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European Commission | Horizon 2020
European Union funding
for Research & Innovation

What cosmology can say about neutrino mass ordering and additional neutrinos

VI Meeting on Fundamental Cosmology, Granada (ES), 28–30/05/2018

Neutrino Oscillations

Analogous to CKM mixing for quarks:

[Pontecorvo, 1958]
[Maki, Nakagawa, Sakata, 1962]

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

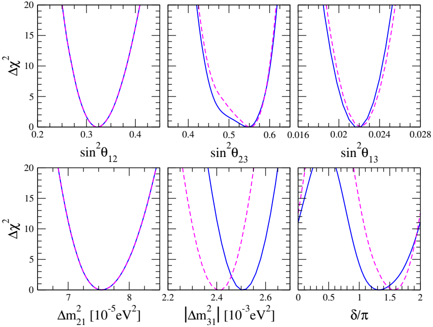
ν_α flavour eigenstates, $U_{\alpha k}$ PMNS mixing matrix, ν_k mass eigenstates.

Current knowledge of the 3 active ν mixing: [de Salas et al. (2018)]

$\Delta m^2_{ji} = m^2_j - m^2_i$, θ_{ij} mixing angles
NO: Normal Ordering, $m_1 < m_2 < m_3$
IO: Inverted Ordering, $m_3 < m_1 < m_2$

$$\begin{aligned}
\Delta m^2_{21} &= (7.55^{+0.20}_{-0.16}) \cdot 10^{-5}\ \mathrm{eV}^2 \\
|\Delta m^2_{31}| &= (2.50 \pm 0.03) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO}) \\
&= (2.42^{+0.03}_{-0.04}) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO})
\end{aligned}$$

$$\begin{aligned}
\sin^2(\theta_{12}) &= 0.320^{+0.020}_{-0.016} \\
\sin^2(\theta_{13}) &= 0.0216^{+0.008}_{-0.007}\ (\mathrm{NO}) \\
&= 0.0222^{+0.007}_{-0.008}\ (\mathrm{IO}) \\
\sin^2(\theta_{23}) &= 0.547^{+0.020}_{-0.030}\ (\mathrm{NO}) \\
&= 0.551^{+0.018}_{-0.030}\ (\mathrm{IO})
\end{aligned}$$



First hints for $\delta_{\mathrm{CP}} \simeq 3/2\pi$

Short Baseline (SBL) anomaly

[SG et al., JPG 43 (2016) 033001]

Problem: anomalies in SBL experiments ⇒ $\begin{cases} \text{errors in flux calculations?} \\ \text{deviations from 3-}\nu\text{ description?} \end{cases}$

A short review:

LSND	search for $\bar{\nu}_\mu \to \bar{\nu}_e$, with $L/E = 0.4 \div 1.5$ m/MeV. Observed a 3.8σ excess of $\bar{\nu}_e$ events [Aguilar et al., 2001]
Reactor	re-evaluation of the expected anti-neutrino flux ⇒ disappearance of $\bar{\nu}_e$ events compared to predictions ($\sim 3\sigma$) with $L < 100$ m [Azabajan et al, 2012]
Gallium	calibration of GALLEX and SAGE Gallium solar neutrino experiments give a 2.7σ anomaly (disappearance of ν_e) [Giunti, Laveder, 2011]
MiniBooNE	(inconclusive) search for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$, with $L/E = 0.2 \div 2.6$ m/MeV. No ν_e excess detected, but $\bar{\nu}_e$ excess observed at 2.8σ [MiniBooNE Collaboration, 2013]

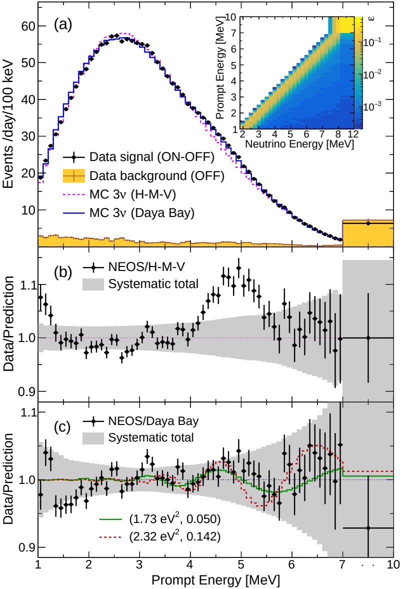
Possible explanation:

Additional squared mass difference

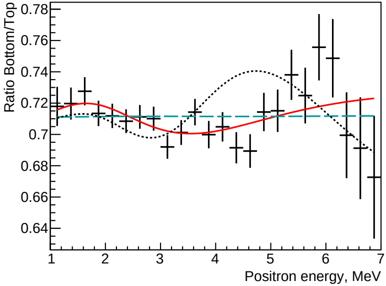
$$\Delta m^2_{\text{SBL}} \simeq 1\ \text{eV}^2$$

More recently. . .

[NEOS, PRL 118 (2017) 121802]



[DANSS, arxiv:1804.04046]



first *model independent* indications in favor of SBL oscillations

DANSS alone gives a $\Delta\chi^2 \simeq 13$ in favor of a light sterile neutrino!

3+1 Neutrino Model

new $\Delta m^2_{\mathrm{SBL}} \Rightarrow$ 4 neutrinos!

$\downarrow$

ν_4 with $m_4 \simeq 1$ eV,
no weak interactions

$\downarrow$

light sterile neutrino (LSν)

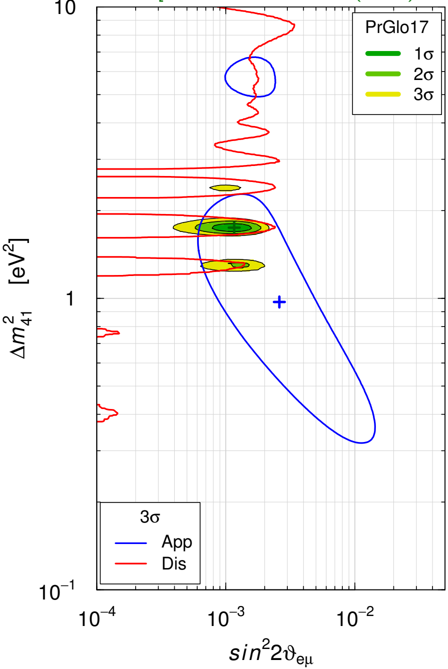
3 (active) + 1 (sterile) mixing:

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

ν_s is mainly ν_4:

$$m_s \simeq m_4 \simeq \sqrt{\Delta m^2_{41}} \simeq \sqrt{\Delta m^2_{\mathrm{SBL}}}$$

assuming $m_4 \gg m_i$ $(i = 1, 2, 3)$



[SG et al., JHEP 06 (2017) 135]

3+1 Neutrino Model

[SG et al., PLB 782 (2018) 13]

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↓

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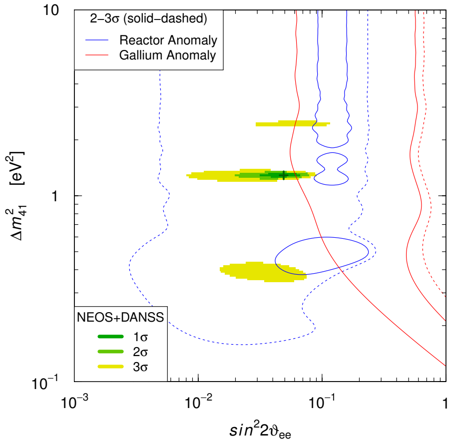

3+1 oscillations favored

$(\Delta\chi^2 \gtrsim 14,\ 3.4\sigma)$

3+1 Neutrino Model

[SG et al., PLB 782 (2018) 13]

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↓

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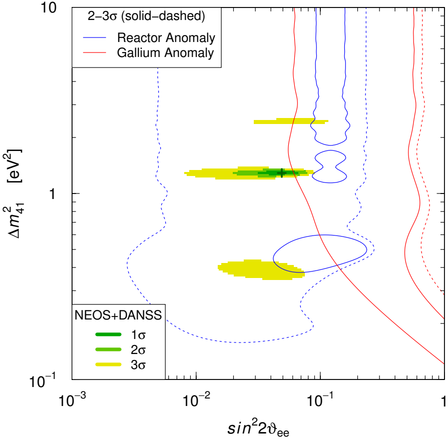


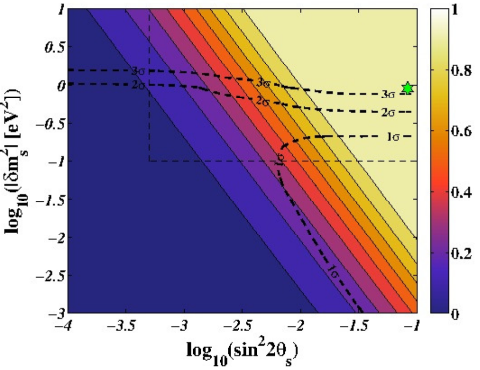
3+1 oscillations favored
$(\Delta\chi^2 \gtrsim 14,\ 3.4\sigma)$

can ν_4 thermalize in the early Universe through oscillations?

