Neutrino cosmology: measuring the extremely tiny by observing the extremely huge

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Trento Institute for Fundamental Physics and Applications (TIFPA),
Trento, May 2018

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NORDITA
The Nordic Institute for Theoretical Physics

What's in a name?

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 the only **direct evidence** *for physics beyond the Standard Model*

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + i\bar{\psi}\not{D}\psi + |D_\mu\Phi|^2 - V(\Phi) - Y^{ij}\bar{\psi}_i\Phi\psi_j$$

$$-Y^{ij}\bar{\psi}_i\Phi\psi_j = -Y_e^{ij}\bar{E}_L^i\Phi e_R^j - Y_d^{ij}\bar{Q}_L^i\Phi d_R^j - Y_u^{ij}\epsilon^{ab}\bar{Q}_{La}^i\Phi_b^\star u_R^j + \mathrm{h.c.}$$

No right-handed neutrino field ν_R in the Standard Model

Overview: Qs (& As)

- Q: What can cosmology tell us about massive neutrinos?
  A: **Quite a lot**!

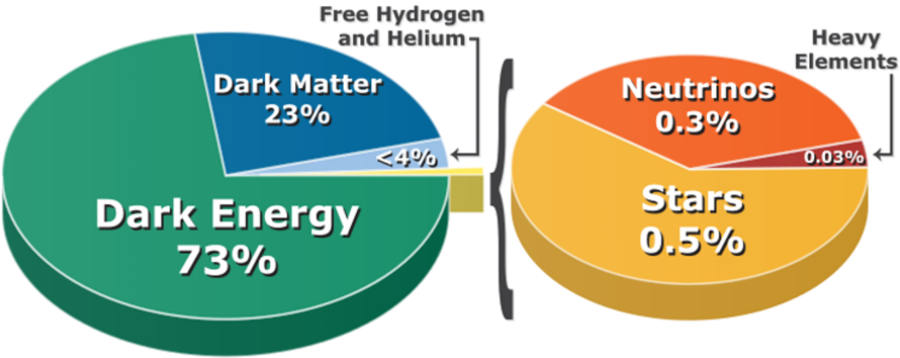
- Q: Can you elaborate a bit more?
  A: **Cosmology is sensitive to the sum of the three neutrino masses M_ν and gives the tightest upper bounds on this quantity**.

- Q: Is that all? Can it tell us something about the mass hierarchy?
  A: **Yes, if one is careful...**

- Q: I heard there's some connection between νs and dark energy...?
  A: **Yes, νs could shed light on what is (not) driving cosmic acceleration**!

- Q: How does the future of neutrino cosmology look?
  A: **VERY EXCITING!!!**

The Standard Cosmological Model



The Cosmic Neutrino Background (CνB)

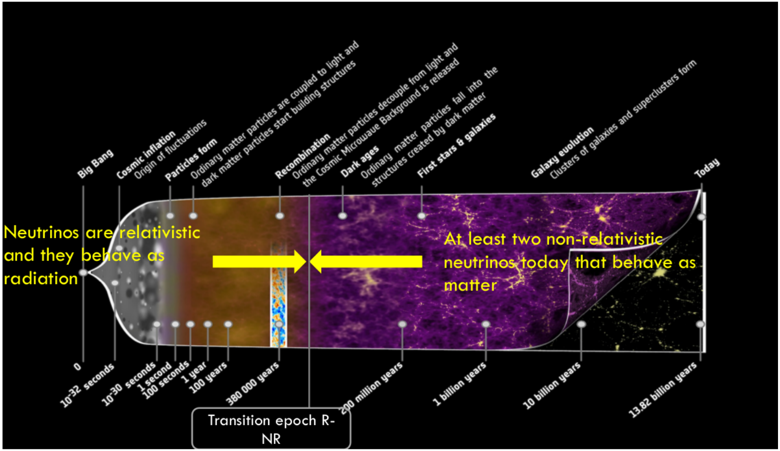
- The presence of a background of relic neutrinos (CνB) is a basic prediction of the standard cosmological model
- Weak interactions maintain νs in thermal equilibrium with the primeval cosmological plasma until $T \sim 1\,\mathrm{MeV}$ ($z \sim 10^{10}$)
- Below $T \sim 1\,\mathrm{MeV}$ νs free-stream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

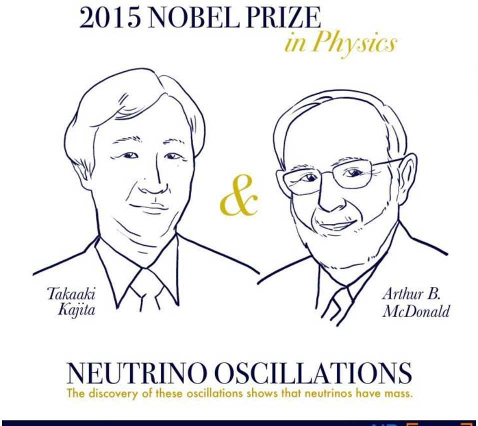
Neutrinos behave as radiation at early times, as matter at late times

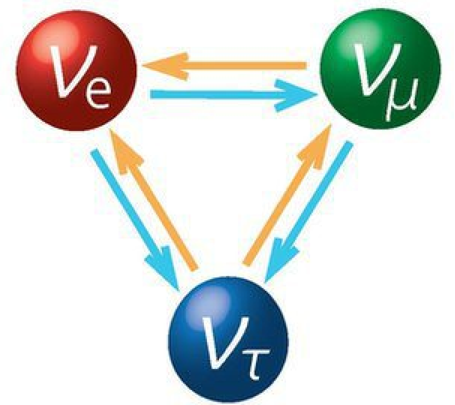


Courtesy of Elena Giusarma

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:

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

So we have two non-zero $\Delta m^2 \to$ at least 2 out of 3 mass eigenstates have non-zero mass.

