Neutrino Mass & the Lyman-α Forest

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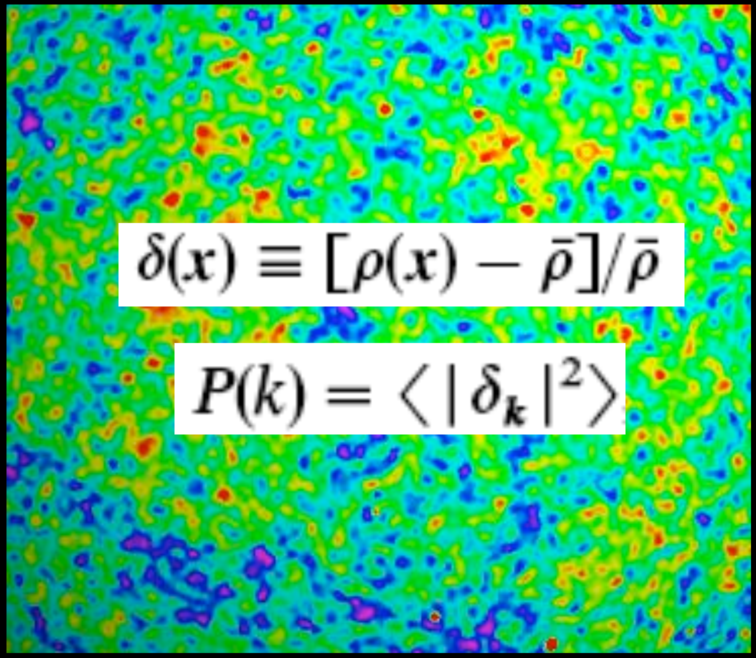
INT Workshop: The Future of Neutrino Mass Measurements
February 9, 2010

Dynamics: the cosmological density perturbation spectrum



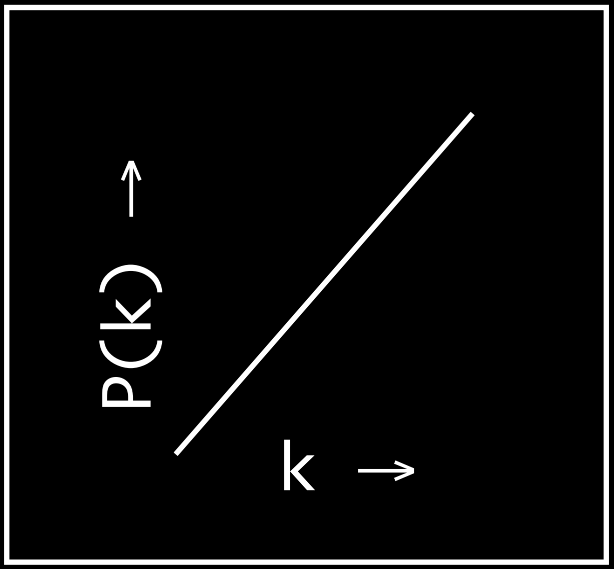
- Power spectrum of cosmological density fluctuations

$$P(k) = \langle |\delta_k|^2 \rangle$$

- Primordial Harrison-Zeldovich: from scale invariance

$$P(k) \propto k$$

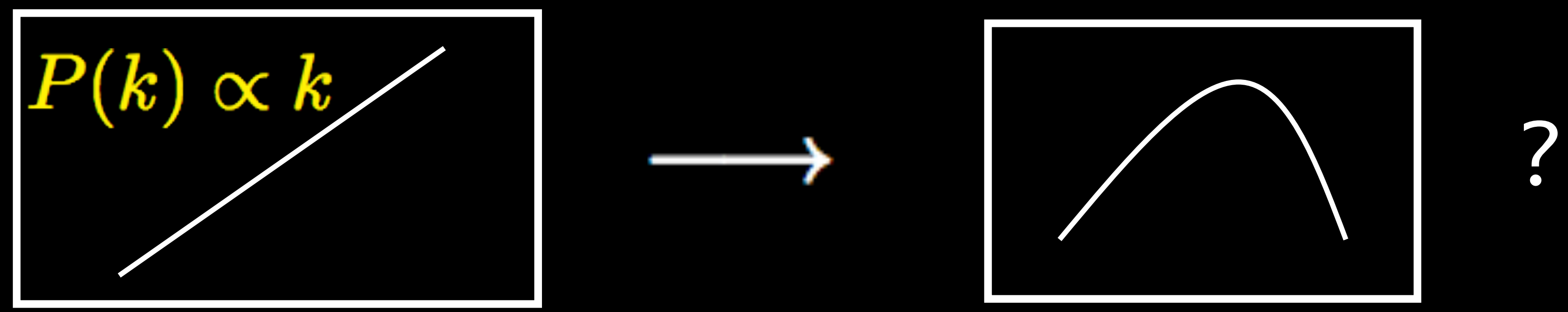
  - Natural solution to perturbation spectrum: self-similar evolution



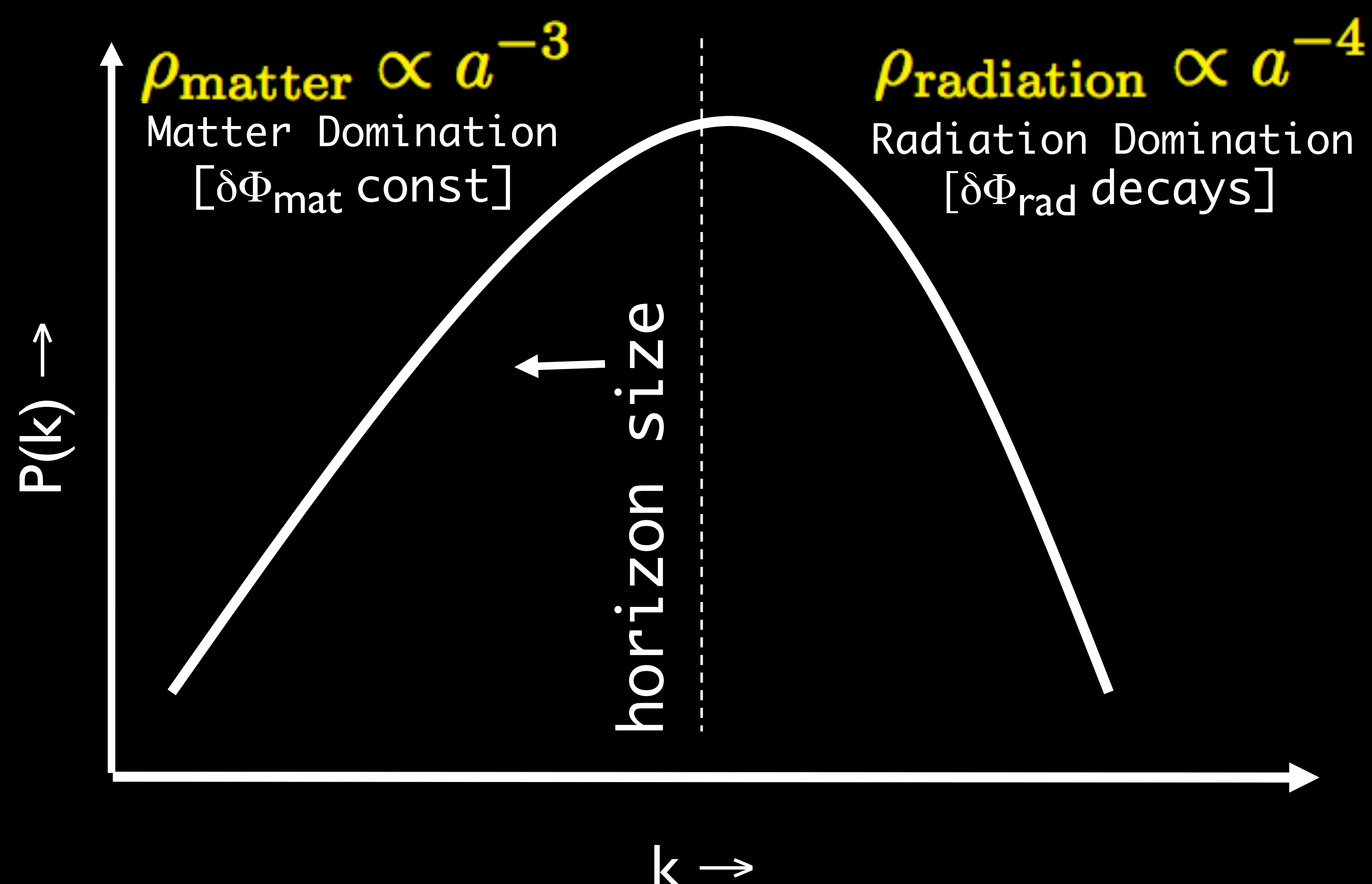
- Predicted by inflation

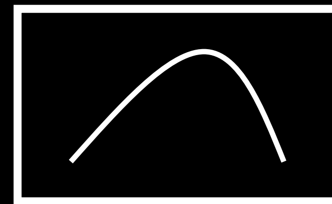
$$P(k) \propto k^n \qquad n \lesssim 1$$

The Cosmological Matter Power Spectrum



Perturbations enter horizon:



How does  probe neutrinos?

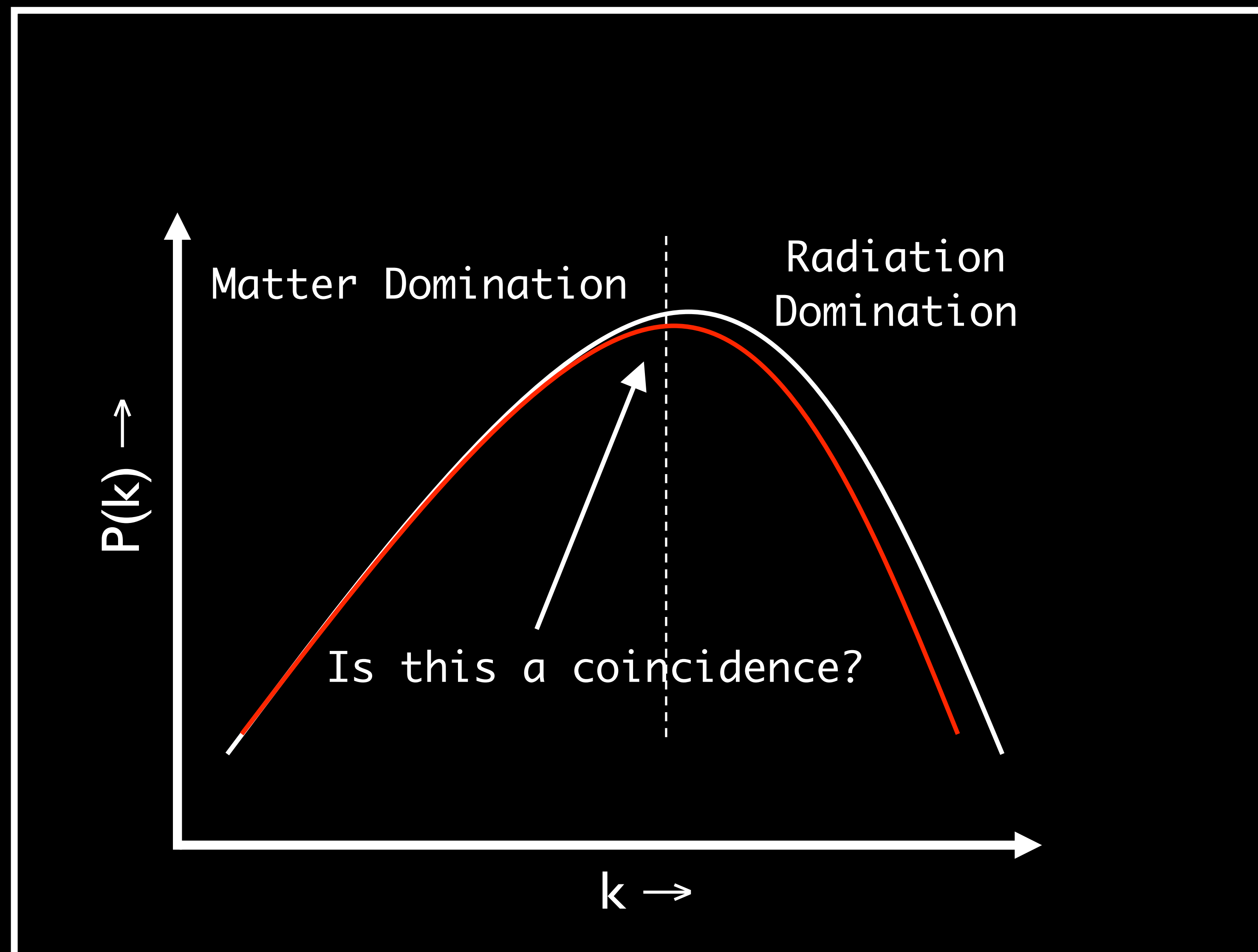
$$n_\nu = N_\nu \times \left(\frac{3}{11}\right) n_\gamma \approx 340 \text{ cm}^{-3}$$

