Neutrino cosmology

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Fredagskollokvium, Institute of Theoretical Astrophysics
Oslo, 6 March 2020

What's in a name?

Let's go back in time...

"Nomen [est] omen"

What's in a νame?

Language	**Word tree**	*…Some branches*	**Meaning**
Physics (Fermi 1934)	**NEUTR-INO**		**Little neutral one**
Italian	**NEUTRO**		**Neutral**
Latin	**NE-UTER**		**Not either; neutral**
Latin	**UTER**		**Either**
Greek	↑	*OUDETEROS*	*Neutral*
Old High German		↗ *HWEDAR*	*Which of two; whether*
Phonetic change/loss	[K]**UOTER**[US]		**Which of the two?**
Ionic Greek	**KOTEROS**		**Which of the two?**
Sanskrit	**KATARAS**		**Which of the two?**
Latin	↑	*QUANTUS*	*How much?*
Sanskrit		*KATAMAS*	*Which out of many?*
Sanskrit		*KATHA*	*How?*
Sanskrit		↗ *KAS*	*Who?*
Indo-European root	**KA** *or* **KWA**		**Interrogative base**

Answer: ν's destiny is to raise kwastions!

Courtesy of Eligio Lisi, Summary Talk (Theory) at Neutrino 2010, Athens

Preliminary kwastion

Why care about neutrino masses and neutrino cosmology?

Preliminary kwastion

Because neutrino masses are the only **direct evidence** *for BSM physics*

- Because neutrinos are the only SM particles of unknown mass
- Because cosmology *should* measure the total neutrino mass in the next years
- Because measuring the neutrino mass could be a step forward towards unveiling other properties (mass ordering, Dirac/Majorana nature,...)

Asking the right questions

- `Q1`: How strong are cosmological bounds on M_ν (neutrino mass sum)?
- `Q2`: Can cosmology tell us something about the mass ordering?
- `Q3`: Large-scale structure data seems to be a powerful probe for M_ν, but I heard there's a complication called galaxy bias...?
- `Q4`: Can neutrinos shed light on dark energy and cosmic acceleration?
- `Q5`: Can neutrinos confuse our conclusions about inflation and the initial conditions for the hot Big Bang model?

Asking the right questions

- Q1: How strong are cosmological bounds on M_ν (neutrino mass sum)?
- A1: **Very (with some caveats)**

- Q2: Can cosmology tell us something about the mass ordering?
- A2: **Yes (with some caveats)**

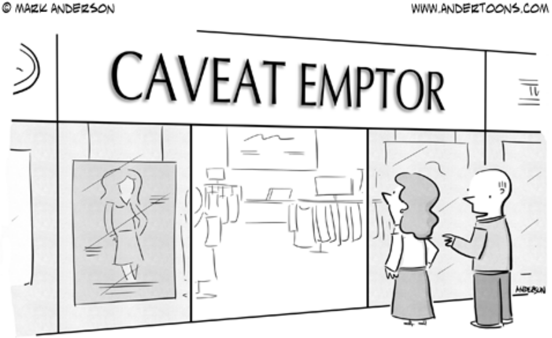
- Q3: Large-scale structure data is a powerful probe of M_ν, but I heard there's a complication called (scale-dependent) galaxy bias...?
- A3: **Yes, but we're working to deal with it...**

- Q4: Can neutrinos shed light on cosmic acceleration?
- A4: **In principle (with some caveats)**

- Q5: Can neutrinos confuse our conclusions about inflation and the initial conditions for the hot Big Bang model?
- A5: **In principle, but it's unlikely**

Asking the right questions

- Q6: Is cosmology full of caveats?
- A6: **Yes (with some caveats)**



"It sounds fancy, and we don't have to worry about refunds."

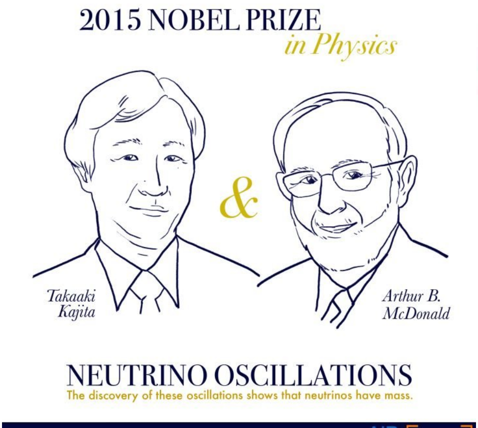
My contributions to the field

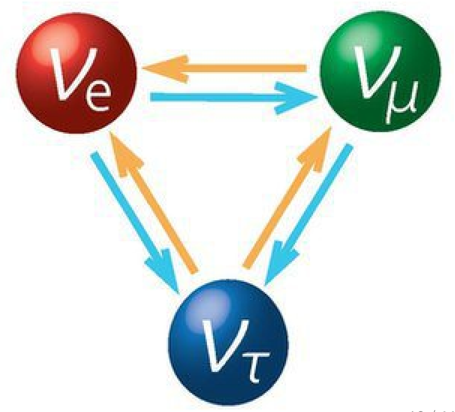
Based on:

- **SV**, E. Giusarma, O. Mena, K. Freese, M. Gerbino, S. Ho, M. Lattanzi, *Phys. Rev.* D **96** (2017) 123503 [arXiv:1701.08172]
  What does current data tell us about the neutrino mass scale and mass ordering? How to quantify how much the normal ordering is favoured?
- E. Giusarma, **SV**, S. Ho, S. Ferraro, K. Freese, R. Kamen-Rubio, K. B. Luk, *Phys. Rev.* D **98** (2018) 123526 [arXiv:1802.08694]
  Nailing the scale-dependent galaxy bias through CMB lensing-galaxy cross-correlations?
- **SV**, T. Brinckmann, M. Archidiacono, K. Freese, M. Gerbino, J. Lesgourgues, T. Sprenger, *JCAP* **1809** (2018) 001 [arXiv:1807.04672]
  Scale-dependent galaxy bias induced by neutrinos: should we worry?
- **SV**, S. Dhawan, M. Gerbino, K. Freese, A. Goobar, O. Mena, *Phys. Rev.* D **98** (2018) 083501 [arXiv:1801.08553]
  Can the neutrino mass ordering and lab experiments tell us something about dark energy?
- M. Gerbino, K. Freese, **SV**, M. Lattanzi, O. Mena, E. Giusarma, S. Ho, *Phys. Rev.* D **95** (2017) 043512 [arXiv:1610.08830]
  Neutrinos as a nuisance: can they mess up our conclusions about inflation?

Neutrino masses

Nobel Prize 2015: "*för upptäckten av neutrinooscillationer, som visar att neutriner har massa*" ("for the discovery of neutrino oscillations, which shows that neutrinos have mass")





Neutrinos from the lab

Flavour transition probability in vacuum:

$$P_{\alpha\to\beta} \propto \sin^2\left(\frac{\Delta m^2 L}{E}\right)$$

2 non-zero $\Delta m^2 \to$ at least 2 out of 3 mass eigenstates are massive

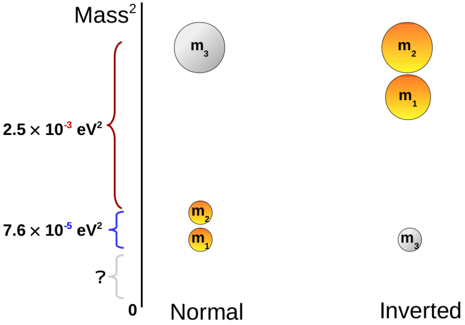
$$\begin{aligned}\Delta m^2_{21} &\equiv m_2^2 - m_1^2 = (7.6 \pm 0.2) \times 10^{-5}\,\mathrm{eV}^2\,,\\ |\Delta m^2_{31}| &\equiv |m_3^2 - m_1^2| = (2.48 \pm 0.06) \times 10^{-3}\,\mathrm{eV}^2\,.\end{aligned}$$

Esteban *et al.*, JHEP 1701 (2017) 087

Note uncertainty in sign of $\mathbf{\Delta m^2_{31}}$ $\to$ two possible mass orderings

Neutrino mass ordering

Lower limit on the absolute mass scale depending on the mass ordering

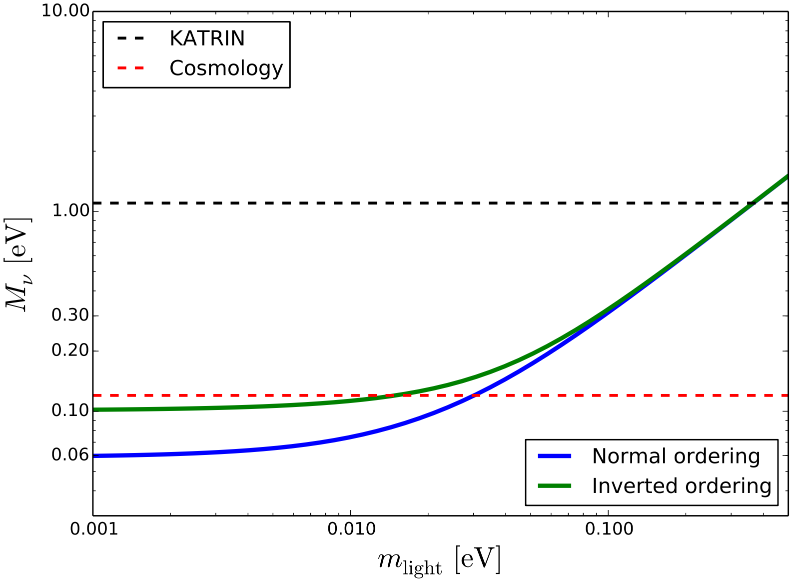


Credits: Hyper-Kamiokande collaboration

Normal ordering (NO)
$M_\nu > 0.06\,\mathrm{eV}$

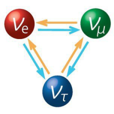
Inverted ordering (IO)
$M_\nu > 0.1\,\mathrm{eV}$

Neutrino mass ordering



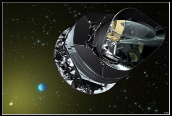
Neutrino oscillations

- Sensitive to mass-squared differences $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$
- Exploits quantum-mechanical effects
- Currently not sensitive to the mass ordering



