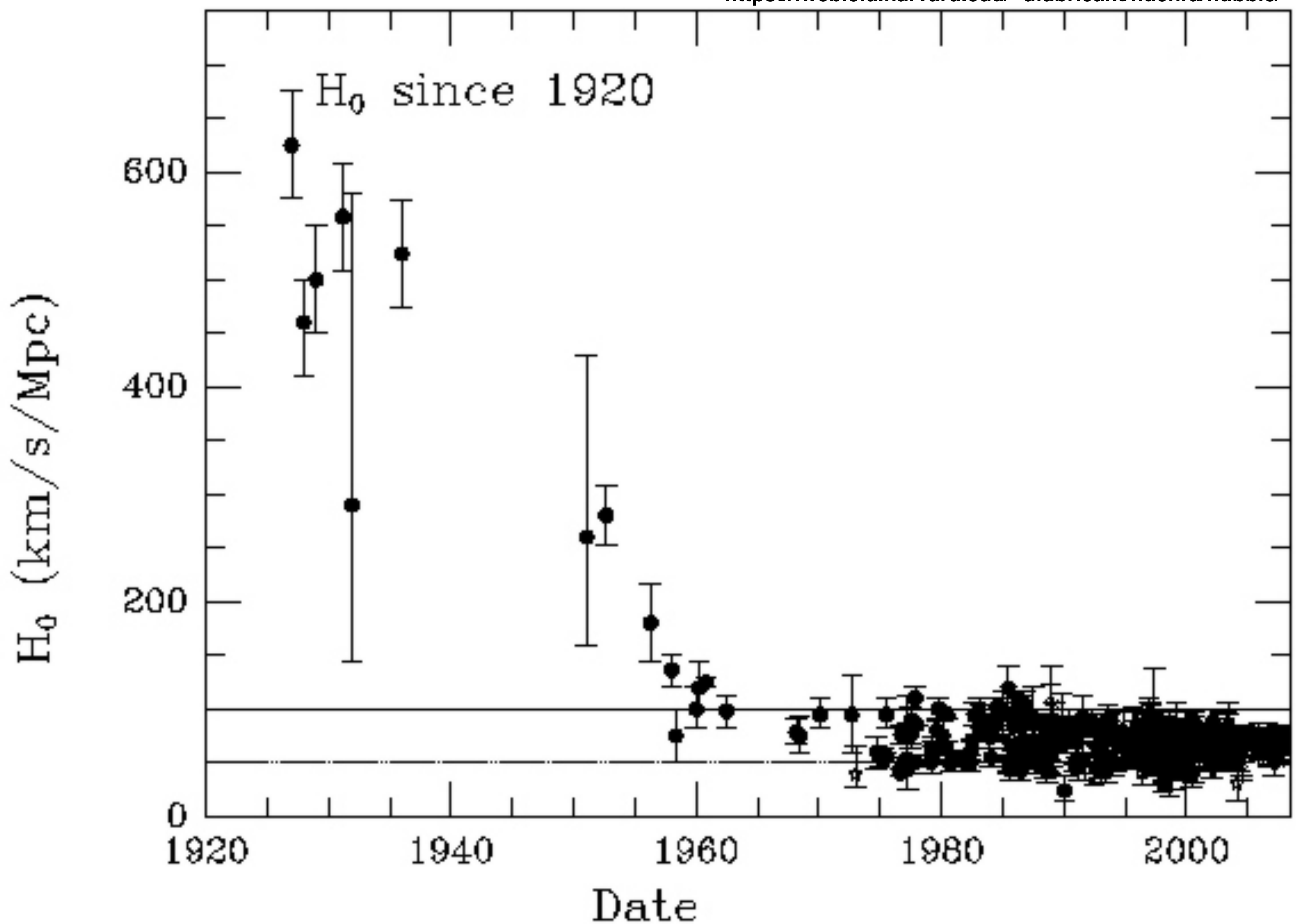
Hubble (1929): $v = H_0 \, d$



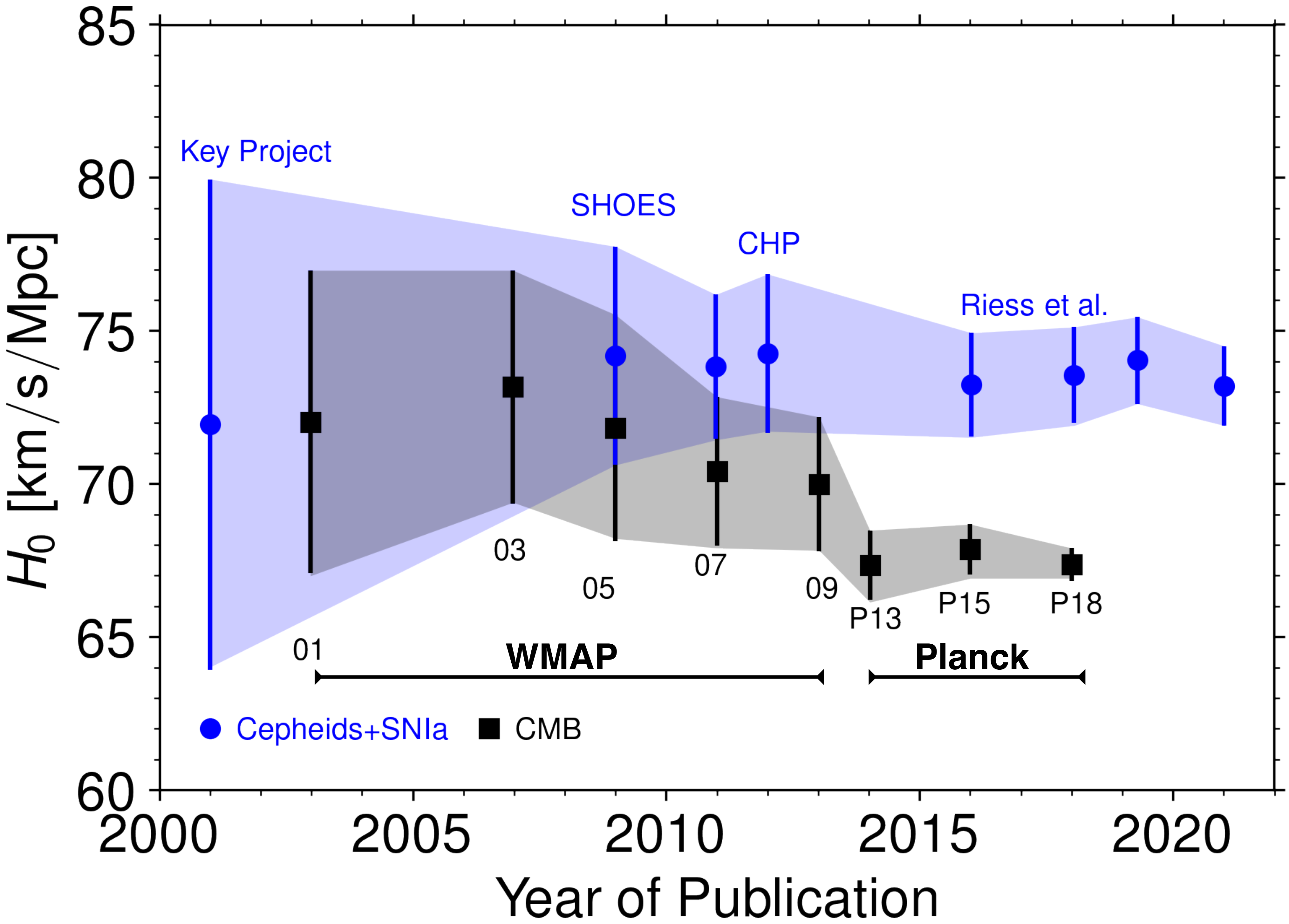
The Hubble Tension in Perspective

Hubble law (1929): $v = H_0\, d$

