

# Recent developments in neutrino cosmology

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Department of Physics, Harvard University, 5 December 2018



(Mostly) 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, accepted in *Phys. Rev. D* [[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: why we should worry, and a simple correction implemented in CLASS
- **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?

Why care about neutrino masses?

*Why care about neutrino masses  
and neutrino cosmology?*

## Why care about neutrino masses?

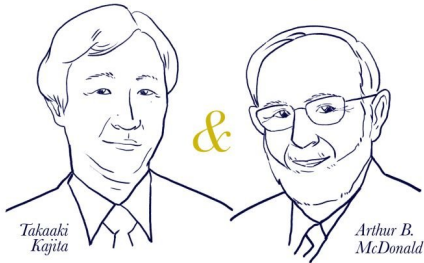
*Because neutrino masses are the only **direct evidence** for BSM physics*

- 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,...)
- Because neutrino masses *might* shed light on what is (NOT) driving cosmic acceleration
- Because neutrino masses could act as a nuisance parameter

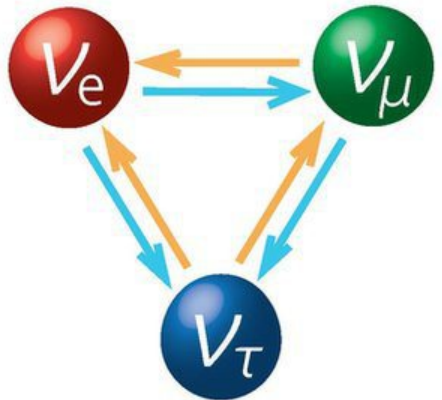
# Neutrino masses

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”)

2015 NOBEL PRIZE  
*in Physics*



**NEUTRINO OSCILLATIONS**  
The discovery of these oscillations shows that neutrinos have mass.



## Neutrinos from the lab

Flavour transition probability:

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

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

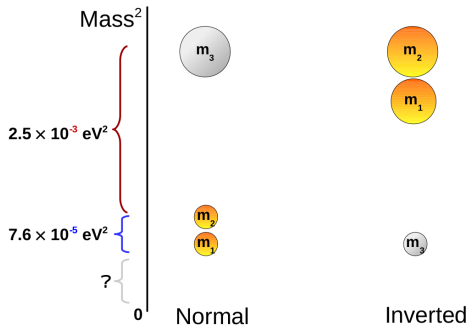
$$\begin{aligned} \Delta m_{21}^2 &\equiv m_2^2 - m_1^2 = (7.6 \pm 0.2) \times 10^{-5} \text{ eV}^2, \\ |\Delta m_{31}^2| &\equiv |m_3^2 - m_1^2| = (2.48 \pm 0.06) \times 10^{-3} \text{ eV}^2. \end{aligned}$$

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

**Note uncertainty in sign of  $\Delta m_{31}^2$**   $\rightarrow$  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**

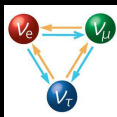
$$M_\nu > 0.06 \text{ eV}$$

**Inverted ordering**

$$M_\nu > 0.1 \text{ eV}$$

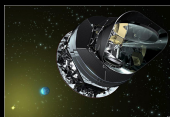
## Neutrino oscillations

- 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



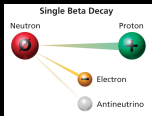
## Cosmology

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



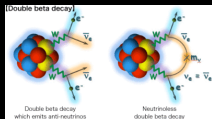
## Beta decay

- 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

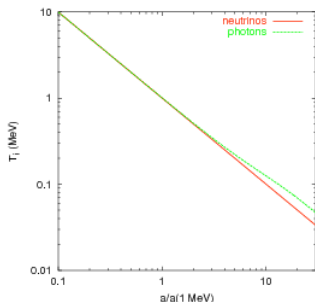
- Sensitive to effective Majorana mass  
 $m_{\beta\beta} \equiv \sum_i |U_{ei}|^2 m_i$
- Exploits  $0\nu 2\beta$  decay (if  $\nu$ s are Majorana)
- Limited by NME uncertainties and  $\nu$  nature





