NEUTRINO MASS AND DARK RADIATION: THE MINIMALIST CONTEXT

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‘Neutrinos win the minimalist contest: zero charge, zero radius, and very probably zero mass.’

– Leon M. Lederman

In *Leon Lederman and Dick Teresi*, ‘The God Particle: If the Universe is the Answer, What is the Question’ (1993, 2006)

Key Results

Individual constraints on $\sum m_\nu$ (95% CL)

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

Joint constraints on $N_{\rm eff}$ and $\sum m_\nu$ (95% CL)

$N_{\rm eff} = 2.88^{+0.20}_{-0.20}$ and $\sum m_\nu < 0.14$ 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 $\rightarrow$ strongest upper bound to date

2. *Sterile neutrino* thermalized with active neutrinos *ruled out* at more than 5σ and $N_{\rm eff} = 0$ rejected at more than 15σ $\rightarrow$ most robust evidence for the CNB from $N_{\rm eff} \sim 3$

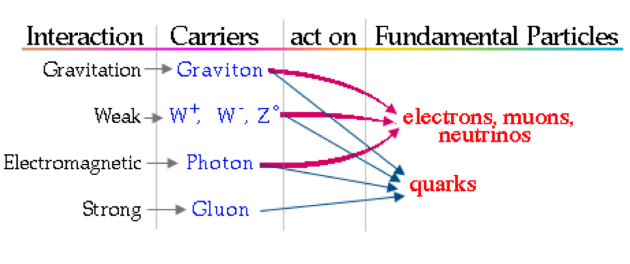
OUTLINE

- Neutrino Science
- Simulations and Datasets
- Neutrino Mass Constraints
- Dark Radiation Constraints
- Neutrino Effects
- Summary

MAIN REFERENCES

- **Rossi** et al. (2015), arXiv: 1412.6763
- **Rossi** et al. (2014), A&A, 567, A79
- Palanque-Delabrouille et al. (2015a), arXiv: 1506.05976
- Palanque-Delabrouille et al. (2015b), JCAP, 2, 045

Standard Model & Neutrinos



Neutrino → Lepton

- Electrically neutral
- Weakly interacting
- Half-integer spin

Neutrino Flavors

- Electron neutrinos
- Muon neutrinos
- Tau neutrinos

What about **sterile neutrinos**?

MASSIVE NEUTRINOS: WHY SHOULD WE CARE?

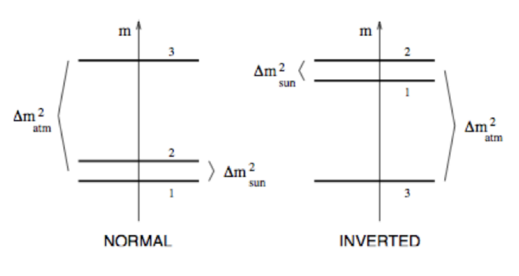
- Solar, atmospheric $\rightarrow$ cannot obtain absolute mass scale of neutrinos
- Fixing **absolute mass scale of neutrinos** $\rightarrow$ main target of terrestrial experiments

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

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

NEUTRINO MASS HIERARCHY, CNB & $N_{\rm eff}$

- Neutrino mass hierarchy?
- Number of effective neutrino species ($N_{\rm eff}$)?



CNB, $N_{\rm eff}$, STERILE ν

- CNB generic prediction of HBB model
- 3 active relativistic relic neutrinos in standard model
- Sterile neutrinos ?