https://lweb.cfa.harvard.edu/~dfabricant/huchra/hubble/



The Hubble Tension in Perspective



The Hubble Tension

- **The Hubble Tension:**

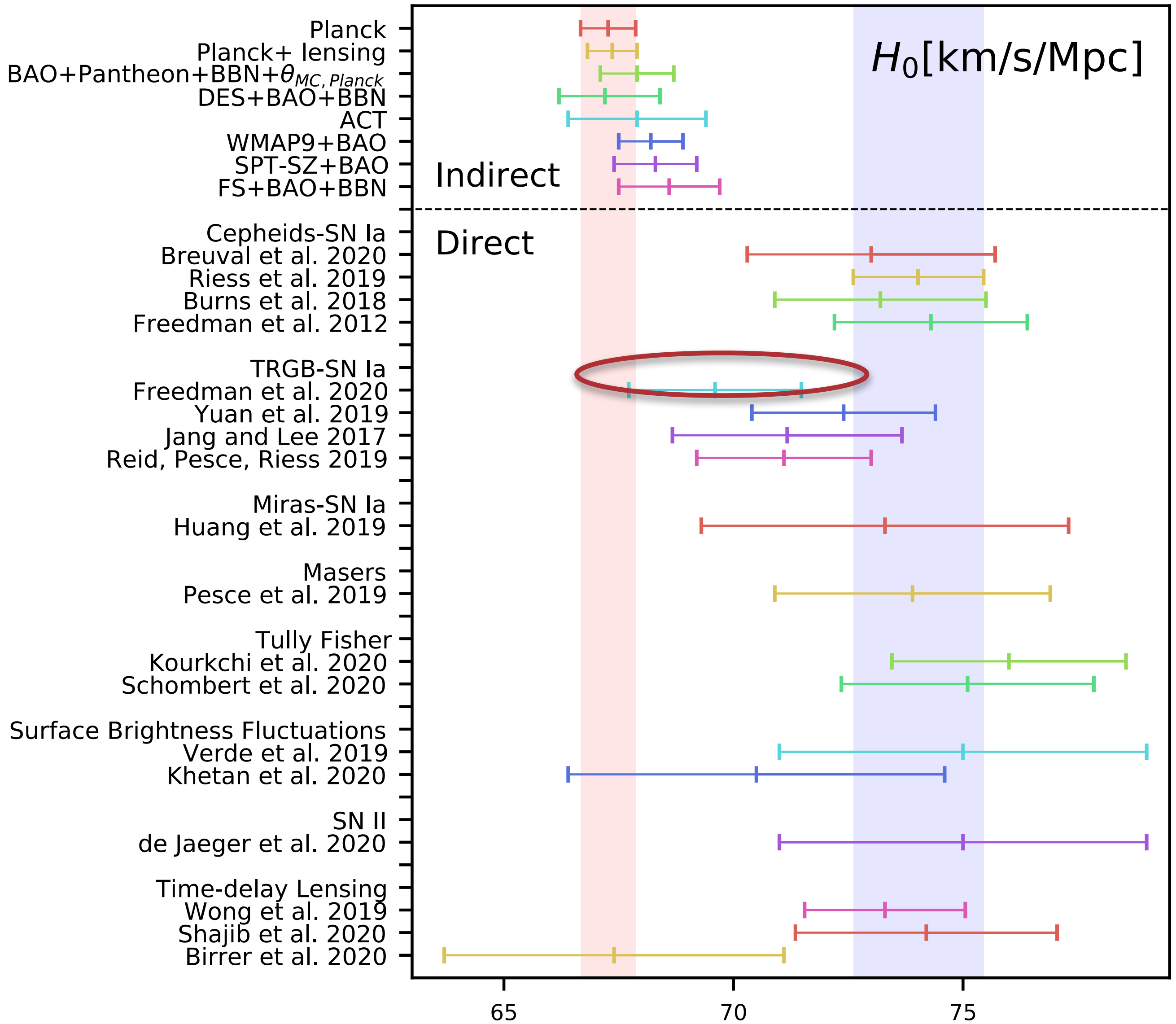
$$H_0 = 73.04 \pm 1.04\,\mathrm{km/s/Mpc}$$ **Riess *et al.* 2112.04510**

$$H_0 = 67.4 \pm 0.5\,\mathrm{km/s/Mpc}$$ **Planck 2018 1807.06209**

5σ tension within ΛCDM!