## Basic facts of neutrino cosmology

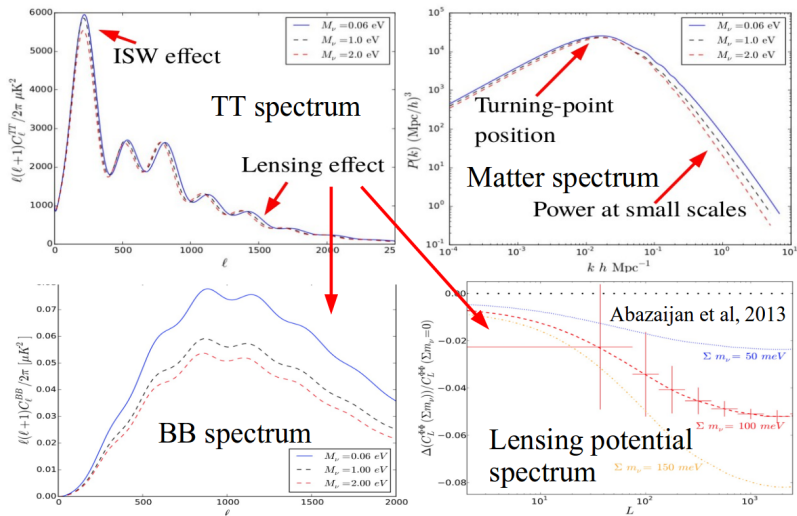
- $T \gtrsim 1 \text{ MeV}$ : weak interactions maintain  $\nu$ s in thermal equilibrium with the primeval cosmological plasma [ $T_\nu = T_\gamma$ ]
- $T \lesssim 1 \text{ MeV}$ :  $\nu$ s free-stream keeping an equilibrium spectrum



Lesgourgues & Pastor, AHEP 2012 (2012) 608515

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

# How can cosmology measure neutrino masses?



SV, E. Giusarma, O. Mena, K. Freese, M. Gerbino, S. Ho, M. Lattanzi, *Phys. Rev. D* **96** (2017) 123503 [[arXiv:1701.08172](https://arxiv.org/abs/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 $\nu$ 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,  $M_\nu$ , within the assumption of a background flat  $\Lambda$  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 ( $\tau$ ), the tightest 95% confidence level upper bound we find is  $M_\nu < 0.151$  eV. The addition of Planck high- $\ell$  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  $\sim 51\%$  C.L., respectively. In addition, we compare the constraints

Issue

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## What does data have to say about all this?

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

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

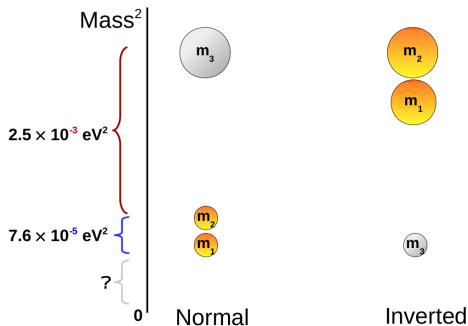
- $+P(k)$ : **0.30** eV
- $+P(k)$ +BAO: **0.19** eV
- $+P(k)$ +BAO+ $\tau$ : **0.15** eV

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

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

# What can cosmology say about the mass ordering?

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



Credits: Hyper-Kamiokande collaboration

**Normal ordering**

$$M_\nu > 0.06 \text{ eV}$$

**Inverted ordering**

$$M_\nu > 0.1 \text{ eV}$$

# 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

$$\frac{p_{NO}}{p_{IO}} \approx \frac{\int_{0.06 \text{ eV}}^{\infty} dM_{\nu} p(M_{\nu}|\mathbf{x}) \mathcal{P}(M_{\nu})}{\int_{0.10 \text{ eV}}^{\infty} dM_{\nu} p(M_{\nu}|\mathbf{x}) \mathcal{P}(M_{\nu})} > 1$$

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

## Constraints on $M_\nu$ and mass ordering: take home messages

- Bounds on  $M_\nu$  from cosmology are **VERY** strong (compare to  $M_\nu \lesssim 2 \text{ eV}$  from  $\beta$ -decay)
- Robust 95% C.L. upper bound is about  $M_\nu \lesssim \mathbf{0.15} \text{ eV}$
- 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*  $M_\nu \lesssim 0.1 \text{ eV}$  ( $\sigma \sim 0.02 \text{ eV}$  for a  $2\sigma$  determination)

