Is Fuzzy Dark Matter in Tension with Lyman-alpha Forest?

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Doktoratskolleg Particles and Interactions

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Abstract

With recent Lyman-alpha forest data from BOSS and XQ-100, some studies suggested that the lower mass limit on the fuzzy dark matter (FDM) particles is lifted up to 10^{-21} eV. However, such a limit was obtained by ΛCDM simulations with the FDM initial condition, and the quantum pressure (QP) was not taken into account which could have generated non-trivial effects on large scale structures. We investigate the QP effects in cosmological simulations systematically, and find that the QP leads to further suppression of the matter power spectrum on small scales. Furthermore, we estimate the flux power spectrum of Lyman-alpha forest, and compare it with the data from BOSS and XQ-100 to set the lower bound on the FDM particle mass to 10^{-23} eV. We carefully estimate the uncertainty in the calculation of one-dimensional flux power spectrum due to the uncertainty of the gas temperature, and conclude that unless the effect of the QP and the uncertainty of the gas temperature are properly taken into account, one cannot exclude the FDM of mass larger than 10^{-22} eV at statistically significant levels.

Fuzzy Dark Matter and Quantum Pressure

The FDM paradigm, in which the dark matter is made of ultra-light bosons in Bose-Einstein condensate. The mass of FDM particles are in $\mathcal{O}(10^{-22}\,\text{eV})$, corresponding to the de Broglie wavelength of order $\mathcal{O}(\text{kpc})$. The nature of FDM can be described by the Schrödinger-Poisson equations. It is useful to think of FDM as superfluid in the simulation by relating the fluid density ρ and its velocity $\boldsymbol{v}$ to the wave function ψ with the definition in quantum hydrodynamics:

$$\psi \equiv \sqrt{\frac{\rho}{m_\chi}} e^{i\theta}, \quad \boldsymbol{v} \equiv \frac{\hbar}{a m_\chi} \boldsymbol{\nabla}\theta = \frac{\hbar}{2 m_\chi i a}\left(\frac{1}{\psi}\boldsymbol{\nabla}\psi - \frac{1}{\psi^*}\boldsymbol{\nabla}\psi^*\right), \qquad (1)$$

where m_χ and a are the mass of the FDM particle and the scale factor. With Eq. (1), we can solve the Schrödinger-Poisson equations to obtain the equation of motion of FDM known as the Madelung equations:

$$\frac{d\rho}{dt} + 3H\rho + \frac{1}{a}\boldsymbol{\nabla}\cdot(\rho\boldsymbol{v}) = 0,$$
$$\frac{d\boldsymbol{v}}{dt} + H\boldsymbol{v} + \frac{1}{a}(\boldsymbol{v}\cdot\boldsymbol{\nabla})\boldsymbol{v} = -\frac{1}{a}\boldsymbol{\nabla}V + \frac{\hbar^2}{2a^3 m_\chi^2}\boldsymbol{\nabla}\left(\frac{\boldsymbol{\nabla}^2\sqrt{\rho}}{\sqrt{\rho}}\right), \qquad (2)$$

where H and V are the Hubble constant and the gravitational potential. The QP is identified as

$$Q \equiv -\frac{\hbar^2}{2a^2 m_\chi^2}\frac{\boldsymbol{\nabla}^2\sqrt{\rho}}{\sqrt{\rho}}, \qquad (3)$$

which is related to the curvature of the density and the mass of the FDM particles. Adopting the effective particle-particle method, we can derive the acceleration due to the QP which is formulated as

$$\ddot{\boldsymbol{r}} = \frac{4M\hbar^2}{M_0 m_\chi^2 \lambda^4 a^2}\sum_j \mathcal{B}_j \exp\left(-\frac{2|\boldsymbol{r}-\boldsymbol{r_j}|^2}{\lambda^2}\right)\left(1-\frac{2|\boldsymbol{r}-\boldsymbol{r_j}|^2}{\lambda^2}\right)(\boldsymbol{r_j}-\boldsymbol{r}), \qquad (4)$$

where M, M_0, λ, and $\mathcal{B}_j$ are the mass of the simulation particle, a normalization factor accounting for the volume ΔV_j occupied by simulation particles, the size of the Gaussian kernel, and the correction factor for high density region, respectively.

