An analytic model for the sub-galactic matter power spectrum in fuzzy dark matter halos

Workshop on Very Light Dark Matter (2021/09/28)

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Contents

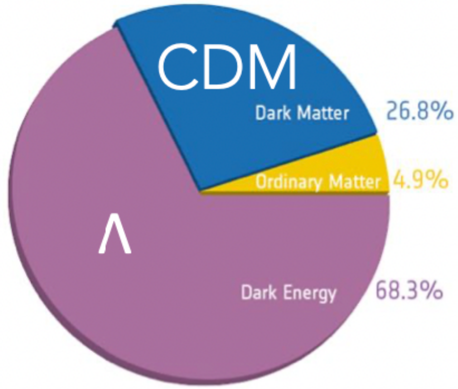
CDM and Small Scale Problems

Standard cosmology : Cold Dark Matter (CDM)

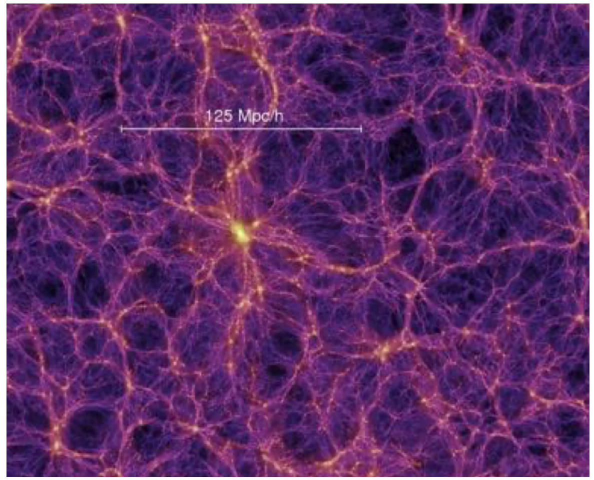
→ succeed in explaining the large scale structure

→ However, there are several small scale problems (< 1 Mpc)

- Core-cusp problem
- Missing-satellite problem
- Diversity problem
- Too-big-to-fail problem



ESA - Planck Satellite



Springel+ 2006

Other dark matter model?

What is Fuzzy Dark Matter ?

Fuzzy Dark Matter (FDM) = a scalar particle coupled to gravitational field without self-interaction whose mass is around $m \sim 10^{-22}$ eV

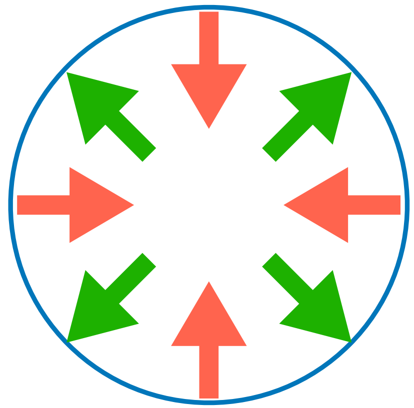
→ de Broglie wavelength $\lambda \sim \mathcal{O}(1)\mathrm{kpc}$

→ Wave nature can be seen on cosmological scale within $\mathcal{O}(1)\mathrm{kpc}$.

→ Missing satellite problem can be solved.

On large scale, FDM behaves the same way as CDM.

→ Succeed in generating the large scale structure



Gravitational Collapse

||

Uncertainty Principle

The property of FDM halos

FDM simulation reveals the nature of FDM halos.

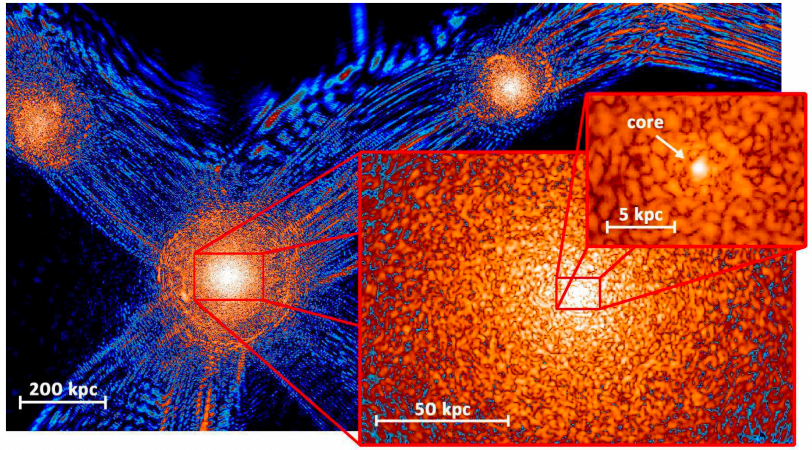
Two distinct features in FDM halos :

Granular structures & Soliton core

→ Core-cusp problem can be solved.

