Constraints on dark matter annihilation cross section with the Fornax cluster

Shin’ichiro Ando
University of Amsterdam

Galaxy clusters: Why interesting?

- The largest virialized dark-matter structure
- The largest number of dark matter particles
- Presence of *collisionless* dark matter clearly seen in bullet cluster
- Good probe of cosmological parameters

Bullet cluster (1E0657-56)
Cluster constraints on DM properties

Ackermann et al., JCAP 1005, 025 (2010)

Factor >30 gap from canonical cross section

Dugger et al., JCAP 1012, 015 (2010)

Most stringent constraint on decay lifetime
Annihilation boost in substructure

Millennium Simulation

Flux boosted by a factor of \( \sim 1000 \)

Gao et al., arXiv:1107.1916

\[
M_{\text{min}} = 10^{-12} \, M_\odot
\]

\[
M_{\text{min}} = 10^{-6} \, M_\odot
\]

\[
M_{\text{min}} = 5 \times 10^7 \, M_\odot
\]

\( > 13 \, \text{dex gap} \)

Resolution limit

Extrapolation
Annihilation boost in substructure

Huang et al., arXiv:1110.1529

Cluster limits with subhalos

Dwarf limits (no subhalos)

Ackermann et al., arXiv:1108.3546
Geringer-Sameth & Koushiappas, arXiv:1108.2914
Motivation

- Does stacking help? If so, how much?
  - There are many more clusters than dwarfs!!

  **No! It doesn’t help**

- What is the effect of baryons (stars+gas)?
  - Baryons dominate gravitational potential at central regions
  - This should modify dark matter profile (adiabatic contraction)

  **It improves limits by a factor ~4**
Dark matter annihilation in galaxy clusters

Gamma-ray intensity from annihilation

\[ I_\gamma(\theta, E) = \frac{1}{4\pi} \frac{1}{(1 + z)^2} \langle \sigma v \rangle \frac{dN_\gamma((1 + z)E)}{dE} \int dl \rho^2(r(l, \theta)) \]

- Depends on three factors
  - Particle physics: annihilation cross section and dark-matter mass; depends on SUSY models, etc.
  - Astrophysics: density profile and subhalos
  - Cosmological redshift: straightforward if redshift is measured
Astrophysical factor: density profile


- Numerical simulations imply universal form of density profile: NFW
  \[ \rho = \frac{\rho_s}{(r/r_s)(r/r_s + 1)^2} \]
- \( \rho \sim r^{-1} \) for small radii, and \( \rho \sim r^{-3} \) for large radii
- NFW profile is confirmed with lensing observations
Gamma-ray intensity

- Intensity due to subhalos is much more extended than the smooth component
- Subhalo boost factor is ~1000 for cluster-size halos, if minimum subhalos are of Earth size

<table>
<thead>
<tr>
<th></th>
<th>$z$</th>
<th>$M_{\text{vir}}$ ($10^{14} , h^{-1} , M_{\odot}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fornax</td>
<td>0.005</td>
<td>1.2</td>
</tr>
<tr>
<td>Coma</td>
<td>0.023</td>
<td>9.6</td>
</tr>
</tbody>
</table>
Analysis of Fermi-LAT data

- We analyze data of Fermi-LAT for 2.8 years around 49 relatively large galaxy clusters
  - DIFFUSE and DATACLEAN class of photon data between MET = 239557417 s and 329159098 s
  - 23 clusters from X-ray (Reiprich & Boehringer 2002) and 34 from cosmology catalogs (Vikhlinin et al. 2009); 3 are found in both and 5 are at low Galactic latitudes

- We first perform likelihood analysis of the data using the known sources (from 2FGL catalog) as well as both Galactic and extragalactic backgrounds
  - Use photons between 1 GeV and 100 GeV, and divide them into 20 energy bins equally spaced logarithmically
  - Models are convolved with P6_V11 instrumental response functions
There is no gamma-ray source at cluster location.

We then add cluster component at the center of the best-fit model map, to put upper limit on that component.