LSν thermalization

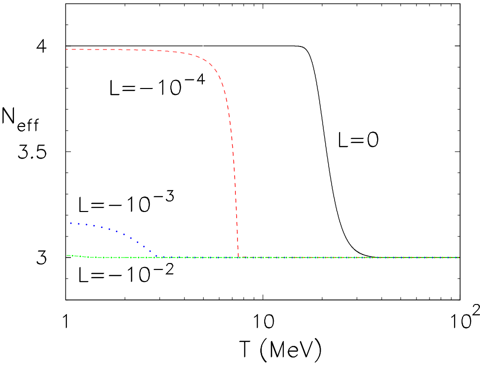
Using SBL best-fit parameters for the LSν (Δm^2_{41}, θ_s):

[Hannestad et al., JCAP 07 (2012) 025]



(colors coding $\Delta N_{\rm eff}$)

[Mirizzi et al., PRD 86 (2012) 053009]



(L: lepton asymmetry)

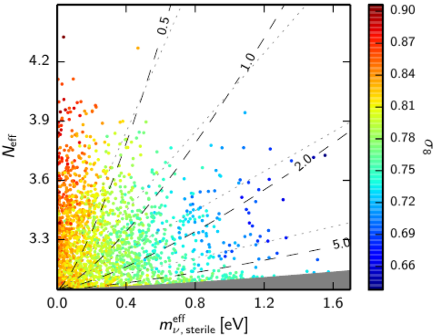
Unless $L \gtrsim \mathcal{O}(10^{-3})$, $\Delta N_{\rm eff} \simeq 1$

See also: [Saviano et al., PRD 87 (2013) 073006], [Hannestad et al., JCAP 08 (2015) 019]

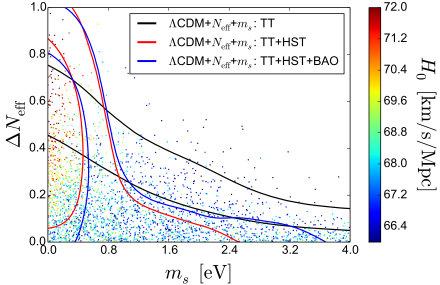
[to be precise: $\Delta N_{\rm eff}$ is slightly smaller at CMB decoupling, when the LSν starts to be non-relativistic]

LSν constraints from cosmology

CMB+local: [Planck Collaboration, 2015]



[Archidiacono et al., JCAP 08 (2016) 067]



$$\begin{cases} N_{\rm eff} < 3.7 \\ m_s^{\rm eff} < 0.52 \text{ eV} \end{cases}$$

(TT+lensing+BAO)
[$m_s < 5$ eV]

dataset	free $\Delta N_{\rm eff}$ [$m_s < 10$ eV]	$\Delta N_{\rm eff} = 1$
(TT)	$N_{\rm eff} < 3.5$	$m_s < 0.66$ eV
(+H_0)	$N_{\rm eff} < 3.9$	$m_s < 0.55$ eV
(+BAO)	$N_{\rm eff} < 3.8$	$m_s < 0.53$ eV

BBN constraints: $N_{\rm eff} = 2.90 \pm 0.22$ (BBN+Y_p) [Peimbert et al., 2016]

Summary: $\Delta N_{\rm eff} = 1$ from LSν incompatible with $m_s \simeq 1$ eV!

TT=Planck 2015 TT + lowTEB

All the constraints are at 2σ CL

Incomplete Thermalization

Active-sterile oscillations in the early Universe:

mixing parameters from SBL data $\Longrightarrow \Delta N_{\rm eff} \simeq 1$

[Hannestad et al., 2012] [Mirizzi et al., 2012]

Many probes constrain $\Delta N_{\rm eff} < 1$. Do we need

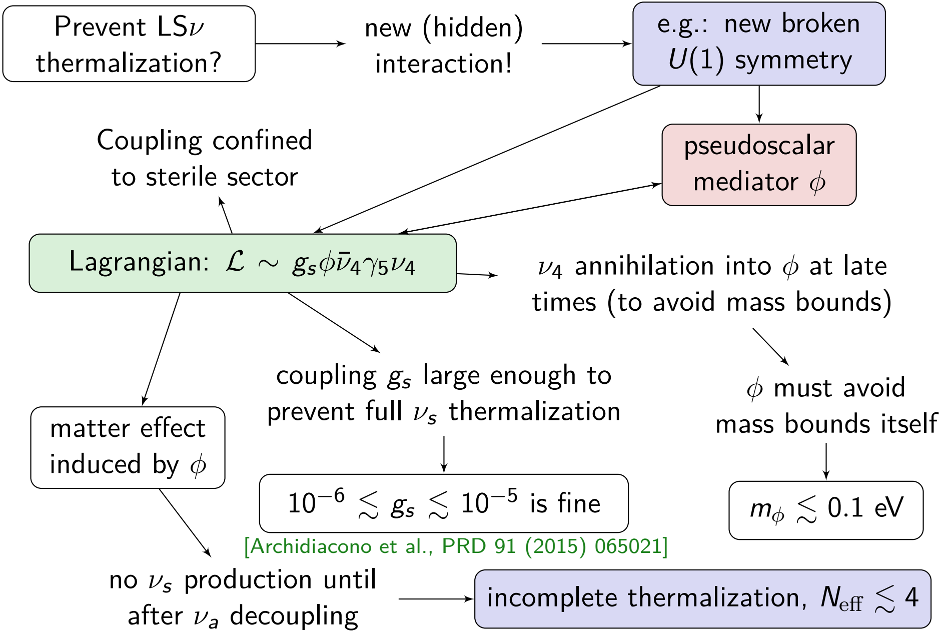
- a mechanism to suppress oscillations and full thermalization of ν_s?
- to compensate $\Delta N_{\rm eff} = 1$ with additional mechanisms in Cosmology?

Some ideas (an incomplete list!):

- large lepton asymmetry [Foot et al., 1995; Mirizzi et al., 2012; many more]
- new neutrino interactions [Bento et al., 2001; Dasgupta et al., 2014; Hannestad et al., 2014; Saviano et al., 2014; many more]
- entropy production after neutrino decoupling [Ho et al., 2013]
- very low reheating temperature [Gelmini et al., 2004; Smirnov et al., 2006]
- time varying dark energy components [Giusarma et al., 2012]
- larger expansion rate at the time of ν_s production [Rehagen et al., 2014]

Adding a new interaction

[Archidiacono, SG et al., JCAP 08 (2016) 067]



Prevent LSν thermalization?

new (hidden) interaction!

e.g.: new broken $U(1)$ symmetry

pseudoscalar mediator ϕ

Coupling confined to sterile sector

Lagrangian: $\mathcal{L} \sim g_s \phi \bar{\nu}_4 \gamma_5 \nu_4$

ν_4 annihilation into ϕ at late times (to avoid mass bounds)

coupling g_s large enough to prevent full ν_s thermalization

ϕ must avoid mass bounds itself

matter effect induced by ϕ

$10^{-6} \lesssim g_s \lesssim 10^{-5}$ is fine

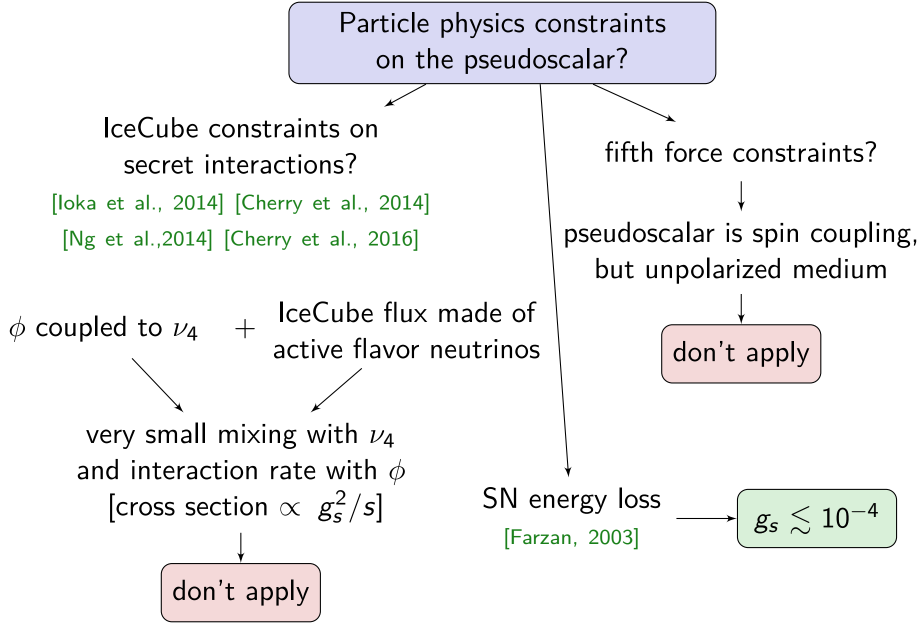
$m_\phi \lesssim 0.1$ eV

[Archidiacono et al., PRD 91 (2015) 065021]

no ν_s production until after ν_a decoupling

incomplete thermalization, $N_{\rm eff} \lesssim 4$

Constraints on the pseudoscalar interaction?



