# Unveiling $\nu$ secrets with cosmology

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Based on:

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

with Katherine Freese, Shirley Ho, Olga Mena,
Martina Gerbino, Elena Giusarma, Massimiliano Lattanzi

Cosmology on Safari, Zulu Nyala, South Africa, February 2017

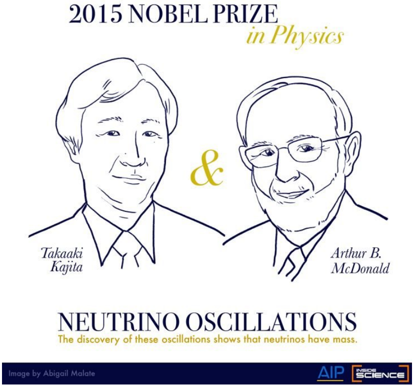
# Overview: Qs (& As)

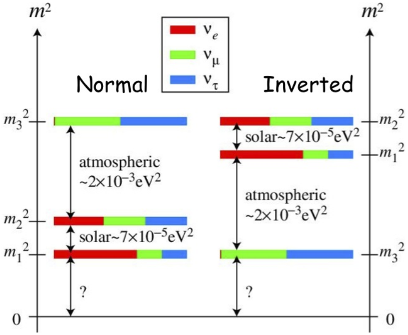
- Q: How constraining are the bounds on $M_\nu$ from cosmology *if we believe some of the most recent datasets?*
  A: **VERY**
- Q: *Within a flat $\Lambda$CDM background and with recent datasets*, is shape $[P(k)]$ or geometrical (BAO) information more constraining?
  A: **GEOMETRICAL** [1]
- Q: Can we say something quantitatively interesting and statistically correct about the $\nu$ mass hierarchy?
  A: **YES, WE CAN**
- Q: Do assumptions on the distribution of mass among the three eigenstates matter?
  A: **NOT MUCH**

[1] with caveats

# Neutrino masses

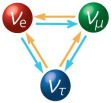
Nobel Prize 2015: "*för upptäckten av neutrinooscillationer, som visar att neutriner har massa*" ("for the discovery of neutrino oscillations, which shows that neutrinos have mass")



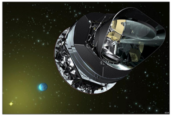
# Neutrino oscillations

- 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



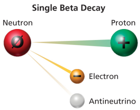
# Cosmology

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



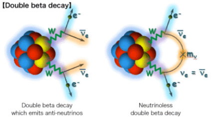
# Beta decay

- 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

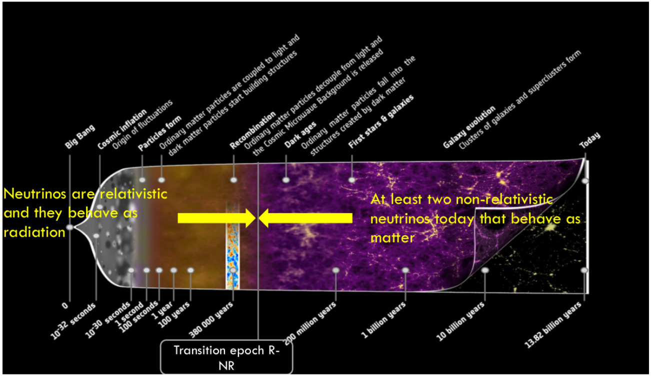
- Sensitive to effective Majorana mass $m_{\beta\beta} \equiv \sum_i |U_{ei}^2 m_i|$
- Exploits GR+Boltzmann equations
- Limited by NME uncertainties and $\nu$ nature



## The C$\nu$B

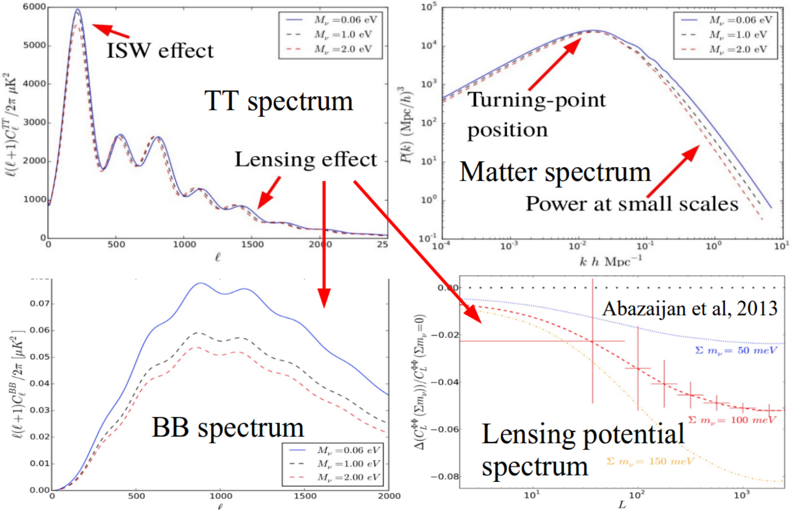
Background of relic $\nu$s generic prediction of standard cosmological model:

- $\nu$s kept in thermal equilibrium with the plasma until $T \sim 1\,\mathrm{MeV}$ ($z \sim 10^{10}$)
- Below $T \sim 1\,\mathrm{MeV}$ $\nu$s free-stream keeping an equilibrium spectrum
- Today $T_\nu \simeq 1.9\,\mathrm{K}$, $n_\nu \simeq 113\,\mathrm{cm}^{-3}$, $N_{\mathrm{eff}} = 3.046$



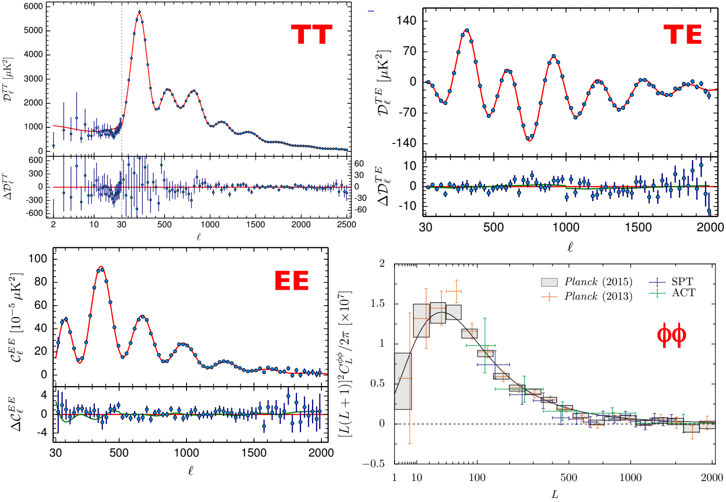

Courtesy of Elena Giusarma

# How can cosmology measure $\nu$ masses?




Courtesy of Martina Gerbino; see Lyman's talk

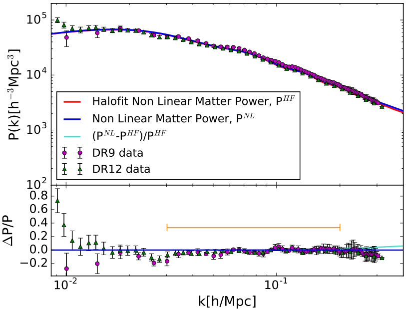
# Datasets: CMB temperature and polarization




Courtesy of Massimiliano Lattanzi; see François' talk

# Datasets: galaxy power spectrum

BOSS DR12 CMASS $P(k)$




Modelling of data and theory within likelihood:

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

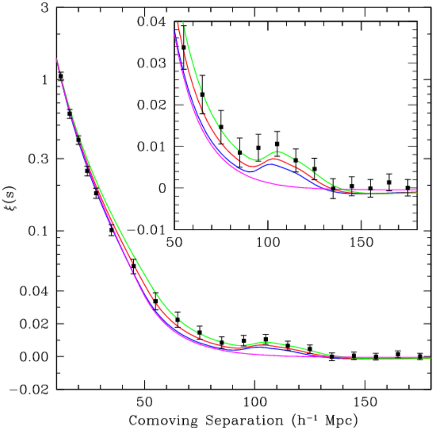
$$P^g_{\text{th}}(k, z) = b^2_{\text{HF}} P^m_{\text{HF}\nu}(k, z) + P^s_{\text{HF}}$$

- 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

# 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 $\Omega_m$ and $H_0$)
- Substantially less affected by systematics (bias, non-linear evolution)

# Other "external" datasets

Consider 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

Each of them is important for resolving parameter degeneracies:

- Degeneracy between $M_\nu$ and $\tau$ in CMB and $P(k)$: $\tau \downarrow \implies M_\nu \downarrow$
- Degeneracy between $M_\nu$ and $H_0$ with CMB, affects distance to last scattering: $H_0 \uparrow \implies M_\nu \downarrow$ (careful with tensions see Adam's talk )
- Cluster mass function probes $\Omega_m$ and $\sigma_8$, important for fixing the normalization of $P(k)$

# Results

Results reported assuming a spectrum of three massive degenerate $\nu$s

*PlanckTT+lowP*: $M_\nu < 0.716\,\mathrm{eV}$ @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+SZ: $< \mathbf{0.239}\,\mathrm{eV}$
- $+P(k)$+BAO+$H_0$: $< \mathbf{0.164}\,\mathrm{eV}$
- $+P(k)$+BAO+$H_0$+$\tau$: $< \mathbf{0.140}\,\mathrm{eV}$
- $+P(k)$+BAO+$H_0$+$\tau$+SZ: $< \mathbf{0.136}\,\mathrm{eV}$

*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+SZ: $< \mathbf{0.208}\,\mathrm{eV}$
- $+P(k)$+BAO+$H_0$: $< \mathbf{0.132}\,\mathrm{eV}$
- $+P(k)$+BAO+$H_0$+$\tau$: $< \mathbf{0.109}\,\mathrm{eV}$
- $+P(k)$+BAO+$H_0$+$\tau$+SZ: $< \mathbf{0.117}\,\mathrm{eV}$

