Neutrino Cosmology: Lecture II

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XX LNF Summer School
Bruno Touschek
Frascati
14-07-2022

Unterstützt von / Supported by
Alexander von Humboldt
Stiftung/Foundation

Outline

Neutrino Masses in Cosmology

Bounds in ΛCDM

Cosmological model dependence

The Hubble tension and neutrinos

What is the status?

Could neutrinos be related to it?

Conclusions & Outlook

Set Up

Unlike neutrinos, I like to interact 😃

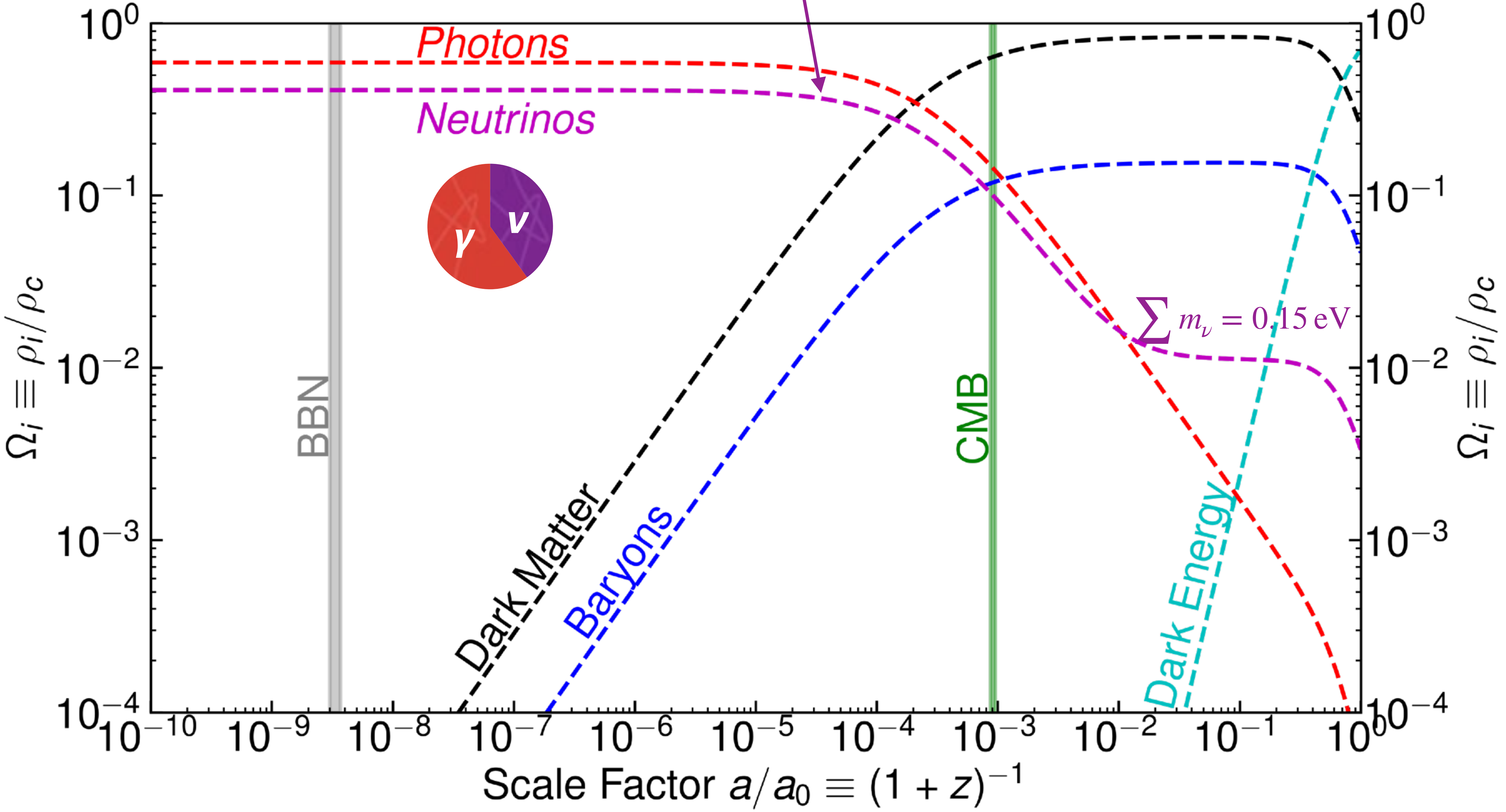
The plan is to learn and discuss. Therefore:

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

(great thanks to those who asked questions yesterday!)

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

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:** $N_{\rm eff}^{\rm SM} = 3.044(1)$
- **Data is in excellent agreement with the Standard Model prediction**
- **This provides strong (albeit indirect) evidence for the Cosmic Neutrino Background.**

Implications:

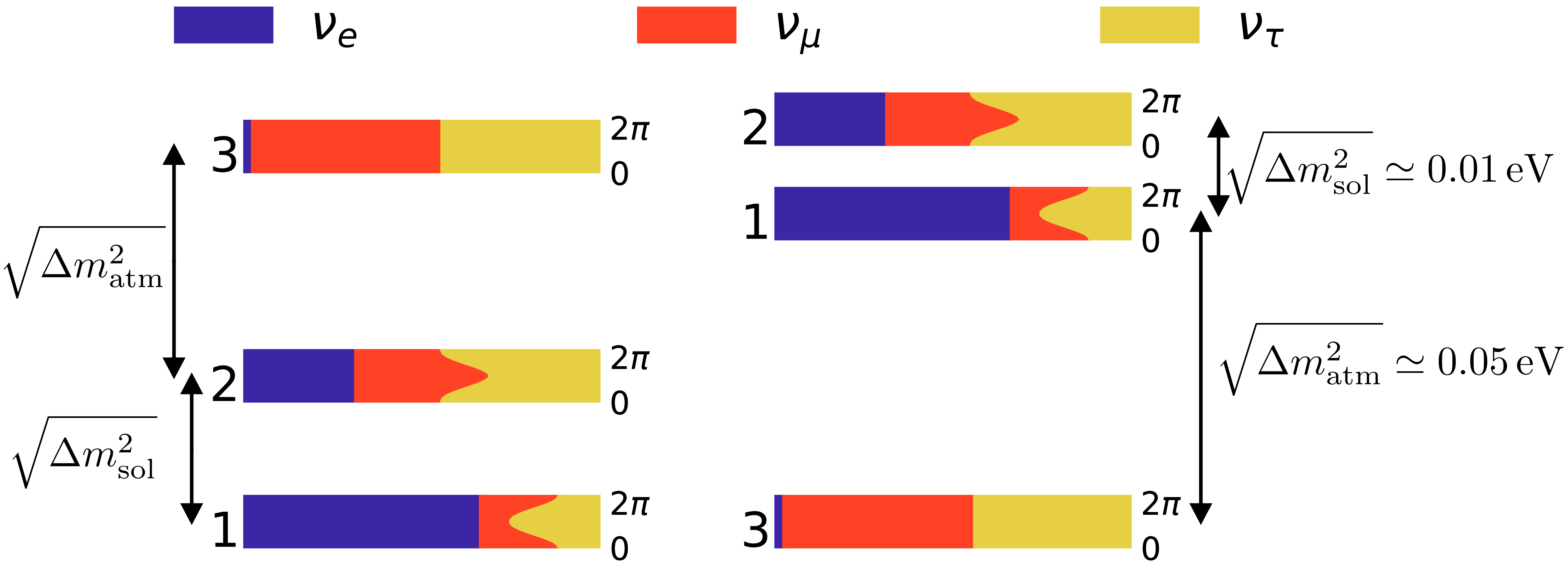
Yesterday! **Today!**

1) Stringent constraint on many BSM settings

2) We can use cosmological data to test neutrino properties

Neutrino Properties

Figure from de Salas et al. 1806.11051



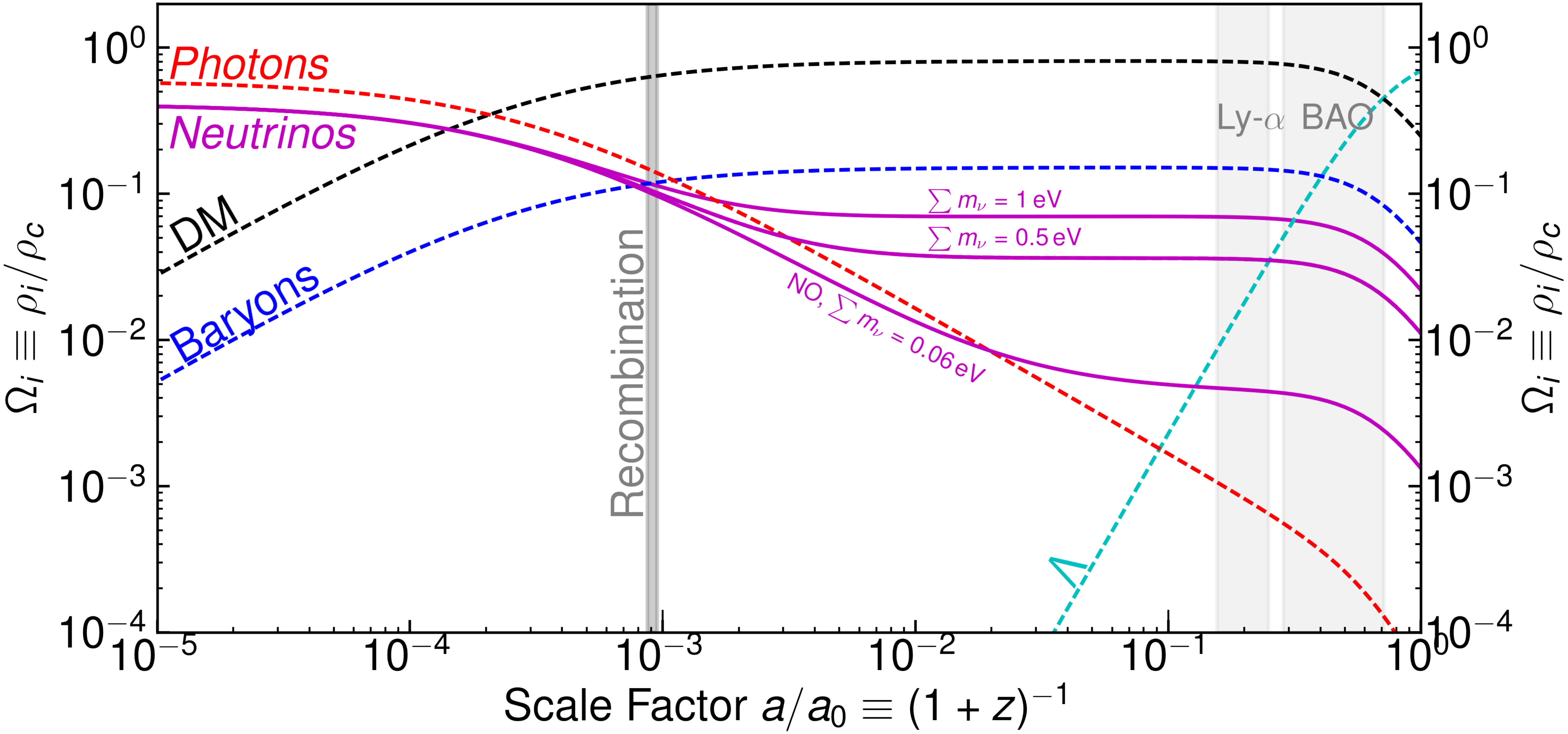
Normal **Inverted**

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

- **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. $m_{\rm lightest}$?** **Cosmology**

Neutrino Masses in Cosmology

- **1) Massive neutrinos modify the expansion history**



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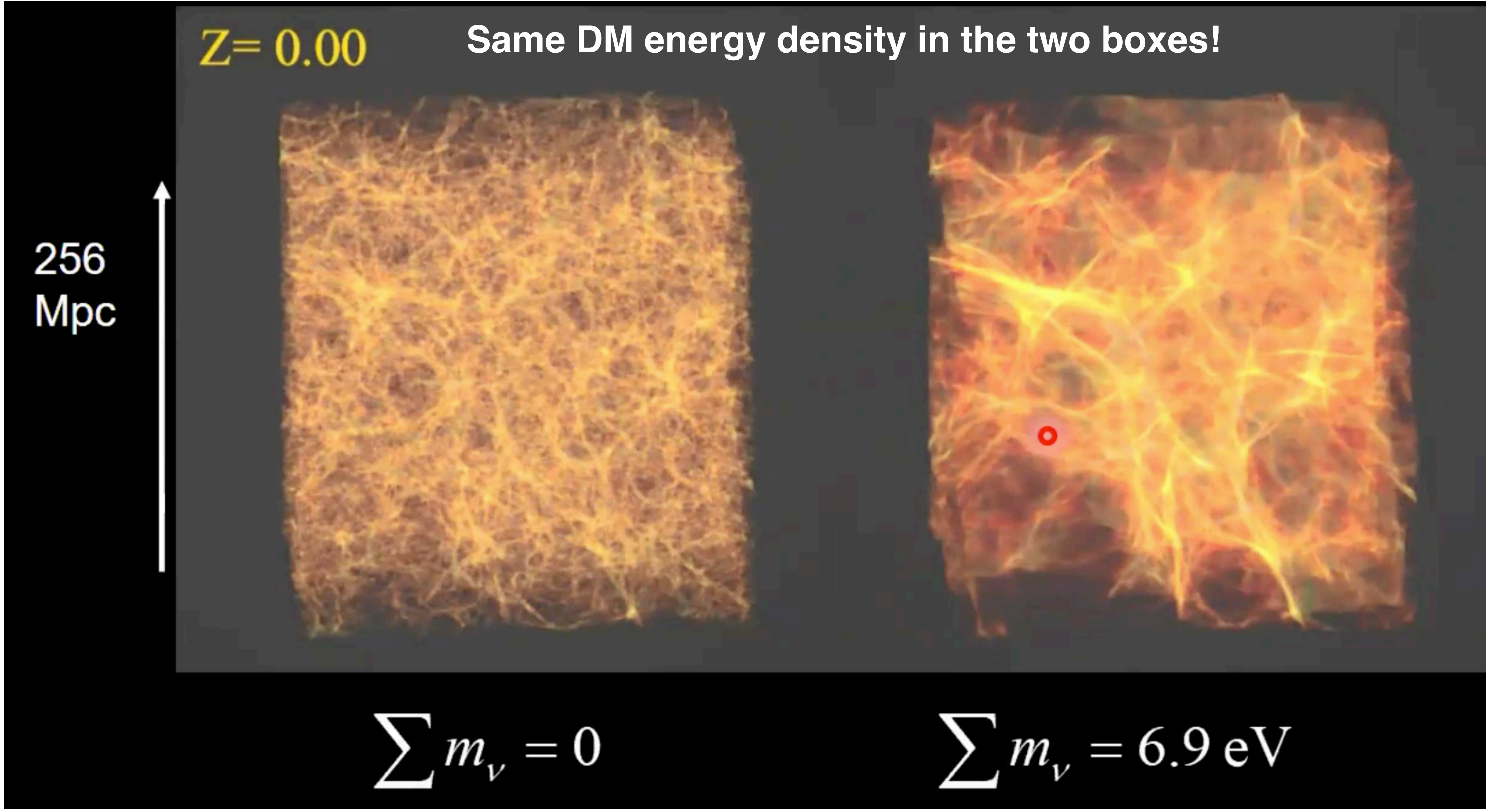
Hot DM: $\Omega_\nu h^2 = \sum m_\nu/(93.14\,\text{eV})$