Particle physics constraints on the pseudoscalar?

IceCube constraints on secret interactions?

[Ioka et al., 2014] [Cherry et al., 2014] [Ng et al.,2014] [Cherry et al., 2016]

ϕ coupled to ν_4 + IceCube flux made of active flavor neutrinos

very small mixing with ν_4 and interaction rate with ϕ [cross section $\propto$ g_s^2/s]

don't apply

SN energy loss

[Farzan, 2003]

$g_s \lesssim 10^{-4}$

fifth force constraints?

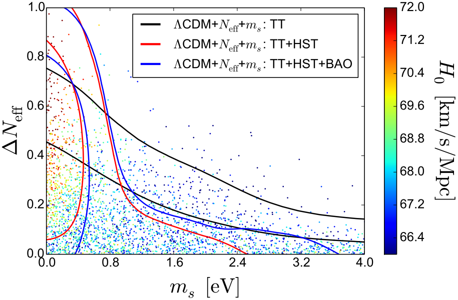
pseudoscalar is spin coupling, but unpolarized medium

don't apply

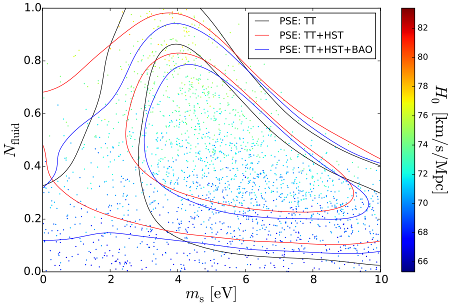
Results - I

[Archidiacono, SG et al., JCAP 08 (2016) 067]

Standard LSν model:
$\mathbf{\Lambda CDM}+\mathbf{N}_{\mathrm{eff}}+\mathbf{m_s}$
(ΛCDM params+free N_{eff} and m_s)



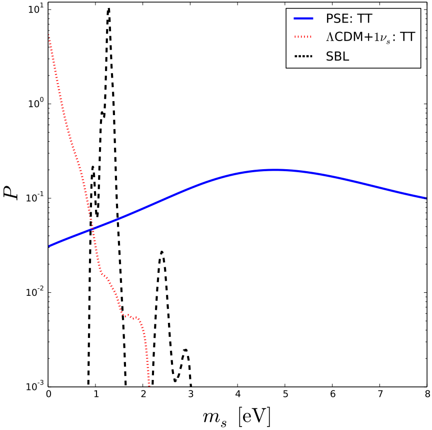
Pseudoscalar model (**PSE**):
$N_{\mathrm{eff}}=3.046+N_{\mathrm{fluid}}$
N_{fluid}: $\nu_s+\phi$ contributions

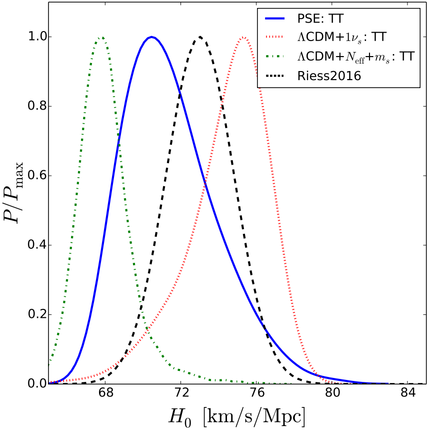


- Problems with $\Delta N_{\mathrm{eff}}=1$? solved (incomplete thermalization due to suppression of active-sterile oscillations in primordial plasma);
- mass bounds avoided
  $\Rightarrow$ large m_s allowed and (mild) preference for $m_s\simeq 4$ eV;
- high values of H_0 predicted by cosmology
  $\Rightarrow$ more compatible with local measurements.

Results - II

[Archidiacono, SG et al., JCAP 08 (2016) 067]





- PSE: posterior on m_s wider
- WARNING: the SBL constraints have changed meanwhile. . .

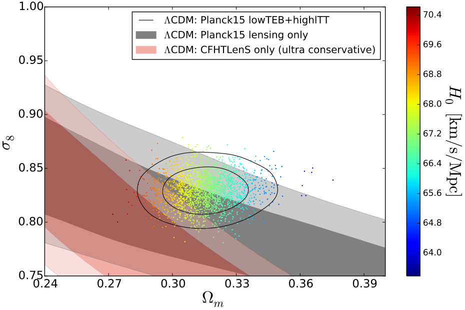
- PSE: very close to **Riess2016** results (better than ΛCDM+$N_{\rm eff}+m_s$)
- ΛCDM+$1\nu_s$: even higher H_0, but from $\Delta N_{\rm eff}=1$ and $m_s\simeq 0$.

Results - III

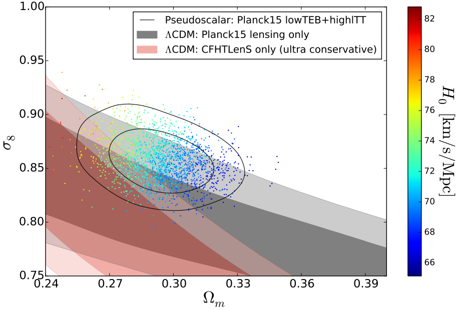
[Archidiacono, SG et al., JCAP 08 (2016) 067]

What about the σ_8 tension (matter perturbations at small scales)?

ΛCDM model:



Pseudoscalar model:



- smaller Ω_m today. Good?
- Also higher $\sigma_8 \Longrightarrow$ no improvement! The tension remains.
- due to higher H_0, not to reduced matter fluctuations.

1 ***Light sterile neutrino***

- Why a sterile neutrino
- Cosmological constraints
- A new interaction to solve the thermalization problem

2 ***Neutrino mass ordering***

- Constraints on neutrino masses
- Subtleties in the Bayesian analysis
- Constraints on the mass ordering

3 ***Conclusions***

Neutrinos and their masses

Normal ordering (NO)

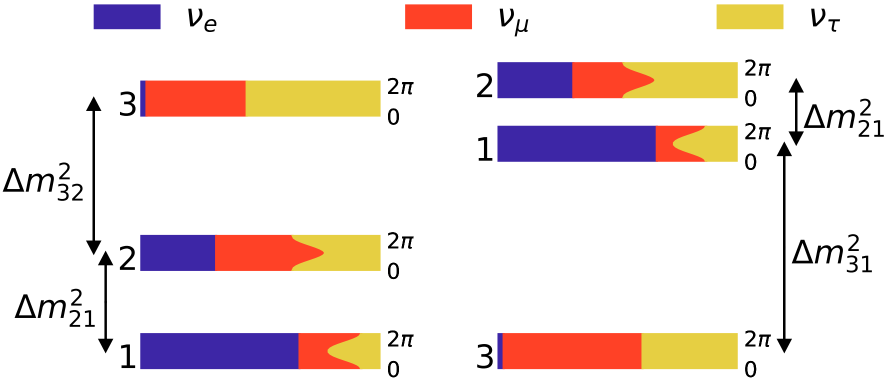
$m_1 < m_2 < m_3$

$\sum m_k \gtrsim 0.06$ 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 $\sum m_\nu$?

