Answering ν *kwa*stions with cosmology

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The Oskar Klein Centre for Cosmoparticle Physics

Advances in theoretical cosmology in light of data
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Let's go back in time...

"Nomen [est] omen"

What's in a νame?

Language	Word tree	…*Some branches*	Meaning
Physics (Fermi 1934)	**NEUTR-INO**		**Little neutral one**
Italian	**NEUTRO**		**Neutral**
Latin	**NE-UTER**		**Not either; neutral**
Latin	**UTER**		**Either**
Greek	↑	*OUDETEROS*	*Neutral*
Old High German	↑ ↗	*HWEDAR*	*Which of two; whether*
Phonetic change/loss	[K]**UOTER**[US]		**Which of the two?**
Ionic Greek	**KOTEROS**		**Which of the two?**
Sanskrit	**KATARAS**		**Which of the two?**
Latin	↑	*QUANTUS*	*How much?*
Sanskrit	↑	*KATAMAS*	*Which out of many?*
Sanskrit	↑	*KATHA*	*How?*
Sanskrit	↑ ↗	*KAS*	*Who?*
Indo-European root	**KA** *or* **KWA**		**Interrogative base**

Answer: ν's destiny is to raise kwastions!

Courtesy of Eligio Lisi, Summary Talk (Theory) at Neutrino 2010, Athens

Preliminary Q: why care about neutrinos?

Neutrinos are most likely to be the key to physics beyond the Standard Model

See José's talk

Asking the right *Kwa*stions

- How strong are the bounds on M_ν from cosmology?
- Can cosmology tell us something about the mass hierarchy?
- Does shape (power spectrum) or geometry (BAO) currently tell us more about M_ν?

Answers

- Q: How strong are the bounds on M_ν from cosmology?

  A: **VERY**

- Q: Can cosmology tell us something about the mass hierarchy?

  A: **YES**

- Q: Does shape (power spectrum) or geometry (BAO) currently tell us more about M_ν?

  A: **GEOMETRY** [1]

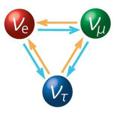
[1] With many caveats.

Neutrino unknowns

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

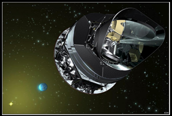
Neutrino oscillations

- 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



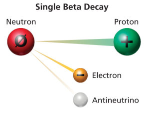
Cosmology

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



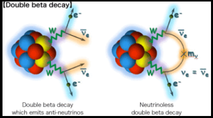
Beta decay

- 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 double-beta decay
- Limited by NME uncertainties and ν nature

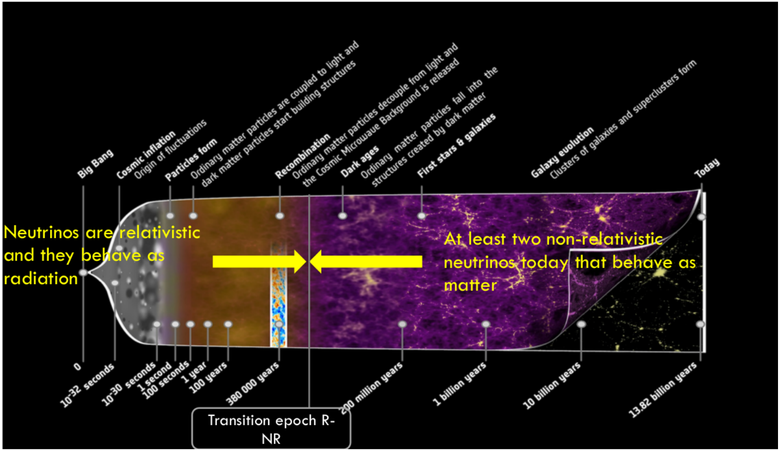


ν story

- CνB is a basic prediction of the standard cosmological model
- Weak interactions maintain νs in equilibrium until $T \sim 1\,\mathrm{MeV}$
- Below $T \sim 1\,\mathrm{MeV}$ νs free-stream keeping an equilibrium spectrum
- When the $T \lesssim M_\nu$, neutrinos turn non-relativistic, free-streaming **suppresses growth of structure** on small scales
- Today $T_\nu \simeq 1.9\,\mathrm{K}$, $n_\nu \simeq 113\,\mathrm{cm}^{-3}$, $N_{\mathrm{eff}} = 3.046$