(Assuming thermal equilibrium)

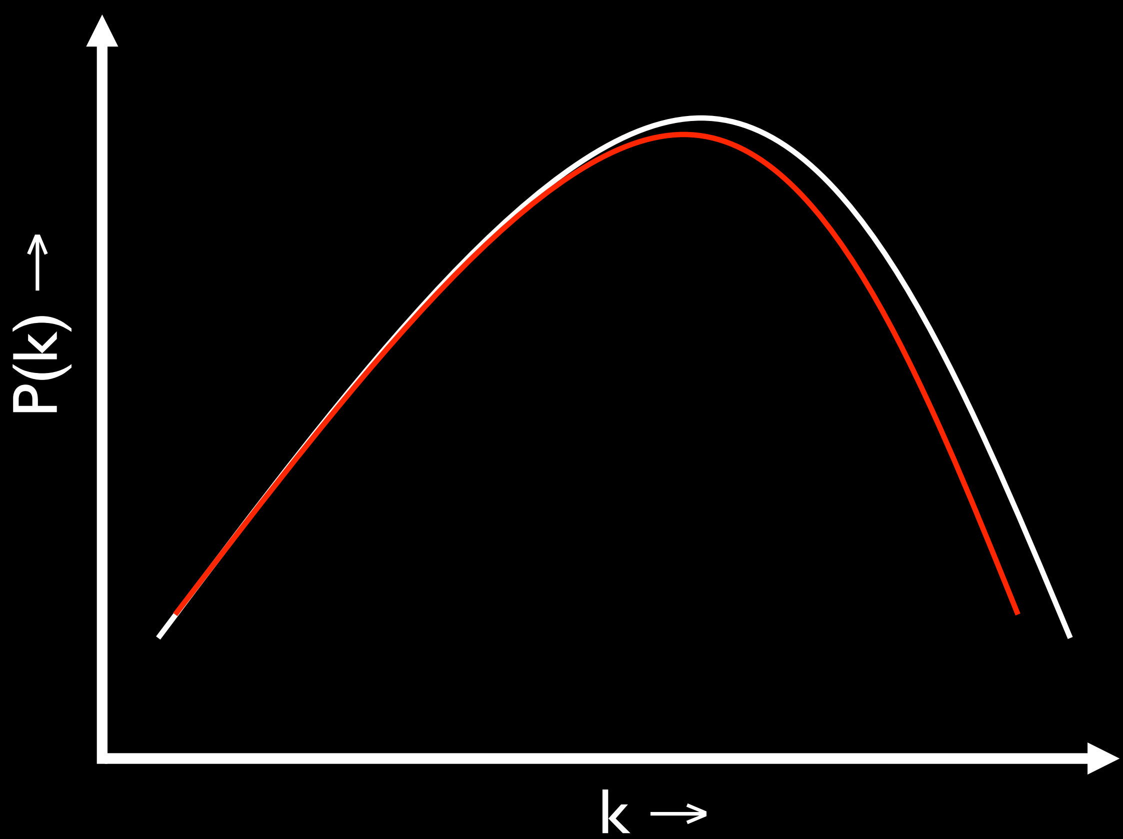
$$\rho_\nu = \sum m_i n_{\nu_i}$$

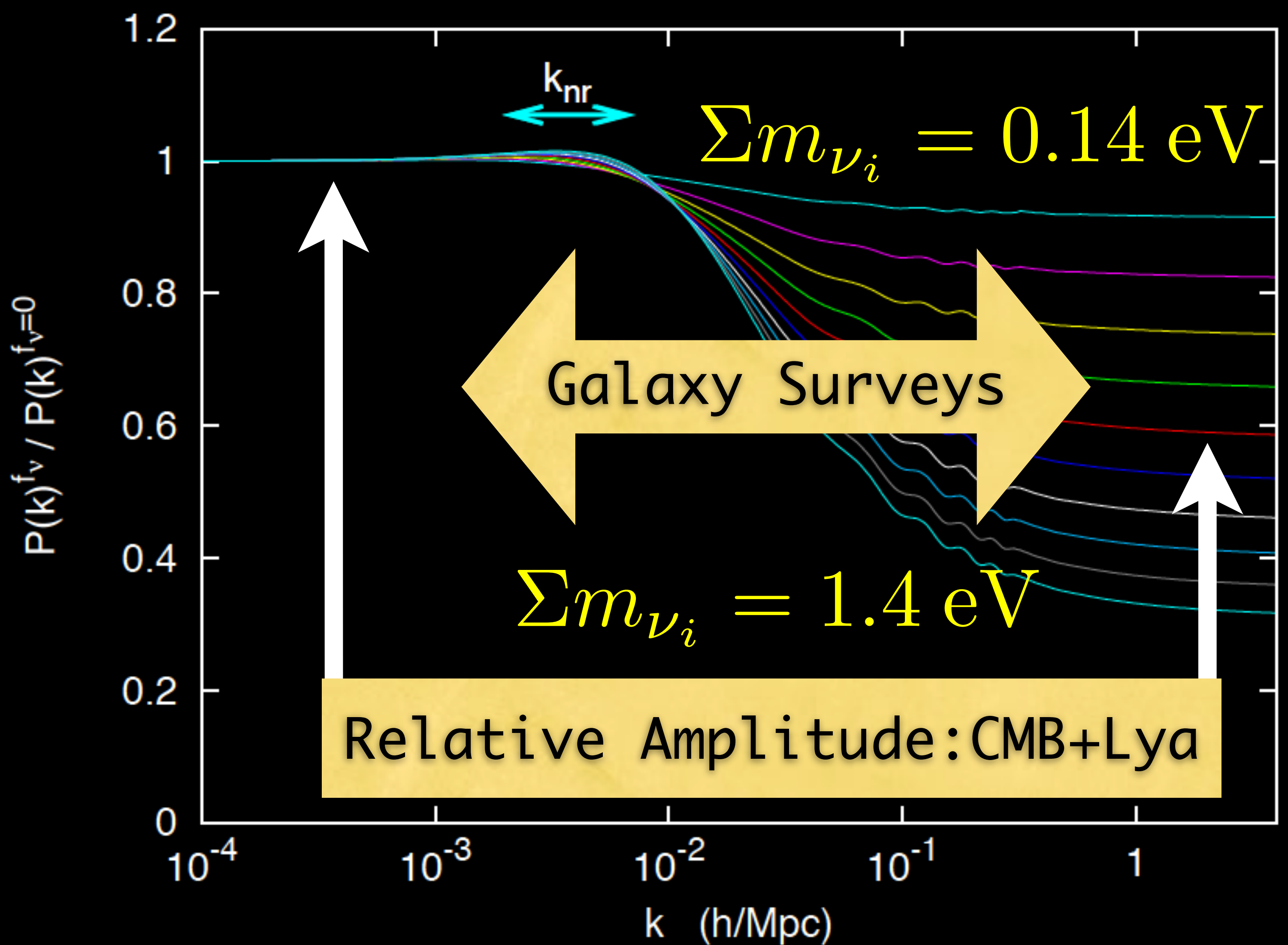
$$\Omega_\nu \approx \frac{\sum m_{\nu_i}}{93\ h^2\ \mathrm{eV}}$$

$$E^2 = p^2 + m^2$$



Distinguishing Features in the Power Spectrum



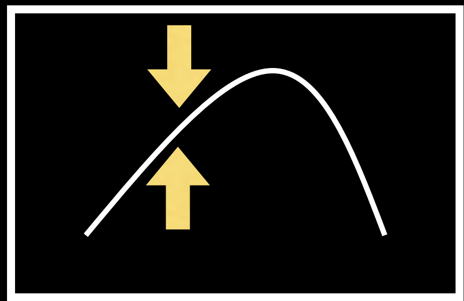


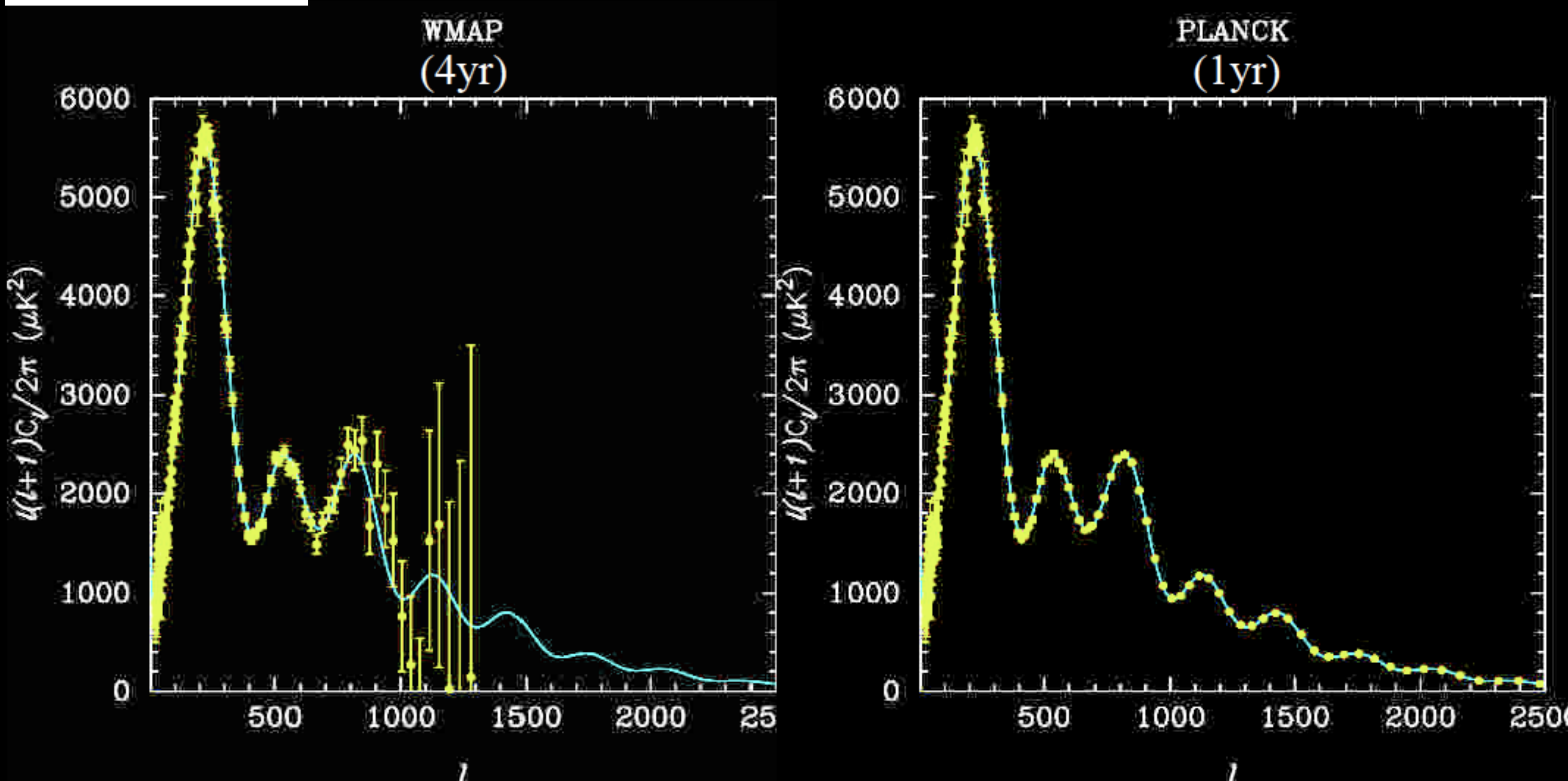
1. Shape Information:
   Galaxy Surveys (Future: Weak Lensing Surveys)

