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Neutrino mass bounds from cosmology

The 8th Shanghai Symposium on Particle Physics and Cosmology, TLDI
Shanghai, 14/11/2024

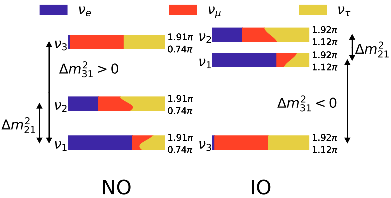
1 ***Neutrino masses***

2 *Neutrino masses in cosmology*

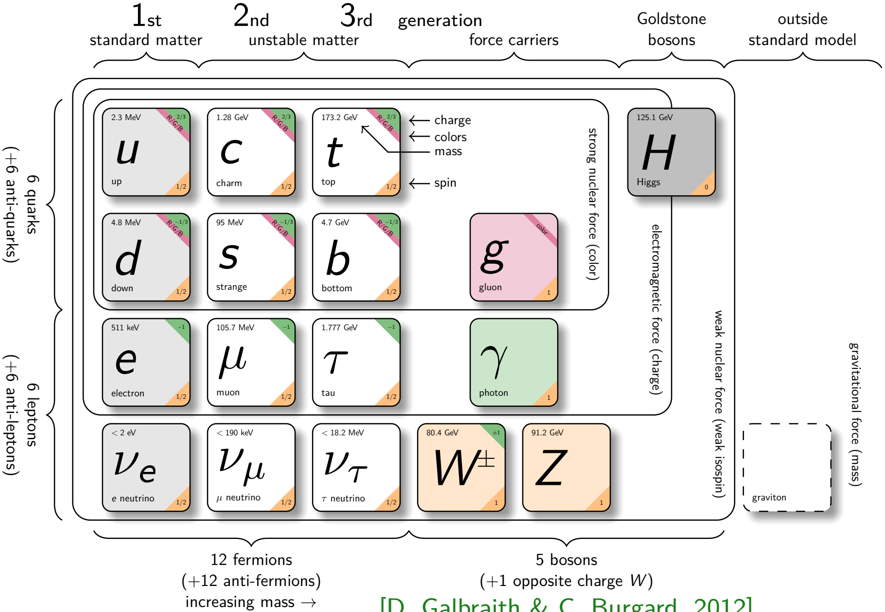
3 *Constraining neutrino masses*

4 *Constraining the mass ordering*

5 *Conclusions*



The Standard Model of Particle Physics



[D. Galbraith & C. Burgard, 2012]

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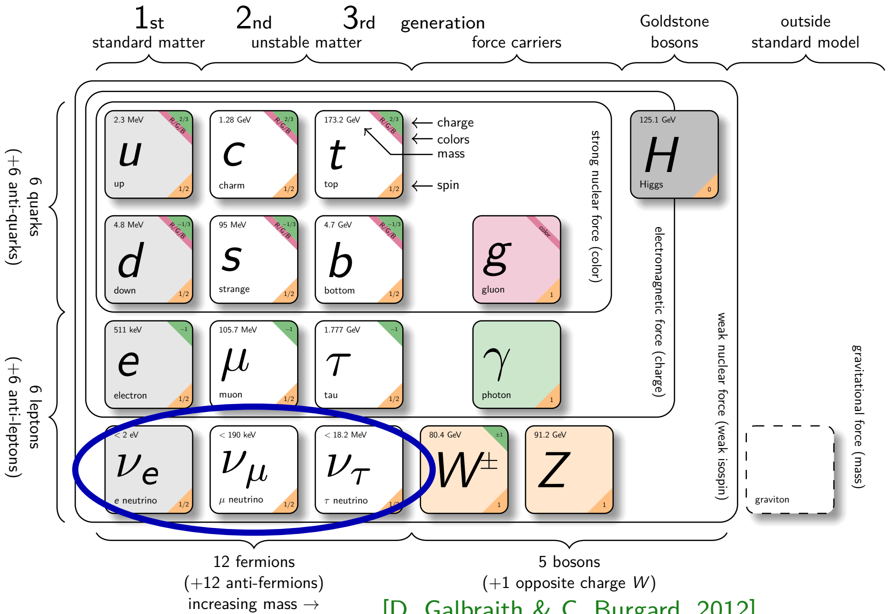
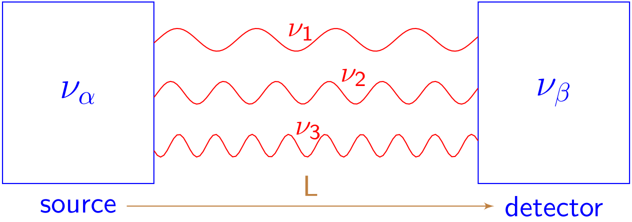


[D. Galbraith & C. Burgard, 2012]

Two neutrino bases

flavor neutrinos ν_α | $|\nu_\alpha\rangle = \sum_k U_{\alpha k}|\nu_k\rangle$ | massive neutrinos ν_k

$$|\nu(t=0)\rangle = |\nu_\alpha\rangle = U_{\alpha 1}|\nu_1\rangle + U_{\alpha 2}|\nu_2\rangle + U_{\alpha 3}|\nu_3\rangle$$



$$|\nu(t>0)\rangle = |\nu_\beta\rangle = U_{\alpha 1}\, e^{-iE_1 t}|\nu_1\rangle + U_{\alpha 2}\, e^{-iE_2 t}|\nu_2\rangle + U_{\alpha 3}\, e^{-iE_3 t}|\nu_3\rangle \neq |\nu_\alpha\rangle$$

$E_k^2 = p^2 + m_k^2 \longleftarrow$ define $\longrightarrow t = L$

$$\boxed{P_{\nu_\alpha \to \nu_\beta}(L) = |\langle \nu_\alpha|\nu(L)\rangle|^2 = \sum_{k,j} U_{\beta k} U^*_{\alpha k} U^*_{\beta j} U_{\alpha j} \exp\left(-i\frac{\Delta m^2_{kj} L}{2E}\right)}$$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

Three Neutrino Oscillations

$$\nu_\alpha = \sum_{k=1}^{3} U_{\alpha k}\nu_k \quad (\alpha = e, \mu, \tau)$$

$U_{\alpha k}$ described by 3 mixing angles θ_{12}, θ_{13}, θ_{23} and one CP phase δ

