Recent developments in neutrino cosmology

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Outline and bibliography

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]
  Scale-dependent galaxy bias: can we nail it 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?

Why care about neutrino masses and neutrino cosmology?

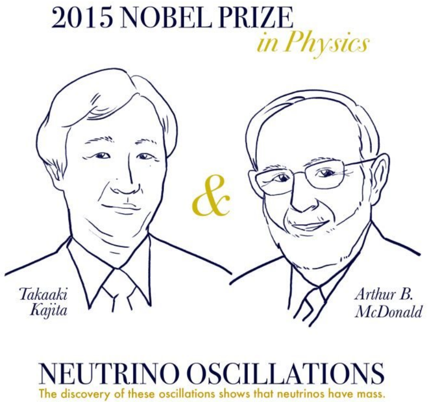
Why care about neutrino masses?

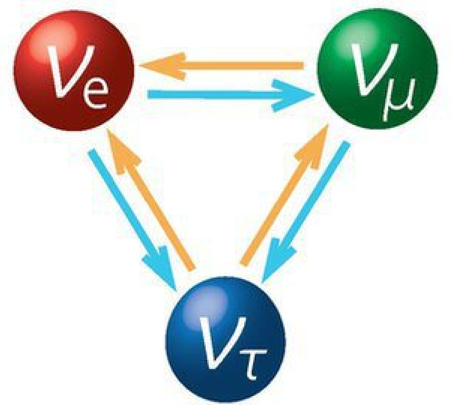
Because neutrino masses are the only **direct evidence** *for BSM physics*

- 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 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

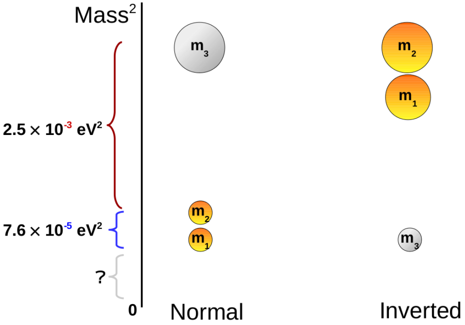
$$\begin{aligned} \Delta m^2_{21} &\equiv m^2_2 - m^2_1 = (7.6 \pm 0.2) \times 10^{-5}\,\mathrm{eV}^2\,, \\ |\Delta m^2_{31}| &\equiv |m^2_3 - m^2_1| = (2.48 \pm 0.06) \times 10^{-3}\,\mathrm{eV}^2\,. \end{aligned}$$

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

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

Neutrino mass ordering

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



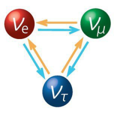
Credits: Hyper-Kamiokande collaboration

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

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

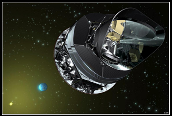
Neutrino oscillations

- Sensitive to mass-squared differences $\Delta m^2_{ij} \equiv m^2_i - m^2_j$
- Exploits quantum-mechanical effects
- Currently not sensitive to the mass ordering



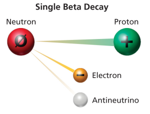
Cosmology

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



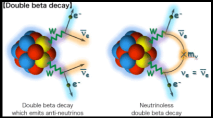
Beta decay

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



Neutrinoless double-beta decay

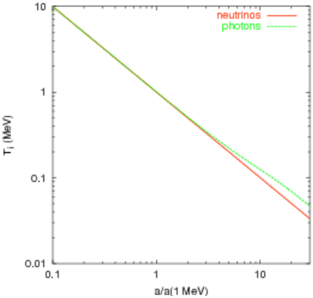
- Sensitive to effective Majorana mass $m_{\beta\beta} \equiv \sum_i |U^2_{ei} m_i|$
- Exploits $0\nu 2\beta$ decay (if νs are Majorana)
- Limited by NME uncertainties and ν nature



