NEUTRINOS FROM COSMOLOGY

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KEY RESULTS

INDIVIDUAL CONSTRAINTS ON $\sum m_\nu$ (95% CL)

$\sum \mathbf{m}_\nu < \mathbf{0.12\ eV} \rightarrow$ CMB + Lyman-α + BAO

JOINT CONSTRAINTS ON N_{eff} AND $\sum m_\nu$ (95% CL)

$\mathbf{N}_{\text{eff}} = \mathbf{2.88}^{+0.20}_{-0.20}$ & $\sum \mathbf{m}_\nu < \mathbf{0.14\ eV} \rightarrow$ CMB + Lyman-α + BAO

1. Results on $\sum m_\nu$ tend to favor the *normal hierarchy scenario* for the masses of the active neutrino species

2. *Sterile neutrino* thermalized with active neutrinos *ruled out* at more than 5σ and $N_{\text{eff}} = 0$ rejected at more than $14\sigma \rightarrow$ most robust evidence for the CNB from $N_{\text{eff}} \sim 3$

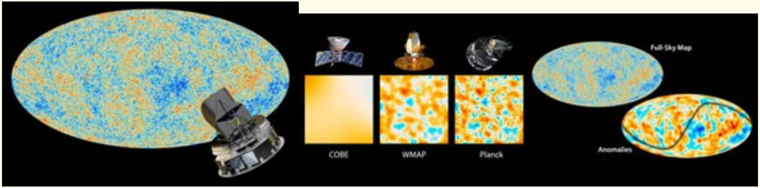
OUTLINE

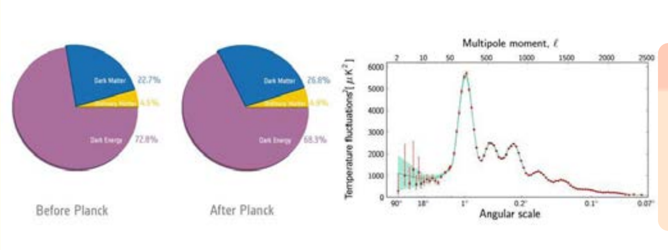
1. Cosmological Primer
2. Cosmology with Massive Neutrinos
3. Particle Physics Synergies & Prospects

MAIN REFERENCES

- **Rossi** et al. (2015), PRD, 92, 063505
- **Rossi** et al. (2014), A&A, 567, A79
- Palanque-Delabrouille et al. (2015a), JCAP, 11, 011
- Palanque-Delabrouille et al. (2015b), JCAP, 2, 045

COSMOLOGY TODAY: LARGE-VOLUME SURVEYS





BEST-FIT PARAMETERS

$\Omega_b h^2 = 0.02225$
$\Omega_c h^2 = 0.11198$
$100\theta_{MC} = 1.04077$
$\tau = 0.079$
$n_s = 0.9645$
$\ln(10^{10} A_s) = 3.094$

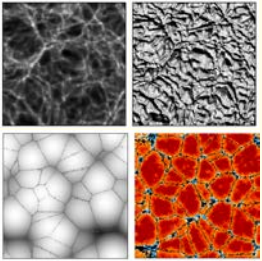
NEW FUNDAMENTAL PHYSICS?

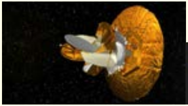
Grand Unified Model of Dark Energy →

FUNDAMENTAL QUESTIONS

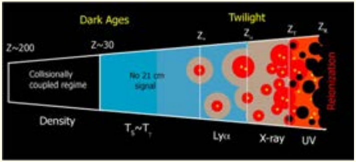
- Dark Energy: a cosmological constant?
- Dark Energy: isotropic - homogeneous?
- Acceleration caused by modified gravity?
- Dark matter?
- Massive neutrinos?

