Planck results: Massless and Massive neutrinos

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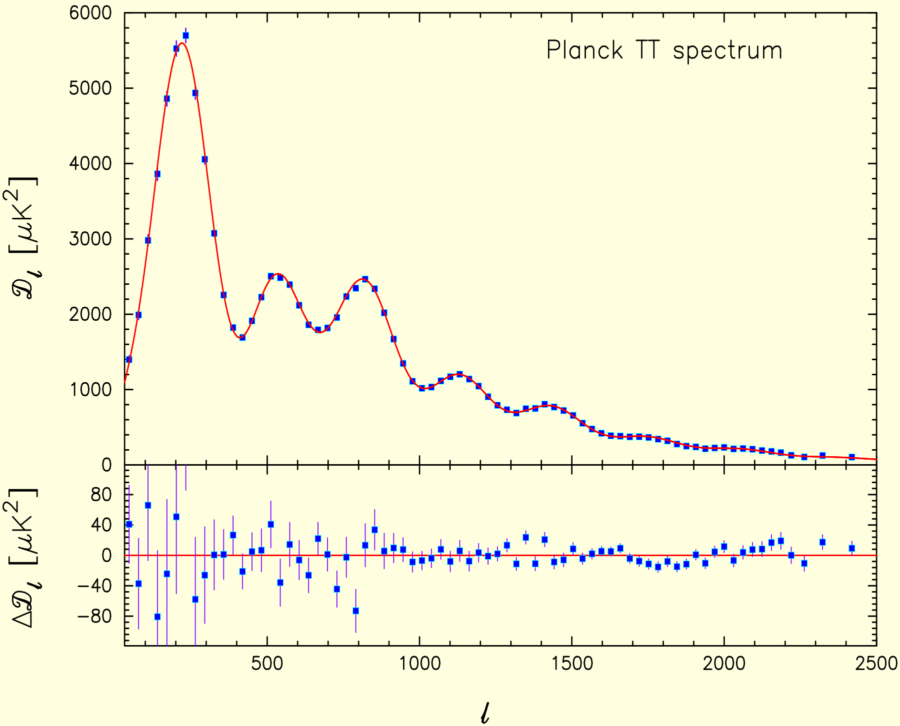
April 15, 2013

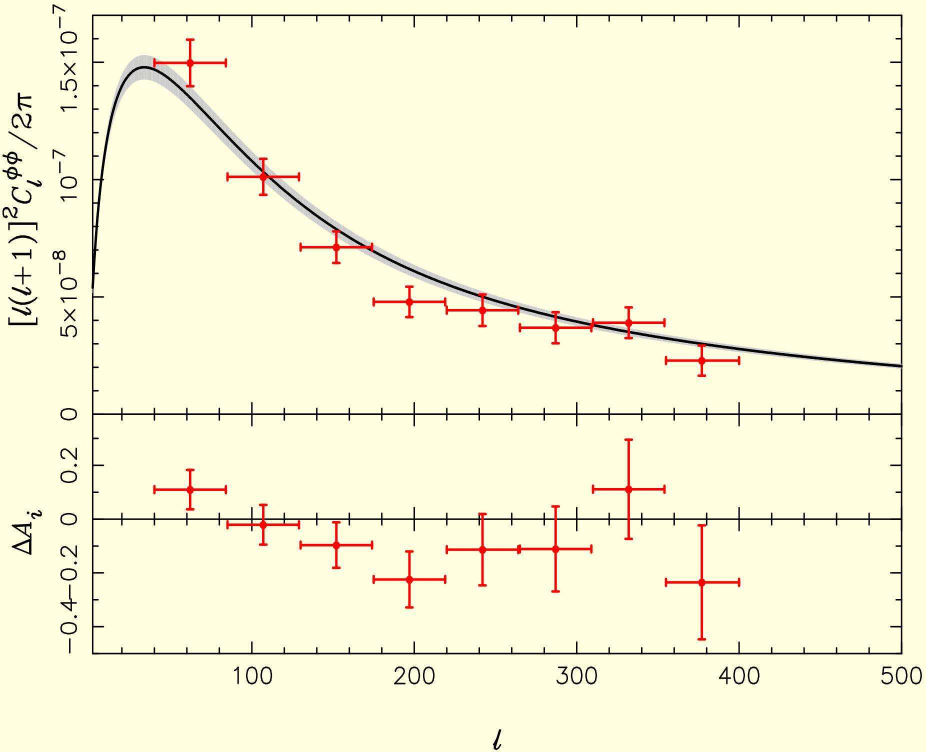
1. Planck results: Temperature power spectrum



