Ultra-light scalar (Fuzzy) Dark Matter
probed with the Lyman-alpha forest

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Rencontres de Moriond - 2018

MNRAS 471 (2017) 4, 4606 [1703.09126]
EA, N. Palanque, C. Yèche, D.J.E. Marsh, J. Baur
Fuzzy dark matter (FDM)

The lowest possible mass for particle dark matter
\[ m \sim 10^{-22} \text{ eV} \]

ultra-light axions (ULA)
wave dark matter (WDM)
fuzzy dark matter (FDM)
   \textit{Hu et al., PRL 2000}

\begin{align*}
\text{de Broglie wavelength:} & \\
\frac{\lambda_{dB}}{2 \text{kpc}} & \sim \left( \frac{10^{-22} \text{ eV}}{m} \right) \left( \frac{10 \text{ km/s}}{v} \right)
\end{align*}

wave effects smooth density fluctuations on scales relevant to structure formation or DM halo dynamics
DM solutions to the small-scale « issues »

**Strongly-Interacting DM (SIDM)**

$\sigma/m \sim 0.1-1 \text{ cm}^2/\text{g}$

best solve cusp-core

eg. sub-GeV thermal relic

with $3 \to 2$ annihilation

[Shaposhnikov+ PRL 2005]

**Fuzzy Dark Matter (FDM)**

« no Catch 22 problem » - could solve both halo statistics & core profile

**keV-scale relic (WDM)**

free-streaming

best solve missing satellites

eg. sterile neutrino

[Shaposhnikov+ PLB 2005]

*Baur+ 1706.03118*
Massive scalar relic

**Misalignment mechanism for scalar relic**

Classical field (occupation nb >> 1)

\[ \ddot{\psi}_0 + 3H(z) \dot{\psi}_0 + m_a^2 \psi_0 = 0 \]

- $H > m_a$: DE regime
- $H < m_a$: DM regime

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Structure formation in FDM

Linear perturbations: FDM ~ fluid with effective speed of sound

Related Jeans scale:

\[ k_J = 67 a^{1/4} \left( \frac{\Omega_a h^2}{0.12} \right)^{1/4} \left( \frac{m_a}{10^{-22} \text{ eV}} \right)^{1/2} \text{ Mpc}^{-1} \]

Cut-off in linear matter power spectrum

for scales smaller than Jeans scale at equality
Constraints on FDM: linear structures (~CMB)

Linear cosmology excludes $m_a \sim 10^{-24}$ eV

Larger masses $\sim 10^{-22}$ eV probed by eg. galaxy luminosity function, reionization, Lyman-α forest
FDM phenomenology at the halo scale

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

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

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

Pure FDM cosmological simulations in \(~ few Mpc \) boxes

Key prediction: **solitonic core**

Fit dwarf kinematics with \( m_a \sim 10^{-22} \) eV
The Lyman-α forest

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

Closely related to the small-scale matter power spectrum - however through:
- non-linear structure growth
- IGM physics
Lyman-α data used in this study

SDSS DR9 catalog: 60000 quasar spectra
⇒ flux power spectra with near-% precision
- z=2.4-4.2
- scales down to ~ Mpc

High resolution spectra
(VLT/X-SHOOTER, Magellan/MIKE, Keck/HIRES))
Smaller scales, higher z

Palanque-Delabrouille et al., A&A 2013
Yèche et al. JCAP2017
Lyman-α forest predictions in FDM

**Similar to Warm Dark Matter**

**Initial linear power spectrum**

@ z=30

modified version of CAMB

WDM-FDM scaling law

\[ m_X = 0.79 \left( \frac{m_a}{10^{-22} \text{ eV}} \right)^{0.42} \text{ keV} \]

Shape different from WDM

**Non-linear evolution + hydrodynamics : Gadget simulations**

Predict flux spectrum \( P_{1D}(k) \) and compare with data
FDM dynamics in cosmological simulations?