The Cosmic Web





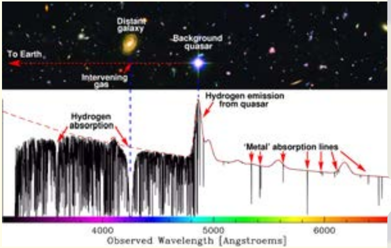
SDSS III



Call for physics beyond standard model? → **THEORY CHALLENGES**

Call for breakthrough facilities? → **OBSERVATIONAL CHALLENGES**

LYA FOREST: BASICS



LY-α: IMPORTANCE

- Probes the intergalactic medium at high-z
- Maps the primordial density fluctuations
- Synergy with other LSS probes

LYA: DIFFICULTIES

- Need numerical simulations with full hydro
- IGM thermal history uncertain
- Star formation uncertain
- Non-trivial frequency dependence
- Systematics and other technical issues

LYA: ADVANTAGES

- Mildly nonlinear scales i.e. $\rightarrow$ k [0.1 – 2] h/Mpc, [0.002 – 0.02] s/km
- High redshift ($2 \lesssim z \lesssim 5$)
- Complementary to other probes
- Special role in probing free-streaming of neutrinos on matter PS

MASSIVE NEUTRINOS: WHY SHOULD WE CARE?

- Solar, atmospheric → cannot obtain absolute mass scale of neutrinos
- Fixing **absolute mass scale of neutrinos** → main target of terrestrial experiments

- *Oscillation experiments* → tight lower bounds on total neutrino mass ($\sum m_\nu > 0.05$ eV)
- *Cosmology* → more competitive upper bounds on total neutrino mass ($\sum m_\nu < 0.15$ eV)

- Neutrino mass scale important for **Standard Model** → leptogenesis, baryogenesis, right-handed neutrino sector + cosmological implications

Nobel Prize in Physics 2015 for the Neutrino Mass!

ABSOLUTE NEUTRINO MASS

PROBING THE NEUTRINO MASS SCALE

1. Direct measurements through β decay kinematics
2. Neutrinoless double β decay ($0\nu2\beta$)
3. Cosmological observations

① **Direct β decay** → squared effective electron neutrino mass

$$m_\beta^2 = \sum_{\mathrm{i}} |U_{\mathrm{ei}}|^2 m_{\mathrm{i}}^2$$

② **Neutrinoless double β decay ($0\nu2\beta$)** → effective Majorana mass

$$m_{\beta\beta} = |\sum_{\mathrm{i}} U_{\mathrm{ei}}^2 m_{\mathrm{i}}|, \quad \Phi_2 = \alpha_1, \Phi_3 = \alpha_2 - 2\delta$$

③ **Cosmological observations** → total neutrino mass

$$M_\nu = \sum_{\mathrm{i}} m_{\mathrm{i}} = m_1 + m_2 + m_3$$

BOUNDS ON NEUTRINO MASSES

LABORATORY EXPERIMENTS

- Solar, atmospheric, reactors, accelerators → $M_\nu > 0.05$ eV
- β-decay → $M_\nu < 2.2$ eV

The Ground-Based Stage IV BAO Experiment

BigBOSS

SDSS III

LSST Large Synoptic Survey Telescope

Pan-STARRS

COSMOLOGY: NOW (95% CL)

- LyA → $M_\nu < 0.9$ eV
- WMAP9 → $M_\nu < 0.44$ eV
- WMAP7+LRG+H_0 → $M_\nu < 0.44$ eV
- WMAP7+ACT+BAO+H_0 → $M_\nu < 0.39$ eV
- WMAP7+WiggleZ+BAO+H_0 → $M_\nu < 0.29$ eV
- WMAP7+MegaZ+BAO+SNIa+H_0 → $M_\nu < 0.281$ eV
- Planck+WP+highL+BAO → $M_\nu < 0.23$ eV
- Planck+WiggleZ+BAO → $M_\nu < 0.18$ eV
- Latest claims → $M_\nu < 0.11$ eV

COSMOLOGY: NEAR FUTURE

- eBOSS LyA + CMB → $M_\nu \sim 0.1$ eV
- ACTPol + Planck → $M_\nu \sim 0.07$ eV
- Planck + eBOSS, LSST, DES → $M_\nu \sim 0.06$ eV
- Surveys in 2020 (DESI) → $M_\nu \sim 0.03$ eV

WARNING

Systematic offset between estimates of the matter PS obtained with different methods!

