Detecting the high energy Fermi sources with air shower arrays: the case for LHAASO

new entry into the arena

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Outlook

Second HAWC catalog (2HWC) : 39 sources detected in 507 days of data taking

20 associated (angular distance < 0.5°) to known TeV sources (TeV cat)

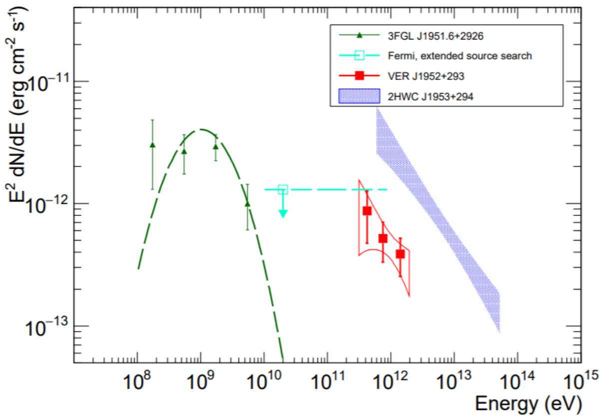
12 (+1) of them associated to sources in Fermi-LAT catalogs

19 new sources , not associated to known TeV sources

Fermi-VERITAS follow up study of 14 of these sources

without known counterparts (arXiv:1808.10423v1)

1 source confirmed by VERITAS (flux difference)



Some low energy (GeV) Fermi-LAT sources in the vicinity of HAWC sources,

but fluxes extrapolated to 1 TeV much lower than the HAWC measurements

LHAASO : appreciable sensitivity at sub-TeV energies

how many Fermi-LAT sources could be detected by LHAASO ?

We present the result of a ‘ population study’ carried out on the 2FHL sources

LHAASO

- large instrumented area up to 1 km^2
- 4 different types of detectors operated at an altitude of 4410 m a.s.l.

  3 water ponds (WCDA) to measure the energy flow of low energy showers

  array of > 5000 scintillation detectors (ED) to measure the particle number

  array of > 1000 muon detectors underneath the soil to measure the muon number

  12 wide FOV Cherenkov telescopes to estimate the shower energy

Impressive deployment of instruments designed to fulfill the physics goal in gamma-ray astronomy and cosmic ray physics over a wide energy range from sub-TeV to 10^5 TeV (more than 5 energy decades !)

LHAASO will monitor the Northern Sky with increased sensitivity wrt HAWC

WCDA will observe the sub-TeV energy range with good sensitivity down to about 300 GeV

A look at the Fermi gamma-ray sources

The Fermi-LAT catalogs

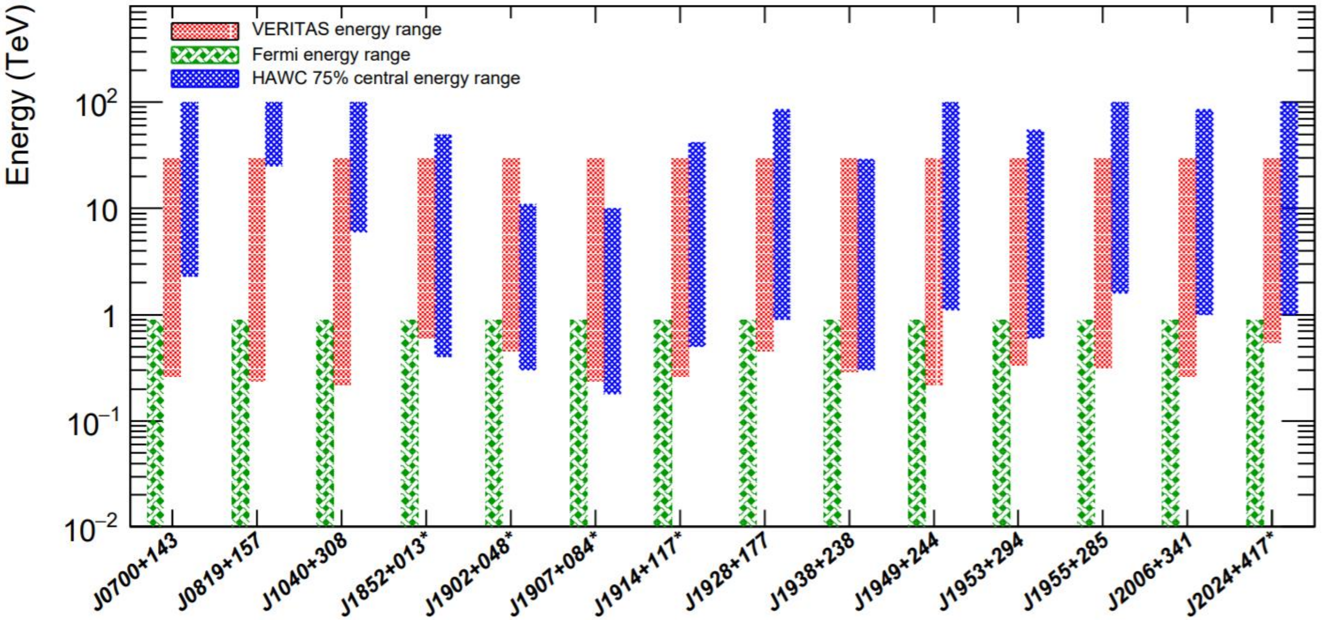
Acronym	Data/IRF/Diffuse model	Energy range/Duration	Sources	Analysis/Reference
1FGL	P6_V3_DIFFUSE	0.1 – 100 GeV	1451 point	Unbinned, F/B
	gll_iem_v02	11 months		Abdo et al. (2010a)
2FGL	P7SOURCE_V6	0.1 – 100 GeV	1873 point	Binned, F/B
	gal_2yearp7v6_v0	2 years		Nolan et al. (2012)
3FGL	P7REP_SOURCE_V15	0.1 – 300 GeV	3033 point	Binned, F/B
	gll_iem_v06	4 years		Acero et al. (2015)
FGES	P8R2_SOURCE_V6	10 GeV – 2 TeV	46 extended	Binned, PSF, $\|b\| < 7°$
	gll_iem_v06	6 years		Ackermann et al. (2017)
3FHL	P8R2_SOURCE_V6	10 GeV – 2 TeV	1556 point	Unbinned, PSF
	gll_iem_v06	7 years		Ajello et al. (2017)
FHES	P8R2_SOURCE_V6	1 GeV – 1 TeV	24 extended	Binned, PSF, $\|b\| > 5°$
	gll_iem_v06	7.5 years		Ackermann et al. (2018)
4FGL	P8R3_SOURCE_V2	0.05 GeV – 1 TeV	5098 point	Binned, PSF
	new (§ 2.4.1)	8 years		this work

