Ultralight Dark Matter

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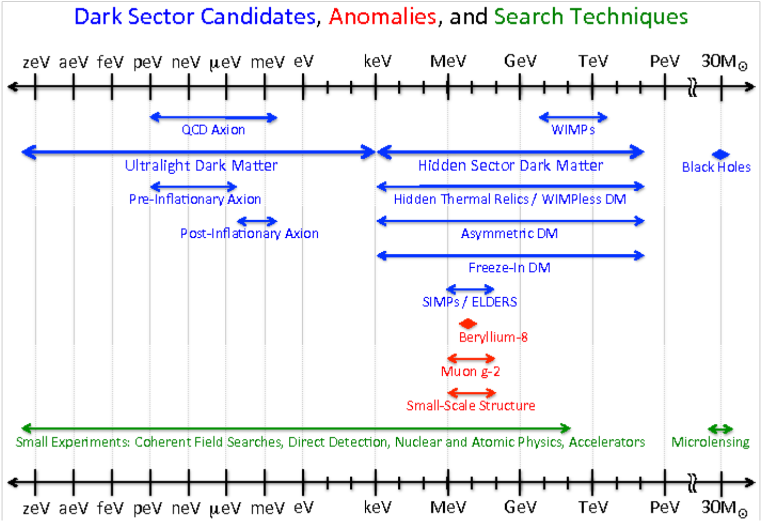
Outline

Dark Matter mass



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Ultralight Dark Matter: Motivation

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- Exploration of DM parameter space
- Small scale structure problems

Production

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- Decay of topological defects
- Misalignment mechanism

Misalignment production of axion DM

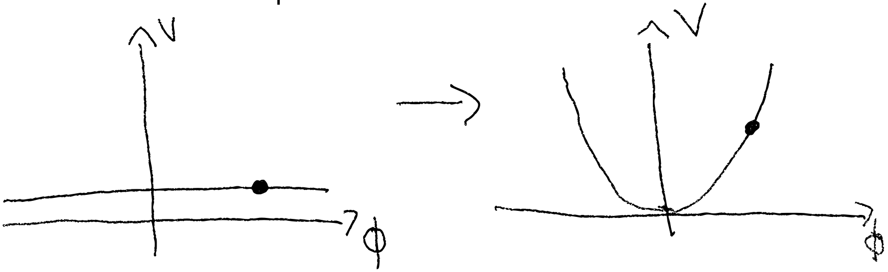
$U(1)_A$ symmetry spontaneously broken. Massless axion field created.

$\downarrow$

Axion follows random walk in field space.

$\downarrow$

Non-perturbative effects generate axion mass. Axion field is now displaced from its minimum.



Misalignment production of axion DM

- Coherently oscillating scalar field: $\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$
- Oscillations are damped by the expansion of the universe
- Energy density redshifts like dark matter

Classical field description

The ultra-light DM field is the coherent state:

$$|\phi\rangle = \exp\left[\int \frac{dq^3}{(2\pi)^3}\tilde{\phi}(q)\hat{a}^\dagger(q)\right]|0\rangle\,,$$

such that:

$$\langle\phi|\,\hat{\phi}\,|\phi\rangle = \phi(x),$$

where $\phi(x)$ is the classical field.

Classical field description

$$\phi \sim A(x,t)\cos(mt - \alpha(x,t))$$

If we write $\psi = A\mathrm{e}^{i\alpha}$, ψ obeys a Schrodinger-Poisson equation:

$$i\partial_t\psi = \left(-\frac{1}{2m}\nabla^2 + m\Phi\right)\psi$$

$$\nabla^2\Phi = 4\pi Gm|\psi|^2$$

We cannot use this framework for cold DM, as A and α would not be well defined.

Classical field description

$$i\partial_t \psi = \left(-\frac{1}{2m}\nabla^2 + m\Phi \right) \psi$$

- Ultralight DM is well approximated by a classical field limit of quantum field theory. Large occupation numbers lead to a low fractional uncertainty in the amplitude and phase dispersion.
- ψ is not a wavefunction.