EFFECTS OF NEUTRINO MASSES ON COSMOLOGY

COSMOLOGICAL EFFECTS

- Fix expansion rate at BBN
- Change background evolution → PS effects
- Slow down growth of structures

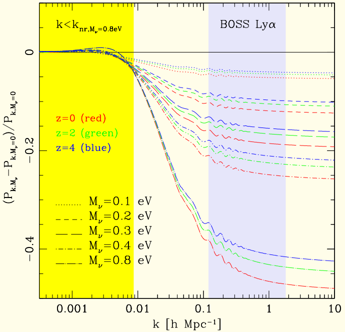
NEUTRINO FREE-STREAMING

- After thermal decoupling → ν collisionless
- Minimum free-steaming wavenumber $k_{\rm nr}$

OBSERVABLES AND TECHNIQUES

- CMB anisotropies → PS, lensing
- LSS probes
  - Galaxy PS
  - Cluster mass function
  - Galaxy weak lensing
  - **Ly-α forest**
  - 21-cm surveys

Rossi et al. (2014)



Linear matter power spectra (ratios) with 3 degenerate species of massive neutrinos

GENERAL STRATEGY

SIMULATION GRID
massive neutrinos, cosmology, astrophysics
$\Downarrow$
Extract LyA flux power spectra
$\Downarrow$
Taylor expansion of flux around best guess
$\Downarrow$
Construct multidimensional likelihood $\mathcal{L}$
(also with nuisance parameters + **COSMOLOGICAL DATA**)
$\Downarrow$
Multidimensional likelihood analysis
$\swarrow \quad \searrow$
Bayesian approach Frequentist approach
$\Downarrow$
Cosmological parameters, Neutrino mass, N_{eff}

SIMULATIONS WITH MASSIVE NEUTRINOS

A suite of 48 hydrodynamical simulations with massive neutrinos

- Typical set (3 sims.) → (a) 100 $h^{-1}\mathrm{Mpc}/768^3$, (b) 25 $h^{-1}\mathrm{Mpc}/768^3$, (c) 25 $h^{-1}\mathrm{Mpc}/192^3$
- With splicing technique → equivalent of 100 $h^{-1}\mathrm{Mpc}/3072^3$
- Full snapshots at a given redshift ($z = 4.6 - 2.2$, $\Delta z = 0.2$)
- 100,000 quasar sightlines per redshift interval per simulation

Group I

Simulation Set	M_ν [eV]
BG a/b/c	0
NUBG a/b/c	0.01
NU01 a/b/c	0.1
NU01-norm a/b/c	0.1
NU02 a/b/c	0.2
NU03 a/b/c	0.3
NU04 a/b/c	0.4
NU04-norm a/b/c	0.4
NU08 a/b/c	0.8
NU08-norm a/b/c	0.8