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:

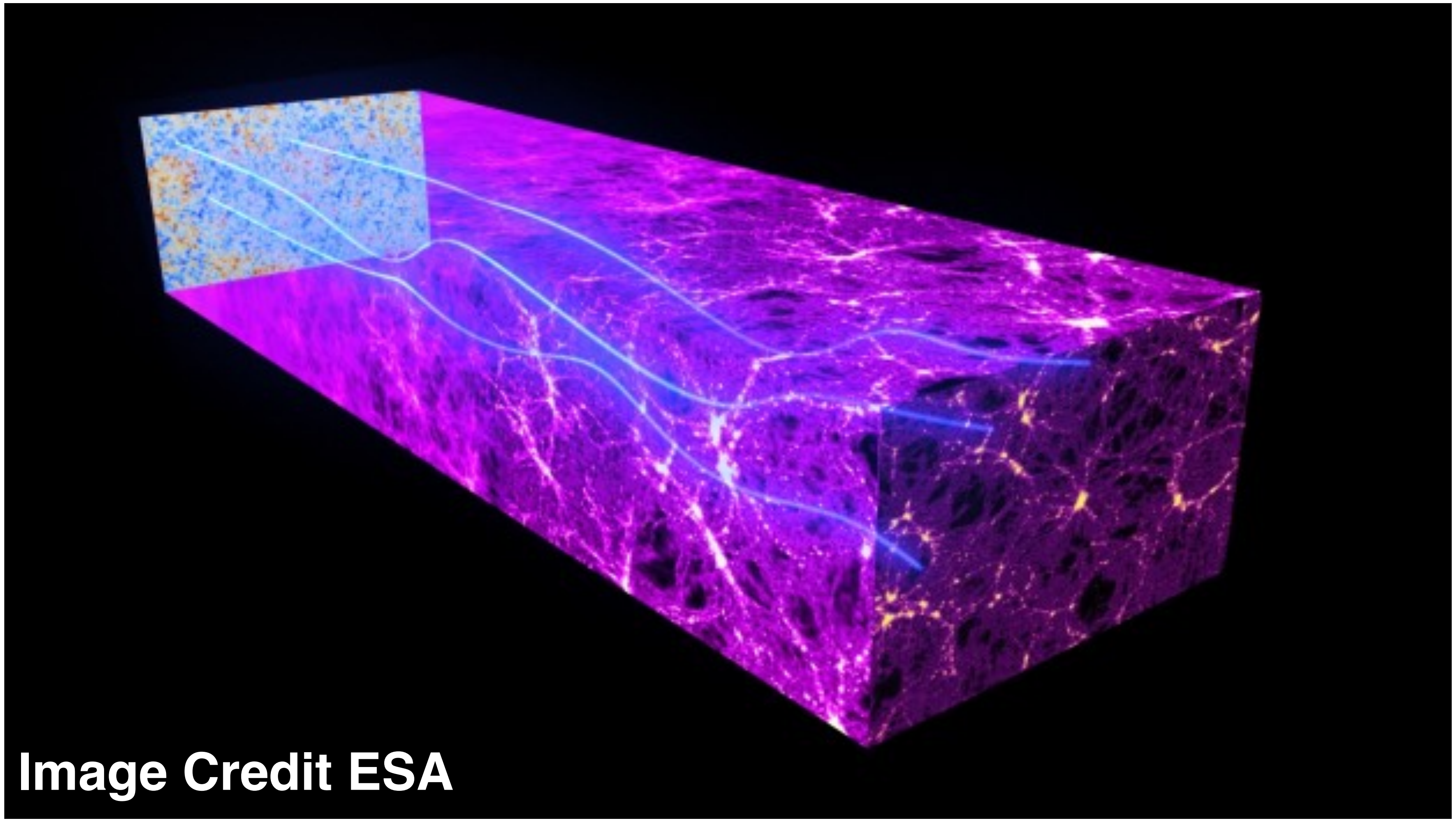


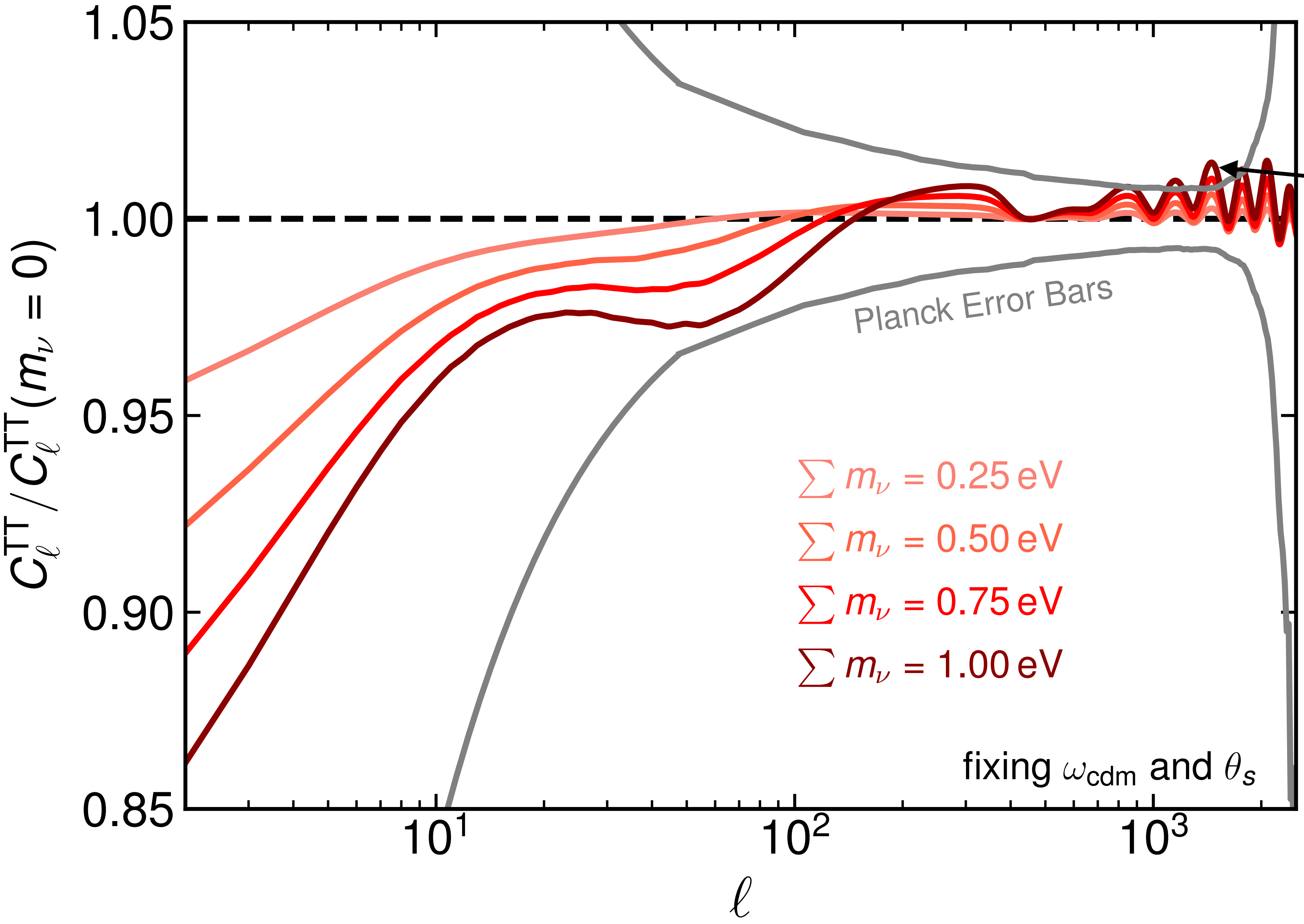
Image Credit ESA

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:



Main constraining power

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

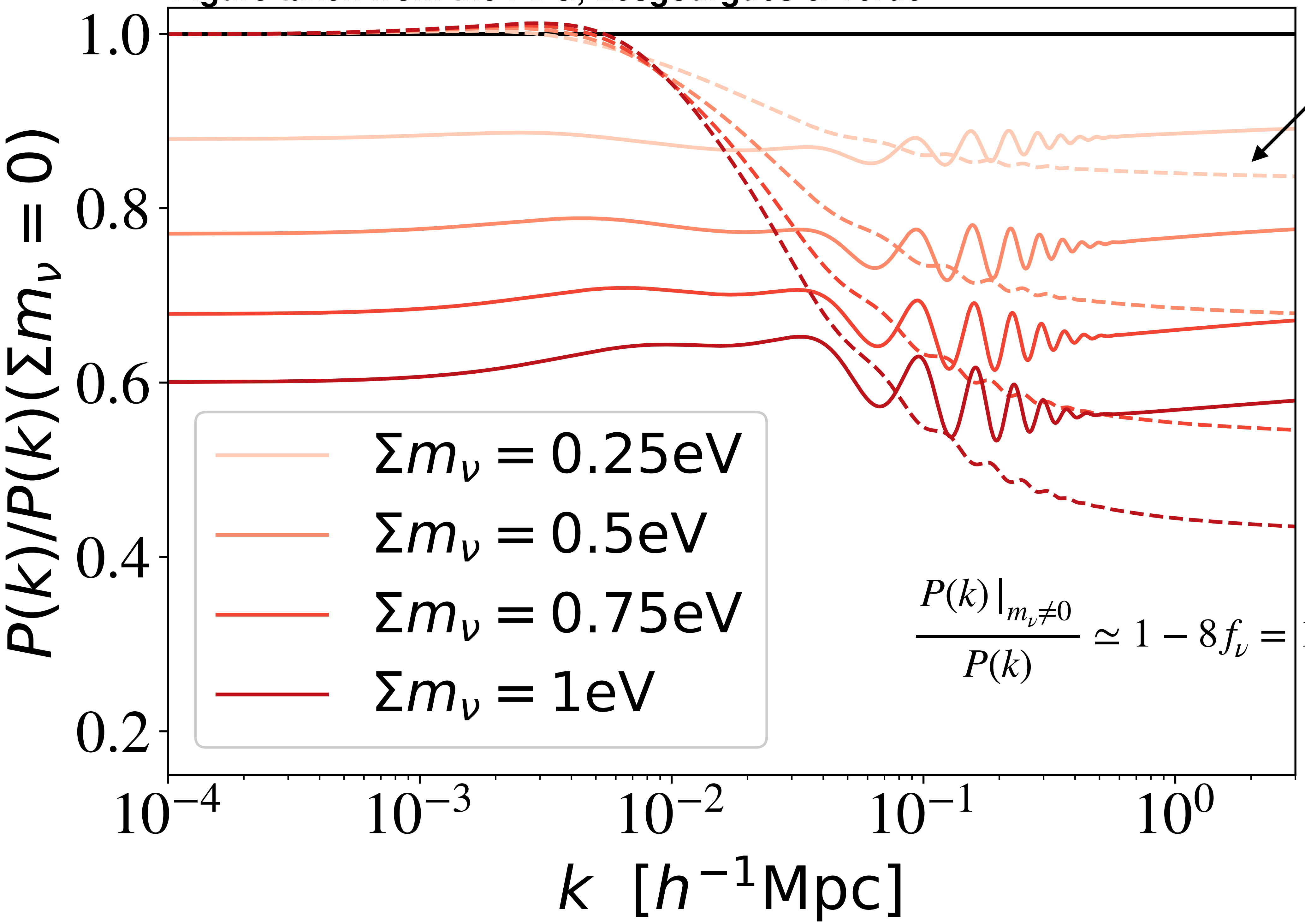
(95 % CL, TT+lowE)

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 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)**

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

To be compared to the KATRIN bound: $\sum m_\nu < 2.4\,\mathrm{eV}$

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 data?

And, all cosmological bounds are cosmological model dependent

What is the dependence upon the assumed Cosmological Model?

