Neutrino and Dark Radiation Bounds

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Key Results

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

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

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

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

1. Results on $\sum m_\nu$ tend to favor the *normal hierarchy scenario* for the masses of the active neutrino species $\rightarrow$ one of the strongest upper bounds to date

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

Key Points

1. World-leading constraints on $\sum m_\nu$ and $N_{\rm eff}$ from cosmology

2. Novel sophisticated techniques for obtaining constraints, based on state-of-the-art high-resolution hydro simulations & on the Lyα forest

3. Rushing activity in neutrino science lately – detection of neutrino mass from cosmology expected soon (i.e. DESI)

4. Important synergies with particle physics experiments (i.e., CUORE, Cuoricino, KamLAND, KATRIN, GERDA, ...)

Outline

- Neutrino Cosmology: Basics
- Neutrinos & Dark Radiation: Bounds from the LyA Forest
- Neutrinos & Dark Radiation: Latest Developments
- Summary & Future Challenges

Neutrino Cosmology: Basics

Massive Neutrinos

KEY WORDS → Neutrinos, Lyman-Alpha Forest, Hydrodynamical Simulations

NECESSITY

- *Rushing activity in neutrino science from cosmology*
- *Standard cosmology (**LCDM**) → Small-scale flaws, massive neutrinos not included!*
- *Lyman-α Forest → new cosmological frontier, unique high-z tracer, need simulations*

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

Photo: K. MacFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015

- Takaaki Kajita
- Arthur B. McDonald

"for the discovery of neutrino oscillations"

Neutrino Formalism

- ν_α $(\alpha = e, \mu, \tau) \rightarrow$ neutrino flavor eigenstates
- ν_i $(i = 1, 2, 3) \rightarrow$ neutrino mass eigenstates
- m_i $(i = 1, 2, 3) \rightarrow$ neutrino individual masses
- $m_2 > m_1$, $m_2 \simeq m_1$
- $\Delta m^2_{21} \equiv \delta m^2 = m^2_2 - m^2_1 > 0 \rightarrow$ solar mass splitting
- $|\Delta m^2_{31}| \equiv |\Delta m^2| = |m^2_3 - m^2_1| \rightarrow$ atmospheric mass splitting
- $\Delta m^2_{31} > 0 \rightarrow$ normal hierarchy (NH)
- $\Delta m^2_{31} < 0 \rightarrow$ inverted hierarchy (IH)
- Relation flavor-mass eigenstates $\rightarrow$

$$|\nu_\alpha >= \sum_i U_{\alpha i} \, |\nu_i >$$

- $U_{\alpha i} \rightarrow$ mixing matrix, elements parameterized by $(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \alpha_1, \alpha_2)$

Massive Neutrinos: So What?

- 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

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** $\rightarrow$ squared effective electron neutrino mass

$$m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2$$

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

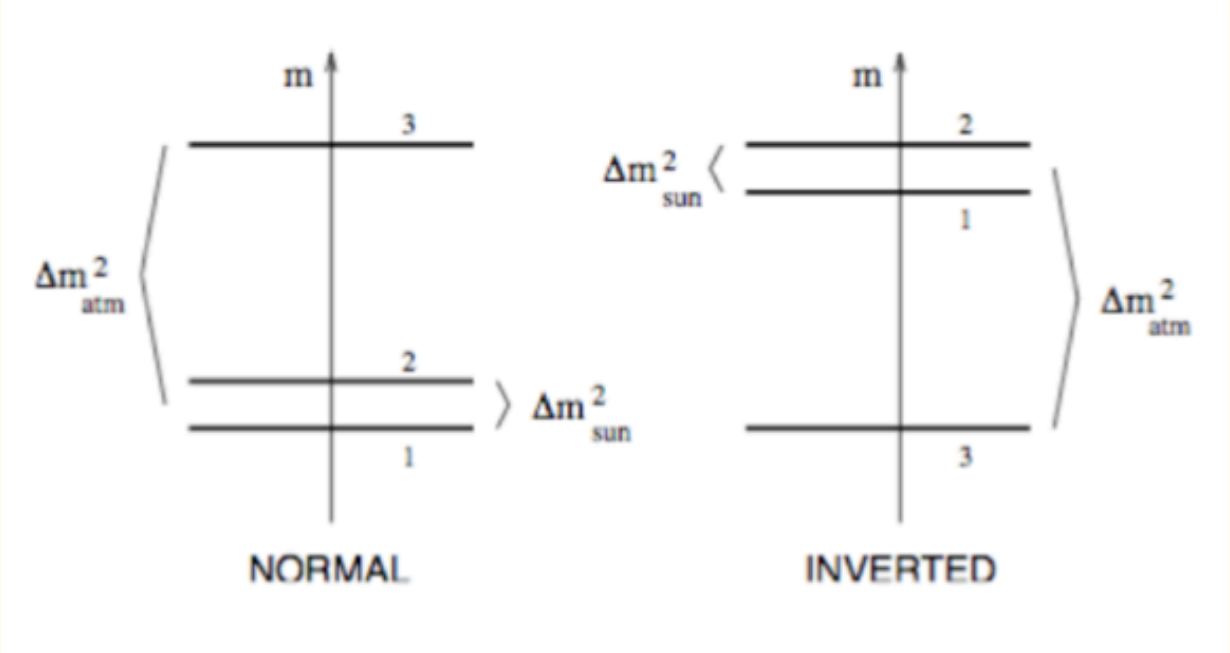
$$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|, \quad \Phi_2 = \alpha_1, \Phi_3 = \alpha_2 - 2\delta$$

3. **Cosmological observations** $\rightarrow$ total neutrino mass

$$M_\nu = \sum_i m_i = m_1 + m_2 + m_3$$

Neutrino Mass Hierarchy

- Neutrino mass hierarchy?



CNB, N_{eff}, STERILE ν

- CNB generic prediction of HBB model $\rightarrow$ relic sea of neutrinos
- 3 active relativistic relic neutrinos in standard model
- Sterile neutrinos? Number of effective neutrino species (N_{eff})?

Current Neutrino Bounds

Laboratory Experiments

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

Cosmology: Now (95% CL)

- LyA $\rightarrow$ $M_\nu < 0.9$ eV
- WMAP9 $\rightarrow$ $M_\nu < 0.44$ eV
- WMAP7+LRG+H_0 $\rightarrow$ $M_\nu < 0.44$ eV
- WMAP7+ACT+BAO+H_0 $\rightarrow$ $M_\nu < 0.39$ eV
- WMAP7+WiggleZ+BAO+H_0 $\rightarrow$ $M_\nu < 0.29$ eV
- WMAP7+MegaZ+BAO+SNIa+H_0 $\rightarrow$ $M_\nu < 0.281$ eV
- Planck+WP+highL+BAO $\rightarrow$ $M_\nu < 0.23$ eV
- Planck+WiggleZ+BAO $\rightarrow$ $M_\nu < 0.18$ eV
- Latest claims $\rightarrow$ $M_\nu < 0.11$ eV $\rightarrow$ 0.13 eV

Cosmology: Near Future

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

Warning

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

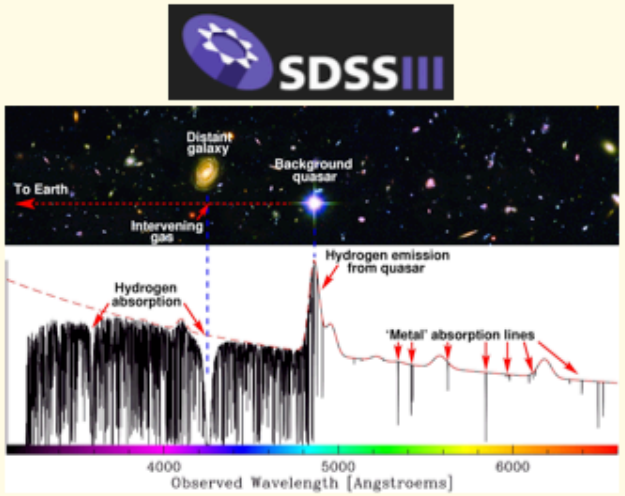
Lyman-Alpha Forest

LyA: Advantages

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

LyA: Difficulties

- Need numerical simulations with full hydro
- Complicated thermodynamical evolution if IGM
- Star formation uncertain
- Non-trivial frequency dependence
- Systematics and other technical issues



