Recent developments in neutrino cosmology

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RPM, Lawrence Berkeley National Laboratory, 20 December 2018

Outline and bibliography

(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, *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: why we should worry, and a simple correction implemented in `CLASS`
- Outlook for future directions (especially related to DESI)

Why care about neutrino masses and neutrino cosmology?

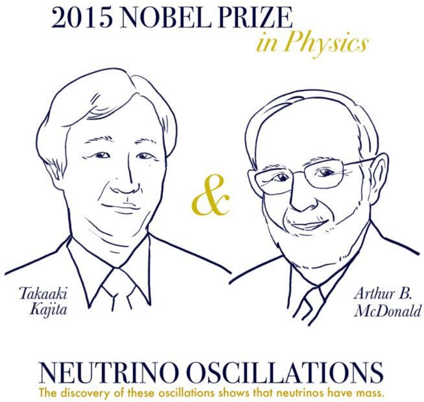
Why care about neutrino masses?

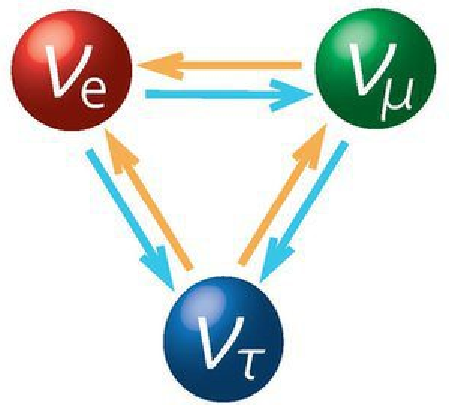
Because neutrino masses are the only **direct evidence** *for BSM physics*

- 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:

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

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

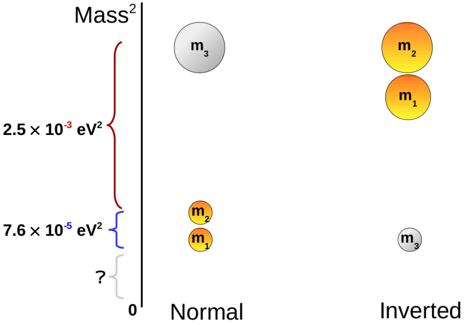
$$\begin{aligned}\Delta m^2_{21} &\equiv m_2^2 - m_1^2 = (7.6 \pm 0.2) \times 10^{-5}\,\mathrm{eV}^2\,, \\ |\Delta m^2_{31}| &\equiv |m_3^2 - m_1^2| = (2.48 \pm 0.06) \times 10^{-3}\,\mathrm{eV}^2\,.\end{aligned}$$