Neutrino Masses from Cosmology

Data beyond Planck and BAO within ΛCDM

$\sum m_\nu < 0.26\,\mathrm{eV}$	**Planck**	**Planck 1807.06209**
$\sum m_\nu < 0.12\,\mathrm{eV}$	**Planck+BAO**	**Planck 1807.06209**
$\sum m_\nu < 0.86\,\mathrm{eV}$	**BOSS P(k)**	**Ivanov et al. 1909.05277**
$\sum m_\nu < 0.16\,\mathrm{eV}$	**Planck+BOSS 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**	
$\sum m_\nu < 0.08\,\mathrm{eV}$	**Planck+BAO+H_0**	**Choudhury & Hannestad 1907.12598**
$\sum m_\nu < 0.09\,\mathrm{eV}$	**Planck+BAO+SN+RSD**	**di Valentino, Gariazzo & Mena 2106.15267**

- **Planck is driving current cosmological constraints**
- **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

Neutrino masses and the Planck lensing anomaly

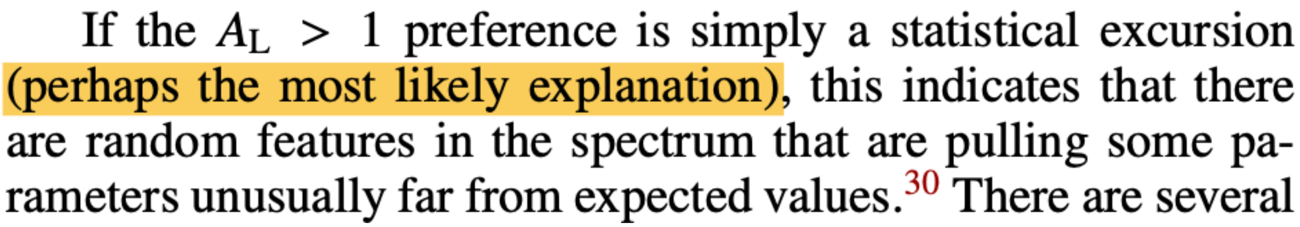
There is an anomaly in the Planck data at high multipoles which could potentially have relevant implications for the neutrino mass constraints

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

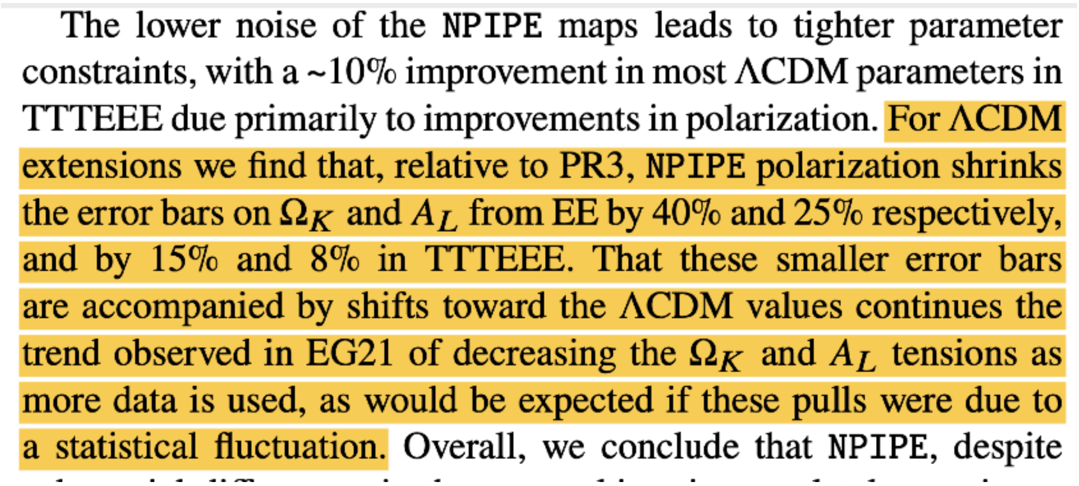
***Planck* 2018 results. VI. Cosmological parameters**



If the $A_{\rm L} > 1$ 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:

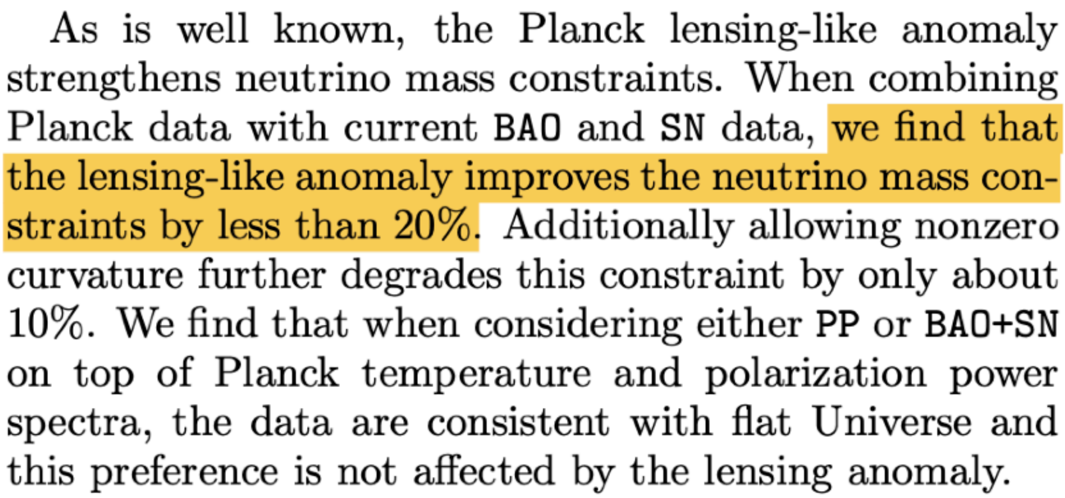
see Rosenberg, Gratton & Efstathiou 2205.10869



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

Finally, even in the presence of this anomaly the effect on the neutrino mass bound is expected to be of only 20% within ΛCDM!

Motloch and Hu 1912.06601



As is well known, the Planck lensing-like anomaly strengthens neutrino mass constraints. When combining Planck data with current BAO and SN data, we find that the lensing-like anomaly improves the neutrino mass constraints by less than 20%. Additionally allowing nonzero curvature further degrades this constraint by only about 10%. We find that when considering either PP or BAO+SN on top of Planck temperature and polarization power spectra, the data are consistent with flat Universe and this preference is not affected by the lensing anomaly.

Neutrino Masses from Cosmology

Cosmological Model Dependence

Planck+BAO 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 $N_{\rm eff}$** **Planck 1807.06209**	**ΛCDM+m_ν+$N_{\rm eff}$**
$\sum m_\nu < 0.17\,\mathrm{eV}$	**Varying $N_{\rm eff}$+ω+α_s+m_ν** **di Valentino et al. 1908.01391**	**CDM+m_ν+$N_{\rm eff}$+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, Wong et al. 2203.09075 & 2011.01502
Escudero & Fairbairn 1907.05425

$\nu_i \to \nu_4 \phi$

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

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

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

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

Farzan & Hannestad 1510.02201
Renk et al. 2009.03286

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

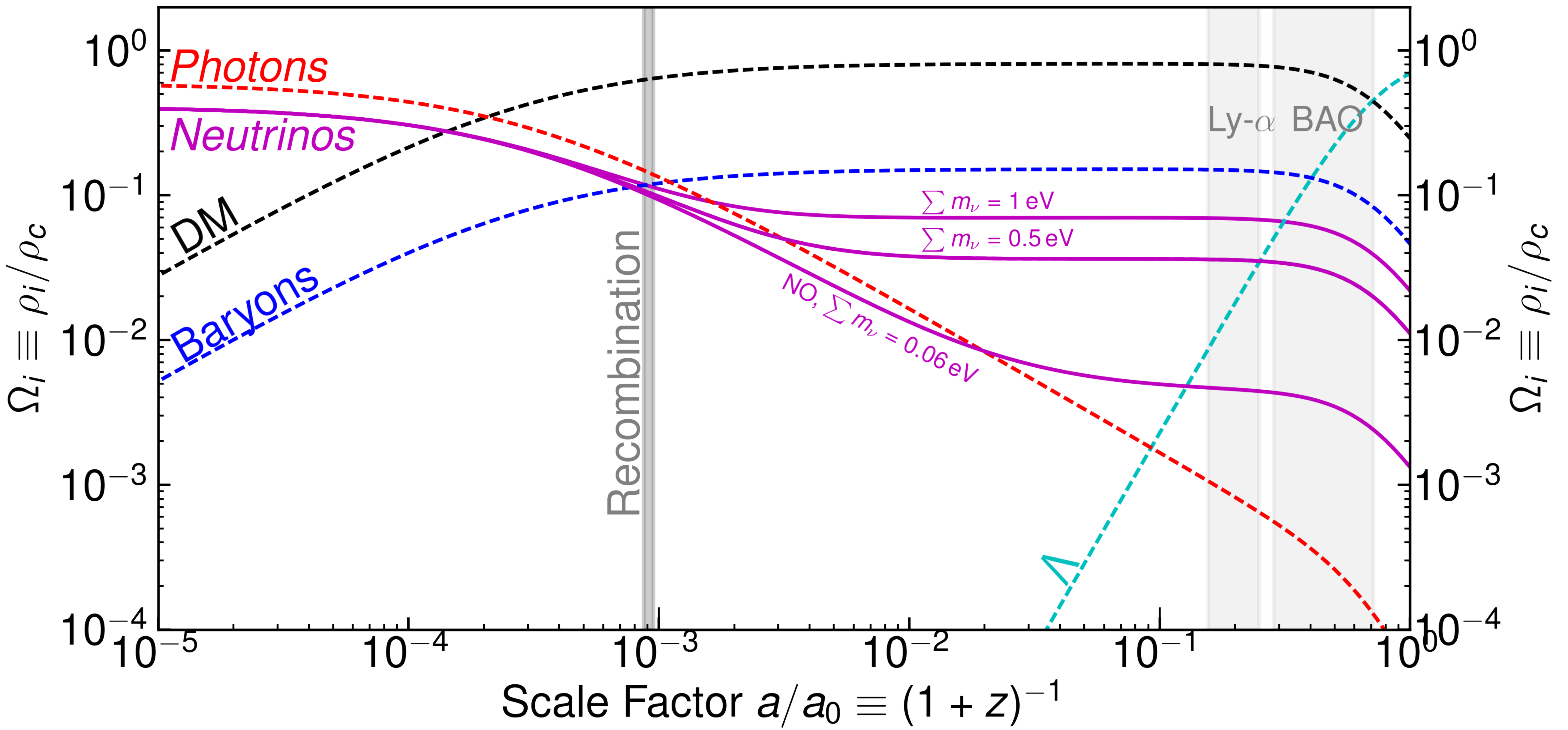
$$\sum m_\nu < 3\,\mathrm{eV}$$

Oldengott et al. 1901.04352
Alvey, Escudero & Sabti 2111.14870

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

But Why? and How?

Neutrino Masses from Cosmology



CMB peaks fix:

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

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

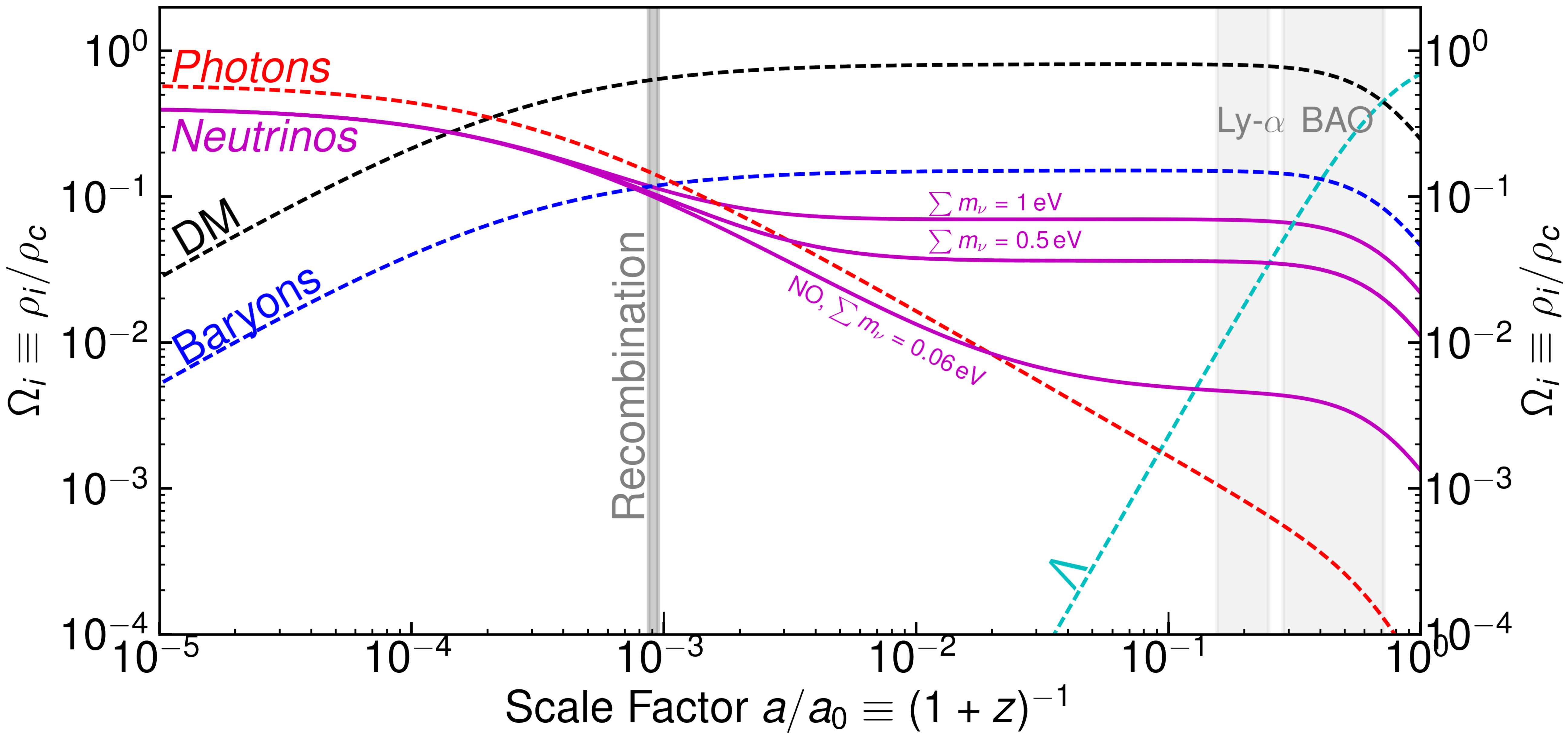
Comoving sound horizon (Early Universe)