Neutrino masses from β decay

$\boxed{\text{Must measure } \beta \text{ decay endpoint}} \longrightarrow$

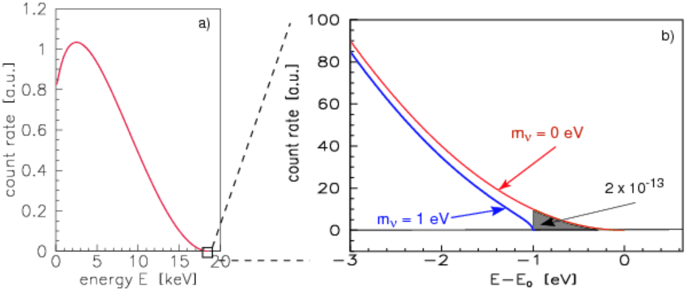
$$m^2_{\nu_e} = \sum_k |U_{ek}|^2\, m^2_k$$

U_{ek} mixing matrix

Mainz/Troitsk limits, $m_{\nu_e} \lesssim 2$ eV

Katrin, (expected) $m_{\nu_e} \lesssim 0.2$ eV

[Katrin L.o.I., 2001]



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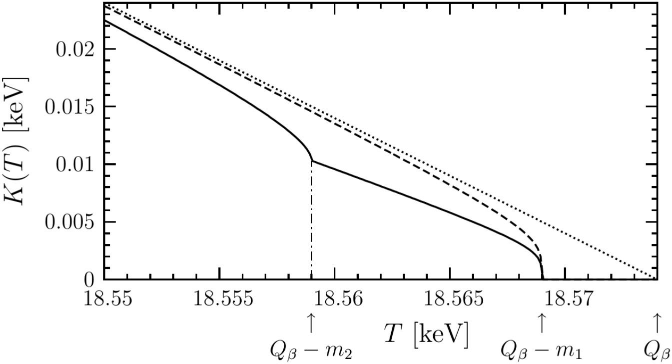
[Giunti&Kim, 2007]



Neutrino masses from neutrinoless double β decay

(if neutrino is Majorana)

[Schechter&Valle, 1982]

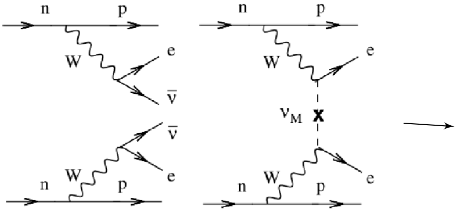
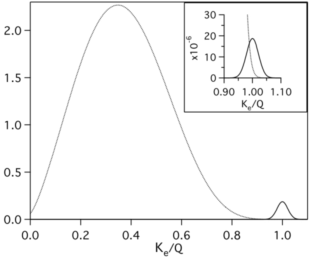
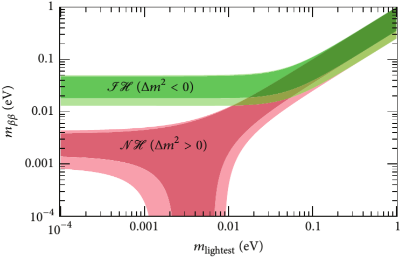


figure from [NEXT] webpage





[Dell'Oro et al., 2016]

$\boxed{\text{Measure } T^{0\nu}_{1/2}}$

m_e electron mass,
$G_{0\nu}$ phase space,
$\mathcal{M}'^{\nu}$ matrix element

convert into $m_{\beta\beta} = \dfrac{m_e}{\mathcal{M}'^{\nu}\sqrt{G_{0\nu}\,T^{0\nu}_{1/2}}}$

α_k Majorana phases

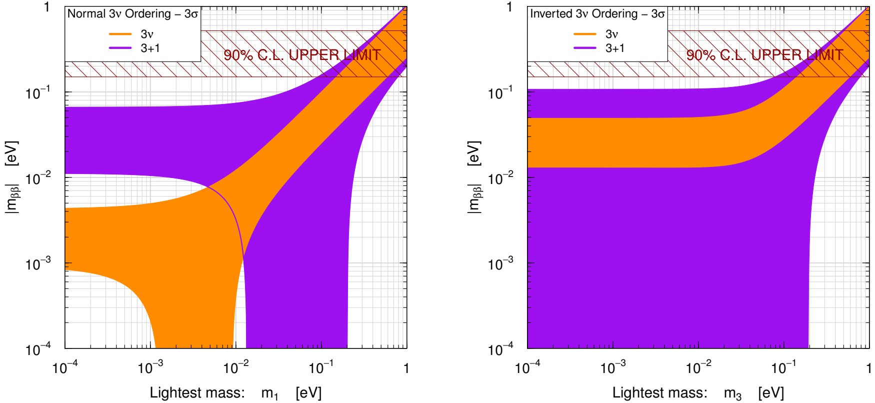
and then use $m_{\beta\beta} = \left|\sum_k e^{i\alpha_k}\,U^2_{ek}\,m_k\right|$

Light sterile neutrino and $0\nu\beta\beta$

[Giunti&Zavanin, JHEP 07 (2015) 171]
[Giunti @ MEDEX 2017]

NO for active neutrinos

IO for active neutrinos



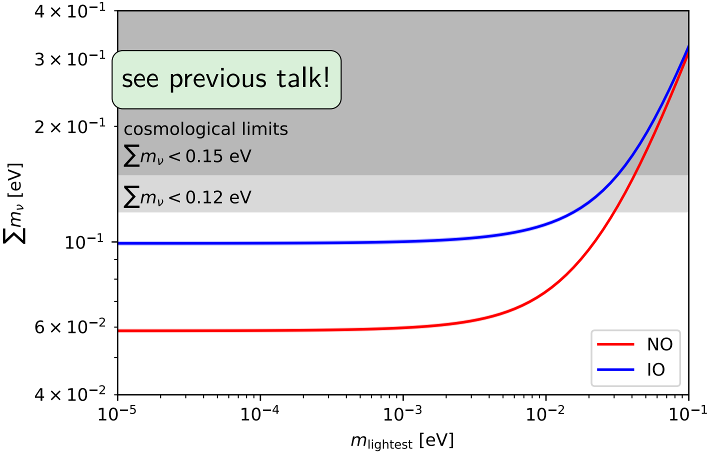
one more neutrino completely changes the picture!

Impossible to distinguish the mass orderings in most of the cases...

From cosmology...

Warning: model dependent content!

How the limit change when considering extensions of the ΛCDM model?


see previous talk!

Warning: $\sum m_\nu \lesssim 0.1$ eV at 95% CL
does not mean IO disfavored at 95% CL!

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 $|\Delta m^2_{31}|$)
Bayesian approach;
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]
readapted oscillation results)
Bayesian approach;
7. [Wang, Xia, 2017]: Bayes factor NO vs IO is not informative
(cosmology only).

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1. [Hannestad, Schwetz, 2016]: extremely weak (2:1, 3:2) preference for NO (cosmology + [Bergstrom et al., 2015] neutrino oscillation fit) Bayesian approach;
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5. [Capozzi et al., 2017]: 2σ preference for NO (cosmology + [Capozzi et al., 2016, updated 2017] neutrino oscillation fit) frequentist approach;
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Parameterizations, priors and data

[SG et al., JCAP 03 (2018) 11]

Neutrino oscillations

full $\chi^2 = -2\log\mathcal{L}_{\rm osc}$
from global fit

[de Salas et al, 2017]

Neutrino mixing

Parameter	Prior
$\sin^2\theta_{12}$	0.1 – 0.6
$\sin^2\theta_{13}$	0.00 – 0.06
$\sin^2\theta_{23}$	0.25 – 0.75

Masses: see later!

Parameterizations, priors and data

[SG et al., JCAP 03 (2018) 11]

$0\nu\beta\beta$ data

Likelihood approximations as in [Caldwell et al, 2017], from [Gerda, 2017] (Ge), [KamLAND-Zen, 2016], [EXO-200, 2014] (Xe)

Neutrino oscillations

full $\chi^2 = -2\log\mathcal{L}_{\rm osc}$ from global fit [de Salas et al, 2017]

$0\nu\beta\beta$		Neutrino mixing	
Parameter	Prior	Parameter	Prior
α_2	$0 - 2\pi$	$\sin^2\theta_{12}$	$0.1 - 0.6$
α_3	$0 - 2\pi$	$\sin^2\theta_{13}$	$0.00 - 0.06$
$\mathcal{M}^{0\nu}_{^{76}Ge}$	$4.07 - 4.87$	$\sin^2\theta_{23}$	$0.25 - 0.75$
$\mathcal{M}^{0\nu}_{^{136}Xe}$	$2.74 - 3.45$		

Masses: see later!

Parameterizations, priors and data

[SG et al., JCAP 03 (2018) 11]

Cosmological data

Full CMB temperature and polarization spectra from [Planck, 2015], working with ΛCDM model as basis

$0\nu\beta\beta$ data

Likelihood approximations as in [Caldwell et al, 2017], from [Gerda, 2017] (Ge), [KamLAND-Zen, 2016], [EXO-200, 2014] (Xe)

Neutrino oscillations

full $\chi^2 = -2\log\mathcal{L}_{\rm osc}$ from global fit [de Salas et al, 2017]

Cosmological		$0\nu\beta\beta$		Neutrino mixing	
Parameter	Prior	Parameter	Prior	Parameter	Prior
ω_b	0.019 – 0.025	α_2	$0 - 2\pi$	$\sin^2\theta_{12}$	0.1 – 0.6
ω_c	0.095 – 0.145	α_3	$0 - 2\pi$	$\sin^2\theta_{13}$	0.00 – 0.06
Θ_s	1.03 – 1.05	$\mathcal{M}^{0\nu}_{76Ge}$	4.07 – 4.87	$\sin^2\theta_{23}$	0.25 – 0.75
τ	0.01 – 0.4	$\mathcal{M}^{0\nu}_{136Xe}$	2.74 – 3.45		
n_s	0.885 – 1.04				
$\log(10^{10}A_s)$	2.5 – 3.7				

Masses: see later!