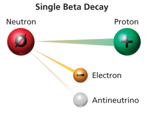
Cosmology

- Sensitive to sum of neutrino masses $M_\nu \equiv \sum_i m_i$
- Exploits GR+Boltzmann equations
- Tightest limits, but somewhat model-dependent



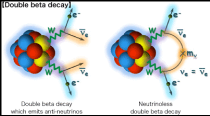
Beta decay

- Sensitive to effective electron neutrino mass $m_\beta^2 \equiv \sum_i |U_{ei}|^2 m_i^2$
- Exploits conservation of energy
- Model-independent, but less tight bounds



Neutrinoless double-beta decay

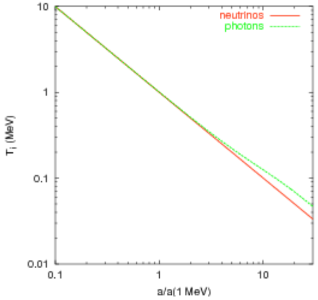
- Sensitive to effective Majorana mass $m_{\beta\beta} \equiv \sum_i |U_{ei}^2 m_i|$
- Exploits $0\nu2\beta$ decay (if νs are Majorana)
- Limited by NME uncertainties and ν nature



Basic facts of neutrino cosmology

- $T \gtrsim 1\,\mathrm{MeV}$: weak interactions maintain νs in thermal equilibrium with the primeval cosmological plasma $[T_\nu = T_\gamma]$
- $T \lesssim 1\,\mathrm{MeV}$: νs free-stream keeping an equilibrium spectrum

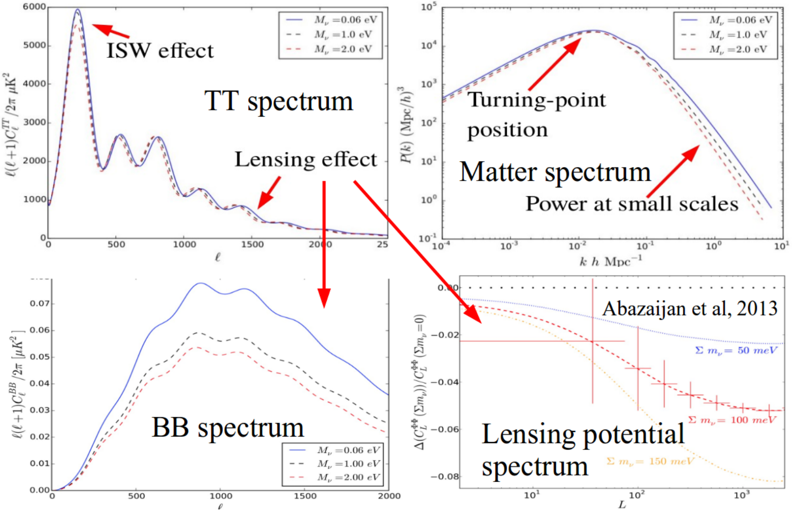
$$T_\nu = (4/11)^{\frac{1}{3}}\, T_\gamma$$



Lesgourgues & Pastor, AHEP 2012 (2012) 608515

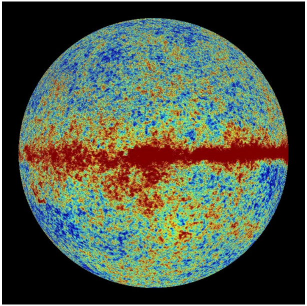
- $T \lesssim M_\nu$: νs turn non-relativistic, free-streaming suppresses the growth of structure on small scales (**VERY IMPORTANT**)

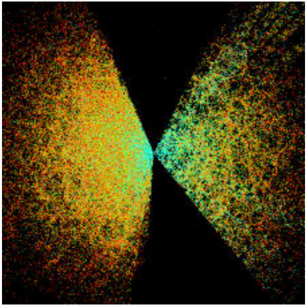
How can cosmology measure neutrino masses?



