Recent developments in neutrino cosmology

Sunny Vagnozzi

The Oskar Klein Centre for Cosmoparticle Physics, Stockholm University

sunny.vagnozzi@fysik.su.se

Pre-defense seminar, Stockholm, 11 April 2019

Outline and bibliography

- Paper I: **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?

- Paper II: E. Giusarma, **SV**, S. Ho, S. Ferraro, K. Freese, R. Kamen-Rubio, K. B. Luk, *Phys. Rev.* D **98** (2018) 123526 [arXiv:1802.08694]
  Scale-dependent galaxy bias: can we nail it through CMB lensing-galaxy cross-correlations?

- Paper III: **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: why we should worry, and how to correct for it easily

- Paper IV: **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?

- Paper V: 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?

Why care about neutrino masses and neutrino cosmology?

Why care about neutrino masses?

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,...)

Neutrino oscillations and neutrino masses

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

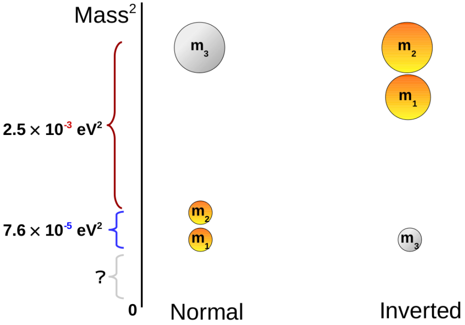
$$\begin{aligned} \Delta m^2_{21} &\equiv m^2_2 - m^2_1 = (7.6 \pm 0.2) \times 10^{-5}\,\mathrm{eV}^2\,, \\ |\Delta m^2_{31}| &\equiv |m^2_3 - m^2_1| = (2.48 \pm 0.06) \times 10^{-3}\,\mathrm{eV}^2\,. \end{aligned}$$

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

Note uncertainty in sign of $\boldsymbol{\Delta m^2_{31}}$ $\to$ 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

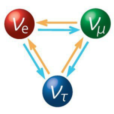
$M_\nu > 0.06\,\mathrm{eV}$

Inverted ordering

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

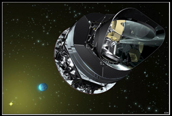
Neutrino oscillations

- 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



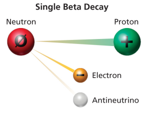
Cosmology

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



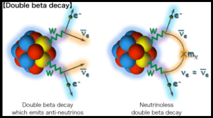
Beta decay

- 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



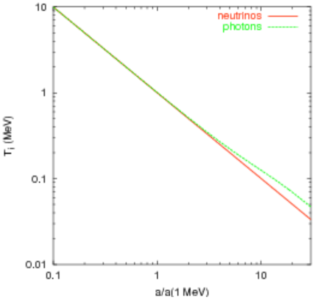
Neutrinoless double-beta decay

- 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

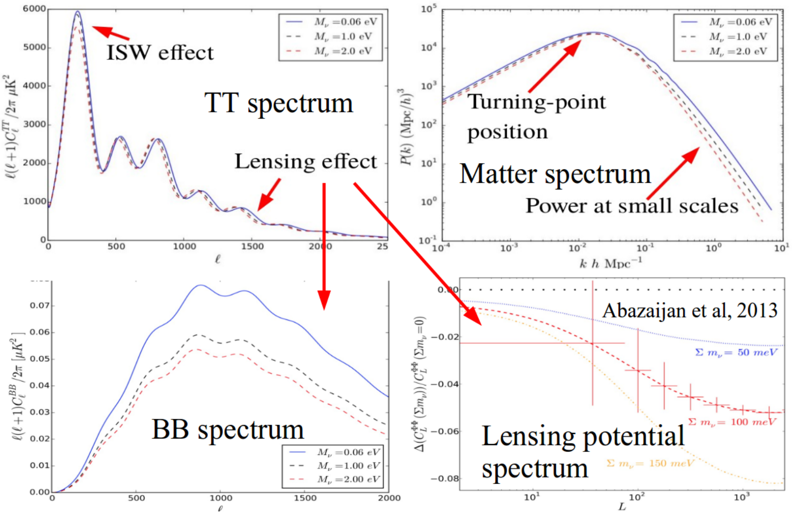
- $T \gtrsim 1\,\mathrm{MeV}$: weak interactions maintain νs in thermal equilibrium with the primeval cosmological plasma $[T_\nu = T_\gamma]$
- $T \lesssim 1\,\mathrm{MeV}$: νs free-stream keeping an equilibrium spectrum