Granular structures originate from the wave nature of FDM.

→ <u>Do these small structures really exist?</u>



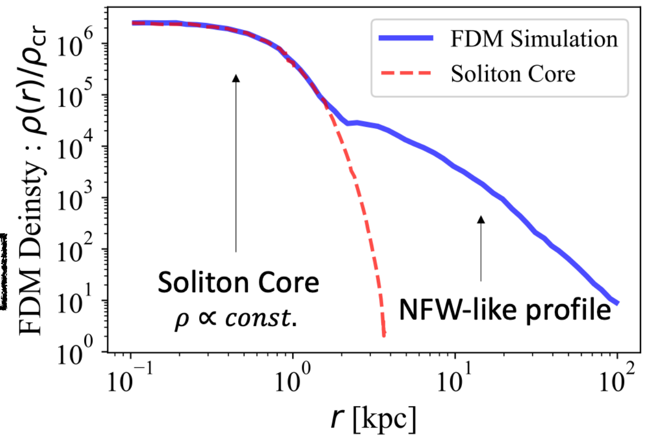
Schive+ 2016

Interference pattern / Granular structure

Soliton core

+

NFW-like profile



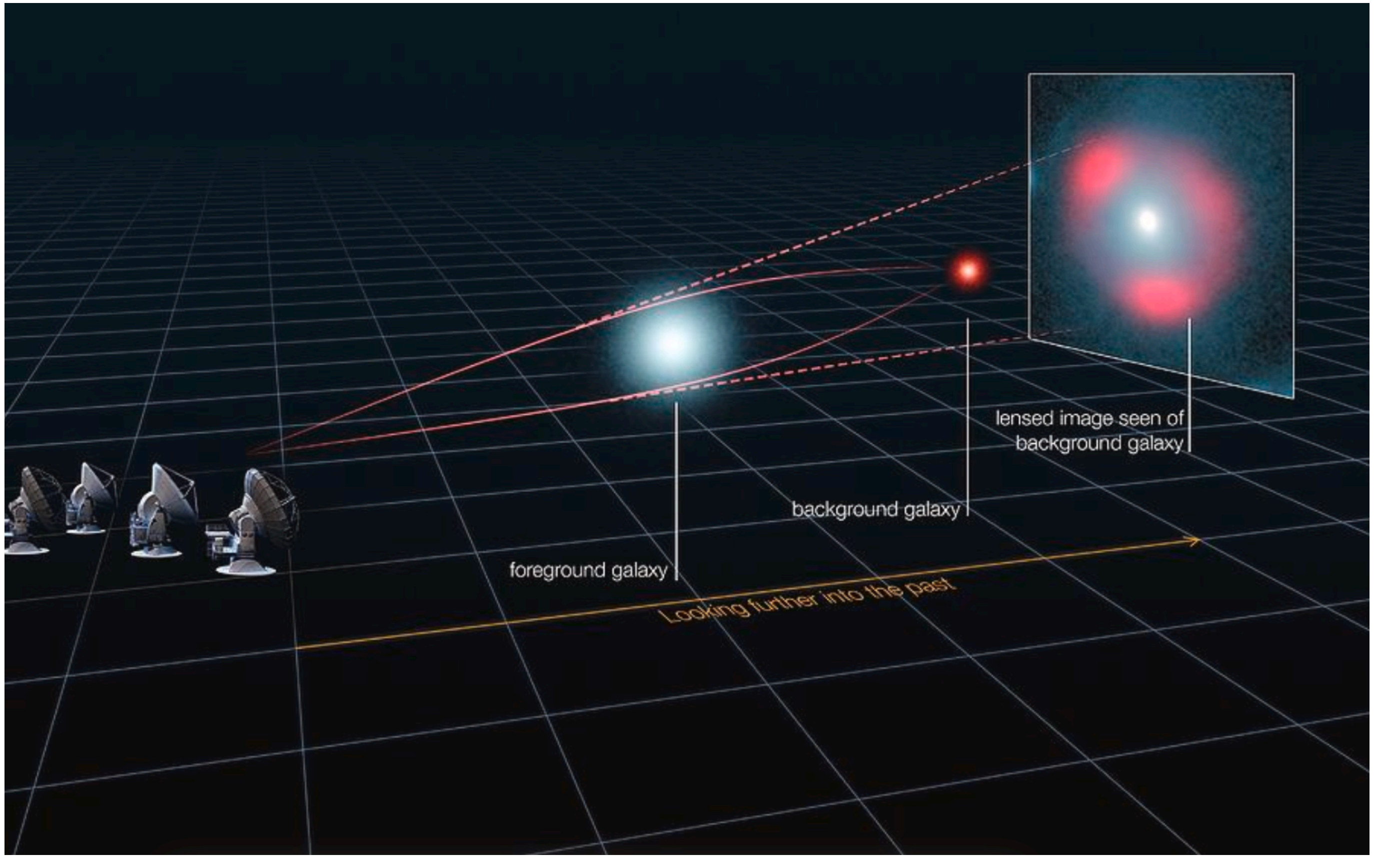
Schive+ 2016

Strong lens systems

Lensed image of background source

↓

Information about the density distribution of foreground source



