Cosmological limits on neutrino masses and species

Olga Mena

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CSIC

“The field has been broad and deep, encompassing astrophysical and particle consequences and ranging from the distant nebulae to the unification of the elementary forces. The searches have led from the ocean deeps to deep inside the earth and sun.

Why indeed should such a weakly interacting particle play such an important role in furthering our understanding of so much of our universe?
As we are beginning to understand, the very weakness which characterizes this class of particles is the reason for its unique role!
Most marvelously this weakness may enable the mysterious missing matter which most of the universe to conceivably be built in large measure of neutrinos.”

F. Reines *1995 Nobel Prize winner for the detection of the neutrino.*

“VENICE IS A GREAT PLACE FOR A CONFERENCE”, 1992

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

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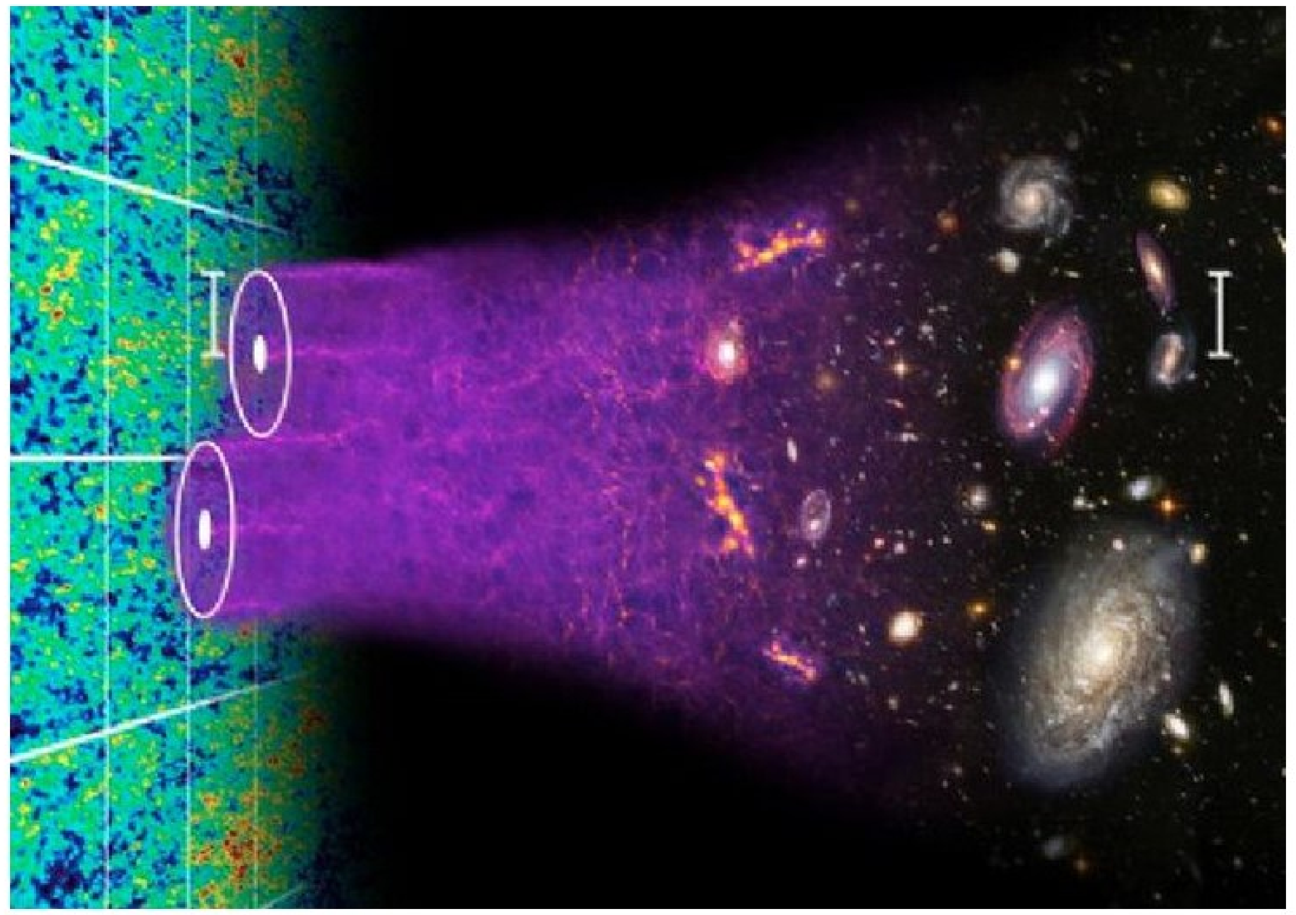
20,733 views | Dec 5, 2017, 10:00am

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
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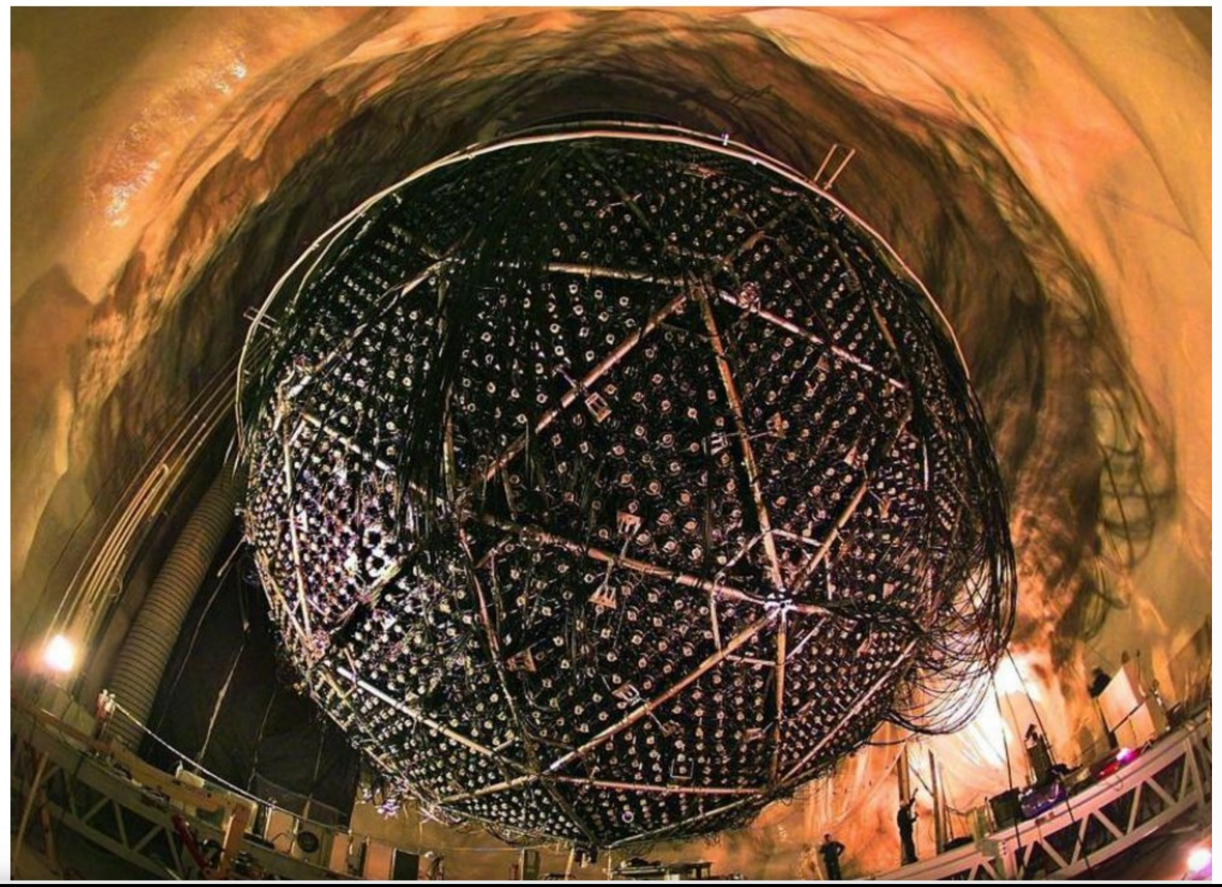
The Universe is out there, waiting for you to discover it.



Jul 13, 2016, 11:28am EDT

Could Dark Energy Be Caused By Frozen Neutrinos?

Ethan Siegel Senior Contributor
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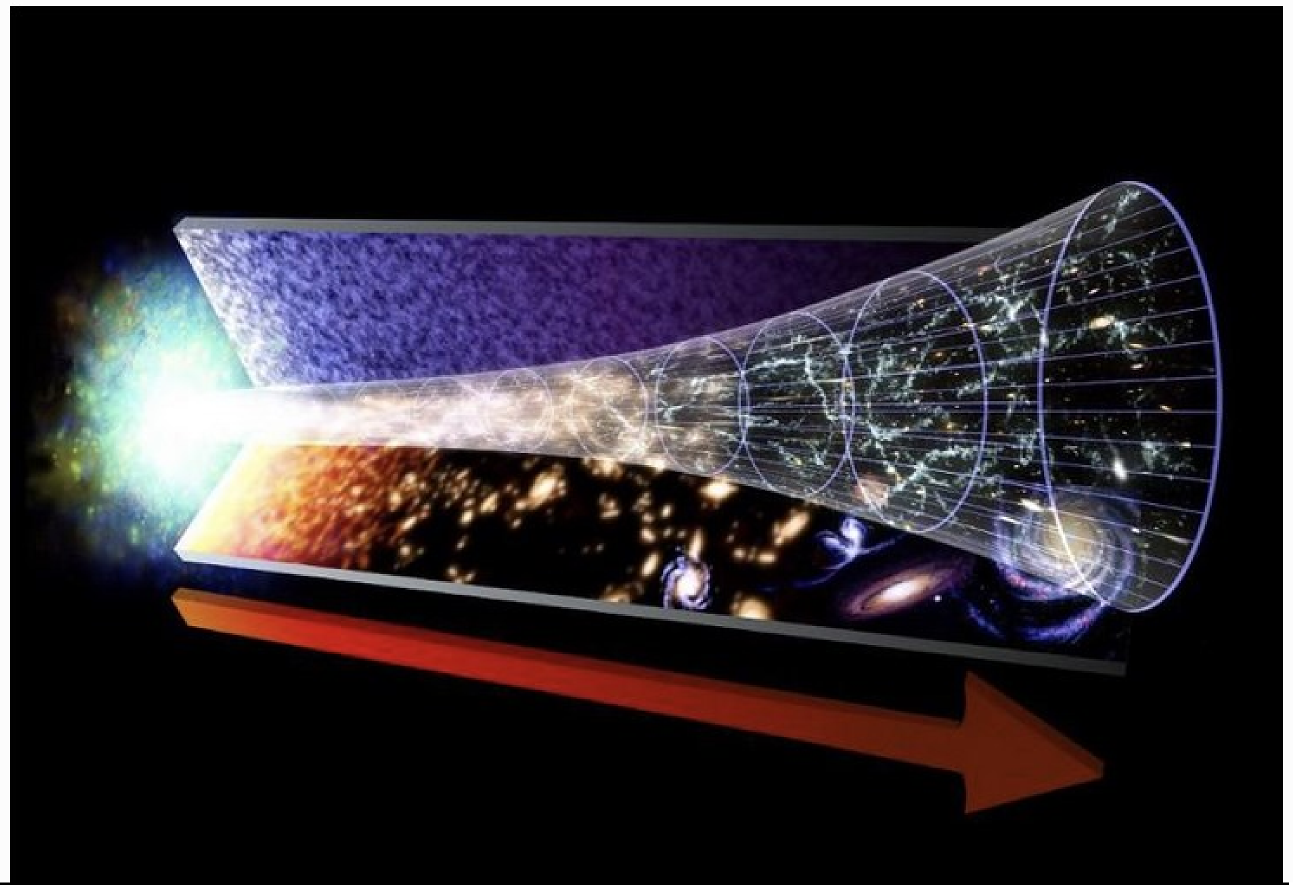
Science
The Universe is out there, waiting for you to discover it.



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

How Much Of The Dark Matter Could Neutrinos Be?

Ethan Siegel Senior Contributor
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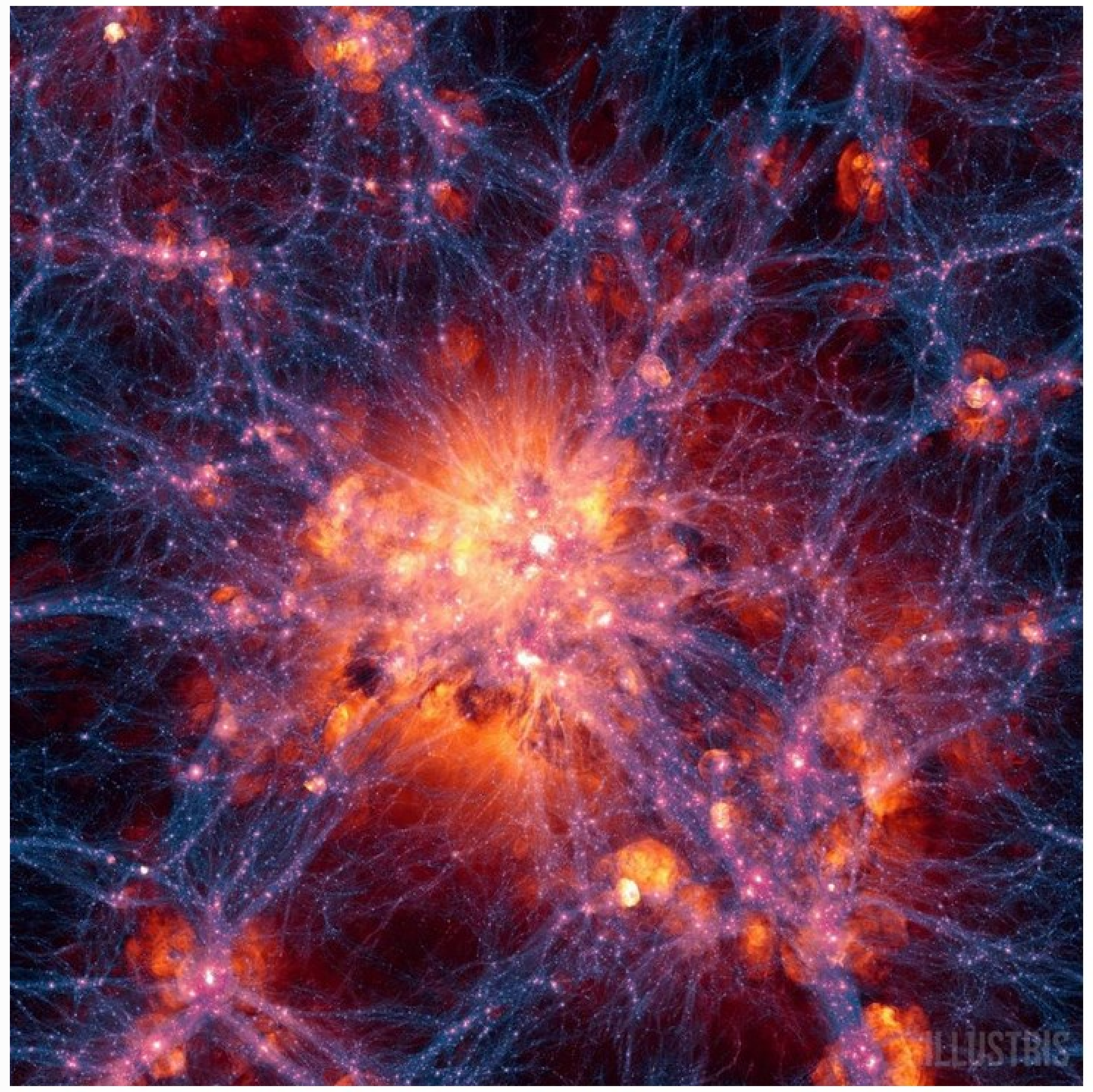
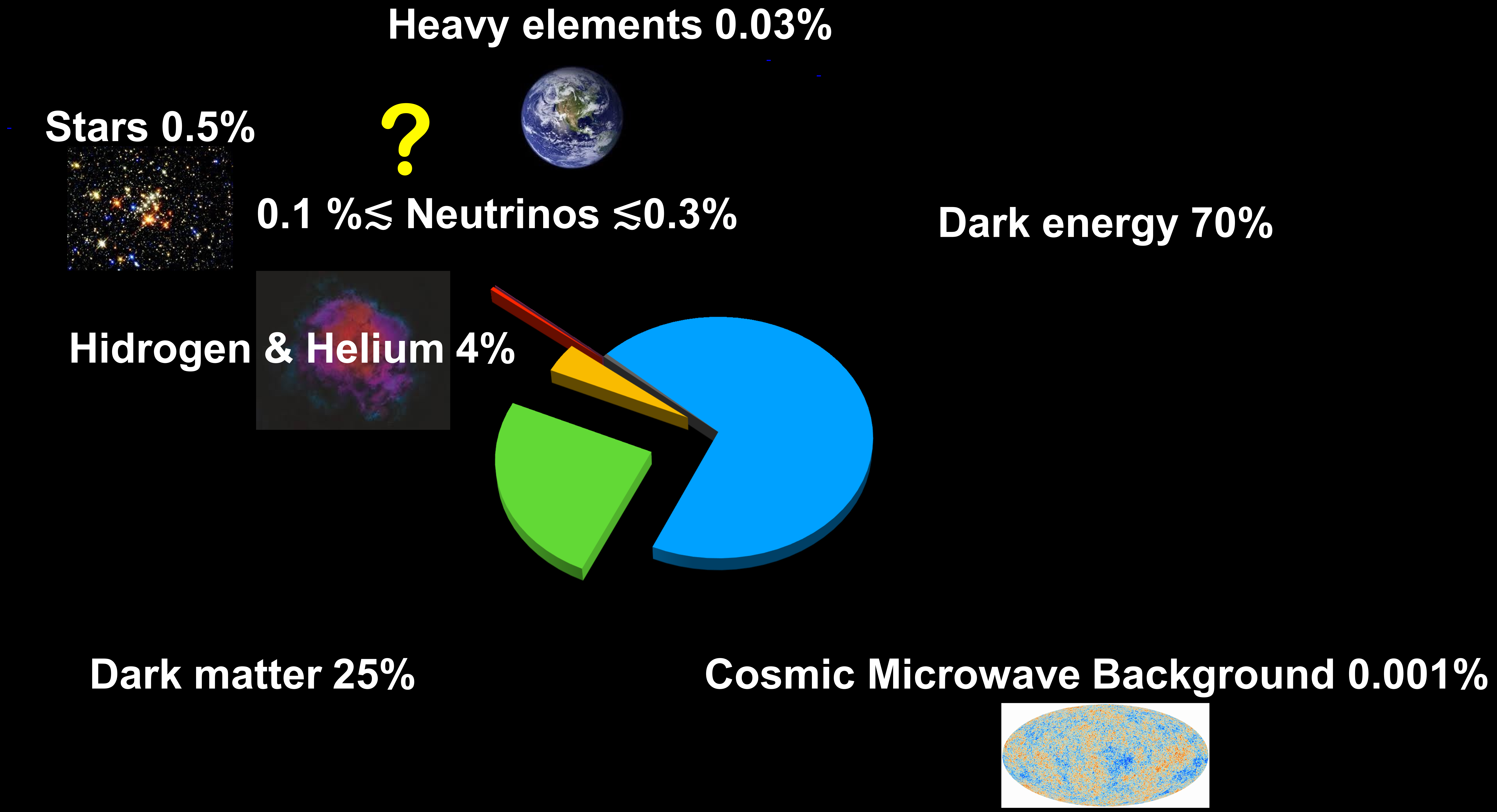
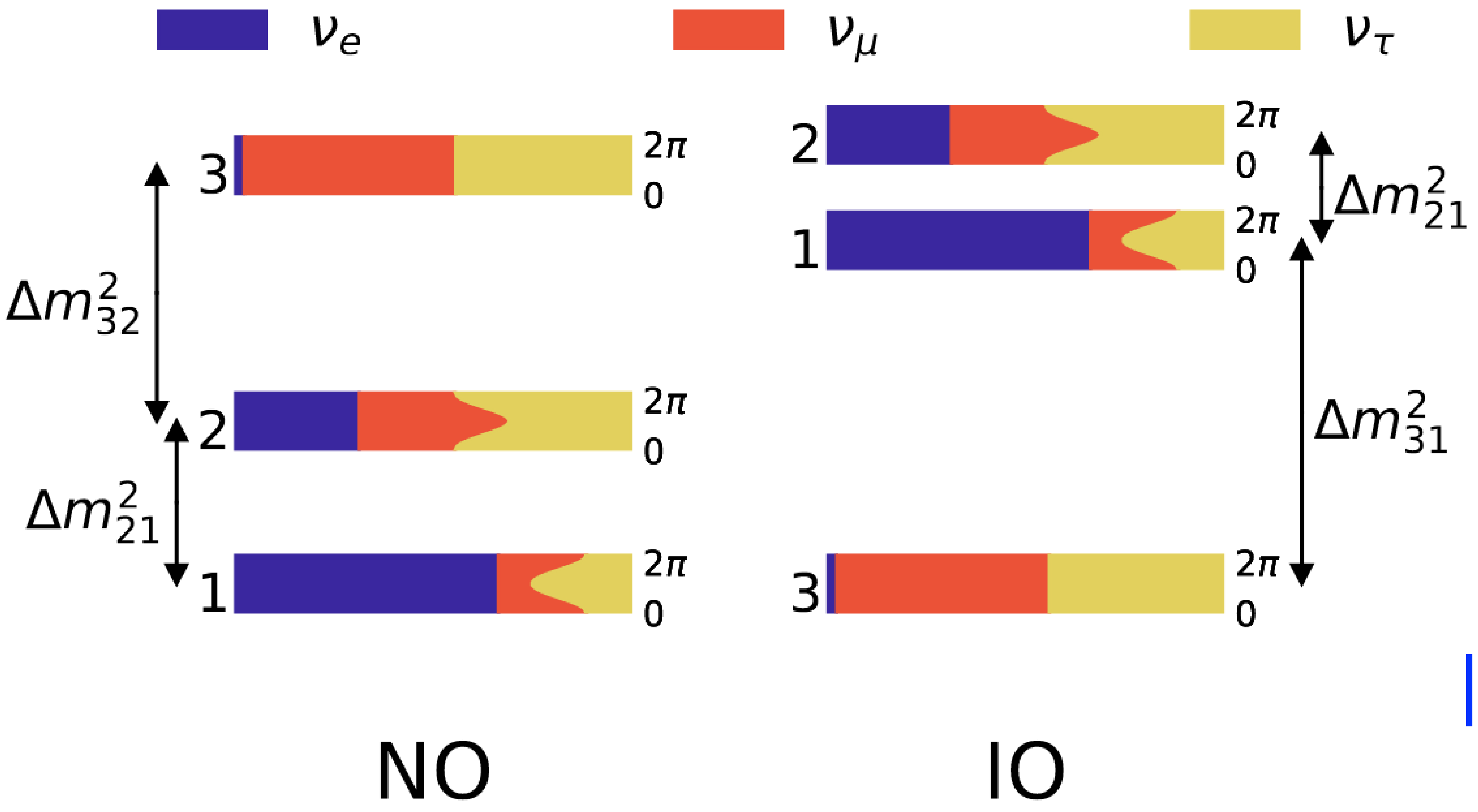
Science
The Universe is out there, waiting for you to discover it.



Our (ΛCDM) universe today



According t[illegible]we know that there are at least two Dirac or Majorana massive neutrinos.