Data extend up to 2 TeV providing promising candidates for detection by ground-based detectors

The 3FHL catalog updates at low energies the 2FHL catalog of > 50 GeV sources

2FHL used for the ‘population study’

	Energy range	Peak sensitivity
Fermi-LAT	10 GeV – 2 TeV	GeV range
VERITAS	300 GeV -20 TeV	around 1 TeV
HAWC	1 TeV -100 TeV	around 7 TeV



The energy ranges of these instruments partially overlap.

In particular, extrapolation of HAWC spectra to the Fermi-LAT energy range results in large uncertainties.

Better overlap expected for LHAASO

	Energy range	Peak sensitivity
LHAASO	300 GeV →	around 2 TeV

GOAL OF THE ANALYSIS

- Starting from the Fermi survey (2FHL) we estimate the source integral flux above 300 GeV = F(300)

We build the logN-LogS distribution, where

S= F(300)

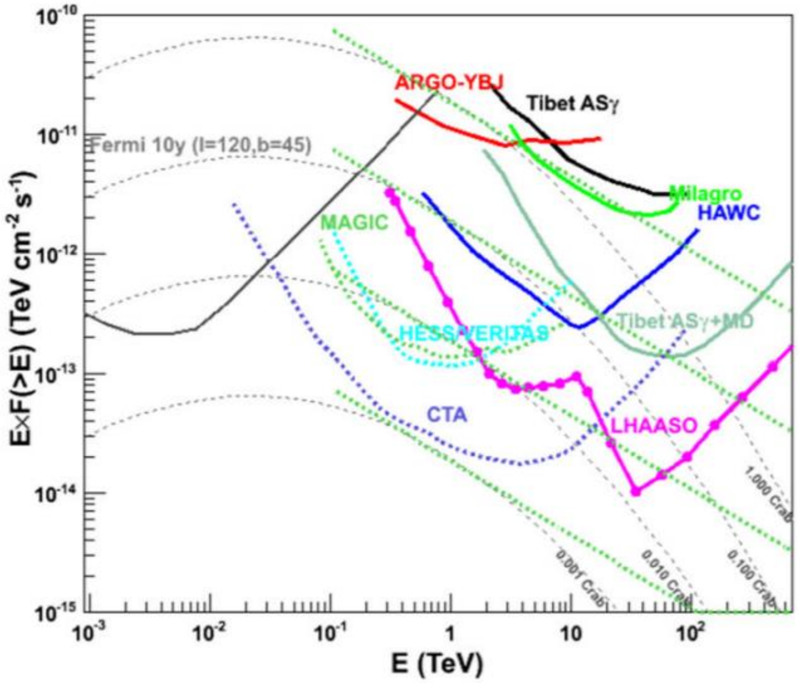
N= number of sources with integral flux > S

The LHAASO sensitivity

Integral flux sensitivity (300 GeV)

$= 10^{-11}\ cm^{-2}\ s^{-1}$

compared to the dN/dS distribution



Fermi CATALOG 2FHL

Fermi survey of VHE photon sources, E > 50 GeV

8 years data (Aug. 2008 – Apr. 2015) , Pass 8 analysis

PSF $\leq 0.1^\circ$

3-4 % C.u. sensitivity at subTeV/TeV energies (HESS 2 % C.u.)