FDM: Schrödinger equation ⇒ Madelung equation:

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

« Quantum pressure »: \[Q \equiv -\left( \frac{\hbar^2}{2m_a} \right) \frac{\nabla^2 \sqrt{\rho}}{\sqrt{\rho}}\]

\(\nabla Q\) hard to compute (small scale variations)

Effect of \(\nabla Q\) can be different from standard pressure

Use standard N-body ⇐ neglect \(\nabla Q\) wrt gravitation force \(\nabla \phi\)

Can at least check a posteriori consistency of approximation
FDM: «Quantum force» vs gravitational force

Density (FDM initial cond.) vs Density (CDM initial cond.)

Gravitational potential vs Quantum pressure
FDM: «Quantum force» vs gravitational force

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

Nori+Baldi, « AX-GADGET » 1801.08144

CDM
linear Tk
lin Tk + Q term in Nbody

See also Zhang+ 1708.04389

Veltmaat +Niemeyer
PRD94 (2016) 12, 123523
Nyx-based
IGM physics

**IGM parameters included in hydro simulation**

- temperature vs z ($T_0, \gamma$)
- optical depth

**Other IGM fluctuations: simple corrections**

- reionization redshift (prior $z = 9 +/- 1.5$)
- discrete ionizing sources (UV fluctuations)
- feedback (AGN & galactic outflows)

**Non-IGM systematics**

- spectrometer resolution, noise
- missed DLA, Si contamination
- splicing artifacts


Example: AGN feedback

$C_{AGN}^{\text{feedback}}(k) = (\alpha_{AGN}(z) + \beta_{AGN}(z) \times k) \times \alpha_{AGN}^{\text{feedback}}$
Example Lyman-α flux spectra prediction

\[ \tau_{\text{eff}} = 0.0025 \left( 1 + z \right)^{3.7} \]
Bounds on FDM mass from the Ly-α forest

Scan over $\Omega_M, \sigma_8, n_s, h, T_0, \gamma, m_a$: interpolate grid of simulations

Frequentist fit including nuisance parameters

SDSS-only:

Using directly FDM simulations:

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

Using WDM simulations (more complete grid of simulations) + best-adapted WDM-FDM mass matching law:

$$m_X > 4.09 \text{ keV} \Rightarrow m_a > 2.3 \times 10^{-21} \text{ eV}$$

Adding high-resolution spectra (XQ100+HIRES+MIKE): $m_a > 2.9 \times 10^{-21} \text{ eV}$

See also Irsic et al. PRL 2017: $m_a > 2.0 \times 10^{-21} - 3.7 \times 10^{-21} \text{ eV}$

Galaxy luminosity function @ high z: $m_a > 1.2 \times 10^{-22} - 1.2 \times 10^{-21} \text{ eV}$
Summary

Fuzzy Dark Matter = (pseudo) scalar particle with $m_a \sim 10^{-22}$ eV :

- a possible solution to the « small scale CDM issues »
- with remarkable phenomenology (incl. solitonic DM cores, …)

Lyman-α forest powerful probe

Data in tension / excludes FDM masse range $10^{-22}$ eV $\leq m_a \leq 2 - 3 \times 10^{-21}$ eV

- Similar to WDM bounds
- Importance of IGM physics modelling to improve robustness
- Impact of « quantum pressure » in the NL regime for $m < 10^{-22}$ eV ? FDM interactions ?
Probes of very light DM bosons

Fermions: Tremaine-Gunn \( m \gtrsim \text{few } 100 \text{ eV} \)

- ULAs
- Lyman-\( \alpha \), High-z, 21cm
- BHSR: supermassive, stellar, eLISA?
- CMB pol. rotation
- Solve CDM crises?
- QCD axion: ADMX, CASPER, stellar
- String theory axions?

\[ \log_{10}(m/eV) \]

spinning BH (GW)

expts search: DM coupling to SM

• Black hole superradiance:

Bosons around a rotating BH have energy levels like the H atom (because of the Newtonian potential). Inside the ergosphere energy can be extracted (Penrose process) and this fills up the energy level by an exponential instability. For each level, the effective potential has a barrier which prevents the energy to be immediately radiated away until it is overcome and for instance GW are emitted. LISA will be sensitive to very low mass axions.