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

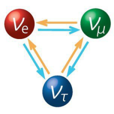
$M_\nu > 0.06\,\mathrm{eV}$

Inverted ordering

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

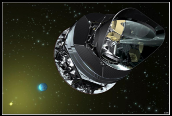
Neutrino oscillations

- 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



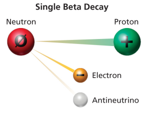
Cosmology

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



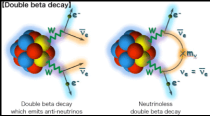
Beta decay

- 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



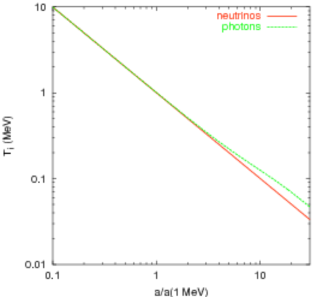
Neutrinoless double-beta decay

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



Basic facts of neutrino cosmology

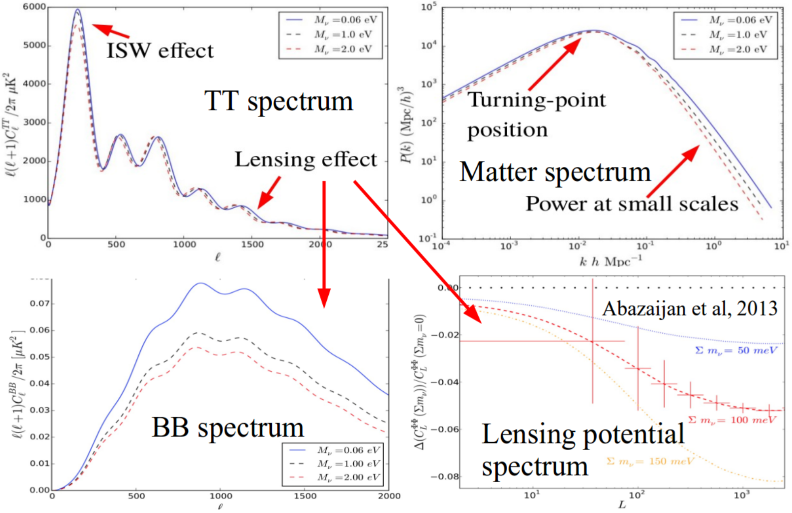
- $T \gtrsim 1\,\mathrm{MeV}$: weak interactions maintain νs in thermal equilibrium with the primeval cosmological plasma $[T_\nu = T_\gamma]$
- $T \lesssim 1\,\mathrm{MeV}$: νs free-stream keeping an equilibrium spectrum



Lesgourgues & Pastor, AHEP 2012 (2012) 608515

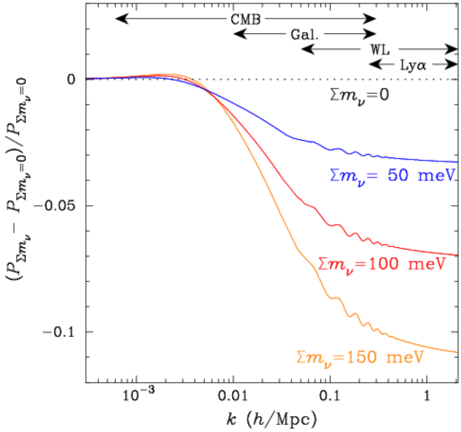
- $T \lesssim M_\nu$: νs turn non-relativistic, free-streaming suppresses the growth of structure on small scales (**VERY IMPORTANT**)

How can cosmology measure neutrino masses?



Courtesy of Martina Gerbino

Effect of neutrino masses on the LSS



On small scales (large k), where the suppression is maximal:

$$\frac{\Delta P_m(k)}{P_m(k)} \sim -8f\nu\,, \quad f_\nu \equiv \frac{\Omega_\nu}{\Omega_m}$$

Abazajian *et al.*, Astropart. Phys. 63 (2015) 66

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 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

Issue

Vol. 96, Iss. 12 — 15 December 2017

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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
τ `simlow` prior $\tau = 0.055 \pm 0.009$

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

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

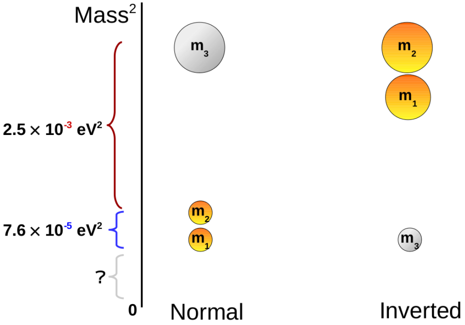
Planck temperature+polarization
$M_\nu <$ **0.49** eV @95% C.L.

