Ultra-light scalar Dark Matter probed with the SDSS Lyman-α forest

arxiv:1703.09126

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Combine analysis of SDSS quasars with cosmological simulations to study particle physics models (neutrinos, WDM, Fuzzy Dark Matter)

Fuzzy dark matter (FDM)

- eg. Hu et al. PRL 2000, Marsh Phys. Rep. 2016, Hui et al. PRD 2017 …
- **Lowest possible mass for DM ?**
  - Fermions : Tremaine-Gunn m ≳ few 100 eV.
  - Bosons : down to $\sim 10^{-24}$ eV
- **de Broglie wavelength for DM large** enough so that wave effects smooth density fluctuations on scales relevant to structure formation or DM halo dynamics

$$\frac{\lambda_{\mathrm{dB}}}{2\,\mathrm{kpc}} \sim \left(\frac{10^{-22}\,\mathrm{eV}}{m}\right)\left(\frac{10\,\mathrm{km/s}}{v}\right)$$

- **A way to solve the CDM « small scale crisis » (DM cores in dwarfs, halo abundance…)**
- Theory motivation ?
  - pseudoscalar Axion-Like-Particles (ALPs) generic prediction in string compactification
  - relic field from misalignment mechanism similar to QCD axions with m~μeV

Structure formation in FDM

- Linear perturbations : FDM ~ fluid with effective sound speed

  Related Jeans scale : $$k_J = 67\, a^{1/4} \left(\frac{\Omega_a h^2}{0.12}\right)^{1/4} \left(\frac{m_a}{10^{-22}\,\mathrm{eV}}\right)^{1/2} \mathrm{Mpc}^{-1}$$

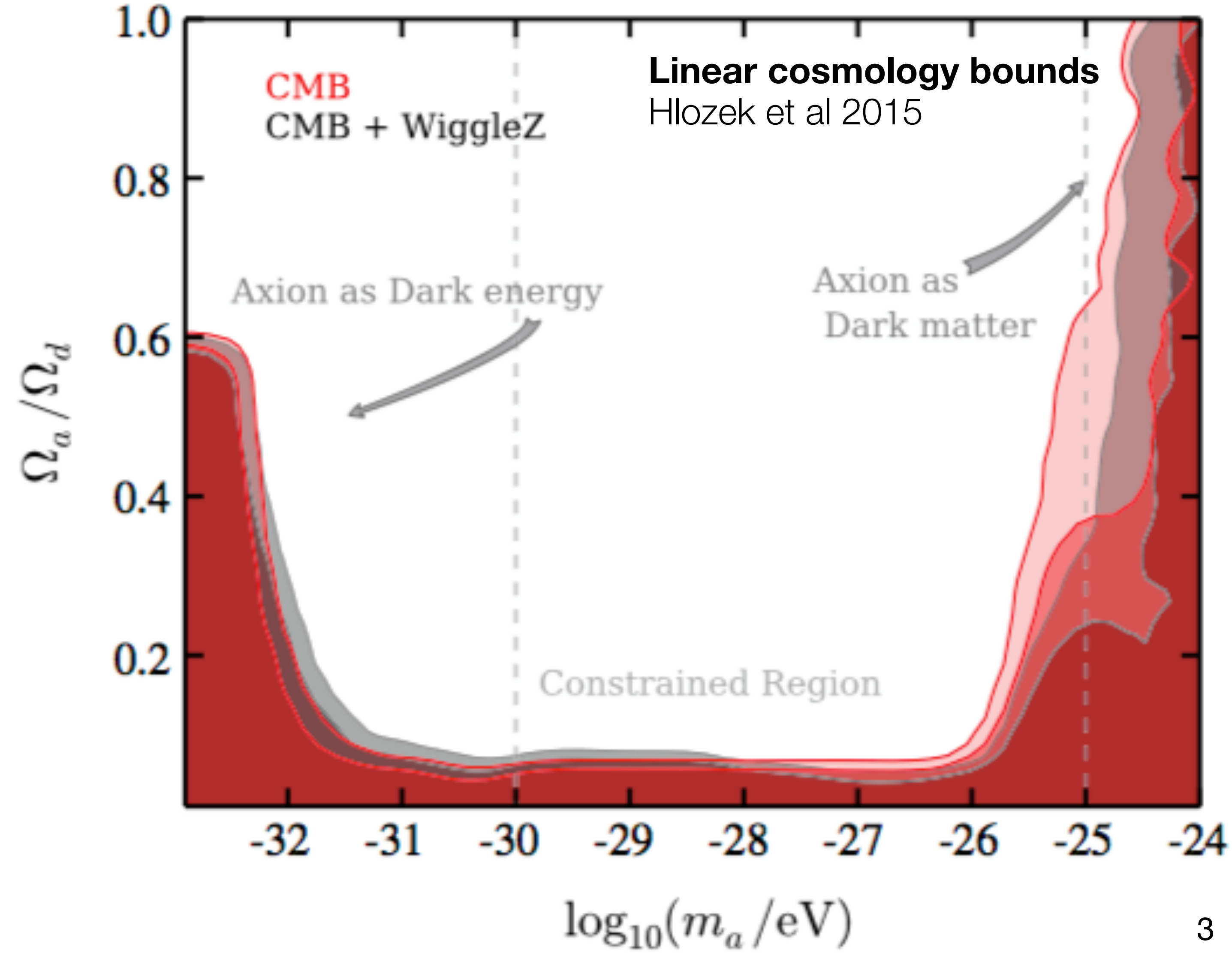
- **Cut-off in matter power spectrum P(k) for scales smaller than Jeans scale at equality**

