# *Neutrino and Dark Radiation Bounds from Cosmology*

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*7th KIAS Workshop on Cosmology and Structure Formation*

*KIAS, Seoul, November 3, 2016*

# Major Results

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

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

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

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

**Bounds on pure Dark Matter particles (95% CL)**

$\mathbf{m_X} \gtrsim 4.35\ \mathrm{keV}$ & $\mathbf{m_s} \gtrsim 31.7\ \mathrm{keV}$

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

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

# Outline

1. **Introduction**
    - Neutrino Science
2. **Cosmology with Massive Neutrinos**
    - Simulations and Datasets
    - Neutrino Mass Constraints
    - Dark Radiation Constraints
3. **Synergies & Prospects**
    - Synergies with Particle Physics
    - Future Prospects

**MAIN REFERENCES**


- Baur et al. (2016), JCAP, 8, 012
- Rossi et al. (2015), PRD, 92, 063505
- Palanque-Delabrouille et al. (2015a), JCAP, 11, 011
- Palanque-Delabrouille et al. (2015b), JCAP, 2, 045
- Rossi et al. (2014), A&A, 567, A79

# NEUTRINOS: FORMALISM

- $\nu_\alpha$ $(\alpha = e, \mu, \tau) \rightarrow$ neutrino flavor eigenstates
- $\nu_{\rm i}$ $({\rm i} = 1, 2, 3) \rightarrow$ neutrino mass eigenstates
- $m_{\rm i}$ $({\rm i} = 1, 2, 3) \rightarrow$ 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 $\rightarrow$

$$|\nu_\alpha >= \sum_{\rm i} U_{\alpha {\rm i}} \, |\nu_{\rm i} >$$

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

# 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

# Absolute Neutrino Mass

## Probing the neutrino mass scale

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

1. **Direct $\beta$ decay** $\rightarrow$ squared effective electron neutrino mass

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

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

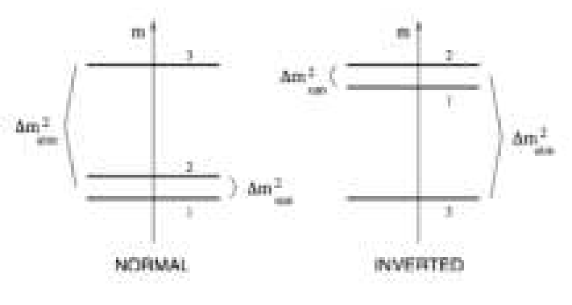
$$m_{\beta\beta} = |\sum_{\mathrm{i}} U_{\mathrm{ei}}^2 m_{\mathrm{i}}|, \quad \Phi_2 = \alpha_1, \Phi_3 = \alpha_2 - 2\delta$$

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

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

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

- Neutrino mass hierarchy?




## CNB, $N_{\rm eff}$, STERILE $\nu$

- 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 ($N_{\rm eff}$)?

# Effects of neutrino masses on cosmology

## Cosmological effects

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

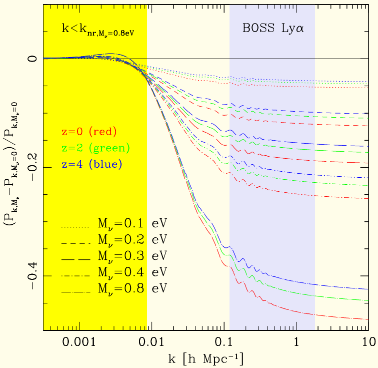
## Neutrino free-streaming

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

## Observables and Techniques

- CMB anisotropies $\rightarrow$ PS, lensing
- LSS probes
  - Galaxy PS
  - Cluster mass function
  - Galaxy weak lensing
  - **Ly-$\alpha$ 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

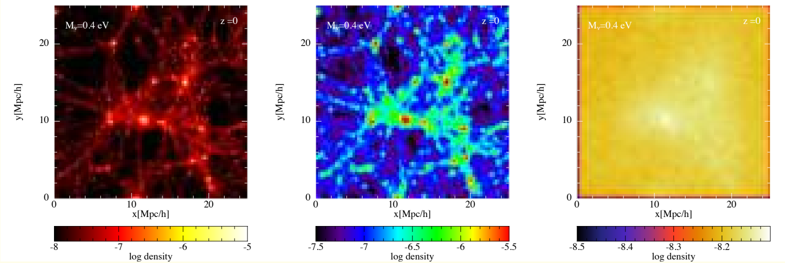
$\Downarrow$

Cosmological parameters, Neutrino mass, $N_{\rm eff}$

# 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$/3072^3$
- 2 groups. Full snapshots at a given redshift ($z = 4.6 - 2.2$, $\Delta z = 0.2$)
- 100,000 quasar sightlines per redshift interval per simulation