- **A pattern has clearly emerged:**
  - **4-6 σ tension depending upon the datasets included**
    see Verde, Treu & Riess 1907.10625 for a review
  - **Baryon Acoustic Oscillations point to small H_0**
  - **Cepheids+Type-Ia SN are by far the most precise and they point to $H_0 \sim (73 \pm 1)\,\mathrm{km/s/Mpc}$ The results have been recently confirmed by JWST**
  - **Some direct measurements do point to smaller values, Freedman et al. 20' and Birrer et al. 20'**

di Valentino 2011.00246



The Hubble Tension: Theory

- **Possible resolutions:**

  1) Systematics in the CMB data — **very unlikely**

  2) Systematics in local measurements — **none so far**

  3) New feature of ΛCDM

  4) Drastic change to the cosmological paradigm

     — Can we be living in a large void?
     This can be tested and data suggests that no: Riess et al. 1901.08681

     — Is the Universe isotropic?
     Some suggest that no: Sarkar et al. 2206.05624. However, these findings appear to be in disagreement with other studies, see Trotta et al. 2108.12497. In addition, it seems somewhat complicated to arrange theoretically explain it in light of CMB data, see 2207.01569 by Sarkar et al.

- **Possibilities beyond ΛCDM:** See 2103.01183 by di Valentino et al. for a review (over 1000 references …)

  1) Late Universe Modifications — **very unlikely**

  2) Early Universe Modifications — **hard but doable**

The Hubble Tension: Theory

- **Latest results highlight that a combination of the two would be needed:**

1) Late Universe Modifications

+

2) Early Universe Modifications

Poulin et al. 2407.18292

Pedrotti et al. 2408.04530

Theoretically this is not very appealing

Phenomenologically this could work because SN and BAO are then unrelated

Neff as a solution to the H_0 Tension?

- **How large would $\Delta N_{\rm eff}$ need to be to solve the tension?**

$$H_0 \simeq \left[67.4 + 6.2\,\Delta N_{\rm eff}\right]\ {\rm km/s/Mpc}$$

Vagnozzi 1907.07569

😃 $\Delta N_{\rm eff} \simeq 1$ **would yield the value of H_0 reported by Riess**

😐 **Problem 1) BBN constraints indicate that:** $\Delta N_{\rm eff}^{\rm BBN} < 0.5$ **Pisanti et al. 2011.11537**

- **Constraints are dominated by Helium measurements (that could suffer from systematics)**
- **In many models $\Delta N_{\rm eff}^{\rm CMB} \neq \Delta N_{\rm eff}^{\rm BBN}$**

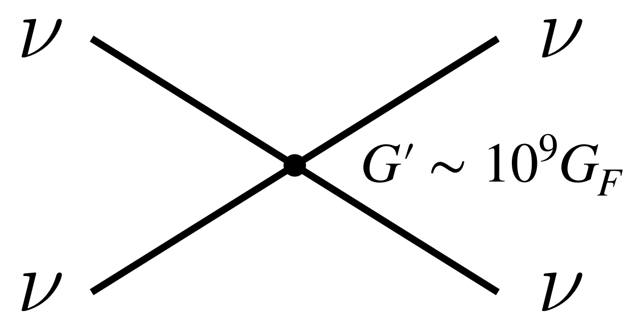
☹️ **Problem 2) Within the framework of ΛCDM Planck is compatible with $N_{\rm eff} \simeq 3$**

$$N_{\rm eff}^{\rm CMB+BAO} = 2.99 \pm 0.17$$

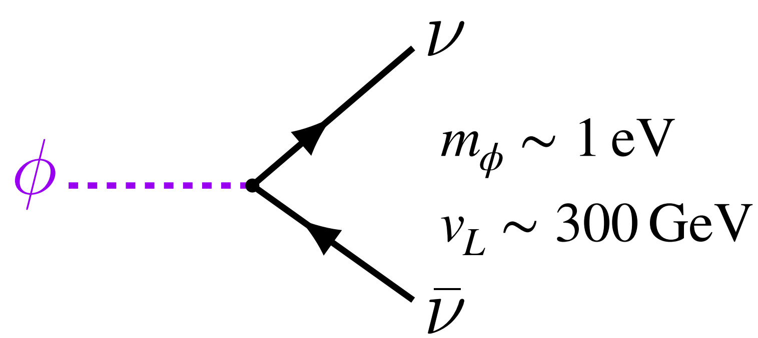
Planck 2018

Neutrinos and the Hubble Tension

- **Dark Radiation**
- **Strong Neutrino Scattering + Dark Radiation** Kreisch, Cyr-Racine, Doré 1902.00543