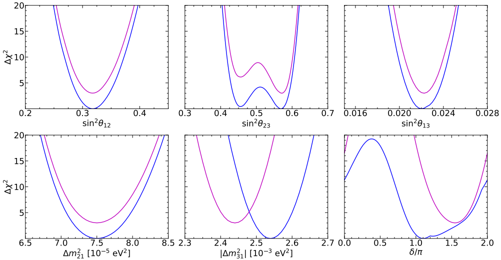
Current knowledge of the 3 active ν mixing: [JHEP 02 (2021) update]

NO/NH: Normal Ordering/Hierarchy, $m_1 < m_2 < m_3$ IO/IH: Inverted O/H, $m_3 < m_1 < m_2$

$$\begin{aligned} \Delta m^2_{21} &= (7.50^{+0.22}_{-0.20}) \cdot 10^{-5}\ \mathrm{eV}^2 \\ |\Delta m^2_{31}| &= (2.54 \pm 0.03) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO}) \\ &= (2.44 \pm 0.03) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO}) \end{aligned}$$

$$\begin{aligned} 10\sin^2(\theta_{12}) &= 3.18 \pm 0.16 \\ 10^2\sin^2(\theta_{13}) &= 2.200^{+0.069}_{-0.062}\ (\mathrm{NO}) \\ &= 2.225^{+0.064}_{-0.070}\ (\mathrm{IO}) \\ 10\sin^2(\theta_{23}) &= 4.55 \pm 0.13 \cup 5.71 \pm 0.12\ (\mathrm{NO}) \\ &= 5.71^{+0.14}_{-0.17}\ (\mathrm{IO}) \end{aligned}$$

$$\begin{aligned} \delta/\pi &= 1.10^{+0.27}_{-0.12}\ (\mathrm{NO}) \\ &= 1.54 \pm 0.14\ (\mathrm{IO}) \end{aligned}$$



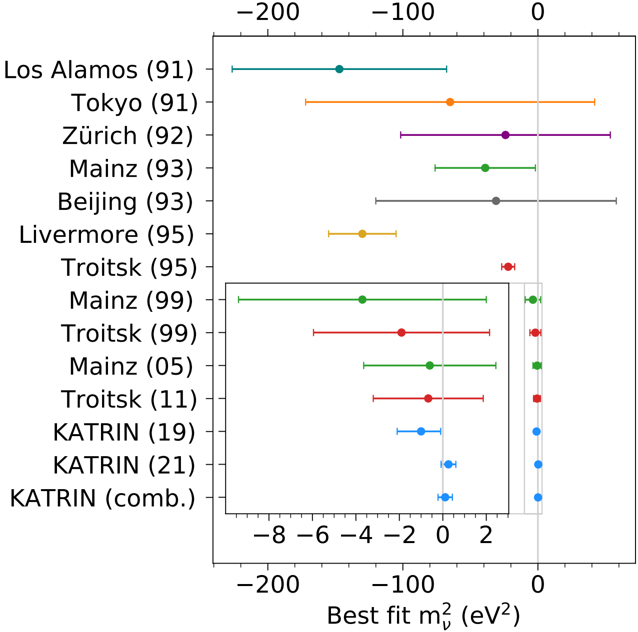
mass ordering still unknown

δ still unknown

see also: `http://globalfit.astroparticles.es`

Absolute neutrino mass scale

[KATRIN 2022 and arxiv:2406.13516]



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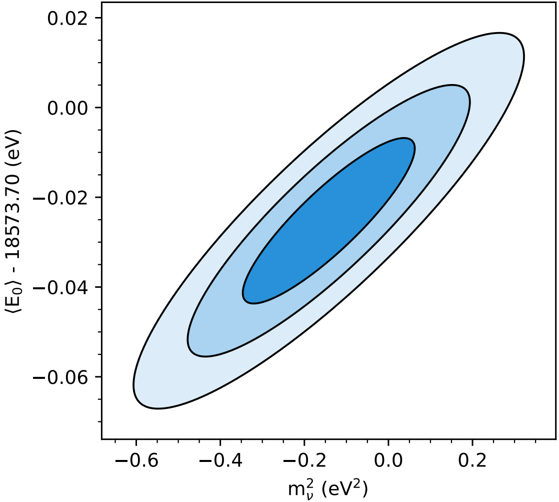
[KATRIN 2022 and arxiv:2406.13516]

strongest bound on $m_\nu (\equiv m_{\bar{\nu}_e})$ are from KATRIN



KNM1 to KNM5:

$m^2_\nu = (-0.14^{+0.13}_{-0.15})$ eV^2

Upper limit 90%:

$m_\nu < 0.45$ eV

expected final sensitivity (90%): $m_\nu \lesssim 0.2$ eV

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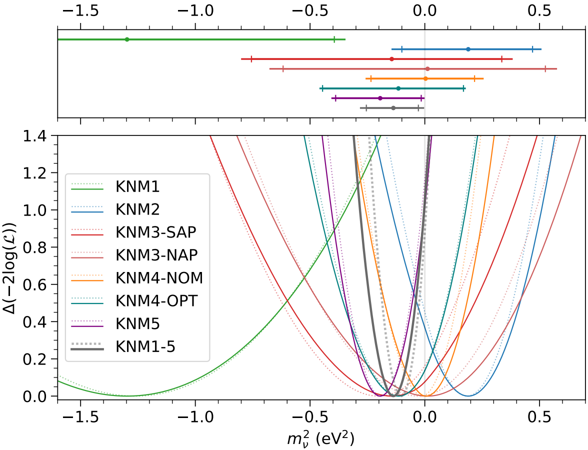

Dotted lines: stat. errors only
Solid lines: stat.+syst. errors

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Neutrinos and their masses

[de Salas+, Frontiers 5 (2018) 36]

Normal ordering (NO)

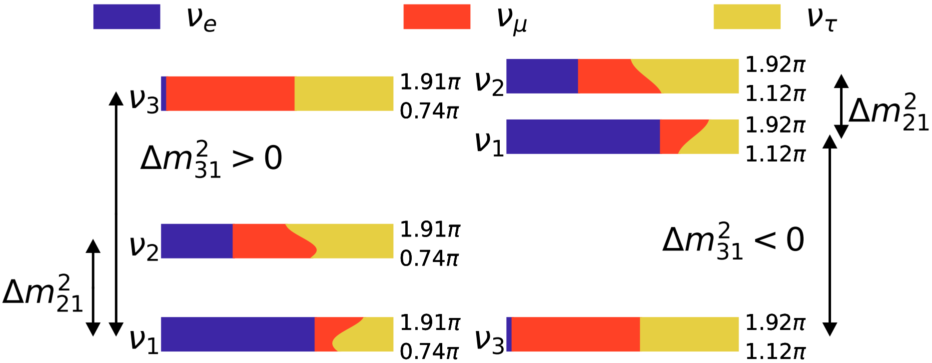
$m_1 < m_2 < m_3$

$\sum m_k \gtrsim 0.06$ eV

Inverted ordering (IO)

$m_3 < m_1 < m_2$

$\sum m_k \gtrsim 0.1$ eV



Absolute scale unknown!