Linear cosmology probes exclude $m_a \sim 10^{-24}$ - 10^{-25} eV

Larger masses ~ 10^{-22} eV constrained by non linear probes eg.

galaxy luminosity function

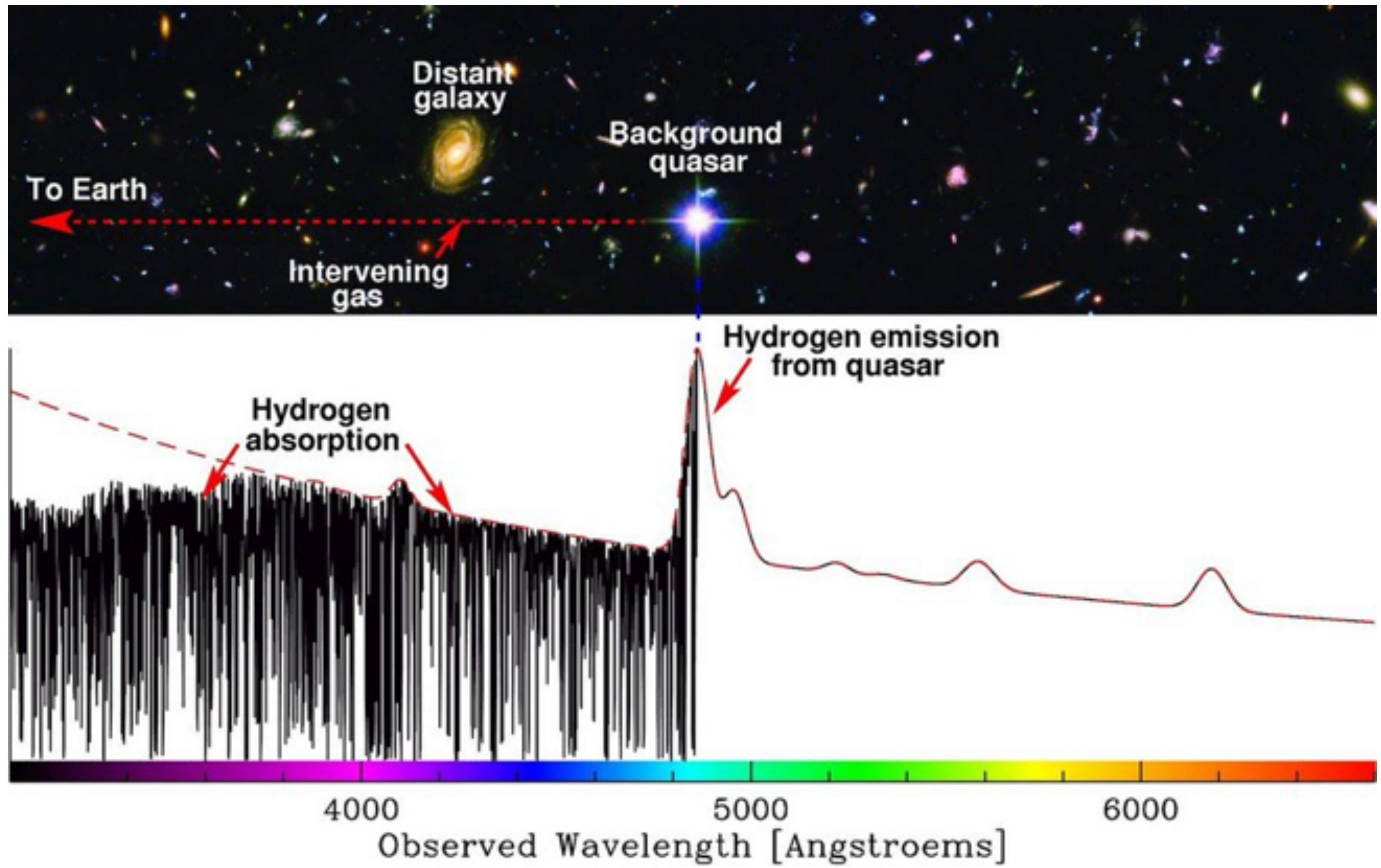
Lyman-α forest



The SDSS Lyman-α forest

Measure fluctuations of Lyman-α flux transmitted by the neutral intergalactic medium (IGM)