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

Comoving angular diameter distance (Late Universe)

Massive neutrinos →

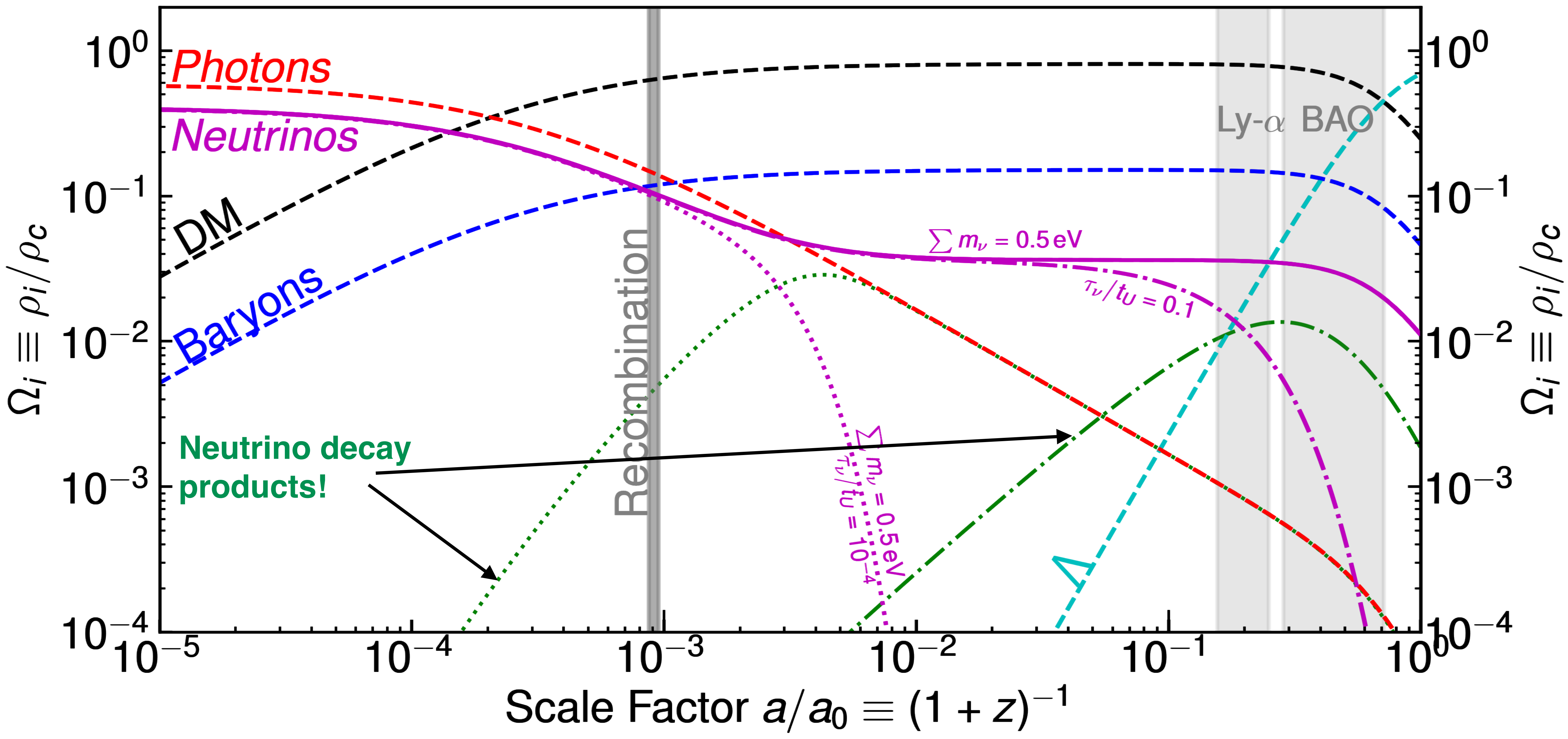
Neutrino Masses from Cosmology



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

Non-standard Neutrino Cosmologies:

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Alvey, Escudero & Sabti 2111.14870

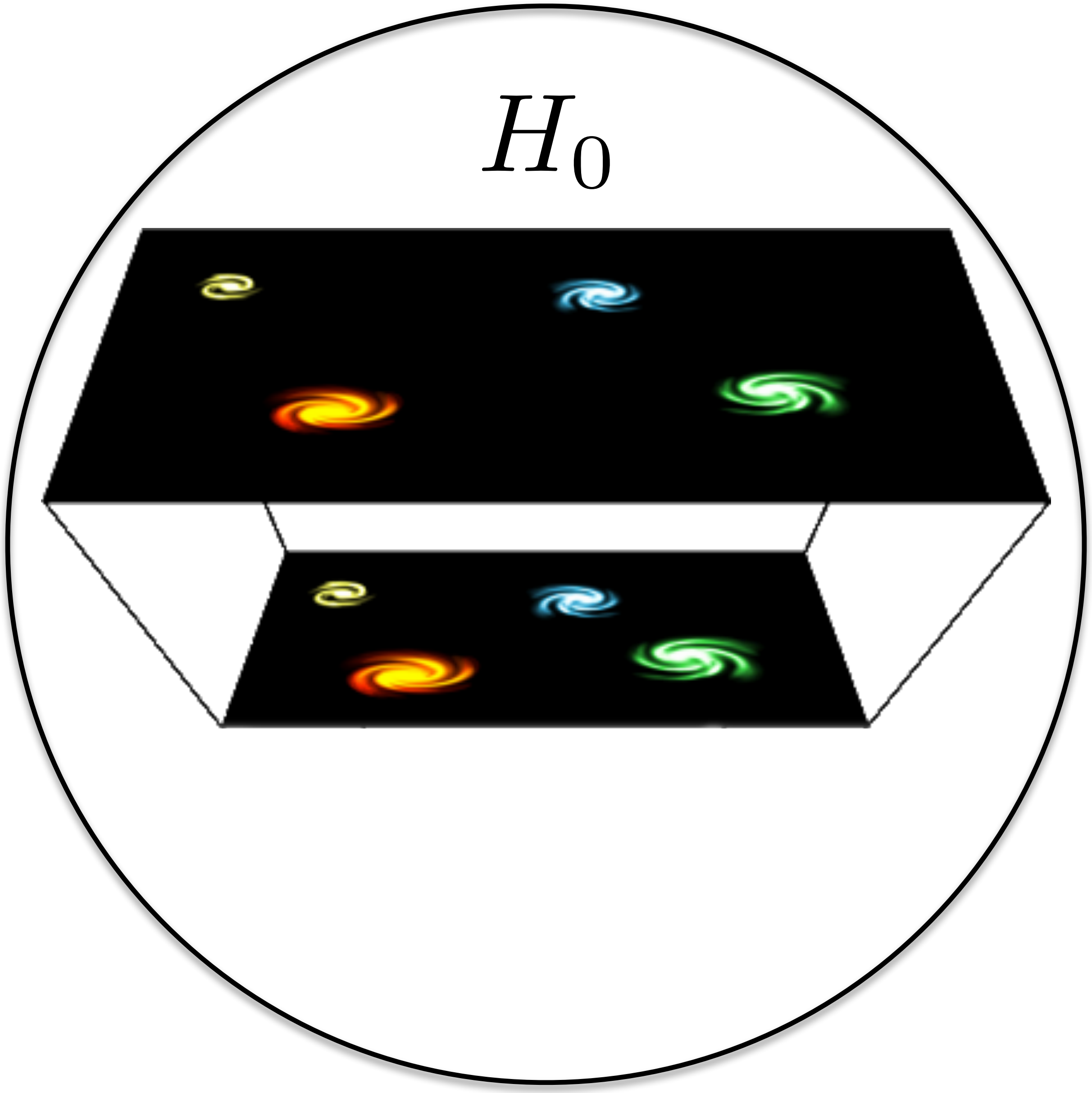
Take Away Messages:

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

— **Of course, in ΛCDM there is a direct link between $\Omega_\nu(z)$ and 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**

— **Importantly, they entail non-standard neutrino properties**



Riess *et al.* 2112.04510

Local Measurements

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

5σ tension within ΛCDM!

Planck 2018 1807.06209

ΛCDM Prediction

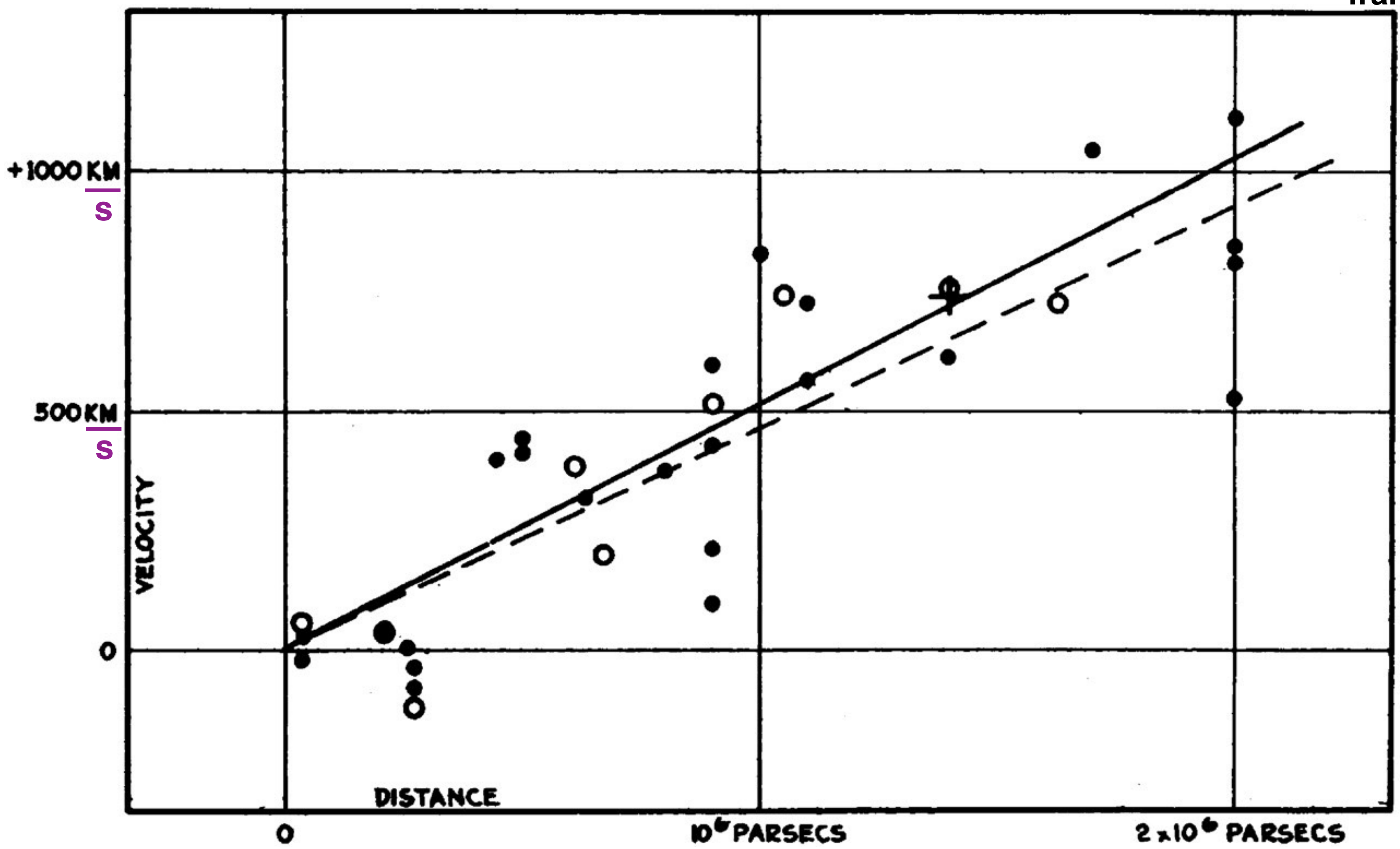
$$H_0 = 67.4 \pm 0.5\,\mathrm{km/s/Mpc}$$

The Hubble Law

The Universe is expanding!

