Lognormal seminumerical simulations of the Lyman-α forest

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in collaboration with
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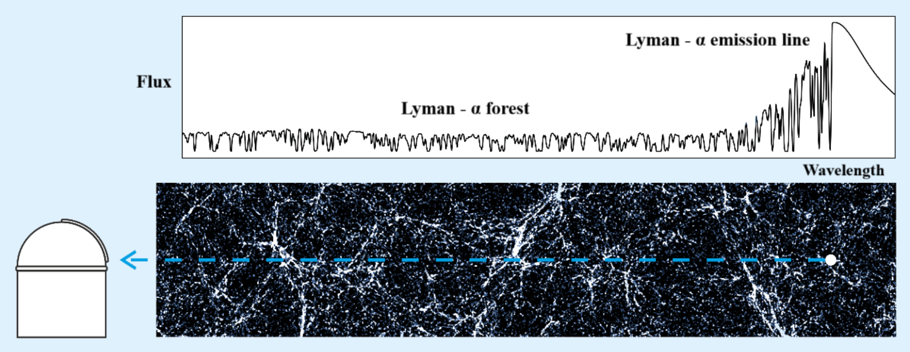
Lyman-α forest



Lyman-α forest

- Baryon Oscillation Spectroscopy Survey (eBOSS)
- DESI
- The UVES Spectral Quasar Absorption Database (SQUAD)
- Keck Observatory Archive: KODIAQ

This imposes a condition to produce computationally inexpensive, but realistic datasets.


COSMIC MICROWAVE BACKGROUND
COSMOLOGISTS
LYMAN-ALPHA FOREST
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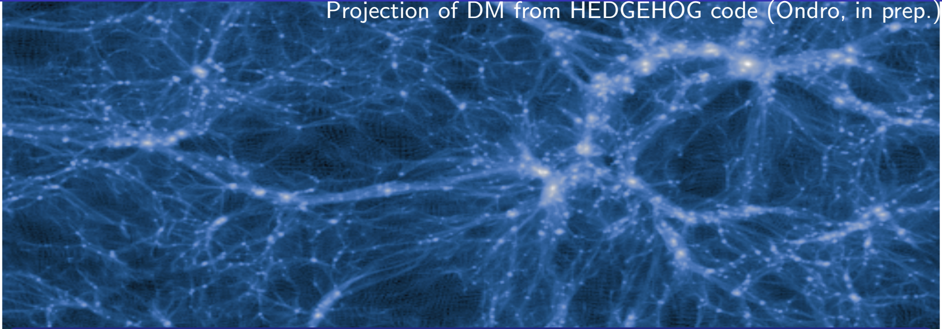
Hydro-simulations



Projection of DM from HEDGEHOG code (Ondro, in prep.)

Pros :)

- more accurate;
- includes most of the relevant physics to model Ly-α forest;

Cons :(

- computationally expensive, limiting their ability to explore large parameter space.

Lognormal seminumerical simulation

- three dimensional power spectrum of the baryonic density fluctuations for any arbitrary z is given by

$$P_{\mathrm{B}}(k,z) = D^2(z) P_{\mathrm{DM}}(k) \exp\left[-2x_{\mathrm{J}}^2(z)k^2\right],$$

- prepare two independent Gaussian fields with power spectra $P_w(k,z)$ and $P_u(k,z)$ as

$$w(k,z) = w_0(k)\sqrt{P_w(k,z)}$$

and

$$u(k,z) = u_0(k)\sqrt{P_u(k,z)},$$

where

$$P_w(k,z) = \beta^{-1}(k,z)\frac{1}{2\pi}\int_{|k|}^{\infty}\frac{\mathrm{d}k'}{k'}P_B(k',z),$$

$$P_u(k,z) = \frac{1}{2\pi}\int_{|k|}^{\infty}\mathrm{d}k'\,k' P_B(k',z) - P_w(k,z),$$

and

$$\beta(k,z) = \frac{\int_{|k|}^{\infty}(\mathrm{d}k'/k'^3)P_B(k',z)}{\int_{|k|}^{\infty}(\mathrm{d}k/k')P_B(k',z)}.$$

