# Tension between the power spectrum of density perturbation measured on large and small scales.

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in collaboration with Adam Moss[1] and Richard Battye[2]

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# Content

# Section 1

# Parameterisation of ΛCDM

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## Successes

- Baryonic Acoustic Oscillations
- Polarisation of CMB
- Weak Gravitational Lensing

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## Problems

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## Parameterisation

$$\mathbf{p} = \{\Omega_b h^2, \Omega_c h^2, \Theta_{MC}, A_S, n_S\}$$

# Section 2

# Data Sets

# CMB and LSS data sets

## CMB

- *Planck* with WMAP Polarisation data
- WMAP with high-$\ell$ data from SPT and ACT
- Combined with BAO data from BOSS DR9, 6dF and SDSS DR7

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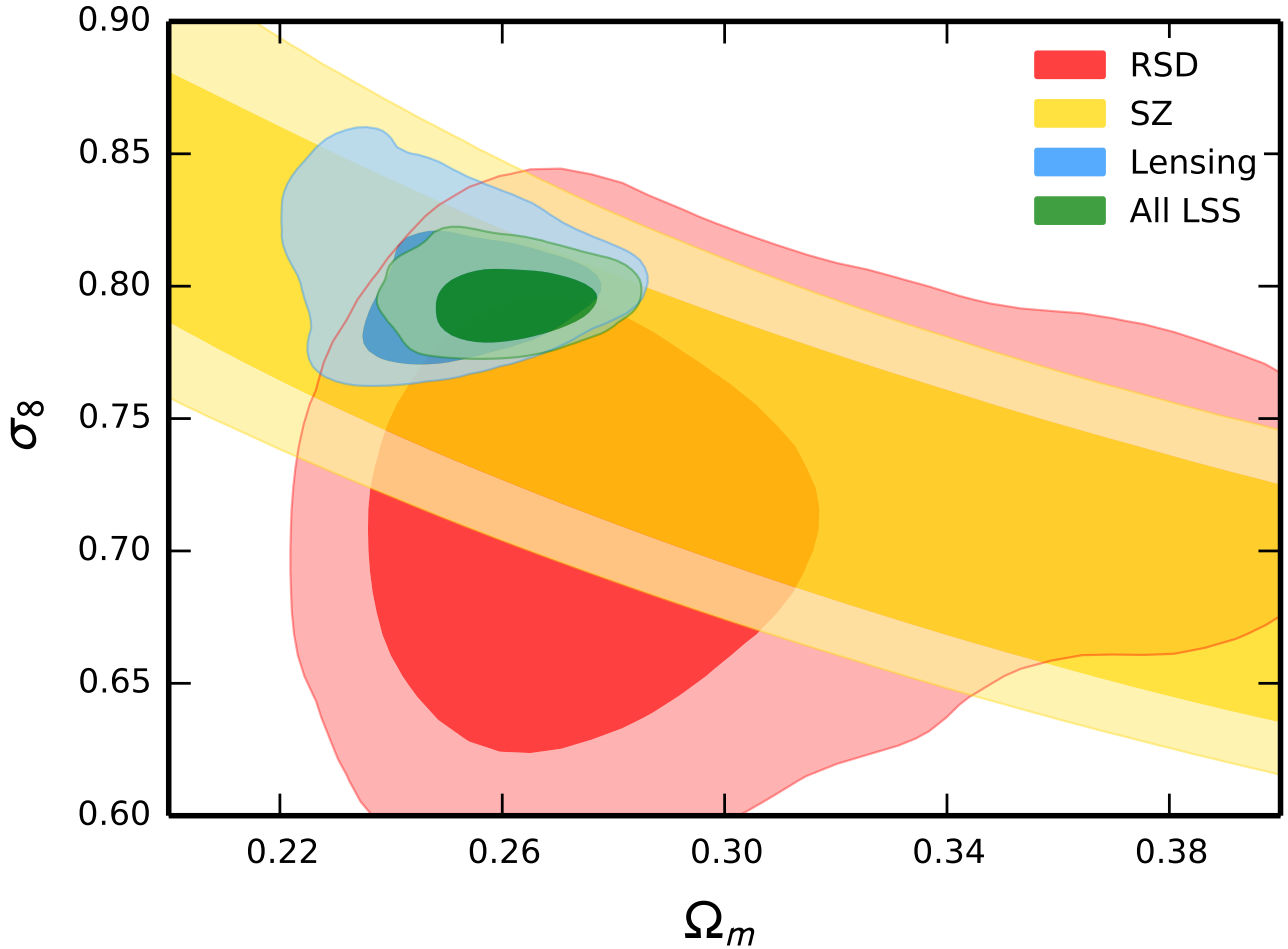
## LSS

