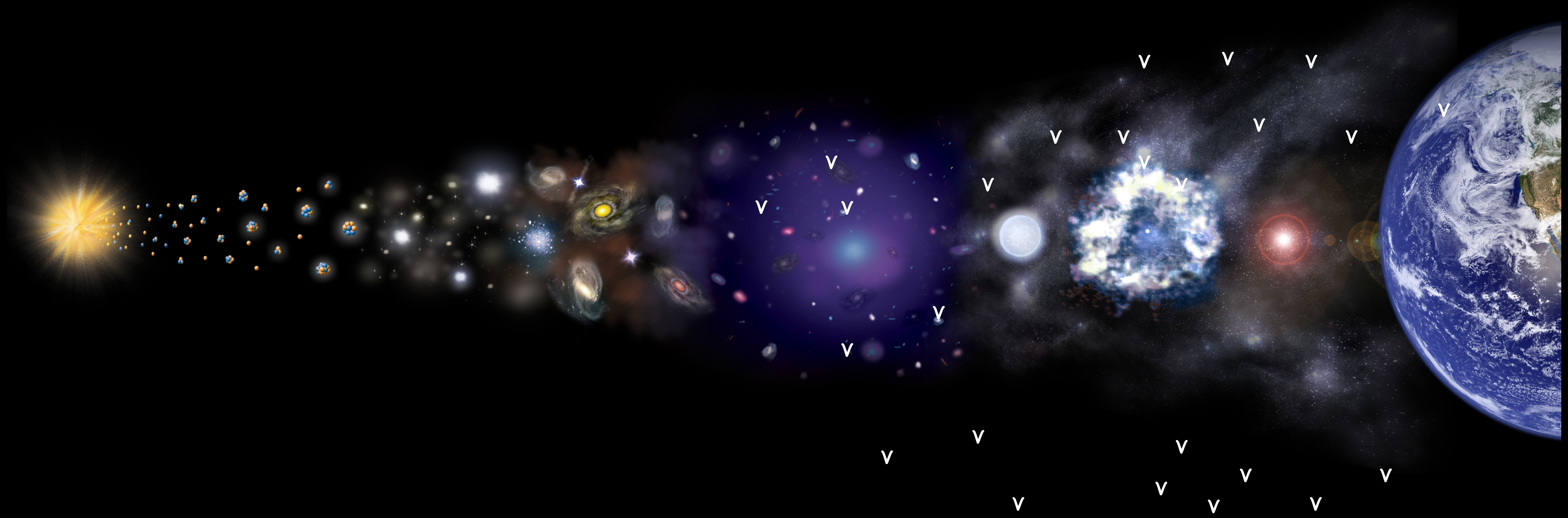
Limits on neutrino masses:
Tension between terrestrial and cosmological results



Olga Mena (IFIC, CSIC-UV)

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Financiado por la Unión Europea NextGenerationEU
Plan de Recuperación, Transformación y Resiliencia
AGENCIA ESTATAL DE INVESTIGACIÓN
IFIC INSTITUT DE FÍSICA CORPUSCULAR
VNIVERSITAT ID VALÈNCIA
CSIC

2015 Nobel Physics Prize to **Takaaki Kajita and Arthur B. McDonald**

"for the discovery of neutrino oscillations, which shows that neutrinos have mass. […] New discoveries about the deepest neutrino secrets are expected to change our current understanding of the history, structure and future fate of the Universe"

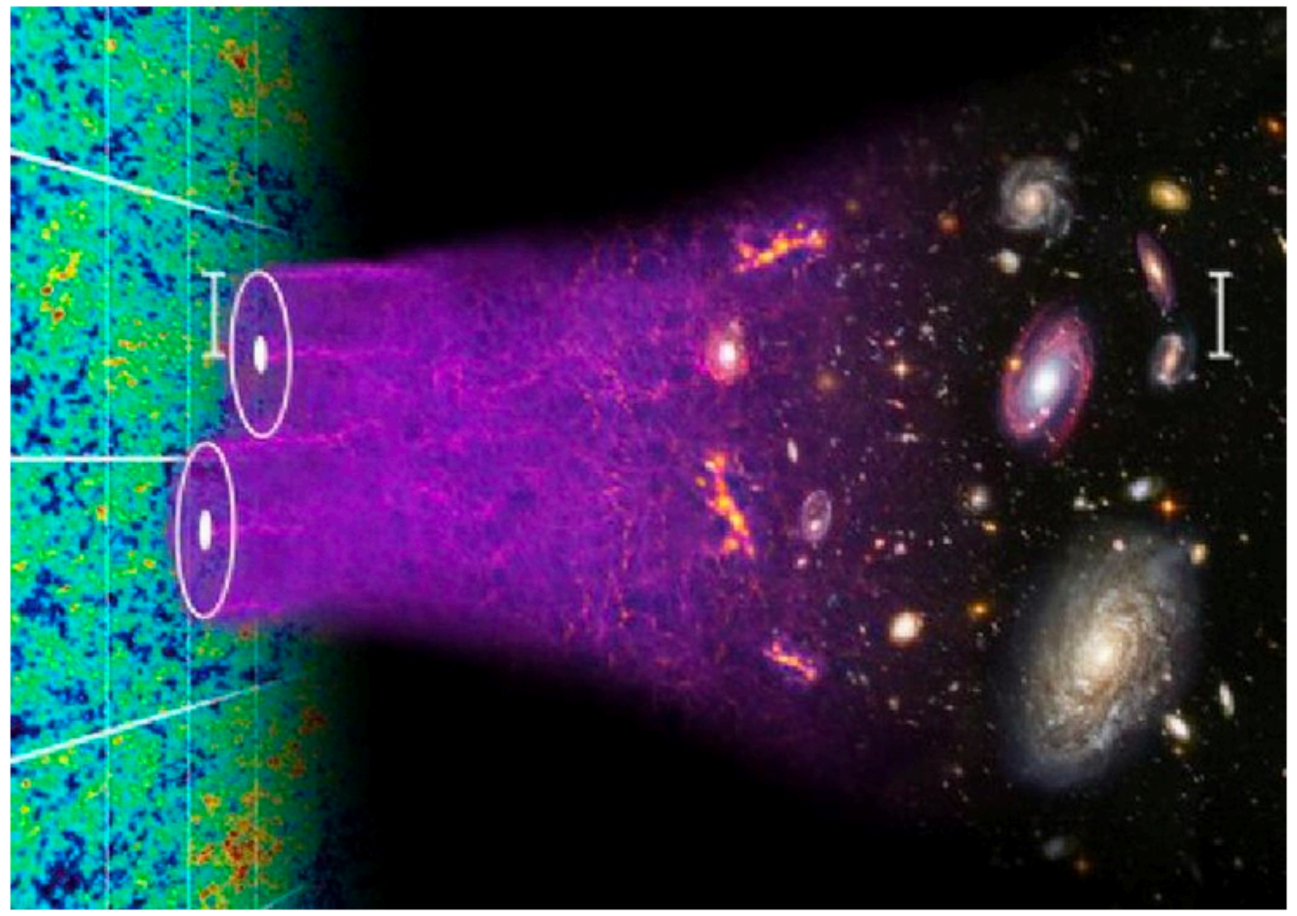
Forbes

Billionaires | Innovation | Leadership | Money | Business | Small Business | Lifestyle

20,733 views | Dec 5, 2017, 10:00am

How Neutrinos Could Solve The Three Greatest Open Questions In Physics

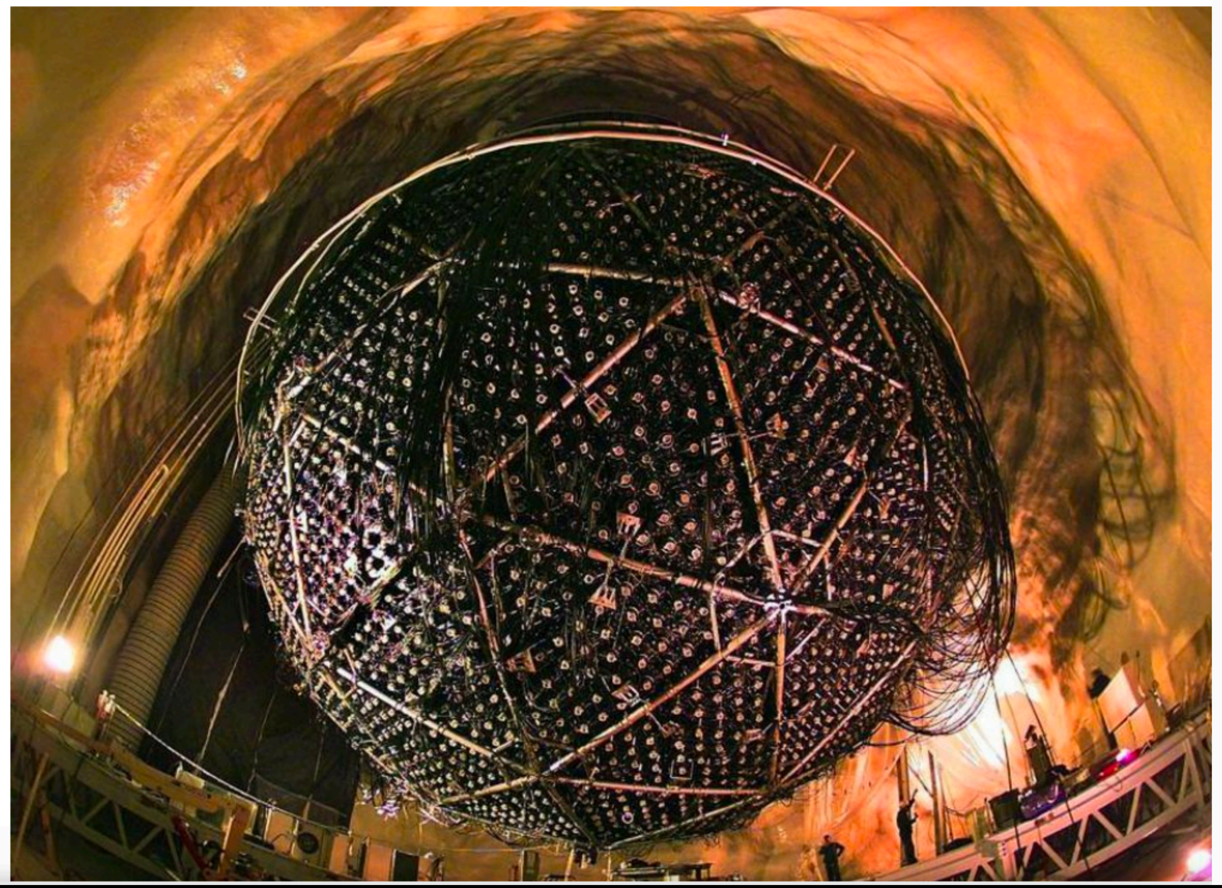
Ethan Siegel Senior Contributor
Starts With A Bang Contributor Group
Science
The Universe is out there, waiting for you to discover it.



