Fuzzy dark matter and Planck

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Fuzzy Dark Matter (FDM)

- **free scalar field with very small mass :** $\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2$
  - **pseudo-NGB with negligible interaction**
  - **ultralight axion in string theory : “string axiverse” [Arvanitaki+ (2010)]**

- **non-thermally produced by misalignment mechanism**
  - **small velocity dispersion -> consistent with structure formation**

- **small scale structure is suppressed => “Fuzzy” [Hu+ (2000)]**
  - **CDM “small scale crisis” resolved? : original motivation for FDM**

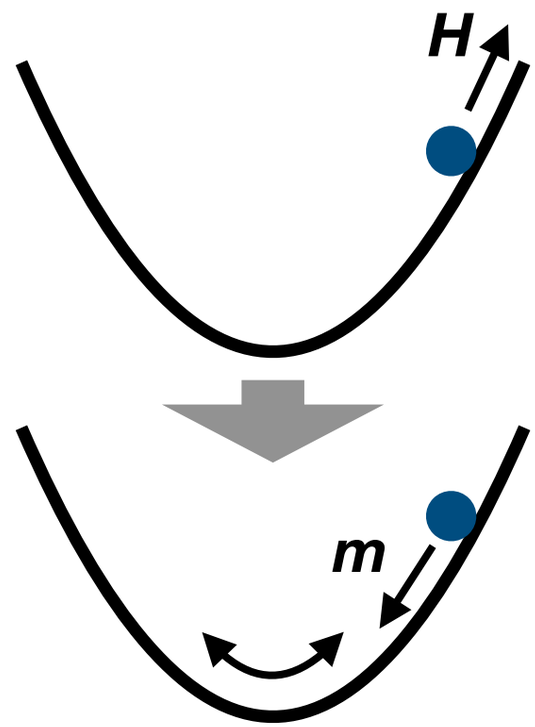
    (overabundance of small scale power)

FDM cosmology : background $\phi(t,\vec{x}) = \bar{\phi}(t) + \delta\phi(t,\vec{x})$