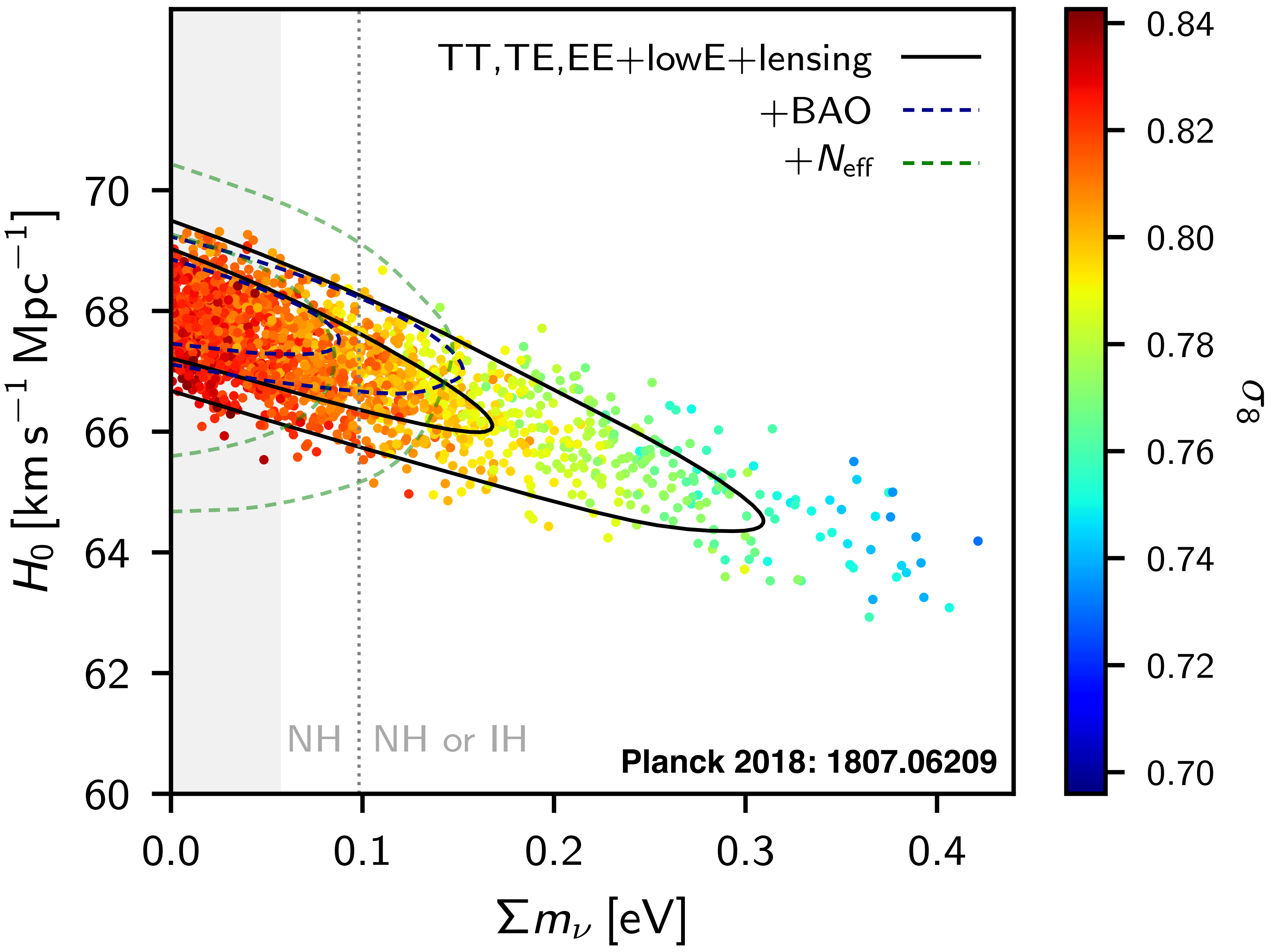
- **Light Neutrinophilic Scalar + Dark Radiation** Escudero & Witte 1909.04044



- **Early Dark Energy sourced by neutrinos** Sakstein & Trodden 1911.11760
- **Dark Matter-Neutrino Interactions** Ghosh, Khatri & Roy 1908.09843
- **An eV-scale Sterile Neutrino interacting with a pseudoscalar**