Can we constrain the mass ordering using bounds on $\sum m_\nu$?

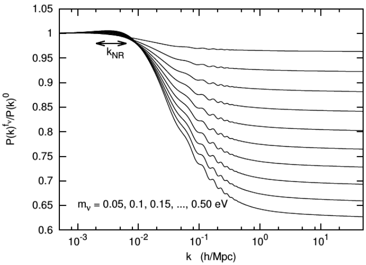
1 Neutrino masses

2 **Neutrino masses in cosmology**

3 Constraining neutrino masses

4 Constraining the mass ordering

5 Conclusions



Neutrino masses from CMB

ω_i energy density of species i,
$i \in$ (radiation, matter, baryons, cold dark matter, ν)
$z_{\rm eq}$ matter-radiation equality redshift

$$1 + z_{\rm eq} = (\omega_b + \omega_c)/\omega_r$$

independent of m_ν

$$\omega_m^0 = \omega_b^0 + \omega_c^0 + \omega_\nu^0 \text{ today}$$

mass of species relativistic at recombination
affects late time evolution only

small effects on the SW plateau
(cosmic variance, degeneracies...)

Effects on the early ISW effect

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

effects on the position of peaks

$$\theta_s = r_s(\eta_{LS})/D_A(\eta_{LS})$$

$$D_A = \int_0^{z_{rec}} \frac{dz}{H(z)}$$

(this effect can be compensated reducing H_0)

correlation m_ν–H_0

[Lesgourgues+, Neutrino Cosmology]

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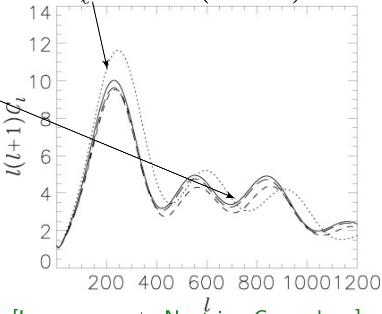


[Lesgourgues+, Neutrino Cosmology]

Free-streaming - I

Non-cold relics $\Longrightarrow$ damping in the perturbations due to free-streaming

Growth equation: $\ddot{\delta} + \underbrace{\boxed{2H\dot{\delta}}}_{\text{Hubble drag}} + \underbrace{\boxed{c_s^2 k^2 \frac{\delta}{a^2}}}_{\text{pressure}} = \underbrace{\boxed{4\pi G_N \rho\, \delta}}_{\text{gravity}}$

Jeans scale: pressure=gravity

$$k_J \equiv \sqrt{\frac{4\pi G_N \rho}{c_s^2 (1+z)^2}}$$

$k < k_J$: growth of density perturbations

$k > k_J$: no growth can occur

neutrino free-streaming scale

$$\boxed{k_{fs}(z) \equiv \sqrt{\frac{3}{2}\frac{H(z)}{(1+z)\sigma_{v,\nu}(z)}} \simeq 0.7 \left(\frac{m_\nu}{1\ \mathrm{eV}}\right) \sqrt{\frac{\Omega_M}{1+z}}\, h/\mathrm{Mpc}}$$

ρ energy density of a given fluid
$\delta = \delta\rho/\rho$ perturbation (single fluid)
c_s sound speed of the fluid

$\sigma_{v,\nu}(z)$ ν velocity dispersion
$H = H(z)$ Hubble factor at redshift z
h reduced Hubble factor today

Free-streaming - II

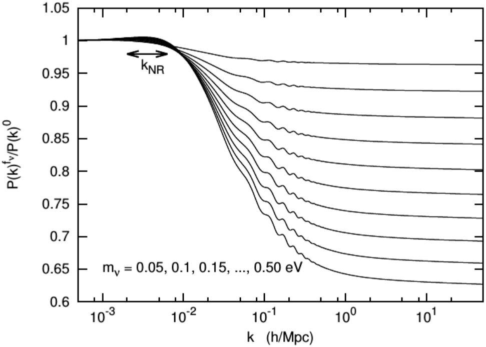
Damping occurs for all $k \gtrsim k_{\rm nr}$

k_{nr}: corresponding
to ν non-relativistic transition

Plot: $\dfrac{P_{m_\nu>0}(k)}{P_{m_\nu=0}(k)}$

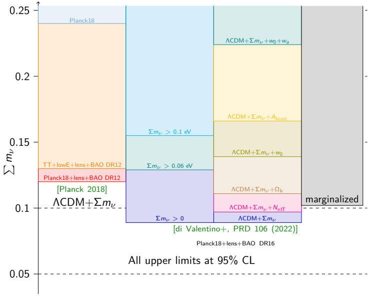
- top to bottom: $m_\nu = 0.05$ eV
  to $m_\nu = 0.5$ eV
- $\dfrac{\Delta P}{P} \simeq -\dfrac{8\Omega_\nu}{\Omega_M} \simeq -\dfrac{\sum m_\nu}{0.01\ \mathrm{eV}}\%$

[Lesgourgues+, Neutrino Cosmology]
(fixed h, ω_m, ω_b, ω_Λ)



Expected constraints from future surveys:

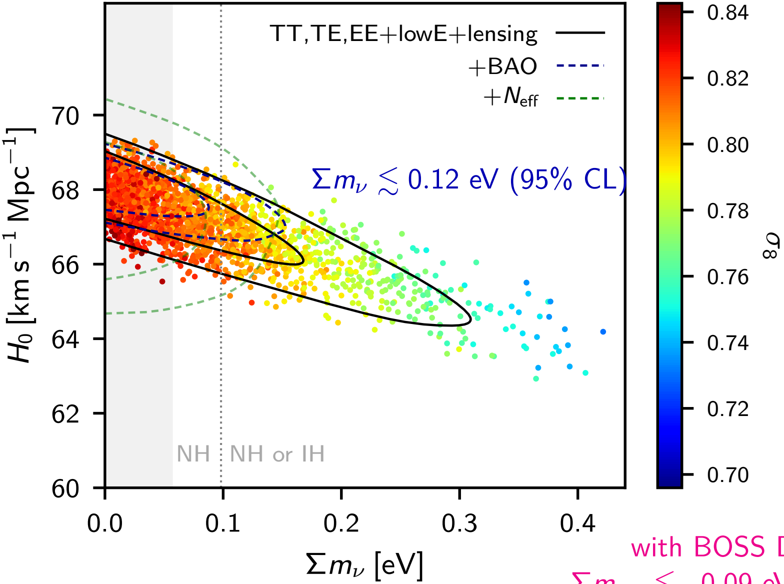
- Planck CMB + DES: $\sigma(m_\nu) \simeq 0.04$–$0.06$ eV [Font-Ribera+, 2014]
- Planck CMB + Euclid: $\sigma(m_\nu) \simeq 0.03$ eV [Audren+, 2013]