- **Klein-Gordon eq. :**

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$

Hubble friction



- **solution**

$$H \gg m\,(\text{early}): \quad \phi = \text{Const.}$$

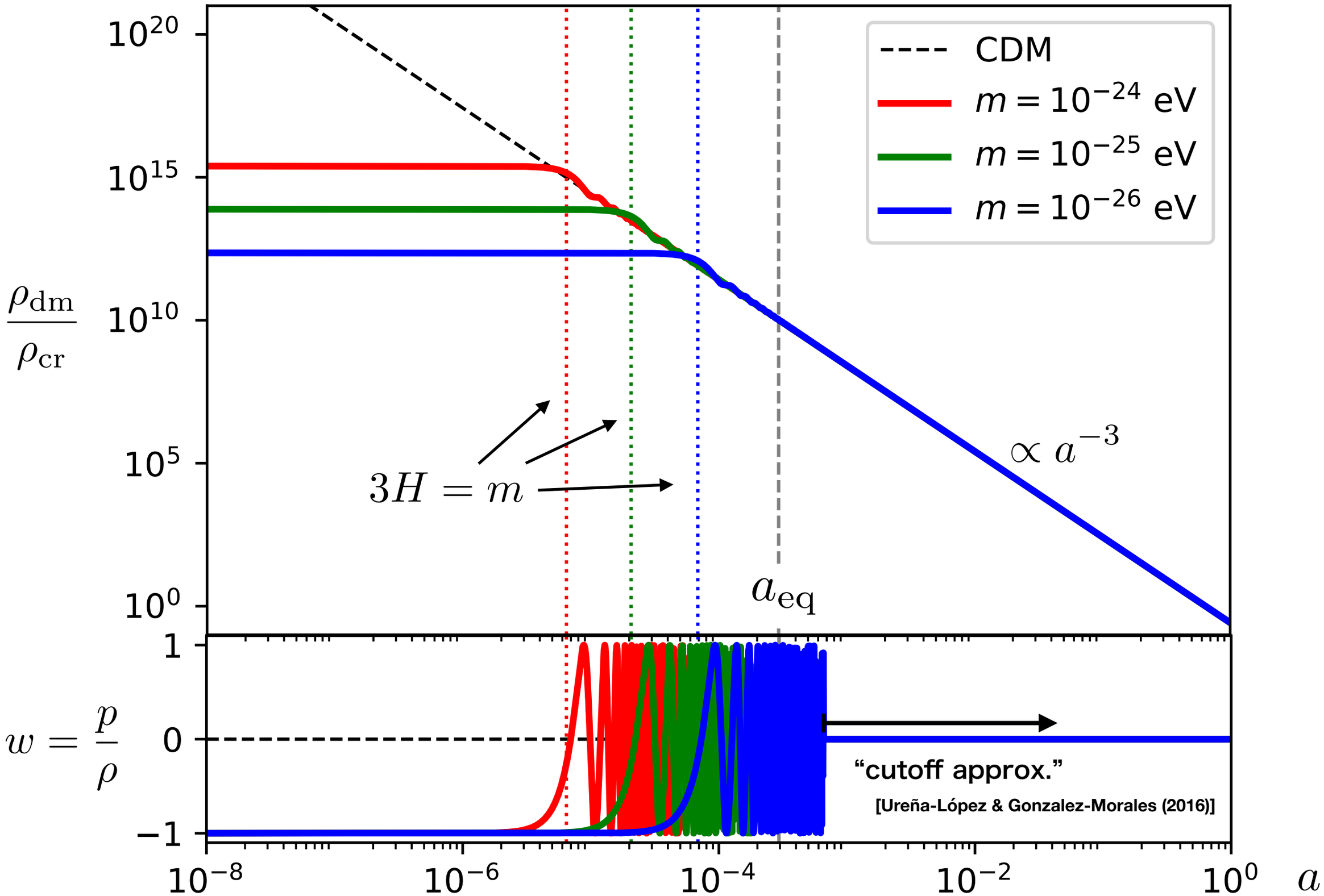
$$\rho = -p = \text{Const.} \quad (\text{DE-/inflaton-like} : w = p/\rho = -1)$$

$$H \ll m\,(\text{late}): \quad \phi = \phi_0 a^{-3/2}\cos(mt) \quad (\text{WKB})$$

$$\rho = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}m^2\phi^2 = \frac{1}{2}m^2\phi_0^2 \cdot \frac{1}{a^3} = \frac{\rho_0}{a^3} \qquad (\text{CDM-like})$$

$$p = \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}m^2\phi^2 = -\frac{\rho_0}{a^3}\cos(2mt) \longrightarrow \langle p\rangle_{\gg m^{-1}} = 0$$

FDM cosmology : background evolution



FDM cosmology : perturbation $\phi(t,\vec{x}) = \bar{\phi}(t) + \delta\phi(t,\vec{x})$

- **Klein-Gordon eq. :**

$$\delta\ddot{\phi} + 3H\delta\dot{\phi} + \left(m^2 + \frac{k^2}{a^2}\right)\delta\phi = -\frac{1}{2}\dot{\phi}\dot{h}$$

