Unveiling ν secrets with cosmology

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`arXiv:1605.04320` [Phys. Rev. D**94** (2016) 083522],
`arXiv:1610.08830` [Phys. Rev. D**95** (2017) 043512],
`arXiv:1701.08172` [Phys. Rev. D, in press],
`arXiv:1703.04585`

with Katherine Freese, Shirley Ho, Olga Mena, Martina Gerbino,
Elena Giusarma, Massimiliano Lattanzi, Thomas Schwetz, Steen Hannestad

Trobada @ Instituto de Fìsica Corpuscolar, Valencia, March 2017

Overview: Qs (& As)

- Q: How constraining are the bounds on M_ν from cosmology *if we believe some of the most recent datasets?*
  A: **VERY**
- Q: *Within a flat ΛCDM background and with recent datasets*, is shape $[P(k)]$ or geometrical (BAO) information more constraining?
  A: **GEOMETRICAL** [1]
- Q: Can we say something quantitatively interesting and statistically correct about the ν mass hierarchy with data from cosmology?
  A: **YES, WE CAN (BUT WE HAVE TO BE VERY CAREFUL)**
- Q: Do assumptions on the distribution of mass among the three eigenstates matter?
  A: **NOT MUCH**
- Q: How does the future of neutrino cosmology look?
  A: **VERY EXCITING!!!**

[1] with caveats

The Cosmic Neutrino Background (CνB)

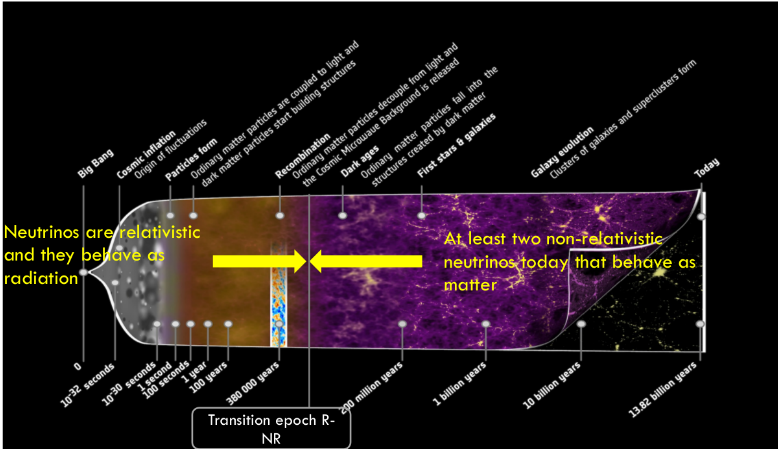
- The presence of a background of relic neutrinos (CνB) is a basic prediction of the standard cosmological model
- Weak interactions maintain νs in thermal equilibrium with the primeval cosmological plasma until $T \sim 1\,\mathrm{MeV}$ ($z \sim 10^{10}$)
- Below $T \sim 1\,\mathrm{MeV}$ νs free-stream keeping an equilibrium spectrum:

$$f_\nu(p, T) = \frac{1}{e^{\frac{p-\mu}{T}} + 1}$$

- When the temperature drops below their mass, neutrinos turn non-relativistic, and their free-streaming suppresses the growth of structure on small scales (**VERY IMPORTANT**)
- Today $T_\nu \simeq 1.9\,\mathrm{K}$, $n_\nu \simeq 113\,\mathrm{cm}^{-3}$, $N_{\mathrm{eff}} = 3.046$

The Cosmic Neutrino Background (CνB)

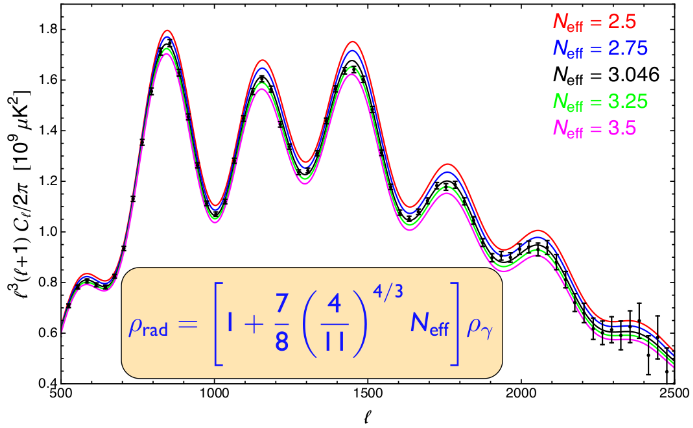
Neutrinos behave as radiation at early times, as matter at late times



Courtesy of Elena Giusarma

The Cosmic Neutrino Background (CνB)