Effects of neutrino masses on cosmology

Cosmological effects

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

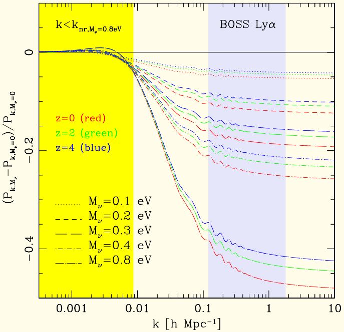
Neutrino free-streaming

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

LyA Forest

- Mildly nonlinear scales
  i.e. $\rightarrow$ k [0.1 – 2] h/Mpc, [0.002 – 0.02] s/km
- High redshift ($2 \leq z \leq 5$)
- Maps the primordial density fluctuations
- Complementary & orthogonal to $\neq$ probes

Rossi et al. (2014)



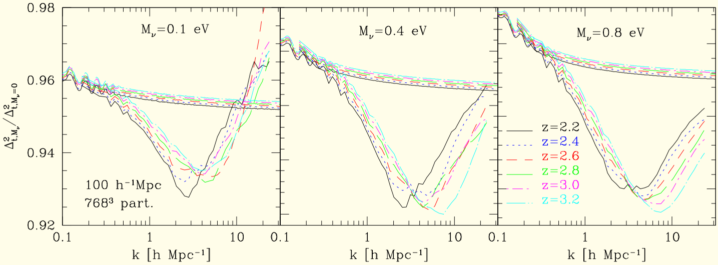
Linear matter power spectra (ratios) with 3 degenerate species of massive neutrinos

Spoon-Like effect on Matter Power Spectrum

Impact on matter PS ($k > k_{nr}$)

1. Massive neutrinos do not cluster
2. z_{eq} or baryon-to-CDM ratio affected
3. Growth rate of CDM perturbations reduced

Rossi et al. (2014), see also Viel et al. (2010), Bird et al. (2012)



Methods, Objectives, Improvements

Main goal → Improving on Viel et al. (2010)

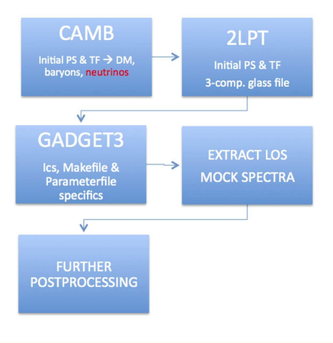
"Reaching an accuracy below 1% level at scales relevant for the Lyα forest or weak lensing data will be challenging, but should be doable and will be an important step in turning the exciting prospect of an actual measurement of neutrino masses into reality"

Simulating Massive Neutrinos

- Neutrinos included as a new type of particle
- Short-range gravitational tree force for neutrinos not computed

Novel Features

- 2LPT ICs + CAMB
- Planck cosmological parameters
- Splicing technique → higher resolution
- Updated prescriptions for radiative cooling and heating processes



Curie thin node architecture → 7M CPU hrs

Simulations with Massive Neutrinos

A suite of 48 hydrodynamical simulations with massive neutrinos

- Typical set (3 sims.) $\rightarrow$ (a) 100 h^{-1}Mpc$/768^3$, (b) 25 h^{-1}Mpc$/768^3$, (c) 25 h^{-1}Mpc$/192^3$
- With splicing technique $\rightarrow$ equivalent of 100 h^{-1}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** $\rightarrow$ Best-guess and neutrino runs
- **Group II** $\rightarrow$ Cross-terms

DATASETS

BARYON OSCILLATION SPECTROSCOPIC SURVEY

- Dark Energy and the Geometry of Space
- Maps 1.5M LRGs and 150,000 quasars
- Uses the acoustic scale as a ruler
- Measures $H(z)$ with $1-2\%$ precision at different z

- 1D Lyα forest flux power spectrum from DR9 BOSS quasar data
- BAO scale in the clustering of galaxies from the BOSS DR11
- Planck (2013) temperature data from March 2013 public release (both high and low-ℓ)
- Planck (2015) temperature data from January 2015 public release (TT+TE+EE+lowP)
- High-ℓ public likelihoods from the Atacama Cosmology Telescope (ACT) and South Pole Telescope (SPT)
- Some low-ℓ WMAP polarization data

General Strategy

SIMULATION GRID
massive neutrinos, cosmology, astrophysics

⇓

Extract LyA flux power spectra

⇓

Taylor expansion of flux around best guess

⇓

Construct multidimensional likelihood $\mathcal{L}$
(also with nuisance parameters + **COSMOLOGICAL DATA**)