effective fluid approx. : average over $\Delta t \gg m^{-1}$

- **fluid eq. for** $\delta \equiv \delta\rho/\rho$

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

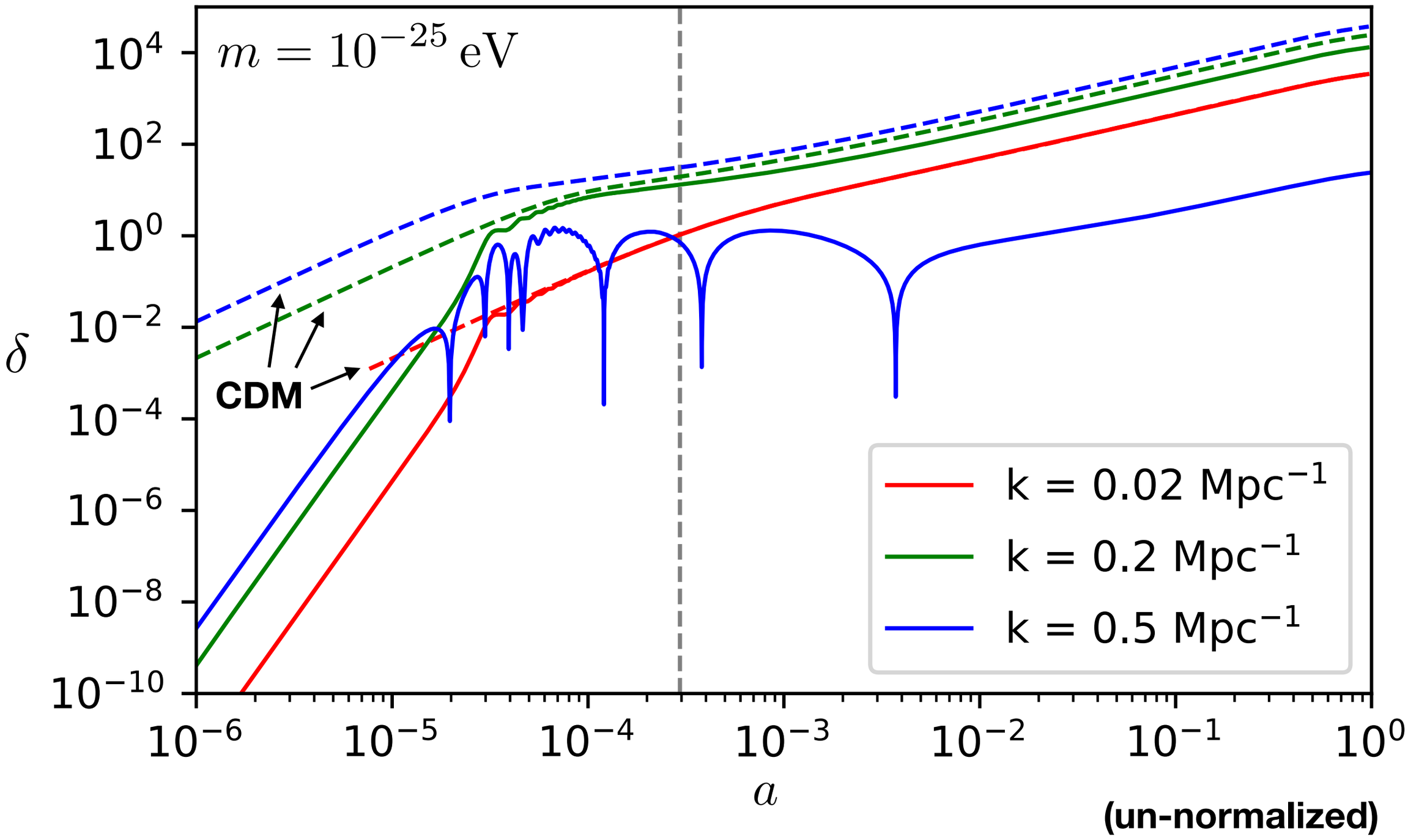
effective pressure

- **Jeans scale : gravity = pressure**

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