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

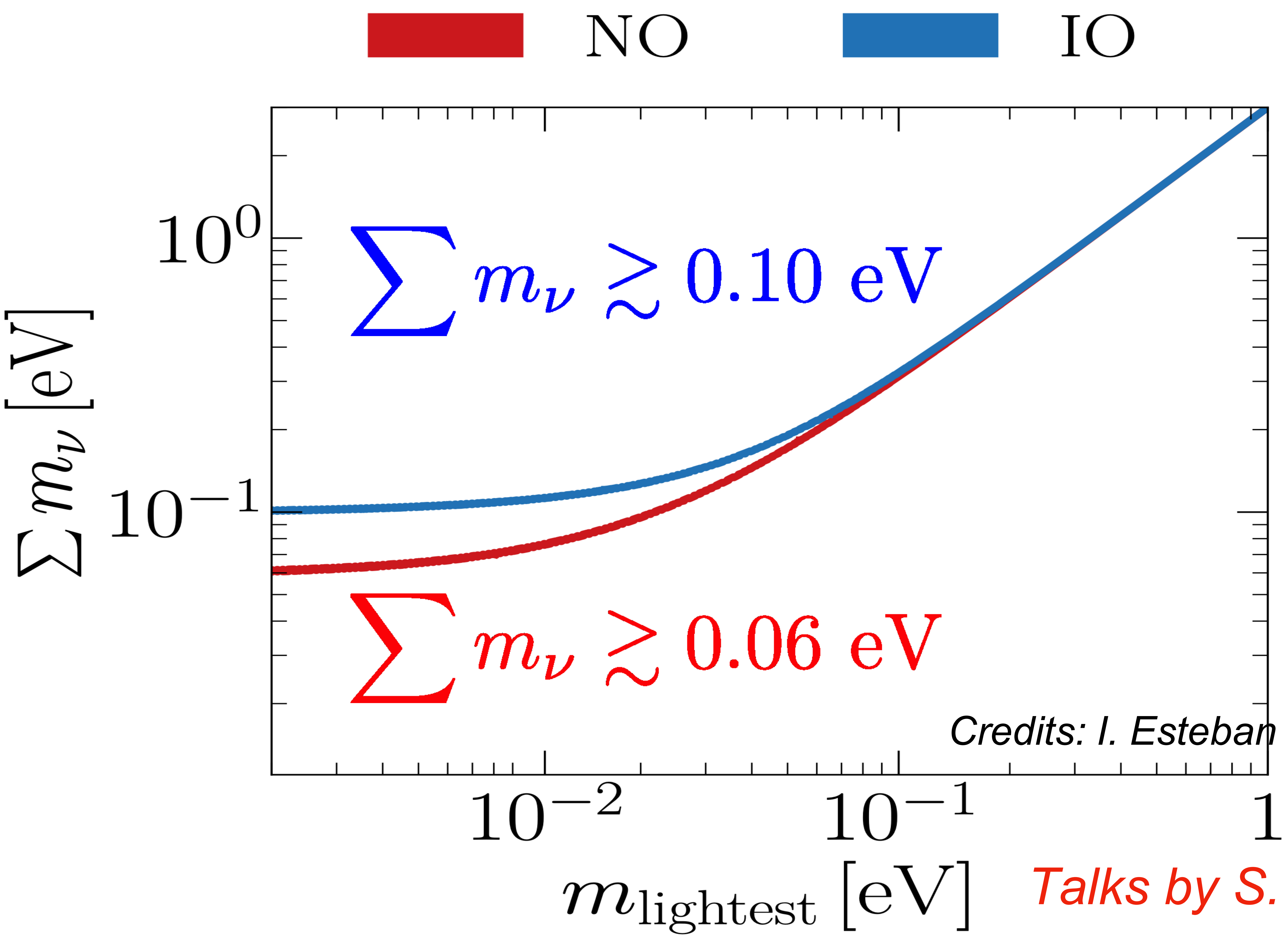
$$|\Delta m^2_{31}|_{\mathrm{NO}} = (2.47 - 2.63) \times 10^{-3}\, eV^2$$

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

Credits: S. Gariazzo

Talks by S. Petcov, S. Parke and E. Lisi

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



Talks by S. Petcov, S. Parke and E. L

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

$$\sqrt{\Delta m_{21}^2} \simeq 0.008 eV$$

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

$$\sqrt{|\Delta m_{31}^2|} \simeq 0.05 eV$$

Talks by S. Petcov, S. Parke and E. Lisi

Number of neutrinos: N_{eff}

The total radiation in the universe can be written as:

$$\Omega_r h^2 = \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\mathrm{eff}}\right)\Omega_\gamma h^2$$

N_{eff} = 3.0440 ± 0.0002 standard scenario: electron, muon and tau neutrinos

Bennett et al, 2012.02726

N_{eff} = 3.0432 ± 0.0002 *Cielo et al, 2306.05460*

N_{eff} < 3.044 (less neutrinos): Neutrino decays ?

N_{eff} > 3.044 (more neutrinos): Sterile neutrino species ?

THE NEUTRINO MENU

- Antipasto: State of the art
- Primo piatto: Cosmology & Neff
- Secondo piatto: Cosmology & Σm_ν
- Dolce: Future perspectives: What if?
- Expresso: Take home messages


Once upon a time…..

A. Masiero, NEUTEL'88

From SN1987A we can infer the bound (roughly) although some authors claim a more stringent result.

Also for the question concerning the number of neutrino flavours (N_ν), although we have not come up with a definite answer yet,we have tighter bounds:

i) $N_\nu < 4.6$ (90% c.l) $\Rightarrow$ γ tagging of "nothing" at e^+e^- colliders;

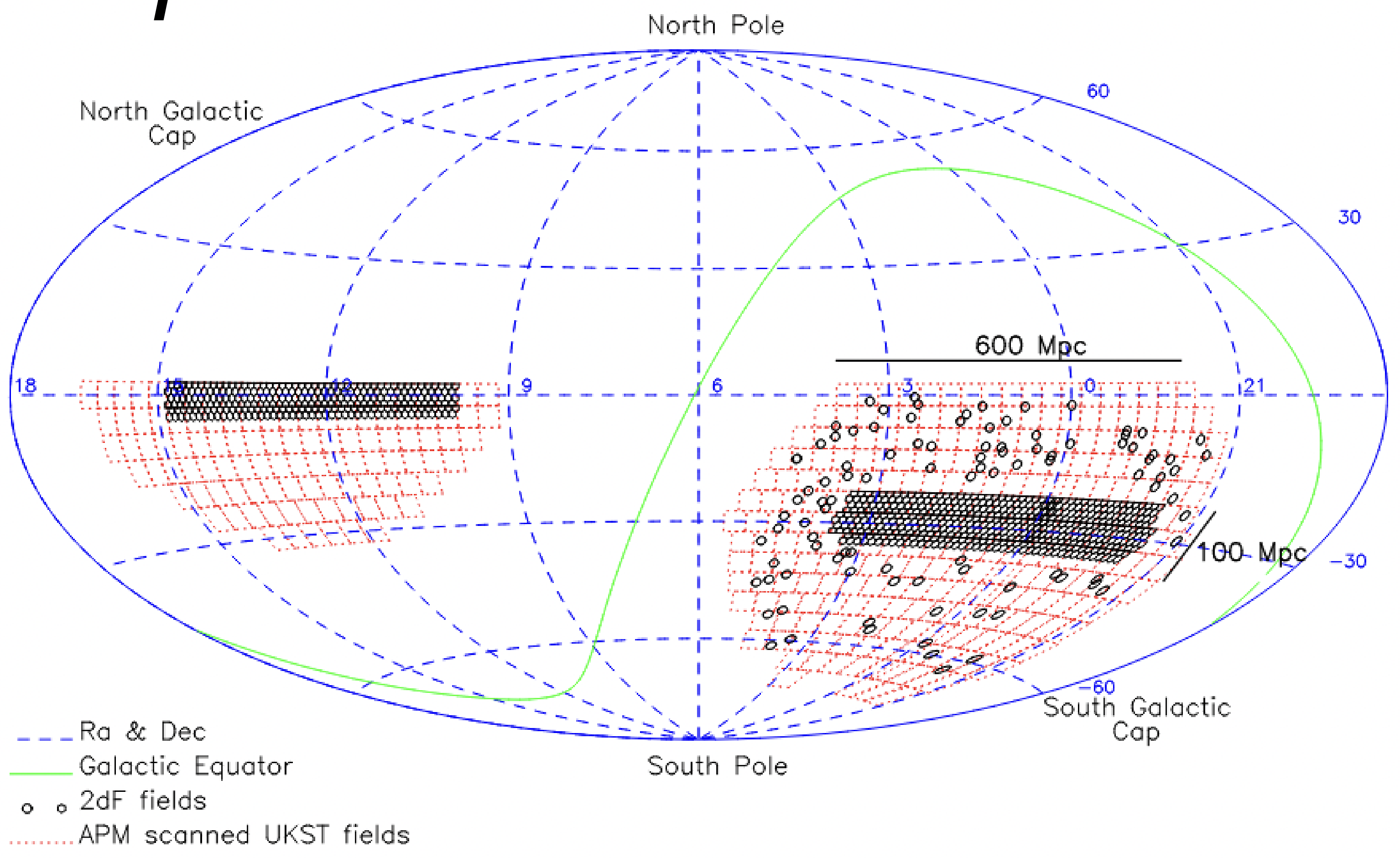
ii) $N_\nu < 10 \Rightarrow$ gluon tagging of "nothing" at $Sp\bar{p}S$;

iii) $N_\nu < 5$ (90% c.l) $\Rightarrow$ ratio of $W_{e\nu}$ and Z_{ee} yields at $Sp\bar{p}S$.

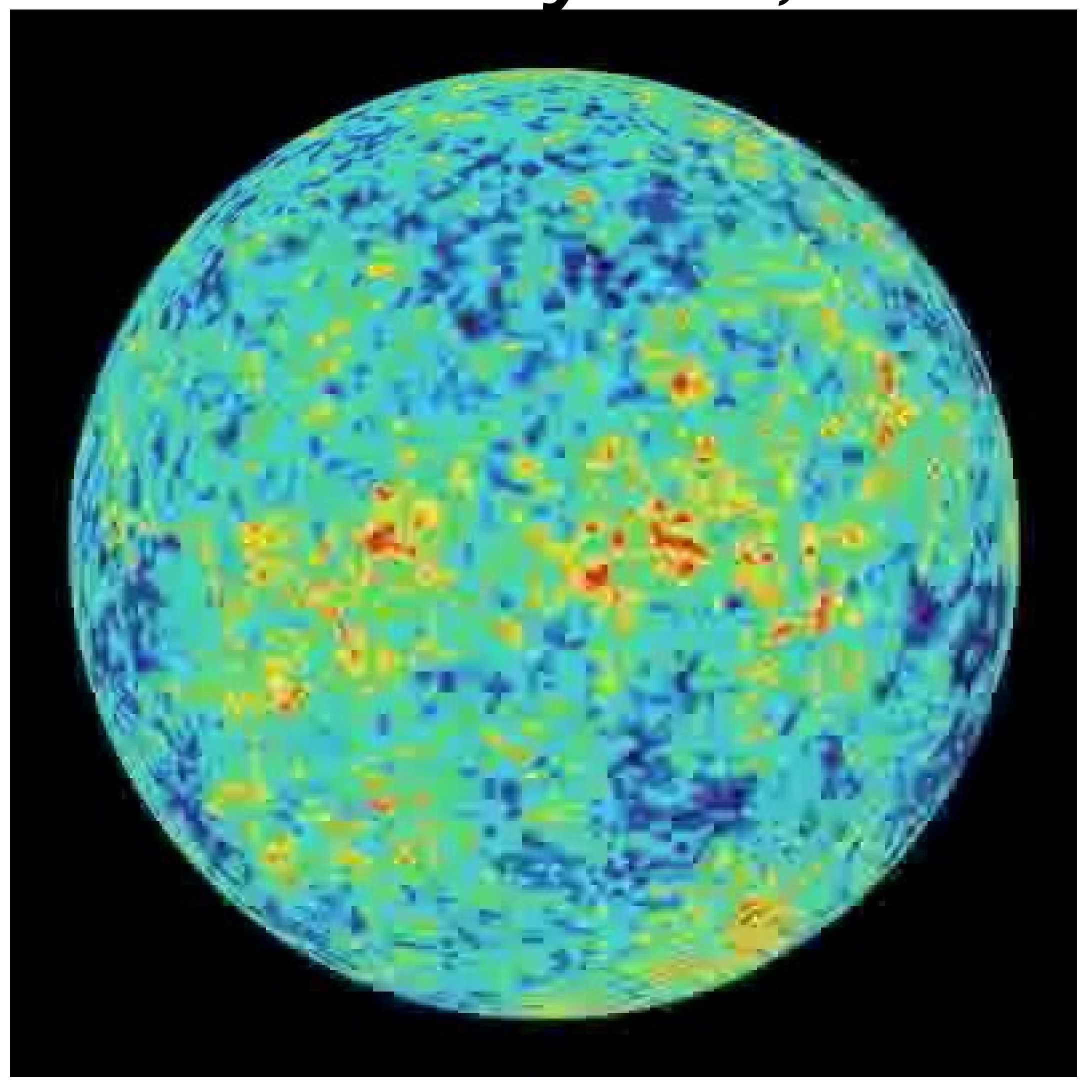
We should add the bound which comes from our standard scenario of nucleosynthesis. It is known that there are at least three major uncertainties

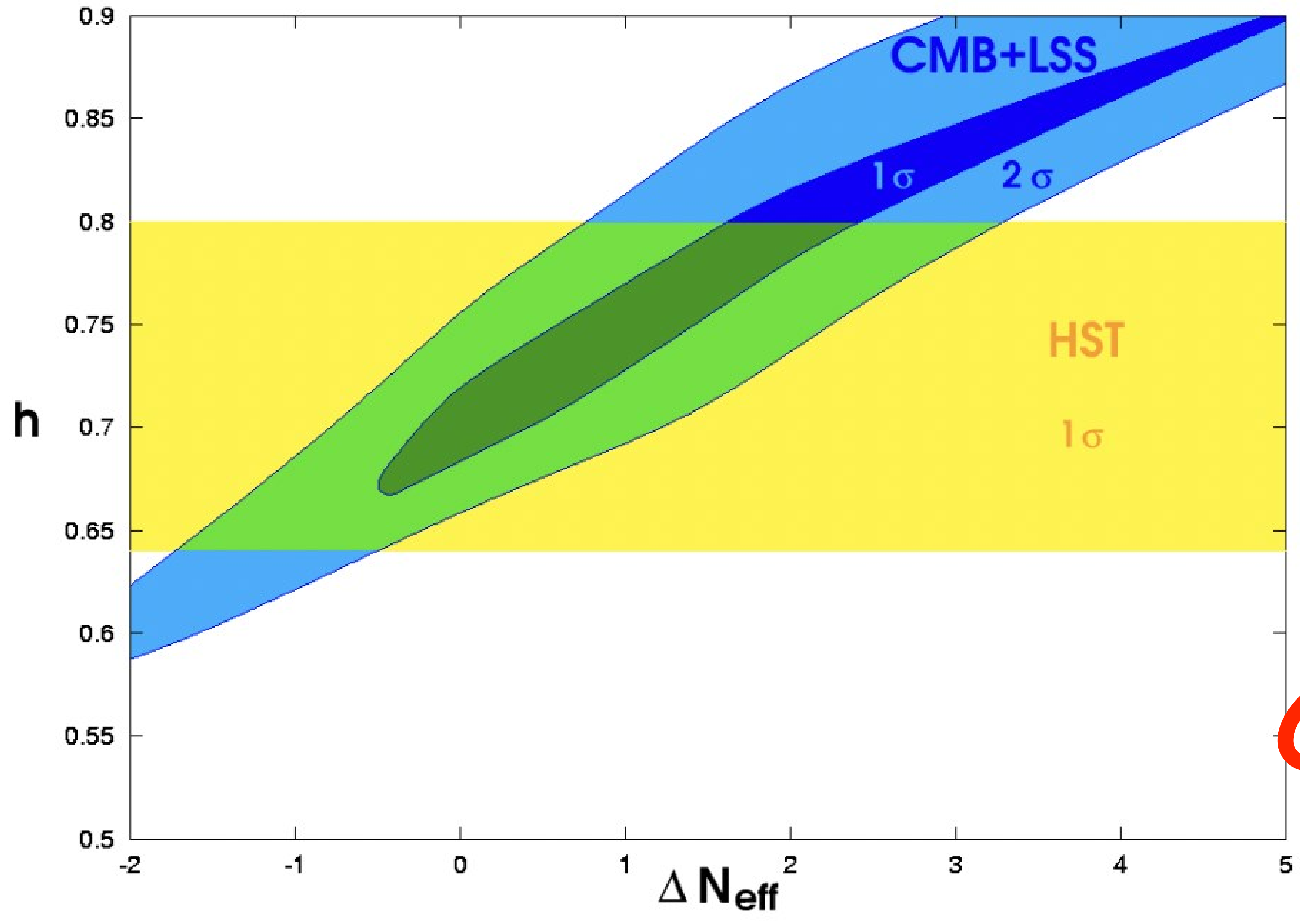
2003 constraints on Neff

astro-ph/0204239



WMAP 1st year, NASA





S. Pastor, NEUTEL'03

95% CL limits

BBN

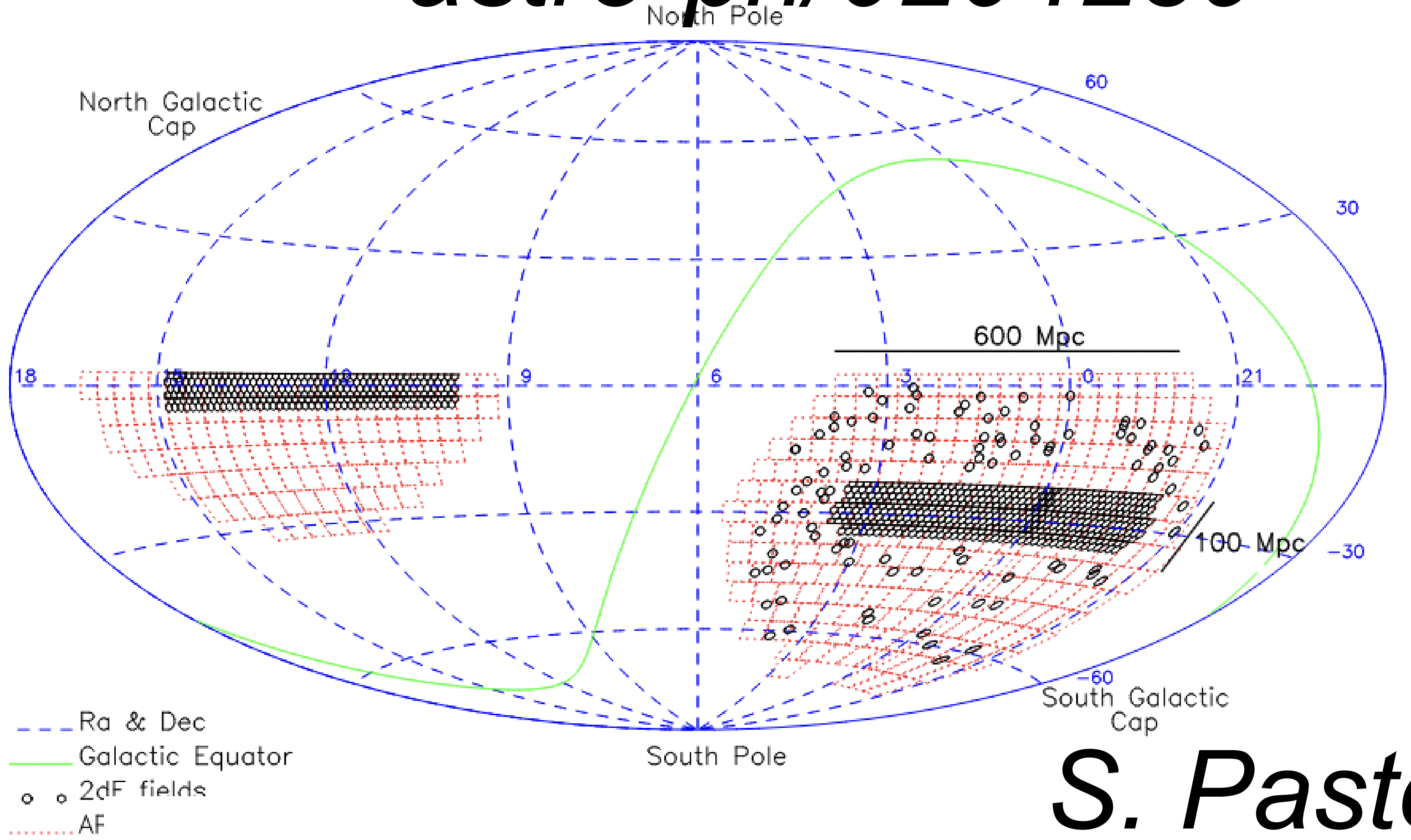
$$1.22 < N_{\rm eff} < 5.25$$

CMB + LSS

$$\Delta N_{\rm eff} = 0.5^{+3.3}_{-2.1}$$

2003 Absolute neutrino mass status

astro-ph/0204239



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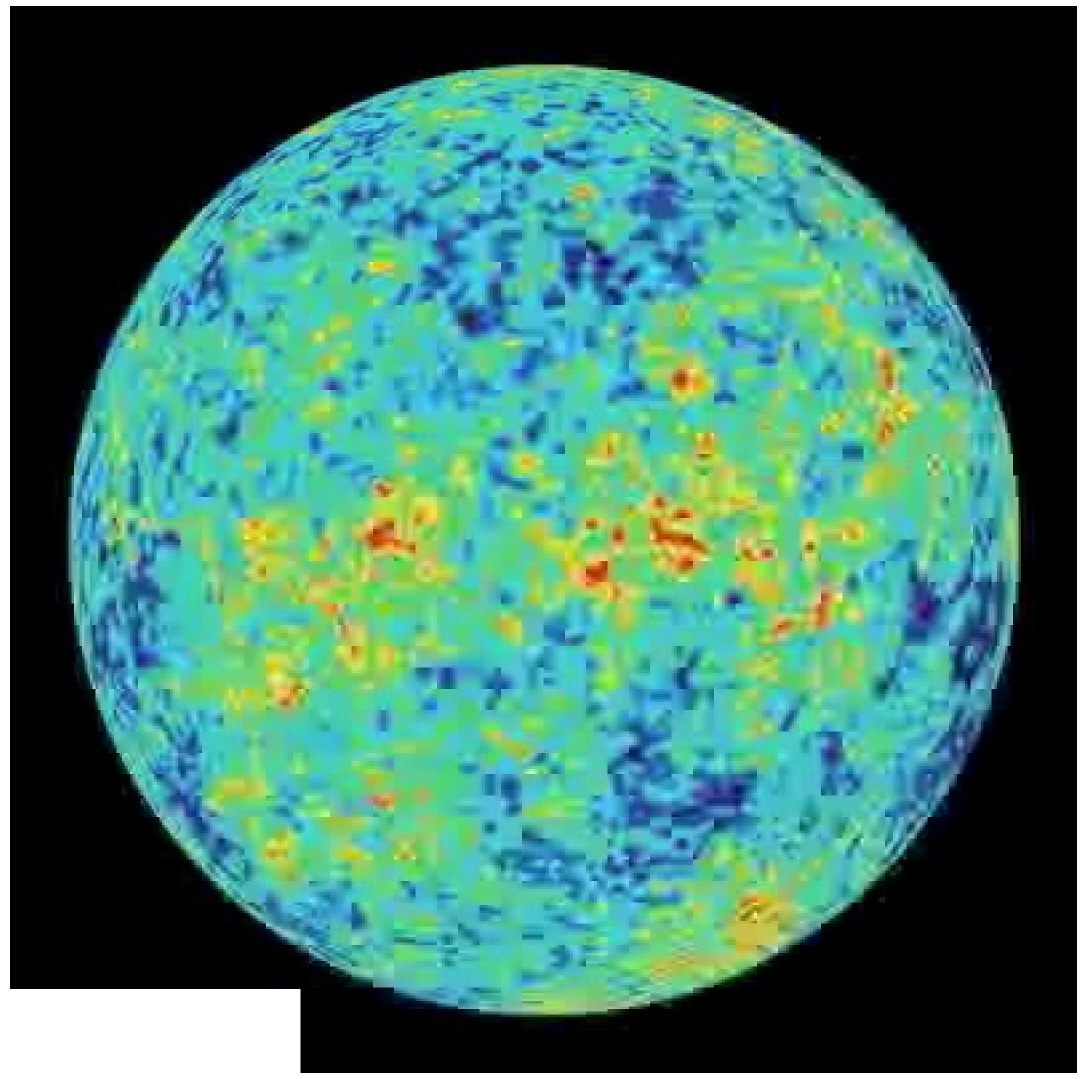
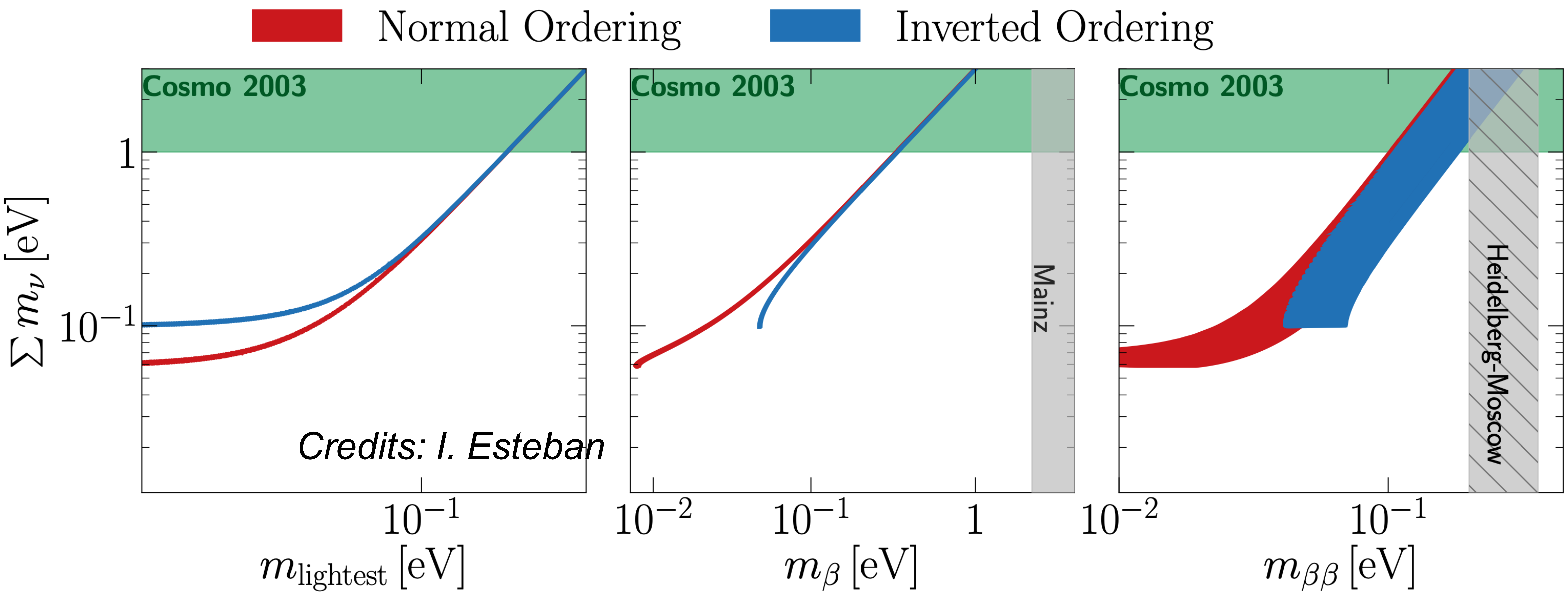