2. Planck results: Probe of multiple eras in the universe

- **The epoch of recombination**: Located at $z \simeq 1000$, 90% of the observed CMBR photons arrive from this epoch.
- **The epoch of reionization**: Roughly 10% of CMBR photons re-scatter at $z \simeq 10$, creating secondary CMBR temperature and polarization anisotropies.
- **Gravitational Lensing of CMBR**: CMBR temperature fluctuations are lensed by the matter distribution between $z \simeq 1000$ and the present epoch (deflection angles of many arc minutes). The signal-to-noise for matter reconstruction peaks at $z \simeq 2$.

3. Gravitational Lensing of CMBR



4. Neutrinos in Cosmology

- `Neutrino Hierarchy:`

$$\Delta m^2_{12} = (7.6 \pm 0.6) 10^{-5}\,\mathrm{eV}^2 \quad (1)$$
$$\Delta m^2_{23} = \pm(2.4 \pm 0.4) 10^{-3}\,\mathrm{eV}^2 \quad (2)$$

  At least one neutrino of mass $m_\nu \simeq 0.05\,\mathrm{eV}$ exists (Normal Hierarchy) or two such neutrinos (Inverted Hierarchy).

- `Relativistic phase:`

$$\rho_\nu = N_{\mathrm{eff}} \frac{7}{8} \left(\frac{4}{11}\right)^{4/3} \rho_\gamma \quad (3)$$

  $N_{\mathrm{eff}} = 3.04$.

- `Nonrelativistic phase: Free streaming length scale:` Roughly H^{-1} at $T \simeq m_\nu$, e.g. for $m_\nu \simeq 0.2\,\mathrm{eV}$, $\mathbf{k}_{\mathrm{fs}} \simeq \mathbf{0.01}\,\mathrm{Mpc}^{-1}$

5. CMBR anisotropies: The impact of massless neutrinos

- **Background expansion and related effects**: Matter radiation equality: $z_{\rm eq} \simeq 3400$ and $z_{\rm rec} \simeq 1090$. Addition of extra radiation brings these two epochs closer and increases the expansion rate of the universe, resulting in: (a) time variation of potential (early ISW effect), (b) a small change in angular-diameter distance, (c)delay in recombination, increasing Silk damping scale

  The effect (c) dominates because its impact is exponential. Planck's unprecedented angular resolution allows its probe

- **Neutrino density fluctuations**: More important for massive neutrinos at later epochs.

6. Massive Neutrinos

- **Energy density**:

$$\Omega_\nu h^2 = \frac{\sum_i m_\nu^i}{93\,\mathrm{eV}} \tag{4}$$

  Cowsik-Mclleland bound.

- **Neutrino hierarchy**: At least one neutrino of $m_\nu \simeq 0.05$ (Normal hierarchy) or two of the same mass (inverted hierarchy). $\Omega_\nu > 0.0006$.

- **Matter power spectrum**:

$$\Delta P_m(k) \propto 7\frac{\rho_\nu}{\rho_m} \tag{5}$$

  Or the impact of massive neutrino on matter power spectrum is far more significant than naively expected.