None of these models can substantially resolve the H0 tension

Implications for neutrinos

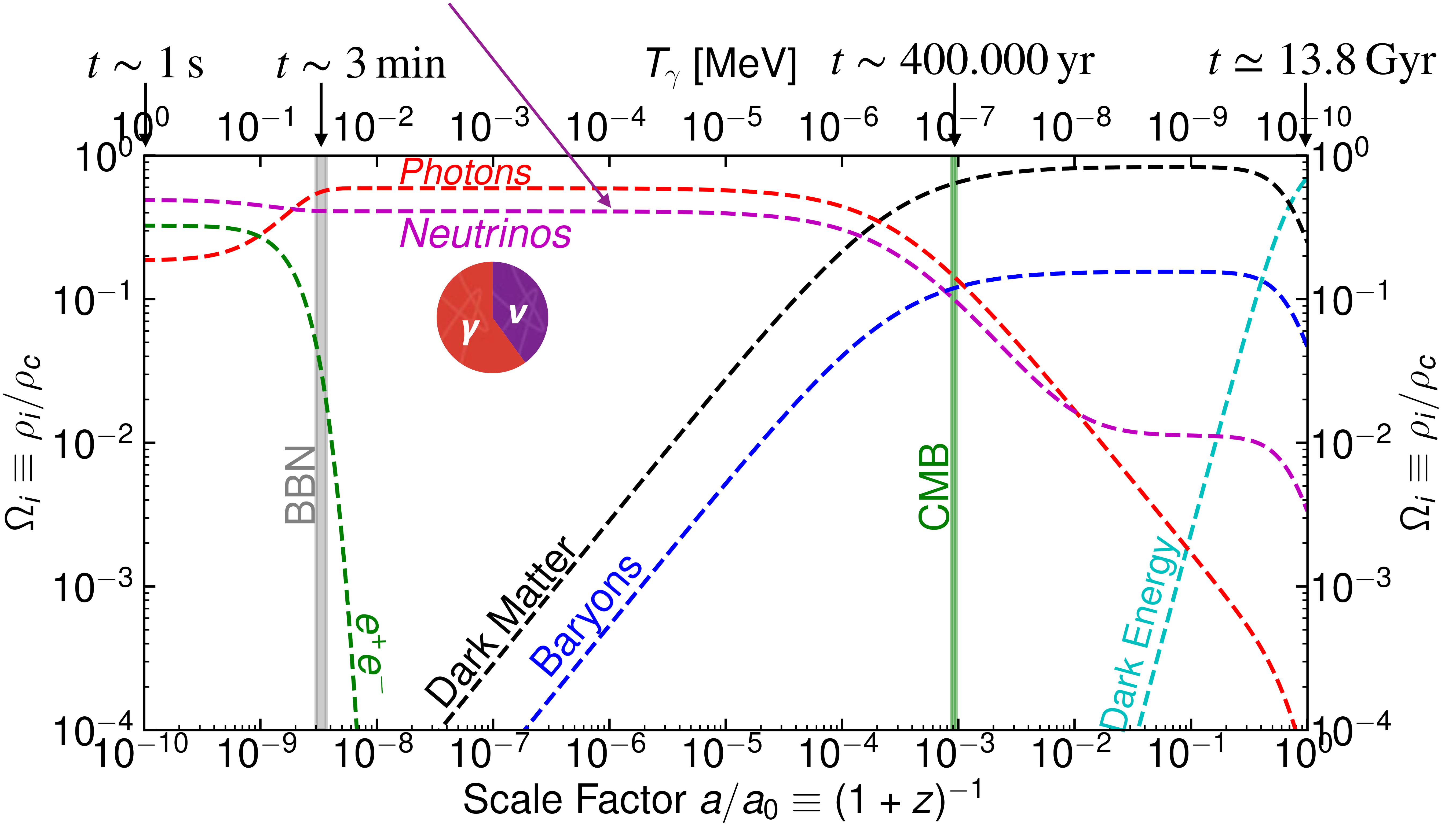


1) Will alter our inferences about neutrinos

2) If true, can neutrinos or particles related to them be at its origin?

