Constraints on Fuzzy Dark Matter Models from Planck 2015 Data

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Summary

- **Fuzzy dark matter (FDM) = free ultralight scalar field DM**

- **We modified "CLASS" and performed MCMC analysis w/ MontePython**

- **We considered two models and obtained following constraints:**

(1) ΛFDM model : DM = FDM

$$\begin{aligned} m &> 10^{-24.1}\,\mathrm{eV} \quad (2\sigma) \\ &> 10^{-24.9}\,\mathrm{eV} \quad (3\sigma) \end{aligned}$$

(2) Λ(F+C)DM model : DM = FDM + CDM

$$\begin{aligned} f = \frac{\Omega_{\mathrm{FDM}}}{\Omega_{\mathrm{DM}}} &< 0.06 \quad (3\sigma) \quad \text{for} \quad m = 10^{-26}\,\mathrm{eV} \\ &< 0.19 \quad (3\sigma) \quad \text{for} \quad m = 10^{-25.5}\,\mathrm{eV} \\ &< 0.96 \quad (3\sigma) \quad \text{for} \quad m = 10^{-25}\,\mathrm{eV} \end{aligned}$$

Fuzzy Dark Matter (FDM)

- **Free scalar field with very small mass :** $\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2$

  candidate : axion with negligible self-interaction

- **"Quantum pressure"**

$$\ddot{\delta} + 2H\dot{\delta} - \left(4\pi G\bar{\rho} - \frac{k^2}{a^2}c_s^2\right)\delta = 0 \qquad \left(\delta \equiv \frac{\delta\rho}{\bar{\rho}}\right)$$

  $\boxed{\textbf{effective fluid approx.}}$ **sound speed :** $c_s^2 = \left[1 + \left(\frac{2ma}{k}\right)^2\right]^{-1}$

  deviation from CDM on small scales (large k)

- **Jeans scale : gravity = pressure**

$$k_J \sim \frac{1}{1\,\mathrm{Mpc}}\left(\frac{m}{10^{-25}\,\mathrm{eV}}\right)^{1/2}$$

  CMB is sensitive to $m \lesssim 10^{-25}\,\mathrm{eV}$

Independent Variables

[Ureña-López & Gonzalez-Morales (2016)]

- **Polar coordinate in phase space**

Background : (Ω_ϕ, θ)

$$-\frac{\kappa m \phi}{\sqrt{6}H} = \sqrt{\Omega_\phi}\cos(\theta/2)$$

$$\frac{\kappa \dot{\phi}}{\sqrt{6}H} = \sqrt{\Omega_\phi}\sin(\theta/2)$$

$$\rho_\phi = \frac{3H}{\kappa^2}\Omega_\phi$$

$$p_\phi = -\cos\theta \cdot \rho_\phi$$

$$(\kappa^2 = 8\pi G)$$

Perturbation : (α, ϑ)

$$\sqrt{\frac{2}{3}}\frac{\kappa m \delta\phi}{H} = -\sqrt{\Omega_\phi}e^\alpha \sin(\theta/2 - \vartheta/2)$$

$$\sqrt{\frac{2}{3}}\frac{\kappa \delta\dot{\phi}}{H} = -\sqrt{\Omega_\phi}e^\alpha \cos(\theta/2 - \vartheta/2)$$

$$\delta_\phi = -e^\alpha \sin(\vartheta/2)$$

$$\delta p_\phi = -\rho_\phi e^\alpha \sin(\theta - \vartheta/2)$$

$$(\rho_\phi + p_\phi)\Theta_\phi = -\frac{k^2}{2ma}\rho_\phi e^\alpha[\cos\vartheta - \cos(\theta - \vartheta/2)]$$

: rapidly oscillating terms

Klein-Gordon eq. & Approximation

Background :

$$\Omega'_\phi = 3(w_{\rm tot} - w_\phi)\Omega_\phi$$

$$\theta' = -3\sin\theta + \frac{2m}{H}$$

$$\left(w_{\rm tot} \equiv \sum_i \Omega_i w_i, \;\; w_\phi = -\cos\theta \right)$$

$$(\dots)' \equiv \frac{d}{d\ln a}(\dots)$$

approximation :

$$\{\cos\varphi, \sin\varphi\} \to \{\cos_\star\varphi, \sin_\star\varphi\}$$

$$\begin{pmatrix} \cos_\star\varphi \\ \sin_\star\varphi \end{pmatrix} \equiv \frac{1}{2}\left[1-\tanh(\varphi^2-\varphi_\star^2)\right]\begin{pmatrix} \cos\varphi \\ \sin\varphi \end{pmatrix}$$

