Ultra-Light Dark Matter: Current Constraints and Future Possibilities

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What is ULDM?

- “Ultra-Light” / “Fuzzy” / “ψ” / “BEC” / “Scalar Field” / “Axion-like”
- Class of DM models in which the constituent particle is an extremely light scalar (~ 10^{-22}eV)
- In the non-relativistic limit, ULDM (without self-interactions) is governed by the Schrödinger-Poisson system

$$i\hbar\dot{\Psi} = -\frac{\hbar^2}{2ma^2}\nabla^2\Psi + m\Phi\Psi$$

$$\nabla^2\Phi = \frac{4\pi G}{a}(\rho - \bar{\rho})$$

$$\rho = m|\Psi|^2$$

Start with a minimally coupled real scalar field

$$S = \int \frac{d^4x}{\hbar}\sqrt{-g}\left\{\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \frac{m^2}{2\hbar^2}\phi^2\right\}$$

Adopt the perturbed FLRW metric in the Newtonian gauge

$$ds^2 = -\big(1+2\Phi(\vec{r},t)\big)dt^2 + a(t)^2\big(1-2\Phi(\vec{r},t)\big)d\vec{r}^{\,2}$$

Expand the E-L equations to linear order in the potential

$$\ddot{\phi} - \frac{\big(1+4\Phi\big)}{a(t)^2}\nabla^2\phi + 3H\dot{\phi} - 4\dot{\Phi}\dot{\phi} + \big(1+2\Phi\big)\frac{m^2}{\hbar^2}\phi = 0$$

Re-express the field in terms of a complex scalar

$$\phi = \frac{\hbar}{\sqrt{2}m}\left(\psi e^{-imt/\hbar} + \psi^* e^{imt/\hbar}\right)$$

Non-relativistic assumptions

$$m|\psi| \gg \hbar|\dot{\psi}|$$

$$H \ll m/\hbar$$

ULDM Madelung fluid representation

$$\Psi = \sqrt{\frac{\rho}{m}} e^{i\theta} \qquad \mathbf{v} = \frac{\hbar}{am}\nabla\theta$$

Continuity Equation

$$\dot{\rho} + \frac{1}{a}\nabla \cdot (\rho \mathbf{v}) = 0$$

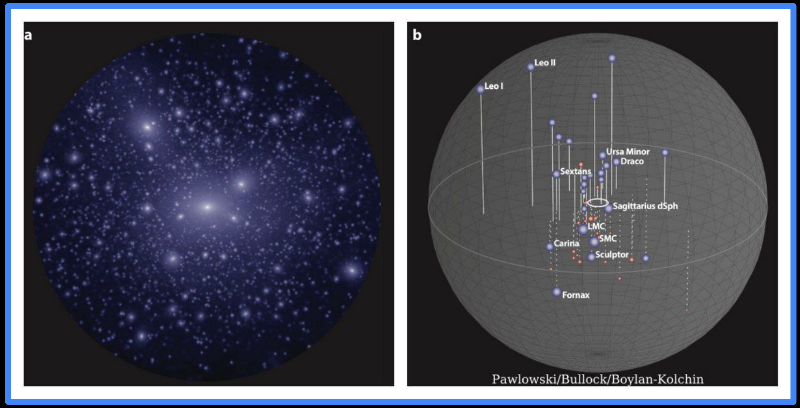
Euler Equation +
"quantum pressure"
term

$$\dot{\mathbf{v}} + \frac{1}{a}(\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{1}{a}\nabla\Phi + \boxed{\frac{\hbar^2}{2a^3m^2}\nabla\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)}$$

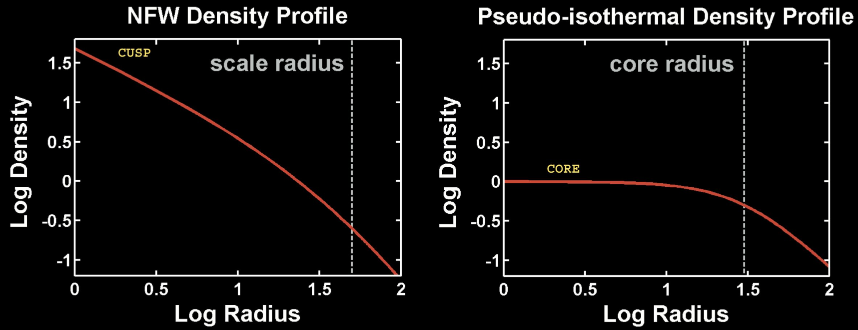
Motivation for ULDM

- The "quantum pressure" (QP) resists gravitational compression of the ULDM fluid
- The effects of QP are most significant on the scale of the de Broglie wavelength, whereas large scale behaviour is indistinguishable from CDM
- With an appropriately small particle mass, ULDM could provide a resolution to the small-scale crisis**, while preserving CDM's successes on cosmological scales