- $+P(k)$: **0.28** eV
- $+P(k)$+BAO: **0.15** eV
- $+P(k)$+BAO+τ: **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

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

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

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

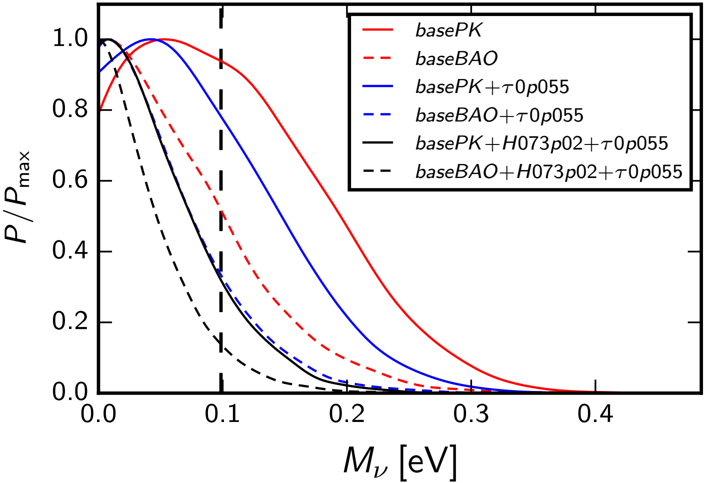
- Preference for NO driven by **volume effects**
- Even for the most constraining dataset, $p_{NO} : p_{IO} \sim 3.3 : 1$
- After our work others explored other physical priors/methodologies, preference for NO *typically* never $> 5 : 1$... Gerbino+2017, Simpson+2017, Caldwell+2017, Long+2018, Gariazzo+2018,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

Constraints on M_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? 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

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 ($k_{\rm max} = 0.2\,h\,\mathrm{Mpc}^{-1}$ 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

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ABSTRACT

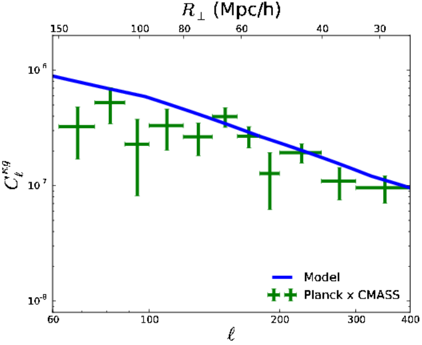
One of the most powerful cosmological data sets when it comes to constraining neutrino masses is represented by galaxy power spectrum measurements, $P_{gg}(k)$. The constraining power of $P_{gg}(k)$ is however severely limited by uncertainties in the modeling of the scale-dependent galaxy bias $b(k)$.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

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

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

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

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

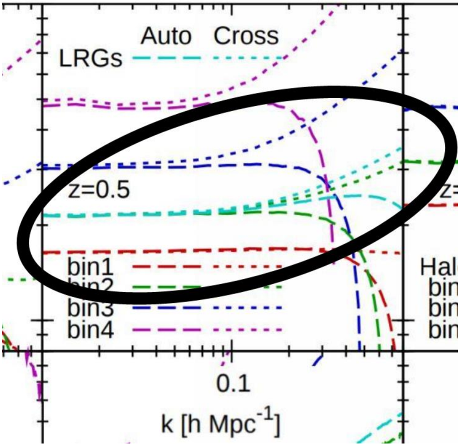
Leading-order correction is k^2, as k would break statistical isotropy

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

Abstract

+ Article information

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 $\sim f_\nu$

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[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

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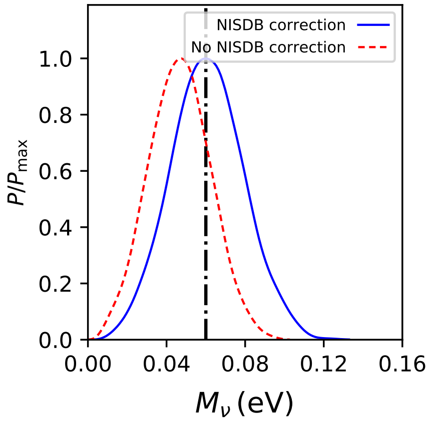
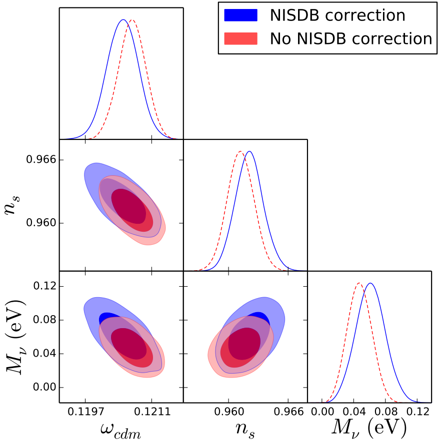
SV *et al.*, JCAP 1809 (2018) 001

Neutrino-induced scale-dependent bias (NISDB)



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



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

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?