$\varphi_\star$: cutoff parameter (We chose $\varphi_\star = 200$)

Perturbation :

$$\alpha' = -\frac{3}{2}[\cos(\theta-\vartheta)+\cos\theta] - \frac{\omega}{2}\sin(\theta-\vartheta) + \frac{1}{2}e^{-\alpha}h'[\sin(\vartheta/2)+\sin(\theta-\vartheta/2)]$$

$$\vartheta' = -3[\sin\theta+\sin(\theta-\vartheta)] - [1-\cos(\theta-\vartheta)]\omega + e^{-\alpha}h'[\cos(\vartheta/2)-\cos(\theta-\vartheta/2)]$$

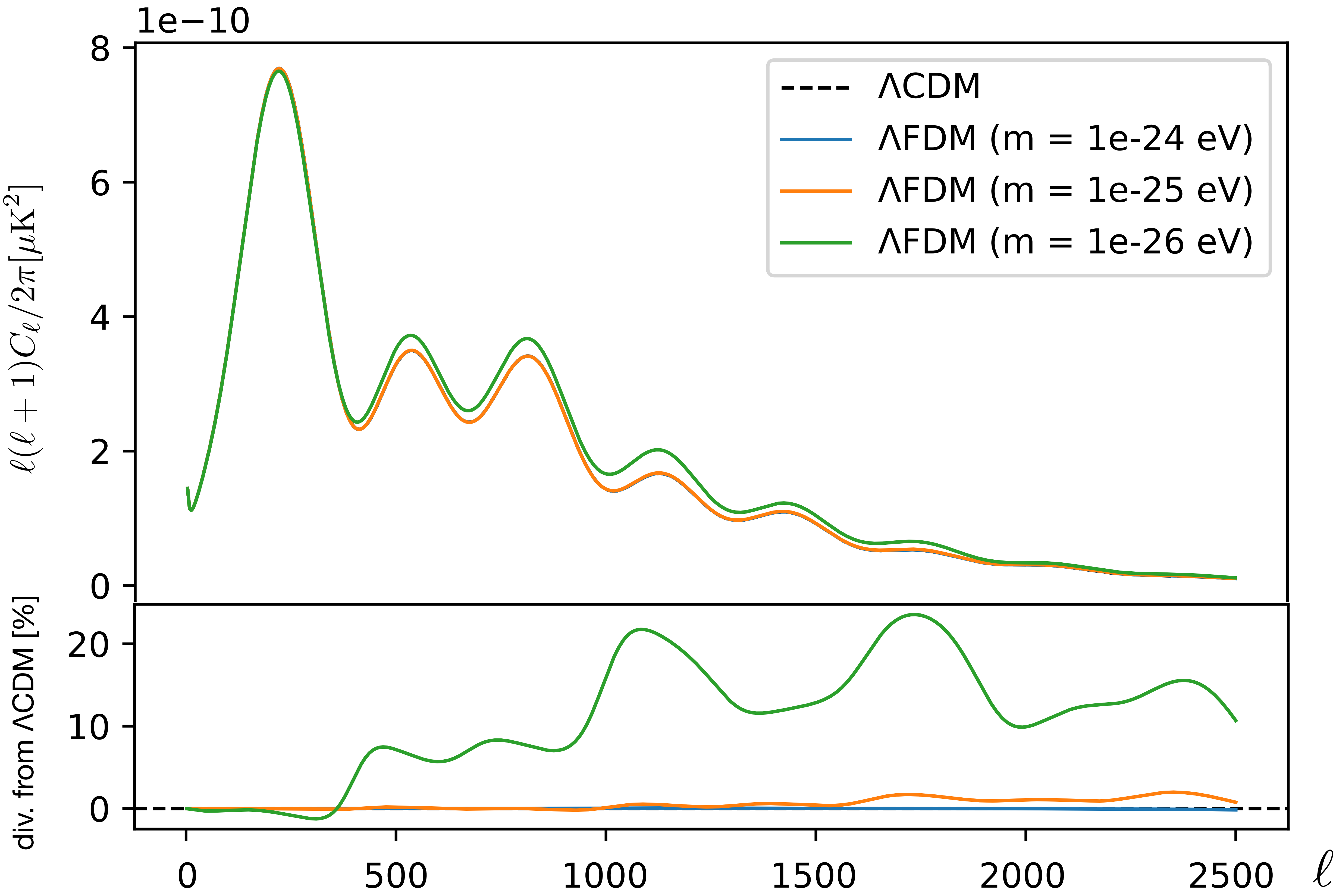
$\omega \equiv k^2/k_J^2$ ($k_J \equiv a\sqrt{mH}$: Jeans scale)

h : metric perturbation (synchronous gauge)