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

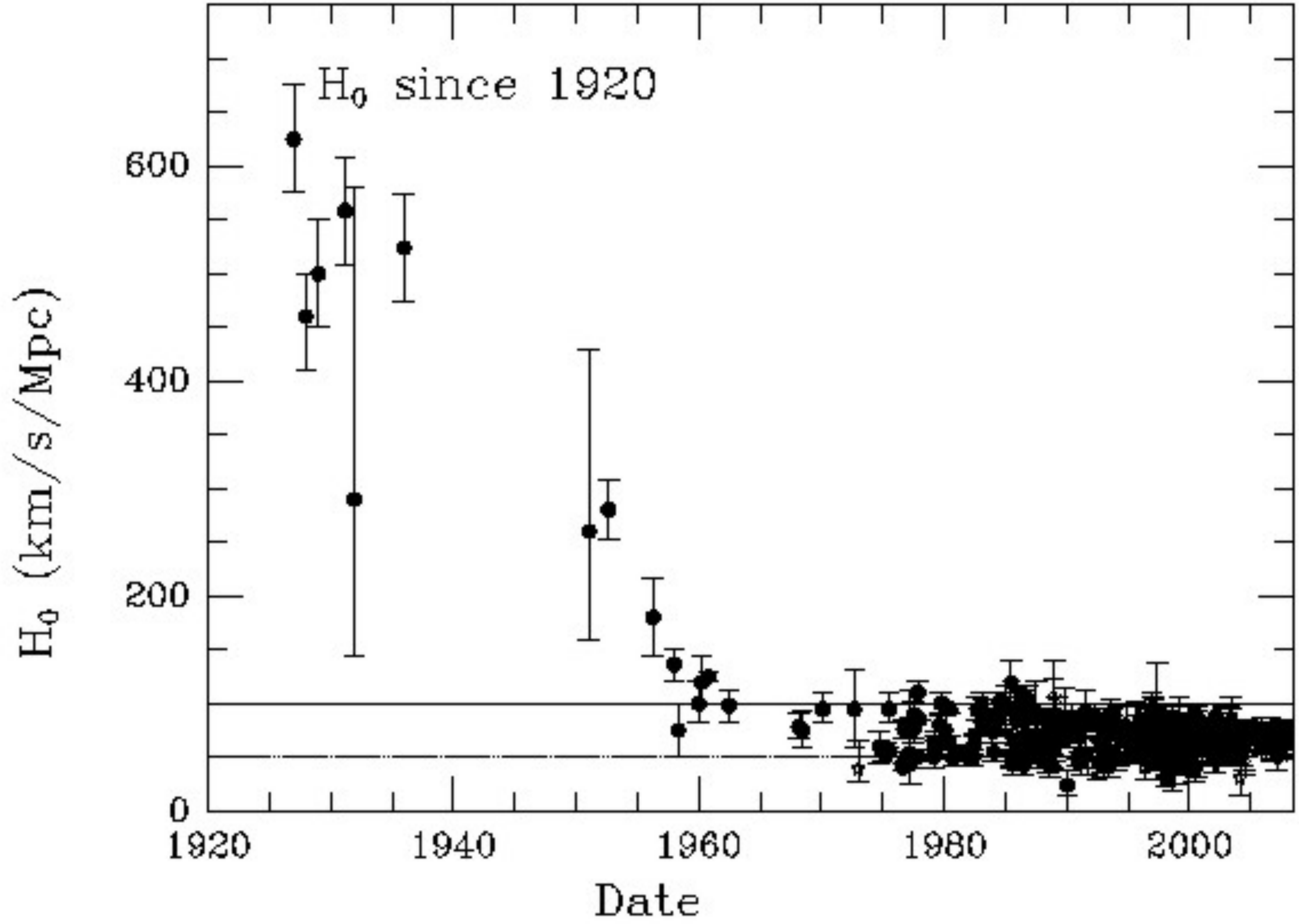
Exercise: derive it in the framework of FLRW!



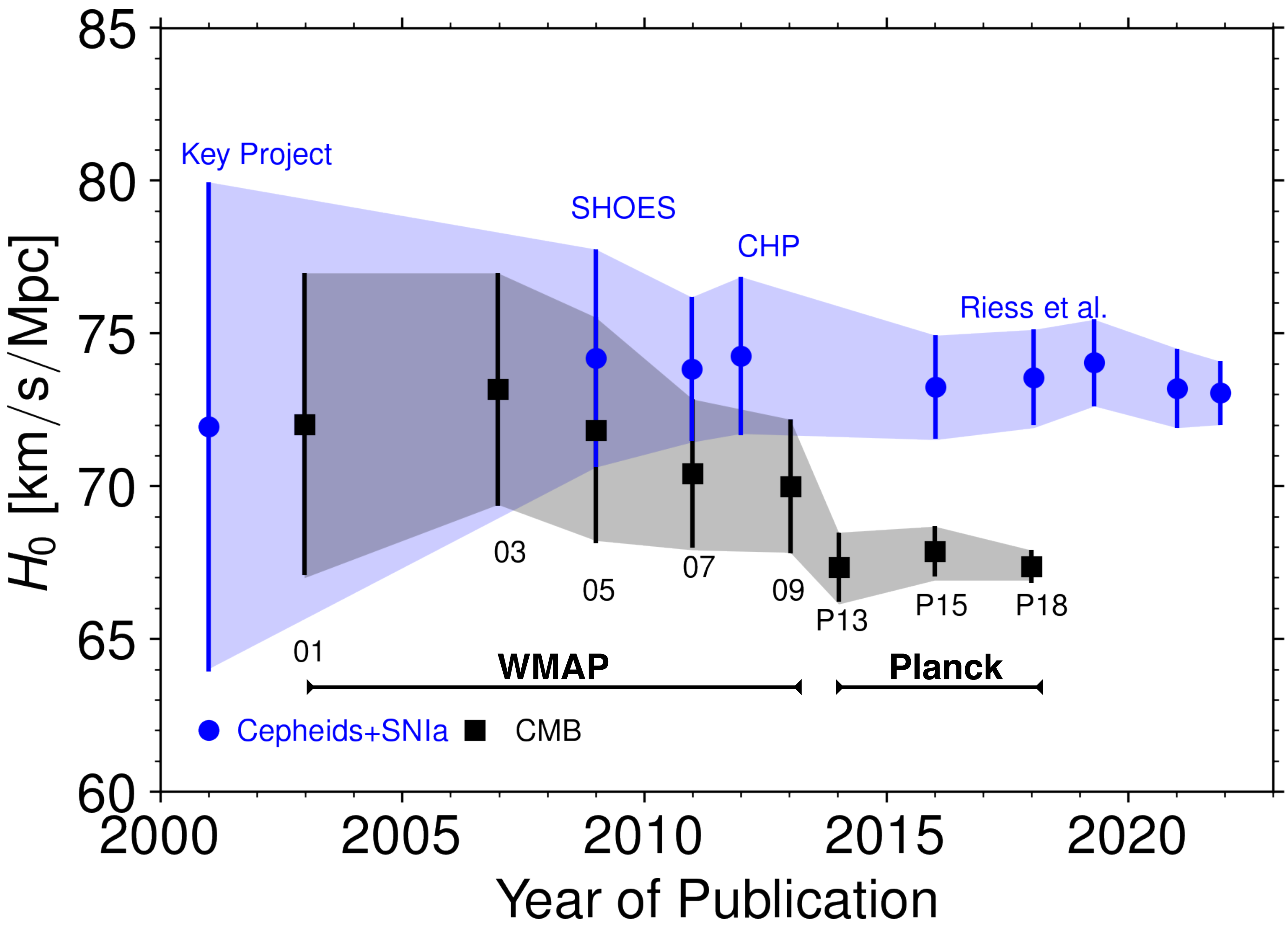
The Hubble Tension in Perspective

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:**

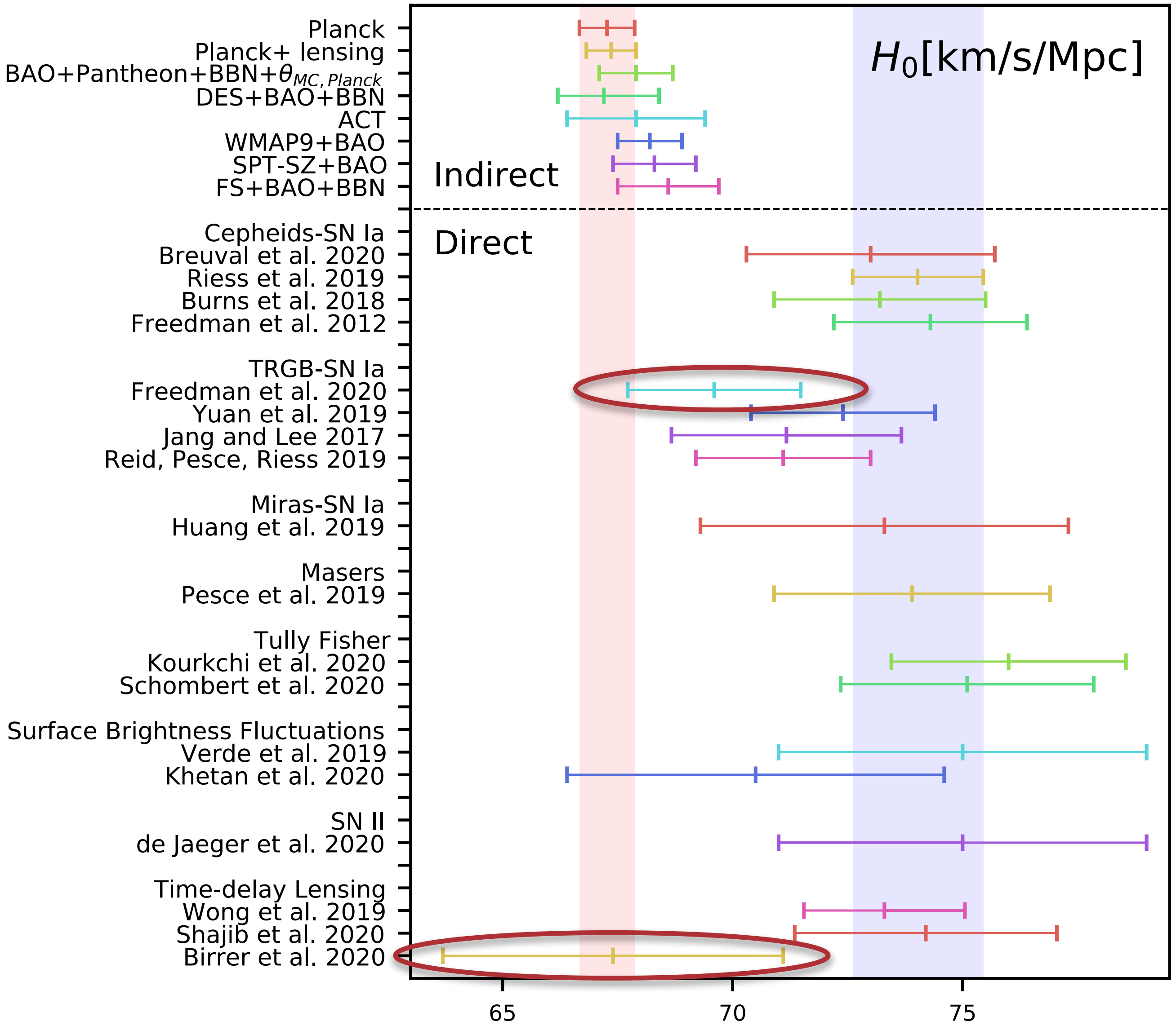
$$H_0 = 73.04 \pm 1.04\,\mathrm{km/s/Mpc}$$ **Riess *et al.* 2112.04510**

$$H_0 = 67.4 \pm 0.5\,\mathrm{km/s/Mpc}$$ **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 among the most precise and they point to $H_0 \sim (73 \pm 1)\,\mathrm{km/s/Mpc}$**
  - **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

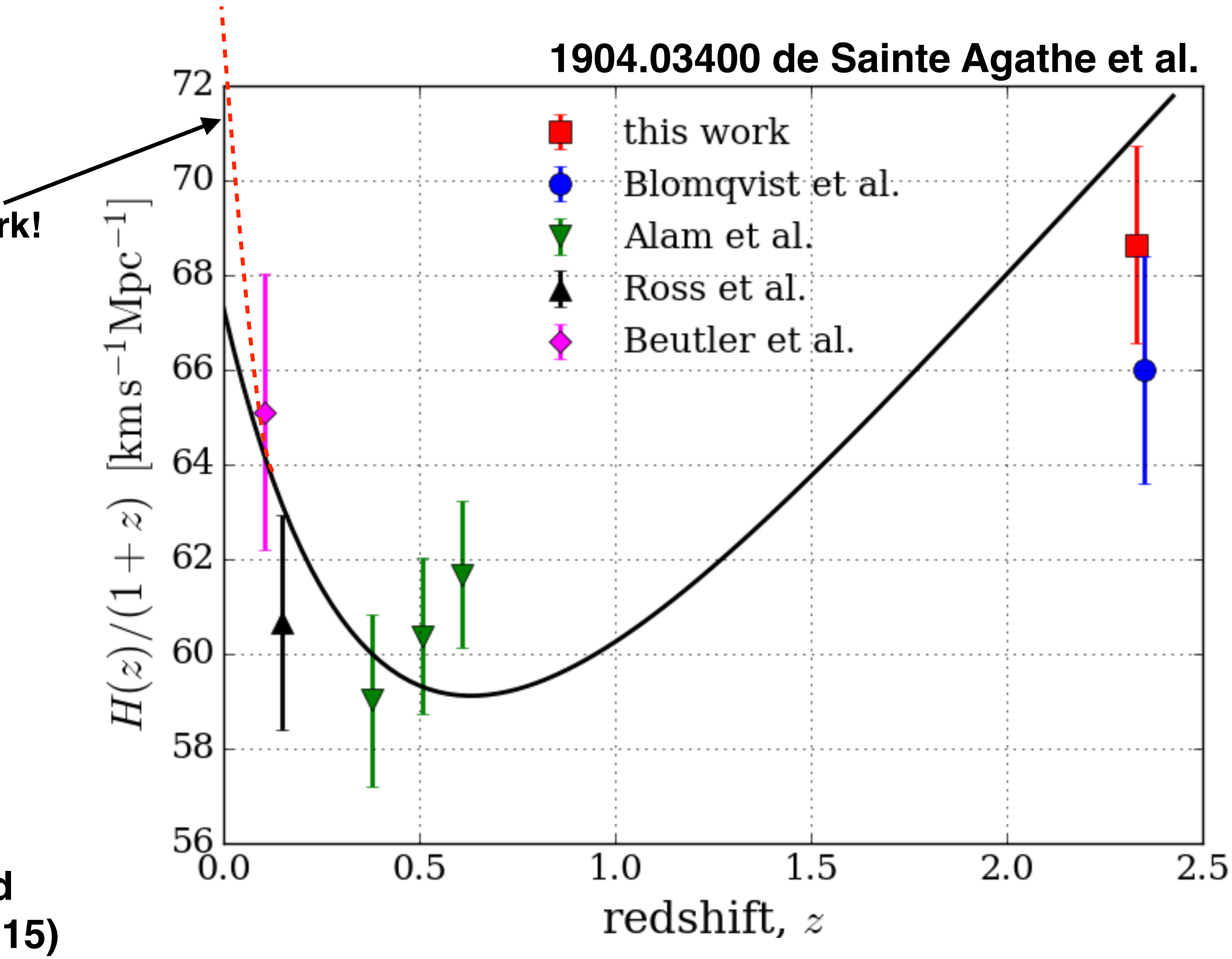
The Hubble Tension: Theory

Why late Universe modifications do not work?

see e.g. 2103.08723 by Efstathiou

Because type Ia SN and Baryon Acoustic Oscillations constrain the expansion history of the Universe at $z < 2.5$ and they agree with the predictions of ΛCDM

1904.03400 de Sainte Agathe et al.