12,337 views | Sep 17, 2019, 02:00am

This Is Why Neutrinos Are The Standard Model's Greatest Puzzle

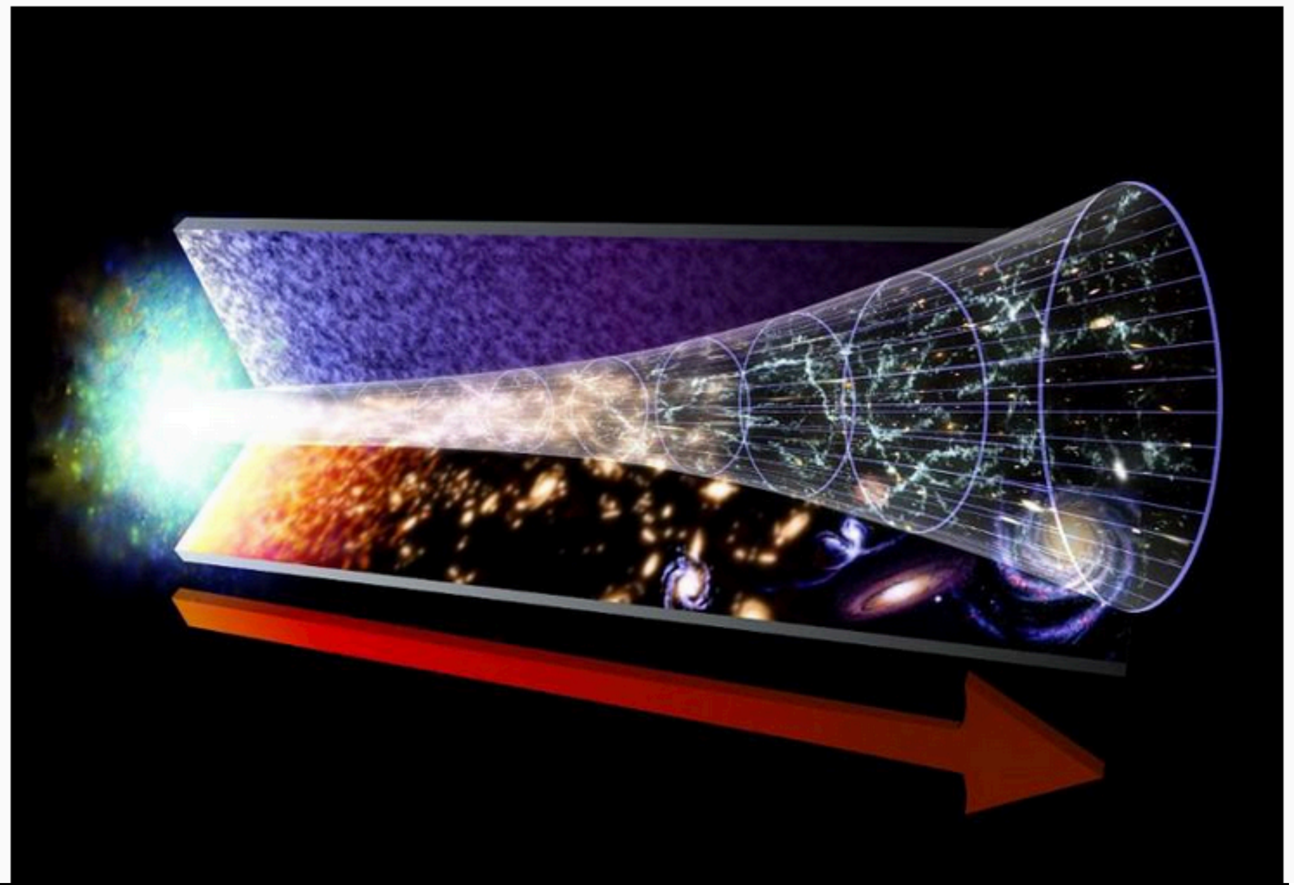
Ethan Siegel Senior Contributor
Starts With A Bang Contributor Group
Science
The Universe is out there, waiting for you to discover it.



Jul 13, 2016, 11:28am EDT

Could Dark Energy Be Caused By Frozen Neutrinos?

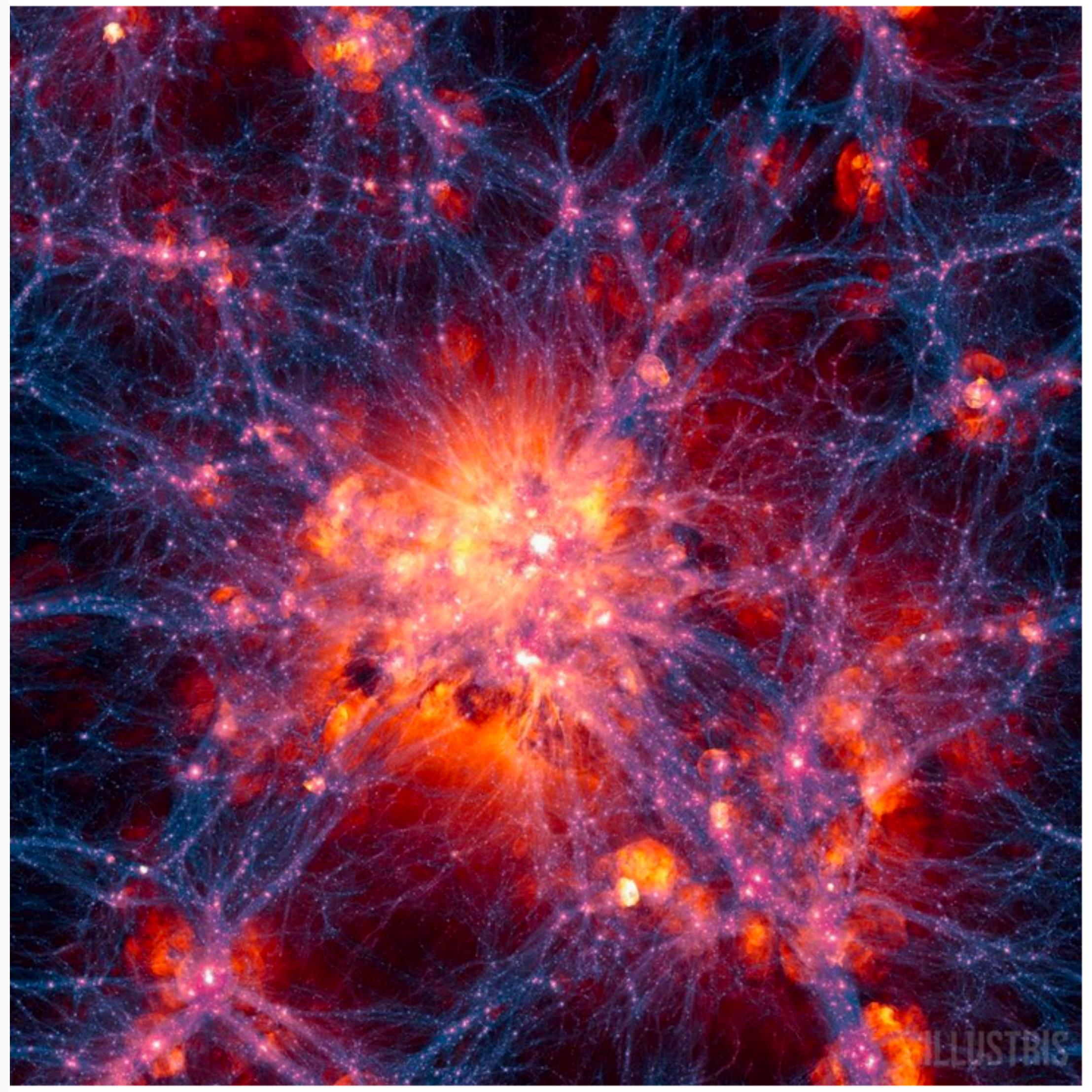
Ethan Siegel Senior Contributor
Starts With A Bang Contributor Group
Science
The Universe is out there, waiting for you to discover it.



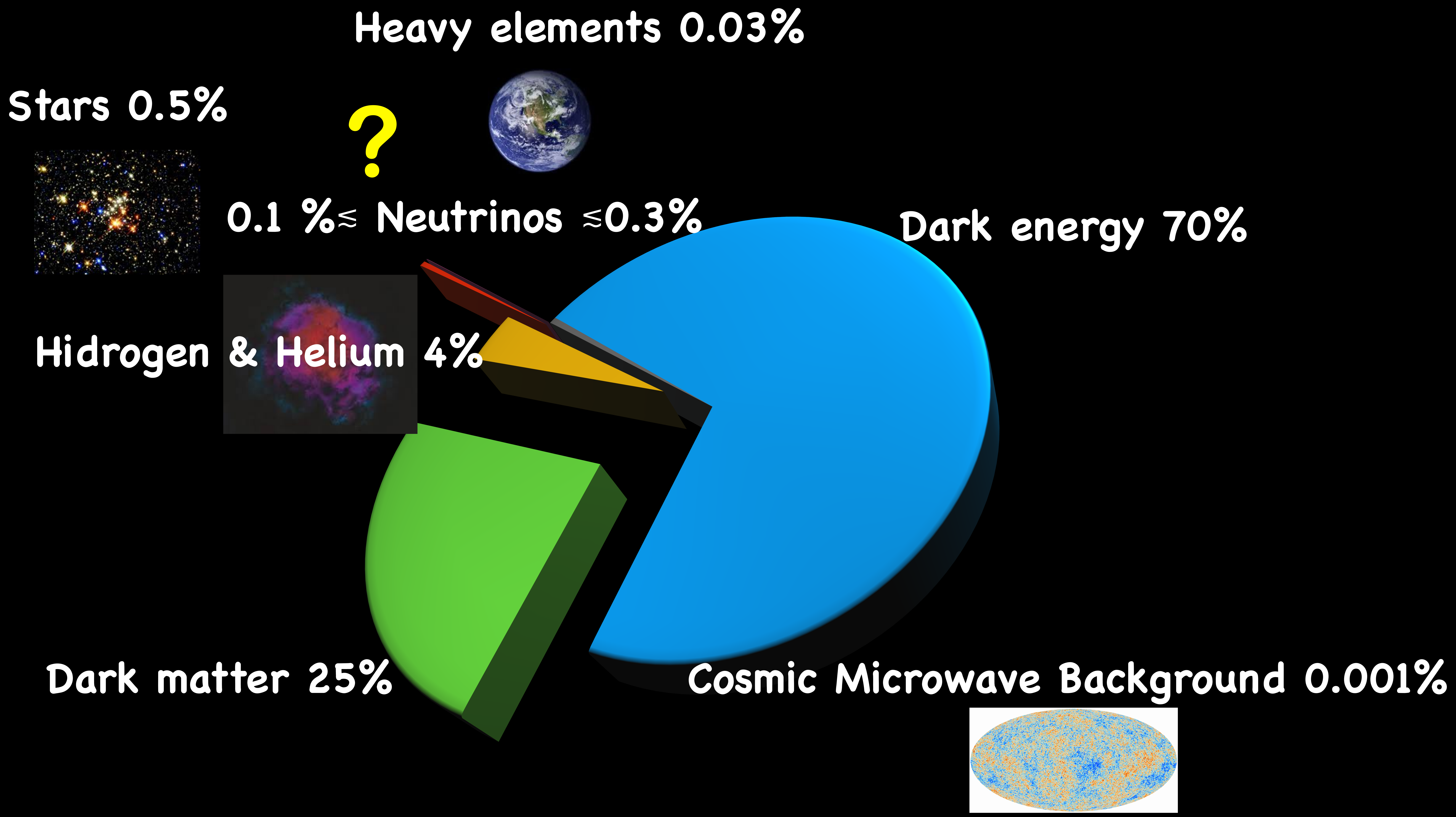
3,070 views | Mar 7, 2019, 02:00am

How Much Of The Dark Matter Could Neutrinos Be?

Ethan Siegel Senior Contributor
Starts With A Bang Contributor Group
Science
The Universe is out there, waiting for you to discover it.