Ly-α: Importance

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

Effect of Neutrino Masses on Cosmology

Cosmological Effects

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

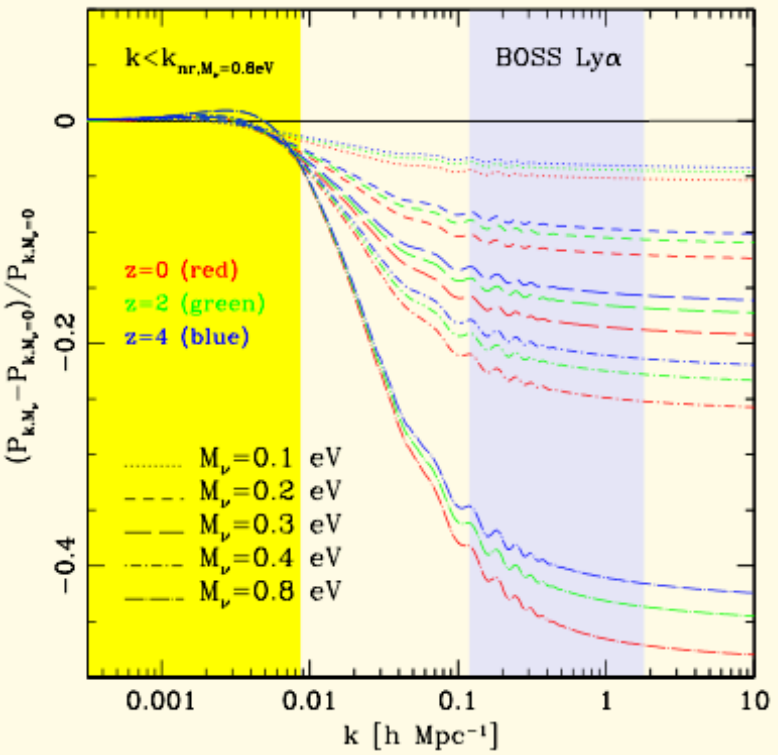
Neutrino Free-Streaming

- After thermal decoupling → ν collisionless fluid
- 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

Neutrinos & Dark Radiation: Bounds from the LyA Forest

Basic 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, $N_{\rm eff}$

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

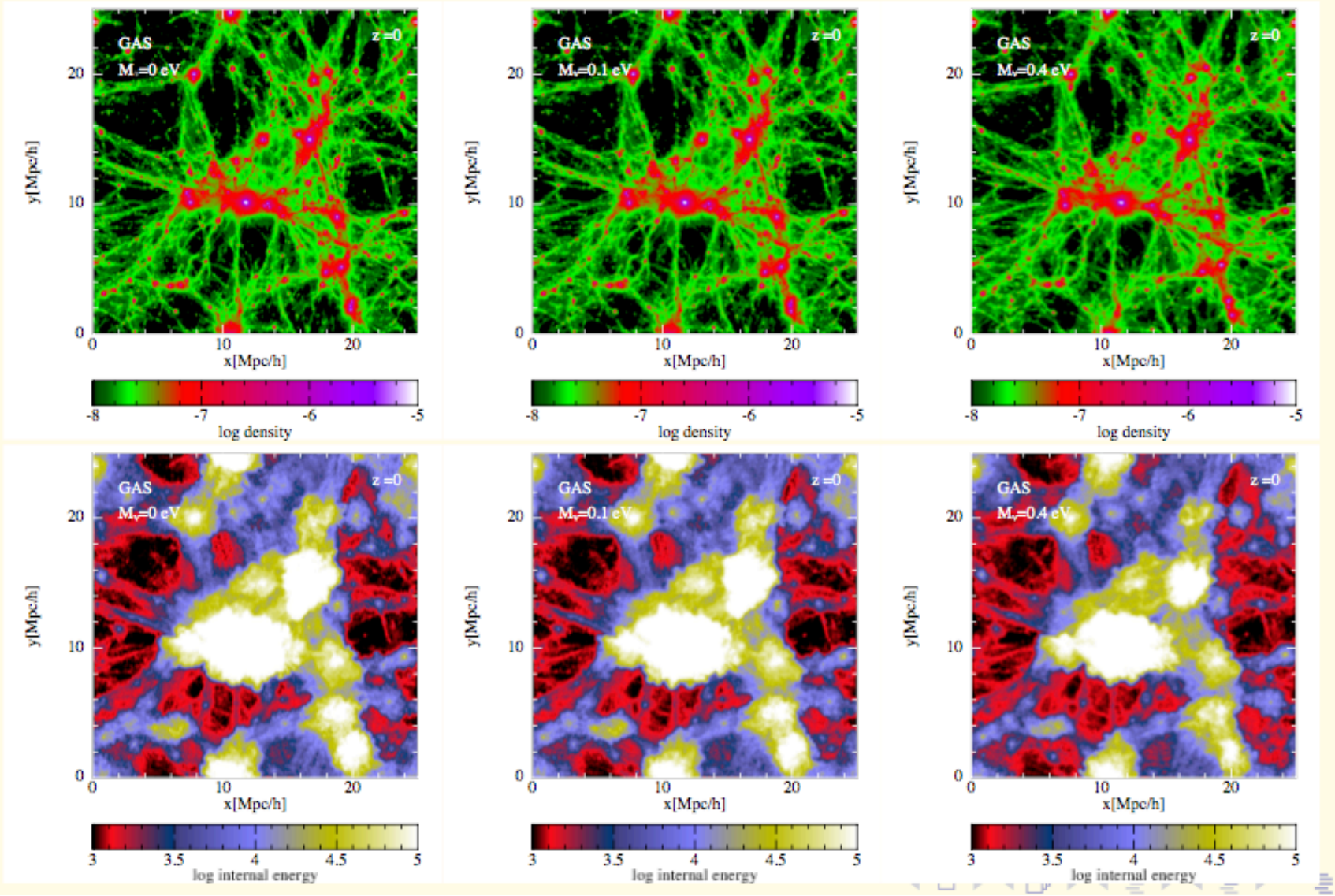
Group II

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

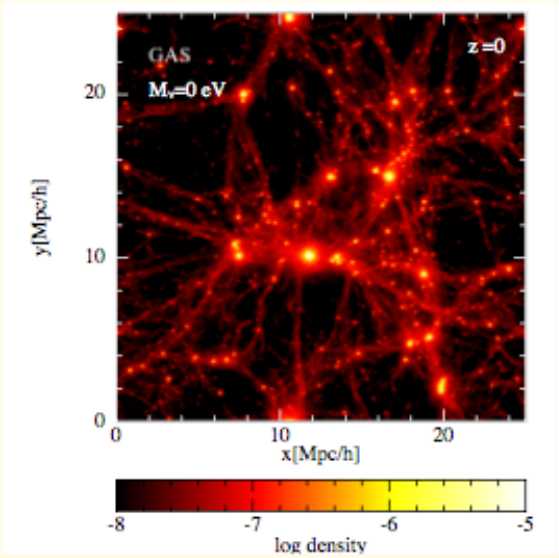
ROSSI ET AL. (2014)

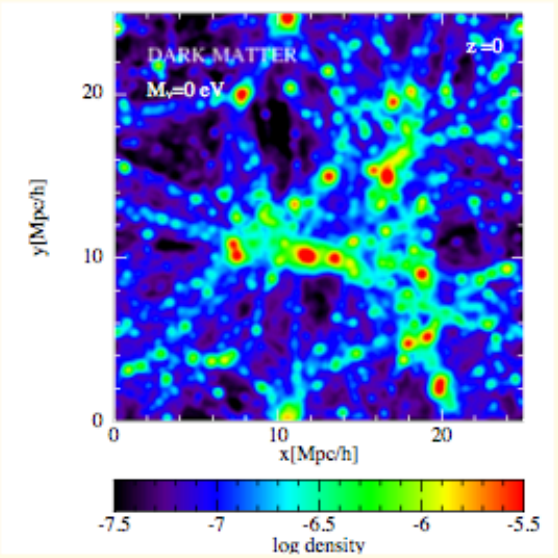
- **Group I** $\rightarrow$ Best-guess and neutrino runs
- **Group II** $\rightarrow$ Cross-terms