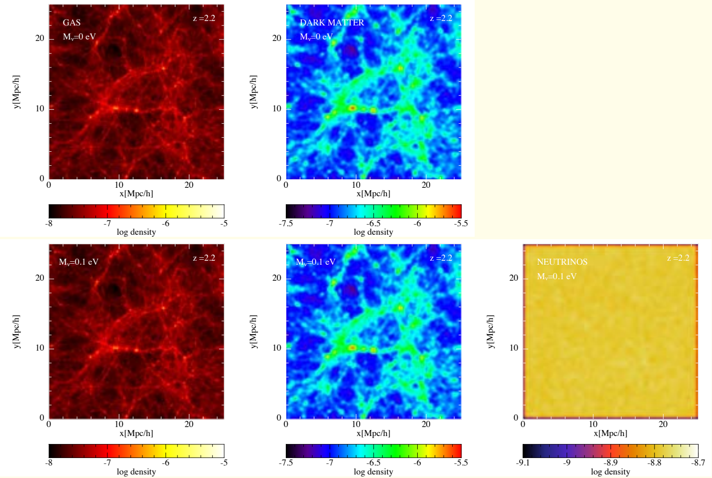
Group II

Simulation Set	M_ν [eV]
γ+NU08 a/b/c	0.8
H_0+NU08 a/b/c	0.8
n_s+NU08 a/b/c	0.8
Ω_m+NU08 a/b/c	0.8
σ_8+NU08 a/b/c	0.8
T_0+NU08 a/b/c	0.8

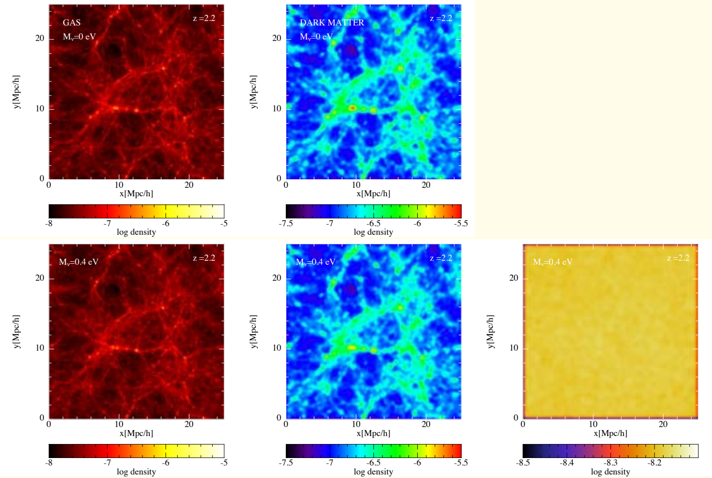
ROSSI ET AL. (2014)

- **Group I** → Best-guess and neutrino runs
- **Group II** → Cross-terms

VISUALIZATIONS: GAS, DM, NEUTRINOS



VISUALIZATIONS: GAS, DM, NEUTRINOS



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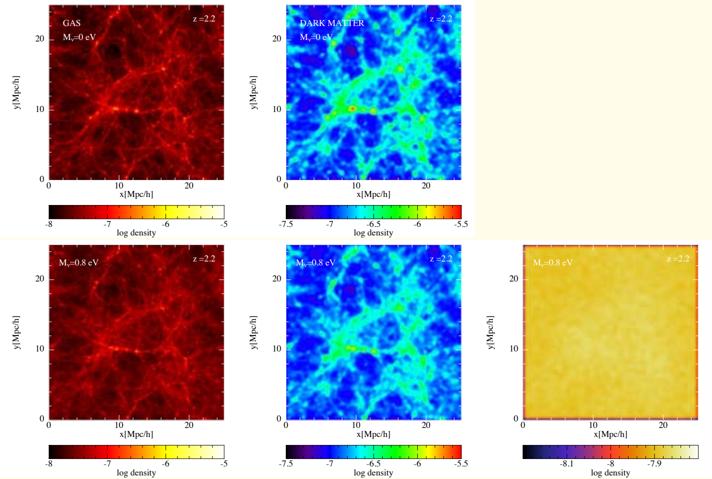

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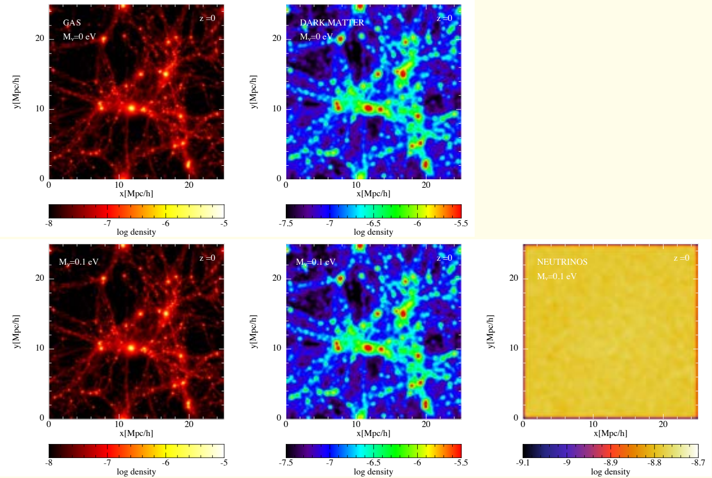