7. Matter power spectrum

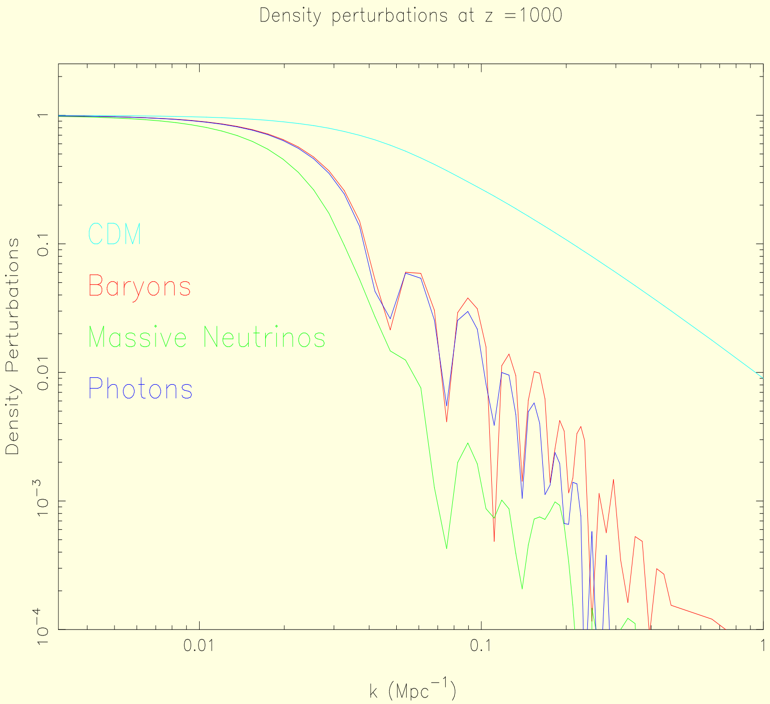
$$P(k,t) = P(k,t_i)T(k,t_i,t)$$

- $\mathbf{P(k,t_i) = Ak^n}$: initial power spectrum—generated at the time of inflation, superhorizon scales
- $\mathbf{T(k,t_i,t)}$: transfer function—growth of perturbations, sub-horizon physics
- $\mathbf{T(k,t_i,t) \equiv T(k)D_+^2(t_i,t)}$

$$\mathbf{T(k)} = \left(\frac{\sum_{\mathbf{i}} \delta_{\mathbf{i}}(\mathbf{k})\bar{\rho}_{\mathbf{i}}}{\sum_{\mathbf{i}} \bar{\rho}_{\mathbf{i}}}\right)^{\mathbf{2}} \tag{6}$$

$i =$
$\{\mathrm{CDM, Baryons, neutrinos(massive, massless), photons}\}$

8. Evolution of Density perturbations: z = 1000



9. Scales in the problem

- **Matter-radiation equality:**

$$\mathbf{k_{eq} \simeq 0.2\,\Omega_m h^2}\,\mathrm{Mpc}^{-1} \tag{7}$$

Determines the shape of CDM perturbations

- **Sound velocity of baryon-photon fluid:** $c_s \simeq c/\sqrt{3} \Rightarrow$, at $z \simeq 1000$:

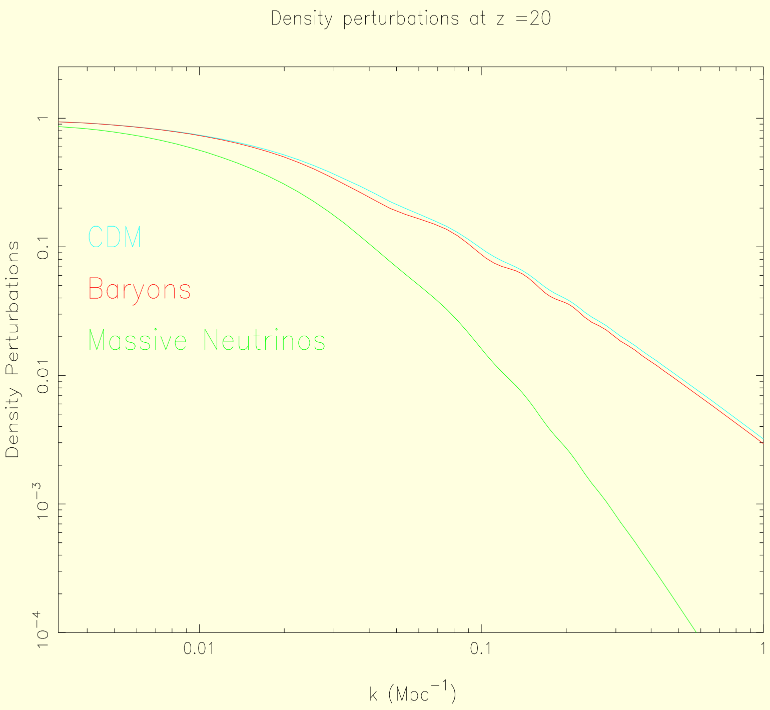
$$\mathbf{k_{sound} \simeq \sqrt{3}H(z) \simeq 0.02(\Omega_m h^2)^{1/2}}\,\mathrm{Mpc}^{-1} \tag{8}$$

- **Silk damping:** The damping scale of baryon-photon fluid owing to viscosity.