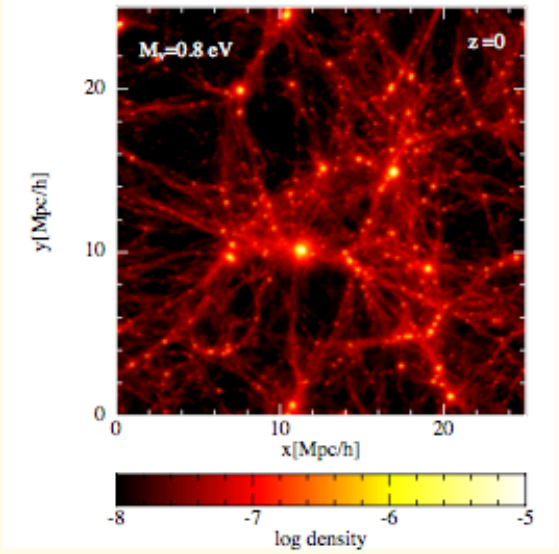
Gas Properties

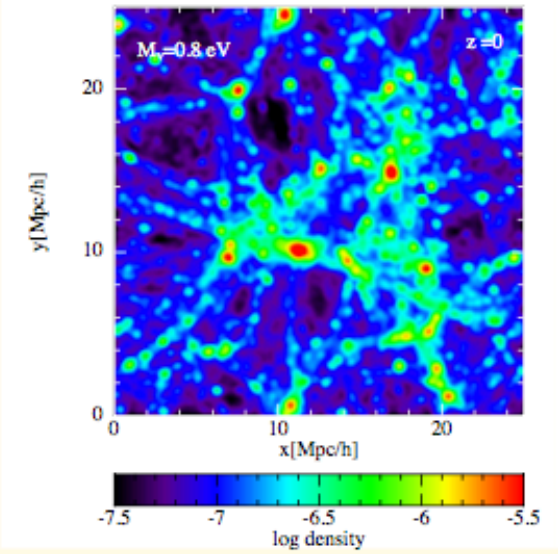


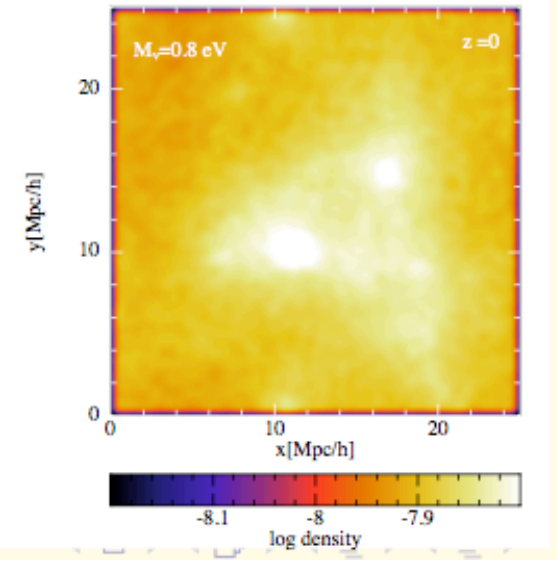
Visualizations: Gas, DM, Neutrinos











LyA Likelihood Construction

- Model $\mathcal{M}$ defined by three categories of parameters – **cosmological** (α), **astrophysical** (β), **nuisance** (γ) – globally indicated with $\Theta = (\alpha, \beta, \gamma)$
- $N_k \times N_z$ dataset $\boldsymbol{X}$ of power spectra $P(k_i, z_j)$ measured in N_k bins in k and N_z bins in redshift with experimental Gaussian errors $\sigma_{i,j}$, with $\boldsymbol{\sigma} = \{\sigma_{i,j}\}$, $i = 1, N_k$ and $j = 1, N_z$
- $$\mathcal{L}^{Ly\alpha}(\boldsymbol{X}, \boldsymbol{\sigma}|\Theta) = \frac{\exp[-(\Delta^T C^{-1} \Delta)/2]}{(2\pi)^{\frac{N_k N_z}{2}} \sqrt{|C|}} \mathcal{L}^{Ly\alpha}_{\text{prior}}(\gamma)$$
- Δ is a $N_k \times N_z$ matrix with elements $\Delta(k_i, z_j) = P(k_i, z_j) - P^{\text{th}}(k_i, z_j)$
- $P^{\text{th}}(k_i, z_j)$ predicted theoretical value of the power spectrum for the bin k_i and redshift z_j given the parameters (α, β) and computed from simulations
- C is the sum of the data and simulation covariance matrices
- $\mathcal{L}^{Ly\alpha}_{\text{prior}}(\gamma)$ accounts for the nuisance parameters, a subset of the parameters Θ

Analysis Techniques

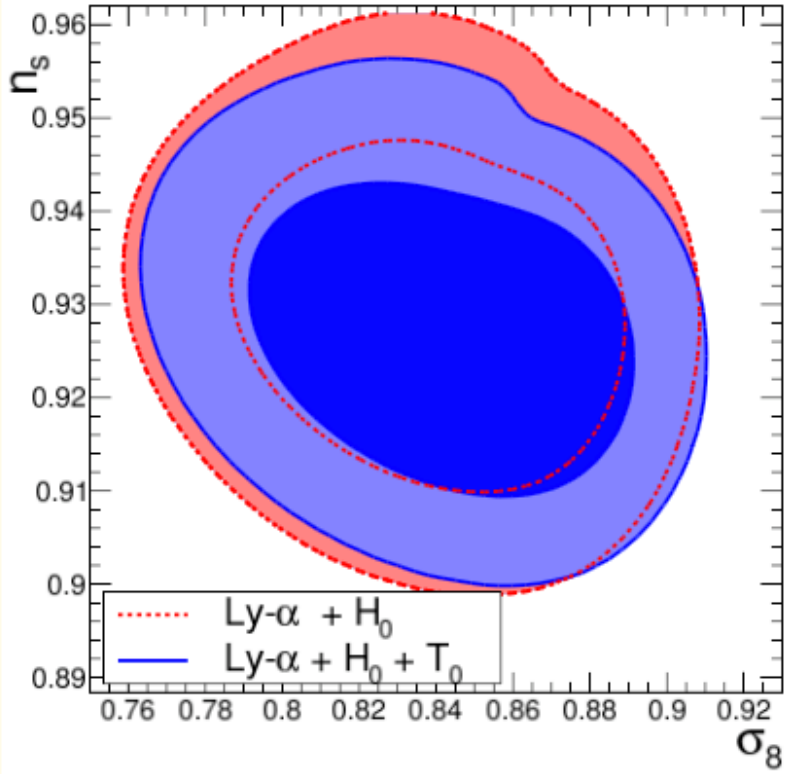
Analysis Strategies

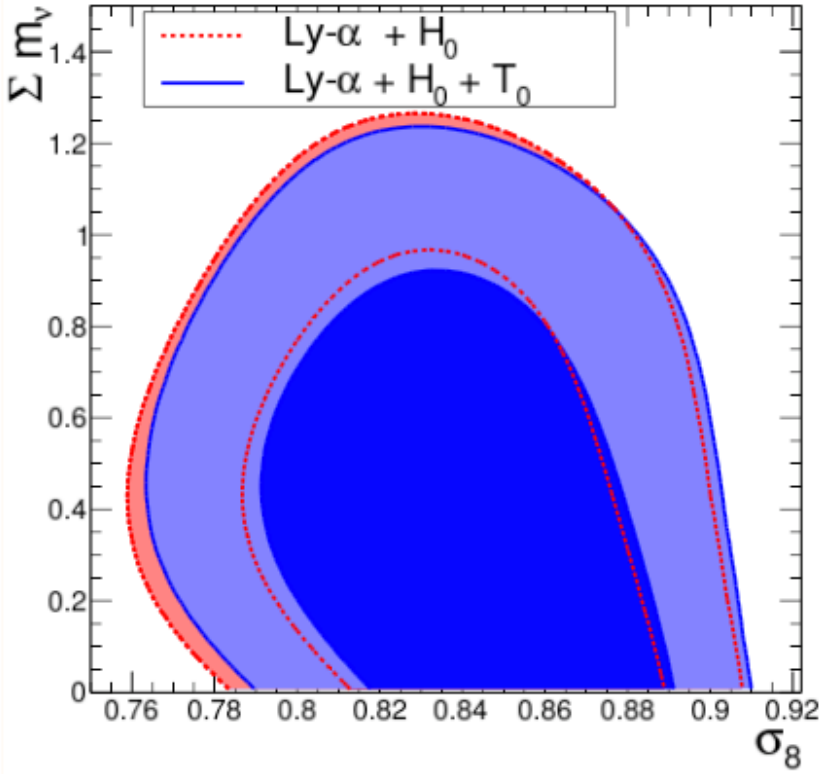
- Bayesian Approach
- Frequentist Approach

