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Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676

DM subhalos: The observational challenge

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INTERNATIONAL CONFERENCE

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IDENTIFICATION OF DARK MATTER

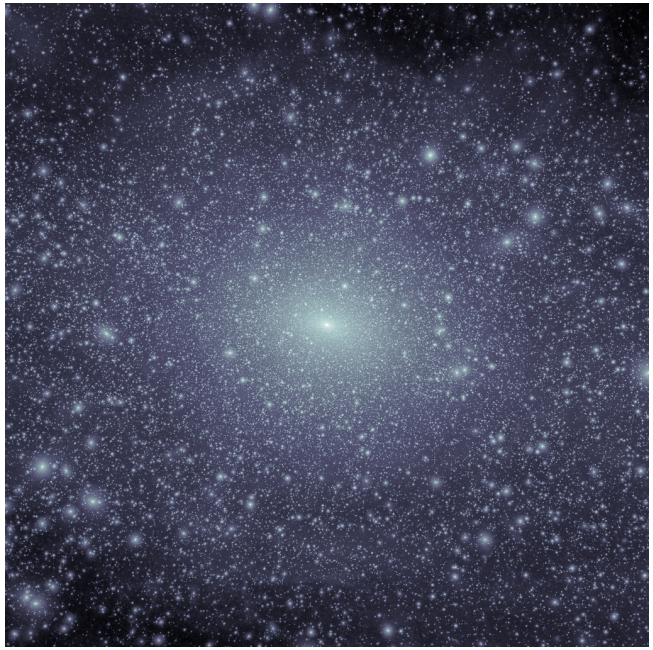
CHICAGO JULY 23-27

IDM 2012

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"

Via Lactea II simulation



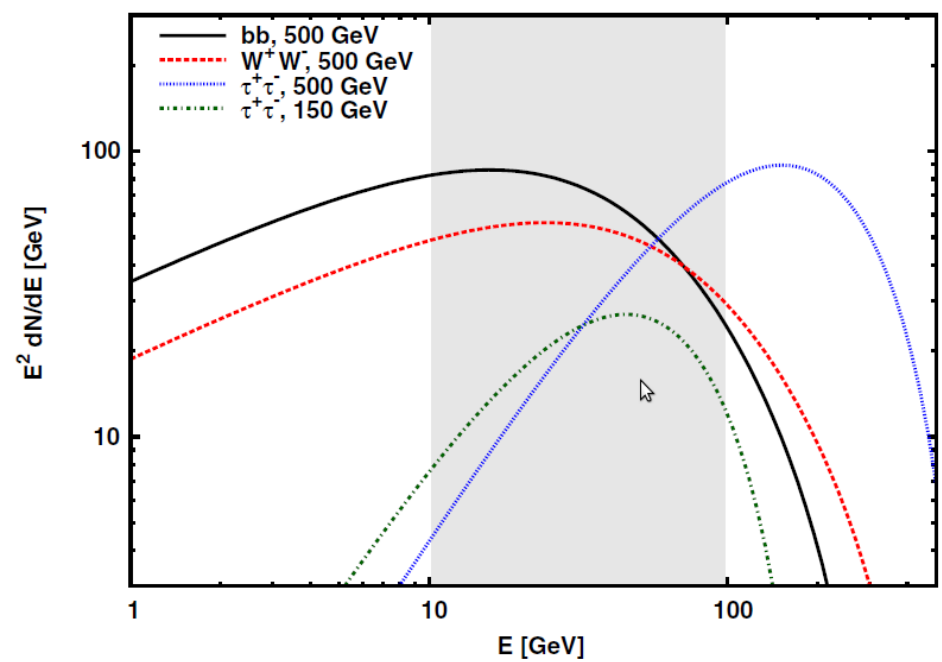
Refs.: Aquarius simulation: Springel et al., '08, Via Lactea II: Diemand et al., '08

Assumption: WIMP dark matter

e.g., Bertone '10

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

DM subhalo →



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

Gamma-ray instruments

http://fermi.gsfc.nasa.gov/ssc/

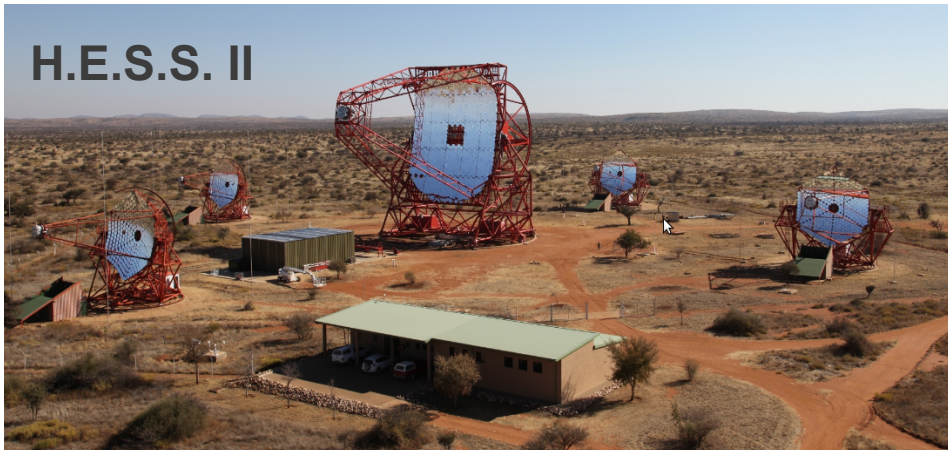


Image credit: C. Medina

Fermi-LAT:

→ since Aug. 2008
→ pair production strip tracker + calorimeter
→ 20 MeV – 300 GeV
→ eff. area ~0.8 m^2
→ FoV: O(1) sr
→ energy resolution: 10%

IACTs:

→ Imaging Air Cherenkov Telescopes
→ Cherenkov light from air showers
→ ~50 GeV – 100 TeV
→ eff. area ~10^5 m^2
→ FoV: O(10^{-2}) sr
→ energy resolution: 15%

planned: CTA

Expectations for Fermi-LAT

- **photon rate from DM annihilation:**

$$\mathcal{L} = \frac{\langle \sigma v \rangle_{\rm eff} N_\gamma}{2 m_\chi^2} \int {\rm d}V \rho^2(r), \quad \int {\rm d}V \rho^2(r) \propto M c_{\rm vir}^3$$

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

Bullock et al., '01,
Pieri et al., '09

- **method: derive effective cross section $\langle \sigma v \rangle_{\rm eff}$ needed to explain a high-energy gamma-ray source (flux ϕ, extent θ_{68}) with DM subhalo**
- **compare $\langle \sigma v \rangle_{\rm eff}$ with observational constraints**

Gamma-ray properties of subhalos

- **subhalos detectable with Fermi-LAT:**
  - very faint flux (at detection level)
  - detection above 10 GeV
  - moderately extended, *~0.5°*
  - temporally constant flux
  - no astrophysical association