$\sum m_\nu$
0.25
0.2
0.15
0.1
0.05
Planck18
TT+lowE+lens+BAO DR12
Planck18+lens+BAO DR12
[Planck 2018]
ΛCDM+Σm_ν
$\Sigma m_\nu > 0.1$ eV
$\Sigma m_\nu > 0.06$ eV
$\Sigma m_\nu > 0$
ΛCDM+Σm_ν+w_0+w_a
ΛCDM+Σm_ν+$A_{\rm lens}$
ΛCDM+Σm_ν+w_0
ΛCDM+Σm_ν+Ω_k
ΛCDM+Σm_ν+$N_{\rm eff}$
ΛCDM+Σm_ν
[di Valentino+, PRD 106 (2022)]
Planck18+lens+BAO DR16
marginalized
All upper limits at 95% CL

Σm_ν and CMB

[Planck Collaboration, 2018]



with BOSS DR16 BAO:
$\Sigma m_\nu \lesssim 0.09$ eV (95% CL)

Playing with priors

Bayes theorem:

$$\boxed{p(\theta|d,\mathcal{M}) = \mathcal{L}(\theta)\frac{\pi(\theta|\mathcal{M})}{Z_{\mathcal{M}}}}$$

posterior depends on prior!

parameters θ, model $\mathcal{M}$, data d $\pi(\theta|\mathcal{M})$ prior $p(\theta|d,\mathcal{M})$ posterior $\mathcal{L}(\theta)$ likelihood $Z_{\mathcal{M}}$ Bayesian evidence

Playing with priors

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$$\boxed{p(\theta|d,\mathcal{M}) = \mathcal{L}(\theta)\frac{\pi(\theta|\mathcal{M})}{Z_\mathcal{M}}}$$

posterior depends on prior!

[Planck 2018]: prior
$0 < \Sigma m_\nu < \mathcal{O}(1)$ eV

strongest upper limit (95%):
$\Sigma m_\nu < 113$ meV
(CMB+lens+BAO+SN)

corresponding to
$\Sigma m_\nu < 53.6$ meV (68%)

below minimum for NO!
does it make sense?

parameters θ, model $\mathcal{M}$, data d $\pi(\theta|\mathcal{M})$ prior $p(\theta|d,\mathcal{M})$ posterior $\mathcal{L}(\theta)$ likelihood $Z_\mathcal{M}$ Bayesian evidence

Playing with priors

Bayes theorem:

$$\boxed{p(\theta|d,\mathcal{M}) = \mathcal{L}(\theta)\frac{\pi(\theta|\mathcal{M})}{Z_\mathcal{M}}}$$

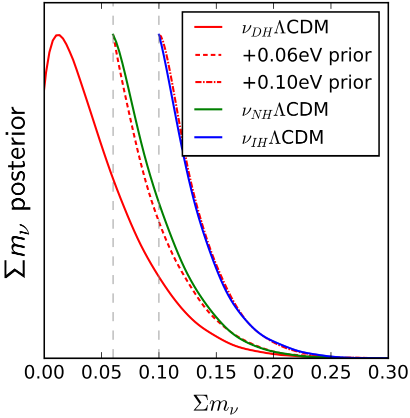
posterior depends on prior!

[Wang+, 2017]

degenerate (DH)
vs normal (NH)
vs inverted (IH) hierarchy

(i.e. change the prior lower bound)

Different limits if you consider simply $\Sigma m_\nu > 0$ or you take into account oscillation results...



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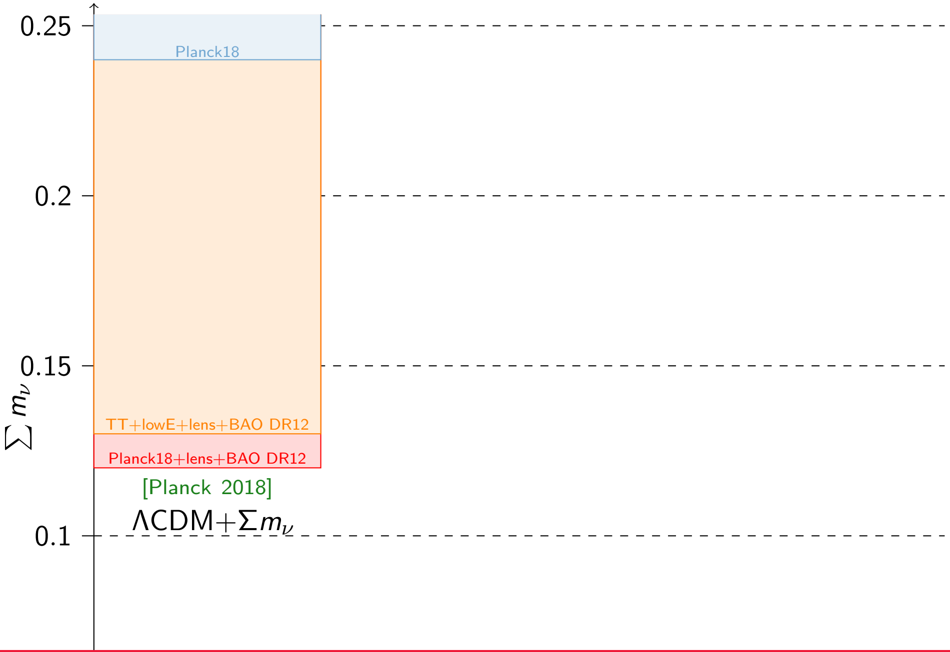
Cosmological neutrino mass bounds in 2022 (95% CL)