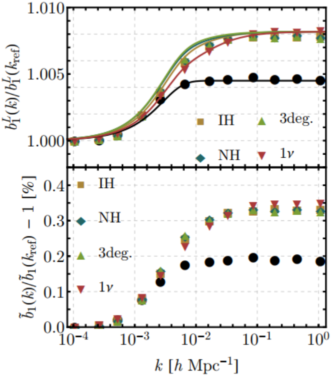
- Actually $b_{cb}(k)$ still depends on M_ν and is scale-dependent on large scales...

  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, arXiv:1811.12412



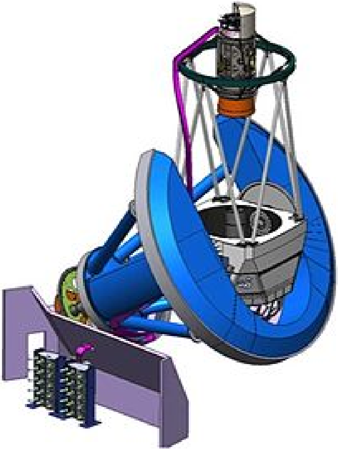
Muñoz & Dvorkin, PRD 98 (2018) 043503

Scale-dependent bias and neutrinos: take home messages

It is time to start worrying about scale-dependent galaxy bias, especially when dealing with massive neutrinos

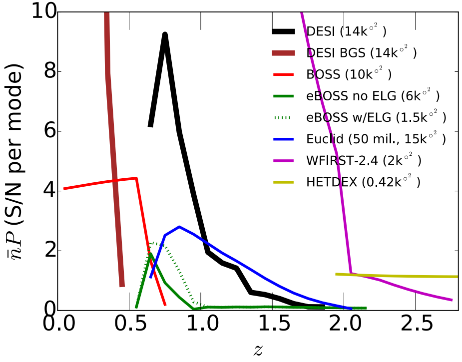
Outlook for the future: DESI

- Stage-IV ground based dark energy experiment
- 5-year survey, 14000 deg^2
- $\sim$ 30 million spectra from quasars and galaxies
- Tracers: LRGs ($z < 1.0$), ELGs ($z < 1.7$), QSOs ($z < 3.5$), BGS ($z \sim 0.2$)
- Lots of science to be done besides BAO and RSD: neutrinos, inflation, modified gravity, Milky Way stars...!

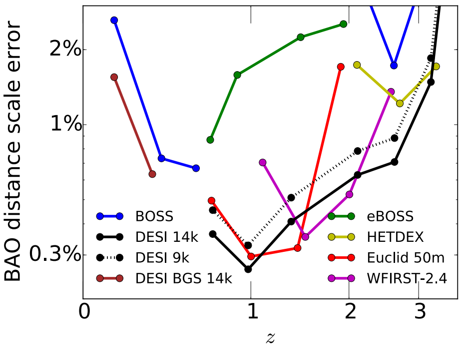


Outlook for the future: DESI

Comparison to other experiments



Credits: DESI collaboration, arXiv:1611.00036

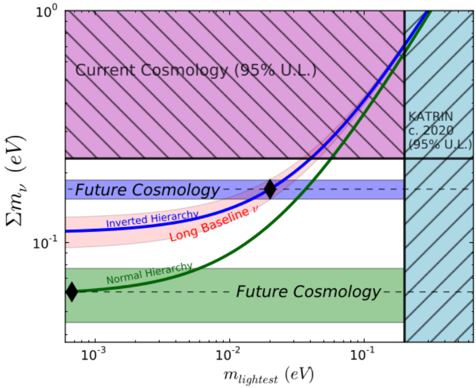


Credits: DESI collaboration, arXiv:1611.00036

High number density and large area key to DESI's success!