HSZ, Fernandes, Elsaesser, Horns, A&A 538, A93 (2012)

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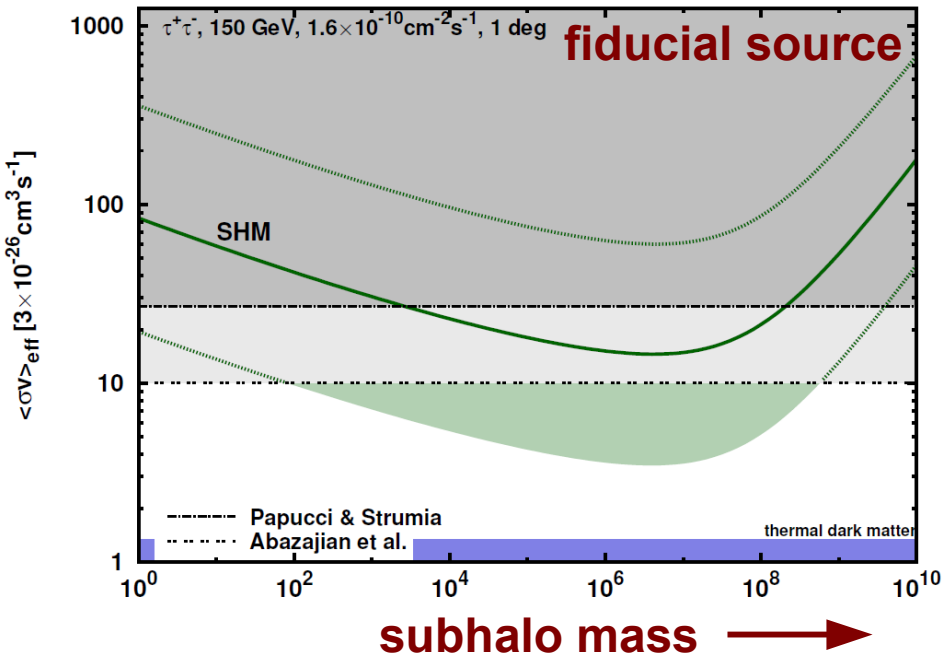


- distance range: 1 – 10 kpc
- O(1) sources in 1 or 2-year data!

HSZ, Fernandes, Elsaesser, Horns, A&A 538, A93 (2012)

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 ($\Gamma<2$)

- **results:**

1FGL:

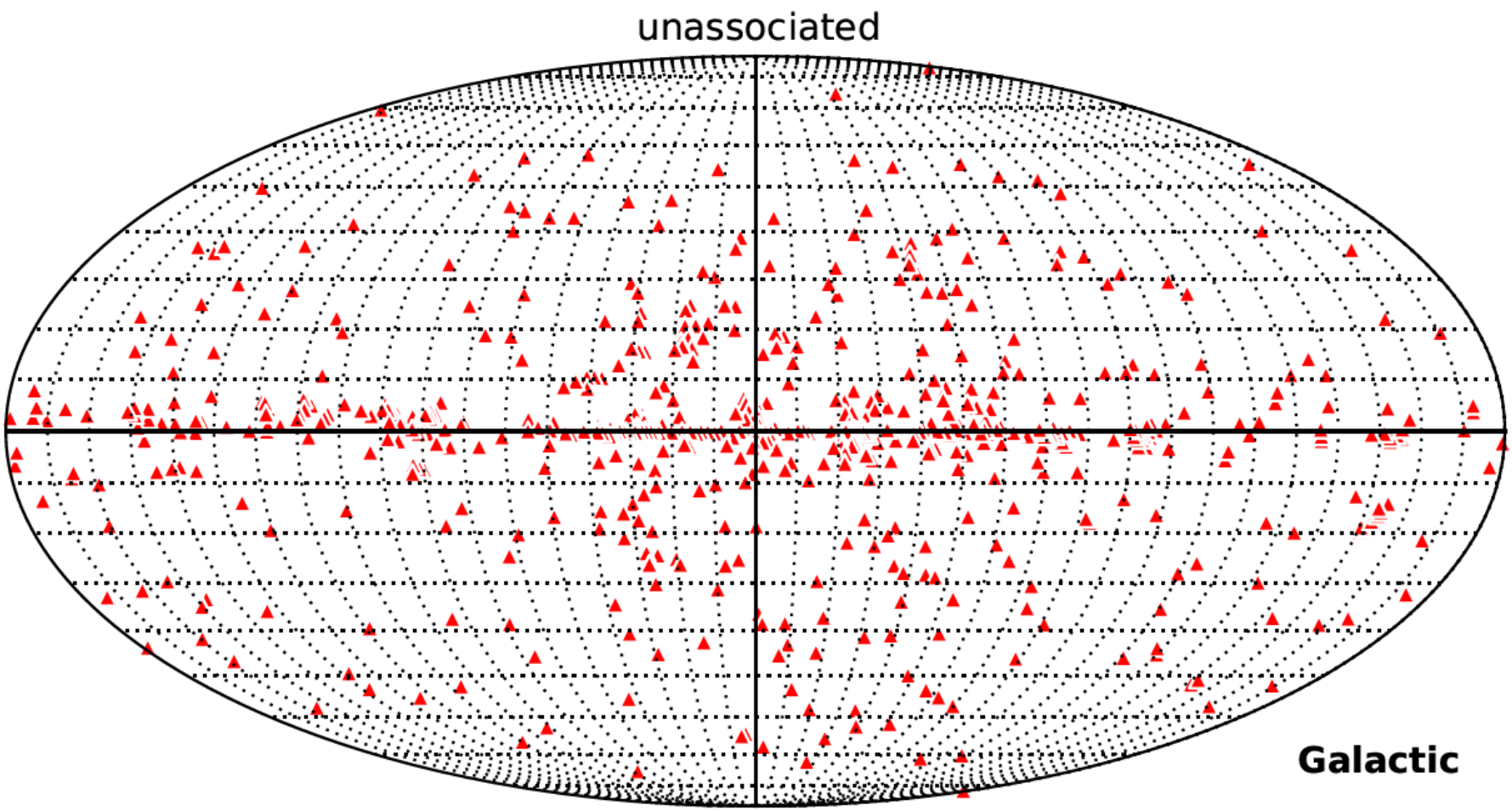
- 12 sources pass cuts

2FGL:

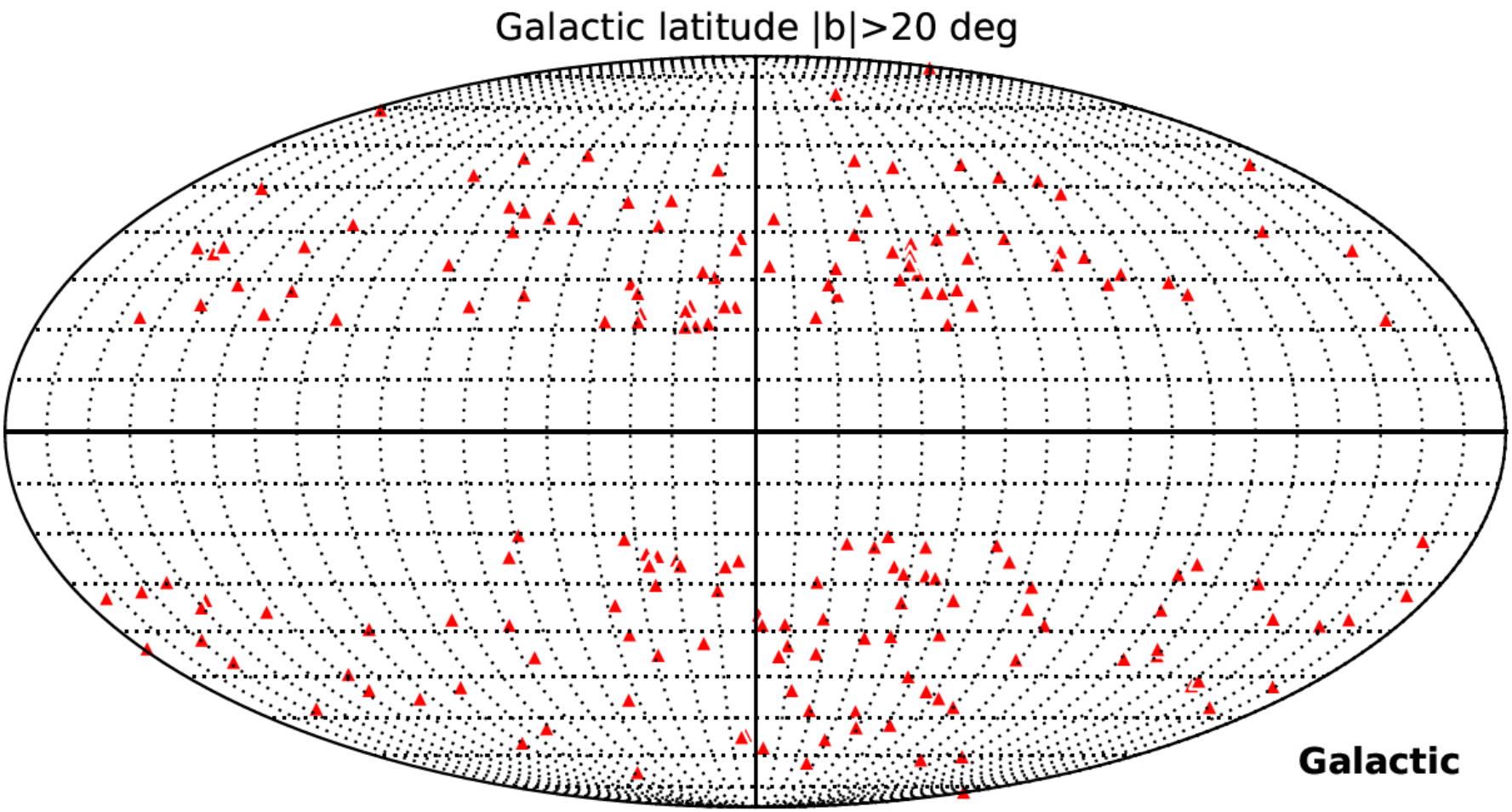
- 13 sources pass cuts

HSZ, Fernandes, Elsaesser, Horns, A&A 538, A93 (2012)
HSZ, D. Horns, 2012, to be submitted soon

