Galaxy Clusters as Laboratories for Astroparticle Physics

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in collaboration with

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Outline

1. Dark matter searches
   - Models
   - Sources
   - Boost factors

2. DM constraints from $\gamma$ rays
   - Spectra
   - Constraints
   - Conclusions

3. $\Lambda$CDM small-scale problems
   - Problems
   - Solutions
   - Our Model
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Searching for dark matter (DM)

correct relic density $\rightarrow$ DM annihilation in the Early Universe

DM production: particle colliders

DM scattering: direct detection

DM annihilation: indirect detection

(slides concept Feng)
consider benchmark models of *supersymmetric DM*
2. DM with Yukawa-type interactions

- heavy DM interacts through light force carrier $\phi$
- repeated exchange of $\phi$ $\rightarrow$ Sommerfeld effect
- multiply cross-section by enhancement factor $S$

\[ S(v) \quad \sigma_{\chi\chi \rightarrow \phi\phi} \]
2. DM with Yukawa-type interactions

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- multiply cross-section by enhancement factor $S$
- near bound state resonances expected:
  - off resonance: $S \propto \nu^{-1}$
  - on resonance: $S \propto \nu^{-2}$
2. DM with Yukawa-type interactions

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- near bound state resonances expected:
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- for $m_\phi \lesssim 100$ MeV, $\phi$ can only decay into leptons ($e, \mu$) → leptophilic DM

$Lattanzi, Silk (2009)$
Diagrams of DM with Yukawa-type interactions

- Annihilation
- Self-scattering
- Scattering
Thermal history of WIMPs

**chemical decoupling:**

- annihilations cease at $x = m_\chi / T \sim 25$ (rate $\propto n_\chi n_\chi$)
- “freeze out” of comoving number density
- *sets relic abundance*

![Graph showing the thermal history of WIMPs](image)
Thermal history of WIMPs

**chemical decoupling:**
- annihilations cease at $x = m_\chi / T \sim 25$ (rate $\propto n_\chi n_\chi$)
- “freeze out” of comoving number density
- sets relic abundance

**kinetic decoupling:**
- scattering off standard model particles in thermal heat bath
- ceases at $x \gg 25$ (rate $\propto n_\chi n_{\text{SM}}$)
- WIMPs cool down faster
- sets cutoff mass for smallest subhalos, $M_{\text{min}}$
Indirect DM searches: sources

Galactic center:
Good statistics, but source confusion and diffuse background

Milky Way halo:
Very good statistics, but diffuse background

Galaxy clusters:
Low background, but low statistics

Satellites:
Low background, but low statistics

Extra galactic:
Very good statistics, but astrophysics and galactic diffuse foregrounds
Dark matter searches
DM constraints from $\gamma$ rays
$\Lambda$CDM small-scale problems

Models
Sources
Boost factors

DM searches in clusters vs. dwarfs

Galaxy clusters:

Upper limits on DM annihilation rate; 95% C.L.

$\psi\psi \rightarrow b\bar{b}$

$\langle \sigma v \rangle$ [cm$^3$ s$^{-1}$]

$10^{-26}$

$10^{-25}$

$10^{-24}$

$10^{-23}$

$10^{-22}$

$10^{-21}$

$10^{1}$

$10^{2}$

$10^{3}$

$m_\psi$ [GeV]

- Combined
- A1367
- S636
- Fornax
- A1060
- NGC4636
- Coma
- AWM7
- NGC5813

Huang et al. 2011 (see also Ando & Nagai 2012)

Dwarf galaxies:

Upper limits, $bb$ channel

$\langle \sigma v \rangle$ [cm$^3$ s$^{-1}$]

$10^{-26}$

$10^{-25}$

$10^{-24}$

$10^{-23}$

$10^{-22}$

$10^{-21}$

$10^{-20}$

WIMP cross section [cm$^2$/s]

$3-10^{-26}$

$10^1$

$10^2$

$10^3$

WIMP mass [GeV]

- 3-10$^{-26}$
- Draco
- Sextans
- Ursa Major II
- Ursa Minor
- Boötes I
- Fornax
- Sculptor
- Coma Berenices
- Segue 1
- joint likelihood, 10 dSphs

Ackermann et al. (Fermi-LAT) 2011

- combined limits for dwarf galaxies $\sim$ 20 times more constraining
- is this really true? → consider substructure!
Enhancement from DM substructures

M$_{\text{res}}$: Constant offset in the luminosity from substructures between different mass resolutions in the simulation (M$_{\text{res}}$).