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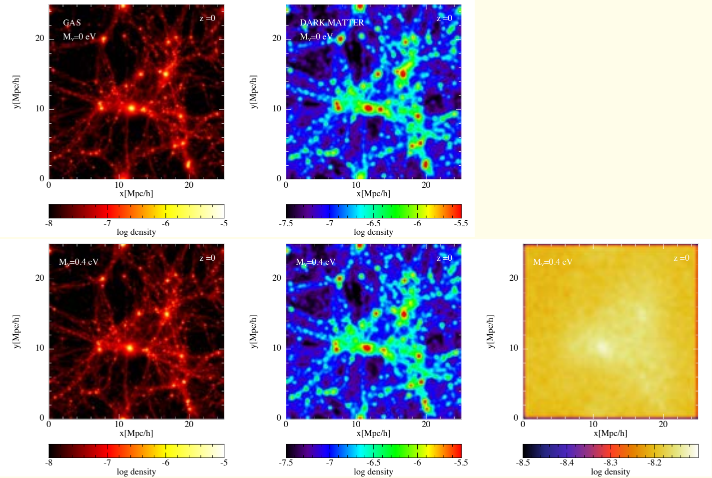
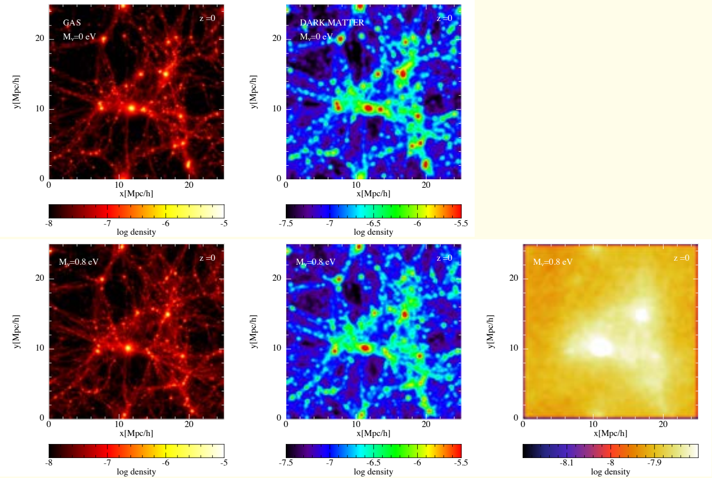
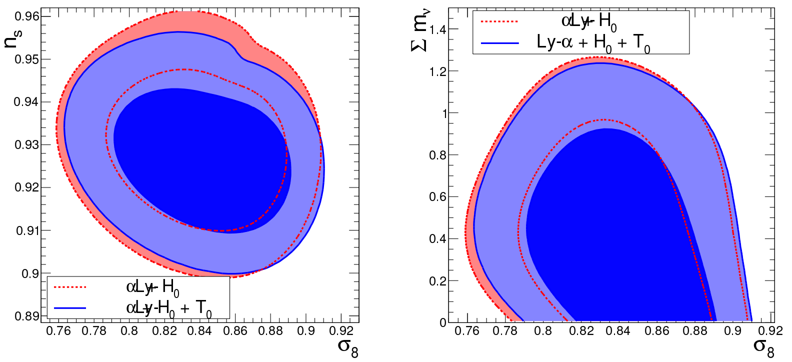