2. Relative Amplitude Information:
   CMB plus Lyman-alpha Forest, Galaxy Bias

$$\frac{\Delta P(k)}{P(k)} = -12\frac{\Omega_\nu}{\Omega_m}$$

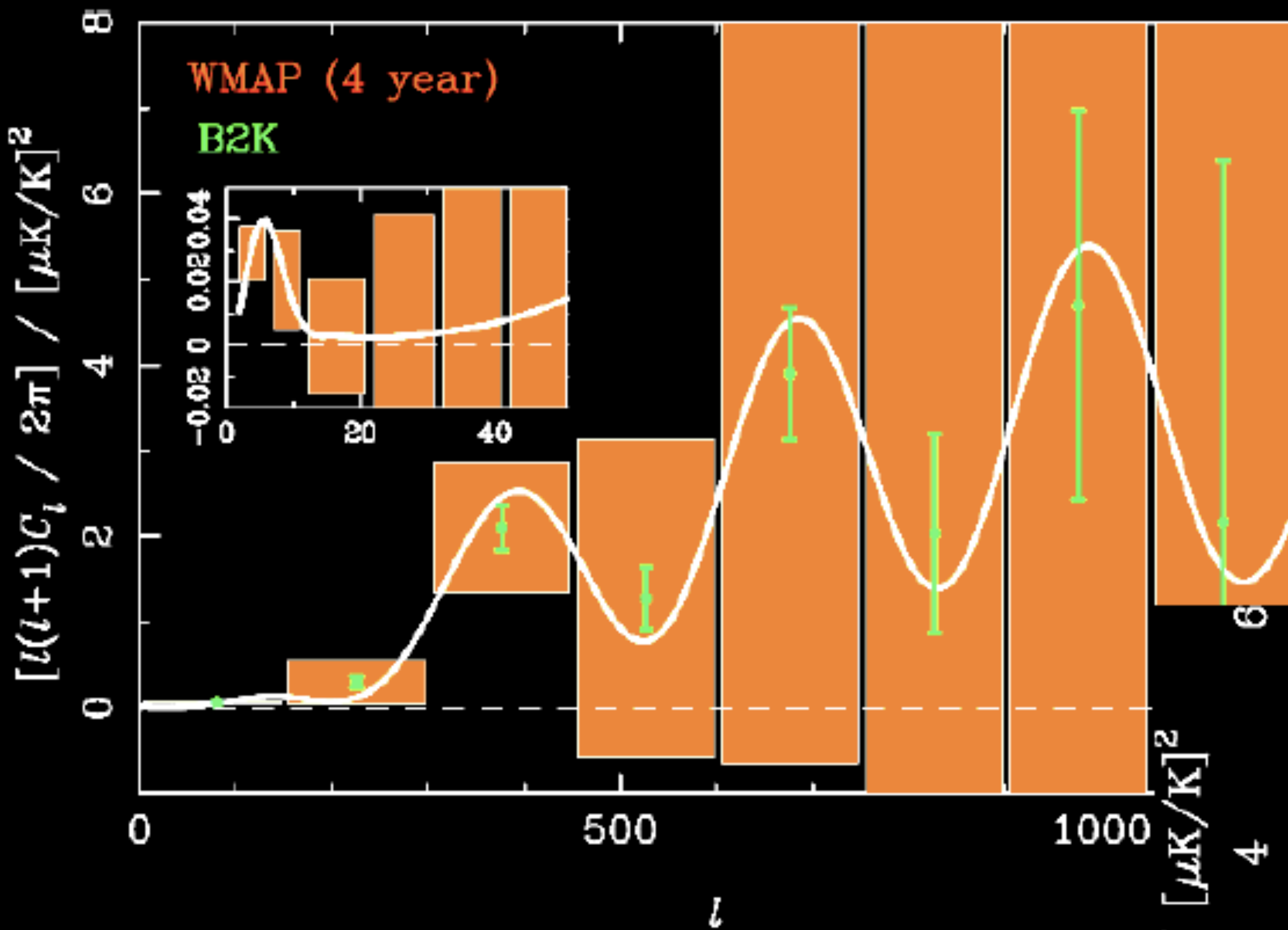
Relative Large Scale Amplitude: PLANCK



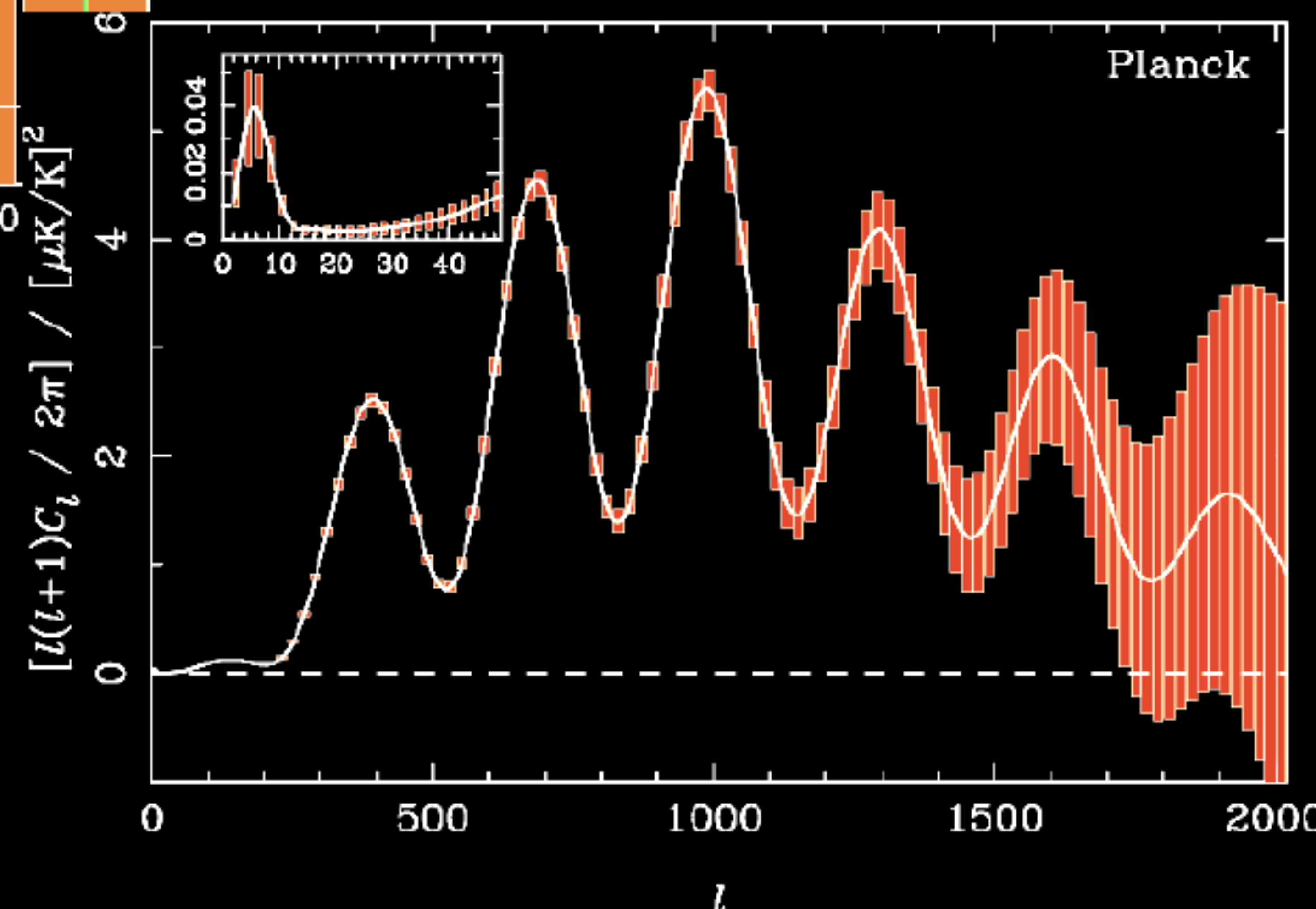


(Martin White)

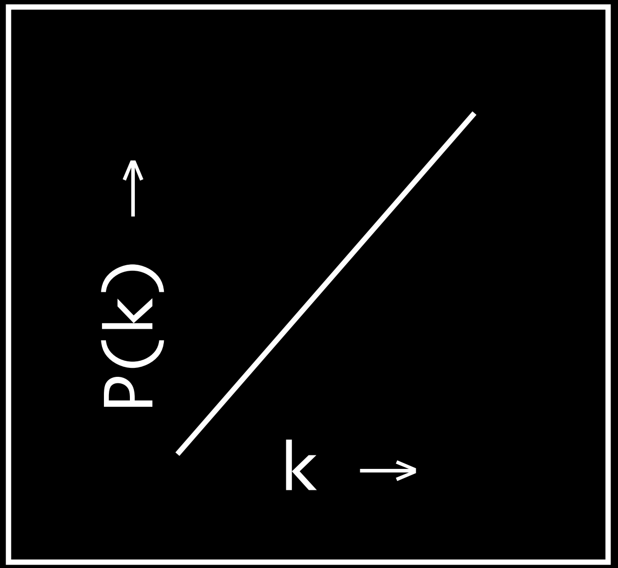
Forecast Precision Cosmology: PLANCK



(Martin White)



A precise measurement of the E-mode polarization power spectrum.



The Primordial Spectrum: Precision Determination at Large Scales

$$P(k) = Ak^n$$

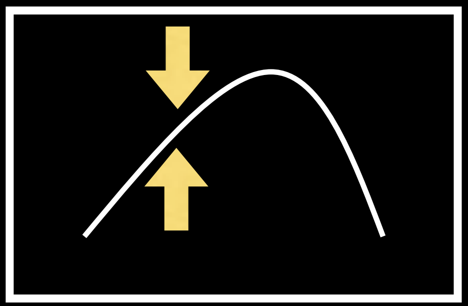
WMAP 5 + BAO + SN:

(Komatsu et al. 2008)

$$A = 2.445 \pm 0.096 \quad (3.4\%)$$
$$n = 0.96 \pm 0.013 \quad (1.4\%)$$

PLANCK + SDSS LRG:

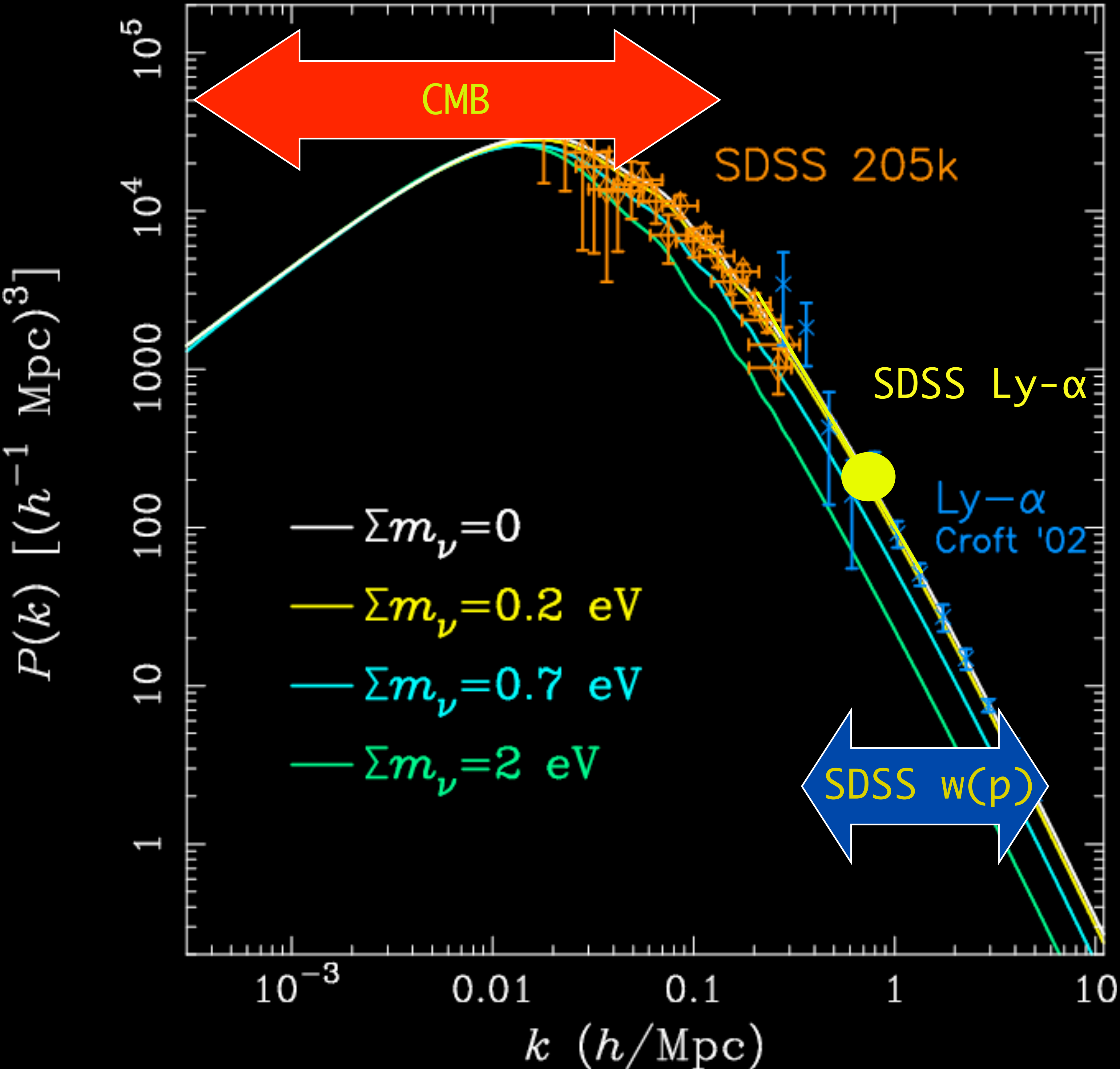
(Eisenstein, Hu, Tegmark 1998)