⟹ closely related to the small-scale matter power spectrum



SDSS DR9 catalog : 60000 quasar spectra

⟹ flux power spectra with near-% precision

- z=2.4-4.2
- scales down to ≲ Mpc

Constraining FDM with the Lyman-α forest

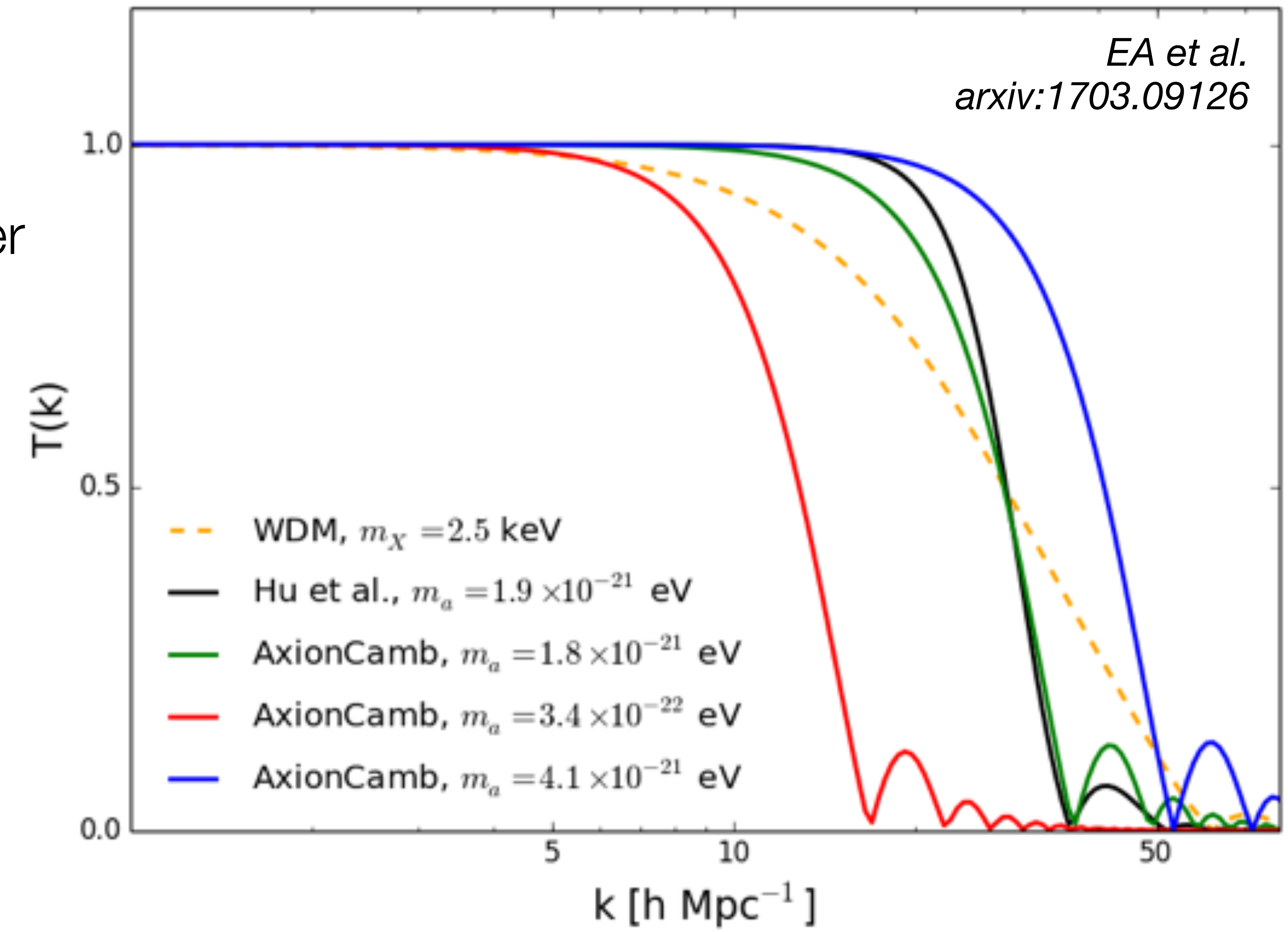
- **Similar to WDM / $\sum m_\nu$ bounds**
- **Linear power spectrum** @z=30
    - From AxionCAMB Boltzmann solver
    - WDM-FDM scaling law, such that $T(k_c)=0.5$:

$$m_X = 0.79 \left(\frac{m_a}{10^{-22}\,\mathrm{eV}}\right)^{0.42} \mathrm{keV}$$