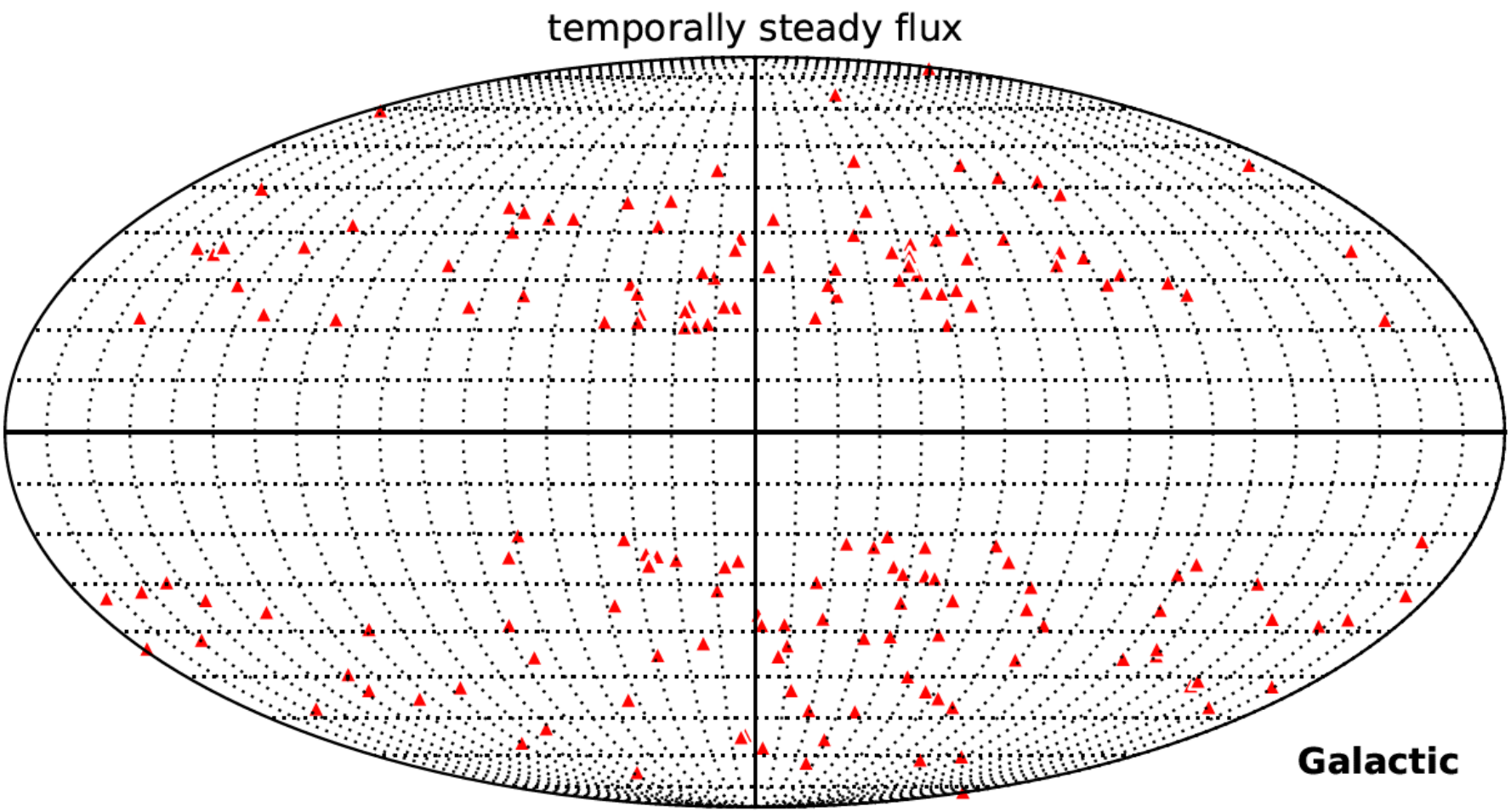
Unassociated 2FGL sources



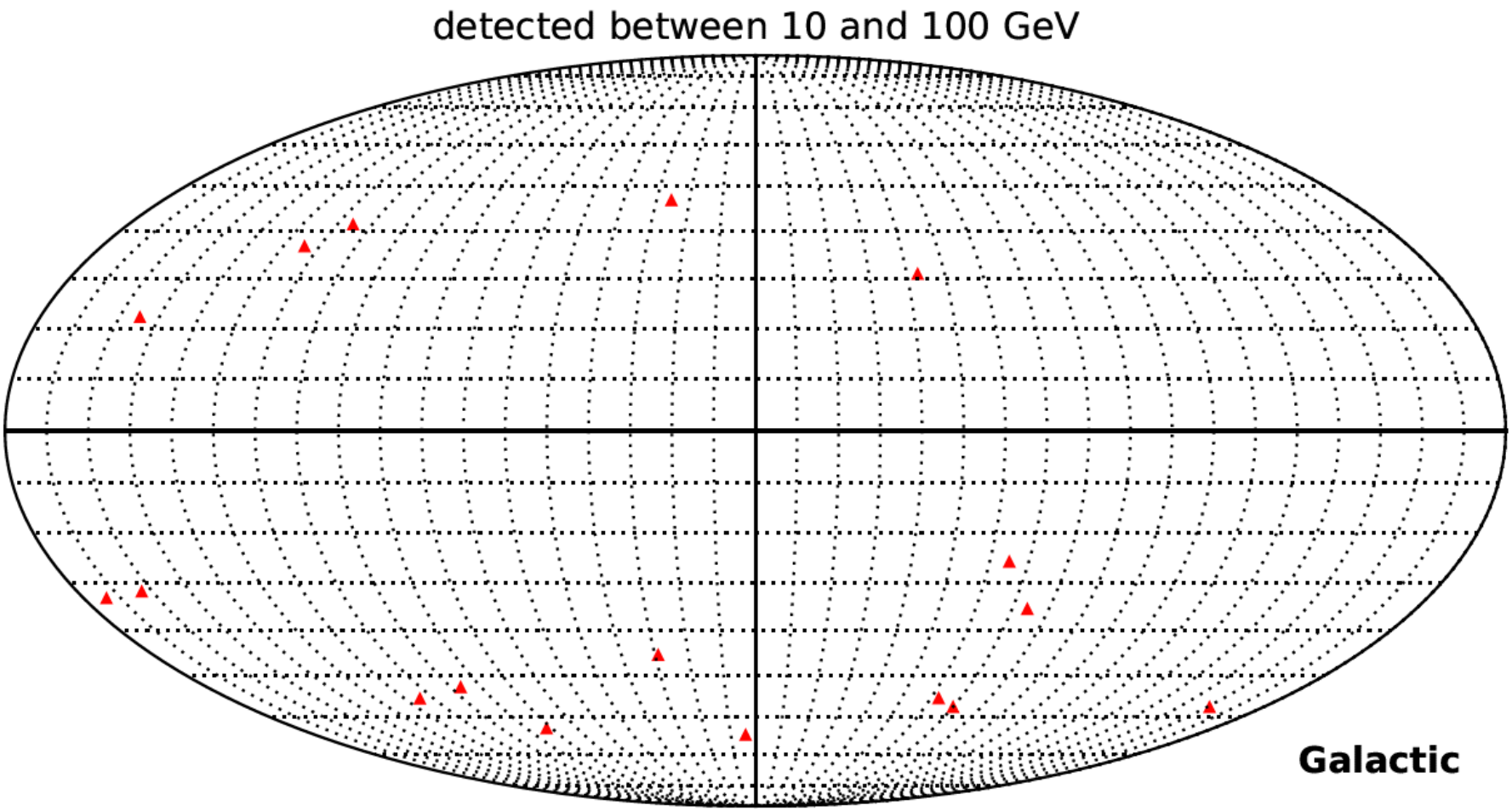
Galactic latitude |b|>20 deg



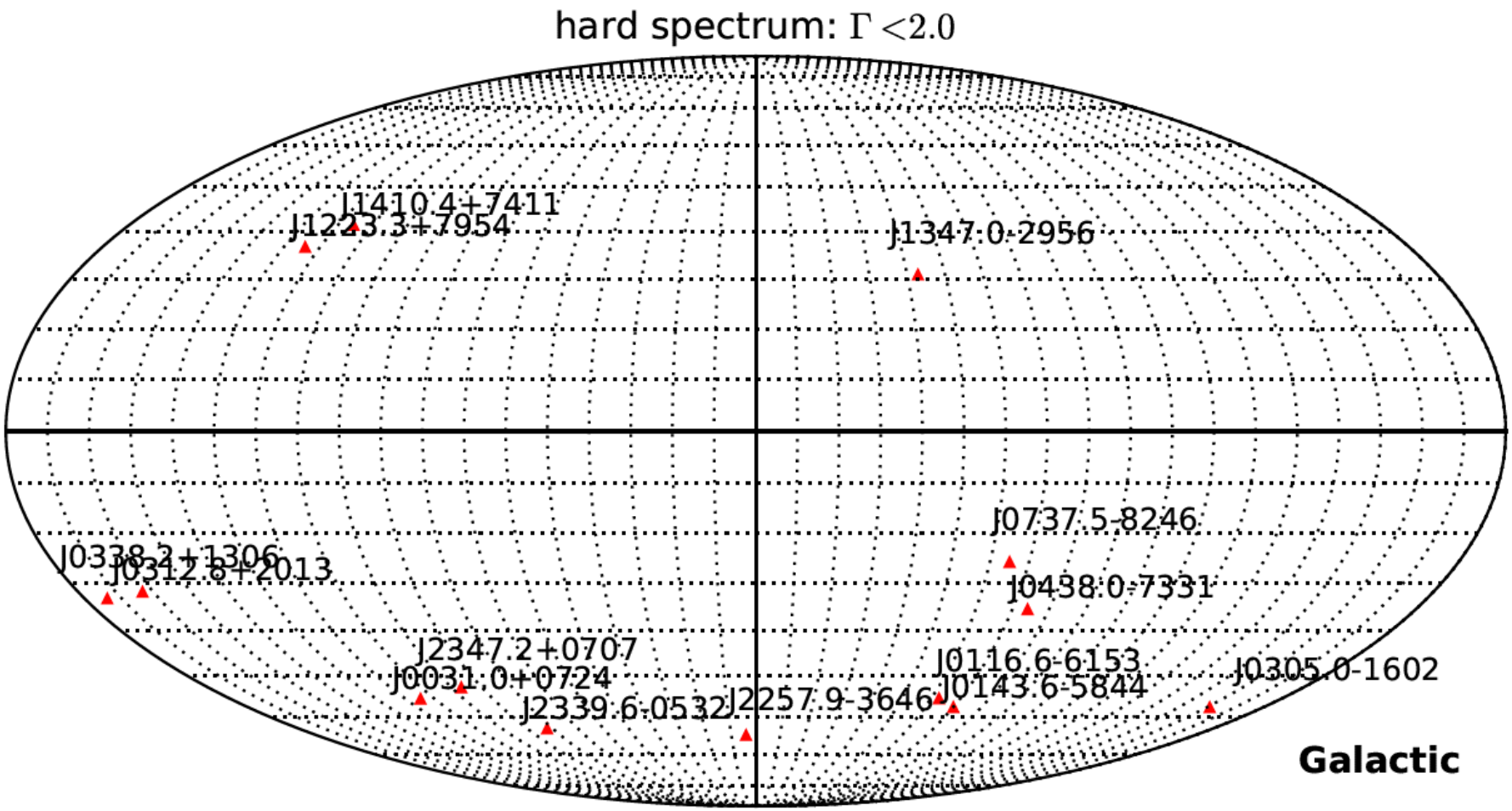
Temporally steady



Detected above 10 GeV



Hard spectrum, Γ<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

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- **for 2FGL candidates:**
  - test for a spectral cutoff:

$$\mathrm{TS}_{\mathrm{exp}} = -2 \ln \left(\frac{\mathcal{L}(H_{\mathrm{pl}})}{\mathcal{L}(H_{\mathrm{exp}})} \right)$$

