Ultralight Dark Matter and Axions

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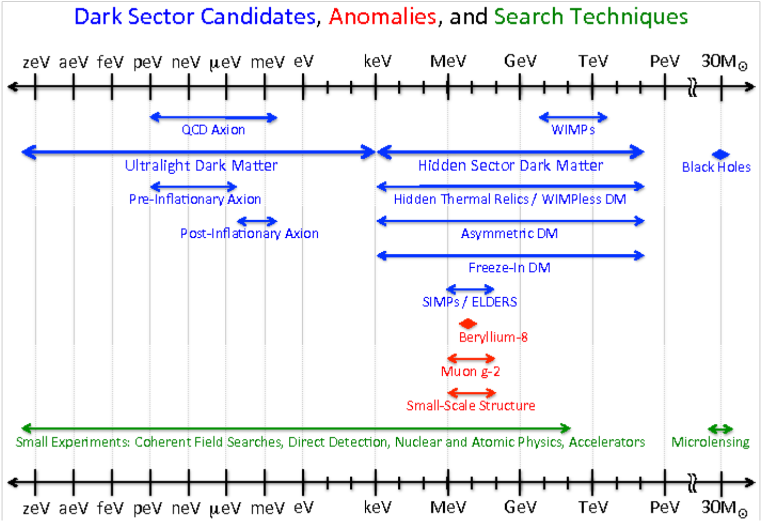
BCVSPIN-2021
January 2022

Outline

1. Introduction
2. Classical field description
3. Ultralight DM structure
4. Axions
5. Detecting axions

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 parent particle
- Decay of topological defects
- Misalignment mechanism

Misalignment production of axion DM

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

↓

Axion follows random walk in field space.

↓

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
- Axion stars and miniclusters

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:

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

$$\nabla^2\Phi = 4\pi G m|\psi|^2$$

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

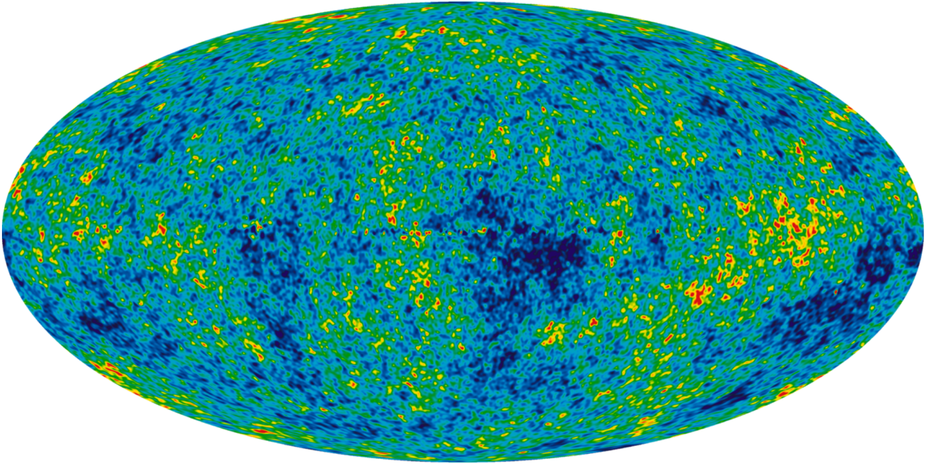
$$\partial_t \mathbf{v} + (\mathbf{v} \cdot \nabla)\mathbf{v} + \nabla(Q + \Phi) = 0$$

- 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



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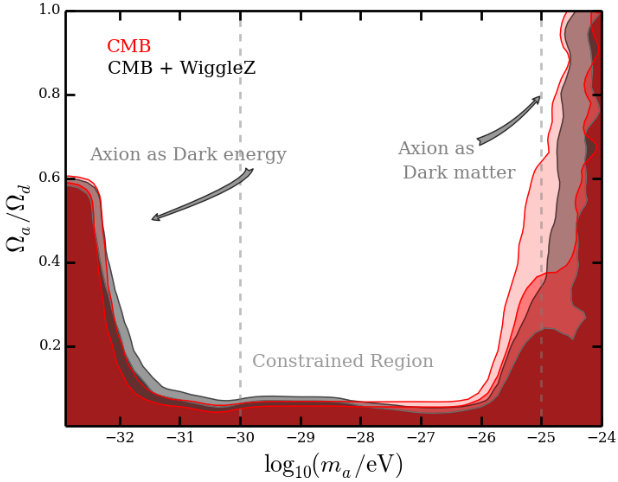