    - Shape different from WDM

- **Non-linear evolution + hydrodynamics of IGM : GADGET simulations**

  resolution 768^3 particles 25 h^{-1} Mpc
- Predict flux power spectrum $P_{1D}(k)$ and compare with data



Model parameters :
Ω_M, σ_8, n_s, h, m_a
T_0, γ (IGM heating), α,β (opt. depth)
a_{Si}, noise, splicing

Bounds on the FDM mass

- **Based on SDSS quasars only :**

  $m_a > 2.0 \times 10^{-21} - 2.3 \times 10^{-21}$ eV depending on the method

- **Including high-resolution spectra** (XQ100+HIRES+MIKE)

  $m_a > 2.9 \times 10^{-21}$ eV

- See also Irsic et al. arXiv:1703.04683 :

  $m_a > 2.0 \times 10^{-21} - 3.7 \times 10^{-21}$ eV

  different systematics

- **Current limitation : IGM modeling**
  - **Average IGM parameters** : temperature and optical depth vs z : (T_0,γ) and (α,β) free parameters.
  - **IGM fluctuations of non-gravitational origin** (discrete ionizing sources, reionization-induced inhomogeneities, feedback eg. galactic outflows…) : simple parameterizations for related deviations of P(k,z), with amplitudes left as free parameters.

Validity of the N-body approximation for FDM ?

Non-linear (newtonian) regime :

Schrödinger equation ⇒ Madelung equation :

wavefunction : amplitude^2 = ρ; ∇(phase) = v

$$\partial_t \vec{v} + H\,\vec{v} + \frac{1}{a}(\vec{v}\cdot\nabla)\vec{v} = -\frac{1}{a}\nabla\left[\phi - \frac{\hbar^2}{2m_a^2\,a^2}\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)\right]$$