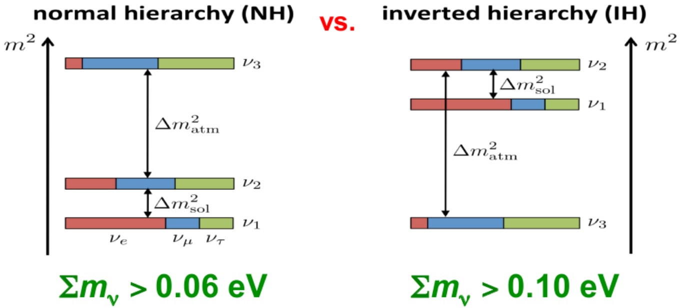
From oscillation experiments accurate measurements of two mass-squared differences:

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

Note uncertainty in sign of Δm^2_{31}!!!.

Neutrino mass hierarchy

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



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

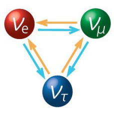
$$M_{\nu,\text{min}} = \sqrt{\Delta m^2_{31}} + \sqrt{\Delta m^2_{31} + \Delta m^2_{21}} \simeq 0.1\,\text{eV (IH)}$$

Neutrino unknowns

- Absolute mass scale $M_\nu \equiv \sum_i m_{\nu_i}$
- Mass hierarchy
- θ_{23} octant
- Dirac vs Majorana nature
- CP violation
- Sterile eigenstates

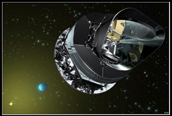
Neutrino oscillations

- 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 hierarchy



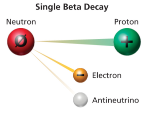
Cosmology

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



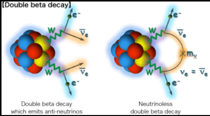
Beta decay

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

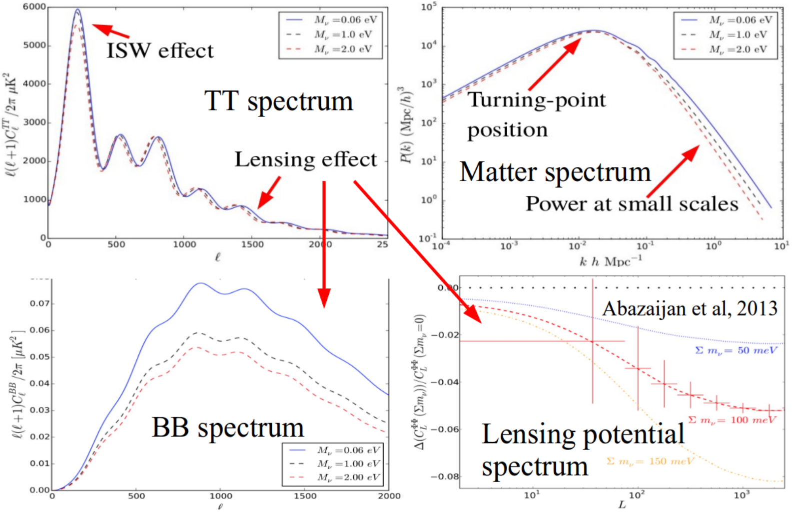


Neutrinoless double-beta decay

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

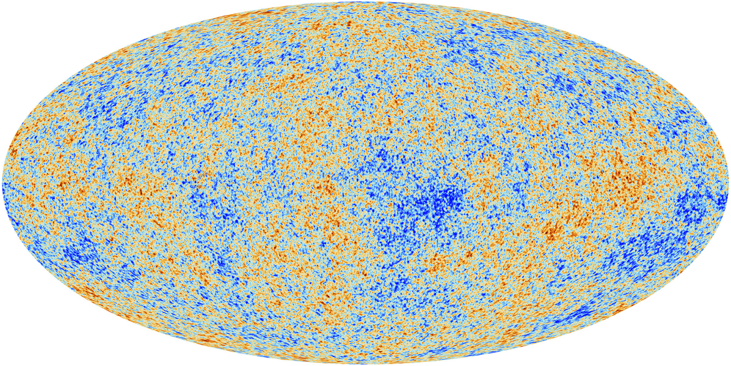


How can cosmology measure neutrino masses?