⇓

Multidimensional likelihood analysis

↙ ↘

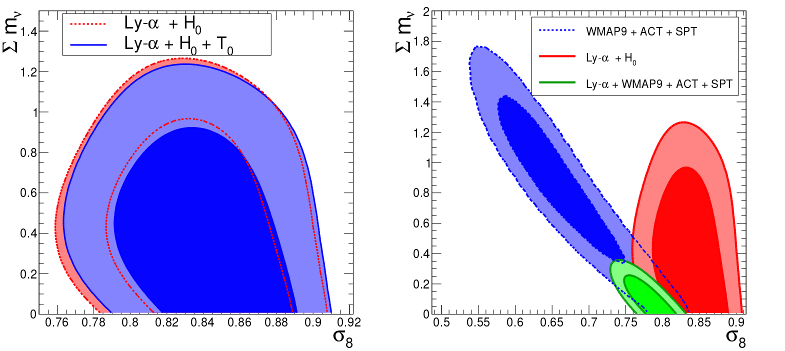
Bayesian approach — Frequentist approach

⇓

Cosmological parameters & Neutrino mass

The Power of Combining Probes (1)

N. Palanque-Delabrouille et al. (2015a)

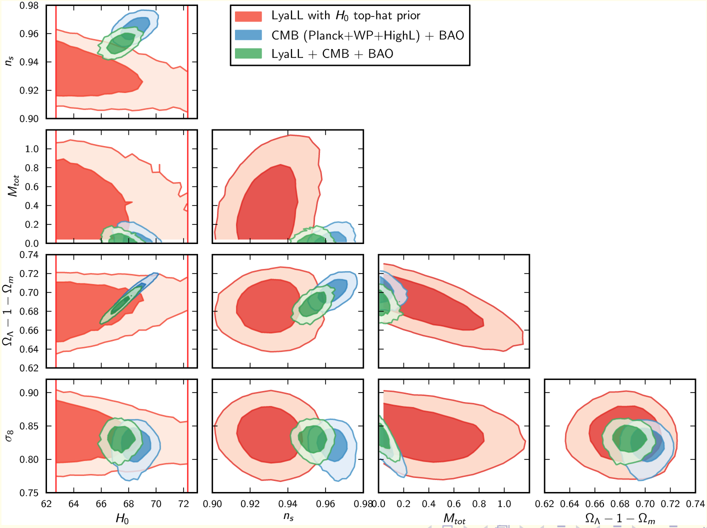


Key is orthogonality of LyA forest with other LSS probes

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

Combinations with Bayesian Techniques

Palanque-Delabrouille et al. (2015a)



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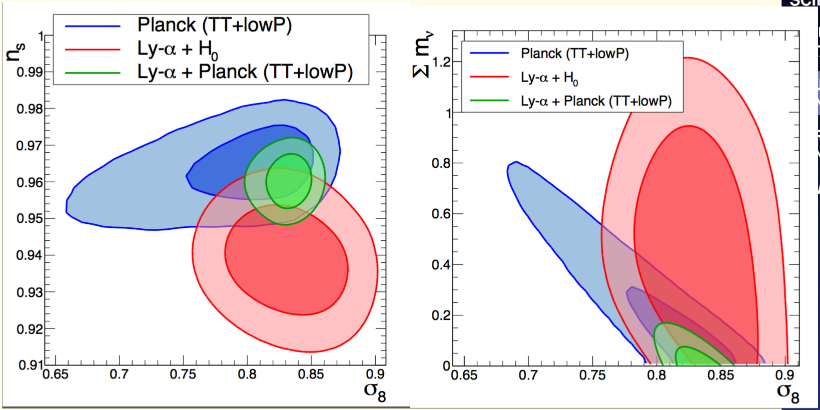
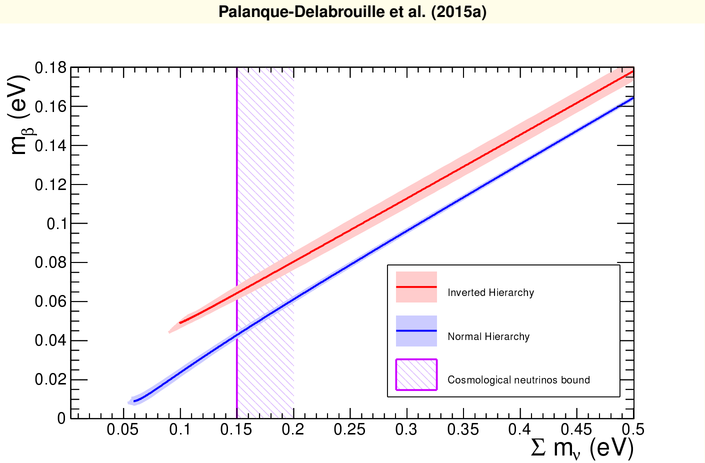
THE POWER OF COMBINING PROBES (2)