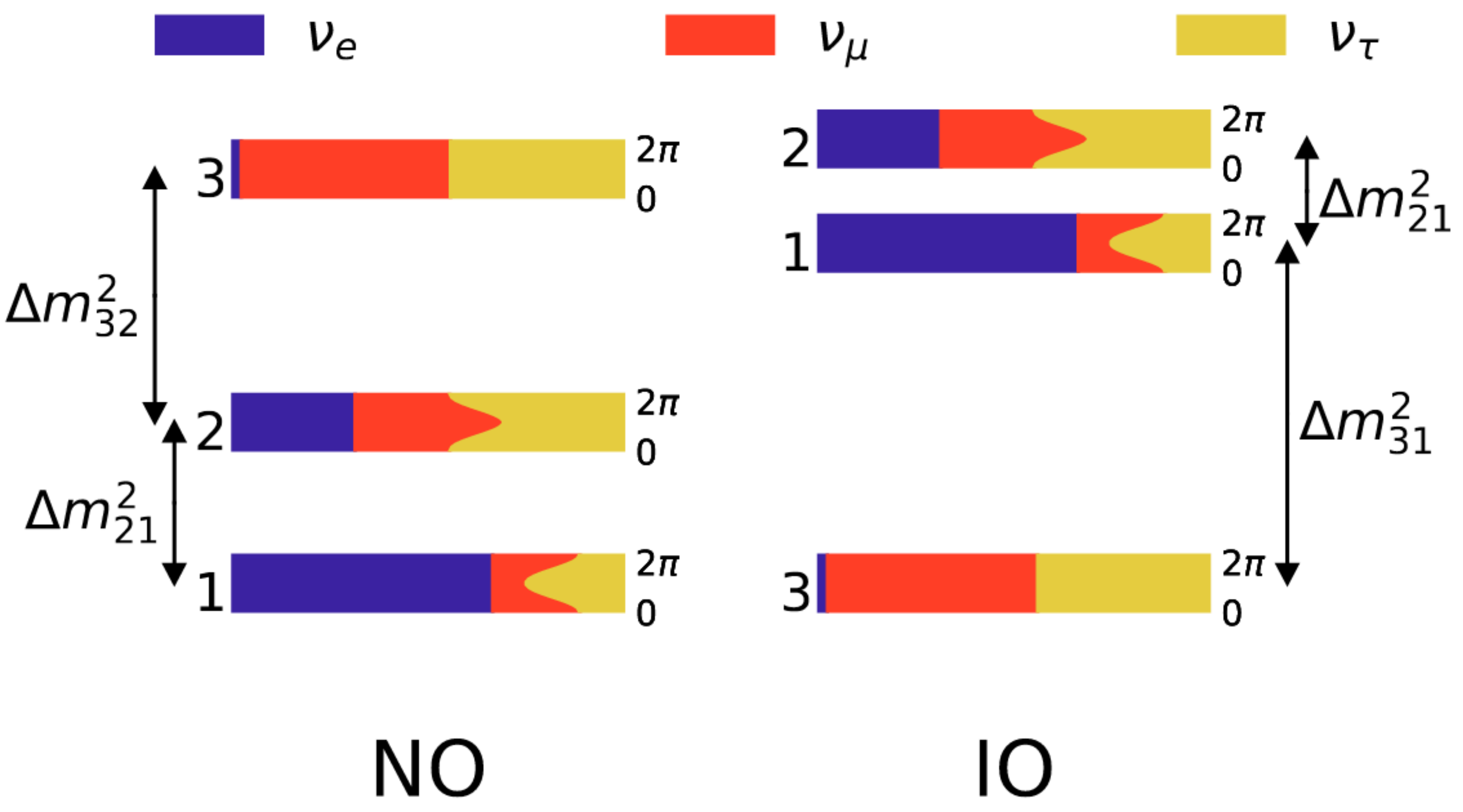
Our (ΛCDM) universe today



THE NEUTRINO MENU

- Antipasto: Neutrino oscillation bounds
- Primo piatto: Cosmology & $\sum m_\nu$
- Secondo piatto: Tightest neutrino mass bounds
- Dolce: Take home messages

According to neutrino oscillation physics, we know that there are at least two Dirac or Majorana massive neutrinos:



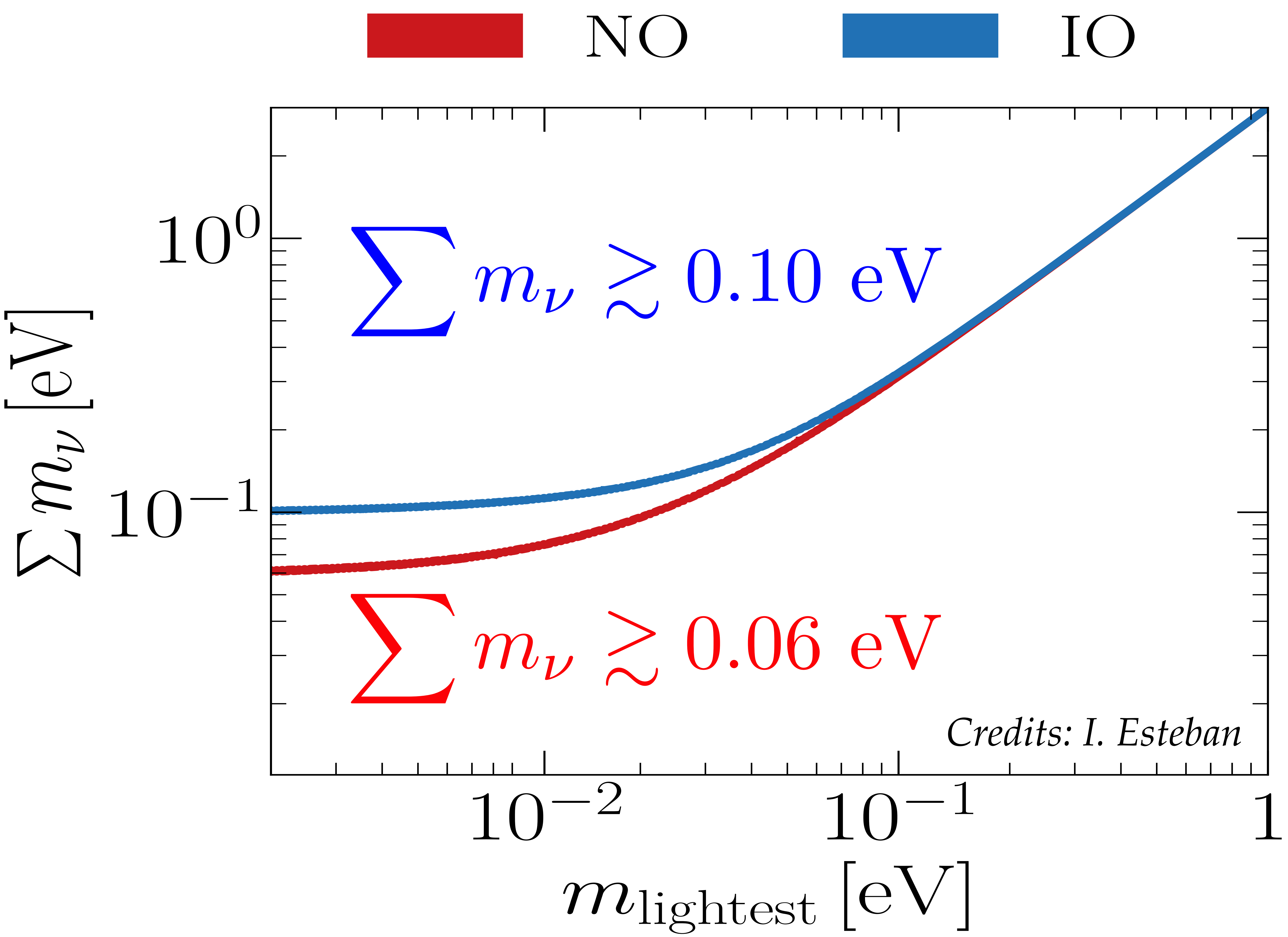
$$\Delta m^2_{21} = (6.94 - 8.14) \times 10^{-5}\ \text{eV}^2$$

$$|\Delta m^2_{31}|_{\text{NO}} = (2.47 - 2.63) \times 10^{-3}\ \text{eV}^2$$

$$|\Delta m^2_{31}|_{\text{IO}} = (2.37 - 2.53) \times 10^{-3}\ \text{eV}^2$$

Credits: S. Gariazzo

Oscillation measurements of the mass splittings translate into a lower bound for the neutrino mass, depending on the mass ordering:



We are sure then that two neutrinos have a mass above:

$$\sqrt{\Delta m^2_{21}} \simeq 0.008 \text{ eV}$$

and that at least one of these neutrinos has a mass larger than

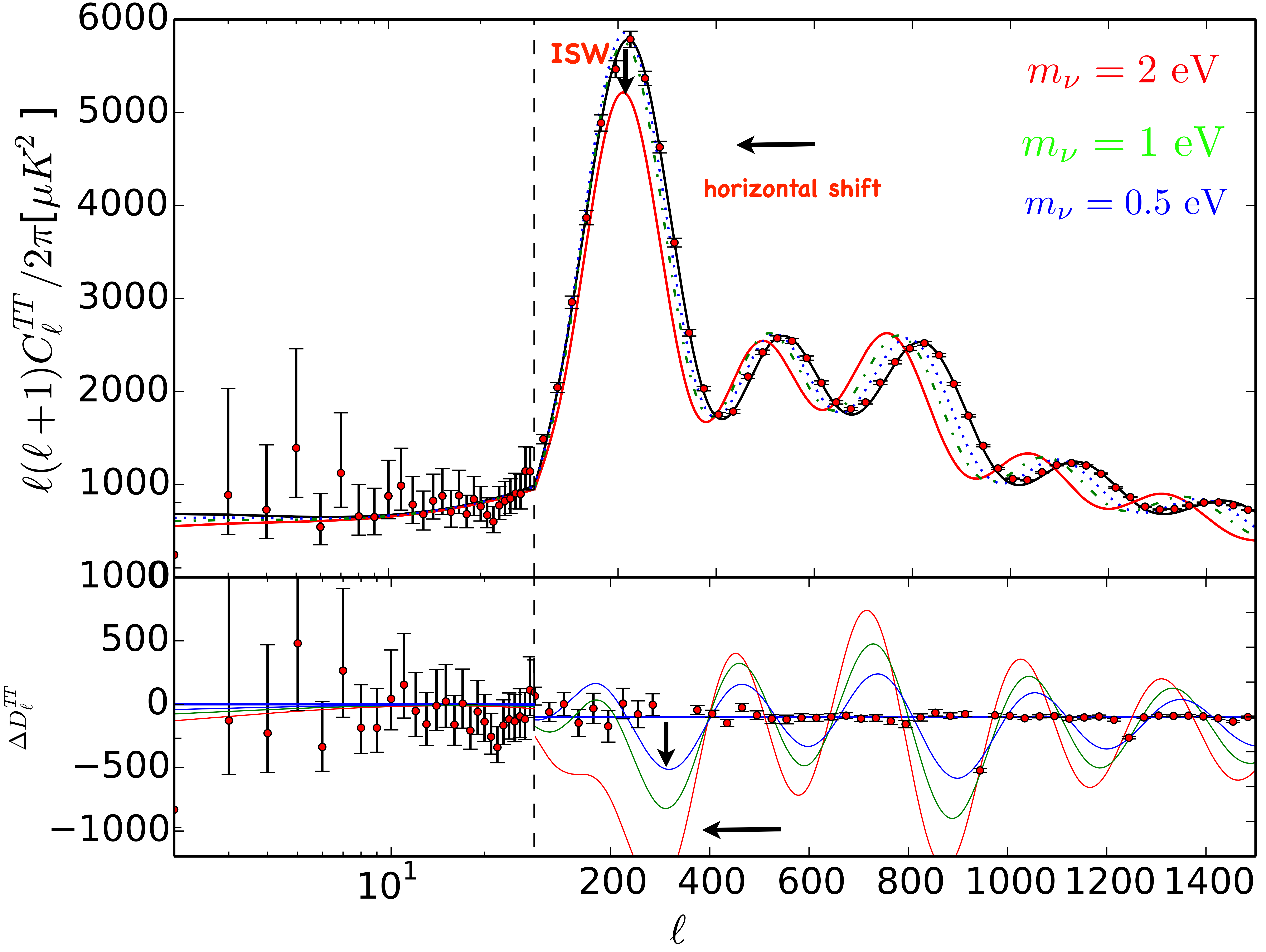
$$\sqrt{|\Delta m^2_{31}|} \simeq 0.05 \text{ eV}$$

THE NEUTRINO MENU

- Antipasto: Neutrino oscillation bounds
- Primo piatto: Cosmology & $\sum m_\nu$
- Secondo piatto: Tightest neutrino mass bounds
- Dolce: Take home messages

CMB: $\sum m_\nu$

Early Integrated Sachs Wolfe effect (ISW).
Shift in the angular position of the peaks.