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

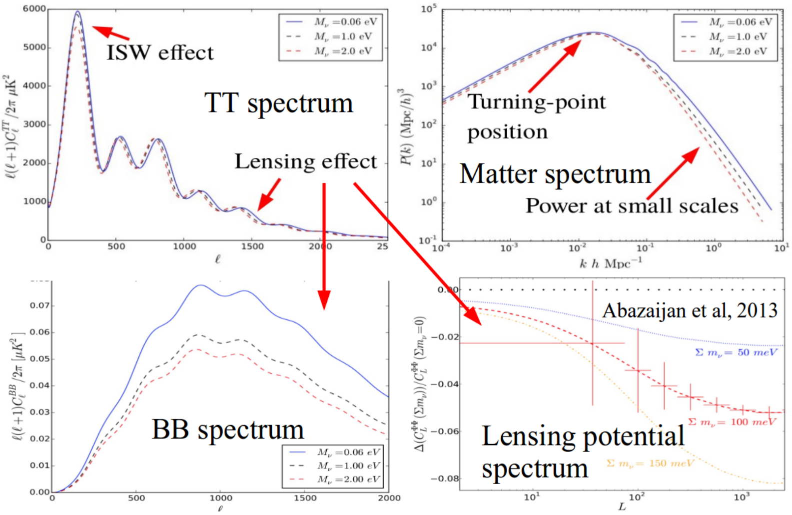
$$T_\nu = (4/11)^{\frac{1}{3}}\, T_\gamma$$



Lesgourgues & Pastor, AHEP 2012 (2012) 608515

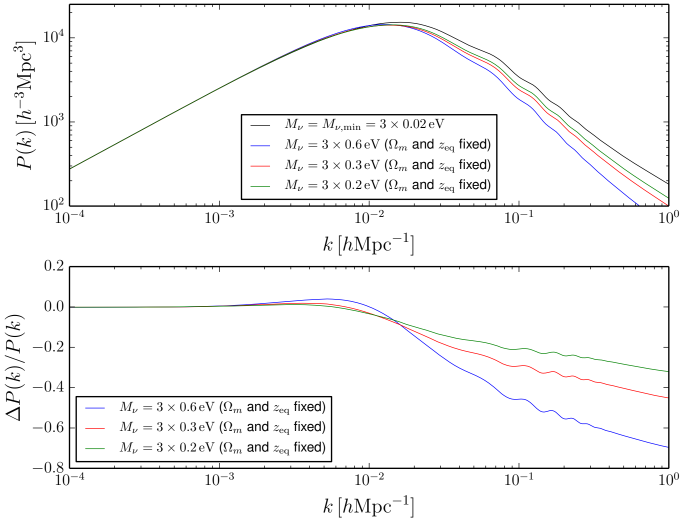
- $T \lesssim M_\nu$: νs turn non-relativistic, free-streaming suppresses the growth of structure on small scales (**VERY IMPORTANT**)

How can cosmology measure neutrino masses?

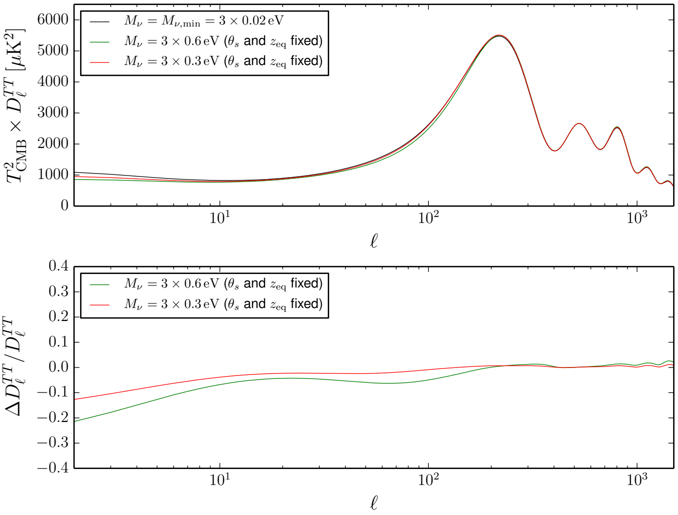


Courtesy of Martina Gerbino

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

Issue

Vol. 96, Iss. 12 — 15 December 2017

What does data have to say about all this?

$P(k)$ from BOSS DR12 (at the time novel dataset)
BAO distance measurements from 6dFGS, BOSS DR11 LOWZ, SDSS-MGS
τ `simlow` prior $\tau = 0.055 \pm 0.009$

Planck temperature
$M_\nu < \mathbf{0.72}\,\mathrm{eV}$ @95% C.L.