Parameterizing neutrino masses

[SG et al., JCAP 03 (2018) 11]

[Simpson et al, 2017]

using m_1, m_2, m_3 (A)

[Caldwell et al, 2017]

using $m_{\rm lightest}$, Δm^2_{21}, $|\Delta m^2_{31}|$ (B)

intuition says: (B) is closer to observable quantities! Better than (A)?

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

Can data help to select (A) or (B), linear or log?

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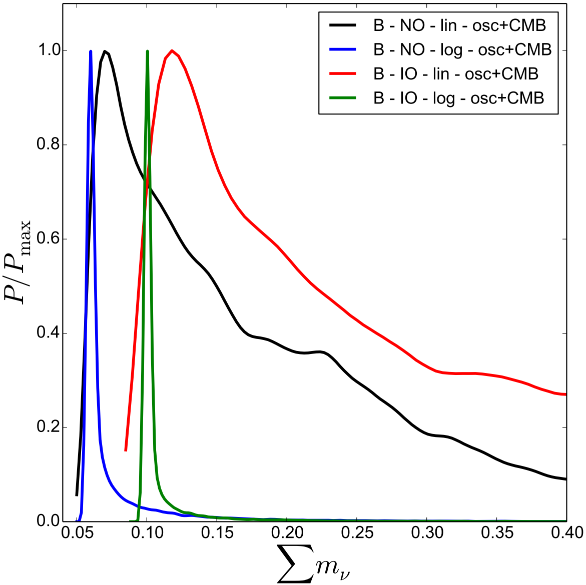
Case A			Case B		
Parameter	Prior	Range	Parameter	Prior	Range
m_1/eV	linear log	$0 - 1$ $10^{-5} - 1$	$m_{\rm lightest}/{\rm eV}$	linear log	$0 - 1$ $10^{-5} - 1$
m_2/eV	linear log	$0 - 1$ $10^{-5} - 1$	$\Delta m^2_{21}/{\rm eV}^2$	linear	$5 \times 10^{-5} - 10^{-4}$
m_3/eV	linear log	$0 - 1$ $10^{-5} - 1$	$|\Delta m^2_{31}|/{\rm eV}^2$	linear	$1.5 \times 10^{-3} - 3.5 \times 10^{-3}$

The role of priors: $\sum m_\nu$

[SG et al., JCAP 03 (2018) 11]

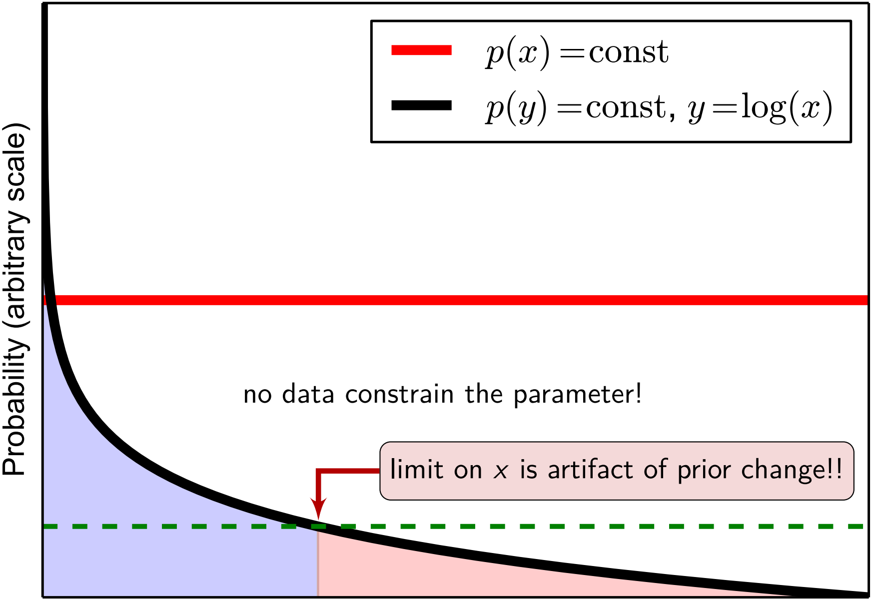


showing case B
(1 mass parameter)

would be the same for case A, but amplified (3 mass parameters!)

The role of priors: $\sum m_\nu$

[SG et al., JCAP 03 (2018) 11]



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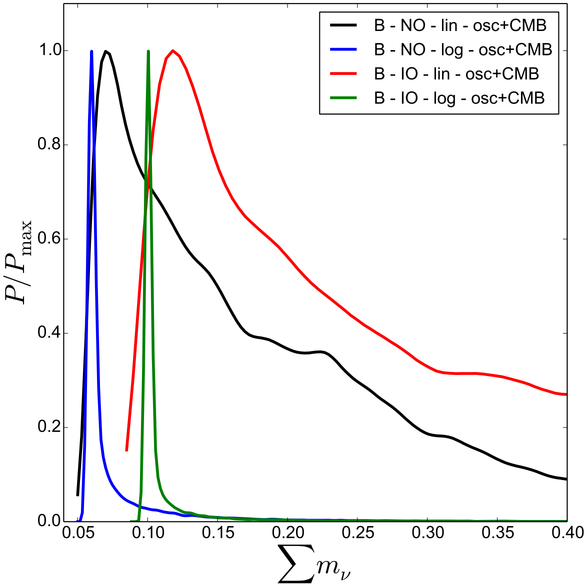

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would be the same for case A, but amplified
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logarithmic prior corresponds to $1/m_k$ probability!

↓

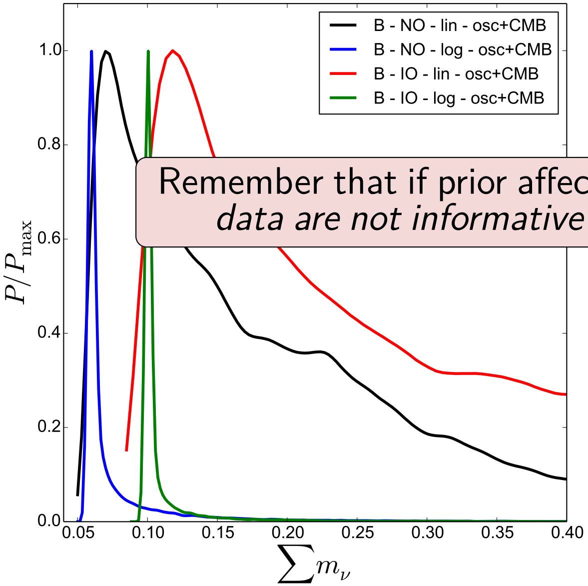
more importance to smaller masses

↓

limits closer to minimum allowed value of $\sum m_\nu$

The role of priors: $\sum m_\nu$

[SG et al., JCAP 03 (2018) 11]



Remember that if prior affects posterior,
data are not informative enough!

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would be the same for
case A, but amplified
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The role of priors: $\sum m_\nu$

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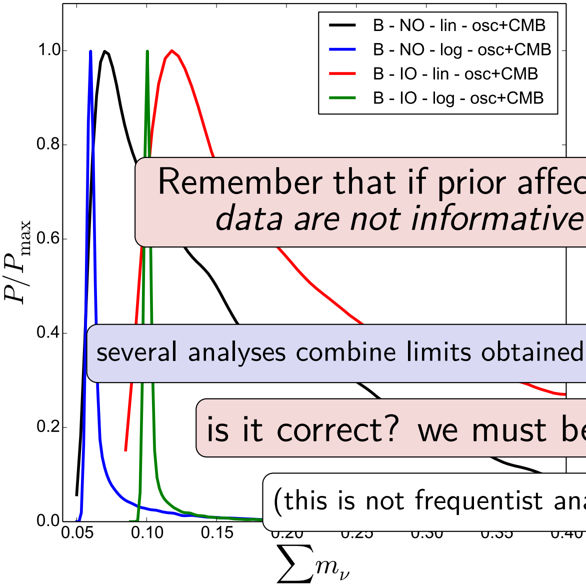

showing case B
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would be the same for case A, but amplified
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logarithmic prior corresponds to $1/m_\nu$ probability!

more importance
aller masses
↓
limits closer to
minimum allowed
value of $\sum m_\nu$

Remember that if prior affects posterior,
data are not informative enough!