Frequentist Approach: Insights

- Minimize $\chi^2(\boldsymbol{X}, \boldsymbol{\sigma}|\boldsymbol{\Theta}) = -2\ln[\mathcal{L}(\boldsymbol{X}, \boldsymbol{\sigma}|\boldsymbol{\Theta})]$
- Compute the global minimum χ^2_0, leaving all the N cosmological parameters free
- Set confidence levels (CL) on a chosen parameter α_i by performing the minimization for a series of fixed values of α_i – thus with $N-1$ degrees of freedom
- Difference between χ^2_0 and the new minimum allows us to compute the CL on α_i

Results: LyA Alone

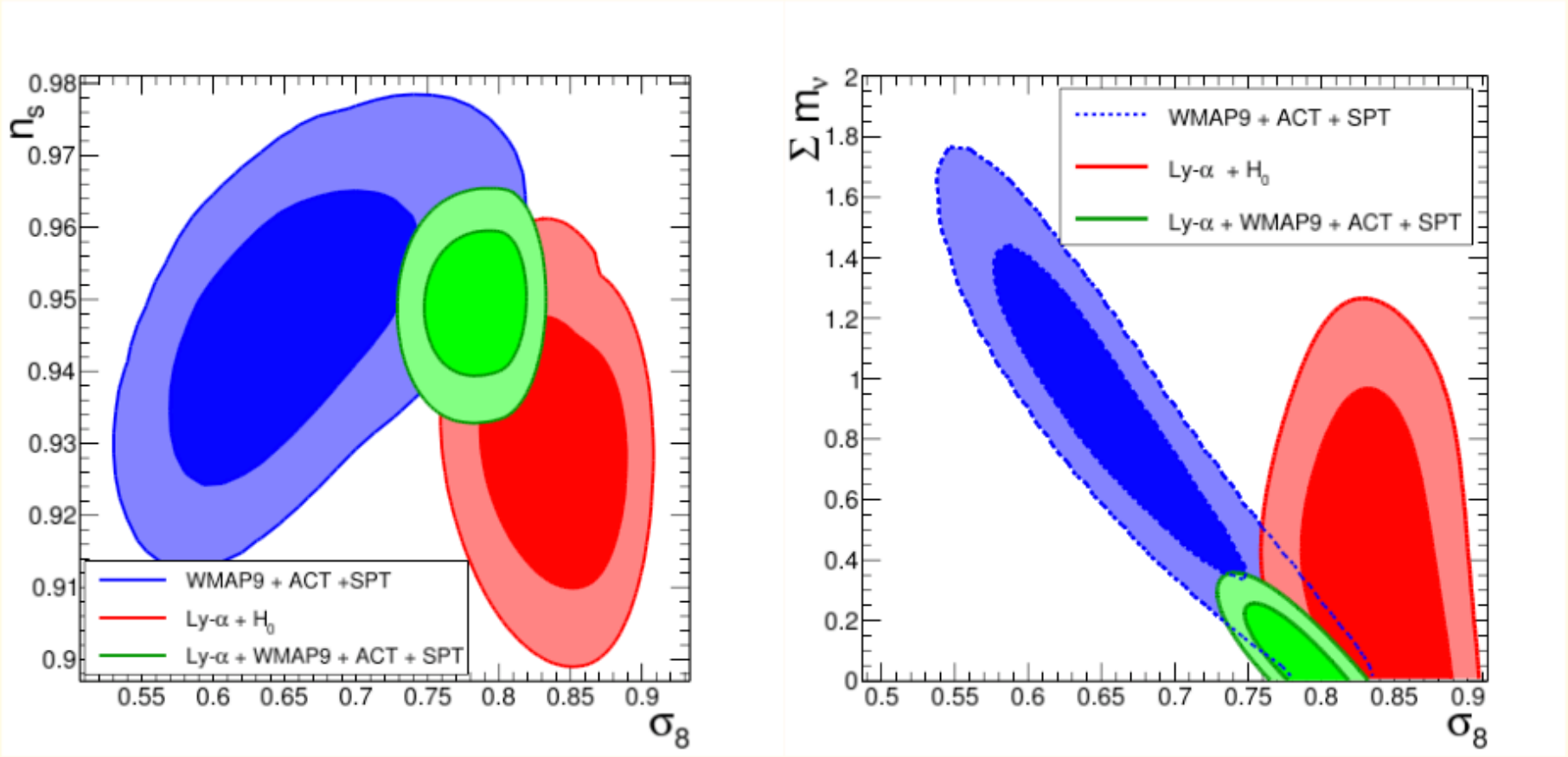




Palanque-Delabrouille et al. (2015a)