- $+P(k)$: $\mathbf{0.30}\,\mathrm{eV}$
- $+P(k)$+BAO: $\mathbf{0.19}\,\mathrm{eV}$
- $+P(k)$+BAO$+\tau$: $\mathbf{0.15}\,\mathrm{eV}$

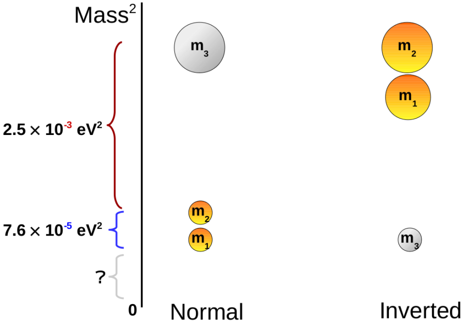
Planck temperature+polarization
$M_\nu < \mathbf{0.49}\,\mathrm{eV}$ @95% C.L.

- $+P(k)$: $\mathbf{0.28}\,\mathrm{eV}$
- $+P(k)$+BAO: $\mathbf{0.15}\,\mathrm{eV}$
- $+P(k)$+BAO$+\tau$: $\mathbf{0.12}\,\mathrm{eV}$

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 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

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

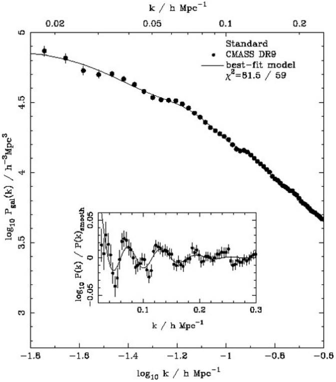
- Preference for NO driven by **volume effects**
- Even for the most constraining dataset, $p_{\mathtt{NO}}/p_{\mathtt{IO}} \sim 3.3{:}1$

Constraints on M_ν and mass ordering: take home messages

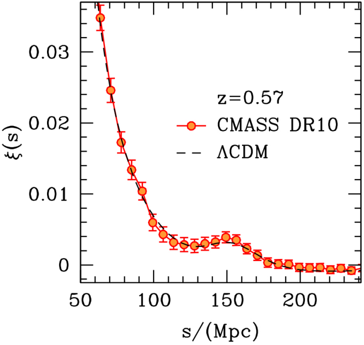
- Bounds on M_ν from cosmology are **VERY** strong (compare to $M_\nu \lesssim 2\,\mathrm{eV}$ from β-decay)
- Robust 95% C.L. upper bound is about $M_\nu \lesssim \mathbf{0.15}\,\mathrm{eV}$
- Weak preference ($\sim 2-3:1$) for the `NO` from cosmology driven by volume effects and not physical effects
- Corollary 1: think carefully about how you weigh your prior volume!
- Corollary 2: cosmology will only determine the mass ordering if it is normal *and* $M_\nu \lesssim 0.1\,\mathrm{eV}$ ($\sigma \sim 0.02\,\mathrm{eV}$ for a 2σ determination)