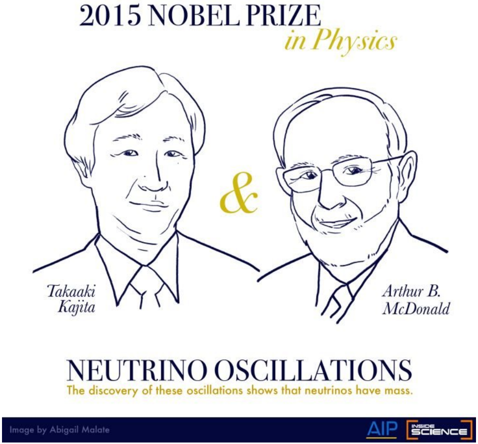
This picture is consistent with current CMB observations:



Courtesy of Massimiliano Lattanzi

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 eigenstates are linear superposition of mass eigenstates:

$$|\nu_\alpha\rangle = U^\star_{\alpha i}\,|\nu_i\rangle$$

The observation of flavour oscillations indicates that the mass eigenstates are non-degenerate. From oscillation experiments we measure the mass-squared differences very well:

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

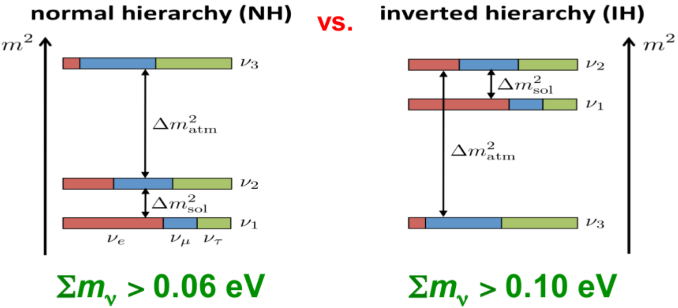
3 mixing angles are also quite well known.

Neutrino unknowns

- Absolute mass scale $M_\nu \equiv \sum_i m_{\nu_i}$
- Mass hierarchy (normal or inverted), i.e. sign of m_{31}^2
- θ_{23} octant
- Dirac vs Majorana nature
- CP violation
- Sterile eigenstates

Neutrino mass hierarchy

Oscillation data put a lower limit on the absolute mass scale according to the mass hierarchy:

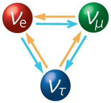


$$M_{\nu,\text{min}} = \sqrt{\Delta m^2_{21}} + \sqrt{\Delta m^2_{31}} \simeq 0.06\,\text{eV} \text{ (NH)}$$

$$M_{\nu,\text{min}} = \sqrt{\Delta m^2_{31}} + \sqrt{\Delta m^2_{31} + \Delta m^2_{21}} \simeq 0.1\,\text{eV} \text{ (IH)}$$

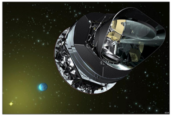
Neutrino oscillations

- 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 hierarchy



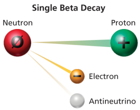
Cosmology

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



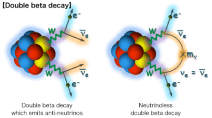
Beta decay

- 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

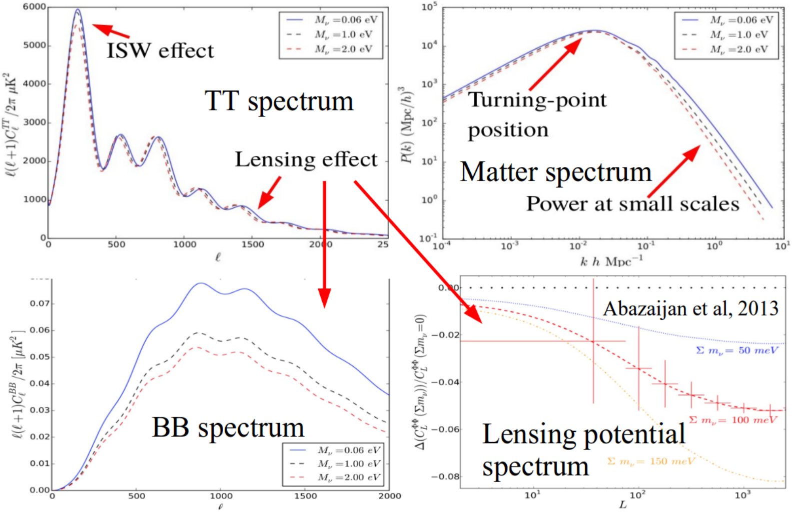


Neutrinoless double-beta decay

- Sensitive to effective Majorana mass $m_{\beta\beta} \equiv \sum_i |U_{ei}^2 m_i|$
- Exploits GR+Boltzmann equations
- Limited by NME uncertainties and ν nature

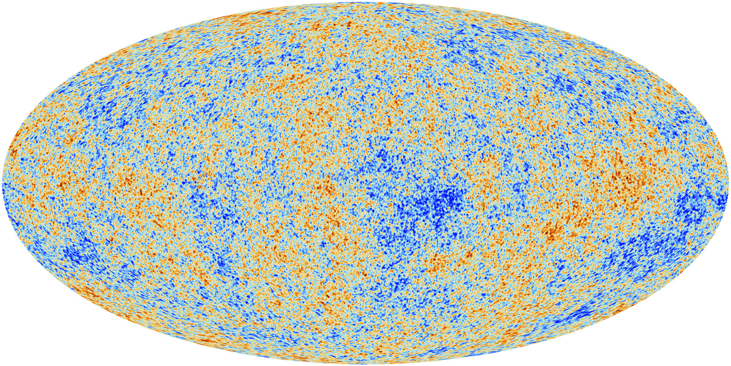


How can cosmology measure neutrino masses?