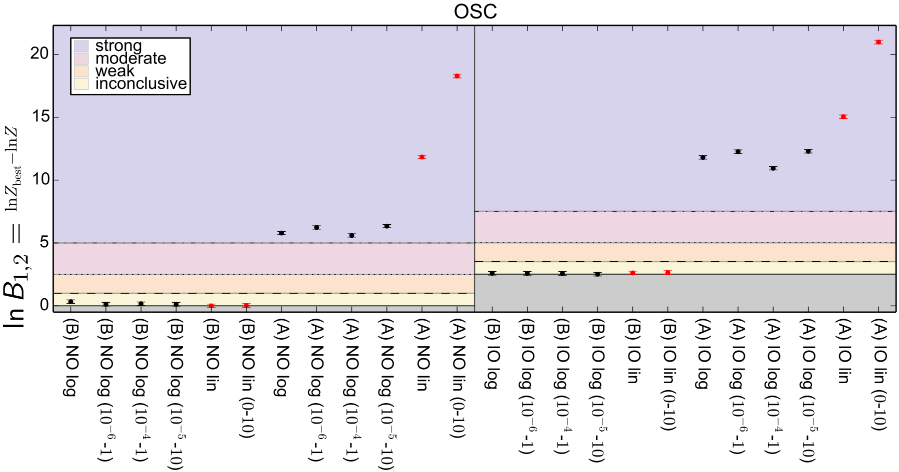
several analyses combine limits obtained with different priors

is it correct? we must be careful!

(this is not frequentist analysis)

Comparing parameterizations/priors

[SG et al., JCAP 03 (2018) 11]



Comparing parameterizations/priors

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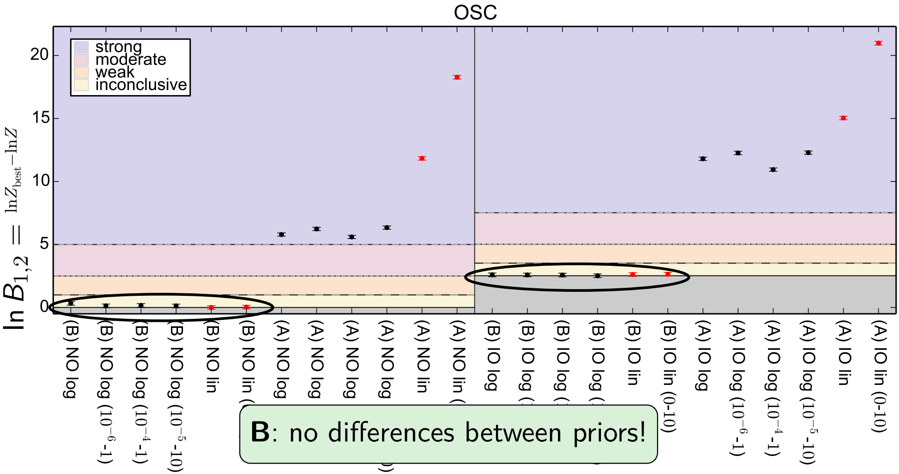

B: no differences between priors!

(no penalty for unconstrained parameter $m_{\rm lightest}$!)

Comparing parameterizations/priors

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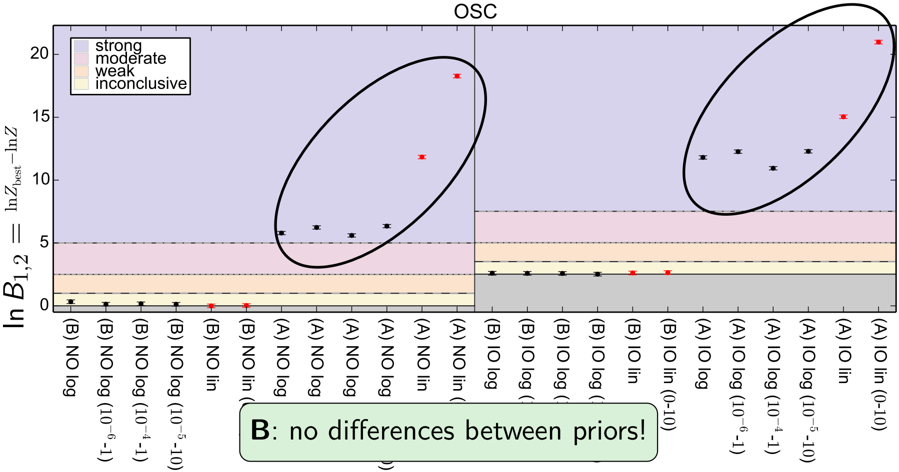


B: no differences between priors!

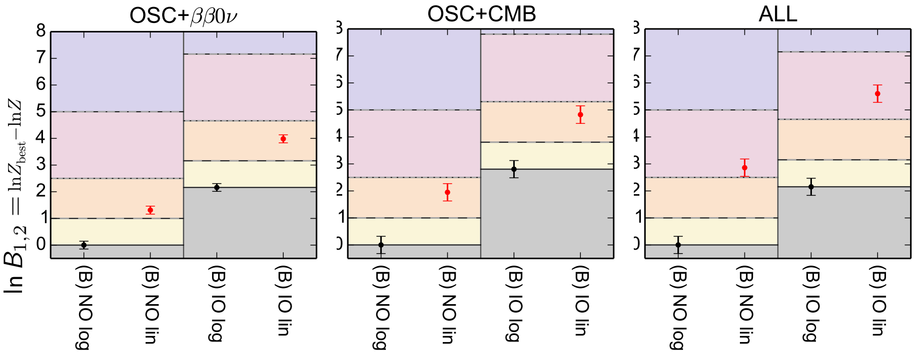
(no penalty for unconstrained parameter $m_{\rm lightest}$!)

A: always strongly disfavored!

(waste of parameter space, no unconstrained parameters due to Δm^2_{i1}!)

Comparing parameterizations/priors

[SG et al., JCAP 03 (2018) 11]



compare linear versus **logarithmic**

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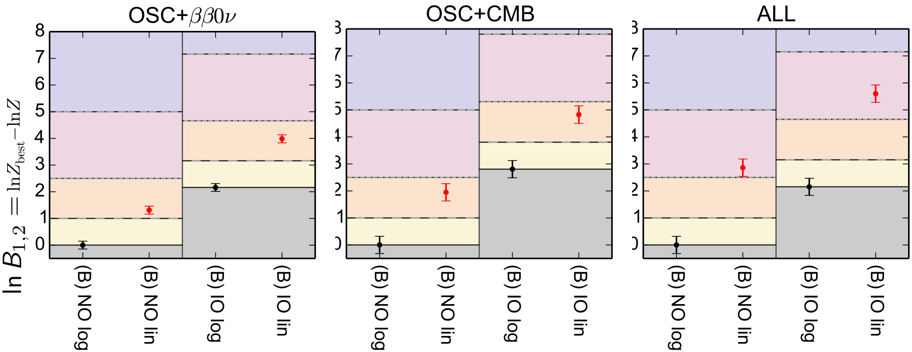

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log priors are
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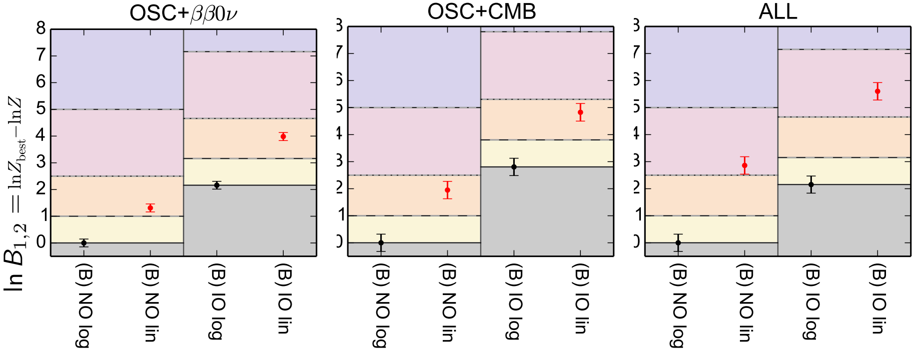

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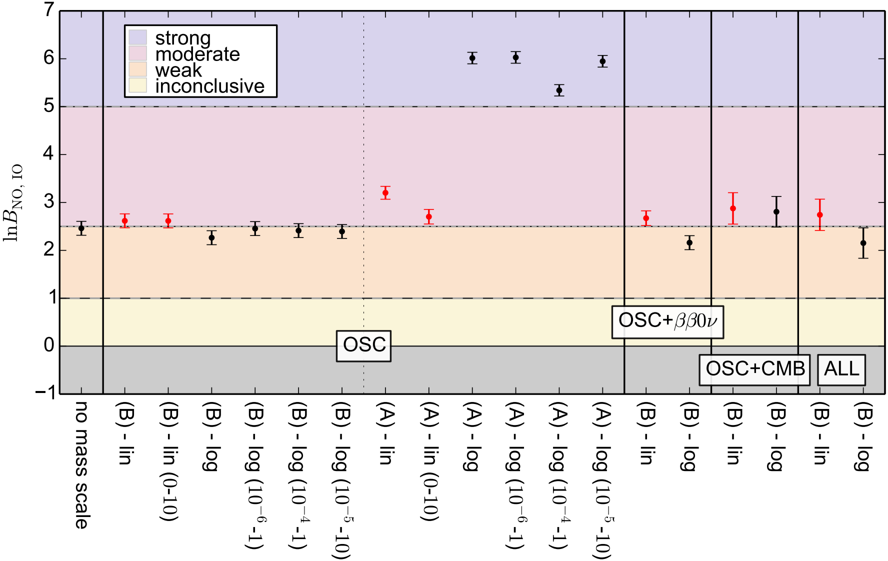
summary: case B, log prior is better!

