The effect of a 0.1eV neutrino on the Lyα forest

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Outline

- Effect of $m_\nu \sim 0.1$eV on linear power spectrum, $P_L(k)$
- Effect on 3D Lyα flux transmission power spectrum
  P. McDonald (2003), "Toward a measurement of the cosmological geometry at $z \sim 2$: predicting Lyα forest correlation in three dimensions and the potential for future data sets."
- Effect on 1D Lyα flux transmission power spectrum
  P. McDonald et al. (2005) "The linear theory power spectrum from the Lyα forest in SDSS"
- Combination with CMB $\Rightarrow m_\nu$
  Seljac et al (2005,2006)
  Palanque-Delabrouille et al. (2015)

Effect of $m_\nu = 0.1\text{eV}$ on CMB

Recombination:

- $z \sim 1000 \;\Rightarrow\; kT_\gamma \sim 0.2\text{eV}$
- $kT_\nu \sim 0.15\text{eV} \Rightarrow \langle p_\nu \rangle \sim 3T_\nu >> m_\nu$

$\Rightarrow m_\nu \sim 0.1\text{eV}$ has little effect on shape of CMB spectrum.

$H(z < 100)$ is modified $\Rightarrow$ modified distance to LSS.

$\Rightarrow$ peak positions slightly modified.

(For fixed $\Omega_{\rm CDM}h^2$: determined by CMB peak heights.)

Effect of $m_\nu = 0.1\text{eV}$ on late-time $P_L(k, z)$

First, what is $P_L(k, z)$?

$$\rho(\vec{r}, z) = \bar{\rho}(z)\left[1 + \delta_{\vec{k}}(z)\exp(i\vec{k}\cdot\vec{r}\Big)\right] \qquad P(k) \propto \left\langle \delta_{\vec{k}}^2 \right\rangle$$

Power spectrum, $P(k)$, is Fourier trans. of correlation function, $\xi(r)$.

At early times, $|\delta(k, z)| \ll 1$ and obeys linear ordinary differential equations (modes independent).

$P_L(k, z)$ is late time extrapolation of early-time $P(k, z)$ using linear ordinary differential equations (modes independent.)

Effect of $m_\nu = 0.1\text{eV}$ on late-time $P_L(k)$

Free streaming while $T_\nu > m_\nu$ suppresses power on small scales:

$$k_{fs} \sim 0.0017 \left[\frac{\Omega_{\rm CDM} \sum m_\nu}{0.3 \times 0.1 eV}\right]^{1/2} (h^{-1}{\rm Mpc})^{-1}$$

$$\lambda_{fs} \sim 3600 \left[\frac{\Omega_{\rm CDM} \sum m_\nu}{0.3 \times 0.1 eV}\right]^{-1/2} (h^{-1}{\rm Mpc})$$

Suppression factor (fixed $\Omega_{\rm CDM} h^2$):

$$\frac{\Delta P_L}{P_L}(k > k_{fs}) \sim 8 \frac{\Omega_{\nu 0}}{\Omega_{\rm CDM}} \sim 0.06 \frac{\sum m_\nu}{0.1 eV}$$

λ_{fs} bigger than current surveys $\Rightarrow$ step not observable.
$\Delta P_L / P_L$ observable if P_L can be deduced from observed P_{NL} and then compared with prediction of CMB (function of m_ν).

m_ν from CMB and Lyα(simplified)

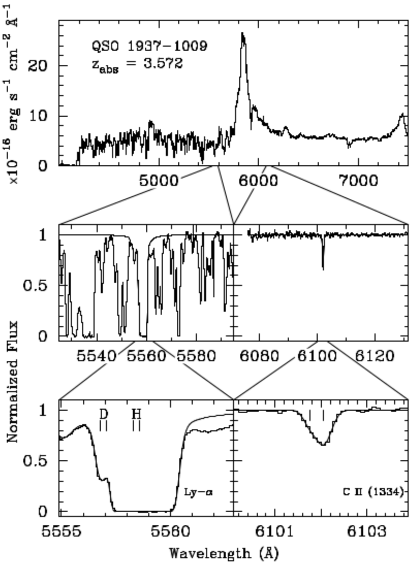
$$P_L(k > k_{fs}) \sim P_L(k, A_s, n_s, \Omega_{\rm CDM}h^2, \Sigma m_\nu \sim 0) \left[1 - 0.06\frac{\Sigma m_\nu}{0.1eV}\right]$$

- Simulate IGM to establish relation between $P_L(k)$ and $P_{NL}(k)$.
- Deduce l.h.s. from Lyα forest measurement of $P_{NL}(k)$
- Deduce $(A_s, n_s, \Omega_{\rm CDM}h^2)$ from CMB anisotropy $\Rightarrow P_L(k, m_\nu \sim 0)$
- Use $(h, \Omega_{\rm CDM}h^2)$ to put CMB anisotropies and Lyα inhomogeneities on the same distance scale (same k scale).
- Deduce $\sum m_\nu$

  Precision of 0.12 on $\Delta P_L/P_L \Rightarrow m_\nu < 0.2$eV
- mass limit depends on assumed form of primordial spectrum.