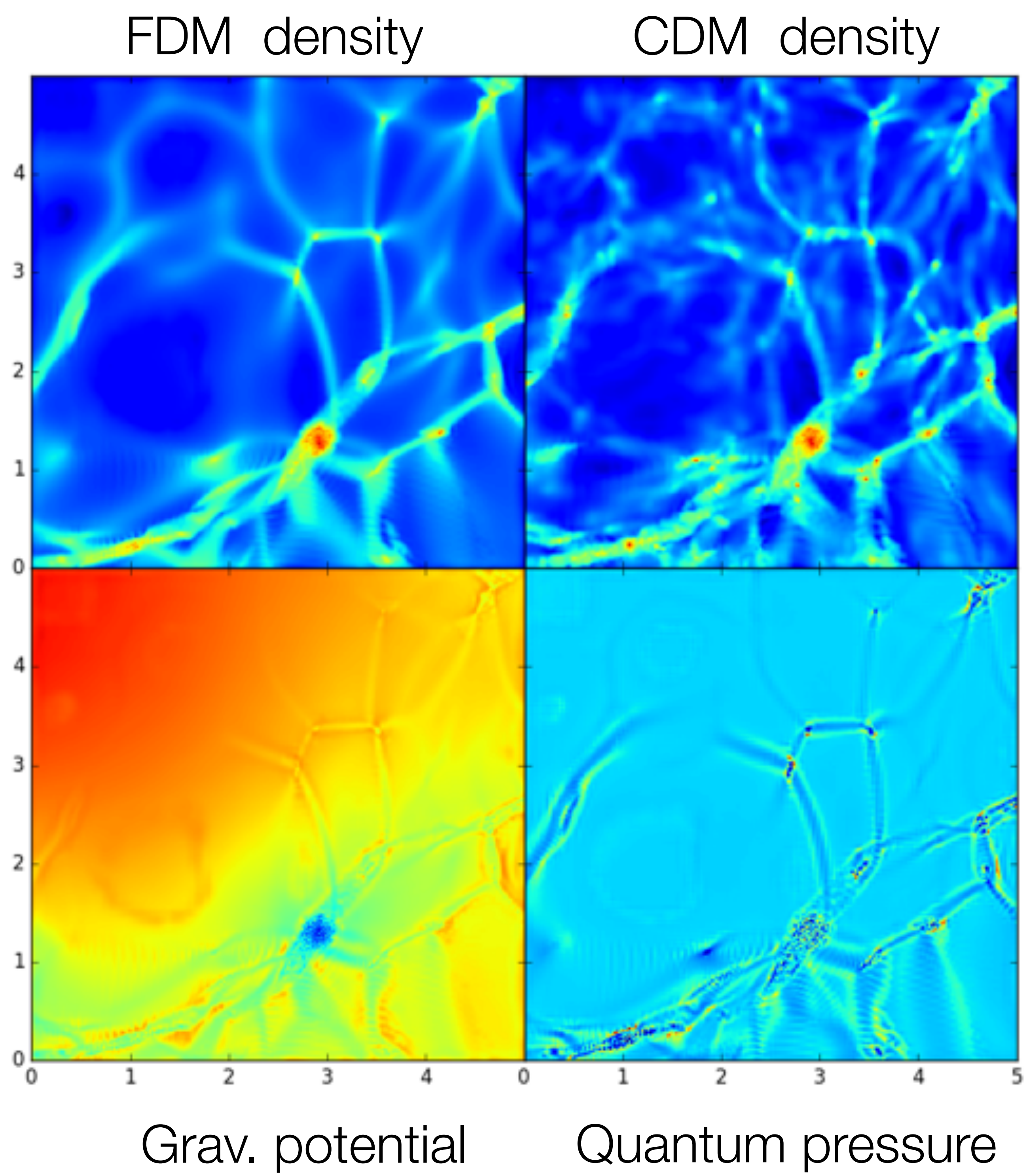
« Quantum pressure » Q

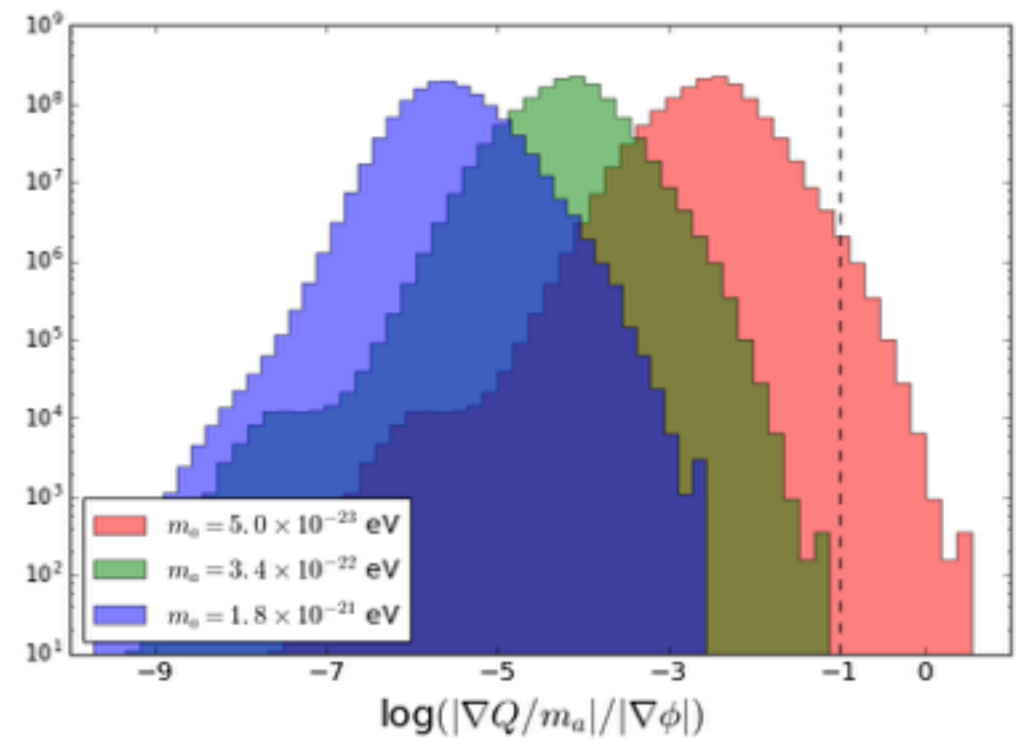
N-body (GADGET) codes solve the Euler-Poisson system

∇Q hard to compute (small scale variations)

Use standard N-body ⟺ neglect ∇Q wrt gravitation force ∇ϕ

FDM : « Quantum force » vs gravitational force





⟹ N-body ok at the scales considered here at least for $m_a \gtrsim 10^{-22}$ eV

Summary

- **Fuzzy Dark Matter = axion-like particle with $m_a \sim 10^{-22}$ eV :**

  a possible solution to the « small scale CDM crisis »

  with interesting phenomenology

- **Lyman-α forest currently provides the strongest constraints :**

  $m_a \gtrsim$ 2-3 x 10^{-21} eV

- If taken seriously, it closes this interesting FDM window.