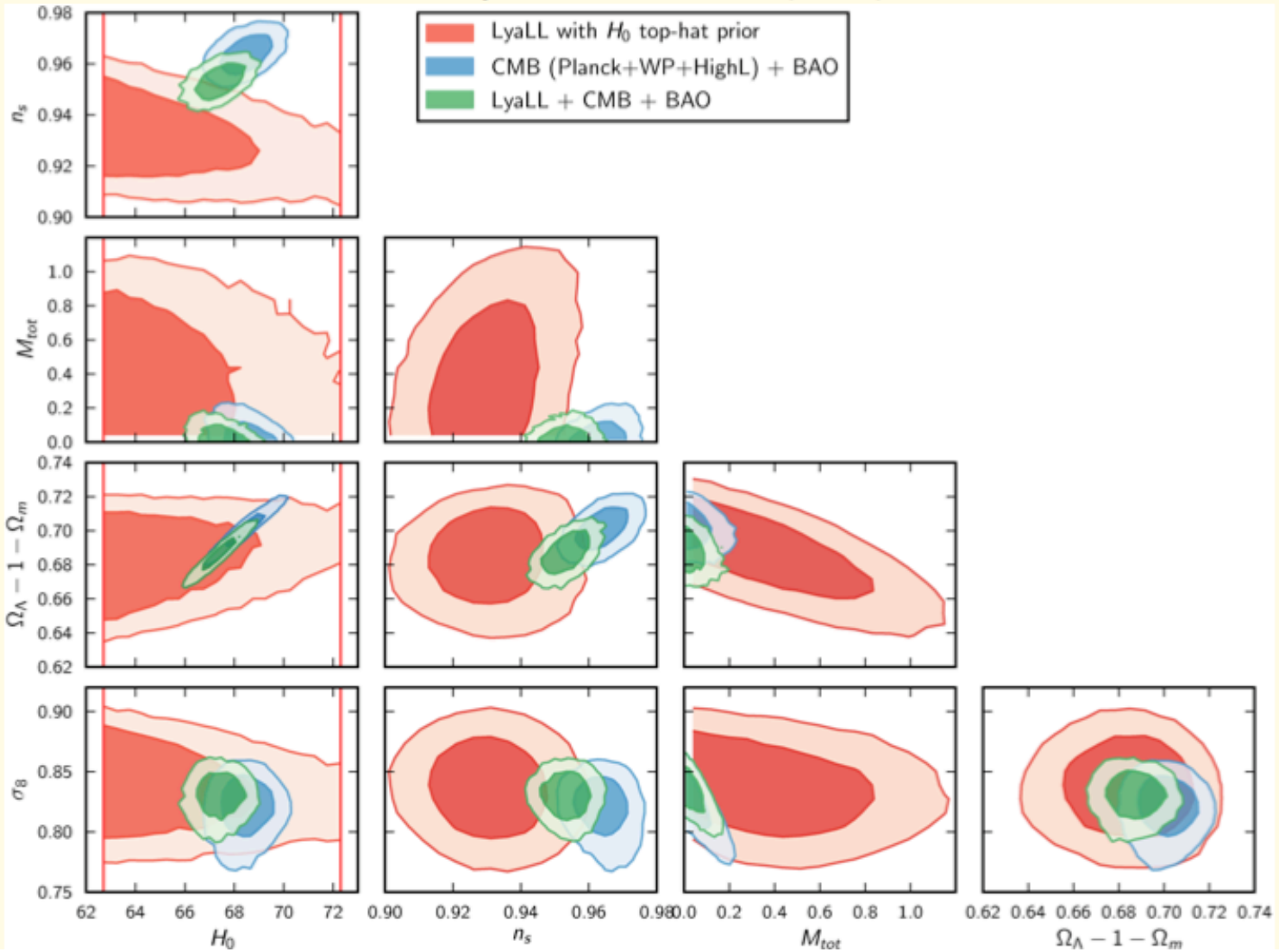
Results: Adding CMB Information

Palanque-Delabrouille et al. (2015a)



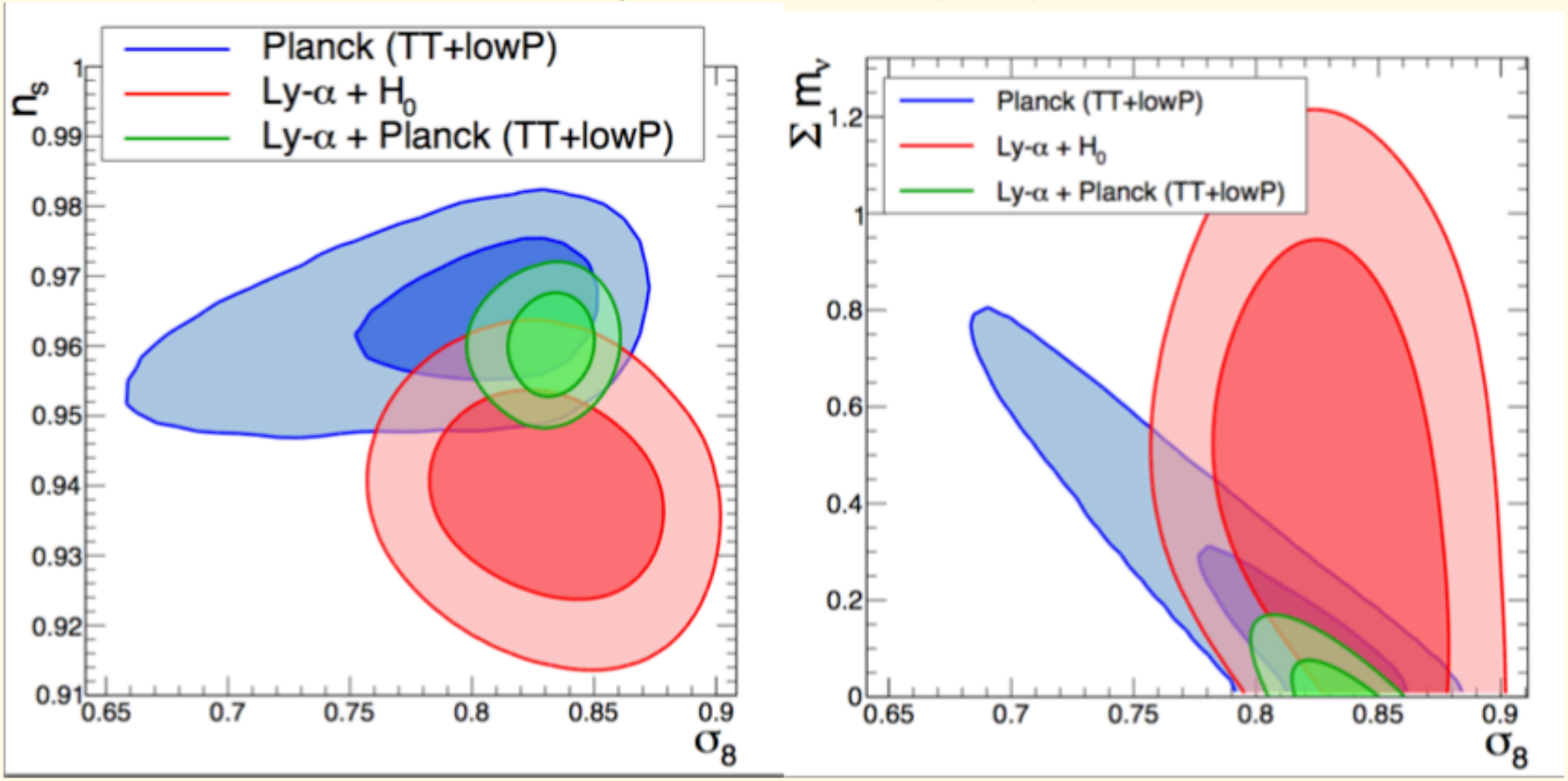
$\sum m_\nu < 0.14$ eV $\rightarrow$ CMB + Lyman-α + BAO

Results: Adding CMB Information



Improving Neutrino Constraints

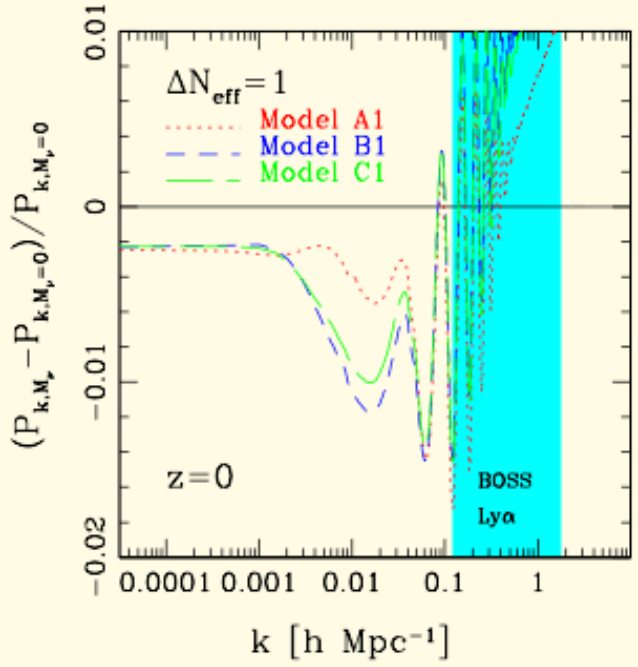
Palanque-Delabrouille et al. (2015b)

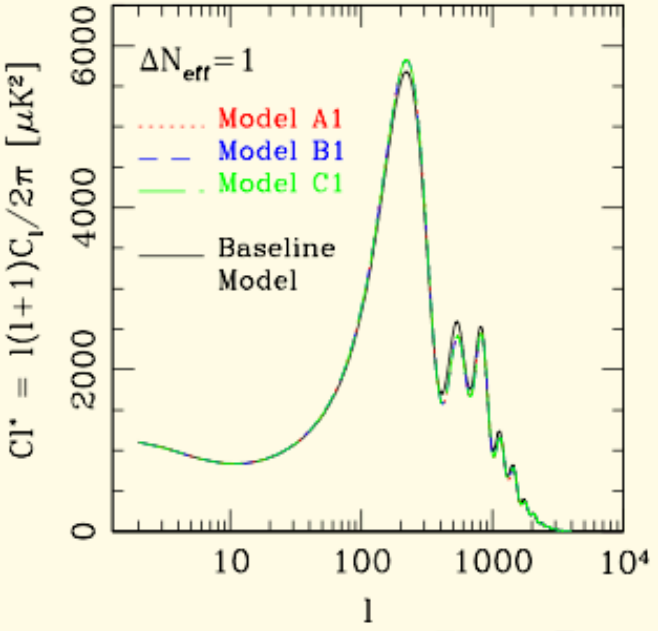


$\sum m_\nu < 0.12$ eV $\rightarrow$ CMB + Lyman-α + BAO

Number of Effective Neutrino Species?