Galactic Plane Survey: Fermi/HESS 36/69 sources

360 sources , 86 % associated with counterparts at other wavelengths

75 % AGNs , 11 % Galactic sources (274/38)

BL Lacs the largest population

181 dec. > 0

179 dec. < 0

93 in TeVCat

48 UNID not associated (6 of them in TeVCat)

Only 25 % already observed by IACTs , 282 not yet detected

ESTIMATING FLUX > 300 GeV for the 2FHL sources

Data include photon fluxes in 3 energy intervals (GeV) :

f0(50-171) , f1(171-585) , f2(585-2000)

Assumed model : power law spectrum above 171 GeV with a sharp cut-off at E_m > 2 TeV

Photon flux f0(50-171) not taken into account to avoid averaging effects on the spectral shape

Statistical uncertainty effects not evaluated (a very preliminary work !)

With these assumptions we can obtain the photon spectrum and the integral flux above 300 GeV

$$\mathbf{F(300) = K(f1,\gamma) \times 300^{-\gamma} \times \left(1 - \left(\frac{E_m/\mathrm{GeV}}{300}\right)^{-\gamma}\right)} \ \textbf{photons}\ cm^{-2}\ s^{-1}$$

γ (integral spectral index) obtained solving f1/ (f1+f2) = R (γ)

K and R functions obtained by combining the f1 and f2 fluxes

We have assumed E_m = 5000 GeV. With $E_m \rightarrow \infty$ F(300) increase < 5%

HIGH-FREQUENCY PEAKED SOURCES

Power law spectrum above 100 GeV with $\gamma > 1$ → f2 < f1

f2/f1 > 1 reasonable criterium to identify high-frequency peaked sources in 2FHL
65 sources in 2FHL with f2/f1 > 1

Our model fails to reproduce correctly the spectrum if the Compton peak is in the VHE range (HBL)

For HBL sources we use only f2(585-2000) according to formula (see also Aleksic A&A 2014)

$$j(E) = f2 \times (\gamma - 1) \times \frac{(E/TeV)^{-\gamma}}{(0.585^{(-\gamma+1)} - 2^{(-\gamma+1)})} \quad TeV^{-1}\ cm^{-2}\ s^{-1}$$

Spectral index borrowed from IACT measurements , or fixed to 2.8

15 with estimated F(300) > 10^{-13} cm^{-2} s^{-1}

8 bll , 1 snr/pwn , 1 bin , 5 UNID

Only 6 in TeVCat , large spread of f2

SOURCE COUNT DISTRIBUTION log N – log S

S = F(300)

N = source count with flux > S

79 sources with F(300) > 10^{-13} cm^{-2} s^{-1}

30 UNID

51 in TeVCat

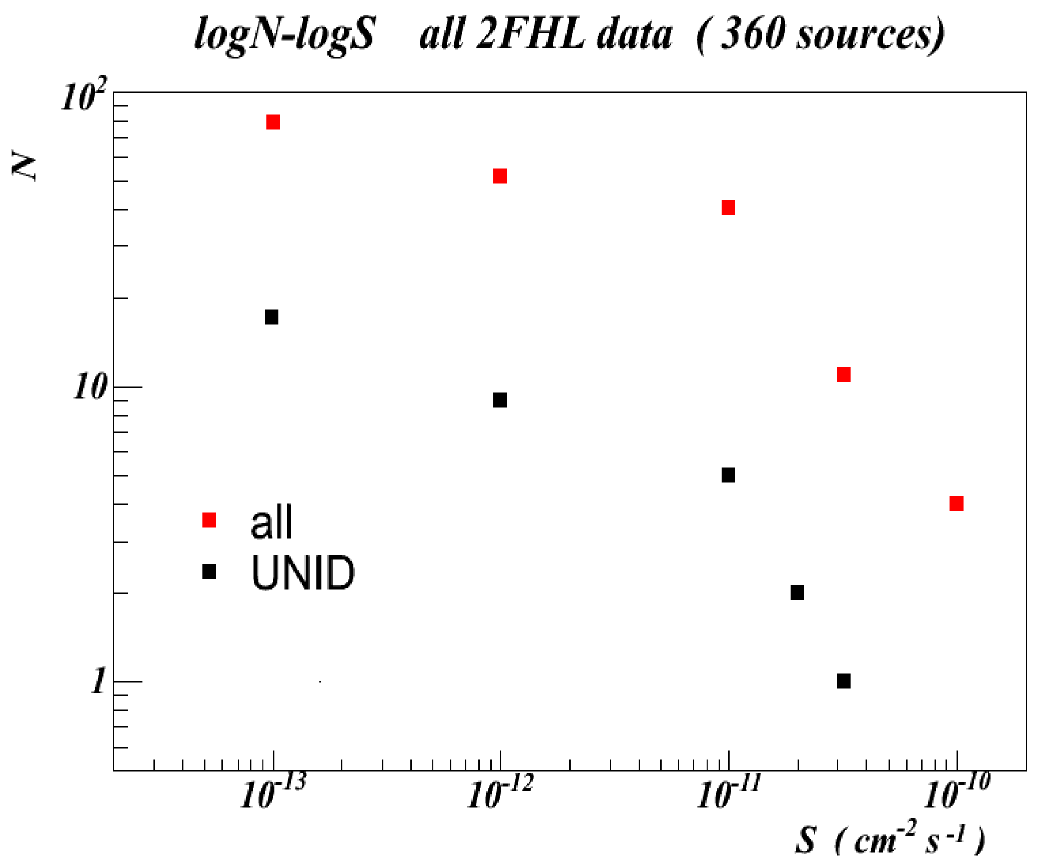
40 sources with F(300) > 10^{-11} cm^{-2} s^{-1}