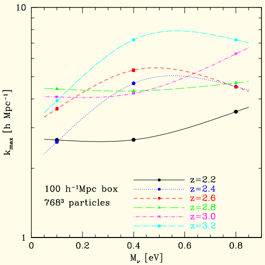

**Rossi et al. (2014)**

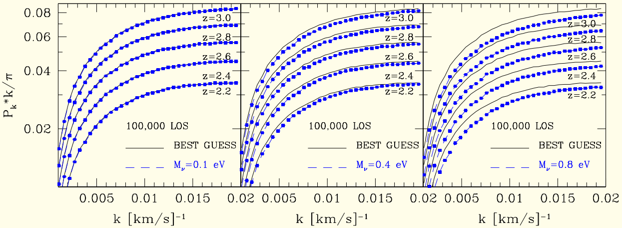
# POWER SPECTRUM STATISTICS

**Rossi et al. (2014, 2015), Rossi (2015)**

## RELEVANT SCALES FOR $\nu$

1. Scales where PS suppression is maximized (BOSS Ly$\alpha$) $\uparrow$
2. Scales where PS suppression is maximized (general) $\rightarrow$



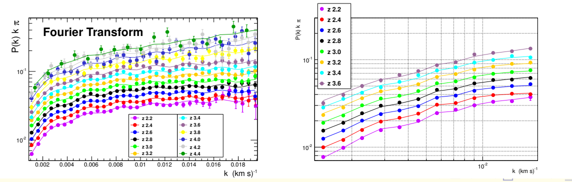
# LY$\alpha$ LIKELIHOOD CONSTRUCTION

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

# DATASETS

- 1D Ly$\alpha$ 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-$\ell$)
- Planck (2015) temperature data from January 2015 public release (TT+TE+EE+lowP)
- High-$\ell$ public likelihoods from the Atacama Cosmology Telescope (ACT) and South Pole Telescope (SPT)
- Some low-$\ell$ WMAP polarization data

**Palanque-Delabrouille et al. (2013)**



# Analysis Techniques

## Analysis Strategies

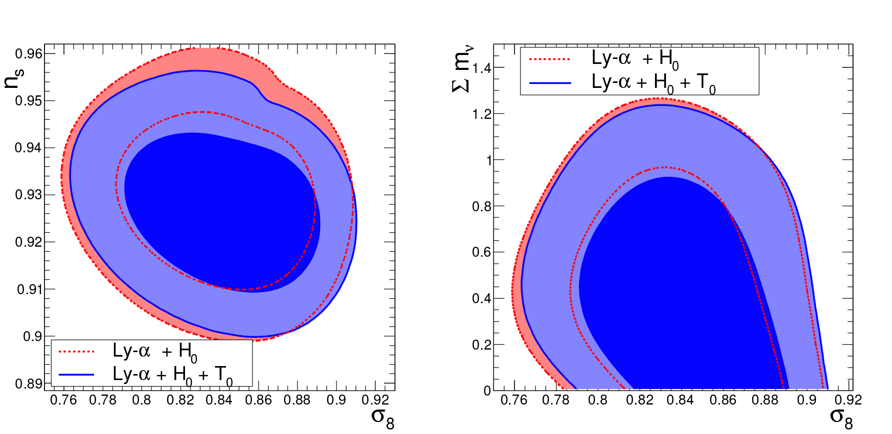
- Bayesian Approach
- Frequentist Approach

## 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 $\chi_0^2$, leaving all the $N$ cosmological parameters free
- Set confidence levels (CL) on a chosen parameter $\alpha_{\rm i}$ by performing the minimization for a series of fixed values of $\alpha_{\rm i}$ – thus with $N - 1$ degrees of freedom
- Difference between $\chi_0^2$ and the new minimum allows us to compute the CL on $\alpha_{\rm i}$

