Light Dark Matter

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- Two concrete examples
  - Sterile neutrino DM
    - Production mechanism
  - Axion(-like) Particle
    - Radio (SKA-like) survey

- Conclusion
A concrete example for the warm dark matter: Sterile Neutrinos

Dodelson-Widrow mechanism: Thermal active neutrinos conversion to sterile neutrinos

\[ L = -\gamma N L H - \frac{1}{2} M N N \]  
\[ \theta = \frac{\gamma \langle H \rangle}{M} \]

Figure 18

The decay width of this process is about 0.10 keV.

Figure 17

The WDM model does not fit the data at small scales and high redshift.

The morphology is incompatible with the DM interpretation.

The authors of the paper also cannot explain the origin of the line in the Andromeda galaxy reported in the literature. The calibration systematics was explored to take into account possible uncertainties in the DM content of a given object. A lower bound on the mixing angle was obtained.

The integrated flux in clusters and the expectations from known plasma lines (see however the subsequent discussion) can only be attributed to emission from these K XVIII plasma lines. Ref. [784] who demonstrated that no line is detected in an extremely long exposure combination of the Milky way M87.

The systematic errors in instrumental calibration and/or systematics induced by the analysis may impact the significance of weak lines. The calibration systematics was explored in [482] to account for possible uncertainties in the DM content of a given object. A lower bound on the mixing angle was obtained.

The strongest uncertainty comes from two potassium lines, K XVIII at 3.47 and 3.51 keV. Given the spectral resolution of the XMM-Newton, within the systematic uncertainty the flux could be attributed to emission from these K XVIII plasma lines. Ref. [784] who demonstrated that no line is detected in an extremely long exposure combination of the Milky way M87.

Systematic errors in instrumental calibration and/or systematics induced by the analysis may impact the significance of weak lines. The calibration systematics was explored to take into account possible uncertainties in the DM content of a given object. A lower bound on the mixing angle was obtained.

The confidence in interpreting the origin of a weak emission line is inherent uncertainty in the theoretical models. The broad band analysis and the dependence of the ratio of the expectations from known plasma lines on the interaction strength Sin (θ) imply that its surface brightness profile must trace the density of the plasma (more precisely: the mixture of plasma and DM). If it is a DM line it should, on the other hand, trace the overall matter distribution (pointing towards DM). The authors of the paper also cannot explain the origin of the line in the Andromeda galaxy reported in the literature. The calibration systematics was explored to account for possible uncertainties in the DM content of a given object. A lower bound on the mixing angle was obtained.

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Production from (active-sterile) neutrino oscillation

Cherry, Horiuchi (2017)
DM constraints heavily depend on the production mechanism!

1) Active-Sterile neutrino oscillation (e.g. Dodelson-Widrow)

2) Active-Sterile neutrino oscillation with the resonance (e.g. Shi-Fuller)

3) Decay of a heavier particle, Thermal freeze-out, variable mixing angle, ...
   (e.g. Kusenko, Petraki, Asaka, Shaposhnikov, Merle, Schneider, Berlin, Hooper,..)

4) Sterile-sterile oscillation! (KK and Kaneta (2018))

Also the left-handed neutrino masses via the seesaw mechanism!

\[ \mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_N, \]
\[ \mathcal{L}_N = \bar{\nu}_R i \bar{\phi} \nu_R - \left[ \nu^c_R y_\nu L H - \frac{1}{2} \nu^c_R T M_N \nu^c_R + h.c. \right] \]
\[ \Omega_{N1} h^2 \propto \sin^2 2\theta_N M_1 (y_\nu y^*_\nu)_{22} \]
Two concrete examples

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Conclusion
Primakoff effect

\[
\frac{g_{\gamma \gamma}}{4} a F \tilde{F} = -g_{\gamma \gamma} a E \cdot B
\]

QCD axion as a CDM candidate: mass range $\mu$eV $\sim$ meV (0.1GHz $\sim$ 100GHz)

Previous works: CDM axions converted into photon in the labs.

New works: How about the astrophysically sourced magnetic fields?