Courtesy of Martina Gerbino

Cosmology in 6 numbers

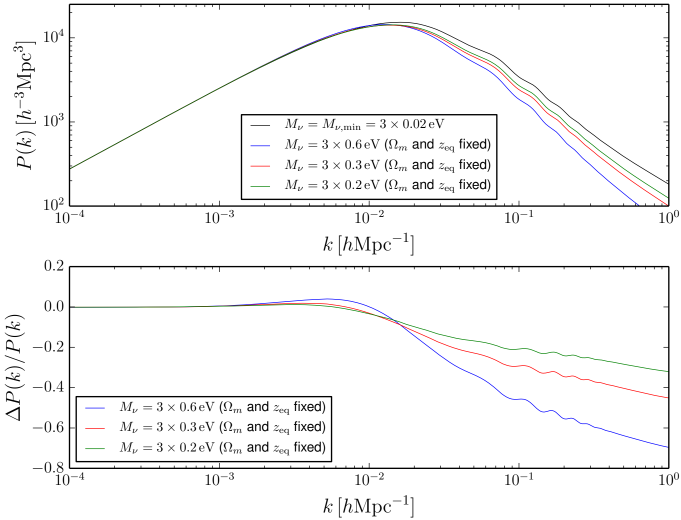




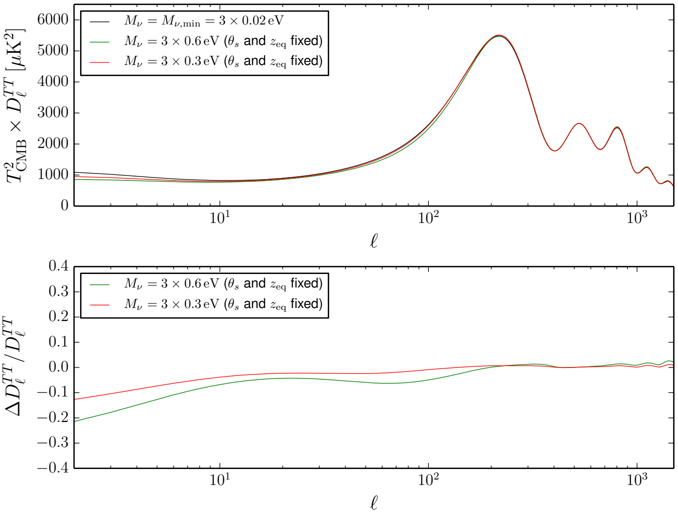
- θ_s: key angular scale (related to H_0)
- ω_b, ω_c ($+M_\nu$): matter/energy content
- A_s, n_s: spectrum of primordial (scalar) fluctuations
- τ: late-time effects (reionization)

Simplifying a bit, less well-measured physical effects than parameters $\rightarrow$ **parameter degeneracies** (underconstrained system)

Effect of neutrino masses on the LSS

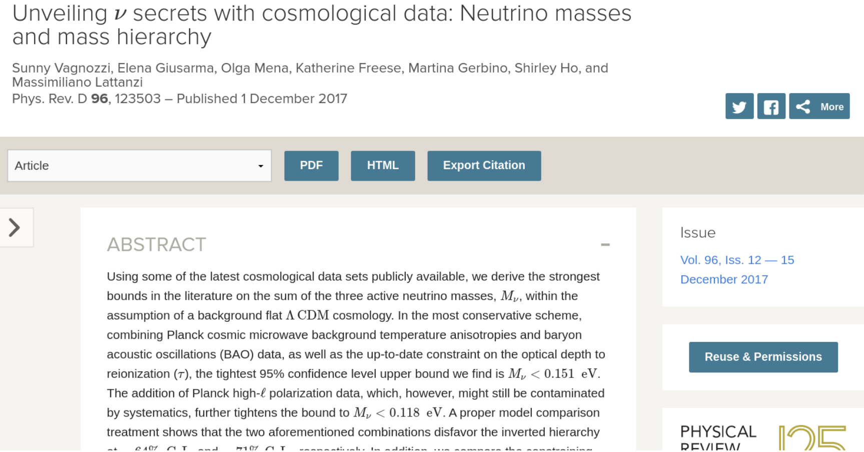


Effect of neutrino masses on the CMB



SV, E. Giusarma, O. Mena, K. Freese, M. Gerbino, S. Ho, M. Lattanzi, *Phys. Rev.* D **96** (2017) 123503 [arXiv:1701.08172]

What does current data tell us about the neutrino mass scale and mass ordering? How to quantify how much the normal ordering is favoured?



Unveiling ν secrets with cosmological data: Neutrino masses and mass hierarchy

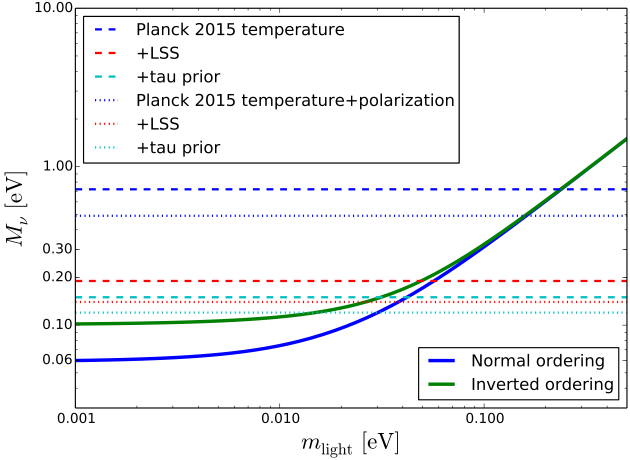
Sunny Vagnozzi, Elena Giusarma, Olga Mena, Katherine Freese, Martina Gerbino, Shirley Ho, and Massimiliano Lattanzi

Phys. Rev. D **96**, 123503 – Published 1 December 2017

ABSTRACT

Using some of the latest cosmological data sets publicly available, we derive the strongest bounds in the literature on the sum of the three active neutrino masses, M_ν, within the assumption of a background flat Λ CDM cosmology. In the most conservative scheme, combining Planck cosmic microwave background temperature anisotropies and baryon acoustic oscillations (BAO) data, as well as the up-to-date constraint on the optical depth to reionization (τ), the tightest 95% confidence level upper bound we find is $M_\nu < 0.151$ eV. The addition of Planck high-ℓ polarization data, which, however, might still be contaminated by systematics, further tightens the bound to $M_\nu < 0.118$ eV. A proper model comparison treatment shows that the two aforementioned combinations disfavor the inverted hierarchy

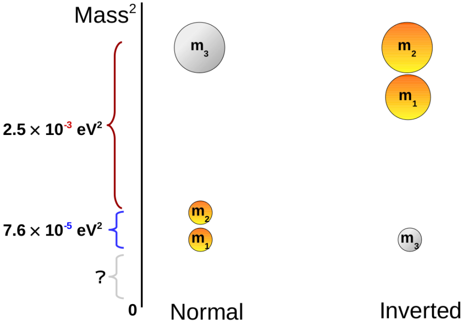
What does data have to say about all this?