- SZ Cluster Counts (Marginalised 1-b=[0.7,1.0])
- Weak Lensing from CFHTLenS, *Planck* and SPT
- RSD from BOSS DR11

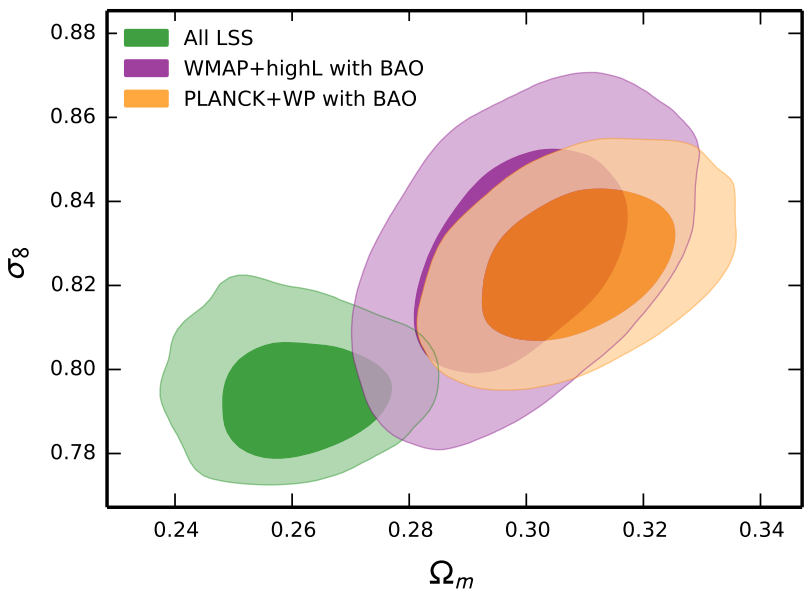
# Constrained LSS results

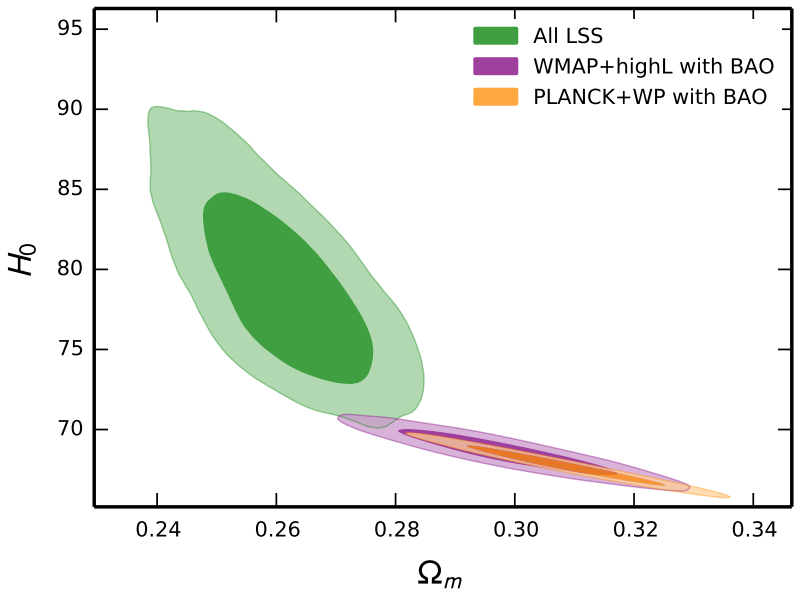


# Section 3

# Tension

# Tension between large and small scale



# Total amount of tension

## Parameter Likelihoods

- Marginalised likelihoods, $P(\mathbf{p}|d, M)$
- Integrate to find mean, $\mu_{\mathbf{p},d}$ and covariance matrix, $\Sigma_d$
- Difference in the means, $\delta\mu = \mu_{\mathbf{p},\mathrm{CMB}} - \mu_{\mathbf{p},\mathrm{LSS}}$
- Multivariate gaussian distribution
- Evaluate at $\delta\mu = 0$