Lesgourgues & Pastor, AHEP 2012 (2012) 608515

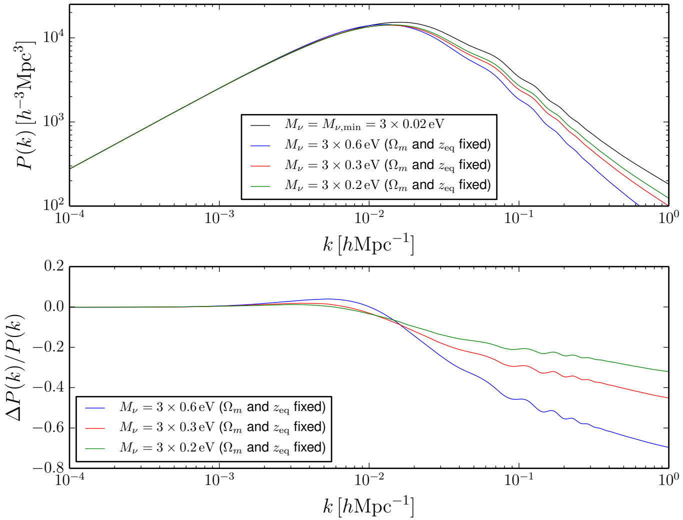
- $T \lesssim M_\nu$: νs turn non-relativistic, free-streaming suppresses the growth of structure on small scales (**VERY IMPORTANT**)

How can cosmology measure neutrino masses?

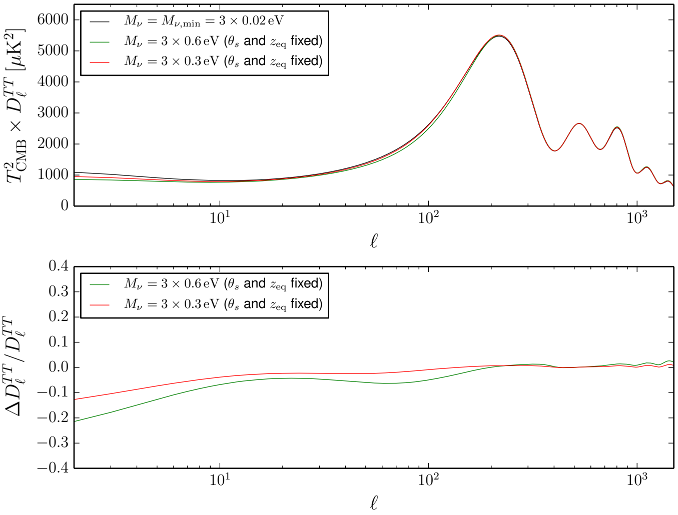


Courtesy of Martina Gerbino

Effect of neutrino masses on the LSS



Effect of neutrino masses on the CMB



Paper I

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

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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 ΛCDM 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 at $\sim 64\%$ C.L. and $\sim 71\%$ C.L., respectively. In addition, we compare the constraining

Issue

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PHYSICAL REVIEW

Foreword: concordance ΛCDM model

Work within assumption of "simplest" 6-parameter ΛCDM model:

- ω_c physical energy density of cold dark matter
- ω_b physical energy density of baryons
- θ_s angular scale of sound horizon at photon decoupling
- A_s amplitude of primordial power spectrum of scalar fluctuations
- n_s tilt of primordial power spectrum of scalar fluctuations
- τ optical depth to reionization

...with one extra parameter:

- M_ν sum of neutrino masses (*3deg* approximation)

What does data have to say about all this?