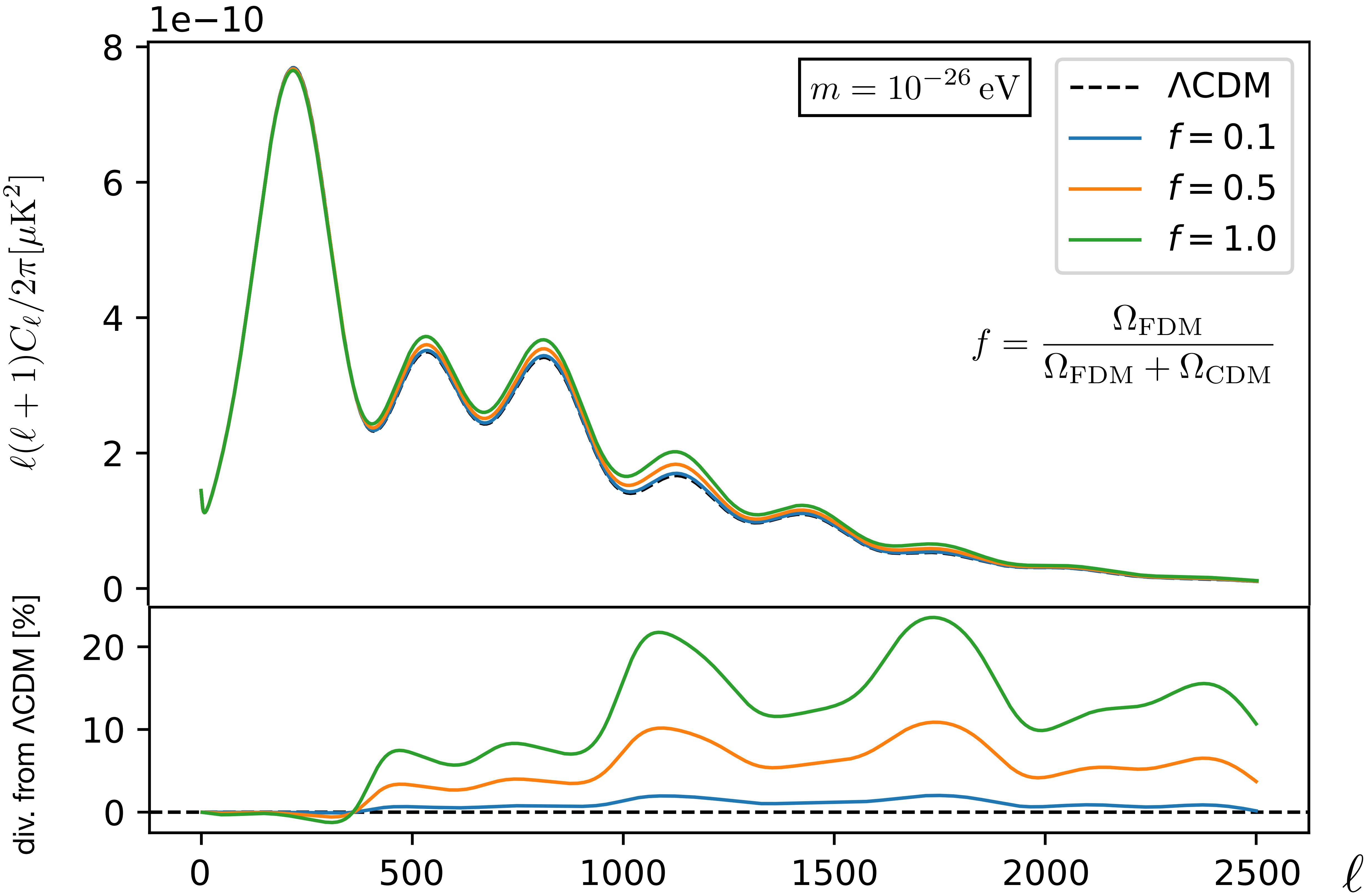
implement into Boltzmann code "CLASS"

[Blas *et al*. (2011)]