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## Tension

- Exceeds $5\sigma$

# Section 4

# Neutrinos

# Neutrinos

## Active Neutrinos

- Additional parameter, $\sum m_\nu$
- Assumed mass eigenstate degeneracy

$$m_1 = m_2 = m_3 = \sum m_\nu / 3$$

- Closer last-scattering, anisotropies at larger scales

# Neutrinos

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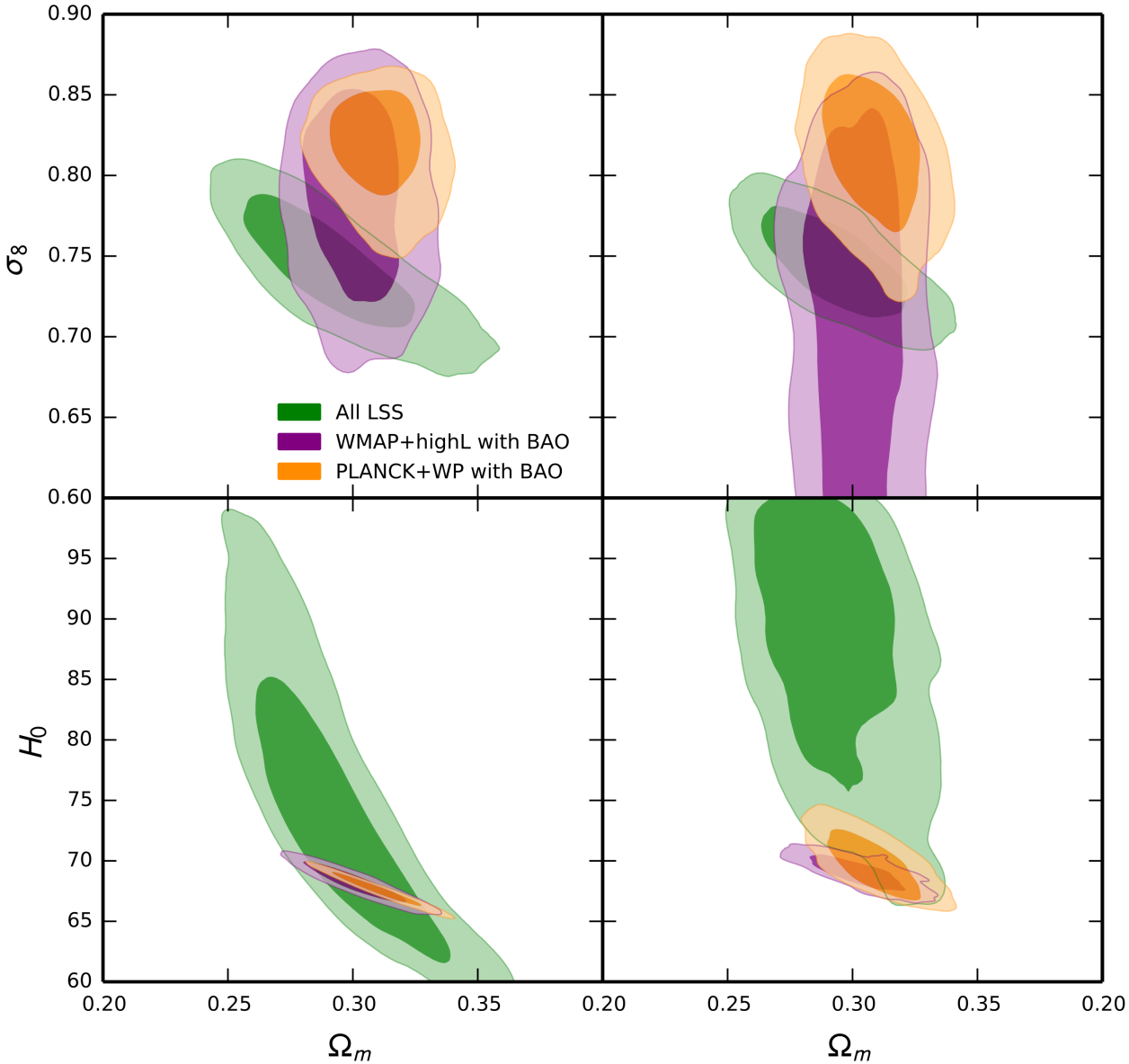
## Sterile Neutrinos