Norm $\propto M_{\text{res}}^{-0.226}$

Extrapolate to the minimal mass of dark matter halos (M$_{\text{min}}$) that can form. The cold dark matter scenario suggests M$_{\text{min}} \sim 10^6 M_\odot$.

Hofmann, Schwarz and Stöcker, 2008
Green, Hofmann and Schwarz, 2005

$L_{\text{sub}}(<r) \propto (M_{200} / M_{\text{res}})^{0.226}$

Luminosity boosted by $\sim 1000$ in clusters

Pinzke et al. 2011, Gao et al 2011
Galaxy clusters vs. dwarf galaxies

- DM annihilation flux of smooth (unresolved) halo:

\[ F \propto \int dV \frac{\rho^2}{D^2} \sim f(c) \frac{M}{D^2} \]
Galaxy clusters vs. dwarf galaxies

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→ smooth component of best dwarf and cluster targets are equally bright!
Galaxy clusters vs. dwarf galaxies

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→ smooth component of best dwarf and cluster targets are equally bright!

- DM substructure is less concentrated compared to the smooth halo (dynamical friction, tidal heating and disruption): the DM luminosity is dominated by substructure at the virial radius, if present!

→ these regions are tidally stripped in dwarf galaxies
→ in cluster, subhalos enhance DM luminosity by up to 1000

(e.g., Pinzke, C.P., Bergström 2011; Gao et al. 2011)
Spatial DM distribution

- form of smooth density profile only important for central region, majority of smooth flux accumulates around $r \sim r_s/3$
- emission from substructures dominated by outer regions → spatially extended
- large boost in clusters ($\sim 1000$); smaller boost in dwarf satellites ($\sim 20$) → much smaller if outskirts are tidally stripped

Pinzke, C.P., Bergström 2011

Christoph Pfrommer  Astroparticle Physics in Galaxy Clusters
**Clusters with substructures:**

U.L. on DM annihilation; effect of DM subhalos

<table>
<thead>
<tr>
<th>m_{\psi} [GeV]</th>
<th>\langle \sigma v \rangle [cm^3/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^1</td>
<td>10^{-28}</td>
</tr>
<tr>
<td>10^2</td>
<td>10^{-27}</td>
</tr>
<tr>
<td>10^3</td>
<td>10^{-26}</td>
</tr>
</tbody>
</table>

Solid: with subs. (M_{lim} = 10^{-6} M_\odot)
Dotted: w/o subs.

Huang et al. 2011 (see also Ando & Nagai 2012)

**Dwarf galaxies:**

Upper limits, \(b\bar{b}\) channel

<table>
<thead>
<tr>
<th>WIMP mass [GeV]</th>
<th>WIMP cross section [cm^2/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^1</td>
<td>10^{-26}</td>
</tr>
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<td>10^2</td>
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</tr>
<tr>
<td>10^3</td>
<td>10^{-24}</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Draco</td>
<td>3.10^{-30}</td>
</tr>
<tr>
<td>Bootes I</td>
<td>3.10^{-29}</td>
</tr>
<tr>
<td>Carina</td>
<td>3.10^{-28}</td>
</tr>
<tr>
<td>Sculptor</td>
<td>3.10^{-27}</td>
</tr>
<tr>
<td>Ursa Minor</td>
<td>3.10^{-26}</td>
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</table>

Ackermann et al. (Fermi-LAT) 2011

- **galaxy clusters** \(\sim 10\) times more constraining than dwarf satellites when accounting for substructures!
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Annihilation rate in these models enhanced by **Sommerfeld effect** as well as **DM substructures**.

**Gamma-ray emission components:**
- Final state radiation
- IC on background radiation fields (CMB, starlight and dust)
DM-induced gamma rays: *SUSY benchmark models*

Representation of high mass (~1 TeV) DM models with high gamma-ray emission.

**Luminosity boosted by substructures** in the smooth DM halo.

**Gamma-ray emission components:**
- Annihilating neutralinos emitting continuum emission
- Final state radiation
- IC on background radiation fields (CMB, starlight and dust)
Gamma-ray spectrum: benchmark DM model vs. CRs

Pinzke, C.P., Bergström 2011
Comparing clusters and emission processes

- **Fornax**: comparably high DM-induced gamma-ray flux and low CR-induced emission → tight limits on DM properties

- **Coma**: CR-induced emission soon in reach for Fermi

Pinzke, C.P., Bergström 2011
Emission from leptophilic models in most clusters detectable with Fermi-LAT after 18 months of operation.

Supersymmetric DM models will start being probed in coming years.