Classical field description

$$\psi(t,\mathbf{x}) = \sqrt{n(t,\mathbf{x})}\mathrm{e}^{i\hbar S(t,\mathbf{x})}$$

$$\nabla S(t,\mathbf{x}) = m\mathbf{v}(t,\mathbf{x})$$

Number density

$$\partial_t n + \nabla \cdot \mathbf{j} = 0$$

$$\mathbf{j} = \frac{N}{2\mathrm{i}m}(\psi^* \nabla \psi - \psi \nabla \psi^*)$$

Velocity

$$\partial_t \mathbf{v} + (\mathbf{v} \cdot \nabla)\mathbf{v} + \nabla(Q + \Phi) = 0$$

$$Q = -\frac{1}{2m^2}\frac{\nabla^2\sqrt{n}}{\sqrt{n}}$$

Quantum Pressure

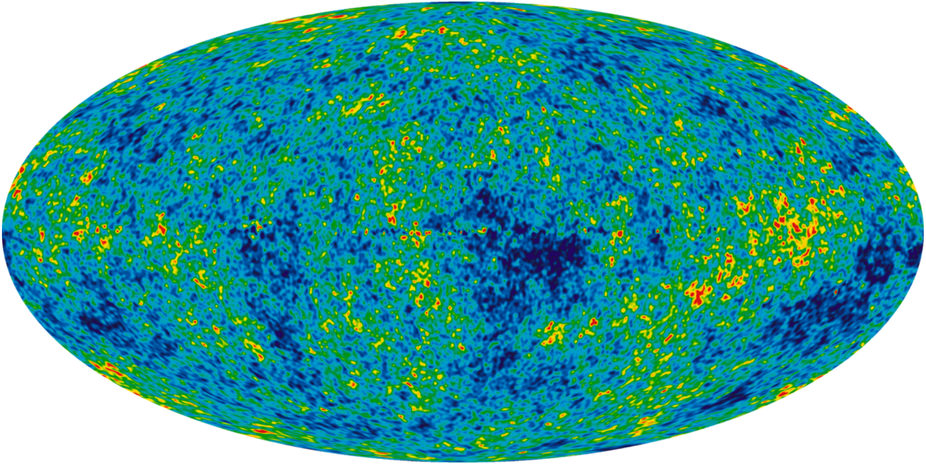
$$\partial_t \mathbf{v} + (\mathbf{v} \cdot \nabla)\mathbf{v} + \nabla(Q + \Phi) = 0$$

- Ultralight DM does not behave like a perfect fluid.
- The 'quantum pressure' Q is a repulsive term that counteracts the gravitational potential.
- Q can be understood as arising from the zero point motion of the ultra-light particles.

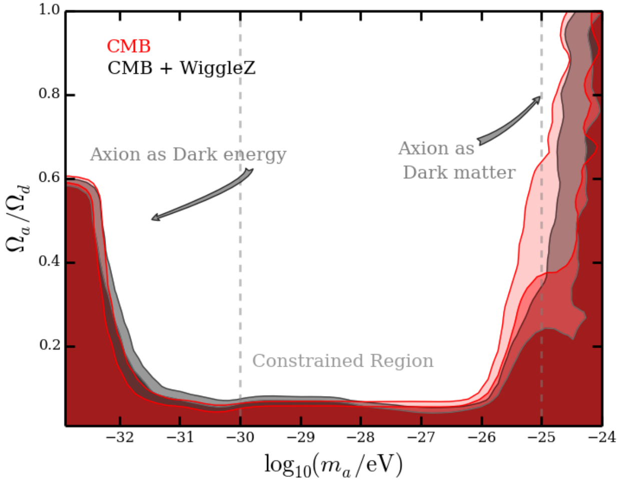
Ultralight DM structure

- Ultralight DM possess a natural scale, the Jeans scale, equal to the de Broglie wavelength of the ground state.
- Stability below the Jeans scale is guaranteed by the Uncertainty Principle.
- Power on scales below the Jeans is suppressed.