This would not work!

(H_0 is measured locally, at $z < 0.15$)

The Hubble Tension: Theory

- **Why Early Universe modifications could work?**

Because the CMB does not measure H_0 directly!

Planck measures the positions of the peaks: $\theta_s \equiv r_s / D_M(z_\star)$

(0.03% precision)

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

Comoving sound horizon (Early Universe)

$$D_M(z) = \int_0^z \frac{1}{\underset{\nwarrow H_0}{H(z')}}\, dz'$$

Comoving angular diameter distance (Late Universe)

Model Building task: **The game is to make r_s smaller by ~8% so that H_0 can be the one reported by Riess. But, not spoiling the fit to ultra precise CMB data from Planck!**

simplest:

Knox and Millea 1908.03663

Enhance the expansion history of the Universe prior and close to recombination!

The Hubble Tension: Theory

- **Hundreds of Models in the market** **See 2103.01183 by di Valentino et al.**

Most of them do not work well. They either lead to a bad CMB fit or do not shift H_0 enough

Schöneberg et al. 2107.10291: ***The H_0 Olympics: A fair ranking of proposed models***

Model	$\Delta N_{\rm param}$	M_B	Gaussian Tension	$Q_{\rm DMAP}$ Tension		$\Delta\chi^2$	ΔAIC		Finalist
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	X	0.00	0.00	X	X

How large is the Hubble tension?

small values here are better!

How good is the CMB fit?

negative values are good here!

The Hubble Tension: Theory

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ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	✗	0.00	0.00	✗	✗
$\Delta N_{\rm ur}$	1	-19.395 ± 0.019	3.6σ	3.9σ	✗	-4.60	-2.60	✗	✗
SIDR	1	-19.385 ± 0.024	3.2σ	3.6σ	✗	-3.77	-1.77	✗	✗
DR-DM	2	-19.413 ± 0.036	3.3σ	3.4σ	✗	-7.82	-3.82	✗	✗
mixed DR	2	-19.388 ± 0.026	3.2σ	3.7σ	✗	-6.40	-2.40	✗	✗
SIν+DR	3	-19.440 ± 0.038	3.7σ	3.9σ	✗	-3.56	2.44	✗	✗
Majoron	3	-19.380 ± 0.027	3.0σ	2.9σ	✓	-13.74	-7.74	✓	✓ ②
primordial B	1	-19.390 ± 0.018	3.5σ	3.5σ	✗	-10.83	-8.83	✓	✓ ③
varying m_e	1	-19.391 ± 0.034	2.9σ	3.2σ	✗	-9.87	-7.87	✓	✓ ③
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.7σ	✓	-16.11	-12.11	✓	✓ ①
EDE	3	-19.390 ± 0.016	3.6σ	1.6σ	✓	-20.80	-14.80	✓	✓ ②
NEDE	3	-19.380 ± 0.021	3.2σ	2.0σ	✓	-17.70	-11.70	✓	✓ ②
CPL	2	-19.400 ± 0.016	3.9σ	4.1σ	✗	-4.23	-0.23	✗	✗
PEDE	0	-19.349 ± 0.013	2.7σ	2.0σ	✓	4.76	4.76	✗	✗
MPEDE	1	-19.400 ± 0.022	3.6σ	4.0σ	✗	-2.21	-0.21	✗	✗
DM $\rightarrow$ DR+WDM	2	-19.410 ± 0.013	4.2σ	4.4σ	✗	-4.18	-0.18	✗	✗
DM $\rightarrow$ DR	2	-19.410 ± 0.011	4.3σ	4.2σ	✗	0.11	4.11	✗	✗

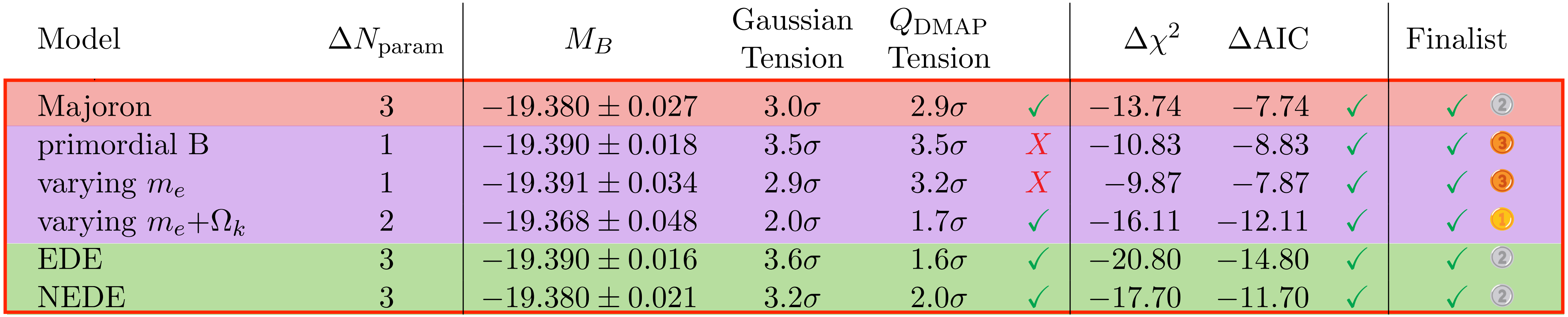
best performance:

- **None of them fully solves the Hubble tension!**

The Hubble Tension: Theory

A critical review of the best performing models

Schöneberg et al. 2107.10291: ***The H_0 Olympics: A fair ranking of proposed models***



Model	$\Delta N_{\rm param}$	M_B	Gaussian Tension	$Q_{\rm DMAP}$ Tension		$\Delta\chi^2$	ΔAIC		Finalist	
Majoron	3	-19.380 ± 0.027	3.0σ	2.9σ	✓	-13.74	-7.74	✓	✓	②
primordial B	1	-19.390 ± 0.018	3.5σ	3.5σ	X	-10.83	-8.83	✓	✓	③
varying m_e	1	-19.391 ± 0.034	2.9σ	3.2σ	X	-9.87	-7.87	✓	✓	③
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.7σ	✓	-16.11	-12.11	✓	✓	①
EDE	3	-19.390 ± 0.016	3.6σ	1.6σ	✓	-20.80	-14.80	✓	✓	②
NEDE	3	-19.380 ± 0.021	3.2σ	2.0σ	✓	-17.70	-11.70	✓	✓	②

- **Primordial magnetic fields & $m_e(t) + \Omega_k$**

The idea here is that recombination happens earlier than in ΛCDM by either

a) **using primordial magnetic fields of ~ 1 nGauss on kpc scales** **[Jedamzik & Pogosian 2004.09487]**
b) **enhancing $m_e(t)$ at recombination by ~ 2%** **[Hart & Chluba 1912.03986]**

😐 **Good exercises, not much theoretical motivation for $m_e(t)$ but maybe yes for B fields!**

- **Early Dark Energy** **Poulin, Smith, Karwal, Kamionkowski 1811.04083 Agrawal, Cyr-Racine, Pinner, Randall 1904.01016**

The idea is that there is an early dark energy component just acting right before recombination

This can be done with a very light scalar field with $m_\phi \sim 10^{-27}\,\mathrm{eV}$
that yields $f_{\rm EDE} \sim 10\,\%$ but with a very particular potential:

$$V_\phi \sim m^2 f^2 \left[1 - \cos\phi/f\right]^3 \sim m^2\phi^6/f^4$$

😐 **Highly unclear where such potential could come from and there is a coincidence problem …**

- **New Early Dark Energy**

Another possibility is to trigger a 1st order phase transition at $T \sim \mathrm{eV}$ **[Niedermann & Sloth 1910.10739]**

😐 **It appears rather involved … Dark gauge sector, DM, neutrinos, inverse seesaw…** **see [Niedermann & Sloth 2112.00759, 2112.00770]**

Neutrinos and the Hubble Tension

Why Neutrinos?

1) Neutrinos are always a relevant species in the Universe evolution

2) Neutrino masses are the only Laboratory evidence of Physics Beyond the Standard Model

Neutrinos and the Hubble Tension

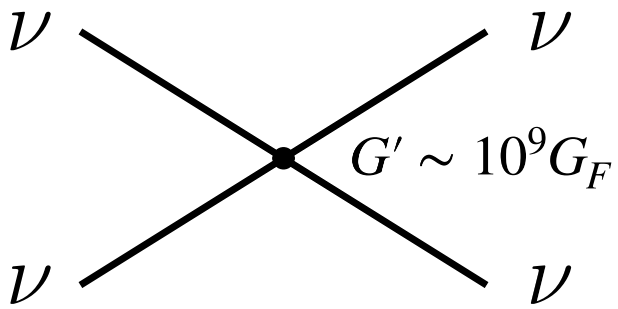
- **Dark Radiation**

$$\Delta N_{\rm eff} = 0.23 \pm 0.15$$

(68 % CL, Planck+BAO+H0)

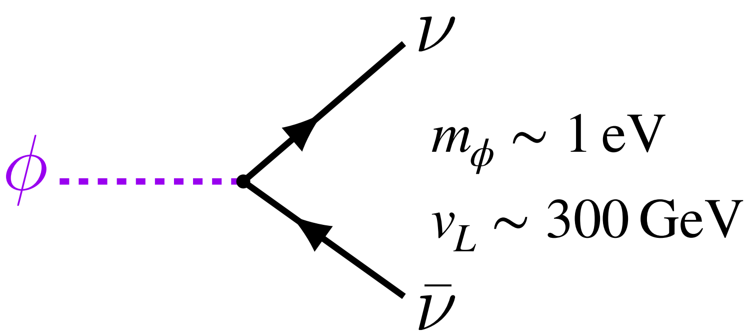
Clear Interpretation 😃
H_0 tension from 4.4σ to 3.6σ 😐
CMB fit is degraded ☹️

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



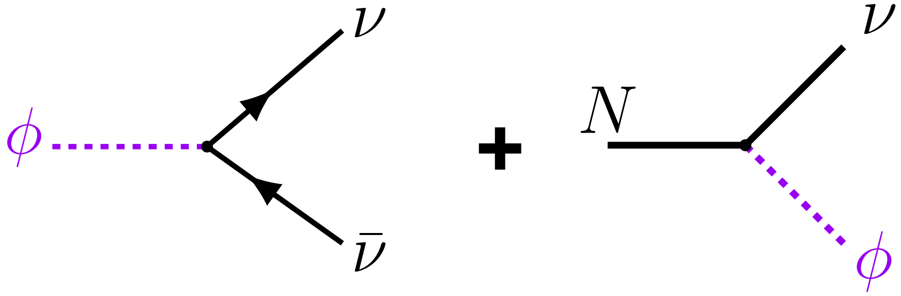
H_0 tension solved if TEEE data is ignored 😃
If pol data is included no solution for H_0 ☹️
Almost excluded by Lab data (Kelly++1905.02727) ☹️
ACT data seems points to it again 2207.03164 🧐

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



H_0 tension from 4.4σ to 2.5σ 😐
CMB fit is not degraded 😃
Direct connection with Seesaw 😃
Ad hoc $\Delta N_{\rm eff} \sim 0.5$ 😐

- **Primordial population of Majorons** Escudero & Witte 2103.03249



Sterile neutrinos can source $\Delta N_{\rm eff}^{\rm BBN} \sim 0.4$
Sterile neutrinos can lead to Leptogenesis
H_0 tension from 5σ to 2.6σ

Revisiting the cosmological analysis without many simplifying approximations: Sandner, Escudero & Witte 22'

Neutrinos and the Hubble Tension

- **Early Dark Energy sourced by neutrinos** Sakstein & Trodden 1911.11760
  - Nice way to solve the coincidence problem 😃
  - Use $\sum m_\nu = 1.5\,\mathrm{eV}$ (10% of DM) which can be dangerous 😐
  - But the Cl's have not been calculated yet … 😐
  - Some progress has been made Carrillo González et al. 2011.09895 😃
- **Dark Matter-Neutrino Interactions** Ghosh, Khatri & Roy 1908.09843
  - Nice idea to allow for a large H_0 without an enhanced expansion history 😃
  - Latest analysis done with Planck 2015 data 😐
  - Rather large interactions needed. Model may be complicated to build! 😐
- **An eV-scale Sterile Neutrino interacting with a pseudoscalar**
  Archidiacono, Gariazzo, Giunti, Hannestad, Tram 2006.12885
  - Clearly motivated by short-baseline neutrino experiments 😃
  - Nice idea to try to avoid the cosmo problems with $m_s \sim \mathrm{eV}$ 😃
  - The Hubble Tension could be solved if $\Delta N_{\rm eff} = 1$ 😃
  - But that leads to a very bad CMB fit $\Delta\chi^2 = 13 - 32$ ☹️