Palanque-Delabrouille et al. (2015b)



$$\sum m_\nu < 0.12 \text{ eV} \rightarrow \text{CMB + Lyman-}\alpha\text{ + BAO}$$

Implications for Particle Physics

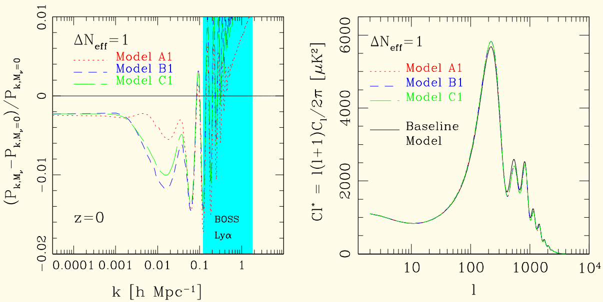


$\sum m_\nu < 0.15$ eV $\rightarrow m_\beta < 0.04$ eV $\rightarrow$ If KATRIN detects $m_\beta > 0.2$ eV the 3-neutrino model is in trouble!

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_{eff} to confirm analytic proxy

Rossi et al. (2015)



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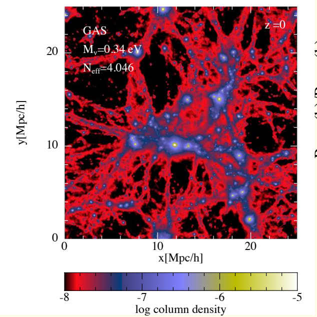
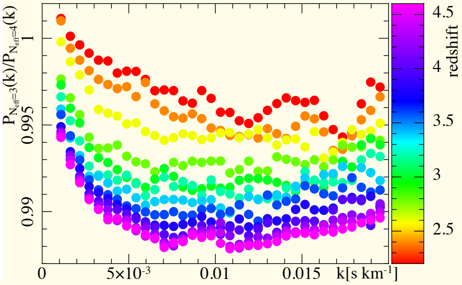
Nonlinear Regime

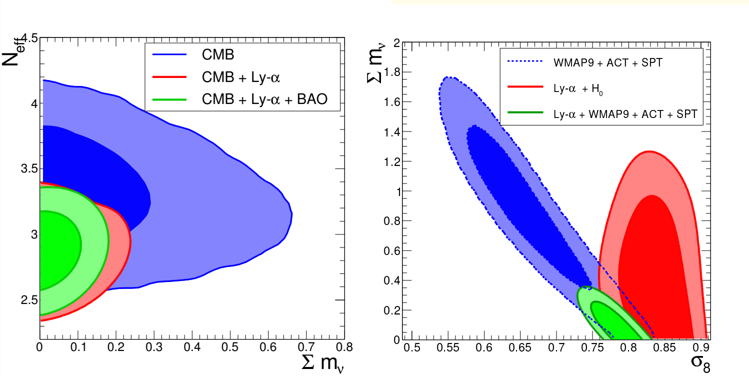
Rossi et al. (2015)





- Deviations in flux PS all within 1% of baseline model
- Analytic proxy for LyA likelihood fully validated in NL regime