Ultralight DM in the CMB



Ultralight DM in the CMB

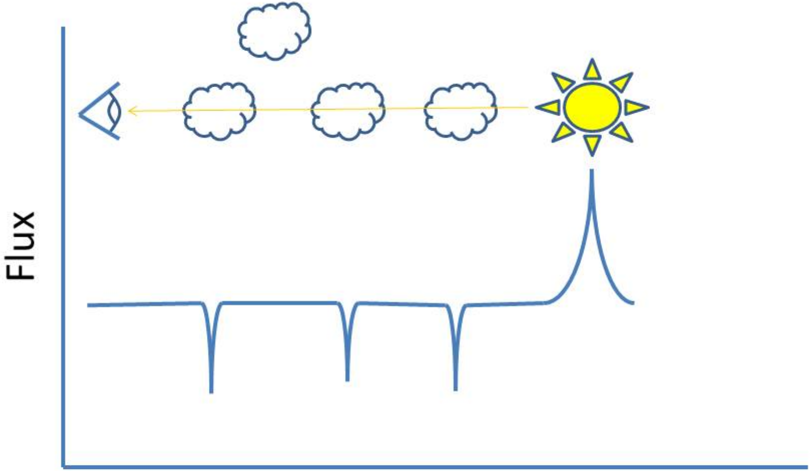


Reproduced from Hlozek *et al* (1410.2896)

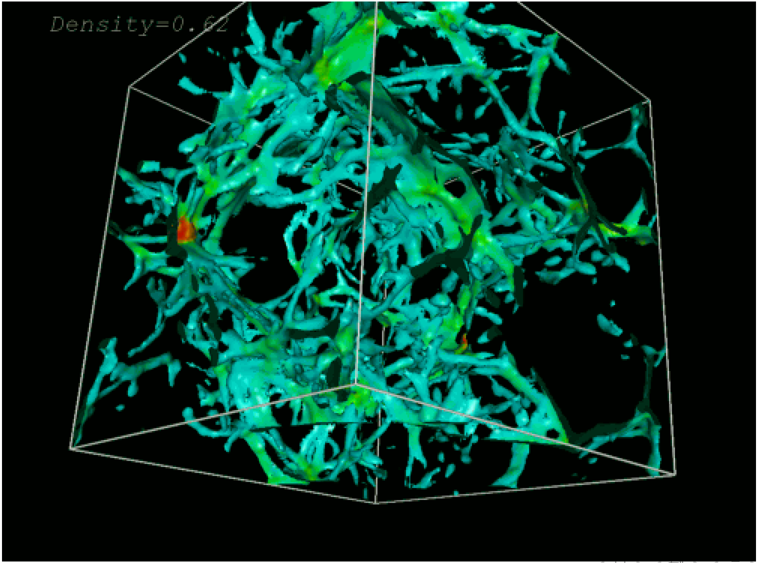
Ultralight DM in the Lyman-α forest

- Light from distant galaxies and quasars is absorbed by intergalactic gas clouds.
- We observe the Lyman-α absorption line from the ground state to the first excited state of neutral hydrogen.
- The absorption line is redshifted.
- From the gas distribution, we infer the DM distribution.