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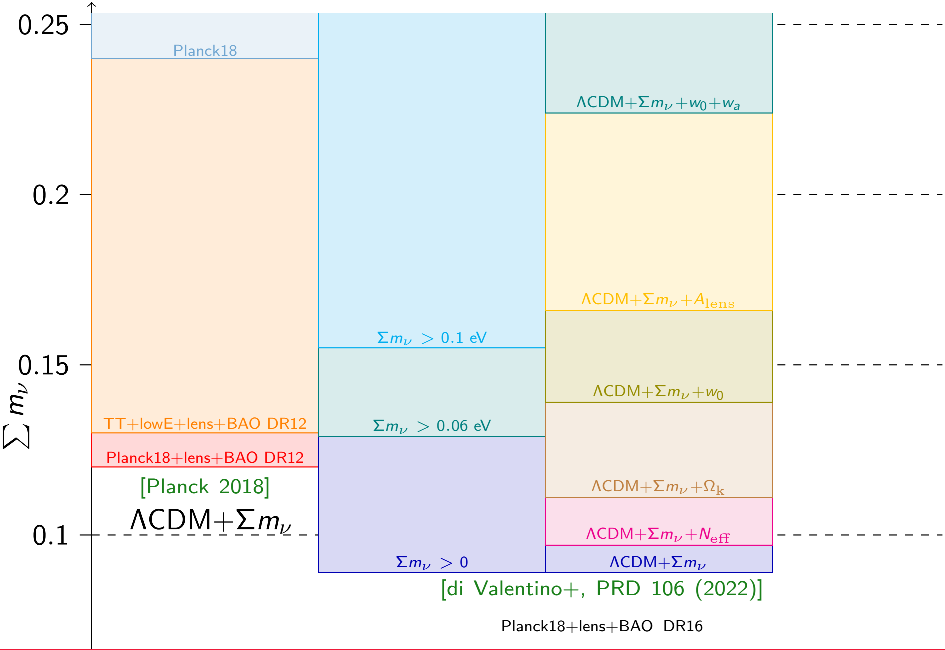

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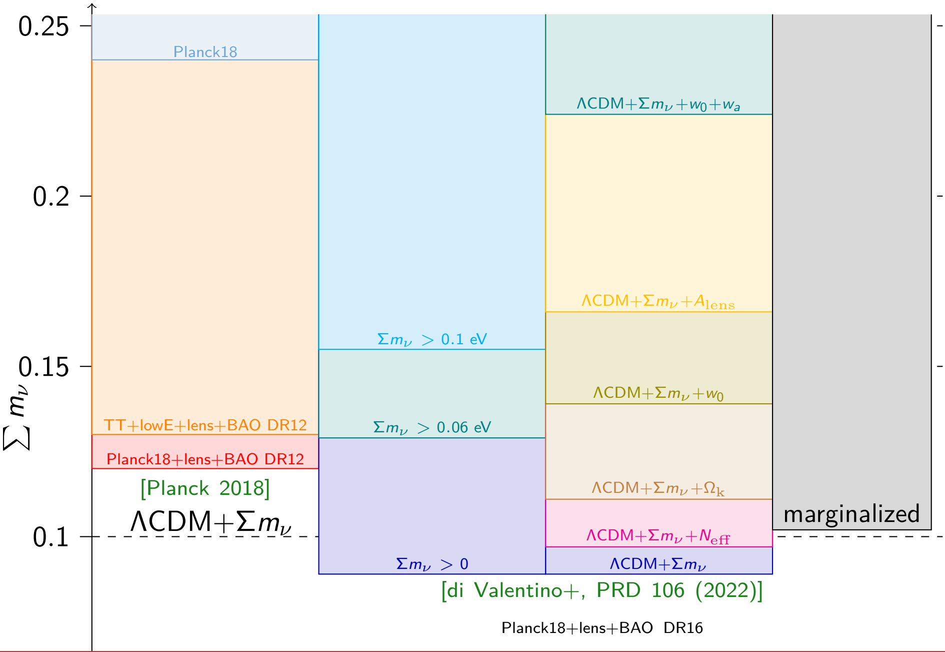
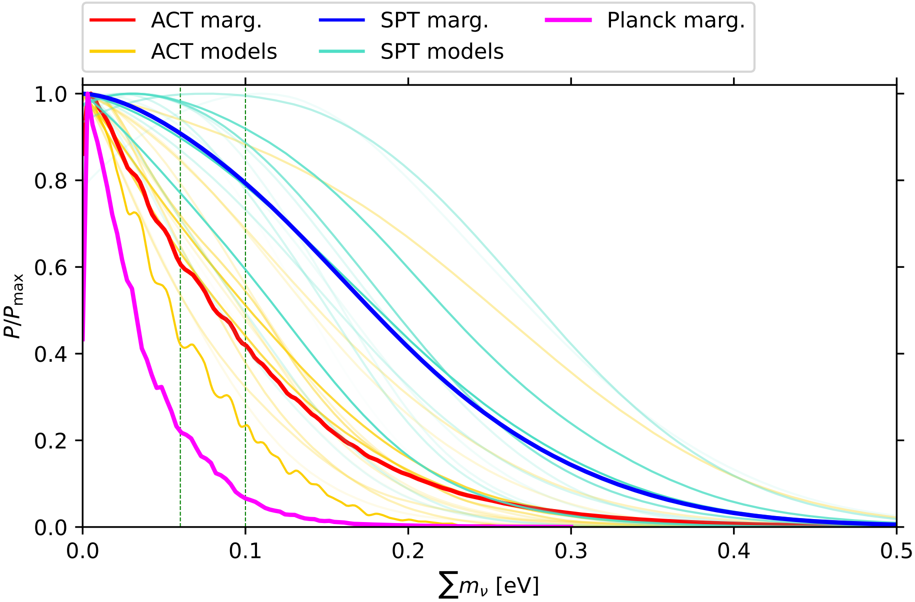