- Two additional parameters, $m^{\text{eff}}_{\text{sterile}}$ and $N_{\text{eff}} = 3.046 + \Delta N_{\text{eff}}$
- True mass depends on model
- Well motivated by short-baseline experiments

# Reduction of tension



# Neutrino Likelihoods

## Active Neutrinos

- $\sum m_\nu = 0.357 \pm 0.099\text{eV}$
- Tension in $\Lambda$CDM parameters $\sim 2.6\sigma$
- $\Delta\chi^2$ greatly reduced
- $\Delta\chi^2$ for CMB data worsened

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## Sterile Neutrinos

- $m^{\text{eff}}_{\text{sterile}} = 0.66 \pm 0.18\text{eV}$ and $\Delta N_{\text{eff}} = 0.32 \pm 0.21$
- Tension in $\Lambda$CDM parameters $\sim 2.2\sigma$
- $\Delta\chi^2$ greatly reduced
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# Section 5

# Other Models

# Ignoring WMAP Polarisation

## Measuring $\sigma_8$

- $A_S e^{-2\tau_R}$ constrained by CMB anisotropies
- $\sigma_8 \propto \sqrt{A_S}$ so $\sigma_8 \propto e^{\tau_R}$

# Ignoring WMAP Polarisation

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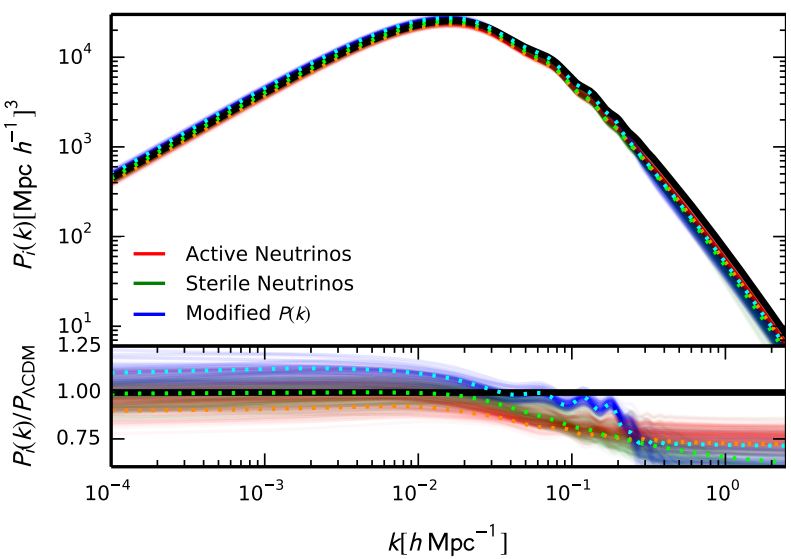
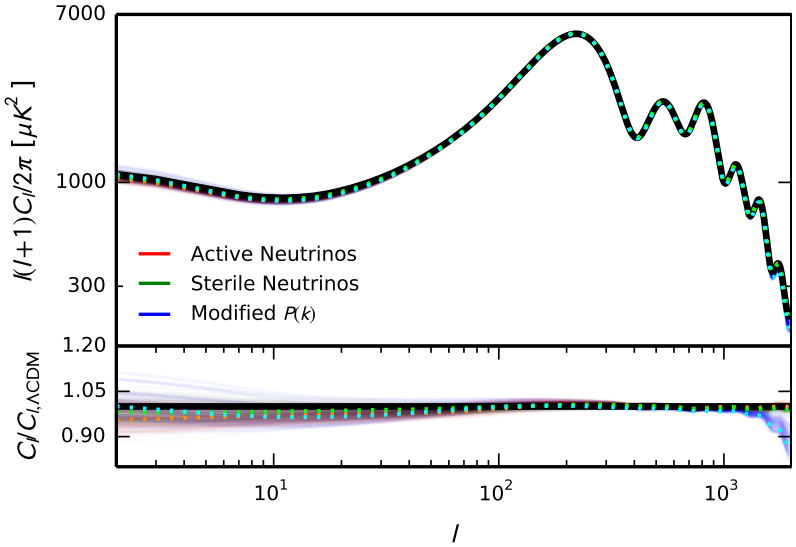
## Measuring $z_{rei}$