SV *et al.*, PRD 96 (2017) 123503

What can cosmology say about the mass ordering?

Naïvely might think that $M_\nu < 0.1\,\mathrm{eV}$ is enough to exclude IO!



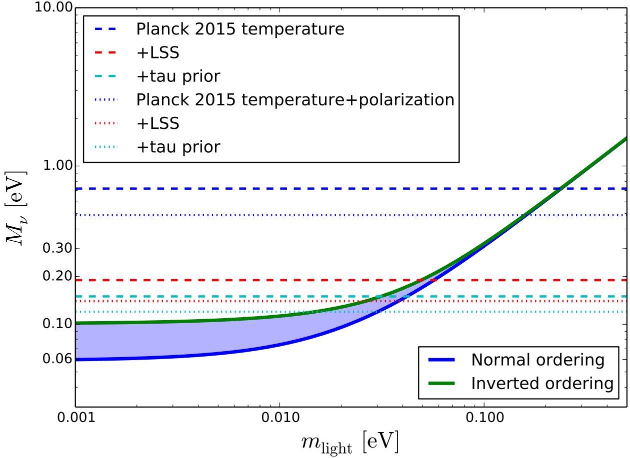
Credits: Hyper-Kamiokande collaboration

Normal ordering
$M_\nu > 0.06\,\mathrm{eV}$

Inverted ordering
$M_\nu > 0.1\,\mathrm{eV}$

What can cosmology say about the mass ordering?

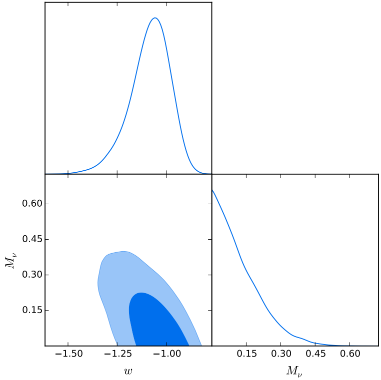
Bayesian model selection problem between normal and inverted ordering



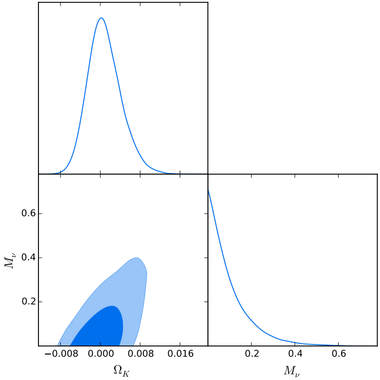
Weak (3:1) preference for normal due to volume effects SV *et al.*, PRD 96 (2017) 123503

Degeneracies and model-dependence

Previous limits derived assuming 7-parameter ΛCDM+M_ν. What happens if we leave the dark energy equation of state w or the curvature parameter Ω_k free?



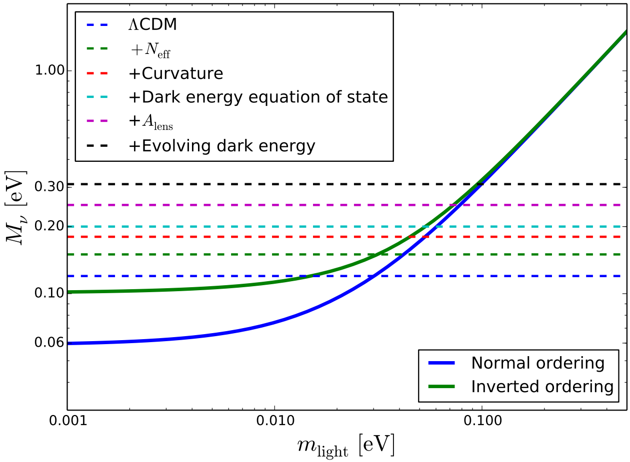
SV *et al.*, PRD 96 (2017) 123503



SV *et al.*, PRD 96 (2017) 123503

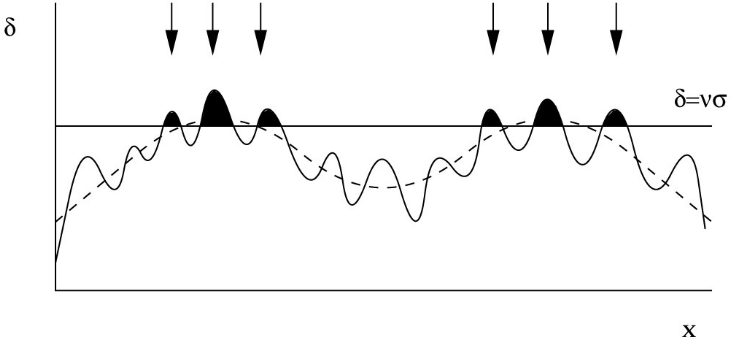
Degeneracies and model-dependence

The weakness of cosmology: limits on M_ν degrade in extended parameter spaces due to **parameter degeneracies**



Galaxy bias

Galaxy bias



$$P_g(k) = b^2(k) P_m(k)$$

$P_m(k)$: what we want to measure (neutrino mass signature is here)
$P_g(k)$: what we measure
$b^2(k)$: what makes life hard (usually assumed constant)

We need a better handle on the (scale-dependent) bias!