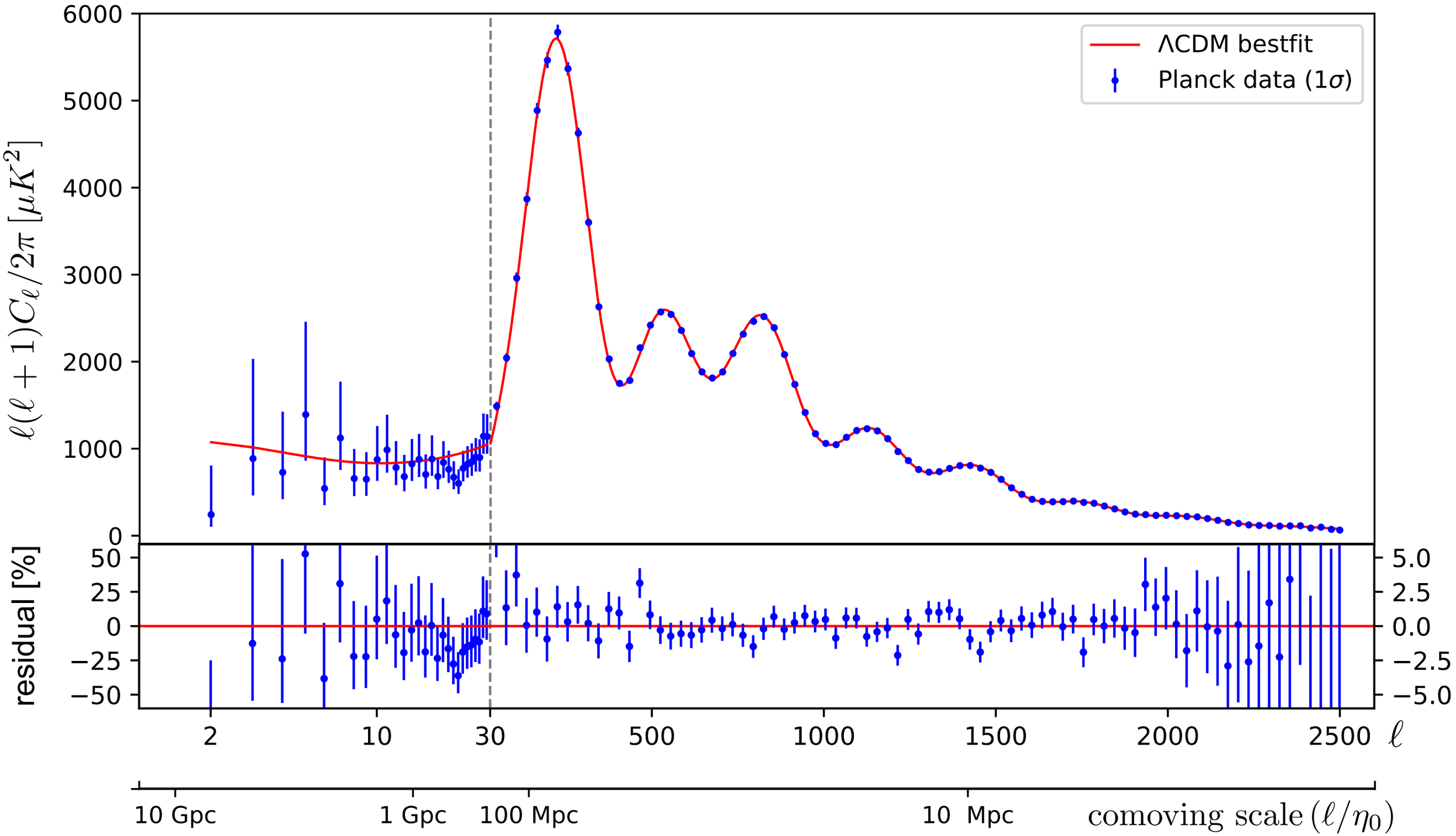
deviation from CDM on small scales $k \gtrsim k_J$

FDM cosmology : perturbation evolution



impact on CMB

CMB TT spectrum : ΛCDM vs Planck



FDM models

ΛFDM model

DM = FDM

6 ΛCDM params. (Ω_{DM} -> Ω_{FDM})

+ *m* (FDM mass)