Courtesy of Martina Gerbino

Cosmological datasets: Cosmic Microwave Background

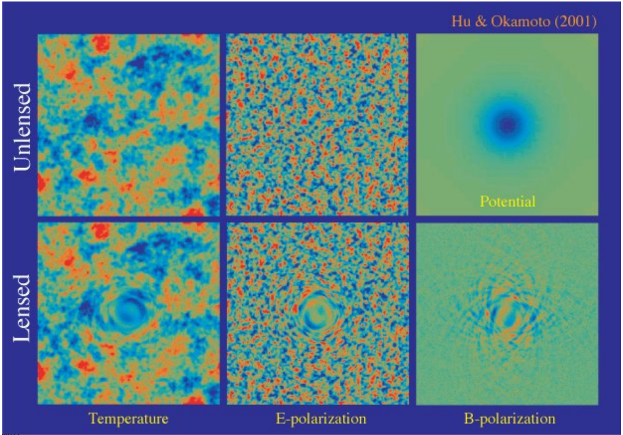


Blackbody radiation at $T = 2.7\text{K}$, uniform to 1 part in 10^5 across the whole sky, emitted at the time of recombination ($z \simeq 1100$). Contains tiny temperature and polarization anisotropies which encode a wealth of cosmological information.

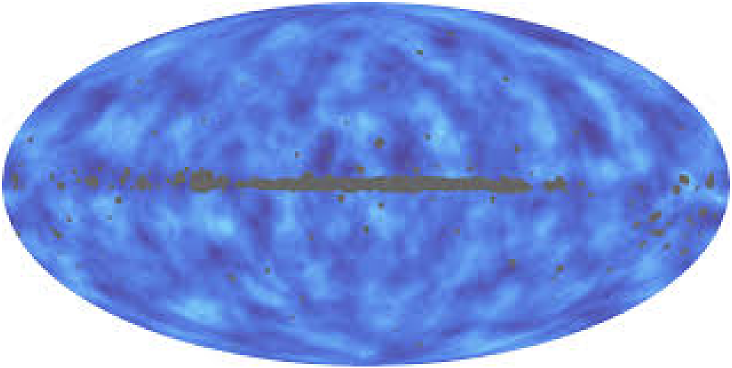
Cosmological datasets: CMB lensing

CMB photons deflected according to the deflection field $\vec{d} = \vec{\nabla}\phi$, with lensing potential ϕ given by:

$$\phi = -\int_0^{\chi^\star} d\chi \, \frac{\chi^\star - \chi}{\chi^\star \chi} (\Phi + \Psi)$$

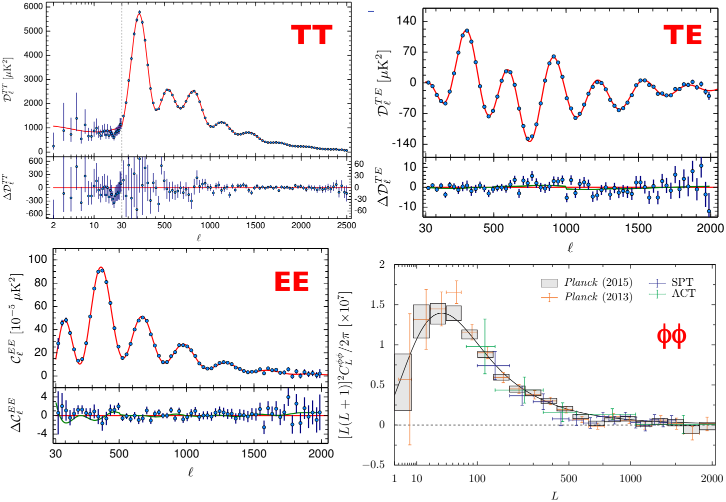


Cosmological datasets: CMB lensing



Credits: Planck collaboration

Cosmological datasets: CMB spectra



Note: red curve obtained from 6-parameter ΛCDM model fit to TT **only**

Cosmological datasets: CMB spectra

- *PlanckTT+lowP*: temperature data (TT for $2 < \ell < 2508$) and large-scale polarization data (EE, BB, TE for $2 < \ell < 29$)
- *PlanckTTTEEE+lowP*: same as above with the addition of small-scale polarization data (TE, EE for $30 < \ell < 1996$), less conservative as might still be contaminated by systematics (temperature-polarization leakage)
- *lensing*: lensing potential spectrum ($\phi\phi$ for $40 < \ell < 400$)
- Planck 2017 re-analysis? New likelihoods not public yet, can use new measurements of optical depth to reionization $\tau = 0.055 \pm 0.009$ as a proxy for the large-scale polarization spectra