$P(k)$ from BOSS DR12 (at the time novel dataset)
BAO distance measurements
τ `simlow` prior $\tau = 0.055 \pm 0.009$ (to mimic *Planck* 2019)

Planck temperature
$M_\nu <$ **0.72** eV @95% C.L.

- $+P(k)$: **0.30** eV
- $+P(k)$+BAO: **0.19** eV
- $+P(k)$+BAO$+\tau$: **0.15** eV

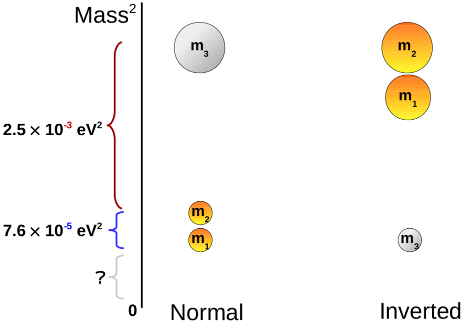
Planck temperature+polarization
$M_\nu <$ **0.49** eV @95% C.L.

- $+P(k)$: **0.28** eV
- $+P(k)$+BAO: **0.15** eV
- $+P(k)$+BAO$+\tau$: **0.12** eV

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

What can cosmology say about the mass ordering?

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



Credits: Hyper-Kamiokande collaboration

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

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

What can cosmology say about the mass ordering?

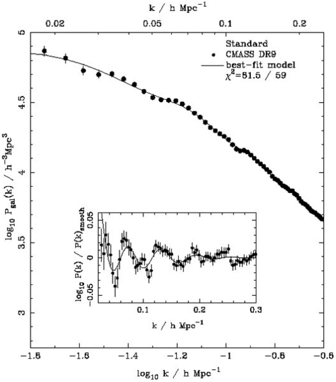
- **Bayesian model selection** problem between two models: `NO` and `IO`
- **Posterior odds** for `NO` vs `IO` SV *et al.*, PRD 96 (2017) 123503, different formulation which leads to approximately same result in Hannestad & Schwetz, JCAP 1611 (2016) 035

$$\underbrace{\frac{p_{\mathtt{NO}}}{p_{\mathtt{IO}}}}_{\text{posterior odds}} \approx \frac{\int_{0.06\,\mathrm{eV}}^{\infty} dM_\nu \, \overbrace{p(M_\nu|\mathbf{x})}^{\text{posterior}} \overbrace{\mathcal{P}(M_\nu)}^{\text{prior}}}{\int_{0.10\,\mathrm{eV}}^{\infty} dM_\nu \, p(M_\nu|\mathbf{x}) \mathcal{P}(M_\nu)} > 1$$

- Preference for `NO` driven by **volume effects**
- Even for the most constraining dataset, $p_{\mathtt{NO}}/p_{\mathtt{IO}} \sim 3.3{:}1$
- After our work others explored other physical priors/methodologies, preference for `NO` *typically* never $>$ 5:1... Gerbino+2017, Simpson+2017, Caldwell+2017, Long+2018, Gariazzo+2018, Heavens & Sellentin 2018, Handley & Millea 2018, de Salas+2018