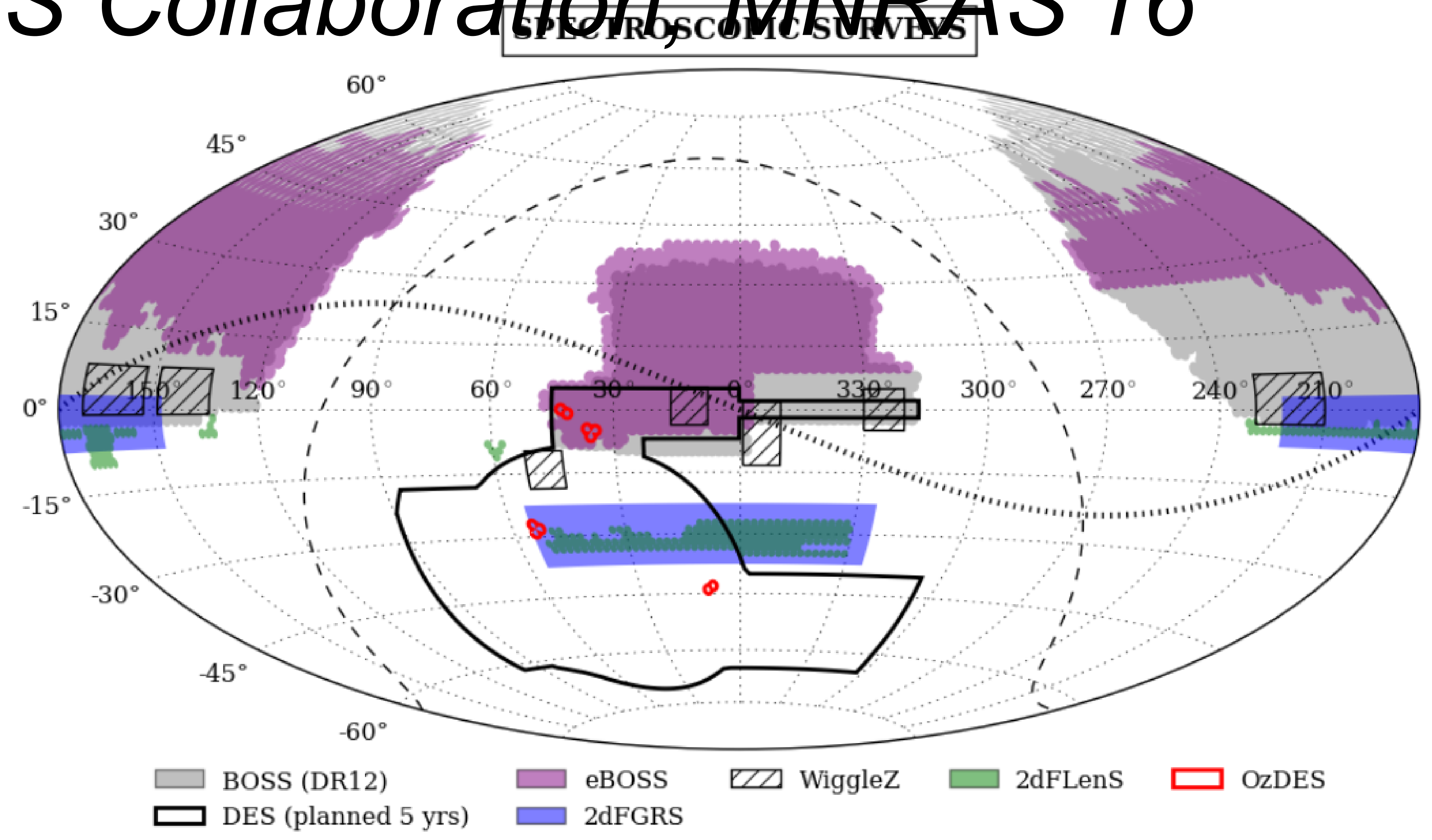
S. Pastor & C. Weinheimer, NEUTEL'03

95% CL limits

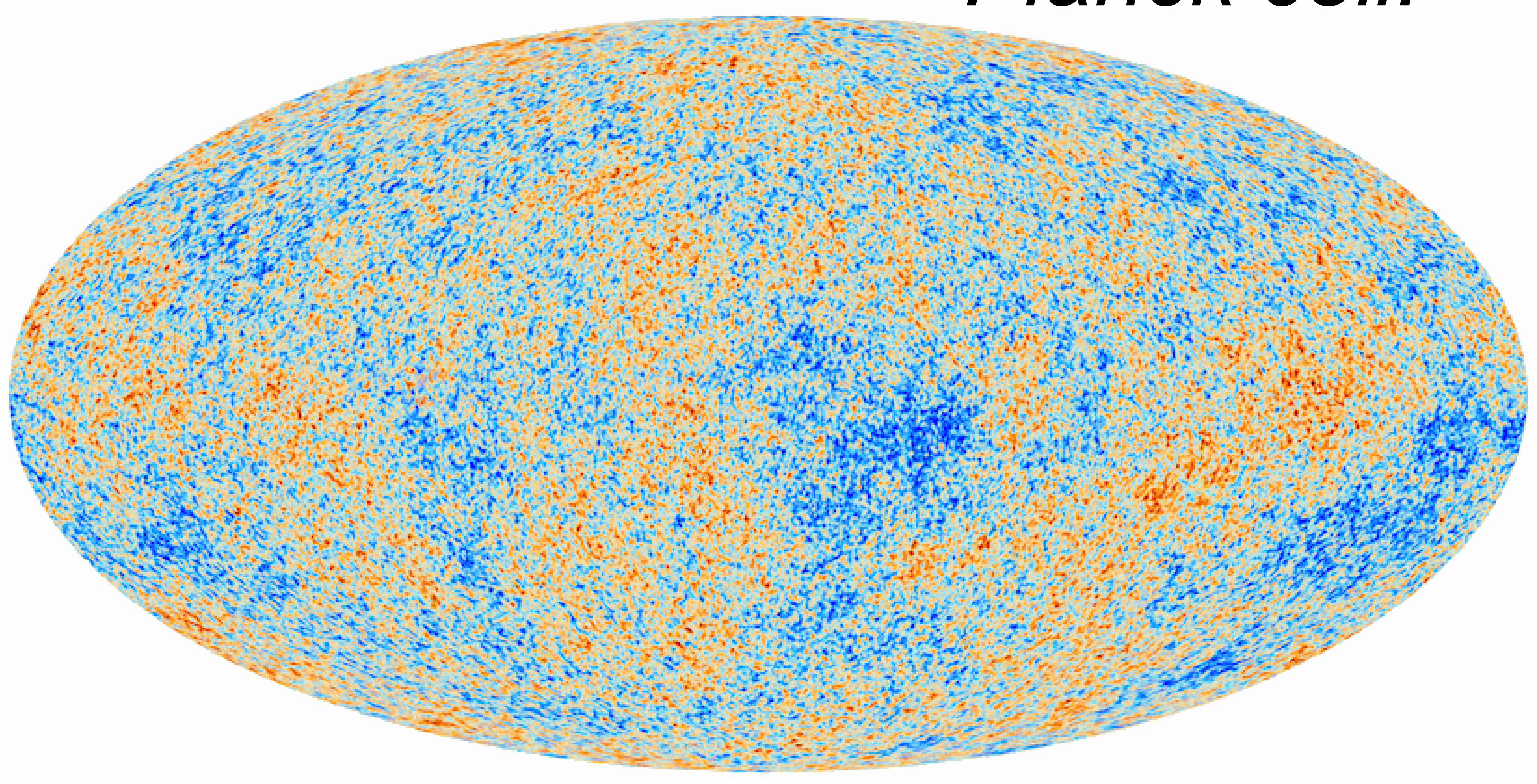


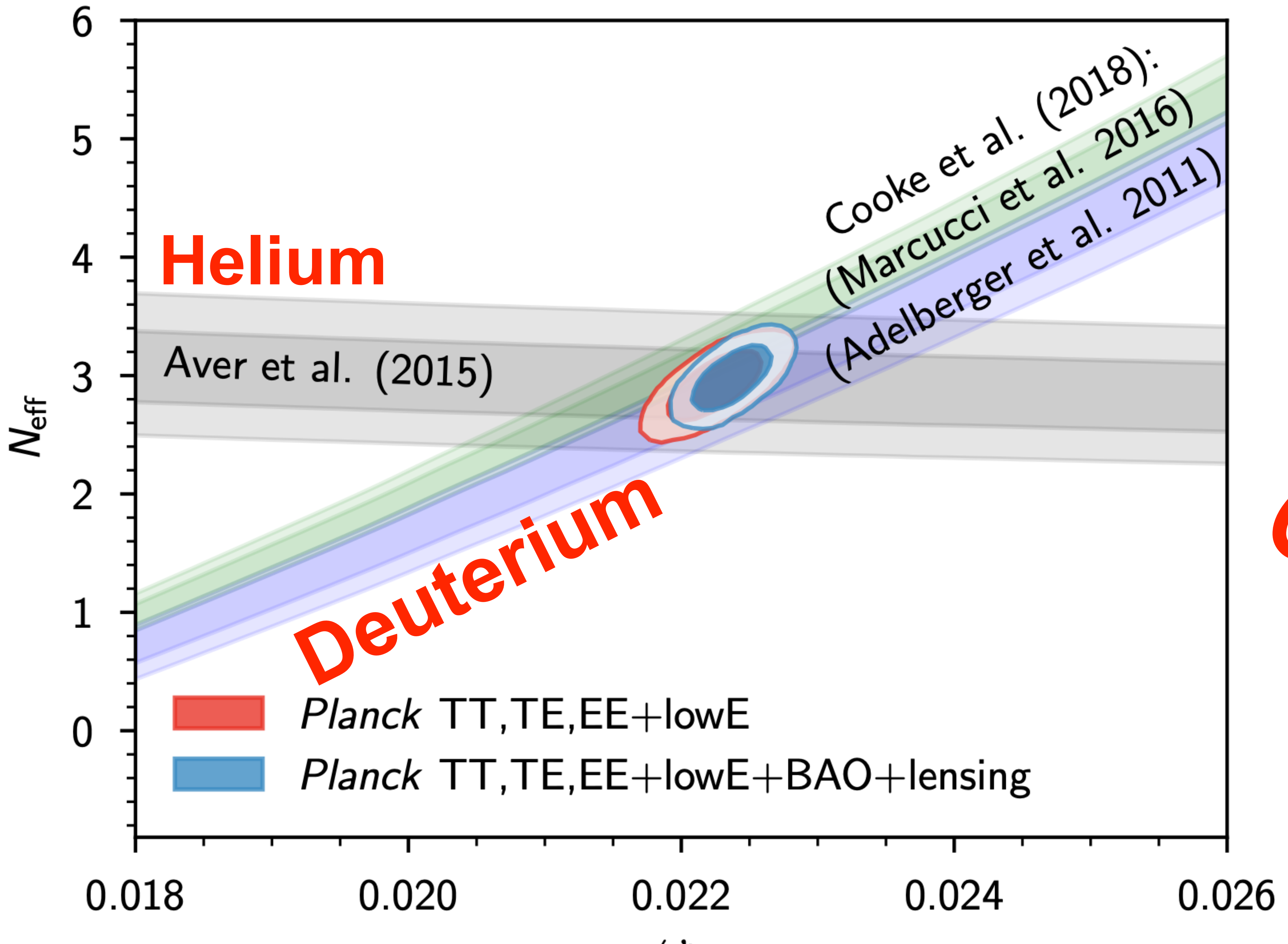
2023 constraints on Neff

DES Collaboration, MNRAS'16



Planck coll.





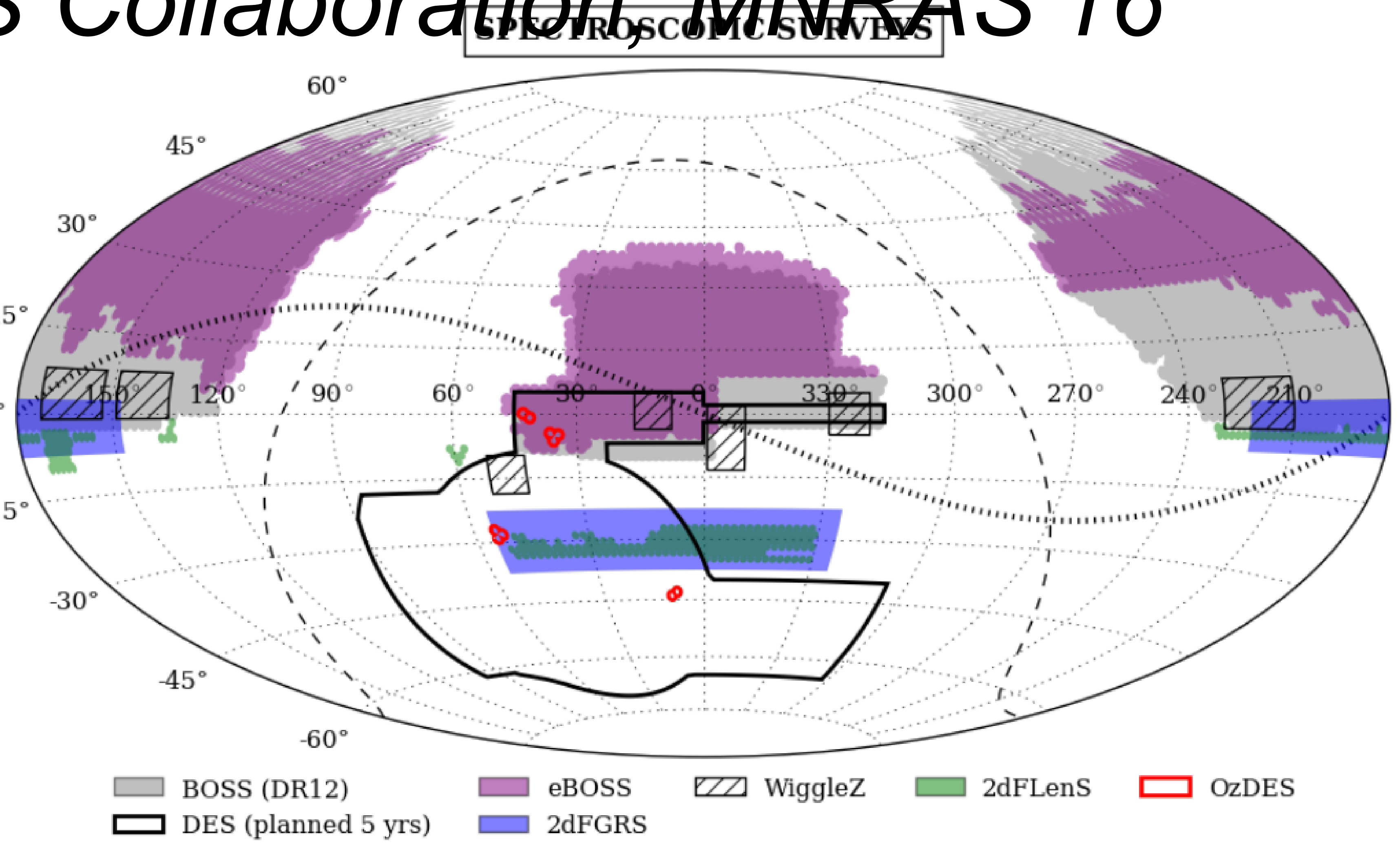
Planck coll. A&A'21

95% CL limits

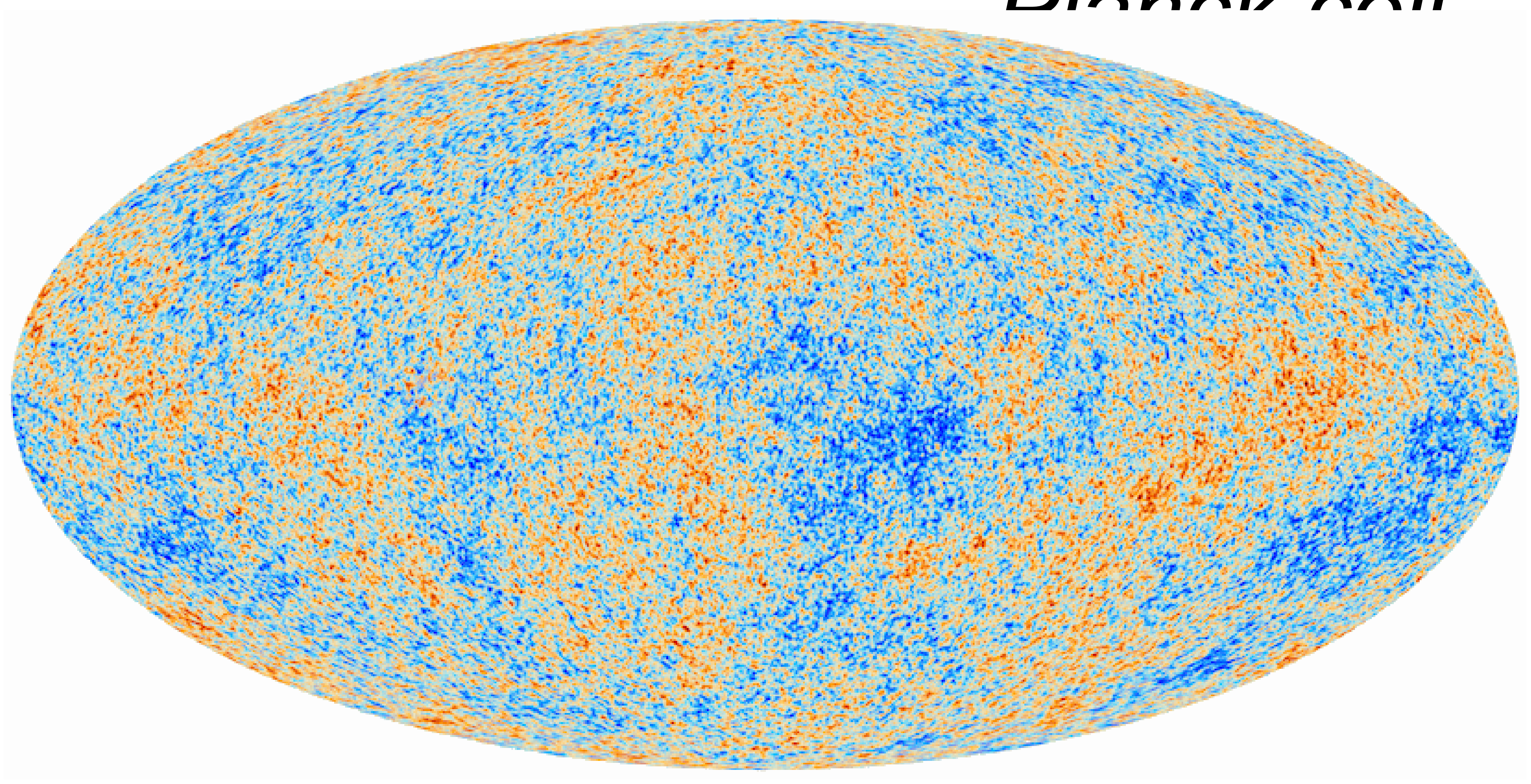
CMB + BAO $N_{eff} = 2.99^{+0.34}_{-0.33}$

2023 absolute neutrino mass status

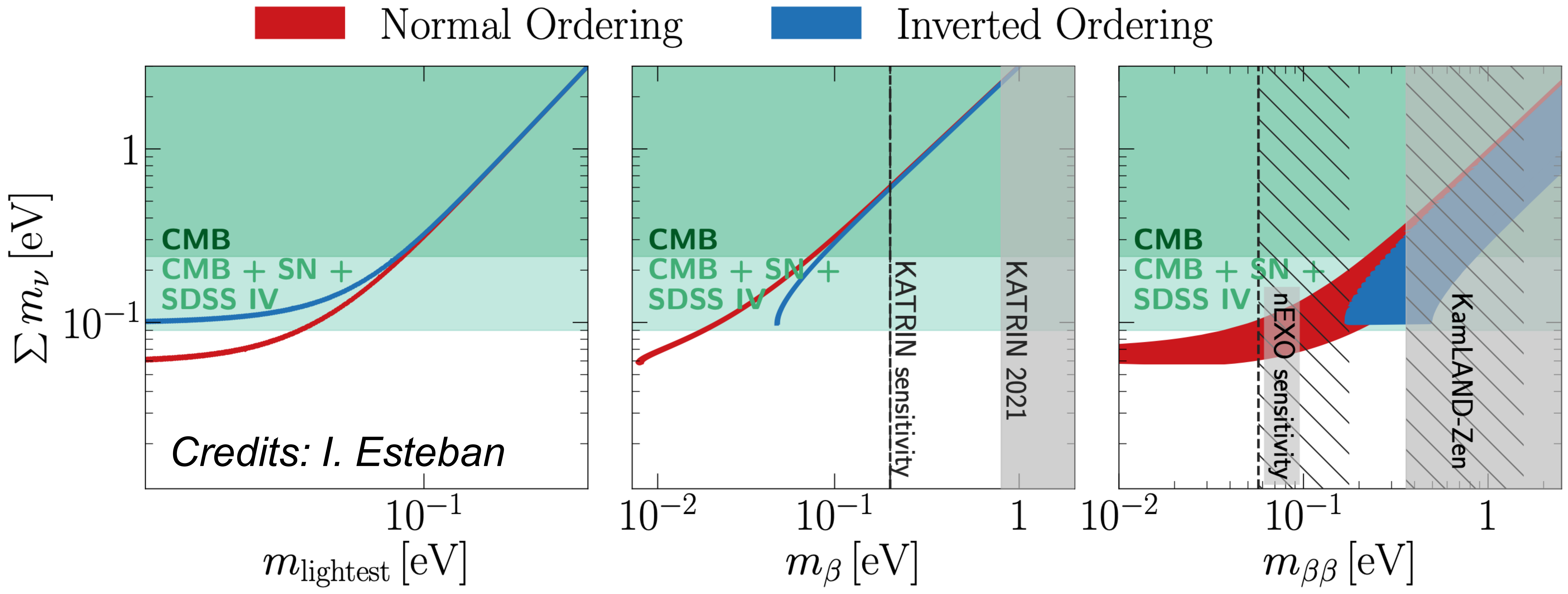
DES Collaboration, MNRAS'16



Planck coll



Talks by S. Petcov, S. Parke, M. Agostini, J. Formaggio and E. Lisi



95% CL limits

THE NEUTRINO MENU

- Antipasto: State of the art
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- Dolce: Future perspectives: What if?
- Expresso: Take home messages

Big Bang Nucleosynthesis: N_{eff}

BBN theory predicts the abundances of D, ^{3}He, ^{4} nd ^{7}Li which, fixed by t≃180 s.
They are observed at late times: low metallicity sites are "ideal".