- $z_{rei} \sim 11.13 \pm 1.08$ inferred from polarisation measurements
- $z_{rei} \sim 6.91 \pm 2.20$ when ignoring polarisation measurements
- Astrophysical phenomena prefer low $\tau_R$

# Modified Primordial Power Spectrum



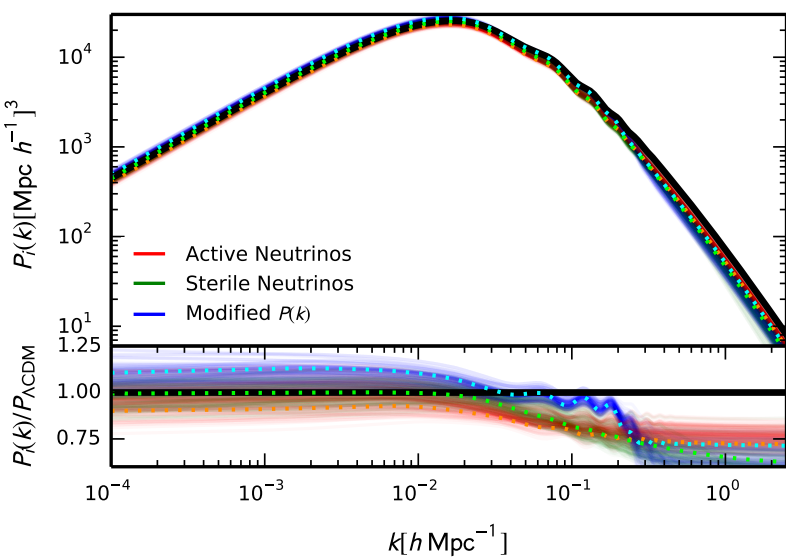



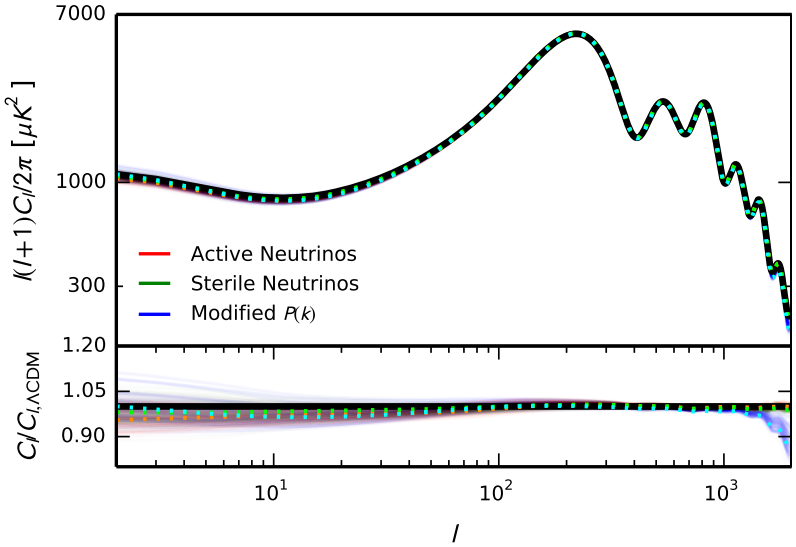

$$P(k) = \left[1 - \frac{\alpha}{2}\left(1 + \tanh\left(\frac{\log \beta k}{\log \delta}\right)\right)\right] P_{\Lambda\mathrm{CDM}}(k)$$

- $\alpha = 0.32 \pm 0.11$, $\beta = 5.96 \pm 0.70$Mpc and $\delta = 1.24 \pm 0.11$

$$(\alpha = 0.07 \pm 0.05)$$

# Modified Primordial Power Spectrum

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- $\alpha = 0.32 \pm 0.11$, $\beta = 5.96 \pm 0.70$Mpc and $\delta = 1.24 \pm 0.11$