# 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: $< \mathbf{0.114}\,\mathrm{eV}$

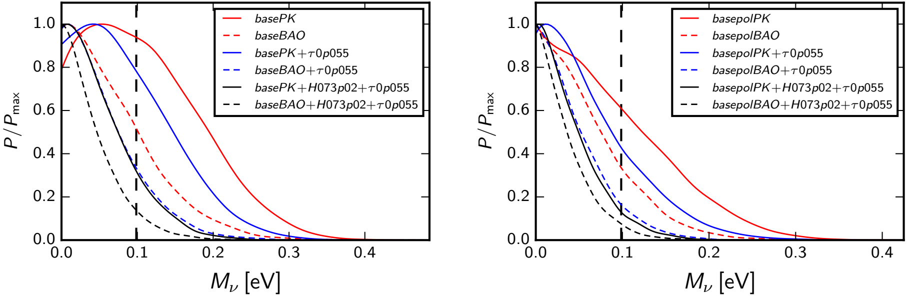
*PlanckTT+lowP+TTTEEEE*:
$M_\nu < \mathbf{0.153}\,\mathrm{eV}$ @95% C.L.

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

# Shape vs geometry

$M_\nu$ posteriors: compare shape information (solid) with geometrical information (dashed), for a given color

Without small-scale polarization | With small-scale polarization

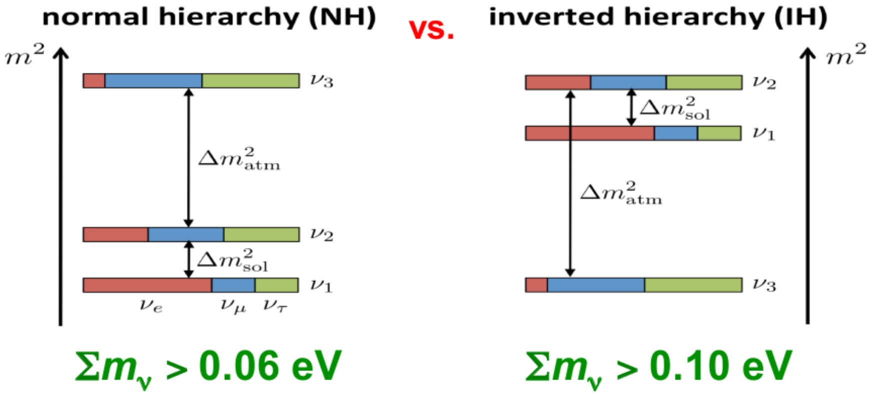



**Geometrical** information more constraining than shape (*win-win*, as BAO also less prone to systematics), **BUT**:

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

# What about the mass hierarchy?

For each mass hierarchy, there exists a minimal allowed value for $M_\nu$



# Sensitivity to the mass hierarchy

- Current cosmological data is mainly sensitive to $M_\nu$
- Sensitivity to the mass hierarchy is only due to volume effects
- We are approaching region of parameter space where these effects are important
- Current data cannot distinguish between the two mass orderings, futuristic data might be able to measure individual neutrino masses through their free-streaming imprint on $P(k)$ and on the EISW
- In the most optimistic case, need a sensitivity of $0.02\,\mathrm{eV}$ to distinguish between NH and IH at $2\sigma$ (reachable with CMB-S4/COrE+DESI BAO) through volume effects alone

# Model comparison for mass hierarchies

Probability for a given mass hierarchy $H = N, I$ given data:

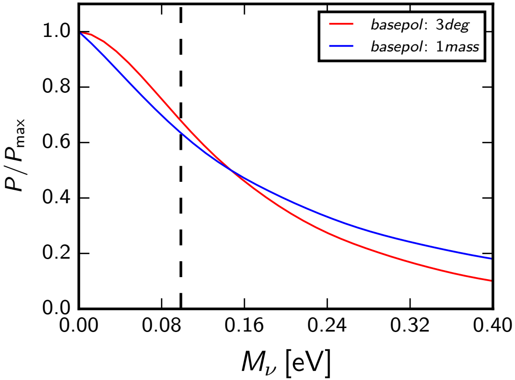
$$p_H = \frac{p(H) \int_0^\infty dm_0 \ \mathcal{L}(D|m_0, H)}{p(N) \int_0^\infty dm_0 \ \mathcal{L}(D|m_0, N) + p(I) \int_0^\infty dm_0 \ \mathcal{L}(D|m_0, I)}$$

Can then report posterior odds for NH vs IH, *or* exclusion C.L. for IH $\mathrm{CL_{IH}} = 1 - p_I$ ($\neq$ C.L. at which we exclude the minimal mass in the IH, $0.1\,\mathrm{eV}$, $\mathrm{CL}_{0.1}$). Examples:

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

# Assumptions on the neutrino mass spectrum

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



# Conclusions

- Cosmology provides tightest constraints on $\nu$ masses ($M_\nu < 0.093\,\mathrm{eV}$)
- Geometrical surpasses shape information in constraining power
- Data are starting to put the inverted hierarchy under pressure
- Model comparison excludes inverted hierarchy at most @77% C.L.
- Weak dependence on assumptions about $\nu$ mass spectrum