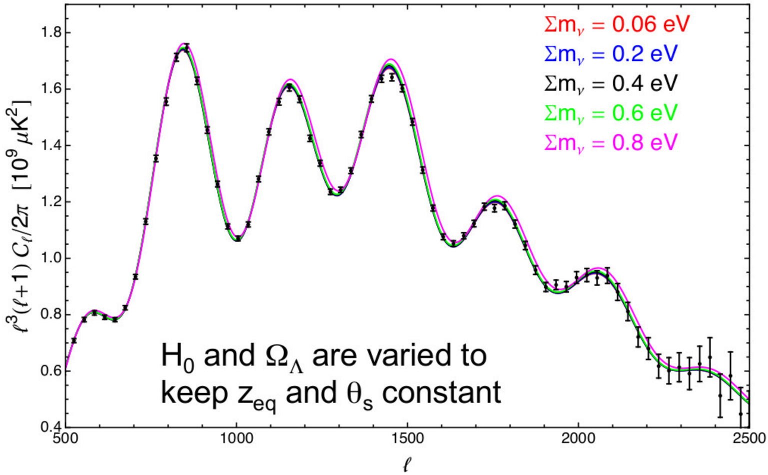
Neutrino masses and the CMB: background level

Neutrinos can affect the CMB at both background and perturbation level. At the background level: see e.g. reviews by Wong 2011, Lesgourgues & Pastor 2012

- Since Ω_m is precisely known, increasing M_ν leads to shift in background quantities such as $z_{\rm eq}$ and $d_A(z_{\rm eq})$ which mostly affect the first peak through the early ISW effect[2]...
- ...however, due to parameter degeneracies, these shifts can be compensated by acting on other parameters, notably H_0
- If one varies M_ν, and simultaneously H_0 and Ω_Λ as to keep $z_{\rm eq}$ and $d_A(z_{\rm eq})$ fixed, the largest remaining effects are small shifts of the first peaks to higher ℓ (WMAP: $M_\nu < 1\,{\rm eV}$ @95% C.L.)...
- ...small changes to the Silk damping scale...
- ...and larger changes at low-ℓ due to the late ISW effect, which however is essentially unconstrained

[2] Contribution to the CMB temperature anisotropies due to the time-variation of gravitational potentials around the time of recombination

Neutrino masses and the CMB: background level

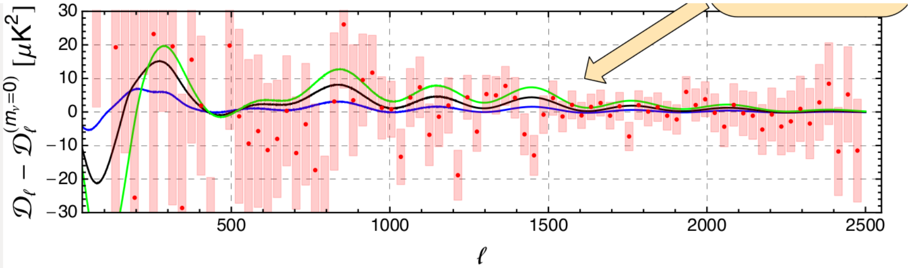


Courtesy of Massimiliano Lattanzi

Neutrino masses and the CMB: perturbation level

At the perturbation level:

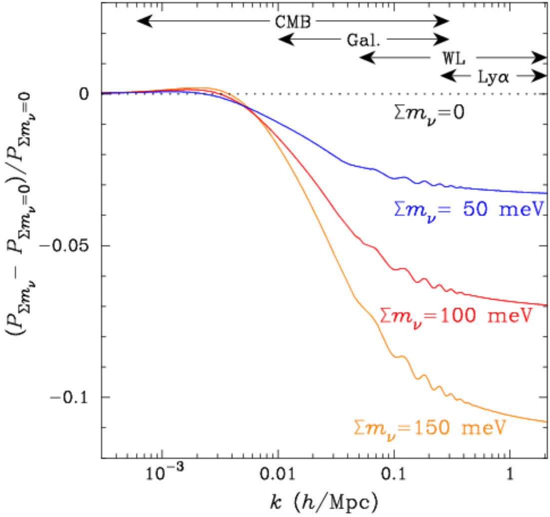
- Massive neutrinos free-streaming damps small-scale perturbations...
- ...less structure=less lensing=less smearing of the small-scale power spectrum of the CMB (Planck: $M_\nu < 0.72\,\mathrm{eV}$ @95% C.L.)
- This is a secondary anisotropy effect, i.e. it acts after the CMB has formed, but is affecting the way the CMB photons travel to us!