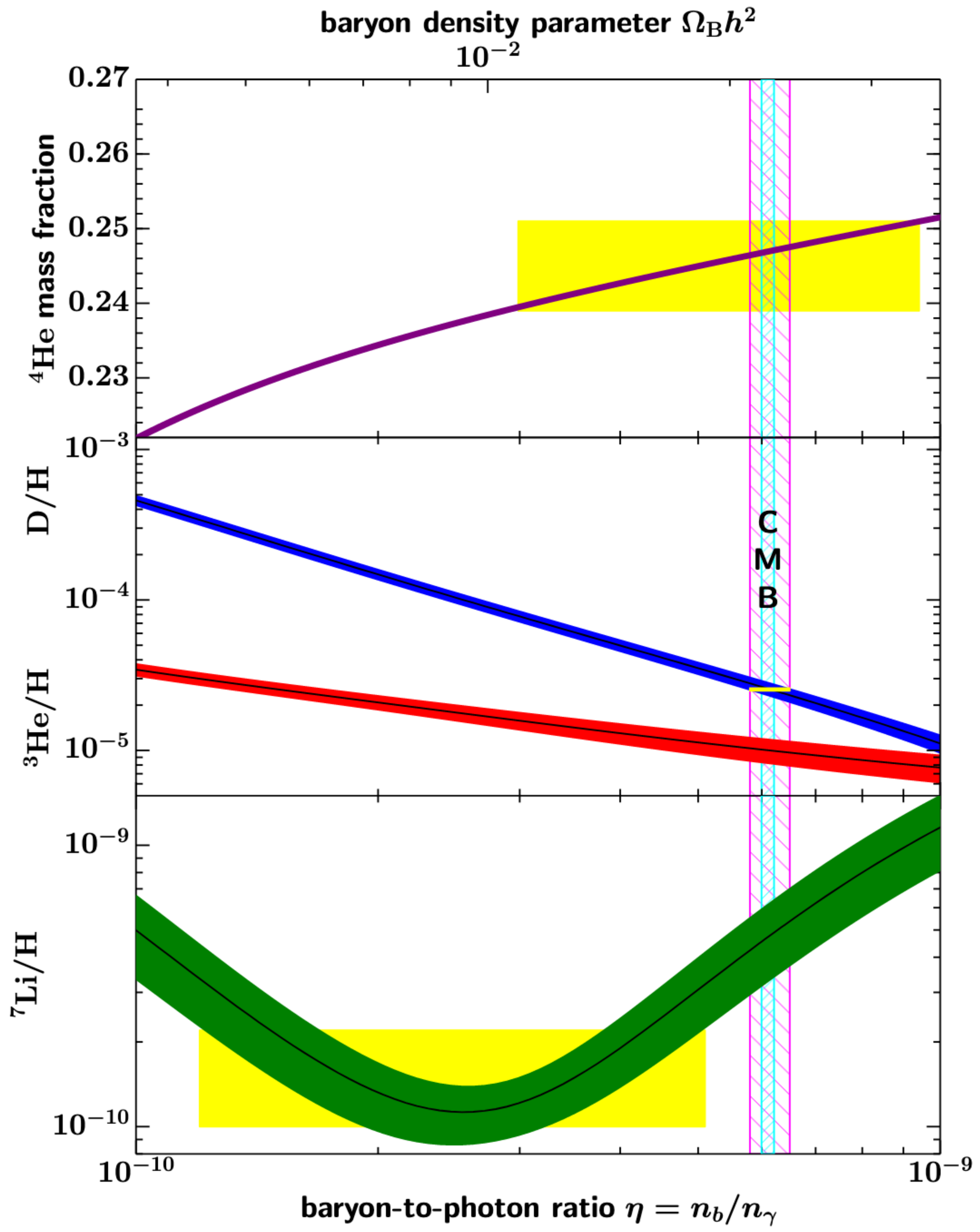


Figure 24.1: The primordial abundances of ^{4}He, D, ^{3}He, and ^{7}Li as predicted by the standard model of Big-Bang nucleosynthesis — the bands show the 95% CL range [47]. Boxes indicate the observed light element abundances. The narrow vertical band indicates the CMB measure of the cosmic baryon density, while the wider band indicates the BBN D+^{4}He concordance range (both at 95% CL).

Low metallicity extragalactic HII regions. 

Produced in stars. 

P.A. Zyla et al. (Particle Data Group),
Prog. Theor. Exp. Phys. ***2020****, 083C01 (2020).*

Big Bang Nucleosynthesis: N_{eff}

N_{eff} **changes the freeze out temperature of weak interactions:**

$$\Gamma_{n \leftrightarrow p} \sim H$$

Higher N_{eff}, Larger freeze out temperature,

MORE NEUTRINOS: MORE HELIUM 4

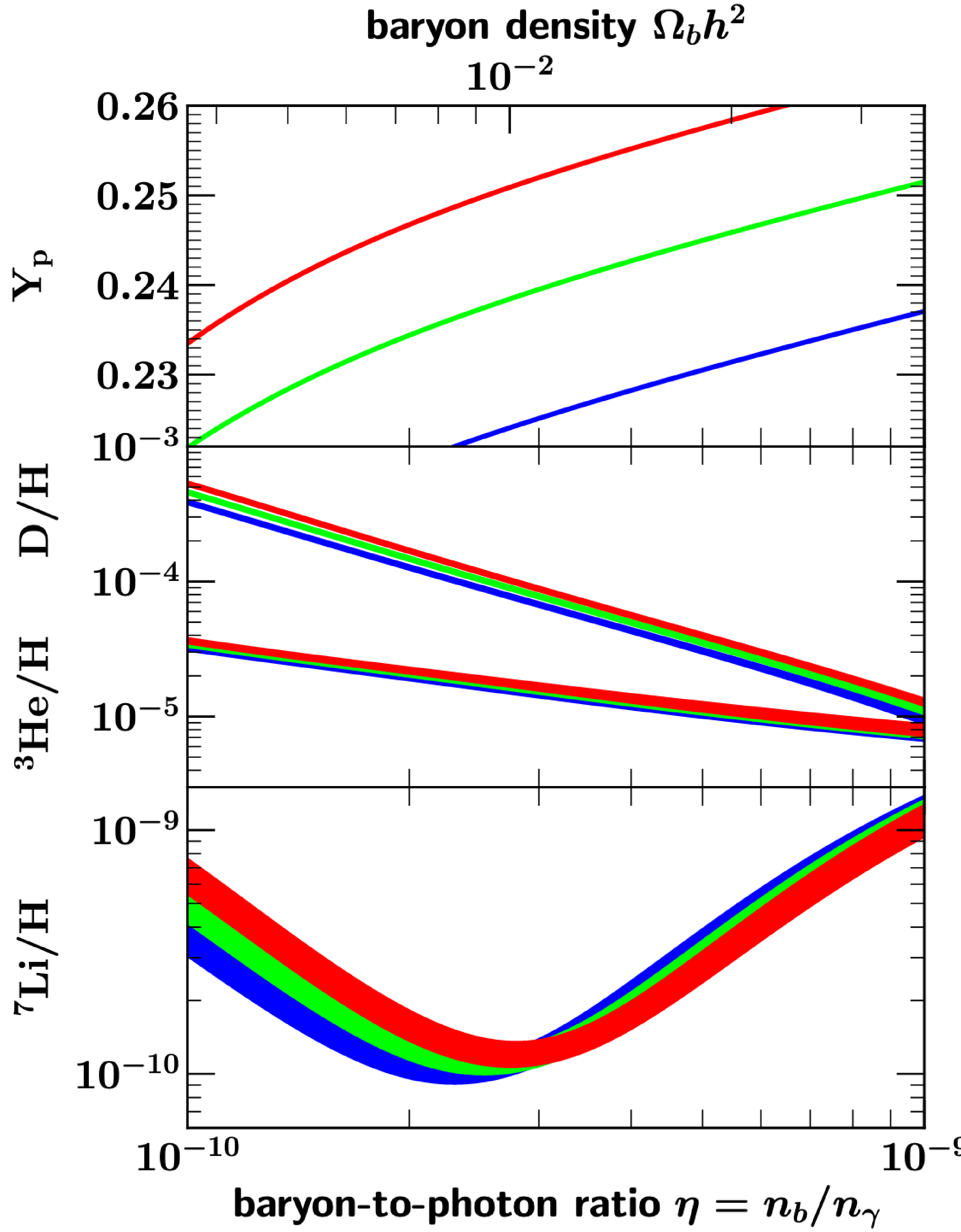
$$n/p \simeq e^{-\frac{m_n - m_p}{T_{freeze}}}$$

$$Y_p = \frac{2(n/p)}{1 + n/p}$$

$N_{eff} = 2$

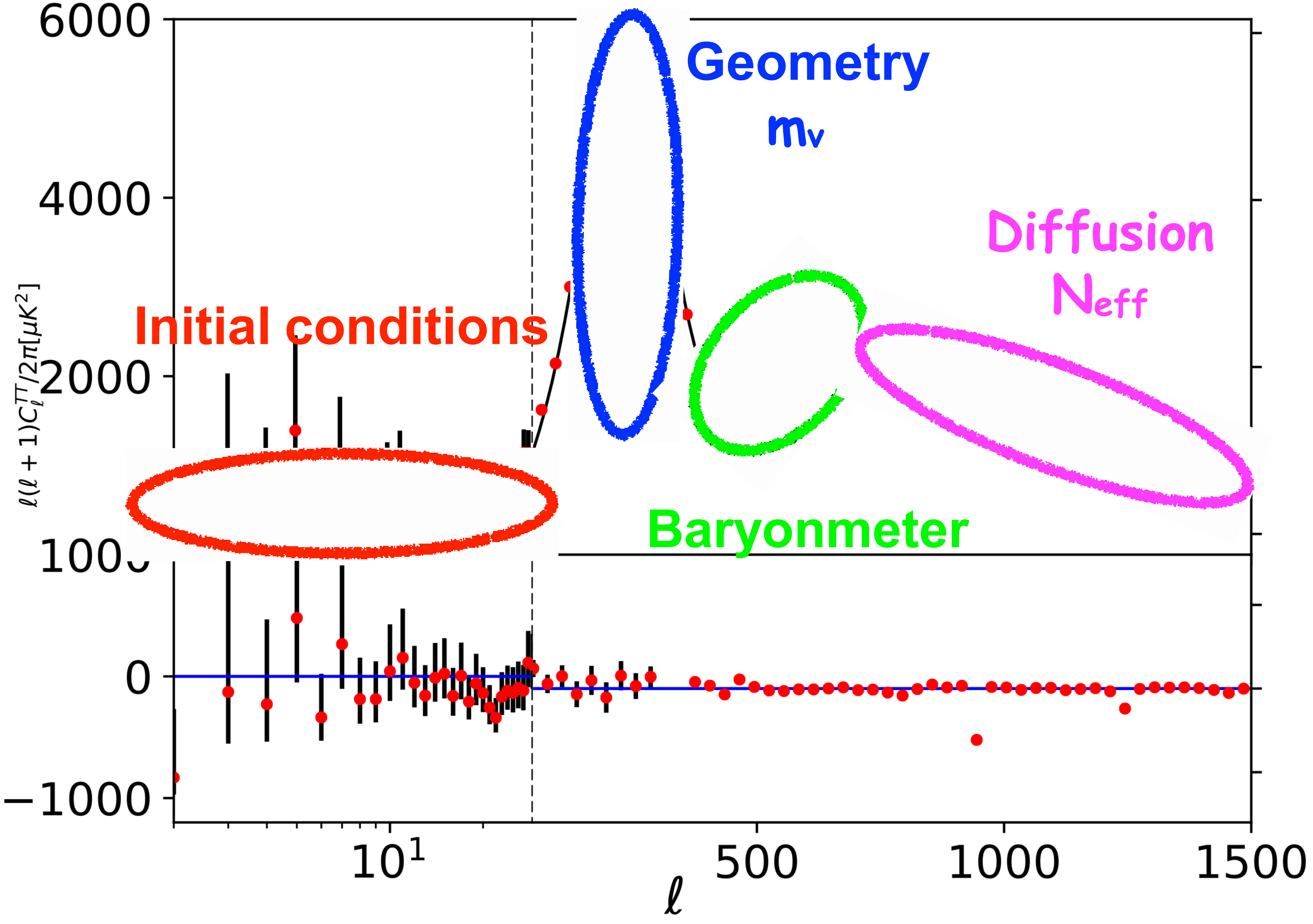
$N_{eff} = 3$

$N_{eff} = 4$

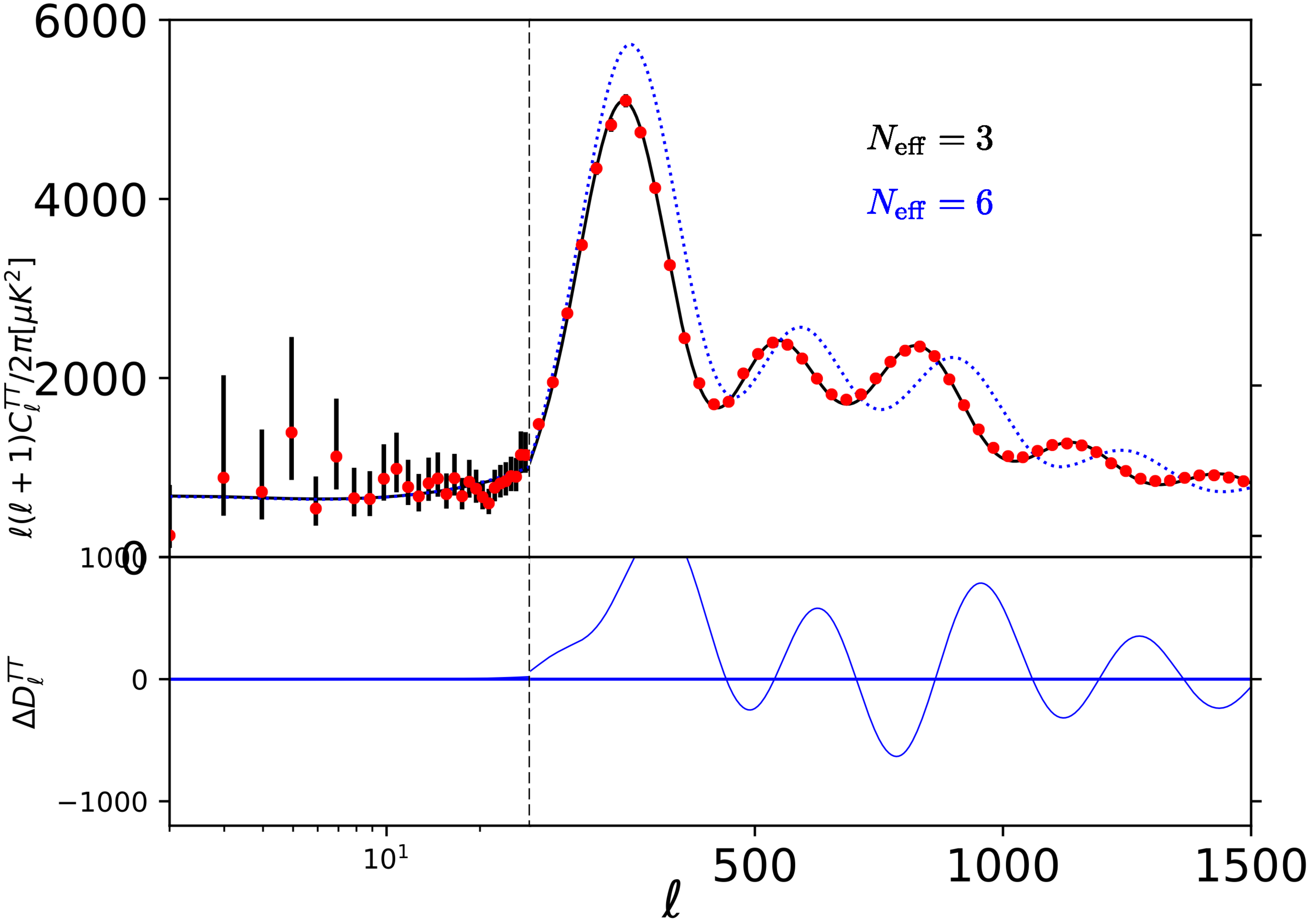


Fields, Olive, Yeh & Young JCAP '2

CMB: a lot to learn about….



CMB: N_{eff}



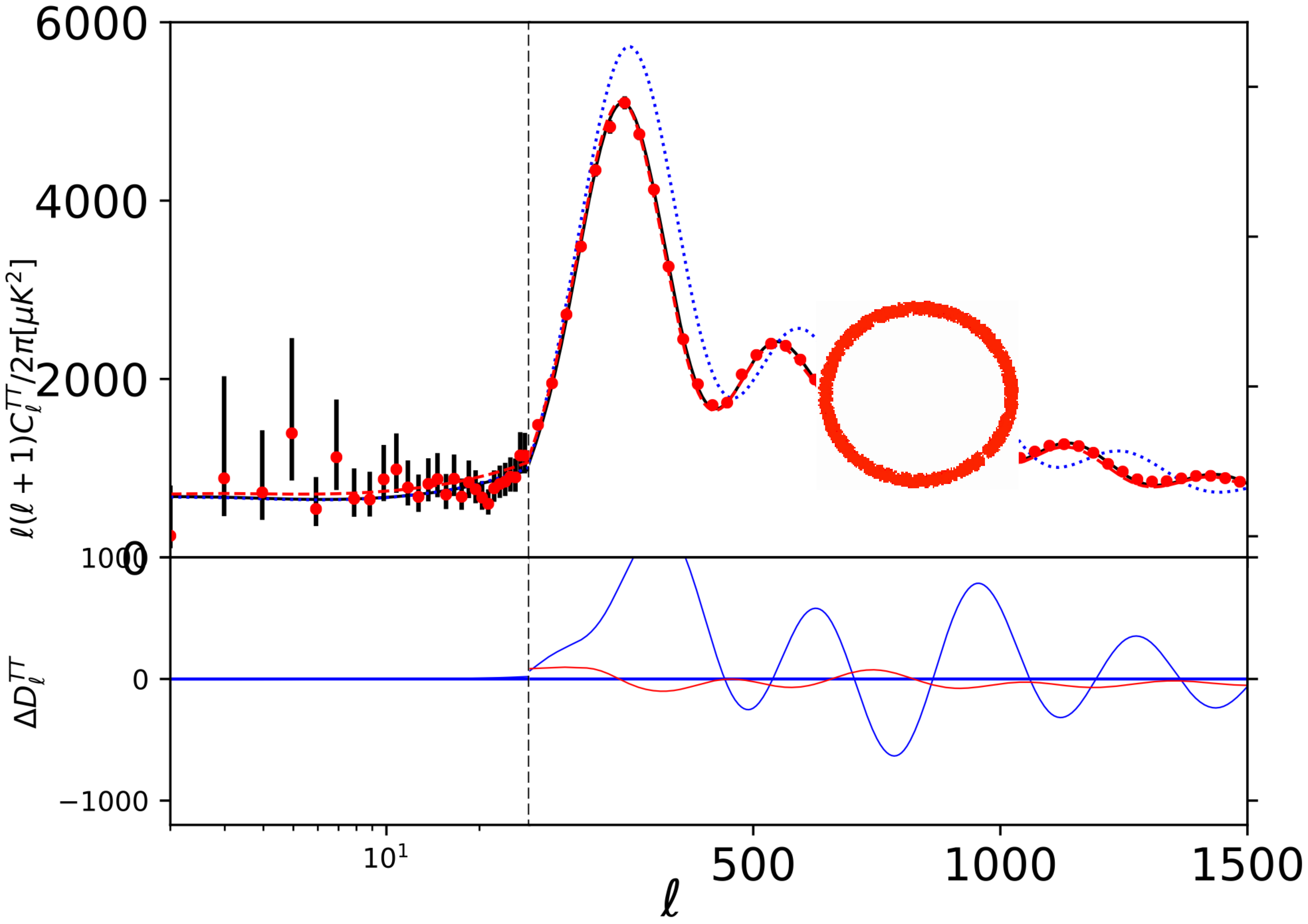
6000
4000
2000
0
1000
0
−1000
$\ell(\ell+1)C_\ell^{TT}/2\pi[\mu K^2]$
ΔD_ℓ^{TT}
$N_{\rm eff} = 3$
$N_{\rm eff} = 6$
10^1
500
1000
1500
ℓ

CMB: N_{eff}

$N_{eff} = 6$ $N_{eff} = 3$ $N_{eff} = 6$

$(\omega_b, \omega_m, h, A_s, n_s, \tau, N_{eff})$

Warning!

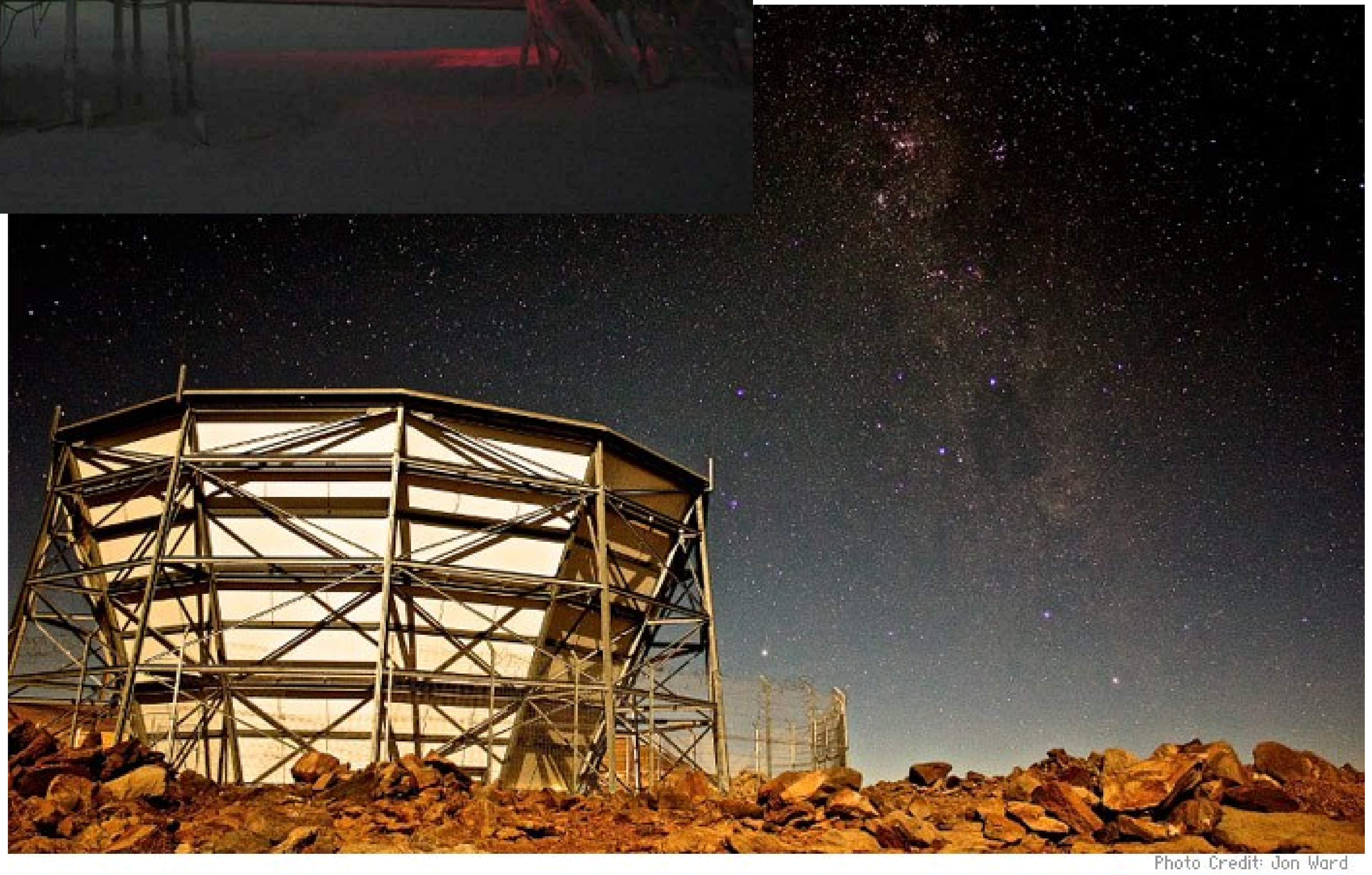


Only effect at l<1000 that can not be mimicked: anisotropic stress, around 3rd peak
Neutrinos are free-streaming particles propagating at the speed of light, faster than the sound speed in the photon fluid, suppressing the oscillation amplitude of CMB modes that entered the horizon in the radiation epoch.