Common features of all approaches:
An enhanced expansion history and new interactions

Summary I: Neutrino Masses

Neutrino Masses:

Cosmological bounds are very stringent within the standard cosmological model, ΛCDM:

$$\sum m_\nu < 0.12\,\mathrm{eV}$$

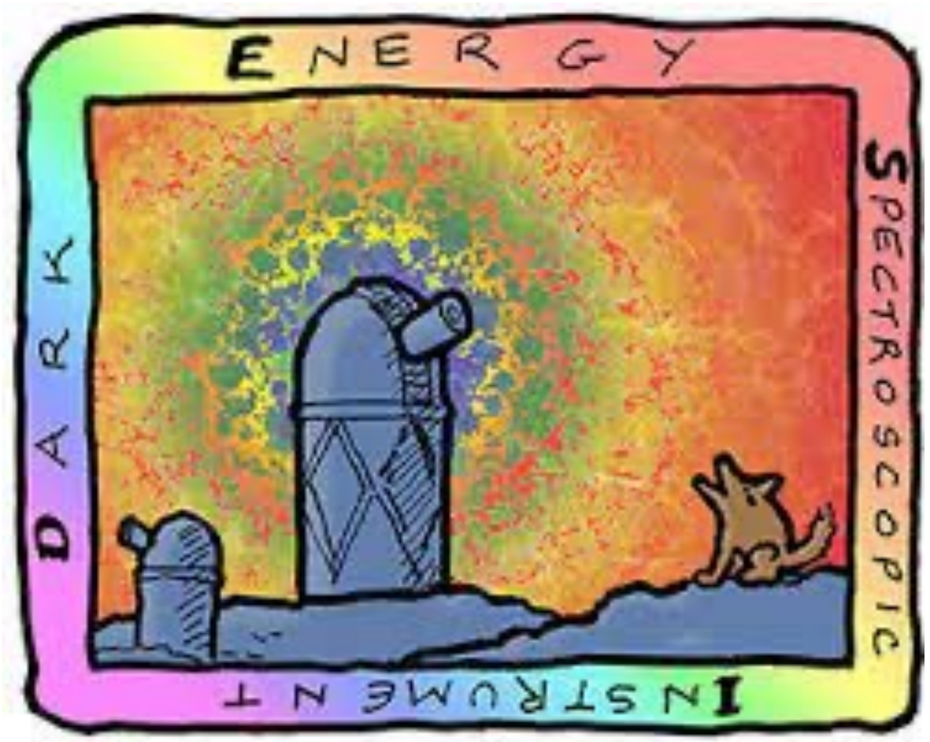
However, all cosmological neutrino mass bounds are cosmological model dependent

There are several non-standard cosmologies where this bound can be evaded. *These models are exotic*, but current data cannot differentiate them wrt ΛCDM

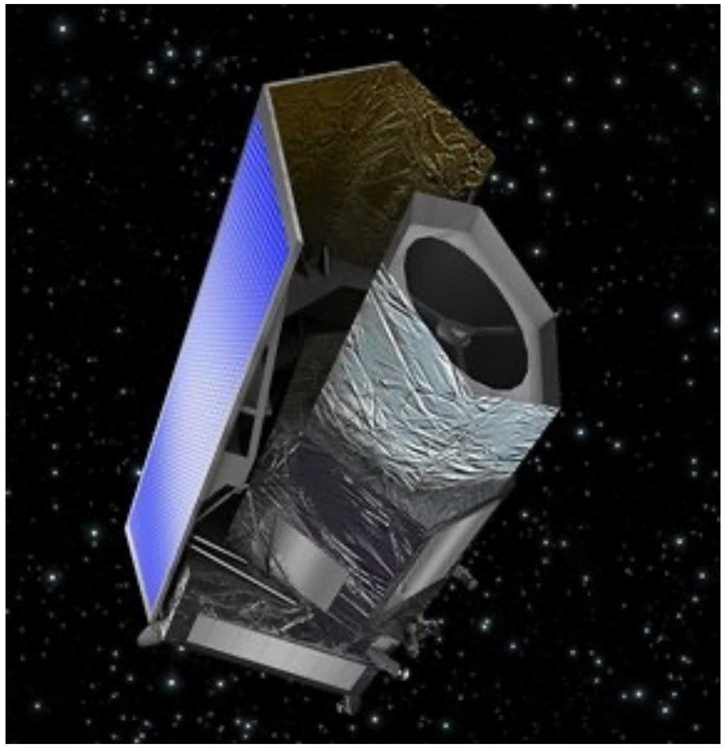
Outlook I: Neutrino Masses

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.

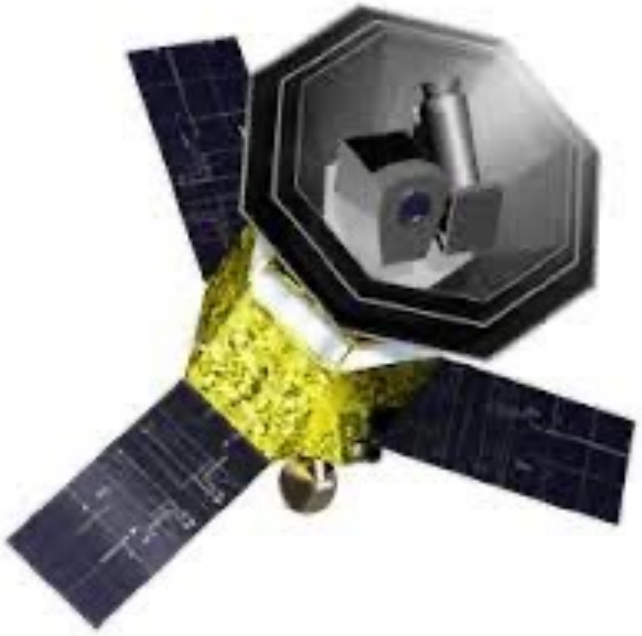
DESI



EUCLID



LiteBIRD



This is expected to happen in the next 5-7 years: $\sigma(\sum m_\nu) = 0.02$

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 ~ 4 years.

Summary II: The Hubble Tension

1) Observational evidence

There is strong observational evidence from Cepheids+SNIa

However, it is still just a tension. It needs to be confirmed by other methods

We expect significant improvements in ~3-4 years, particularly with upcoming data from Gaia & the James Webb telescope

2) Theoretical modeling

Despite the strong efforts, we have no perfect model so far

Most of the models lack theoretical motivation

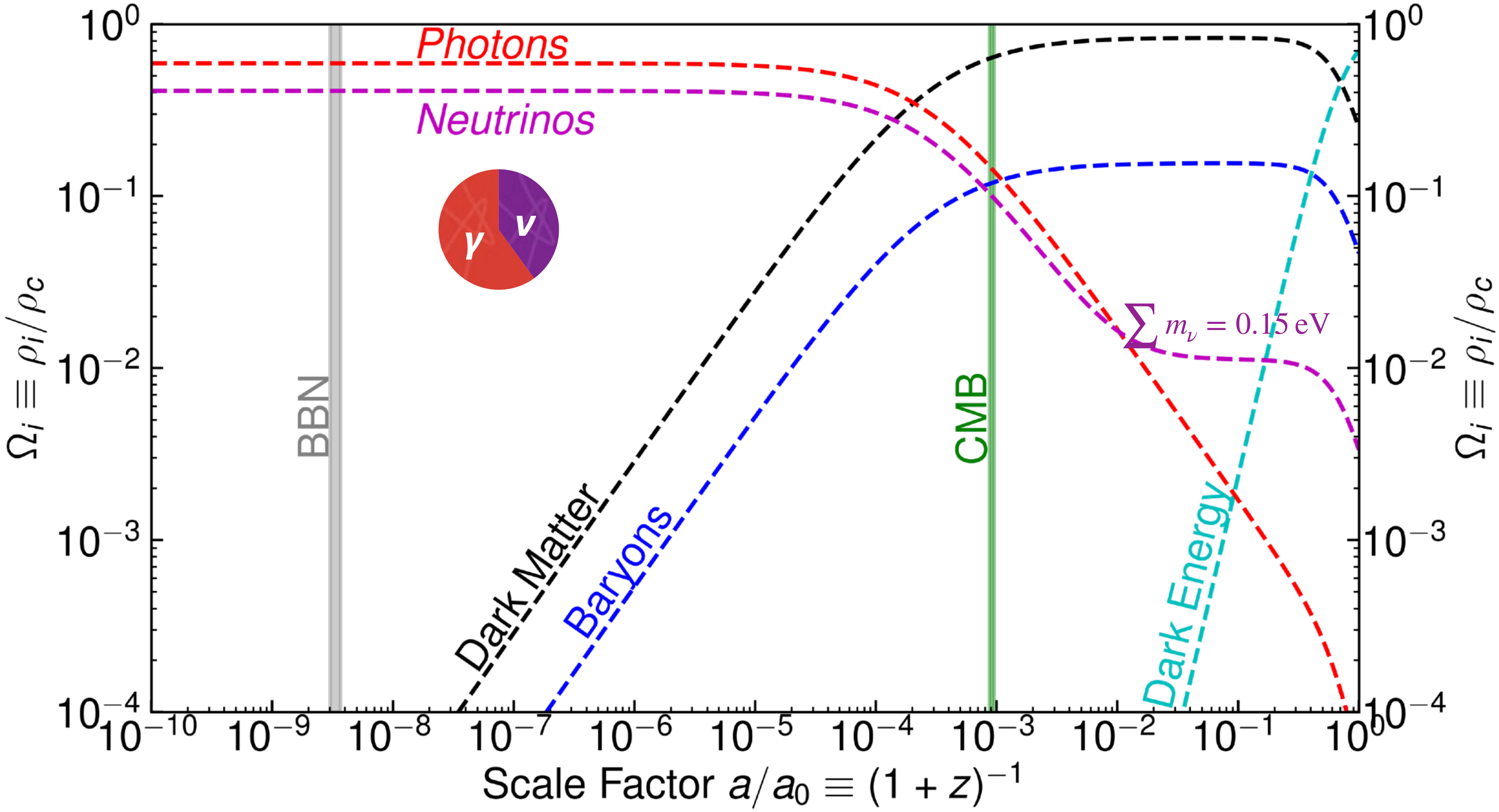
3) Neutrinos and the Hubble Tension

There are many models involving neutrinos to solve the H_0 tension.

They require new interactions and an enhanced expansion history but none is able to fully solve the H_0 tension.

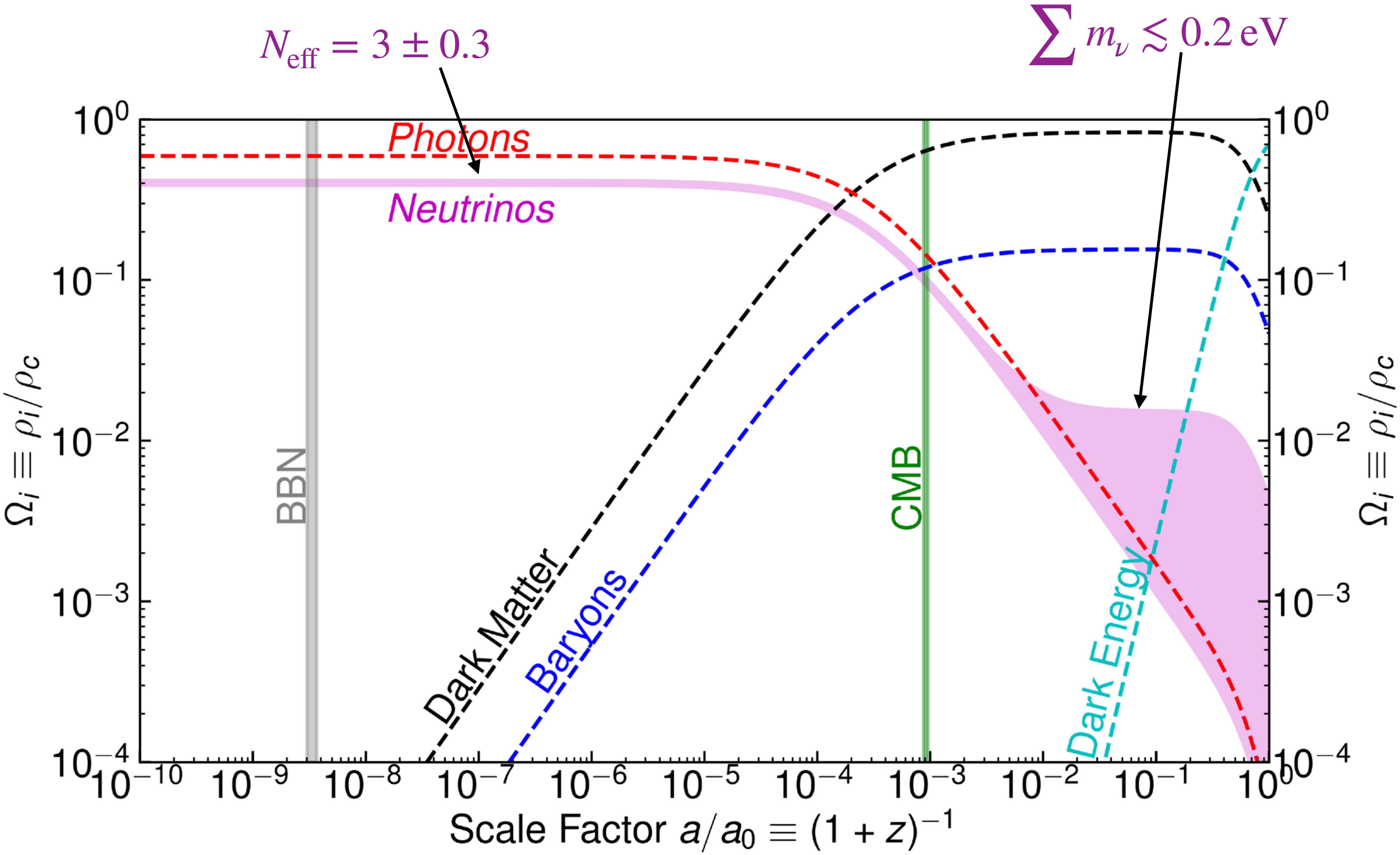
Summary of the Lectures

Neutrinos in the SM:



Summary of the Lectures

Current knowledge:

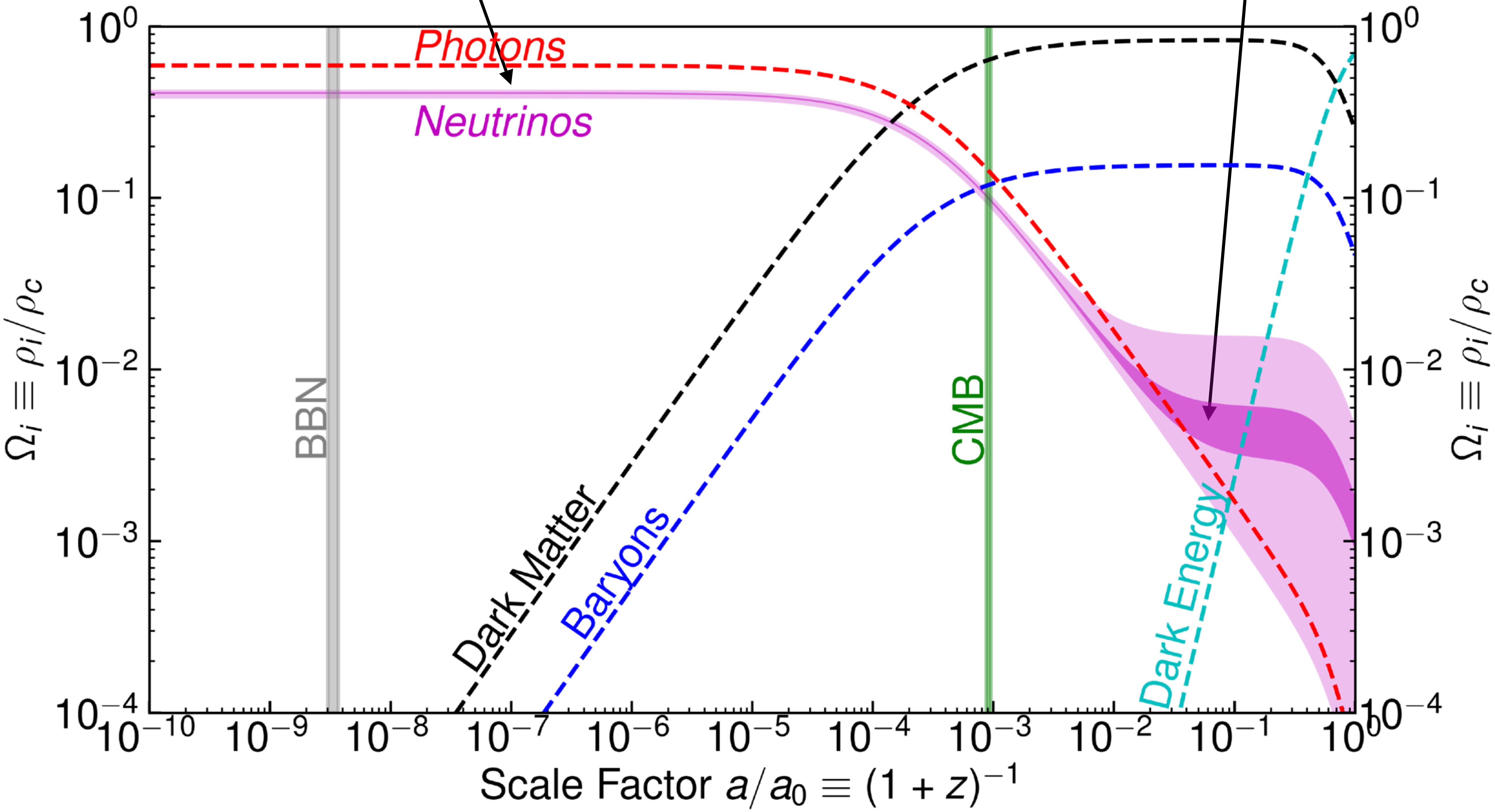


Summary of the Lectures

In the next 5-6 years:

$N_{\rm eff} = 3.044 \pm 0.06$

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



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!

End of Lecture II

ν

Thank you for your attention!

miguel.escudero@tum.de

A Small Tribute to Ann Nelson

Precisely today there is a workshop in honor of the memory of Ann E. Nelson:

https://indico.fnal.gov/event/22915/

Summiting The Unknown

New Physics, New Opportunities, New Voices

University of Washington

7/14 - 7/16, 2022

A Small Tribute to Ann Nelson

Ann Nelson passed away 3 years ago in a climbing accident

Who was she?

A role model

A leader of the community

An outstanding theoretical physicist

e.g.: Sakurai Prize winner 2018!

For comments from the community see:

https://physicstoday.scitation.org/do/10.1063/pt.6.4.20190808a/full/

including **David B. Kaplan, Howard Georgi, Lisa Randall, Nima Arkani-Hamed, Michael Dine, Kathryn Zurek & Mary K Gaillard**

A Small Tribute to Ann Nelson

Some of Ann's contributions:

Solving the Strong CP problem with spontaneous CP violation

Naturally Weak CP Violation

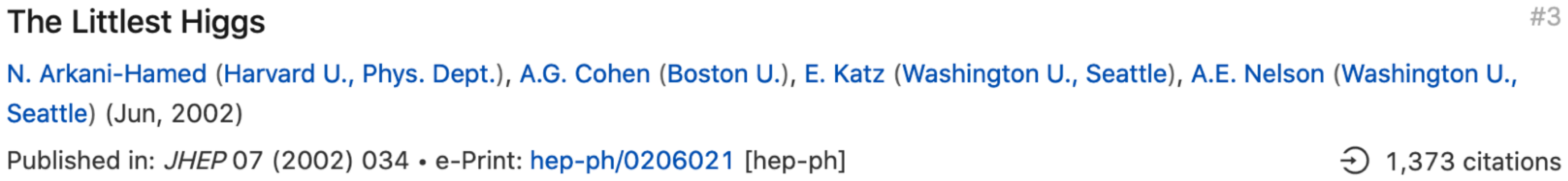
#10

Ann E. Nelson (Harvard U.) (Dec, 1983)

Published in: *Phys.Lett.B* 136 (1984) 387-391

391 citations

Little Higgs:



The Littlest Higgs

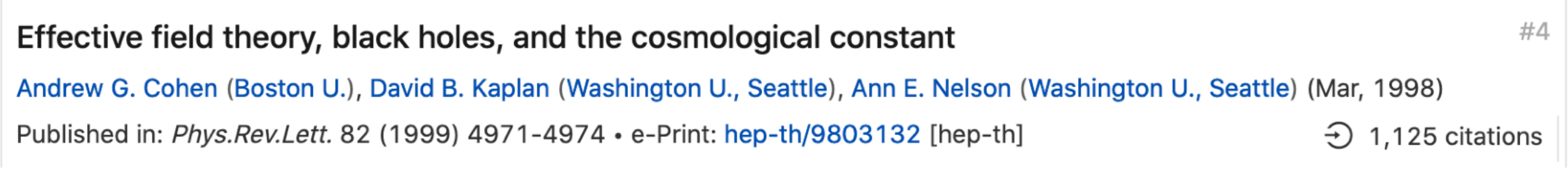
#3

N. Arkani-Hamed (Harvard U., Phys. Dept.), A.G. Cohen (Boston U.), E. Katz (Washington U., Seattle), A.E. Nelson (Washington U., Seattle) (Jun, 2002)

Published in: *JHEP* 07 (2002) 034 • e-Print: hep-ph/0206021 [hep-ph]

1,373 citations

IR-UV connections in gravity



Effective field theory, black holes, and the cosmological constant

#4

Andrew G. Cohen (Boston U.), David B. Kaplan (Washington U., Seattle), Ann E. Nelson (Washington U., Seattle) (Mar, 1998)

Published in: *Phys.Rev.Lett.* 82 (1999) 4971-4974 • e-Print: hep-th/9803132 [hep-th]

1,125 citations

Dynamical SUSY breaking

Dynamical supersymmetry breaking at low-energies

#9

Michael Dine (UC, Santa Cruz), Ann E. Nelson (UC, San Diego) (Mar, 1993)

Published in: *Phys.Rev.D* 48 (1993) 1277-1287 • e-Print: hep-ph/9303230 [hep-ph]

1,181 citations

Electroweak Baryogenesis

Progress in electroweak baryogenesis

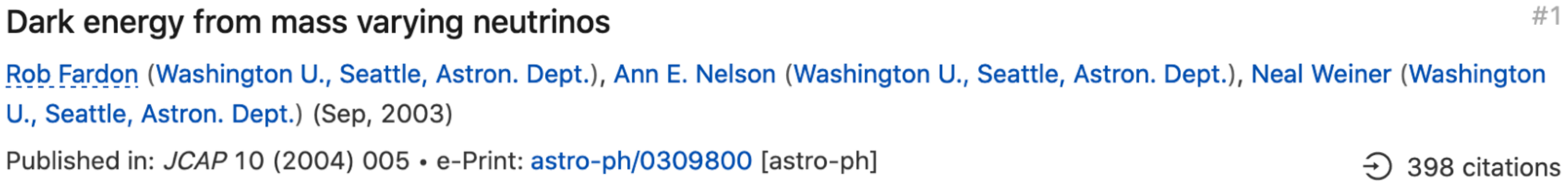
#10

Andrew G. Cohen (Boston U.), D.B. Kaplan (UC, San Diego), A.E. Nelson (UC, San Diego) (Jan, 1993)

Published in: *Ann.Rev.Nucl.Part.Sci.* 43 (1993) 27-70 • e-Print: hep-ph/9302210 [hep-ph]

1,004 citations

Dark Energy-Neutrino Connection!



Dark energy from mass varying neutrinos

#1

Rob Fardon (Washington U., Seattle, Astron. Dept.), Ann E. Nelson (Washington U., Seattle, Astron. Dept.), Neal Weiner (Washington U., Seattle, Astron. Dept.) (Sep, 2003)

Published in: *JCAP* 10 (2004) 005 • e-Print: astro-ph/0309800 [astro-ph]

398 citations

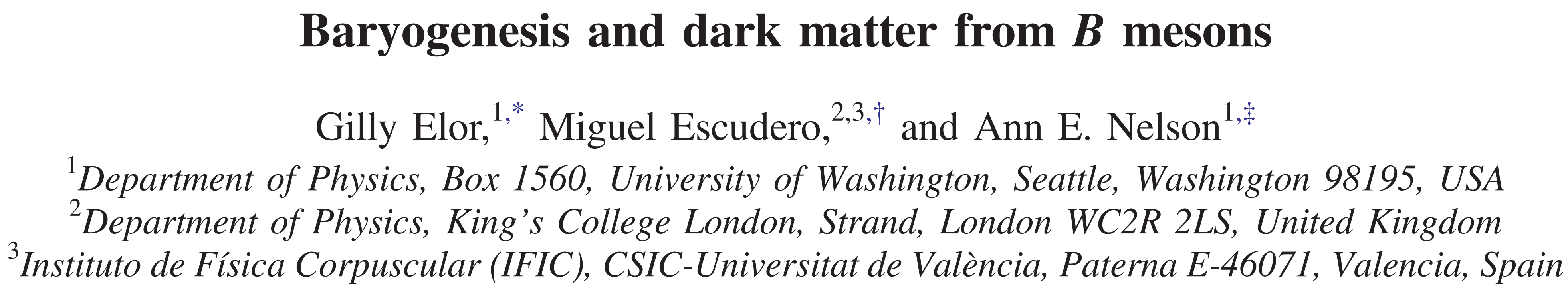
A Small Tribute to Ann Nelson

How did I met Ann?

She gave an amazing seminar at Fermilab about Baryogenesis in 2017. I thought, wow, that’s who I would like to be when I am old!

I got funding to visit her and so I did for a month in April 2018

We wrote a paper about a very ambitious Baryogenesis and Dark Matter mechanism using a naturally occurring CP violating system in the Standard Model: the neutral B meson system:



Baryogenesis and dark matter from B mesons

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[2]*Department of Physics, King’s College London, Strand, London WC2R 2LS, United Kingdom*

[3]*Instituto de Física Corpuscular (IFIC), CSIC-Universitat de València, Paterna E-46071, Valencia, Spain*

My experience at the UW with her was incredibly illuminating. She was the most brilliant physicist I have ever met, but also a very generous, inclusive and friendly person.

We deeply miss her

Motivation, Method and Philosophy

Ann E. Nelson (1958-2019)

A sentence from her "Commentary: Diversity in physics: Are you part of the problem?" in Physics Today that I find very motivating:

I often get asked, "Why are there so few women in physics?" That anyone would ask that question shows how oblivious many people are to the sexism and bias that permeate our society and physics culture. I may not be able to fully answer the question, but I can tell you why there are women like me in physics. Because we love math and nature. Because we like doing computations and figuring things out, step by systematic step. We love the flashes of insight and the excitement of revelations from new data. We revel in breathtaking moments of awe. And we had support, mentors, encouragement, opportunities, and colleagues who gave us a positive view of ourselves as physicists.