E. Giusarma, **SV**, S. Ho, S. Ferraro, K. Freese, R. Kamen-Rubio, K. B. Luk, *Phys. Rev.* D **98** (2018) 123526 [arXiv:1802.08694]

Nailing the scale-dependent galaxy bias through CMB lensing-galaxy cross-correlations?

Scale-dependent galaxy bias, CMB lensing-galaxy cross-correlation, and neutrino masses

Elena Giusarma, Sunny Vagnozzi, Shirley Ho, Simone Ferraro, Katherine Freese, Rocky Kamen-Rubio, and Kam-Biu Luk

Phys. Rev. D **98**, 123526 – Published 20 December 2018

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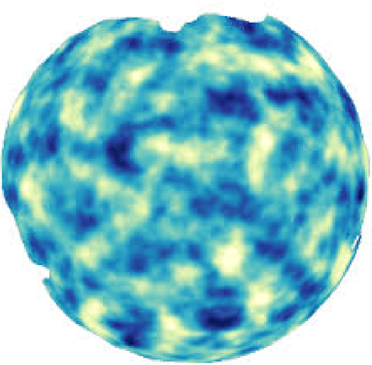
ABSTRACT

One of the most powerful cosmological data sets when it comes to constraining neutrino masses is represented by galaxy power spectrum measurements, $P_{gg}(k)$. The constraining power of $P_{gg}(k)$ is however severely limited by uncertainties in the modeling of the scale-dependent galaxy bias $b(k)$. In this work we present a new proof-of-principle for a method to constrain $b(k)$ by using the cross-correlation between the cosmic microwave background (CMB) lensing signal and galaxy maps ($C_\ell^{\kappa g}$) using a simple but theoretically well-motivated parametrization for $b(k)$. We apply the method using $C_\ell^{\kappa g}$ measured by cross-correlating

Cross-correlating CMB lensing and galaxies



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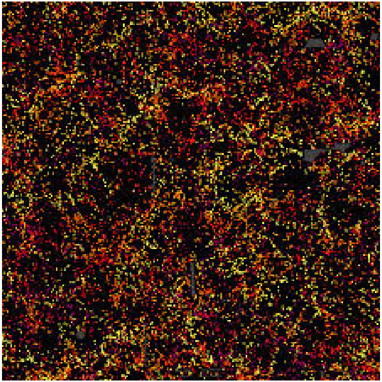

$$
\begin{aligned}
P_{gg}(k) &\propto b^2(k) \\
C_\ell^{\kappa g} &\propto b^1(k) \\
b(k) &\propto c_1 + c_2 k^2
\end{aligned}
$$

This works, *with some caveats*... Giusarma, SV et al., PRD 98 (2018) 123526

Bias in the presence of massive neutrinos

SV, T. Brinckmann, M. Archidiacono, K. Freese, M. Gerbino, J. Lesgourgues, T. Sprenger, *JCAP* **1809** (2018) 001 [arXiv:1807.04672]

Scale-dependent galaxy bias induced by neutrinos: should we worry?

SISSA

Bias due to neutrinos must not uncorrect'd go

Sunny Vagnozzi[a,b], Thejs Brinckmann[c], Maria Archidiacono[c], Katherine Freese[a,b,d], Martina Gerbino[a], Julien Lesgourgues[c] and Tim Sprenger[c]

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Abstract

Abstract

It is a well known fact that galaxies are biased tracers of the distribution of matter in the Universe. The galaxy bias is usually factored as a function of redshift and scale, and approximated as being scale-independent on large, linear scales. In cosmologies with massive neutrinos, the galaxy bias defined with respect to the total matter field (cold dark matter, baryons, and non-relativistic neutrinos) also depends on the sum of the neutrino masses M_ν, and becomes scale-dependent even on large scales. This effect has been usually neglected given the sensitivity of current surveys. However, it becomes a severe systematic

Neutrino-induced scale-dependent bias (NISDB)

In cosmologies with massive neutrinos, the bias as usually defined is scale-dependent *even on large scales* and depends on M_ν

$$P_g(k) = b^2_m(M_\nu)P_m(k)$$

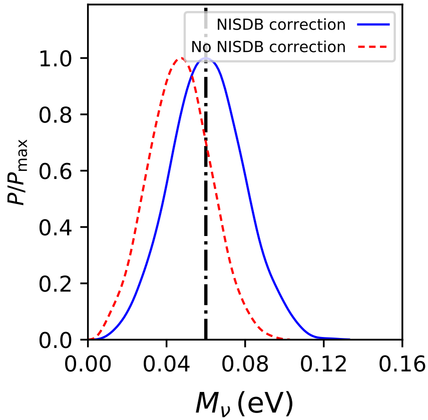
vs

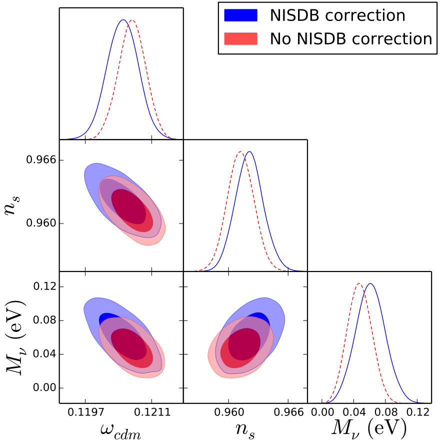
$$P_g(k) = b^2_{cb}P_{cb}(k)$$

Physical reason: halo formation to leading order responds to CDM+baryons field (galaxies form in peaks of CDM+baryon density field)