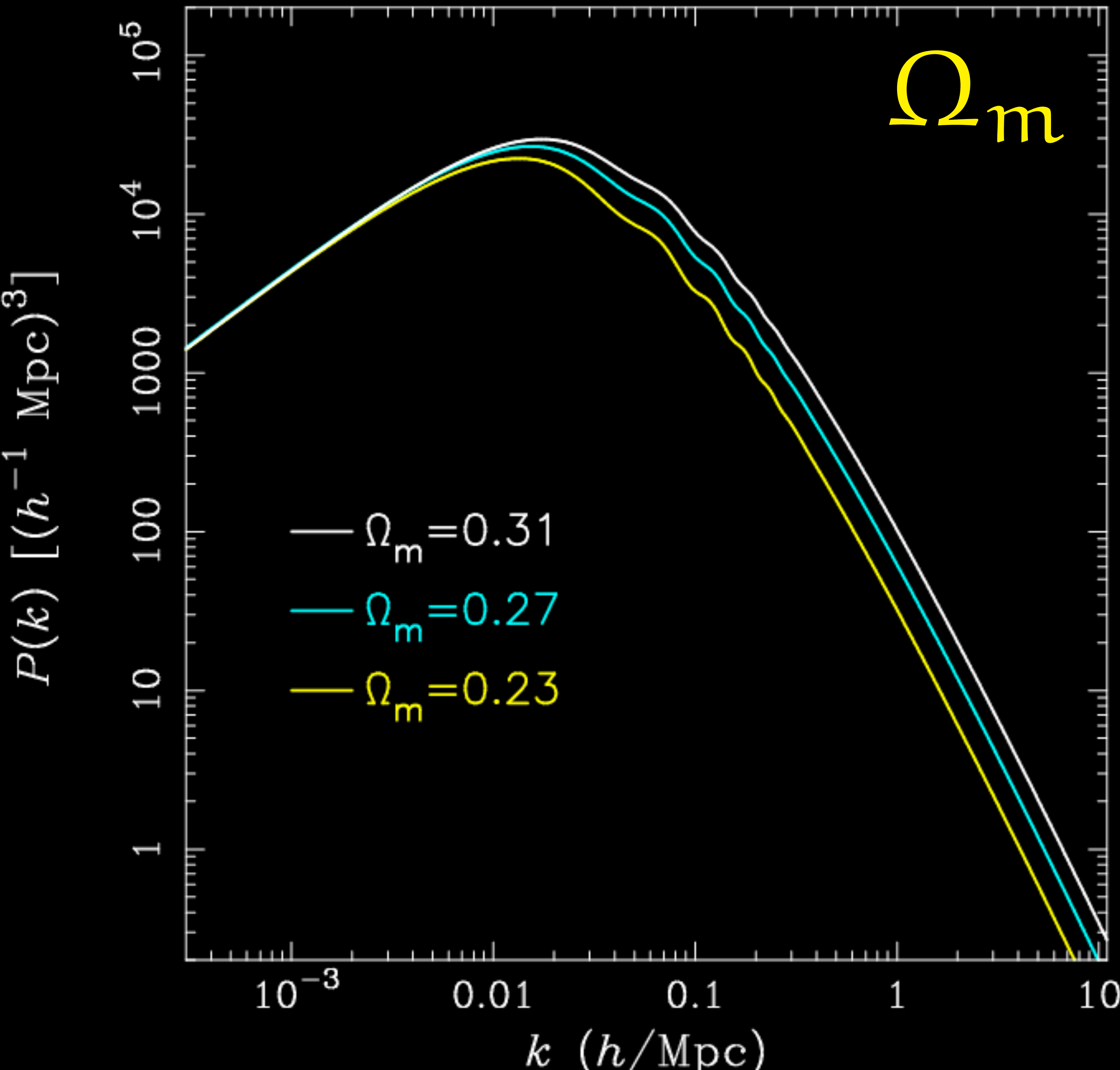
$$A = 2.4450 \pm 0.0085 \quad (0.35\%)$$
$$n = 0.9600 \pm 0.0077 \quad (0.8\%)$$

forecast!

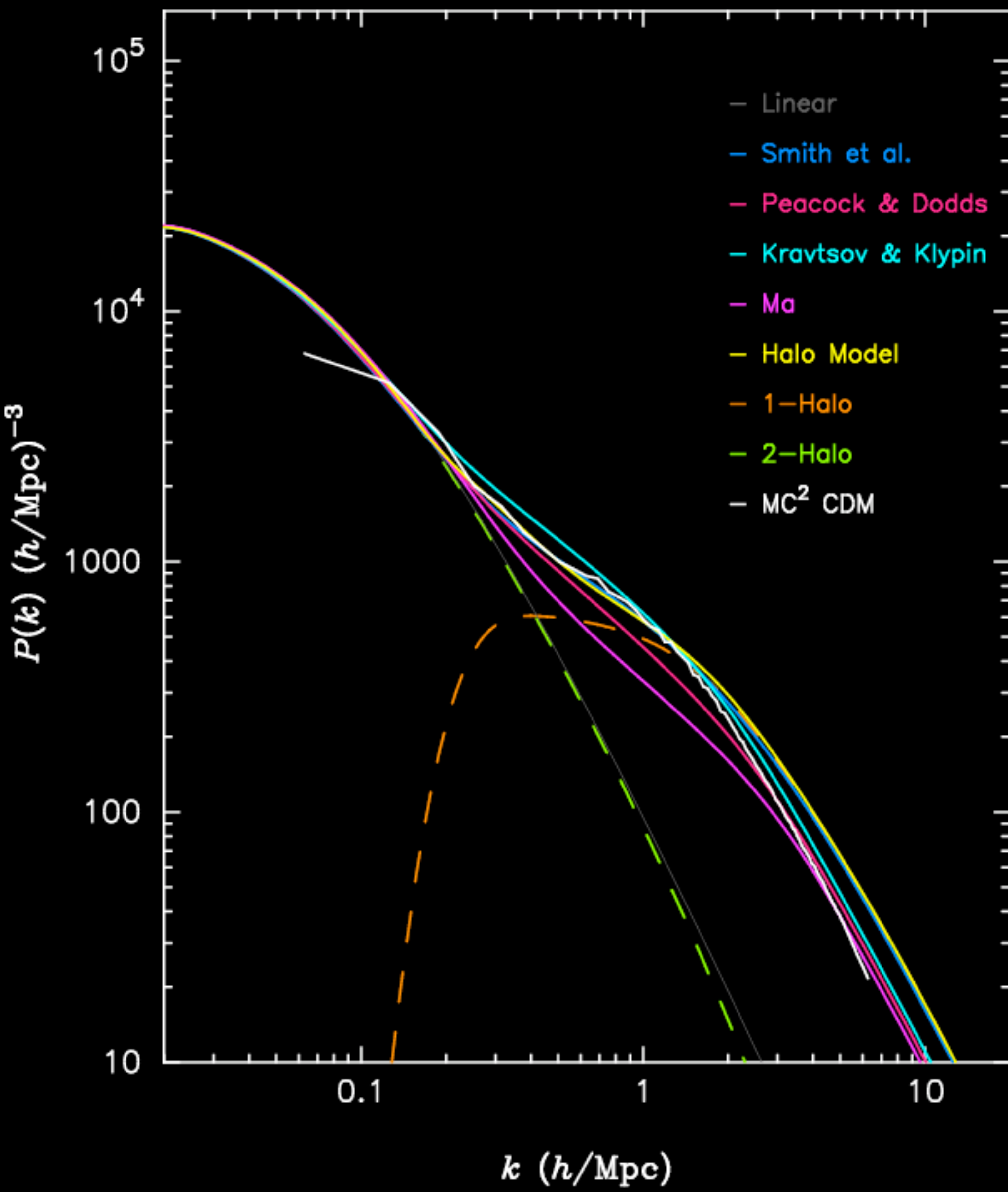
Measuring P(k)