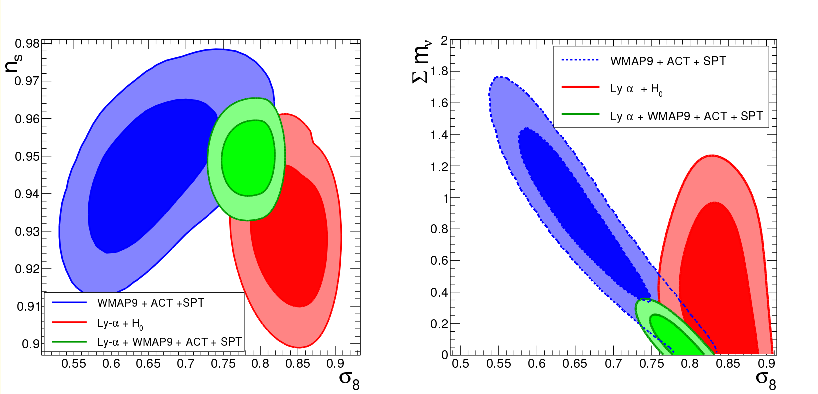
# BOSS APPLICATIONS → LYA ALONE

Palanque-Delabrouille et al. (2015a)



# BOSS APPLICATIONS → COMBINATIONS

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

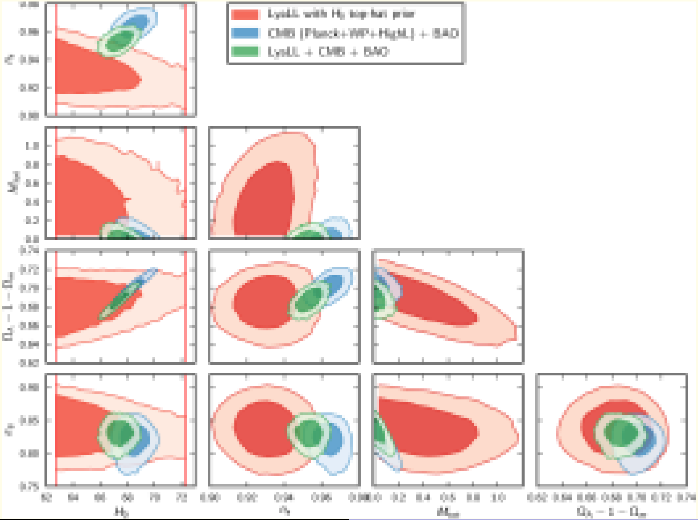



Key is orthogonality of LyA forest with other LSS probes

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

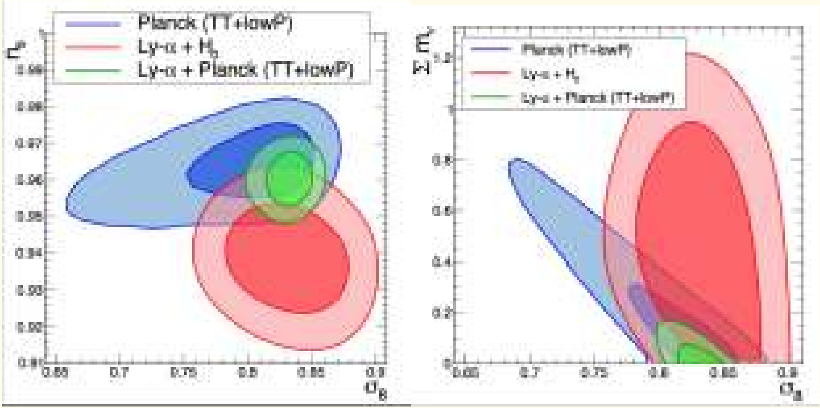
# COMBINATIONS WITH BAYESIAN TECHNIQUES

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



# THE POWER OF COMBINING PROBES

**Palanque-Delabrouille et al. (2015b)**

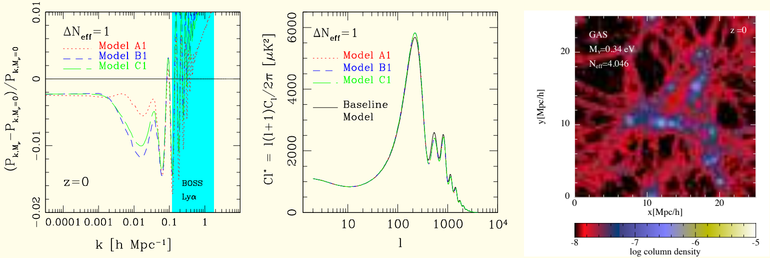



$\sum m_\nu < 0.12$ eV $\rightarrow$ CMB + Lyman-$\alpha$ + BAO

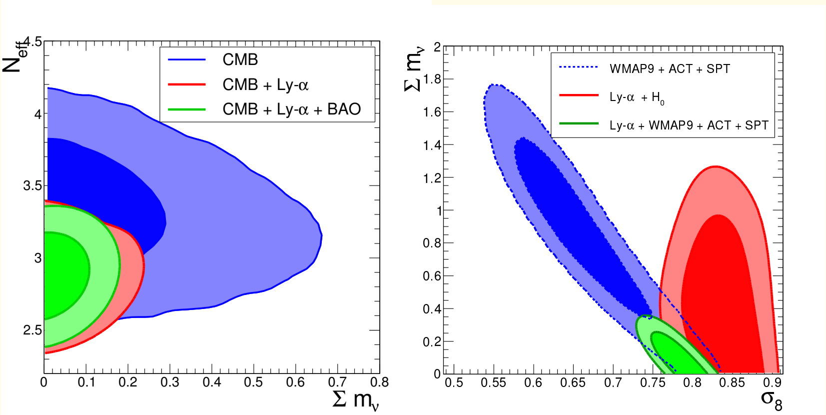
# Trick → Analytic Proxy for Ly$\alpha$ Likelihood

- Technique of Palanque-Delabrouille et al. (2015) extended with analytic proxy for dark radiation models in Ly$\alpha$ 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

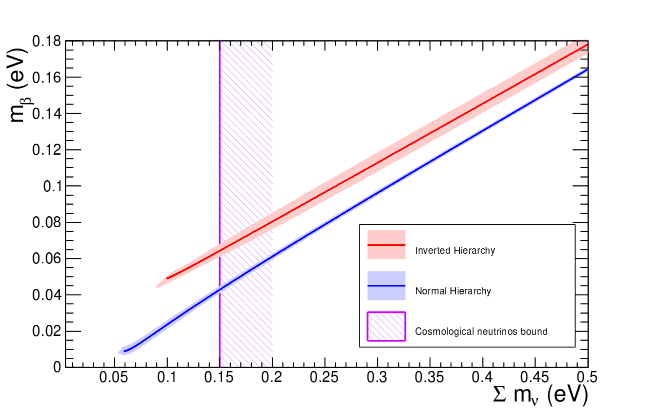



**Rossi et al. (2015)**

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

# 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!

# MORE IMPLICATIONS

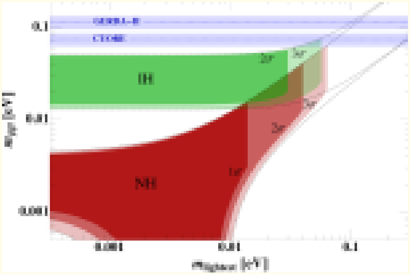
- Potential relevance of our neutrino bounds on neutrinoless double beta decay (see *Dell'Oro et al. 2015*)
- Crucial impact, because the possibility of detecting a signal will be out of the reach of the next generation of experiments

