Self-interacting dark matter and monochromatic lines

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Dark Side of the Universe 2015


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Outline

1. Evidences and features of dark matter
2. Self-interacting dark matter and monochromatic lines
   - Offset of the cluster Abell 3827
   - Monochromatic lines from DM annihilations
3. Simple model with pseudo-scalar dark matter
   - Self-interacting cross section
   - Monochromatic lines with constraints
   - Direct detection
4. Summary
Evidences of dark matter

There are many evidences of dark matter.

- Rotation curves of spiral galaxies
- Observation of CMB \((\Omega h^2 = 0.12)\)
- Gravitational lensing effect
- Large scale structure of the universe
- Collision of the bullet cluster

- Existence of dark matter is crucial.
- But its mass and interactions are not known yet.
- The evidences are all indirect through gravitational force.
Cluster Abell3827

- $z = 0.099 \, (\sim 430 \, \text{Mpc from the Earth})$.
- Four galaxies (N1, N2, N3, N4) are localized.
- Offset between center of DM sub-halo and stars is suggested.
- N1 $\Delta = 1.62^{+0.47}_{-0.49} \, \text{kpc offset (3.3 } \sigma \text{ significance)}$
- Consistent between two independent approaches.
Cluster Abell3827

- Drag force is induced by self-interaction of DM
- 1.62 kpc offset may be interpreted as DM self-interaction
  \[ \sigma/m \sim 1.7 \times 10^{-4} \left( \frac{10^9 \text{yrs}}{t_{\text{infall}}} \right)^2 \text{ cm}^2/\text{g} \]
  \[ \gtrsim 10^{-4} \text{ cm}^2/\text{g} \quad \text{arXiv:1504.03388} \]
  \[ \sigma/m \sim 1.5 \text{ cm}^2/\text{g} \quad \text{arXiv:1504.06576} \]
- Not easy to understand by WIMP with \( \mathcal{O}(100) \) GeV.
  \[ \rightarrow \sigma/m \lesssim 10^{-11} \text{ cm}^2/\text{g} \]
  \[ \rightarrow \text{other scenarios: } \mathbb{Z}_3 \text{ SIMP, Sommerfeld enhancement with light mediator, hidden sector DM etc} \]
Monochromatic lines can be a smoking-gun signature of DM.

- Flux measured by HEAO-1, INTEGRAL, COMPTEL, EGRET.
- 3.5 keV X-ray excess observed in Perseus cluster and Andromeda galaxy. This may be interpreted by DM decay or annihilation.
- Non-detection from smaller galaxies.

- Milky Way \(\text{arXiv:1405.7943}\),
- stacked galaxies \(\text{arXiv:1408.4115}\)

In the case of 7.1 keV decaying DM

We discuss correlation between self-interacting dark matter and monochromatic lines.
The simple model

- add a SM singlet $\Phi = \frac{s + ia}{\sqrt{2}}$

- Self-interaction $\frac{\lambda}{4} |\Phi|^4$ is always allowed for a scalar DM.

- CP-odd particle $a$ is massless under the exact global $U(1)$ symmetry. But at some high energy, $U(1) \to \mathbb{Z}_N$ breaking is expected by non-perturbative effect. $\to m_a \ll m_s$

Scalar potential

$$V = -\mu^2 |\Phi|^2 + \frac{\lambda}{4} |\Phi|^4 + \lambda_{H\Phi} |H|^2 |\Phi|^2$$

After symmetry breaking ($m_s = \sqrt{\lambda \langle \Phi \rangle}$)

$$V = m_s^2 s^2 + \frac{m_a^2}{2} a^2 + \frac{1}{2} \sqrt{\frac{\lambda}{2}} m_s s (s^2 + a^2) + \frac{\lambda}{16} (s^2 + a^2)^2$$
**Self-interacting cross section**

\[
\frac{\sigma_{aa}}{m_a} = \frac{\lambda^2 m_a}{32\pi \left(4m_a^2 - m_s^2\right)^2} \approx \frac{\lambda^2 m_a}{32\pi m_s^4} \quad \text{for} \quad m_a \ll m_s
\]

**Features**

- The cross section \(\sigma_{aa}\) is proportional to \(m_a^2\).