CMB power spectrum : ΛFDM model

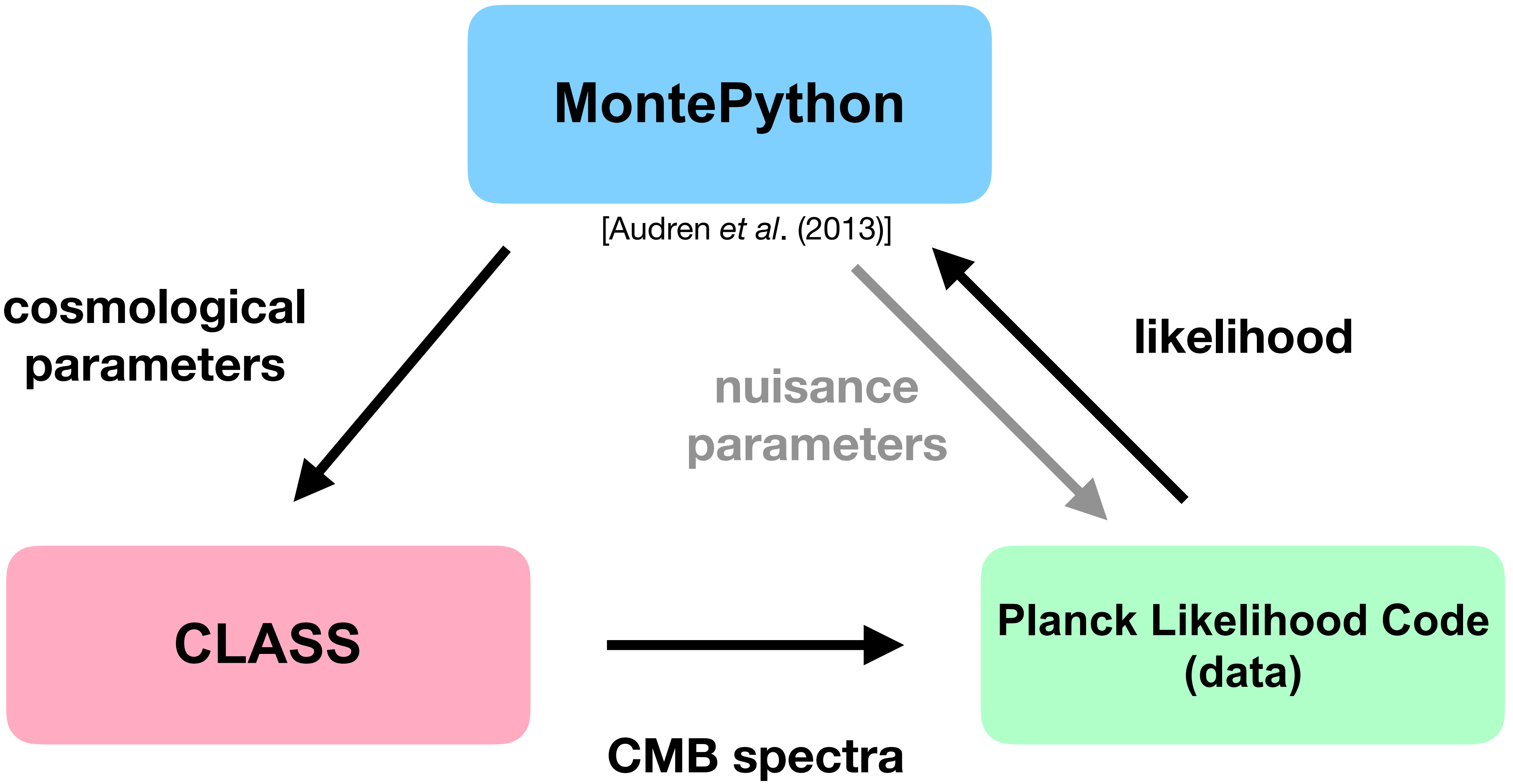


CMB power spectrum : Λ(F+C)DM model



Constraints : Method

Markov chain Monte Carlo analysis



Constraints : ΛFDM model

MCMC parameters :

$$\{\Omega_{\rm b}h^2,\ \boxed{\Omega_{\rm fdm}}h^2,\ H_0,\ \ln(10^{10}A_s),\ n_s,\ \tau_{\rm reio},\ \boxed{\ln(m)}\}$$

+ 30 nuisance parameters

Data : Planck 2015 TT, TE, EE, lensing

- **plik_dx11dr2_HM_v18_TTTEEE (l = 30 ~ 2508)**
- **lowl_SMW_70_dx11d_2014_10_03_v5c_Ap (l < 30)**
- **smica_g30_ftl_full_pp (lensing)**

Constraints on mass :

Prior	1σ	2σ	3σ	
$-26 < \log_{10}(m\,/\,\mathrm{eV}) < -22$	> -23.6	> -24.1	> -24.9	**(conservative)**
< -20	> -23.0	> -23.7	> -24.8	
< -18	> -22.1	> -23.3	> -24.7	