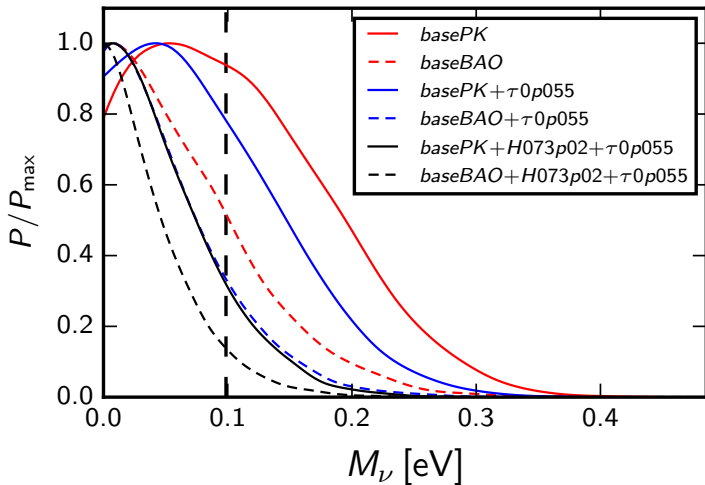


THE

**TAKE-HOME MESSAGE**

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

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





# 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 ( $k_{\max} = 0.2 h \text{ Mpc}^{-1}$  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, accepted in *Phys. Rev. D* [[arXiv:1802.08694](https://arxiv.org/abs/1802.08694)]

Scale-dependent galaxy bias: can we nail it through CMB lensing-galaxy cross-correlations?

arXiv.org > astro-ph > arXiv:1802.08694

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Astrophysics > Cosmology and Nongalactic Astrophysics

## 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, Kam-Biu Luk

(Submitted on 23 Feb 2018)

One of the most powerful cosmological datasets 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 Letter we present a new method to constrain  $b(k)$  by using the cross-correlation between the Cosmic Microwave Background (CMB) lensing signal and galaxy maps ( $C_{\ell}^{K\ell g}$ ) using a simple but theoretically well-motivated parametrization for  $b(k)$ . We apply the method using  $C_{\ell}^{K\ell g}$  measured by cross-correlating Planck lensing maps and the Baryon Oscillation Spectroscopic Survey (BOSS) Data Release 11 (DR11) CMASS galaxy sample, and

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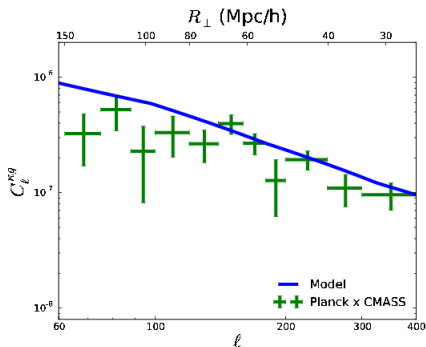
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# Using CMB lensing-galaxy cross-correlations

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

**Cross-correlate** CMB lensing with galaxy survey Giusarma, SV, et al., arXiv: 1802.08694

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



# Scale-dependent galaxy bias

Series expansion around  $\mathbf{x}$  of deterministic bias expansion:

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

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

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

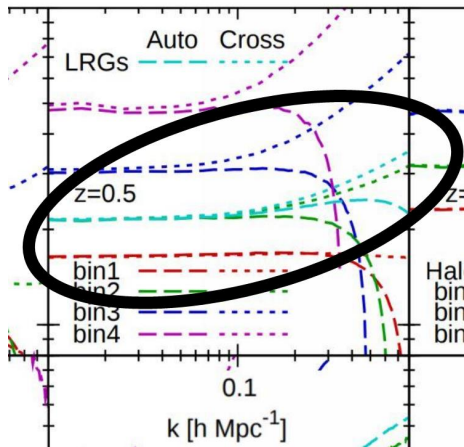
Leading-order correction is  $k^2$ , as  $k$  would break statistical isotropy

**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!



## First applications to real data

CMB lensing from Planck 2015, galaxies from BOSS DR12 CMASS  
Bias model  $b_{\text{cross}} = a + ck^2$ ,  $b_{\text{auto}} = a + dk^2$  (ad hoc, OK to begin with)

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

Giusarma, SV, et al., arXiv: 1802.08694

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

## Further improvements

- Use more physical bias model (terms beyond  $k^2$ ) to push to more non-linear scales
- Combine with bispectra ( $\kappa\kappa\kappa$ ,  $\kappa\kappa g$ ,  $\kappa g g$ ,  $g g g$ ) to better constrain bias terms
- Need a better understanding/modelling of stochasticity
- Model relation (assuming there is one) between  $b_{\text{auto}}$  and  $b_{\text{cross}}$  (calibrate to N-body simulations?)
- Understand low- $\ell$  systematics in  $C_{\ell}^{\kappa g}$
- Look at forecasts (Simons Observatory/CMB-S4  $\times$  LSST/DESI)
- Ultimately aim for a perturbation theory-based approach (e.g. convolution Lagrangian effective field theory)

