DM subhalos: The observational challenge

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DM subhalos in the Milky Way

- concordance cosmology requires non-baryonic DM
- hierarchical structure formation (simulations):
  - smooth DM halos around galaxies
  - up to $\sim 10^{16}$ subhalos per halo
- mass range and distribution:
  - $10^{-6}$ to $10^{10} \, M_\odot$; $dN/dM \propto M^{-1.9}$
- density profile $\rho_{DM}(r)$:
  - NFW-like
- spatial distribution:
  - “anti-biased“

Refs.: Aquarius simulation: Springel et al., '08, Via Lactea II: Diemand et al., '08
Assumption: WIMP dark matter

- **WIMPs** (weakly interacting massive particles):
  - predicted by theories beyond Standard Model
  - assumed mass scale $m_\chi > 100$ GeV
  - self-annihilation to gamma-rays
  - $\langle \sigma v \rangle$ consistent with relic density: $\langle \sigma v \rangle_0 = 10^{-26}$ cm$^3$ s$^{-1}$

- e.g., Baltz et al., '07; Pieri et al., '08, '09; Buckley & Hooper, '10, Zechlin et al., '12

H. Zechlin (Uni HH)
**Gamma-ray instruments**

**Fermi-LAT:**
- since Aug. 2008
- pair production strip tracker + calorimeter
- 20 MeV – 300 GeV
- eff. area $\sim 0.8 \text{ m}^2$
- FoV: $\mathcal{O}(1)$ sr
- energy resolution: 10%

**IACTs:**
- Imaging Air Cherenkov Telescopes
- Cherenkov light from air showers
- $\sim 50$ GeV – 100 TeV
- eff. area $\sim 10^5 \text{ m}^2$
- FoV: $\mathcal{O}(10^{-2})$ sr
- energy resolution: 15%

**planned:** CTA
Expectations for Fermi-LAT

- photon rate from DM annihilation:

\[
\mathcal{L} = \frac{\langle \sigma v \rangle_{\text{eff}} N_{\gamma}}{2m_{\chi}^2} \int dV \rho^2(r), \quad \int dV \rho^2(r) \propto M c_{\text{vir}}^3
\]

assumptions: density profile: NFW, concentration: based upon Bullock model

- method: derive effective cross section \( \langle \sigma v \rangle_{\text{eff}} \) needed to explain a high-energy gamma-ray source (flux \( \phi \), extent \( \theta_{68} \)) with DM subhalo

- compare \( \langle \sigma v \rangle_{\text{eff}} \) with observational constraints

Bullock et al., '01, Pieri et al., '09
Gamma-ray properties of subhalos

- Subhalos detectable with Fermi-LAT:
  - Very faint flux (at detection level)
  - Detection above 10 GeV
  - Moderately extended, \( \sim 0.5^\circ \)
  - Temporally constant flux
  - No astrophysical association

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- distance range: 1 – 10 kpc
- O(1) sources in 1 or 2-year data!

Source candidates in 1FGL/2FGL

- Fermi catalog 1FGL/2FGL:
  - 1451/1873 γ-ray sources
  - 671/576 unassociated!

- imposed properties:
  - no association
  - high Galactic latitude (|b|>20°)
  - no significant variability
  - detection above 10 GeV
  - hard spectrum (Γ<2)

- results:
  - 1FGL:
    - 12 sources pass cuts
  - 2FGL:
    - 13 sources pass cuts

HSZ, D. Horns, 2012, to be submitted soon
Unassociated 2FGL sources
Galactic latitude $|b|>20$ deg

![Galactic latitude $|b|>20$ deg]
Temporally steady
Detected above 10 GeV

detected between 10 and 100 GeV

Galactic
Hard spectrum, $\Gamma < 2$
In-depth investigation

- developed in-depth analysis to
  - constrain variability
  - constrain angular extent
  - refine positional uncertainty
  - check for compatibility with DM scenario

- multi-wavelength study:
  - astronomical catalogs
  - archival data
  - dedicated radio/X-ray follow-ups
In-depth investigation

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- **multi-wavelength study:**
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- for 2FGL candidates:
  - test for a spectral cutoff:
    \[
    TS_{\text{exp}} = -2 \ln \left( \frac{\mathcal{L}(H_{\text{pl}})}{\mathcal{L}(H_{\text{exp}})} \right)
    \]
  - distribution of TS$_{\text{exp}}$:
    MC simulations
  - 24-month/42-month data used

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Results

- no source candidate favored by all imposed criteria
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- except for one, none can be firmly excluded
What do we actually see?

- possible origin:

  - WISE data hint for a BL Lac scenario (using Massaro et al., 2012, arXiv:1203.1330)
  - 2FGL J0031.0: from distance modulus of optical data: $z \sim 0.4$
What do we actually see?

- **possible origin:**
  
  - High-energy peaked BL Lacs!
  
  - WISE data hint for a BL Lac scenario (using Massaro et al., 2012, arXiv:1203.1330)
  
  - 2FGL J0031.0: from distance modulus of optical data: \( z \sim 0.4 \)
related to the sensitivity of Fermi-LAT:

- **limited photon number**
  - large positional uncertainty
  - large spectral uncertainty
  - uncertain angular extent
  - source confusion for associations
    - [O(1) radio source within pos. uncertainty]

- **rareness**
  - too few objects expected for population studies
Capabilities of IACTs

- large effective area → large number of photons
  → improves positional and spectral accuracy
- use dedicated follow-up observations with IACTs to probe selected candidates
The way to go, so far...

(1) search catalogs, imposing basic selection cuts
   ✔ no association, HE detection, no variability, hard spectrum

(2) analyse for required $\gamma$-ray properties
   ✔ check spectrum, variability, angular extent; extract position

(3) multi-wavelength association

(4) radio/X-ray follow-up observations

(5) very high-energy follow-up (IACTs) to improve positional and spectral information
The gamma-ray to radio connection

- final products of DM annihilation also contain light charged particles (electrons)
  - synchrotron and inverse Compton radiation, depending on B-fields and photon fields
  - extended radio/X-ray emission, $\theta(\text{radio}) \gg \theta(\text{gamma})$
  - in principle, tracer to distinguish DM driven from astrophysical sources
- subhalos may not be completely dark!

![Graph showing gamma-ray and radio emission in Draco]
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Summary

- in standard WIMP scenarios, O(1) subhalos may be detected in first Fermi catalogs
- candidate searches require in-depth gamma-ray and multi-wavelength analysis
- catalog searches in 1FGL/2FGL revealed no favored candidate
- VHE follow-up with IACTs necessary to improve positional and spectral accuracy

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Backup
Expectations for Fermi-LAT II

- Observational properties
  - HE flux $\phi$
  - Extent $\theta_{68}$
  - Unassociated, steady $\gamma$-ray source

Fermi-LAT
Expectations for Fermi-LAT II

observational properties

theoretical modeling

unassociated, steady γ-ray source

Fermi-LAT

HE flux $\phi$

extent $\theta_{68}$

constraints $D \approx r_s / (2\theta_{68})$

distance $D$

WIMP model $m_\chi, N_\gamma$

$\mathcal{L} = 4\pi D^2 \phi$

$\langle \sigma v \rangle_{\text{eff}}$

NFW profile $M_c, C_{\text{vir}}$
The gamma-ray sky