  - distribution of $\mathrm{TS}_{\mathrm{exp}}$: MC simulations
  - 24-month/42-month data used

HSZ, D. Horns, 2012, to be submitted soon

Results

- **no source candidate favored by all imposed criteria**

Results

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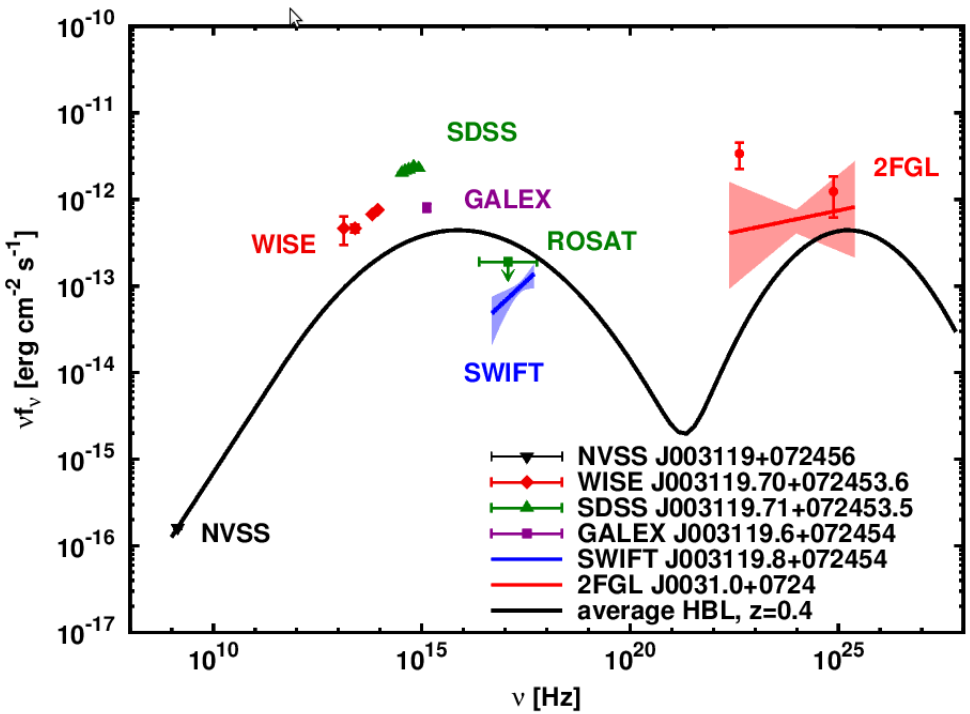
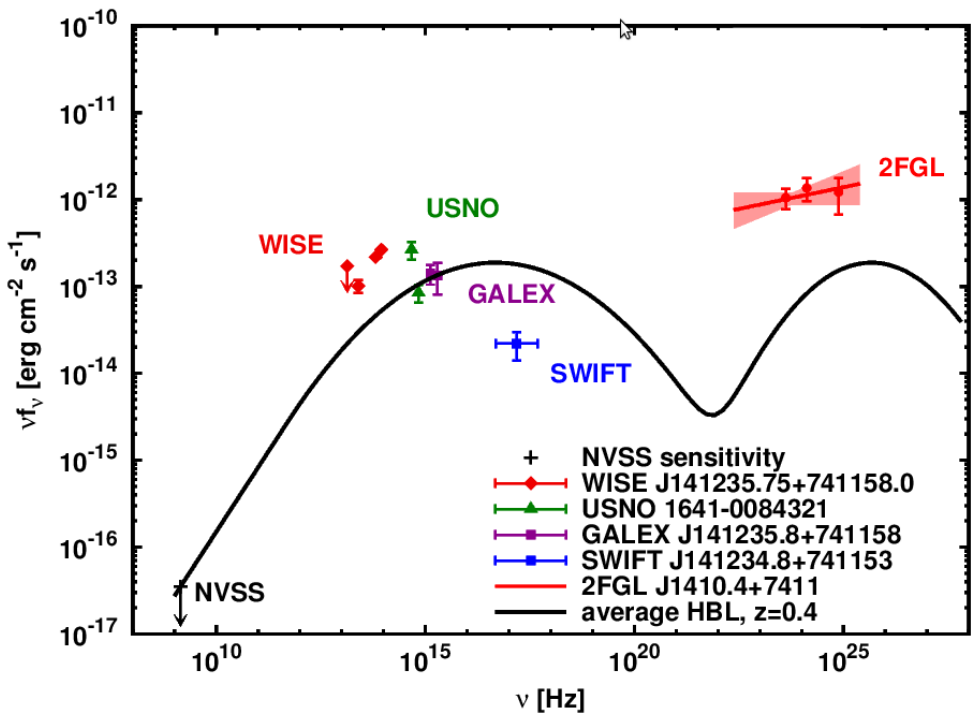
- **except for one, none can be firmly excluded**

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∼0.4

What do we actually see?