**Highly contested!



From: Annu. Rev. Astron. Astrophys. 2017. 55:343–87

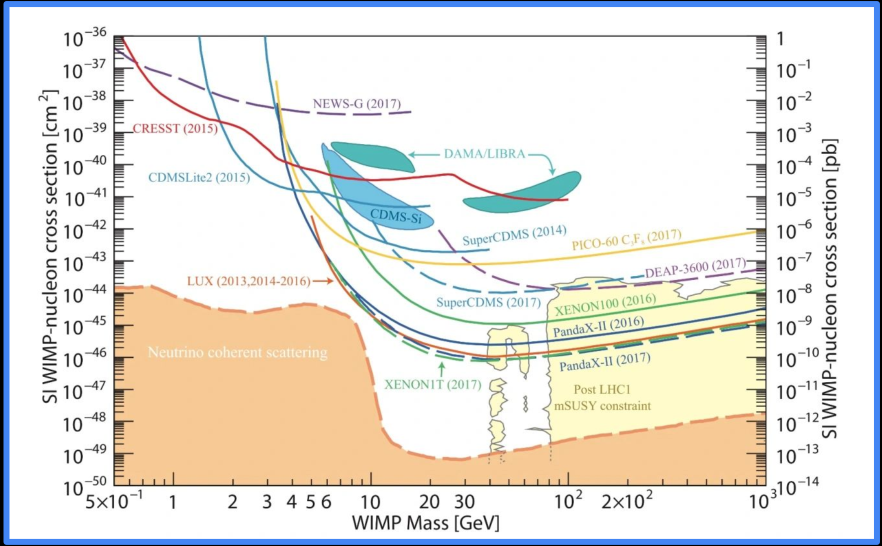


From: Arxiv:2209.14151

Motivation for ULDM

- Scalar fields offer simple solutions to a number of problems in particle physics and cosmology e.g. Inflaton, QCD axion, Quintessence, Higgs…

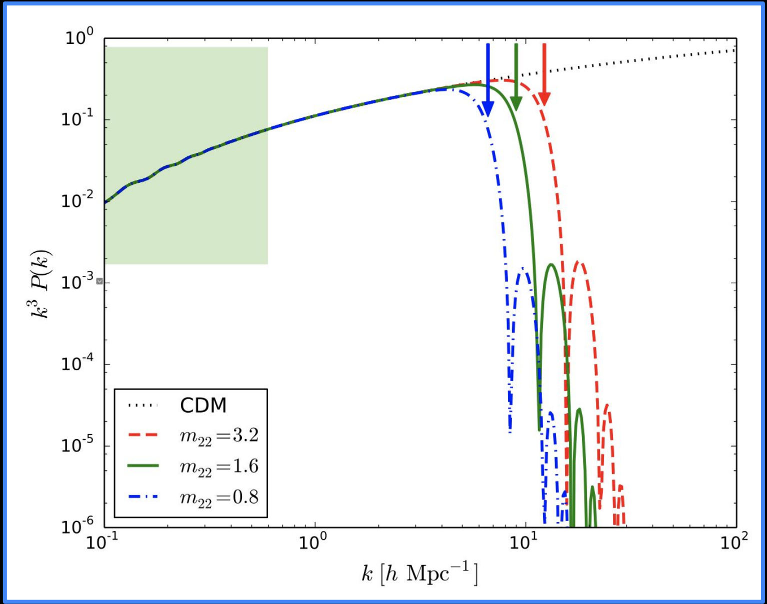
- Such scalar fields arise naturally in string theoretic approaches to high-energy physics and seem to provide natural candidates in the absence of direct detection evidence for WIMPs



From: PDG RPP 2017

Structure Formation in ULDM

- The interplay between gravity and QP yields a redshift-dependent Jeans scale, below which structures cannot form
- This means that the linear density power spectrum of ULDM is suppressed relative to CDM at small scales
- To assess the effect this has on the halo mass function in the non-linear regime, simulations are needed - but these are difficult due to the wave nature of ULDM