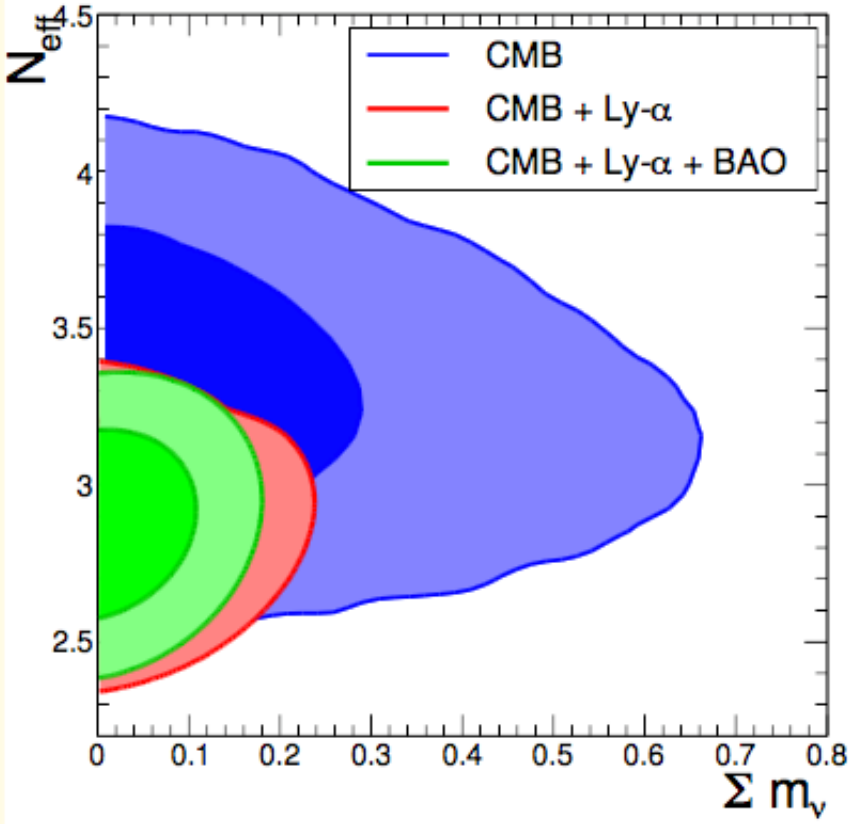
- Technique of Palanque-Delabrouille et al. (2015) extended with analytic proxy for dark radiation models in Lyα likelihood
- **Trick** $\rightarrow$ *If two models have same linear matter PS* $\rightarrow$ *nearly identical NL matter and flux PS*
- Simulations with non-standard $N_{\rm eff}$ to confirm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

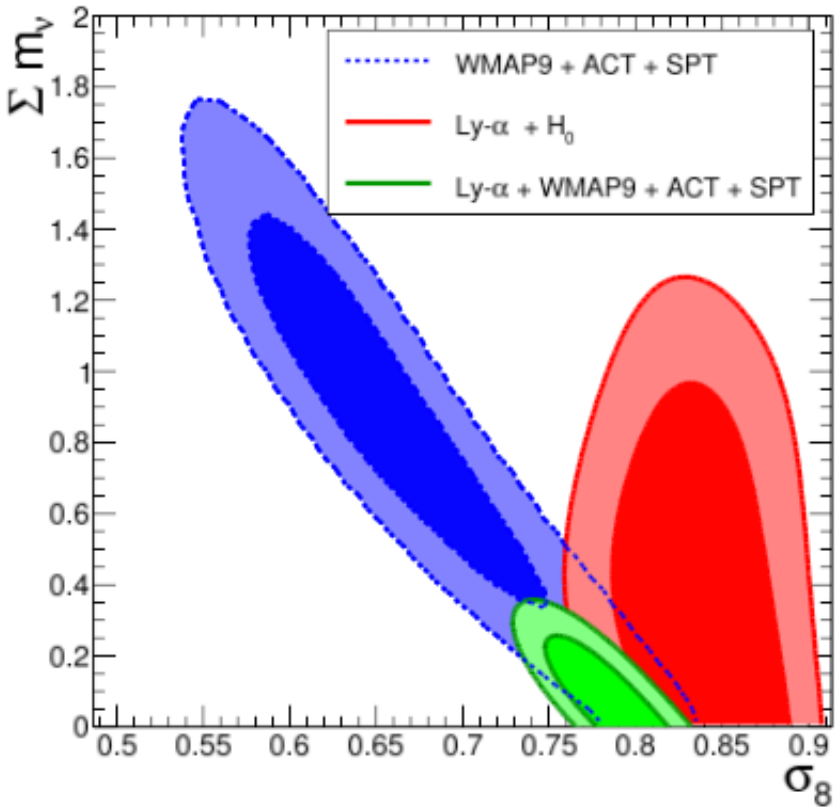




Rossi et al. (2015)

Joint Constraints





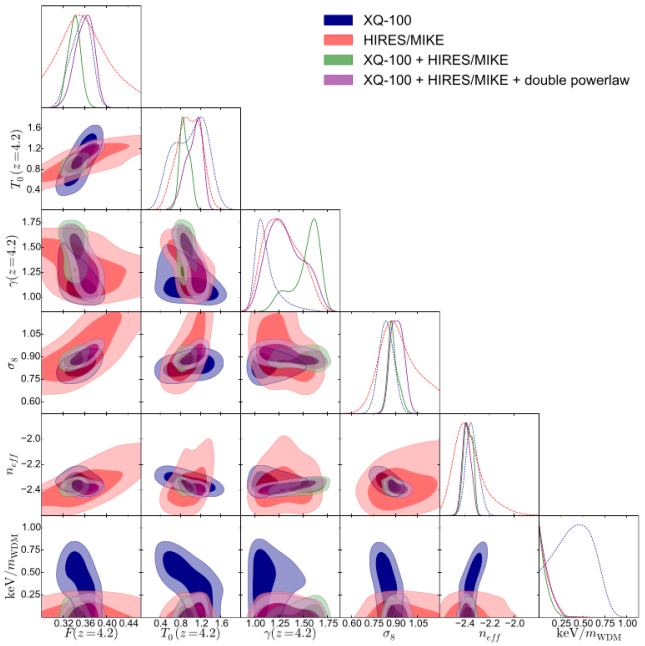
Rossi et al. (2015)

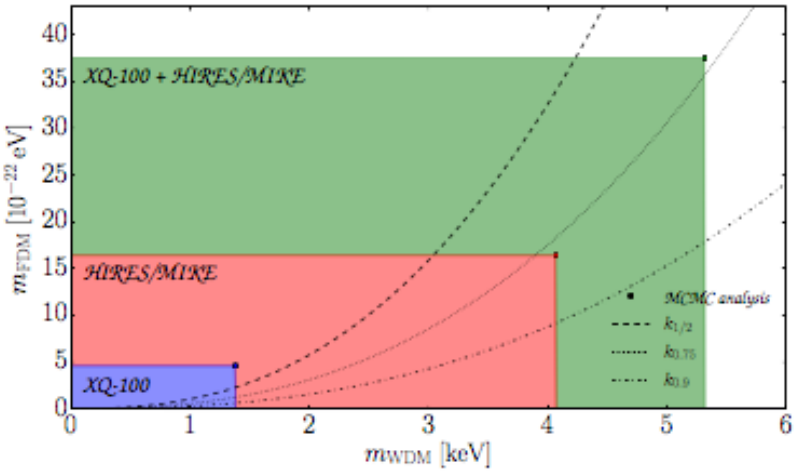
- $N_{\rm eff} = 2.91^{+0.21}_{-0.22}$ and $\sum m_\nu < 0.15$ eV (all at 95% CL) → CMB + Lyman-α