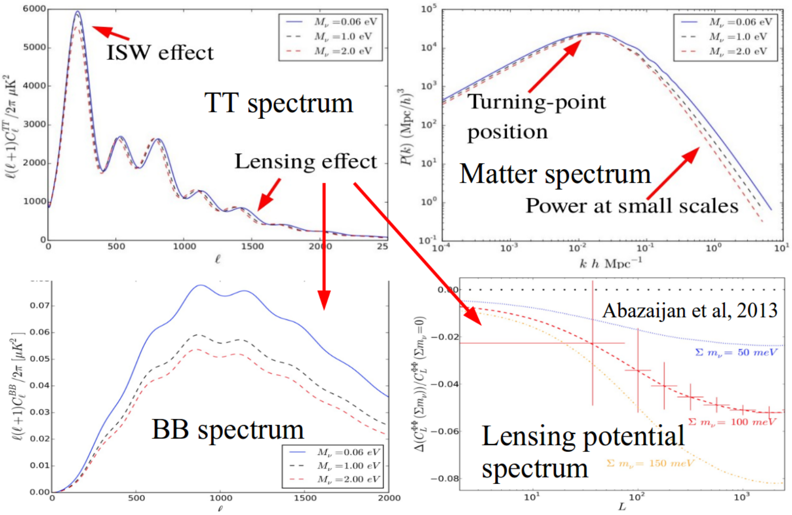
ν story

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



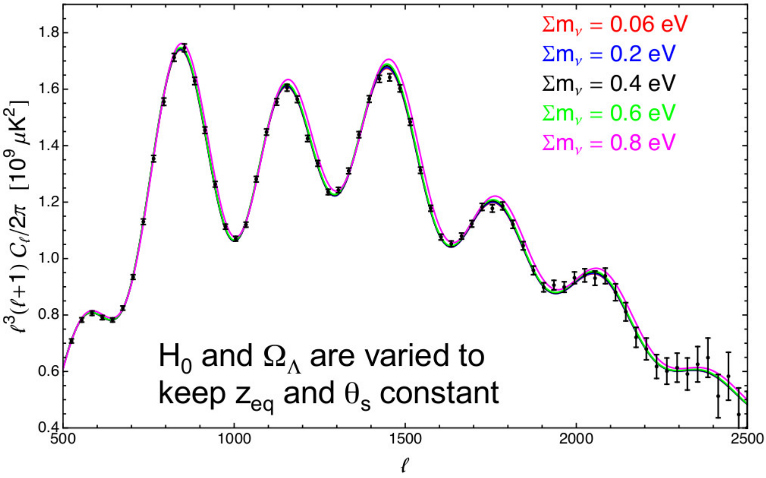
Courtesy of Elena Giusarma

How can cosmology measure neutrino masses?



Courtesy of Martina Gerbino

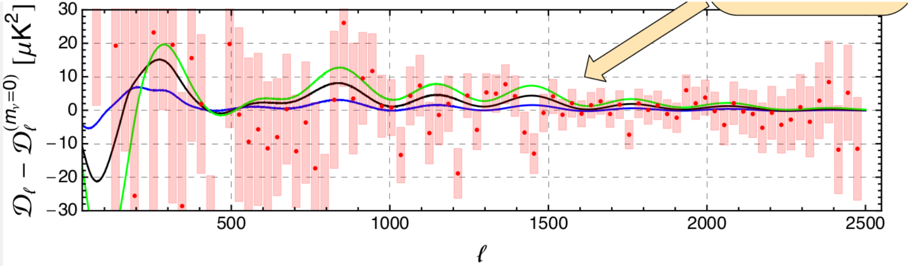
Neutrino masses and the CMB: background level