  Generally assume non-running n_s

The Lyα forest



Transmitted flux fraction in forest $F(\lambda) = e^{-\tau(\lambda)}$.

Correlation function of $F(\lambda)$:
Within individual forests
$\Rightarrow \xi_{F1d}(\Delta\lambda) \Rightarrow P_{F1d}(k_{\parallel})$

Between different forests
$\Rightarrow \xi_{F3d}(\Delta\lambda, \Delta\theta) \Rightarrow P_{F3d}(\vec{k})$

P_{F3d} is a biased and z-distorted version of $P_{NL}(k)$
(big $\rho_m \Rightarrow$ small F and vice versa)

P_{F1d} is an integral over P_{F3d}

Optical depth, τ, at redshift z

$$\tau(z) \propto \Omega_{\rm B}^2 \frac{(1+z)^6\,\bar{T}(z)^{-0.7}}{H(z)J_\gamma(z)}\;\frac{(1+\delta(z))^\beta}{(1+\eta(z))^1} \qquad \eta \equiv \frac{v_p'(z)}{H(z)}$$

where $\beta = 2 - 0.7(\gamma(z)-1) \sim 1.6$.
Formula assumes well defined $v_p(z)$ (no thermal broadening or trajectory crossings!).
Fluctuations of density, δ, and velocity gradient, η, $\Rightarrow \tau$ fluctuations

Power spectrum of $F = e^{-\tau}$ depends on

- $\Omega_{\rm B}^2\,\bar{T}/J_\gamma \rightarrow \bar{F}$
- $P_L(k) \Rightarrow$ statistics of δ and η
- $(\bar{T},\gamma) \Rightarrow$ thermal broadening
- Non-linear astrophysics: Supernovae, shock-heating.....

McDonald strategy to measure $P_L(k)$

Simulate the hydrodyamics of the IGM to predict $P_{F1d}(k_{\|})$ as a function of.

- $\Omega_{\rm B}^2 \bar{T}/J_\gamma \rightarrow \bar{F}$
- $(\bar{T}, \gamma)$
- $P_L(k)$ parameterized by

$$\Delta_L^2(k_p, z_p) \equiv k^3 P_L(k_p, z_p)/2\pi^2, \qquad n_{eff}(k_p, z_p) = \frac{dlogP_L}{dlogk}(k_p, z_p)$$

$$k_p = 0.009(km/sec)^{-1} \sim 1(h^{-1}{\rm Mpc})^{-1} \qquad z_p = 3$$

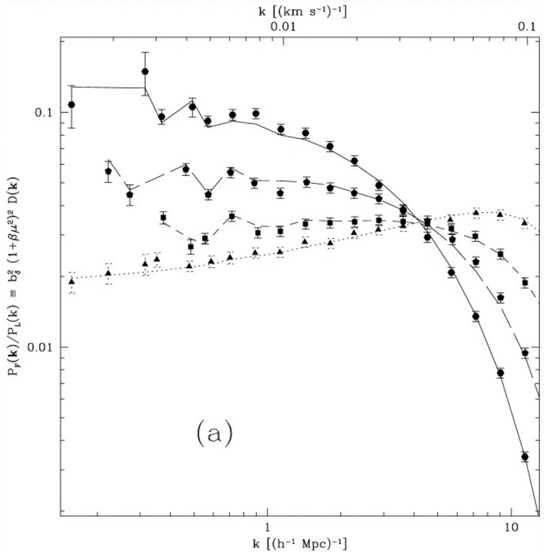
In ΛCDM, $\Delta_L^2(k_p, z_p)$,$n_{eff}(k_p, z_p)$ determined by $(A_s, n_s, \Omega_{\rm CDM}, \Omega_k, h)$

Hopefully, the poorly known astrophysics $(\bar{F}, T, \gamma, SN, shocks....)$ will not spoil the $P_{F1d} - P_L$ connection.

