DM subhalos as *Fermi* gamma-ray sources and first candidates in the 1FGL catalog

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Summary: Within the current framework of annihilating dark matter and realistic subhalo models we show that one massive Galactic subhalo between 10^6 and 10^8 $M_\odot$ may already show up in the first 11 months catalog of Fermi-LAT data (1FGL). Applying selection cuts to the 1FGL catalog we find twelve possible subhalo candidates and in-depth investigations of the most promising object are presented.

Abstract: Based on the theory of hierarchical structure formation Milky Way-sized galaxies are expected to host numerous dark matter (DM) subhalos. Anticipated subhalo masses range from 10^{10} down to a cut-off between 10^{-3} and 10^{-11} $M_\odot$. In self-annihilating DM models these subhalos could be visible in the gamma-ray band as faint and non-variable sources without astrophysical counterpart. Regarding realistic subhalo models and current observational constraints we predict that about one massive Galactic subhalo may already show up in the 11 months catalog of Fermi-LAT data (1FGL). Selection cuts applied to the 1FGL catalog reveal twelve possible candidates and in-depth studies of the most promising object, 1FGL J0030.7+0724, are presented. In an X-ray follow-up observation with the Swift XRT seven point-like X-ray sources have been discovered. Within the positional uncertainty derived from the 24 months data set one previously unknown counterpart candidate for 1FGL J0030.7+0724 has been found in the radio which coincides with a Swift source. The broad-band spectral energy distribution is consistent with a high-energy-peaked blazar. However, flux and extent of the LAT source may also be compatible with a DM subhalo. A decision between the two scenarios requires further multi-wavelength observations. Strategies to identify gamma-ray sources associated with self-annihilating DM subhalos are discussed.

Galactic subhalos in ΛCDM cosmology

[Diemand et al., 2008]
[Kuhlen et al, 2008]

- numerical *N*-body simulations of structure formation (Aquarius, VL II):
  - ➔ up to 10^{16} subhalos in Milky Way-sized galaxy
  - ➔ 10^{-11} (10^{-3}) to 10^{10} $M_\odot$
  - ➔ power law distribution in mass, $\mathrm{d}N/\mathrm{d}M \propto M^{-\alpha}$, $\alpha = 1.9 - 2.0$
  - ➔ "anti-biased" distribution in volume, i.e., dominant fraction in outer regions

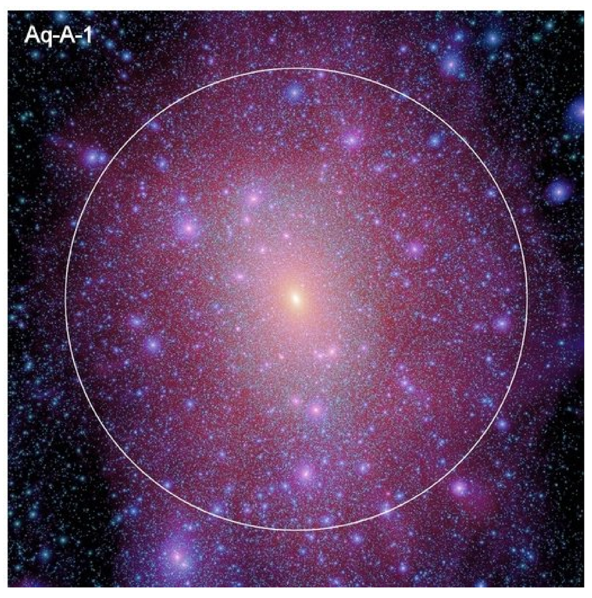


Fig.: Aq-A-1 halo, Springel et al., 2008. The circle indicates r_{50}=433 kpc.

Subhalos as high-energy gamma-ray sources

- self-annihilating WIMP DM:
  - ➔ point-like or moderately extended
  - ➔ potentially detectable with *Fermi*-LAT (20 MeV – 300 GeV) and Cherenkov telescopes (*E* > 100 GeV)

[Buckley & Hooper 2010]
[Pieri et al., 2011]