Courtesy of Massimiliano Lattanzi

Neutrino masses and the CMB: perturbation level

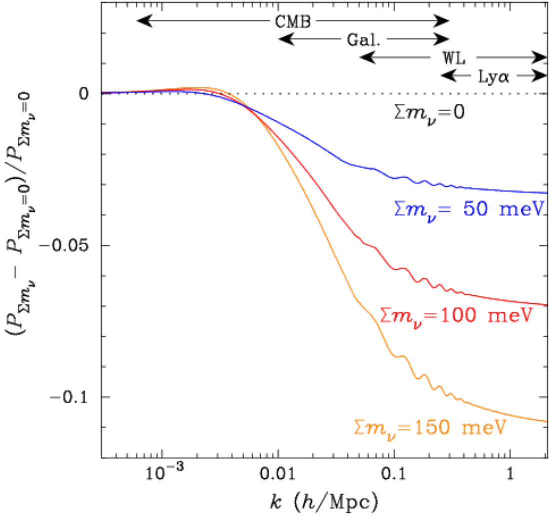
- Massive neutrinos free-streaming damps small-scale perturbations...
- ...less structure=less lensing=less smearing of the small-scale power spectrum of the CMB



Courtesy of Massimiliano Lattanzi

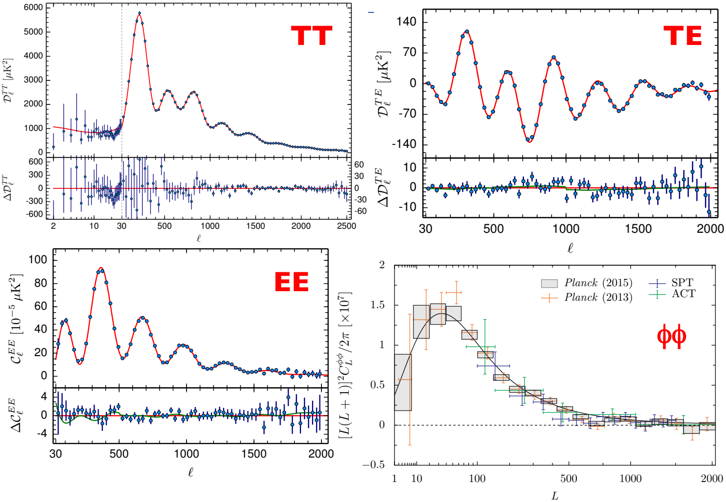
Neutrino masses and the large-scale structure

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



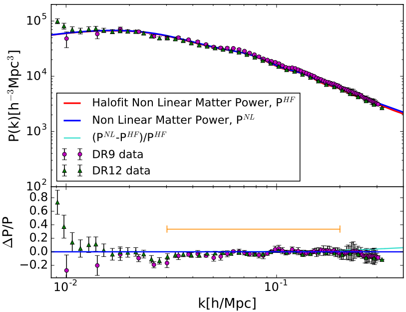
Credits: K. Abazajian et al., arXiv:1309.5383

Cosmological data: CMB



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

Cosmological data: galaxy power spectrum



Modelling of data within likelihood:

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

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

$$\frac{\Delta P(k)}{P(k)} \sim -8 f_\nu$$

Cosmological data: galaxy power spectrum, issues

- (Scale-dependent) bias and shot noise:

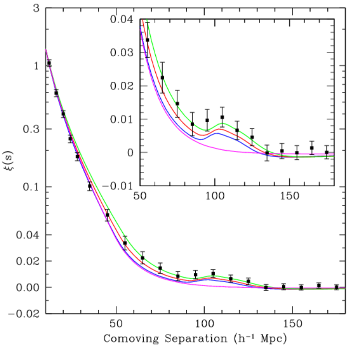
$$P^g = b^2 P^m(k, z) + P^s$$

- Non-linear effects: conservative cut-off $k_{\mathrm{max}} = 0.2\, h\ \mathrm{Mpc}^{-1}$

- Systematics modelled at the level of data:

$$P_{\mathrm{meas}}(k) = P_{\mathrm{meas,w}}(k) - S[P_{\mathrm{meas,nw}}(k) - P_{\mathrm{meas,w}}(k)]$$

Cosmological datasets: Baryon Acoustic Oscillations



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

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

- Standard ruler: helpful in breaking degeneracies involving Ω_m and H_0
- Substantially less affected by systematics

Cosmological datasets: other "external" datasets

- Optical depth to reionization τ (*lowP2016*)
- Direct measurements of the Hubble parameter H_0
- Planck SZ clusters