SV, T. Brinckmann, M. Archidiacono, K. Freese, M. Gerbino, J. Lesgourgues, T. Sprenger, *JCAP* **1809** (2018) 001 [[arXiv:1807.04672](https://arxiv.org/abs/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<sup>a,b</sup>, Thejs Brinckmann<sup>c</sup>, Maria Archidiacono<sup>c</sup>, Katherine Freese<sup>a,b,d</sup>,  
Martina Gerbino<sup>a</sup>, Julien Lesgourgues<sup>c</sup> and Tim Sprenger<sup>e</sup>

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[Journal of Cosmology and Astroparticle Physics, Volume 2018, September 2018](#)



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### 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  $M_\nu$ , 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

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## 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)

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

**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** ( $M_\nu$ -independent), and  $k$ -independent on linear scales

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

Size of effect  $\sim f_\nu$

**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

Raccanelli et al., arXiv:1704.07837 (MNRAS accepted)

## Full MCMC analysis

Journal of Cosmology and Astroparticle Physics

### Bias due to neutrinos must not uncorrect'd go

Sunny Vagnozzi<sup>1,2,3</sup>, Thejs Brinckmann<sup>4</sup>, Maria Archidiacono<sup>5</sup>, Katherine Freese<sup>6,7,8</sup>, Martina Gerbino<sup>9</sup>, Julien Lesgourgues<sup>4</sup> and Tim Spranger<sup>6</sup>

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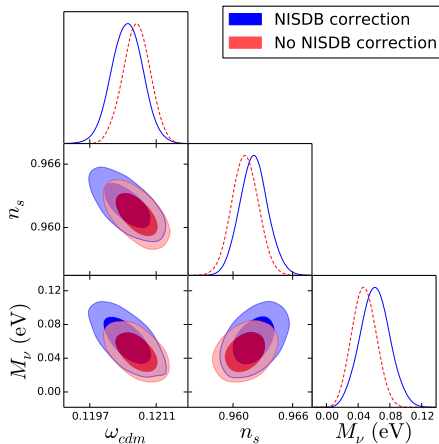
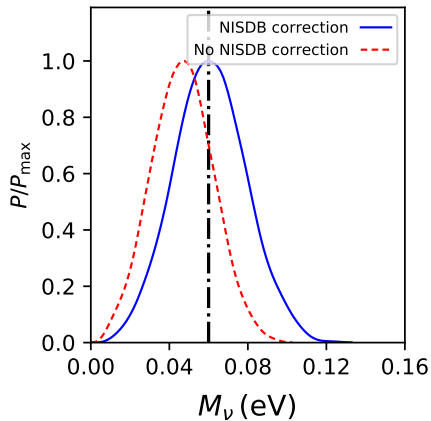
*Journal of Cosmology and Astroparticle Physics*, Volume 2018, September 2018

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SV et al., JCAP 1809 (2018) 001

# Neutrino-induced scale-dependent bias (NISDB)



# Neutrino-induced scale-dependent bias

**Bad news:** if you don't correct for the NISDB, you mess up not only  $M_\nu$  but also other parameters (e.g.  $\sigma_8$  and  $n_s$ )

**Good news:** our patch to CLASS is now public with v2.7 → use it!

## Version history

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

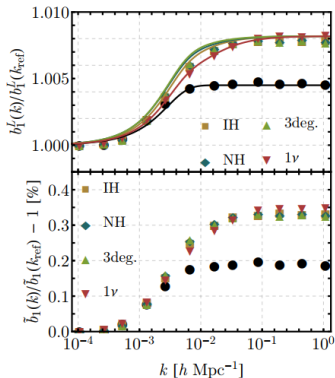
In case you are interested in downloading an old version, go to the [class\\_public](#) page. There is a horizontal bar with *commits*, *branches*, *releases*, *contributors*. Click releases and you'll get `zip` or `tar.gz` archives of all previous versions.