5 UNID

$$N = 40 \times (S / 10^{-11})^{-\alpha}$$

α = 0.15 S< 10^{-11} cm^{-2} s^{-1}

= 1.0 S>10^{-11} cm^{-2} s^{-1}



Evident break at F(300) = 10^{-11} cm^{-2} s^{-1}, ~ 7% C.u.

Flattening related to the Fermi sensitivity (?)

REMARKS & CAVEATS

Comparing Fermi / TeVCat fluxes f2 (585–2000)

--general agreement better than 50% (Crab, Mrk421, Mrk501, CasA, W41, SgrA*, …)

--many sources with larger mismatch (factor of 2 or more) , mainly sources with extended morphology and high-frequency peaked sources

HESS J1841- 055 ancient PWN or SNR extended morphology

F(300) = $9.2\ 10^{-11}$ Fermi/model prediction fluxes in $cm^{-2}\ s^{-1}$

$1.1\ 10^{-10}$ ARGO-YBJ

$5.0\ 10^{-11}$ HESS

Check

f2(2FHL) = $4.1\ 10^{-11}$

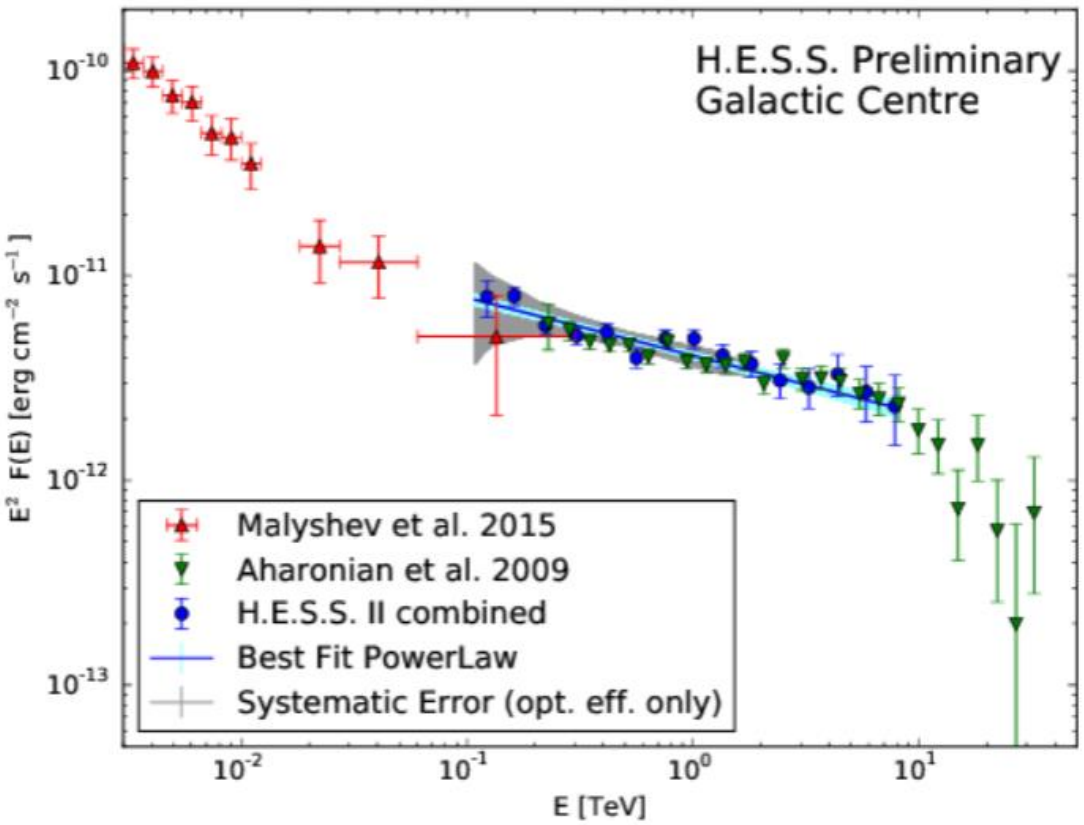
f2 (HESS) = $1.6\ 10^{-11}$

SgrA* (HESS VER J1745-2900) Galactic Center

F(300) = 9.6 10^{-12} 2FHL/model

F(300) = 9.3 10^{-12} HESS

F(300) = 9.0 10^{-12} VERITAS



Galactic Center Ridge (~ 2°)

--complex gamma ray morphology

--a wealth of structures (point and extended sources, diffuse component from CR +molecular clouds , unresolved sources , annihilating dark matter (?) ….)