CMB: N_{eff}

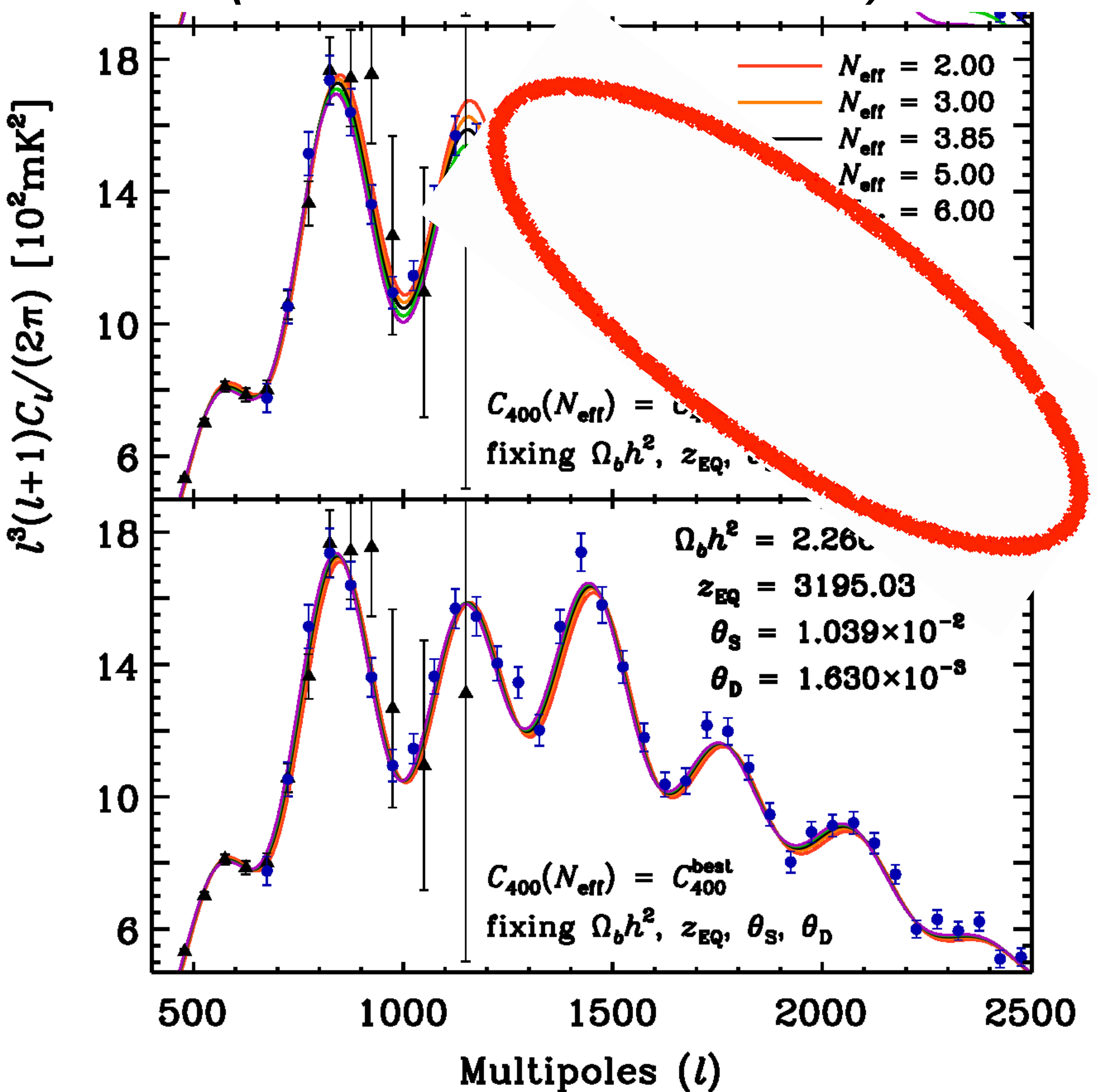
Cosmic Microwave Background in the damping tail, measured by SPT, ACT& Planck:

higher N_{eff} will increase the expansion rate AND the damping at high multipoles.

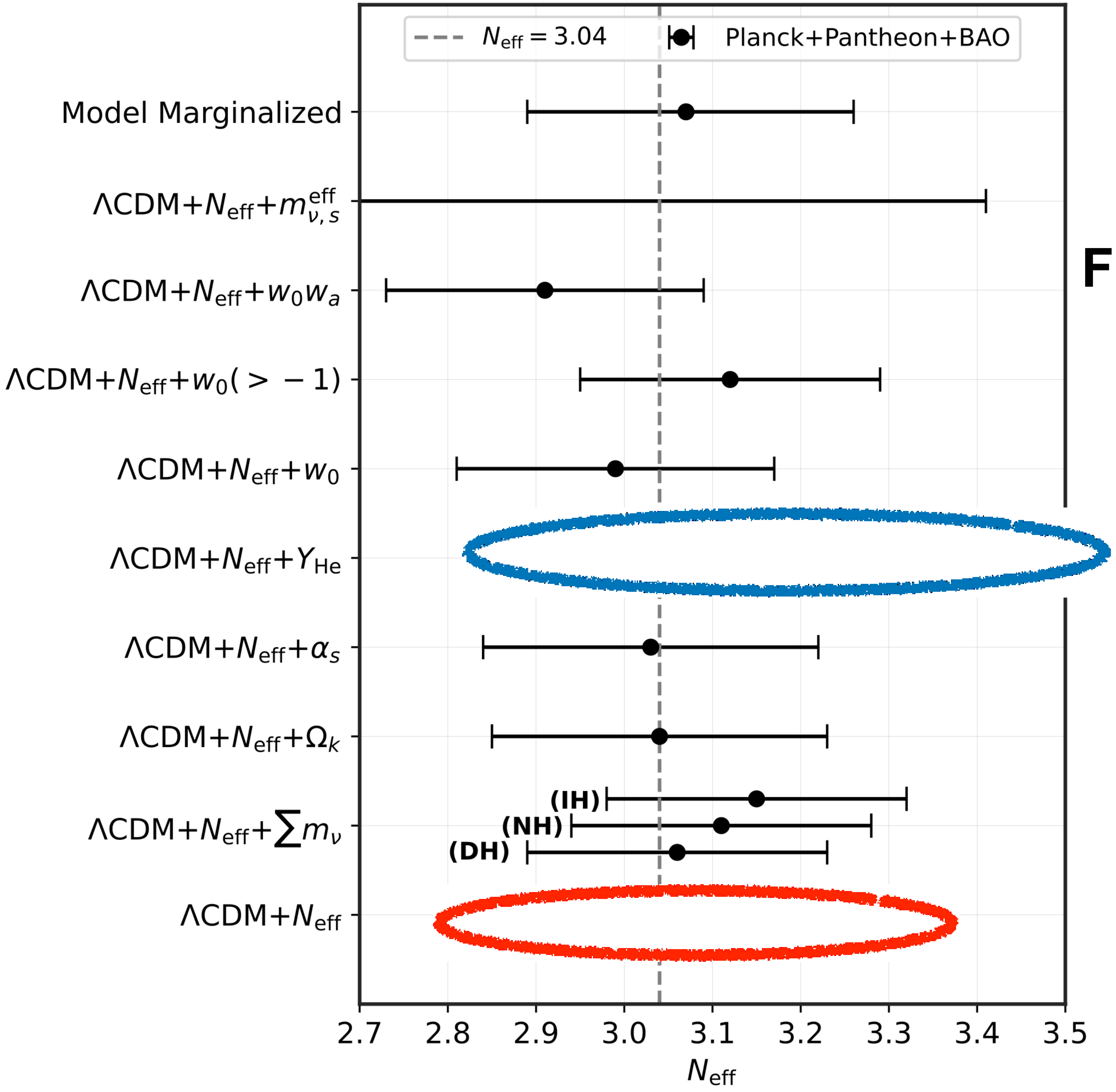


$$r_d^2 \propto \int_0^{a_\star} \frac{da}{a^3 \sigma_T n_e H}$$

(Hou et al, PRD'13)



2023 errors on N_{eff}



Fixing data set to Planck CMB + BAO + SN

$\Lambda CDM \rightarrow N_{\rm eff} = 3.06 \pm 0.36 at 95\% CL$

$+Y_{\rm He} \rightarrow N_{\rm eff} = 3.17^{+0.54}_{-0.62} at 95\% CL$

Courtesy of William Giaré, based on [2207.05167]

THE NEUTRINO MENU

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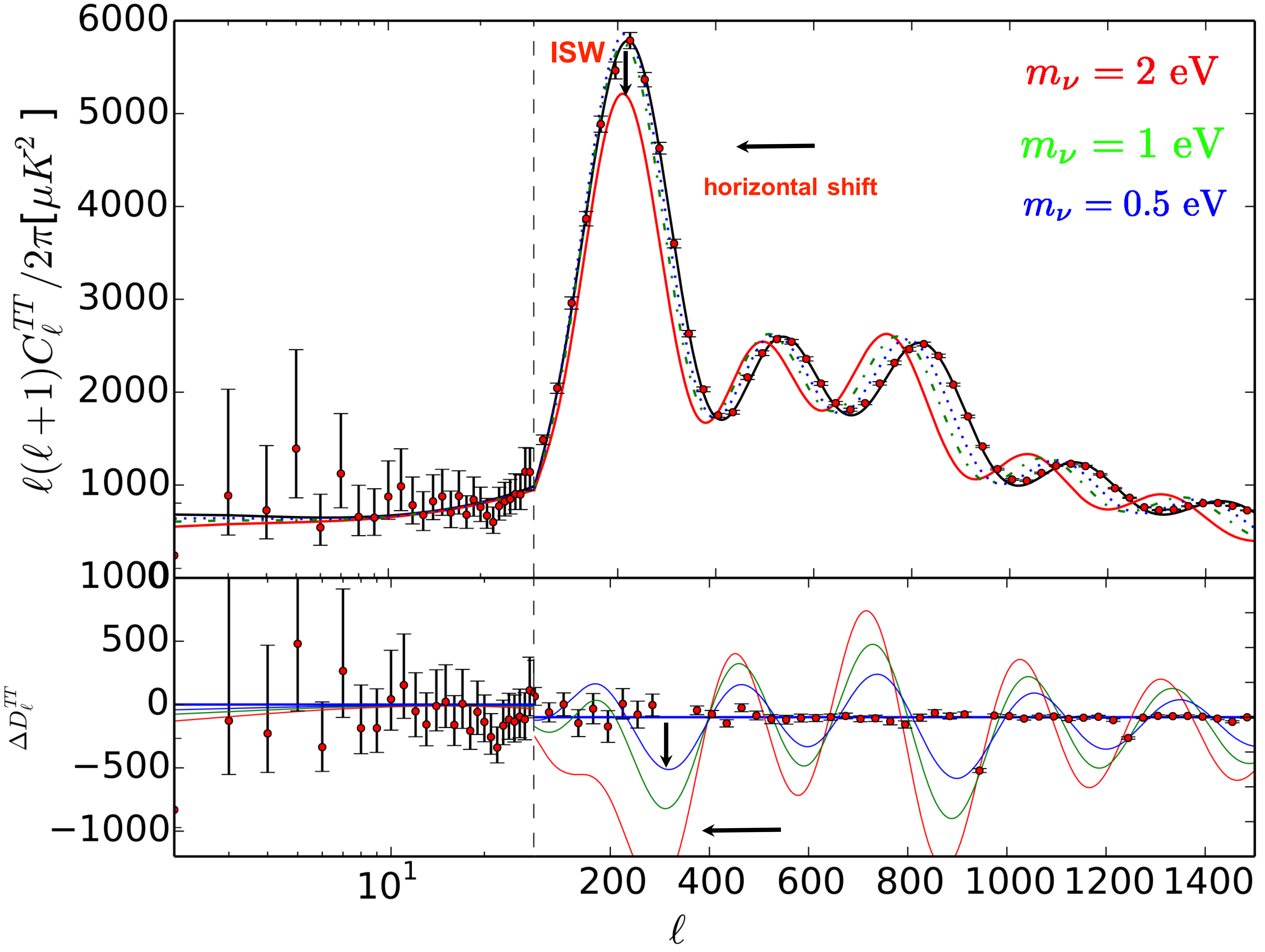
- Expresso: Take home messages

CMB: Σm_ν

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

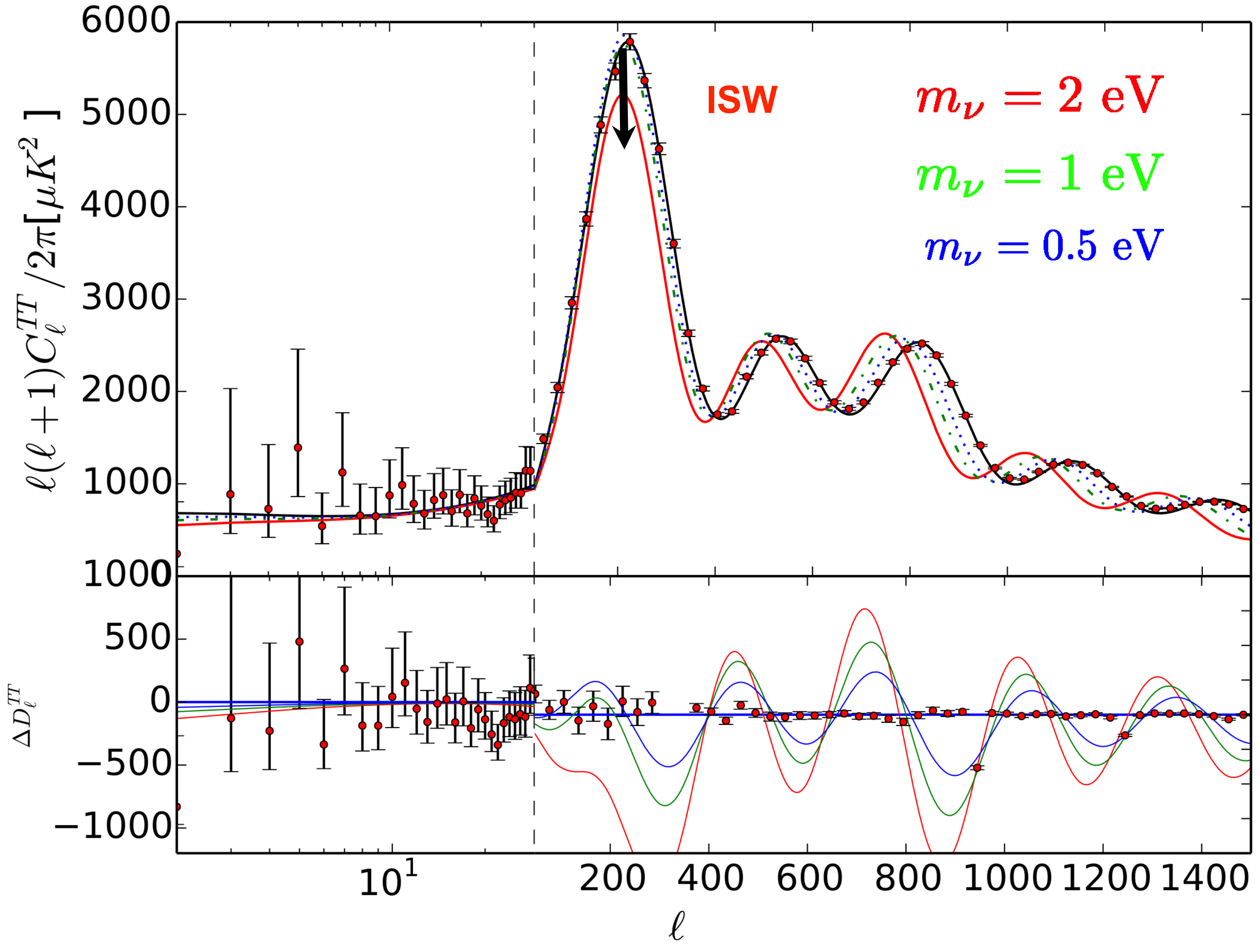


CMB: Σm_ν

Early Integrated Sachs Wolfe effect (ISW)

$$\Theta(\hat{n}) = \frac{\delta T}{T}(\hat{n}) \simeq \Theta_0 + \Psi + \hat{n}(\hat{v}_e - v) + \int$$

In matter domination, the gravitational potential is constant: NO ISW effect!
Transition from the relativistic to the non relativistic regime gets imprinted in the decays of the gravitational potentials, contributing to the ISW effect!



This early ISW effect leads to a depletion:

$$\frac{\Delta C_\ell}{C_\ell} = -\left(\sum m_\nu / 0.1 \text{ eV}\right)\%$$

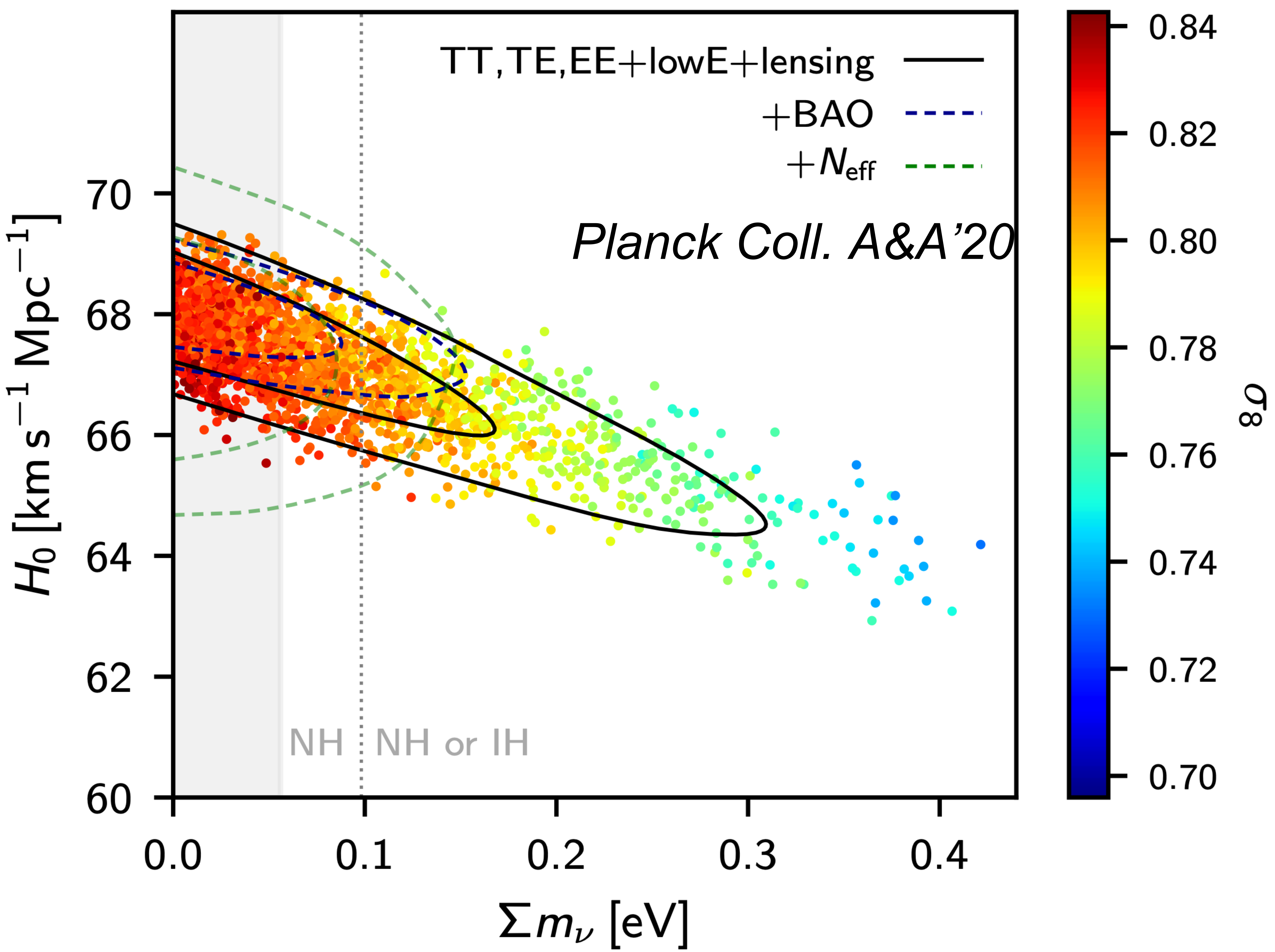
on multipoles:

$$20 < \ell < 200$$

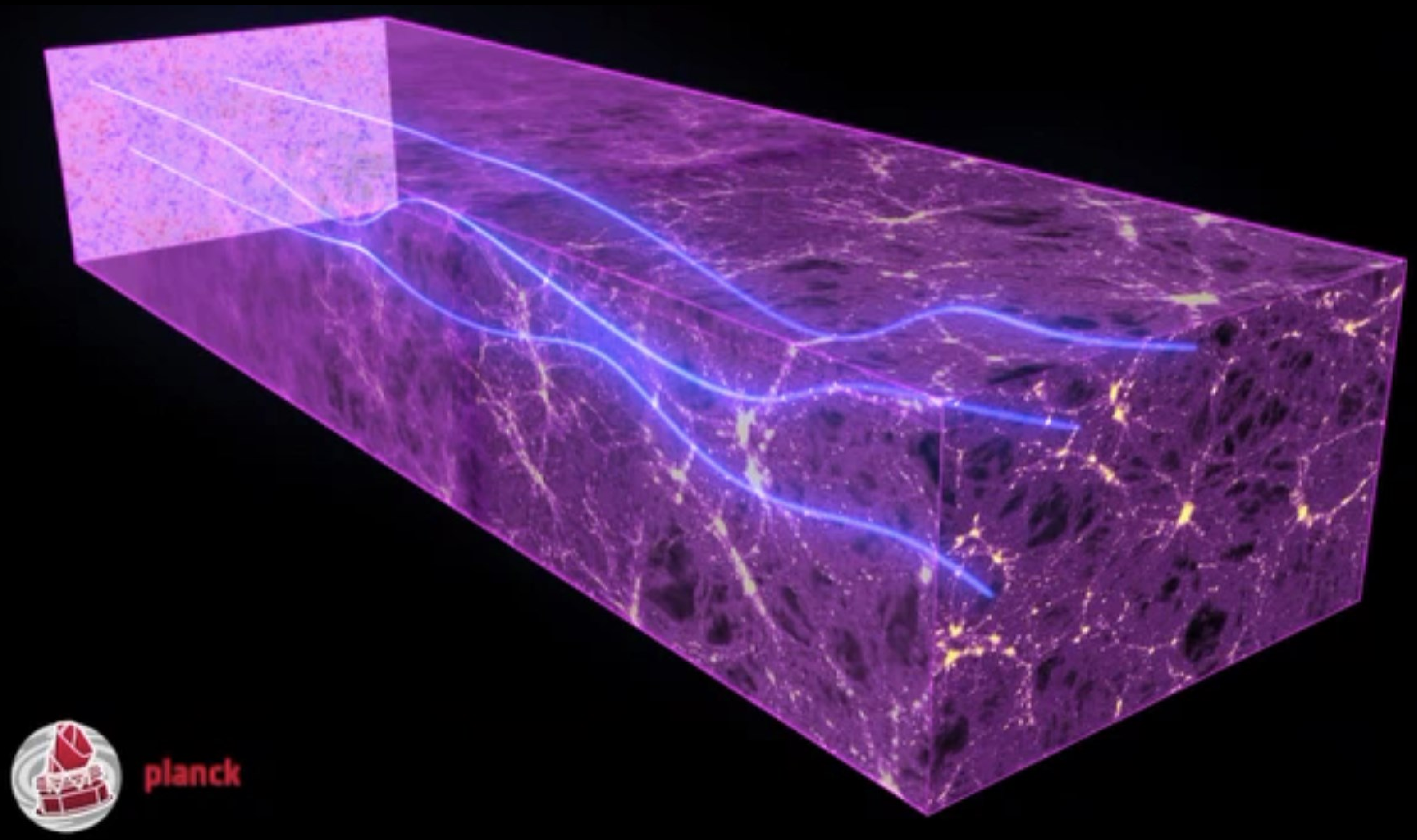
(Lesgourgues & Pastor, Phys.Rept'06)

CANCELLED

Strong degeneracy between Σm_ν and the Hubble constant H_0!