- Need to :

  Improve modeling of the IGM physics

  Take into account the « quantum pressure » in the NL regime for low masses

Homogenous evolution of the FDM fluid

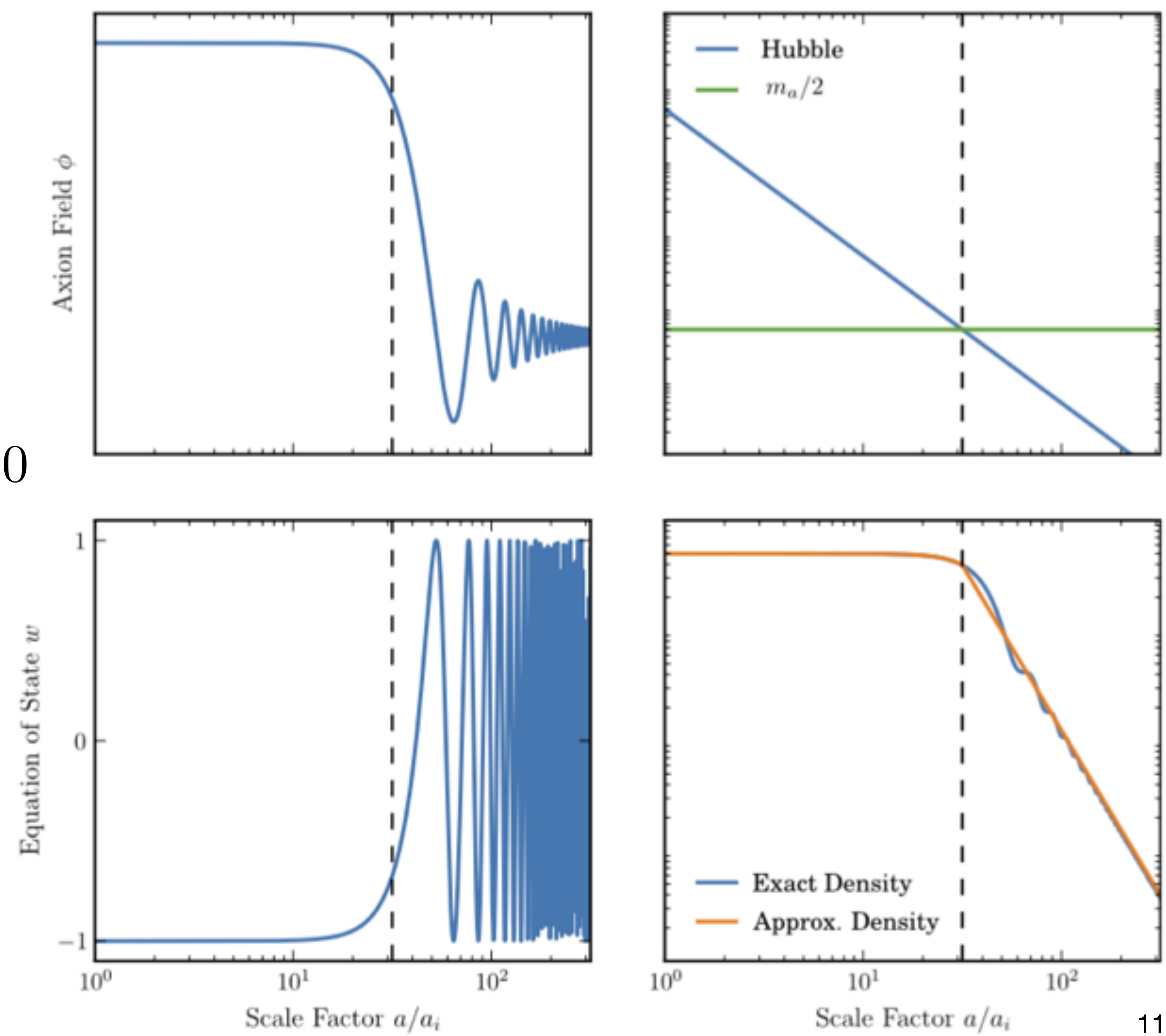
- Classical field
  (occupation nb >> 1)
- Klein Gordon equation
  (no interactions)