Outlook for the future: DESI

DESI in combination with future CMB missions will reach $\sigma_{M_\nu} \sim 0.016 - 0.030\,\mathrm{meV}$: nail down M_ν and possibly mass ordering!



	$\sigma\left(\sum m_\nu\right)$ [meV]
CMB Lensing (current galaxy clustering):	
Stage-IV CMB	45
Stage-IV CMB + BOSS BAO	**25**
CMB Lensing + Galaxy clustering:	
Stage-IV CMB + eBOSS BAO	23
Stage-IV CMB + DESI BAO	**16**
Stage-IV CMB no lensing + DESI galaxy clustering	15/20
Galaxy Weak Lensing:	
Planck + LSST [51]	23
Planck + Euclid [48]	25

Credits: K. Abazajian et al., arXiv:1309.5383

Neutrinos and other light relics with DESI

The road towards robust neutrino mass measurements:

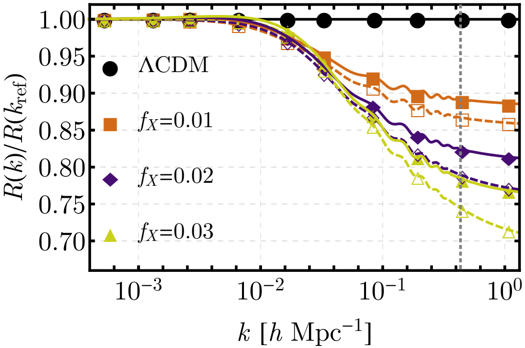
- Carefully model all effects described in this talk, including effect of neutrinos on galaxy bias!
- Alternative routes towards measuring M_ν: use effect on scale-dependent bias to cancel sample variance? Seljak, PRL 102 (2009) 021302
- Can we beat sample variance to measure the individual masses?

Other things to think about:

- What happens if we don't detect M_ν? Consider other scenarios (mass varying neutrinos, neutrino annihilation to light bosons,...), cross-check their effect in $P(k)$
- Sterile neutrinos, synergy with laboratory experiments (*e.g.* KATRIN)

Neutrinos and other light relics with DESI

For relics becoming non-relativistic during radiation domination
$\Delta P(k)/P(k) \sim -14 f_X$ (cf. $-8 f_\nu$ for neutrinos) Boyarsky *et al.*, JCAP 0905 (2009) 012



Muñoz & Dvorkin, PRD 98 (2018) 043503

Search for these relics with DESI *modelling galaxy bias properly*

Cross-correlation science with DESI

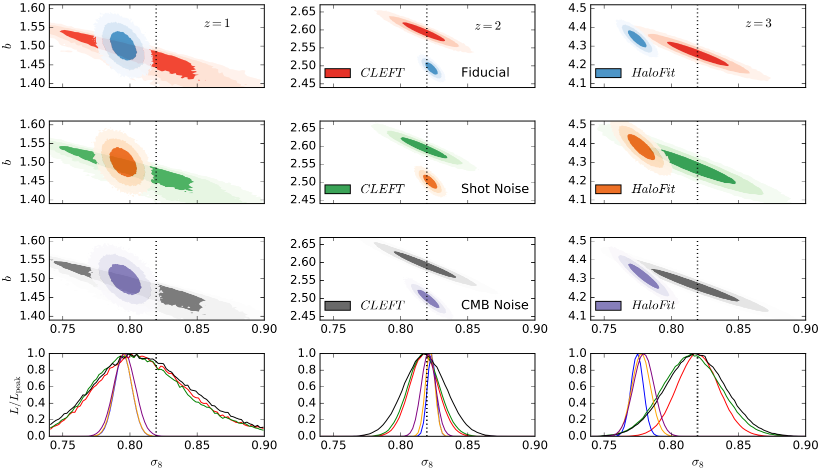
High S/N cross-correlation with CMB (lensing), opens many challenges/opportunities:

- Use more physical bias model (terms beyond k^2) to push to more non-linear scales
- Combine with bispectra ($\kappa\kappa\kappa$, $\kappa\kappa g$, κgg, ggg) to better constrain bias terms
- Need a better understanding/modelling of stochasticity
- Model relation (assuming there is one) between $b_{\rm auto}$ and $b_{\rm cross}$ (calibrate to N-body simulations?)

Also opportunities for cross-correlating with other LSS surveys (DES, LSST, Euclid), DESI will help with photometric redshift calibration

Cross-correlation science with DESI

At high z and large scales physics is linear: use perturbation theory?



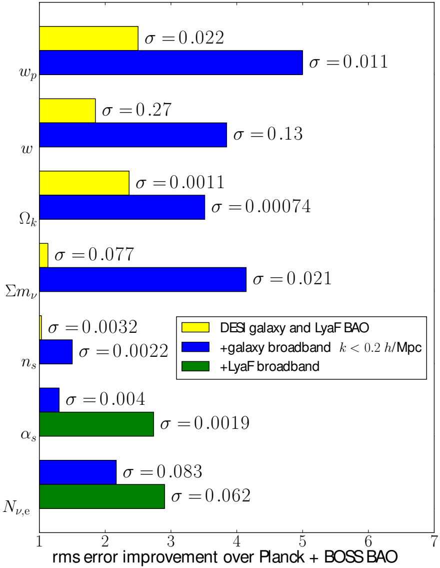
Modi, White, Vlah, JCAP 1708 (2017) 009

Other DESI science goals beyond neutrinos

Other very important science targets:

- Inflation (measure n_s, α_s, non-Gaussianity through scale-dependent correction to galaxy bias)
- Effective number of relativistic species
- Modified gravity

Credits: DESI collaboration, arXiv:1611.00036



Other DESI science goals beyond neutrinos

Other very important science targets:

- Inflation (measure n_s, α_s, non-Gaussianity through scale-dependent correction to galaxy bias)
- Effective number of relativistic species
- Modified gravity

At least some of these effects are partially degenerate with neutrino masses...

Given DESI's sensitivity to neutrino masses, we need to model their effects properly or risk biasing other science targets

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
- Beware and correct for **systematic** effects as scale-dependent galaxy bias due to neutrinos (correct for it in `CLASS v2.7`)!
- Amazing opportunities for neutrino (and non-) science in the next years with **DESI**, provided their effects are modelled correctly!

Thank you!

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Martina Gerbino
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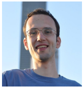

Simone Ferraro
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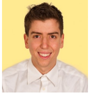

Rocky Kamen-Rubio
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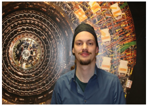
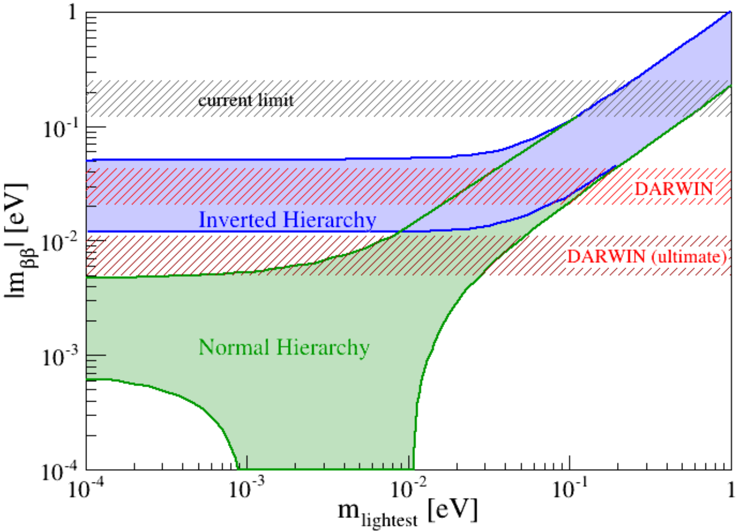