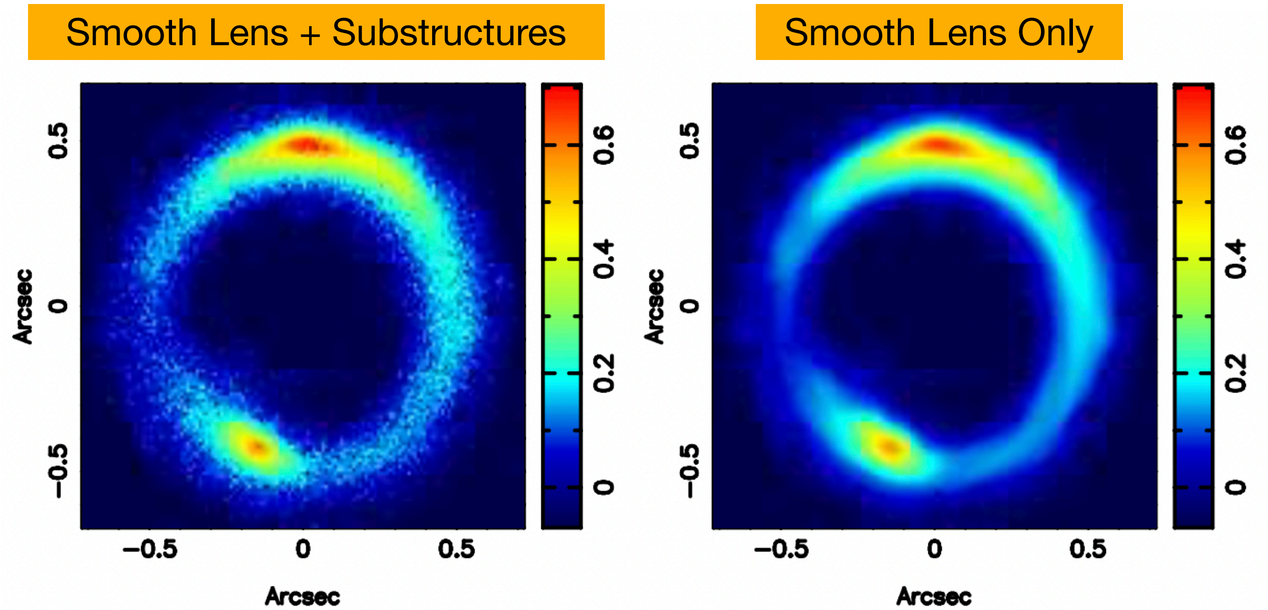
ALMA (ESO,NRAO,NAOJ)

Sub-galactic matter power spectrum estimation by strong lens systems

Substructures in Lens galaxy

Perturbation to smooth lensing potential

Surface-brightness anomalies in Lensed images



Vegetti+ 2012

Bayer et.al.(2018) obtained the upper bound of sub-galactic matter power spectrum from the strong lens system SDSS J0252+0039.