**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)**

# SDSS DR12 & NEUTRINOS

## SDSS DR12 'Consensus Paper'

- **Alam et al. (2016)** $\rightarrow \sum m_\nu \leq 0.16$ eV (95%)

## SDSS DR12 'Supporting Papers'

- **Pellejero-Ibanez et al. (2016)** $\rightarrow \sum m_\nu \leq 0.22$ eV (95%) with 'double-probe' method

## Future Constraints

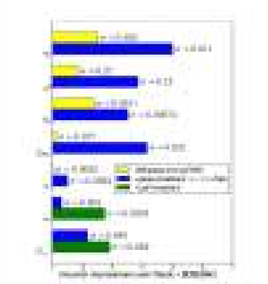
- **eBOSS** $\rightarrow$ **Zhao et al. (2016)** forecasts $\rightarrow \sigma(\sum m_\nu) = 0.03$ eV (68%) with combination of probes

# FUTURE SURVEYS: DESI

**DESI Collaboration I (arXiv:1611.00036)**

## 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



| Data | $\sigma_{\Sigma m_\nu}$ [eV] | $\sigma_{N_{eff}}$ |
|---|---|---|
| Planck | 0.56 | 0.19 |
| Planck + BAO | 0.087 | 0.18 |
| Gal ($k_{max} = 0.1h$ Mpc$^{-1}$) | 0.030 | 0.13 |
| Gal ($k_{max} = 0.2h$ Mpc$^{-1}$) | 0.021 | 0.083 |
| Ly-$\alpha$ forest | 0.041 | 0.11 |
| Ly-$\alpha$ forest + Gal ($k_{max} = 0.2$) | 0.020 | 0.062 |

DESI will measure the sum of neutrino masses with an uncertainty of 0.020 eV (for $k_{\rm max} < 0.2$ h Mpc$^{-1}$), sufficient to make the first direct detection of the sum of the neutrino masses at $3\sigma$ significance and rule out the the inverted mass hierarchy at 99% CL, if the hierarchy is normal and the masses are minimal