Gamma-ray emission of subhalos

- NFW density profile [Navarro et al., 1997]
  - ➔ characterized by subhalo mass *M* and concentration *c*
- concentration *c*:
  - ➔ low-mass extrapolation of Bullock et al., 2001. Formation history of subhalos (e.g., tides) included adopting empirical correction from numerical simulations (Diemand et al., 2007)
  - ➔ *c* depends on mass *M* and galactocentric distance
- luminosity for self-annihilating DM:

$$\mathcal{L} \propto \langle \sigma v \rangle \frac{N_\gamma}{m_{\rm DM}^2} \frac{M c^3}{f(c)^2}, \qquad f(c) = \ln(1+c) - c/(1+c)$$

annihilation cross-section

Subhalo model

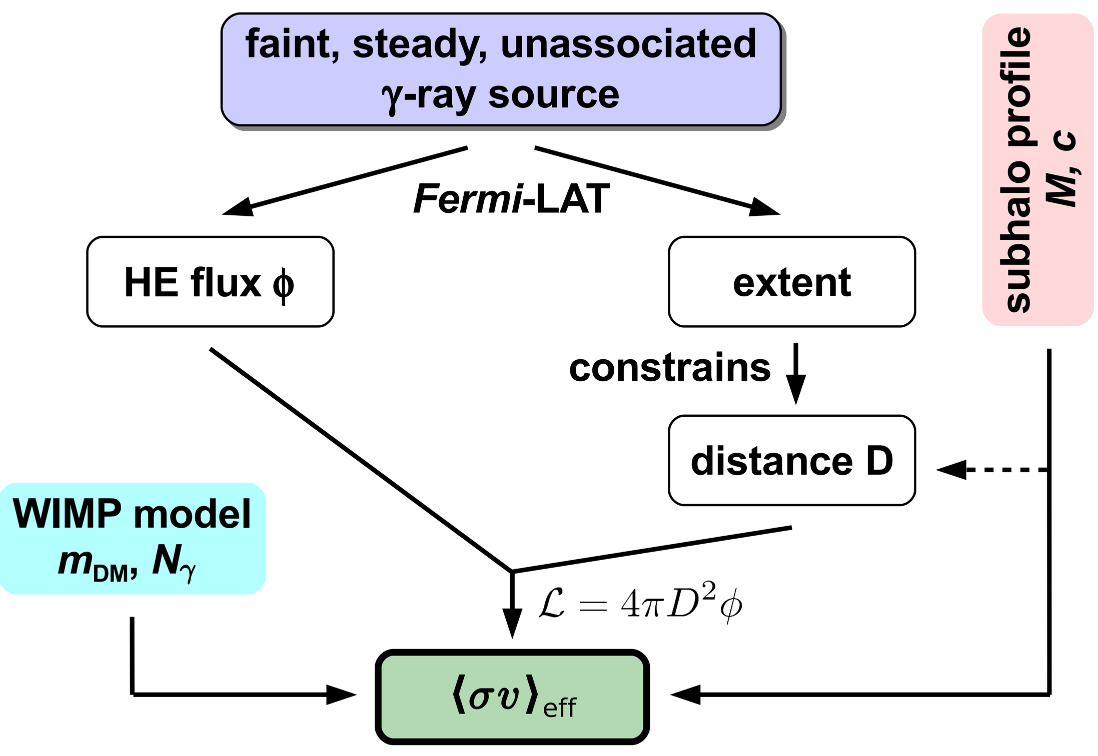
WIMP-annihilation models
$\chi\overline{\chi} \to b\overline{b}, m_{\rm DM} = 500\,{\rm GeV}$
$\chi\overline{\chi} \to \tau^+\tau^-, m_{\rm DM} = 150\,{\rm GeV}$

N_γ: photon yield (10-100 GeV)
thermal freeze-out:
$\langle \sigma v \rangle_0 = 3 \times 10^{-26}\,{\rm cm^3\,s^{-1}}$

[Fornengo et al., 2004]