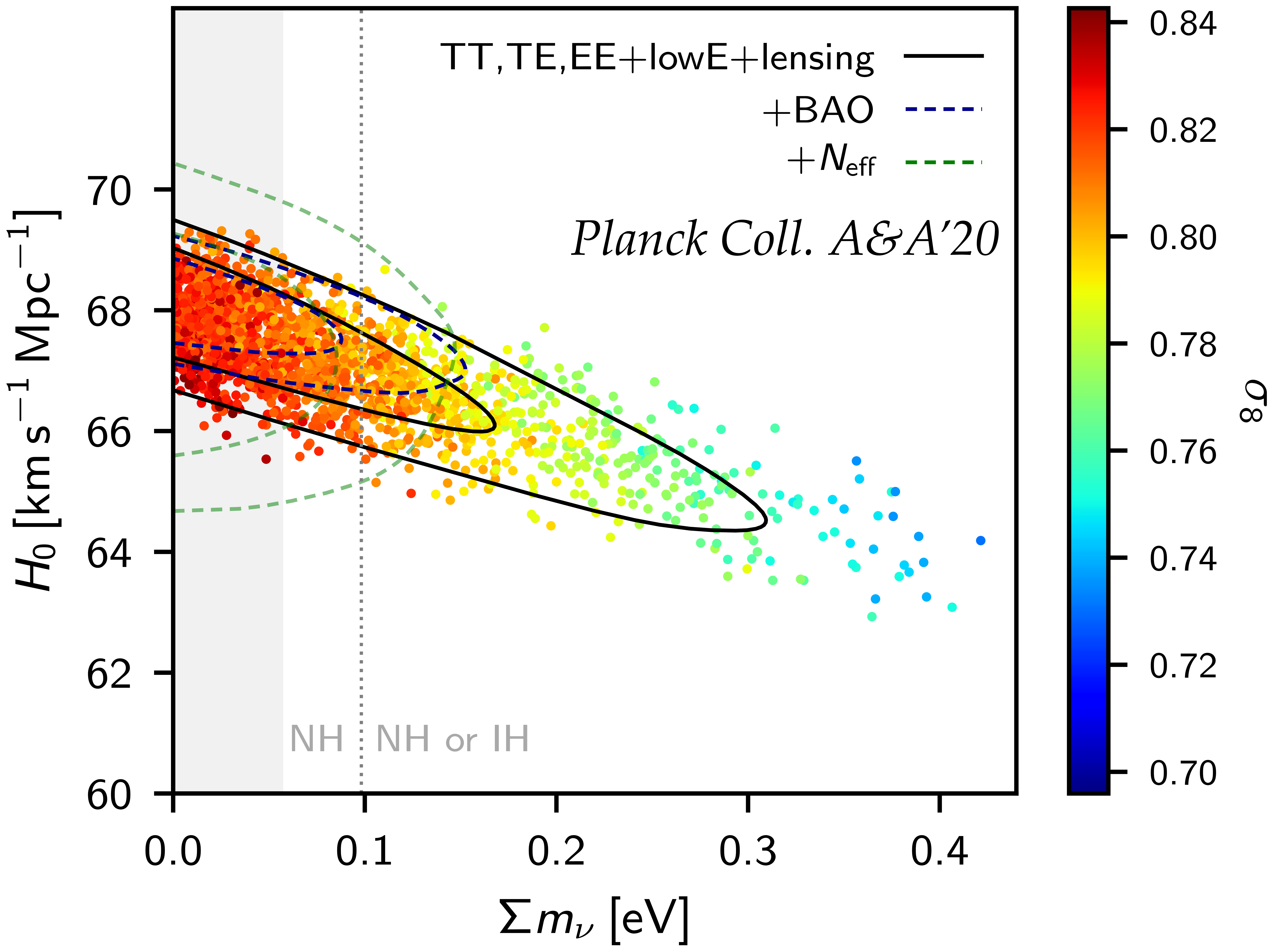


CMB: $\sum m_\nu$

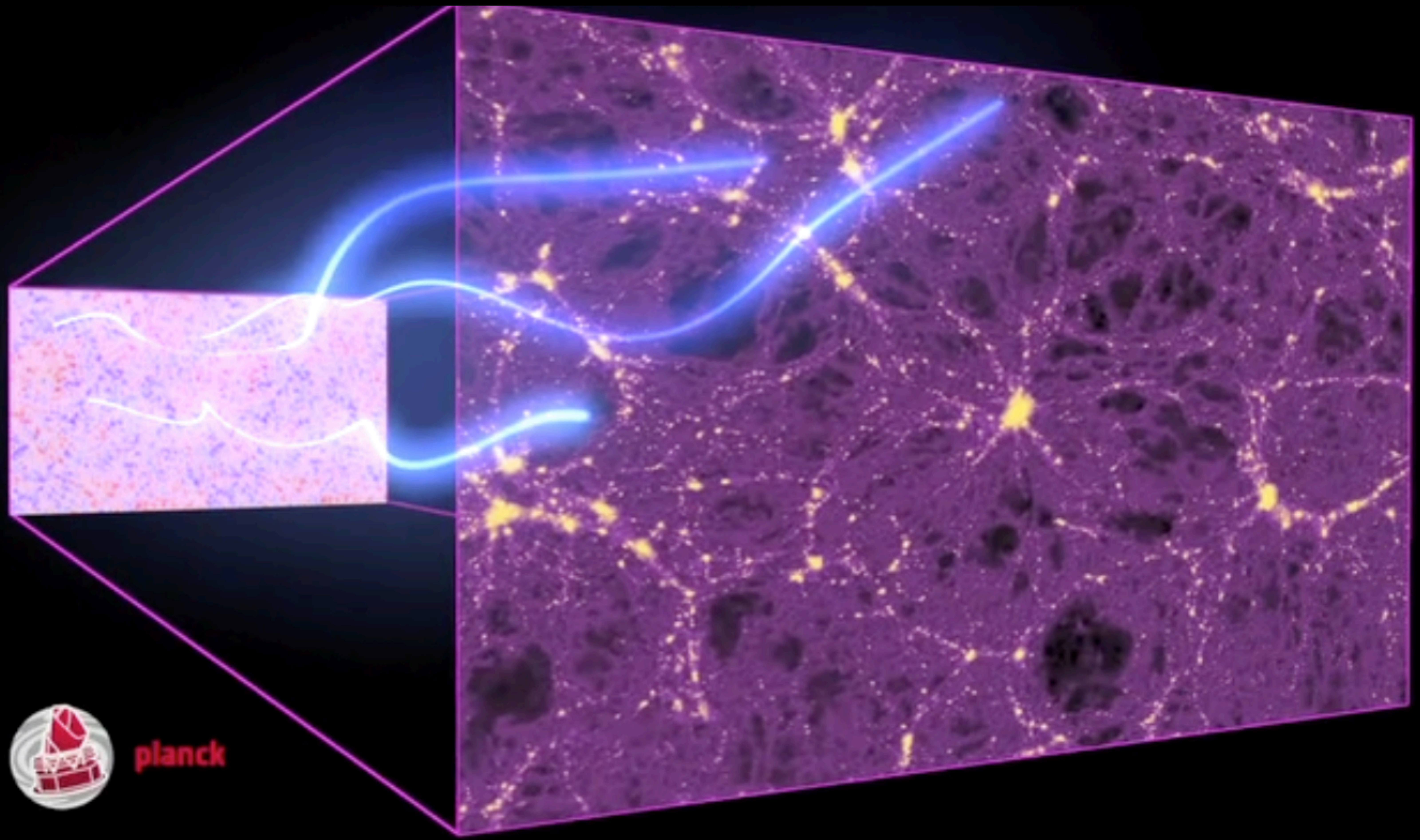
Early Integrated Sachs Wolfe effect (ISW).

Shift in the angular position of the peak

Strong degeneracy between Σm_ν and the Hubble constant H_0!



Gravitational Lensing



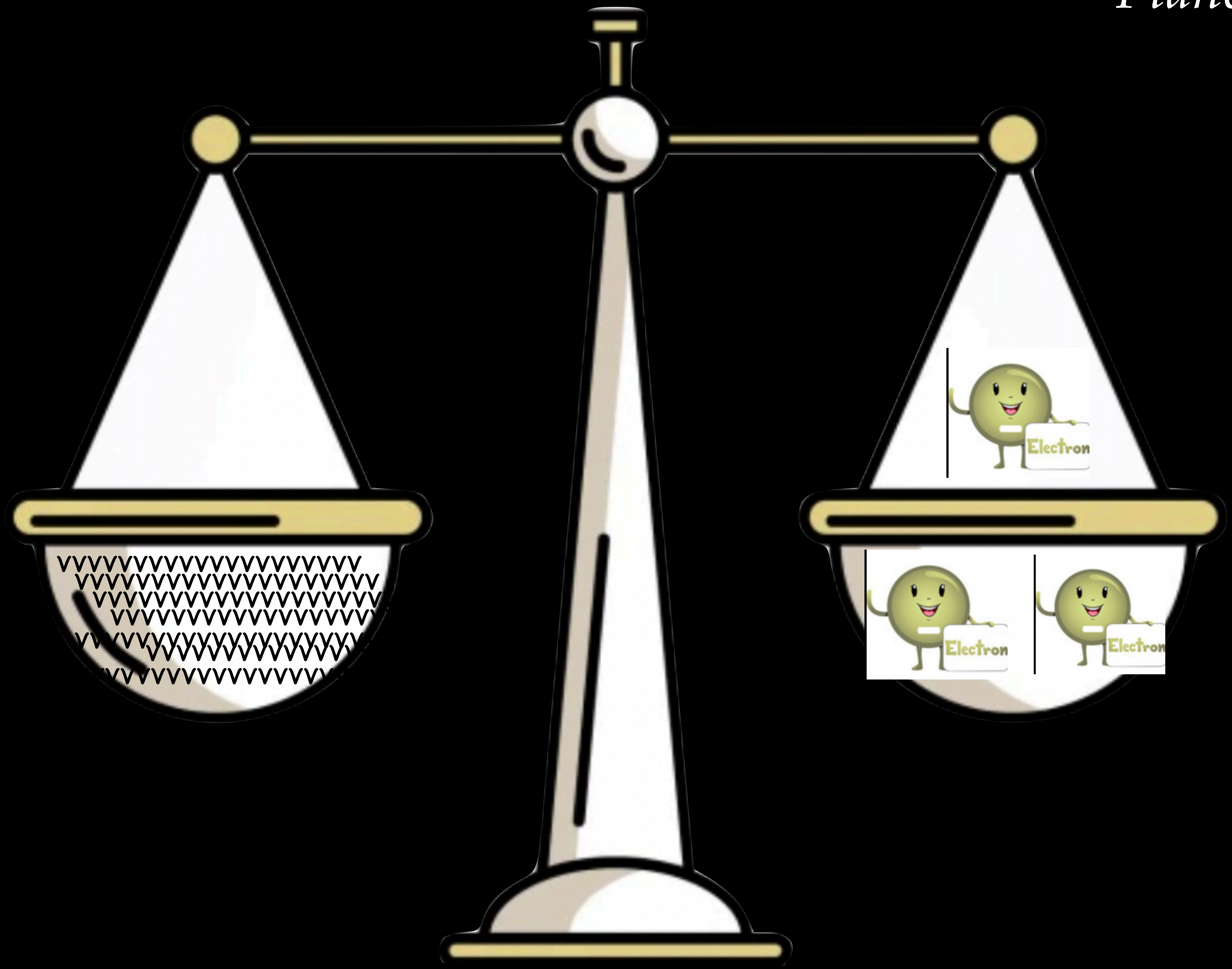
Credits: ESA and Planck collaboration

CMB: $\sum m_\nu$

Planck TTTEEE+lowT+lowE+lensing

$$\sum m_\nu < 0.24 \text{ eV } 95\%\text{CL}$$

Planck Coll. A&A'20



6 million neutrinos can't weigh more than 3 electrons

THE NEUTRINO MENU

- Antipasto: Neutrino oscillation bounds
- Primo piatto: Cosmology & $\sum m_{\nu}$
- Secondo piatto: Tightest neutrino mass bounds
- Dolce: Take home messages