Λ(F+C)DM model

DM = FDM + CDM

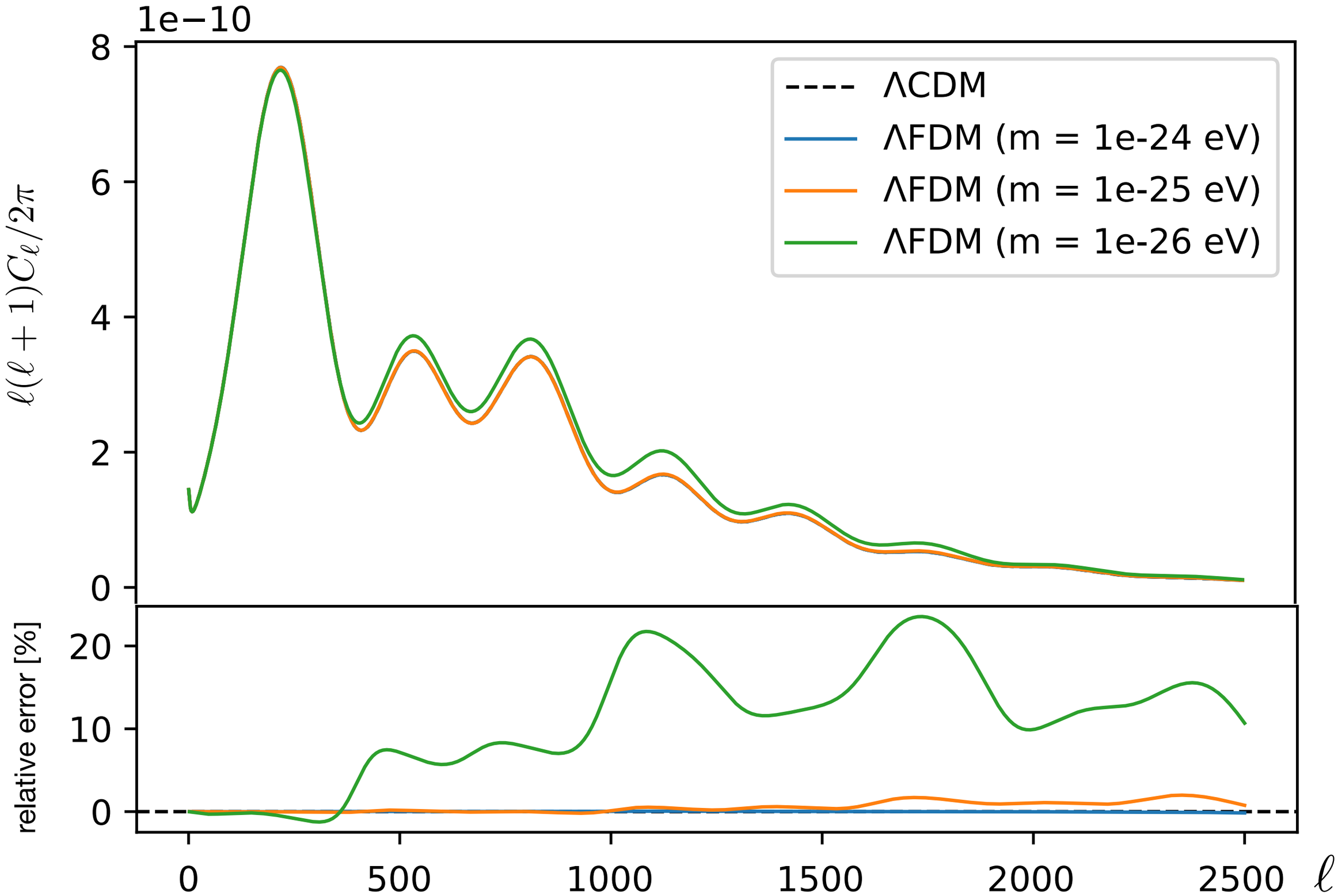
6 ΛCDM params.