Neutrino Evolution

Neutrinos are always a relevant species in the Universe's evolution



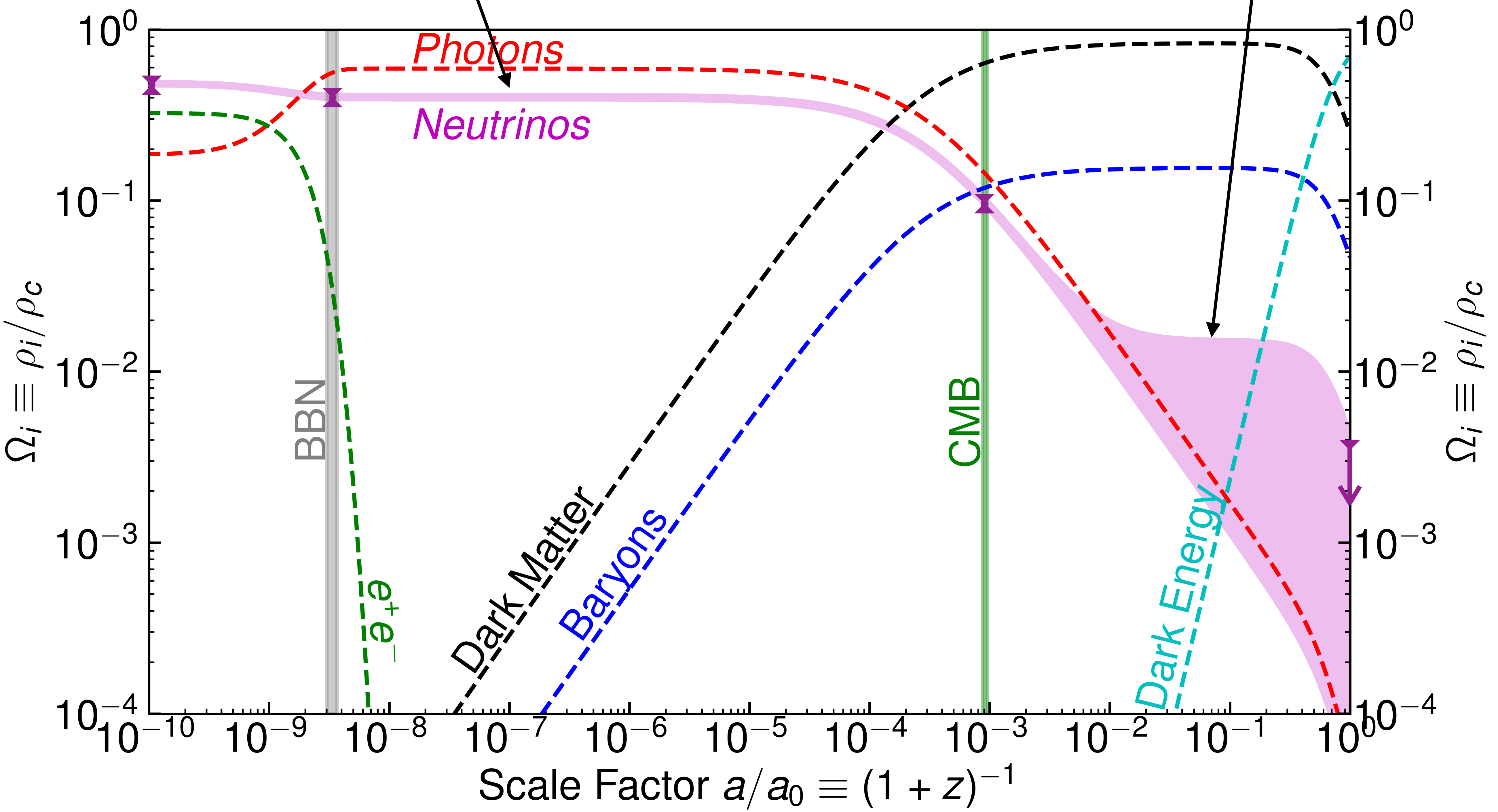
Global Perspective

Current knowledge:

$N_{\mathrm{eff}} = 3.0 \pm 0.3$ **(Planck/BBN)**

(Planck+BAO)