Ultralight DM in the Lyman-α forest



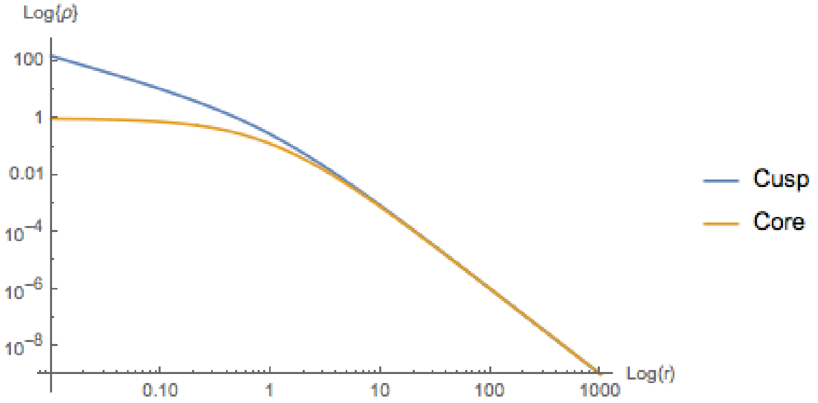
Ultralight DM in the Lyman-α forest



Ultralight DM in the Lyman-α forest

- Lyman-α forest data rules out ultralight DM with $m = 1 - 10 \times 10^{-22}$ eV. (Iršič *et al*, 1703.04683)
- Recent work using machine learning to emulate the power spectrum improves the bound to $m > 2 \times 10^{-20}$ eV. (Rogers & Peiris, 2007.12705)

The Cuspy Halo Problem



Ultralight DM candidates

- vector (i.e. dark photons)
- scalar
- pseudo-scalar (i.e. axions)

The Strong CP Problem

- The CP violating term $\mathcal{L} \supset \theta \frac{g^2}{32\pi^2} G^{\mu\nu} \tilde{G}_{\mu\nu}$ is allowed in the QCD Langrangian
- Null measurements of the neutron electric dipole moment constrain $\theta < 10^{-9}$
- Weak interactions transform θ: $\theta \rightarrow \theta + \arg \det M$.
- Need very fine tuned cancellations to explain observations.

The Vafa-Witten Theorem

"In parity-conserving vector-like theories such as QCD, parity conservation is not spontaneously broken."

Dynamical parity violating terms have zero vacuum expectation value.
(Vafa and Witten, 1984)

The Peccei-Quinn solution

- Promote θ to a dynamical variable - the QCD axion: $\mathcal{L} \supset (\theta + \frac{\xi a}{f_a}) \frac{g^2}{32\pi^2} G^{\mu\nu} \tilde{G}_{\mu\nu}$
- The Vafa-Witten theorem guarantees that the *total* θ term is zero in the ground state.
- A potential is generated for the axion such that the total coefficient of $G^{\mu\nu} \tilde{G}_{\mu\nu}$ is zero.

The Peccei-Quinn solution

- The θ term arises from the $U(1)_A$ anomaly of QCD
- To make θ dynamical, we introduce an additional global chiral symmetry $U(1)_{PQ}$, which is spontaneously broken.
- The axion is the Goldstone boson of $U(1)_{PQ}$.
- The QCD chiral anomaly causes non-perturbative explicit breaking of $U(1)_{PQ}$, generating a potential for the axion:

$$V \sim -\cos(\theta + \frac{\xi a}{f_a})$$

- The axion retains a discrete shift symmetry.

Axion-like particles

- ALPs are ultra-light particles that exist in many extensions of the Standard Model.
- They are pseudo-Nambu Goldstone bosons of global $U(1)$ symmetries.
- String theory compactificiations typically give rise to many ALPs at a range of masses.
- String ALPs in many cases have measurable effective couplings to electromagnetism (Halverson *et al*, 1909.05257).
- ALPs can act as both dark matter and dark energy.

Interactions

$$\mathcal{L} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}m_a^2 a^2 + g_{agg} a G\tilde{G} - \frac{g_{a\gamma\gamma}}{4} aF\tilde{F} + g_{aff}\overline{\Psi}_f \gamma^\mu \gamma_5 \Psi_f \partial_\mu a$$

- Pseudo-scalar interactions with the Standard Model
- Derivative interactions/coupling to topological terms
- $g \sim \frac{1}{f_a}$
- QCD axion: $m_a f_a = m_\pi f_\pi$
- String ALP: m_a and f_a are free parameters.

Conclusions

- Ultralight DM may make up all or some of the Dark Matter density.
- At small scales, ultralight DM behaves very differently to Cold Dark Matter.
- Ultralight DM is well described by a classical field.
- The axion is a well motivated ultralight DM candidate.

References

- Axion Cosmology, Marsh (1510.07633)
- Ultra-Light Dark Matter, Ferreira (2005.03254)