A FEW EXAMPLES (1)

RX J0852 – 4622 Vela Jr Shell-type SNR about 1°

f2(2FHL) = 4.7 10^{-11}

f2 (HESS) = 2.3 10^{-11}

HESS J0835 – 455 Vela X

PWN extended morphology > 1°

Vela X

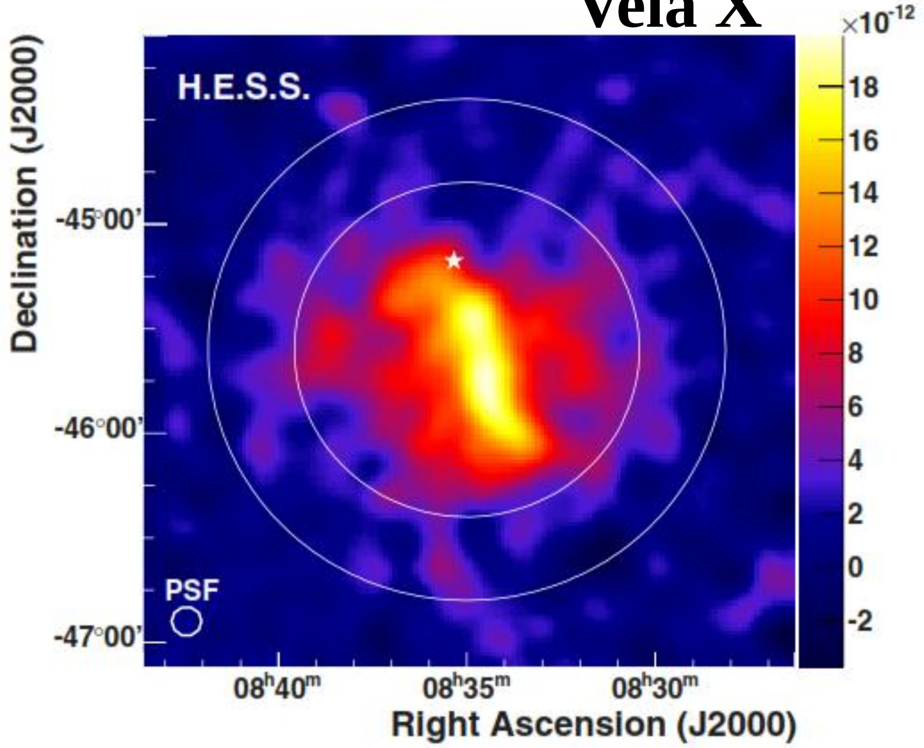


Table 3. Best fit results of the differential energy spectra extracted for the inner and the external ring test regions as well as integrating over the total Vela X extension.

Region	Γ	E_{cut} (TeV)	N_0 (10^{-12} cm^{-2} s^{-1} TeV^{-1})	$\Phi_{>1TeV}$ (10^{-12} cm^{-2} s^{-1})
Inner	$1.36 \pm 0.06_{stat} \pm 0.12_{sys}$	$13.9 \pm 1.6_{stat} \pm 2.6_{sys}$	$11.6 \pm 0.6_{stat} \pm 2.4_{sys}$	$16.0 \pm 1.3_{stat} \pm 3.3_{sys}$
Ring	$1.14 \pm 0.2_{stat} \pm 0.12_{sys}$	$9.5 \pm 2.7_{stat} \pm 1.7_{sys}$	$3.3 \pm 0.6_{stat} \pm 0.7_{sys}$	$4.9 \pm 1.4_{stat} \pm 1.1_{sys}$
Total	$1.32 \pm 0.06_{stat} \pm 0.12_{sys}$	$14.0 \pm 1.6_{stat} \pm 2.6_{sys}$	$14.6 \pm 0.8_{stat} \pm 3.0_{sys}$	$21.0 \pm 1.9_{stat} \pm 4.4_{sys}$