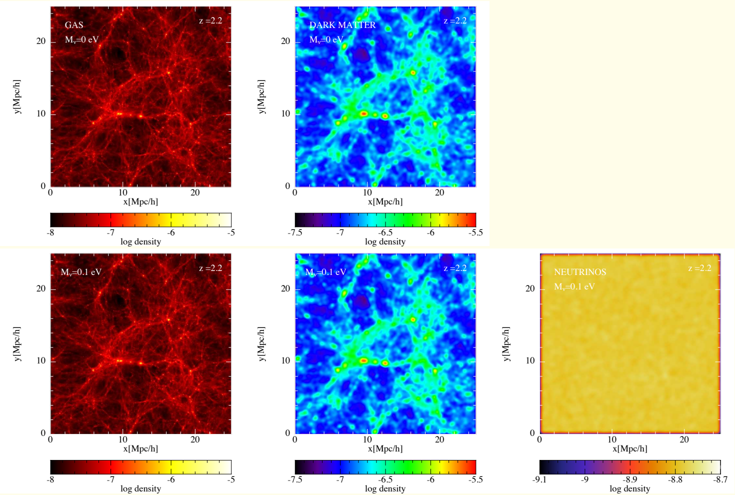
Final Joint Constraints



Rossi et al. (2015)

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

COSMOLOGIES WITH MASSIVE NEUTRINOS



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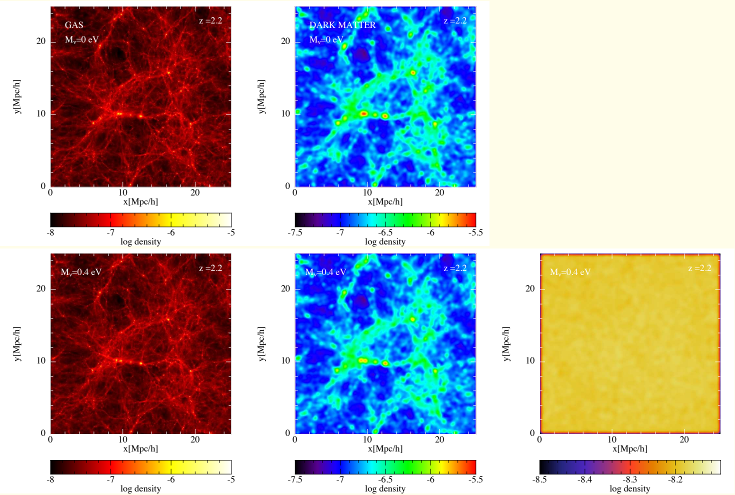

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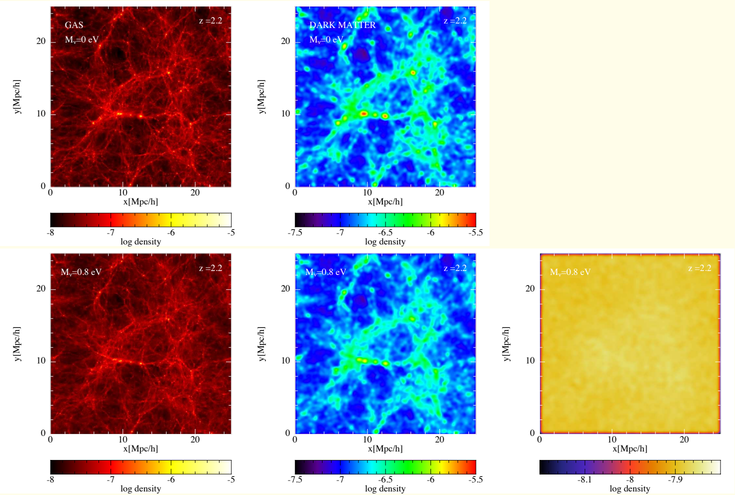