Each of them is important for resolving parameter degeneracies:

- $M_\nu - \tau$ degeneracy in CMB and $P(k)$: $\tau \downarrow \implies M_\nu \downarrow$
- $M_\nu - H_0$ degeneracy with distance to last scattering: $H_0 \uparrow \implies M_\nu \downarrow$

Standard analysis method

- Assume background ΛCDM: $\boldsymbol{\theta} \equiv (\Omega_b h^2, \Omega_c h^2, \Theta_s, \tau, n_s, A_s, M_\nu)$
- Assume degenerate neutrino mass spectrum: $m_i = M_\nu/3$
- Prior $M_\nu > 0\,\mathrm{eV}$ (using **only** cosmology information)
- Bayes' theorem: $P(\boldsymbol{\theta}|\mathbf{x}) \propto \mathcal{L}(\mathbf{x}|\boldsymbol{\theta}) \times \Pi(\boldsymbol{\theta})$
- Sample posterior using MCMC methods

Results: overview

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

- $+P(k)$: $< \mathbf{0.299}\,\mathrm{eV}$
- $+P(k)$+BAO: $< \mathbf{0.246}\,\mathrm{eV}$
- $+P(k)$+BAO$+\tau$: $< \mathbf{0.205}\,\mathrm{eV}$
- $+P(k)$+BAO$+H_0$: $< \mathbf{0.164}\,\mathrm{eV}$
- $+P(k)$+BAO$+H_0+\tau$: $< \mathbf{0.140}\,\mathrm{eV}$

PlanckTT+lowP+TTTEEEE: $M_\nu < \mathbf{0.485}\,\mathrm{eV}$ @95% C.L.

- $+P(k)$: $< \mathbf{0.275}\,\mathrm{eV}$
- $+P(k)$+BAO: $< \mathbf{0.215}\,\mathrm{eV}$
- $+P(k)$+BAO$+\tau$: $< \mathbf{0.177}\,\mathrm{eV}$
- $+P(k)$+BAO$+H_0$: $< \mathbf{0.132}\,\mathrm{eV}$
- $+P(k)$+BAO$+H_0+\tau$: $< \mathbf{0.109}\,\mathrm{eV}$

Shape vs geometry

What's stronger: shape [$P(k)$] or geometrical (BAO) information?
Examined by replacing DR12 CMASS $P(k)$ by DR11 CMASS BAO

PlanckTT+lowP+BAO:
$M_\nu <$ **0.186** eV @95% C.L.

- $+\tau$: $<$ **0.151** eV
- $+H_0$: $<$ **0.148** eV
- $+H_0+\tau$: $<$ **0.115** eV

SV et al. 2017

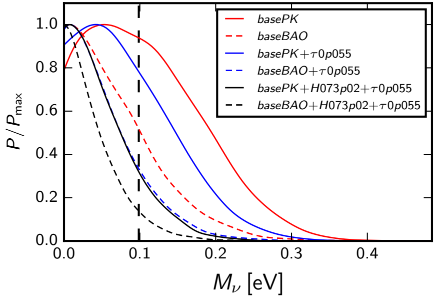
PlanckTT+lowP+TTTEEEE:
$M_\nu <$ **0.153** eV @95% C.L.

- $+\tau$: $<$ **0.118** eV
- $+H_0$: $<$ **0.113** eV
- $+H_0+\tau$: $<$ **0.094** eV

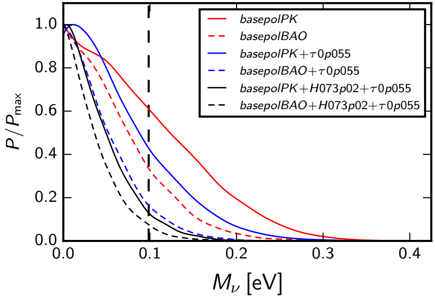
Shape vs geometry

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

Without small-scale polarization



With small-scale polarization



Shape vs geometry

Geometrical information more constraining than shape (this is a *win-win*, as BAO data also less affected by systematics).