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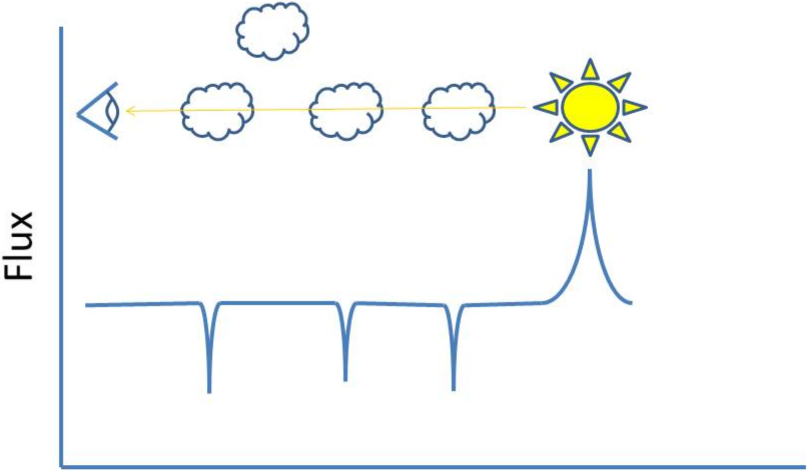
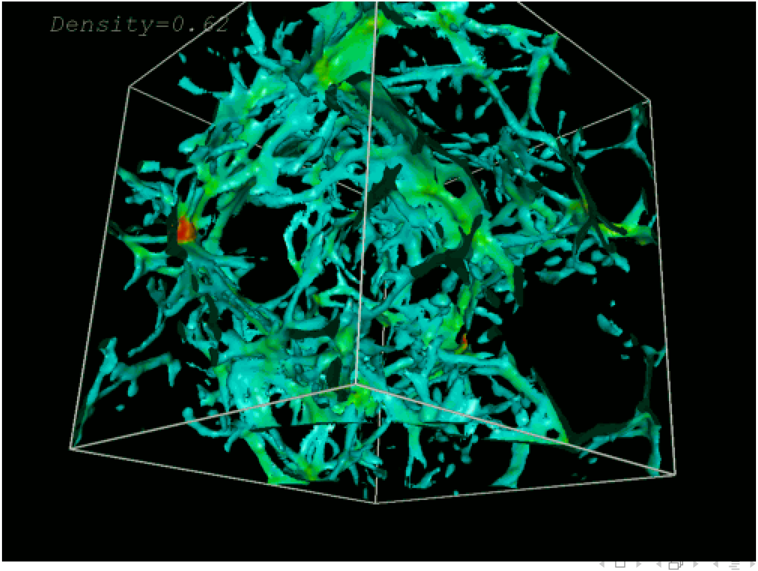
Ultralight DM in the Lyman-α forest

- 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



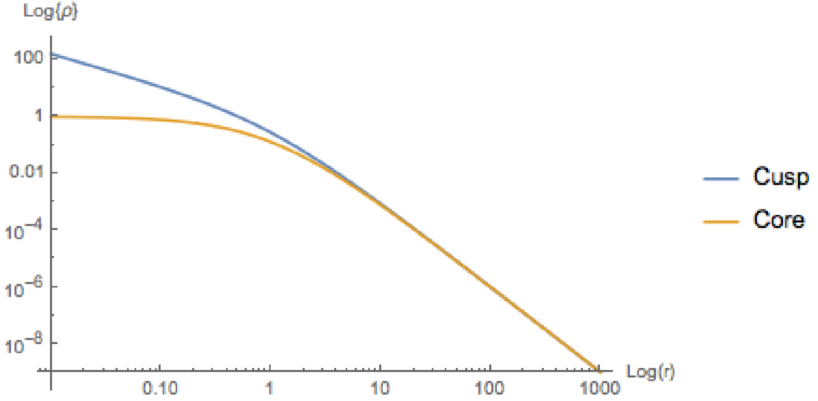
Ultralight DM in the Lyman-α forest



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: $\theta \to \theta + \arg\det M$.
- Need very fine tuned cancellations to explain observations. (but see Ai, Cruz, Garbrecht & Tamarit, 2001.07152).