Fermi sources as DM subhalos

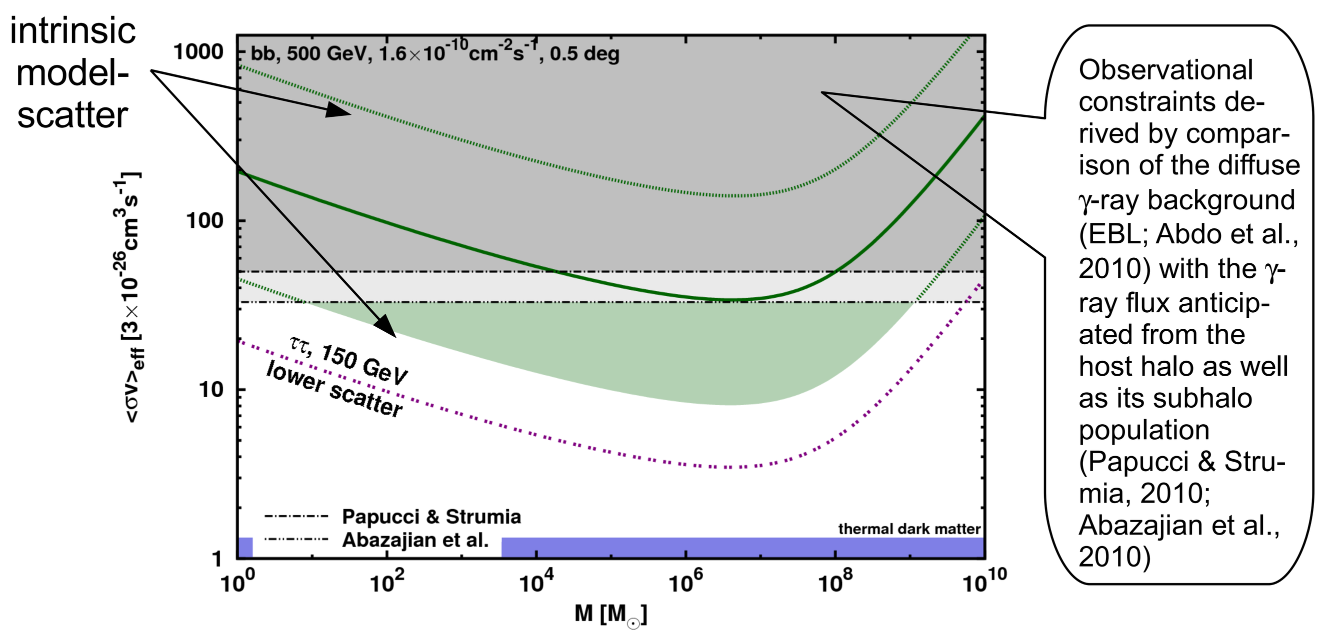
Aim: derive effective cross-section $\langle \sigma v \rangle_{\rm eff}$ required to explain a high-energy γ-ray source (at detection level of *Fermi*-LAT) by DM subhalo:



LAT-detectable subhalos (1 yr):

- flux peaks between 10 and 100 GeV
- moderately extended (about 0.5 deg [68% c.l.])
- at high Galactic latitudes *b*

⇒ **1yr sensitivity:** $\phi \approx 10^{-10}\,{\rm cm^{-2}\,s^{-1}}$

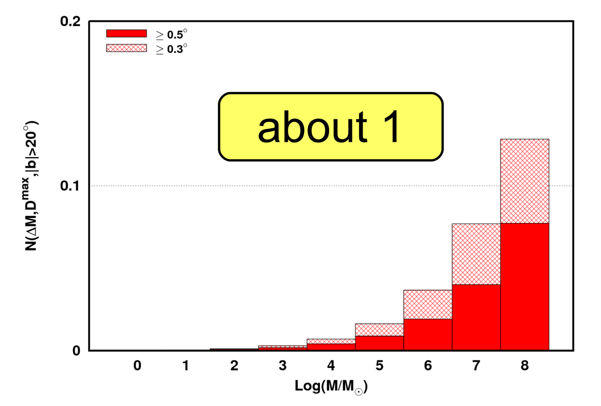


favored: $M = 10^6 - 10^8\,M_\odot$, $D = 1 - 10$ kpc

required enhancement:
- **moderate: 3 to 30**
- lower for cuspier profile (factor 1.5)
- explainable by sub-substructure and particle physics

to satisfy observational constraints: subhalo candidates in 1FGL should not be brighter than ~2×10^{-10} $\mathrm{cm^{-2}\,s^{-1}}$

number:



Search for subhalo candidates in the 1FGL

1FGL catalog: 11 months data set, 1451 sources, 100 MeV – 100 GeV, 671 sources unassociated

requirements (cuts):
- ➔ dark (unassociated)
- ➔ "extragalactic" position ($|b| \geq 20^\circ$)
- ➔ steady in flux (*var* < 23)
- ➔ detection in 10 – 100 GeV band

⇒ 12 unassociated high-energy sources pass cuts
⇒ most promising object (faintest, index $\Gamma \approx 1.7(4)$):
1FGL J0030.7+0724
→ no conclusive counterparts in radio, optical, X-ray