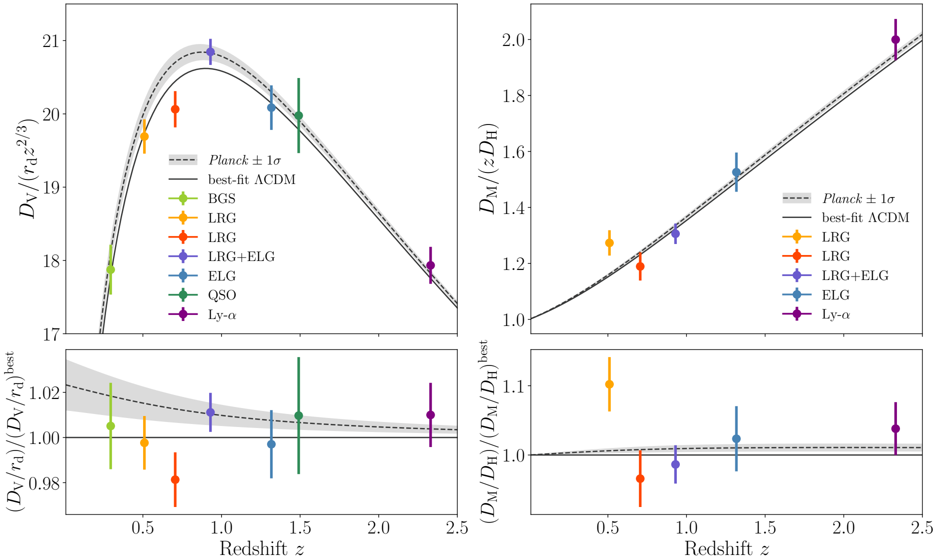
Constraints on the sum of neutrino masses

[PRD 108 (2023)]



DESI BAO data from DR1

[arxiv:2404.03002]



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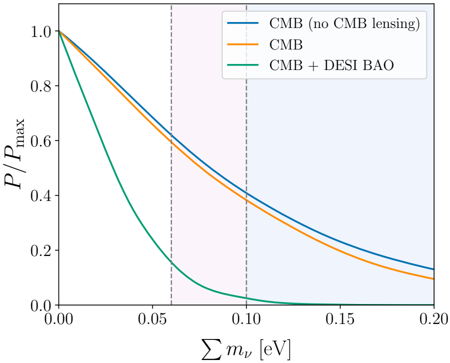
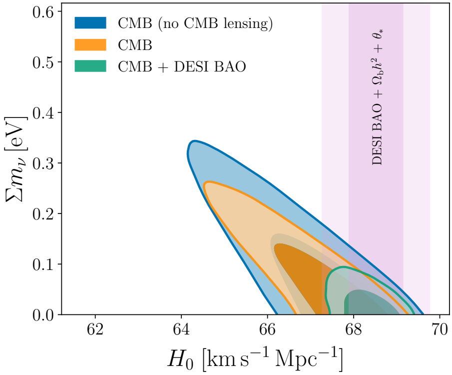




$\sum m_\nu < 0.072$ eV (95%, DESI BAO+CMB)

close to disfavoring normal ordering minimum value

$\sum m_\nu \sim 0.06$ eV

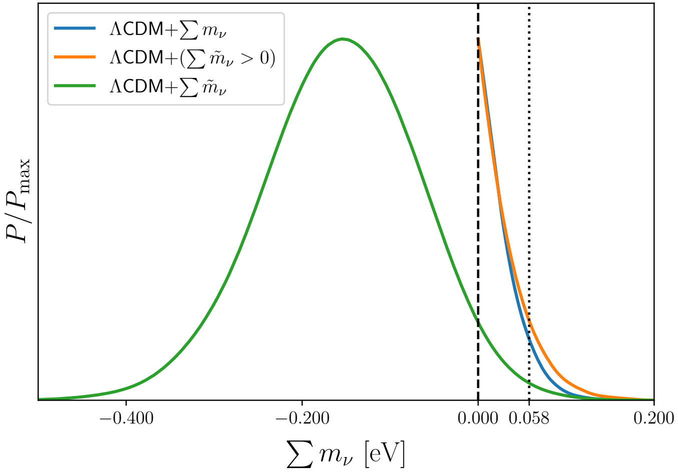
at 95%!

Negative neutrino masses?

[Craig+, JHEP 09 (2024)]
[Green+, arxiv:2407.07878]

"Effective ν mass $\Sigma\tilde{m}_\nu$" by extrapolating the effect of Σm_ν on lensing

"Negative neutrino mass": increased matter clustering
compared to a model with only massless neutrinos



Planck 2018 CMB, ACT+Planck lensing, DESI BAO

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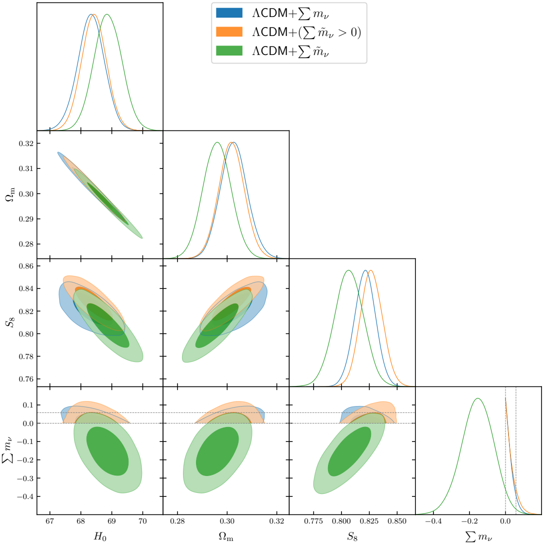

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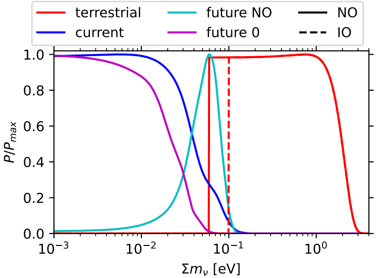

Can current data tell us the neutrino mass ordering?

1. [Hannestad, Schwetz, 2016]: extremely weak (2:1, 3:2) preference for NO
(cosmology + [Bergstrom et al., 2015] neutrino oscillation fit)
Bayesian approach;
2. [Gerbino et al, 2016]: extremely weak (up to 3:2) preference for NO
(cosmology only), Bayesian approach;
3. [Simpson et al., 2017]: strong preference for NO
(cosmological limits on $\sum m_\nu$ + constraints on Δm^2_{21} and $|\Delta m^2_{31}|$)
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4. [Schwetz et al., 2017], "Comment on ..."[Simpson et al., 2017]: effect of prior?
5. [Capozzi et al., 2017]: 2σ preference for NO
(cosmology + [Capozzi et al., 2016, updated 2017] neutrino oscillation fit)
frequentist approach;
6. [Caldwell et al., 2017] very mild indication for NO
(cosmology + neutrinoless double-beta decay + [Esteban et al., 2016]
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7. [Wang, Xia, 2017]: Bayes factor NO vs IO is not informative
(cosmology only).
8. ...

