Revisiting Quadratic Scalar Field (Fuzzy, Wave, Ultralight) Dark Matter in Light of DESI DR2 and Current Cosmological Observations

Hafiz Inam Ullah

Ph.D. Student, ESFM-IPN / CINVESTAV-IPN

Supervisors: Prof. Rubén Cordero and Prof. Tonatiuh Matos

Interests: lya, cosmological parameter estimation, dark matter and dark energy

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Motivation

- ΛCDM successfully describes the large-scale Universe using CMB, BAO, and SN Ia data [1, 4, 5].
- However, the physical nature of dark matter remains unknown.
- Ultra-light scalar-field dark matter is a motivated alternative that can modify structure formation on small scales [6, 7, 8].
- In the quadratic model,

$$V(\phi) = \frac{1}{2} m_\phi^2 \phi^2,$$

  the field behaves like pressureless matter after coherent oscillations begin.

Main question

Can current cosmological observations place meaningful constraints on the scalar-field mass m_ϕ?

What is DESI?

Dark Energy Spectroscopic Instrument

- DESI is a Stage-IV spectroscopic survey on the Mayall 4-m telescope at Kitt Peak.
- It measures galaxy and quasar redshifts to construct a 3D map of large-scale structure.
- The survey targets galaxies and quasars across a large cosmic volume, reaching look-back times of about 11 billion years.

Why it is powerful for cosmology

- BAO acts as a standard ruler for the expansion history.
- DESI uses multiple tracers: BGS, LRG, ELG, quasars, and Lyα forest.
- DR2 BAO results use the first three years of DESI survey data.

Connection to this talk

DESI gives precise distance and structure information. This makes it an ideal dataset to test whether dark matter behaves exactly like CDM or shows scale-dependent departures, as expected in ultra-light scalar-field models.

Sources: DESI public webpages and DESI DR2 guide [2, 3, 4].

Why dark matter is important with DESI

DESI observes structure

- Galaxies, quasars, and Lyα absorption trace the matter distribution.
- BAO fixes cosmological distances, while clustering and Lyα probe growth and small scales.
- Dark matter determines how density perturbations grow into the cosmic web.

SFDM prediction

- Quadratic SFDM can mimic CDM at the background level.
- Its key signature is a suppression of matter power at sufficiently small scales.
- DESI BAO constrains the expansion history, while Lyα information probes smaller-scale matter clustering where SFDM deviations from CDM are expected to be strongest.

Main physical idea

If m_ϕ is too small, wave-like pressure suppresses structure too strongly. Observations therefore impose a lower bound on m_ϕ.

Model and methodology

Model

- Single ultra-light scalar field
- Quadratic potential:

$$V(\phi) = \frac{1}{2} m_\phi^2 \phi^2$$

- Implemented in modified `CLASS` [9]
- MCMC inference with `MontePython`

Datasets

- Planck 2018 CMB
- DESI DR2 BAO
- Pantheon+ SN Ia
- Lyα / small-scale matter-power information [10]

Physical expectation

Background evolution remains close to CDM, but linear perturbations show a scale-dependent suppression at small scales.

MontePython setup: datasets and main priors

Likelihoods used

- Planck high-ℓ TTTEEE
- Planck low-ℓ EE
- Planck low-ℓ TT
- DESI DR2 BAO
- `cmb_baryon`
- Pantheon+

SFDM assumption

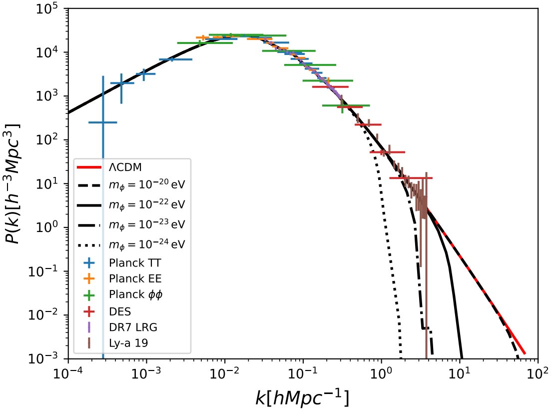
- Minimal quadratic scalar field
- Tiny residual CDM fixed: $\Omega_{\rm cdm} = 10^{-4}$
- Main sampled SFDM quantity: $\log_{10}(m_\phi/{\rm eV})$

Main sampled parameters

Displayed parameter	Initial value	Prior range	Proposal step
$100\omega_b$	2.2377	[0.5, 10.0]	0.015
$\Omega_{\rm sfdm,1}$	0.15	[0, 1.0]	0.0013
H_0	60.0	[20, 100]	0.1
$\ln(10^{10}A_s)$	3.0447	[2.7, 4.0]	0.015
n_s	0.9659	[0.9, 1.1]	0.0042
$\tau_{\rm reio}$	0.0543	[0.01, 0.8]	0.008
$\log_{10}(m_\phi/{\rm eV})$	-20	$[-24, -17]$	0.1

The MontePython input samples `omega_b` with scale 0.01, so $100\omega_b = 2.2377$ corresponds to $\omega_b = 0.022377$. Planck nuisance parameters are included in the run but omitted here for readability.