Neutrinos & Dark Radiation: Latest Developments

Extensions

- **XQ-100 Legacy Survey (LyA power spectrum)** → Irsic et al. (2017a)
- **Fuzzy dark matter from LyA forest** → Irsic et al. (2017b)
- **Warm dark matter from LyA forest** → Irsic et al. (2017c)
- **Non-cold dark matter at small scales** → Murgia et al. (2017)
- **Non-thermal dark matter** → Baur et al. (2017)
- **Bosonic dark matter from LyA forest** → Armengaud et al. (2017)

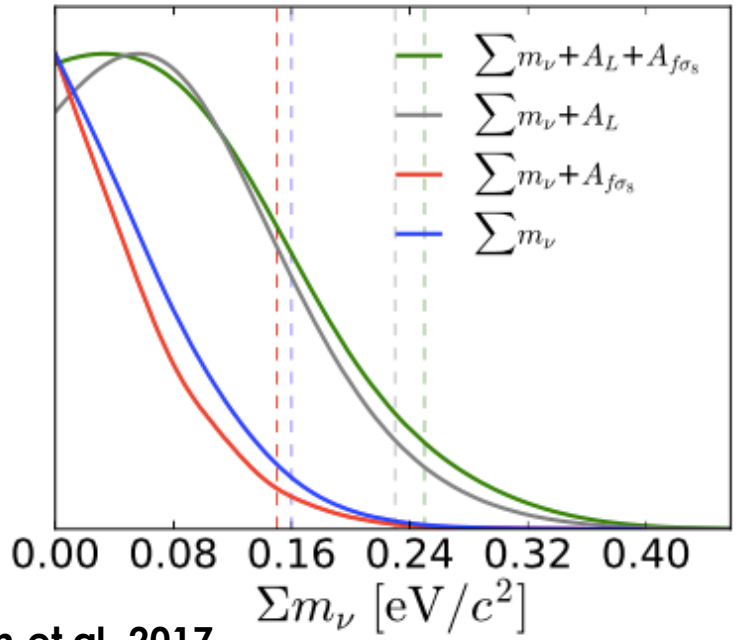




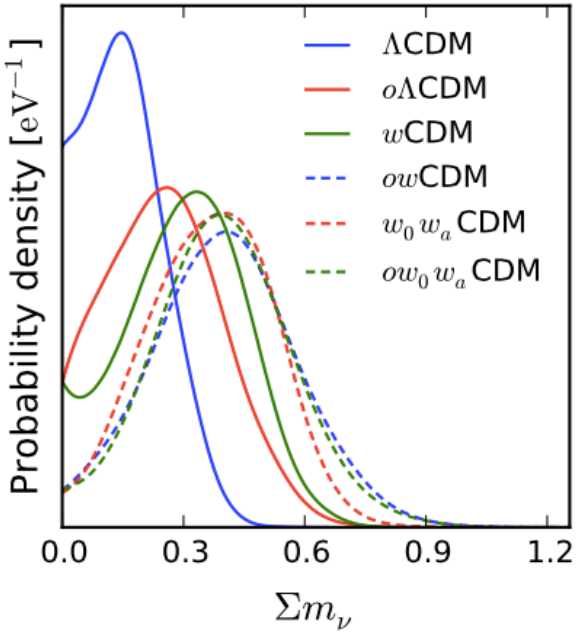
Irsic et al. (2017b,c)

Other Techniques

- **SDSS DR12 GC (Alam et al. 2017)** → $M_\nu < 0.16$ eV at 95% CL
- **Pellejero-Ibanez et al. (2017)** → $M_\nu < 0.22$ eV at 95% CL double-probe
- **Cuesta et al. (2016)** → $M_\nu < 0.13$ eV at 95% CL
- **Simpson et al. (2017)** → Strong Bayesian evidence for normal hierarchy



Alam et al. 2017



Pellejero-Ibanez et al. (2017)

Summary & Future Challenges

Main Results: Summary

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

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

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

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

1. Results on $\sum m_\nu$ tend to favor the *normal hierarchy scenario* for the masses of the active neutrino species $\rightarrow$ one of the strongest upper bounds to date

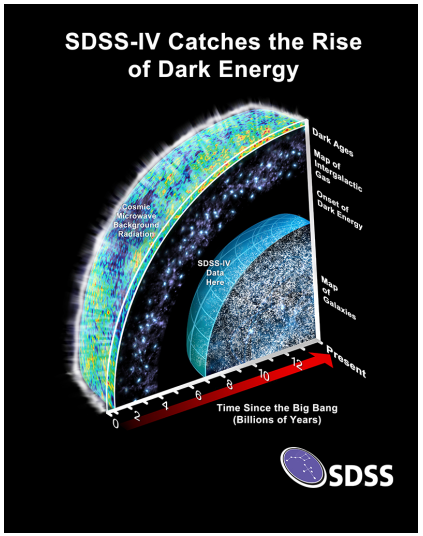
2. *Sterile neutrino* thermalized with active neutrinos *ruled out* at more than 5σ and $N_{\rm eff} = 0$ rejected at more than $14\sigma \rightarrow$ most robust evidence for the CNB from $N_{\rm eff} \sim 3$

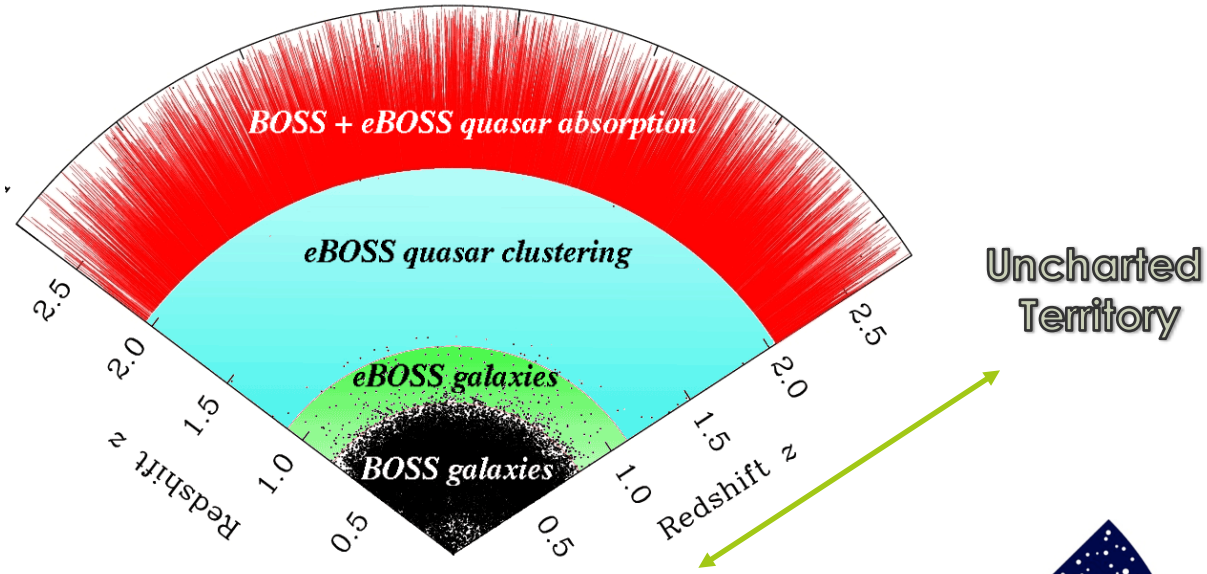
SDSS-IV eBOSS

eBOSS will precisely measure the expansion history of the Universe throughout 80% of cosmic history, back to when the Universe was less than 3 billion years old, and improve constraints on the nature of dark energy

eBOSS concentrates its efforts on the observation of galaxies and in particular quasars, **in a range of redshifts currently left completely unexplored by other 3D maps of large-scale structure in the Universe**

In filling this gap, **eBOSS will create the largest volume survey of the Universe to date.**





eBOSS

eBOSS Forecasts: Examples

Table 9
Basic Parameters Expected for Each EBOSS Sample, Together with Predictions for the Effective Volumes and Fractional Constraints on BAO Distance Measurements and Growth of Structure