Motivation of our study

Can we constrain the granular structures in FDM halos by the sub-galactic matter power spectrum?

↓

We make an analytic model of the power spectrum, and compare it with the observational constraints obtained by the strong lens system.

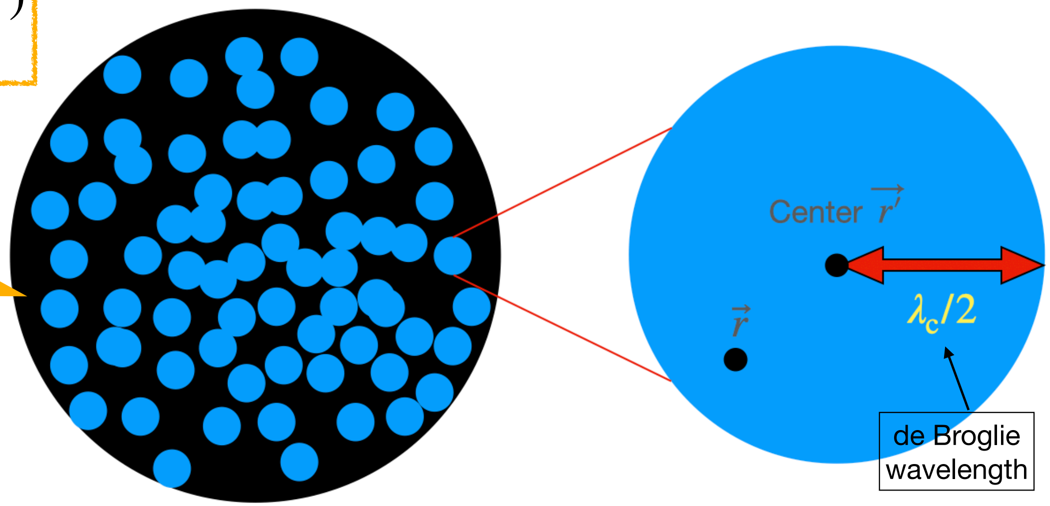
Sub-galactic matter power spectrum in FDM halos

FDM-only case

Halo profile : $\rho_{\rm h}(\boldsymbol{r})$
(smooth)

distribute randomly

$$\langle n(\boldsymbol{r})\rangle = \frac{1}{V_{\rm c}}$$



FDM halo

Each clump

Each clump

Mass : $M_{\rm c}(\boldsymbol{r}') = \rho_{\rm h}(\boldsymbol{r}')V_{\rm c}$

Volume : $V_{\rm c} = \frac{4}{3}\pi\left(\frac{\lambda_{\rm c}}{2}\right)^3$

Density profile inside each clump

$$\rho_{\rm c}(\boldsymbol{r}\ ;\boldsymbol{r}') = M_{\rm c}(\boldsymbol{r}')\underbrace{u(\boldsymbol{r}-\boldsymbol{r}')}_{\text{Normalized mass density function}}$$

FDM profile : $\rho_{\rm f}(\boldsymbol{r}) = \int_V d^3r'\rho_{\rm c}(\boldsymbol{r}\ ;\boldsymbol{r}')n(\boldsymbol{r}')$

Superposition of clumps

Sub-galactic matter power spectrum

Projected density field

$$\Sigma_{\rm f}(\boldsymbol{x}) \equiv \int_Z dz\ \rho_{\rm f}(\boldsymbol{r})$$

Matter fluctuation around the position $\boldsymbol{x}$

$$\delta(\boldsymbol{x}) \equiv \frac{\Sigma_{\rm f}(\boldsymbol{x}) - \Sigma_{\rm h}(\boldsymbol{x})}{\Sigma_{\rm h}(\boldsymbol{x})}$$

Ensemble average of projected density $\Sigma_{\rm f}(\boldsymbol{x})$

The sub-galactic matter power spectrum is

$$\left\langle \widetilde{\delta}_{\boldsymbol{k}}\ \widetilde{\delta}_{\boldsymbol{k}'} \right\rangle \equiv S_\epsilon \delta^{(2)}_{\boldsymbol{k}+\boldsymbol{k}',\boldsymbol{0}}\ P(k)$$

$$\boxed{P_{\rm f}(k) = \frac{V_{\rm c}}{r_{\rm h}(x)}\ |\,\widetilde{u}_k\,|^2}$$