- 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 `n_cdm` (non cold dark matter) while asking for the matter power spectrum `mPk`, you will automatically get both the total non-relativistic matter spectrum  $P_m(k,z)$  and the baryons-plus-cdm-only (`cb`) spectrum  $P_{cb}(k,z)$ . 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()`,

## Further improvements

- Actually  $b_{cb}(k)$  depends on  $M_\nu \dots$   
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:

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



Muñoz & Dvorkin, PRD 98 (2018) 043503

## Further improvements

- Size of effect  $\approx 0.6b_L f_\nu \rightarrow$  very likely important for future surveys
- Step enhances bias where neutrinos suppress  $P(k)$ , so LSS forecasts perhaps are too optimistic? What about BAO? **Check!**
- RelicFast calculates this effect: should we make it talk to Montepython or CosmoMC? **Done by Julián and Linda?**
- Clarify effect of stochasticity, non-spherical collapse, non-linear RSD...
- Find effect convincingly in simulations. **Done?** Chiang, LoVerde, Villaescusa-Navarro, *arXiv:1811.12412, "First detection of scale-dependent linear halo bias in N-body simulations with massive neutrinos"*
- Even more optimistically: can we measure effect of individual  $m_i$  on  $b(k)$  (can beat cosmic variance as bias is **not** a random field)?

$$\sigma_{b(k)} \approx \frac{1}{\bar{n}N_k P(k)}$$

## 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:  $\sim 0.6b_L f_\nu$

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



THE

**TAKE-HOME MESSAGE**



## Conclusions

- Cosmology provides **tightest** constraints on sum of  $\nu$  masses,  $M_\nu \lesssim 0.12 - 0.15 \text{ eV}$  (assuming  $\Lambda\text{CDM}$ )
- **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
- Beware and correct for **systematic** effects as scale-dependent galaxy bias due to neutrinos (correct for it in CLASS v2.7)!
- At least 3 sources of **scale-dependent galaxy bias**, need to model all 3 for robust analysis of galaxy power spectrum data

# Thank you!



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Maria Archidiacono  
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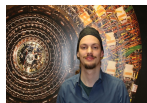
Suhail Dhawan  
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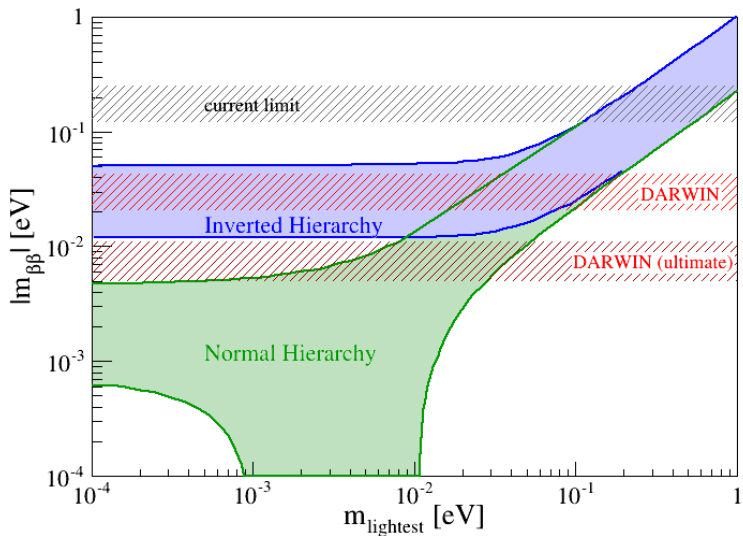


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Aachen

# Synergy between cosmology and laboratory experiments



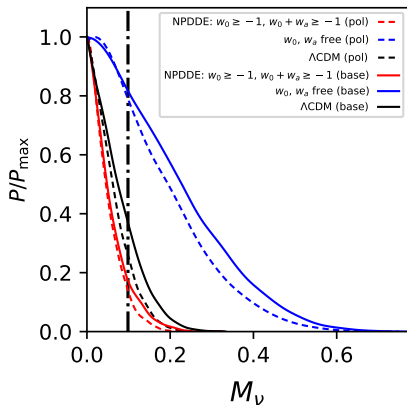
## Can $M_\nu$ limits get tighter in extended parameter spaces?