Gravitational Lensing



Credits: ESA and Planck collaborati

CMB Lensing: Σm_ν

Lensing remaps the CMB fluctuations: $\Theta_{\rm lensed}(\hat{n}) = \Theta(\hat{n} + \nabla\phi(\hat{n}))$

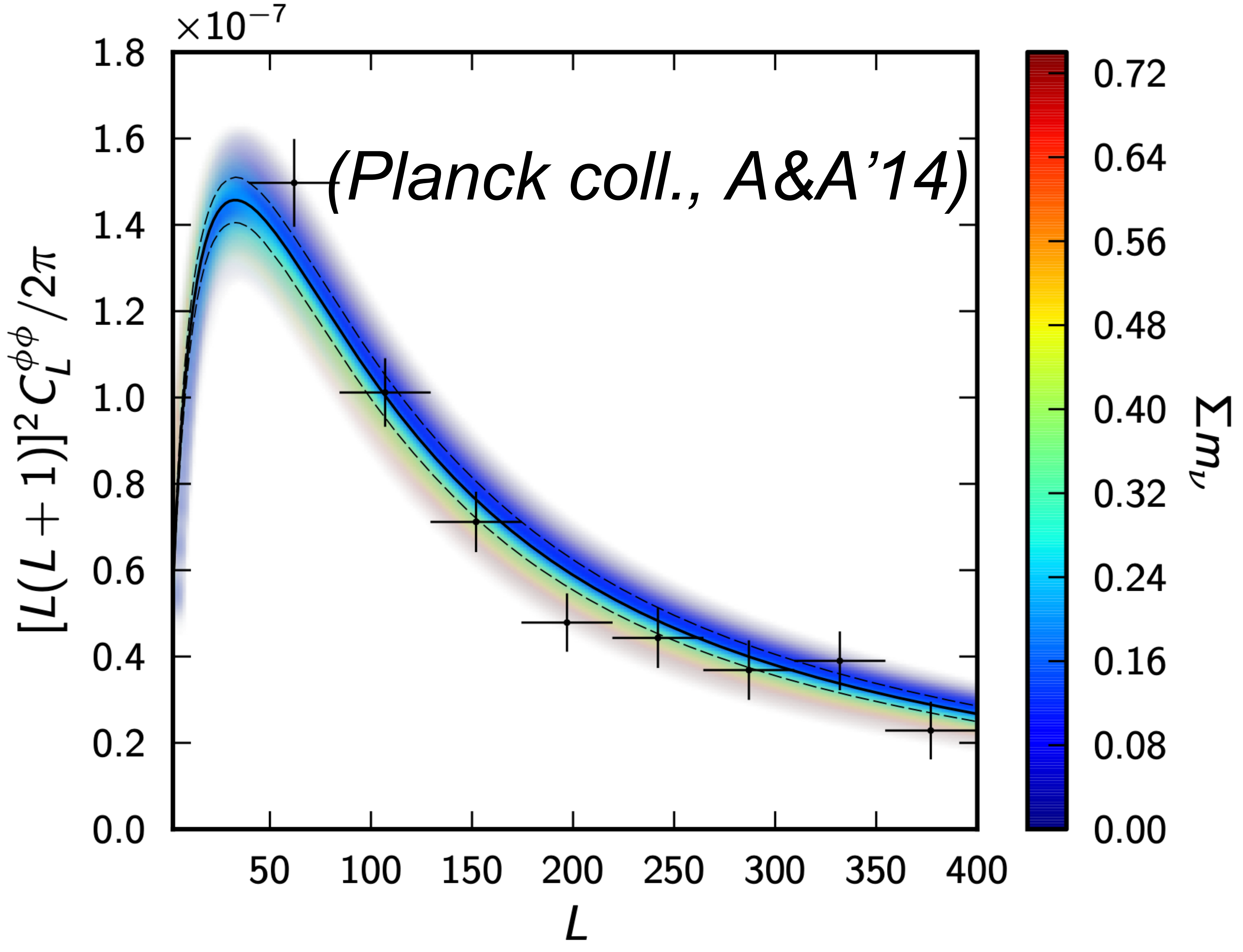
Lensing potential ϕ is a measure of the integrated mass distribution back to the last scattering surface

Matter distribution — Geometry

$$\phi(\hat{n}) = -2\int_0^{z_{rec}} \frac{dz}{H(z)} \Psi(z, D(z)\hat{n}) \left(\frac{D(z_{rec}) - D(z)}{D(z_{rec})D(z)}\right)$$

$$C_L^{\phi\phi} = \frac{8\pi^2}{L^3}\int_0^{z_{rec}} \frac{dz}{H(z)} D(z) \left(\frac{D(z_{rec}) - D(z)}{D(z_{rec})D(z)}\right)^2 P_\Psi(z, k = L/D(z))$$

Neutrinos are hot relics with large thermal velocities, implying less clustering on small scales, reducing CMB lensing!

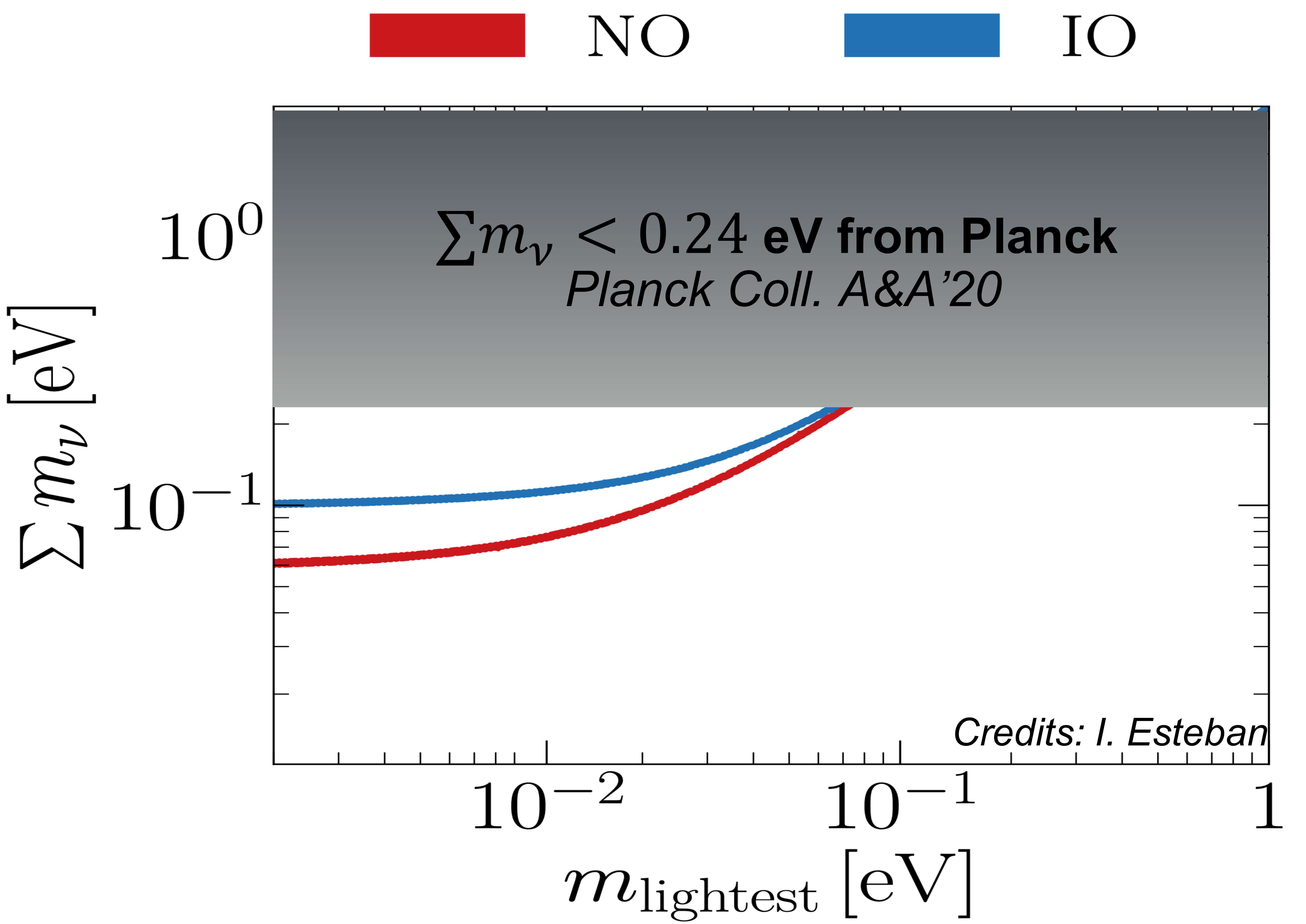


(Kaplinghat et al PRL'03, Lesgourgues et al PRD'06)

2023 CMB bounds on Σm_ν

Planck TTTEEE+lowT+lowE+lensing

$\sum m_\nu < 0.24\, eV$ *95% CL*

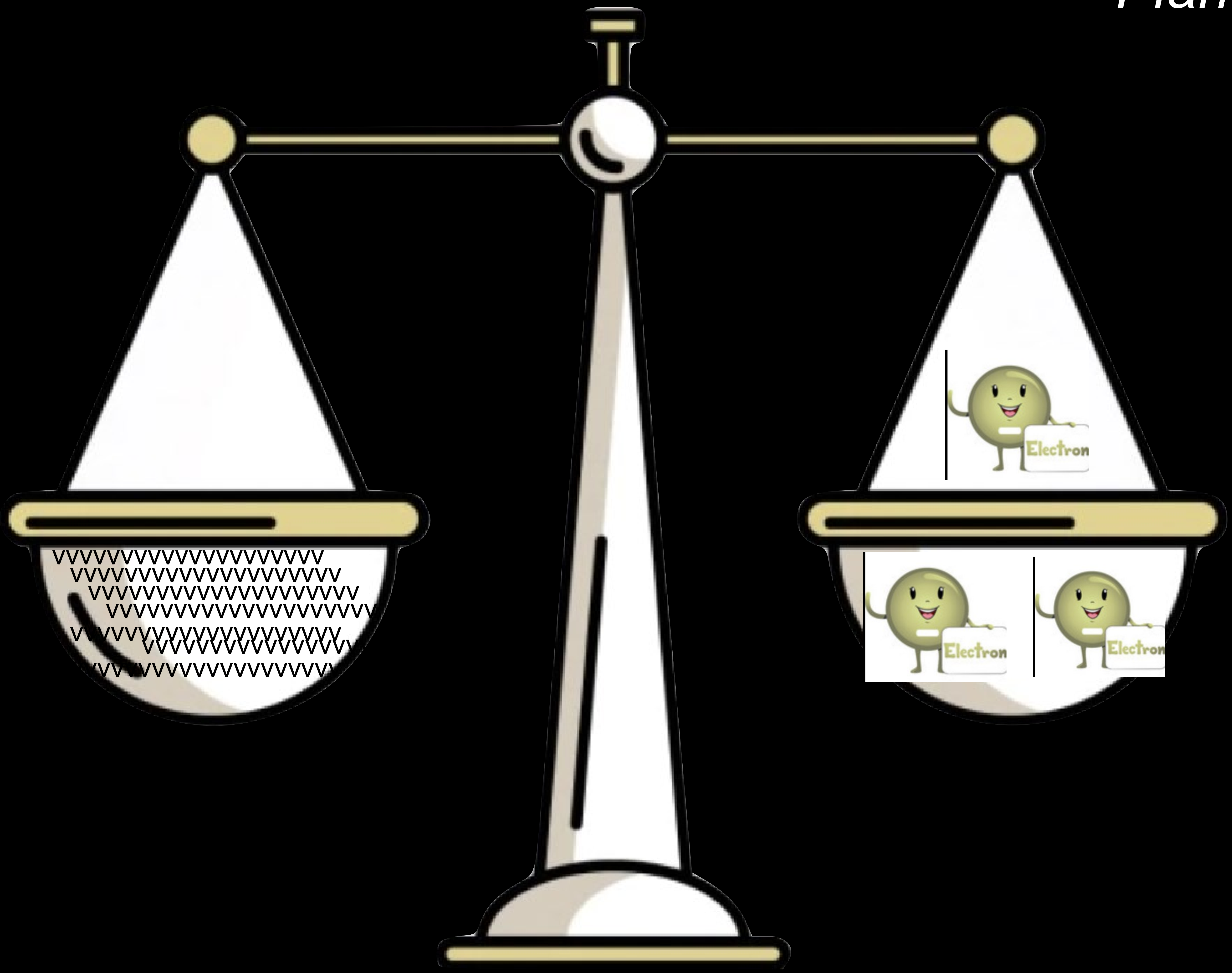


CMB: Σm_ν

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

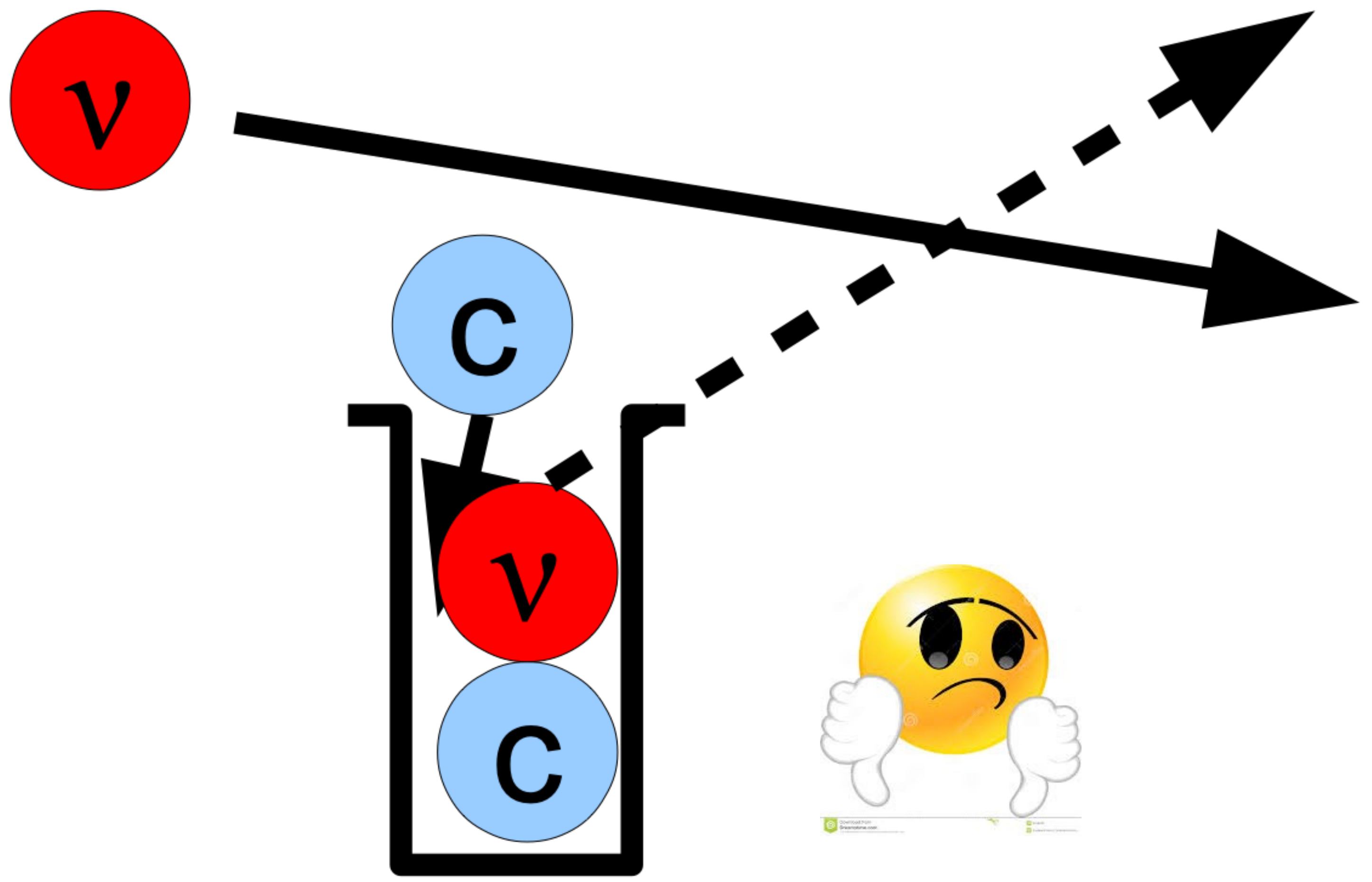
Large scale structure: Σm_ν

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

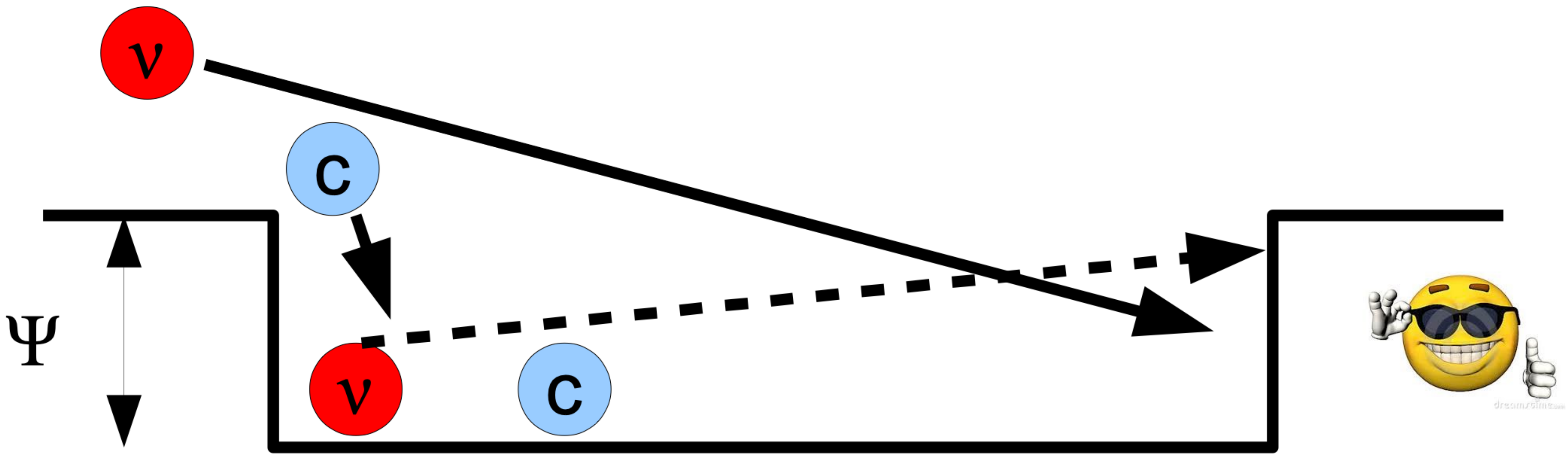
Neutrinos with eV or sub-eV masses are HOT relics with LARGE thermal velocities!

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

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



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



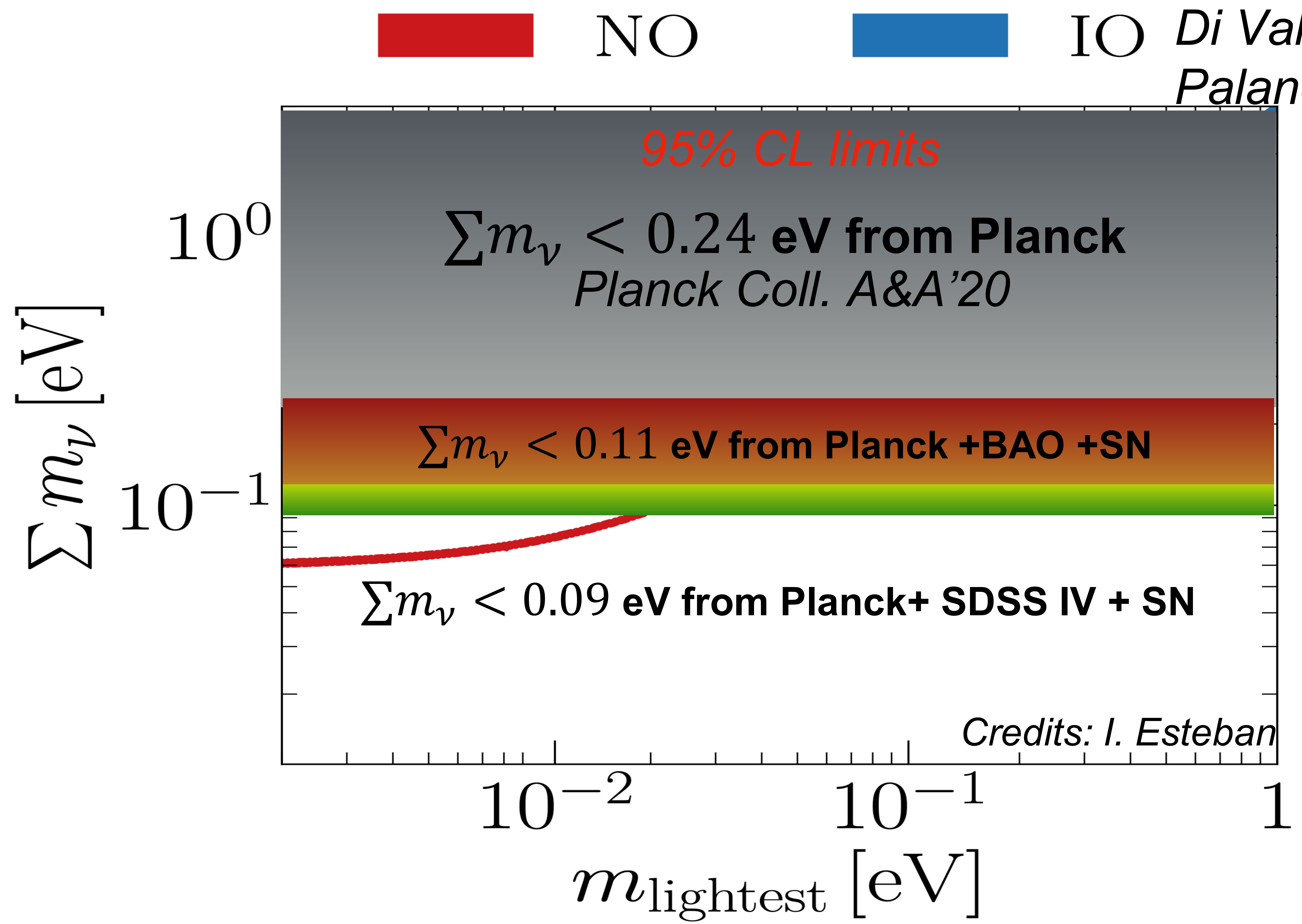
$\lambda \gg \lambda_{fs,\nu} \rightarrow k \ll k_{fs,\nu}$