Spherical system

We define an effective radius :

$$r_{\rm h}(x) \equiv \frac{\Sigma_{\rm h}^2(x)}{\int_Z dz\ \rho_{\rm h}^2(r)} = \frac{\left(\int_Z dz\ \rho_{\rm h}(r)\right)^2}{\int_Z dz\ \rho_{\rm h}^2(r)}$$

Sub-galactic matter power spectrum in FDM halos

Include baryon

Baryon profile : smooth function $\rho_{\rm b}(r)$

Independent of granular structures

Total density is

$$\rho(r) = \rho_{\rm f}(r) + \rho_{\rm b}(r)$$

The projected density is

$$\Sigma(x) = \Sigma_{\rm f}(x) + \Sigma_{\rm b}(x)$$

$$\Sigma_{\rm b}(x) \equiv \int_Z dz\ \rho_{\rm b}(r)$$

The sub-galactic matter power spectrum can be obtained by the same calculation.

$$\boxed{P(k) = \left(\frac{\Sigma_{\rm h}(x)}{\Sigma_{\rm h}(x) + \Sigma_{\rm b}(x)}\right)^2 P_{\rm f}(k)}$$

Smaller amplitude

FDM mass dependence

Large dependence !!

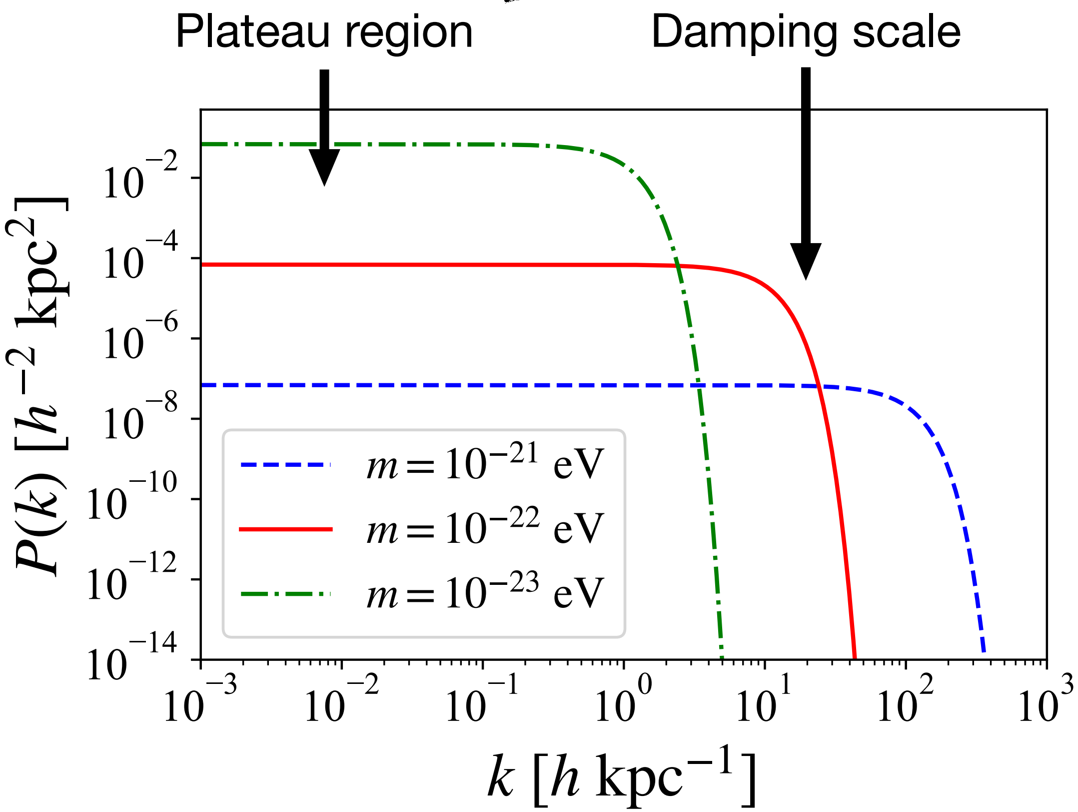
Damping scale :

$$k \sim 1/\lambda_c \propto m$$

Plateau region :

$$P(k) \propto \lambda_c^3 \propto m^{-3}$$

Larger FDM mass
→ Smaller de Broglie wavelength
→ Larger amount of clumps along the line of sight
→ Matter fluctuation is averaged