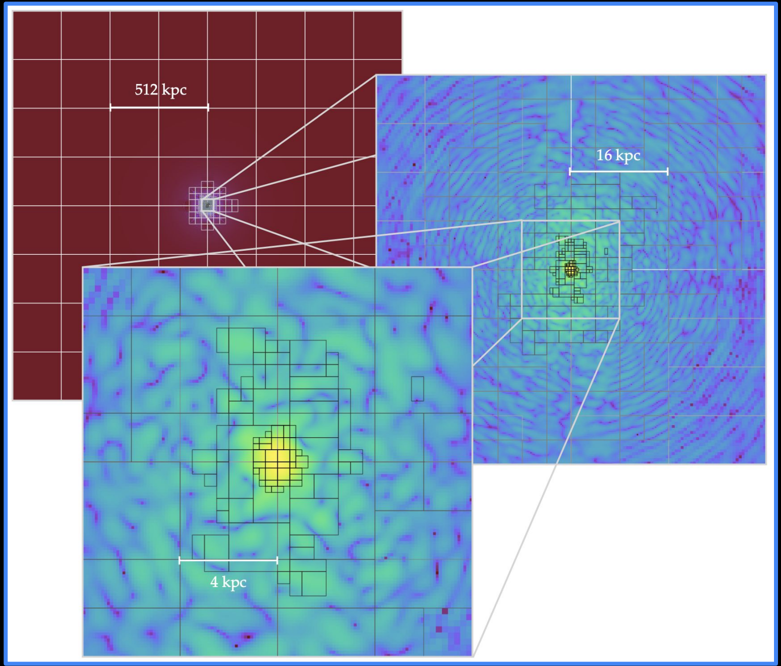
Linear matter power spectra at z=30 for CDM and ULDM with different particle masses. From: Arxiv:1508.04621

Simulating ULDM

- Exceptionally high spatial and temporal resolutions are required to accurately evolve the ULDM wave function, especially in regions of high-velocity flows

- Consequently, CDM simulations initialised with ULDM power spectra have been used to approximate real ULDM evolution, however this approach misses key details

- Full SP simulators using adaptive mesh refinement increase resolution in areas of interest while minimising computational overheads



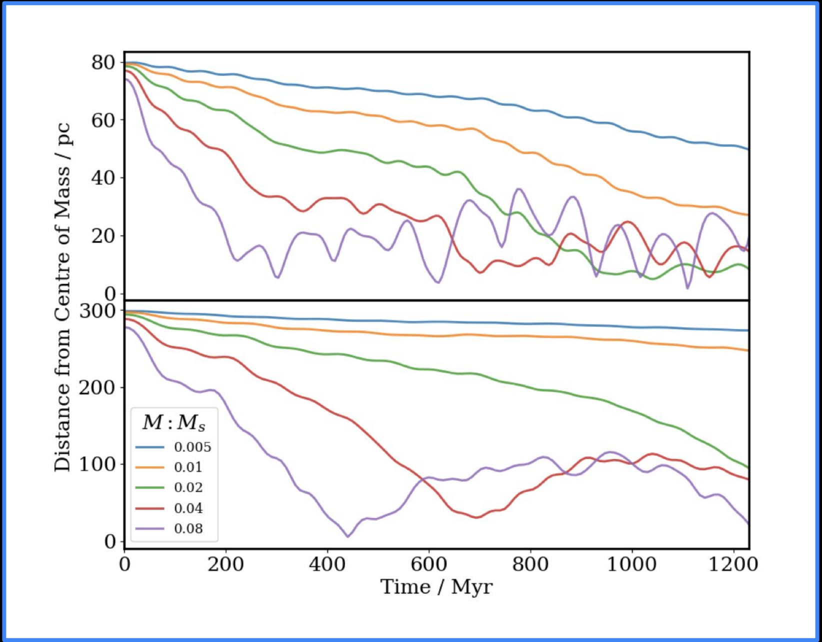
AxioNyx AMR. From: Arxiv:2007.08256

Simulating ULDM

- AxioNyx is an extension to the Nyx cosmological hydrodynamics simulation code, built on top of the massively parallelised AMReX AMR framework

- AxioNyx solves the full SP system with the ability to use (6th order) pseudospectral methods on the base grid and (fourth order) finite differencing on (up to six) refined levels