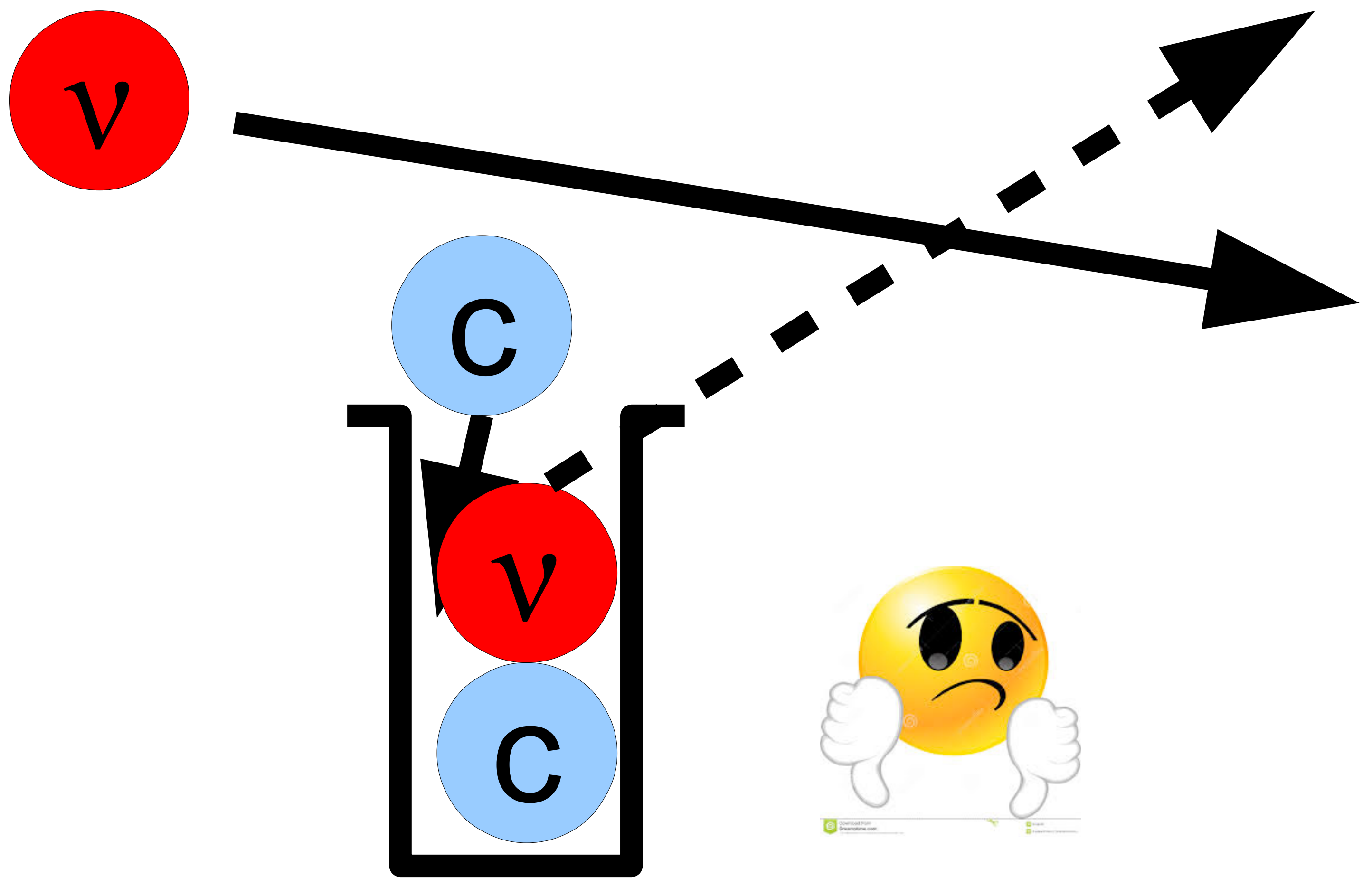
Large scale structure: $\sum m_\nu$

Neutrino masses suppress structure formation on scales larger than their free streaming scale when they turn non relativistic.

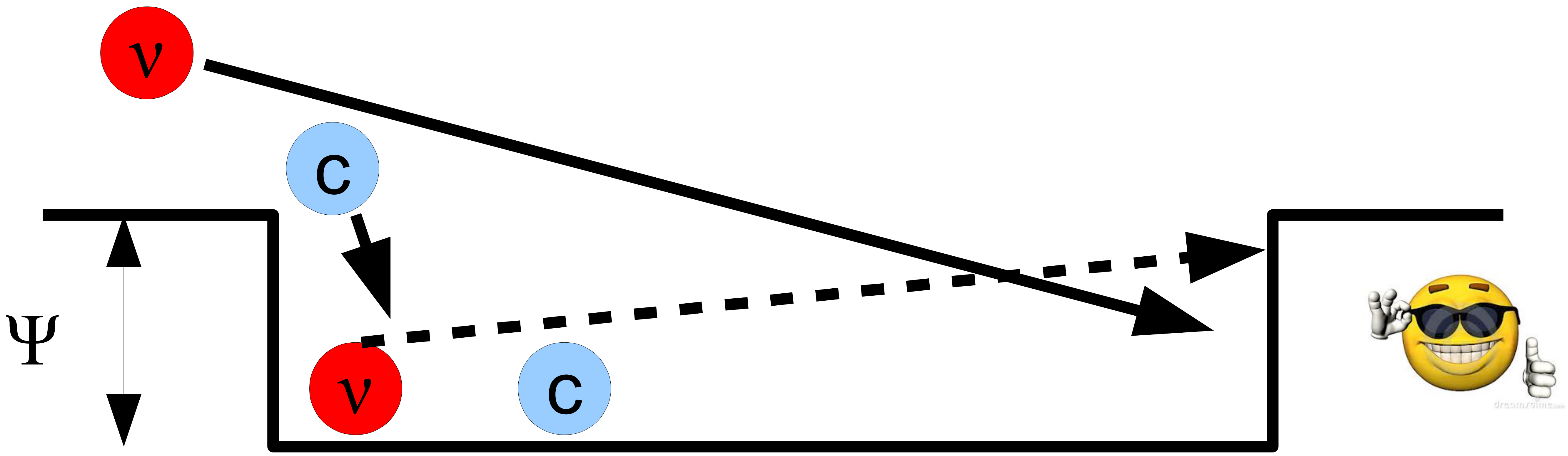
Neutrinos with eV or sub-eV masses are HOT relics with LARGE thermal velocities!

$$\langle v_{\rm thermal} \rangle \simeq 81(1+z)\left(\frac{\rm eV}{m_\nu}\right)\ {\rm km\ s}^{-1}$$

Cold dark matter instead has zero velocity and therefore it clusters at any scale!



$\lambda \ll \lambda_{fs,\nu} \rightarrow k \gg k_{fs,\nu}$



$\lambda \gg \lambda_{fs,\nu} \rightarrow k \ll k_{fs,\nu}$ *(From Y. Wong)*

Baryon Acoustic Oscillations

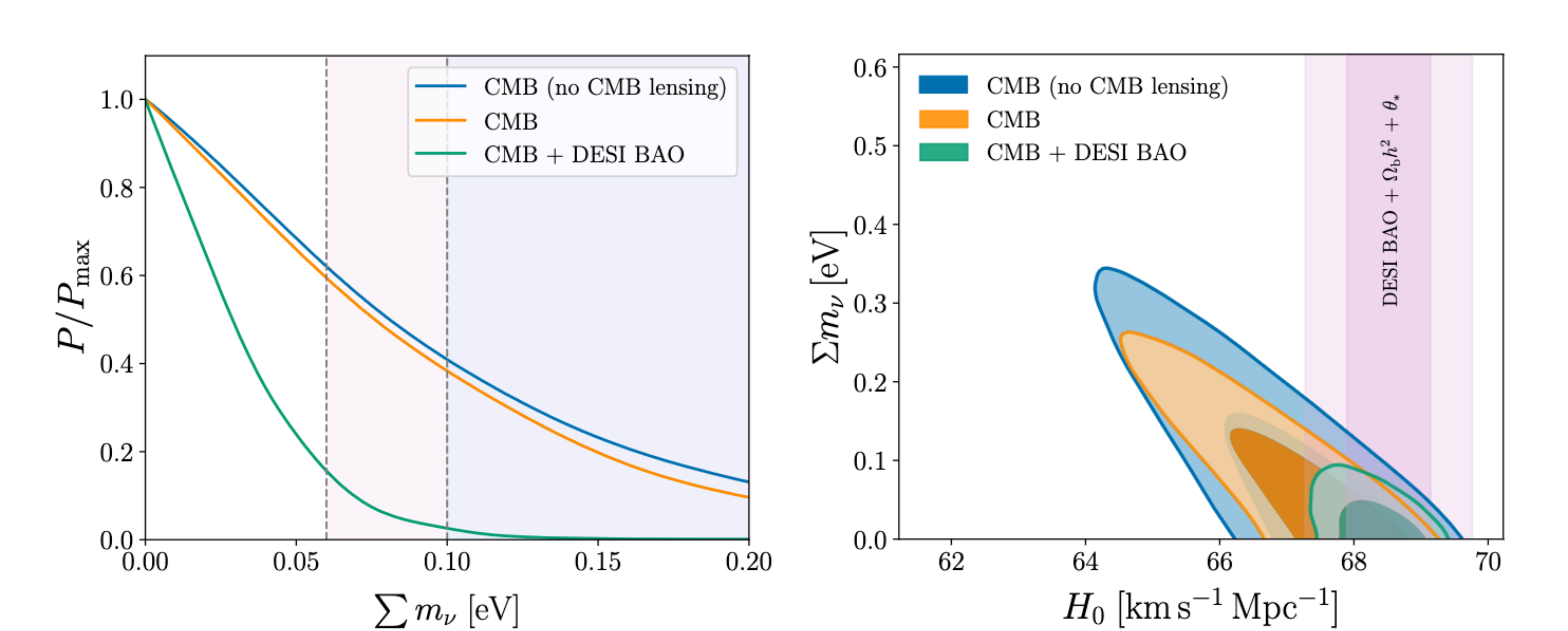
2021-2022=DESI Y1

tracer	redshift	$N_{\rm tracer}$	$z_{\rm eff}$	$D_{\rm M}/r_{\rm d}$	$D_{\rm H}/r_{\rm d}$	r or $D_{\rm V}/r_{\rm d}$	$V_{\rm eff}$ ($\rm Gpc^3$)
BGS	0.1 – 0.4	300,017	0.30	—	—	7.93 ± 0.15	1.7
LRG	0.4 – 0.6	506,905	0.51	13.62 ± 0.25	20.98 ± 0.61	-0.445	2.6
LRG	0.6 – 0.8	771,875	0.71	16.85 ± 0.32	20.08 ± 0.60	-0.420	4.0
LRG+ELG	0.8 – 1.1	1,876,164	0.93	21.71 ± 0.28	17.88 ± 0.35	-0.389	6.5
ELG	1.1 – 1.6	1,415,687	1.32	27.79 ± 0.69	13.82 ± 0.42	-0.444	2.7
QSO	0.8 – 2.1	856,652	1.49	—	—	26.07 ± 0.67	1.5
Lya QSO	1.77 – 4.16	709,565	2.33	39.71 ± 0.94	8.52 ± 0.17	-0.477	—