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Parameterizing neutrino masses

[SG+, JCAP 03 (2018) 11]

[Simpson et al, 2017]

use $m_1,\ m_2,\ m_3$ (3M)

[Caldwell et al, 2017]

use $m_{\rm lightest},\ \Delta m^2_{21},\ |\Delta m^2_{31}|$ ($M\Delta$)

Alternatively:

$\sum m_\nu,\ \Delta m^2_{21},\ |\Delta m^2_{31}|$ ($\Sigma\Delta$)

intuition says: $\Sigma\Delta$ is closer to observable quantities! Better than 3M?

Cosmology measures $\sum m_\nu$, oscillations $\Delta m^2_{21},\ |\Delta m^2_{31}|$

$M\Delta$ should be equivalent to $\Sigma\Delta$

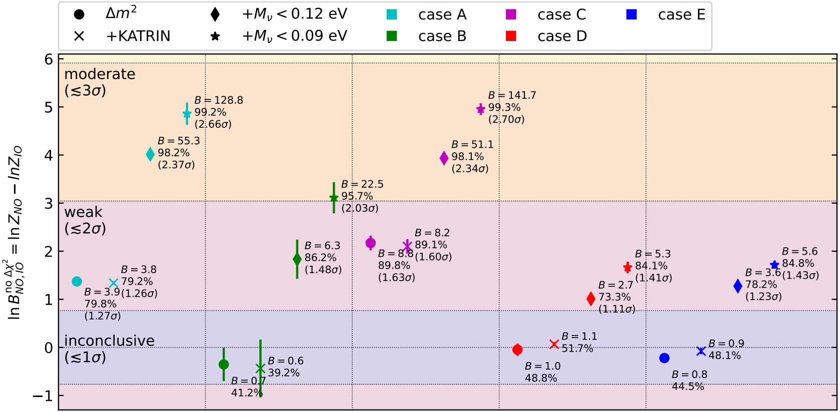
Should we use linear or logarithmic priors on m_k ($m_{\rm lightest}$)?

Can data help to select 3M or $M\Delta/\Sigma\Delta$, linear or log?

Mass ordering and Bayesian analyses

[JCAP 10 (2022)]

→ oscillation Δm^2 alone should not generate a difference



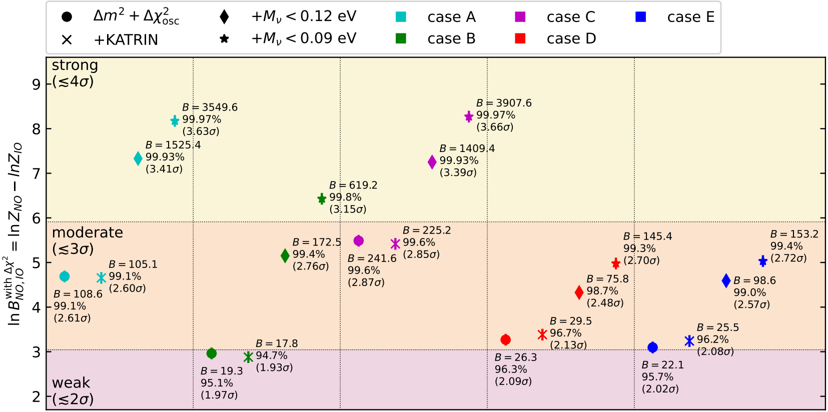
A, B, C:
Gauss. prior on
ln m_1, ln m_2, ln m_3,
different prior ranges or sampling

D, E:
linear prior on
Δm^2_{21}, $|\Delta m^2_{31}|$, $m_{\rm lightest}/\sum m_\nu$

Mass ordering and Bayesian analyses

[JCAP 10 (2022)]

oscillation $\Delta\chi^2$ DOES prefer NO over IO at $\sim 2\sigma$



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Can a cosmological limit on Σm_ν disfavor IO?

[PDU 40 (2023)]

standard factor

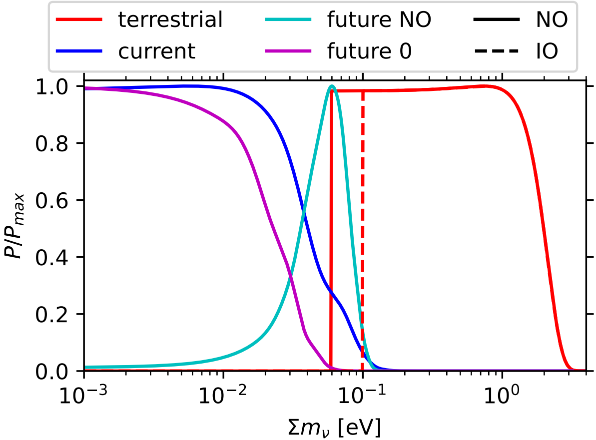
Cosmology measures $\omega_\nu = \Omega_\nu h^2 = \Sigma m_\nu/(94.12\ \text{eV})$

NO: $\Sigma m_\nu \gtrsim 0.06$ eV   Current: $\Sigma m_\nu \lesssim 0.1$ eV (95%)   IO: $\Sigma m_\nu \gtrsim 0.1$ eV

Future sensitivity: $\sigma(\Sigma m_\nu) \simeq 0.02$ eV

Still preferring $\Sigma m_\nu = 0$?   Will measure e.g. $\Sigma m_\nu = 0.06$ eV?

tension even with NO!



confirm NO, disfavor IO

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[PDU 40 (2023)]

standard factor

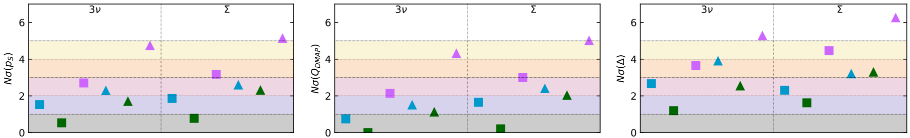
Cosmology measures $\omega_\nu = \Omega_\nu h^2 = \Sigma m_\nu/(94.12\text{ eV})$

Is there a tension between cosmology and oscillations?

or will there be a tension?

several possible tests can be considered, similar results

$\Sigma m_\nu \lesssim 0.1$ eV (95%)	●	current	■	NO
$\Sigma m_\nu = 0.06 \pm 0.02$ eV (1σ)	●	future NO	▲	IO
$\Sigma m_\nu = 0.00 \pm 0.02$ eV (1σ)	●	future 0		



currently only mild tension between cosmology and oscillations

future NO can be at $\sim 2\sigma$ tension with IO

future 0 can be at $\sim 2-3\sigma$ tension with NO, $\gtrsim 4\sigma$ with IO

Can a cosmological limit on Σm_ν disfavor IO?