Now consider  $w_0 w_a$ CDM but impose  $w_0 \geq -1$ ,  $w_0 + w_a \geq -1$  (NPDDE)

**NOTE:**  $\Lambda$ CDM is still a particular case of NPDDE when  $w_0 = -1$ ,  $w_a = 0$

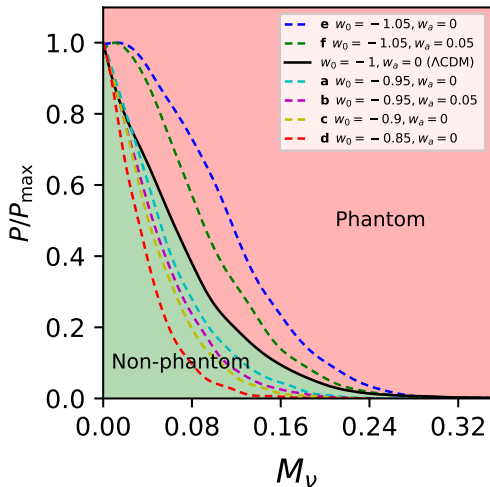
95% C.L. upper limits

- $\Lambda$ CDM: 0.17 eV
- $w_0 w_a$ CDM: 0.41 eV
- NPDDE: **0.12 eV!!!**  
 $\approx 40\%$  tighter



## Can $M_\nu$ limits get tighter in extended parameter spaces?

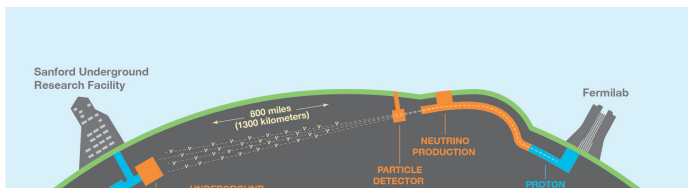
Why does this happen even though  $\Lambda$ CDM is a limiting case of NPDDE?



# Connecting dark energy to neutrino laboratory experiments: take home messages

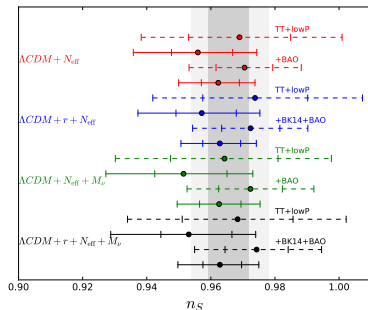
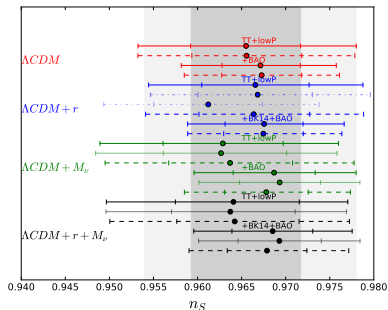
- In non-phantom dark energy models the preference for the normal neutrino ordering is stronger ( $\approx 3 - 4 : 1$ ) than in  $\Lambda$ CDM ( $\approx 2 : 1$ )
- Long-baseline experiments (e.g. DUNE) targeting mass ordering...
- ...if ordering inverted, dark energy very unlikely to be quintessence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

SV et al., PRD 98 (2018) 083501



# Neutrinos as a nuisance for inflationary parameters

Left: solid for exact NO, dashed for 3 degenerate approximation.  
Right: solid for “hard” marginalization ( $N_{\text{eff}} \leq 3.046$ ; low-reheating models), dashed for “broad” marginalization ( $0 \leq N_{\text{eff}} \leq 10$ )

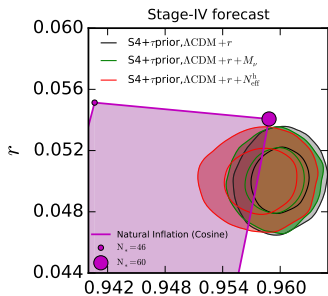


Gerbino, Freese, SV, et al., PRD 95 (2017) 043512

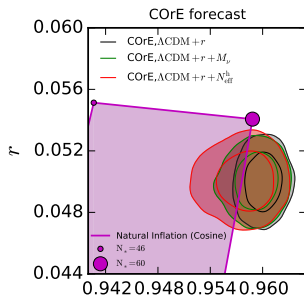
# Neutrinos as a nuisance for inflationary parameters

Forecasts for S4 and COrE with fiducial NO  $M_\nu = 0.06$  eV,  $r = 0.05$ .

	COre	S4
$\Lambda$ CDM + $r$	$0.9601 \pm 0.0014$	$0.9599 \pm 0.0019$
$\Lambda$ CDM + $r + M_\nu$	$0.9593 \pm 0.0016$	$0.9595 \pm 0.0020$
$\Lambda$ CDM + $r + N_{\text{eff}}^{\text{h}}$	$0.9580^{+0.0024}_{-0.0017}$	$0.9580^{+0.0027}_{-0.0023}$



$n_s$



$n_s$