Alam et al, SDSS IV Coll. PRD'21

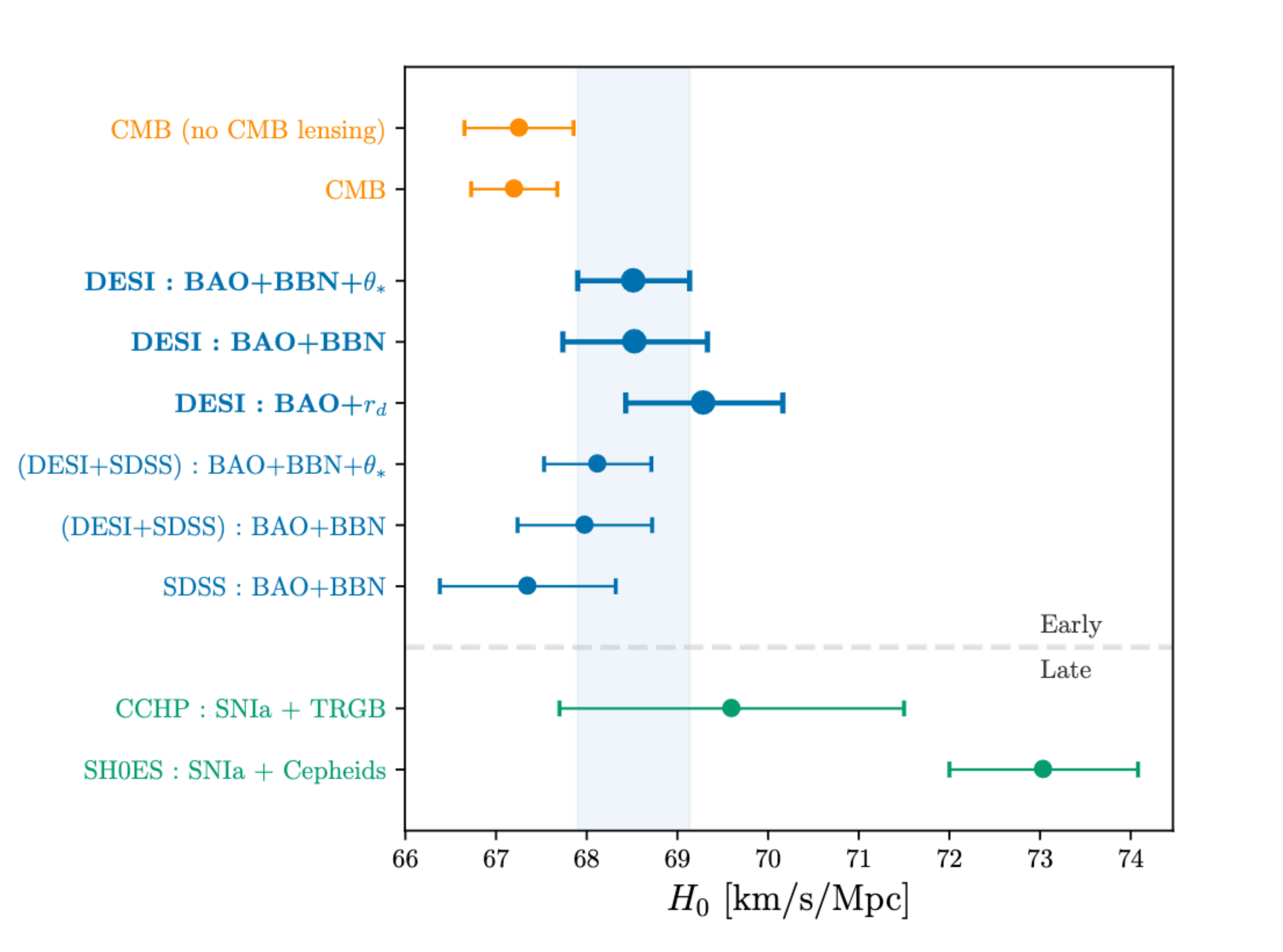
Tightest bounds on $\sum m_\nu$

DESI Collaboration: DESI 2024 VI: Cosmological Constraints from the Measurements of Baryon Acoustic Oscillations



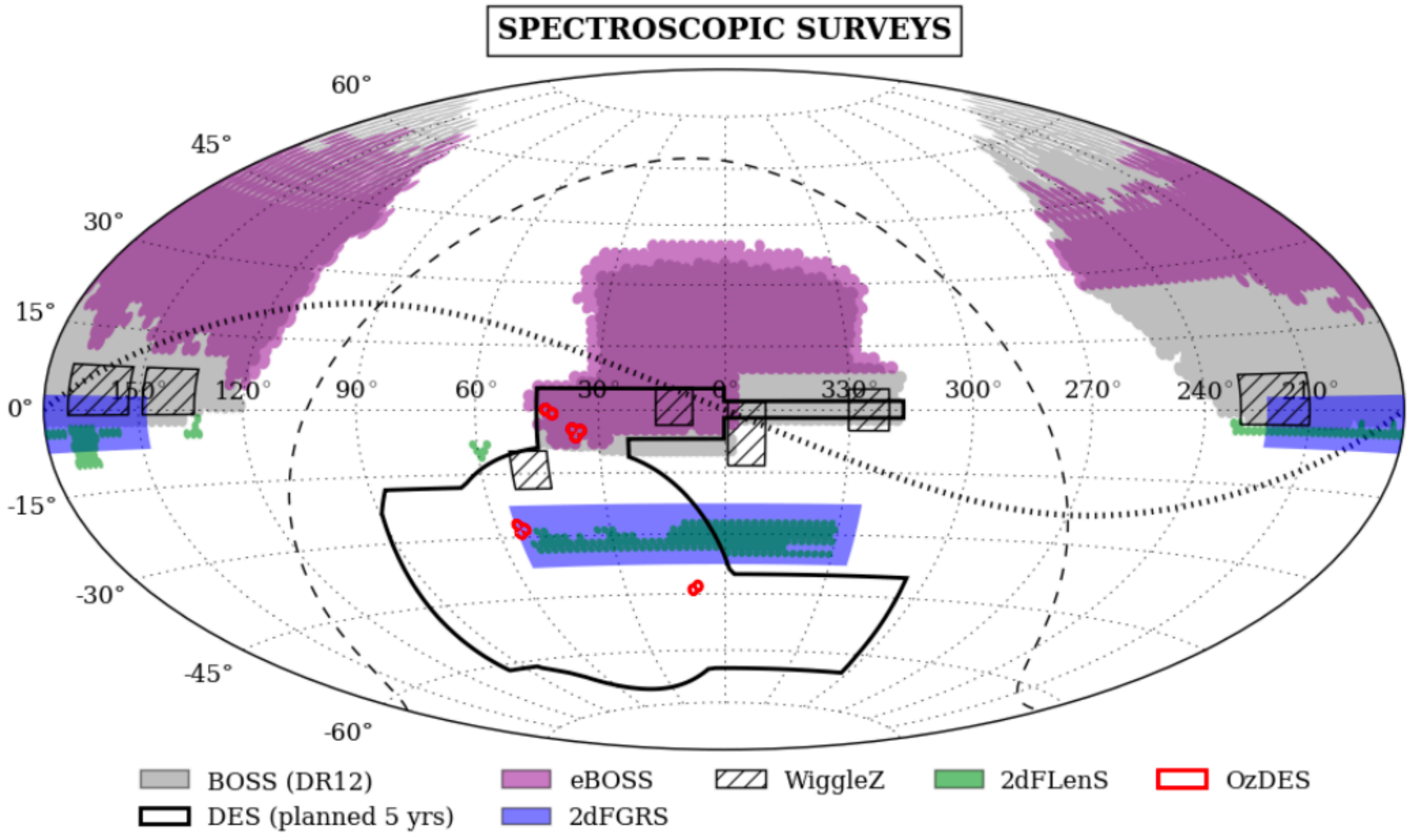
Tightest bounds on $\sum m_\nu$

DESI Collaboration: DESI 2024 VI: Cosmological Constraints from the Measurements of Baryon Acoustic Oscillations

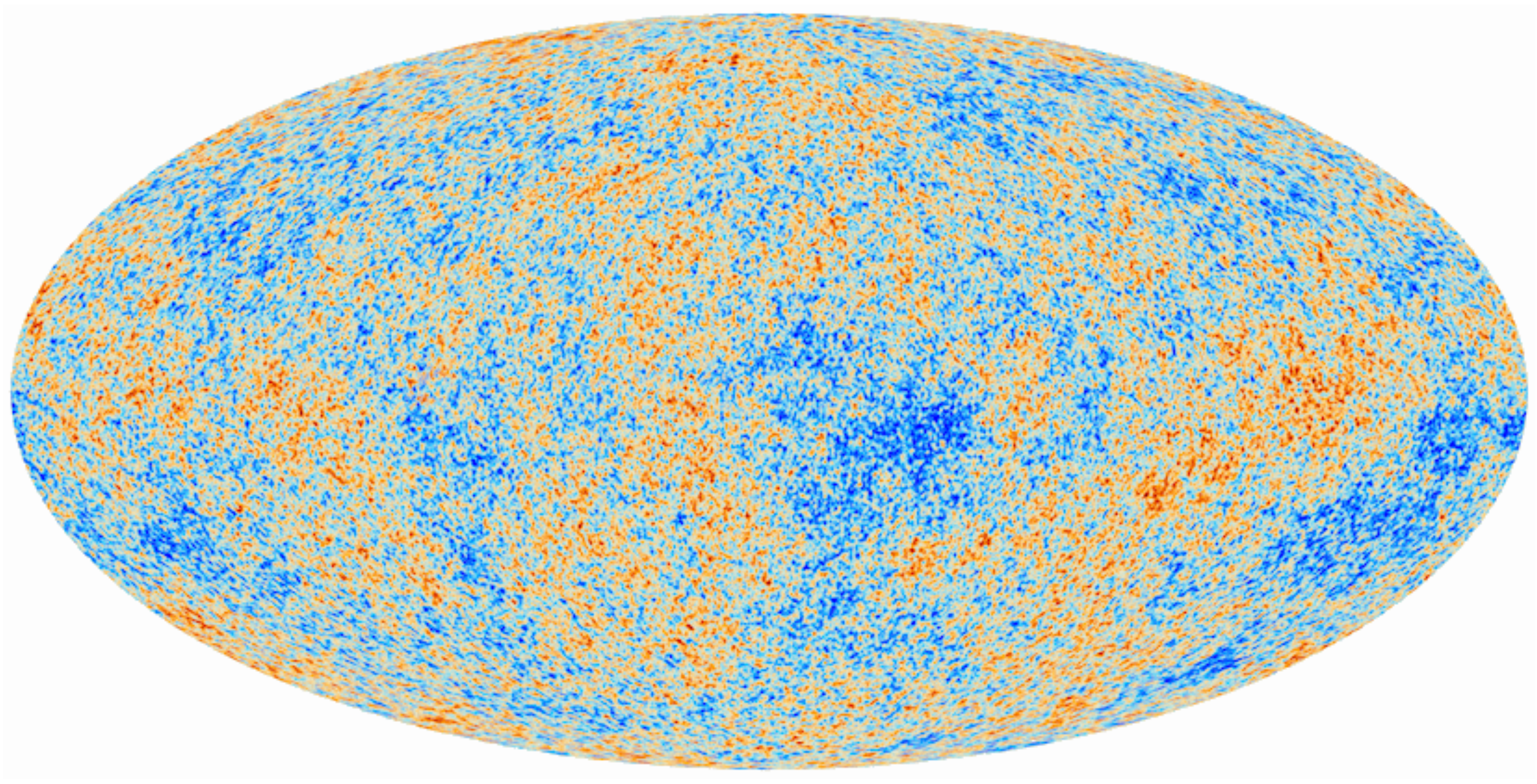


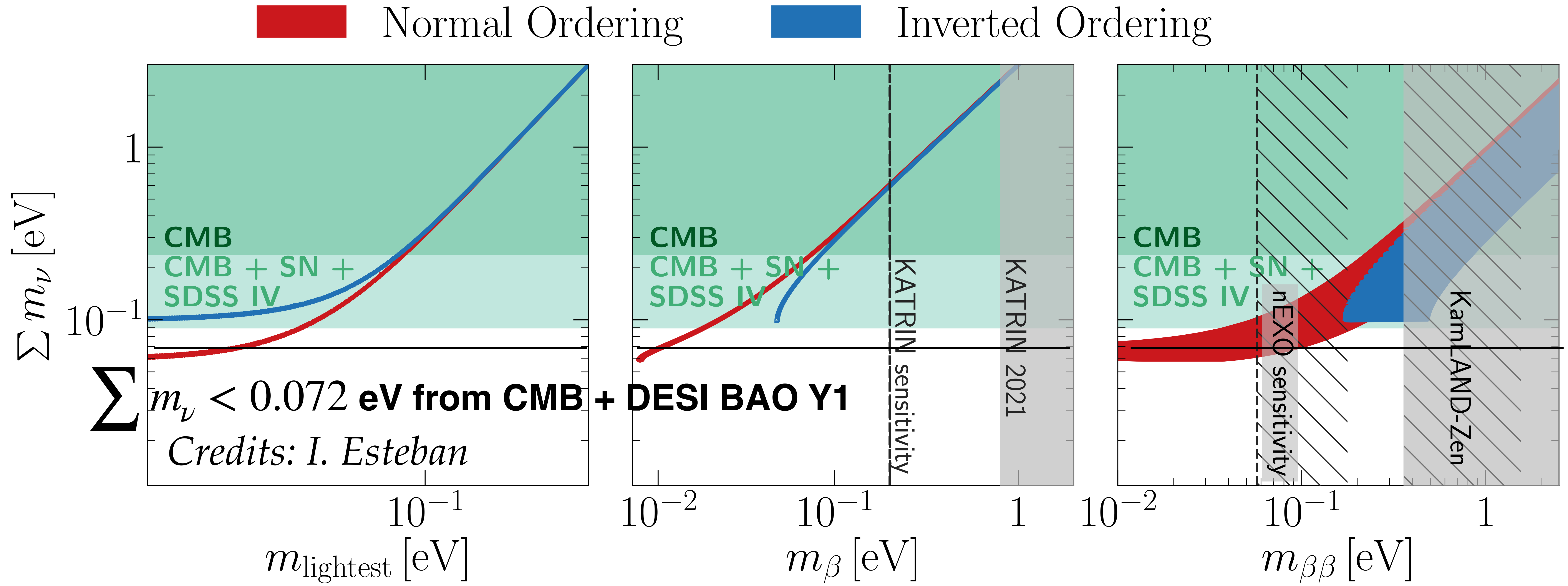
2024 absolute neutrino mass status

DES Collaboration, MNRAS’16



Planck coll.