f2(2FHL) = 1.5 10^{-11}

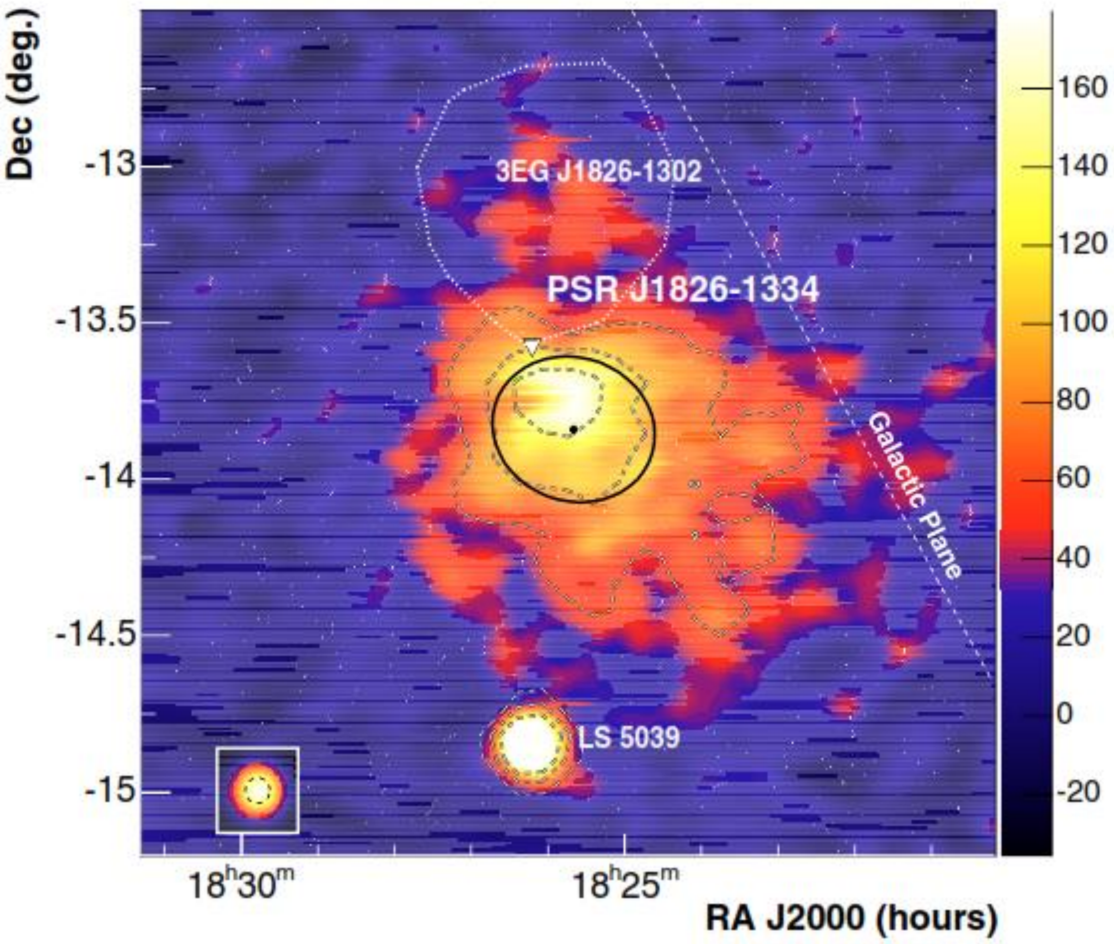
f2(HESS) = 8.1 10^{-12}

A FEW EXAMPLES (2)

