LECTURE 4

COSMOLOGY WITH THE LYMAN-ALPHA FOREST

1. The fluctuating Gunn-Peterson approximation
2. The mean baryon density
3. The physical significance of continuous flux statistics
4. Measuring the primordial mass power spectrum
5. Conclusions

The Fluctuating Gunn-Peterson Approximation

Assumes that thermal broadening is negligible and that absorbing gas is in photoionization equilibrium and has an "equation of state"

$$T = \overline{T}\left(\frac{\rho}{\bar{\rho}}\right)^{\gamma}.$$

Result:

$$\begin{aligned}\tau \; &= 0.172\left(\frac{\rho}{\bar{\rho}}\right)^{2-0.7\gamma}\left(1+\frac{dv_{\rm pec}}{H(z)dx}\right)^{-1}\times \\ &\left(\frac{1+z}{4}\right)^{6}\left(\frac{H(z)/H_0}{5.51}\right)^{-1} h^{-1}\times \\ &\left(\frac{\Omega_{\rm b}h^2}{0.0125}\right)^{2}\left(\frac{\overline{T}}{10^4\ {\rm K}}\right)^{-0.7}\left(\frac{\Gamma}{10^{-12}\ {\rm s}^{-1}}\right)^{-1}.\end{aligned}$$

Lyα optical depth is tied in direct and simple way to underlying density and velocity fields.

$$H(z)/H_0 = \left[\Omega_0(1+z)^3 + (1-\Omega_0-\lambda_0)(1+z)^2+\lambda_0\right]^{1/2}$$

$$\left(\frac{\Gamma}{10^{-12}\ {\rm s}^{-1}}\right) \approx \left(\frac{J_{\rm HI}}{2.3\times10^{-22}}\right) \approx \left(\frac{J_{912\mathring{A}}}{3.3\times10^{-22}}\right)$$

Implications for baryon density

The FGPA implies

$$\begin{aligned}\Omega_{\rm WIGM} &\equiv f_{\rm WIGM}\Omega_{\rm b} \\ &= 0.021h^{-3/2}\left(\frac{\left[\int_0^\infty \tau^{1/\beta}P(\tau)d\tau\right]^{\beta/2}}{0.70}\right)\left(\frac{4}{1+z}\right)^3 \\ &\quad \left(\frac{H(z)/H_0}{5.51}\right)^{1/2}\left(\frac{\overline{T}}{10^4\ {\rm K}}\right)^{0.35}\left(\frac{\Gamma}{10^{-12}\ {\rm s}^{-1}}\right)^{1/2}\end{aligned}$$

$$\beta \equiv 2 - 0.7\gamma \approx 1.6.$$

Big bang nucleosynthesis implies

$$\Omega_{\rm b,BBN} = 0.02h^{-2}$$

for Tytler & Burles (1997) D/H ratio.

Recovering the primordial mass power spectrum

Key facts

- Shape of $P_F(k)$ matches $P_\rho(k)$ for $k \lesssim (1\ \mathrm{Mpc})^{-1}$
- For fixed D_A, amplitude of $P_F(k)$ depends only on amplitude of $P_\rho(k)$

Steps

1. Monotonically map $F(\lambda)$ to 1-d field with Gaussian PDF
2. Measure $P_{1d}(k)$ of this field
3. Convert to $P_{3d}(k) = \frac{-2\pi}{k} \frac{d}{dk} P_{1d}(k)$
4. Using PM approximation, compute $P_F(k)$ for Gaussian initial conditions with this $P_{3d}(k)$ shape, various amplitudes, always matching observed D_A
5. Choose $P_\rho(k)$ amplitude that yields observed $P_F(k)$

For details, see Croft et al. 1998 (ApJ, in press, astro-ph/9708018)

Cosmology with the Lyα Forest

The physical simplicity of the Lyα forest makes it an excellent tool for cosmology. A Lyα spectrum is a non-linear, 1-d map of the underlying density field.

For a given model, normalization to observed D_A fixes the parameter combination $\Omega_{\rm b}^2 h^3 \overline{T}^{-0.7} \Gamma^{-1} H_0/H(z)$.

Continuous flux statistics:

- Flux PDF depends on $P(k)$ amplitude, shape of primordial PDF.
- Threshold crossing frequency depends on $P(k)$ shape, $P(k)$ amplitude, $H(z)$.
- Tail of flux gradient PDF depends on $\overline{T}$.
- Flux power spectrum depends on shape and amplitude of $P(k)$.

Possible to reconstruct shape and amplitude of primordial $P(k)$ from Lyα forest data.

Results to date $\Longrightarrow$ $P(k)$ amplitude at $\lambda \sim 1$ Mpc, $z = 3$, is not too far from SCDM prediction.

Needed: Resolution tests, matched comparison to data

An Optimist's Conclusions

As cosmological simulations incorporate progressively more realistic physics, they account for a progressively wider range of observational phenomena.

gravity $\longrightarrow$ large-scale structure

voids, sheets, filaments, and clusters

+ gas dynamics + radiative cooling $\longrightarrow$ galaxies

distinct entities within common halos

some problems with baryonic masses, sizes

lots of star-forming galaxies at $z = 2 - 6$

+ photoionization $\longrightarrow$ Lyman-α forest

produced by fluctuating intergalactic medium

main reservoir of high-redshift baryons

good tool for cosmological tests