- A simpler pseudospectral Python code, PyUltraLight, is available for small-scale simulations where expansion is not important. Many extensions to this code exist, including, for example, BH dynamics



“Stone-skipping” solutions to black hole orbital decay within a ULDM soliton due to excited modes. From: Phys. Rev. D 105, 063523 (2022)

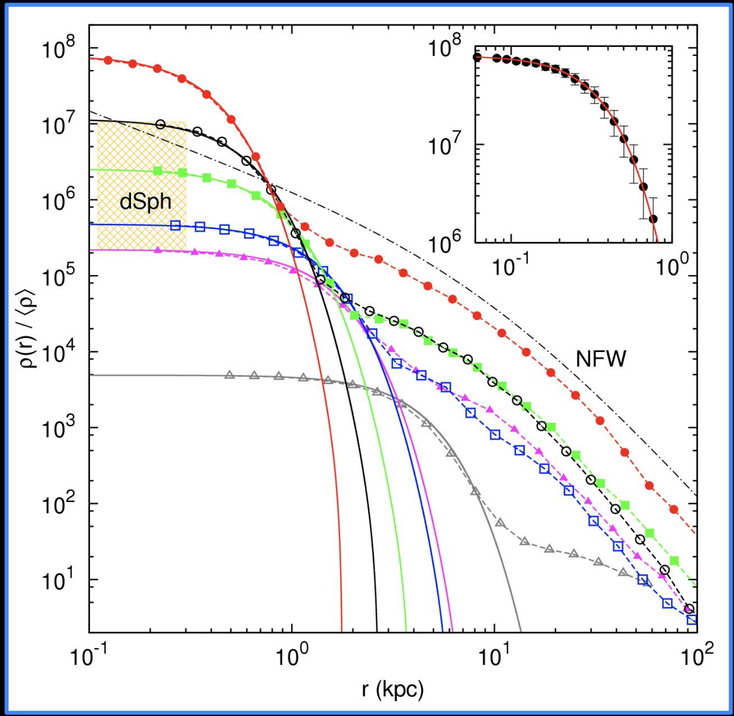
Generic features of ULDM halos

- Early simulations suggested a generic core-halo structure where the cores are well fit by the solitonic ground state solution to the SP equations and the outer halo is NFW

$$\rho_c(r) = \frac{1.9 \times 10^7 m_{22}^{-2} (r_c/\mathrm{kpc})^{-4}}{(1 + 0.091(r/r_c)^2)^8} \mathrm{M}_\odot \mathrm{kpc}^{-3}$$

- A corresponding core-halo mass scaling relation was observed:

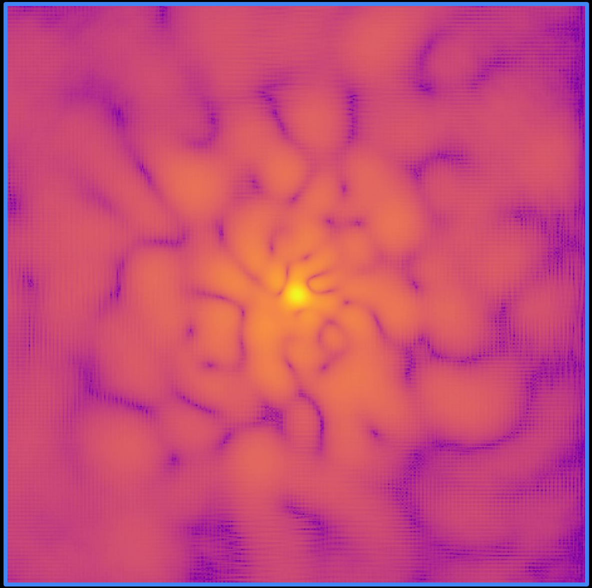
$$r_c = 1.6\, m_{22}^{-1} a^{1/2} \left(M_h/10^9 M_\odot\right)^{-1/3} \mathrm{kpc}$$



Spherically-averaged density profiles for a selection of halos.
From: Arxiv:1406.6586

Generic features of ULDM halos

- Another distinctive feature present in simulated ULDM halos is local (order unity) density fluctuations caused by wave interference
- These fluctuations resemble a random ‘granular’ structure where individual transient granules have coherence lengths ~ $\lambda/2\pi$
- Granules passing by stars would perturb the stars’ velocities, and over time several such encounters would lead to increased variance in stellar velocities