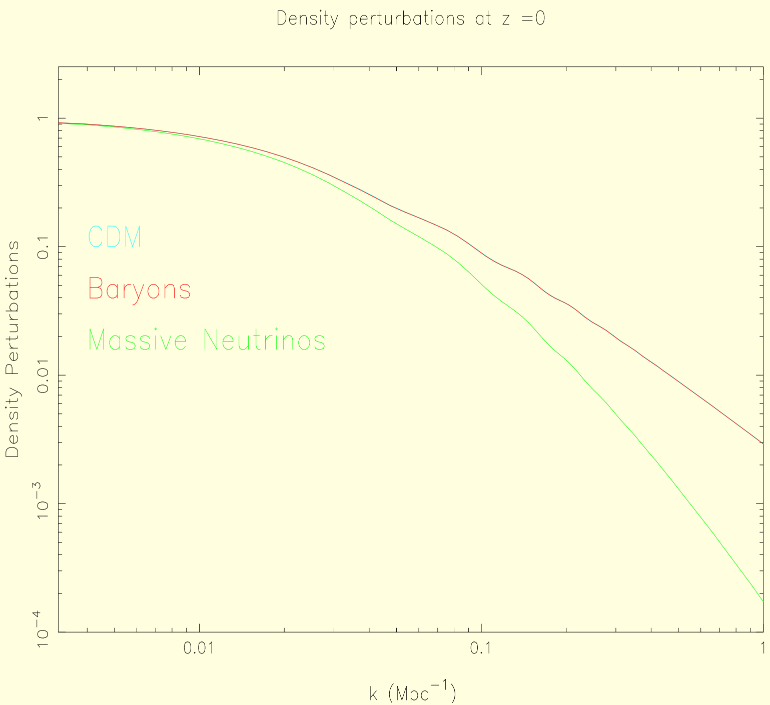
$$\mathbf{k_s \simeq 0.5 \left(\frac{\Omega_b h^2}{0.022}\right)^{1/2} (\Omega_m h^2)^{1/4}} \tag{9}$$

- **Free streaming of massive neutrino:** Roughly H^{-1} at $T \simeq m_\nu$, e.g. for $m_\nu \simeq 0.2\,\mathrm{eV}$, $\mathbf{k_{fs} \simeq 0.01}\,\mathrm{Mpc}^{-1}$

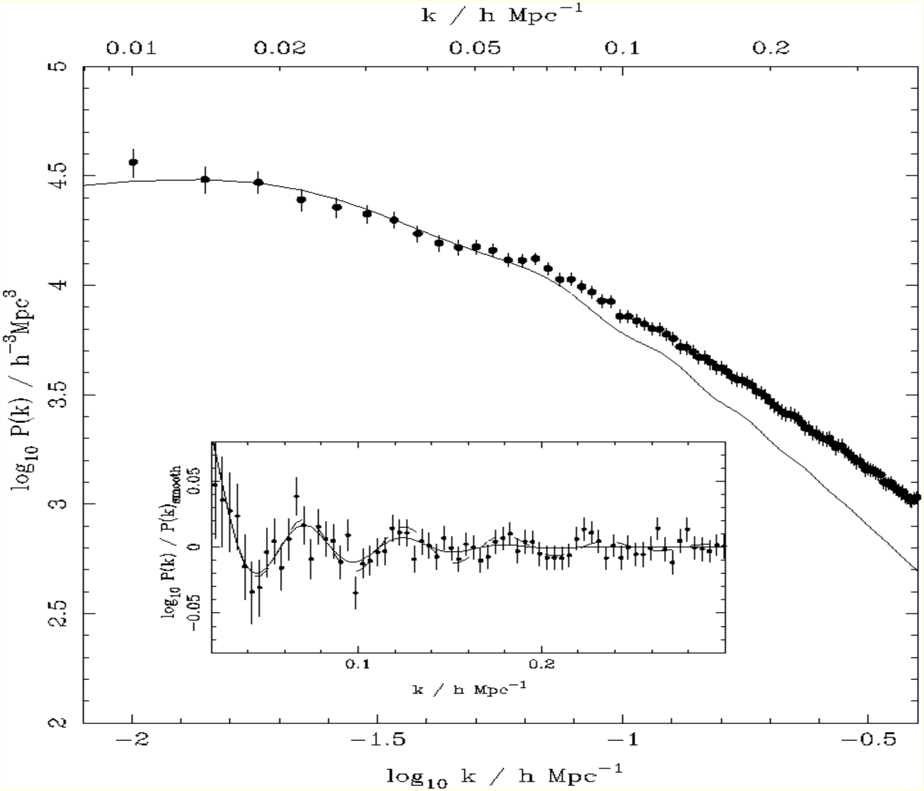
10. Evolution of Density perturbations: $z = 20$