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.

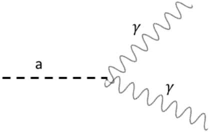
Interactions

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

- 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.

Detecting Axion Dark Matter

Axion decay to two photons:



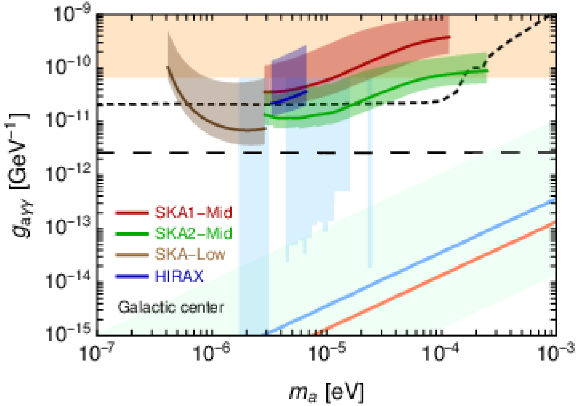
$$\Gamma_{a\rightarrow\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$

$$E_\gamma = m_a/2$$

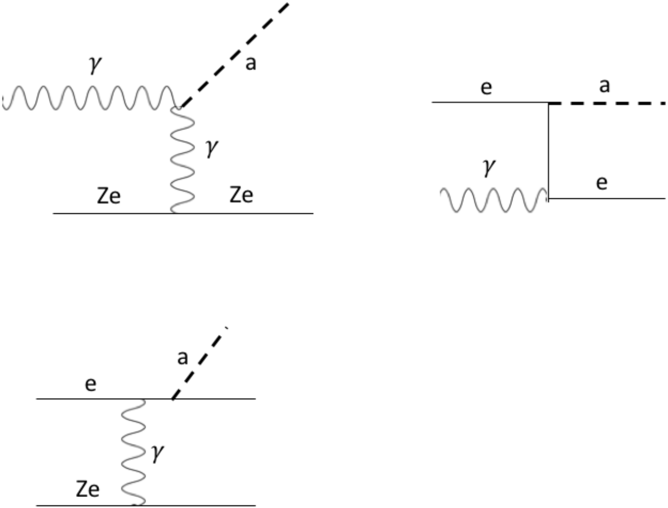
$$\Delta E_\gamma = E_\gamma \frac{\sigma}{c}$$

Detecting Axion Dark Matter

For $m_a \sim 1\,\mu\text{eV}$ and $g_{a\gamma\gamma} \sim 10^{-10}$ GeV, $\tau \sim 10^{32}$ years. The decay rate could be significantly enhanced by stimulated decay from ambient photons. From Caputo, Regis, Taoso & Witte (1811.08436):



Production in stars



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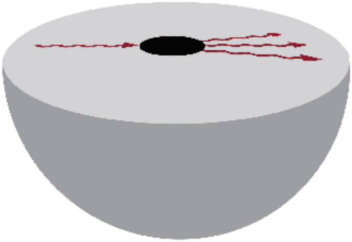
- Axion hints from stellar cooling?

Superradiance



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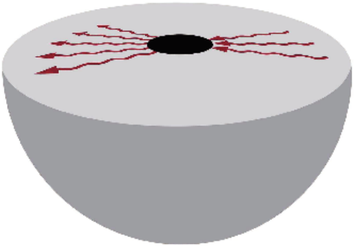

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Axion Black Hole Superradiance

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- Advanced Ligo will be sensitive to $m_a \lesssim 10^{-10}\,\mathrm{eV}$. (Arvanitaki *et al*, 1604.03958).
- Constraints on the axiverse mass spectrum (Stott & Marsh, 1805.02016)