Tim Sprenger
Aachen

Synergy between cosmology and laboratory experiments



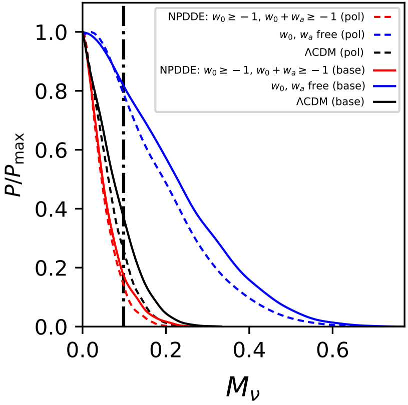
Credits: DARWIN collaboration

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

95% C.L. upper limits

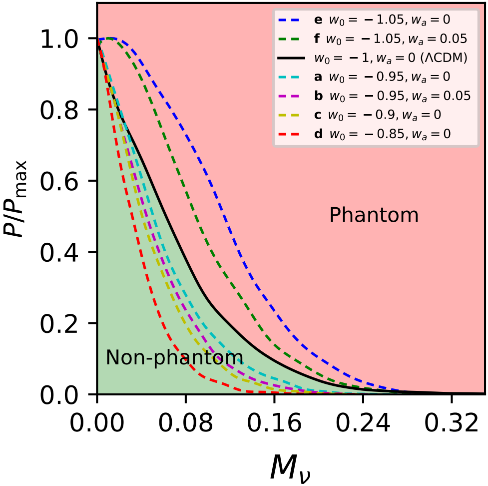
- ΛCDM: 0.17 eV
- $w_0 w_a$CDM: 0.41 eV
- NPDDE: **0.12** eV!!! $\approx$ 40% tighter



SV et al., PRD 98 (2018) 083501

Can M_ν limits get tighter in extended parameter spaces?

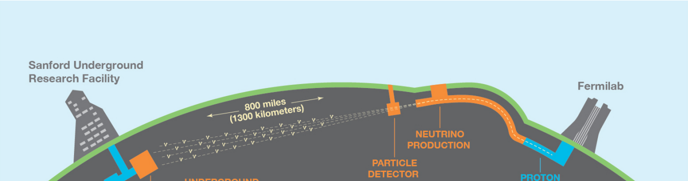
Why does this happen even though ΛCDM is a limiting case of NPDDE?



Connecting dark energy to neutrino laboratory experiments: take home messages

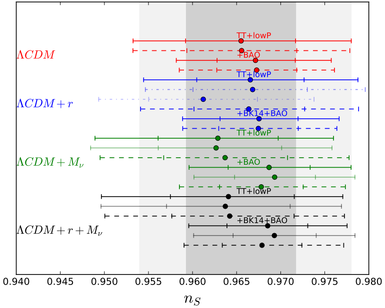
- In non-phantom dark energy models the preference for the normal neutrino ordering is stronger ($\approx 3-4:1$) than in ΛCDM ($\approx 2:1$)
- Long-baseline experiments (*e.g.* DUNE) targeting mass ordering...
- ...if ordering inverted, dark energy very unlikely to be quintessence (**proof by contradiction**: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

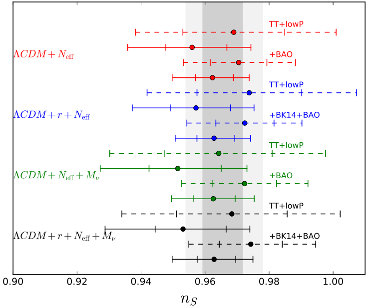
SV et al., PRD 98 (2018) 083501



Neutrinos as a nuisance for inflationary parameters

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





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

Neutrinos as a nuisance for inflationary parameters

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

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