Result 1: Linear matter power spectrum



Linear matter power spectrum at $z = 0$.

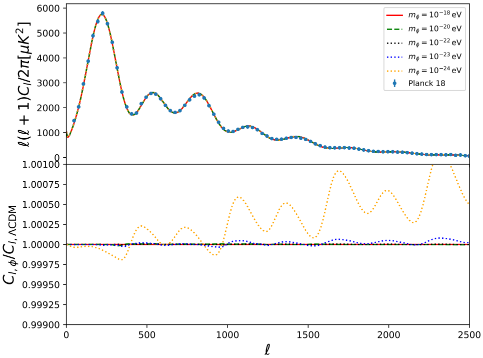
Main message

- Quadratic SFDM suppresses power on small scales.
- Lower scalar-field masses produce stronger suppression.
- For larger masses, the model approaches the ΛCDM limit.

Interpretation

This is the main phenomenological signature of the model: the difference from CDM appears mainly in the growth of structure, not in the background expansion.

Result 2: CMB temperature anisotropy spectrum



CMB temperature spectrum and ratio relative to ΛCDM.

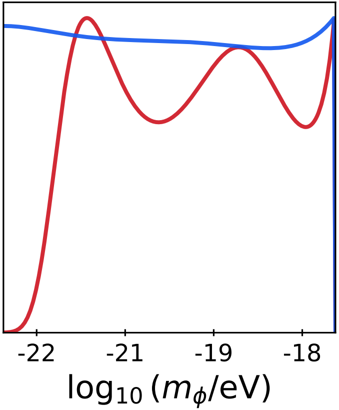
Main message

- The CMB spectra remain very close to ΛCDM.
- The largest deviations appear mainly at low multipoles.
- For allowed masses, the deviations are small.

Interpretation

Current CMB data alone do not strongly distinguish quadratic SFDM from ΛCDM. Small-scale structure probes are more constraining.

Result 3: Posterior of the scalar-field mass



One-dimensional posterior of $\log_{10}(m_\phi/\mathrm{eV})$.

Main result: Lyα-driven lower bound

- Baseline data,

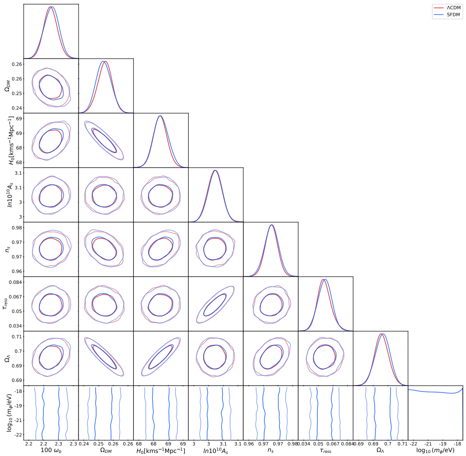
  Planck + DESI DR2 + Pantheon+,

  leave the mass posterior broad.
- Adding Lyα excludes very small masses because they suppress small-scale power too strongly.
- In our analysis, the combined data give:

$$\boxed{\log_{10}(m_\phi/\mathrm{eV}) > -22.15}$$

at 95% C.L.

Result 4: Standard cosmological parameters remain close to ΛCDM



Triangle plot comparing ΛCDM and quadratic SFDM with baseline data.

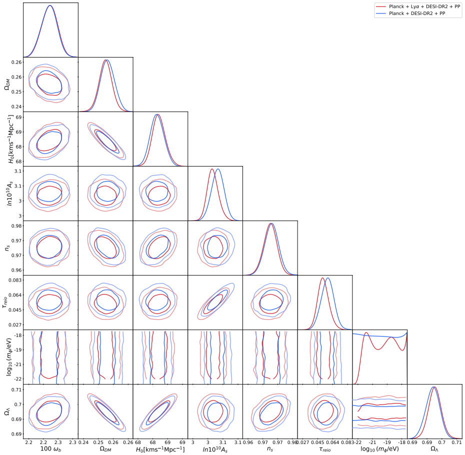
Main message

- Standard cosmological parameters remain very similar in both models.
- No strong shifts are seen in:
  - $100\omega_b$
  - Ω_{DM}
  - H_0
  - n_s
  - τ_{reio}
  - $\ln(10^{10}A_s)$

Interpretation

Quadratic SFDM does not significantly alter the preferred background cosmology from current observations.

Result 5: Impact of Lyα data



Triangle plot with and without Lyα data.

Main message

- Adding Lyα mainly affects $\log_{10}(m_\phi/\mathrm{eV})$.
- The standard cosmological parameters remain almost unchanged.
- This matches the expected SFDM phenomenology.

Interpretation

Lyα is the dominant dataset for constraining the scalar-field mass because it probes the small-scale matter distribution directly.

conclusions

- Quadratic SFDM remains compatible with current cosmological observations.
- Its main signature is the suppression of the linear matter power spectrum on small scales.
- The CMB temperature spectrum remains very close to ΛCDM.
- Baseline data alone do not strongly constrain the scalar-field mass.
- In this analysis, Lyα information gives the strongest model-specific constraint:

$$\boxed{\log_{10}(m_\phi/\mathrm{eV}) > -22.15 \quad (95\%\ \mathrm{C.L.})}$$