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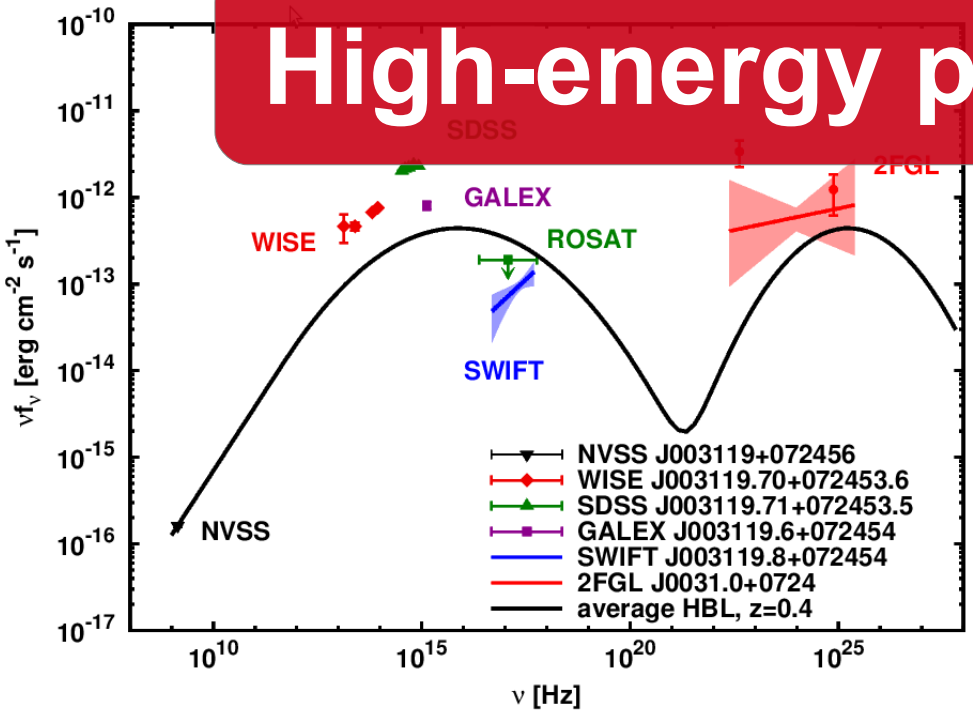
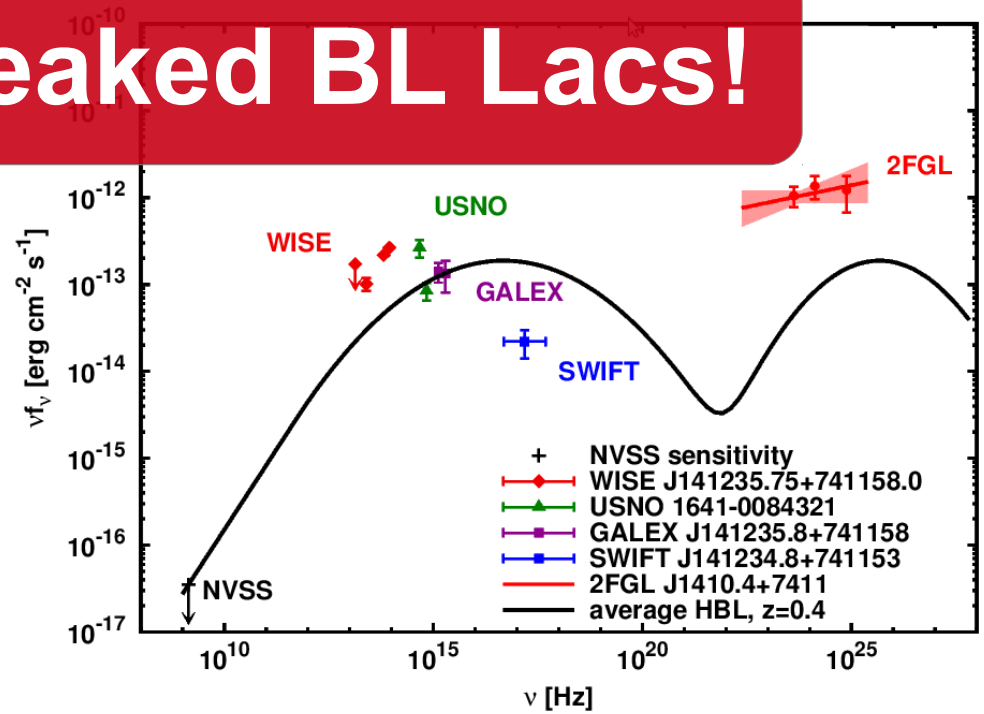
High-energy peaked BL Lacs!





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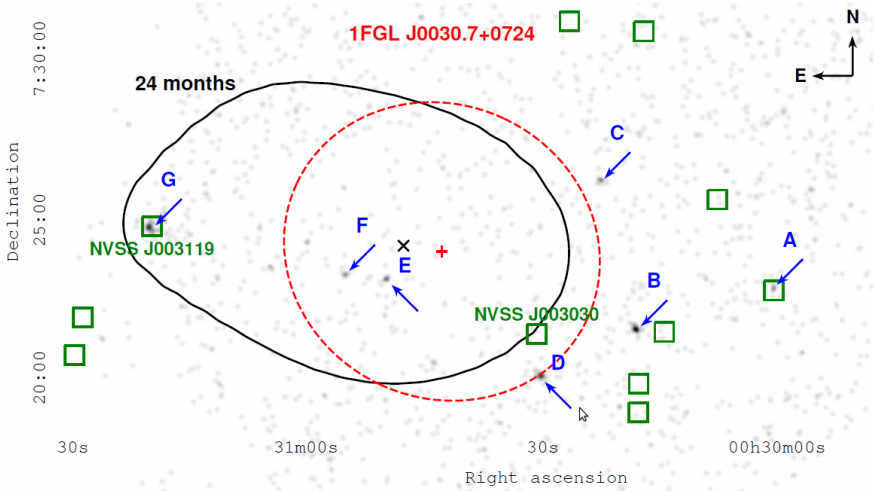
Issues

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]