Neutrino-induced scale-dependent bias (NISDB)

Notice *degeneracy* with n_s!





SV *et al.*, JCAP 1809 (2018) 001

SV *et al.*, JCAP 1809 (2018) 001

M_ν-n_s degeneracy

Inflation sets initial conditions for the Universe...

...whose signature is messed up by massive neutrinos?

M. Gerbino, K. Freese, **SV**, M. Lattanzi, O. Mena, E. Giusarma, S. Ho, *Phys. Rev.* D **95** (2017) 043512 [arXiv:1610.08830]

Neutrinos as a nuisance: can they mess up our conclusions about inflation?

Impact of neutrino properties on the estimation of inflationary parameters from current and future observations

Martina Gerbino, Katherine Freese, Sunny Vagnozzi, Massimiliano Lattanzi, Olga Mena, Elena Giusarma, and Shirley Ho

Phys. Rev. D **95**, 043512 – Published 15 February 2017

Article PDF HTML Export Citation

ABSTRACT

We study the impact of assumptions about neutrino properties on the estimation of inflationary parameters from cosmological data, with a specific focus on the allowed contours in the n_s/r plane, where n_s is the scalar spectral index and r is the tensor-to-scalar ratio. We study the following neutrino properties: (i) the total neutrino mass $M_\nu = \sum_i m_i$ (where the index $i = 1, 2, 3$ runs over the three neutrino mass eigenstates); (ii) the number of relativistic degrees of freedom $N_{\rm eff}$ at the time of recombination; and (iii) the neutrino hierarchy. Whereas previous literature assumed three degenerate neutrino masses or two massless neutrino species (approximations that clearly do not match neutrino oscillation data), we study the cases of normal and inverted hierarchy. Our basic result is that these three neutrino properties induce $< 1\sigma$ shift of the probability contours in

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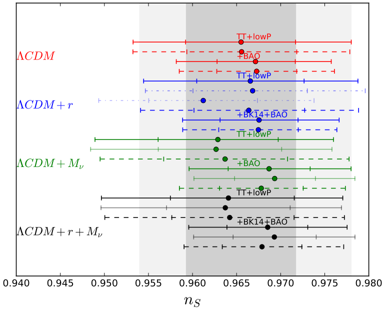
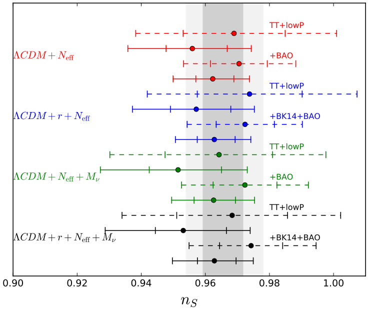
Neutrinos as a nuisance for inflationary parameters

Focusing on M_ν and modelling of neutrino mass ordering



Gerbino, Freese, SV, et al., PRD 95 (2017) 043512

Focusing on effective number of neutrino species $N_{\rm eff}$



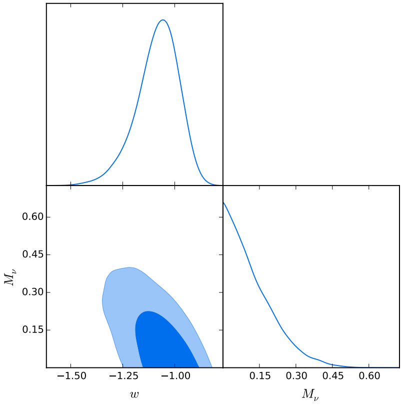
Gerbino, Freese, SV, et al., PRD 95 (2017) 043512

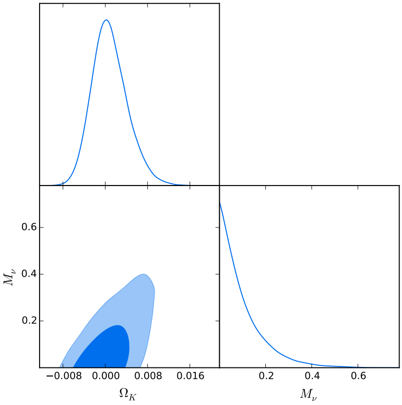
What can cosmology do for neutrinos?

⇓

What can neutrinos do for cosmology?