$$\ddot{\Psi}_0 + 3H(z)\,\dot{\Psi}_0 + m_a^2\,\Psi_0 = 0$$

$H > m_a$: DE regime

$H < m_a$: DM regime

D.J.E. Marsh / Physics Reports 643 (2016) 1–79



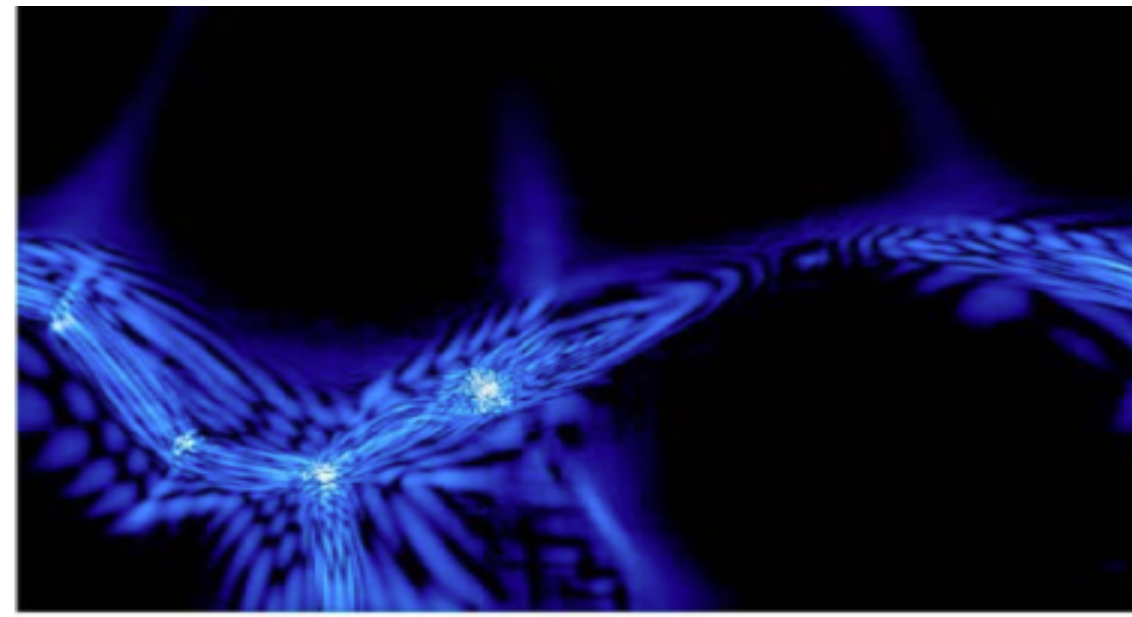
Small-scale FDM halo properties

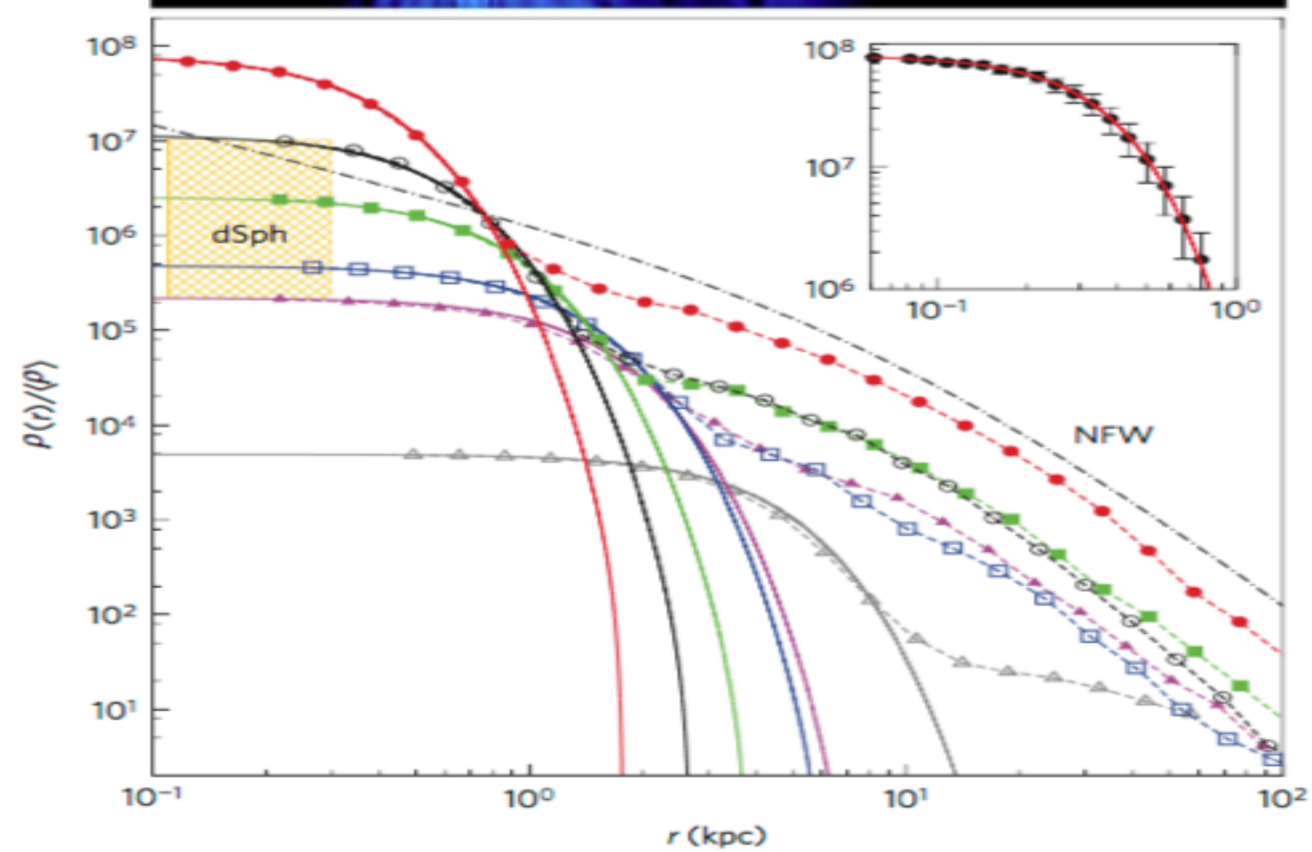
- Non-linear, non-relativistic : Schrödinger-Poisson system