Courtesy of Martina Gerbino

Cosmological datasets: Cosmic Microwave Background

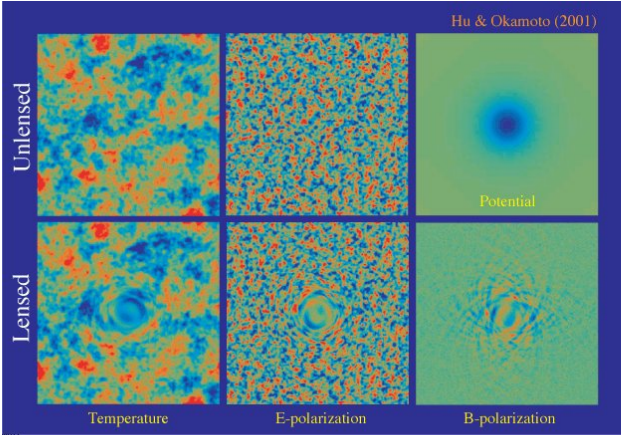


Credits: Planck collaboration

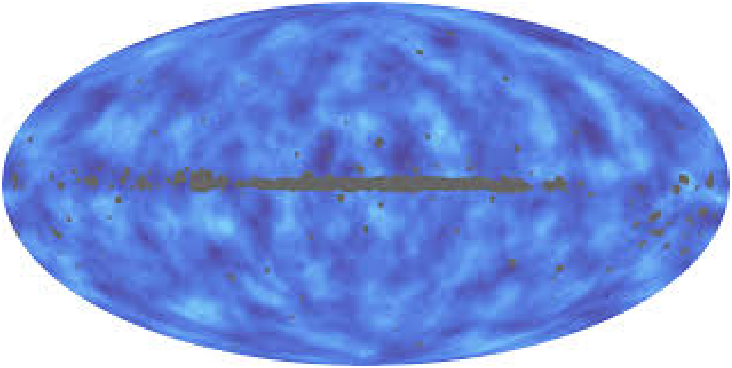
Cosmological datasets: CMB lensing

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

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

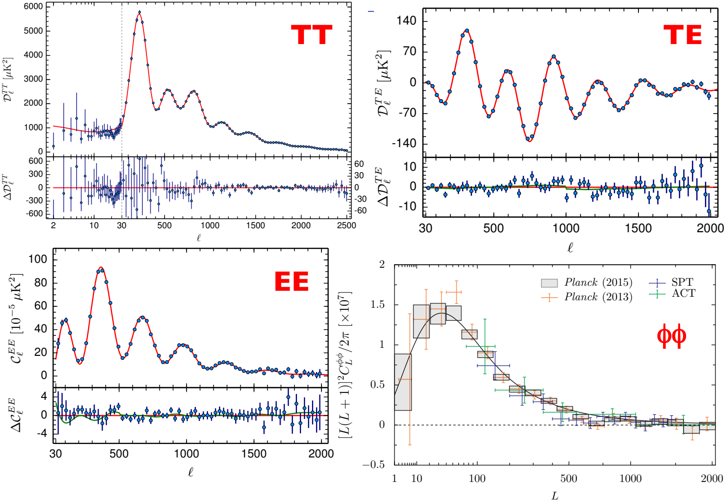


Cosmological datasets: CMB lensing



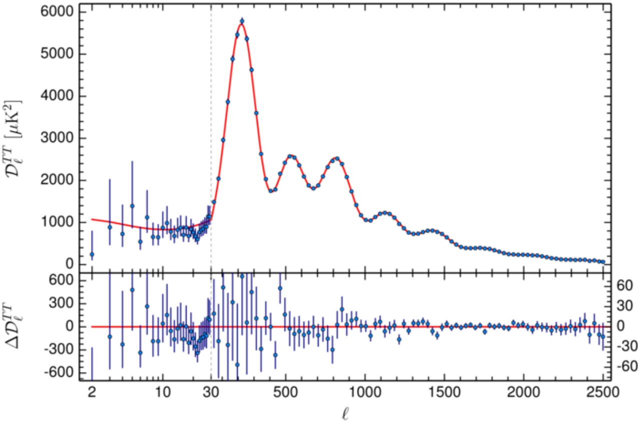
Credits: Planck collaboration

Cosmological datasets: CMB spectra



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

CMB temperature power spectrum



- Small ℓ (large angular scales): late ISW plateau
- $\ell \approx 200$: first acoustic peak carries a lot of cosmological information
- $\ell \gtrsim 500$: damped acoustic peaks (*Silk damping*), but damping is smeared by gravitational lensing

Effect of neutrino masses on the CMB: background level

- Shift in matter-radiation equality redshift:

$$1 + z_{\rm eq} = \frac{\Omega_b + \Omega_{cdm}}{\Omega_\gamma \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\rm eff}\right]}$$

  Affects height of first peak through early ISW effect

- Shift in distance to the CMB:

$$d_A(z_{\rm CMB}) \propto \frac{1}{H_0}\int_0^{z_{\rm CMB}} \frac{dz}{\sqrt{(\Omega_b + \Omega_{cdm})(1+z)^3 + \Omega_\Lambda + \Omega_\nu(z)}}$$

  Affects position of first peak, since:

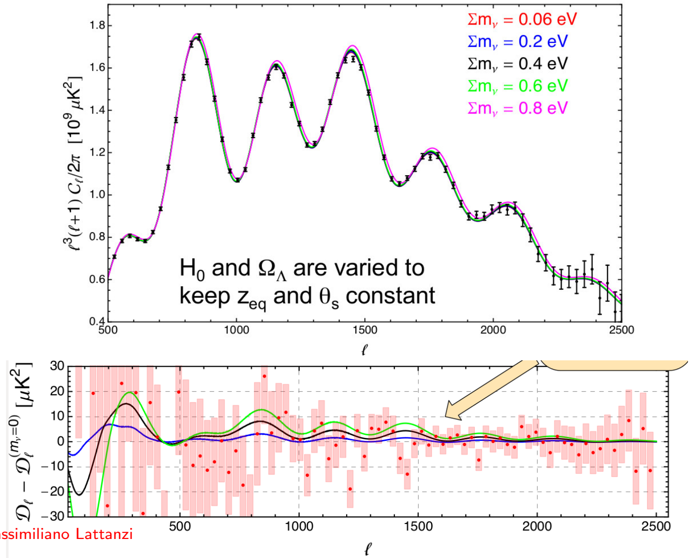
$$\ell_{\rm peak} \simeq \frac{\pi}{\theta_{\rm peak}}\,, \quad \theta_{\rm peak} \approx \frac{r_s(z_{\rm CMB})}{d_A(z_{\rm CMB})}$$

These effects were the ones mainly driving the WMAP bound ($M_\nu < 0.1\,{\rm eV}$ @95% C.L.)

Effect of neutrino masses on 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 (Planck: $M_\nu < 0.72\,\mathrm{eV}$ @95% C.L.)
- Small effect on the late ISW plateau (but large error bars)
- Small changes around the first peak
- Small effect on the damping tail

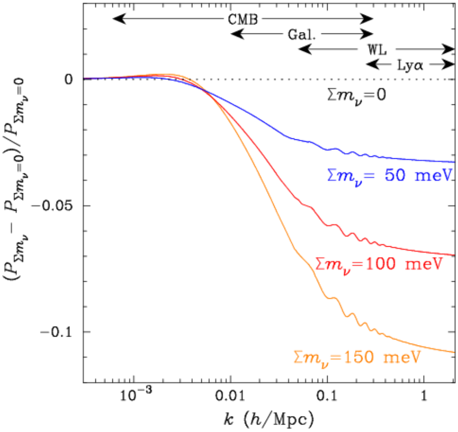
Effect of neutrino masses on the CMB



Courtesy of Massimiliano Lattanzi

Neutrino masses and the large-scale structure

Free-streaming of neutrinos suppresses growth of structure on small scales and hence **matter** power spectrum

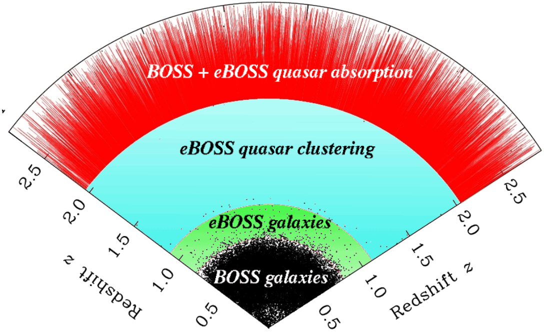


On small scales (large k), where the suppression is maximal:

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

Cosmological data: galaxy redshift surveys

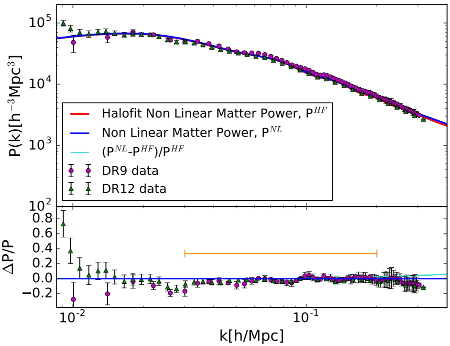
Sloan Digital Sky Survey (SDSS) - Baryon Oscillation Spectroscopic Survey (BOSS)



Essentially get two types of measurements out:

- Galaxy power spectrum $P(k)$: measurement of amount of clustering
- Baryon Acoustic Oscillation (BAO): distance measurement

Galaxy power spectrum



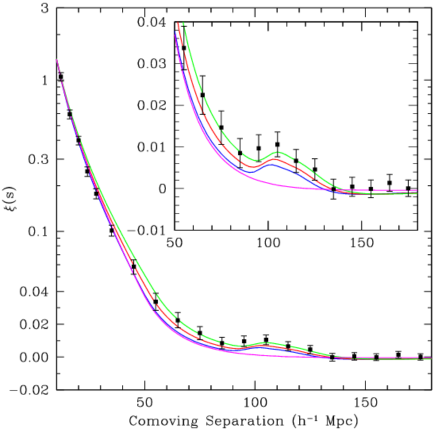
Issues:

- (Scale-dependent) bias

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

  $P_m(k)$: what we would like to measure
  $P_g(k)$: what we measure
  $b^2(k)$: what makes life hard
- Non-linearities
- Redshift-space distortions
- Systematics

Baryon Acoustic Oscillations



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

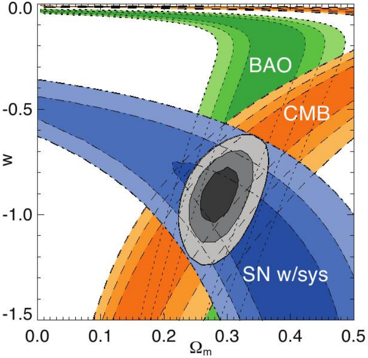
$$D_v(z) = \left[(1+z)^2 D_A(z)^2 \frac{cz}{H(z)} \right]^{\frac{1}{3}}$$