Lognormal seminumerical simulation

- linear density and velocity fields in the k-space are given by

$$\delta_B(k,z) = w(k,z) + u(k,z)$$

$$v(k,z) = i\dot{a}k\beta(k,z)w(k,z),$$

  where $\dot{a}$ is the scale factor;
- $\delta_B(x,z)$ and $v(x,z)$ in real comoving space are obtained by using Fourier transforms.
- to account the effect of non-linearities we assuming the number density distribution of the baryons n_B to be a lognormal field

$$n_B(x,z) = n_0(z)\frac{\exp\left[\delta_B(x,z)\right]}{\langle\exp\left[\delta_B(x,z)\right]\rangle}$$

  where $\delta_B(x,z)$ is the linear density contrast in baryons and

$$n_0 = \frac{\Omega_B \rho_C}{\mu_B m_p}(1+z)^3.$$

Lognormal seminumerical simulation

- number density of n_{HI}

$$n_{HI} = \frac{\alpha(T) n_p n_e}{\Gamma_{HI}(z)}$$

- assuming a fully ionized IGM, number densities of protons and free electrons are given by

$$n_p(x,z) = \frac{4(1-Y)}{4-3Y} n_B(x,z)$$

and

$$n_e(x,z) = \frac{4-2Y}{4-3Y} n_B(x,z),$$

where Y is the helium weight fraction.

- temperature field can be related to the baryonic density using the following equation

$$T(x,z) = T_0(z) \left(\frac{n_b(x,z)}{n_0(z)} \right)^{\gamma(z)-1},$$

where T_0 is the temperature at the mean density and $(\gamma - 1)$ is a power-law index.

- Ly-α optical depth is calculated as

$$\tau(x_i, z) = \frac{c I_\alpha}{\sqrt{\pi}} \sum_j \delta x \frac{n_{HI}(x_j, z)}{b(x_j, z)[1 + z(x_j)]} \times V_\alpha \left(\frac{c[z(x_j - z(x_i))]}{b(x_j, z)[1 + z(x_i)]} + \frac{v_b[x_j, z]}{b(x_j, z)} \right),$$

where I_α is the Ly-α absorption cross-section.


Hjerting function
or
Lookup table
Faddeeva function
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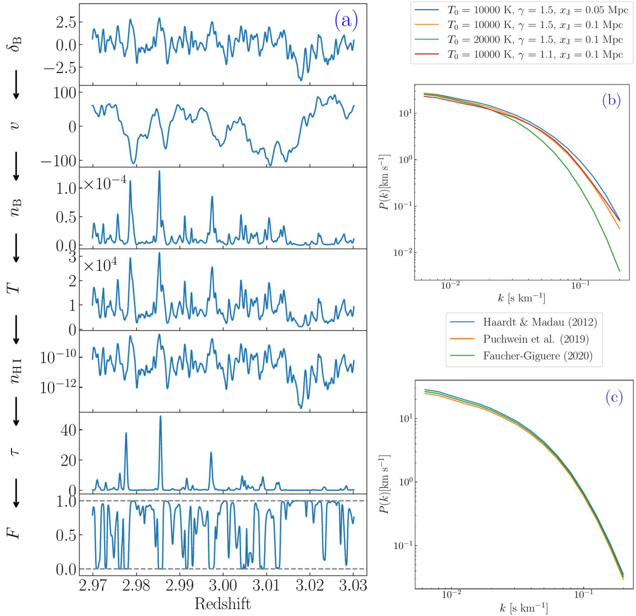
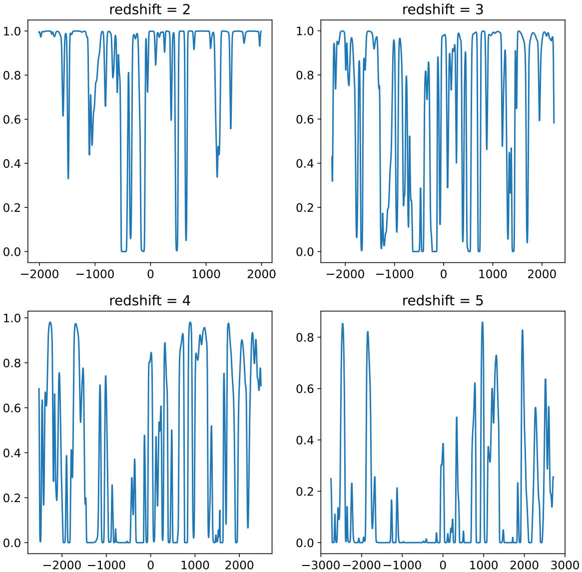
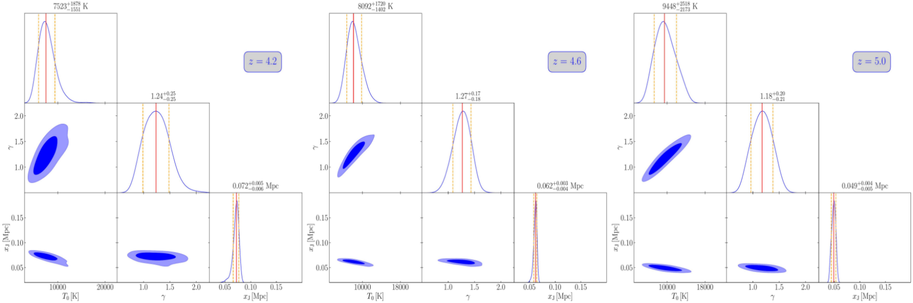