Integrated maps for 1–100 GeV
Upper limits on cluster component

Analyze

Counts Map (Fornax)

Declination
-36.0
-35.5
-35.0
-34.5
Right ascension
55.5
55.0
54.5
54.0
53.5

Data

Cluster model

Fornax (host halo only)

Fornax (with subhalos)

Model Map with Cluster (Fornax)

Declination
-36.0
-35.5
-35.0
-34.5
Right ascension
55.5
55.0
54.5
54.0
53.5

Outcome

Best-fit model (almost isotropic background) and cluster component (no subhalos) allowed by 5%

95% CL upper limits on annihilation cross section
Limits on annihilation cross section from Fornax

NFW halo with no subhalos

Cross section limits for all clusters

**NFW halo only**

*bb channel*
Cross section limits from stacking analysis

- Procedure
  - Remove clusters with $>3\sigma$ excess compared with (fixed) background
  - This reduces to 38 clusters to be analyzed

- Result
  - Stacking does not help
  - Better to model Fornax more precisely

The Fornax cluster

- $M \sim 10^{14} M_{\text{sun}}$
- $D \sim 20 \text{ Mpc}$
- $(l, b) = (236.72 \text{ deg}, -53.64 \text{ deg})$
- The second largest cluster locally
- Central massive elliptical (cD) galaxy: NGC 1399

http://heritage.stsci.edu/2005/09-supplemental.html
Baryons in Fornax

HST photometry (4''x4'' region)

ROSAT observations

Stars

Precise measurement down to 1 pc!


Gas

Density profiles of Fornax

- Surface brightness $\rightarrow$ luminosity profile $\rightarrow$ density profile
- Stars dominate the gravitational potential at the central region
- What is the feedback effect of this deepened potential?

Profiles from DM-only simulations
Adiabatic contraction

Angular momentum conservation:

\[ M_i(r_i) r_i = M_f(r_f) r_f \]

\[ M_f(r_f) = [M_{dm,f}(r_f) + M_{b,f}(r_f)] r_f = [M_{dm,i}(r_i) + M_{b,f}(r_f)] r_f \]

Modified halo contraction


\[ M_i(\bar{r}_i)r_i = [M_{dm,i}(\bar{r}_i) + M_{b,f}(\bar{r}_f)]r_f \]

\[ \frac{\bar{r}}{0.03r_{vir}} = A_0 \left( \frac{r}{0.03r_{vir}} \right)^w \]

- \( A_0 = 1.6, w = 0.8 \) well explain simulation results
- Uncertainty range: \( w = 0.6-1 \)
- There is no firm observational evidence for/against this effect yet
Effect of halo contraction


- Canonical contraction model ($A_0=1.6$, $w=0.8$)
- Density is enhanced at the center for both NFW and Einasto profiles
Gamma-ray intensity enhanced


- Contraction produces sub-PSF structure at $10^{-4}$–$10^{-3}$ deg (30–300 pc)
- Gamma-ray flux is boosted by a factor of
  - ~4 (NFW)
  - ~2 (Einasto)
Cross section upper limits

- Limits improve by a factor of
  - 4.1 (NFW)
  - 2.4 (Einasto)
- This is almost independent of mass and annihilation channel
- \( \langle \sigma v \rangle < (2–3) \times 10^{-25} \text{ cm}^3/\text{s} \) for low-mass WIMPs

Other model parameters

- “Adiabatic”: $A_0 = 1, w = 1$
- “Break”: no contraction within 1 kpc ($\sim$ current resolution limit)
- Uncertainty range of the boost: 2–6

How important is this?: Compare with subhalos

To boost the limit by a factor of 4, the minimum subhalo mass has to be smaller than $1 \, M_{\text{sun}}$

Otherwise, one cannot ignore the effect of halo contraction

Conclusions

• Galaxy clusters are potentially strong source of gamma rays from dark matter annihilation

• We showed that stacking ~50 clusters does not improve the limits obtained with Fornax

• The detailed mass modeling of Fornax is therefore important

• We computed the halo contraction of Fornax and showed that the cross section limits improved by a factor of ~4

• The limits for low-mass WIMPs are within a factor of 10 from the canonical annihilation cross section after ~3 years