$\sum m_\nu \lesssim 0.2\,\mathrm{eV}$



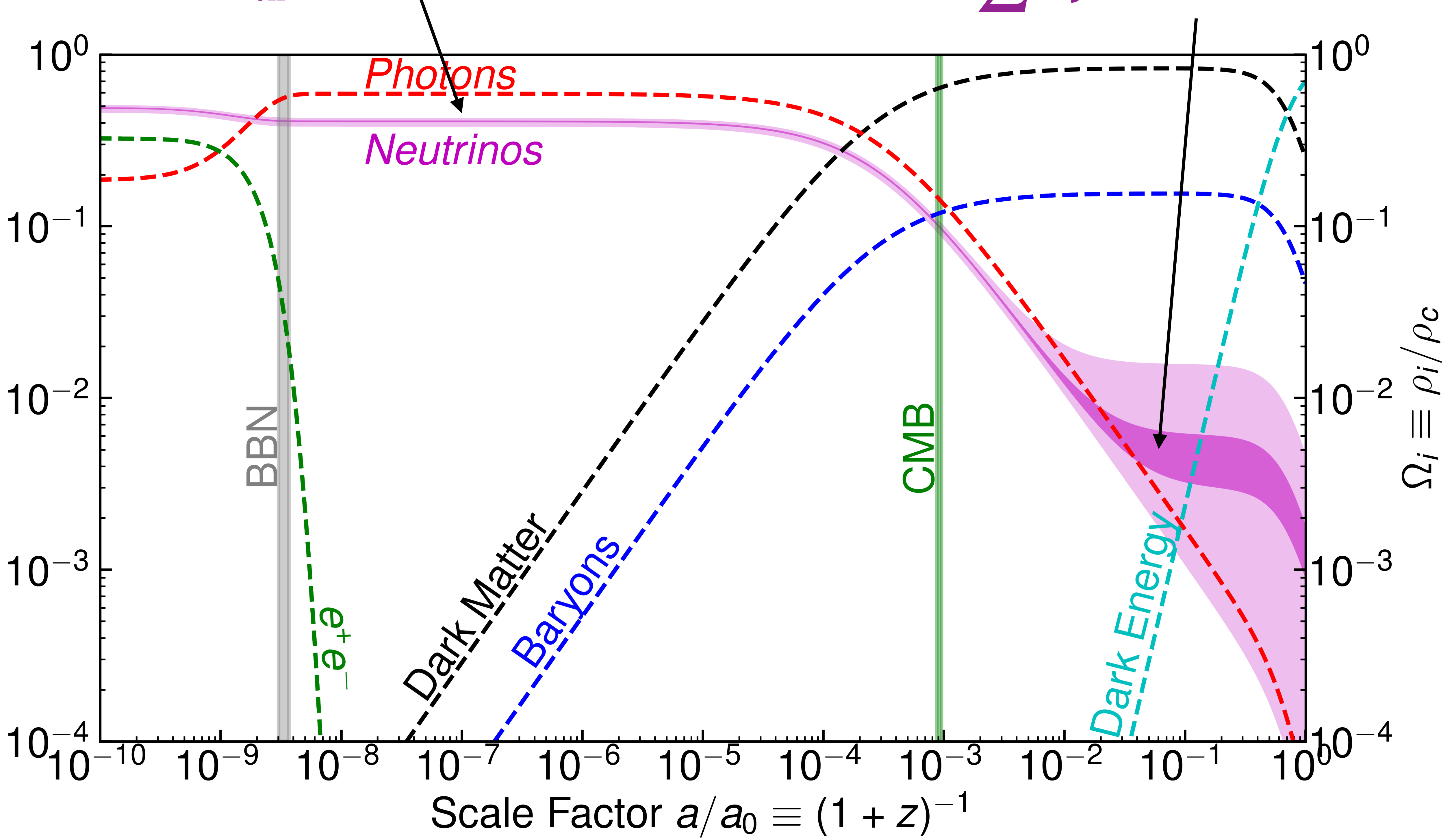
Global Perspective

In the next 5-6 years:

(DESI/Euclid + Planck)

$N_{\rm eff} = 3.043 \pm 0.06$ **(Simons Observatory)**

$\sum m_\nu = 0.06 \pm 0.02\,{\rm eV}$



Global Perspective

I think we are living exciting times in Cosmology

In particular in Neutrino Cosmology:
We expect to detect the neutrino mass in 5-6 years!

If that were not to happen, then we need to reconsider the standard cosmological model

At the same time, in the background, there is the Hubble tension. Despite strong efforts both theoretically and and observationally it is still an open issue. It can affect our inferences of neutrino properties.

End of Lecture II

$$\nu$$

Thank you for your attention!

miguel.escudero@cern.ch