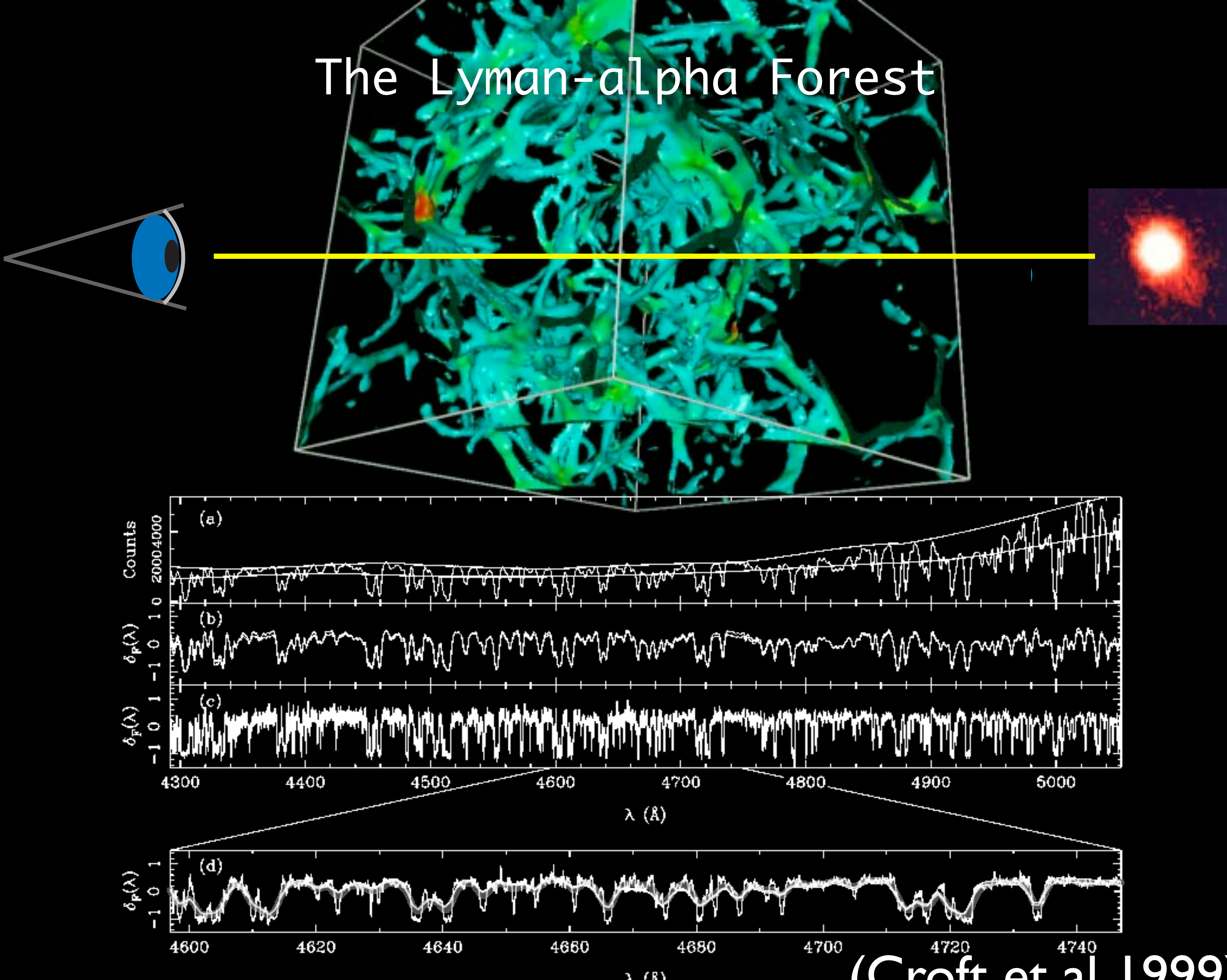
Ω_m Degeneracy



The Onset of Nonlinearity at Small Scales

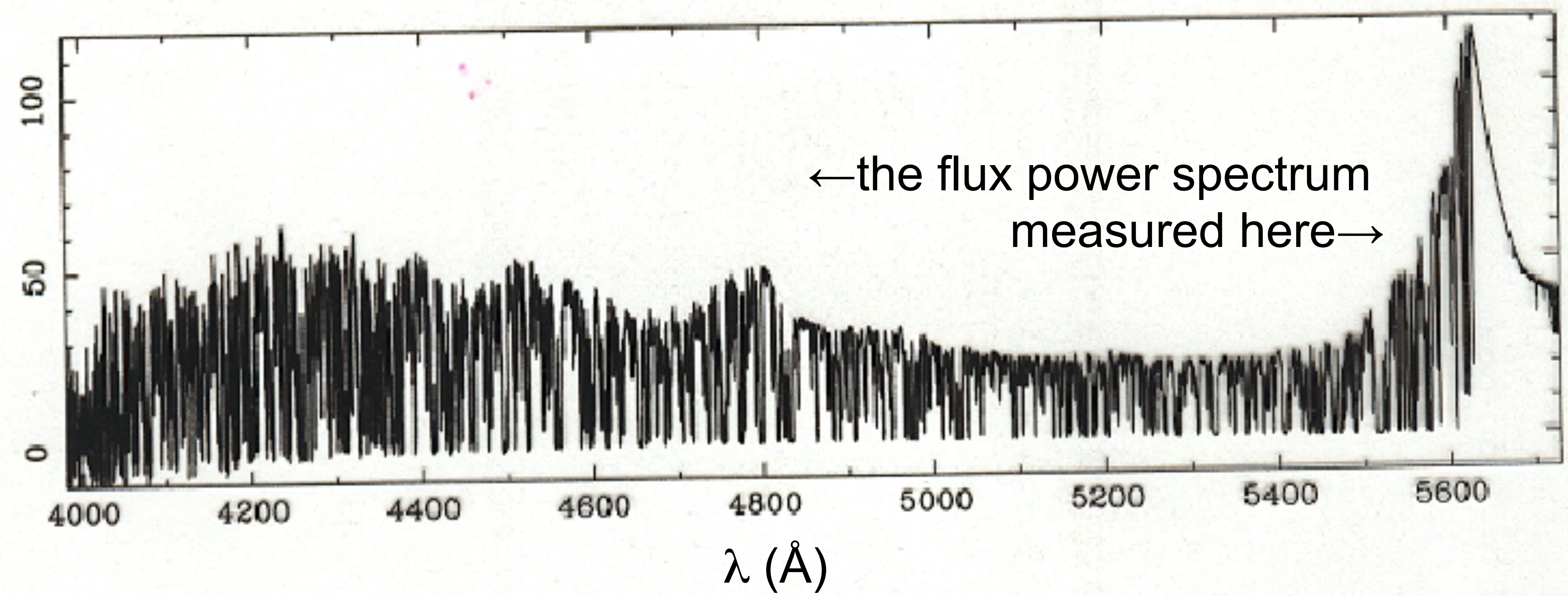


The Lyman-alpha Forest



(Croft et al 1999)

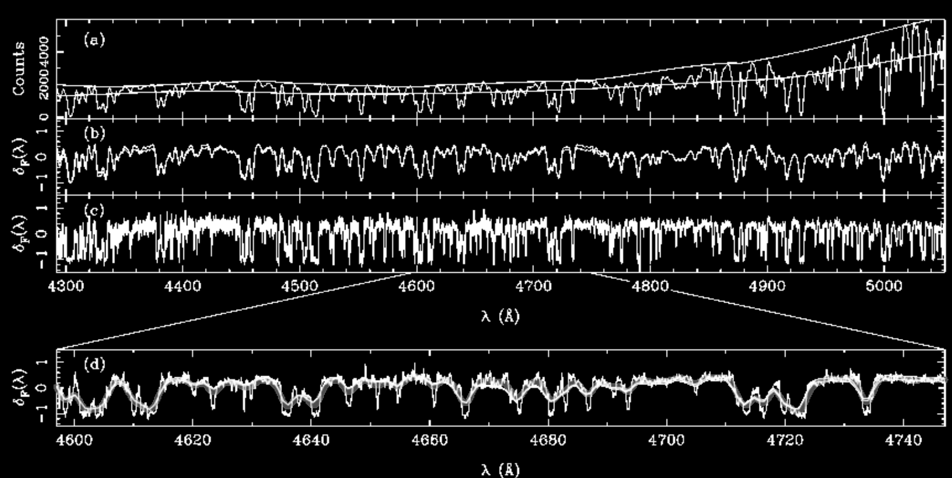
Example Lyman-alpha Forest Flux Spectrum

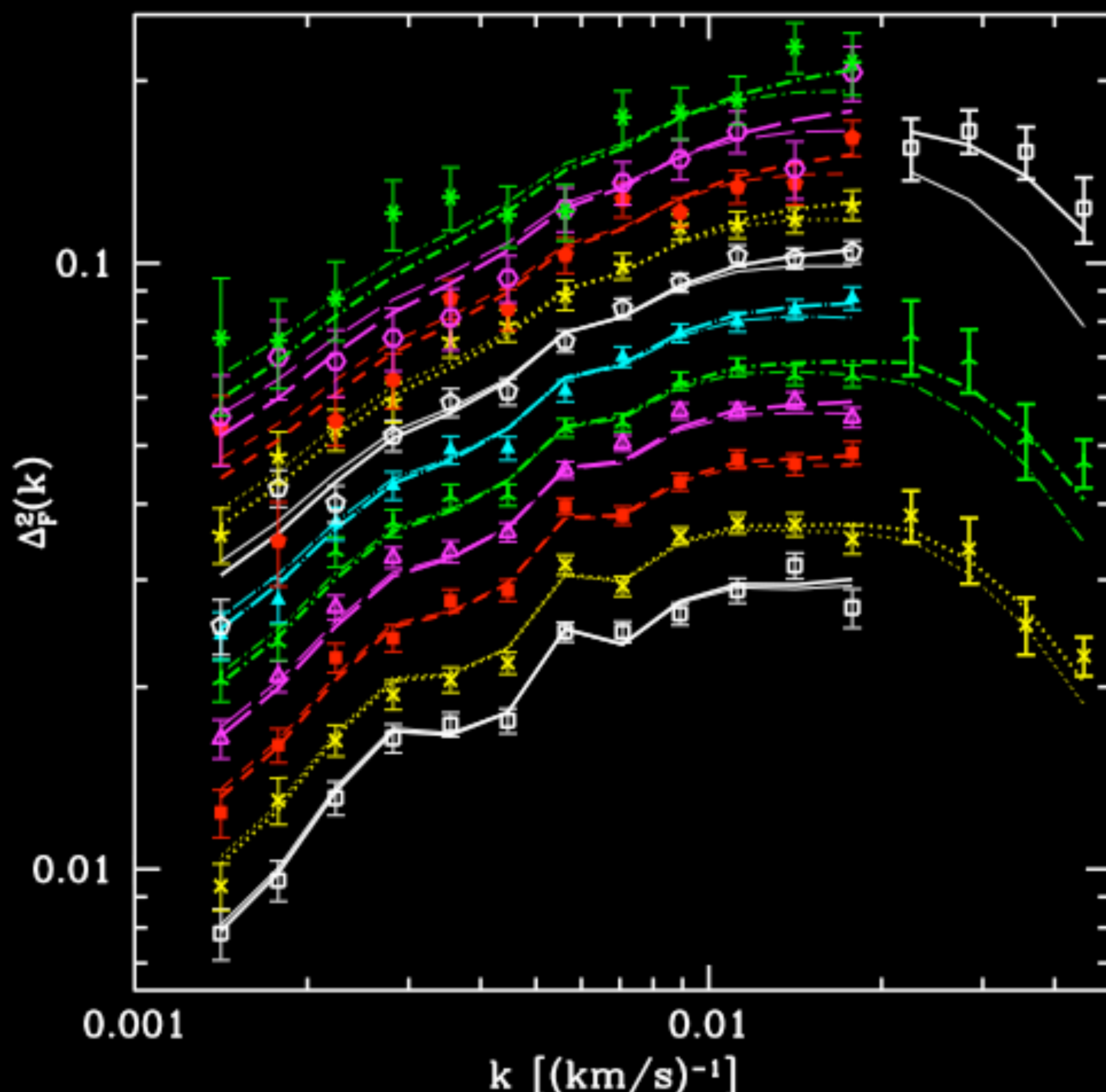


The SDSS Ly-α Flux Power Spectrum Measurement

- Simply a 1D power spectrum of the flux in relevant bins
- However, power is measured simultaneously in the:
  - the transmitted flux/absorption
  - intrinsic quasar spectrum variation
  - *sky, continuum quasar, and count noise*
- $S/N \sim 3$
- Leads to a need to accurately disentangle sources of power and noise in the measurement

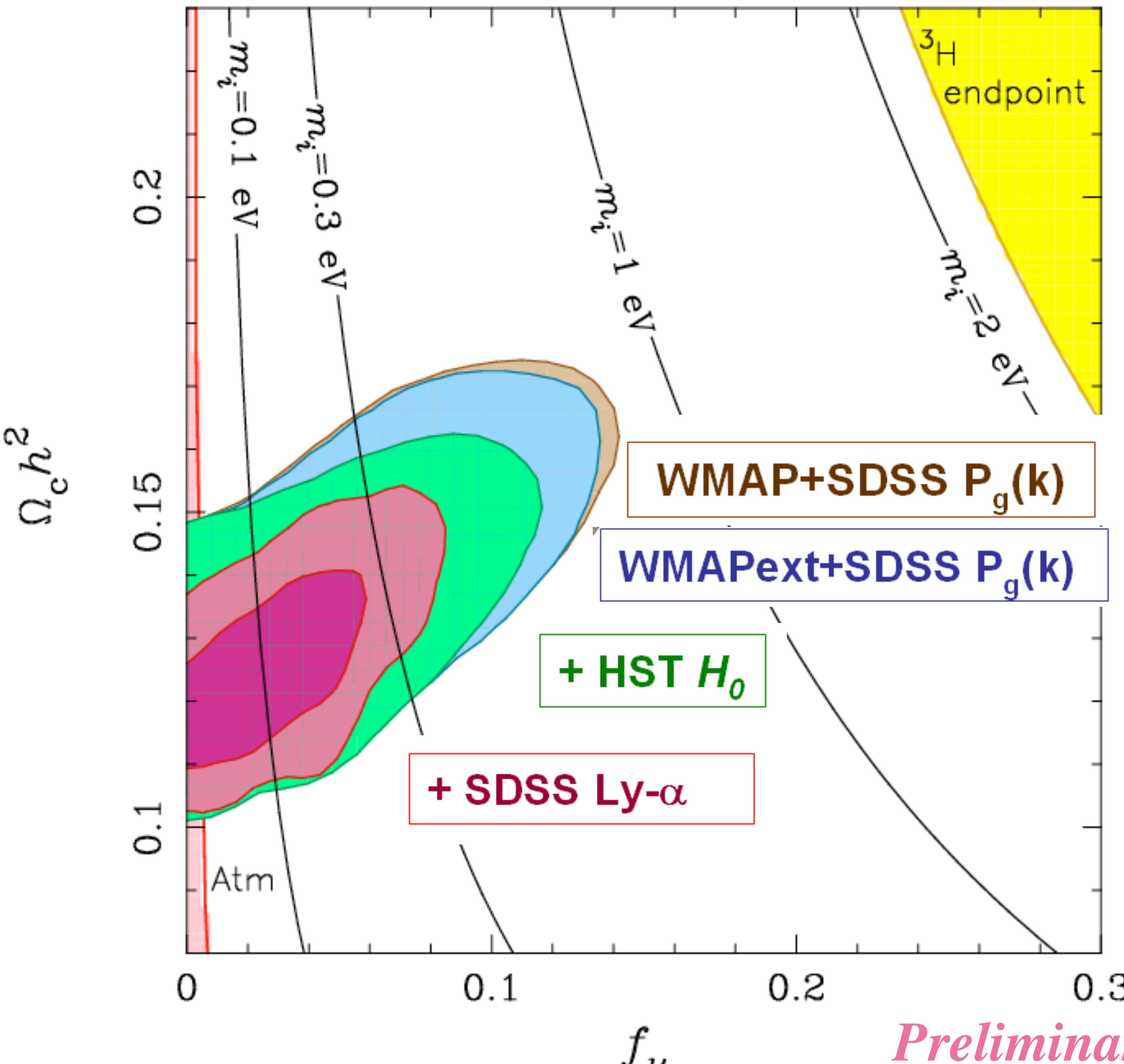
Lyman-alpha Forest Constraints on m_ν





Only public set: McDonald et al. (2006) SDSS $P_F(k)$ Measurement

WMAP+ACBAR+CBI + SDSS + HST: ν mass limits



Preliminary

Summary of Cosmological Neutrino Mass Constraints

WMAP1

- 2dFGRS Shape (conservative but very important limits on Ω_m)
  [Elgaroy et al 2002]: $\boxed{\Sigma m_{\nu_i} \leq 1.8 \text{ eV}}$

95% CL

- SDSS 3D $P_g(k)$ shape + WMAP I
  [Tegmark et al, 2003]: $\boxed{\Sigma m_{\nu_i} \leq 1.8 \text{ eV}}$