Courtesy of Massimiliano Lattanzi

Neutrino masses and the large-scale structure

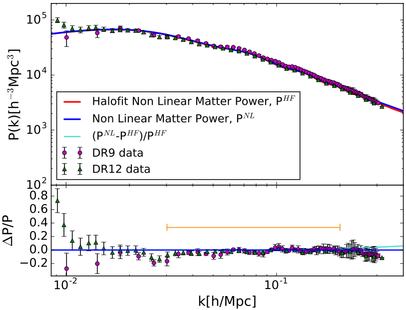
Free-streaming of neutrinos suppresses growth of structure on small scales



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

Cosmological datasets: galaxy power spectrum

BOSS DR12 CMASS $P(k)$



Modelling of data and theory within likelihood:

$$P^g_{\text{meas}}(k_i) = \sum_j W(k_i, k_j) P^g_{\text{true}}(k_j)$$

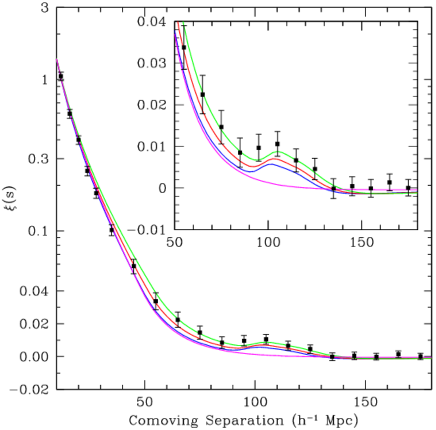
$$P^g_{\text{th}}(k, z) = b^2_{\text{HF}} P^m_{\text{HF}\nu}(k, z) + P^s_{\text{HF}}$$

- Power on small scales is affected by free-streaming of neutrinos:

$$\frac{\Delta P(k)}{P(k)} \sim -8 f_\nu \,, \qquad k_{\text{nr}} \simeq 0.018 \Omega_m^{\frac{1}{2}} \left(\frac{m}{1 \text{ eV}}\right)^{\frac{1}{2}} \; h \; Mpc^{-1}$$

- Issues: (scale-dependent?) bias, non-linearities, redshift-space distortions, systematics

Cosmological datasets: Baryon Acoustic Oscillations



Approximately constrain the quantity $D_v(z_{\rm eff})/r_s(z_{\rm drag})$, where:

$$D_v(z) = \left[(1+z)^2 D_A(z)^2 \frac{cz}{H(z)}\right]^{\frac{1}{3}}$$

Several BAO measurements available (BOSS DR11/DR12 CMASS/LOWZ, WiggleZ, 6dFGS)

- Standard ruler: constrain expansion history and break degeneracies (mainly involving Ω_m and H_0)
- Substantially less affected by systematics (bias, non-linear evolution)
- Help constraining neutrino masses by pinning down background quantities

Cosmological datasets: other "external" datasets

- Optical depth to reionization $\tau = 0.055 \pm 0.009$ from Planck HFI
- Direct measurements of the Hubble parameter $H_0 = 73.02 \pm 1.79\,\mathrm{km/s/Mpc}$
- Planck SZ clusters
- Weak lensing measurements (e.g. CHFTLenS)

Each of them is important for resolving parameter degeneracies:

- Degeneracy between M_ν and τ in CMB and $P(k)$: $\tau \downarrow \implies M_\nu \downarrow$
- Degeneracy between M_ν and H_0 with CMB, affects distance to last scattering: $H_0 \uparrow \implies M_\nu \downarrow$ (careful with tensions)
- Cluster mass function probes Ω_m and σ_8, important for fixing the normalization of $P(k)$
- Weak lensing also probes Ω_m and σ_8, and in particular the combination $S_8 = \sigma_8 \Omega_m^{0.5}$ (careful with tensions)

Analysis method

Bayes' theorem (datasets=$\mathbf{x}$, cosmological parameters=$\boldsymbol{\theta}$):

$$\begin{array}{rcl} p(\boldsymbol{\theta}|\mathbf{x}) & \propto & \mathcal{L}(\mathbf{x}|\boldsymbol{\theta})p(\boldsymbol{\theta}) \\ p(\boldsymbol{\theta}) & : & \text{posterior} \\ \mathcal{L}(\mathbf{x})|\boldsymbol{\theta}) & : & \text{likelihood} \\ p(\boldsymbol{\theta}) & : & \text{prior} \end{array}$$

Vary 6 basic cosmological parameters $\Omega_b h^2, \Omega_c h^2, \Theta_s, \tau, n_s, \log\left(10^{10} A_s\right) +$ $M_\nu +$ many other nuisance parameters.
Sample posterior using Markov chain Monte Carlo (MCMC) techniques, implemented in the `CosmoMC` code.
Then report 95% C.L. upper limit on M_ν, M_{95}, such that:

$$\frac{\int_{M_0}^{M_{95}} dM_\nu \; p(M_\nu)}{\int_{M_0}^{\infty} dM_\nu \; p(M_\nu)} = 0.95$$

Results: overview

Results reported assuming a spectrum of three massive degenerate νs

SV et al. 2017

PlanckTT+lowP: $M_\nu < 0.716\,\mathrm{eV}$ @95% C.L.