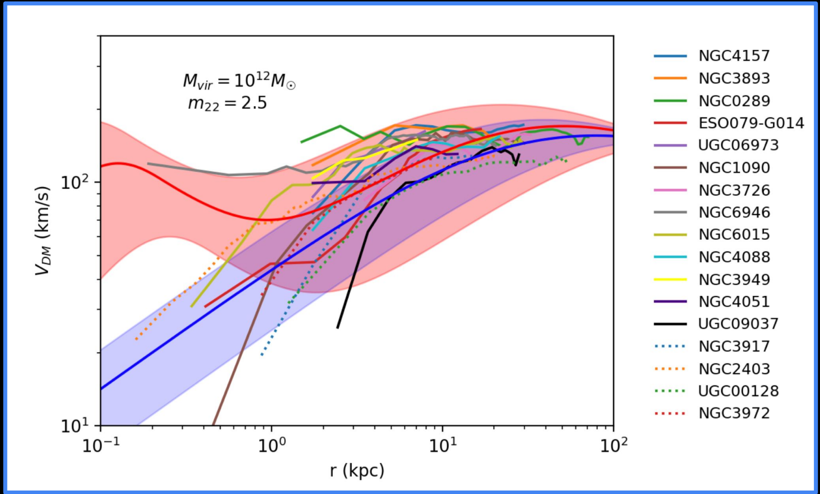
From: Arxiv:1908.02508

ULDM constraints - core-halo relation

- Attempts have been made to constrain the plausible ULDM mass range using the putative core-halo mass relation**

- A recent example* uses rotation curves from the SPARC database to exclude ULDM in the mass range $m = (0.14–3.11) \times 10^{-22}$ eV

- However, these analyses assume the core-halo relation is universally applicable and may not properly account for dynamical timescales of tracer objects



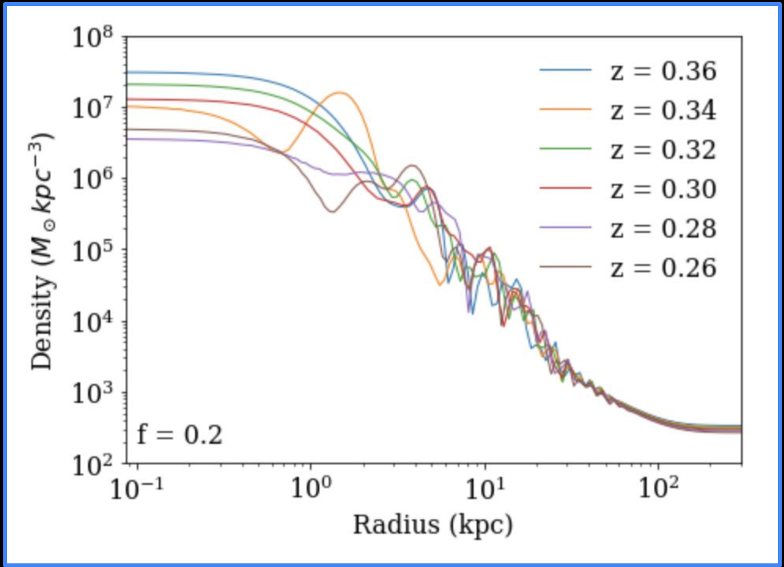
Velocity distributions for galaxies in the SPARC database plotted alongside theoretical NFW (blue) and ULDM (red) predictions, assuming a virial mass of $10^{12} M_{\odot}$, $m_{22} = 2.5$. Shaded regions show ±50% scatter in the core-halo mass relation and ±2σ scatter in NFW concentration. From: Arxiv:1908.02508

*The Astrophysical Journal, 913:25, 2021

**Phys. Rev. Lett., 113(26):261302, 2014

ULDM constraints - core-halo relation

- But simulations show strong, undamped oscillations in the solitonic core which lead to variability around the core-halo relationship
- Simulations of isolated overdensity collapse show that these oscillations also distort the core morphology, deviating from the solitonic profile
- Furthermore, high-resolution simulations show that the core-halo mass ratio is dependent on formation history* and that stable artificial halos can be constructed with a wide range of masses**