- Standard ruler
- Substantially less affected by bias, non-linear evolution, than $P(k)$

Cosmological data: other types of data

- Measurement of optical depth to reionization $\tau = 0.055 \pm 0.009$ (proxy for *Planck* 2018 final data release)
- Direct measurements of H_0 from *HST*
- Sunyaev-Zel'dovich cluster counts
- Redshift-space distortions measurements from galaxy redshift surveys
- Weak lensing measurements (*CFHTLens*, *KiDS*, *Euclid*)
- Supernovae Ia luminosity distance measurements (*JLA*, *Pantheon*)
- Cosmic chronometers
- Lyman-α forest power spectrum (*BOSS*, *eBOSS*)
- In the future: 21-cm intensity mapping (*SKA*)

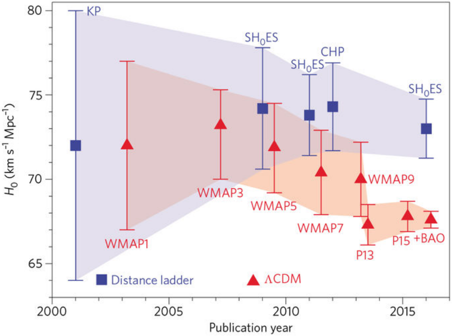
Things to be aware about: degeneracies



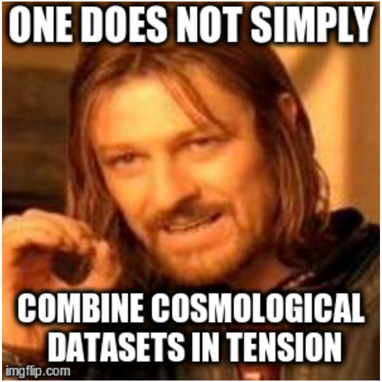
Example: geometrical degeneracy

$$d_{\mathrm{CMB}} \propto \frac{1}{H_0} \int_0^{z_{\mathrm{CMB}}} \frac{dz}{\sqrt{(\Omega_b + \Omega_{cdm})(1+z)^3 + \Omega_\Lambda + \Omega_\nu(z, M_\nu) + \Omega_k(1+z)^2}}$$

Things to be aware about: tensions



- H_0 CMB vs local measurements
- $\sigma_8\sqrt{\Omega_m}$ CMB vs weak lensing
- Lyman-α with pretty much everything else
- ...



Analysis method

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

$$\begin{aligned} p(\boldsymbol{\theta}|\mathbf{x}) &\propto \mathcal{L}(\mathbf{x}|\boldsymbol{\theta})\mathcal{P}(\boldsymbol{\theta}) \\ p(\boldsymbol{\theta}) &: \text{posterior (what you want to get)} \\ \mathcal{L}(\mathbf{x}|\boldsymbol{\theta}) &: \text{likelihood (easy to model, hard to code up)} \\ \mathcal{P}(\boldsymbol{\theta}) &: \text{prior (what you have to choose)} \end{aligned}$$

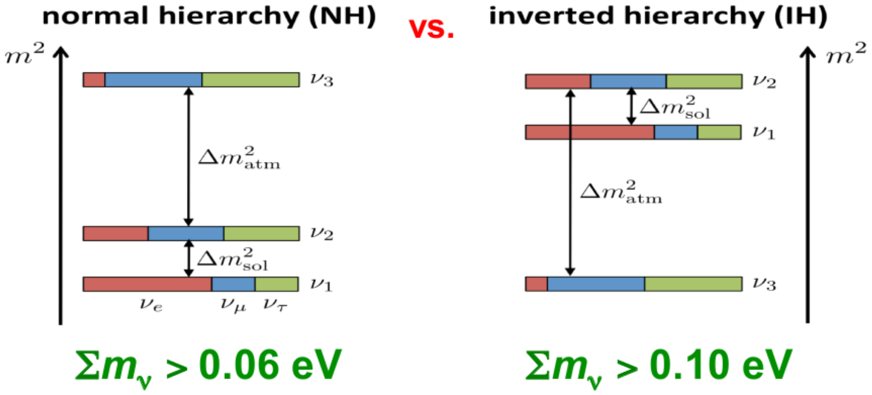
Vary 6 basic cosmological parameters $\Omega_b h^2, \Omega_c h^2, \Theta_s, \tau, n_s, \log\left(10^{10} A_s\right) + M_\nu +$ many other nuisance parameters, sample posterior using Markov chain Monte Carlo (MCMC) techniques

Note: cosmology is only sensitive to the sum of the neutrino masses M_ν, not to the masses of the individual eigenstates

Report 95% C.L. upper limit on M_ν, M_{95}, such that:

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

Recap: neutrino mass hierarchy



Results: overview

SV et al., arXiv: 1701.08172

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

- $+P(k)$: $\mathbf{0.30}\,\mathrm{eV}$
- $+P(k)$+BAO: $\mathbf{0.19}\,\mathrm{eV}$
- $+P(k)$+BAO$+\tau$: $\mathbf{0.15}\,\mathrm{eV}$
- $+P(k)$+BAO$+H_0$: $\mathbf{0.15}\,\mathrm{eV}$
- $+P(k)$+BAO$+H_0+\tau$: $\mathbf{0.12}\,\mathrm{eV}$

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

- $+P(k)$: $\mathbf{0.28}\,\mathrm{eV}$
- $+P(k)$+BAO: $\mathbf{0.15}\,\mathrm{eV}$
- $+P(k)$+BAO$+\tau$: $\mathbf{0.12}\,\mathrm{eV}$
- $+P(k)$+BAO$+H_0$: $\mathbf{0.11}\,\mathrm{eV}$
- $+P(k)$+BAO$+H_0+\tau$: $\mathbf{0.09}\,\mathrm{eV}$

These are the tightest bounds on M_ν ever derived in the literature!

Constraints on M_ν: take home messages

- Bounds on M_ν from cosmology are **VERY** strong (compare to $M_\nu \lesssim 2\,\mathrm{eV}$ from β-decay)
- A robust 95% C.L. upper bound is about $M_\nu \lesssim 0.15\,\mathrm{eV}$
- We are approaching the region of parameter space where the inverted hierarchy is **disfavored**

How to improve from here? Measuring the scale-dependent bias

$$\textit{What we measure} \rightarrow P_g(k) = b^2(k) P_m(k) \leftarrow \textit{What we would like to measure}$$

Idea: Giusarma, SV, et al., arXiv: 1802.08694

- **cross-correlate** CMB lensing with galaxy survey!

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

- Use a well-motivated form for the bias: $b(k) = a + ck^2$ Desjacques et al., arXiv: 1611.09787

Results:

- Factor of $\approx$ **2** improvement in constraints! Upper limit with *Planck* temperature+$P(k)$ improves from $0.3\,\mathrm{eV}$ to $0.15\,\mathrm{eV}$
- Better treatment of non-linearities

A complication: neutrino-induced scale-dependent bias

Neutrinos induce an additional scale-dependence in the bias (always neglected) Castorina et al., arXiv: 1311.1212

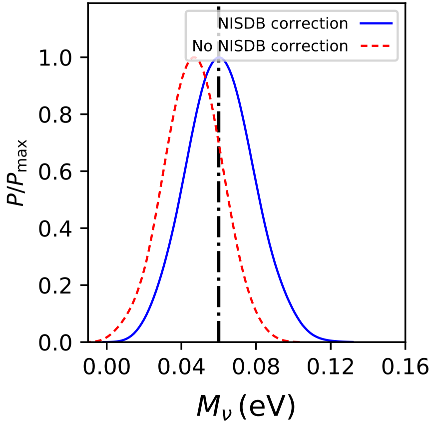
$$P_g(k) = b^2(k, M_\nu) P_m(k)$$

Problem: $b^2(k, M_\nu)$ hard to model

Solution: define the bias with respect to CDM+baryons **only**

$$P_g(k) = b_{cb}^2(k) P_{cb}(k)$$

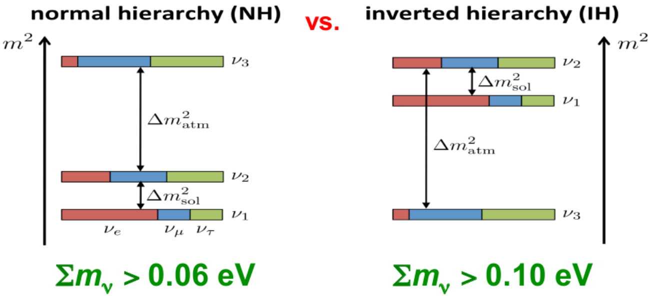
The bias $b_{cb}(k)$ no longer depends on M_ν!



Brinckmann, SV, et al., paper in preparation (2018)

What can cosmology say about the mass hierarchy?

- Cosmology is sensitive to $M_\nu = m_1 + m_2 + m_3$, not to the m_is...
- 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*)



What can cosmology say about the mass hierarchy?

- What we really have to solve is a **Bayesian model selection** problem between two models: normal hierarchy (NH) and inverted hierarchy (IH)
- In other words, compute **posterior odds** for normal vs inverted hierarchy, *after having observed cosmological data*:

$$\frac{p_{\rm NH}}{p_{\rm IH}} \approx \frac{\int_{0.06\,{\rm eV}}^{\infty} dM_\nu\, p(M_\nu|\mathbf{x})\mathcal{P}(M_\nu)}{\int_{0.10\,{\rm eV}}^{\infty} dM_\nu\, p(M_\nu|\mathbf{x})\mathcal{P}(M_\nu)}$$

  where $p(M_\nu|\mathbf{x})$ is your posterior distribution and $\mathcal{P}(M_\nu)$ your prior distribution SV et al., arXiv: 1701.08172, different formulation leading to approximately same answer in Hannestad & Schwetz, arXiv: 1606.04691
- Note that $\mathcal{P}(M_\nu)$ appears: dependence on how you weigh your prior volume $\rightarrow$ preference for normal hierarchy driven not by physical effects but **volume effects**

What can cosmology say about the mass hierarchy?