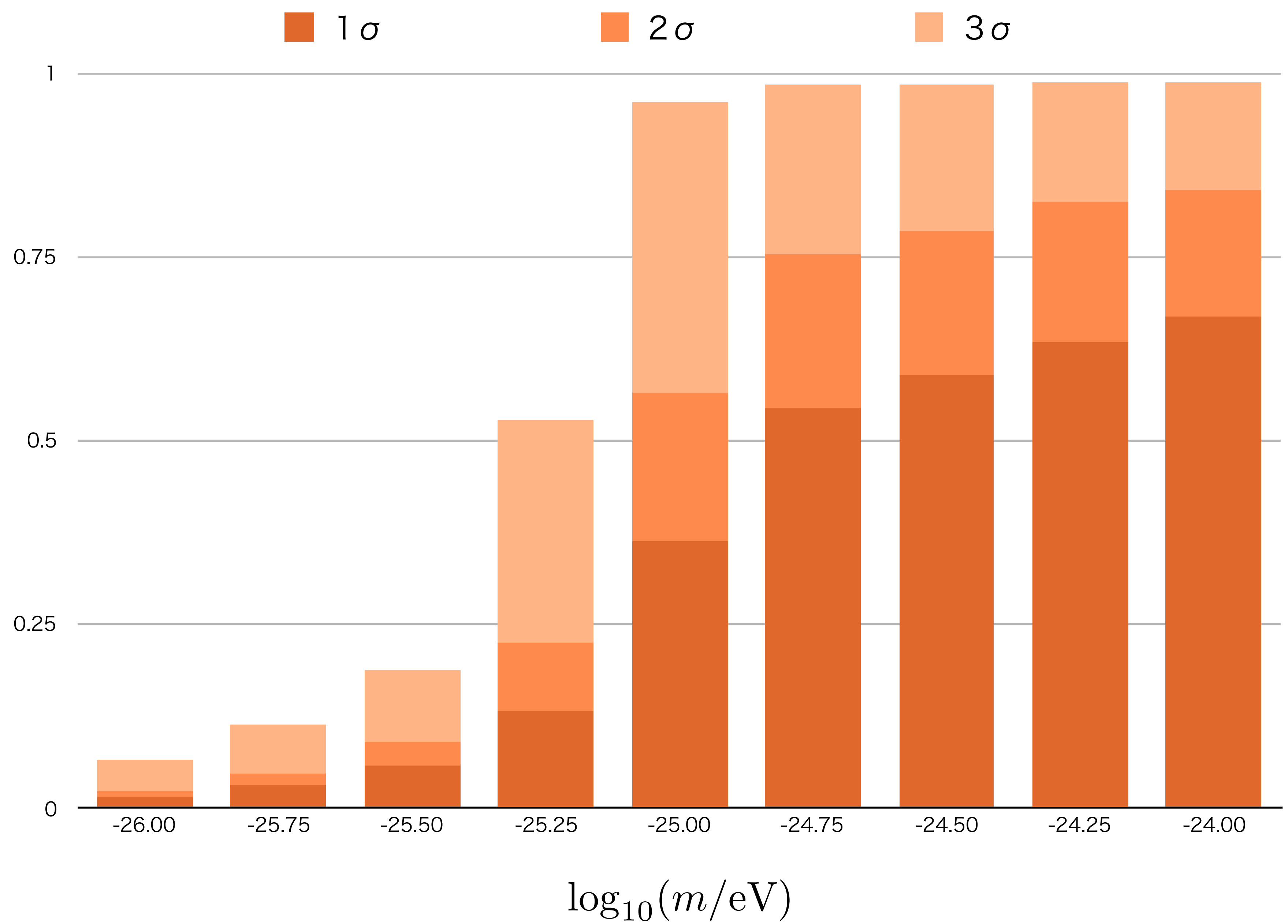
(Metropolis-Hastings, ~10^6 steps, acceptance rate ~ 0.25)

Constraints : Λ(F+C)DM model

$\{\Omega_{\rm b}h^2,\ \Omega_{\rm dm}h^2,\ H_0,\ \ln(10^{10}A_s),\ n_s,\ \tau_{\rm reio},\ f=\Omega_{\rm fdm}/\Omega_{\rm dm}\}$ **(m : fixed)**

Constraints on $f=\Omega_{\rm FDM}/\Omega_{\rm DM}$ **for each fixed mass**

$f=\dfrac{\Omega_{\rm FDM}}{\Omega_{\rm DM}}$



Appendix : CLASS vs AxionCAMB

AxionCAMB : effective fluid approximation [Hlozek *et al*. (2013)]