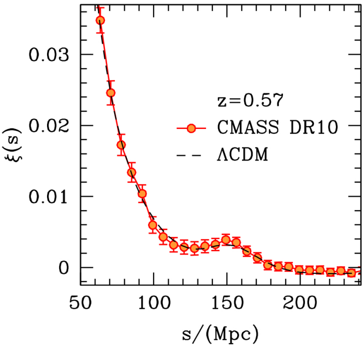
How to improve from here? *P(k)* vs BAO

Power spectrum



$\implies$ BAO information in wiggles

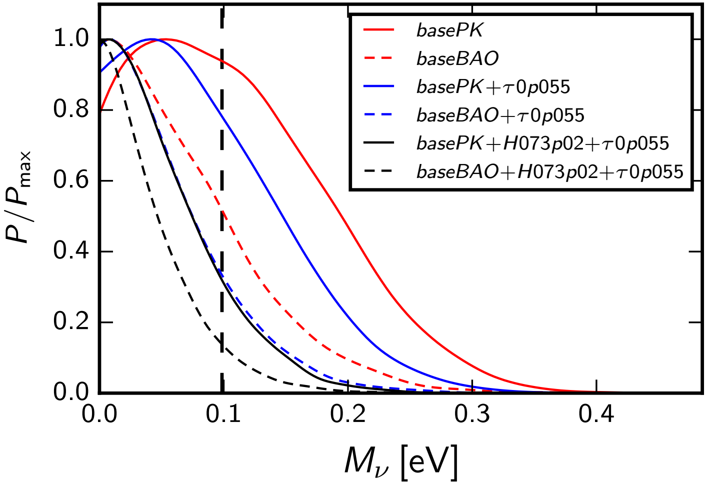
Correlation function



$\implies$ BAO distance measurement

How to improve from here? *P(k)* vs BAO

Let's check the relative constraining power of BAO vs $P(k)$...



SV *et al.*, PRD 96 (2017) 123503; supported by earlier findings of Hamann *et al.*, JCAP 1007 (2010) 002

How to improve from here? Need to improve use of $P(k)$

Issues:

- (Scale-dependent) bias (usually treated as constant)

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

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

- Non-linearities ($k_{\mathrm{max}} = 0.2\, h\, \mathrm{Mpc}^{-1}$ at $z = 0.57$)
- Redshift-space distortions
- Systematics

We need a better handle on the bias!

Paper II

E. Giusarma, **SV**, S. Ho, S. Ferraro, K. Freese, R. Kamen-Rubio, K. B. Luk, *Phys. Rev.* D **98** (2018) 123526 [arXiv:1802.08694]
Scale-dependent galaxy bias: can we nail it 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

Article | PDF | HTML | Export Citation

ABSTRACT

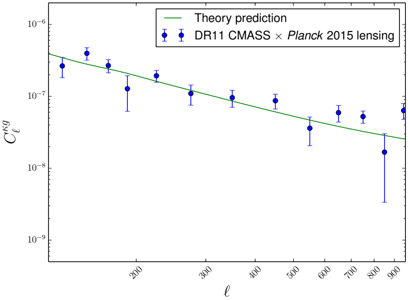
One of the most powerful cosmological data sets when it comes to constraining neutrino masses is represented by galaxy power spectrum measurements, $P_{gg}(k)$. The constraining power of $P_{gg}(k)$ is however severely limited by uncertainties in the modeling of the scale-dependent galaxy bias $b(k)$. 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

Using CMB lensing-galaxy cross-correlations

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

Cross-correlate CMB lensing with galaxies Giusarma, SV, *et al.*, PRD 98 (2018) 123526

$$C_\ell^{\kappa g} = \frac{3H_0^2\Omega_m}{2c^2} \int_{z_1}^{z_2} dz\, \frac{\chi^\star - \chi(z)}{\chi(z)\chi^\star}(1+z) b\left(k = \frac{\ell}{\chi(z)}\right) P_m\left(\frac{\ell}{\chi(z)}, z\right) \propto b^1$$