- $+P(k)$: $<$ **0.299** eV
- $+P(k)$+BAO: $<$ **0.246** eV
- $+P(k)$+BAO$+\tau$: $<$ **0.205** eV
- $+P(k)$+BAO+SZ: $<$ **0.239** eV
- $+P(k)$+BAO$+H_0$: $<$ **0.164** eV
- $+P(k)$+BAO$+H_0+\tau$: $<$ **0.140** eV
- $+P(k)$+BAO$+H_0+\tau$+SZ: $<$ **0.136** eV

PlanckTT+lowP+TTTEEEE: $M_\nu <$ **0.485** eV @95% C.L.

- $+P(k)$: $<$ **0.275** eV
- $+P(k)$+BAO: $<$ **0.215** eV
- $+P(k)$+BAO$+\tau$: $<$ **0.177** eV
- $+P(k)$+BAO+SZ: $<$ **0.208** eV
- $+P(k)$+BAO$+H_0$: $<$ **0.132** eV
- $+P(k)$+BAO$+H_0+\tau$: $<$ **0.109** eV
- $+P(k)$+BAO$+H_0+\tau$+SZ: $<$ **0.117** eV

Constraints on M_ν: take home messages

- Bounds on M_ν from cosmology are **VERY** strong
- Pay attention to tensions between datasets which can drive very strong M_ν constraints or spurious detections of non-zero M_ν
- A robust 95% C.L. upper bound is about $M_\nu < 0.15\,\mathrm{eV}$
- We are approaching the region of parameter space where the inverted hierarchy is disfavoured
- Some residual model dependency in the bounds as they assume a background flat ΛCDM Universe
- In any case we can safely say that $M_\nu \ll 1\,\mathrm{eV}$

Shape vs geometry

What's more constraining: shape [$P(k)$] or geometrical (BAO) information? To answer this question we replace the DR12 CMASS $P(k)$ by the DR11 CMASS BAO information

PlanckTT+lowP+BAO:
$M_\nu < \mathbf{0.186}\,\mathrm{eV}$ @95% C.L.

- $+\tau$: $< \mathbf{0.151}\,\mathrm{eV}$
- $+H_0$: $< \mathbf{0.148}\,\mathrm{eV}$
- $+H_0+\tau$: $< \mathbf{0.115}\,\mathrm{eV}$
- $+H_0+\tau+$SZ: $< \mathbf{0.114}\,\mathrm{eV}$

PlanckTT+lowP+TTTEEEE:
$M_\nu < \mathbf{0.153}\,\mathrm{eV}$ @95% C.L.

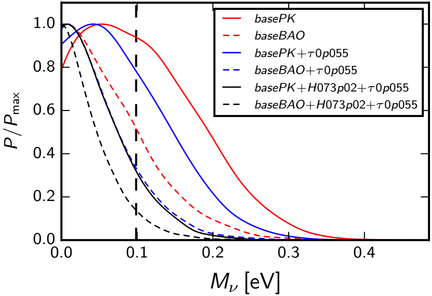
- $+\tau$: $< \mathbf{0.118}\,\mathrm{eV}$
- $+H_0$: $< \mathbf{0.113}\,\mathrm{eV}$
- $+H_0+\tau$: $< \mathbf{0.094}\,\mathrm{eV}$
- $+H_0+\tau+$SZ: $< \mathbf{0.093}\,\mathrm{eV}$

SV et al. 2017

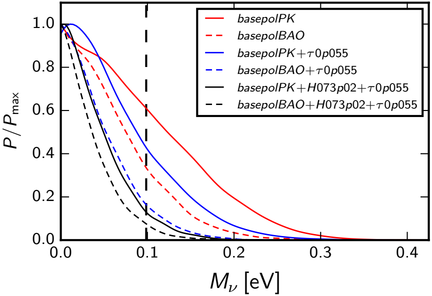
Shape vs geometry

M_ν posteriors: compare shape information (solid) with geometrical information (dashed), for a given color SV et al. 2017

Without small-scale polarization



With small-scale polarization



Geometrical information more constraining than shape (*win-win*, as BAO also less prone to systematics), **BUT**:

- True within the assumption of a background flat ΛCDM
- Limit of our analysis methodology (e.g. we don't know the bias)

How to make shape measurements more constraining?

The biggest limitation is our ignorance of the (scale-dependent) galaxy bias b, $P_{gg} = b^2 P_{mm}$. There are some clean ways for measuring it

- CMB lensing convergence-galaxy angular cross-spectrum:

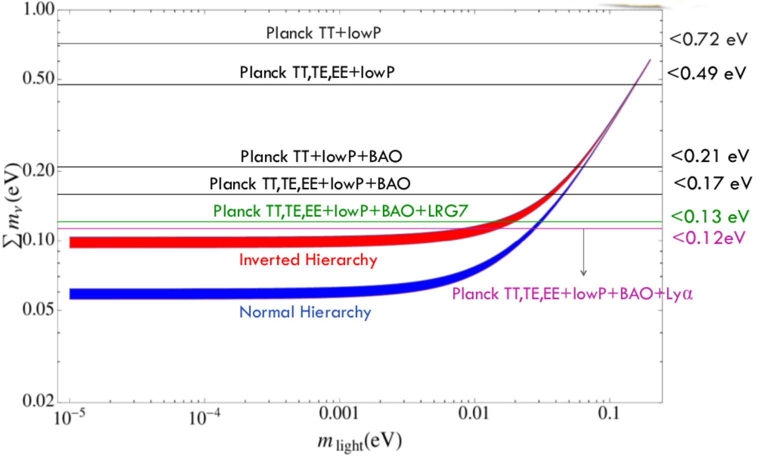
$$C_\ell^{\kappa g} = \frac{3H_0^2\Omega_m}{2c^2}\int_{z_1}^{z_2} dz\ \frac{\chi^\star - \chi(z)}{\chi(z)\chi^\star}(1+z)b\left(\frac{\ell}{\chi(z)}\right)P\left(\frac{\ell}{\chi(z)}, z\right)$$

- The simplest form of (scale-dependent) bias is given by:

$$b(k) = a + ck^2$$

- Work in progress: with a Gaussian prior $a = 2.1 \pm 0.1$ measured from $C_\ell^{\kappa g}$, 95% C.L. upper bound on M_ν using *PlanckTT+lowP+P(k)* improves from $\sim \mathbf{0.30}\,\mathrm{eV}$ to $\sim \mathbf{0.16}\,\mathrm{eV}$!!

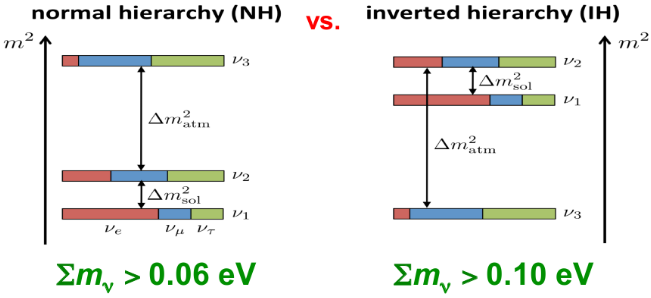
Where are we in the greater picture?



Courtesy of Elena Giusarma

What about the mass hierarchy?

- For each mass hierarchy, there exists a minimal allowed value for M_ν...
- ...so näively you would say that if we set a limit $M_\nu < 0.1\,\mathrm{eV}$ we know the neutrino hierarchy is normal! (and have a paper in *Nature*/*Science*/*PRL*)



Bayesian model comparison between hierarchies

- What we really have to solve is a model comparison problem between two models: normal hierarchy (NH) and inverted hierarchy (IH).
- In other words, compute the **evidence** for given hierarchy $\mathcal{E}(\mathbf{x}|m_0, H)$ as a function of lightest neutrino mass m_0 and hierarchy $H = N, I$:

$$\mathcal{E}_H = \int_0^\infty dm_0 \; \pi(m_0) \int d\boldsymbol{\theta} \; \pi(\boldsymbol{\theta}) \mathcal{L}(\mathbf{x}|m_0, \boldsymbol{\theta}, H)$$

- Then posterior odds for a given hierarchy $H = N, I$, p_H, is simply given by:

$$p_H = \frac{\pi(H)\mathcal{E}_H}{\pi(N)\mathcal{E}_N + \pi(I)\mathcal{E}_I}$$

Hannestad & Schwetz 2016

Odds for mass hierarchies

From odds for given hierarchy p_H the confidence level at which IH is excluded is $\mathrm{CL}_{\mathsf{IH}} = 1 - p_I$. This is $\neq$ confidence level at which we exclude the minimal mass in the IH ($0.1\,\mathrm{eV}$), $\mathrm{CL}_{0.1}$. Examples: SV et al. 2017

- *PlanckTT+lowP*+BAO+τ: $M_\nu < 0.151\,\mathrm{eV}$ @95% C.L.
  $p_N/p_I = \mathbf{1.8} : \mathbf{1}$, $\mathrm{CL}_{\mathsf{IH}} = \mathbf{64\%}$, $\mathrm{CL}_{0.1} = \mathbf{82\%}$
- $+$*TTTEEE* $M_\nu < 0.118\,\mathrm{eV}$ @95% C.L.
  $p_N/p_I = \mathbf{2.4} : \mathbf{1}$, $\mathrm{CL}_{\mathsf{IH}} = \mathbf{71\%}$, $\mathrm{CL}_{0.1} = \mathbf{91\%}$
- $+H_0$+SZ: $M_\nu < 0.093\,\mathrm{eV}$ @95% C.L.
  $p_N/p_I = \mathbf{3.3} : \mathbf{1}$, $\mathrm{CL}_{\mathsf{IH}} = \mathbf{77\%}$, $\mathrm{CL}_{0.1} = \mathbf{96\%}$

You might have seen claims of huge (42:1, 95:1, >100:1) odds in favour of NH in a recent paper Simpson et al. 2017
That's what happens when you play around with your priors $\pi(N)$ and $\pi(H)$ in an inappropriate way! See rebuttal paper, Schwetz et al. (incl. SV) 2017

Where is the sensitivity to the hierarchy coming from?