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

Power spectrum



Correlation function

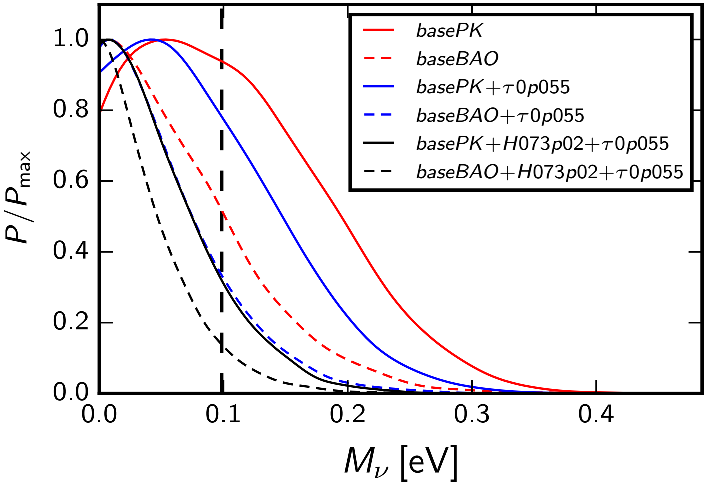


$\Longrightarrow$ BAO information in wiggles

$\Longrightarrow$ BAO distance measurement

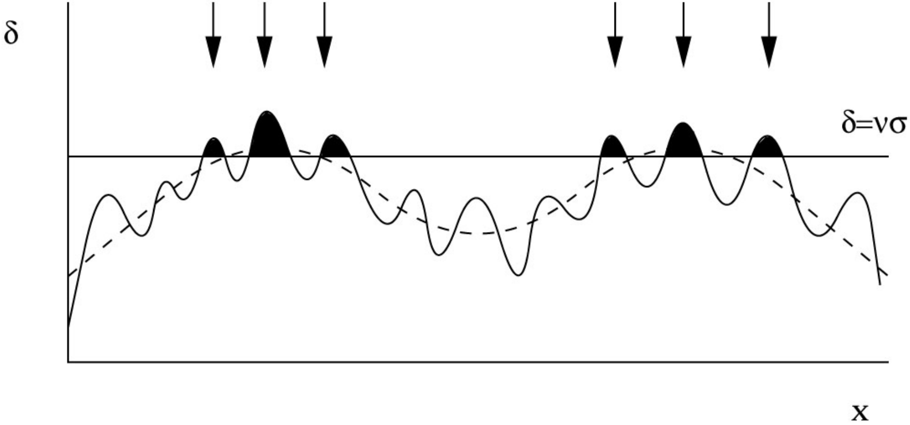
How to improve from here? Need to improve use of $P(k)$

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

Galaxy bias



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!

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

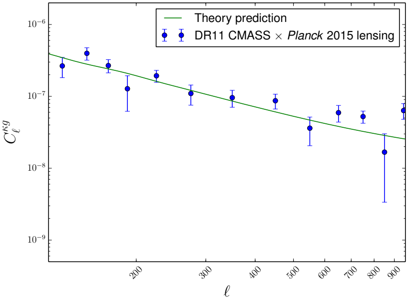
One of the most powerful cosmological data sets when it comes to constraining neutrino masses is represented by galaxy power spectrum measurements, $P_{gg}(k)$. The constraining power of $P_{gg}(k)$ is however severely limited by uncertainties in the modeling of the scale-dependent galaxy bias $b(k)$.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

Series expansion around **x** of deterministic bias expansion:

$$\delta_g(\mathbf{x},\tau) = b_\delta(\tau)\delta(\mathbf{x},\tau) + b_{\nabla^2\delta}(\tau)\nabla_x^2\delta(\mathbf{x},\tau) + \ldots$$

In Fourier space: Desjacques, Jeong & Schmidt, Phys. Rept. 733, 1

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

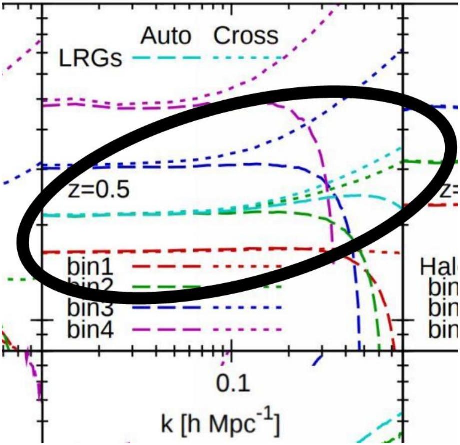
Leading-order correction is k^2, as k would break statistical isotropy

NOTE k^2 correction predicted independently by at least 3 approaches to biasing: peaks theory, excursion set approach, and EFTofLSS

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

Scale-dependent galaxy bias in auto- and cross-correlations

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 $b_{\rm cross} = a + ck^2$, $b_{\rm auto} = a + dk^2$ (ad hoc, OK to begin with)

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 $db_{\rm auto}/dk < 0$

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 a simple correction implemented in CLASS

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

Article PDF

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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 (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: $b^2(k, M_\nu)$ 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}

Warning: need to worry about (non-linear) RSD, non-linearities, etc.

We explain how to do it in detail in SV *et al.*, JCAP 1809 (2018) 001

Does all of this affect $P(k)$ 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

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]

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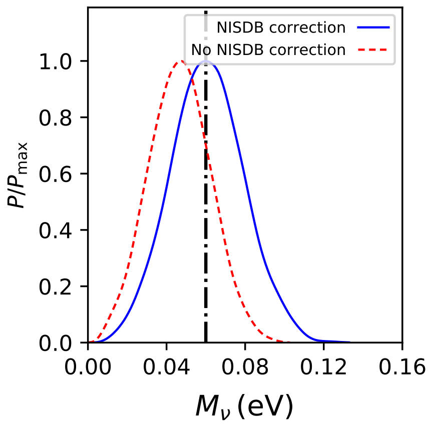
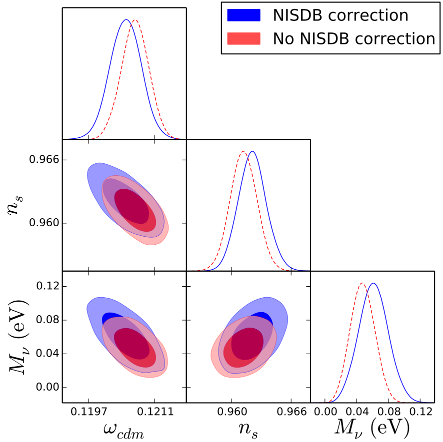
Raccanelli *et al.*, MNRAS 483 (2019) 734