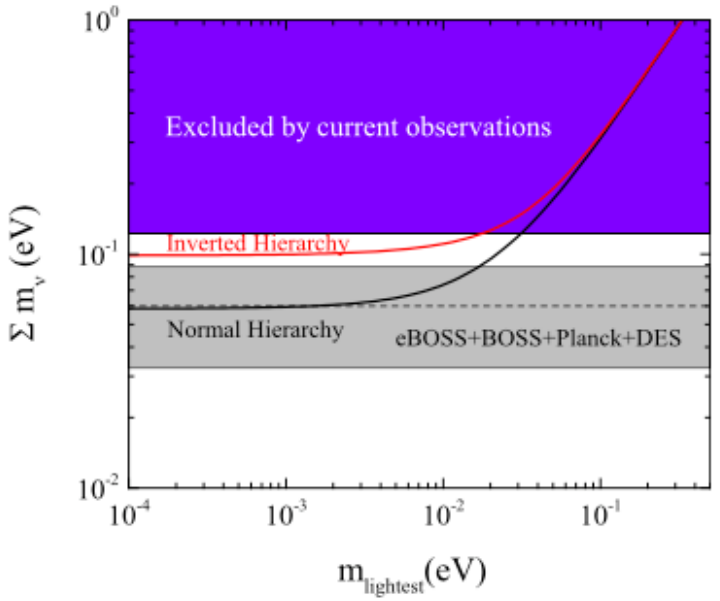
Sample	Epoch	Area ($\deg^{-2}$)	σ_H/H	σ_{D_A}/D_A	σ_R/R	$\sigma_{f\sigma_8}/f\sigma_8$
LRG	year 2	2790	0.032	0.017	0.012	0.040
	year 4	4185	0.026	0.015	0.010	0.034
	year 6	6975	0.021	0.012	0.008	0.026
ELG (High Density DECam)	year 4	1100	0.047	0.031	0.020	0.038
Quasar	year 2	3000	0.066	0.043	0.028	0.050
	year 4	4500	0.054	0.036	0.023	0.041
	year 6	7500	0.042	0.028	0.018	0.032
BOSS Lyα Quasars	...	10,400	0.02	0.025	...	...
BOSS + eBOSS Lyα Quasars	year 2	3000	0.017	0.021	...	...
	year 4	4500	0.016	0.020	...	...
	year 6	7500	0.014	0.017	...	...

Zhao et al. (2016)
Dawson et al. (2016)
Blanton et al. (2017)

Table 10
Predicted Precision From the Combination of CMB and Large-scale Structure Measurements

Parameter	Constraint From CMB	Constraint From BOSS and CMB	Constraint From BOSS, eBOSS, and CMB
$\Omega_M h^2$	0.008	0.0028	0.0017
w_0	0.52	0.17	0.15
w_a	1.4	0.67	0.48
γ	30.0	0.13	0.10
$\sum m_\nu$	0.81 eV	0.29 eV	0.16 eV
n_s	0.0045	0.0026	0.0022

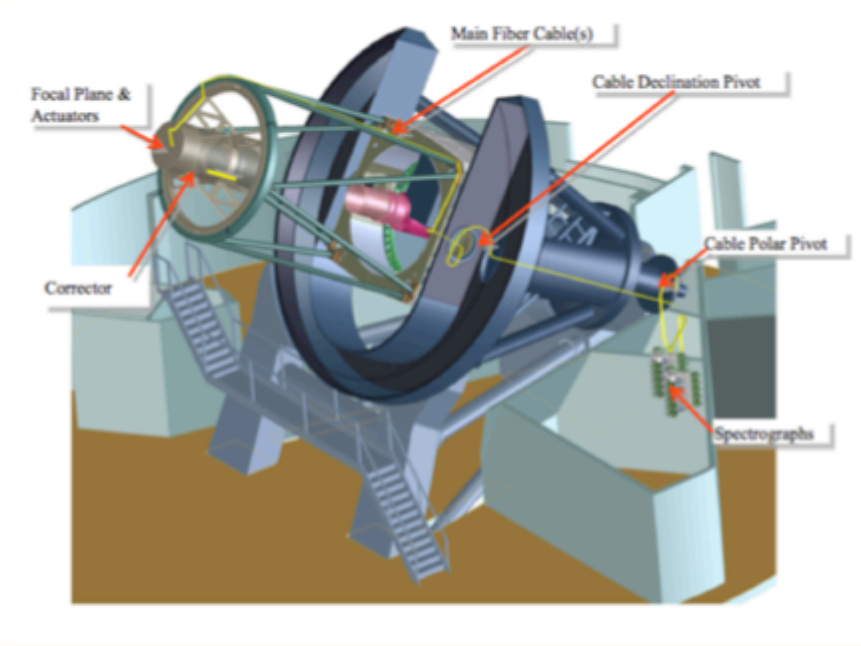
Note. All values correspond to the estimated $1-\sigma$ uncertainties.



New Windows into the Universe: DESI

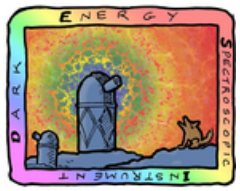
DESI

- Dark Energy Spectroscopic Instrument
- Massively multiplexed fiber-fed spectrograph
- On the Mayall telescope, USA
- Spectra and redshifts for 18 million ELGs, 4 million LRGs, 3 million QSOs
- Probes the effects of dark energy on the expansion history
- Targets: BAO, RSD, neutrino masses, modified gravity, inflation
- 1% level measurements of the distance scale in 35 redshift bins

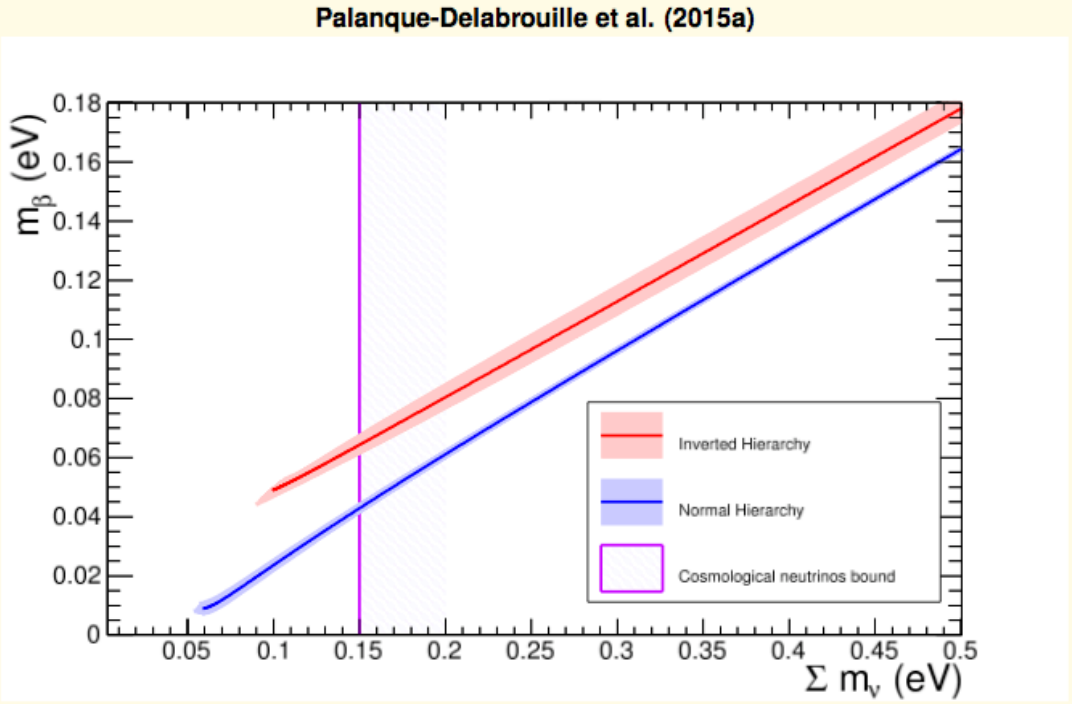


DESI, a world-leading experiment, will make the next major science advance in 2018–2022

DESI will measure the sum of neutrino masses with an uncertainty of 0.020 eV for $k_{max} < 0.2h\ Mpc^{-1}$ (Aghamousa et al. 2016a), sufficient to make the first direct detection of the summed neutrino mass at 3 sigma level



Particle Physics Implications



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

`Neutrino physics is largely an art of learning a great deal by observing nothing'

- Haim Harari