Predicted $P_{F3d}(\vec{k})/P_L(k)$ (McDonald,2003)

radial

transverse



In radial direction, peculiar velocity fluctuations:

enhance power (Kaiser factor) at small k;

suppress power at large k.
(like FOG for galaxies)

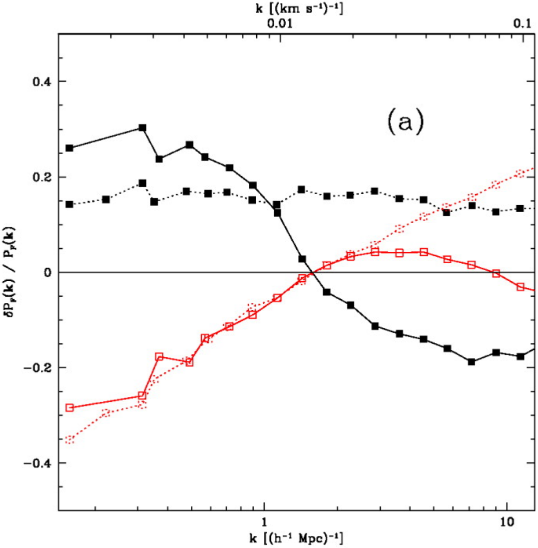
Suppression of small scale radial power

- velocity spread at one point in real-space (thermal or trajectory crossing) $\Rightarrow$ high density regions contribute to many redshifts

and/or

- More than one real-space point at same velocity $\Rightarrow$ more than one density contributes to one redshift.

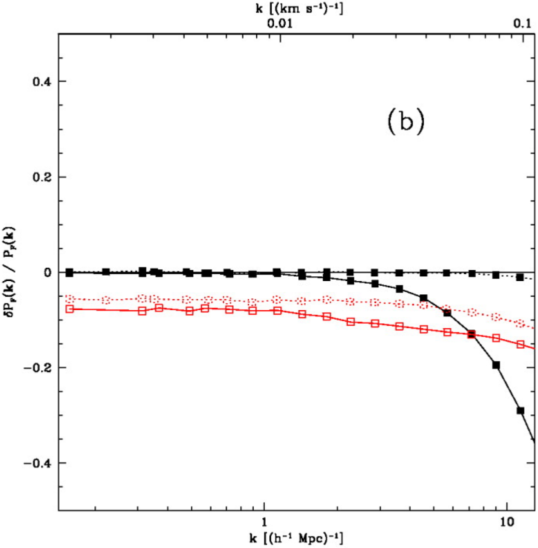
Effect of increasing $P_L(k_0)$ or n_{eff} on P_{F3d}



Solid lines: radial direction
dotted lines: transverse

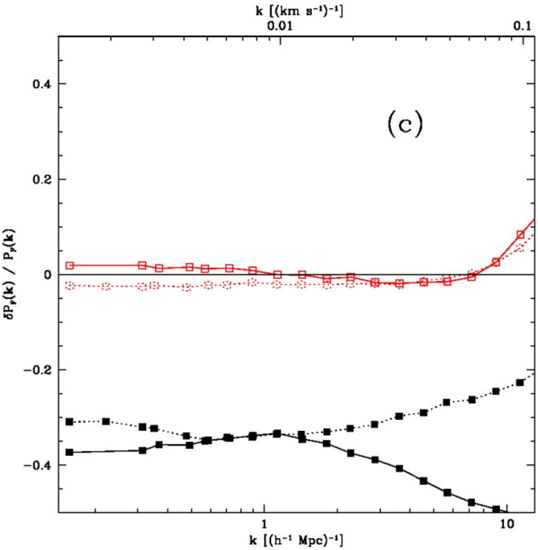
"For $k > 1(h^{-1}\mathrm{Mpc})^{-1}$, it is interesting to note that increasing the mass power actually decreases the flux power along the line of sight, presumably by increasing the power suppression by nonlinear peculiar velocities." (McDonald, 2003)

Effect of increasing $\bar{T}$ or γ on P_{F3d}



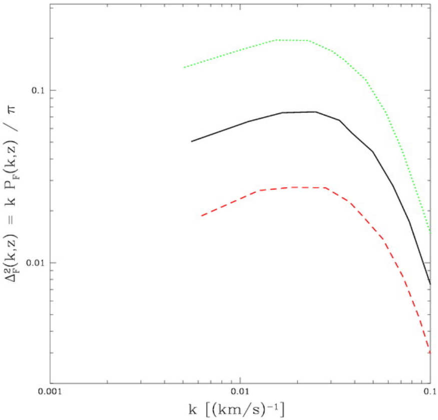
Solid lines: radial direction
dotted lines: transverse