Brightest clusters: Fornax, Ophiuchus, M49, Centaurus (and Virgo).
Constraining boost factors (leptophilic models)

Pinzke, C.P., Bergström 2011

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Constraining boost factors \textit{(leptophilic models)}

\begin{itemize}
\item Fornax and M49 constrain the saturated boost from \textit{Sommerfeld} enhancement (SFE) to \(< 5\)
\end{itemize}

Pinzke, C.P., Bergström 2011
Constraining boost factors \textit{(leptophilic models)}

- Alternatively, if SFE is realized in Nature, this would limit the substructure mass to $M_{\text{lim}} > 10^4 M_\odot$ — a challenge for structure formation and most particle physics models \textit{(van den Aarssen et al. 2012)
Conclusions on dark matter searches in clusters

Galaxy clusters are competitive sources for constraining dark matter:

- cluster luminosity boosted by $\sim 1000$ (for $M_{\min} \sim 10^{-6} M_\odot$)
- flat brightness profiles and spatially extended $\rightarrow$ challenging for IACTs, better probed by Fermi-LAT
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Leptophilic DM models:

- Fermi-LAT data constrains the Sommerfeld enhancement to $< 5$
- if DM interpretation of lepton excess seen by PAMELA/Fermi is correct, then smallest subhalos have $M > 10^4 M_\odot$
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SUSY benchmark models:

- Accounting for substructure boost allows to constrain interesting DM parameter space ($\langle \sigma v \rangle \lesssim 3 \times 10^{-26} \, \text{cm}^3 \text{s}^{-1}$, $m_\chi \gtrsim 100 \, \text{GeV}$)
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\( \Lambda \)CDM small-scale problems

1. Missing satellites?

Moore et al. 1999

\( \rightarrow \) many more satellites in simulations of MW-sized galaxies than observed
\section*{CDM small-scale problems}

1. Missing satellites?
   - Moore et al. 1999
   - \rightarrow \text{many more satellites in simulations of MW-sized galaxies than observed}

2. Cusps or cores?
   - Blok et al. 2001
   - $\rightarrow$ cuspy inner density profiles predicted by simulations not found in observations
ΛCDM small-scale problems

1. Missing satellites?

Moore et al. 1999

→ many more satellites in simulations of MW-sized galaxies than observed

2. Cusps or cores?

Blok et al. 2001

→ cuspy inner density profiles predicted by simulations not found in observations

3. Too big to fail?

Boylan-Kolchin et al. 2011

→ most massive sub-halos in simulations too dense to host observed brightest dwarf satellites

HITS
many possibilities, no consensus reached yet:

- **astrophysical solutions:**
  increased gas entropy, suppress cooling efficiency, SN feedback, large velocity anisotropy, other baryonic feedback, increased stochasticity of galaxy formation, small MW mass, . . .

- **dark matter solutions:**
  warm DM, interacting DM, DM from late decays, large annihilation rates, condensates, . . .

- **all have shortcomings** and/or solve at most 2 problems at the time!
velocity-dependent self-interacting dark matter:

- scattering cross-section for **Yukawa potential** Khrapak et al. (2003)
  \[ \sigma_{\chi \bar{\chi}} = \text{const. unnatural from particle physics viewpoint!} \]
- elastic DM self-scattering is completely analogous to screened Coulomb scattering in a plasma
velocity-dependent self-interacting dark matter:

- scattering cross-section for Yukawa potential Khrapak et al. (2003)
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- elastic DM self-scattering is completely analogous to screened Coulomb scattering in a plasma

- cored profiles possible without violating astrophysical constraints Feng et al. (2010), Loeb & Weiner (2011)

- N-body simulations: “too big to fail” problem avoided Vogelsberger et al. (2012)

- what about missing satellites?
Our model

- assume **light vector mediator** coupling to dark matter and neutrinos:

\[ \mathcal{L}_{\text{int}} \supset -g_\chi \bar{\chi} \mathcal{V} \chi - g_\nu \bar{\nu} \mathcal{V} \nu \]

- **annihilation**
  - → relic density
  - → indirect 4ν detection signal
  - from galactic center(?)