HESS J1825 – 137 PWN about 1°

f2(2FHL) = 5.2 10^{-11}

f2(HESS) = 2.4 10^{-11}



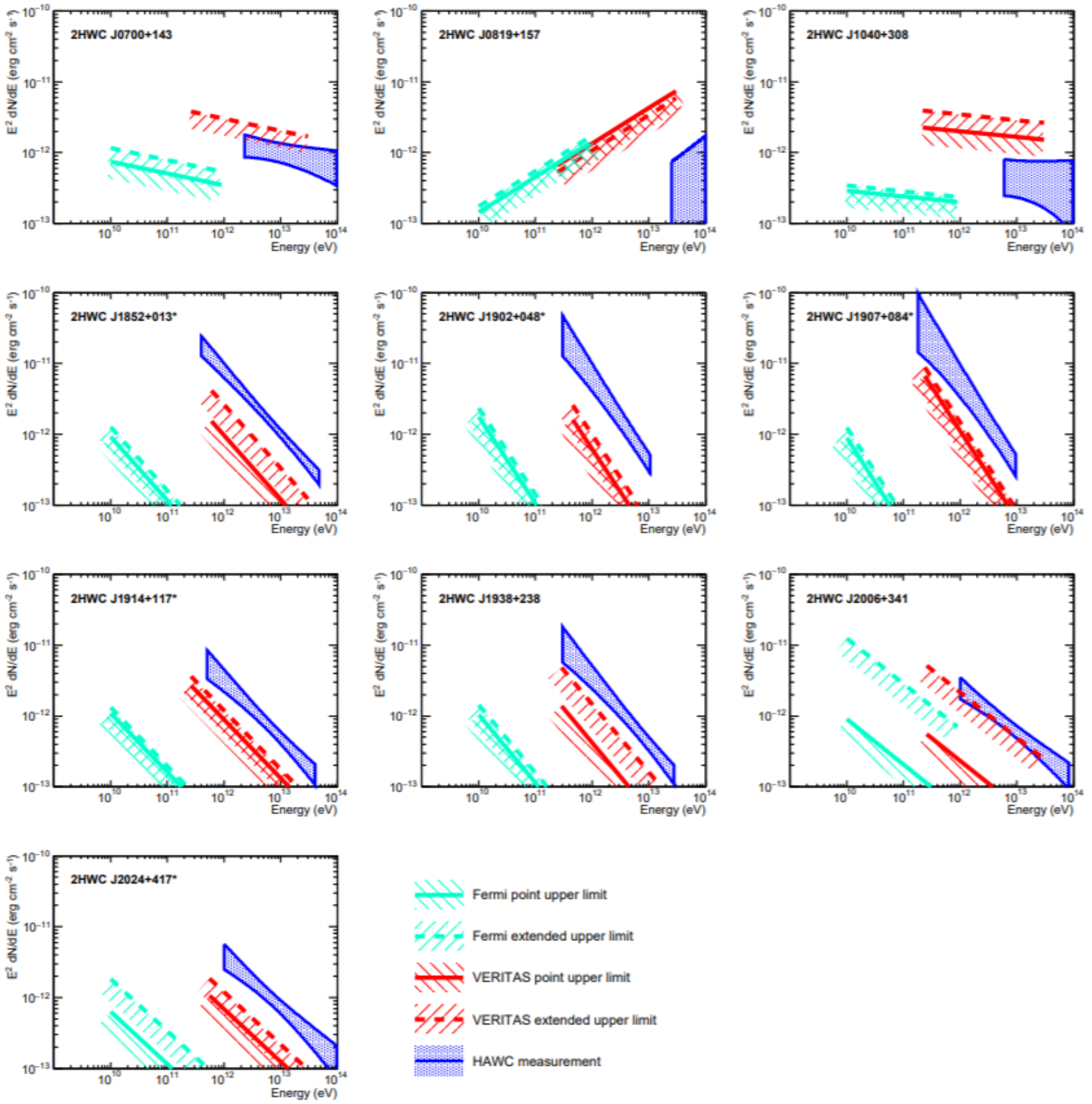


Figure 11. SEDs of undetected HAWC sources. Upper limits for *Fermi*-LAT(teal lines) and VERITAS(red lines) were calculated by using the spectral index estimated by HAWC.

COMPARING 2FHL with TeVCat

Differences up to a factor of 2 (1.5 s.d. for 30% flux uncertainty) and more

Fermi-LAT and IACT very different detectors, not surprising

f2 (2FHL) > f2(TeVCat) for many extended sources and high-frequency peaked sources

Effect likely related to different integration radius, background subtraction, variability and statistics

Some sources like HESS J1731-347 and Geminga not in 2FHL

logN-logS obtained only from 2FHL data

F(300) for 15 sources with f2 > f1 using only f2 (2FHL) [8 bll 1 pwn 1 bin 5 UNID]
spectral index from TeVCat (6 sources) or a fixed value 2.8 (9 sources)

F(300) predictions based on 2FHL used to give a picture of the sky observed by LHAASO

logN-logS for the sky observed by LHAASO (-10º<dec.<70º)