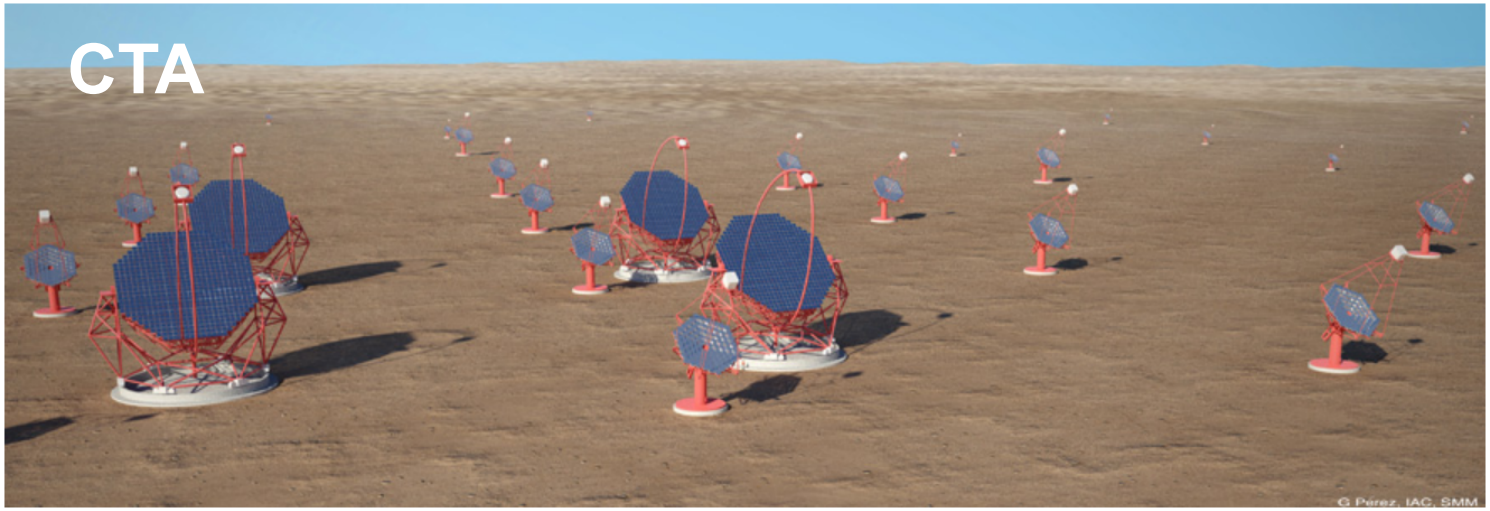


- **rareness**
  - too few objects expected for population studies

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 variablility, hard spectrum

(2) analyse for required γ-ray properties

- ✓ check spectrum, variability, angular extent; extract position

(3) multi-wavelength association

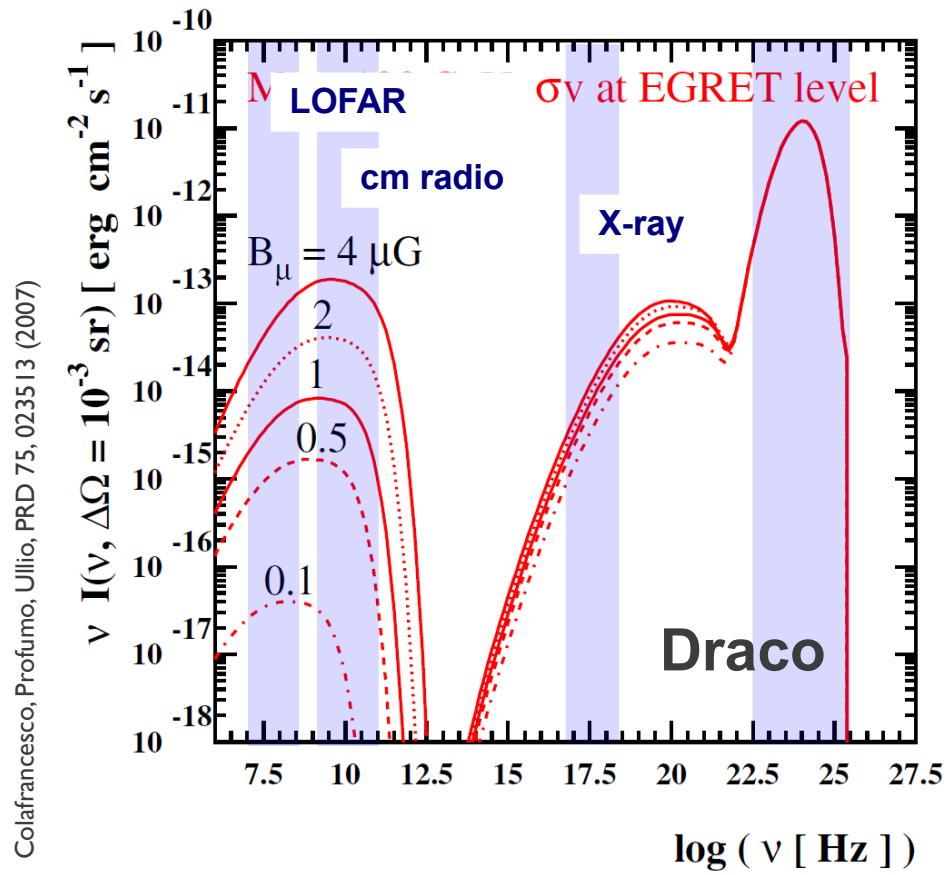
(4) radio/X-ray follow-up observations

(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, θ(radio) >> θ(gamma)
  - in principle, tracer to distinguish DM driven from astrophysical sources

- subhalos may not be completely dark!