⋮

- CMB + SDSS 2-point correlation function (*nonlinear modeling*):
  [Abazajian et al 2005]: $\Sigma m_{\nu_i} \leq 0.69 \text{ eV}$

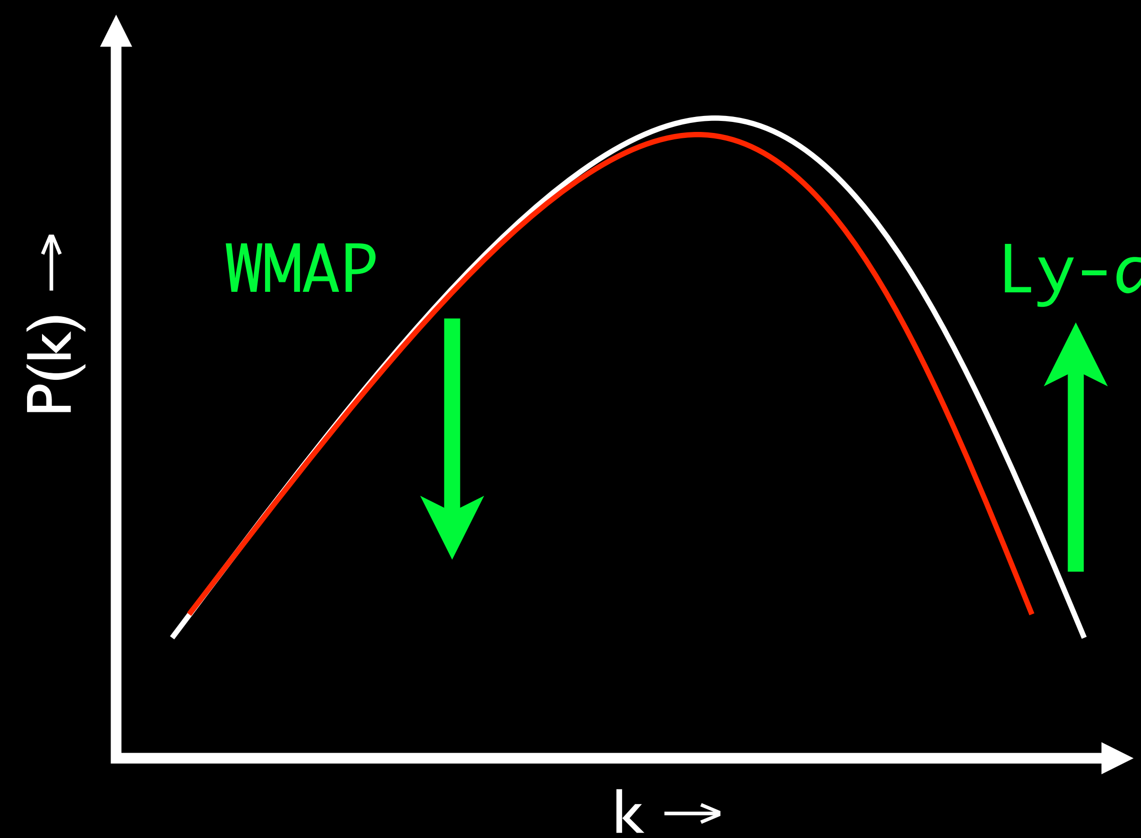
WMAP7

- WMAP 7 alone
  [Komatsu et al 2010]: $\boxed{\Sigma m_{\nu_i} < 1.3 \text{ eV}}$
- SDSS Ly-alpha forest + WMAP 3-year
  [Seljak et al., 2006]: $\Sigma m_{\nu_i} \leq 0.17 \text{ eV}$
- WMAP 7 + SDSS LRG BAO + H_0 [Komatsu et al, 2010]:
  $\boxed{\Sigma m_{\nu_i} < 0.58 \text{ eV}}$

SDSS+WMAP3 Lyman-alpha Constraints (Seljak et al 2006)

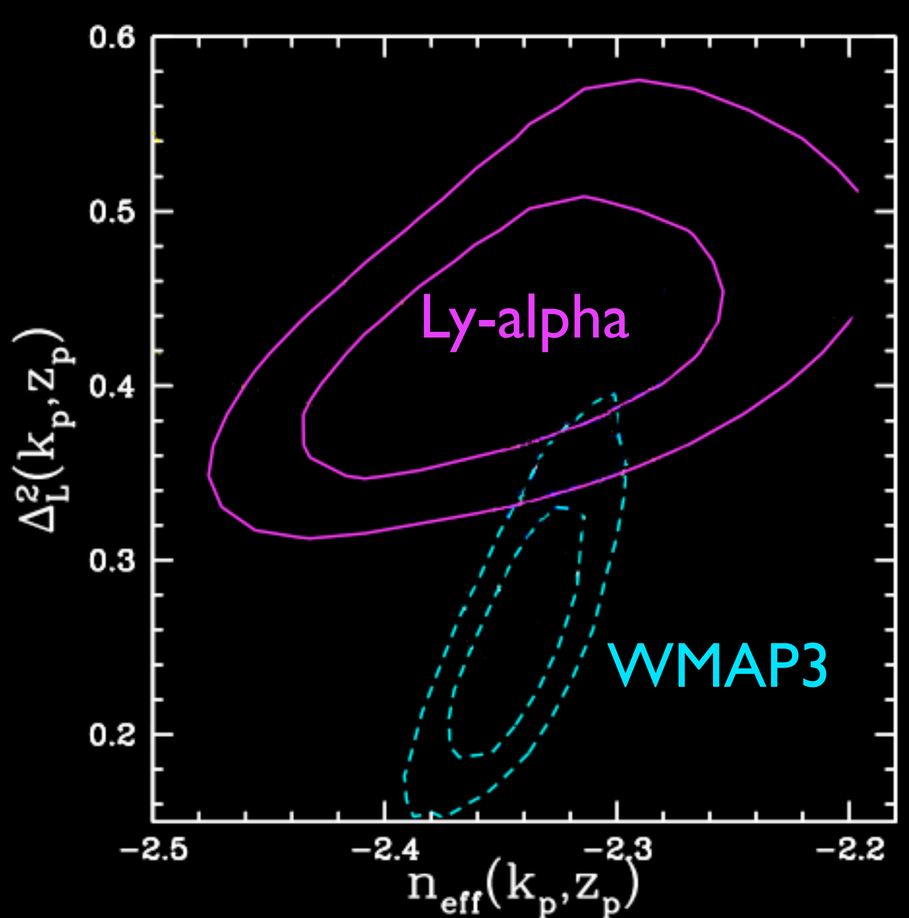
WMAP3:

$$\sigma_8 = 0.74^{+0.05}_{-0.04}$$



SDSS Ly-alpha (Seljak et al 2003):

$$\sigma_8 = 0.9^{+0.03}_{-0.03}$$



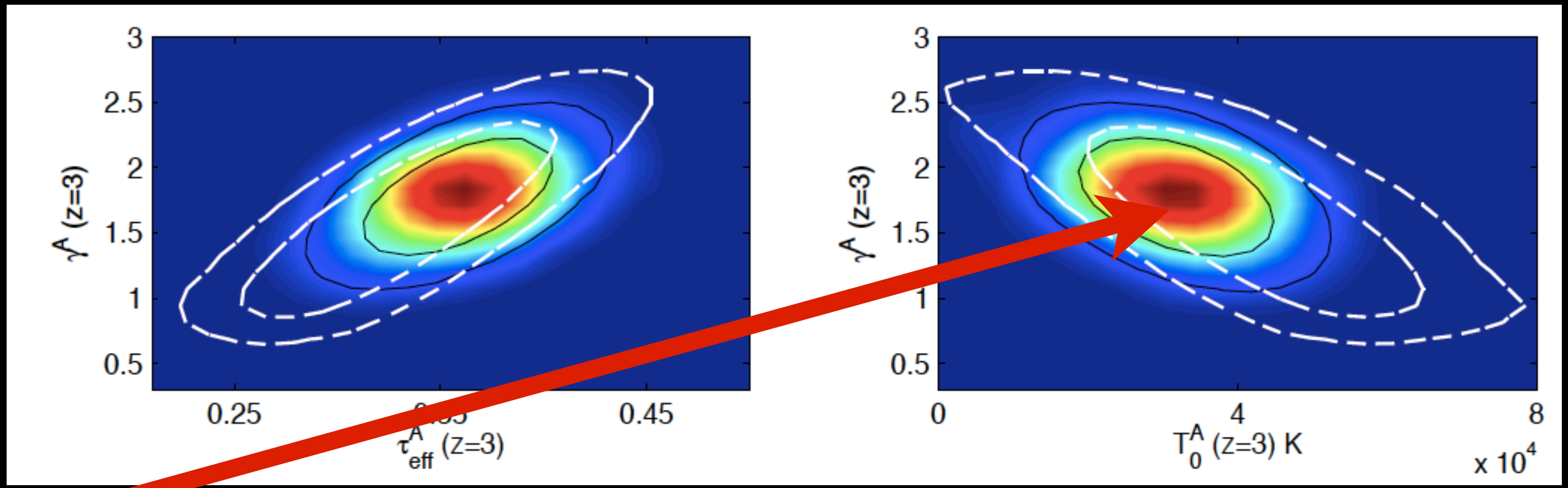
$N_\nu = 5.4^{+0.4}_{-0.6}$ Seljak et al. Lyα

$N_\nu = 3.08^{+0.74}_{-0.68}$ BBN, Cyburt et al. 2004

$N_\nu = 3.04$ (standard model)

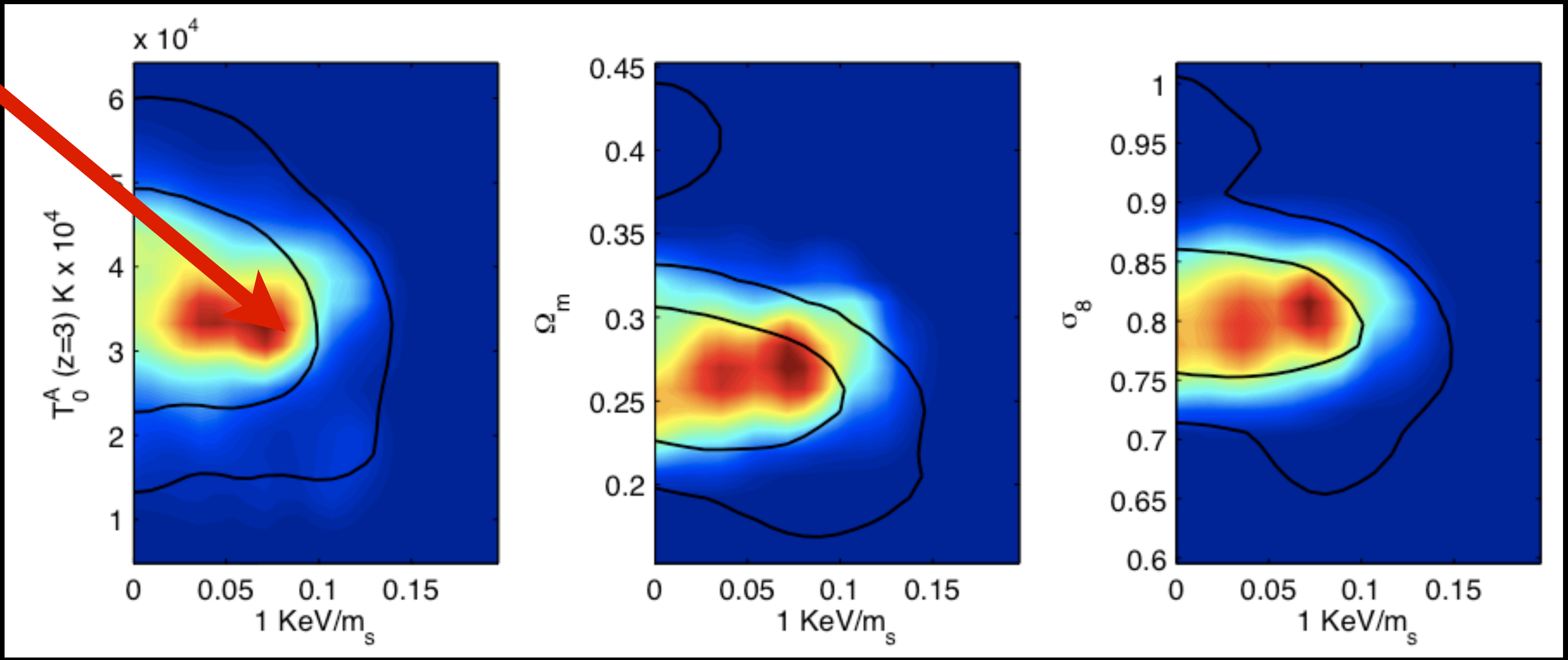
Problems in Temperature Requirements of the IGM?