+ *m* & *f* = Ω_{FDM} / Ω_{DM}

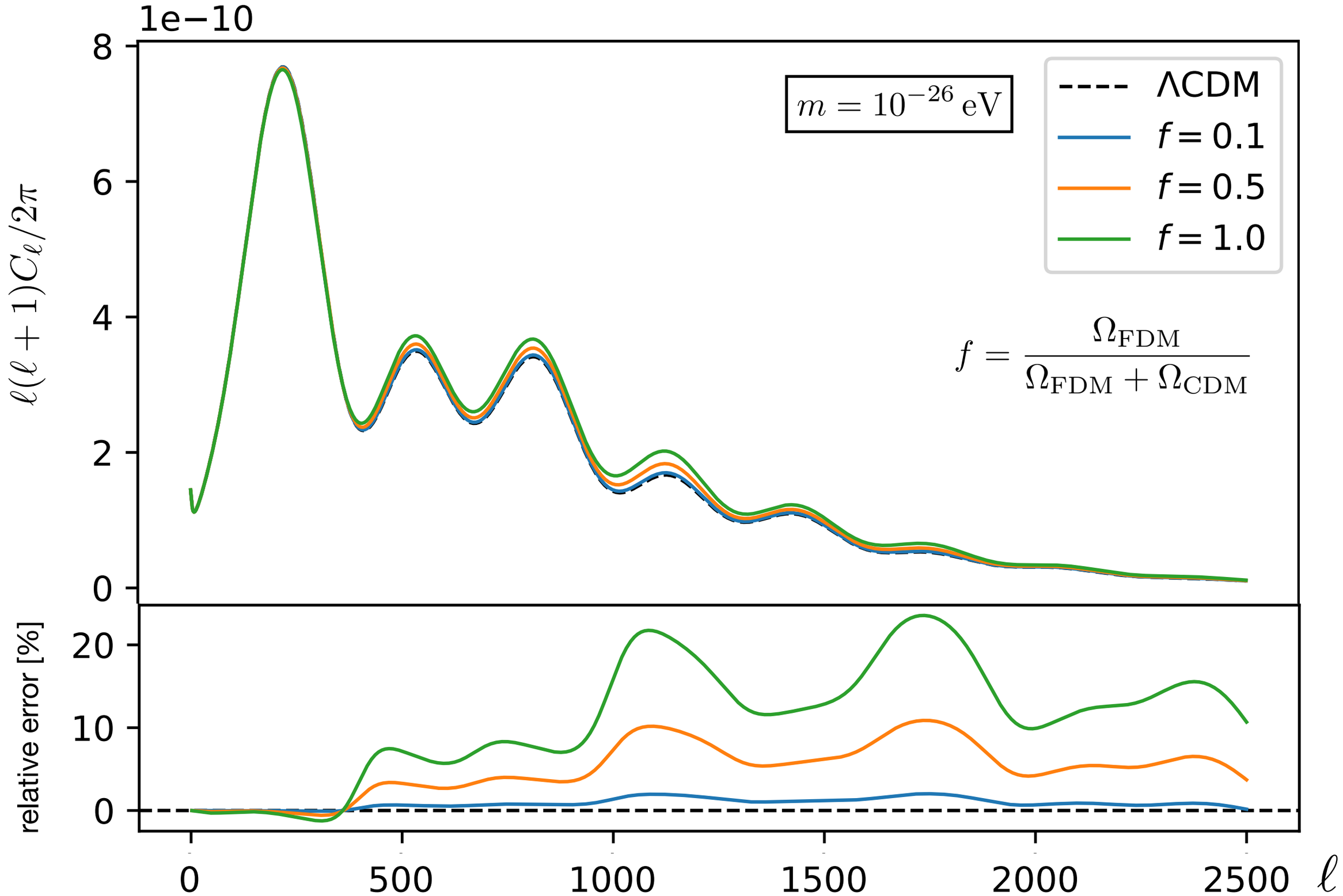
*** ΛFDM ⊂ Λ(F+C)DM (*f* = *1*)**

but # of free parameters are different

CMB TT spectrum : ΛFDM model

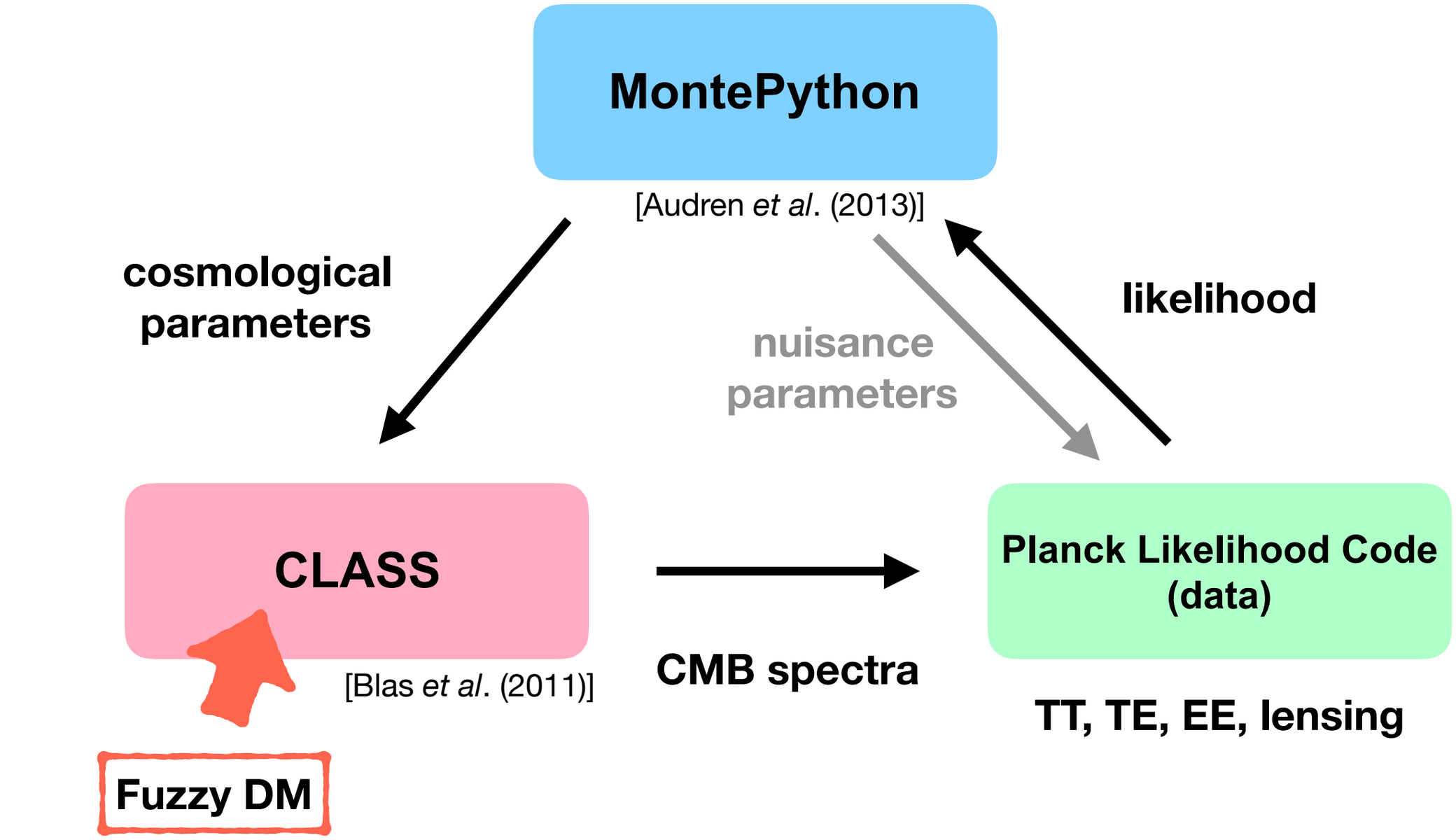


CMB TT spectrum : Λ(F+C)DM model



Constraints : Method

Markov chain Monte Carlo analysis



w/ "cutoff" approx. [Ureña-López & Gonzalez-Morales JCAP 07 (2016) 048]
(not using fluid approx.)

Constraints : ΛFDM model

MCMC parameters :

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

+ 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 :