VISUALIZATIONS: GAS, DM, NEUTRINOS

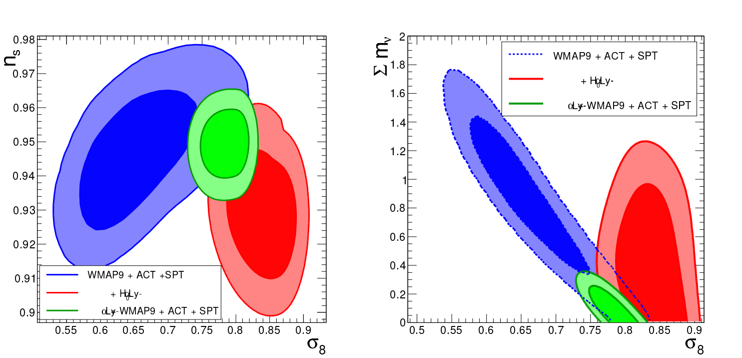


BOSS APPLICATIONS → LYA ALONE

Palanque-Delabrouille et al. (2015a)



BOSS APPLICATIONS → COMBINATIONS

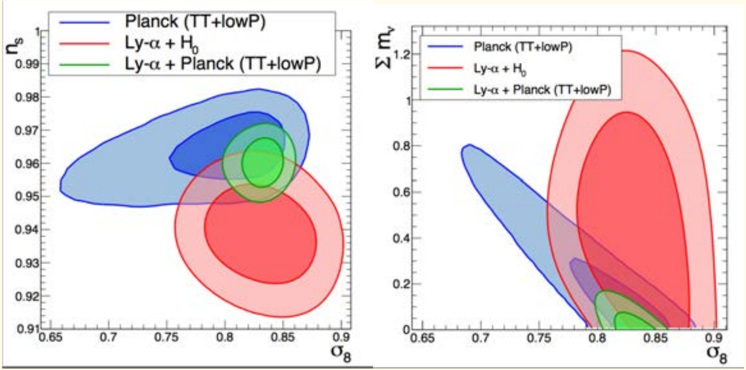


Palanque-Delabrouille et al. (2015a)

$\sum m_\nu < 0.14$ eV → CMB + Lyman-α + BAO

THE POWER OF COMBINING PROBES

Palanque-Delabrouille et al. (2015b)

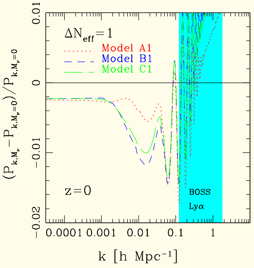


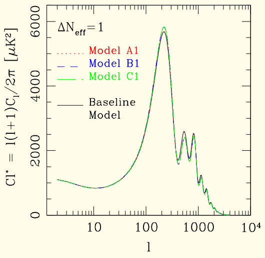
$\sum m_\nu < 0.12$ eV → CMB + Lyman-α + BAO

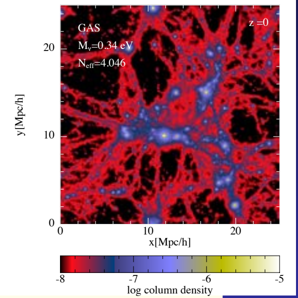
TRICK → ANALYTIC PROXY FOR LYα LIKELIHOOD

- Technique of Palanque-Delabrouille et al. (2015) extended with analytic proxy for dark radiation models in Lyα likelihood
- **Trick** → *If two models have same linear matter PS → nearly identical NL matter and flux PS*
- Simulations with non-standard $N_{\rm eff}$ to confirm analytic proxy

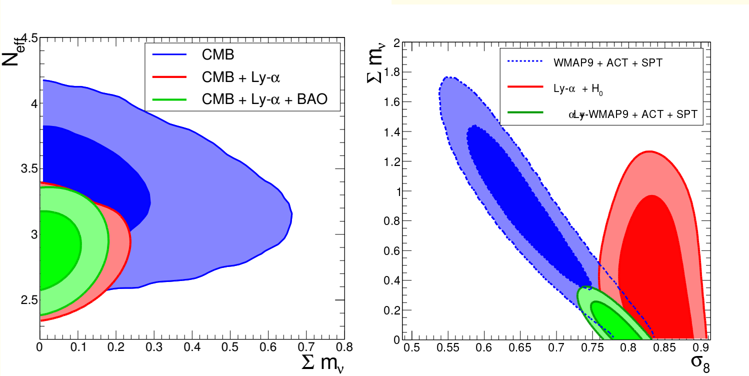
Rossi et al. (2015)