(CDM & WDM analysis)

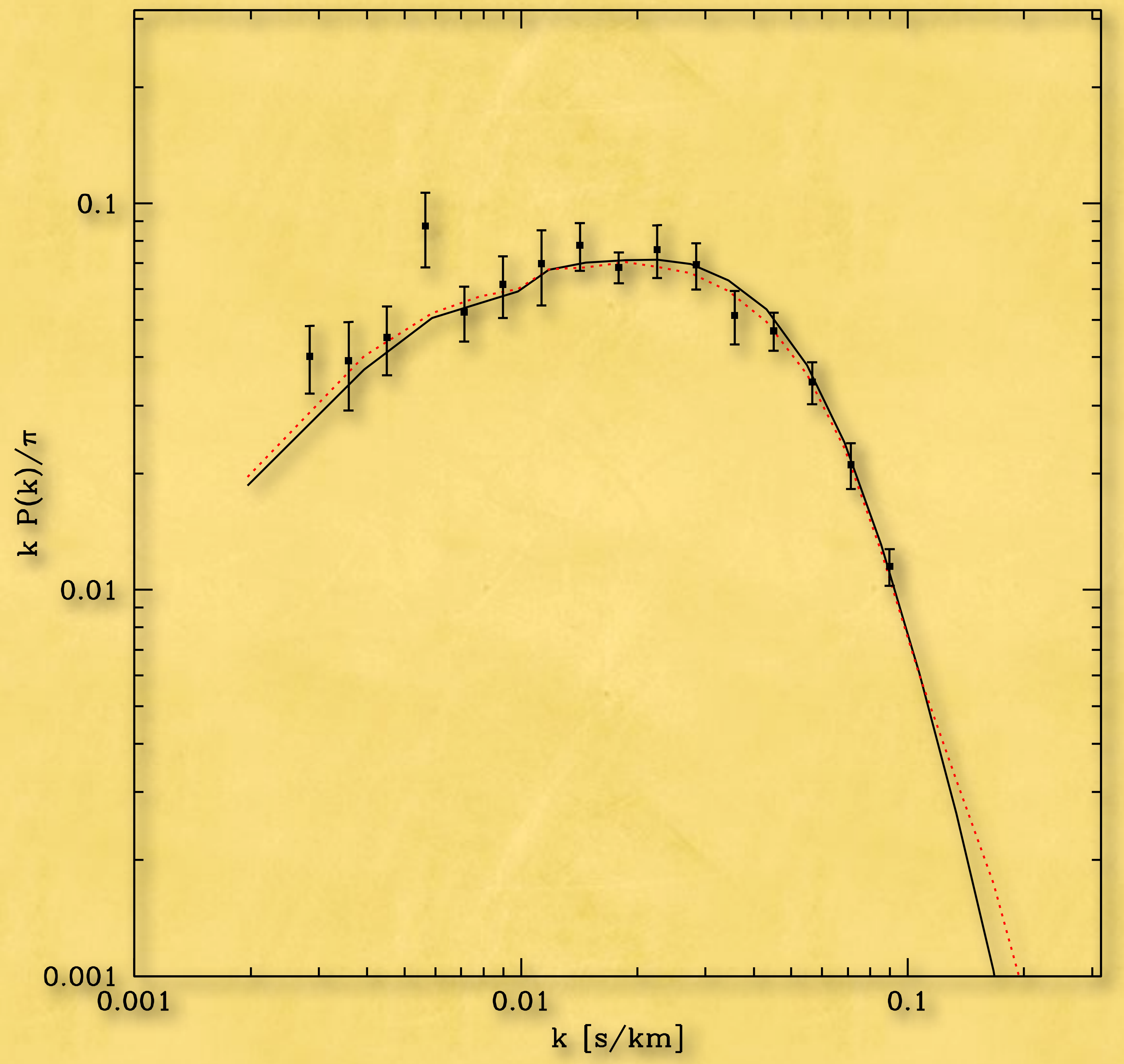


Very high T_0
~35000 K

Viel & Haehnelt (2005); Viel et al 2006



T impacts structure of HI Ly-a Forest



Abazajian, Lidz, Ricotti, in prep.

The SDSS Ly-α Flux Power Spectrum Measurement

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- However, power is measured simultaneously in the:
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- $S/N \sim 3$
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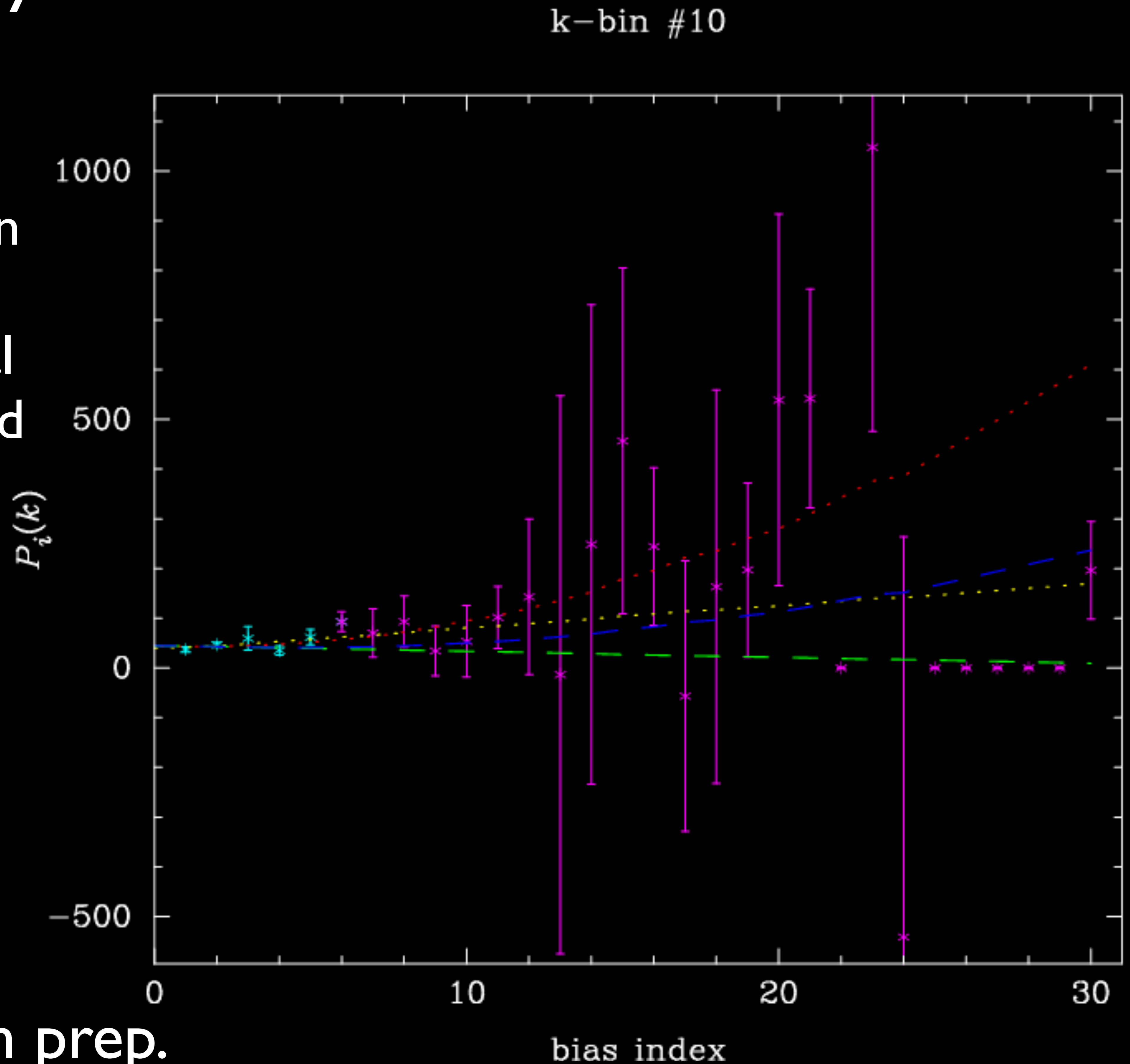
SDSS Lyα Flux Power & Noise

There exists a positive correlation between an increase in spectral noise and increased primordial power

Noticed in McDonald et al 2005



Abazajian et al in prep.

SDSS Lyα Flux Power & Noise

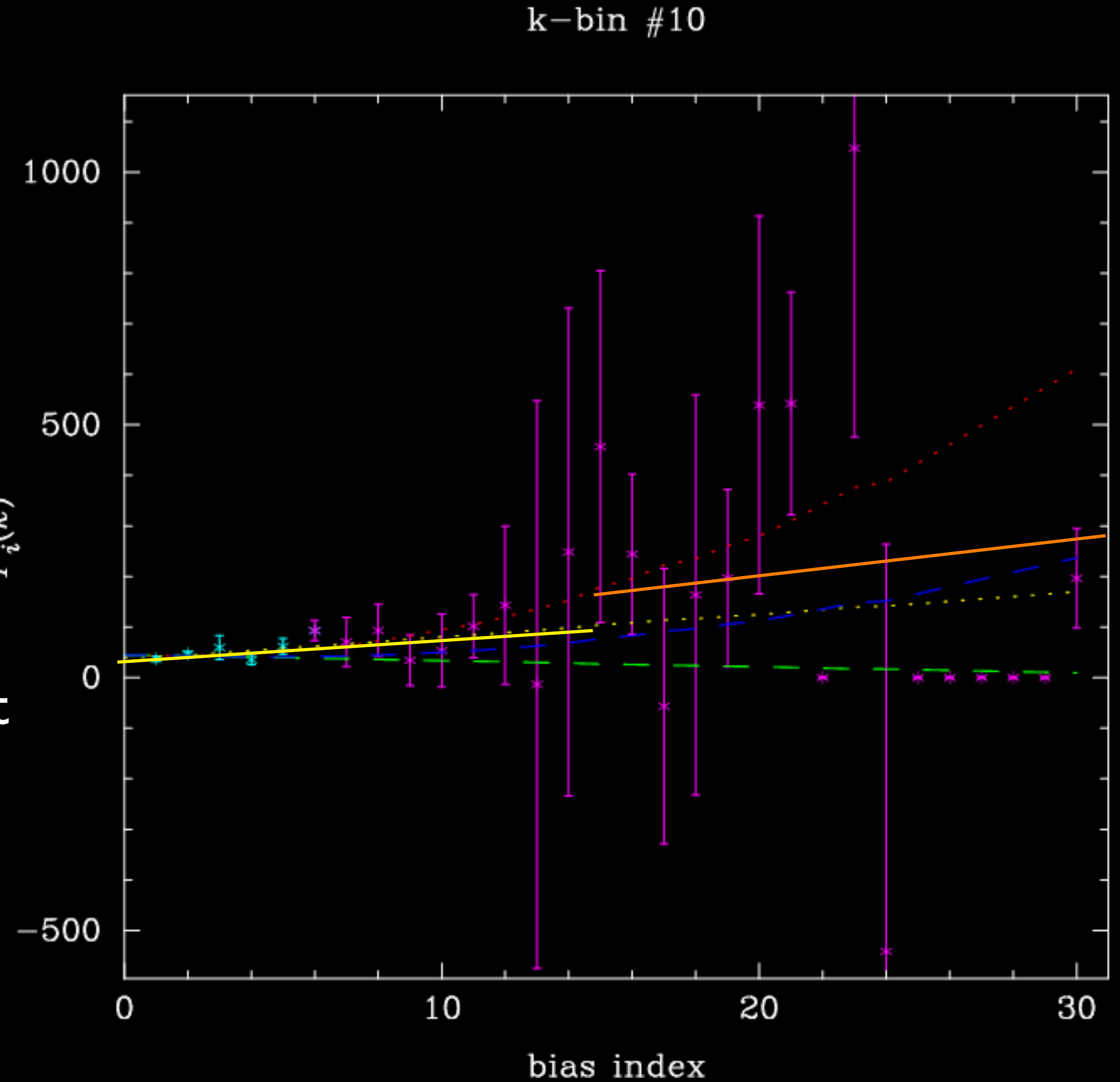
McDonald et al 2005

noticed, but was it properly corrected?