24 months data & *Swift*-XRT observations of 1FGL J0030.7+0724

- 6 photons between 10 – 100 GeV
- $\phi_{10-100\,{\rm GeV}} \geq 5 \times 10^{-11}\,{\rm cm^{-2}s^{-1}}$
- pos. uncertainty contour (95% c.l.)
- extent ≤ 0.3 deg (95% c.l.)
- p(steady flux) ≈ 0.5 (KS test)
- follow-up *Swift*-XRT observations, exposure 10.1 ks

⇒ discovery of 7 X-ray sources

⇒ possible association:
radio: NVSS source (12 mJy)
optical: SDSS source (r=17[m])
X-ray: SWIFT source (*)

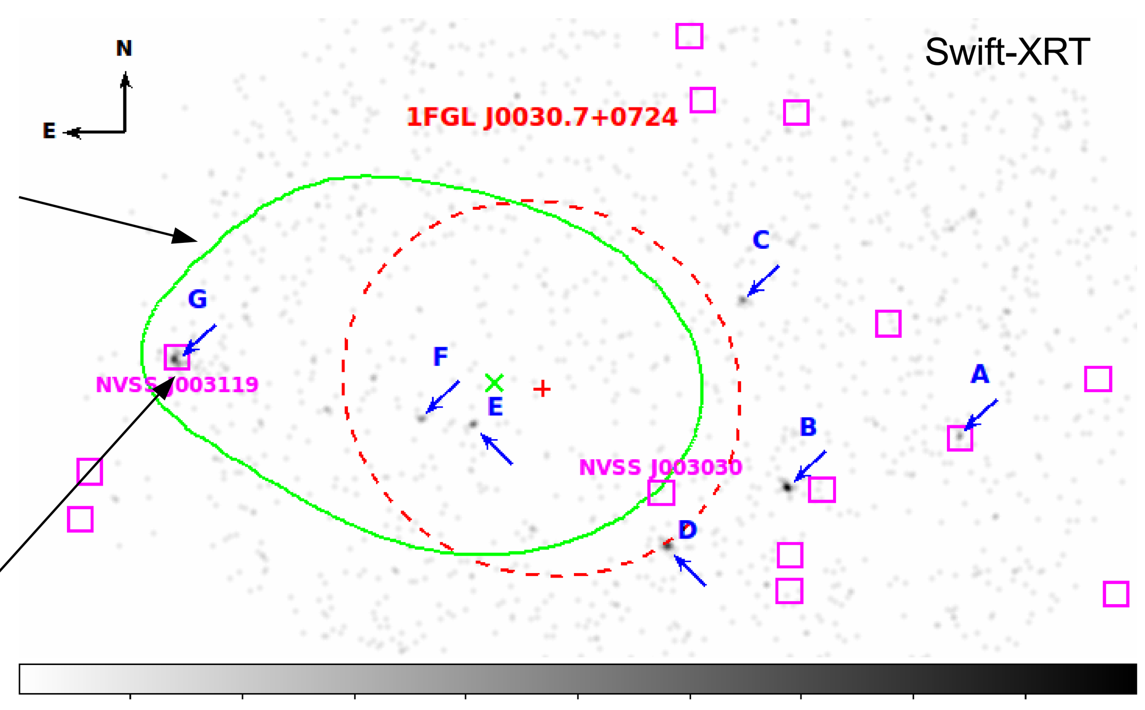


Fig.: 28' x 16'. 11 months data (red), 24 months data (green). Radio sources (NVSS) are indicated by magenta boxes. Blue arrows indicate discovered X-ray sources (*Swift*-XRT, 10.1 ks). ⇒ Possible associations of 1FGL J0030.7+0724 in radio (NVSS J003119+072456) and X-ray (SWIFT J003119.8+072454)
(*) $\nu f_\nu (0.2 - 2\,{\rm keV}) \approx 2 \times 10^{-13}\,{\rm erg\,cm^{-2}\,s^{-1}}$

Possible origins of 1FGL J0030.7+0724

(a) extreme (HE peaked) BL Lac
- ➔ supported by (uncertain) associations
- ➔ astrophysically most plausible

(b) DM subhalo
- ➔ required enhancement: ≥ 3 (7) for $\tau^+\tau^-$ (bb) channel
- ➔ consistent picture

crucial: variability

VHE follow-up:

- about 0.7% Crab for E>50 GeV
- detectable in < 50 hours with MAGIC, H.E.S.S.-II, and CTA
- ➔ go for MAGIC and H.E.S.S. in summer 2011!

Reference
Zechlin et al., 2011, in prep.

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