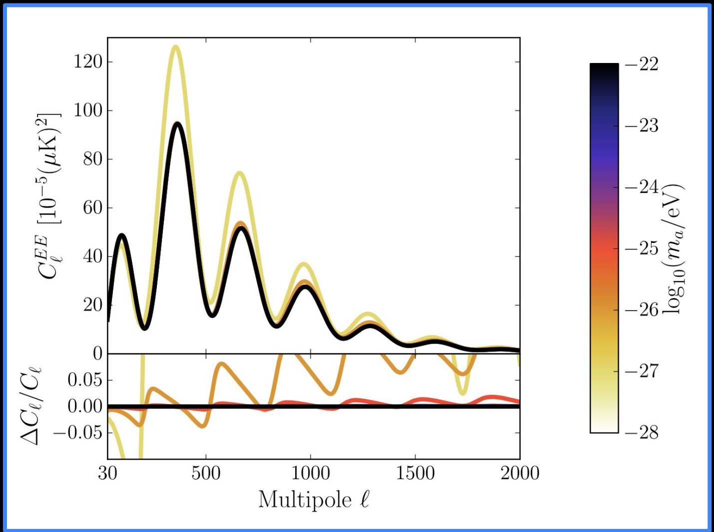
Strong oscillations in the core of a collapsed ULDM halo leading to changes in core morphology (publication in prep.)

*Phys. Rev. D 107, 083513, 2023

**Phys. Rev. D 105, 023512, 2022

ULDM constraints - CMB

- Once generated in the early universe, the ultra-light scalar begins to roll down its potential, and only begins to behave like DM once it is oscillating near the minimum, this happens when H ~ m. Before this, it is DE-like
- The change in the equation of state from $w \approx -1$ to 0 means that the expansion rate differs from that in the standard CDM model, affecting the Silk damping scale and Sachs–Wolfe effects in the CMB
- QP on scales at or below the de Broglie wavelength suppresses the axion density power spectrum compared to CDM
- Recent work* has found no evidence of ULDM in the range $10^{-33} \le m \le 10^{-24}$ eV, but cannot constrain higher masses



E-mode polarization autopower. The EoS transition affects both the diffusion damping scale and the amplitude of the early ISW effect.

*MNRAS 476, 3063–3085 (2018)

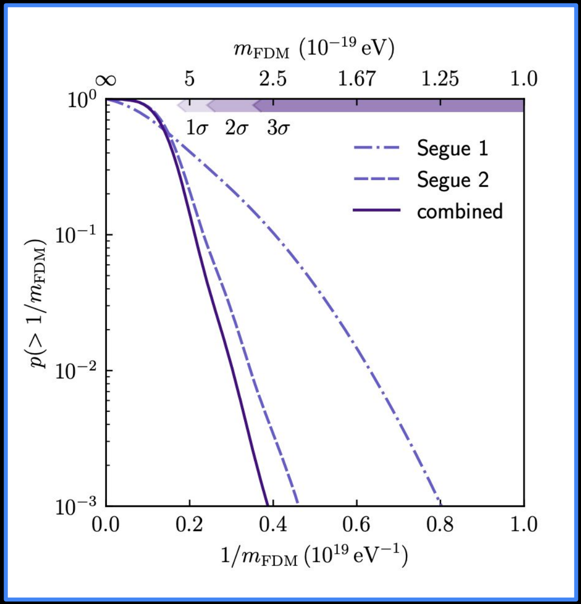
ULDM constraints - Stellar heating

- The order unity fluctuations in the local ULDM halo density can gravitationally heat stellar systems. Over time, multiple interactions lead to an increase in the stellar velocity dispersion according to:

$$\Delta\sigma_*^2 \approx 9\left(\frac{\sigma_*}{\sigma_{\rm dm}}\right)^4\left(\frac{\hbar}{m}\right)^3\frac{t}{r_{1/2}^4}$$

- UFDs provide a useful test scenario, with an expected doubling of stellar velocity dispersion over a 10 Gyr time scale if m ~ 10^{-19} eV

- Simulations of stars in FDM halos (using an approximate perturbative treatment of FDM wave interference) compared to data for Segue 1 and 2 exclude m < 3 × 10^{-19} eV at 99% confidence*