Effect of increasing $\bar{z}$ or $\bar{F}$ on P_{F3d}



Solid lines: radial direction
dotted lines: transverse

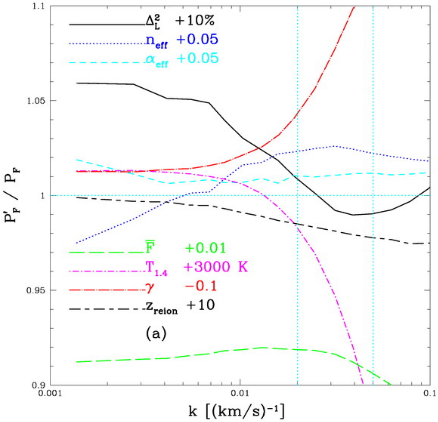
Predicted $P_{F1d}(k_\parallel)$ (McDonald et al., 2005)



$$\Delta^2_{F1d}(k_\perp) \equiv k P_{F1d}(k_\parallel)/\pi$$

$$P_{F1d}(k_\parallel) \sim \int_0^\infty k_\perp dk_\perp P_{F3d}(k_\perp, k_\parallel)$$

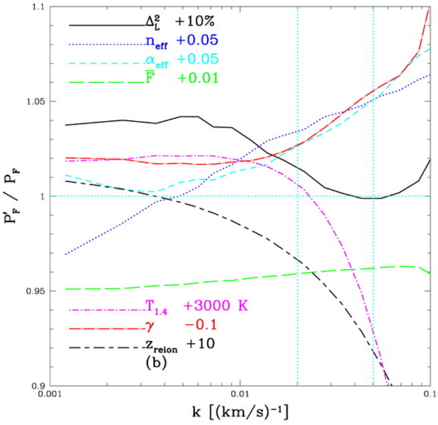
Effect of increasing P_L or $\bar{F}$ on $P_{F1d}(k, z = 2.12)$



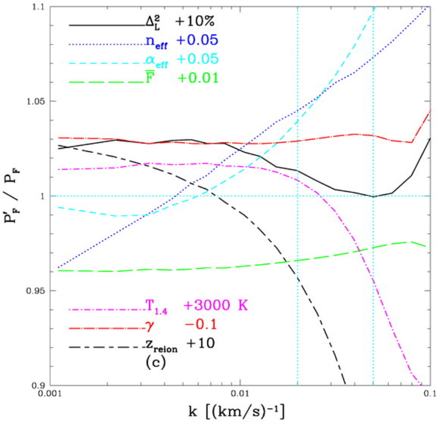
"Increasing $\Delta_L^2(k_p, z_p)$ enhances the power on large scales put actually suppresses the power on small scales"

"(Increasing) $\bar{F}$ produces a relatively flat, large change, which is commonly assumed to be degenerate with Δ_L, although we see that the shapes are not the same, nor are the relative effects at different redshifts:" (McDonald et al., 2005)

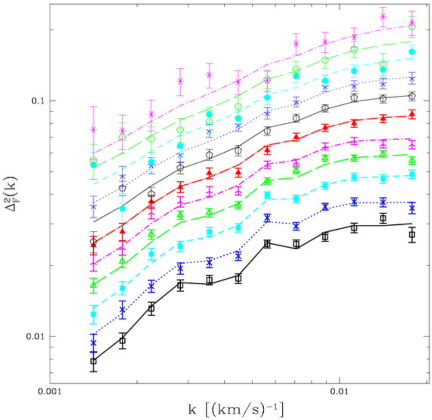
Effect of increasing P_L or $\bar{F}$ on $P_{F1d}(k, z = 3.17)$