  $(\alpha = 0.07 \pm 0.05)$
- Fits incomplete 4K line removal

# Summary

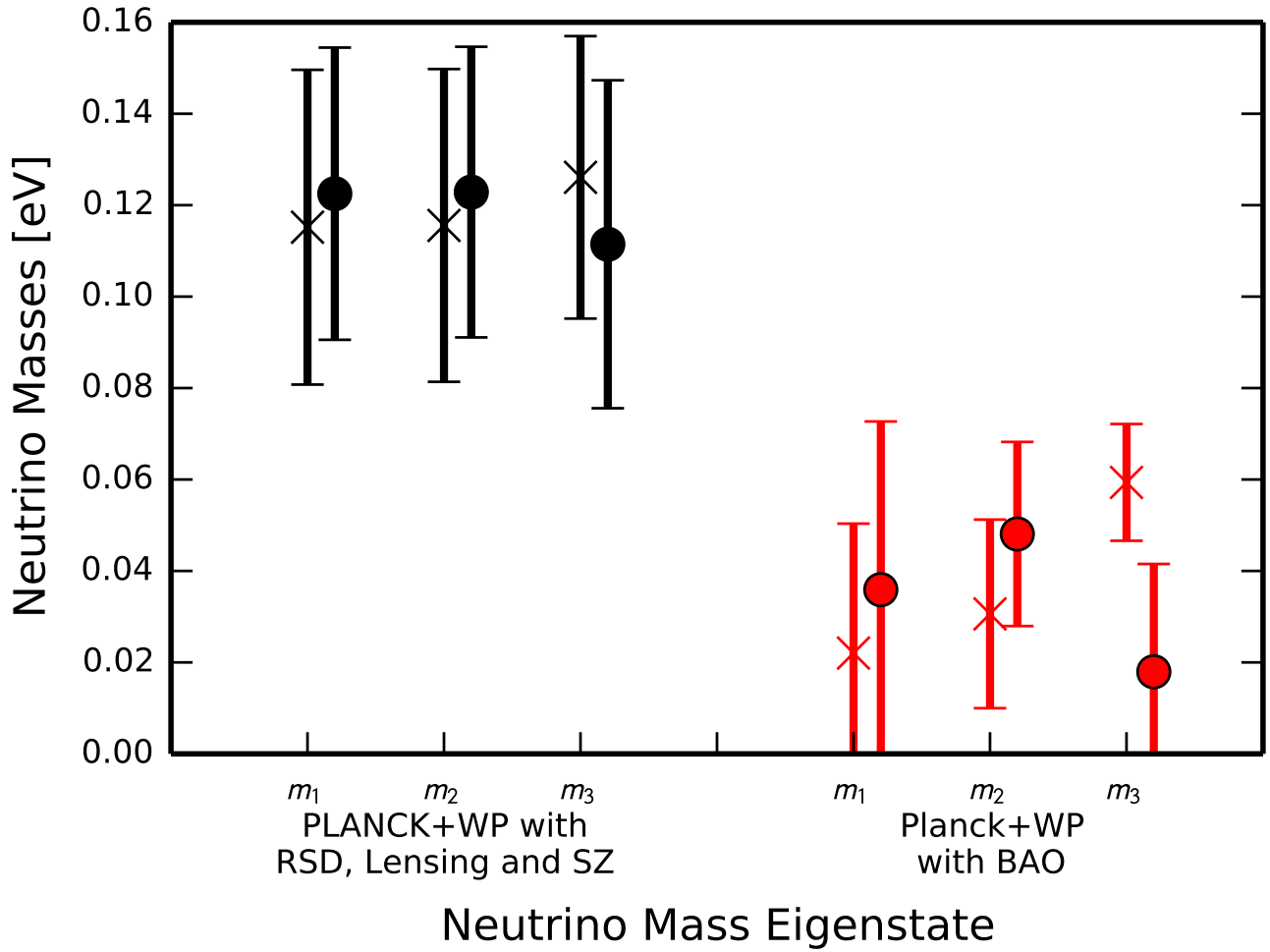
Parameterisation of ΛCDM

Data Sets

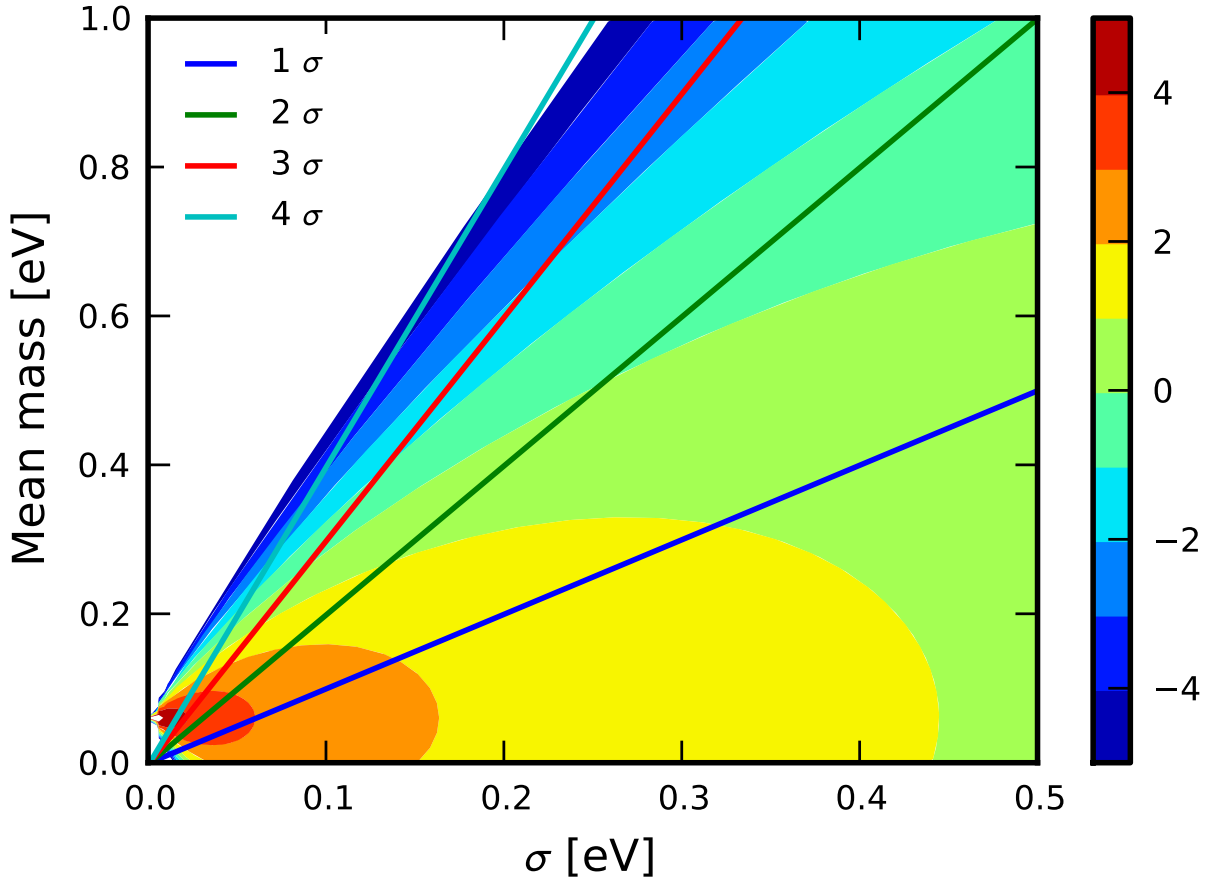
Tension

Neutrinos

Other Models


0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Neutrino Masses [eV]
$m_1$
$m_2$
$m_3$
PLANCK+WP with
RSD, Lensing and SZ
$m_1$
$m_2$
$m_3$
Planck+WP
with BAO
Neutrino Mass Eigenstate

# Bayesian Statistics




## Evidence

- $\Theta = E_2/E_1$
- $\log(\Theta_{\text{Active}}) = -1.8$ and $\log(\Theta_{\text{Sterile}}) = -2.67$