(From Y. Wong)

2023 Tightest bounds on Σm_ν

Planck+ SDSS-IV (DR16 + DR12) + SN $\sum m_\nu < 0.09\, eV$ *95% CL*

Di Valentino et al PRD'21
Palanque-Delabrouille et al JCAP'2



Tightest bounds on Σm_ν

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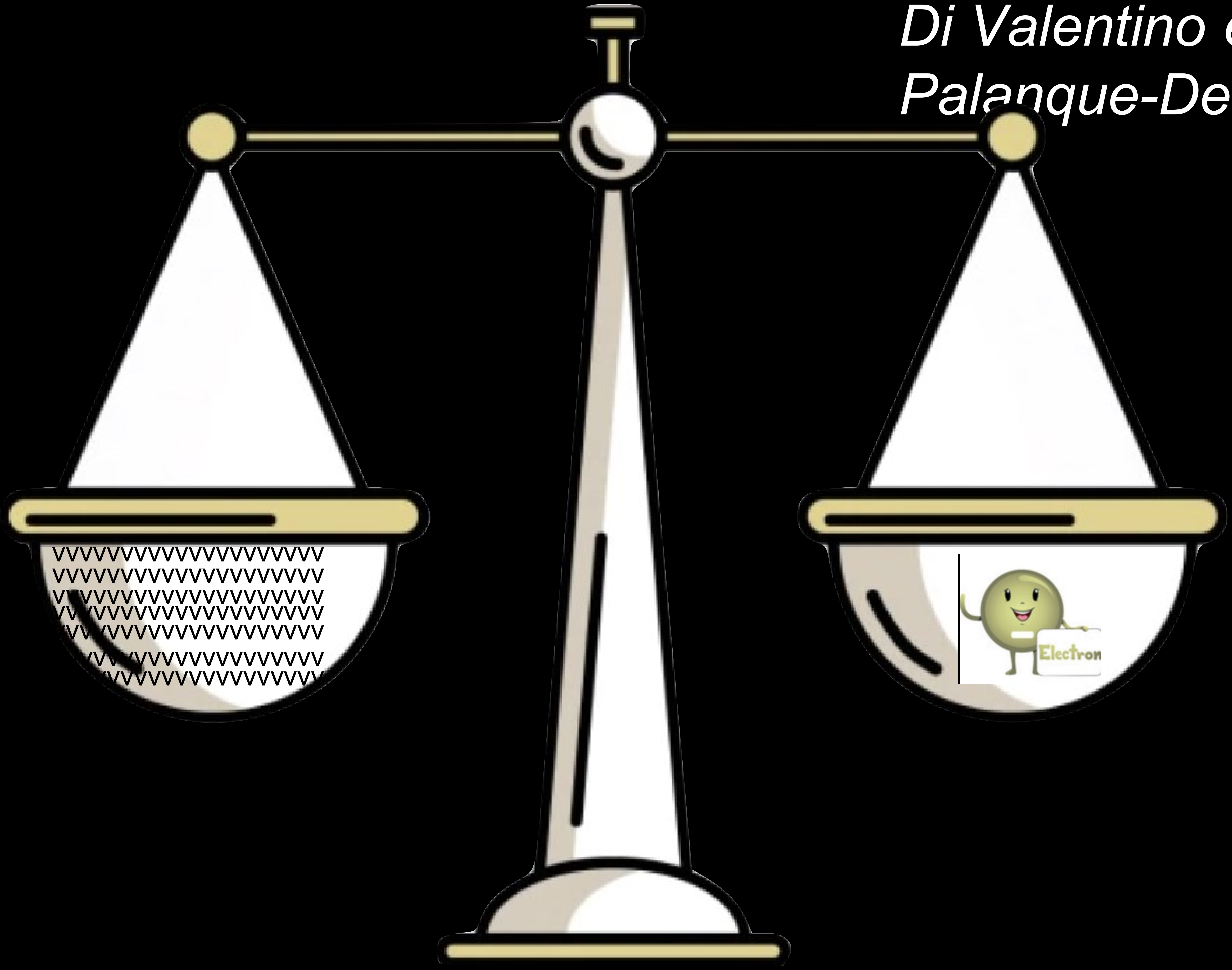
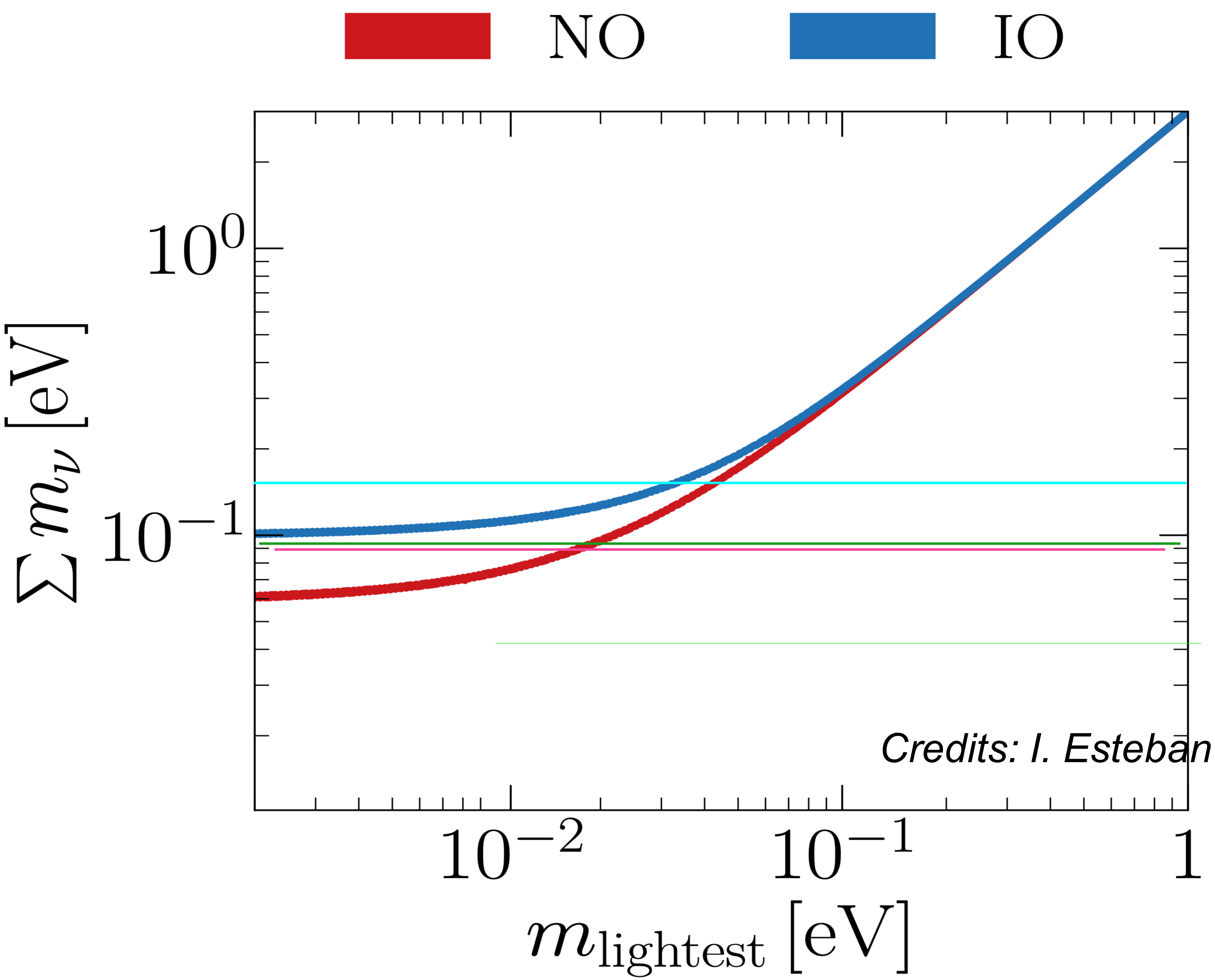
Di Valentino et al PRD’21,
Palanque-Delabrouille et al JCAP’2



6 million neutrinos can't weigh more than 1 electron

2023 Tightest bounds on Σm_ν

Robust: difficult to avoid in close-to-minimal models ("simple" extensions of ΛCDM)



95% CL limits

$\sum m_\nu < 0.14$ **eV with Ω_k and w**

$\sum m_\nu < 0.095$ **eV with N_{eff}**

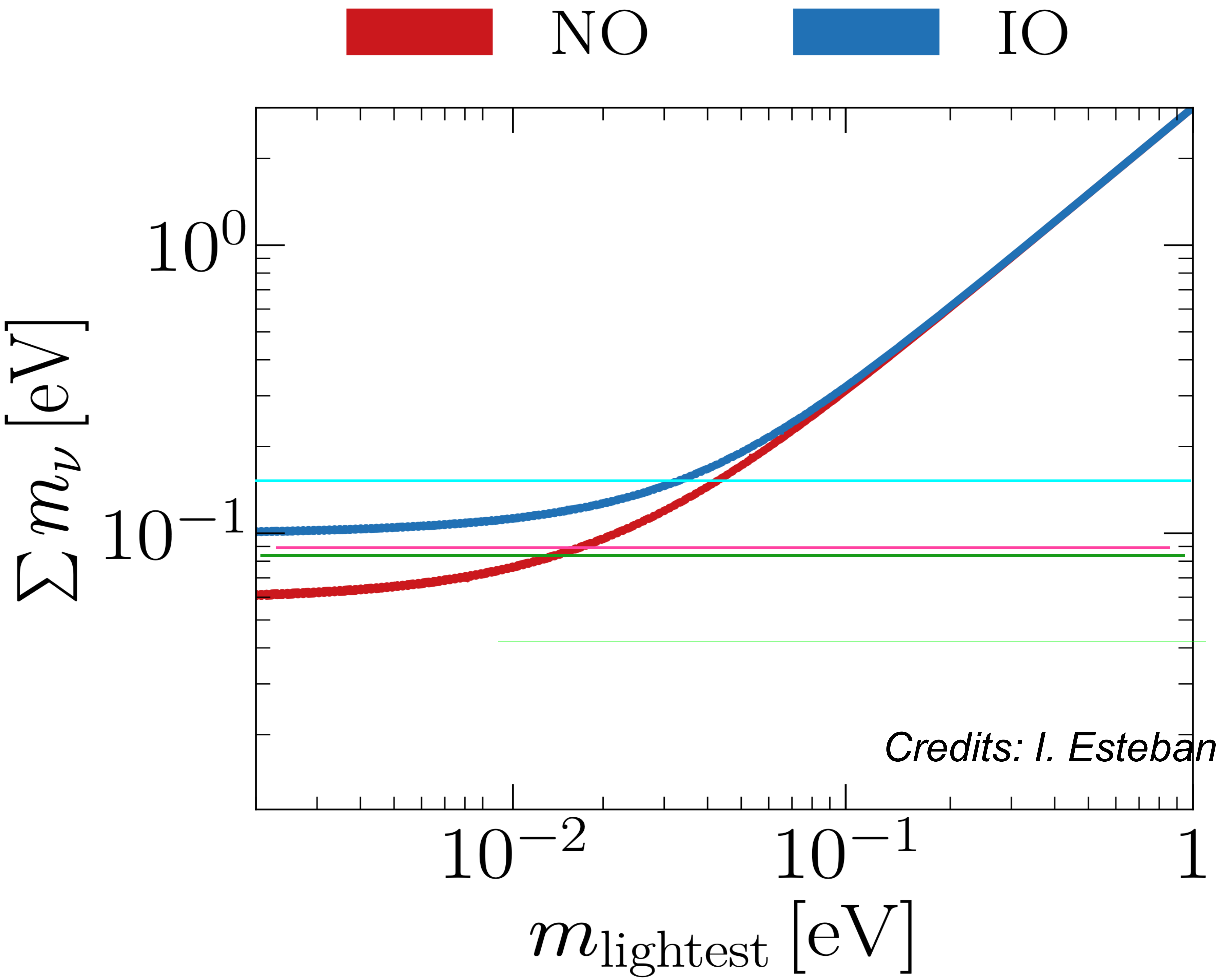
$\sum m_\nu < 0.09$ **eV**

Di Valentino et al PRD'21

Gariazzo & Mena PRD'19

2023 Tightest bounds on Σm_ν

Robust: difficult to avoid in close-to-minimal models ("simple" extensions of ΛCDM)



95% CL limits

$\sum m_\nu < 0.08$ **eV with w (> -1)**

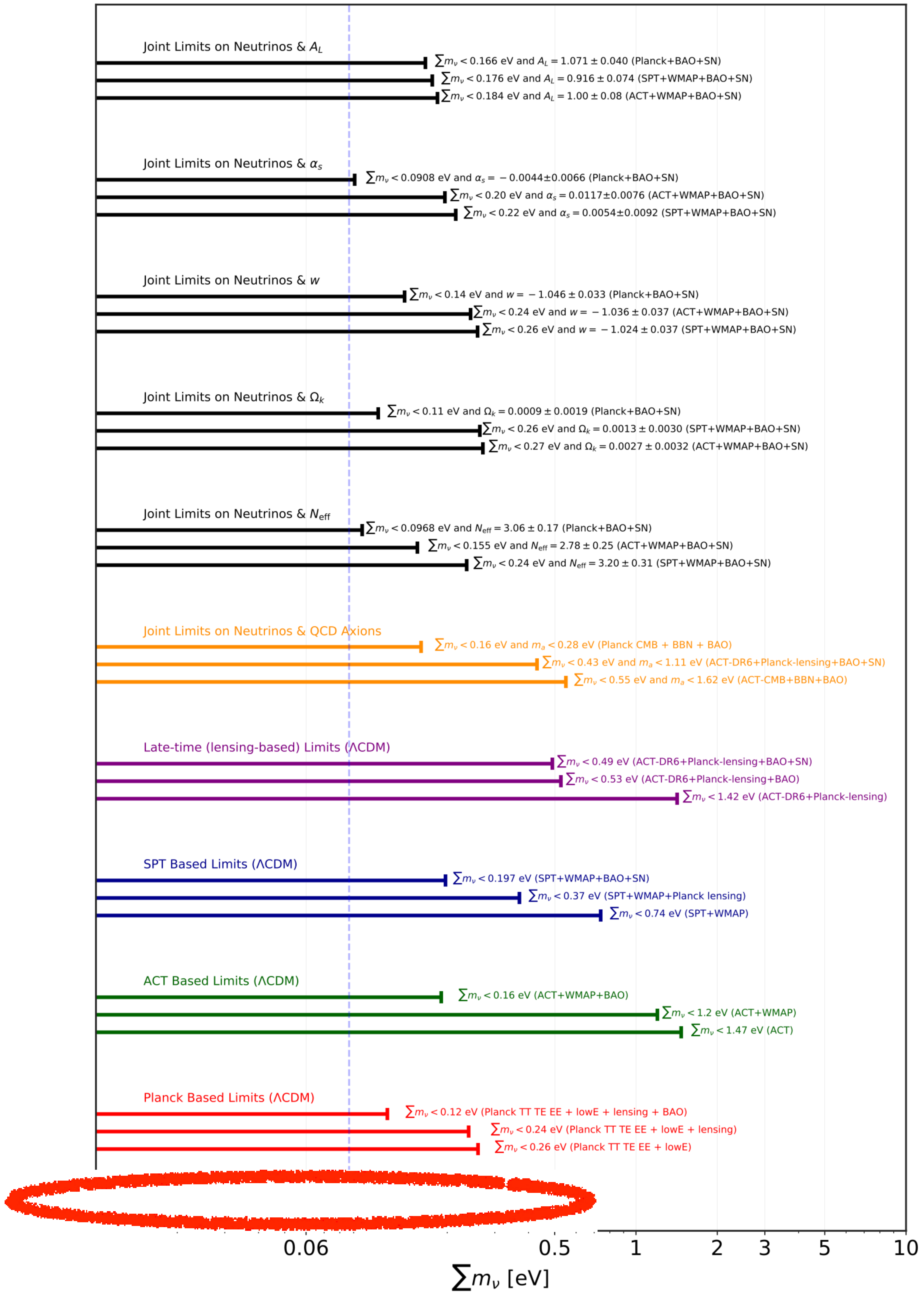
$\sum m_\nu < 0.09$ **eV**

Di Valentino et al PRD'21

Vagnozzi et al PRD'18

Choudhury & Choubey JCAP'18

2023 95% CL bounds on Σmν



Fixing data set to Planck CMB + BAO + SN

$$\Lambda CDM \rightarrow \sum m_\nu < 0.09\, eV\, at 95\%\, CL$$

$$+A_L \rightarrow \sum m_\nu < 0.17\, eV\, at 95\%\, CL$$

Fixing fiducial cosmology to ΛCDM

$$Planck + BAO + SN \rightarrow \sum m_\nu < 0.09\, eV\, at 95\%\, CL$$

$$ACT + WMAP + BAO + SN \rightarrow \sum m_\nu < 0.17\, eV\, at 95\%\, CL$$

Courtesy of Willian Giaré

Model-marginalized bounds on Σm_ν and N_{eff}

Di Valentino et al, PRD'22

Cosmological model		lnBF	$N_{\rm eff}$	$\sum m_\nu$[eV]	Ω_k	α_s	r	$m_{\nu,s}^{\rm eff}$[eV]	$Y_{\rm He}$	w_0
$+\sum m_\nu + N_{\rm eff}$	DH	0.0	3.06 ± 0.17	< 0.0968	–	–	–	–	–	–
	NH	1.79	3.11 ± 0.17	< 0.131	–	–	–	–	–	–
	IH	3.31	3.15 ± 0.17	< 0.163	–	–	–	–	–	–
$+\sum m_\nu + N_{\rm eff} + \Omega_k$	DH	4.63	3.02 ± 0.19	< 0.112	0.0011 ± 0.0021	–	–	–	–	–
	NH	6.34	3.05 ± 0.18	< 0.149	0.0019 ± 0.0021	–	–	–	–	–
	IH	7.34	3.06 ± 0.19	< 0.179	0.0025 ± 0.0022	–	–	–	–	–
$+\sum m_\nu + N_{\rm eff} + \alpha_s$	DH	4.76	2.98 ± 0.19	< 0.0892	–	-0.0057 ± 0.0077	–	–	–	–
	NH	6.59	3.06 ± 0.19	< 0.129	–	-0.0041 ± 0.0075	–	–	–	–
	IH	8.15	3.11 ± 0.19	< 0.161	–	-0.0036 ± 0.0076	–	–	–	–
$+\sum m_\nu + N_{\rm eff} + m_{\nu,s}^{\rm eff}$	DH	4.16	< 3.39	< 0.0901	–	–	–	< 0.304	–	–
	NH	6.06	< 3.43	< 0.130	–	–	–	< 0.280	–	–
	IH	7.72	< 3.45	< 0.159	–	–	–	< 0.247	–	–
$+\sum m_\nu + N_{\rm eff} + w_0$	DH	3.11	2.99 ± 0.18	< 0.124	–	–	–	–	–	-1.047 ± 0.034
	NH	4.39	3.00 ± 0.18	< 0.165	–	–	–	–	–	-1.061 ± 0.034
	IH	5.24	3.02 ± 0.18	< 0.194	–	–	–	–	–	-1.071 ± 0.035
$+\sum m_\nu + N_{\rm eff} + (w_0 > -1)$	DH	5.23	3.08 ± 0.17	< 0.0894	–	–	–	–	–	< -0.959
	NH	6.90	3.14 ± 0.17	< 0.130	–	–	–	–	–	< -0.963
	IH	8.58	3.17 ± 0.17	< 0.159	–	–	–	–	–	< -0.967
model marginalized										

THE NEUTRINO MENU

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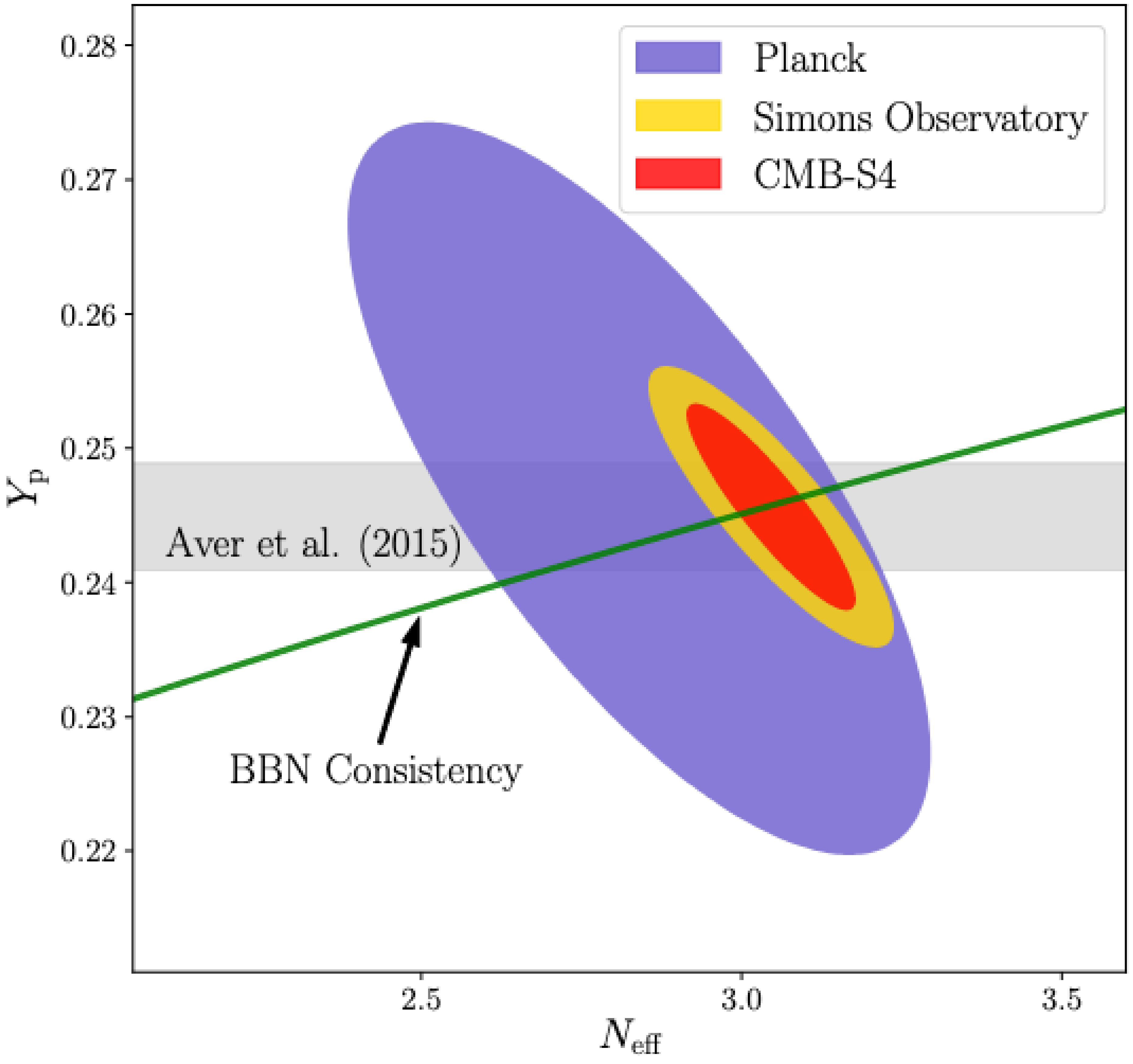
20XX, with X > 2 (X>>2?), N_{eff} status