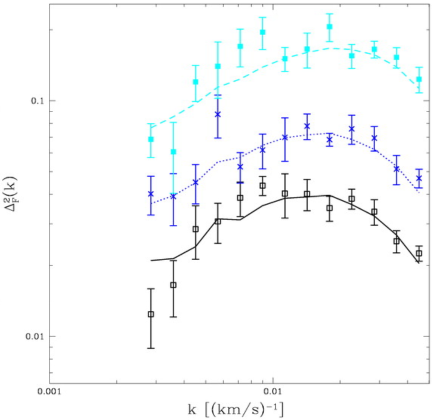


Effect of increasing P_L or $\bar{F}$ on $P_{F1d}(k, z = 4)$

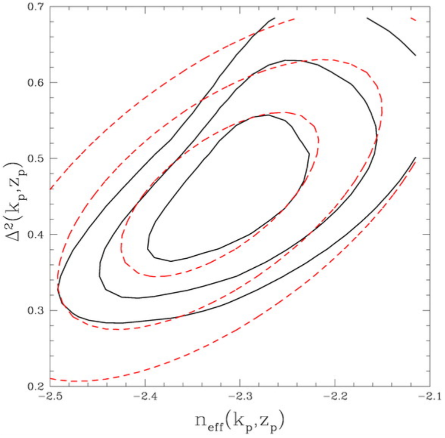


Observed 1d flux power spectrum

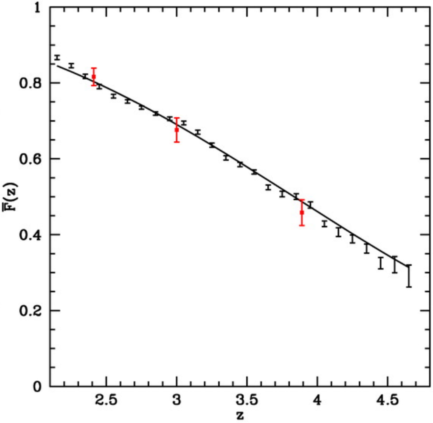




Deduced $P_L(k)$ (McDonald et al 2005)

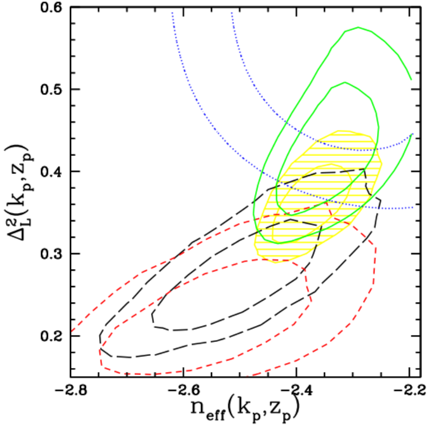


Deduced mean transmission



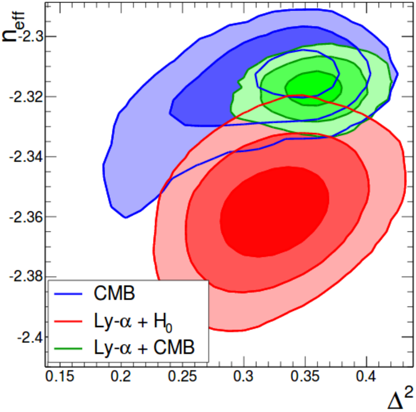
Deduced $P_L(k)$ (Seljak, Slosar, McDo 0604335)

Add measurement of $\bar{F}(z)$ from high-resolution spectre.



Lyα with $\bar{F}(z)$ measurement
WMAP3, running n
WMAP3 + galaxies + SN, running n
Combined

Deduced $P_L(k)$ (Palanque-Delabrouille et al 1410.7244)



$$k_p = 0.009(km/sec)^{-1}$$
$$z_p = 3$$

Combination with CMB

Need to put CMB and Lyα inhomogenities on same comoving distance (r) or wavenumber (k) scale.

- CMB: $r = \Delta\theta \times D_M(z \sim 1000, \Omega_{\mathrm{CDM}} h^2, \Omega_k h^2, h)$
- Lyα: $r = \Delta z / H(z, \Omega_{\mathrm{M}} h^2, h)$

Need $(\Omega_{\mathrm{M}} h^2 \sim \Omega_{\mathrm{CDM}} h^2, \Omega_k h^2, h)$ to compare CMB and Lyα.
$\Omega_{\mathrm{CDM}} h^2$ determined by CMB peak heights.
Further input or hypotheses needed for $(h, \Omega_k h^2)$

Limits on m_ν

- Seljac et al. (2005) $m_\nu < 0.42$ eV
  $P_L(k_p)$ from McDonald et al (2005)
  CMB from WMAP 1yr
- Seljac, Slosar & McDonald (2006) $m_\nu < 0.17$ eV
  $P_L(k_p)$ from McDonald et al (2005)
  $\bar{F}(z)$ measurement with high-resolution spectra
  CMB from WMAP 3yr
- Palanque-Delabrouille et al. (2015) $m_\nu < 0.15$ eV
  New (better) simulations.
  fit directly for $(m_\nu, \sigma_8) + (\Omega_{\rm CDM}, h, n_s)$
  CMB from Planck 1yr

All assume n_s not running.
Different fit parameters for Lyα fit, different simulations, and different CMB data makes comparison difficult.