Non-resonant conversion: Kelley and Quinn (2017), Sigl (2017)


Line-like radio signal for non-relativistic axion conversion:

\[
f \sim \frac{m_a}{2\pi} \sim 240 \left(\frac{m_a}{\mu eV}\right) \text{MHz}
\]
The Square Kilometre Array (SKA) is a radio telescope project that aims to observe the universe across a wide range of wavelengths. SKA operates in two frequency bands: SKA low (50-350 MHz) and SKA mid (350 MHz-14 GHz).

**Gammas:**
- Gamma rays, X-rays, and ultraviolet light are observable from space but blocked by Earth's atmosphere.

**Infrared:**
- The infrared spectrum is absorbed by atmospheric gases and is not directly observable from Earth.

**Radio:**
- Radio waves are observable from space and are crucial for the SKA project.

**Axion Mass:**
- Axions, proposed particles that could be candidates for dark matter, have a mass range of 0.2 – 60 μeV.

**QCD Axion:**
- An axion that behaves as dark matter, with a mass in the range of 0.1 GHz to 100 GHz.

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**Additional Information:**
- Don Campbell, Director, NAIC
- Fred Lo, Director, NRAO
Figure 2

By assuming a simple NFW profile (Navarro et al. 1997) for the CDM density, and a magnetic field strength along the Galactic disk, we can estimate the additional magnetic field displayed net rotation with respect to the conservative position, that neither the dark halo nor the real photons. The frequency of the real photons produced will be 522.6 MHz and 783.9 MHz based on an axion of mass $m_a$.

The higher CDM density and magnetic field strengths displayed will enhance the flux as compared to that observed further from the Galactic Centre. This 2D Fourier Transform represents the spatial structure, for example when two NG bosons are attached to one fermion line as in axion structure, for example when two NG bosons are attached to one fermion line as in axion.

For nucleons, the $d$ emission by nucleon bremsstrahlung has recently been determined as

$\gamma \gamma \rightarrow n p$, where $\gamma$ is the virtual photon, $n$ and $p$ are nucleons, and providing a good opportunity for detection of both the KSVZ and DFSZ axion.

Figure 3

Kelley and Quinn (2017)

Hook, Kahn, Safdi and Sun (2018)
Model: ALP (Axion-like particles) i.e. Ultra-light scalars

- Ultra-light mass:

  \[ m_u \sim H_0 \sim 10^{-33} \text{eV} \]
  \[ m_u \sim 10^{-22} \text{eV} \]
  \[ m_u \sim 10^{-22} \text{eV} - 10^{-10} \text{eV} \]

  \[ m_u, f_u = \Omega_u / \Omega_m \sim O(0.01) \]
  \[ m_u \leq H(t) : \rho_u = \text{const} \]
  \[ m_u > H(t) : \rho_u \propto 1 / a^3 \]

  KK, Mao, Ichiki, Silk (2014)

DE (Barbieri et al (2005),...)
Fuzzy DM (Hu (2000),...)
String axiverse (Arvanitaki et al (2009),...)

\[ \mu \sim 10^{-22} \text{eV} \]
\[ H_0 \sim 2 \times 10^{-33} \text{eV} \]
21 cm signals
1420 MHz
Brief History of Universe

- **Big Bang**: The Universe is filled with ionized gas.
- **Recombination**: The gas cools and becomes neutral.
- **The first structures begin to form.**
- **Reionization starts** \((z \approx 12)\)
- **Reionization is complete**
- **Today's structures**

### Years since the Big Bang
- ~300,000 years \((z \approx 1000)\)
- ~100 million years \((z \approx 20-40)\)
- ~1 billion years \((z \approx 6)\)
- ~13 billion years \((z = 0)\)
What can we do with 21cm?

High precision on small-scale power spectrum

$$\Delta P / P \sim 1 / \sqrt{N}$$

Kleban+ (2007)

[Graph showing power spectrum and neutrino mass hierarchy]

Oyama+ (2013)

KK, Mao, Ichiki, Silk (2014)
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Let us be open minded.
Can go beyond the electroweak scale dark matter mass range.
Can go beyond CDM paradigm in LambdaCDM.
Many production mechanisms, many detection methods.