- Even for the most constraining data combination ($M_\nu < 0.09\,\mathrm{eV}$), $p_{\mathrm{NH}} : p_{\mathrm{IH}} \sim 3.3 : 1$, inverted hierarchy excluded at 77% C.L.
- All sensitivity to the mass hierarchy is entirely due to **volume effects**, i.e. the possibility of excluding the region above $0.1\,\mathrm{eV}$ at increasing confidence level
- Recent claims of huge preference (42:1, 95:1, $>$100:1) for normal hierarchy... Simpson et al., arXiv: 1703.03425
- ...result of "weird" (unphysical) choice of prior $\mathcal{P}(M_\nu)$ See rebuttal paper, Schwetz et al. (incl. SV), arXiv: 1703.04585
- Other papers have explored other physical priors/methodologies, but preference for normal hierarchy is never $> 5:1$

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 $\sim 3:1$ preference
- All preference for the NH is driven by volume effects (i.e. at what significance I can exclude the region $> 0.1\,\mathrm{eV}$)
- Corollary of the above: be careful how you weigh your prior volume!

Model-dependency of cosmology bounds

The bounds so far assumed a background ΛCDM model, i.e. only 6 parameters. Introducing other parameters **degrades** the bound on M_ν

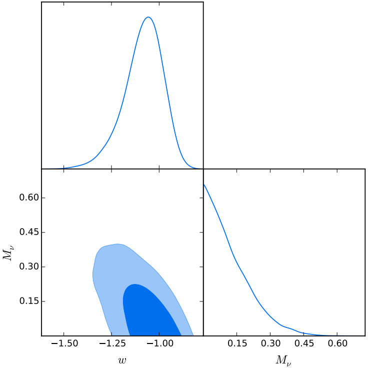
Planck temperature + BAO assuming ΛCDM: $M_\nu < \mathbf{0.25}\,\mathrm{eV}$

- $< \mathbf{0.37}\,\mathrm{eV}$ if allow curvature Ω_k to vary ($\Omega_k = 0$ in ΛCDM)
- $< \mathbf{0.37}\,\mathrm{eV}$ if allow dark energy EoS w to vary ($w = -1$ in ΛCDM)
- In modified gravity models you can get a **detection** of non-zero M_ν instead of an upper bound (e.g. cubic/quartic/quintic Galileon gravity, $M_\nu \simeq (0.51 \pm 0.19)\,\mathrm{eV}$) Renk et al., arXiv: 1707.02263
- ...several other possible examples including evolving dark energy, effective number of neutrino species, tensor-to-scalar ratio, running of scalar spectral index, primordial Helium fraction, lensing amplitude

Although most of these extensions are *statistically disfavoured* from a Bayesian evidence point of view (**Occam's razor**) Heavens et al., arXiv: 1704.03467

Model-dependency of cosmology bounds

Why do the bounds degrade? **Degeneracies**, again! M_ν-w example:



$$d_{\rm CMB} \propto \int \frac{dz}{\sqrt{(\Omega_b + \Omega_{cdm})(1+z)^3 + \Omega_{\rm DE}(z,w) + \Omega_\nu(z, M_\nu)}}\,, \quad \frac{d\Omega_{\rm DE}}{dw} < 0\,, \quad \frac{d\Omega_\nu}{dM_\nu} > 0$$

A remarkable counterintuitive exception: quintessence

Single, **minimally-coupled** scalar ϕ, with **canonical kinetic term**

Ratra & Peebles 1988; Wetterich 1988; Caldwell, Dave & Steinhardt 1998

$$\mathcal{L}_\phi = -\frac{1}{2}\partial^\mu \phi \partial_\mu \phi - V(\phi)$$

Pressure and energy density:

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi)\,, \quad P_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

Equation of state is **non-phantom**:

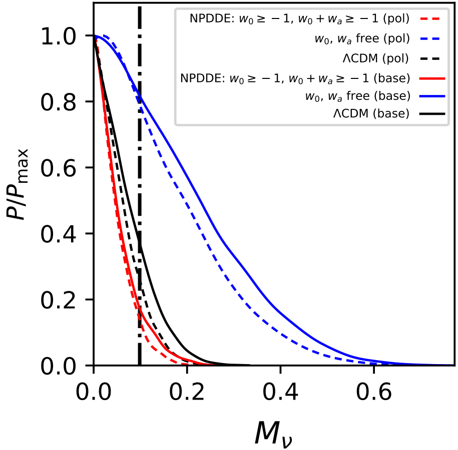
$$w_\phi = \frac{P_\phi}{\rho_\phi} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \geq \mathbf{-1}$$

At the cosmological level well modelled as Linder, arXiv: 0704.2064, SV et al., arXiv: 1801.08553
:

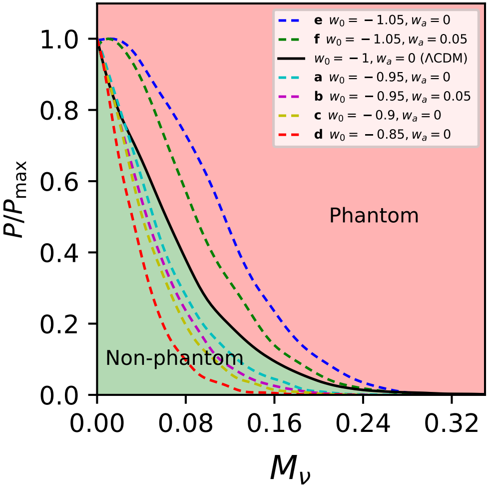
$$w(z) = w_0 + w_a\frac{z}{1+z}\,, \quad \mathbf{w_0} \geq \mathbf{-1}\,, \quad \mathbf{w_0} + \mathbf{w_a} \geq \mathbf{-1} \rightarrow w(z) \geq -1\,\forall z$$

A remarkable counterintuitive exception: quintessence

In quintessence (and more generally non-phantom dark energy) models the bounds on M_ν become $\approx 25\%$ **tighter than in ΛCDM despite having more parameters** SV et al., arXiv: 1801.08553



A remarkable counterintuitive exception: quintessence



SV et al., arXiv: 1801.08553

A remarkable counterintuitive exception: quintessence

Implications: SV et al., arXiv: 1801.08553

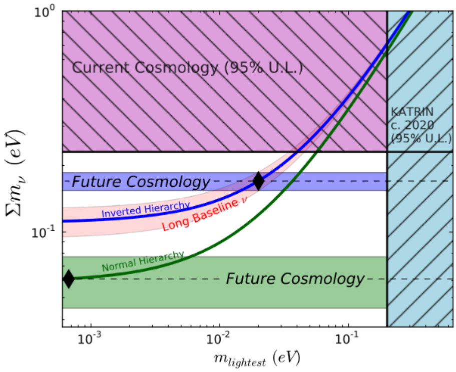
- In non-phantom dark energy models the preference for the normal neutrino hierarchy is significantly stronger ($\approx 3-4:1$) than in ΛCDM ($\approx 2:1$)
- If independent laboratory experiments measure the hierarchy to be inverted, we can be **almost sure** dark energy is phantom ($\rightarrow$ Big Rip?) $\rightarrow$ **insight into the nature of dark energy/cosmic acceleration from neutrino laboratory measurements**
- Similar considerations might apply to certain modified gravity models
- Similar exception happens in other extended models (e.g. negative curvature, low-scale reheating, negative running), currently being examined $\rightarrow$ **insight into extremely early Universe physics from neutrino laboratory measurements** SV et al., paper in preparation (2018)

The future of neutrino cosmology

- Future CMB experiments (improvements especially in lensing): e.g. Advanced ACTPol, SPT-3G, Simons Observatory, CMB-S4
- Future cluster surveys
- Future galaxy surveys: e.g. eBOSS, DESI, LSST, WFIRST
- Galaxy weak lensing (cosmic shear): e.g. Euclid
- Lyman α power spectrum: can probe very small scales
- 21-cm intensity mapping: e.g. SKA

The future of neutrino cosmology

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



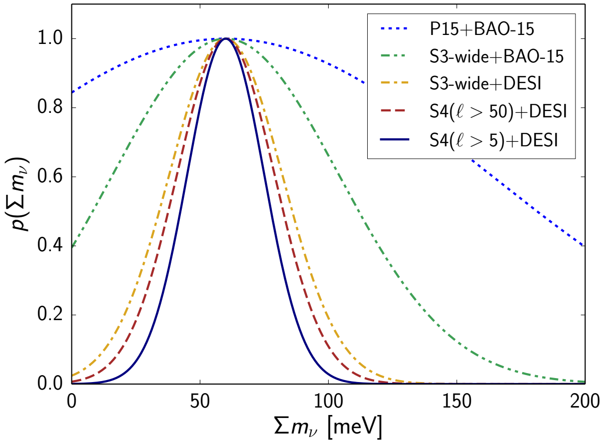
	$\sigma\left(\sum m_\nu\right)$ [meV]
CMB Lensing (current galaxy clustering):	
Stage-IV CMB	45
Stage-IV CMB + BOSS BAO	**25**
CMB Lensing + Galaxy clustering:	
Stage-IV CMB + eBOSS BAO	23
Stage-IV CMB + DESI BAO	**16**
Stage-IV CMB no lensing + DESI galaxy clustering	15/20
Galaxy Weak Lensing:	
Planck + 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 (but only if the detected M_ν is substantially smaller than $0.1\,\mathrm{eV}$)!

P.S.: optimists suggest we could measure the individual masses m_i

The future of neutrino cosmology



Allison et al., arXiv: 1509.7471

...and wide time and scale coverage from future data will help breaking degeneracies (e.g. with w, distinguish effects of ν vs dark energy)

Conclusions

- Cosmology provides **tightest** constraints on sum of ν masses, $M_\nu \lesssim 0.15\,\mathrm{eV}$ (assuming ΛCDM)
- Lots of room for **improvement** (use cross-correlations?), but beware **systematic** effects (neutrino-induced scale-dependent bias)
- **Mild preference** for normal hierarchy due to volume effects $\rightarrow$ beware your choice of prior!
- Upper limits on M_ν usually degrade when relaxing assumptions on underlying cosmology $\rightarrow$ **model-dependence**
- An important exception: **non-phantom dark energy** (quintessence) $\rightarrow$ ν lab experiments illuminate the nature of dark energy?
- 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!

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