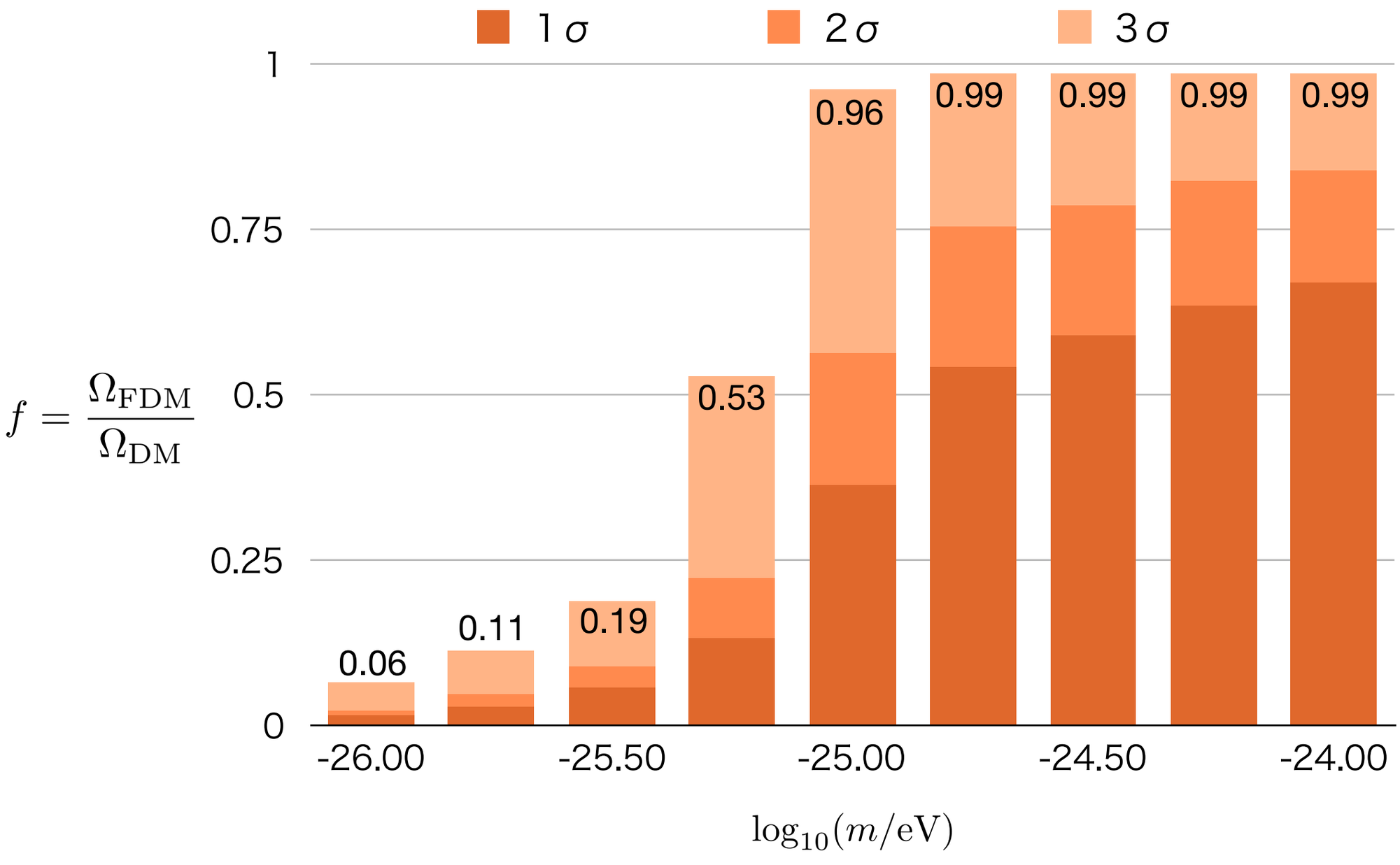
Prior	1σ	2σ	3σ	
-26 < $\log_{10}$ (m / eV) < -22	> -23.6	> -24.1	> -24.9	**(conservative)**
< -20	> -23.0	> -23.7	> -24.8	
< -18	> -22.1	> -23.3	> -24.7	

(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 $f=\Omega_{\rm FDM}/\Omega_{\rm DM}$



Summary

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

- **FDM affects small scale perturbations :** $k \gtrsim k_J \sim \frac{1}{1\,\mathrm{Mpc}} \left(\frac{m}{10^{-25}\,\mathrm{eV}}\right)^{1/2}$

- **Constraints on FDM models from Planck 2015 data:**

(1) ΛFDM model : DM = FDM

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

(2) Λ(F+C)DM model : DM = FDM + CDM

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