189 sources

17 UNID

53 in TeVCat

35 sources with F(300) > 10^{-13} cm^{-2} s^{-1}

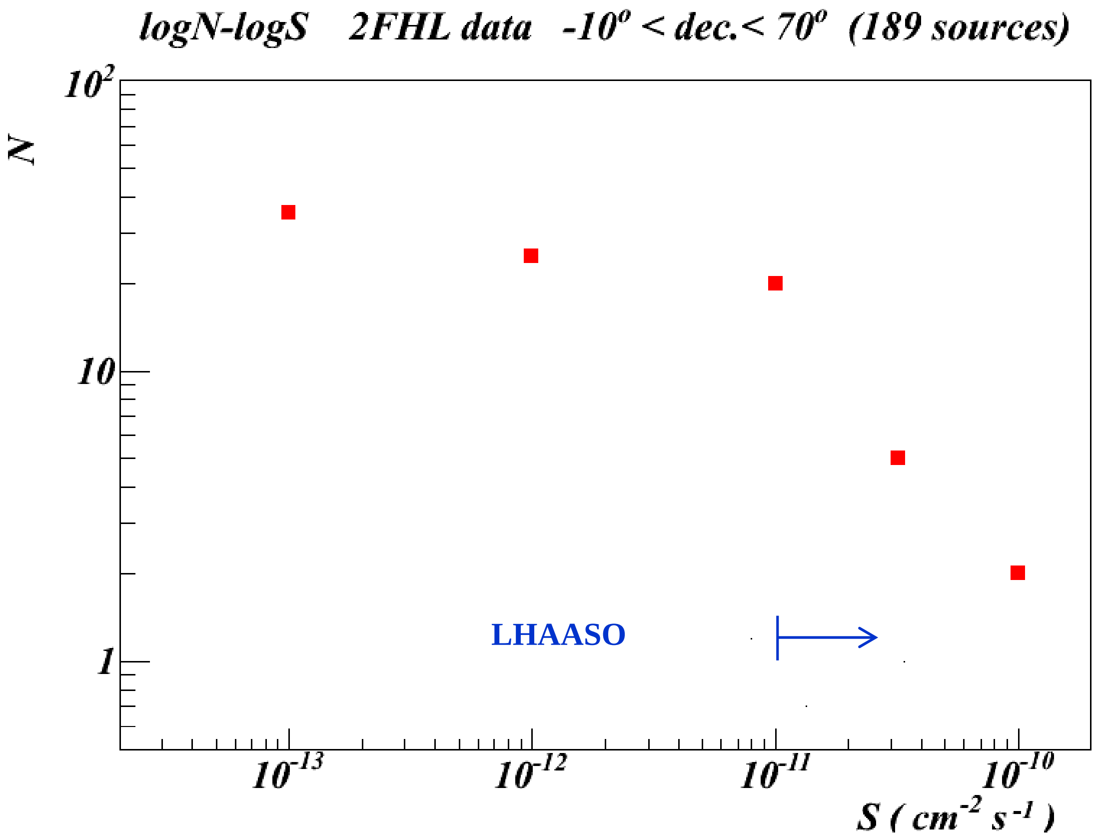
5 UNID

20 sources with F(300) > 10^{-11} cm^{-2} s^{-1}

11 of these BL Lacs (or candidates)

17 of these in TeVCat

1 UNID (2FHL J1834-0701)



$$N = 20 \times (S / 10^{-11})^{-\alpha}$$

α = 0.12 S < 10^{-11} cm^{-2} s^{-1}

= 1.0 S > 10^{-11} cm^{-2} s^{-1}

LHAASO project (5 years),

SUMMARY (1)

- A simple model developed to estimate the integral flux > 300 GeV of the high energy Fermi-LAT sources of 2FHL

- Model estimates checked by comparing 2FHL with TevCat

- Large disagreement found for many sources , general compatibility at 2 s.d. accuracy

- logN-logS source count obtained and compared to the LHAASO minimum detectable flux at 300 GeV threshold

About 20 2FHL sources candidates for LHAASO

Uncertainty of this estimate not assessed

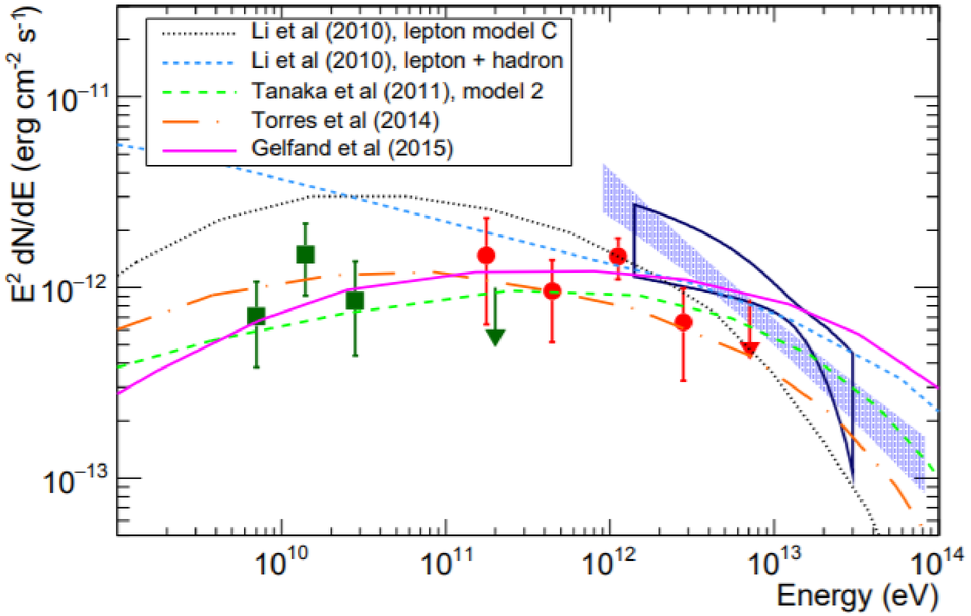
SUMMARY (2)

How to improve this estimate :

- using 3FHL (1556 point sources characterized up to 2 TeV)
- using catalogs of extended sources (FGES ,FHES)
- taking into account sensitivity versus declination
- repeating at different energy threshold (500 GeV, 1 TeV) to meet the LHAASO sensitivity curve and comparing with TeVcat

LHAASO expected to push forward the synergy between Fermi-LAT , IACTs and air shower arrays

sinergy at work



2HWC-J1930 +188
VER-1930+188
Fermi follow up