- **self-scattering**
  - → changes inner density and velocity profiles of dwarf galaxies

- **scattering**
  - → large \( M_{\text{min}} \)

van den Aarssen, Bringmann, C.P. (2012)
Dark matter searches
| Problems |
| Solutions |
| Our Model |

“Cusp vs. core” and “too big to fail” problems

- demand correct relic density
  → unique relation between \((\nu_{\text{max}}, \sigma_{\text{max}})\) and \((m_\chi, m_V)\)

\[ \nu_{\text{max}} \gtrsim 10^2 \text{ km s}^{-1}, \quad \sigma_{\text{max}} \gtrsim 10^{-5} \text{ cm}^2 \text{ g}^{-1} \]

- ruled out by astrophysics
- not enough flattening of cuspy profiles

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van den Aarssen, Bringmann & Pfrommer (2012)

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$\Lambda$CDM small-scale problems

**Problems**

- Solutions
- Our Model

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**DM scattering off standard model particles**

- free-streaming of WIMPs after *kinetic decoupling* creates cutoff in power spectrum
- acoustic oscillations leads to similar cutoff
- cutoff scale is set by size of horizon at KD: late KD $\rightarrow$ high $M_{\text{min}}$
- $M_{\text{min}} = \max(M_{fs}, M_{ao})$: only objects with $M \geq M_{\text{min}}$ form

---

van den Aarssen et al. (2012)

$m_{\phi} = (0.1, 0.5, 1.5, 5) \text{ GeV}$
DM scattering off standard model particles

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**Scalar mediator:**
- scatters off $\phi, \mu^\pm, e^\pm$
- saturation at $M_{\text{min}} \sim 10^3 M_\odot$
- $\nu$’s negligible: $|M_{\phi l \rightarrow \phi l}|^2 \propto m_l^2$

**Vector mediator:**
- $\nu$’s contribute:
  - $|M_{\nu \nu \rightarrow \nu \nu}|^2 \propto E_{\nu}^2$
  - $M_{\text{min}}$ increases to $\mathcal{O}(10^{11} M_\odot)$

$m_\phi = (0.1, 0.5, 1, 5) \text{ GeV}$

van den Aarssen et al. (2012)
“Missing satellites” problem

- now compute $M_{\text{min}}$ from kinetic decoupling temperature ...

\[ m_V [\text{MeV}] \]
\[ g_{\nu} \]

\[ \begin{align*}
10^{-5} & \quad 10^{-4} & \quad 10^{-3} & \quad 10^{-2} & \quad 10^{-1} \\
0.05 & \quad 0.1 & \quad 0.5 & \quad 1 & \quad 5
\end{align*} \]

cutoff too small to address abundance problem

in this simple phenomenological model, it is possible to simultaneously solve all small-scale problems of $\Lambda$CDM!
Cored central density profiles of clusters

- velocity-dependent DM self-scattering cores out central density slopes in clusters with rate
  \[ \Gamma \sim \frac{\rho}{m_\chi} \langle \sigma v \rangle \sim H \]

- ellipticals/clusters, \( f_s = 10 - 100 \):
  \[ \Gamma \sim \frac{f_s \rho}{m_\chi} \frac{\langle \sigma v \rangle}{f_s} \]

Loeb & Weiner (2011)
Cored central density profiles of clusters

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  \[ \Gamma \sim \frac{f_s \rho}{m_\chi} \frac{\langle \sigma v \rangle}{f_s} \mid_{\text{max}} \]

- Using \( \rho \sim 1/r \) for \( r \ll r_s \):
  \[ \frac{r_{\text{core}}}{r_{200}} \bigg|_{\text{cluster}} \sim \frac{1}{f_s} \frac{r_{\text{core}}}{r_{200}} \bigg|_{\text{dwarf}} \sim \frac{1}{f_s 10} \Rightarrow \ r_{\text{core}}(10^{15}\, M_\odot) \sim \mathcal{O}(1-10\, \text{kpc}) \]

- Need simulations to understand interplay of hierarchical evolution and determination of cluster-\( r_{\text{core}} \): merging history \( \rightarrow \) scatter
Conclusions on small-scale problems of $\Lambda$CDM

Small-scale problems of $\Lambda$CDM can be solved by a DM model with:

- velocity-dependent self-interactions mediated by (sub-)MeV vector:
  $\rightarrow$ transforms cusps to cores and solves “too big to fail” problem

- much later kinetic decoupling than in standard case follows naturally for vector mediator coupling to neutrinos:
  $\rightarrow$ potentially solves “missing satellites” problem

- predicts cores in clusters on scales $\mathcal{O}(1 \text{ – } 10 \text{ kpc})$

$\rightarrow$ need further model building and simulations to confirm
Dark matter constraints from clusters:


Small-scale problems of $\Lambda$CDM:

Additional slides
Interplay between chemical and kinetic decoupling

\[
\langle \sigma v \rangle \quad \text{enhanced for } v \to 0
\]

DM velocity decreases faster after KD

DM population depleted of lowest velocity particles

relic density

WIMP "temperature"

important: self-scattering ensures the Maxwellian velocity distribution!

(use set of coupled Boltzmann equations to solve for thermal history of WIMPs)