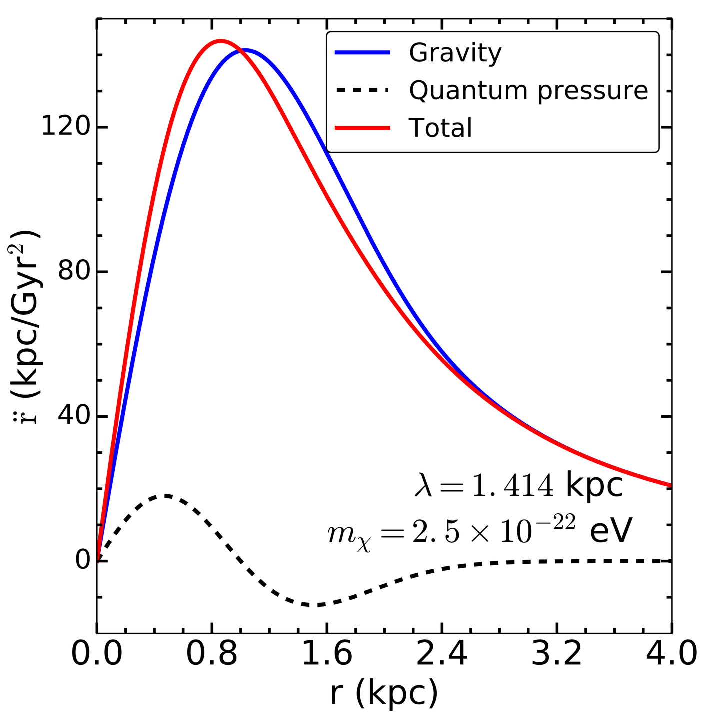

Figure 1: The demonstration of the effect of QP.

Conclusion

We conclude that the current data from BOSS and XQ-100 cannot strongly constrain the FDM particle with $m_\chi > 10^{-22}$ eV, if we consider the effect of QP and the uncertainties of hydrodynamics simulations and the gas temperature. A further comprehensive hydrodynamic simulation including QP and a precise constraint on the gas temperature of Lyman-alpha forest is needed to robustly set a lower bound on the FDM particle mass.

Numerical Result

Abbreviations	Initial Conditions	Dynamics	FDM mass m_χ
CDM	CDM-Standard	CDM-Standard	—
FIC	FDM-modified	CDM-Standard	2.5×10^{-22} eV
FDM	FDM-modified	FDM-modified	2.5×10^{-22} eV
F23	FDM-modified	FDM-modified	2.5×10^{-23} eV

Table 1: The abbreviations and details of simulations we have performed.

We perform four simulations given in Table. 1 and calculate the corresponding flux power spectrum to compare with the Lyman-alpha Forest data. The result is demonstrated in Fig. 2. One can see that the difference between different simulations is subtle, but the effect of QP is important on small scale. A χ^2 test is performed, which indicates that it is not statistically significant to exclude **FIC** and **FDM** with the data from BOSS and XQ-100.

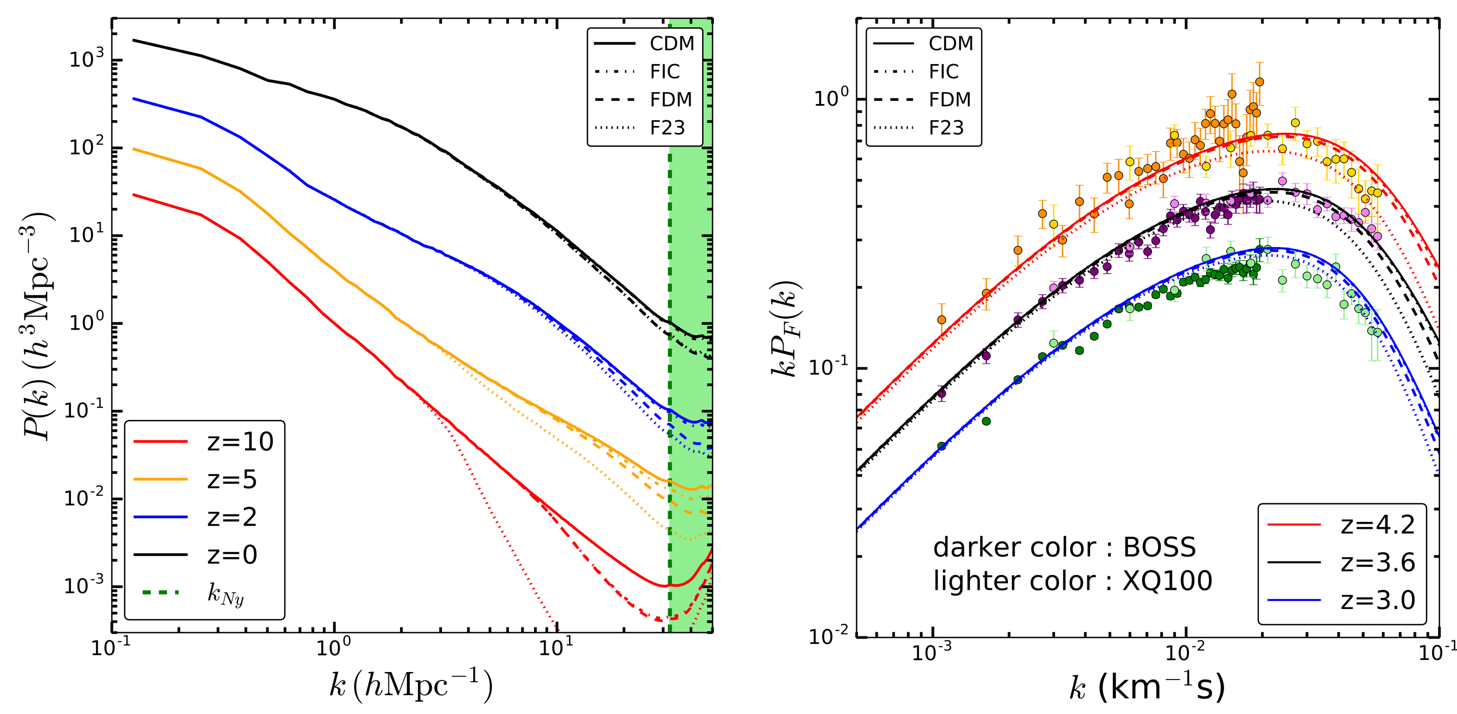

Figure 2: Left panel: the matter power spectrum measured from our simulations. Right panel: the comparison of the flux power spectrum and the data from BOSS and XQ-100.