Other parameters are set to
$M_h = 10^{13} h^{-1} M_\odot,\ M_s/M_h = 0.01,\ x = R_{vir}/10$

Compare with observation

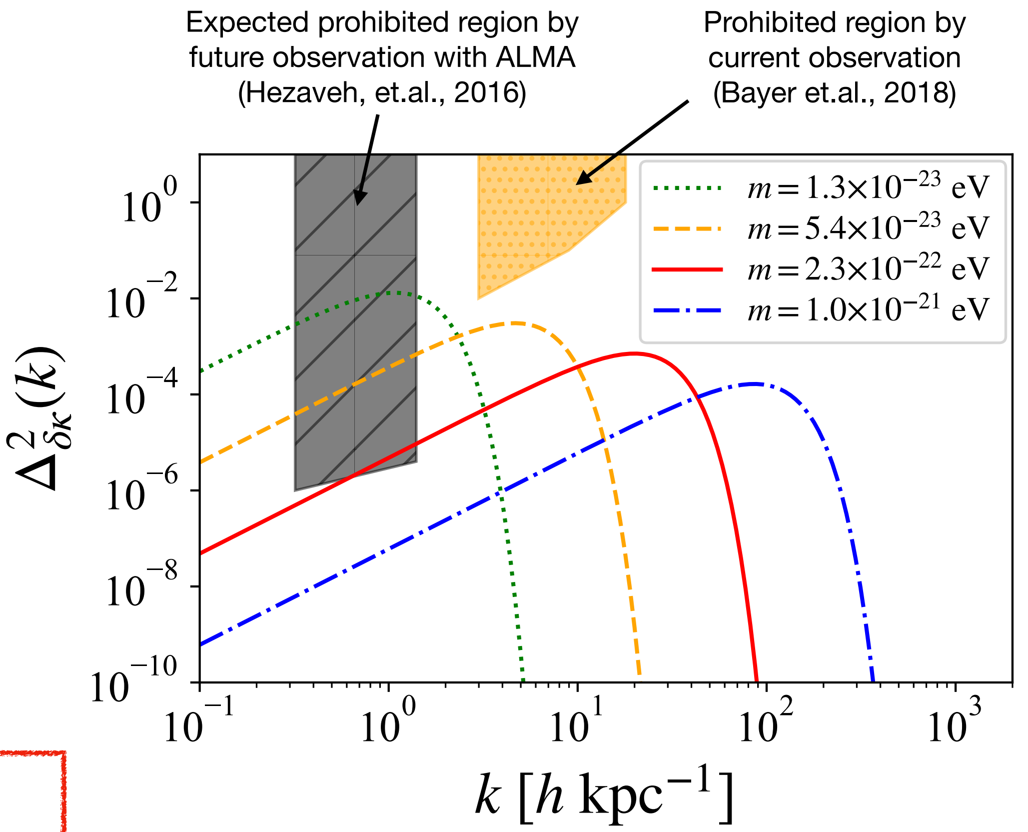
The upper limit of the sub-galactic matter power spectrum is obtained by strong lens system SDSS J0252+0039.

Dimensionless convergence power spectrum :

$$\Delta^2_{\delta\kappa}(k) = 2\pi k^2 \left(\frac{\Sigma(x)}{\Sigma_{\rm cr}}\right)^2 P(k)$$

Current : No constraint on FDM mass

Future : Constraints on interesting region



Comparison of power spectrum with different FDM mass with SDSS J0252+0039.

$M_{\rm h} = 6.3\times10^{12}h^{-1}M_\odot$, $M_{\rm s}^{\rm Salp} = 2.0\times10^{11}h^{-1}M_\odot$, $x = 3.1h^{-1}$ kpc

Summary

1. We construct the analytic model for the sub-galactic matter power spectrum in FDM halos.
2. Since FDM mass dependence on the sub-galactic matter power spectrum is large, it is useful to study FDM model with it.
3. Current observation gives no constraint on FDM mass, but future observation can constrain on the interesting mass range.