$$\Delta N_{\rm eff} < 0.06 \ 95\%{\rm CL}$$

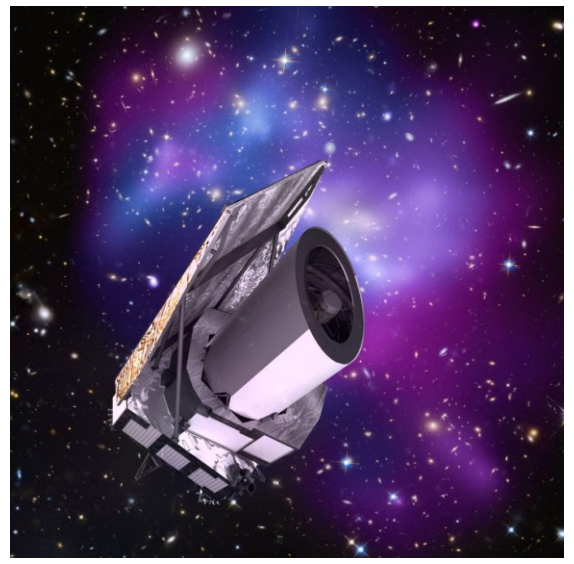


CMB-S4 Science Case, 1907.04473

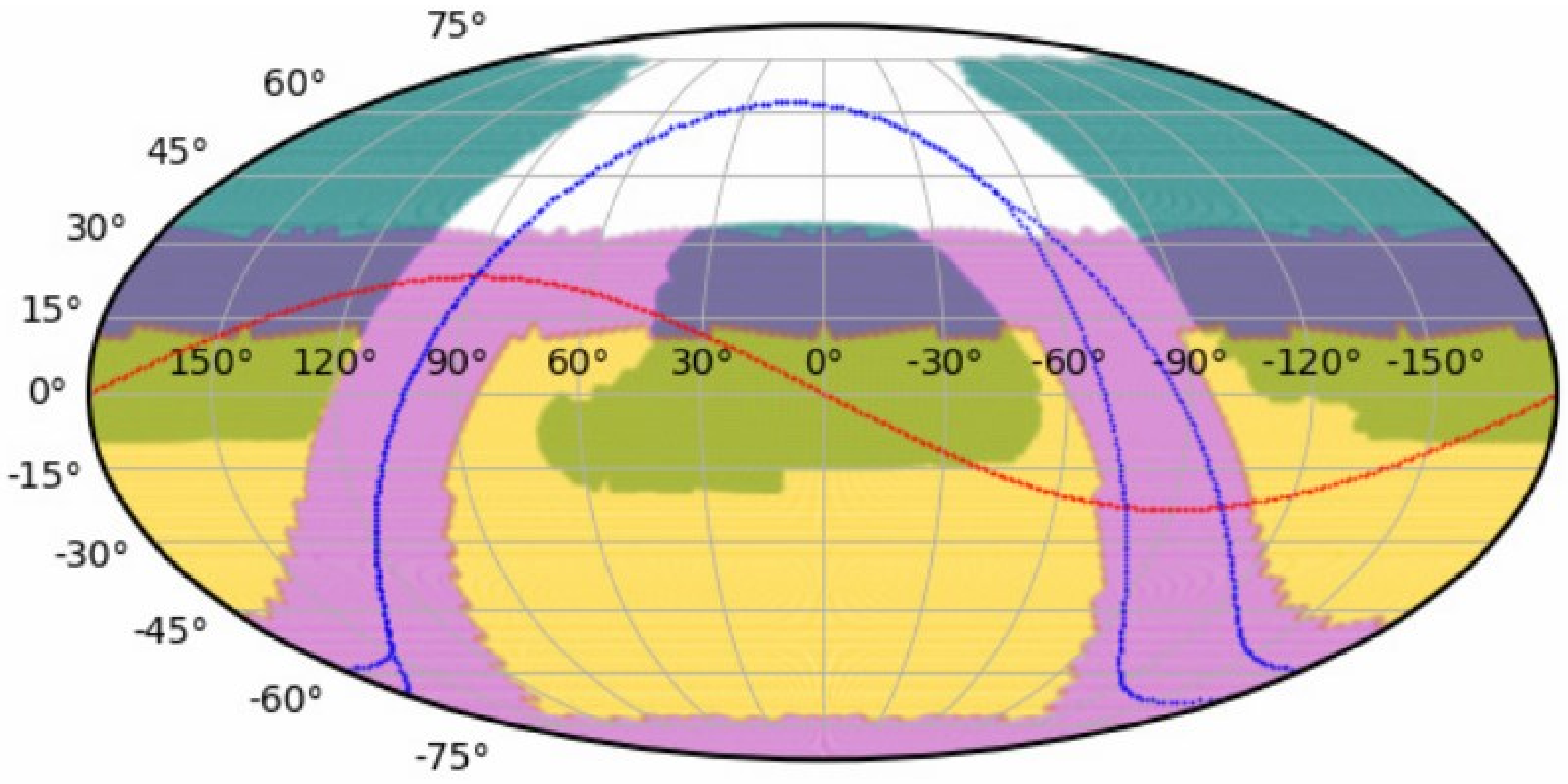
M. Gerbino & M. Lattanzi, Front. in Physics'18

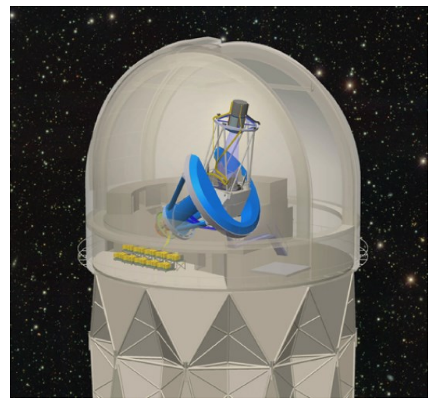
CORE TT,TE,EE,PP [a]	$\Delta N_{\rm eff} < 0.040$
CORE TT,TE,EE,PP [b]	$N_{\rm eff} = 3.045 \pm 0.041$
S4 TT,TE,EE,PP [c]	
CORE TT,TE,EE,PP+DESI BAO+Euclid BAO [a]	$\Delta N_{\rm eff} < 0.038$
CORE TT,TE,EE,PP+DESI BAO+Euclid BAO [b]	$N_{\rm eff} = 3.046 \pm 0.039$

202X, with 3 < X < 9, absolute neutrino mass status



Euclid Coll.
IAU Symp’14
Talk by Rene Laureijs

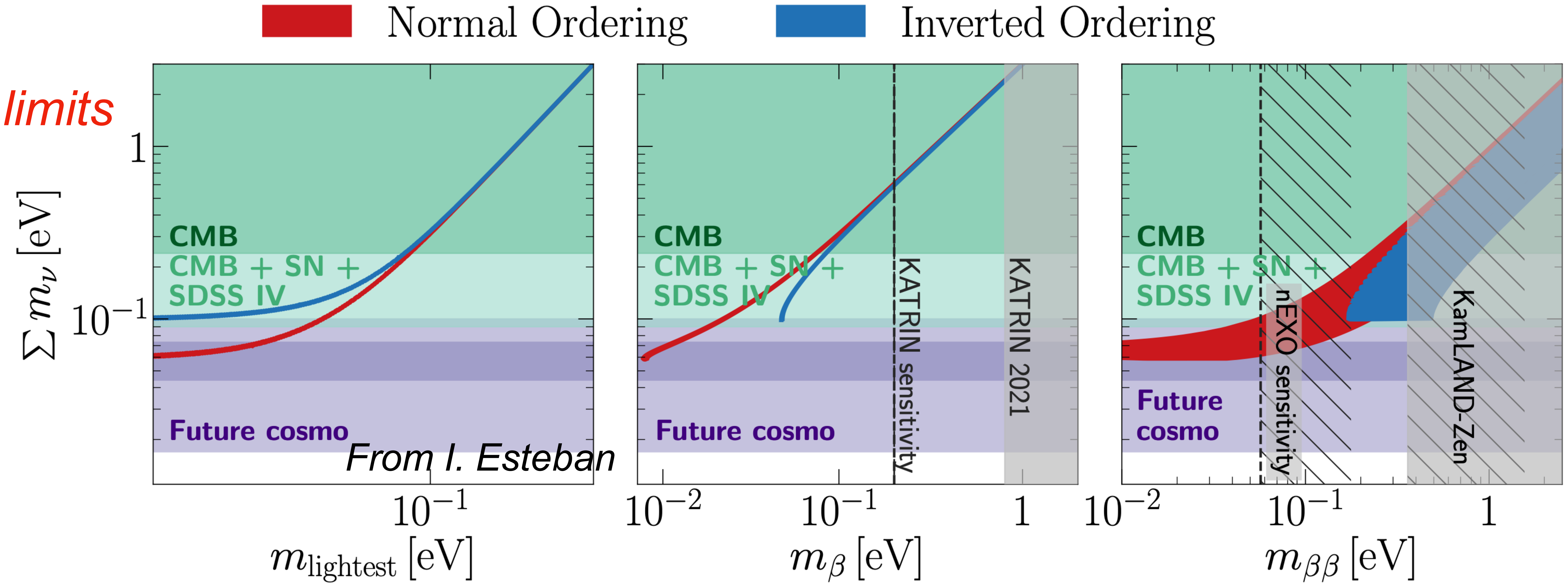




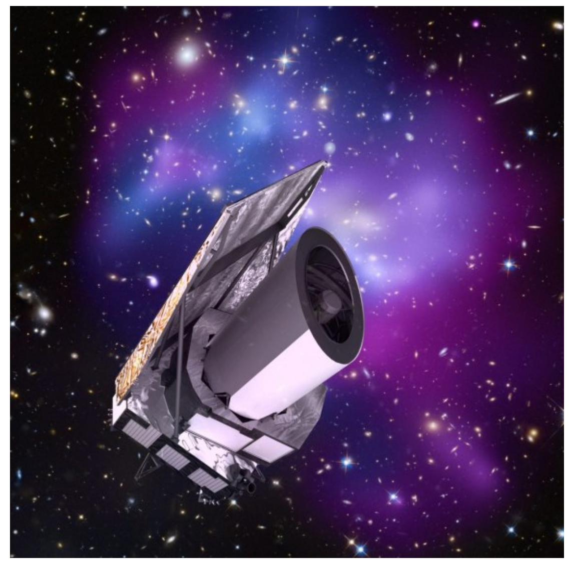
Olsen et al’18

Talks by S. Petcov, S. Parke, M. Agostini and E. Lisi

95% CL limits

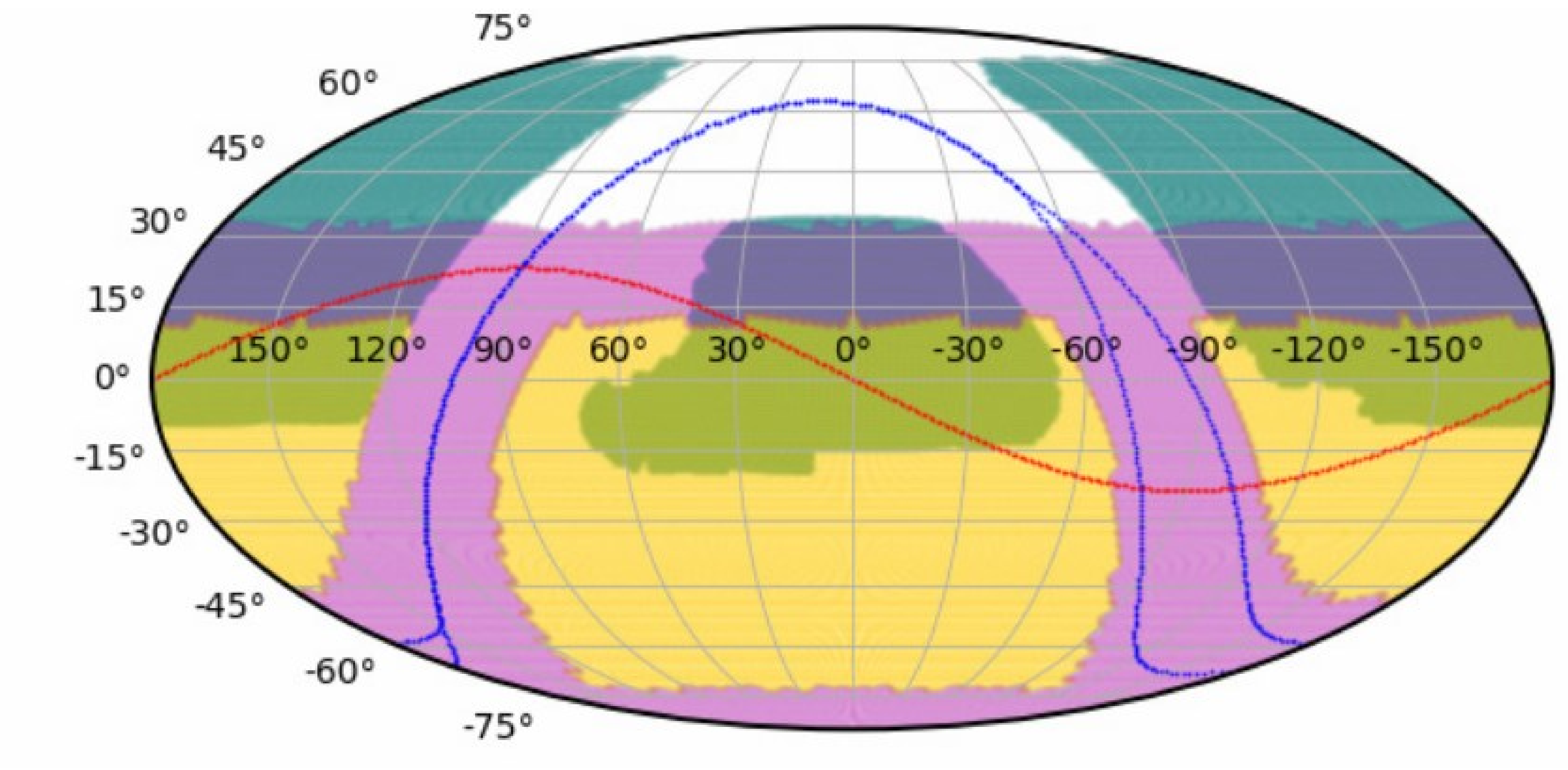


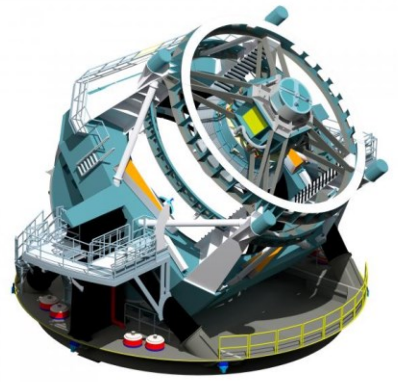
20XX, with X > 2 (X>>2?), absolute neutrino mass status

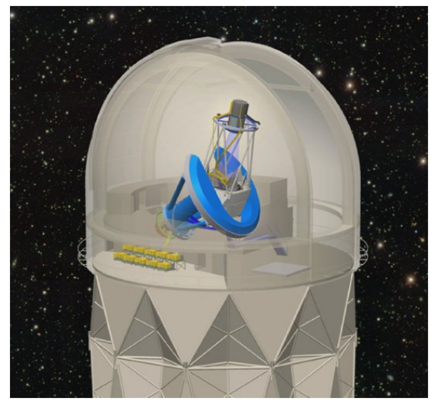


Euclid Coll. IAU Symp'14

Talk by Rene Laureijs







Olsen et al'18

Dataset	$\sigma(\Sigma m_\nu)$[meV]
CORE TT,TE,EE,PP	44
S4 TT,TE,EE,PP	73
CORE TT,TE,EE,PP+DESI	21
S4 TT,TE,EE,PP[b]+DESI	15
Planck CMB+LSST-shear	30[c]
Planck+Euclid-FS	40
Stage-III CMB (ACTPol)+WFIRST BAO+FS	30
Stage-III CMB+WFIRST+Euclid+LSST	8

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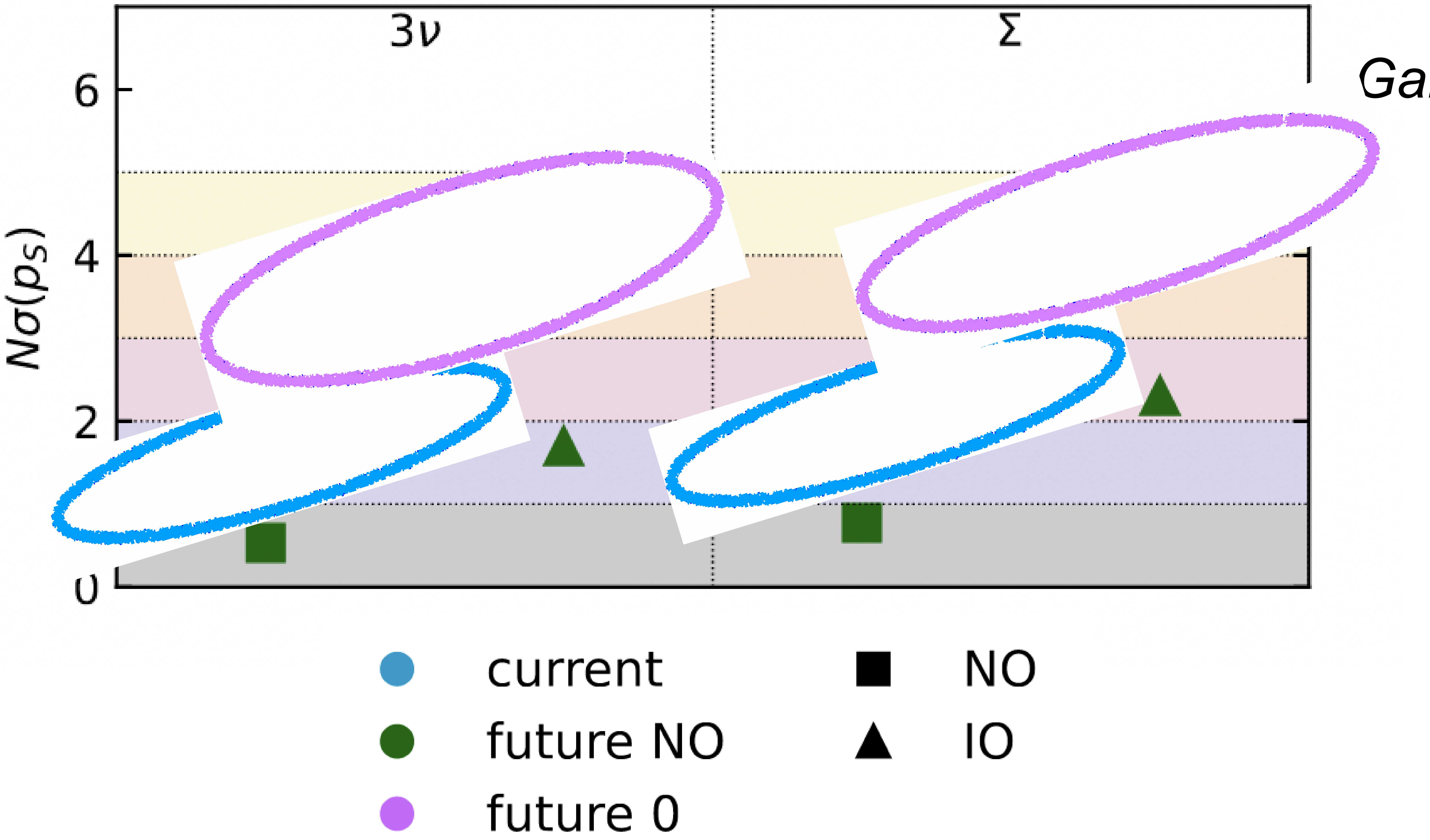
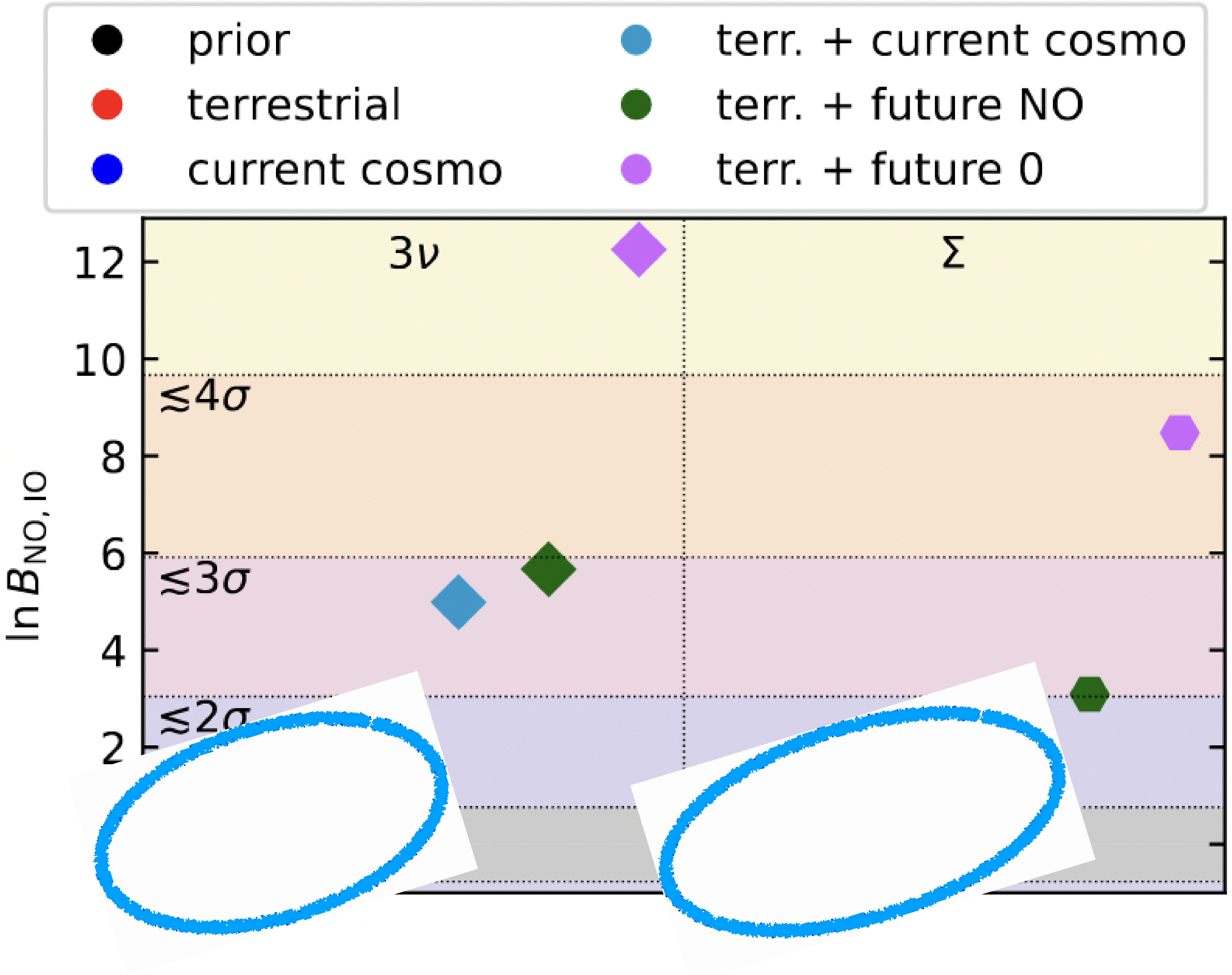
Potential tension between terrestrial and cosmological bounds?



Gariazzo et al PDU'23

Currently, only modest tension between cosmology and terrestrial data.
If future cosmological measurements do not find evidence for **Σm_ν**,
tension with terrestrial data: 2 − 3σ (NO) & 4σ (IO)

Mass ordering status and perspectives



Gariazzo et al PDU'23

If future cosmology finds $\sum m_\nu = 0.06 \pm 0.02$eV:3σ tension with Inverted Ordering


What if?

A tension is also found in the NO case?
Or beta/neutrinoless decay detect a signal but cosmology prefers Σm_ν=0?

Neutrino decays
Long-range neutrino interactions
Time-dependent neutrino masses
Non ideal-gas fluids
……………
Keep thinking in other mechanisms!

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- N_{eff} @CMB: Silk damping & N_{eff} @BBN: Light element (^{4}He) abundances.
- $N_{\rm eff} = 2.99^{+0.34}_{-0.33}$ (95% CL) from Planck TTTEEE+lensing+BAO, perfectly consistent with BBN determinations.
- 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".
- Tightest bound: $\Sigma\, m_\nu < 0.09$eV (95% CL) Planck TTTEEE+lensing+BAO+SN
- Cosmological limits on neutrino properties: EXTREMELY ROBUST.
- Future weak lensing and galaxy surveys may measure the neutrino mass hierarchy and detect both the minimum neutrino mass and the small theoretical deviation of N_{eff} from 3.
- Crucial to confront future cosmological mass limits with neutrino oscillation results to constrain BSM interactions in the invisible sector.