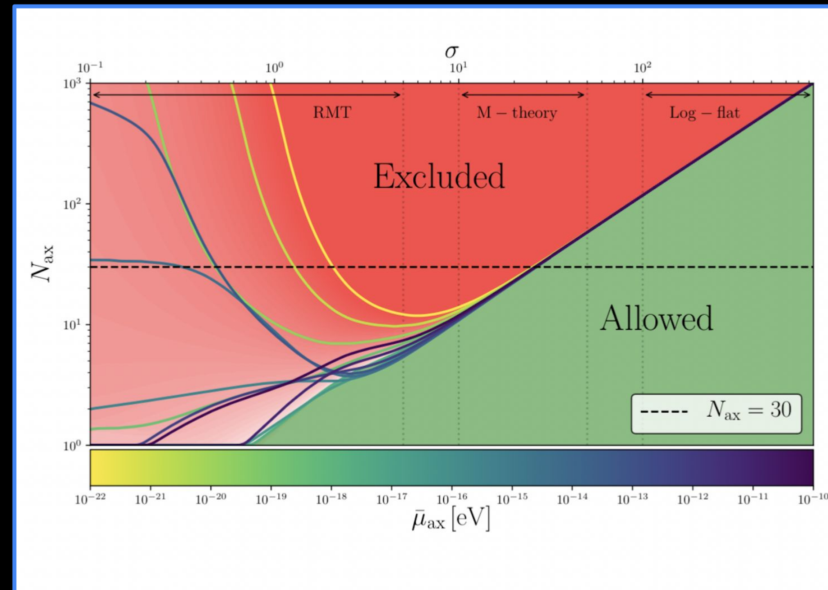


Cumulative posterior pdfs of the ULDM mass for Segue 1 and 2 (arrowheads indicate the derived 1, 2, and 3−σ exclusion regions for joint constraints)

*Arxiv:2203.05750v2, Arxiv:2303.08846v2

ULDM constraints - Superradiance

- Rotating BHs can become unstable against the production of ULDM particles, forming a gravitational ‘atom’
- This spins the BH down, transferring ~ few % of the BH’s mass and angular momentum to a persistent ULDM “cloud” outside the horizon
- This effect is greatest when Compton wavelength ~ BH gravitational radius. This means that stellar mass BHs to SMBHs allow us to probe ULDM mass $10^{-10} > m > 10^{-21}$ eV
- Note that this mechanism is independent of whether the bosonic particles constitute dark matter or not

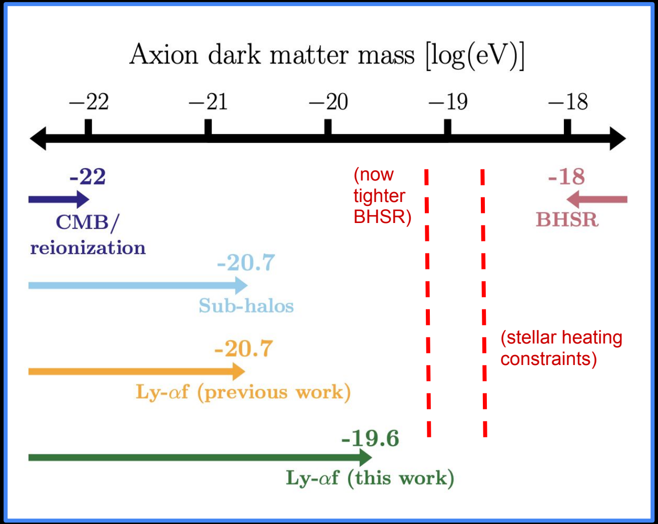


SMBHs exclude 7×10^{-20} eV < m < 10^{-16} eV at the 95% confidence level for single field ULDM without self-coupling.

*Phys. Rev. D 98, 083006 (2018)

ULDM constraints - Lyman-α and others

- Neutral hydrogen absorption lines (Lyman-α forest) seen in high-redshift quasar spectra ($2 < z < 6$) trace fluctuations in the IGM and therefore the linear matter power spectrum
- Modelling the effect of ULDM quantum pressure only by modified initial conditions (sufficient for the current sensitivity of data) and comparing to observed Lyman-α spectra disfavours 10^{-22} eV < m < 10^{-21} eV at > 99.7% credibility*
- These results compliment others derived from, e.g. inferences of the subhalo mass function from Milky Way data, the high-redshift UV luminosity function (sensitive to the reionization model), CMB power spectrum, and more



Ly-α constraints alongside similar constraints from other methods. These constraints can be partially weakened if ULDM is a sub-dominant component of the overall DM density

*Phys. Rev. Lett. 126, 071302 (2021)