BUT, three caveats:

- True within a background flat ΛCDM: shape information is *crucial* in extended cosmologies
- Depends *strongly* on conservative cut-off $k_{\rm max} = 0.2\, h \ {\rm Mpc}^{-1}$
- Depends *decisively* on our ignorance of the scale-dependent bias $b(k) \to$ determine $b(k)$ using cross-correlation between CMB lensing and galaxies, $C_\ell^{\kappa g}$? Work in progress with Elena Giusarma, Simone Ferraro, Katherine Freese, Shirley Ho; talk in two weeks by Elena Giusarma

Scale-dependent bias

- CMB lensing convergence-galaxy angular cross-spectrum:

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

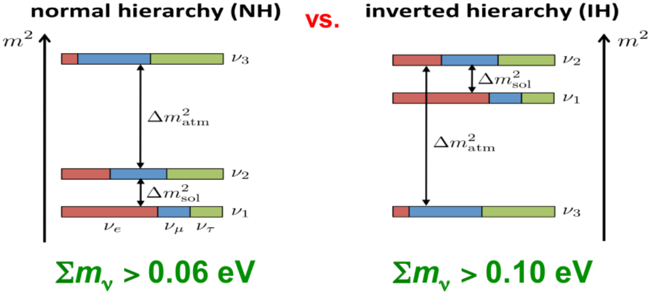
- The simplest form of (scale-dependent) bias is given by:

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

- The bound from *PlanckTT+lowP+P(k)* can improve from $\sim \mathbf{0.30}\,\mathrm{eV}$ to $\sim \mathbf{0.15}\,\mathrm{eV}$!!

What about the mass hierarchy?

For each mass hierarchy, there exists a minimal allowed value for M_ν



Bayesian model comparison between hierarchies

Which of the two hierarchies?

- All cosmological sensitivity to hierarchy is entirely due to **volume effects**: how much parameter space is still available to the IH after I observed my data? see Massimiliano's talk
- In the most optimistic case need a $0.02\,\mathrm{eV}$ sensitivity for a 2σ discrimination between NH and IH
- No sensitivity to hierarchy if upper limit on M_ν not better than $0.1\,\mathrm{eV}$
- **Posterior odds** for NH vs IH:

$$\frac{P(h = NH|\mathbf{x})}{P(h = IH|\mathbf{x})} = \frac{\int_{0.06\,\mathrm{eV}}^{\infty} dM_\nu \; \mathcal{L}(M_\nu)}{\int_{0.10\,\mathrm{eV}}^{\infty} dM_\nu \; \mathcal{L}(M_\nu)}$$

see also Hannestad & Schwetz 2016

Posterior odds for NH vs IH

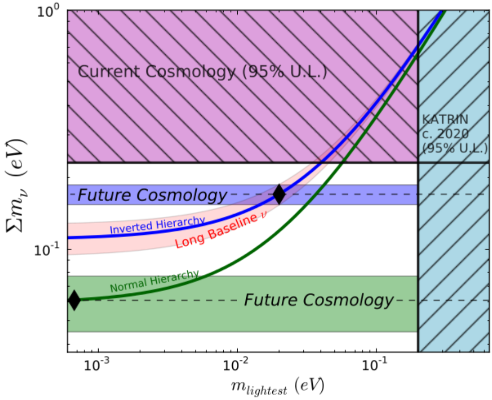
Examples: SV et al. 2017

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

...and be careful with your priors!!! See Massimiliano's talk

The future of neutrino cosmology

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



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

A: a sure detection of M_ν and possibly of the mass hierarchy! See also Massimiliano's talk

Conclusions

- Cosmology provides very tight constraints on ν masses, most robust $M_\nu < 0.151\,\mathrm{eV}$ @95% C.L.
- Geometrical information stronger than shape, but with several caveats and room for improvement
- Data sensitive to hierarchy through volume effects if $M_\nu \lesssim 0.1\,\mathrm{eV}$
- Weak ($< 3:1$) preference for the normal hierarchy
- The future of ν cosmology is very bright!

What's in a νame?

Language	Word tree	*...Some branches*	Meaning
Physics (Fermi 1934)	NEUTR-INO		Little neutral one ↑
Italian	NEUTRO		Neutral
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Indo-European root	KA *or* KWA		Interrogative base