Constraints from the observation of spinning BH both stellar (left) or supermassive (right)
Theoretical motivation for DM with $m \sim 10^{-22}$ eV?

**Axion-like particles (ALPs)** - periodic pseudo-scalar fields generic prediction eg. in string-theory compactification

$$\phi = F \times \alpha$$

**high-energy scale**

GUT $\leq F \leq M_{Pl}$

$$\mathcal{L} \sim \sqrt{g} \left[ \frac{1}{2} F^2 g^{\mu \nu} \partial_\mu a \partial_\nu a - \mu^4 (1 - \cos a) \right]$$

**effective potential from non-perturbative effects**

mass $m = \mu^2 / F$

Oscillation starts for $H \sim m$ ie. $T_{osc} \sim \sqrt{m M_{Pl}}$

At that time $\rho \sim \mu^4$

Then $\rho \sim 1/a^3$

$$\Rightarrow \Omega_a = \frac{m^{1/2} F^2 T_{CMB}^3}{\rho_c M_{Pl}^{3/2}} \sim 0.1 \left( \frac{F}{10^{17} \text{ GeV}} \right)^2 \left( \frac{m}{10^{-22} \text{ eV}} \right)^{1/2}$$

« an interesting coincidence, somewhat reminiscent of the WIMP miracle »

Hui, Ostriker, Tremaine, Witten, PRD 2017
Self-interacting FDM

Linares Cedeño et al. PRD 2017

\[ T(k) \]

- \( m_\alpha = 10^{-23} \text{ eV} \)
- \( m_\alpha = 10^{-22} \text{ eV} \)
- \( m_\alpha = 10^{-21} \text{ eV} \)

**dashed:**
WDM
Figure 6. Halo mass function computed directly from CAMB for ΛCDM, and aMDM with various $f_c = \Omega_c / \Omega_d$ at fixed total $\Omega_d h^2 = 0.112$ and axion mass $m_a = 10^{-22} \text{ eV}$. Solid lines have $\delta_c(M)$ while dashed lines have $\delta_c = \delta_{\text{EdS}}$. At $f_c = 0.5$
\[ \nabla \rho_i = \sum_{j \in \text{NN}(i)} m_j W_{ij} \frac{\rho_j - \rho_i}{\sqrt{\rho_i \rho_j}} \]

Wij = SPH kernel with smoothing length hi:

\[ \frac{4}{3} \pi h_i^3 \rho_i = \sum_{j \in \text{NN}(i)} m_j = M \]
Zhang+ 1708.04389
Veltmaat-Niemeyer

Particle-mesh (Nyx)
The CDM « small-scale crisis »

Since end of ‘90s

Several ~kpc-scale features of matter distribution cannot be reproduced by CDM-only LSS simulations

- Baryon feedback
- Room for specific dark matter properties which « smooth » density fluctuations
IGM and other systematics

Basic IGM parameters (~free)

\[ T(\rho, z) = T_0(z) (1 + \delta)^{\gamma(z) - 1} \]

\[ \tau_{\text{eff}} = A^\tau \times (1 + z)^{\eta^\tau} \]

SDSS resolution

\[ c_{\text{reso}} = e^{-(\alpha_{\text{reso}} + \beta_{\text{reso}}(z-3)) \times k^2} \quad \text{(gaussian constrain on a,b)} \]

Missed DLA

\[ c_{\text{DLA}}(k) = \left( \frac{1}{15,000k - 8.9} + 0.018 \right) \times 0.2 \times \alpha_{\text{DLA}} \]
SN+AGN feedback

Reionization

McDonald+ 2005 (low-z)

\[ C_*(k) = \alpha_*(z) + \beta_*(z)k + \gamma_*(z)k^2 \]