Modifications to ‘vanilla’ ULDM

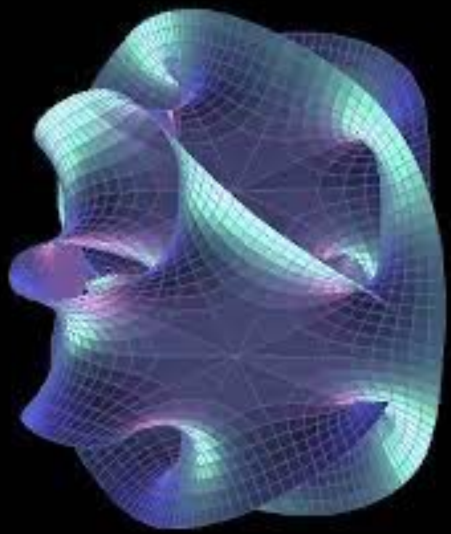
- Many of the existing constraints on ULDM mass are derived for single field, non-interacting models, ULDM only models

- While mixed CDM/ULDM models can relax some constraints, n-field ULDM can also achieve this

- Much of the motivation for ULDM comes from string-theoretic approaches to high-energy physics

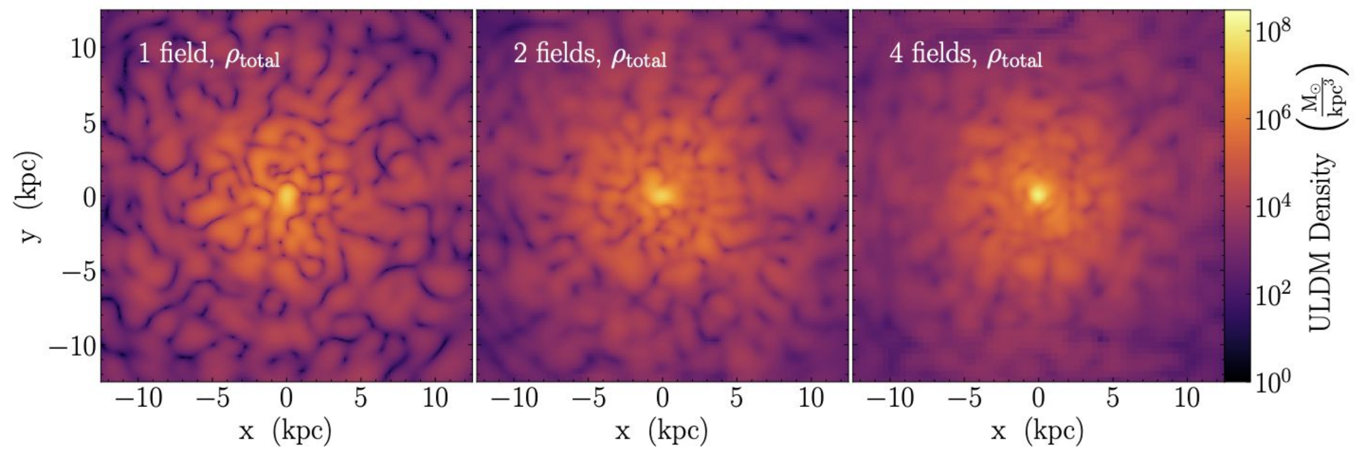
- These typically support many ultra-light fields, associated with the (non-equivalent) closed 2-cycles of the Calabi-Yau manifold that sets the topology of the compact dimensions

- 100’s of ultra-light scalar fields are typical, with masses distributed uniformly on a logarithmic scale*



*Phys. Rev. D 81, 123530 (2010)

N-field ULDM



Recent work illustrating the smoothing of the overall density field when multiple ULDM fields of similar mass are present. This relaxes constraints based on stellar heating, but model choices can be constrained by e.g. BHSR and CMB spectra.

*Phys. Rev. D 107, 083014 (2023)

Conclusions

- Single field ULDM with particle mass $\sim 10^{-22}$ eV was originally motivated by the possibility of a natural resolution to the ‘small scale crisis’
- This model has since been tightly constrained by many measures, (CMB, Lyman-α, High-z luminosity function, Milky Way SHMF, stellar kinematics in dwarf galaxies, density profiles of dwarf galaxies, non-detection of BHSR
- ULDM may also have a host of other consequences in regimes not yet observed, for example excitations in solitonic cores can disrupt the formation of SMBH binaries after galaxy mergers - implications for LISA merger rates
- However, modifications to vanilla ULDM such as mixed DM, self-interacting, or N-field models may alleviate many of these constraints