11. Evolution of Density perturbations: z = 0



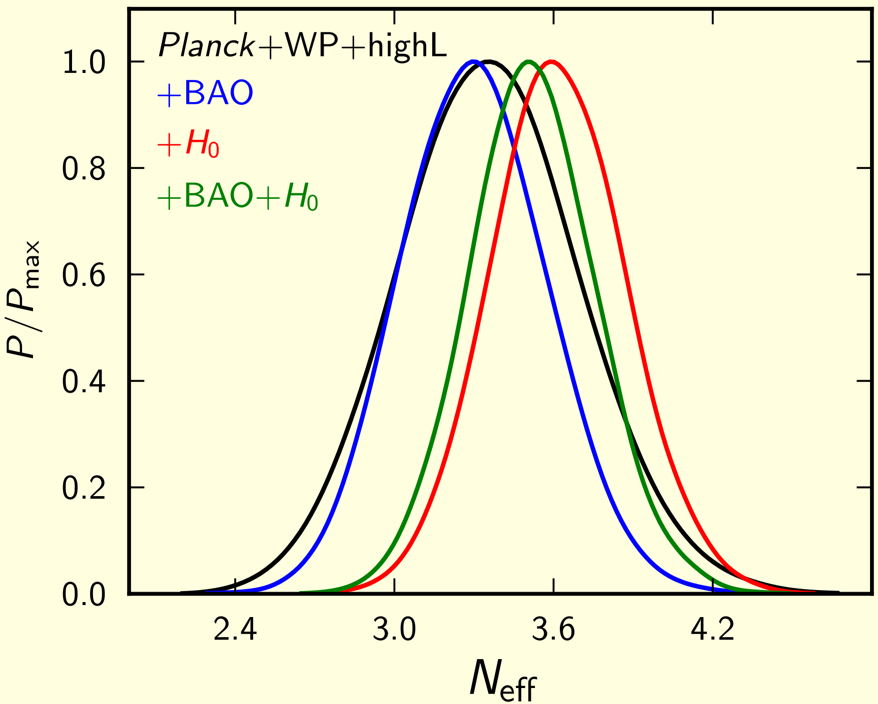
12. SDSS results



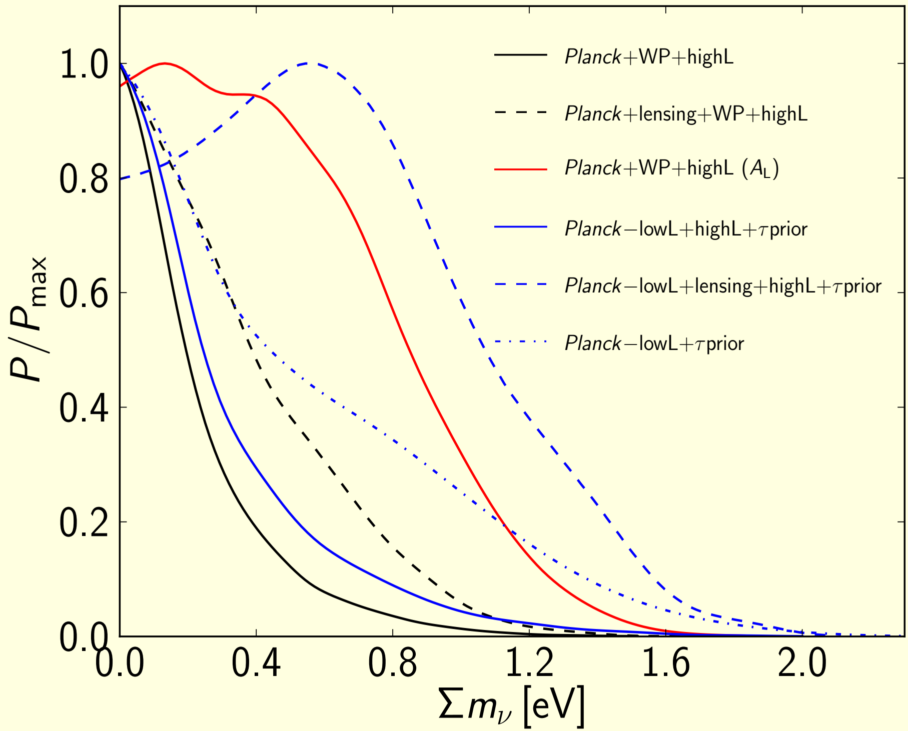
13. Determining the nature of Dark matter: SDSS