Scale-dependent galaxy bias

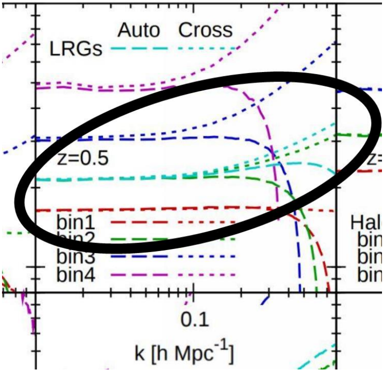
Leading-order correction to constant bias in Fourier space is k^2: Desjacques, Jeong & Schmidt, Phys. Rept. 733, 1

$$\delta_g(k) = b_1\delta(k) + b_{\nabla^2\delta}k^2\delta(k) + \ldots$$

NOTE k^2 correction predicted by various independent approaches to studying galaxy bias

Desjacques *et al.*, PRD 82 (2010) 103529; Musso *et al.*, MNRAS 427 (2012) 3145; Senatore, JCAP 1511 (2015) 007

Bias is **NOT** the same in auto- and cross-correlations!



Okumura *et al.*, JCAP 1211 (2012) 014

First applications to real data

CMB lensing from Planck 2015, galaxies from BOSS DR12 CMASS

Bias model $b_{\rm cross} = a + ck^2$, $b_{\rm auto} = a + dk^2$

Dataset	a (68% C.L.)	c (68% C.L.)	d (68% C.L.)	M_ν [eV] (95% C.L.)	
$CMB \equiv PlanckTT{+}lowP$				< 0.72	$[< 0.77]$
$CMB{+}C_\ell^{\kappa g}$	1.45 ± 0.19	2.59 ± 1.22		**0.06**	
	1.50 ± 0.21	2.97 ± 1.42		< 0.72	$[< 0.77]$
$CMB{+}P_{gg}(\mathrm{k})$	1.97 ± 0.05		-13.76 ± 4.61	**0.06**	
	1.98 ± 0.08		-14.03 ± 4.68	< 0.22	$[< 0.24]$
$CMB{+}P_{gg}(\mathrm{k}){+}C_\ell^{\kappa g}$	1.95 ± 0.05	0.45 ± 0.87	-13.90 ± 4.17	**0.06**	
	1.95 ± 0.07	0.48 ± 0.90	-14.13 ± 4.02	< 0.19	$[< 0.22]$

Giusarma, SV, *et al.*, PRD 98 (2018) 123526

- Data want $c > 0$ and $d < 0$ as we expect from simulations
- $d < 0$ at about 3σ, strong detection of scale-dependent bias *within this simplified model* $\rightarrow$ constant bias model is not sufficient even at linear scales
- Checked other phenomenological bias models, data always prefers parameters such that $db_{\rm auto}/dk < 0$

Paper III

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: why we should worry, and how to correct for it easily

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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Journal of Cosmology and Astroparticle Physics, Volume 2018, September 2018

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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

A complication: neutrino-induced scale-dependent bias

Neutrinos induce an additional scale-dependence in the bias **on linear scales** (always neglected so far), so in reality: Castorina *et al.*, JCAP 1402 (2014) 049

$$P_g(k) = b_m^2(k, M_\nu)P_m(k)$$

Physical reason: halo formation to leading order only responds to the CDM+baryons field (*i.e.* galaxies form at peaks of the CDM+baryon density field)

Problem: $b_m^2(k, M_\nu)$ hard to model

A complication: neutrino-induced scale-dependent bias

Solution: define the bias with respect to CDM+baryons **only**:

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

$b_{cb}(k)$ is **universal** (M_ν-independent), and k-independent on linear scales

Castorina *et al.*, JCAP 1402 (2014) 049

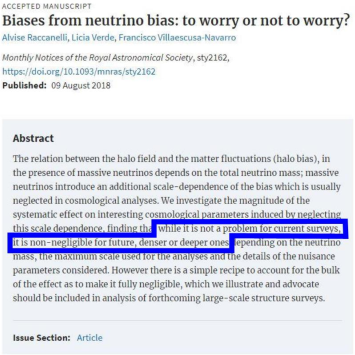
Size of effect $\approx f_\nu \equiv \Omega_\nu/\Omega_m \approx (M_\nu/93.14\,\mathrm{eV})h^{-2}/\Omega_m$

Inconsistency: people had been using b_m but treating it as b_{cb}

Does this inconsistency affect LSS analyses?