Axion-photon conversion

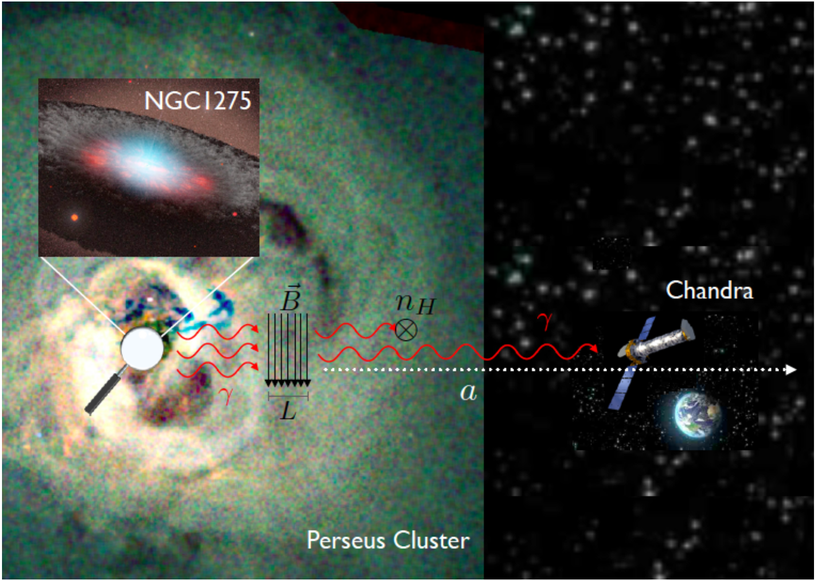
$$\left(\omega + \begin{pmatrix} \Delta_\gamma & 0 & \Delta_{\gamma ax} \\ 0 & \Delta_\gamma & \Delta_{\gamma ay} \\ \Delta_{\gamma ax} & \Delta_{\gamma ay} & \Delta_a \end{pmatrix} - i\partial_z\right) \begin{pmatrix} \mid \gamma_x \rangle \\ \mid \gamma_y \rangle \\ \mid a \rangle \end{pmatrix} = 0$$

- $\Delta_\gamma = \frac{-\omega_{pl}^2}{2\omega}$
- Plasma frequency: $\omega_{pl} = \left(4\pi\alpha\frac{n_e}{m_e}\right)^{\frac{1}{2}}$
- $\Delta_a = \frac{-m_a^2}{\omega}$.
- Here we take $m_a = 0$. This is valid for $m_a \lesssim 10^{-12}\,\mathrm{eV}$.
- Mixing: $\Delta_{\gamma ai} = \frac{g_{a\gamma\gamma}B_i}{2}$

$$P_{a\to\gamma}(L) = \mid \langle 1, 0, 0 | f(L) \rangle \mid^2 + \mid \langle 0, 1, 0 | f(L) \rangle \mid^2$$

Galaxy clusters

Photon-ALP conversion in Galaxy Clusters



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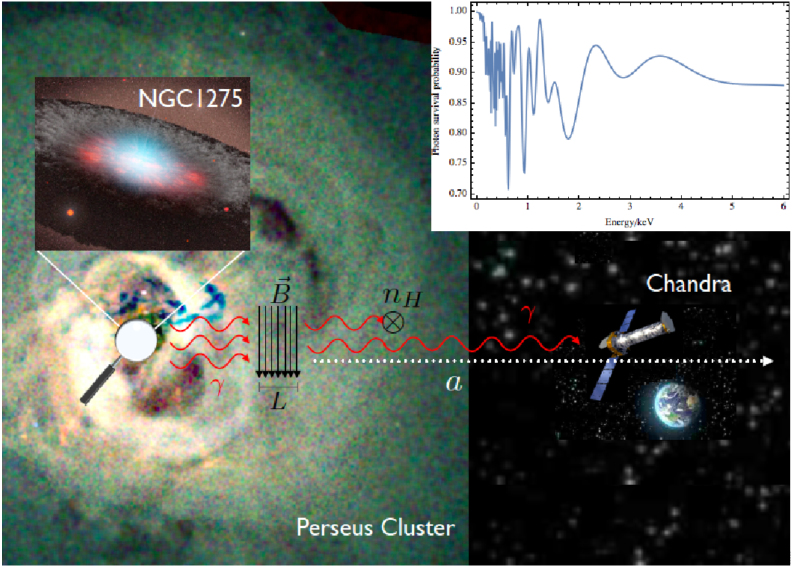
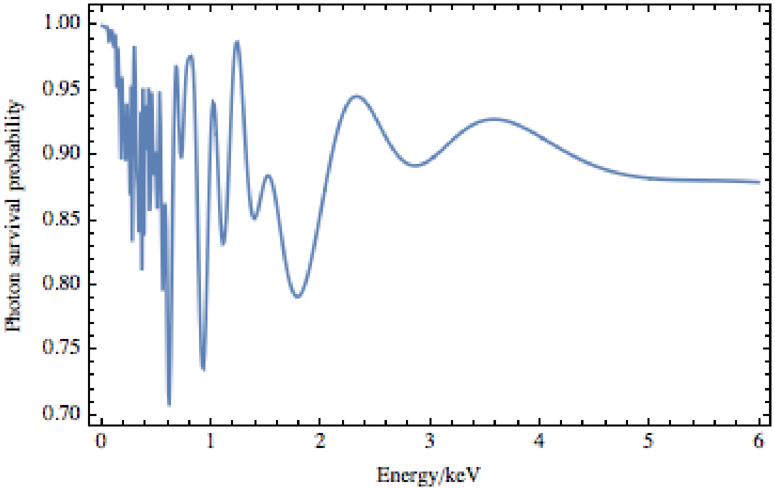