FINAL JOINT CONSTRAINTS

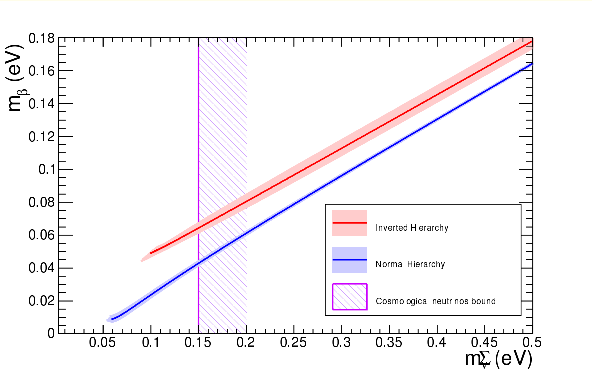


Rossi et al. (2015)

- $N_{\rm eff} = 2.91^{+0.21}_{-0.22}$ and $\sum m_\nu < 0.15$ eV (all at 95% CL) → CMB + Lyman-α
- $N_{\rm eff} = 2.88^{+0.20}_{-0.20}$ and $\sum m_\nu < 0.14$ eV (all at 95% CL) → CMB + Lyman-α + BAO

IMPLICATIONS FOR PARTICLE PHYSICS

Palanque-Delabrouille et al. (2015a)



$\sum m_\nu < 0.15$ eV $\rightarrow$ $m_\beta < 0.04$ eV $\rightarrow$ If KATRIN detects $m_\beta > 0.2$ eV the 3-neutrino model is in trouble!

IMPLICATIONS FOR PARTICLE PHYSICS

- Potential relevance of our neutrino bounds on neutrinoless double beta decay
- Crucial impact, because the possibility of detecting a signal will be out of the reach of the next generation of experiments

NH

$$m_1 = m \text{ (lightest neutrino mass)}$$

$$m_2 = \sqrt{m^2 + \delta m^2}$$

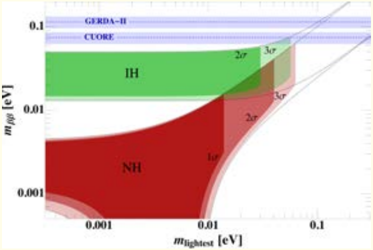
$$m_3 = \sqrt{m^2 + \Delta m^2 + \delta m^2/2}$$

IH

$$m_1 = \sqrt{m^2 + \Delta m^2 - \delta m^2/2}$$

$$m_2 = \sqrt{m^2 + \Delta m^2 + \delta m^2/2}$$

$$m_3 = m \text{ (lightest neutrino mass)}$$



Dell'Oro et al. (2015)

SUMMARY

JOINT CONSTRAINTS ON $N_{\rm eff}$ AND $\sum m_\nu$

- $N_{\rm eff} = 2.91^{+0.21}_{-0.22}$ and $\sum m_\nu < 0.15$ eV (all at 95% CL) → CMB + Lyman-α
- $N_{\rm eff} = 2.88^{+0.20}_{-0.20}$ and $\sum m_\nu < 0.14$ eV (all at 95% CL) → CMB + Lyman-α + BAO

1. Our results on $\sum m_\nu$ tend to favor the normal hierarchy scenario for the masses of the active neutrino species

2. Sterile neutrino thermalized with active neutrinos ruled out at more than 5 σ → strongest bound to date

3. $N_{\rm eff} = 0$ rejected at more than 14 σ → robust evidence for the CNB from $N_{\rm eff} \sim 3$