Not at the moment, but it will!

Fisher matrix analysis



ACCEPTED MANUSCRIPT

Biases from neutrino bias: to worry or not to worry?

Alvise Raccanelli, Licia Verde, Francisco Villaescusa-Navarro

Monthly Notices of the Royal Astronomical Society, sty2162,
https://doi.org/10.1093/mnras/sty2162
Published: 09 August 2018

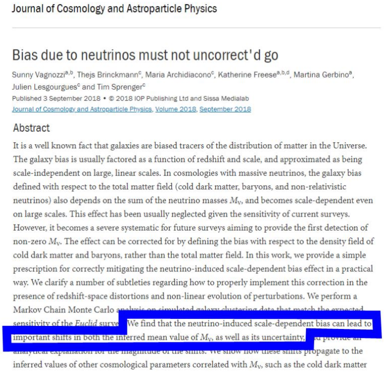
Abstract

The relation between the halo field and the matter fluctuations (halo bias), in the presence of massive neutrinos depends on the total neutrino mass; massive neutrinos introduce an additional scale-dependence of the bias which is usually neglected in cosmological analyses. We investigate the magnitude of the systematic effect on interesting cosmological parameters induced by neglecting this scale dependence, finding that while it is not a problem for current surveys, it is non-negligible for future, denser or deeper ones depending on the neutrino mass, the maximum scale used for the analyses and the details of the nuisance parameters considered. However there is a simple recipe to account for the bulk of the effect as to make it fully negligible, which we illustrate and advocate should be included in analysis of forthcoming large-scale structure surveys.

Issue Section: Article

Raccanelli *et al.*, MNRAS 483 (2019) 734

Full MCMC analysis



Journal of Cosmology and Astroparticle Physics

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]

Published 3 September 2018 • © 2018 IOP Publishing Ltd and Sissa Medialab
Journal of Cosmology and Astroparticle Physics, Volume 2018, September 2018

Abstract

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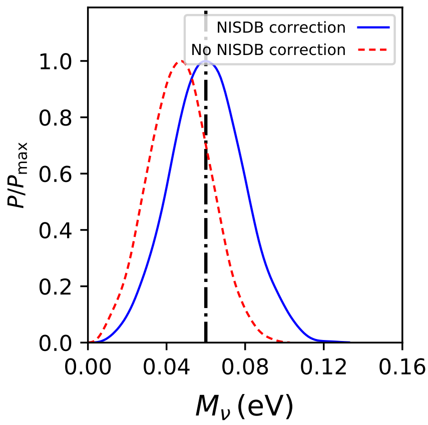
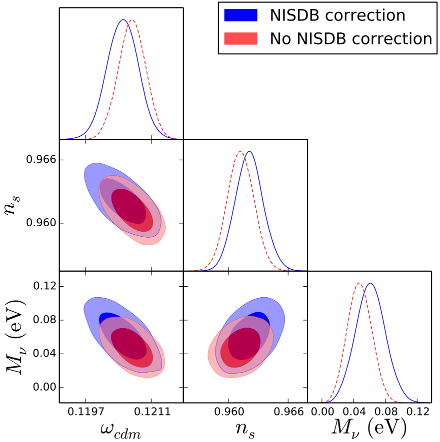
SV *et al.*, JCAP 1809 (2018) 001

Neutrino-induced scale-dependent bias (NISDB)



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



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

Paper IV

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 $\Lambda\,\mathrm{CDM}$

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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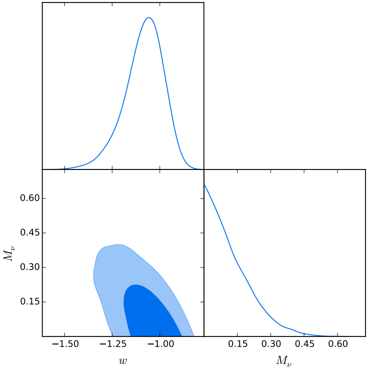
ABSTRACT