Uncertainties Discussion

The uncertainty of hydrodynamics simulations is hard to control compared to DM-only simulations, including the different treatments of the gaseous component and the errors from the gas parameters. Apart from the simulation uncertainty, the effect of changing the gas temperature can mimic the effect of FDM on the flux power spectrum, hence it is difficult to tell whether the suppression is due to the dynamics or different temperatures of the gas. From Fig. 3, it is obvious that the current constraint on the gas temperature is not good enough to exclude FDM with $m_\chi = 2.5\times10^{-22}$ eV, let alone the uncertainties of other thermal parameters of the gas.

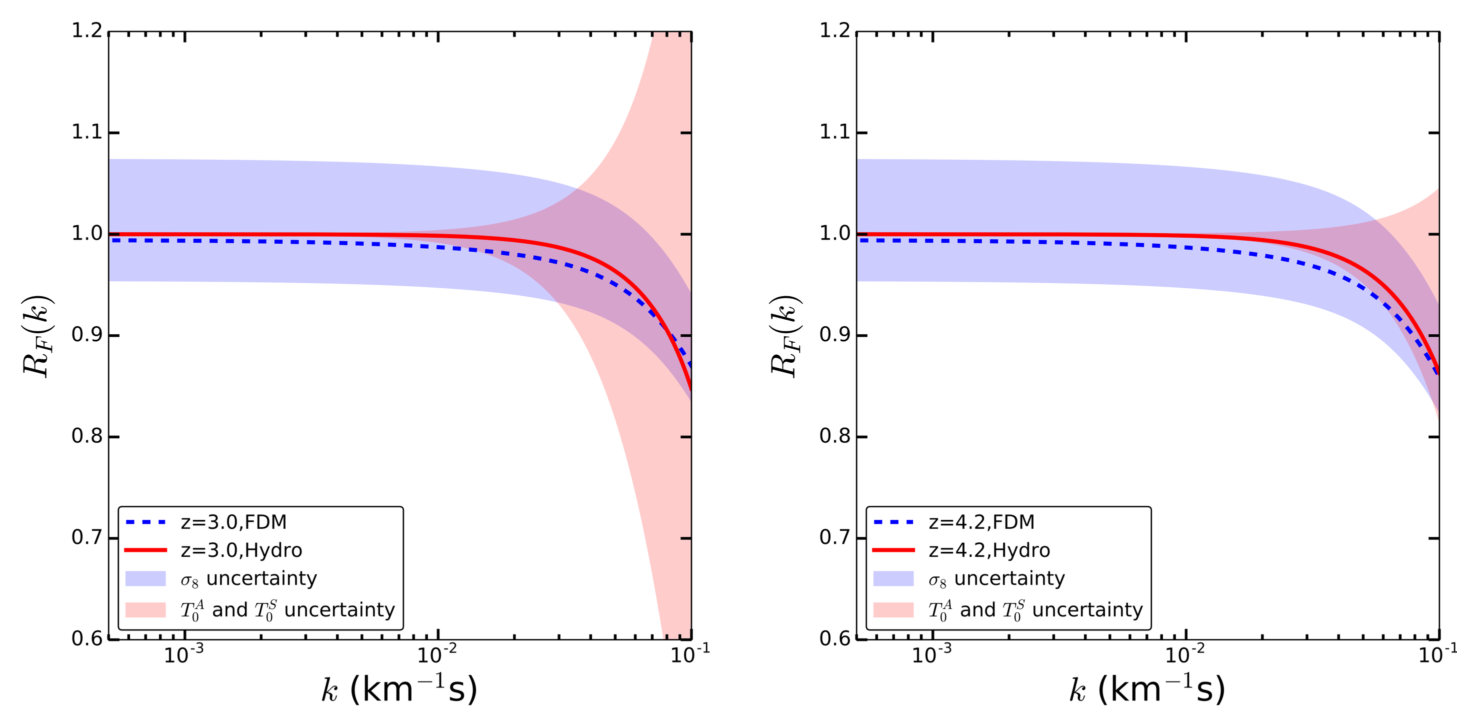

Figure 3: The effect of FDM (blue dashed line) compared with the effect of changing the gas temperature (red solid line) at $z = 3.0$ (left panel) and $z = 4.2$ (right panel). The blue shaded area shows the 1σ uncertainty range of σ_8 and the red shaded area shows the 1σ uncertainty range of the gas temperature T.