Constraining dark matter from X-ray observations of clusters of galaxies

Signe Riemer-Sørensen
GLAST Science Lunch, March 22, 2007

Collaborators: Kristian Pedersen (DARK)
Steen H. Hansen (DARK)
Håkon H. Dahle (University of Oslo, DARK)
Konstantin Zioutas (CAST, CERN)
Anastasios Lioliosa (Aristotle University of Thessaloniki)

Astro-ph/0703342, submitted to PRL
Dark matter solves gravity related problems of cosmology.

General properties of a dark matter candidate:
- Particle behaviour
- Massive (Gravitational effect)
- Not too much interacting
- Long lifetime

No good Standard Model particle candidate -> extensions:
- Super symmetry (SUSY)
- String theory
- Sterile neutrinos
- Extra dimensions -> axions
- Etc...

Some candidates allowed to decay with X-ray emission.

To be continued...
Launched by NASA in 1999. Photon energy range 0.3-10 keV

Spectral resolution: $\sigma_E \sim 0.1-0.15$ keV
Spatial resolution: $\sigma_\theta \sim 0.5$ arcsec
Merging galaxy cluster systems with prominent bow shocks

The Bullet Cluster, 1E0657-558

The galaxies follow the gravitational potential from weak lensing

The gas is displaced and heated because of interaction

Dark matter blob with high mass and low fraction of baryonic matter

Clowe et al. 2006
The Abell 520 dark matter blob

Blob region
$M_{\text{blob}} = 6 \times 10^{13} M_{\text{sun}}$

Reference region with low mass
$M_{\text{ref}} = 0.02 \times 10^{13} M_{\text{sun}}$
Where is the dark matter signal?

Spectrum of the Bullet cluster dark matter blob

\[ F \propto \frac{M \Gamma}{D_L^2} \]

\[ L \propto M \Gamma \]

\[ \Gamma = 1/\tau \]
Sterile neutrinos

Generic example of a mono-energetic signal

Right-handed neutrinos added to the Standard Model by hand -> $\nu_{\text{MSM}}$


Mass 0.5 keV (Tremaine-Gunn limit for fermions) to approx. 400 MeV (structure)

Does not interact except through oscillations

\[
\begin{pmatrix}
\nu_\alpha \\
\nu_s
\end{pmatrix}
= 
\begin{pmatrix}
\cos(\theta) & \sin(\theta) \\
-\sin(\theta) & \cos(\theta)
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
\]

Two-body radiative decay: $\nu_s \rightarrow \nu_\alpha + \gamma$

$E_\gamma = m_s/2$

Dolgov & Hansen, 2000
The signature

Mono-energetic emission -> Gaussian because of instrumental resolution

\[ \nu_s \rightarrow \nu_\alpha + \gamma \]

Chandra ACIS-I resolution: FWHM \sim 0.1 \text{ keV (energy dependent)}
General constraint on decay rate

Applies to all dark matter candidates with a two-body radiative decay

\[ F = \frac{\mathcal{L}}{4\pi D_L^2} = \frac{M_{\text{fov}} \Gamma_\gamma}{8\pi D_L^2} \]

\[ E_\gamma = \frac{m_\chi}{2} \]

Riemer-Sørensen et al. 2006, Boyarsky et al. 2006
Uncertainties

Orders of magnitude estimates

Uncertainties
Flux: \(\approx 10-20\%\)
Mass: \(\approx 10-30\%\)
Distance: \(\approx 10-30\%\)

Distance dominates
Age of the Universe
\(\approx 10^{17}\) sec
The mass-mixing angle parameter space

X-ray:
Boyarsky et al., Abazajian et al., Watson et al.

Ly-alpha:
Viel et al., Seljak et al.

Pulsar kicks:
Kusenko
Axions

Generic example of multi-energy signal with known shape

Extra space dimensions:
- Solution to hierarchy problem of particle physics
- Additional space dimensions are compactified with radius $R$
- Only gravity propagates in higher dimensions

Axions:
- Singlets under the standard model gauge group
- Can propagate in higher dimensions
- Compactification $\rightarrow$ higher dimension axion field decomposed into a Kaluza-Klein tower of states with spacing $1/R$

Arkani-Hamed, Dimopoulos & Dvali, 1998
Solar axions - motivated by X-ray emission from the solar corona region

Kaluza-Klein axions produced in core by $\gamma\gamma \rightarrow a$ and $\gamma Z \rightarrow aZ$.
Trapped in orbits and decay.

DiLella & Zioutas, 2003

Derived X-ray spectrum from the Sun (black)
Orlando, Peres & Reales, 2001

Two-body decay with photon emission. Different masses $\rightarrow$ different energies

All states up to the kinematic limit emitted
Solar axions

\[ L_a \propto \tau_a^{-1} \propto g_{a\gamma\gamma} R^5 \]

ASCA observations of solar minimum (2-8 keV)
Orlando, Peres & Reales, 2001

\[ \tau \approx 10^{20} \text{ sec} \ (g_{a\gamma\gamma} \approx 2 \times 10^{-13} \text{ GeV}^{-1}) \]
DiLella & Zioutas, 2003
Axions created in stars (as solar axions), confined by gravitational potential in clusters of galaxies

Expected signal from decaying axions. Can only move in intensity (and redshift due to distance).

Solar axions does not have to be the dark matter! And dark matter axions does not have to be solar.
The blob region emission

Very conservative upper limit on the luminosity, 2-9.5 keV, $L \leq 10^{44}$ ergs/sec

$\text{red} \chi^2 = 1.0$
The baryonic emission from the reference region

\[ \text{red} \chi^2 = 1.0 \]
The blob region emission II

Reference region model with free normalization plus expected dark matter flux

Integrate to get $3\sigma$ upper limit on luminosity
Constraining the lifetime

Upper limit on the luminosity, \( L \leq 0.2 \times 10^{44} \) ergs/sec

Lower limit on the lifetime

\[
\tau = \frac{1}{\Gamma} = \frac{2X_a M_{DM}}{L} \quad \Rightarrow \quad \tau \geq 10^{24} \text{ sec} \quad \left( g_{a\gamma \gamma} \leq 3 \times 10^{-15} \text{ GeV}^{-1} \right) \text{ for Abell A520}
\]

\[\text{Riemer-Sørensen et al. submitted to PRL}\]

Lifetime for solar axions, \( \tau \approx 10^{20} \) sec

\[\text{DiLella & Zioutas, 2003}\]

Consistent?

**Only if solar axions are <1% of the dark matter**

**Solar axions does not have to be the dark matter! And dark matter axions does not have to be solar.**
Summary

Dark matter dominates the gravity of the Universe

No Standard Model candidate -> extensions

Some particle candidates have X-ray signatures

Models can be constrained from X-ray observations

Sterile neutrinos: Generic example of mono-energetic emission
  Decay rate and mass/mixingangle constrained

Axions: Lifetime constrained for specific model
  Observations not consistent with solar axions being all of the dark matter