- Nonrelativistic component of the matter: $\Omega_m h^2 = 0.141 \pm 0.01$ (use superior determination of $\Omega_B h^2 = 0.02265$ and $n = 0.96$ from WMAP data) (SDSS data; based on measurements between $0.02 < k < 0.2$).
- Massive neutrinos: $\sum m_\nu < 0.62\,\mathrm{eV}$, $\Rightarrow$ $\Omega_\nu < 0.0065$ (SDSS data), $\sum m_\nu < 1.3\,\mathrm{eV}$ (WMAP)
- Massless neutrinos: $N_{\mathrm{eff}} = 4.8^{+1.8}_{-1.7}$ (SDSS). $N_{\mathrm{eff}} = 4.34^{+0.86}_{-0.88}$ (WMAP)

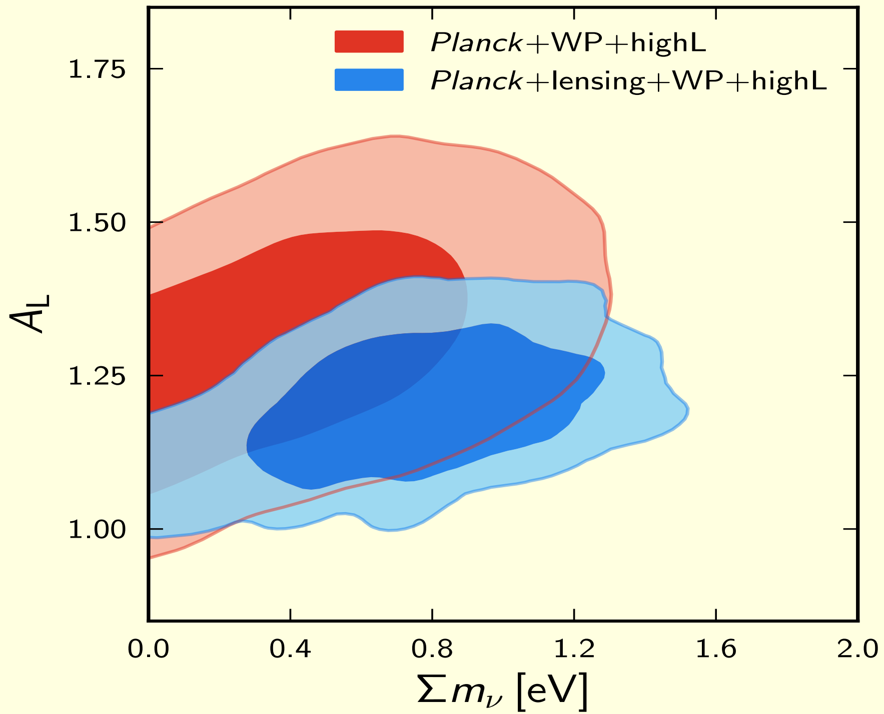
14. Planck results: massless neutrinos



15. Planck results: massive neutrinos



16. Planck results: massive neutrinos–lensing effect



17. Planck results: summary of massless and massive neutrino results

- **Massless neutrinos**:

$$N_{\rm eff} = 3.30^{+0.54}_{-0.51} \tag{10}$$

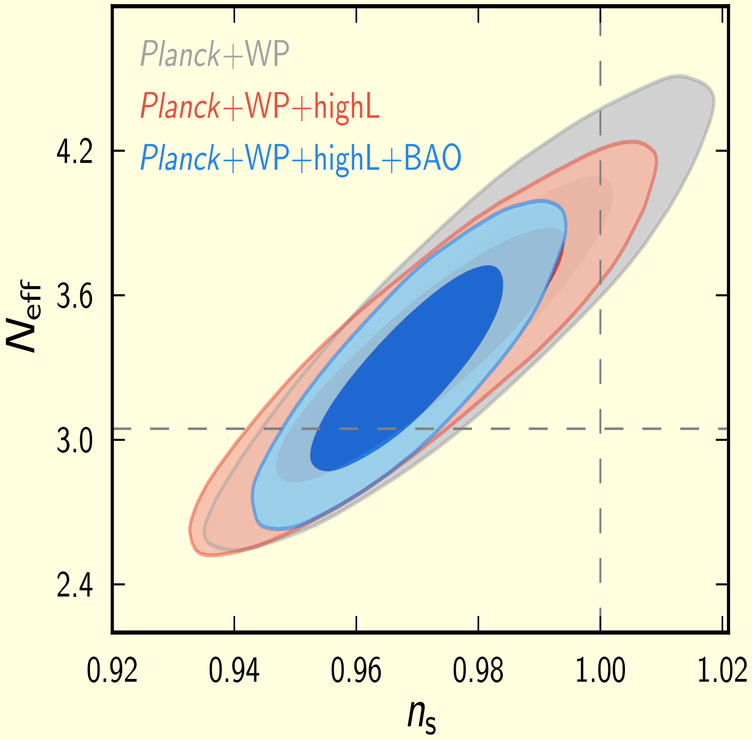
Combining information from Planck temperature, polarization (low-l), ACT, SPT and BAO.

- **Massive neutrinos**:

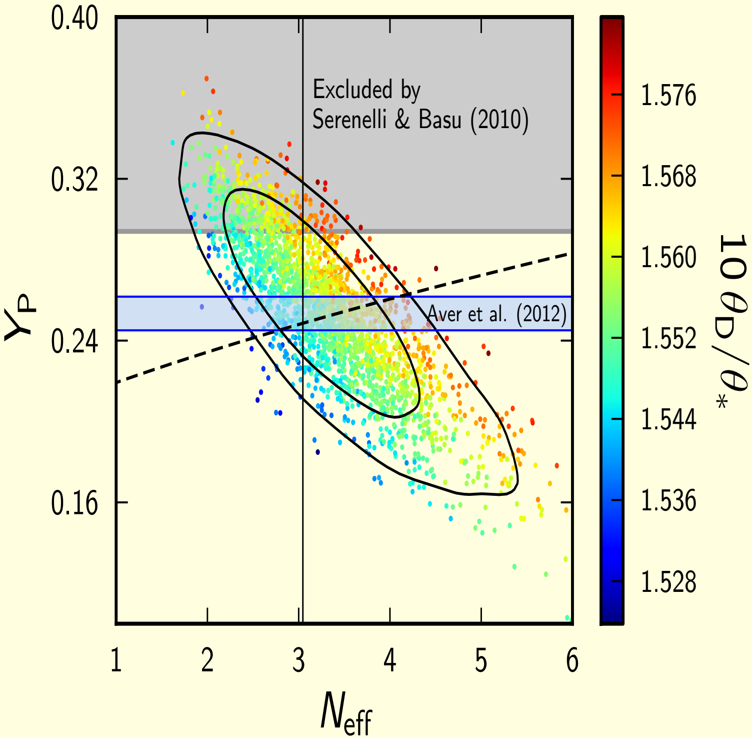
$$\begin{aligned} \sum m_\nu &< 0.66(\text{with lensing; } 95\%) \\ \sum m_\nu &< 1.03(\text{without lensing}) \\ \sum m_\nu &< 0.23(\text{with BAO}) \end{aligned} \tag{11}$$

Information from low redshift data is critical in determining the contribution of massive neutrinos.

18. Other degeneracies: scalar spectral index



19. Other degeneracies: scalar spectral index



20. Ongoing and future surveys

- `CMBR`: Planck. Ongoing. More results expected in coming year
- `Galaxy and Lyman-`α `surveys`: (a) BOSS/SDSSIII: 1.5 million galaxy redshifts to $z \simeq 0.7$; Lyman-α forest spectra of 160,000 quasars for redshifts $2.2 < z < 3$ (b)BigBoss: extend galaxy survey to $z \simeq 1.7$, 20 millions galaxies; 600000 quasars for redshifts $2.2 < z < 3.5$. Expected limits on neutrino masses $\sum m_\nu \simeq 0.05$.
- `HI imaging of Epoch of reionization`: Very precise determination of $P(k)$ at $z \simeq 10$. Ongoing experiments: LOFAR, MWA.