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 $\Lambda\,\mathrm{CDM}$ 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

The weakness of cosmological bounds: degeneracies

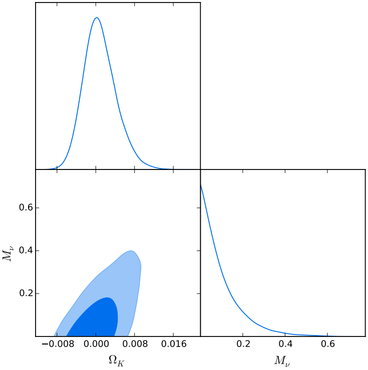
Using *Planck*+BAO assuming ΛCDM+M_ν: $M_\nu < 0.19\,\mathrm{eV}$

Free dark energy EoS w



$M_\nu < 0.31\,\mathrm{eV}$

Free curvature energy density Ω_k



$M_\nu < 0.30\,\mathrm{eV}$

Can M_ν limits get tighter in extended parameter spaces?

Consider w_0w_aCDM extension, two extra parameters (w_0 and w_a) to describe time-varying dynamical dark energy (DDE):

$$w(z) = w_0 + w_a \frac{z}{1+z} = w_0 + w_a(1-a)$$

Now consider w_0w_aCDM but impose $w_0 \geq -1$, $w_0 + w_a \geq -1$

$\implies$ dark energy is *non-phantom* ($w(z) \geq -1$; NPDDE): useful parametrization for *e.g.* quintessence

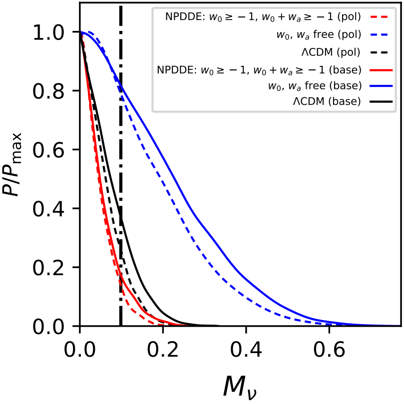
NOTE: ΛCDM is still a particular case of NPDDE when $w_0 = -1$, $w_a = 0$

Can M_ν limits get tighter in extended parameter spaces?

Planck (solid/dashed: no polarization/polarization)+BAO+SNe

Results without polarization:

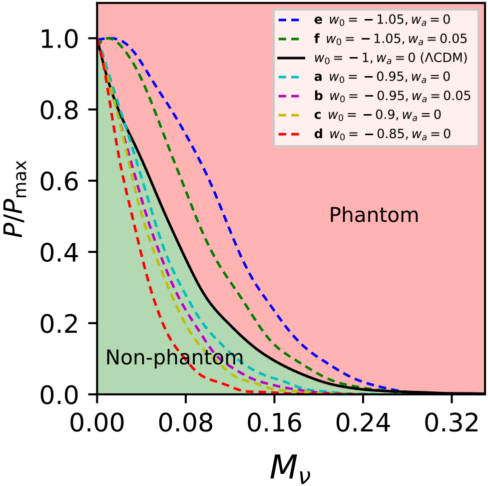
- ΛCDM: $0.17\,\mathrm{eV}$
- $w_0 w_a$CDM: $0.41\,\mathrm{eV}$
- NPDDE: **0.12** eV!!! $\approx$ 40% tighter



SV et al., PRD 98 (2018) 083501

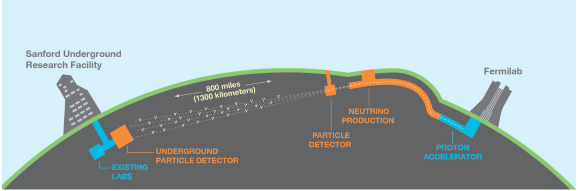
Can M_ν limits get tighter in extended parameter spaces?