(a)
δ_B
v
n_B
T
n_{HI}
τ
F
$\times 10^{-4}$
$\times 10^{4}$
Redshift
$T_0 = 10000$ K, $\gamma = 1.5$, $x_J = 0.05$ Mpc
$T_0 = 10000$ K, $\gamma = 1.5$, $x_J = 0.1$ Mpc
$T_0 = 20000$ K, $\gamma = 1.5$, $x_J = 0.1$ Mpc
$T_0 = 10000$ K, $\gamma = 1.1$, $x_J = 0.1$ Mpc
(b)
$P(k)$[km s^{-1}]
k [s km^{-1}]
Haardt & Madau (2012)
Puchwein et al. (2019)
Faucher-Giguere (2020)
(c)
$P(k)$[km s^{-1}]
k [s km^{-1}]

$T_0 = 10000$ K, $\gamma = 1.3$, $x_J = 100$ kpc



Comparison with Boera et al. (2019)



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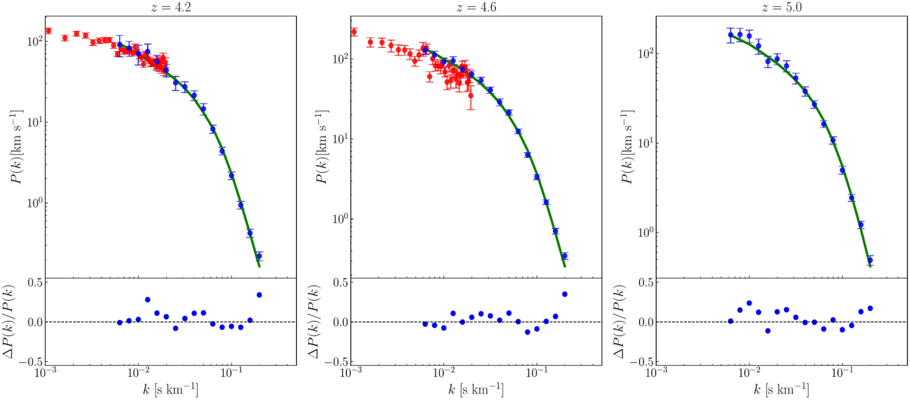


Lognormal seminumerical simulation

Pros :)

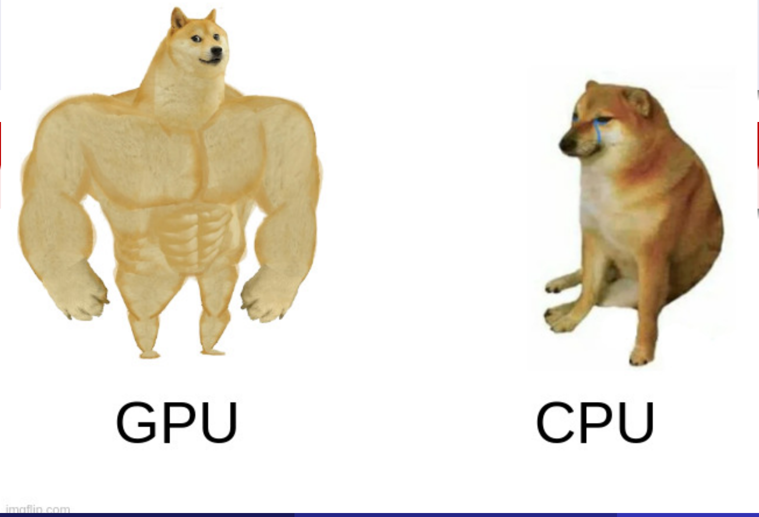
- efficient and flexible;
- capture the essential physics of the intergalactic medium;

Cons :(

- less accurate.

- compared to other lognormal models, our model includes the thermal evolution of the IGM calculated using TECO code (Ondro et al., 2025)
- it is also possible to add emission lines, metals, noise, etc. to create more realistic spectra.

Lognormal seminumerical simulation



the thermal

. to create

Thank you for your attention :)

I am totally keen on the numerical simulations and believe that one day we will be able to simulate entire Universe!

https://github.com/TOndro90