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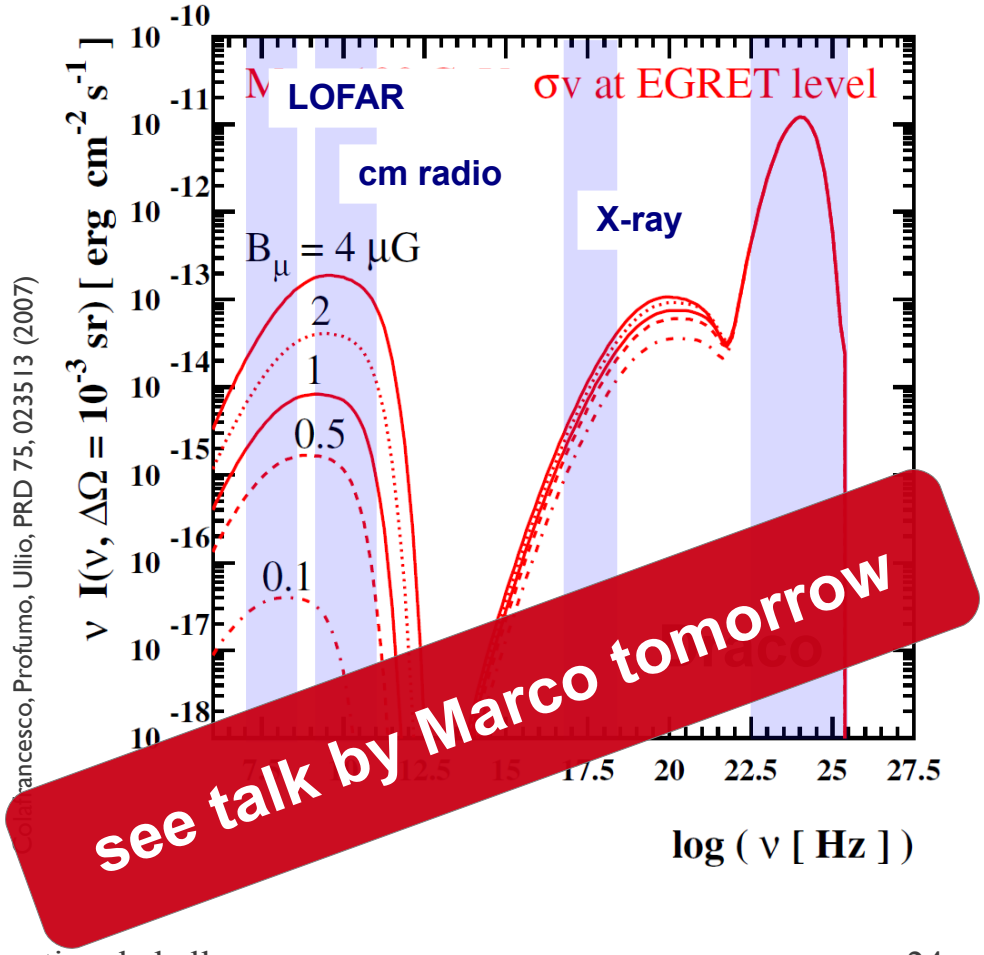

Cirelli, Panci, Sala, Strumia, Cuoco, Donato, Fornengo, Lattanzi, Salati, Serpico, Taoso, Zaharijas, Zandanel, Zechlin, Ullio, Profumo, Ullio, PRD 75, 023513 (2007)

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 positonal and spectral accuracy**

References:
H.-S. Zechlin et al., 2012, A&A 538, A93, arXiv:1111.3514
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Thanks for your attention!

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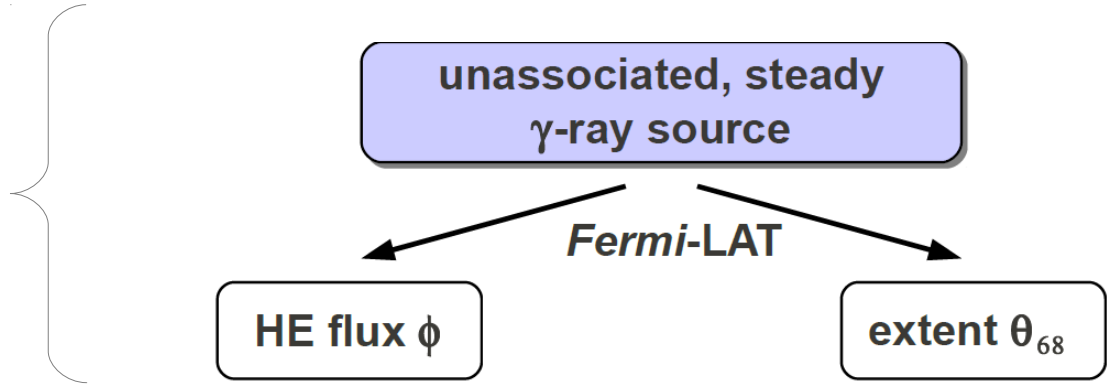
Backup

Backup slides...

Expectations for Fermi-LAT II

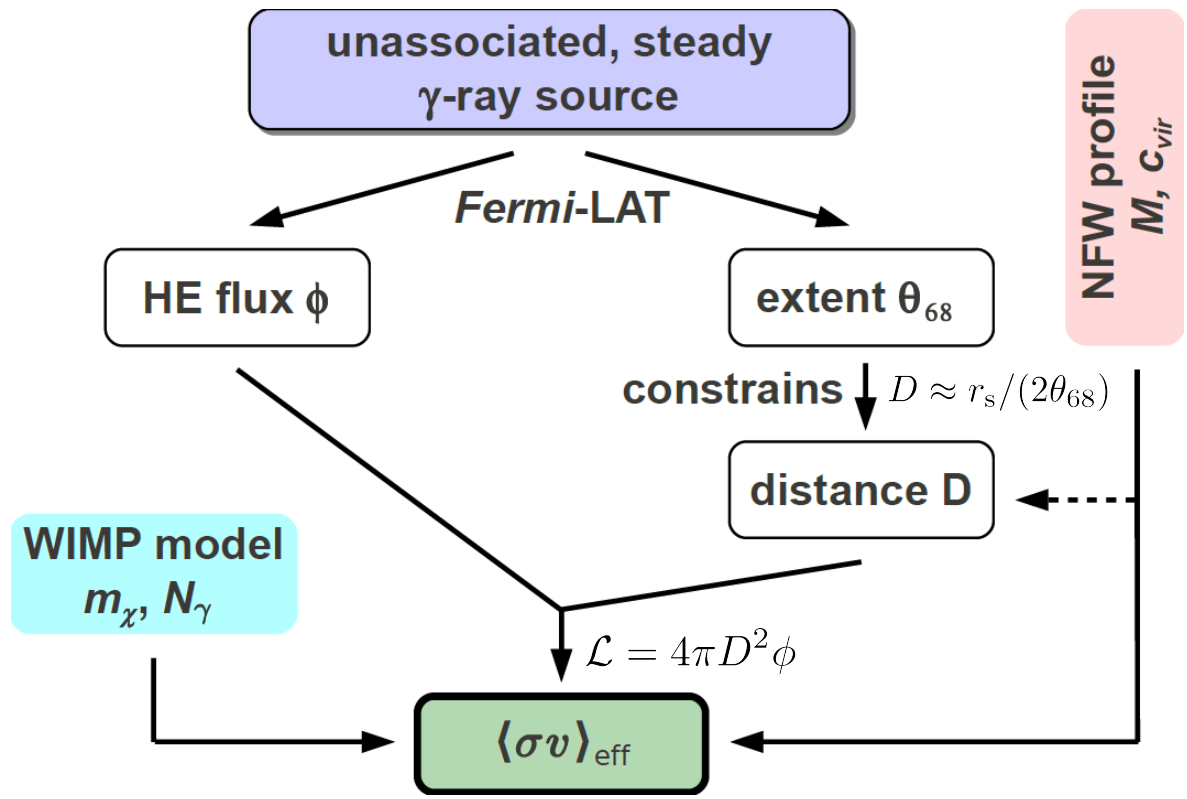
observational properties



Expectations for Fermi-LAT II

observational properties

theoretical modeling



The gamma-ray sky