Why does this happen even though ΛCDM is a limiting case of NPDDE?



Connecting dark energy to neutrino laboratory experiments

- In non-phantom dark energy models the preference for the normal neutrino ordering is stronger ($\approx 3-4:1$) than in ΛCDM ($\approx 2:1$)
- Long-baseline experiments (*e.g.* DUNE) targeting mass ordering through matter effects (*e.g.* MSW effect) in the next few years...
- ...if ordering inverted, dark energy very unlikely to be quintessence (**proof by contradiction**: quintessence wants too light neutrinos)
- Insight into what is not driving cosmic acceleration from neutrino laboratory measurements



Paper V

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

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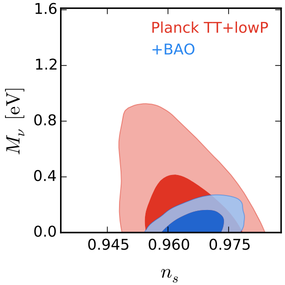
ABSTRACT

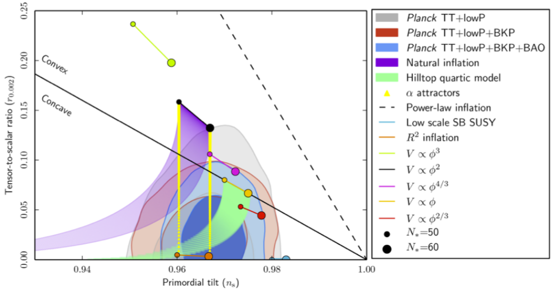
We study the impact of assumptions about neutrino properties on the estimation of inflationary parameters from cosmological data, with a specific focus on the allowed contours in the n_s/r plane, where n_s is the scalar spectral index and r is the tensor-to-scalar ratio. We study the following neutrino 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

Correlation between M_ν and n_s

Strong M_ν-n_s correlation



n_s-r plane of inflationary models

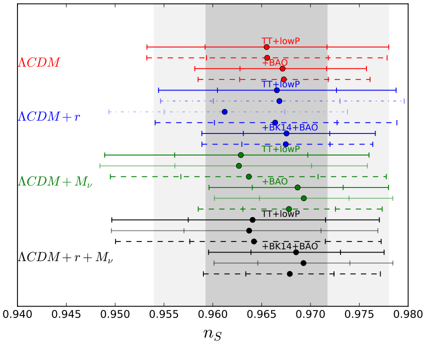


Usual approximations to the neutrino sector:

- When M_ν not varying (*e.g.* ΛCDM, ΛCDM+r models), fixed to 0.06 eV, 1 massive+2 massless eigenstates
- When M_ν varying, 3 degenerate eigenstates of equal mass

Neutrinos as a nuisance for inflationary parameters?

		ΛCDM	ΛCDM+M_ν
Planck	NO	0.9655 ± 0.0063	0.9629 ± 0.0069
	approx	**0.9656 ± 0.0063**	0.9636 ± 0.0071
Planck+BAO	NO	0.9671 ± 0.0045	0.9686 ± 0.0047
	approx	0.9673 ± 0.0045	0.9678 ± 0.0048



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

Conclusions

- Cosmology provides **tightest** constraints on $M_\nu \lesssim 0.12 - 0.15\,\mathrm{eV}$, **mild preference** for normal ordering due to volume effects (Paper I)
- Improvement in treatment of **scale-dependent galaxy bias** through CMB lensing-galaxy cross-correlations (Paper II)
- Crucial to account for **systematic effects** such as scale-dependent galaxy bias due to neutrinos (Paper III)
- Laboratory measurement of the mass ordering could provide insight into the (phantom or not) **nature of dark energy** (Paper IV)
- Conclusions about inflation and the initial conditions of the Universe relatively **robust to neutrino unknowns** (Paper V)