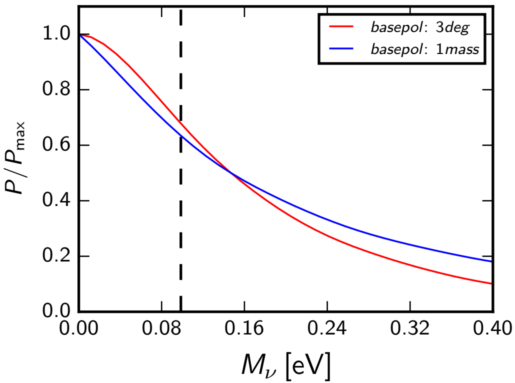
- Current cosmological data is mostly sensitive to M_ν, and not individual masses m_i
- Sensitivity to the mass hierarchy is only due to **volume effects**
- We are approaching the region of parameter space where these volume effects are very important
- Current data cannot distinguish between the two mass hierarchies based on physical effects
- Futuristic data might be able to measure individual neutrino masses through their free-streaming imprint on $P(k)$ and on the early ISW effect
- In the most optimistic case, we need a sensitivity of $0.02\,\mathrm{eV}$ to distinguish between NH and IH at 2σ (reachable with CMB-S4/COrE+DESI BAO) through volume effects alone
- My take: I don't think we'll ever measure individual neutrino masses from cosmology through physical effects

Constraints on mass hierarchy: take home messages

- There is a weak preference ($\sim 2:1$) for the NH from cosmology
- Even with the least conservative datasets at most $\sim 3.3:1$ preference
- All preference for the NH is driven by volume effects
- Corollary of the above: be careful how you weigh your prior volume!

Assumptions on the neutrino mass spectrum

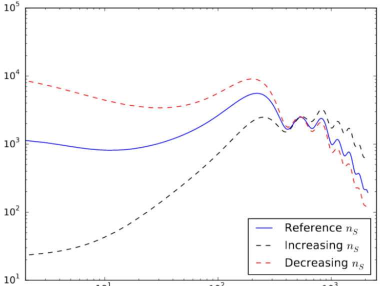
- Bounds derived assuming 3 massive degenerate νs spectrum (*3deg*)
- Compare results when considering 1 massive + 2 massless νs (*1mass*)
- *1mass* more constrained than *3deg* when not using high-ℓ polarization, less constraining otherwise ($\mathcal{O}(0.1)\sigma$ shifts) SV et al. 2017



Do assumptions on neutrinos bias inflationary model selection?

Yes and no! There is a bias if we only consider CMB data:

- Increasing M_ν decreases the amount of lensing and hence the smearing of the damping tail, so gives more power to the damping tail
- Effect can be compensated by decreasing n_s (tilting the primordial power spectrum to give less power to the damping tail)
- M_ν and n_s are partially anti-correlated: $M_\nu \uparrow \implies n_s \downarrow$. This is important for inflationary models! Gerbino, Freese, SV, et al. 2016

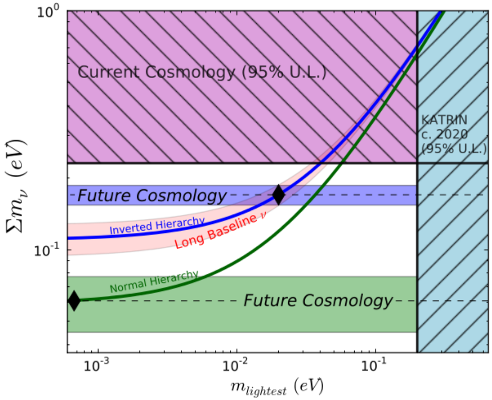


The future of neutrino cosmology

- Future CMB experiments: e.g. Advanced ACTPol, SPT-3G, Simons Observatory, CMB-S4, E4?
- CMB lensing is the next frontier in CMB physics
- Future cluster surveys
- Future galaxy surveys: e.g. eBOSS, DESI, LSST
- Galaxy weak lensing (cosmic shear): e.g. EUCLID
- Lyman α: can go to very small scales
- 21-cm H line survey: e.g. SKA

The future of neutrino cosmology

Q: what do future cosmological surveys have in store for νs?



	$\sigma(\sum m_\nu)$ [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

A: a sure detection of M_ν and possibly of the mass hierarchy!

Conclusions

- Cosmology provides tightest constraints on ν masses, tightest constraint currently is $M_\nu < 0.093\,\mathrm{eV}$ @95% C.L.
- Geometrical surpasses shape information in constraining power, but improvements in the latter can be expected from lensing-galaxy cross-correlation which can nail down the scale-dependent bias
- Data are putting the inverted hierarchy under pressure, excluded at most @77% C.L., but be careful with the choice of prior!
- Unphysical assumptions on the neutrino mass spectrum do not bias M_ν bounds, but could bias inflationary model selection
- The future of ν cosmology is very bright, with a detection of M_ν and possibly the hierarchy expected within the next years: stay tuned!