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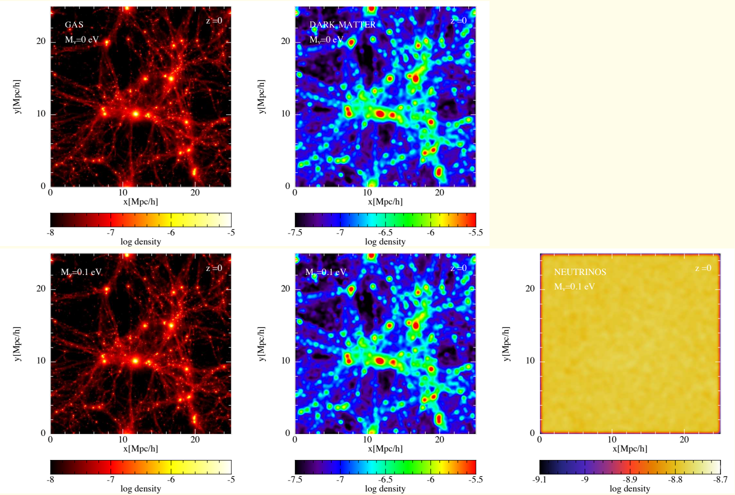

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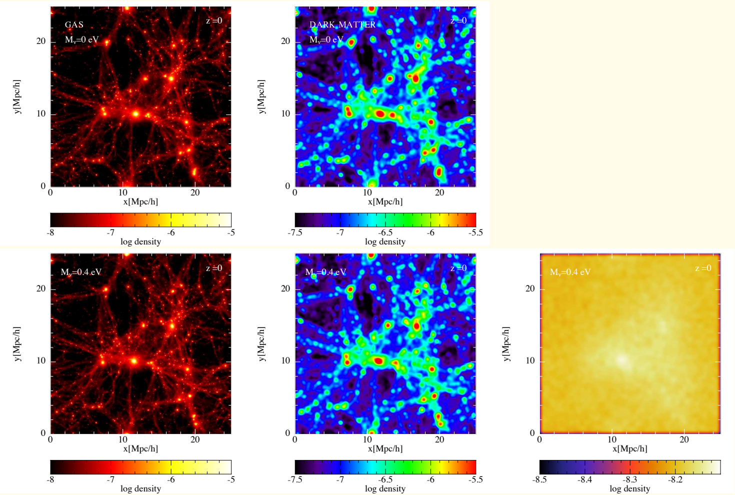
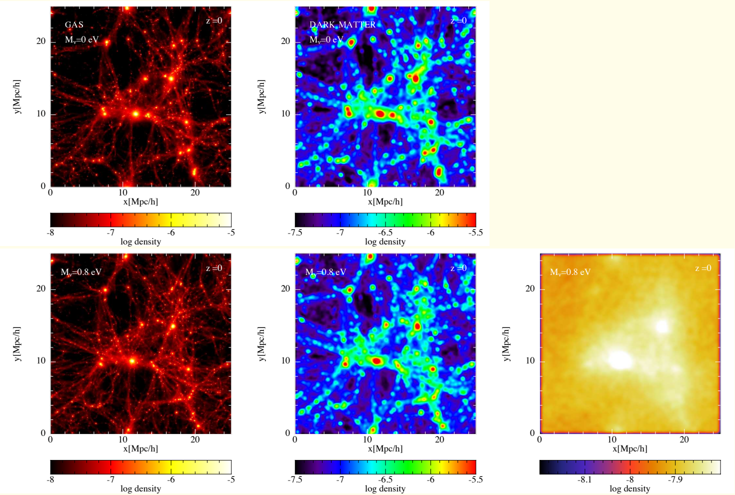


Rossi et al. (2014)

Cosmologies with massive neutrinos



Rossi et al. (2014)

KEY RESULTS

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

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

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

$N_{\rm eff} = 2.88^{+0.20}_{-0.20}$ and $\sum m_\nu < 0.14$ 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 $\rightarrow$ strongest upper bound to date

2. *Sterile neutrino* thermalized with active neutrinos *ruled out* at more than 5σ and $N_{\rm eff} = 0$ rejected at more than 15σ $\rightarrow$ most robust evidence for the CNB from $N_{\rm eff} \sim 3$