$\sum m_\nu < 0.072$ **eV from CMB + DESI BAO Y1**

Credits: I. Esteban

95% CL limits

Tightest bounds on $\sum m_\nu$

DESI Collaboration: DESI 2024 VI: Cosmological Constraints from the Measurements of Baryon Acoustic Oscillations

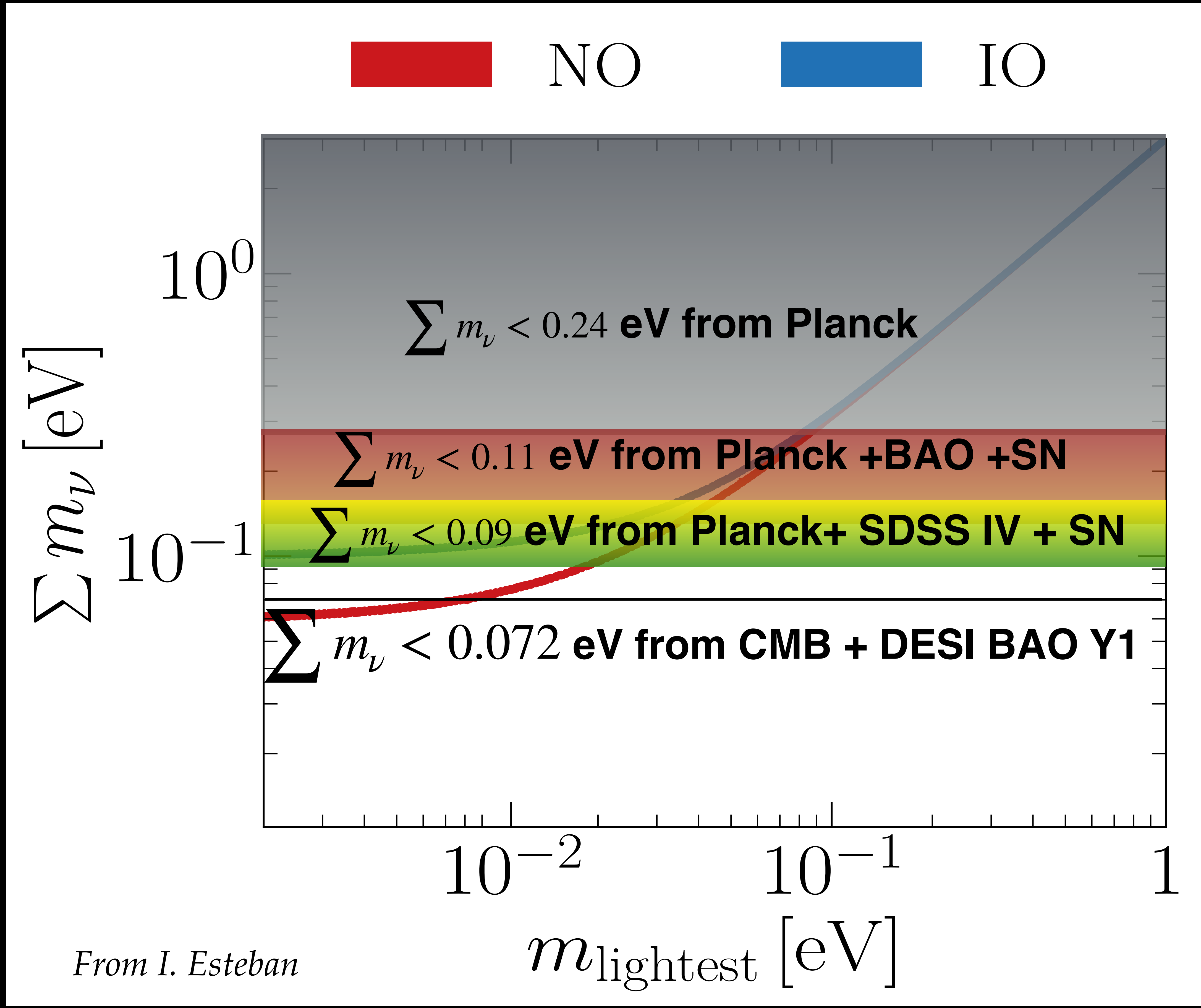
model / dataset	Ω_m	H_0 [km s^{-1} Mpc^{-1}]	Σm_ν [eV]	N_{eff}
ΛCDM+$\sum m_\nu$				
DESI+CMB	0.3037 ± 0.0053	68.27 ± 0.42	< 0.072	—
ΛCDM+N_{eff}				
DESI+CMB	0.3058 ± 0.0060	68.3 ± 1.1	—	3.10 ± 0.17
wCDM+$\sum m_\nu$				
DESI+CMB	0.282 ± 0.013	$71.1^{+1.5}_{-1.8}$	< 0.123	—
DESI+CMB+Panth.	0.3081 ± 0.0067	67.81 ± 0.69	< 0.079	—
DESI+CMB+Union3	0.3090 ± 0.0082	67.72 ± 0.88	< 0.078	—
DESI+CMB+DESY5	0.3152 ± 0.0065	67.01 ± 0.64	< 0.073	—

Tightest bounds on $\sum m_\nu$

CMB+DESI BAO Y1

$$\sum m_\nu < 0.072 \text{ eV} \quad 95\,\% \text{ CL}$$

DESI Collaboration: DESI 2024 VI: Cosmological Constraints from the Measurements of Baryon Acoustic Oscillations

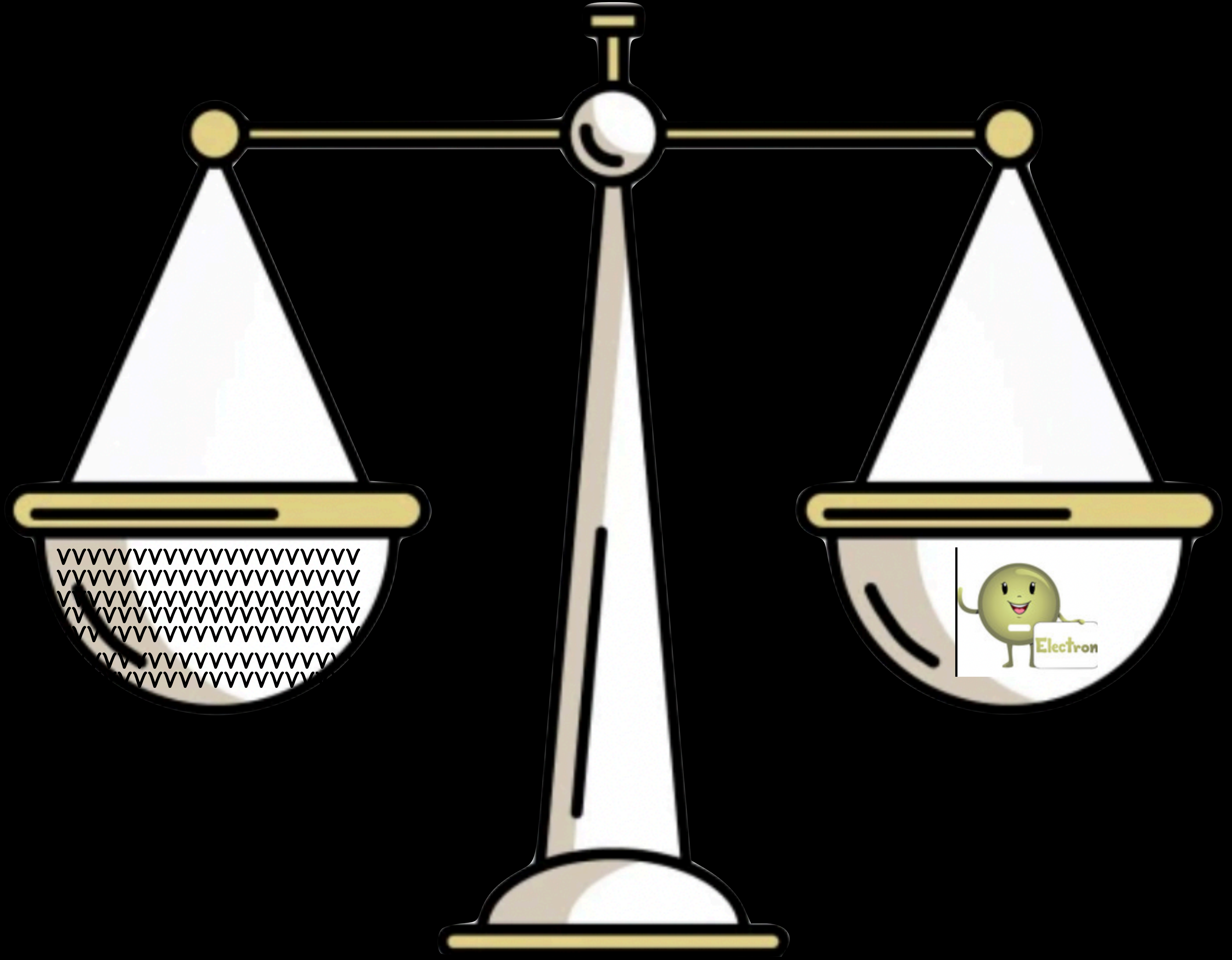


Tightest bounds on $\sum m_\nu$

CMB+DESI BAO Y1

$$\sum m_\nu < 0.072 \text{ eV} \quad 95\,\% \text{ CL}$$

DESI Collaboration: DESI 2024 VI: Cosmological Constraints from the Measurements of Baryon Acoustic Oscillations