$$\left[i\frac{\partial}{\partial\tau}+\frac{\nabla^2}{2}-aV\right]\psi=0$$

$$\nabla^2 V=|\psi|^2-1,$$

- Pure FDM cosmological simulations in ~few Mpc boxes (eg. Schive et al. Nature Phys. 2014)
- Key prediction: **solitonic core**
- Fit dwarf kinematics with m_a~10^{-22} eV
- No « Catch 22 » wrt the Warm Datter Matter scenario





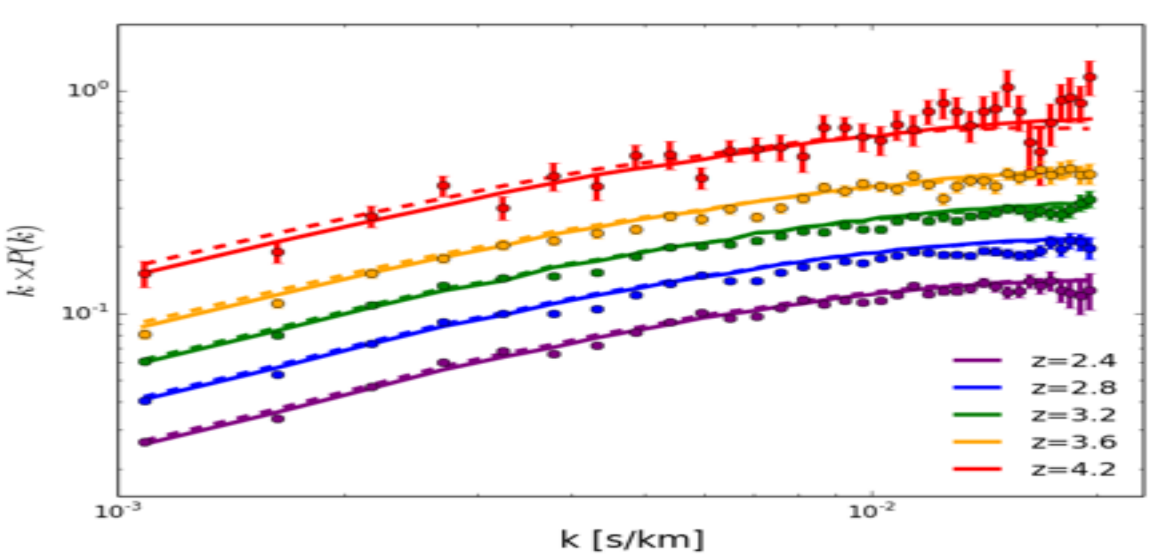
$P_{1D}(k)$ predictions in SDSS window

Similar feature as for WDM

WDM-FDM scaling law best adapted to the measured SDSS flux power spectra :

require $\chi^2(m_a)=\chi^2(m_X)$

$$m_X = 0.715 \times \left(\frac{m_a}{10^{-22}\,\mathrm{eV}}\right)^{0.558} \mathrm{keV}$$



Flux spectra with $\tau_{\rm eff} = 0.0025\,(1+z)^{3.7}$