Photon survival probability



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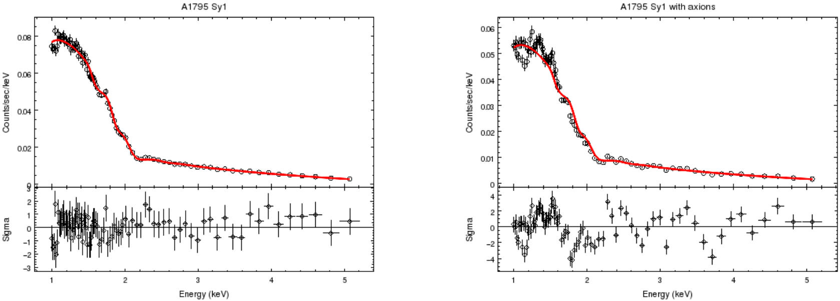
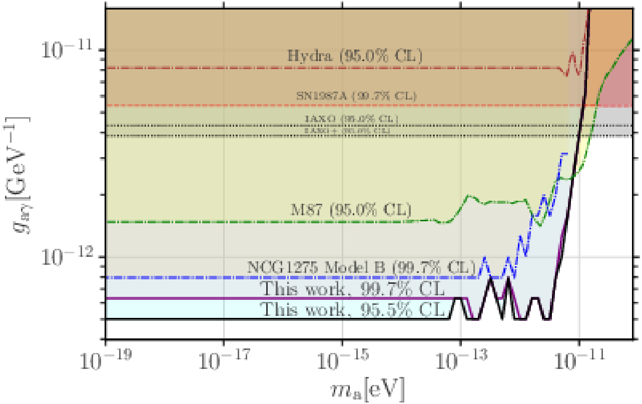


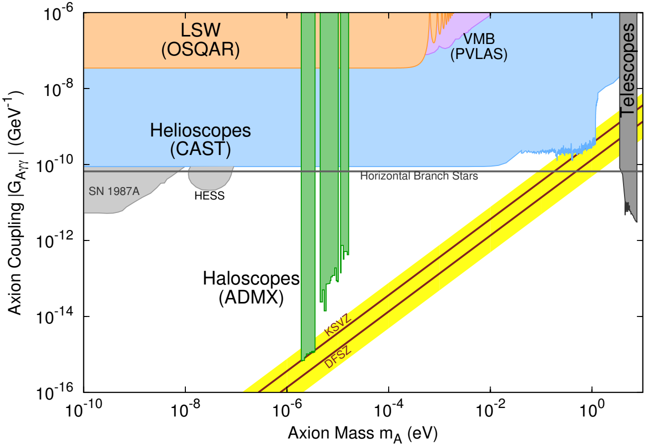
Left: the observed spectrum of the Seyfert galaxy 2E3140 in the galaxy cluster A1795 fitted with an absorbed power law. Right: the same spectrum multiplied by the photon survival probability for a realisation of the A1795 magnetic field and assuming the existence of ALPs with $g_{a\gamma\gamma} = 5 \times 10^{-12}\,\mathrm{GeV}^{-1}$.

Bounds

The leading bounds are from *Chandra* transmission grating spectroscopy of quasar H1821+643 (J S Reynés *et al*, 2109.03261):



More searches



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(But see F Chadha-Day, 2107.12813)

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.