Comparing the mass orderings

[SG et al., JCAP 03 (2018) 11]



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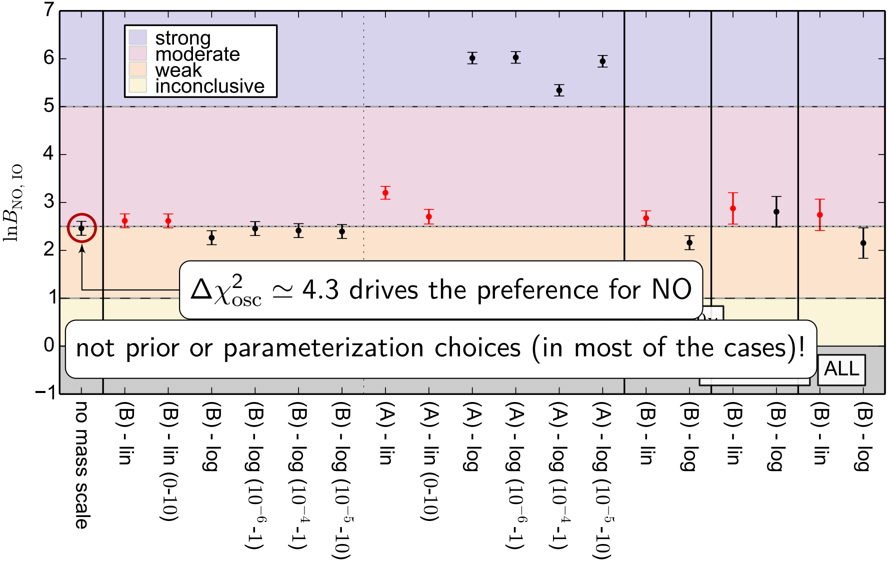
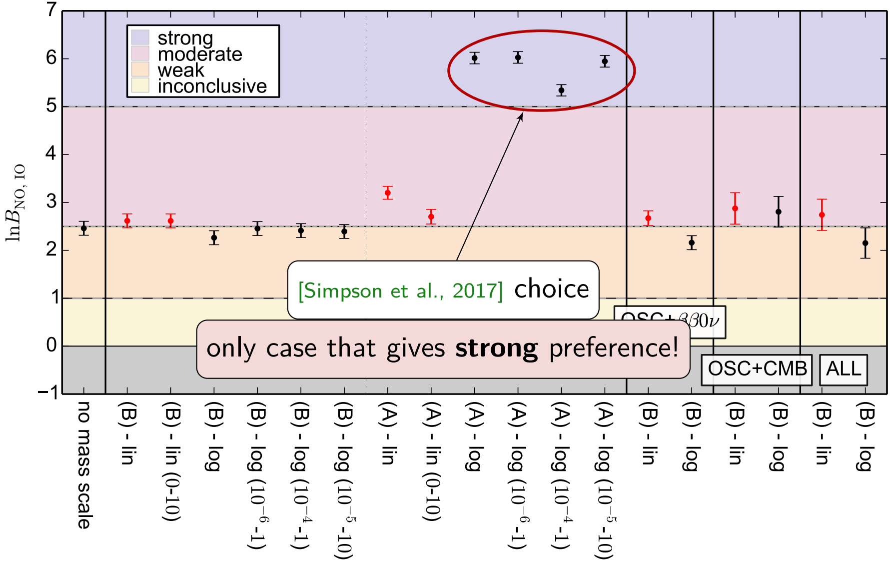


$\Delta\chi^2_{\mathrm{osc}} \simeq$ 4.3 drives the preference for NO

not prior or parameterization choices (in most of the cases)!

Comparing the mass orderings

[SG et al., JCAP 03 (2018) 11]

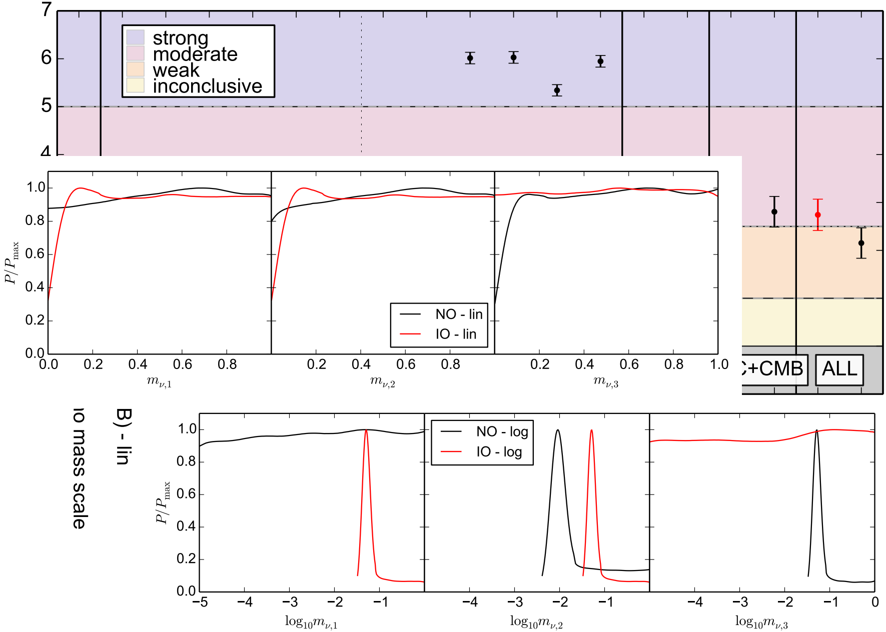


[Simpson et al., 2017] choice

only case that gives **strong** preference!

Comparing the mass orderings

[SG et al., JCAP 03 (2018) 11]



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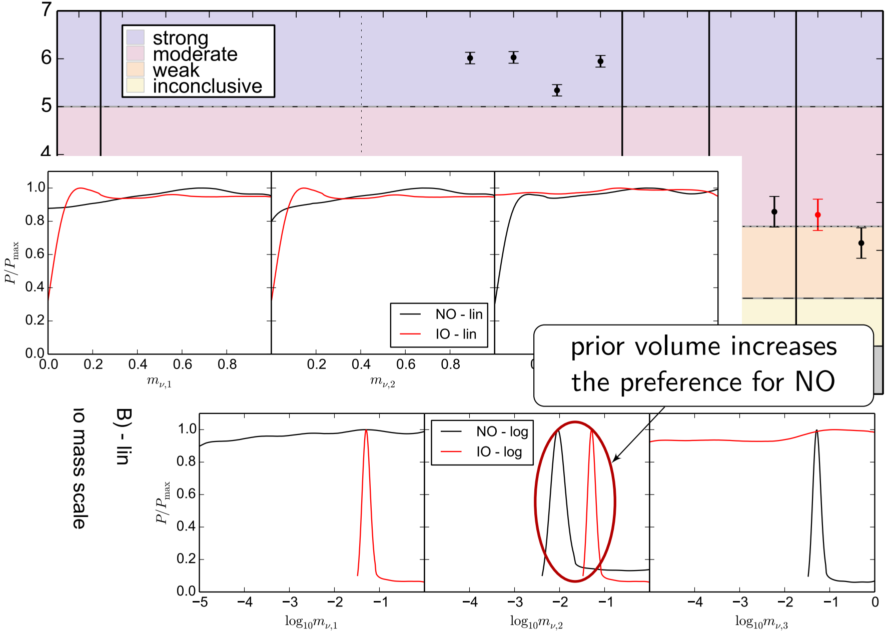


prior volume increases the preference for NO

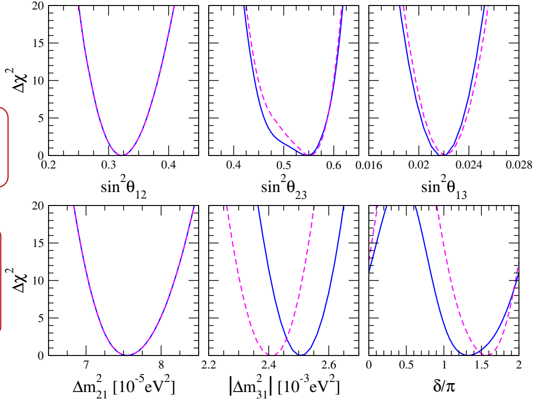
Neutrino oscillations as of 2018

[de Salas et al., arxiv:1708.01186v3]