- This is unusual behaviour (cf: \(\sigma_{aa} \propto 1/m_a^2\)) because of nature of pseudo-Goldstone boson DM.
Annihilation into photons

Effective interaction with photon

\[ \mathcal{L}_\gamma = \frac{s}{\Lambda} F_{\mu\nu} F^{\mu\nu} \]

The cross section

\[ \rightarrow \sigma_{\gamma\gamma} = \frac{\lambda m_a^2 m_s^2}{\pi \Lambda^2 (m_s^2 - 4m_a^2)^2} \approx \frac{\lambda m_a^2}{\pi \Lambda^2 m_s^2} \]

- The cross section is proportional to \(m_a^2\).
- The cut-off scale \(\Lambda\) is constrained by observations.

Combine with the self-interacting cross section

\[ \sigma_{v\gamma\gamma} = \sqrt{\frac{2}{\pi}} \frac{4m_a^{3/2}}{\Lambda^2} \sqrt{\frac{\sigma_{aa}}{m_a}} \]

\[ \approx 1.3 \times 10^{-33} \left( \frac{100 \text{ TeV}}{\Lambda} \right)^2 \left( \frac{m_a}{3 \text{ keV}} \right)^{3/2} \left( \frac{\sigma_{aa}/m_a}{1 \text{ cm}^2/\text{g}} \right)^{1/2} [\text{cm}^3/\text{s}] \]
Constraints on $\Lambda$

- Horizontal Branch stars
  The mediator particle $s$ can be produced in stars helium burning lifetime in stars is shortened $\rightarrow$ give a constraint.

- Mono-photon plus missing energy (ASP and LEP bounds)
  $e^+e^- \rightarrow \gamma \rightarrow s\gamma$

  $s$ decays outside the detector $\Gamma_s = \frac{m_s^3}{4\pi\Lambda^2} < \text{a few m}$

- Perturbativity of self-coupling $\lambda \leq 4\pi$

- DM annihilations into photons
  HEAO-1, INTEGRAL, COMPTEL, EGRET, FERMI
  keV $\rightarrow$ GeV scale of DM mass is constrained.
DM mass is bounded by HB and perturbativity.

For $\sigma_{aa}/m_a = 1.7 \times 10^{-4}$ cm$^2$/g, $10$ keV $\lesssim m_a \lesssim 10$ MeV and $\Lambda \gtrsim 10^5$ GeV

For $\sigma_{aa}/m_a = 1.5$ cm$^2$/g, $10$ keV $\lesssim m_a \lesssim 1$ MeV and $\Lambda \gtrsim 10^6$ GeV
To fit to the 3.5 keV X-ray line

- $m_a$ is fixed to $m_a = 3.5$ keV.
- $J_{astro}$ is astrophysical uncertainty
- $10$ TeV $\lesssim \Lambda \lesssim 1000$ TeV is favoured to fit the excess.
Non-detection of the X-ray excess

\[ \sigma v_{\gamma\gamma} \lesssim 2.5 \times 10^{-36} \text{ cm}^3/\text{s} \text{ from stacked dwarf galaxies.} \]

- Interpretation by DM annihilation (decay) is excluded (NFW).
- Other scenarios like an excited DM model can evade.
Direct detection of light DM

- Future experiment with superconductors
- Exploring scattering event with electron
- DM mass target range: 10 keV — 1 GeV
- Expected sensitivity of recoil energy is up to $\mathcal{O}(\text{meV})$

arXiv:1504.07237
Direct detection of light DM

When the interaction with electron $\mathcal{L} = g_e s \bar{e} e$ is concerned (generated from Higgs mixing)

$$\sigma^{e}_{\text{DD}} = \frac{\lambda^2 g_e^2}{2\pi m_s^4} \frac{m_a^2 m_e^2}{(m_a + m_e)^2} \frac{m_s^2}{4m_a^2}$$

- Coupling up to $g_e \gtrsim 10^{-7}$ can be testable (1kg·year exposure).
- $g_e \lesssim 10^{-7}$ is excluded by perturbativity of $\lambda$. 

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Summary

1. Observation of Abell3827 may imply self-interacting DM.
2. We considered a simple pseudo-scalar DM model.
3. Allowed DM mass scale is keV — MeV in order to have self-interacting cross section being comparable with Abell.
4. This range of DM mass may be searched by future direct detection experiment with superconductors and future gamma-ray experiments like ASTROGAM.