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

Neutrino-induced scale-dependent bias

Bad news: if you don't correct for the NISDB, you mess up not only M_ν but also other parameters (*e.g.* σ_8 and n_s)

Good news: our patch to `CLASS` is now public with `v2.7` $\rightarrow$ use it!

Version history

The developement of CLASS benefits from various essential contributors credited below. In absence of specific credits, developements are written by the main CLASS authors, Julien Lesgourgues and Thomas Tram.

In case you are interested in downloading an old version, go to the class_public page. There is a horizontal bar with *commits, branches, releases, contributors*. Click releases and you'll get `zip` or `tar.gz` archives of all previous versions.

v2.7 (10.09.2018)

- includes a new graphical interface showing the evolution of linear perturbations in real space, useful for pedagogical purposes. To run it on a browser, read instructions in `RealSpaceInterface/README` (credits: Max Beutelspacher, Georgios Samaras)
- when running with `ncdm` (non cold dark matter) while asking for the matter power spectrum `mPk`, you will automatically get both the total non-relativistic matter spectrum *Pm(k,z)* and the baryons-plus-cdm-only (`cb`) spectrum *Pcb(k,z)*. The latter is useful e.g. for computing the power spectrum of galaxies, which traces `bc` instead of total matter (see e.g. 1311.0866, 1807.04672). From the `classy` wrapper you get the `cb` quantities through several new functions like `pk_cb()`,

...the end of the story?

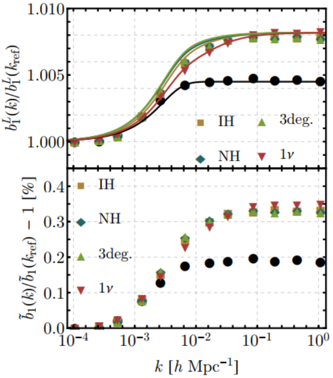
- Actually $b_{cb}(k)$ still depends on M_ν and is scale-dependent on large scales...

  LoVerde PRD 90 (2014) 083530, PRD 93 (2016) 103526; Muñoz & Dvorkin, PRD 98 (2018) 043503

- ...as halo formation cares *mostly* about the CDM+baryons field...
- ...but also about the history of perturbation growths:

$$b(k) \propto \frac{d\delta_{\rm crit}}{d\delta_{L,{\rm coll}}(k)}$$

- Effect recently seen convincingly in simulations Chiang, LoVerde, Villaescusa-Navarro, PRL 122 (2019) 041302



Muñoz & Dvorkin, PRD 98 (2018) 043503

Scale-dependent bias and neutrinos: take-home messages

- **Non-locality** of galaxy formation on small scales: k^2 correction
  Size of effect: $\sim R_\star^2$, with $R_\star \sim$ size of halo
- Halos form from **CDM+baryons density field**: use b_{cb} instead of b_m
  Size of effect: $\sim f_\nu$
- Halo formation still cares about **history of neutrino density field up to large scales**: step-like feature even in b_{cb}
  Size of effect: $\sim 0.6 b_L f_\nu$

Need to model all three effects **on linear and mildly nonlinear scales** for a robust analysis of galaxy power spectrum data!

Conclusions

- Cosmology provides **tightest** constraints on sum of ν masses, $M_\nu \lesssim 0.12 - 0.15\,\mathrm{eV}$ (assuming ΛCDM)
- **Mild preference** for normal ordering due to volume effects $\rightarrow$ think carefully about your prior
- Lots of room for improvement in treatment of **galaxy bias** through CMB lensing-galaxy cross-correlations
- Time to move beyond constant linear bias (**scale-dependent bias**)
- Beware and correct for **systematic** effects as scale-dependent galaxy bias due to neutrinos (correct for it in `CLASS v2.7`)!