10 millions of the heaviest neutrino can't weigh more than 1 electron

Tightest bounds on $\sum m_\nu$

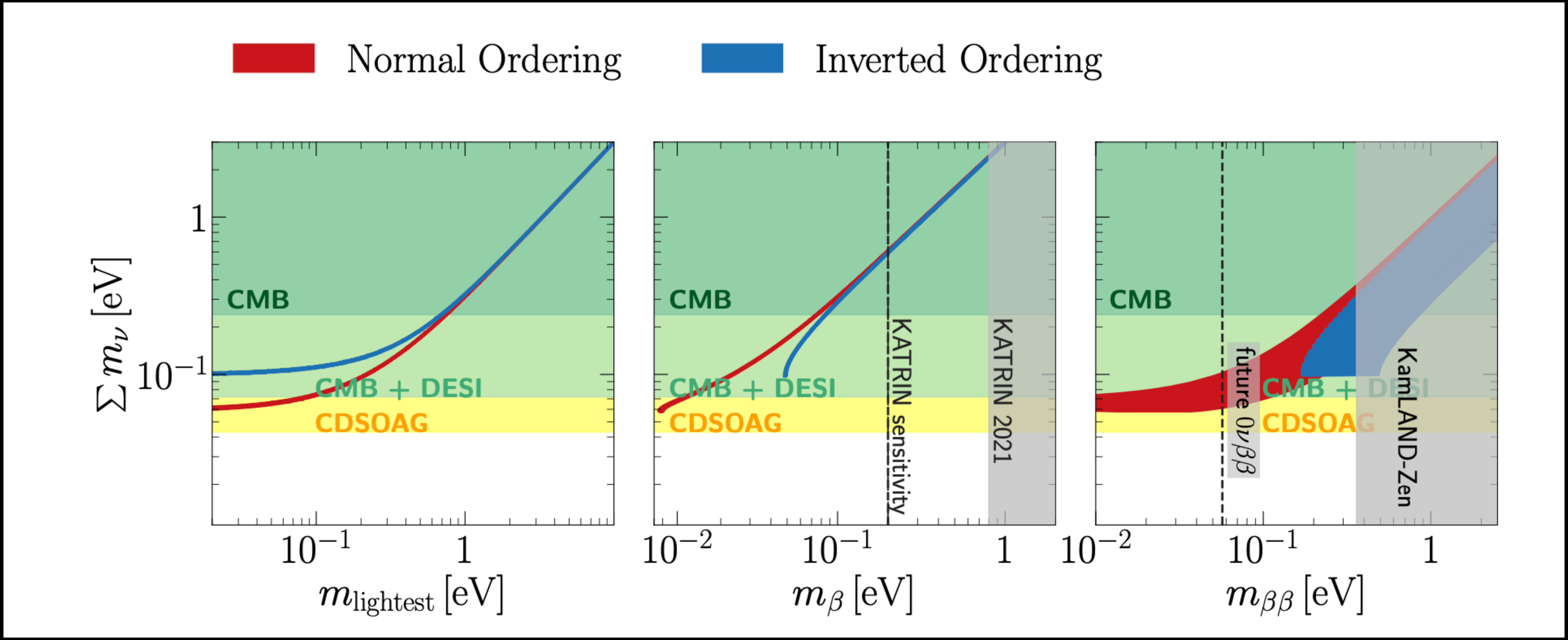
Deng Wang, Olga Mena et al, 2405.03368

Datasets	Σm_ν [eV]	H_0 [km/s/Mpc]	Ω_m	σ_8
CBS	$< 0.137 \quad (2\,\sigma)$	$67.54^{+0.52}_{-0.45}$	$0.3130^{+0.0058}_{-0.0067}$	$0.813^{+0.0110}_{-0.0075}$
CBSO	$< 0.135 \quad (2\,\sigma)$	$67.56^{+0.51}_{-0.43}$	$0.3128^{+0.0056}_{-0.0065}$	$0.813^{+0.0110}_{-0.0077}$
CBSA	$< 0.082 \quad (2\,\sigma)$	68.27 ± 0.38	0.3039 ± 0.0049	$0.8165^{+0.0081}_{-0.0066}$
CBSG	$< 0.059 \quad (2\,\sigma)$	68.70 ± 0.43	0.2991 ± 0.0054	0.8184 ± 0.0068
CBSOA	$< 0.082 \quad (2\,\sigma)$	68.28 ± 0.38	0.3038 ± 0.0049	$0.8167^{+0.0081}_{-0.0063}$
CBSOG	$< 0.056 \quad (2\,\sigma)$	68.70 ± 0.42	0.2991 ± 0.0053	0.8185 ± 0.0068
CBSAG	$< 0.046 \quad (2\,\sigma)$	69.04 ± 0.37	0.2949 ± 0.0047	0.8177 ± 0.0065
CBSOAG	$< 0.049 \quad (2\,\sigma)$	69.02 ± 0.37	0.2951 ± 0.0047	0.8179 ± 0.0068
CDS	$< 0.093 \quad (2\,\sigma)$	68.20 ± 0.44	0.3045 ± 0.0056	$0.8156^{+0.0086}_{-0.0068}$
CDSO	$< 0.091 \quad (2\,\sigma)$	68.20 ± 0.43	0.3045 ± 0.0054	$0.8158^{+0.0084}_{-0.0068}$
CDSA	$< 0.071 \quad (2\,\sigma)$	68.65 ± 0.37	0.2990 ± 0.0047	$0.8160^{+0.0078}_{-0.0064}$
CDSG	$< 0.049 \quad (2\,\sigma)$	69.17 ± 0.40	0.2932 ± 0.0050	0.8179 ± 0.0069
CDSOA	$< 0.065 \quad (2\,\sigma)$	68.69 ± 0.36	0.2984 ± 0.0044	0.8166 ± 0.0071
CDSOG	$< 0.049 \quad (2\,\sigma)$	69.14 ± 0.40	0.2934 ± 0.0050	0.8174 ± 0.0067
CDSAG	$< 0.045 \quad (2\,\sigma)$	69.38 ± 0.36	0.2906 ± 0.0045	0.8172 ± 0.0066
CDSOAG	$< 0.043 \quad (2\,\sigma)$	69.38 ± 0.37	0.2906 ± 0.0045	0.8174 ± 0.0068

Clear tension between oscillation and cosmological neutrino mass bounds

Tightest bounds on $\sum m_\nu$

Deng Wang, Olga Mena et al, 2405.03368



Clear tension between oscillation and cosmological neutrino mass bounds

Mass ordering status (after DESI)

Dataset	ΛCDM+M_ν		ΛCDM+M_ν +$w(z) \geq -1$	
	M_ν	$B_{\rm NO,IO}$	M_ν	$B_{\rm NO,IO}$
baseline (CMB + DESI)	< 0.072 eV	8.1	< 0.064 eV	12.3
baseline + SNeIa	< 0.081 eV	7.0	< 0.068 eV	7.9
baseline + CC	< 0.073 eV	7.3	< 0.067 eV	8.0
CMB (include ACT "extended" data) + DESI	< 0.072 eV	8.0	< 0.065 eV	12.8
baseline + SDSS	< 0.083 eV	6.8	< 0.070 eV	10.6
baseline + SH0ES	< 0.048 eV	47.8	< 0.047 eV	54.6
baseline + XSZ	< 0.050 eV	46.5	< 0.044 eV	39.6
baseline + GRB	< 0.072 eV	8.7	< 0.066 eV	15.4
aggressive combination (baseline + SH0ES + XSZ)	< 0.042 eV	72.6	< 0.041 eV	109.2
CMB + DESI (use HMcode2020 for non-linear corrections)	< 0.074 eV	7.5	< 0.065 eV	10.8
CMB (use ACT v1.2 likelihood)	< 0.082 eV	7.4	< 0.072 eV	6.3

B_{ij}	$\ln B_{ij}$	Evidence
$1 \leq B_{ij} < 3$	$0 \leq B_{ij} < 1.1$	Weak
$3 \leq B_{ij} < 20$	$1.1 \leq B_{ij} < 3$	Definite
$20 \leq B_{ij} < 150$	$3 \leq B_{ij} < 5$	Strong
$150 \leq B_{ij}$	$5 \leq B_{ij}$	Very Strong

Tension metrics for Terrestrial-cosmological tension status

$$\Delta m^2_{21} = (7.50 \pm 0.21) \times 10^{-5}\,\mathrm{eV}^2\,,$$

$$|\Delta m^2_{31}| = \begin{cases} (2.550 \pm 0.025) \times 10^{-3}\,\mathrm{eV}^2 & \text{(NO)} \\ (2.450 \pm 0.025) \times 10^{-3}\,\mathrm{eV}^2 & \text{(IO)} \end{cases}$$

Oscillations

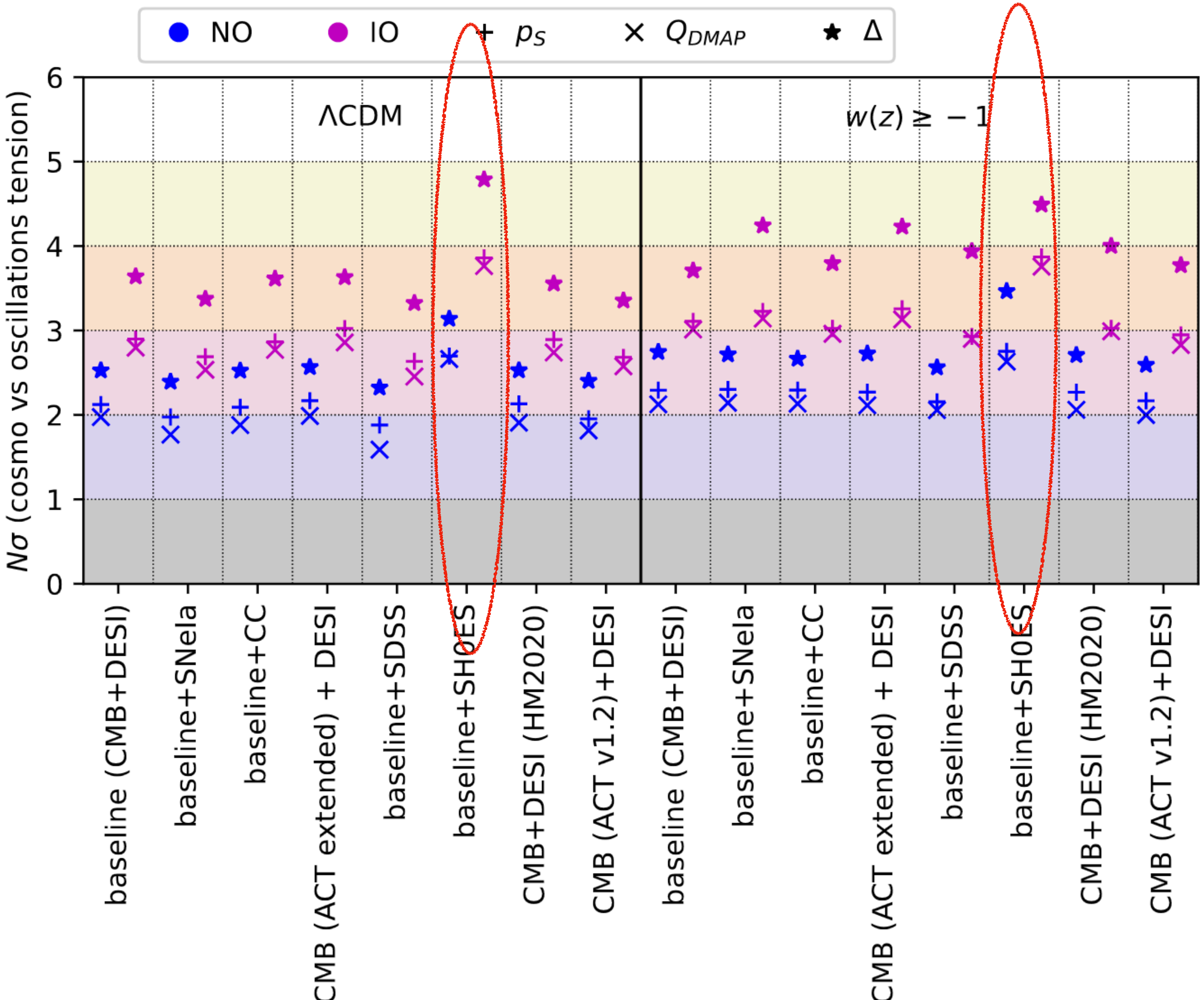
$$m_\nu^2 \equiv \sum |U_{ei}|^2 m_i^2$$

$$m_\nu^2 = 0.26^{+0.34}_{-0.34}\mathrm{eV}^2$$

$$m_\nu < 0.8\,\mathrm{eV}\ \ \text{at}\ \ 90\,\%\ \ \text{CL}$$

KATRIN

Terrestrial-cosmological tension status (after DESI)



2-3σ tension for NO

3-4σ tension for IO

What if also beta/neutrinoless decay detect a signal but cosmology prefers $\sum m_\nu=0$?

Neutrino decays

Long-range neutrino interactions

Time-dependent neutrino masses

Non ideal-gas fluids

……………

Keep thinking in other mechanisms!

THE NEUTRINO MENU

- Antipasto: Neutrino oscillation bounds
- Primo piatto: Cosmology & $\sum m_\nu$
- Secondo piatto: Tightest neutrino mass bounds
- Dolce: Take home messages

- Neutrino masses@CMB: Early ISW, gravitational lensing (Planck data)
- Neutrino masses@LSS: Free-streaming induces a small scale suppression, driving the "cosmo-nu-mass-bounds".
- $\sum m_\nu < 0.072$eV (95% CL) Planck TTTEEE+lensing+DESI BAO
- $\sum m_\nu < 0.043$eV (95% CL) Planck TTTEEE+lensing+DESI BAO+ Cosmic Chronometers + Galaxy Clusters + GRBs
- Cosmological limits on neutrino properties: EXTREMELY ROBUST.
- Clear tension between cosmological mass limits and terrestrial results
- Crucial to confront future cosmological mass limits with neutrino oscillation results to constrain BSM interactions in the invisible sector.

- Work developed on computing resources thanks to the MCIU with funding from the European Union NextGenerationEU (PRTR-C17.I01) and Generalitat Valenciana (ASFAE/2022/020).