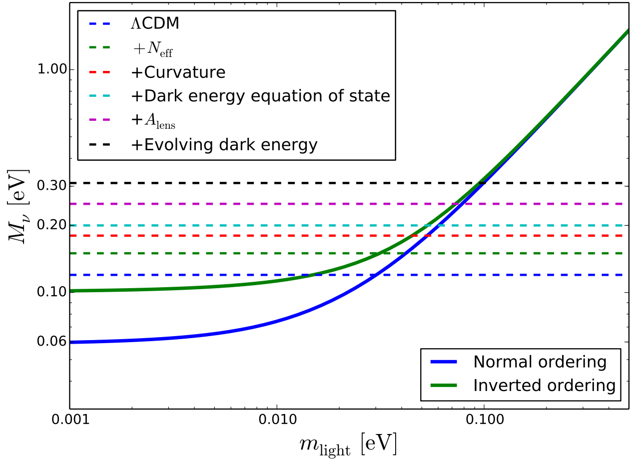
Recap: degeneracies and model-dependence





Recap: degeneracies and model-dependence

Limits on M_ν *usually* degrade in extended parameter spaces



Is this always the case?

SV, S. Dhawan, M. Gerbino, K. Freese, A. Goobar, O. Mena, *Phys. Rev.* D **98** (2018) 083501 [arXiv:1801.08553]

Can the neutrino mass ordering and lab experiments tell us something about dark energy?

Constraints on the sum of the neutrino masses in dynamical dark energy models with $w(z) \geq -1$ are tighter than those obtained in ΛCDM

Sunny Vagnozzi, Suhail Dhawan, Martina Gerbino, Katherine Freese, Ariel Goobar, and Olga Mena

Phys. Rev. D **98**, 083501 – Published 1 October 2018

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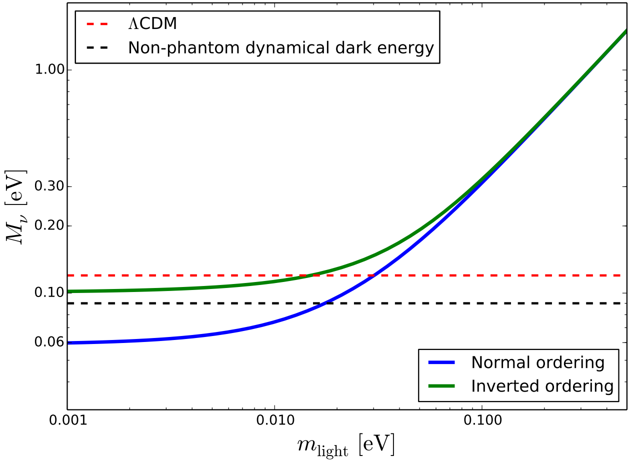
ABSTRACT

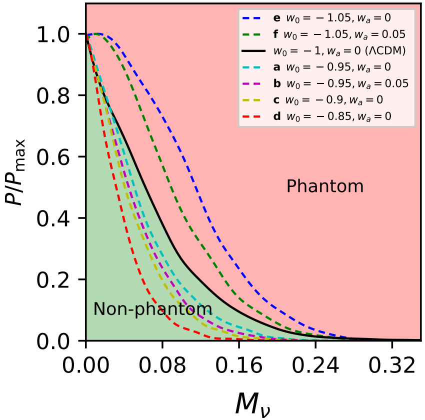
We explore cosmological constraints on the sum of the three active neutrino masses M_ν in the context of dynamical dark energy (DDE) models with equation of state (EoS) parametrized as a function of redshift z by $w(z) = w_0 + w_a z/(1+z)$, and satisfying $w(z) \geq -1$ for all z. We make use of cosmic microwave background data from the Planck satellite, baryon acoustic oscillation measurements, and supernovae Ia luminosity distance measurements, and perform a Bayesian analysis. We show that, within these models, the bounds on M_ν *do not degrade* with respect to those obtained in the ΛCDM case; in fact, the bounds are slightly tighter, despite the enlarged parameter space. We explain our results based on the observation that, for fixed choices of w_0, w_a such that $w(z) \geq -1$ (but not $w = -1$ for all z), the upper limit on M_ν is tighter than the ΛCDM limit because of the

Non-phantom dynamical dark energy

General parametrization for evolving non-phantom ($w(z) \geq -1$) dark energy (representative of e.g. single-field quintessence)



Non-phantom dynamical dark energy



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- Non-phantom dynamical dark energy models prefer normal ordering more strongly than ΛCDM
- A potential discovery of inverted ordering from near-future long-baseline experiments would disfavour quintessence (proof by contradiction: quintessence wants too light neutrinos)...
- ...lab experiments might shed light on dark energy if mass ordering is inverted!

Conclusions

- Cosmology provides **tightest** limits $M_\nu \lesssim 0.12\,\mathrm{eV}$ (assuming ΛCDM)
- **Mild preference** for normal ordering due to volume effects
- Limits partially **model-dependent** (due to parameter degeneracies)
- Room for improvement in nailing (scale-dependent) **galaxy bias**...
- ...including through CMB lensing-galaxy **cross-correlations**
- Neutrinos are not a serious nuisance towards understanding **inflation**
- Neutrino mass ordering could teach us something about **dark energy**

Conclusions

- Neutrino cosmology is an **exciting** field of research!
- First who convincingly measures M_ν books a **trip to Stockholm**!

Neutrinos have mass? I didn't even know they were Catholic!

Robert Langdon to Vittoria Vetra in *Angels and Demons*, Dan Brown (2000), p. 476

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