[PDU 40 (2023)]

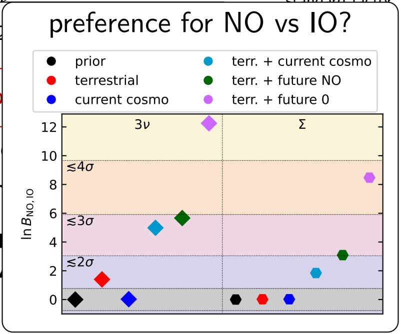
standard factor

Cosmology measures $\omega_\nu = \Omega_\nu h^2$

Is there a tension between cosmo

or will there be a t

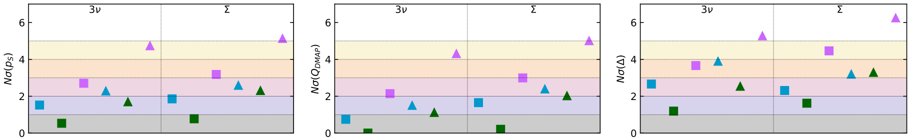
several possible tests can be con



$\Sigma m_\nu \lesssim 0.1$ eV (95%) ● current

$\Sigma m_\nu = 0.06 \pm 0.02$ eV (1σ) ● future NO

$\Sigma m_\nu = 0.00 \pm 0.02$ eV (1σ) ● future 0



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Mass ordering results

[JHEP 02 (2021)]

http://globalfit.astroparticles.es/

Bayes theorem for models:

$$p(\mathcal{M}|d) \propto Z_{\mathcal{M}} \pi(\mathcal{M})$$

Bayesian evidence:

$$Z_{\mathcal{M}} = \int_{\Omega_{\mathcal{M}}} \mathcal{L}(\theta)\, \pi(\theta)\, d\theta$$

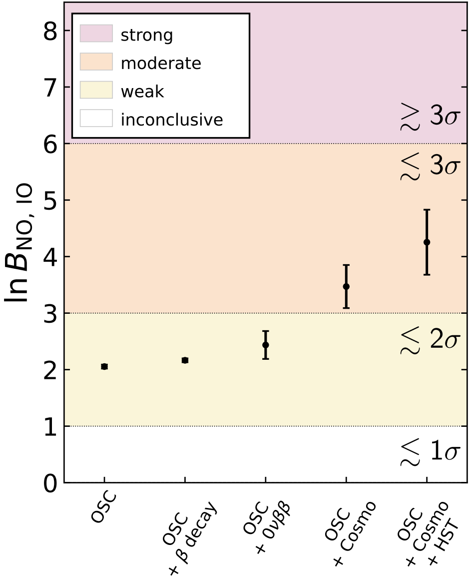
Bayes factor NO vs IO:

$$B_{\mathrm{NO,IO}} = Z_{\mathrm{NO}}/Z_{\mathrm{IO}}$$

Posterior probability:

$$\begin{aligned} P_{\mathrm{NO}} &= B_{\mathrm{NO,IO}}/(B_{\mathrm{NO,IO}}+1) \\ P_{\mathrm{IO}} &= 1/(B_{\mathrm{NO,IO}}+1) \end{aligned}$$

$N\sigma$ from $P_{\mathrm{NO}} = \mathrm{erf}(N/\sqrt{2})$



$\pi(\mathcal{M})$ model prior

$p(\mathcal{M}|d)$ model posterior

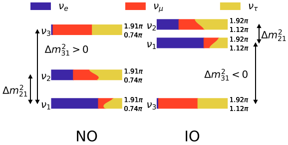
$\mathcal{L}(\theta)$ likelihood

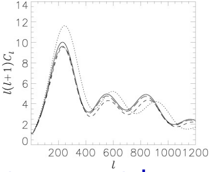
$\Omega_{\mathcal{M}}$ parameter space, for parameters θ

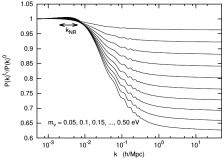
What do we learn on neutrino masses from cosmology?

C

Effects of neutrino masses in cosmology

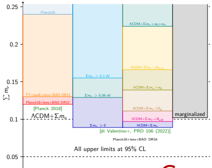


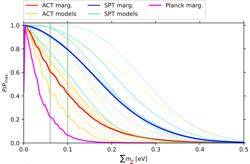


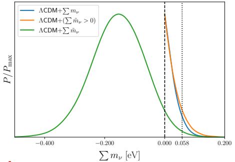


M

Constraints on neutrino masses

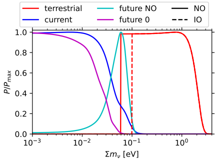


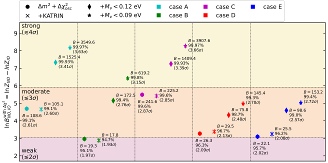


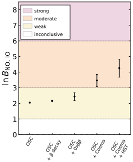


O

Constraints on the mass ordering







What do we learn on neutrino masses from cosmology?

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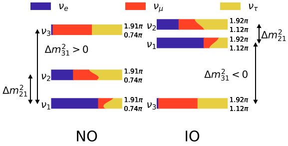
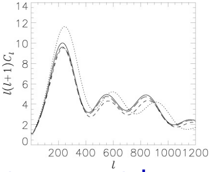
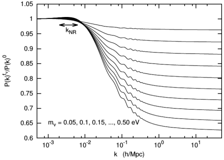
Effects of neutrino masses in cosmology

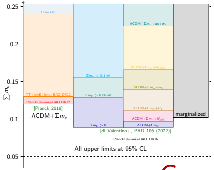


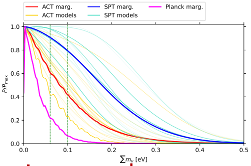


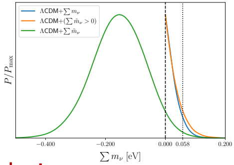


M

Constraints on neutrino masses







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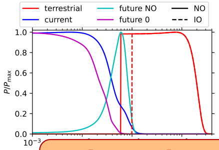

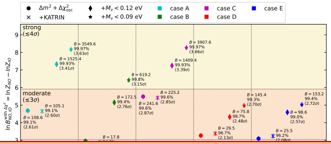

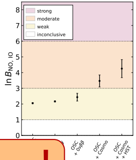

Thanks for your attention!