Current status after NOνA, Super-K and T2K updates:

$\chi^2_{\rm IO}-\chi^2_{\rm NO}$
$\simeq 11.7$

3.4σ
preference
for NO



$$\sin^2(\theta_{12}) = 0.320^{+0.020}_{-0.016}$$
$$\sin^2(\theta_{13}) = 0.0216^{+0.008}_{-0.007}\ \mathrm{(NO)}$$
$$= 0.0222^{+0.007}_{-0.008}\ \mathrm{(IO)}$$
$$\sin^2(\theta_{23}) = 0.547^{+0.020}_{-0.030}\ \mathrm{(NO)}$$
$$= 0.551^{+0.018}_{-0.030}\ \mathrm{(IO)}$$

$$\Delta m^2_{21} = (7.55^{+0.20}_{-0.16})\cdot 10^{-5}\ \mathrm{eV}^2$$
$$|\Delta m^2_{31}| = (2.50\pm 0.03)\cdot 10^{-3}\ \mathrm{eV}^2\ \mathrm{(NO)}$$
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First hints for $\delta_{\rm CP}\simeq 3/2\pi$

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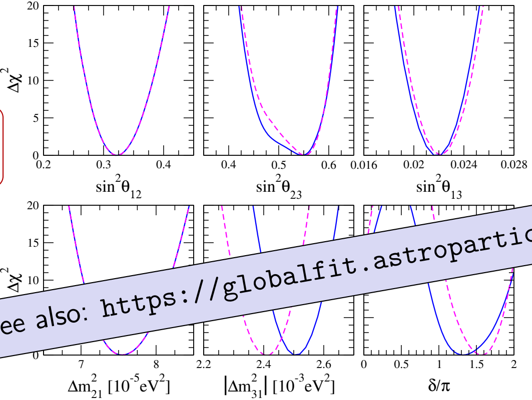

$\chi^2_{\rm IO} - \chi^2_{\rm NO}$
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see also: `https://globalfit.astroparticles.es/`

$$\begin{aligned}
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Conclusions

Is there a light sterile neutrino?

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Not completely clear.

If yes, problems in early universe!

More new physics to be discovered?

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And what about the mass ordering?

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Only oscillations can really tell something.
Cosmology not precise enough *(yet)*

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③ Be **careful** when you play with **priors in Bayesian analysis!**

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Be **careful** when you play with
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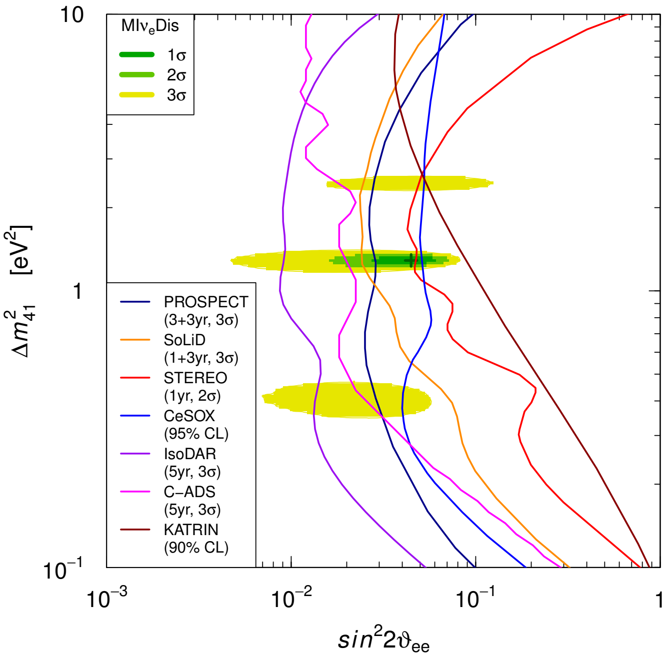
Thank you for the attention!

4 Sterile

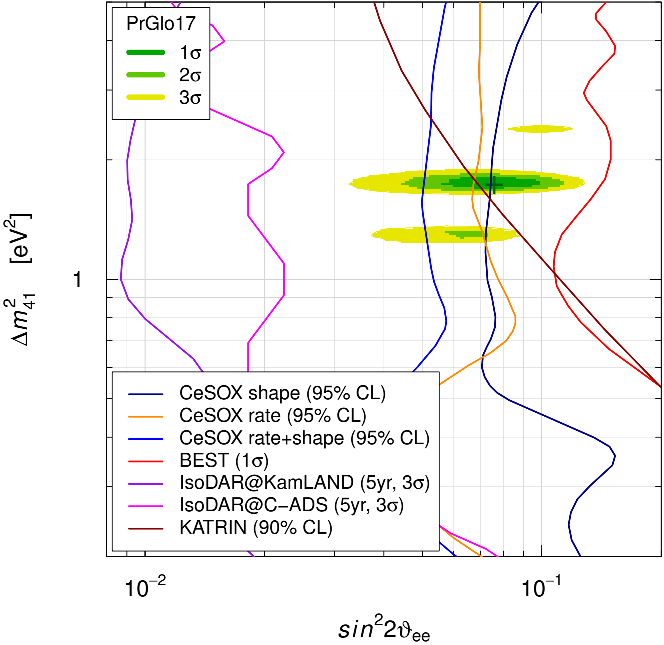
Sensitivity of future experiments - 2018

[SG et al., PLB 782 (2018) 13]



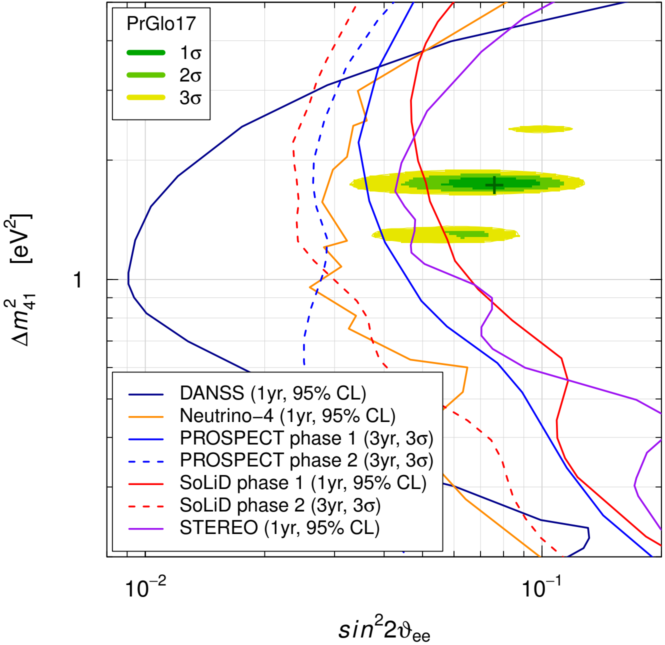
Sensitivity of future experiments - I

[SG et al., JHEP 06 (2017) 135]



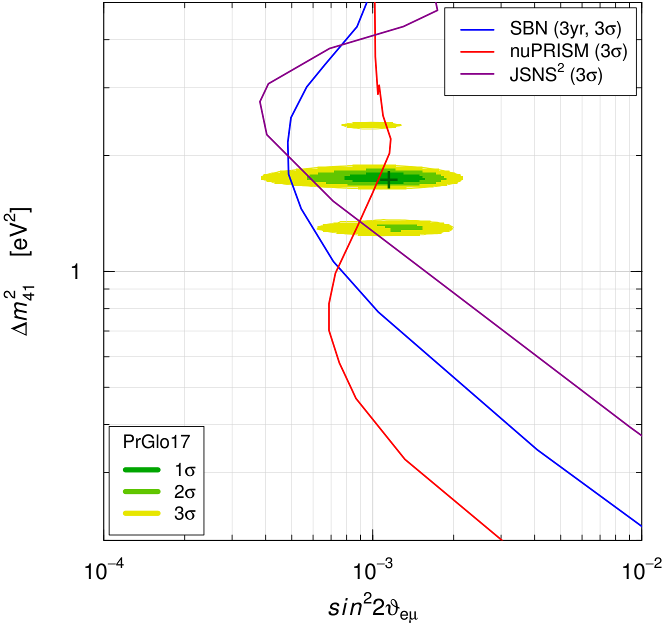
Sensitivity of future experiments - II

[SG et al., JHEP 06 (2017) 135]



Sensitivity of future experiments - III

[SG et al., JHEP 06 (2017) 135]



Sensitivity of future experiments - IV

[SG et al., JHEP 06 (2017) 135]