- split of data into high-noise and low noise halves

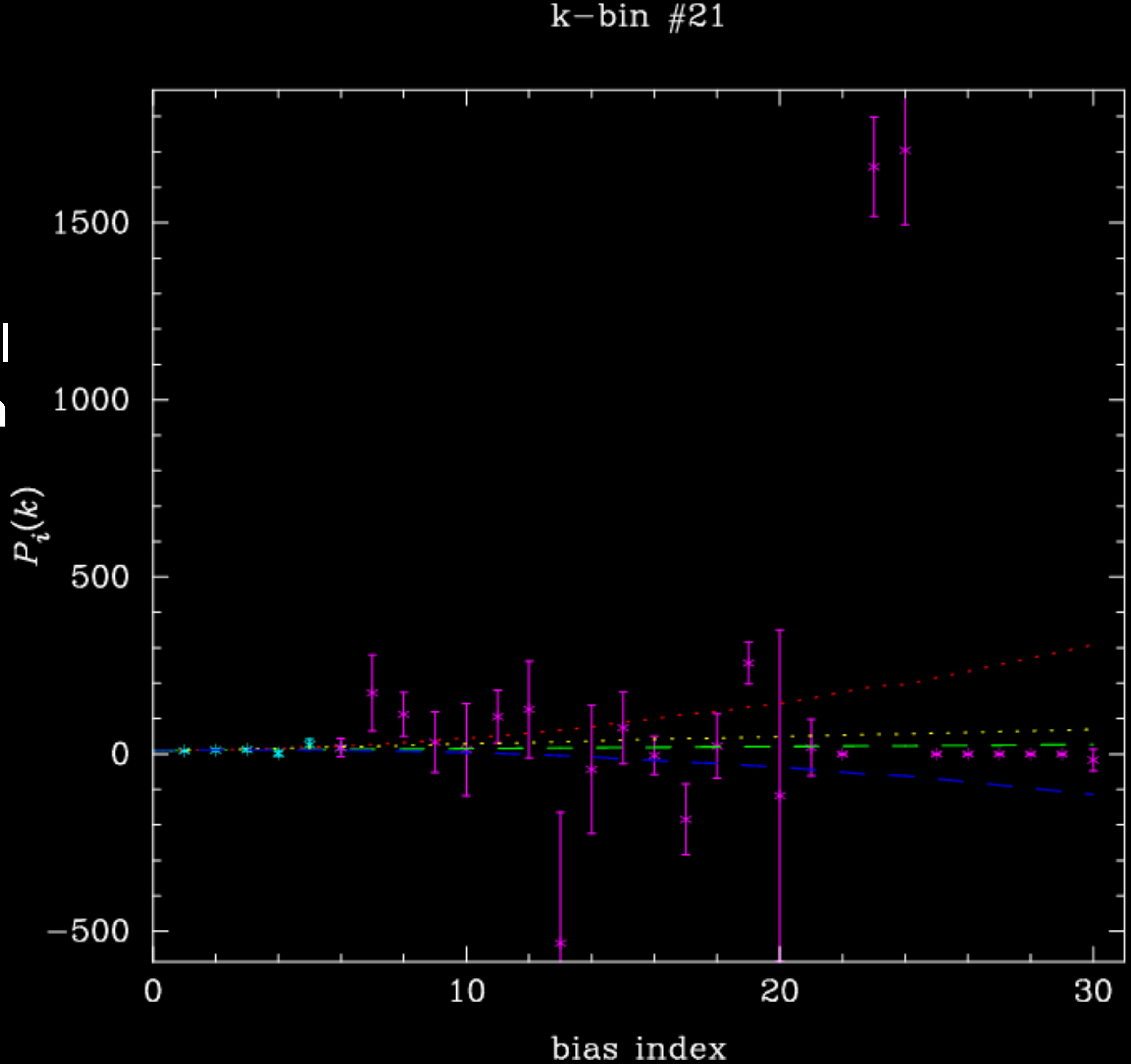
- found same P(k) at zero noise for both splits

- did linear fit to all data

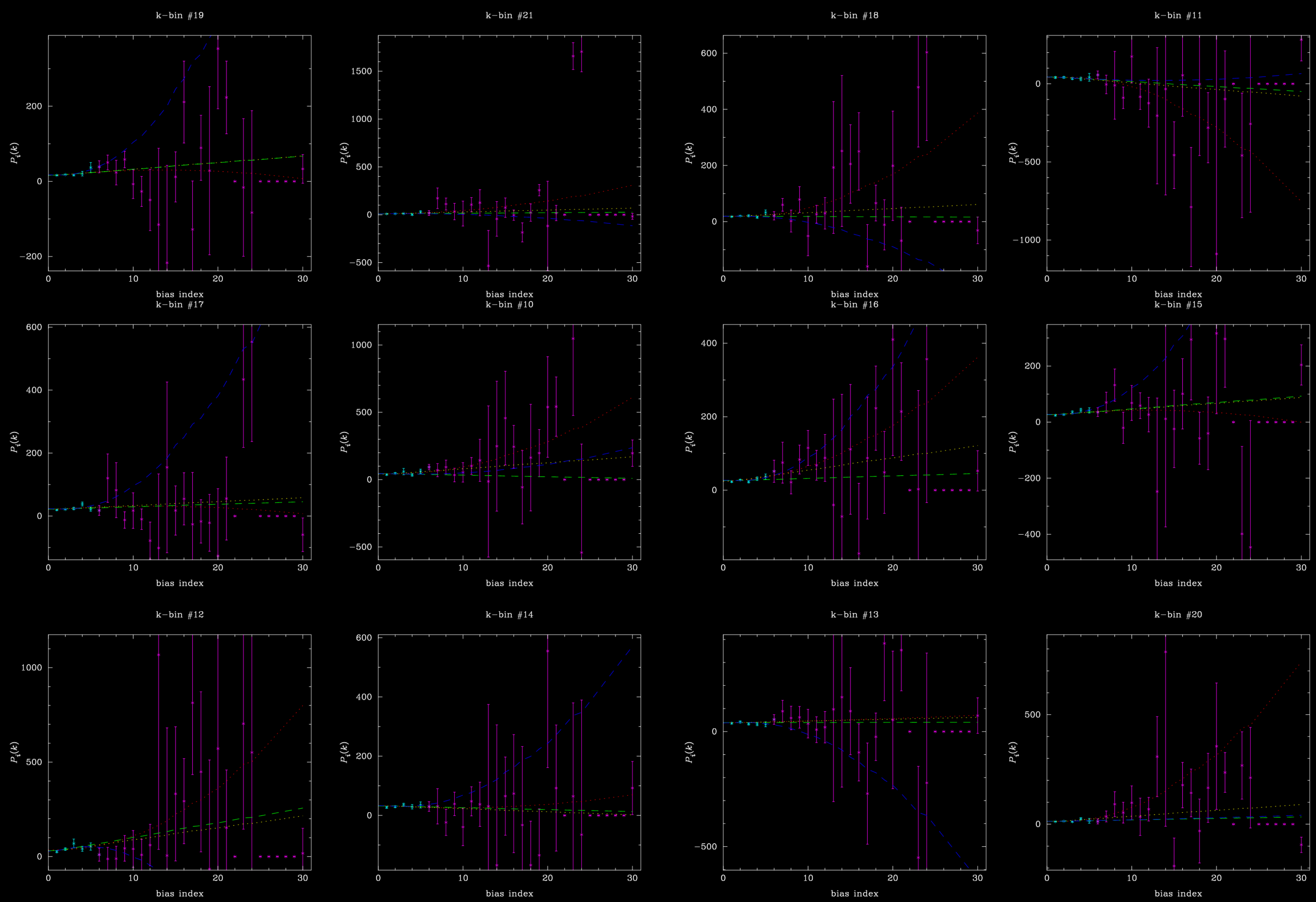


SDSS Lyα Flux Power & Noise

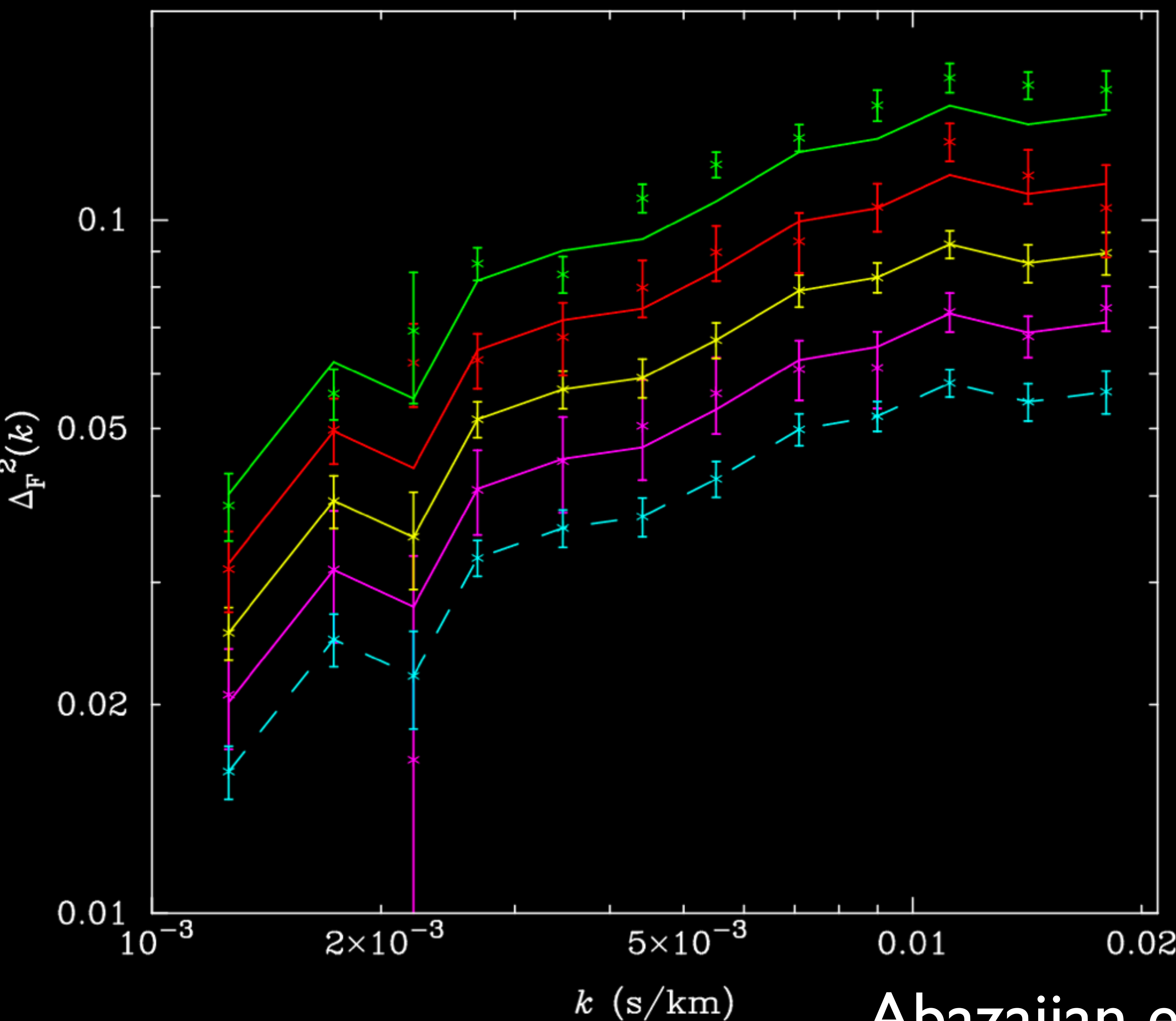
Corrected in our analysis via removal of highest noise bin to a point where the linear fit is statistically sound



Done for each k at each z



Noise-Bias Quantification Dependence



Amplitude shift, larger errors: m_ν, σ_8 ? and implications for CDM / WDM?

Abazajian et al in prep.

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Estimating Upcoming Cosmological Neutrino Mass Constraints

$$\frac{\Delta P}{P} \approx 1\% \approx -12\frac{\Omega_\nu}{\Omega_m}$$

Hu, Eisenstein & Tegmark 1998; Abazajian & Dodelson 2003

$$\Omega_\nu \approx \frac{\sum m_{\nu_i}}{93\ h^2\ \mathrm{eV}}$$

$$\Longrightarrow m_\nu \lesssim (1\%/12) \times \Omega_m (93 h^2\ \mathrm{eV})$$

$$\Longrightarrow m_\nu \lesssim 0.01\ \mathrm{eV}$$

Kaplinghat et al PRL 2003 (CMB WL)
Wang et al PRL 2005 (WL Clusters)
De Bernardis et al. 2009 (Opt. WL)

Summary

- The Lyman-alpha forest is a sensitive probe of gas and dark matter clustering at small scales.
- However, the Lyman-alpha forest may not be as robust as a precision cosmology tool as originally proposed. Degeneracies in the gas temperature-density relation, allowed conservatively to vary, lower sensitivities.
- The SDSS Lyman-α forest flux power spectrum is has strong noise correlations with power that must be corrected appropriately, modifying the amplitude of power. An independent analysis is forthcoming.